Ivan Vitev

# Medium-induced radiative corrections and their application to LHC heavy-ion phenomenology

LoopFest XVI,

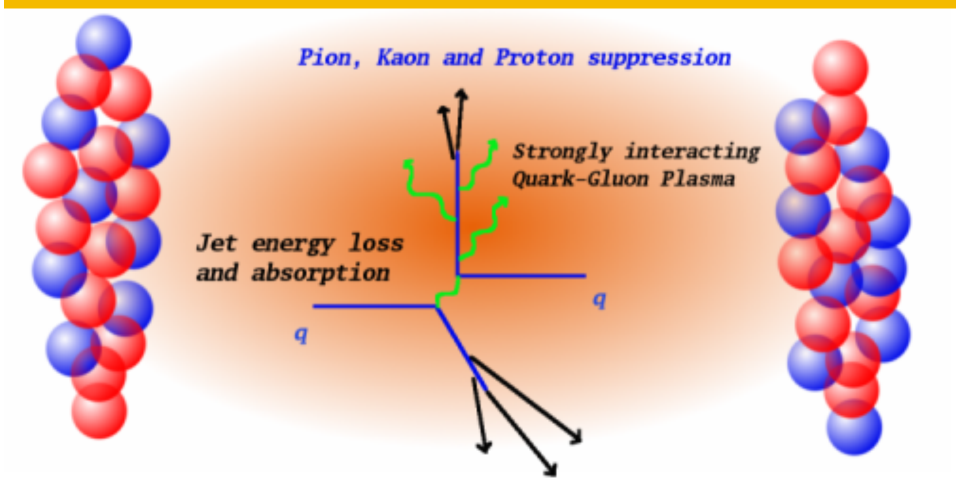
May-June 2017, Argonne National Lab, IL

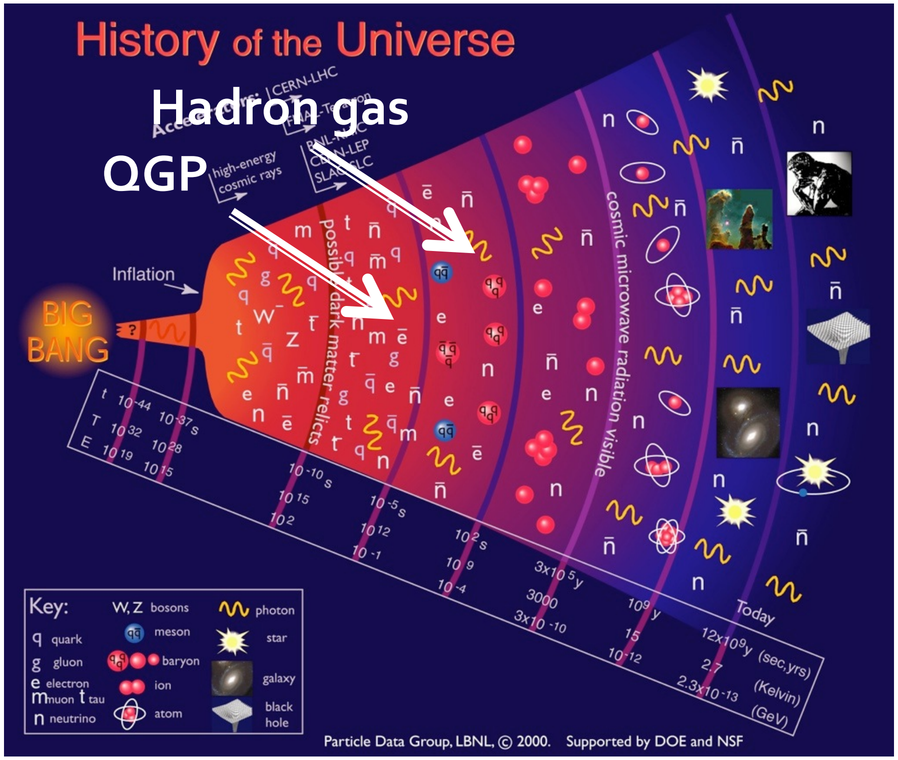
# Background: QGP and the early universe

Thanks to the organizers for the opportunity to discuss the A+A

Collaboration with : Y.-T. Chien, Z.-B. Kang, G. Ovanesyan, F. Ringer, M. Sievert, H. Xing, S. Yoshida …

- Small-x saturation physics, LQCD, relativistic viscous hydrodynamics, thermal field theory, jet and heavy flavor physics in a background QCD medium

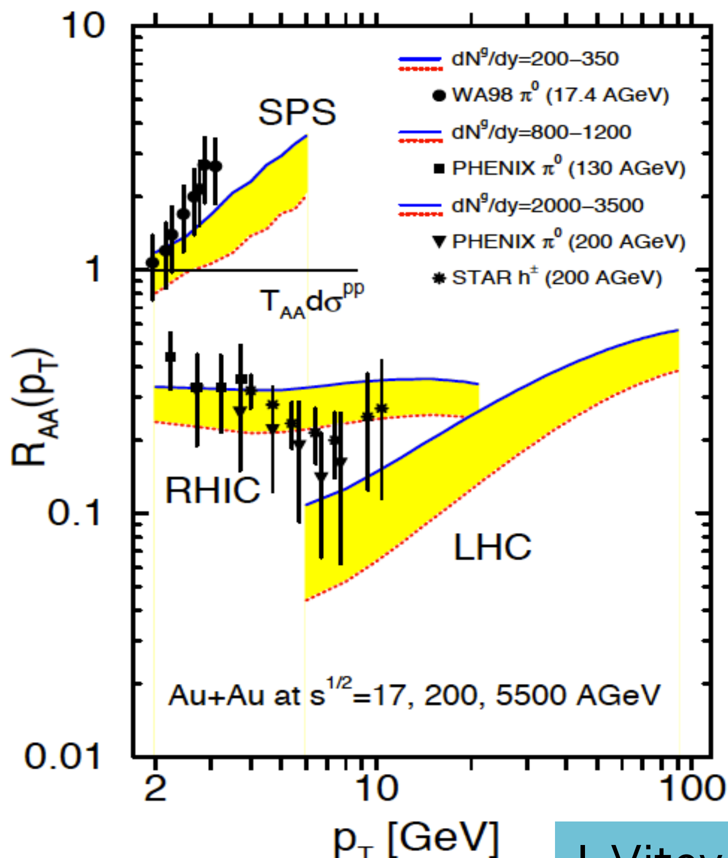



- QGP is the earliest stage in the evolution of the universe that can be directly studied in the laboratory
- Active heavy ion programs at the SPS, RHIC, LHC

# Traditional E-loss approach – successful but incomplete

- There is abundance of heavy ion data on inclusive and tagged jet cross sections, open heavy flavor, quarkonia, asymmetries, jet substructure, fragmentation functions, jet shapes even even groomed soft dropped subjet distributions they all show strong modification in A+A relative to p+p.



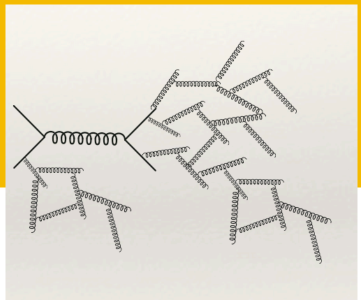

I. Vitev et al. (2002)

## Nuclear modification ratio

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

$N_{binary}$ – the # of elementary p+p like collisions

- Traditional non-Abelian energy loss has been refined. Difficult to make connection to the standard LO, NLO, …; LL, NLL … pQCD approach (higher orders and resummation)
- Bring some of the logs, legs and loops technology to HI

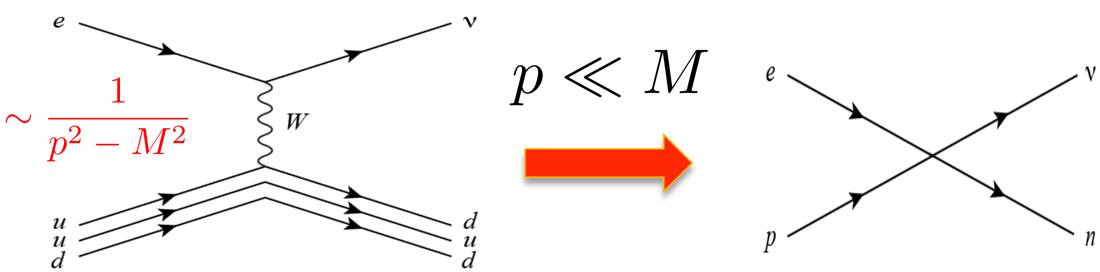


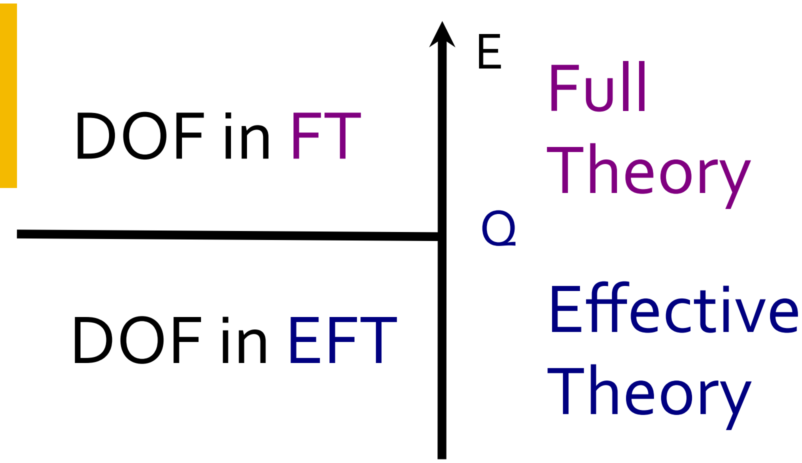
# Framework


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

# EFTs (Effective Field Theories)

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




- Effective theories are ubiquitous. The Standard Model is likely a low energy EFT of a theory at a higher scale
- Particularly well suited to QCD, and nuclear physics: χPT, HQET, NRQCD, …

