Jet Azimuthal Anisotropies in Heavy-Ion Collisions

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in collaboration with Y. Mehtar-Tani & K. Tywoniuk

Based on *Phys.Rev.D* 110 (2024) 1, 014009

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 101155036.

MARIE CURIE ACTIONS

ICHEP 24 - Prague, 20th July 2024

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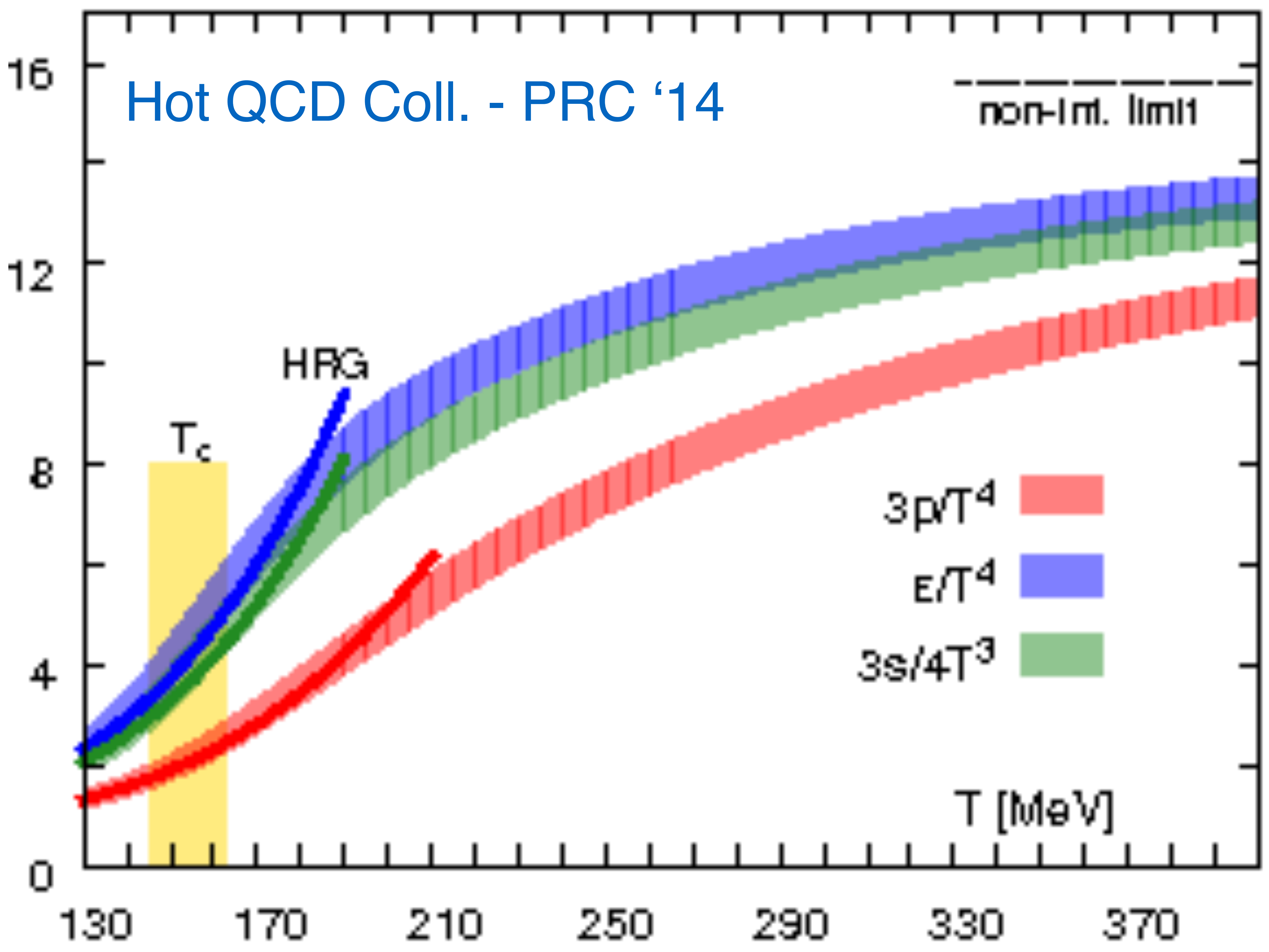
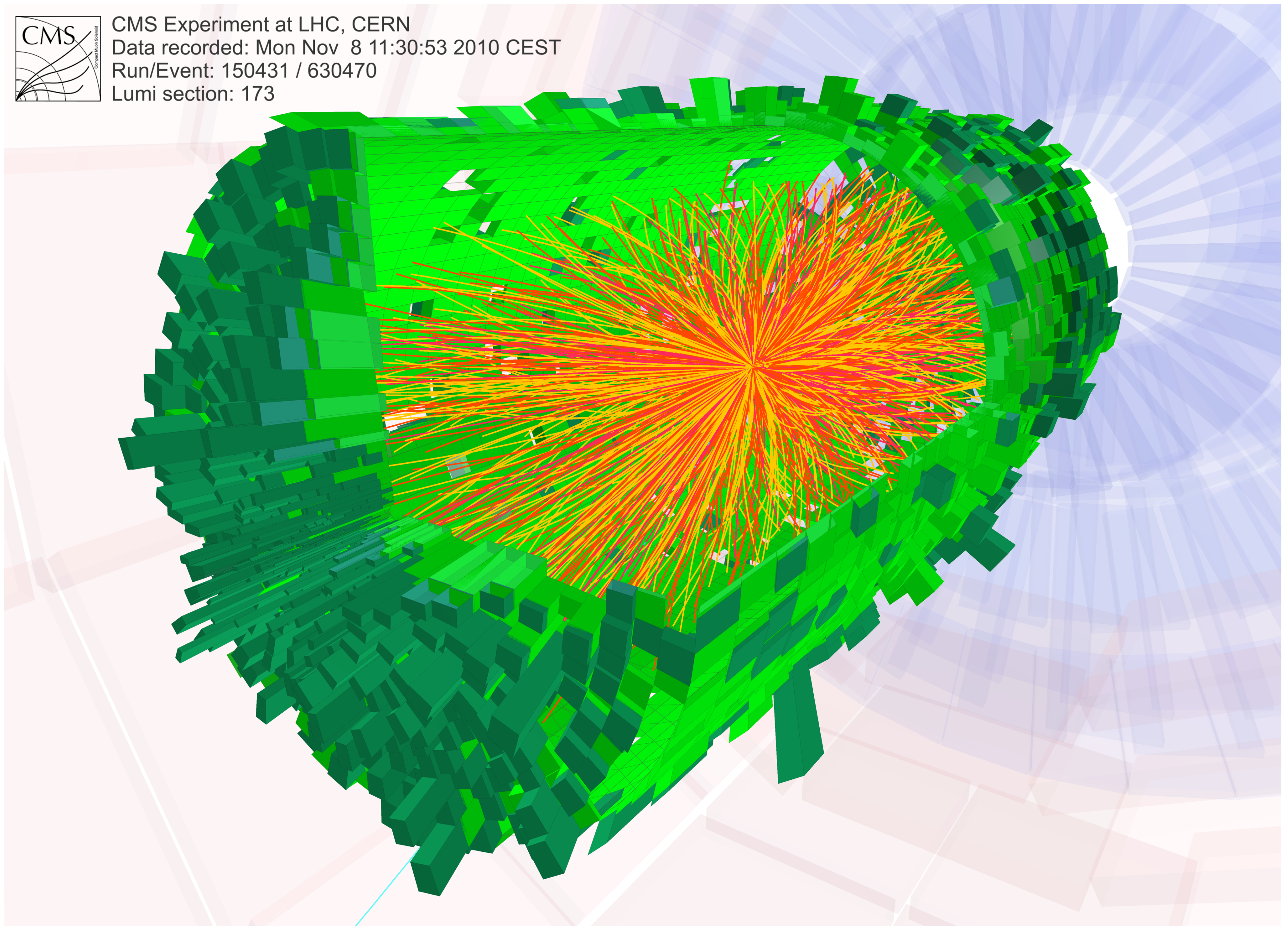
Heavy-Ion Collisions: The Little Bangs

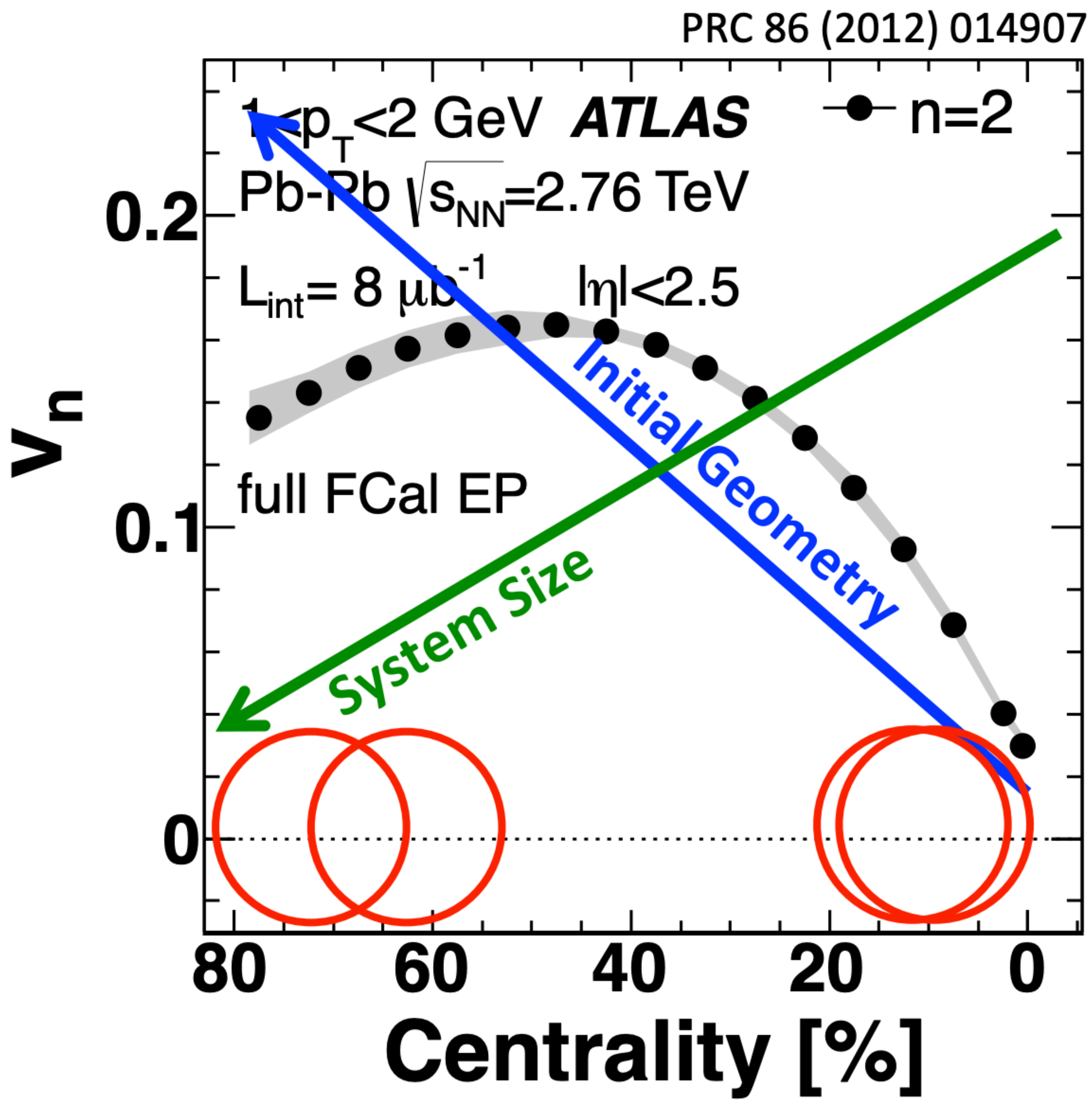


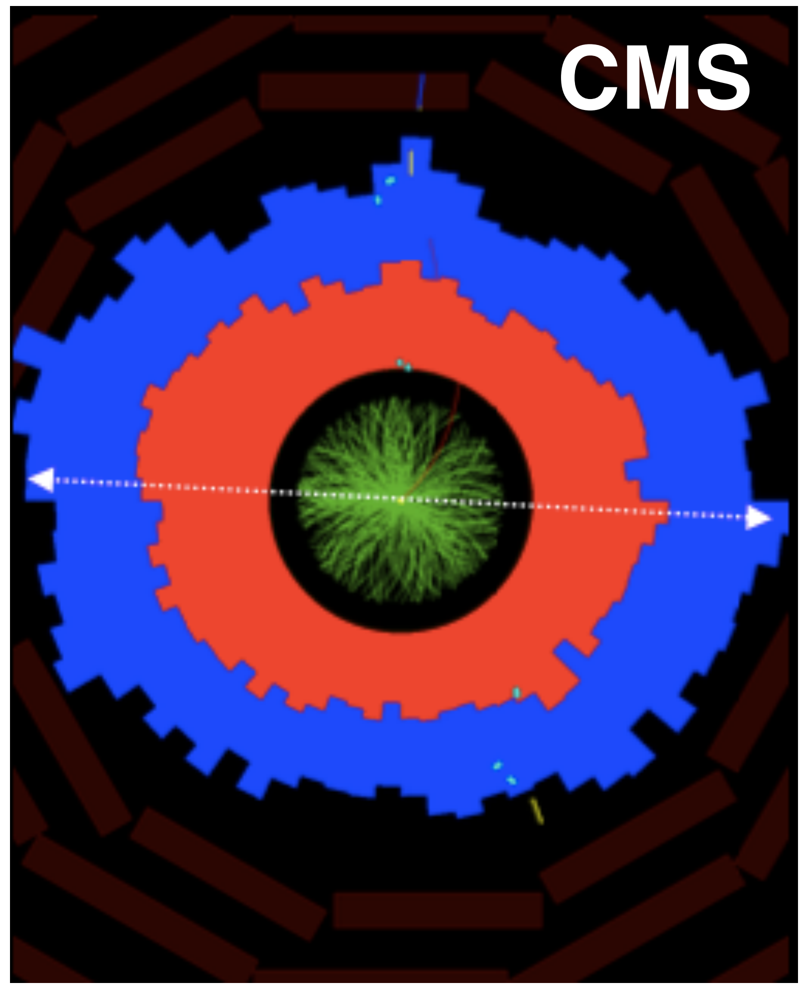


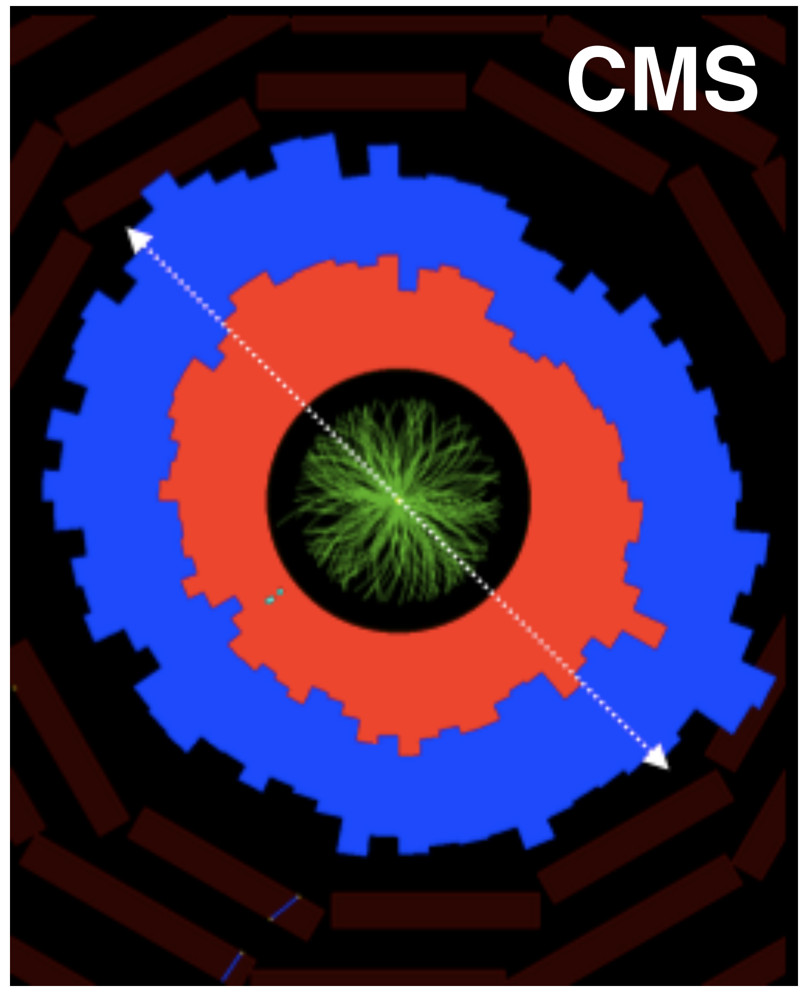
RHIC $\sqrt{s} \sim 0.2 \text{ ATeV}$

LHC $\sqrt{s} \sim 4 \text{ ATeV}$

- Deconfined QCD matter in experiments:
  - Very strong collective effects.
  - Thousands of particles correlated according to initial geometry.
  - Hydrodynamic explosion!







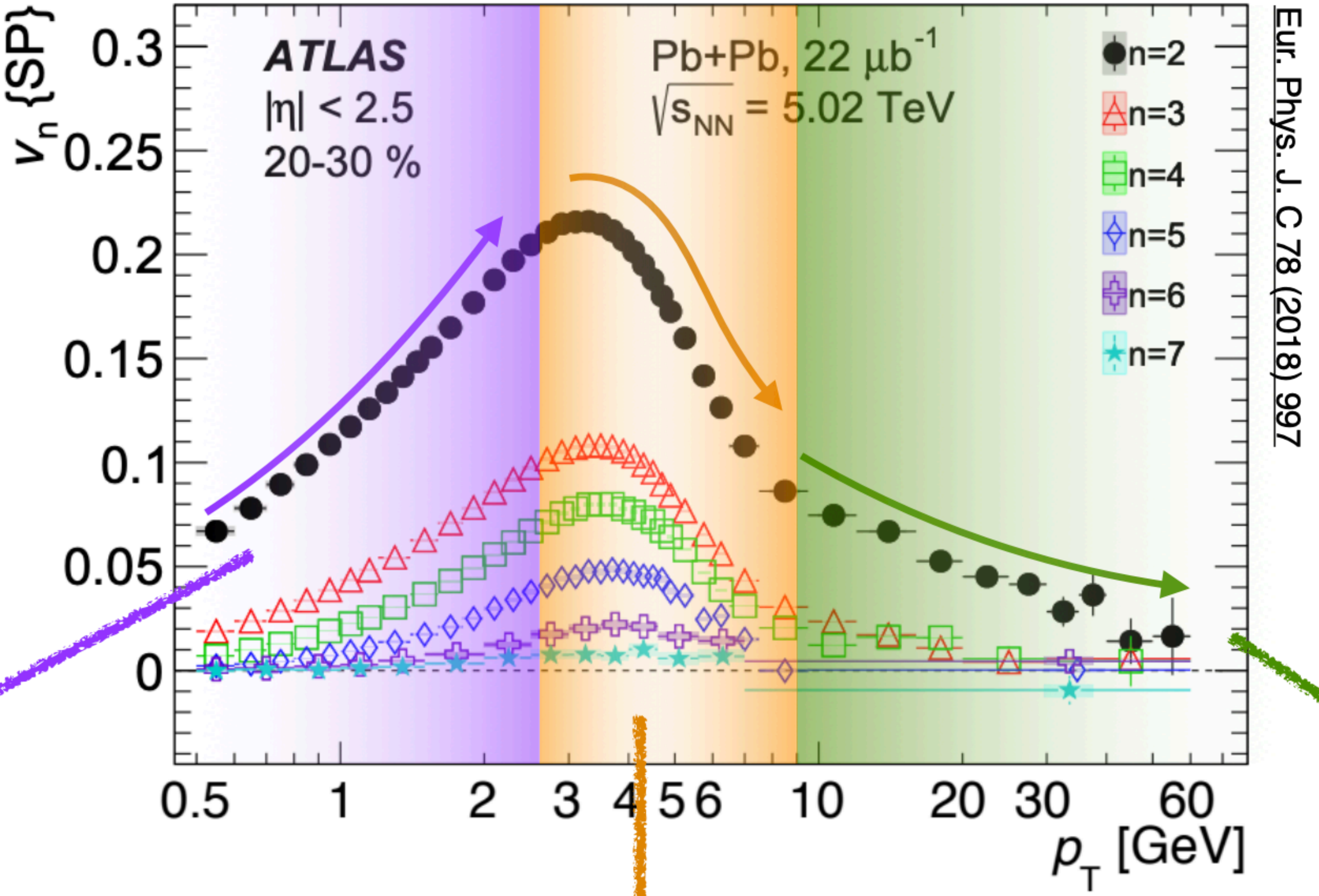
- To leading order $v_n \propto A\varepsilon_n$.
- As system size decreased, less flow.

$$\frac{\mathrm{d}N}{\mathrm{d}\phi \mathrm{d}p_T} = \frac{\mathrm{d}N/\mathrm{d}p_T}{2\pi}\left[1 + 2\sum_n v_n(p_T)\cos(n(\phi - \Psi_n))\right]$$

