Ivan Vitev

Jets in SCET

Precision Spectroscopy of QGP with Jets and Heavy Quarks,

May 2017, Seattle, WA

Outline of the talk

- A brief introduction to effective field theories (EFTs). SCET
- Semi-inclusive jet cross sections in SCET and jet radius resummation.
- Consistent calculation of jet cross sections at NLO in heavy ion reactions
- Application of SCET to jet substructure, splitting and fragmentation
- Conclusions
- … Toward heavy flavor jets

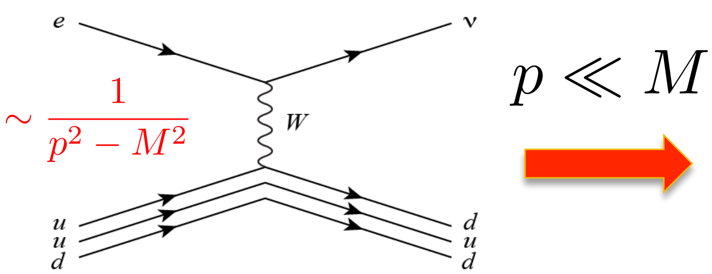
Thanks to the organizers for the invitation and for providing sunny weather on Sunday

Much of the credit for this work goes to my collaborators:
Y.-T. Chien, Z.-B. Kang, G. Ovanesyan, F. Ringer

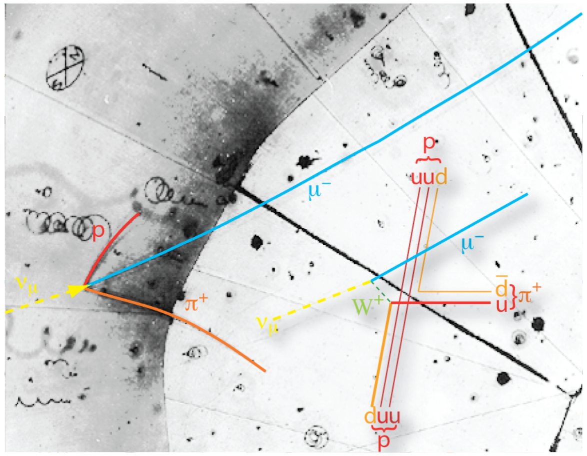
Introduction

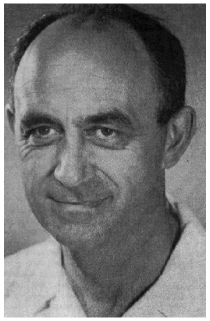
The Fermi interaction

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

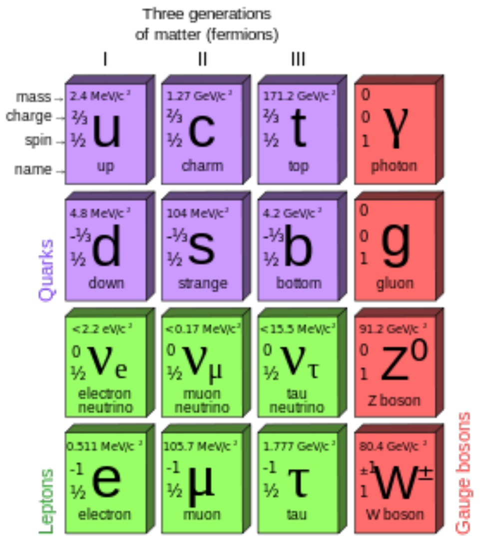


Holds for most relevant neutrino processes. First direct observation of the neutrino, Nov. 1970





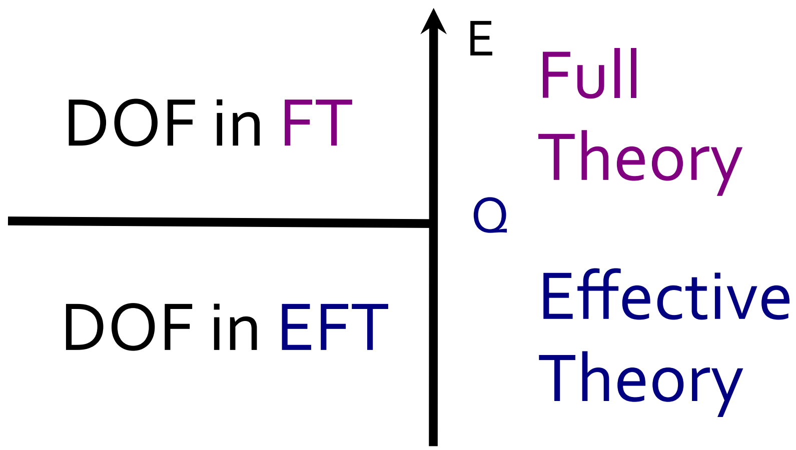
E. Fermi (Nobel Prize)



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

- Particularly well suited to QCD, HEP and nuclear physics

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

SCET formulation

- Modes in SCET

C. Bauer et al. (2001)

D. Pirol 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

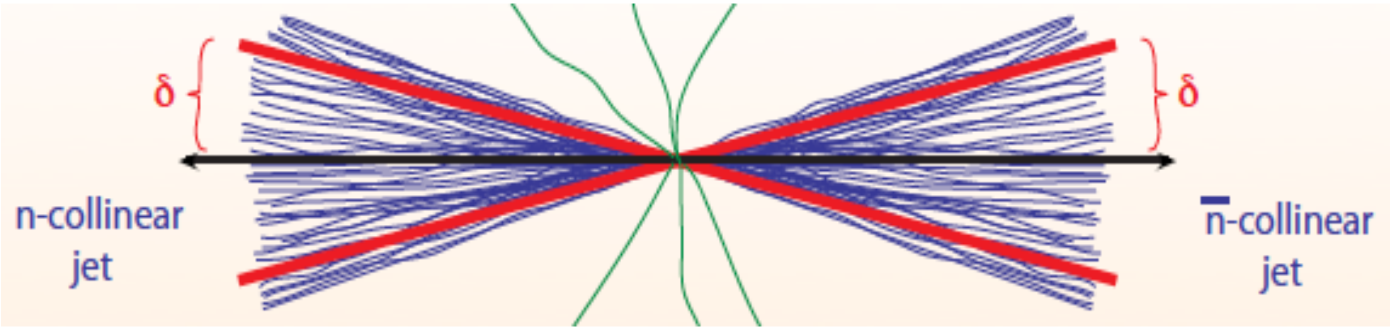
$\mathrm{SCET}_{\mathrm{II}}$

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

D. Neill et al. (2012)

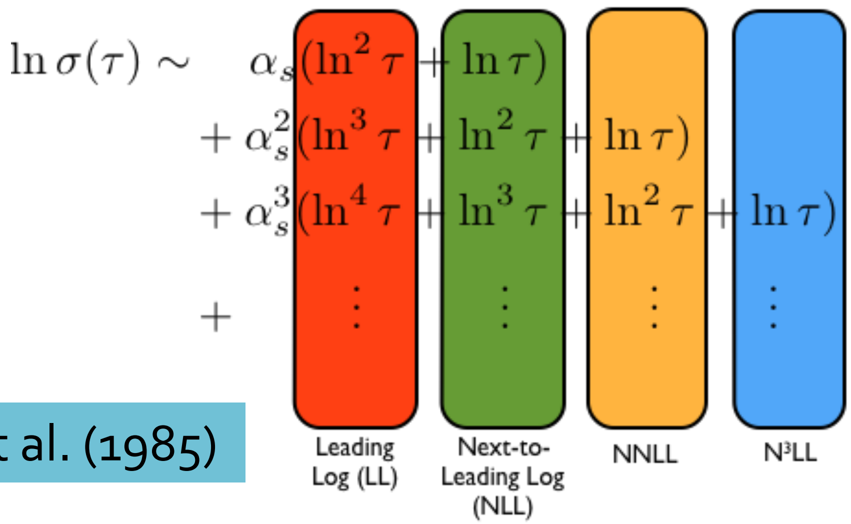
- Other formulations, e.g. $\mathrm{SCET}_{\mathrm{I}}$ and ultrasoft particles

- Especially suited for jet physics

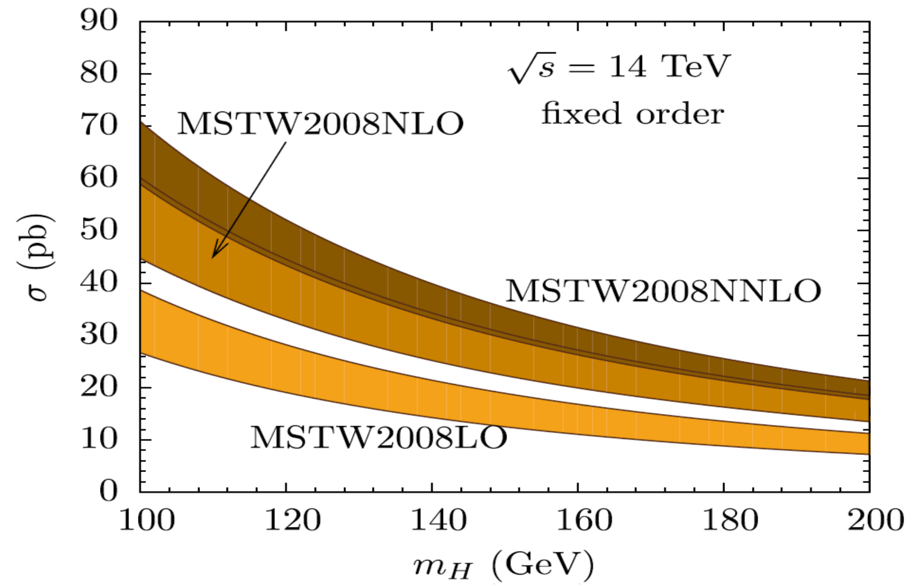


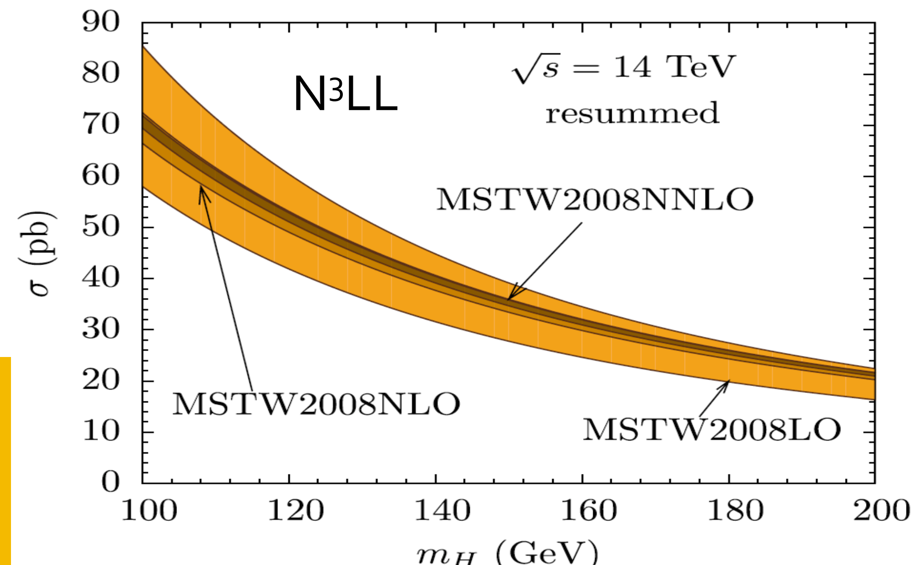
Resummation, RG equations and Higgs production at the LHC

- SCET is very effective in resumming in large logarithms of ratios of energy/mass scales using Renormalization Group equations



J. Collins et al. (1985)

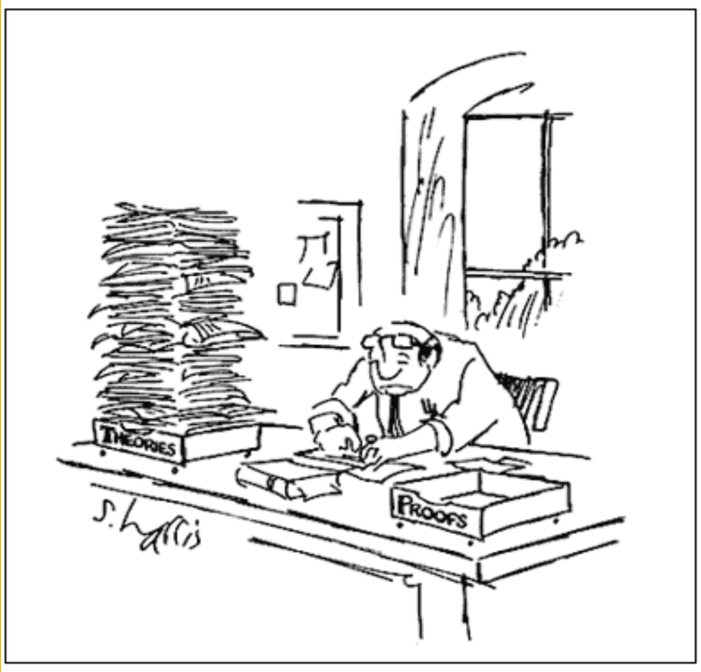




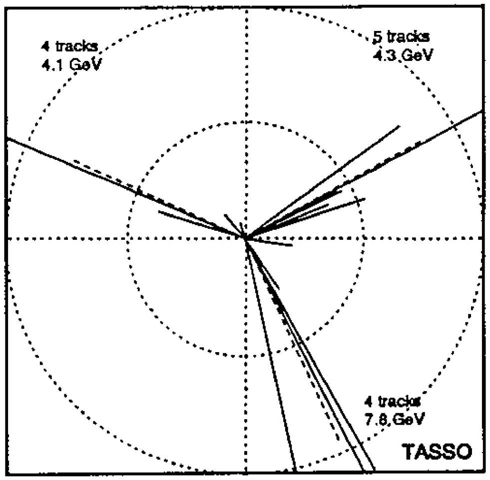
- Traditional techniques such as CCS. SCET systematizes the approach and facilitates resummation