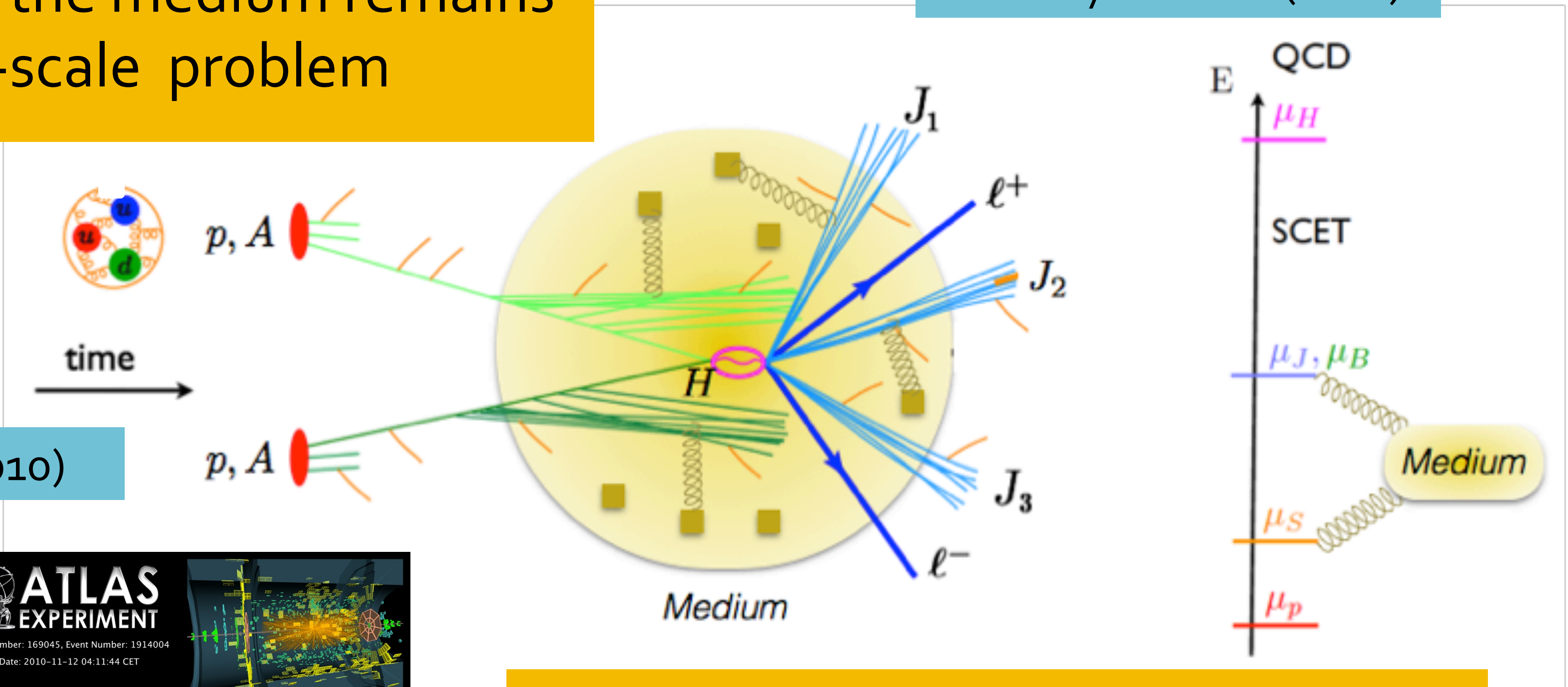
**SCET** C. Bauer et al. (2001) D. Pirol et al. (2004)

**Goal: generalize SCET to jet and heavy flavor physics in a background QCD medium, derive necessary ingredients for one loop calculations, NLO jets and heavy flavor phenomenology in A+A**

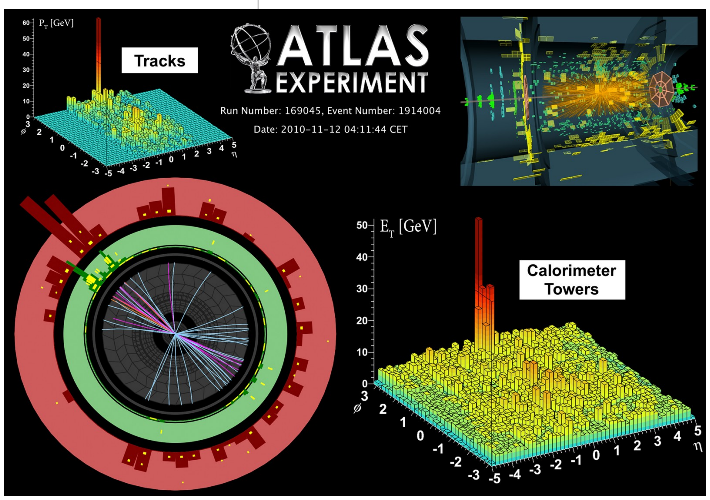
# The HIC picture for hard probes

- QCD in the medium remains a multi-scale problem

Ovanesyan et al. (2011)




Aad et al. (2010)




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

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

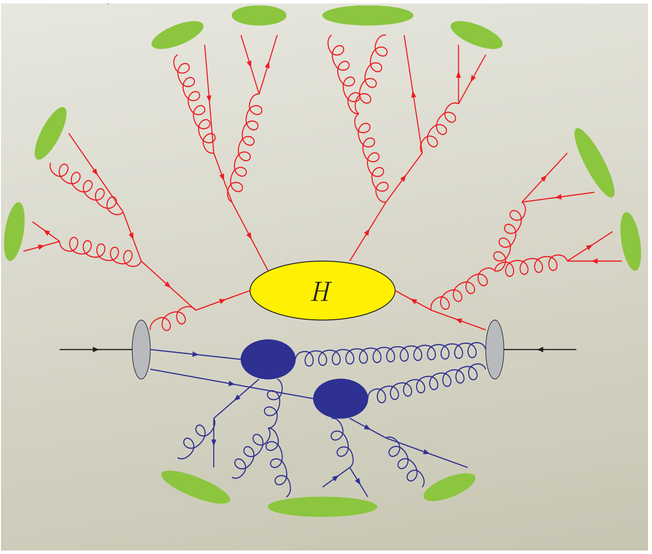
# $\text{SCET}_\text{G}$

- 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

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

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^\mu = \partial^\mu + gA^\mu \qquad A^\mu = A^\mu_c + A^\mu_s + A^\mu_{\rm G}$$

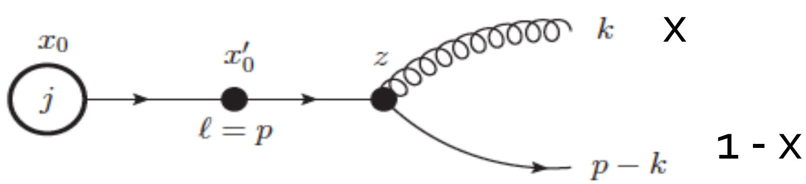
**Feynman rules depend on the scaling of m. The key choice is $m/p^+ \sim \lambda$**

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

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




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

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

The process is not written Q to gQ

F. Ringer et al . (2016)

- You see the dead cone effects

  Dokshitzer et al. (2001)

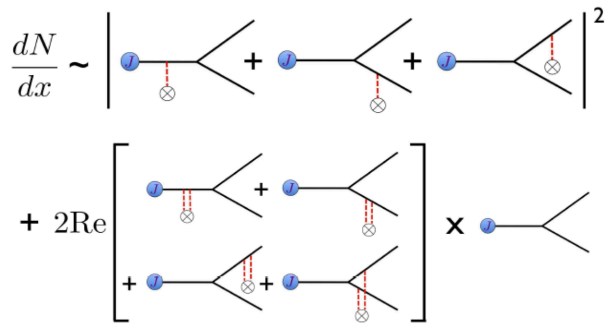
- You also see that it depends on the process – it not simply $x^2m^2$ everywhere: $x^2m^2$, $(1-x)^2m^2$, $m^2$

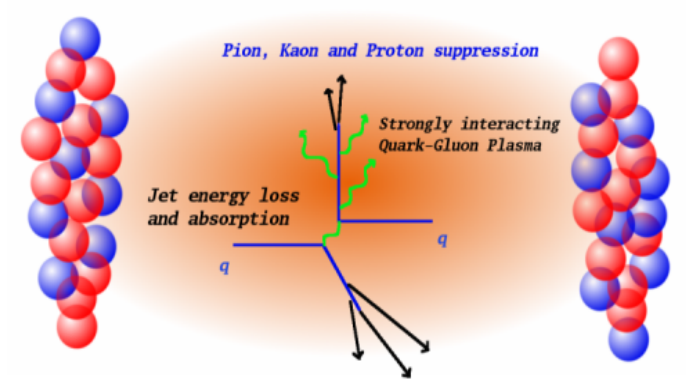
# Heavy quarks splitting functions in the medium

New physics – many-body quantum coherence effects

Quantitatively different longitudinal and transverse structure of the splitting kernels

F. Ringer et al . (2016)



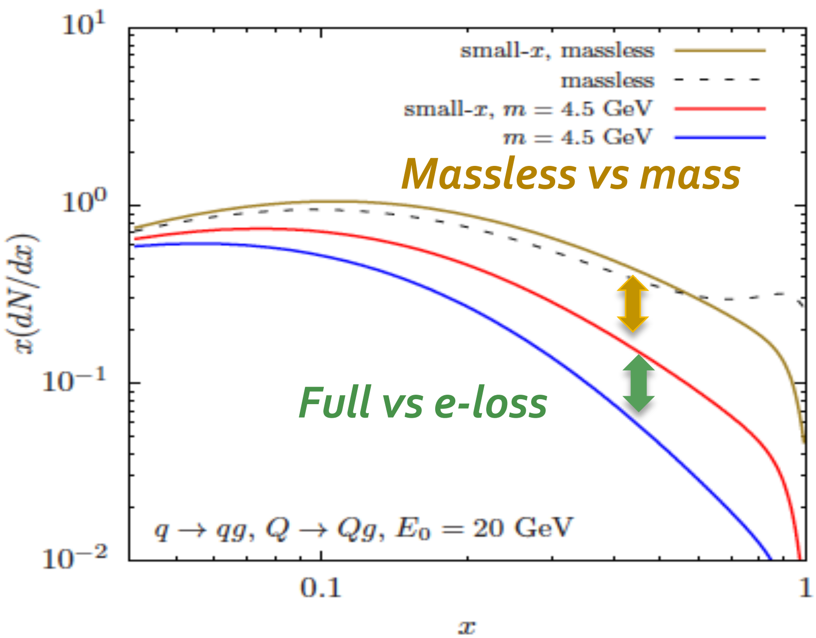

$$\nu \;=\; x m \qquad (Q \to Qg)$$

$$A, B, \ldots \Omega_1, \Omega_2 \ldots \to f(x,k;q)$$

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

- Full massive in-medium splitting functions now available
- Can be evaluated numerically
- ~4,600 core hours for one set of differential in x, $k_T$ medium-induced splitting functions

# Various limits and crosschecks




- In the soft gluon emission (x ➔0) energy loss limit only the diagonal splittings survive (Q to Qg) – check against e-loss calculations

M. Djordjevic et al . (2003)

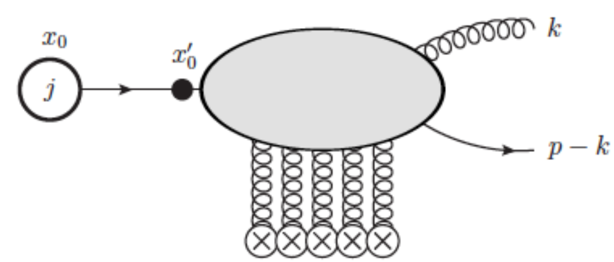
- By taking the massless limit we cross checked the result against massless splitting functions

G. Ovanessyan et al . (2012)

- There is a limitation to the calculation to first order in opacity. Higher order correlations lead to smoother 2D (x,kT) distributions

- Calculation can be done using light cone wavefunctions. Checked for light quarks.

