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# Application of SCET with Glauber gluons to heavy ion observables at NLO

SCET 2017
Wayne State U., Detroit, MI, March 14-16, 2017

# Plan for the talk

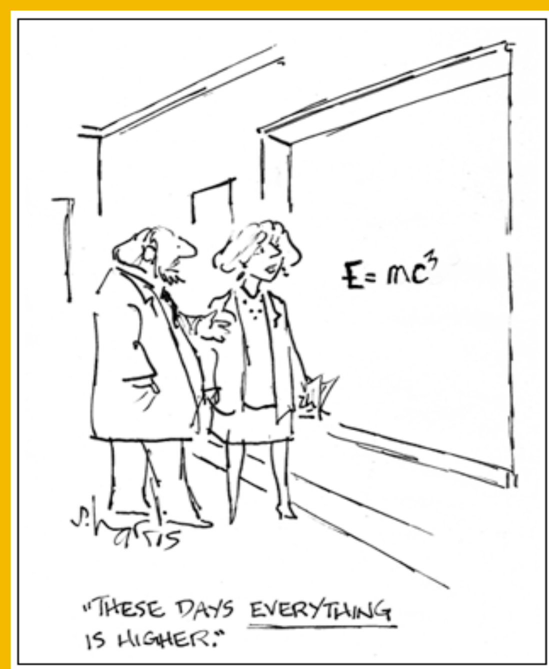
Thanks to the organizer / conveners for the invitation to SCET 2017

- Introduction
- An effective theory for heavy flavor propagation in matter $SCET_{M,G}$
- Applications of $SCET_{M,G}$ to open heavy flavor production at NLO
- Jet production in $SCET_G$ at NLO
- Application of $SCET_G$ in the traditional E-loss limit to V+Jet

Credit for the work shared my collaborators: Y.-T. Chien, A. Emerman, Z. Kang, R. Lashof-Regs, G. Ovanesyan, F. Ringer, P. Saad, H. Xing …

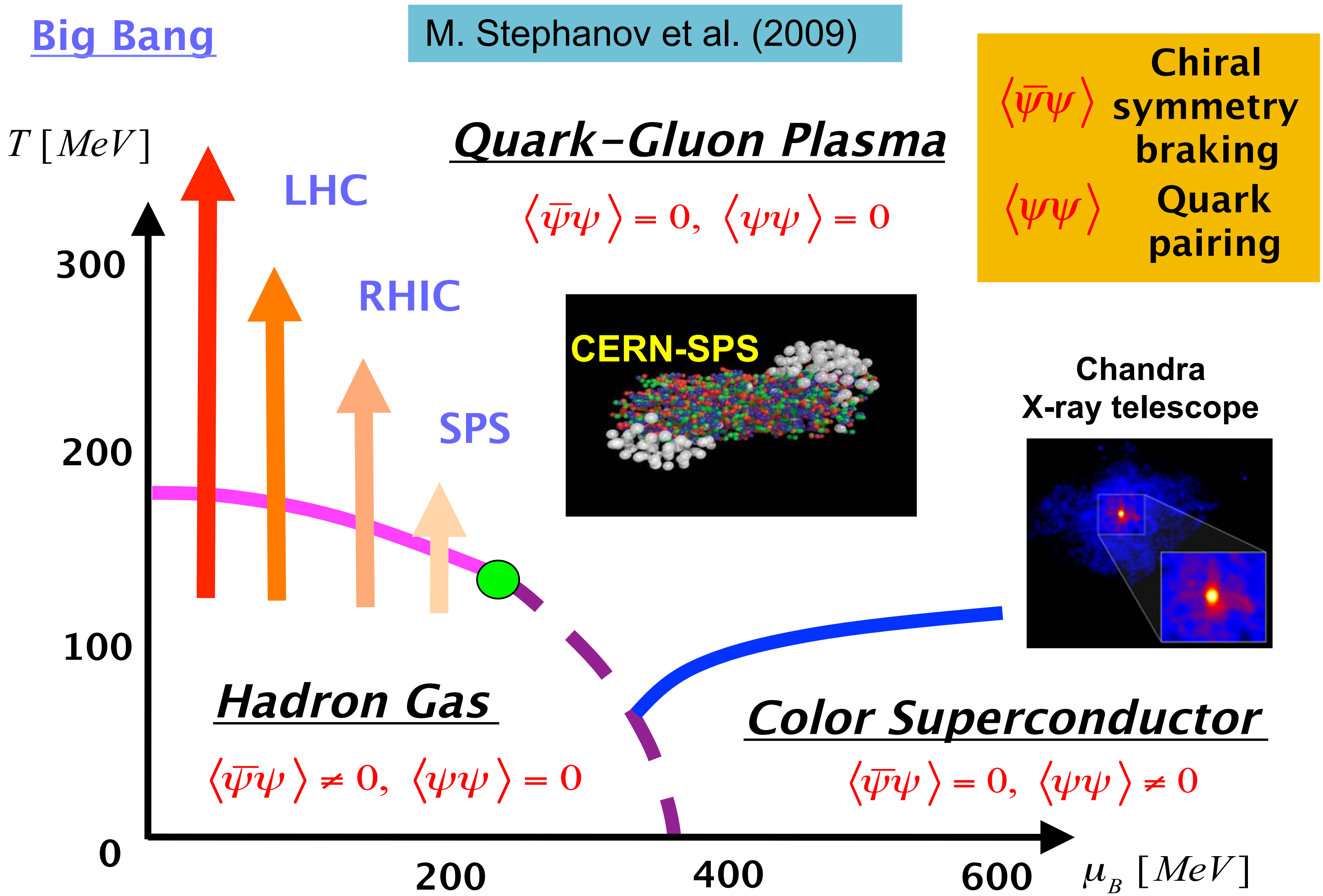
Largely based on ArXiv:1610.02043, ArXiv:1701.05839, ArXiv:1702.07276

# Introduction, motivation

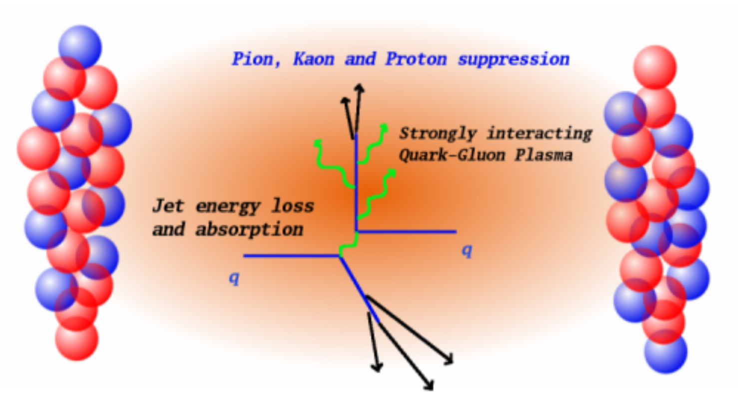


# The phase diagram of QCD



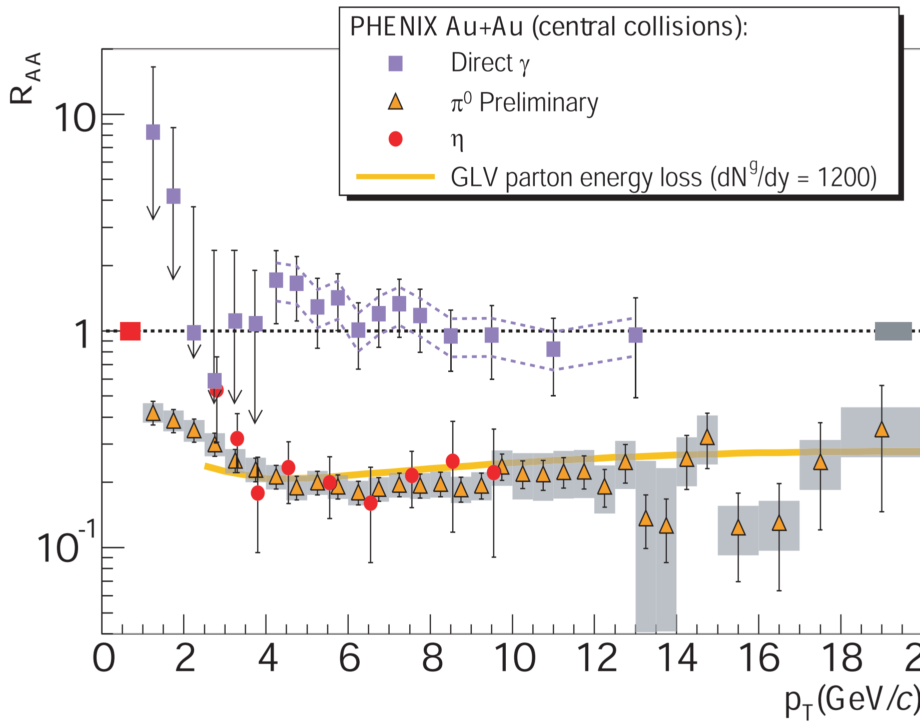
# Quenching of leading particles




▪ Jet quenching: suppression of inclusive particle production relative to a binary scaled p+p result

M. Gyulassy, et al. (1992)

$$R_{AA}(I_{AA}\ldots) = \frac{\mathrm{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\mathrm{Yield}_{pp}} = \frac{1}{\langle N_{binary}\rangle_{AuAu}}\frac{d\sigma_{AuAu}/dp_T dy}{d\sigma_{pp}/dp_T dy}$$




Jet quenching in A+A collisions has been regarded as one of the most important discoveries at RHIC

- Tested against alternative suggestions: CGC and hadronic transport models ✓
- Phenomenologically very successful ✓

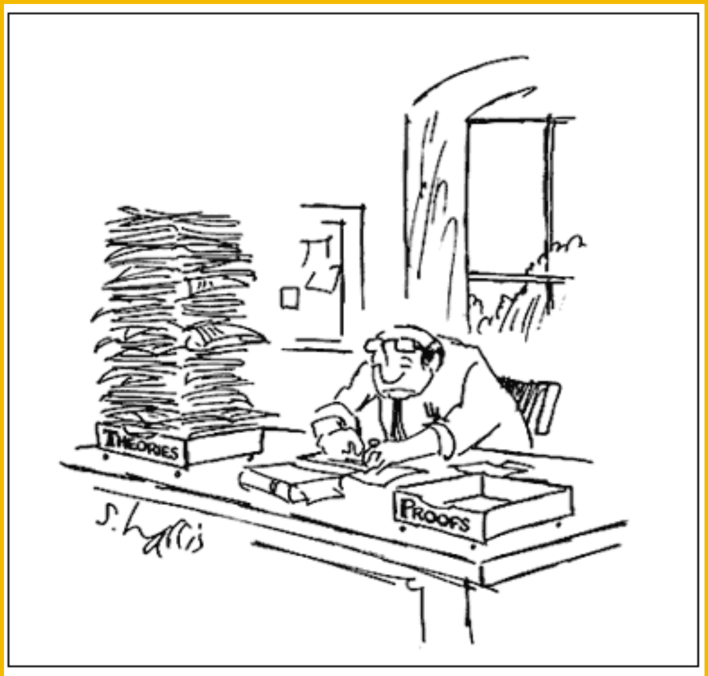
**Final-state interaction origin**

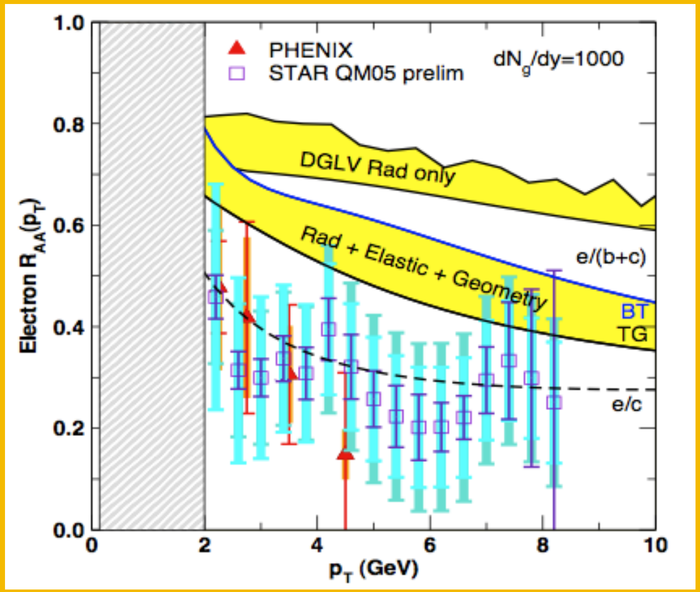
Also tested at LHC with W/Z boson cross sections

Adler, S. et al (2003)

Adams, J. et al. (2003)

# Open heavy flavor



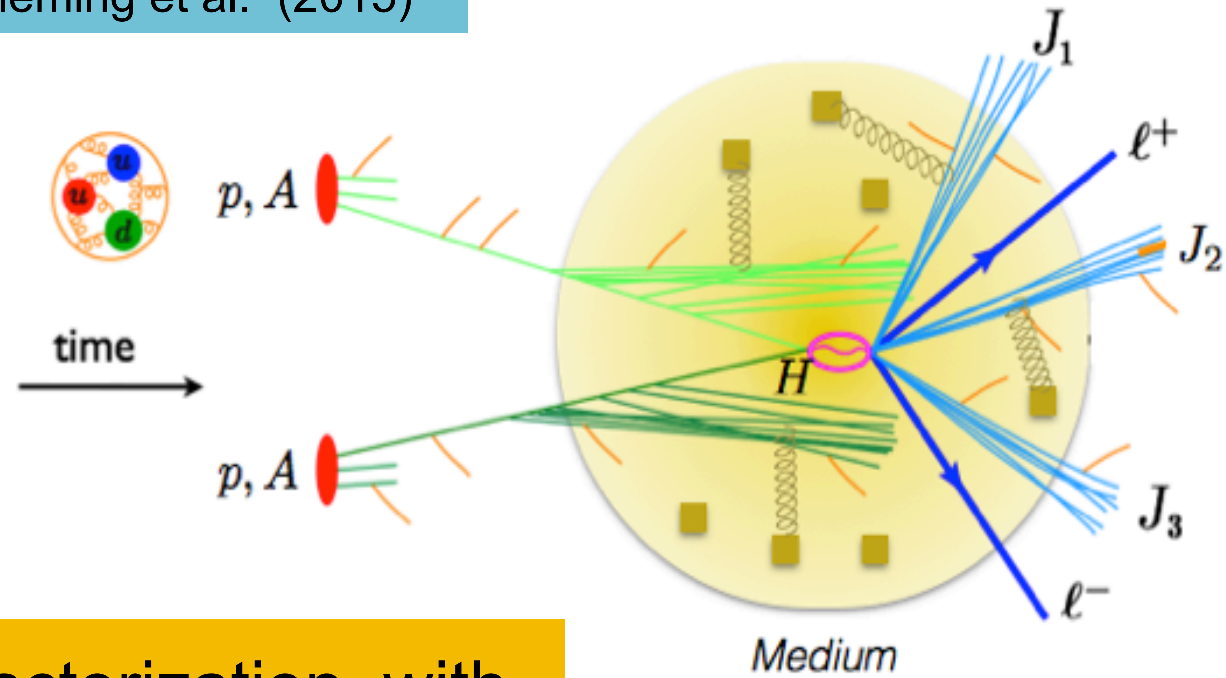
# Jet quenching in SCET

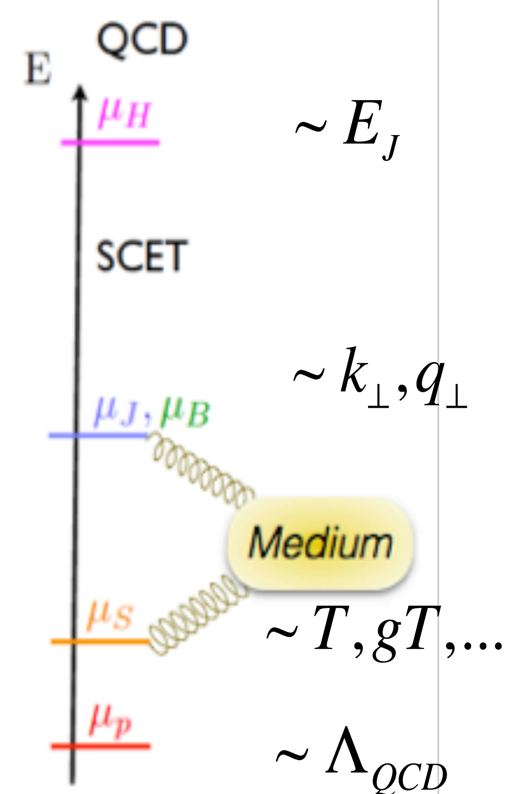
- There is no jet quenching in SCET. Still a multiscale problem, but needs extension