V. Ahrens et al. (2009)

Semi-Inclusive Jet Calculations in SCET

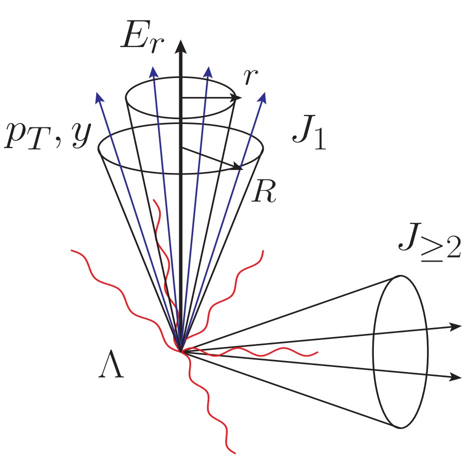


Exclusive approach to jets in SCET



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.
- Leads to multiplicative RG evolution

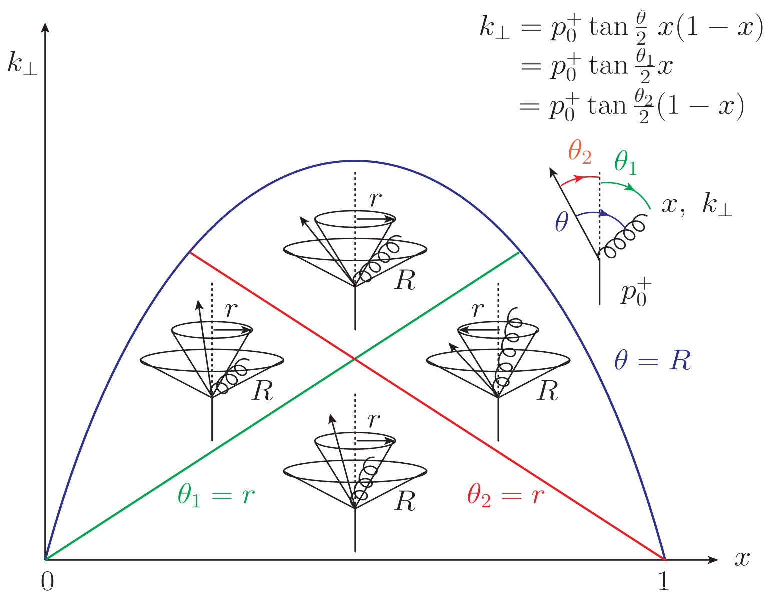
The exclusive view of a process in SCET summarized as

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

- Define a jet energy function

$$J_\omega(E_r, \mu) = \sum_{X_c} \langle 0 | \bar{\chi}_\omega(0) | X_c \rangle \langle X_c | \chi_\omega(0) | 0 \rangle \delta(E_r - \hat{E}^{<r}(X_c))$$

Phase space for the jet energy distribution



Take as an example the jet shape (integral jet shape)

$$\Psi_\omega(r) = \frac{\langle E_r\rangle_\omega}{\langle E_R\rangle_\omega} = \frac{J_\omega^{E_r}(\mu)/J_\omega(\mu)}{J_\omega^{E_R}(\mu)/J_\omega(\mu)} = \frac{J_\omega^{E_r}(\mu)}{J_\omega^{E_R}(\mu)}$$

- To first non-trivial order, the phase space for the jet shape contributions is tractable
- Important to understand that in analytic calculations jet observables are calculated directly from their definition and the splitting kinematics at FO

Y.-T. Chien et al. (2014)

- Integral jet function

$$\frac{2}{\omega} J_\omega^{qE_r}(\mu) = \alpha_s \left[a \ln^2 \frac{\omega^2 \tan^2 \frac{r}{2}}{\mu^2} + b \ln \frac{\omega^2 \tan^2 \frac{r}{2}}{\mu^2} + \text{finite} \right]$$

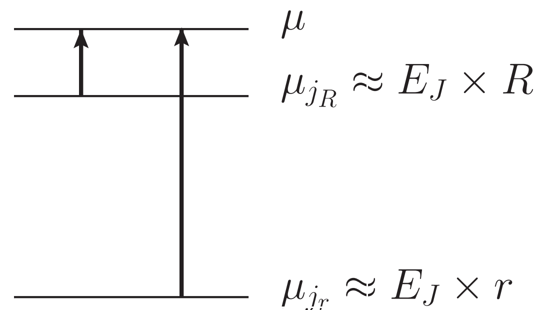
The idea is to eliminate the large logarithms from the fixed order (FO) expression by scale choice and put them in evolution

- Need the distribution of the average energy

$$J_\omega^{E_r}(\mu) = \int dE_r E_r\ J_\omega(E_r,\mu)$$

NLL calculation of jet shapes

- We use SCET resummation techniques and $SCET_G$.



We start form the natural scales that eliminate all large logarithms in the fixed order calculation and evolve to a common scale [resumming ln(r/R)]

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

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

Multiplicative RG evolution
Logarithms of $\alpha_s \ln^2 X$ type

$$\Gamma_{\rm cusp}(\alpha_s) = \left(\frac{\alpha_s}{4\pi}\right)\Gamma_0 + \left(\frac{\alpha_s}{4\pi}\right)^2 \Gamma_1 + \cdots \,,$$
$$\gamma(\alpha_s) = \left(\frac{\alpha_s}{4\pi}\right)\gamma_0 + \left(\frac{\alpha_s}{4\pi}\right)^2 \gamma_1 + \cdots \,.$$

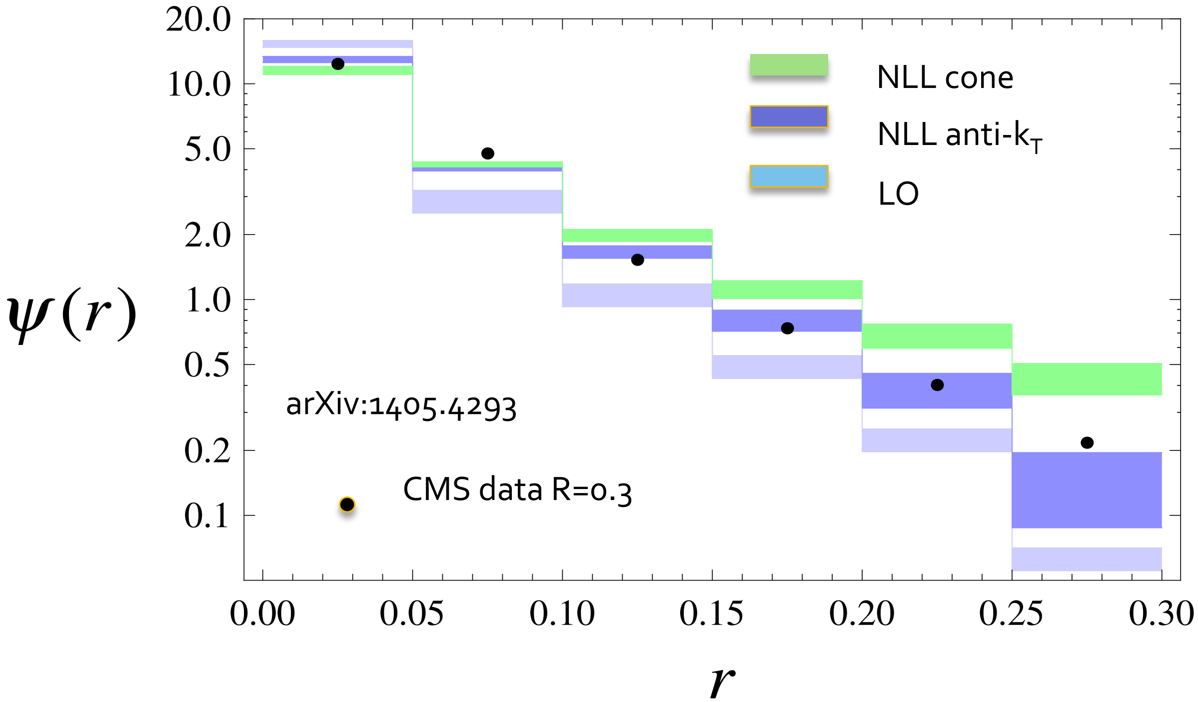
Order	$\Gamma_{\rm cusp}$	γ	β
NLL	2-loop	1-loop	2-loop

- To resum the jet shape to NLL accuracy

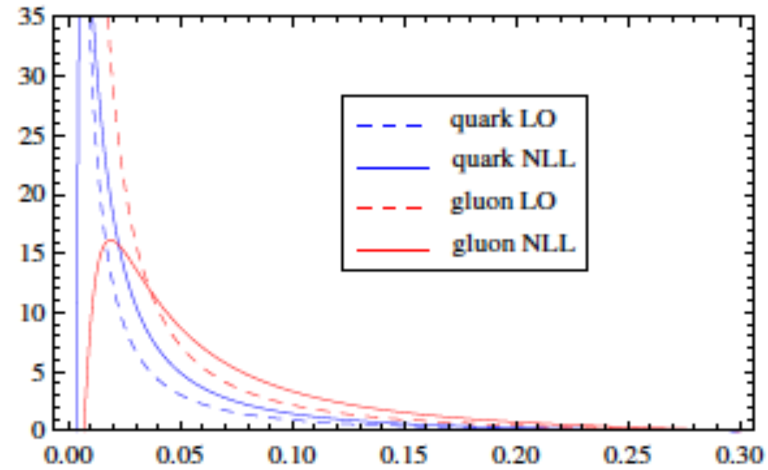
NLL	1-loop	2-loop
β	$\beta_0 = \frac{11}{3}C_A - \frac{4}{3}T_F n_f$	$\beta_1 = \frac{34}{3}C_A^2 - \frac{20}{3}C_A T_F n_f - 4C_F T_F n_f$
$\Gamma_{\rm cusp}$	$\Gamma_0 = 4$	$\Gamma_1 = 4\left[\left(\frac{67}{9} - \frac{\pi^2}{3}\right)C_A - \frac{20}{9}T_F n_f\right]$
γ	$\gamma_0^q = -3C_F,\ \gamma_0^g = -\beta_0$	

Numerical NLL results in p+p collisions

- We can study the algorithm dependence of the jet shapes (anti)k_T vs cone.
- Significant improvement over fixed order calculation
- Works reasonably well, but there can be room for improvement. Different evolution?



Just to show that the fixed order is divergent



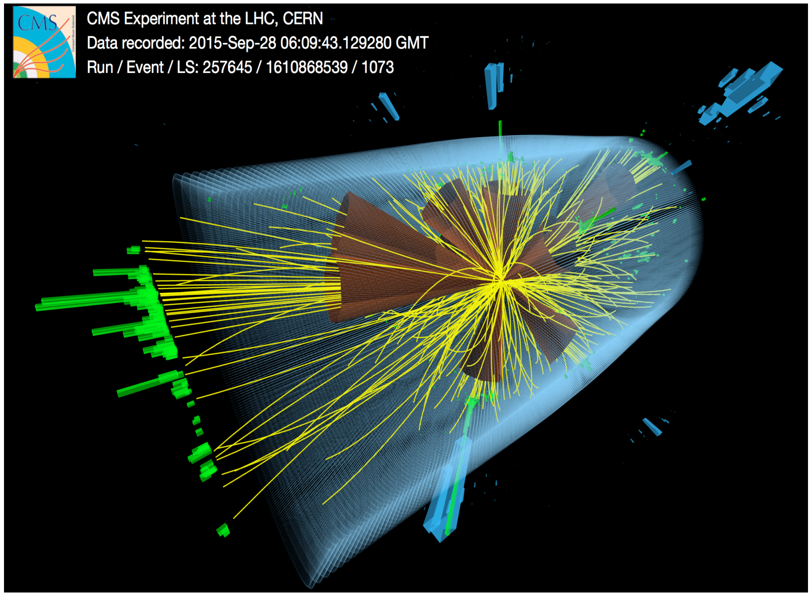
Why may we need inclusive SCET approach?

CERN energies 0.9 TeV < CM energy < 13 TeV

- It is certainly not the case in hadronic collisons (and even more energetic e+ e-) that all the energy goes into jets and beams
- Need to revisit the jet function evolution.
- Conjectured that a different type of evolution may hold, namely DGLAP evolution

Dasgupta et al. (2014)

- Finally, experimental measurements are (semi) inclusive in nature



CMS (2015)

Experiments measure for example

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

Typically no effort to determine what X is

Semi-inclusive jet function in SCET

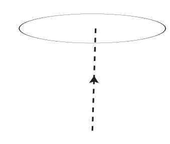
- Allow for the jet to capture only a fraction of the parton shower energy $z=\omega_J/\omega$

Z. Kang et al. (2016)

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

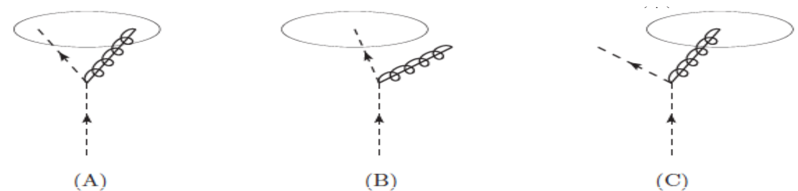
Definition is analogous to the ones for FFs

- At tree level



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

- At one loop order



Single logarithms!