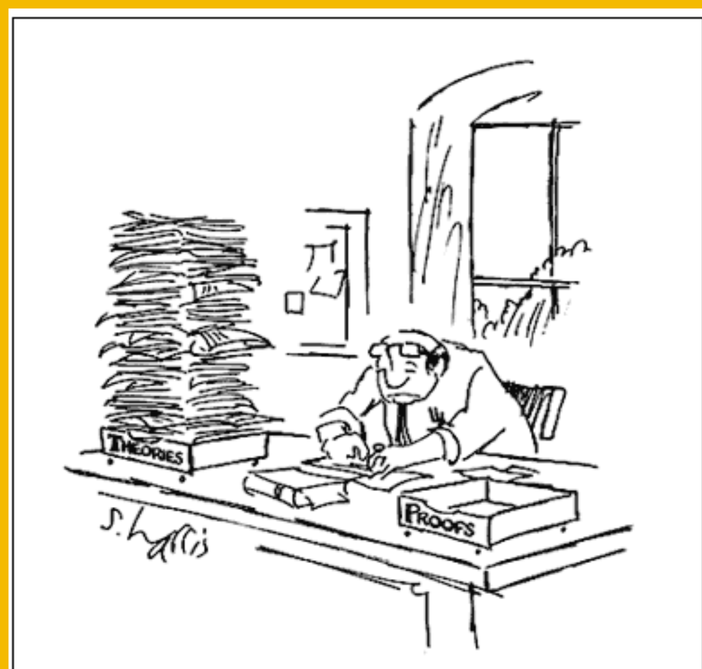
M. Sievert et al . in prep



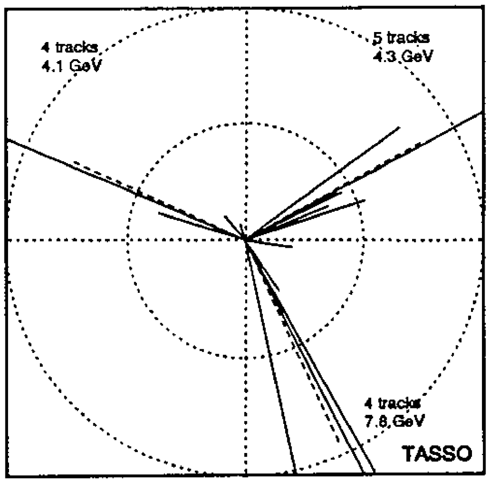

$$\psi(x, \underline{k} - x\underline{p}) \equiv \frac{1}{2p^+}\frac{1}{p^- - (p-k)^- - k^-}\overline{U}(p-k)\left[-g\not\epsilon^*(k)\right]U(p)$$

$$= 2g\sqrt{1-x}\,\frac{\underline{\epsilon}^*_\lambda \cdot (\underline{k} - x\underline{p})}{(\underline{k} - x\underline{p})_T^2}\left[\delta_{\lambda\sigma}\delta_{\sigma\sigma'} + (1-x)\delta_{\lambda,-\sigma}\delta_{\sigma\sigma'}\right]$$

# Semi-Inclusive Jet Calculations HI via $\text{SCET}_{(G)}$

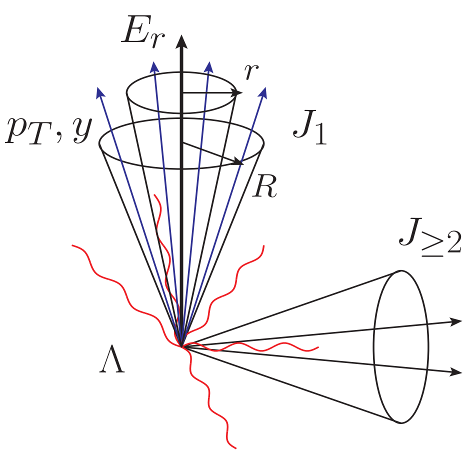


# Exclusive approach to jets in SCET




TASSO (1979)

PETRA at DESY
12 GeV < CM energy < 47 GeV




- Motivated by early e+ e- annihilation, SCET assumes that all energy goes into a well defined number of jets

**Factorized expression**

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

- Nomenclature: H – hard function, S – soft function, B- beam function, J – jet function

**The exclusive view of a process in SCET summarized as**

$$\frac{1}{\sigma_0}\frac{d\sigma}{dE_r\, dp_{T_i}\, dy_i} = H(p_{T_i}, y_i, \mu) J_{\omega_1}(E_r, \mu) J_{\omega_2}(\mu) \ldots J_{\omega_N}(\mu) S_{n_1 n_2 \ldots n_N}(\Lambda, \mu) + \mathcal{O}\left(\frac{\Lambda}{Q}\right) + \mathcal{O}(R) \,.$$

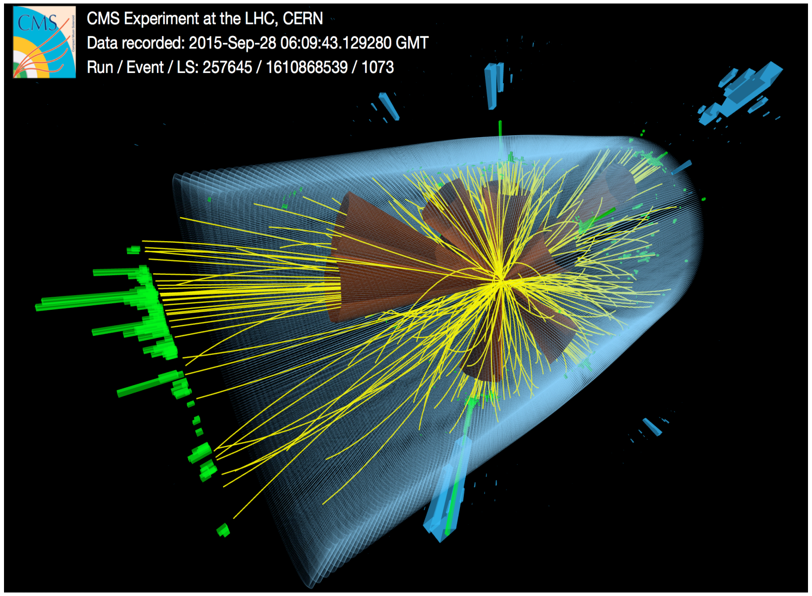
- Evolution of jet energy function

$$\frac{dJ_\omega^{qE_r}(\mu)}{d\ln\mu} = \left[-C_F \Gamma_{\text{cusp}}(\alpha_s) \ln \frac{\omega^2 \tan^2 \frac{R}{2}}{\mu^2} - 2\gamma^q(\alpha_s)\right] J_\omega^{qE_r}(\mu)$$

$$\frac{dJ_\omega^{gE_r}(\mu)}{d\ln\mu} = \left[-C_A \Gamma_{\text{cusp}}(\alpha_s) \ln \frac{\omega^2 \tan^2 \frac{R}{2}}{\mu^2} - 2\gamma^g(\alpha_s)\right] J_\omega^{gE_r}(\mu)$$

# Why may we need inclusive SCET approach?

CERN energies 0.9 TeV < CM energy < 13 TeV




- It is certainly not the case in hadronic collisions (and even more energetic e+ e-) that all the energy goes into jets and beams.

Dasgupta et al. (2014)

- Argued that a different type of evolution may hold, namely DGLAP evolution

CMS (2015)

Kang et al. (2016) | Iidlbi et al. (2016) | Chul et al. (2016)

**Experiments measure for example**

$$A + B \to Jet + X$$

**Typically no effort to determine what X is**

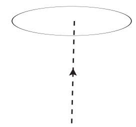
- Allow for the jet to capture only a fraction of the parton shower energy $z=\omega_J/\omega$

**Semi-inclusive jet function**

$$J_q(z = \omega_J/\omega, \omega_J, \mu) = \frac{z}{2N_c} \mathrm{Tr}\left[\frac{\bar{n}\!\!\!/}{2} \langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\chi_n(0)|JX\rangle\langle JX|\bar{\chi}_n(0)|0\rangle\right]$$

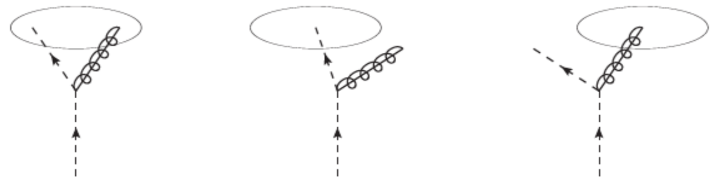
# Semi-inclusive jet function in SCET

- At tree level



$$J_q^{(0)}(z,\omega_J) = \delta(1-z)$$

- At one loop order

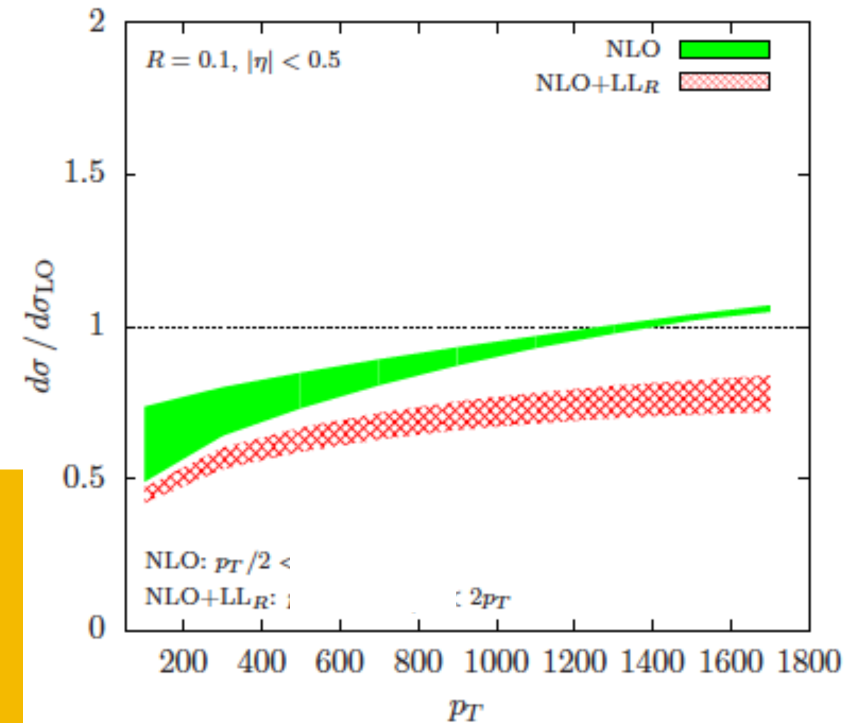


All double poles ($1/\epsilon^2$) and double logarithms ($L^2$) and cross cancel. Single logarithms survive

$$L = \ln \frac{\mu^2}{\omega_J^2 \tan^2 \frac{R}{2}}$$

$$\begin{aligned} J_q^{(1)}(z,\omega_J) =& J_{q\to qg}(z,\omega_J) + J_{q\to q(g)}(z,\omega_J) + J_{q\to (q)g}(z,\omega_J) \\ =& \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)\left[P_{qq}(z)+P_{gq}(z)\right] \\ & - \frac{\alpha_s}{2\pi}\left\{ C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] \right. \\ & \left. - \delta(1-z) d_J^{q,\mathrm{alg}} + P_{gq}(z) 2\ln(1-z) + C_F z \right\} \end{aligned}$$

F. Ringer et al. (2015)

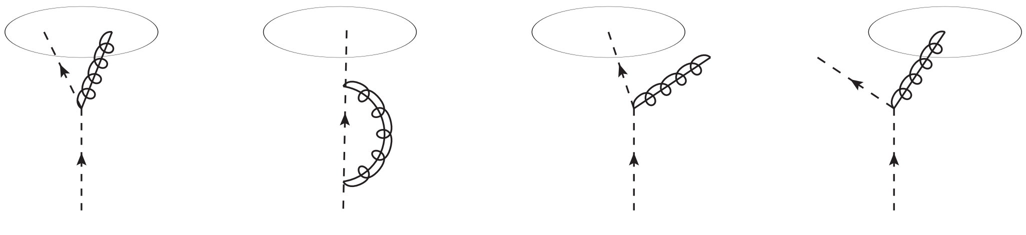



We can perform $LL_R$ resummation. Have generalized to $NLL_R$

- Fixes the unphysical scale dependence of NLO jet
- Resummation can have up to 30% effect for small R

