Ivan Vitev

SCET for jet physics in the vacuum and the medium

Hard Probes 2016, 8th International Conference of Hard and Electromagnetic Probes in High-Energy Nuclear Collisions
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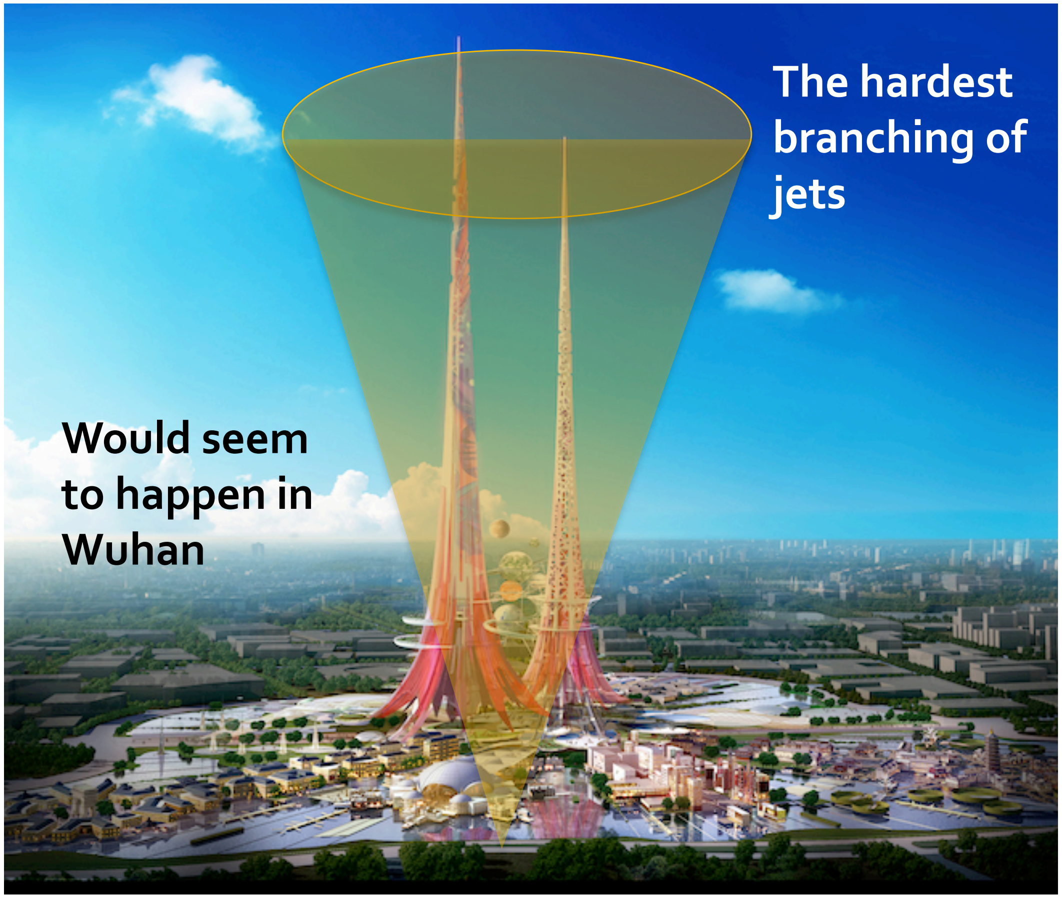
East Lake Conference Center, Wuhan, China

Outline of the talk

Thanks to the organizer for the invitation to HP2016, to my colleagues working on various aspects of SCET for helpful discussion, to DOE Office of Science, LANL LDRD program



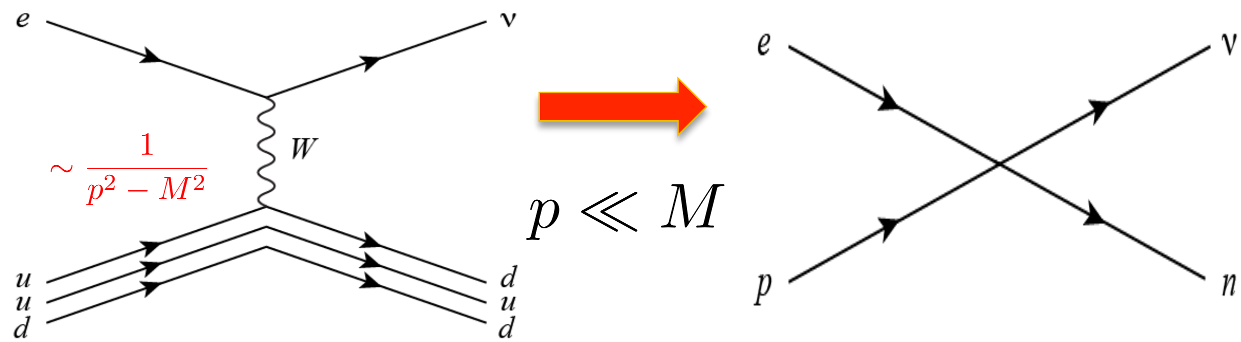
- An effective theory for jets / applications in "vacuum"
- An effective theory for jets in matter / IH applications

It is Hard Probes – many talks: Cacciari, Cassaldery-Solana, Narangh, Qin, Noronha-Hostler,

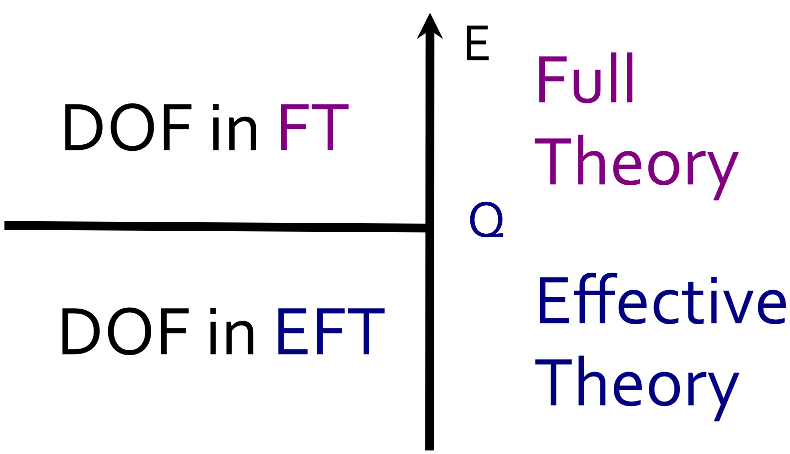
Many of the theory parallel talks

The Fermi interaction

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



Chiral Perturbation Theory (ChPT)	Λ_{QCD}	p/Λ_{QCD}
Heavy Quark Effective Theory (HQET)	m_b	Λ_{QCD}/m_b



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

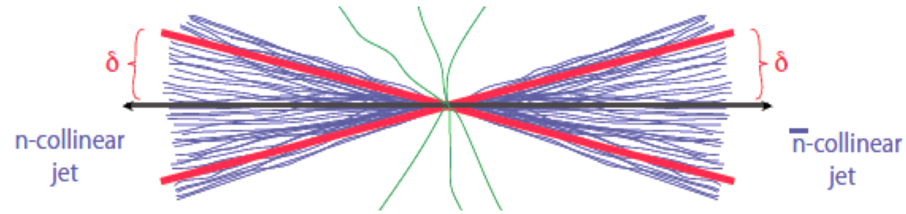
EFT for jets – SCET

- Modes in SCET

C. Bauer et al. (2001)

M. Beneke et al. (2004)

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



- Different SCET formulations exist

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

- Allows to easily write factorization theorems
- Facilitates the resummation of large logarithms through RG evolution equations

$$\begin{aligned}\ln\sigma(\tau) \sim\ & \alpha_s(\ln^2\tau + \ln\tau) \\ &+ \alpha_s^2(\ln^3\tau + \ln^2\tau + \ln\tau) \\ &+ \alpha_s^3(\ln^4\tau + \ln^3\tau + \ln^2\tau + \ln\tau) \\ &+ \quad \vdots \qquad \vdots \qquad \vdots \qquad \vdots\end{aligned}$$

Leading Log (LL) | Next-to-Leading Log (NLL) | NNLL | N³LL

N-subjettiness and DIS

- Generalization of thrust, which counts initial-state radiation (B) and final-state radiation (J)

$$\tau_N = \frac{2}{Q^2} \sum_i \min\{q_B \cdot p_i, q_1 \cdot p_i, \ldots, q_N \cdot p_i\}$$

I. Stewart et al. (2010)

1-jettiness in DIS = 1 B + 1J

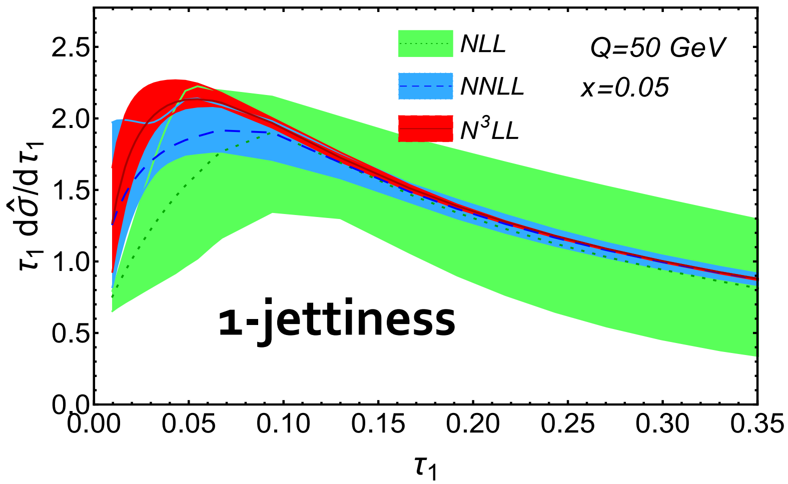
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

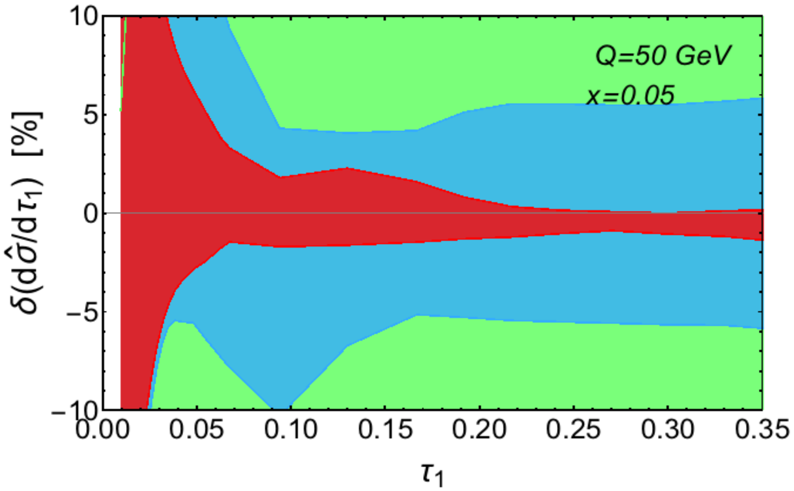
	$\Gamma[\alpha_s]$	$\gamma[\alpha_s]$	$\beta[\alpha_s]$	$\{H, J, B, S\}[\alpha_s]$
LL	α_s	1	α_s	1
NLL	α_s^2	α_s	α_s^2	1
NNLL	α_s^3	α_s^2	α_s^3	α_s
$\mathrm{N^3LL}$	α_s^4	α_s^3	α_s^4	α_s^2

Antonelli et al. (1999)

Z. Kang et al. (2013)

D. Kang et al. (2013)





- Ongoing work toward $\mathrm{N^3LL}$, %-level accuracy achievable at "intermediate" τ
- Extraction of α_s, constraints on PDFs at the EIC.

