Insights into jet quenching within a hybrid strong/weak coupling model

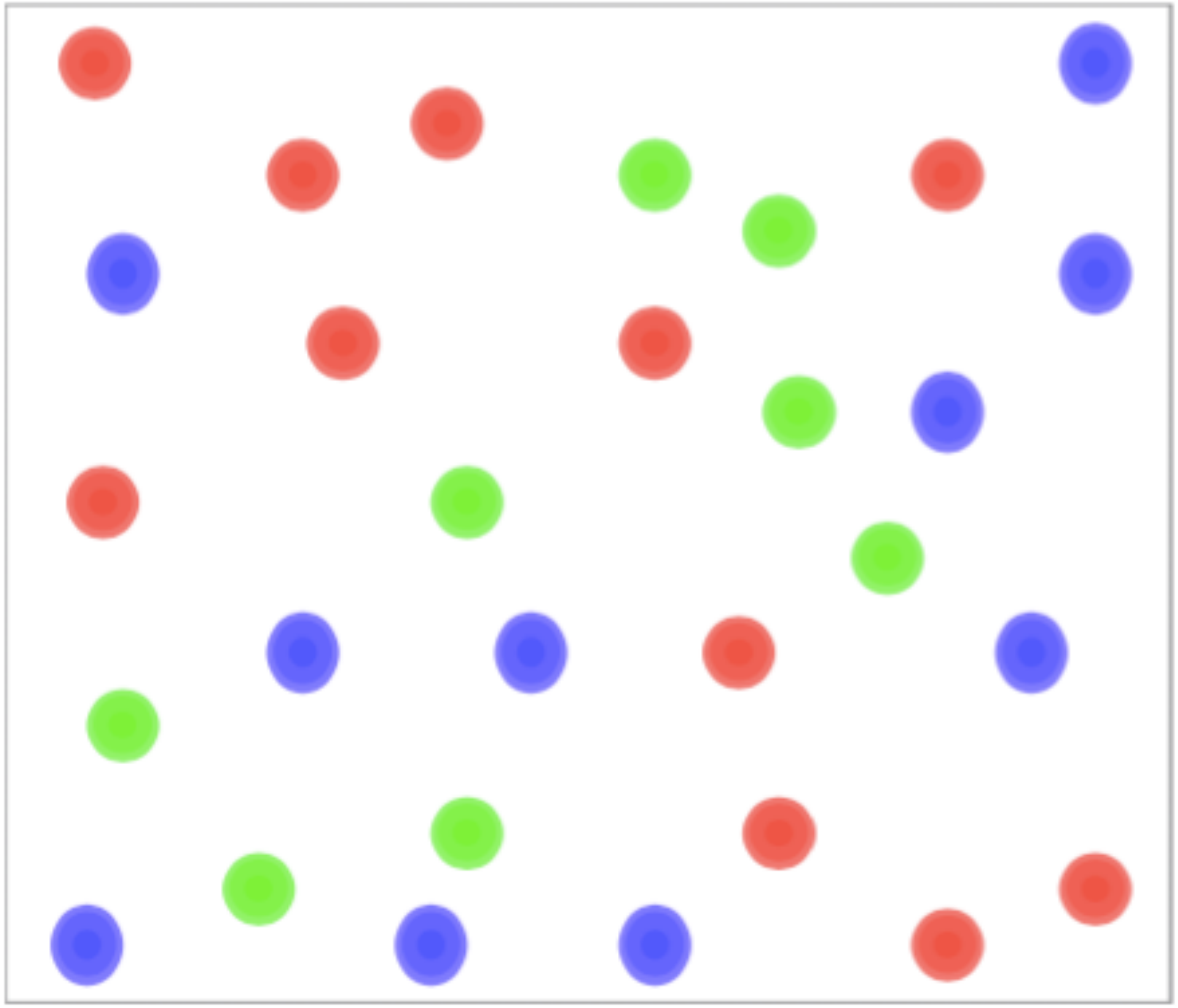
Daniel Pablos

Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
INT, Seattle

25th May 2017

A Gas of Quarks and Gluons

$T > 10^4\,\mathrm{GeV}$

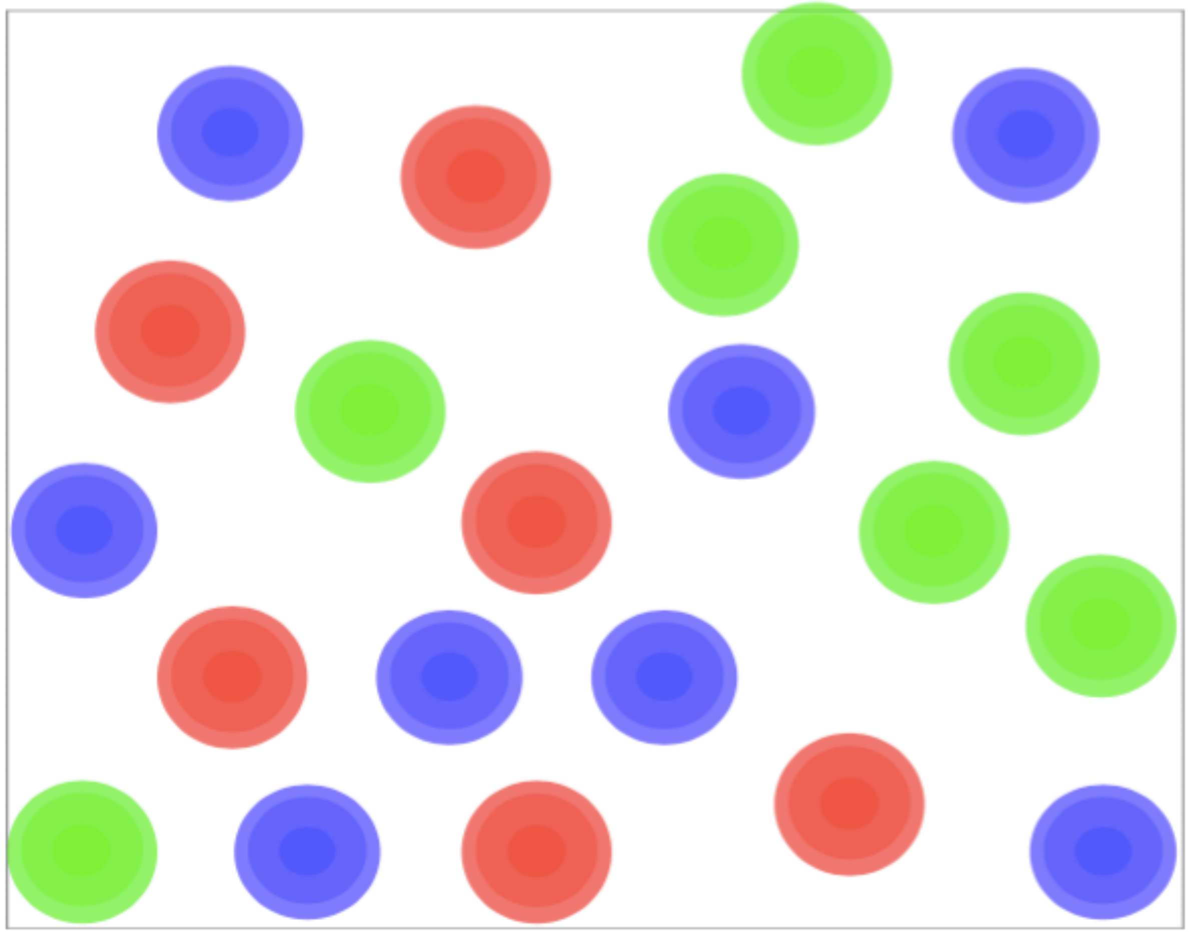


$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2 T}$$

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?

Which is the correct picture of the plasma?

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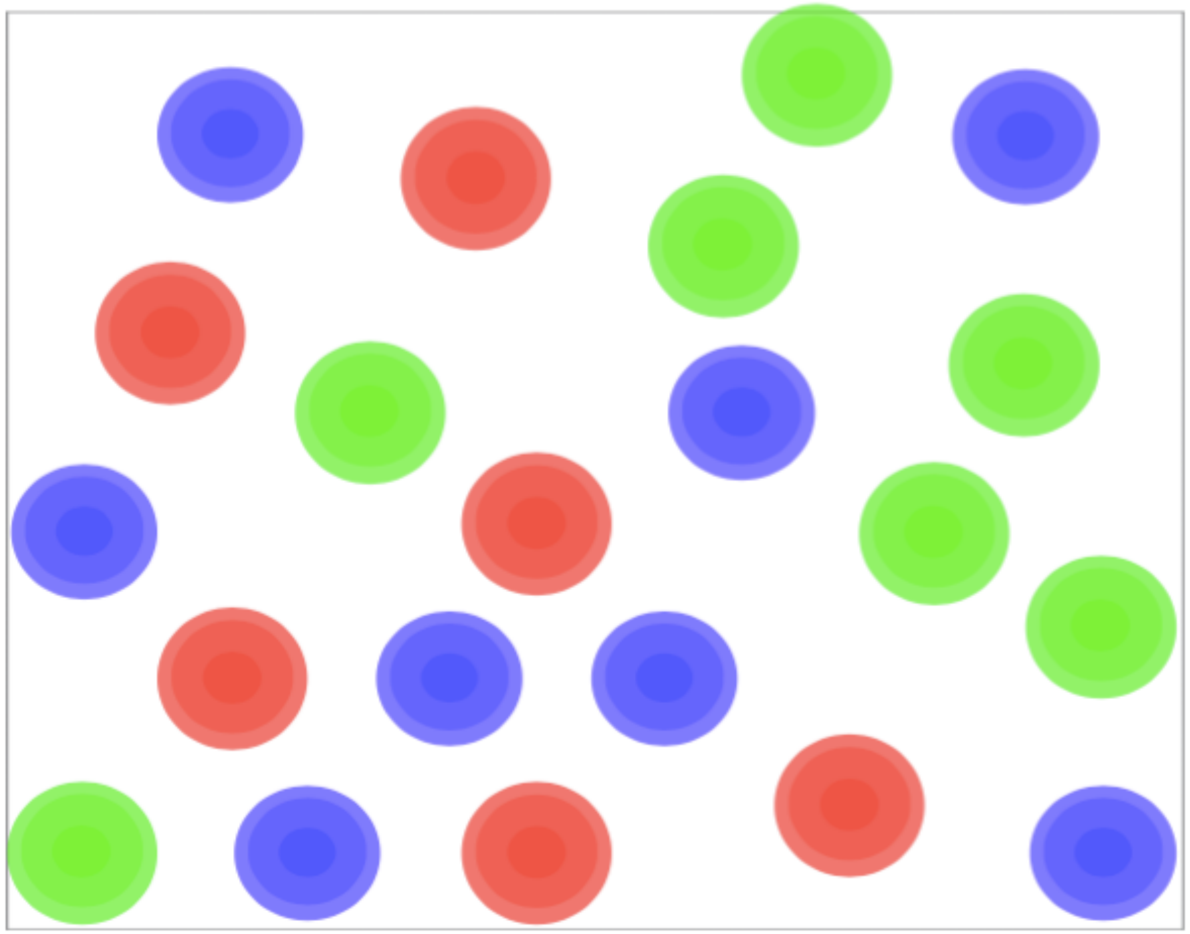

Is it a gas of quarks and gluons?

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

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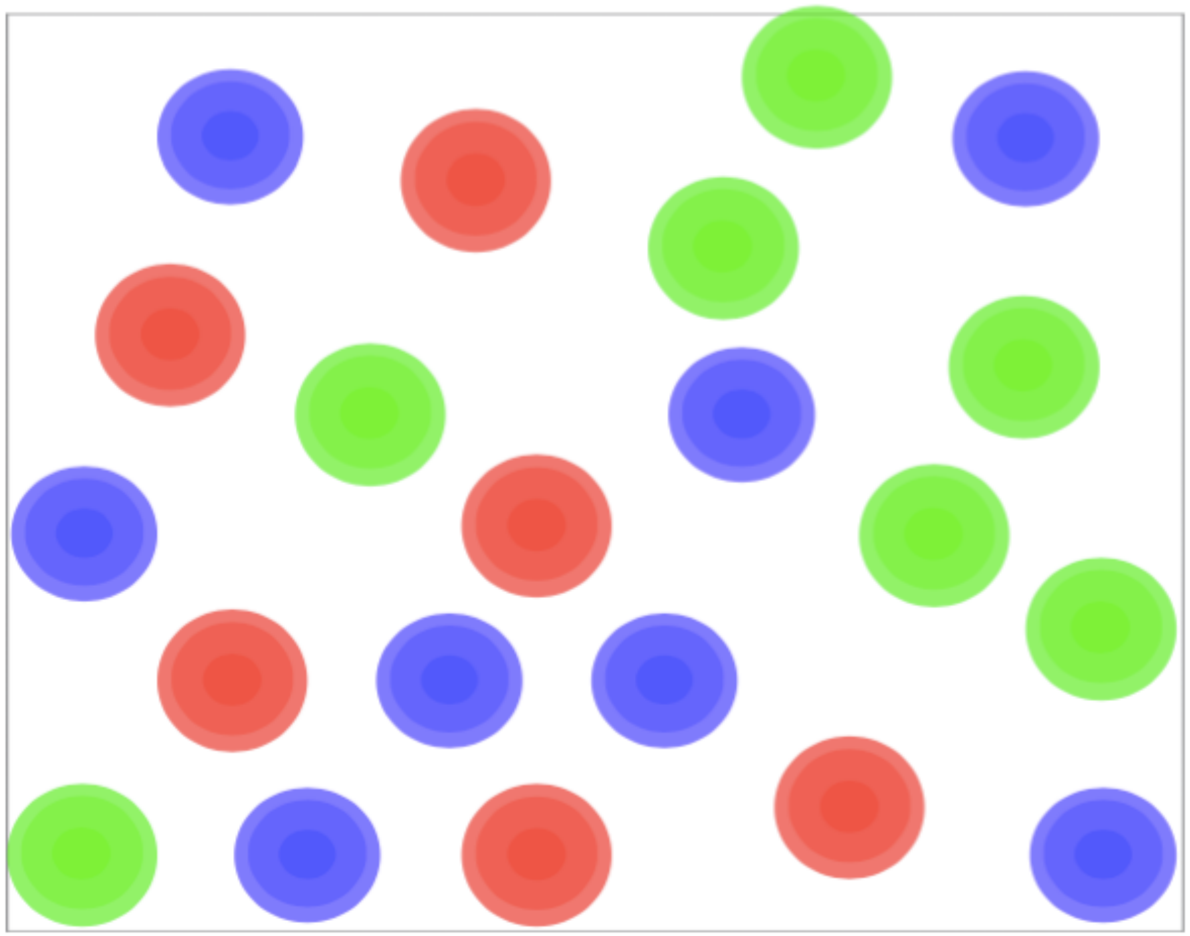

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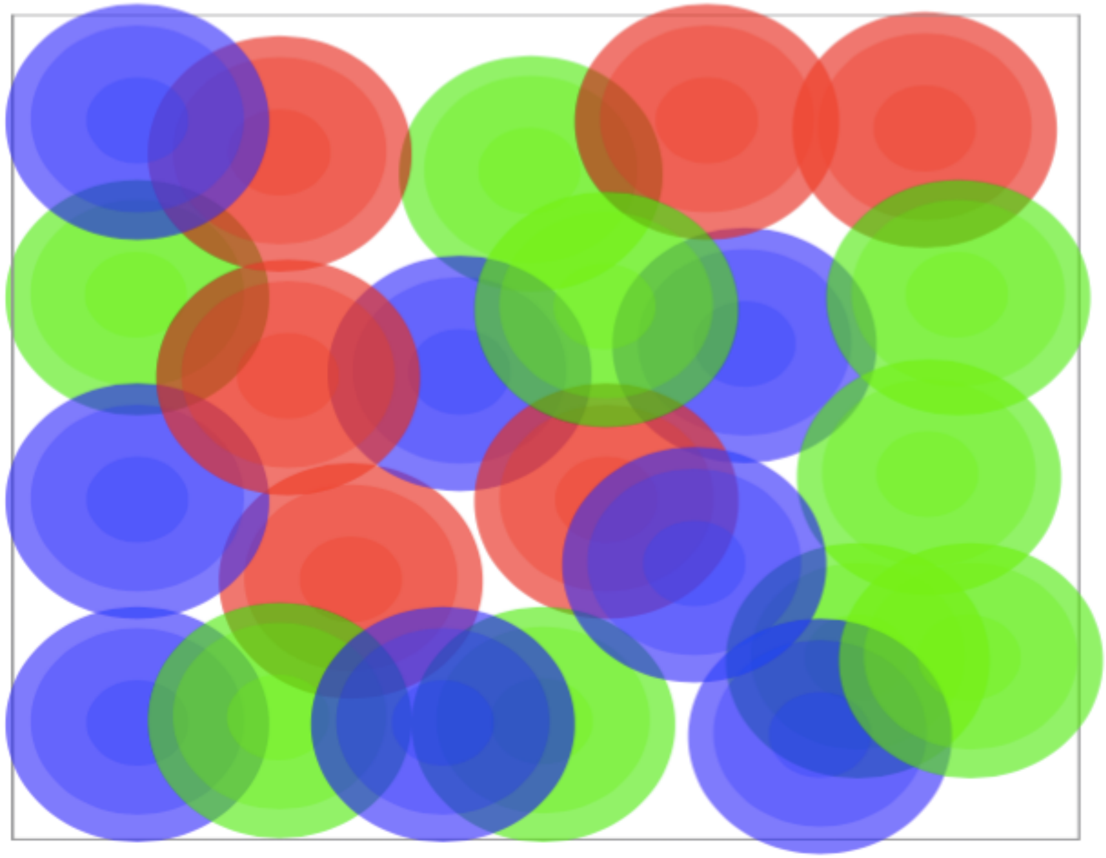

Is it a system with no long lived excitations?

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

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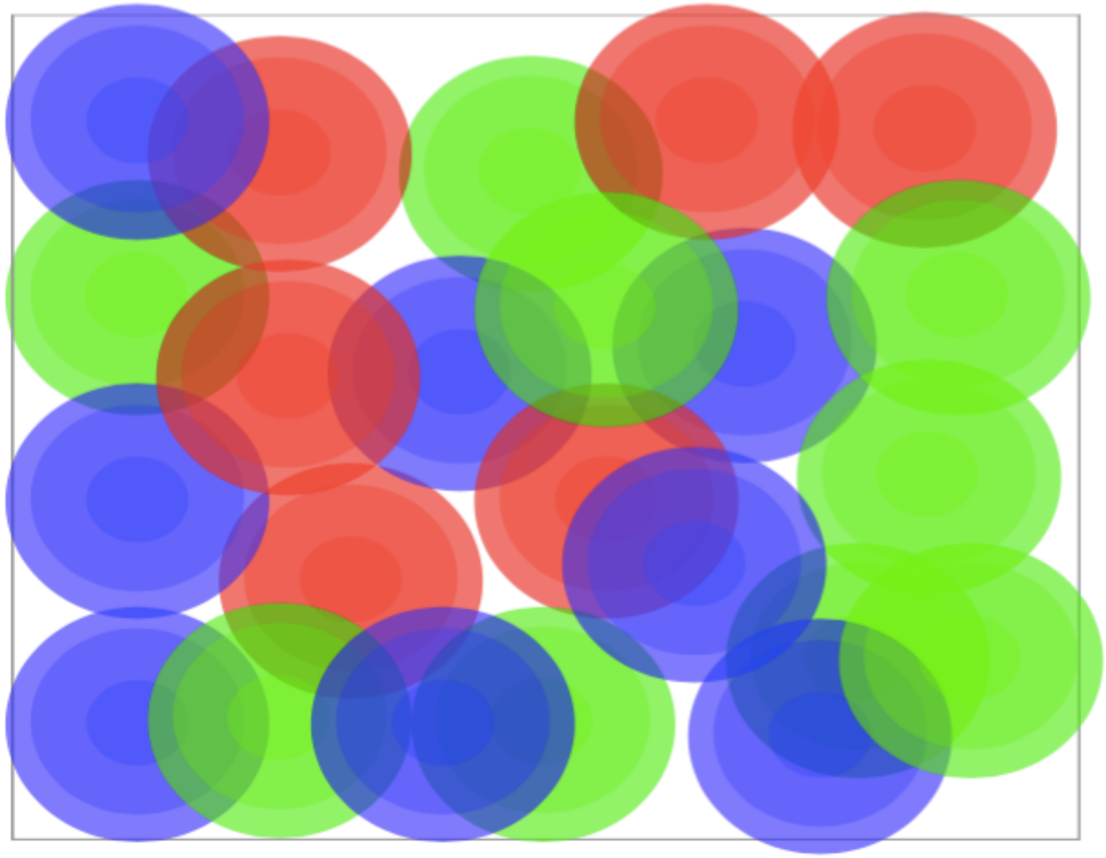


Is it a system with no quasi-particles?

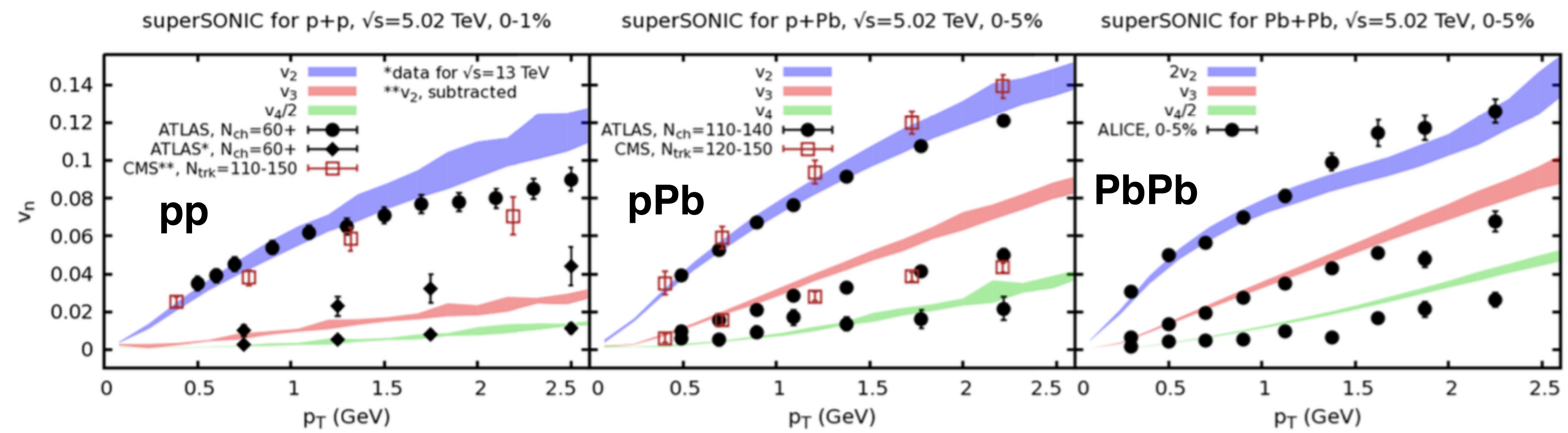
$$\alpha_s = 0.3 \rightarrow g = 2$$

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

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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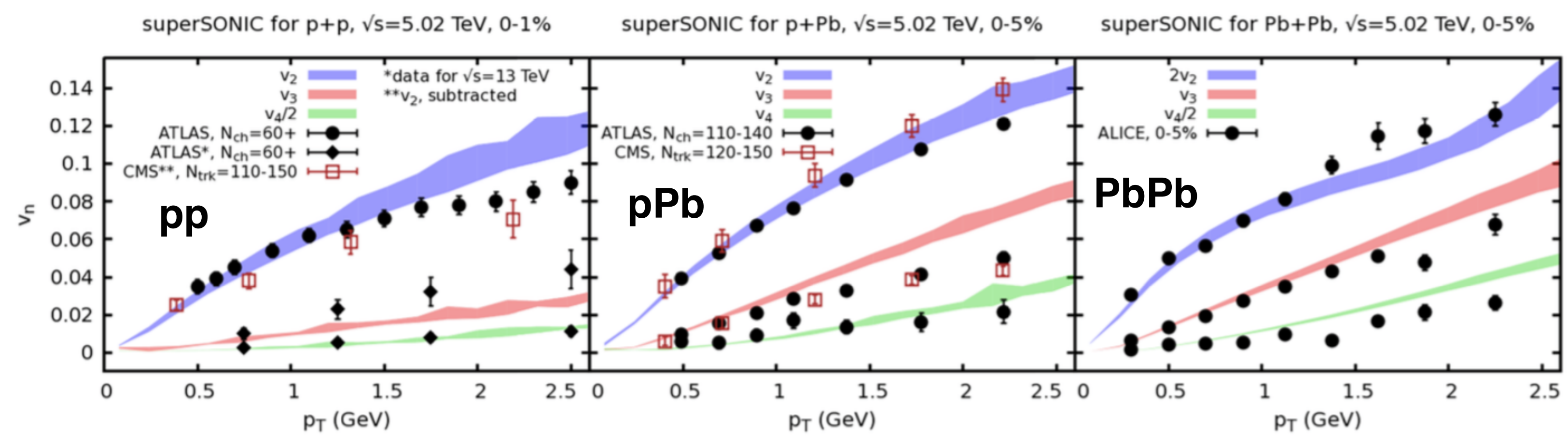

Weller & Romatschke ‘17

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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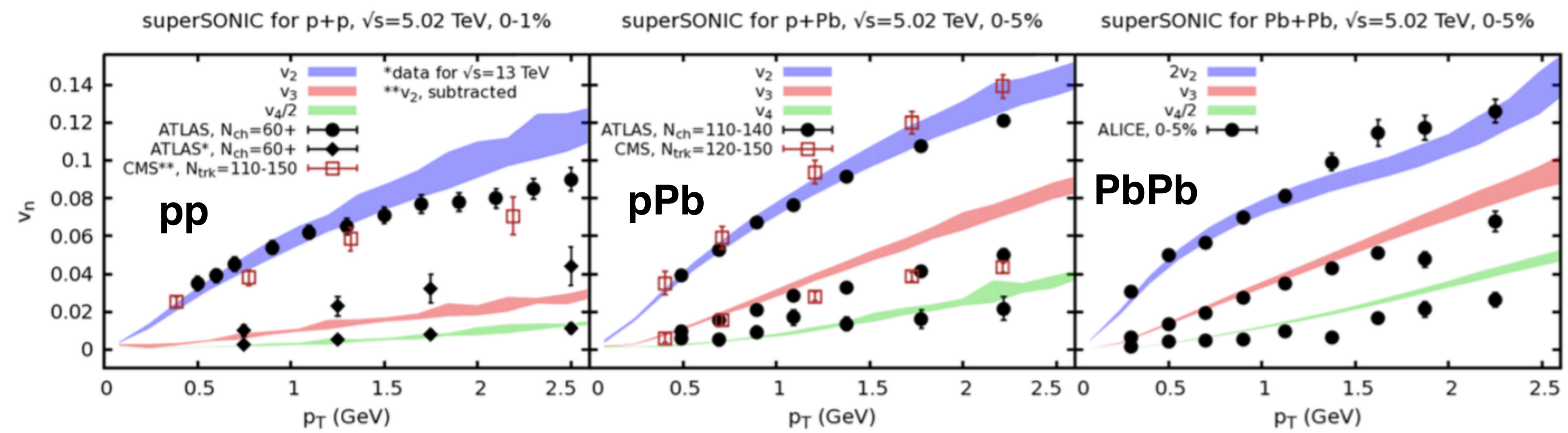


Weller & Romatschke ‘17

➡ Hydrodynamics at work with large gradients at very early times

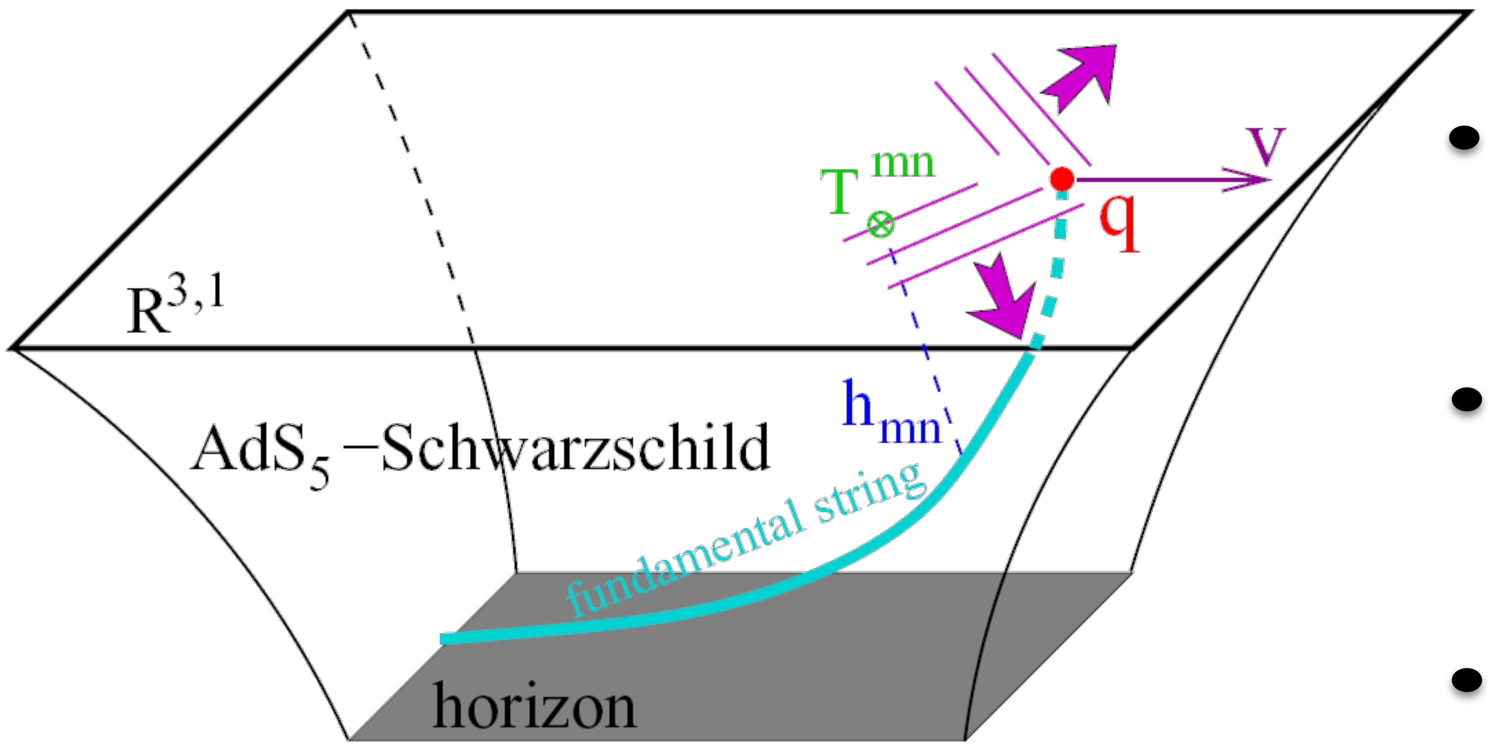
Completely natural situation at strong coupling

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

Chesler ‘15,‘16

Consistent 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

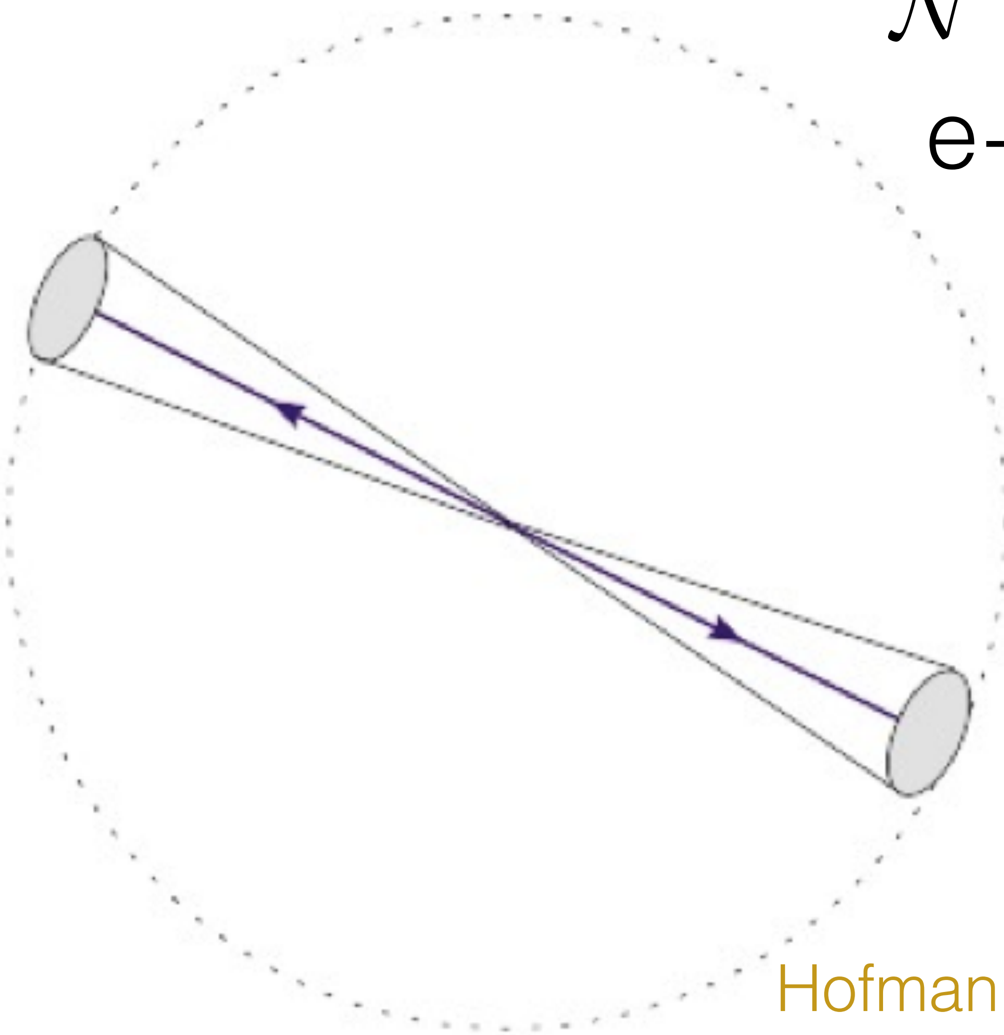
but

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

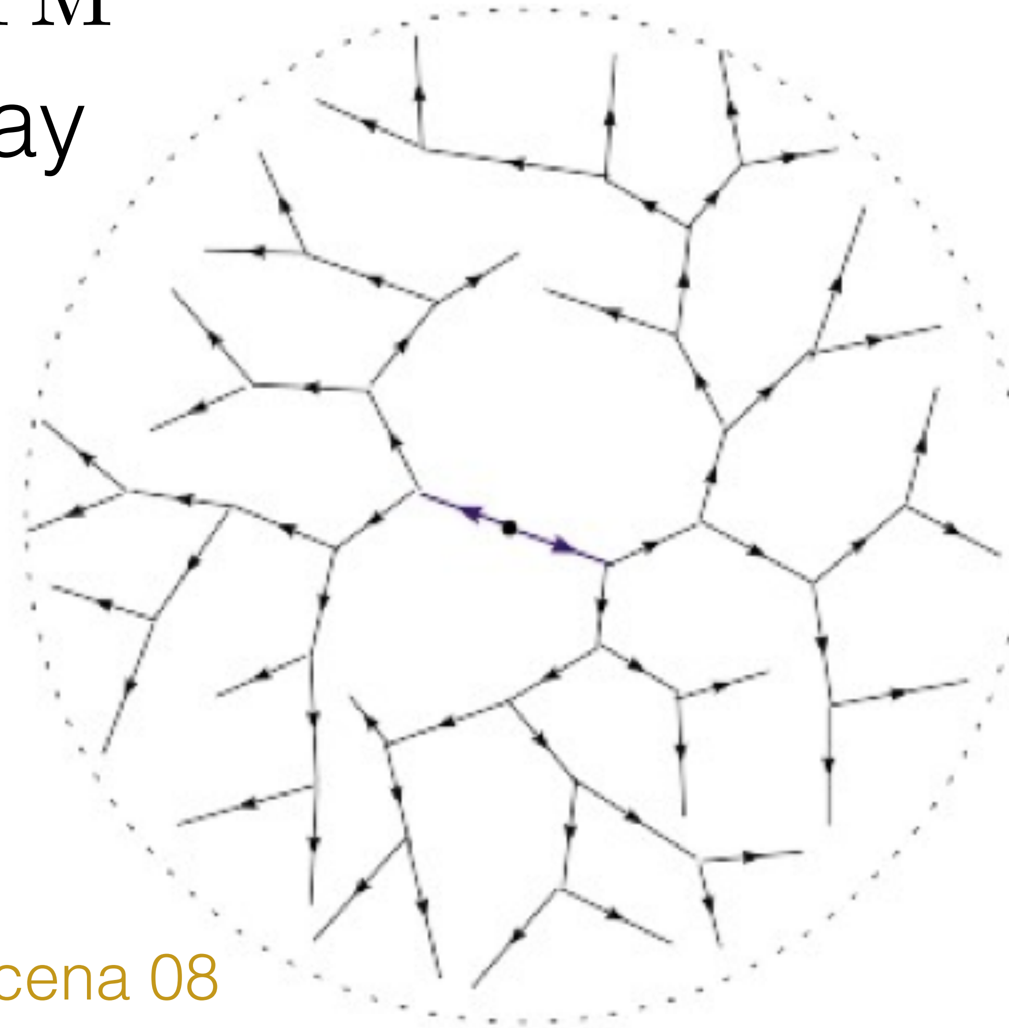
There are no jets at strong coupling

$\mathcal{N} = 4 \quad \mathrm{SYM}$

e+e- decay



Weak

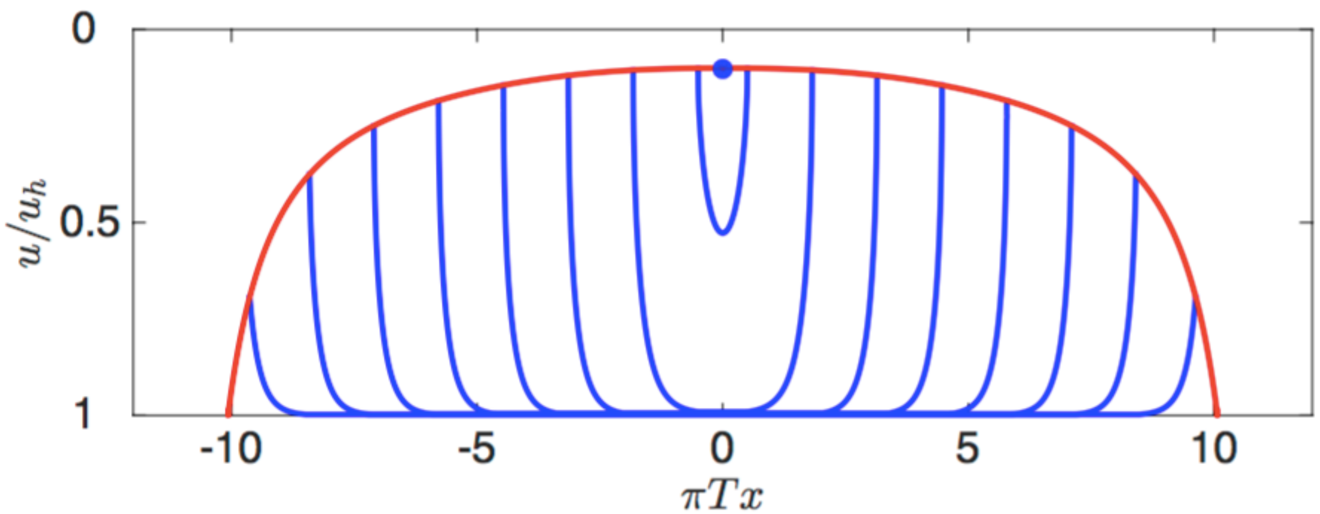


Strong

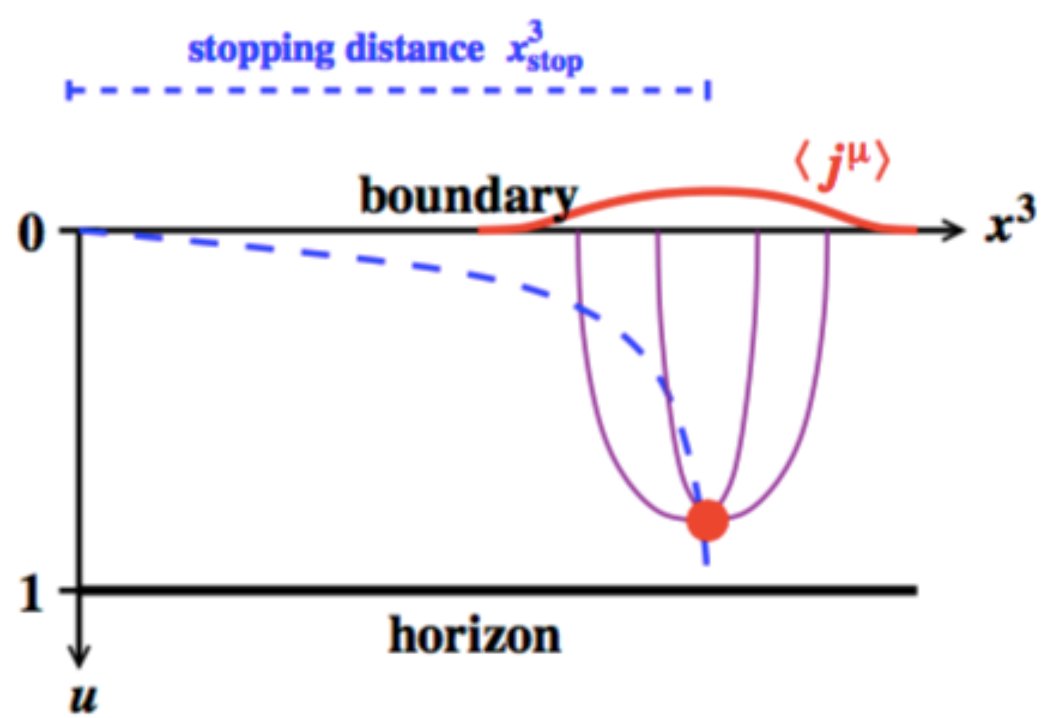
Hofman and Maldacena 08
Hatta, Iancu, Mueller 08

