Heavy quark physics in heavy-ion collisions

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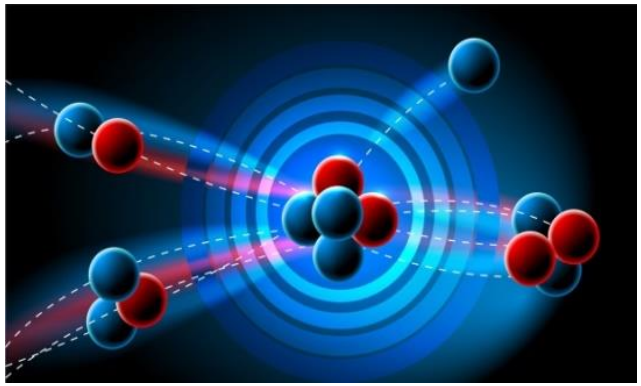
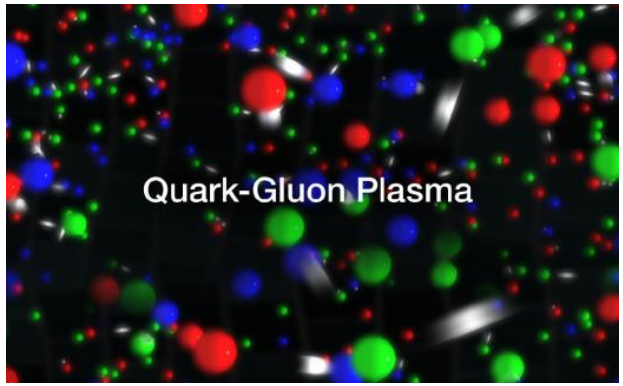
Outline

- Introduction to QGP & HIC
- Heavy quark energy loss and diffusion
- Heavy quark hadronization
- Quarkonia
- Summary

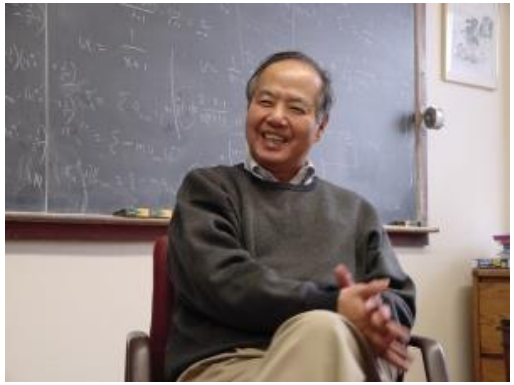
Heating up the matter





How does the matter change when heated?

How to make QGP?

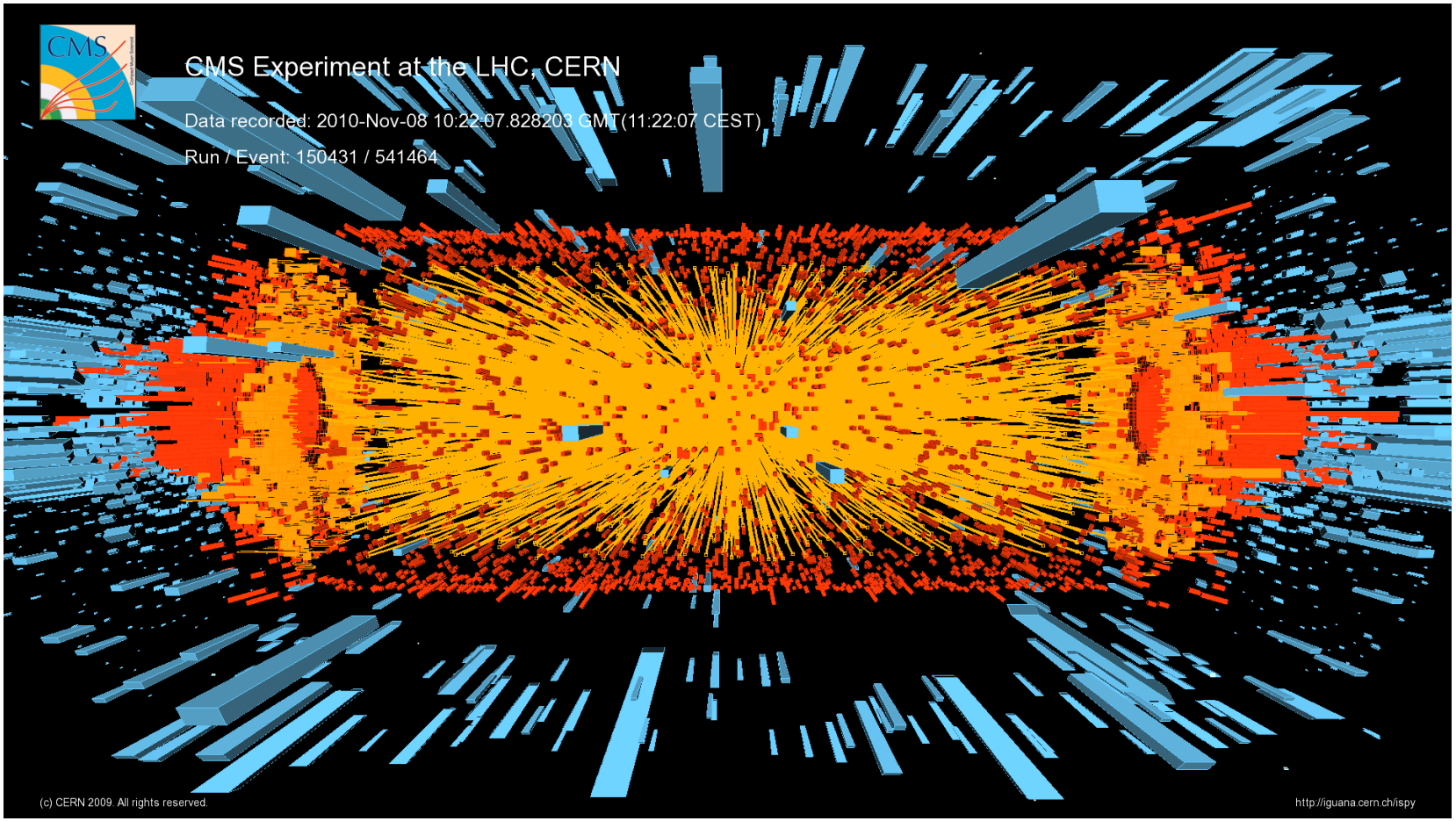


T. D. Lee, “A possible new form of matter”, AIP Conf.Proc. 28 (1976) 65-81

相对论重离子对撞机(RHIC)

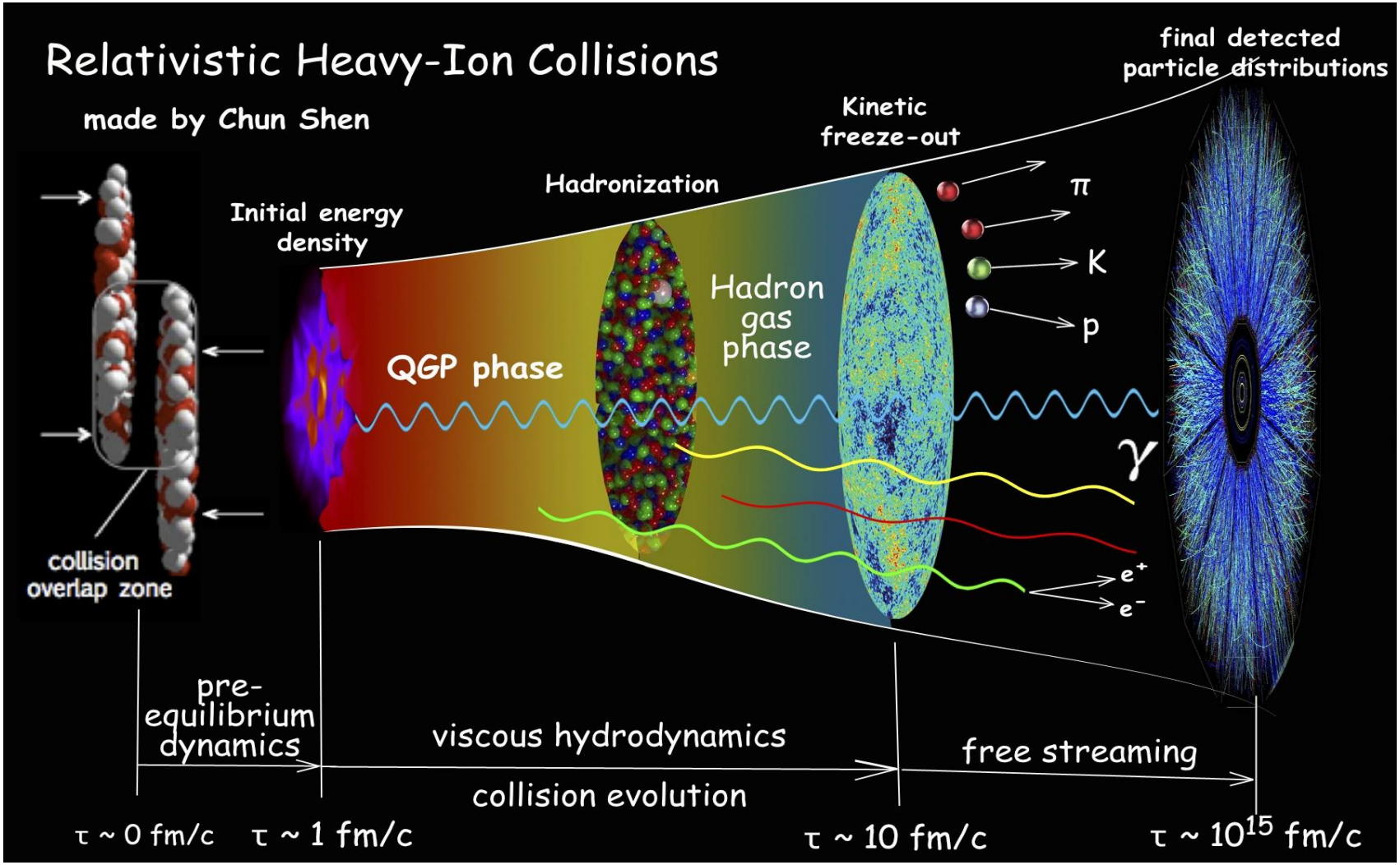
大型强子对撞机(LHC)

Relativstic heavy-ion collisions

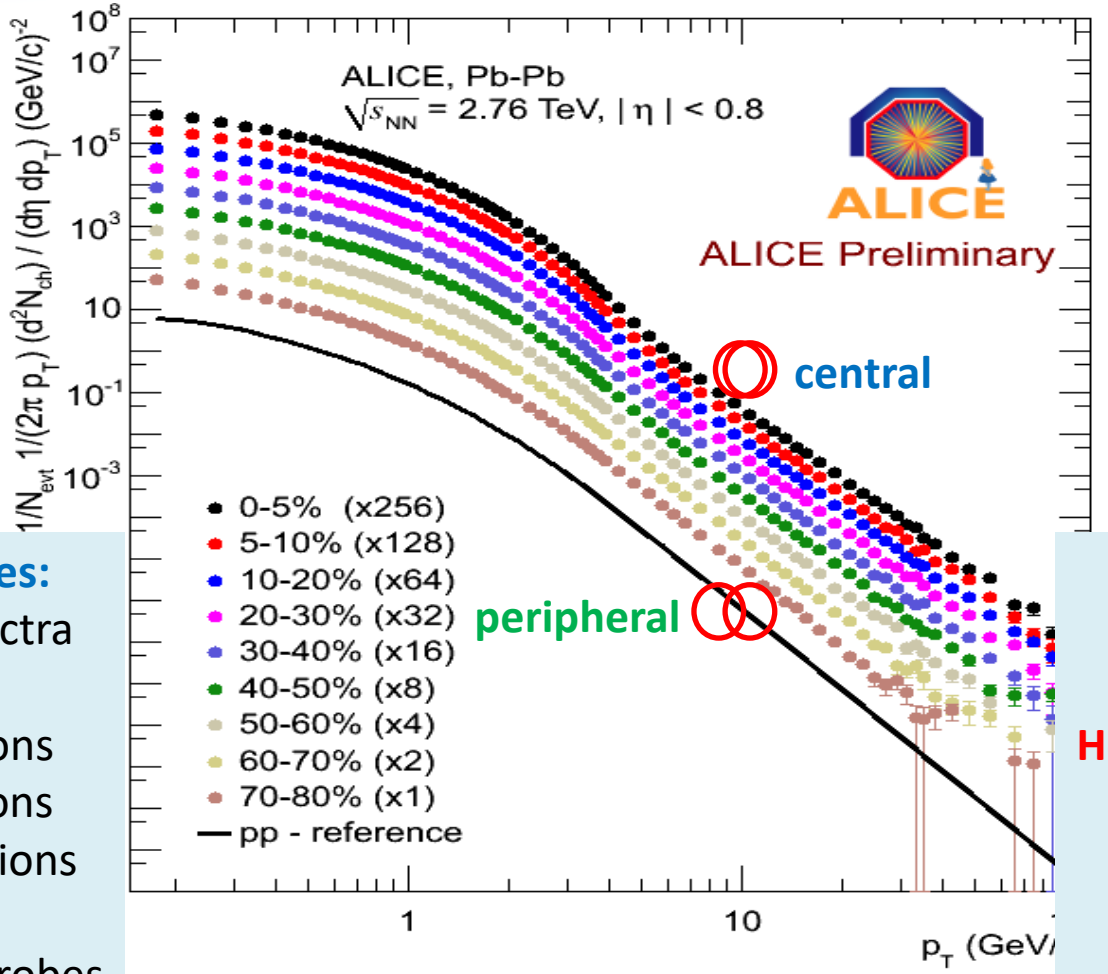


Exploring the novel properties of QGP!