New ideas for SCET applications to precision QCD phenomenology

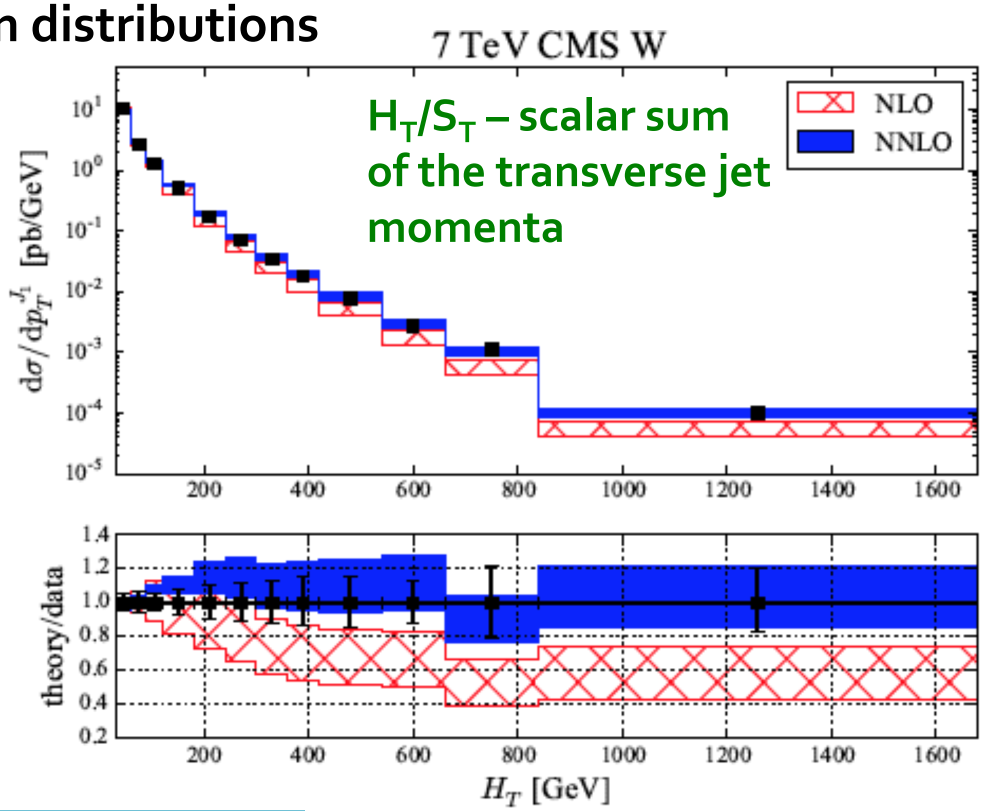
- In the past few years there has been a proliferation of NNLO calculations for LHC (H+J, W/Z+J)

A. Gehrmann de Ritter et al. (2012)

NLO V+N Jet and/or matched to parton showers generally work well, but there are notable exceptions, e.g. scalar momentum distributions

- Local subtraction schemes for IR singularities
- Non-local subtraction schemes for IR, maximum recycle of NLO

$$
\begin{aligned}
\sigma_{NNLO} = & \int d\Phi_N \, |\mathcal{M}_N|^2 + \int d\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^< \\
& + \int d\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^< + \int d\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^> \\
& + \int d\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^> \\
& \equiv \sigma_{NNLO}(\mathcal{T}_N < \mathcal{T}_N^{cut}) + \sigma_{NNLO}(\mathcal{T}_N > \mathcal{T}_N^{cut}).
\end{aligned}
$$



R. Boughezal et al. (2015)

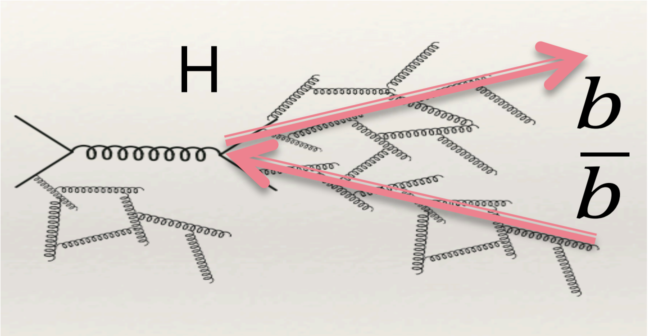
R. Boughezal et al. (2016)

Jet substructure and exclusive processes

- Looking inside reconstructed jets. New jet grooming, jet trimming techniques.

A. Hornig et al. (2010)

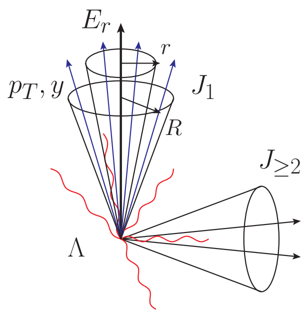
J. Thaler et al. (2011)



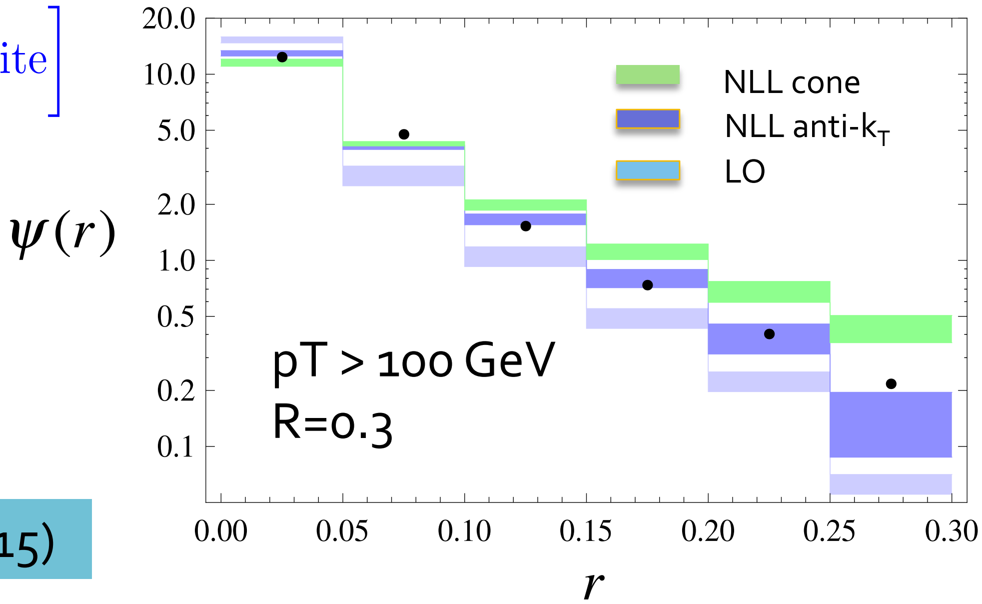
- Traditional jet substructure observables, e.g. jet shapes and jet fragmentation functions only recently addressed

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

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



- **Factorization for exclusive processes – E outside N Jets suppresses O(Λ/Q)**
- **Multiplicative RG evolution**
- **Resums $\alpha_s \ln^2 R$**



- Fragmentation functions

Z. Kang et al. (2015)

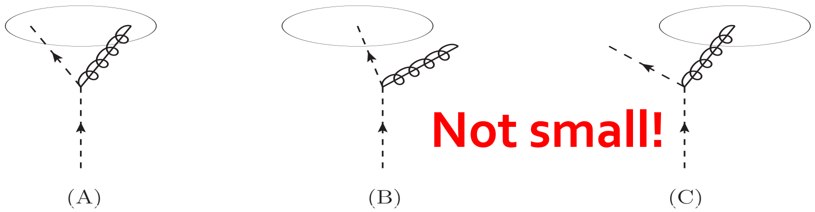
SCET for inclusive jets & small jet radius resummation

- Jet cross section resummation becomes important at small R
- Different log behavior conjectured **~ α_s ln R**

T. Becher et al. (2015)

- **Exclusive SCET ~ α_s ln² R**

Dasgupta et al. (2014)



- Very recent derivation in SCET

Z. Kang et al (2016)

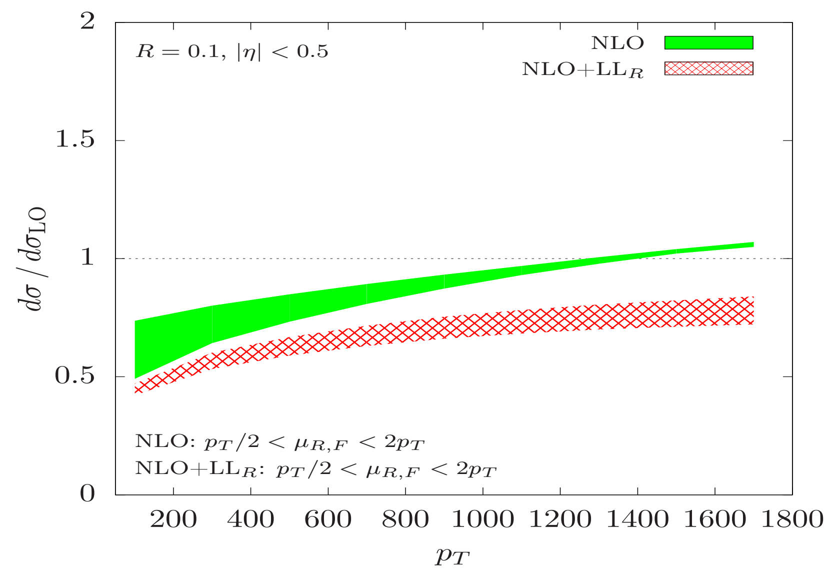
K. Chul et (2016)

A. Idilbi et al . (2016)

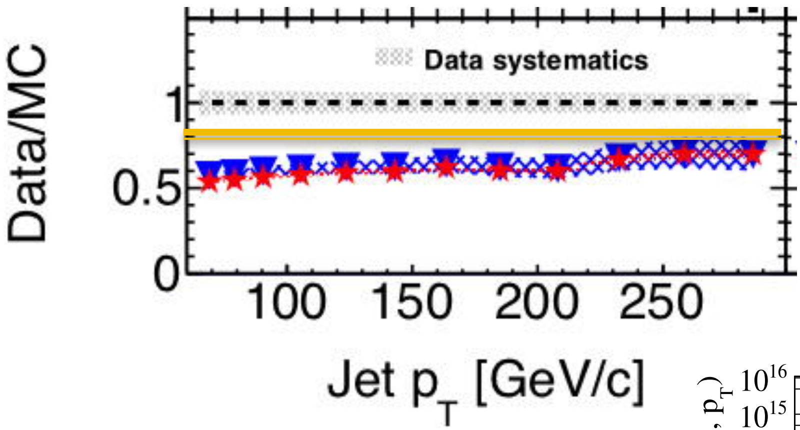
- **Semi-inclusive jet function properly introduced**
- **All α_s ln² R terms cancel**
- **Standard time-like DGLAP evolution equations**

$$\mu \frac{d}{d\mu} J_i(z, \omega_J, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}, \mu\right) J_j(z', \omega_J, \mu)$$

- Achieved NLO+ NLL$_R$. Better control of theoretical uncertainties. Cross section reduction by as much as 30% relative to NLO



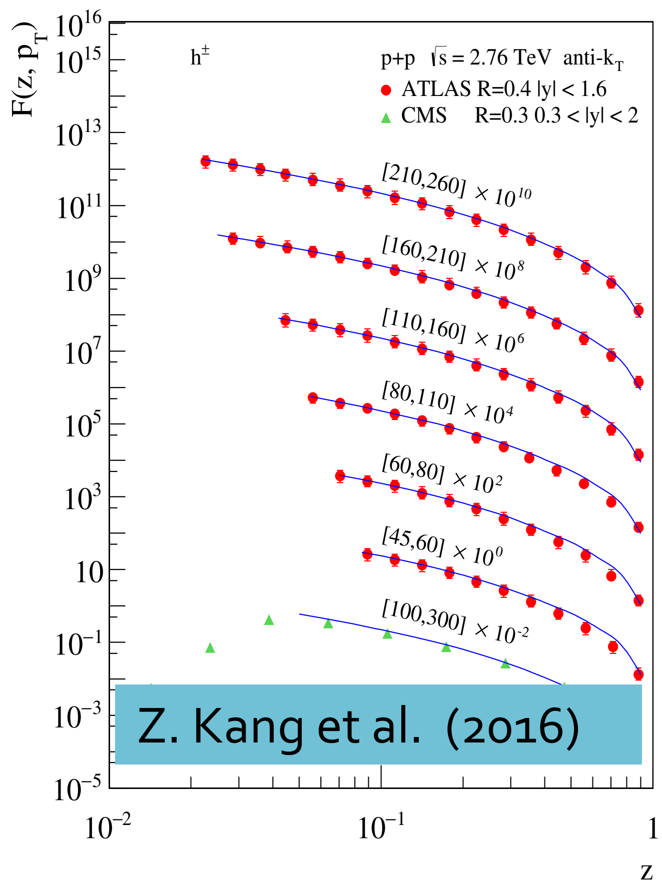
Phenomenological relevance of the latest SCET developments



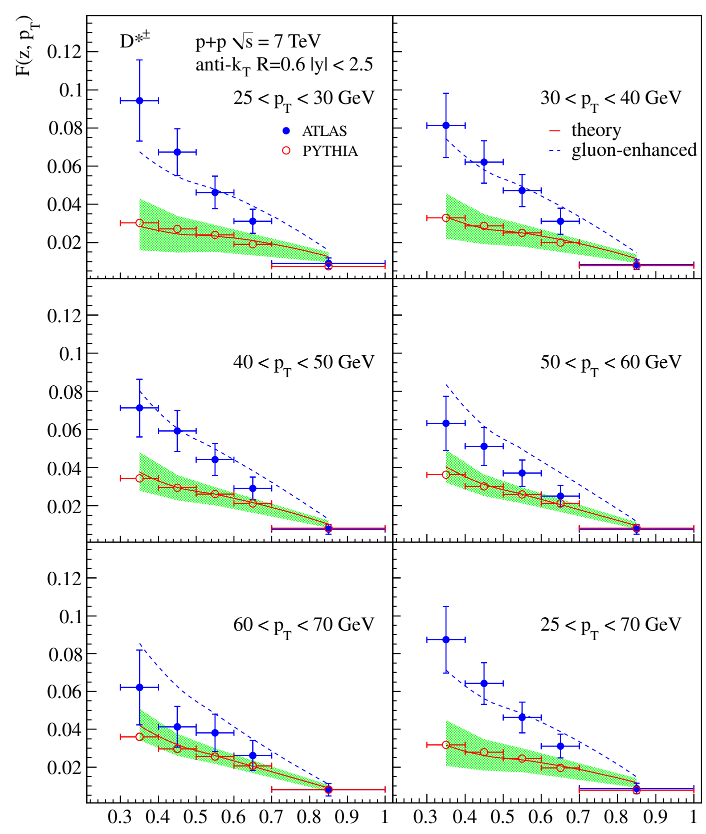
- Very relevant to recent CMS measurements with small R

