Energy loss and heavy flavor jet production

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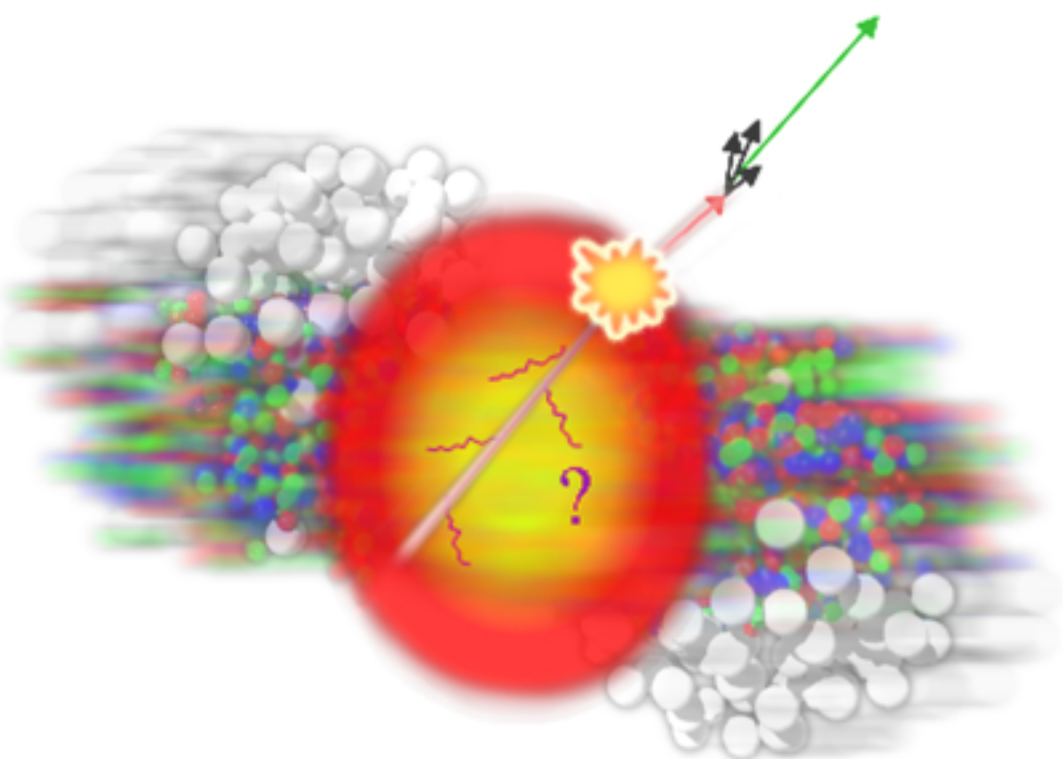
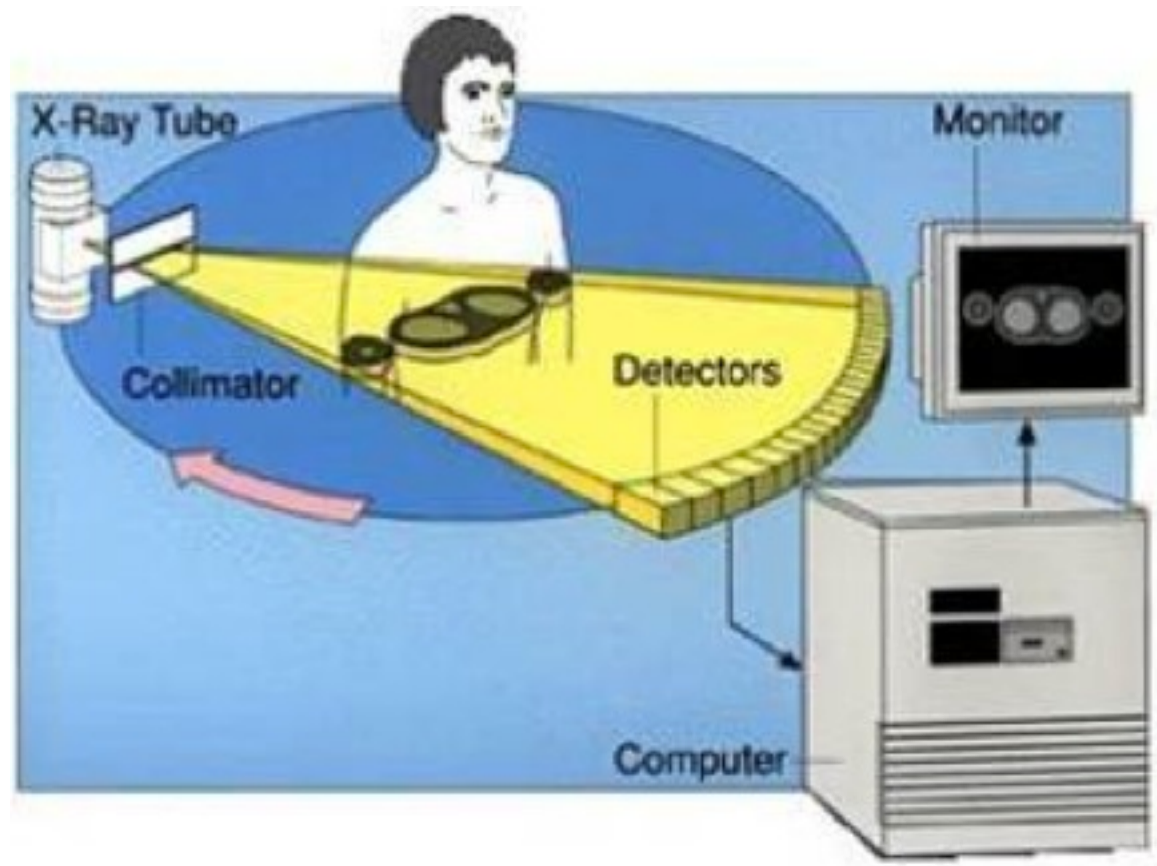
Probe of quark gluon plasma

- Jet quenching has been proposed as an excellent probe of the hot dense matter (quark gluon plasma) created in heavy ion collisions (RHIC and LHC)

