UNIVERSITY OF BERGEN

Jet suppression and v2

Predictions for energy-, centrality- and R-dependence

Konrad Tywoniuk, ECT* Workshop, 12-16 Feb 2024, Trento

Overview

Content

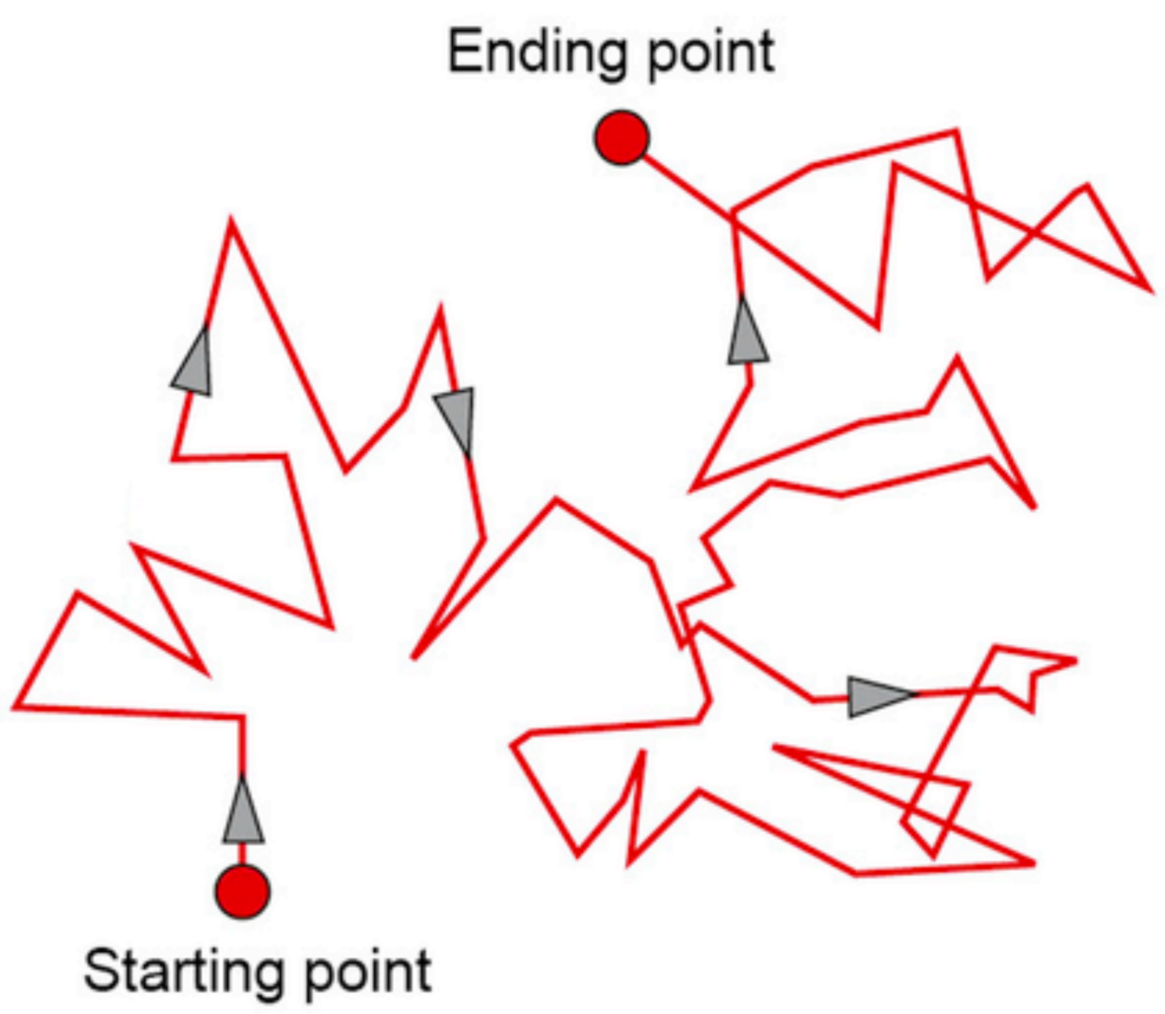
- Role of colour coherence in jet production and jet quenching
- Azimuthal asymmetry as differential quenching
- Predictions for jet R_{AA} and v_2
- Suppression pattern driven by colour coherence
- Outlook

Based on Mehtar-Tani, Pablos, Tywoniuk 2402.07869

Effects of momentum diffusion

Dense medium

- Transverse **momentum broadening**
  - In momentum space $\langle k_\perp^2 \rangle \sim \hat{q} t$
- Also affects **radiation**
  - QM formation time of $|q\rangle \to |q\rangle + |g\rangle$ is $t_\mathrm{f} = \omega / \langle k_t^2 \rangle$
  - This leads to an effective branching time $t_\mathrm{br} \sim \sqrt{\hat{q}\omega}$
- Any process with $t_\mathrm{f} \ll t_\mathrm{br}$ is not driven by multiple scattering in the QGP
  - Can only be attained by **jet scales** (up to higher-twist corrections)!



Color decoherence

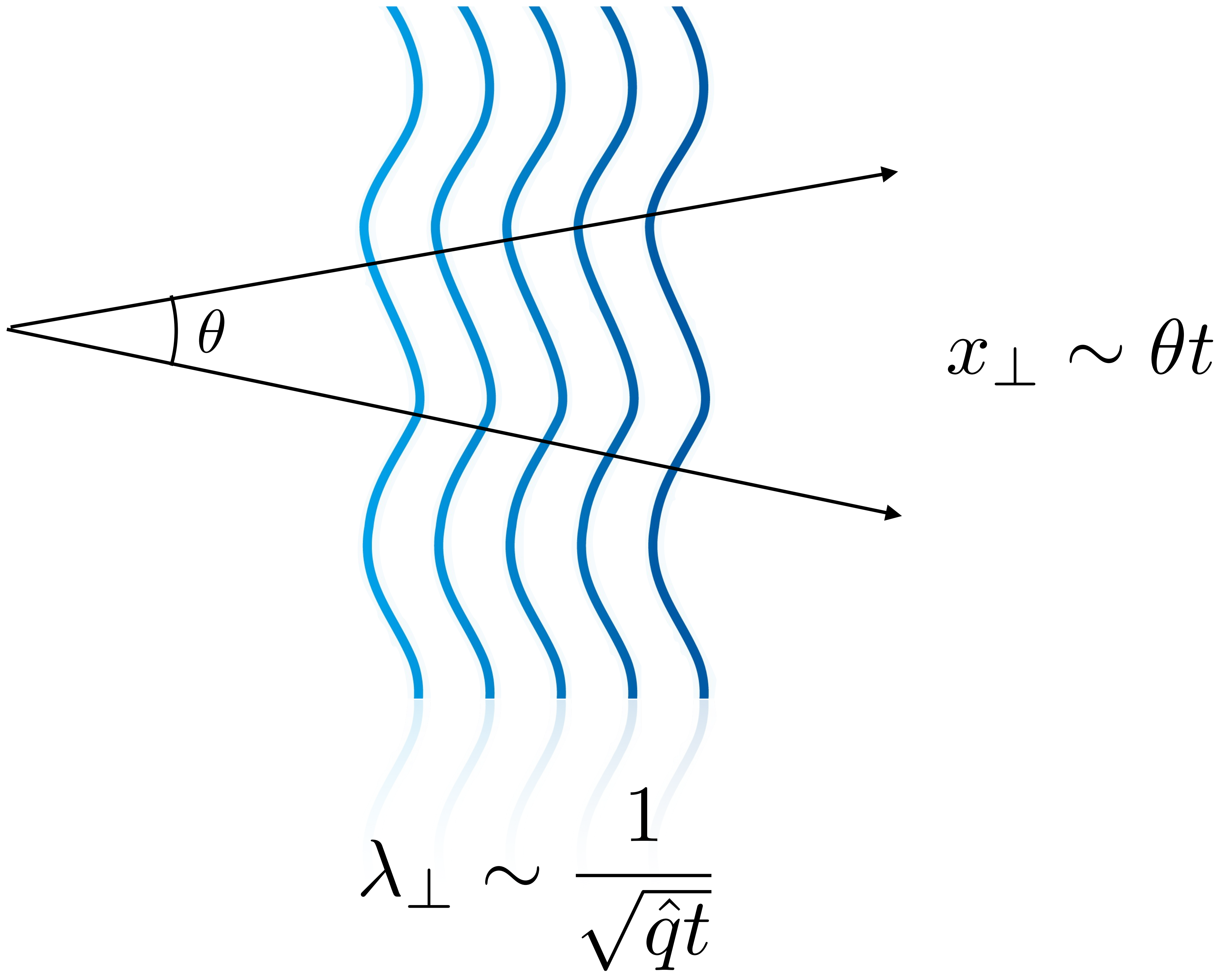
Another angle

- What's the fate of vacuum radiation occurring early in the medium?

- Similar to Chudakov effect in QED (or color transparency for time-like dipoles).

- When $x_\perp \sim \lambda_\perp$ pair of partons are resolved = seen as two distinct color charges

  - Happens at $t = t_\mathrm{d} \sim (\hat{q}\theta^2)^{-1/3}$



Mehtar-Tani, Salgado, Tywoniuk (2011-2013); Casalderrey-Solana, Iancu (2011)

In-medium resolved phase space

Vacuum-like emissions

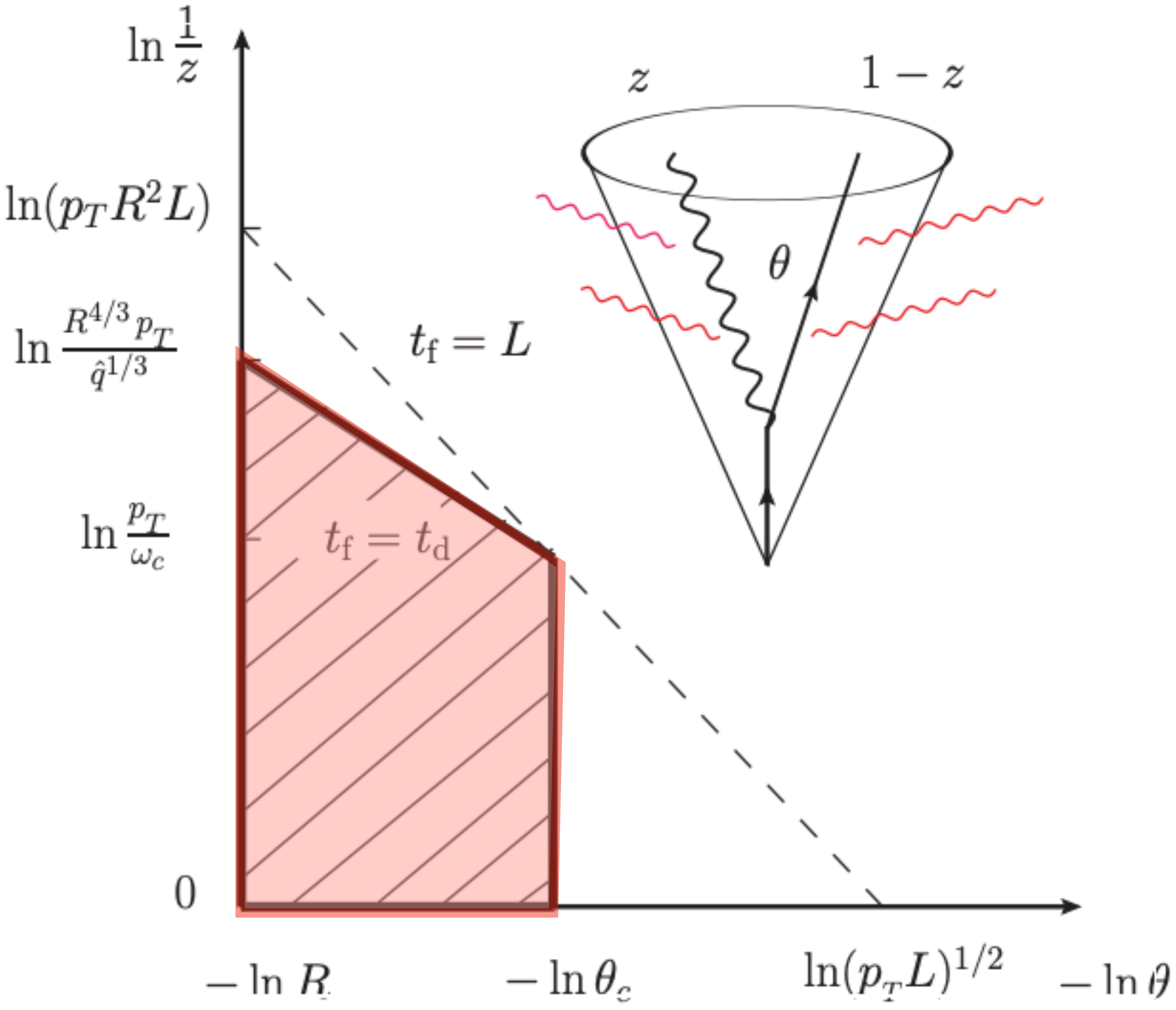
- Hard, large-angle radiation with $t_\mathrm{f} \ll t_\mathrm{d} \ll L$ is resolved and can source further medium-induced emissions

- New source of energy loss!