CMS collab. (2016)

- Similarly, introduced the semi-inclusive fragmenting jet function



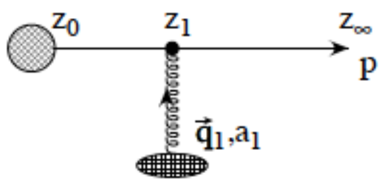
Z. Kang et al. (2016)



- Very good description of the light hadron
- Heavy mesons require large gluon contribution

SCET in the medium ($SCET_G$)

An effective theory of jet propagation in matter - couple the collinear and dense QCD sectors – soft collinear effective theory with Glauber gluons



Forward scattering, t-channel gluon exchanges

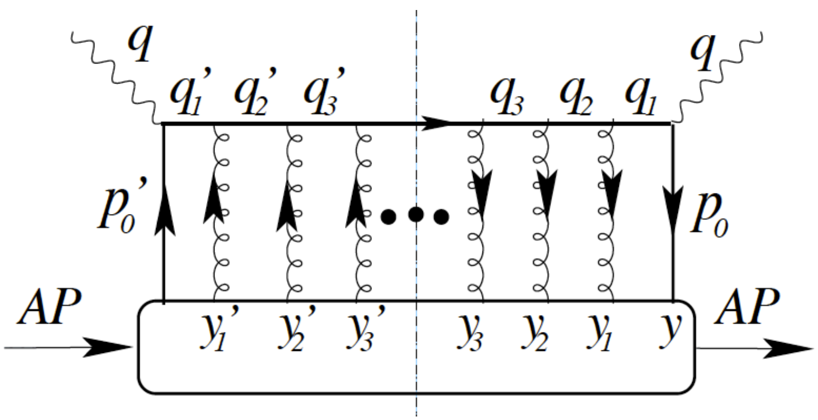
$$q = (\lambda^2, \lambda^2, \lambda)Q$$

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

A. Idilbi et al. (2008)

G. Ovanesyan et al. (2011)

Effective potential



- Feynman rules for different sources and gauges

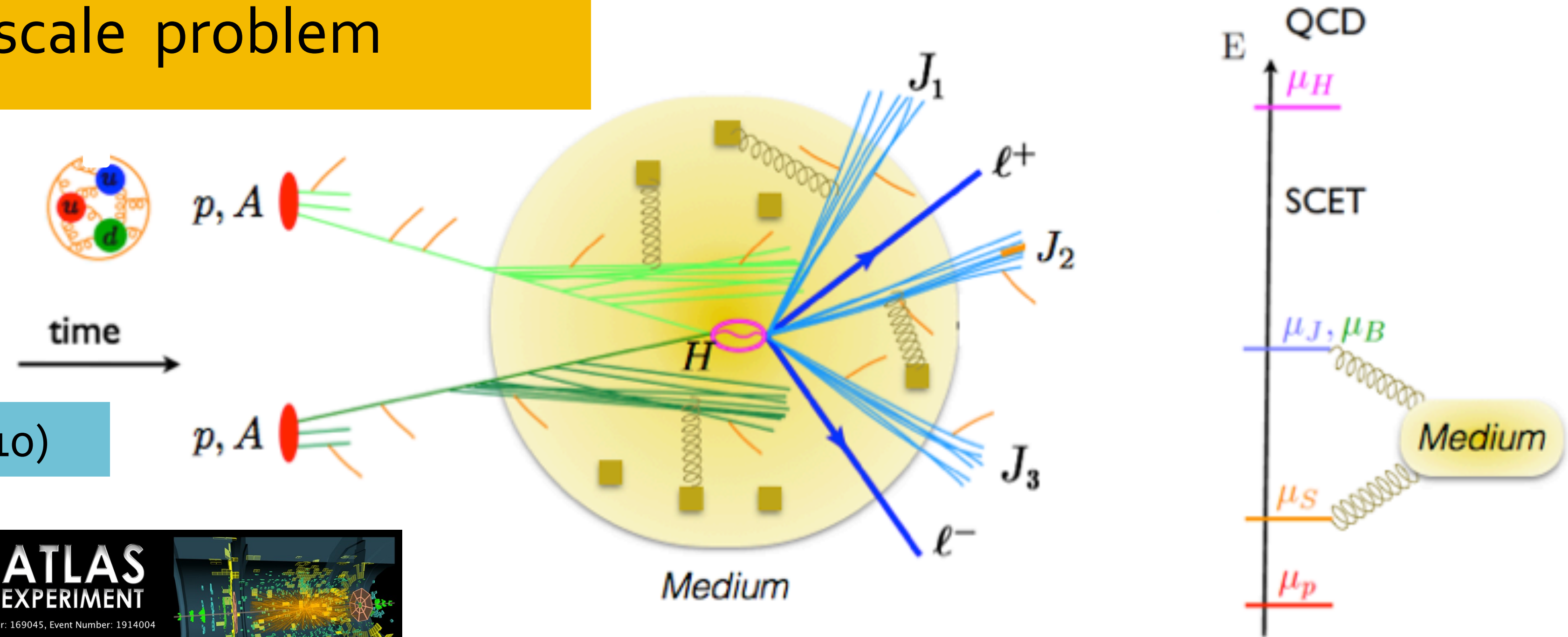
First application - resum tree level quark scattering

D'Erramo et al. (2010)

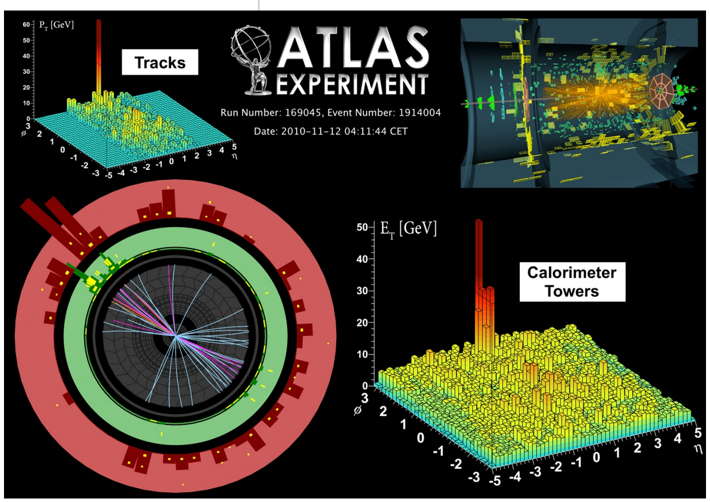
The big picture for hard probes

- QCD in the medium remains a multi-scale problem

Ovanesyan et al. (2011)



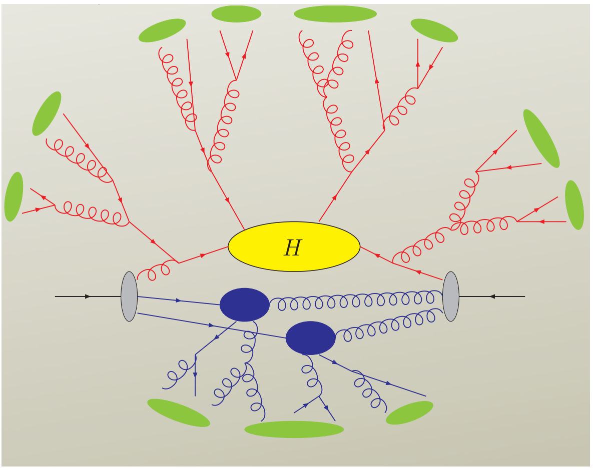
Aad et al. (2010)



- 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 in-medium splitting kernels



G. Altarelli et al. (1977)

- Direct sum

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

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

W. Waalewjin. (2014)

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

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

G. Ovanesyan et al. (2012)

- Unified description of vacuum and in-medium parton showers
- Initial-state splitting kernels recently also became available

G. Ovanesyan et al. (2015)

Evolution of the fragmentation functions

- Yield LLA or MLLA

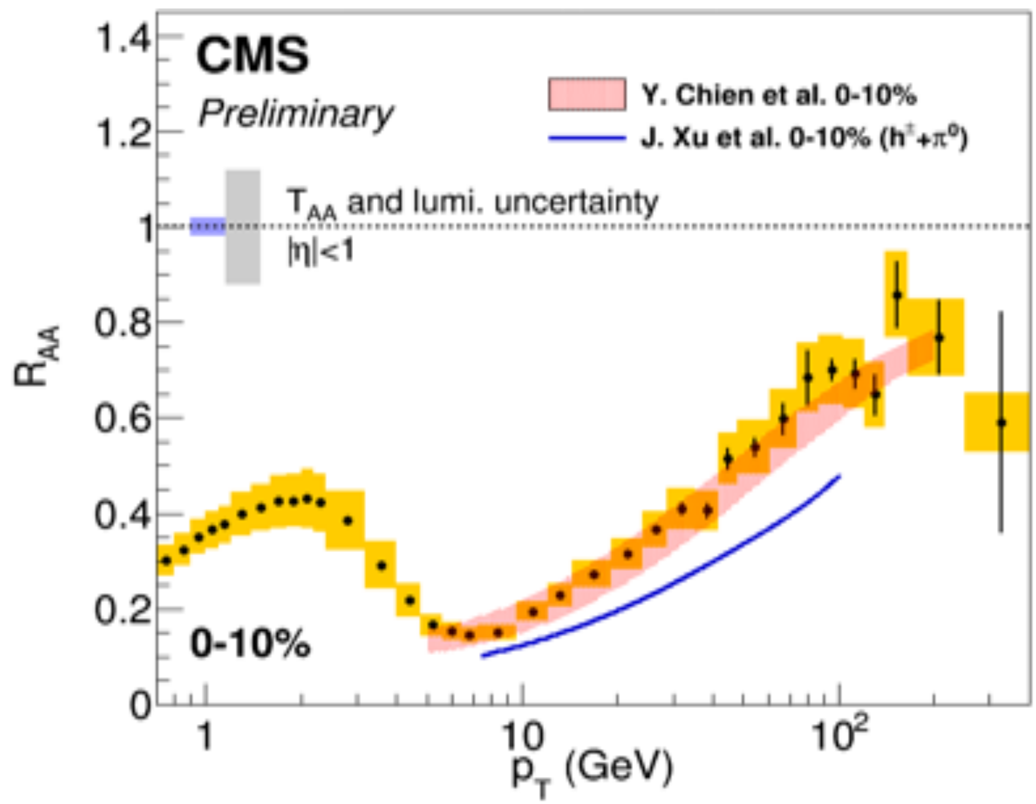
Z. Kang et al. (2014)

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

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

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

$$\left. + P_{g\to q\bar{q}}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + \bar{q}\ \text{term}\right)\right\}.$$



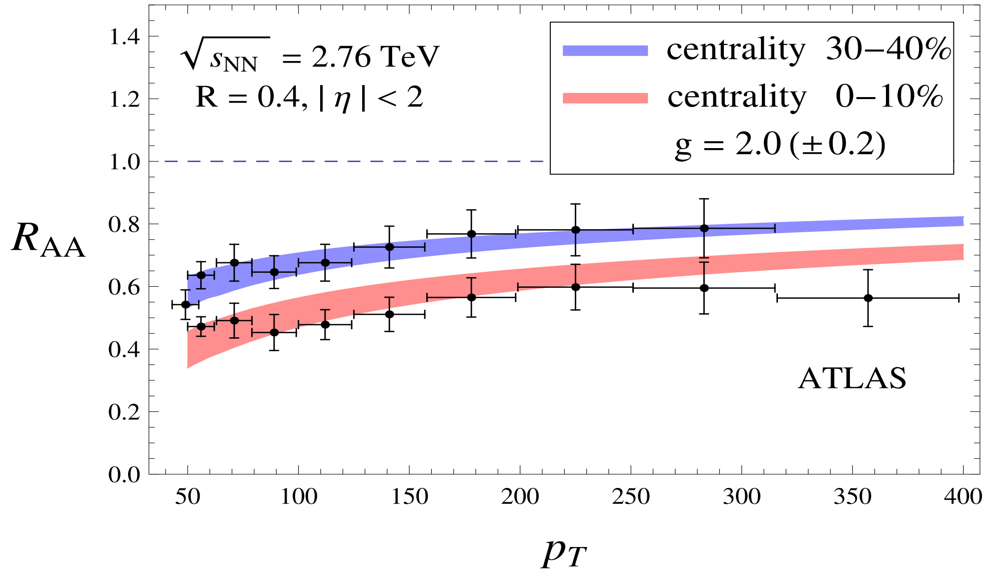
Implement medium –induced splittings as corrections to vacuum evolution

Demonstrated connection to E-loss

Verty goo description of data at 2.76 TeV

Y.T-Chien et al. (2015)