# 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

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

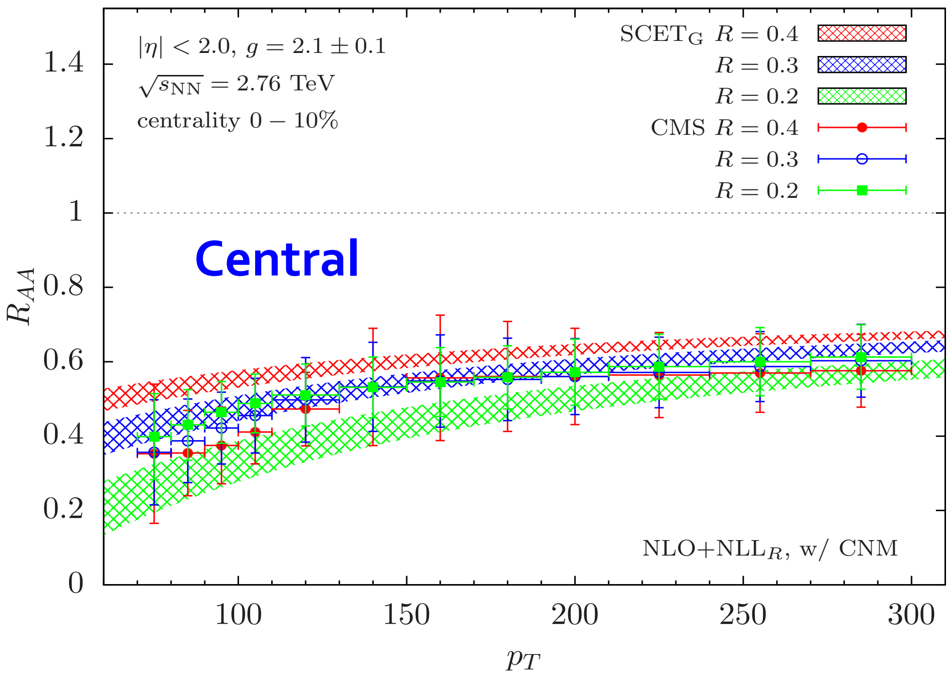
- Stable in numerical implementation
- Similarly for gluon jets

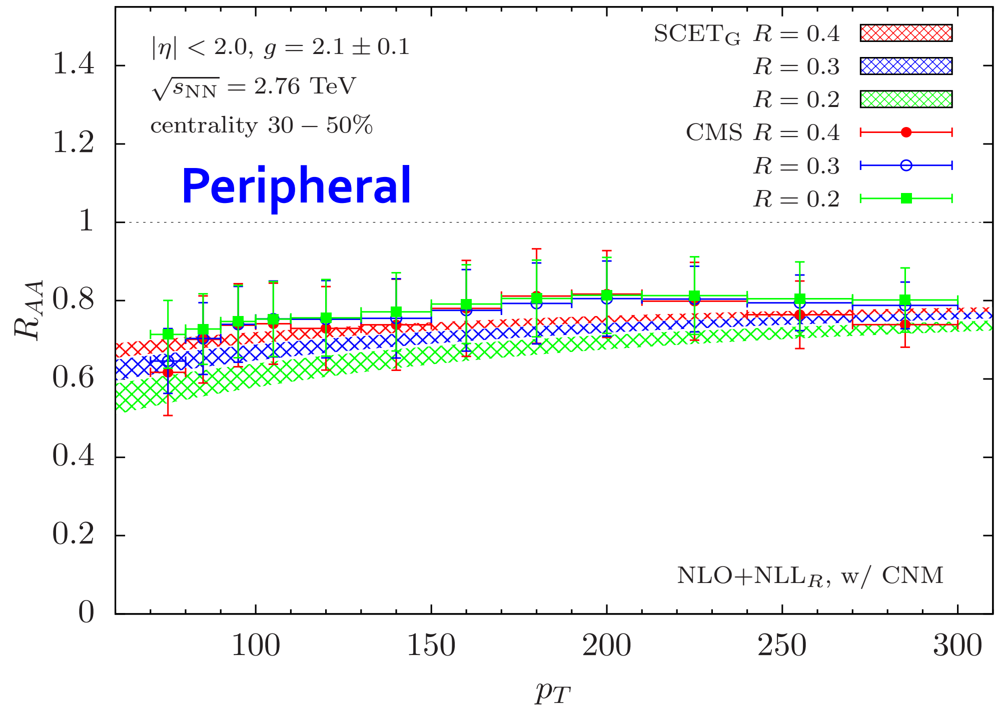
# Centrality dependence of jet suppression

- In the medium it is strictly NLO
- Included cold nuclear matter effects

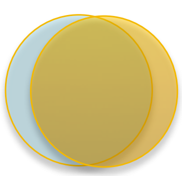
$$d\sigma^{\text{jet}}_{\text{PbPb}} = d\sigma^{\text{jet,vac}}_{pp} + d\sigma^{\text{jet,med}}_{\text{PbPb}}$$

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

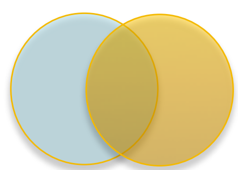



c.f. Y.T. Chien et al. (2015)



**Central**



**Peripheral**

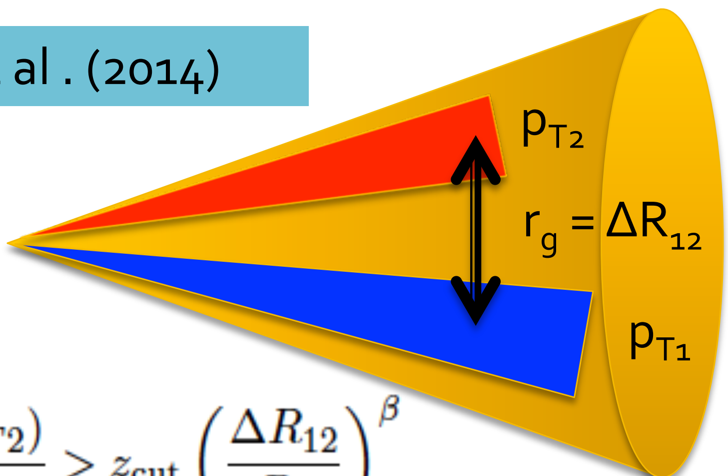
The centrality dependence appears to be well captured

# Jet substructure

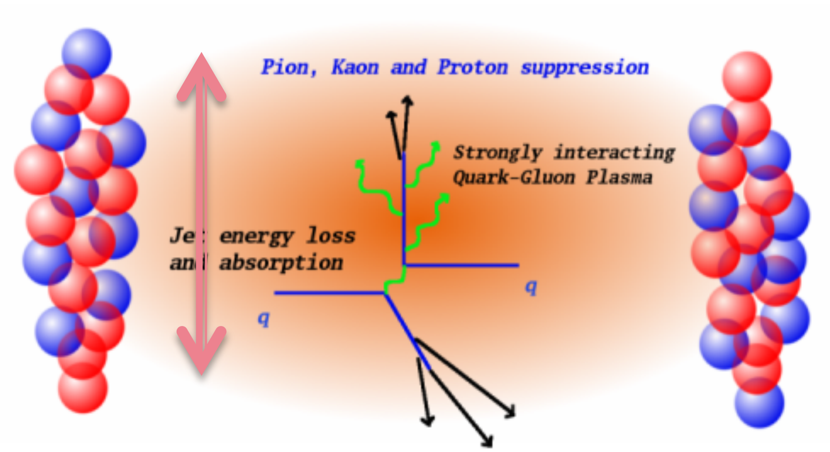
# How to measure splitting kernels

## Groomed jet distribution using "soft drop"

A. Larkoski et al . (2014)




$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$




QGP size ~ 10fm

$$\tau_{br}[\text{fm}] = \frac{0.197 \text{ GeV fm}}{z_g(1 - z_g)\,\omega[\text{GeV}]\,\tan^2(r_g/2)}$$

The great utility of these new distributions:

- Definition eliminates soft and collinear divergences to the observable
- probe the early time dynamics / splitting

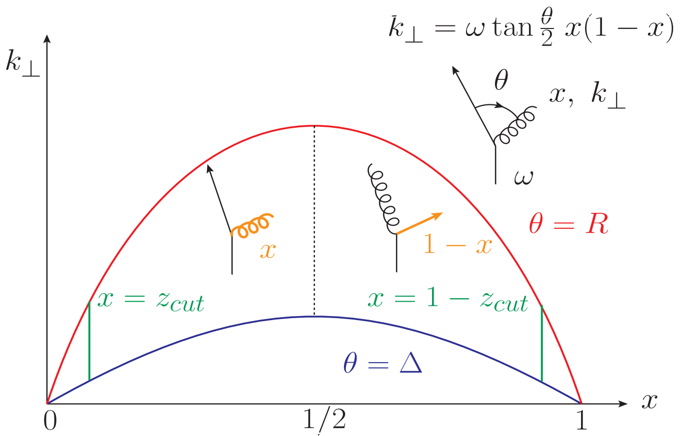
Typical situation: E=200 GeV, $r_g$ = 0.1

Branching time < 2 fm for $z_g$ studied

Y. T. Chien et al . (2016)

# Accessing the hard branching in HIC – longitudinal modification

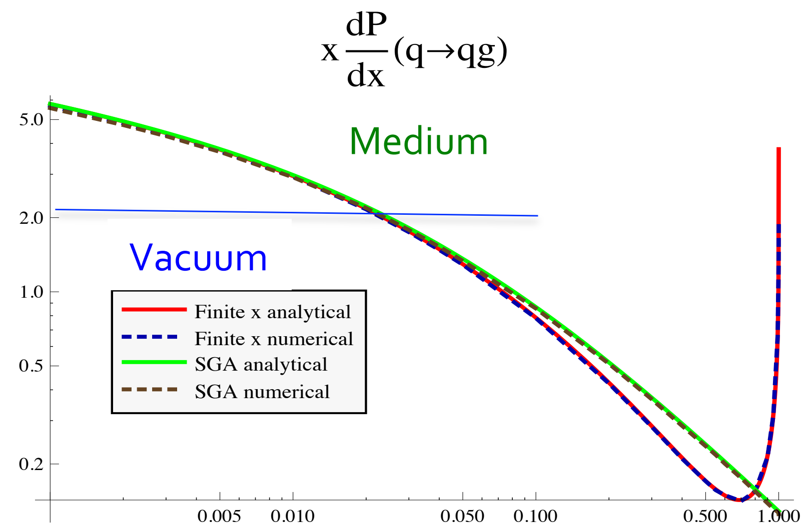
Calculating the soft dropped distribution with β=o

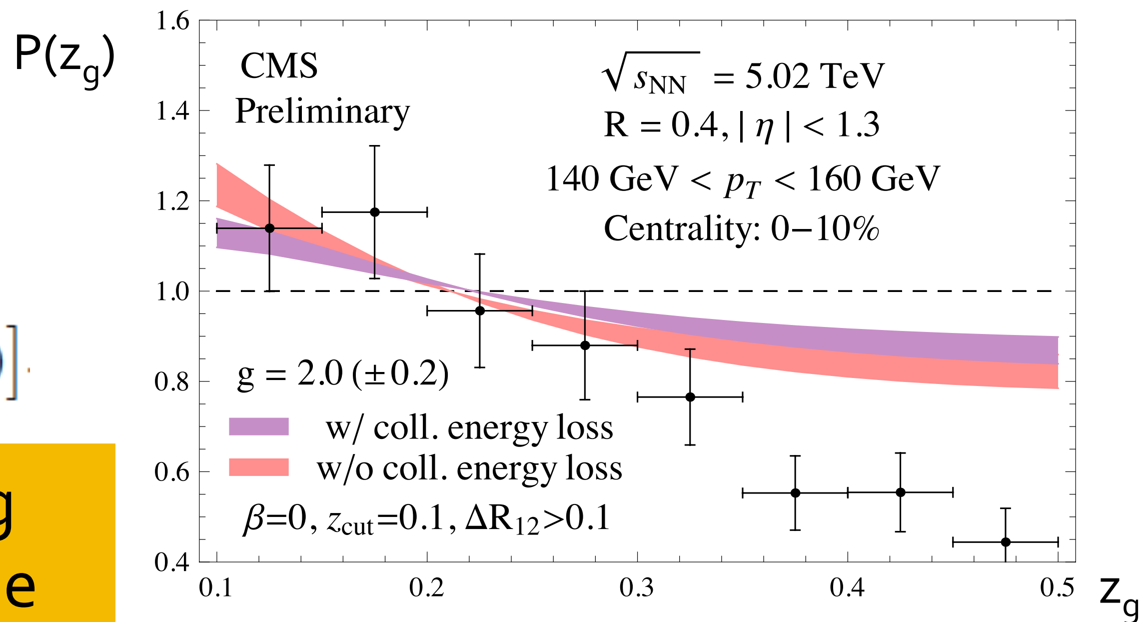



$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

$$\overline{\mathcal{P}}_i(x, k_\perp) = \sum_{j,l} \left[\mathcal{P}_{i\to j,l}(x, k_\perp) + \mathcal{P}_{i\to j,l}(1-x, k_\perp)\right].$$