- Contribute to the quenching of full jet.

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

- Jets with $R \leq \theta_c$ are **coherent**!



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

Mehtar-Tani,Casalderrey, Salgado, Tywoniuk 1210.7765; Mehtar-Tani, Tywoniuk 1707.07361

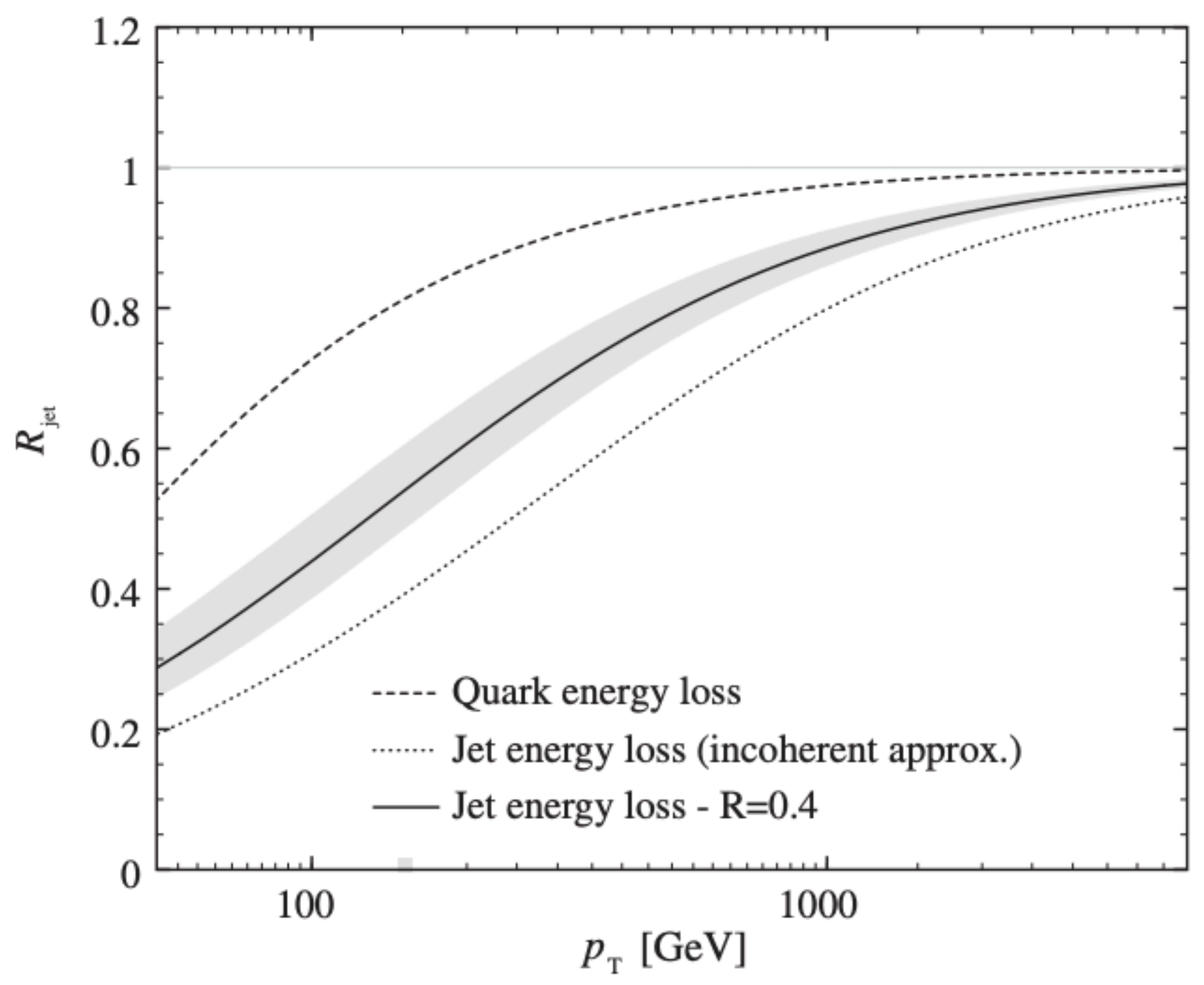
A new evolution equation

Collimator evolution

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

- Initial condition is $Q(p,0) = Q^{(0)}_{\rm rad}(p_T) \times Q^{(0)}_{\rm el}(p_T) \times \ldots$ = quenching of individual color charges (and energy recovery).
- Jet suppression factor expectation:

$$R_{AA}(\text{hadron}) < R_{AA}(\text{jet})$$



Mehtar-Tani, Tywoniuk 1707.0736

Quenching of individual partons

What we all are interested in!

- The "individual" interaction dynamics between an energetic parton and the QGP is encoded in the bare quenching factor (QF).
- QF is Laplace transform of the energy-loss probability: $Q^{(0)}(p_T) = \tilde{P}(\nu = n/p_T)$
- For radiative energy loss:

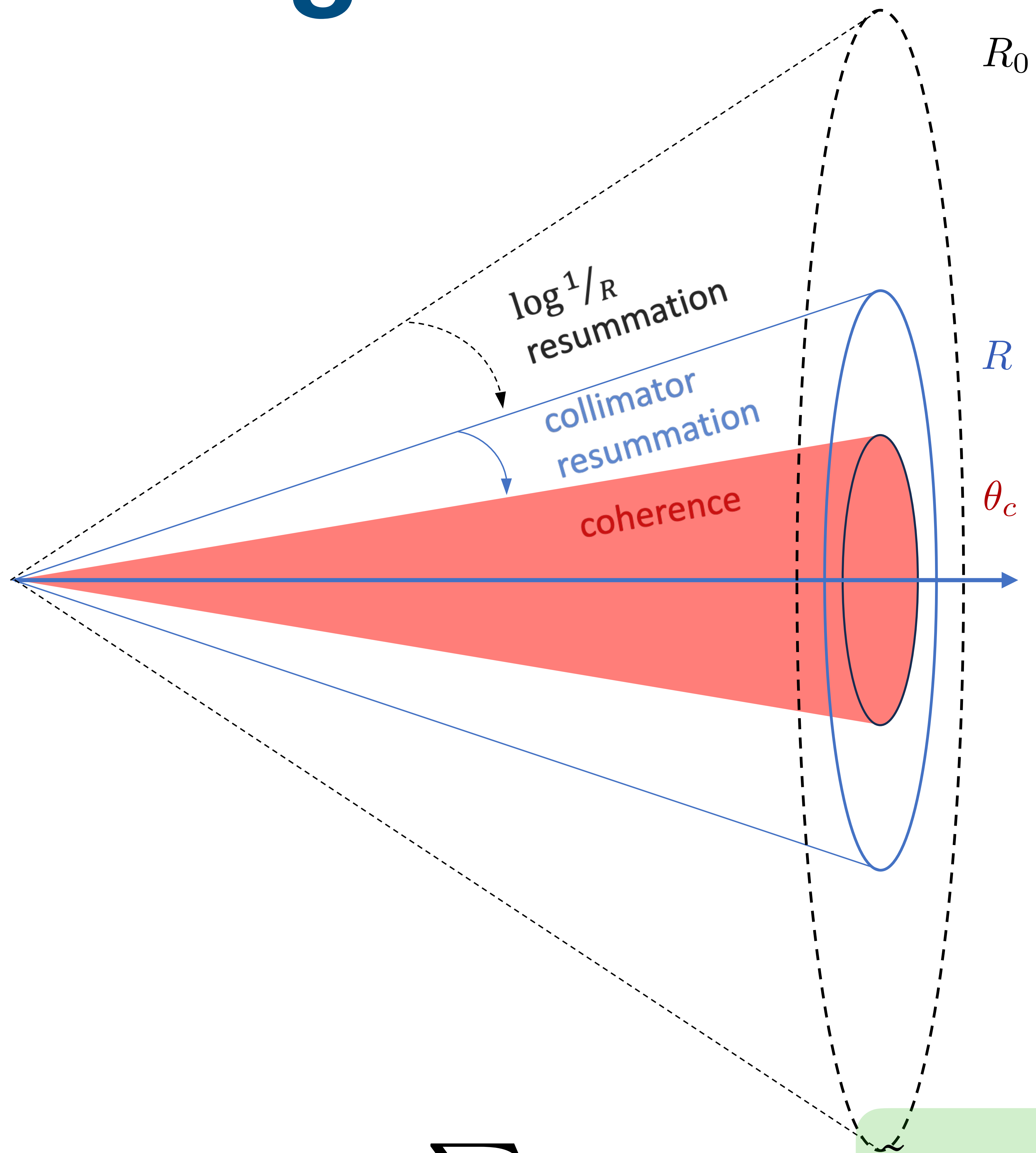
$$\tilde{P}(\nu) = \exp\left[-\int_0^\infty \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega} \left(1 - \mathrm{e}^{-\nu\omega}\right)\right]$$

- Free parameter R_{rec} governs recovery of energy at large angles.
  - Not important for $R \leq 0.4$, starts to matter for large-R jets

Multi-stage evolution of jets in a background

The role of colour coherence

- Collinear factorisation at LO w/ NPDF effects.
- Two resummation schemes:
  - $\log 1/R$ (DGLAP) evolution to compute vacuum spectrum at cone-size R.
  - "collimator resummation" to account for substructure resolved inside the QGP.
- Below the critical angle θ_c the jet acts as a coherent source.
- Semi-analytic calculation propagating jets through realistic hydro background (event-by-event).



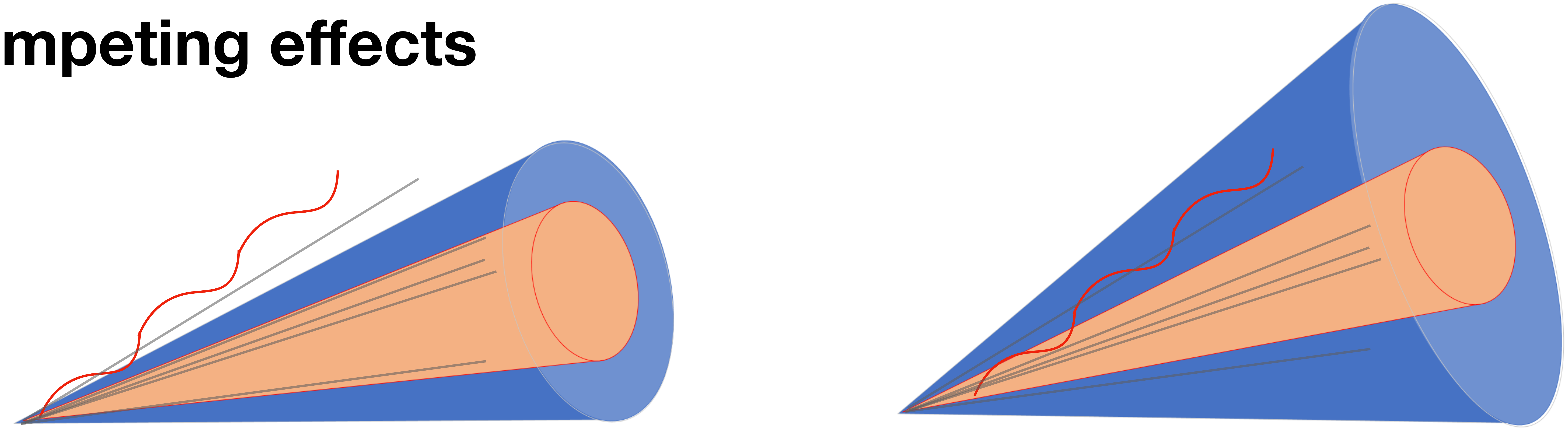
$$R_{\mathrm{AA}}(p_T, R) = \sum_{i=q,g} Q_i(p_T, R)\, f_i(p_T, R)$$

Modified quark/gluon fractions (due to nPDFs).

Mehtar-Tani, Pablos, Tywoniuk arXiv:2402.07869

What happens when we open the cone?