See Thorsten's talk

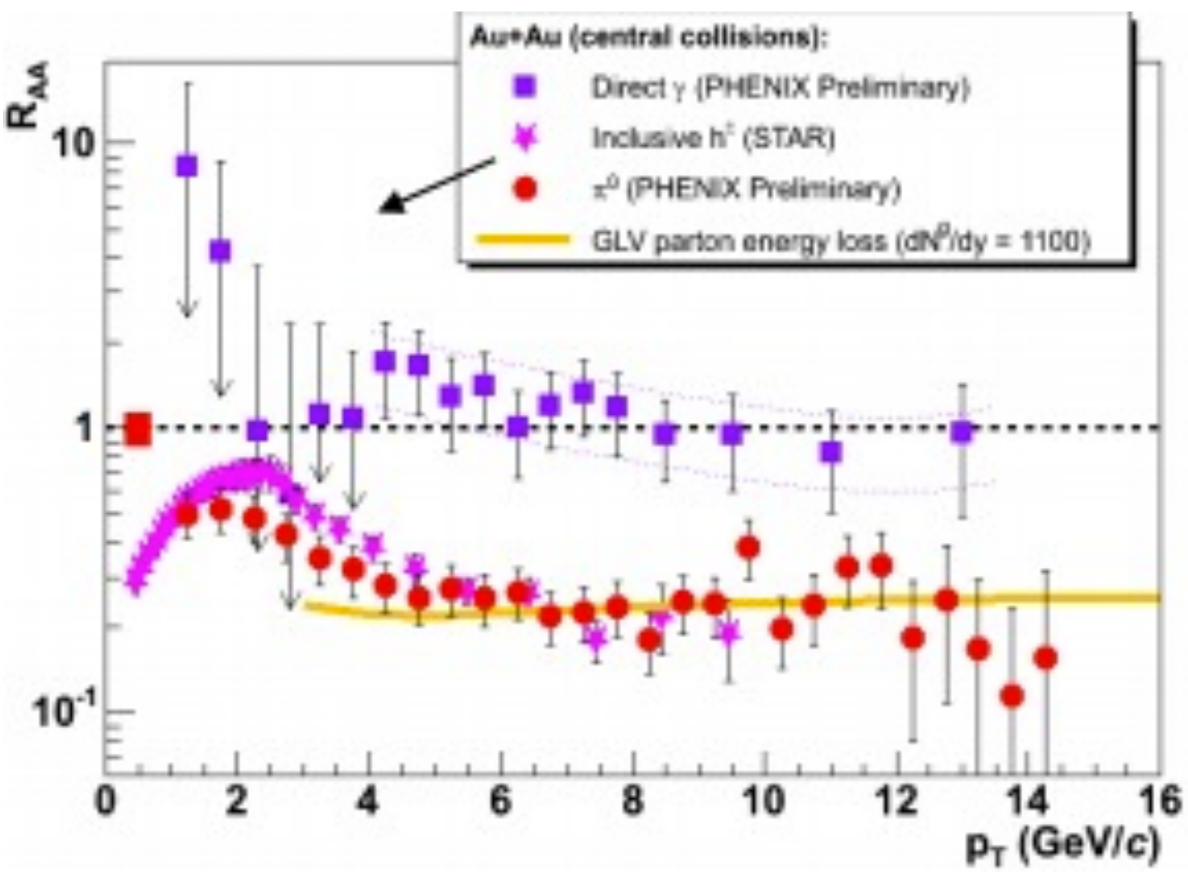


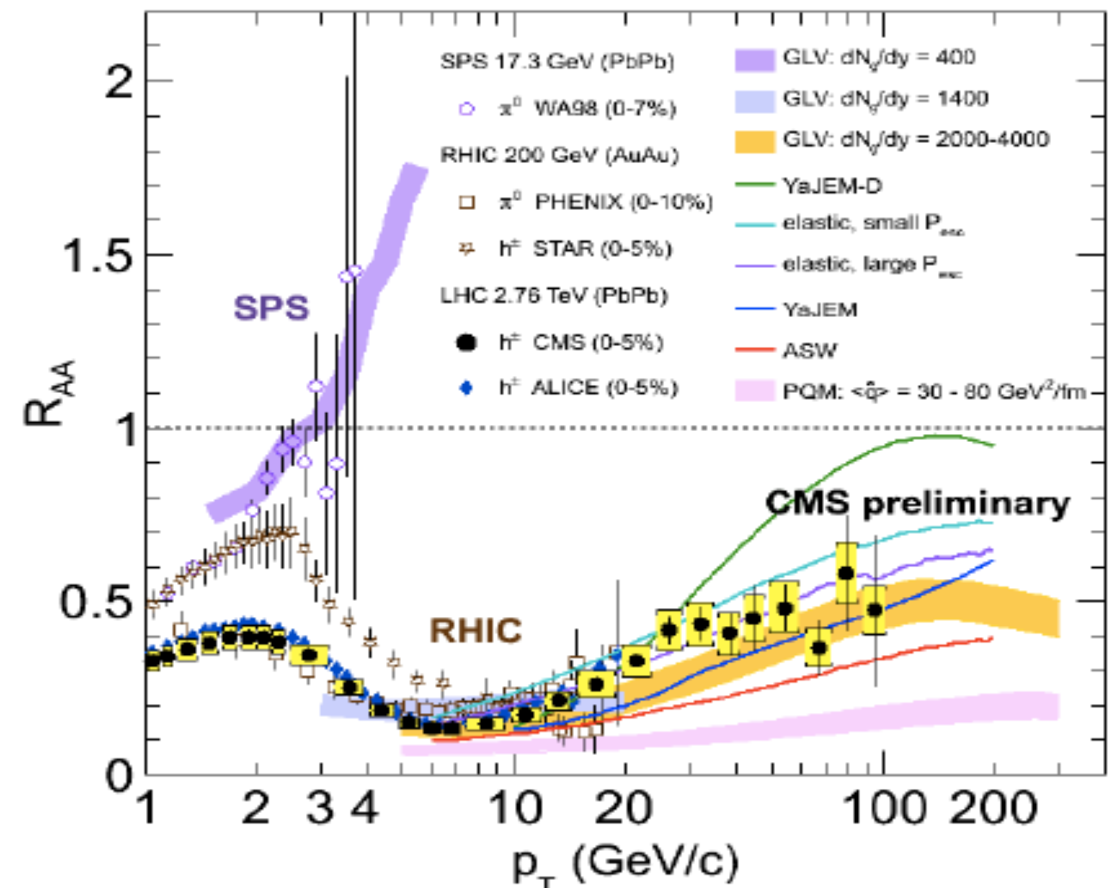


Phenomenology very successful

- Jet quenching for hadron production in both RHIC and LHC

$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$





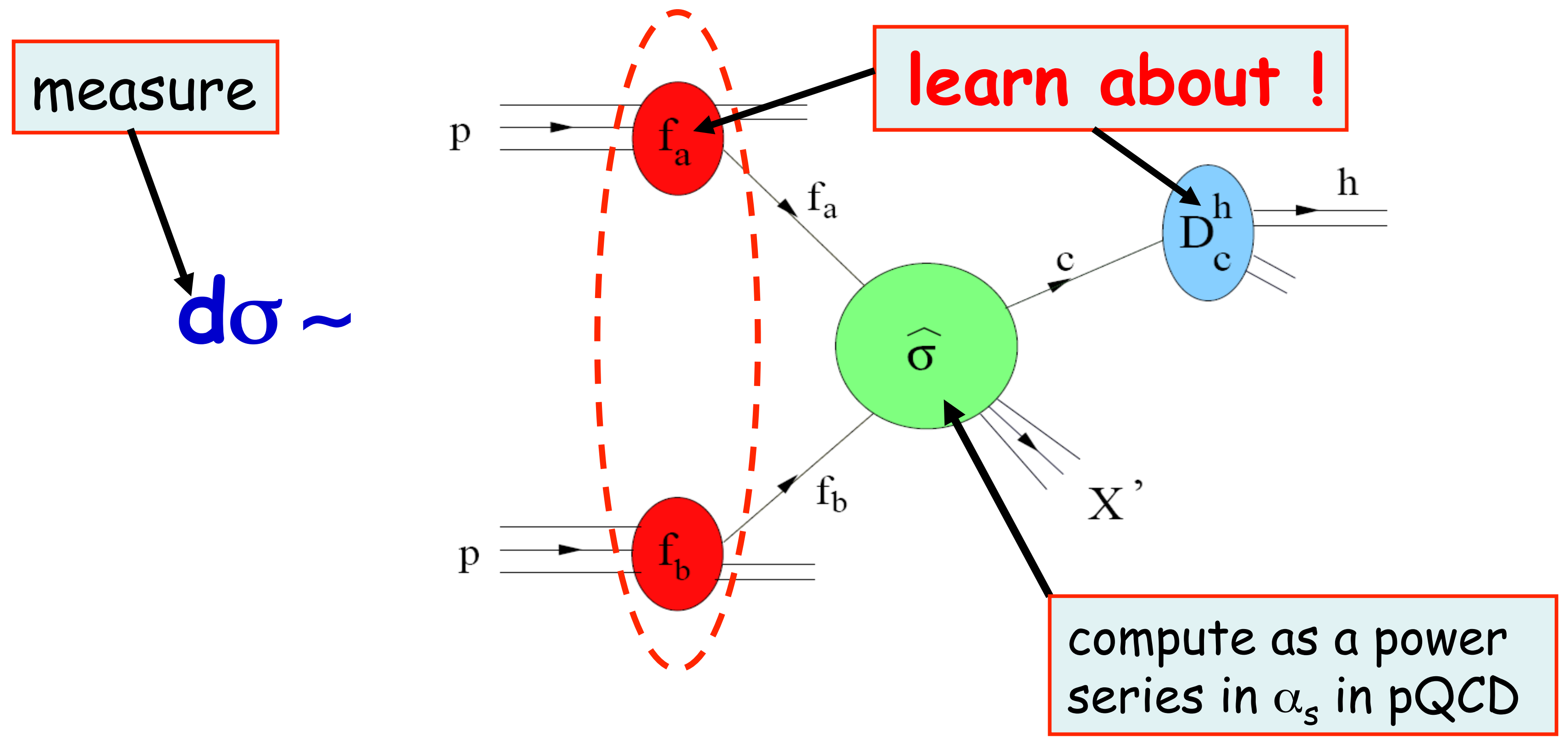
- From phenomenological side, any improvement needed? seems not?!

Theoretical improvements

- Following the standard theory developments in perturbative QCD, there seems to be interesting improvements, which can be done and which could affect our "precise" extraction of medium properties
  - Is the jet transport parameter qhat constant? Does it depend on the hard scale of the external probe?
  - Energy loss: go beyond soft approximation?

Example of perturbative QCD

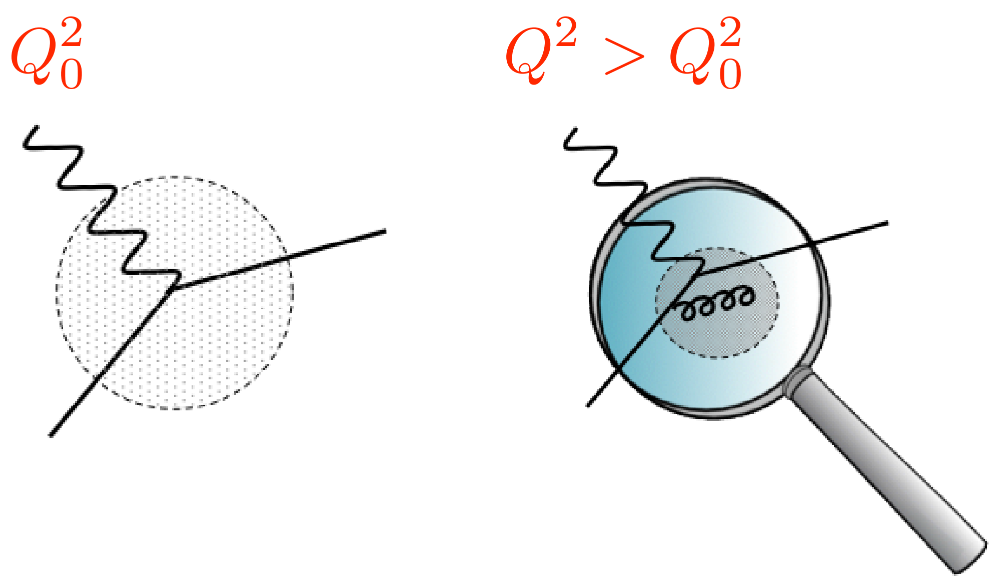
- QCD factorization

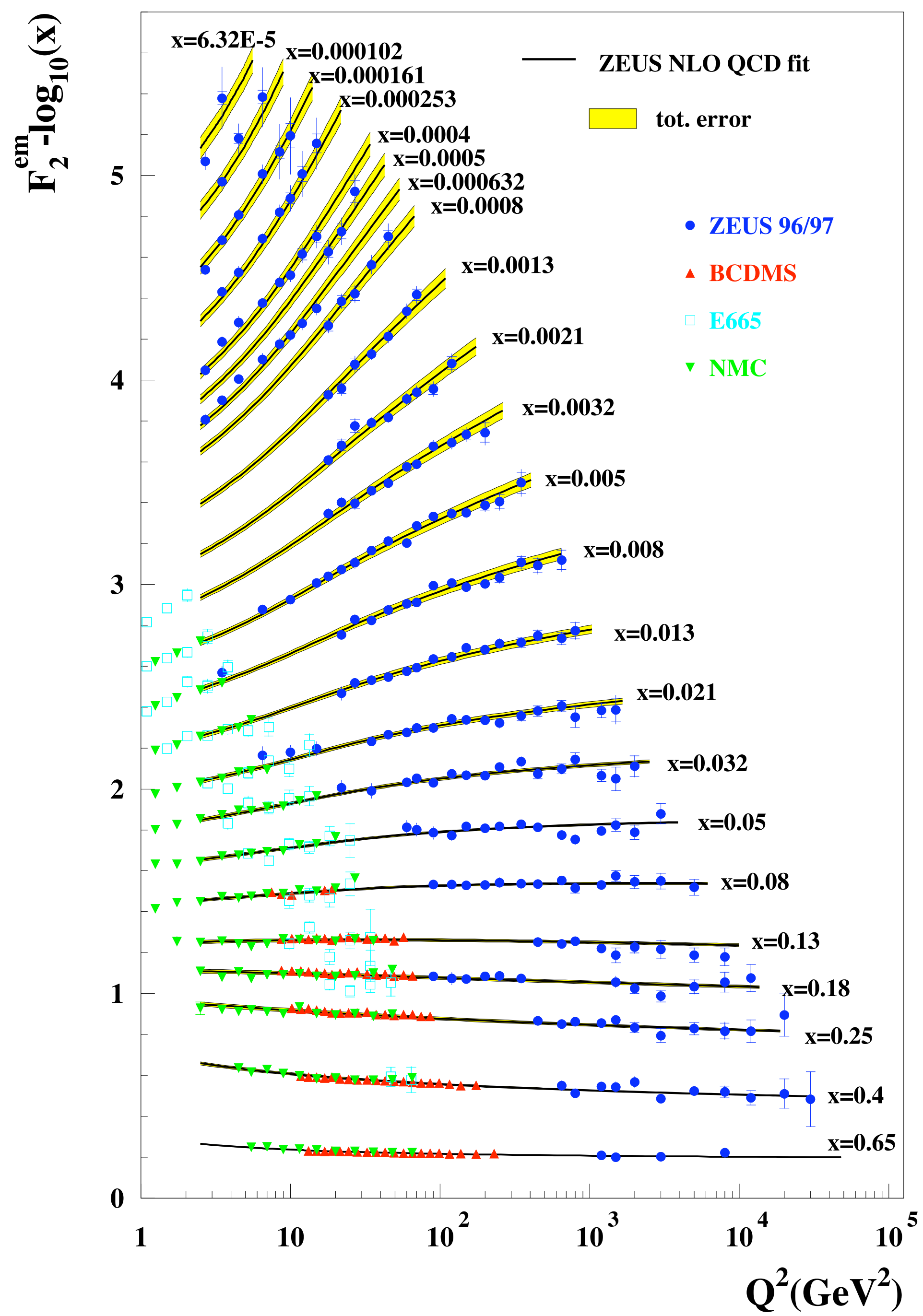


$$d\sigma^{NN\to h+X} = \sum_{abc} f_{a/N}(x_1, Q^2) \otimes f_{b/N}(x_2, Q^2) \otimes \hat{\sigma}_{ab\to c} \otimes D_{c\to h}(z, Q^2)$$

PDFs depends on the scale of the probe

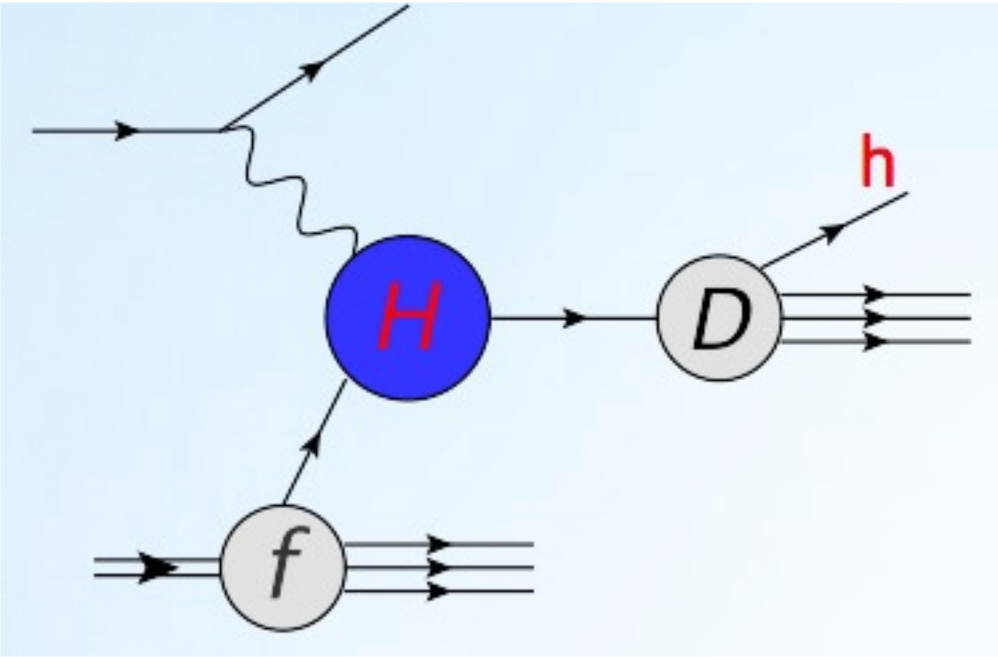
- Increasing the energy scale, one sees parton picture differently





How does it arise?

- SIDIS as an example:

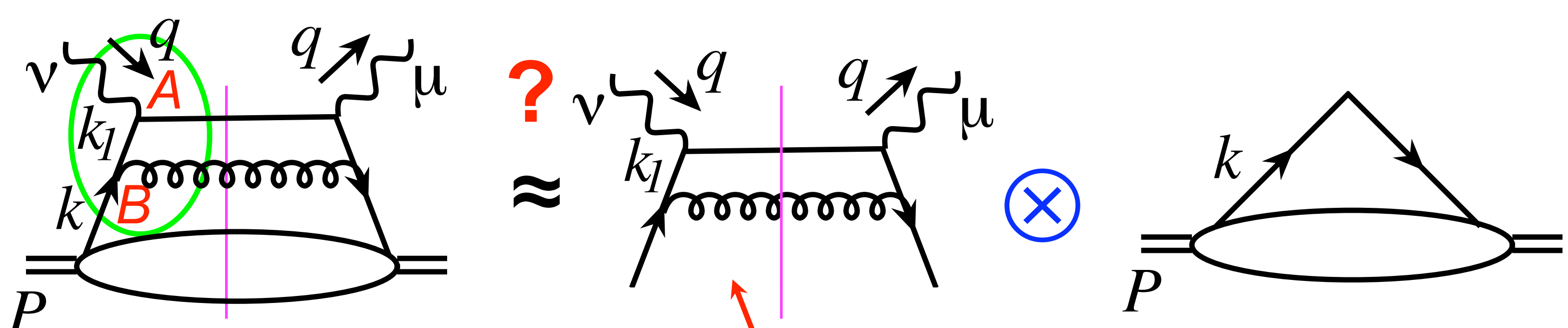


$$\frac{d\sigma^{LO}}{dx_B dy dz_h} = \sigma_0 \sum_q e_q^2 \int \frac{dz}{z} D_{h/q}(z) \int \frac{dx}{x} f_q(x) \delta(1-\hat{x}) \delta(1-\hat{z})$$