“Standard Model” of HIC @ RHIC & LHC



Probes of QGP in heavy-ion collisions



Soft Probes:
Yields/Spectra
Flows
Fluctuations
Correlations
Decorrelations
…
"Internal" probes

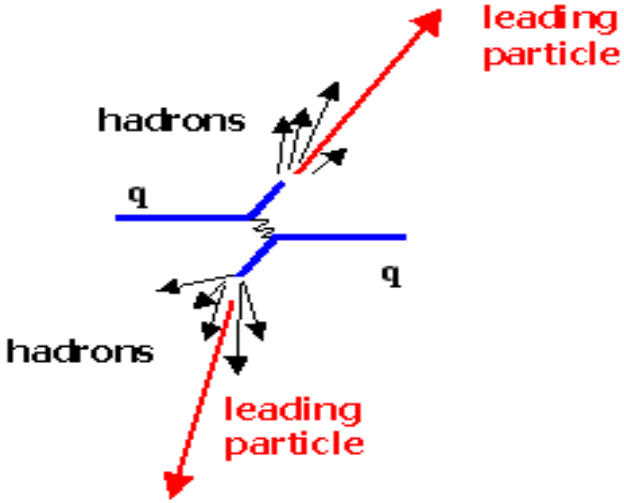
Hard Probes:
Jets
Large p_T hadrons
Heavy quark/hadrons
Quarkonia
EM probes
…
"External" probes

Heavy quarks in heavy-ion collisions

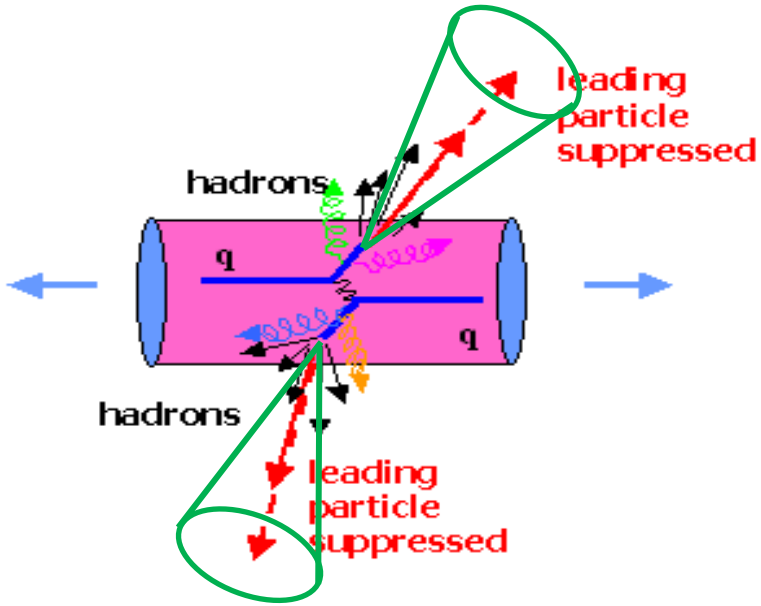
- **Heavy quarks are unique hard probes of QGP**
  - Mainly produced via initial hard scatterings
  - – $M_Q \gg T$, thermal production negligible
  - – $M_Q \gg \Lambda_{QCD}$, pertubative QCD calculable
  - – Experience full QGP evolution
  - – Number conserved during evolution

- **Heavy quarks are versertile probes of QGP**
  - – High p_T: flavor hierarchy of parton energy loss and jet quenching
  - – Low p_T: diffusion and flow
  - – Intermediate p_T: hadronization
  - – Quarkonia: QGP thermometer

Heavy quark energy loss and jet quenching



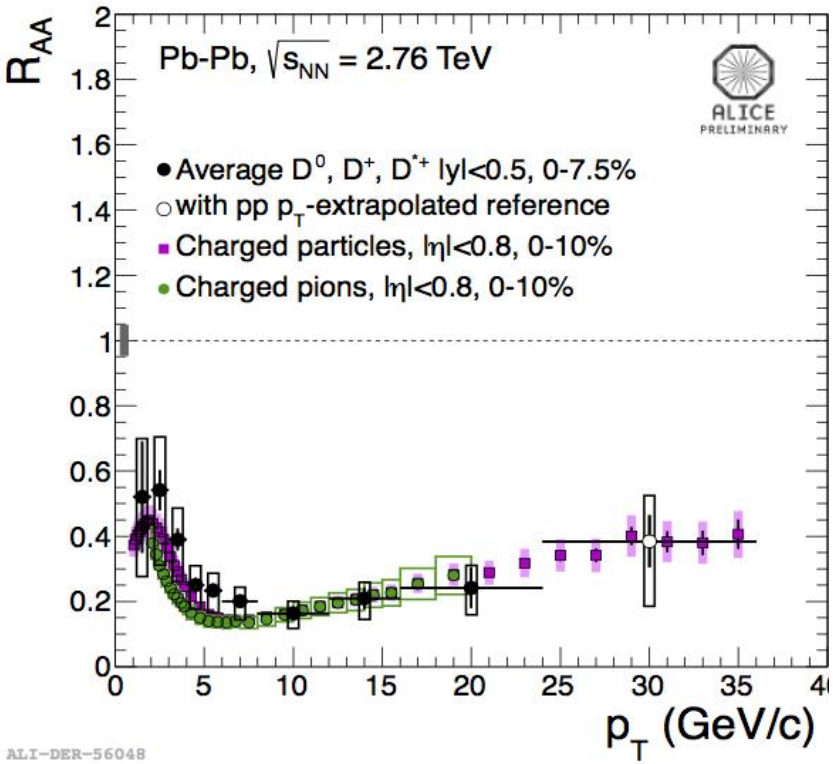
p+p (N+N)

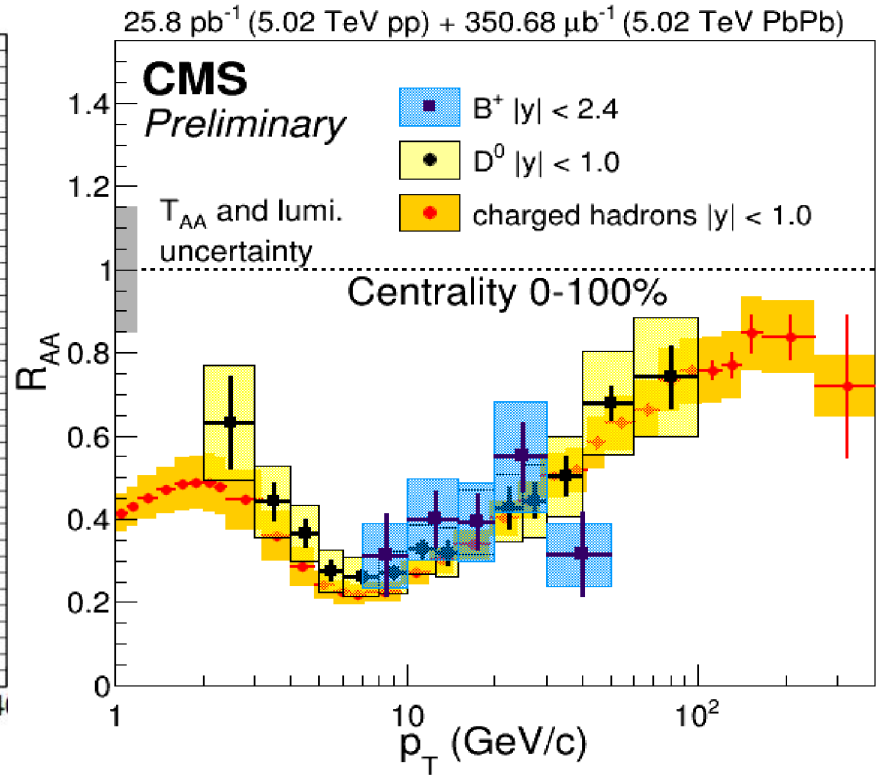


A+A: jet quenching

Flavor hierarchy of parton energy loss: $\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$.

Flavor hierarchy of jet quenching





$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

$\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$,
$R_{AA}(h) \approx R_{AA}(D)$. **Why?**

Linear Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $$p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$$

- **Elastic collisions:**

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right]$$
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)|\mathcal{M}_{12\to34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:** $$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

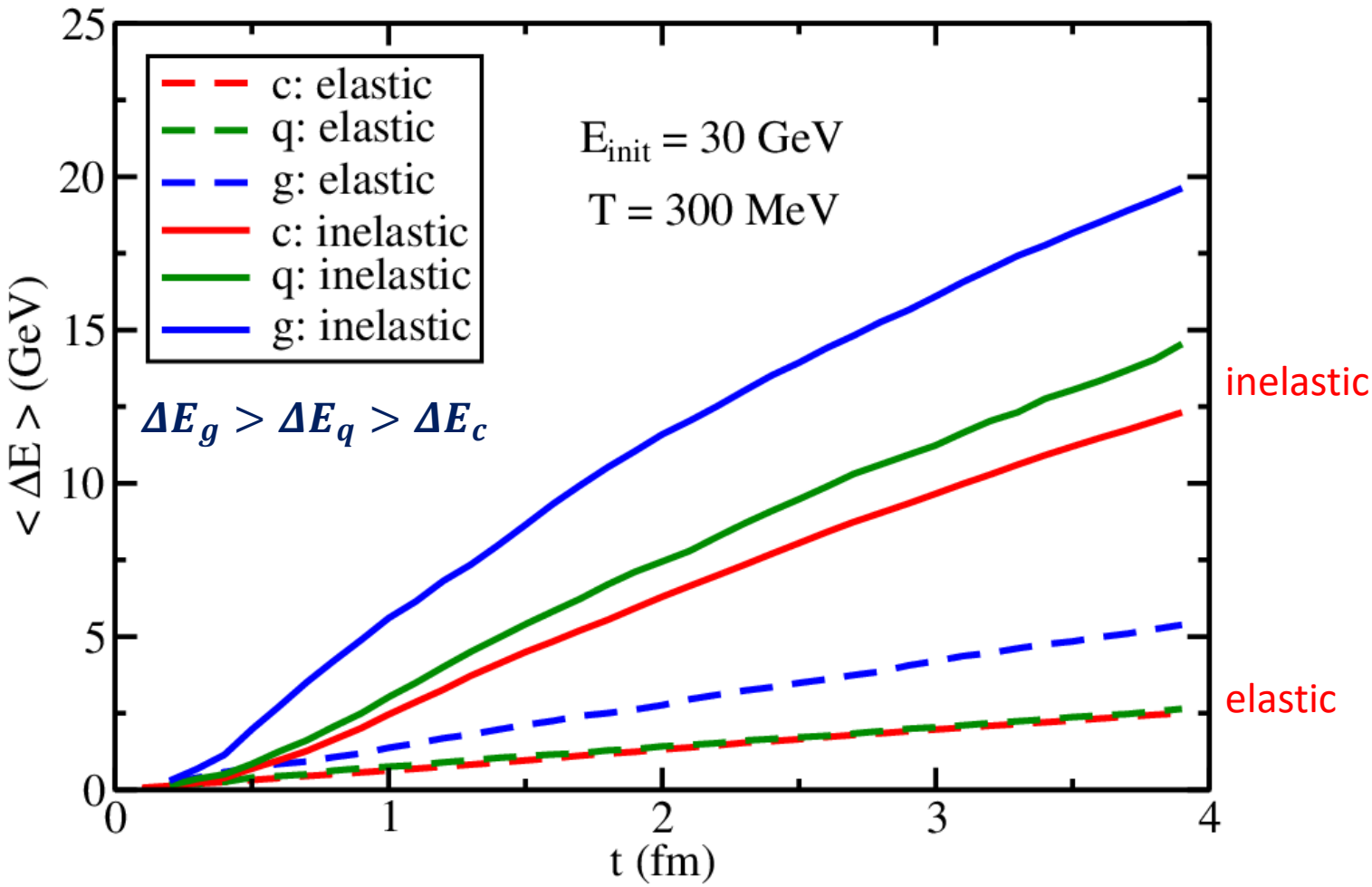
$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

Medium-induced radiation spectra taken from HT: Guo, Wang PRL 2000; Zhang, Wang, Wang, PRL 2004; Zhang, Hou, GYQ, PRC 2019; Zhang, GYQ, Wang, PRD 2019.