Problem for hard probes

Proxies for HE jets



Chesler et al. ‘09



Arnold & Vaman ‘11

semiclassical string description

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

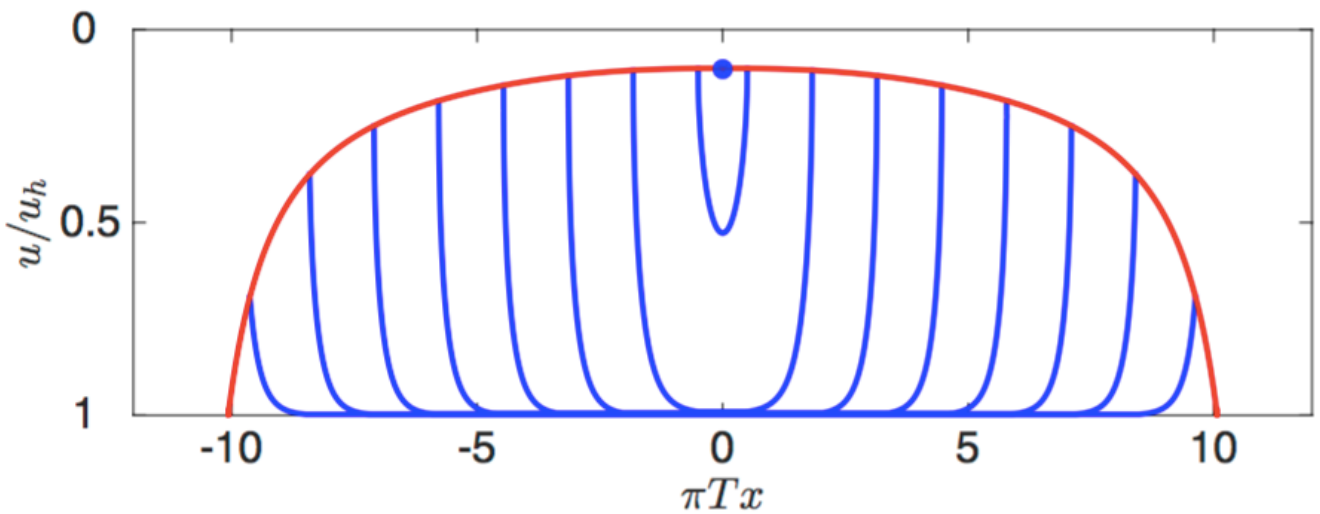
$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}} \frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

robust result at strong coupling

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

external boosted U(1) fields

Proxies for HE jets



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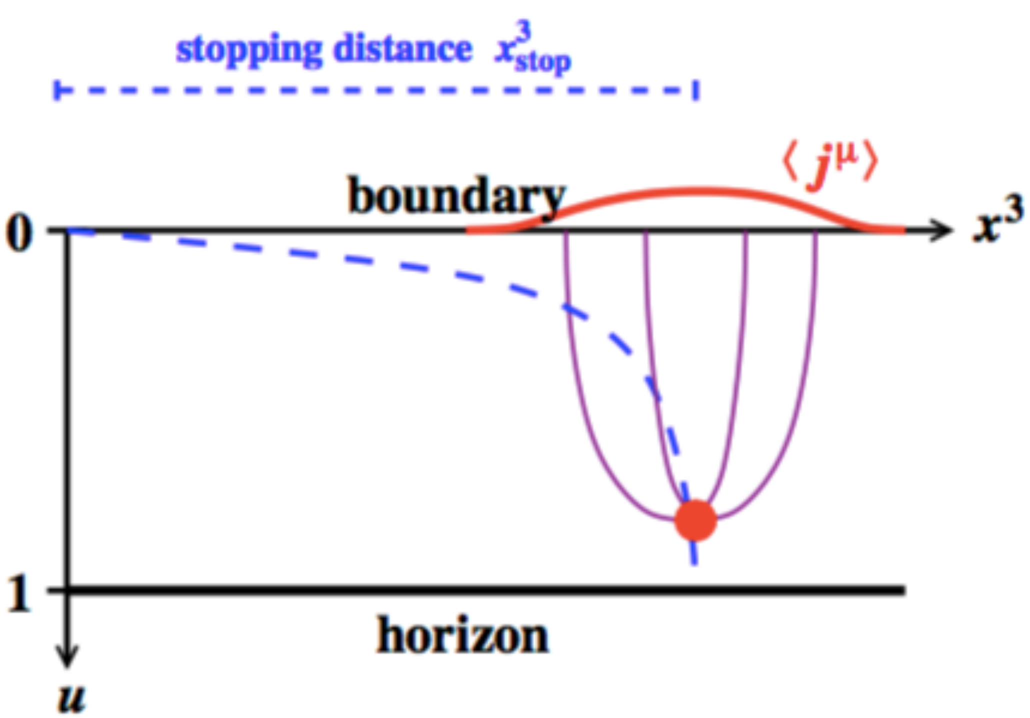

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in this talk

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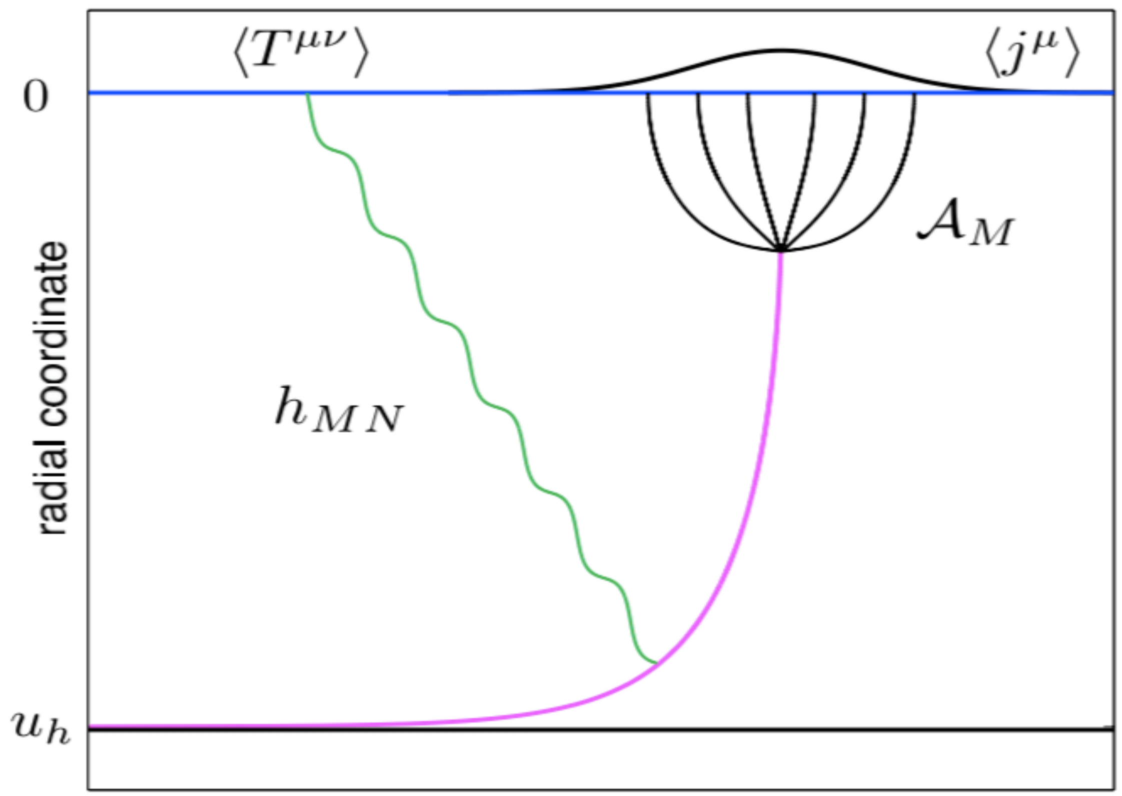
Null falling strings



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

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

string sourced

- near boundary expression of energy-momentum tensor

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

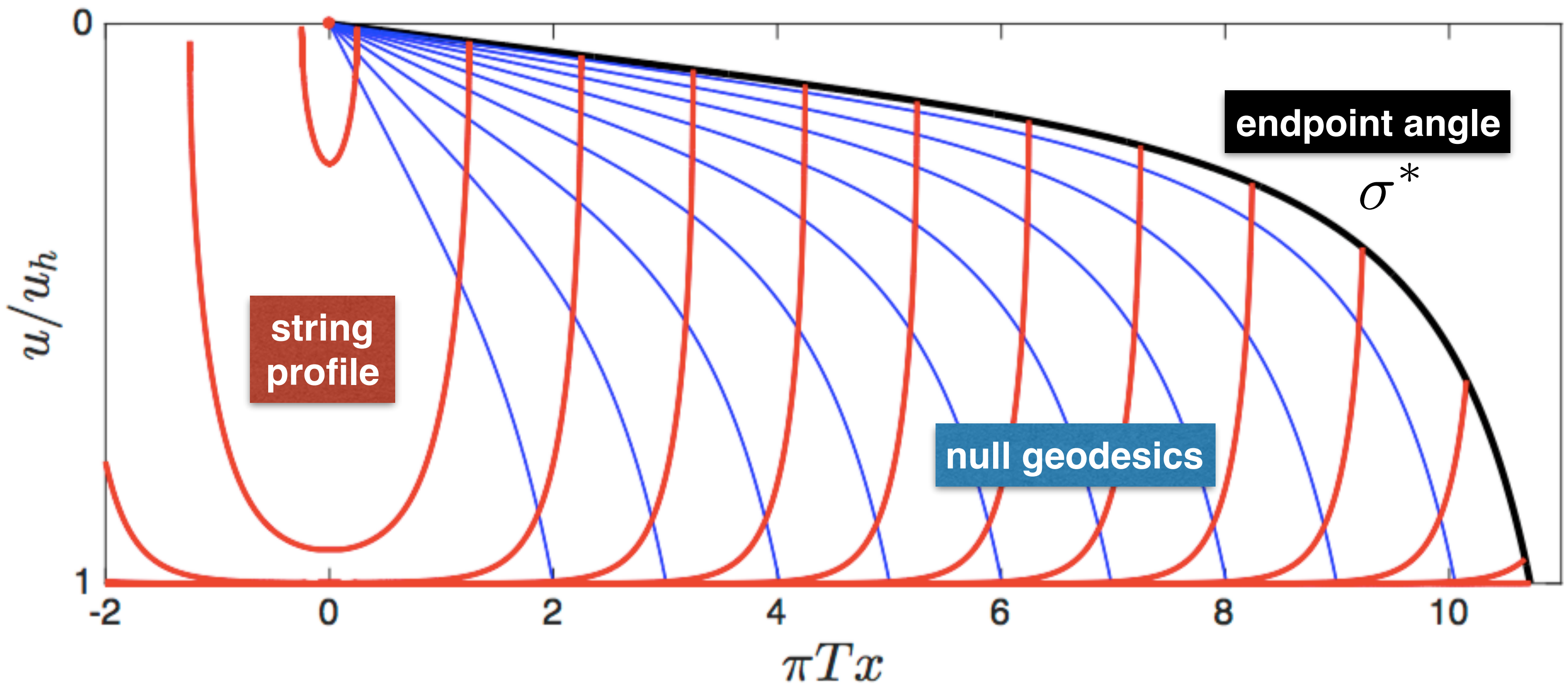
Chesler & Rajagopal '15

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



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

Nambu-Goto action

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

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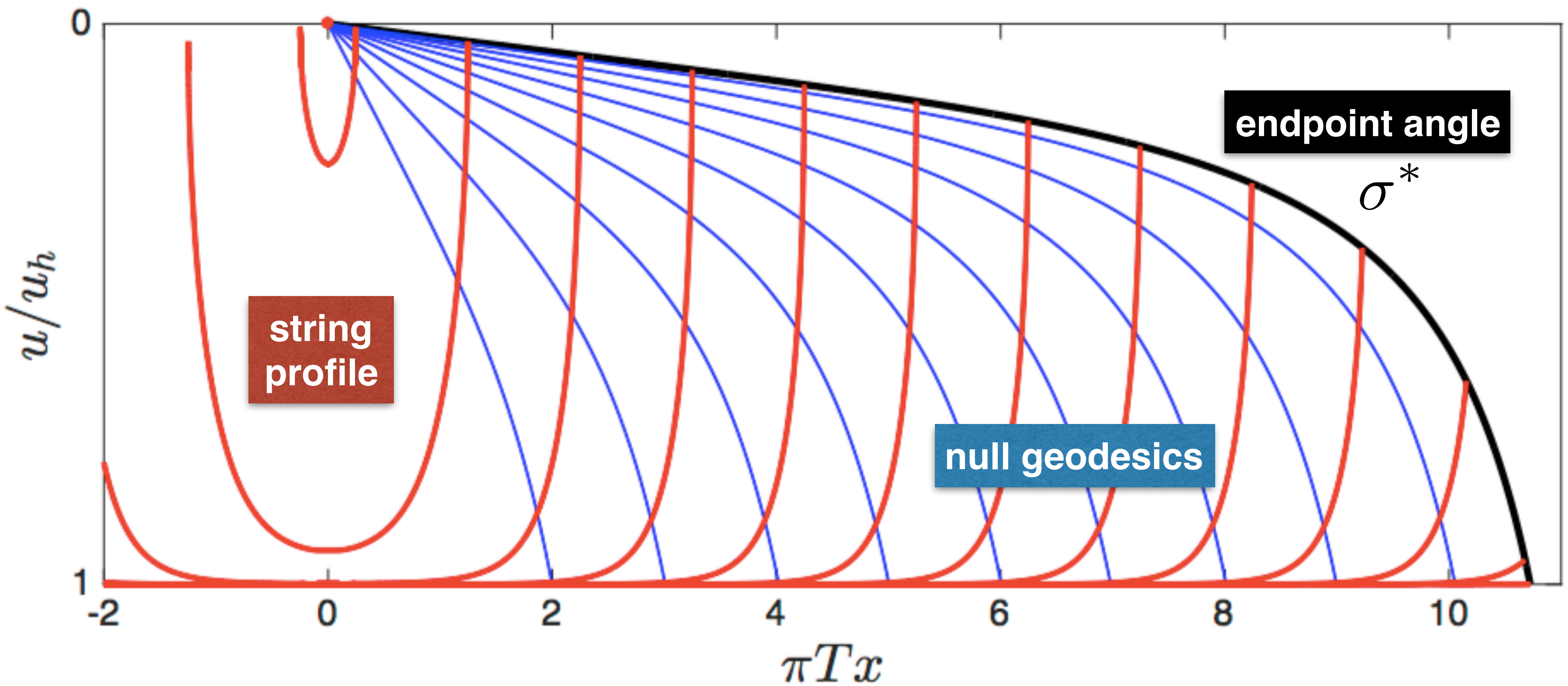

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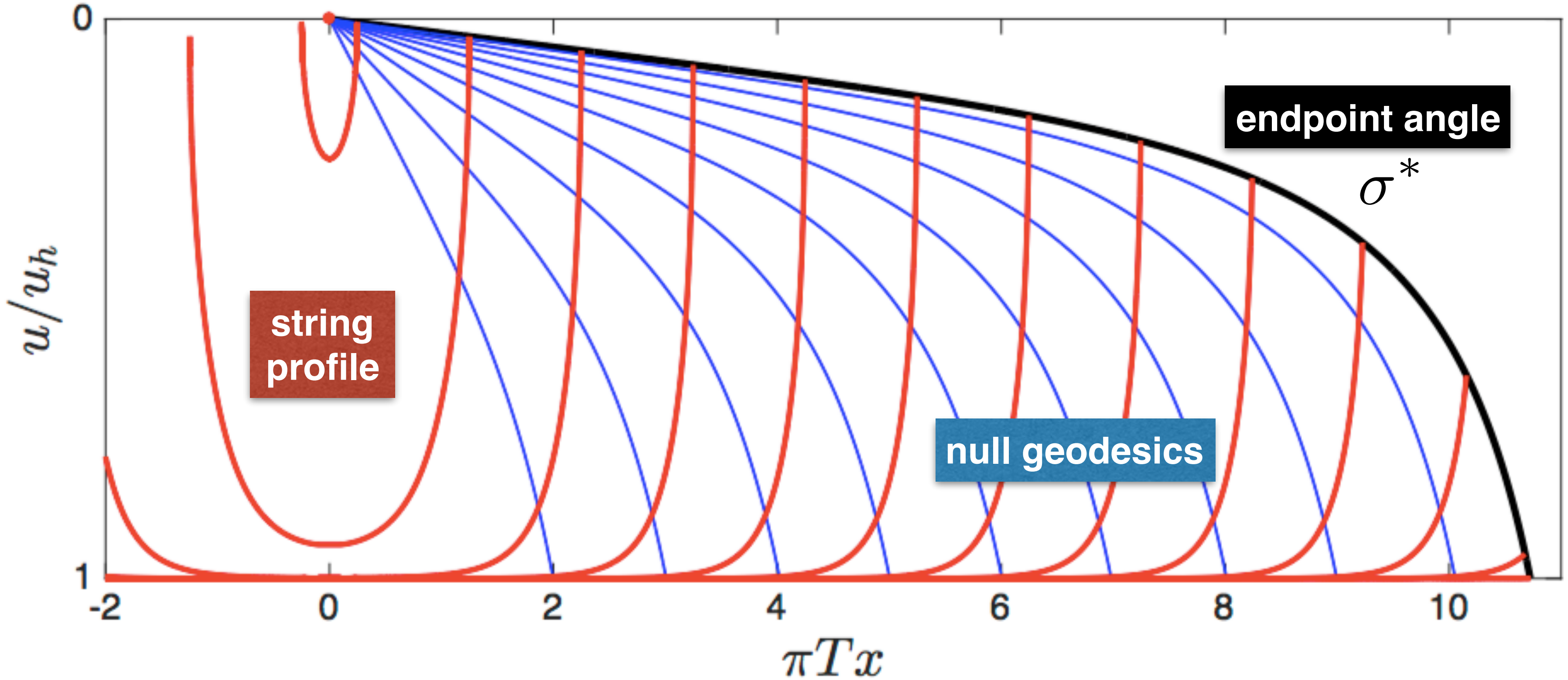
expand around degenerate null configuration

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

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

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

Null falling strings



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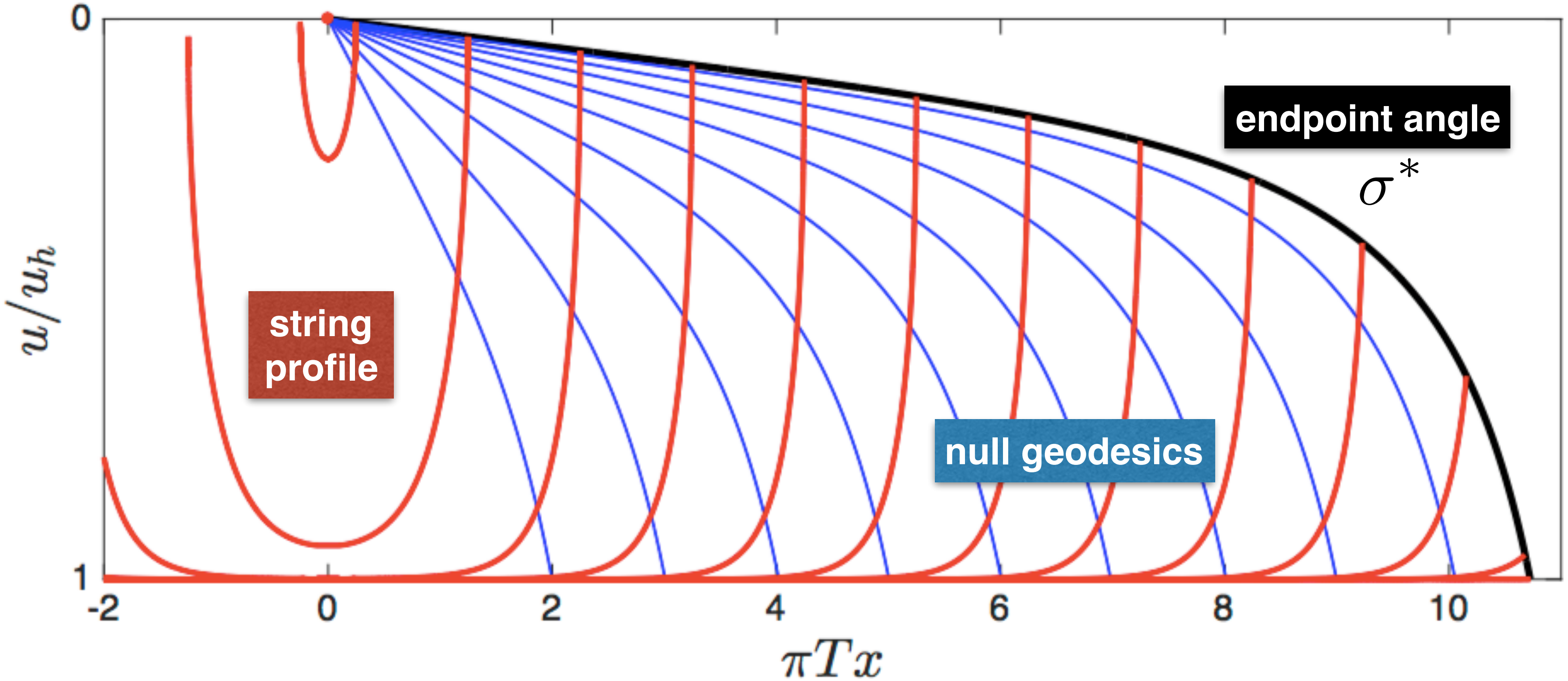
find energy carried by each geodesic

Null falling strings



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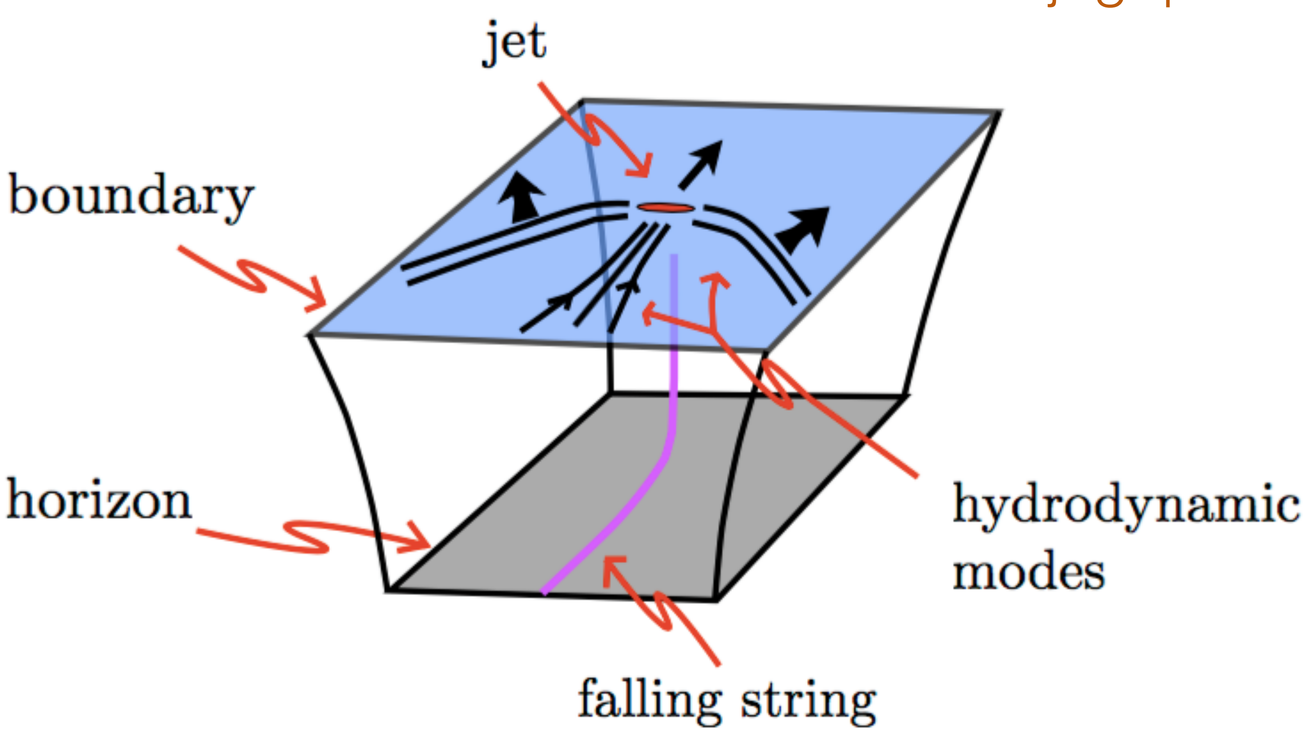
find energy carried by each geodesic

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

Null falling strings

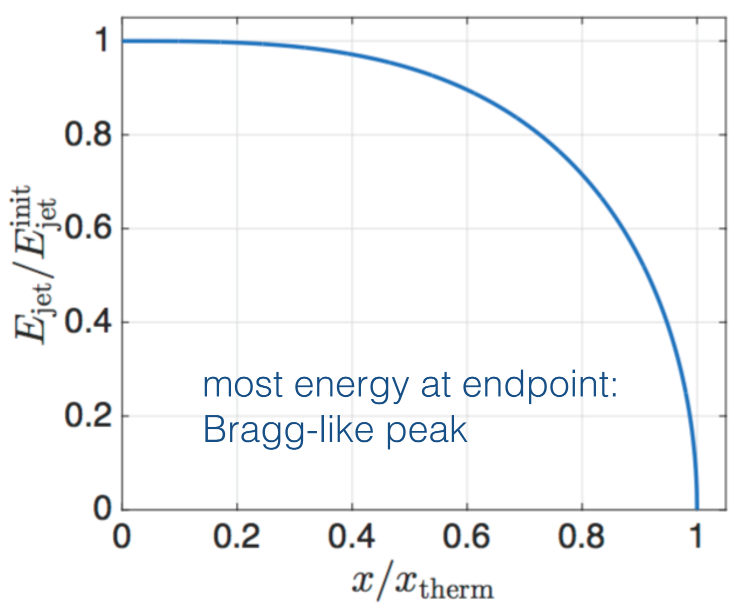
Chesler & Rajagopal '14,'15

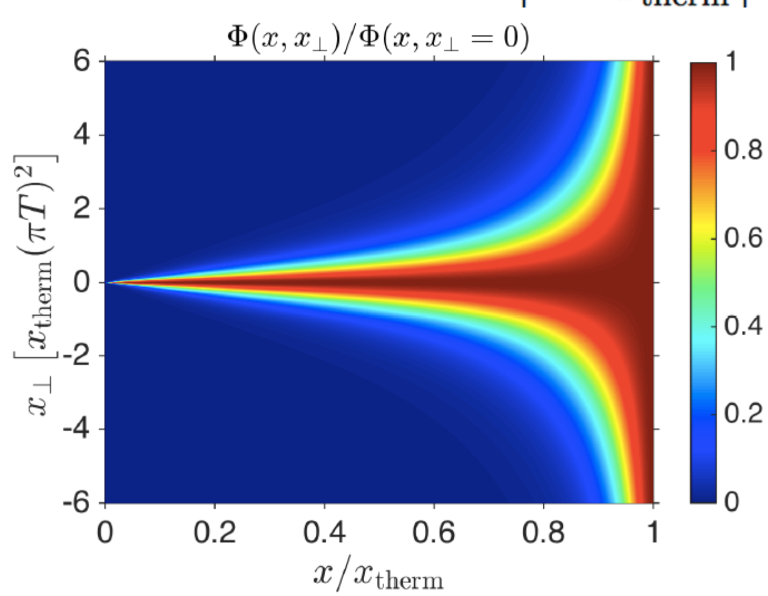


- unambiguous determination of boundary jet properties
- the rate at which energy flows into hydrodynamic modes:

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

as the jet loses energy … it gets wider $\theta_{\rm jet} \sim \dfrac{\theta_{\rm jet}^{\rm init}}{\left[1-\dfrac{x}{x_{\rm therm}}\right]^2}$

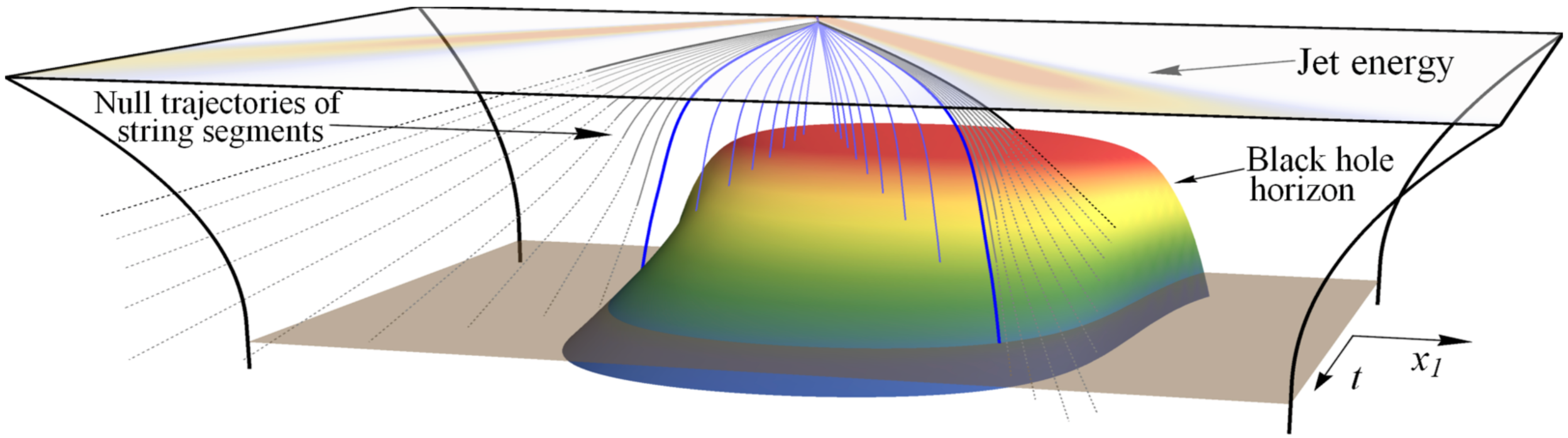




Fractional energy loss only depends on initial jet opening angle

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

Holographic quenching with pure strings

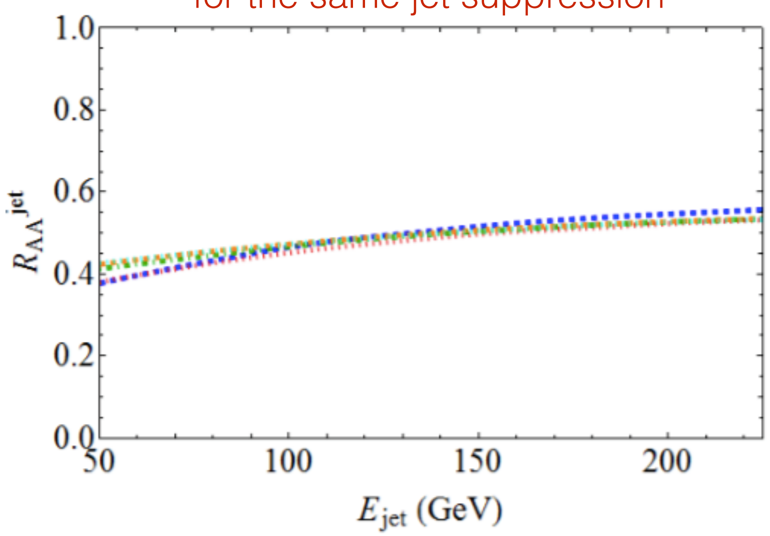


the *string* is treated as a model for the *jet as a whole*

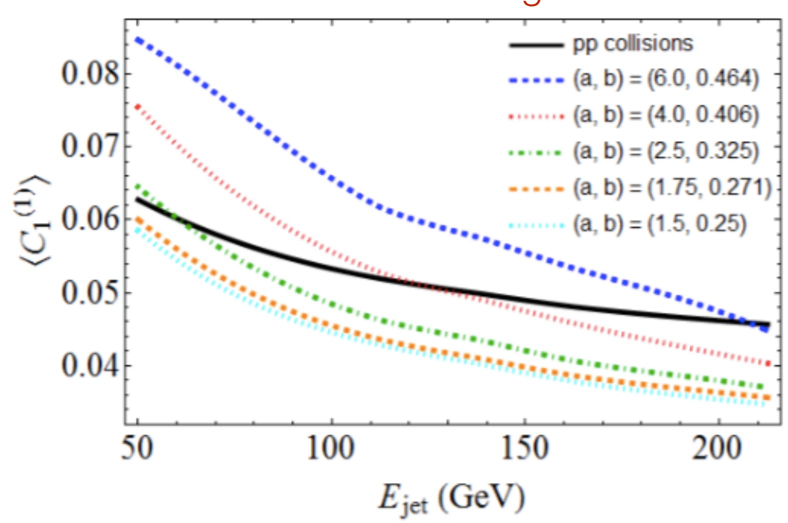
Rajagopal, Sadofyev, van der Schee '16

- 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.



