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Jet Quenching in $SCET_{(G)}$

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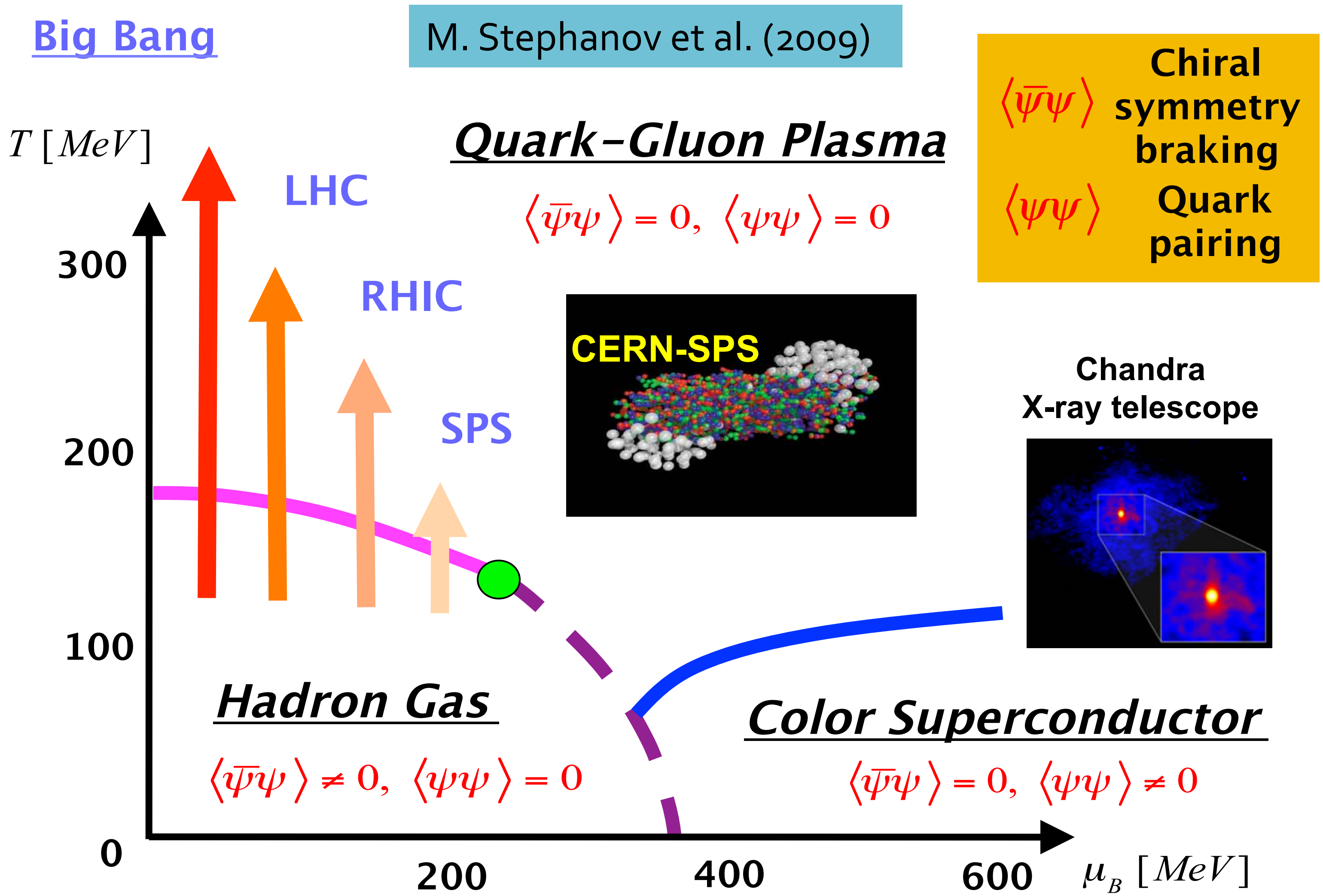
Outline of the talk

- Motivation: an overview of leading particle and jet modification measurements. Energy loss theory in the past decade: successes and challenges
- An effective theory for jet propagation in matter $SCET_{G}$, gauge invariance of jet broadening and energy loss results. Factorization of medium-induced radiative corrections. Medium-induced parton showers
- Connection between the full $SCET_G$ in-medium evolution and the traditional energy loss approach. Insight from higher $O(\alpha_s^2)$ splitting functions. In-medium DGLAP evolution
- Selected $SCET_G$ applications to observables: light hadron cross sections, heavy meson cross sections, jets; jut substructure observables – jet shapes, fragmentation functions and soft dropped distributions

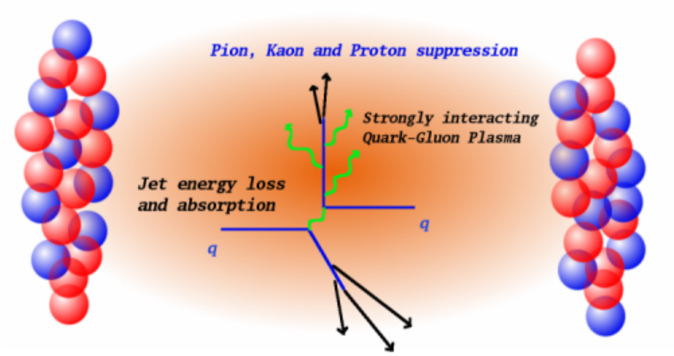
Introduction, motivation

"THESE DAYS EVERYTHING IS HIGHER."

The phase diagram of QCD



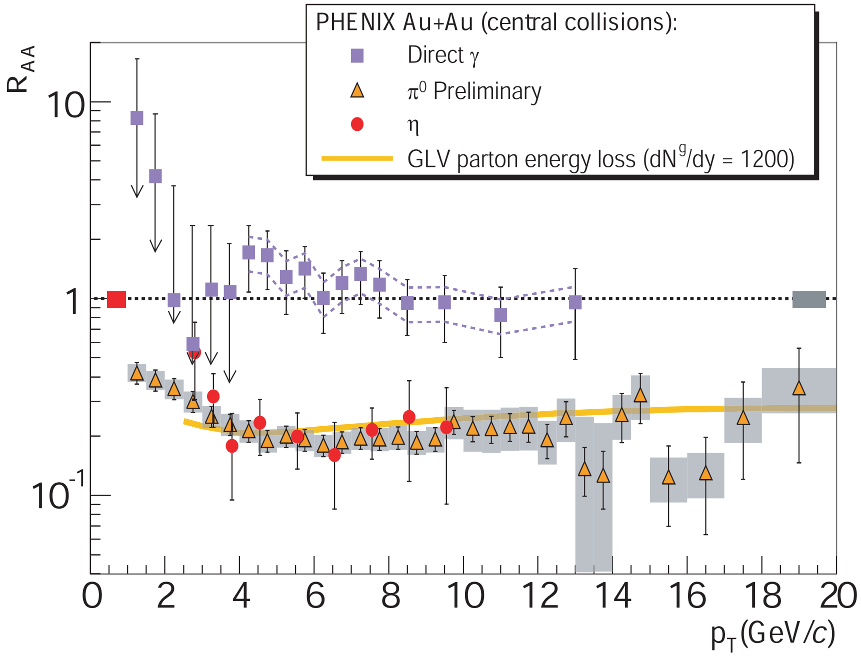
Quenching of leading particles



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

M. Gyulassy, et al. (1992)

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



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

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

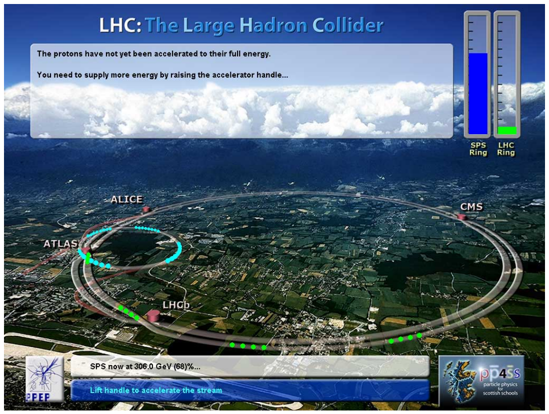
Final-state interaction origin

Also tested at LHC with W/Z boson cross sections

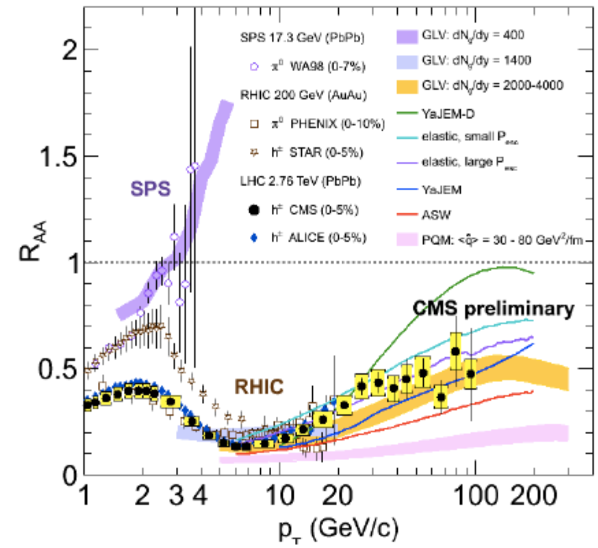
Adler, S. et al (2003)

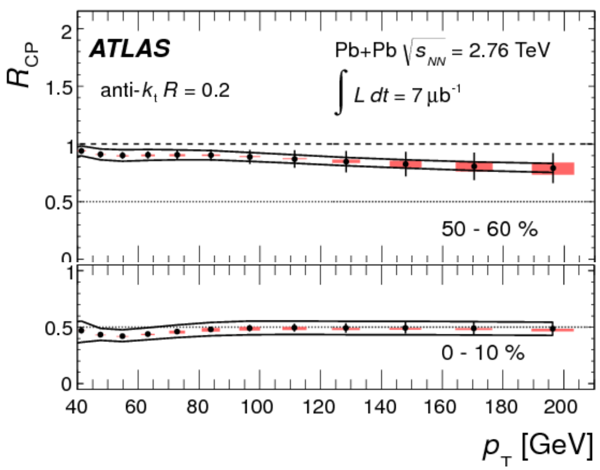
Adams, J. et al. (2003)

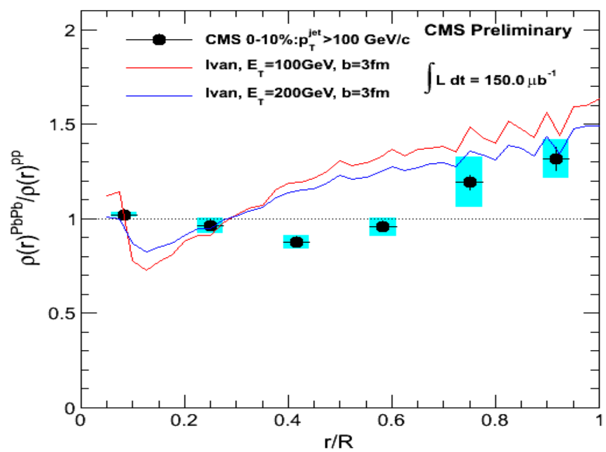
Jets in heavy ion collisions at the LHC

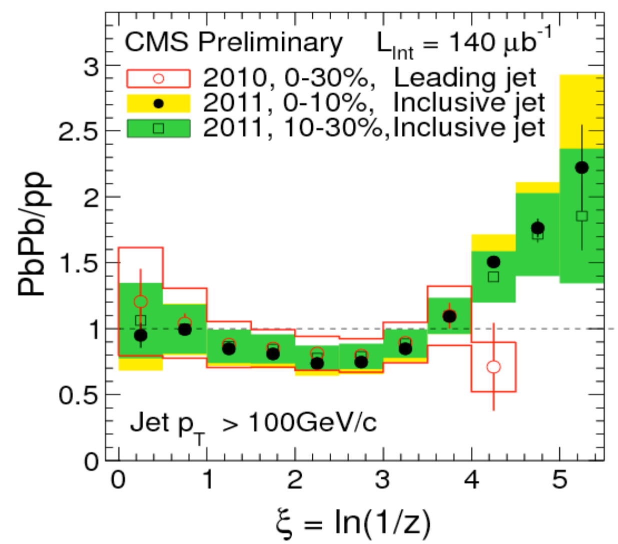


- Jet quenching: to much higher p_T
- Suppression of inclusive jets
- Modified jet substructure



