Jet quenching at strong coupling

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LBNL

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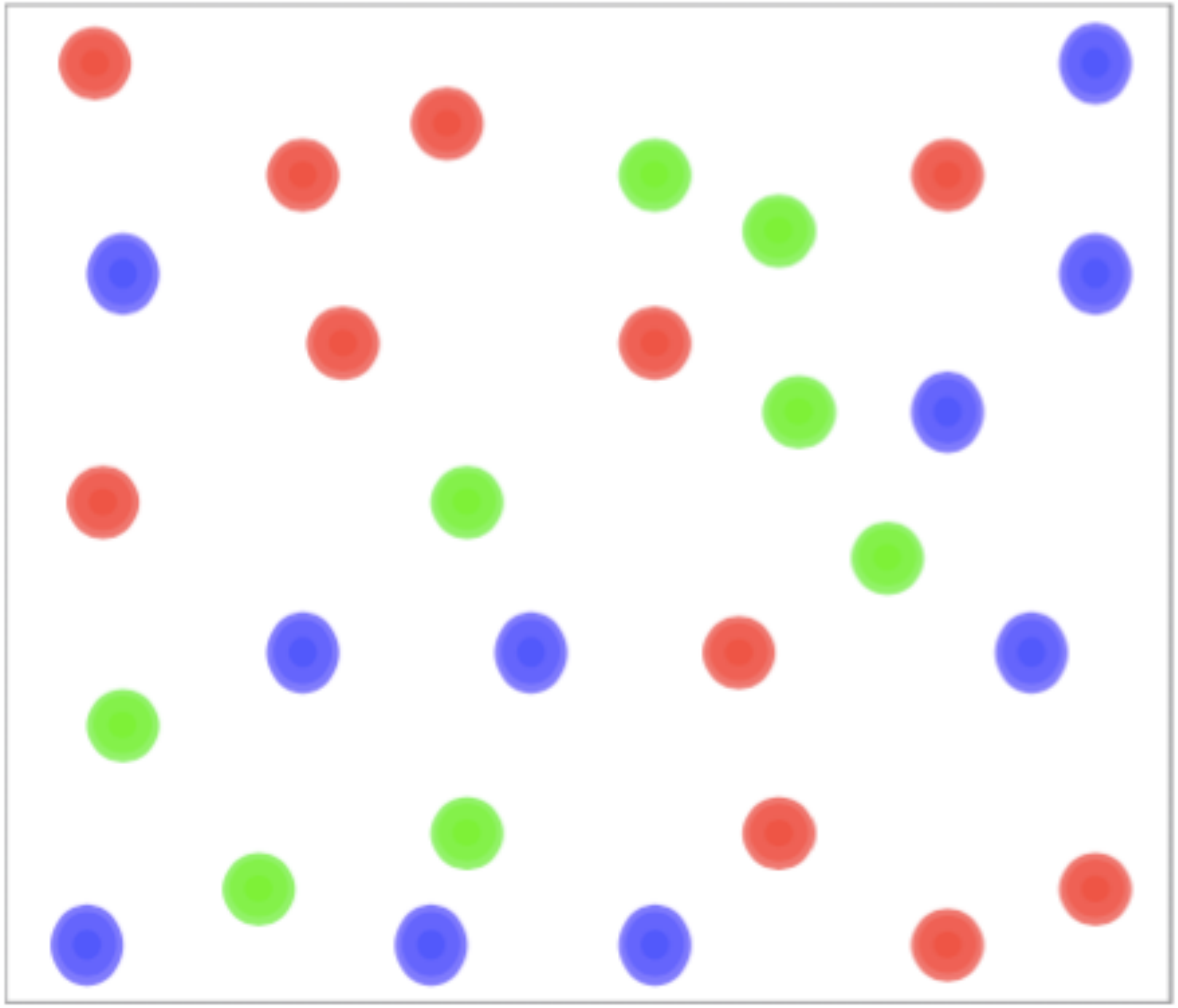
A Gas of Quarks and Gluons

$T > 10^4$ GeV



$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2T}$$

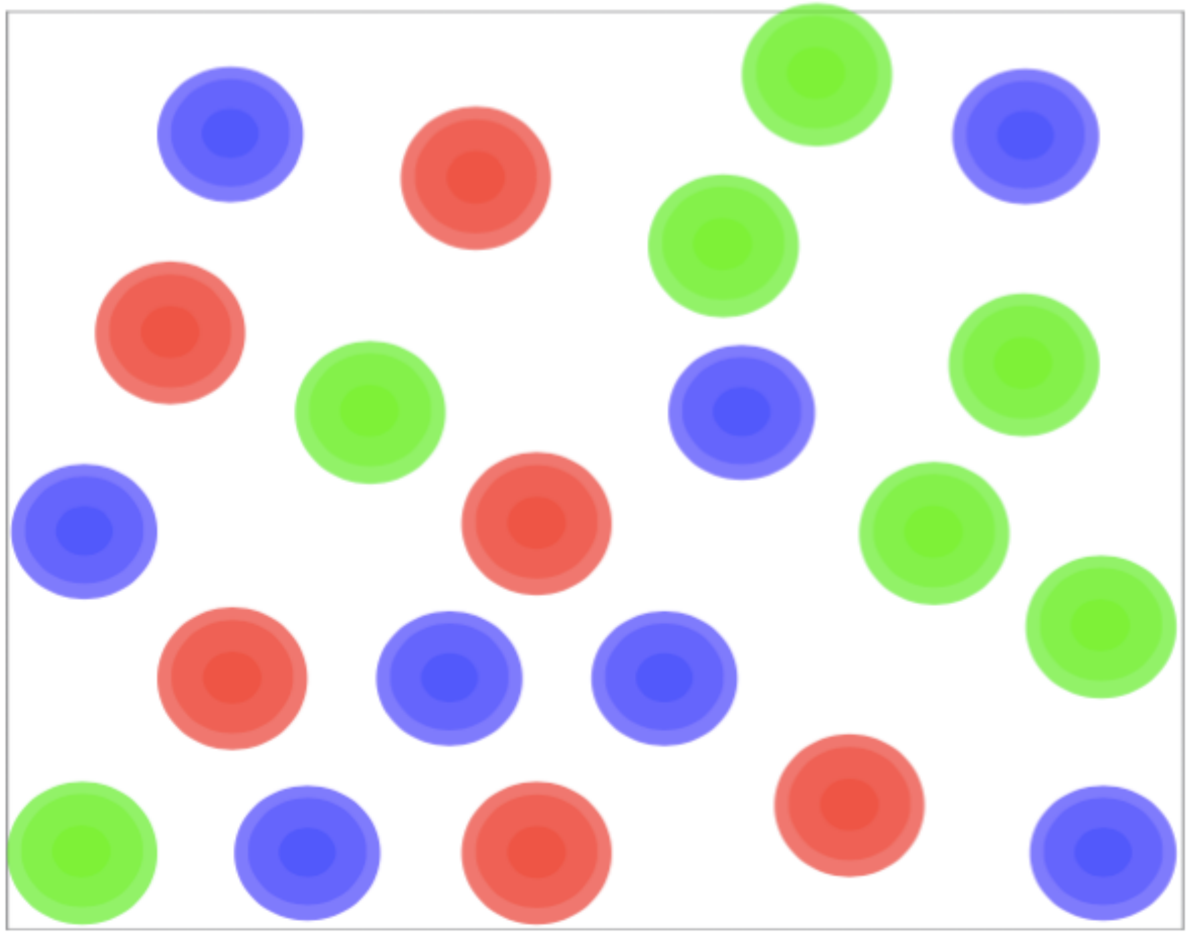
Inter-particle spacing

Interaction range

Mean free path

Which is the correct picture of the plasma?

$T \sim 0.2\,\mathrm{GeV}$



Is it a gas of quarks and gluons?

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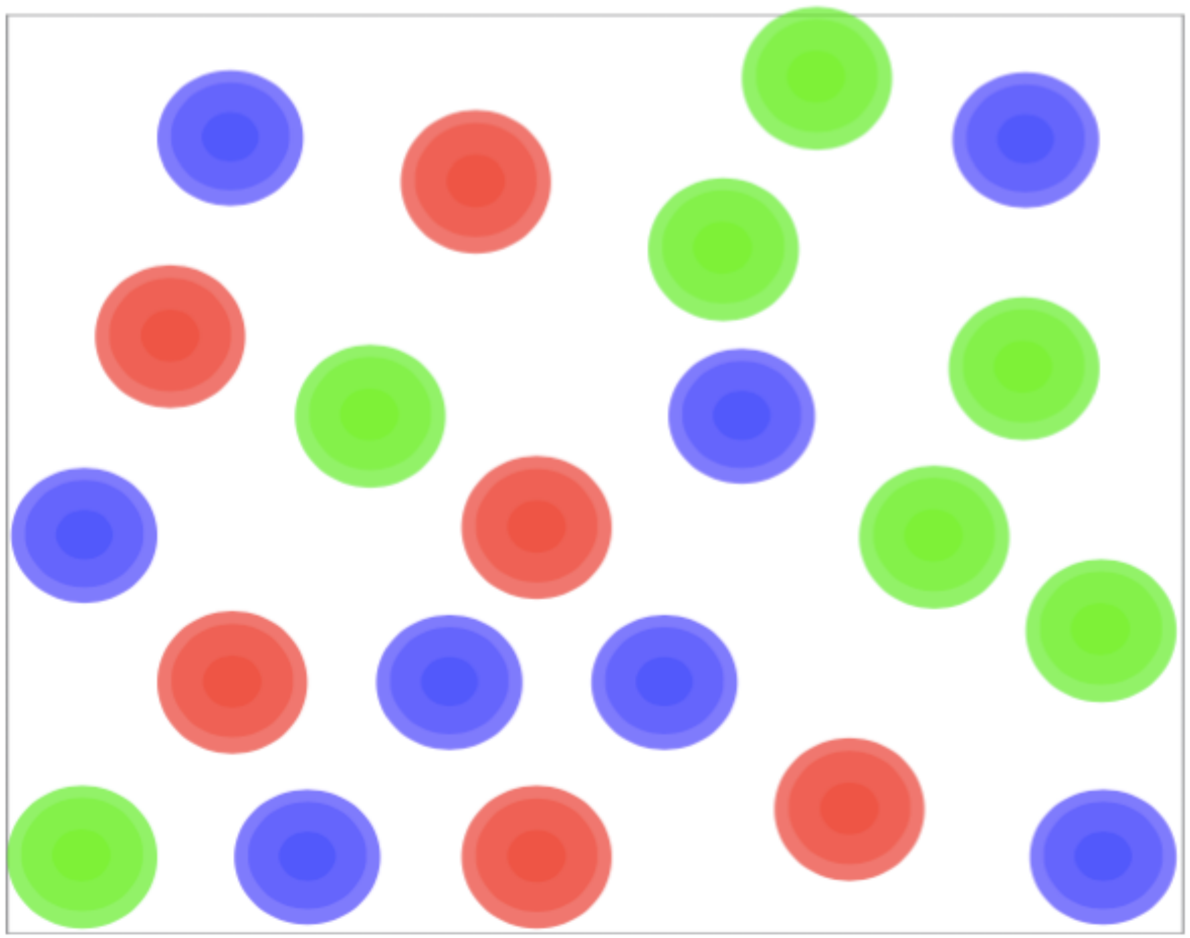
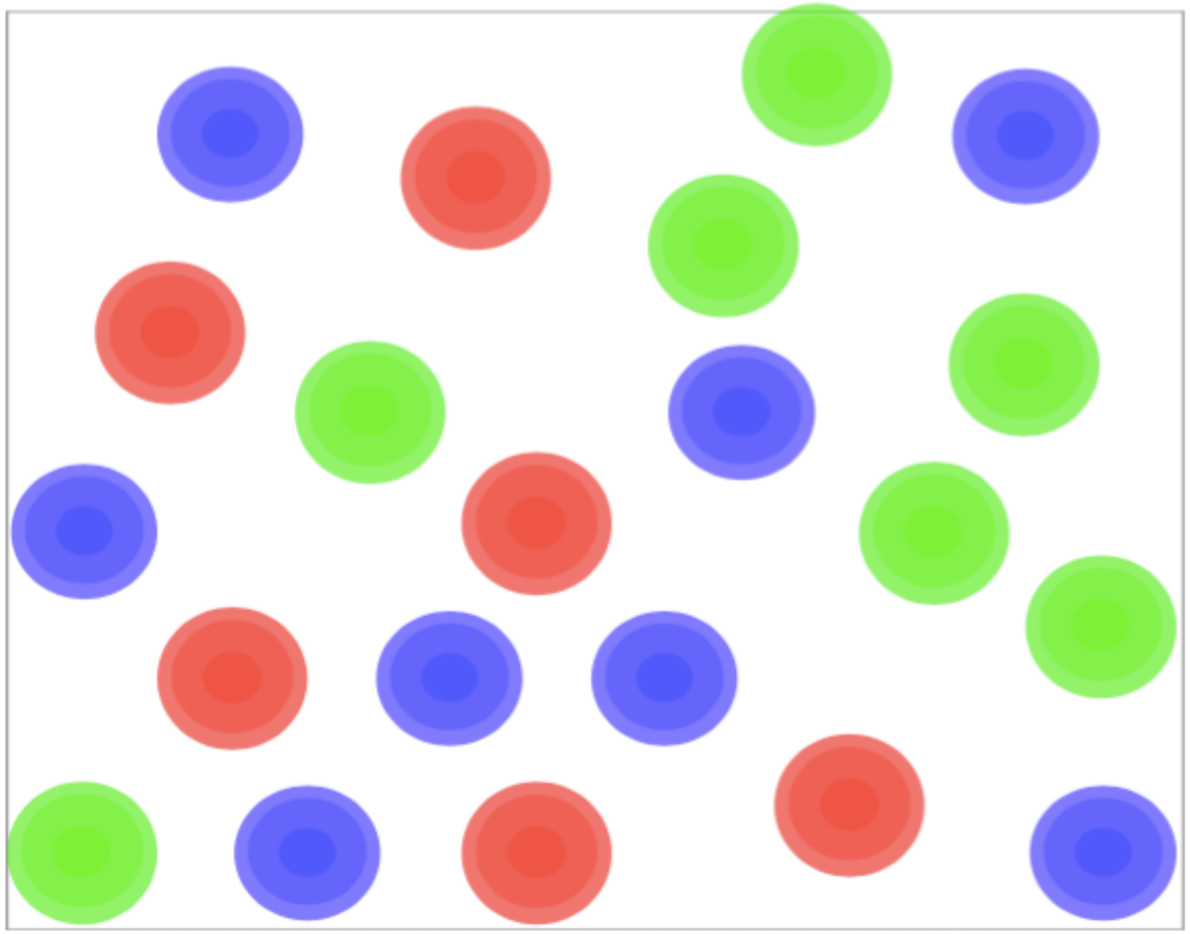


Is it a gas of quarks and gluons?

$$\alpha_s = 0.3 \rightarrow g = 2$$

Which is the correct picture of the plasma?

$T \sim 0.2\,\mathrm{GeV}$



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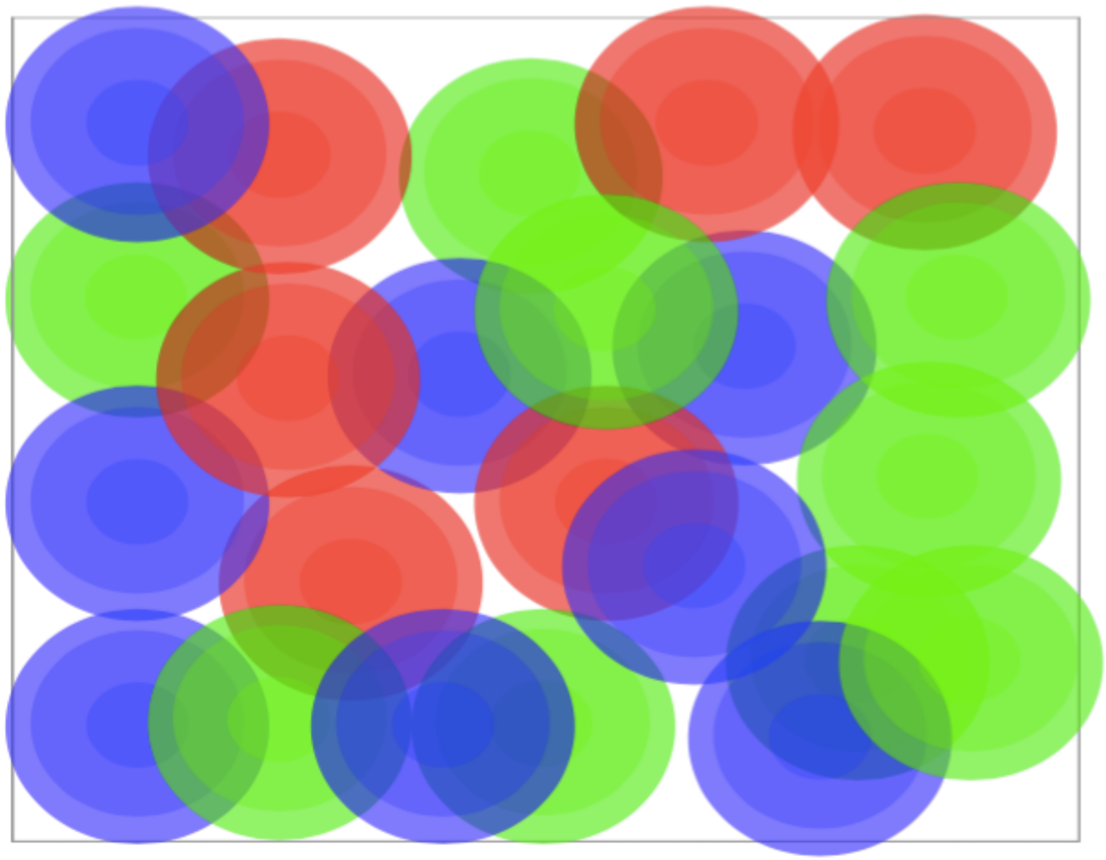


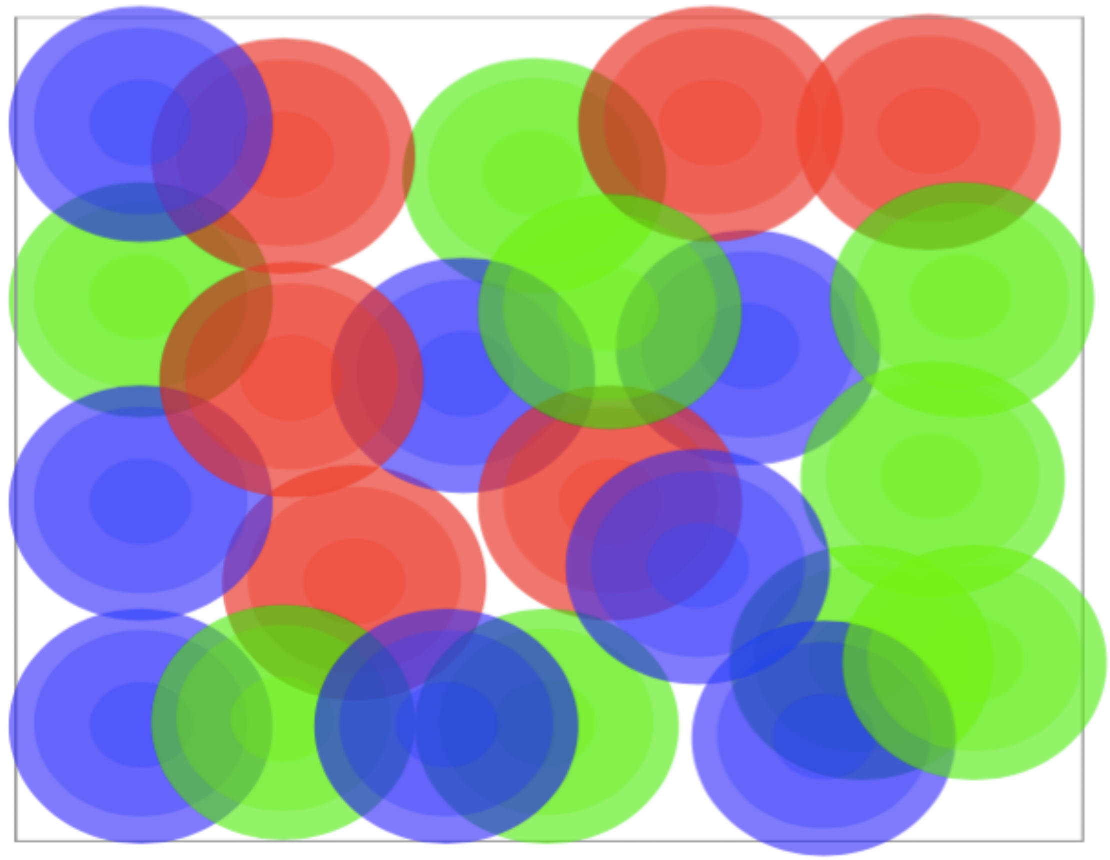
Is it a system with no long lived excitations?

$$\alpha_s = 0.3 \to g = 2$$

$$T \sim gT \sim g^2 T$$

Which is the correct picture of the plasma?

$T \sim 0.2\,\mathrm{GeV}$



Is it a system with no quasi-particles?

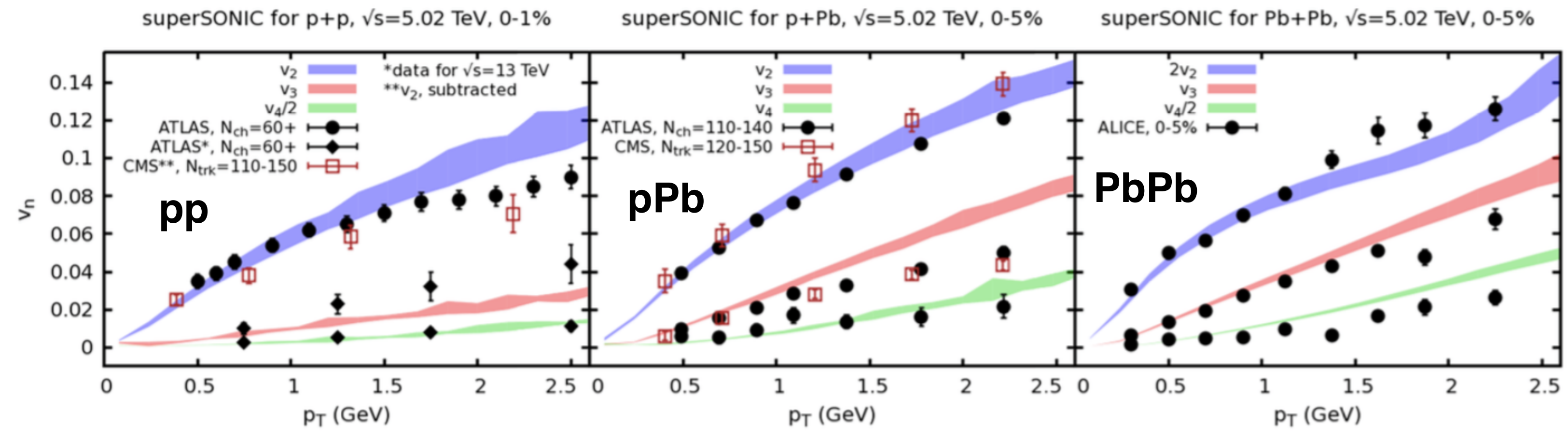
$$\alpha_s = 0.3 \to g = 2$$

$$T \sim gT \sim g^2 T$$

Absence of quasiparticles?

Most satisfactory description of QGP involves an **almost ideal liquid** phase

studies of QGP formation in small systems suggest common hydrodynamic origin for flow effects



Weller & Romatschke ‘17

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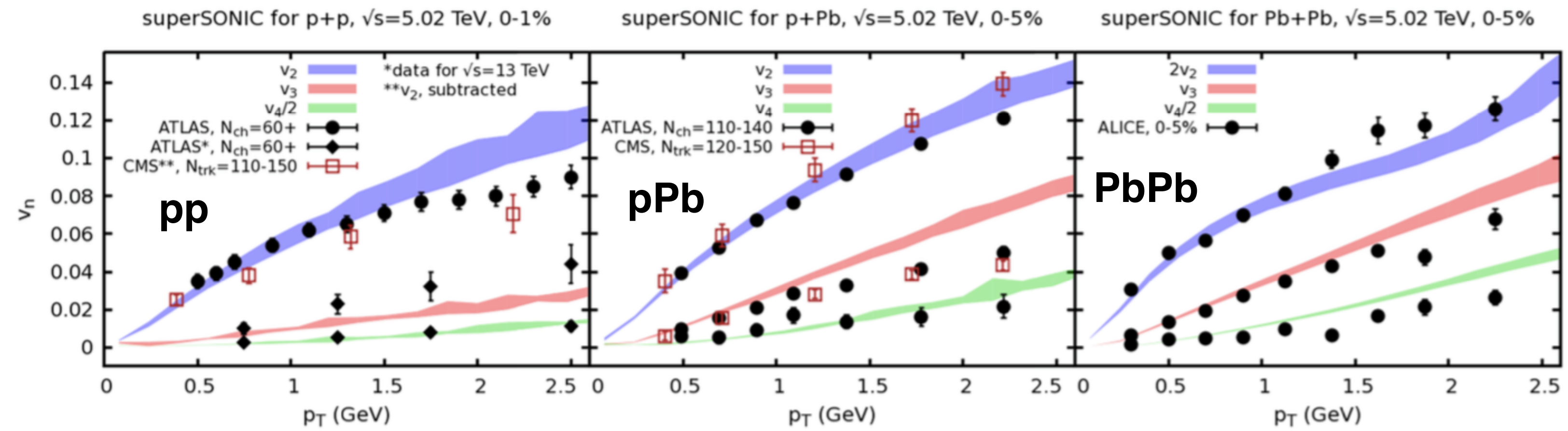

Weller & Romatschke '17

Small value of shear viscosity over entropy density ratio $\left(\frac{\eta}{s}\right)_{T_c} = 0.08 \pm 0.05$

Bernhard et al. '16

challenges quasiparticle description $\tau_{qp} \sim 5\frac{\eta}{s}\frac{1}{T} \sim \frac{1}{T}$

York & Moore '08

Predicted by Policastro, Son and Starinets (2001) for a large class of non-abelian gauge theories at strong coupling which have a gravity dual

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

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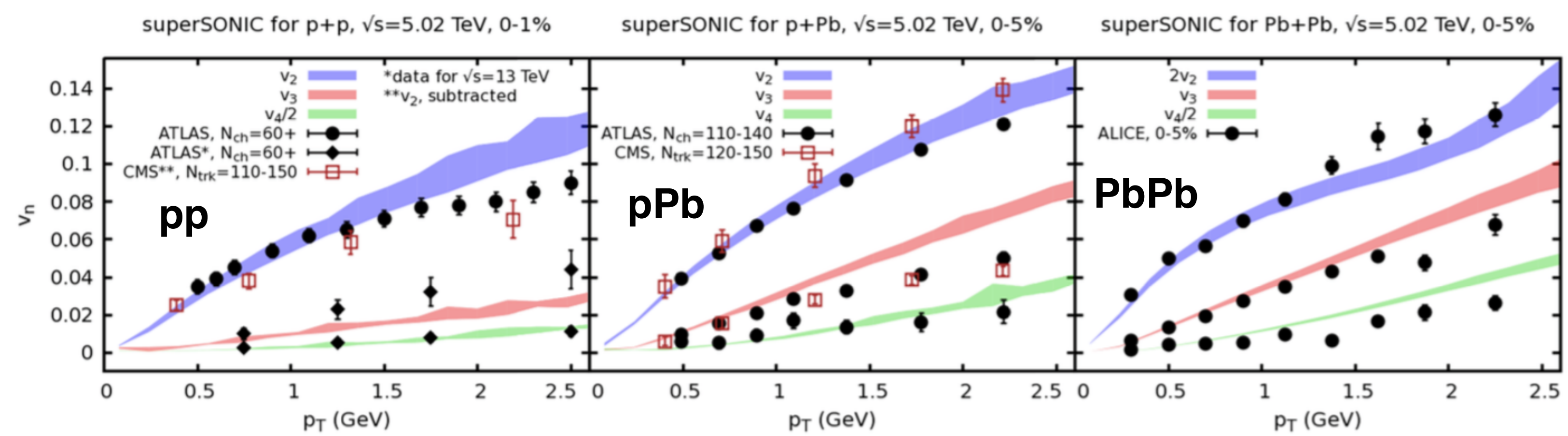


Weller & Romatschke '17

Hydrodynamics at work with large gradients at very early times

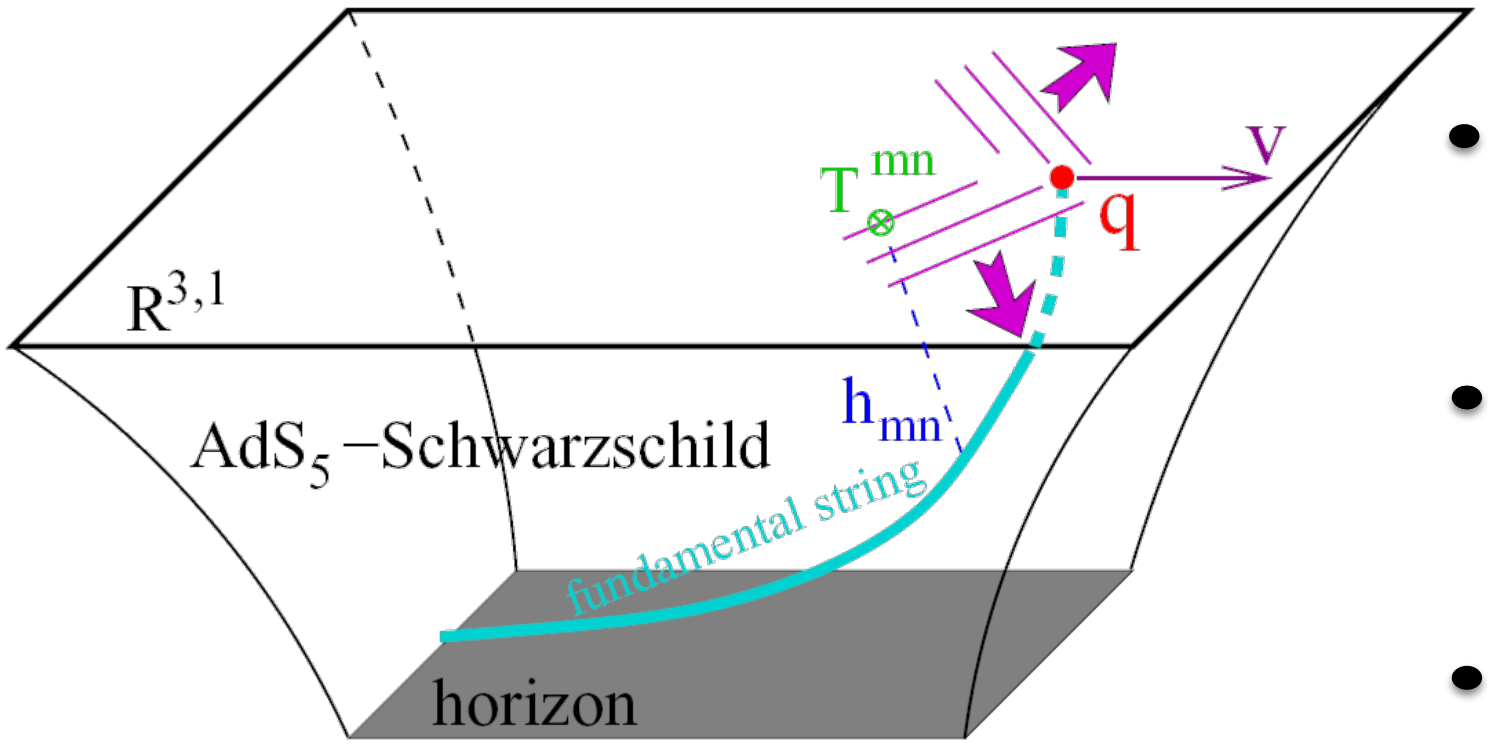
Completely natural situation at strong coupling

Even for system sizes of order $R \sim \frac{1}{T}$ hydrodynamic gradient expansion is well behaved

Chesler '15,'16

Appealing picture of hydrodynamization for all system sizes within strong coupling

Holography: a non-perturbative tool



J Friess, et al., PRD75 (2007)

- quarks are dual to open strings attached to probe flavour branes
- having a plasma in the gauge theory is equivalent to a black hole in the bulk
- bulk metric perturbations encode boundary stress energy variations

! $\mathcal{N} = 4 \quad \mathrm{SYM}$ and QCD have very different vacuums

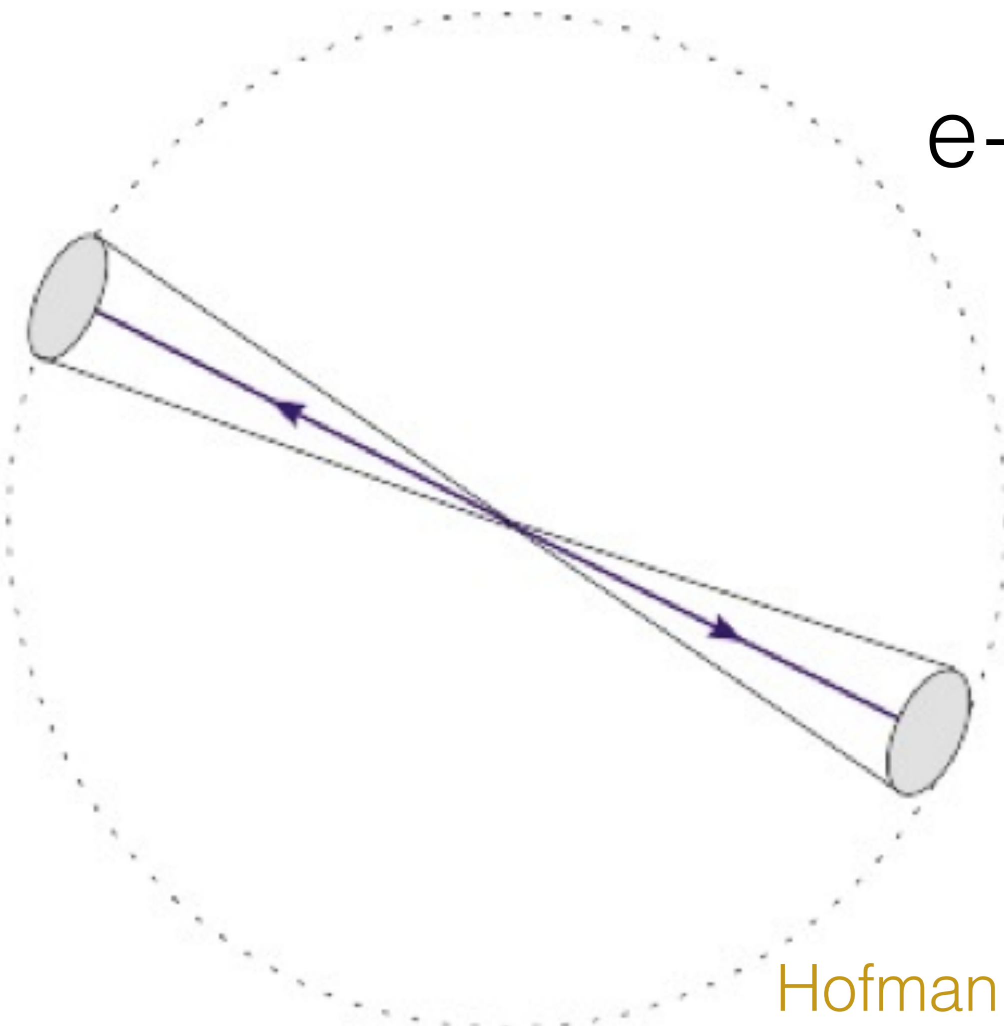
but

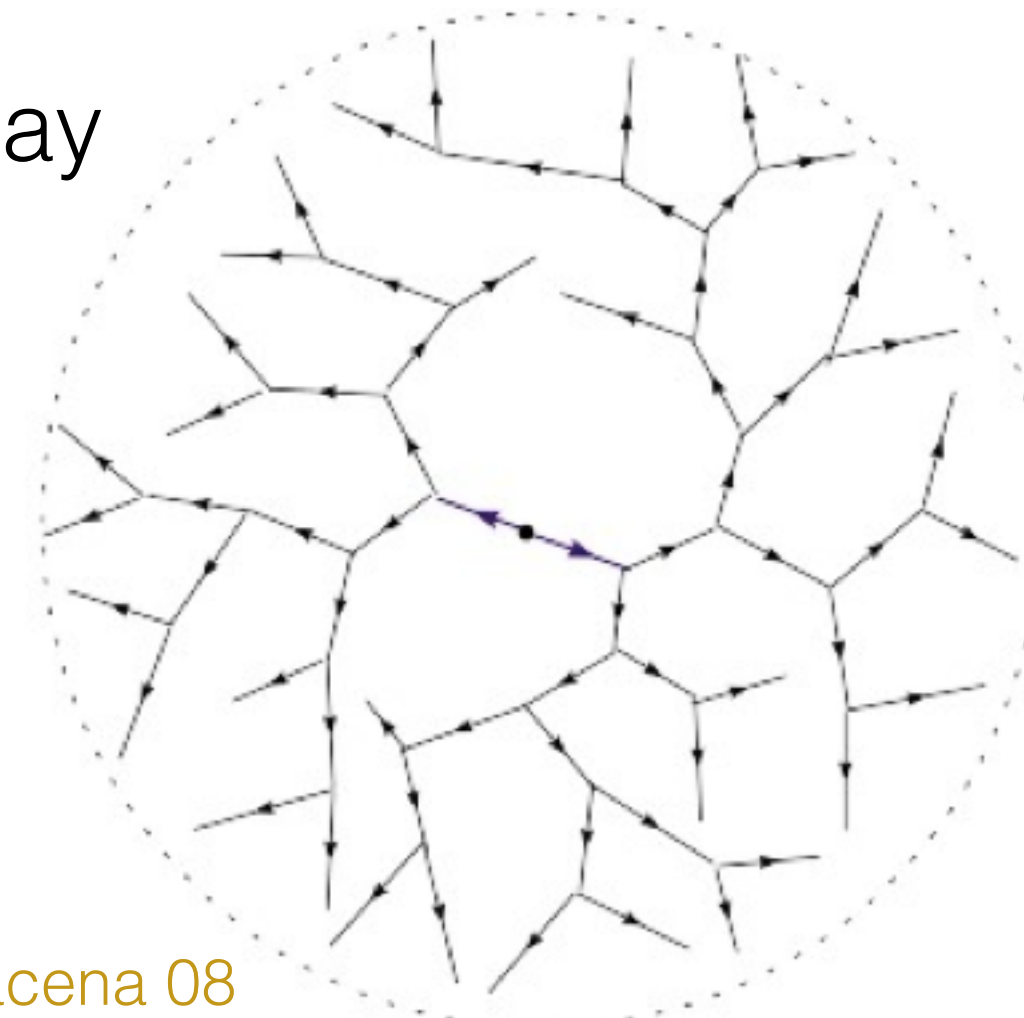
? $\mathcal{N} = 4 \quad T \neq 0$ and QCD $T > T_c$ share similarities

There are no jets at strong coupling

There are no jets in N=4 SYM at strong coupling

e+e- decay





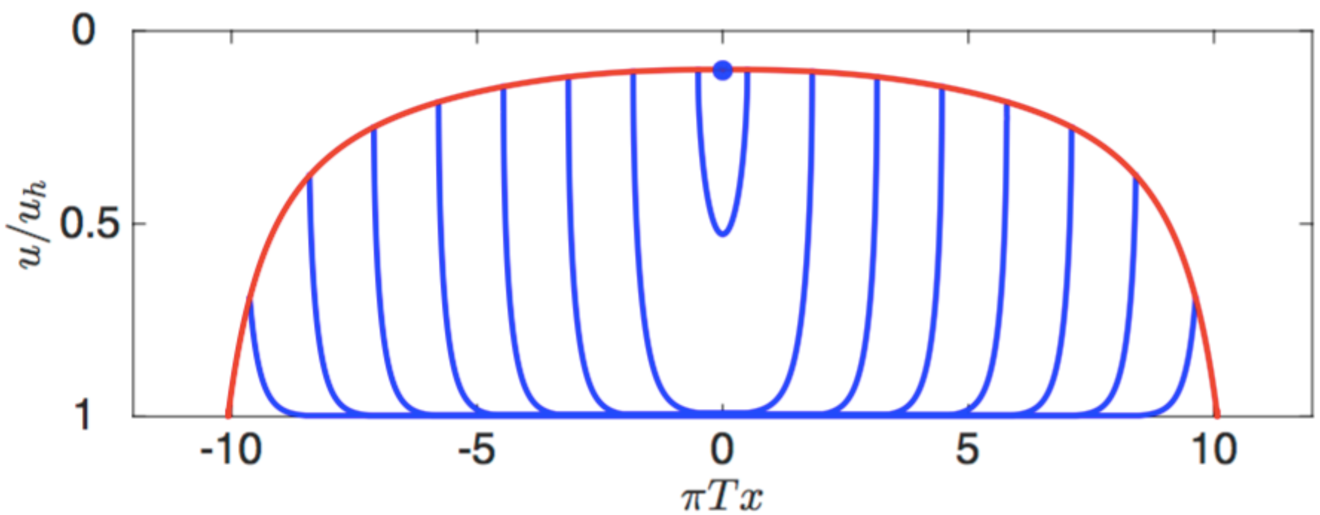
Hofman and Maldacena 08
Hatta, Iancu, Mueller 08