Two competing effects



Opening up the cone

1. recapturing energy deposited at large angles → reducing suppression

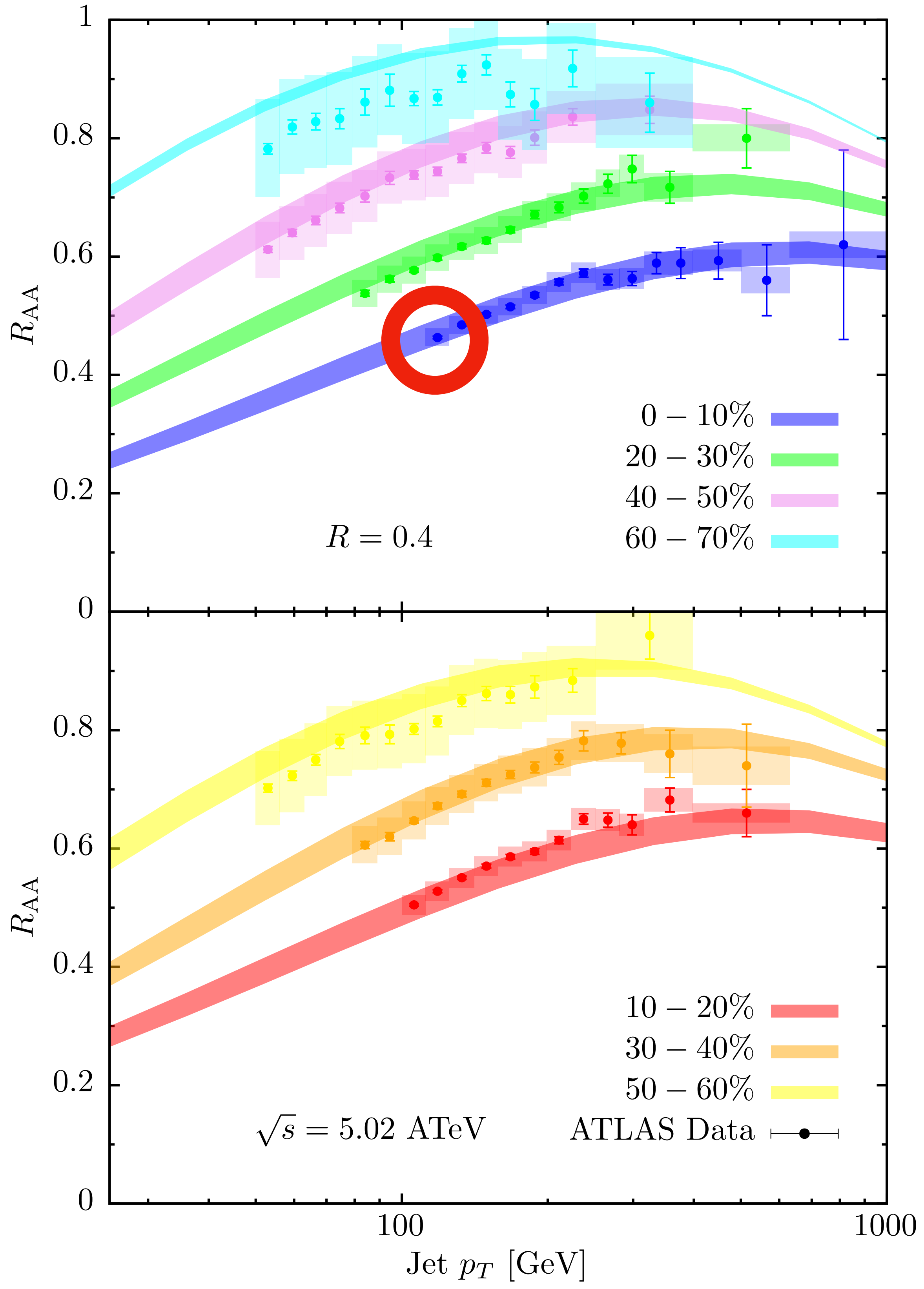
2. increasing phase space for vacuum-like radiation → increasing suppression

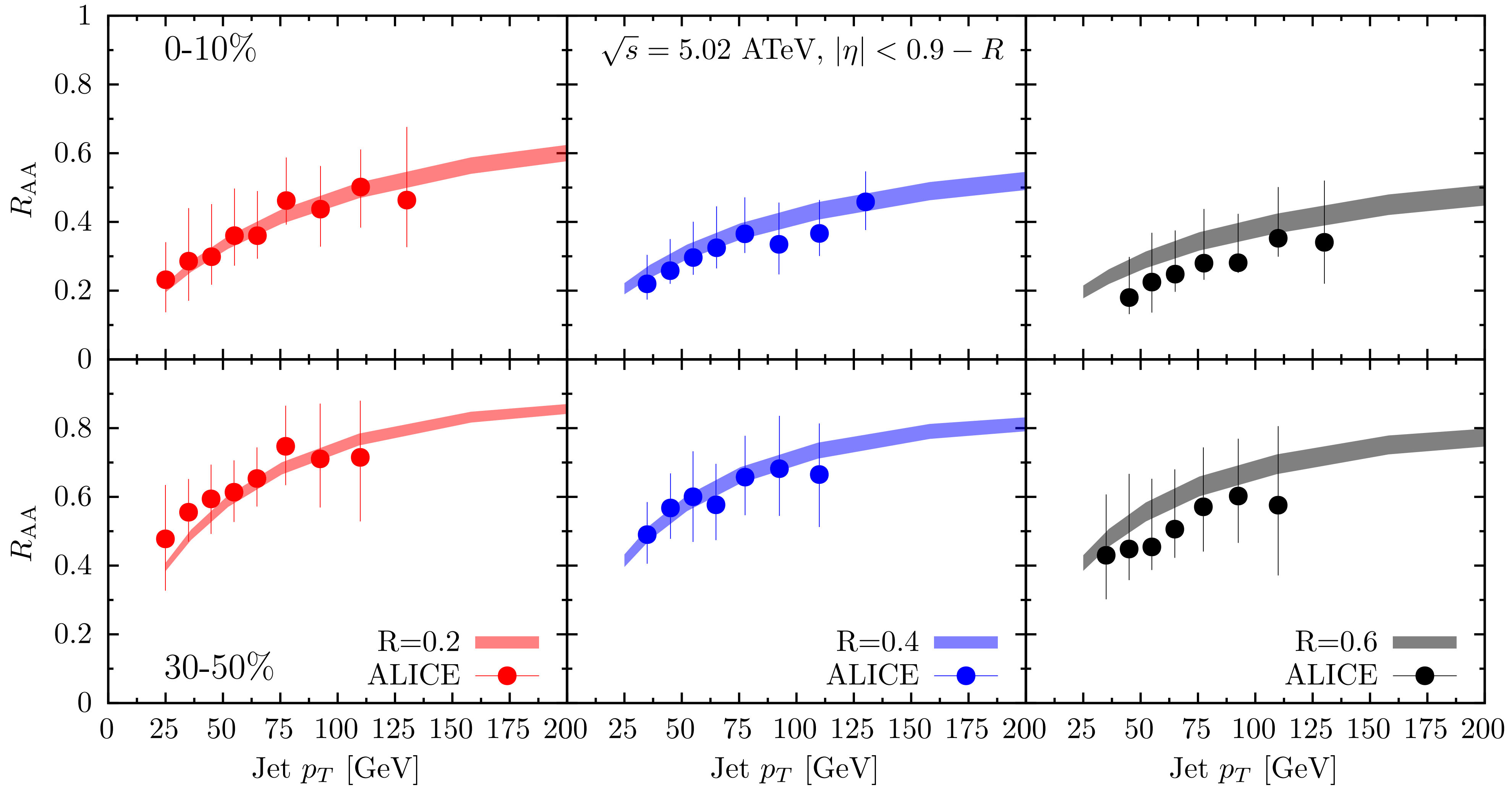
Competing effects ↔ leads to an overall mild R dependence!

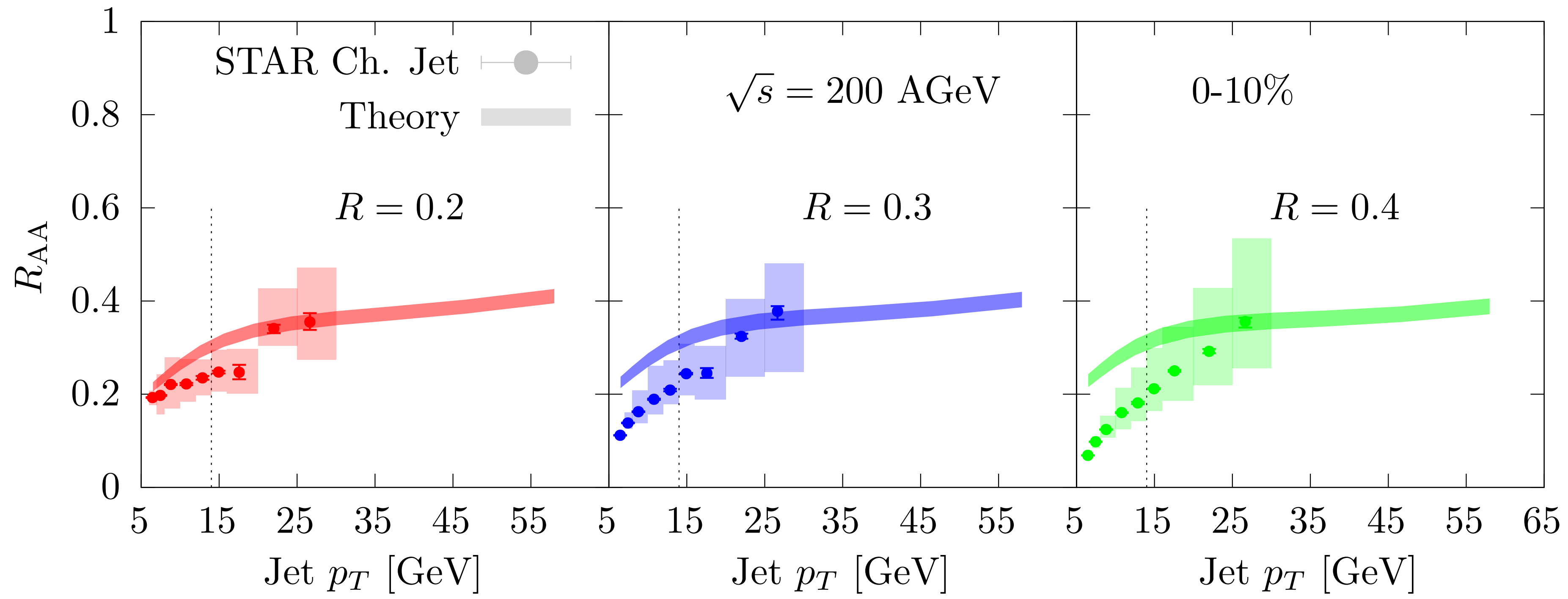
Predictions for LHC

Excellent description of p_T and R behaviour

Two parameters: $g_{\mathrm{med}} \in \{2.2, 2.3\}$ and $R_{\mathrm{rec}} \approx \pi/2$.

