Ivan Vitev

Effective field theories in reactions with nuclei: from jets to quarkonia

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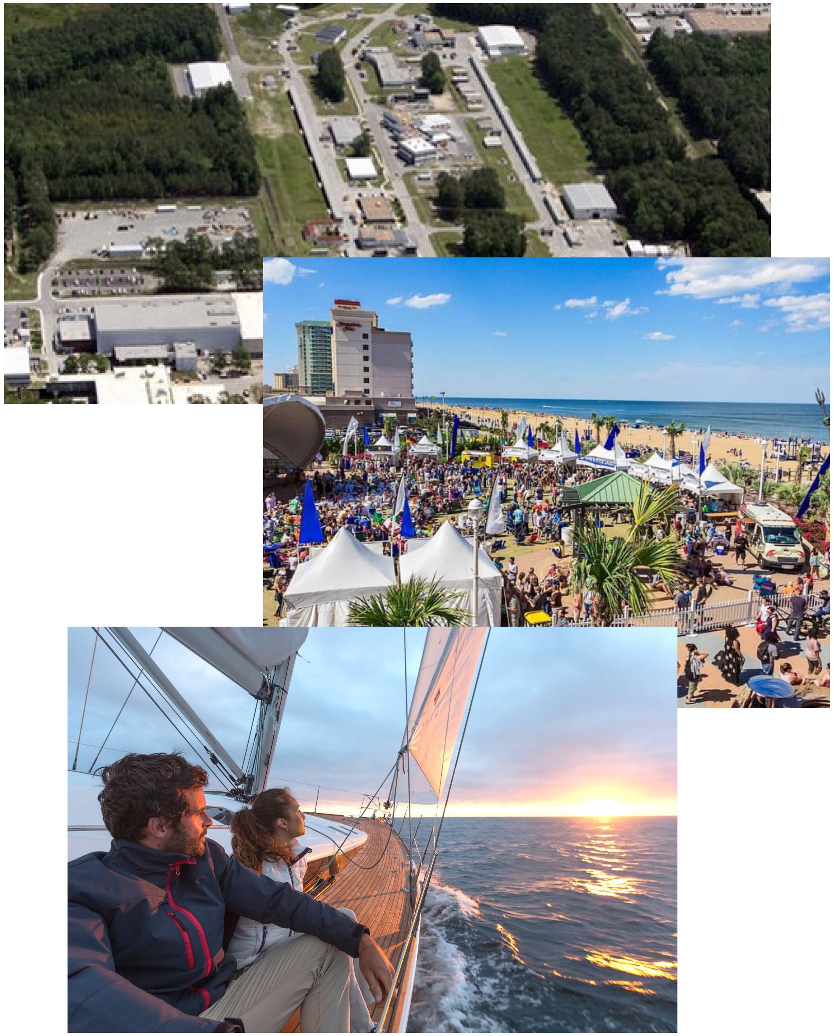
Newport News, VA

Los Alamos NATIONAL LABORATORY EST.1943

Outline of the talk

- A brief introduction to effective field theories (EFTs)
- An effective theory for jet propagation in matter - $SCET_G$. Current status and in-medium splitting functions to arbitrary order in opacity
- Application of $SCET_G$ to heavy ion phenomenology – b-jets and the jet charge
- An effective theory of qaurkonia in matter – $NRQCD_G$. Inapplicability of the energy loss approach to current measurements
- Derivation of the leading order and next to leading order $NRQCD_G$ Lagrangian using different methods
- Connection to quarkonium dissociation in matter and existing phenomenology
- Conclusions

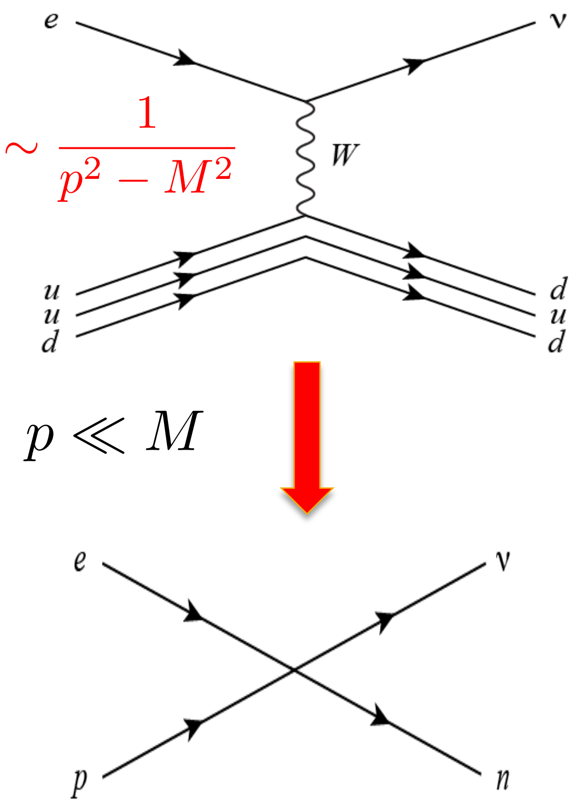


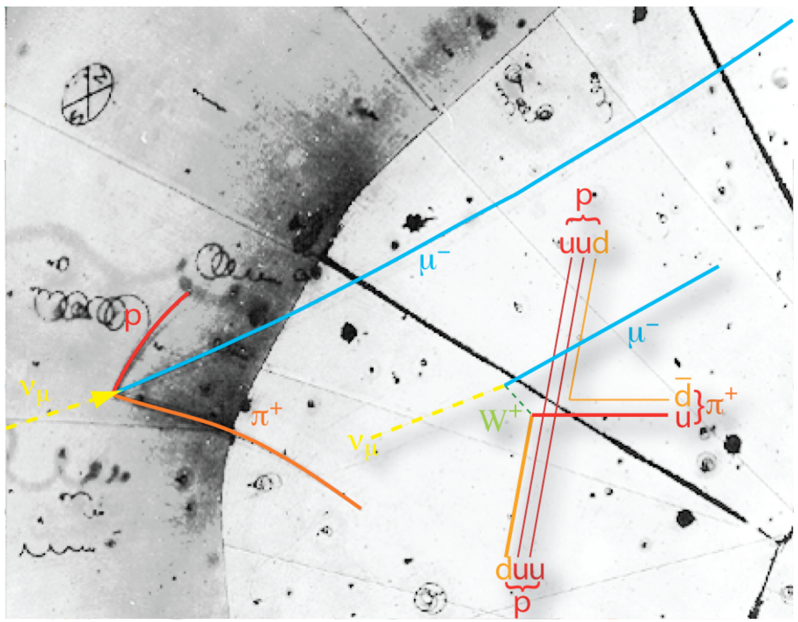
Thanks for the invitation!

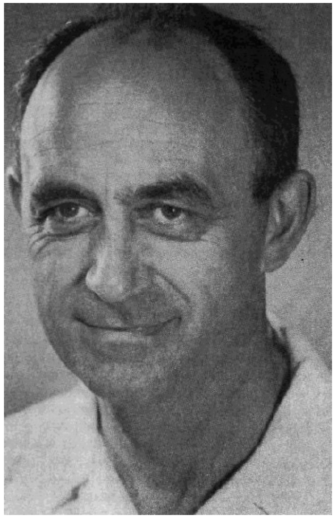
Introduction

The Fermi interaction

- The first, probably best known, effective theory is the Fermi interaction



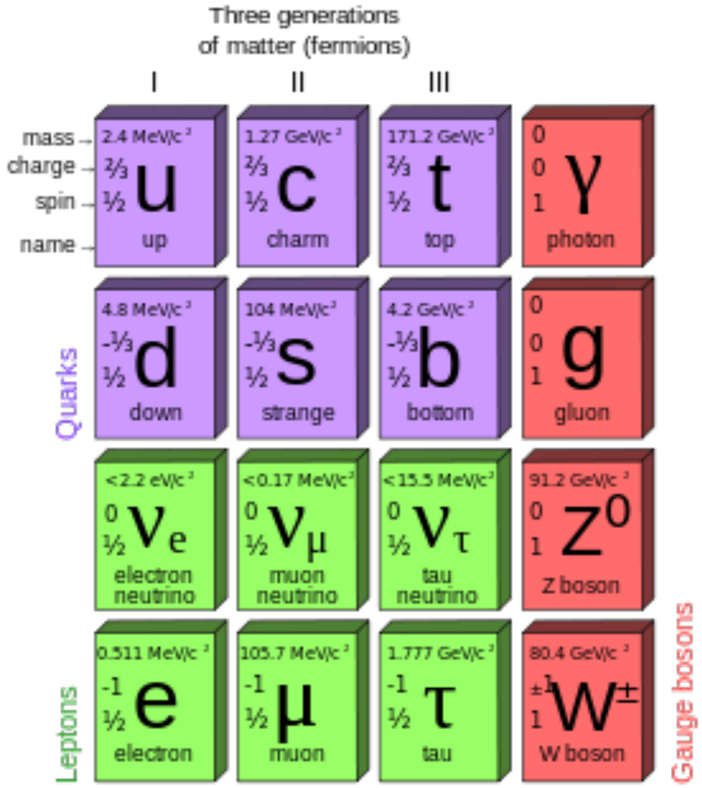




E. Fermi
(Nobel Prize)

- First direct observation of the neutrino, Nov. 1970

Effective field theories

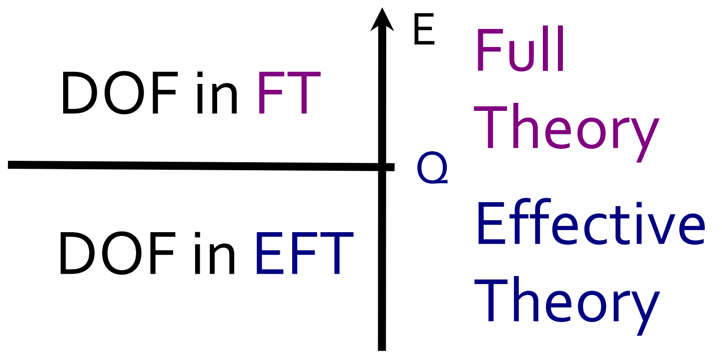


- Powerful framework based on exploiting symmetries and controlled expansions for problems with a natural separation of energy/momentum or distance scales.

- Particularly well suited to QCD and nuclear physics

- Effective theories are ubiquitous. The Standard Model is likely a low energy EFT of a theory at a much higher scale

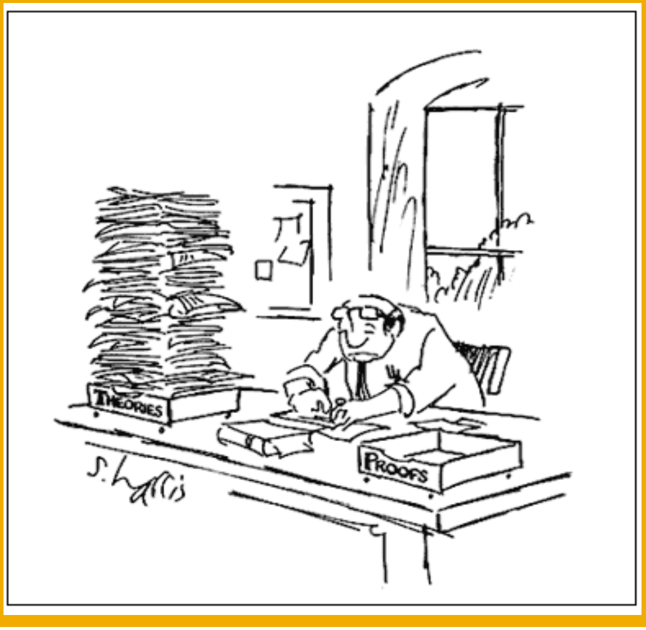
Examples of effective field theories [EFTs]



- Focus on the significant degrees of freedom [DOF]. Manifest power counting

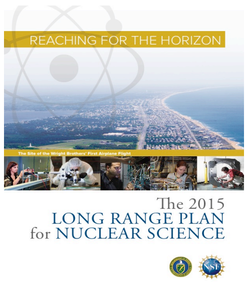
	Q	power counting	DOF in FT	DOF in EFT
Chiral Perturbation Theory (ChPT)	Λ_{QCD}	p/Λ_{QCD}	q, g	K,π
Heavy Quark Effective Theory (HQET)	m_b	Λ_{QCD}/m_b	ψ,A	h_v, A_s
Soft Collinear Effective Theory (SCET)	Q	$p_\perp/Q$	ψ,A	ξ_n, A_n, A_s
Non-Relativistic QCD (NRQCD)	m_Q	p/m_Q	ψ,A	ψ_Q, A_s, A_{us}

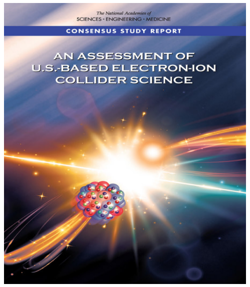
Soft Collinear Effective Theory with Glauber gluons

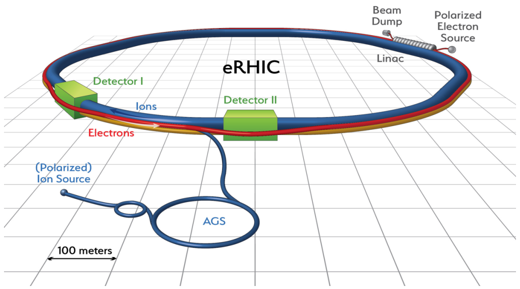


Motivation

- Jet and heavy flavor production in reactions with nuclei is an essential part of modern collider physics. Also at the future electron ion collider. New insights into the transport of energy and matter through a strongly-interacting quantum-mechanical environment







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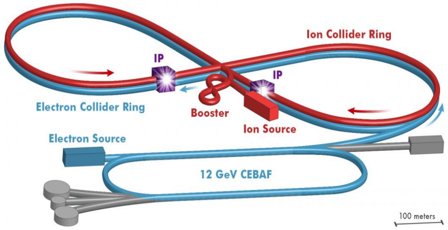
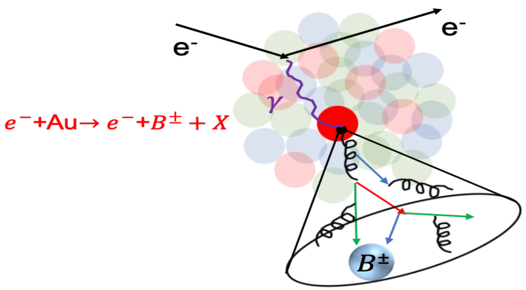
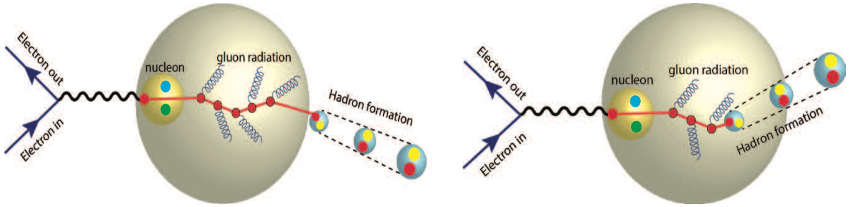






- In the meantime jets and heavy flavor are the bread and butter physics at RHIC and LHC.
- Enormous amount of data exists and new measurements continue

SCET formulation

- Modes in SCET

C. Bauer et al. (2001)

D. Pirol et al. (2004)

M. Beneke et al. (2004)

Collinear quarks, antiquarks	$\xi_n,\ \bar{\xi}_n$
Collinear gluons, soft gluons	$A_n,\ A_s$

Soft quarks are eliminated through the equations of motion

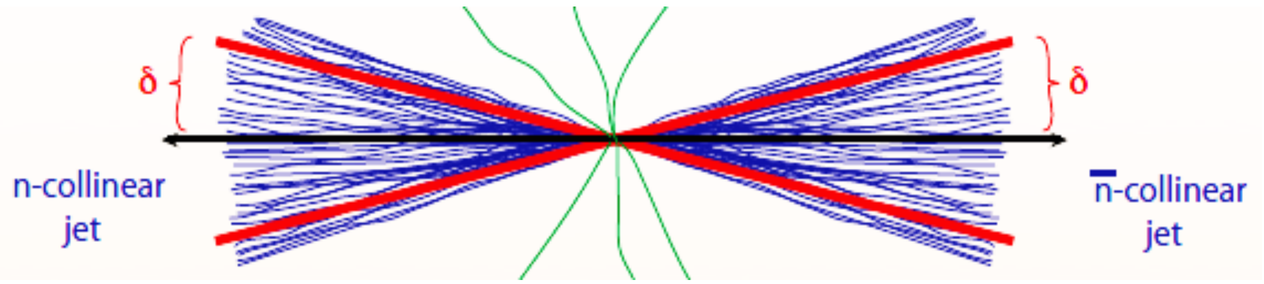
SCET$_{\text{II}}$

modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2,1,\lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda,\lambda,\lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

- Other formulations, e.g. SCET$_{\text{I}}$ and ultrasoft particles

- Especially suited for jet physics

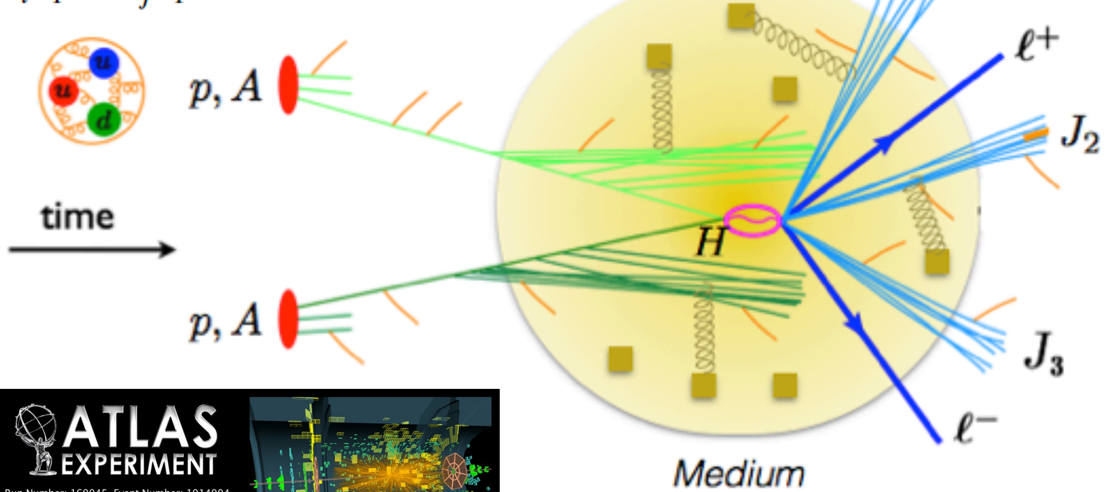
$$\sigma = \mathrm{Tr}(HS)\otimes\prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

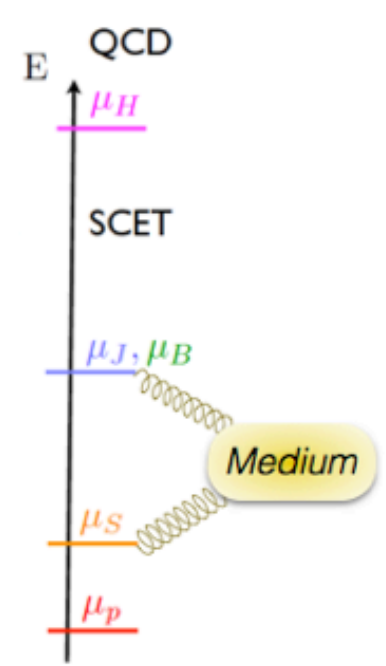


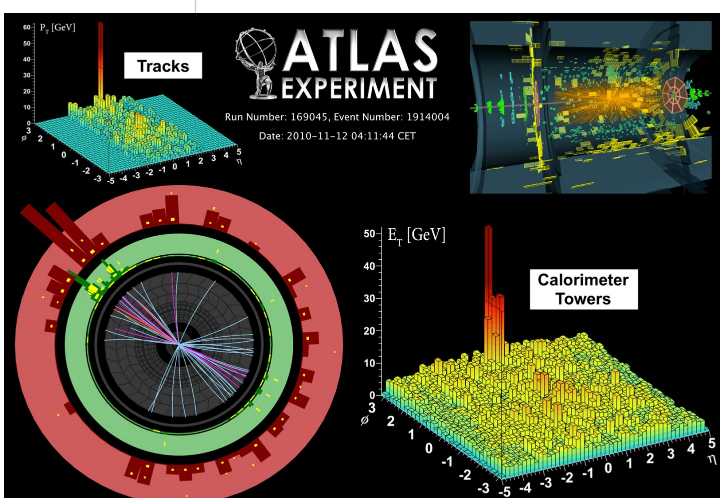
The big picture in QCD matter

- QCD in the medium remains a multiscale problem

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







- Factorization, with modified J, B, S
- Glauber mode

$$q = (\lambda^2, \lambda^2, \lambda)Q$$

Aad et al. (2010)