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

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

Logarithms and scales

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

Renormalization and evolution of the SIJF

- Renormalization matrix to one-loop order

Absorb the remaining 1/ε divergence

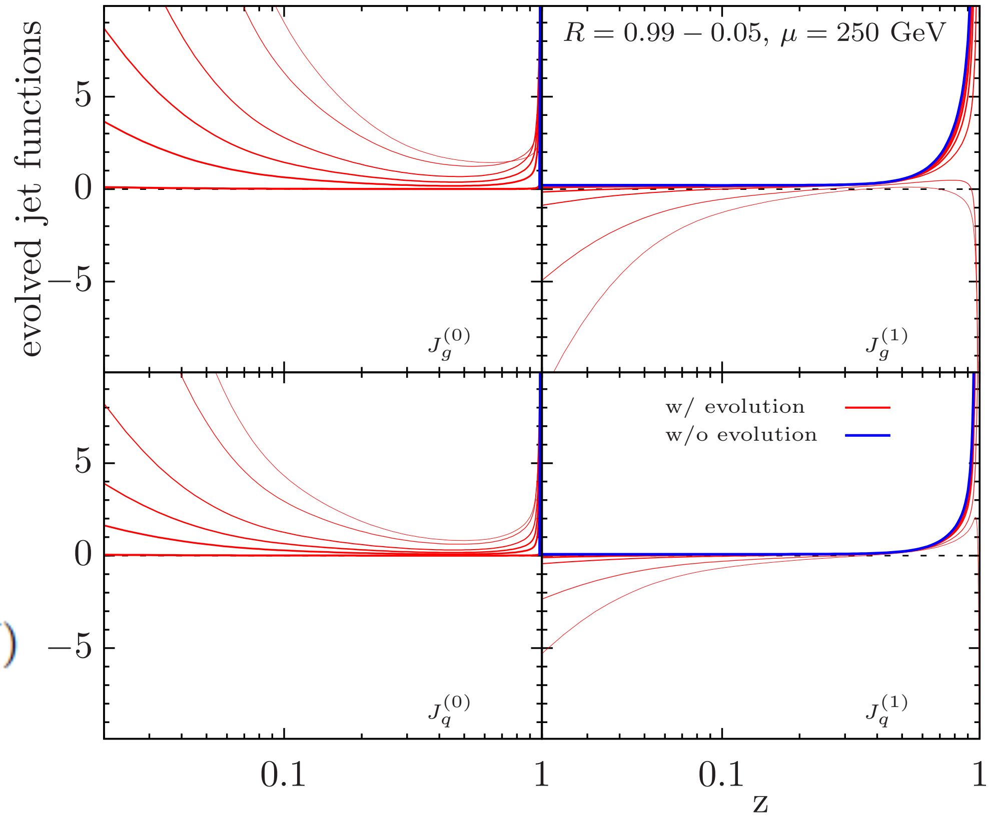
$$Z_{ij}(z,\mu) = \delta_{ij}\delta(1-z) + \frac{\alpha_s(\mu)}{2\pi}\left(\frac{1}{\epsilon}\right) P_{ji}(z)$$

- 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

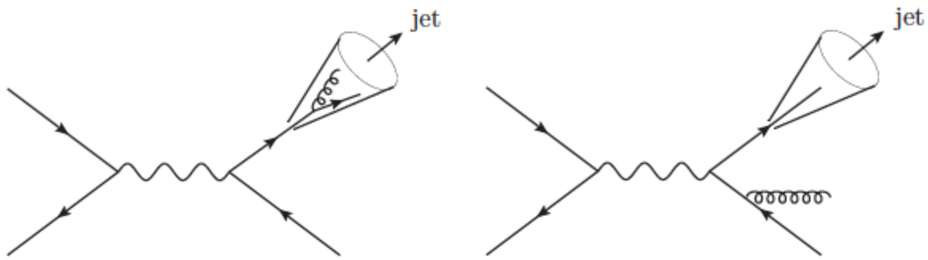
$$f(N) = \int_0^1 dz\, z^{N-1} f(z) \quad (f\otimes g)(N) = f(N)\, g(N)$$

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

Numerical implementation at NLO

- Hard collinear factorization

F. Ringer et al. (2015)



$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^c(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dv dz} J_c(z_c,\omega_J,\mu).$$

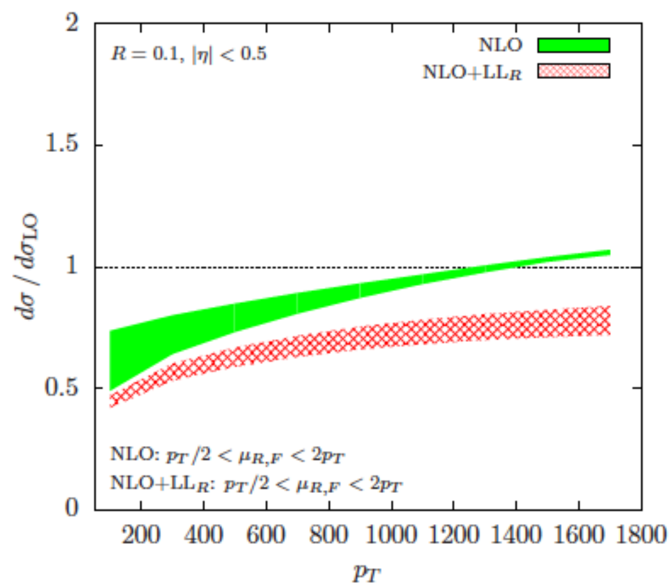
- Terms that we keep at NLO

$$d\sigma^{pp\to \text{jet}X} \sim \left(d\hat{\sigma}_{ab}^{c,(0)} + d\hat{\sigma}_{ab}^{c,(1)}\right)\otimes\left(J_c^{(0)} + J_c^{(1)}\right)$$
$$= \left(d\hat{\sigma}_{ab}^{c,(0)} + d\hat{\sigma}_{ab}^{c,(1)}\right)\otimes J_c^{(0)} + d\hat{\sigma}_{ab}^{c,(0)}\otimes J_c^{(1)} + \mathcal{O}(\alpha_s^2)$$

We can perform LL_R resummation. Have generalized to NLL_R

Z. Kang et al. (2016)

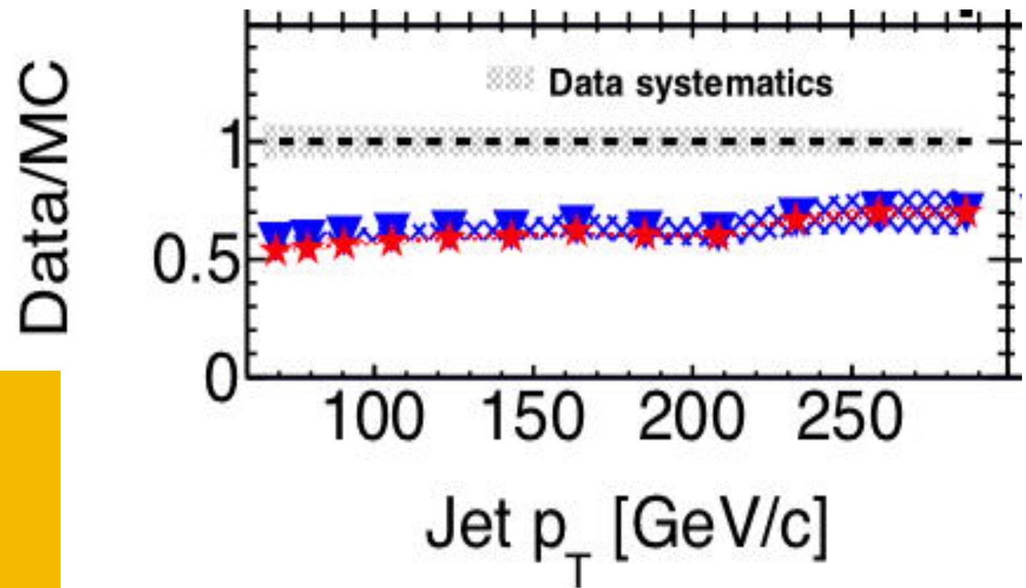
- **Fixes the unphysical scale dependence of NLO jet**
- **Resummation can have up to 30% effect on the inclusive jet cross section for small R**



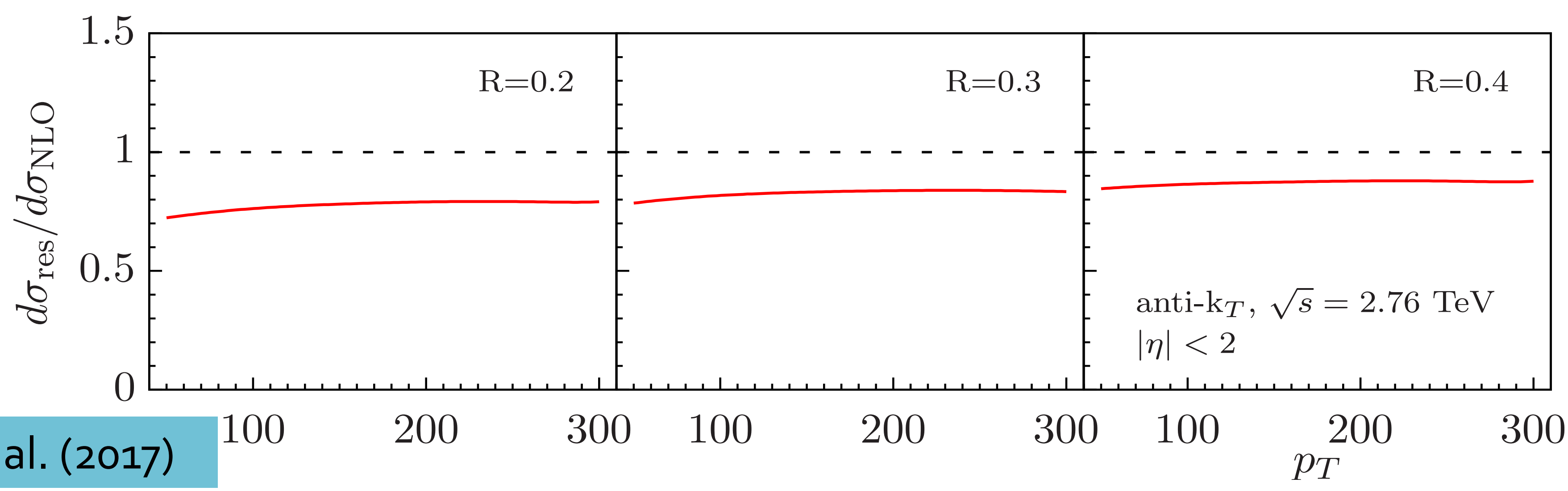
Recent applications to inclusive jet production

- Is it relevant?

CMS appears to see a difference difference between data and NLO calculations

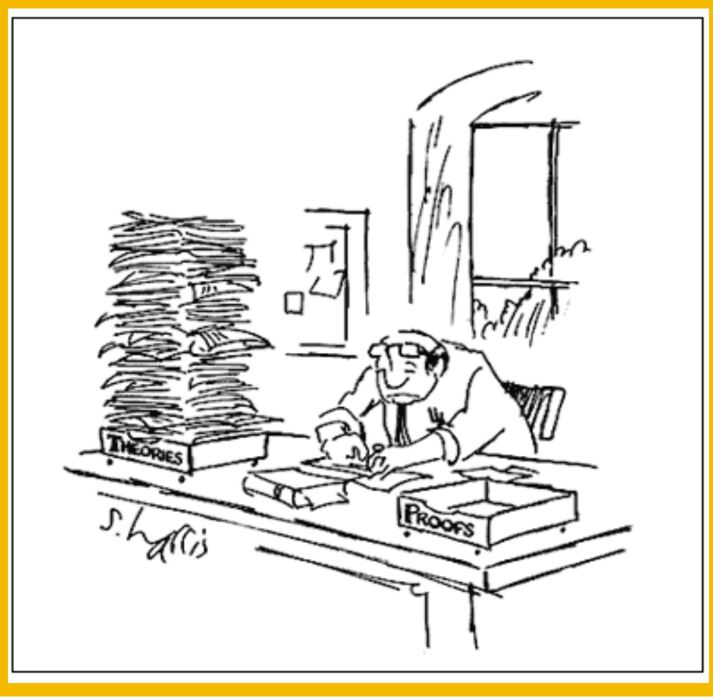


- Resummation can explain large part of the discrepancy between data and NLO calculations



F. Ringer et al. (2017)

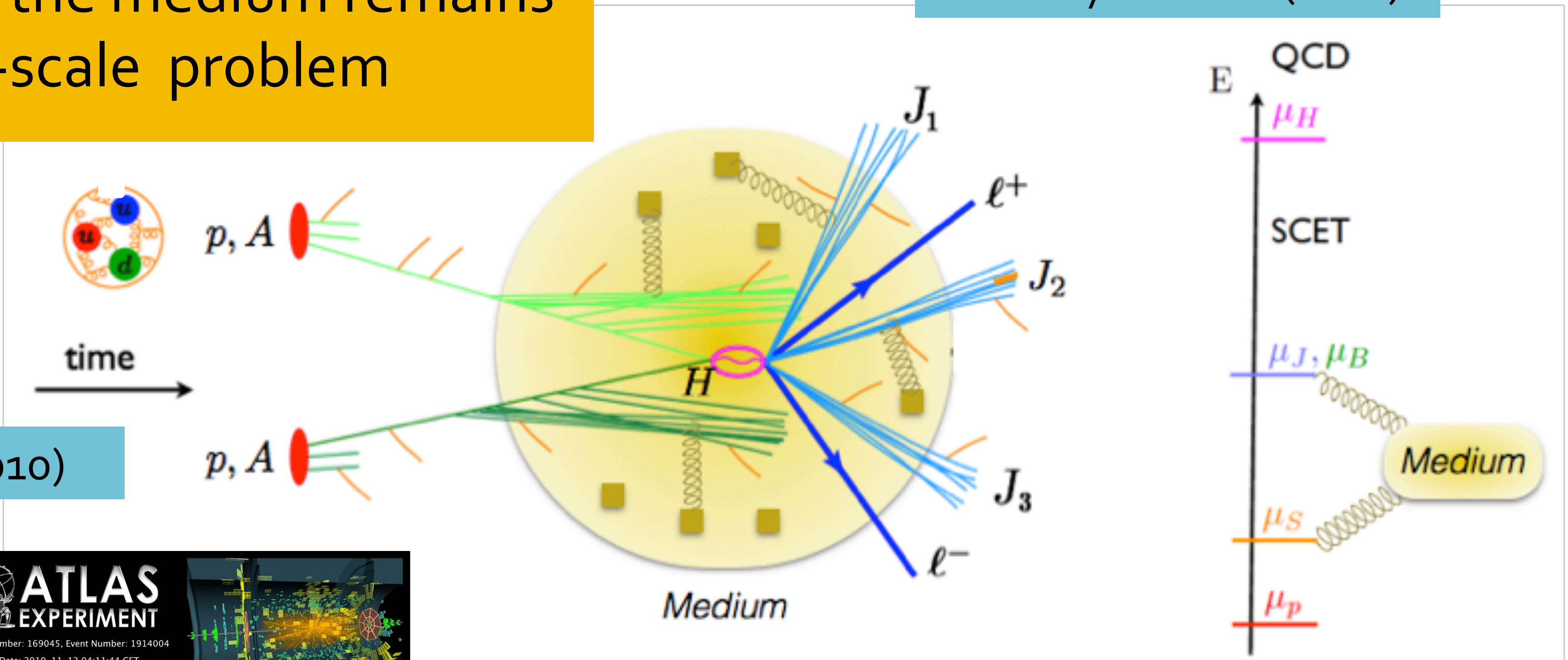
Jets in Soft Collinear Effective Theory with Glauber Gluons