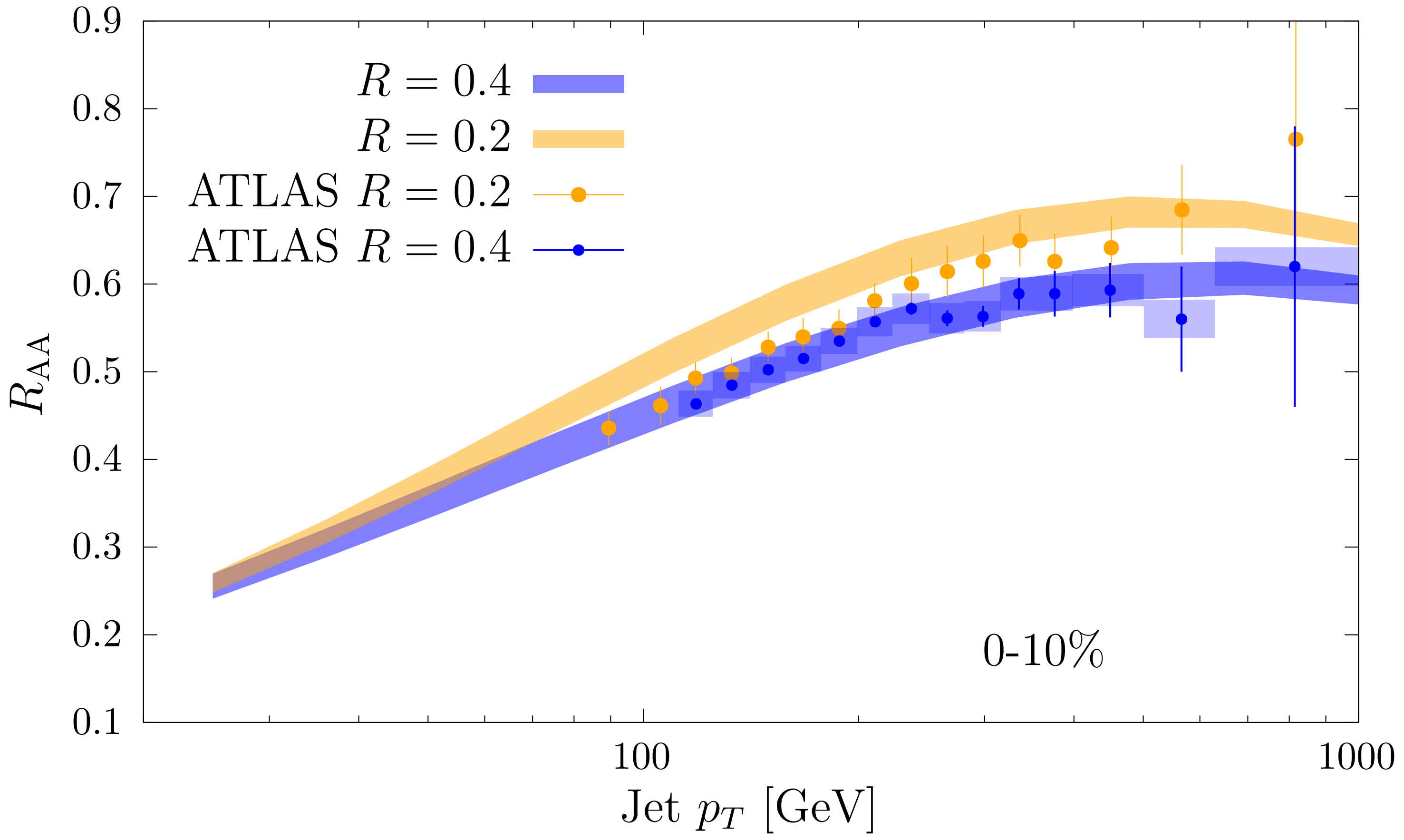


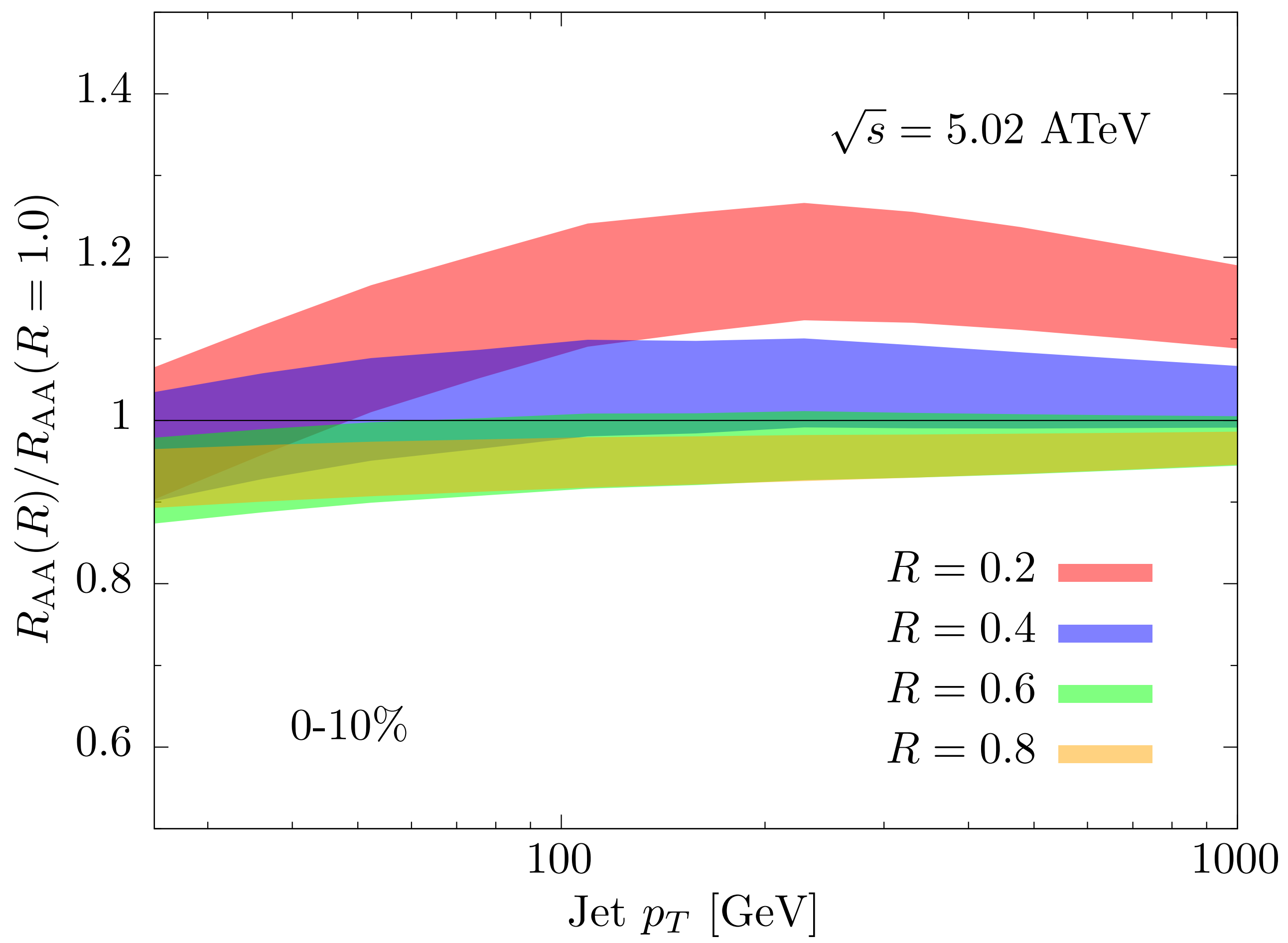




Mehtar-Tani, Pablos, Tywoniuk 2101.0174, 2402.07869

R dependence

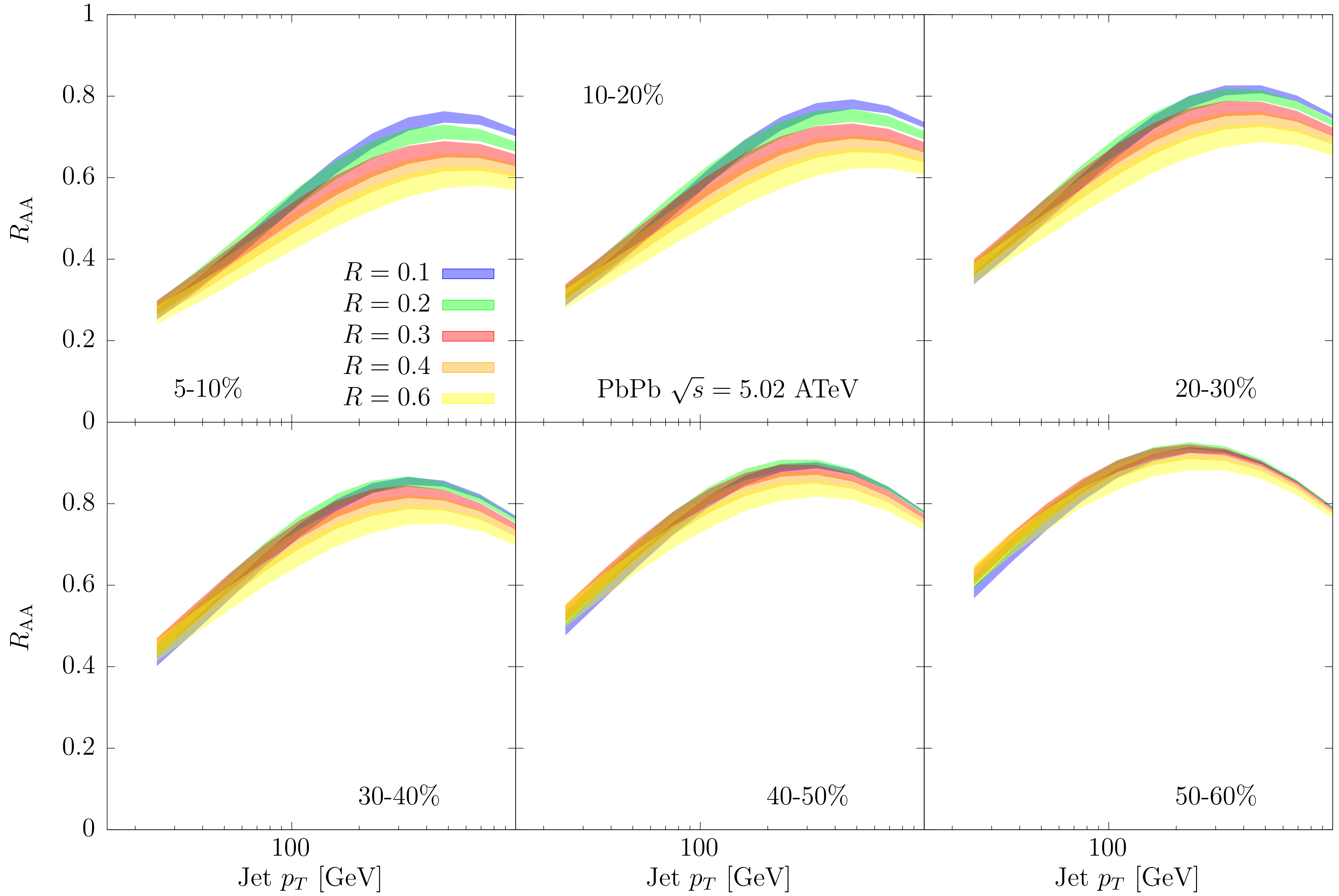


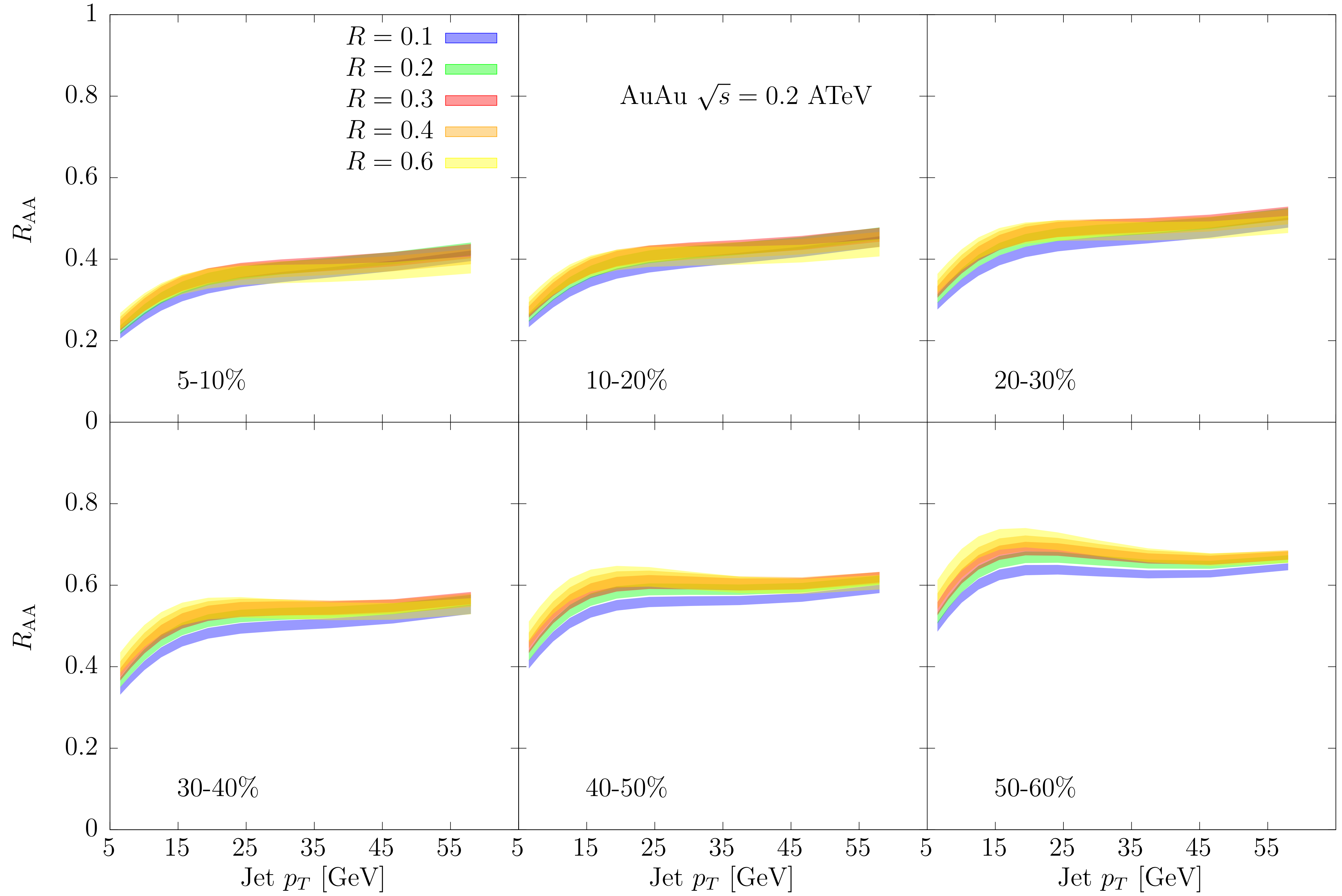


trends ok, but some tension with CMS

Predictions for R_{AA}

Energy-, centrality, transverse momentum & cone-angle



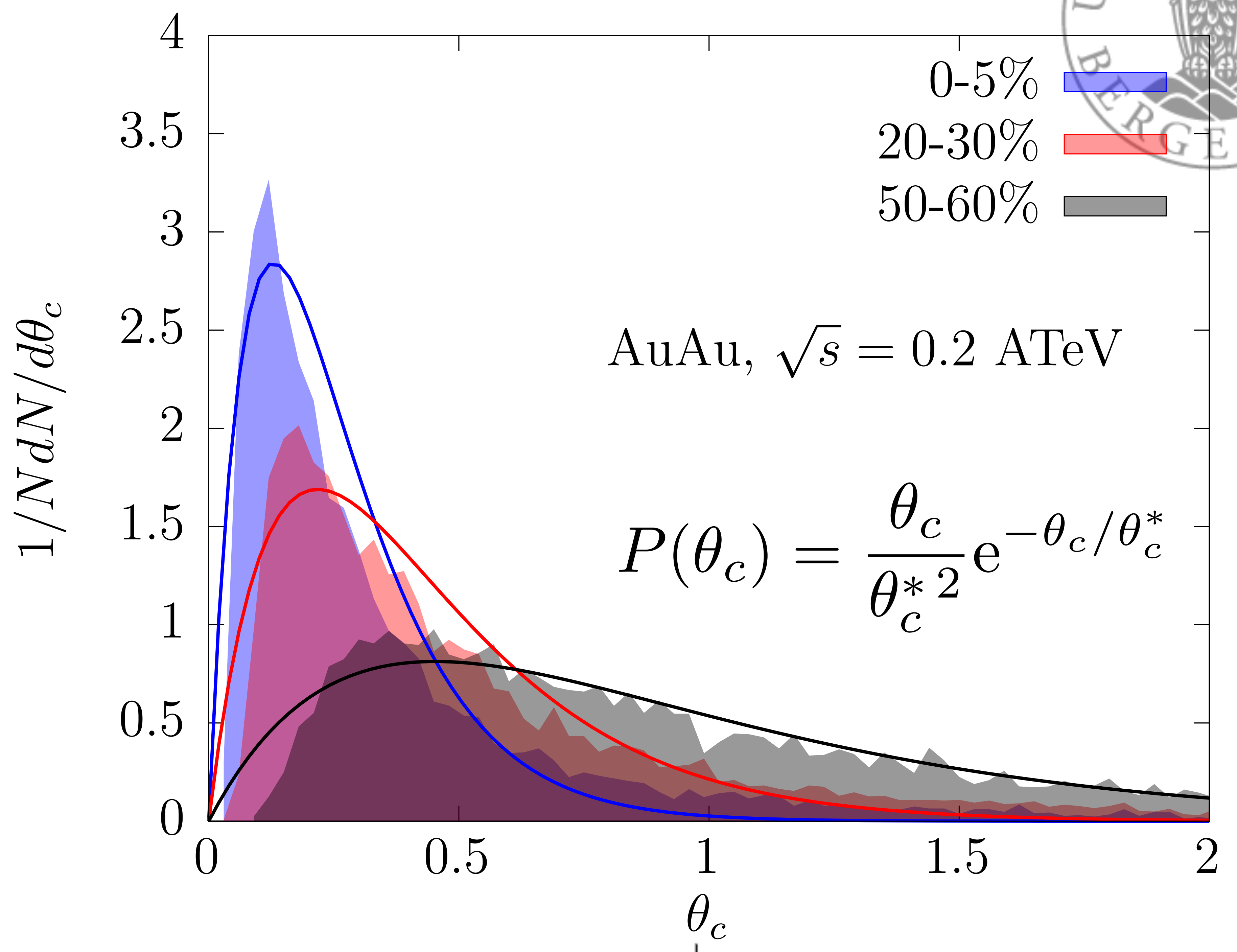


Mehtar-Tani, Pablos, Tywoniuk 2402.07869

Centrality and coherence

A “new” handle

- Very different ranges of θ_c are explored for different centralities.
- Characterised by peak value θ_c^*.
- Probing very different jet quenching:
  - coherent jets at $R \leq \theta_c$ (one parton)