Ovanesyan et al. (2011)

The Glauber gluon Lagrangian

- An effective theory of jet propagation in matter

Effective potential

$$\mathcal{L}_{\rm G}(\xi_n, A_n, \eta) = \sum_{p,p',q} e^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\rm qqA_G} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\rm ggA_G} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu \right) \bar{\eta}\, \Gamma^{\delta,a}_{\rm s}\, \eta\, \Delta_{\mu\delta}(q)$$

A. Idilbi et al. (2008)

- Feynman rules for different sources and gauges

Gauge	Object	Collinear source	Static source	Soft source
	p	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
	$a_{\boldsymbol{p}}, a^\dagger_{\boldsymbol{p}}$	λ^{-1}	$\lambda^{-3/2}$	$\lambda^{-3/2}$
	$u(p)$	1	1	$\lambda^{1/2}$
	$\bar{u}(p_2)\gamma_\nu u(p_1)$	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
R_ξ	$A^\mu(x)$	$[\lambda^4, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda^2, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
	$\Gamma_{\rm qqA_G}$	Γ^μ_1	Γ^μ_1	Γ^μ_1
	$\Gamma_{\rm ggA_G}$	$\Sigma^{\mu\nu\lambda}_1$	$\Sigma^{\mu\nu\lambda}_1$	$\Sigma^{\mu\nu\lambda}_1$
	$\Gamma_{\rm s}$	$\Gamma^\mu_1\,(n \leftrightarrow \bar{n})$	Γ^μ_3	Γ^μ_4
$A^+ = 0$	$A^\mu(x)$	$[0, \lambda^2, \boldsymbol{\lambda}^3]$	$[0, \lambda^2, \boldsymbol{\lambda}]$	$[0, \lambda, \mathbf{1}]$
	$\Gamma_{\rm qqA_G}$	Γ^μ_1	$\Gamma^\mu_1 + \Gamma^\mu_2$	$\Gamma^\mu_1 + \Gamma^\mu_2$
	$\Gamma_{\rm ggA_G}$	$\Sigma^{\mu\nu\lambda}_2$	$\Sigma^{\mu\nu\lambda}_2$	$\Sigma^{\mu\nu\lambda}_2$
	$\Gamma_{\rm s}$	$\Gamma^\mu_2\,(n \leftrightarrow \bar{n})$	Γ^μ_3	Γ^μ_4

$$\Gamma^{\mu,a}_1 = igT^a\, n^\mu\, \frac{\bar{\not{n}}}{2}\,,$$

$$\Gamma^{\mu,a}_2 = igT^a \frac{\gamma^\mu_\perp \not{p}_\perp + \not{p}'_\perp \gamma^\mu_\perp}{\bar{n}\cdot p} \frac{\bar{\not{n}}}{2}\,,$$

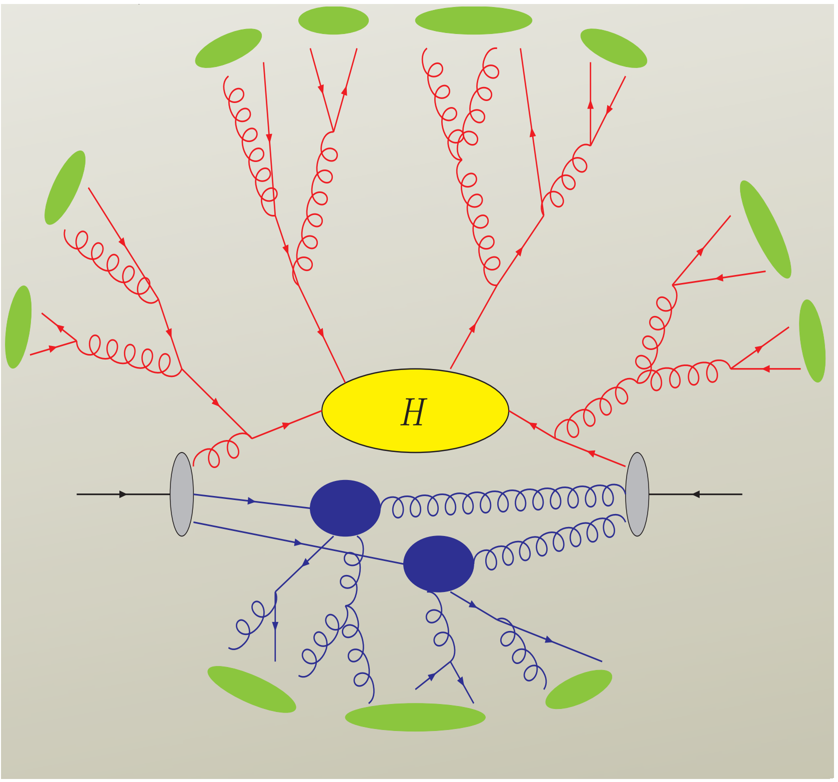
$$\Gamma^{\mu,a}_3 = igT^a\, v^\mu\,,$$

$$\Gamma^{\mu,a}_4 = igT^a\, \gamma^\mu\,,$$

$$\Sigma^{\mu\nu\lambda,abc}_1 = gf^{abc}\, n^\mu \left[g^{\nu\lambda}\, \bar{n}\cdot p + \bar{n}^\nu \left(p'^\lambda_\perp - p^\lambda_\perp\right) - \bar{n}^\lambda \left(p'^\nu_\perp - p^\nu_\perp\right) - \frac{1-\frac{1}{\xi}}{2} \left(\bar{n}^\lambda p^\nu + \bar{n}^\nu p'^\lambda\right) \right],$$

G. Ovanesyan et al. (2011)

The QCD splitting kernels in the vacuum and medium



- In the description of high energy processed significant effort has been devoted to understand the logs, legs and loops

- Splitting functions are related to beam (B) and jet (J) functions in SCET
- Higher order calculations
- Resummation
- Paton showers in Monte Carlos

Gribov et al. (1972)

G. Altarelli et al. (1977)

Y. Dokshitzer (1977)

Ovanesyan et al. (2012)

Kang et al. (2016)

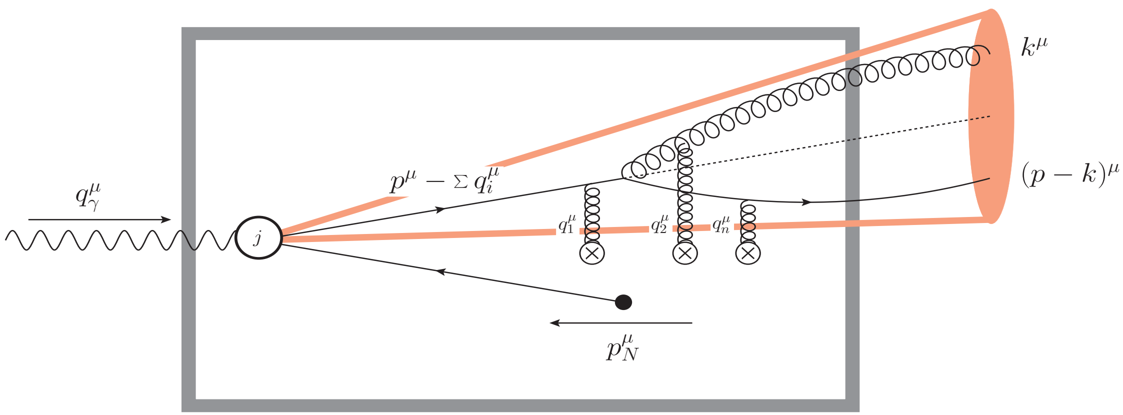
- Derivation of splitting kernels to first order in opacity. How about higher orders?

Theoretical framework for higher orders in opacity

- 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)

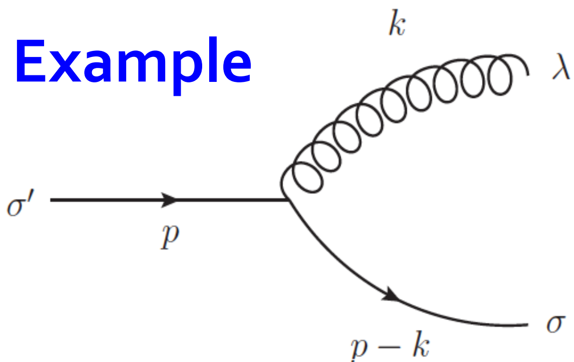
$$\frac{1}{p_N^-} \ll l_f^+ \sim \lambda^+ \sim L^+$$

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

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

Lightcone wave functions and parton branchings

Example



- The technique of lightcone wavefunctions

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

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

Useful to express in Pauli matrixes

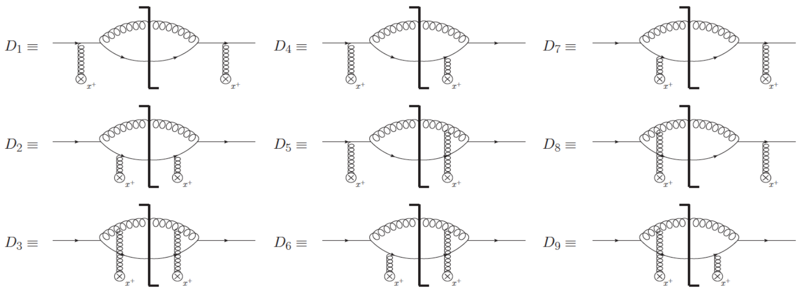
c.f. F. Ringer et al . (2016)

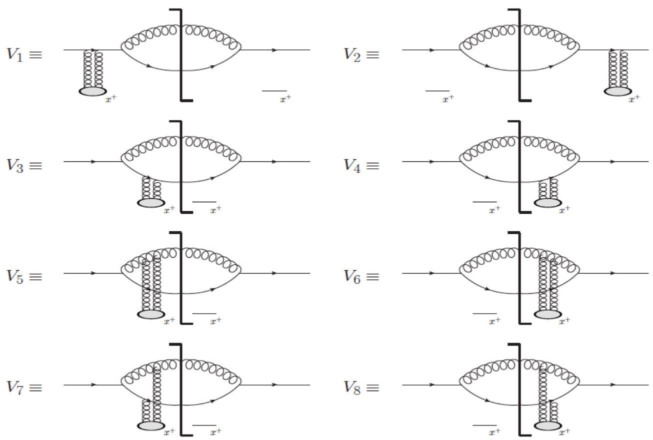
Branchings depending on the intrinsic momentum of the splitting $\underline{\kappa} = \underline{k - xp}.$

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

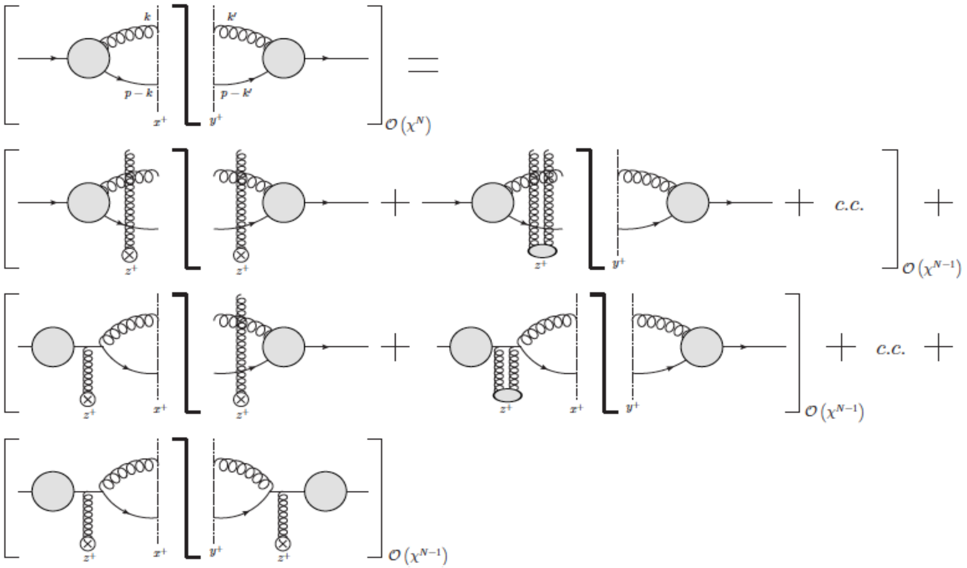
- Certain advantages – can provide in “one shot” both massive and massless splitting functions
- Have checked that results agree for massless and massive DGLAP

Opacity expansion – direct and virtual diagrams





- Interaction in the amplitude and the conjugate amplitude (Direct or single Born diagrams)
- Interaction in the amplitude or the conjugate amplitude (Virtual or double Born diagrams)
- Use them to calculate both the medium evolution kernels & initial conditions



- Finally, relative to the splitting vertex we classify them 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

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

⋮

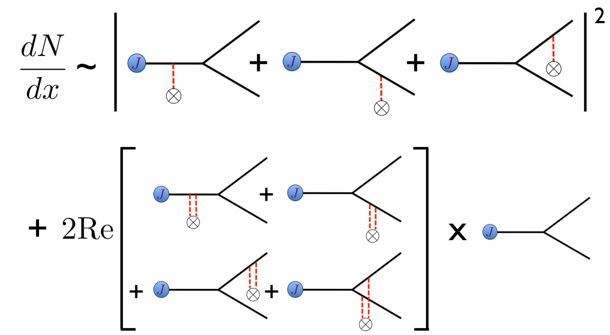
Most complicated kernel

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

+ 8 more lines

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)



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

- Master table that gives all ingredients

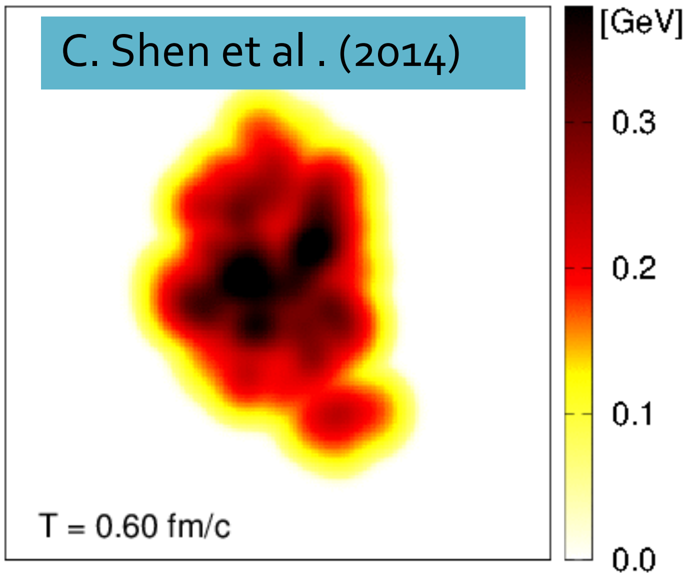
	d_1	d_2	d_3	d_4	d_5	d_6	v_1	v_2	v_3	v_4	λ_R^+	$\mathcal{C}_0$	ν	$f(x)$	$g(x)$
G/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	x	$1-x$	$1+(1-x)^2$
q/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$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

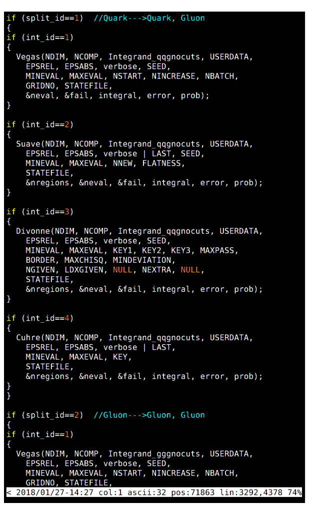
We have now solved the problem for all splitting functions.

Answers exact but lengthy – 2^{nd} order ~ 10 pages

M. Sievert et al . (2019)

Improvements in physics & code





```
if (split_id==1)  //Quark--->Quark, Gluon
{
if (int_id==1)
{
  Vegas(NDIM, NCOMP, Integrand_qqgnocuts, USERDATA,
    EPSREL, EPSABS, verbose, SEED,
    MINEVAL, MAXEVAL, NSTART, NINCREASE, NBATCH,
    GRIDNO, STATEFILE,
    &neval, &fail, integral, error, prob);
}

if (int_id==2)
{
  Suave(NDIM, NCOMP, Integrand_qqgnocuts, USERDATA,
    EPSREL, EPSABS, verbose | LAST, SEED,
    MINEVAL, MAXEVAL, NNEW, FLATNESS,
    STATEFILE,
    &nregions, &neval, &fail, integral, error, prob);
}

if (int_id==3)
{
  Divonne(NDIM, NCOMP, Integrand_qqgnocuts, USERDATA,
    EPSREL, EPSABS, verbose, SEED,
    MINEVAL, MAXEVAL, KEY1, KEY2, KEY3, MAXPASS,
    BORDER, MAXCHISQ, MINDEVIATION,
    NGIVEN, LDXGIVEN, NULL, NEXTRA, NULL,
    STATEFILE,
    &nregions, &neval, &fail, integral, error, prob);
}

if (int_id==4)
{
  Cuhre(NDIM, NCOMP, Integrand_qqgnocuts, USERDATA,
    EPSREL, EPSABS, verbose | LAST,
    MINEVAL, MAXEVAL, KEY,
    STATEFILE,
    &nregions, &neval, &fail, integral, error, prob);
}
}

if (split_id==2)  //Gluon--->Gluon, Gluon
{
if (int_id==1)
{
  Vegas(NDIM, NCOMP, Integrand_gggnocuts, USERDATA,
    EPSREL, EPSABS, verbose, SEED,
    MINEVAL, MAXEVAL, NSTART, NINCREASE, NBATCH,
    GRIDNO, STATEFILE,
< 2018/01/27-14:27 col:1 ascii:32 pos:71863 lin:3292,4378 74%
```

8. boram@pn1615176.lanl.gov: ~/work/qcd/hydrodynamics/splitting_funct..

```
if(cut_id == 1)
{
  switch(split_id)
  {
    case 1:
      func = &Integrand_qqgnocuts; break;
    case 2:
      func = &Integrand_gggnocuts; break;
    case 3:
      func = &Integrand_gqqnocuts; break;
    case 4:
      func = &Integrand_qggnocuts; break;
    default:
      printf("Error: Unknown split_id %d\n", split_id);
      exit(0);
  } // switch(split_id)
} // cur_id == 1
< 2018/01/27-14:28 col:20 ascii:49 pos:44971 lin:1459,1631 91%
```