C. Bauer et al. (2001)

D. Pirol et al. (2004)

S. Fleming et al. (2015)




- Factorization, with modified J, B, S

$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j \, -$$

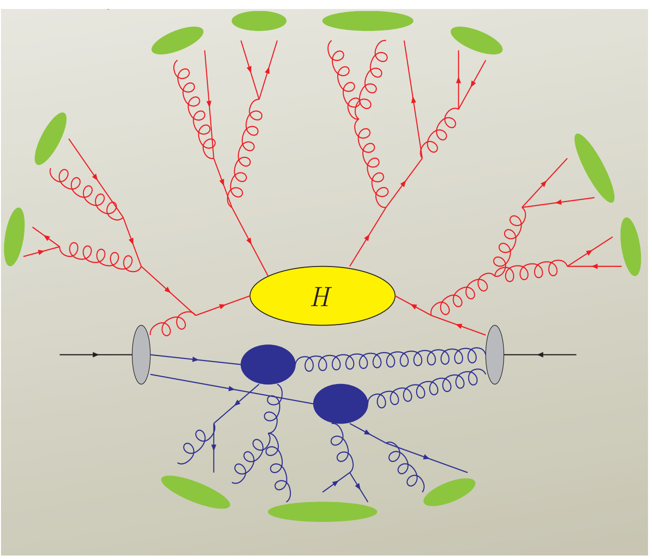
# The splitting kernels

- What is missing in the SCET Lagrangian is the interaction between the jet and the medium
- Background field approach

A. Idilbi et al. (2008)

G. Ovanesyan et al. (2011)

$$\mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_{\mathrm{G}}) = g \sum_{\tilde{p},\tilde{p}'} e^{-i(\tilde{p}-\tilde{p}')\cdot x} \left( \bar{\xi}_{n,p'} T^a \frac{\bar{\not{n}}}{2} \xi_{n,p} - i f^{abc} A^{\lambda c}_{n,p'} A^{\nu,b}_{n,p} g^{\perp}_{\nu\lambda} \bar{n} \cdot p \right) n \cdot A^a_{\mathrm{G}}$$




- Operator formulation for forward scattering / BFKL physics

I. Rothstein et al. (2016)

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

W. Waalewjin. (2014)

Gribov et al. (1972)

G. Altarelli et al. (1977)

Y. Dokshitzer (1977)

# Heavy quarks in the vacuum and the medium

$\mathrm{SCET}_{M,G}$ – for massive quarks with Glauber gluon interactions

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}(i\not{D} - m)\psi \quad iD^\mu = \partial^\mu + gA^\mu \quad A^\mu = A_c^\mu + A_s^\mu + A_{\mathrm{G}}^\mu$$

Feynman rules depend on the scaling of m. The key choice is $m/p^+ \sim\lambda$

I. Rothstein (2003)

A. Leibovich et al. (2003)

With the field scaling in the covariant gauge for the Glauber field there is no room for interplay with mass in the LO Lagrangian

$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2 m^2} \left[ \frac{1 - x + x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2 + x^2 m^2} \right]$$

$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_\perp^2 + m^2} \left[ x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_\perp^2 + m^2} \right]$$

The process is not written Q to gQ

F. Ringer et al . (2016)

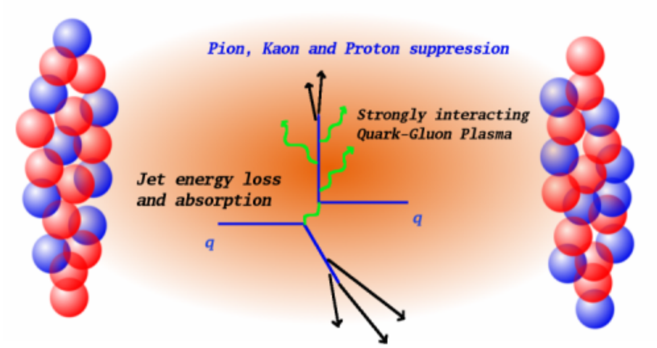
Result: $\mathrm{SCET}_{M,G} = \mathrm{SCET}_M \times \mathrm{SCET}_G$

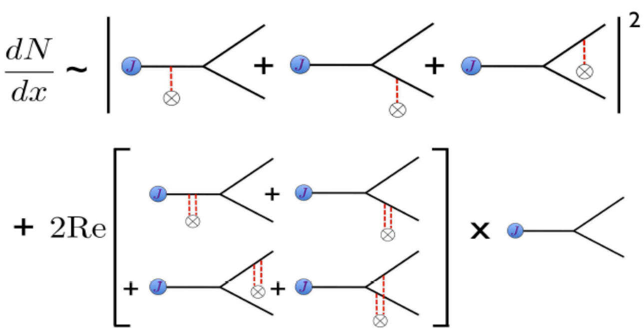
- You see the dead cone effects

  Dokshitzer et al. (2001)

- You also see that it depends on the process – it not simply $x^2m^2$ everywhere: $x^2m^2$, $(1-x)^2m^2$, $m^2$

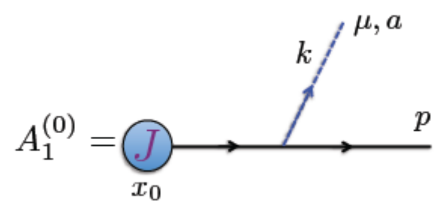
# Main results: in-medium splitting / parton energy loss



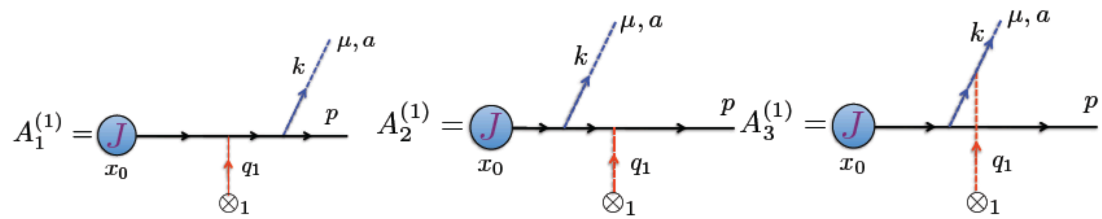



- Organizing principle – build powers of the scattering cross section in the medium

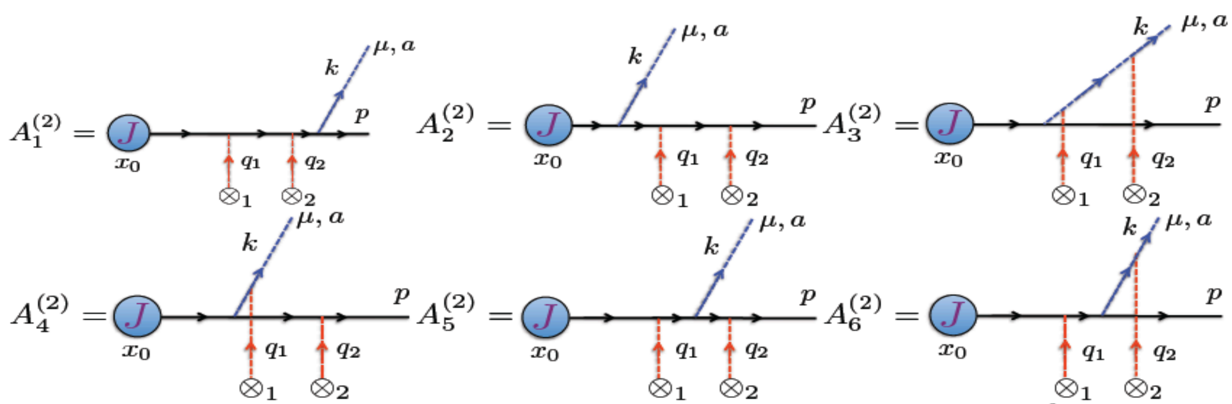
**"Vacuum" diagrams**



**Single Born diagrams**



**Double Born diagrams**



# Heavy quarks splitting functions in the medium

Kinematic variables

New physics – many-body quantum coherence effects

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

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

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

F. Ringer et al . (2016)

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

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

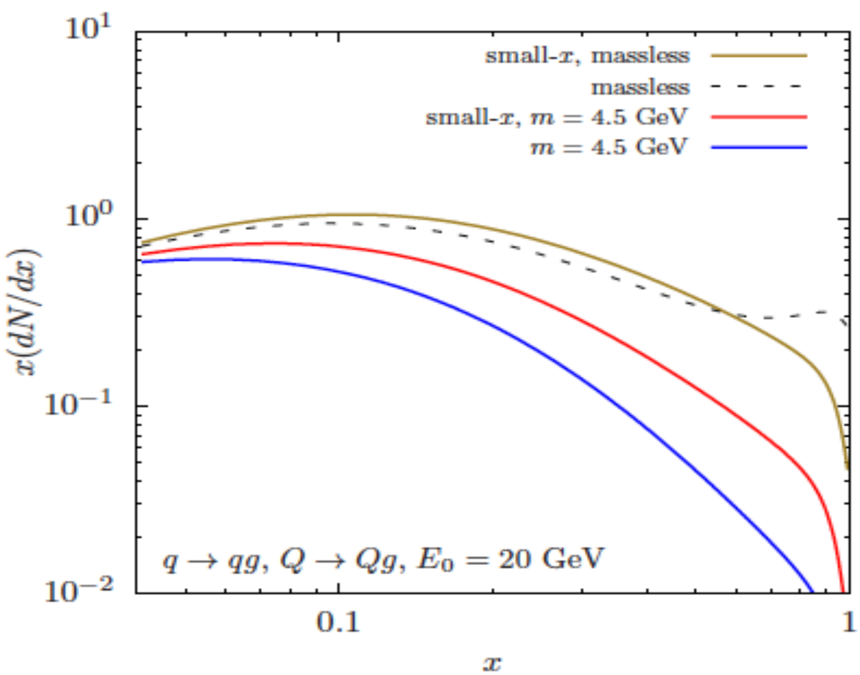
# Heavy quark energy loss limit

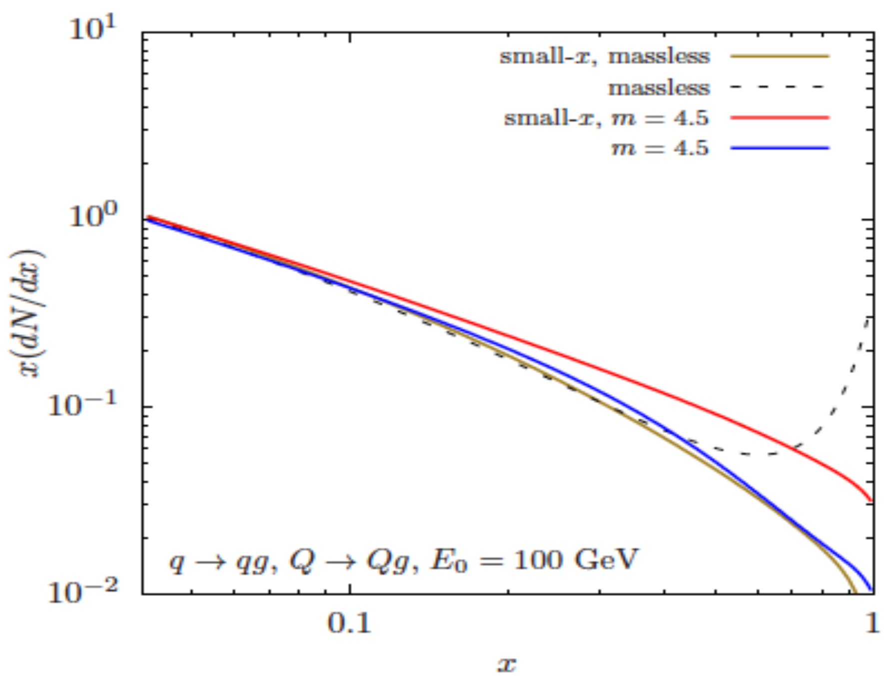
In the soft gluon emission (x → 0) energy loss limit only the diagonal splittings survive (Q to Qg)

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

M. Djordjevic et al . (2016)

$$\times \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2+x^2m^2][(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2]}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2}{xp_0^+}\Delta z\right].$$



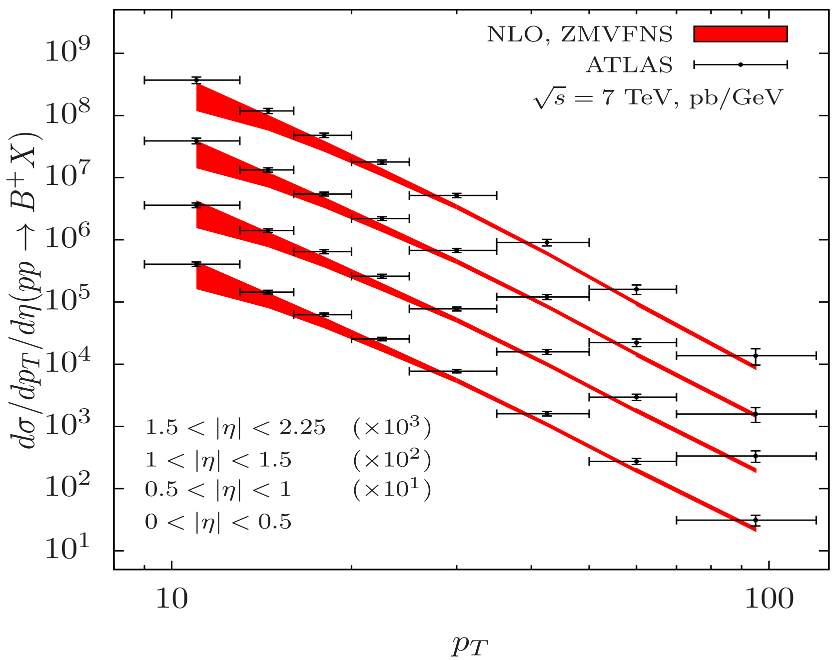



# ZMVFS open heavy flavor at NLO

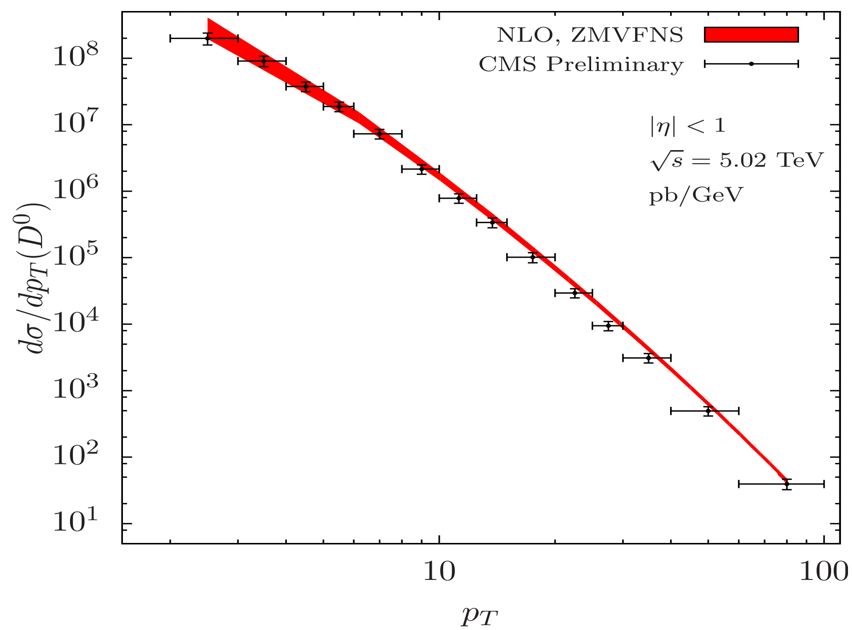
- Typically assumed that only c to D, b to B fragment perturbatively
- Perform an NLO calculation