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

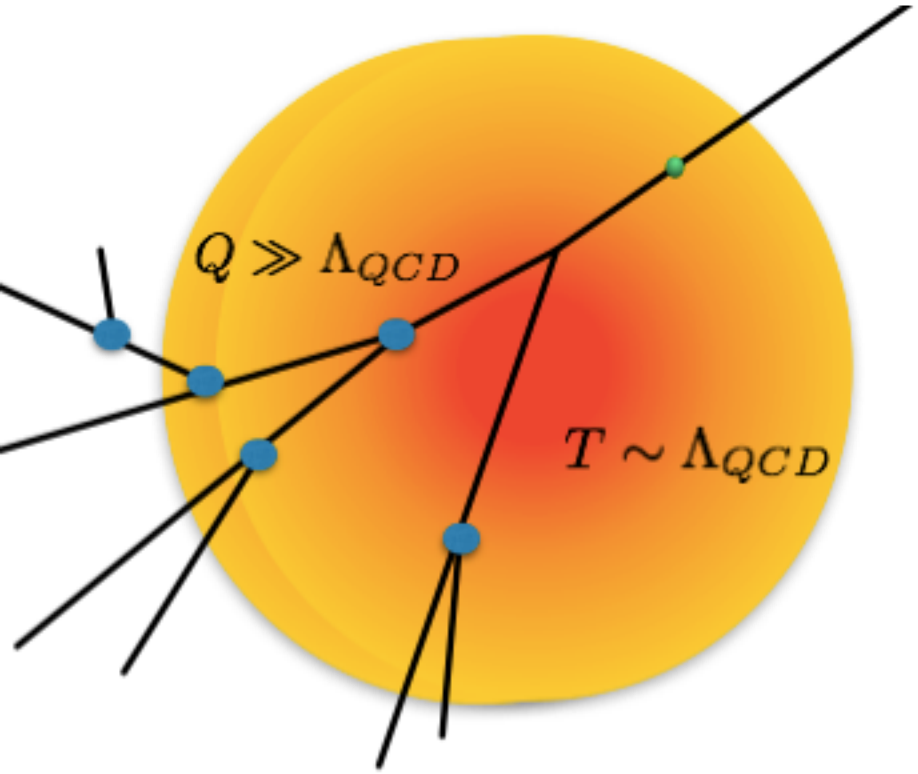
measures jet angle in pQCD

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

also observed in pQCD

Milhano & Zapp '15

Hybrid strong/weak coupling approach



Initial parton from hard scattering carries a high virtuality

will split according to perturbative DGLAP evolution

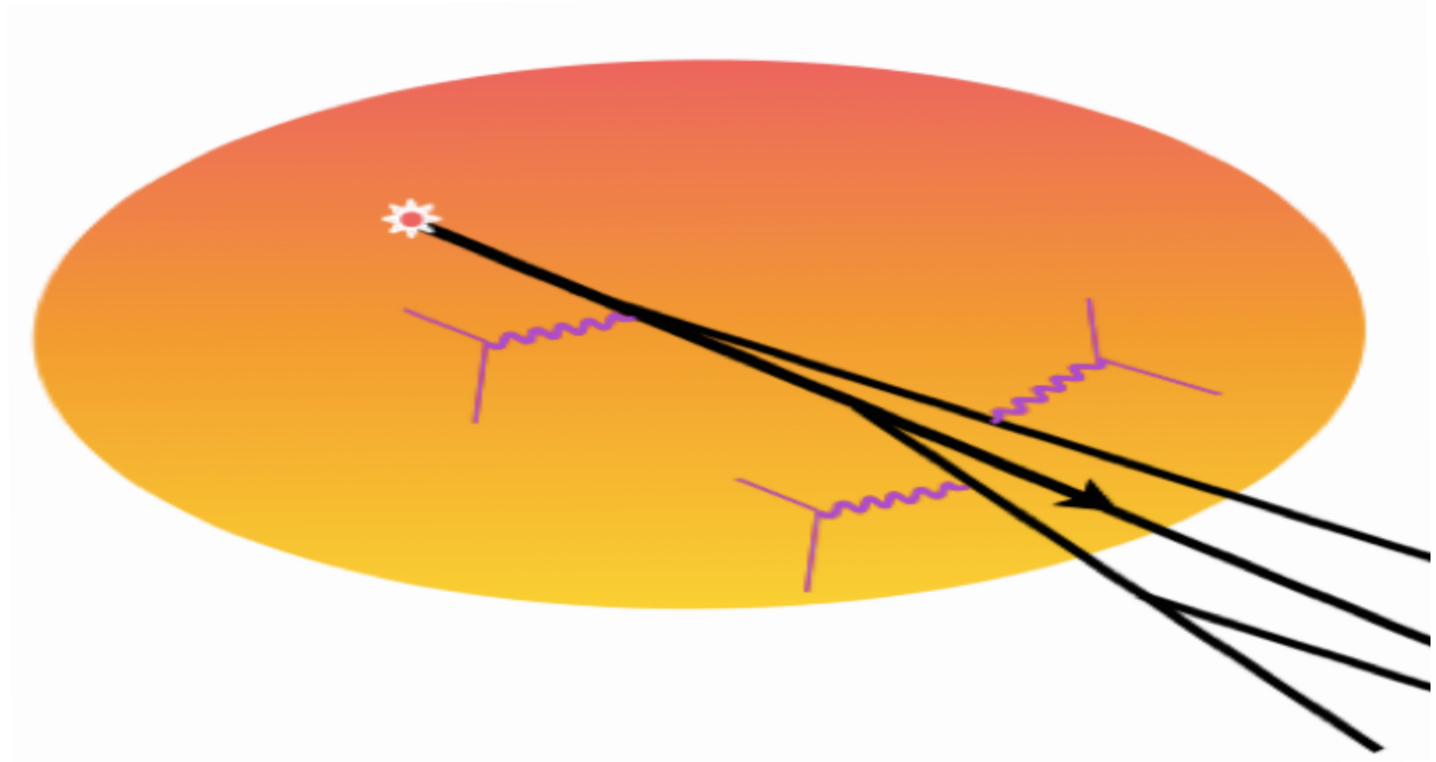
Casalderrey-Solana et al. '14,'15,'16

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) $\tau_f = \frac{2E}{Q^2}$
- 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

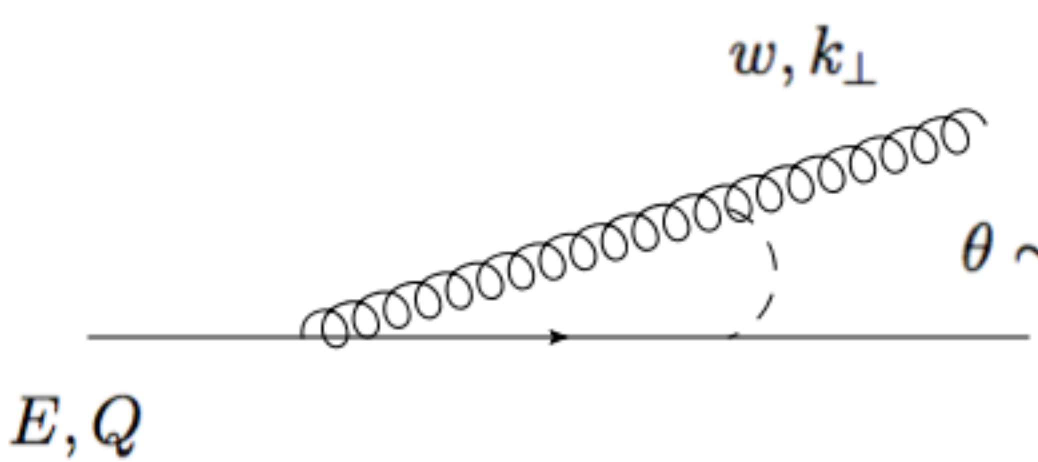
Generate HardQCD pp events with PYTHIA:

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



$\theta \sim k_\perp / w$

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

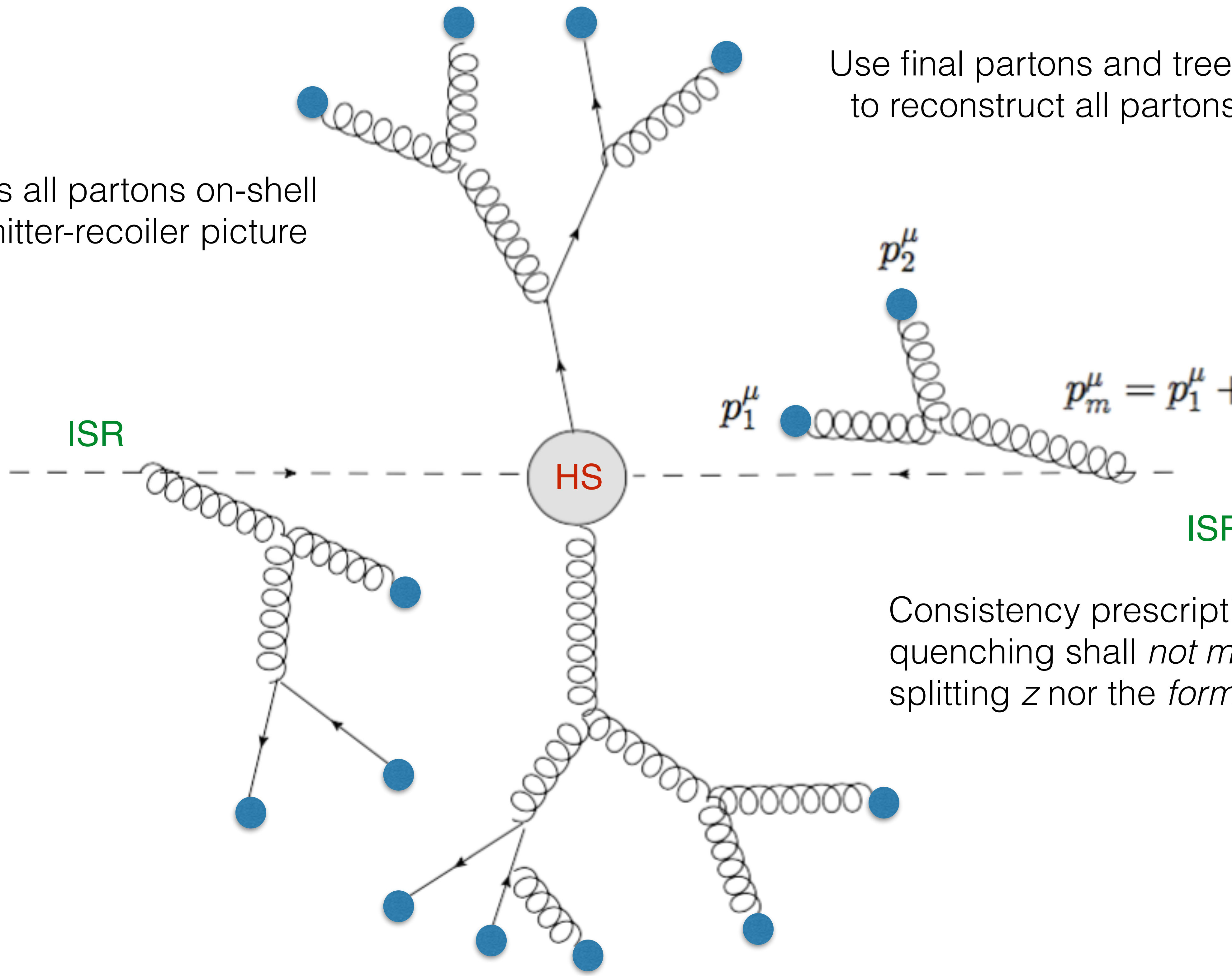
$$\tau_f \sim w/k_\perp^2 \to 2E/Q^2$$

Parton Shower

Use final partons and tree information to reconstruct all partons momenta

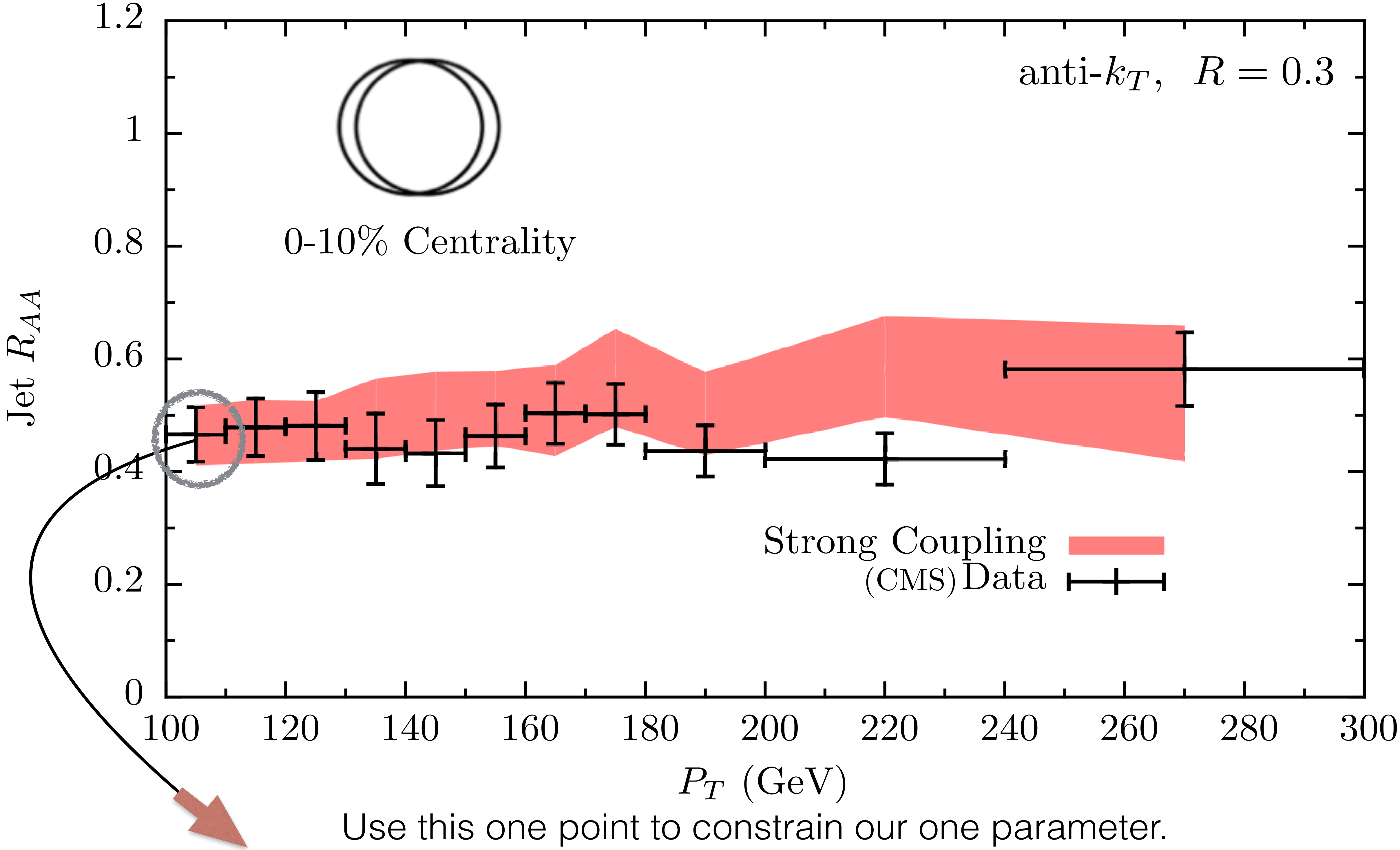
PYTHIA 8 keeps all partons on-shell through the emitter-recoiler picture

t=0, z=0



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

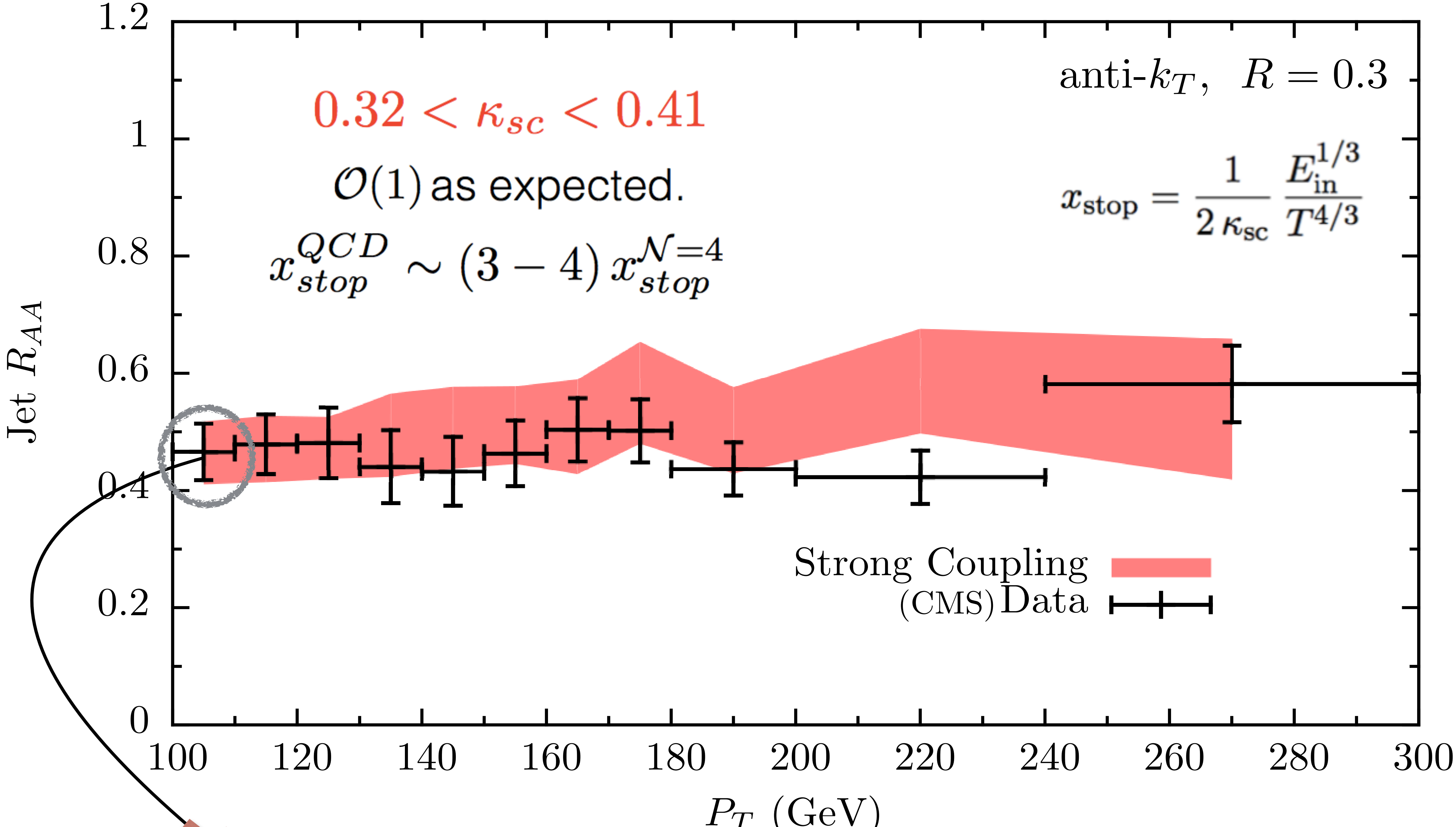
Jet R_{AA}



Use this one point to constrain our one parameter.

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

Jet R_{AA}



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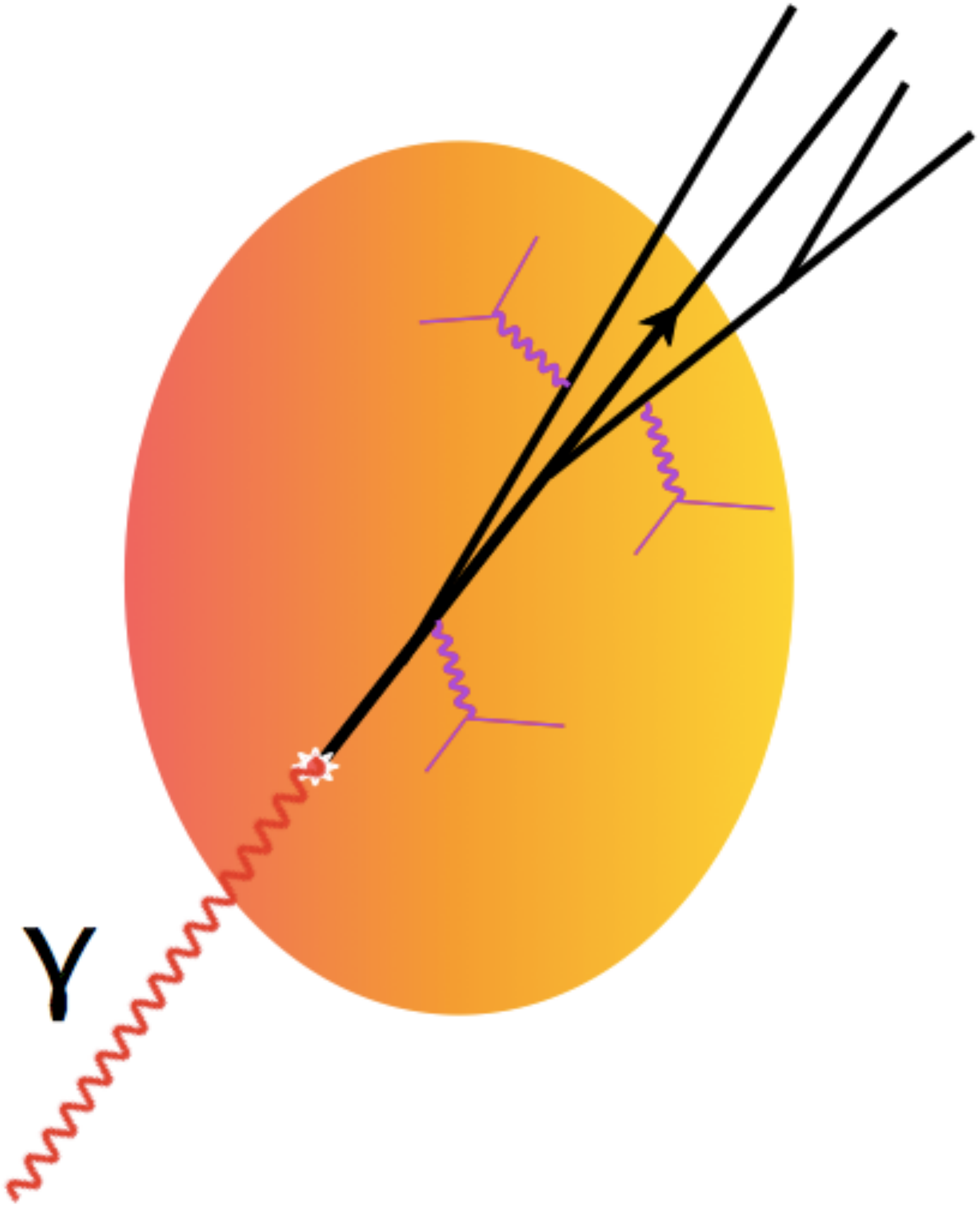
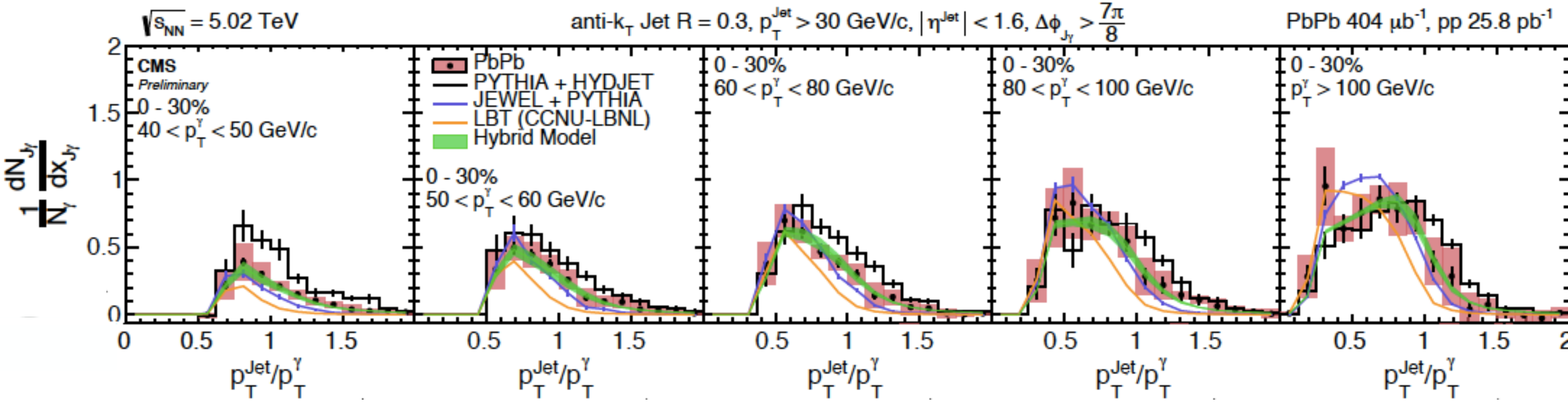
Photon-Jet: the 'golden' channel

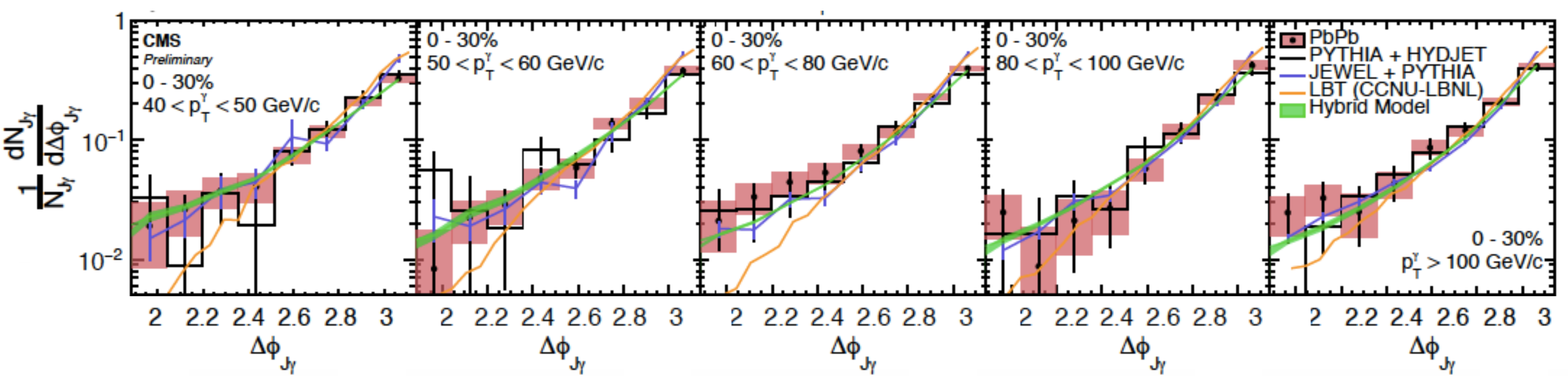


- Photons do not interact with plasma
- Look for associated jet
  - -Different geometric sampling
  - -Different species composition
  - -E_{γ} proxy for E_{jet}

Photon-Jet: the ‘golden’ channel

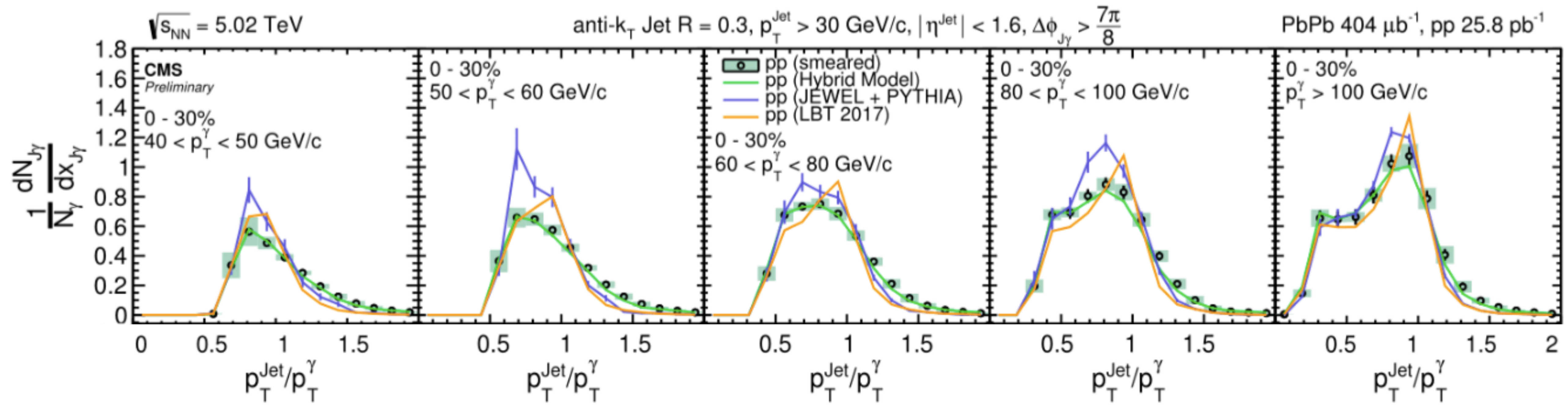


Core features of the model have been validated by e.g. photon-jet observables predictions

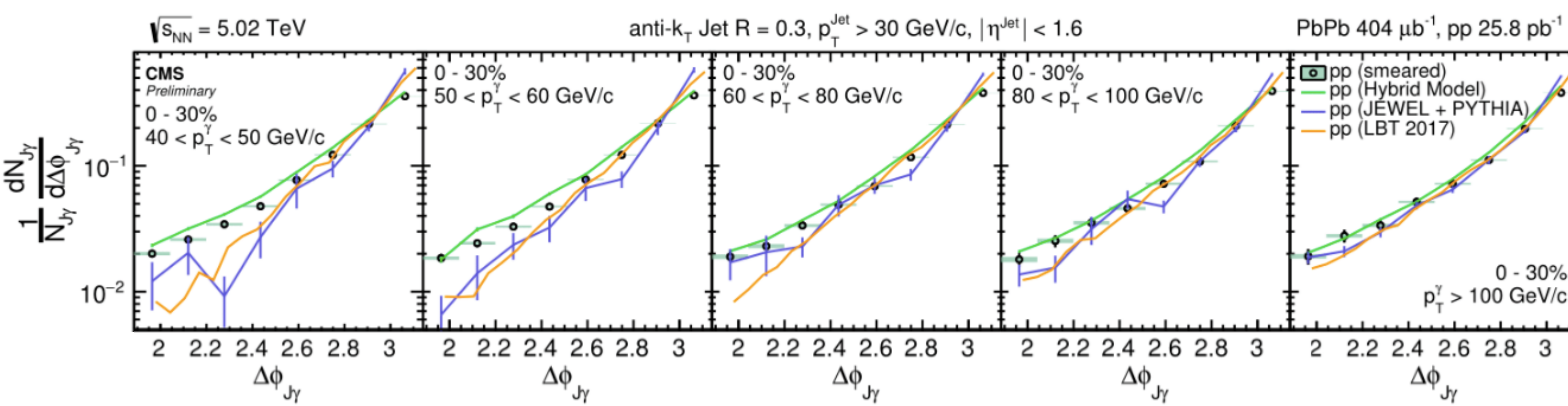


No strong evidence so far of hard point-like scatterers

Photon-Jet: the 'golden' channel

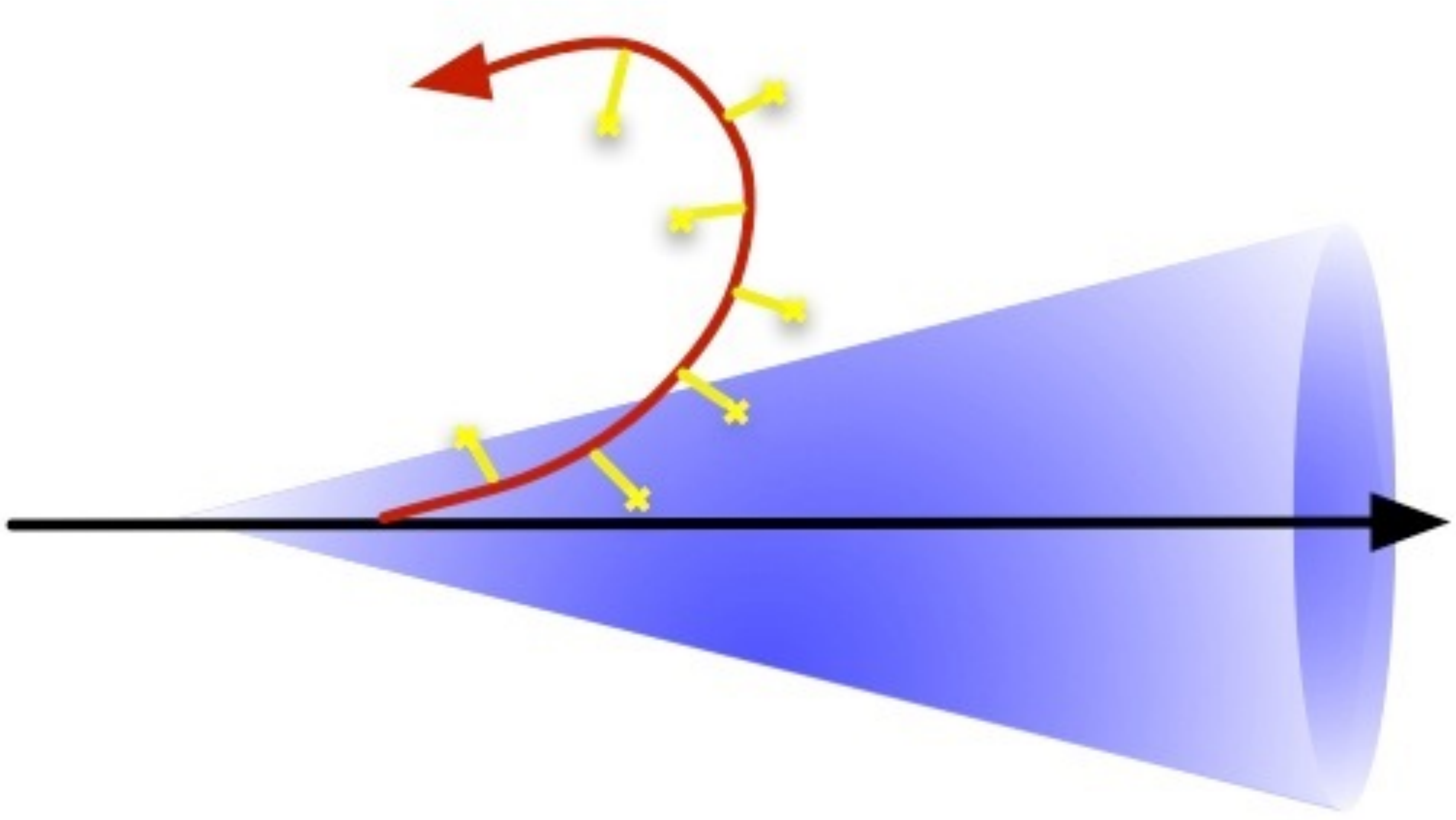


Cannot really compare among models because of different pp reference



Important effects: Jet Pt smearing, bremsstrahlung photons

Intra-jet broadening



Partons receive transverse kicks according to a gaussian distribution

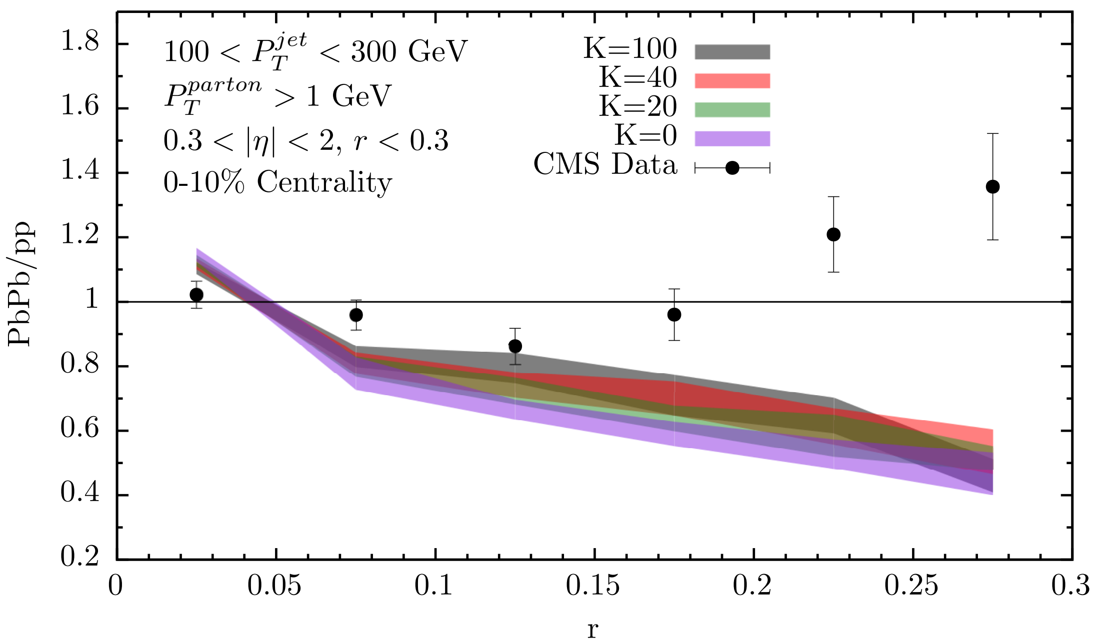
The width of the gaussian is $(\Delta k_T)^2 = \hat{q}\, dx$

