

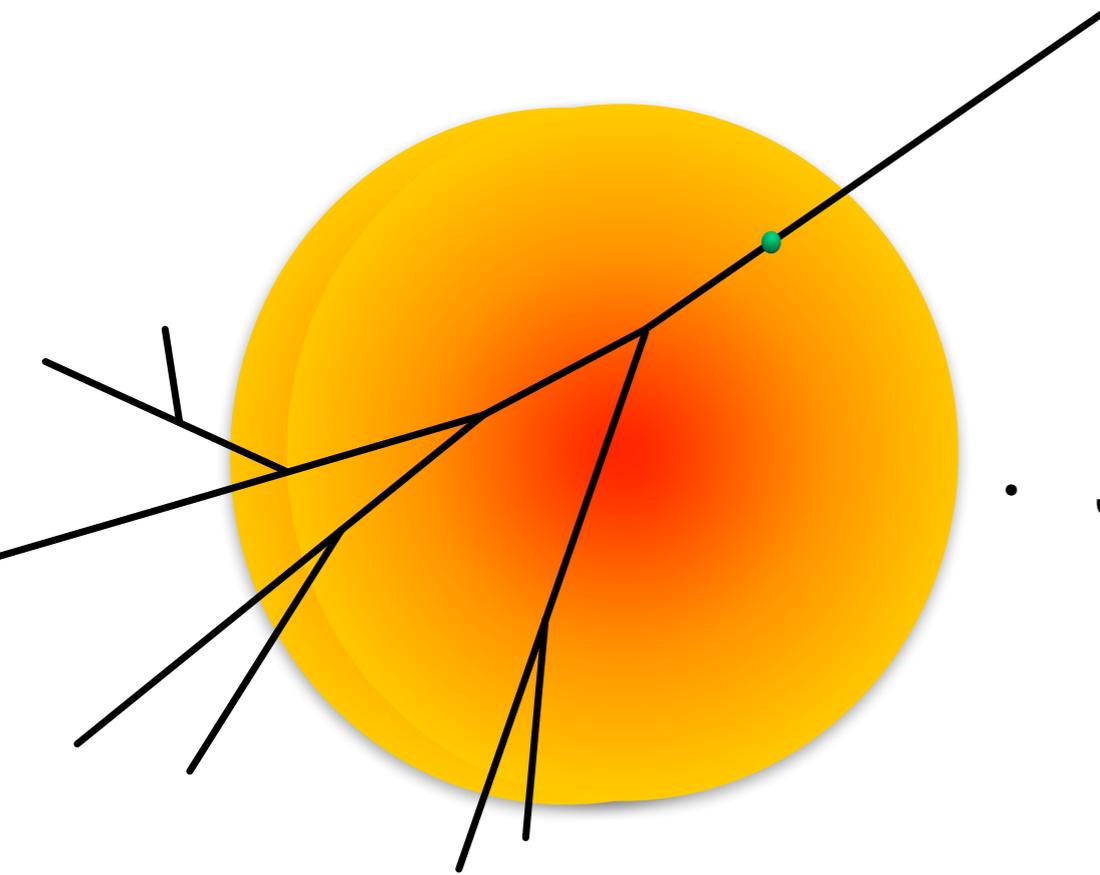
# A Hybrid Strong/Weak Coupling Approach to Jet Quenching

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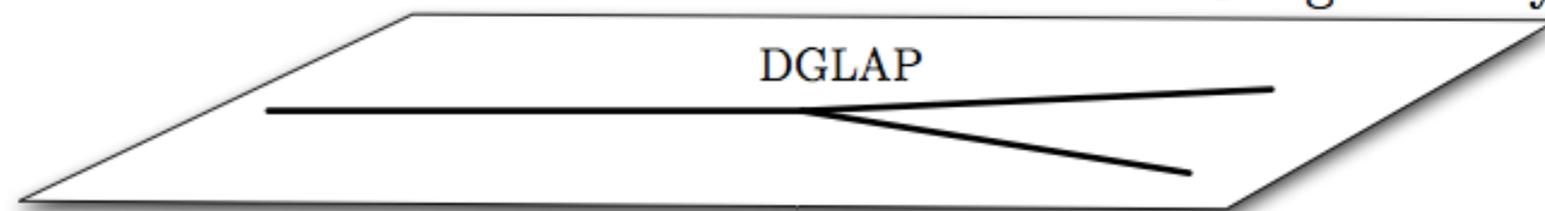


with Jorge Casalderrey-Solana, Doga Can Gülhan, José  
Guilherme Milhano and Krishna Rajagopal

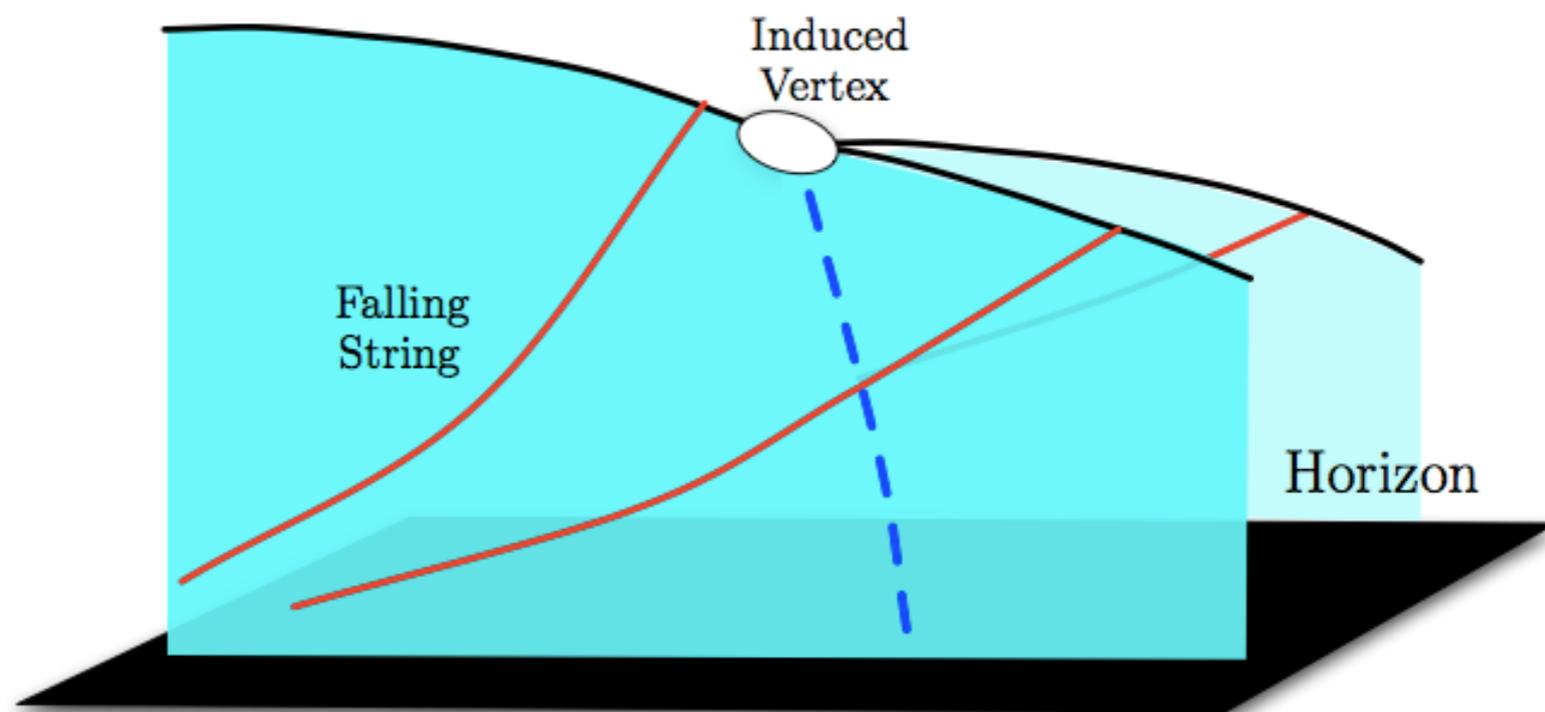
# Motivation



- Jet interaction with medium is a multi-scale problem
  - Hard production (perturbative)
  - Hard evolution (perturbative)
  - Exchanges at medium scale (non-pert.)
  - Soft jet fragments (non-pert.)
- Simple (and phenomenological) approach
  - Leave jet evolution unmodified ( $Q \gg T$ )
  - Each in medium parton loses energy (not necessarily perturbative)
  - Neglect medium induced radiation (first approximation)

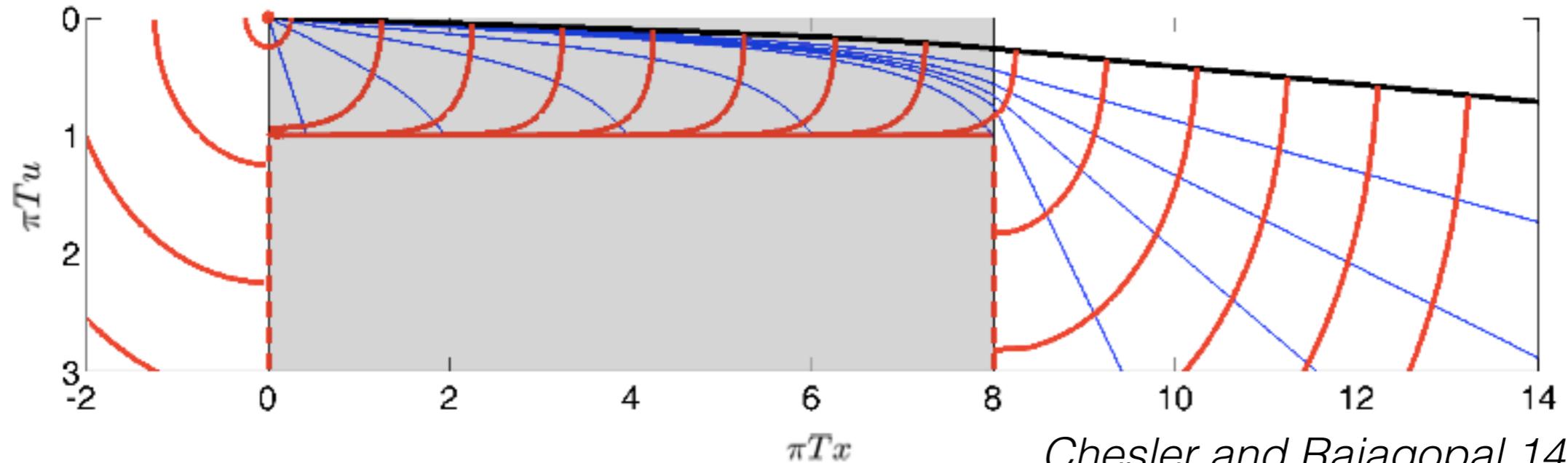


# Hybrid Model



- Jet shower perturbative (PYTHIA)
- Additional loss in rungs → strongly coupled, non-perturbative
- Assign a lifetime  $\tau_f = 2 \frac{E}{Q^2}$  to every rung. Final partons fly until critical temperature is reached
- Embed hard collision into hydrodynamic plasma with  $180 < T_c < 200$  MeV  
*Bazazov et al, 0903.4379*      *Hirano et al, 1012.3955*
- We don't hadronize in order to keep model assumptions minimal; therefore consider jet observables only (we checked we have little sensitivity on  $Q_0$ )

# Energetic light quark traversing a supersymmetric plasma



(as explained in Krishna Rajagopal's talk)

- Rather intrincated path length dependence with a Bragg-like peak

(see P. Arnold's talk)

$$\frac{1}{E_i} \frac{dE}{dx} = - \frac{4x^2}{\pi x_{stop}^2 \sqrt{x_{stop}^2 - x^2}} \quad x_{stop} = \frac{E_i^{1/3}}{2T^{4/3} \kappa_{SC}}$$

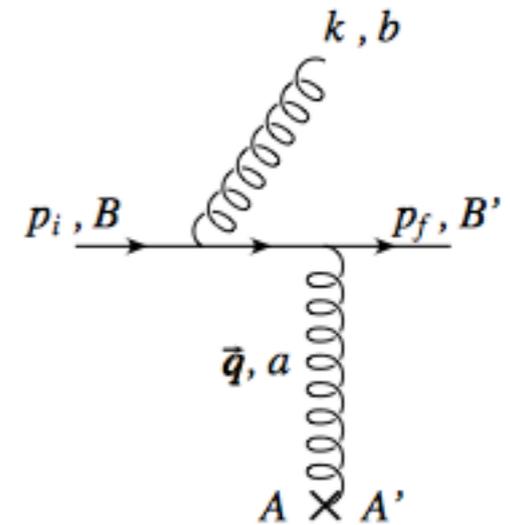
- Gluons get a smaller stopping distance according to  $\kappa_{SC}^G = \kappa_{SC}^Q \left( \frac{C_A}{C_F} \right)^{1/3}$

# Perturbative benchmarks

- To understand the predictivity of our strongly coupled model

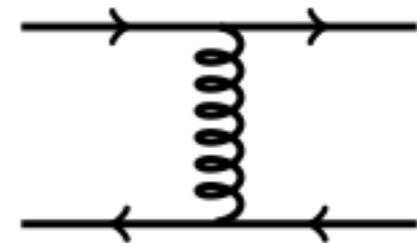
-Radiative

$$\frac{dE}{dx} = -\kappa_R \frac{C_R}{C_F} T^3 x$$



-Collisional

$$\frac{dE}{dx} = -\kappa_C \frac{C_R}{C_F} T^2$$



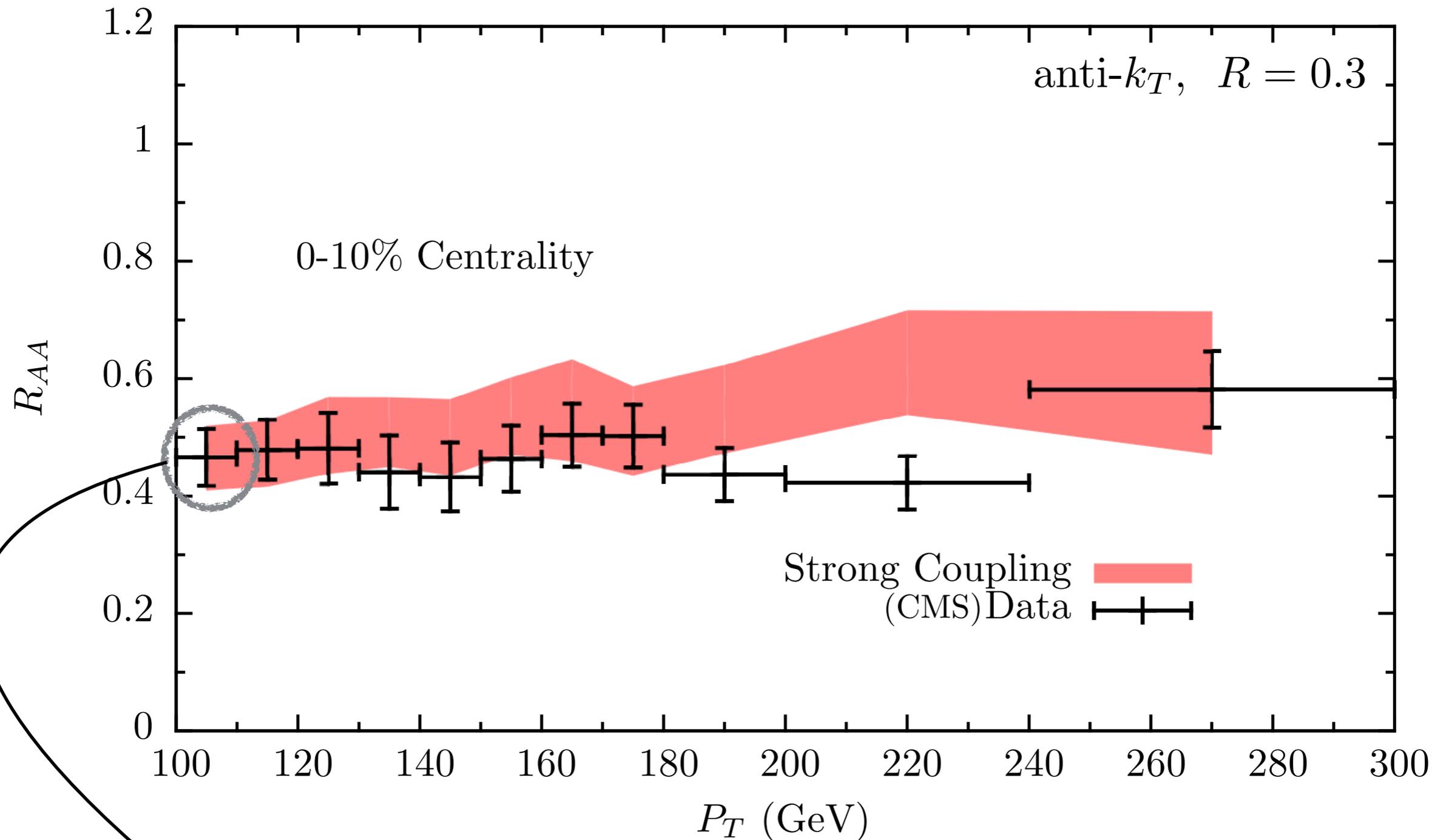
- Not aimed at superseding more sophisticated computations