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

B. Jager et al . (2002)




Kneesch et al . (2008)



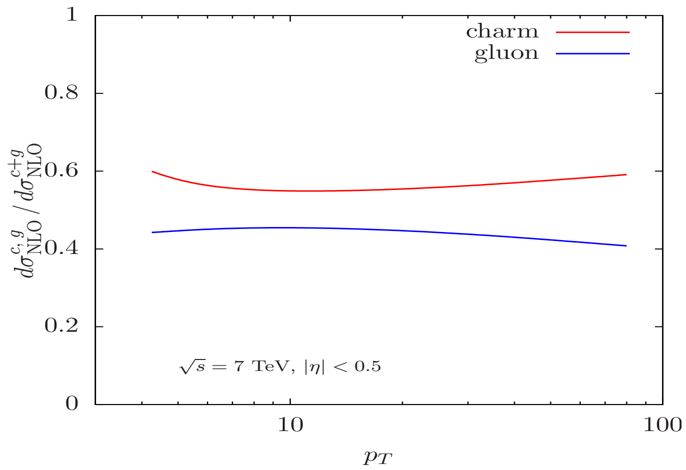

Kniehl et al . (2008)

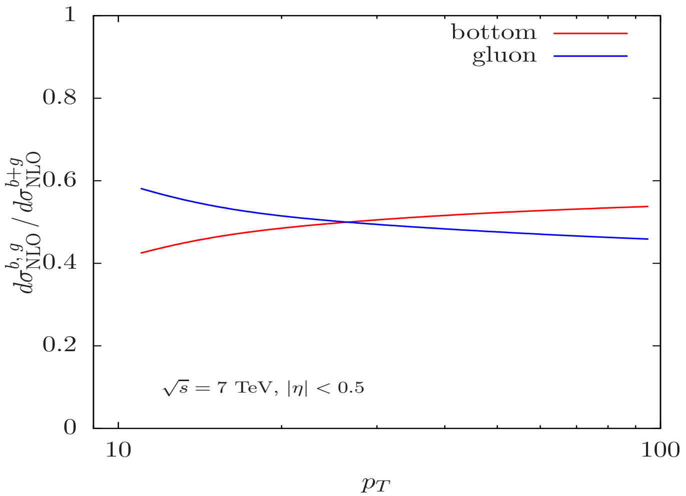
When $p_T > m_c, m_b$ **Factorization, non-perturbative physics is long distance**

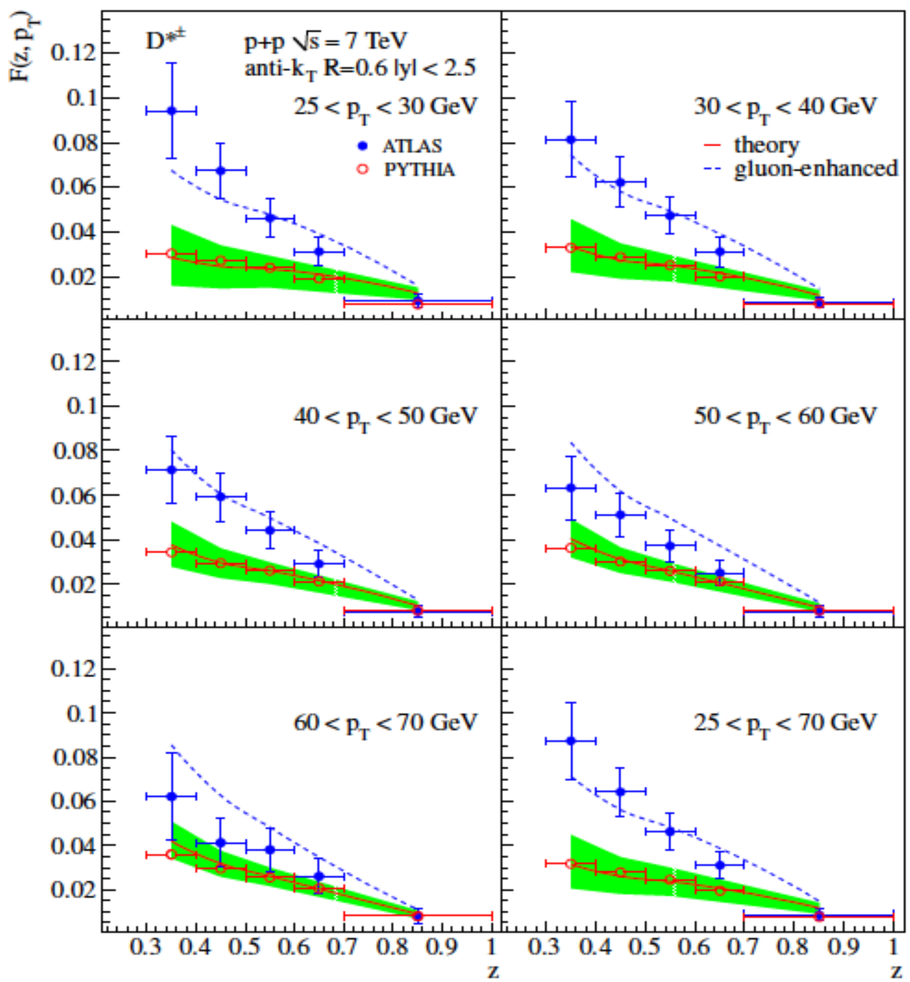
# Implications for heavy flavor modification

- A very large contribution of gluon FF to heavy flavor ~50%

**The important implication of this will affect the nuclear modification factor**




Y.T. Chien et al . (2015)

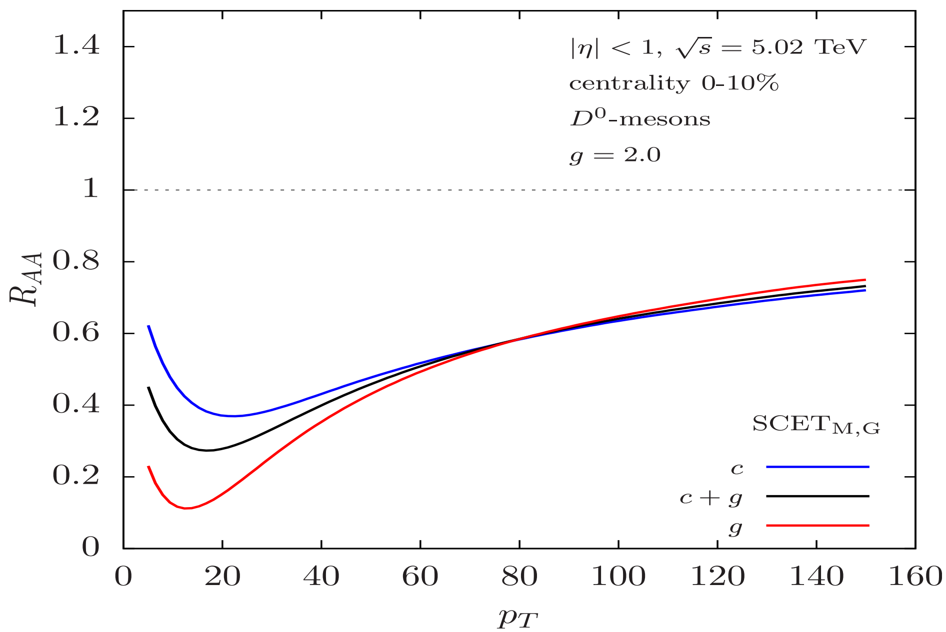
# Cross section calculation in the QCD medium

**Medium contribution**

$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}_{i\to jk}^{\rm med} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,\rm med}$$

$$D_q^{H,\rm med}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_q^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{q\to qg}^{\rm med}(z',\mu) - D_q^H(z,\mu)\int_0^1 dz' \mathcal{P}_{q\to qg}^{\rm med}(z',\mu) + \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{q\to gq}^{\rm med}(z',\mu)\,,$$

$$D_g^{H,\rm med}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{g\to gg}^{\rm med}(z',\mu) - \frac{D_g^H(z,\mu)}{2}\int_0^1 dz' \left[\mathcal{P}_{g\to gg}^{\rm med}(z',\mu) + 2N_f \mathcal{P}_{g\to q\bar{q}}^{\rm med}(z',\mu)\right] + \int_z^1 \frac{dz'}{z'} \sum_{i=q,\bar{q}} D_i^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{g\to q\bar{q}}^{\rm med}(z',\mu)\,.$$

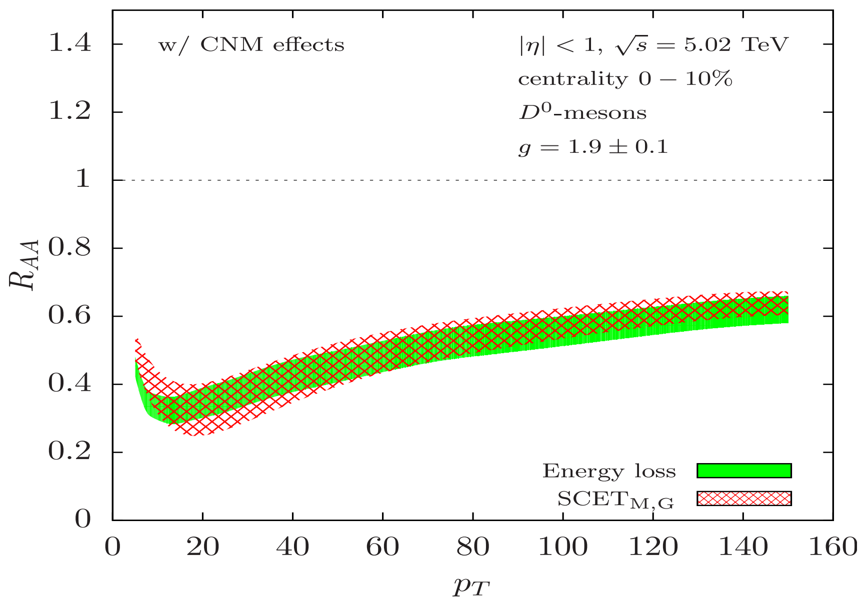


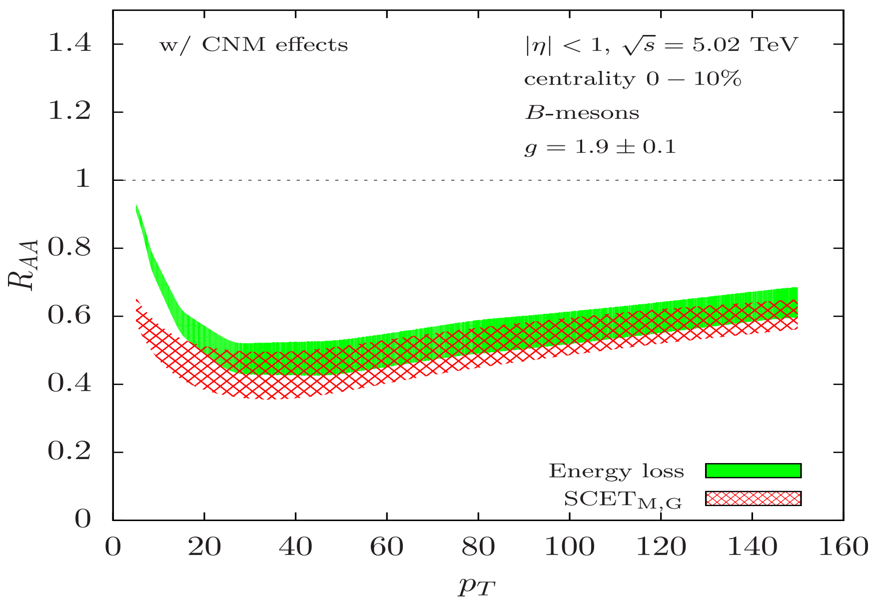

**For numerical implementation one can rewrite these expression in the + prescription and finds that the correction is negative**

**Can lead to larger cross section suppression at smaller $p_T$**

# Combined uncertainty

Includes both production mechanism and e-loss vs NLO



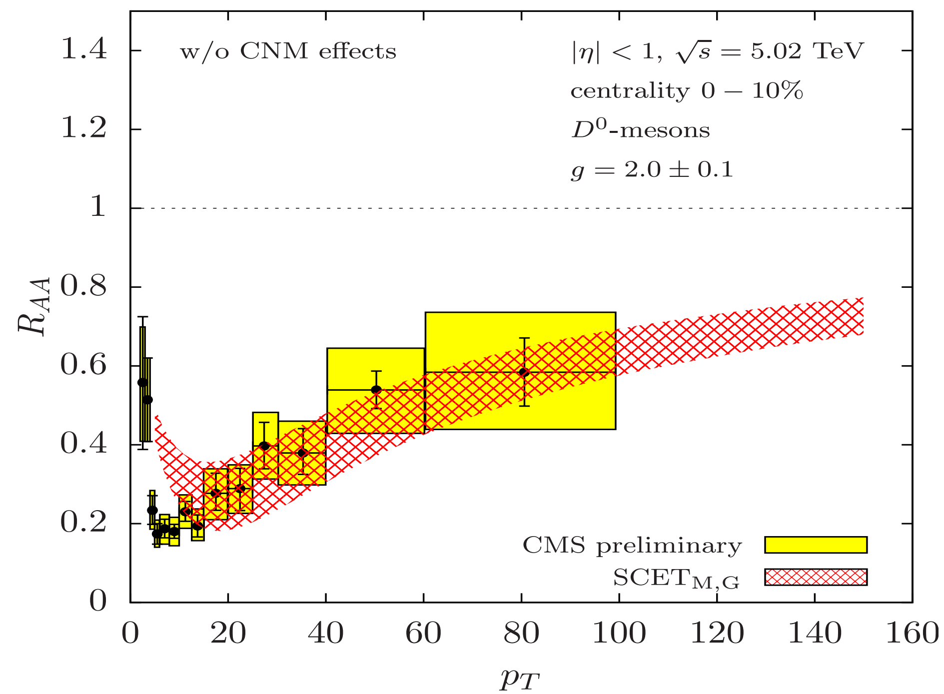



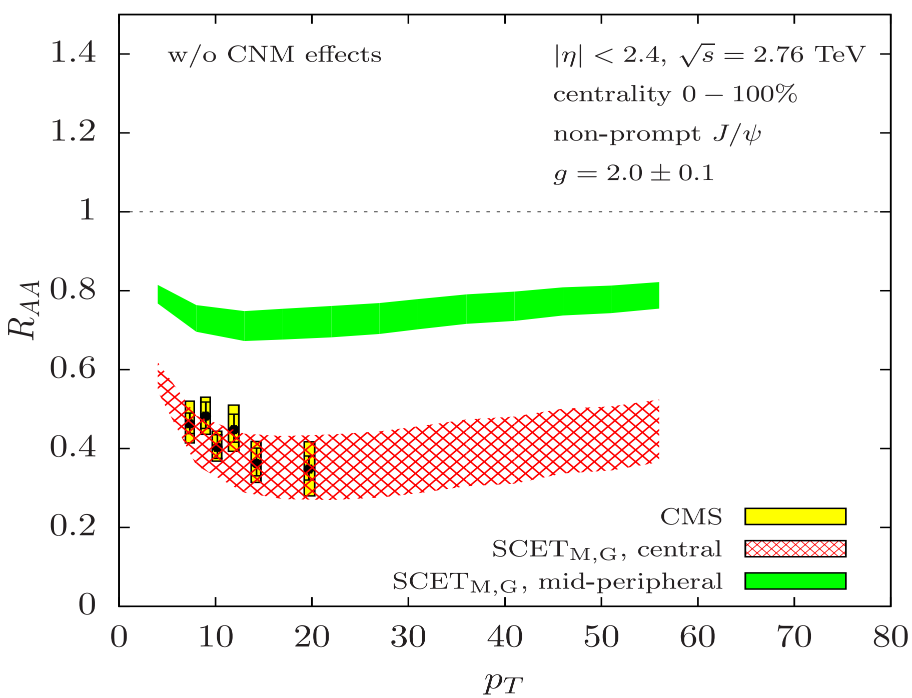

- The pure scale uncertainty largely cancels in the ratio
- At high pT there is at least 20% combined uncertainty. Did not increase much since gluon fragmenatation in H is softer and offsets the difference between quark-gluon enegry loss.
- At low PT  th eucertainties can grow to 30% D and 50+% B.