Weak

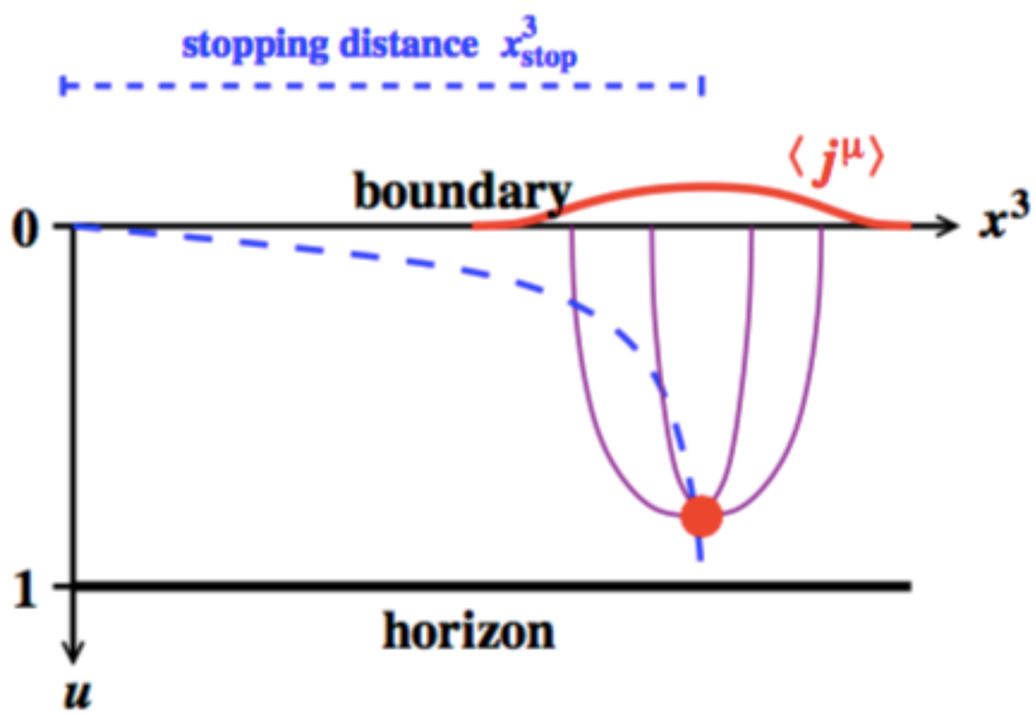
Strong

Problem for hard probes

Proxies for HE jets



Chesler et al. '09



Arnold & Vaman '11

semiclassical string description

$$\kappa_{\rm sc} \;=\; 1.05\,\lambda^{1/6}$$

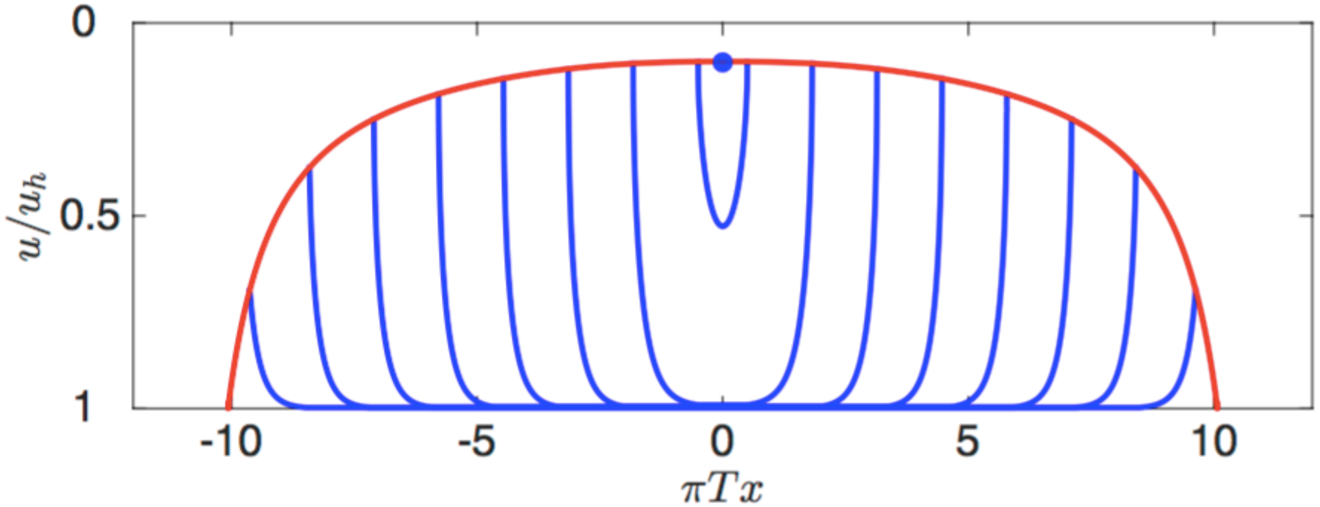
$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}} \frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

robust result at strong coupling

$$\kappa_{sc} \propto \lambda^0$$

external boosted U(1) fields

Proxies for HE jets



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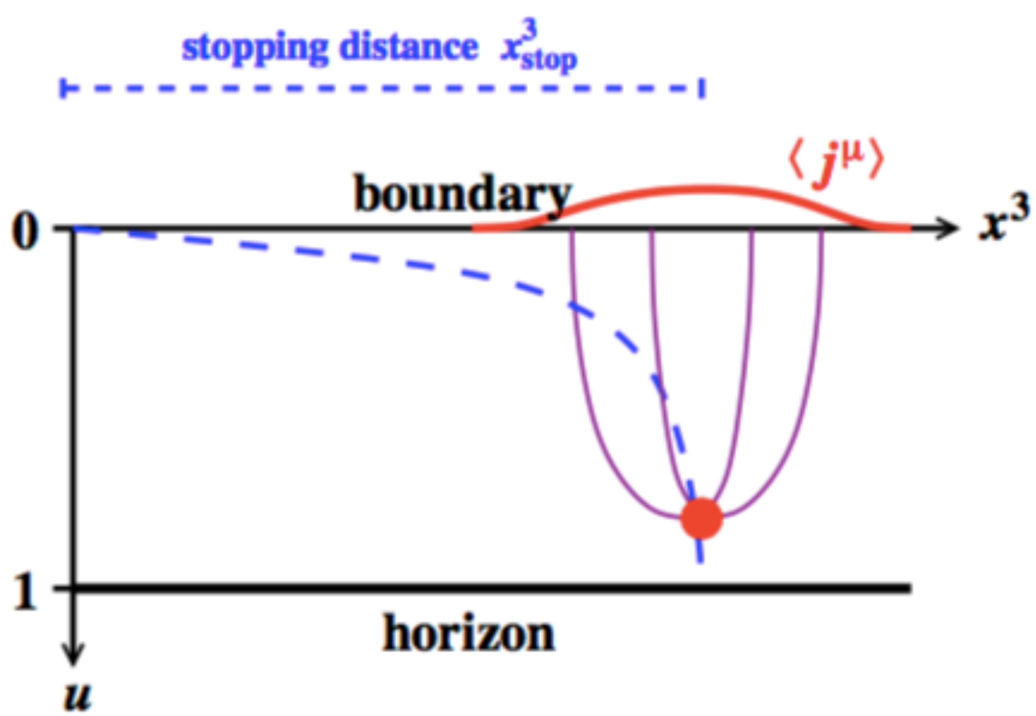

Arnold & Vaman '11

in this talk

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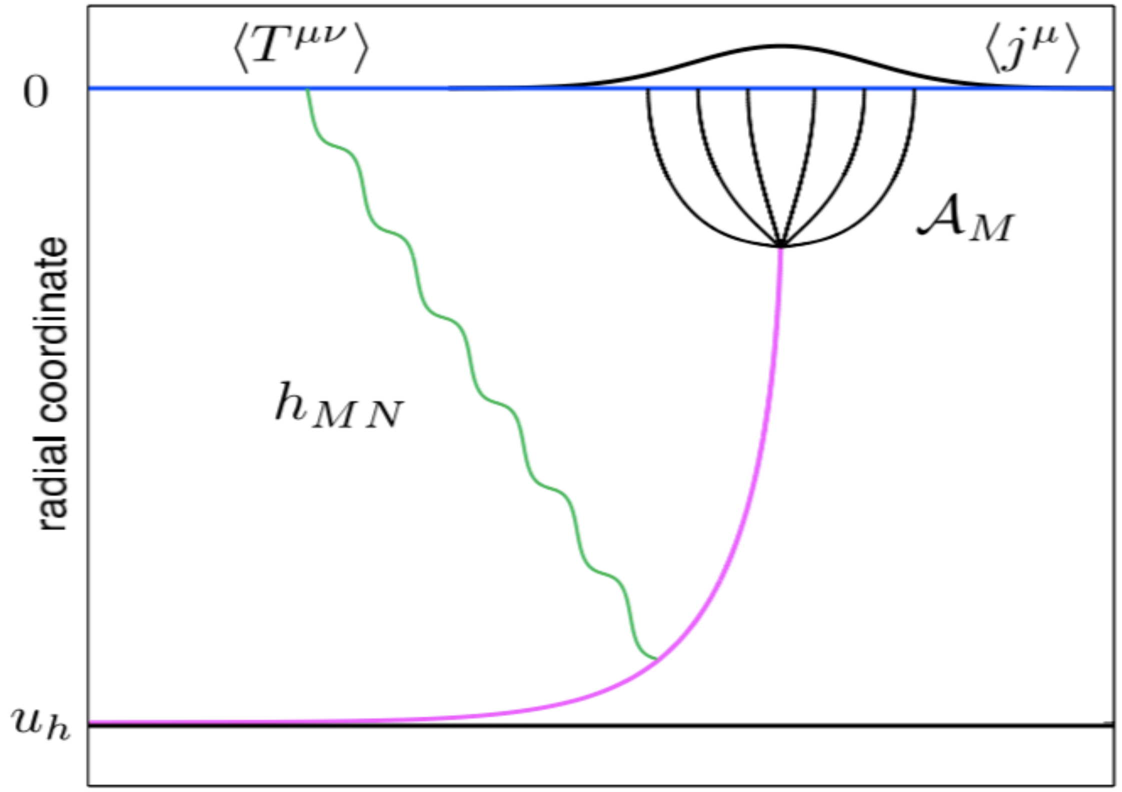
Null falling strings



Chesler et al. '09

- dressed quarks are open strings attached to a D7 flavour brane
- charged under U(1) gauge field sourcing baryon current at boundary
- depth of string endpoint determines localisation of excitation at boundary

- presence of string perturbs metric

$$G_{MN} = G^{(0)}_{MN} + \frac{L^2}{u^2} H_{MN}$$

- satisfies linearised Einstein's equations

$$\mathcal{L}^{MN}_{AB} H_{MN} = 8\pi G_{\text{Newton}} J_{AB}$$

string sourced

- near boundary expression of energy-momentum tensor

$$\langle \Delta T^{\mu\nu}(t,\boldsymbol{x})\rangle = \frac{L^3}{4\pi G_{\text{Newton}}} H^{(4)}_{\mu\nu}(t,\boldsymbol{x})$$

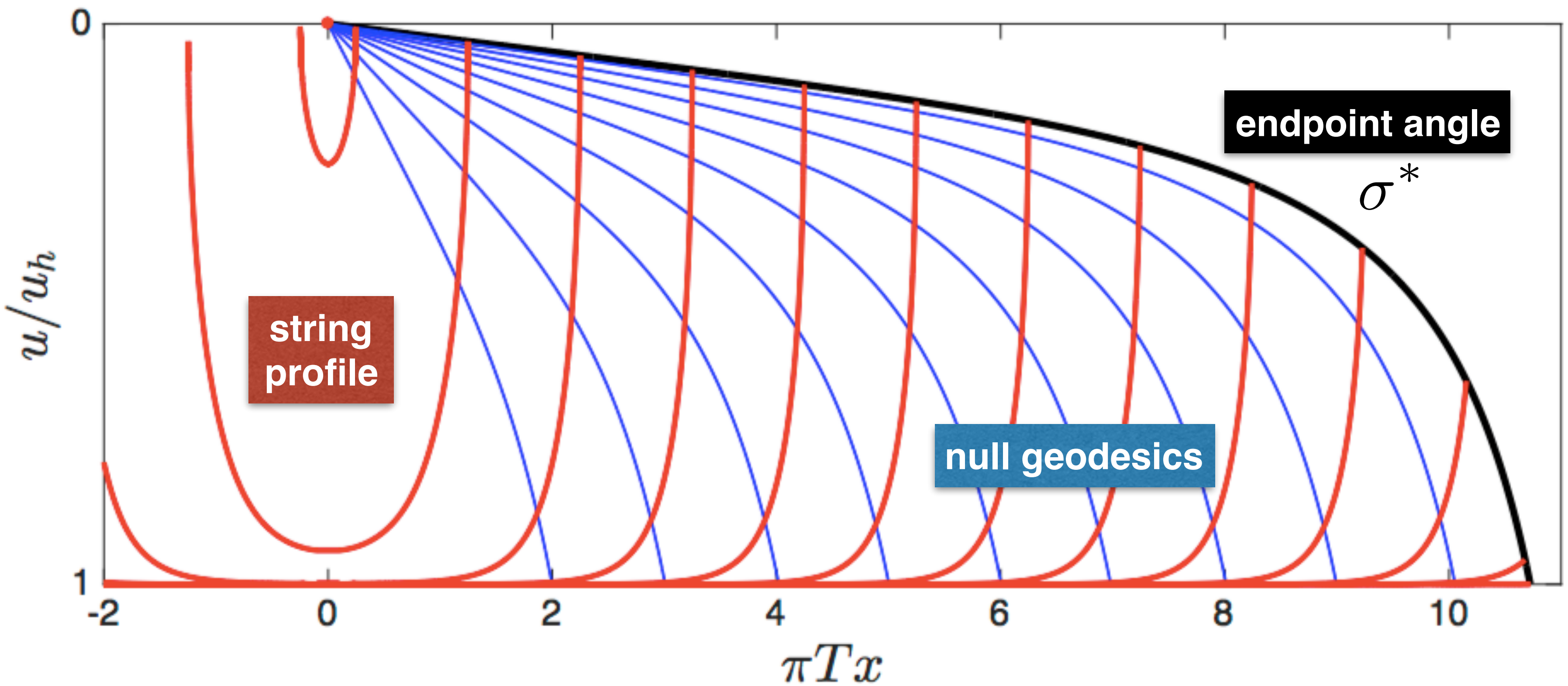
Chesler & Rajagopal '15

hydro (long wavelength)

non-hydro (jet modes)

$$\langle \Delta T^{\mu\nu}\rangle \equiv \langle T^{\mu\nu}\rangle - \langle T^{\mu\nu}_{\text{eq}}\rangle$$

Null falling strings



Schwarzschild-AdS

$$ds^2 = \frac{L^2}{u^2}\left[-f dt^2 + d\boldsymbol{x}^2 + \frac{du^2}{f}\right]$$

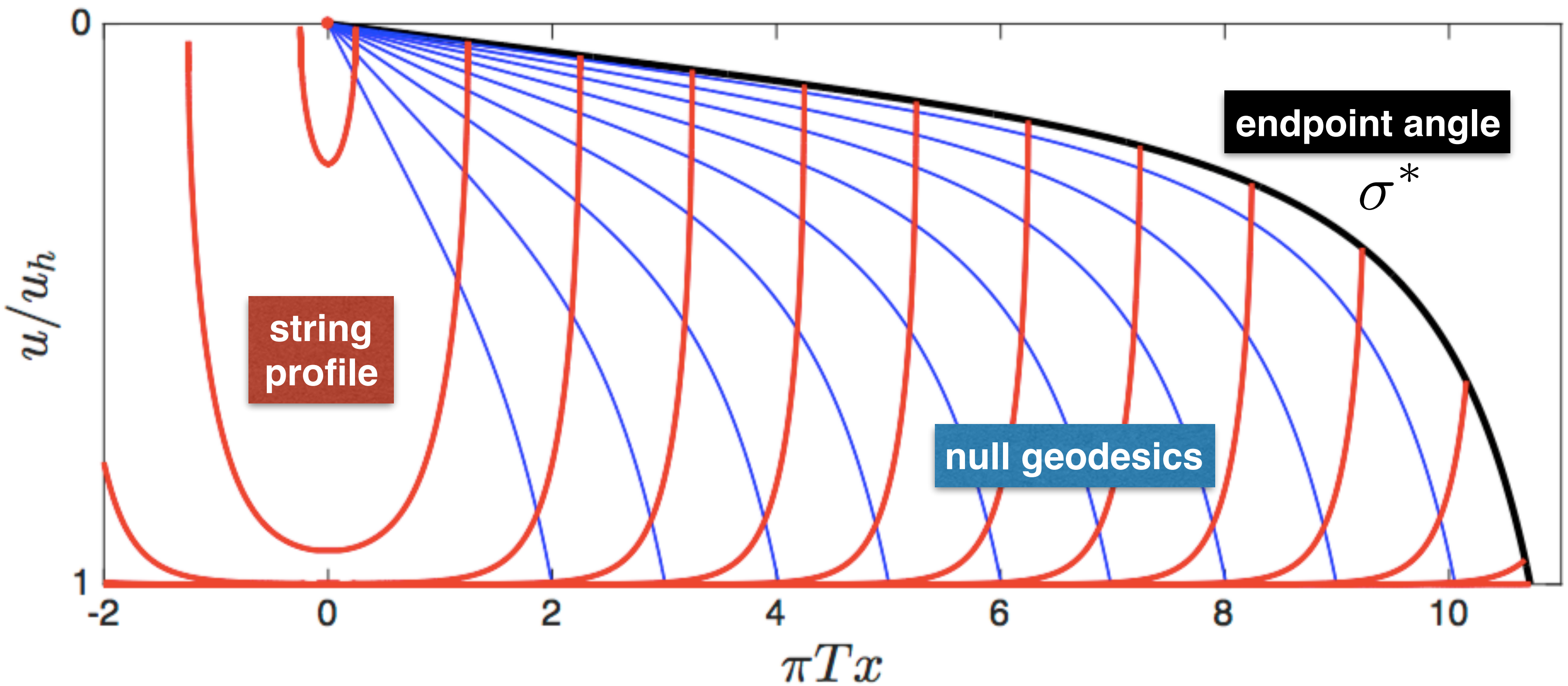
$$f \equiv 1 - \frac{u^4}{u_h^4}$$

Chesler & Rajagopal '14,'15

$$S = -\frac{\sqrt{\lambda}}{2\pi L^2}\int d\tau d\sigma \sqrt{-g}$$

Nambu-Goto action

Null falling strings



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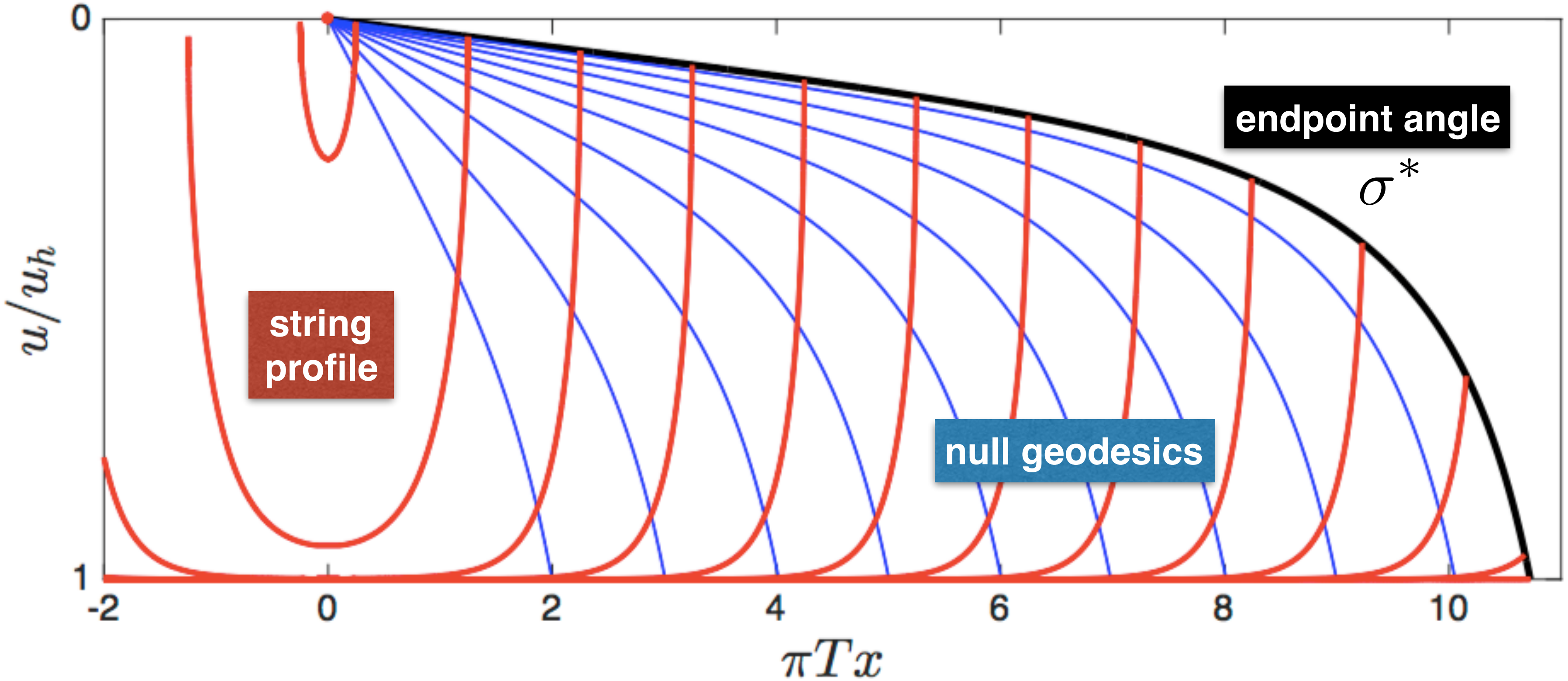
expand around degenerate null configuration

$$X^M = \boxed{X^M_{\text{null}}} + \epsilon\,\delta X^M_{(1)} + \epsilon^2 \delta X^M_{(2)} + \ldots$$

$$\frac{\partial x_{\text{geo}}}{\partial t} = \frac{f}{\xi} \qquad \frac{\partial u_{\text{geo}}}{\partial t} = \frac{f\sqrt{\xi^2 - f}}{\xi}$$

$$\xi = \xi(\sigma)$$

Null falling strings



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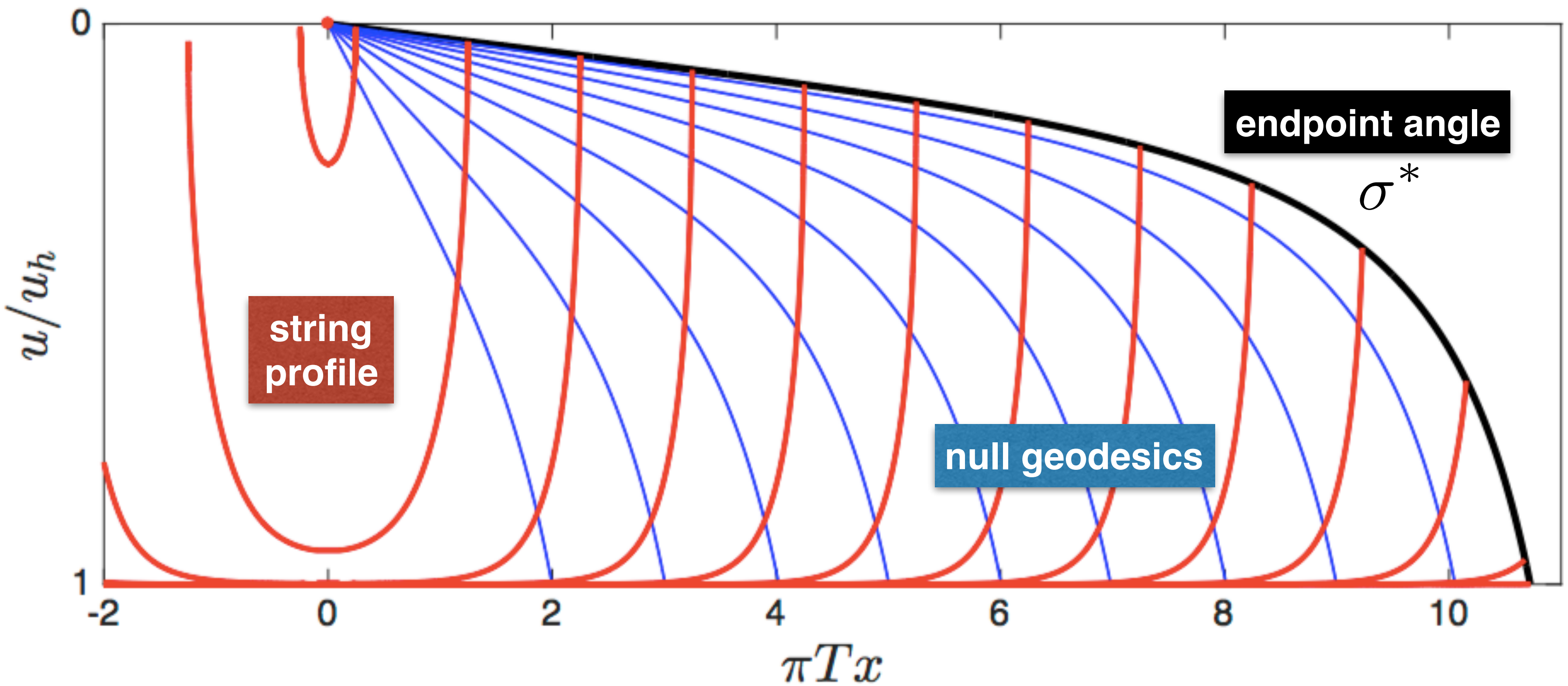
$$\Pi^\tau_0(\sigma) = -\frac{\sqrt{\lambda}}{2\pi}\frac{1}{\sqrt{2\epsilon\,\psi_1}}\frac{1}{\sigma^2\sqrt{\sigma - \sigma_*}}\left[1 - \mathcal{O}(\sigma - \sigma_*)\right]$$

find energy carried by each geodesic



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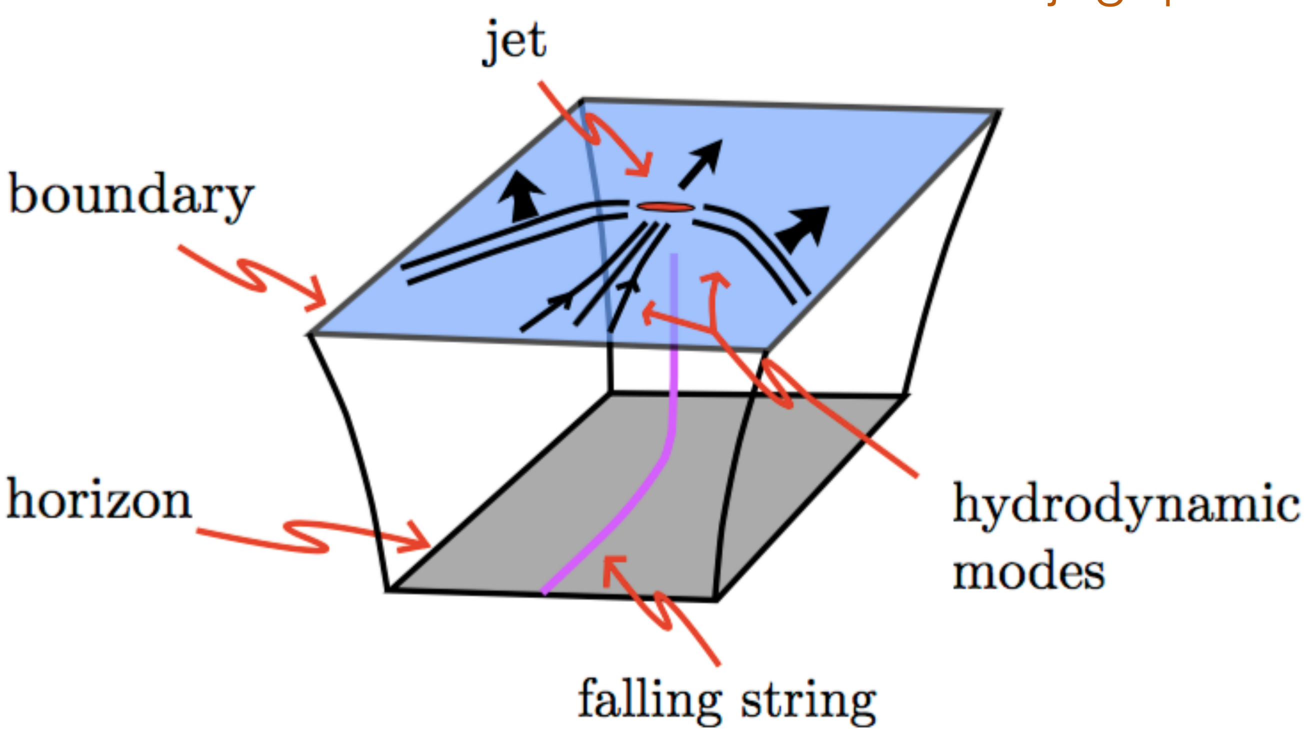
find energy carried by each geodesic

$$J^{MN} = \int d\sigma J^{MN}_{\rm particle}(\sigma) \qquad J^{MN}_{\rm particle} = \frac{\Pi^\tau_0}{G_{00}}\frac{dX^M_{\rm geo}}{dt}\frac{dX^N_{\rm geo}}{dt}\frac{1}{\sqrt{-G}}\delta^3(\boldsymbol{x} - \boldsymbol{x}_{\rm geo})\delta(u - u_{\rm geo})$$

Null falling strings

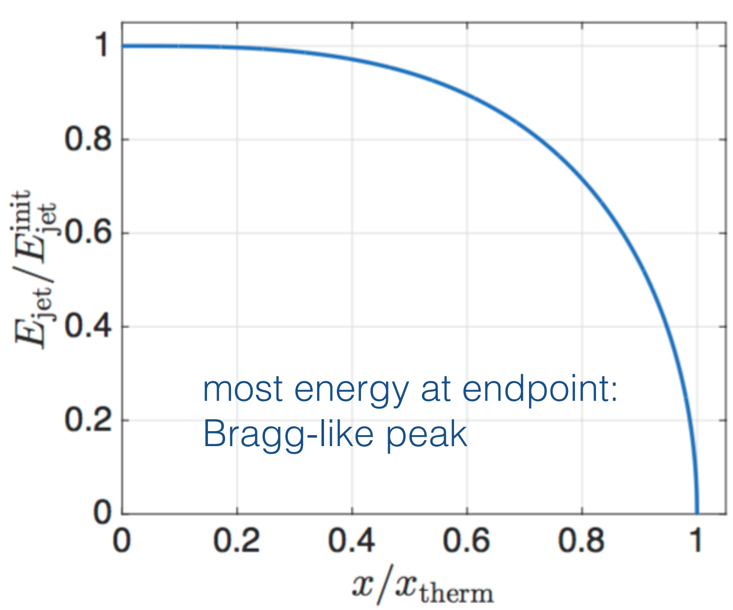
Chesler & Rajagopal '14,'15



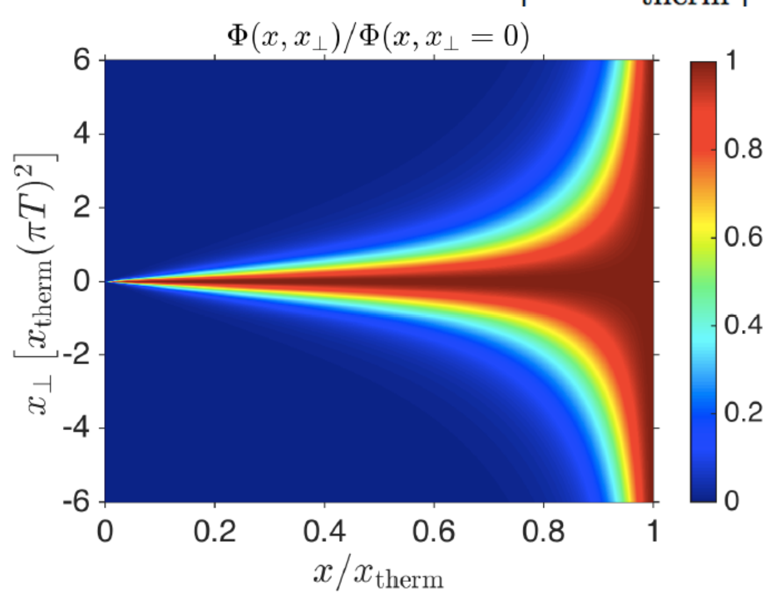
- unambiguous determination of boundary jet properties
- the rate at which energy flows into hydrodynamic modes:

$$\frac{1}{E_{\rm init}}\frac{dE_{\rm jet}}{dx} = -\frac{4x^2}{\pi x_{\rm therm}^2\sqrt{x_{\rm therm}^2 - x^2}}$$

as the jet loses energy …



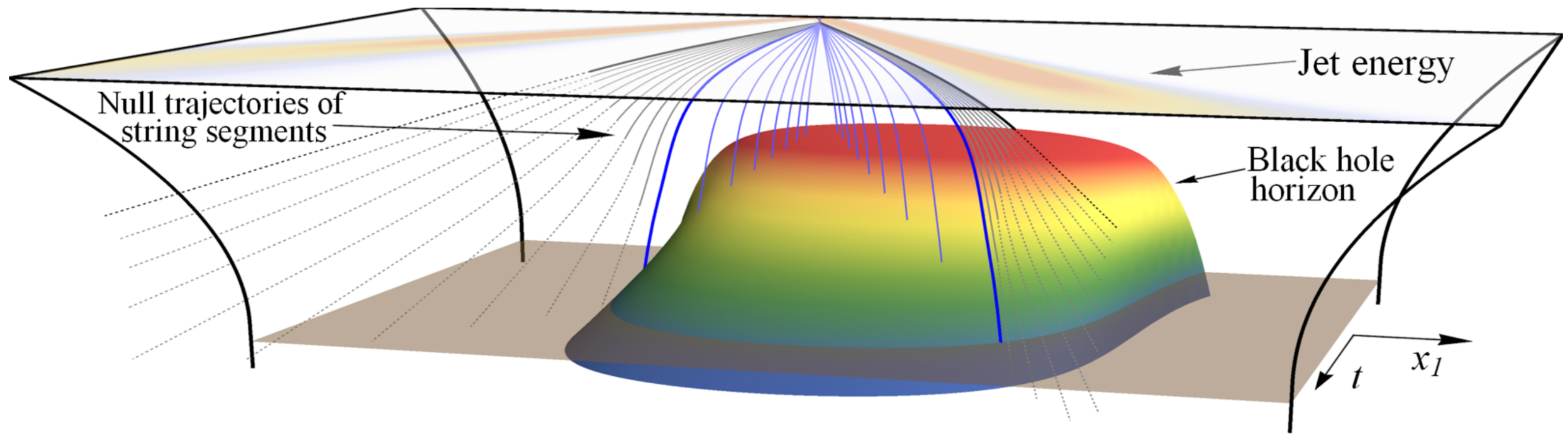
it gets wider $\theta_{\rm jet} \sim \frac{\theta_{\rm jet}^{\rm init}}{\left[1 - \frac{x}{x_{\rm therm}}\right]^2}$



Fractional energy loss only depends on initial jet opening angle

$$x_{\rm therm} = \frac{1}{T}\sqrt{\frac{\kappa}{\theta_{\rm jet}^{\rm init}}}$$

Holographic quenching with pure strings

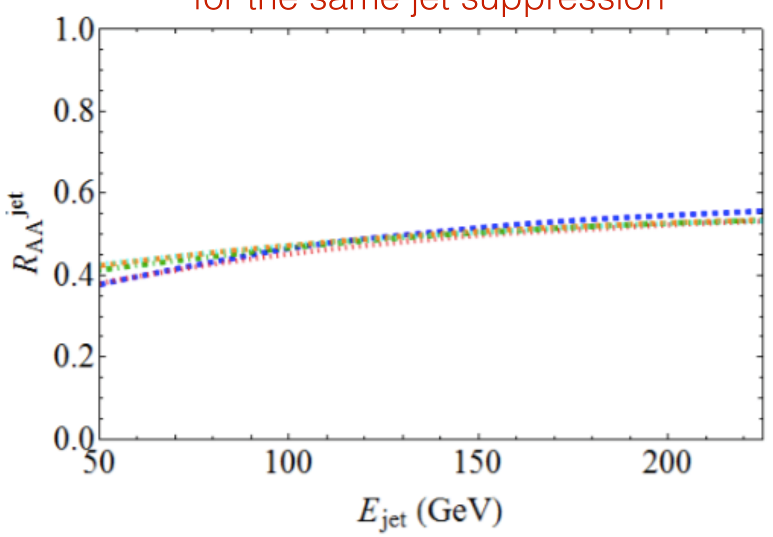


the *string* is treated as a model for the *jet as a whole*

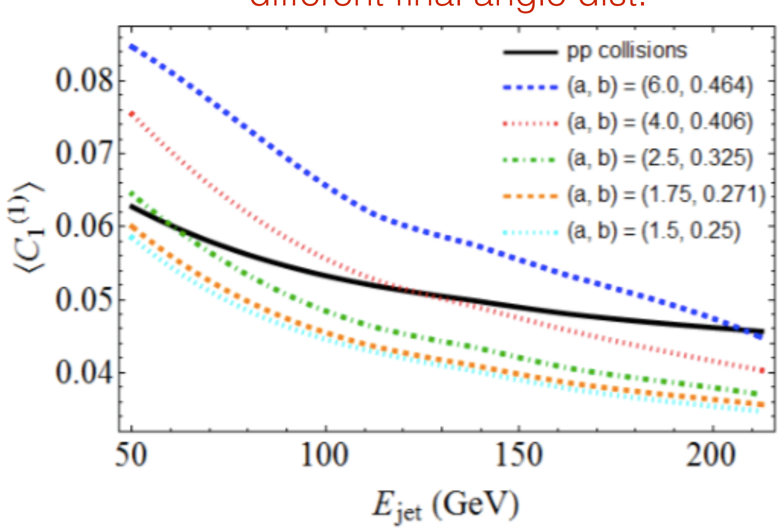
Rajagopal, Sadofyev, van der Schee '16

- consider an *ensemble* of such jets by choosing initial distributions of energy & angle from pQCD
- competing effects: each individual jet widens, while wider jets lose more energy

for the same jet suppression



different final angle dist.