- If going beyond LO, we face all divergence: renormalized PDFs and FFs

QCD dynamics beyond tree level

- Going beyond leading order calculation



Collinear divergence!!! (from $k_1^2 \sim 0$)

$$\Rightarrow \int d^4k_1 \frac{i}{k_1^2+i\epsilon}\frac{-i}{k_1^2-i\epsilon} \Rightarrow \infty$$

$$k_1^2 = (k+k_g)^2 = 2EE_g(1-\cos\theta)$$

- ❖ $k_1^2 \sim 0$ intermediate quark is on-shell

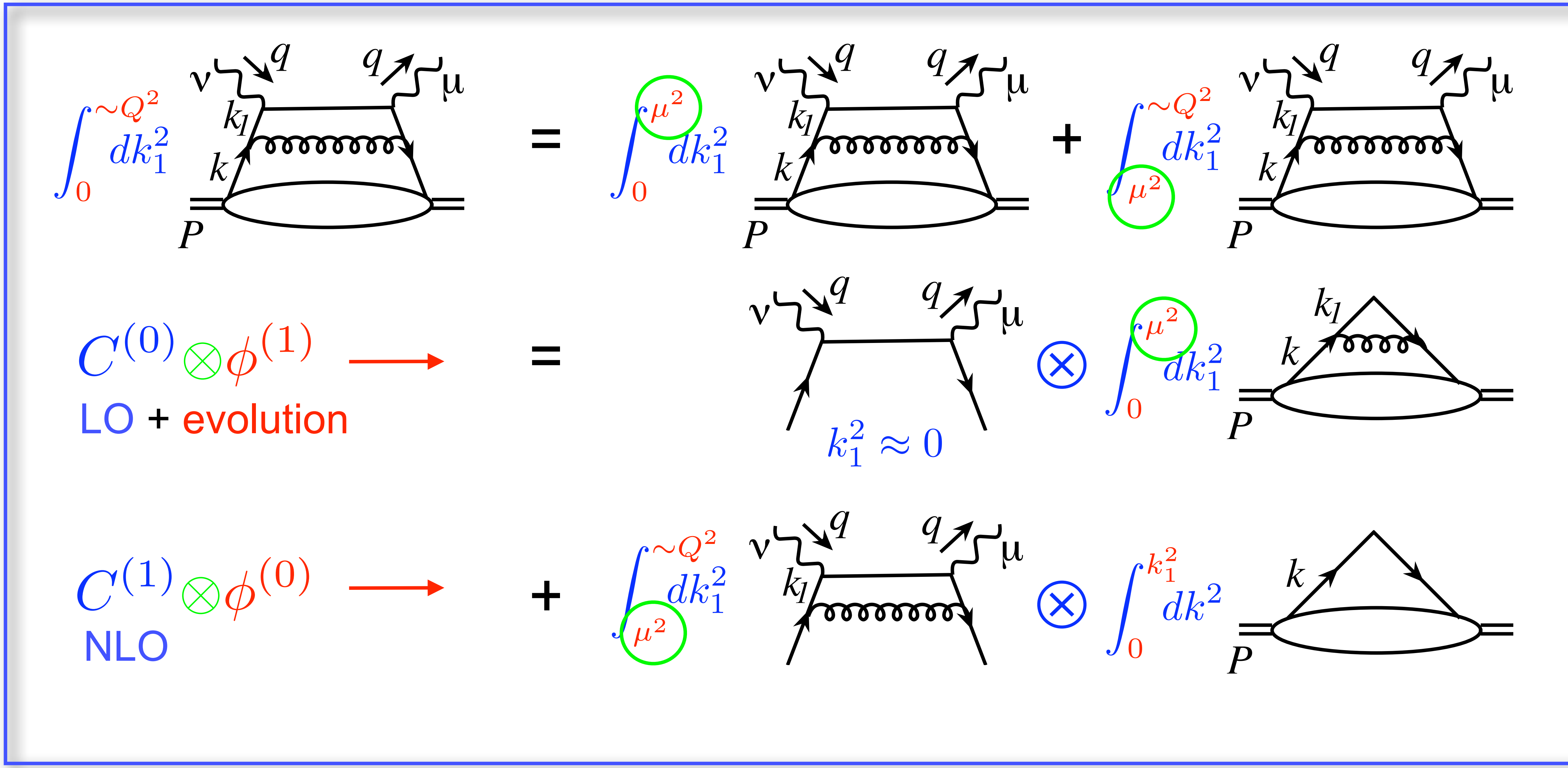
  $t_{AB} \rightarrow \infty$

- ❖ gluon radiation takes place long before the photon-quark interaction
  $\Longrightarrow$ a part of PDF

Partonic diagram has both long- and short-distance physics

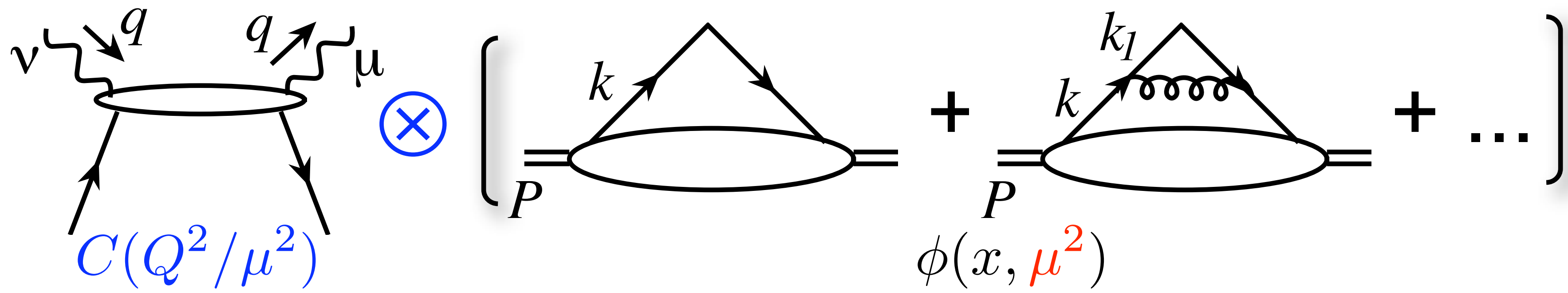
QCD factorization: separation of soft and hard physics

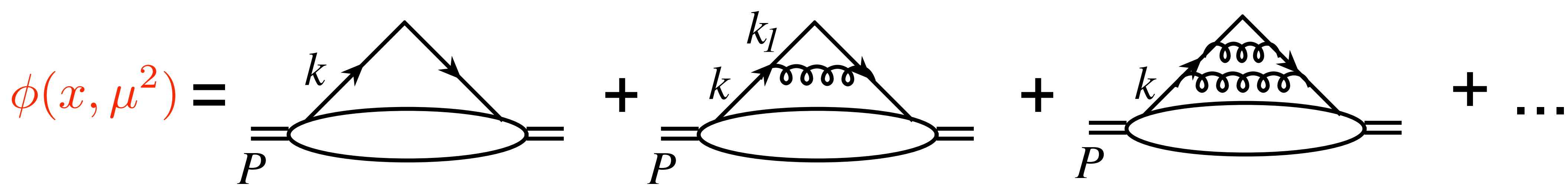
- Systematic remove all the long-distance physics into PDFs



PDFs depend on the scale where one separates them

- Logarithmic contributions into parton distributions





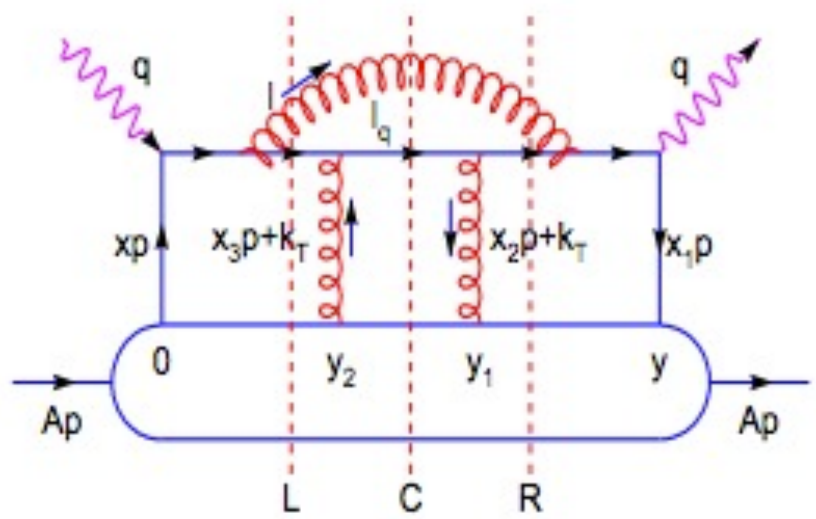
- Such a scale dependence is described by the well-known DGLAP evolution equation

- What happens in the hot medium? Does this have anything to do with qhat?

Recall high-twist approach to jet quenching

- SIDIS as an example: multiple scattering in the medium leads to induced gluon radiation

Wang-Guo, Qin-Majumder, et.al.



- The modification depends on multi-parton correlation function of the type

$$T_F(x_B,0,0) \sim \langle A|\bar{\psi}_q(0)\gamma^+ F_\sigma^+(y_2^-)F^{\sigma+}(y_1^-)\psi_q(y^-)|A\rangle$$

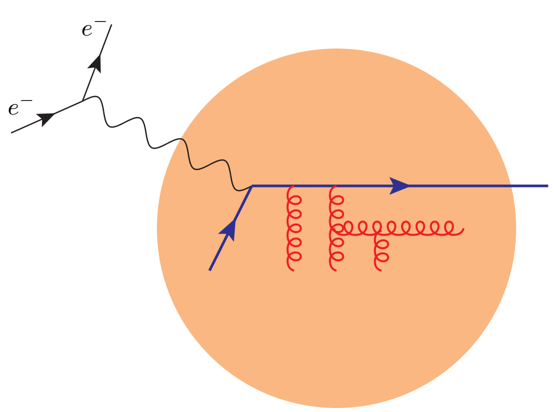
- Does such a correlation function depend on the scale? If it does, naturally the qhat will depend on the scale

$$T_F(x_B,0,0,\mu^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x_B,\mu^2)\int dy^- \hat{q}(\mu^2,y^-)$$

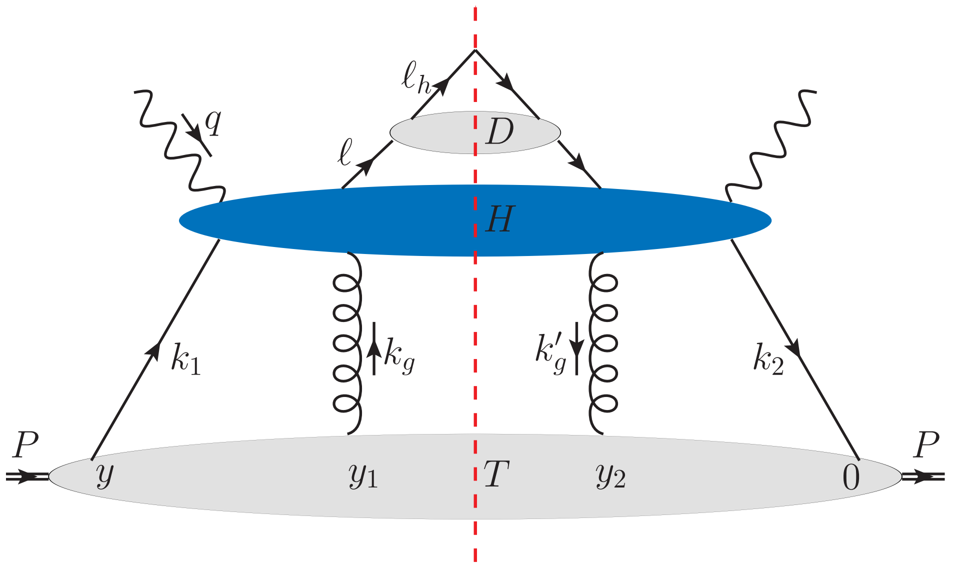
Compute NLO process

- Find a suitable observable, which depends on this correlation function, and then compute its NLO correction
  - The scale dependence follows, similarly like the usual PDFs procedure
- Transverse momentum broadening and double scattering

SIDIS



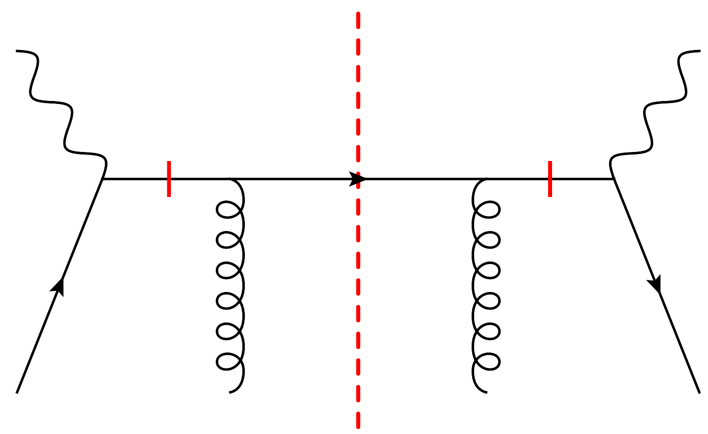
Final state multiple scattering



Kang-Wang-Wang-Xing, 1310.6759, PRL 2014

Double scattering in SIDIS: LO

- Leading order is simple, and proportional to the "desired" correlation function



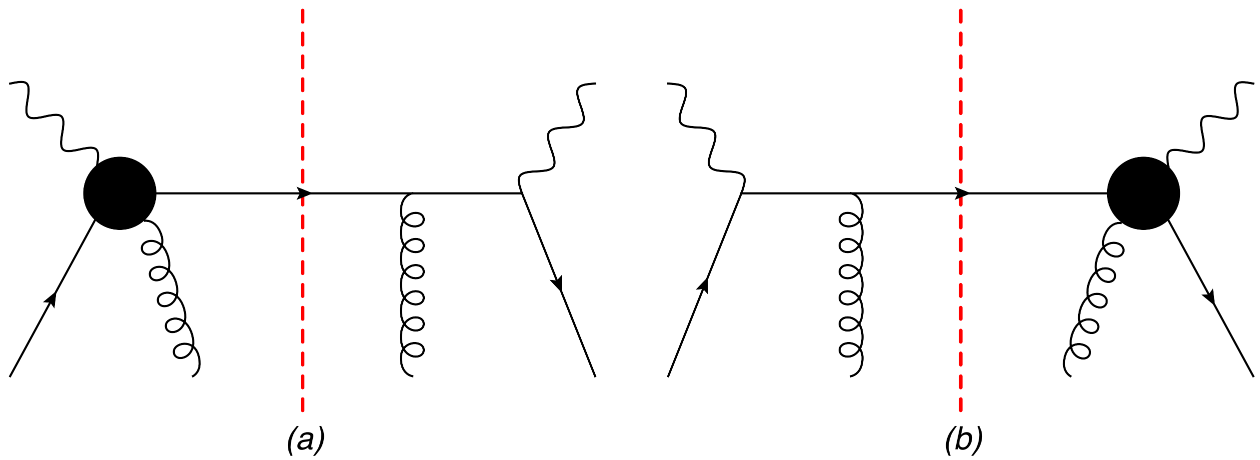
$$\Delta\langle \ell_{hT}^2\rangle = \left(\frac{4\pi^2\alpha_s}{N_c} z_h^2\right) \frac{\sum_q e_q^2 T_F(x_B,0,0) D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B) D_{h/q}(z_h)}$$