# Results

PYTHIA + Quenching + FastJet

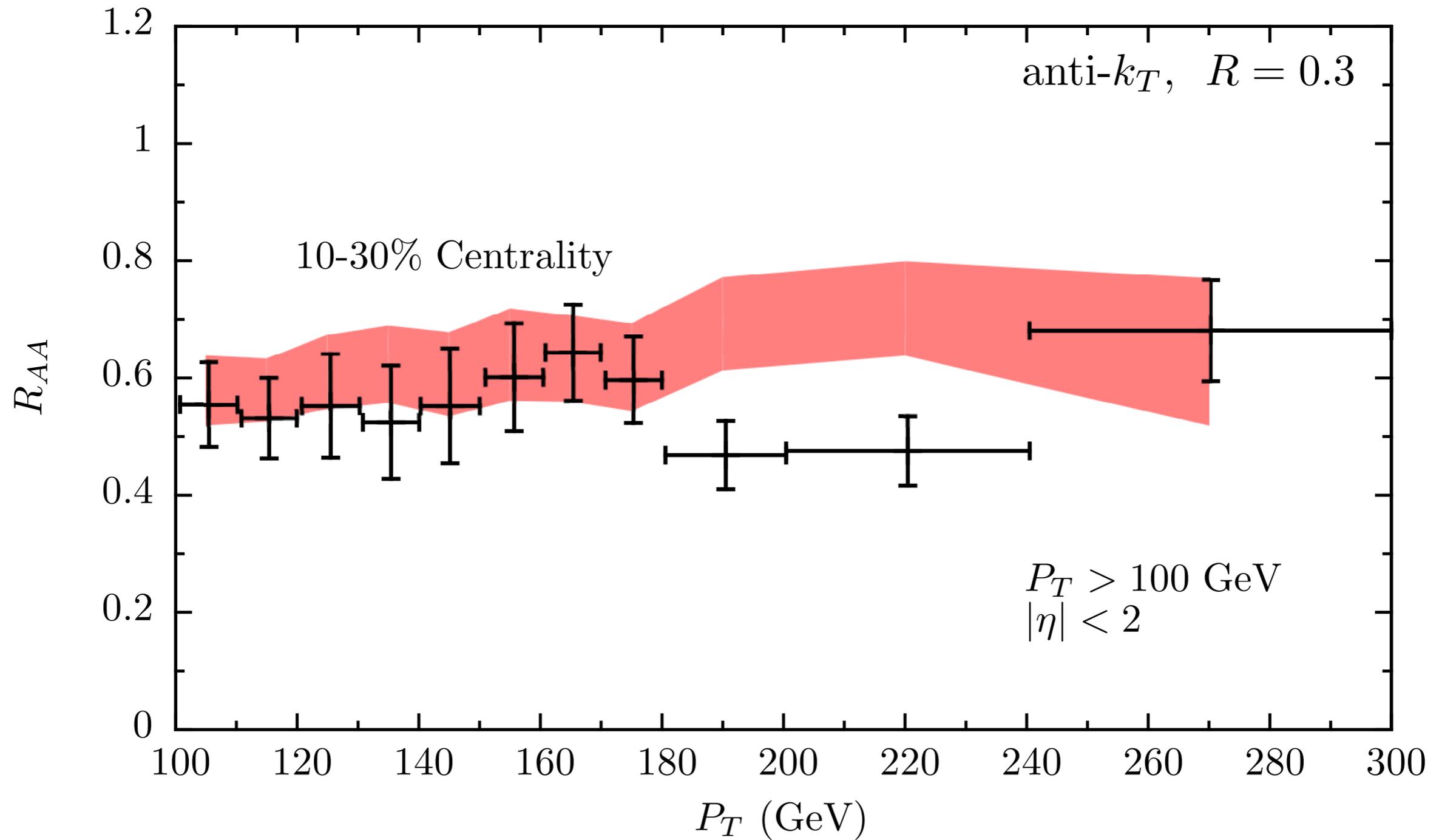
# $R_{AA}$

anti- $k_T$ ,  $R = 0.3$

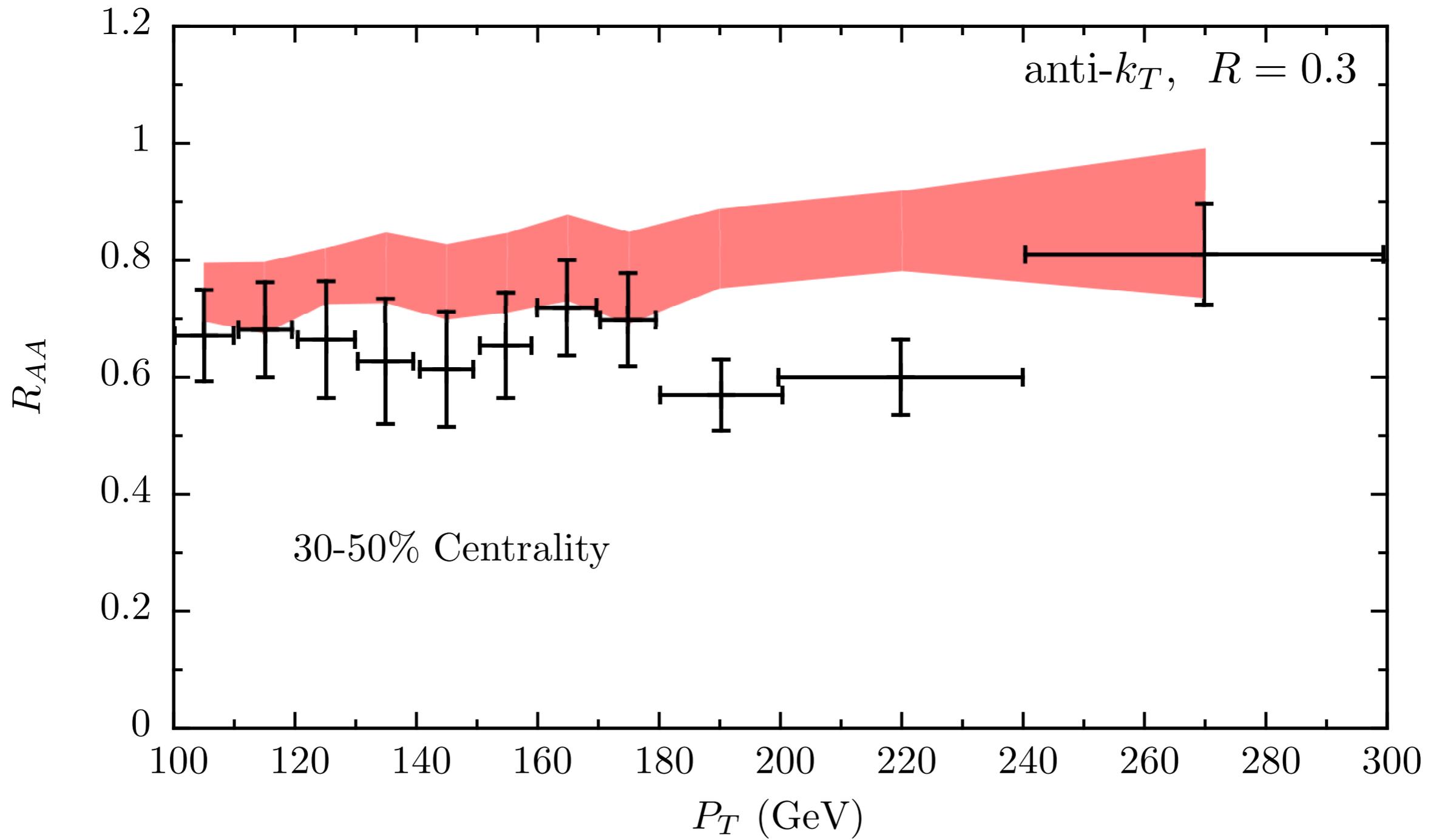


Use this one point to constrain our one parameter  
Rest of  $R_{AA}$  is all postdicted