- **Elastic + Inelastic:** $$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

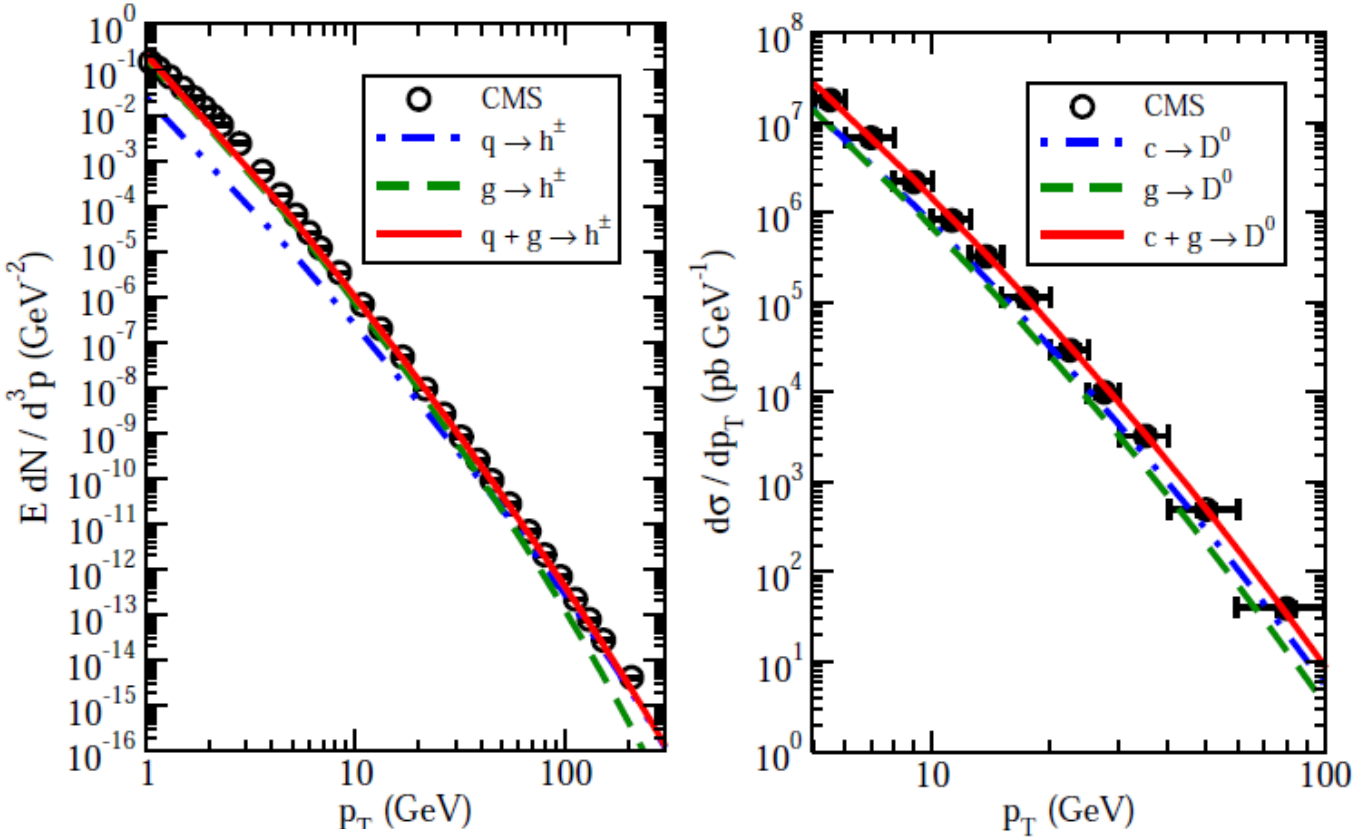
He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

Flavor hierachy of parton energy loss



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

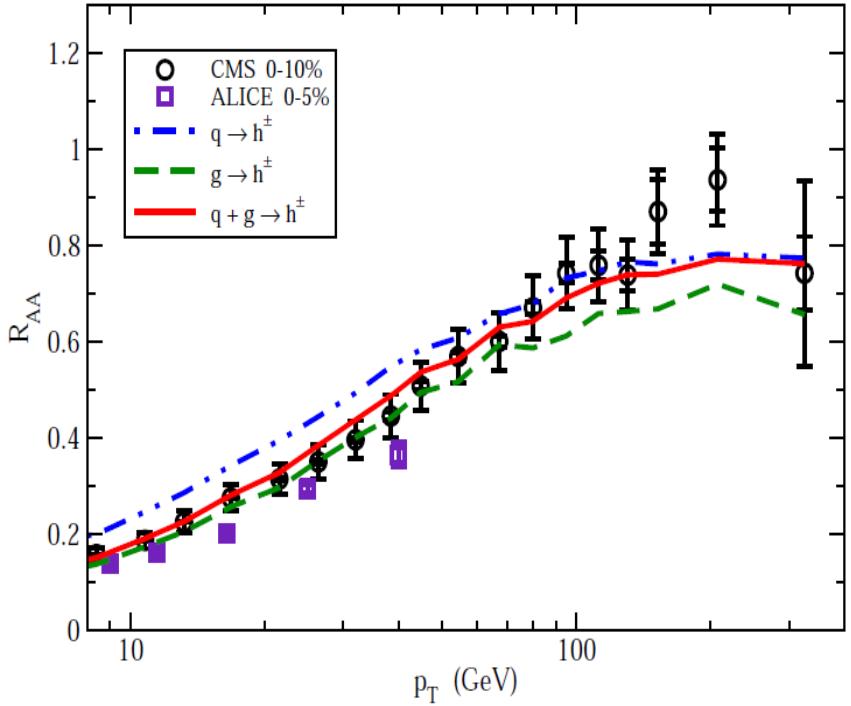
Hadron productions in pp collisions @ NLO

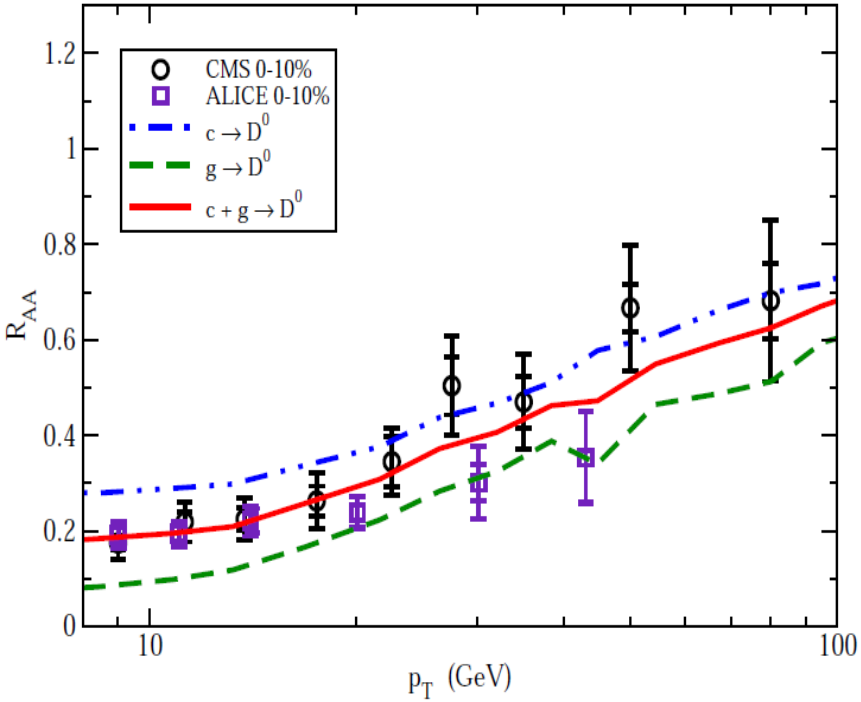


$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

Based on B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B327, 105 (1989).

Flavor hierarchy of jet quenching

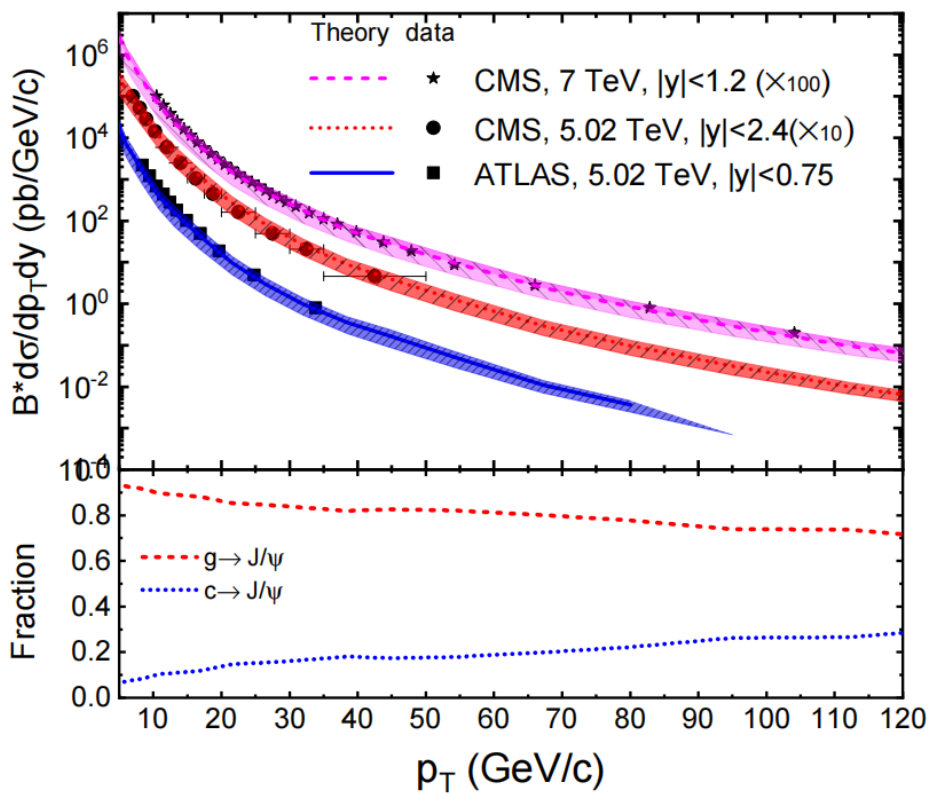


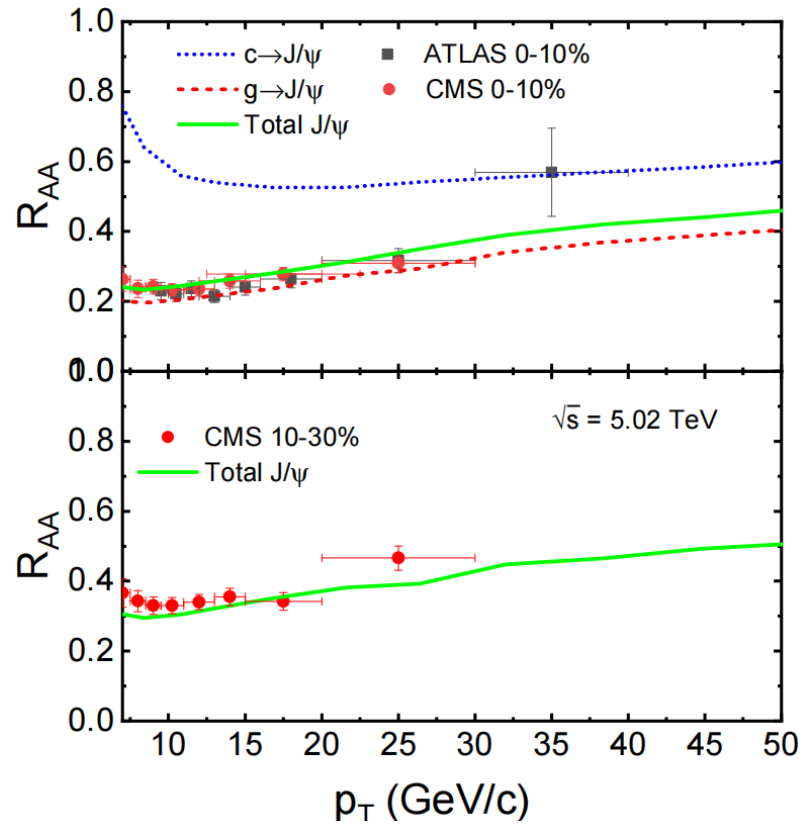


A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.
Combining both quark and gluon contributions provides a nice description of charged hadron & D meson R_{AA} over a wide range of p_T.

W.-J. Xing, S. Cao, GYQ, H. Xing, PLB 2020

Gluons dominate high p_T J/Ψ suppression





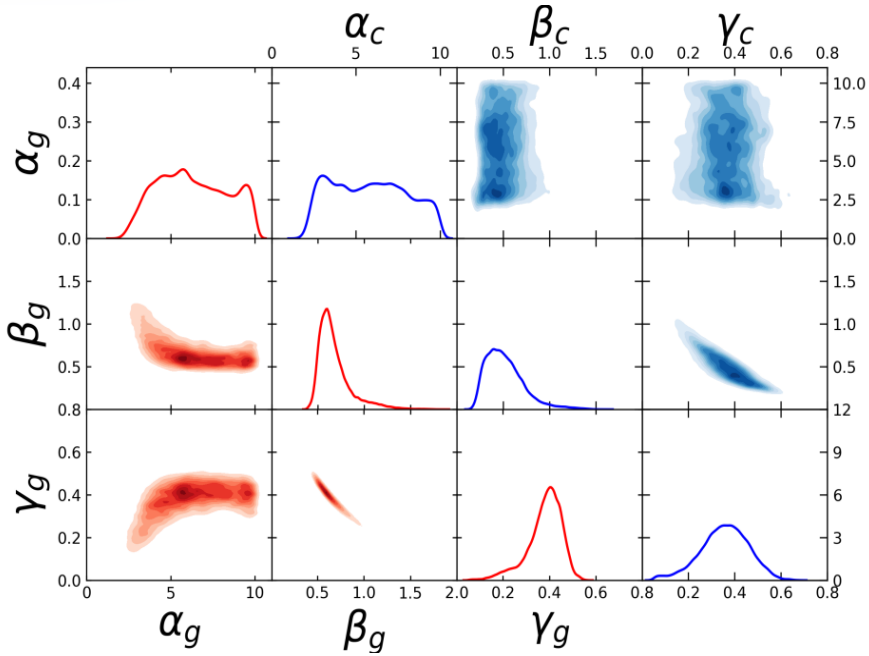
$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi} \quad D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