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

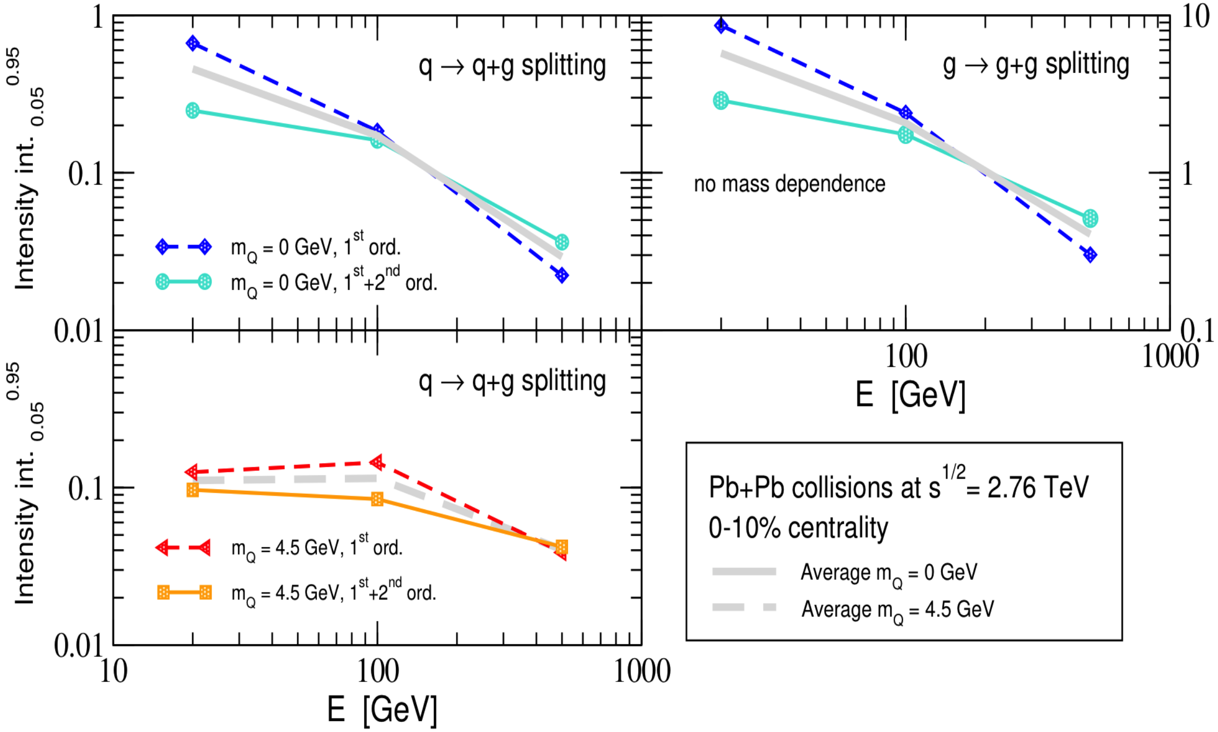
Medium-induced splitting intensity

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

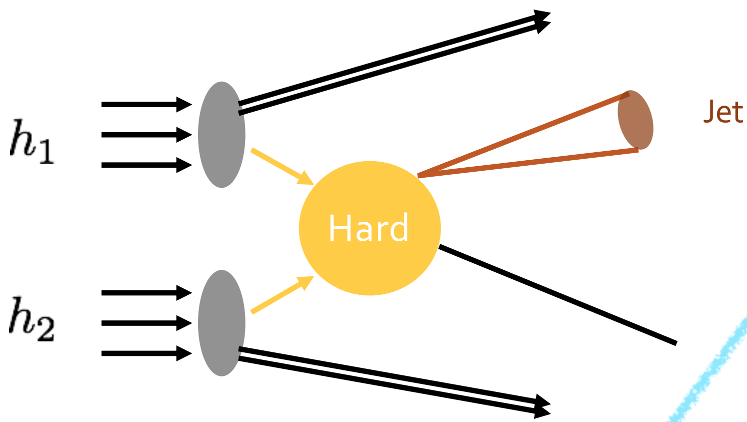
- The main result is a change in the energy dependence of the splitting intensity – smother, or more slowly varying with E (understand jet modification with p_T)

Phenomenological applications of $SCET_G$

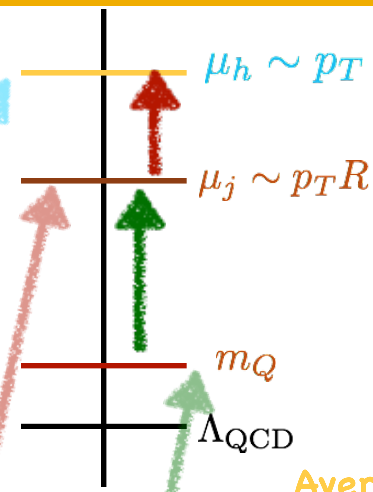
"I'm firmly convinced that behind every great man is a great computer."

Inclusive heavy jet production

- Jet production is one of the cornerstone processes of QCD. Light jets have been studied for a long time. Recent advances for heavy jets (e.g. b) based in SCET



$$h_1 + h_2 \to \text{Jet} + X$$



Scales in the EFT

Aversa et al 1990
Jager et al 2004
Mukherjee et al 2012
Kaufmann et al 2016
....

$$\frac{d\sigma_{pp\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\rm min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\rm min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_{\rm min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat\sigma_{ab\to c}(\hat s, p_T/z_c, \hat\eta, \mu)}{dvdz} J_{J/c}(z_c, w_J \tan(R'/2), m_Q, \mu)$$

Hard scattering kernel

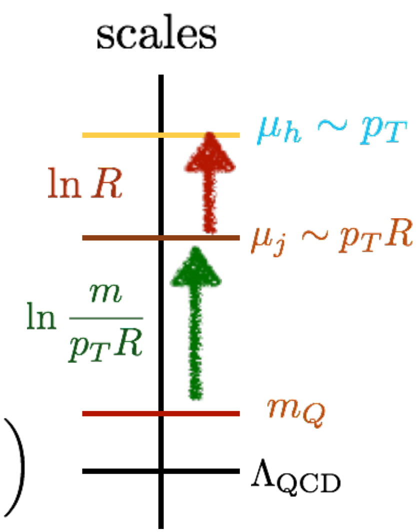
Aversa et al 1989, Jager et al 2002

Semi-inclusive jet function

light jet: Kang et al 2016, Dai et al 2016
heavy flavor jet: Dai et al 2018

Resummation

- Evolution between the jet scale and the hard scale hadle by DGLAP evolution of the SIJF
- Evolution from the heavy quark mass to the jet scale is separated into



The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} P_{qq}(z) & 2P_{gq(z)} \\ P_{qg}(z) & P_{gg}(z) \end{pmatrix}\begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu) \end{pmatrix}$$

We use the Mellin moment space approach to solve this equation

Resums ln $\mu/p_T R$

$$\mathcal{M}^{\text{in-jet}}_{g\to Q\bar{Q}}(p_T R, m) = 2\sum_{l=g,Q} \bar{K}_{l/g}(p_T R, m, \mu_F)\bar{D}_{Q/l}(m,\mu_F)$$

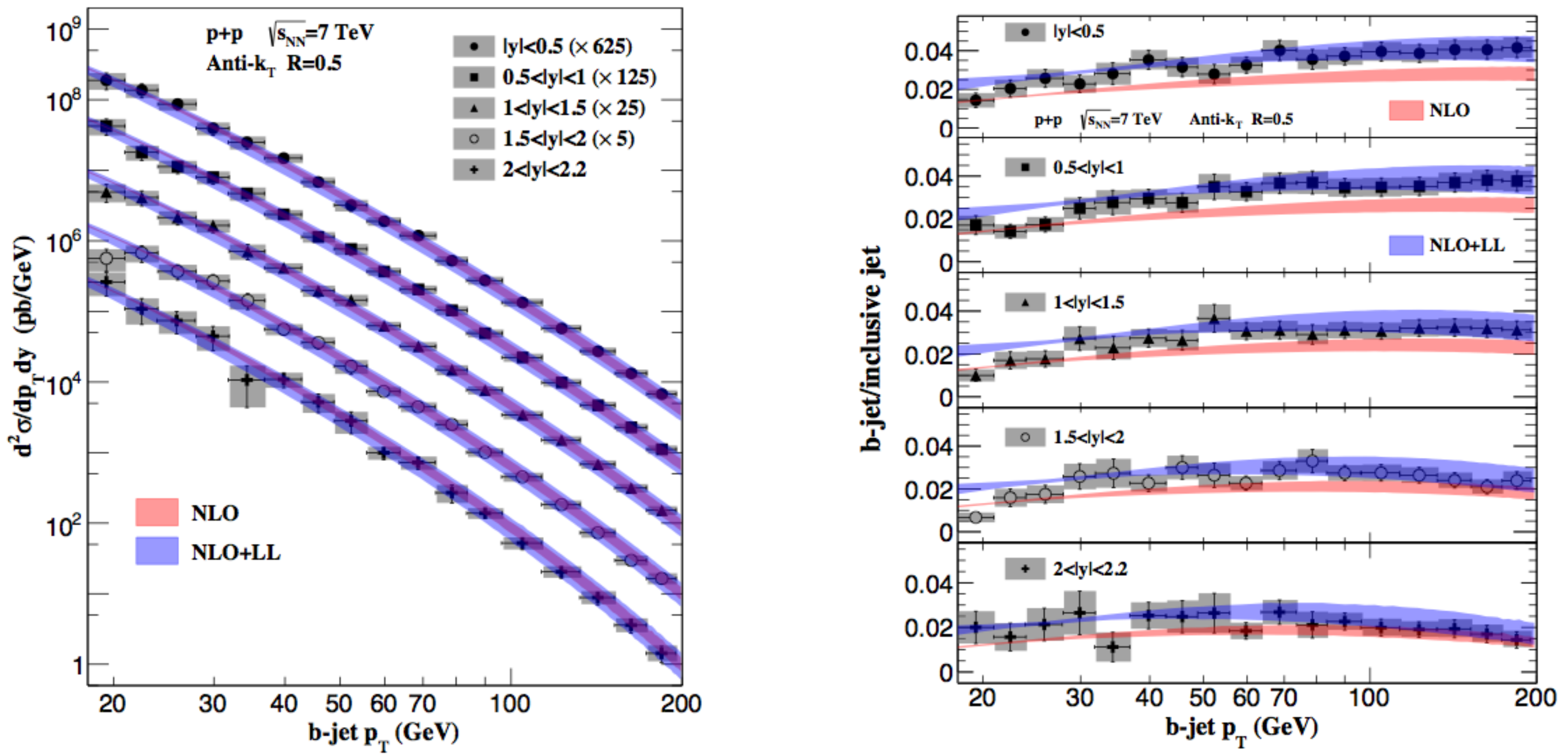
Resums ln $p_T R/m$

The integrated perturbative kernel at the jet typical scale

The integrated parton fragmentation function from parton *l* to parton *Q*

Bauer, Mereghetti 2013, Dai, Kim, Leibovich 2016, 2018

B-jet production in pp collisions



- Data are consistent with the theoretical predictions
- For the ratio b-jets to inclusive jets the difference between NLO+LL and NLO can be traced also to the differences in the inclusive jet cross section

Corrections in A+A collisions

Let us now focus on the jet function and final-state modification in the QGP

$$\frac{d\sigma_{AA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\rm min}}^{1} \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\rm min}}^{1} \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_{\rm min}}^{1} \frac{dz_c}{z_c^2}\frac{d\hat\sigma_{ab\to c}(\hat s, p_T/z_c,\hat\eta,\mu)}{dvdz} J_{J/c}(z_c, w_J\tan(R'/2), m_Q,\mu)$$

CNM effects

The short-distance hard part remains the same

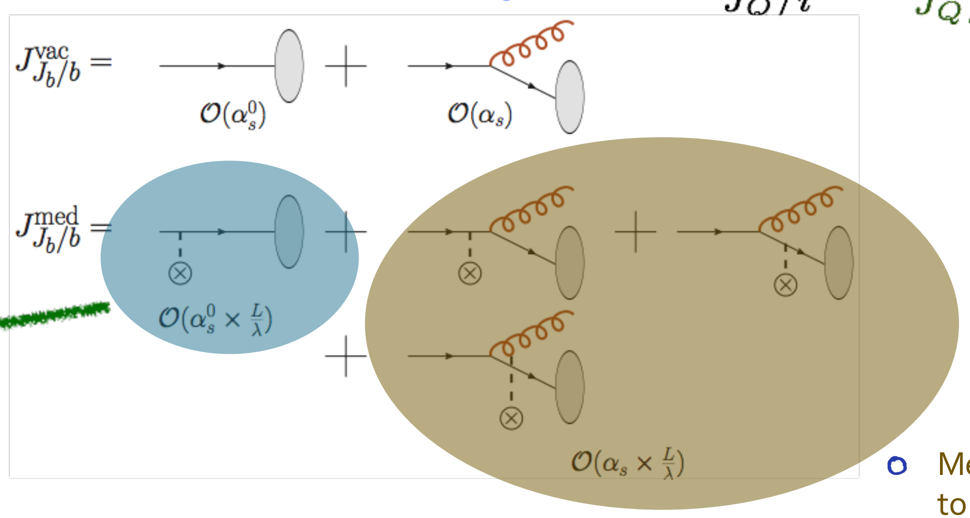
Encodes the effects when the jet evolving in the QCD medium

The jet function receives medium contributions from collisional energy loss and in-medium branching processes

$$J^{\rm med}_{J_Q/i} = J^{{\rm med},(0)}_{J_Q/i} + J^{{\rm med},(1)}_{J_Q/i}$$

Vacuum jet function:

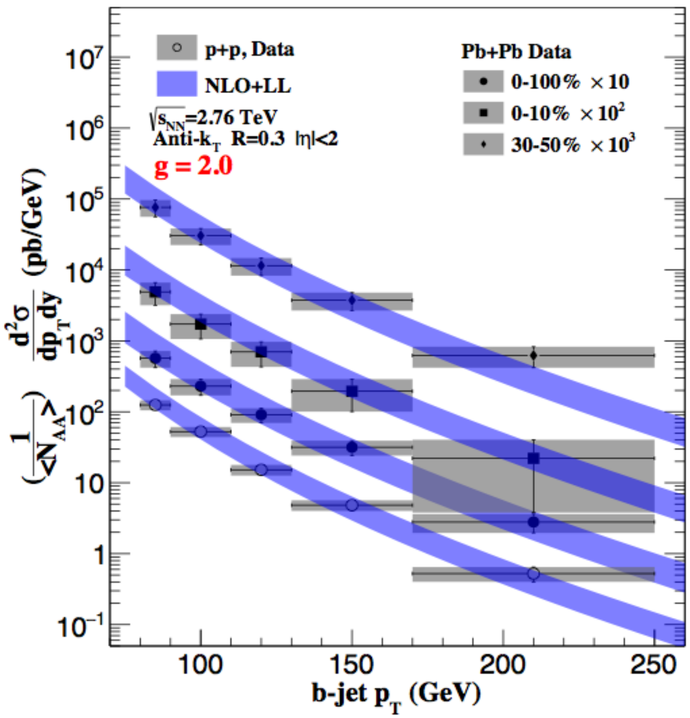
Medium corrections:

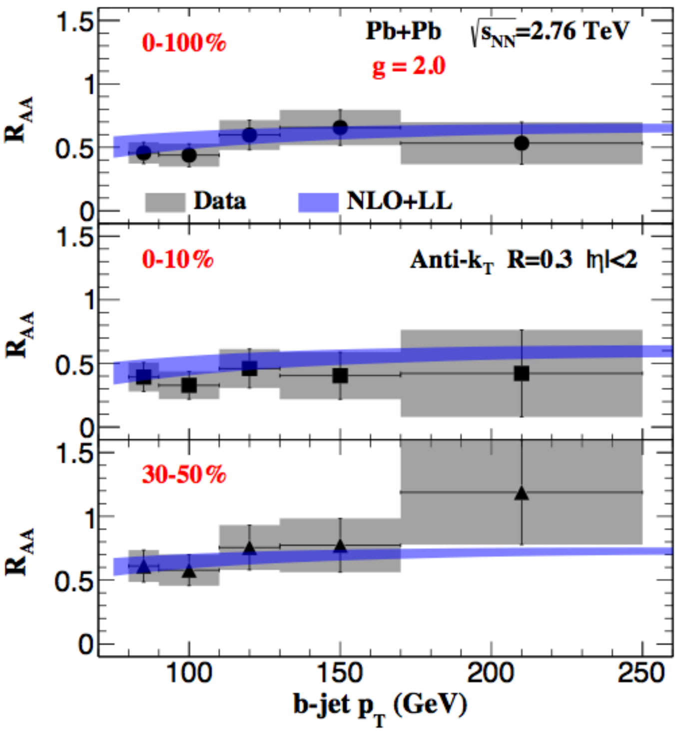


- Medium induced corrections to the LO jet function

- Medium induced corrections to the NLO jet function

B-jet production in A-A collisions

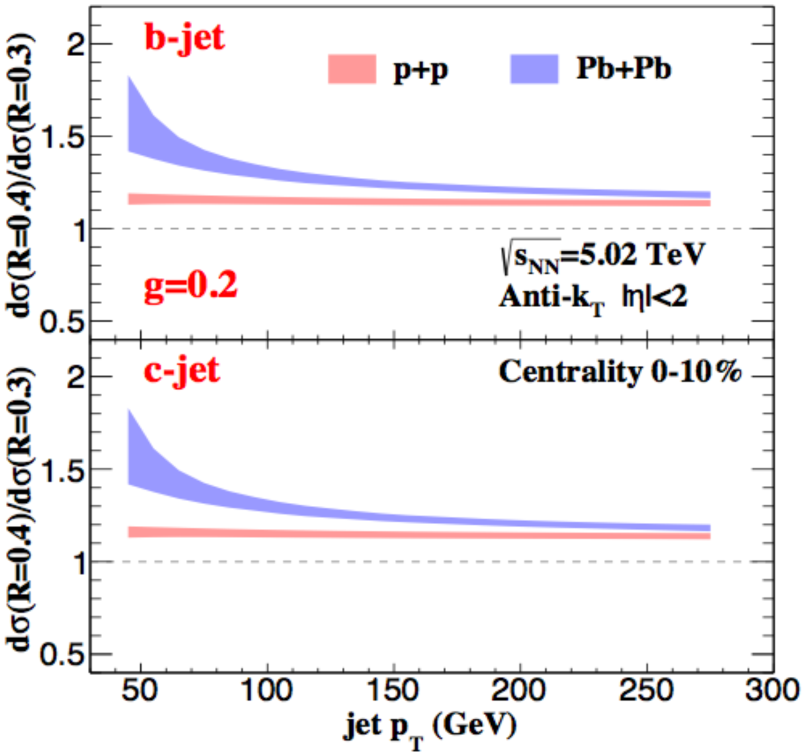


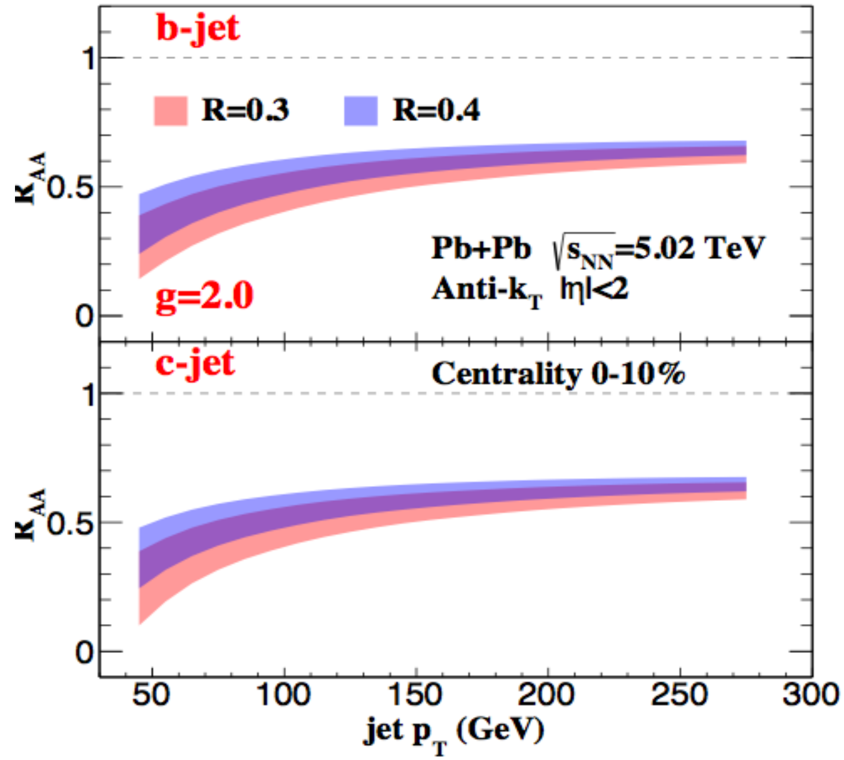


- Slightly less dependence on the centrality when compared to the well-known light jet modification
- Theoretical results agree well with the data for both the inclusive cross sections and the nuclear modification factors

Does not mean there is no room for improvement. Extend to lower p_T

B-jet and c-jet production in A-A collisions





Haitao Li, Vitev, 2018

- Not depend on jet p_T in p+p collisions
- Small dependence on jet p_T in Pb+Pb collisions

- The smaller radius jet tends to dissipate more energy in the medium
- No significant difference between the c-jet and b-jet due to the high transverse momentum