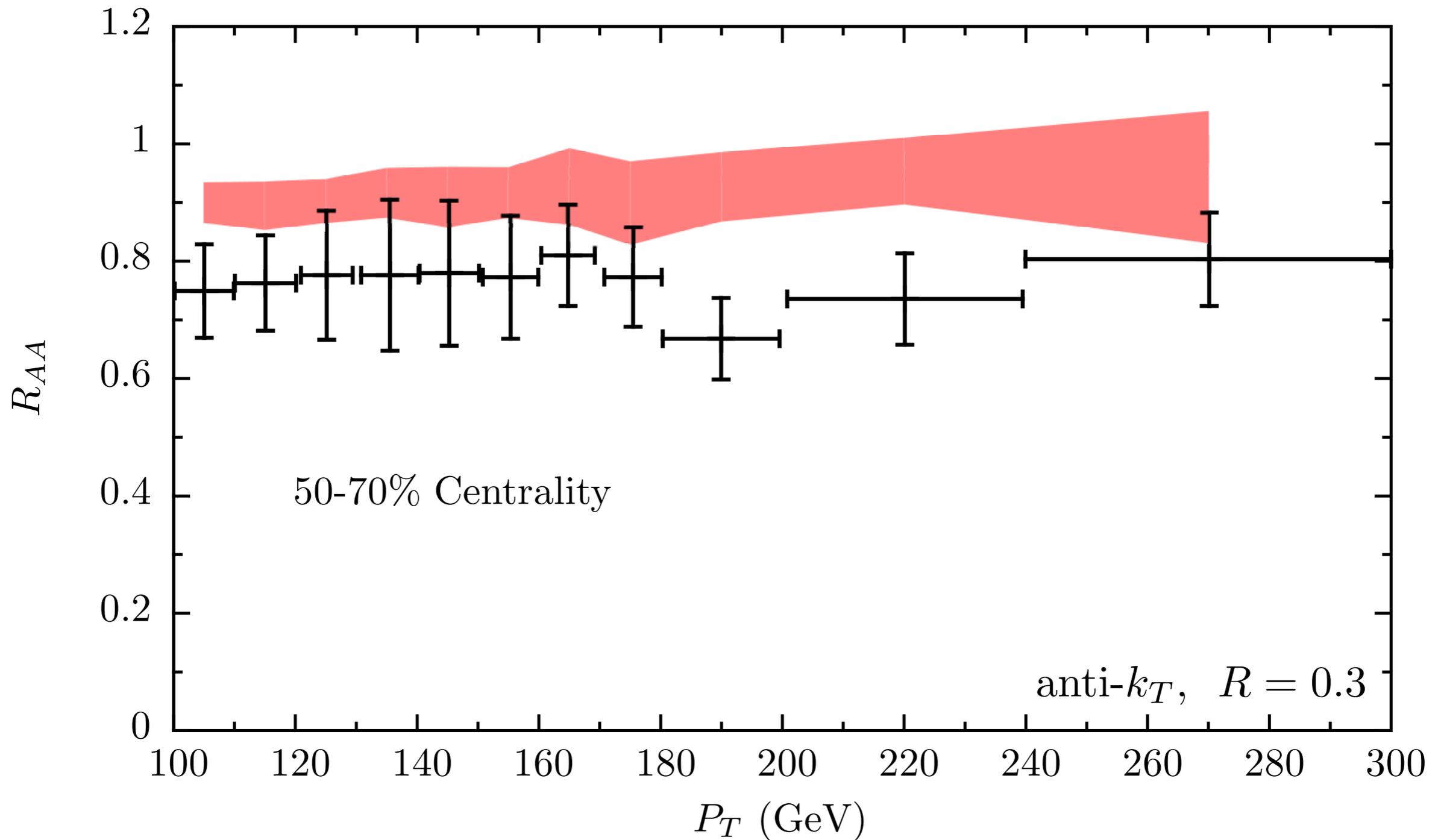
# $R_{AA}$



# $R_{AA}$

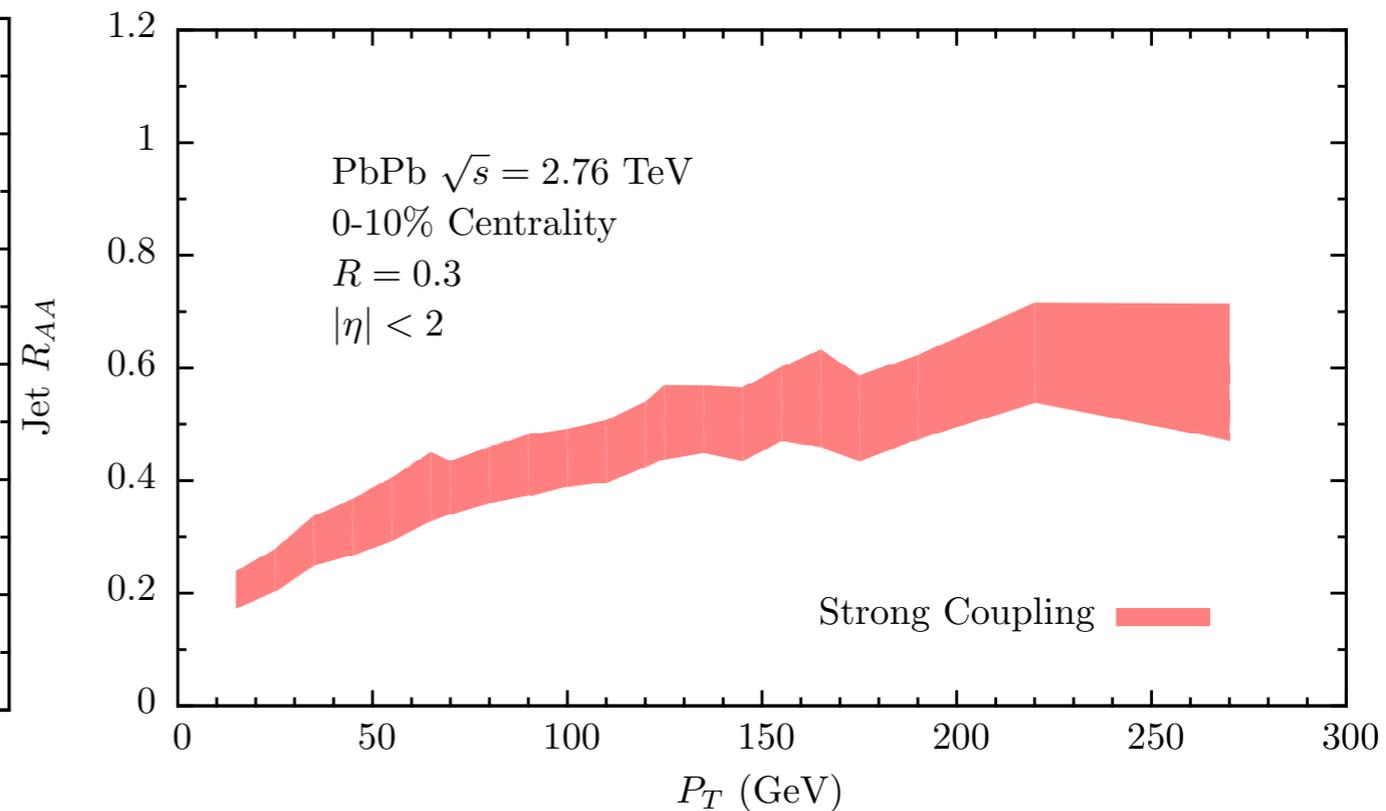
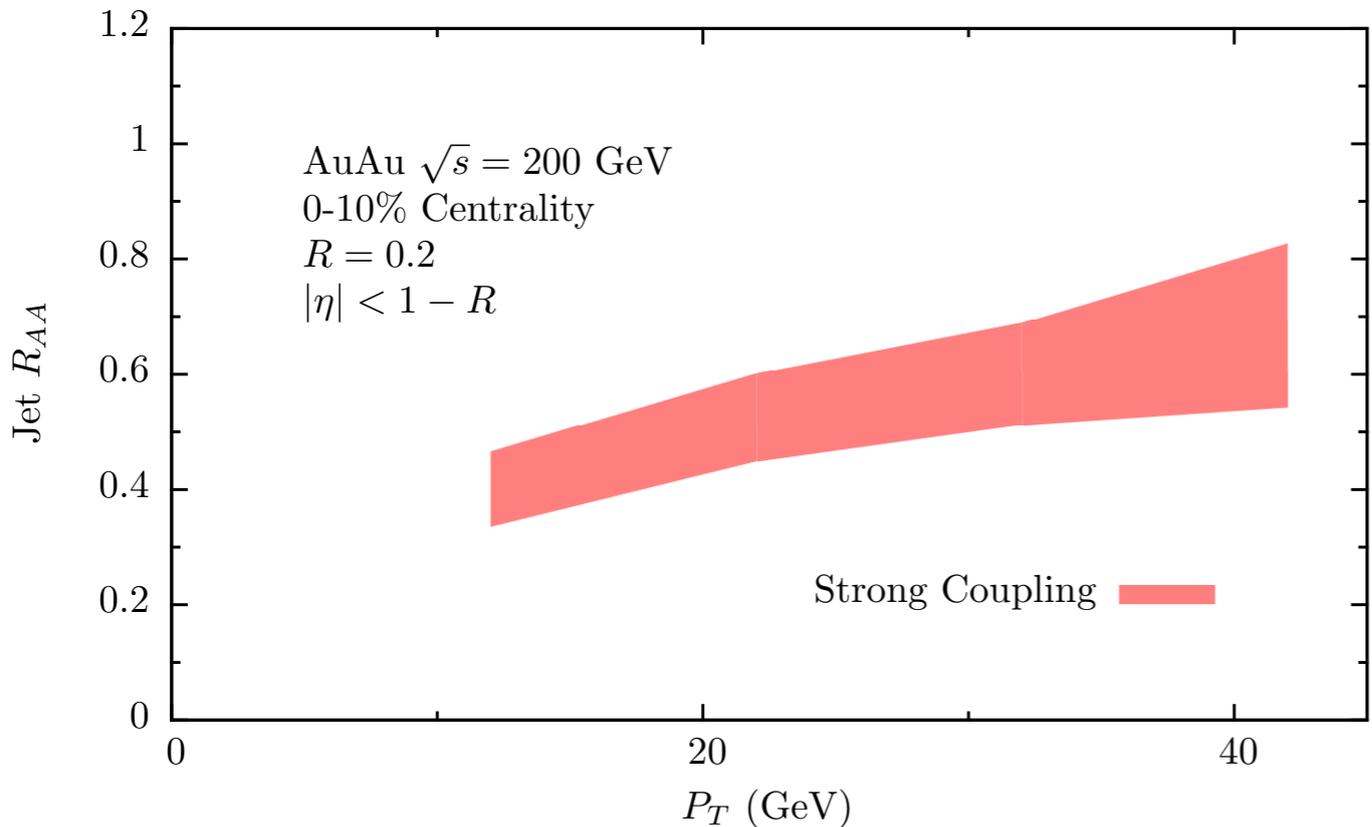


# $R_{AA}$



Mild disagreement towards peripheral bins may indicate the importance of quenching in the hadron gas phase

# RHIC vs LHC

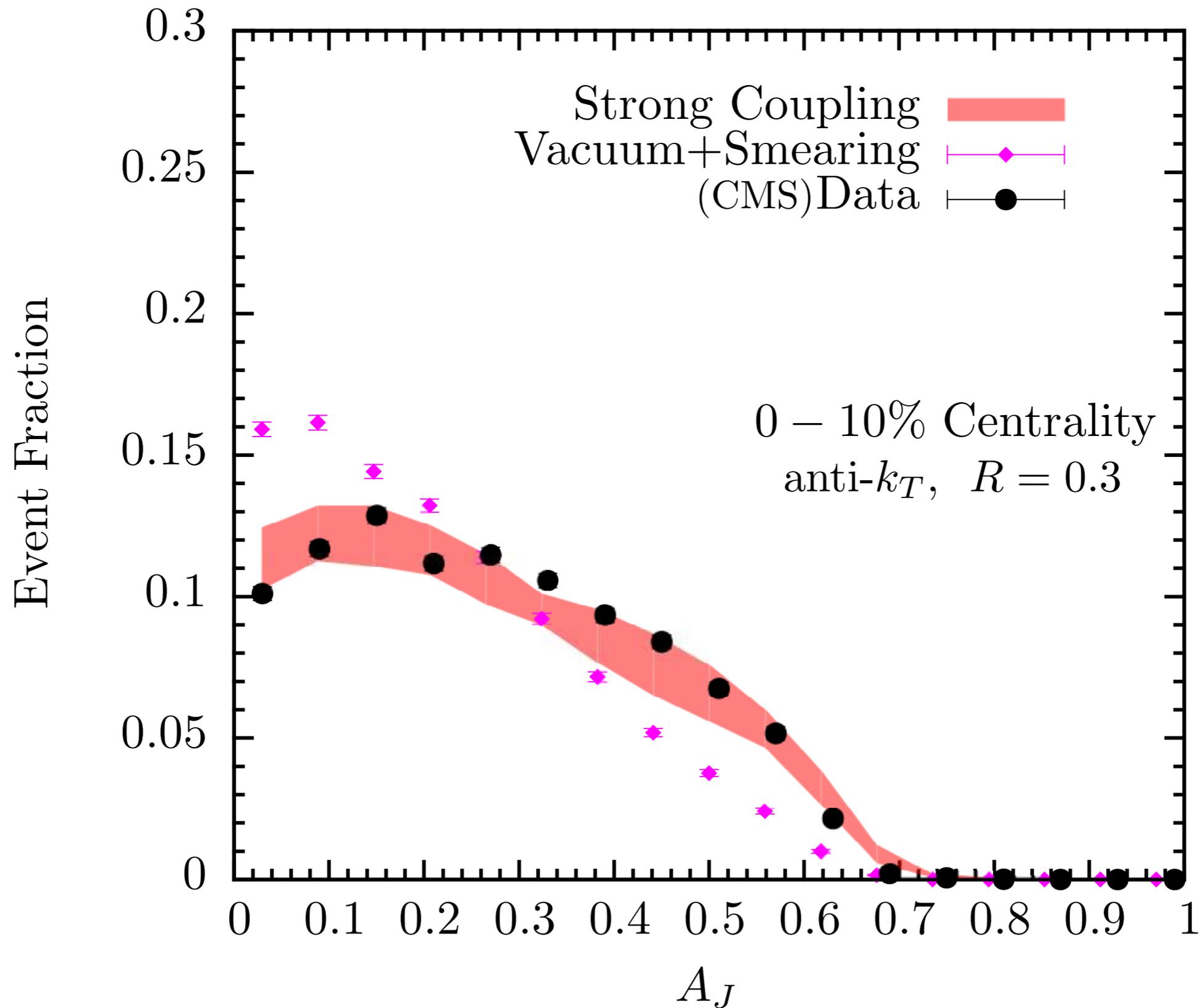


With the same value of the fit parameter we get reasonable results for RHIC as well as for LHC

Our model agrees with RHIC jet data that we have seen so far, eg on charged-jet  $R_{AA}$ . We look forward to further comparisons

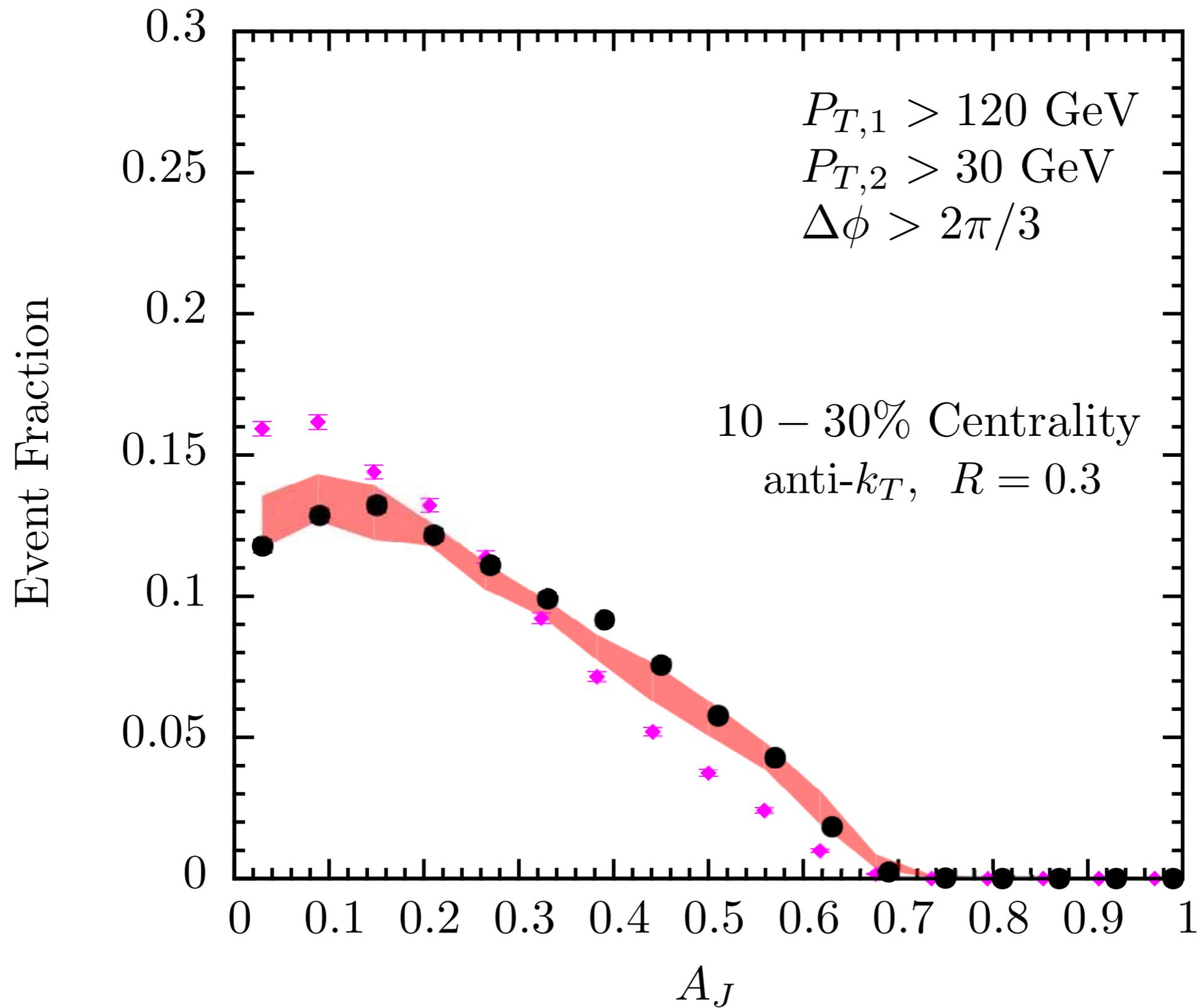
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

# Dijet Asymmetry



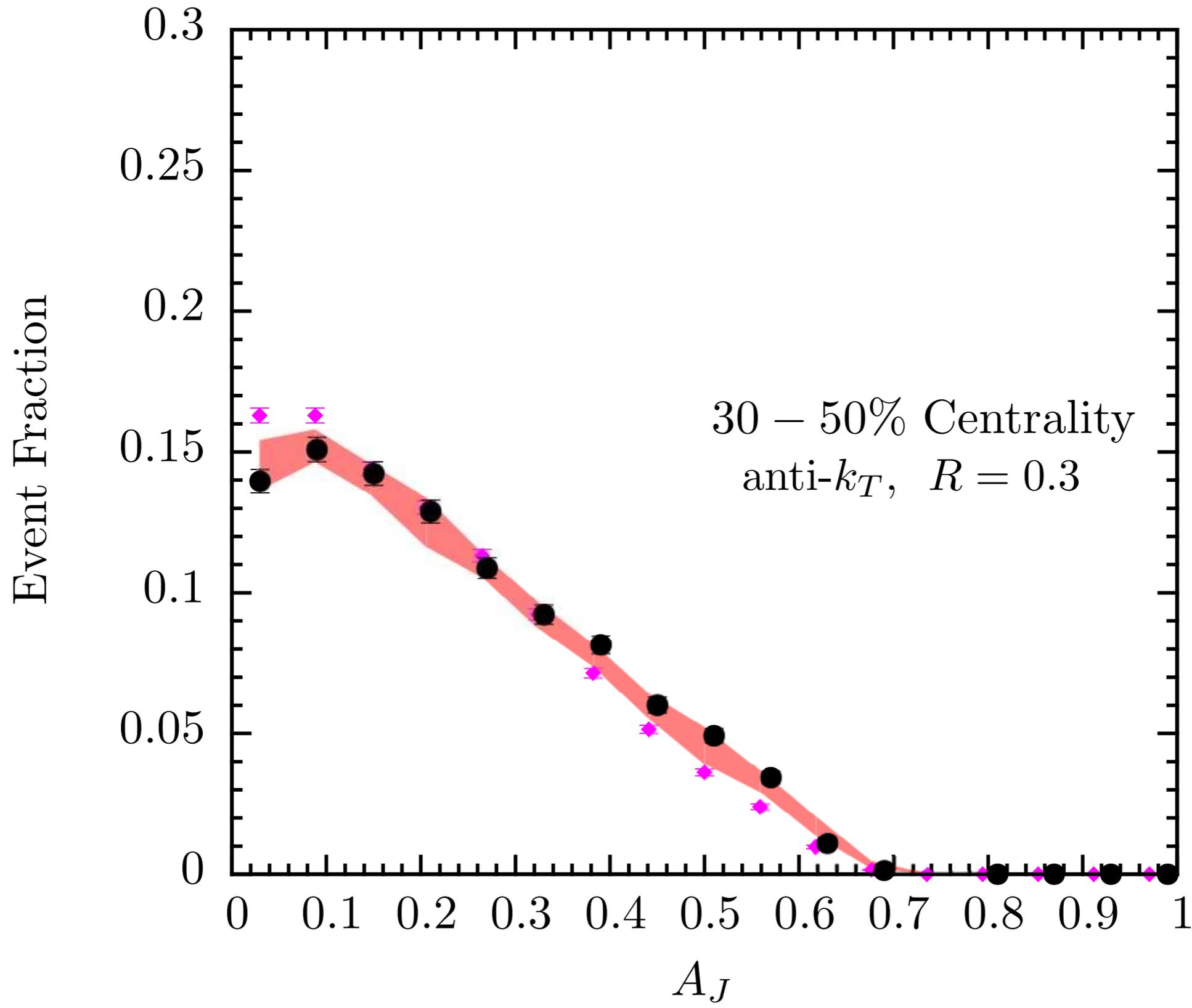
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# Dijet Asymmetry