  - incoherent jets at $R > \theta_c$ (multi-parton)



	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

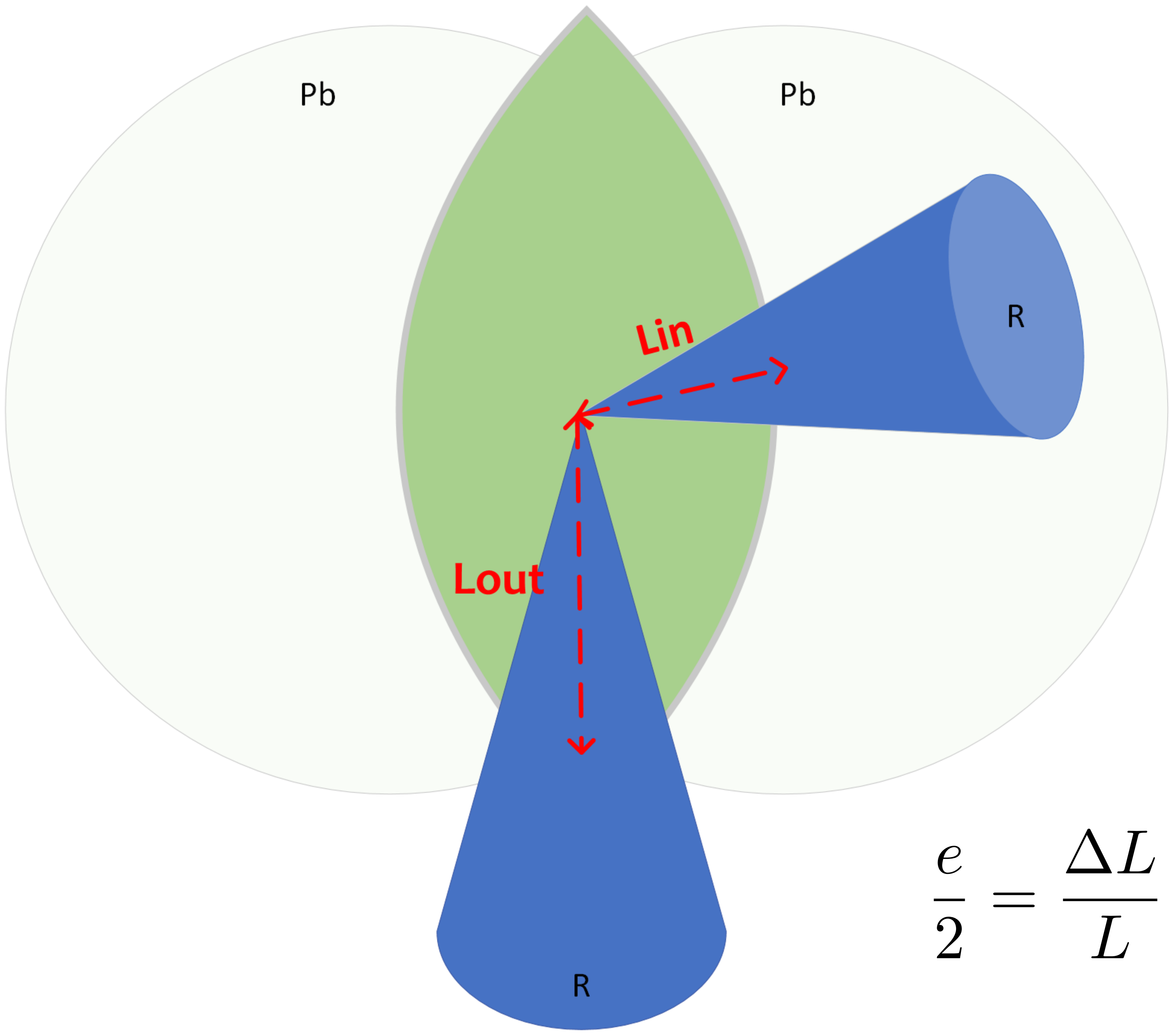
Azimuthal asymmetry

Length differential measure

- Jet suppression path dependence.
- Sensitivity to underlying geometry

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

$$\simeq -\frac{e}{2}\frac{\mathrm{d}\ln R_{\mathrm{AA}}}{\mathrm{d}\ln L}$$



$$\frac{e}{2} = \frac{\Delta L}{L}$$

- Same expectation as for overall jet suppression:

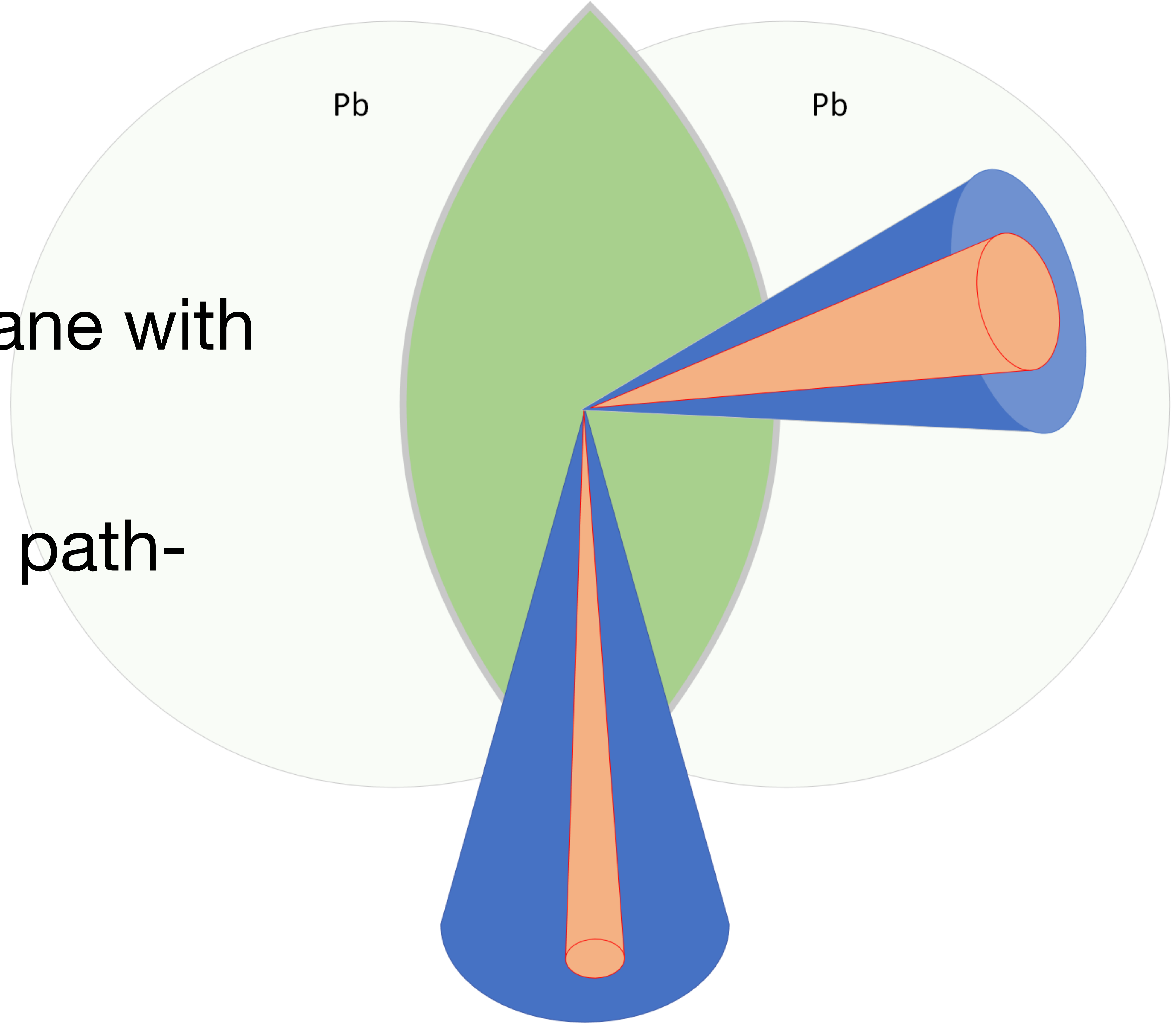
$$v_2(\mathrm{hadron}) < v_2(\mathrm{jet})$$

Note: while $R_{AA} \sim \mathcal{O}(1)$ effect, $v_2 \sim \mathcal{O}(\alpha_s)$, more sensitivity!