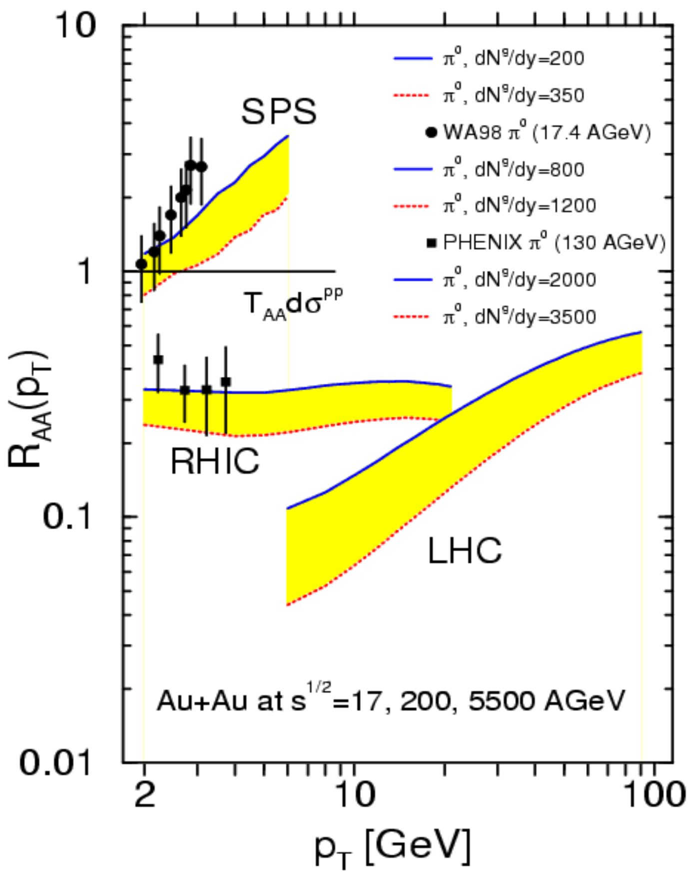






- Advances in jet physics have motivated key detector upgrades at RHIC- sPHENIX. Probe different QGPs, possibly different coupling regimes

Successes and challenges



I.V. et al (2002)

Traditional energy loss approach

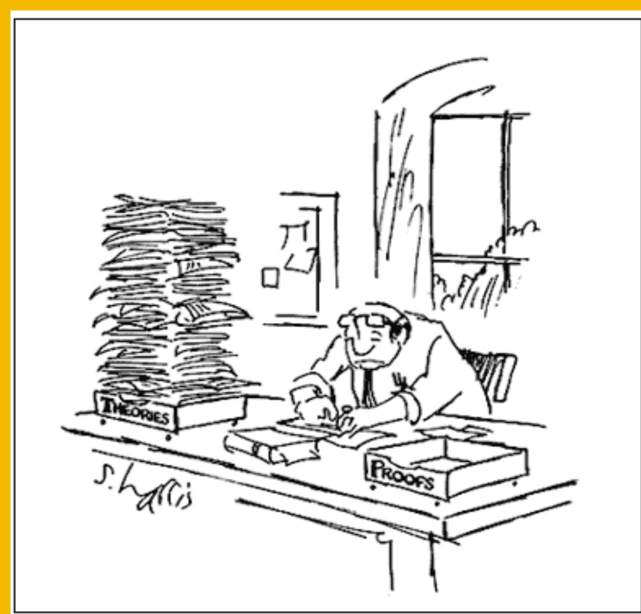
$$I(r) = I_0 e^{-\int_0^r dr'/\lambda_{abs}(r')} = I_0 e^{-\int_0^r dr'\rho(r')\sigma(r')}$$

	τ_0 [fm]	$\tau_{\rm tot}$ [fm]	T_0 [MeV]	ϵ_0 $\left[\frac{\rm GeV}{\rm fm^3}\right]$	$\frac{dN^g}{dy}$
SPS	0.8	1.3 – 2.3	205 – 245	1.2 – 2.6	200 – 350
RHIC	0.6	5.5 – 8	360 – 410	12 – 20	800 – 1200
LHC	0.2	13 – 23	710 – 850	170 – 350	2000 – 3500

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

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

Soft Collinear Effective Theory with Glaubers



Jet quenching in SCET

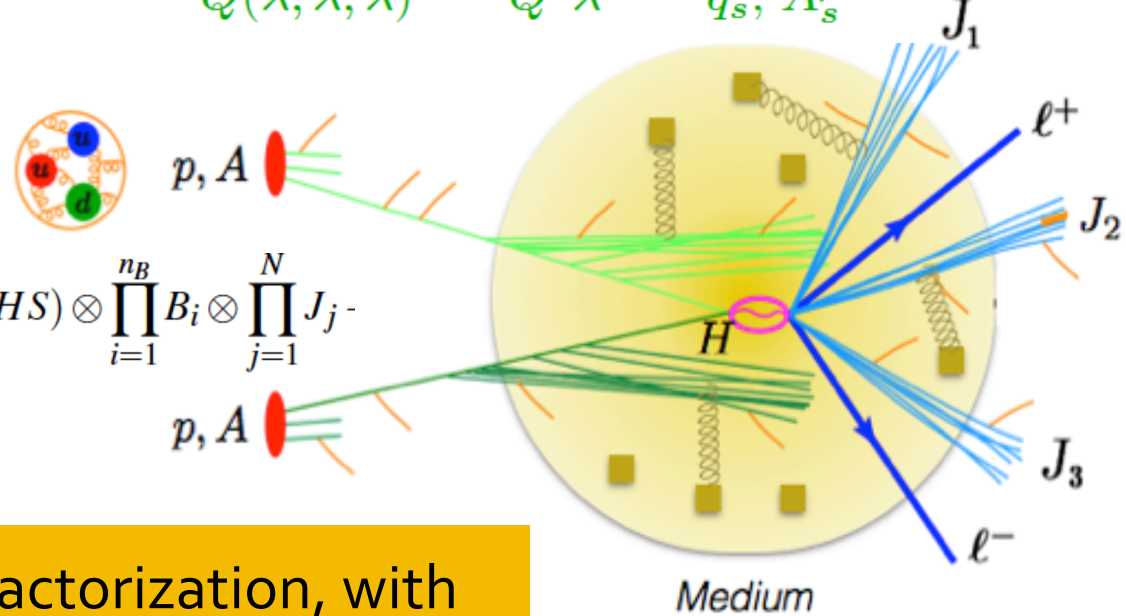
- There is no jet quenching in SCET. Still a multiscale problem, but needs extension

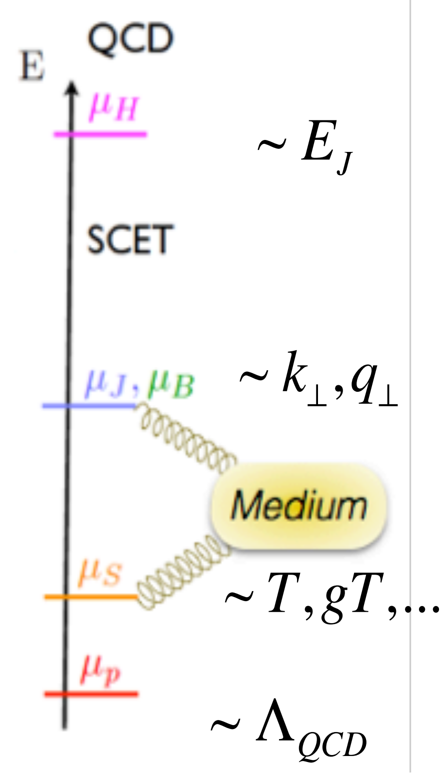
C. Bauer et al. (2001)

D. Pirol et al. (2004)

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

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





- Factorization, with modified J, B, S

S. Fleming et al. (2015)

In more detail: the jet scattering kinematics

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

- Kinematics and channels

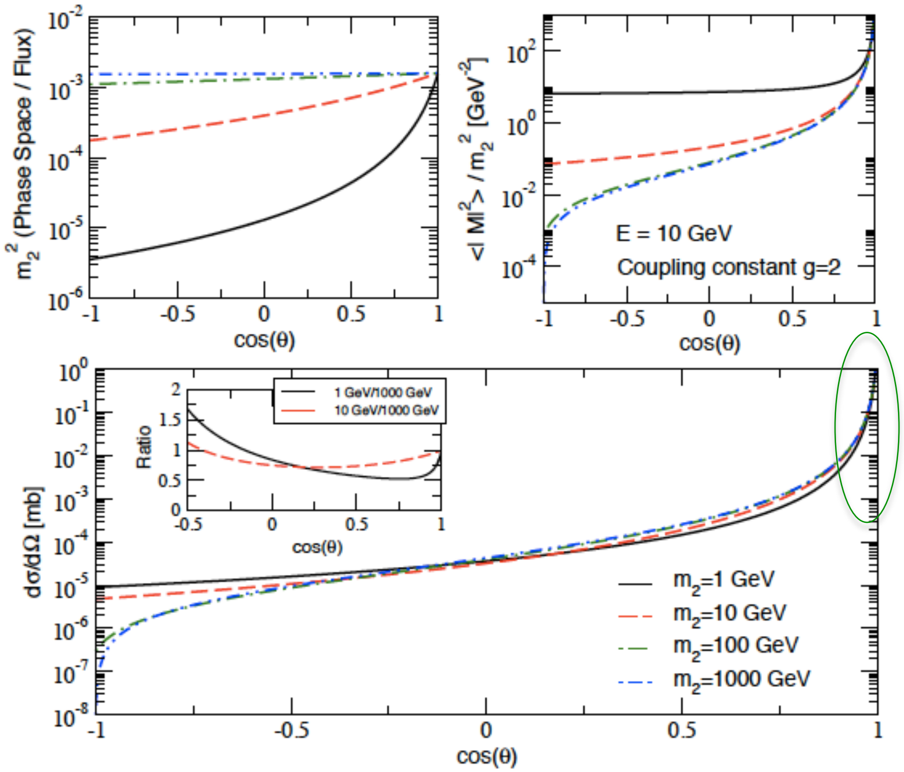
t – jet broadening and energy loss
s– isotropisation
u – backward hard scattering

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

- Operator formulation / factorization violation, BFKL, etc

I. Rothstein et al. (2016)

A. Idilbi et al. (2008)



The Glauber gluon Lagrangian: background field approach

- Glauber gluons (transverse)

$q \sim [\lambda^2, \lambda^2, \boldsymbol{\lambda}]$

A. Idilbi et al. (2008)

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

- Feynman rules for different sources and gauges

G. Ovanesyan et al. (2011)

Gauge	Object	Collinear source	Static source	Soft source
	p	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
	$a_{\boldsymbol{p}}, a^\dagger_{\boldsymbol{p}}$	λ^{-1}	$\lambda^{-3/2}$	$\lambda^{-3/2}$
	$u(p)$	1	1	$\lambda^{1/2}$
	$\bar u(p_2)\gamma_\nu u(p_1)$	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
R_ξ	$A^\mu(x)$	$[\lambda^4, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda^2, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
	Γ_{qqA_G}	Γ_1^μ	Γ_1^μ	Γ_1^μ
	Γ_{ggA_G}	$\Sigma_1^{\mu\nu\lambda}$	$\Sigma_1^{\mu\nu\lambda}$	$\Sigma_1^{\mu\nu\lambda}$
	Γ_s	$\Gamma_1^\mu\ (n \leftrightarrow \bar n)$	Γ_3^μ	Γ_4^μ
$A^+ = 0$	$A^\mu(x)$	$[0, \lambda^2, \boldsymbol{\lambda}^3]$	$[0, \lambda^2, \boldsymbol{\lambda}]$	$[0, \lambda, \mathbf{1}]$
	Γ_{qqA_G}	Γ_1^μ	$\Gamma_1^\mu + \Gamma_2^\mu$	$\Gamma_1^\mu + \Gamma_2^\mu$
	Γ_{ggA_G}	$\Sigma_2^{\mu\nu\lambda}$	$\Sigma_2^{\mu\nu\lambda}$	$\Sigma_2^{\mu\nu\lambda}$
	Γ_s	$\Gamma_2^\mu\ (n \leftrightarrow \bar n)$	Γ_3^μ	Γ_4^μ
$A^- = 0$	$A^\mu(x)$	$[\lambda^2, 0, \boldsymbol{\lambda}]$	$[\lambda^2, 0, \boldsymbol{\lambda}]$	$[\lambda, 0, \mathbf{1}]$
	Γ_{qqA_G}	Γ_2^μ	Γ_2^μ	Γ_2^μ
	Γ_{ggA_G}	$\Sigma_3^{\mu\nu\lambda}$	$\Sigma_3^{\mu\nu\lambda}$	$\Sigma_3^{\mu\nu\lambda}$
	Γ_s	$\Gamma_1^\mu\ (n \leftrightarrow \bar n)$	Γ_3^μ	Γ_4^μ