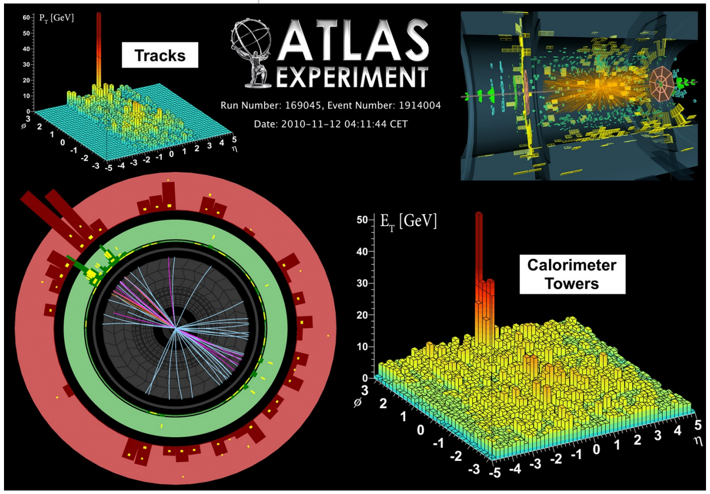
The big picture for hard probes

- 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

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

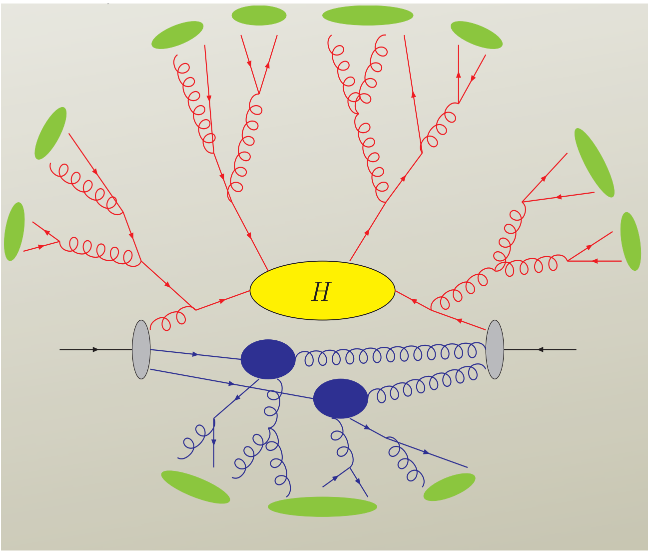
The splitting kernels

- 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)

In-medium parton splittings and medium properties

- Direct sum

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

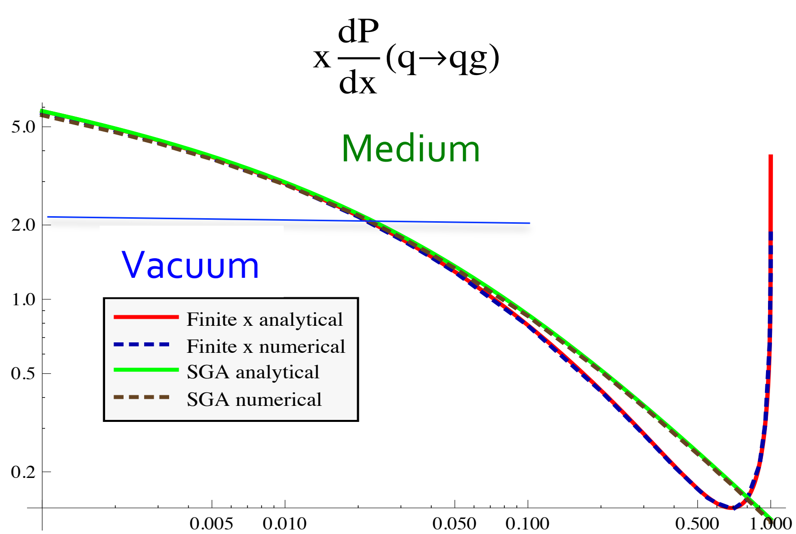
- Derived using $SCET_G$
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium

G. Ovanesyan et al. (2012)

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

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

New physics – many-body quantum coherence effects



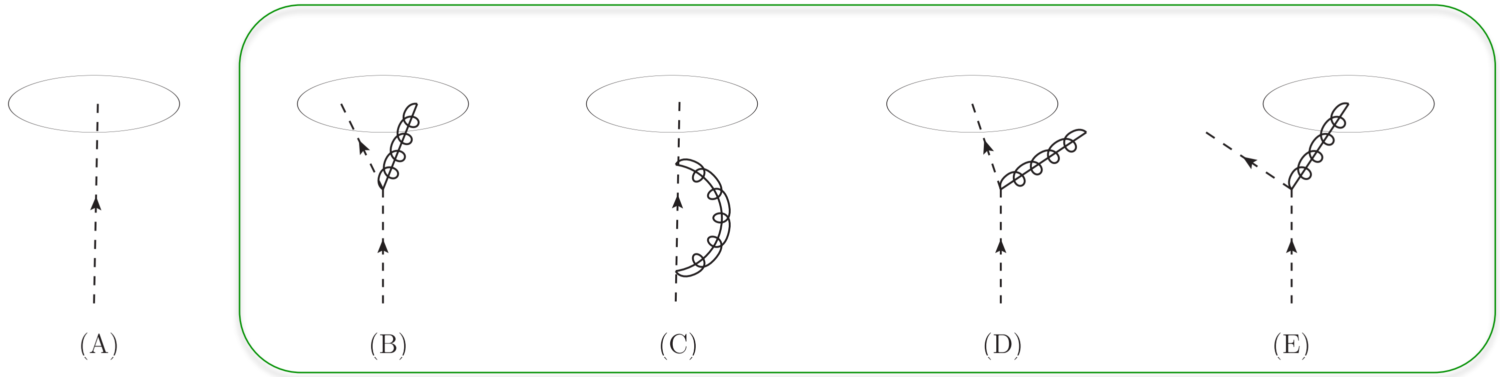
- Can be evaluated numerically
- Need numerical implementation

Calculating the jet cross section at NLO in the medium

- Master formula
- Modified jet function

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

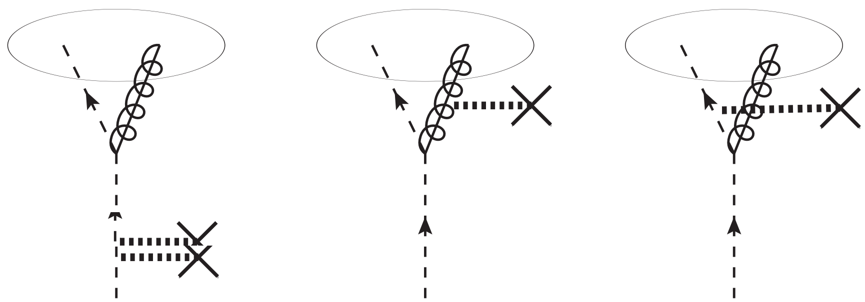
Z. Kang et al. (2017)



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

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

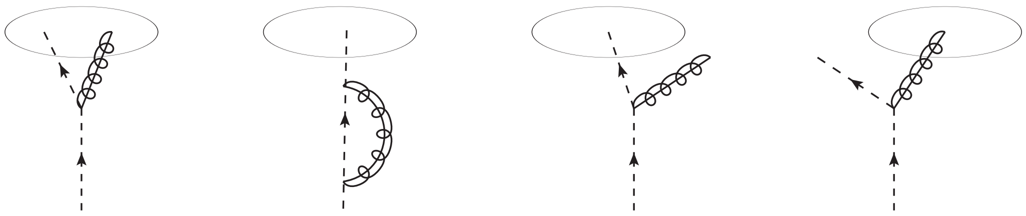
$$|\mathcal{A}_{\rm SB}^{\rm med}|^2 + 2\Re\mathfrak{e}\left\{\mathcal{A}_{\rm DB}^{\rm med} \times \mathcal{A}^{\rm vac}\right\}$$



M. Gyulassy et al. (2000)

Evaluating the in-medium jet function

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



(B) (C) (D) (E)

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 medium it is strictly NLO

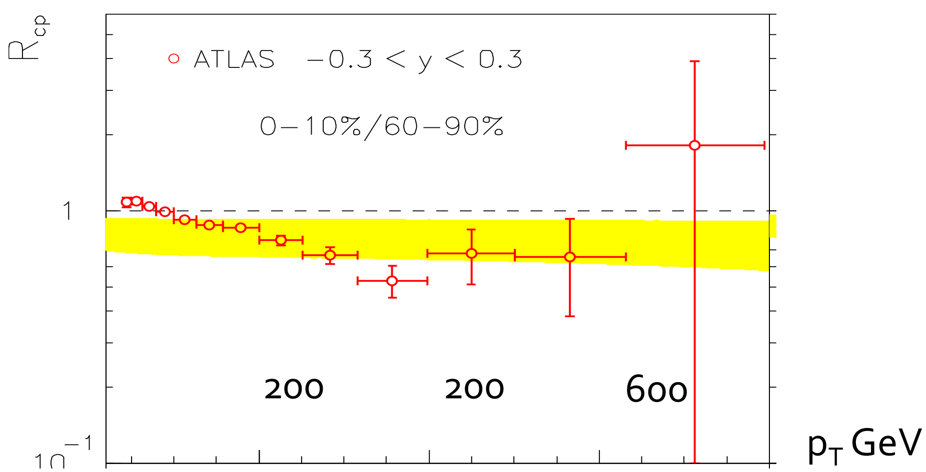
No multiple splittings, no collisional energy loss (to be revisited)

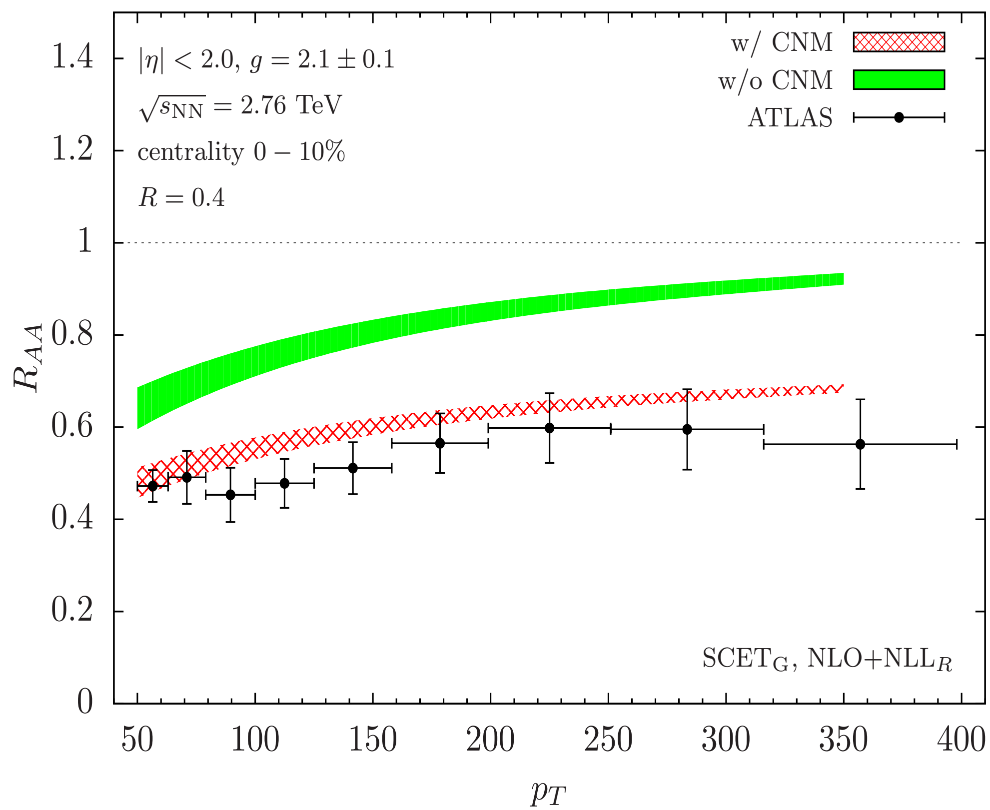
Possibilities: better evaluation of the splitting functions, collisional energy loss, larger jet-medium coupling, …

One possibility is cold nuclear matter effects in the initial state (p+A)

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

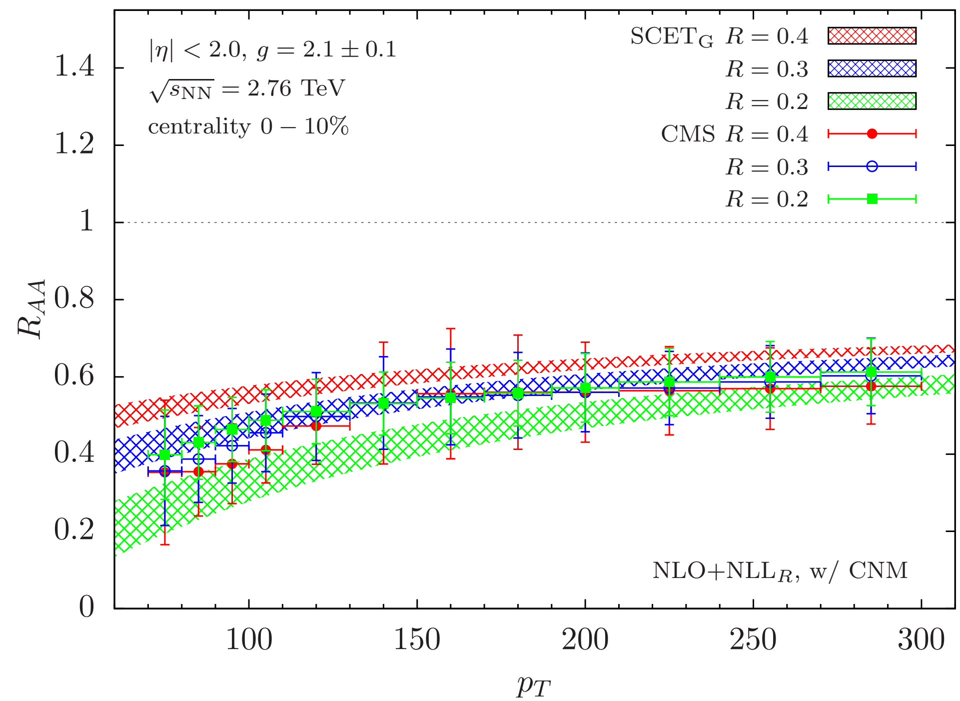
$$d\sigma^{\text{jet,med}}_{\text{PbPb}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\text{med}}$$