Additional dynamics

Differential sensitivity to coherence

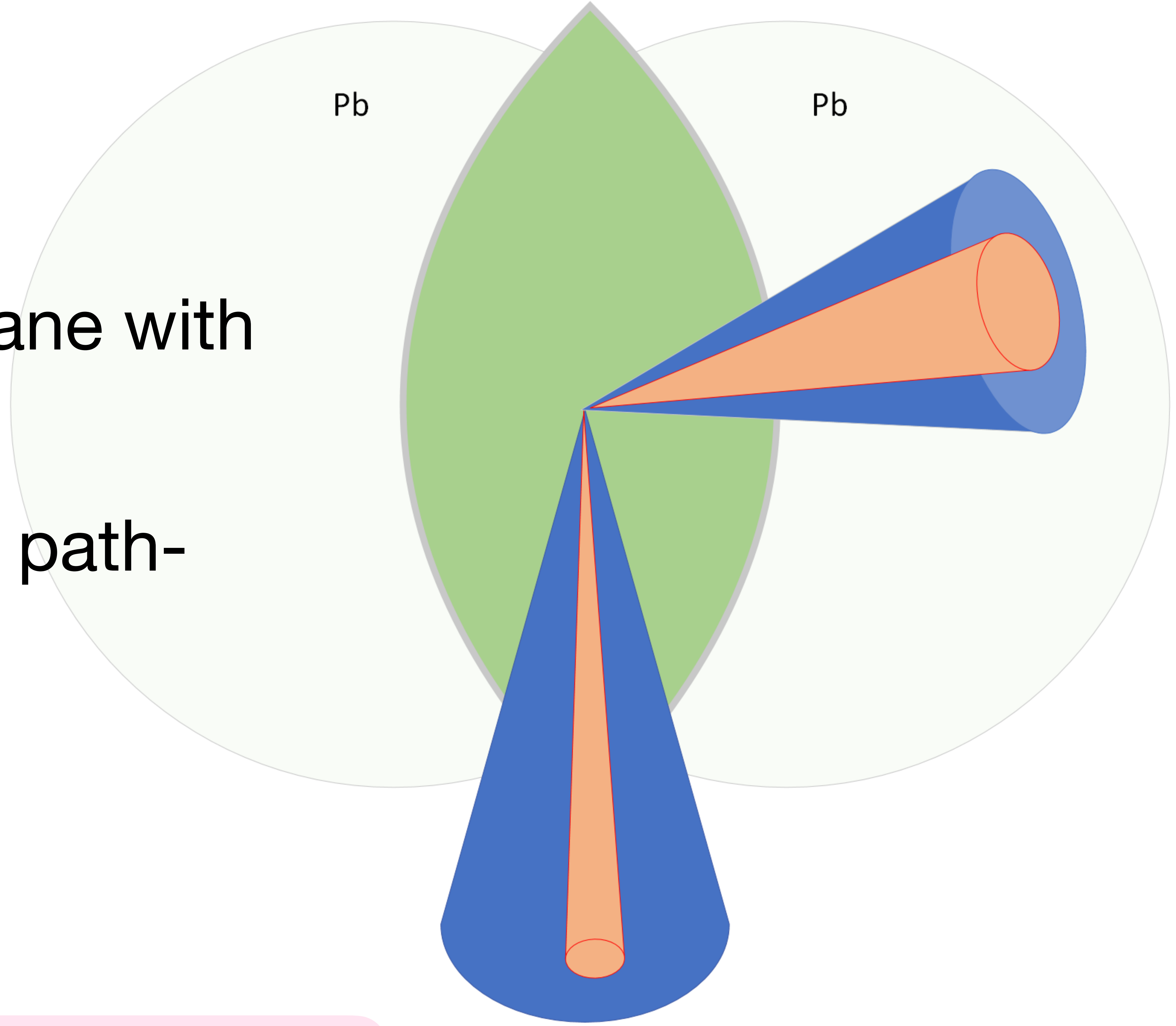
- We compare almost coherent jets in the plane with resolved jets out of the plane.
- **Enhances** in a non-trivial way the effect of path-length differences!



Additional dynamics

Differential sensitivity to coherence

- We compare almost coherent jets in the plane with resolved jets out of the plane.
- **Enhances** in a non-trivial way the effect of path-length differences!



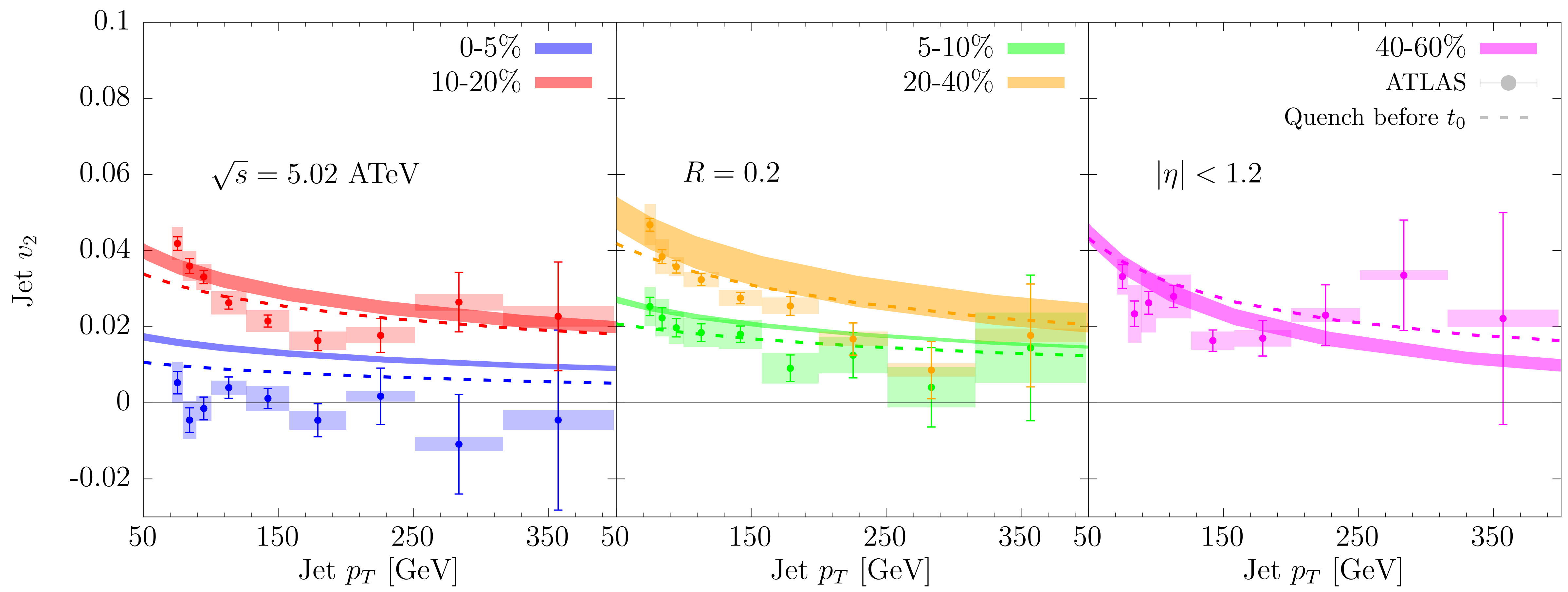
For coherent jet: $$\frac{v_2(\text{coh})}{e} = -\frac{1}{2} \ln R_{\text{AA}}|_{R \leq \theta_c}$$

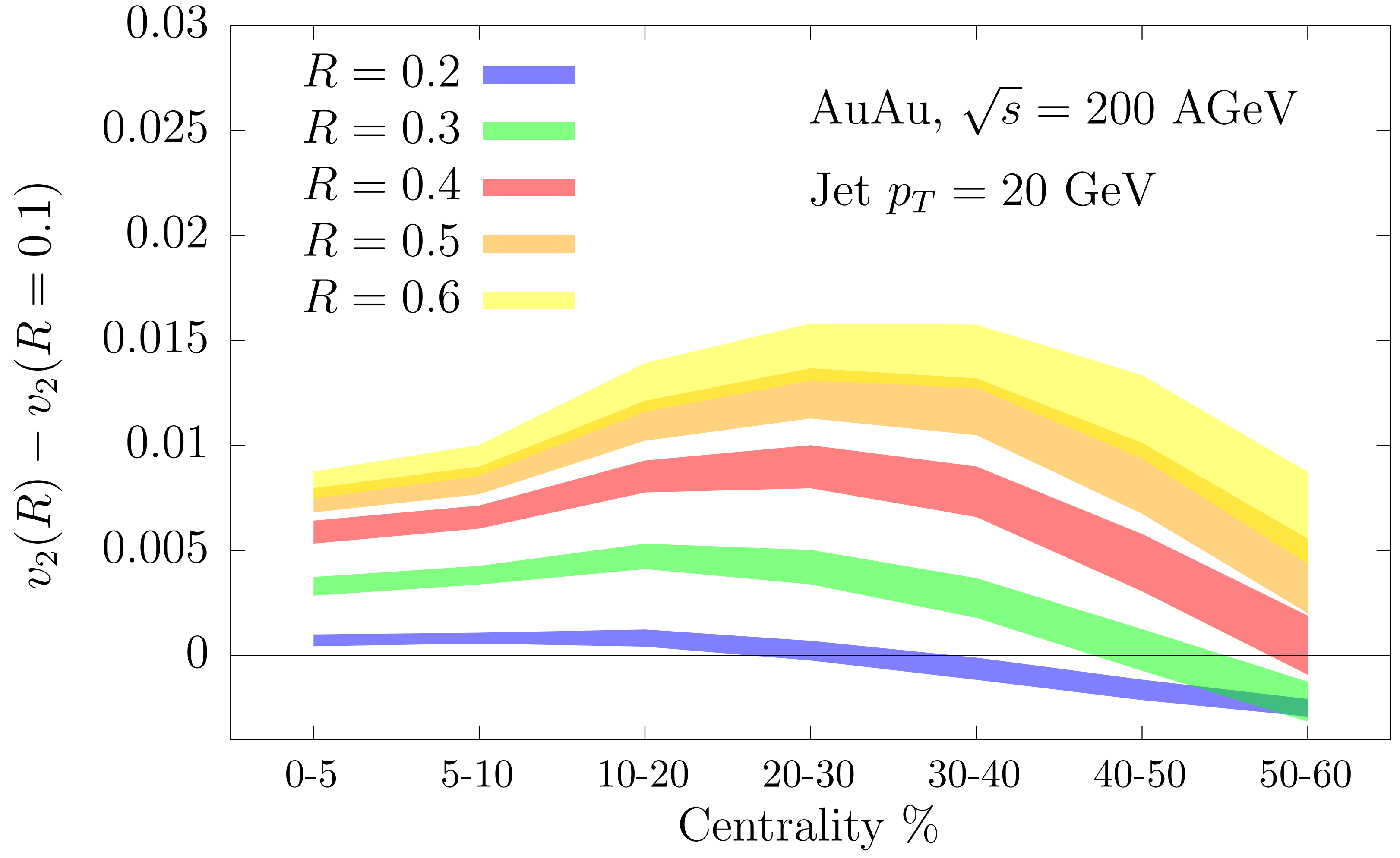
For full jet: $$\frac{v_2(R)}{e} = \frac{v_2(\text{coh})}{e} + \frac{3\bar{\alpha}}{2} \ln \frac{p_T}{\omega_c} \Theta(R - \theta_c)$$

"Sharp" transition from coherence to decoherence!

