Novel Phenomenon of Jet Quenching and Coherent Multiple Scattering in QCD

- Happy birthday – Xin-Nian!
- Jet production and jet quenching
- QCD factorization approach to jet production and jet quenching
- Coherent multiple scattering and color entanglement
- Summary and outlook

Jianwei Qiu
Jefferson Lab, Theory Center

"Shocking Reality"

Xin-Nian is 60!

Really? It is hard to believe!

Everyone, older and younger,
whom I talked to in last a month or so about this symposium
in honor of Xin-Nian's 60th birthday,
cannot believe that Xin-Nian is 60 now

"Shocking Reality"

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Well,
Calendar rolls, Xin-Nian is 60!
LET'S CELEBRATE!

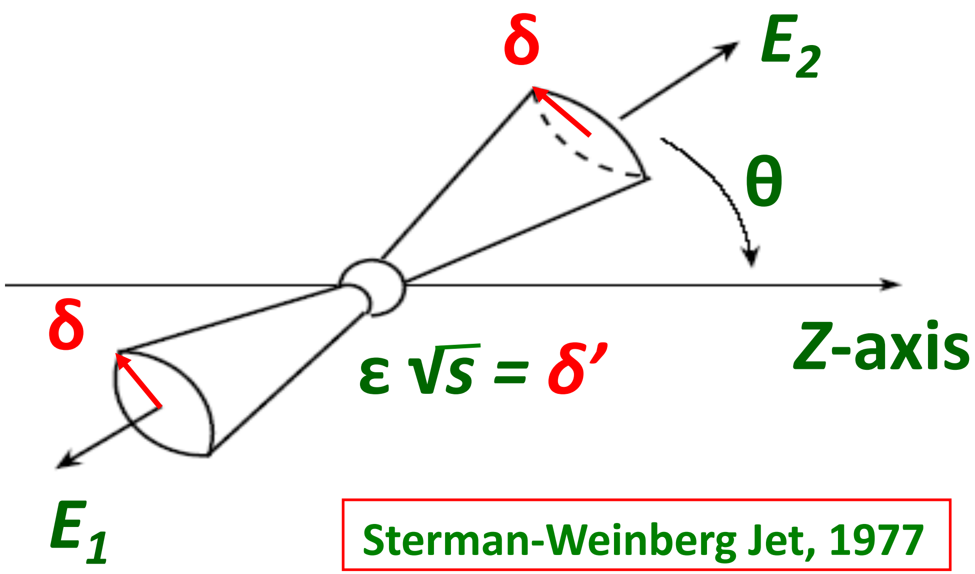
HAPPY BIRTHDAY, XIN-NIAN!

Jet production and jet quenching

- **Jet = Inclusive cross section with limited phase space:**

$$d\sigma(\Gamma) \equiv \frac{1}{2!}\int d\Omega_2 \frac{d\sigma^{(2)}}{d\Omega_2}\Gamma_2(k_1,k_2) + \frac{1}{3!}\int d\Omega_3 \frac{d\sigma^{(3)}}{d\Omega_3}\Gamma_3(k_1,k_2,k_3) + \ldots + \frac{1}{n!}\int d\Omega_n \frac{d\sigma^{(n)}}{d\Omega_n}\Gamma_n(k_1,k_2,\ldots,k_n) + \ldots$$

where $\Gamma_n(k_1,k_2,\ldots,k_n)$ are constraint functions and invariant under interchange of n-particles



Sterman-Weinberg Jet, 1977

Special case: $\Gamma_n(k_1,k_2,\ldots,k_n) = 1 \text{ for all } n \Rightarrow \sigma^{(\text{tot})}$

Different constraint function = different jet algorithm

No any specific hadron!

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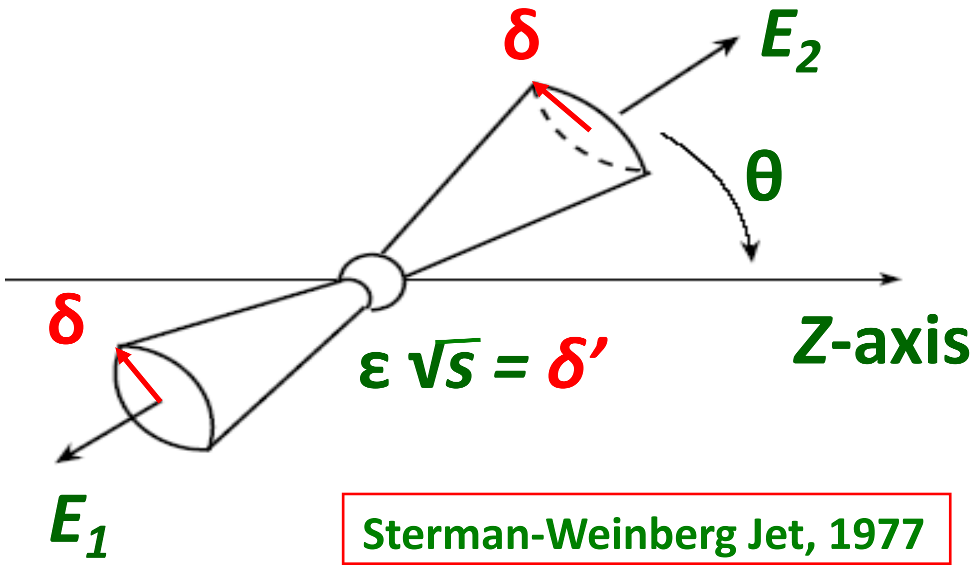

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Special case: $\Gamma_n(k_1,k_2,\ldots,k_n) = 1$ for all n $\Rightarrow$ $\sigma^{(\text{tot})}$

- **Conditions for IR Safety of dσ(Γ):**

$$\Gamma_{n+1}\left(k_1,k_2,\ldots,(1-\lambda)k_n^\mu,\lambda k_n^\mu\right) = \Gamma_n\left(k_1,k_2,\ldots,k_n^\mu\right) \quad \text{with} \quad 0 \le \lambda \le 1$$

Different constraint function = different jet algorithm

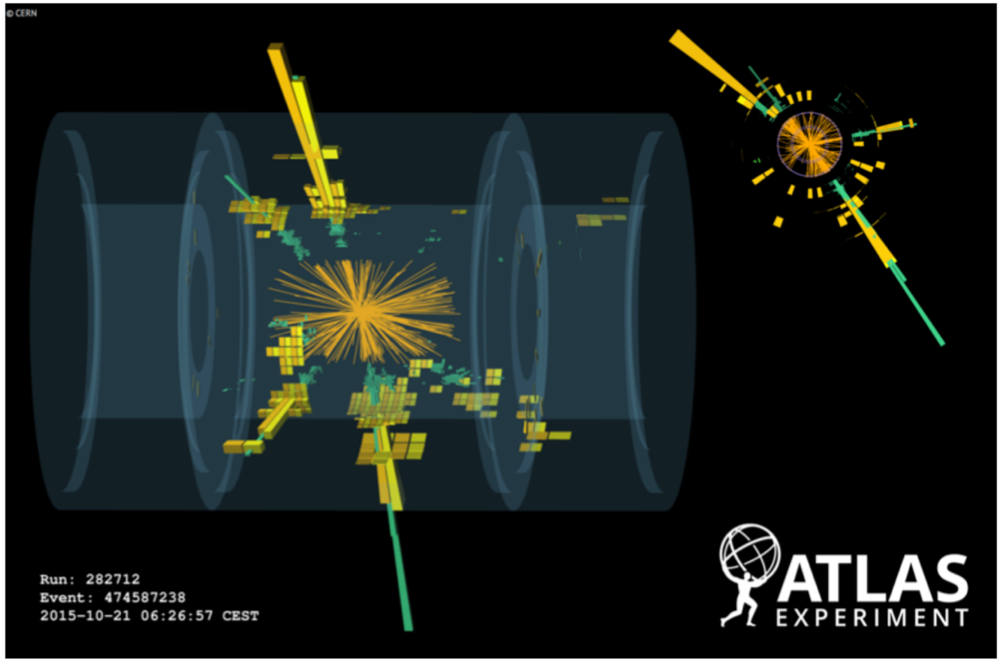
No any specific hadron!

Measurement cannot distinguish a state with a zero/collinear momentum parton from a state without this parton – inclusiveness!