# Suppression of open heavy flavor in the medium

- For D mesons works reasonably well. Below 10 GeV room for some additional effects: collisional energy loss, dissociation

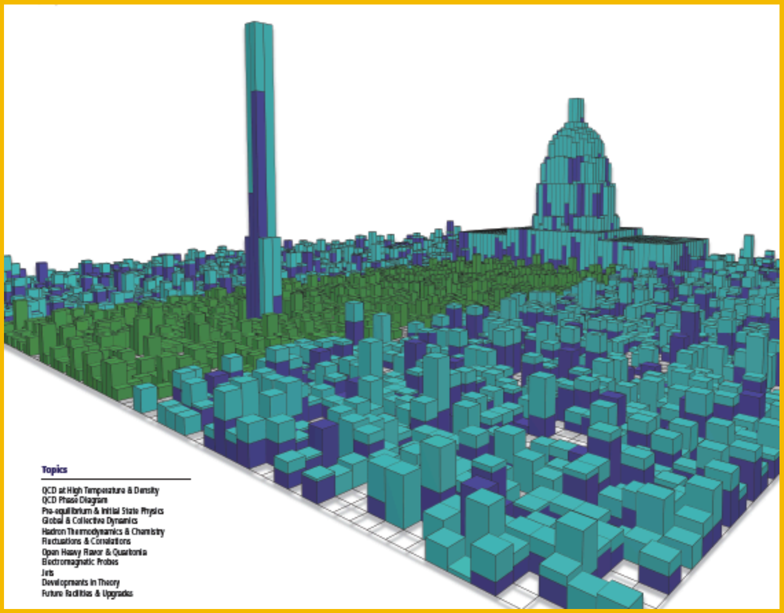
Z. Kang et al . (2016)



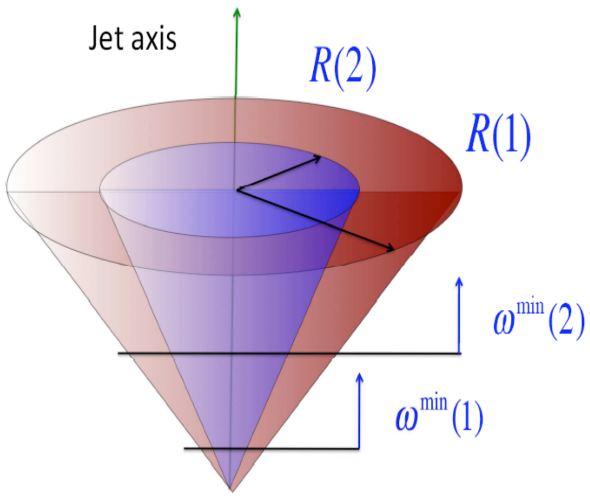

- B mesons there is improvement but not sufficient. Even more room for other nuclear effects
- Nice to extend the approach to include collisional energy losses

# Inclusive jets in HI collisions

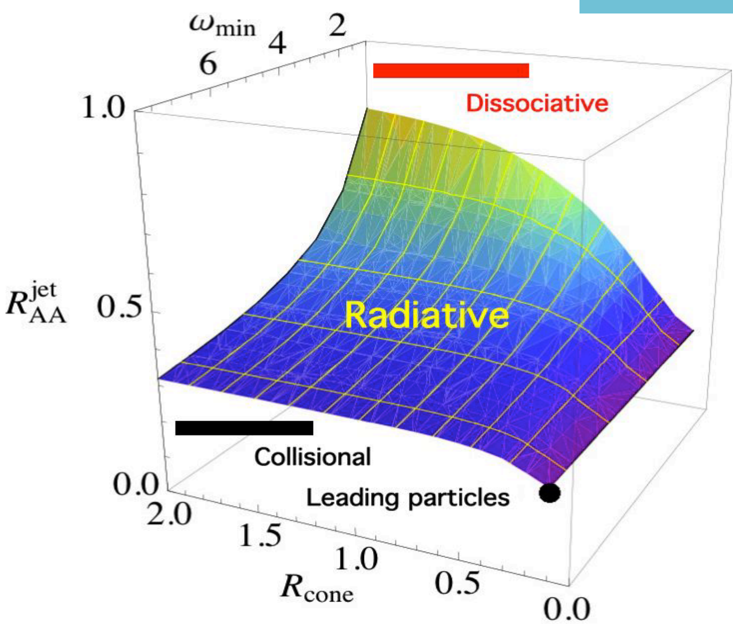



# Exploiting the jet variables in heavy-ion collisions

- One can leverage the differences between the vacuum parton showers, the medium-induced showers and the medium response to jets to experimental signatures of parton interaction in matter




I.V. et al. (2008)




$$R^{\rm jet}_{AA}(E_T;R^{\rm max},\omega^{\rm min}) = \frac{\frac{d\sigma^{AA}(E_T;R^{\rm max},\omega^{\rm min})}{dyd^2E_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}(E_T;R^{\rm max},\omega^{\rm min})}{dyd^2E_T}}$$

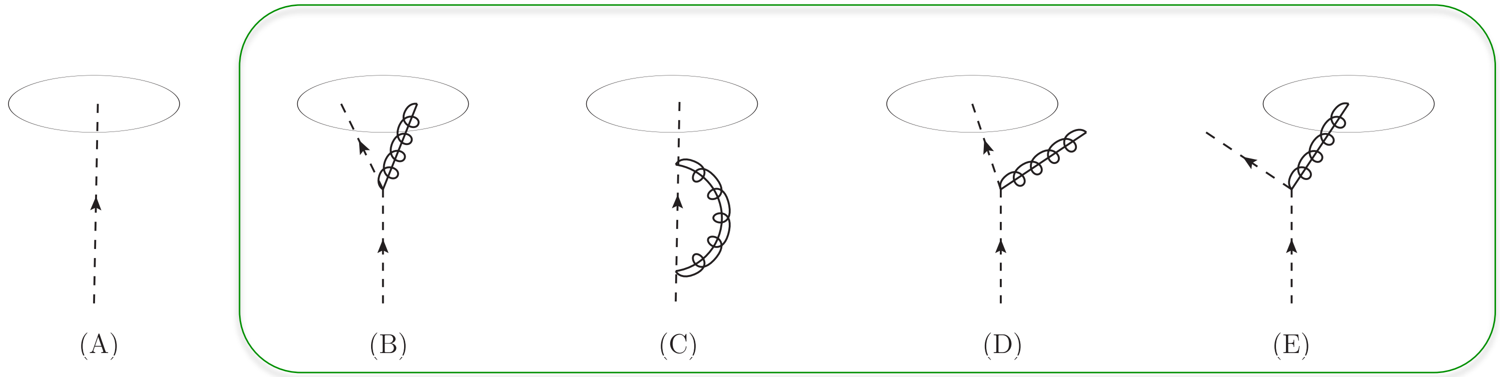
| Mechanism | Signature | Status |
|---|---|---|
| **Radiative** | Variation of $R_{AA}^{jet}$ with R w | ✔ Incl. jets at RHIC, LHC<br>✔ Di-jets at the LHC<br>✔ Z-jets, at the LHC |
| **Collisional** | ~ Constant $R_{AA}^{jet}$= $R_{AA}^{particle}$<br>(Large suppression) | ✗ First application |

# Calculating the jet cross section at NLO

- Master formula
- Modified jet function

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c$$

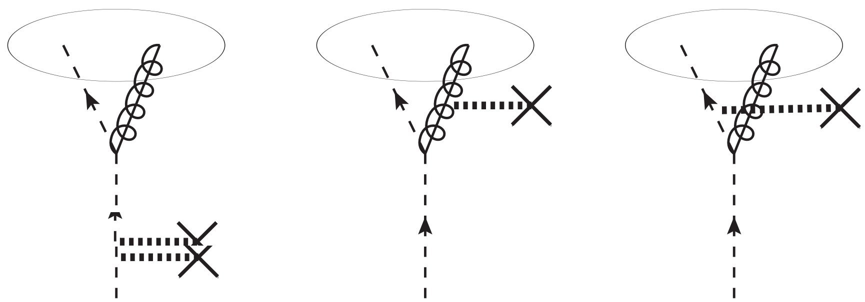
Z. Kang et al. (2017)




The first diagram does not contribute to medium induced radiative corrections (included only once )

One needs to consider single and doube Born interactions with the medium

$$|\mathcal{A}^{\text{med}}_{\text{SB}}|^2 + 2\mathfrak{Re}\left\{\mathcal{A}^{\text{med}}_{\text{DB}} \times \mathcal{A}^{\text{vac}}\right\}$$



M. Gyulassy et al. (2000)

# In-medium parton splittings and their 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)

Y.T. Chien , talk

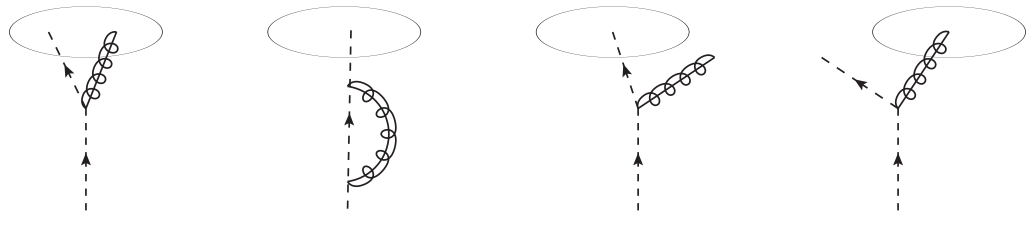
$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}\left[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\pe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

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

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

# Evaluating the in-medium jet function

- Can we formulate the evaluation of the jet function in a way suitable for numerical implementation




Z. Kang et al. (2017)

$$(\mathrm{B}) = \delta(1-z)\int_0^1 dx \int_0^{x(1-x)\omega\tan(R/2)} dq_\perp P_{qq}(x,q_\perp)$$

$$(\mathrm{C}) = -\delta(1-z)\int_0^1 dx \int_0^{\mu} dq_\perp P_{qq}(x,q_\perp)$$

Sum rules

$$(\mathrm{D}) = \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)$$

$$(\mathrm{E}) = \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp)$$

Can be combined.

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

NB has to be understood in the sense of convolution

$$J_q^{\mathrm{med},(1)}(z,\omega R,\mu) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp)\,.$$

- Stable in numerical implementation
- Similarly for gluon jets

# Results for jet cross sections at NLO

- In the vacuum we use $NLL_R$ resummation

F. Ringer, talk

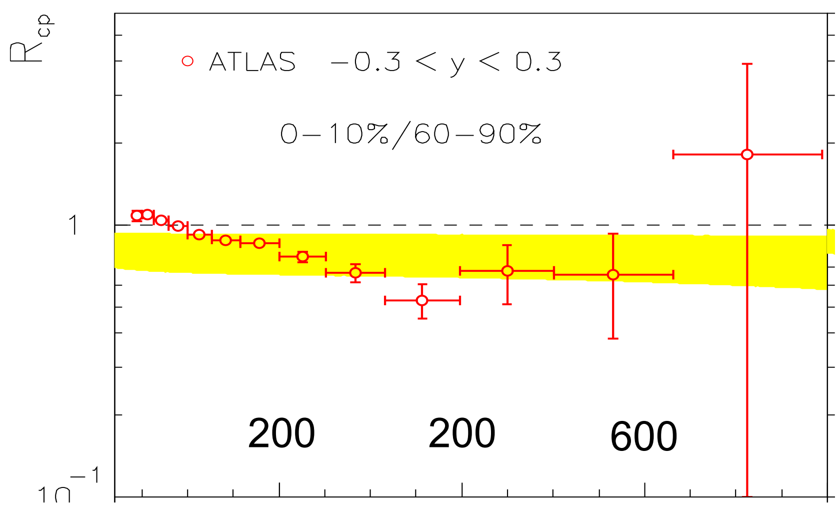
- In the medium it is strictly NLO

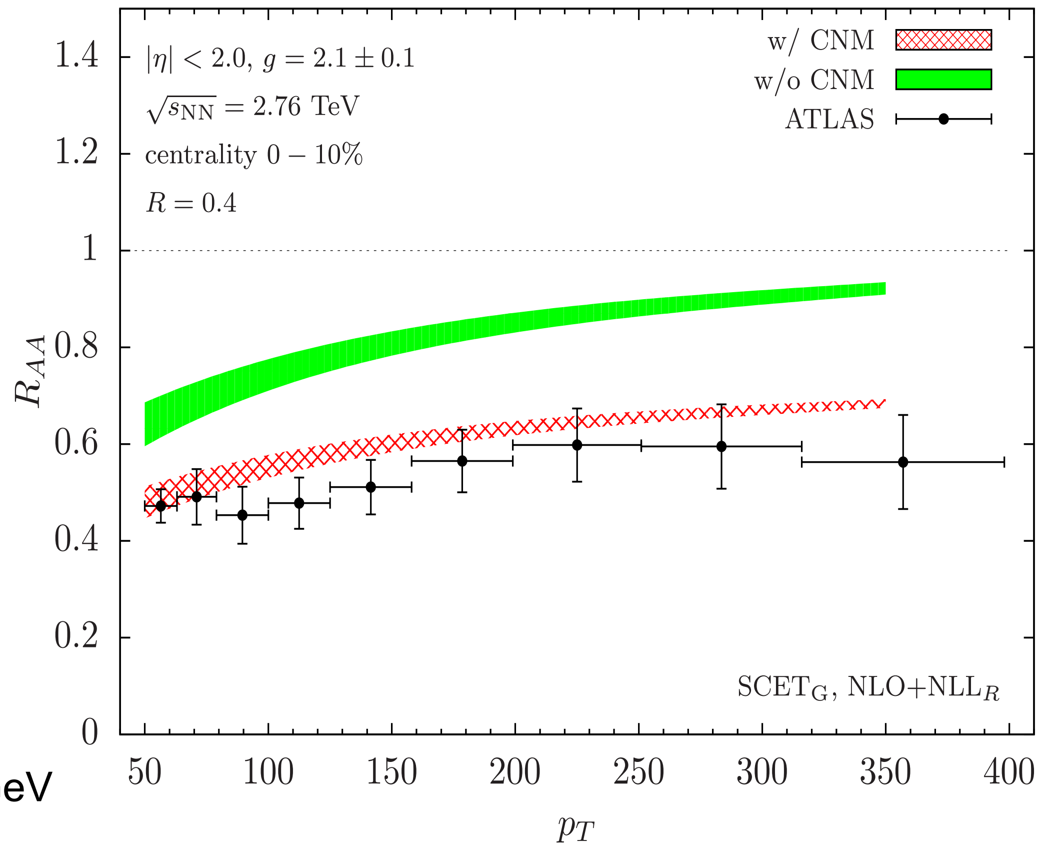
$$d\sigma^{\text{jet}}_{\text{PbPb}} = d\sigma^{\text{jet,vac}}_{pp} + d\sigma^{\text{jet,med}}_{\text{PbPb}}$$

$$d\sigma^{\text{jet,med}}_{\text{PbPb}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\text{med}}$$