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

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

Liu, Rajagopal, Wiedemann 06

Intra-jet broadening



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

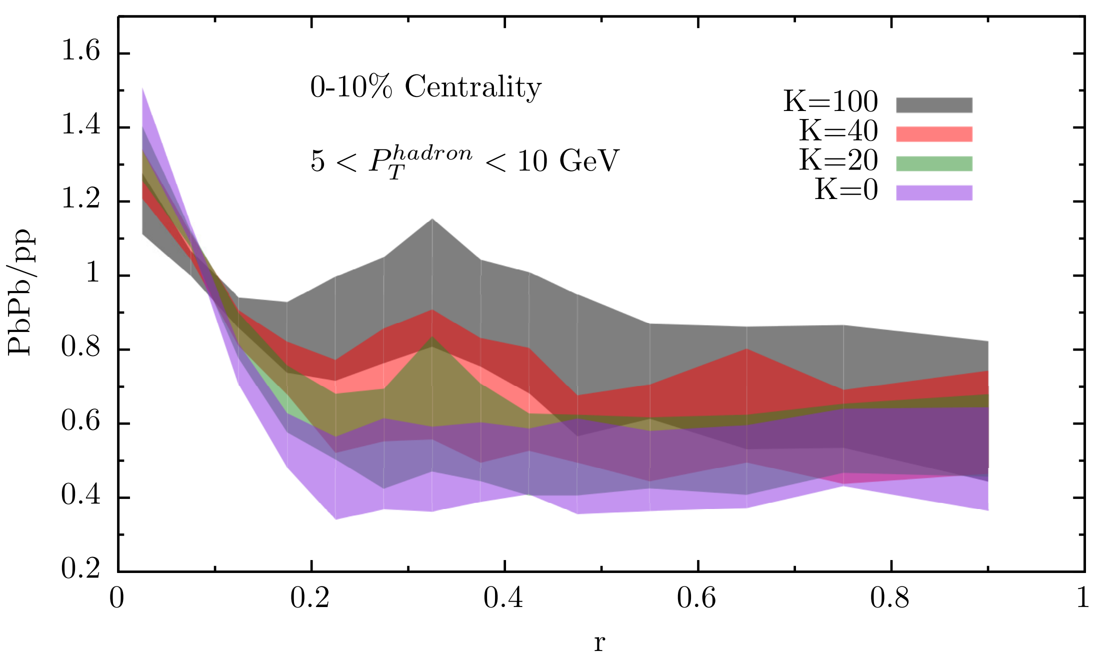
Inclusive jets - all tracks

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

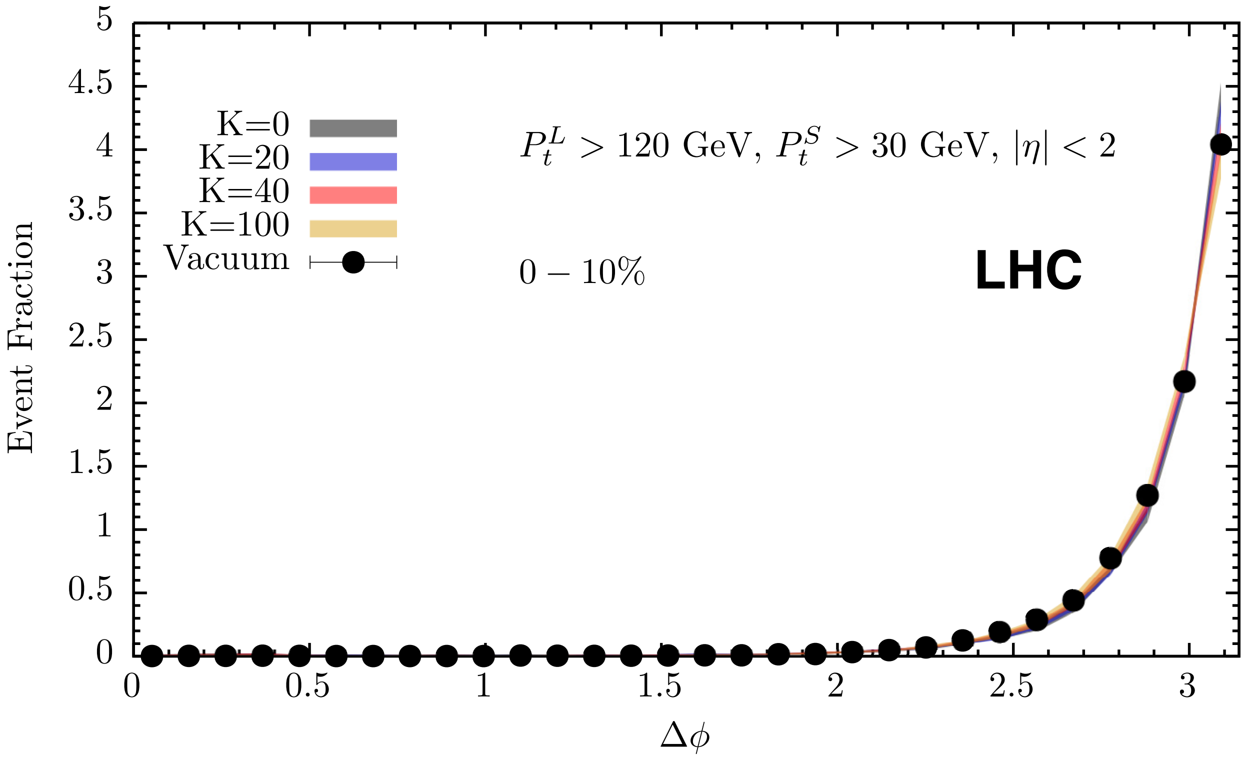
kinematical limits chosen such that:

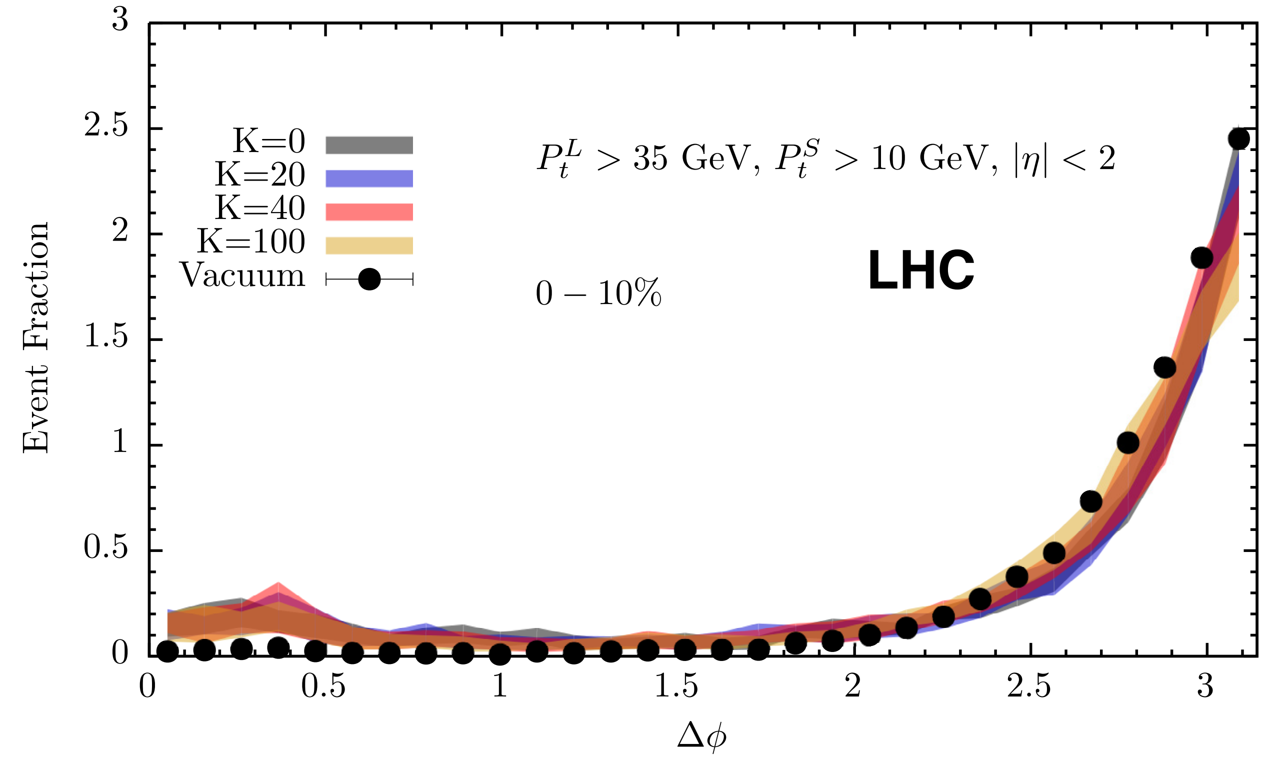
- no effect from background (soft tracks)
- intra-jet activity above average (hard tracks)

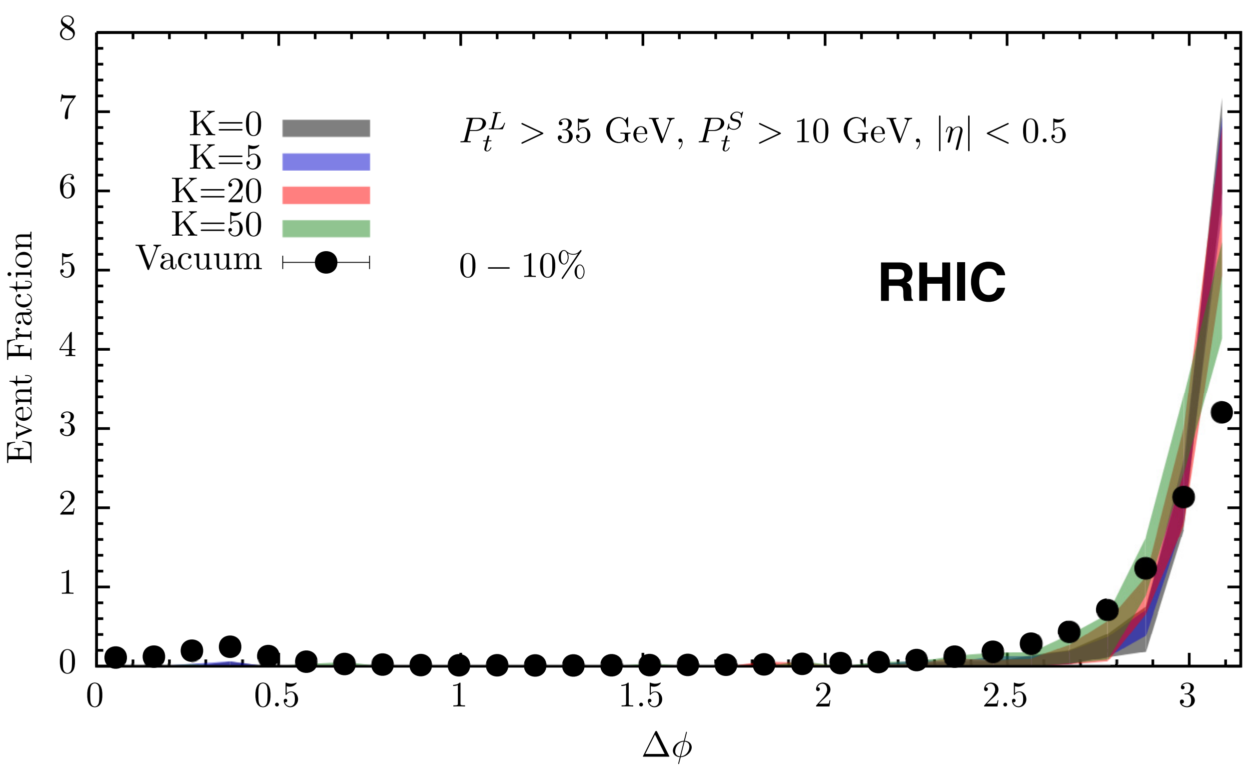
deviations from such Gaussian broadening

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

Jet induced medium excitations

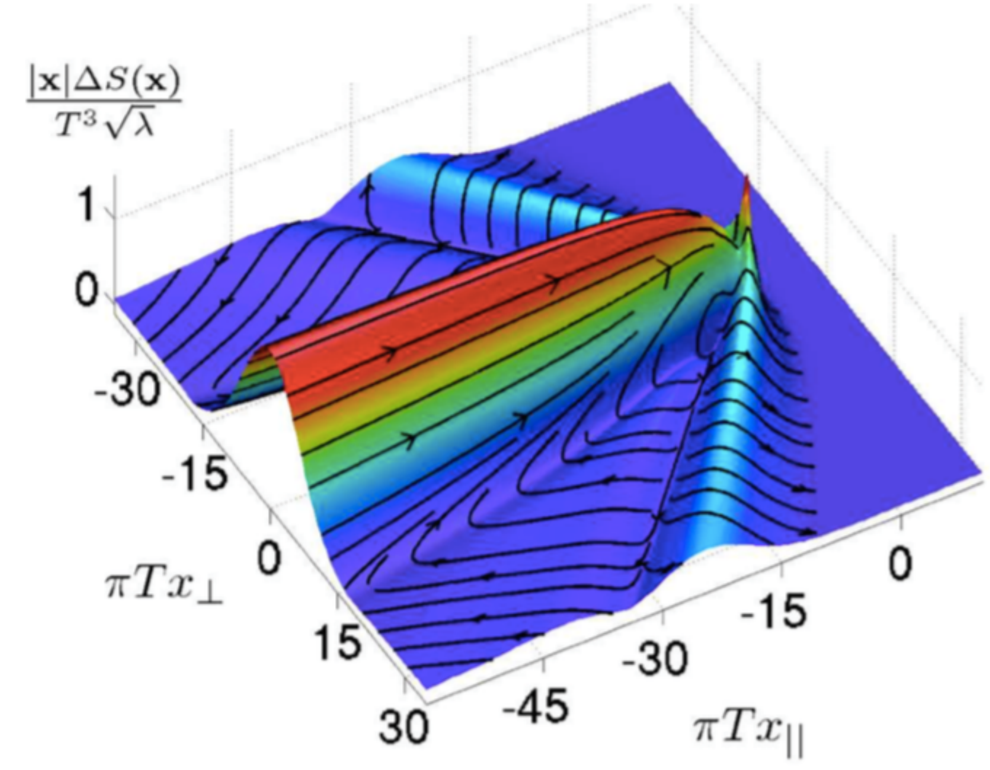
metric perturbation near the AdS boundary

↓

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

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

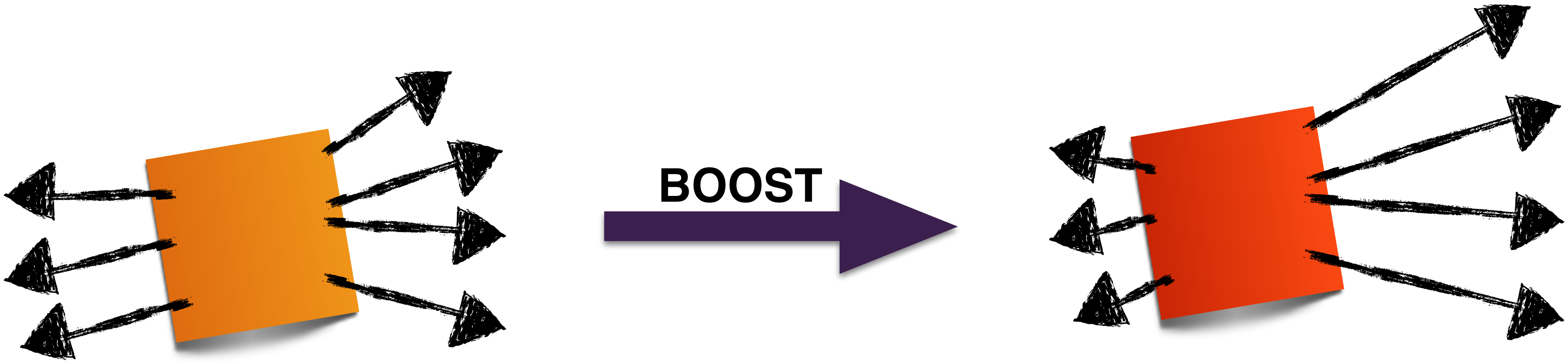
One body distribution

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

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

An estimate of backreaction

One body distribution has negative contributions at large azimuthal separation

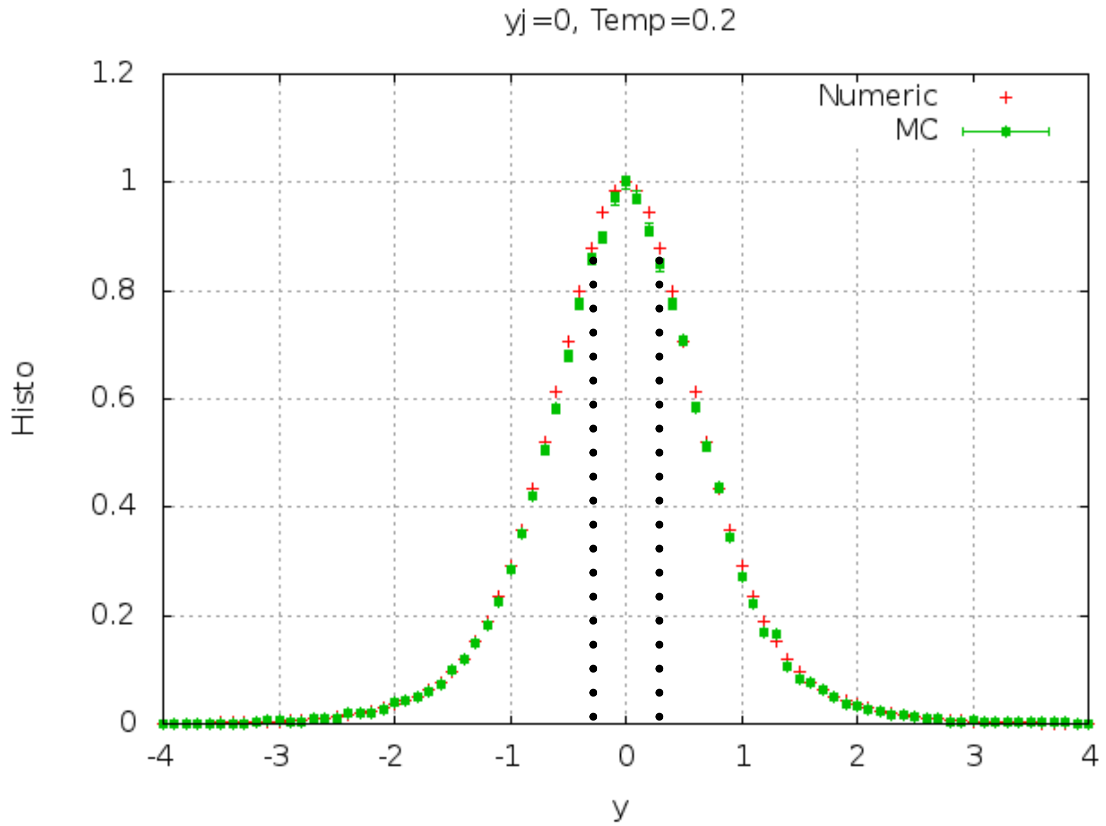


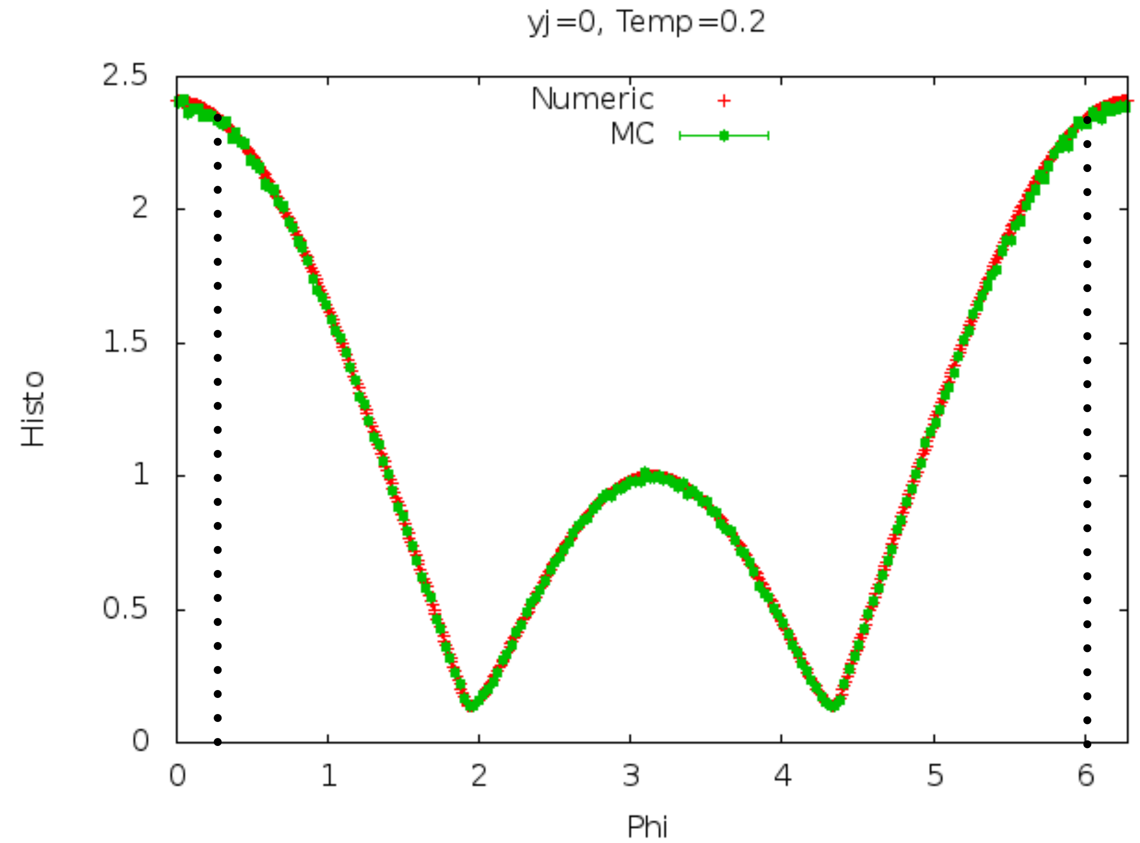
Background diminished w.r.t unperturbed hydro for that region in space

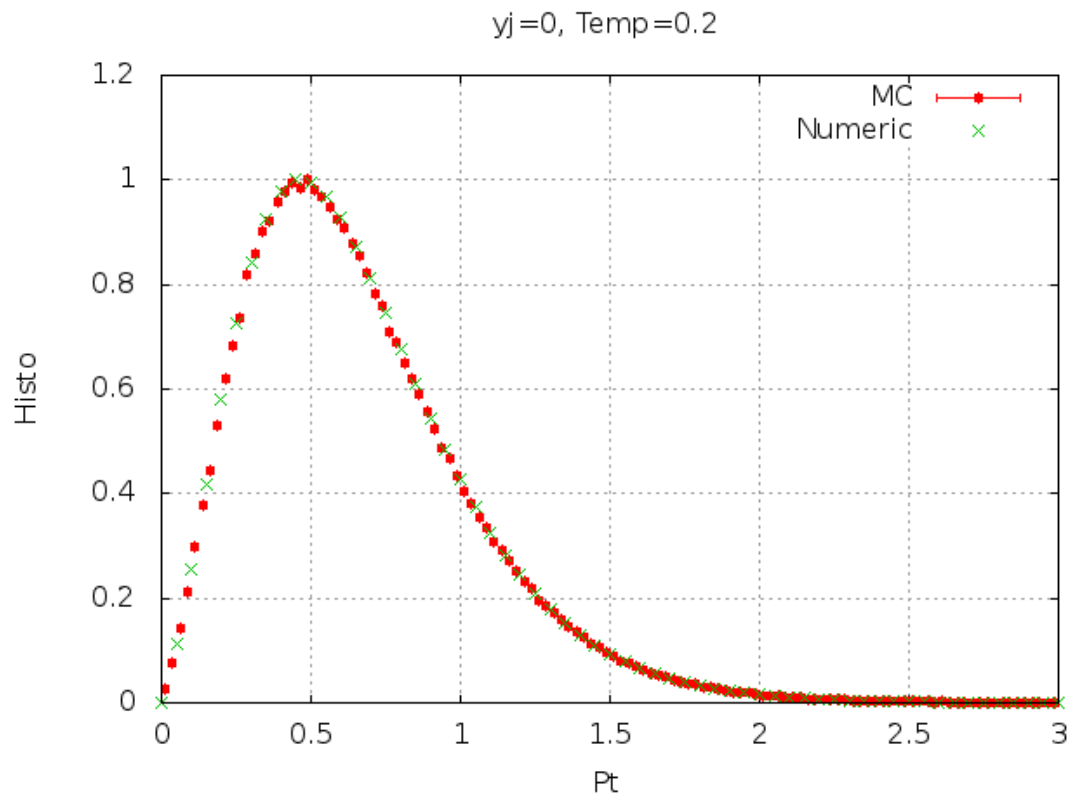
Need to emulate experimental background subtraction (e.g. eta reflection method) due to long range correlations

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

An estimate of backreaction







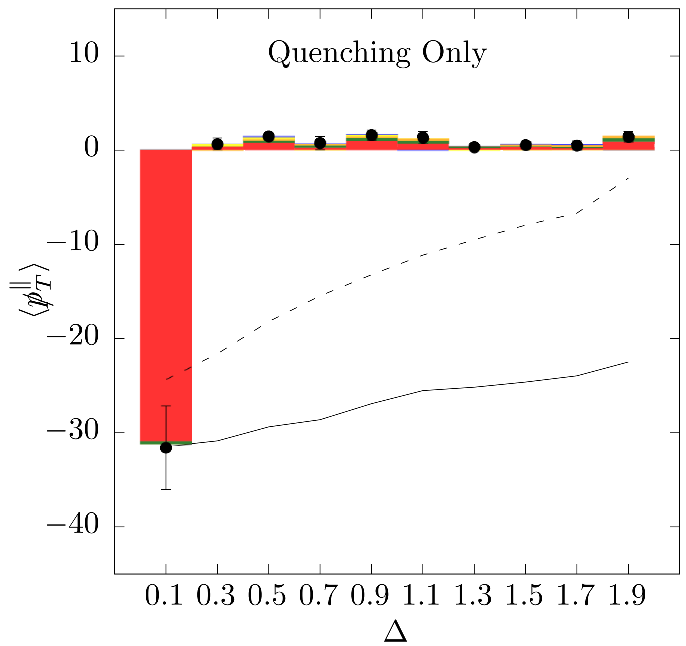
.... r < 0.3

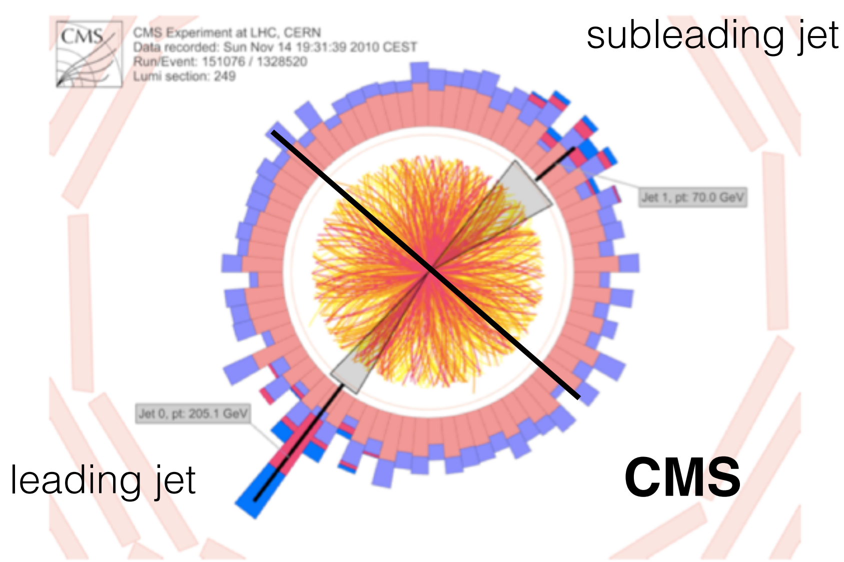
- Wide in azimuthal angle
- Wide in rapidity
- Peaked at very low transverse momentum

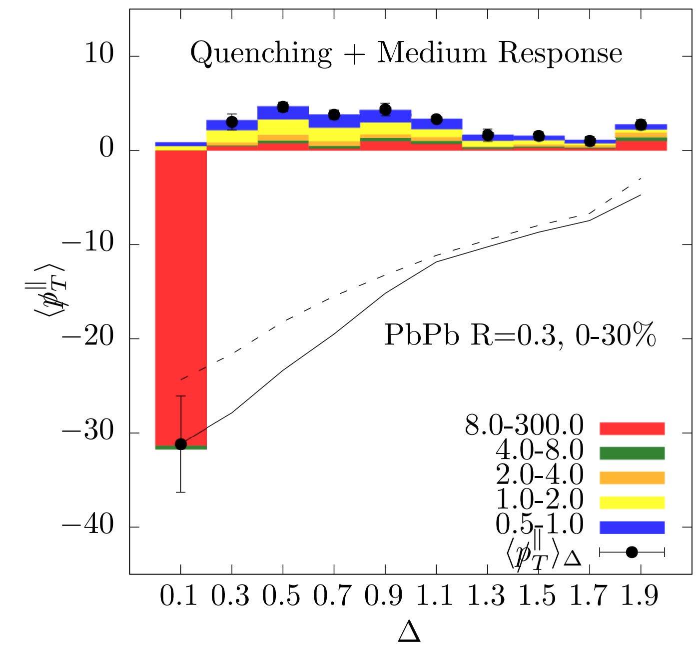
$$y_j = 0,\ \phi_j = 0,\ T = 0.2\,\mathrm{GeV}$$

Where does lost energy go to?

'missing-pt' observables

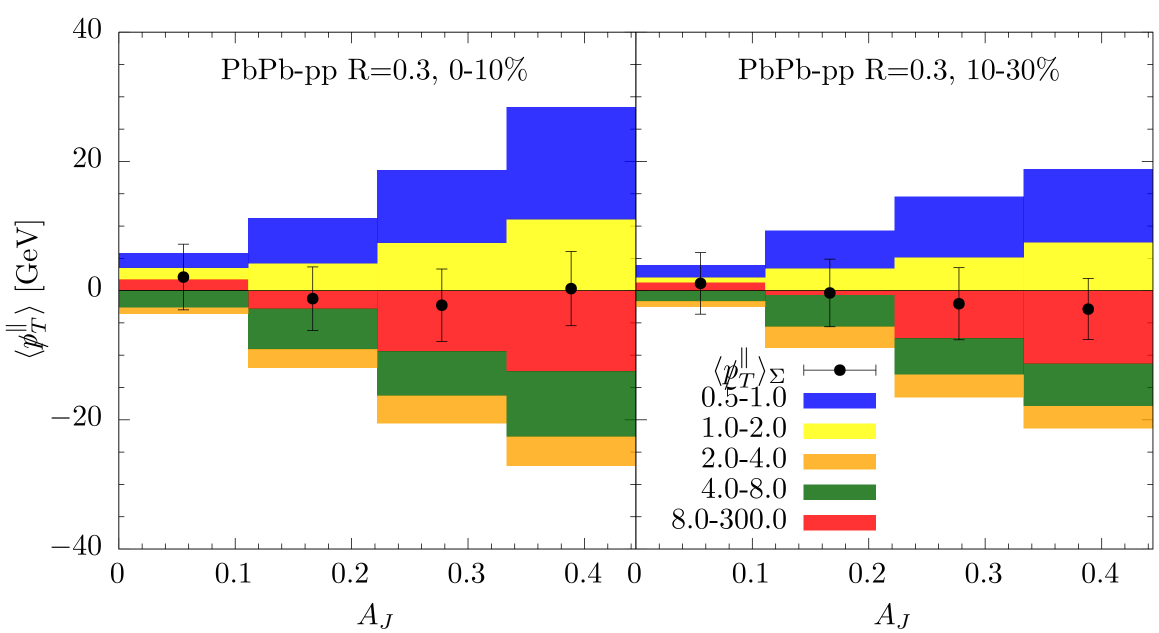


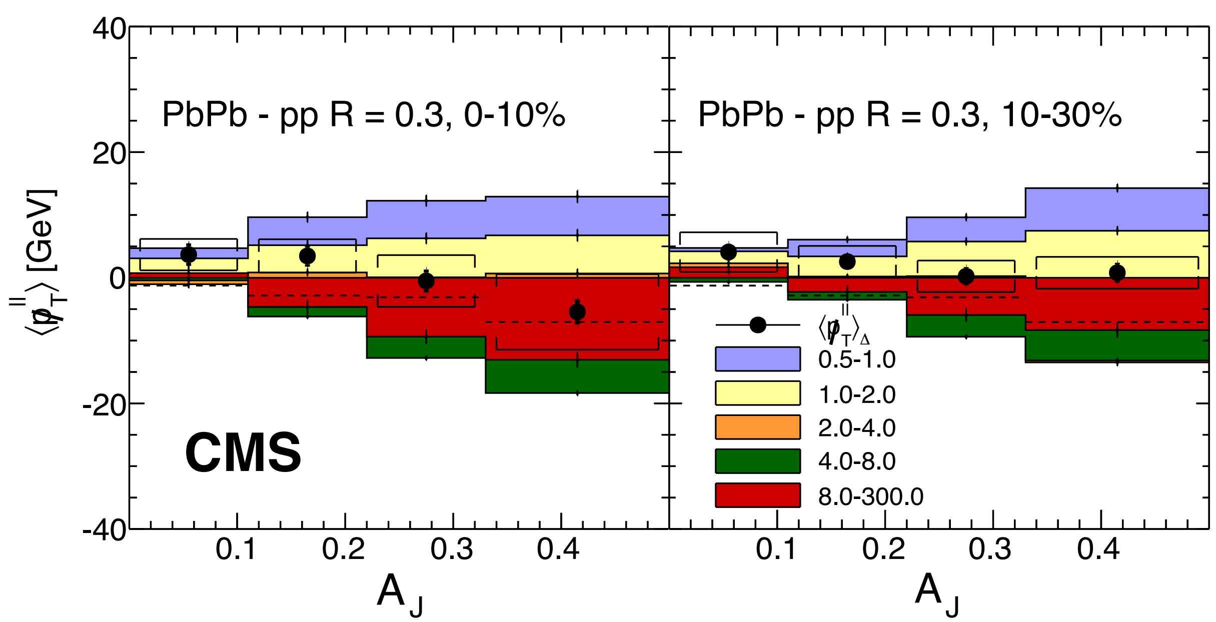




energy is recovered at large angles in the form of soft particles

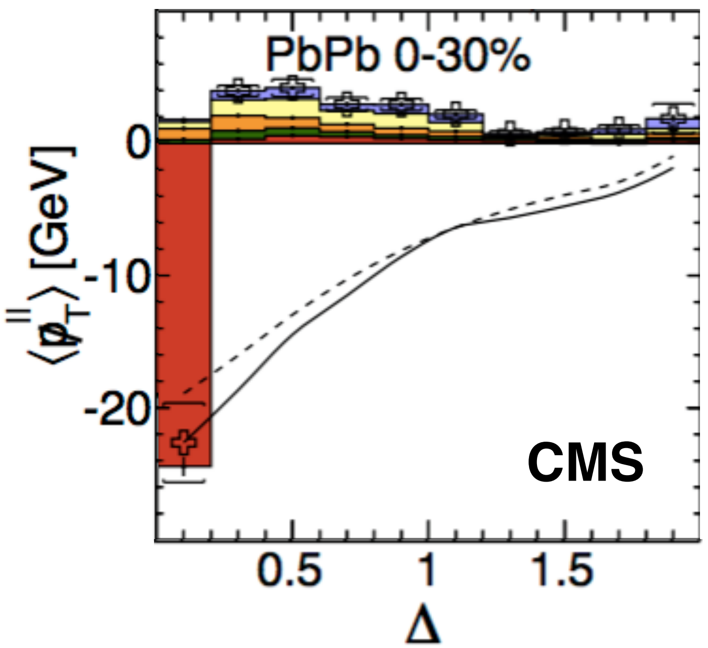
data suggests that implementation of back-reaction might mistreat semi-hard particles

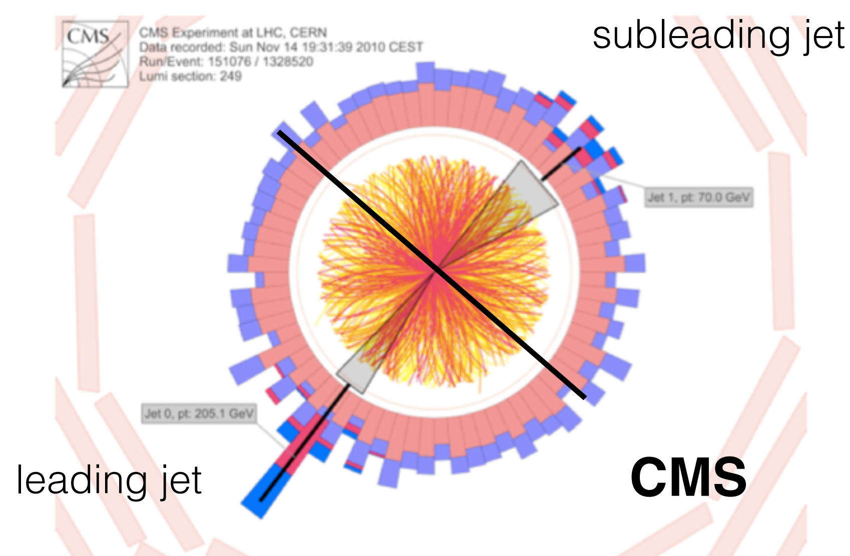


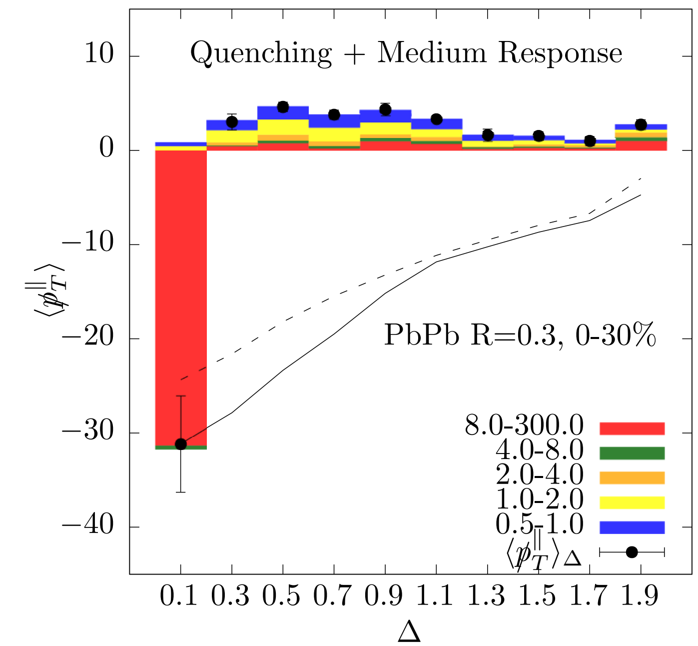


Where does lost energy go to?