Generalizing the concept of energy loss to jets

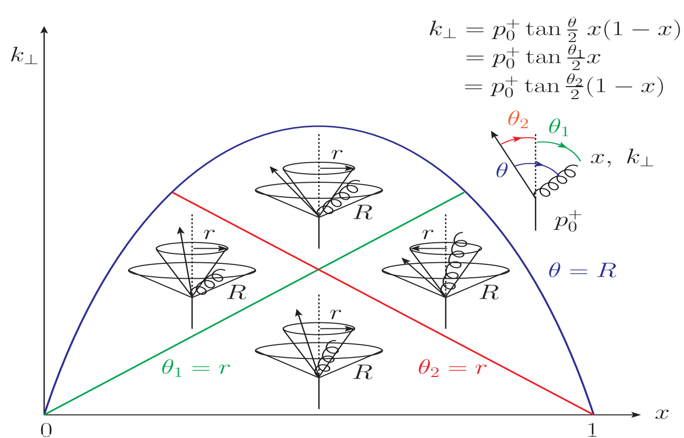


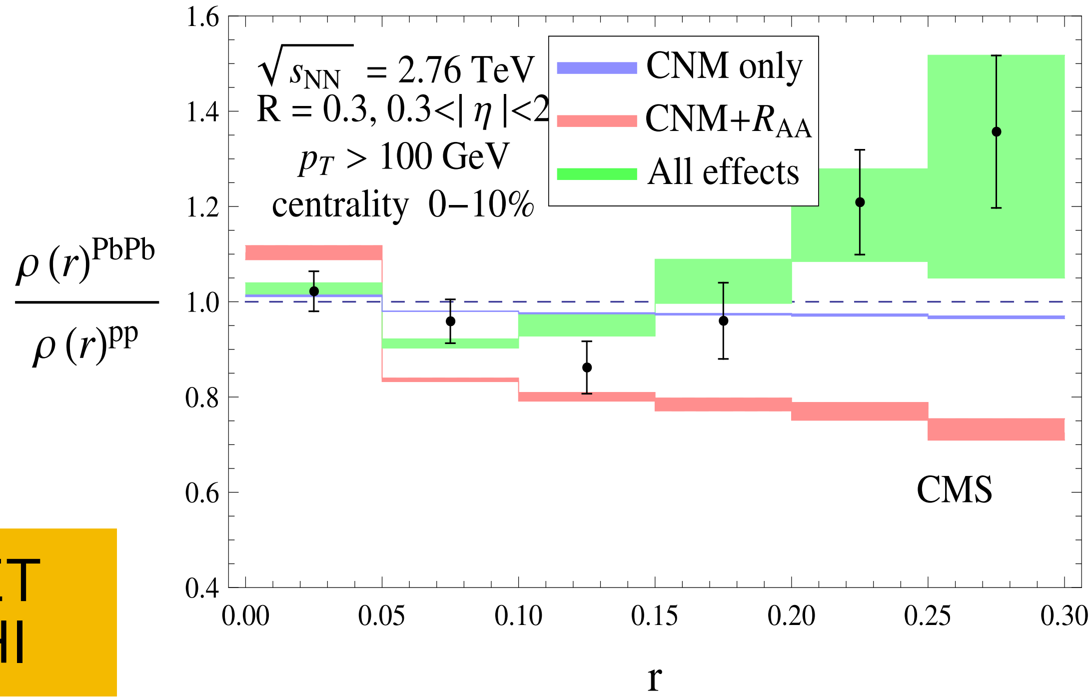
- The jet definition allows to generalize the concept of energy loss

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

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

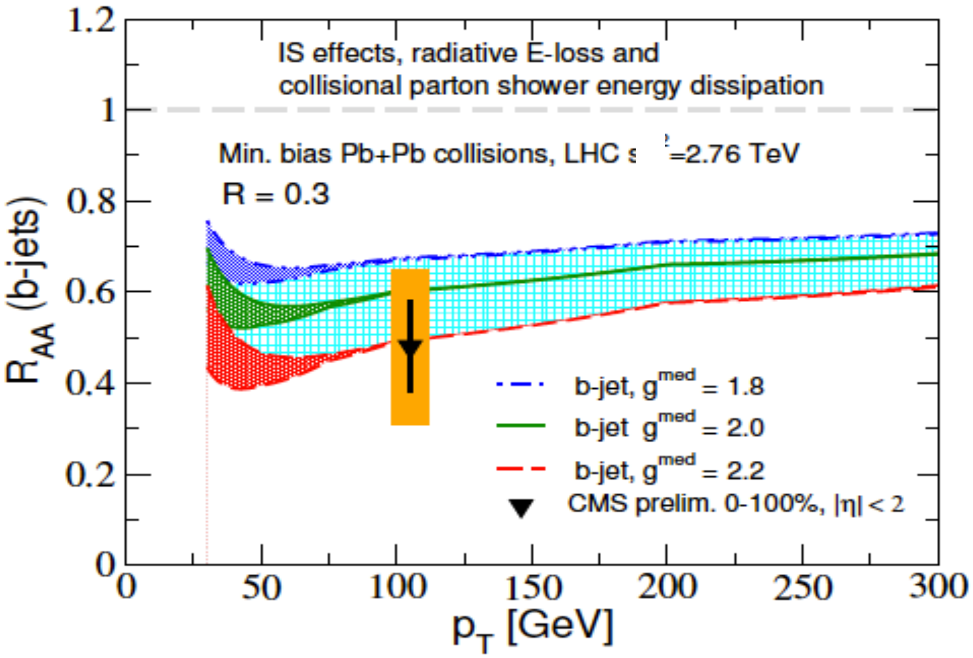
$$J_{\omega,E_r}(\mu) = J^{vac}_{\omega,E_r}(\mu) + J^{med}_{\omega,E_r}(\mu)$$



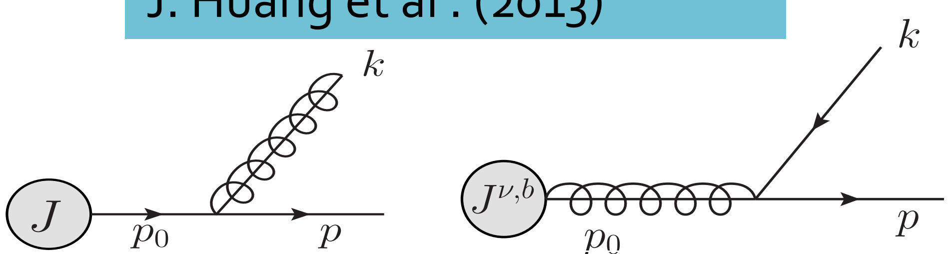


- First quantitative pQCD/SCET description of jet shapes in HI

Heavy quarks in SCET



J. Huang et al . (2013)



F. Ringer et al . (2016)

3 splitting functions (g to gg is the same)

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

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

The process is not written Q to gQ , since x goes to 1-x

- 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

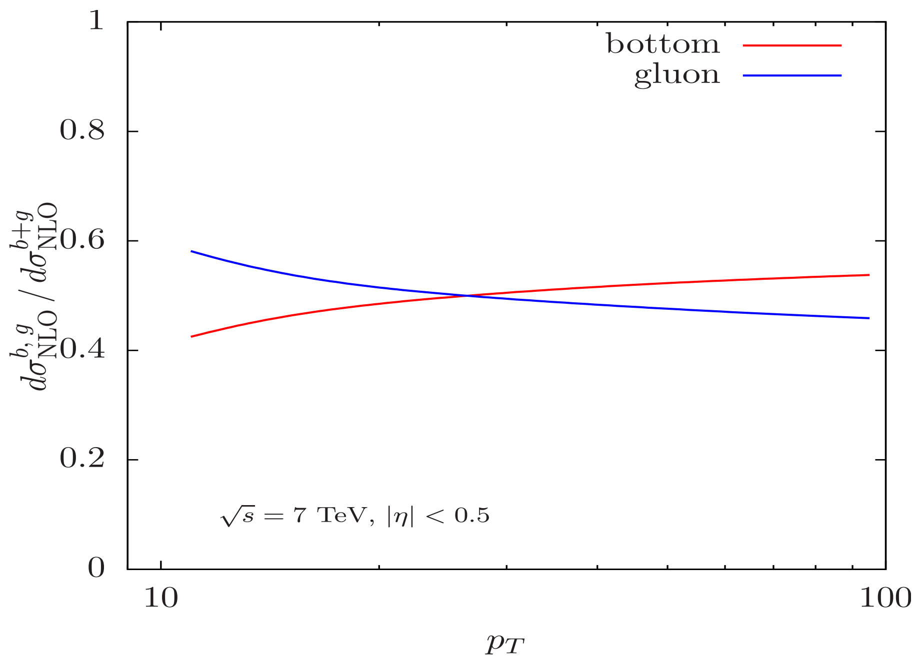
The medium-induced splitting kernels are now derived (1st order in opacity). More complicated than the vacuum ones. Have been numerically evaluated

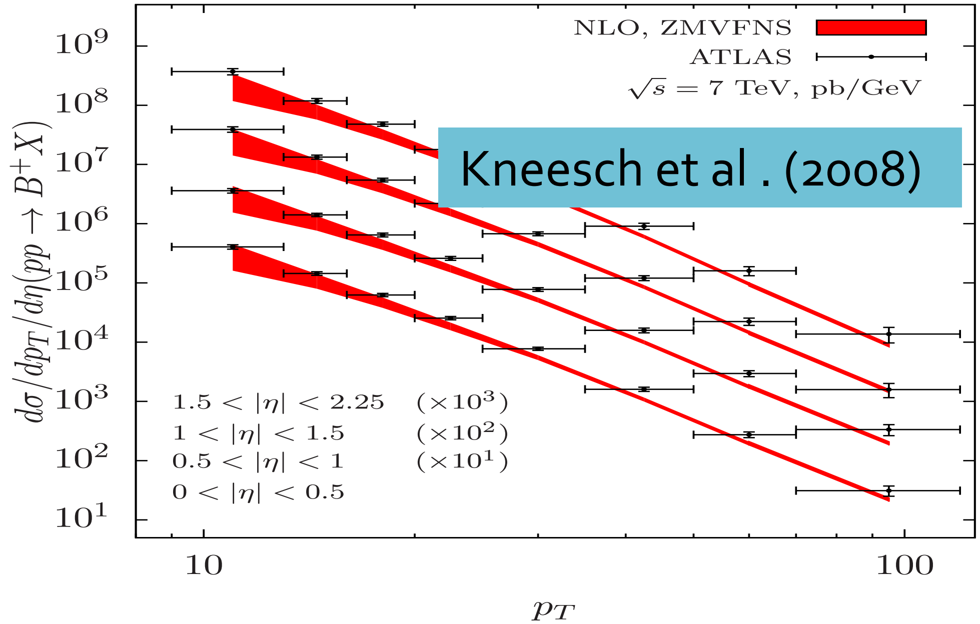
ZMVFS open heavy flavor at NLO

- Perform and NLO calculation
- A very large contribution of gluon FF to heavy flavor

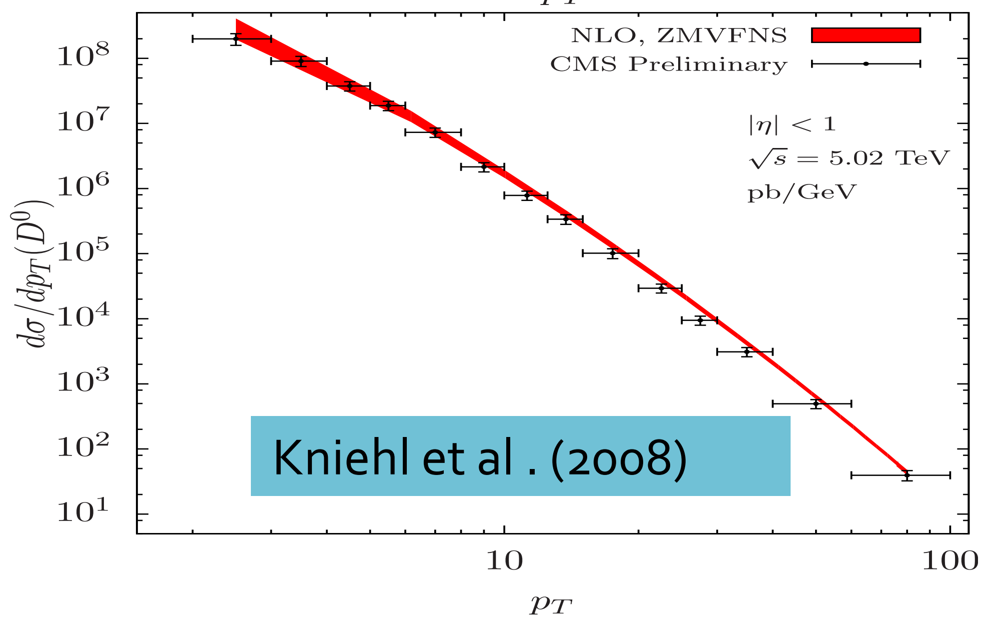
When $p_T > m_c, m_b$

F. Ringer et al . (2016)





Kneesch et al . (2008)