- Twist-4 quark-gluon correlation function

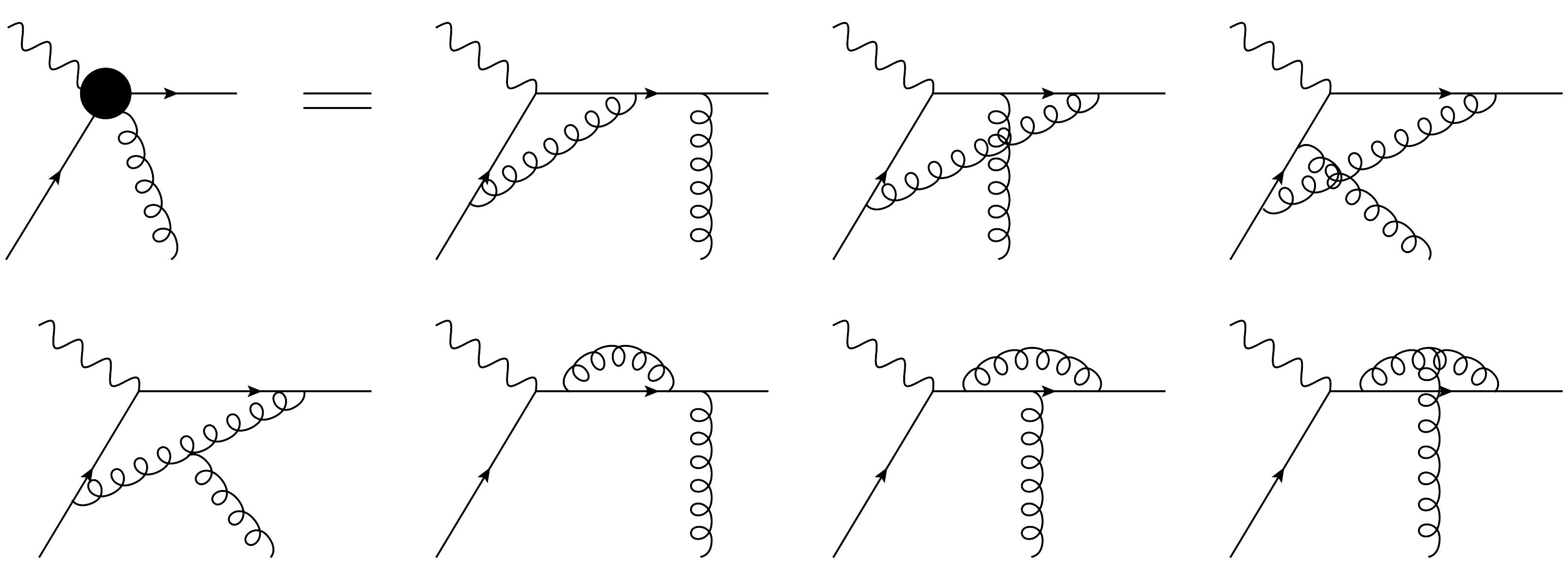
$$T_F(x_1,x_2,x_3) = \int \frac{dy^-}{2\pi} e^{ix_1p^+y^-} \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_2p^+(y_1^- - y_2^-)} e^{ix_3p^+y_2^-}$$
$$\times \langle A|\bar{\psi}_q(0)\gamma^+ F_\sigma^{\ +}(y_2^-) F^{\sigma+}(y_1^-)\psi_q(y^-)|A\rangle \theta(y_2^-)\theta(y_1^- - y^-)$$

Double scattering in SIDIS: NLO - 1

- Virtual diagrams



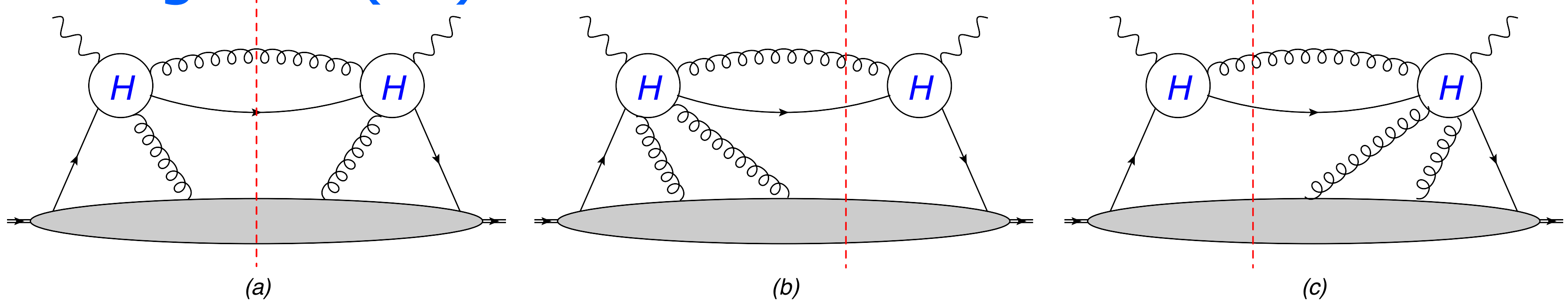
- Here the blob represents



Double scattering in SIDIS: NLO - 2

- Real diagrams (57)

Kang-Wang-Wang-Xing, 1310.6759, PRL 2014



Classical double scattering

Interference

- Soft divergence (double pole $\propto \frac{1}{\epsilon^2}$)

Real + virtual → 0

- Collinear divergence (single pole $\propto \frac{1}{\epsilon}$)

Collinear to FS

$$-\frac{1}{\epsilon}\delta(1-\hat{x})T_F(x,0,0)P_{qq}(\hat{z})$$

$\overline{MS}$

$$D_q(z_h,\mu^2)=D_q^0(z_h)+\frac{\alpha_s}{2\pi}\int\frac{dz}{z}\left(-\frac{1}{\hat{\epsilon}}\right)P_{qq}(\hat{z})D_q(z)$$

DGLAP

Collinear to IS

$$-\frac{1}{\epsilon}\delta(1-\hat{z})\left[T_F(x,0,0)P_{qq}(\hat{x})+P_{qg\to qg}(\hat{x})\otimes T_F(x,x,x_B)\right]$$

$\overline{MS}$

$$T_F(x_B,0,0,\mu^2)=T_F^{(0)}(x_B,0,0)-\frac{\alpha_s}{2\pi}\frac{1}{\hat{\epsilon}}\int_{x_B}^{1}\frac{dx}{x}\left[P_{qq}(\hat{x})T_F(x,0,0)+P_{qg\to qg}(\hat{x})\otimes T_F(x,x,x_B)\right]$$

Evolution equation for qhat

- For quark-gluon correlation function

$$\mu^2 \frac{\partial}{\partial \mu^2} T_F(x_B, 0, 0, \mu^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \left[P_{qq}(\hat{x}) T_F(x, 0, 0, \mu^2) + P_{qg\to qg}(\hat{x}) \otimes T_F(x, x, x_B, \mu^2) \right]$$

$$P_{qg\to qg}(\hat{x}) \otimes T_F(x, x, x_B)$$
$$= C_A \left[\frac{2}{(1-\hat{x})_+} T(x_B, x - x_B, 0) - \frac{1}{2} \frac{1+\hat{x}}{(1-\hat{x})_+} \left(T(x, 0, x_B - x) + T(x_B, x - x_B, x - x_B) \right) \right]$$

  - Large x limit (LPM interference regime)

$$\mu^2 \frac{\partial \hat{q}(\mu^2)}{\partial \mu^2} = 0$$

  - Intermediate x region

$$\frac{\partial \hat{q}(\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} C_A \ln(1/x_B) \hat{q}(\mu^2) \quad \Rightarrow \quad \hat{q}(\mu^2) = \hat{q}(\mu_0^2) Exp\left[\frac{\alpha_s}{2\pi} C_A \ln(1/x_B) \ln(\mu^2/\mu_0^2) \right]$$

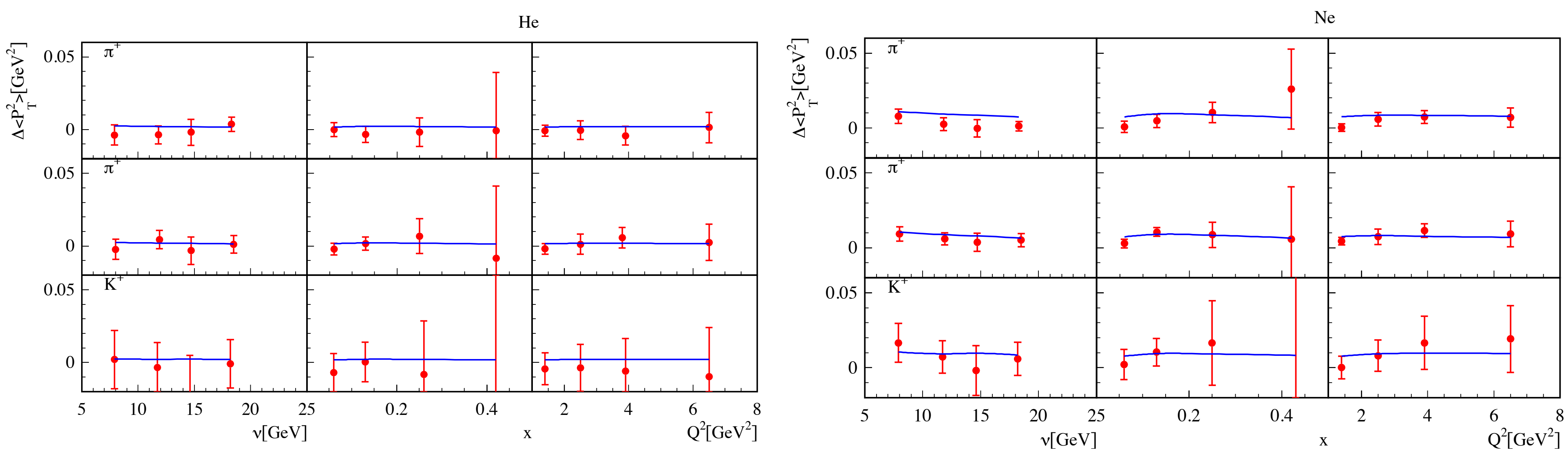
1. mu-dependence → Scaling violation!
2. Energy dependence → consistent with earlier expectation

   J. Casalderrey-Solana and X.-N. Wang (2008)

Comparison to HERMES data

- Cold medium $\hat{q}(\mu_0 = 1) = 0.015 GeV^2/fm$

Kang-Wang-Wang-Xing, in preparation



All kinematic dependence
can be described quite well !

- In the future, study the consequence for hot medium

Improvement in energy loss: beyond soft approximation?

- Soft approximation
  - Under soft approximation, the parton does not change identity, so the energy loss has its true meaning
  - If the incoming quark loses 90% of its energy (through gluon radiation), the gluon has become the main content, which will fragment to the hadron

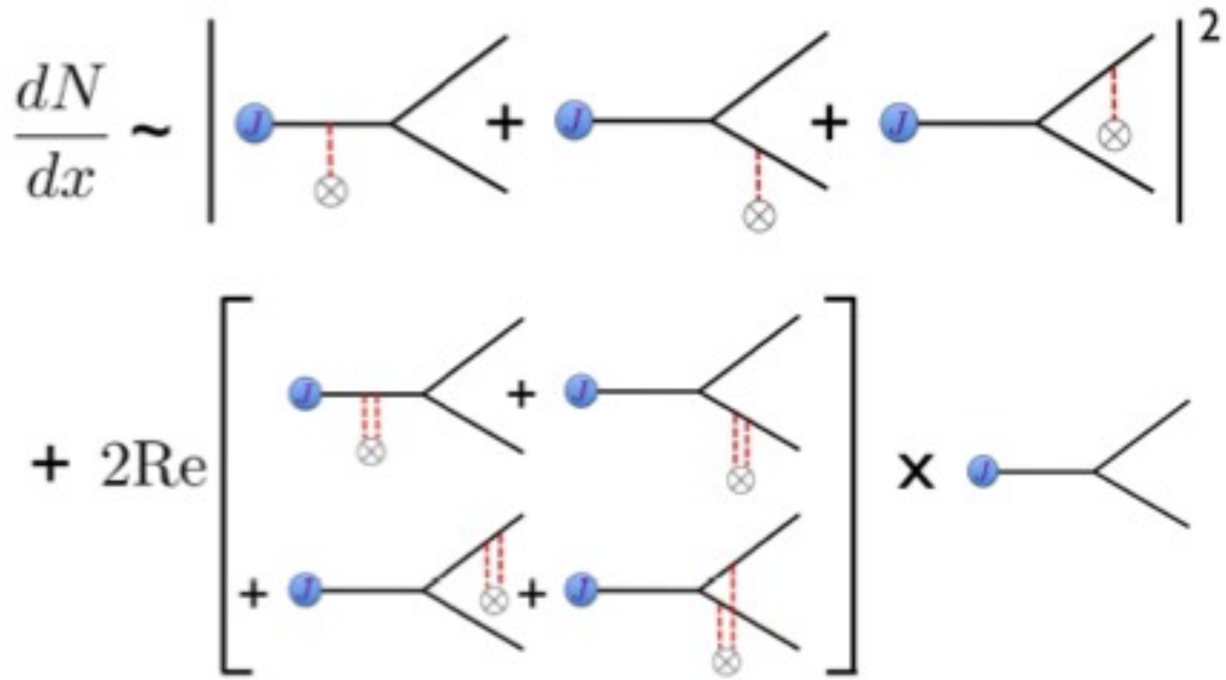
$$D_{h/c}(z) \Rightarrow \int_0^{1-z} d\epsilon\, P(\epsilon) \frac{1}{1-\epsilon} D_{h/c}\left(\frac{z}{1-\epsilon}\right)$$