$$\Gamma_1^{\mu,a} = igT^a n^\mu \frac{\not{\bar n}}{2}\,,$$

$$\Gamma_2^{\mu,a} = igT^a \frac{\gamma_\perp^\mu \not{p}_\perp + \not{p}'_\perp \gamma_\perp^\mu}{\bar n \cdot p} \frac{\not{\bar n}}{2}\,,$$

$$\Gamma_3^{\mu,a} = igT^a v^\mu\,,$$

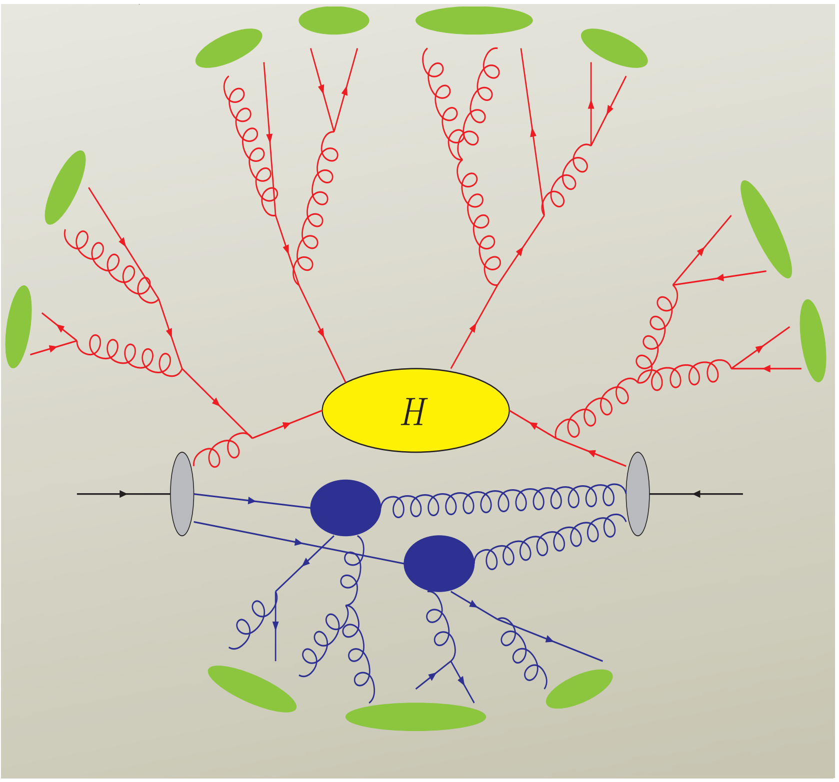
$$\Gamma_4^{\mu,a} = igT^a \gamma^\mu\,,$$

$$\Sigma_1^{\mu\nu\lambda,abc} = gf^{abc} n^\mu \left[g^{\nu\lambda} \bar n\cdot p + \bar n^\nu \left(p'^\lambda_\perp - p^\lambda_\perp\right) - \bar n^\lambda \left(p'^\nu_\perp - p^\nu_\perp\right) - \frac{1-\frac{1}{\xi}}{2} \left(\bar n^\lambda p^\nu + \bar n^\nu p'^\lambda\right) \right],$$

$$\Sigma_2^{\mu\nu\lambda,abc} = gf^{abc} \left[g_\perp^{\mu\lambda} \left(-\frac{n^\nu}{2} p^+ + p^\nu_\perp - 2p'^\nu_\perp \right) + g_\perp^{\mu\nu} \left(-\frac{n^\lambda}{2} p^+ + p'^\lambda_\perp - 2p^\lambda_\perp \right) + g_\perp^{\nu\lambda} \left(n^\mu \bar n \cdot p + p^\mu_\perp + p'^\mu_\perp \right) \right],$$

$$\Sigma_3^{\mu\nu\lambda,abc} = gf^{abc} \left[g_\perp^{\mu\lambda} \left(\frac{\bar n^\nu}{2}(p^- - 2p'^-) + p^\nu_\perp - 2p'^\nu_\perp \right) + g_\perp^{\mu\nu} \left(\frac{\bar n^\lambda}{2}(p'^- - 2p^-) + p'^\lambda_\perp - 2p^\lambda_\perp \right) + g_\perp^{\nu\lambda} \left(p^\mu_\perp + p'^\mu_\perp \right) \right].$$

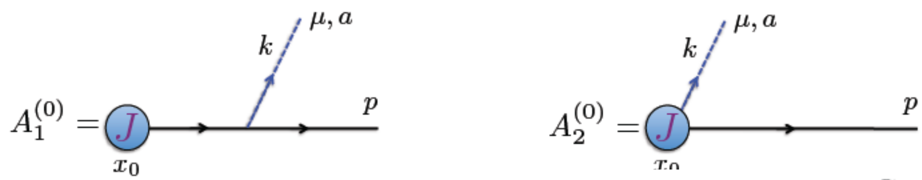
The splitting kernels



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

W. Waalewjin. (2014)

$$
\begin{aligned}
A_{q\to qg} &= \langle J|\, T\, \bar{\chi}_n(x_0)\, \mathrm{e}^{iS}\, |q(\boldsymbol{p})g(\boldsymbol{k})\rangle\,, \\
A_{g\to q\bar{q}} &= \langle J|\, T\, \mathcal{B}^{\lambda c}(x_0)\, \mathrm{e}^{iS}\, |q(\boldsymbol{p})\bar{q}(\boldsymbol{k})\rangle \\
A_{g\to gg} &= \langle J|\, T\, \mathcal{B}^{\lambda c}(x_0)\, \mathrm{e}^{iS}\, |g(\boldsymbol{p})g(\boldsymbol{k})\rangle
\end{aligned}
$$



$$\Gamma_W^{\alpha,a}(k) = g T_r^a \frac{\bar{n}^\alpha}{k^+ + i\epsilon}$$

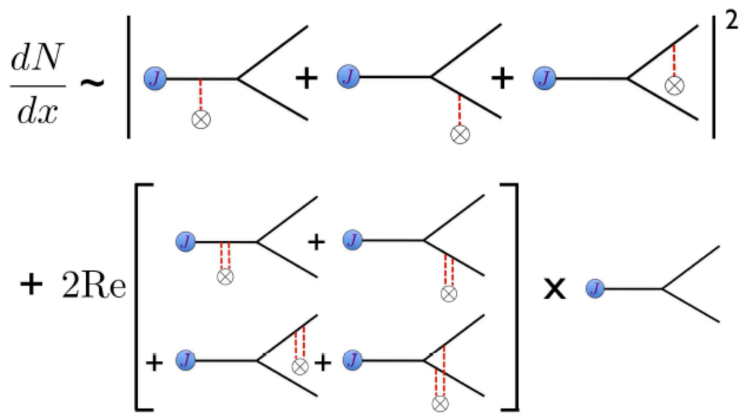
Gribov et al. (1972)

G. Altarelli et al. (1977)

Y. Dokshitzer (1977)

- In the vacuum we have the DGLAP splitting kernels that factorize from the hard scattering cross section and are process independent

Main results: in-medium splitting / parton energy loss



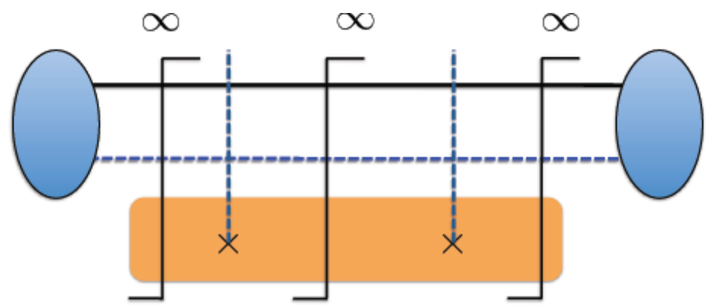
Diagrams that need to be evaluated to first order in opacity

We have two sectors of the theory – different gauges

- Note that a collinear Wilson line appears in the R_ξ gauge

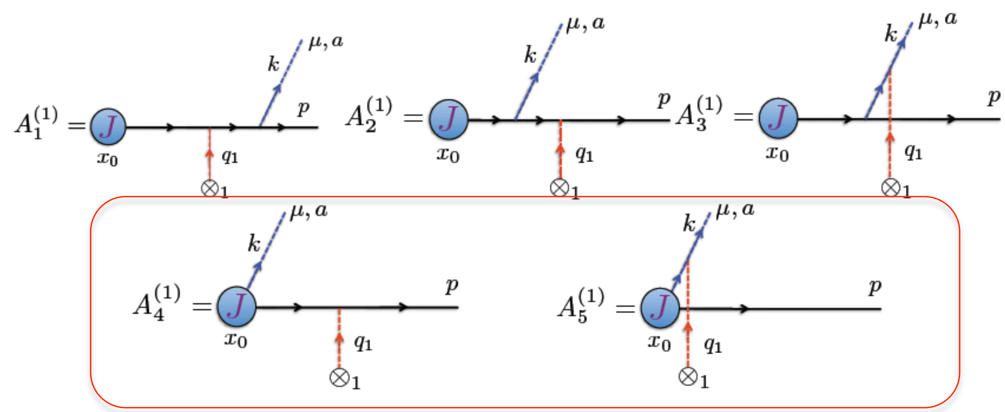
$$\Gamma_W^{\alpha,a}(k) = gT_r^a \frac{\bar{n}^\alpha}{k^+ + i\epsilon}$$

M. Gyulassy et al. (2001)



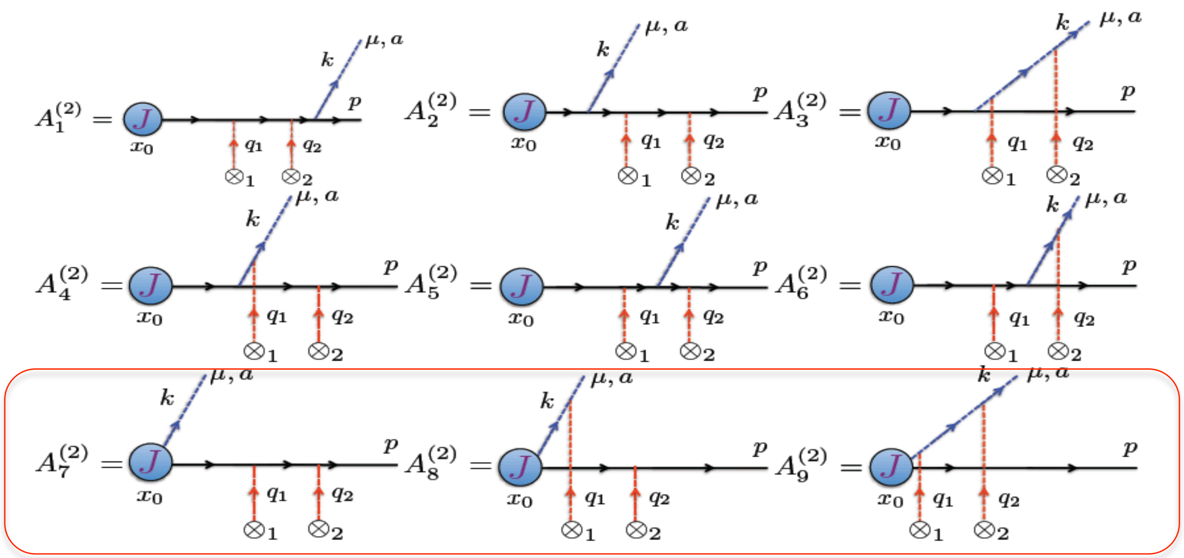
Classes of diagrams (single Born, double Born). Reaction Operator

Single Born diagrams



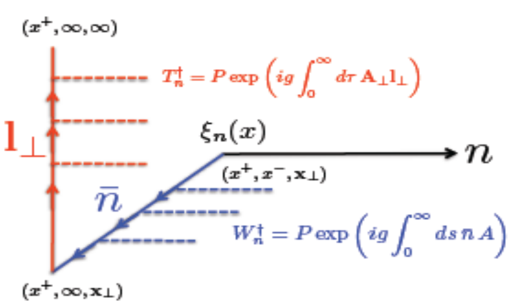
Main results: in-medium splitting / parton energy loss