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R} \right)^{\alpha}$$

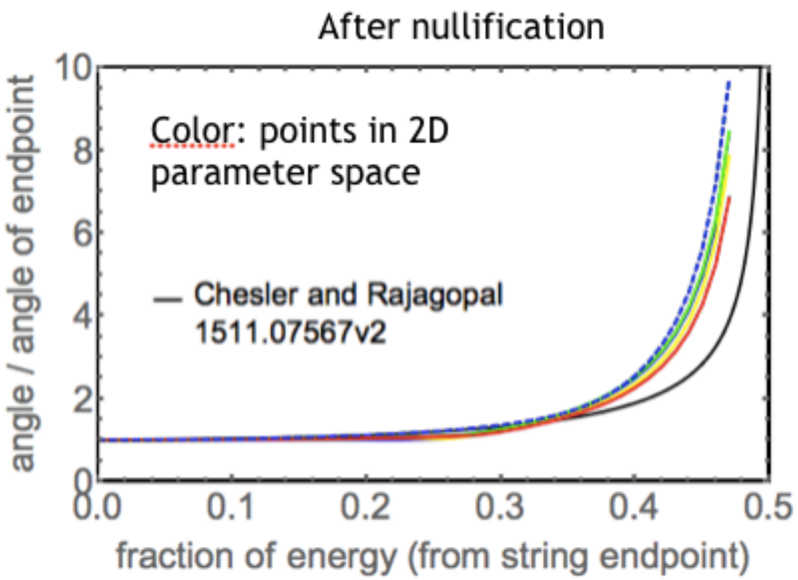
measures jet angle in pQCD

$$C_1^{(1)} = a\,\sigma_0$$
$$T_{\mathrm{SYM}} = b\,T_{\mathrm{QCD}}$$

also observed in pQCD

Milhano & Zapp '15

Holographic quenching with pure strings



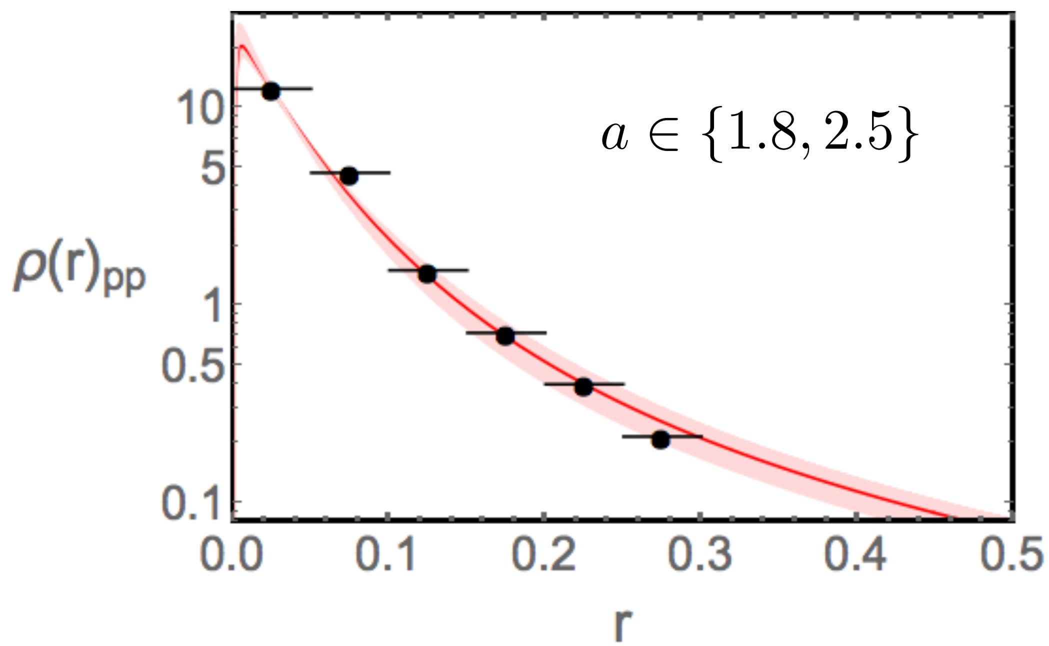
Brewer et al.1710.03237

- determine string energy density by considering different initial profiles evolved within *full string dynamics*

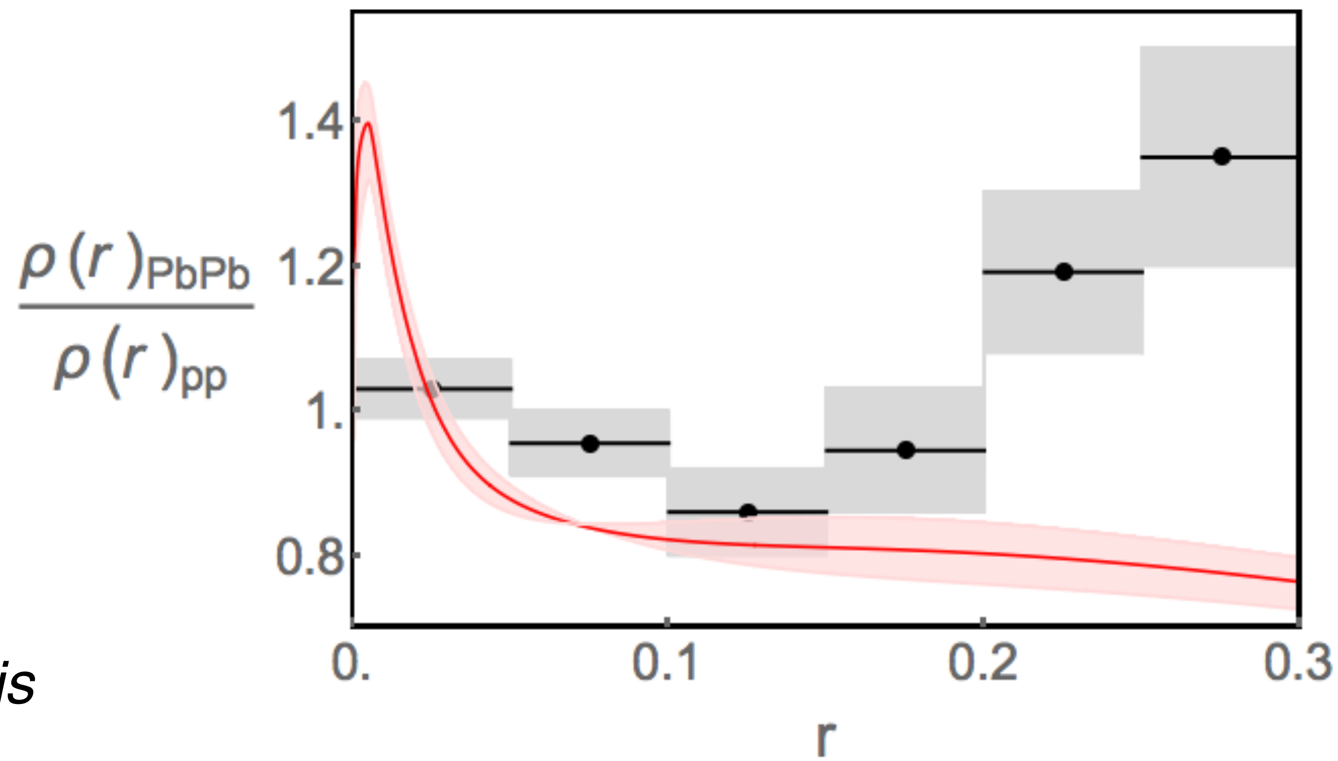
as the string nullifies, different initial choices tend to converge

- nuclear jet shape modification *captures core dynamics* - lacks contribution from medium response

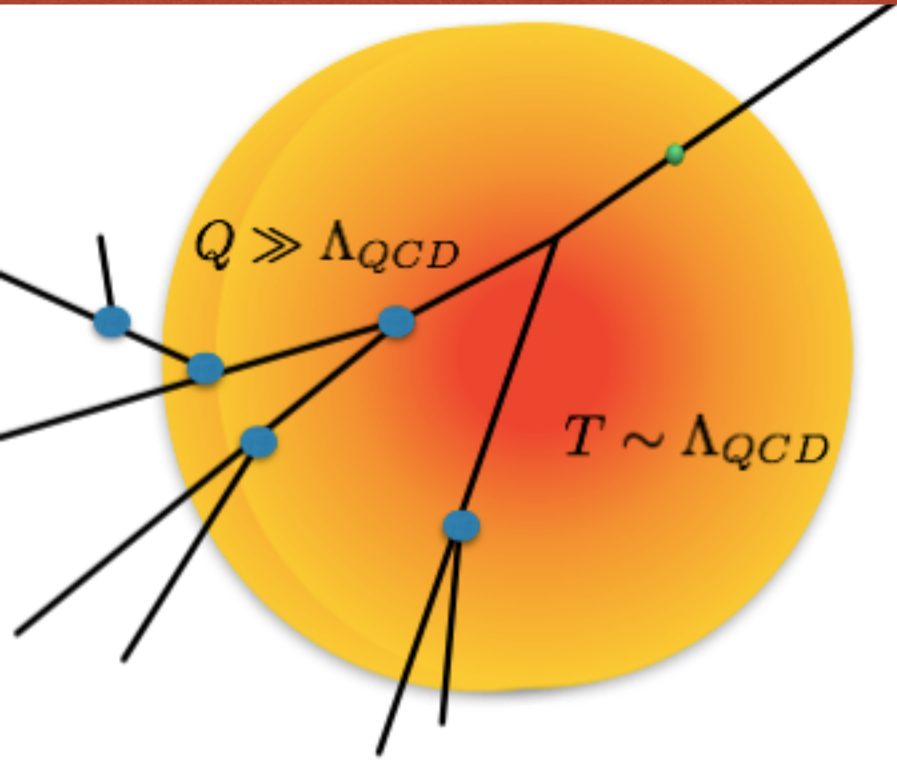
- use pp jet shapes to determine angle distribution



Angular energy distribution around the jet axis



Hybrid strong/weak coupling approach



Initial parton from hard scattering carries a high virtuality

will split according to perturbative DGLAP evolution

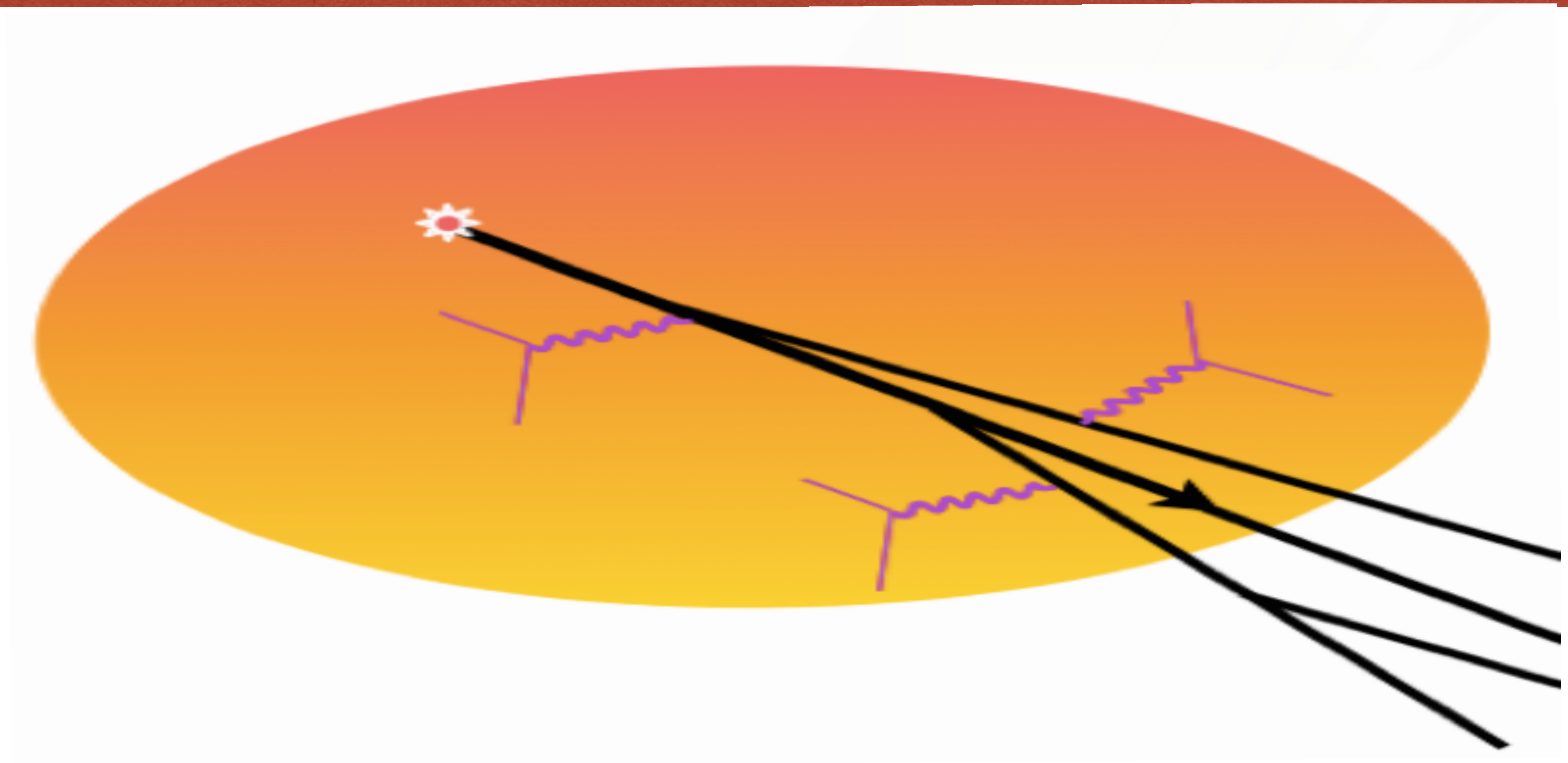
Casalderrey-Solana et al. '14,'15,'16

Interactions with the medium take place at a non-perturbative scale

describe the propagation of partons within QGP using holographic falling strings

- captures multi-scale nature of in-medium HE jets dynamics
- neglects parton shower modifications induced by medium injected virtuality
- useful tool as a benchmark to compare to data

Monte Carlo Implementation



- Jet production and evolution in PYTHIA
- Assign spacetime description to parton shower (formation time argument) $\tau_f = \dfrac{2E}{Q^2}$
- Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)
- Between splittings, partons in the shower interact with QGP, lose energy
- Turn off energy loss below a T_c that we vary over $145 < T_c < 170\,\mathrm{MeV}$
- Extract jet observables from parton shower

Parton Shower

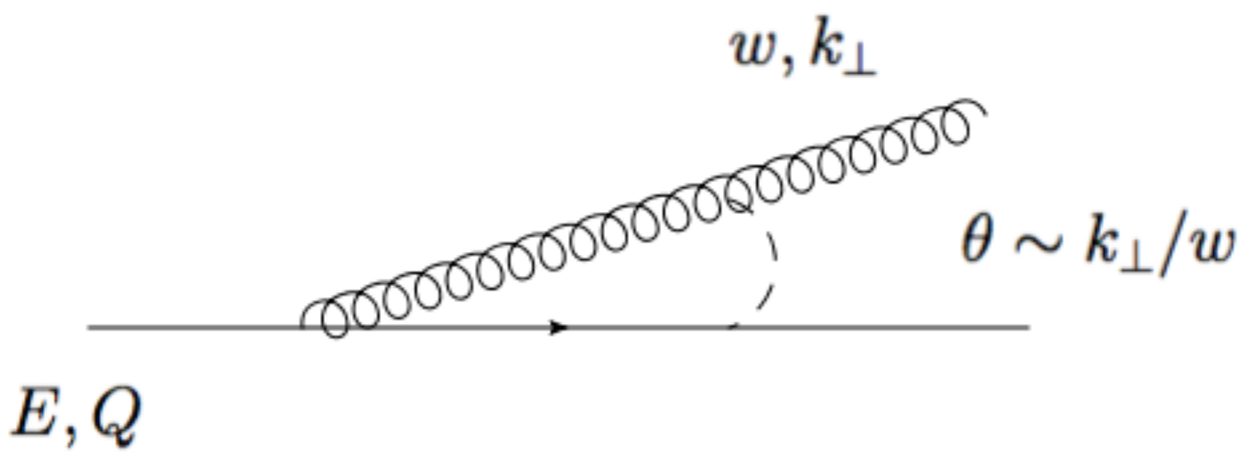
Generate HardQCD pp events with PYTHIA:

version 8.183

- Pt min = 1 GeV (splitting cut-off)
- Initial State Radiation = on
- Multi Partonic Interactions = off
- Stop before hadronization

Where and when do partons effectively split?

Use a formation time argument



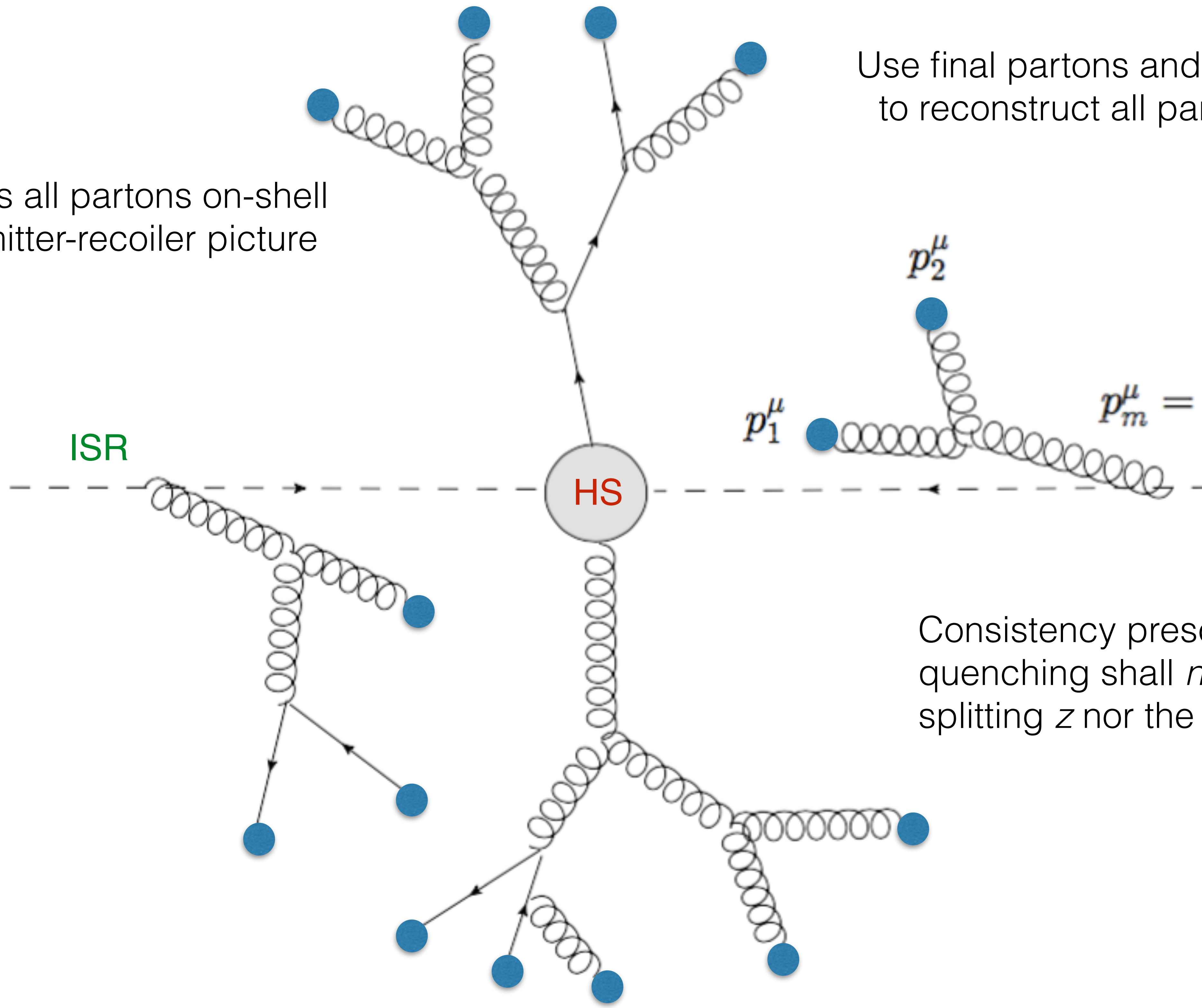
$$\lambda_\perp \sim r \sim \theta \tau_f$$

$$\tau_f \sim w/k_\perp^2 \to 2E/Q^2$$

Parton Shower

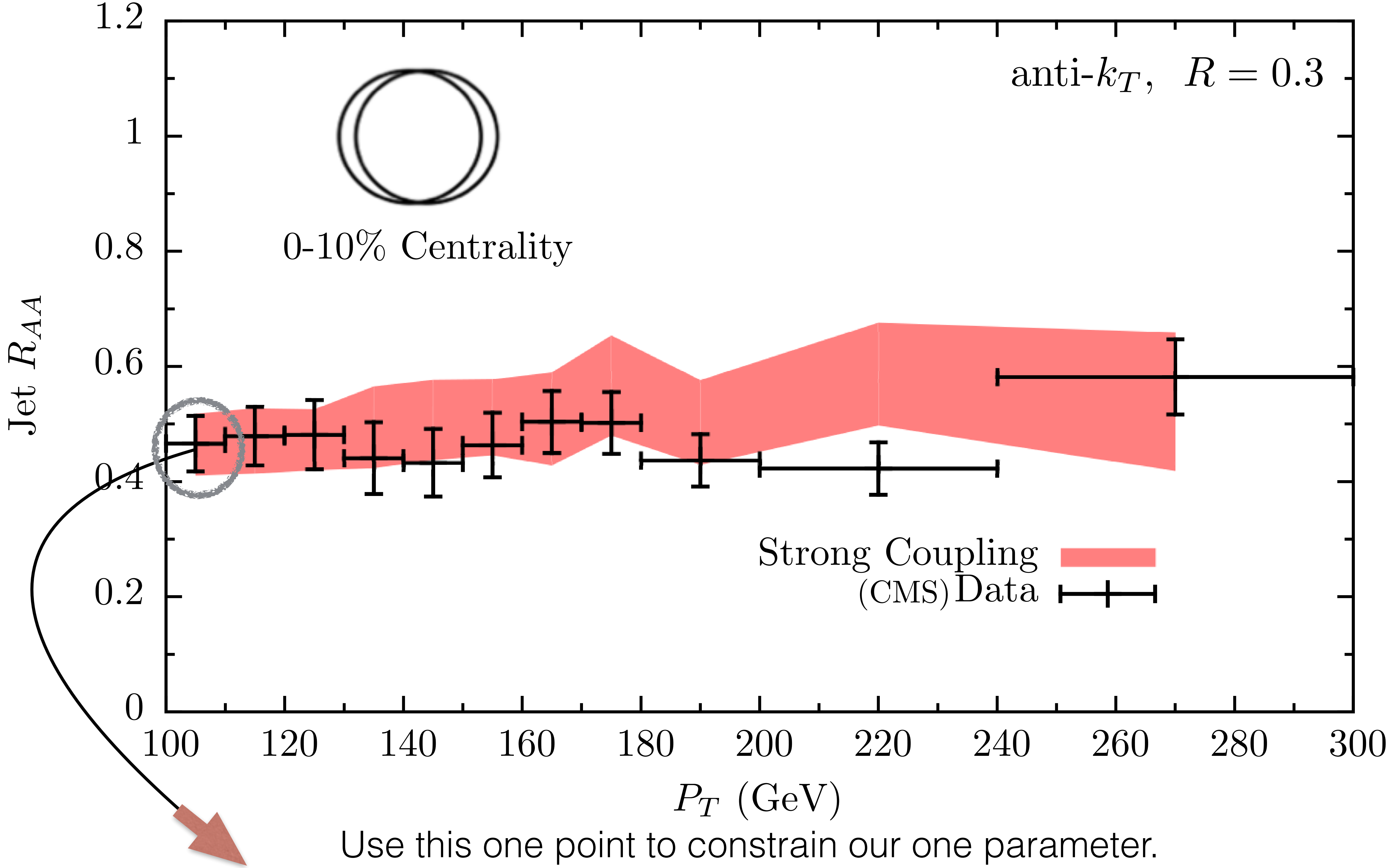
Use final partons and tree information to reconstruct all partons momenta

PYTHIA 8 keeps all partons on-shell through the emitter-recoiler picture



Consistency prescription:
quenching shall *not modify* splitting *z* nor the *formation times*

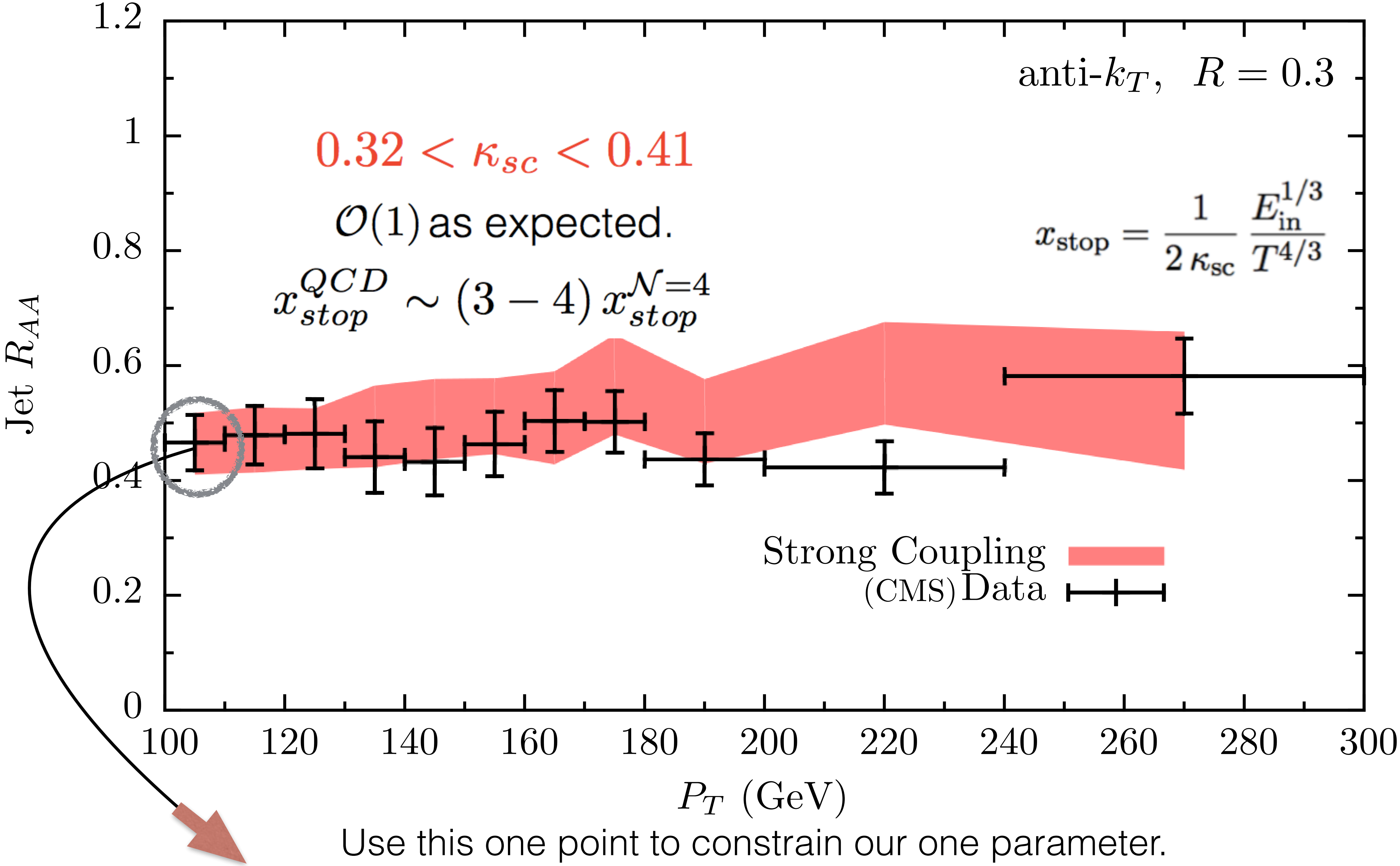
Jet R_{AA}



Use this one point to constrain our one parameter.

Bands come from experimental uncertainty on this point plus varying T_c over $145 < T_c < 170\,\text{MeV}$

Jet R_{AA}



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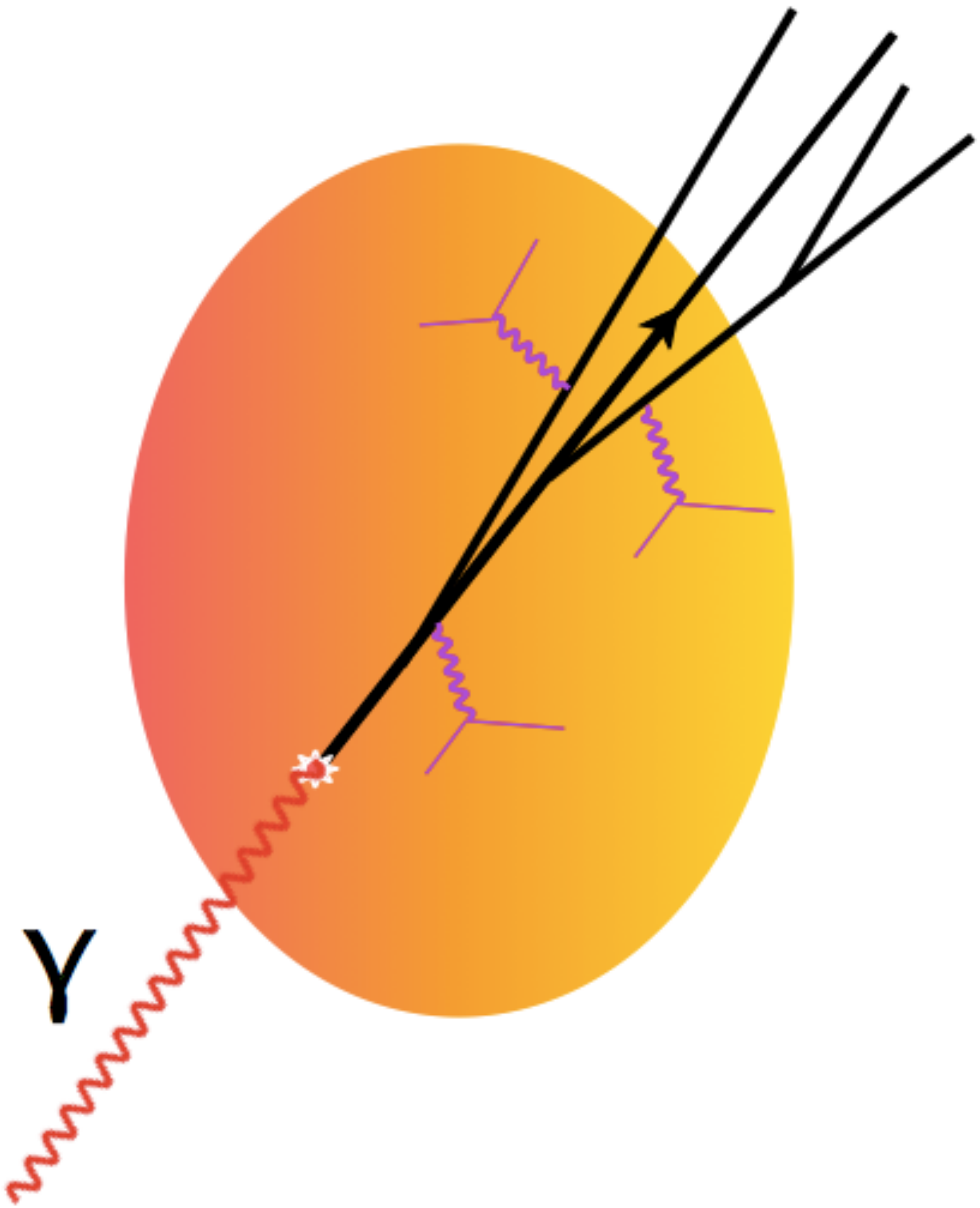
Photon-Jet: the ‘golden’ channel



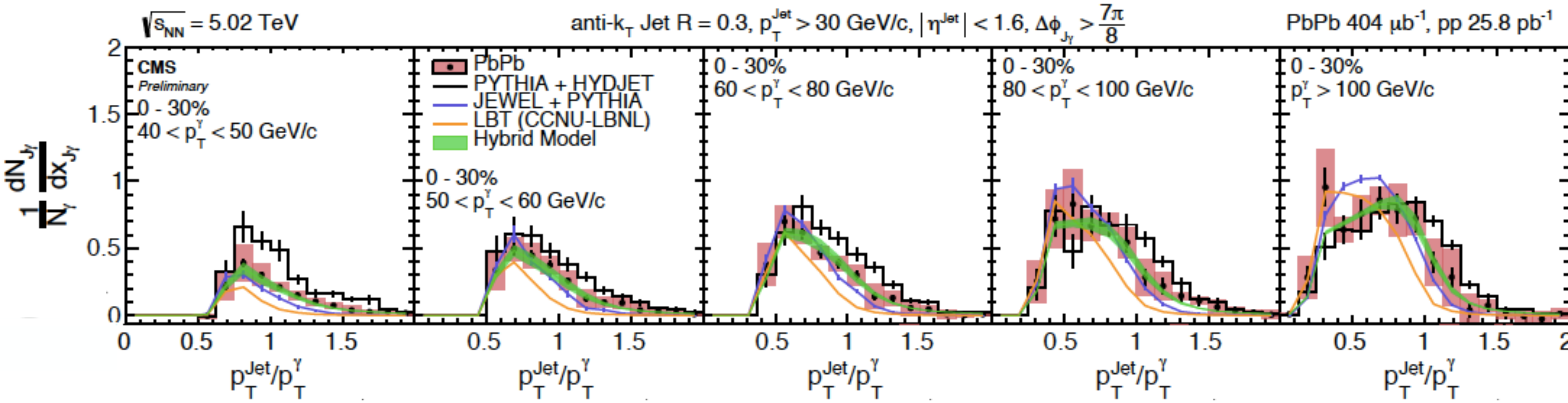
- Photons do not interact with plasma
- Look for associated jet

  -Different geometric sampling

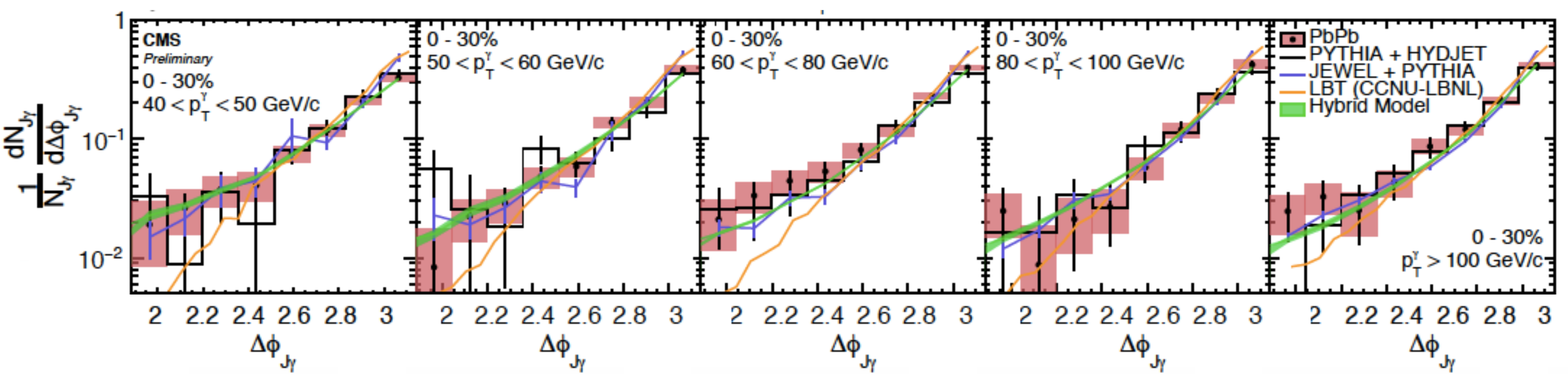
  -Different species composition

  -E_γ proxy for E_{jet}

Photon-Jet: the 'golden' channel

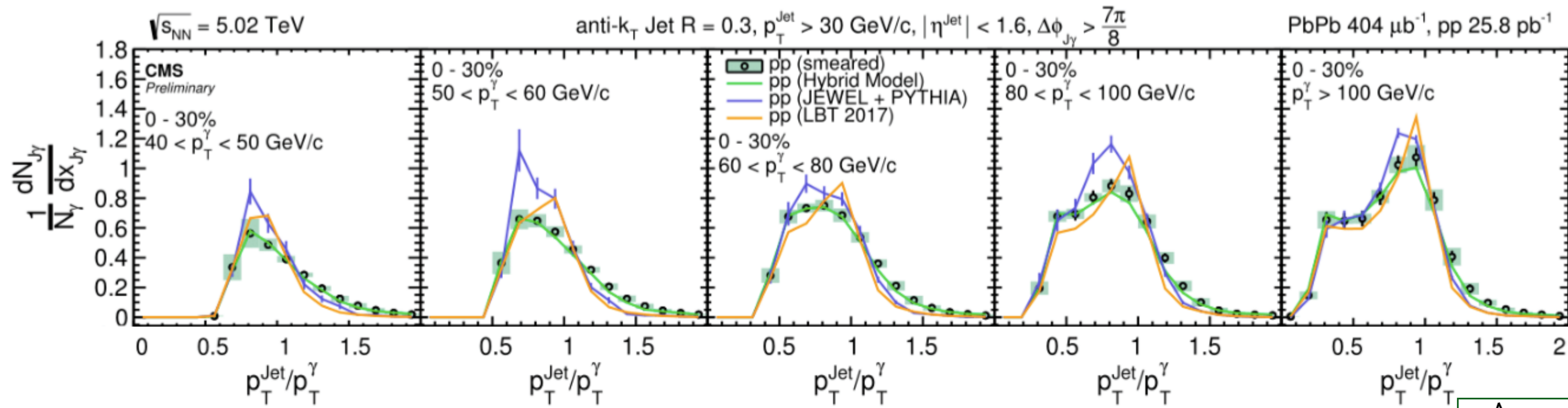


Core features of the model have been validated by e.g. photon-jet observables predictions

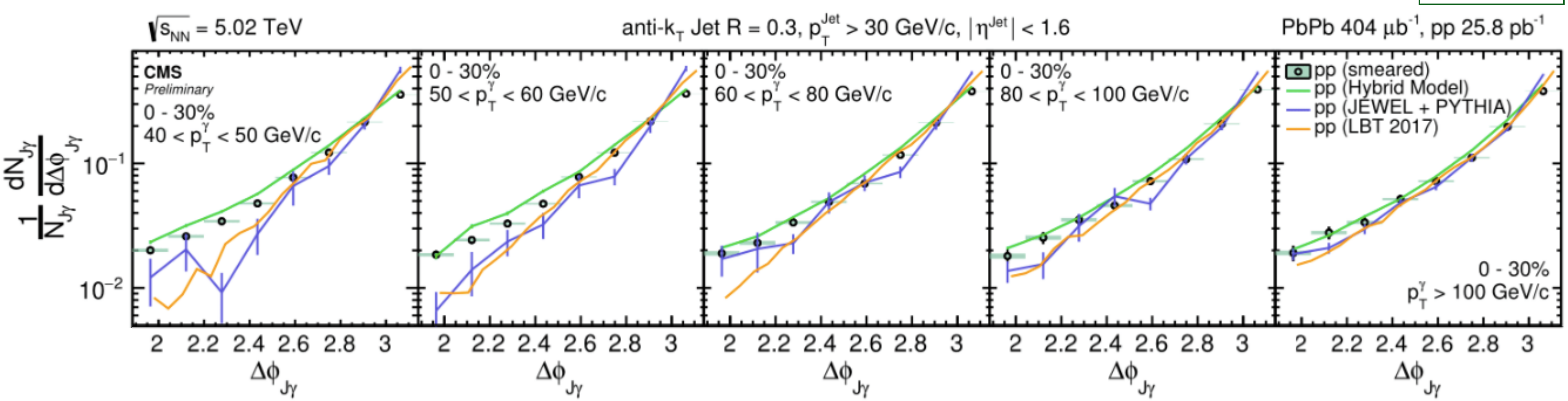


No strong evidence so far of hard point-like scatterers

Photon-Jet: the ‘golden’ channel



Cannot really compare among models because of different pp reference



Important effects: Jet Pt smearing, bremsstrahlung photons

Jet induced medium excitations

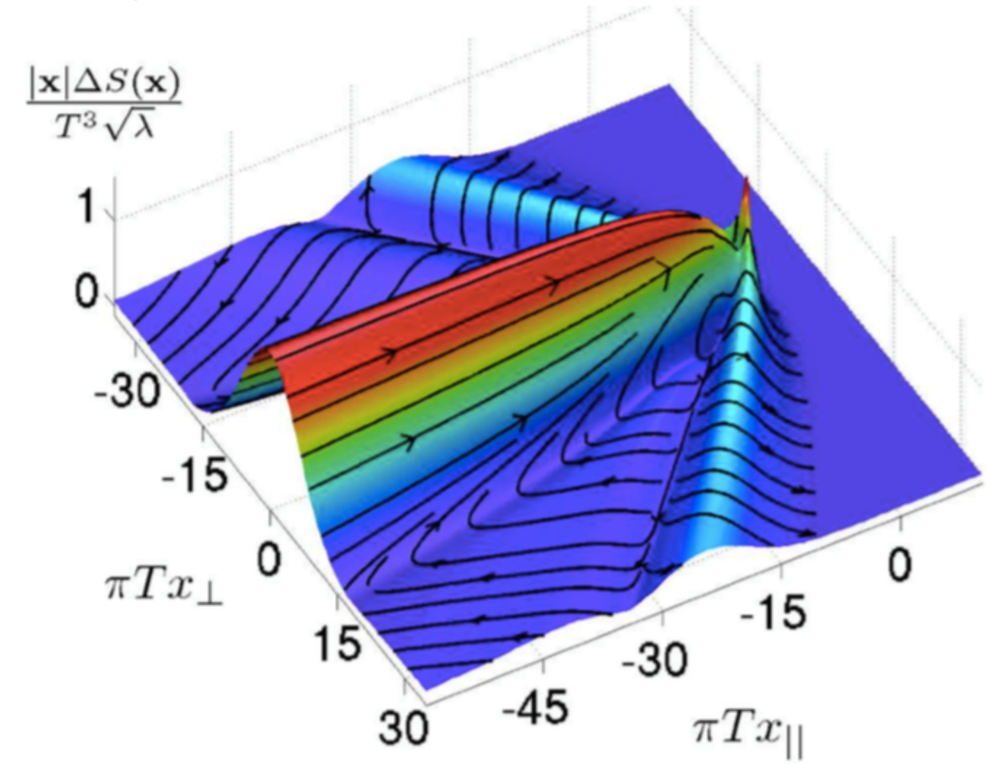
metric perturbation near the AdS boundary

↓

change in the SYM stress-energy tensor

- string acts as a perturbation in the large Nc limit
- agreement between hydrodynamics & wake of a quark in gauge/gravity duality

Chesler & Yaffe '07



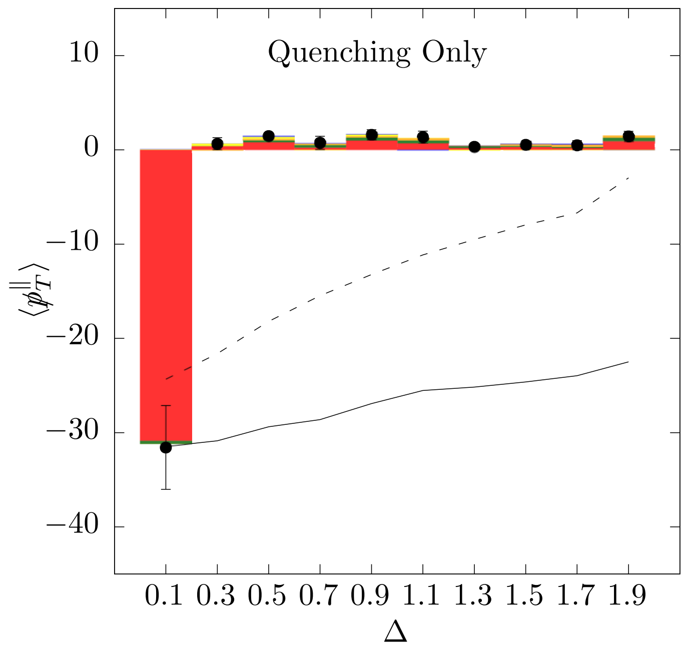
energy-momentum conservation in the jet+plasma interplay

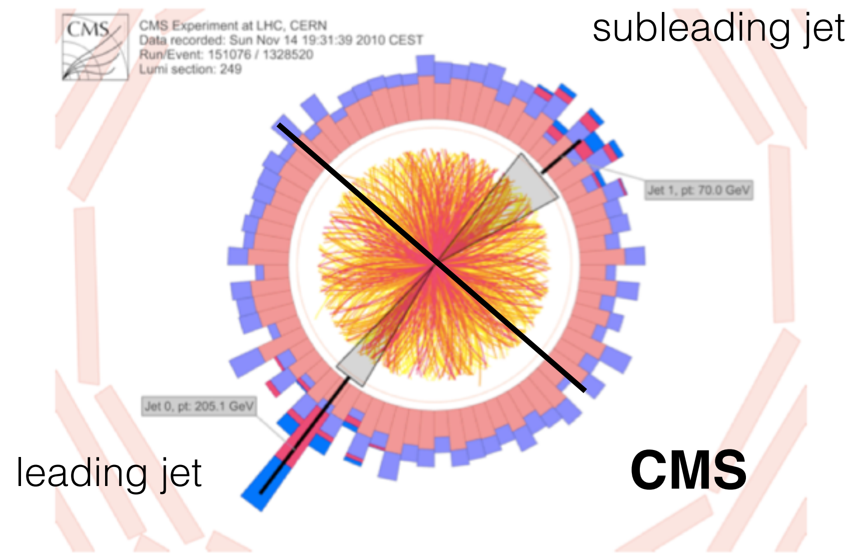
wake hadron distribution *estimate*
(within hybrid model)

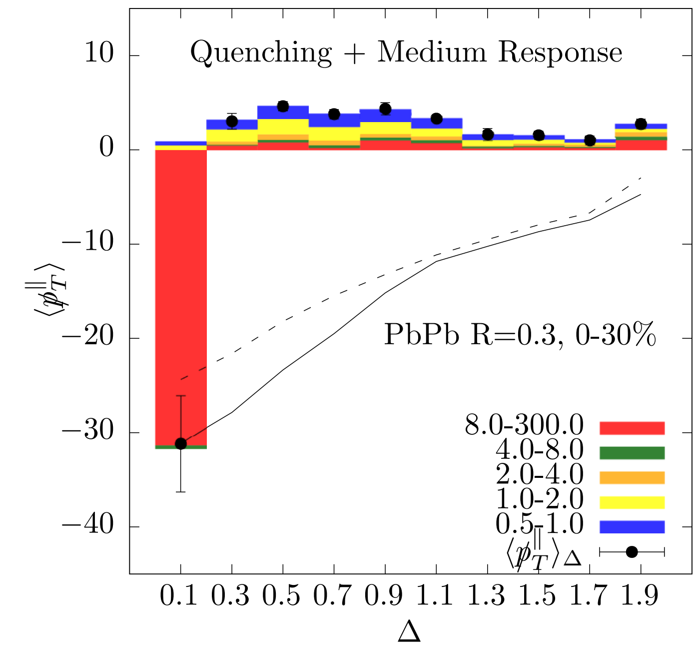
- small perturbation on top of hydro
- only valid for soft hadrons
- no extra free parameter

Where does lost energy go to?