Soft Collinear Effective Theory

- Power counting idea from Soft Collinear Effective Theory
  - Collinear: $k \sim Q(1, \lambda^2, \lambda)$
  - Soft: $k \sim Q(\lambda^2, \lambda^2, \lambda^2)$
  - Glauber: $k \sim Q\ (\lambda^2, \lambda^2, \lambda)$
- The momentum exchange between jets and medium quasi-particles follow the Glauber type, so Glauber gluons are needed
  - SCET with Glauber gluons are derived

Idilbi-Majumder 08, Ovanesyan-Vitev 11

  - Emission of collinear particles is described by SCET Lagrangian
  - Easy implementation to compute medium splitting beyond small x limit



Results of all medium splitting kernels

Ovanesyan-Vitev 11

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

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

Results of all medium splitting kernels

Ovanesyan-Vitev 11

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$$\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2} - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\cdot\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2} - \frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2}\right)\cos[\Omega_4\Delta z]$$
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$$\times\left[2\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\cdot\left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + 2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}\cdot\left(\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])\right.$$
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Don't try to read

Small x approximation

- Under small x approximation, it reproduces GLV splitting kernels for quark-->quark, and gluon-->gluon

$$\begin{pmatrix} x\frac{dN_{q\to qg}}{dx} \\ x\frac{dN_{g\to gg}}{dx} \\ x\frac{dN_{g\to q\bar{q}}}{dx} \\ x\frac{dN_{q\to gq}}{dx} \end{pmatrix}_{\text{SCET}_G}^{x\to 0} \approx \begin{pmatrix} C_F \\ C_A \\ 0 \\ 0 \end{pmatrix} \frac{\alpha_s}{\pi^2}\int d\Delta z \frac{1}{\lambda_g(z)}\int d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp \frac{1}{\sigma_{\text{el}}}\frac{d\sigma_{\text{el}}^{\text{med}}}{d^2\mathbf{q}_\perp}\frac{2\mathbf{k}_\perp\cdot\mathbf{q}_\perp}{\mathbf{k}_\perp^2(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}\left(1-\cos\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}{xp_0^+}\Delta z\right)$$

Gyulassy, Levai, Vitev 2002

- Now a natural place to study the "FINITE x" correction and its consequences

Kang-Ovanesyan-Vitev, et.al., 1405.2612

Using DGLAP evolution

- Now we have four splitting kernels: q-->q, g-->g, q-->g, g-->q
  - Natural framework is to use DGLAP evolution equations to account for multiple gluon emissions

Kang-Ovanesyan-Vitev, et.al., 1405.2612

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

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

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

$$+P_{q\to gq}(z',Q)\left(f_q\left(\frac{z}{z'},Q\right) + f_{\bar{q}}\left(\frac{z}{z'},Q\right)\right)\Bigg\}.$$

$$P=P_{vac}+P_{med}$$

Connection to energy loss

- In the small-x approximation (no flavor mixing)

$$\frac{\mathrm{d}D(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\,[P(z',Q)]_+\, D\left(\frac{z}{z'},Q\right)$$

$$n(z) = -\frac{\mathrm{d}\ln D(z,Q)^{\mathrm{vac}}}{\mathrm{d}\ln z}$$

$$D(z,Q)^{\mathrm{med}} = \mathrm{e}^{-(n(z)-1)\left\langle\frac{\Delta E}{E}\right\rangle_z - \langle N_g\rangle_z}\, D(z,Q)^{\mathrm{vac}}$$

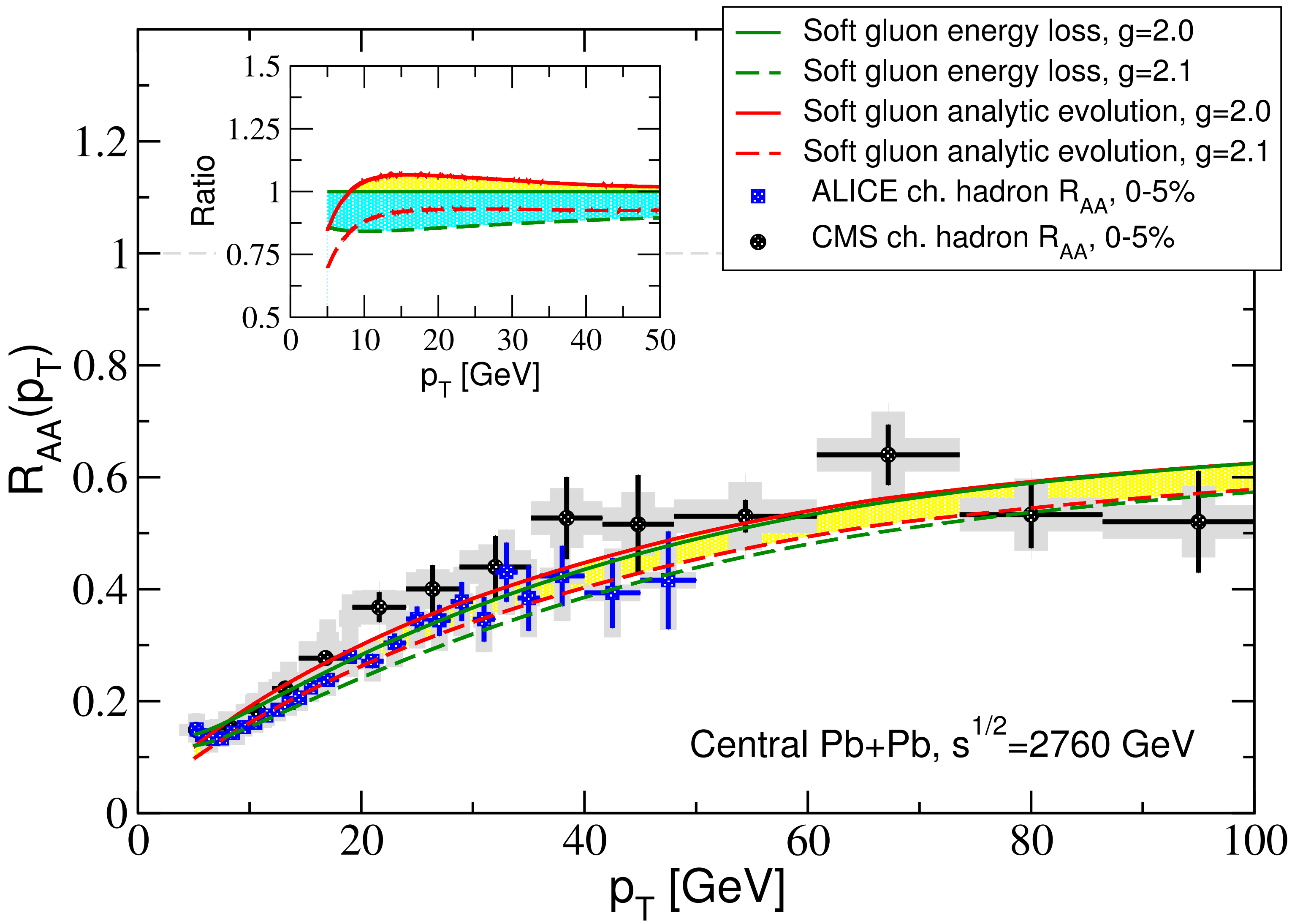
$$\left\langle\frac{\Delta E}{E}\right\rangle_z = \int_0^{1-z}\mathrm{d}x\, x\,\frac{\mathrm{d}N}{\mathrm{d}x}(x) \xrightarrow{z\to 0} \left\langle\frac{\Delta E}{E}\right\rangle,$$

$$\langle N_g\rangle_z = \int_{1-z}^1 \mathrm{d}x\,\frac{\mathrm{d}N}{\mathrm{d}x}(x) \xrightarrow{z\to 1} \langle N_g\rangle\,,$$

Energy loss vs Evolution (soft-approximation)

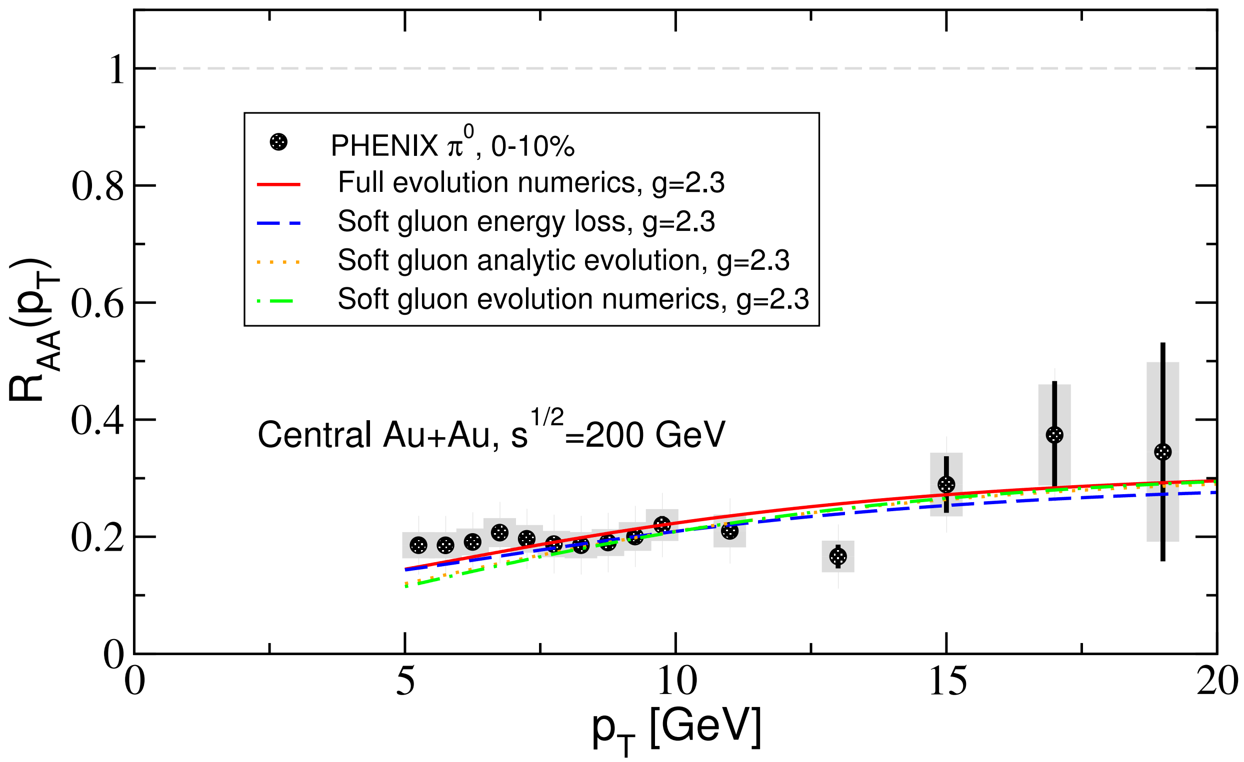
- Energy loss: multiple gluon emission -- Poisson distribution
- Evolution: through DGLAP equation (soft approximation)