‘missing-pt’ observables







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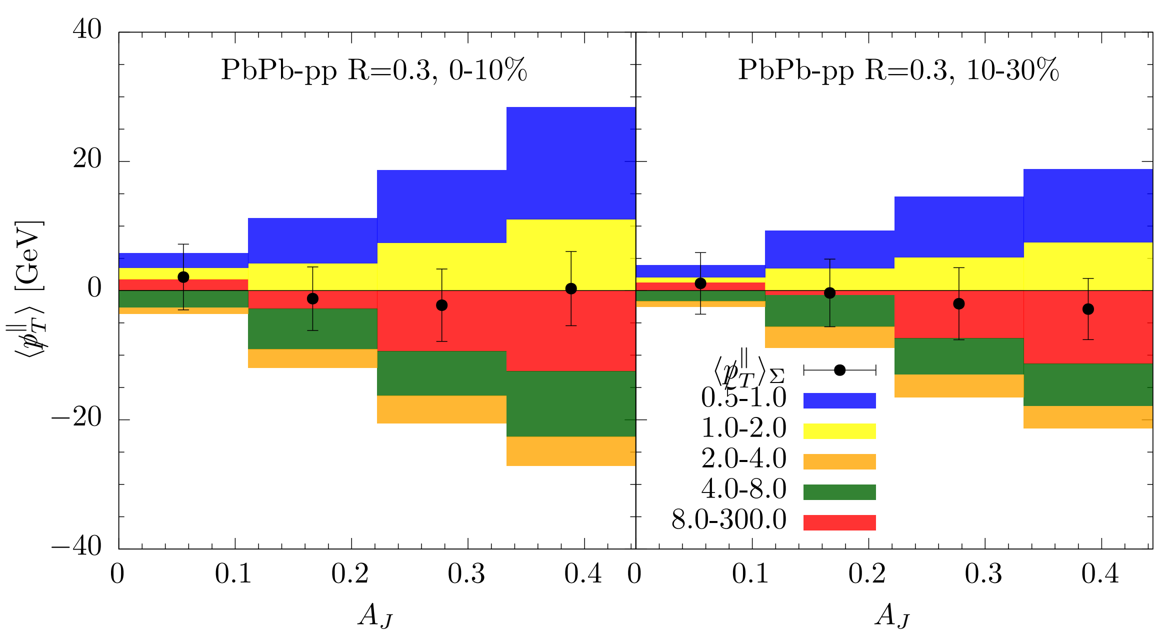
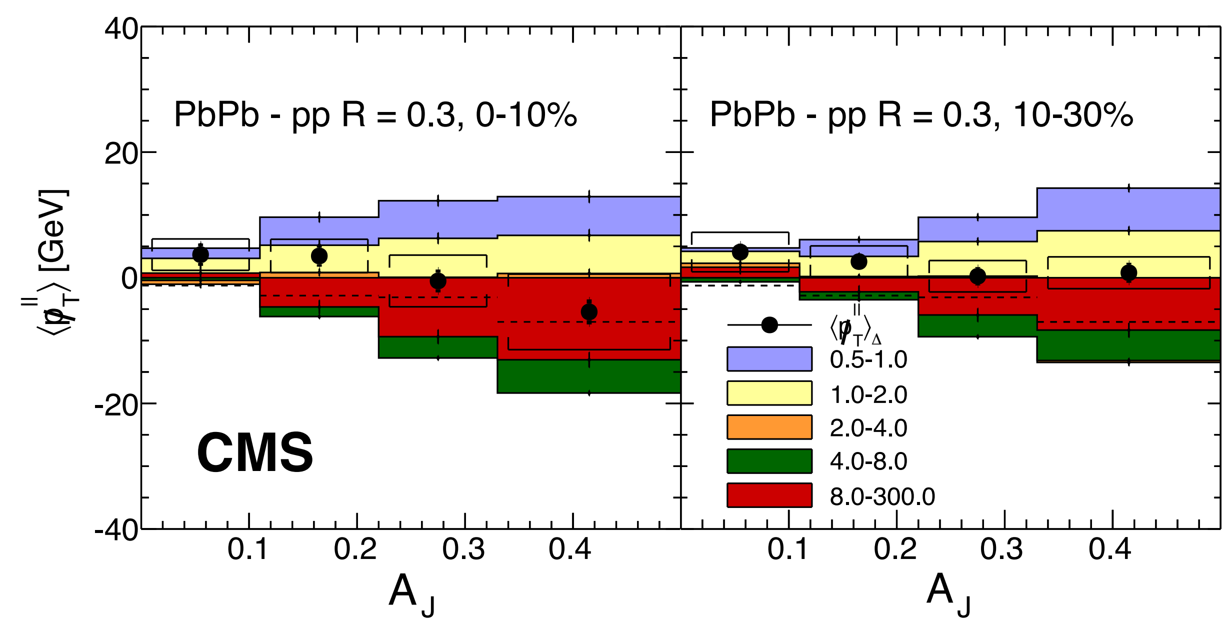
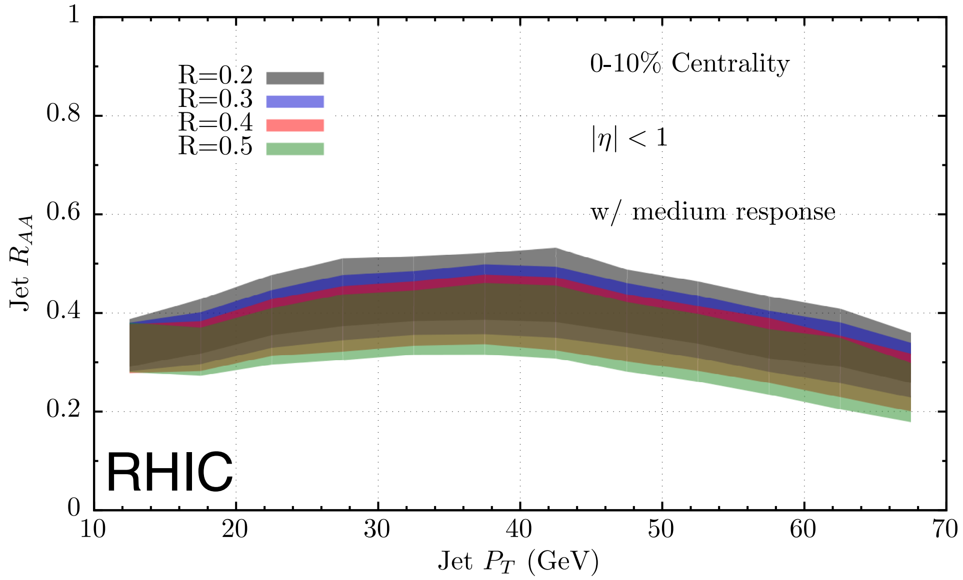


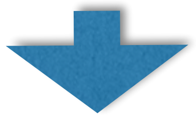


R_{AA} vs R

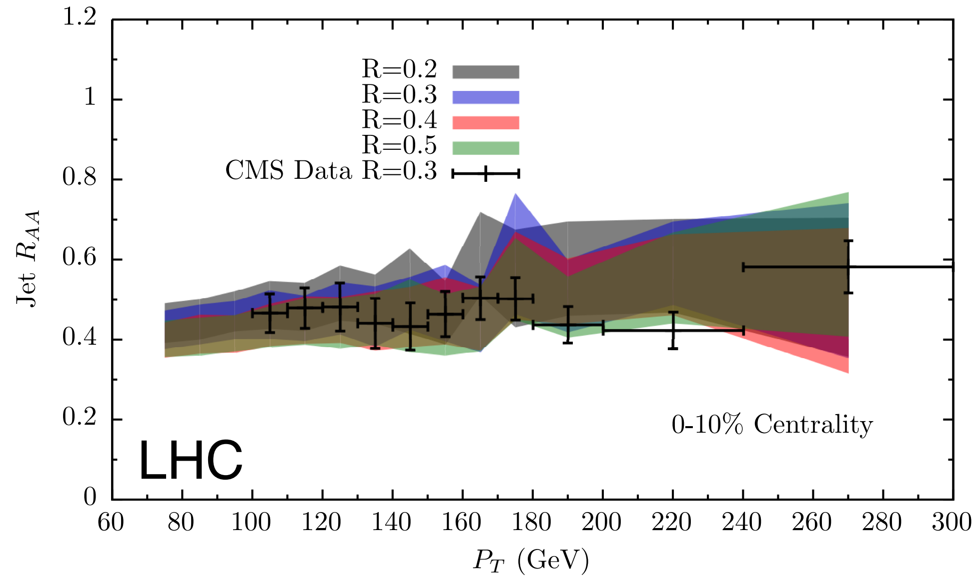
wider, more active jets lose more energy as they have more energy loss sources



lost energy does not stay close to the jet axis

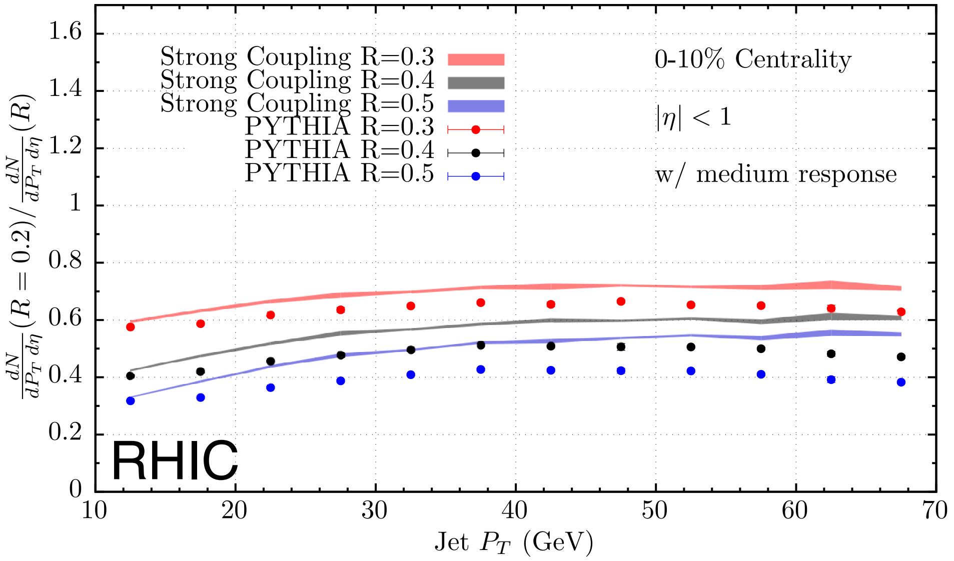


mild recovery by increasing jet radius R

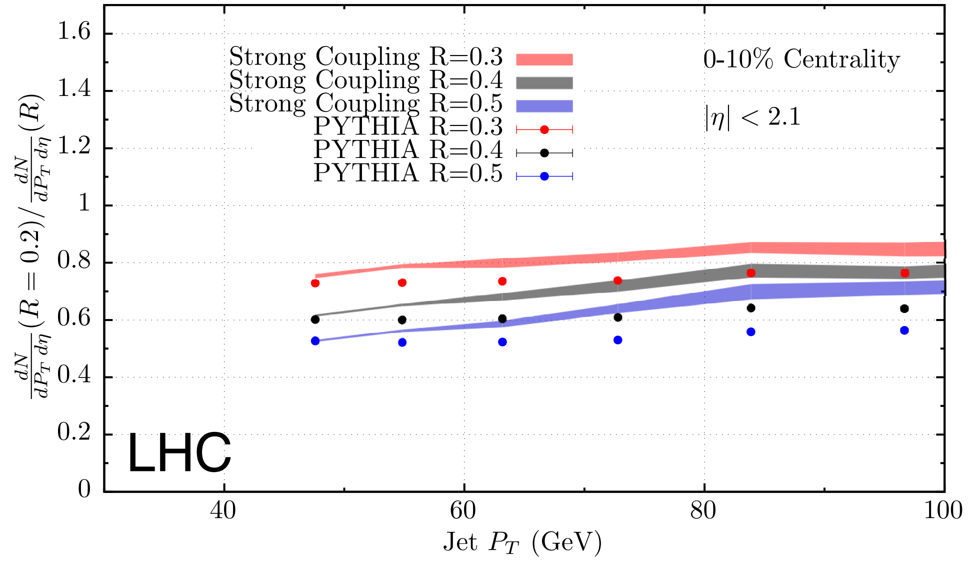


We can use the R dependence of jet suppression to greatly constrain models assumptions

$\Delta R \downarrow$ *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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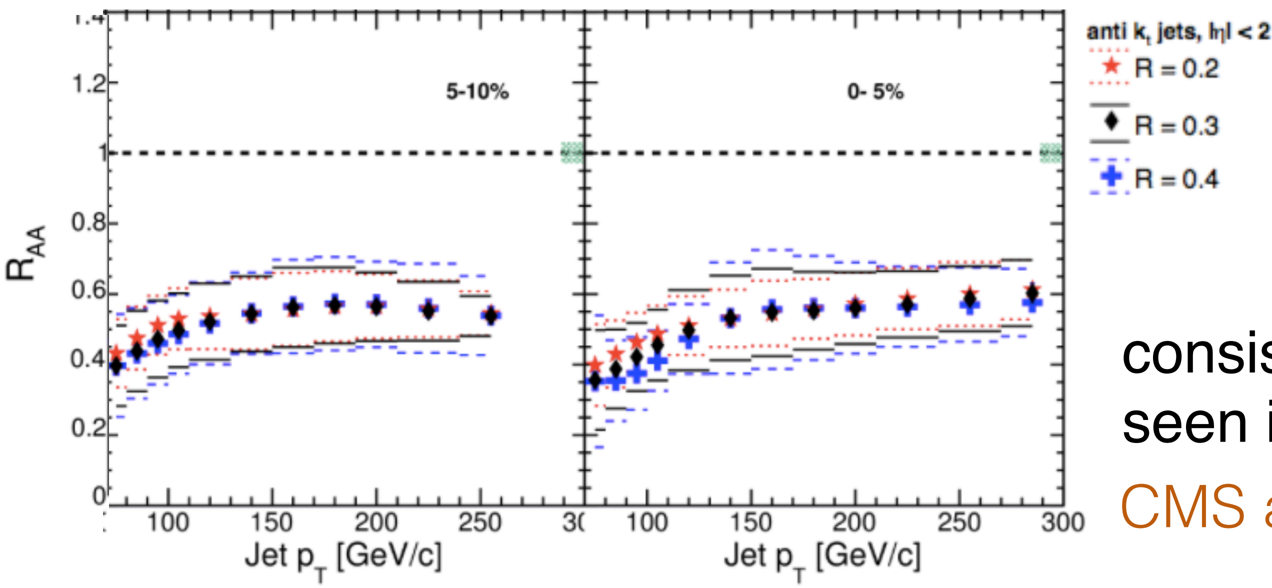
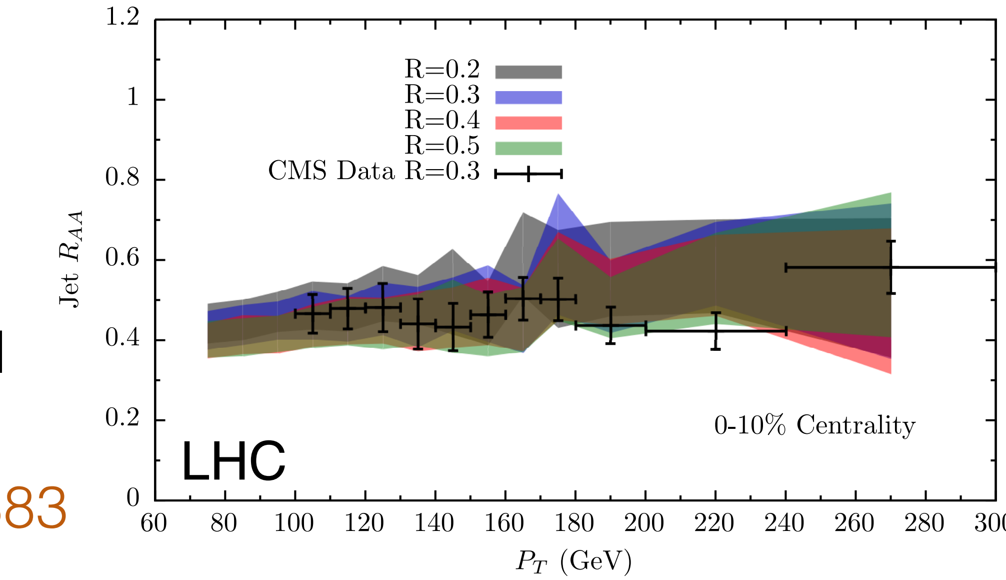


consistent with trend seen in data

CMS arXiv:1609.05383



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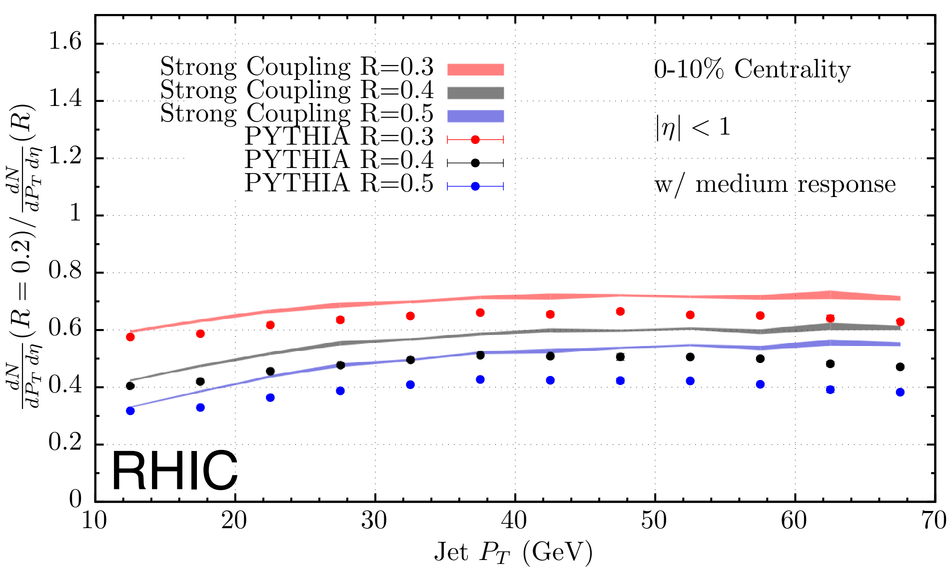

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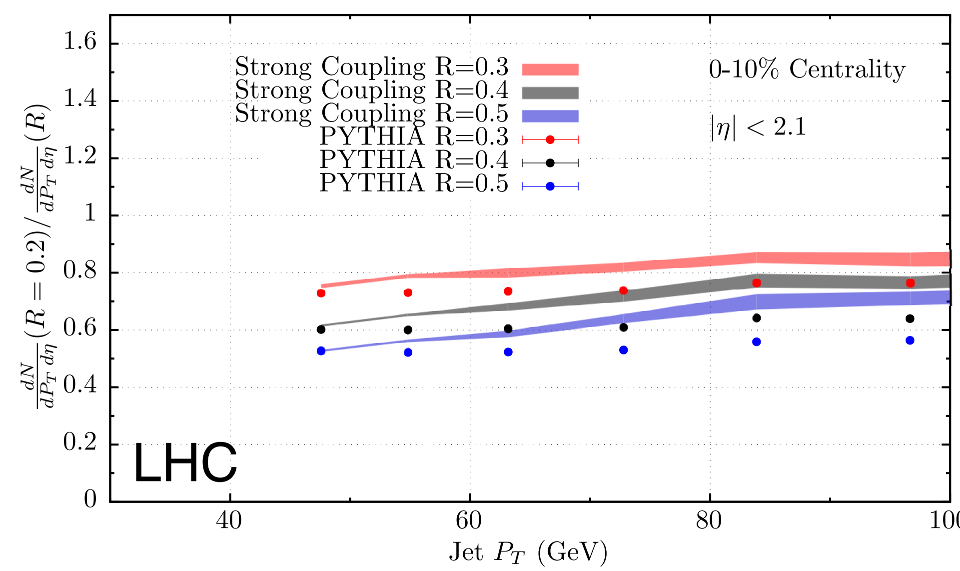
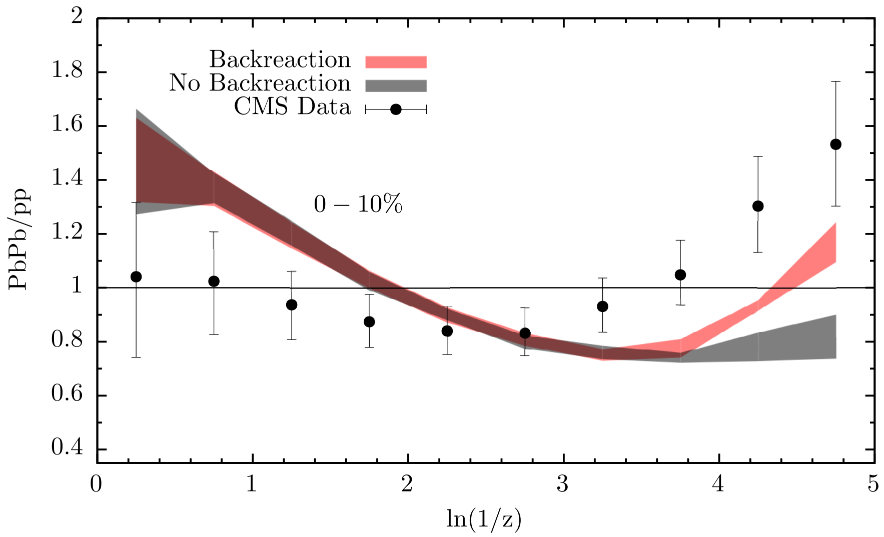


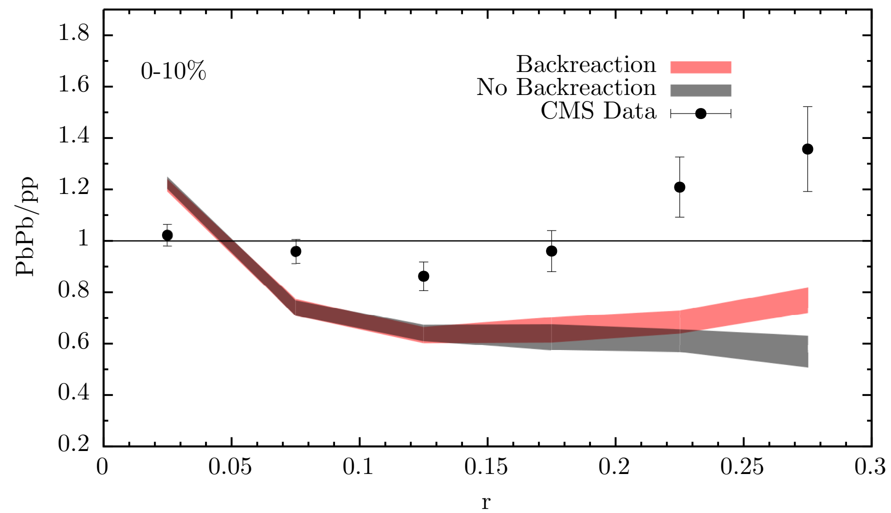
Medium response on jet substructure

Jet fragmentation function



increasing #soft particles

Jet shapes

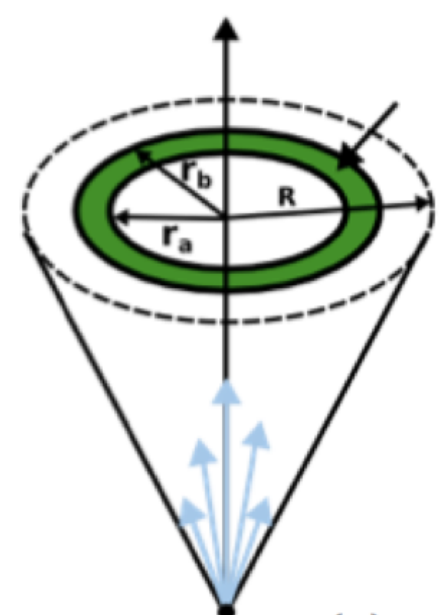


increasing #wide particles

effect in the right direction, but clearly not enough

Longitudinal energy distribution

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

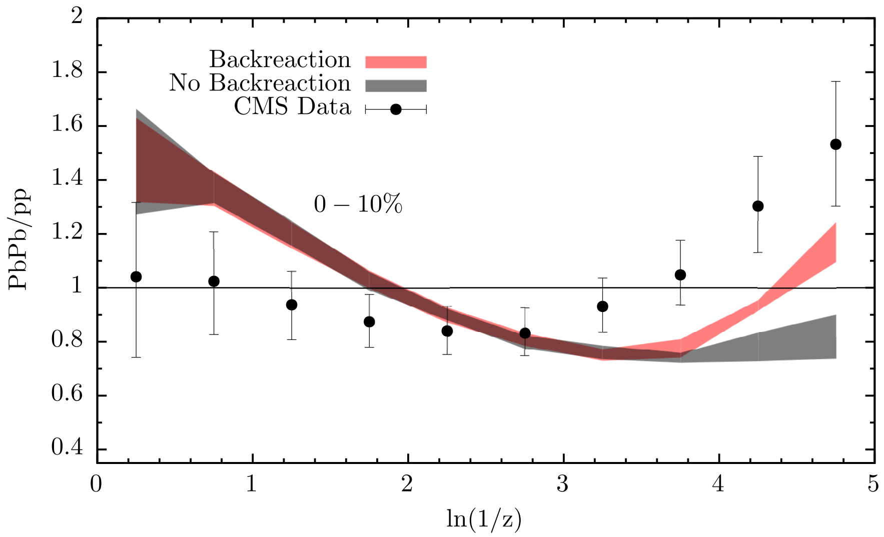


Transverse energy distribution

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

Medium response on jet substructure

Jet fragmentation function



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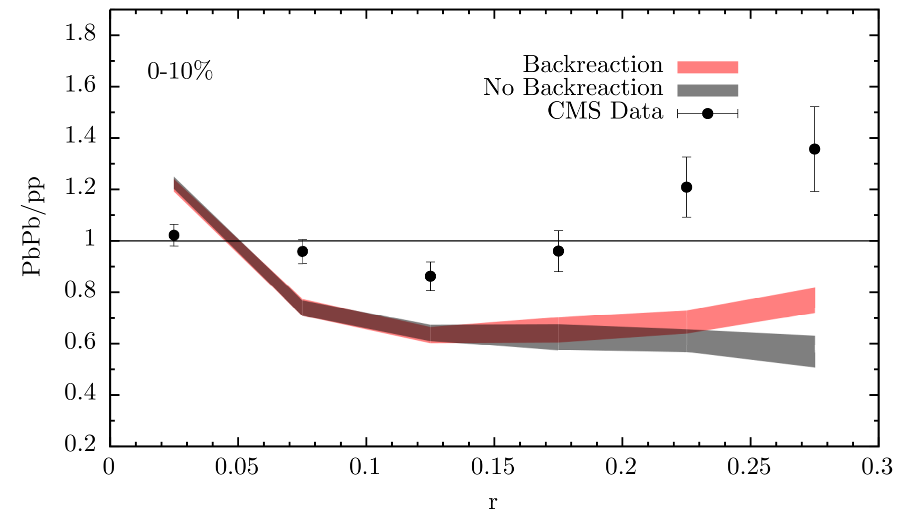


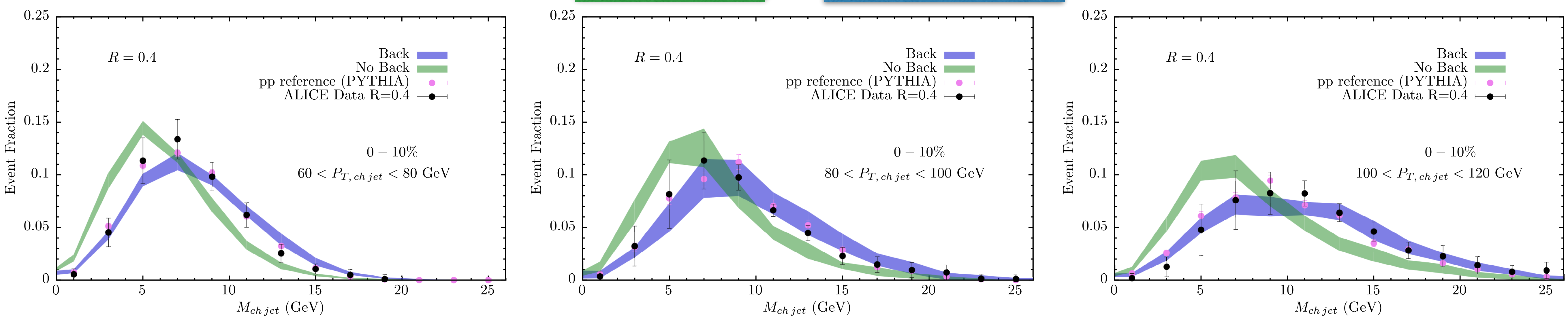
increasing #wide particles

effect in the right direction, but clearly not enough

cancellation between two effects

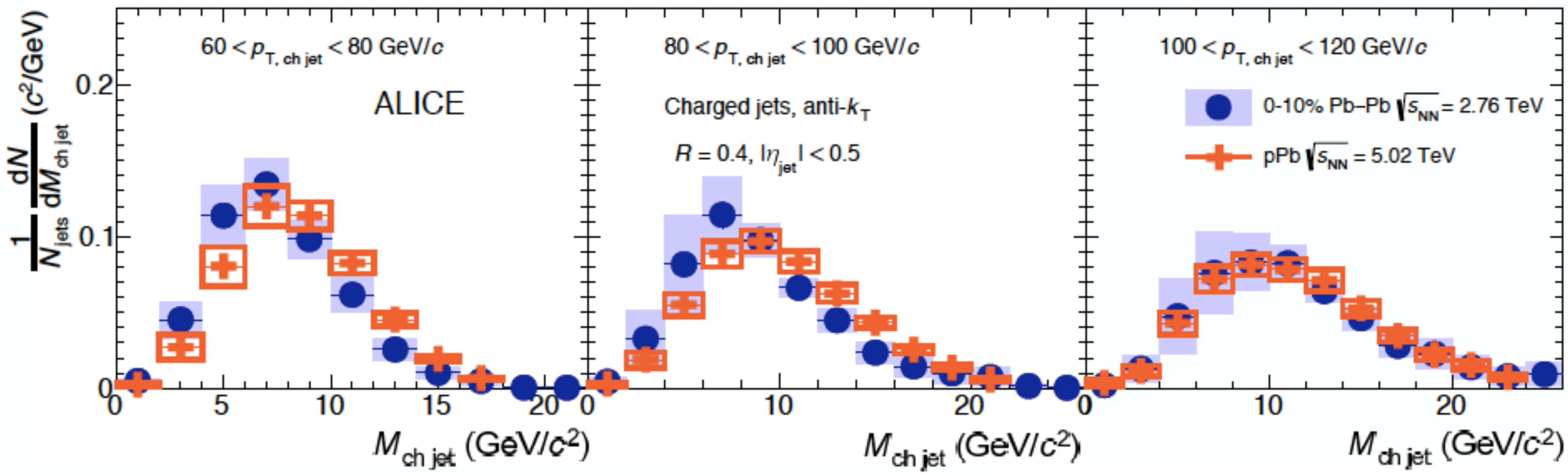
quenching

back-reaction



Charged jet mass

Medium response on jet substructure



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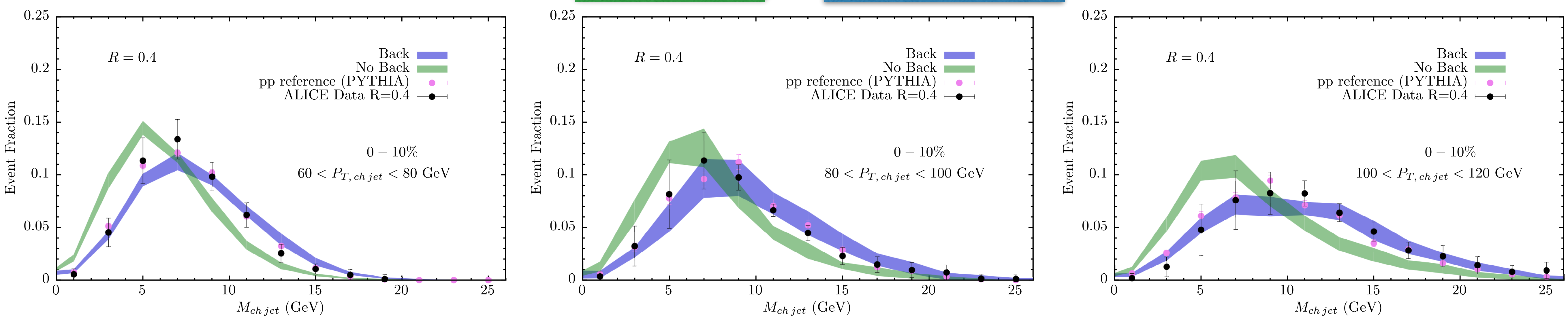
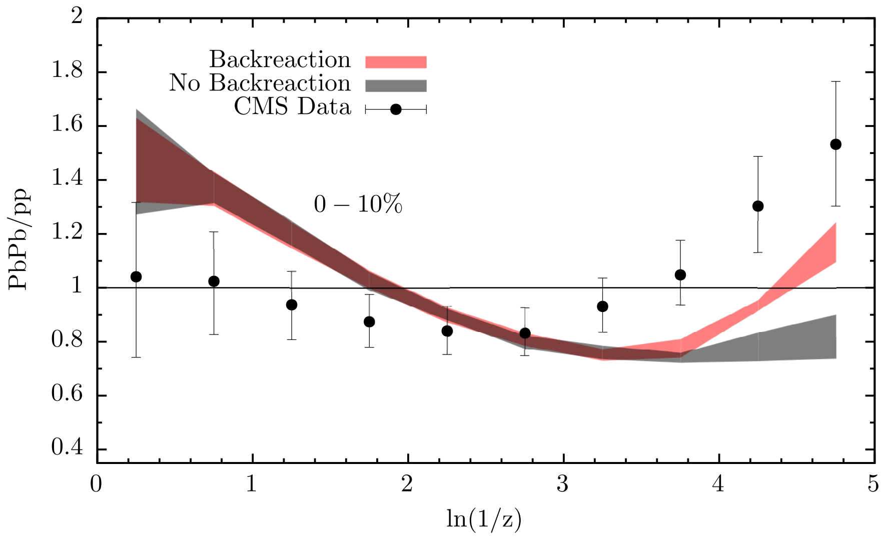


Charged jet mass

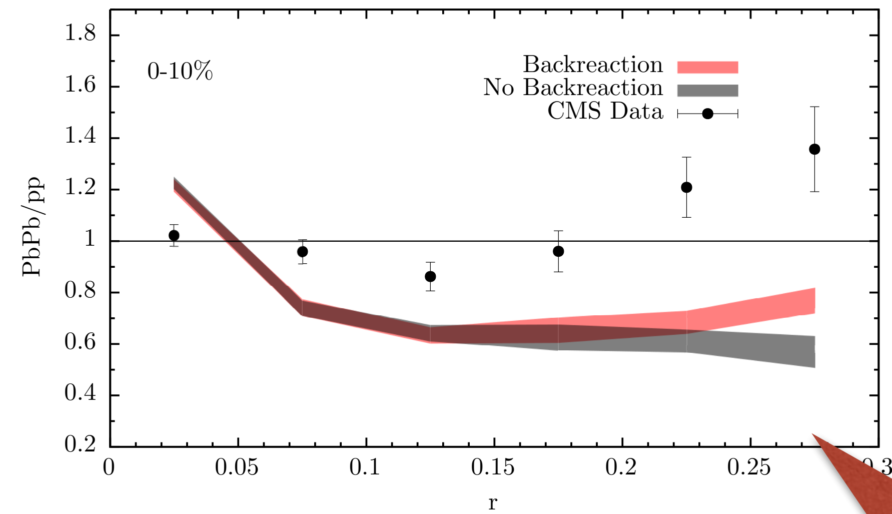
Medium response on jet substructure

Jet fragmentation function



increasing #soft particles

Jet shapes



increasing #wide particles

effect in the right direction, but clearly not enough

....

what physics is missing?