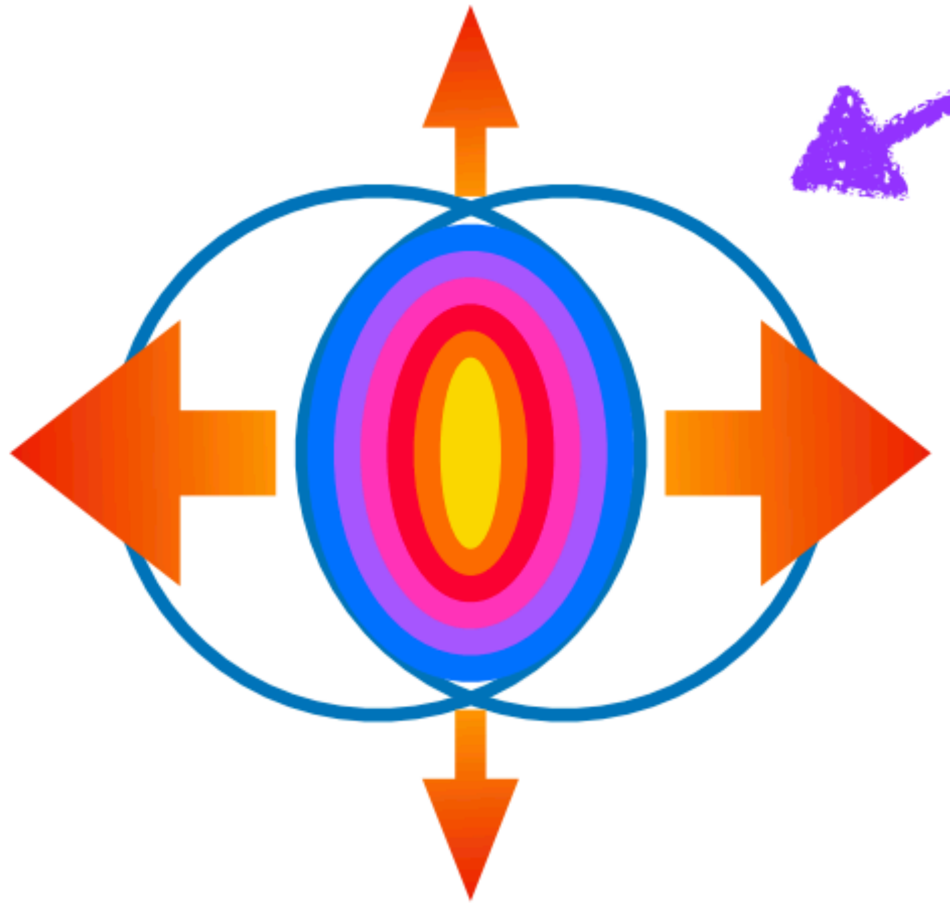
slide adapted from Z. Chen

Jet Azimuthal Anisotropy

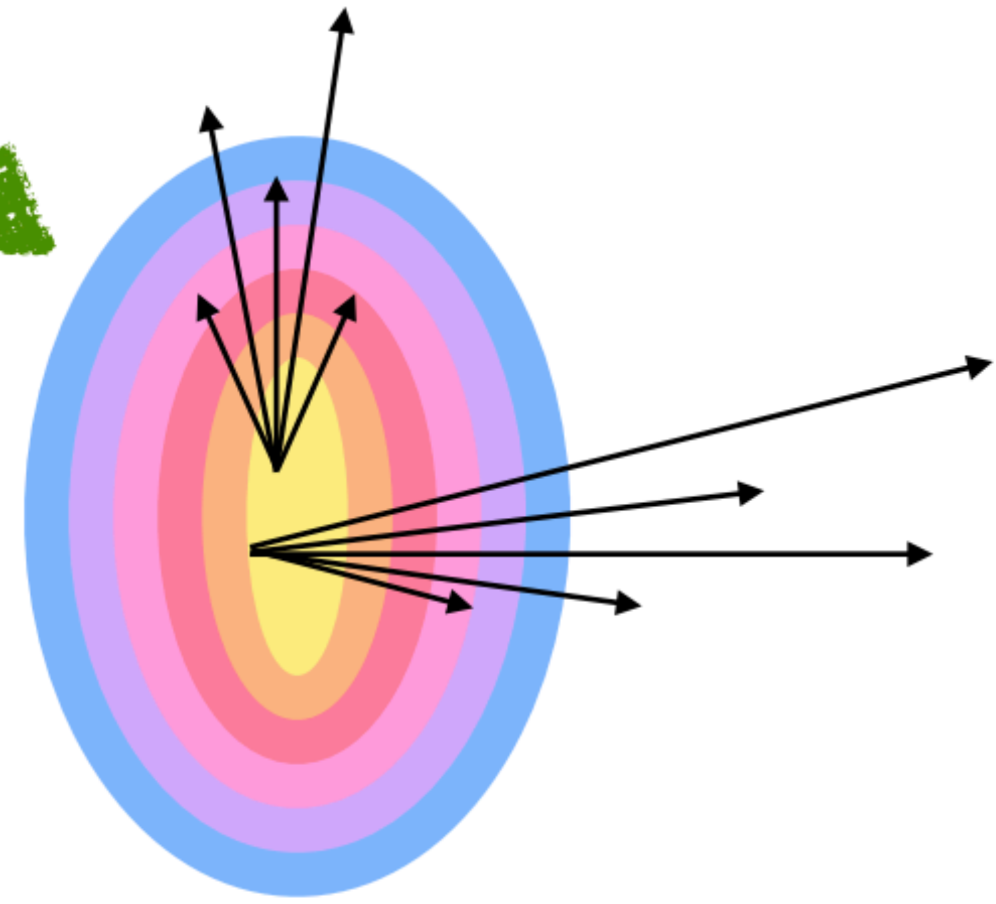
Slide from
K. Hill at QM‘19



Hydrodynamics



Differential energy loss



Transition region

Parton Energy Loss

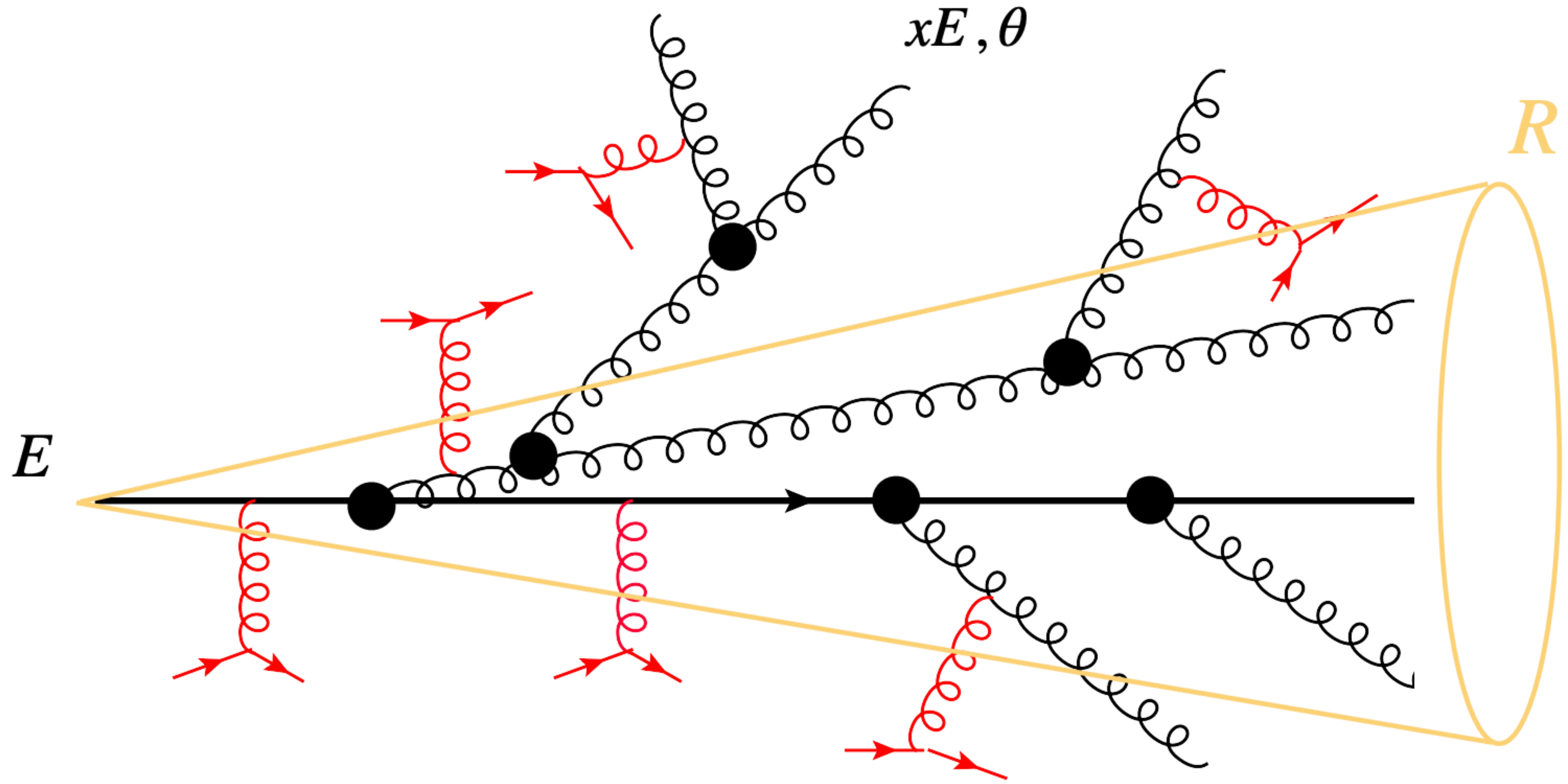
$$E^{\rm jet} \gg T$$

Energy loss with **deconfined QCD matter**, degrade energy down to medium scale.

pQCD:

Energetic parton emits quanta, which in turn emit more quanta.

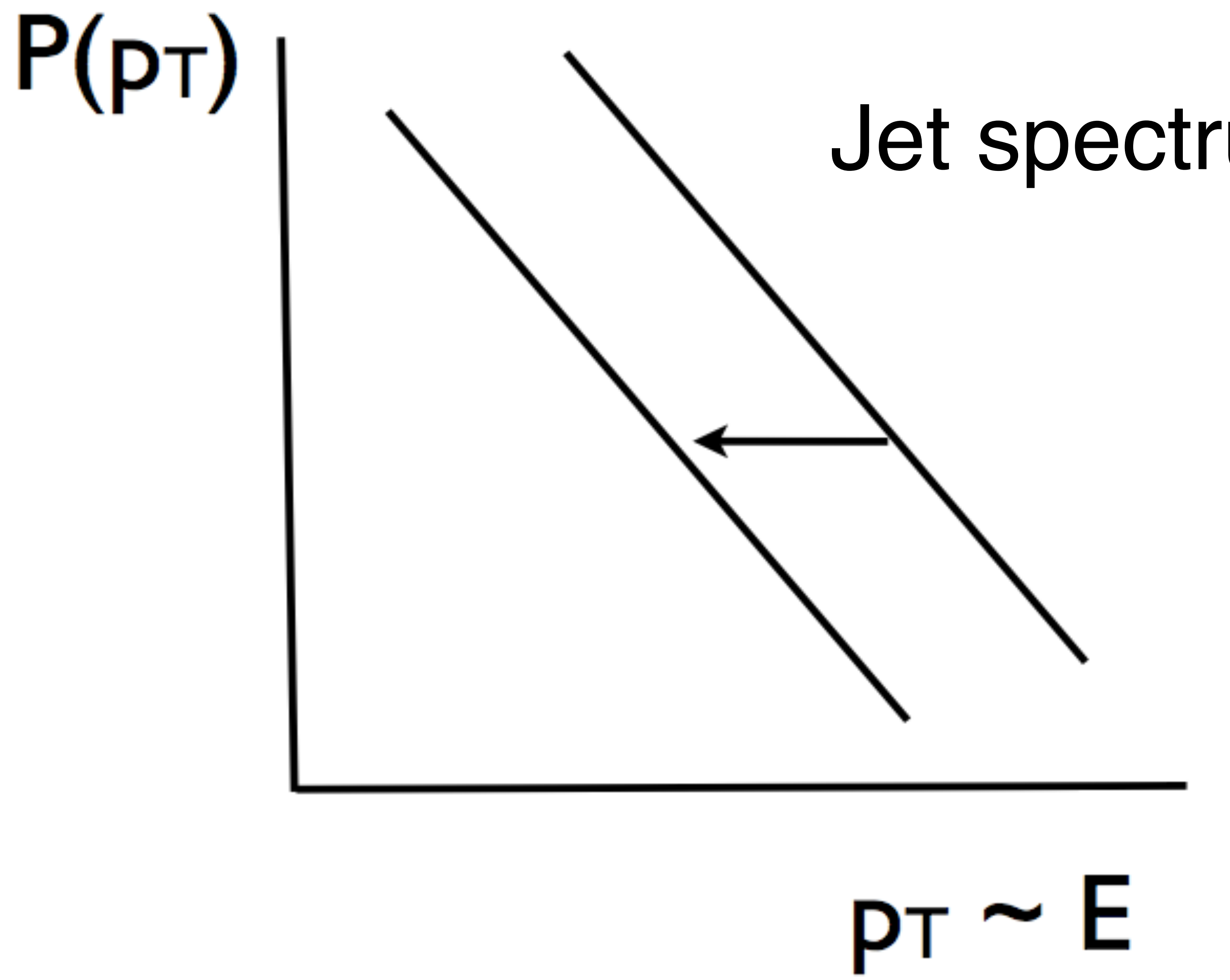
Turbulent cascade with sink at E ~ T.



Mehtar-Tani et al. - 2209.10569

Blaizot et al. - 1209.4585, 1301.6102, 1311.5823

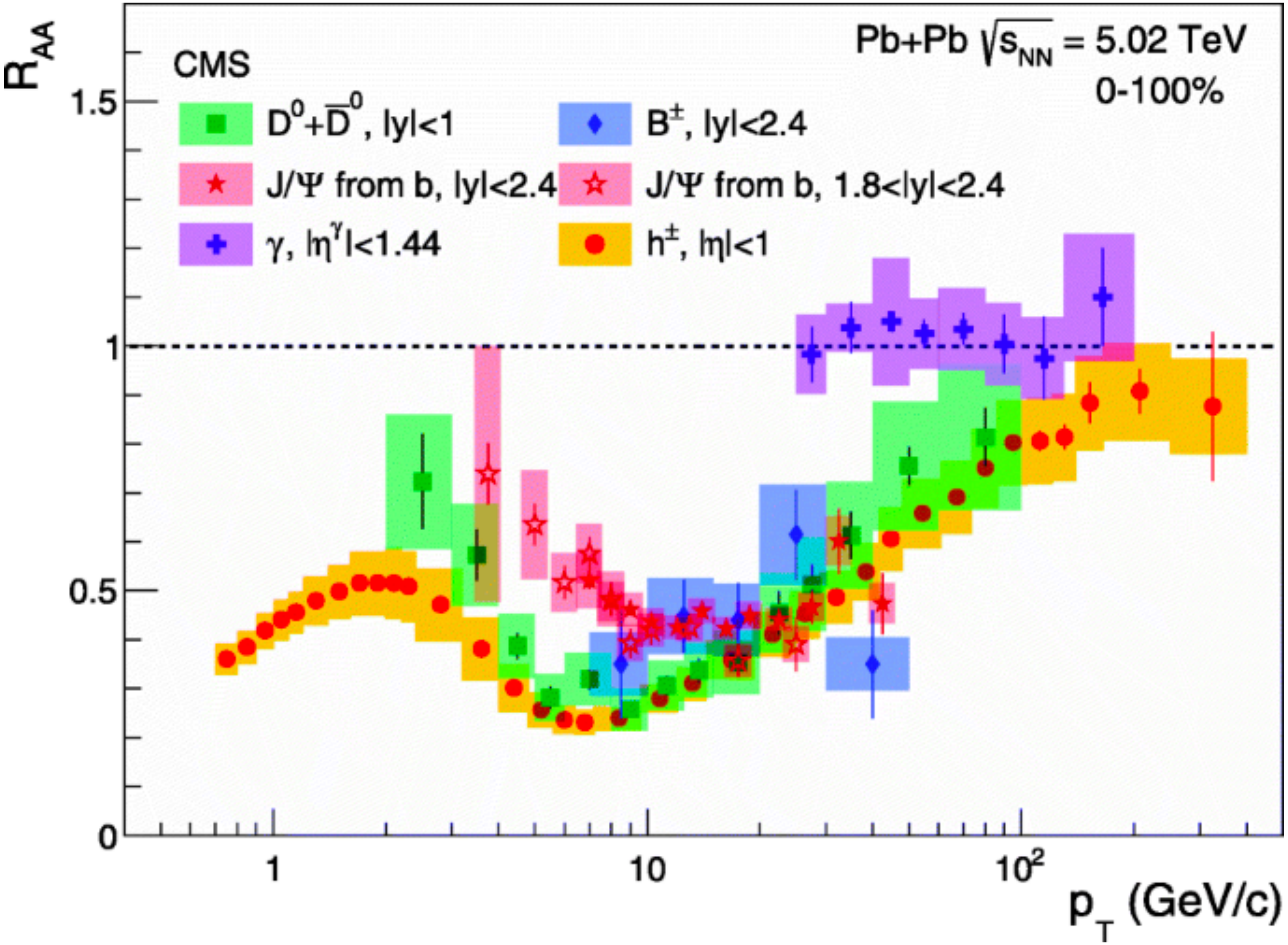
Jet Suppression



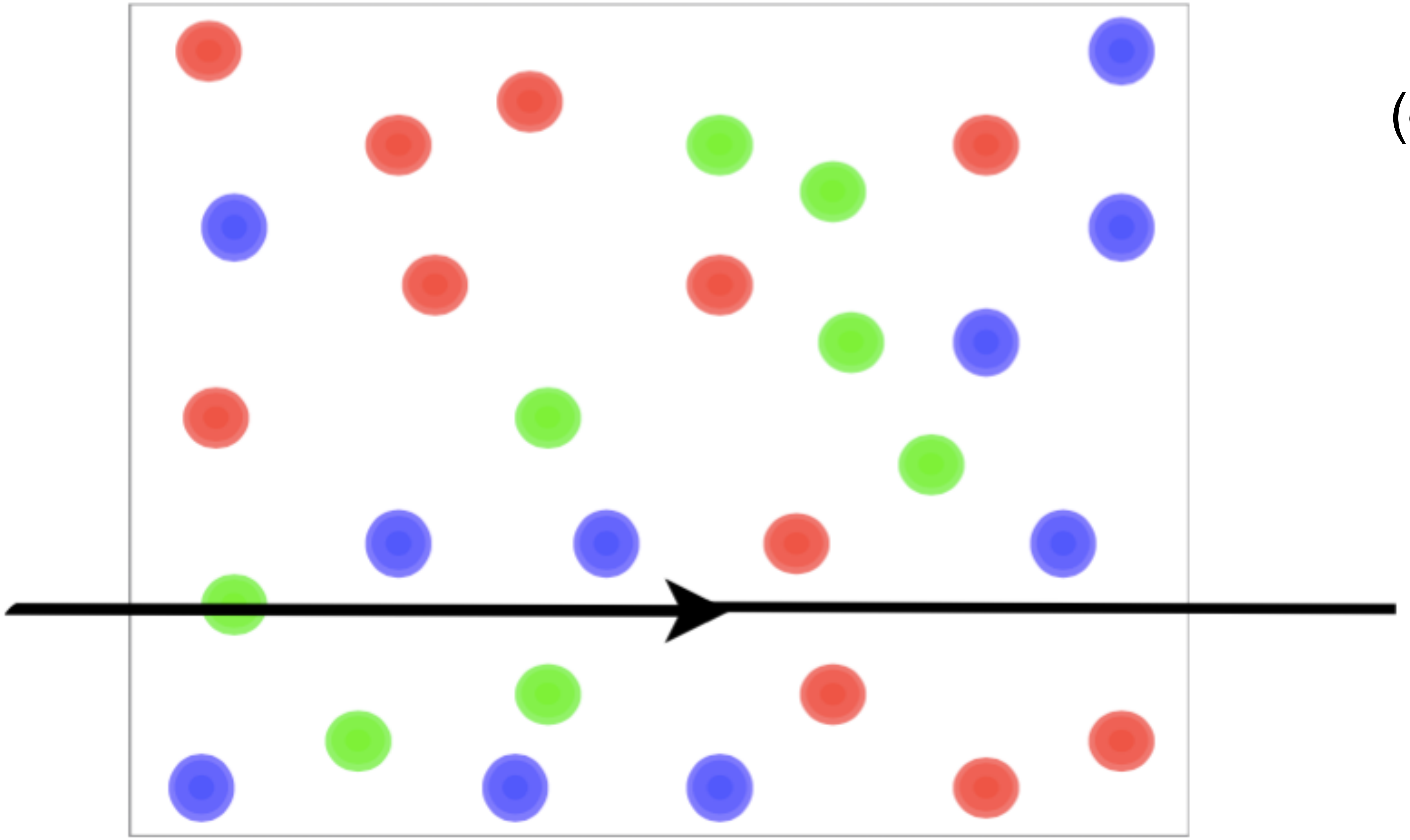
Jet spectrum gets shifted due to energy loss.

$$R_{AA} = \frac{\text{number of jets in A} - \text{A}}{\text{number of collisions } \times \text{ number of jets in p} - \text{p}}$$