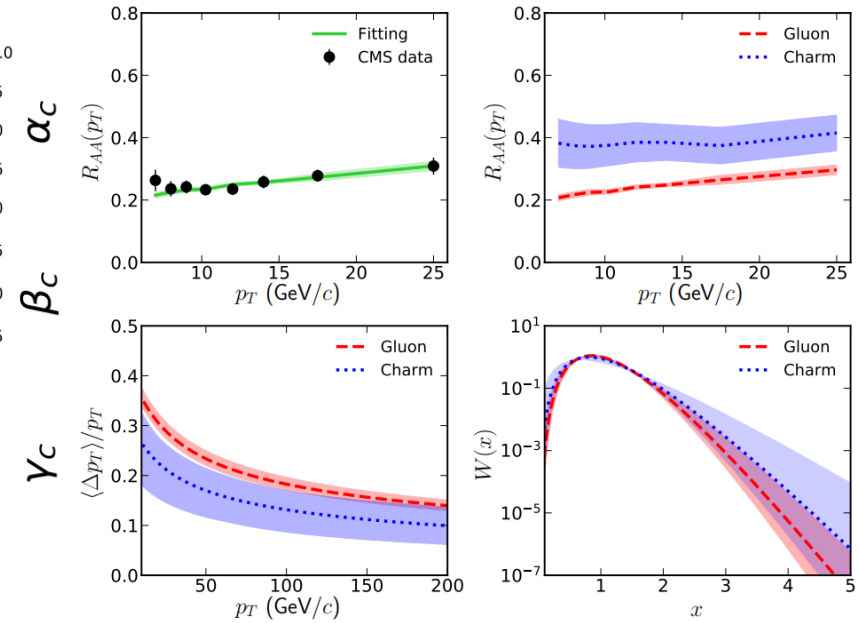
The gluon jet quenching is the driving force for high p_T J/Ψ suppression.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

Gluon ΔE distribution from J/Ψ suppression





$$\frac{d\sigma^{AA}}{dp_T} = \sum_i \int \frac{d\Delta p_T^i}{\langle \Delta p_T^i \rangle} \frac{d\sigma^{pp}(p_T + \Delta p_T^i)}{dp_T} W^i(x) \otimes D_{i \to J/\psi}$$

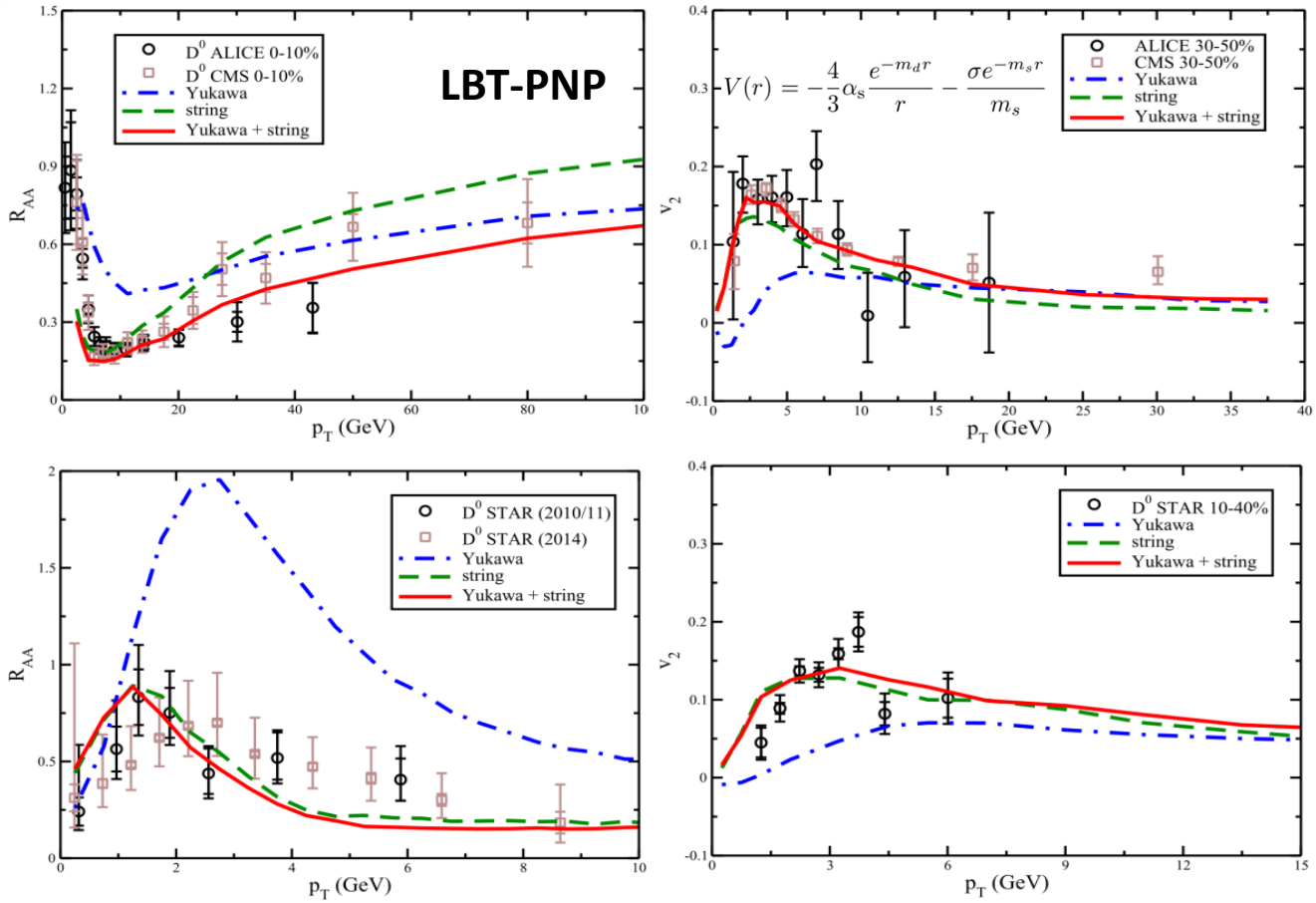
$$\langle \Delta p_T^i \rangle = \beta_i p_T^{\gamma_i} \log(p_T)$$

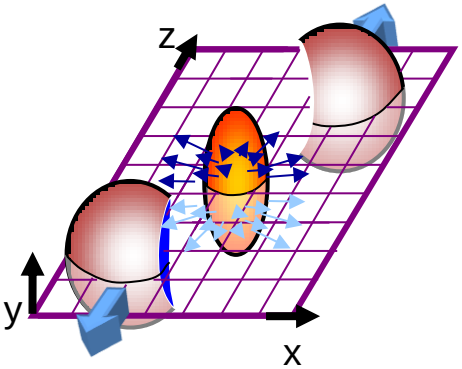
$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}$$

The first quantitative extraction of gluon energy loss distribution in QGP.
Probe the color and flavor dependences of jet quenching!

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323

D meson R_{AA} & v_2 from low to high p_T

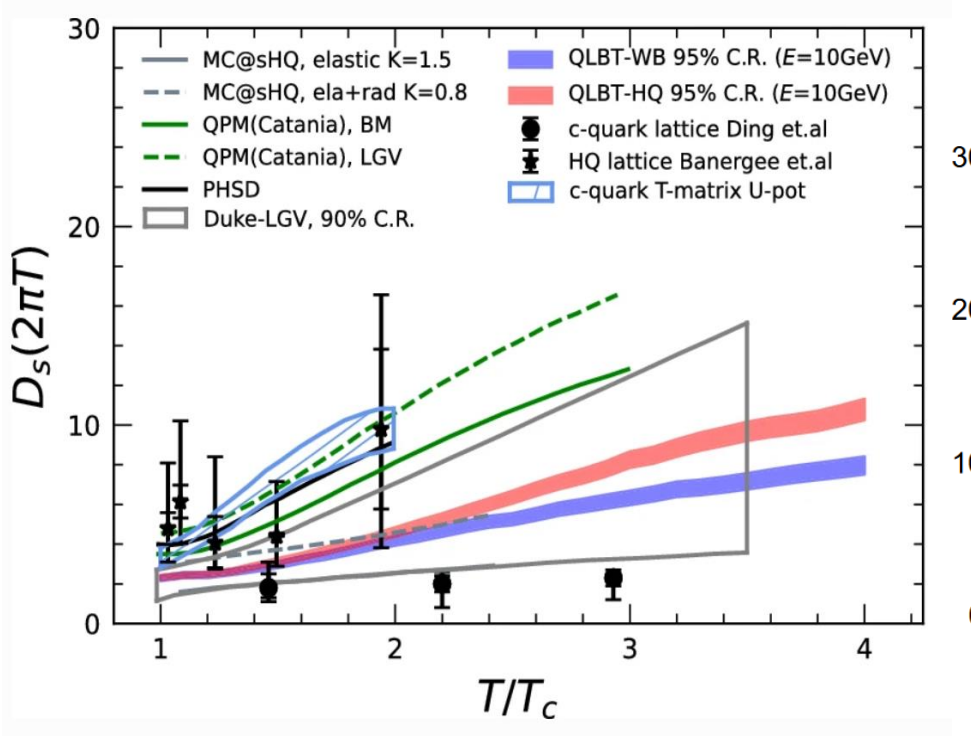


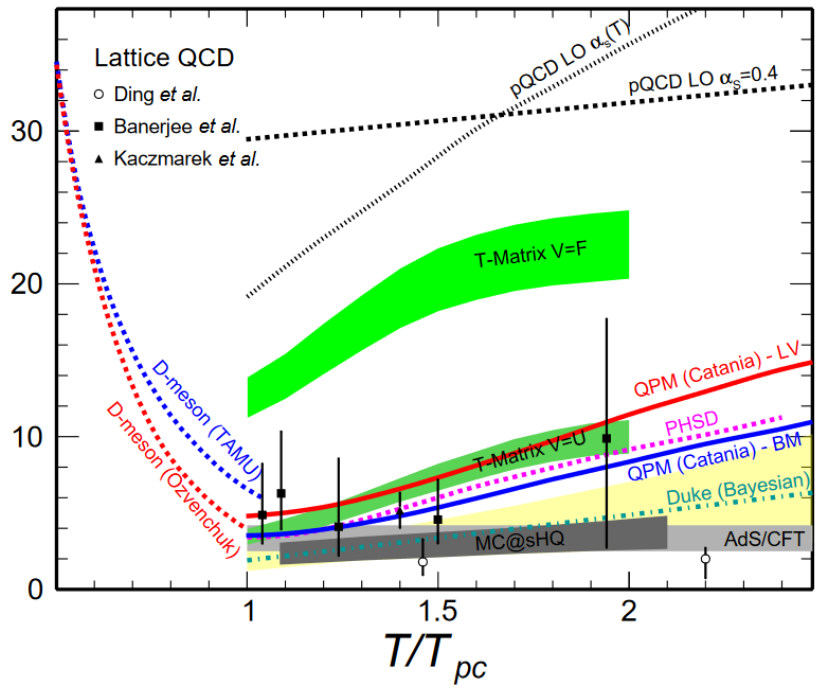


LBT-PNP model can simutaneously describe D meson R_{AA} & v_2 at RHIC & the LHC.
Perturbative interaction dominates D meson R_{AA} and v_2 at high p_T, while non-perturbative interaction dominates at low p_T.

W.-J. Xing, GYQ, S. Cao, 2112.15062

Heavy quark diffusion in QGP



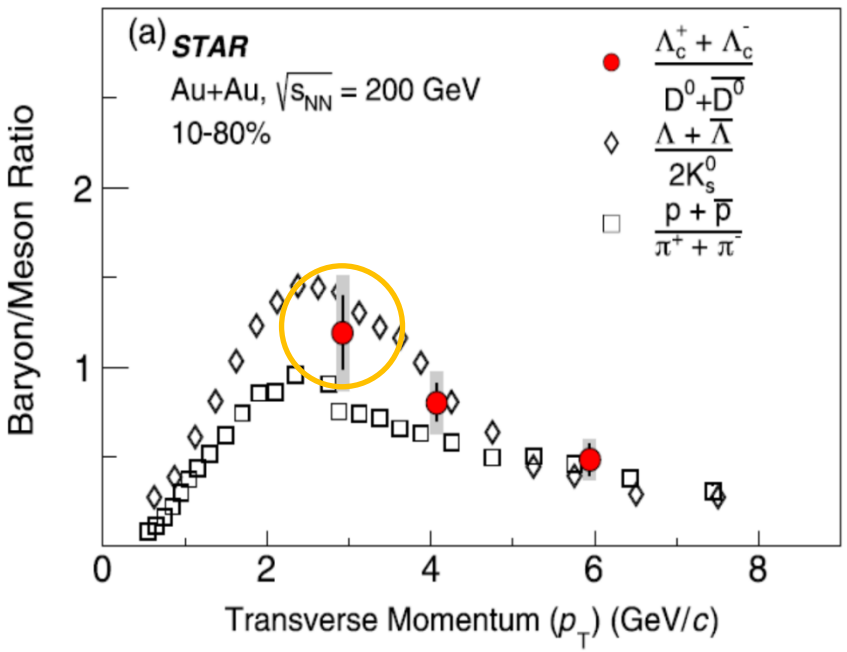


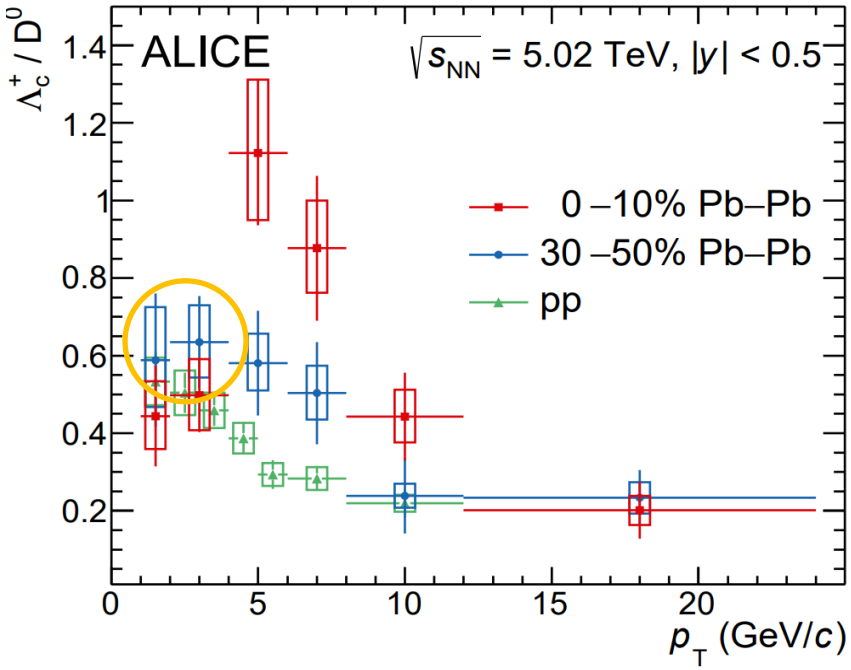
Brown motion: $\langle(\Delta x)^2\rangle = 2D_s\Delta t$