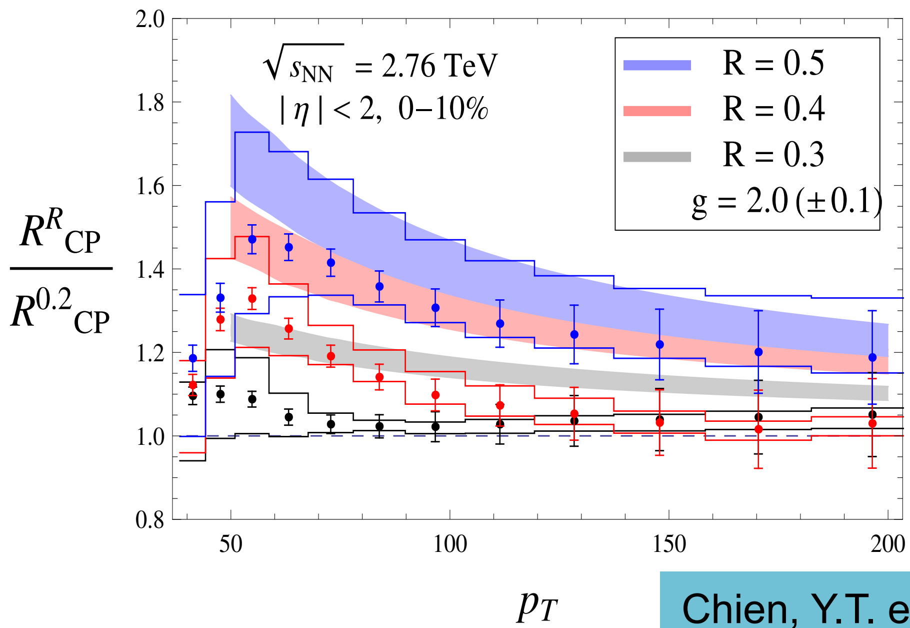




Radius dependence of jet suppression

- 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 jet 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

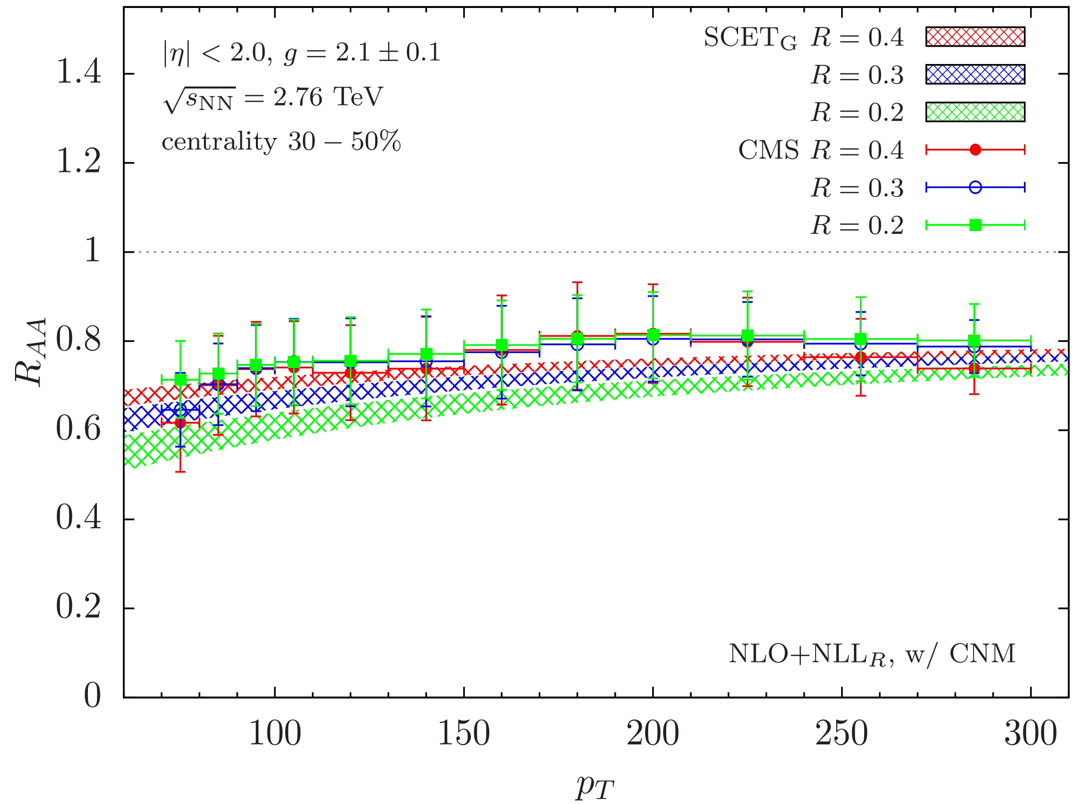
The temperature of the medium

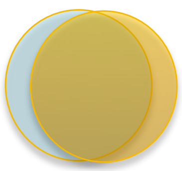
The vacuum and medium contribution to jet functions

The overall level of suppression

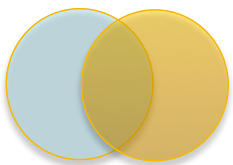
(in the most peripheral collisions expected to disappear)

Z. Kang et al. (2017)





Central



Peripheral

The centrality dependence appears to be well captured

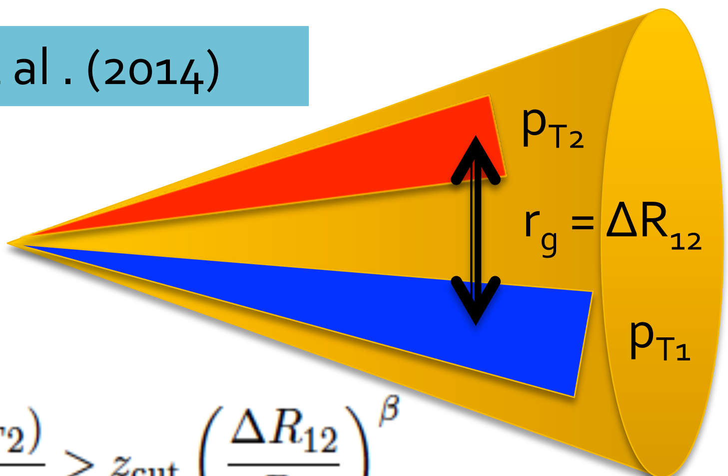
Jet substructure observables in SCET

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

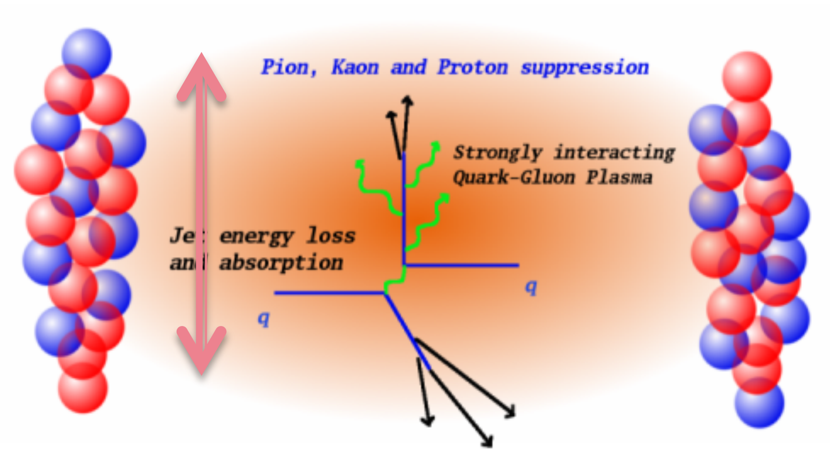
Many observables to access jet substructure have emerged in SCET

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

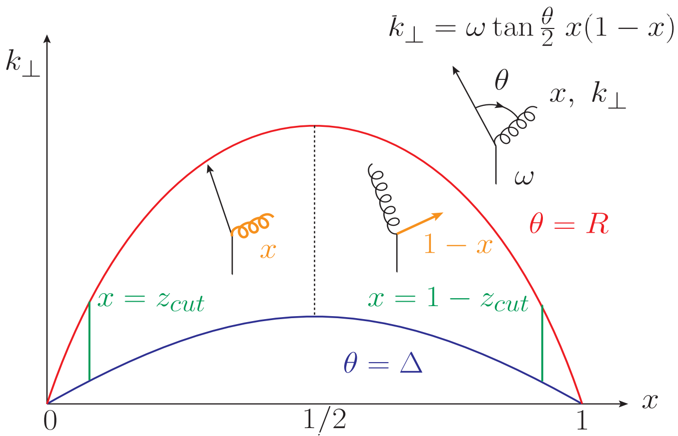
Typical situation: E=200 GeV, r_g = 0.1

Branching time < 2 fm for z_g studied

Y. T. Chien et al . (2016)

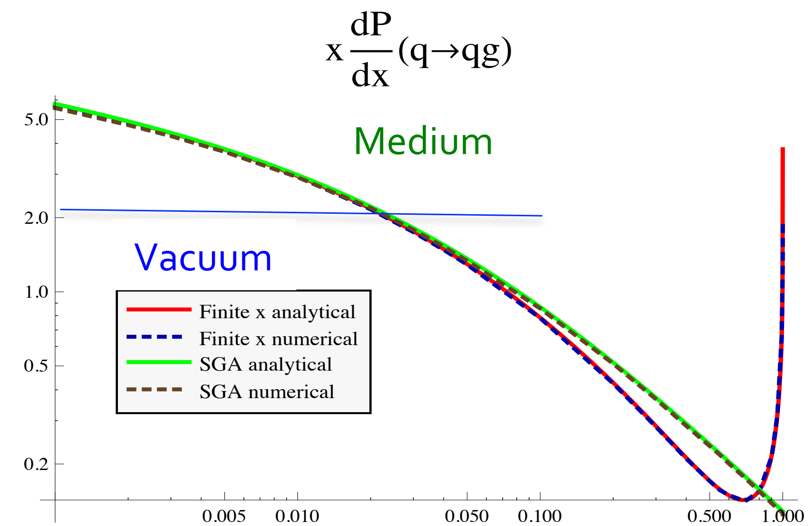
Accessing the hardest branching in HIC – longitudinal modification

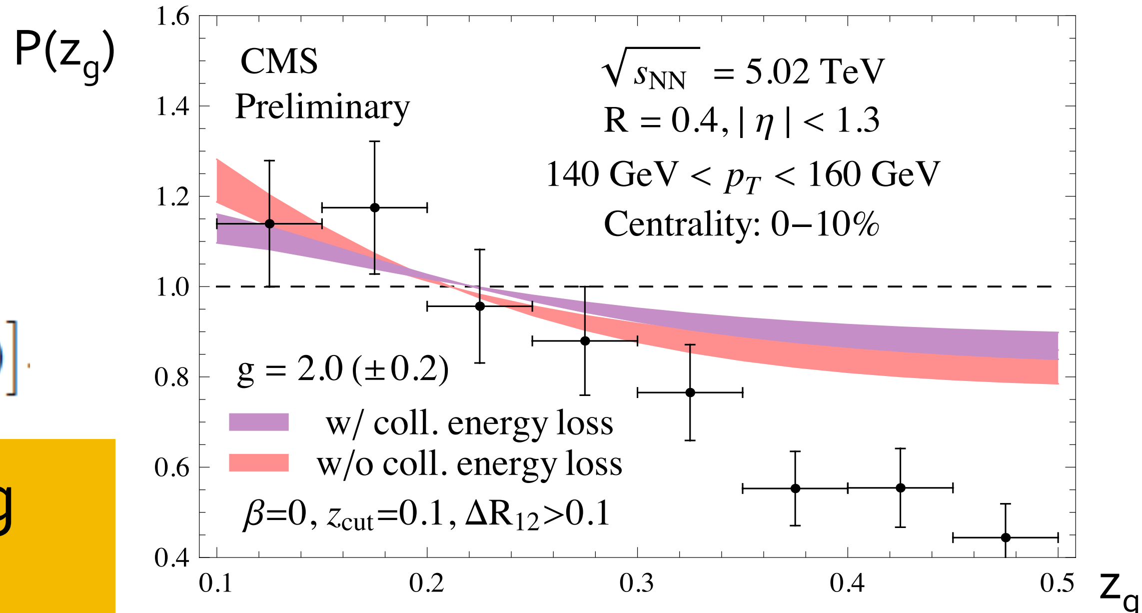
Calculating the soft dropped distribution with β=o