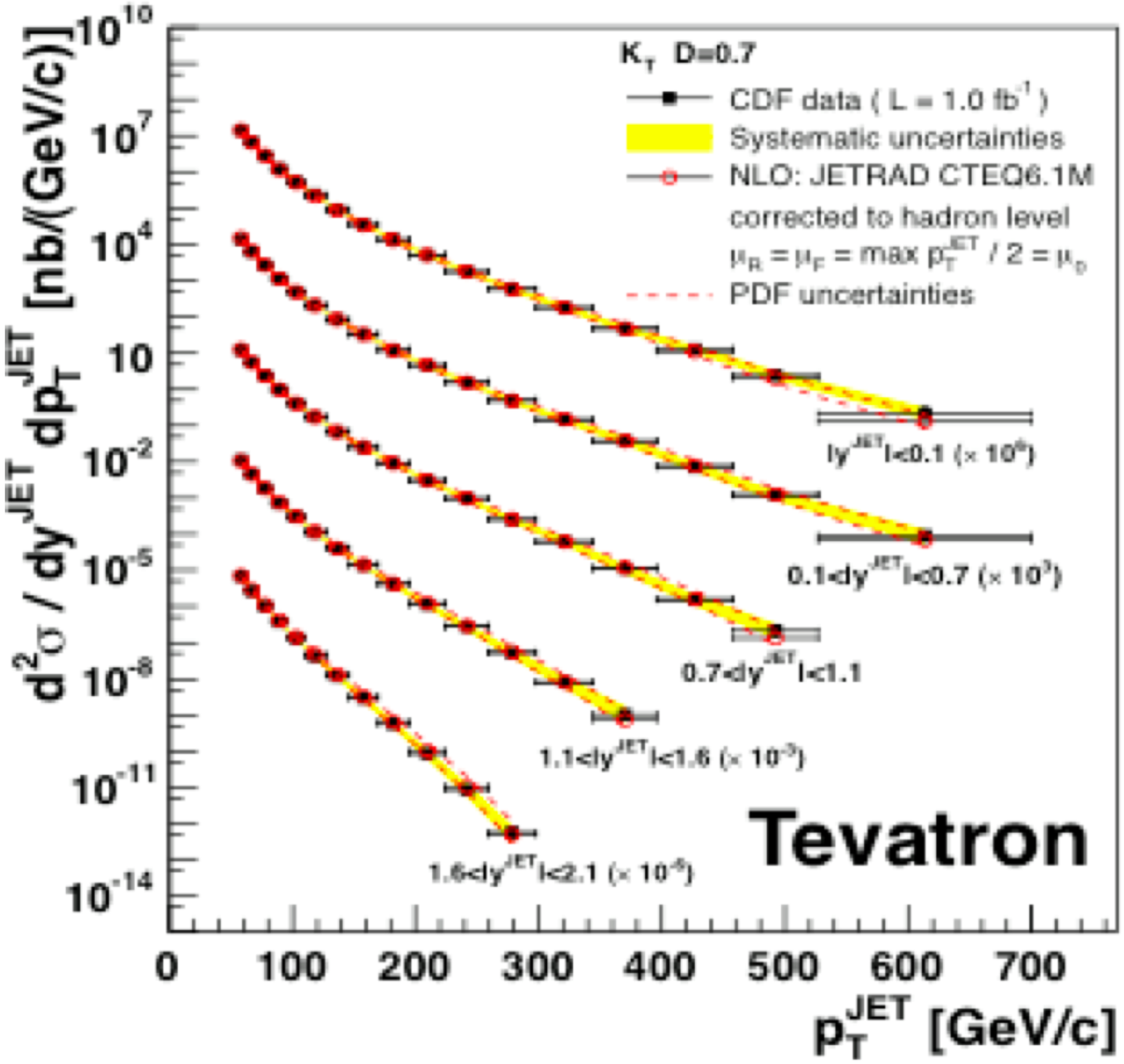
- **Jet provides the "footprint" or "trace" of an energetic quark or a gluon**

Jet production in pp collision

$$pp \to \text{jet} + X$$



- Inclusive jet cross section $\dfrac{d\sigma^{pp\to \text{ jet } +X}}{dp_T d\eta}$
- Precision calculations available in perturbative QCD



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Jet production in pp collision

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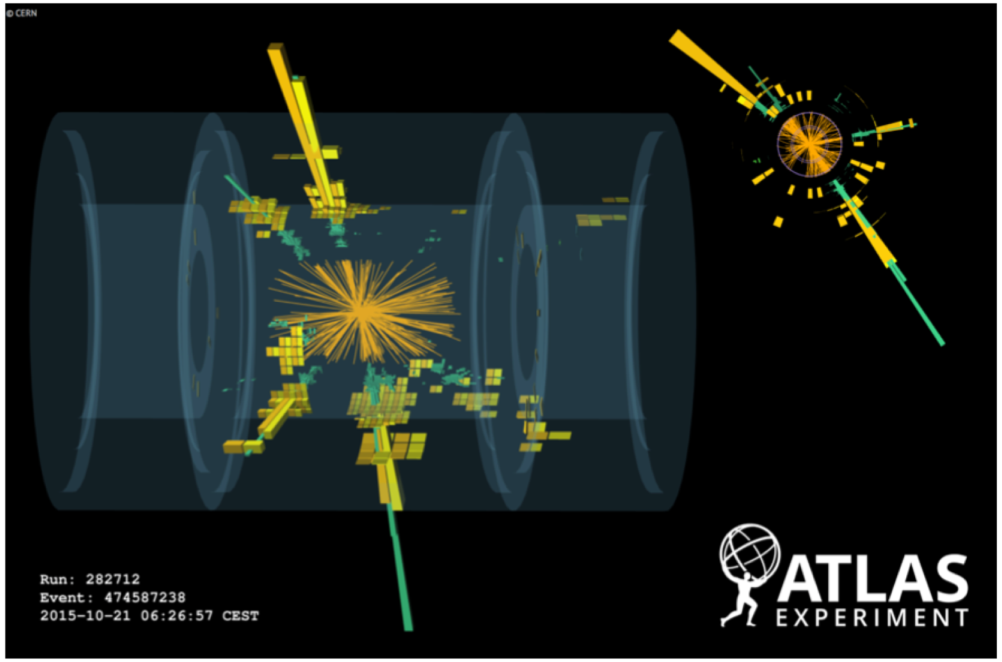

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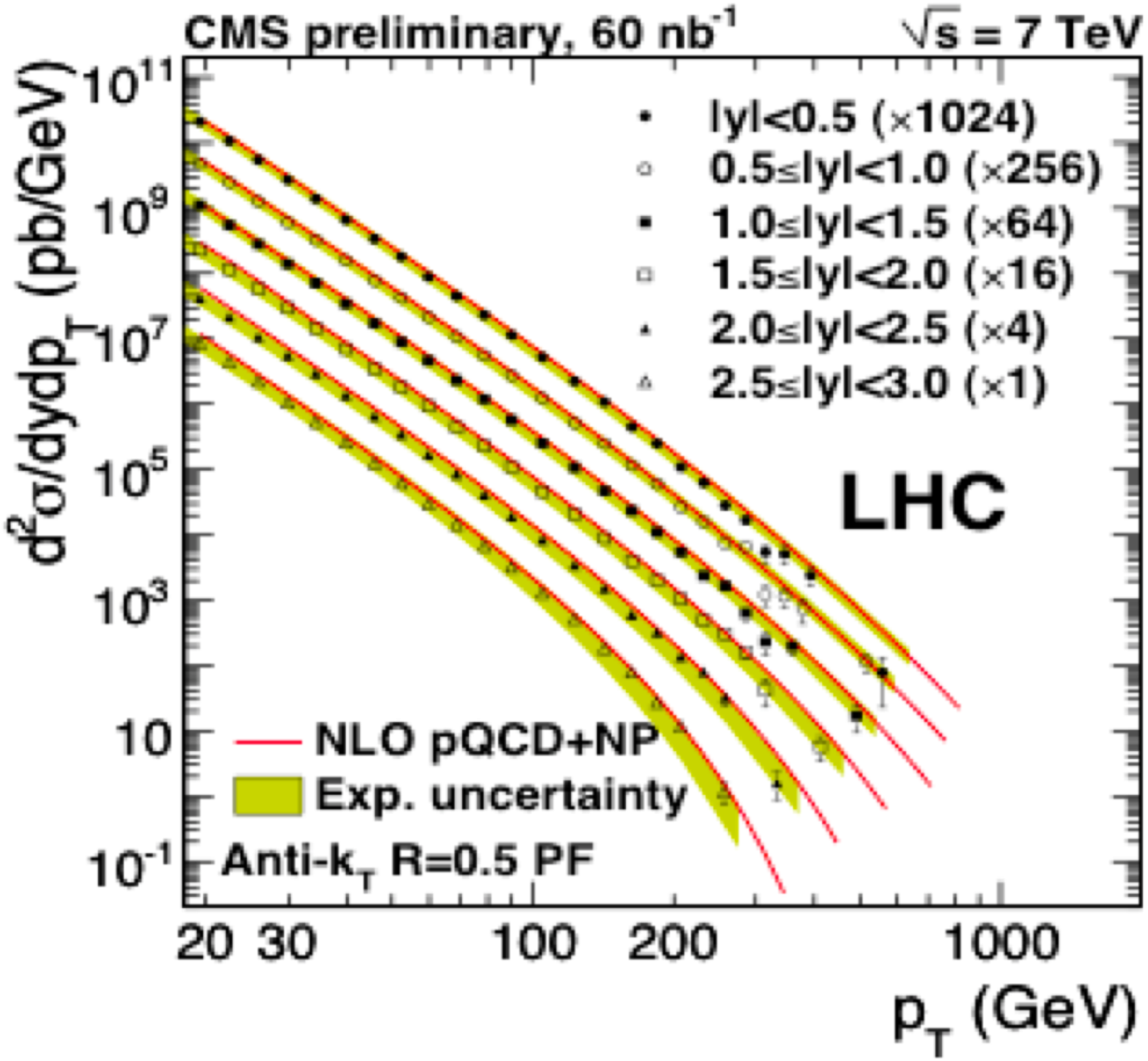