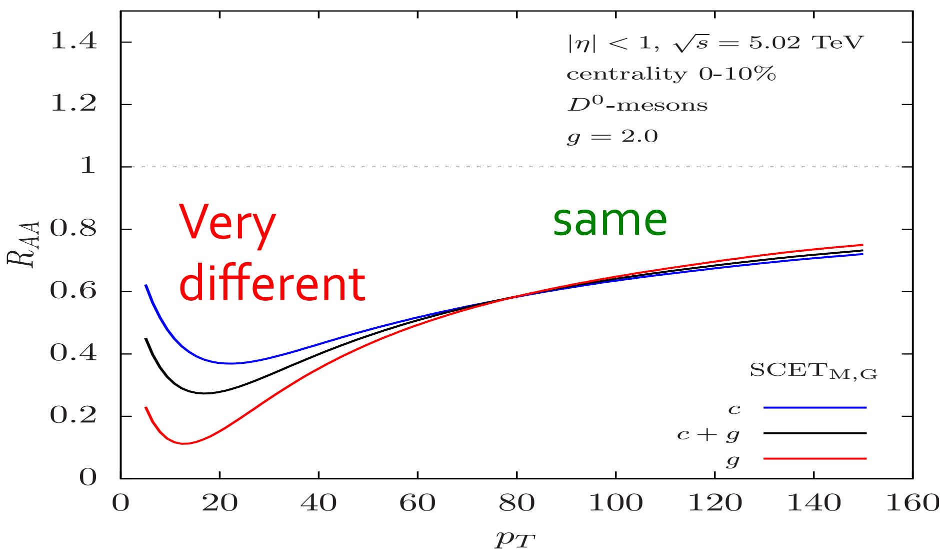
Kniehl et al . (2008)

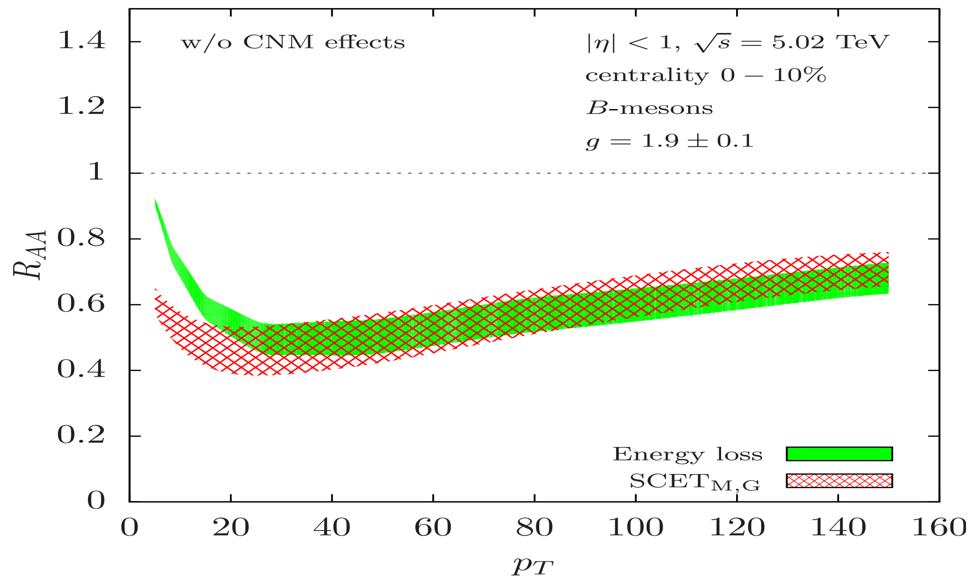
Implications for A+A Collisions

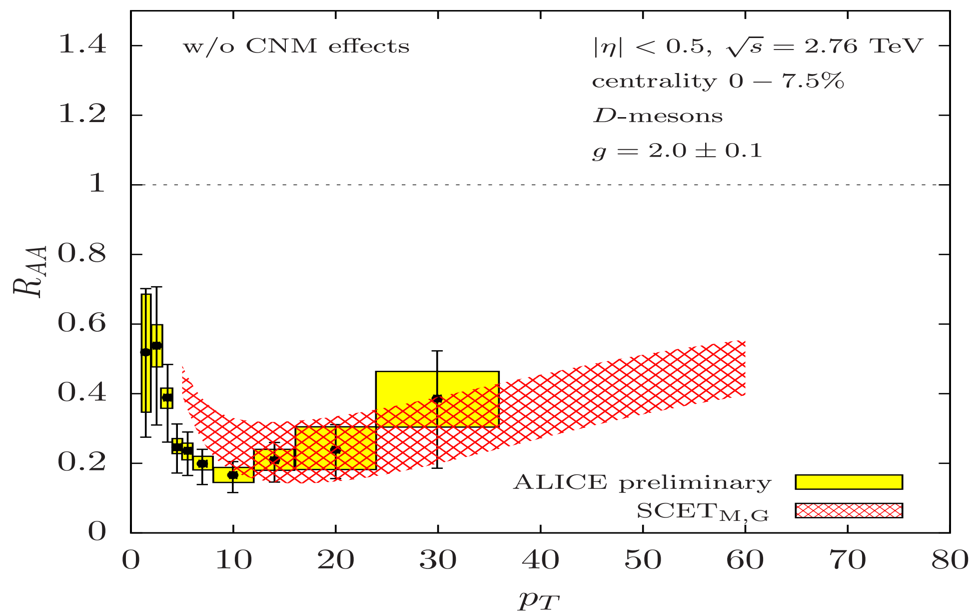
- Heavy flavor still posed many unresolved questions

A. Andronic et al . (2015)

- High-P_T stable, low p_T 30-50% more suppression
- Does not fully eliminate the need for collisional interactions / energy loss or dissociation



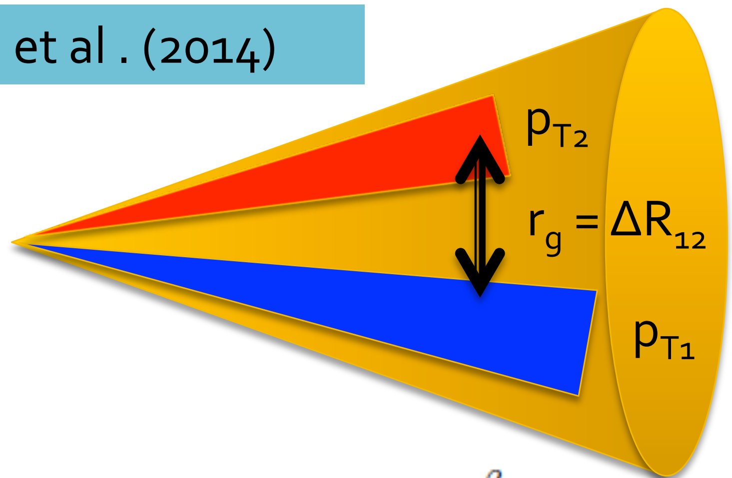


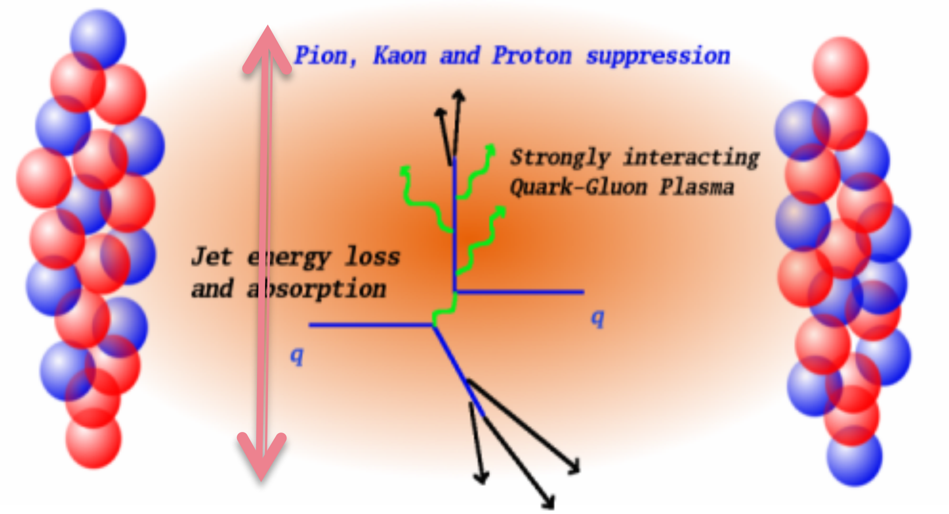


Groomed soft dropped distributions in SCET_G

- Groomed jet distribution using "soft drop"

A. Larkoski et al . (2014)





QGP size ~ 10fm

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

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

Typical situation: E=200 GeV, r_g = 0.1

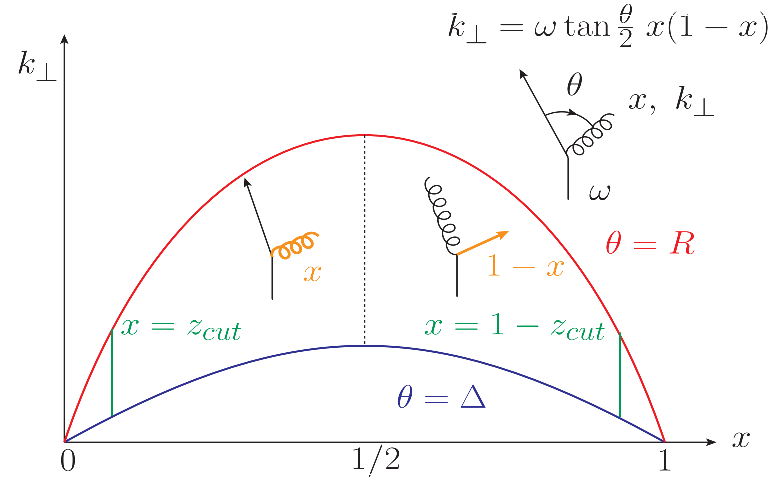
Branching time < 2 fm for z_g studied

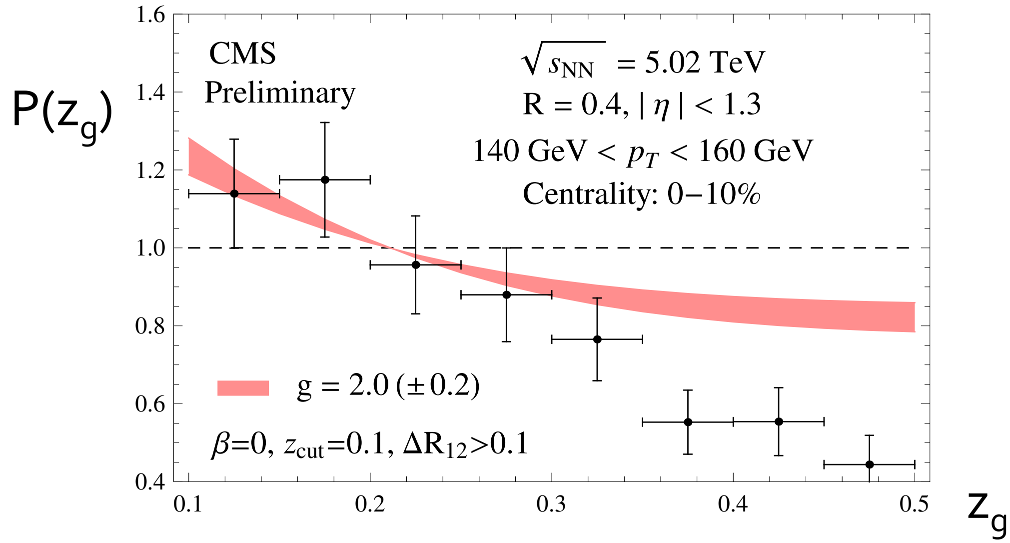
The great utility of these new distributions: probe the early time dynamics / splitting

Y. T. Chien et al . (2016)

Accessing the hardest branching in HIC – longitudinal modification

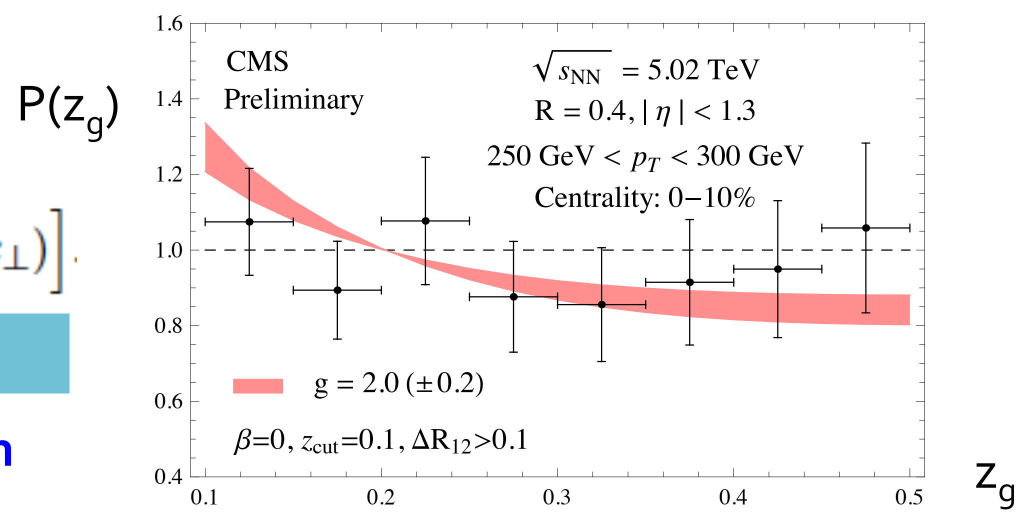
Calculating the soft dropped distribution with β=o