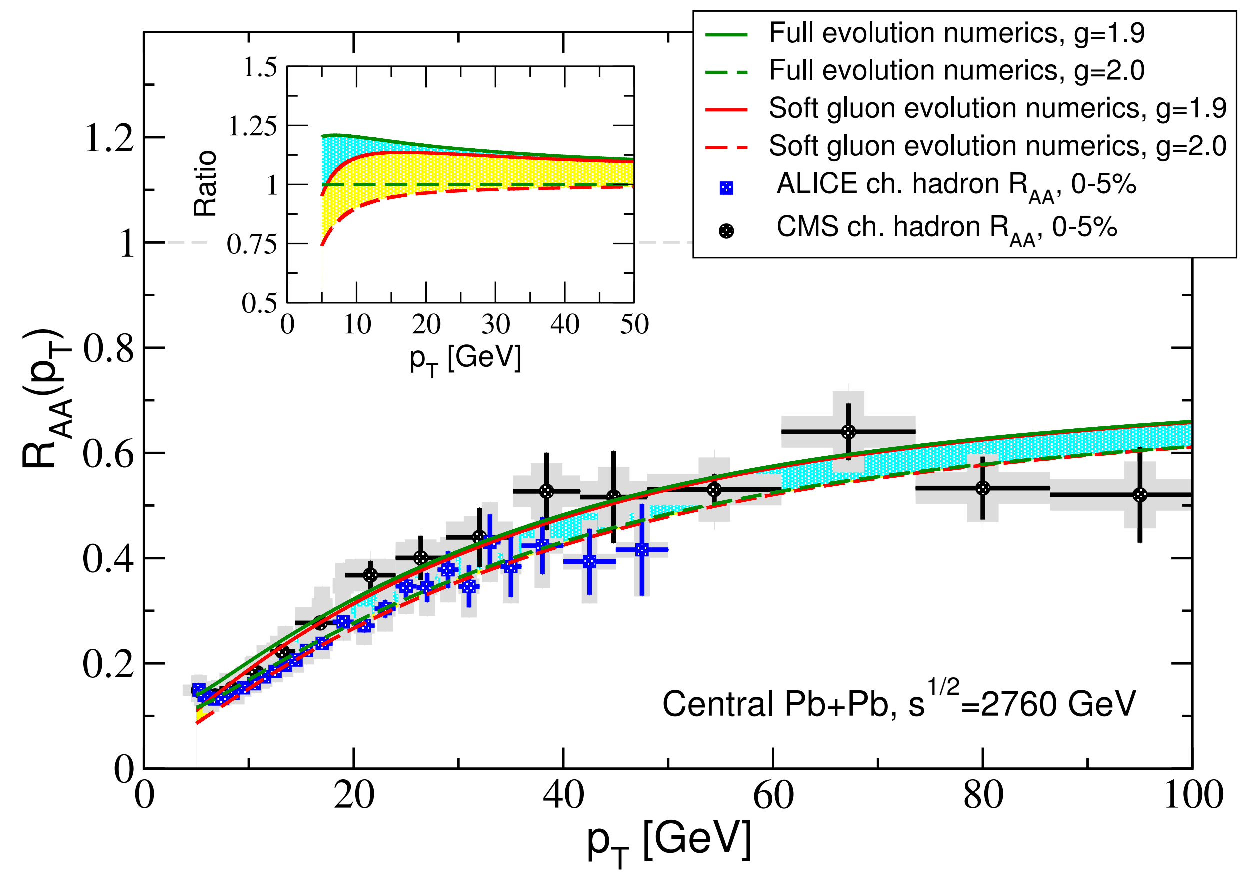
Kang-Ovanesyan-Vitev, et.al., 1405.2612



Evolution: full x vs small x

- Both RHIC and LHC



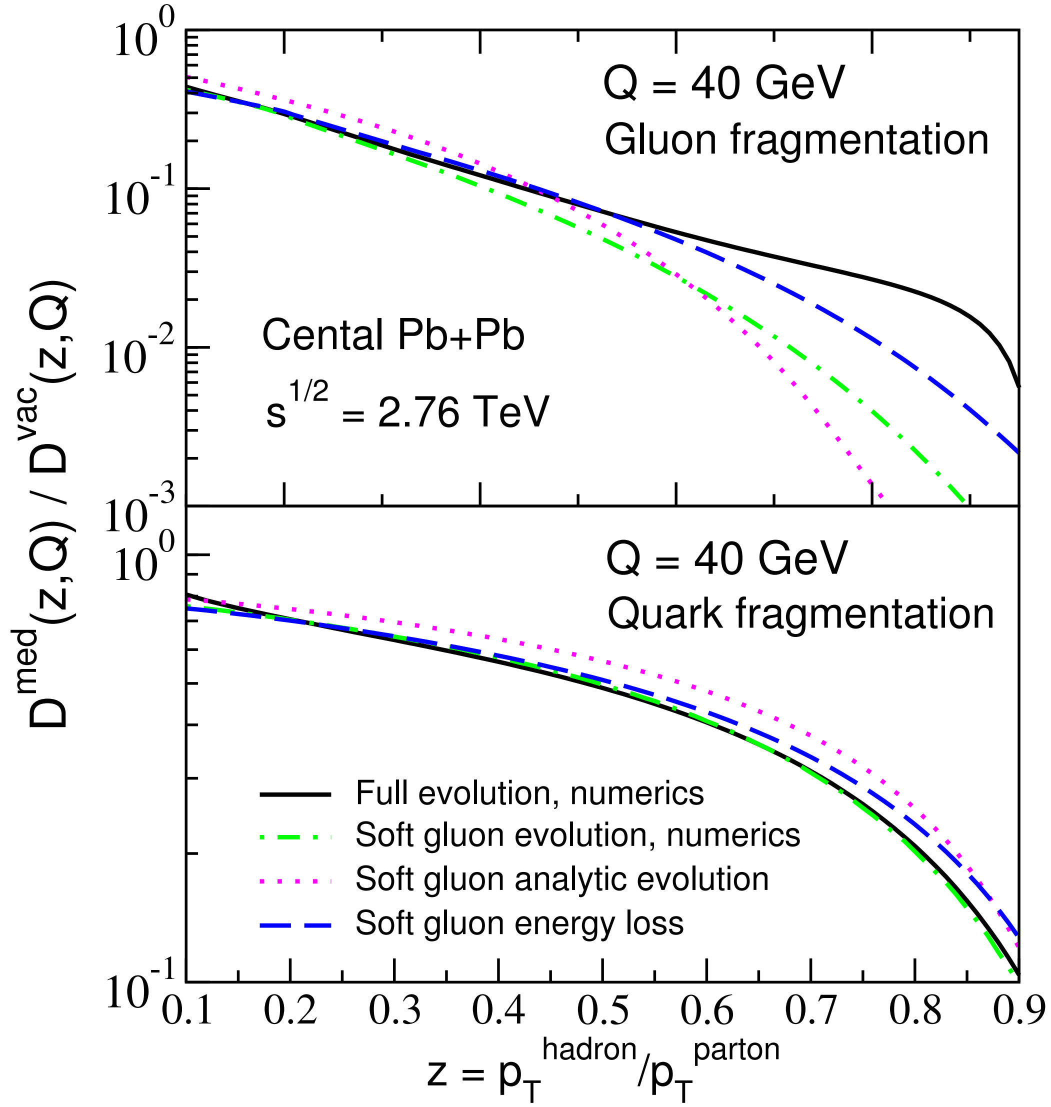


- QCD evolution using full DGLAP evolution in the medium is on the top of the small x approximation to evolution above (6 GeV for RHIC) and (15 GeV for LHC)
- At small and intermediate pt, the shape of full x evolution is in slightly better agreement with the data

Fragmentation functions

- For single inclusive hadron RAA: the finite x correction is SMALL
  - There should be other observables sensitive to large/finite x correction

1. Differences in the fragmentation functions calculated in different approximations are more visible, especially for gluon FF at large values of z.
2. However, the sensitivity of RAA to this is reduced because the gluon FF in the medium is more quenched.



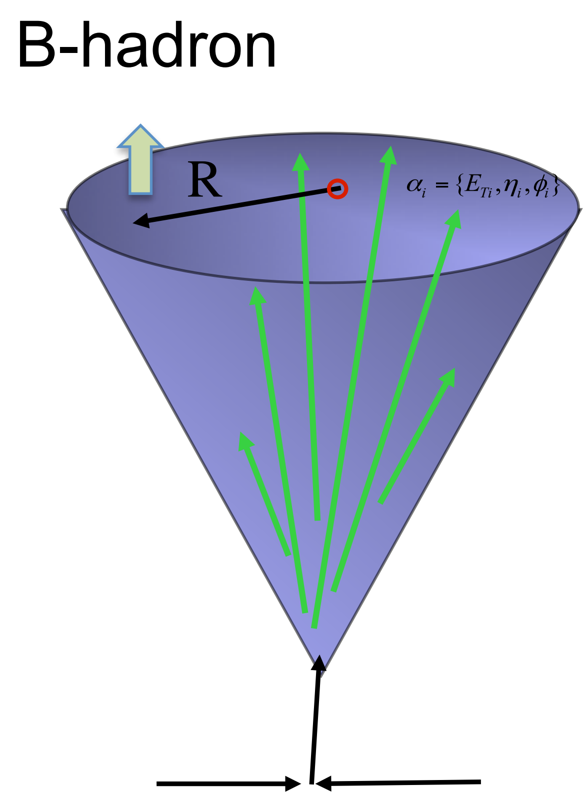
- The coupling between the jet and the medium is ~15% larger at RHIC (g=2.3) than LHC (g=2.0)

Come back to the standard energy loss approach

- Some recent study for heavy flavor jet in nucleus-nucleus collisions

B-jets in p+p collisions

- How to define a jet: need jet finding algorithms
  - kt algorithm, anti-kt algorithm, cone algorithm, ...



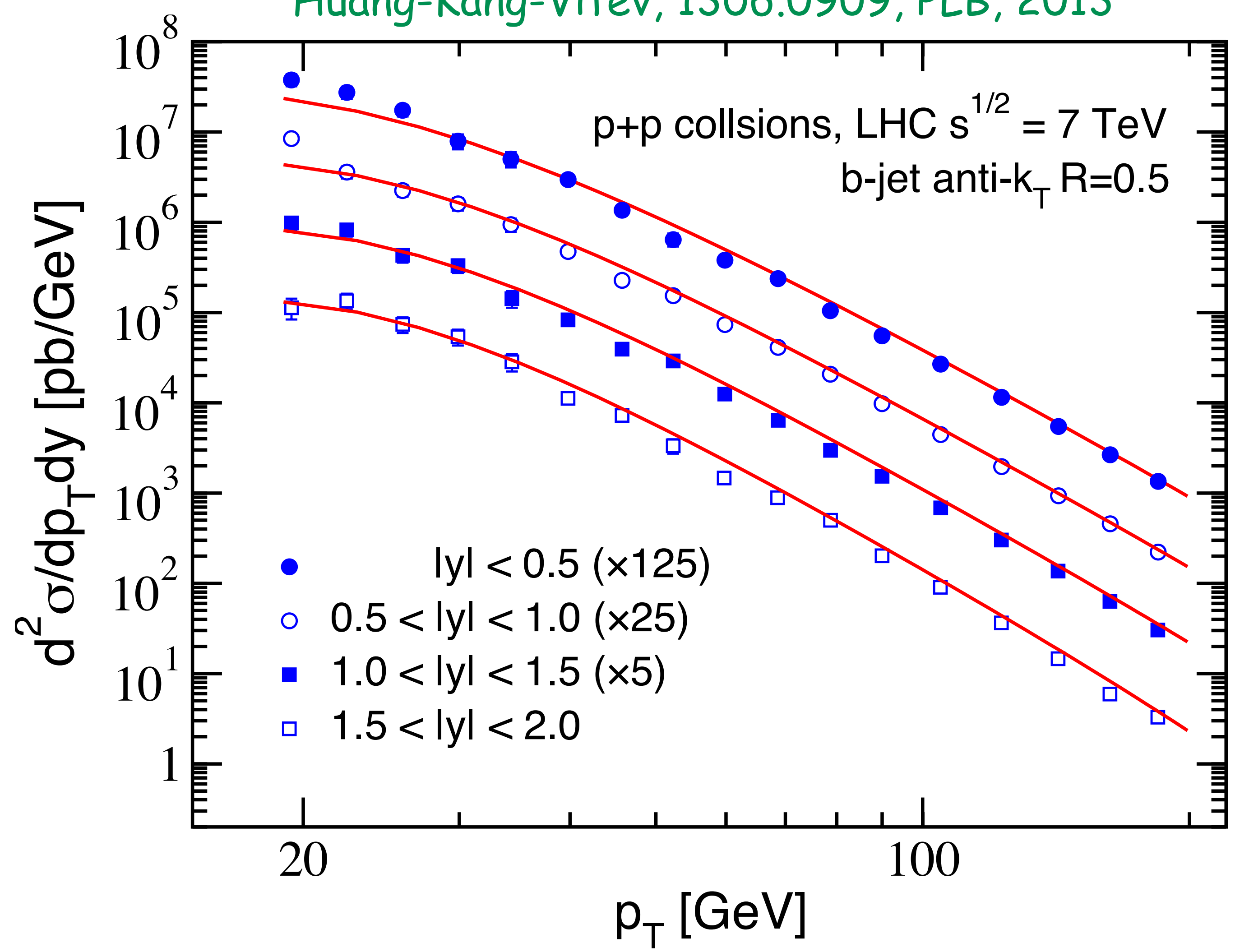
- Define b-jet
  - First find a jet. Next, with the jet radius parameter look for a B-hadron (b-quark for theory). Call it a b-jet ... Or maybe require the b-quark to be leading ... Or maybe some more creative substructure ("single b-quark jet" at Fermilab)
  - Note that the parent parton might have nothing to do with a b-quark

B-jets in p+p collisions

- No readily available NLO calculation for b-jet production (MC@NLO ...)
- PYTHIA 8 (LO+LL parton shower)
- SlowJet program with an anti-kt algorithm versus FastJet shown to give the same result
- Good description to the b-jet cross section as a function of pt and rapidity y

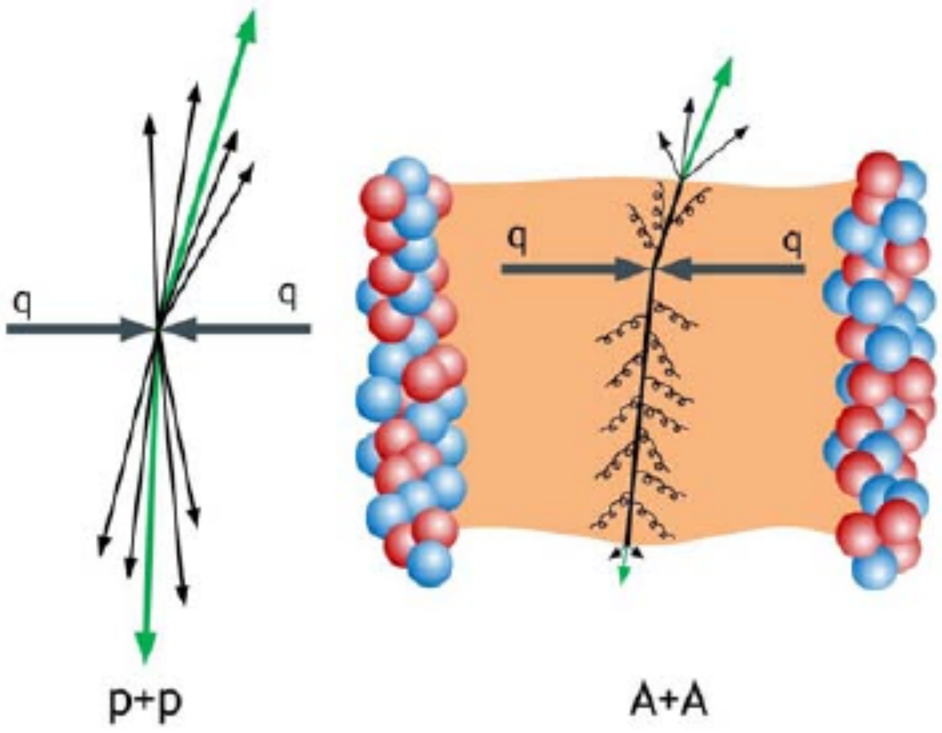
Hadronization corrections:
only important for pt < 30 GeV
and small jet radius R=0.2, 0.3