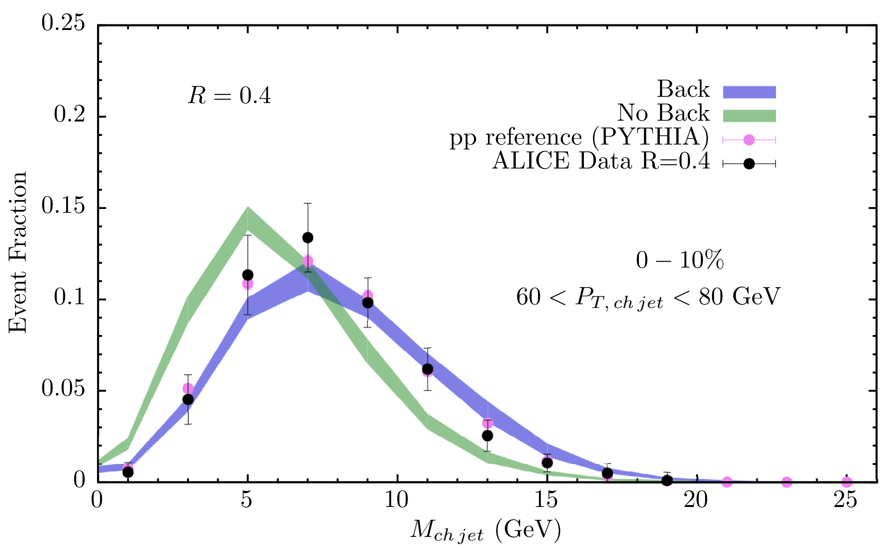
how to reconcile?

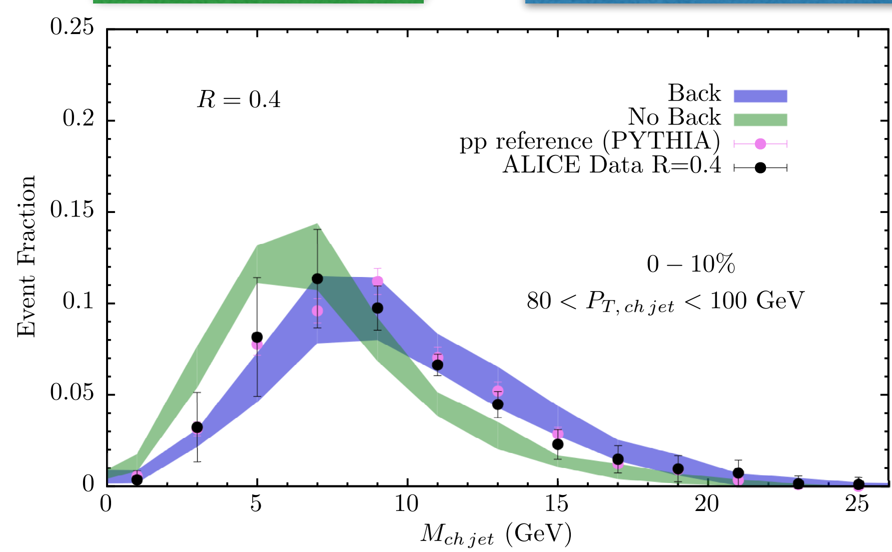
JEWEL w/ recoil describes jet shapes, but overestimates mass

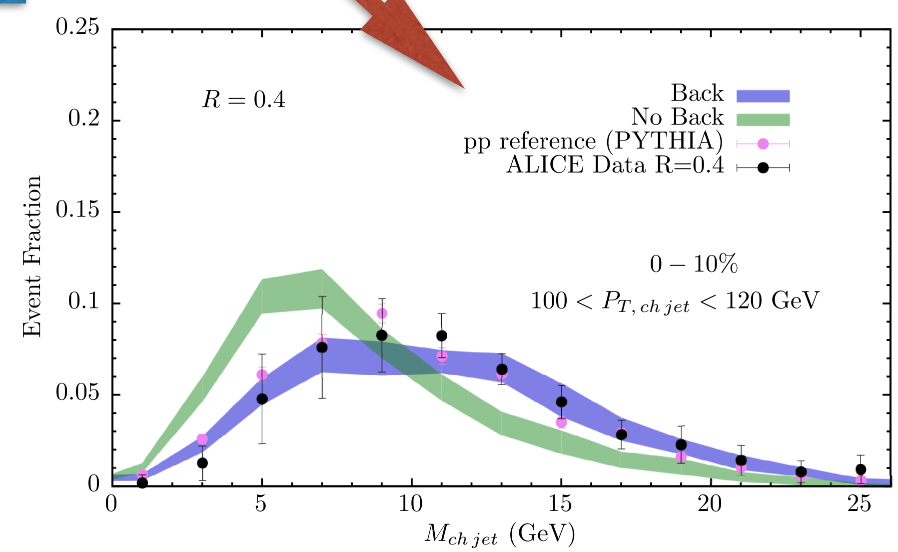
cancellation between two effects

quenching

back-reaction



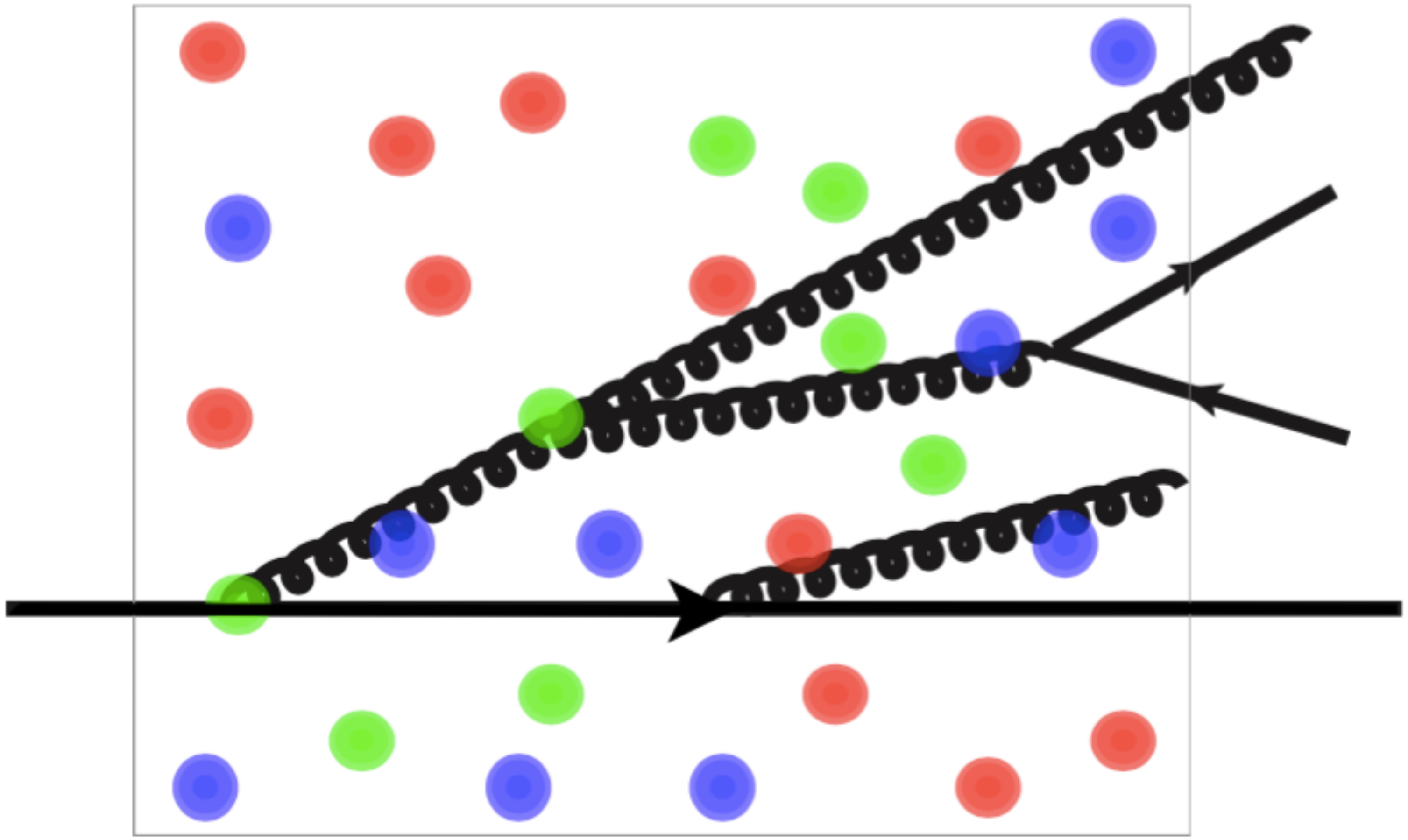




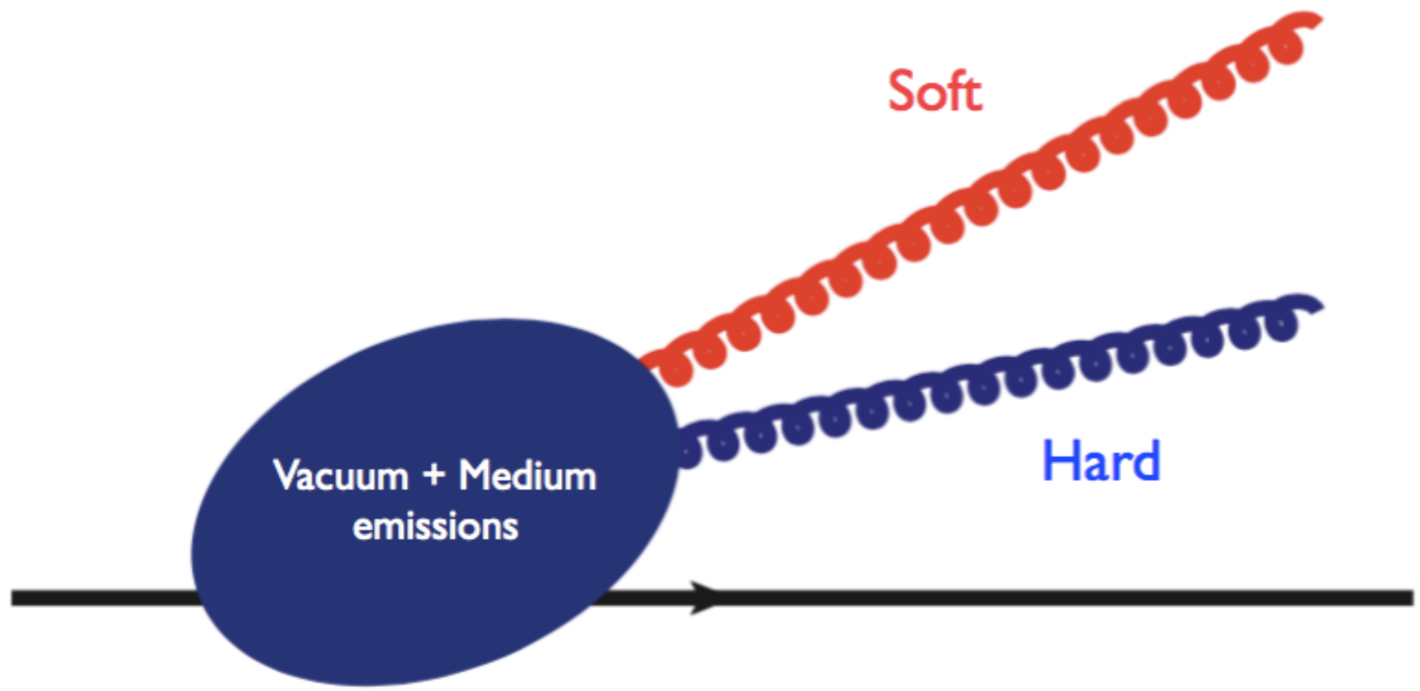
Charged jet mass

Coherence effects

- Model works well for jet (clustered) observables
- Tension for certain intra-jet observables
- Such observables depend on multiple partons correlations
- Which are the effects associated to such correlations?



Two gluon inclusive emission



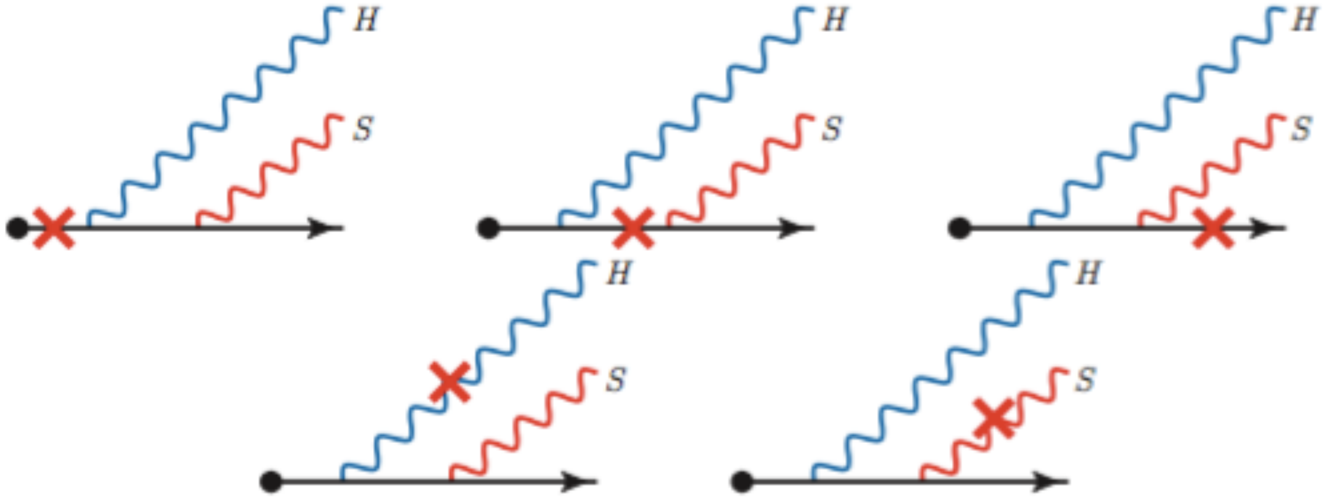
Compute two gluon inclusive emission off a hard quark

pQCD calculation in N=1 opacity (thin medium)

Provides a full characterisation of interferences
in terms of *formation times*

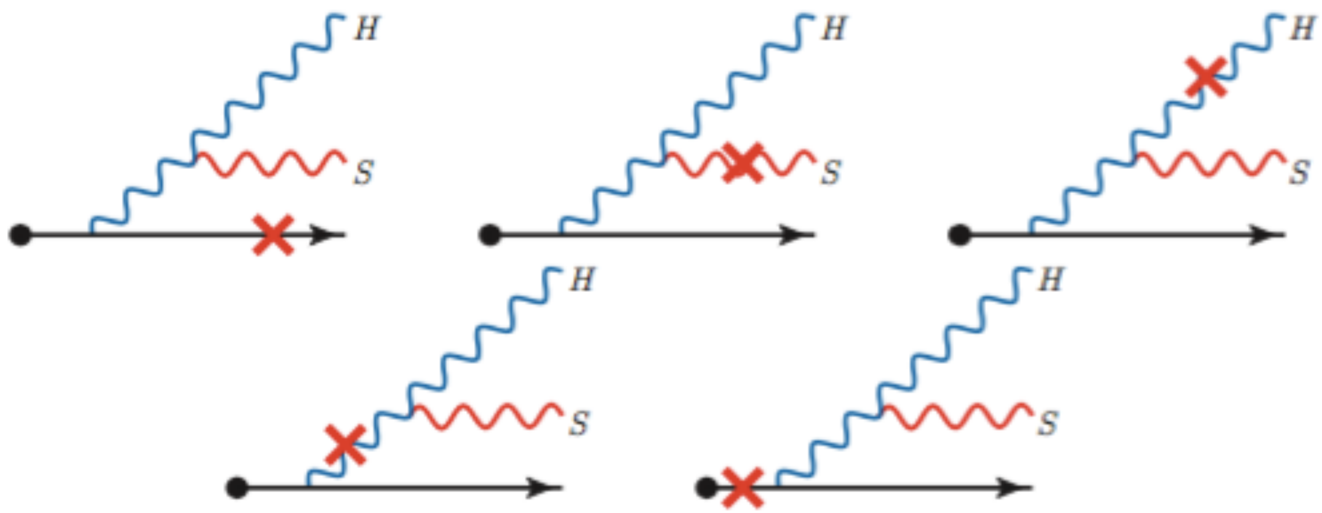
DP, J. Casalderrey-Solana, K. Tywoniuk 1512.07561

Diagrams summary: real terms



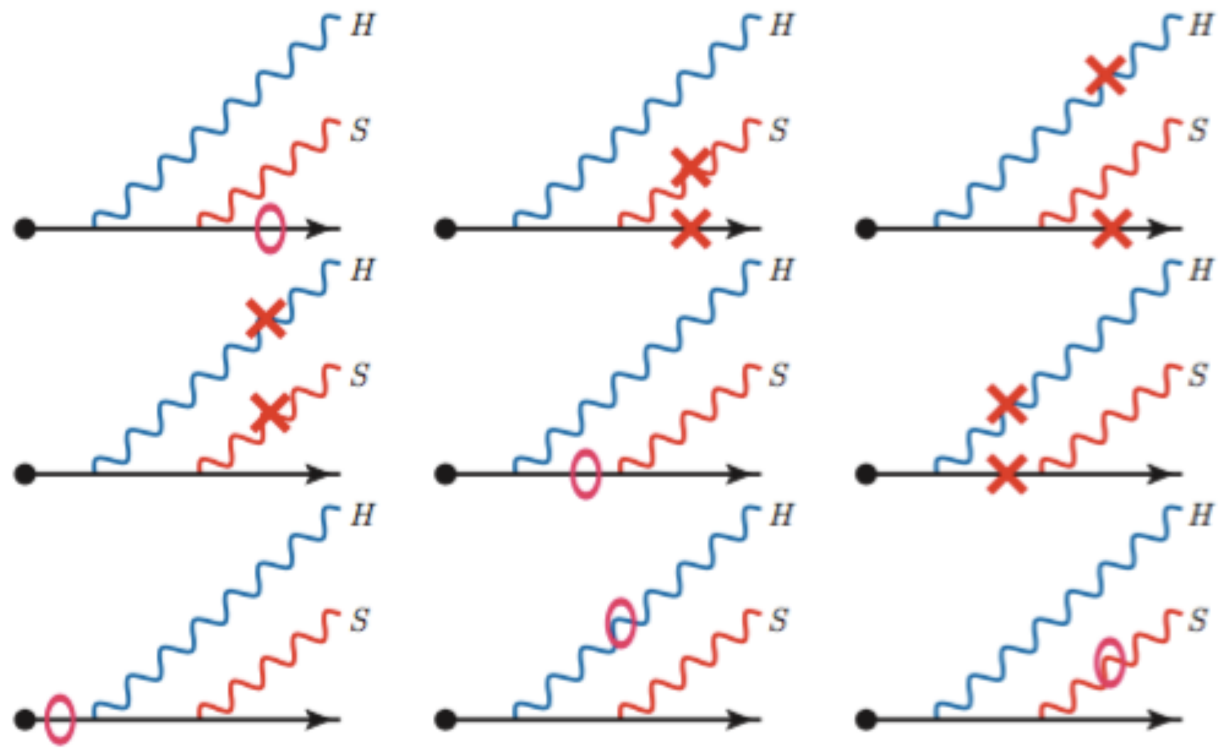
+ interchange Hard and Soft

$$\langle|\mathcal{M}_{1\mathrm{OP}}|^2\rangle = \boxed{\langle|\mathcal{M}_{(1)}|^2\rangle} + 2\mathrm{Re}\langle\mathcal{M}_{(2)}\mathcal{M}^*_{(0)}\rangle$$



(5.2+5)(5.2+5)=225 terms

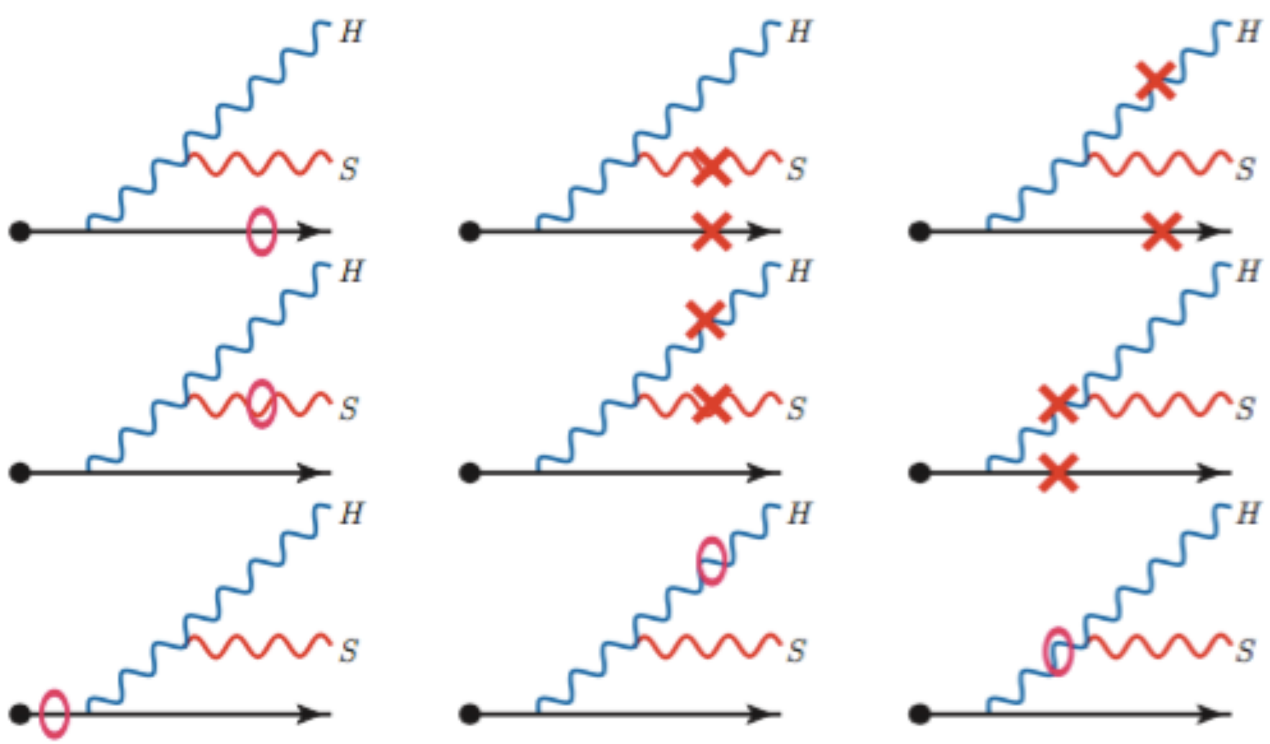
Diagrams summary: virtual terms



+ interchange Hard and Soft

(9.2+9).3=81 terms

$$\langle|\mathcal{M}_{1\mathrm{OP}}|^2\rangle = \langle|\mathcal{M}_{(1)}|^2\rangle + \boxed{2\mathrm{Re}\langle\mathcal{M}_{(2)}\mathcal{M}^*_{(0)}\rangle}$$



Diagrams summary: virtual terms

$$w(x^+;\boldsymbol{q}) = C_F^2 C_A w_Q(x^+;\boldsymbol{q}) + C_F C_A^2 w_G(x^+;\boldsymbol{q})$$

Two gluon emission off the quark

Hard gluon emission off the quark which in turn emits a soft gluon

Full answer can be written as

$$w_I(x^+;\boldsymbol{q}) = \sum_{i=1}^{N_I} \mathcal{P}_I^{(i)}(\boldsymbol{q})\left\{1 - \cos\left[x^+/\tau_I^{(i)}(\boldsymbol{q})\right]\right\}$$

$$I = Q,\, G,\; N_Q = 2 \text{ and } N_G = 19$$

Organise in terms of dimensionless parameters

Ratio of energies (assume small) $\quad z = \dfrac{k_S^+}{k_H^+}$

Ratio of angles $\quad r = \dfrac{\theta_H}{\theta_S}$

Introduce scaling wrt medium

$$\tilde{q} = \frac{q}{k_S} = \frac{1}{z\theta_S}\frac{q}{k_H^+}$$

$$\frac{q}{k_H} = \tilde{q}\,\frac{z}{r}$$

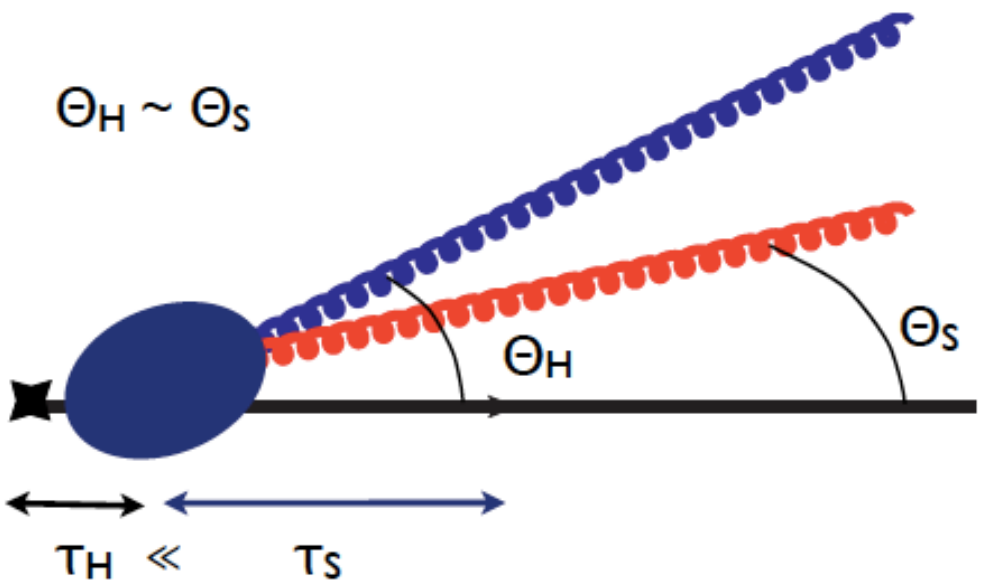
Emission rate in the soft limit

Hard gluon's momentum gets decoupled from the medium scale: cannot be medium induced

$z \to 0\,, \quad \text{with} \quad \{r, \tilde{q}, \theta_S, k_H^+\} \text{ fixed.}$

$$\frac{\tau_H}{\tau_S} = \frac{z}{r^2} \qquad \text{with } \tau_H = 2k_H^+/\boldsymbol{k}_H^2 \text{ and } \tau_S = 2k_S^+/\boldsymbol{k}_S^2$$

being the vacuum formation times



Strong ordering of formation times: hard gluon emitted arbitrarily close to the hard vertex

Quark:

$$w_Q(x^+;\boldsymbol{q}) = \boxed{\frac{4g^2}{\boldsymbol{k}_H^2}} \times \boxed{(-8g^4)\,\frac{\boldsymbol{k}_S\cdot\boldsymbol{q}}{(\boldsymbol{k}_S+\boldsymbol{q})^2\,\boldsymbol{k}_S^2}\left\{1-\cos\left[\frac{(\boldsymbol{k}_S+\boldsymbol{q})^2}{2k_S^+}x^+\right]\right\}}$$

Hard gluon vacuum emission

Soft gluon induced N=1 spectrum

Define $\boldsymbol{A}_q = \frac{\boldsymbol{k}_S+\boldsymbol{q}}{(\boldsymbol{k}_S+\boldsymbol{q})^2}\,, \quad \boldsymbol{B}_q = \frac{\boldsymbol{k}_S}{\boldsymbol{k}_S^2}\,, \quad \boldsymbol{L}_q = \boldsymbol{A}_q - \boldsymbol{B}_q$ so that $\frac{-\boldsymbol{k}_S\cdot\boldsymbol{q}}{\boldsymbol{k}_S^2(\boldsymbol{k}_S+\boldsymbol{q})^2} = \frac{1}{2}\left(\boldsymbol{L}_q^2 + \boldsymbol{A}_q^2 - \boldsymbol{B}_q^2\right)$

Emission rate in the soft limit

Gluon:

$$w_G(x^+;\boldsymbol{q}) = \boxed{\frac{4g^2}{\boldsymbol{k}_H^2}} \times 4g^4 \left\{ \left(\boldsymbol{L}_g^2 + \boldsymbol{A}_g^2 - \boldsymbol{B}_g^2 - \boldsymbol{A}_q \cdot \boldsymbol{L}_g\right) \left\{1 - \cos\left[\frac{(\boldsymbol{\kappa}_S + \boldsymbol{q})^2}{2k_S^+} x^+\right]\right\} \right.$$
$$- \boldsymbol{L}_q \cdot \boldsymbol{A}_g \left\{1 - \cos\left[\frac{(\boldsymbol{k}_S + \boldsymbol{q})^2}{2k_S^+} x^+\right]\right\}$$
$$+ \boldsymbol{L}_q \cdot \boldsymbol{L}_g \left\{1 - \cos\left[\left(\frac{(\boldsymbol{\kappa}_S + \boldsymbol{q})^2}{2k_S^+} - \frac{(\boldsymbol{k}_S + \boldsymbol{q})^2}{2k_S^+}\right) x^+\right]\right\}$$
$$\left. + \mathcal{C}\left(k_H^+, \boldsymbol{k}_H; k_S^+, \boldsymbol{k}_S\right) \sin\left[\frac{\boldsymbol{k}_S^2}{2k_S^+} x^+\right] \sin\left[\frac{\boldsymbol{q} \cdot \boldsymbol{k}_H}{k_H^+} x^+\right] \right\},$$

$\kappa_s \equiv \mathbf{k}_S - z\mathbf{k}_H$

with $\boldsymbol{A}_g = \frac{\boldsymbol{\kappa}_S + \boldsymbol{q}}{(\boldsymbol{\kappa}_S + \boldsymbol{q})^2}, \quad \boldsymbol{B}_g = \frac{\boldsymbol{\kappa}_S}{{\boldsymbol{\kappa}_S}^2}, \quad \boldsymbol{L}_g = \boldsymbol{A}_g - \boldsymbol{B}_g \qquad \tau_q = \frac{2k_S^+}{(\boldsymbol{k}_S + \boldsymbol{q})^2}, \quad \tau_g = \frac{2k_S^+}{(\boldsymbol{\kappa}_S + \boldsymbol{q})^2}$

and the term with the function $\mathcal{C}\left(k_H^+, \boldsymbol{k}_H; k_S^+, \boldsymbol{k}_S\right) = -\frac{1}{4}\frac{k_S^+}{k_H^+}\frac{\boldsymbol{\kappa}_S \cdot \boldsymbol{k}_H}{\boldsymbol{k}_H^2\, \boldsymbol{k}_S^2\, {\boldsymbol{\kappa}_S}^2}$ vanishes by construction (isotropic medium)

One concludes $\langle|\mathcal{M}_{1\mathrm{OP}}|^2\rangle\Big|_{z\ll r} = \mathcal{P}_{\mathrm{vac}}(\boldsymbol{k}_H) \times \mathcal{P}^{(1)}_{\mathrm{ant}}(\boldsymbol{k}_S)$ with $\mathcal{P}_{\mathrm{vac}}(\boldsymbol{k}_H) = \frac{2C_F\, g^2}{\boldsymbol{k}_H^2}$

the medium interacts with a quark-gluon antenna from the start

Emission rate in the collinear limit

$$r \to 0,\ z \to 0, \quad \text{with} \quad \{\tilde{q}, \theta_S, k_H^+\} \text{ fixed}$$

Formation time of hard gluon is parametrically longer than the one of the soft gluon

same as previous limit

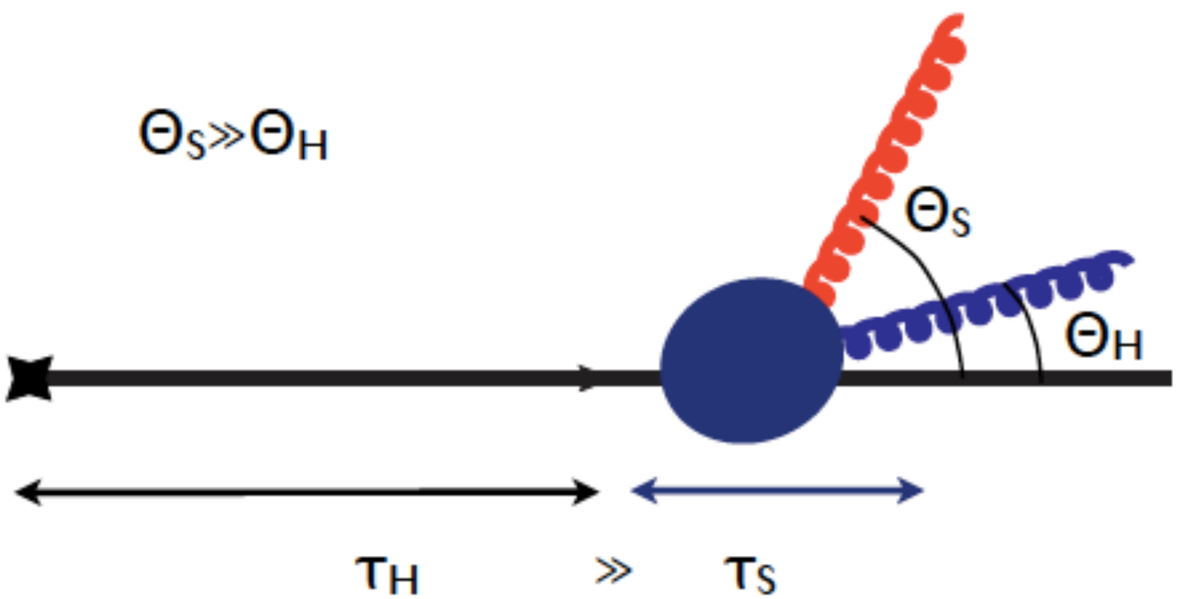
Quark: $$w_Q(x^+; \boldsymbol{q}) = \frac{4g^2}{\boldsymbol{k}_H^2} \times (-8g^4) \frac{\boldsymbol{k}_S \cdot \boldsymbol{q}}{\boldsymbol{k}_S^2 (\boldsymbol{k}_S + \boldsymbol{q})^2} \left\{1 - \cos\left[\frac{(\boldsymbol{k}_S + \boldsymbol{q})^2}{2k_S^+} x^+\right]\right\},$$

Gluon: $$w_G(x^+; \boldsymbol{q}) = \frac{4g^2}{\boldsymbol{k}_H^2} \times 4g^2 \frac{q^2}{\boldsymbol{k}_S^2 (\boldsymbol{k}_S + \boldsymbol{q})^2} \left\{1 - \cos\left[\frac{\boldsymbol{k}_H^2}{2\,k_H^+} x^+\right]\right\}.$$

$$\tau_H = 2k_H^+ / \boldsymbol{k}_H^2$$

new time scale

Hard gluon momentum much smaller than medium scale: emitted as in vacuum since medium rate is collinear finite



Hard gluon formation time is largest time scale

$$\frac{\tau_H}{\tau_q} = \mathcal{O}\left(\frac{z}{r^2}\right), \quad \frac{\tau_H}{\tau_g} = \mathcal{O}\left(\frac{z}{r^2}\right), \quad \frac{\tau_H}{\tau_q} - \frac{\tau_H}{\tau_g} = \mathcal{O}\left(\frac{z}{r}\right)$$

Compare to incoherent antenna, when $x^+ \to \infty$,

$$\lim_{r \to 0} \left(\boldsymbol{L}_g^2 + (\boldsymbol{A}_g^2 - \boldsymbol{A}_q \cdot \boldsymbol{A}_g) - (\boldsymbol{B}_g^2 - \boldsymbol{B}_q \cdot \boldsymbol{B}_g)\right) = \frac{q^2}{\boldsymbol{k}_S{}^2 (\boldsymbol{k}_S + \boldsymbol{q})^2}$$