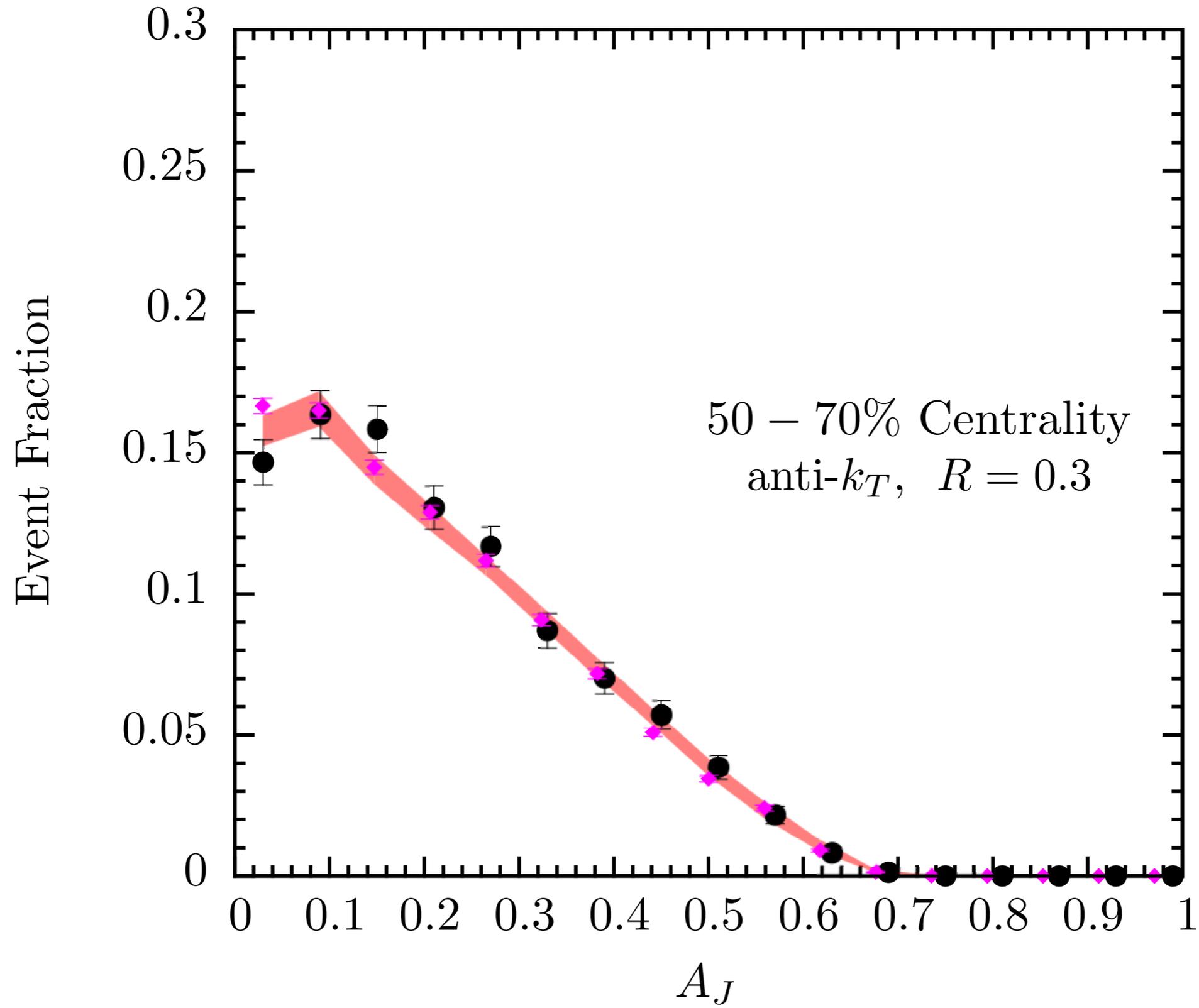
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# Dijet Asymmetry

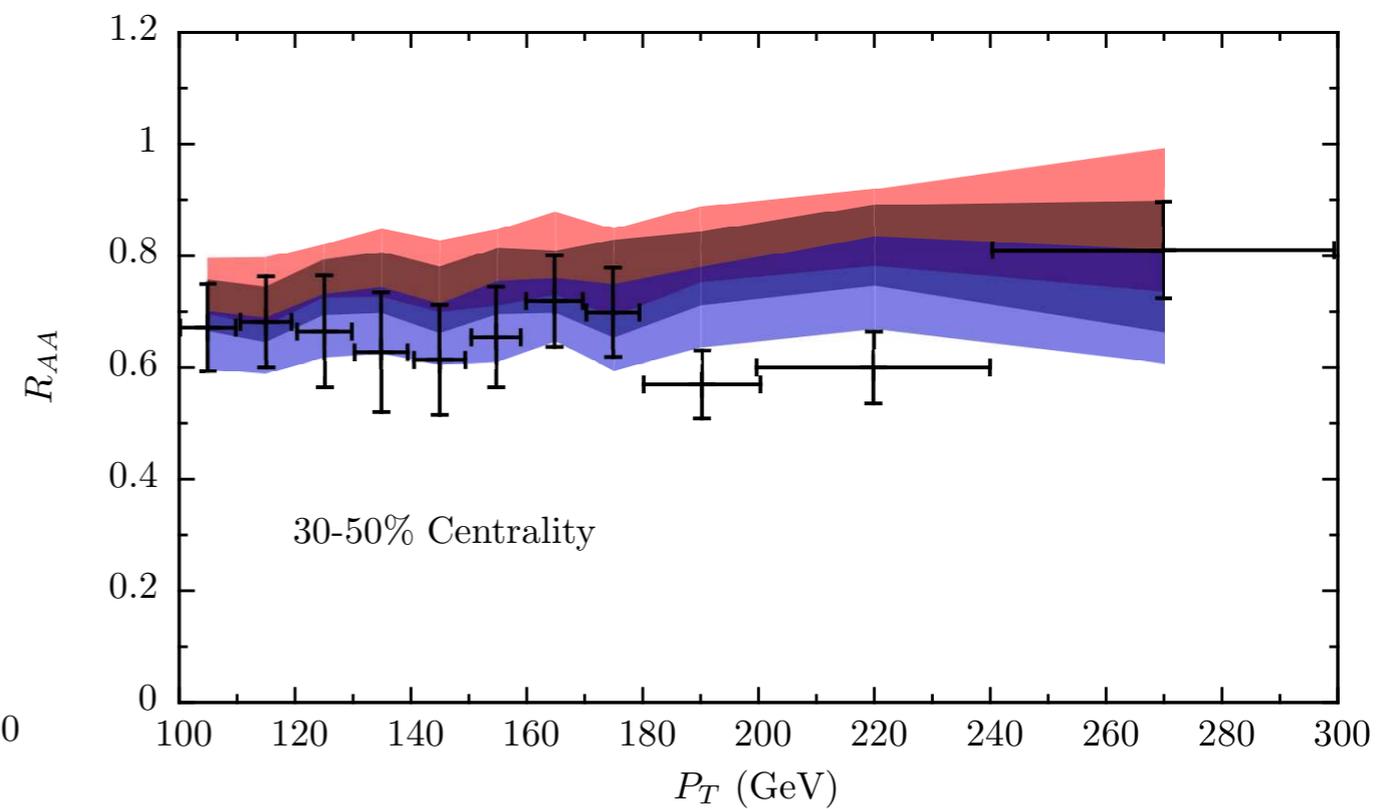
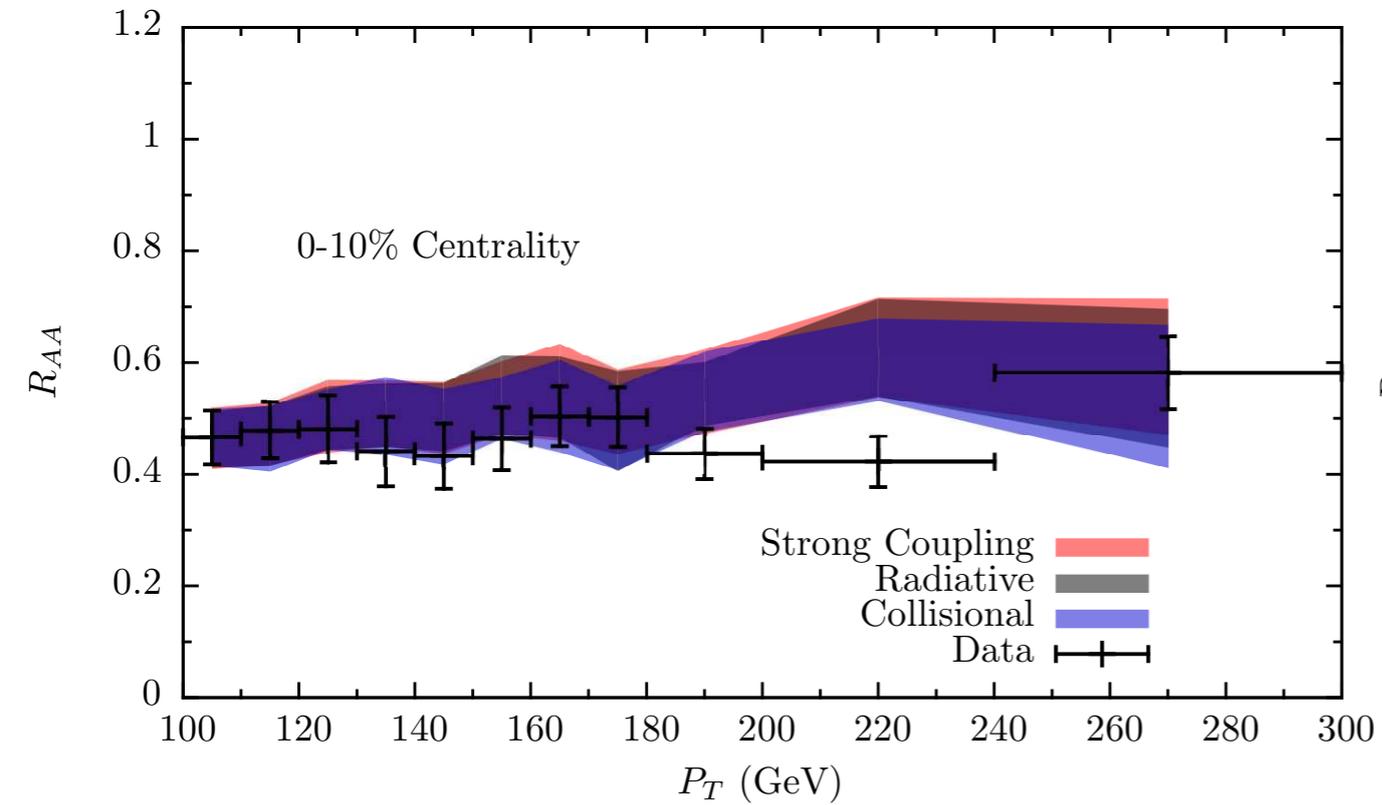


$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

# Dijet Asymmetry



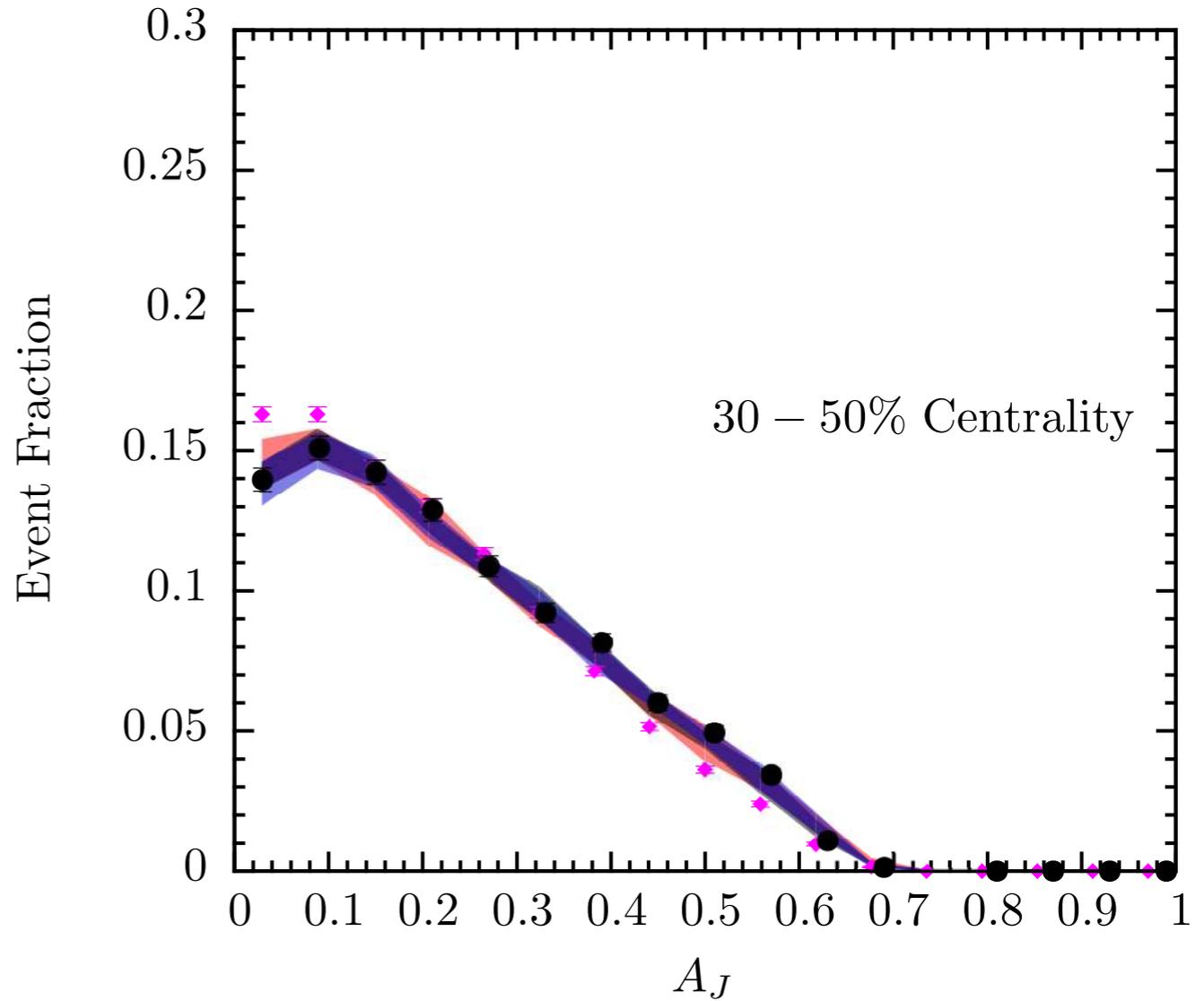
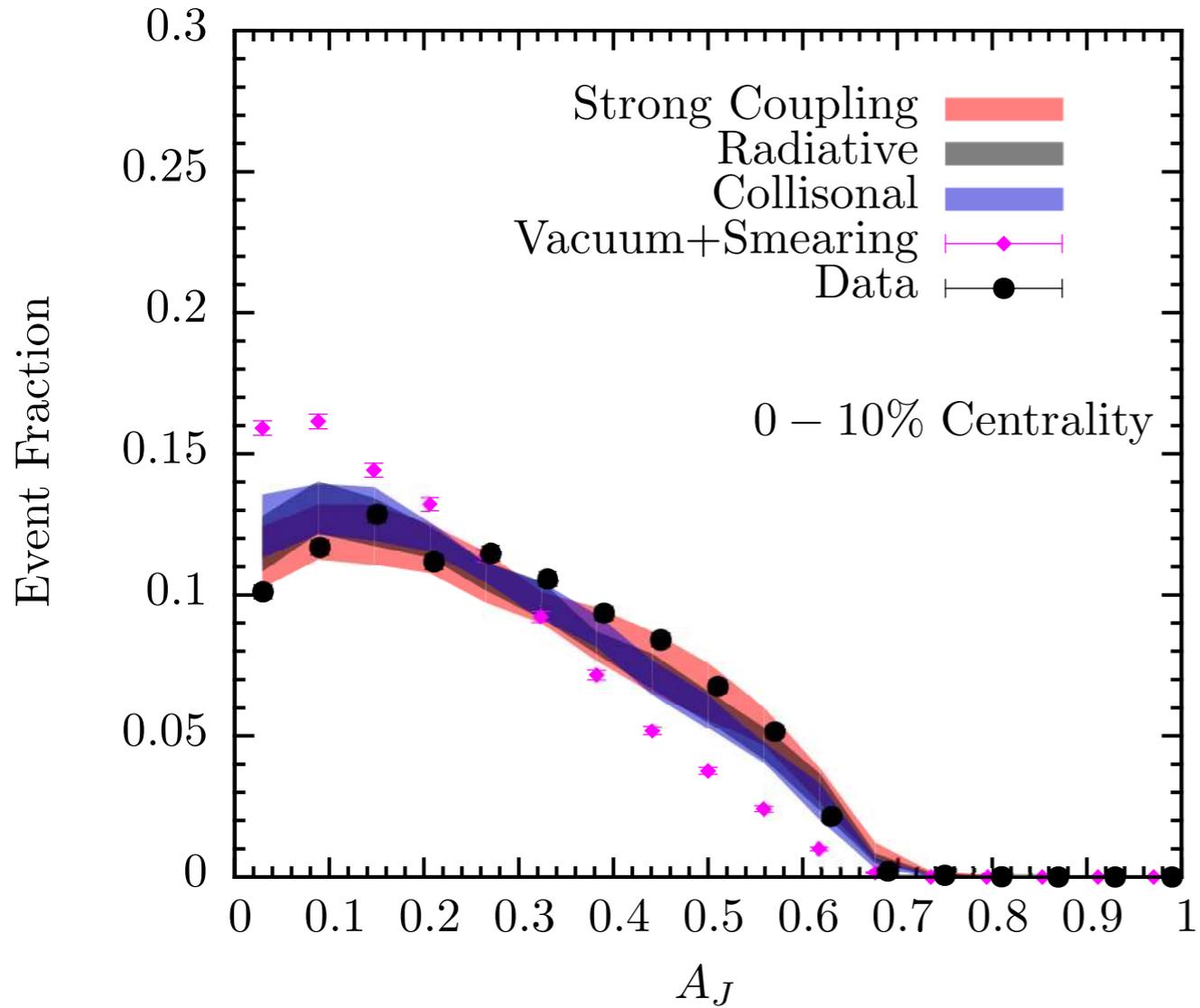
# $R_{AA}$