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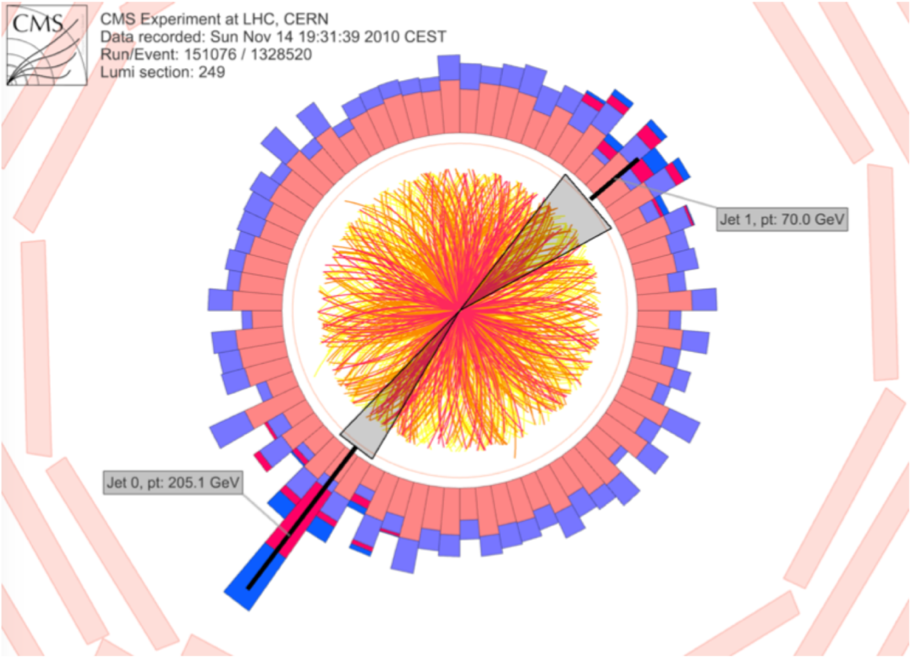
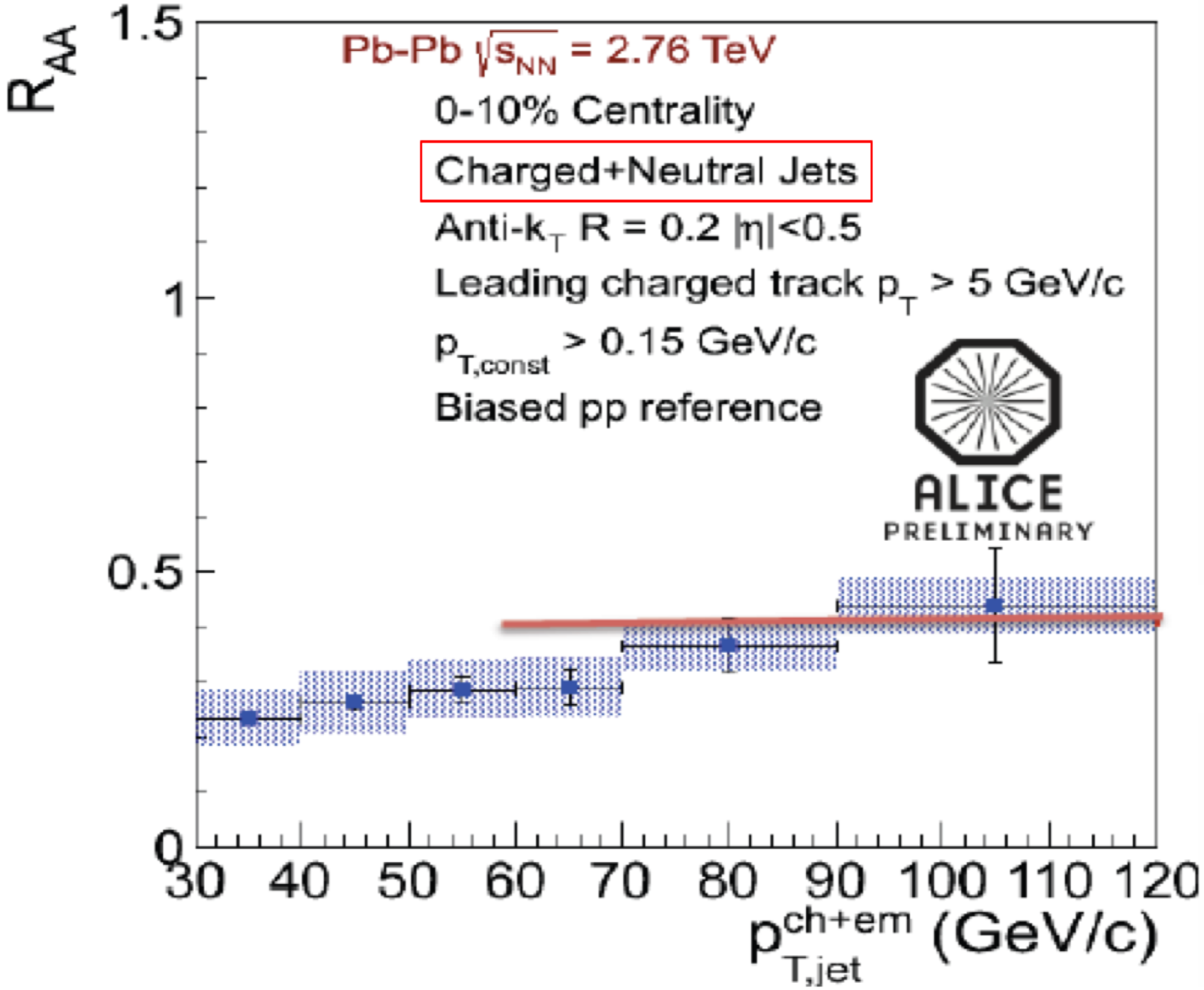
Jet production in AA collision

$$AA \to \text{jet} + X$$



- Nuclear modification factor $R_{AA}^{\text{jet}} = \dfrac{d\sigma^{\text{PbPb}\to\text{jet}+X}}{\langle T_{AA}\rangle\, d\sigma^{pp\to\text{jet}+X}}$
- QCD Factorization?