Suppression of Colored Objects

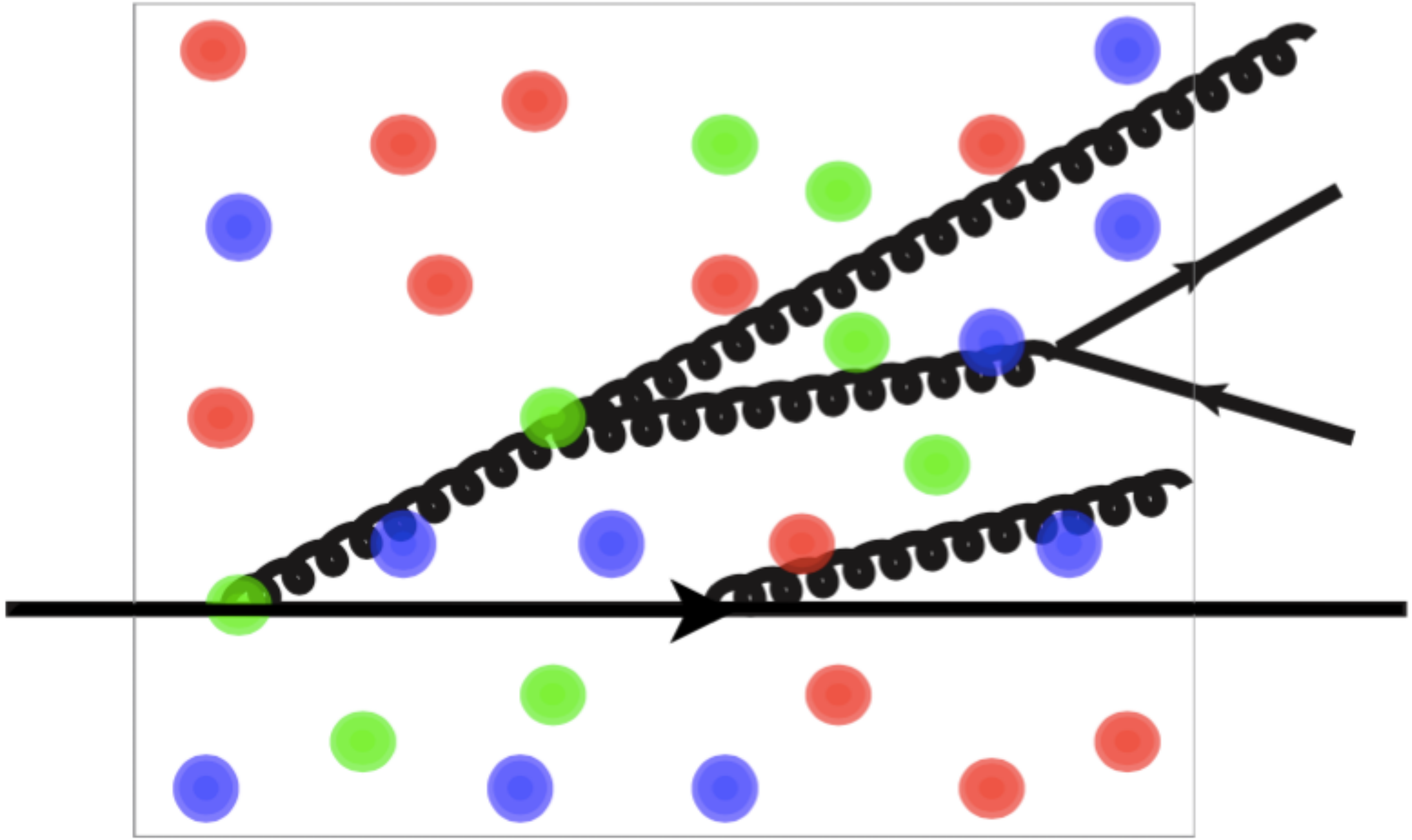


In-Medium Jet Propagation



This is an
(on-shell) parton.
Not a jet.

In-Medium Jet Propagation

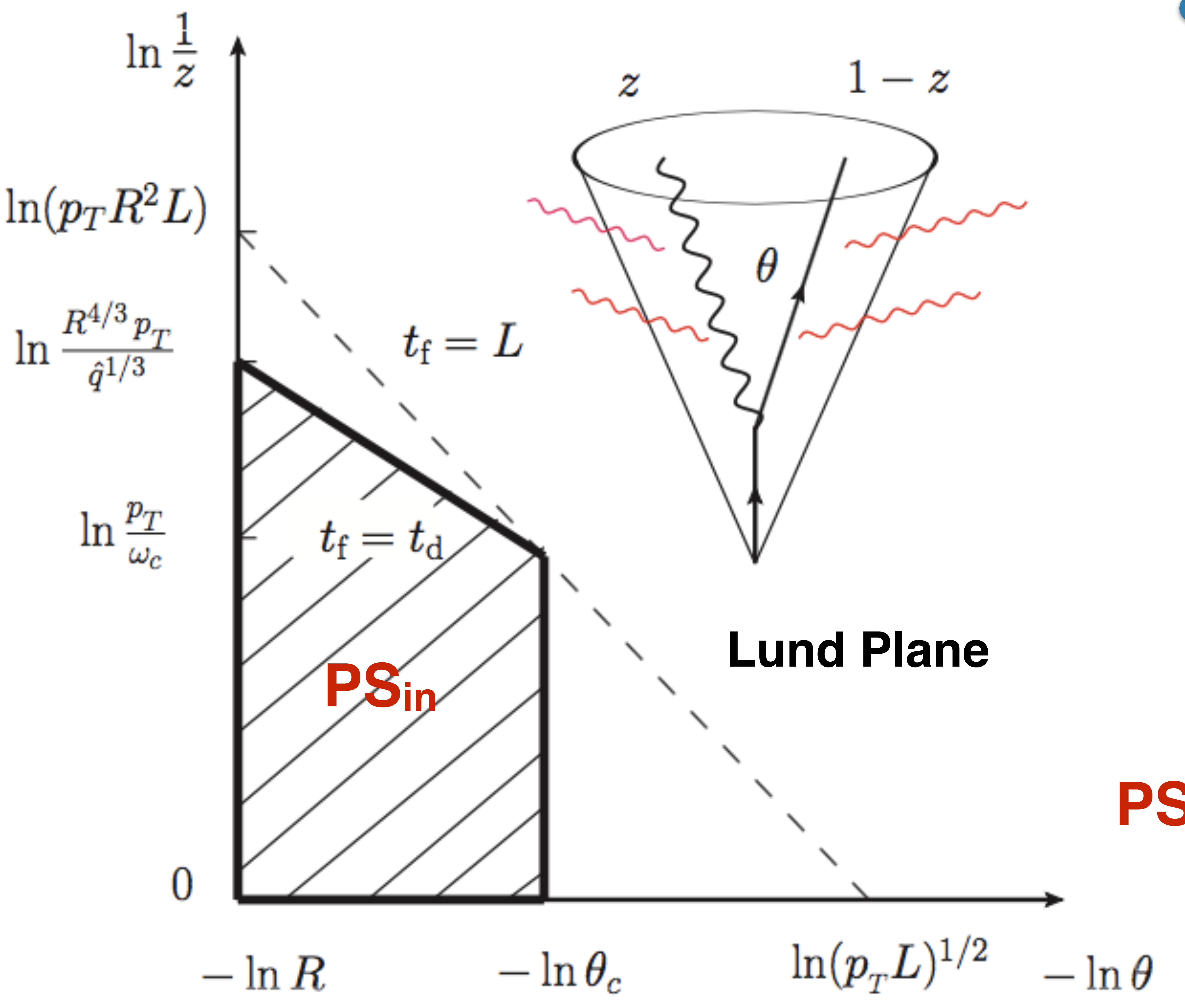


This is a jet.

Highly virtual modes have vacuum dynamics (scale separation).

Each resolved vacuum mode is a source of energy loss.

Quenched Phase Space of a Jet



- Only those jet modes that:
  - are formed inside the medium, and,
    $$t_f < L$$
  - are **resolved** by the medium,
    $$t_f < t_d$$

contribute to double-logarithmic enhancement of quenched phase space:

$$\mathrm{PS_{in}} = \bar{\alpha} \int_{t_f < t_d < L} \frac{d\theta}{\theta} \int \frac{dz}{z} \equiv \bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right)$$

Mehtar-Tani, Tywoniuk - PRD '18

see also Caucal, Iancu, Mueller, Soyez - PRL '18

Jet Suppression: Framework

- Use **microjet distributions** derived using Generating Functional (GF) framework:

Dasgupta et al. - JHEP '14

Vacuum evol. obeys DGLAP:

$$\frac{df^{\mathrm{incl}}_{j/i}(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{jk}(z')\, f^{\mathrm{incl}}_{k/i}(z/z',t)$$

- Extend GF in the medium to **resum energy loss effects** due to multi-particle nature of jet:

PS$_{\mathrm{in}}$ constraint

$$\frac{\partial Q_i(p,\theta)}{\partial \ln\theta} = \int_0^1 \mathrm{d}z\, \frac{\alpha_s(k_\perp)}{2\pi} p^{(k)}_{ji}(z)\, \Theta_{\mathrm{res}}(z,\theta) \times \left[Q_j(zp,\theta) Q_k((1-z)p,\theta) - Q_i(p,\theta)\right]$$

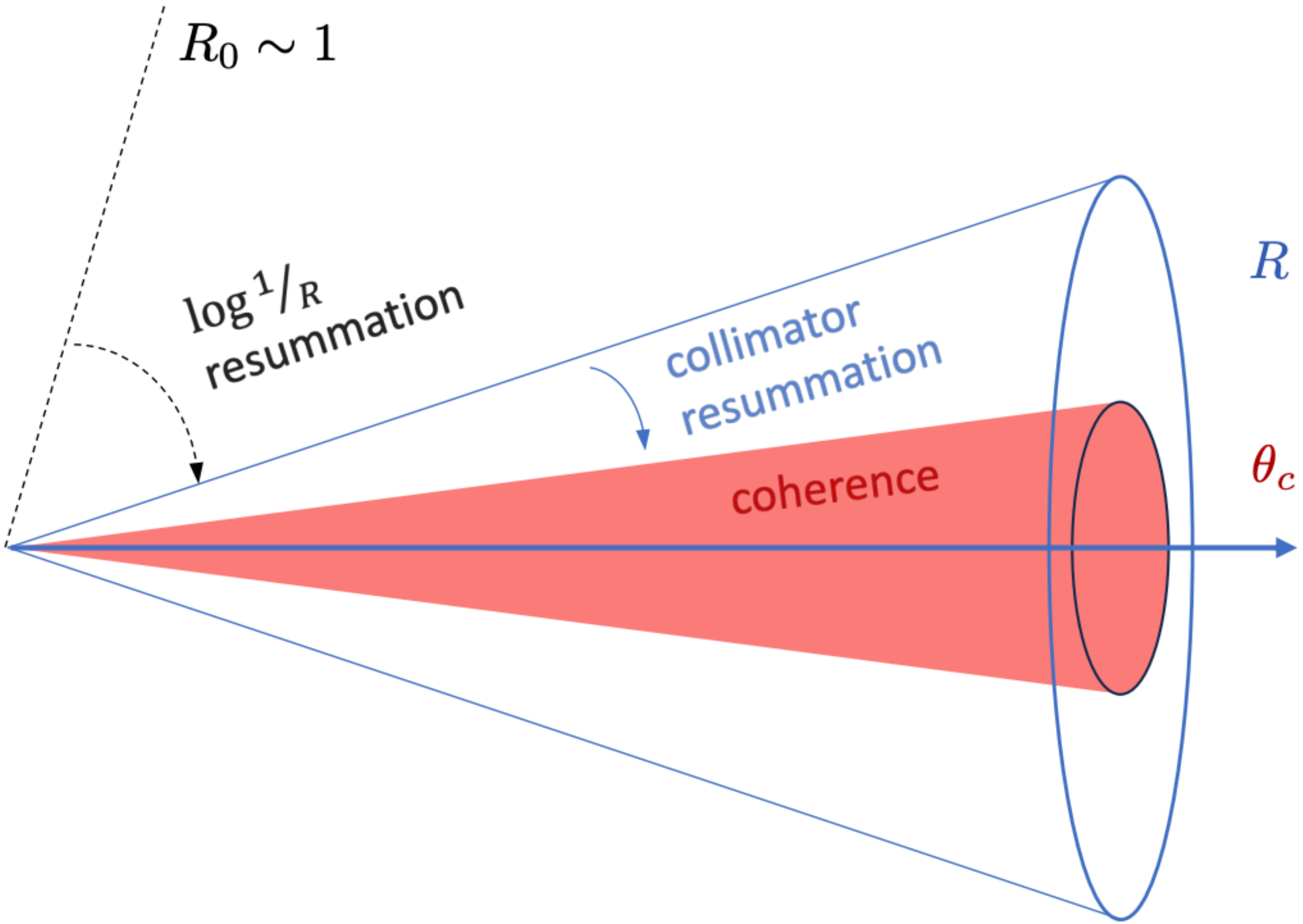
Initial condition at zero angle is single charge quenching factor:

$$Q_i(p,0) = Q^{(0)}_{\mathrm{rad},i}(p_T)\, Q^{(0)}_{\mathrm{el},i}(p_T)$$

Radiative energy loss — Elastic energy loss

Mehtar-Tani, DP, Tywoniuk - PRL '21

Jet Suppression: Framework

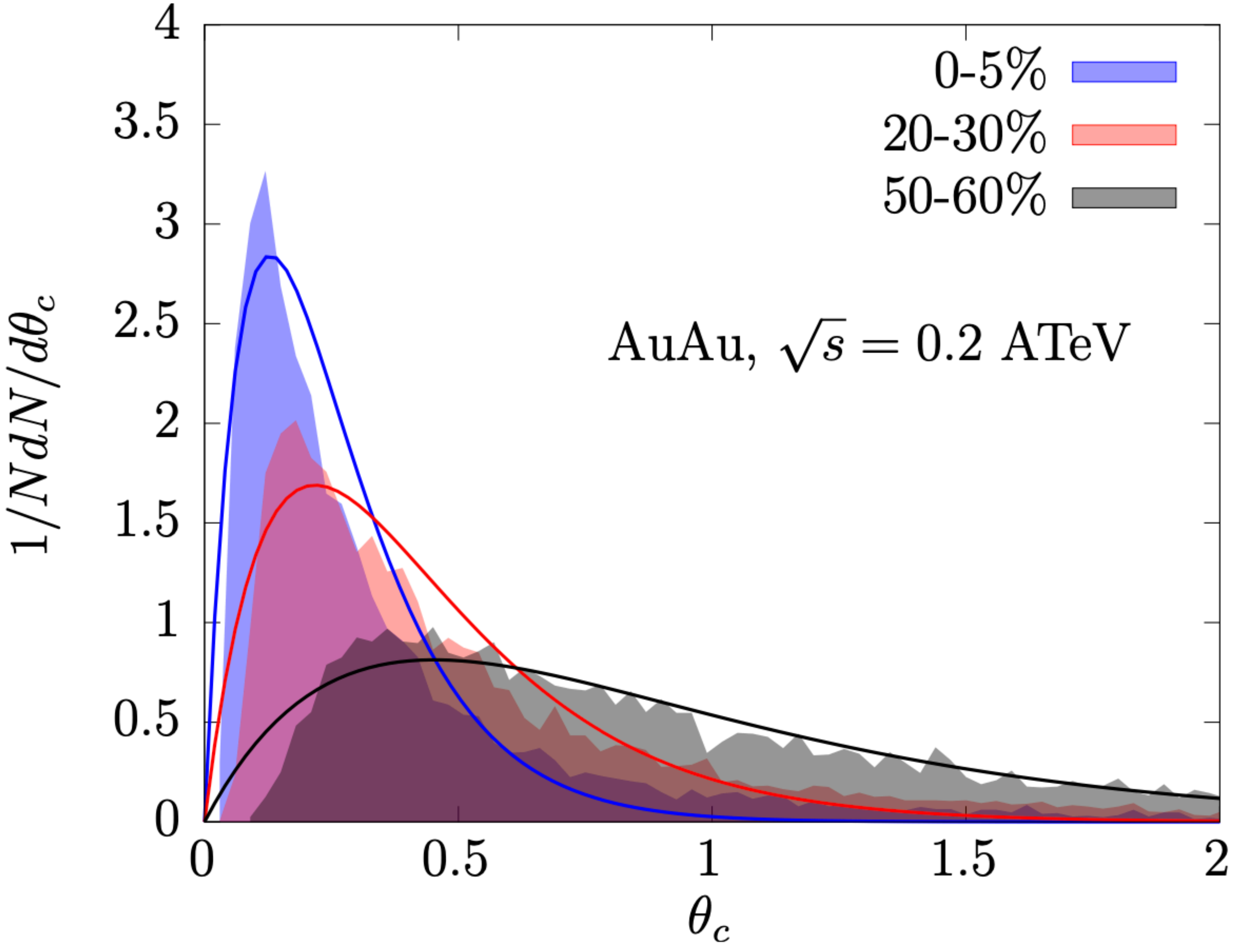


$$\theta_c \sim \frac{1}{\sqrt{\hat{q} L^3}}$$

Coherence Angle vs. Centrality

Important example:

$$\theta_c^{-\frac{1}{2}} \propto 3 \int_{\gamma(t)} \mathrm{d}x_F \, L^2(t) \, T^3(x) \, \left(\frac{p \cdot u(x)}{p^0} \right)$$

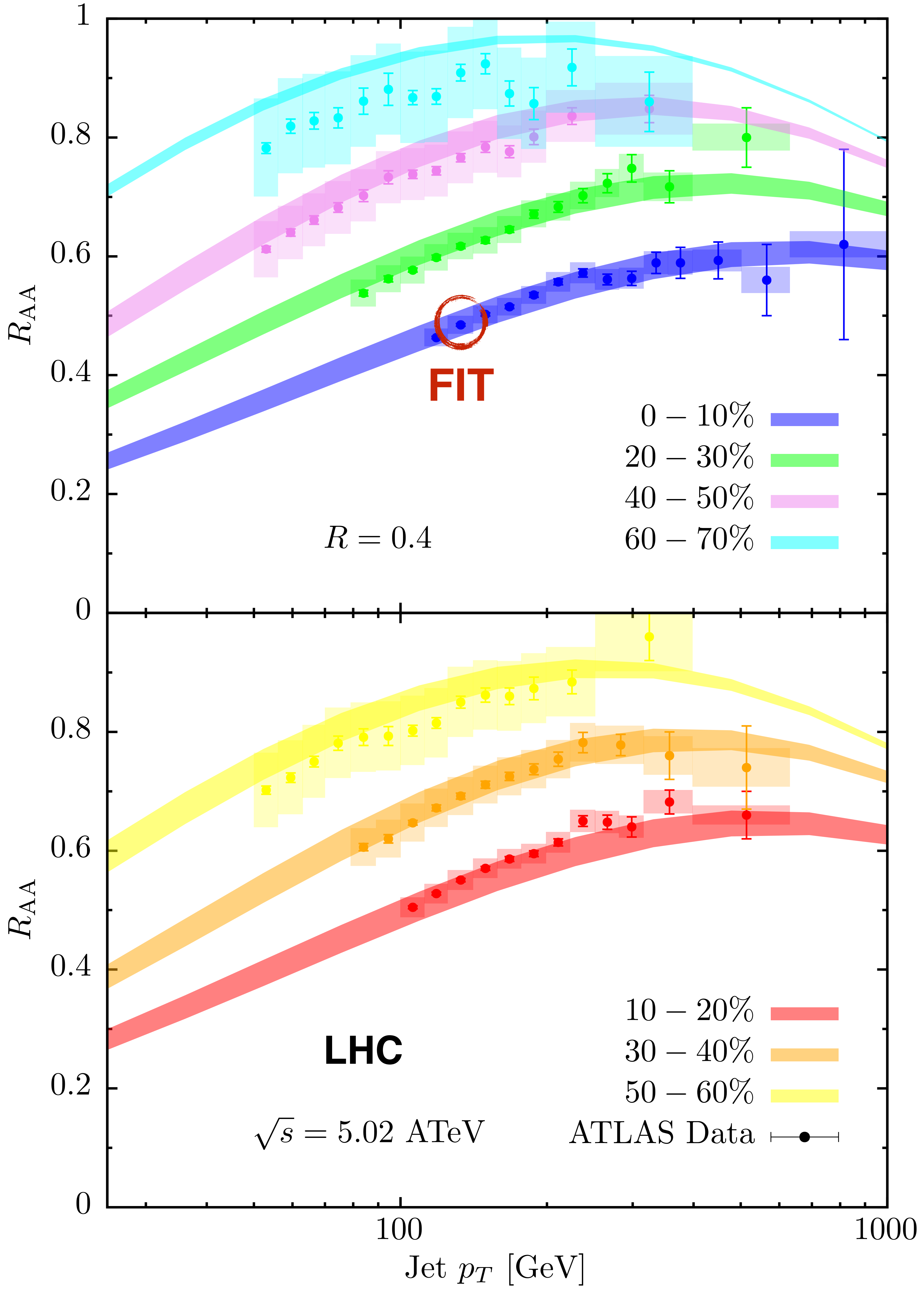


- Embed framework in realistic heavy-ion environment.
- Average over many in-medium jet histories.