Gunion-Bertsch

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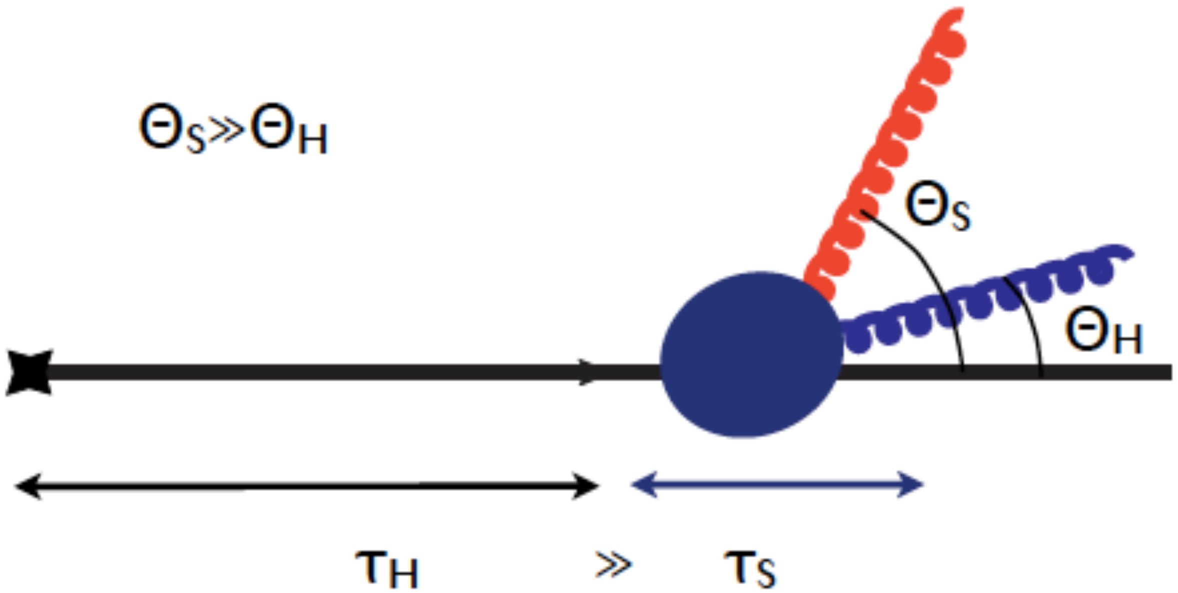

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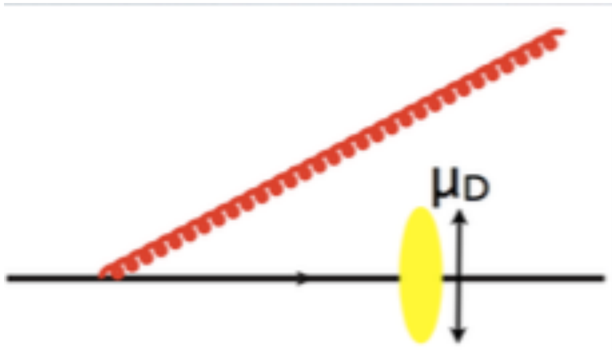
the medium interacts with a quark until hard gluon is formed, then resolved antenna

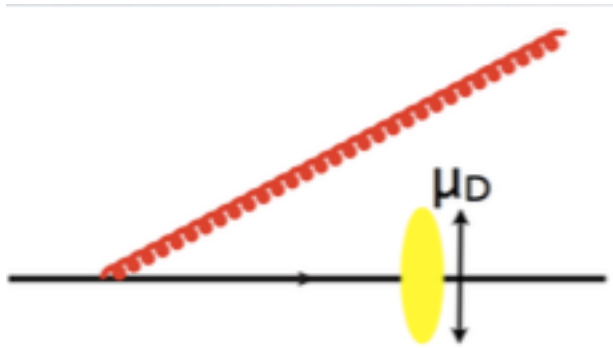
Antenna qualitative lessons



- If the antenna opening angle is larger than the emission angle:

  incoherent superposition of emissions off the quark and off the hard gluon

Antenna qualitative lessons



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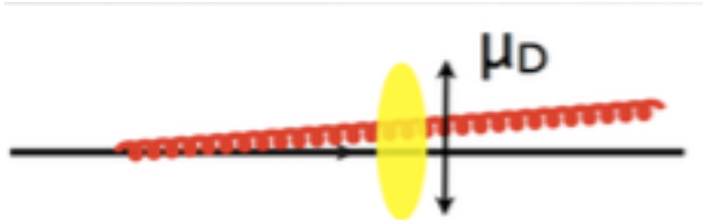


- If the emission angle is larger than the opening angle:

strong interferences

$$w_{\text{ant}}^{(1)}\left(x^+;\boldsymbol{k}_S,k_S^+\right)\Big|_{\theta_H\ll\theta_{\text{med}}} = C_F\left[1-\cos\frac{x^+}{\tau_q}\right]\left(\boldsymbol{L}_q^2+\boldsymbol{A}_q^2-\boldsymbol{B}_q^2\right) + C_A\left[1-\cos\frac{x^+}{\tau_{\text{res}}}\right]\boldsymbol{L}_q^2,$$

If at the scattering time the dipole size is $\lambda=\theta_H x^+ \ll \lambda_{\text{res}}$

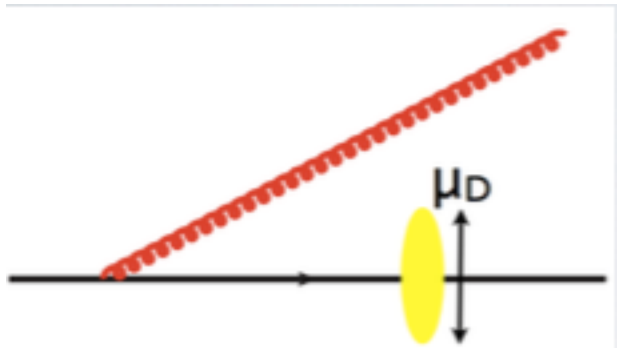
interferences suppress emissions off the hard gluon

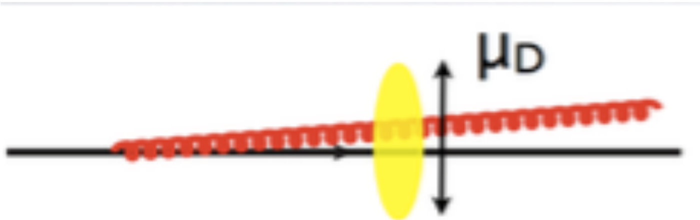
$$\tau_{\text{res}}^{-1}=\frac{1}{\tau_q}-\frac{1}{\tau_g}=\frac{2\boldsymbol{q}-\boldsymbol{k}_S-\boldsymbol{\kappa}_S}{2}\mathbf{n} \qquad \tau_{\text{res}}^{-1}\sim m_D\theta_H$$

$$\boldsymbol{\kappa}_S\approx\boldsymbol{k}_S\sim m_D$$

$$\lambda_{\text{res}}=\frac{1}{m_D}$$

Qualitative lessons





- If the antenna opening angle is larger than the emission angle:

  incoherent superposition of emissions off the quark and off the hard gluon

- If the emission angle is larger than the opening angle:

  strong interferences

Our take home messages

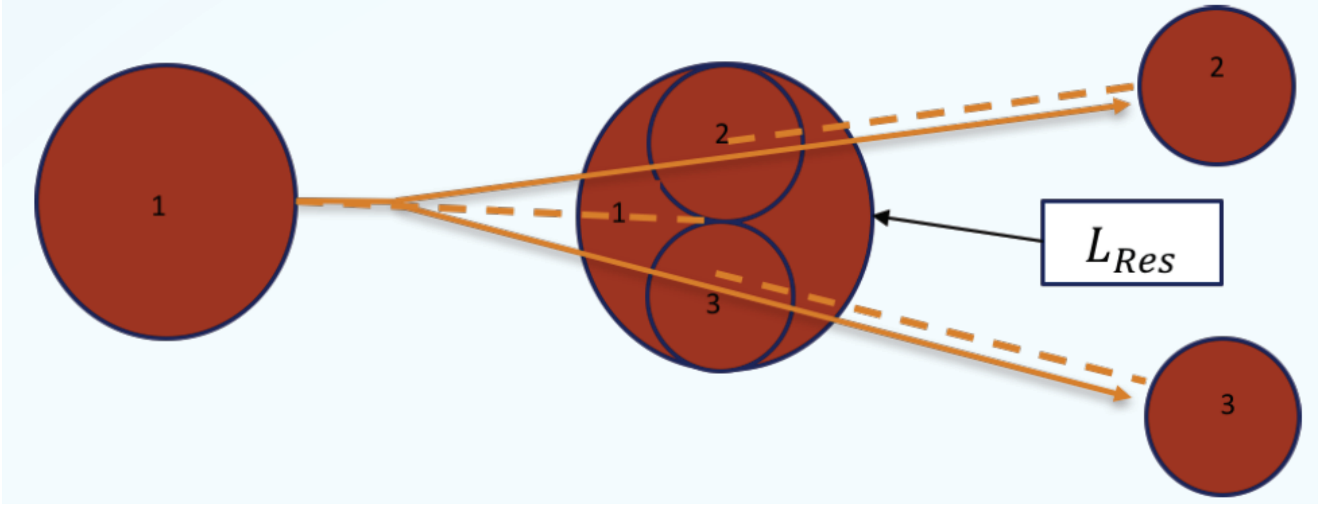
Partons perceived by the plasma after their formation time

Coherent multipartonic interaction with plasma due to finite resolution power

An *estimate* of finite resolution effects

within the hybrid strong/weak coupling model

Hulcher et al.
in preparation



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

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

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

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

$Y \sim 0.3$

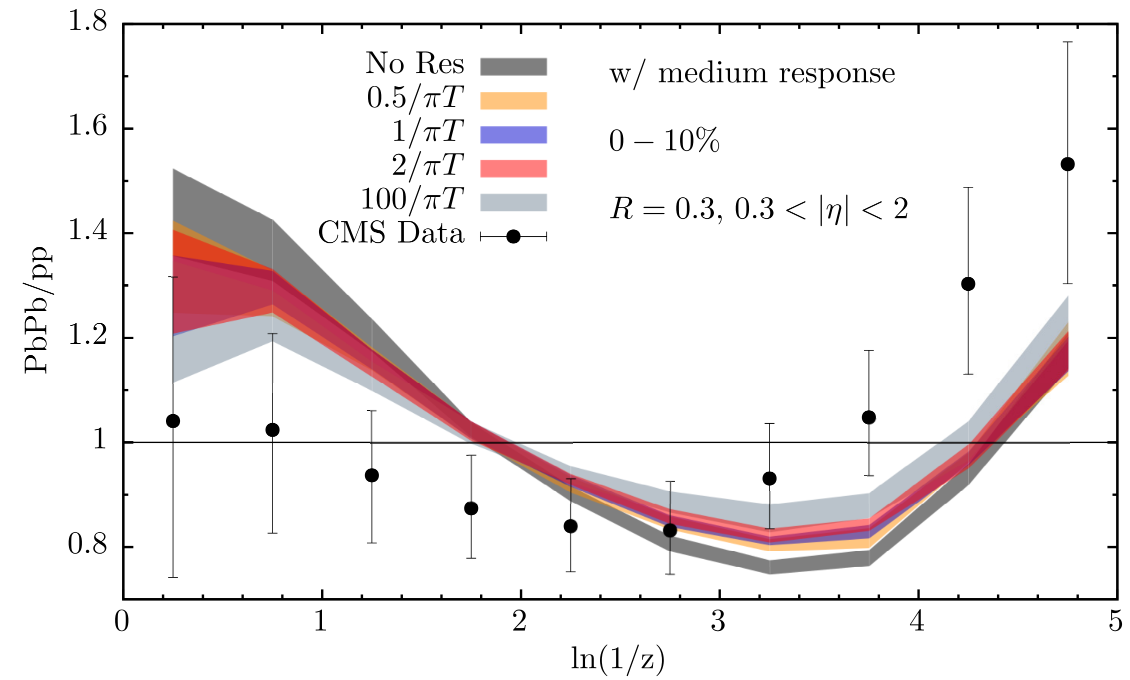
(but greater in QCD)

fewer # of effective energy loss sources

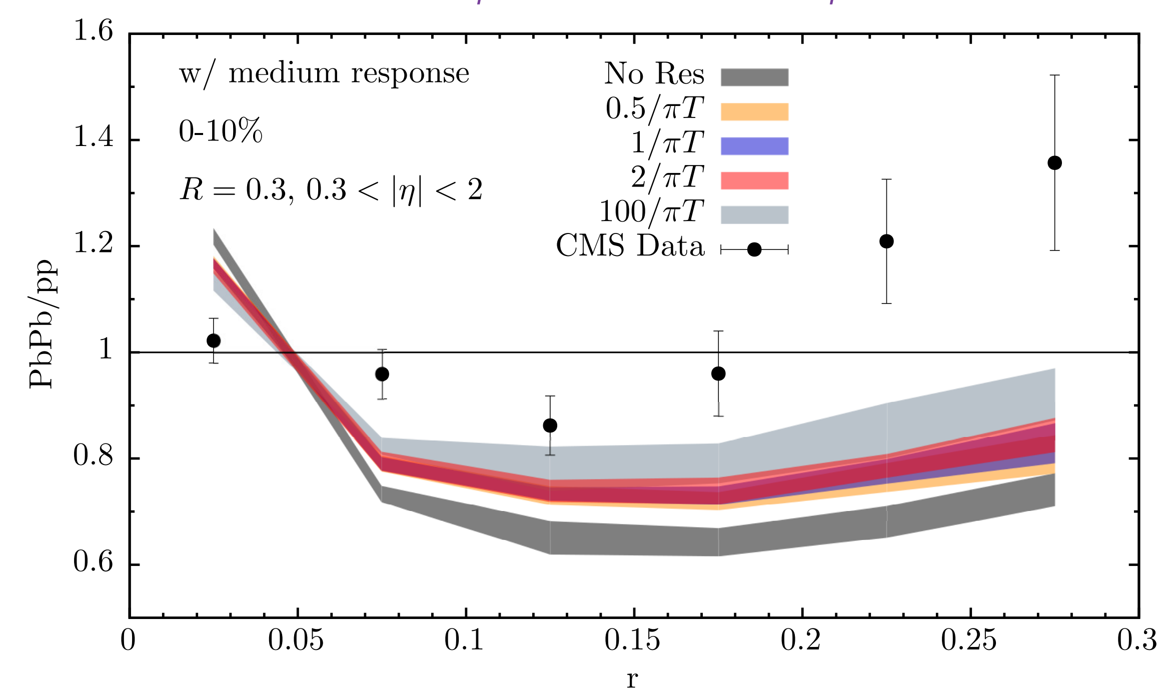
reduce stopping distances

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

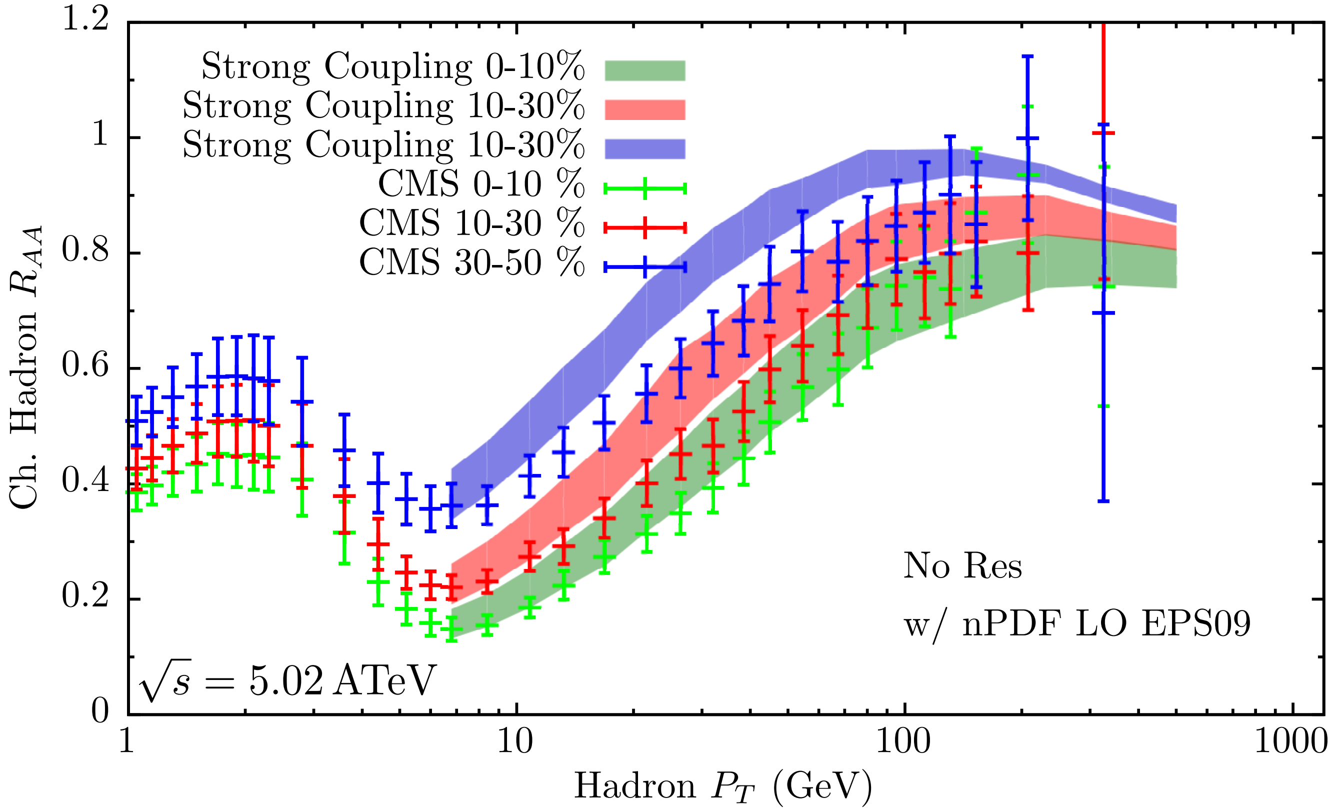


oversimplified medium response?



Hulcher et al.
in preparation

Hadron suppression at LHC



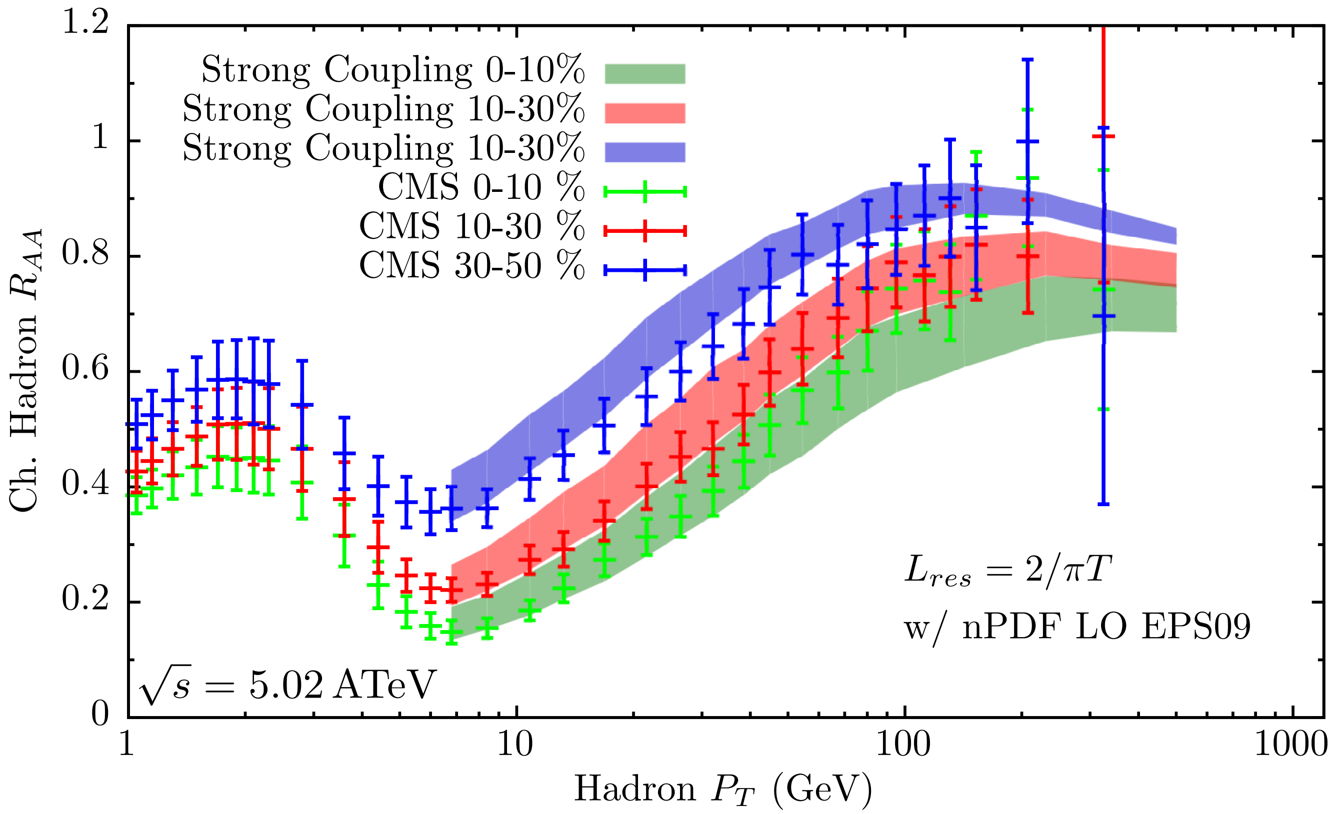
tension in
centrality evolution

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

Hulcher et al.
in preparation

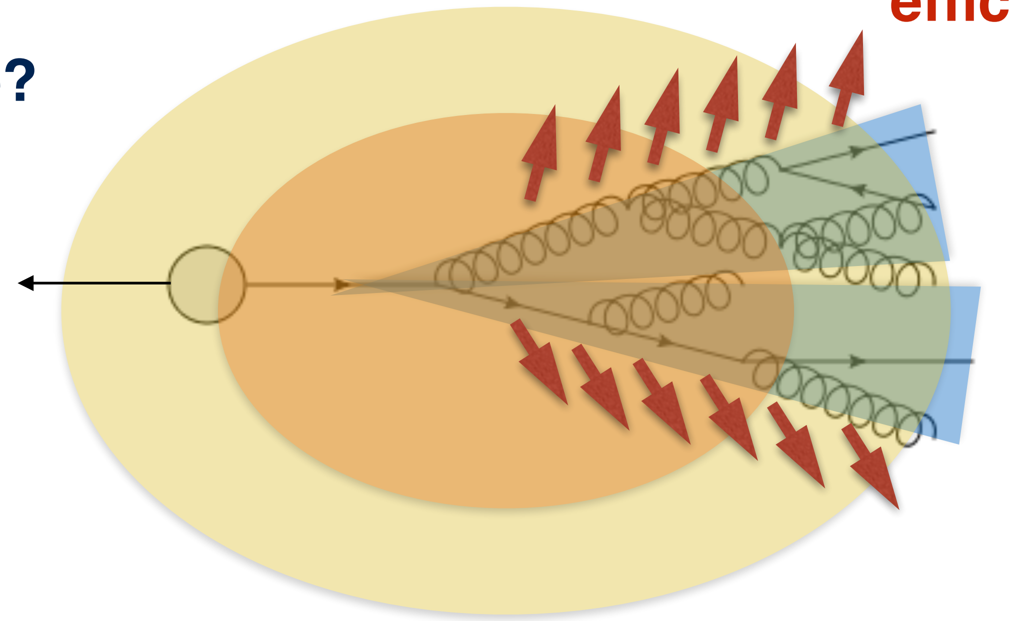
Summary

- energy loss at strong coupling is a necessary tool to assess the true nature of QGP dynamics
- much progress has been made in developing models that can be compared to data
- degree of hydrodynamization of lost energy can be tested with currently available observables
- further effort is needed on bringing holographic models to a next level of sophistication

Summary

- energy loss at strong coupling is a necessary tool to assess the true nature of QGP dynamics
- much progress has been made in developing models that can be compared to data
- degree of hydrodynamization of lost energy can be tested with currently available observables
- further effort is needed on bringing holographic models to a next level of sophistication

is data pointing towards this picture?



efficient energy transfer into hydro

fairly unresolved system

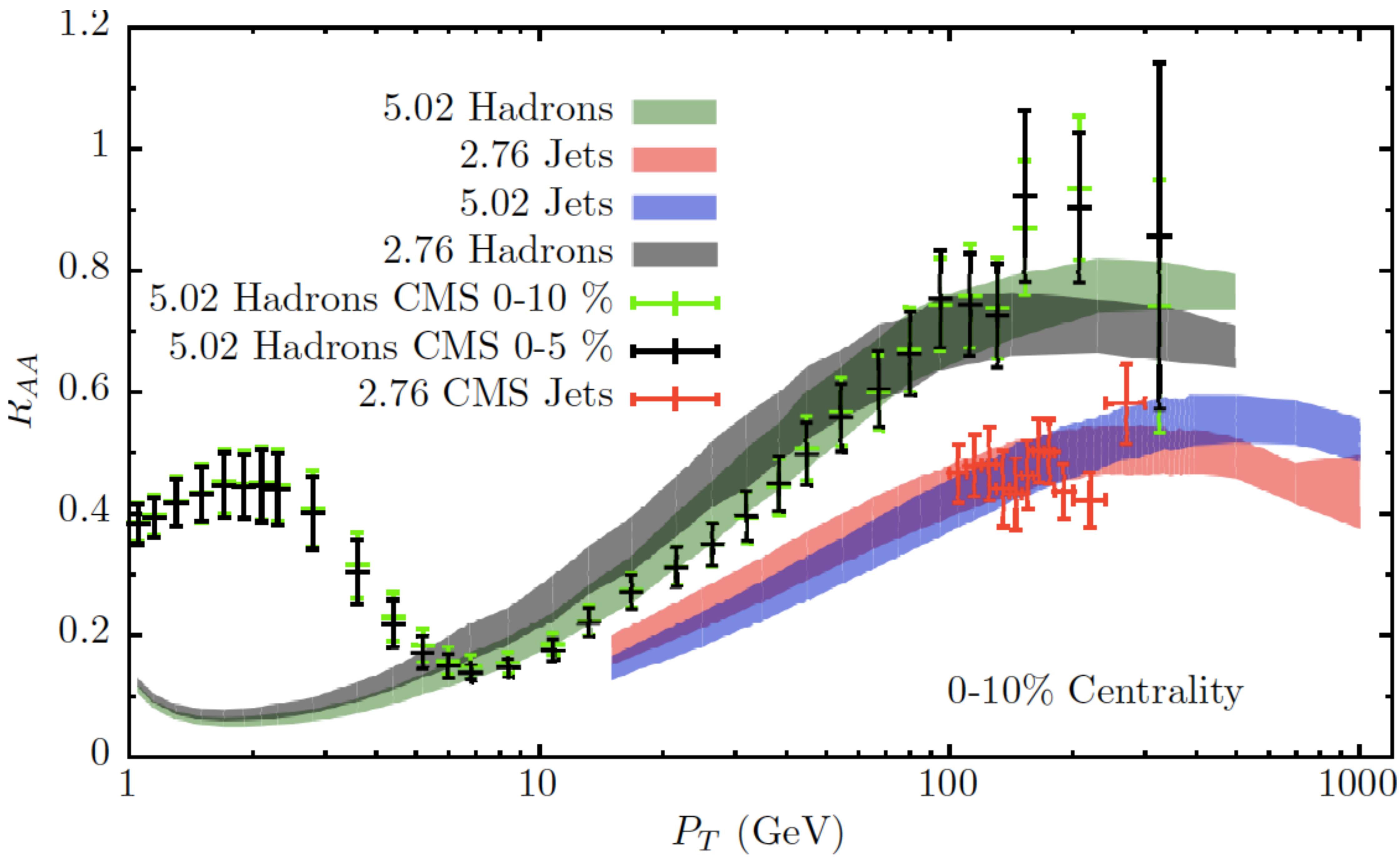
vacuum-like showering

Backup Slides

Jet Vs Hadron Suppression

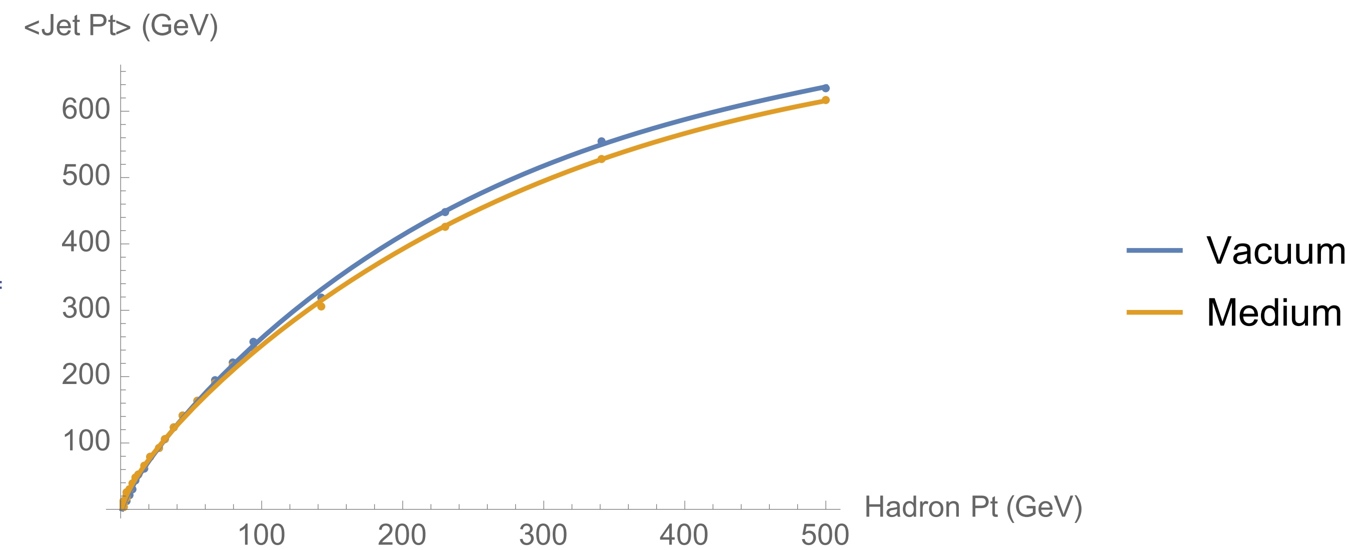
No resolution effects

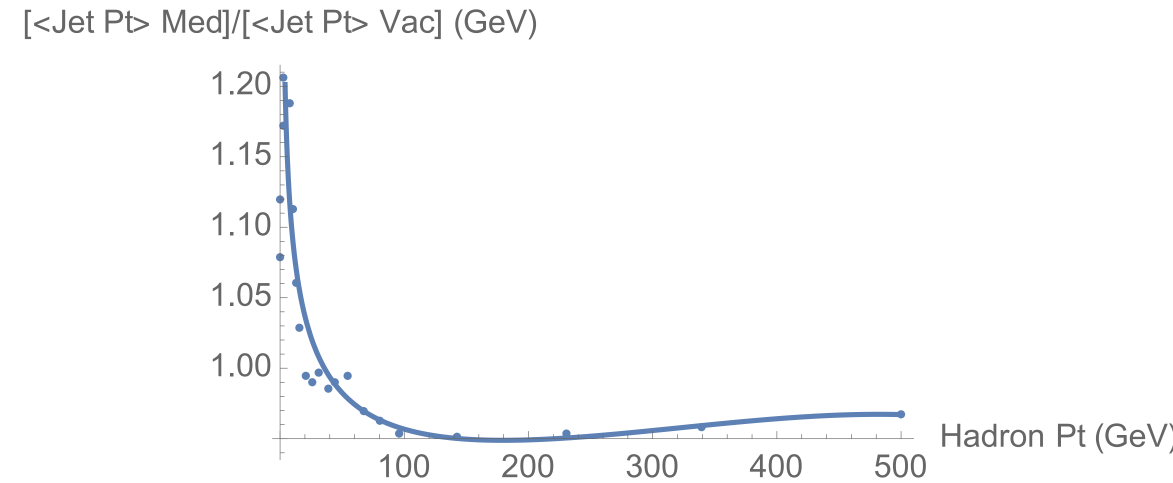
VERY PRELIMINARY



A crude attempt

From which jet does a hadron come in average? **VERY** PRELIMINARY

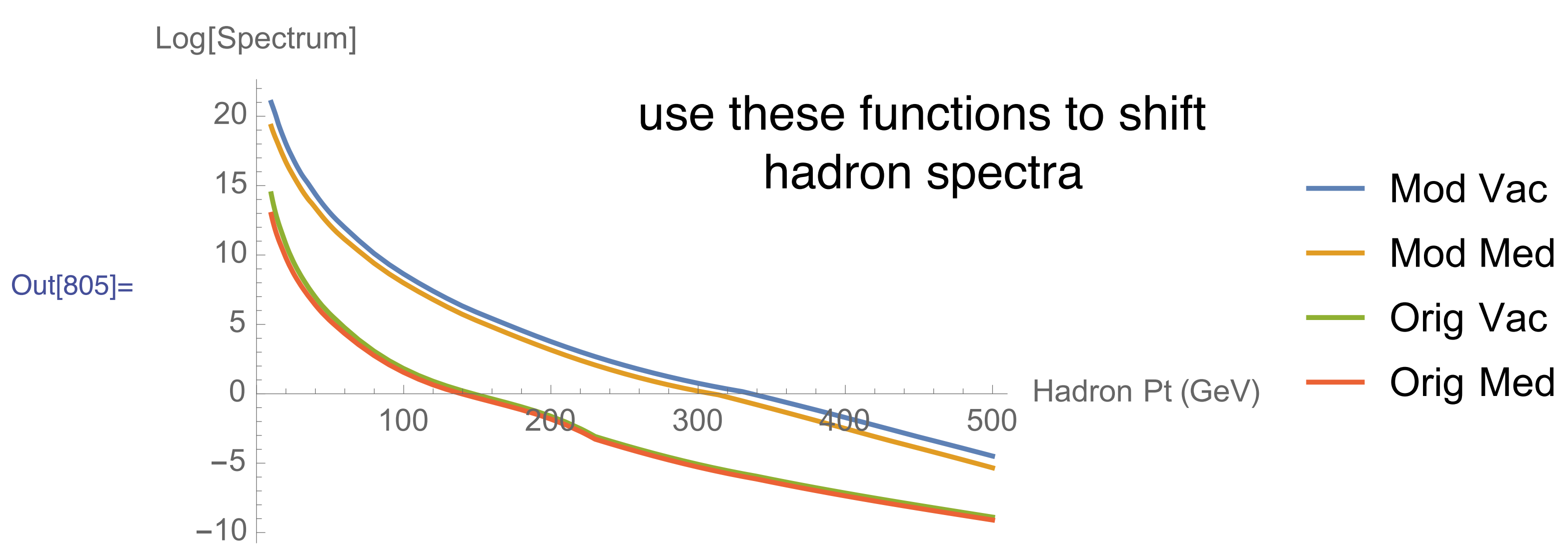




At high pt, hadrons of a certain pt come from jets with a smaller pt in PbPb than in pp (due to hardening of FF?)