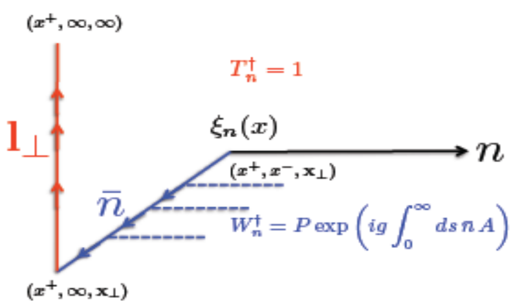
Double Born diagrams

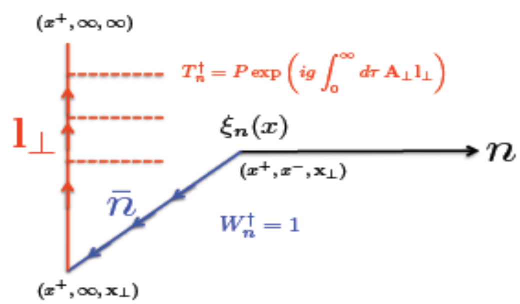


G. Ovanesyan et al. (2011)

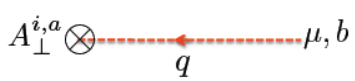
- The lightcone gauge







- New Feynman rule



$$= \; i\,\delta^{ab}\,\frac{\bar{n}^\mu q^i}{q^2 + i\varepsilon} C_\infty^{(\mathrm{Pres})} \left(\frac{1}{q^+ + i\varepsilon} - \frac{1}{q^+ - i\varepsilon}\right)$$

A. Idilbi et al. (2010)

In-medium parton splitting and gauge independence

	R_ξ	A^+	Hyb.
W^+	✔	✖	✖
T_n	✖	✔	✖

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

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

- Proof of gauge invariance

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

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

G. Ovanesyan et al. , 2011

The soft gluon energy loss imit

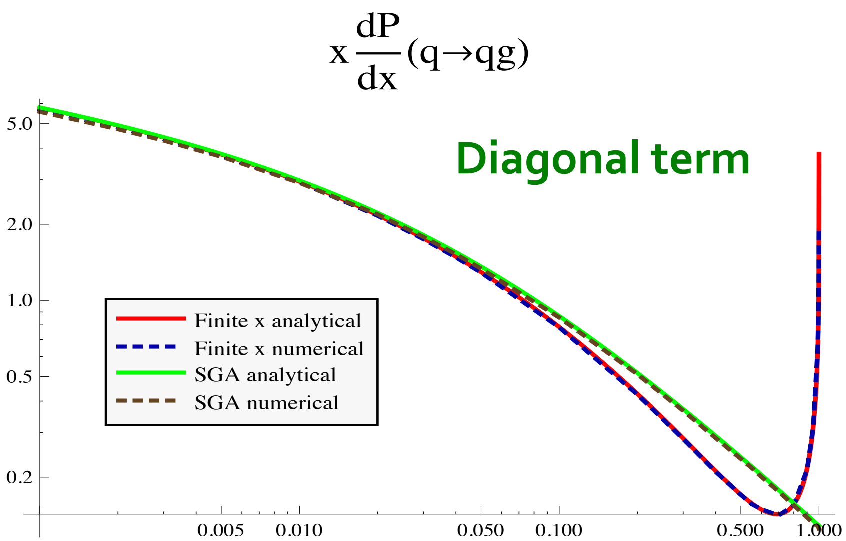
- In the soft limit we recover the GLV results
- Only in this limit there is a natural energy loss interpretation (a leading parton loses energy)

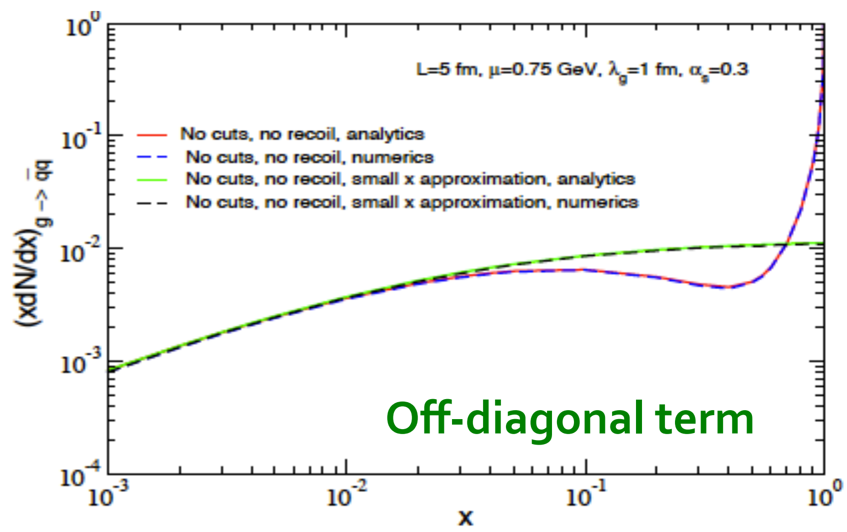
$$x\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{\left\{\begin{array}{c} q\to qg \\ g\to gg \\ q\to gq \\ g\to q\bar{q}\end{array}\right\}} = \frac{\alpha_s}{\pi^2}\left\{\begin{array}{c} C_F[1+\mathcal{O}(x)] \\ C_A[1+\mathcal{O}(x)] \\ C_F[0+\frac{x}{2}+\mathcal{O}(x^2)] \\ T_R[0+\frac{x}{2}+\mathcal{O}(x^2)]\end{array}\right\}$$

$$\times\int d\Delta z\left\{\begin{array}{c} \frac{1}{\lambda_g(z)} \\ \frac{1}{\lambda_g(z)} \\ \frac{1}{\lambda_q(z)} \\ \frac{1}{\lambda_q(z)}\end{array}\right\}\int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm medium}}{d^2\mathbf{q}_\perp}$$

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

But beyond this limit, new way of thinking is required, parton showers, cascades, evolution





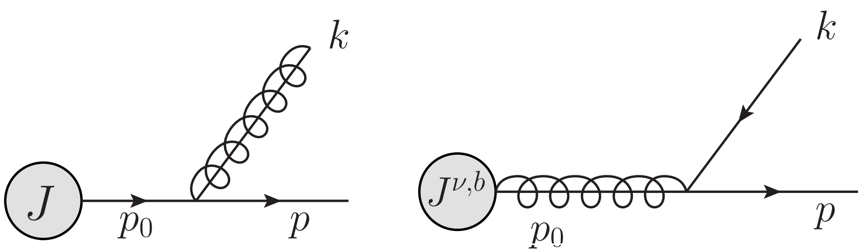
Heavy quarks in the vacuum

3 splitting functions (g to gg is the same)

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

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

The process is not written Q to gQ but it should have been since x goes to 1-x



F. Ringer et al . (2016)

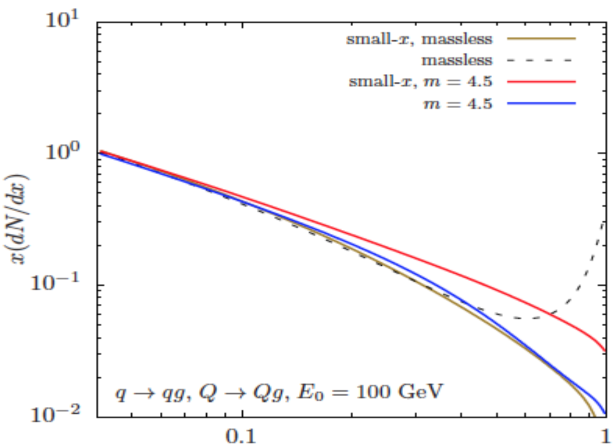
- You see the dead cone effects

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

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

Heavy quarks in the medium



Kinematic variables

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

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

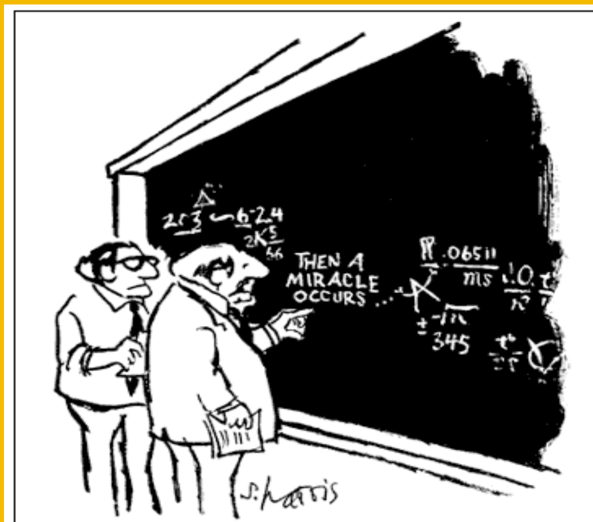
$$\begin{aligned} \nu &= m && (g \to Q\bar{Q}), \\ \nu &= x\, m && (Q \to Qg), \\ \nu &= (1-x)\, m && (Q \to gQ), \end{aligned}$$

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

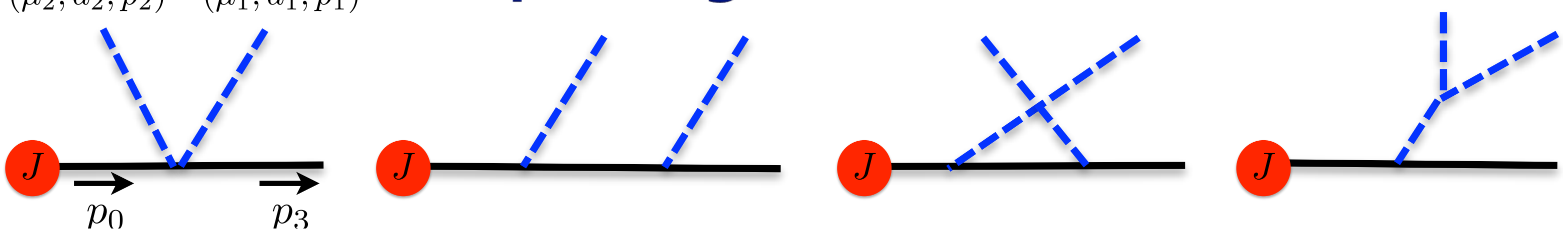
Higher order corrections and application of cascades



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

o(α_s^2) splitting functions in the vacuum

Splitting $q \to ggq$



$z_i=E_i/(E_1+E_2+E_3)$ $s_{ij}=(p_i+p_j)^2$

$$\langle \hat{P}_{g_1 g_2 q_3} \rangle = C_F^2 \langle \hat{P}^{(\mathrm{ab})}_{g_1 g_2 q_3} \rangle + C_F C_A \langle \hat{P}^{(\mathrm{nab})}_{g_1 g_2 q_3} \rangle$$

$$\langle P_{g_1 g_2 q_3} \rangle (z_1 \ll z_2, z_3)$$

$$z_1 = 0.03 \ll z_2, z_3$$

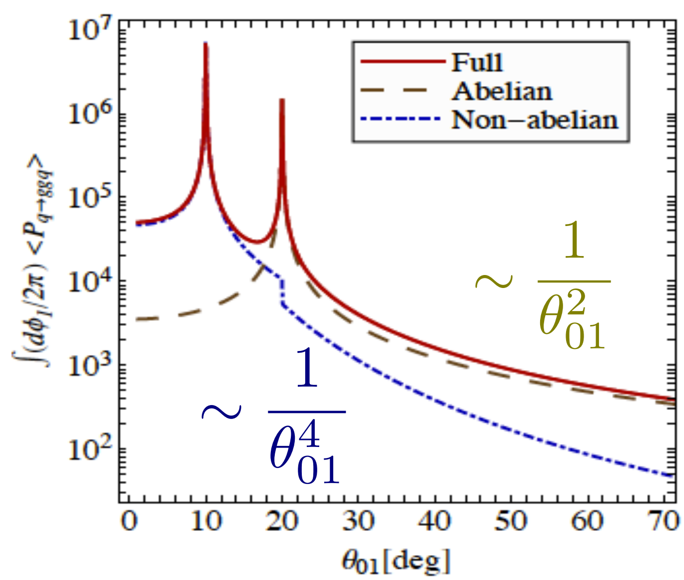
- We use the Feynman rules of SCET, reproduce Catani-Grazzini's result exactly. Only the collinear sector enters

$$q \to \bar{q}' q' q, q \to \bar{q} q q, q \to g g q, \; g \to g q \bar{q}, g \to g g g$$

There is always a regular / Abelian contribution.