Huang-Kang-Vitev, 1306.0909, PLB, 2013



Hard partonic structure for b-jets

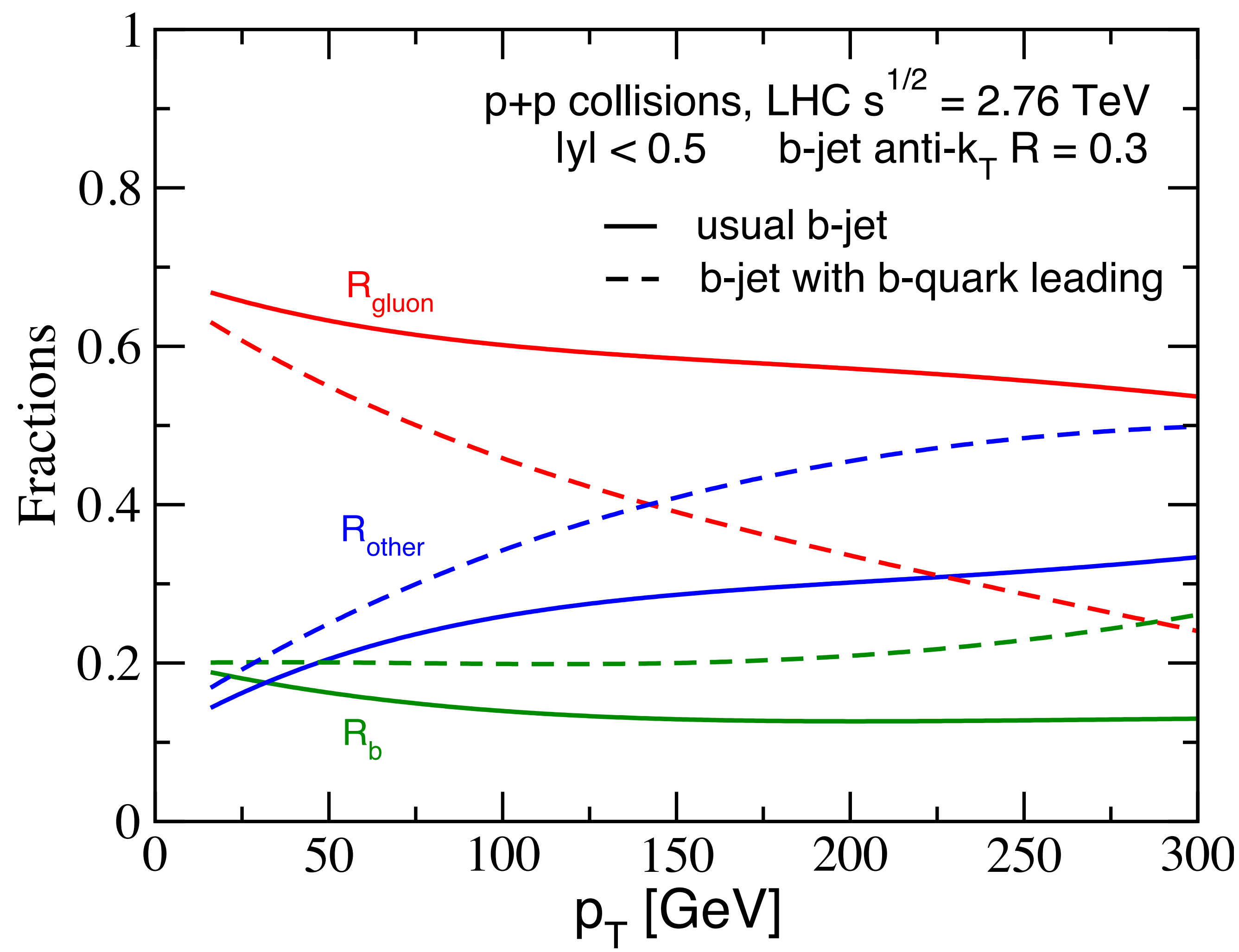
- Medium modification for b-jets in heavy ion collisions comes from both initial-state and final-state effects
  - Initial-state: cold nuclear matter (CNM) effects ⇒ small at high pt as we will show
  - Final-state: parton energy loss ⇒ have to understand the hard partonic structure for b-jets (whether light quark, gluon, or b quark)



Hard partonic structure for b-jets

- Simulation in Pythia

Huang-Kang-Vitev, 1306.0909, PLB, 2013



  - $R_{\rm gluon}$: fraction of $g \to b(\bar{b})$, i.e., hard process generates gluons, which then split into heavy quark pair as contained in b-jets (initiated by gluon)
  - $R_{\rm b-quark}$: fraction of $b(\bar{b}) \to b(\bar{b})$
  - $R_{\rm other}$: fraction of $q(\bar{q}) \to b(\bar{b})$
- A very small fraction of b-jets originate from a b-quark produced in the hard scattering

B-jet cross section calculation in heavy ion collisions

- Only a fraction of lost energy (medium induced parton shower) falls inside the cone, which can be computed as follows

$$f(R,\omega^{\rm coll})_{(s)} = \frac{\int_0^R dr \int_{\omega^{\rm coll}}^E d\omega \, \frac{\omega d^2 N^g_{(s)}}{d\omega dr}}{\int_0^{R^\infty} dr \int_0^E d\omega \, \frac{\omega d^2 N^g_{(s)}}{d\omega dr}}$$

  - (1 - f) is lost

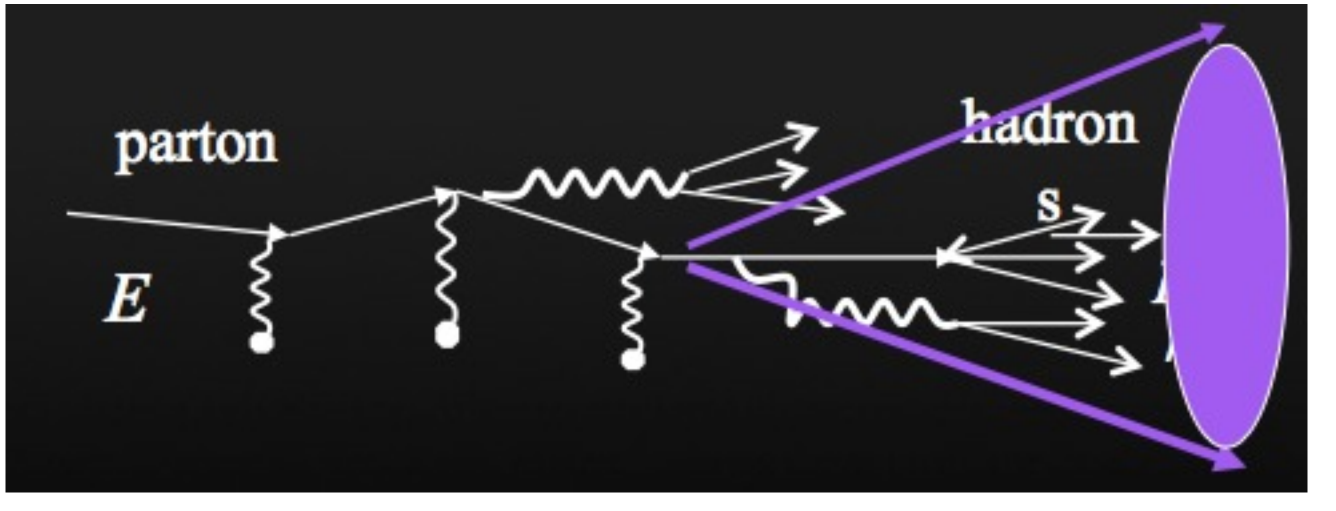
- In such a formalism, adjust $\omega^{\rm coll}$ such that

$$f(R^\infty,\omega^{\rm coll})_{(s)} = \Delta E^{\rm coll}/E$$

  - The right-hand side is simulated independently

- In order to get the jet with same energy, one has to start with a "higher" energy jet before the quenching

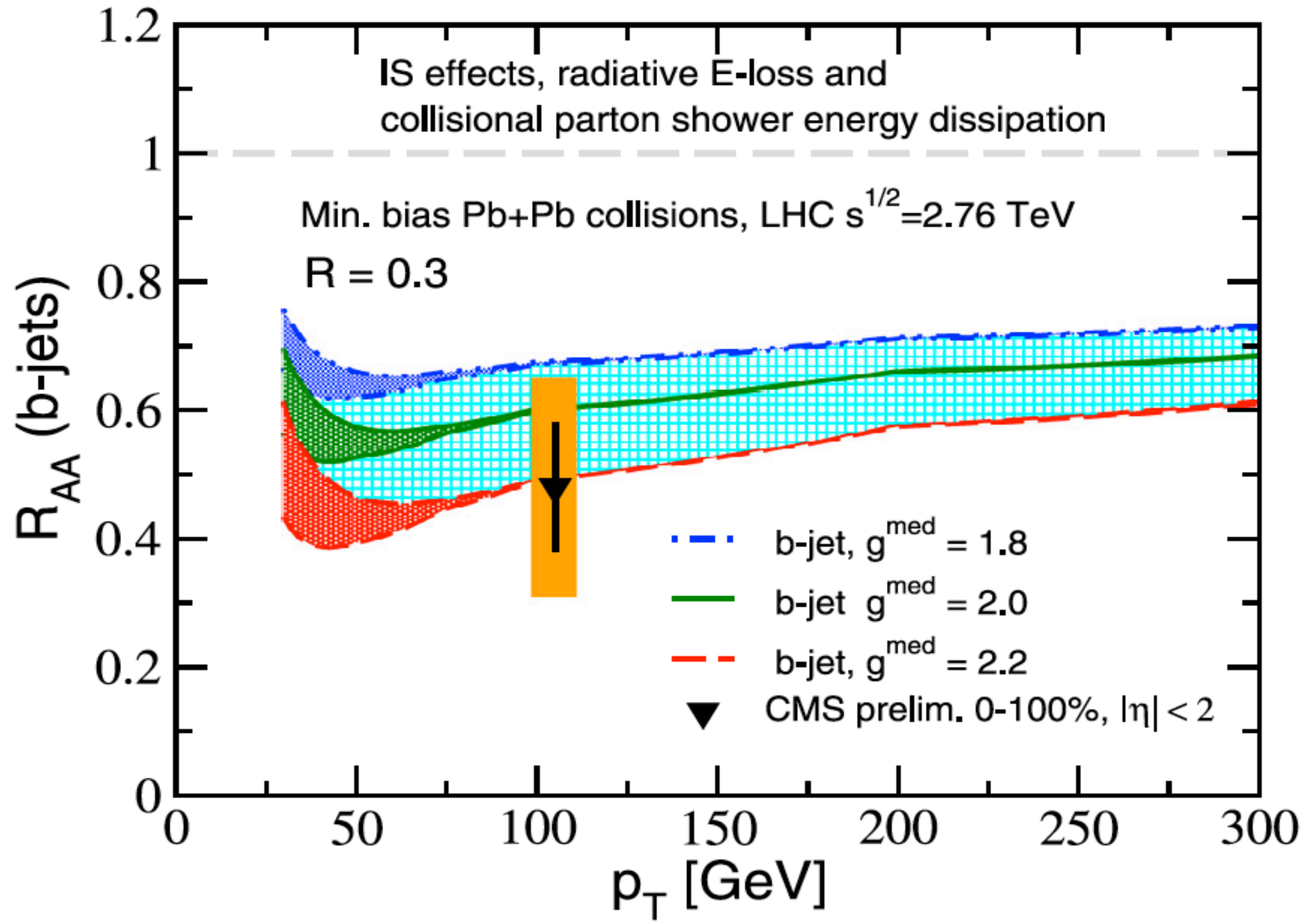
$$E_T' = E_T/(1-(1-f_{q,g})\cdot\epsilon)$$



Works fine

- Compared with the most recent CMS b-jet data

Huang-Kang-Vitev, 1306.0909, PLB, 2013



- b-jet at high pt is not really sensitive to the b-quark energy loss

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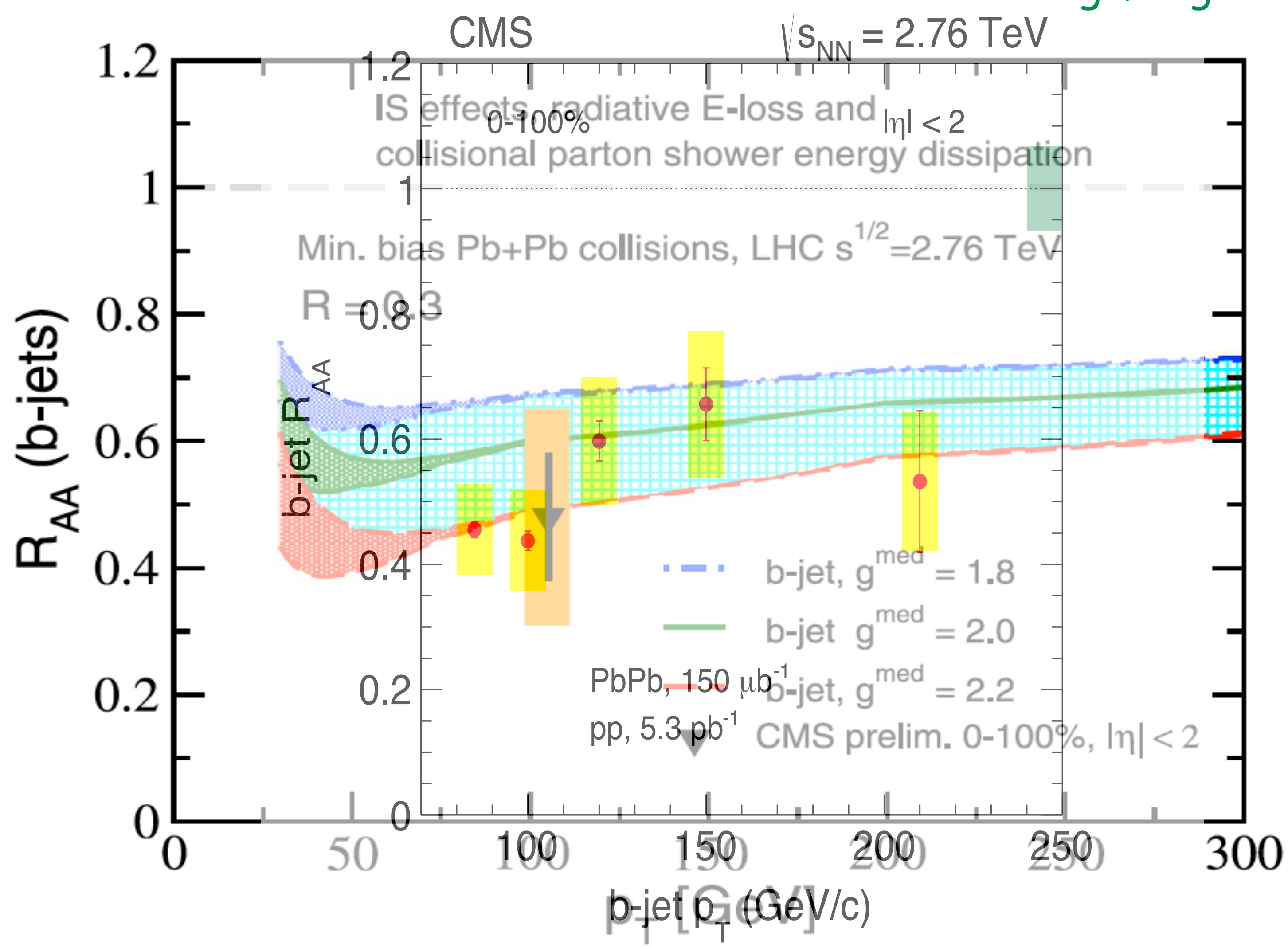
Huang-Kang-Vitev, 1306.0909, PLB, 2013