The jet charge

- Weighted sum of the charges of all particles in a jet. Proxy for the charge of the quark or gluon
- Allows for jet flavor separation (up-quark vs down quark) quark-antiquark separation. Modern machine learning techniques

K. Fraser *et al. (2018)*

$$Q_{\kappa,\mathrm{jet}} = \frac{1}{\left(p_T^{\mathrm{jet}}\right)^{\kappa}} \sum_{i\in \mathrm{jet}} Q_i \left(p_T^i\right)^{\kappa}$$

R. Field *et al.* (1978)

J. Berge *et al. (1981)*

J. Erickson *et al. (1979)*

SCET factorization

W. Waalewijn (2012)

D. Krohn et al. (2013)

$$\langle Q_{\kappa,q}\rangle = \int dz\; z^{\kappa} \sum_h Q_h \frac{1}{\sigma_{\text{q-jet}}} \frac{d\sigma_{h\in\text{q-jet}}}{dz}$$

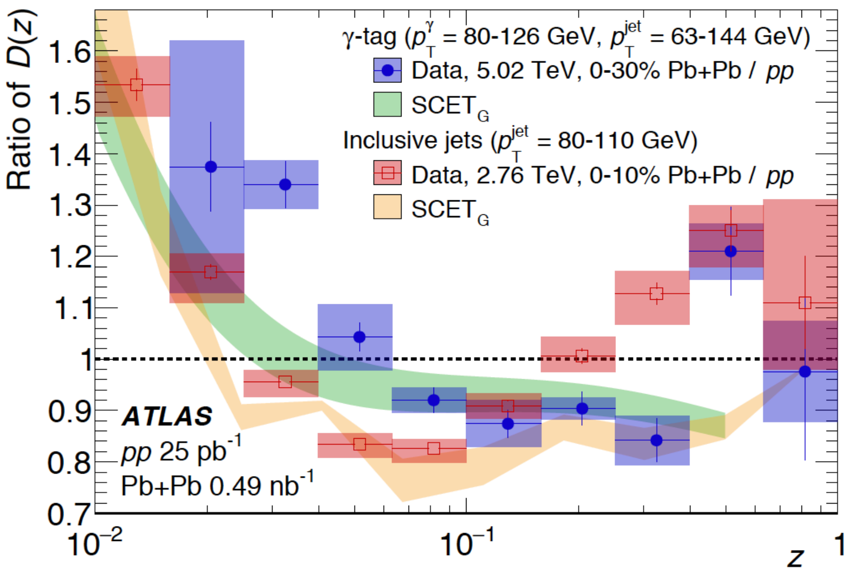
$$\langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu)$$

- Expressed in (k+1) Mellin moment of the jet matching coefficient and charge-weighted frag. function

$$\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu) = \int_0^1 dz\; z^{\kappa} \mathcal{J}_{qq}(E,R,z,\mu)\,,$$

$$\tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\; z^{\kappa} \sum_h Q_h D_q^h(z,\mu)$$

Significance: different flavor jets in HIC



M. Aaboud et al . (2019)

Phenomenological results in proton collisions

- Calculation of the jet maching coefficient & jet function
- It is important that it can be expressed as an integral over splitting kernels. In medium only numerical grids possible

$$\mathcal{J}_{qq}^{(1)}(E,R,x,\mu) = \frac{C_F\alpha_s}{2\pi}\frac{e^{\epsilon\gamma_E}}{\Gamma(1-\epsilon)}\int\frac{dl_\perp^2}{l_\perp^2}\left(\frac{\mu^2}{l_\perp^2}\right)^\epsilon\frac{1+x^2-\epsilon(1-x)^2}{1-x}$$

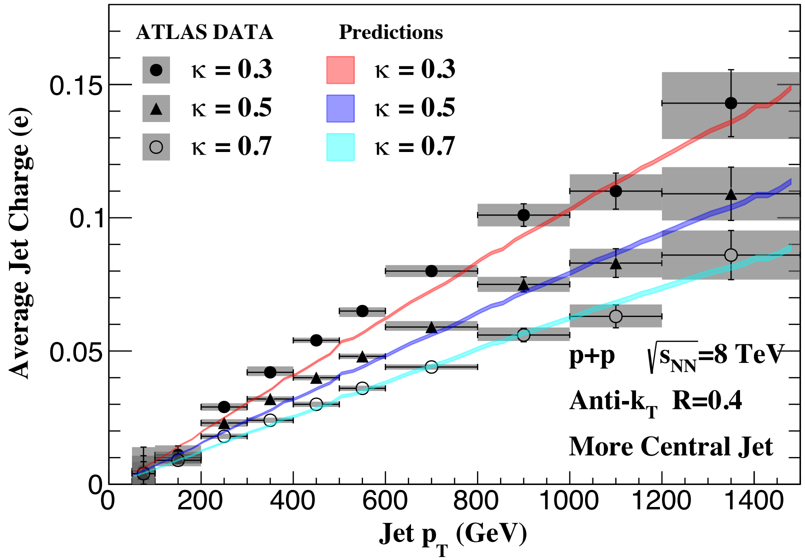
$$J_q(E,R,\mu) = \int_0^1 dz z\left[\mathcal{J}_{qq}(E,R,z,\mu)+\mathcal{J}_{qg}(E,R,z,\mu)\right]$$

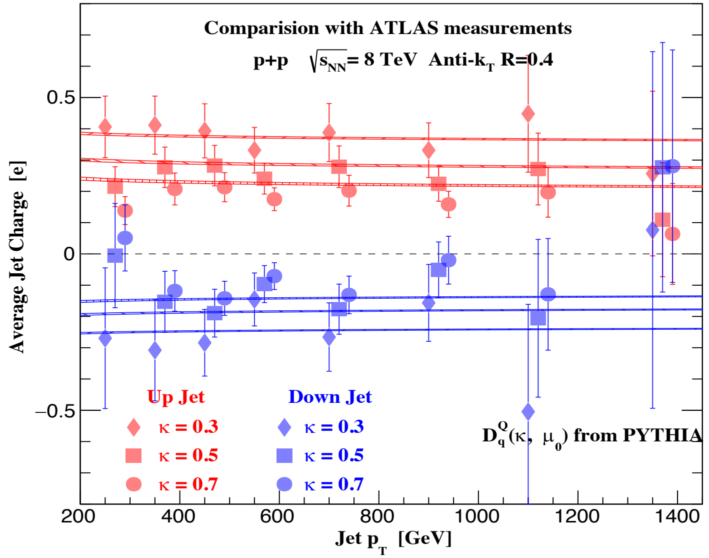
H. Li *et al.* (2019)

$$\mu\frac{d}{d\,\mu}\tilde{D}_q^Q(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\tilde{P}_{qq}(\kappa)\tilde{D}_q^Q(\kappa,\mu)$$

Phenomenology

ATLAS *et al.* (2015)





Derivation in heavy ion collisions

- Jet matching coefficient in matter
- Note that the virtual correction does not give a contribution. All contained in the LO result

$$\mathcal{J}_{qq}^{\text{med}}(E,R,x,\mu) = \frac{\alpha_s(\mu)}{2\pi^2}\Big[-\delta(1-x)\int_0^1 dz \int_0^\mu \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P_{q\to qg}^{\text{med}}(z,\mathbf{k}_\perp) + \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P_{q\to qg}^{\text{med}}(x,\mathbf{k}_\perp)\Big] = \frac{\alpha_s(\mu)}{2\pi^2}\int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P_{q\to qg}^{\text{med}}(x,\mathbf{k}_\perp)$$

$$J_q^{\text{med}}(E,R,\mu) = \int_0^1 dx\, x\Big(\mathcal{J}_{qq}^{\text{med}}(E,R,x,\mu) + \mathcal{J}_{gq}^{\text{med}}(E,R,x,\mu)\Big) = \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\Big(xP_{q\to qg}^{\text{med,real}}(x,\mathbf{k}_\perp) + xP_{q\to gq}^{\text{med,real}}(x,\mathbf{k}_\perp)\Big) = \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P_{q\to qg}^{\text{med,real}}(x,\mathbf{k}_\perp),$$

- The in-medium jet function

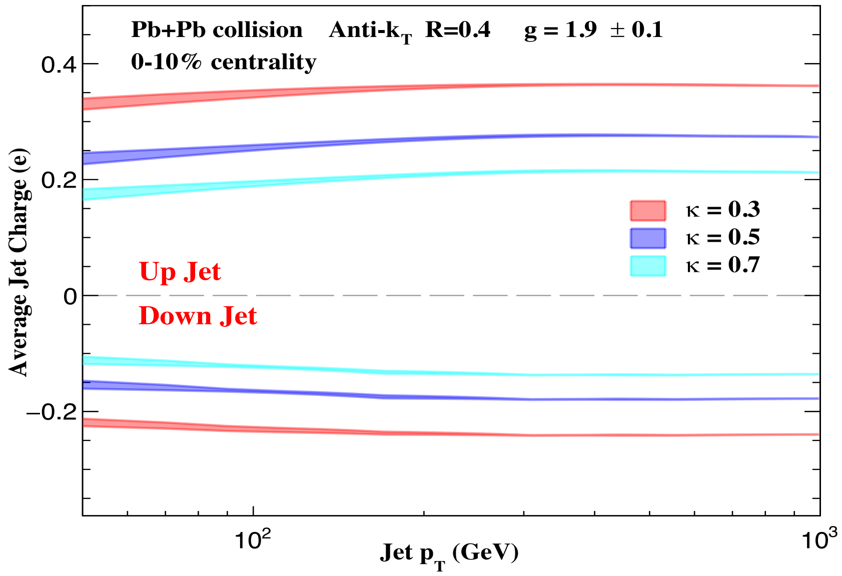
- Medium evolution of the fragmentation function
- Boundary condition obtained from PYTHIA

$$\frac{d}{d\ln\mu}\tilde{D}_q^{Q,\text{full}}(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\Big(\tilde{P}_{qq}(\kappa) + \tilde{P}_{qq}^{\text{med}}(\kappa,\mu)\Big)\tilde{D}_q^{Q,\text{full}}(\kappa,\mu)$$

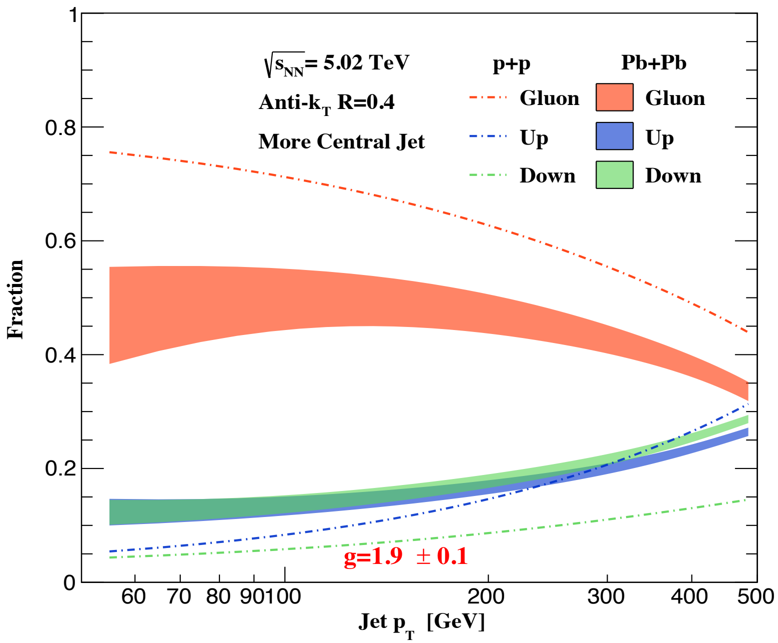
H. Li *et al.* (2019)

Phenomenological predictions for heavy ion collisions

- The effects that are important
- Isospin, many more down quarks
- Energy loss effects, quark jets lose less energy than gluon jets (C_F vs C_A)
- Medium induced splitting effects on the jet functions ands the fragmentation function evolution



H. Li *et al.* (2019)

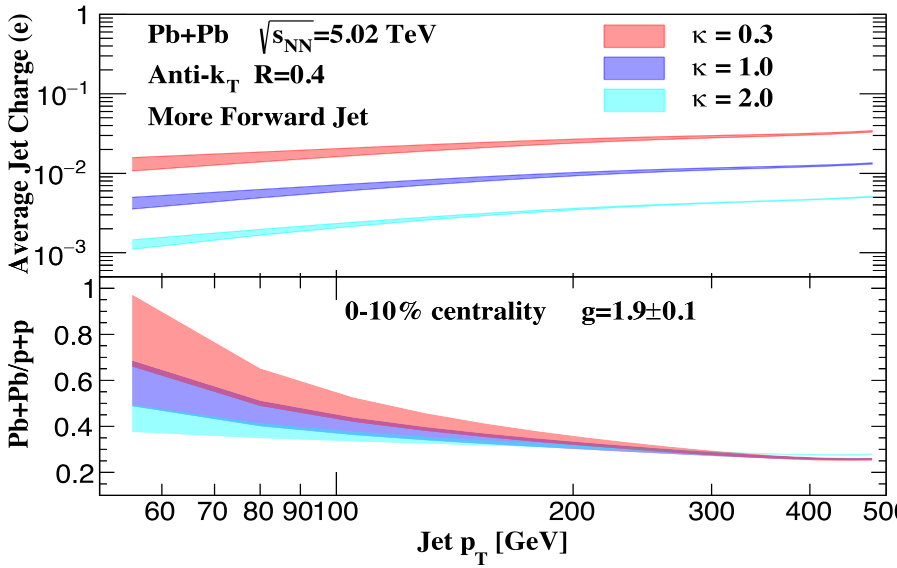


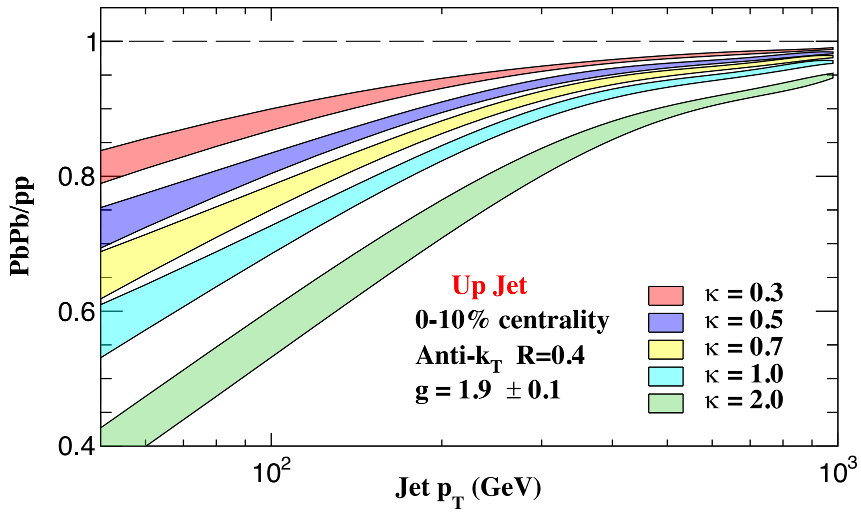
Individual flavor jets can still be separated

Phenomenological predictions for heavy ion collisions

H. Li *et al.* (2019)

- At very large transverse momenta isospin effects dominate.
- At lower transverse momenta p_T<200 GeV we are beginning to see the effects of in-medium parton showers and different evolution





Proposed new measurement – the charge of individual flavor jets

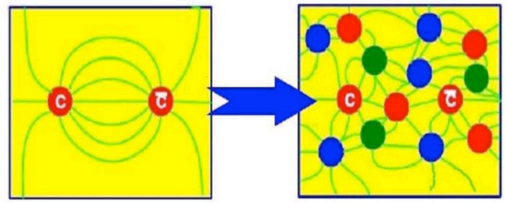
- Isolate the medium induced contribution to jet functions and fragmentation functions evolution.
- Mellin moments of in-medium splittings

NQCD, Leading power factorization & E-loss

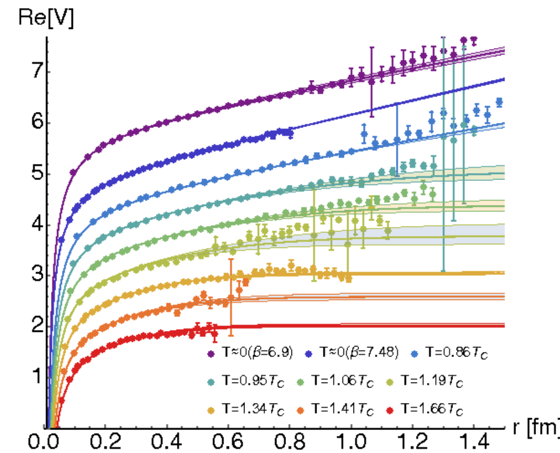
Quarkonia in the QGP

- Quarkonia (e.g. J/ψ,ϒ), bound states of the heaviest elementary particles, long considered standard candle to characterize QGP properties

- Most sensitive to the space-time temperature profile



Matsui *et al.* (1986)



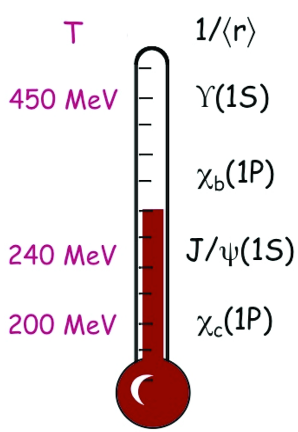
Rothkopf *et al.* (2016)

$$\left[-\frac{1}{2\mu_{\mathrm{red}}}\frac{\partial^2}{\partial r^2}+\frac{l(l+1)}{2\mu_{\mathrm{red}}r^2}+V(r)\right]rR_{nl}(r)=(E_{nl}-2m_Q)rR_{nl}(r)$$

$$\psi(\mathbf{r}) = Y_l^m(\hat{r})R_{nl}(r)$$

Mocsy *et al.* (2007)

Bazavov *et al.* (2013)

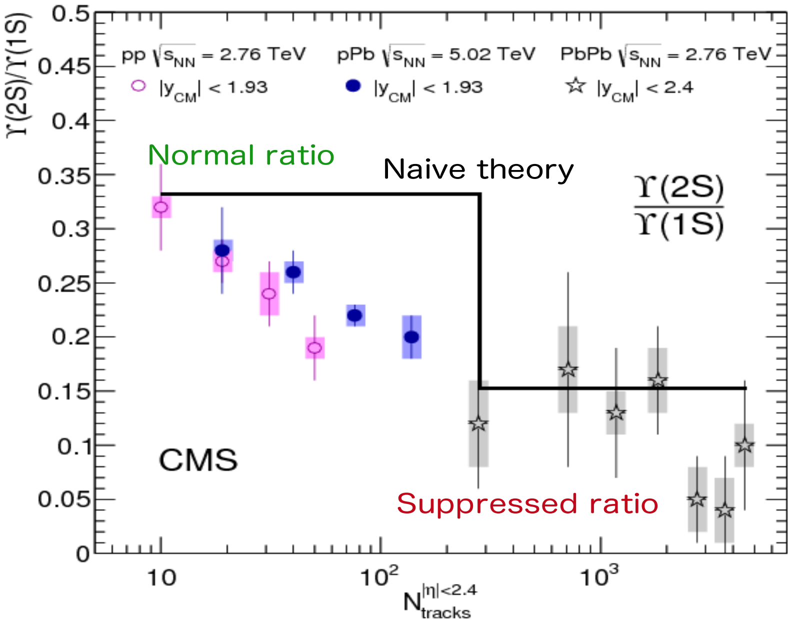


l	n	E_{nl} (GeV)	$\sqrt{\langle r^2\rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.700	2.24	0.30	J/ψ
0	2	0.086	5.39	0.05	$\psi(2S)$
1	1	0.268	3.50	0.20	χ_c
0	1	1.122	1.23	0.99	$\Upsilon(1S)$
0	2	0.578	2.60	0.22	$\Upsilon(2S)$
0	3	0.214	3.89	0.10	$\Upsilon(3S)$
1	1	0.710	2.07	0.58	$\chi_b(1P)$
1	2	0.325	3.31	0.23	$\chi_b(2P)$
1	3	0.051	5.57	0.08	$\chi_b(3P)$