Similar trend in all models

$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

# Dijet Asymmetry



Similar trend in all models

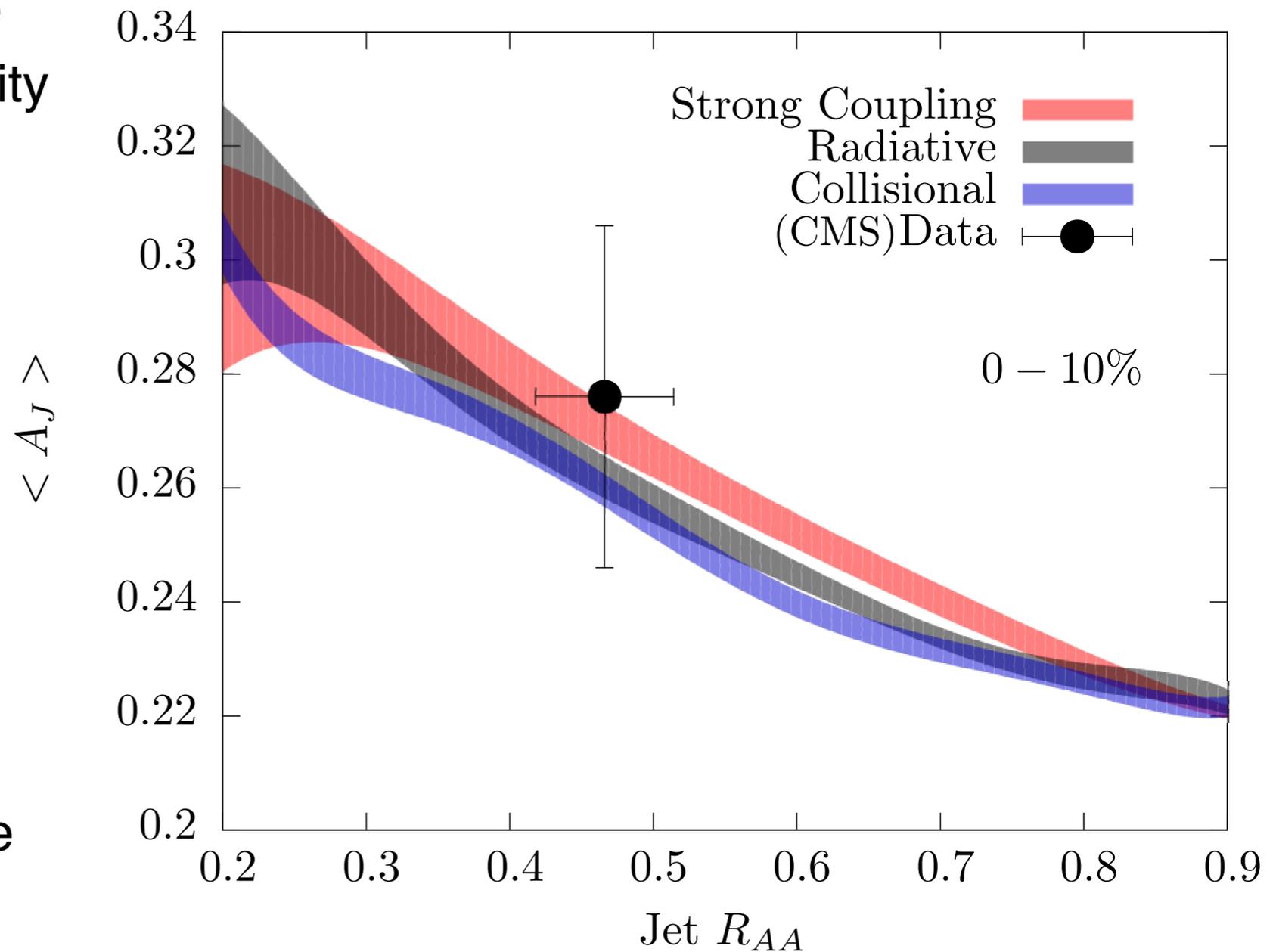
# Parameter Space Scan of Inclusive Observables

All three models can reproduce  $R_{AA}$  and  $A_J$  data; little sensitivity of inclusive observables

Strongly Coupled agrees slightly better with the data

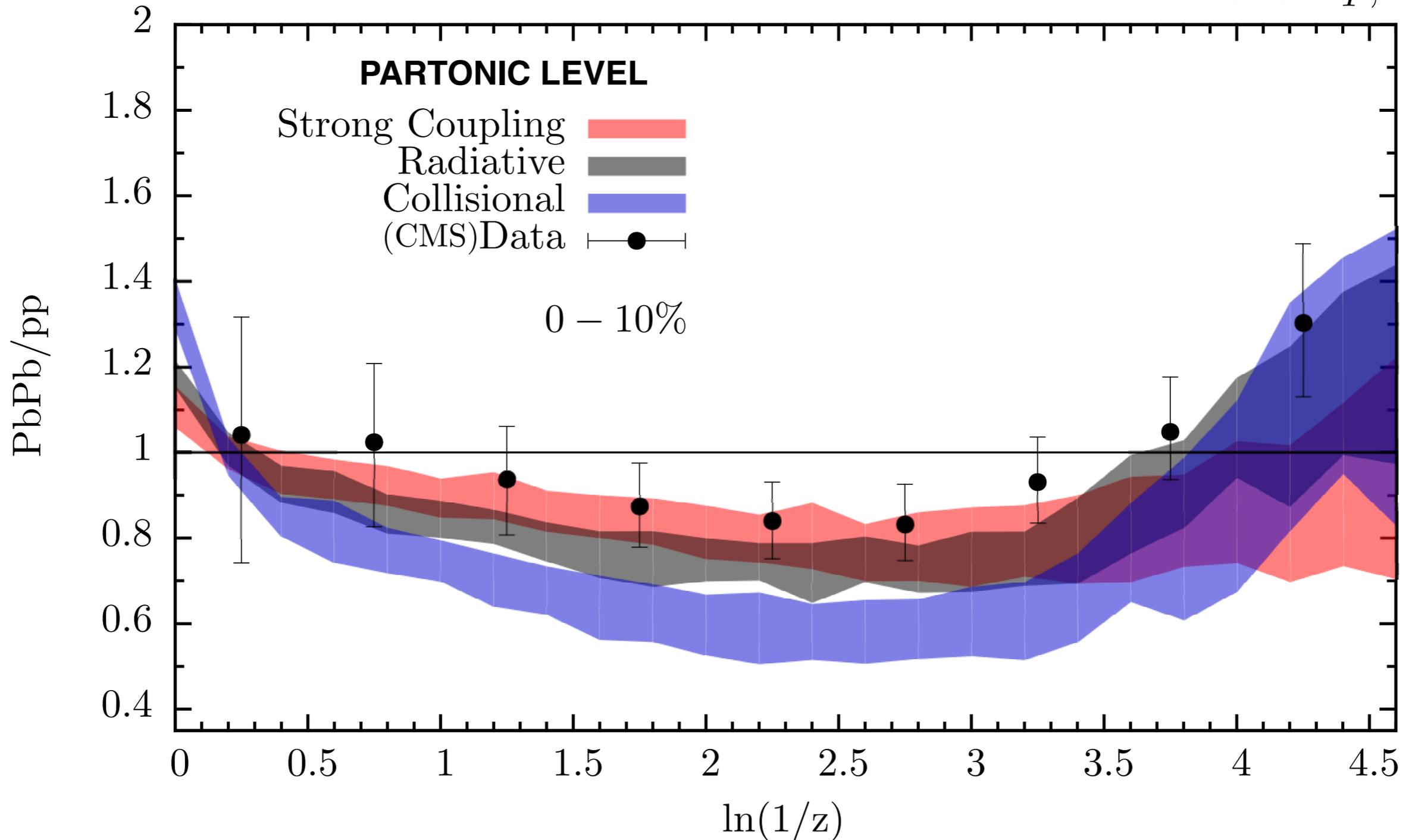
Less inclusive observables required in order to discriminate

*We need better systematics to distinguish*



# Fragmentation Functions Ratio

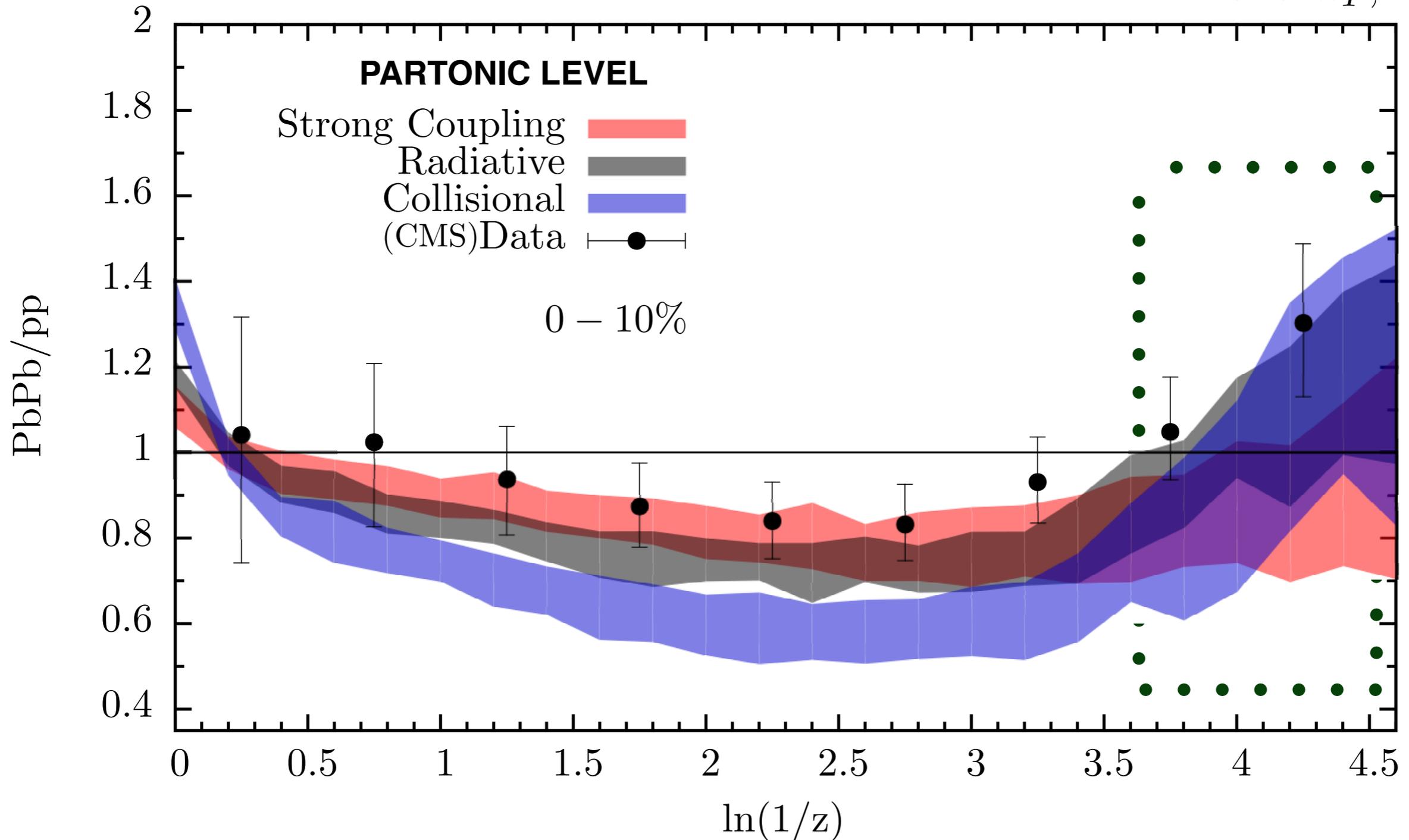
anti- $k_T$ ,  $R = 0.3$



Data requires mild modification of fragmentation functions with respect to vacuum