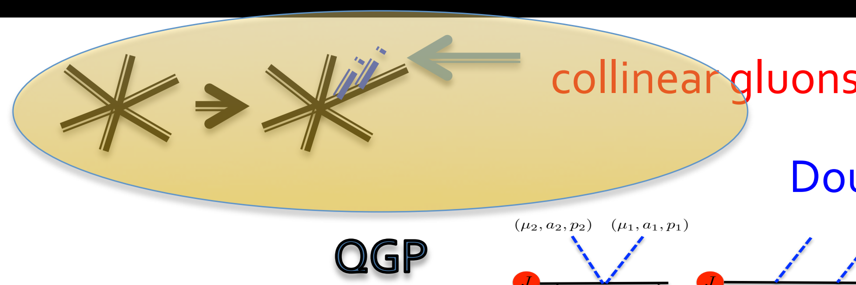
Neither of the 5 branchings is strictly angular ordered

Splitting function q→ggq

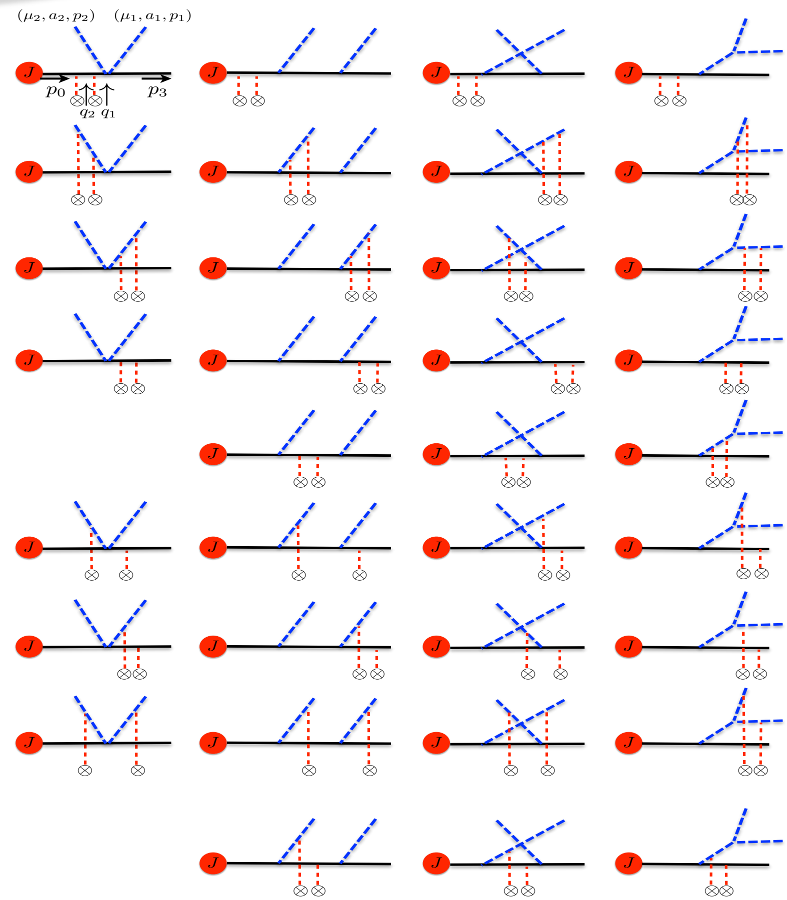


Feynman graphs for q->qgg in dense QCD matter

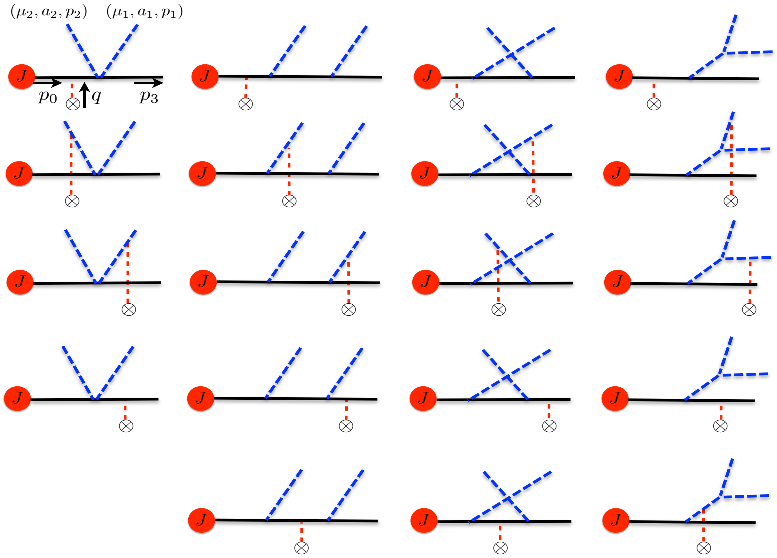
- SCET with Glauber gluons, hybrid gauge



Double Born (34)



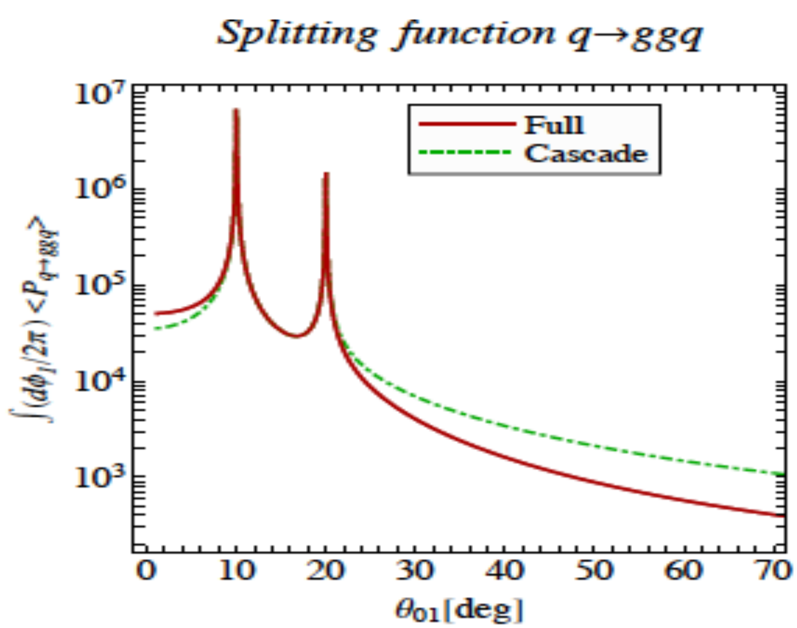
Single Born (19)

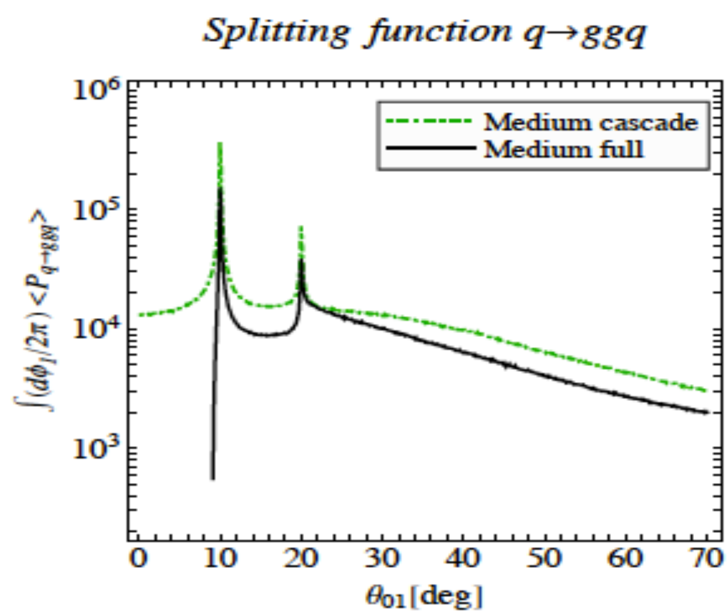


- We checked every Feynman diagram by comparing analytical calculation with FeynCalc

Numerical results

- The medium splitting function is much broader than the vacuum one. It falls off less steeply in parts of the tail region
- Vacuum, medium cascade works reasonably well in the tail region in shape. Norm is off by a factor of 2. Along the original direction it does not get the LPM cancellation
- In summing multiple emissions in the medium we make qualitatively the same approximations as in vacuum





Evolution of the fragmentation functions

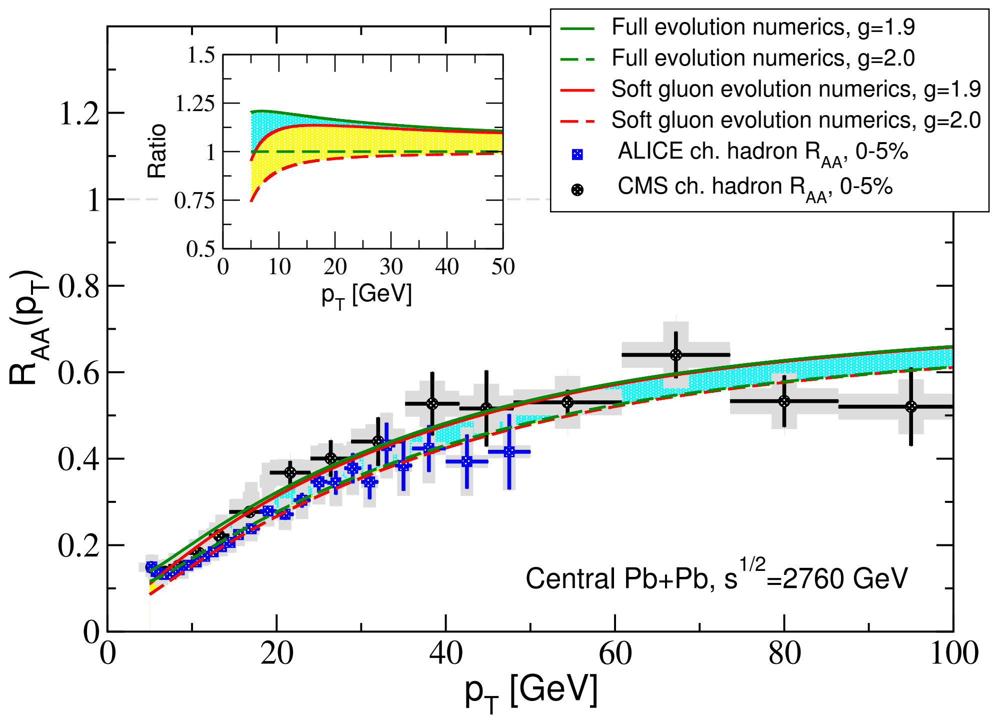
- Yield LLA or MLLA

Z. Kang et al. (2014)

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

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

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



In the medium: effective thermal masses, finite α_s

Implement medium –induced splittings as corrections to vacuum evolution

Demonstrated connection to E-loss

Vacuum evolution in the soft gluon limit

$$P_{q\to qg} = \frac{2C_F}{x_+} + \left(\frac{2C_F}{x}\, g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to gg} = \frac{2C_A}{x_+} + \left(\frac{2C_A}{x}\, g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to q\bar{q}} = 0,$$

$$P_{q\to gq} = 0,$$

- If a connection is to be found between the energy loss and the evolution approach, it is in the soft gluon limit

$$\frac{\mathrm{d}D_{h/c}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left[P_{c\to cg}(z',Q)\right]_+ D_{h/c}(z/z',Q).$$

$$\frac{\mathrm{d}D_{h/c}(z,Q)}{\mathrm{d}\ln Q} = 2C_R\frac{\alpha_s}{\pi}\left\{\int_z^1 \mathrm{d}z'\,\frac{1}{1-z'}\left[\frac{1}{z'}\,D_{h/c}(z/z',Q) - D_{h/c}(z,Q)\right] + D_{h/c}(z,Q)\,\ln(1-z)\right\}$$

$$\left(1 + z\frac{\partial}{\partial z}\right) D_{h/c}(z,Q) \approx [1-n(z)]\,D_{h/c}(z,Q)$$

- Using the "+" function, expanding around z' = 1 and relating derivatives to local slope we obtain the evolution to LLA

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

Medium-modified evolution of the fragmentation functions

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

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

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

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

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

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

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

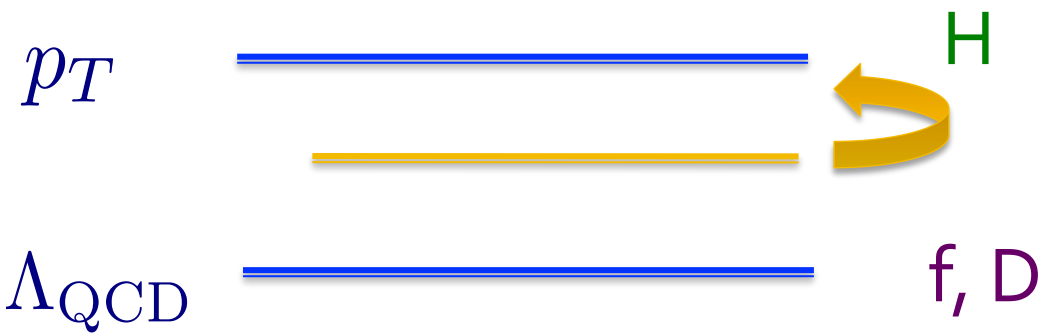
$$\langle\tilde{N^g}\rangle_z = \int_{1-z}^{1}\mathrm{d}z'\int_{Q_0}^{Q}dQ'\frac{dN}{dz'dQ'}(z',Q') = \int_{1-z}^{1}\mathrm{d}z'\frac{dN}{dz'}(z') \qquad \to_{z\to 1}\langle N^g\rangle\,.$$