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

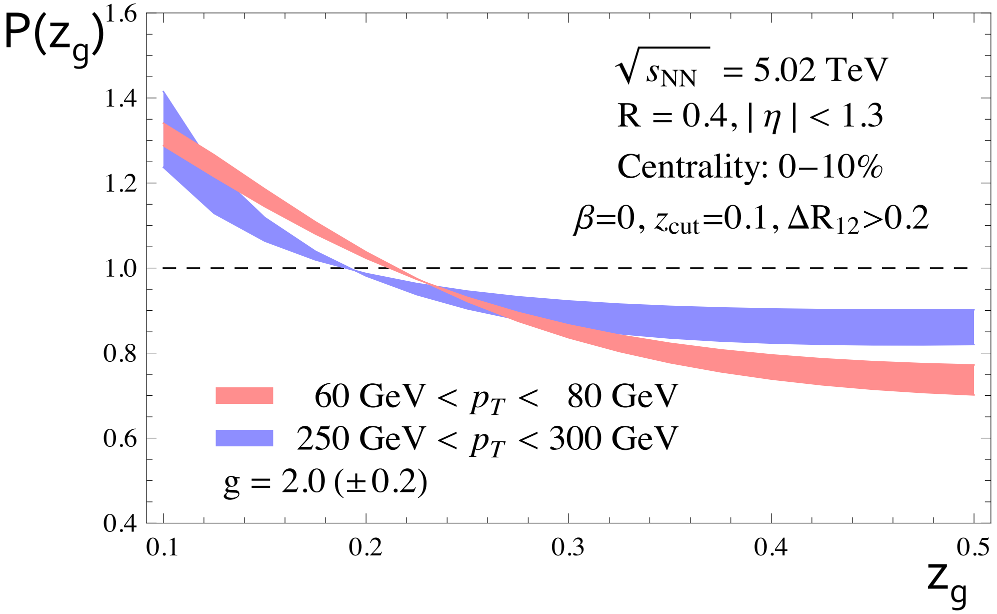
$$\overline{\mathcal{P}}_i(x, k_\perp) = \sum_{j,l} \left[\mathcal{P}_{i\to j,l}(x, k_\perp) + \mathcal{P}_{i\to j,l}(1-x, k_\perp)\right].$$



Y.T. Chien et al . (2016)

NB: STAR does not see such effect within error bars at RHIC

Modification of the angular distribution of hardest branchings

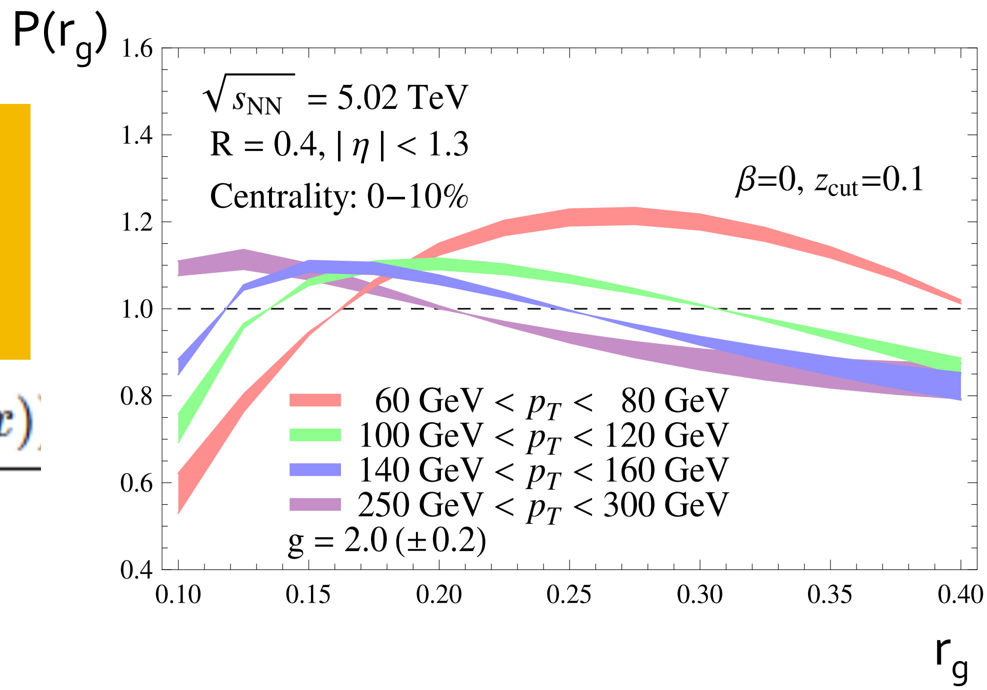


Flexibility in selecting angular separation r_g

Found that inetrmediate values r_g = 0.2 give the strongest p_T dependence.

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)

Vector boson tagged jets

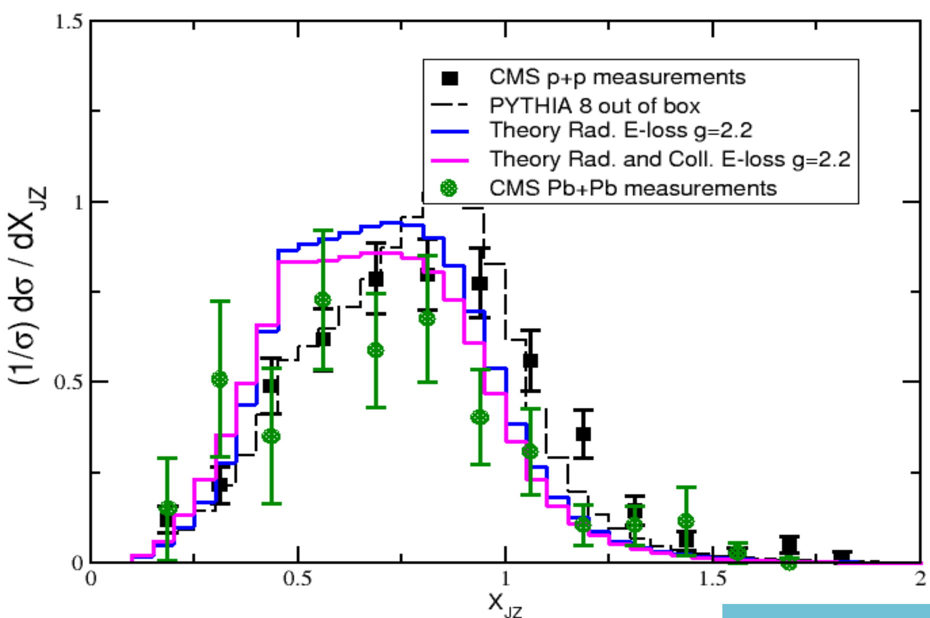
The Glauber and soft gluons are not yet coupled in the $SCET_G$ with a background medium

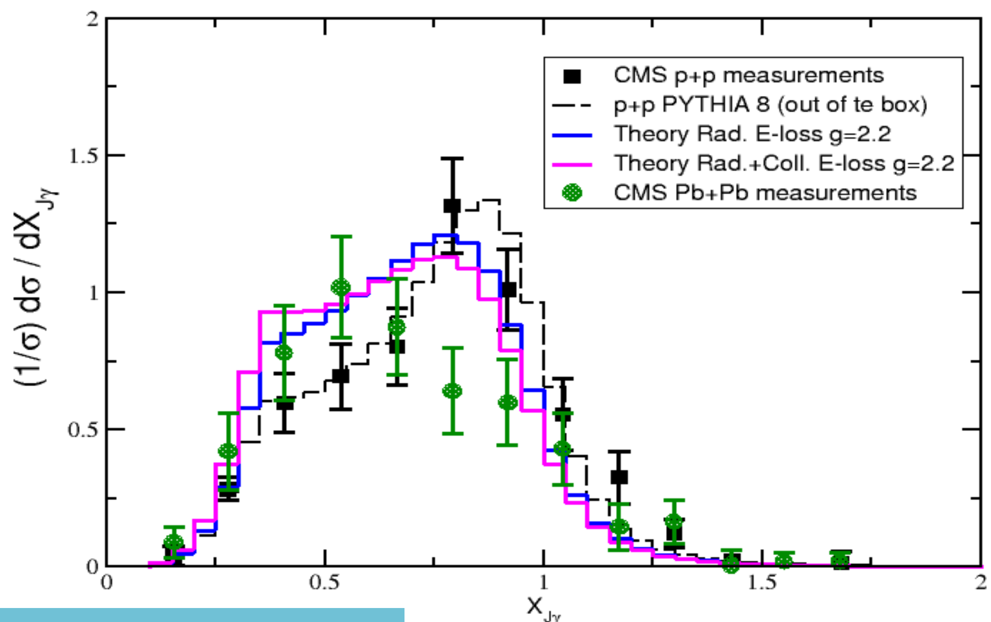
NB: There is work to filly include Glaubers to jets, BFKL evolution

I. Rothstein et al . (2016)

S. Fleming (2014)

The baseline not great, the physics – magnitude of ΔX_{VJ} e.g.





H.-Xing et al . (2016)

In place of conclusions

2017
Jets and Heavy Flavor Workshop

Immediately after QM2017

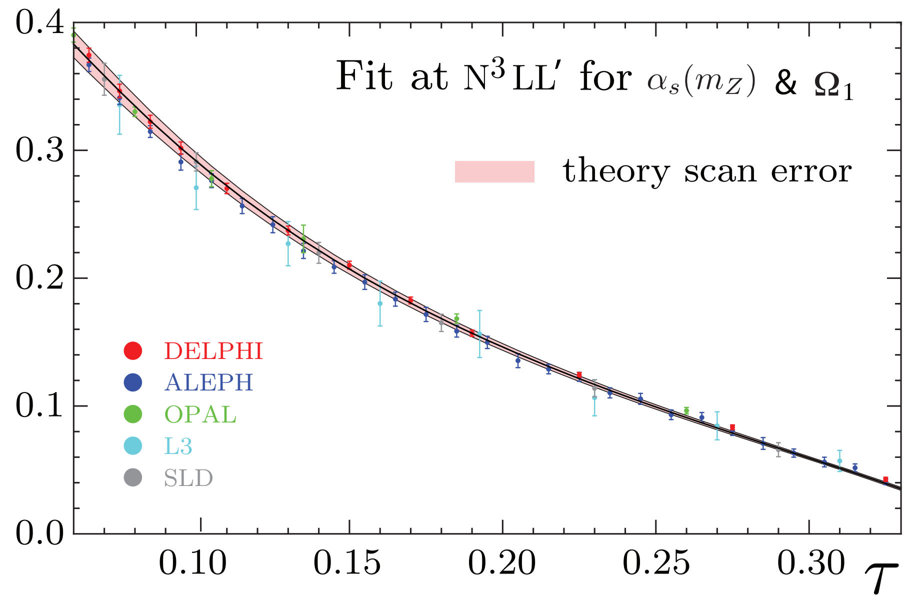
- Second in a series of workshops to bring together the NP and HEP communities working on jets and heavy flavor, with emphasis on QCD and SCET

α_s from $e^+ e^-$ thrust distributions

- Thrust distribution among the first global event shapes

$$\tau_{ee} = 1 - \frac{1}{Q} \max_{\vec{n}} \sum_i |\vec{p}_i \cdot \vec{n}|$$

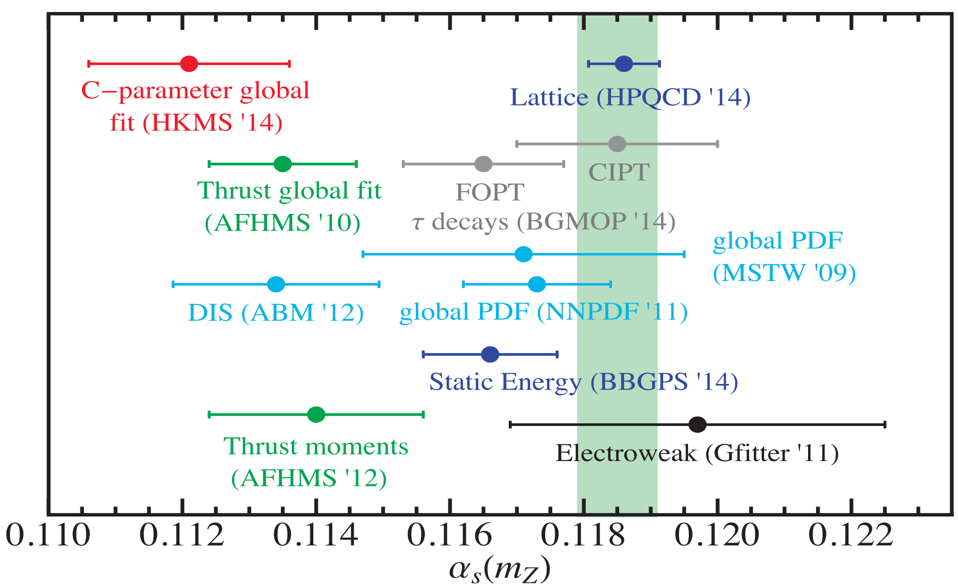
E. Farhi (1977)