Approximate function:

$$P(\theta_c) = \frac{\theta_c}{\theta_c^{*\,2}} \mathrm{e}^{-\theta_c/\theta_c^*}$$

	θ_c^*	
Centrality	RHIC	LHC
0-5%	0.13	0.09
5-10%	0.15	0.10
10-20%	0.17	0.12
20-30%	0.22	0.15
30-40%	0.27	0.19
40-50%	0.35	0.24
50-60%	0.45	0.32
60-70%	0.58	0.41



- Modelling sensitivity at p_T=110 GeV for **R** between **0.2 and 0.6**:

Mehtar-Tani, DP, Tywoniuk - PRL ‘21

Parameter	Variation	Effect
θ_c	$[\theta_c/2,\, 2\theta_c]$	$\lesssim 20\%$
IOE	LO/NLO	$\sim 2\%$
n	± 1	$\sim 10\%$
$R_{\rm rec}$	$[1,\, \infty]$	$\lesssim 10\%$
ω_s	$[\omega_s/2,\, 2\omega_s]$	$\lesssim 8\%$

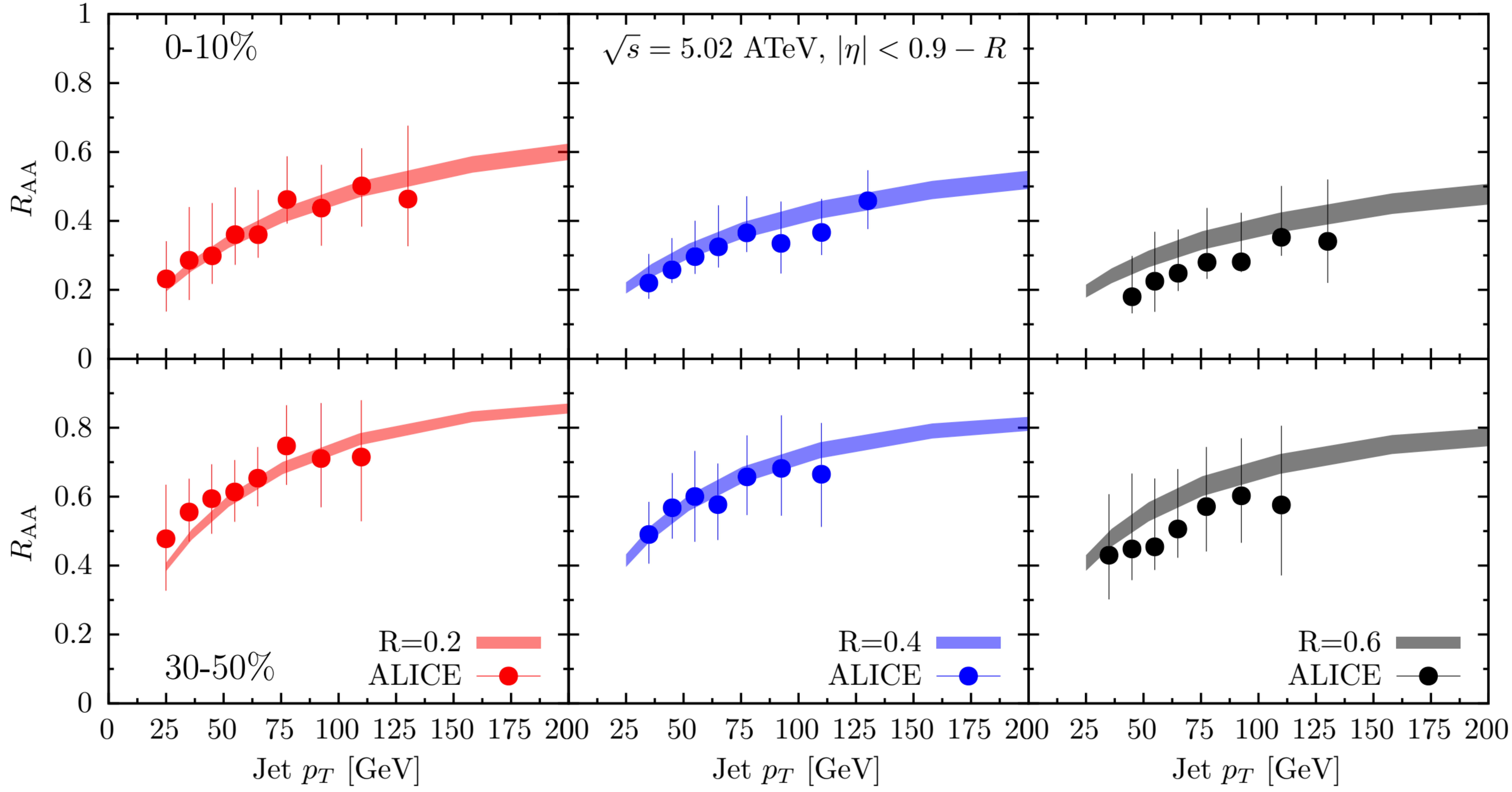
→ NLO contribution very small (hard emissions tend to be collinear).

→ Modeling of fate of lost energy relatively small.

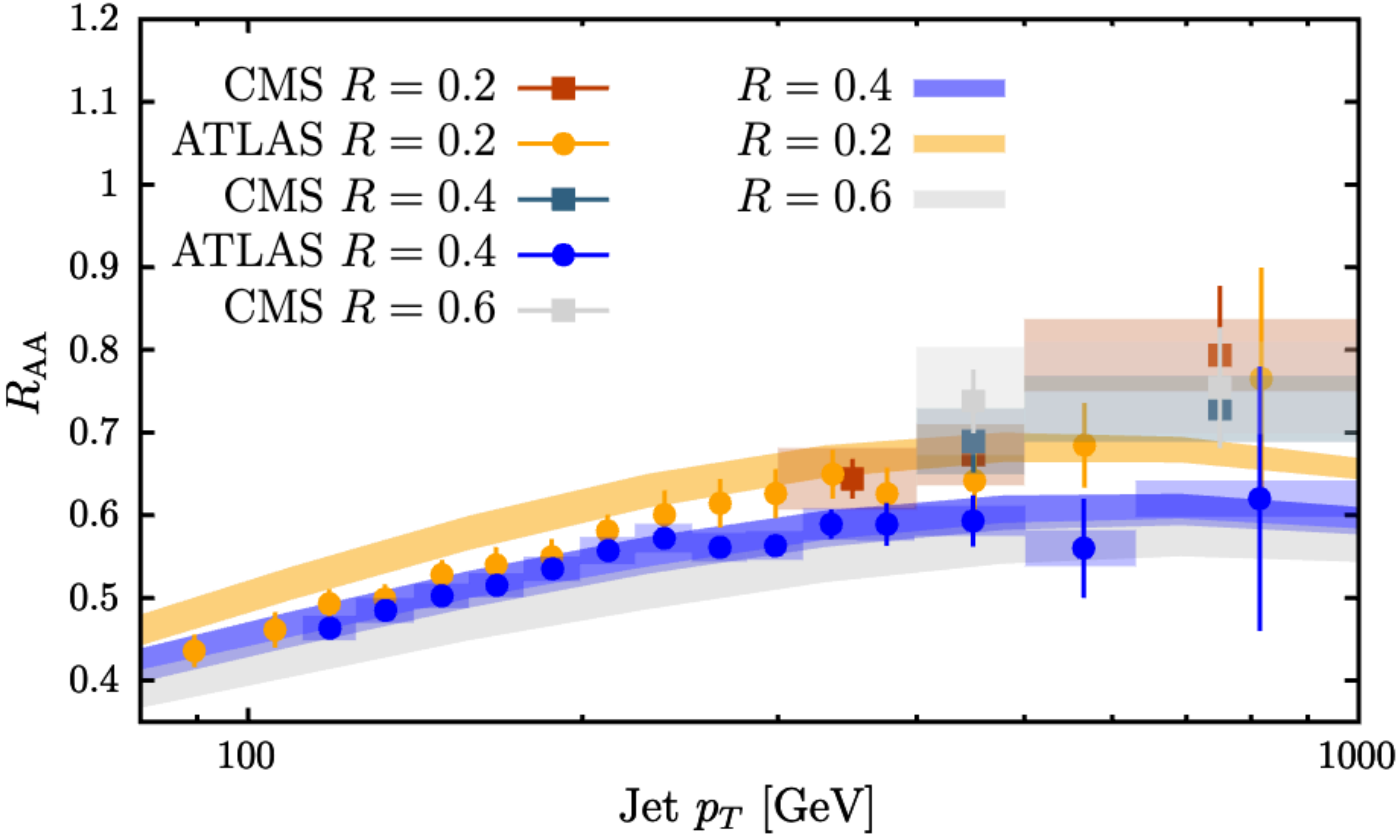
→ Determination of quenched phase space relatively large. Improvable in pQCD.

Need to improve perturbative sector before non-perturbative becomes relevant (for R<0.6!)

Jet Suppression at LHC

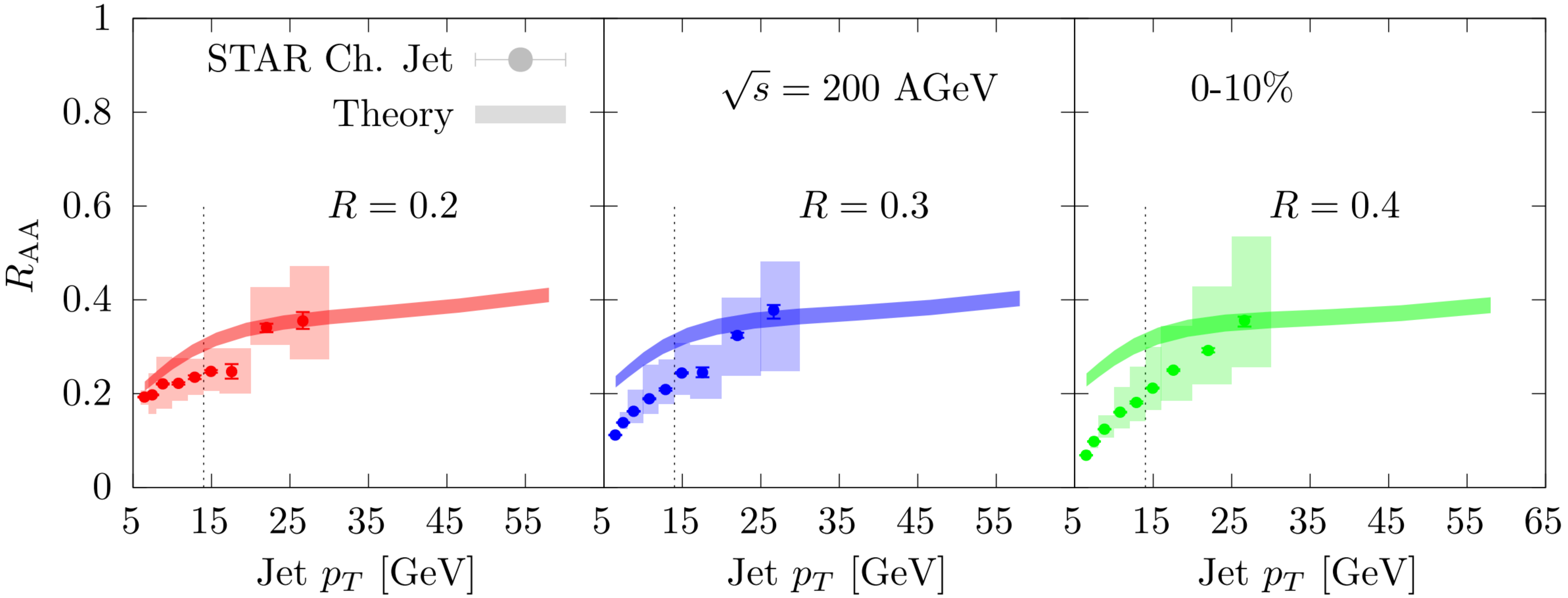


Jet Suppression at LHC



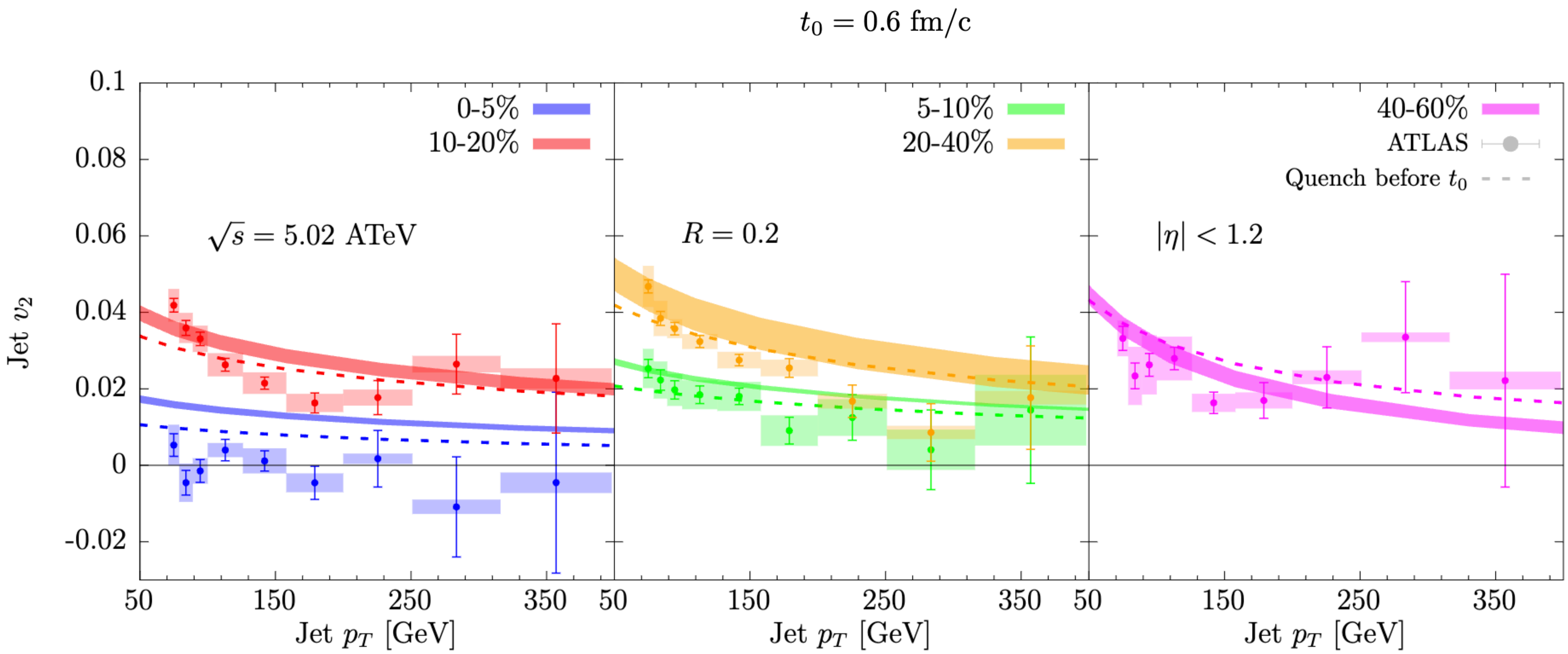
- Some tension with CMS data (also tension between ATLAS and CMS).

Jet Suppression at RHIC



- Below dashed line: biased region (experimental limitation).

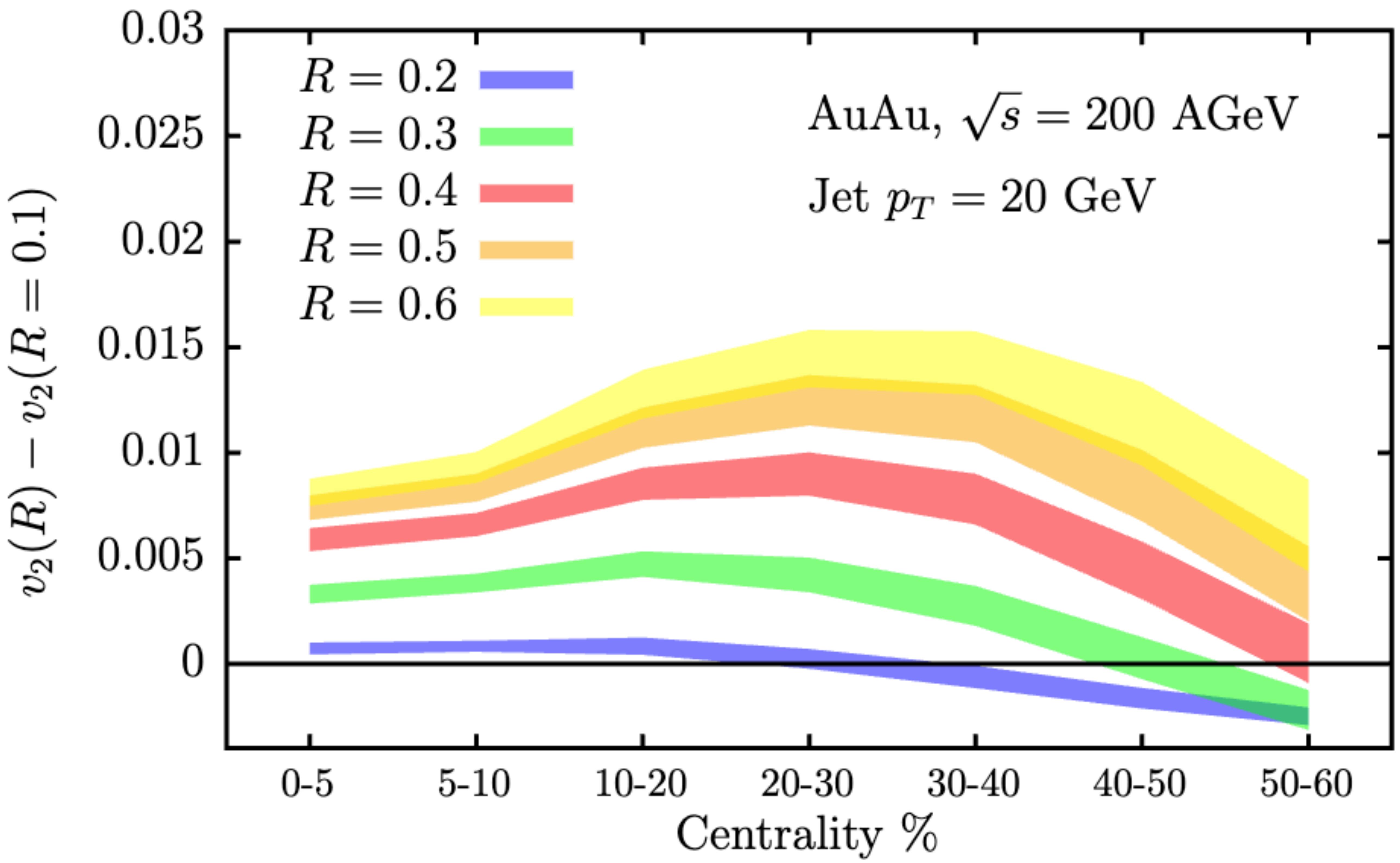
Jet v_2 at LHC for R=0.2



- Good description of centrality and p_T dependence.
- Quenching in initial stages improves agreement with most central class.

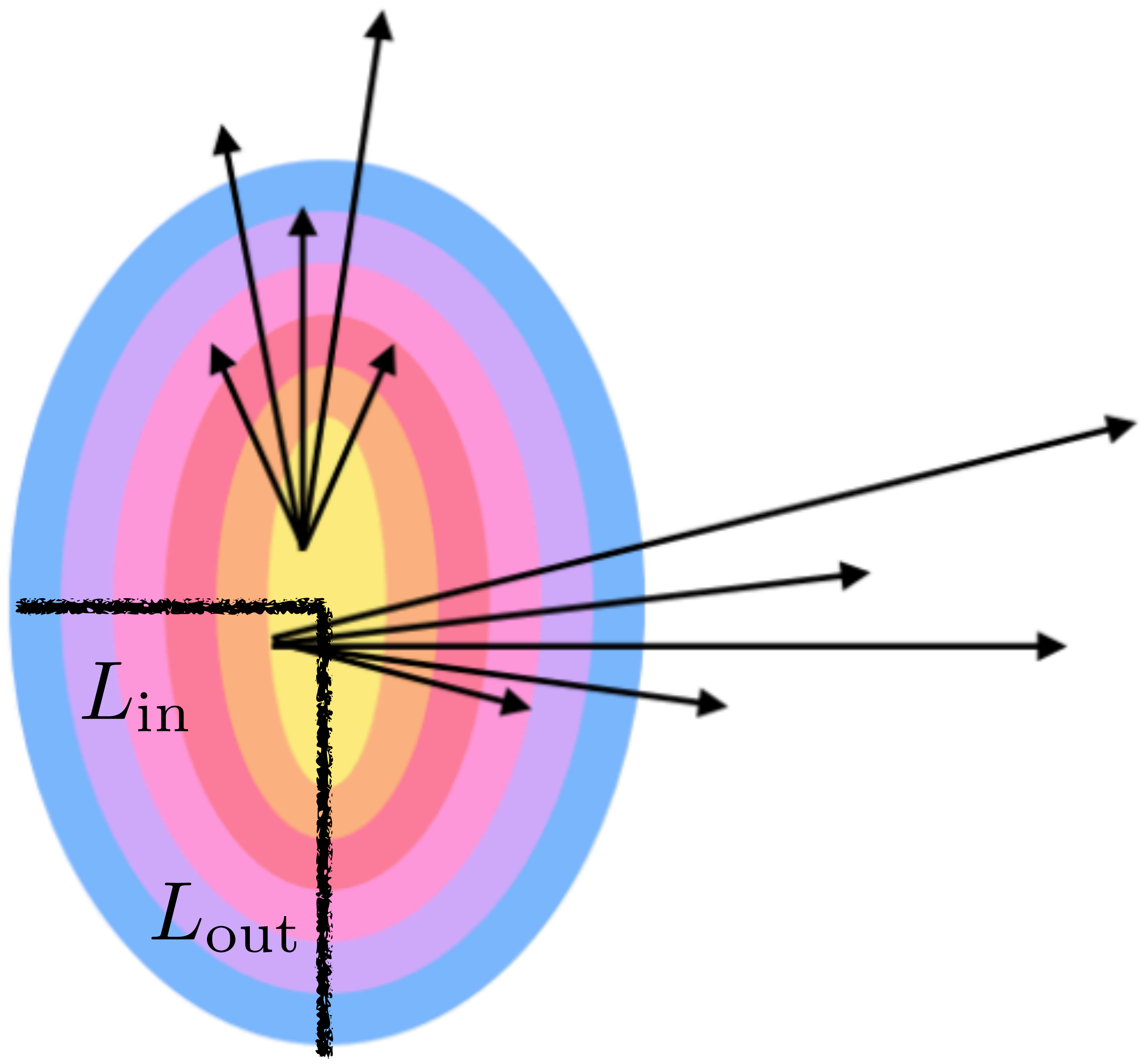
R-dependence of v_2 at RHIC

v_2 difference between various R and R=0.1 at fixed p_T.