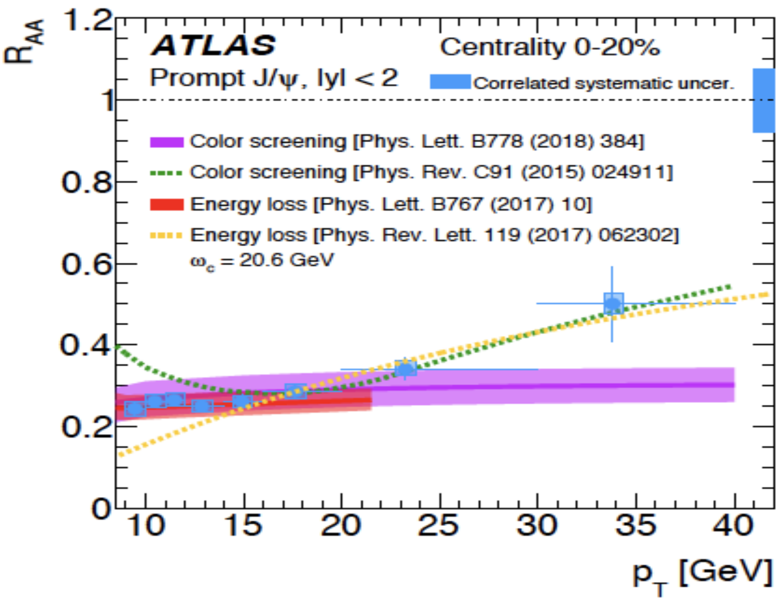
Challenges and hypothesae

- Suppression puzzle - similar dissociation behavior observed in small system, p+A and even in p+p (where QGP is not expected)
- Co-mover dissociation model, energy loss model – need cross check and microscopic explanation

E. Ferreiro (2014)



Chatrachyan *et al.* (2014)



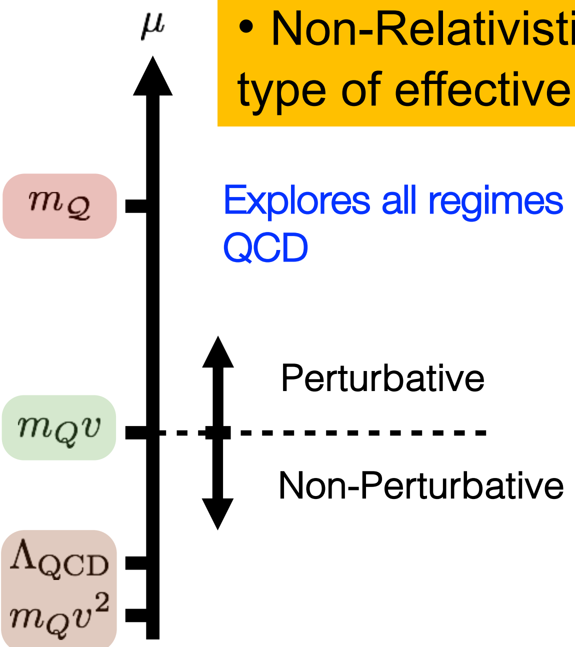
- EFT - capture the interactions without explicitly specifying their nature

Production of quarkonia at intermediate and high p_T

- Non-Relativistic QCD (NRQCD) -a particular type of effective theory (EFT)

Bodwin *et al.* (1995)

Cho *et al.* (1996)



Explores all regimes of QCD

$b\bar{b}: \quad v^2 \sim 0.1$

$c\bar{c}: \quad v^2 \sim 0.3$

Ultra-soft

$p_s^\mu \sim m_Q v(1,1,1,1)$

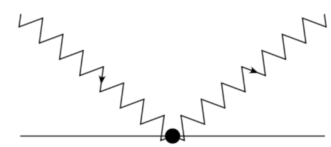
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

$$\mathcal{L}_{\rm NRQCD} = \mathcal{L}_{\rm light} + \psi^\dagger\left(iD_0 + \frac{\mathbf{D}^2}{2M}\right)\psi + \chi^\dagger\left(iD_0 - \frac{\mathbf{D}^2}{2M}\right)\chi$$

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO



typical momentum if heavy quark: $|\mathbf{p}_Q| \sim m_Q v$

typical kinetic energy if heavy quark: $K_Q \sim m_Q v^2$

- NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

$$d\sigma(a+b\to\mathcal{Q}+X) = \sum_n d\sigma(a+b\to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

NRQCD examples

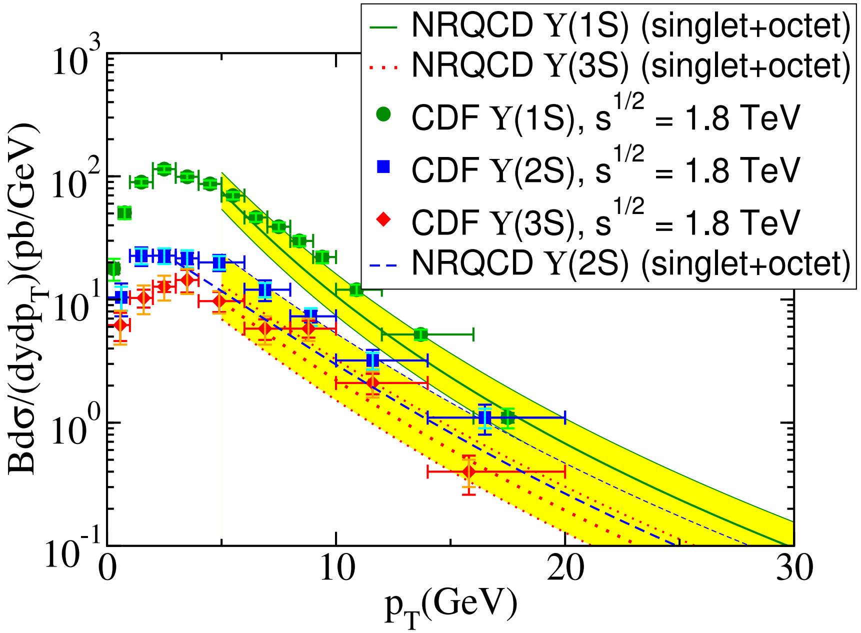
• One has to be careful, the simple power counting approximately manifest in the LDMEs can be affected by the partonic cross section – a large number of singlet and octet; S wave and P wave terms enter

$$d\sigma(J/\psi) = d\sigma(Q\bar{Q}([^3S_1]_1))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle\mathcal{O}(Q\bar{Q}([^1S_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3S_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3P_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_2]_8) \to J/\psi)\rangle + \cdots$$

• The situation is similar for bottomonia

• Excited states have their own expansion

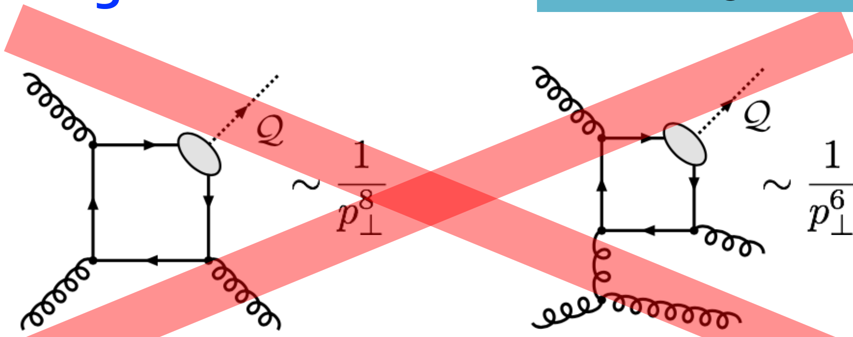
The question is – is there a simplification at high p_T where the p_T dependence of the short distance cross section dominates



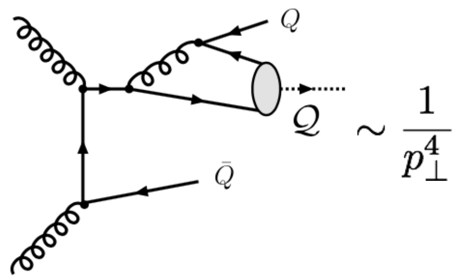
Leading power factorization

Singlet contribution

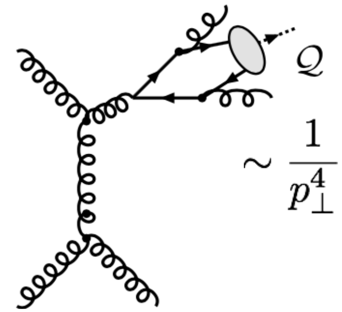
S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)



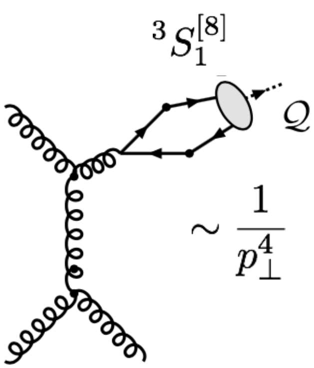
LO NLO



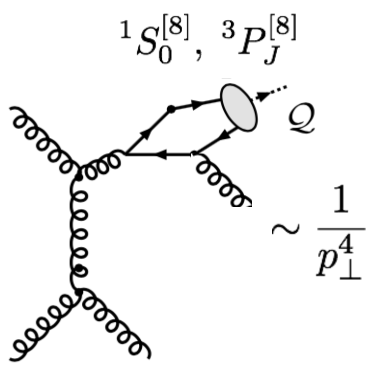
NLO



NNLO

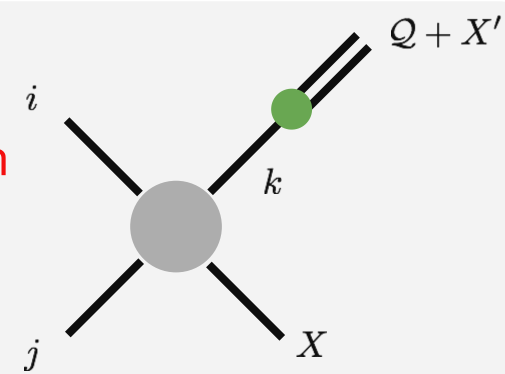


LO



NLO

(single) Parton fragmentation process



Octet contribution

Only a subset of contributions survive, now interpretable as parton fragmentation in quarkonia

LP example and applicability

$$\frac{d\sigma_h}{dp_\perp}(p_\perp)=\sum_i\int_z^1\frac{dx}{x}\,\frac{d\sigma_i}{dp_\perp}\left(\frac{p_\perp}{x},\mu\right)D_{i/h}(x,\mu)+\mathcal{O}\left(\frac{m_h^2}{p_\perp^2}\right)$$

$p_T \gg m_Q$

$$\ln\left(\frac{\mu}{p_T}\right)-\ln\left(\frac{\mu}{2m_Q}\right)\qquad d_{i/n}(x,\mu)\langle\mathcal{O}_n^h\rangle$$

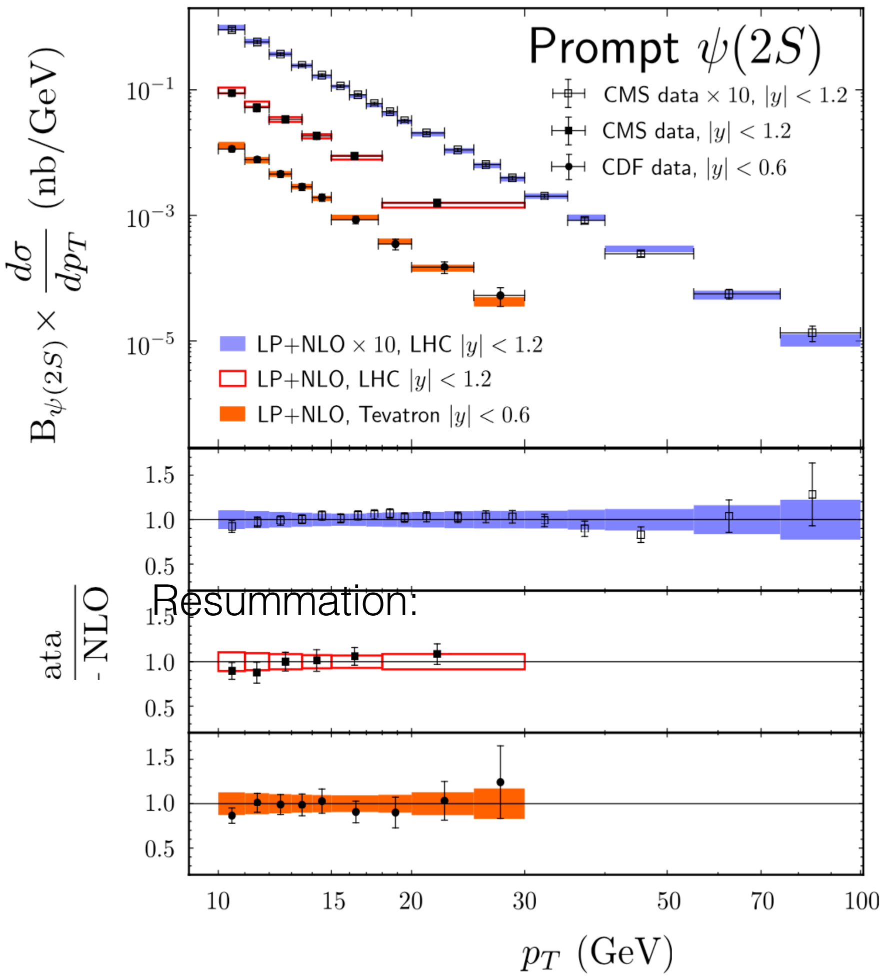
DGLAP Evolution

$$\mu\frac{d}{d\mu}D_{i/h}(z,\mu)=\sum_i\int_z^1\frac{dx}{x}\,P_{ij}(x)D_{i/h}\left(\frac{z}{x},\mu\right)$$

Resummation of $\ln(p_T/m_h)$

Contributions we take

Initiating parton / Mechanism	χ_{cJ}: ${}^3P_J^{[1]}$	χ_{cJ} and $J/\psi(1S)/\psi(2S)$: ${}^3S_1^{[8]}$	$J/\psi(1S)/\psi(2S)$: ${}^3P_J^{[8]}/{}^1S_0^{[8]}$	$J/\psi(1S)/\psi(2S)$: ${}^3S_1^{[1]}$
g	α_s^2	α_s	α_s^2	α_s^3
Q	α_s^2	α_s^2	α_s^3	α_s^2
q	α_s^3	α_s^2	α_s^3	α_s^4



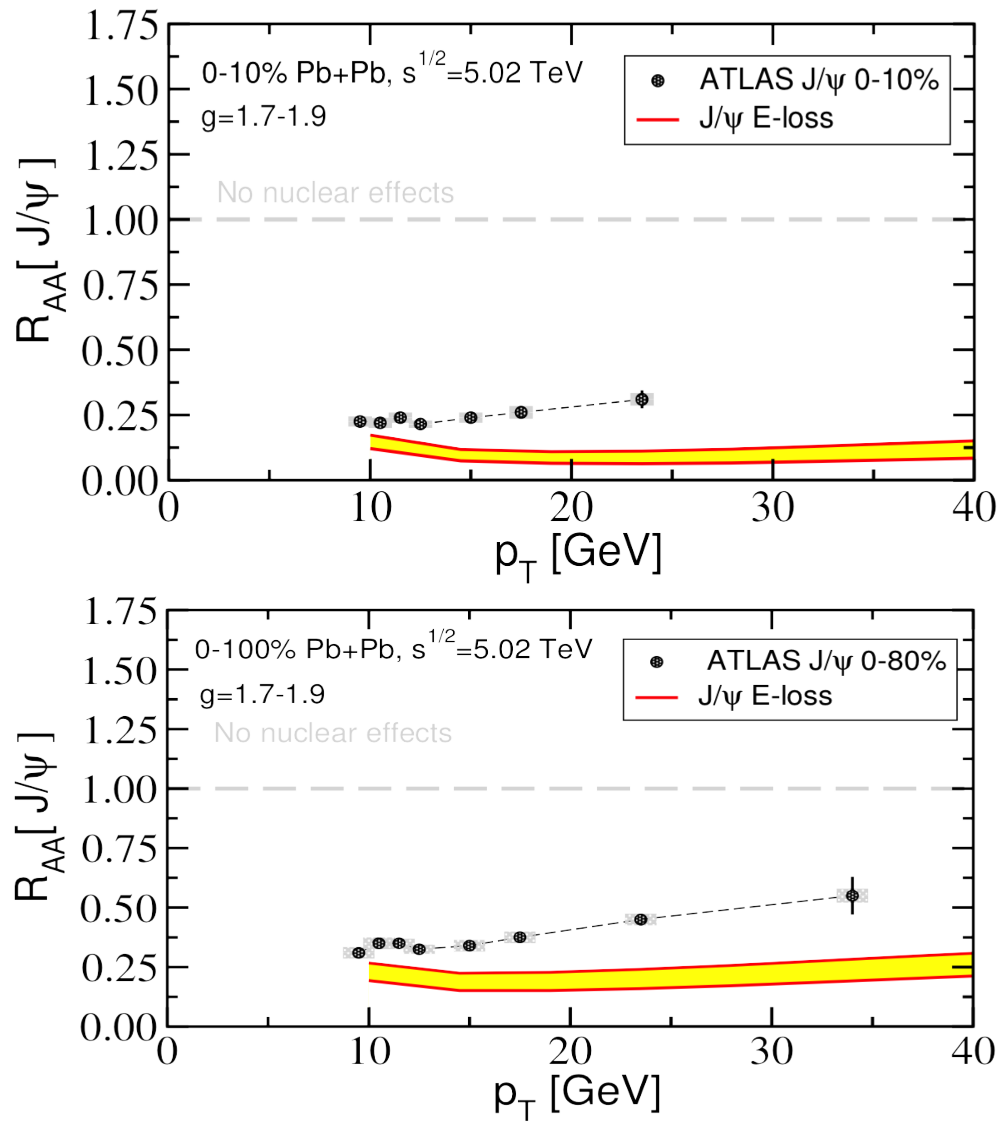
G. Bodwin *et al. (2016)*

Comparison of energy loss phenomenology to data

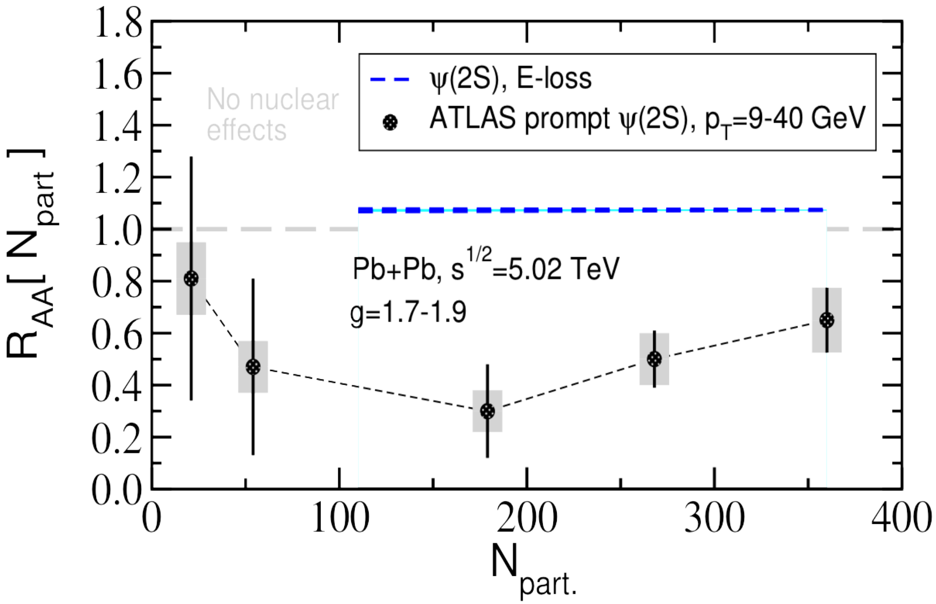
- Suppression of J/ψ overestimated by factor of 2 to 3. Included χ_c and ψ(2S) feeddown.
- Persists over centralities. Somewhat different p_T dependence
- Differences are significan

$$R_{AA}^{\text{min. bias}}(p_T) = \frac{\sum_i R_{AA}(\langle b_i \rangle) W_i}{\sum_i W_i}$$

$$W_i = \int_{b_{i\ \min}}^{b_{i\ \max}} N_{\text{coll.}}(b)\, \pi\, b\, db$$



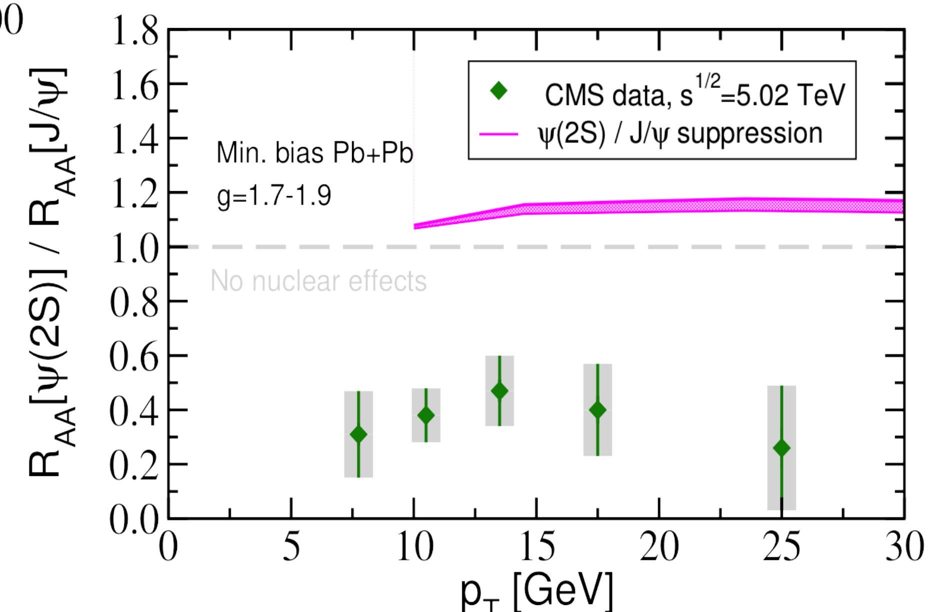
Double suppression ratio ψ(2S) / J/ψ



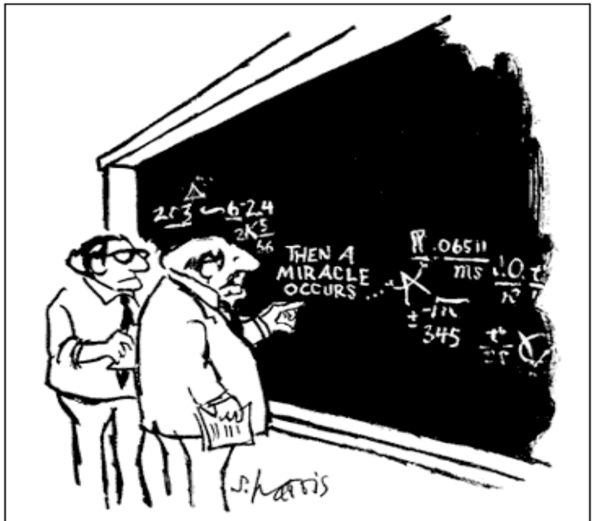
Makris and Vitev (2019)