R. Abate et al. (2010)

- Factorization theorem in SCET

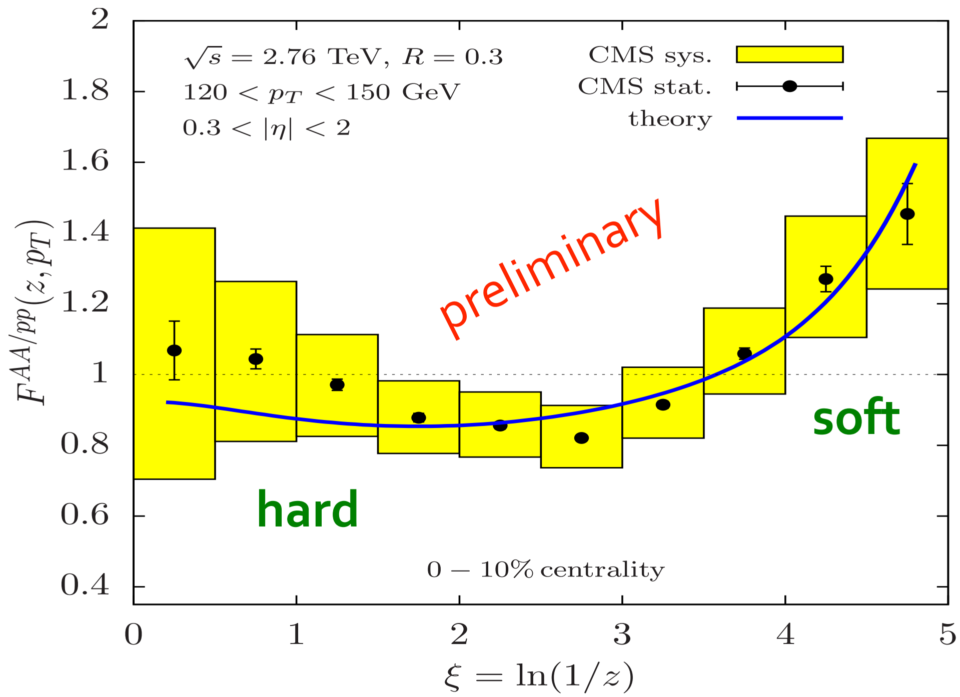
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$



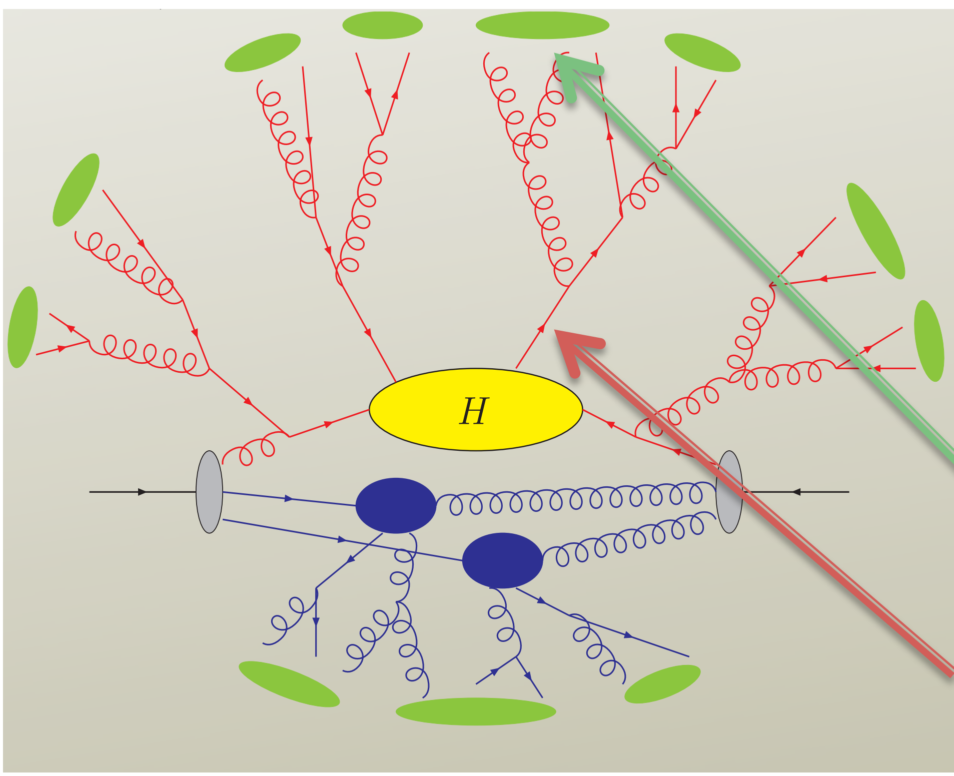
- α_s at the Z pole from event shapes differ by ~ 2σ from the average (weighed by LQCD)
- Need to extract α_s in other reactions, e.g. DIS

Probing the hardest splitting in jets in heavy ion collisions

Jet substructure modifictaion in HIC well established: jet shapes, jet fragmentation functions



Y. T Chien et al . in progress



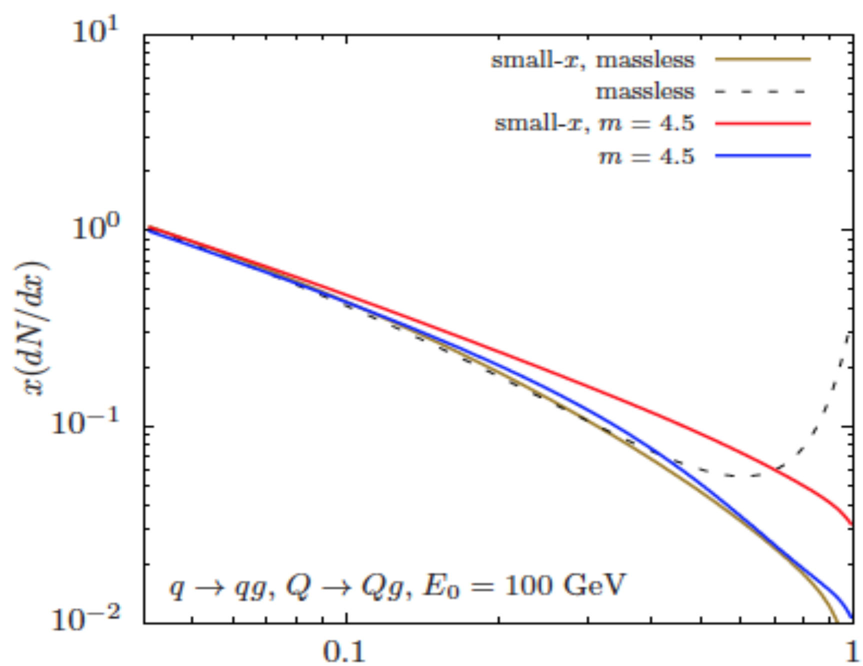
Is substructure modification set by late time soft gluon emission ?

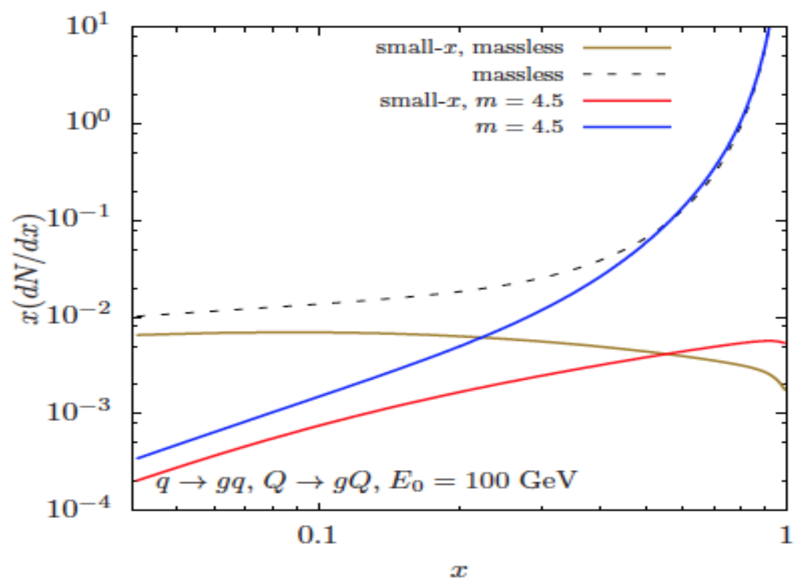
Or is it manifest in the hard early time splittings?

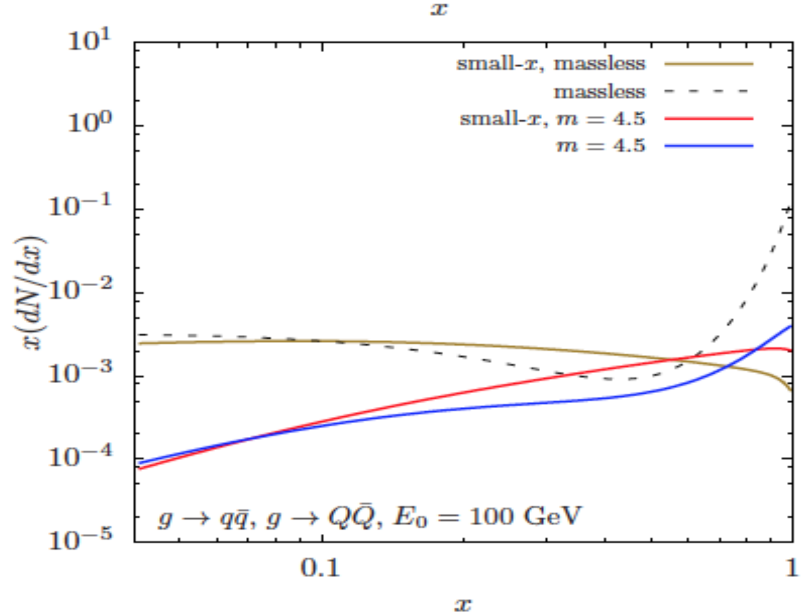
Results for the massive in-medium splitting intensities

The massive in-medium splitting functions differ considerably from the massless ones

The differences persist even for large energies (E=100 GeV)





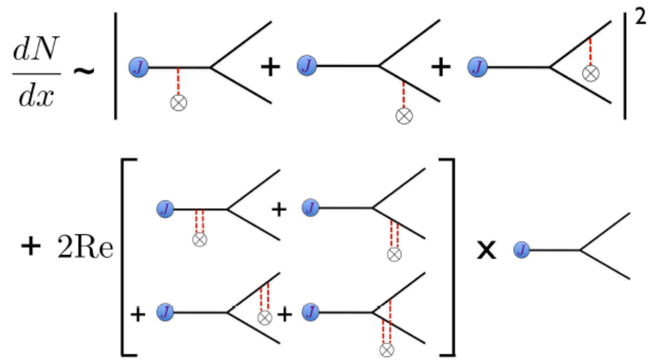


Felix Ringer et al . (2016)

Heavy quarks in the medium

Kinematic variables

$$A_\perp = \mathbf{k}_\perp,\ B_\perp = \mathbf{k}_\perp + x\mathbf{q}_\perp,\ C_\perp = \mathbf{k}_\perp - (1-x)\mathbf{q}_\perp,\ D_\perp = \mathbf{k}_\perp - \mathbf{q}_\perp$$



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

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

F. Ringer et al . (2016)

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

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

In-medium parton splittings and their properties

- Direct sum

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

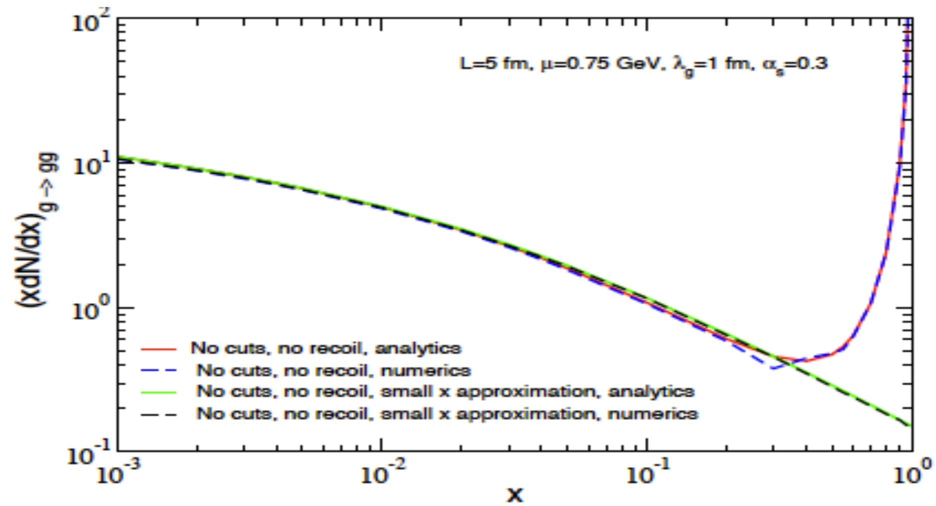
- Derived using SCET$_G$
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium