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

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





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

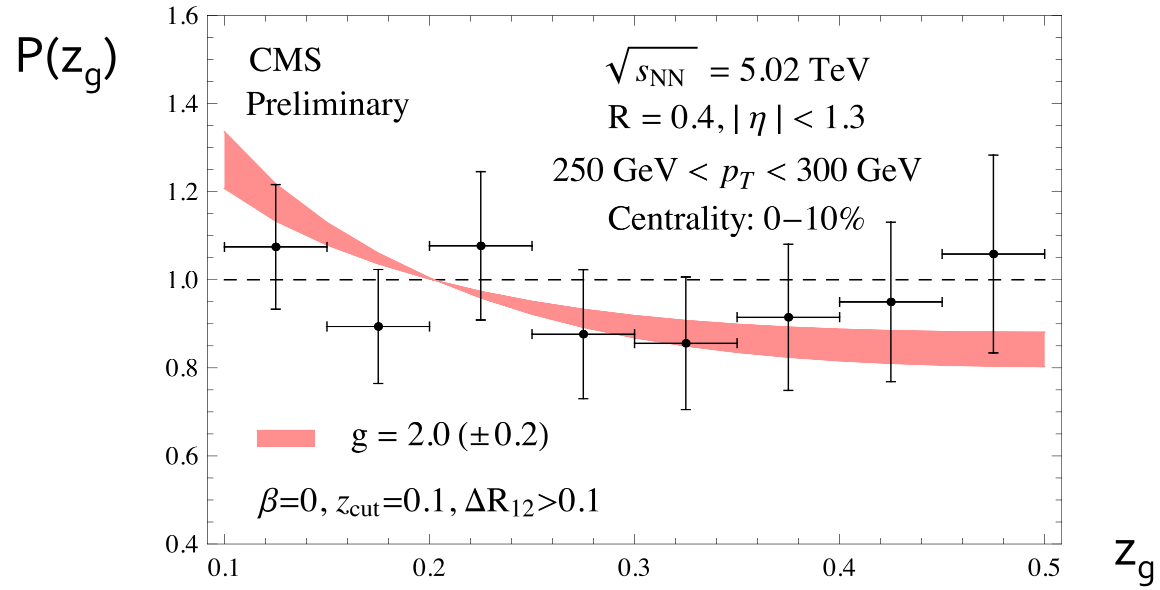
Centrality and p_T dependence

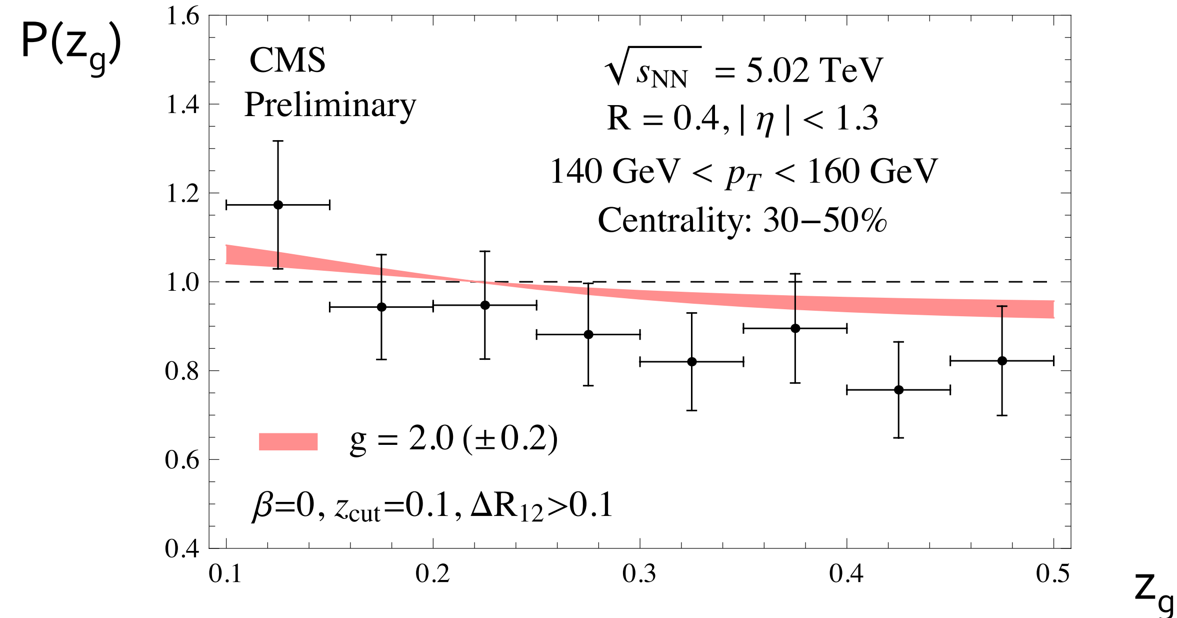
(Collisional) energy loss of individual branches does not help

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

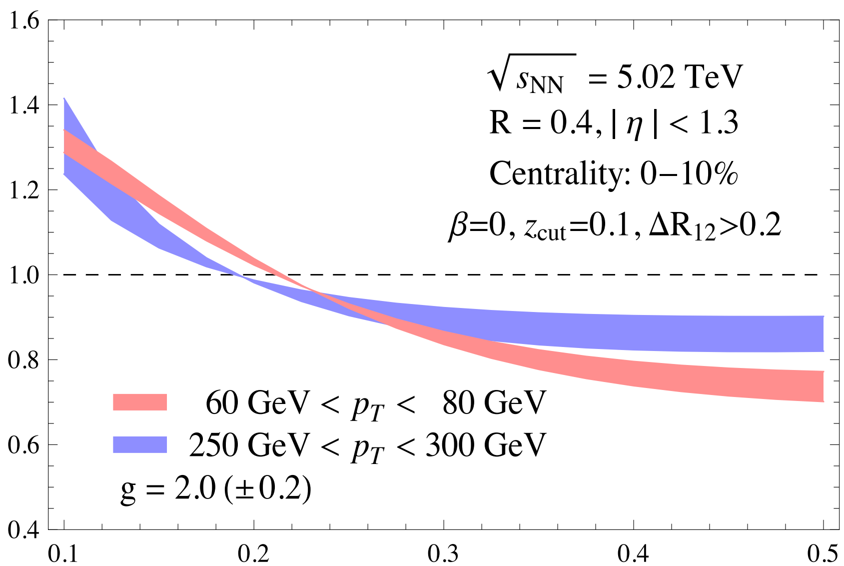
Centrality dependence as expected – reduced effect for peripheral collisions

Y.T Chien et al . (2016)





Modification of the angular distribution of hardest branchings



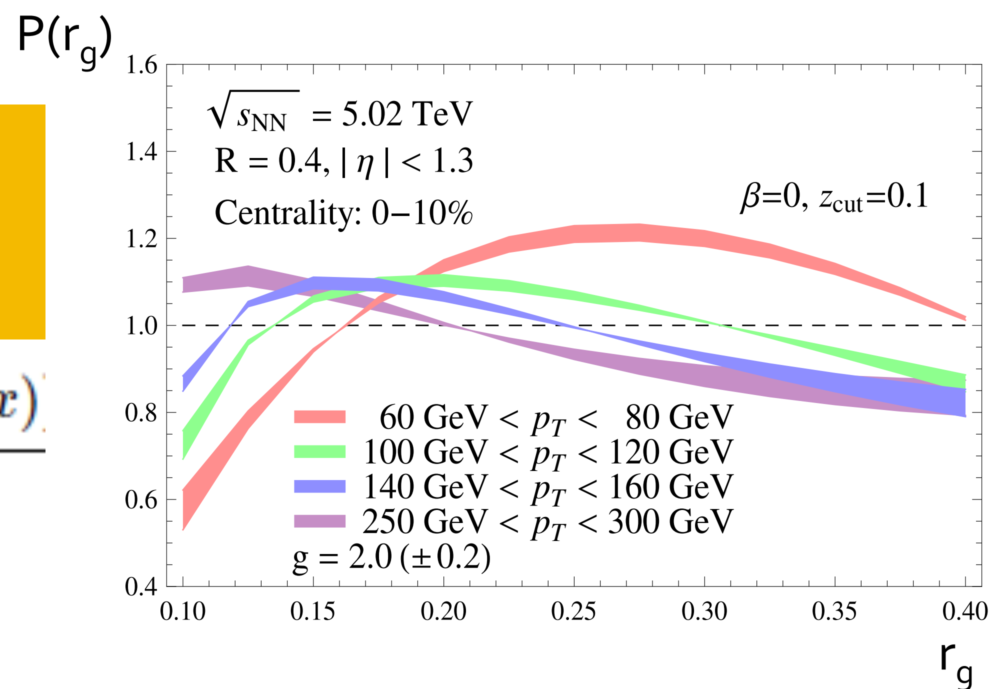
Flexibility in selecting angular separation r_g

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

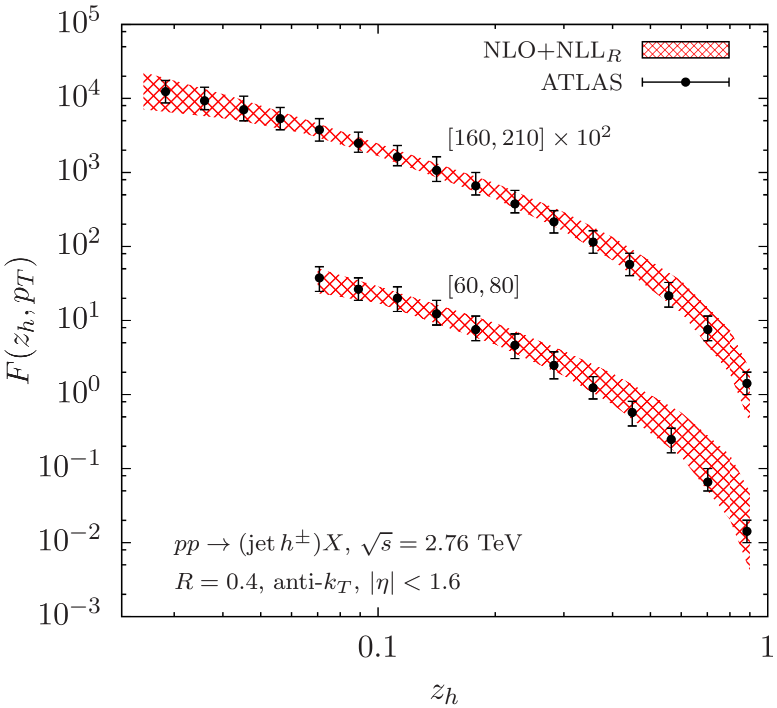
Generalize the definition to jet and a hadron, sequences of fractions

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

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

Modification of the fragmentation function

One can carry through the calculation for the jet function for the semi-inclusive jet function

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

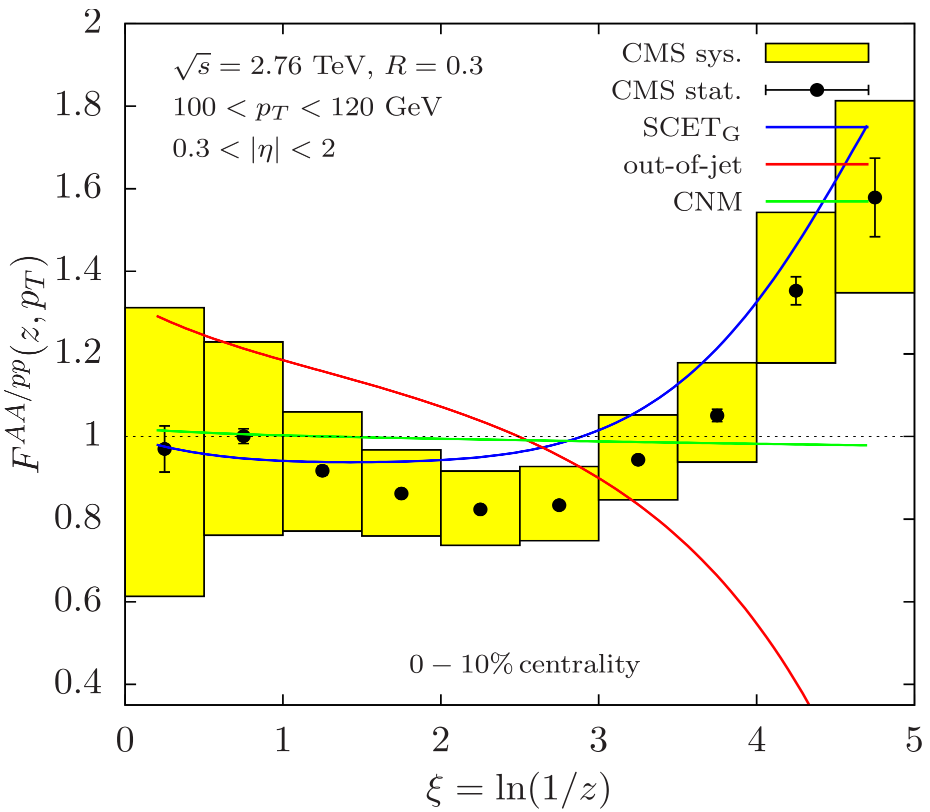
$$\delta(1-z_h)\left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} P_{qq}(z, q_\perp)\right]_+$$

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

- 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)

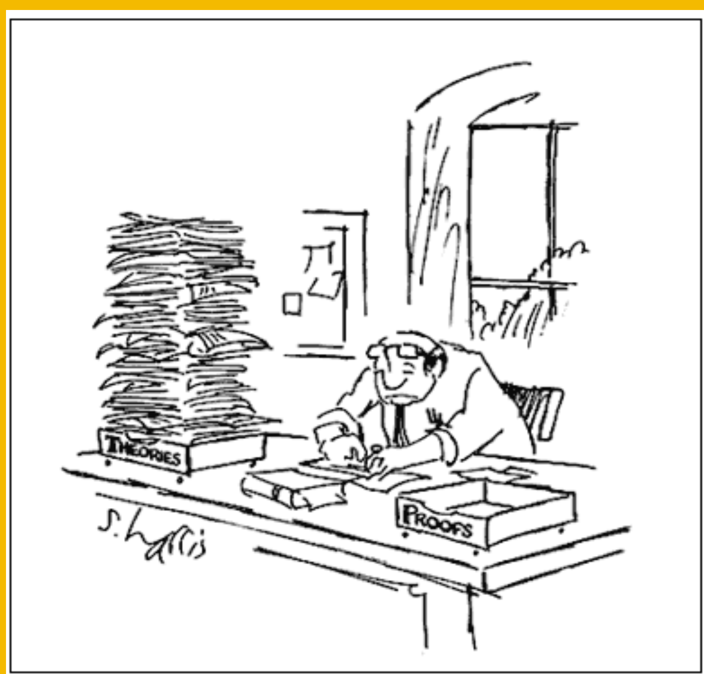


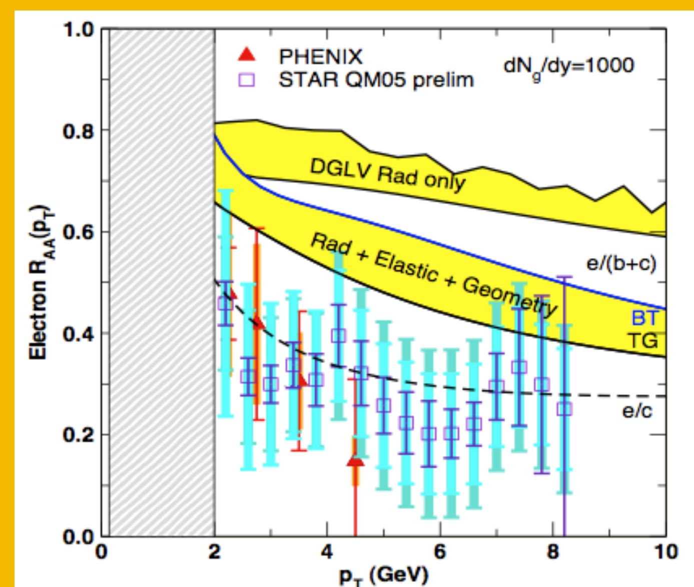
F. Ringer et al . (2037)