NB: data is preliminary, being reanalyzed, points can change



# Conclusions

- Heavy ion physics is an important part of the LHC program, and the driver for RHIC detector upgrades
- $SCET_G$ - an effective theory for jet propagation in matter constructed. One-loop in-medium splitting functions derived for massless and massive partons to first order in opacity. Ongoing work using lightcone wavefunction techniques to improve results beyond this order
- Recently semi-inclusive jet functions were introduced and computed to one loop. Found that they satisfy standard time-like DGLAP evolution equations. Allowed to perform jet R resummation to $NLL_R$. Appear to have immediate relevance to the small radius jet measurements at LHC
- Performed first NLO calculation of inclusive jet production in $SCET_G$. Large uncertainties remain (cold nuclear matter effects, collisional energy loss) but first results look promising
- Progress in applying $SCET_G$ calculations of jet substructure connecting splitting functions to groomed soft-dropped momentum sharing distributions. Direct measurement of medium-induced splitting functions

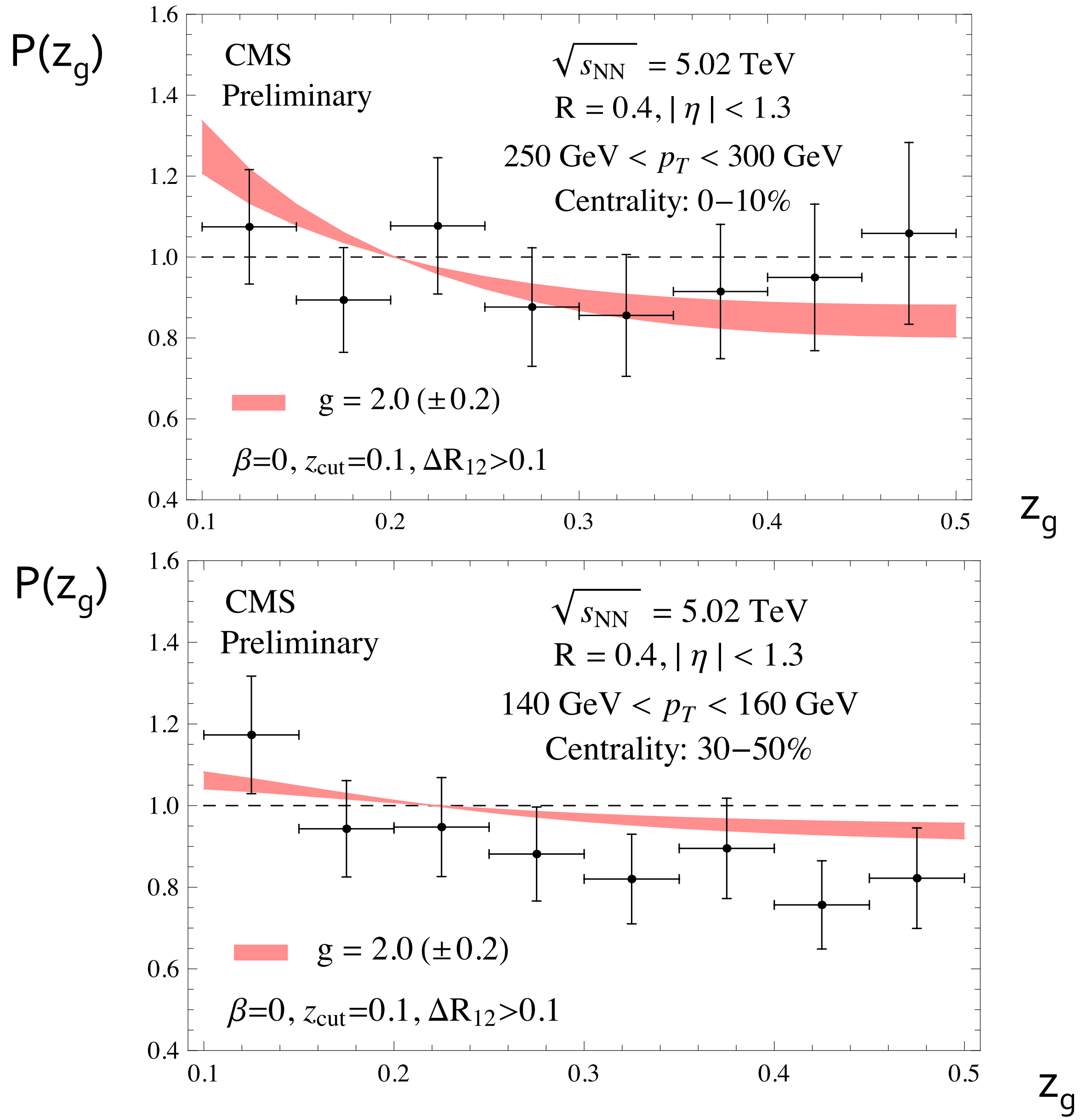
# Centrality and $p_T$ dependence

(Collisional) energy loss of individual branches does not help

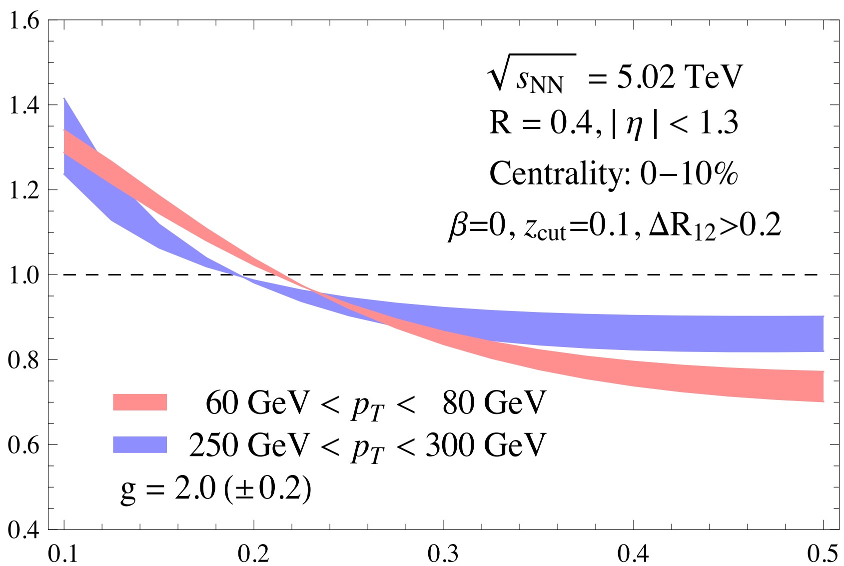
Evolution in pT is slowish theoretically .
Experimental data fluctuates more but beware of error bars

Centrality dependence as expected – reduced effect for peripheral collisions

Y.T Chien et al . (2016)



# Modification of the angular distribution of hardest branchings



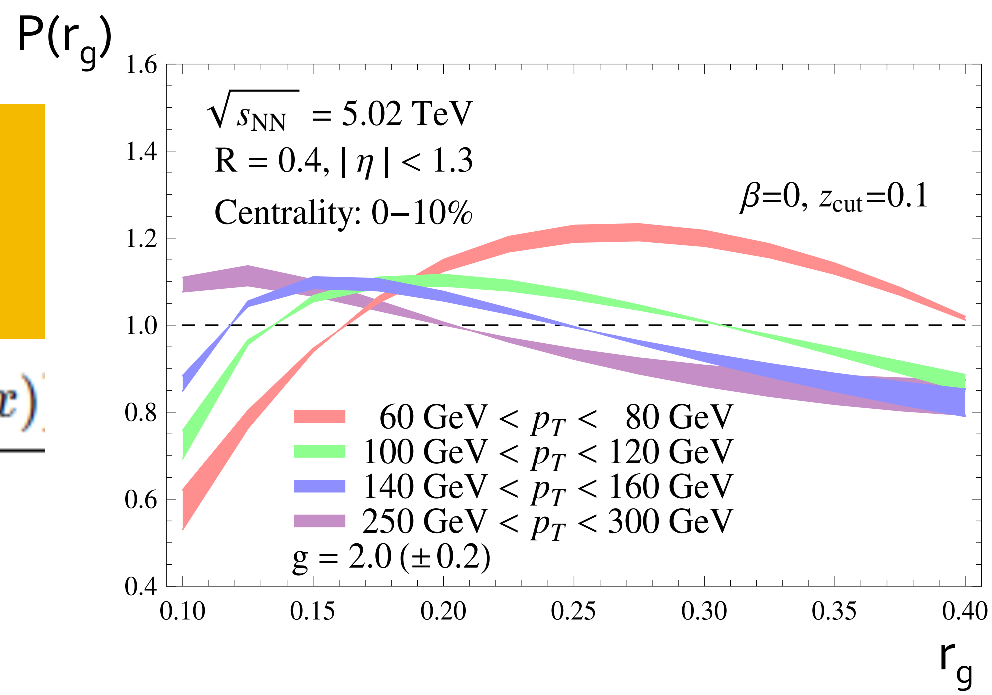

Flexibility in selecting angular separation $r_g$

Found that inermediate values $r_g$ = 0.2 give the strongest $p_T$ dependence. Though not nearly as strong as preliminary data

New observable proposed – measures the typical splitting angle modification in HIC

$$p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x)\overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

Y.-T. Chien et al . (2016)



# Semi-inclusive fragmenting jet function

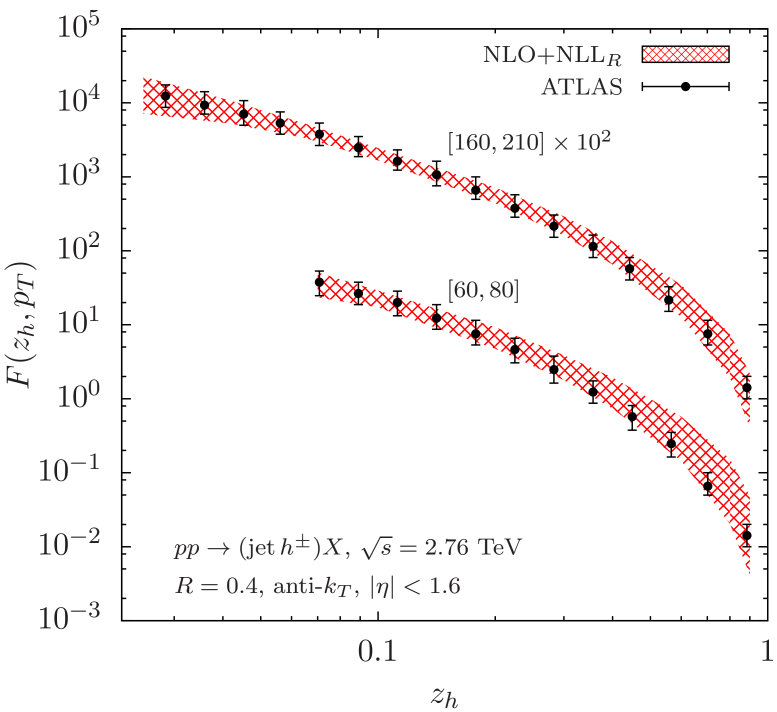
Generalize the definition to jet and a hadron, sequences of fractions

$$\mathcal{G}_g^h(z, z_h, \omega_J, \mu) = -\frac{z\,\omega}{(d-2)(N_c^2-1)}\delta\left(z_h - \frac{\omega_h}{\omega_J}\right)\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|(Jh)X\rangle \times \langle (Jh)X|\mathcal{B}_{n\perp}^{\mu}(0)|0\rangle,$$