Suppression of jets – Jet quenching



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Jet production in AA collision

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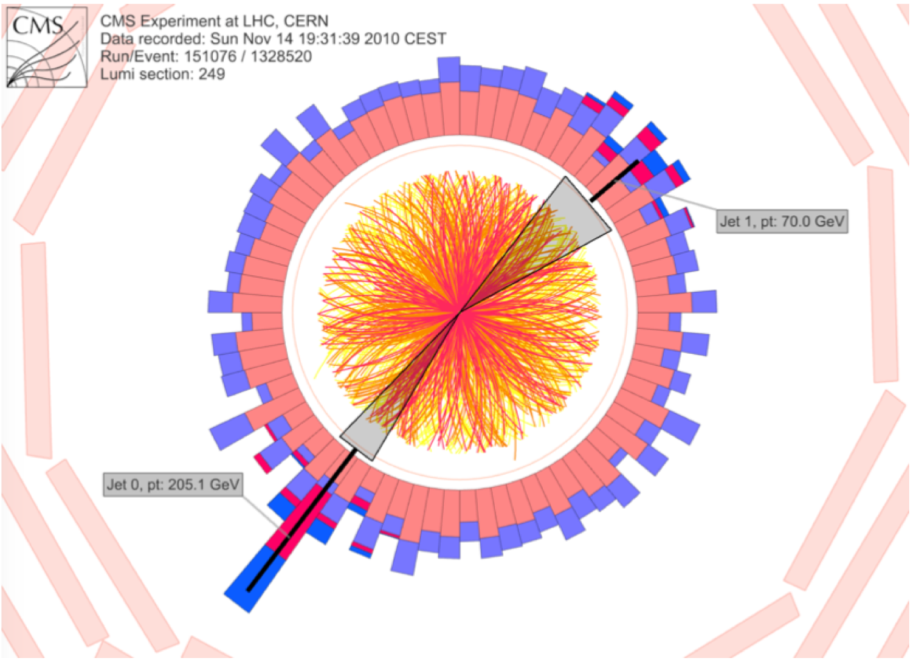

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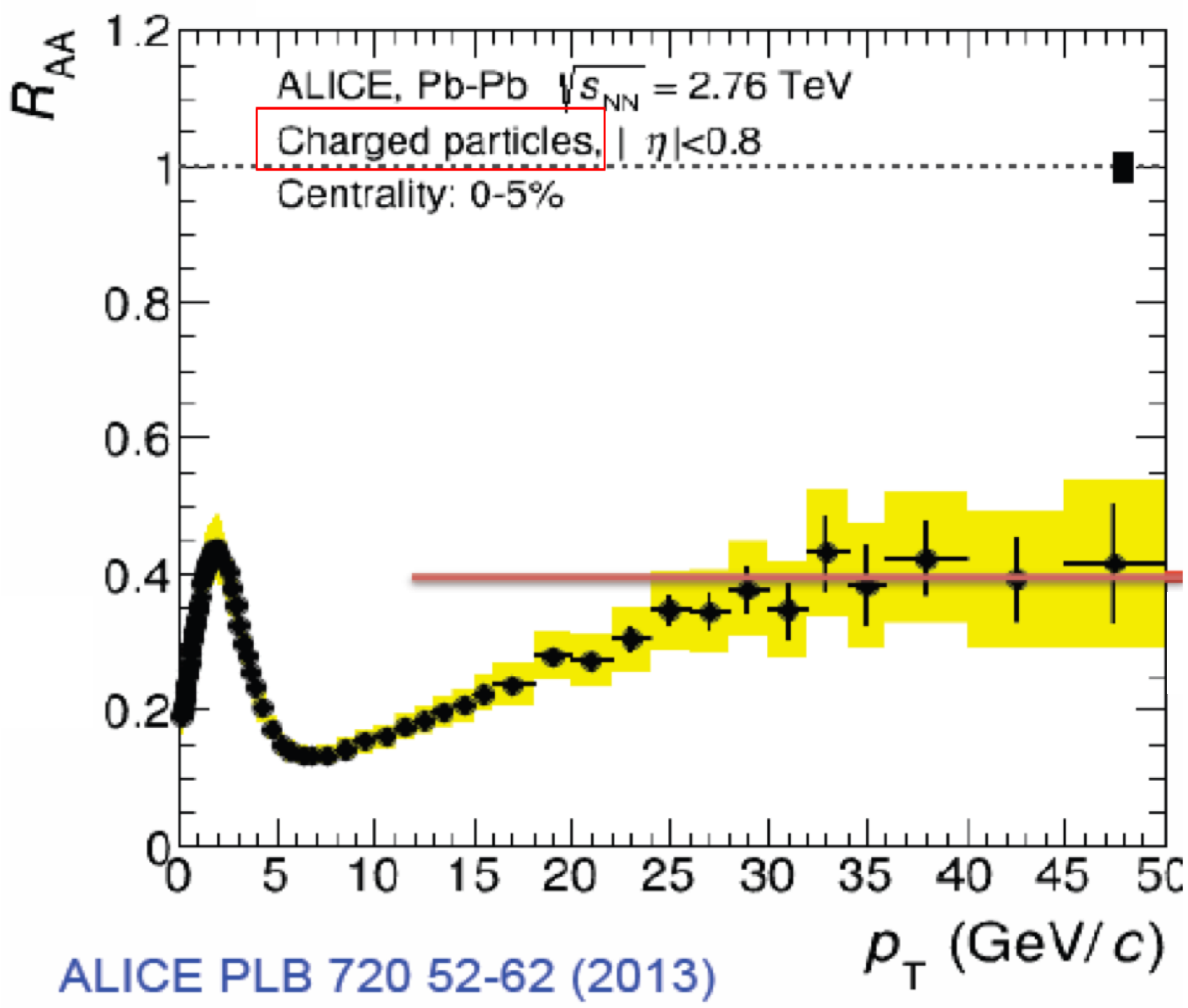

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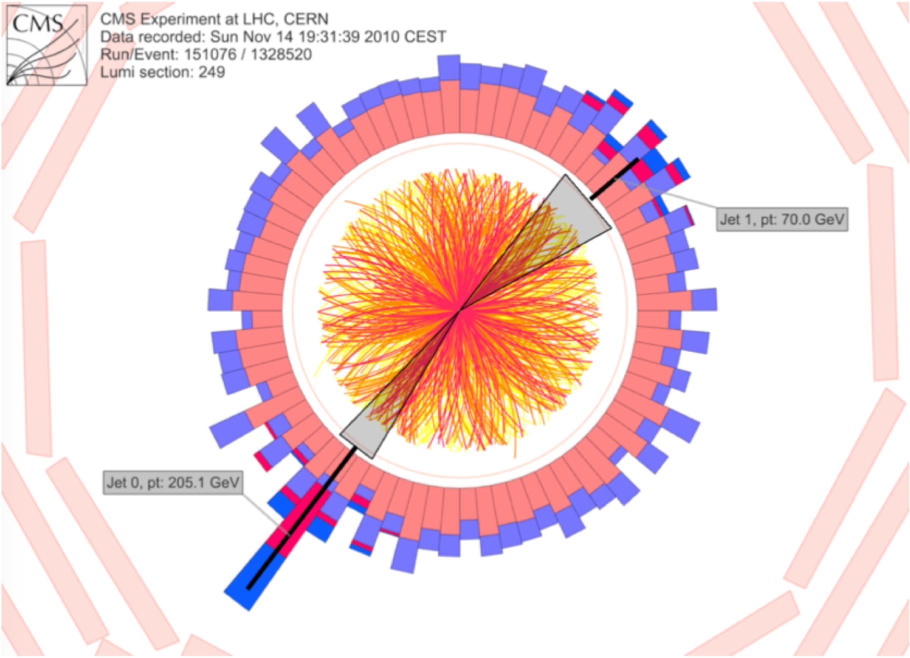
Jet production in AA collision