G. Ovanesyan et al. (2014)

Application of the evolution / resummation appraoch

- The goal is to evaluate the nuclear modification and the related cross sections

$$R_{AA}(p_T) = \frac{H(\mu, p_T) \otimes f(\mu) \otimes f(\mu) \otimes D^{\mathrm{med}}(\mu)}{H(\mu, p_T) \otimes f(\mu) \otimes f(\mu) \otimes D(\mu)}$$



The simplest choice is:

$\mu = p_T$

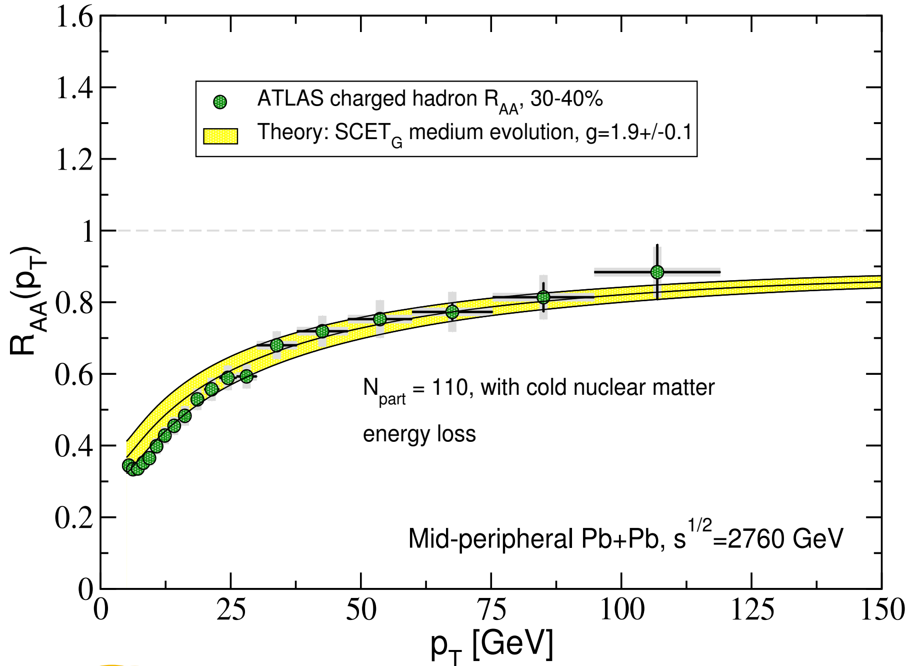
- Again the soft gluon approximation, but the evolution approach

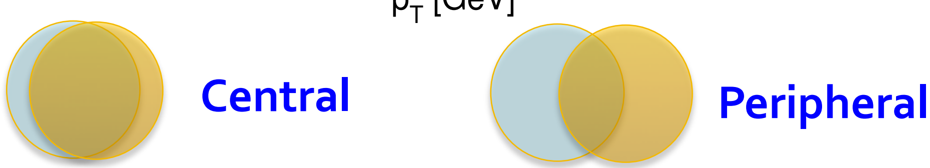
Selected phenomenological applications

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

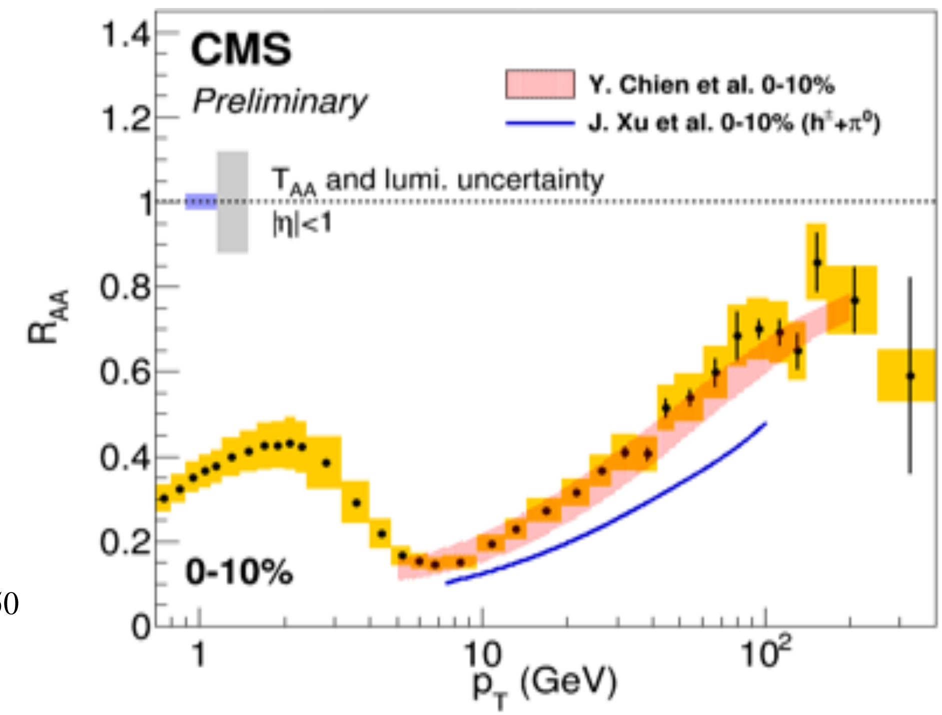
Predictions for HIC beyond E-loss

- Different centralities, CM energies (QGP properties)





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



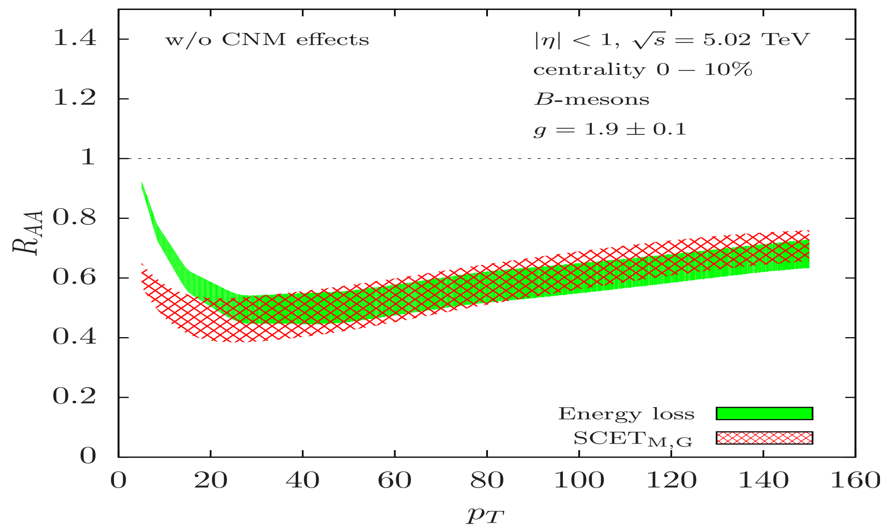
Y.-T. Chien et al. (2015)

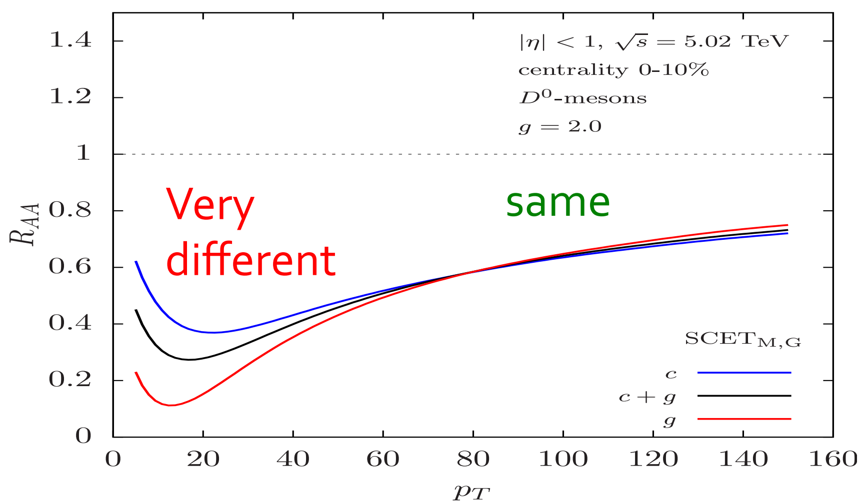
Suppression of heavy flavor

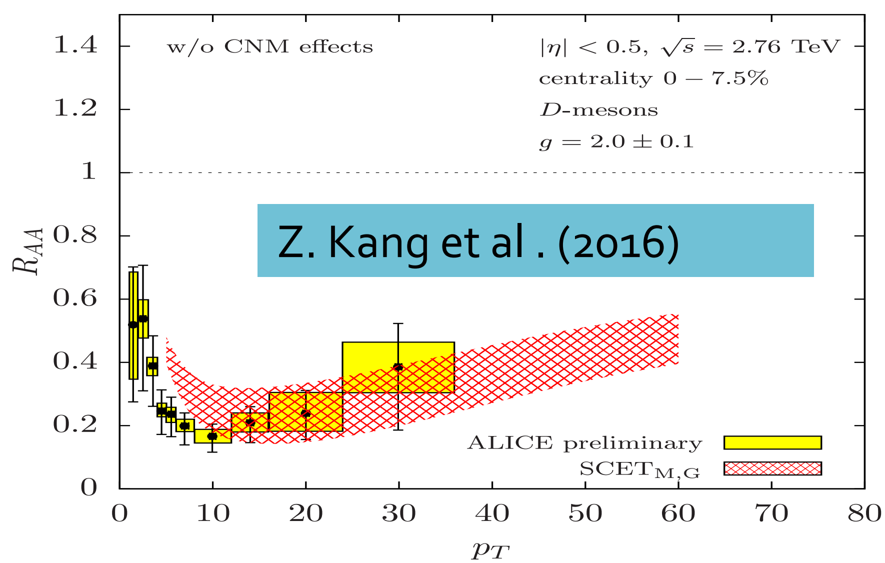
- Heavy flavor still posed many unresolved questions

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





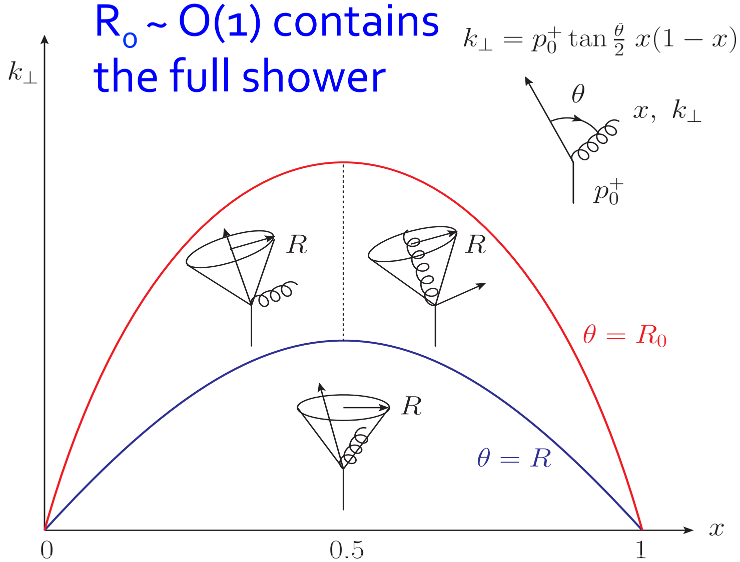


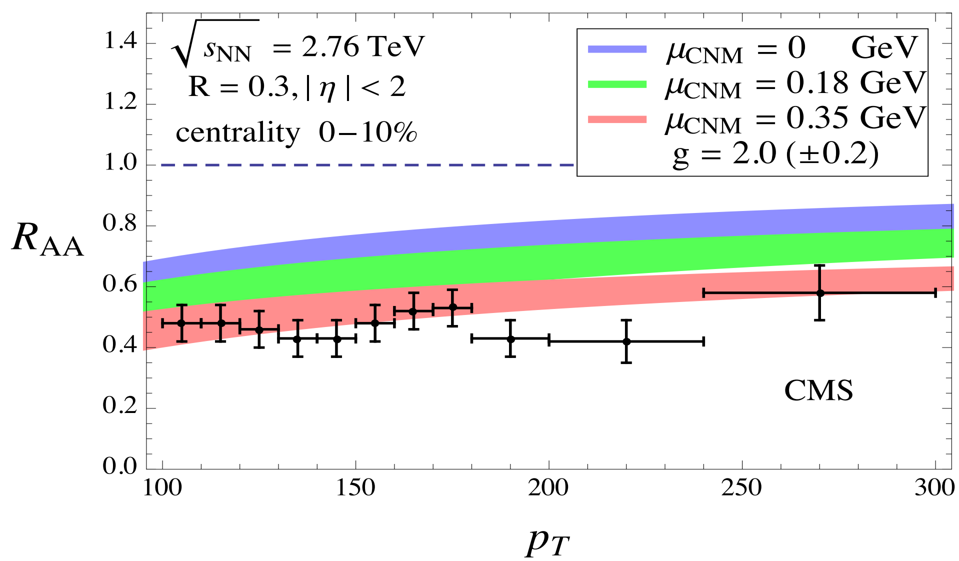
Generalizing the concept of energy loss to jets