‘missing-pt’ observables

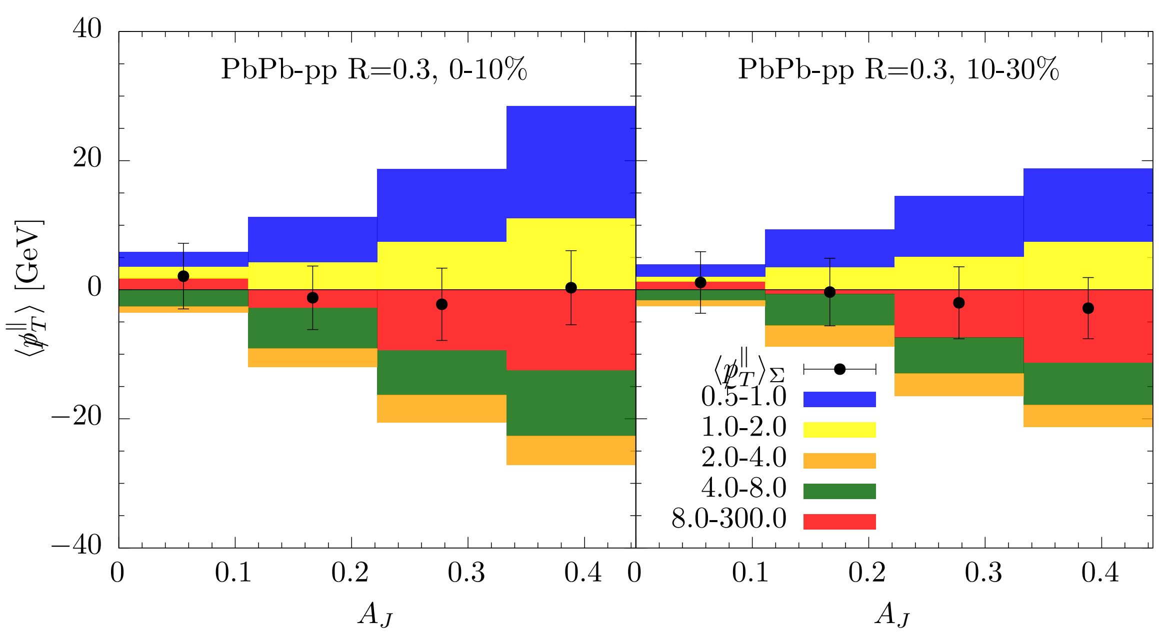


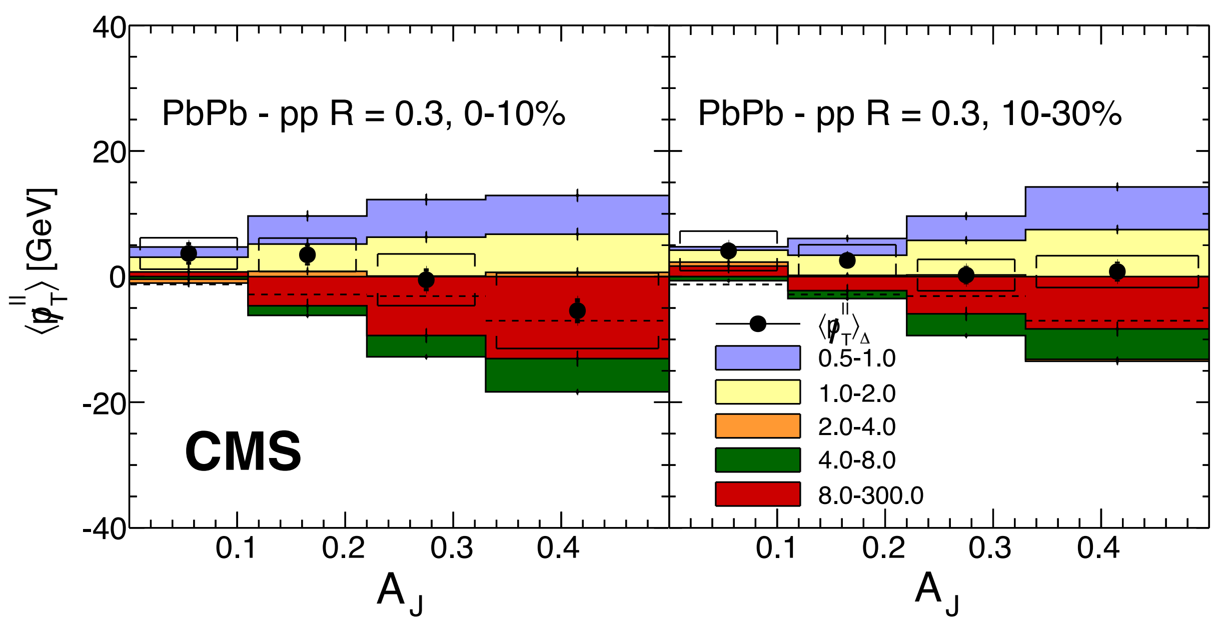




energy is recovered at large angles in the form of soft particles

data suggests that implementation of back-reaction might mistreat semi-hard particles





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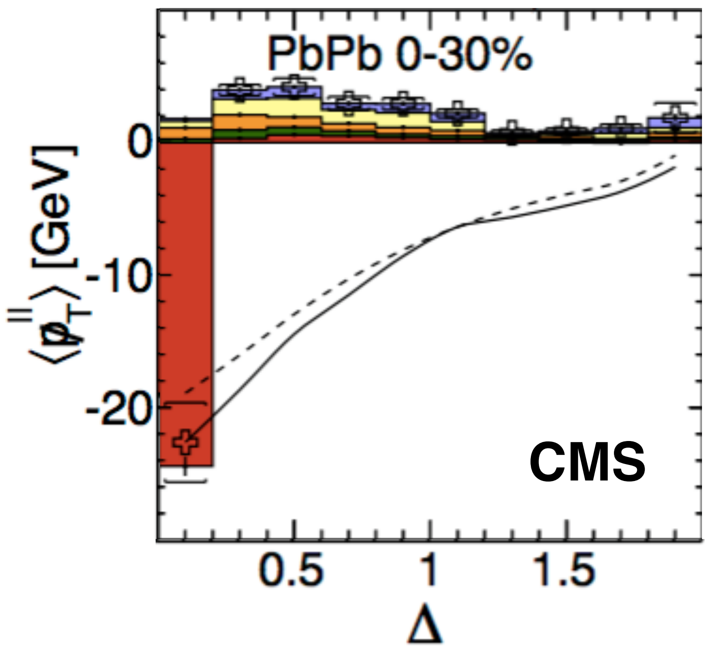

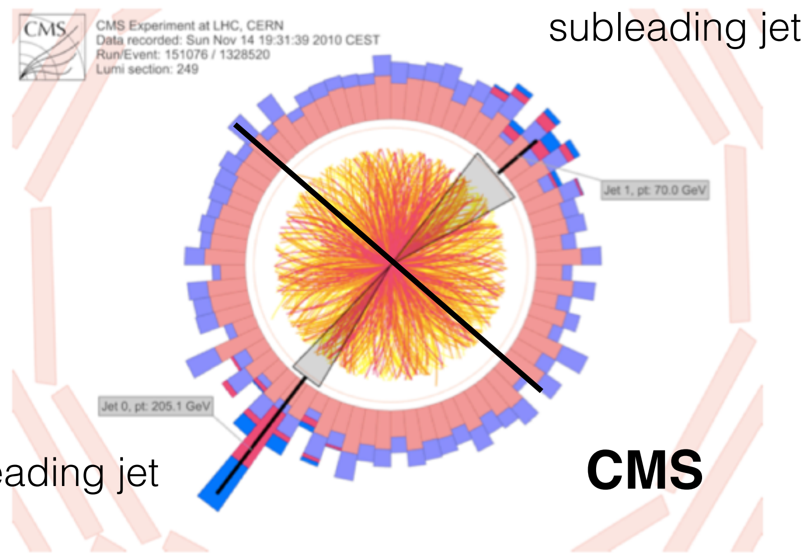

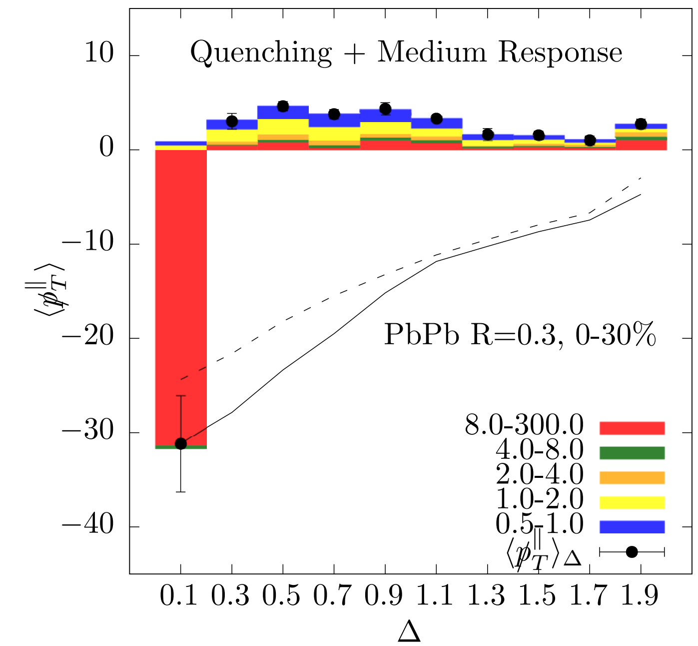

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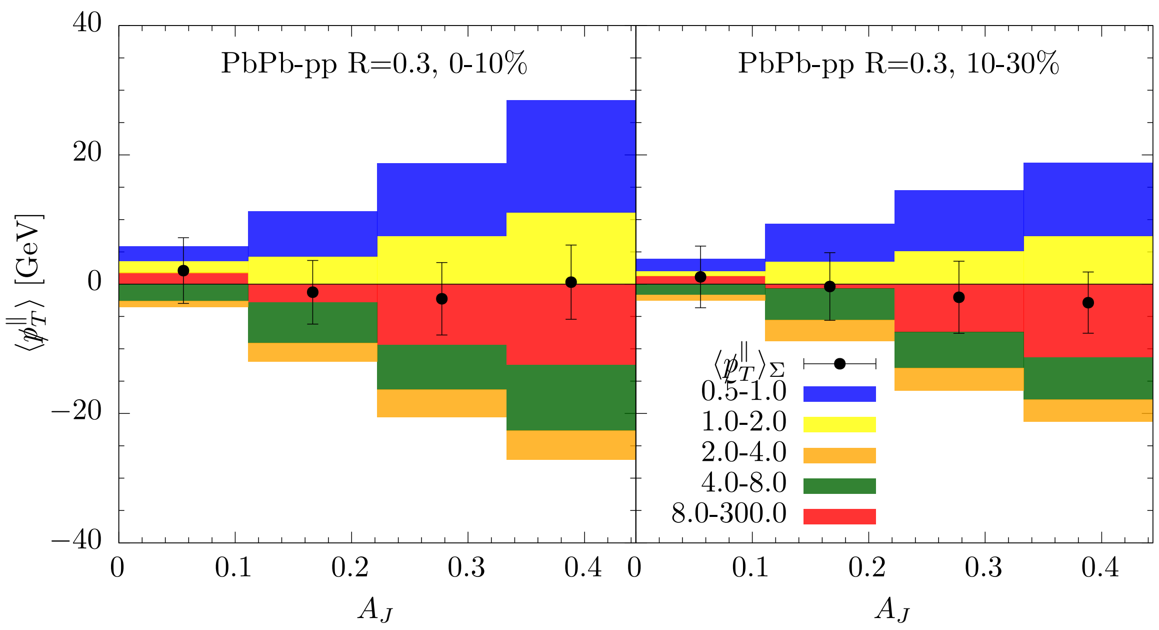

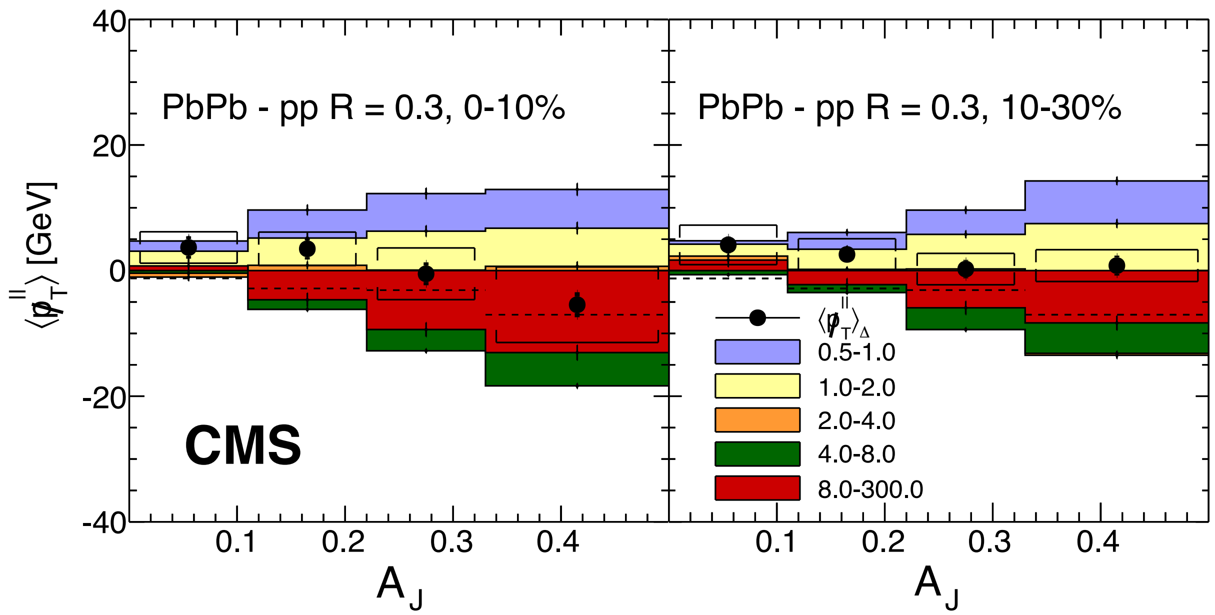

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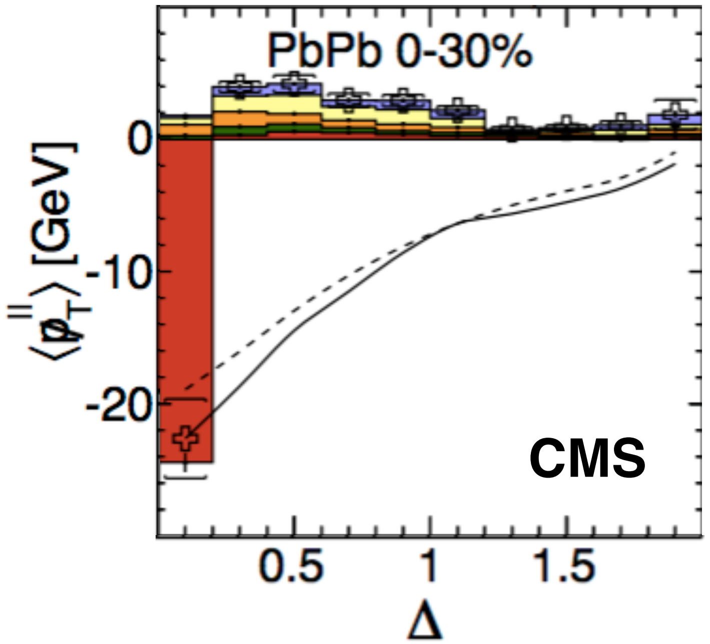

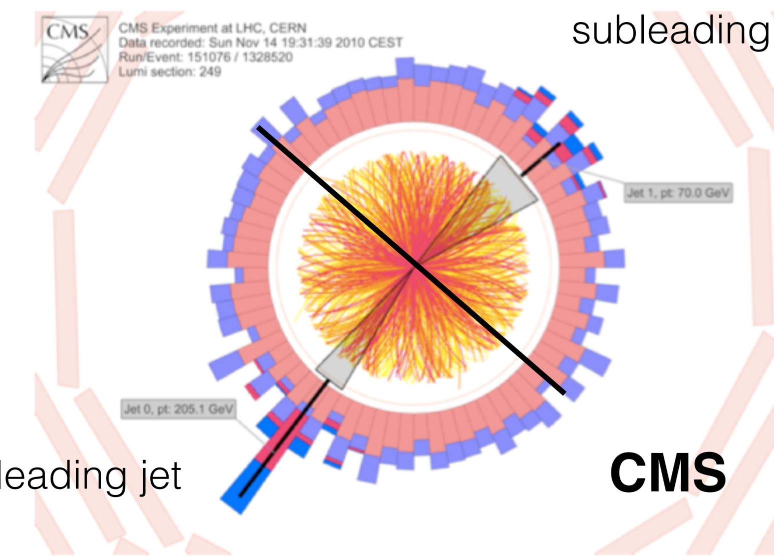

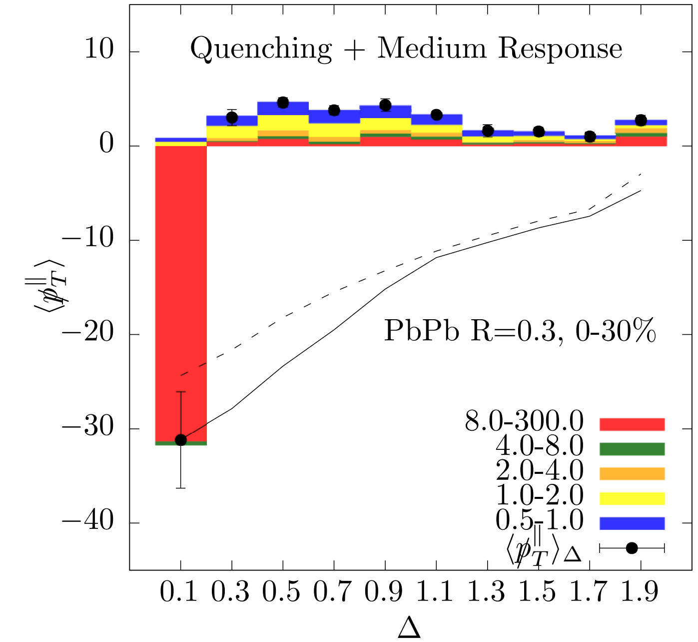

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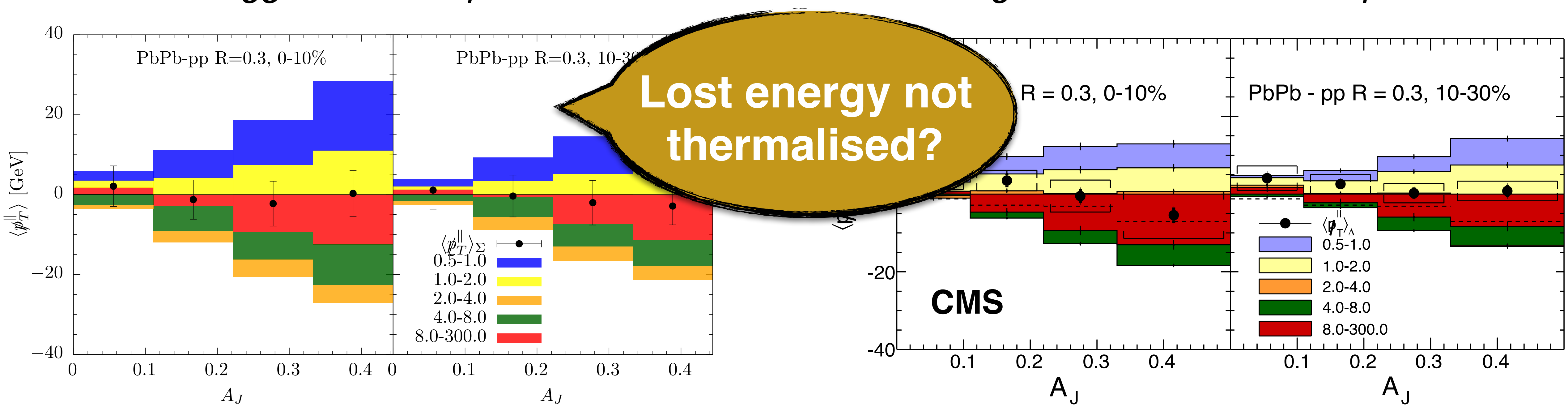
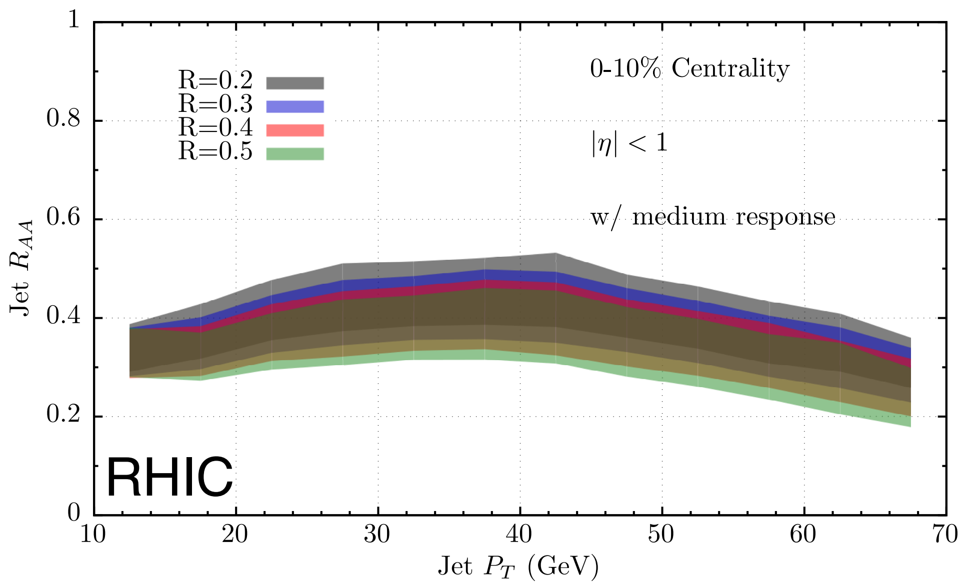


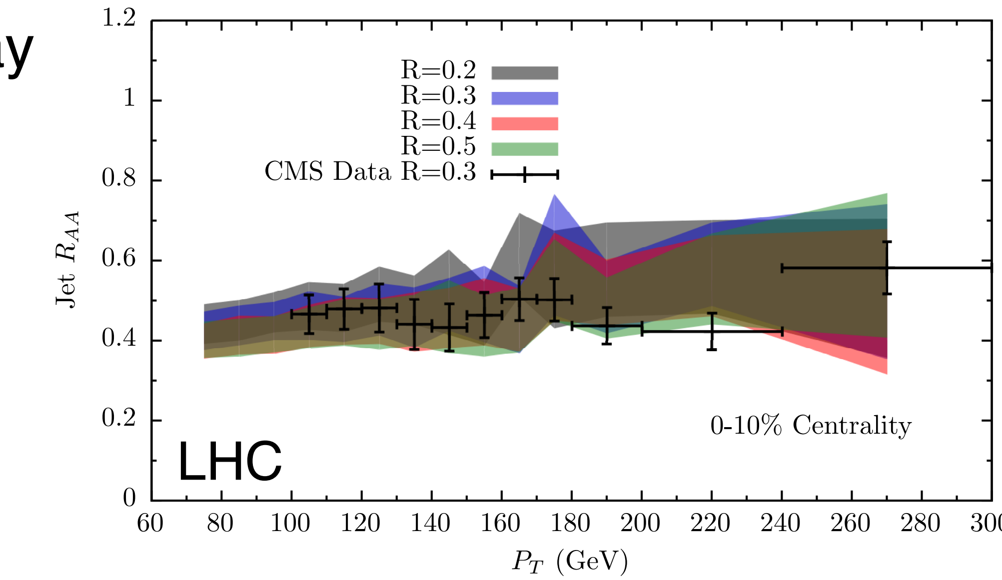
R_{AA} vs R

wider, more active jets lose more energy as they have more energy loss sources



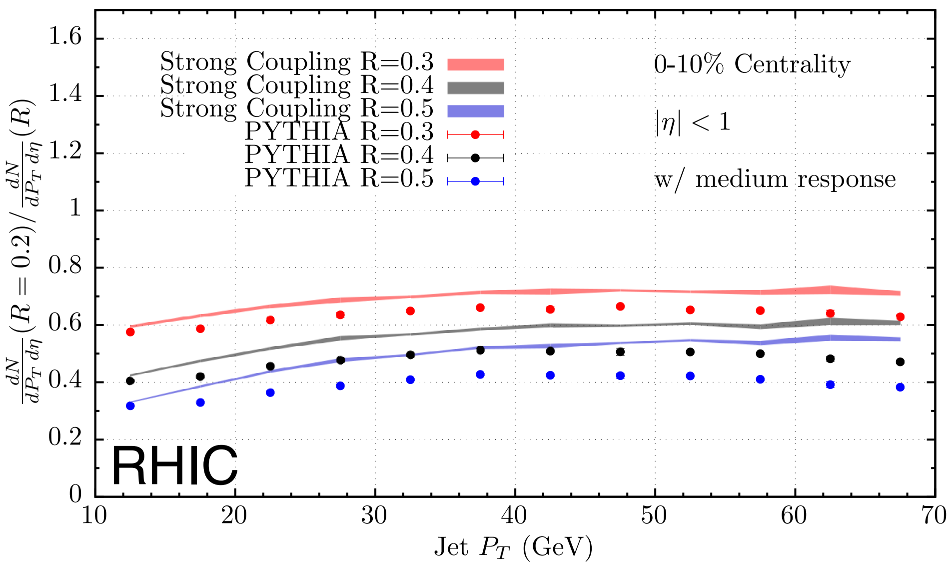
lost energy does not stay close to the jet axis

mild recovery by increasing jet radius R

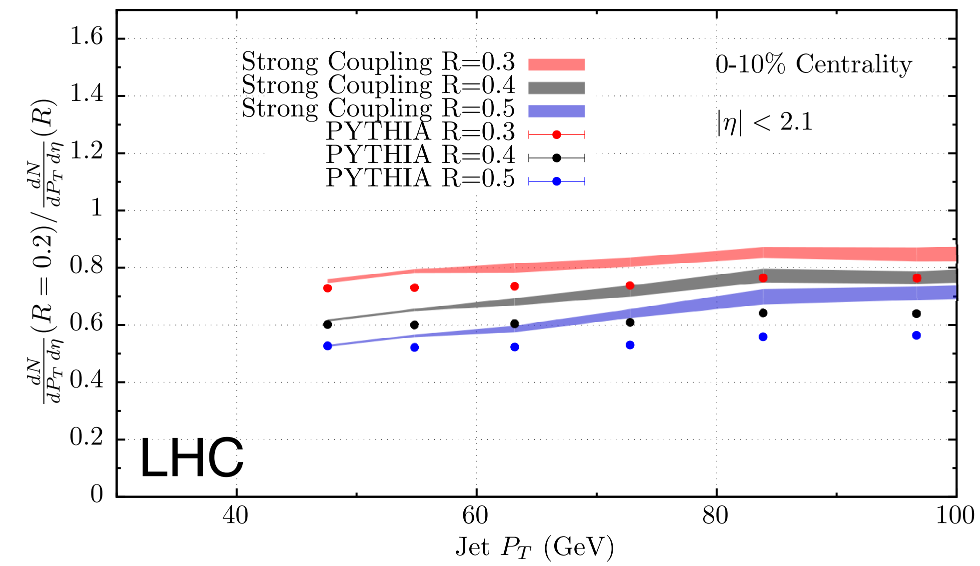


We can use the R dependence of jet suppression to greatly constrain models assumptions

$\Delta R \downarrow$ *has energy been thermalised?* *need strong gluon re-scattering?* $\Delta R \uparrow$



jet spectra ratio among different R offer great systematic uncert. cancellation



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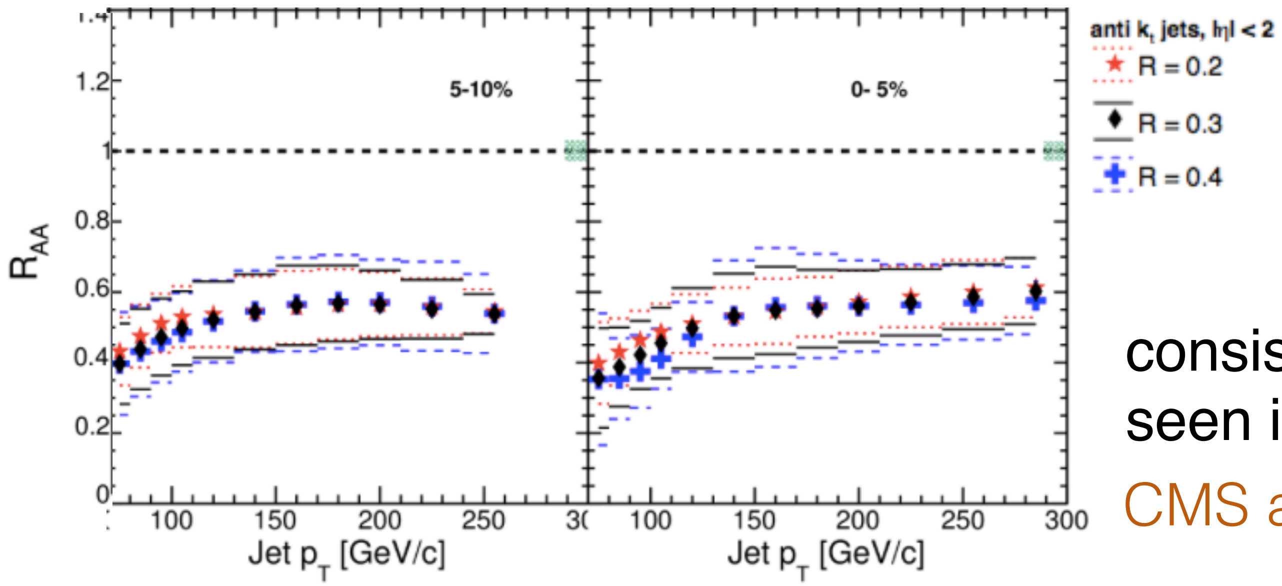
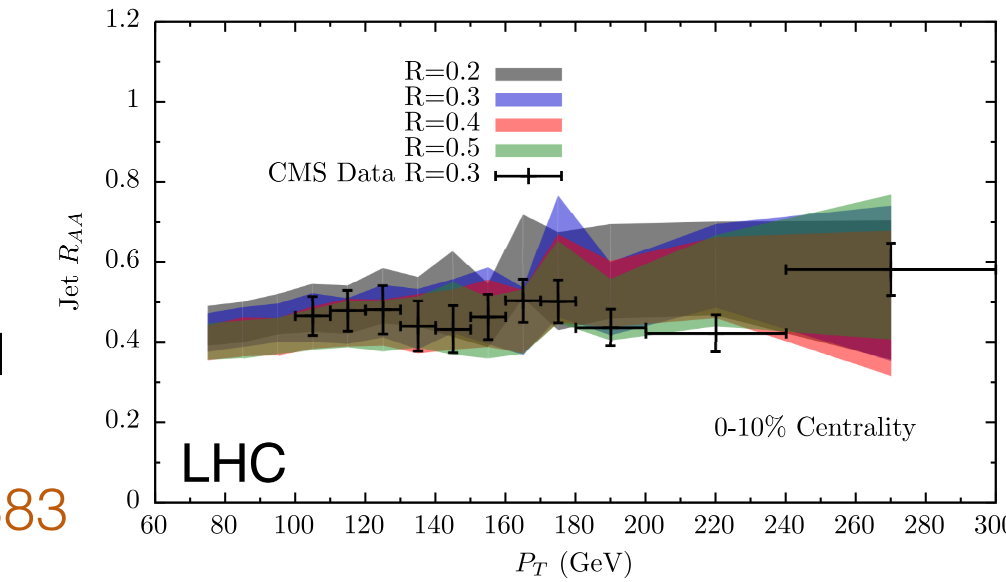


consistent with trend seen in data

CMS arXiv:1609.05383



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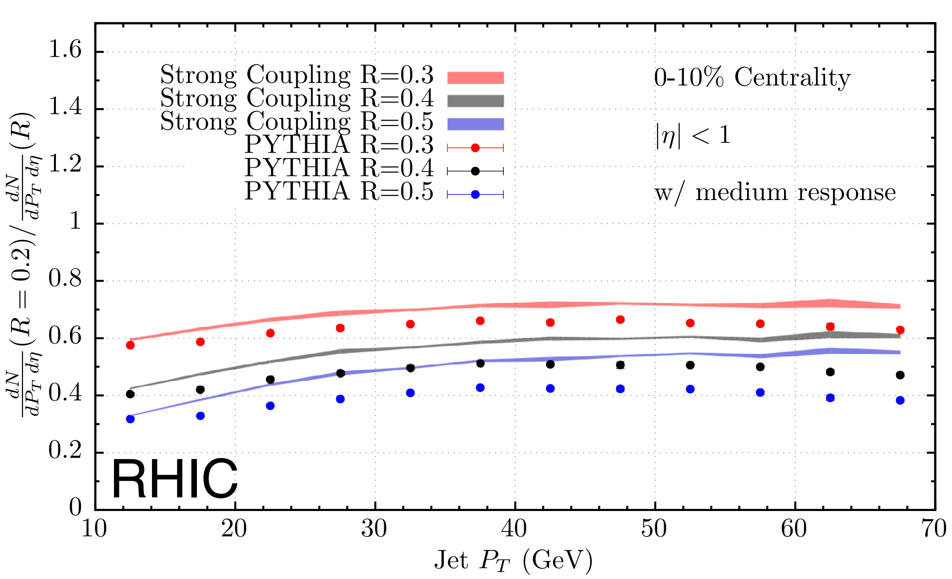
JETSCAPE



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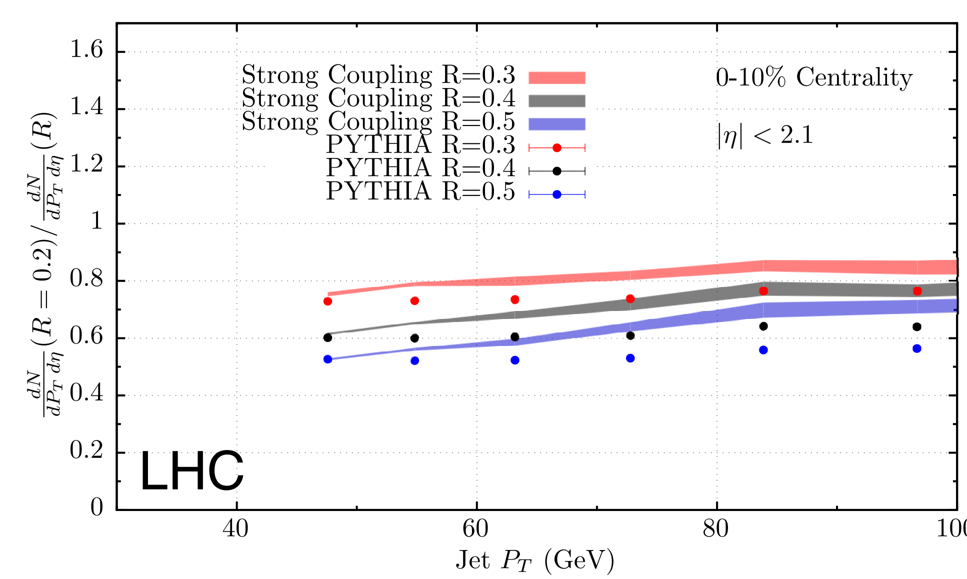
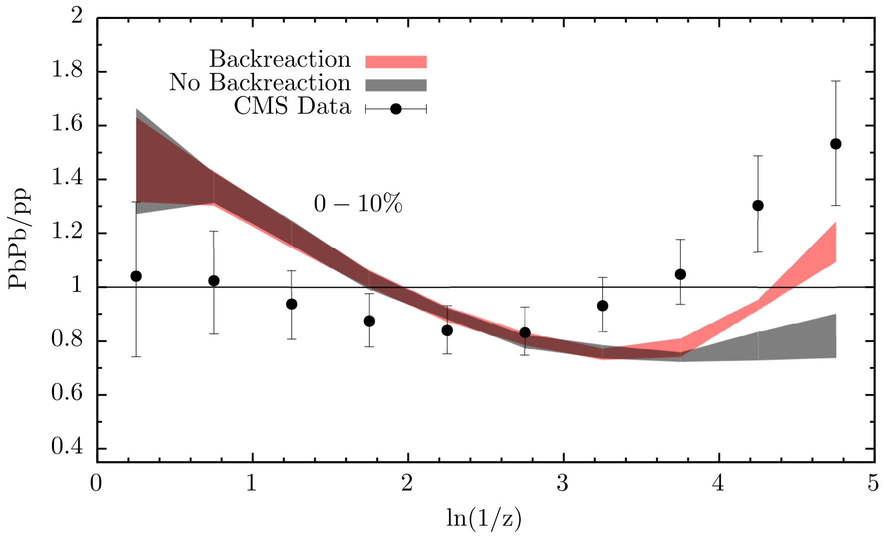


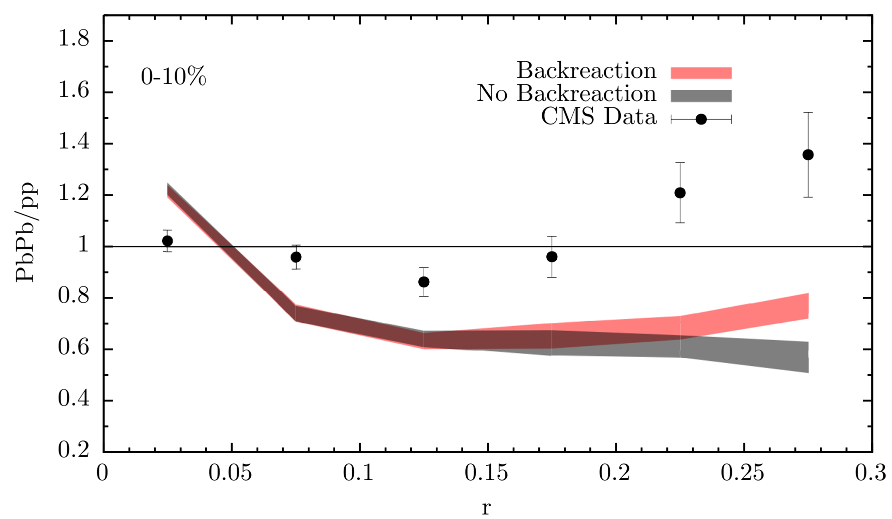
Medium response on jet substructure

Jet fragmentation function



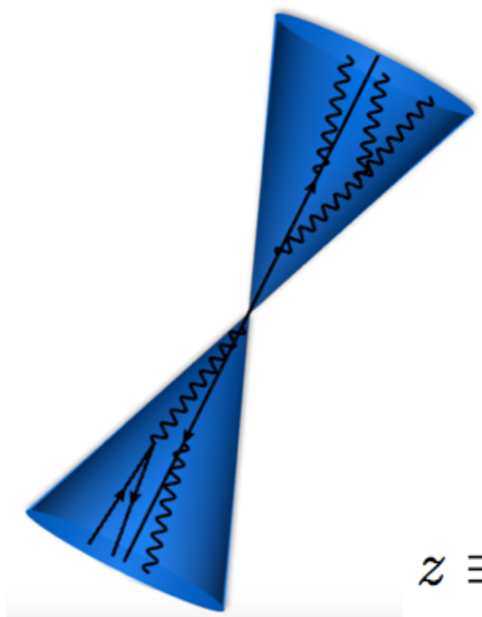
increasing #soft particles

Jet shapes



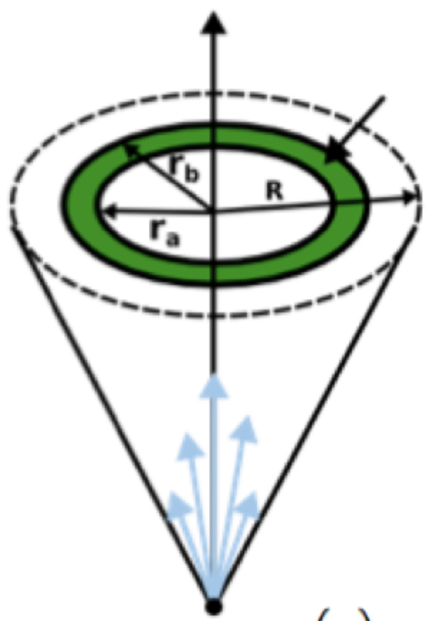
increasing #wide particles

effect in the right direction, but clearly not enough



Longitudinal energy distribution

$$z \equiv \frac{p^{||}}{p^{jet}}$$



Transverse energy distribution

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}$$

Medium response on jet substructure

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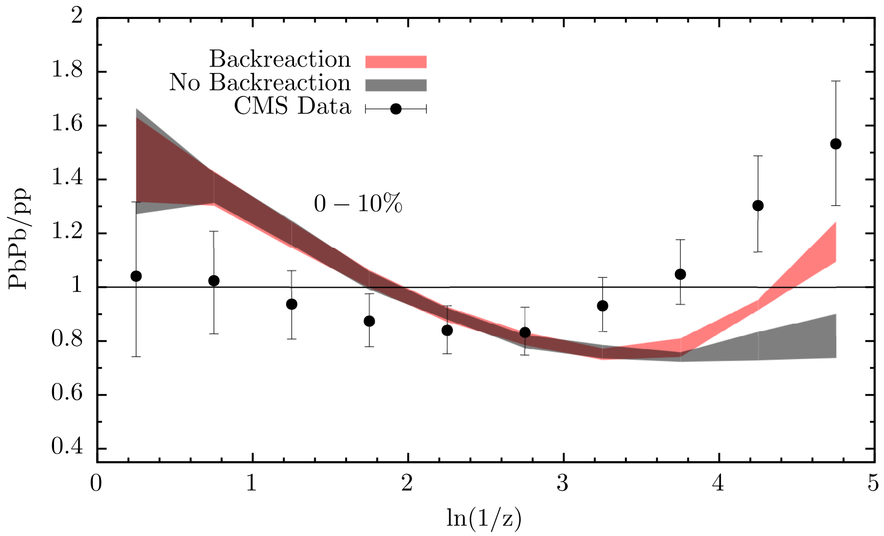

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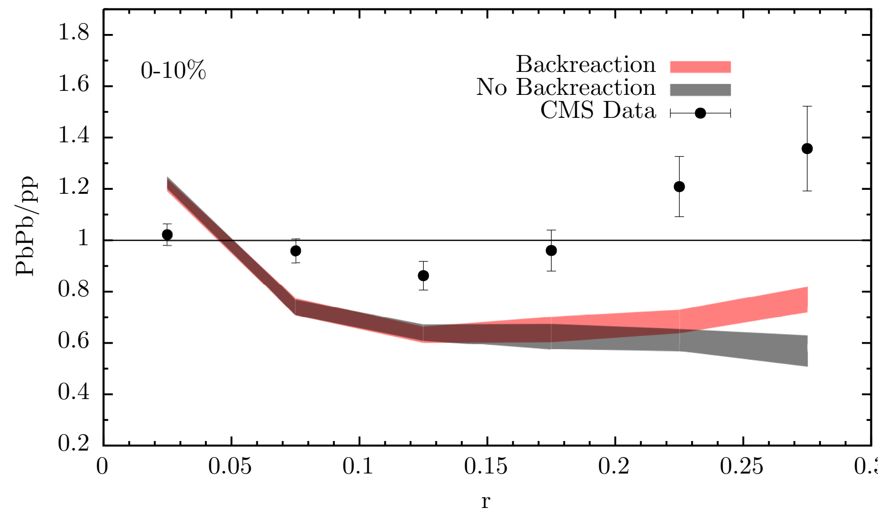

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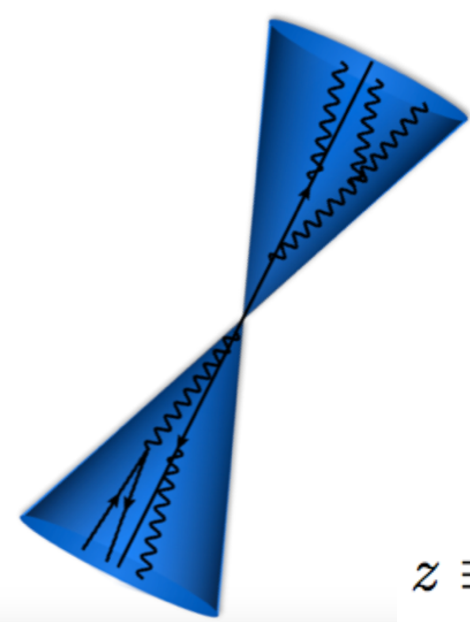
Lost energy not thermalised?