Results for jet azimuthal asymmetry

Complementary handle on jet suppression dynamics

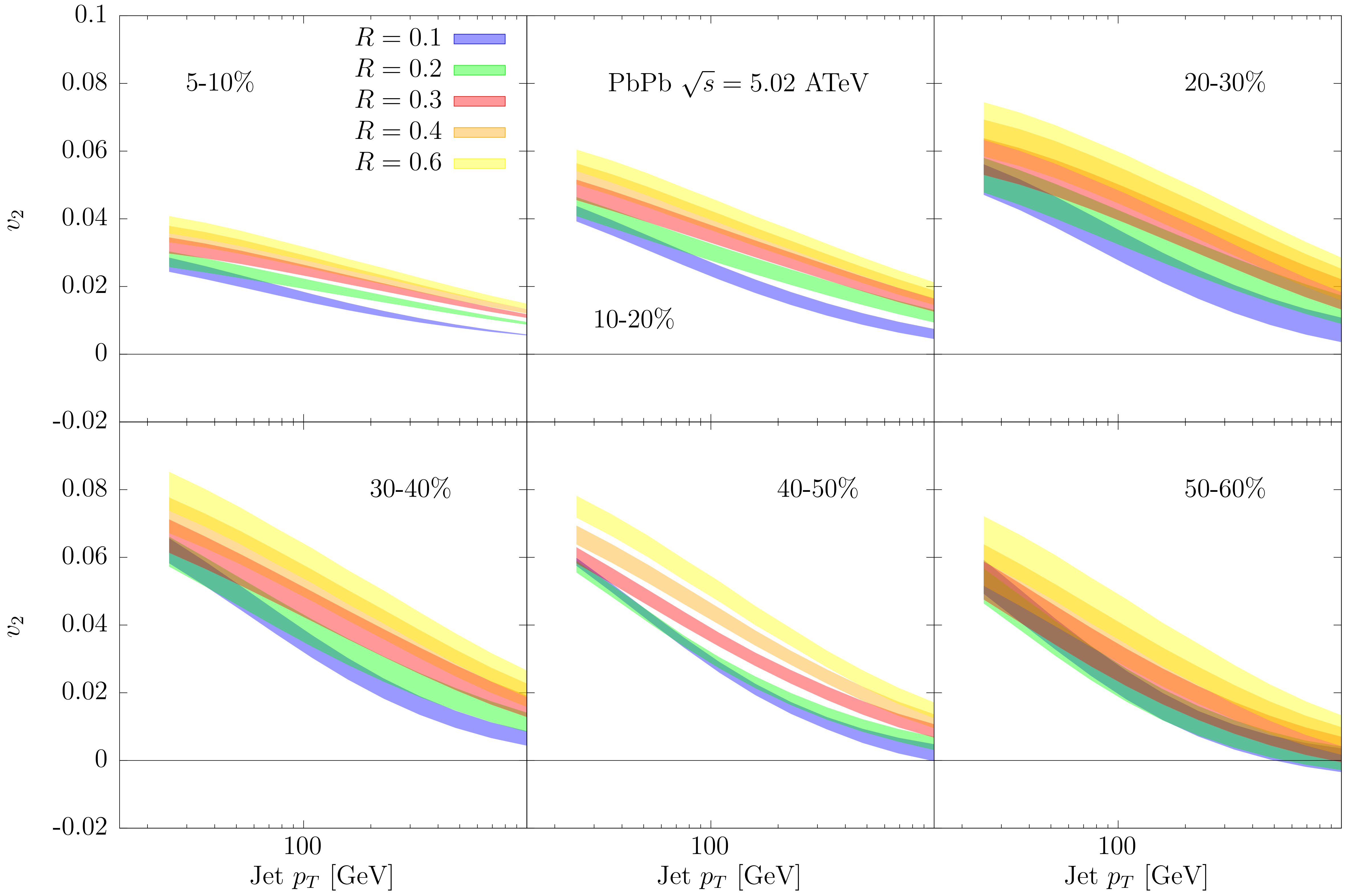


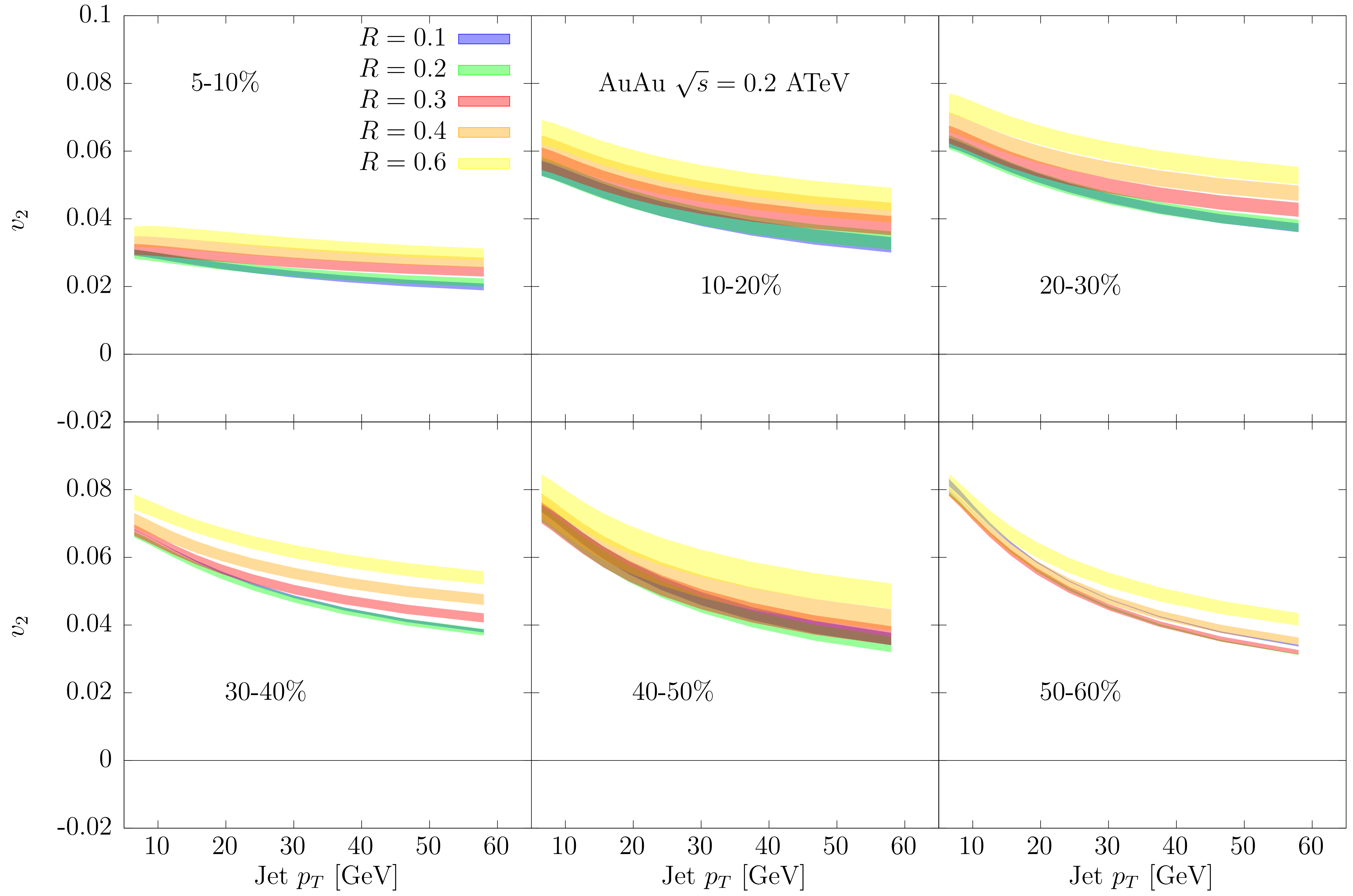


- Excellent description of jet v_2 as well!
- Sensitivity to early-time quenching.
- p_T-, R-, centrality-, energy dependences well described!

Predictions for v_2

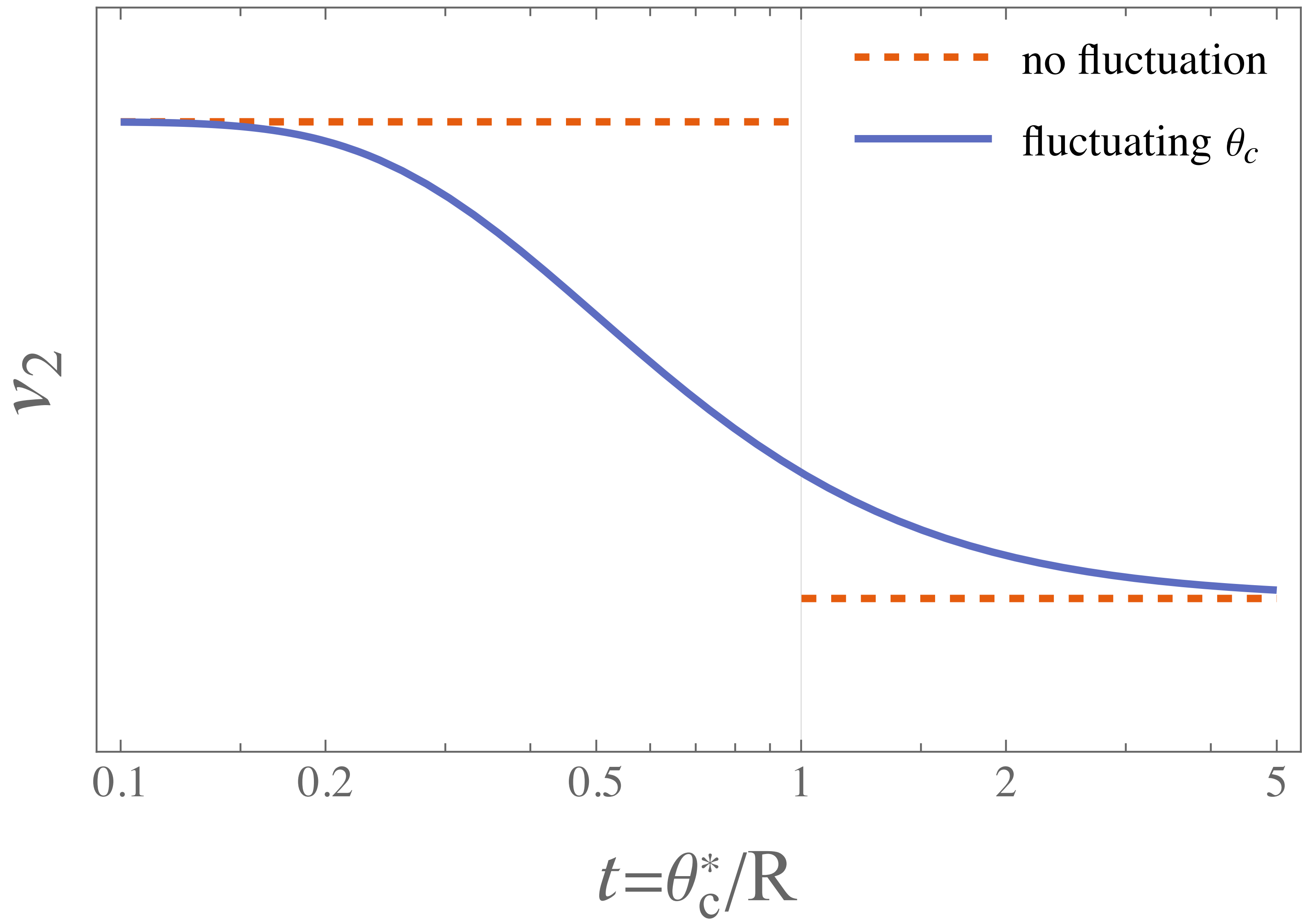
Energy-, centrality, transverse momentum & cone-angle