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

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

R_0 ~ O(1) contains the full shower



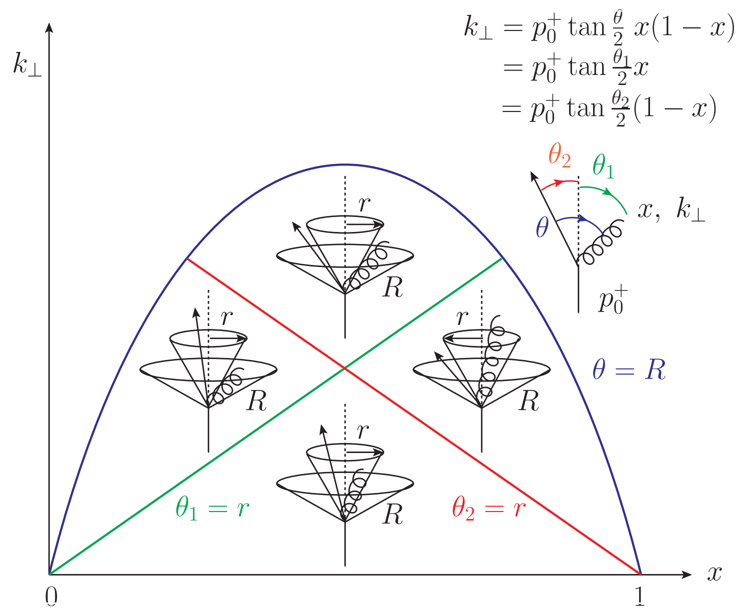


$$\epsilon_q = \frac{2}{\omega}\Big[\int_0^{\frac{1}{2}} dx k^0 + \int_{\frac{1}{2}}^1 dx(p^0 - k^0)\Big] \int_{\omega x(1-x)\tan\frac{R}{2}}^{\omega x(1-x)\tan\frac{R_0}{2}} dk_\perp \frac{1}{2}\Big[\mathcal{P}^{med}_{q\to qg}(x,k_\perp) + \mathcal{P}^{med}_{q\to gq}(x,k_\perp)\Big]$$

$$\epsilon_g = \frac{2}{\omega}\Big[\int_0^{\frac{1}{2}} dx k^0 + \int_{\frac{1}{2}}^1 dx(p^0 - k^0)\Big] \int_{\omega x(1-x)\tan\frac{R}{2} x(1-x)}^{\omega x(1-x)\tan\frac{R_0}{2}} dk_\perp \frac{1}{2}\Big[\mathcal{P}^{med}_{g\to gg}(x,k_\perp) + \sum_{q,\bar{q}} \mathcal{P}^{med}_{g\to q\bar{q}}(x,k_\perp)\Big]$$

Fractional energy loss outside of the jet beyond the soft gluon approximation

Medium-modified jet shapes at NLL



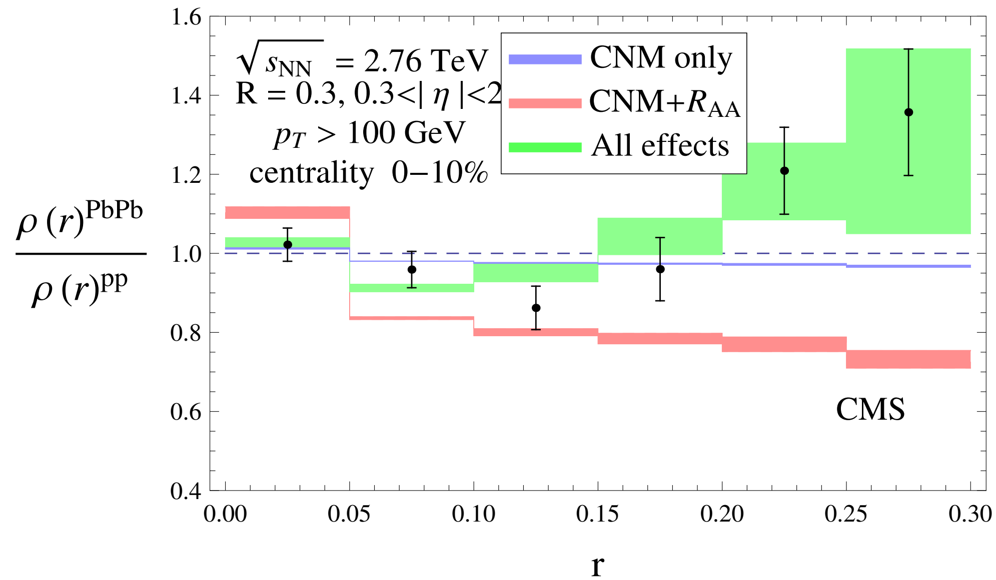
$$E_r(x, k_\perp) = \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3 + \mathcal{M}_4$$

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

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

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

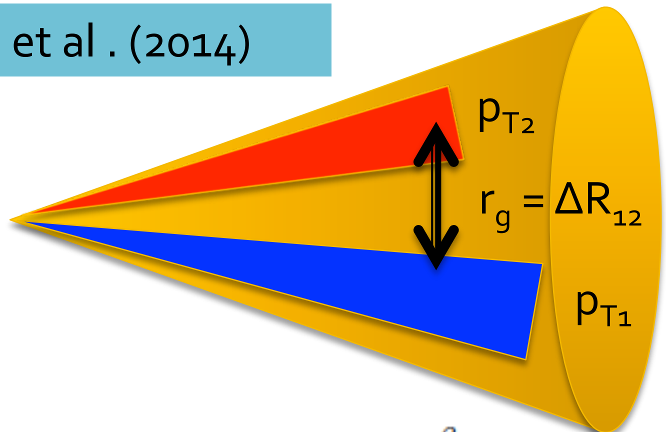


- First quantitative pQCD/SCET description of jet shapes in HI

Groomed soft dropped distributions in $SCET_G$

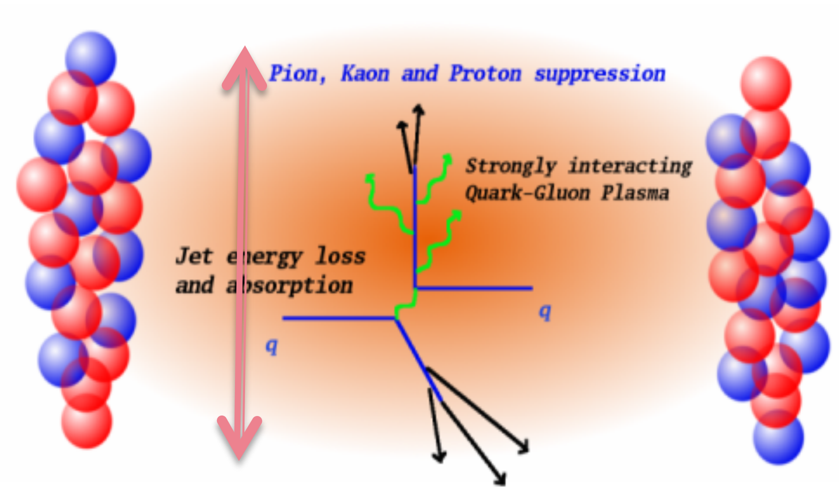
- Groomed jet distribution using "soft drop"

A. Larkoski et al . (2014)



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

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



QGP size ~ 10fm

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

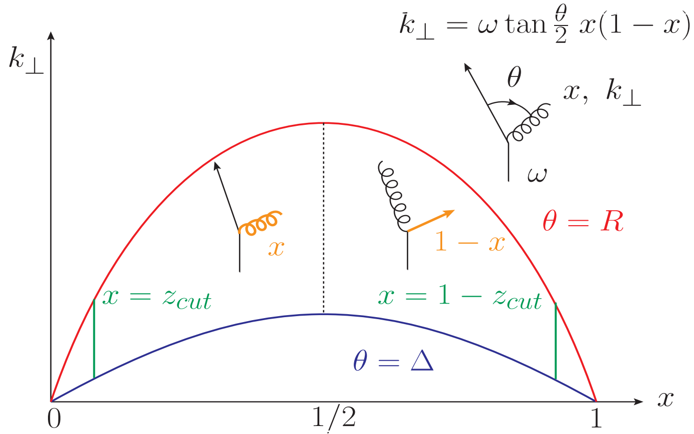
Typical situation: E=200 GeV, r_g = 0.1

Branching time < 2 fm for z_g studied

Y. T. Chien et al . (2016)

Accessing the hardest branching in HIC – longitudinal modification

Calculating the soft dropped distribution with β=0

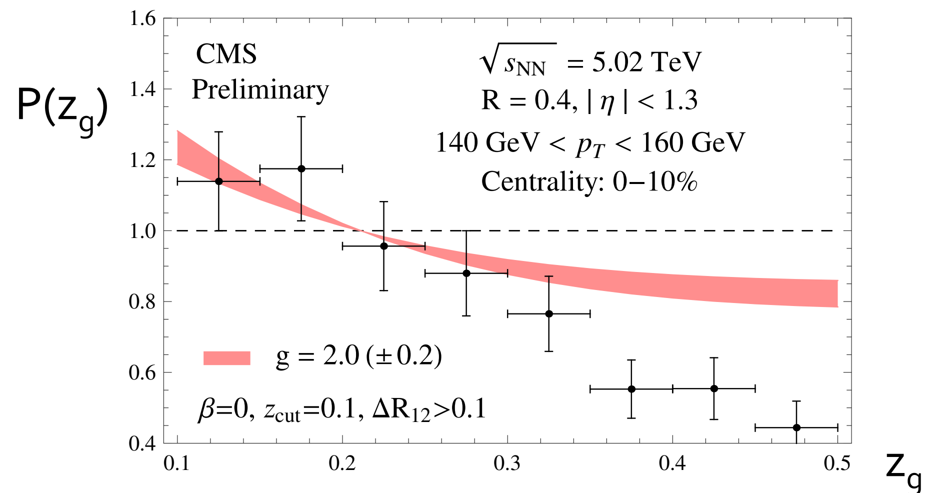


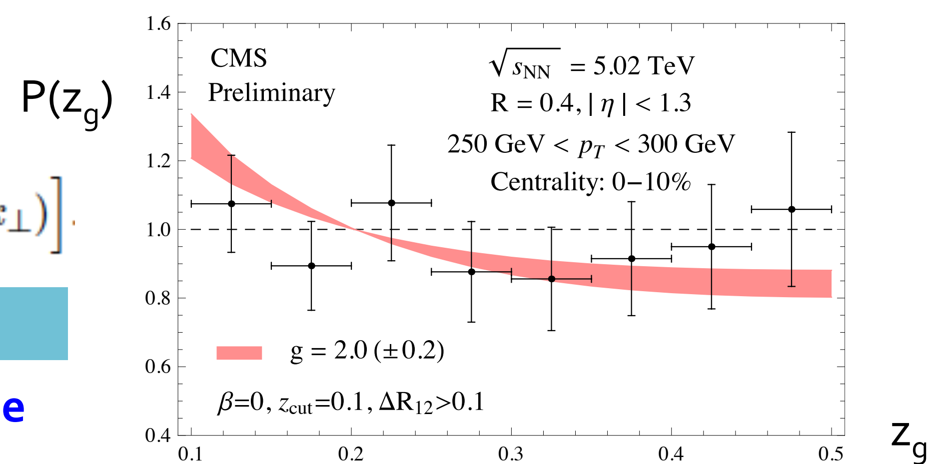
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

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

Y.T. Chien et al . (2016)