$$AA \to \text{jet} + X$$



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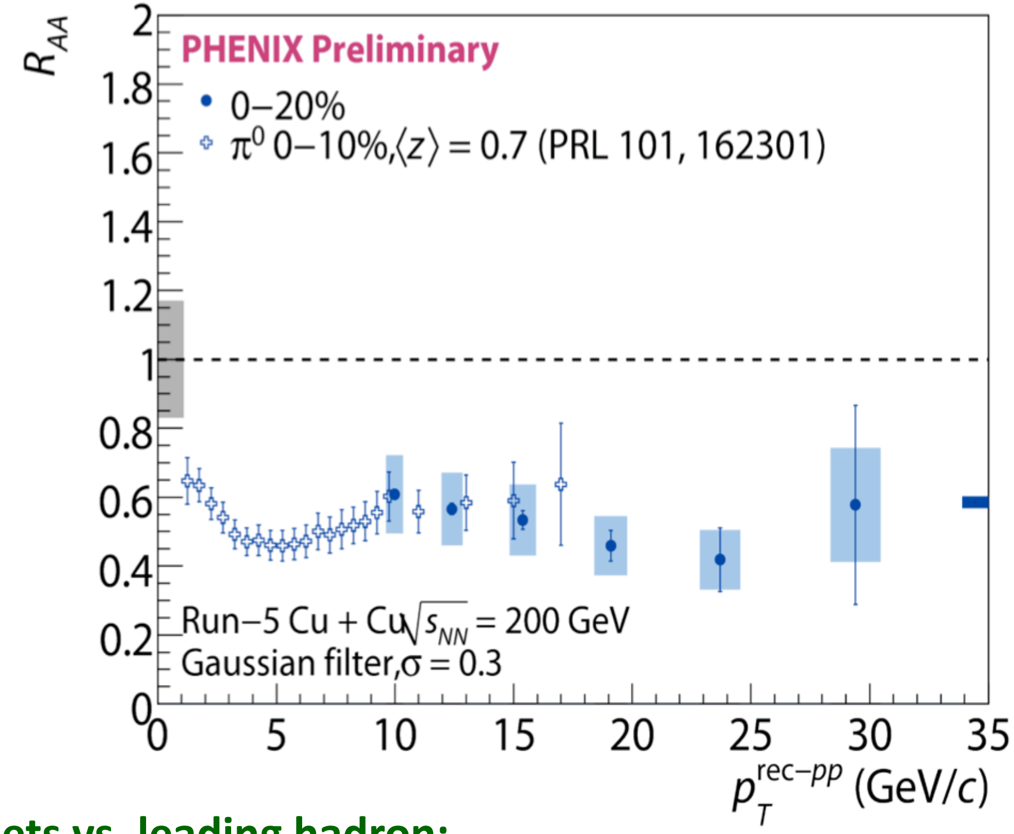
Qiu, Ringer, Sato, & Zurita, PRL 122 (2019) 252301, …

Suppression of jets – Jet quenching



Jets vs. leading hadron:

Narrow jet → ***Same suppression as leading hadron***

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QCD factorization for Jet production

❑ Inclusive jet production in pp collision:

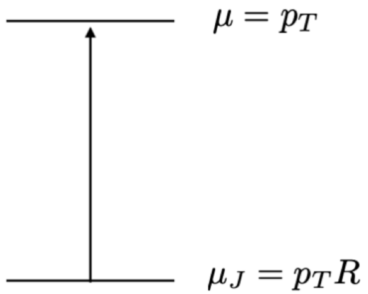
PDFs | Jet functions

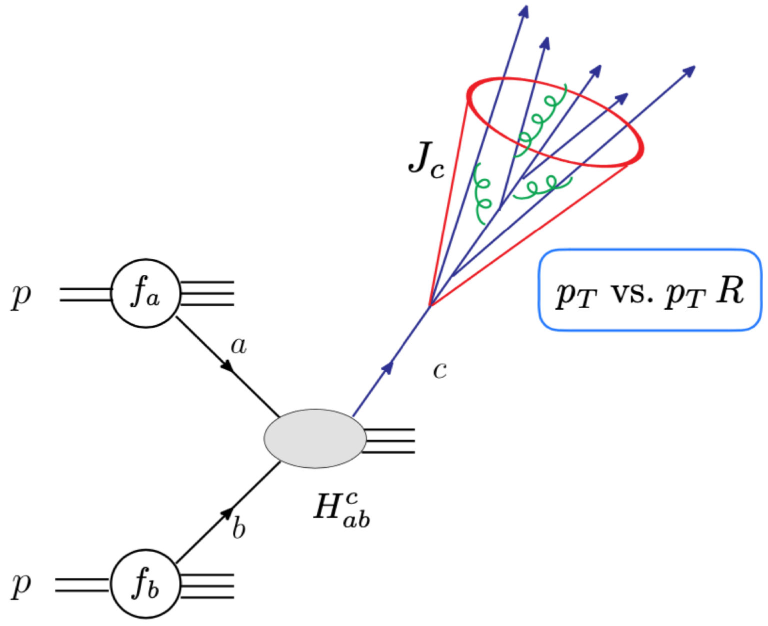
$$\frac{d\sigma^{pp\to \text{jet}+X}}{dp_T d\eta} \approx \sum_{a,b} f_a \otimes f_b \otimes \mathcal{H}_{ab\to \text{jet}+X} \approx \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

Hardpart to produce a single parton

- Hard and jet function calculable
- DGLAP evolution equation
- Resummation of $\alpha_s^n \ln^n R^2$

$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$





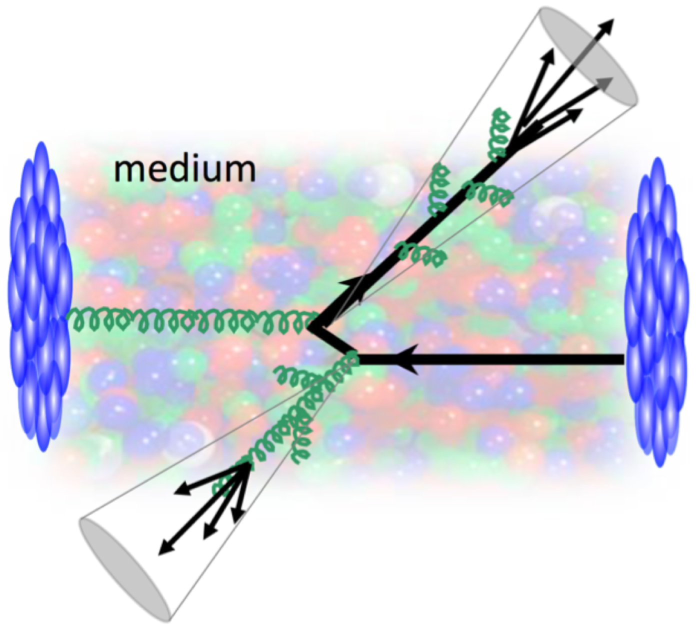
Ellis, Kunszt, Soper `90
Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16
…

❑ Predictive power of factorization approach relies on:

(1) Ability to calculate IRS functions, (2) Universality of long-distance functions, (3) can neglect power corrections

QCD factorization for Jet production

- **Inclusive jet production in AA collision:**



Q: Can we have the similar factorization formalism for jet production in AA collision?

Yes!
for the LP contribution in power of $1/p_T$ expansion!

Q: How large the hard scale needs to be for us to be able to neglect the power corrections?

Q: Can we understand/calculate the medium-induced power corrections to be able to predict the jet production in AA collision (or the suppression) for not too large p_T?

QCD factorization for Jet production

❑ Example: hard probes in eA collisions:

$$\frac{d\sigma^{eA\to e+X}}{dx_B dQ^2} \approx \sum_a f_{a/A} \otimes \mathcal{H}_{ea\to e+X} + \mathcal{O}\left(\frac{1}{Q^n}\right)$$

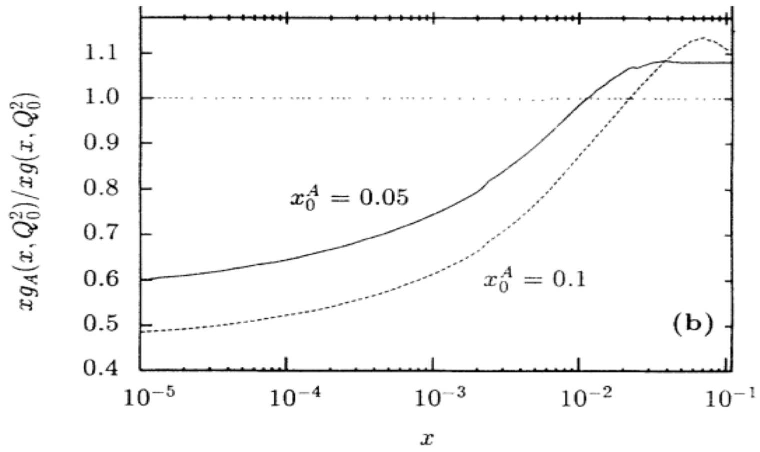
Understand the A-dependence of $f_{g/A}$

VOLUME 72, NUMBER 1 PHYSICAL REVIEW LETTERS 3 JANUARY 1994

Perturbative Gluon Shadowing in Heavy Nuclei

K. J. Eskola,[1,2] Jianwei Qiu,[3] and Xin-Nian Wang[1]
[1] *Nuclear Science Division, MS70A-3307, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
[2] *Laboratory of High Energy Physics, P.O. Box 9, SF-00014 University of Helsinki, Finland*
[3] *Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
(Received 26 July 1993)

We study how much gluon shadowing can be perturbatively generated through the modified QCD evolution in heavy nuclei. We model in simultaneously fusions from independent constituents and from the same constituent, both in a proton and in a large loosely bound nucleus of $A \sim 200$. In addition to the actual distributions at small x, we study the ratios of the distributions at an initial scale $Q_0 = 2$ GeV, and show that a strong nuclear shadowing can follow from the modified QCD evolution.