- Sequential collapse of v_2 difference at different centralities…
- What exactly is driving this behaviour?

Simplified Analytics



$$v_2 \simeq \frac{1}{2}\frac{R_{\mathrm{AA}}(L_{\mathrm{in}}) - R_{\mathrm{AA}}(L_{\mathrm{out}})}{R_{\mathrm{AA}}(L_{\mathrm{in}}) + R_{\mathrm{AA}}(L_{\mathrm{out}})}$$

For small length differences:

$$v_2 \approx -\frac{\Delta L}{4}\frac{\mathrm{d}\ln R_{AA}}{\mathrm{d}L}$$

- For a single species:

$$R_{\mathrm{AA}} \simeq Q(p_T, R)$$

- Resummed quenching weight in the soft *z* and strong quenching approx:

$$Q_i(p_T, R) \simeq Q_i^{(0)}(p_T)\,\mathrm{e}^{-\Omega_{\mathrm{res}}(p_T, R)}$$

Bare quenching weight　　Resolved phase-space

Simplified Analytics

$$\Omega_{\rm res} = 2\bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{3p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right)$$

$$\Delta L / L = 2e$$

e is eccentricity.

Derivative of resolved phase space is *independent* of R and θ_c:

$$\delta\Omega_{\rm res}(p_T, R) = \frac{3\bar{\alpha}}{L} \mathcal{L}_c$$

$$\mathcal{L}_c \equiv \ln(3p_T/\omega_c)$$

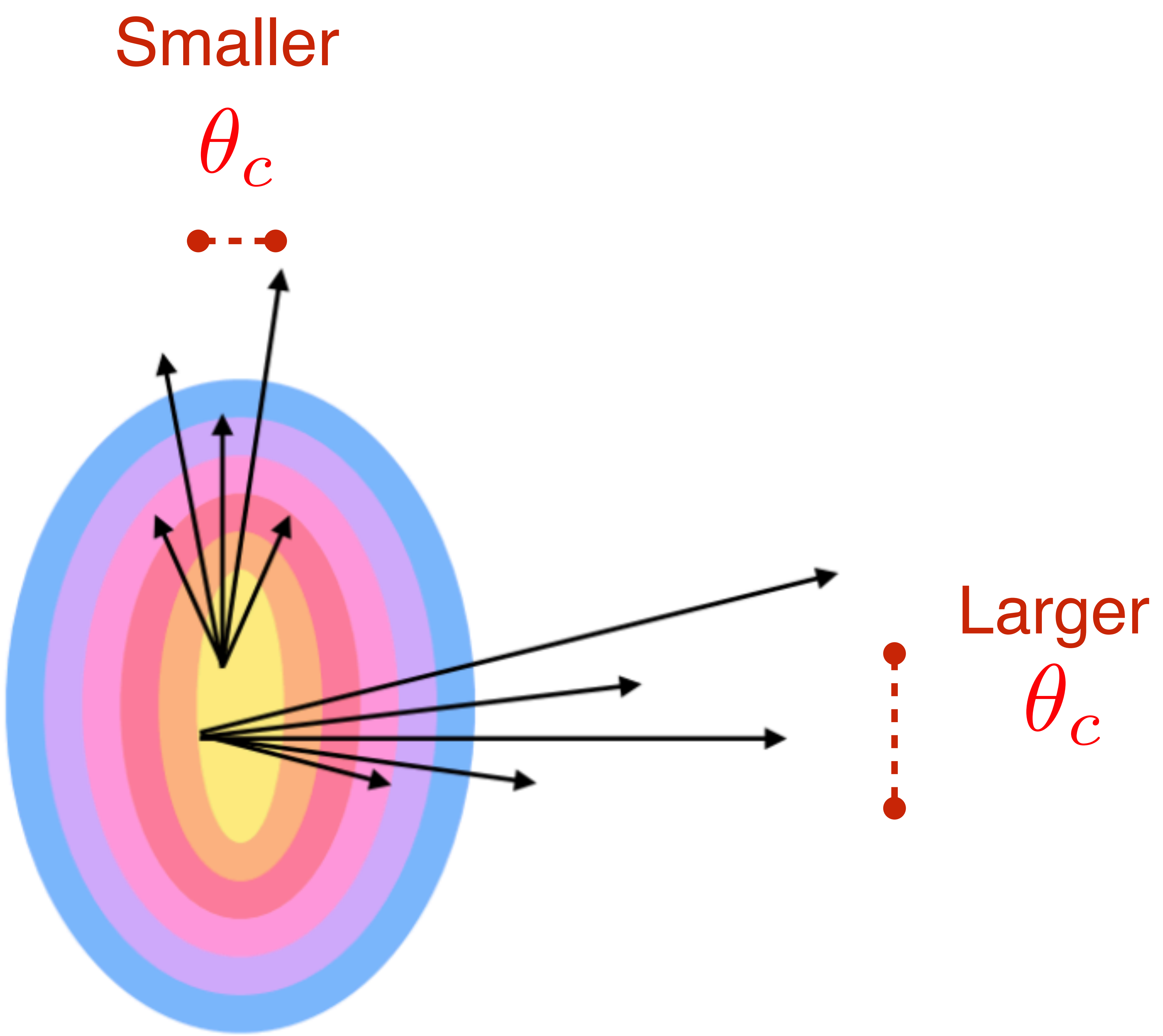
$$\frac{v_2}{e} \simeq \bar{\alpha} \left(\sqrt{\frac{\pi \omega_c n}{p_T}} + \frac{3}{2} \mathcal{L}_c \Theta(R - \theta_c) \right)$$

Jet v_2 larger than single charge v_2 by a *fixed amount* if $R > \theta_c$.

Otherwise $\left.\frac{v_2}{e}\right|_{R\leq\theta_c} \approx -\frac{1}{2} \ln R_{\rm AA}\big|_{R\leq\theta_c}$

Simplified Analytics

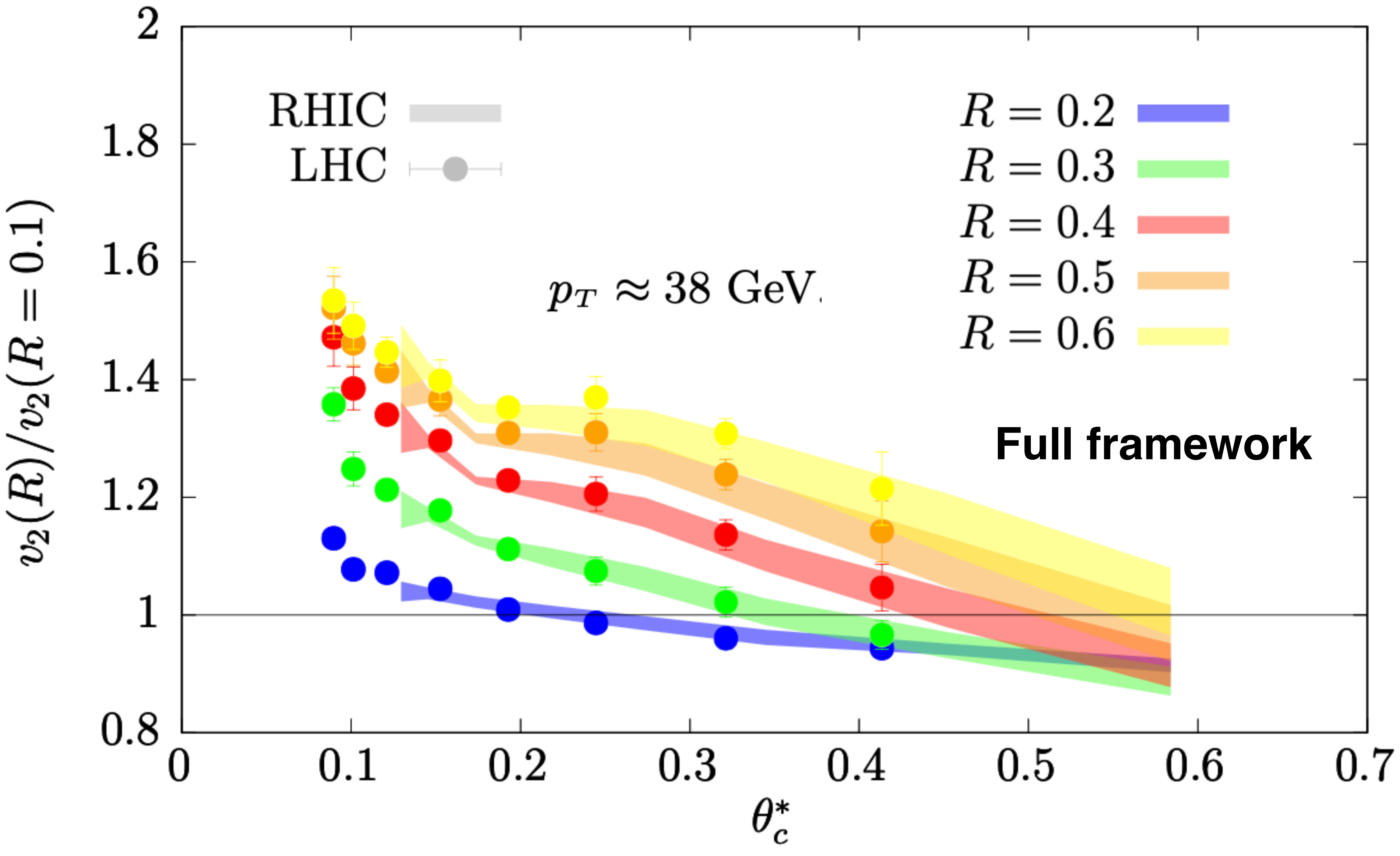
$$\theta_c \sim \frac{1}{\sqrt{\hat{q}L^3}}$$



Smaller traversed length → Less quenching per se (only effect in single color charge).

→ Less quenching due to smaller resolved phase-space.
(Unless $R<\theta_c$, both for L_{in} and L_{out}!).

Jet v_2 Probes Color Coherence

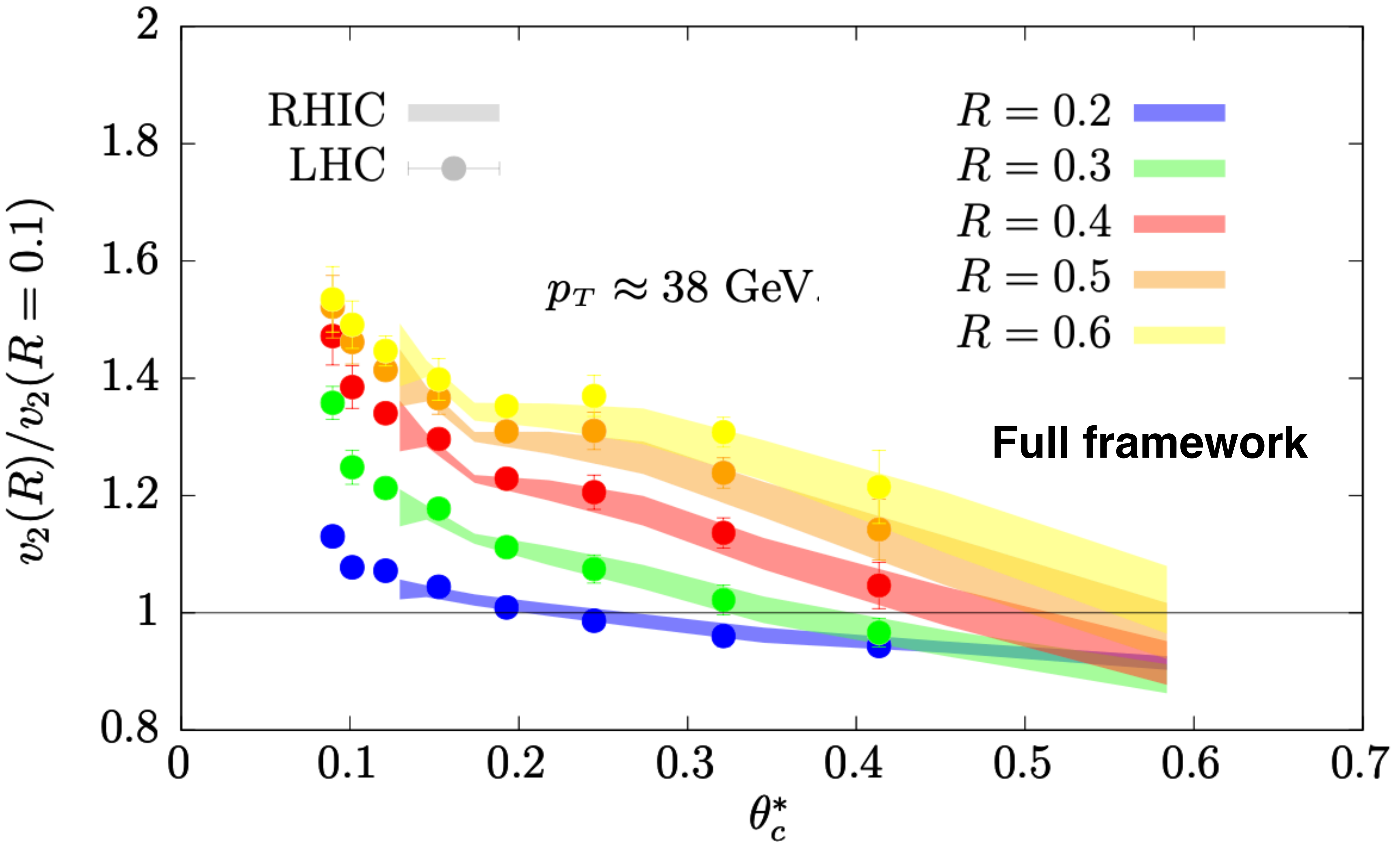


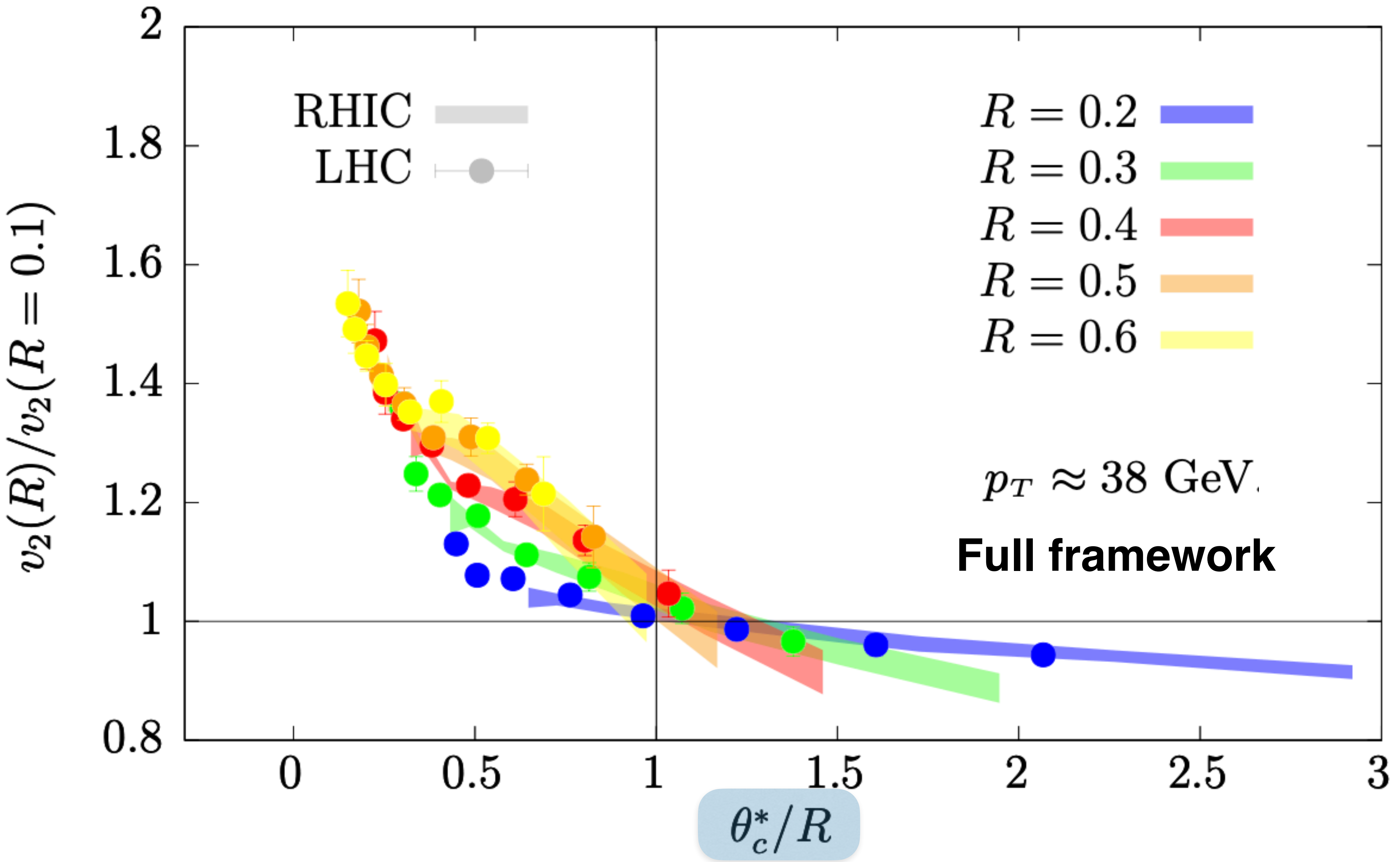
- Map between collision system and centrality with typical θ_c (the table in slide 13!)

$$\theta_c^*(\sqrt{s}, \text{cent.})$$

reveals common dependence on color coherence between RHIC and LHC.

Jet v_2 Probes Color Coherence





- Map between collision system and centrality with typical θ_c (the table in slide 13!)

$$\theta_c^*(\sqrt{s}, \text{cent.})$$

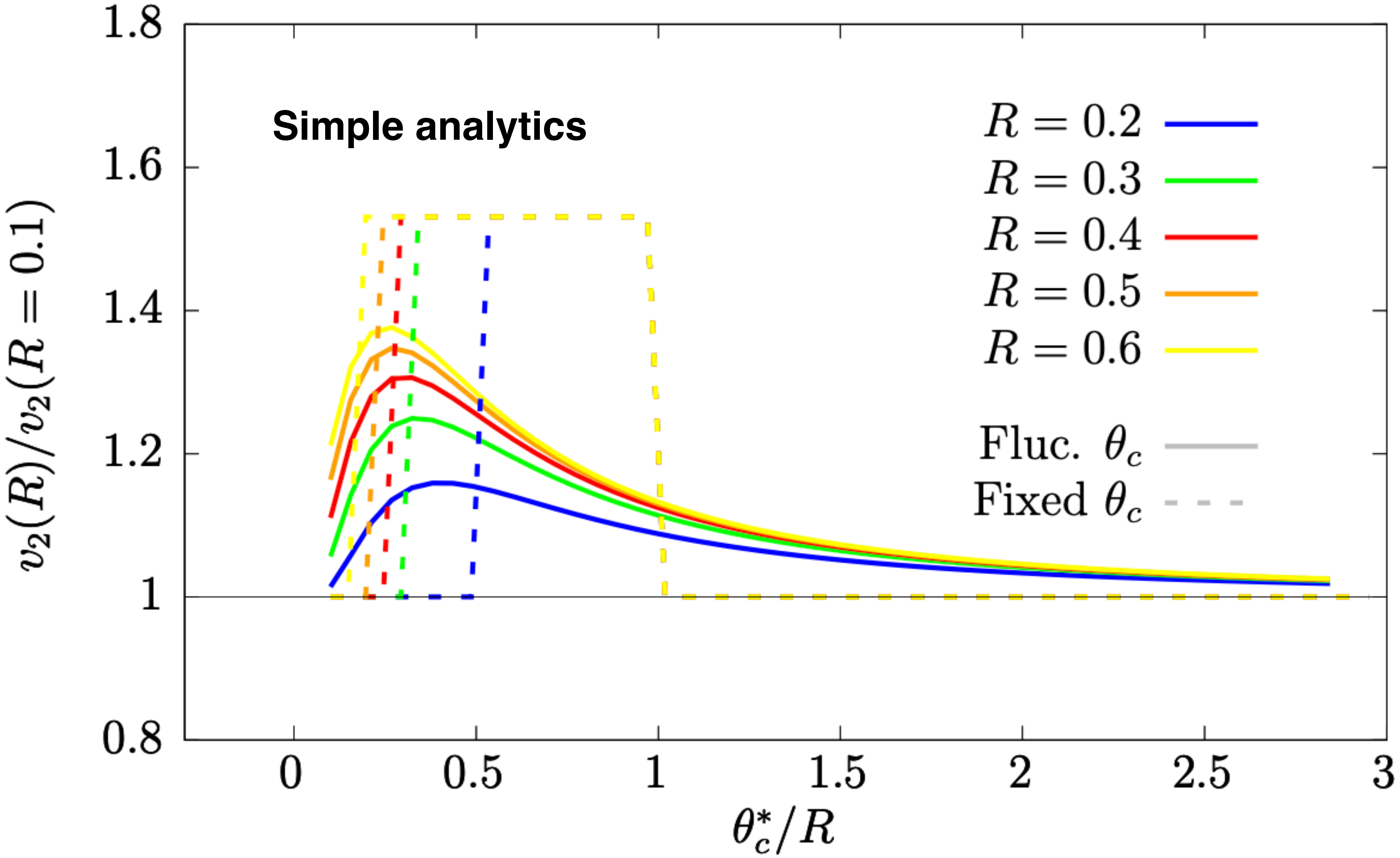
reveals common dependence on color coherence between RHIC and LHC.