No multiple splittings, no collisional energy loss (to be revisited)

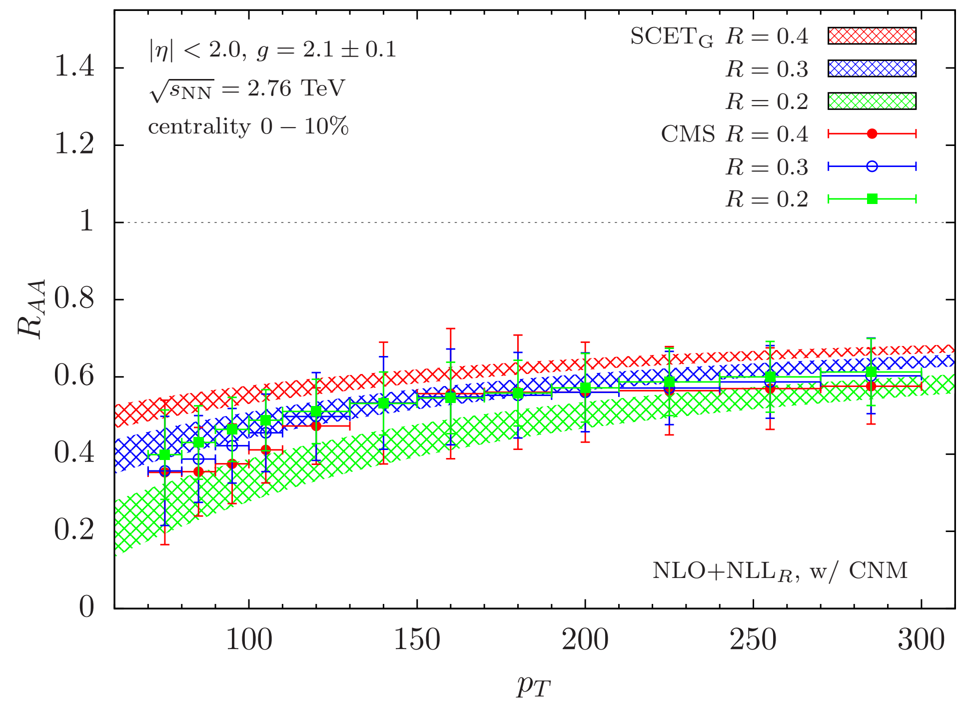
One possibility is cold nuclear matter effects in the initial state

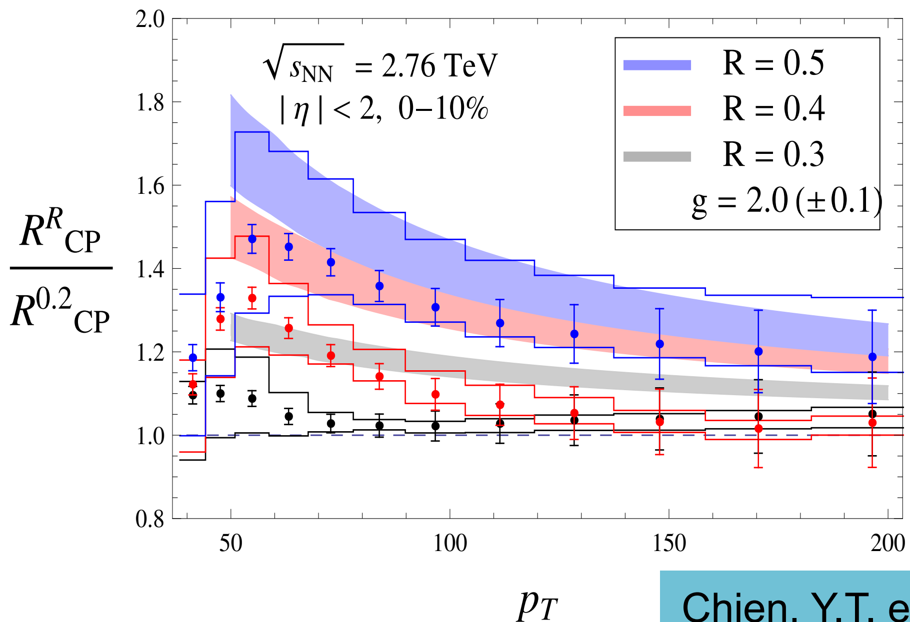


# Radius dependence of jet suppression

- For medium-induced radiative corrections – smaller R jets more suppressed
- For collisional energy loss - approx. constant with R (up to R~1)
- Strong coupling models have argued larger suppression with larger jer R




Consistent within error bars. But then any small separation ordering will be

Resolution deferred to earlier ATLAS measurements. Sees R ordering but weaker than predicted

Chien, Y.T. et al. (2015)

# Centrality dependence of jet suppression

Nuclei are macroscopic objects. One can define centrality of the collision

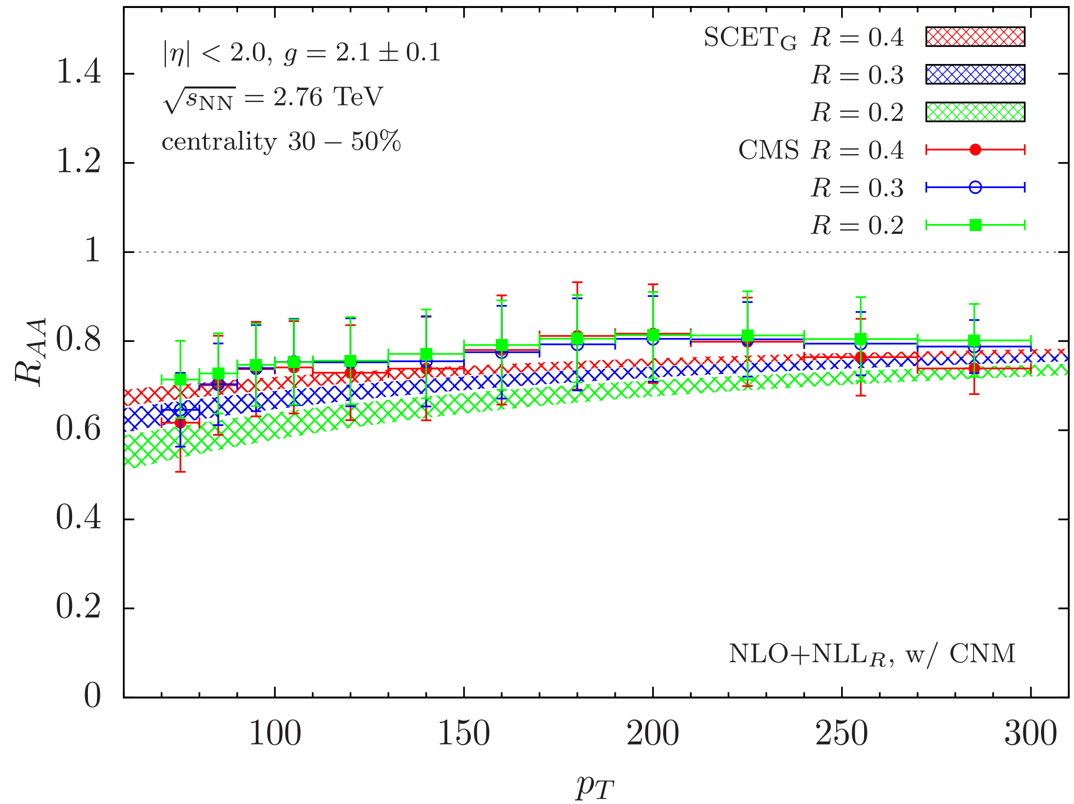
Changes the size of the medium

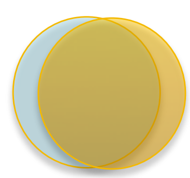
The temperature of the medium

The vacuum and medium contribution to jet functions

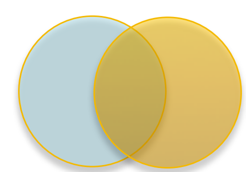
The overall level of suppression

(in the most peripheral collisions expected to disappear)



**Central**

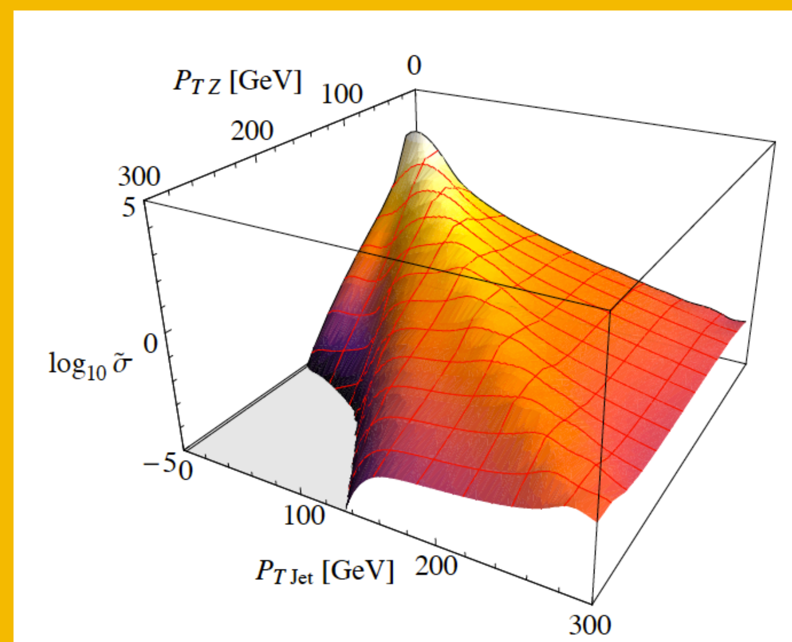


**Peripheral**

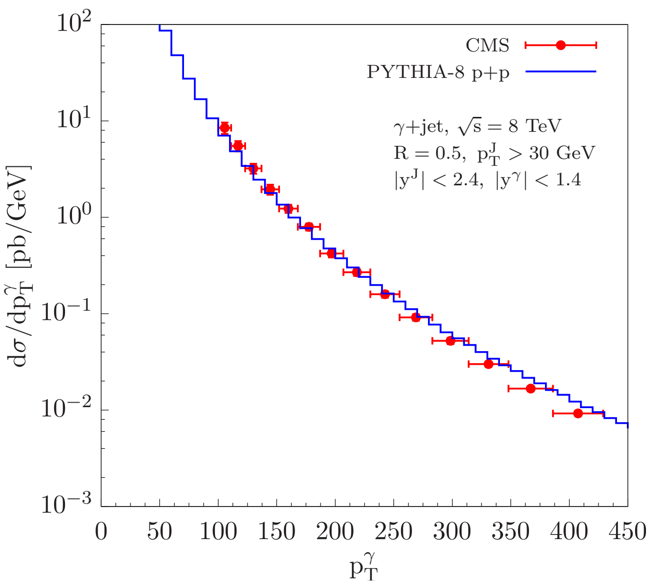
Z. Kang et al. (2017)

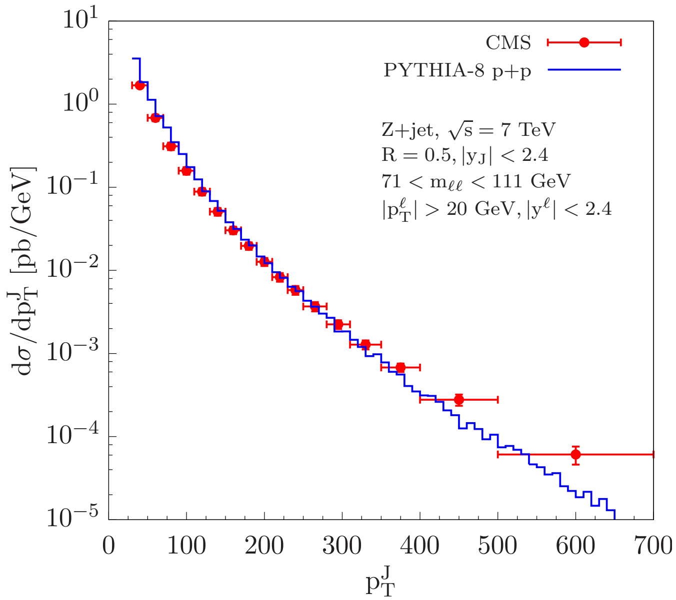
The centrality dependence appears to be well captured

# Vector boson-tagged jets

# Baseline for flavor studies of parton energy loss



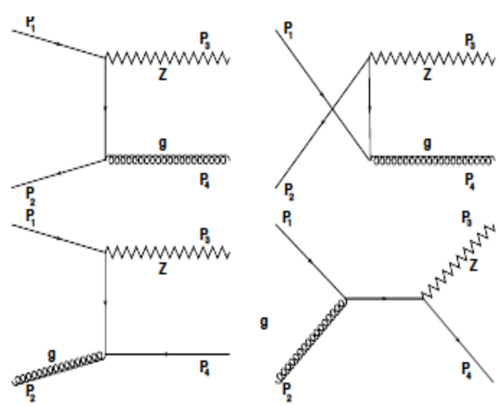

- Pythia 8 baseline.
LO cross sections + LL parton shower

- Parton shower for resummation at $p_{TV} = p_{TJ}$

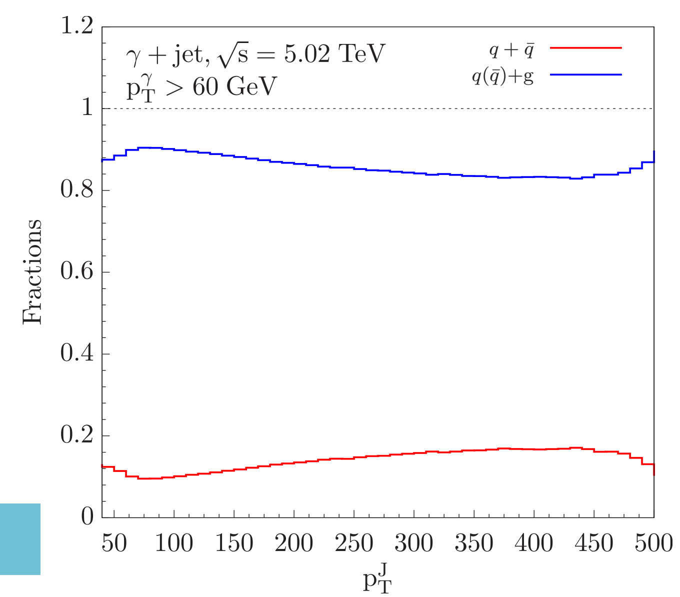
T. Sjostrand, et al. (2007)