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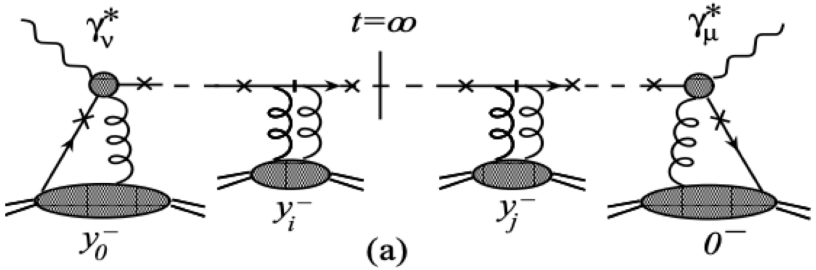
A result of my visit to Xin-Nian at LBNL

QCD factorization for Jet production

- **Example: hard probes in eA collisions:**

$$\frac{d\sigma^{eA\to e+X}}{dx_B dQ^2} \approx \sum_a f_{a/A} \otimes \mathcal{H}_{ea\to e+X} + \mathcal{O}\left(\frac{1}{Q^n}\right)$$

Coherent final-state multiple scattering



Medium-induced and medium-size enhanced coherent power corrections can be calculated and resummed

$$F_T^A(x,Q^2) \approx \sum_{n=0}^{N} \frac{A}{n!}\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(LT)}(x,Q^2)}{d^n x}$$

$$\approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right)$$

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Yes!
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Qiu & Vitev, PRL 93 (2004) 262301

Able to describe the A, x, Q dependence of exiting showing data in small-x region

QCD factorization for Jet production

- **Example: hard probes in pA collisions:**

$$\frac{d\sigma^{pA\to\gamma^*+X}}{dy\,dQ^2} \approx \sum_{a,b} f_a \otimes f_{b/A} \otimes \mathcal{H}_{ab\to\gamma*+X} + \mathcal{O}\left(\frac{1}{Q^n}\right)$$

Medium-induced and medium-size enhanced coherent power corrections can be calculated and resumed, such as transverse momentum broadening

$$\langle q_T^n \rangle^{pA} = \int dq_T^2\, q_T^n \frac{d\sigma^{pA\to\gamma^*+X}}{dy\,dQ^2\,dq_T^2} \Big/ \frac{d\sigma^{pA\to\gamma^*+X}}{dy\,dQ^2}$$

$$\langle q_T^2 \rangle^{pA} - \langle q_T^2 \rangle^{pp}$$

Is calculable, & its A-dependence is sensitive to the range of color correlation!

Q: Can we have the similar factorization formalism for jet production in AA collision?

Yes!
for the LP contribution in power of $1/p_T$ expansion!

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Qiu & Sterman Int.J.Mod.Phys.E 12 (2003) 149

QCD factorization for Jet production

Qiu, Ringer, Sato, & Zurita
PRL 122 (2019) 252301, …

❑ Can we do the same for the jet production in AA collisions?

- Proton-proton

$$\frac{d\sigma^{pp\to \mathrm{jet}+X}}{dp_T d\eta} \approx \sum_{abc} f_a \otimes f_b \otimes \mathcal{H}_{ab}^c \otimes J_c$$

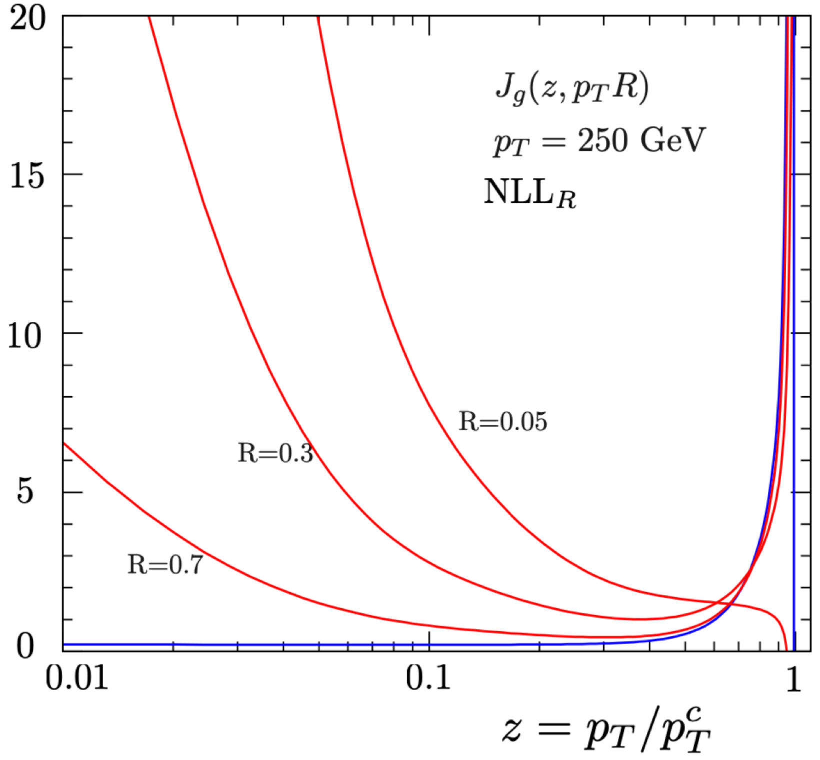
At LP!

- Heavy-ion

$$\frac{d\sigma^{AA\to \mathrm{jet}+X}}{dp_T d\eta} \approx \sum_{abc} f_{a/A} \otimes f_{b/A} \otimes \mathcal{H}_{ab}^c \otimes J_c^{\mathrm{med}}$$

Initial-state: nPDFs

Medium-modified Jet-function
Nonperturbative!



see also: Kang, FR, Vitev `17
He, Pang, Wang `18
Sirimanna, Cao, Majumder `19
…

Medium effect from the modified jet functions:

Medium modification to the jet function

- Introduce a modification at the initial scale $\mu = p_T R$

$$J_c^{\rm med}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c} (1-z)^{\beta_c}$$

- Momentum sum rule

$$\int_0^1 {\rm d}z\, z J_c\,(z, p_T^c R, \mu) = 1$$

- Monte Carlo sampling approach

NNPDF `17, JAM `16

nPDFs Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16
de Florian, Sassot, Zurita, Stratmann `12 …

nFFs Sassot, Stratmann, Zurita `10

- A modification of the evolution?

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} J_i = \sum_j P_{ji} \otimes J_j$$

⇓

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} J_i = \sum_j P_{ji} \otimes J_j + \frac{1}{\mu^2} \Gamma \otimes T$$

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} T = \gamma \otimes T$$

Kang, Ma, Qiu, Sterman `14

If the production cross section is accurate to NLP

Medium modification to the jet function

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$$J_c^{\mathrm{med}}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

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nFFs *Sassot, Stratmann, Zurita `10*

- A modification of the evolution?
- Comparison to medium parton shower

vacuum shower

$\sim \mathcal{O}(10\,\mathrm{GeV})$

medium modified shower

- LBT *Li, Liu, Ma, Wang, Zhu `11*
- MATTER *Majumder `13, Kordell, Majumder `17*

see also Hybrid, JEWEL, Martini, Q-Pythia, JETSCAPE …

Medium modification to the jet function

- Introduce a modification at the initial scale $\mu = p_T R$

$$J_c^{\mathrm{med}}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c}(1-z)^{\beta_c}$$

- Momentum sum rule

$$\int_0^1 \mathrm{d}z\, z J_c\left(z, p_T^c R, \mu\right) = 1$$

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NNPDF `17, JAM `16

nPDFs *Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16*
de Florian, Sassot, Zurita, Stratmann `12 …