- In the double suppression ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ the discrepancy is not simply in magnitude. There is a discrepancy in the sign of prediction

The energy loss picture of quarkonium suppression in the p_T range measured by ATLAS and CMS (up to 40 GeV) is definitively excluded

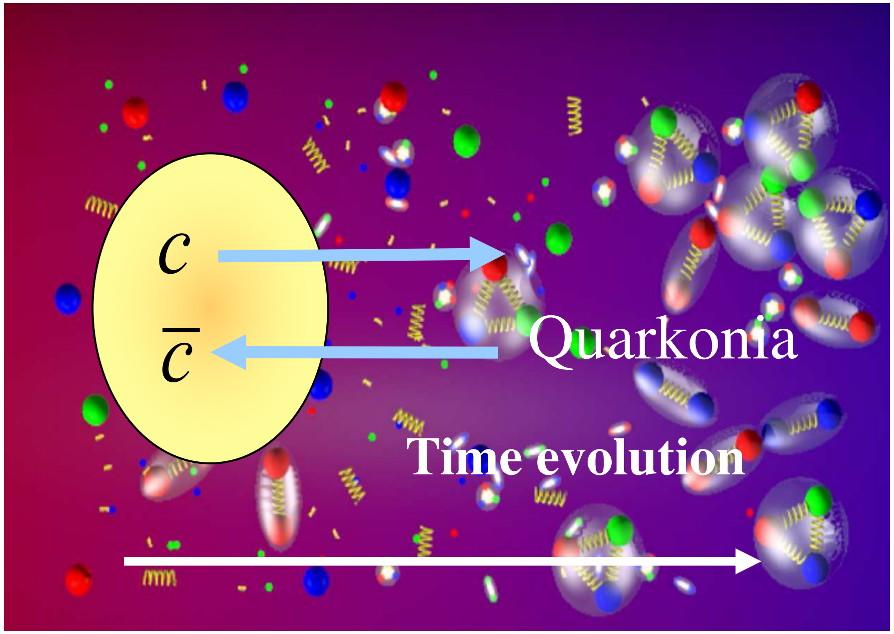


NRQCD with Glauber Gluons & phenomenology



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

NRQCD in a background medium



- Take a closer look at the NRQCD Lagrangian below

Scales in the problem

$p_s^\mu \sim m_Q v(1,1,1,1)$ soft ~ λ

$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$ ultrasoft ~ λ²

- Ultrasoft gluons included in covariant derivatives

- Soft gluons are included explicitly

  - Double soft gluon emission
  - Heavy quark-antiquark potential
  - (can also be interaction with soft particles)

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_p \left|p^\mu A_p^\nu - p^\nu A_p^\mu\right|^2 + \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \left\{ iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m} \right\}\psi_{\mathbf{p}}$$

$$-4\pi\alpha_s \sum_{q,q'\mathbf{p},\mathbf{p}'} \left\{ \frac{1}{q^0}\psi^\dagger_{\mathbf{p}'}\left[A^0_{q'},A^0_q\right]\psi_{\mathbf{p}} \right.$$

$$\left. + \frac{g^{\nu0}(q'-p+p')^\mu - g^{\mu0}(q-p+p')^\nu + g^{\mu\nu}(q-q')^0}{(\mathbf{p}'-\mathbf{p})^2}\psi^\dagger_{\mathbf{p}'}\left[A^\nu_{q'},A^\mu_q\right]\psi_{\mathbf{p}}\right\}$$

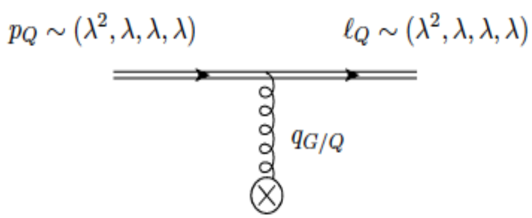
$$+\psi\leftrightarrow\chi,\ T\leftrightarrow\bar{T}$$

$$+\sum_{\mathbf{p},\mathbf{q}} \frac{4\pi\alpha_s}{(\mathbf{p}-\mathbf{q})^2}\psi^\dagger_{\mathbf{q}}T^A\psi_{\mathbf{p}}\chi^\dagger_{-\mathbf{q}}\bar{T}^A\chi_{-\mathbf{p}} + \dots$$

Allowed interactions in the medium

- At the level of the Lagrangian

$$\mathcal{L}_{\mathrm{NRQCD}_G} = \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A^{\mu,b}_{s}, A^{\mu,a}_{G/C}) + \psi \longleftrightarrow \chi$$



Possible scaling for the virtual gluons interacting with the heavy quarks

$$\begin{array}{lll} & & \quad\; 0 \quad 1 \quad 2 \quad 3 \qquad\; + \quad - \quad \perp \\ (1) & q_G \sim & (\lambda^2, \lambda^1, \lambda^1, \lambda^2) \sim (\lambda^2, \lambda^2, \boldsymbol{\lambda}_{\perp})_n \\ (2) & q_C \sim & (\lambda^2, \lambda^1, \lambda^1, \lambda^1) \sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_{\perp})_n \end{array}$$

- Energy component must always be suppressed
- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

- Calculated the leading power and next to leading power contributions 3 different ways

Background field method	**Perform a shift in the gluon field in the NRQCD Lagrangian then perform the power-counting**
Hybrid method	**From the full QCD diagrams for single effective Glauber/Coulomb gluon perform the corresponding power-counting, read the Feynman rules**
Matching method	**Full QCD diagrams describing the forward scattering of incoming heavy quark and a light quark or a gluon. We also derive the tree level expressions of the effective fields in terms of the QCD ingredients**

Example of the background field method

- Perform the label momentum representation and field substitution (u.s. -> u.s. + Glauber)

$$\psi(x) \to \sum_{\mathbf{p}} \psi_{\mathbf{p}}(x) \,,$$

$$iD_\mu \to \mathcal{P}_\mu + i\partial_\mu - g(A^\mu_U + A^\mu_{G/C})$$

$$iD_t = \underbrace{i\partial_t - gA^0_U - gA^0_G}_{\sim \lambda^2} \,,$$

$$i\mathbf{D} = \underbrace{\boldsymbol{\mathcal{P}}}_{\sim\lambda} - \underbrace{(i\boldsymbol{\partial} + g\mathbf{A}_U + g\mathbf{n}A^{\mathbf{n}}_G)}_{\sim\lambda^2} + \mathcal{O}(\lambda^3) \,,$$

$$\mathbf{E} = \partial_t(\mathbf{A}_U + \mathbf{A}_G) + (\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}})(A^0_U + A^0_G) + gT^c f^{cba}(A^0_U + A^0_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a$$
$$= \underbrace{i\boldsymbol{\mathcal{P}}_\perp A^0_G}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) \,,$$

$$\mathbf{B} = -(\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}}) \times (\mathbf{A}_U + \mathbf{A}_G) + \frac{g}{2}T^c f^{cba}(\mathbf{A}_U + \mathbf{A}_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a$$
$$= -\underbrace{(i\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})\, A^{\mathbf{n}}_G}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) \,.$$

Example for a collinear source (note results depend on the type of source)

Substitute, expand and collect terms up to order λ^3

- Results: depend on the type of the source of scattering in the medium

Leading medium corrections

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^0_{G/C}\Big)\psi_{\mathbf{p}} \quad (collinear/static/soft).$$

Sub-leading medium corrections

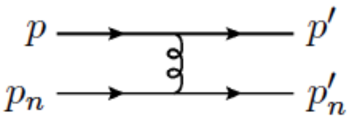
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_G) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\big[(\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})A^{\mathbf{n}}_G\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = 0 \quad (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2\mathbf{A}_C\cdot\boldsymbol{\mathcal{P}} + [\boldsymbol{\mathcal{P}}\cdot\mathbf{A}_C] - i\big[\boldsymbol{\mathcal{P}}\times\mathbf{A}_C\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (soft)$$

The QCD forward scattering diagram expansion

- Looking at t-channel scattering we can also extract the form of the Glauber/Coulomb fields in terms of QCD ingredients (and recover Lagrangian)

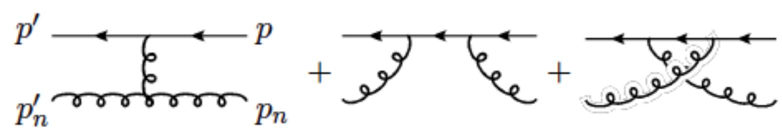
$t_{coll.} =$ 

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \bar{\xi}_{n,\ell-\mathbf{q}_T} \frac{\bar{\not{n}}}{2} (gT^a) \xi_{n,\ell}$$

Coulomb field for soft source

$$A_C^{\mu,a} \equiv \frac{1}{\mathbf{q}^2} \sum_\ell \bar{\phi}_{\ell-\mathbf{q}} \gamma^\mu (gT^A) \phi_\ell$$

$t_{g-coll.} =$ 

$$= t^{(0)}_{g-coll.} + t^{(1)}_{g-coll.} + \mathcal{O}(\lambda^2) \,.$$

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{i}{2} g f^{abc} \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \left[\bar{n} \cdot \mathcal{P} \left(\mathbf{B}^{b(0)}_{n\perp,\ell-\mathbf{q}_T} \cdot \mathbf{B}^{c(0)}_{n\perp,\ell} \right) \right]$$

Coulomb field for soft source

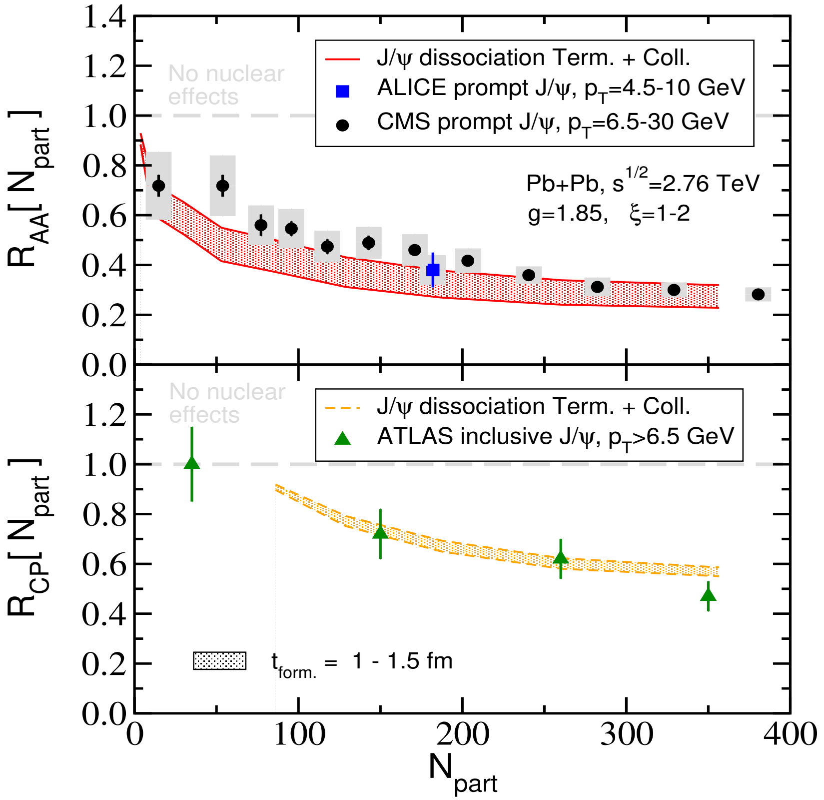
Y. Makris et al. (2019)

$$A_C^{\mu,a} = f^{abc} \frac{ig}{2\,\mathbf{q}^2} \sum_\ell \left\{ \left[\mathcal{P}^\mu \left(\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \mathbf{B}^{c(0)}_{s,\ell} \right) \right] - 2 (\mathbf{B}^{c(0)}_{s,\ell} \cdot \left[\boldsymbol{\mathcal{P}}) B^{\mu,b(0)}_{s,\ell-\mathbf{q}} \right] - 2 (\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \left[\boldsymbol{\mathcal{P}}) B^{\mu,c(0)}_{s,\ell} \right] \right\}$$

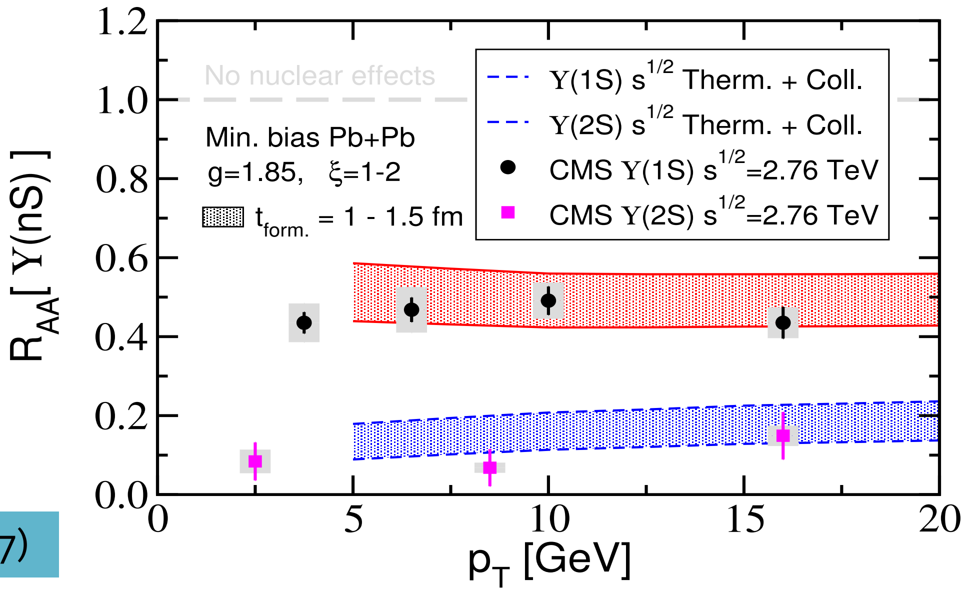
- Note that for the gluon the last 2 diagrams are necessary for gauge invariance but the first diagram the leading forward scattering contribution
- In the medium the momentum exchange can get dressed ~ Debye screening

Possible phenomenology applications

- Phenomenology built so far is cobnnected the leading term – collisional dissociation, thermal effects put in quarkonium wavefunctions. Also there is the approximation of averaging over all final color states



- If one takes into account the modification of the heavy quark potential in the medium - distinct suppression of ground and excited states



R. Sharma et al. (2012)

S. Aronson et al. (2017)

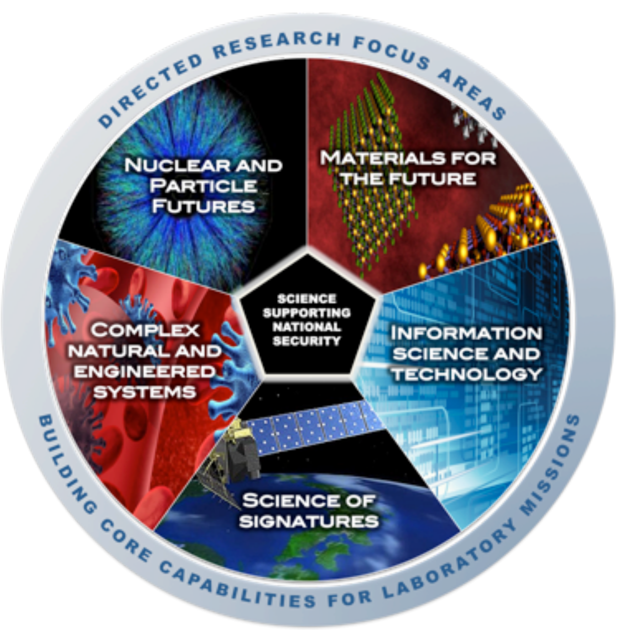
Conclusions

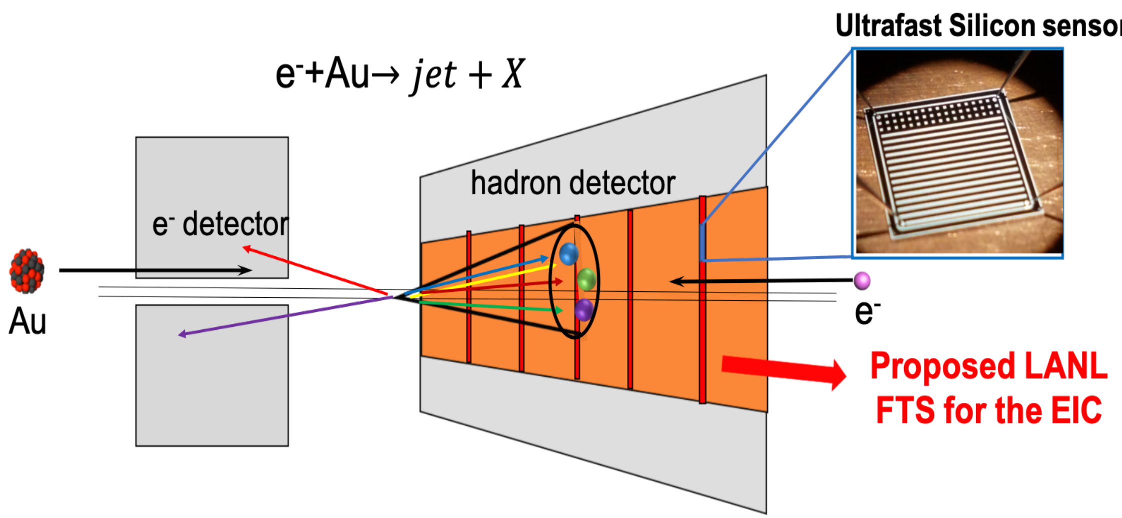
- Effective theories of QCD have enabled important conceptual and technical breakthroughs in our understanding of strong interactions and very significant improvement in the accuracy of the theoretical predictions
- An effective theory for jet propagation in matter $SCET_G$ was constructed (collinear and Glauber sectors). Derived all medium-induced parton splittings now to any order in opacity. Developed a new code for plitting kernel grids to second order in opacity
- Performed the first calculation of inclusive heavy jet production (c-jets, b-jets) in heavy ion reactions using the semi-inclusive jet function approach and presented a framework/evaluation of the jet charge in reactions ith nuclei
- In the the leading power factorization (high p_T) limit of NRQCD we investigated energy loss phenomenology and showed that it severely overpredicts the J/ψ modification and gives the wrong hierarchy of ground/excited suppression
- Motivated by this we constructed an effective theory of quarkonia in matter - $NRQCD_G$. Derived the Feynman rules (3 different ways) to leading and subleading power for different sources of interactions in the medium. We showed the connection to existing quarkonium dissociation phenomenology