G. Ovanesyan et al. (2012)

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

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

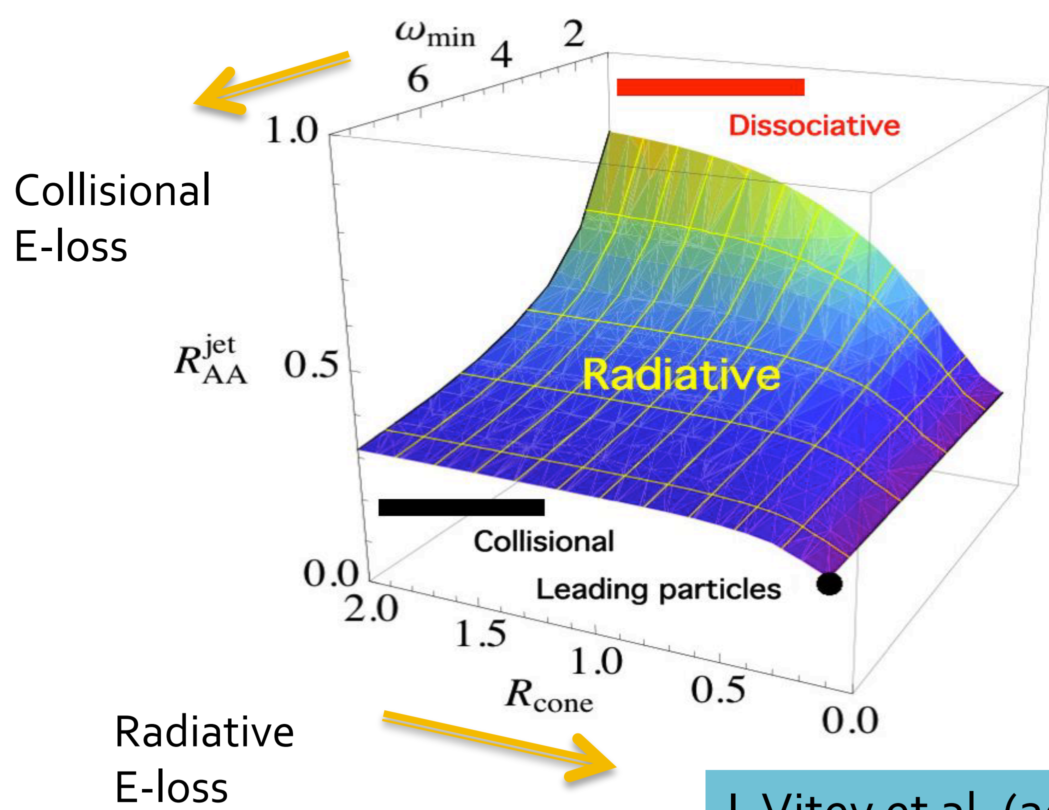
Example why traditional energy loss interpretation is not possible in a unified parton shower picture



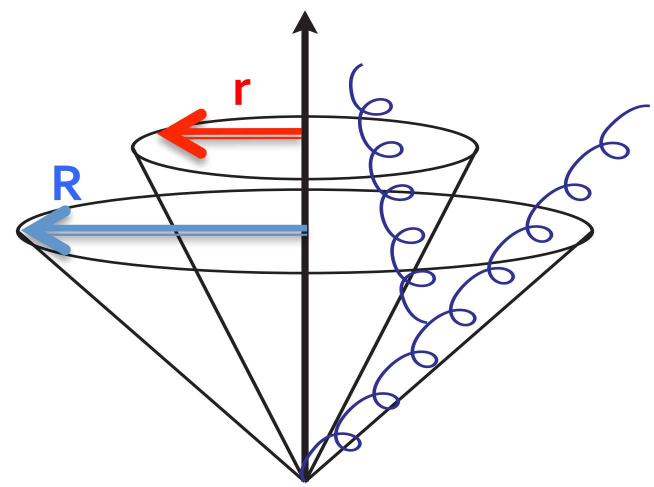
Applications of SCET_G to jet shapes and jet cross sections

- Jet cross sections reflect the total amount of energy retained in the jet cone

- Jet shapes reflect the energy density inside the jet and the structure of the parton shower



I. Vitev et al. (2008)

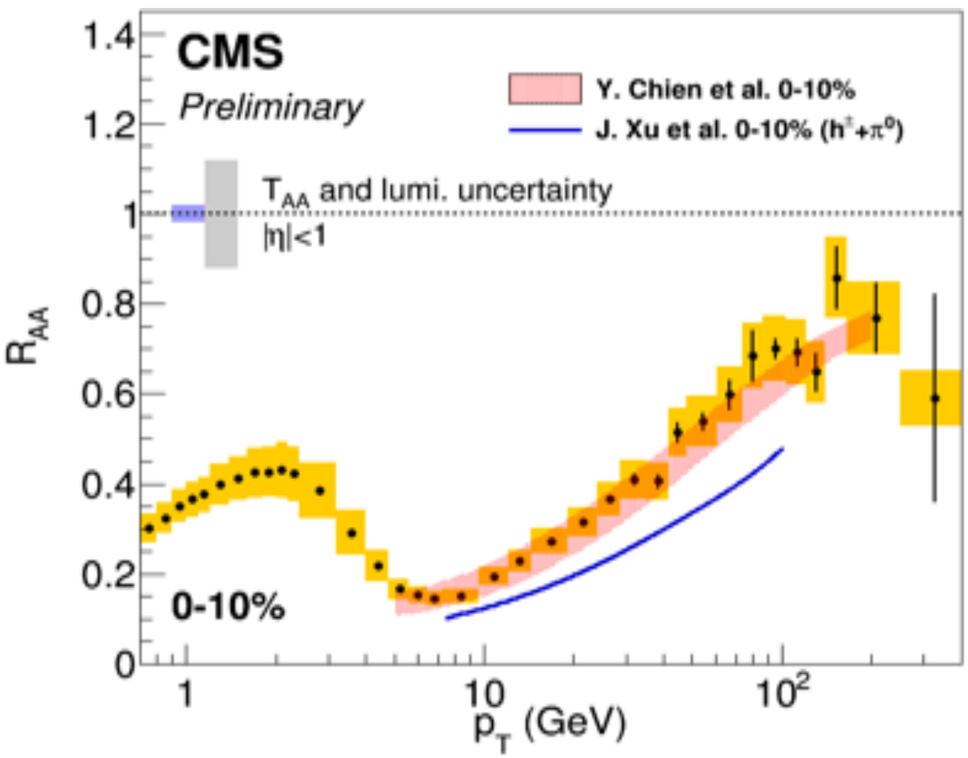


$$\Psi_{\text{int}}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\text{jet}})_i)},$$

$$\psi(r;R) = \frac{d\Psi_{\text{int}}(r;R)}{dr}.$$

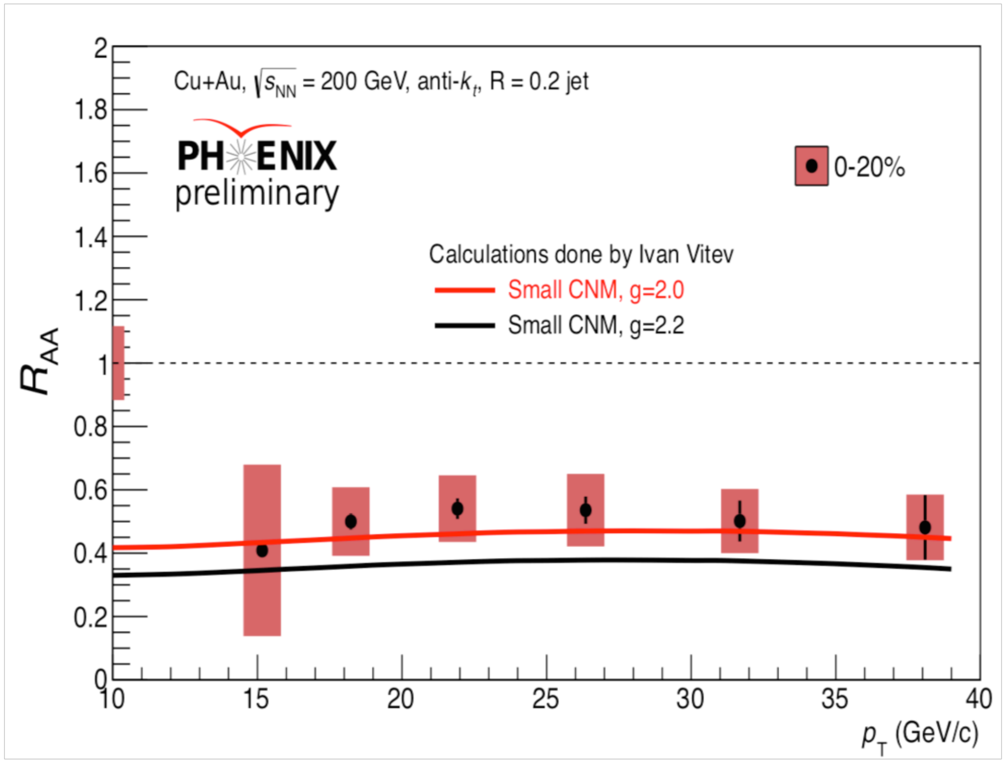
Predictions for HIC beyond E-loss

- Inclusive charged hadron production (and also π⁰) at 5.02 TeV in Pb+Pb



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

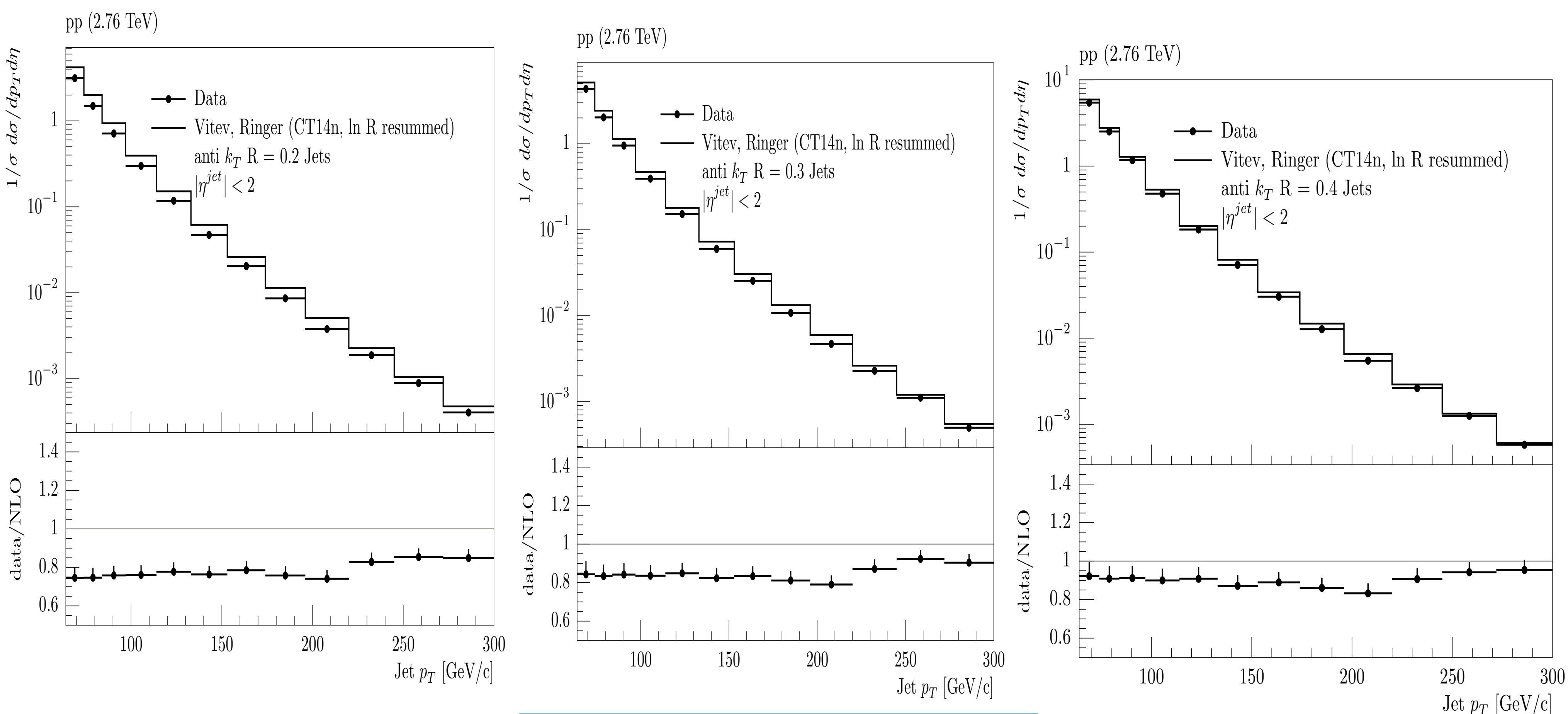
- Jet production in Cu+Au collisions at 200 GeV. Also γ-jet at the LHC



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

Detailed R comparison

- We stop at 5 – 7 GeV. It is still important to investigate collisional energy loss, heavy flavor dissociation, for low p_T



CMS collab. (2016)