Validation of results. Works reasonably well but a multi-log scale. Some deviation in more differential distributions

Useful to study the flavor structure of jet quenching, quark energy loss



Chien, Y.T. et al. (2015)



# Calculating V+Jet suppression

- The suppressed di-jet cross section is calculated as follows (differentially over the collisions geometry, $L_{2,}$ Real time P(ε), Determination of out-of-cone radiation

$$\frac{d\sigma^{AA}(|\mathbf{b}_\perp|)}{dp_T^V dp_T^J} = \int d^2\mathbf{s}_\perp T_A\left(\mathbf{s}_\perp - \frac{\mathbf{b}_\perp}{2}\right) T_A\left(\mathbf{s}_\perp + \frac{\mathbf{b}_\perp}{2}\right) \sum_{q,g} \int_0^1 d\epsilon \frac{P_{q,g}(\epsilon; s_\perp, |\mathbf{b}_\perp|)}{1 - f_{q,g}^{\rm loss}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon} \times \frac{d\sigma_{q,g}^{NN}\left(p_T^V, p_T^J/\{1 - f_{q,g}^{\rm loss}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon\}\right)}{dp_T^J dp_T^V},$$

Z. Kang et al. (2017)

- In the soft gluon emission limit only the diagonal splitting functions survive. The soft limit has the interpretation of radiative energy loss

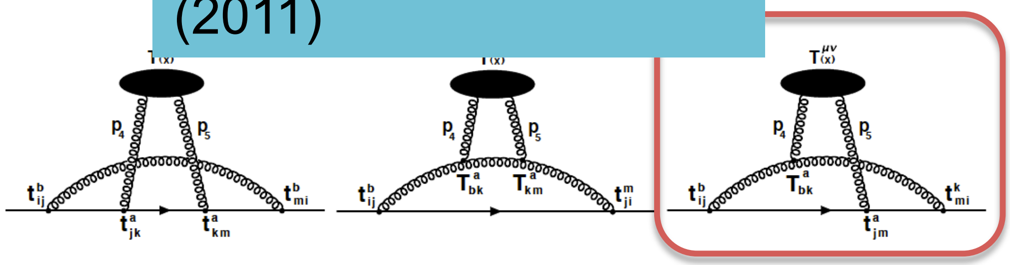
- Collisional energy losses dissipate the energy of the parton shower through the excitation of the QCD medium

$$f_{q,g}^{\rm loss}(R; {\rm rad} + {\rm coll}) = 1 - \left(\int_0^R dr \int_{\omega_{\rm min}}^E d\omega \frac{dN_{q,g}^g(\omega, r)}{d\omega dr}\right) \Big/ \left(\int_0^{R_{\rm max}} dr \int_0^E d\omega \frac{dN_{q,g}^g(\omega, r)}{d\omega dr}\right)$$

# Parton showers as sources of energy deposition in the QGP

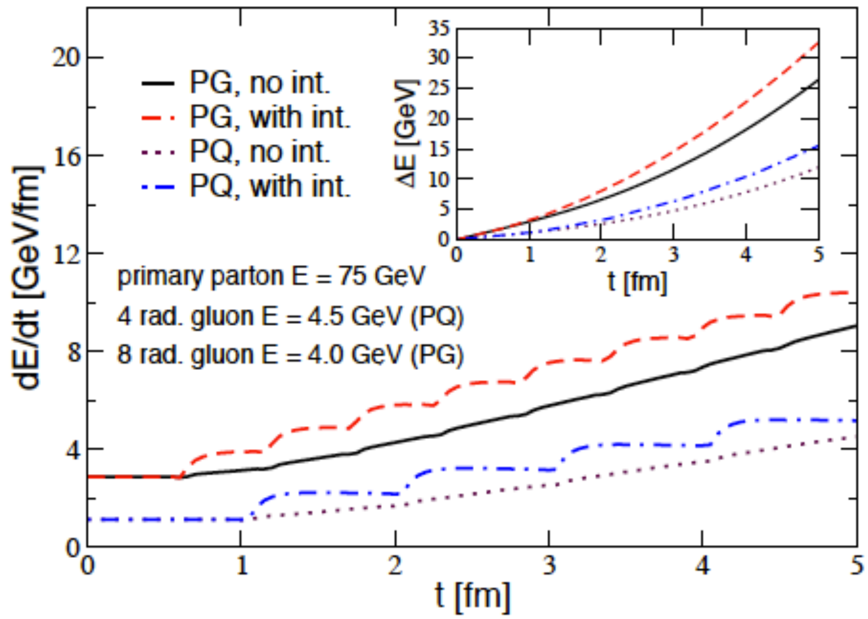
- The splitting parton system as a source term, including quantum color interference effects
- Think of it schematically as the energy transferred to the QGP through collisional interactions at scales ~ T, gT, …

R.B. Neufeld et al. (2011)



- Calculated diagrammatically from the divergence of the energy-momentum tensor (EMT)

$$\partial_\mu T^{\mu\nu} = C_p J_a^\nu(x, u_1, u_1) + C_A J^\nu(x, u_2, u_2) - \frac{C_A}{2}\left[J^\nu(x, u_1, u_2) + J^\nu(x, u_2, u_1)\right]$$



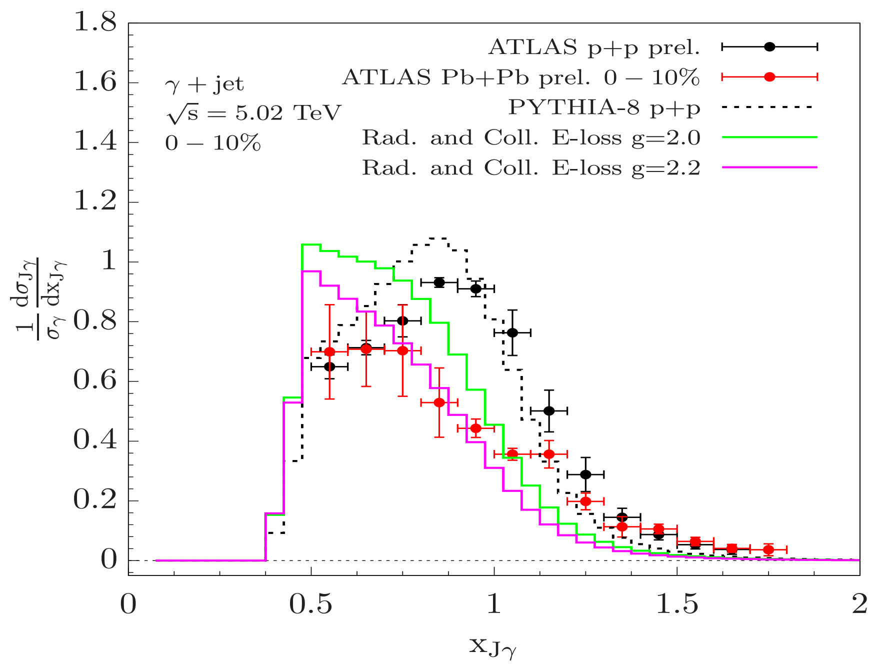

- 10-20 GeV from the shower energy can be transmitted to the QGP

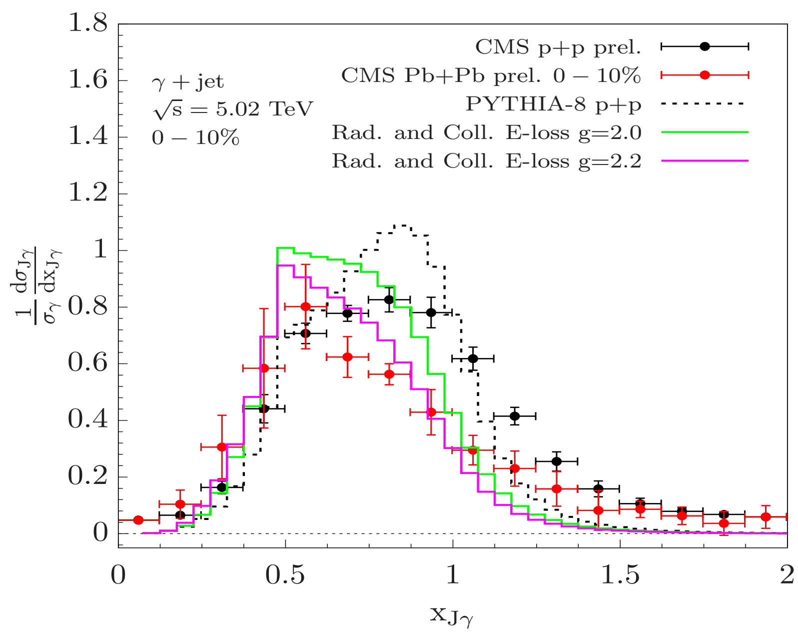
# Momentum imbalance distributions of V+Jet at the LHC

- Can be evaluated from the suppressed V+jet cross sections

Jacobian transformation $x_{JV} = p_T^J / p_T^V$
integration over kinematic cuts

$$\frac{d\sigma}{dx_{JV}} = \int_{p_T^{J,\min}}^{p_T^{J,\max}} dp_T^J \frac{p_T^J}{x_{JV}^2} \frac{d\sigma(p_T^V = p_T^J / x_{JV}, p_T^J)}{dp_T^V dp_T^J}$$




- Qualitative and in most cases quantitative agreement between data and theory. Can use improvement in the baseline description

# Quantifying quark jet energy loss at the LHC

- Uncertainties in the baseline description and detector resolution effects that make the comparison more difficult can be minimized by looking at moments of $x_{VJ}$.

$$\langle x_{JV} \rangle = \left( \int dx_{JV} x_{JV} \frac{d\sigma}{dx_{JV}} \right) \Big/ \left( \int dx_{JV} \frac{d\sigma}{dx_{JV}} \right) \qquad \Delta\langle x_{JV} \rangle = \langle x_{JV} \rangle_{pp} - \langle x_{JV} \rangle_{PbPb}$$

- The difference PbPb-pp can quantify jet energy loss (in this case quark jets). Results for Z-jet and gamma-jet similar

| | $\Delta\langle x_{J\gamma} \rangle$ | | | | |
|---|---|---|---|---|---|
| $p_T^\gamma$ (GeV) | $40 - 50$ | $50 - 60$ | $60 - 80$ | $80 - 100$ | $100 - 120$ |
| CMS prel. [25] | $0.008 \pm 0.074$ | $0.043 \pm 0.069$ | $0.081 \pm 0.059$ | $0.054 \pm 0.044$ | $0.115 \pm 0.047$ |
| Rad. + Coll. $g = 2.0$ | 0.021 | 0.044 | 0.065 | 0.075 | 0.065 |
| Rad. + Coll. $g = 2.2$ | 0.025 | 0.055 | 0.085 | 0.103 | 0.115 |

Quark jets with R = 0.3 – 0.4 lose ~ 8-10% of their energy at the LHC due to medium effects

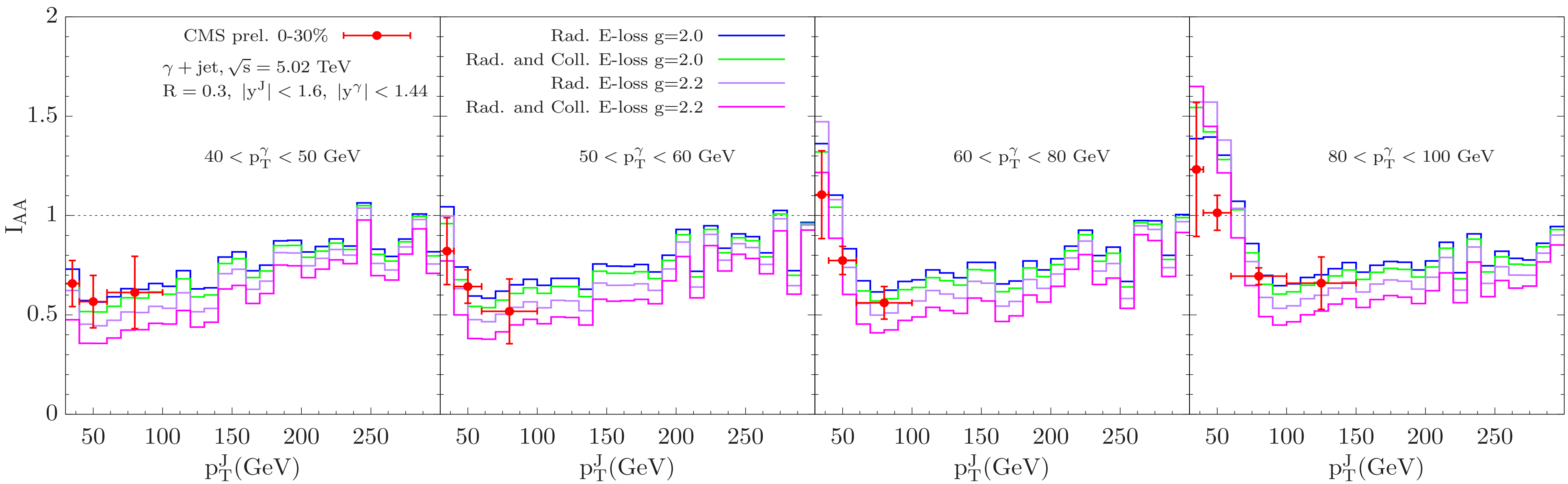
# Tagged jet suppression

- Generally good description of the CMS data. Still difficult to differentiate Rad. E-loss (larger coupling) and Rad. + Col. E-loss smaller coupling

$$\frac{d\sigma}{[p_T^V]dp_T^J} \equiv \int_{p_T^{V,min}}^{p_T^{V,max}} \frac{d\sigma}{dp_T^V dp_T^J}$$

Suppression of tagged jets

$$I_{AA} = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^{AA}}{[p_T^V]dp_T^J} \Big/ \frac{d\sigma^{pp}}{[p_T^V]dp_T^J}$$



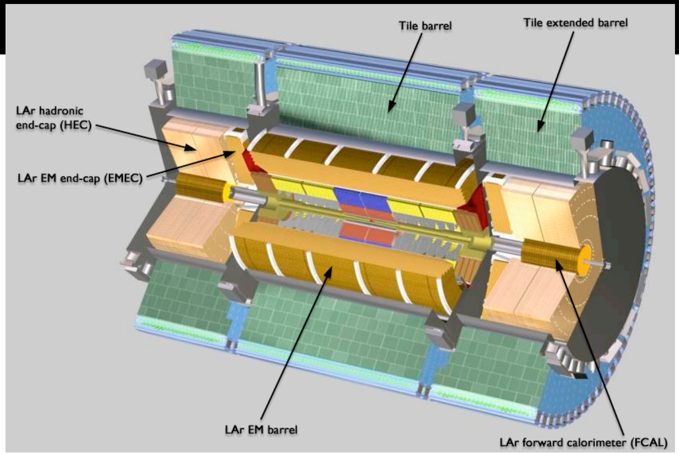

- Qualitatively similar behavior for Z+jet $I_{AA}$

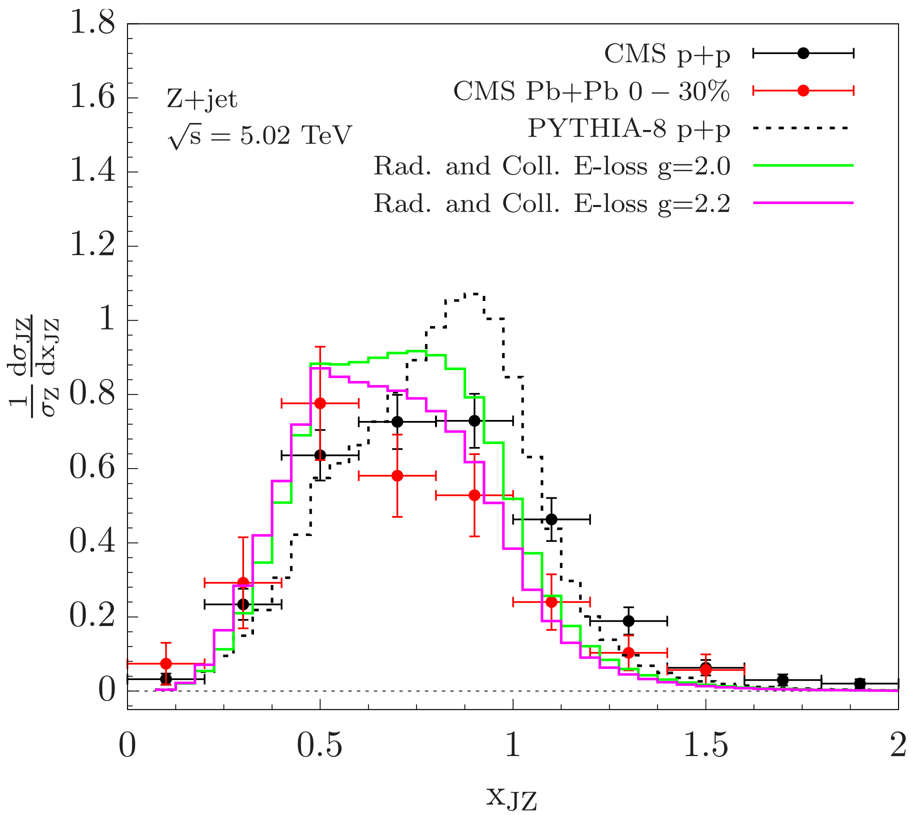
CMS collab. (2016, 2017)