F.-L. Liu, W.-J. Xing, X.-Y. Wu, GYQ, S. Cao, EPJC 2022

X. Dong, Y.-J. Lee, R. Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

Heavy quark hadronization

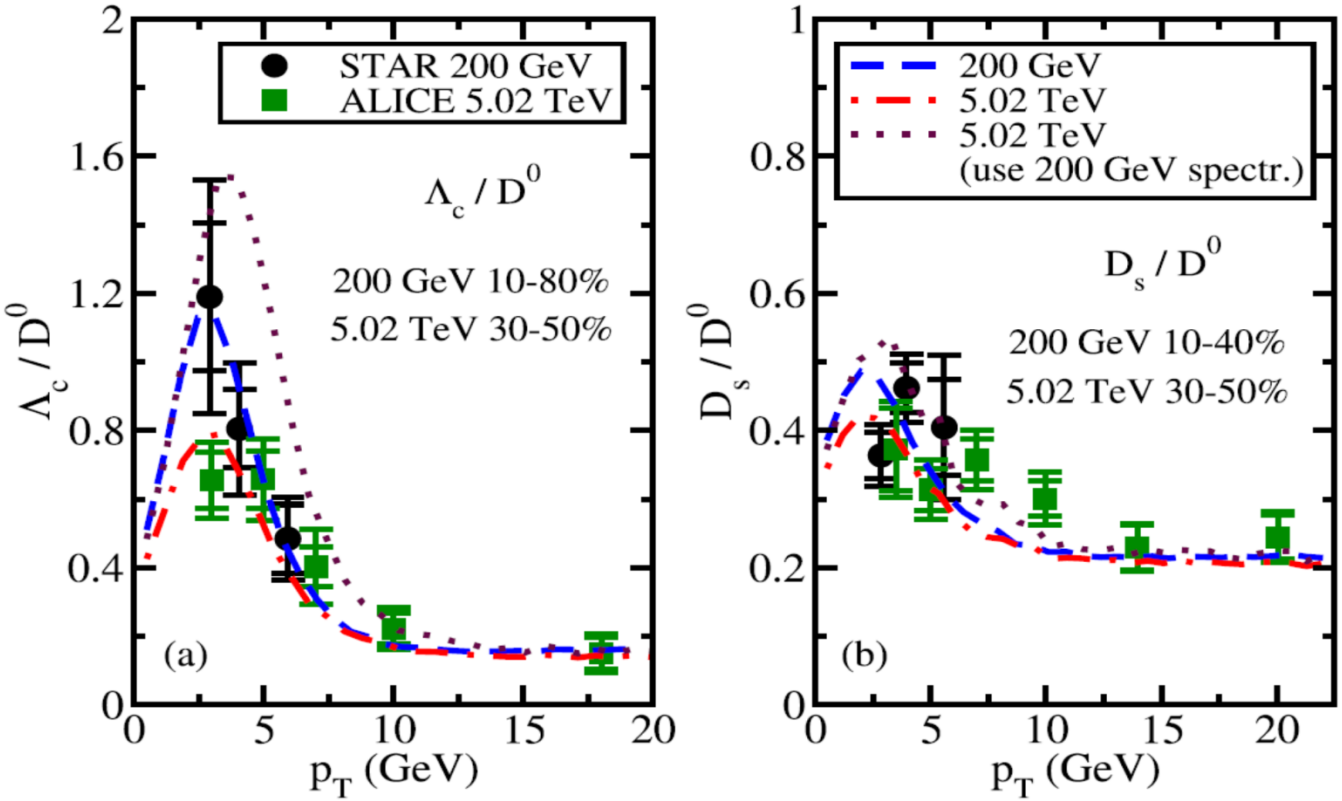




The enhancement of baryon to meson ratios in AA relative to pp can be successfully explained by the quark coalescence mechanism (which can also explain the NSQ scaling of bulk v_2)

The baryon to meson ratios are smaller at the LHC than at RHIC. Why?

Baryon/meson enhancement



Smaller B/M ratios at the LHC than at RHIC can be explained by the interplay between the QGP flow and the charm quark p_T spectrum.

The harder charm quark p_T spectrum at the LHC suppresses the QGP flow effect, yielding a smaller B/M ratio.

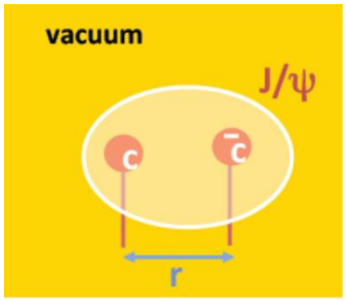
S. Cao, K.-J. Sun, S.-Q. Li, S. Liu, W.-J. Xing, GYQ, C.M. Ko, PLB 2020

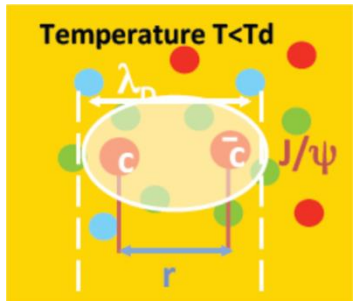
Heavy quarkonia

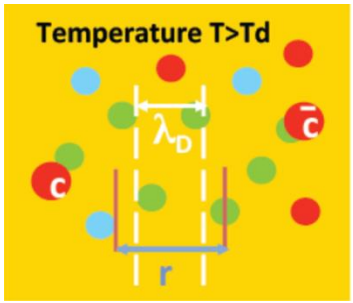
J/Ψ suppresion proposed as signature of QGP [Matsui, Satz, PLB 1986; Karsch, Satz, ZPC , 1991]

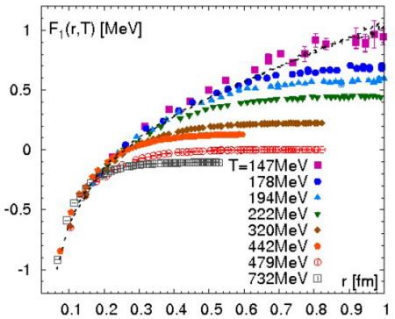
In QGP medium, heavy quark pair is color-screened by surrounding partons.

When $T > T_c$ & $\lambda_D(T) \sim 1/T < r_{q\bar{q}} \sim 1/E_b$, the bound state melt (dissociate).





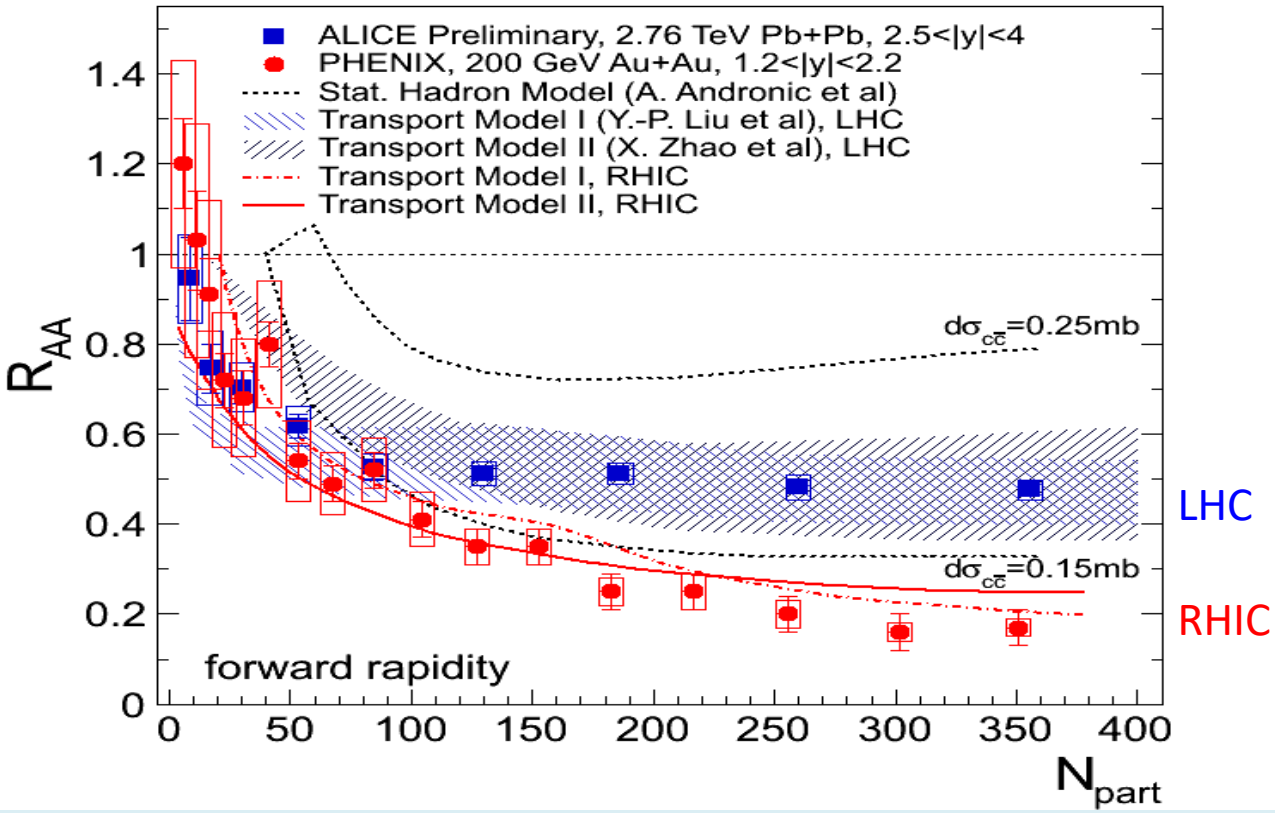




	J/Ψ	$\Psi(2s)$	$\Upsilon(1s)$	$\Upsilon(2s)$	$\Upsilon(3s)$
E_b(MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200

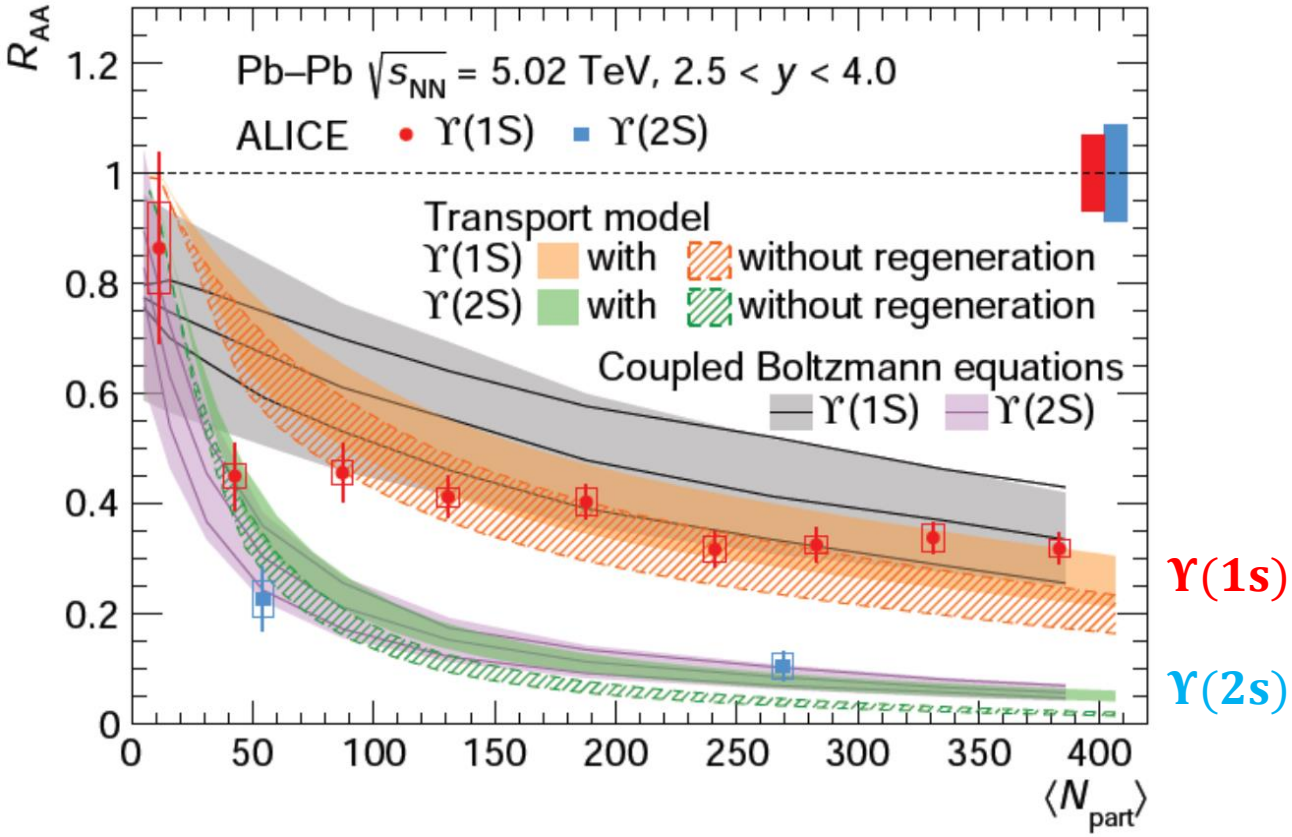
Due to different binding energy, quarkonia dissociate at different temeperatures (sequential suppression), which can serve as the thermometer of QGP

J/Ψ suppression



Centrality dependence of J/Ψ R_{AA} consistent with the melting (dissociation) picture.
Less suppression at the LHC than RHIC can be explained by regeneration mechanism.
Higher temperature at the LHC leads to: more effective melting and dissociation, but also much more frequent recombination of heavy quark pairs into quarkonia.