Z. Kang et al . (2016)

Derive to one loop the SIFJF

$$\mathcal{G}_q^q(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\left(-\frac{1}{\epsilon} - L\right)P_{qq}(z_h)\delta(1-z) + \frac{\alpha_s}{2\pi}L\,P_{qq}(z)\delta(1-z_h)$$
$$+\delta(1-z)\frac{\alpha_s}{2\pi}\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + 2P_{qq}(z_h)\ln z_h\right]$$
$$-\delta(1-z_h)\frac{\alpha_s}{2\pi}\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right], \qquad (2.33a)$$

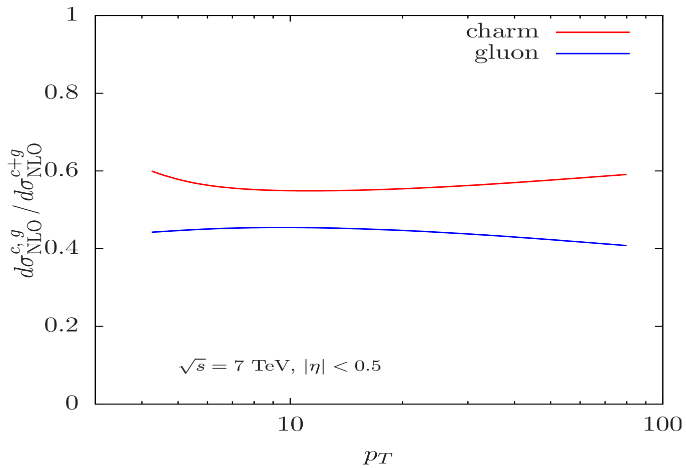


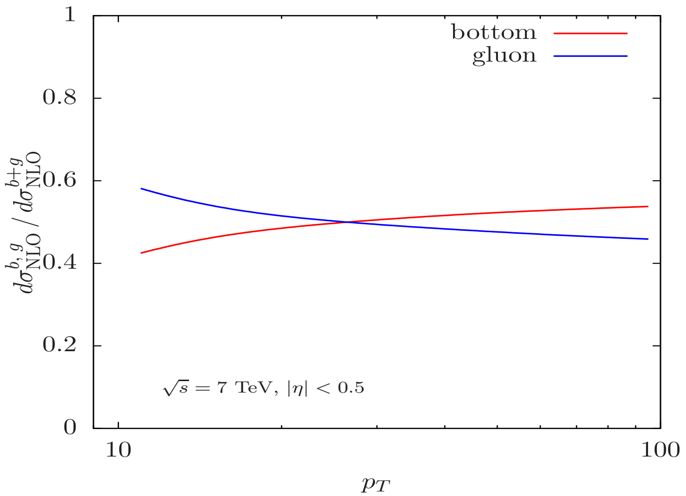

- Agrees with data within uncertainties.
- However the central values can deviate by 20% and small z even 40%
- Can be used to constrain FFs

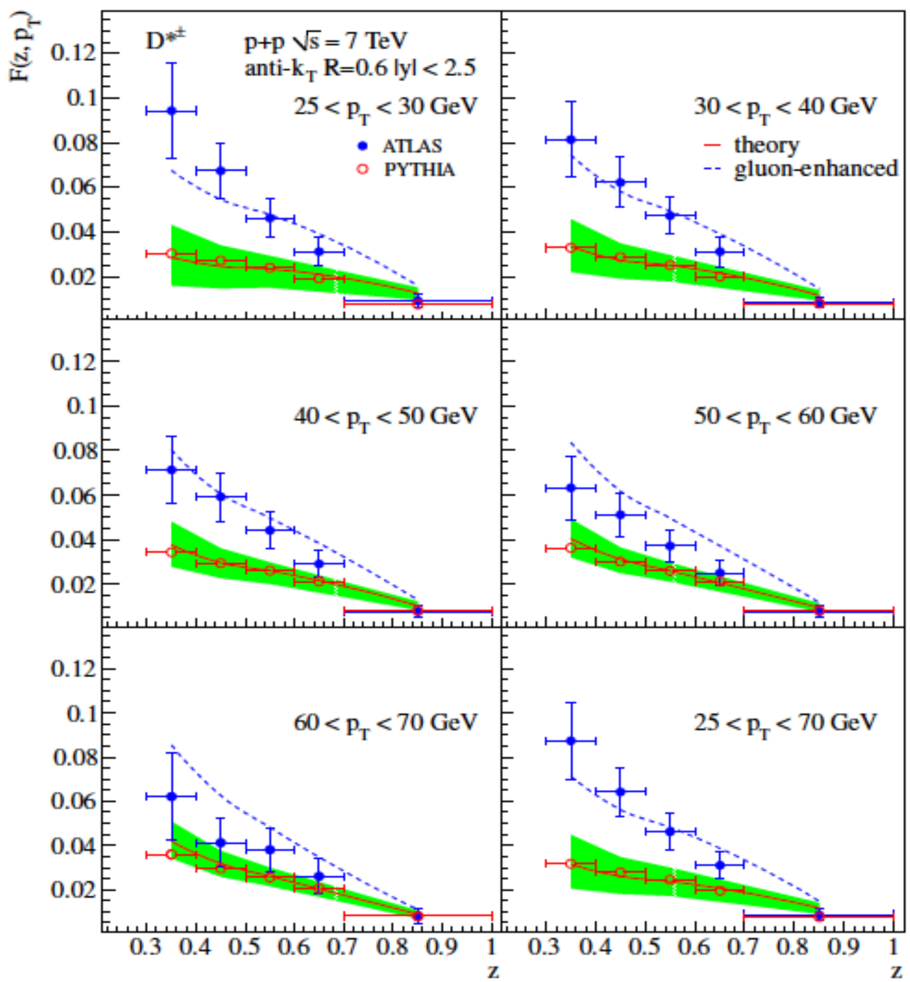
# Implications for heavy flavor modification

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

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

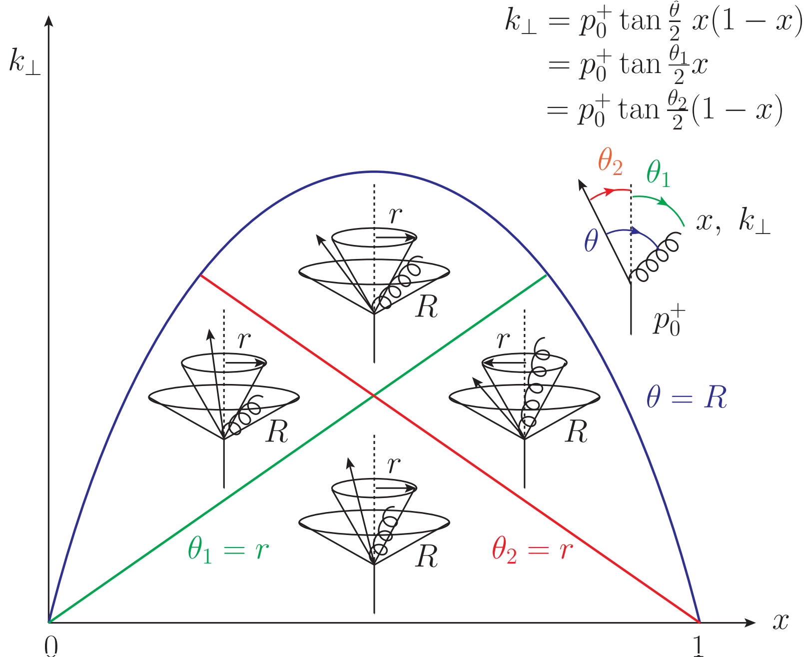



Y.T. Chien et al . (2015)

# Medium-modified jet shapes at NLL



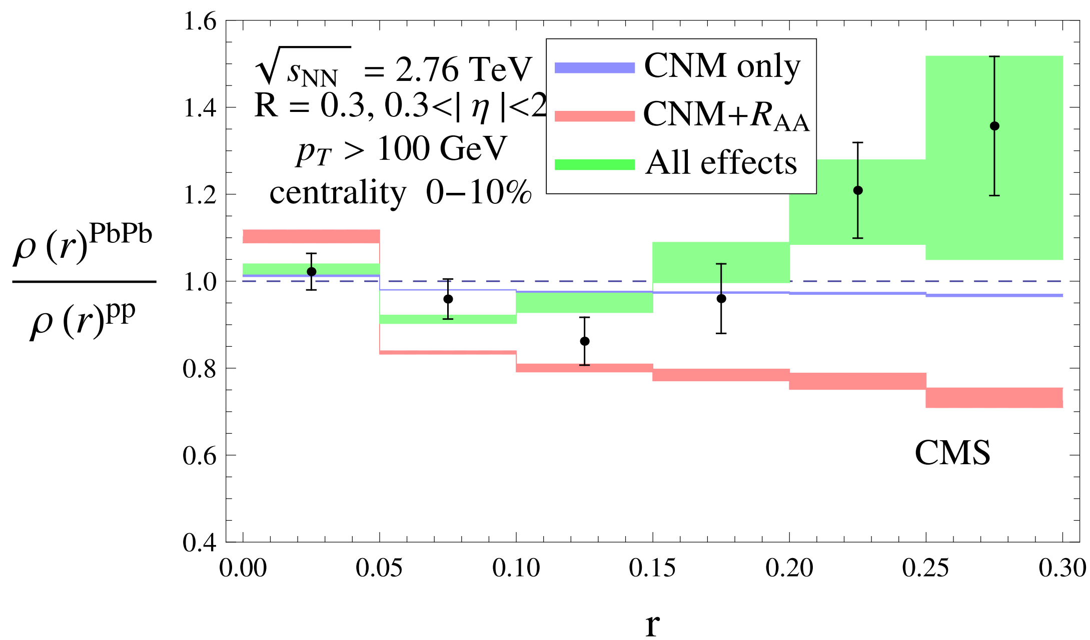

$$E_r(x, k_\perp) = \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3 + \mathcal{M}_4$$