# Fragmentation Functions Ratio

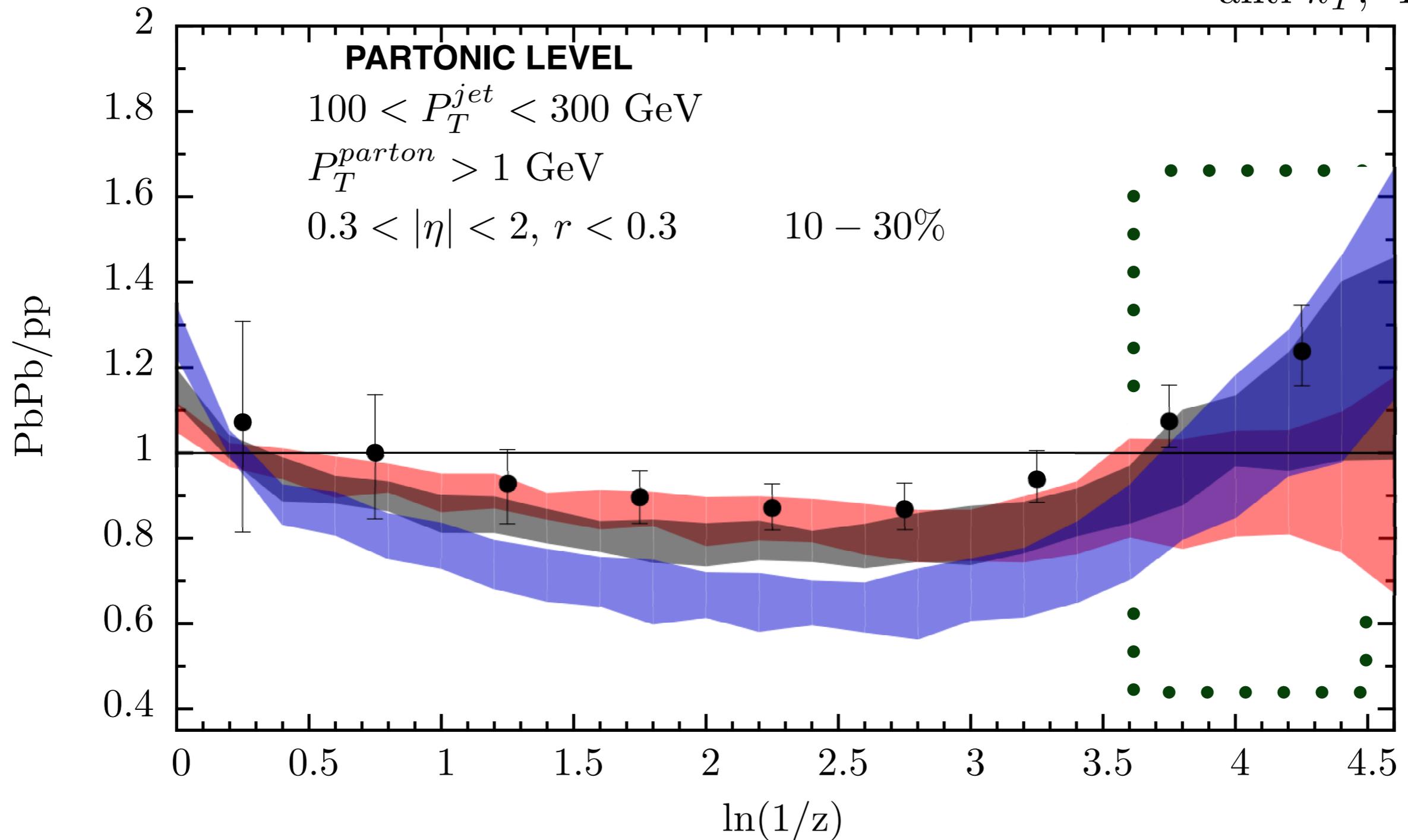
anti- $k_T$ ,  $R = 0.3$



Very soft region highly sensitive to background subtraction

# Fragmentation Functions Ratio

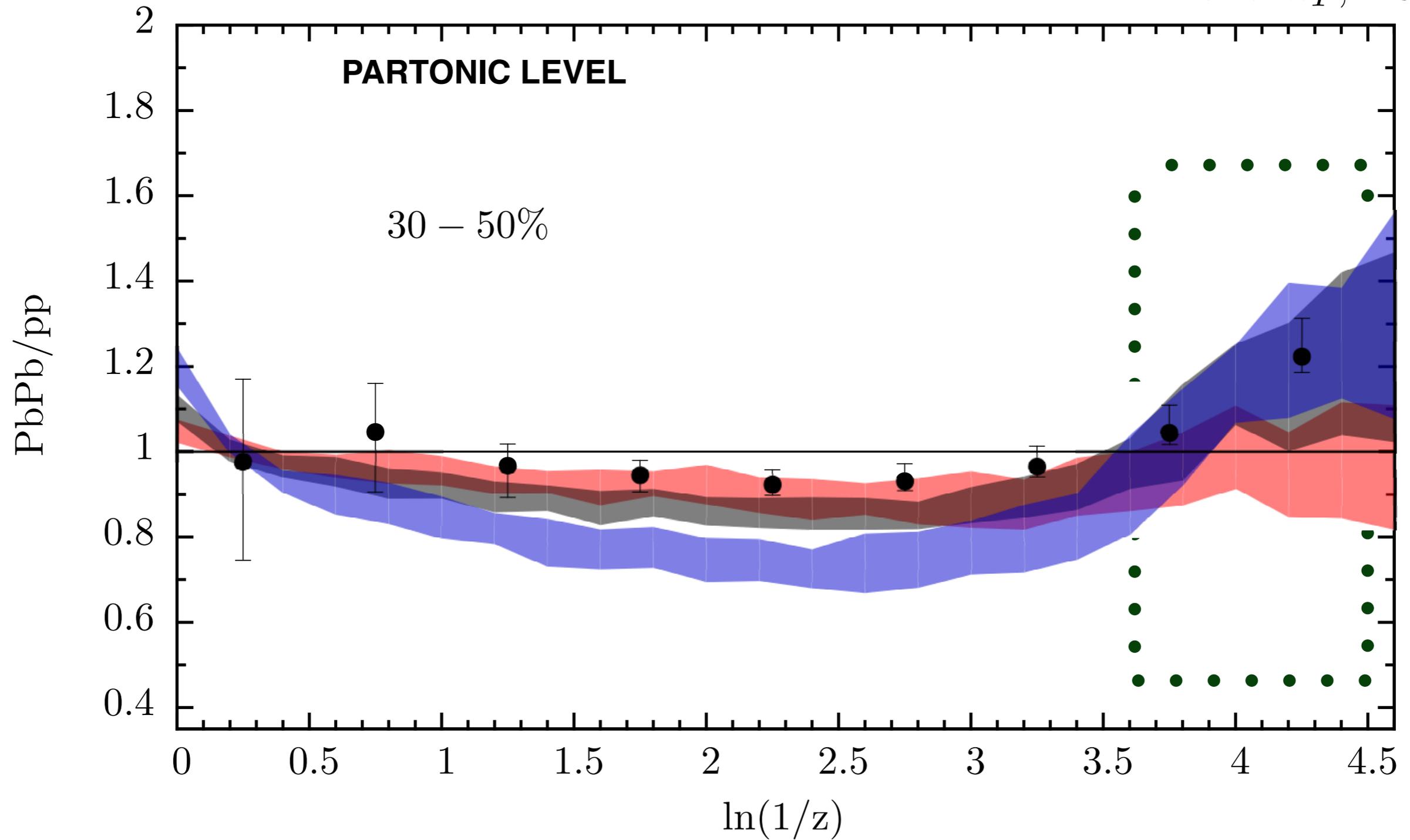
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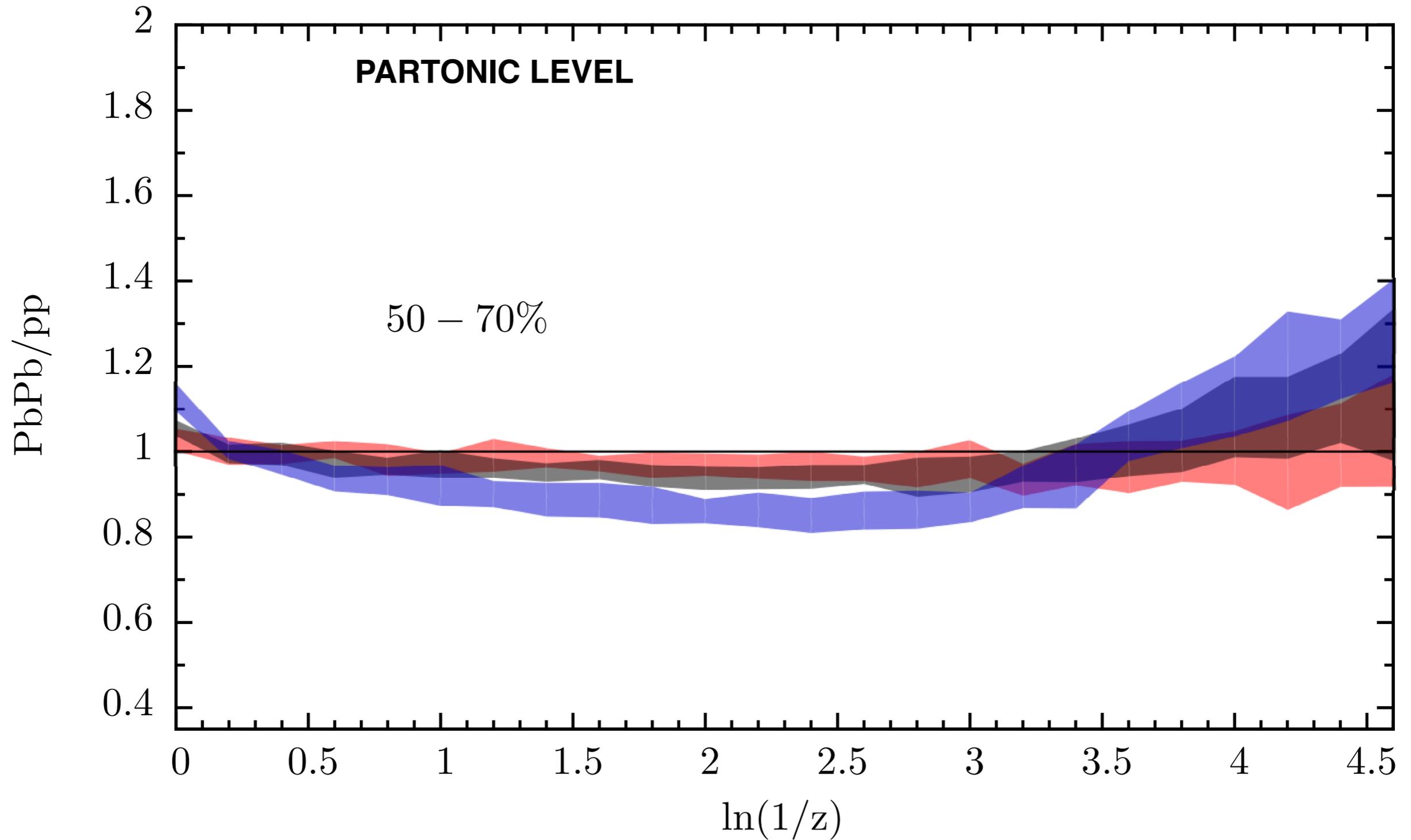
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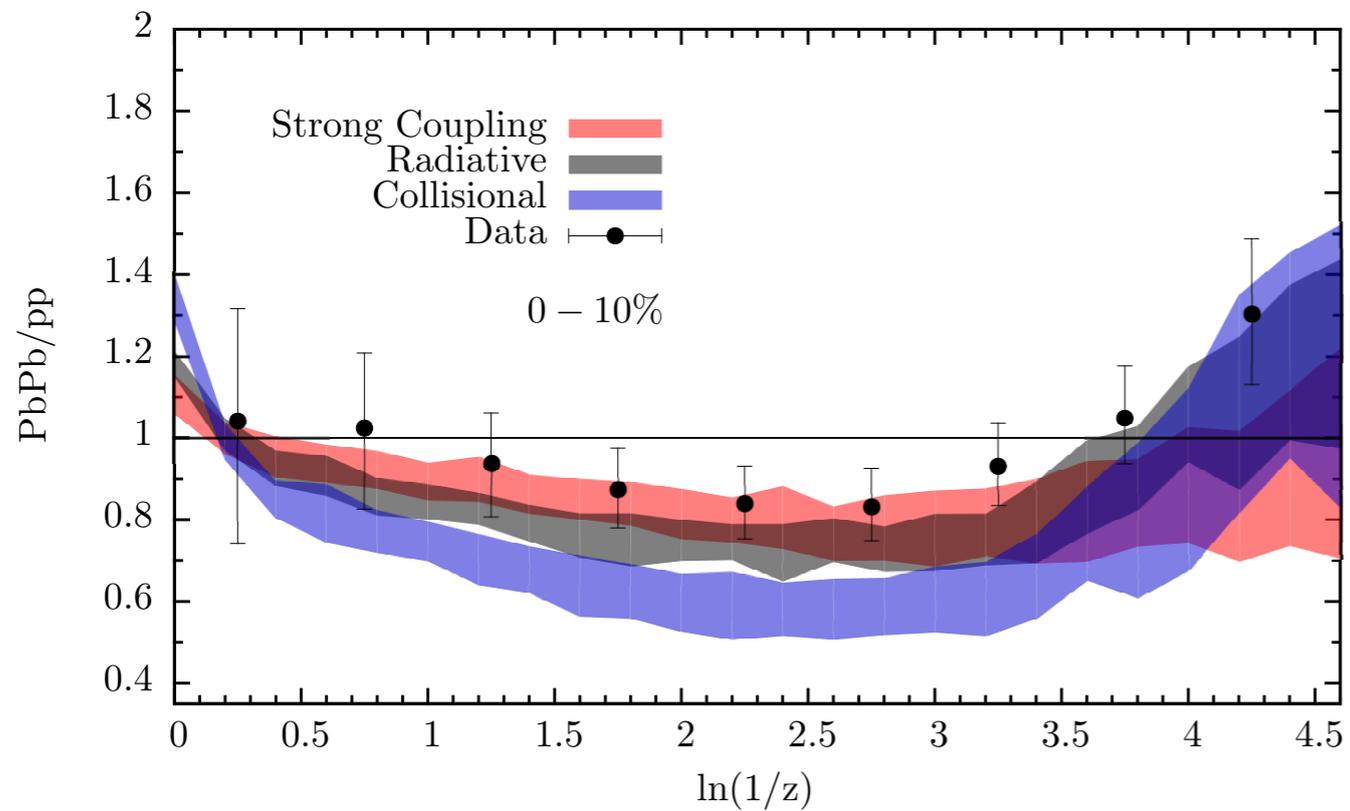
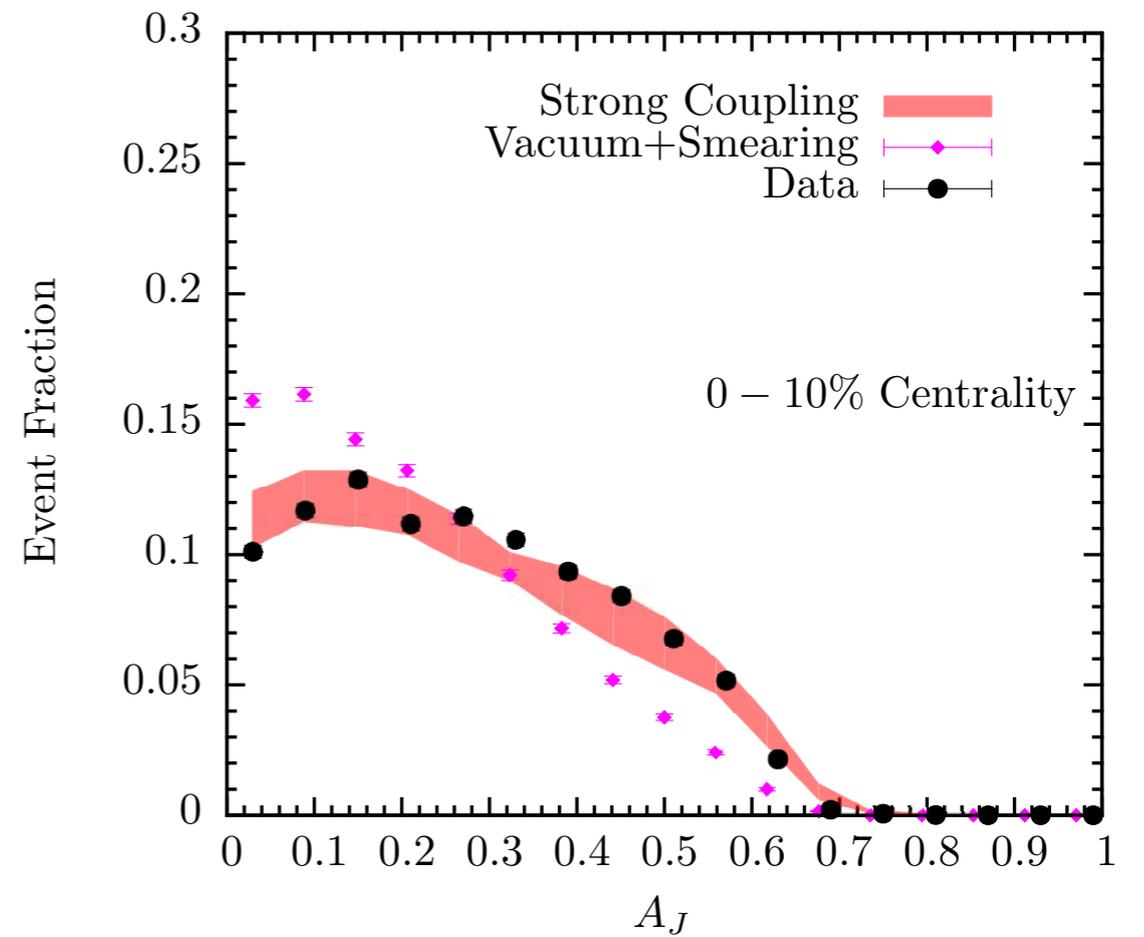
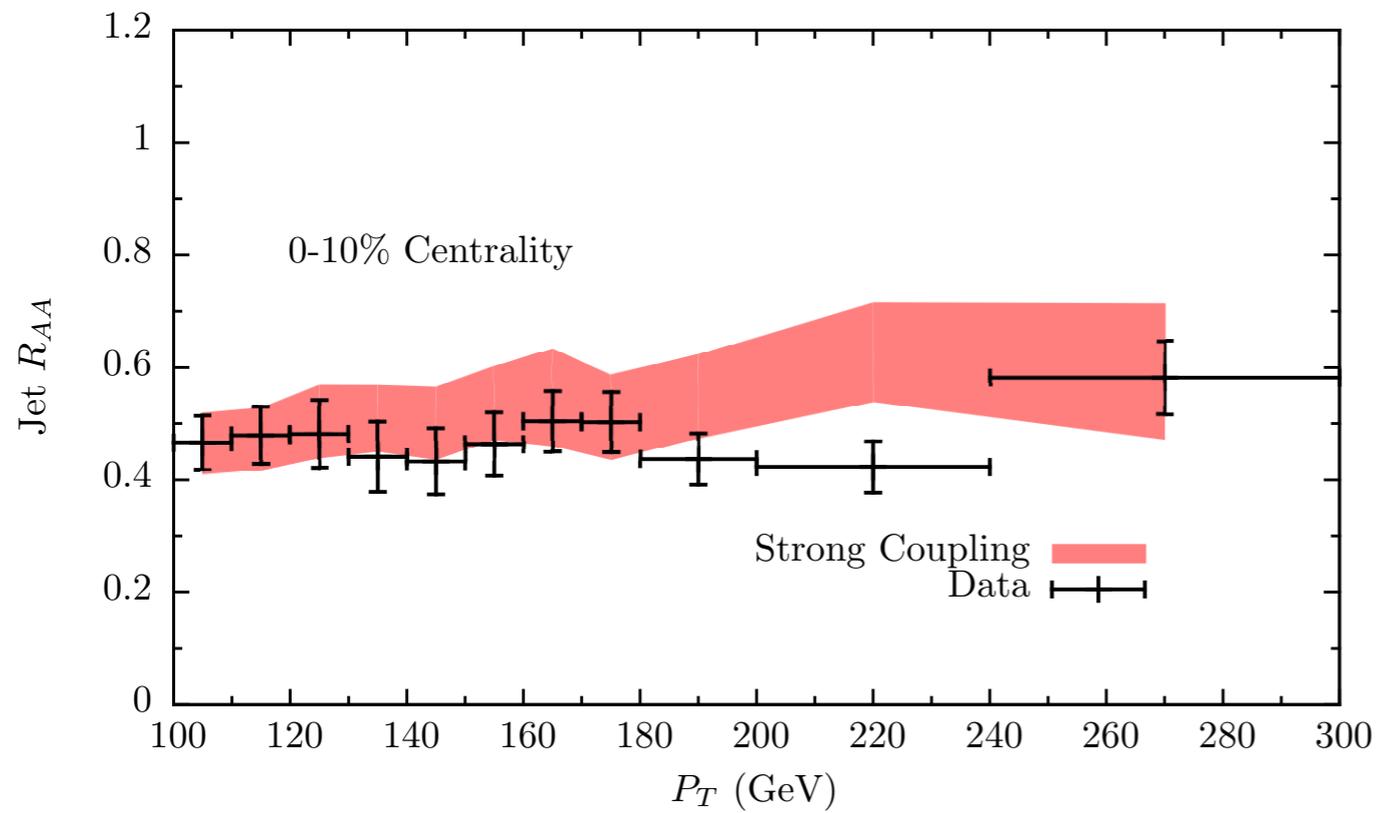
anti- $k_T$ ,  $R = 0.3$