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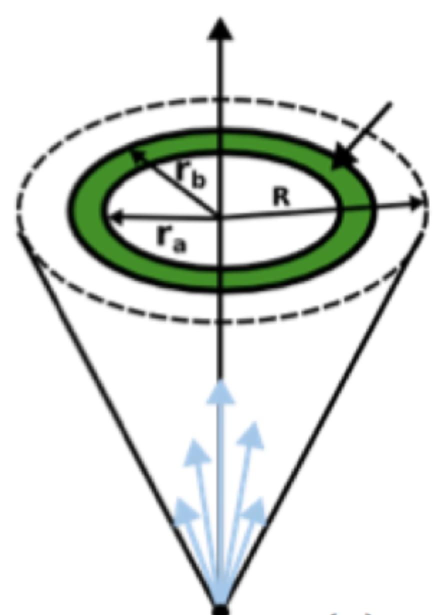

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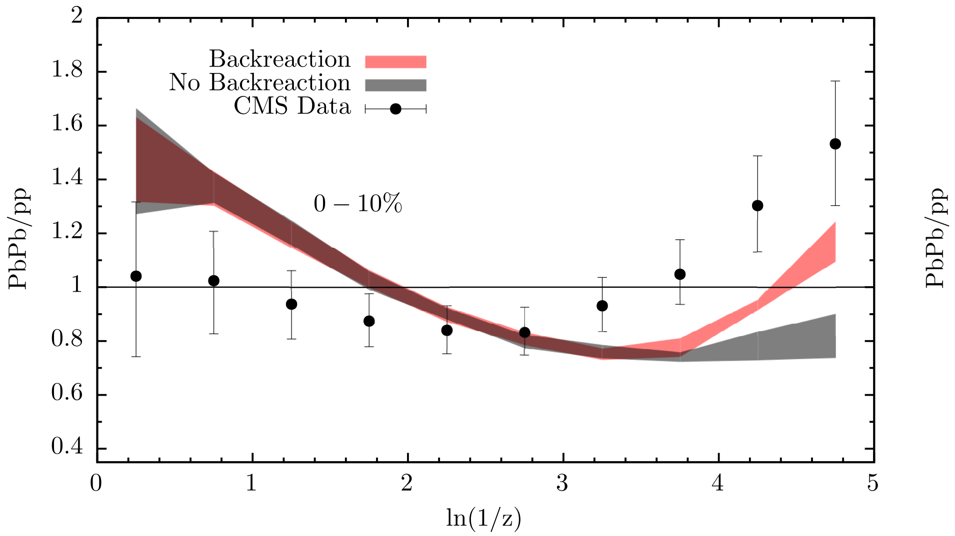

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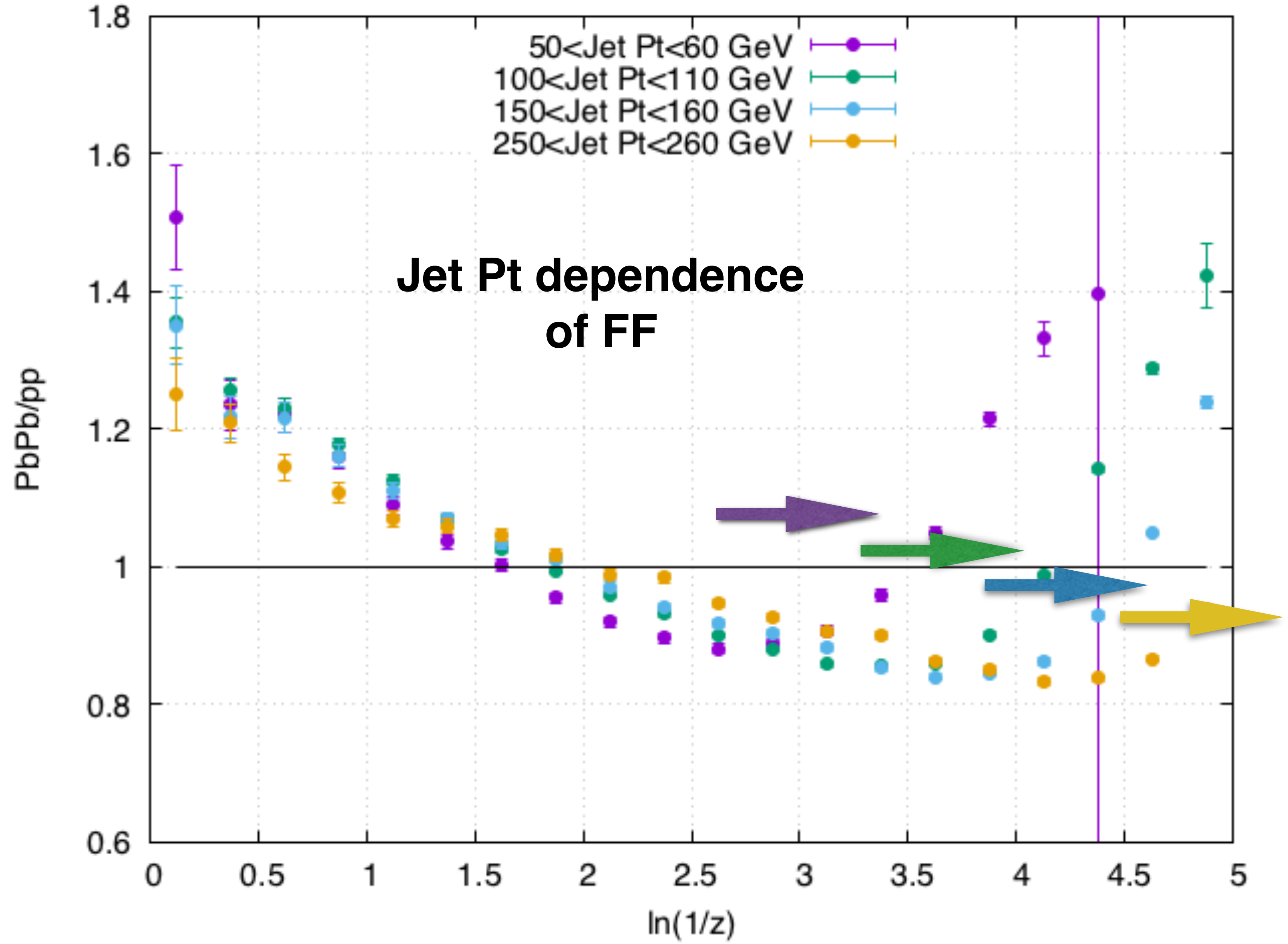

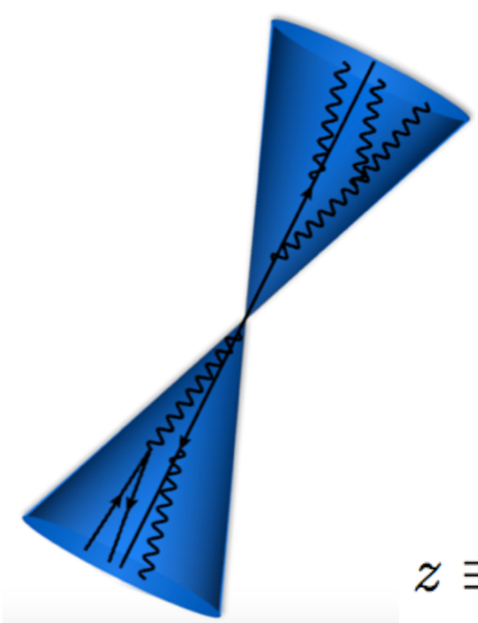

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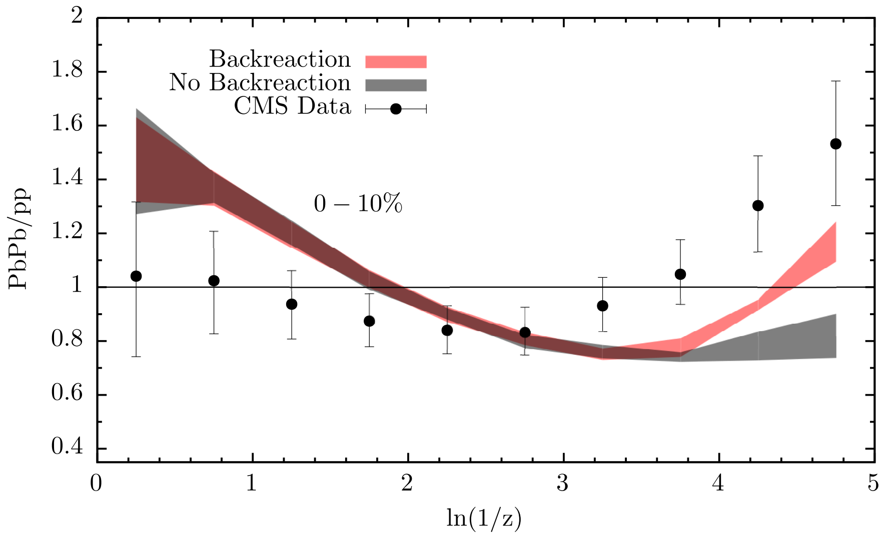
Longitudinal energy distribution

Soft enhancement displaced as Jet Pt grows: fixed medium scale

(better look at Pt instead of z)

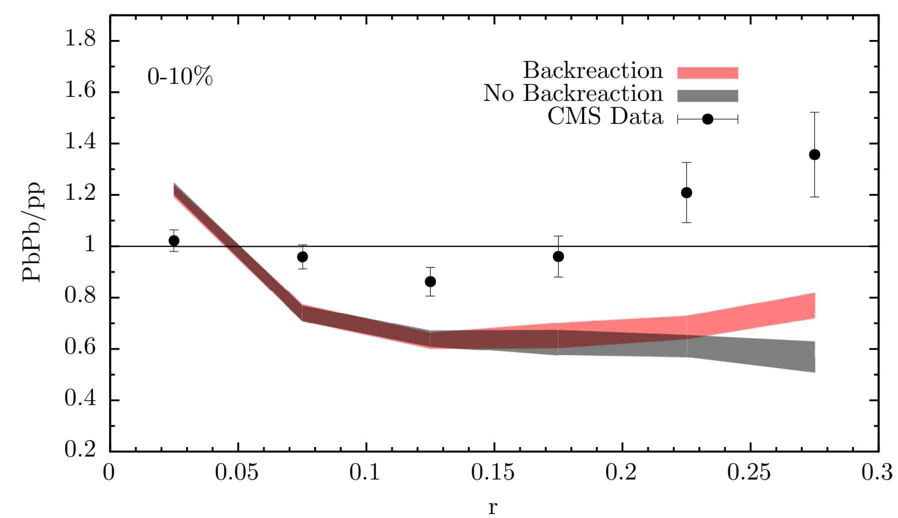
Medium response on jet substructure

Jet fragmentation function



increasing #soft particles

Jet shapes



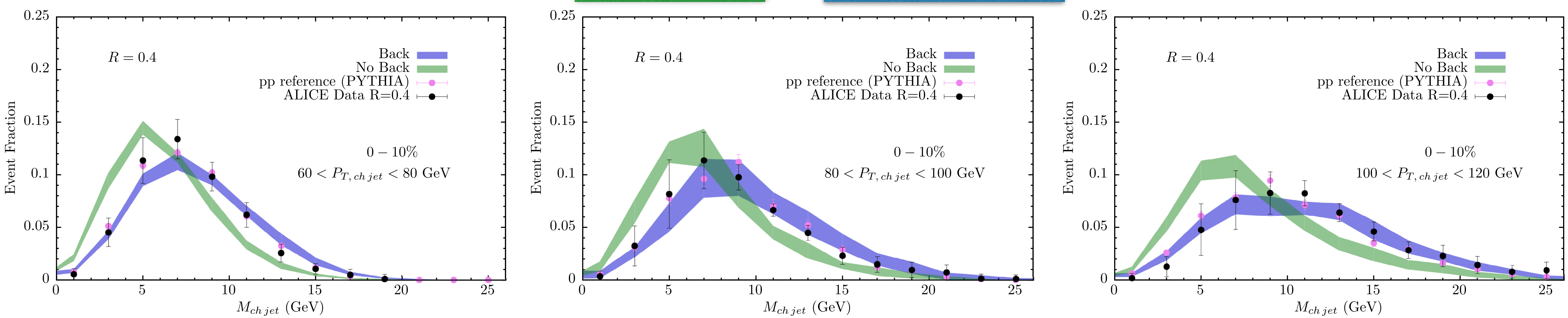
increasing #wide particles

effect in the right direction, but clearly not enough

cancellation between two effects

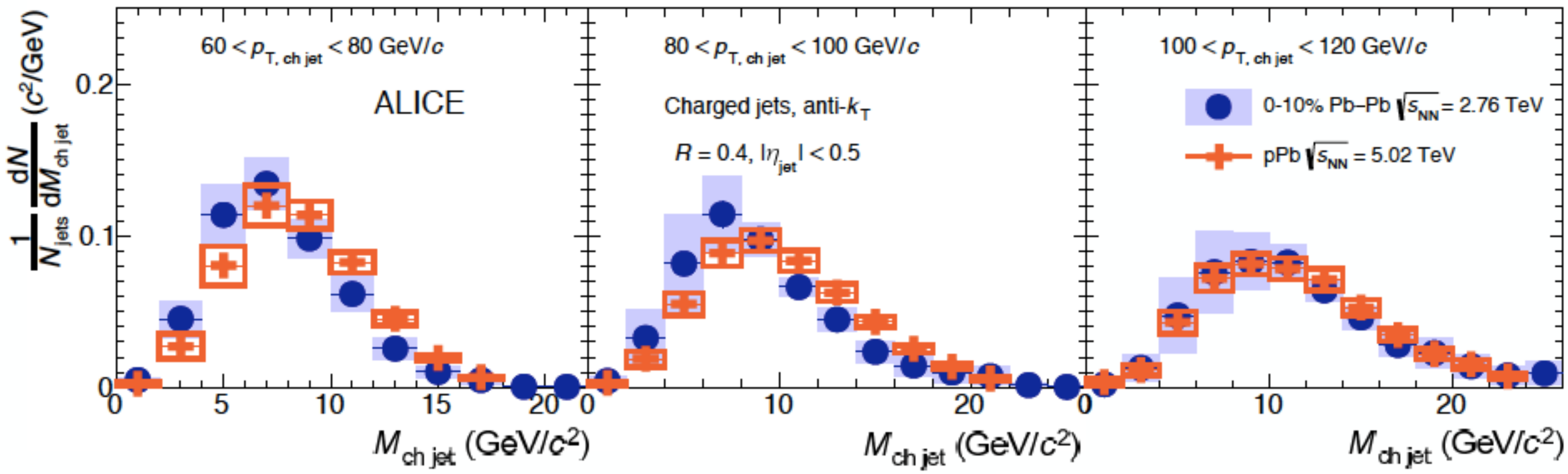
quenching

back-reaction



Charged jet mass

Medium response on jet substructure



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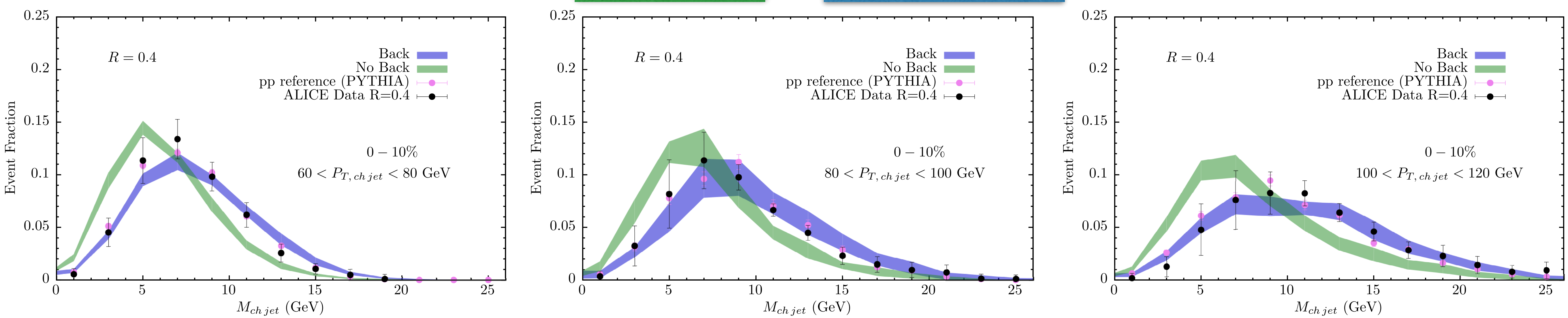

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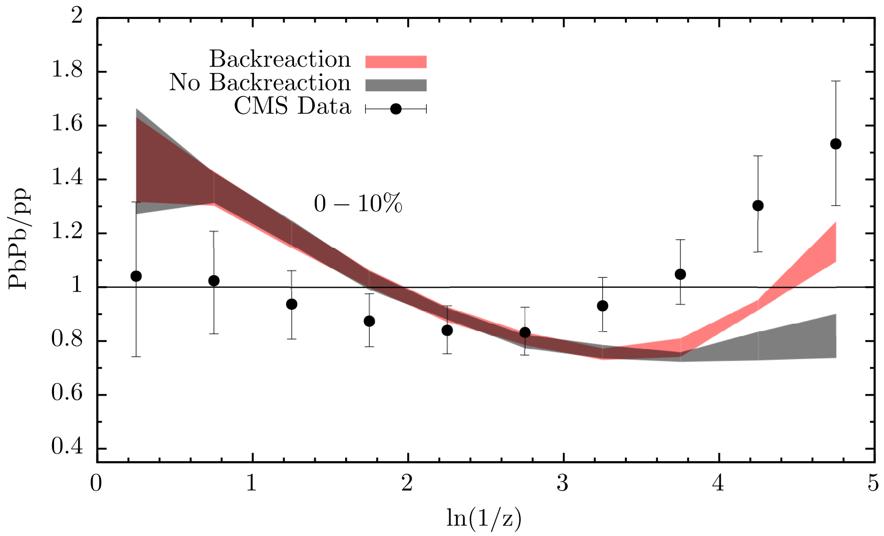

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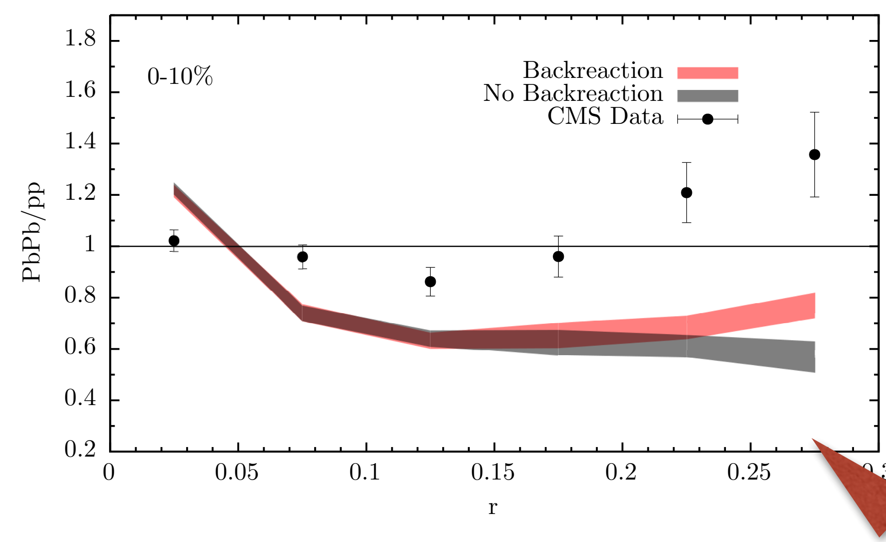


increasing #wide particles

effect in the right direction, but clearly not enough

....

what physics is missing?

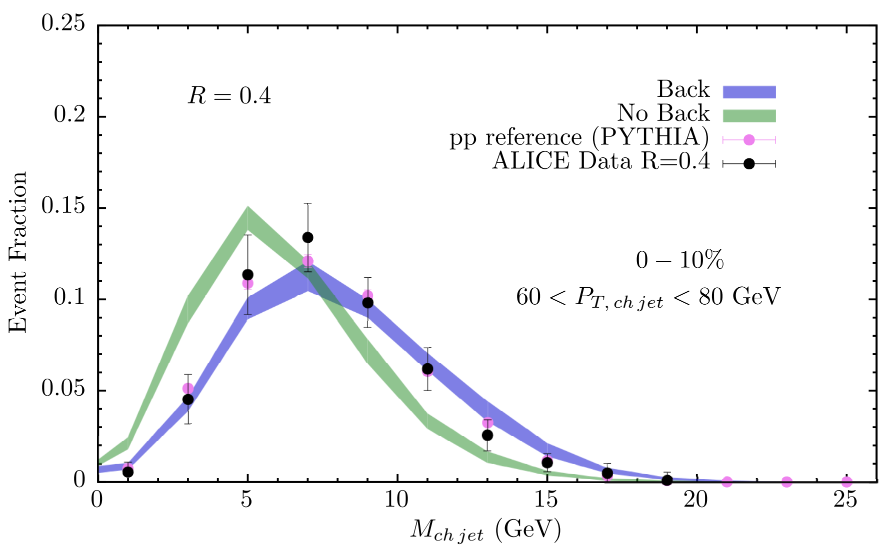
how to reconcile?

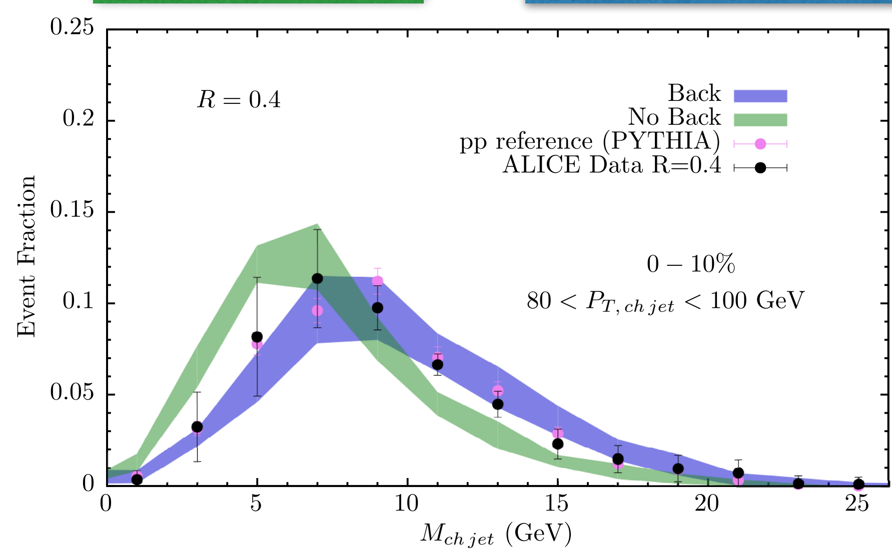
JEWEL w/ recoil describes jet shapes, but overestimates mass

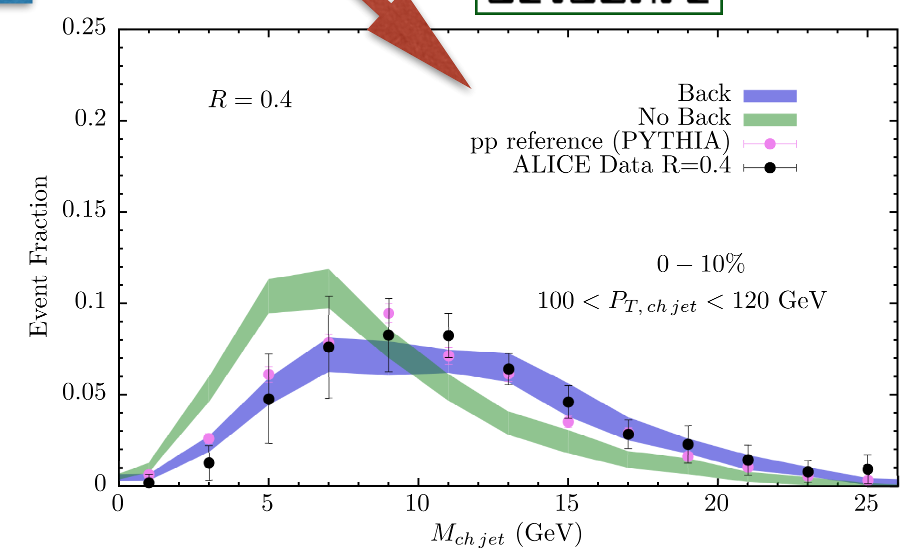
cancellation between two effects

quenching

back-reaction





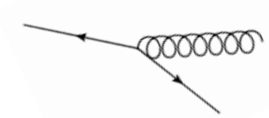


Charged jet mass

Finite resolution effects in holography

Casalderrey-Solana & Ficnar ‘15

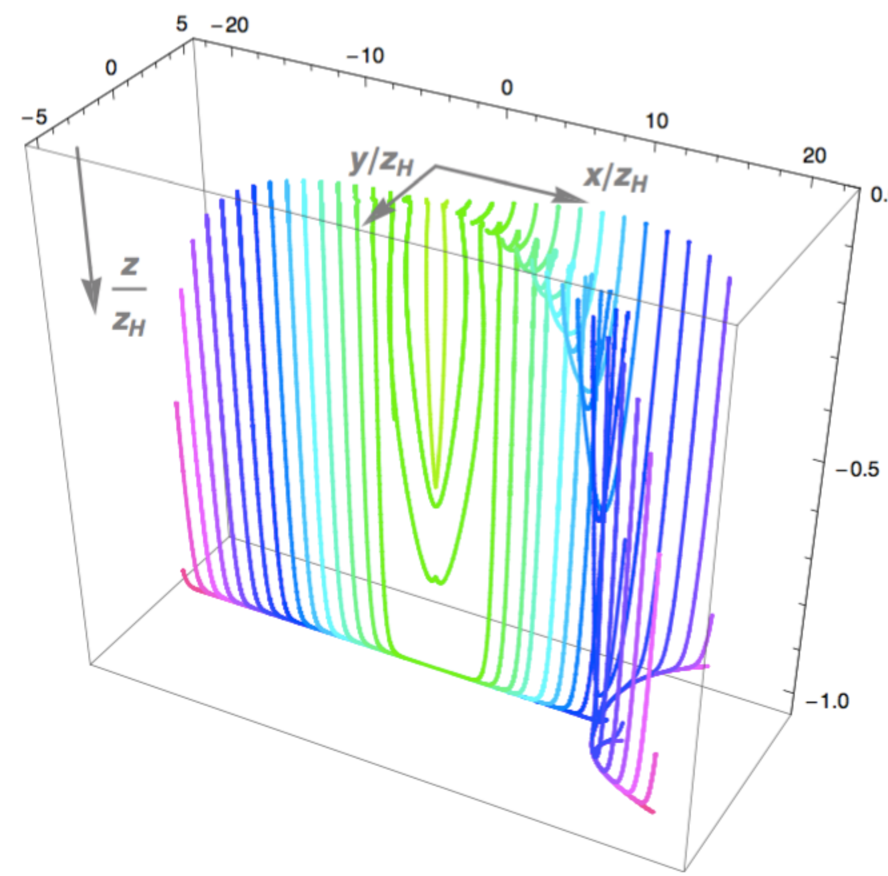
holographic description of 3-jet events

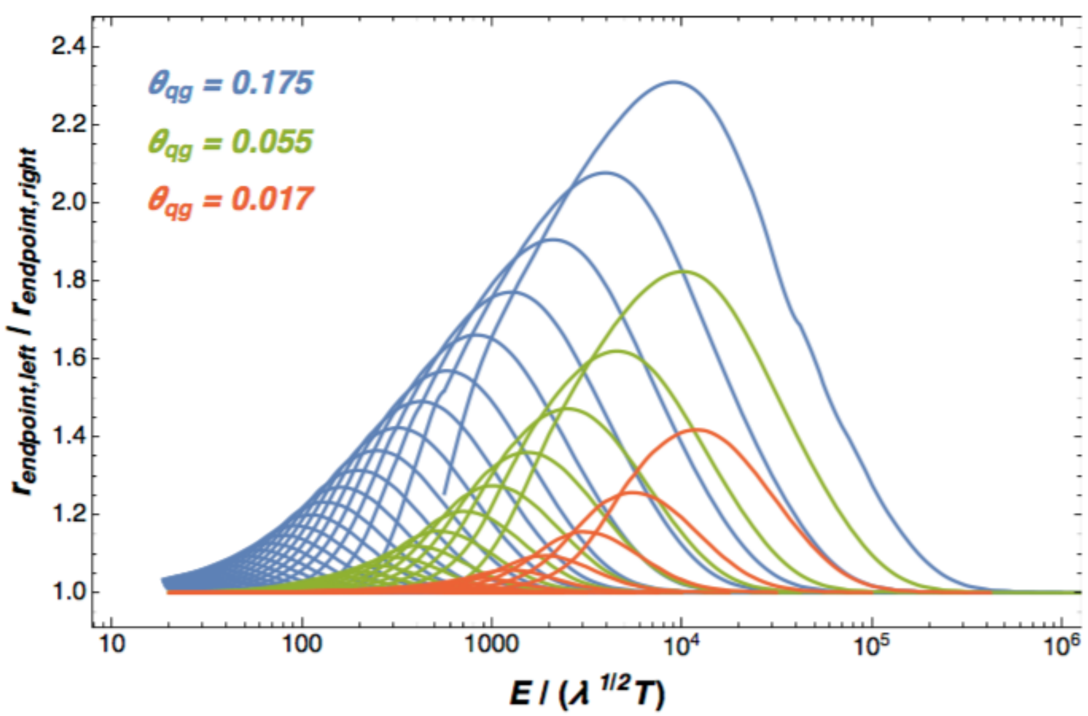


smallest angular separation between two jets that the medium can resolve?

assign a transverse structure to the string such that a quark-gluon system is emulated

study the stopping distances as a function of opening angle and energy





$$\theta_{\rm res} = \frac{2^{4/3}}{\pi}\frac{\Gamma(3/4)^2}{\Gamma(5/4)^2}\left(\frac{E}{\sqrt{\lambda}T}\right)^{-2/3}$$

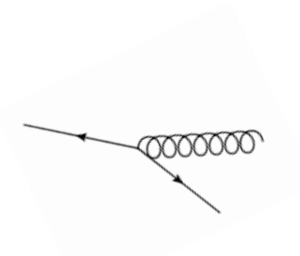
different scaling than pQCD in a dense plasma

$$\theta_{\rm res}^{\rm pQCD} \propto E^{-3/4}$$

Finite resolution effects in holography

Casalderrey-Solana & Ficnar '15

holographic description of 3-jet events



smallest angular separation between two jets
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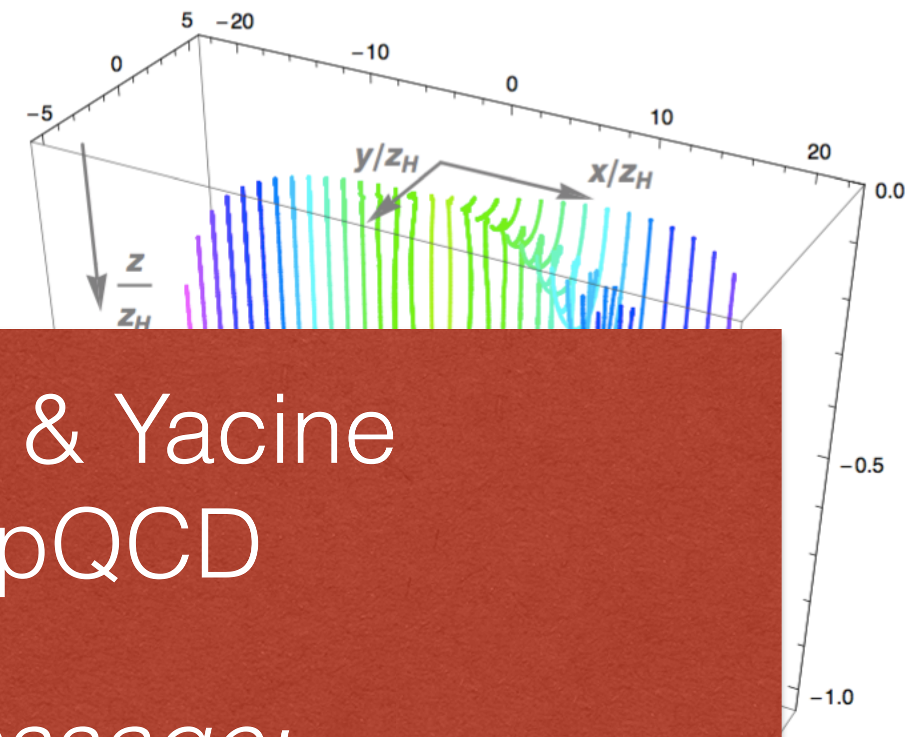
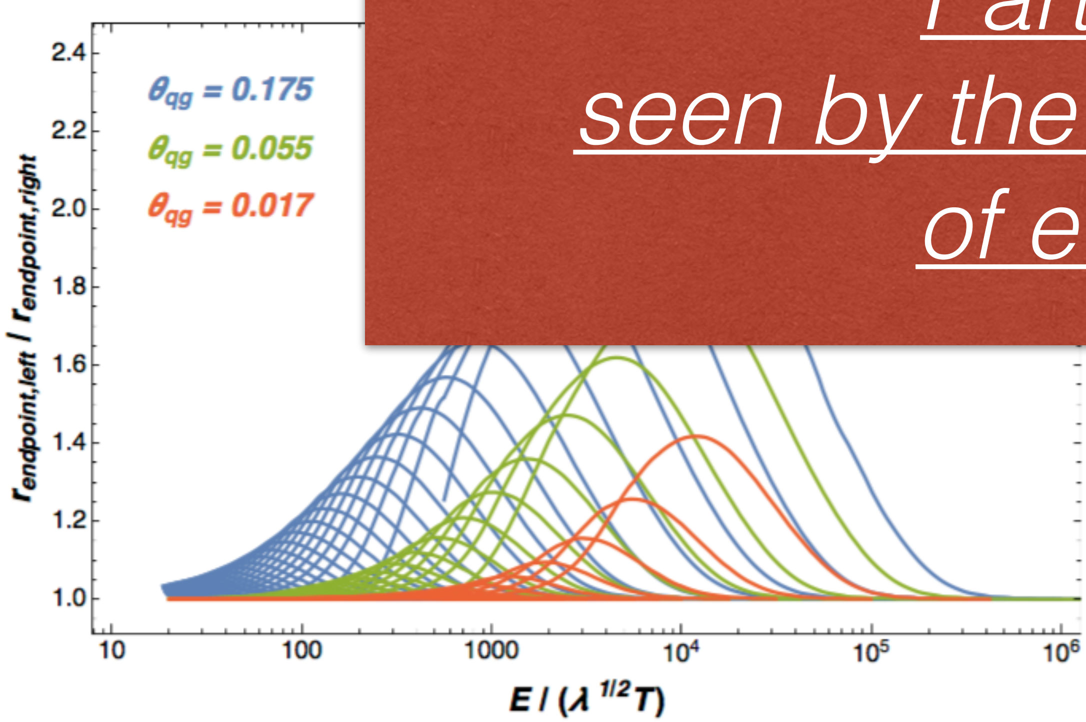




See talks by Konrad & Yacine
for coherence in pQCD

My take home message:
<u>Parton showers are seen by the medium as a collection of effective emitters</u>