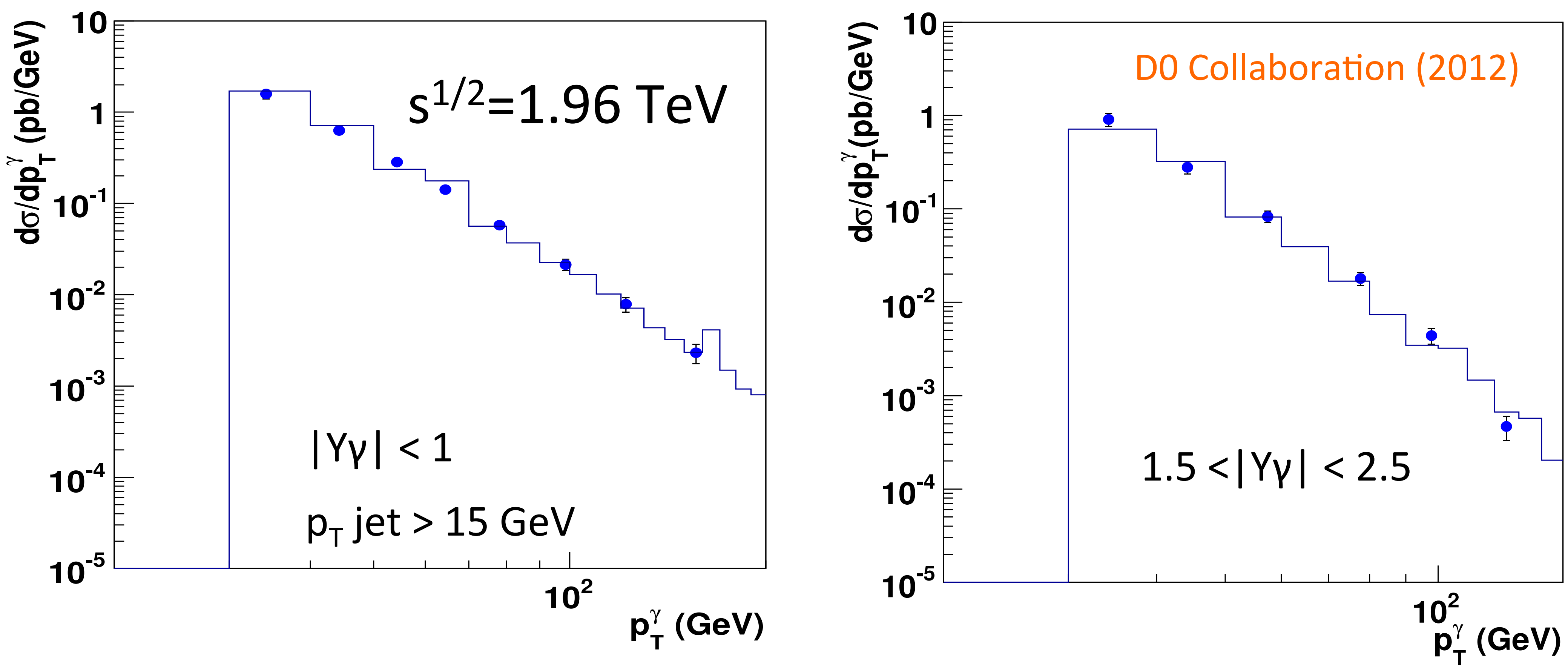


- b-jet at high pt is not really sensitive to the b-quark energy loss

Photon-tagged b-jet in p+p collisions

- Motivated by the need to increase the fraction of b-jets initiated by prompt b quarks
  - PYTHIA simulation

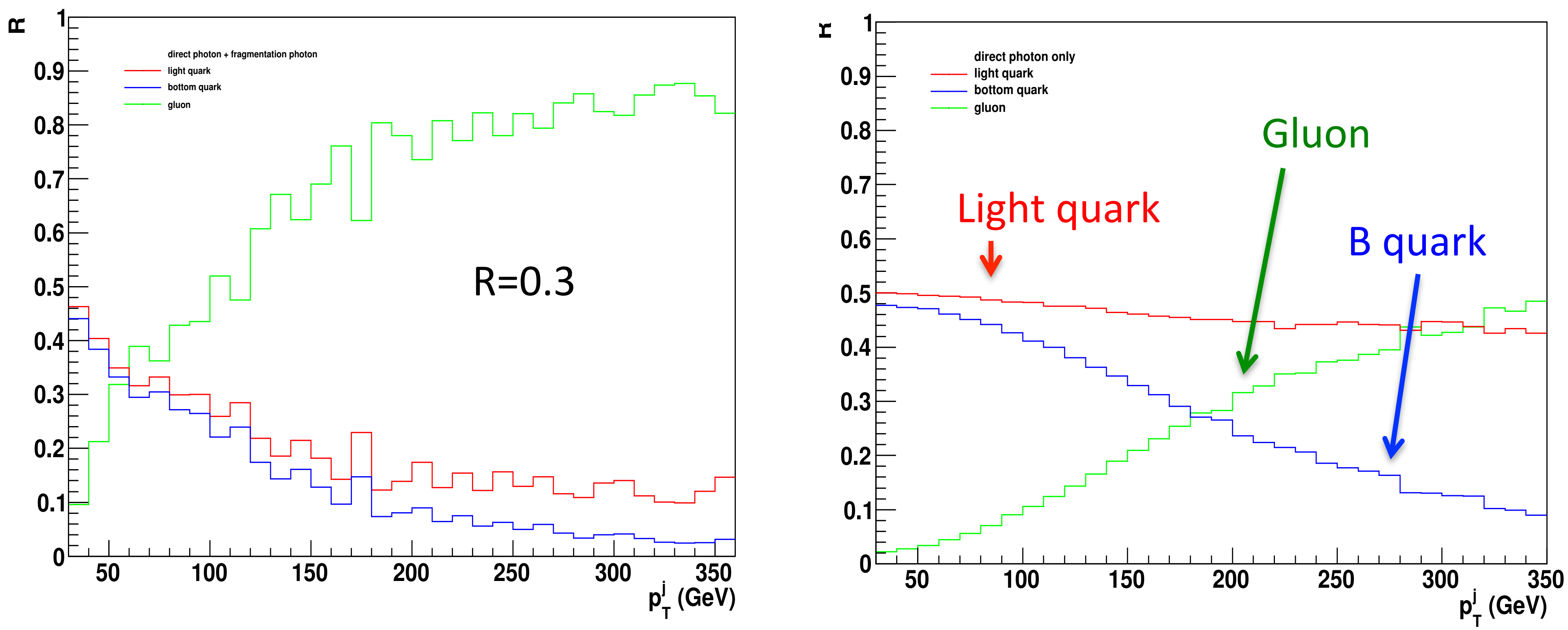
Huang-Kang-Vitev-Xing, 2014, in preparation



Contribution from different processes

- Left: both fragmentation and direct photon
- Right: direct photon only

Huang-Kang-Vitev-Xing, 2014, in preparation



$$g+b\to q+b \quad q+g\to q+\gamma\to(qb\bar{b}....)+\gamma \quad q+\bar{q}\to g+\gamma\to(b\bar{b}....)+\gamma$$

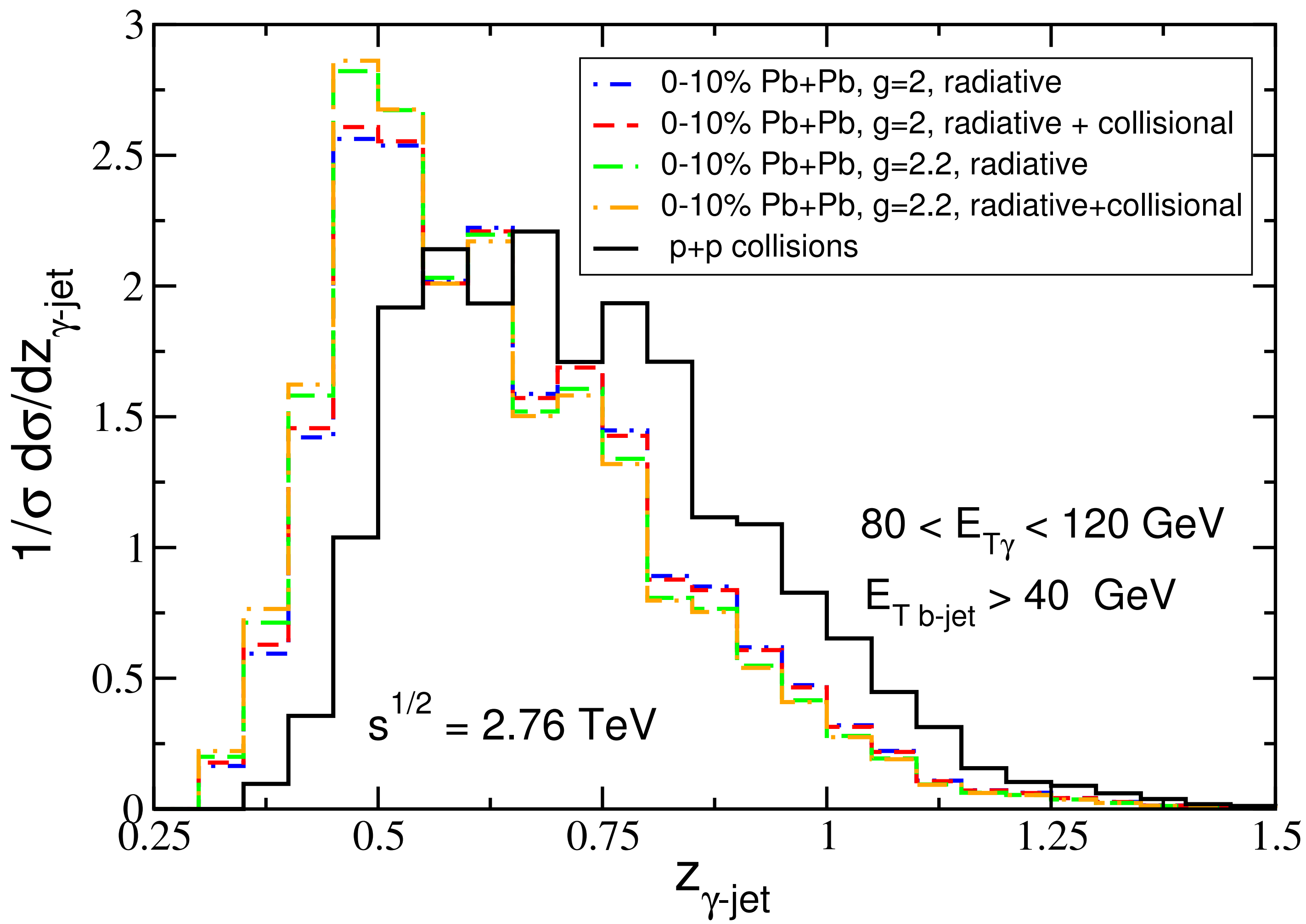
- On the region of pT < 150 GeV, strong isolation cut could increase the fraction of b-jets coming from prompt b-quarks by 2-3. We will work on this limit for the moment.

Photon-tagged b-jet momentum imbalance

- Imbalance variables

Huang-Kang-Vitev-Xing, 2014, in preparation

$$Z_J = \frac{p_{T\ jet}}{p_{T\ \gamma}} \qquad \frac{d\sigma}{dz_{J\gamma}} = \int_{p_{T_{\rm jet}}^{min}}^{p_{T_{\rm jet}}^{max}} dp_{T_{\rm jet}} \frac{p_{T_{\rm jet}}}{z_{J\gamma}^2} \frac{d\sigma[z_{J\gamma}, p_{T_\gamma}(z_{J\gamma}, p_{T_{\rm jet}})]}{dp_{T_\gamma} dp_{T_{\rm jet}}}$$



- Little effect of collisional energy loss, quenching and asymmetric effects dominated by radiative energy loss

Goal of Jet collaboration

- Quote from Jet proposal

Proposal for a Topical Collaboration on

Quantitative Jet and Electromagnetic Tomography (JET) of Extreme Phases of Matter in Heavy-ion Collisions

Abstract

emission can be calculated within pQCD. Through a network of theorists and in collaboration with experimentalists and external associates, the JET Collaboration will: (a) extend the theoretical framework for jet-medium interaction beyond soft and collinear approximations and thereby reduce uncertainties intrinsic to the current theoretical studies; (b) develop new and powerful Monte

1.3 JET Collaboration: Scientific Goals

- Extend the calculation of medium induced gluon bremsstrahlung beyond collinear and soft approximation and explore matching schemes connecting collinear and hard gluon radiation, thereby reducing a major theoretical uncertainty in jet tomographic studies.

Summary

- Along the way we develop the powerful MC tools for jet quenching, there are also important theoretical improvements/progress we can make
  - See talk by Tseh Liu
- We study the QCD evolution of qhat in terms of standard factorization framework
- We investigate the energy loss beyond soft approximation
- Heavy flavor jets are very interesting ...

Summary

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Thank you