# Fragmentation Functions Ratio

anti- $k_T$ ,  $R = 0.3$





Simultaneous description of several data sets, including centrality dependence, after fitting only one parameter

# Significance of extracted parameters

Success of models depends on the freedom to choose the fitting parameter

	Strong Coupling	Radiative	Collisional
Parameter	$0.29 < \kappa_{sc} < 0.41$	$1.1 < \kappa_{rad} < 2.3$	$3.1 < \kappa_{coll} < 5.9$

## *For Perturbative Benchmarks*

Either the strong coupling constant is large (non-perturbative regime)

or

the kinematical logarithms are large (resummation needed)

*Casalderrey-Solana and Wang, 0705.1352*

*(see Yacine's talk)*

*Blaizot and Mehtar-Tani, 1403.2323*

## *For Strong Coupling*

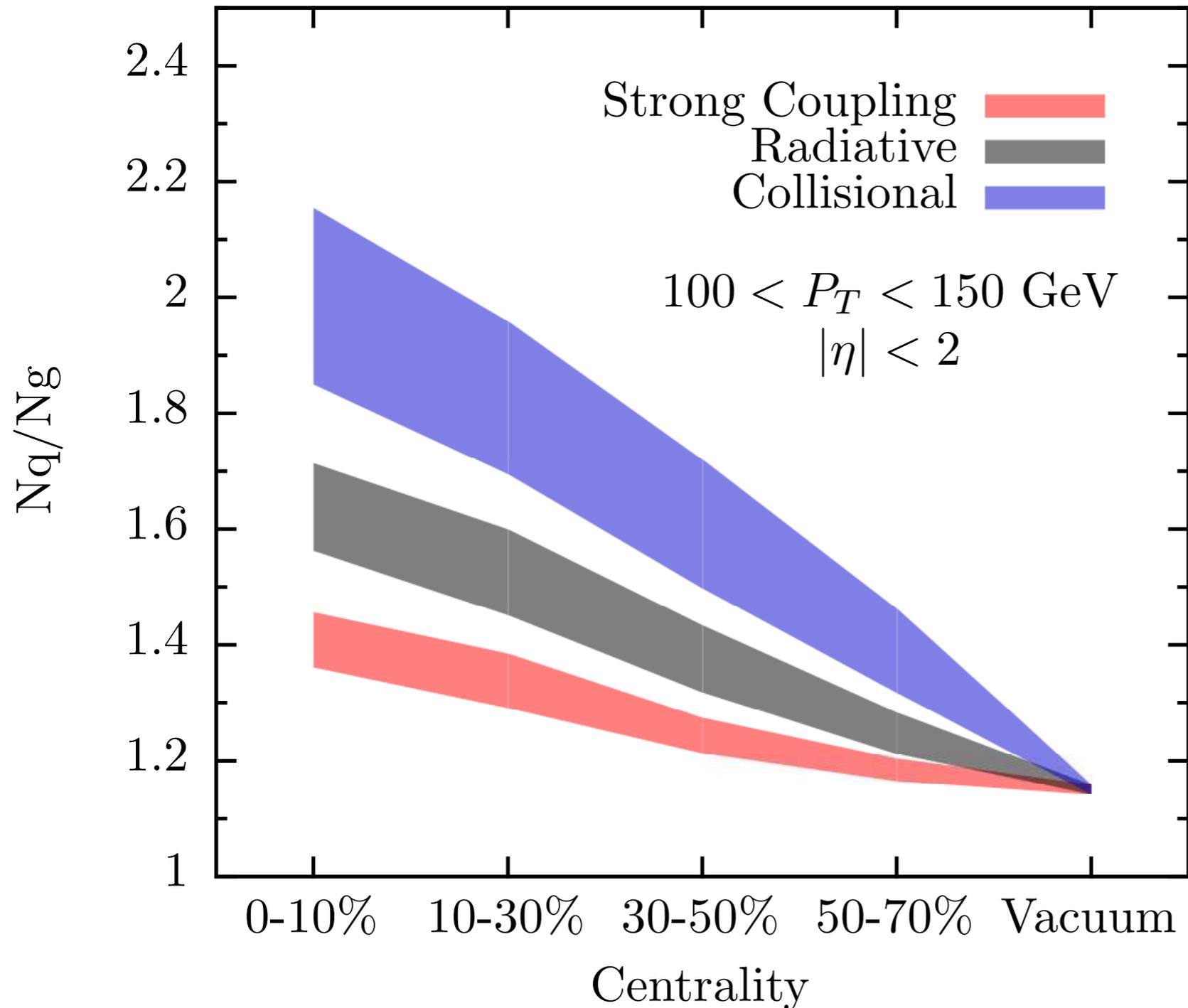
$$1.2 \lesssim \kappa_{SC}^{\mathcal{N}=4} \lesssim 1.6 \quad (\text{not robust})$$

*(see P. Arnold's talk)*

$x_{stop}$  in QCD plasma is three or four times longer than in  $\mathcal{N} = 4$  plasma,  
as expected due to fewer degrees of freedom at same T

# Colour charge dependence

# Quark Initiated Jets / # Gluon Initiated Jets



Non-trivial  $C_R$  dependence  
yields change of species

Additional discriminant  
between models

To be studied:

b to inclusive yield as a  
potential observable

# Conclusions

- Strongly Coupled Hybrid Model describes qualitatively and rather quantitatively all tested features of jet quenching
- No clear distinction w.r.t. perturbative benchmarks observed through most inclusive observables
- Less inclusive ones, as fragmentation functions, allow a more critical discussion
- Further discrimination between underlying microscopic energy loss mechanisms is expected with:
  - ✱ reduction of jet measurements uncertainties
  - ✱ species dependent observables such as  $N_q/N_g$
- We provided a calculational framework with which to test and explore the consequences of strongly coupled plasma. Many improvements can still be implemented

**Thank you** for your  
attention!

Wicks et al, nucl-th/0512076

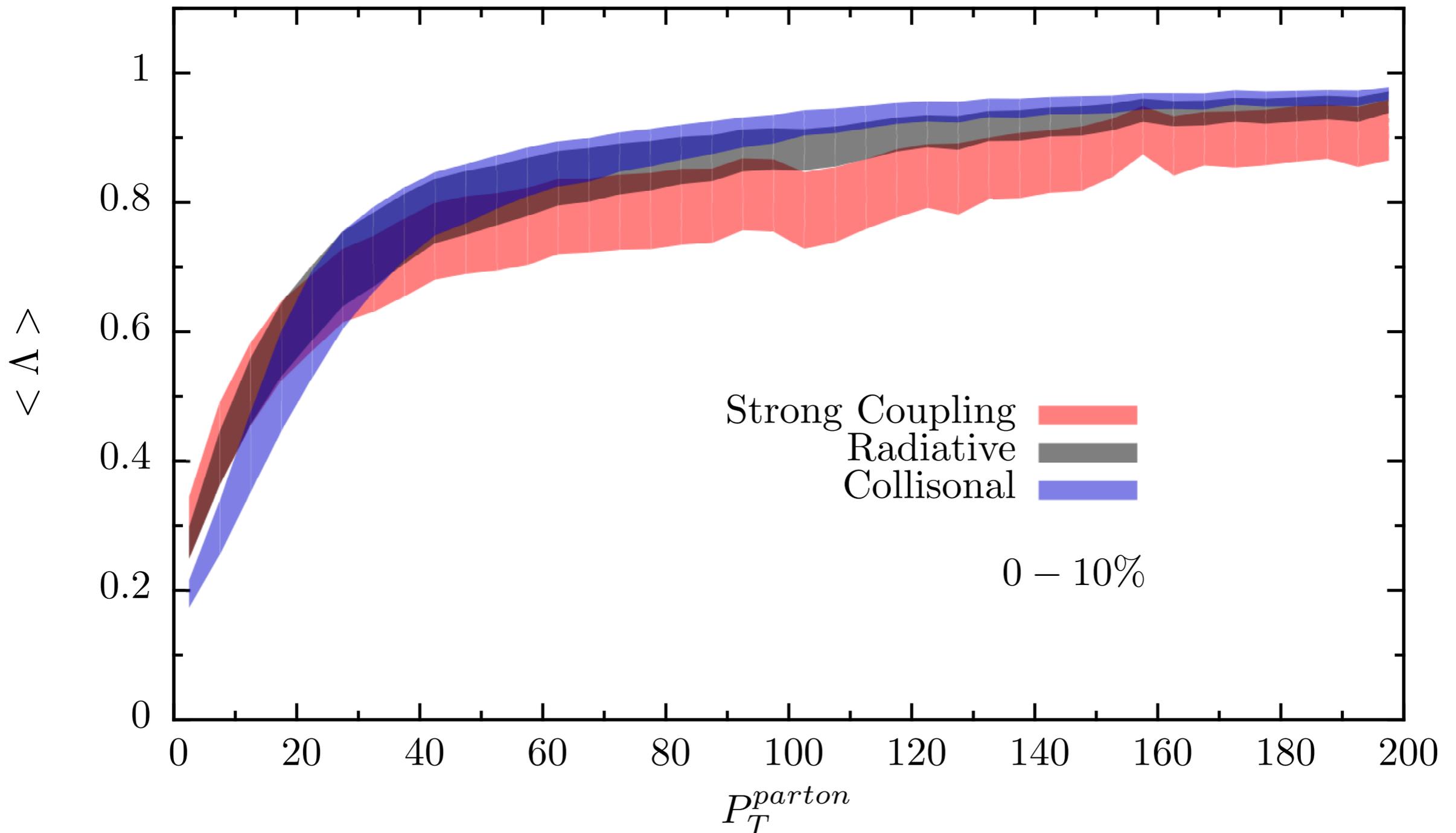
Burke et al, 1312.5003

Collisional		Radiative	
$\alpha_C$	$C_F \pi \alpha_s^2 \left(1 + \frac{n_f}{6}\right) \log B_C$	$\alpha_R$	$2\pi \alpha^4 C_F C_A \left(1 + \frac{n_f}{6}\right) \log B_C$
$\alpha_s \log^{1/2} B_C$	0.6 - 0.9	$\alpha_s \log^{1/4} B_R$	0.4 - 0.5

Either the strong coupling constant is large (non-perturbative regime)  
or  
the kinematical logarithms are large (resummation needed)