Bottomonia



Centrality dependence of ϒ R_{AA} is consistent with the dissociation mechanism, while the regeneration effect is small.

Due to different binding energies, stronger suppression of ϒ(2s) than ϒ(1s) (sequential suppression).

Summary

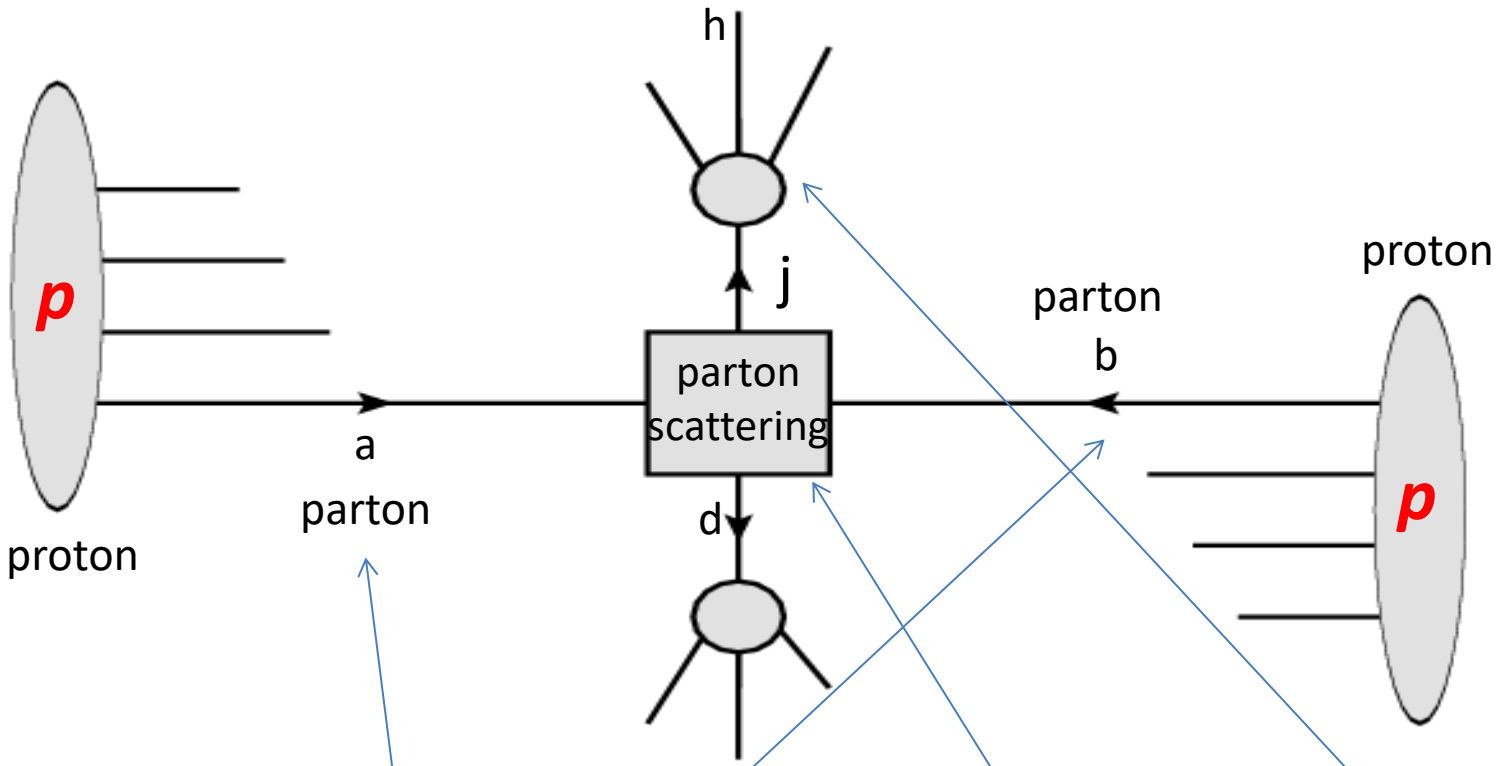
- **Heavy quarks are comprehensive probes of QGP**

- **Heavy quark quenching and flow**
  - **Flavor hierarchy of parton energy loss and jet quenching**
  - **Heavy quark diffusion and interaction**

- **Heavy quark hadronization**
  - **Baryon/meson enhancement**
  - **Critical role of coalescence, interplay of flow and spectra**

- **Quarkonia**
  - **J/Ψ: dissociation and regeneration**
  - **Bottomonia: sequencial suppression**

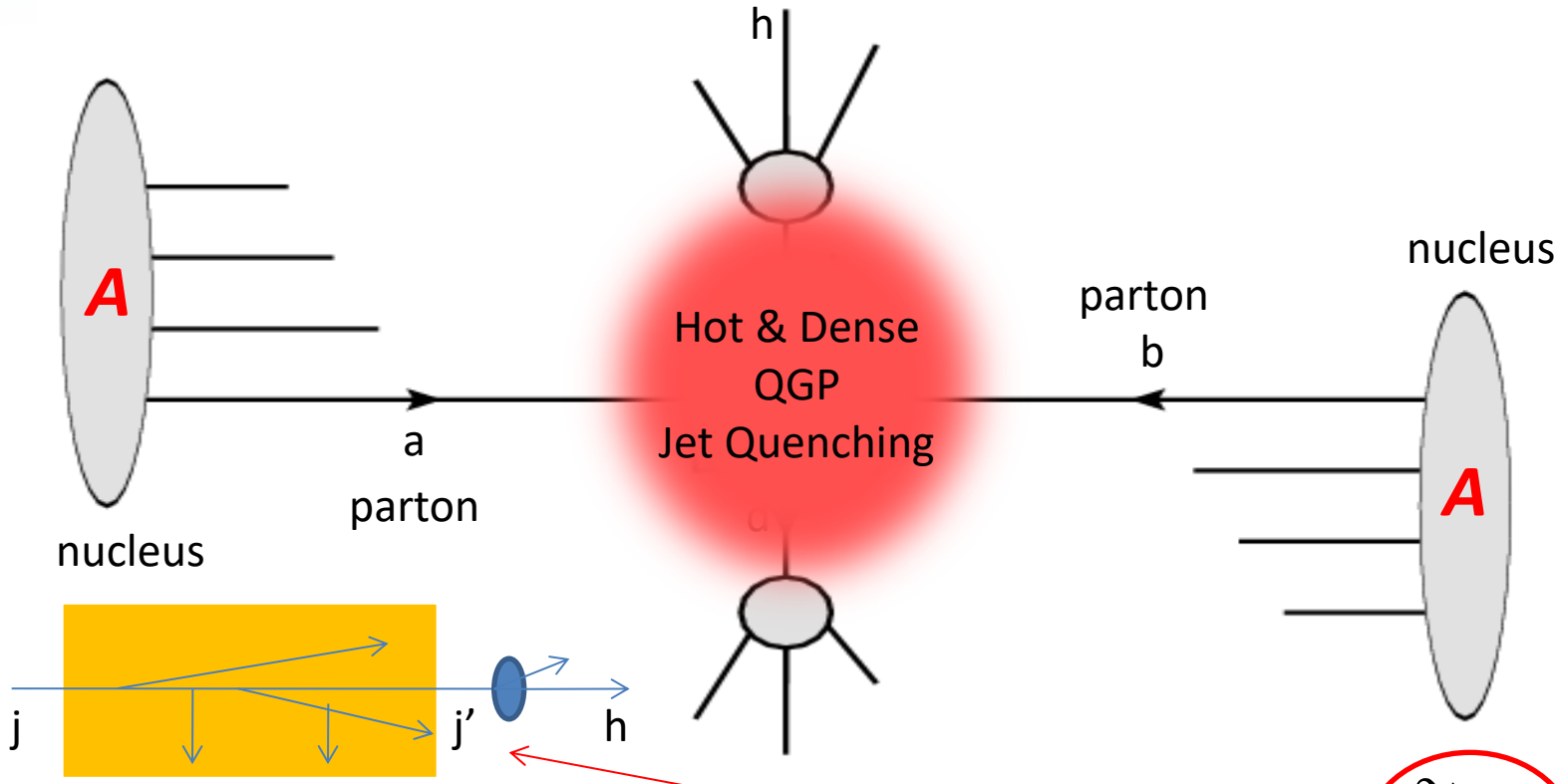
Leading hadron production in pp collisions



$$d\sigma_h = \sum_{abj} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes D_{h/j}$$

pQCD factorization: Large-p_T processes may be factorized into long-distance pieces in terms of PDF & FF, and short-distance parts describing hard interactions of partons.

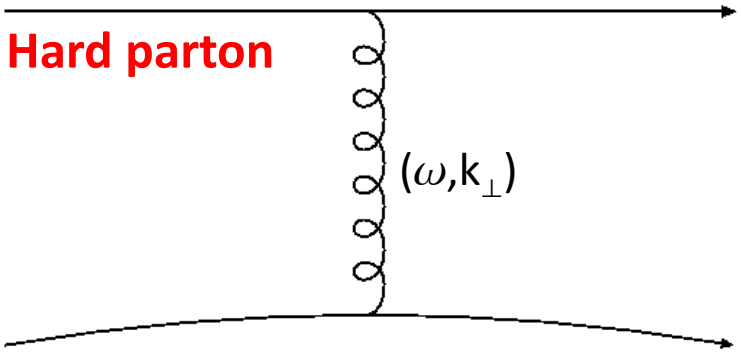
Leading hadron production in AA collisions



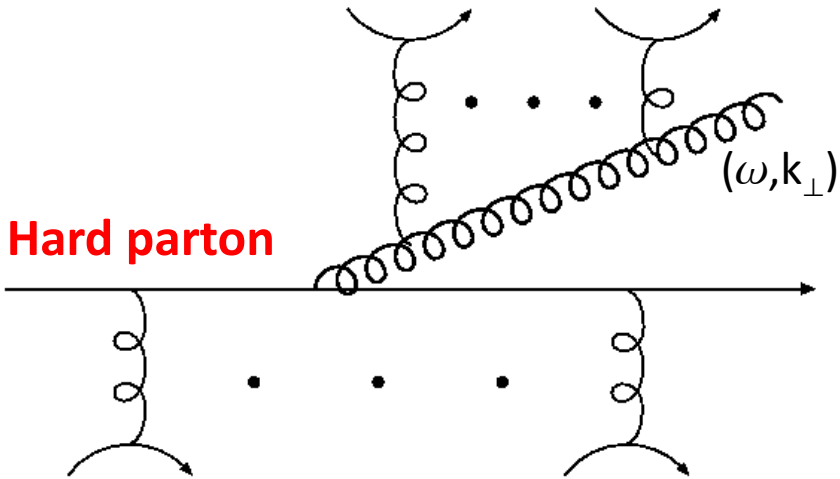
$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'} f_a \otimes f_b \otimes d\sigma_{ab\to jX} \otimes P_{j\to j'} \otimes D_{h/j'}$$

Jet-medium interaction



Elastic (collisional)



Inelastic (radiative)

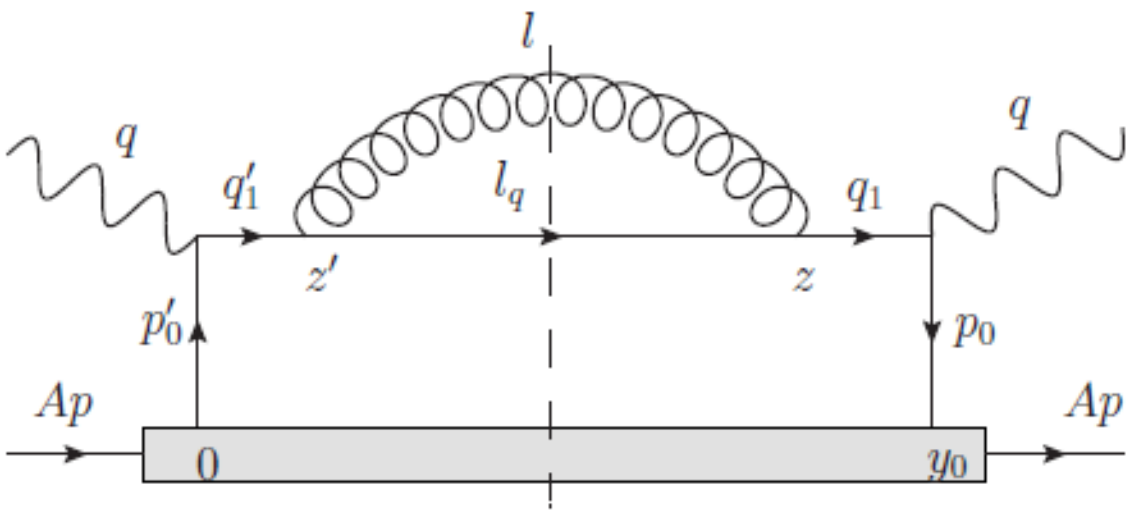
$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …

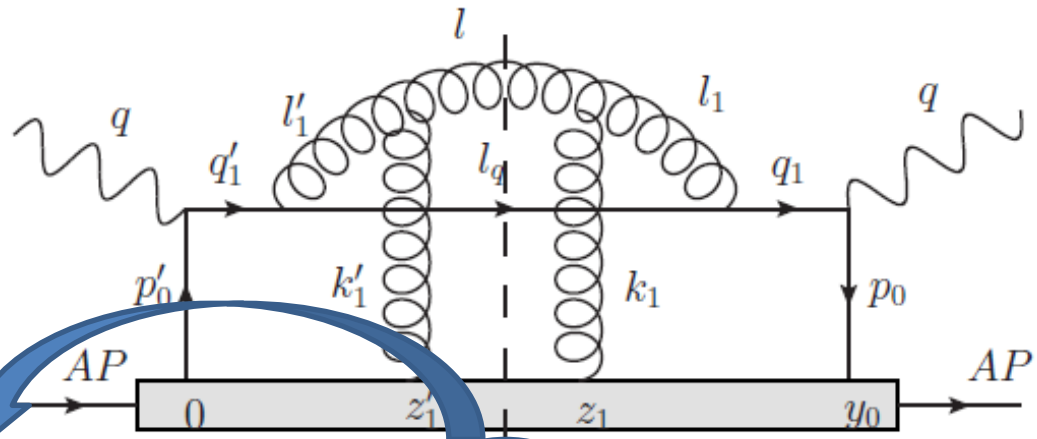
BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

Gluon emission in vacuum



$$\frac{dN_g^{\rm vac}}{dy\, d^2 l_\perp} = C_F \frac{\alpha_s}{2\pi^2} P(y) \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{(l_\perp^2 + y^2 M^2)^2}.$$

Medium-induced radiation



Zhang, Hou, GYQ, PRC 2018 & PRC 2019; Zhang, GYQ, Wang, PRD 2019.

+ other 20 diagrams

$$\frac{dN_g^{med}}{dy d^2 l_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int \frac{dk^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathcal{D}(k_1^-, \mathbf{k}_{1\perp})$$

$$\times \left\{ \left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)(1+\lambda_1^- - y)} \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}_{\rm form}^-} \right) \right] \right.$$

$$C_A \left[\frac{1 + (1+\lambda_1^- - y)^2}{1+(1-y)^2} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right)^2 \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{(y-\lambda_1^-)^4 M^2}{1+(1+\lambda_1^- - y)^2}}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2\right]^2} \right.$$

$$- \frac{1 + (1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)} M^2}{[l_\perp^2 + y^2 M^2]\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2\right]}$$

$$\mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = (2\pi)^3 \frac{dP_{\rm el}}{dk_1^- d^2\mathbf{k}_{1\perp} dZ_1^-}$$

$$\left. - \frac{1 + (1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) \cdot \left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right) + \frac{\left(\frac{y}{1+\lambda_1^-}\right)^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})} M^2}{\left[\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right)^2 + (\frac{y}{1+\lambda_1^-})^2 M^2 \right] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2\right]} \right] + \ldots\ldots \right\}$$

Medium-induced gluon emission spectrum is directly controlled by differential scattering rate (or generalized $\hat{q}$)

Medium-induced gluon emission beyond collinear expansion & soft gluon emission limit with transverse & longitudinal scatterings for massive/massless quarks

Only transverse scatterings

- Modeling the traversed nuclear medium by heavy static scattering centers (only transverse scatterings)

$$
\begin{aligned}
\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} &= \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^-\int d^2\mathbf{k}_{1\perp}\frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp}dZ_1^-} \\
&\times\Bigg\{C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}_{\rm form}^-}\right)\right]\times\left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}\right. \\
&\left.-\frac{1}{2}\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{1}{2}\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\right] \\
&+\left(\frac{C_A}{2}-C_F\right)\left[2-2\cos\left(\frac{Z_1^-}{\tilde{\tau}_{\rm form}^-}\right)\right]\left[\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right] \\
&+C_F\left[\frac{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right]\Bigg\}.
\end{aligned}
$$

Soft gluon emission approximation

- Further taking soft gluon emission approximation: $y^2 M \ll yM \sim l_\perp \sim k_{1\perp}$

$$\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int d^2\mathbf{k}_{1\perp} \frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp} dZ_1^-} \times C_A \left[2 - 2\cos\left(\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2}{l_\perp^2 + y^2M^2} \frac{Z_1^-}{\tilde{\tau}_{\rm form}^-} \right) \right]$$
$$\times \left[\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2\right]^2} - \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp})}{[l_\perp^2 + y^2M^2]\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2M^2\right]} \right].$$

- This agrees with the DGLV first-order-in-opacity formula.

- Jet transport parameter is related to the differential elastic scattering rate as follows:

$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2 \rangle}{dL^-} = \int \frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathbf{k}_{1\perp}^2 \mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = \int \frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2} \mathbf{k}_{1\perp}^2 \mathcal{D}_\perp(\mathbf{k}_{1\perp}) = \int d^2\mathbf{k}_{1\perp} \mathbf{k}_{1\perp}^2 \rho^- \frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}.$$

Implementation of inelastic radiation in LBT

- **Average number of radiated gluons in Δt:**

$$\langle N_g \rangle (E, T, t, \Delta t) = \Gamma_g \Delta t = \Delta t \int dx\, dk_\perp^2 \frac{dN_g}{dx\, dk_\perp^2 dt}$$

- **Poisson distribution for the number *n* of radiated gluons during *Δt*:**

$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

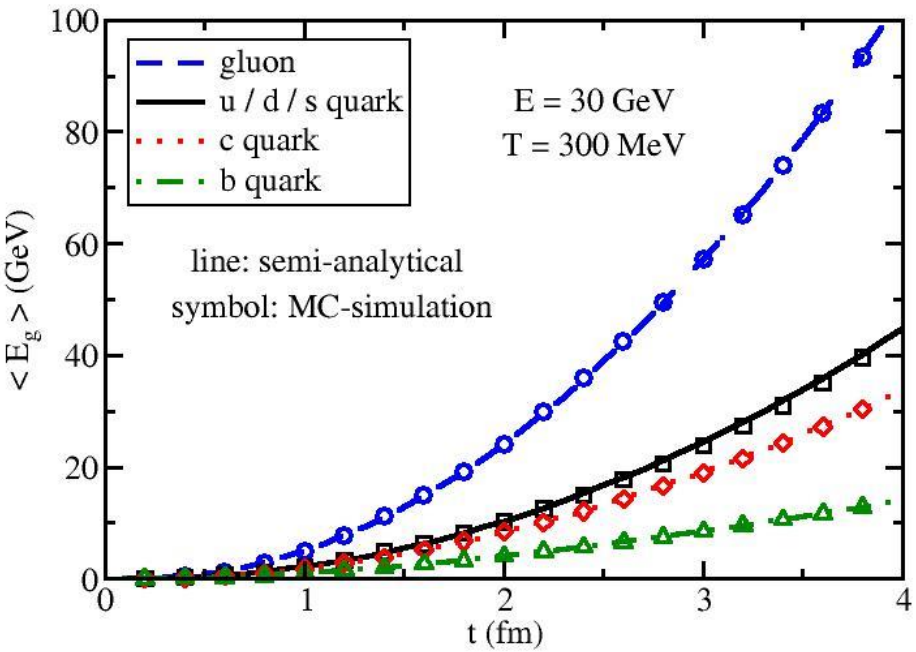
- **Probability of inelastic interaction during *Δt*:**

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

- **Zhu, Wang, PRL 2013; He, Luo, Wang, Zhu, PRC 2015; Cao, Tan, GYQ, Wang, Phys.Rev.C 94 (2016) 1, 014909; Phys.Lett.B 777 (2018) 255-259**

Model implementation of inelastic radiation

- **Calculate $\langle N_g \rangle$ and P_{inel}**
- **If gluon radiation happens, sample *n* gluons from Poisson distribution**
- **Sample *E&p* of radiatied gluons using the differential radiation spectrum**
- **First do $2 \rightarrow 2$ process, then adjust *E&p* of $2+n$ final partons to guarantee *E&p* conservation for $2 \rightarrow 2+n$ process**



$\langle E_g \rangle$ from our MC simulation agrees with the semi-analytical result.

Combine elastic & inelastic

- **Total probability:**

$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

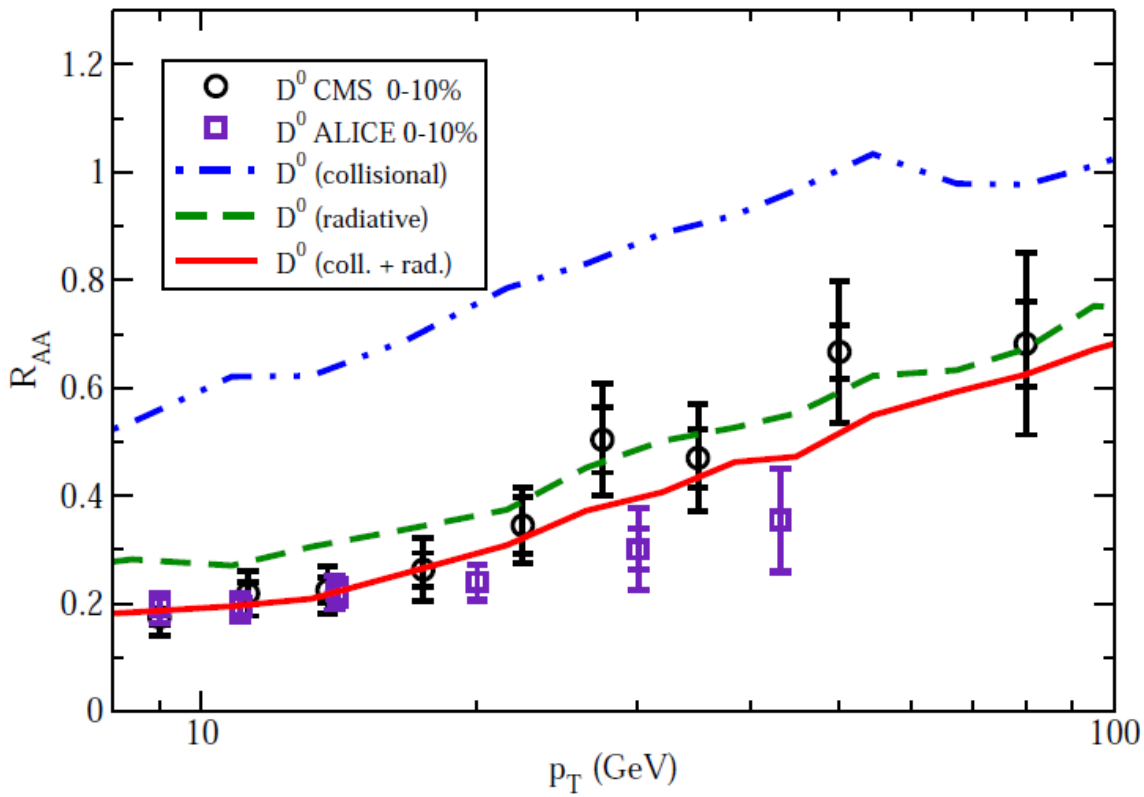
  - **Pure elastic scattering without gluon radiation: $P_{el}(1 - P_{inel})$**
  - **Inelastic scattering: P_{inel}**

- **Use P_{tot} to determine whether jet parton interact with thermal medium**

- **If jet-medium interaction happens, then determine whether it is pure elastic or inelastic**

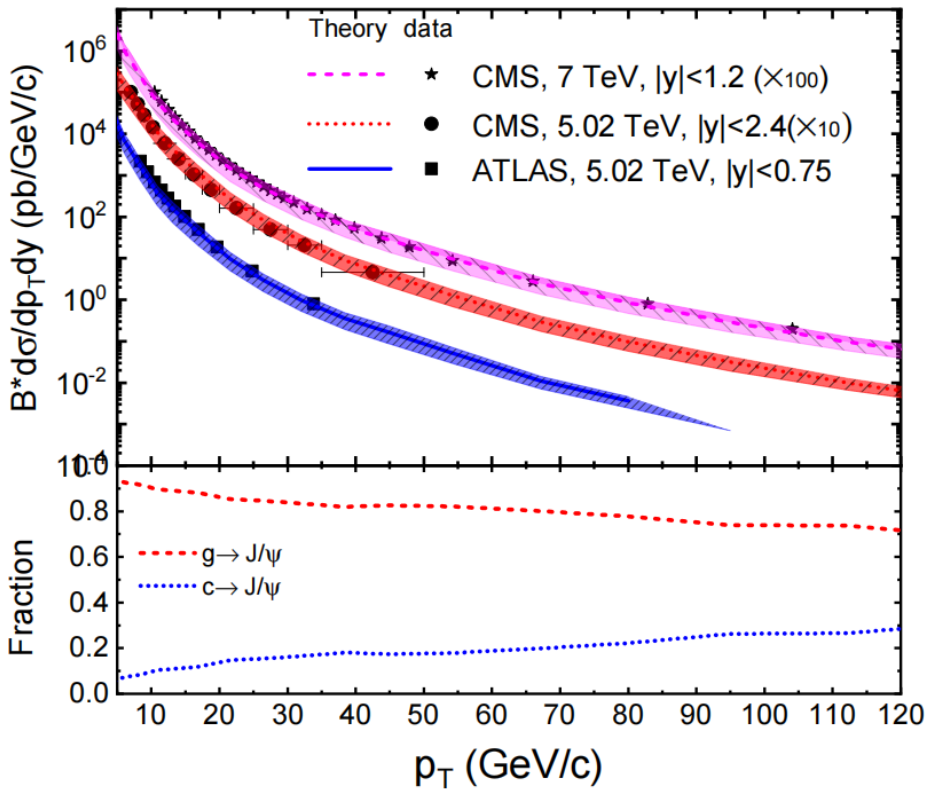
- **Then simulate $2 \to 2$ or $2 \to 2 + n$ process**

Radiative and collisional contributions



Radiative E loss provides more dominant contributions to R_{AA}, collisional E loss also has sizable contributions to R_{AA} at not-very-high p_T regime and diminishes with increasing p_T.