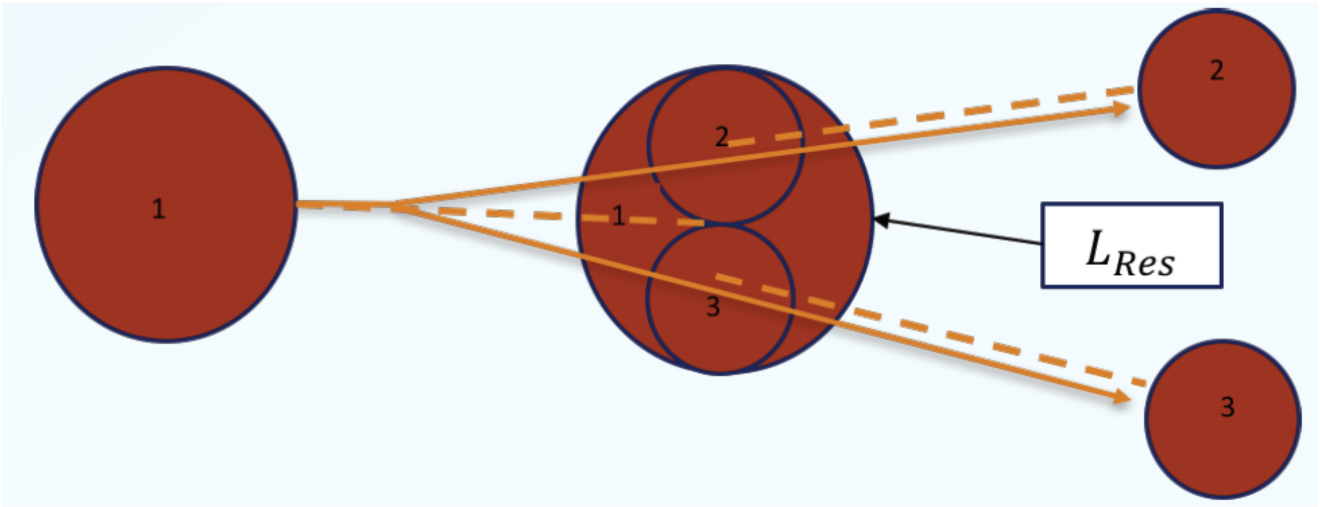
different scaling than pQCD in a dense plasma

$$\theta_{\mathrm{res}}^{\mathrm{pQCD}} \propto E^{-3/4}$$

An *estimate* of finite resolution effects

within the hybrid strong/weak coupling model

Hulcher et al. 1707.05245



the medium perceives the system as a collection of effective emitters

the number and rearrangement of the effective emitters is governed by the resolution length

the effect modifies the space-time picture of the parton shower

JETSCAPE

need to agree on framework model
needs for coherence effects

resolution length in a **finite** plasma at strong coupling is currently not known

assume as an *exploratory study* that the screening length is the relevant scale

$$L_{\mathrm{res}} \sim \lambda_D$$

Finite resolution on observables

2nd free parameter

$$L_{\text{res}} = \frac{Y}{\pi T}$$

$\alpha_s = 0.3$

weak coupling

$Y \sim 1.3$

Bak et al. '07

strong coupling

$Y \sim 0.3$

(but greater in QCD)

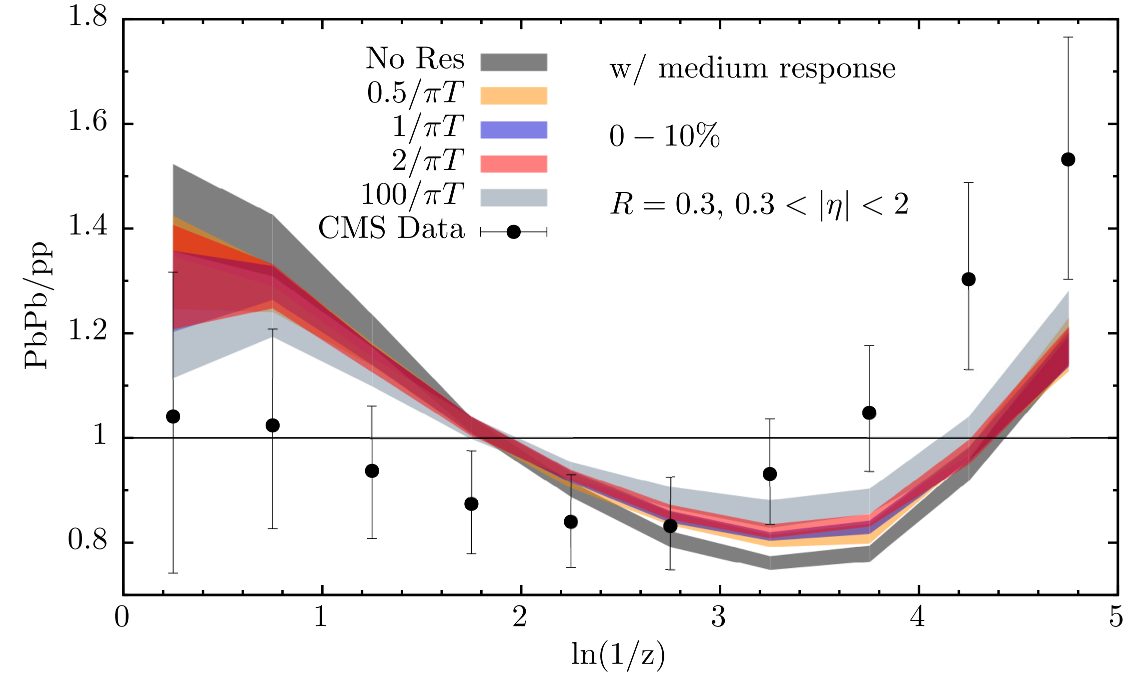
fewer # of effective energy loss sources

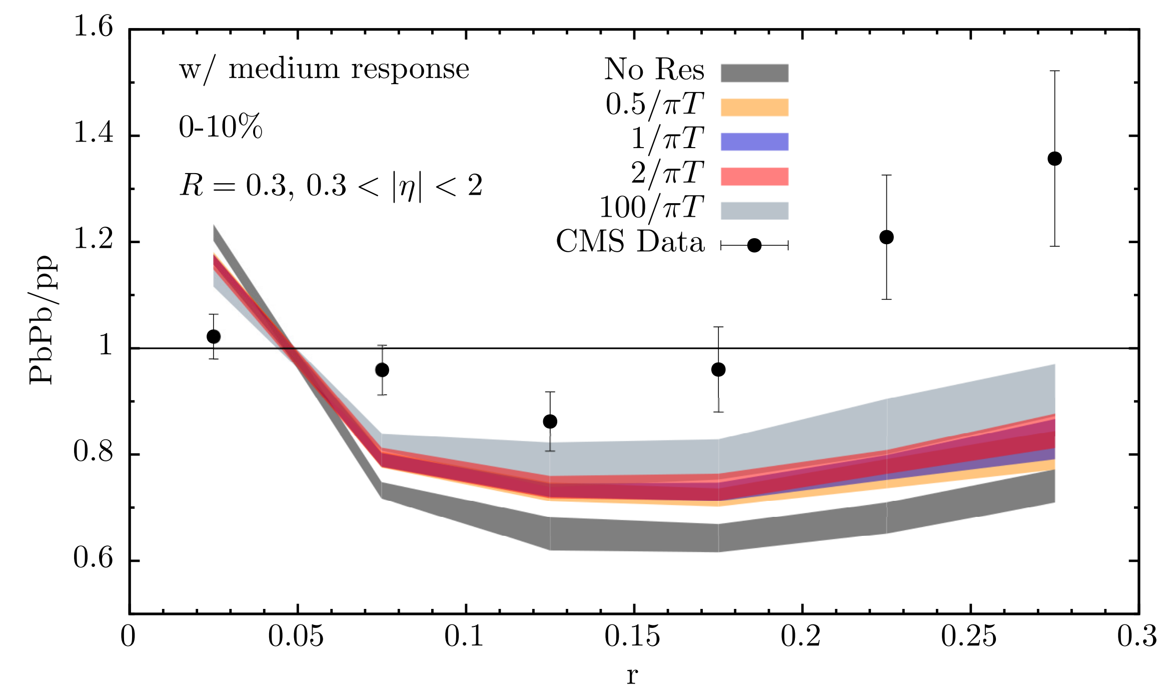
reduce stopping distances
(to keep jet RAA the same)

jet substructure is modified due to finite resolution:

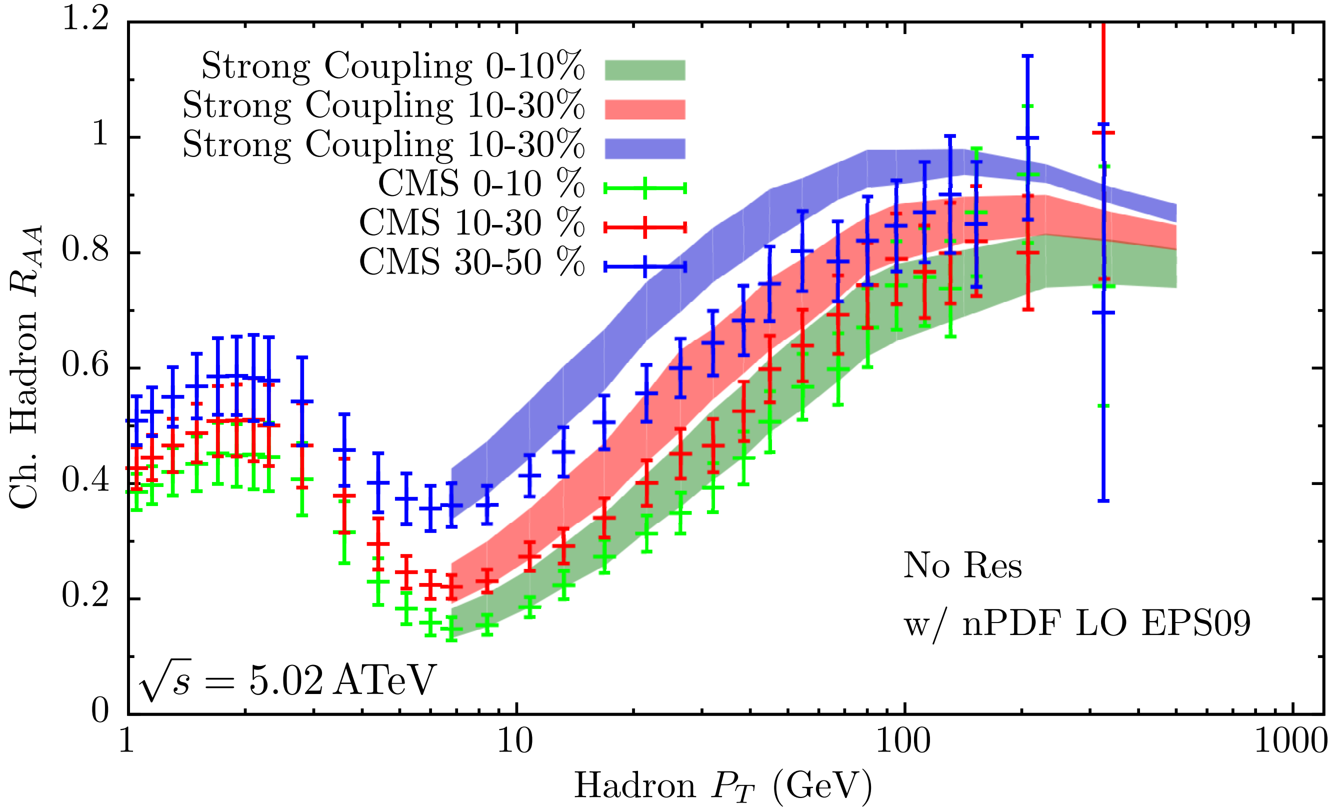
- energy loss more democratic among partons
- increases survival rate of softer, wider radiation
- leading track gets more quenched

Hulcher et al. 1707.05245





Hadron suppression at LHC



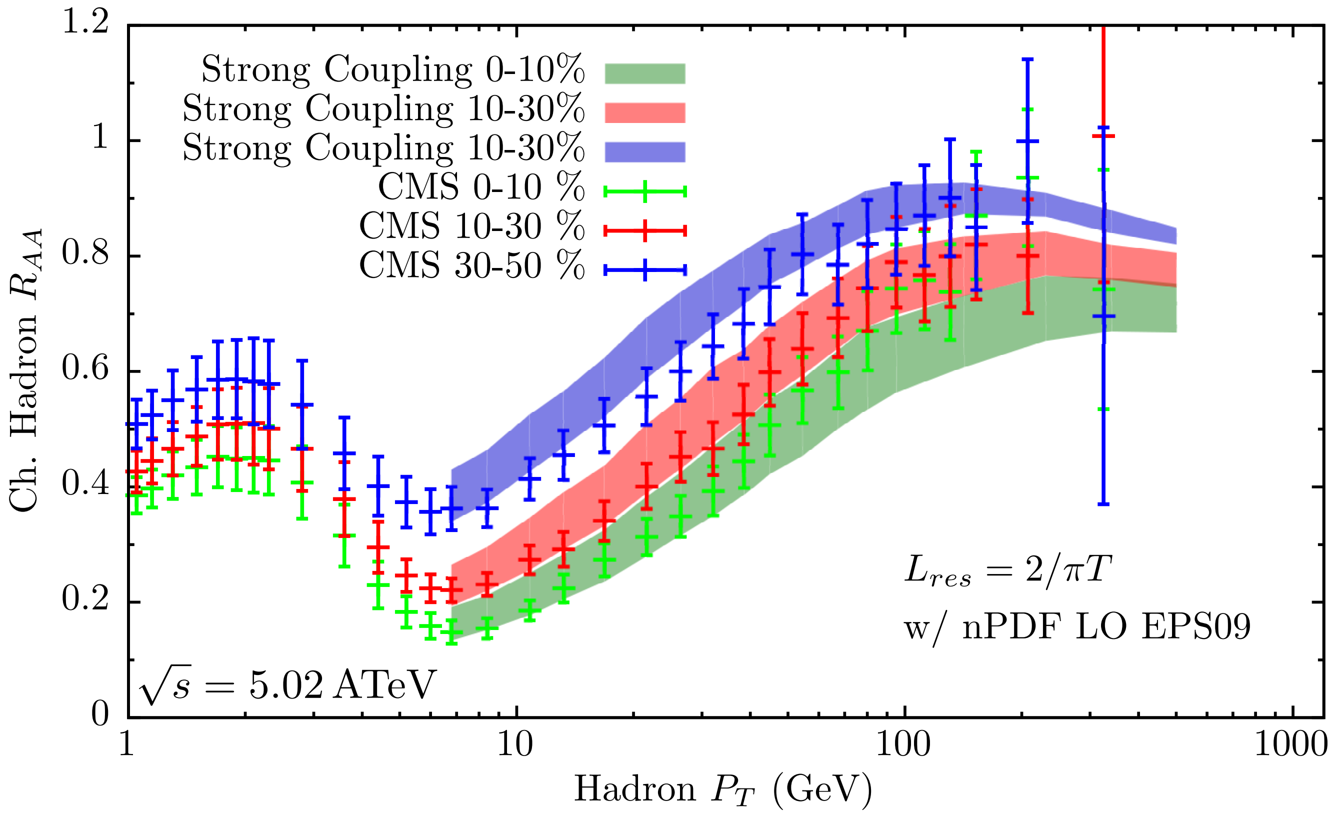
tension in centrality evolution

triggering on a high energy hadron

selects narrow jets that lost little energy

$$R_{AA}^{\text{had}} > R_{AA}^{\text{jet}}$$

....



improved agreement

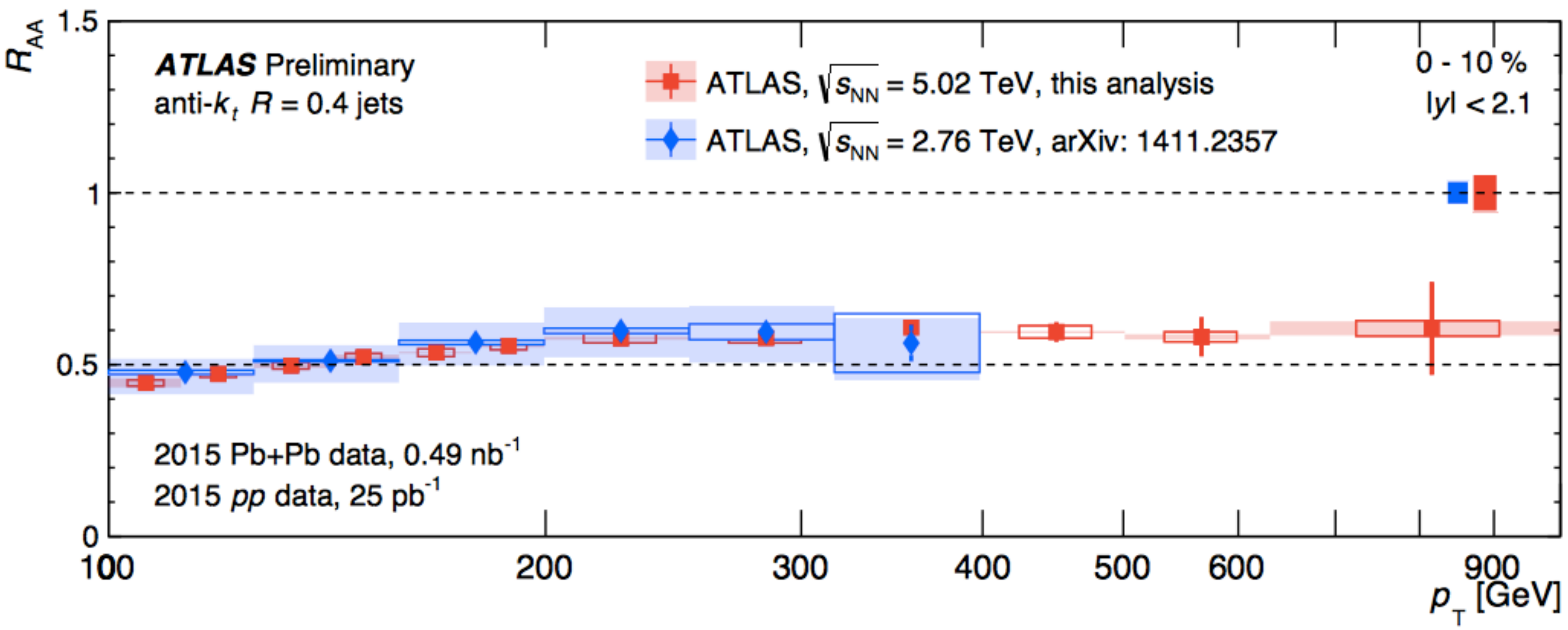
decrease of stopping distances due to finite resolution

greater quenching on leading tracks

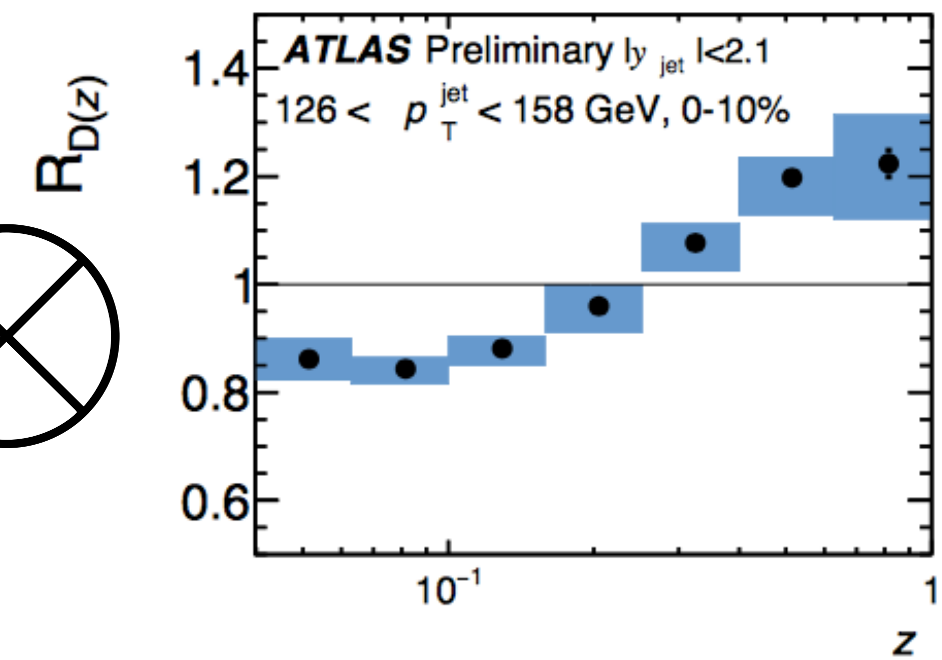
in preparation

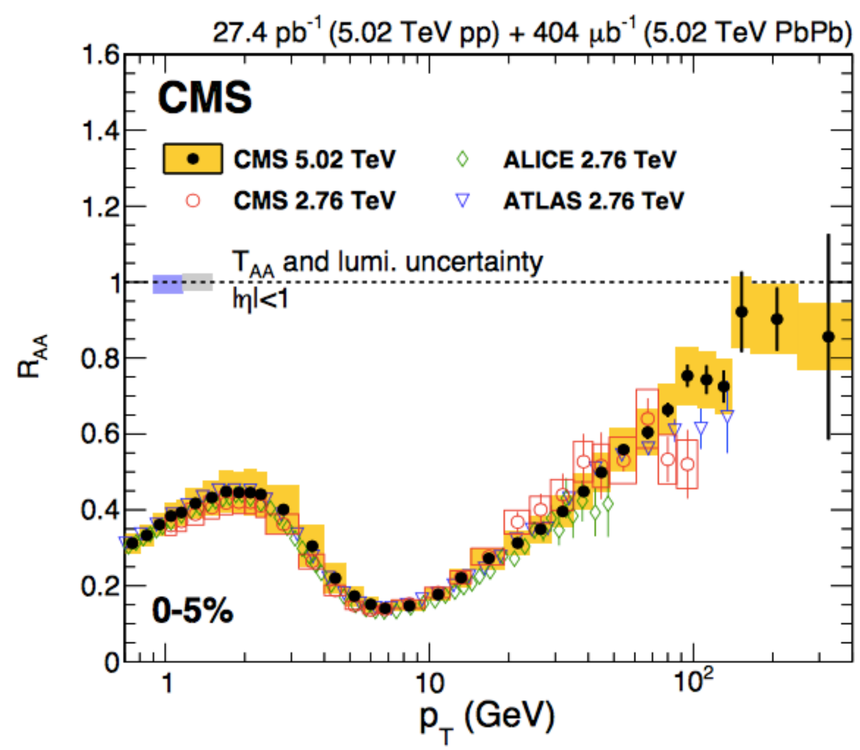
Hadron vs Jet Suppression

Jet spectra **convoluted with** **jet FF**



$\otimes$

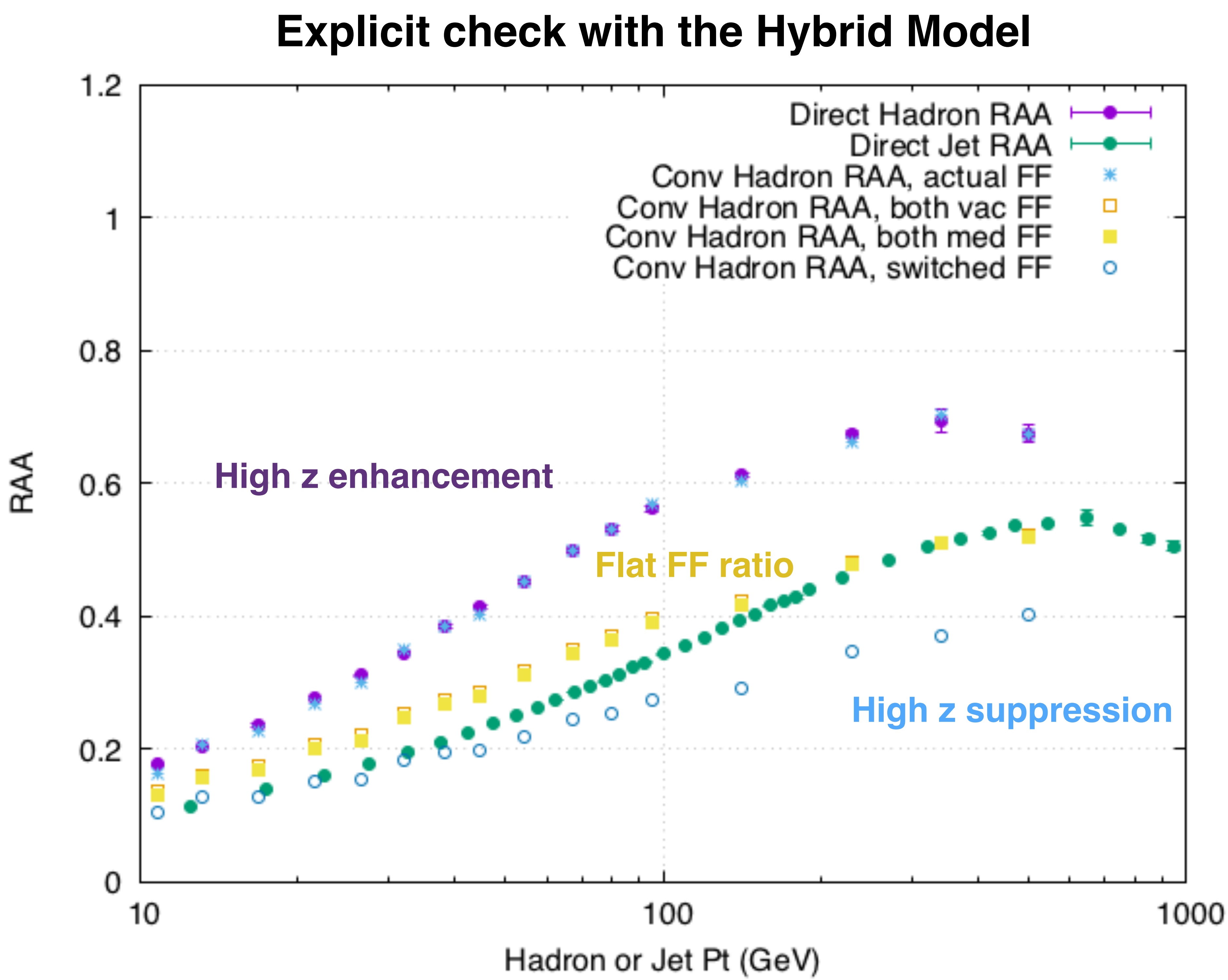




generates Hadron spectra

in preparation

Hadron vs Jet Suppression

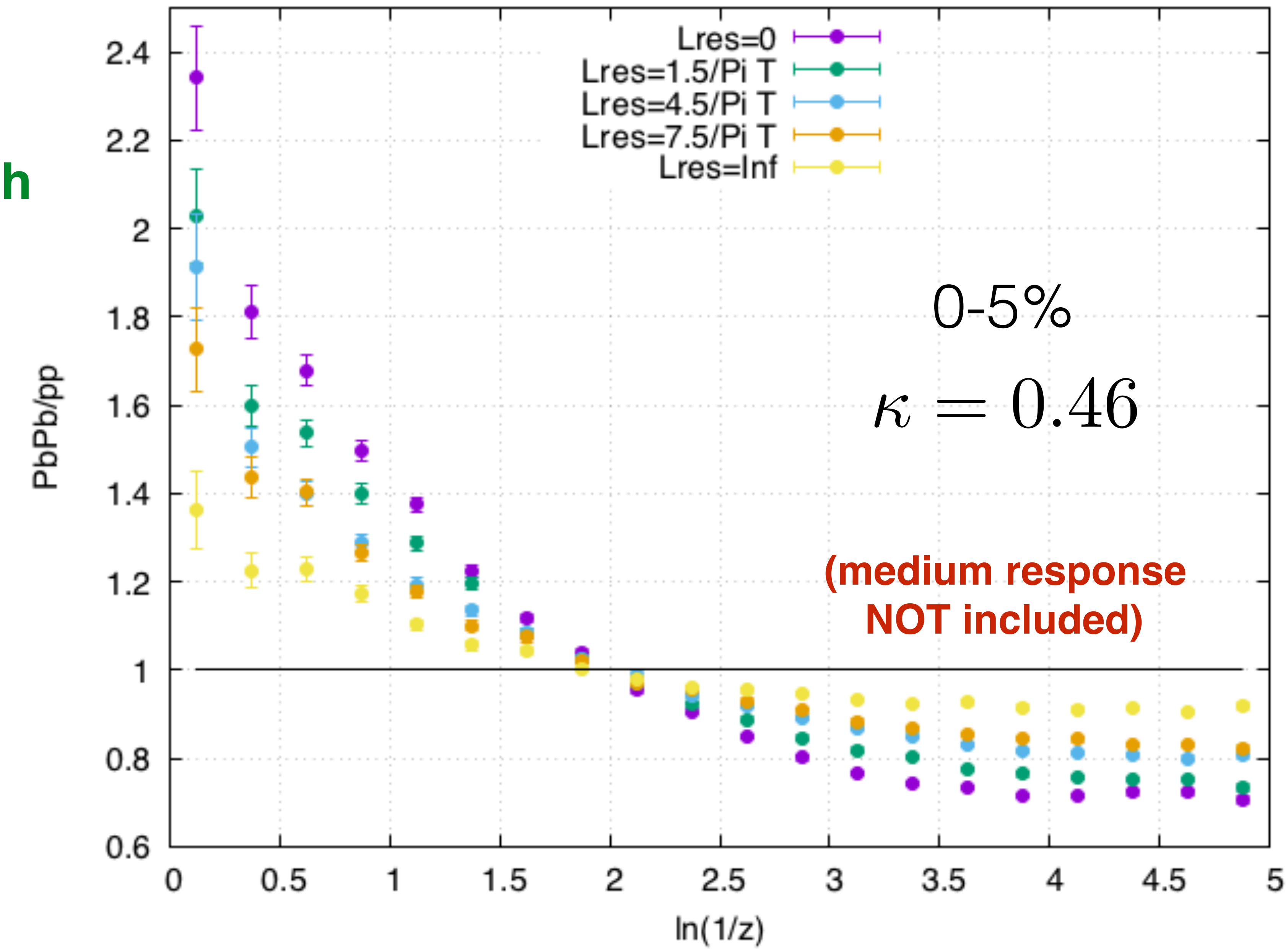


in preparation

Hadron vs Jet Suppression

High z enhancement modulated by plasma resolution length

$z \downarrow$ as $L_{res} \uparrow$

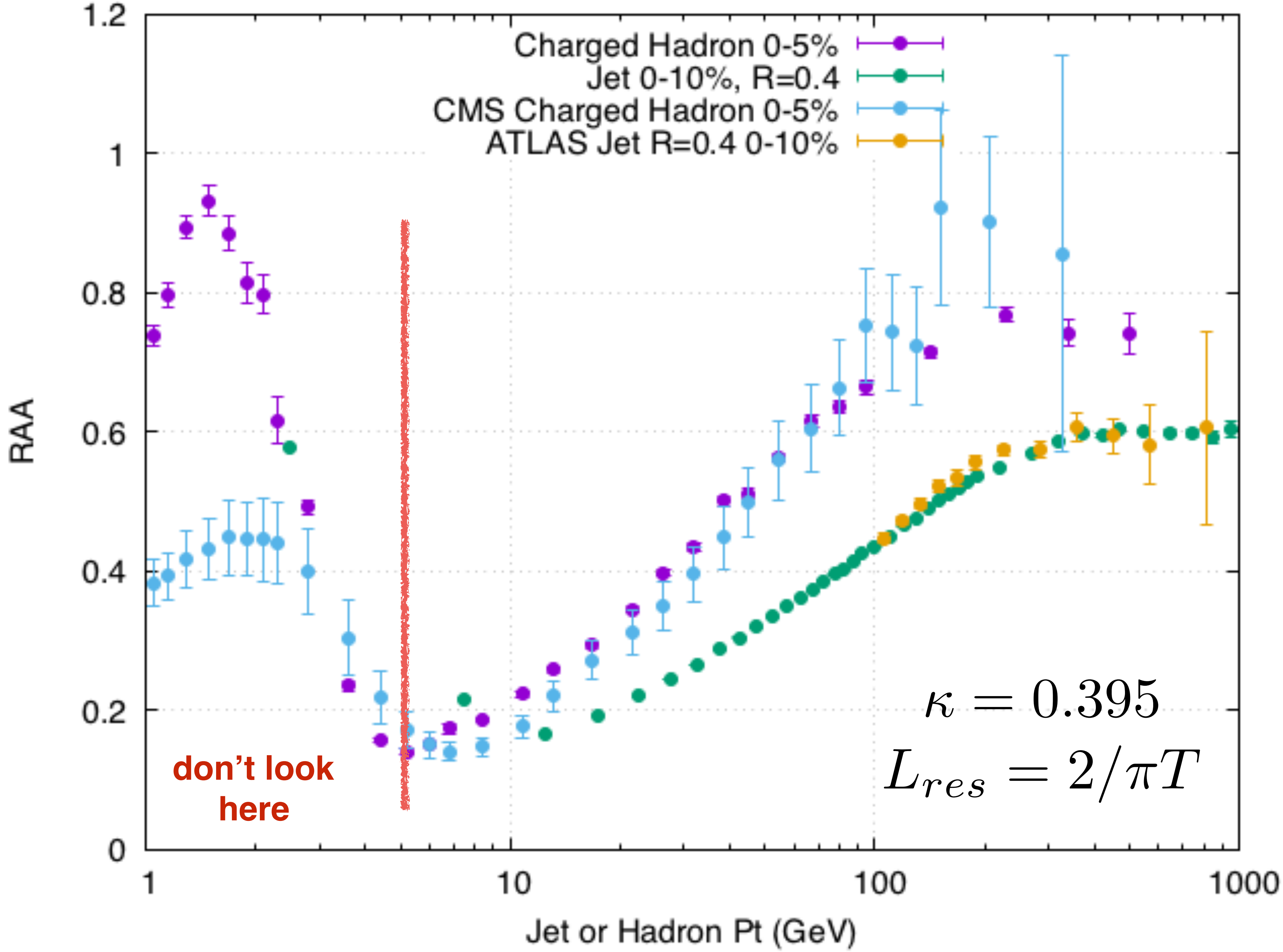


Narrowing of jet core explains Hadron vs Jet suppression

Such narrowing depends on the ability of the medium to resolve the shower internal structure (with increasing Lres, wider jets and narrow jets will be quenched more similarly)

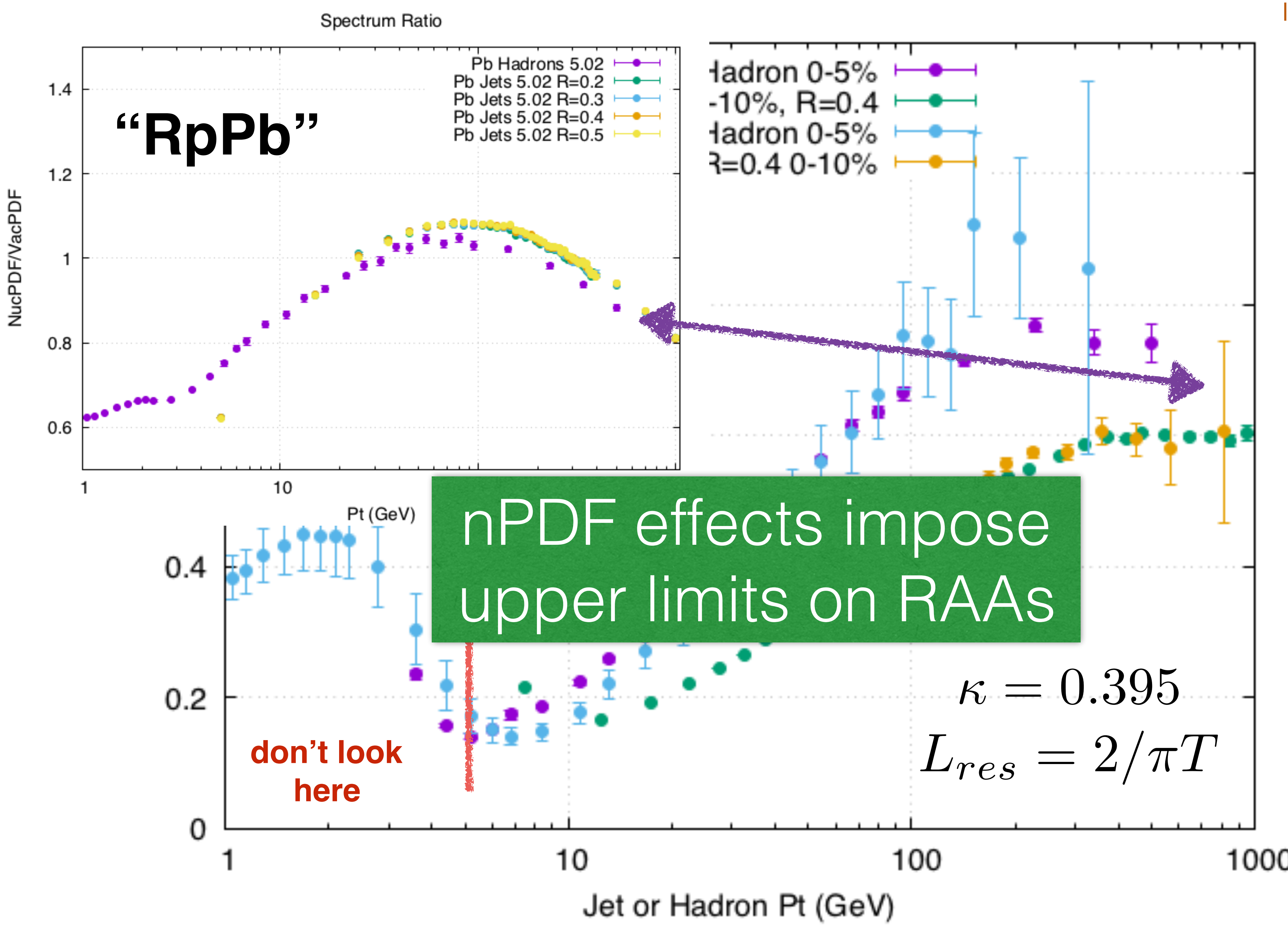
Hadron vs Jet Suppression

in preparation

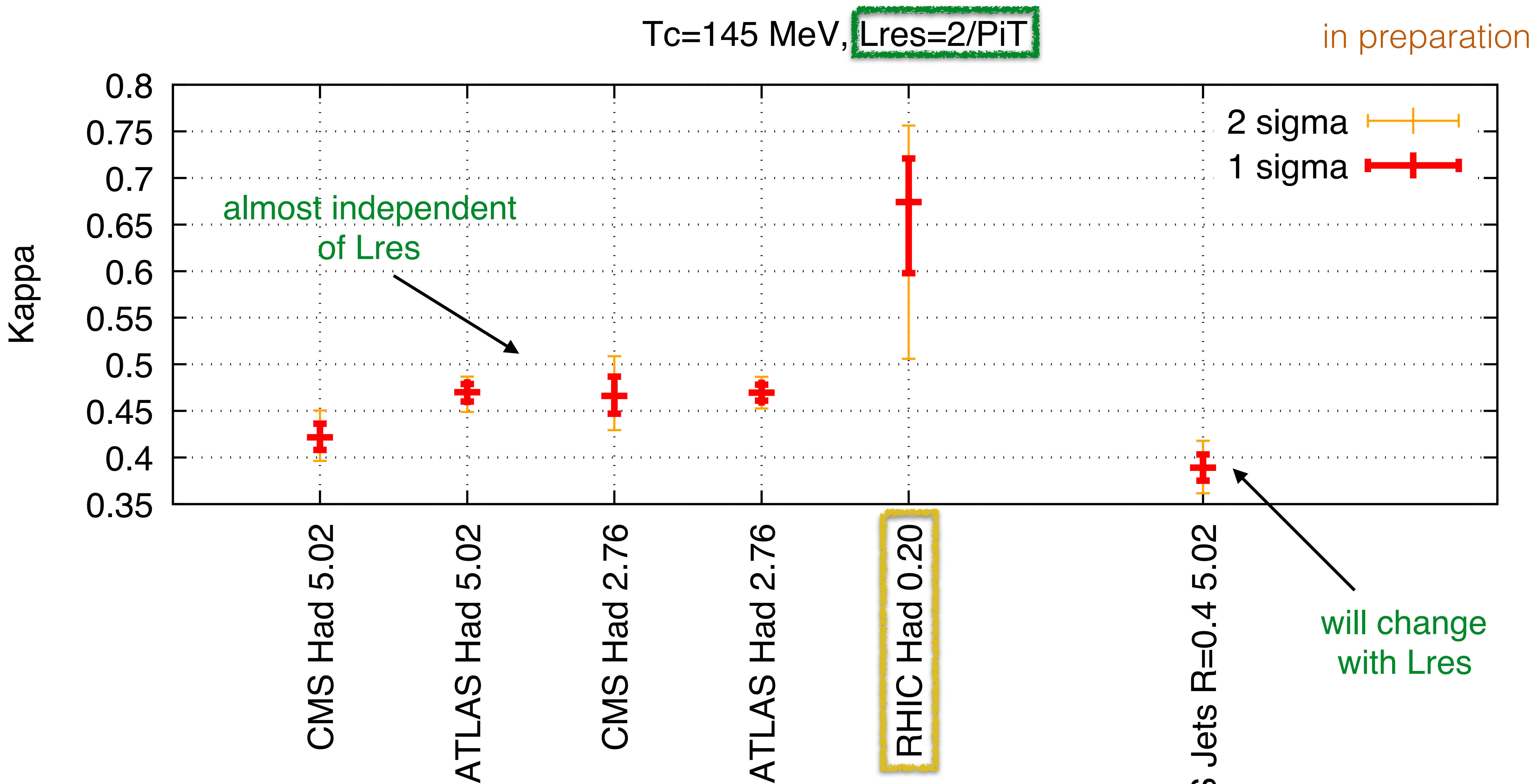


Hadron vs Jet Suppression

in preparation



Chi square goodness of fit test



some (expected?) tension between RHIC & LHC

to be completed…

Conclusions

- energy loss at strong coupling is a necessary tool to assess the true nature of QGP dynamics
  orthogonal to pQCD radiative based energy loss paradigm
- much progress has been made in developing models that can be compared to data
  by taking the core ingredients from pQCD that apply in HIC due to scale separation
- degree of hydrodynamization of lost energy can be tested with currently available observables
  need a comprehensive and systematic confrontation with data within a common framework
- further effort is needed on bringing holographic models to a next level of sophistication
  proper medium response, modified hadronization, possibility of (rare?) hard momentum transfers