# Partons quenching distribution

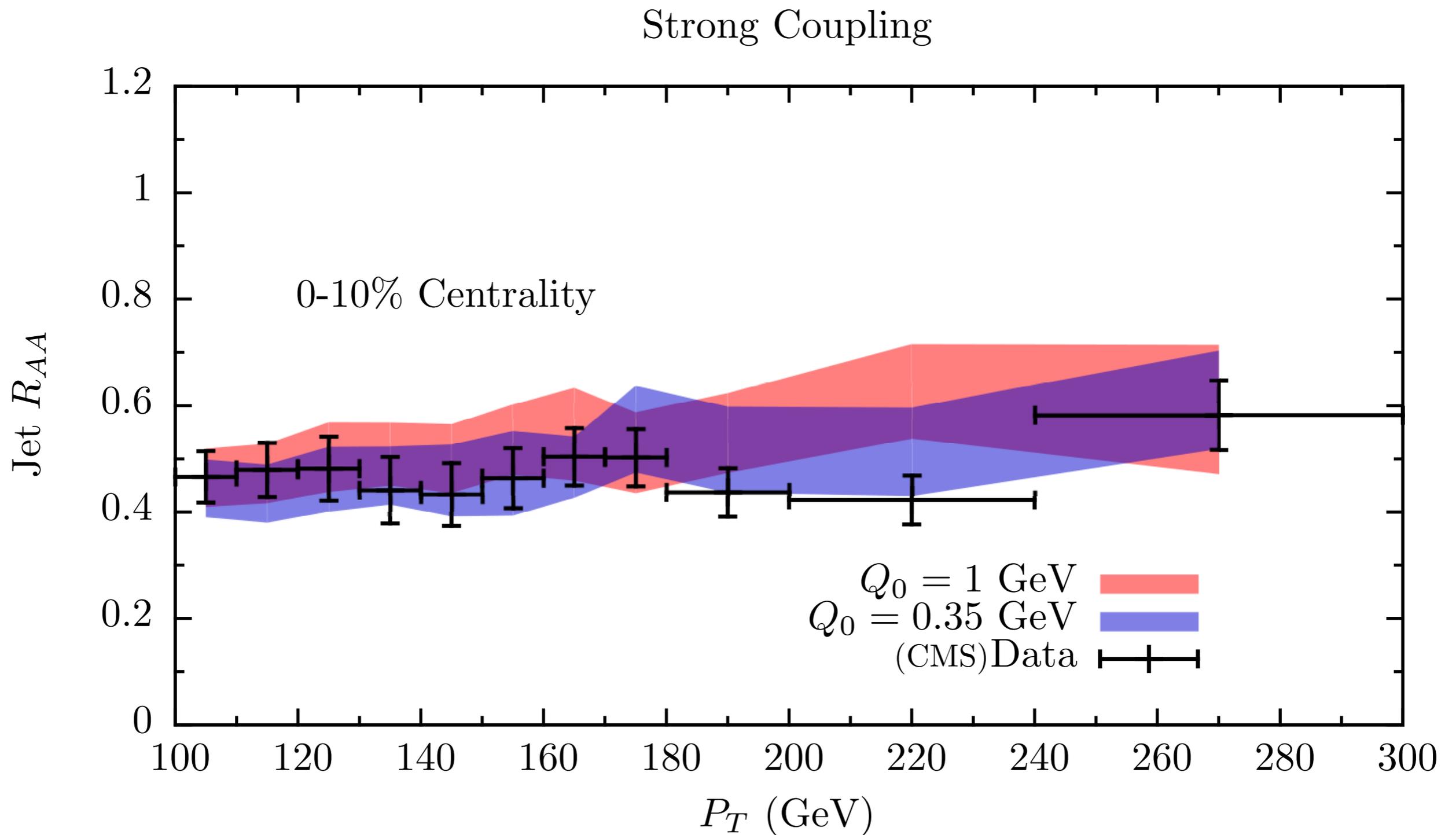
$$\Lambda \equiv \frac{p_{T,Q}^{parton}}{p_T^{parton}}$$



# Plasma embedding

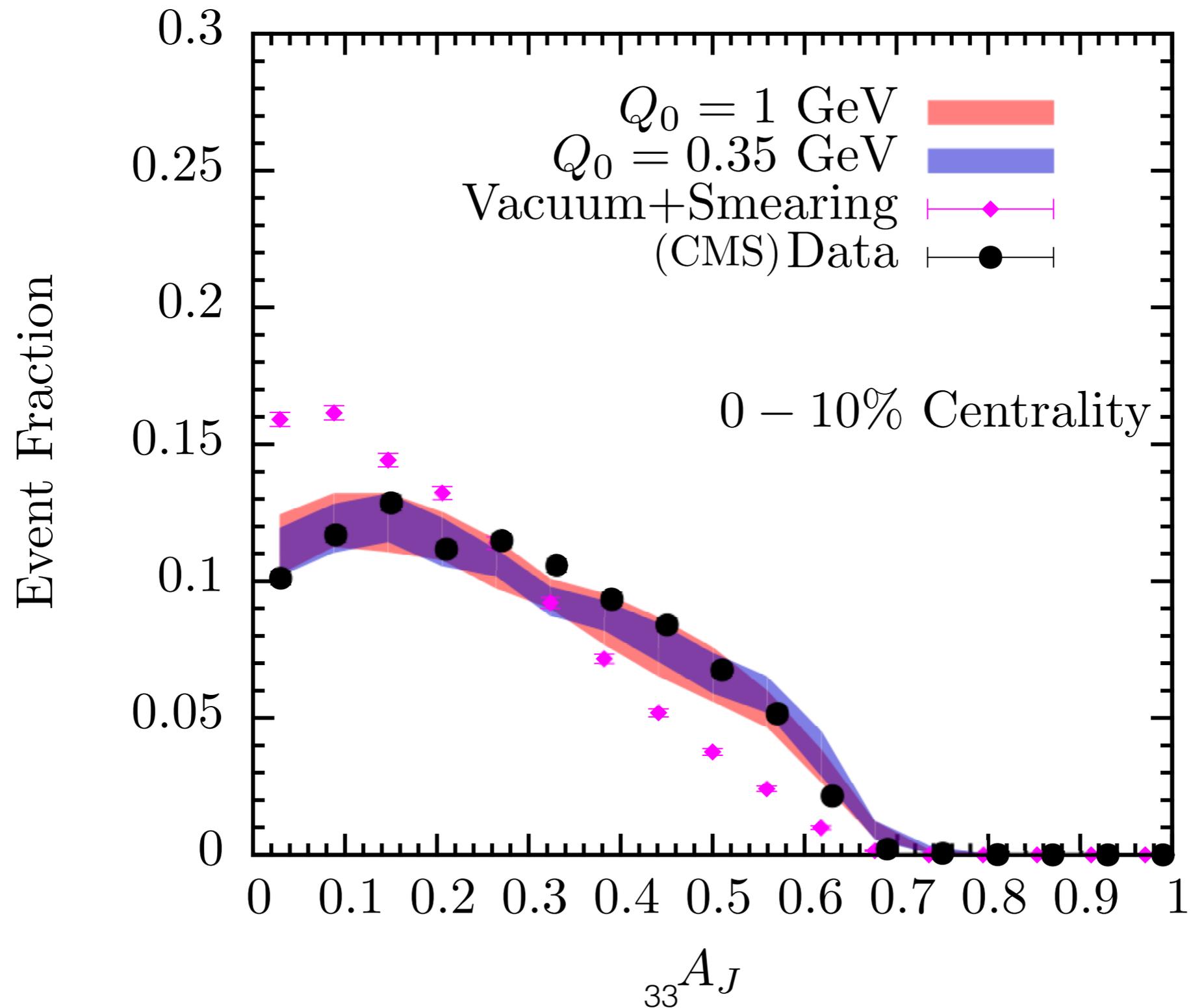
- Assign a random position in transverse plane for the hard scattering with a probability proportional to the number of binary collisions at that location
- Embed the parton shower into a hydrodynamic plasma evolution  
 $\rightarrow T(x, y, \tau, \eta)$  *Hirano et al, 1012.3955*
- Lattice equation of state contains a cross-over, critical temperature not sharply defined. The range  $180 < T_c < 200$  MeV gauges our theoretical uncertainty *Bazazov et al, 0903.4379*

# PYTHIA Splitting $Q_0$ Dependence



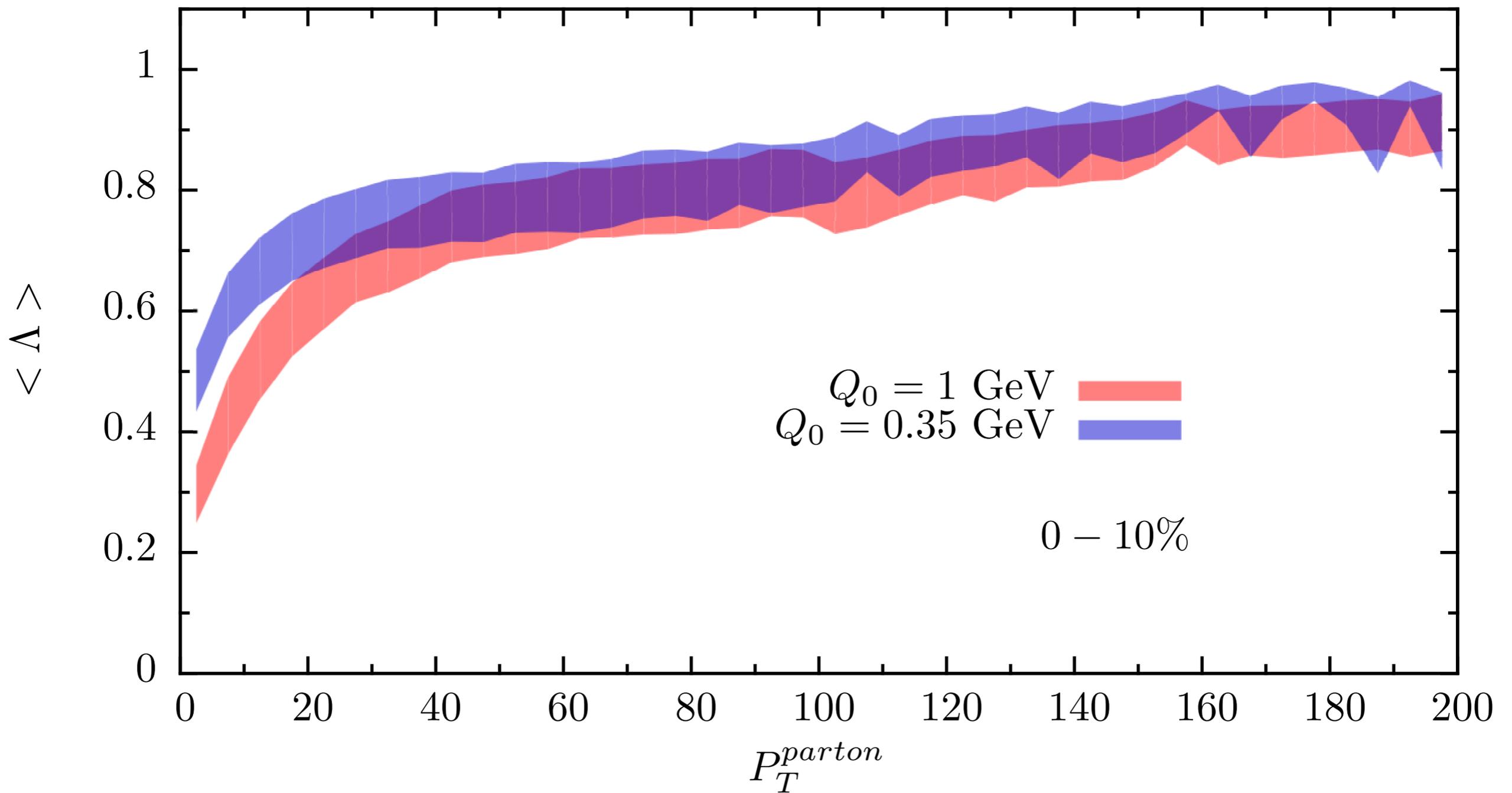
# PYTHIA Splitting $Q_0$ Dependence

Strong Coupling



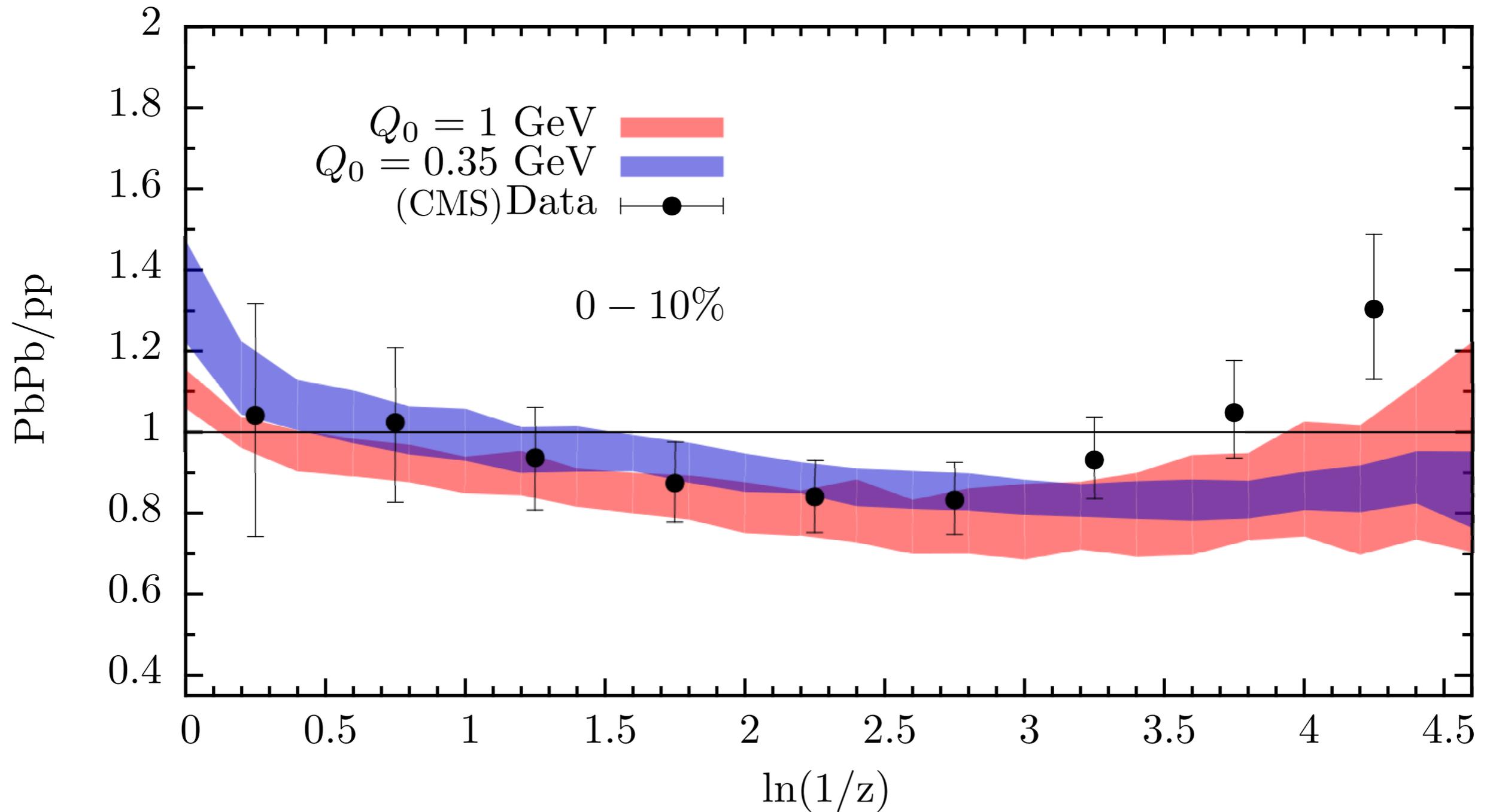
# PYTHIA Splitting $Q_0$ Dependence

Strong Coupling



# PYTHIA Splitting $Q_0$ Dependence

Strong Coupling



# Opportunities on our current implementation

- Reduction of phase space
- Transverse momentum broadening
- Finite resolution effects for in-medium transfers
- Consider different mechanisms simultaneously
- Keep track of subtracted energy