**Measurement operator – tells us how the above configurations contribute energy to J (jet function)**

- One can evaluate the jet energy functions from the splitting functions

$$J^i_{\omega,E_r}(\mu) = \sum_{j,k} \int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x,k_\perp) E_r(x,k_\perp)$$

$$J_{\omega,E_r}(\mu) = J^{vac}_{\omega,E_r}(\mu) + J^{med}_{\omega,E_r}(\mu)$$




- First quantitative pQCD/SCET description of jet shapes in HI

# Renormalization and evolution of the SIJF

- Renormalization matrix to one-loop order

**Absorb the remaining 1/ε divergence**

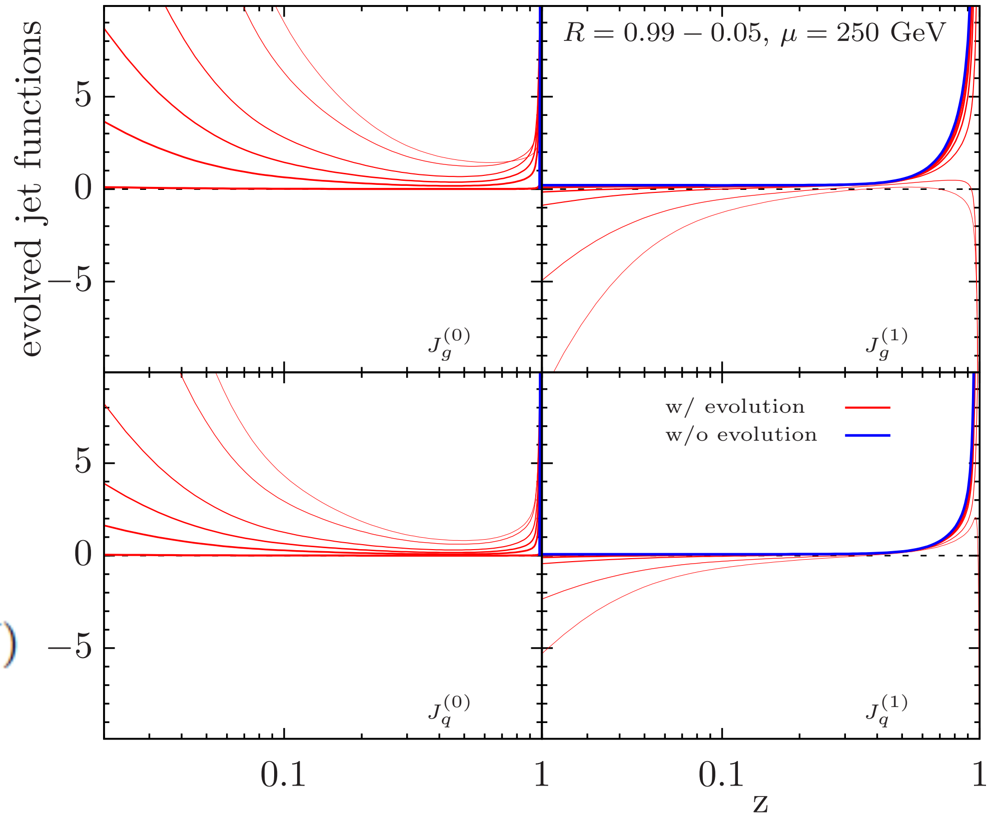
$$Z_{ij}(z,\mu) = \delta_{ij}\delta(1-z) + \frac{\alpha_s(\mu)}{2\pi}\left(\frac{1}{\epsilon}\right)P_{ji}(z)$$

- Anomalous dimensions

$$\gamma_{ij}^J(z,\mu) = -\sum_k \int_z^1 \frac{dz'}{z'}(Z)_{ik}^{-1}\left(\frac{z}{z'},\mu\right)\mu\frac{d}{d\mu}Z_{kj}(z',\mu)$$

**Standard single logarithmic time-like DGLAP evolution**

$$\frac{d}{d\log\mu^2}\begin{pmatrix} J_S(z,\omega_J,\mu) \\ J_g(z,\omega_J,\mu) \end{pmatrix} = \frac{\alpha_s(\mu)}{2\pi}\begin{pmatrix} P_{qq}(z) & 2N_f P_{gq}(z) \\ P_{qg}(z) & P_{gg}(z) \end{pmatrix} \otimes \begin{pmatrix} J_S(z,\omega_J,\mu) \\ J_g(z,\omega_J,\mu) \end{pmatrix}$$

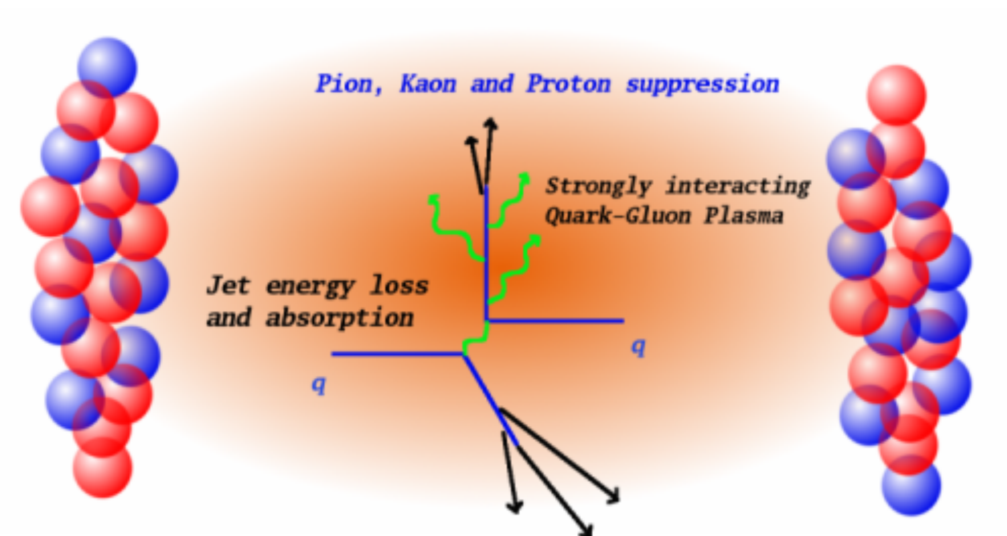


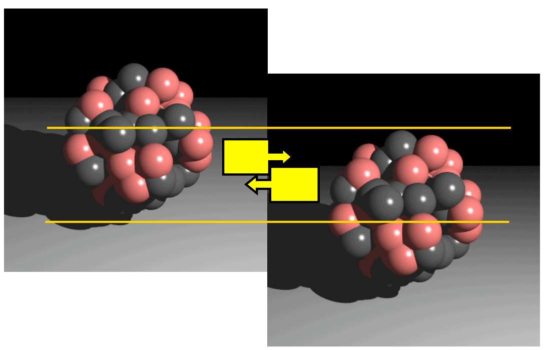

- The semi-inclusive jet function is evolved in Melin space

$$f(N) = \int_0^1 dz\, z^{N-1} f(z) \quad (f\otimes g)(N) = f(N)\,g(N)$$

$$\mu_J = \omega_J \tan\frac{\mathcal{R}}{2} = (2p_T\cosh\eta)\tan\left(\frac{R}{2\cosh\eta}\right) \approx p_T R$$

# Discovery of jet quenching

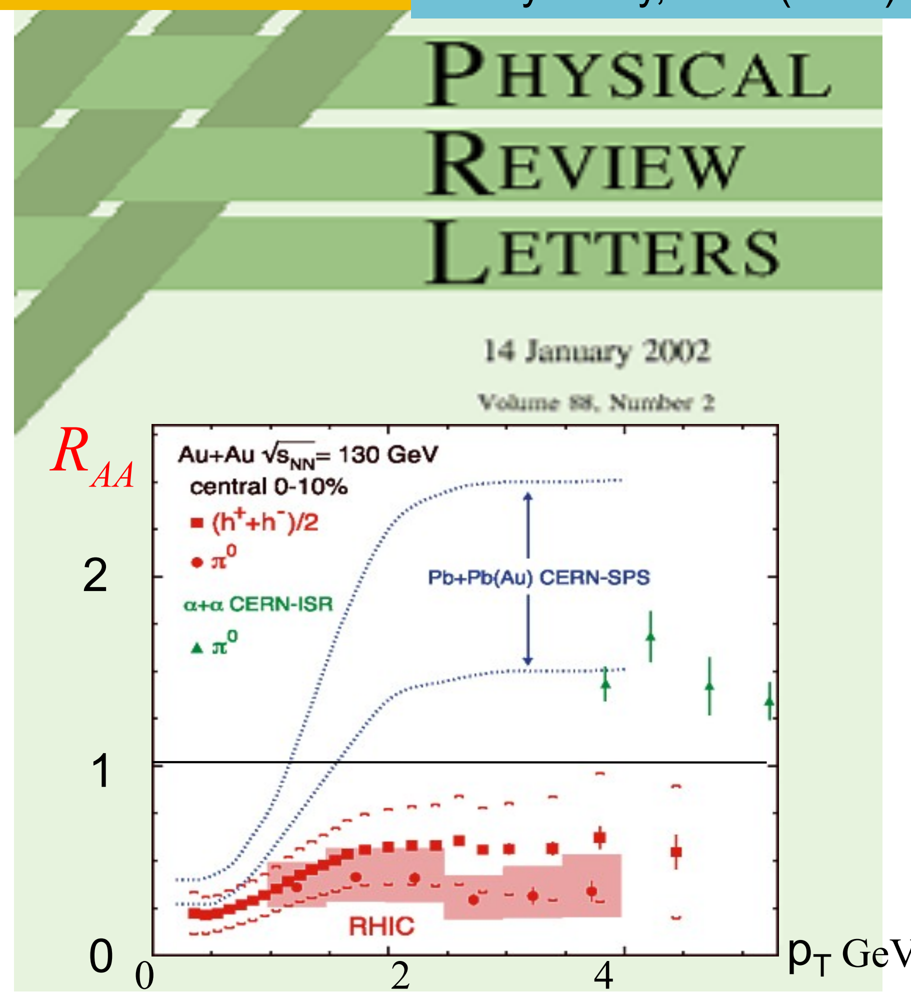


$N_{binary}$ – the # of elementary p+p like collisions

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

M. Gyulassy, et al. (1992)




- Quantify via the nuclear modification ratio

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

# Modification of Fragmentation Functions

A wide variety of jet substructure observable measurements are available: jet shapes, jet fragmentation functions, jet splitting functions

$$\mathcal{G}_q^{q,(1)}(z, z_h, \omega R, \mu) = \text{(B)} + \text{(C)} + \text{(D)} =$$

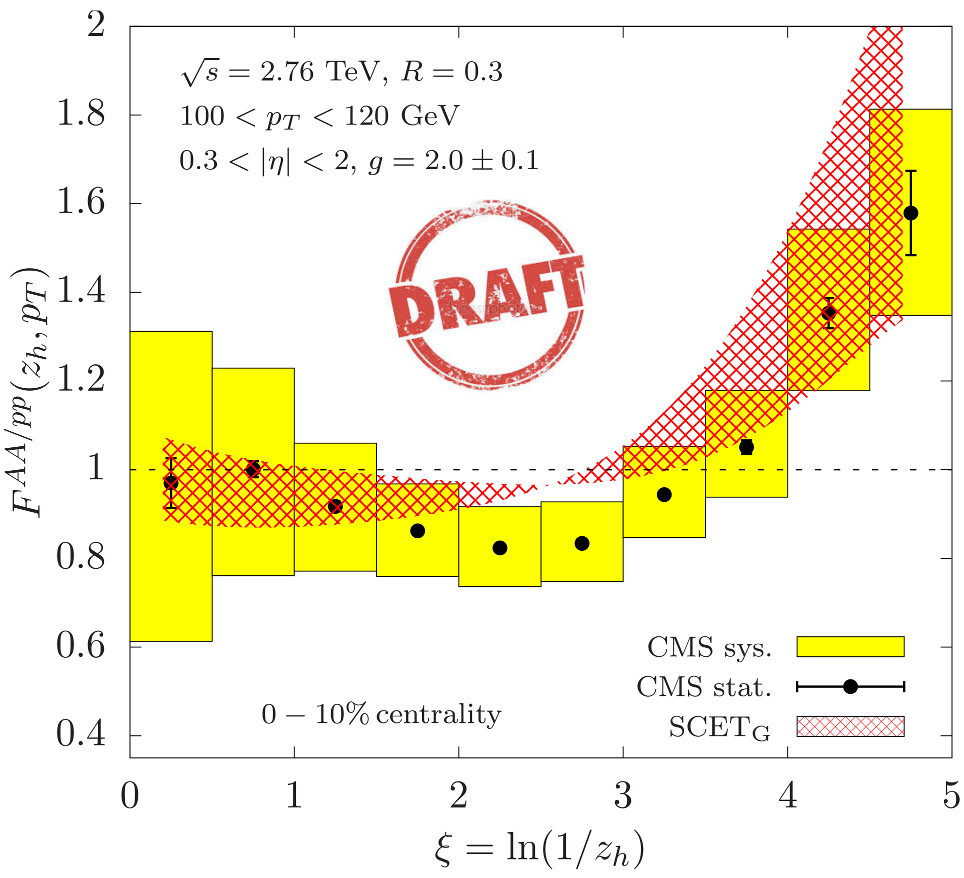
$$\delta(1-z_h)\left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} P_{qq}(z, q_\perp)\right]_+$$

$$+\,\delta(1-z)\left[\int_{\mu_0}^{z_h(1-z_h)\omega\tan(R/2)} dq_\perp P_{qq}(z_h, q_\perp)\right]_+$$