Conclusions

- LANL just made a very large investment in EIC science - $1.5M over 3 years
- Comes in the form of a LDRD project. PI. I. Vitev, Co-PI Xuan Li

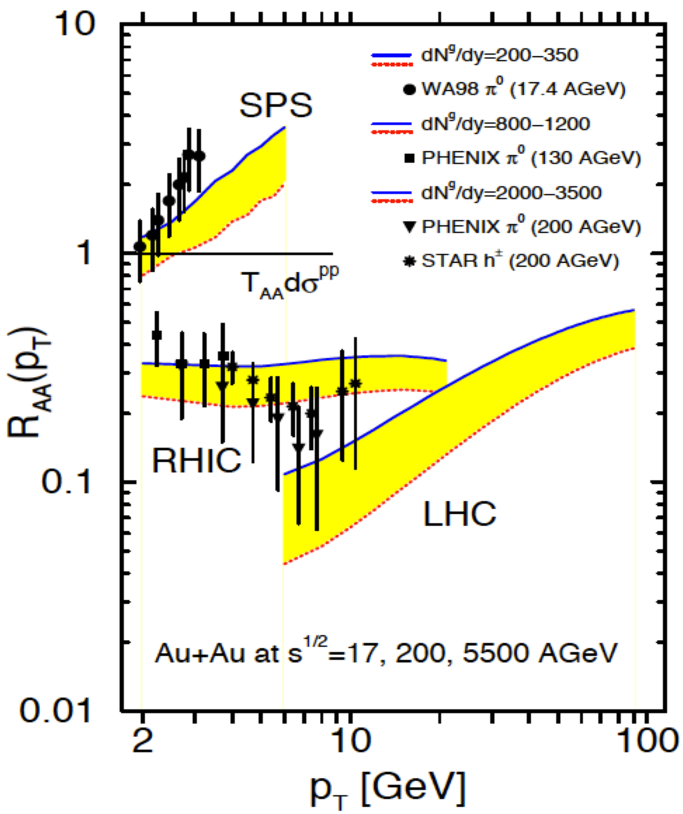
- Develop a prototype forward silicon tracker. Heavy flavor physics and jets
- Develop associated theory





Improving upon traditional E-loss

- While still LO, it predicted in 2002, 2006 – the R_{AA} at high p_T for both RHIC and LHC



Include the quenched parton and the radiative gluon fragmentation

- Difficult to make connection to the standard LO, NLO, …; LL, NLL … pQCD approach (higher orders and resummation)
- There is considerable model dependence and it is difficult to systematically improve this approach

I. Vitev et al. (2002)

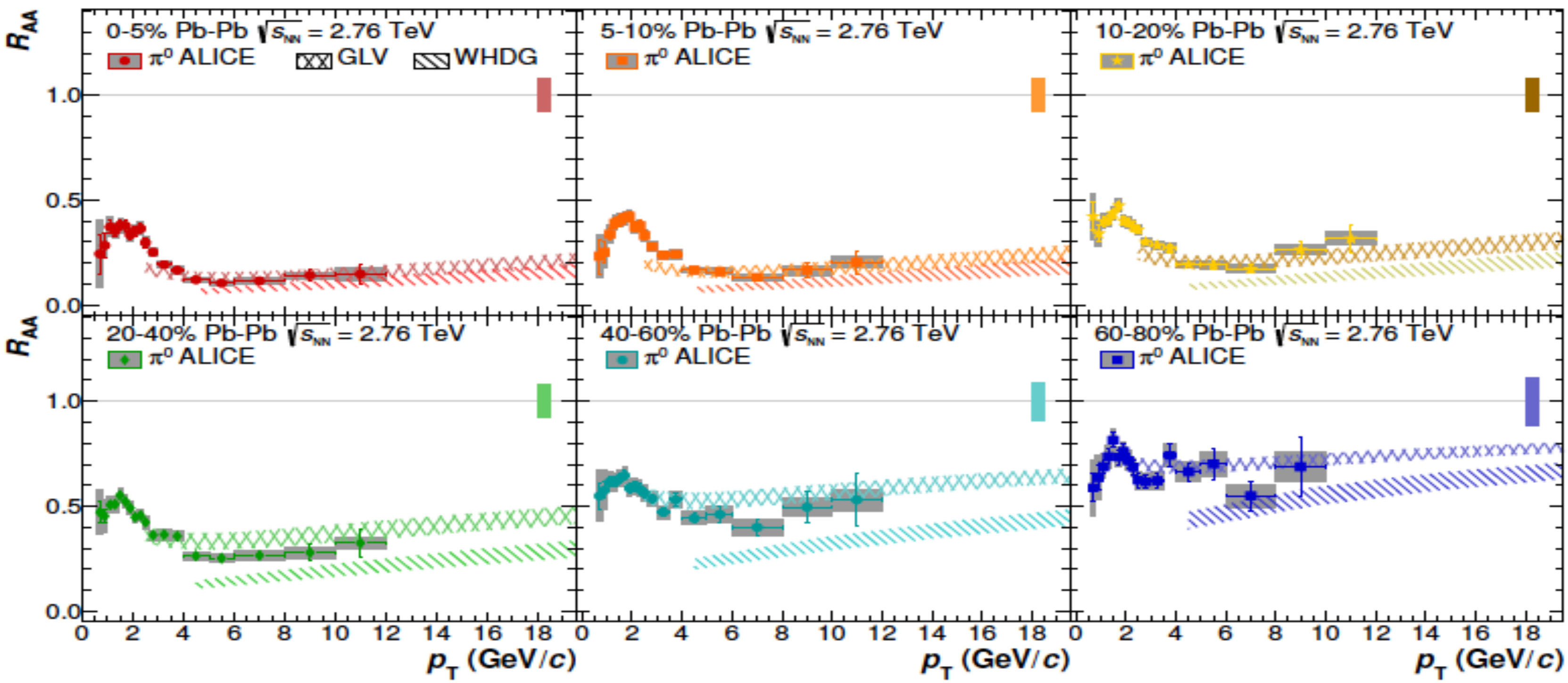
Reminder – traditional energy loss phenomenology

$$\int_0^1 d\epsilon\, P(\epsilon) = 1\ , \quad \int_0^1 d\epsilon\, \epsilon\, P(\epsilon) = \left\langle \frac{\Delta E}{E} \right\rangle \qquad D_c^{\mathrm{quench}}(z) = \int_0^{1-z} d\epsilon\, \frac{P_c(\epsilon)}{(1-\epsilon)} D_c\left(\frac{z}{1-\epsilon}\right)$$

M. Gyulassy et al. (2002)

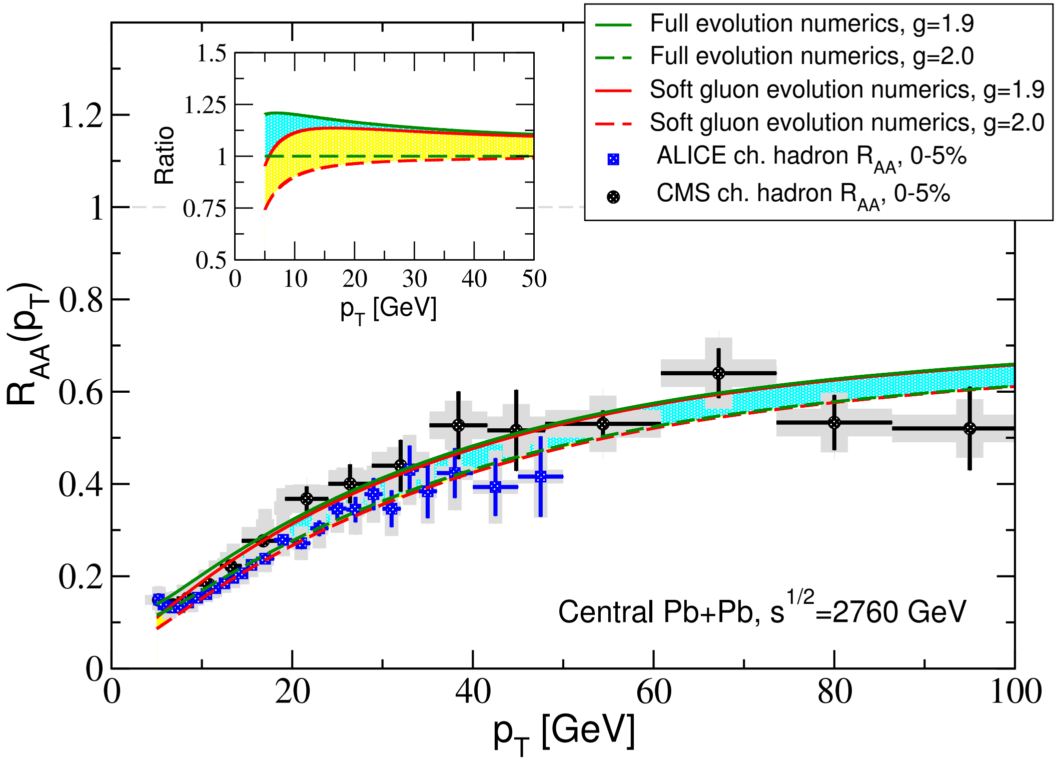
Successfully predicted the energy and transverse momentum dependence of R_{AA}

ALICE Collab. (2014)



Numerical results: full-x vs small-x evolution

- Implement the fully numerical solution of the DGLAP evolution equations: the full splitting kernels and the soft gluon limit (small x)



- The coupling between the jet and the medium can be constrained to the same accuracy - 5%
- Full evolution woks slightly better at low virtualities

The jet scattering kinematics

- Kinematics and channels

t – jet broadening and energy loss

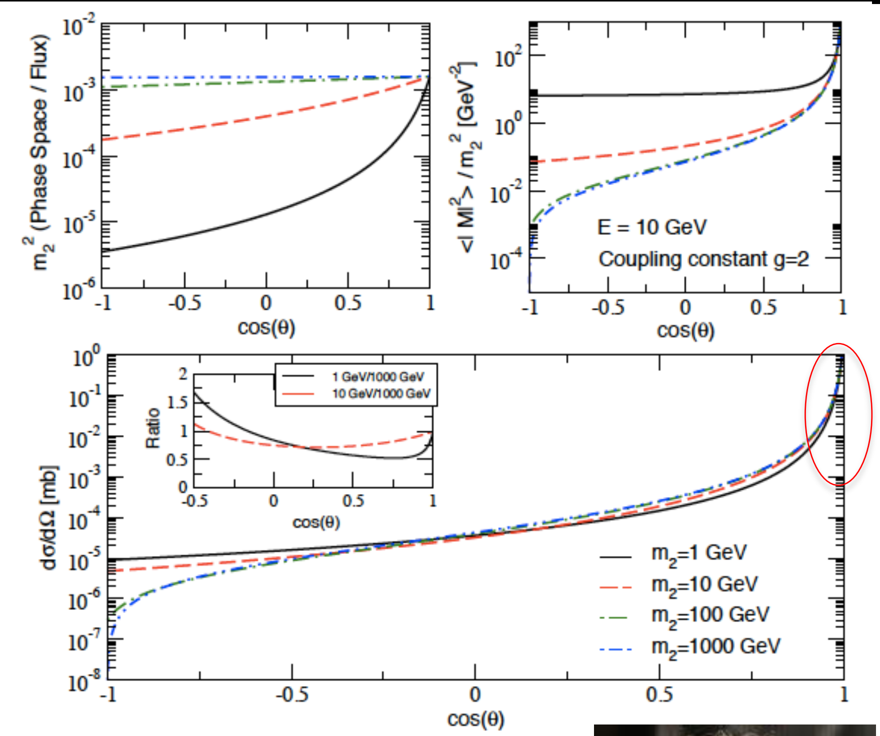
s– isotropisation

u - backward hard scattering

- Fully dynamic medium recoil, cross section reduction (5% – 15%). Completely dominated by forward scattering

$$\frac{d\sigma}{d\Omega} \rightarrow \frac{d\sigma}{d^2\mathbf{q}_\perp} = \frac{C_2(R)C_2(T)}{d_A}\frac{|v(\mathbf{q}_\perp; E, m_1, m_2)|^2}{(2\pi)^2}$$

- Galuber gluon / Glauber mode



$$q = (\lambda^2, \lambda^2, \lambda)Q$$

A. Idilbi et al. (2008)

In-medium parton splittings and properties

- Direct sum

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

- Derived using $\mathrm{SCET_G}$
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium

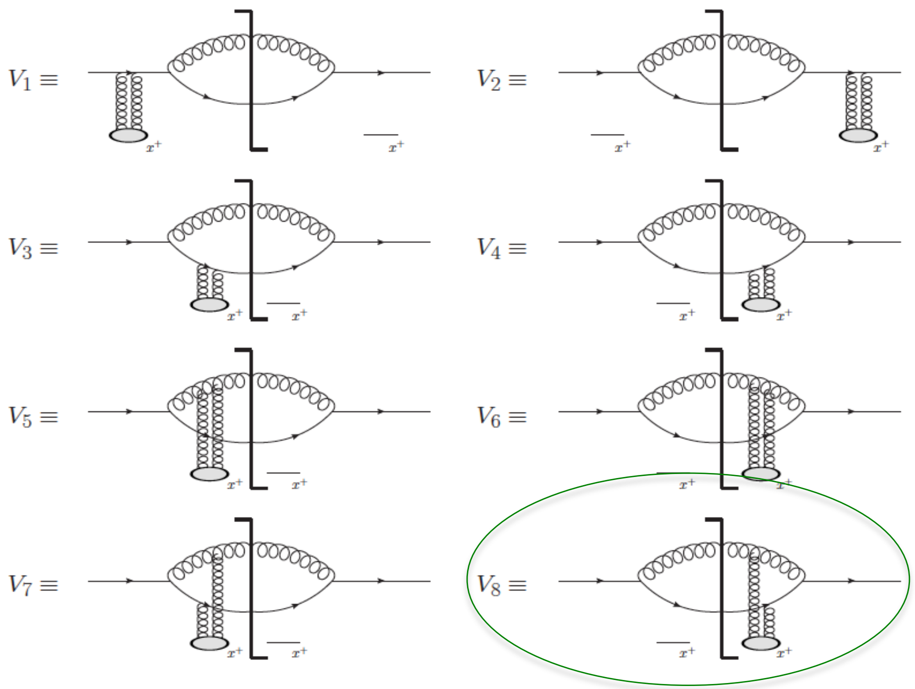
G. Ovanesyan et al. (2012)

$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp}\left[-\left(\frac{A_\perp}{A_\perp^2}\right)^2+\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2}-\frac{C_\perp}{C_\perp^2}\right)\right.$$
$$\times(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\frac{C_\perp}{C_\perp^2}\cdot\left(2\frac{C_\perp}{C_\perp^2}-\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+\frac{B_\perp}{B_\perp^2}\cdot\frac{C_\perp}{C_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])+\frac{A_\perp}{A_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{D_\perp}{D_\perp^2}\right)\cos[\Omega_4\Delta z]$$
$$\left.+\frac{A_\perp}{A_\perp^2}\cdot\frac{D_\perp}{D_\perp^2}\cos[\Omega_5\Delta z]+\frac{1}{N_c^2}\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right].$$

$N.B.\ x \to 1-x \qquad A,\ldots D,\Omega_1\ldots\Omega_5 - functions(x,k_\perp,q_\perp)$

$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{\left\{\begin{array}{c} g\to q\bar{q} \\ g\to gg \end{array}\right\}} = \left\{\begin{array}{c}\frac{\alpha_s}{2\pi^2}T_R\left(x^2+(1-x)^2\right) \\ \frac{\alpha_s}{2\pi^2}2C_A\left(\frac{x}{1-x}+\frac{1-x}{x}+x(1-x)\right)\end{array}\right\}\int d\Delta z\left\{\begin{array}{c}\frac{1}{\lambda_q(z)} \\ \frac{1}{\lambda_g(z)}\end{array}\right\}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp}$$
$$\times\left[2\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2}-\frac{A_\perp}{A_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+2\frac{C_\perp}{C_\perp^2}\cdot\left(\frac{C_\perp}{C_\perp^2}-\frac{A_\perp}{A_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])\right.$$
$$+\left\{\begin{array}{c}\frac{1}{N_c^2-1} \\ -\frac{1}{2}\end{array}\right\}\left(2\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{C_\perp}{C_\perp^2}\right)+2\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{C_\perp}{C_\perp^2}\right)\cos[(\Omega_1-\Omega_2)\Delta z]\right.$$
$$+2\frac{C_\perp}{C_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\cos[(\Omega_1-\Omega_3)\Delta z]+2\frac{C_\perp}{C_\perp^2}\cdot\frac{B_\perp}{B_\perp^2}\cos[(\Omega_2-\Omega_3)\Delta z]$$
$$\left.\left.-2\frac{A_\perp}{A_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{D_\perp}{D_\perp^2}\right)\cos[\Omega_4\Delta z]-2\frac{A_\perp}{A_\perp^2}\cdot\frac{D_\perp}{D_\perp^2}\cos[\Omega_5\Delta z]\right)\right].$$

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)

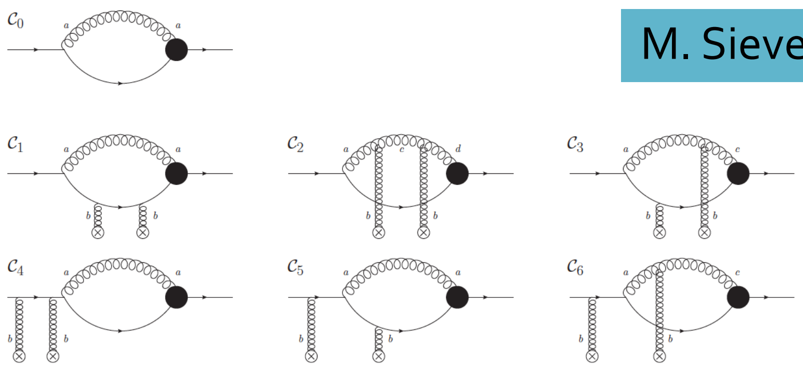
- A more interesting diagram- Double born can contribute to virtuality changes

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

Parton branching to any order in opacity

- Treating color (one complication in QCD).