Gluons dominate high p_T J/Ψ production



Leading power (p_T^2/m_c^2) NRQCD:

$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$$D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

Gluon fragmentation-improved PYTHIA (GFIP)

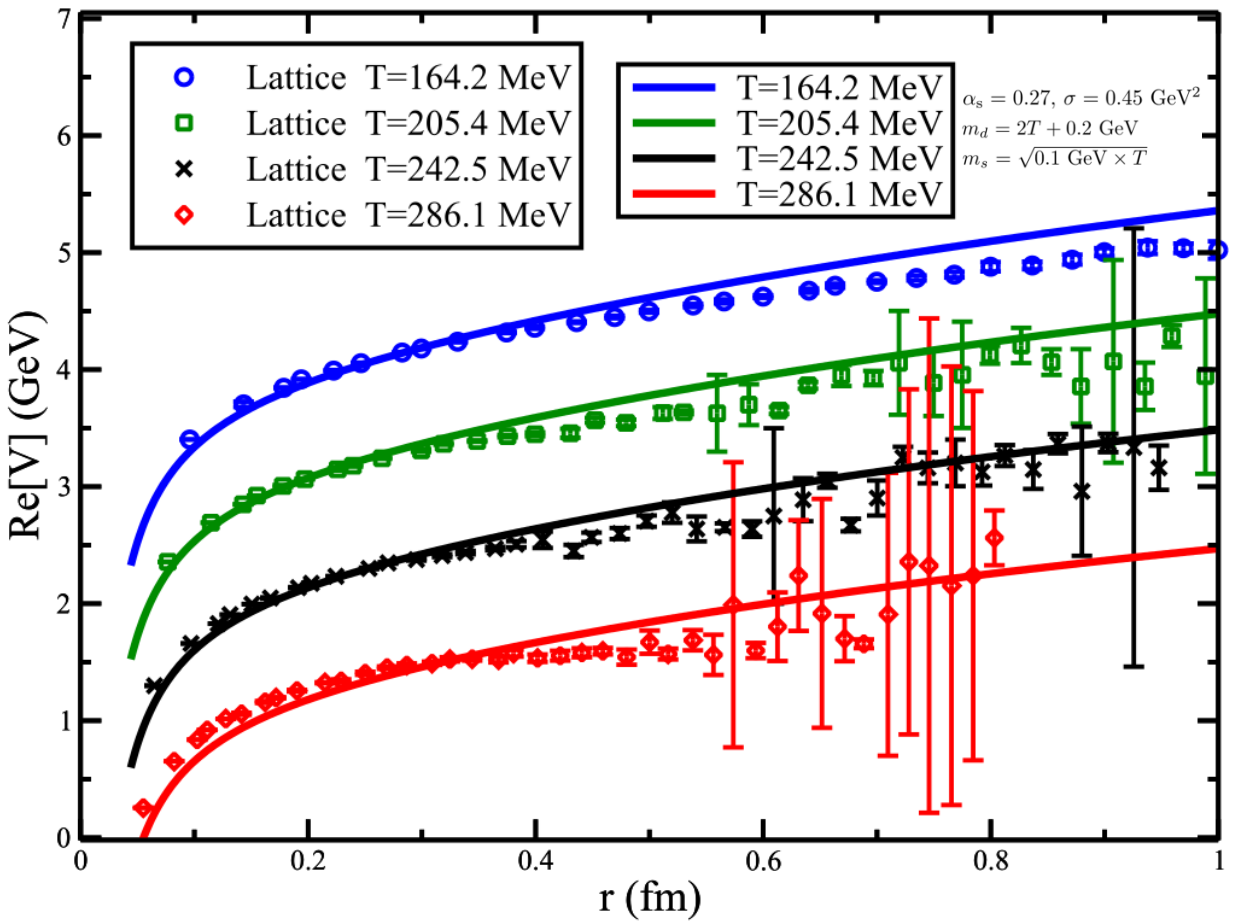
MadGraph for hard parton creation
PYTHIA8 for parton shower
Short-distance coefficients from 1311.7078, 1208.5301
Long-distance matrix element from 1403.3612.

Within the framework of leading power NRQCD, gluons dominate high p_T J/Ψ production.

S.-L. Zhang, J. Liao, GYQ, E. Wang, H. Xing, 2208.08323

Ma, Qiu, Zhang, PRD, 2014; Bodwin, Kim, Lee, JHEP 2012; Bodwin, Chung, Kim, Lee, PRL 2014

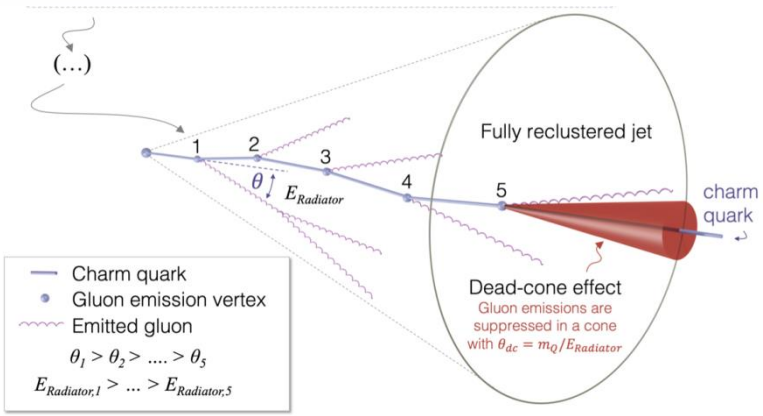
Heavy quark potential from open HF R_{AA} & v_2

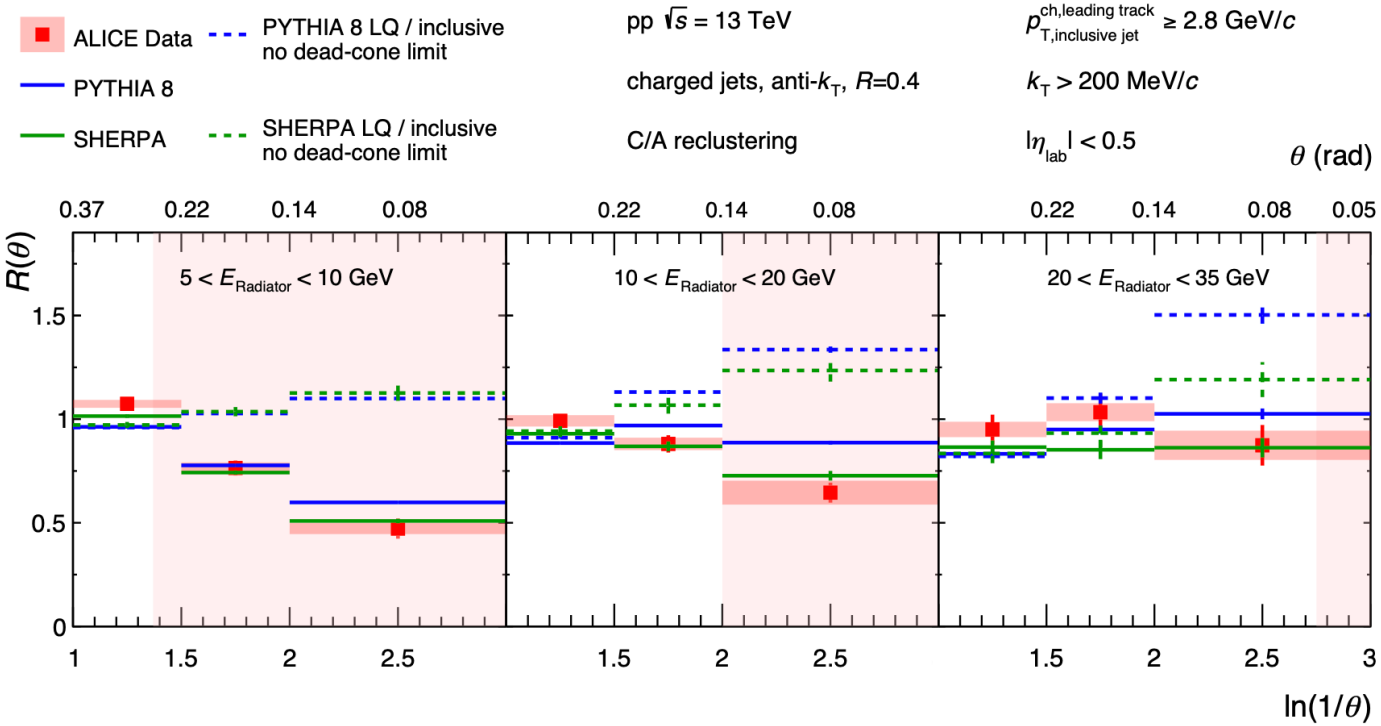


First extraction of heavy quark potential from open HF observables.

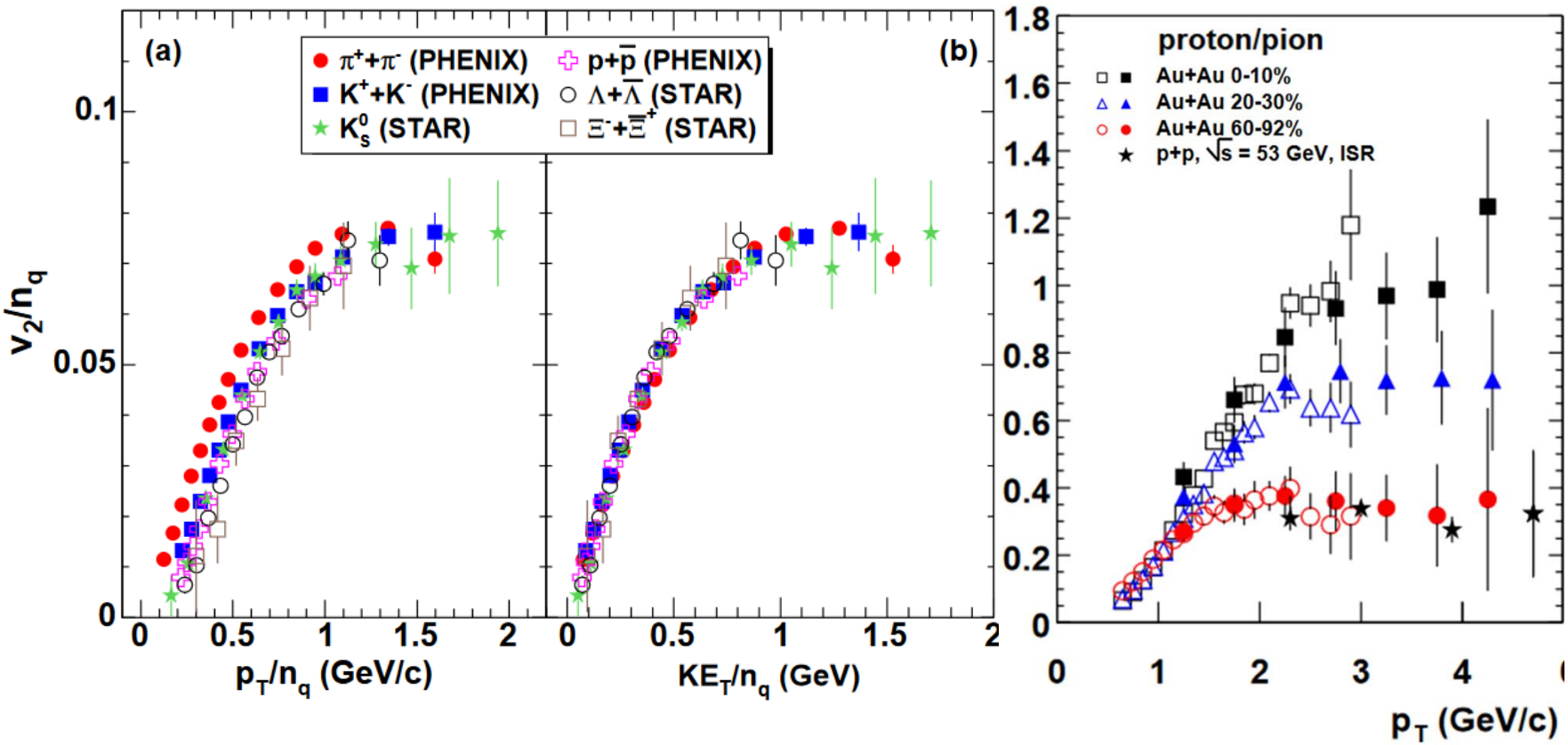
W.-J. Xing, GYQ, S. Cao, 2112.15062

Dead cone effect





Number of constituent quark (NSQ) scaling



Coalescence of thermal partons from QGP can naturally explain the NSQ scaling of v_2 and the enhancement of baryon/meson ratio at intermediate p_T.