Generalized to angular distribution of the hard splitting





2017
Jets and heavy flavor workshop

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

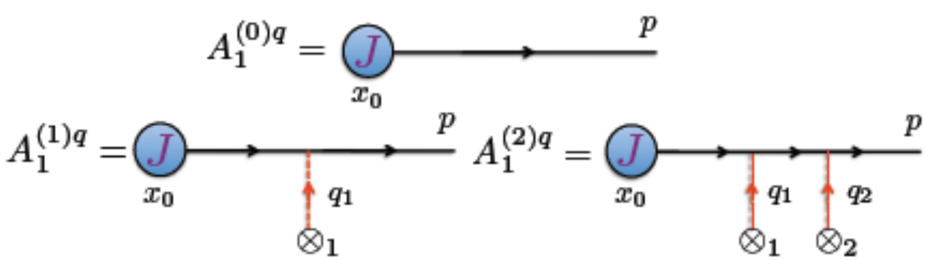
Conclusions

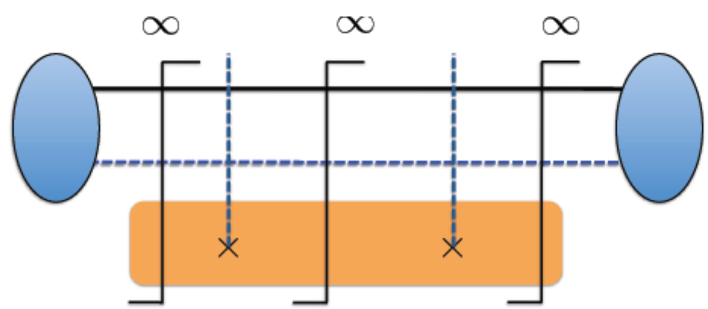
- New theoretical developments are needed to address the physics of jets in heavy ion collisions
- Developed an effective theory of jet propagation in matter with complete set of Feynman rules in different sources and gauges. Gauge invariance of the jet broadening and energy loss results. Showed factorization of the medium-induced radiative corrections for the hard scattering, results beyond the soft gluon approximation. Recent results for initial-state and massive splitting kernels
- Phenomenological application range form light and heavy flavor suppression to jets and jet substructure in heavy ion collisions. Mpre reliable predictions and first successful description of jet substructure observables in a perturbative approach
- Future: couple the soft and Glauber sector in the background field approach. Evaluate and incorporate collisional energy losses. Look at improved phenomenology that combines ln(R) resummation with medium-induced showers. B-jets, …

Main results: jet broadening

- Jet broadening and its gauge invariance

M. Gyulassy et al. (2001)





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

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

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

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

Starting with a collinear beam of quarks/gluons

we recover M. Gyulassy et al. (2002)

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

Splitting kernel results

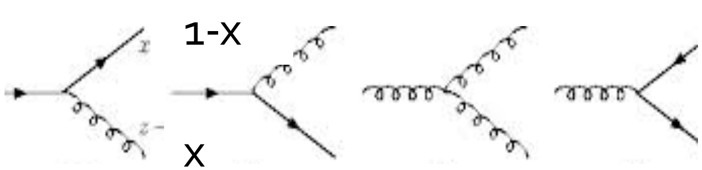
- Explicitly verified the gauge invariance and factorization in QCD

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

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

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

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



Reversed convention

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

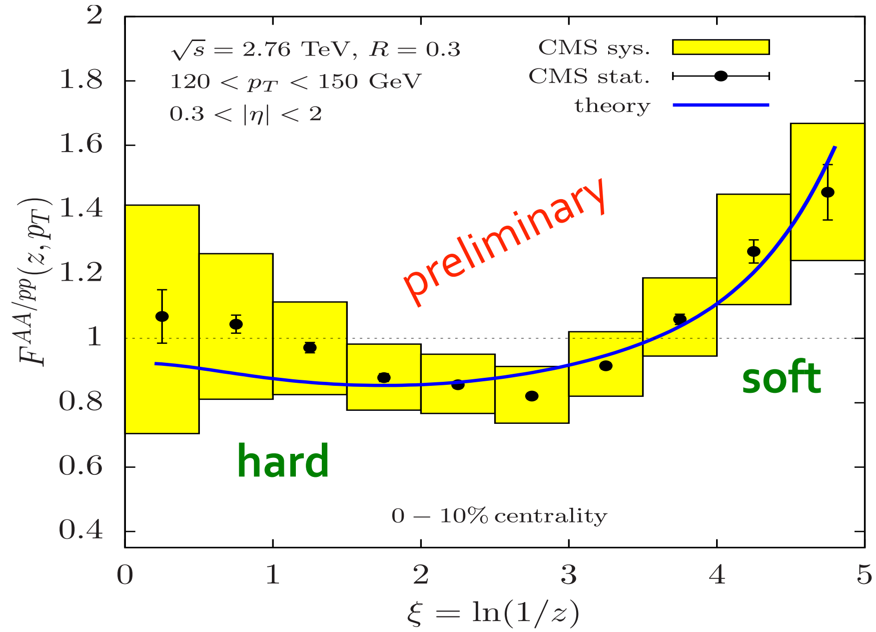
$$\int_0^1 P_{qq}(x)\, \mathrm{d}x = 0,$$

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

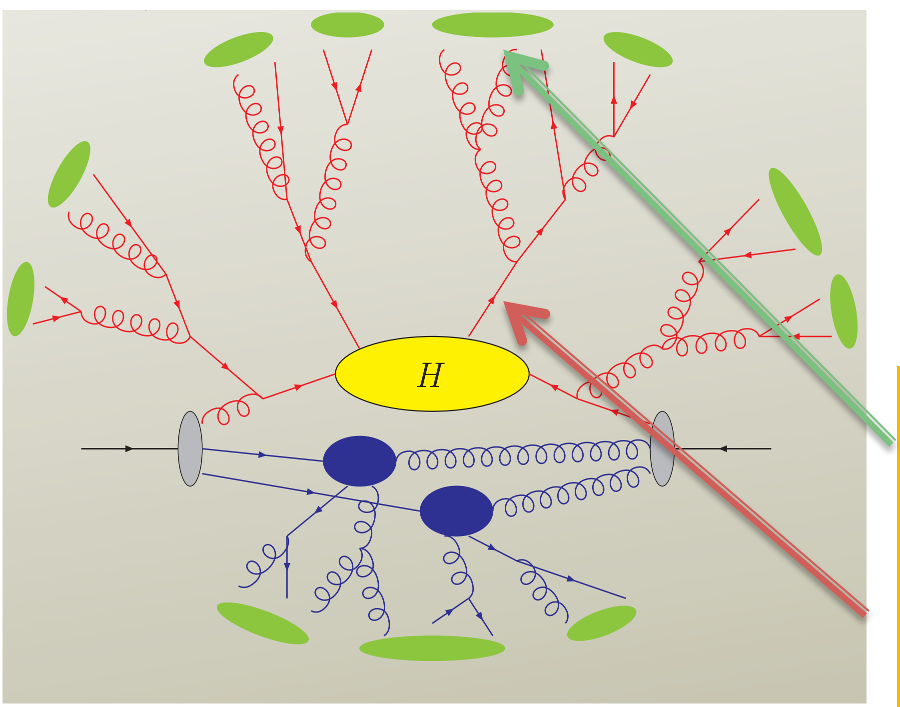
$$\int_0^1 \left[2n_f P_{qg}(x) + P_{gg}(x)\right](1-x)\, \mathrm{d}x = 0.$$

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 ?

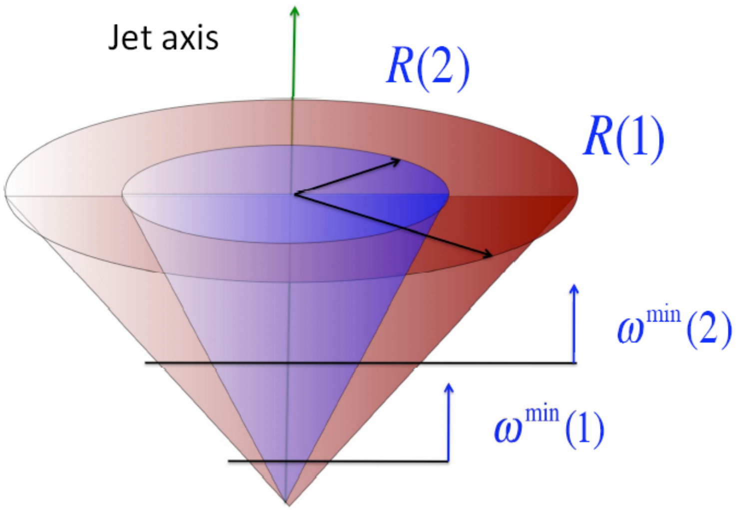
Or is it manifest in the hard early time splittings?

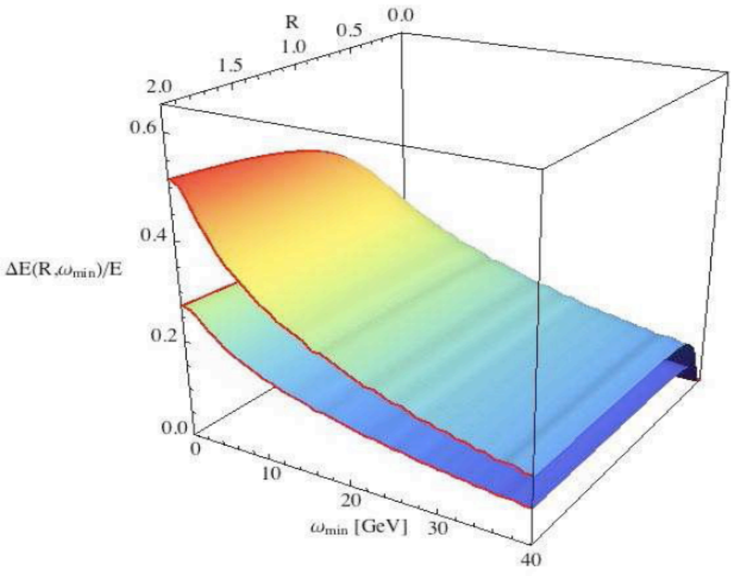
Bremsstrahlung distributions

$$\frac{\Delta E^{in}}{E}(R^{\max},\omega^{\min}) = \frac{1}{E}\int_{\omega^{\min}}^{E} d\omega \int_0^{R^{\max}} dr \frac{dI^g}{d\omega dr}(\omega,r)$$

- The medium induced energy loss can be evaluated for any phase space for the jet particles
- The same has to be true for bremsstrahlung from hard scattering

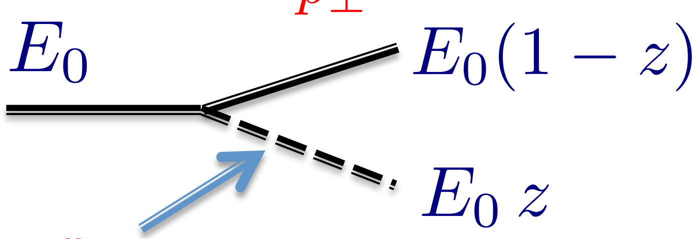
- For a 100 GeV parton at the LHC





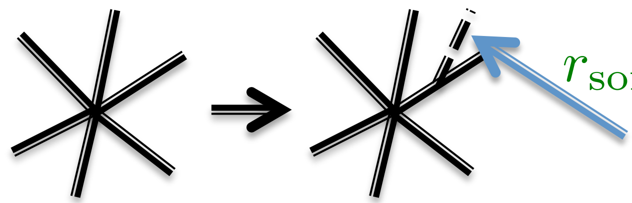
Altarelli-Parisi splitting functions versus corehent branching

$$r_{\text{shower}} \sim \frac{1}{p_\perp}$$



$$|\mathcal{M}_{a_1,a_2,\ldots}(p_1,p_2,\ldots)|^2 \simeq \frac{2}{s_{12}}\, 4\pi\mu^{2\epsilon}\alpha_{\rm S}\, \mathcal{T}^{ss'}_{a,\ldots}(p,\ldots)\, \hat{P}^{ss'}_{a_1a_2}(z,k_\perp;\epsilon)$$

- Comes at the scale of collinear radiation inside the parton shower
- Factorize and are process independent



$$d\sigma_{n+1} = d\sigma_n \frac{d\omega}{\omega}\frac{d\Omega}{2\pi}\frac{\alpha_S}{2\pi}\sum_{i,j} C_{ij}\, W_{ij}$$

W_{ij} is the antenna function that leads to angular ordering

$$W_{ij} = \frac{\omega^2\, p_i\cdot p_j}{p_i\cdot q\, p_j\cdot q} = \frac{1-\cos\theta_{ij}}{(1-\cos\theta_{iq})(1-\cos\theta_{jq})}$$

- Comes from the physics at the soft scale
- At soft (long distance) scales the emissions are angular ordered

Coherence branching effects incorporated into splitting functions,

HERWIG - a Monte Carlo generator for parton showers