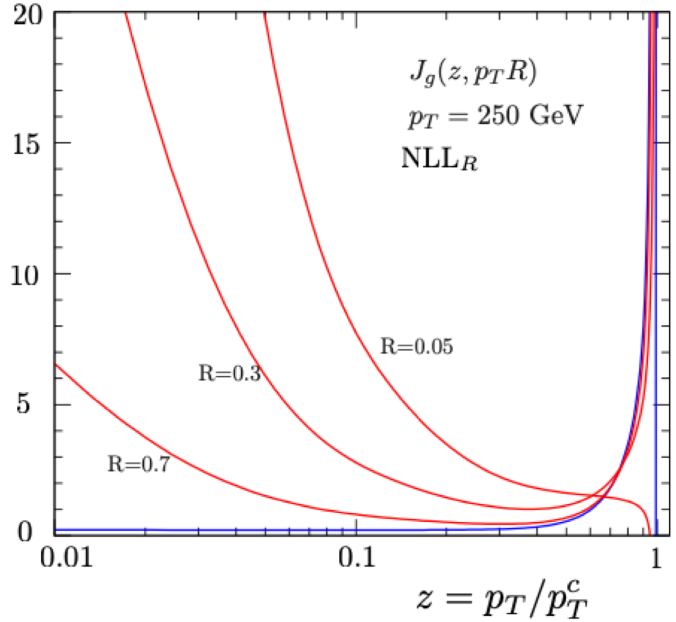
nFFs *Sassot, Stratmann, Zurita `10*

To keep at the LP approximation, we use the data to fit the J^{med} at lower scale of the evolution:

vacuum shower

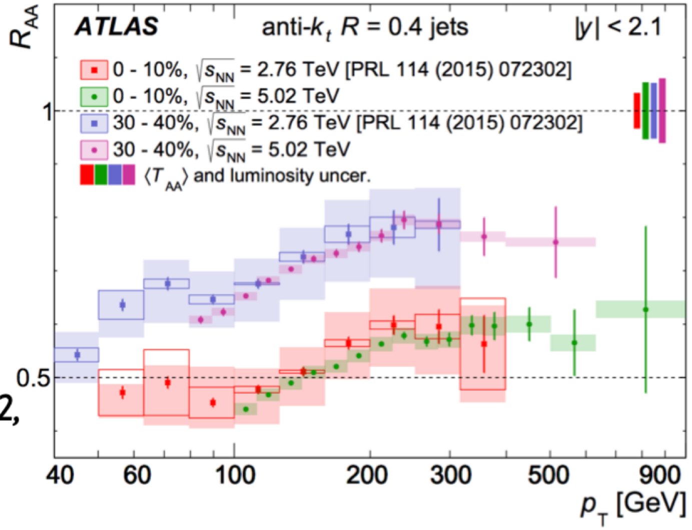
$p_T R$

Fit to data

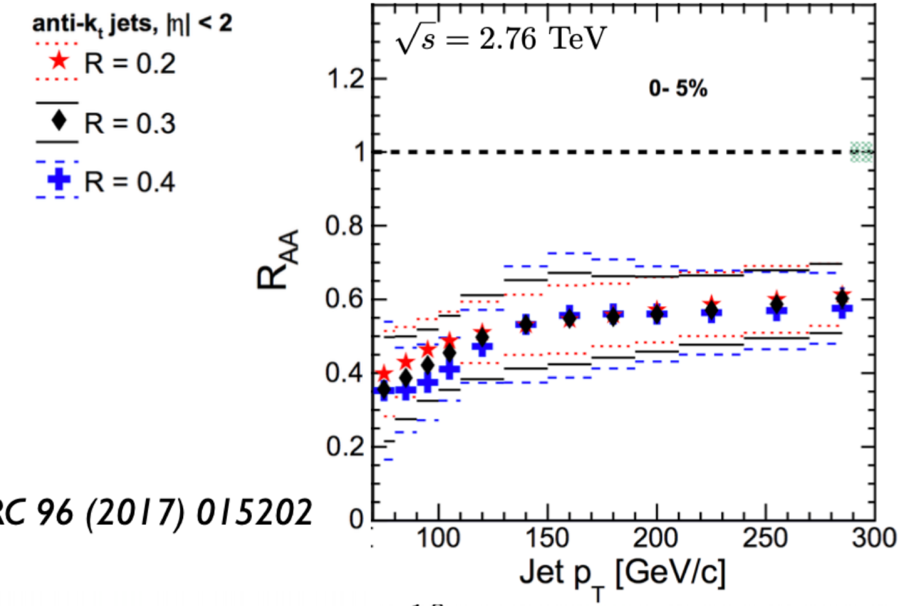


Q: can we get a consistent set of J^{med} at lower scale that can fit all data (at a given kinematic regime?

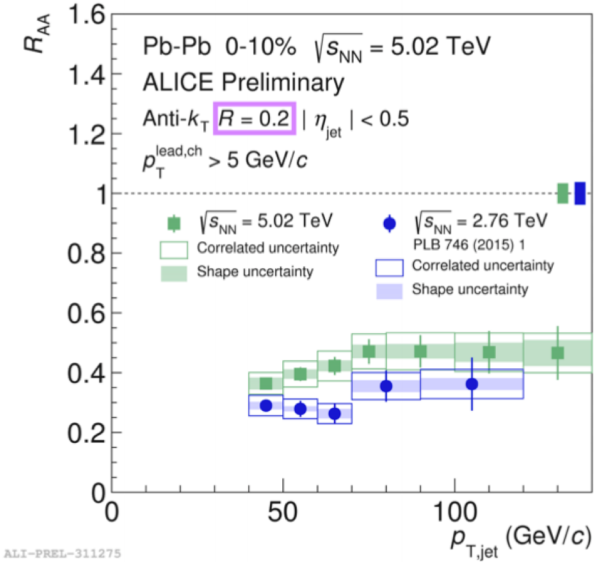
Data included in our initial analysis



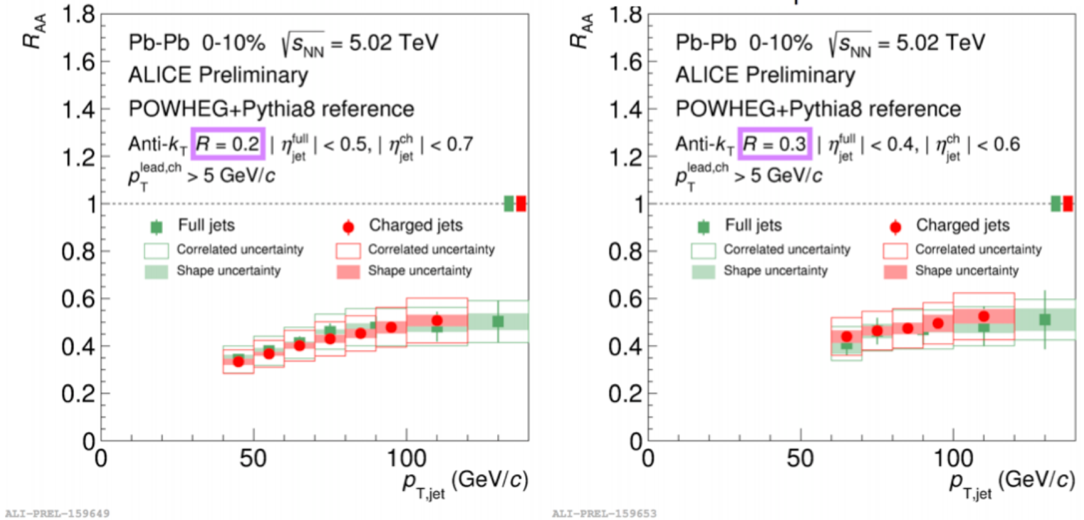
ATLAS, PRL 114 (2015) 072302,
PLB 790 (2019) 108



CMS, PRC 96 (2017) 015202



ALICE, PLB 746 (2015)