Conclusions

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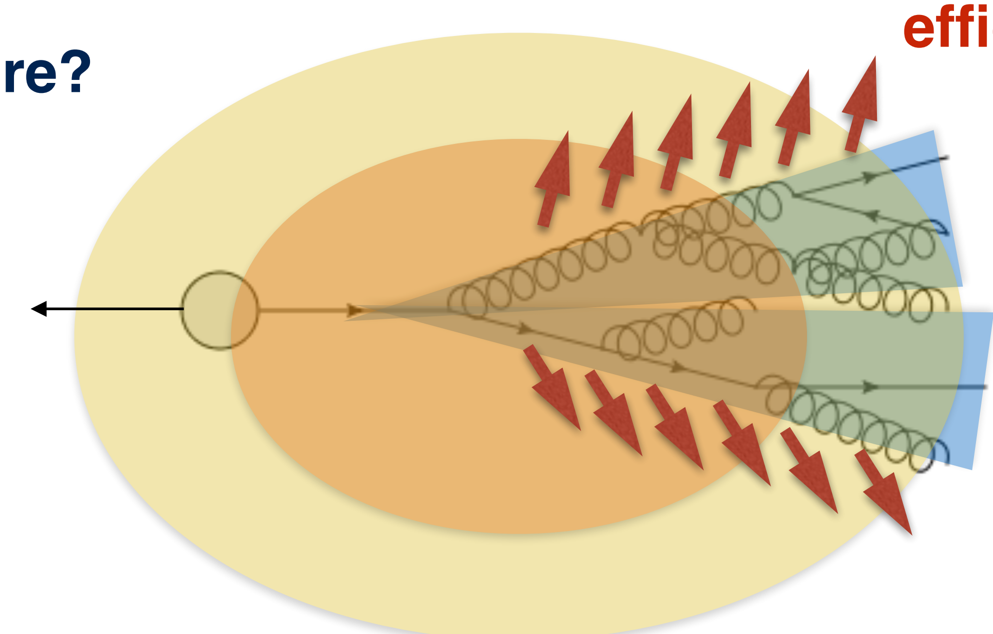
is data pointing towards this picture?



efficient energy transfer into hydro

fairly unresolved system

vacuum-like showering

Backup Slides

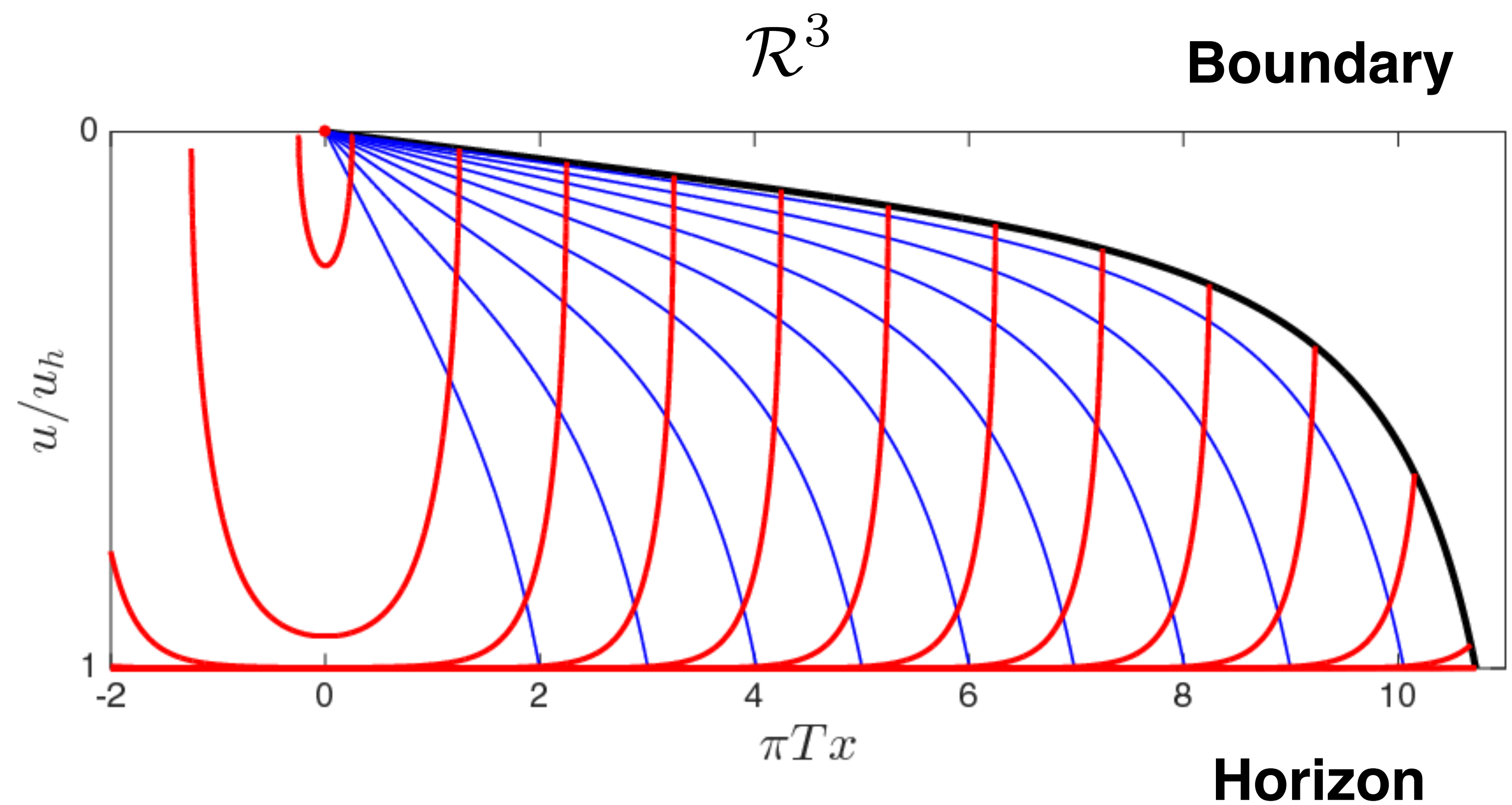
arXiv:1511.07567

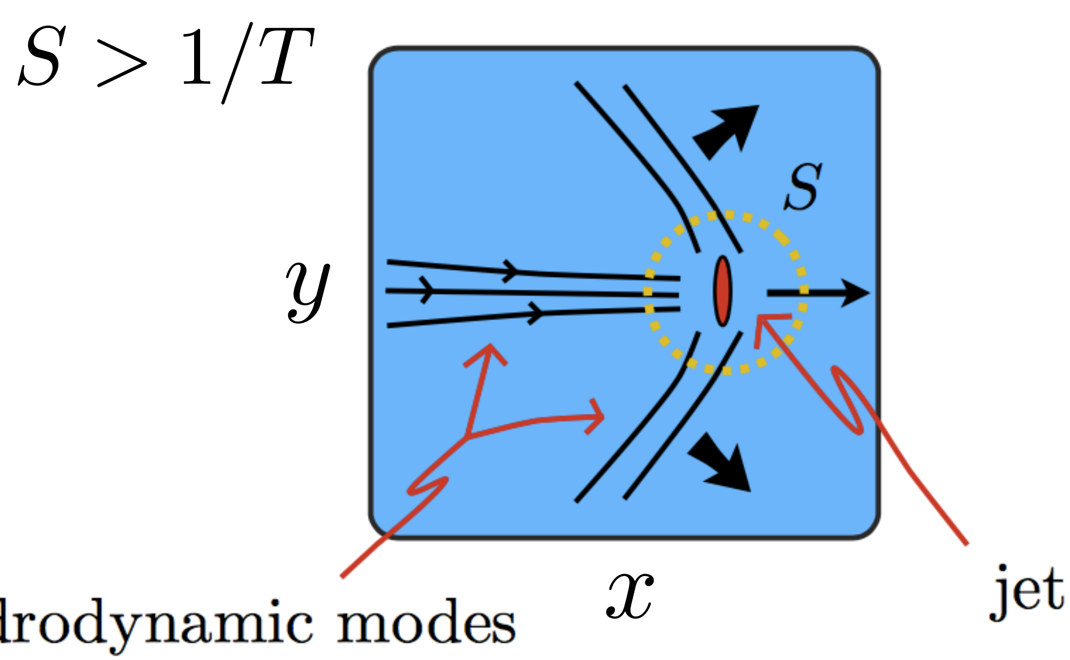
Determining the shape of the source term

Depth into holographic dimension:
- Width at the boundary

Geodesics falling below horizon:
- Long wavelength modes

flowing through **S** (provides dE/dx)





Linearised Einstein's eqs.

$$\mathcal{L}_{AB}^{MN} H_{MN} = 8\pi G_{\text{Newton}} J_{AB}$$

Boundary perturbation *String stress tensor*

$$\langle \Delta T^{\mu\nu}(t, \boldsymbol{x}) \rangle = \frac{L^3}{4\pi G_{\text{Newton}}} H_{\mu\nu}^{(4)}(t, \boldsymbol{x})$$

Boundary jet+wake stress tensor

Go beyond long wavelength limit and study the spatial dependence

An estimate of backreaction

Perturbations on top of a Bjorken flow

$$\Delta P_\perp^i = w\tau \int d\eta\, d^2x_\perp\, \delta u_\perp^i$$

$$\Delta P^\eta = 0$$

$$\Delta S = \tau c_s^{-2} s \int d\eta\, d^2x_\perp \frac{\delta T}{T}$$

$$c_s^2 = \frac{s}{T}\frac{dT}{ds}$$

Cooper-Frye $$E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int d\sigma^\mu p_\mu f(u^\mu p_\mu)$$

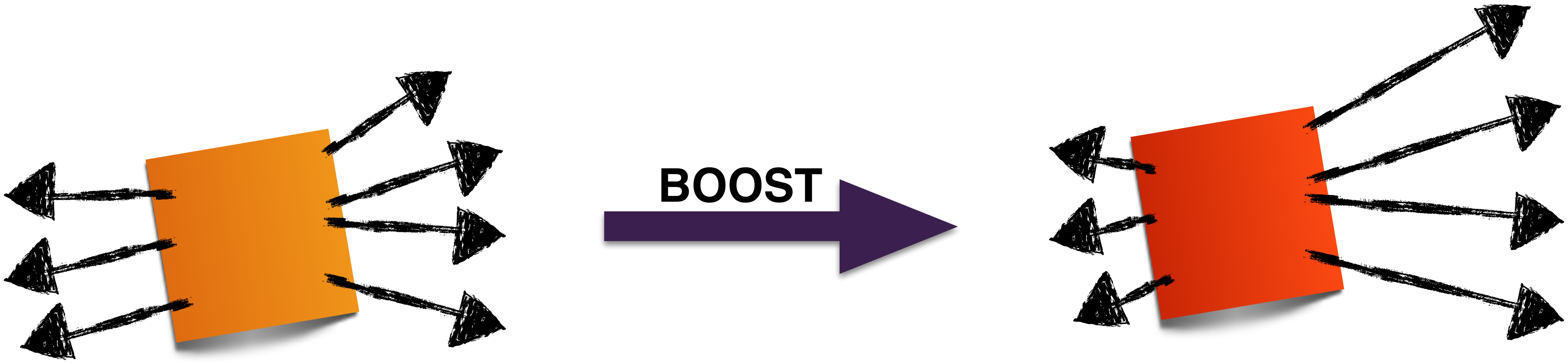
One body distribution

$$E\frac{dN}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)e^{-\frac{m_T}{T}\cosh(y-y_j)}$$

$$\left[p_T\Delta P_T\cos(\phi-\phi_j) + \frac{1}{3}m_T\Delta M_T\cosh(y-y_j)\right]$$

An estimate of backreaction

One body distribution has negative contributions at large azimuthal separation

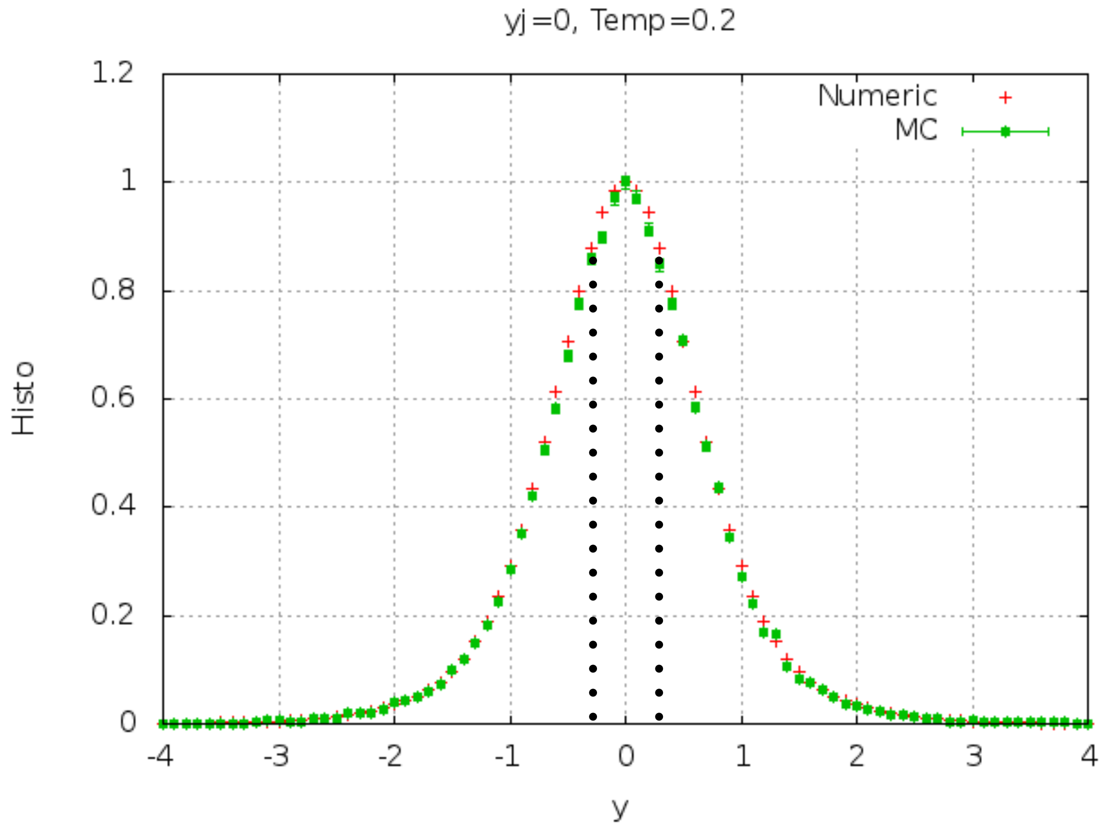


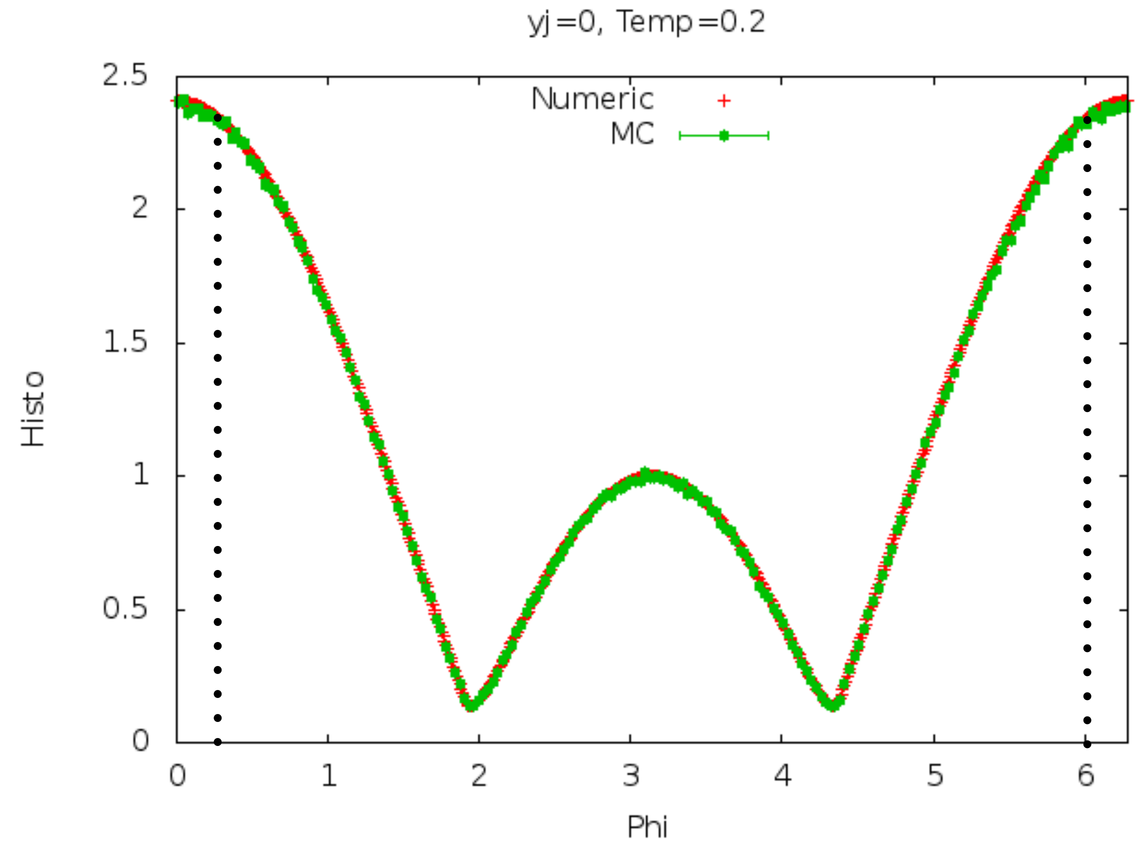
Background diminished w.r.t unperturbed hydro for that region in space

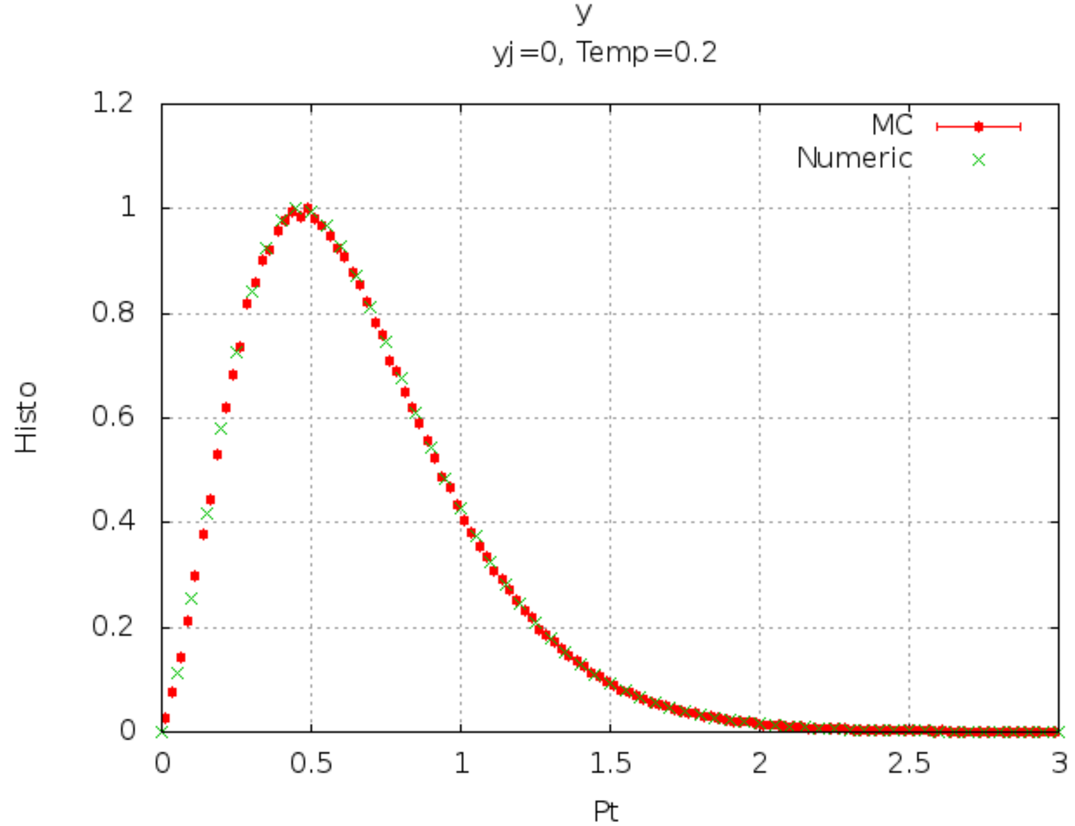
Need to emulate experimental background subtraction (e.g. eta reflection method) due to long range correlations

Event by event, determine the extra particles distribution enforcing energy/momentum conservation via Metropolis algorithm

An estimate of backreaction





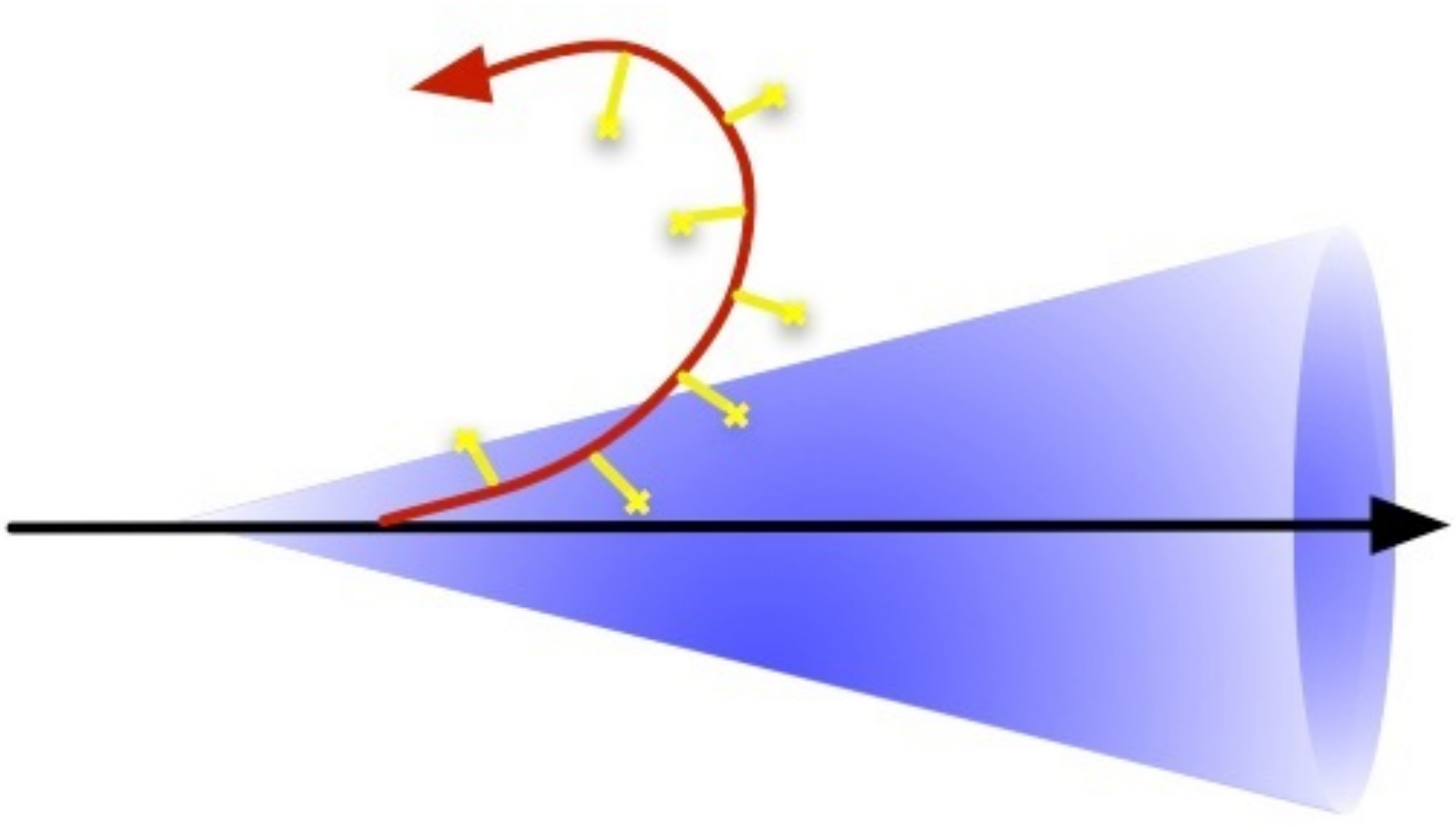


.... r < 0.3

- Wide in azimuthal angle
- Wide in rapidity
- Peaked at very low transverse momentum

$$y_j = 0,\ \phi_j = 0,\ T = 0.2\,\mathrm{GeV}$$

Intra-jet broadening



Partons receive transverse kicks according to a gaussian distribution

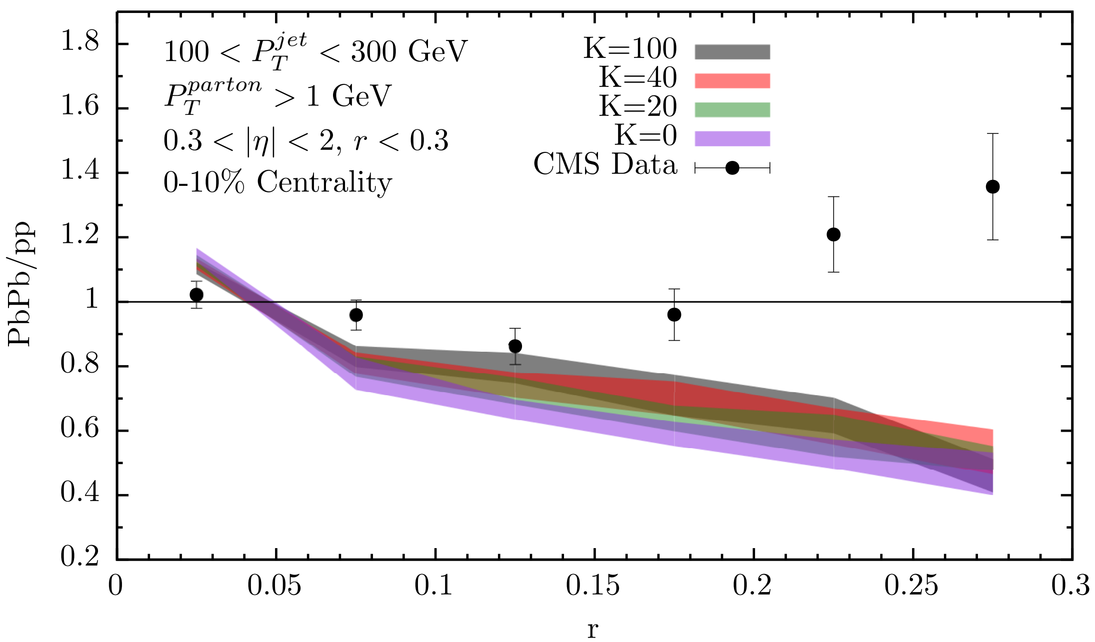
The width of the gaussian is $(\Delta k_T)^2 = \hat{q}\, dx$

Such mechanism introduces a new parameter $K = \frac{\hat{q}}{T^3}$

Transverse kicks can broaden the jet and kick particles out of the jet

Liu, Rajagopal, Wiedemann 06

Intra-jet broadening



$$\hat{q} = KT^3$$

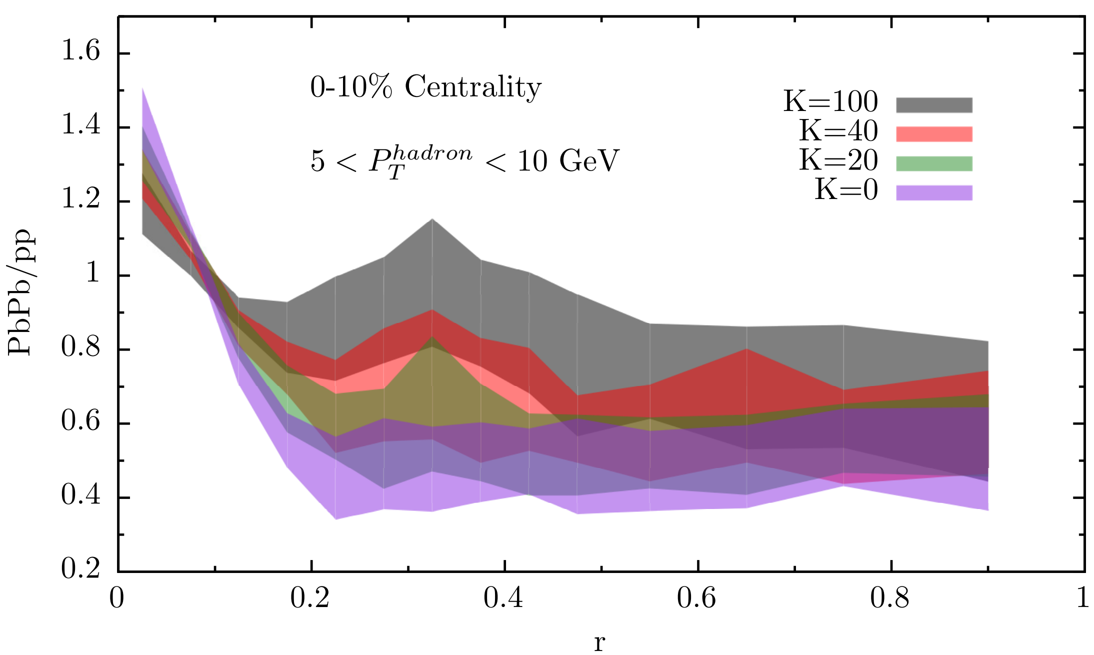
Inclusive jets - all tracks

strong quenching suppresses the effect of broadening

$Q \uparrow, \theta \uparrow, \tau_f \downarrow$ early wide fragments quenched

$Q \downarrow, \theta \downarrow, \tau_f \uparrow$ late narrow fragments survive

selection bias towards narrower jets,
merely a jet axis deflection



Subleading jets - semi-hard tracks

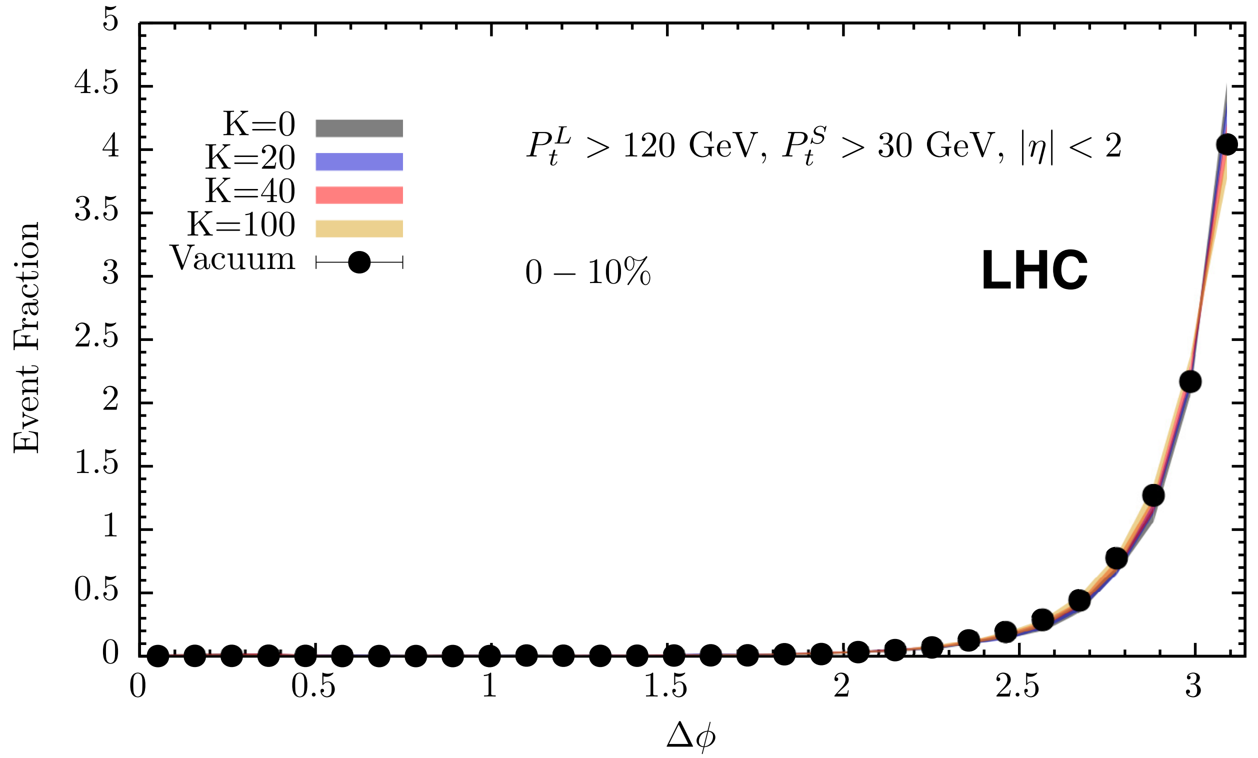
kinematical limits chosen such that:

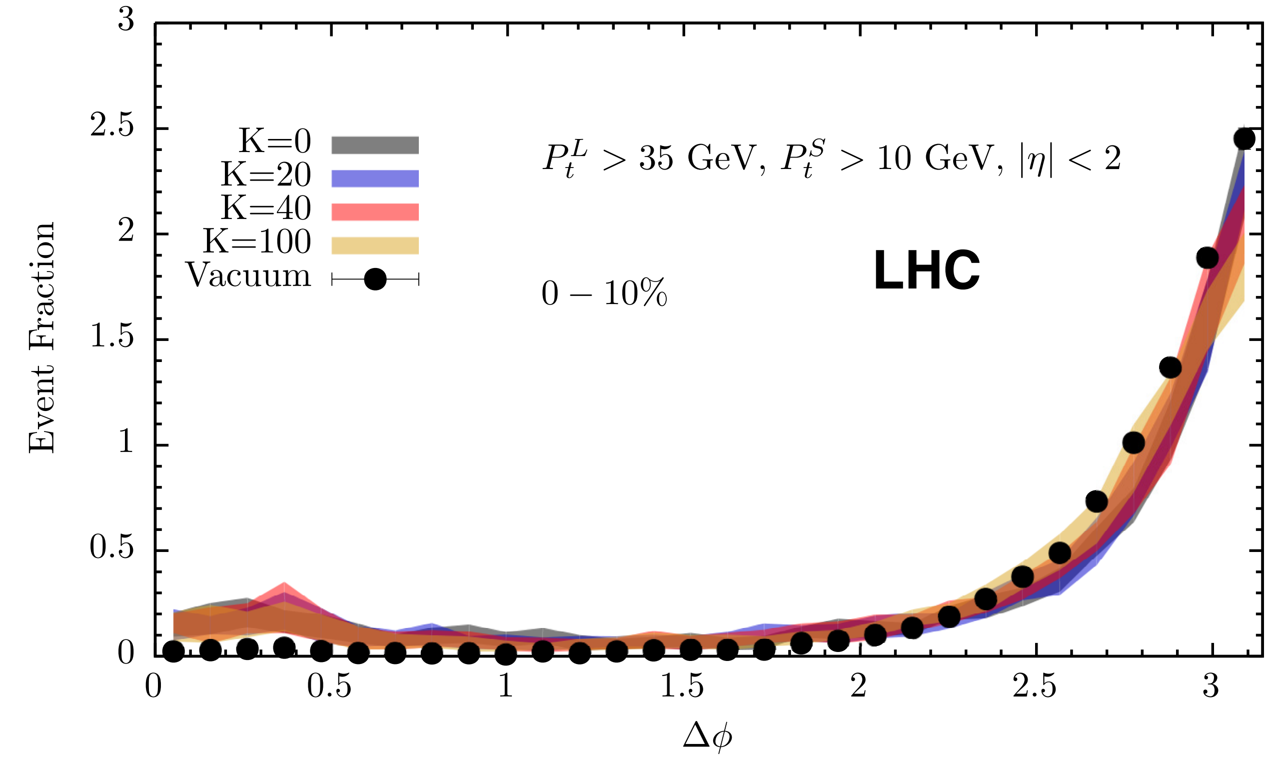
- no effect from background (soft tracks)
- intra-jet activity above average (hard tracks)

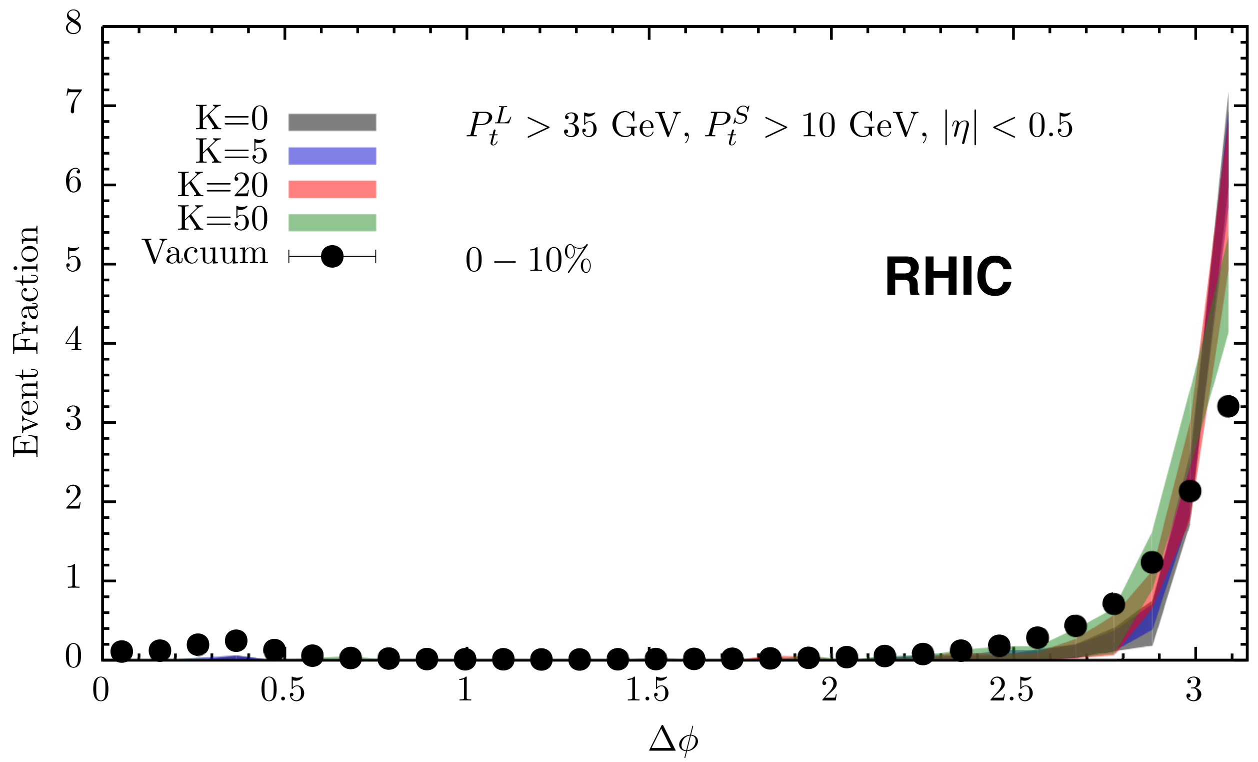
deviations from such Gaussian broadening

hard momentum transfers from QGP quasiparticles

Dijet acoplanarities







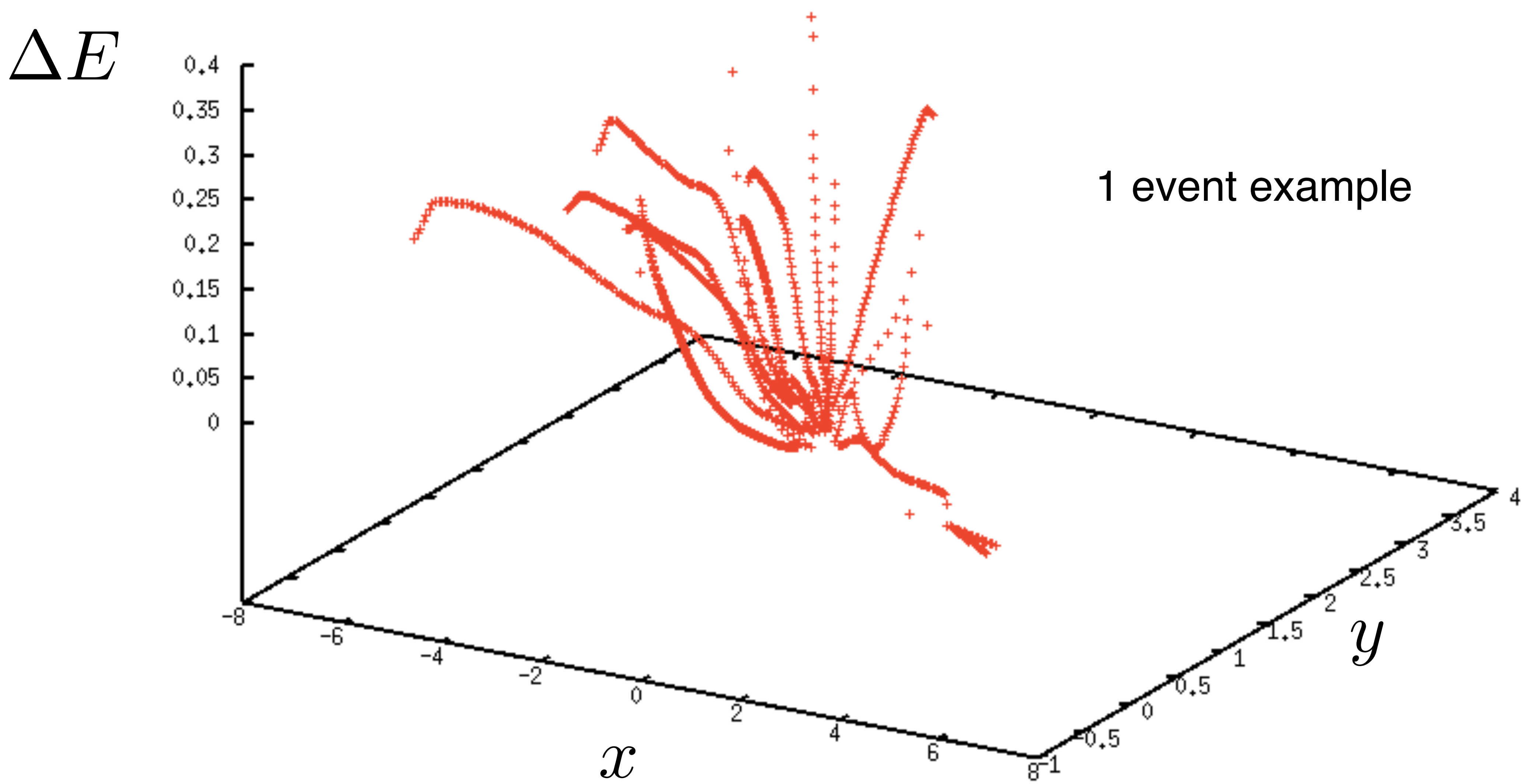
Higher energy jets are narrower: less acoplanar