M. Sievert et al . (2018)



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

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

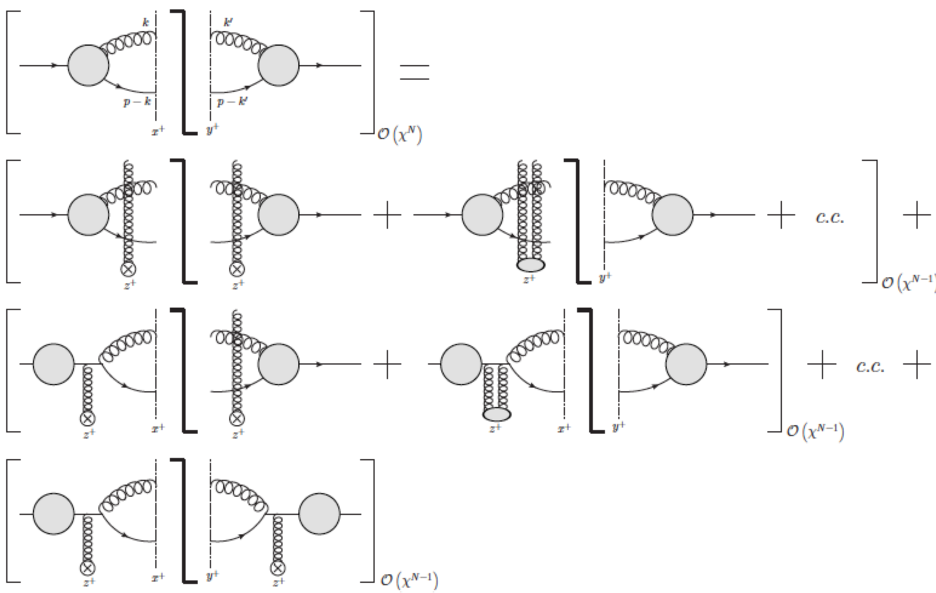
$$\mathcal{C}_3 = \frac{1}{N_c C_F} f^{acb}\mathrm{tr}[t^b t^a M^c] = \frac{iN_c}{2C_F}\,\mathcal{C}_0\,,$$

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

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

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

- 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



Explicit solution to second order in opacity

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

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

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

$$\mathcal{N}_1 =$$

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

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

⋮

+ 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

Corrections in QCD medium

Collisional energy loss evaluated from operator definition. Included in the LO splitting function

Neufeld, Vitev, Xing, 2014

$$J^{\text{med},(0)}_{J_Q/i}(z, p_T, \delta p^i_T) = z\delta_{iQ}\left[\delta\left(1 - z - \frac{\delta p^i_T}{p_T + \delta p^i_T}\right) - \delta(1-z)\right]$$

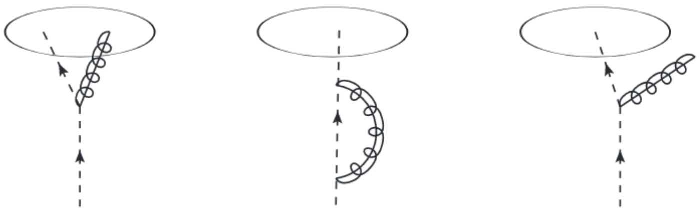
Medium corrections to the NLO jet function are written in terms of integrals over splitting functions. First developed for light jets.

Kang, Ringer, Vitev, 2017

For the heavy quark example

$$Q \to J_Q \quad B = \delta(1-z)\int_0^1 dx \int_0^{x(1-x)p_T R} dq_\perp P^{\text{med}}_{QQ}(z, m, q_\perp)$$

$$C = -\delta(1-z)\int_0^1 dx \int_0^{\mu} dq_\perp P^{\text{med}}_{QQ}(z, m, q_\perp)$$



After summing over all diagrams

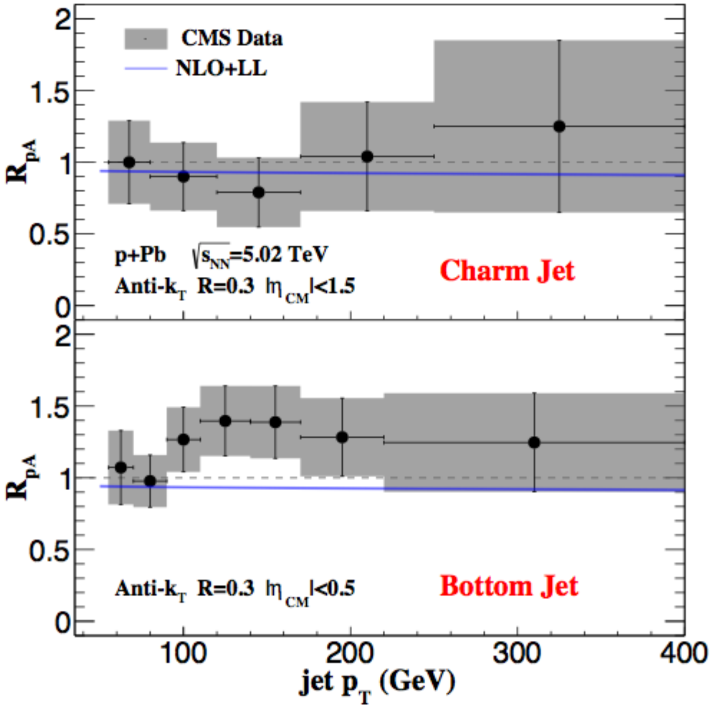
Haitao Li, Vitev, 2018

$$J^{\text{med},(1)}_{J_Q/Q}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\text{med}}_{QQ}(z, m, q_\perp)\right]_+$$

$$J^{\text{med},(1)}_{J_s/g}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\text{med}}_{Qg}(z, m, q_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\text{med}}_{Qg}(z, m, q_\perp)$$

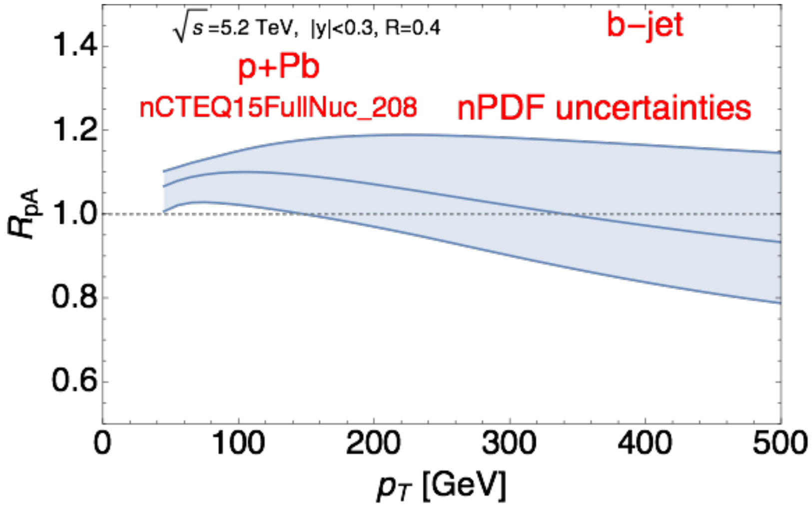
Full in-medium splitting functions are now evaluated in the hydro medium

R_{AA} in p-A collisions



Measurements:

- Large uncertainty
- Not enough to fully constrain the cold nuclear matter effects



Theory:

- Very little with jet transverse momentum and scale variation
- There is not an obvious difference between c-jet and b-jet
- In Pb+Pb collisions the effects will be amplified

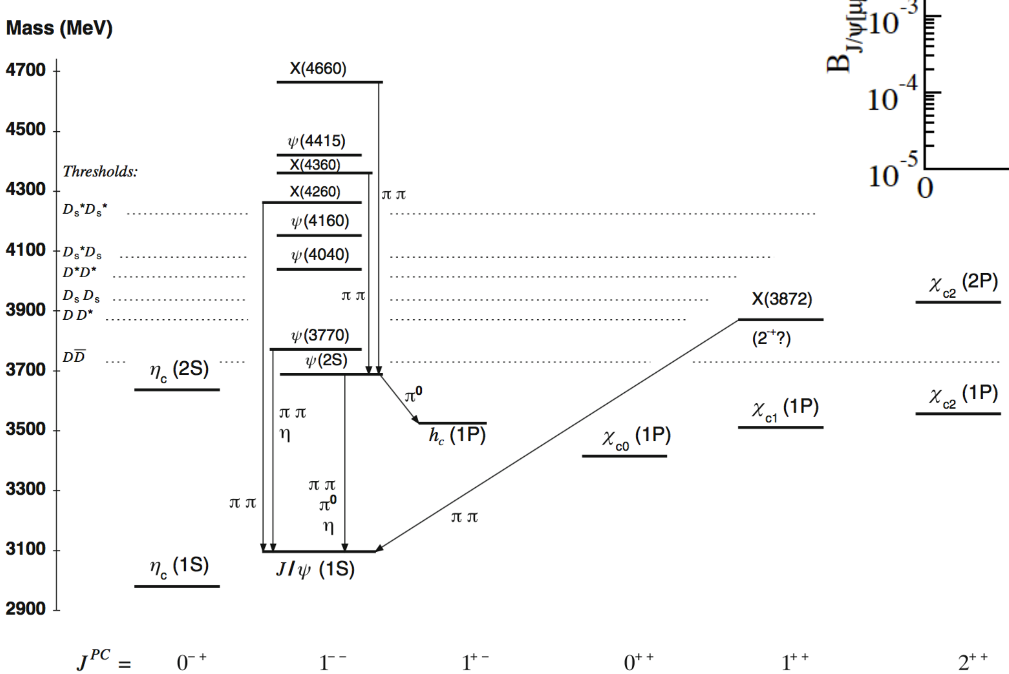
Naively speaking:

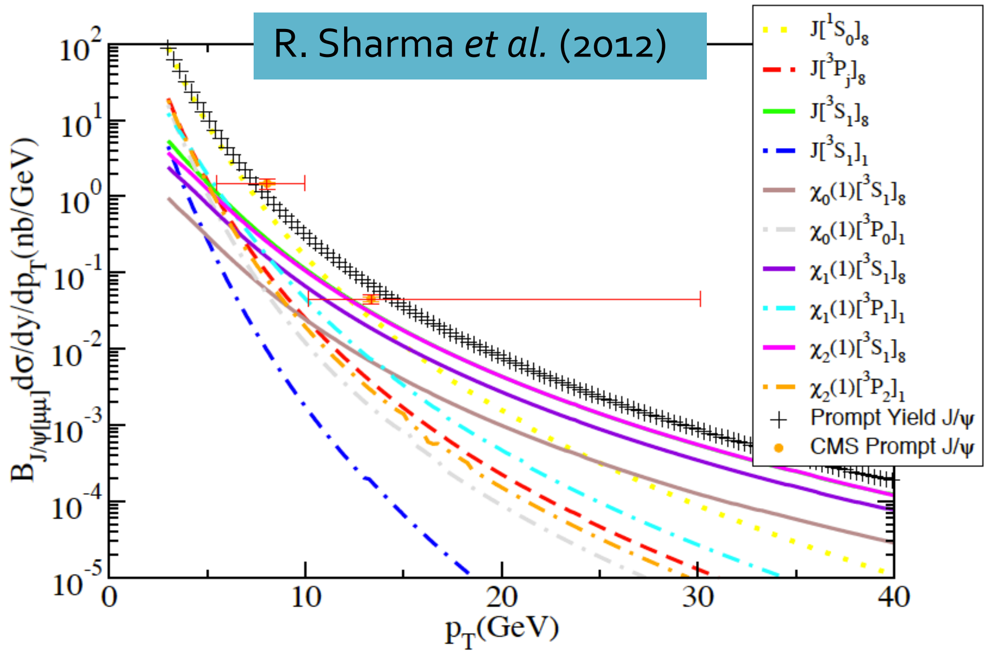
$$\mathrm{Pb+Pb}: \quad \underbrace{(1\pm\epsilon)}_{\mathrm{Pb}}\underbrace{(1\pm\epsilon)}_{\mathrm{Pb}}$$

Feeddown is important

- Example of NRQCD calculation. You see both different high p_T behavior and feeddown

Charmonium states





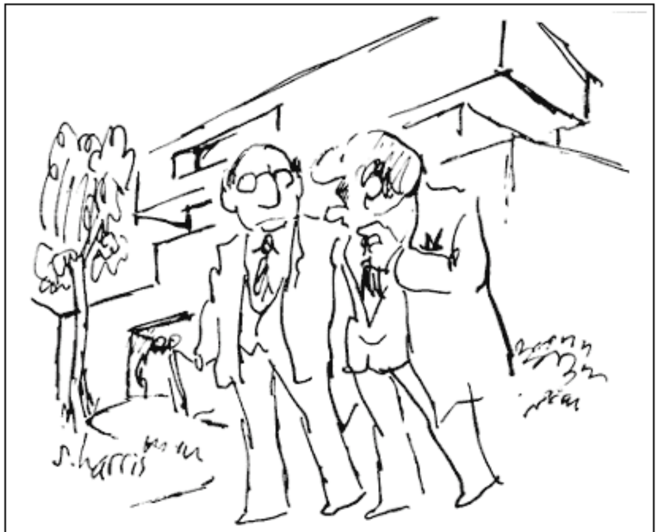
Following feeddown contributions taken, others small

$$\psi(2S): \quad \mathrm{Br}\left[\psi(2S) \to J/\psi + X\right] = 61.4 \pm 0.6\%$$

$$\chi_{c1}: \quad \mathrm{Br}\left[\chi_{c1} \to J/\psi + \gamma\right] = 34.3 \pm 1.0\%$$

$$\chi_{c2}: \quad \mathrm{Br}\left[\chi_{c2} \to J/\psi + \gamma\right] = 19.0 \pm 0.5\%$$

Energy loss results for quarkonia, constraints



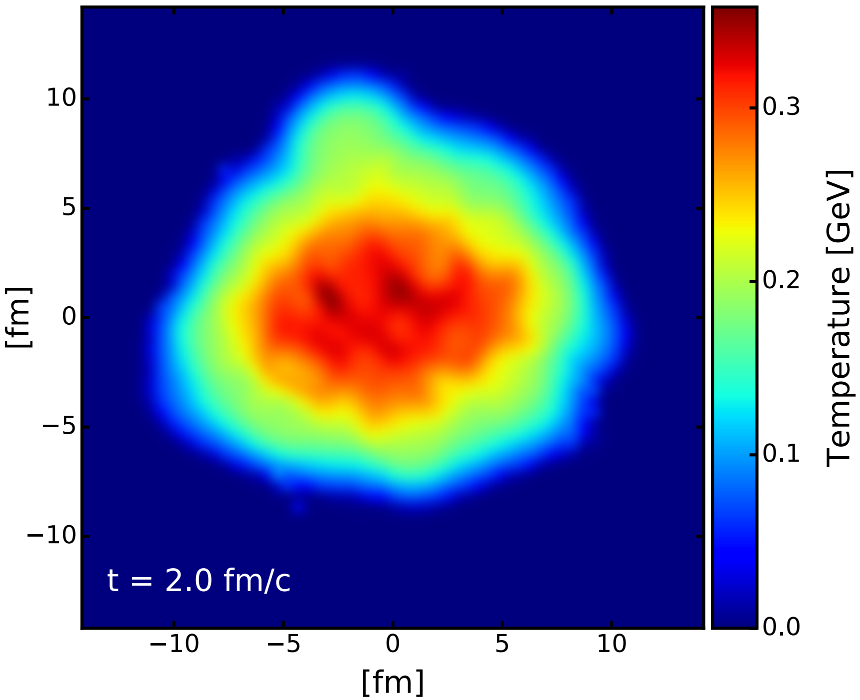
"I'm firmly convinced that behind every great man is a great computer."

Energy loss evaluation in hydrodynamic medium

- Evaluate the splitting functions in the small x limit – corresponds to traditional energy loss phenomenology

Z. Kang *et al.* (2016)

- Can make contact with other claims in the literature



Evaluate the medium-induced emission spectrum. Construct the probability of energy loss due to multiple gluon emission

$$\int_0^1 d\epsilon P(\epsilon) = 1, \qquad \int_0^1 d\epsilon \epsilon P(\epsilon) = \left\langle \frac{\Delta E}{E} \right\rangle$$

M. Gyulassy *et al.* (2003)

C. Shen *et al.* (2014)

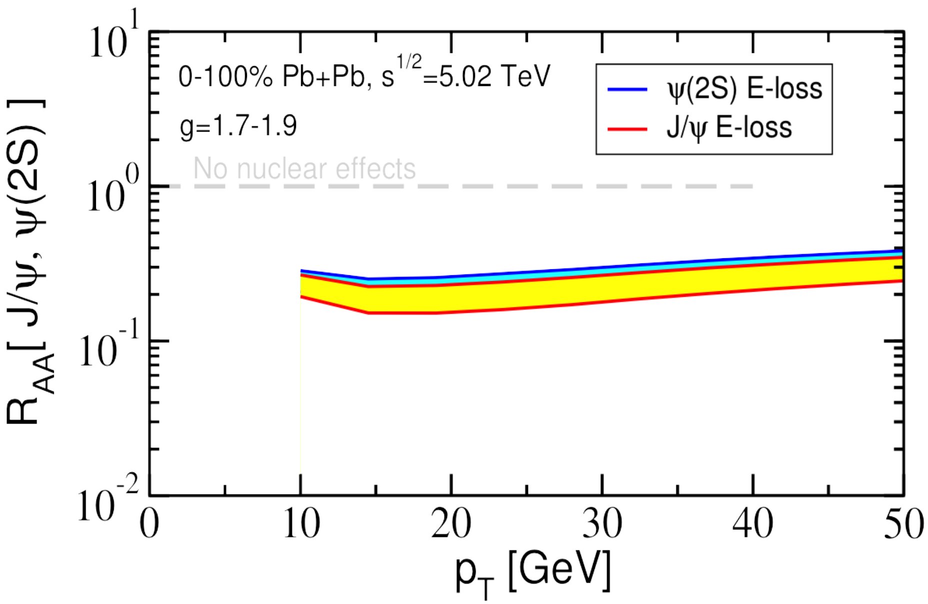
Obtain quenched partonic spectra with effective mass m_c and $2m_c$ where necessary

$$\frac{d\sigma_{AB}^{q,g\ Quench}(\mathbf{p})}{dyd^2\mathbf{p}} = \int_0^1 d\epsilon\ P(\epsilon) \frac{1}{(1-\epsilon)} \frac{d\sigma_{AB}^{q,g}\left(\frac{\mathbf{p}}{1-\epsilon}\right)}{dyd^2\mathbf{p}}$$

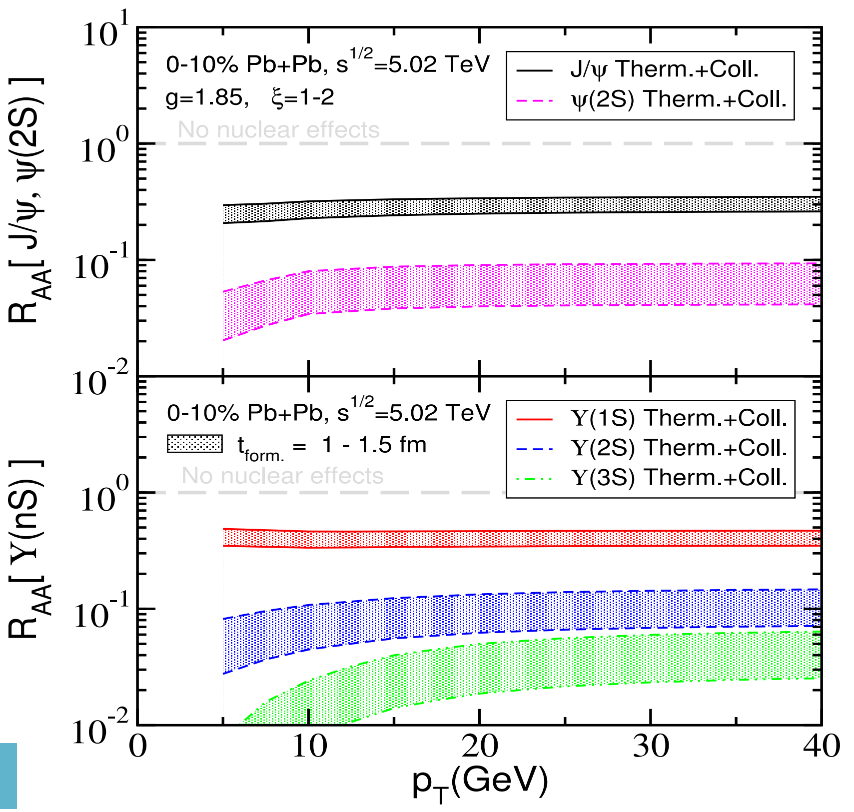
- Viscous second order Israel-Stewart event-by-event hydrodynamics

Comparison of energy loss vs dissociation models

- Completely different predictions for ground and excited states' suppression. Dissociation models depend on bunding, energy loss models depend on the flavor of partonic cross sections as steepness of spectra



Makris and Vitev (2019)



S. Aranson et al. (2017)