- Out of cone contribution – this is quenching –more quark jets
- In cone contribution – enhance the soft particle, reduce hard

Still in the process of assessing the sensitivity, centrality dependence, etc

CNM-no effect (like on all other substructure observables)



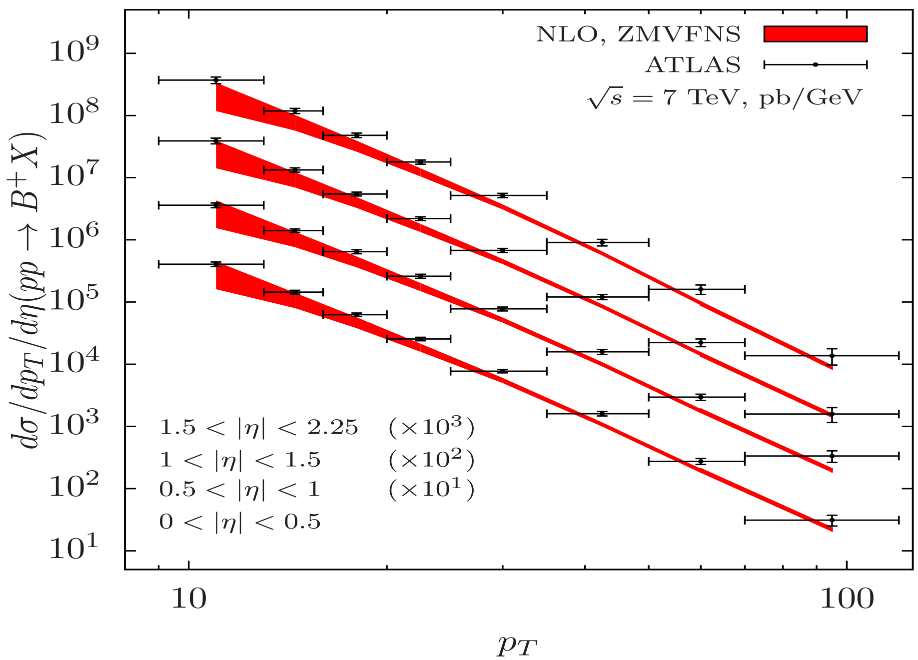
# Heavy Flavor in HI collisions

# ZMVFS open heavy flavor at NLO

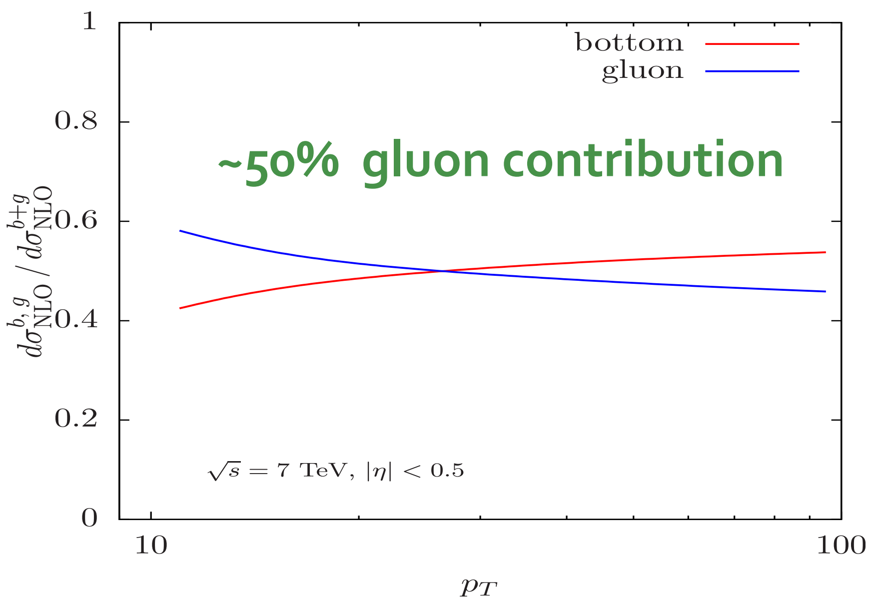
- Typically assumed that only c to D, b to B fragment perturbatively
- Perform an NLO calculation

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

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**

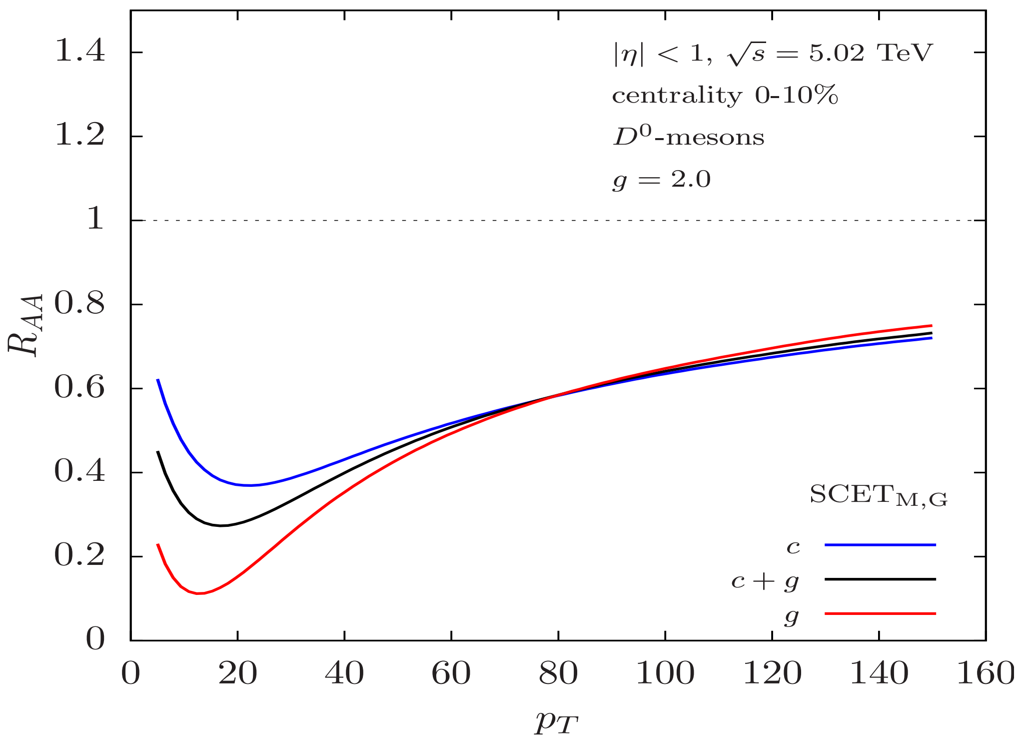
# Cross section calculation in the QCD medium

Medium contribution

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

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

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

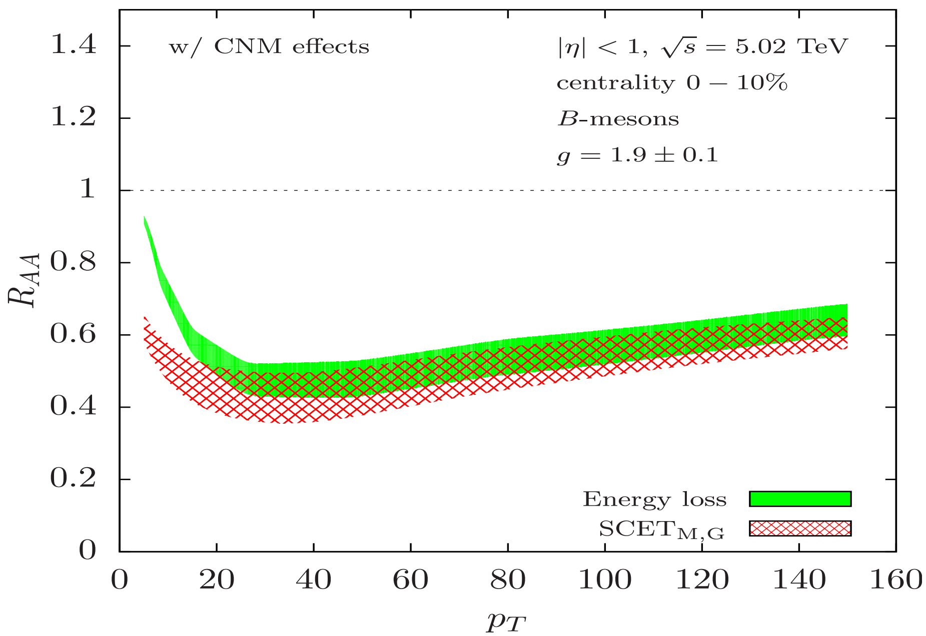


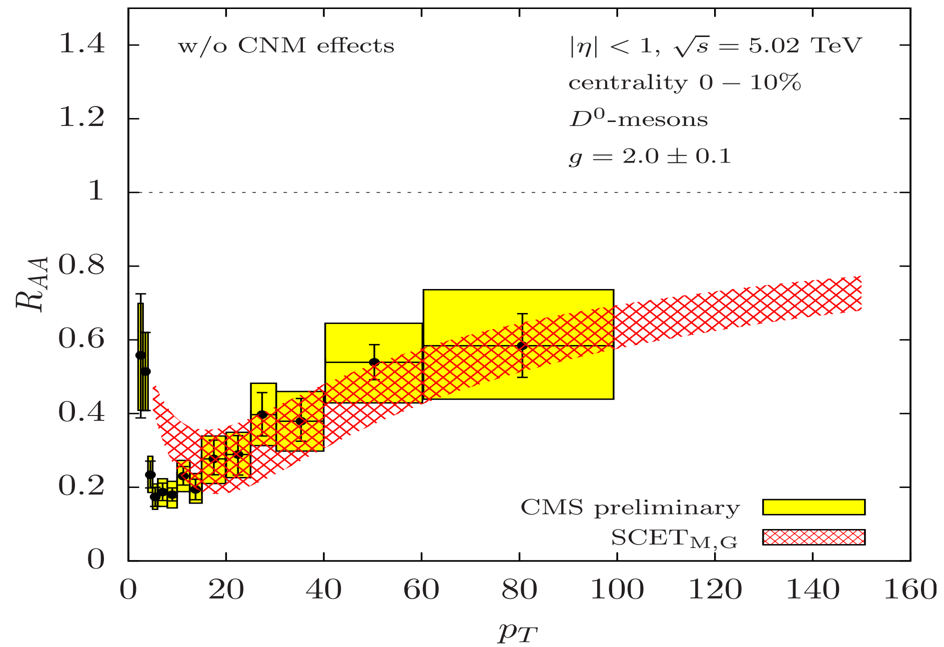

For numerical implementation one can rewrite these expression in the + prescription and finds that the cross section correction is negative

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

# Uncertainty and data comparison

Includes both production mechanism and e-loss vs NLO




- The pure scale uncertainty largely cancels in the ratio
- At low $P_T$ the uncertainties can grow to 30% D and 50+% B
- For D mesons works reasonably well. Below 10 GeV room for some additional nuclear effects: collisional energy loss, or may be even higher gluon contribution

D. Anderle et al . in prep