ATLAS collab. (2016, 2017)

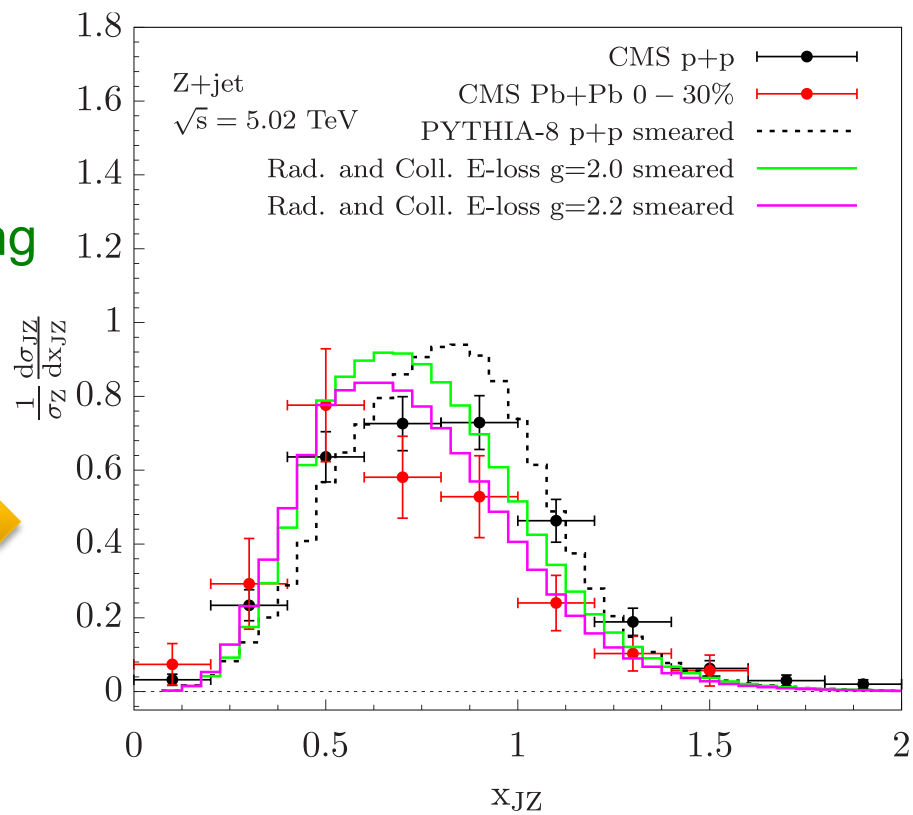
# A note on detector resolution effects

- Preliminary and often published data not unfolded for detector resolution effects
- Introduces smearing, smearing function provided to us by CMS




CMS smearing



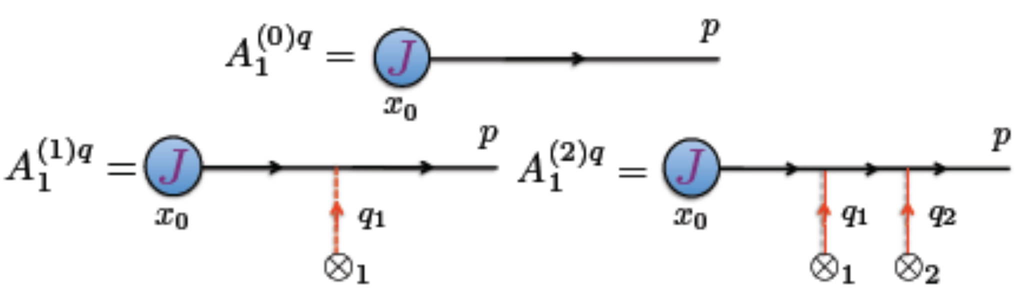
# Conclusions

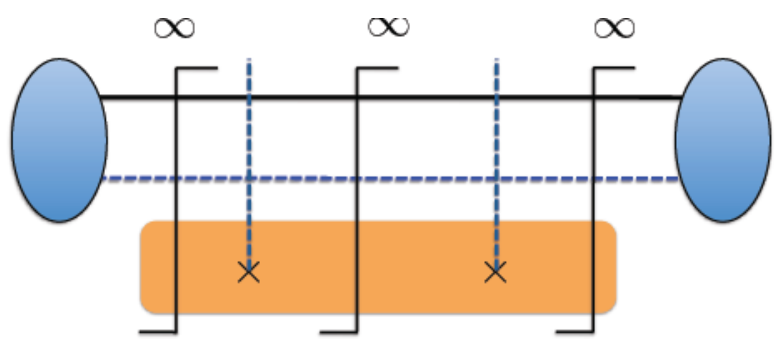
- New theoretical developments that address the physics of jets in heavy ion collisions emerge in the EFT framework
- Developed an effective theory of heavy quark propagation in QCD matter. Obtained heavy quark splitting functions and clarified certain aspects of the energy loss limit traditionally used
- Phenomenological application to open heavy flavor at NLO. Implemented q, g fragmentation functions to B,D. Large g contribution~50%. We can validate e-loss model predictions at high $p_T$. At low $p_T$ get larger suppression. Still need additional effect – collisional nature, CNM
- Formulated an evaluation of jet cross section in QCD matter to NLO. Combined with $NLL_R$ baseline. Showed that it can be formulated in a way suitable for numerical implementation with what the splitting functions are evaluated numerically. Showed that the medium induced radiative corrections can only account for part of the suppression. Remaining effects CNM of collisional energy loss. Consider multiple emissions/evolution
- Vector boson tagged jets – traditional energy loss approach (radiative and collisional e-losses). Constrain quark out-of-cone energy loss ~8-10%. Very relevant to recent CMS, ATLAS measurements. Reality check for theory / experiment comparison

# Main results: jet broadening

- Jet broadening and its gauge invariance

M. Gyulassy et al. (2001)





Classes of diagrams (single Born, double Born). Reaction Operator

- General result. Will evaluate the broadening (or lack off) of jets

$$\frac{dN^{(n)}(\mathbf{p}_\perp)}{d^2\mathbf{p}_\perp} = \prod_{i=1}^{n}\int_{z_{i-1}}^{L}\frac{dz_i}{\lambda}\int d^2\mathbf{q}_{\perp i}\left[\frac{1}{\sigma_{el}(z_i)}\frac{d\sigma_{el}(z_i)}{d^2\mathbf{q}_{\perp i}}\left(e^{-\mathbf{q}_{\perp i}\cdot\vec{\nabla}_{\mathbf{p}_\perp}}\right)-\delta^2(\mathbf{q}_\perp)\right]\frac{dN^{(0)}(\mathbf{p}_\perp)}{d^2\mathbf{p}_\perp}$$

- In special cases such as constant density and the Gaussian approximation

Starting with a collinear beam of quarks/gluons we recover

M. Gyulassy et al. (2002)

$$\frac{dN(\mathbf{p}_\perp)}{d^2\mathbf{p}_\perp} = \frac{1}{2\pi}\frac{e^{-\frac{p^2}{2\chi\mu^2\xi}}}{\chi\,\mu^2\,\xi} \qquad \chi = \frac{L}{\lambda}$$

# Splitting kernel results

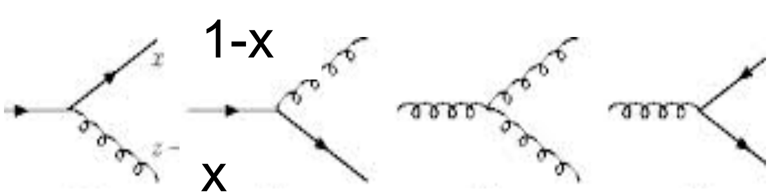
- Explicitly verified the gauge invariance and factorization in QCD

$$\left(\frac{dN}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x}\frac{1}{\mathbf{k}_\perp^2}, \quad (\ldots]_+ + A\delta(x))$$

$$\left(\frac{dN}{dx\, d^2\mathbf{k}_\perp}\right)_{g\to gg} = \frac{\alpha_s}{2\pi^2} 2C_A \left(\frac{1-x}{x} + \frac{x}{1-x} + x(1-x)\right)\frac{1}{\mathbf{k}_\perp^2}, \quad (\ldots]_+ + B\delta(x))$$

$$\left(\frac{dN}{dx\, d^2\mathbf{k}_\perp}\right)_{g\to q\bar{q}} = \frac{\alpha_s}{2\pi^2} T_R \left(x^2+(1-x)^2\right)\frac{1}{\mathbf{k}_\perp^2}$$

$$\left(\frac{dN}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to gq} = \left(\frac{dN}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} (x \to 1-x)$$




Reversed convention

- The singular pieces A, B can be obtained form flavor and momentum conservation sum rules

$$\int_0^1 P_{qq}(x)\,\mathrm{d}x = 0,$$

$$\int_0^1 \left[P_{qq}(x) + P_{gq}(x)\right](1-x)\,\mathrm{d}x = 0,$$

$$\int_0^1 \left[2n_f P_{qg}(x) + P_{gg}(x)\right](1-x)\,\mathrm{d}x = 0.$$

# Evolution of the fragmentation functions

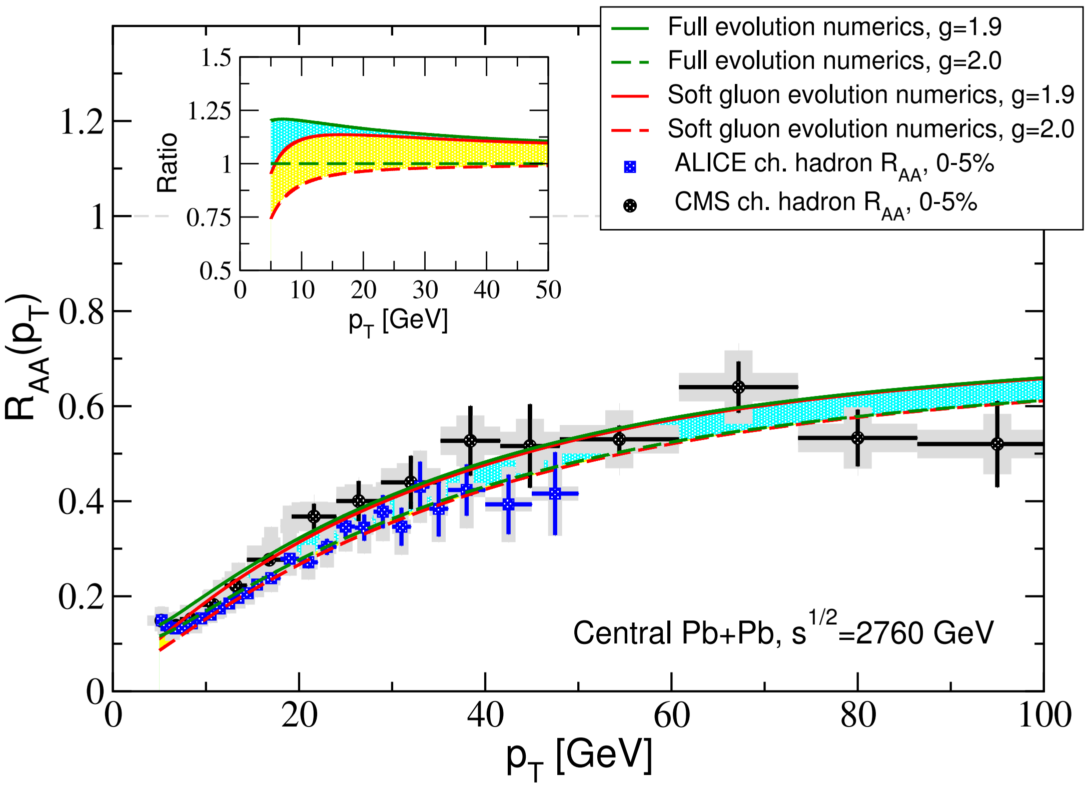
- Yield LLA or MLLA

Z. Kang et al. (2014)

$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_{\bar q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar q}\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right) + P_{g\to q\bar q}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + \bar q \text{ term}\right)\right\}.$$




In the medium: effective thermal masses, finite $\alpha_s$

Implement medium –induced splittings as corrections to vacuum evolution

Demonstrated connection to E-loss

# Medium-modified evolution of the fragmentation functions

- Using the same techniques. The vacuum and the medium induced evolution factorize

$$\frac{\mathrm{d}\ln D_{h/c}^{\mathrm{med.}}(z,Q)}{\mathrm{d}\ln Q} = [\cdots]_{\mathrm{vac.}} - [n(z)-1]\left\{\int_0^{1-z} \mathrm{d}z'\, z'Q\frac{dN}{dz'dQ}(z',Q)\right\} - \int_{1-z}^{1} \mathrm{d}z' Q\frac{dN}{dz'dQ}(z',Q)\,.$$

$$D_{h/c}^{\mathrm{med.}}(z,Q) = \mathrm{e}^{-2C_R\frac{\alpha_s}{\pi}\left[\ln\frac{Q}{Q_0}\right]\{[n(z)-1](1-z)-\ln(1-z)\}}\, D_{h/c}(z,Q_0)$$

$$\times e^{-[n(z)-1]\left\{\int_0^{1-z}\mathrm{d}z'\, z'\int_{Q_0}^{Q} dQ' \frac{dN}{dz'dQ'}(z',Q')\right\} - \int_{1-z}^{1}\mathrm{d}z' \int_{Q_0}^{Q} dQ' \frac{dN}{dz'dQ'}(z',Q')}$$

$$= D_{h/c}(z,Q)e^{-[n(z)-1]\left\langle\frac{\Delta\tilde{E}}{E}\right\rangle_z - \langle\tilde{N^g}\rangle_z}\,.$$