→ Universal scaling for sufficiently large R!

→ Merging at $\theta_c^*/R \approx 1$.

→ *Suggestive of an experimental strategy.*

Jet v_2 Probes Color Coherence



Universal curve directly sensitive to θ_c fluctuations!

$$\Theta(R-\theta_c) \to \int_0^R \mathrm{d}\theta_c \, P(\theta_c) = 1 - \frac{1+t}{t\, \mathrm{e}^{\frac{1}{t}}}$$

$$t \equiv \theta_c^*/R$$

Conclusions

- Jet v_2 is a length-differential jet suppression observable. Also present in pPb, without quenching!?
- Critical coherence angle θ_c strongly depends on traversed length.

  It determines the size of resolved phase space of a jet.

Jet v_2 is remarkably sensitive to color coherence physics.

- Made first analytical predictions for jet v_2 at RHIC and LHC for many R.

  Using realistic framework with excellent description of available data (jet p_T, R, centrality…) after fitting a single parameter.

- Proposal: measure jet v_2 for as many R, as many centralities, and as many systems as possible for AuAu and PbPb, and should add OO!

  Target a variety of θ_c values.

  Study relative size of v_2 between different R and small R.

  Confront universal scaling picture based on color coherence physics.

Backup Slides

Jets in Vacuum

- Through Generating Functional framework:

$f^{\mathrm{incl}}_{j/i}(z,t) \rightarrow$ **inclusive dist. of microjets** with energy fraction z, flavour j, at scale t, with initial parton with flavour i.

- Microjet fragmentation function satisfies DGLAP style evolution:

$$\frac{df^{\mathrm{incl}}_{j/i}(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{jk}(z')\, f^{\mathrm{incl}}_{k/i}(z/z',t)$$

Dasgupta et al. - JHEP '14

- Relates to inclusive jet spectrum:

$$\frac{d\sigma_{\mathrm{jet}}}{dp_t} \simeq \frac{d\sigma_i}{dp_t} \int_0^1 dz\, z^{n-1} f^{\mathrm{incl}}_{\mathrm{jet}/i}(z,t)$$

for power-law initial spectrum: $d\sigma_i/dp_t \sim p_t^{-n}$

- Interpret scale t as an angular scale $t \equiv \theta$

in angular ordered shower: $\theta_1 \gg \theta_2 \gg \theta_3 \ldots$

- Use running coupling constant: $\alpha_s(k_t) = \dfrac{2\pi}{\beta_0 \ln \frac{k_t}{Q_0}}$

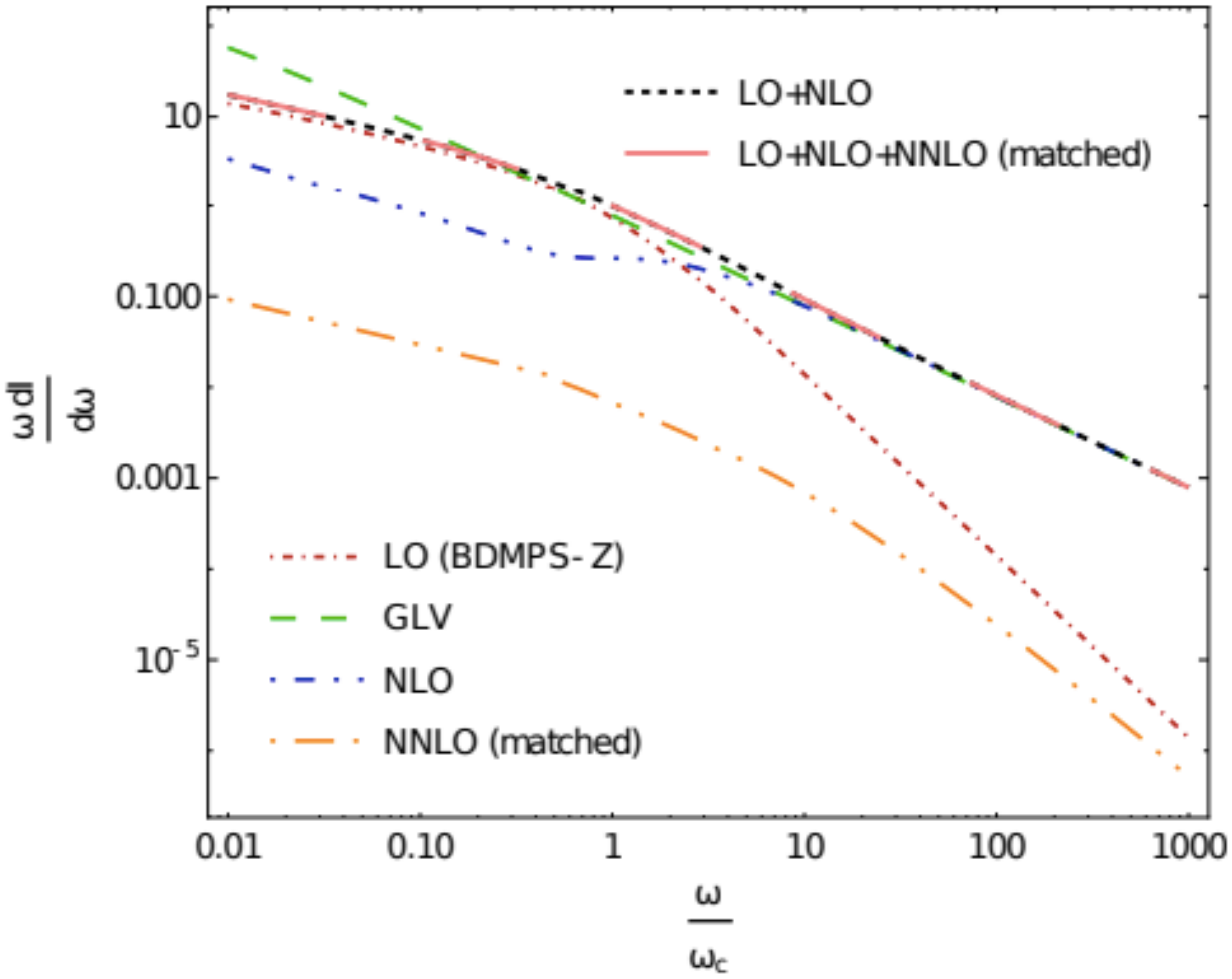
$$k_t = z(1-z)p\theta$$

$$\beta_0 = (11N_c - 4n_f T_R)/3$$

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP ‘20

$$t_{\rm coh} = \omega/k_\perp^2 \qquad k_\perp^2 \sim \hat{q}\, t_{\rm coh} \qquad t_{\rm coh} \equiv \sqrt{\frac{\omega}{\hat{q}}}$$



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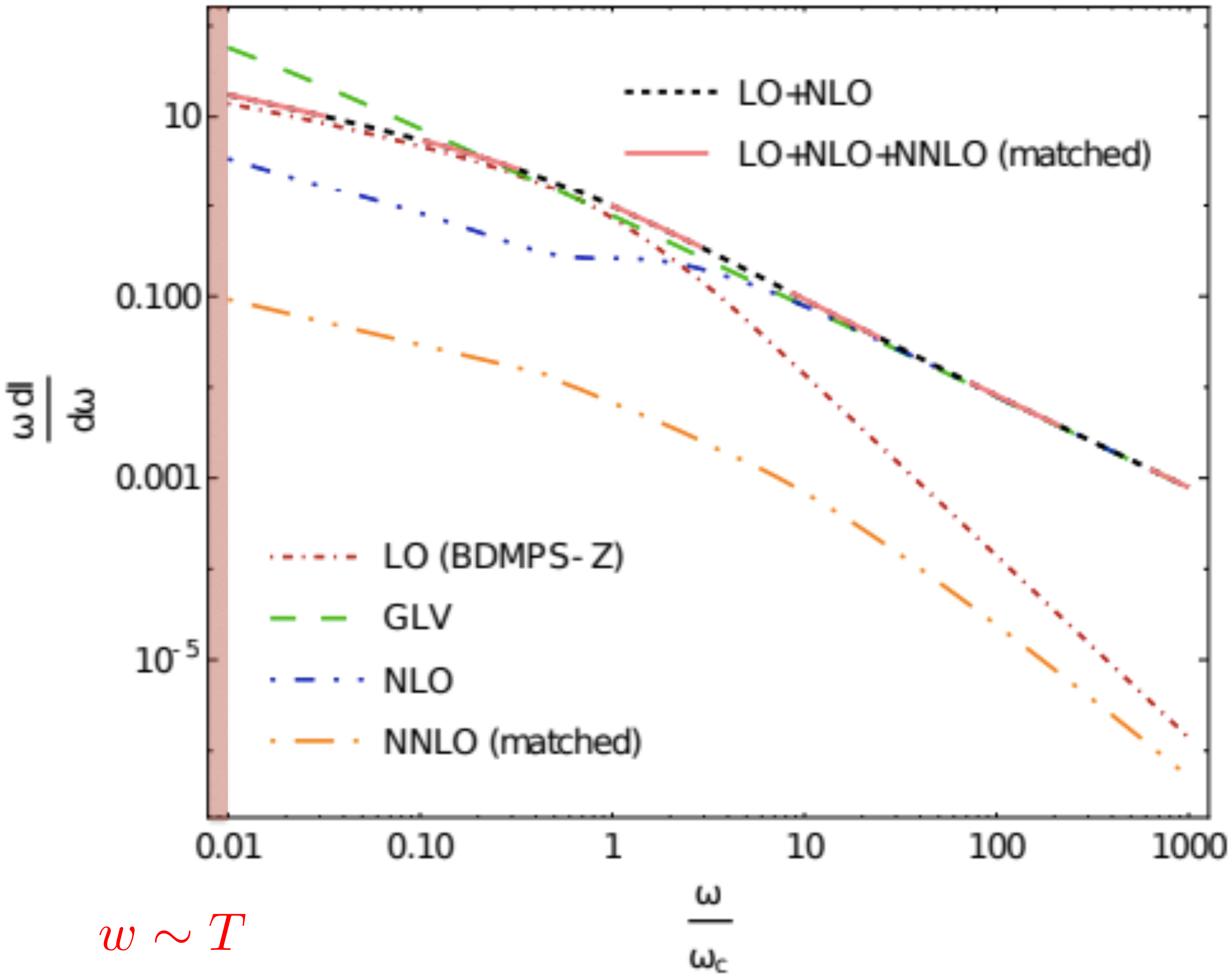
Barata, Mehtar-Tani - JHEP '20



$w \sim T$

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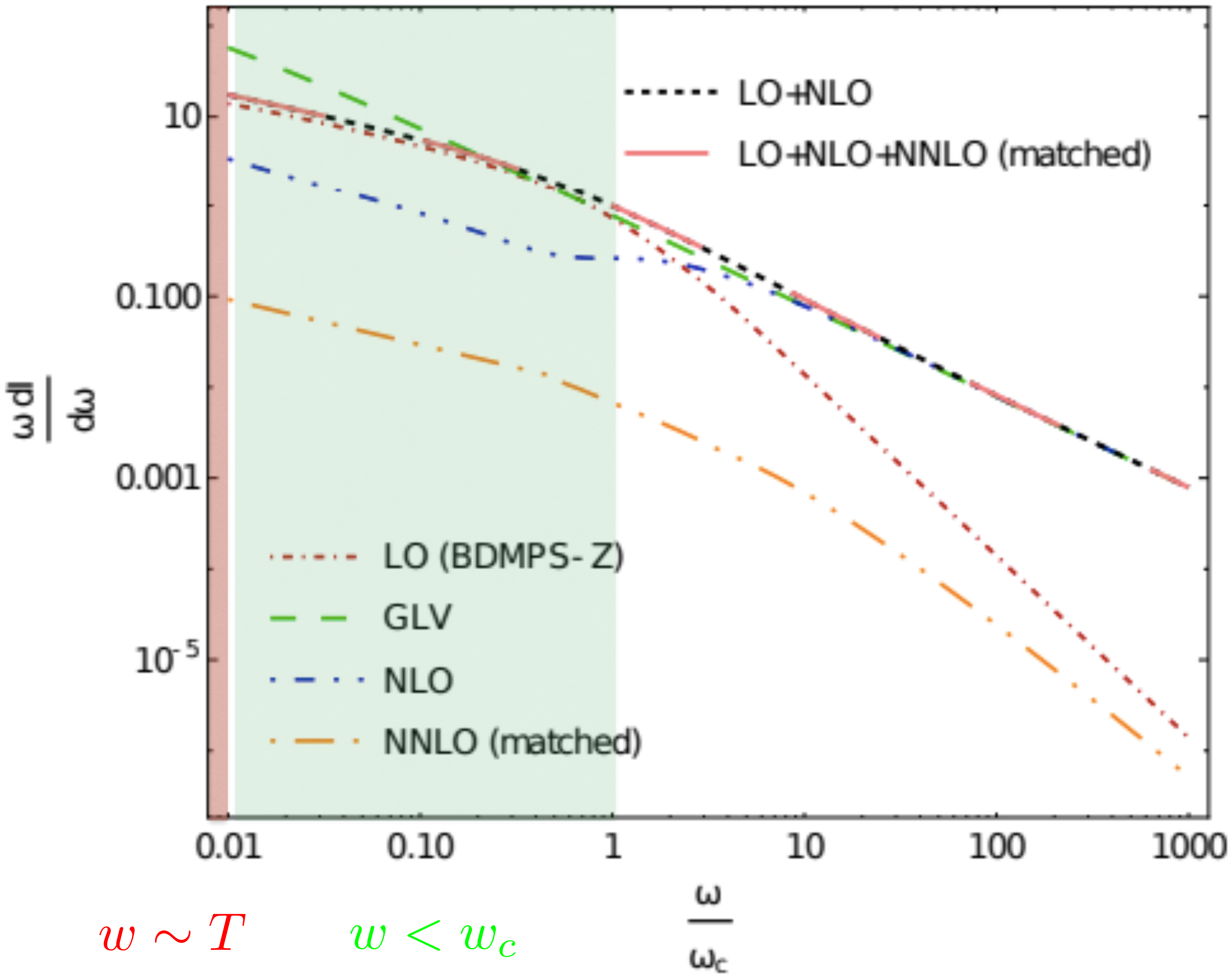
- Bethe-Heitler regime $t_{\rm coh} \sim \ell_{\rm mfp}$

$$\omega \frac{dI_{\rm BH}}{d\omega} \simeq \alpha_s \frac{L}{\ell_{\rm mfp}} = \alpha_s N_{\rm scatt}$$

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP ‘20



$w \sim T$ $\quad$ $w < w_c$

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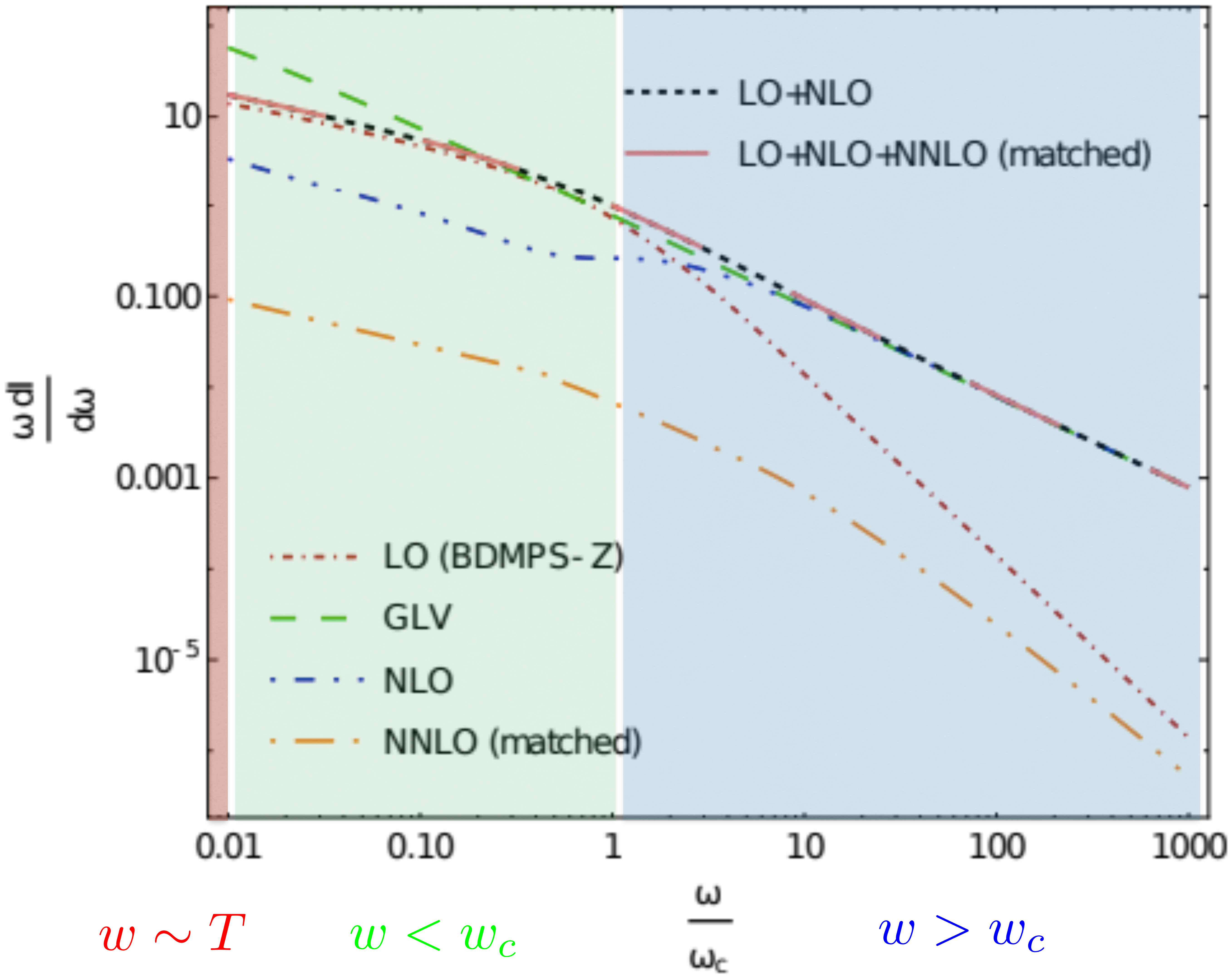
- BDMPS-Z regime $\ell_{\rm mfp} \ll t_{\rm coh} \ll L$

$$\omega \frac{{\rm d}I}{{\rm d}\omega} \simeq \alpha_s \frac{L}{t_{\rm coh}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP '20



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- BDMPS-Z regime $\ell_{\rm mfp} \ll t_{\rm coh} \ll L$

$$\omega \frac{dI}{d\omega} \simeq \alpha_s \frac{L}{t_{\rm coh}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

- GLV regime $k_\perp^2 \gg Q_s^2 \equiv \hat{q} L$

$$\omega \frac{dI}{d\omega} \sim \alpha_s^3 n L \int_{\omega/L}^{\infty} \frac{dk_\perp^2}{k_\perp^4} \simeq \alpha_s \frac{\omega_c}{\omega}$$

Radiative Energy Loss

- Framework: Light-Cone Perturbation Theory.
  - Integrated medium induced spectrum:

Baier, Dokshitzer, Mueller, Peigne, Schiff - NPB ‘97
Zakharov - JETP Lett. ‘96
Arnold, Moore, Yaffe - JHEP ‘03

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{\omega^2} \int_0^\infty dt_2 \int_0^{t_2} dt_1 \, \boldsymbol{\partial_x} \cdot \boldsymbol{\partial_y} \left[\mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) - \mathcal{K}_0(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) \right]_{\boldsymbol{x}=\boldsymbol{y}=0}$$

  - Resummed propagator due to multiple interactions with the medium satisfies 2D Schrödinger-like equation:

$$\left[i\partial_t + \frac{\boldsymbol{\partial}^2}{2\omega^2} + iv(\boldsymbol{x}) \right] \mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) = i\delta(\boldsymbol{x} - \boldsymbol{y})\delta(t_2 - t_1)$$

  - With potential: $v(\boldsymbol{x}, t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}} (1 - e^{i\boldsymbol{k}\cdot\boldsymbol{x}})$