ALICE preliminary, J. Mulligan, HardProbes

Jefferson Lab

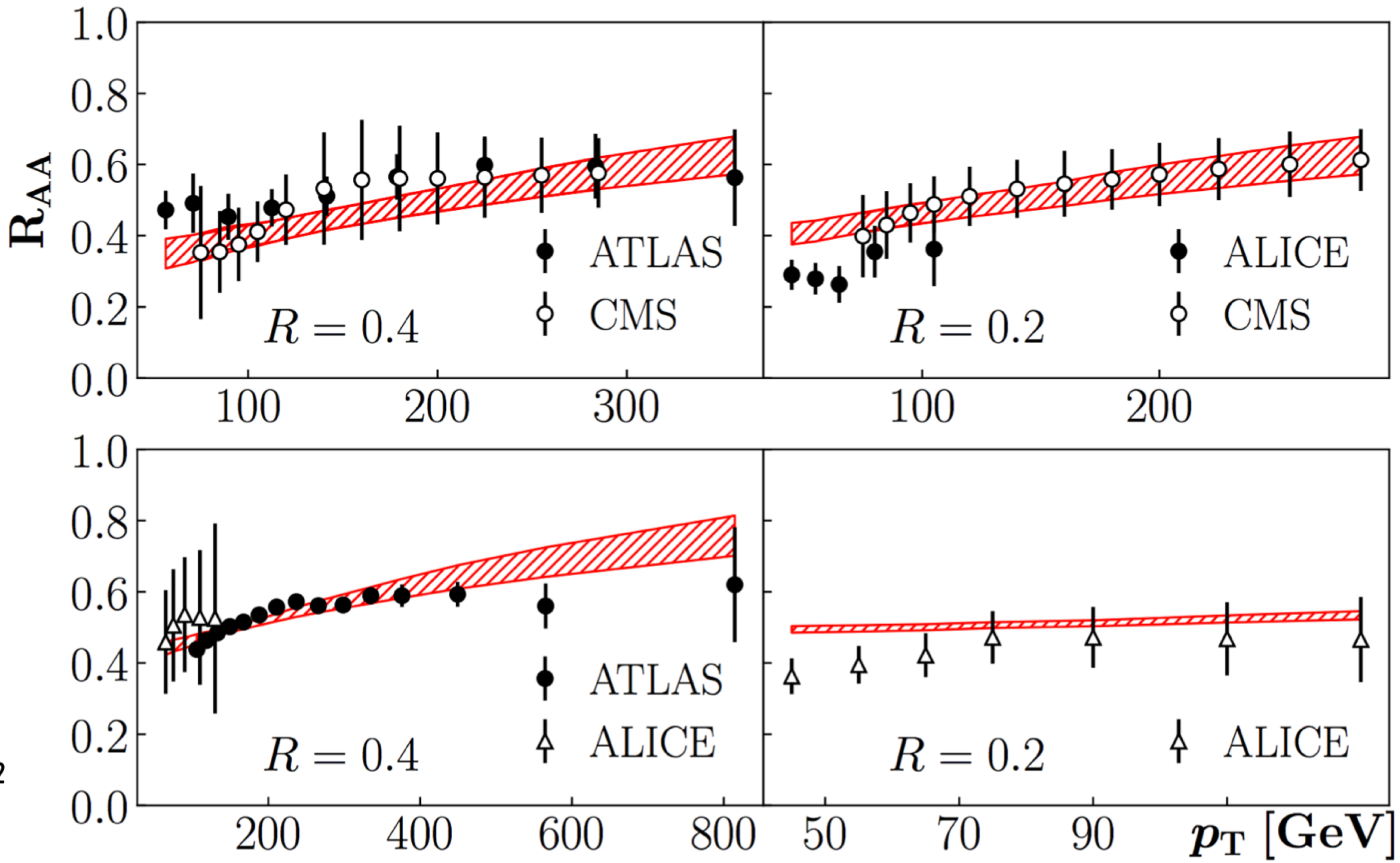
Inclusive jet production in PbPb collision at the LHC

$\sqrt{s_{NN}} = 2.76$ TeV

$\chi^2/\text{d.o.f.} = 1.1$

$\sqrt{s_{NN}} = 5.02$ TeV

$\chi^2/\text{d.o.f.} = 1.7$



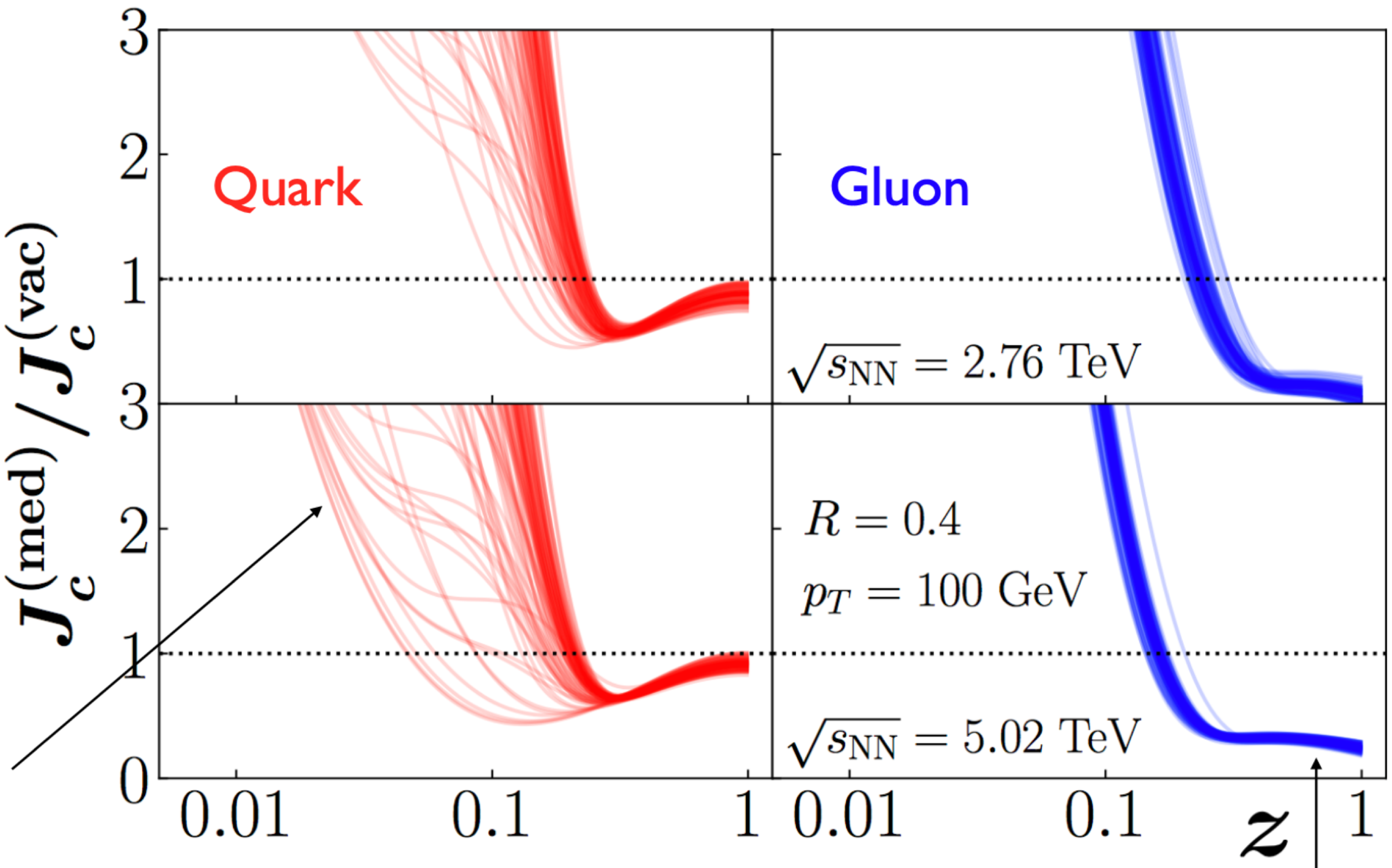
ALICE, PLB 746 (2015) 1
ATLAS, PRL 114 (2015) 072302
CMS, PRC 96 (2017) 015202

ALICE preliminary, J. Mulligan, HardProbes18
ATLAS, PLB 790 (2019) 108

No initial state effects or nPDFs

Fit well if p_T is large enough!

Extracted medium-modified jet functions



Small-z region less constrained

Significant suppression of gluons

Due to two steeply falling PDFs, the dominated configuration to the cross section is from small-x and large-z region!

Berger, Qiu & Zhang, Phys.Rev.D 65 (2002) 034006

Summary and Outlook

- High energy Jet production and its quenching is a good probe for medium property
- Leading power factorization formalism should be valid when the hard scale is sufficiently high, but, how high and how useful if putting all medium effect into the boundary condition?
- QCD factorization approach (a special EFT approach) should help control unknown "high order" effects.
- It is critically important for understanding the coherent multiple scattering in QCD (power corrections) to have the confidence on the jet quenching as a precision hard probe
- Lot of work have been done, thanks to Xin-Nian, his collaborators and many others, more works are still needed for diagnosing the properties of hot medium precisely!

Thanks!