Energy loss narrows the distributions, while broadening widens them back

Effects strongest for lower energies due to more steeply falling spectrum

First steps into hydro with source

PRELIMINARY



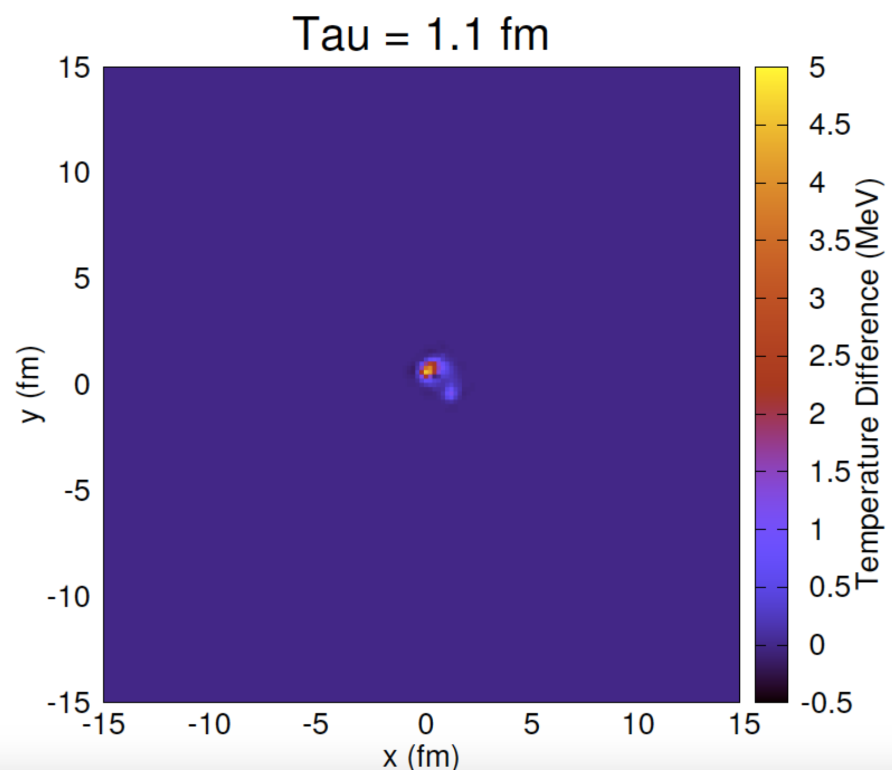
1 event example

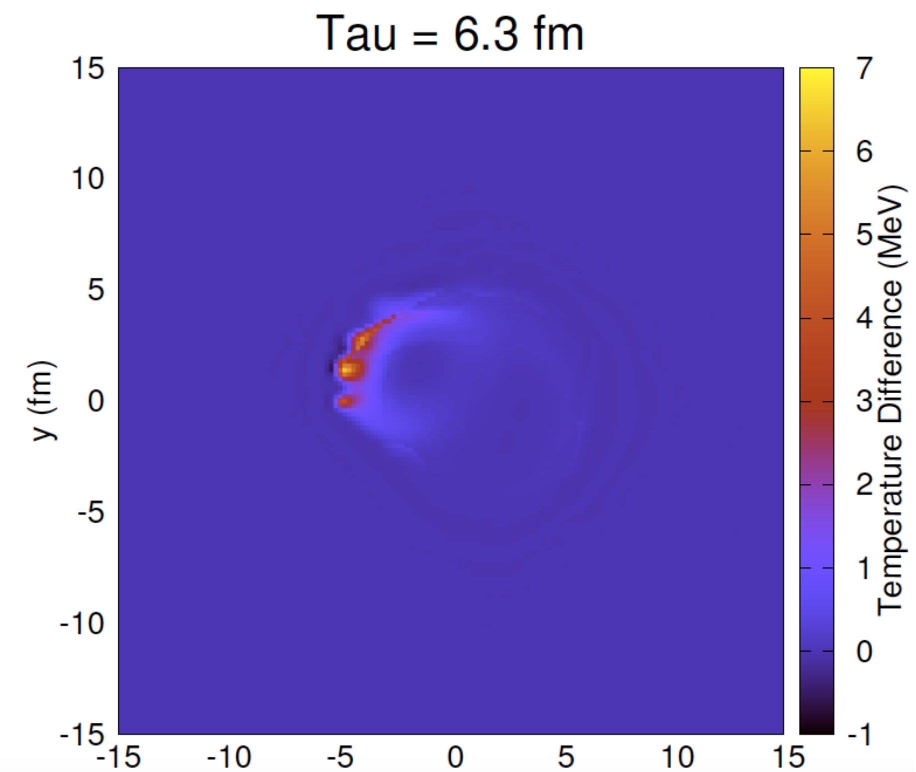
Energy deposited into medium according to holographic energy loss rate

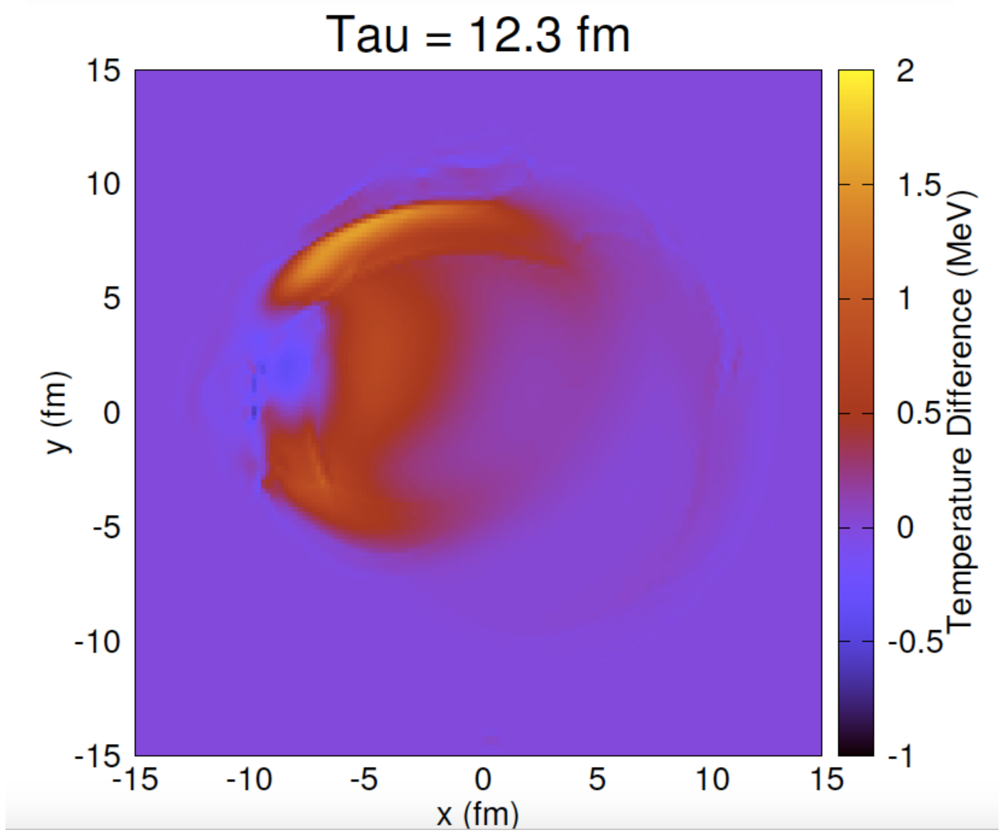
Most of the energy deposited at late times (strongly coupled "Bragg peak")

JETSCAPE

First steps into hydro with source







work with Mayank Singh & Chun Shen

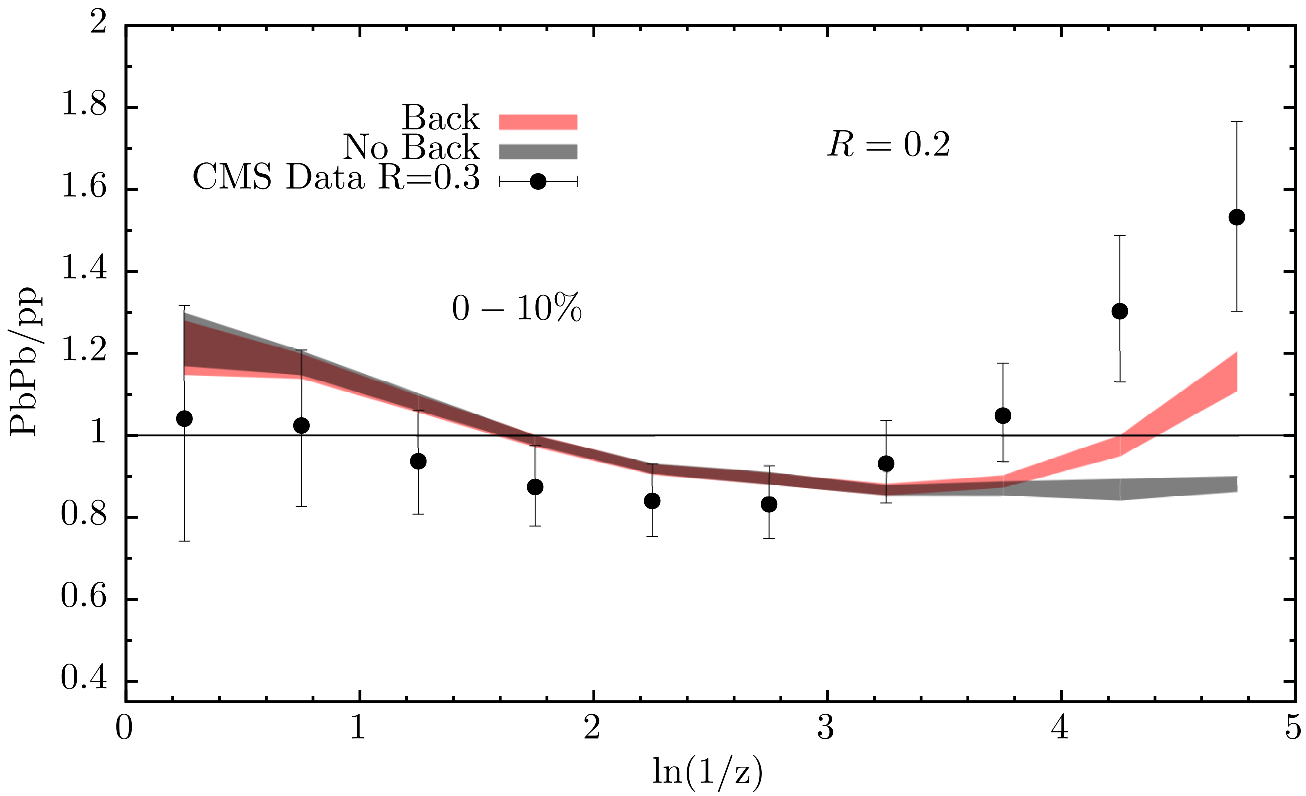
PRELIMINARY

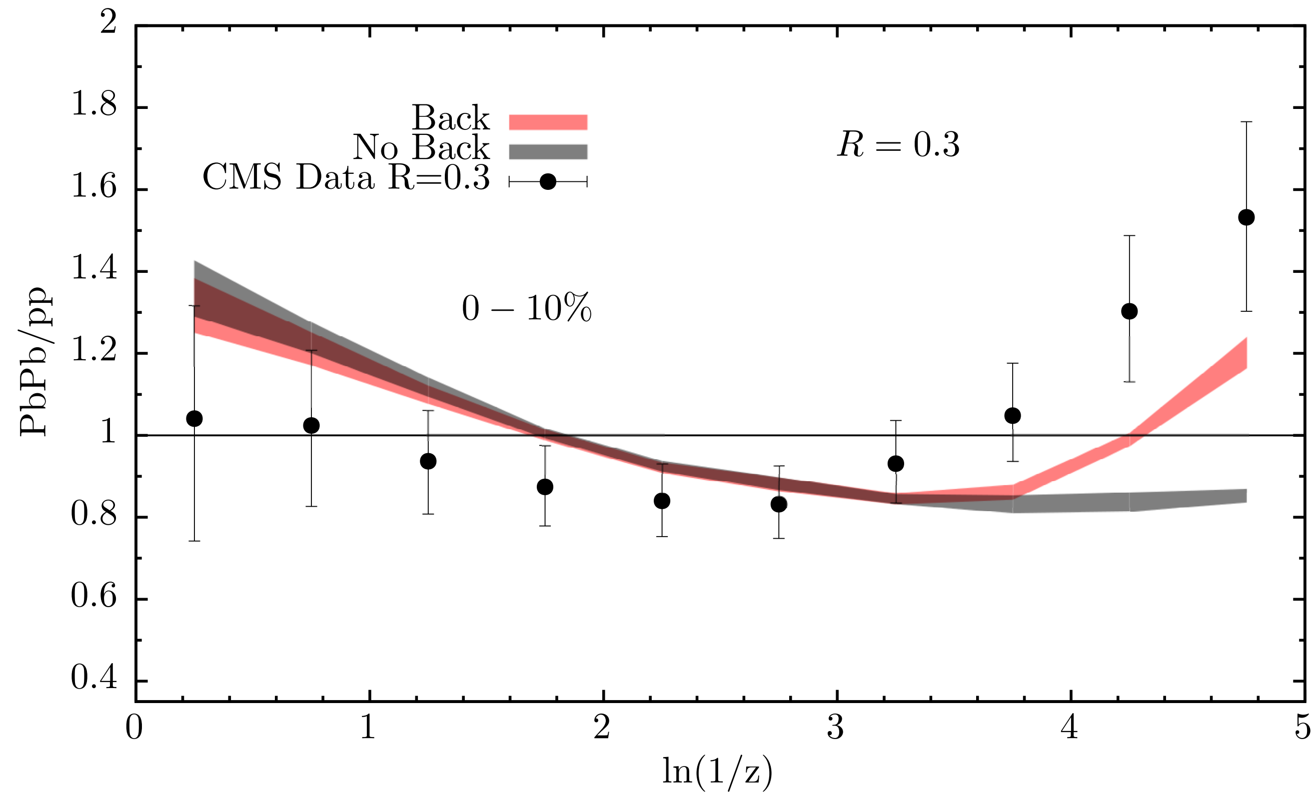
1 event example

(w/ novel simplified background subtraction)

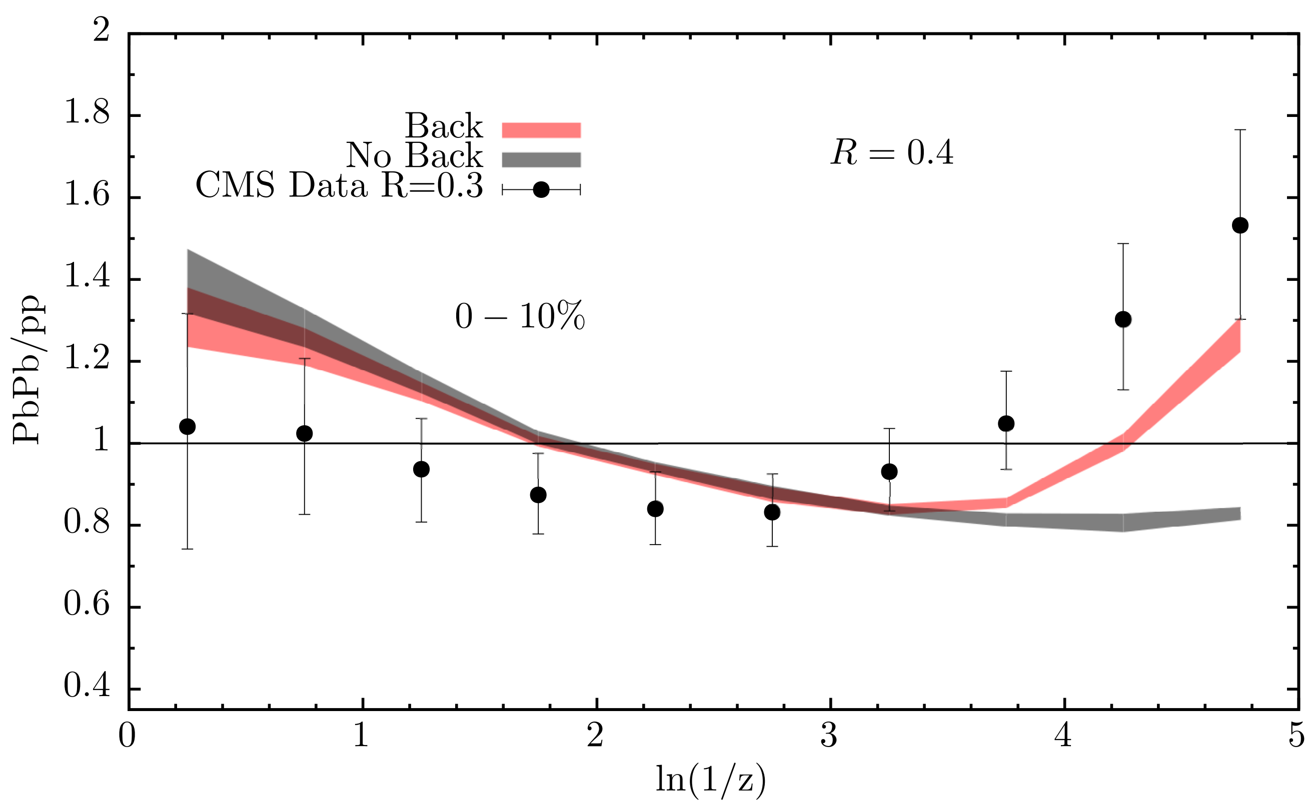
PRELIMINARY

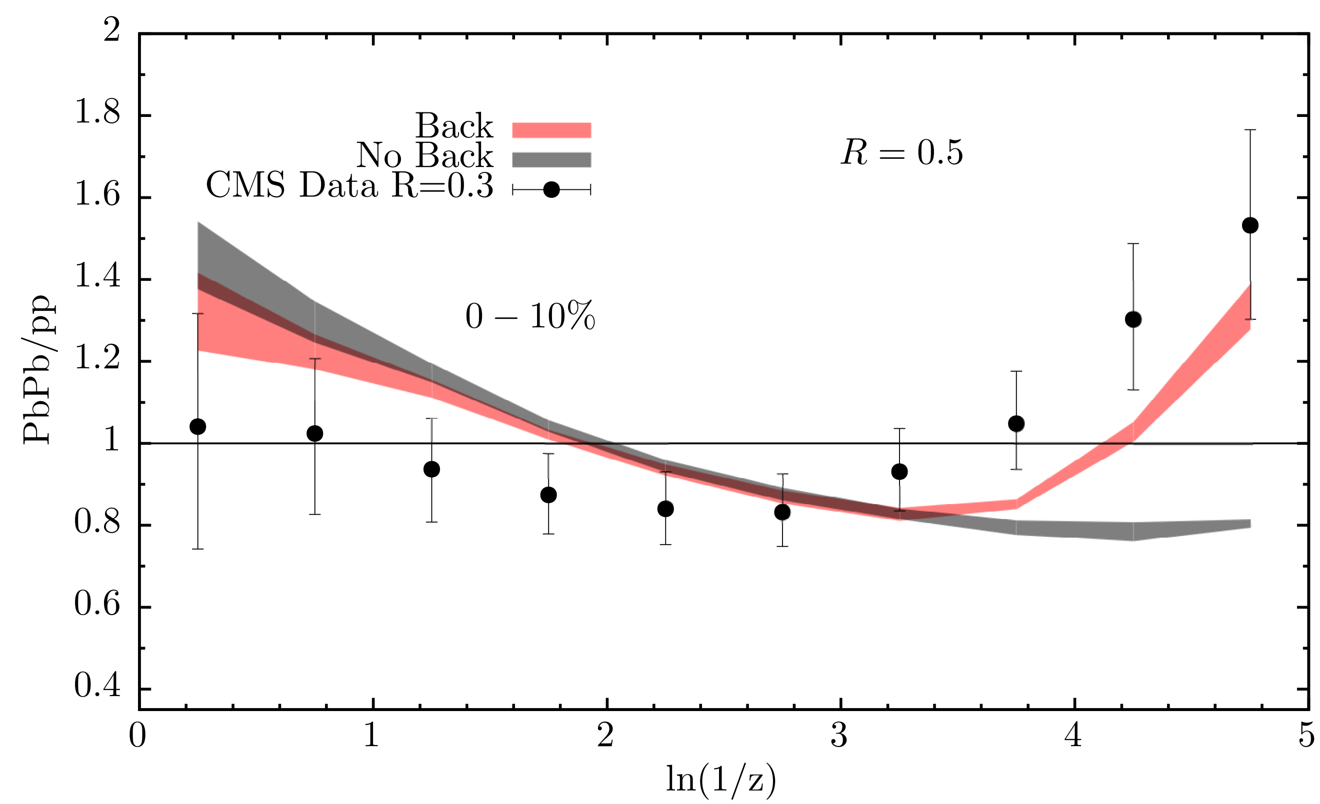
FF vs R





effect strongest towards greatest angles

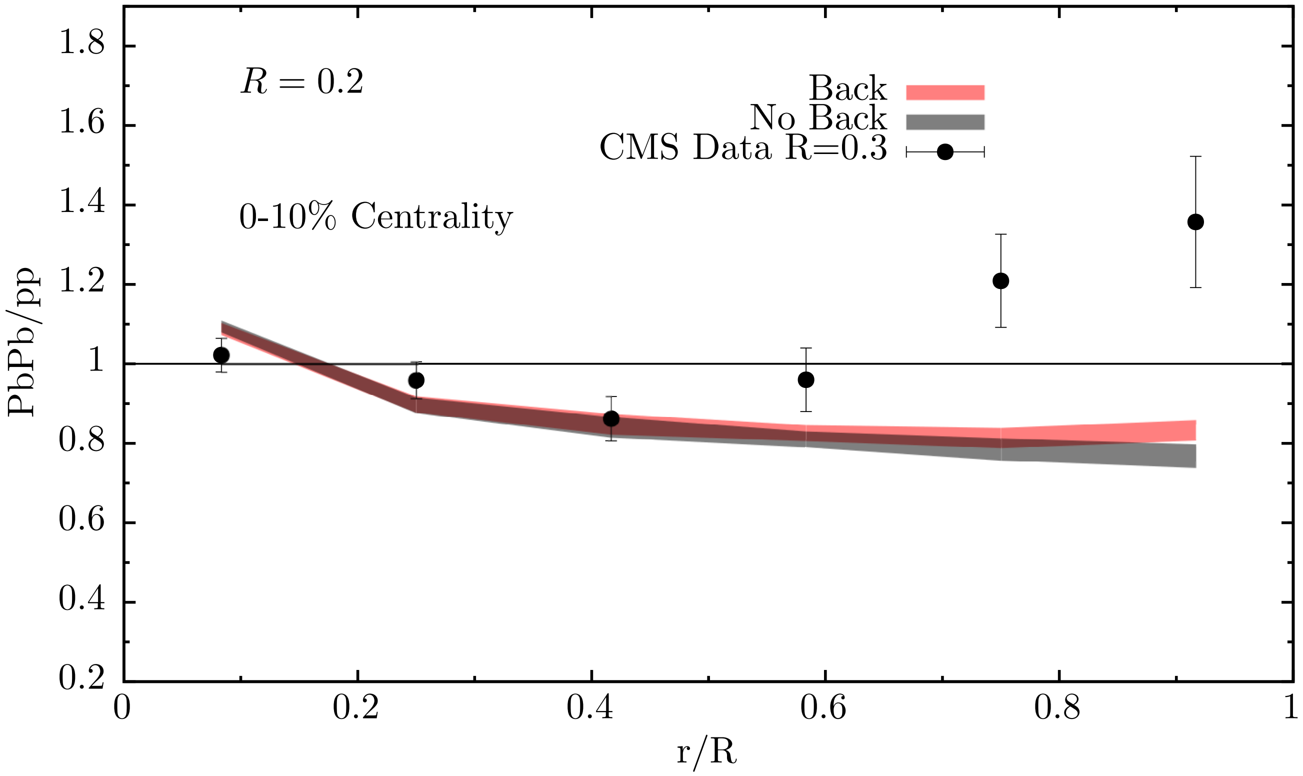


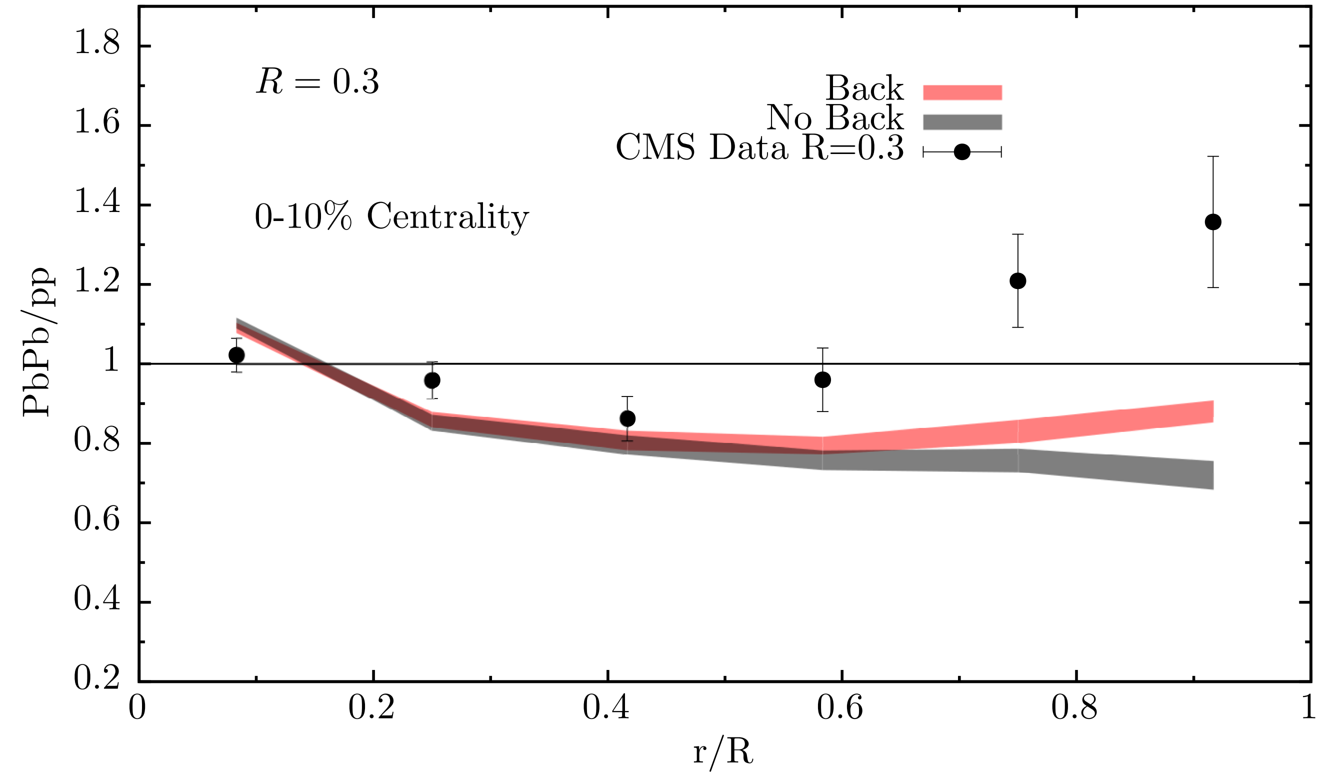


PRELIMINARY

(w/ novel simplified background subtraction)

Jet Shapes vs R





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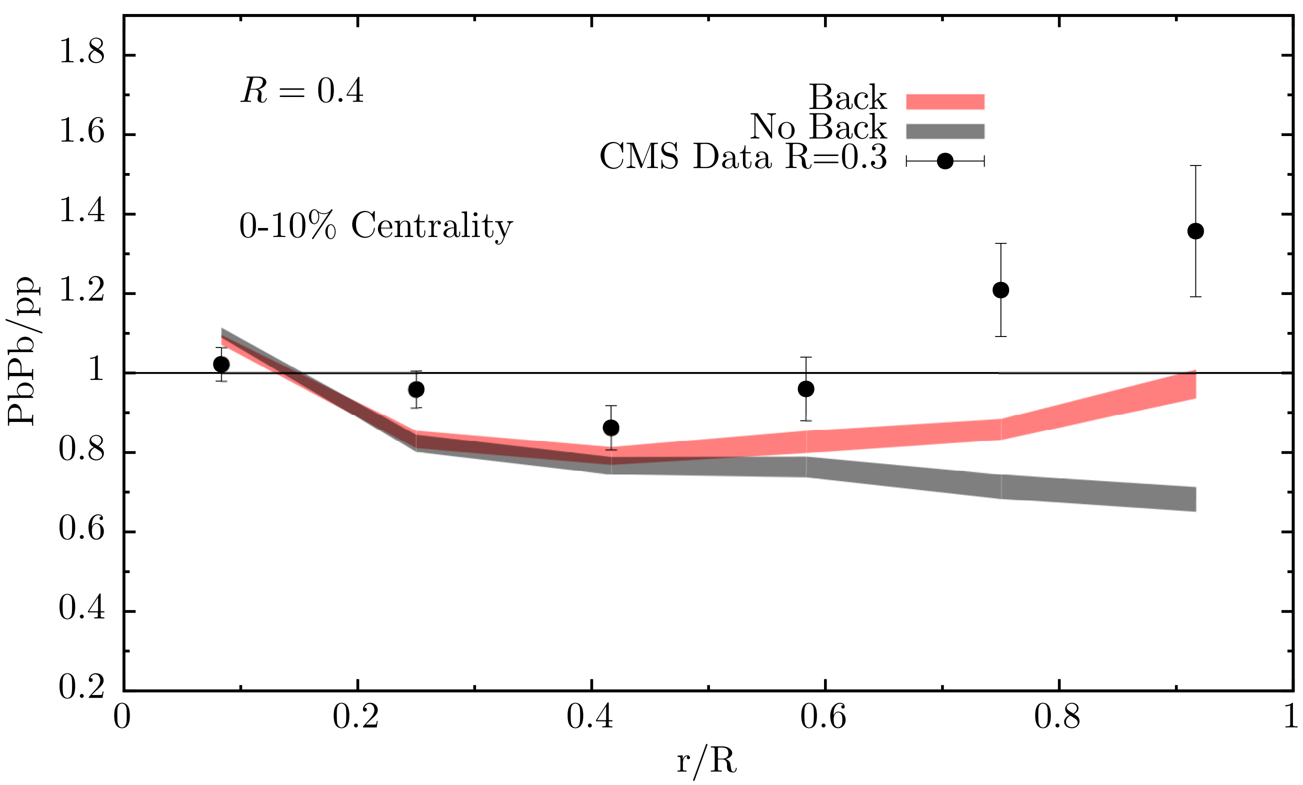
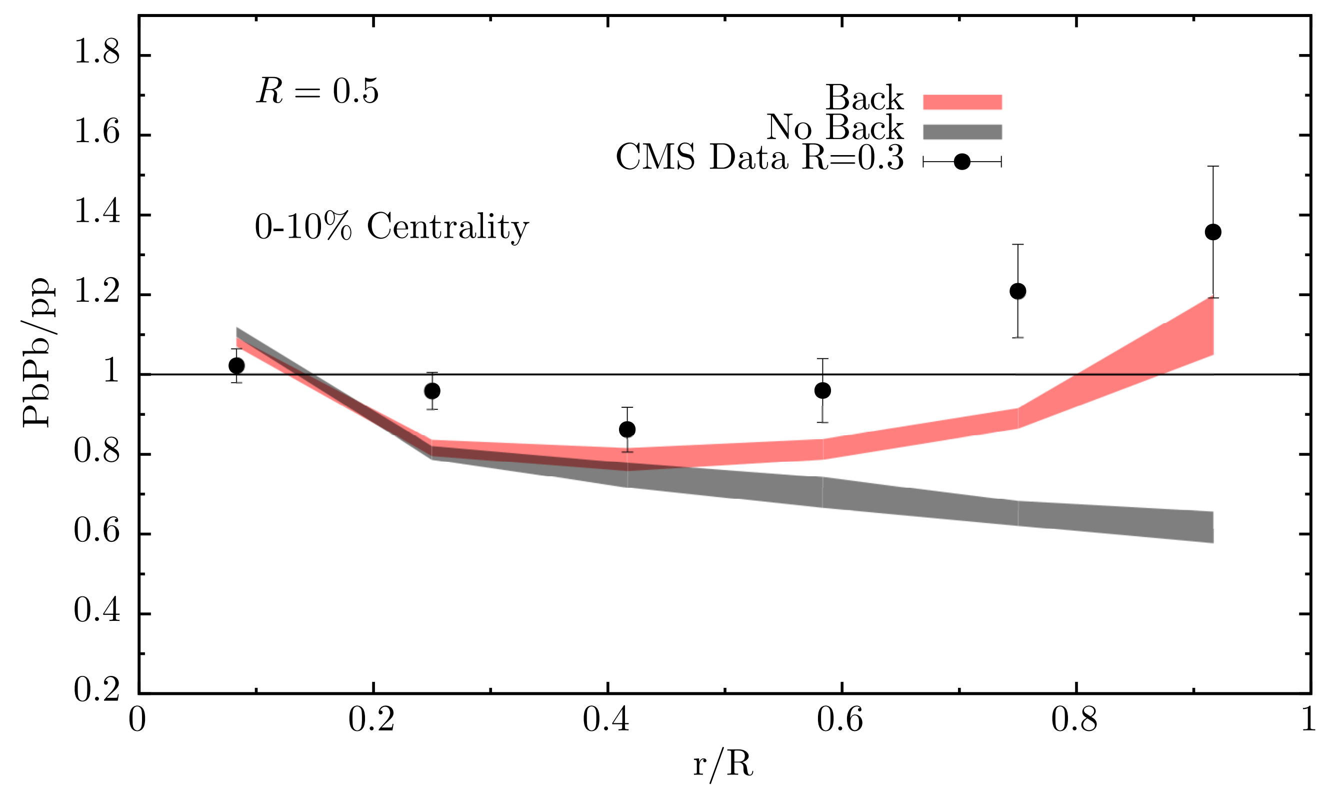
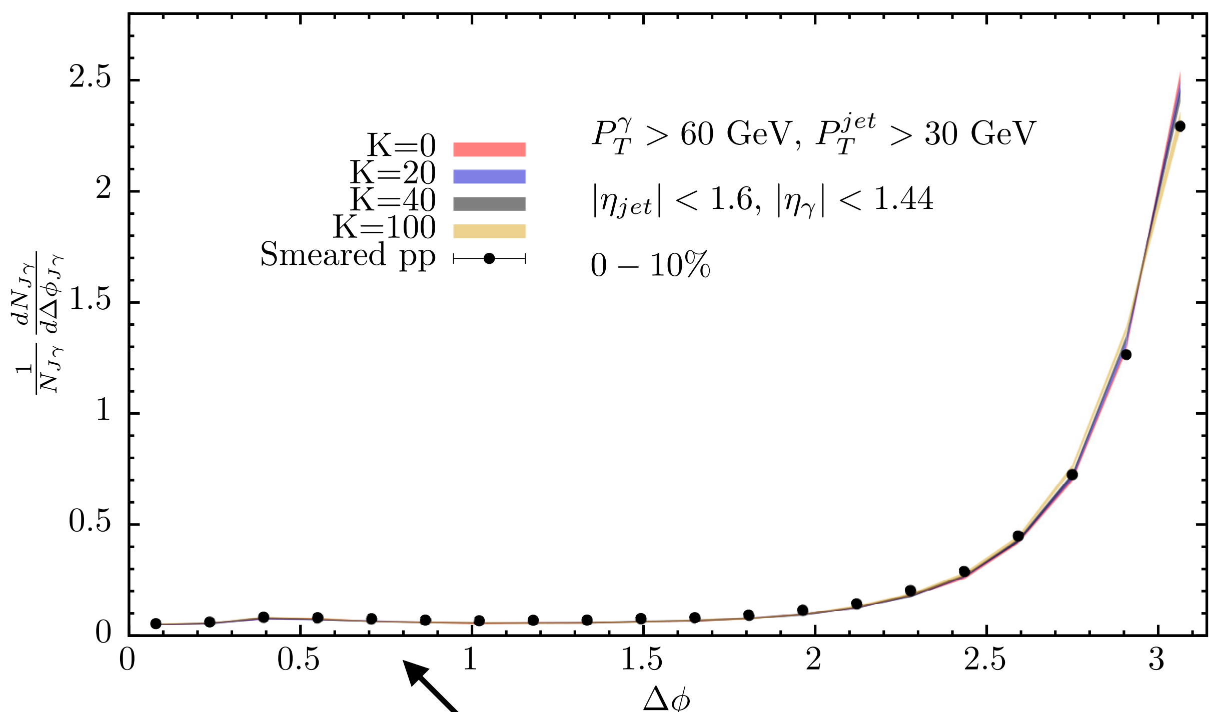


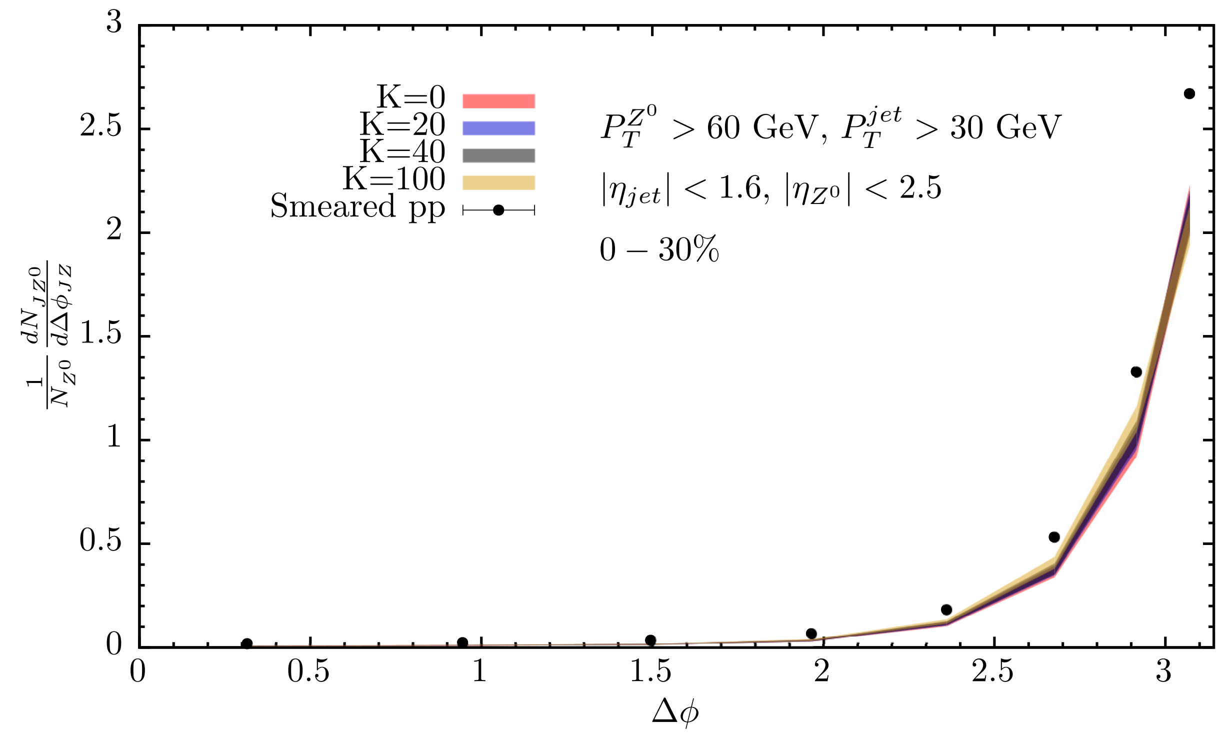


Boson Jet Acoplanarities

Photon Jet



Z Jet



frag. photon contamination

different normalisation

Photon Jet: over the number of photon jet pairs

Z Jet: over the number of Zs