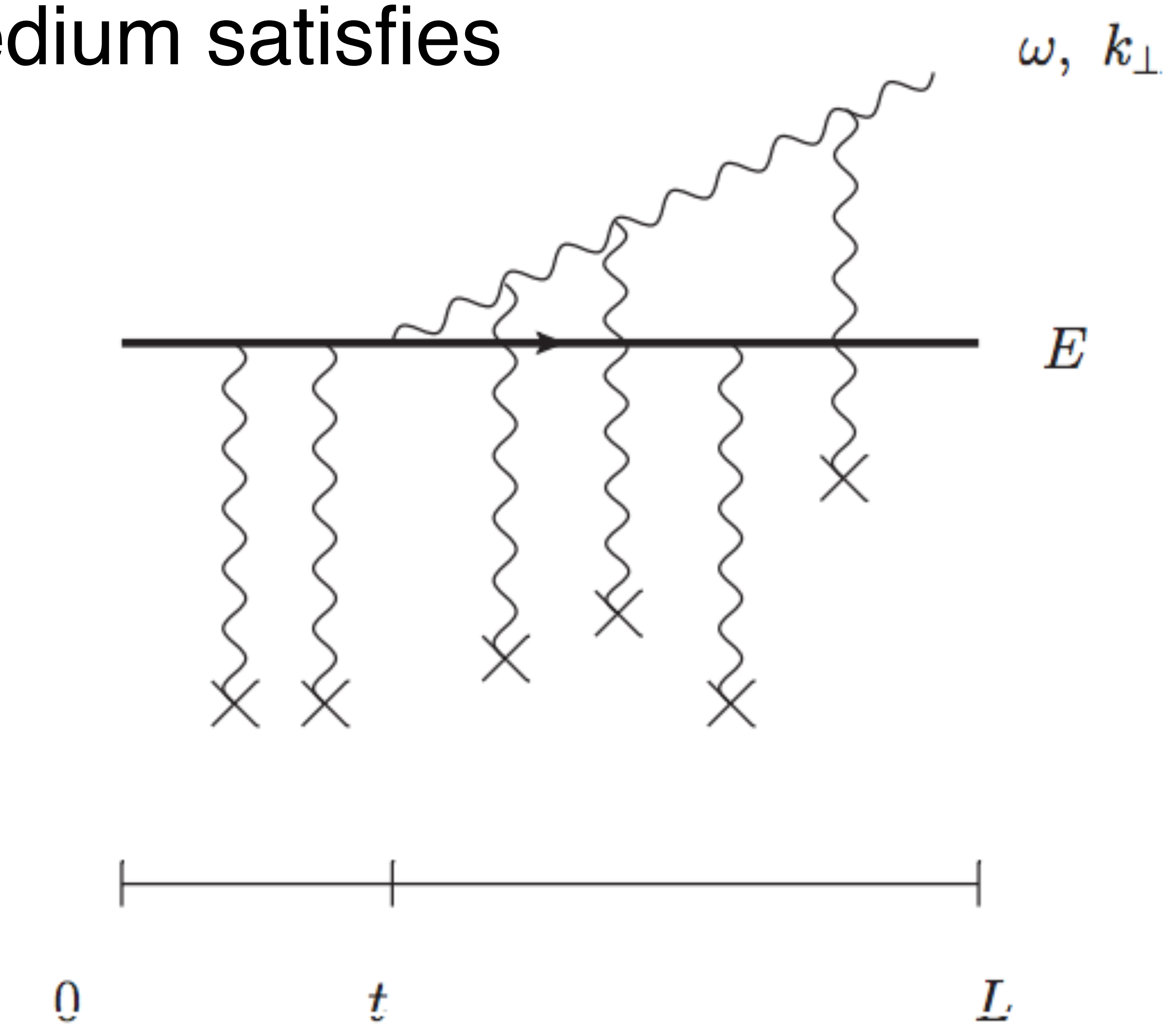
    and scattering cross-section:

Hard Thermal Loop:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{HTL}} = \frac{g^2 m_{\mathrm{D}}^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_{\mathrm{D}}^2)}$$

Gyulassy-Wang:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{GW}} = \frac{g^4 n(t)}{(\boldsymbol{q}^2 + \mu^2)^2}$$



Mehtar-Tani - JHEP ‘19

Usual Approximations of the Spectrum

- Dilute medium: expand to leading order in $v(\boldsymbol{x})$ (N=1 opacity expansion):

$$\omega \frac{\mathrm{d}I_{\mathrm{GLV}}}{\mathrm{d}\omega} = 32\pi\, \alpha_s\, C_R\, \hat{q}_0 \int_0^L \mathrm{d}s \int_{\boldsymbol{p},\boldsymbol{q}} \frac{\boldsymbol{p}\cdot\boldsymbol{q}}{\boldsymbol{p}^2(\boldsymbol{p}-\boldsymbol{q})^2(\boldsymbol{q}^2+\mu^2)^2} \left\{1-\cos\left[\frac{(\boldsymbol{p}-\boldsymbol{q})^2}{2\omega}s\right]\right\}$$

Gyulassy-Levai-Vitev spectrum

Single hard scattering, preserves full form of potential.

Wiedemann - NPB ‘00
Gyulassy, Levai, Vitev - NPB ‘00
Wang, Guo - NPA ‘01
Majumder - PRD ‘12
Sievert, Vitev, Yoon - PLB ‘19

- Harmonic oscillator (diffusion) approximation:

$$v(\boldsymbol{x},t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}}\left(1-e^{i\boldsymbol{k}\cdot\boldsymbol{x}}\right) \equiv \frac{1}{4}\hat{q}(\boldsymbol{x}^2,t)\boldsymbol{x}^2 = \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right)$$

neglect logarithmic dependence
$\mu^{*2} \sim 1/\mathbf{x}^2$

$$\omega \frac{\mathrm{d}I_{\mathrm{HO}}}{\mathrm{d}\omega} = 2\bar{\alpha}\ln\left|\cos(\Omega L)\right| \qquad \Omega(t) = \frac{1-i}{2}\sqrt{\frac{\hat{q}(t)}{\omega}}$$

BDMPS - ASW spectrum

Large medium, resums multiple soft interactions.

BDMPS-Z
Salgado, Wiedemann - PRD ‘03
Armesto, Salgado, Wiedemann - PRD ‘04

Improved Opacity Expansion (IOE)

- Perform "opacity" expansion on top of harmonic oscillator solution:

$$v(\boldsymbol{x},t) = \frac{1}{4}\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right) = \frac{1}{4}\boldsymbol{x}^2\left(\log\left(\frac{Q^2}{\mu^{\star 2}}\right) + \log\left(\frac{1}{Q^2\boldsymbol{x}^2}\right)\right) \equiv v_{\rm HO}(\boldsymbol{x},t) + \delta v(\boldsymbol{x},t)$$

$$\mathcal{K}(\boldsymbol{x},t,\boldsymbol{y},s) = -\int_{\boldsymbol{z}}\int_s^t du\, \mathcal{K}_{\rm HO}(\boldsymbol{x},t|\boldsymbol{z},u)\delta v(\boldsymbol{z},u)\mathcal{K}(\boldsymbol{z},u|\boldsymbol{y},s)$$

Mehtar-Tani - JHEP '19
Mehtar-Tani, Tywoniuk - JHEP '19
Barata, Mehtar-Tani - JHEP '20

- Can systematically compute corrections up to arbitrary order in $\delta v(\boldsymbol{x},t)$:

$$\omega\frac{{\rm d}I}{{\rm d}\omega} = \omega\frac{{\rm d}I^{\rm HO=LO}}{{\rm d}\omega} + \omega\frac{{\rm d}I^{\rm NLO}}{{\rm d}\omega} + \cdots = \omega\frac{{\rm d}I^{\rm LO}}{{\rm d}\omega} + \sum_{m=1}^{\infty}\omega\frac{{\rm d}I^{{\rm N}^m{\rm LO}}}{{\rm d}\omega}$$

- Spectrum should be independent of Q^2 scale when all orders are included:

→ This leads to $Q^4 = \hat{q}_0\omega \ln Q^2/\mu_*^2$ (trans. mom. acquired by radiated gluon — natural scale)

Spectrum @ NLO in the soft limit in IOE:

$$\frac{{\rm d}I^{(0)}}{{\rm d}\omega} = \frac{2\alpha_s C_R}{\pi\omega}\ln|\cos\Omega L|\ ,$$

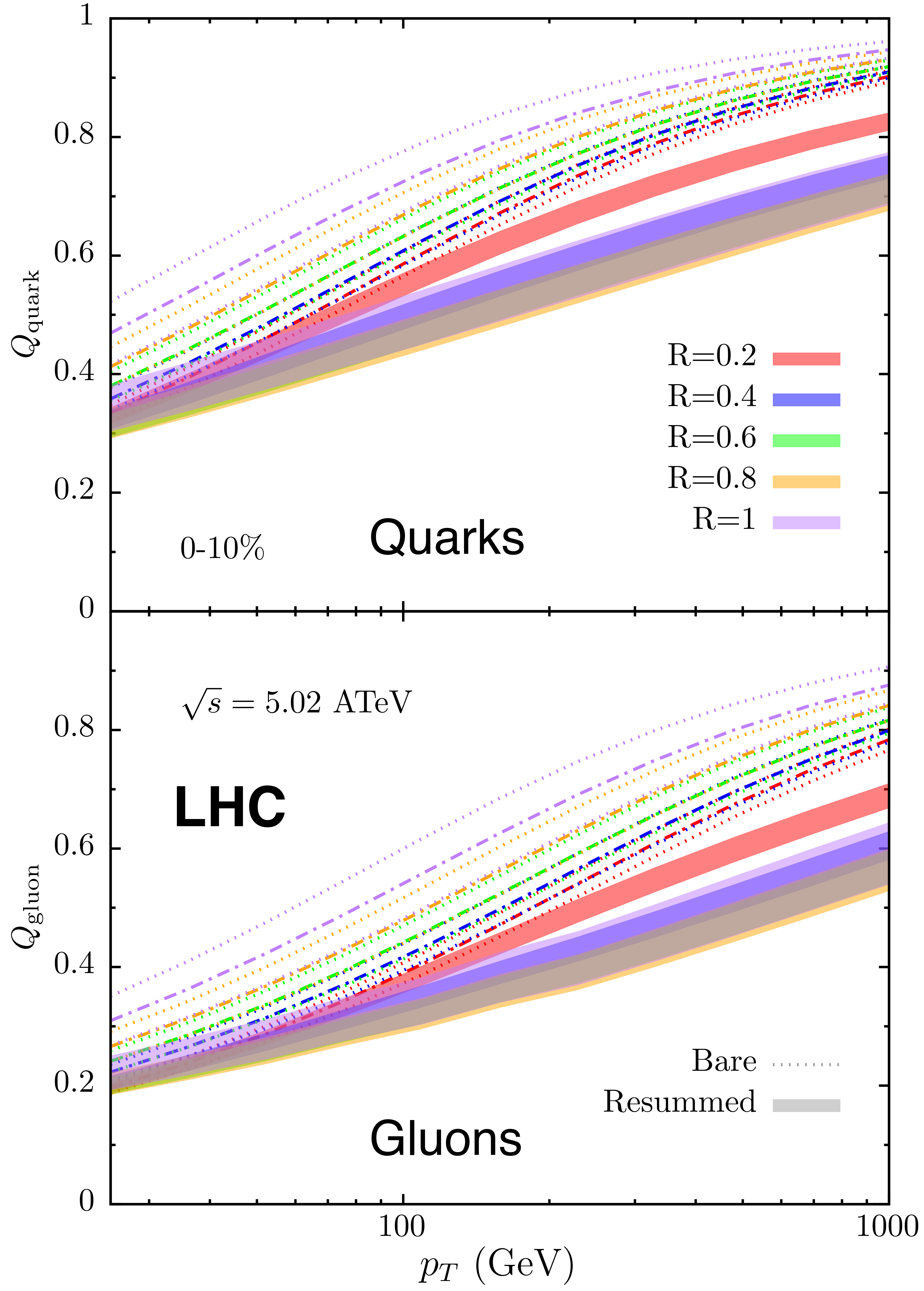
$$\frac{{\rm d}I^{(1)}}{{\rm d}\omega} = \frac{\alpha_s C_R \hat{q}_0}{2\pi}{\rm Re}\int_0^L {\rm d}s\,\frac{-1}{k^2(s)}\ln\frac{-k^2(s)}{Q^2\,{\rm e}^{-\gamma_E}}$$

$$\hat{q} = \hat{q}_0 \ln\frac{Q^2}{\mu_*^2}$$

$$\Omega = (1-i)\sqrt{\hat{q}/(4\omega)}$$

$$k^2(s) = i\frac{\omega\Omega}{2}[\cot\Omega s - \tan\Omega(L-s)]$$

Resumed Quenching Factor



- Bare quenching factors (dashed):
  - → less quenching for larger R.
    - → Easier to keep (recover) the emitted (thermalised) modes.
- Resummed quenching factors (solid):
  - → larger R can lead to more quenching.
    - → Interplay between energy recovery and size of quenched phase space.

Mehtar-Tani, DP, Tywoniuk - PRL '21

Out of Cone Radiation

- Only emissions that end up out of the cone R should be accounted for:

Multiplicative Ansatz:

$$\omega \frac{\mathrm{d}I_>}{\mathrm{d}\omega} = \int_{(\omega R)^2}^{\infty} \mathrm{d}k_\perp^2 \, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega\, \mathrm{d}k_\perp^2} \simeq B\big(\omega R; Q^2_{\mathrm{broad}}\big) \times \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}$$

Mehtar-Tani, DP, Tywoniuk - PRL '21

$$B\big(\omega R; Q^2_{\mathrm{broad}}\big) = \frac{Q^2_{\mathrm{broad}}}{4\pi} \int_y^\infty \mathrm{d}x \, \mathcal{P}(x) \qquad y = (\omega R)^2 / Q^2_{\mathrm{broad}}$$

Broadening dist.

Characteristic broadening scale

$$\mathcal{P}(\boldsymbol{k}) \simeq \begin{cases} \frac{4\pi}{Q_s^2} \mathrm{e}^{-\boldsymbol{k}^2/Q_s^2} & k_\perp^2 \ll Q^2_{\mathrm{med}} \\ \frac{4\pi Q_s^2}{\boldsymbol{k}^4} & k_\perp^2 \gg Q^2_{\mathrm{med}} \end{cases}$$

$$\frac{\partial}{\partial L} \mathcal{P}(\boldsymbol{k}, L) = C_R \int_{\boldsymbol{q}} \gamma(\boldsymbol{q}) \, [\mathcal{P}(\boldsymbol{k} - \boldsymbol{q}, L) - \mathcal{P}(\boldsymbol{k}, L)]$$

- Use Molière expansion around multiple soft scatterings (a.k.a. IOE). Barata et al. - PRD '21

- Can be improved with fully differential spectrum. Barata et al. - JHEP '21

Bare Quenching Factor

- For steeply falling spectrum and small energy loss:

Baier, Dokshitzer, Mueller - JHEP '01
Salgado, Wiedemann - PRD '03

$$\frac{d\sigma_{\rm med}}{dp_T} = \int_0^\infty d\epsilon\, \mathcal{P}(\epsilon)\, \frac{d\sigma_{\rm vac}}{dp'_T}\Big|_{p'_T = p_T+\epsilon} \approx \frac{d\sigma_{\rm vac}}{dp_T} \underbrace{\int_0^\infty d\epsilon\, \mathcal{P}(\epsilon) e^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

Mehtar-Tani, DP, Tywoniuk - PRL '21

- Quenching factor of a single parton for multiple independent emissions (R dependent):

$$Q^{(0)}_{\rm rad}(p_T) = \exp\left[- \int_{\omega_s}^\infty d\omega\, \frac{dI_>}{d\omega}\left(1 - e^{-\nu\omega}\right) - \int_T^{\omega_s} d\omega\, \frac{dI^{(0)}}{d\omega}\left(1 - e^{-\nu\omega(1-(\frac{R}{R_{\rm rec}})^2)}\right)\right]$$

$$\nu \equiv \frac{n}{p_T}$$

Full out-of-cone spectrum for semi-hard emissions

$$\omega_s \equiv (g^2_{\rm med} N_c/(2\pi)^2)^2 \pi \hat{q}_0 L^2$$

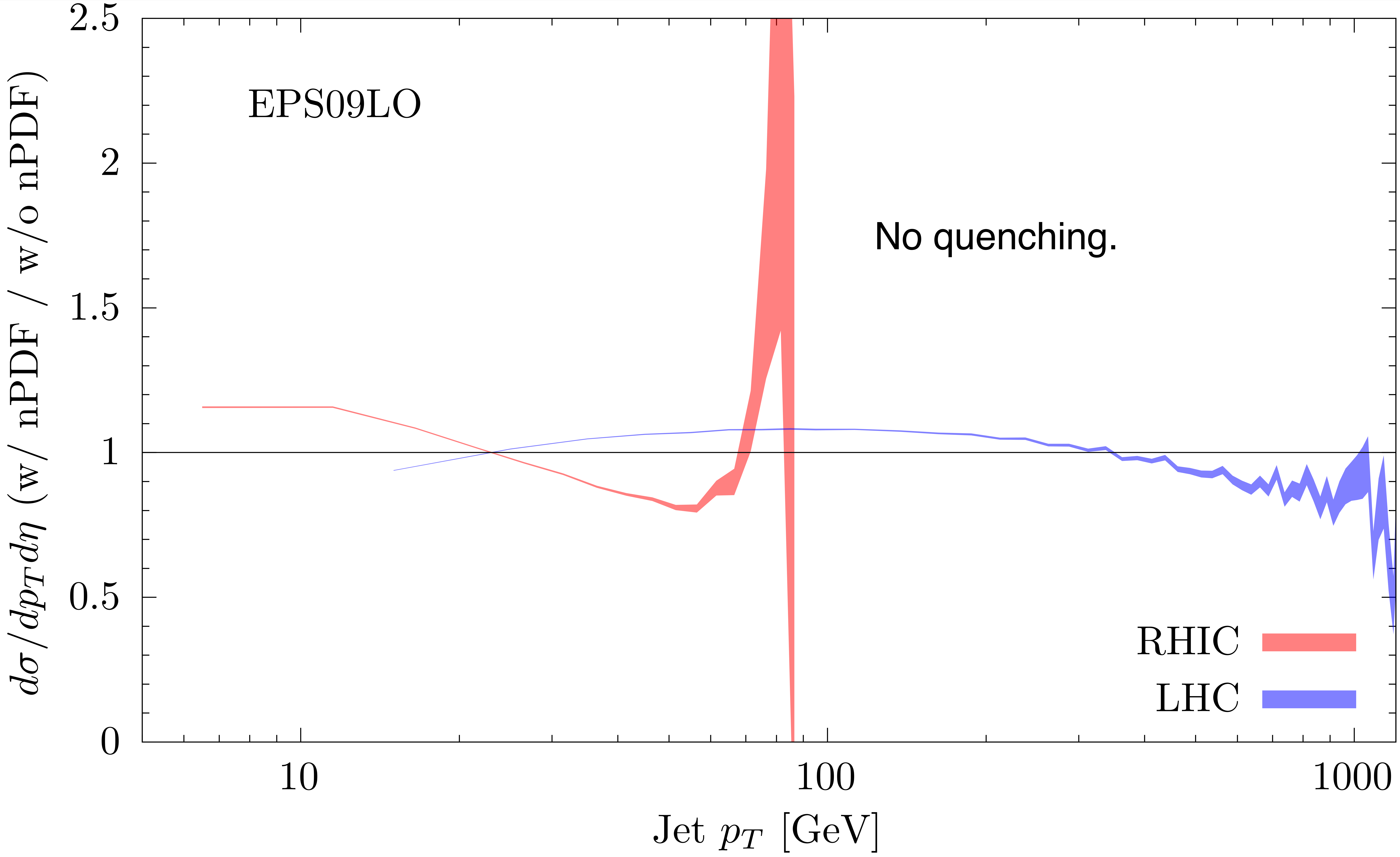
- O(1) emission probability
- undergo turbulent cascade, thermalise
- if uniformly distributed in jet hemisphere

$$R_{\rm rec} \sim \pi$$

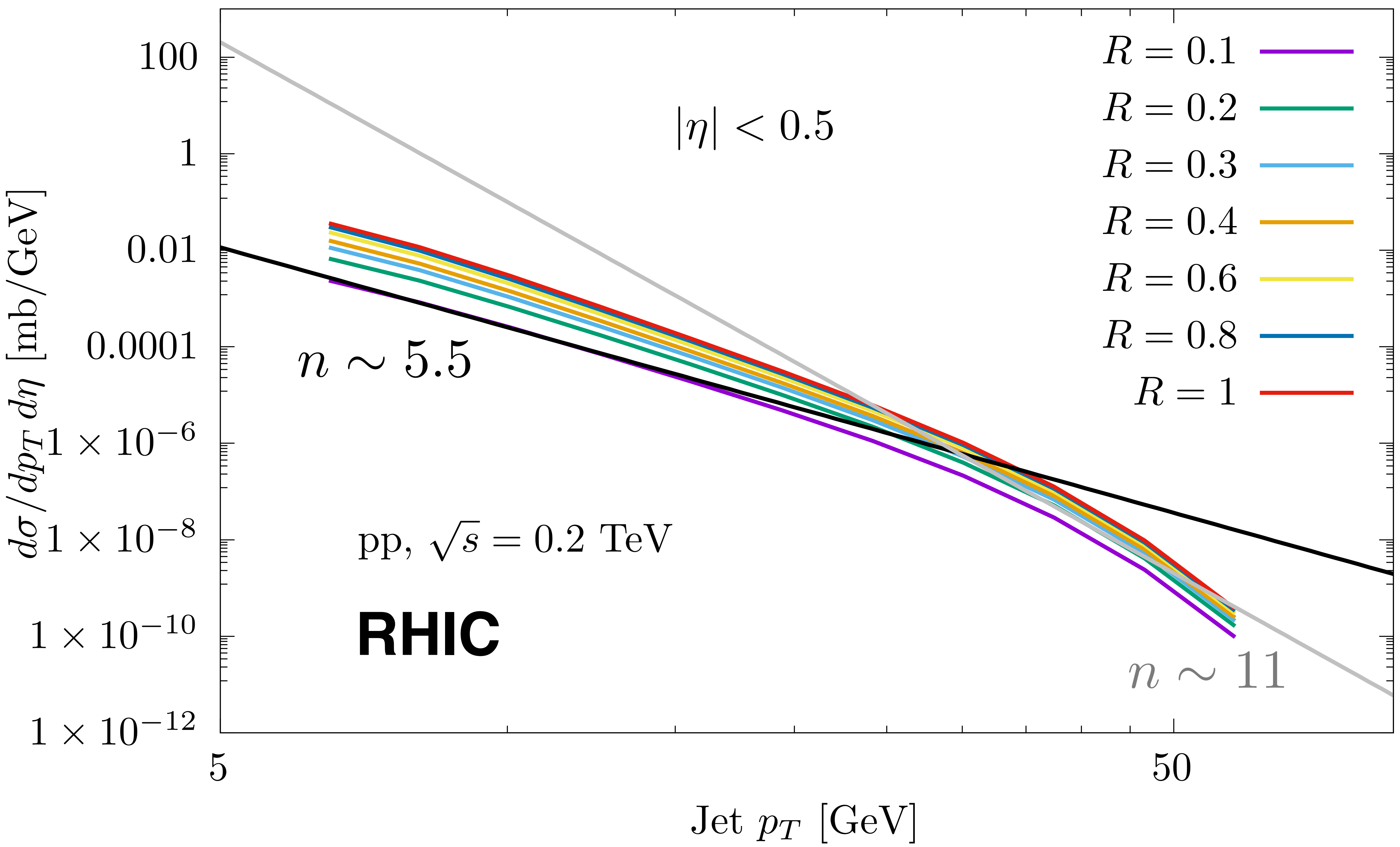
Note that:

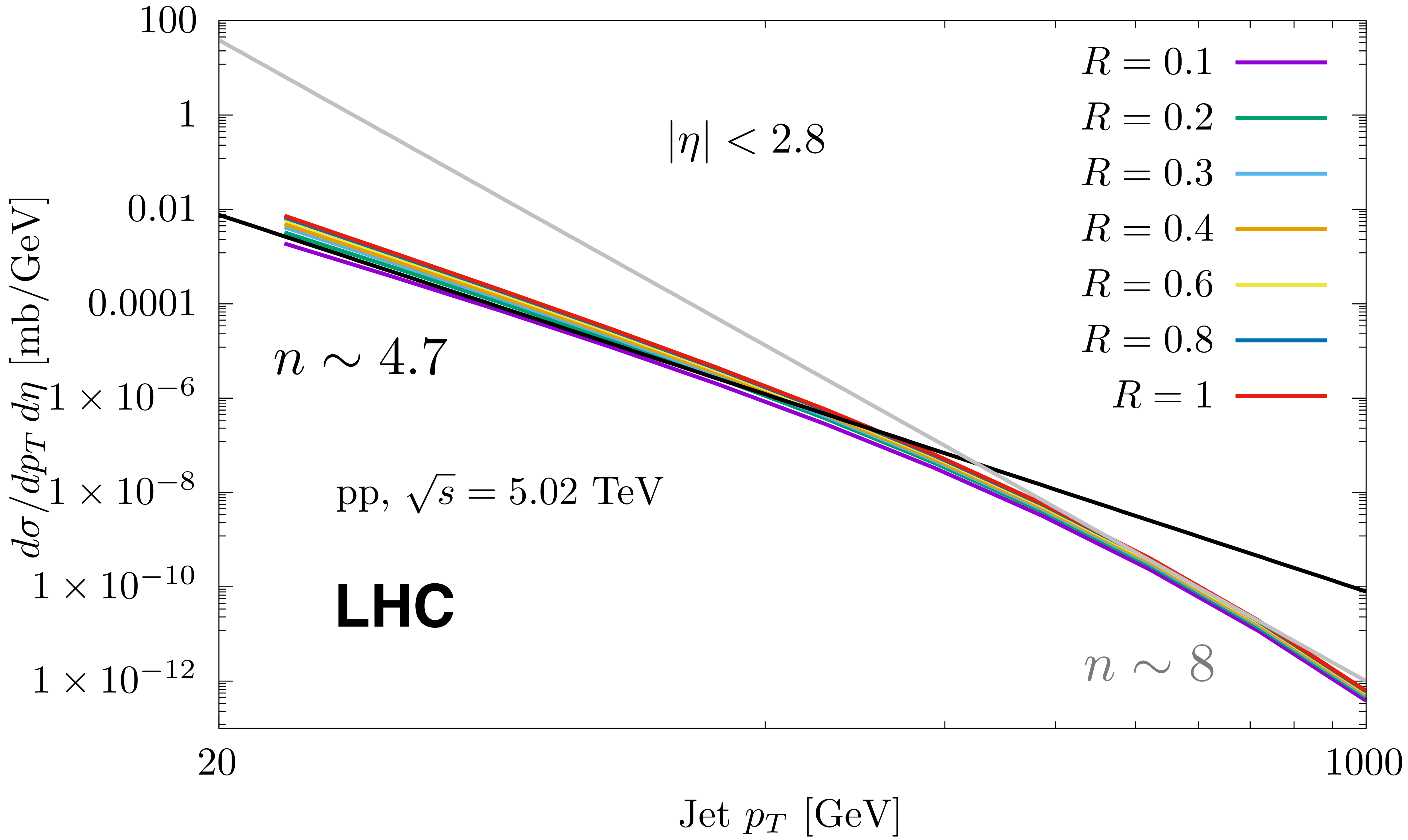
$$\Delta E = (1 - (\frac{R}{R_{\rm rec}})^2) \int_T^{\omega_s} dw\, w \frac{dI^{(0)}}{dw} = -\frac{d}{d\nu} Q^{(0),{\rm turb}}_{\rm rad}(p_T)\Big|_{\nu=0}$$

Effect of Nuclear PDF



RHIC vs LHC Vacuum Spectra





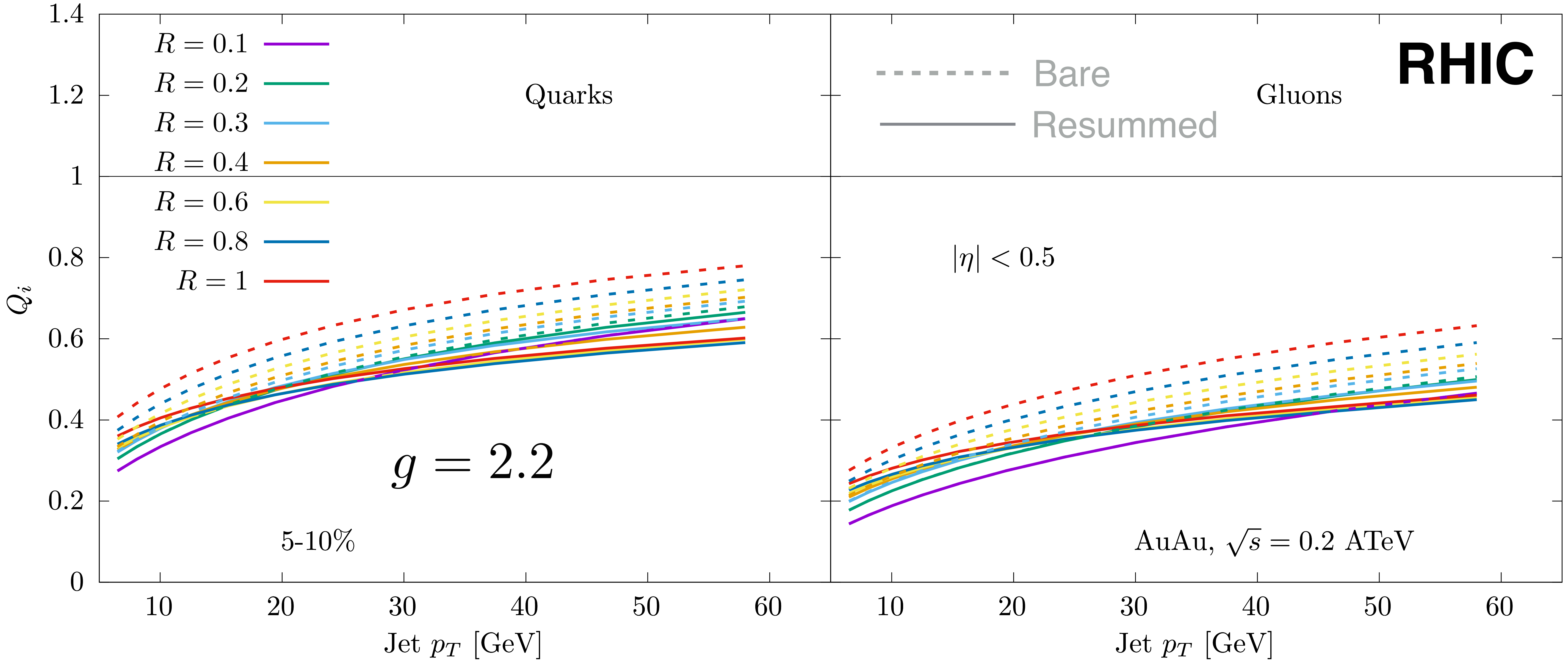
- Spectra increases with increasing R due to recapturing out-of-cone radiation.
- Steeper spectrum at RHIC energies, will push R_{AA} down.

RHIC vs LHC Vacuum Quark Fraction

- Quark-initiated jet fraction decreases with increasing R, as gluon-initiated jets are more active.

- Larger quark-initiated jet fraction at RHIC, should push total R_{AA} up.

RHIC vs LHC Quenching Factor

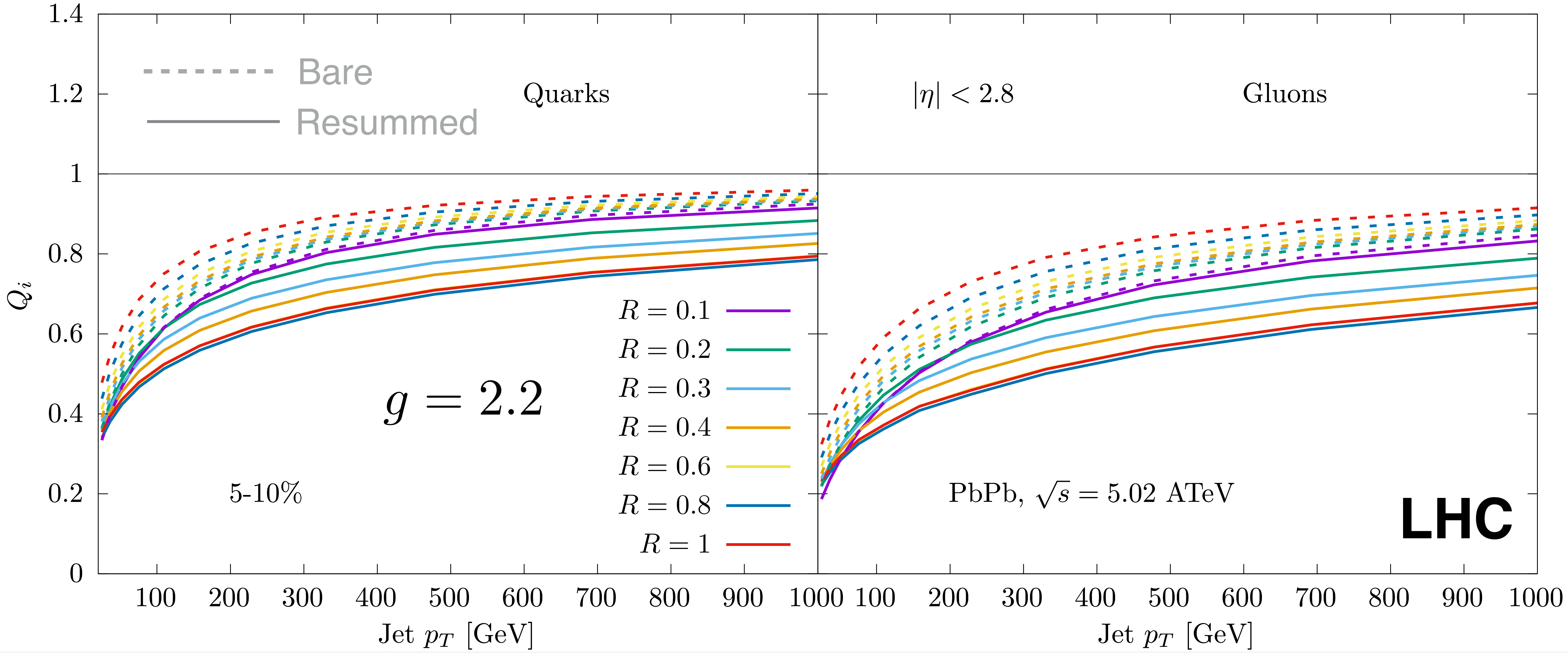


$\langle \hat{q}_0 \rangle^{\rm RHIC} \simeq 0.25\,{\rm GeV}^2/{\rm fm}$

$\langle \hat{q} \rangle^{\rm RHIC} \simeq 1.22\,{\rm GeV}^2/{\rm fm}$

$\langle L \rangle^{\rm RHIC} \simeq 4.5\,{\rm fm}$

- Similar quenching factors between LHC and RHIC (@ ~ p_T) when considering medium properties.
- Resummation more significant at LHC due to larger phase space.



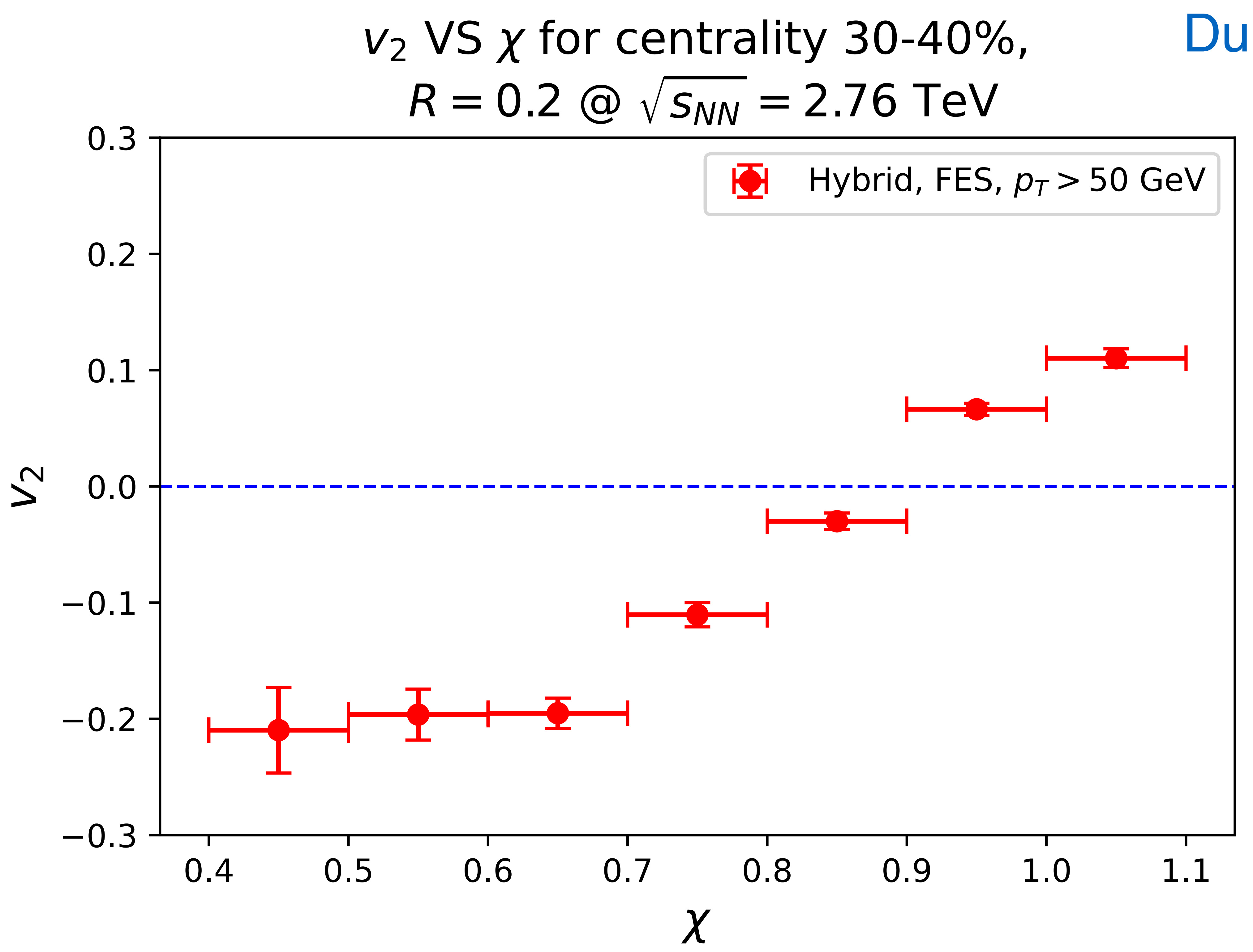
$\langle \hat{q}_0 \rangle^{\rm LHC} \simeq 0.44\,{\rm GeV}^2/{\rm fm}$

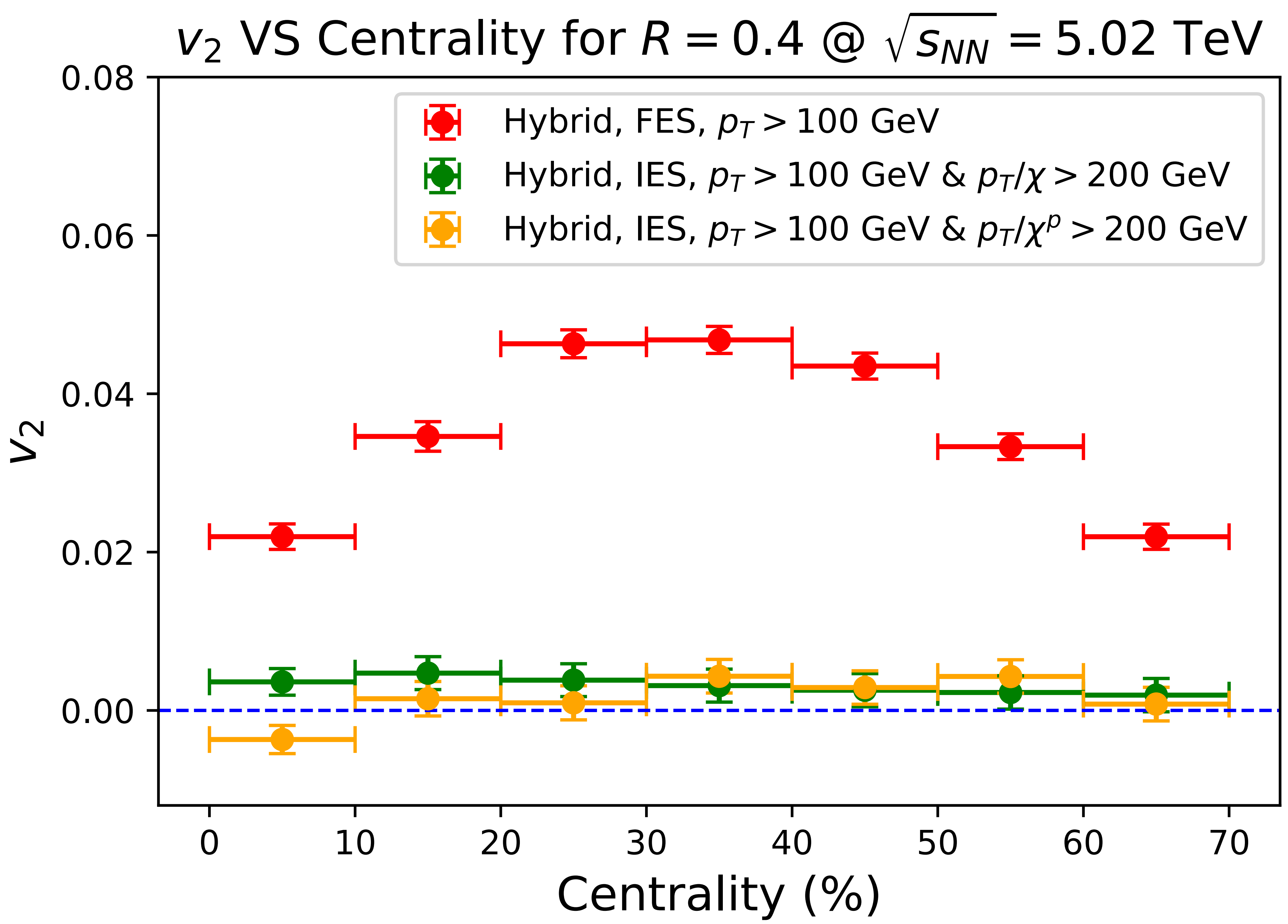
$\langle \hat{q} \rangle^{\rm LHC} \simeq 2.34\,{\rm GeV}^2/{\rm fm}$

$\langle L \rangle^{\rm LHC} \simeq 5.6\,{\rm fm}$

Accessing Initial Jet Anisotropies

Du, DP, Tywoniuk - PRL '21





- Intuitive origin of high-p_T jet anisotropies:

  Small χ (large energy loss):

  → longer path length;

  → $v_2 < 0$.

  and viceversa for large χ.

- However, if use IES:

  Reveals initial azimuthal anisotropies.

  In this model: none → $v_2 \sim 0$.

  And in experiments?