Conclusions

- Effective theories of QCD have enabled important conceptual and breakthroughs in our understanding of strong interactions and very significant improvement in the accuracy of the theoretical predictions
- Only recently were semi-inclusive jet functions (and fragmenting jet functions) introduced and computed to one loop. Found that they satisfy standard time-like DGLAP evolution equations. Allowed to understand jet R resummation to NLL_R. Appear to have immediate relevance to th small radius jet measurements at LHC
- Performed a consistent NLO calculation of jet production in $SCET_G$ (an effective theory for jet propagation in matter). Allows us now to also look at jet substructure. Found that at high p_T only part of the suppression can be explained. CNM or collisional energy loss of the shower TBD.
- Progress in performing pQCD / SCET calculations of jet substructure connecting splitting functions through groomed soft-dropped momentum sharing distributions. Jet shapes discussed before and jet fragmentation functions.
- … Recently extended to heavy flavor and NLO calculations

Open heavy flavor





Heavy quarks in the vacuum and the medium

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

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

Feynman rules depend on the scaling of m. The key choice is m/p$^+$ ~λ

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

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

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

The process is not written Q to gQ

F. Ringer et al . (2016)

Result: SCET$_{M,G}$ =SCET$_M$ × 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

Heavy quarks splitting functions in the medium

Kinematic variables

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

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

New physics – many-body quantum coherence effects

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

F. Ringer et al . (2016)

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

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

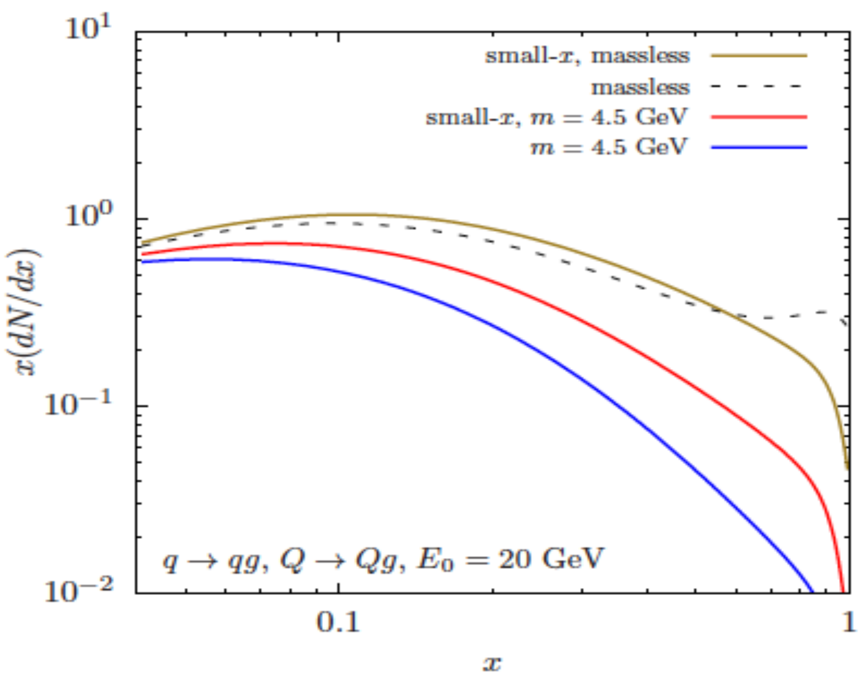
Heavy quark energy loss limit

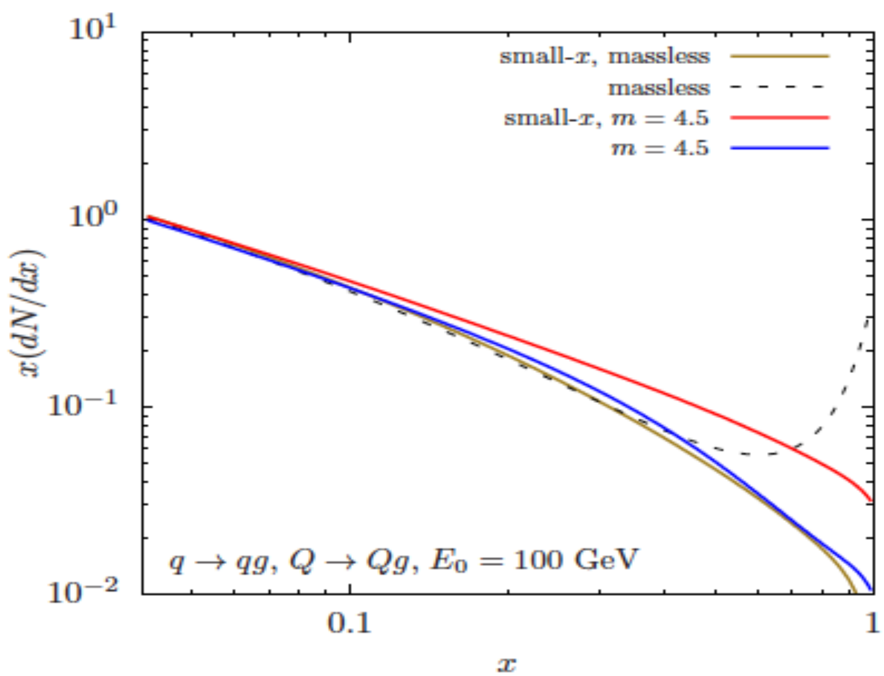
In the soft gluon emission (x → 0) energy loss limit only the diagonal splittings survive (Q to Qg)

M. Djordjevic et al . (2003)

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

$$\times \frac{2\mathbf{k}_\perp \cdot \mathbf{q}_\perp}{[\mathbf{k}_\perp^2 + x^2 m^2][(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + x^2 m^2]} \left[1 - \cos\frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + x^2 m^2}{x p_0^+}\Delta z\right].$$



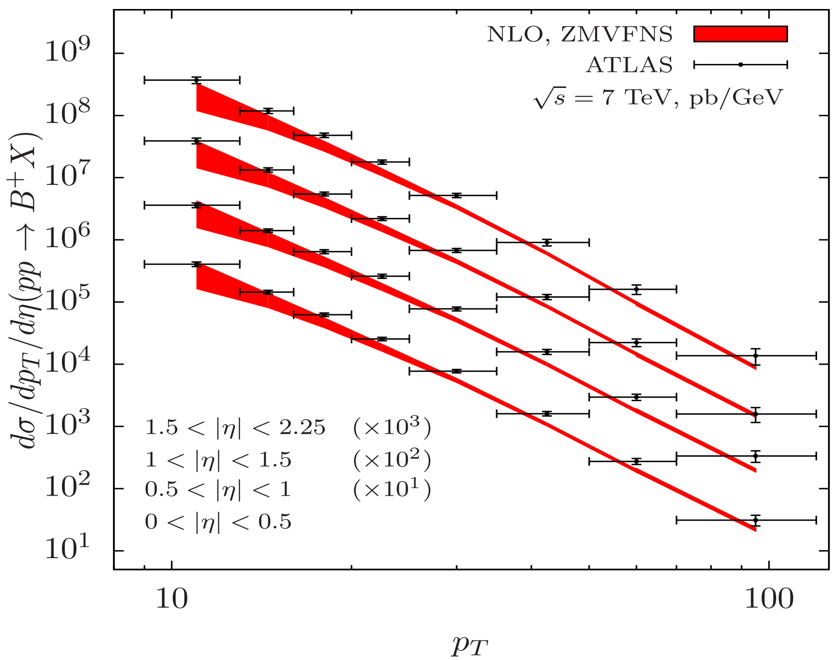


ZMVFS open heavy flavor at NLO

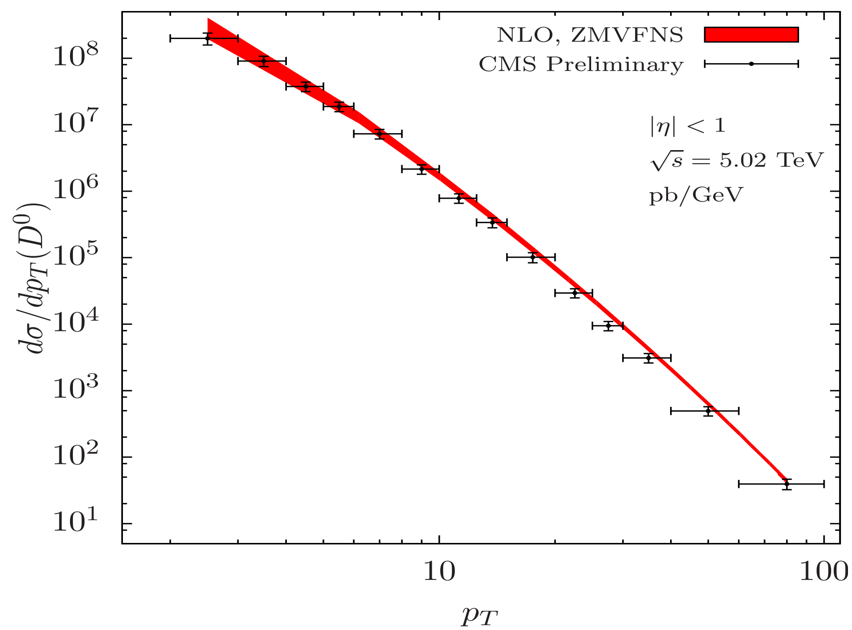
- Typically assumed that only c to D, b to B fragment perturbatively
- Perform an NLO calculation

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

B. Jager et al . (2002)



Kneesch et al . (2008)



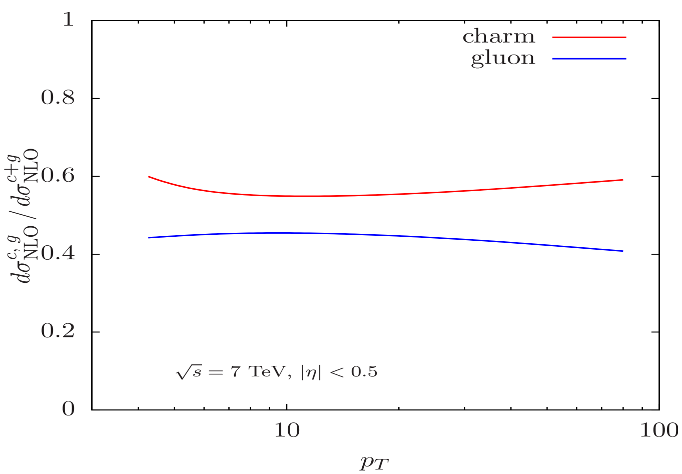
Kniehl et al . (2008)

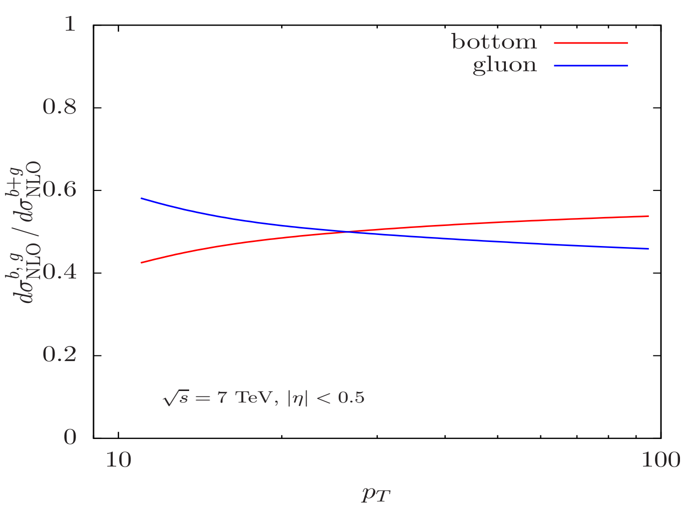
When $p_T > m_c, m_b$ **Factorization, non-perturbative physics is long distance**

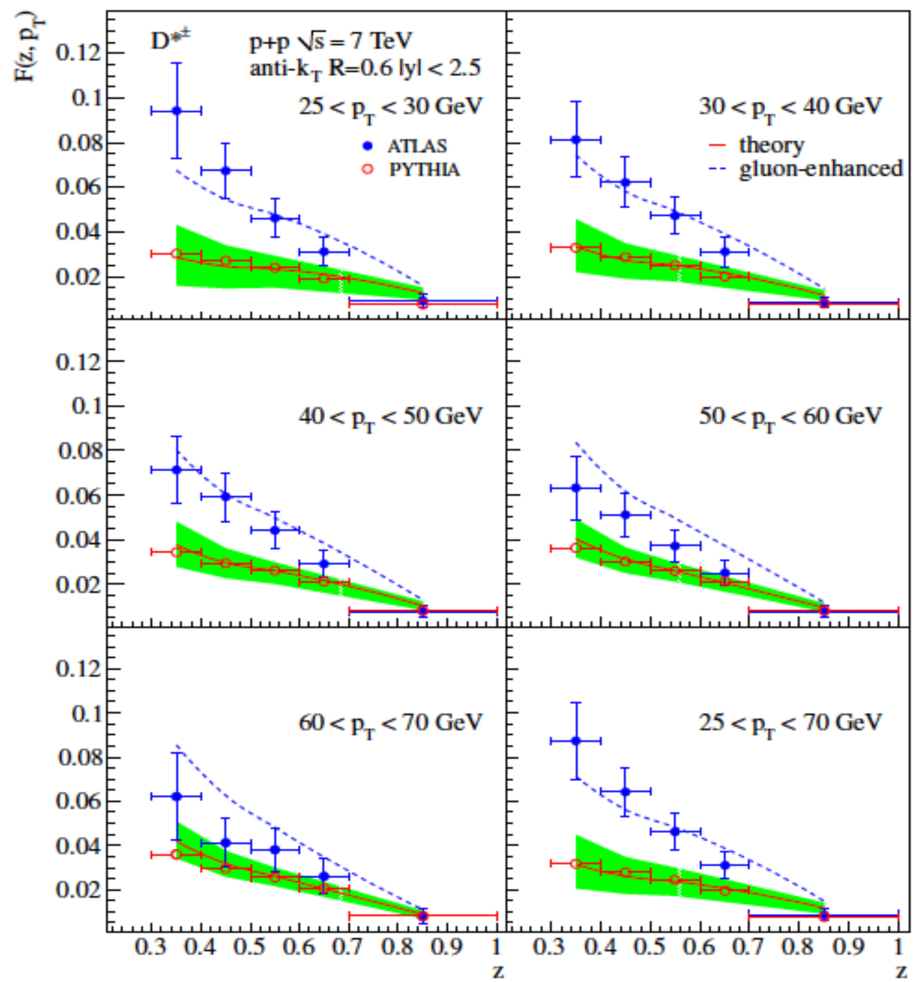
Implications for heavy flavor modification