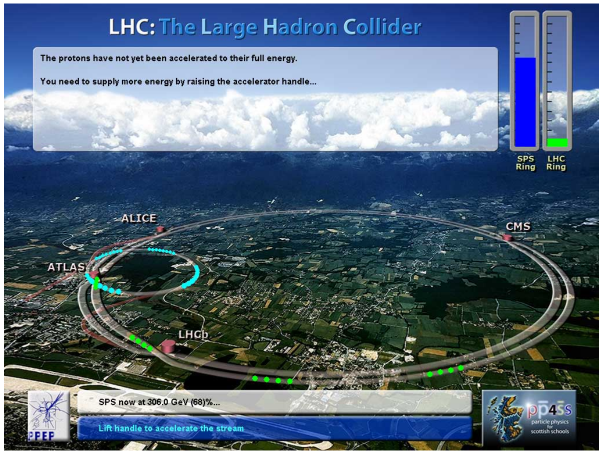
- *The main result*: direct relation between the evolution and energy loss approaches first established here

$$\left\langle\frac{\Delta\tilde{E}}{E}\right\rangle_z = \int_0^{1-z}\mathrm{d}z'\, z'\int_{Q_0}^{Q} dQ'\frac{dN}{dz'dQ'}(z',Q') = \int_0^{1-z}\mathrm{d}z'\, z'\frac{dN}{dz'}(z') \quad \to_{z\to 0} \left\langle\frac{\Delta E}{E}\right\rangle,$$

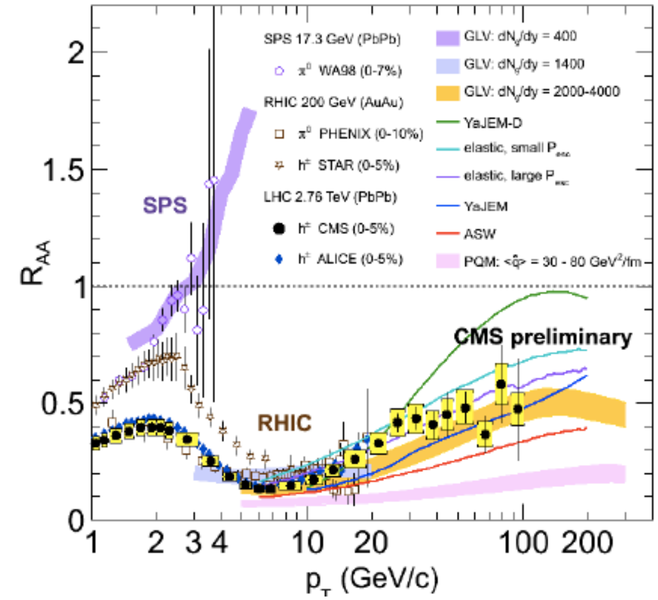
$$\langle\tilde{N^g}\rangle_z = \int_{1-z}^{1}\mathrm{d}z' \int_{Q_0}^{Q} dQ'\frac{dN}{dz'dQ'}(z',Q') = \int_{1-z}^{1}\mathrm{d}z'\frac{dN}{dz'}(z') \quad \to_{z\to 1} \langle N^g\rangle\,.$$

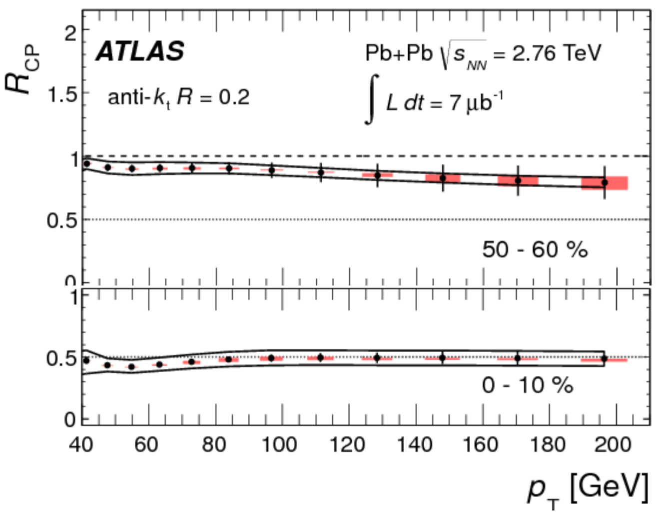
G. Ovanesyan et al. (2014)

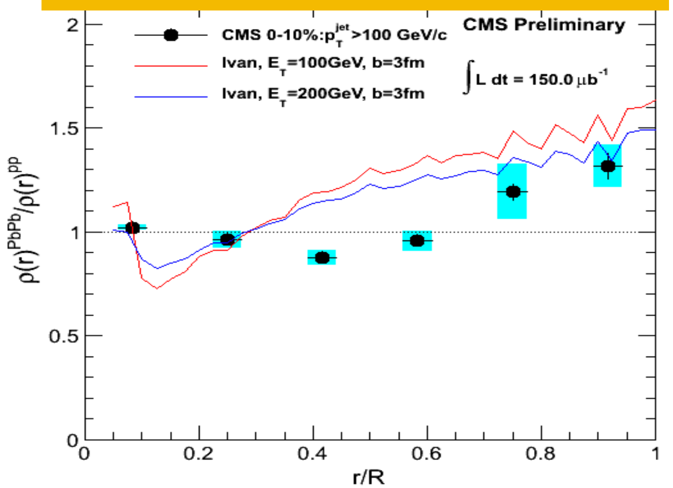
# Jets in heavy ion collisions at the LHC

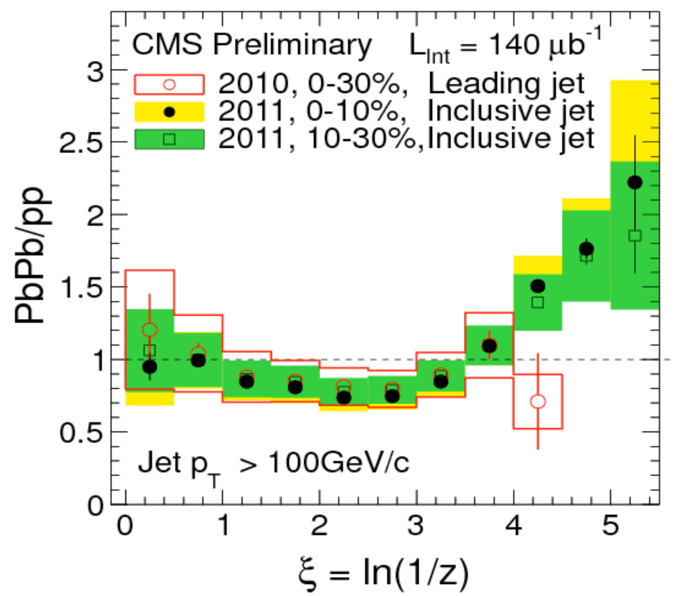



- Jet quenching: to much higher $p_T$
- Suppression of inclusive jets
- Modified jet substructure



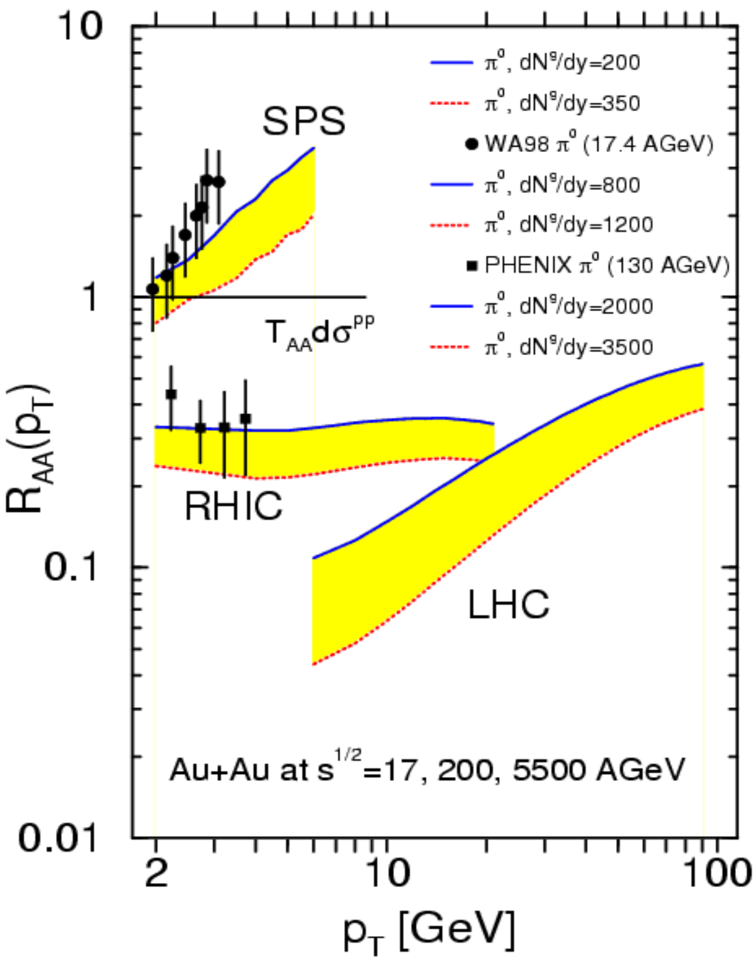




- Advances in jet physics have motivated key detector upgrades at RHIC- sPHENIX. Probe different QGPs, possibly different coupling regimes

# Successes and challenges




I.V. et al (2002)

**Traditional energy loss approach**

$$I(r) = I_0 e^{-\int_0^r dr'/\lambda_{abs}(r')} = I_0 e^{-\int_0^r dr' \rho(r')\sigma(r')}$$

| | $\tau_0$ [fm] | $\tau_{tot}$ [fm] | $T_0$ [MeV] | $\epsilon_0$ $\left[\frac{GeV}{fm^3}\right]$ | $\frac{dN^g}{dy}$ |
|---|---|---|---|---|---|
| SPS | 0.8 | 1.3 – 2.3 | 205 – 245 | 1.2 – 2.6 | 200 – 350 |
| RHIC | 0.6 | 5.5 – 8 | 360 – 410 | 12 – 20 | 800 – 1200 |
| LHC | 0.2 | 13 – 23 | 710 – 850 | 170 – 350 | 2000 – 3500 |

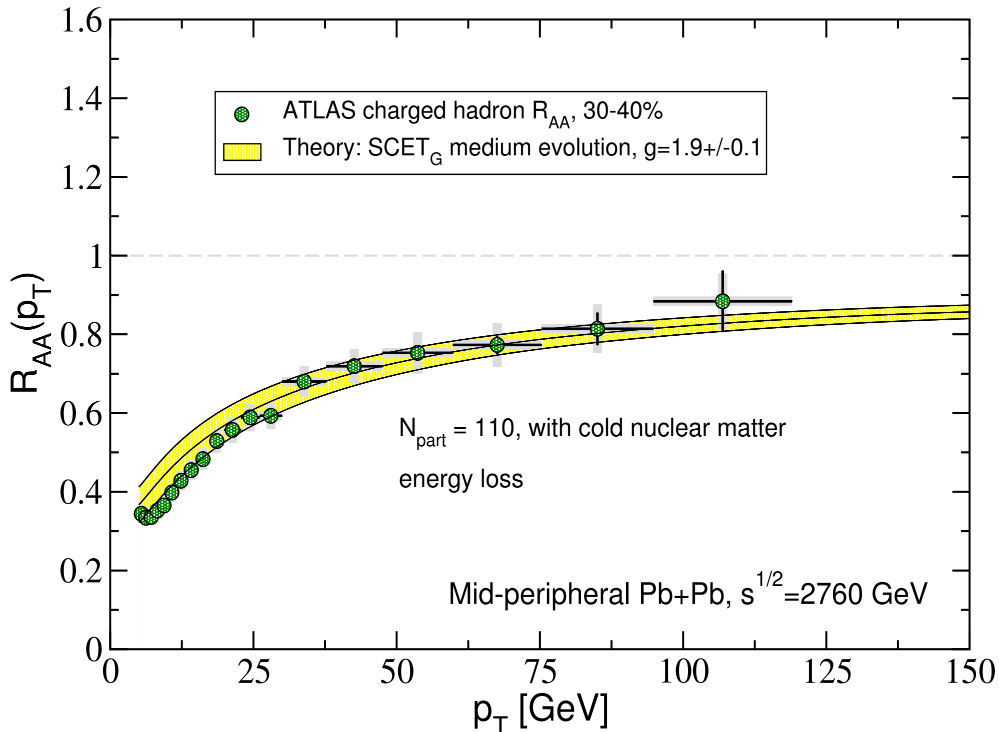
- Advantage of $R_{AA}$ : providing useful information for the hot/dense medium within a simple physics picture

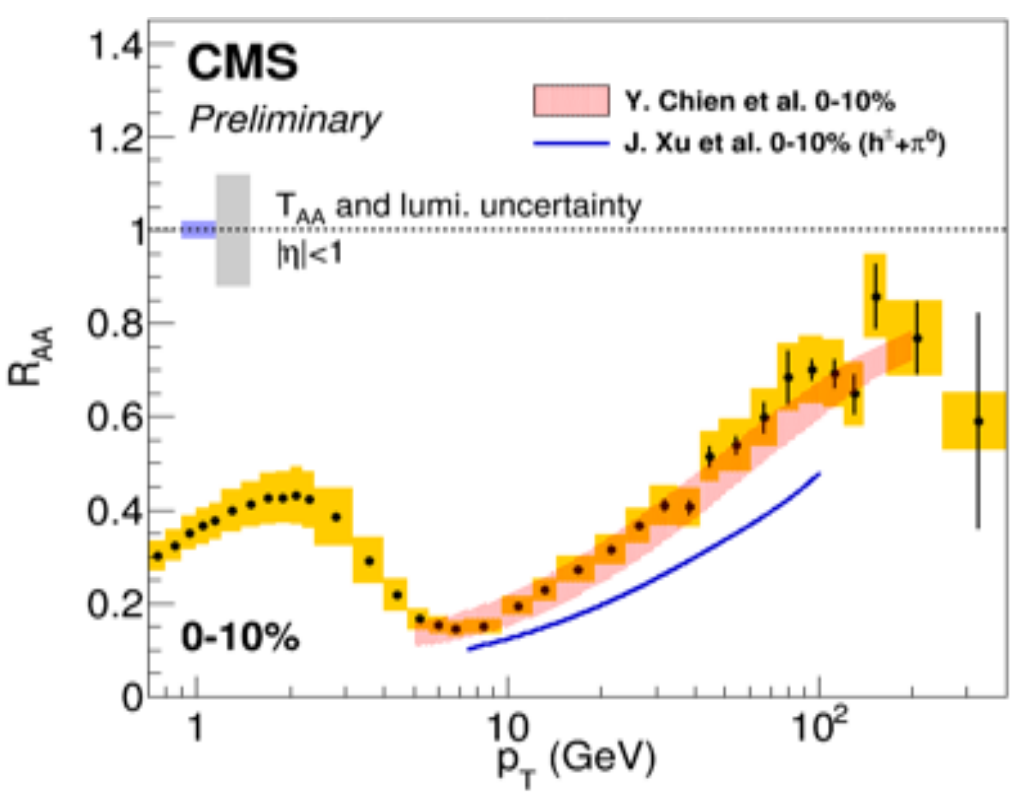
- Difficult to make connection to the standard LO, NLO, …; LL, NLL … pQCD approach (higher orders and resummation)
- There is considerable model dependence and it is difficult to systematically improve this approach

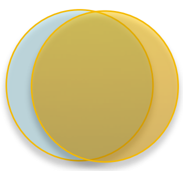
# Predictions for HIC beyond E-loss

- Different centralities, CM energies (QGP properties)

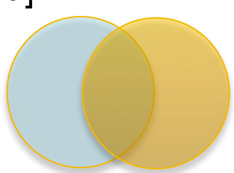
- Inclusive charged hadron production (and also $\pi^0$) at 5.02 TeV in Pb+Pb



**Central**



**Peripheral**

Y.-T. Chien et al. (2015)