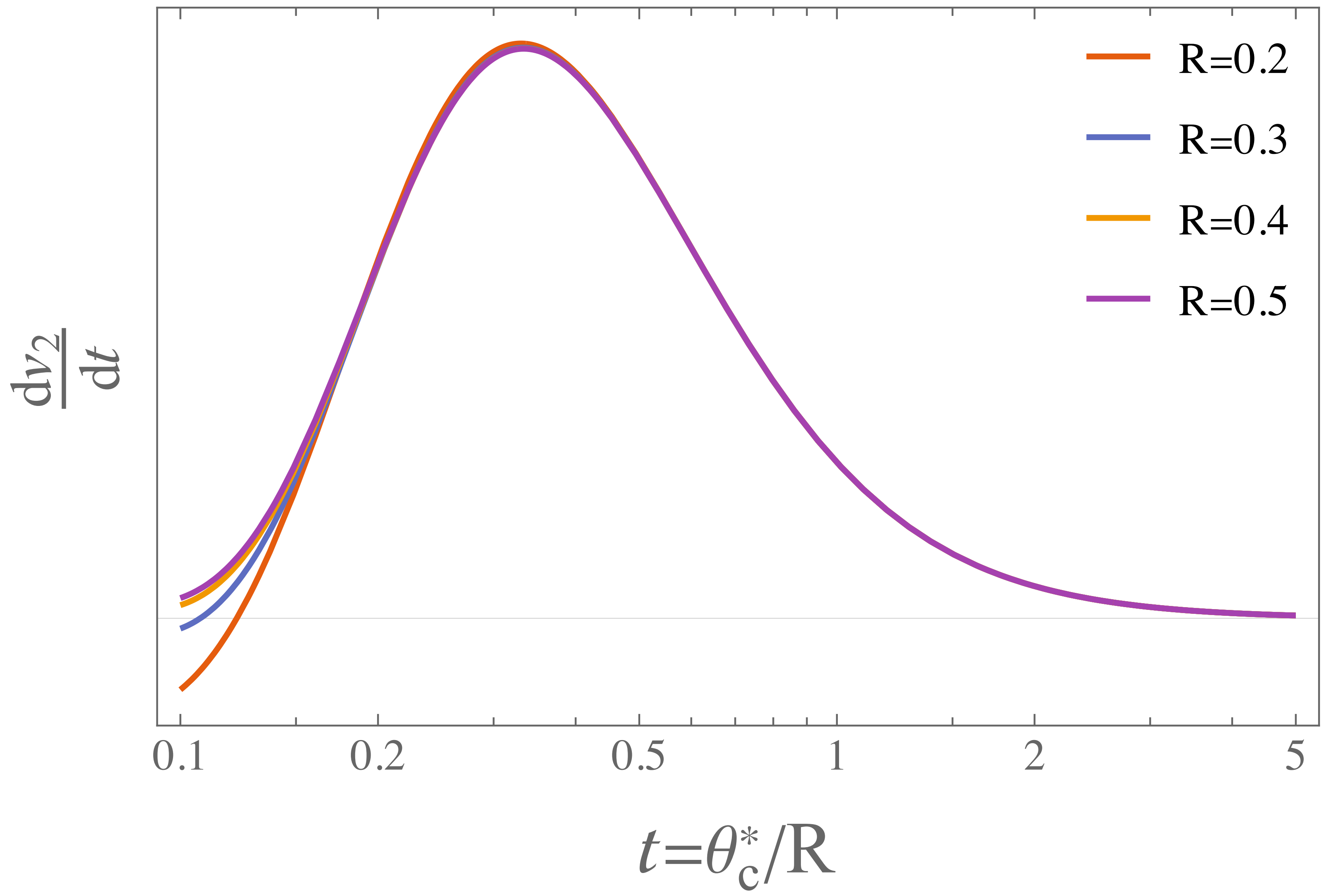




Mehtar-Tani, Pablos, Tywoniuk 2402.07869

Effects of smearing





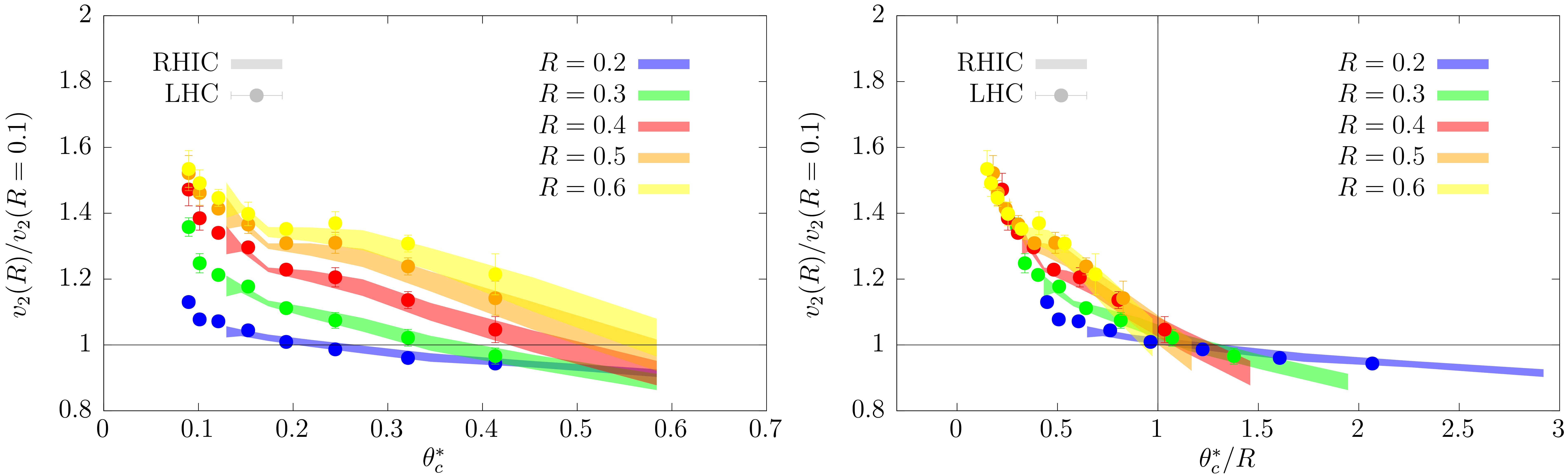
$$\frac{v_2(R)}{e} = \frac{v_2(\text{coh})}{e} + \frac{3\bar{\alpha}}{2} \ln \frac{p_T}{\omega_c} \Theta(R - \theta_c)$$

- Sharp transition is smoothed out by fluctuations in θ_c
- Striking sensitivity to new variable:

$$t = \frac{\theta_c^*}{R}$$

Sensitivity to angular scale

Emergence of θ_c



- Data from full model calculation.
- θ_c^* as a measure of centrality = characteristic length of QGP!
- All data fall on a characteristic curve as a function of t (deviations due to ratio).

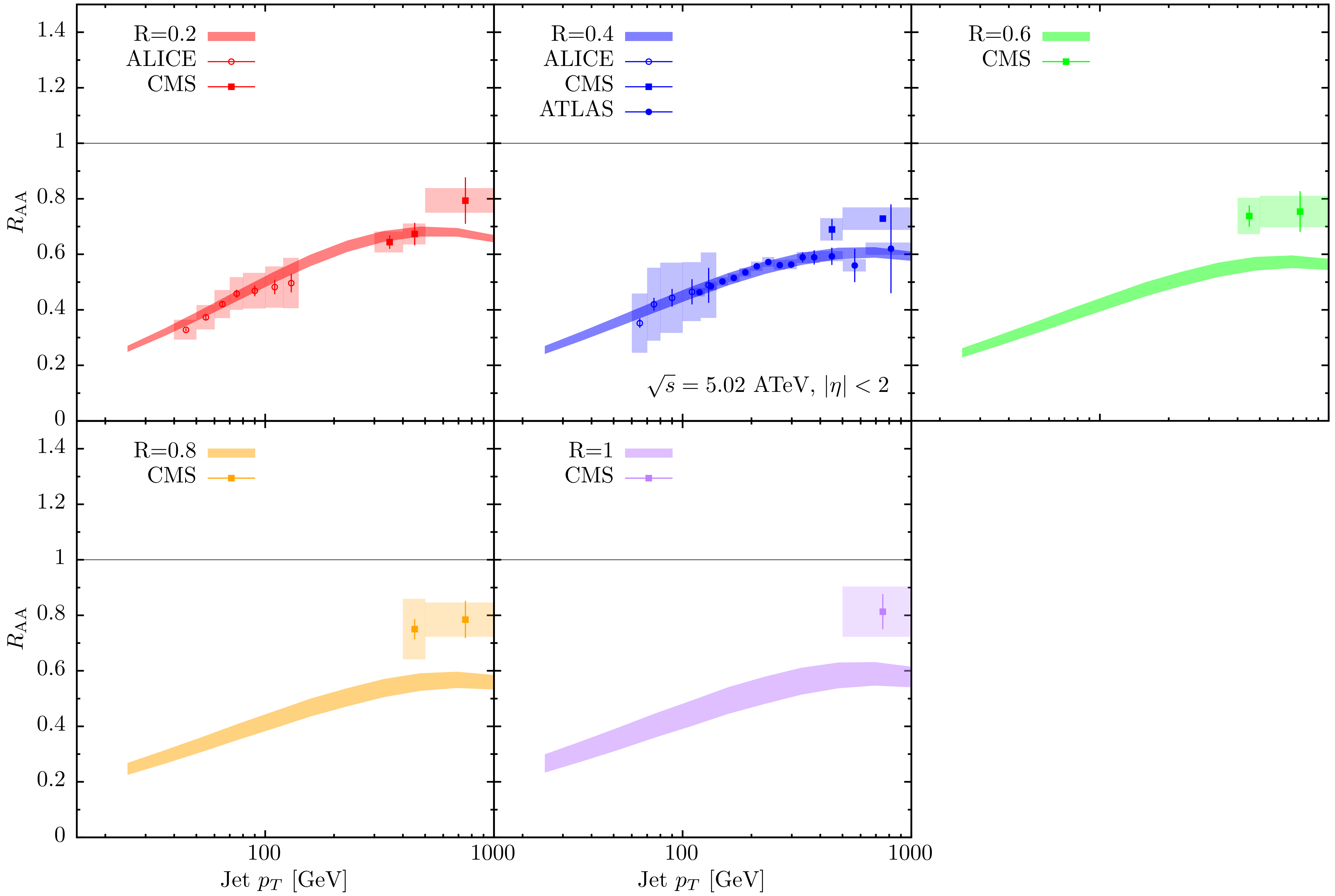
Outlook

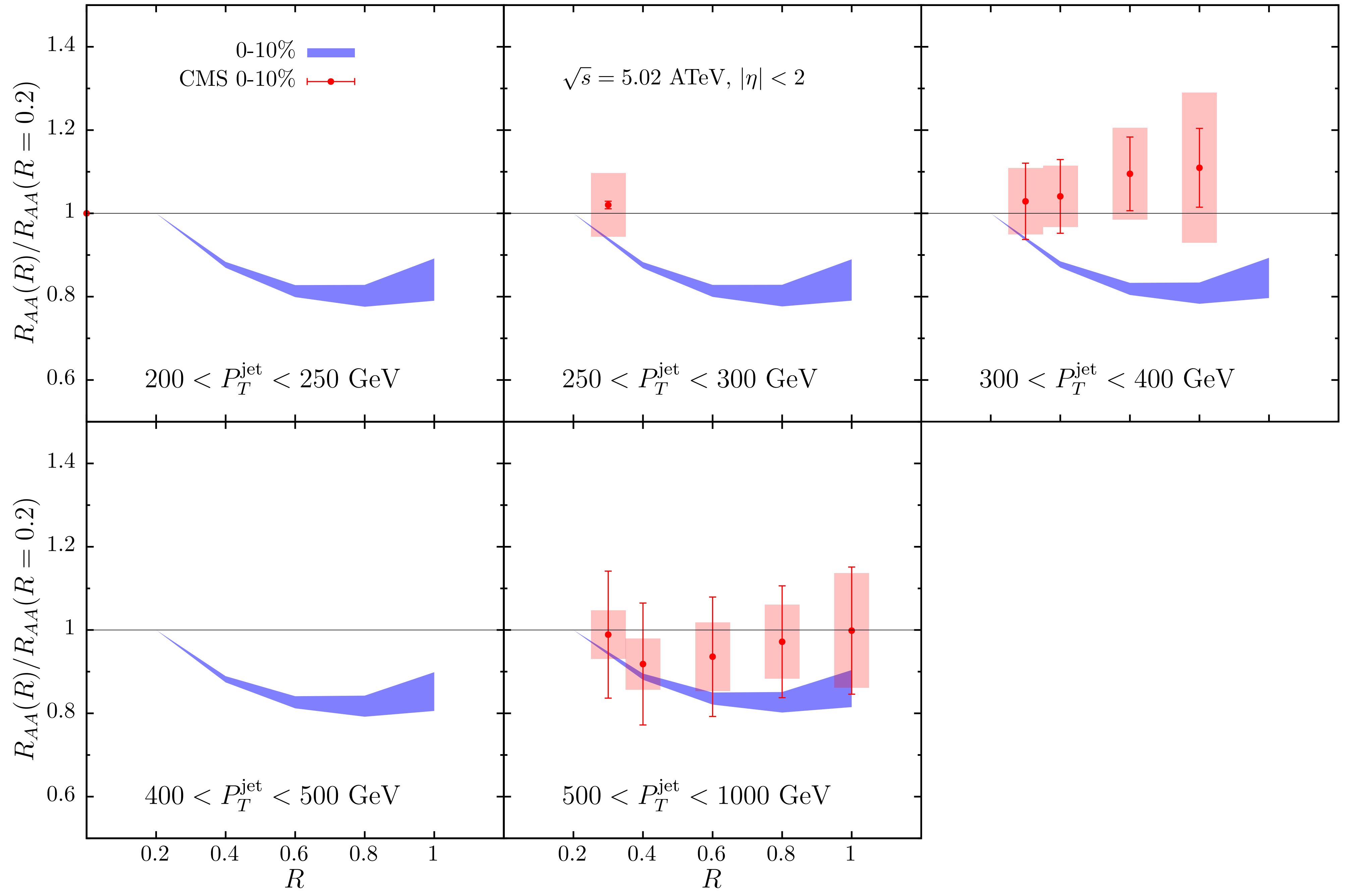
Systematic scan of system and jet scales

- Excellent agreement with data across the board ($g_{\rm med} \approx 2$).
- Relies heavily on modelling of jet coherence in medium.
  - Source of biggest uncertainties: needs further refinement beyond LL.
- Strategy: scan of relevant variables gives access to relevant phase space.
- Clear trends seen in data when organised according to relevant variables!
- Further plans: inclusion of new observables (substructure), model-agnostic analysis,…

Back-up

Jet R-dependence at LHC





- some tension between ATLAS and CMS at $R = 0.4$
- missing ingredients for large-R predictions (better modeling of energy recovery & wake).