- 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)

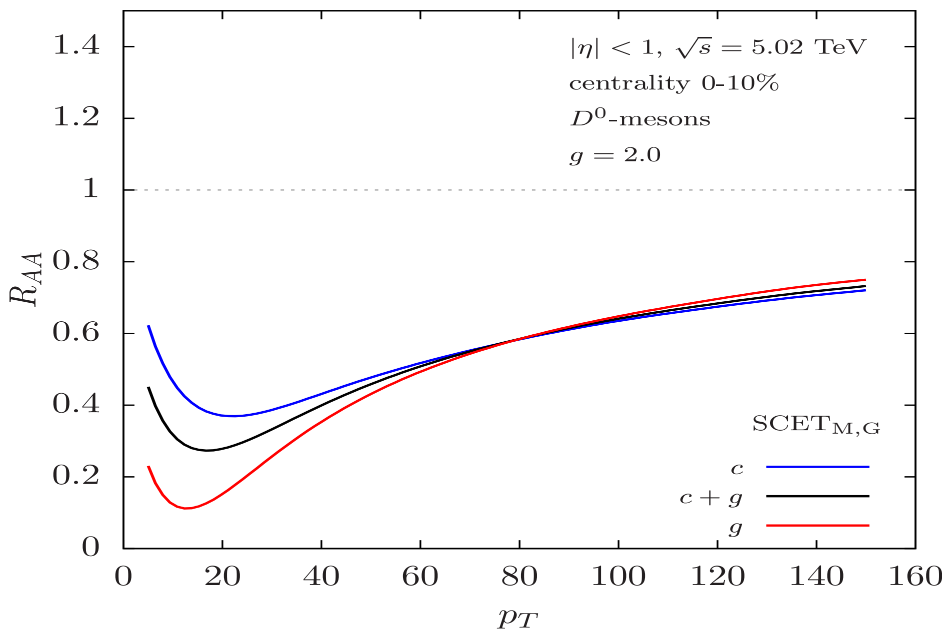
Cross section calculation in the QCD medium

Medium contribution

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

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

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

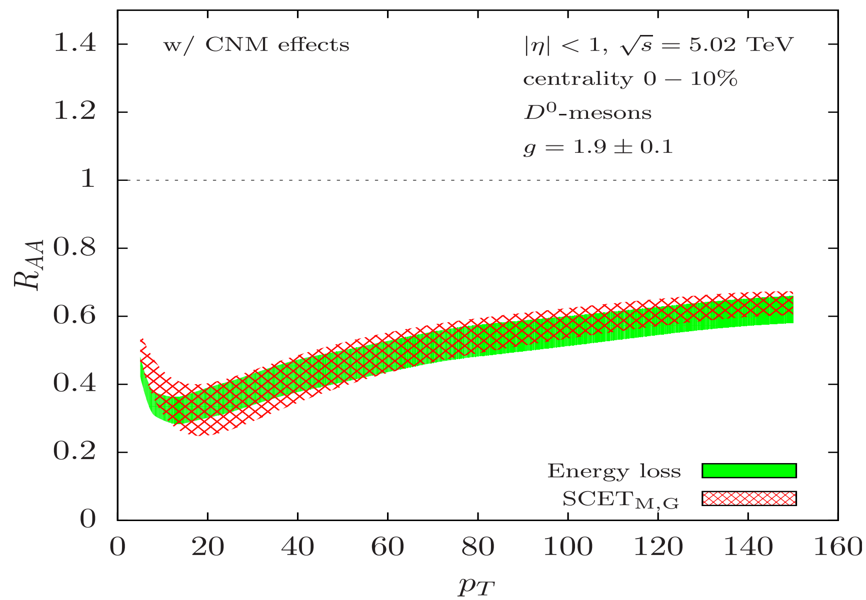


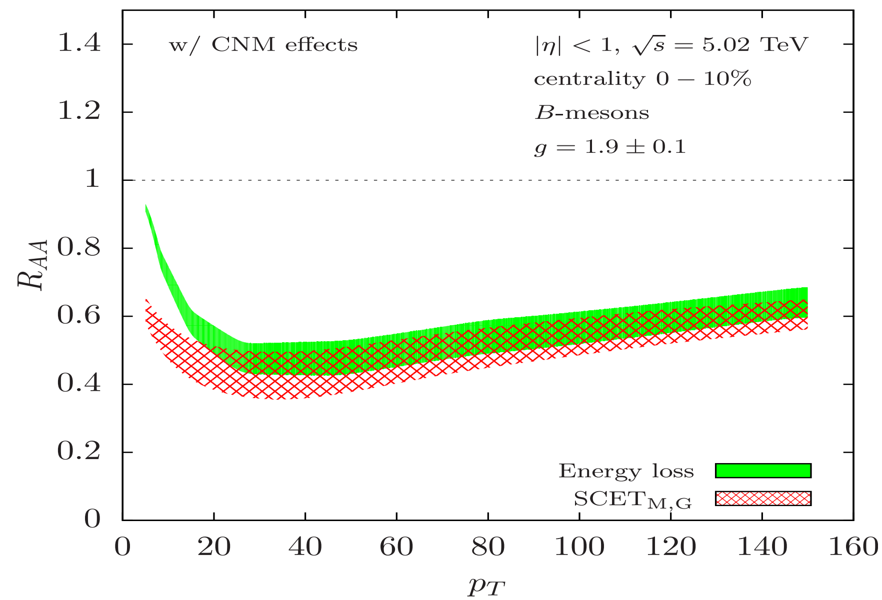
For numerical implementation one can rewrite these expression in the + prescription and finds that the correction is negative

Can lead to larger cross section suppression at smaller p_T

Combined uncertainty

Includes both production mechanism and e-loss vs NLO



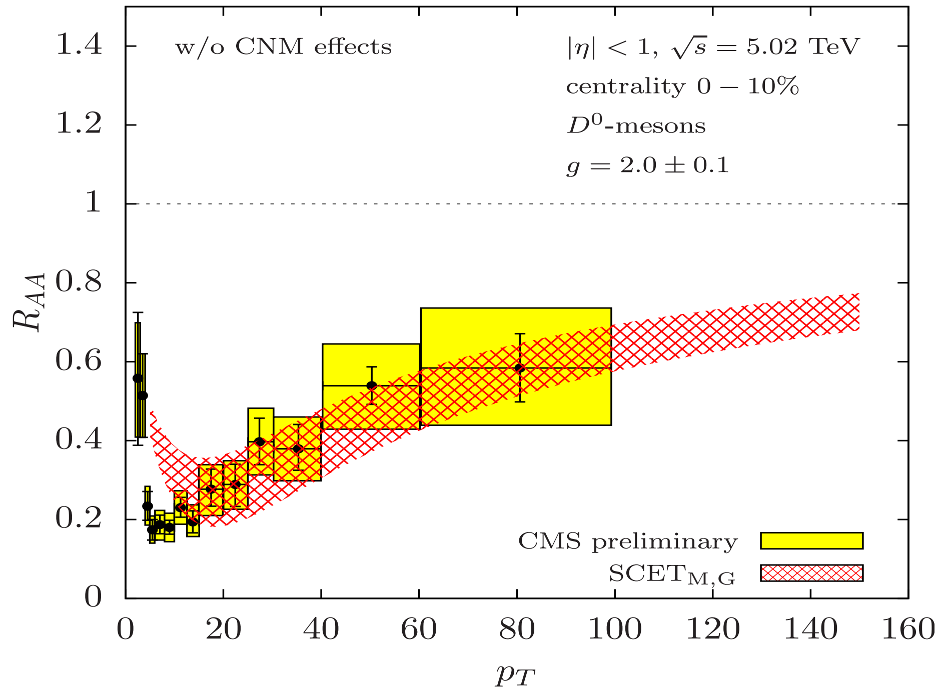


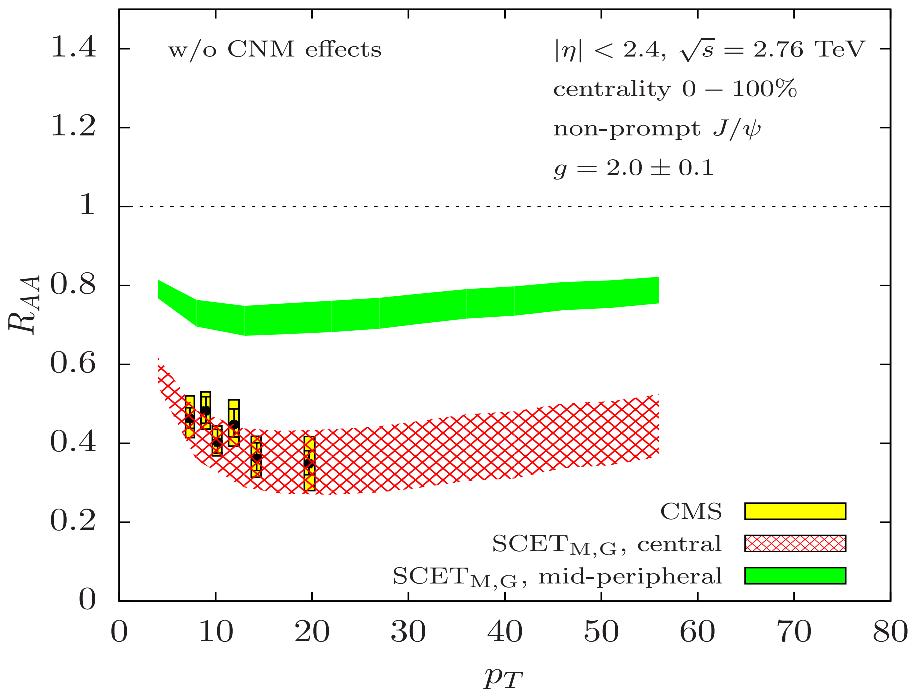
- The pure scale uncertainty largely cancels in the ratio
- At high pT there is at least 20% combined uncertainty. Did not increase much since gluon fragmenatation in H is softer and offsets the difference between quark-gluon enegry loss.
- At low PT th eucertainties can grow to 30% D and 50+% B.

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

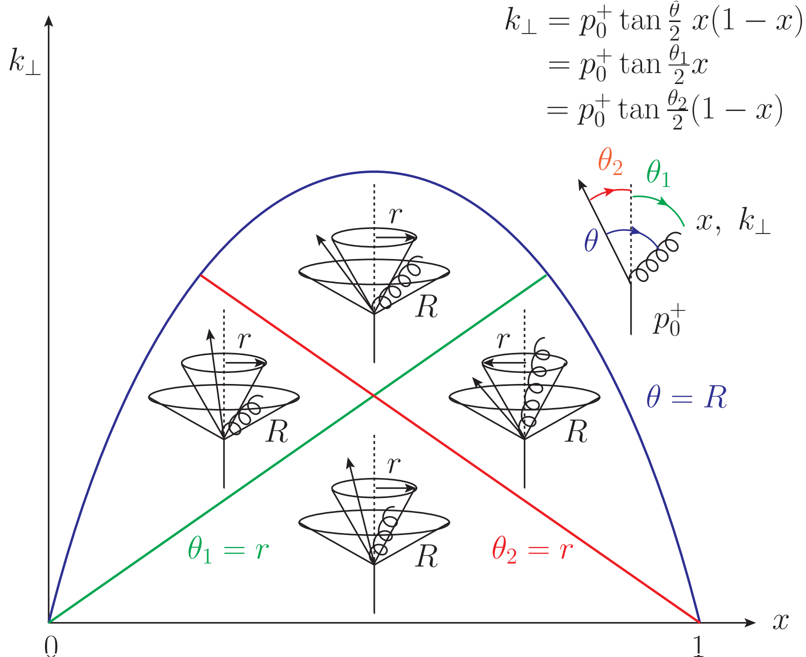
Z. Kang et al . (2016)





- 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

Medium-modified jet shapes at NLL



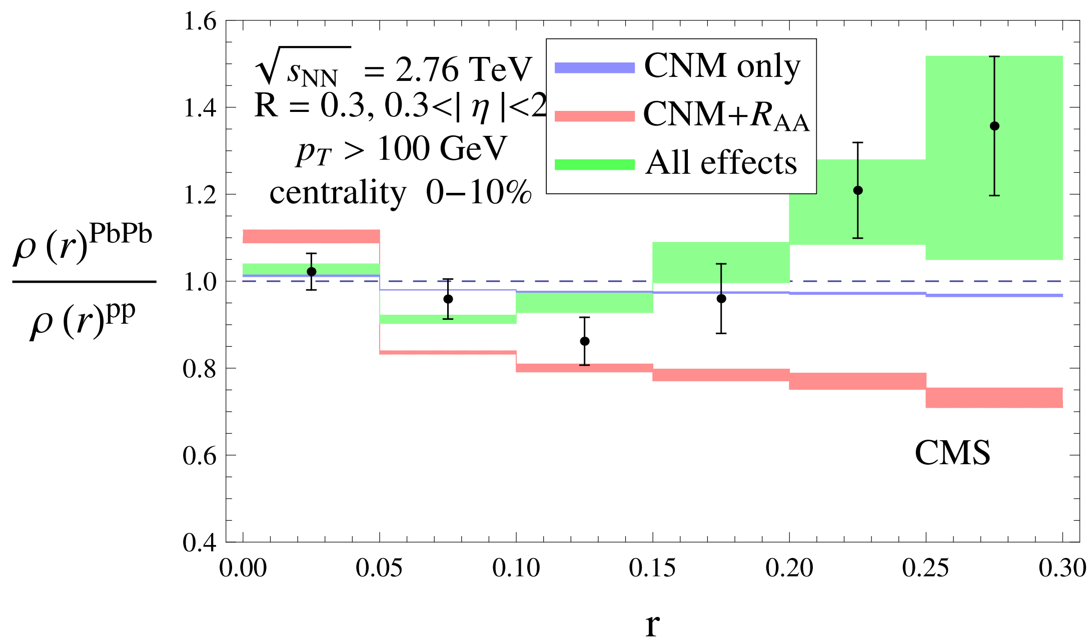
$$E_r(x, k_\perp) = \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3 + \mathcal{M}_4$$

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