Order reversed towards lower pt (due to jet suppression?)

use these functions to shift hadron spectra



(assumes that #jets can be mapped to #leading hadrons)

A crude attempt

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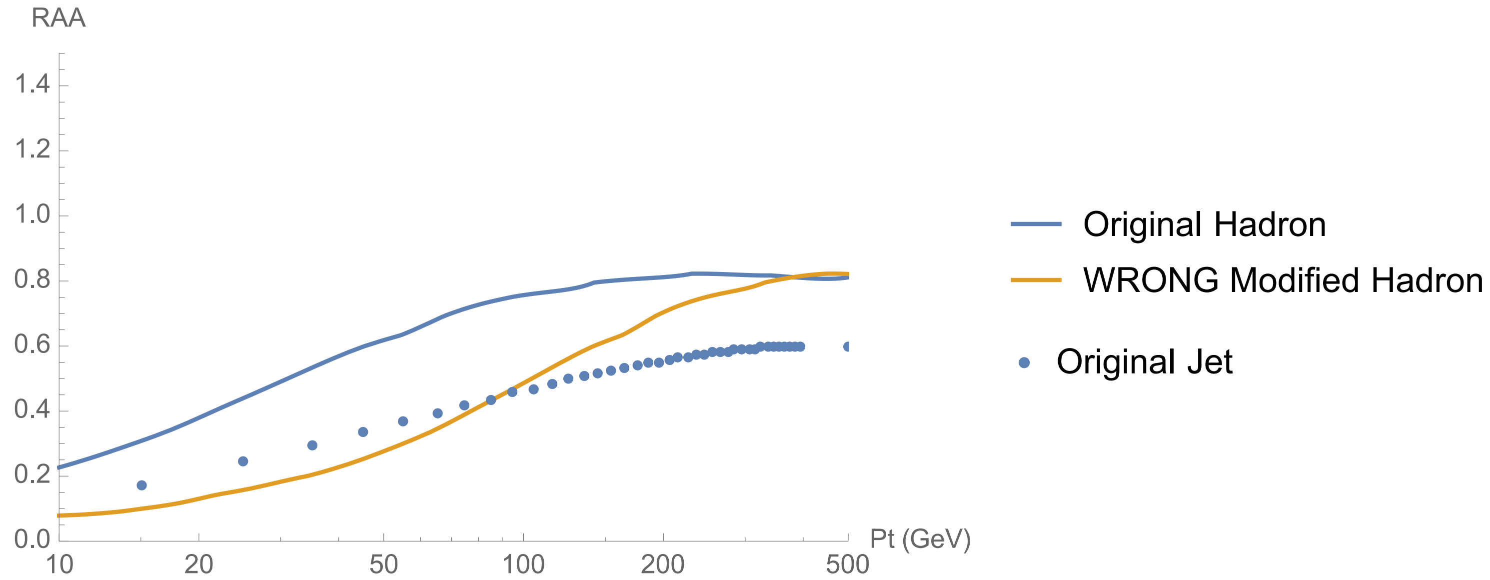
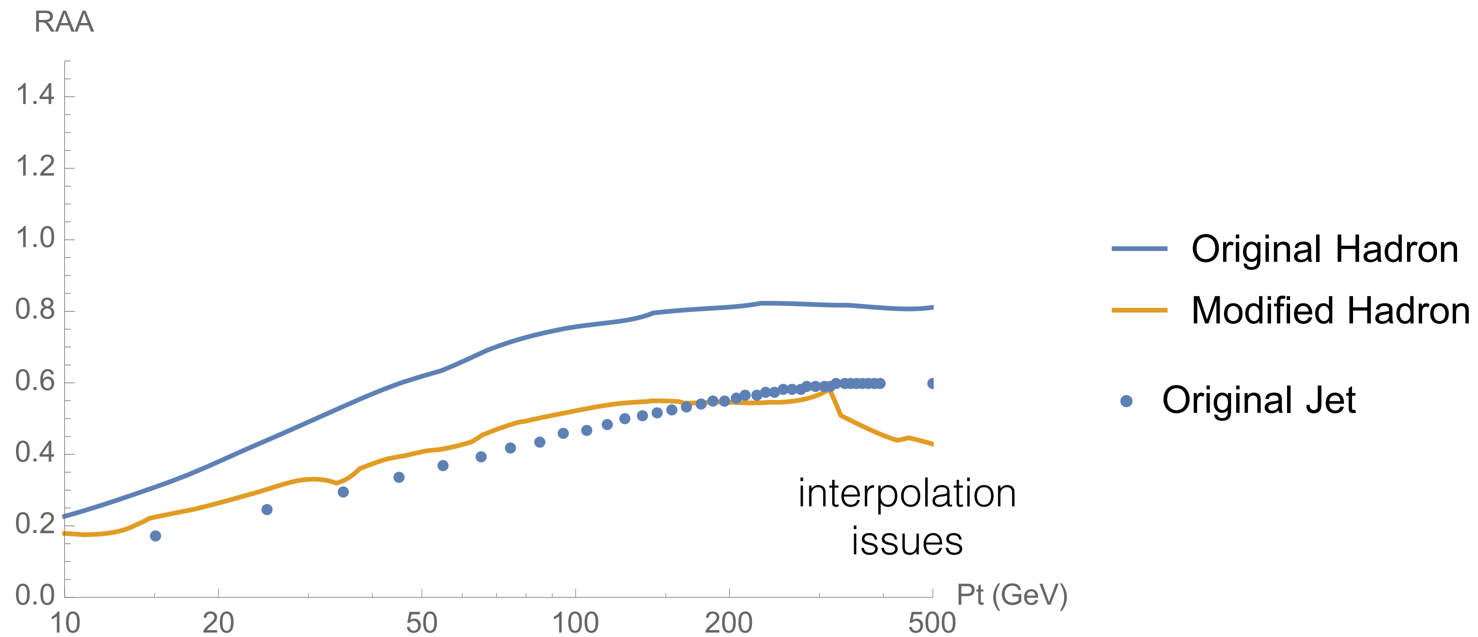


By using same function
for both spectra
one merely obtains
a pure shift of RAA

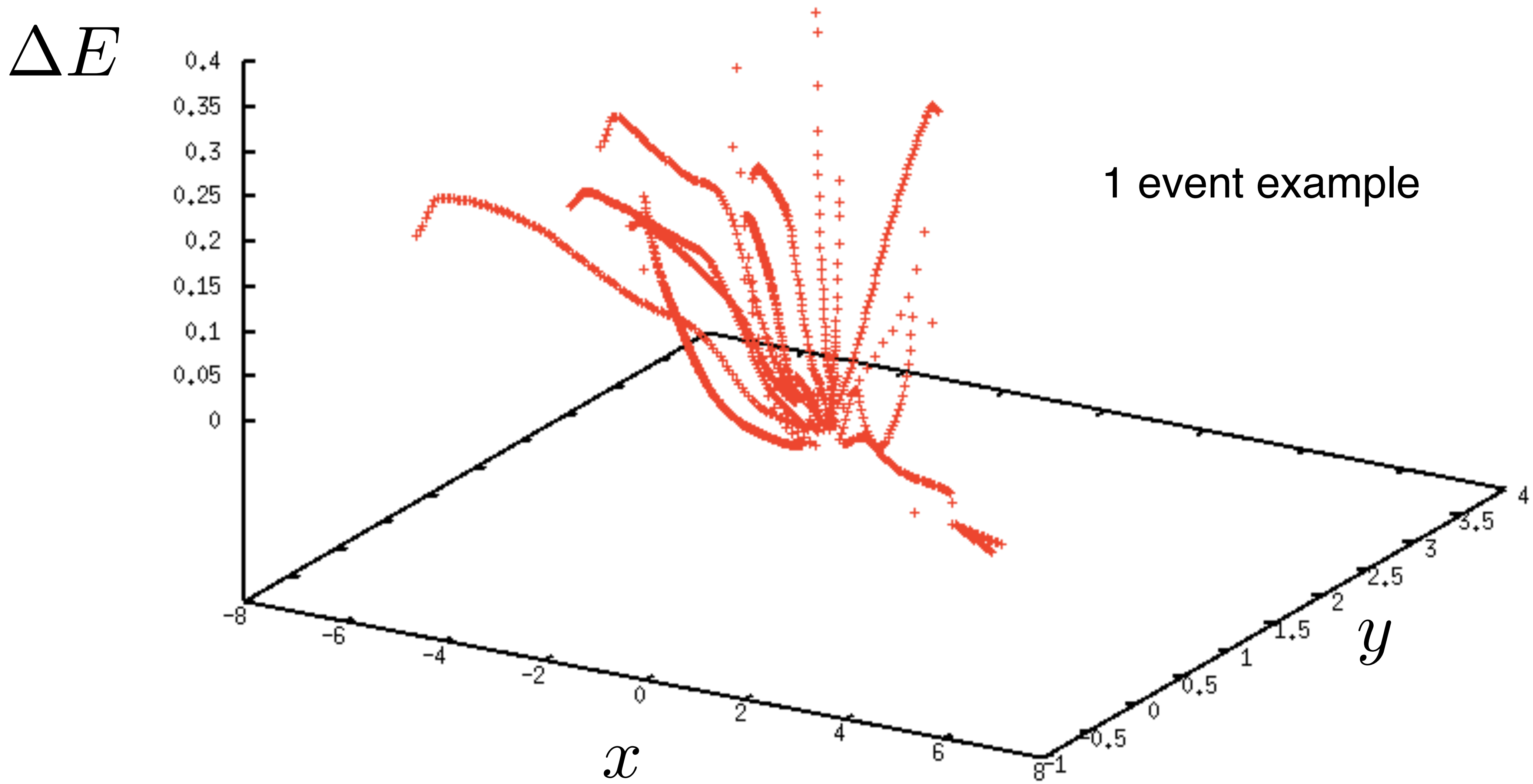


However, using the
different dependence
the hardening of the jet structure
is taken into account

effectively: convoluting hadron spectra with jet fragmentation functions

First steps into hydro with source

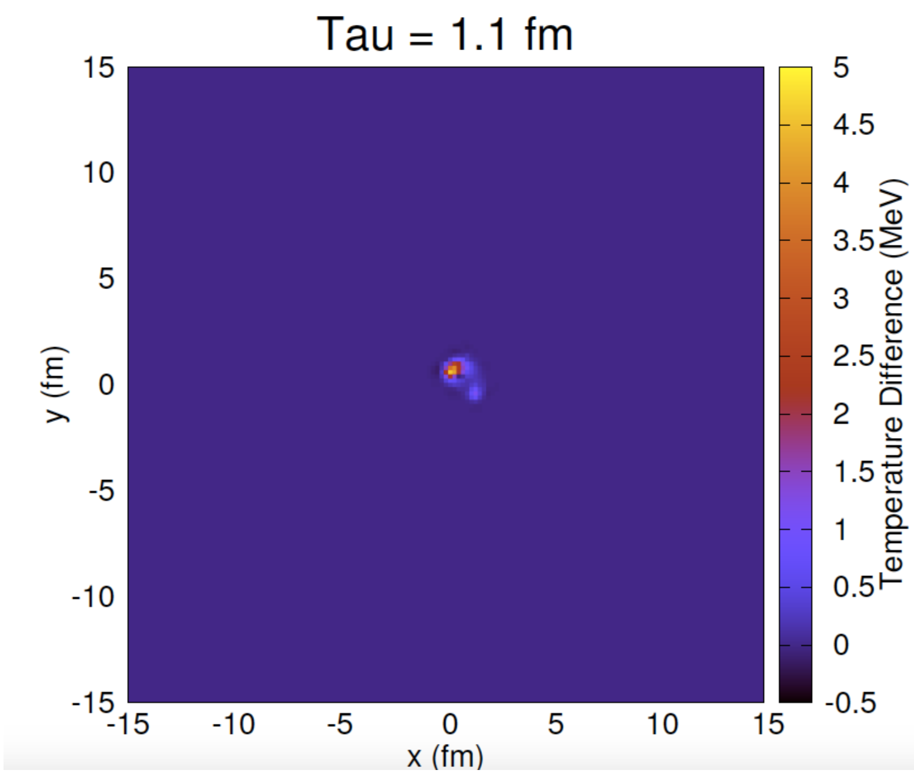
VERY PRELIMINARY

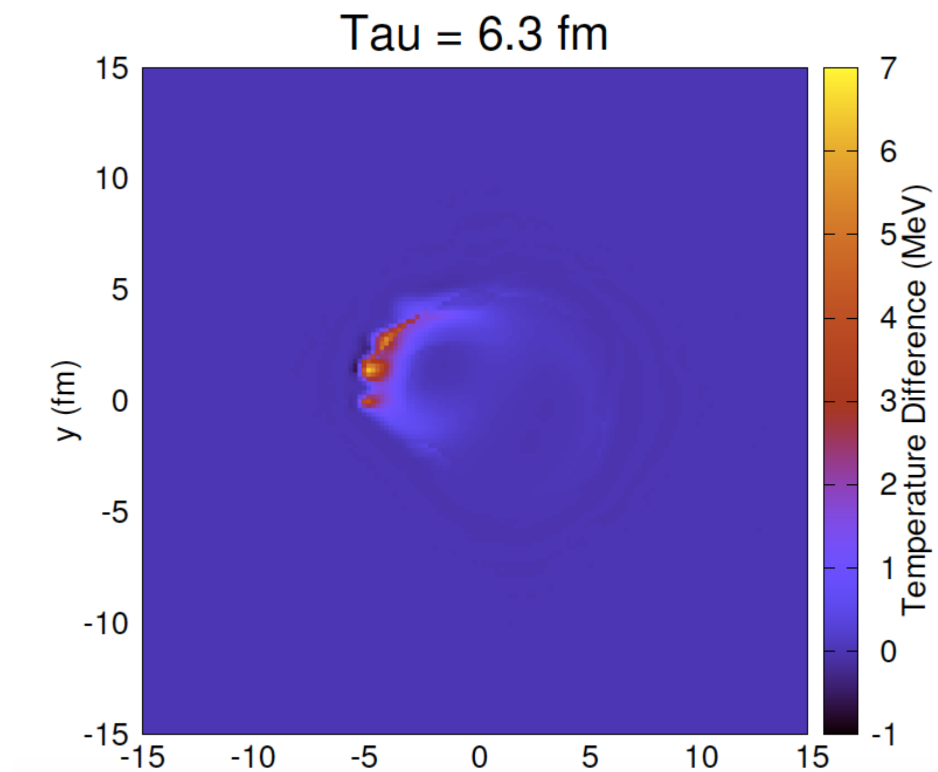


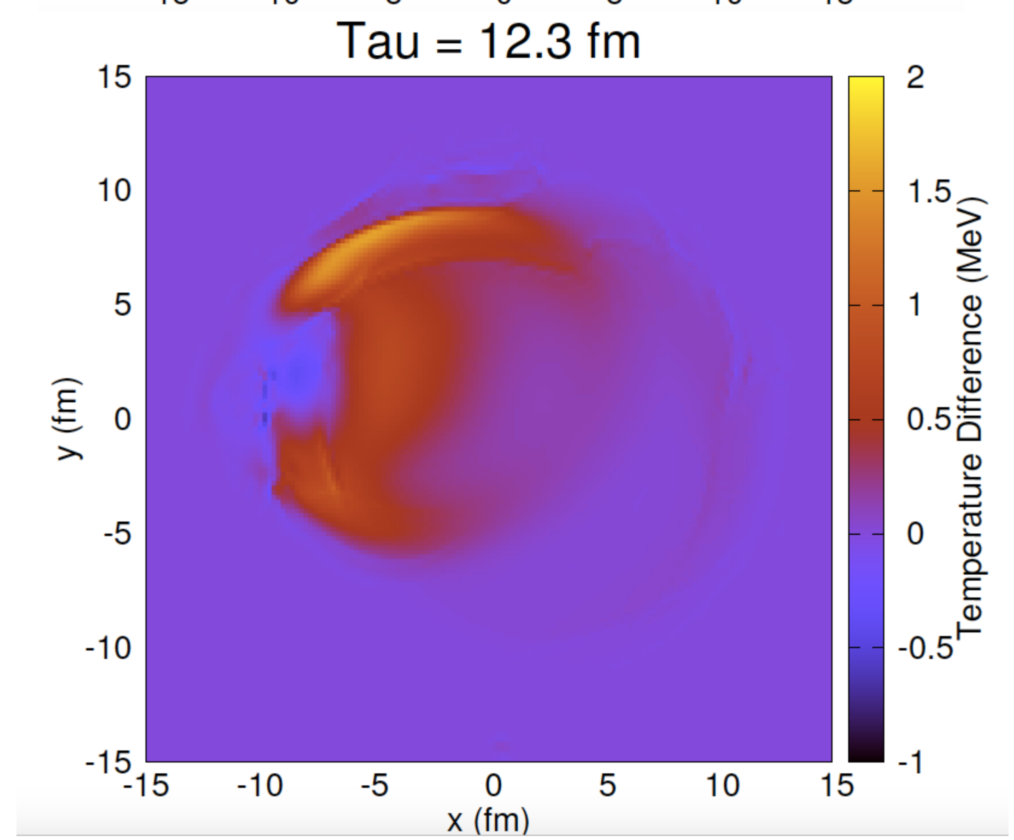
Energy deposited into medium according to holographic energy loss rate

Most of the energy deposited at late times

First steps into hydro with source







work with Mayank Singh & Chun Shen
(same source setup as in Chun's talk)

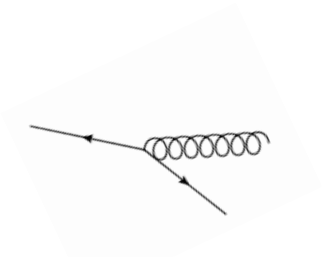
VERY PRELIMINARY

1 event example

Finite resolution effects

Casalderrey-Solana & Ficnar '15

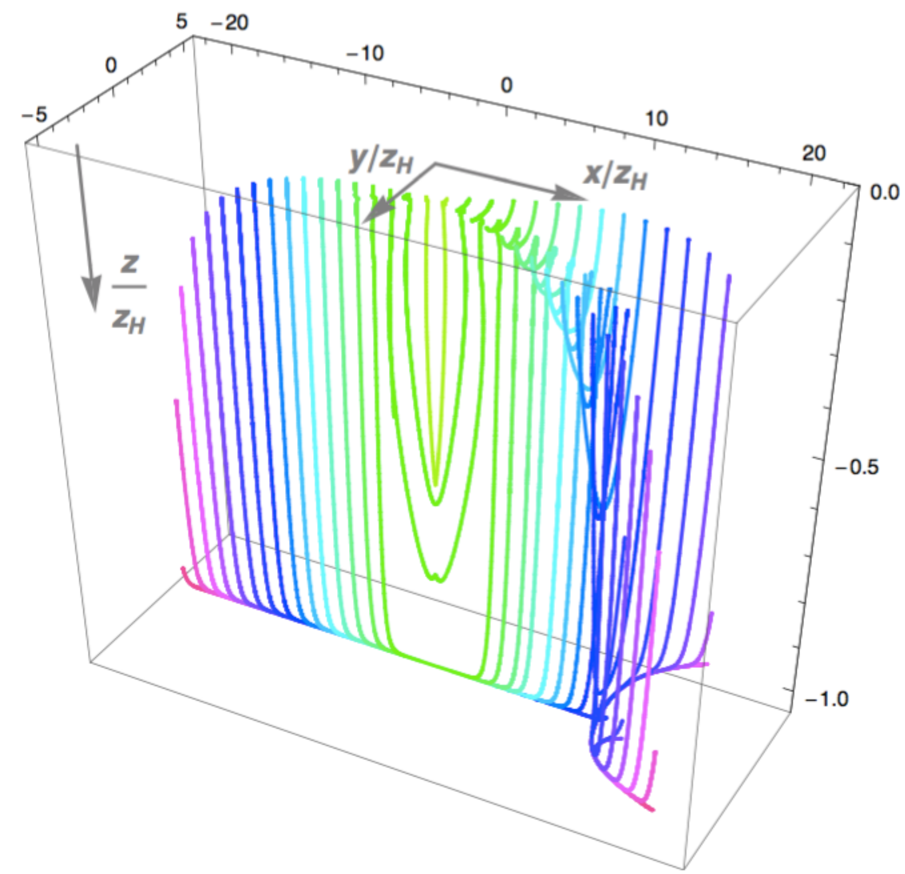
holographic description of 3-jet events

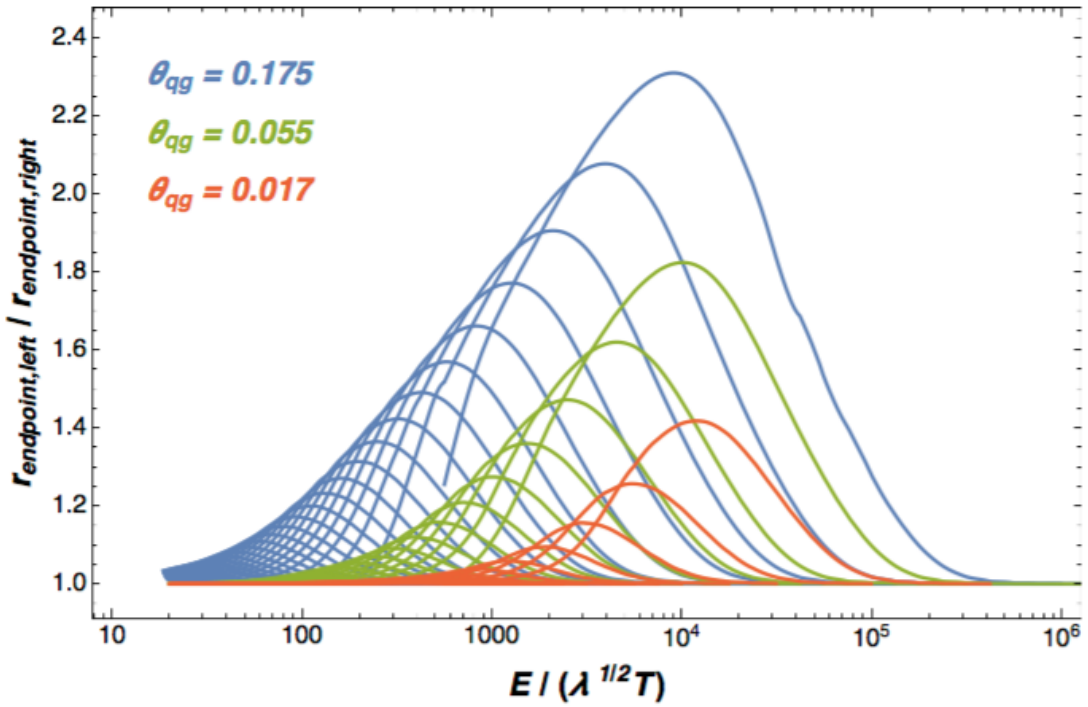


smallest angular separation between two jets that the medium can resolve?

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





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

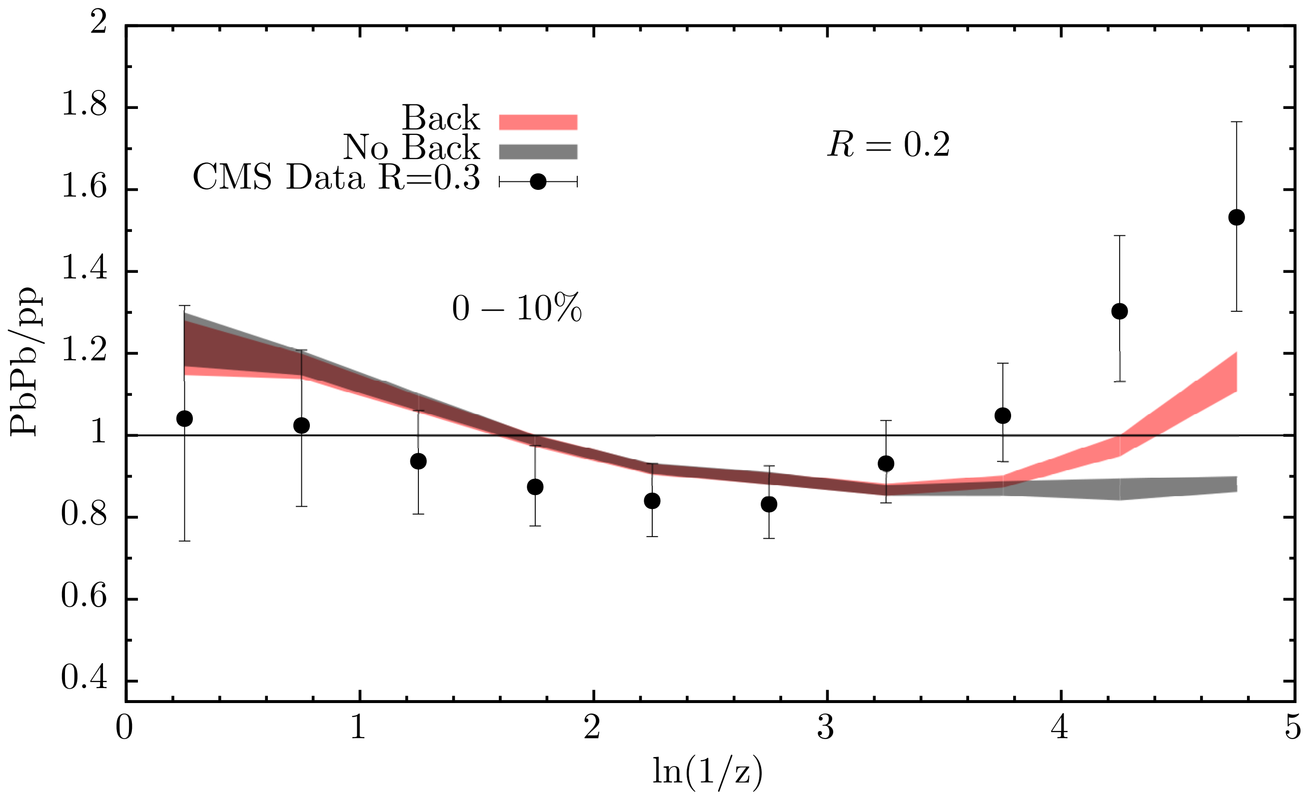
different scaling than pQCD in a dense plasma

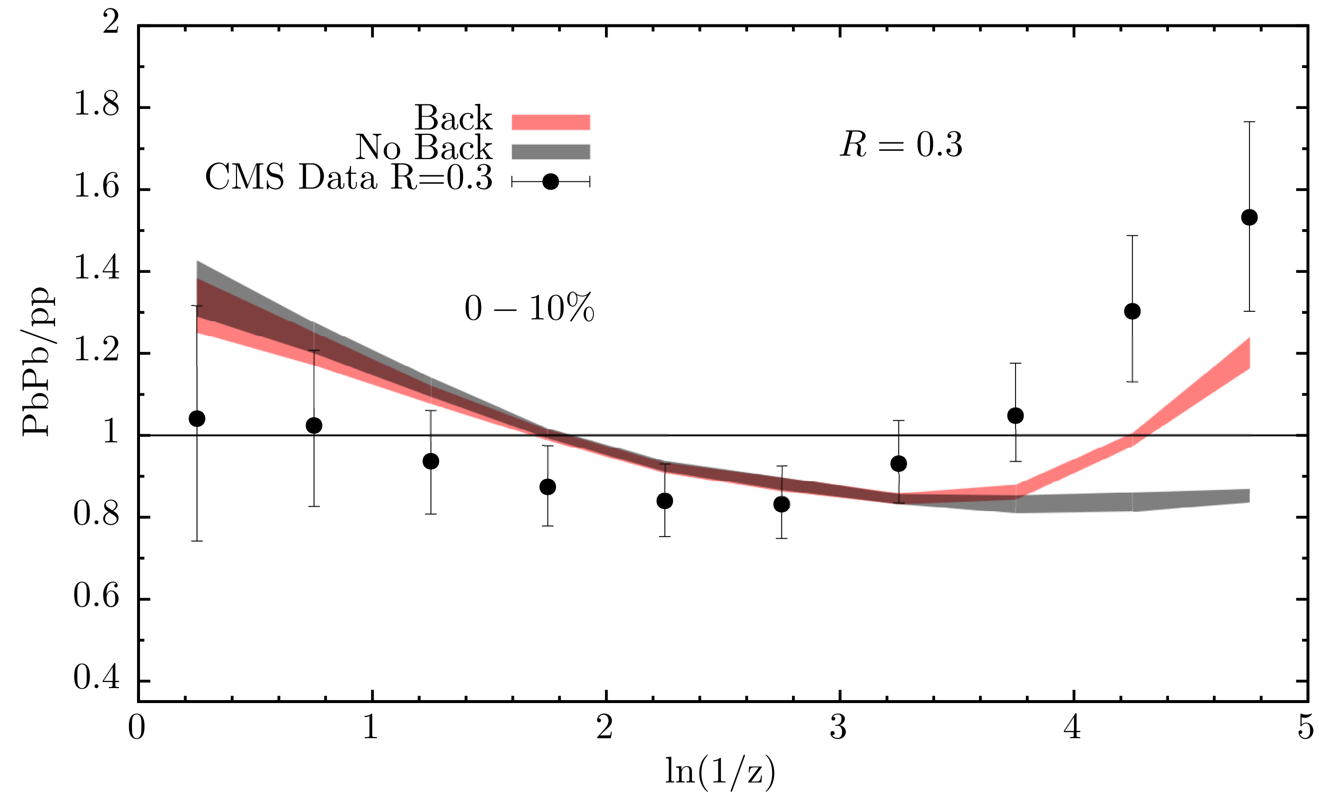
$$\theta_{\mathrm{res}}^{\mathrm{pQCD}} \propto E^{-3/4}$$

(w/ novel simplified background subtraction)

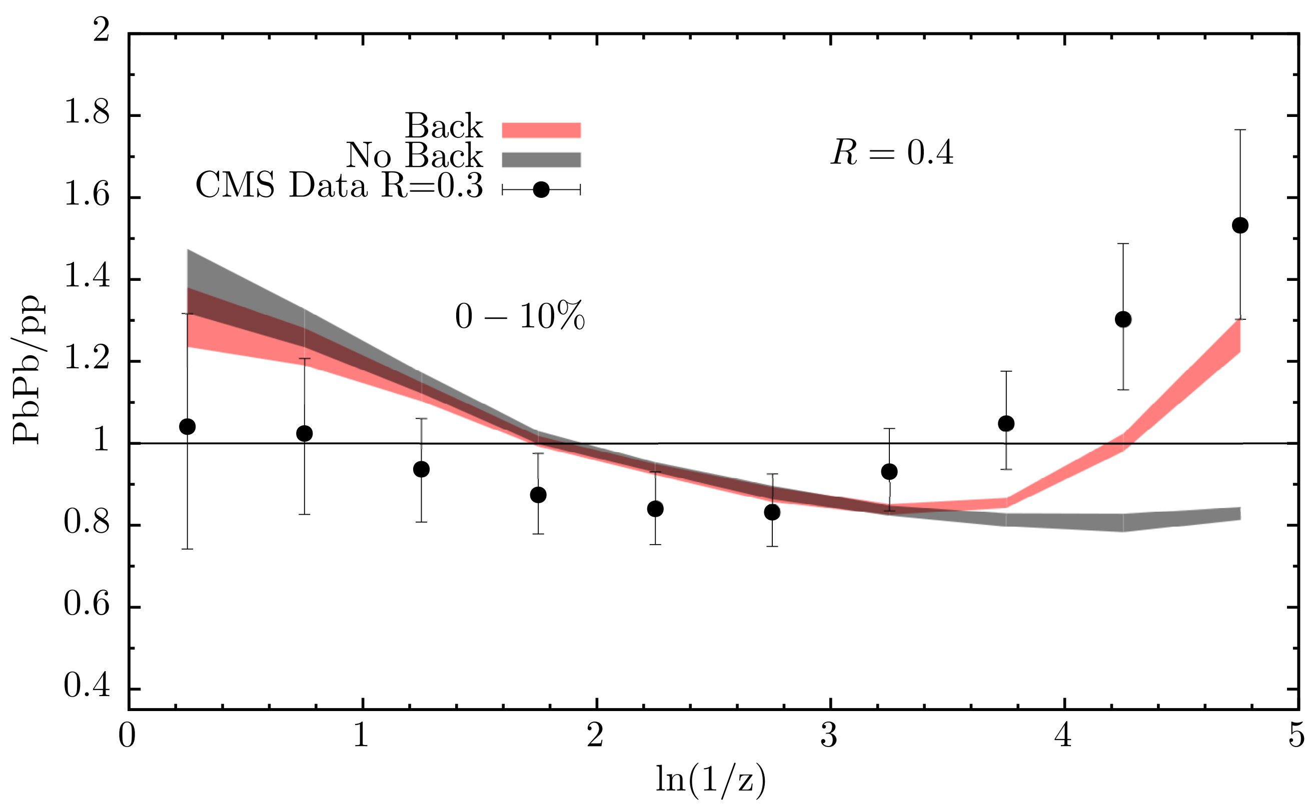
FF vs R

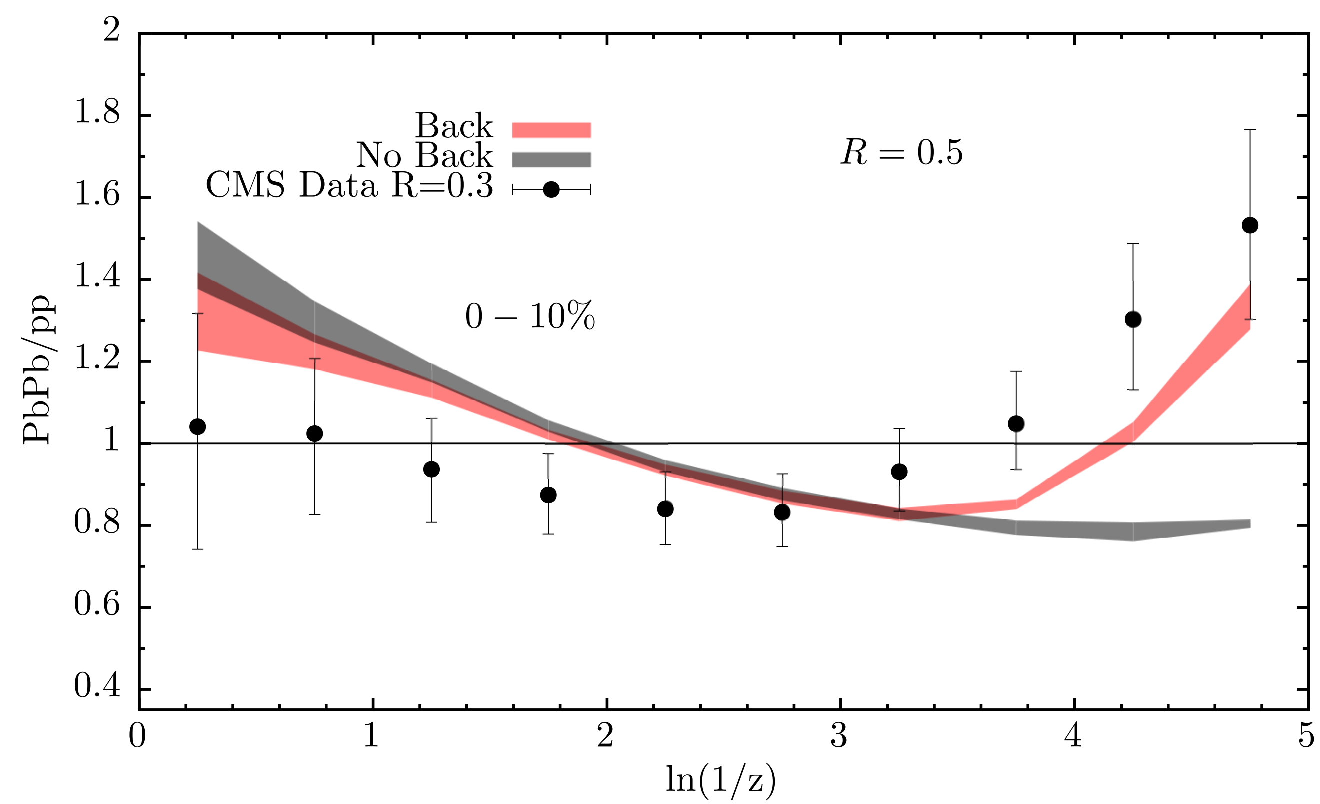
PRELIMINARY





effect strongest towards greatest angles

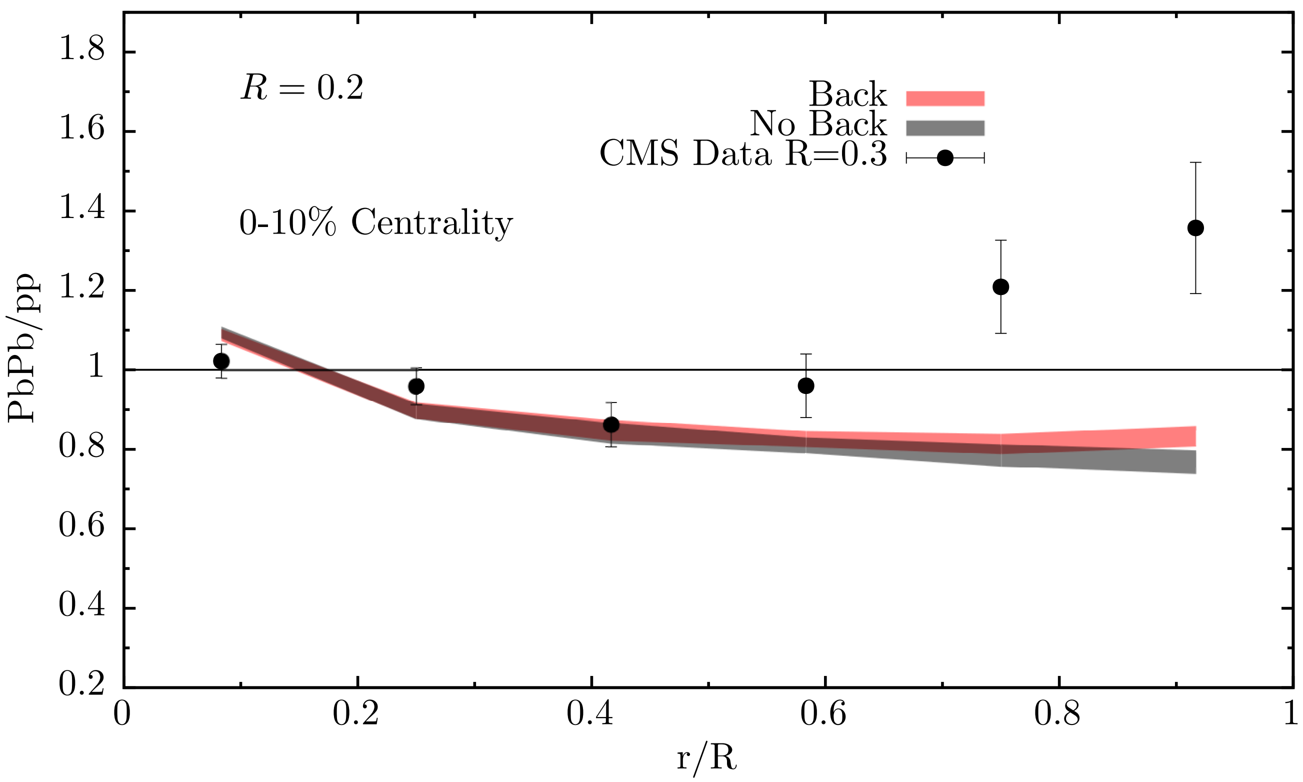


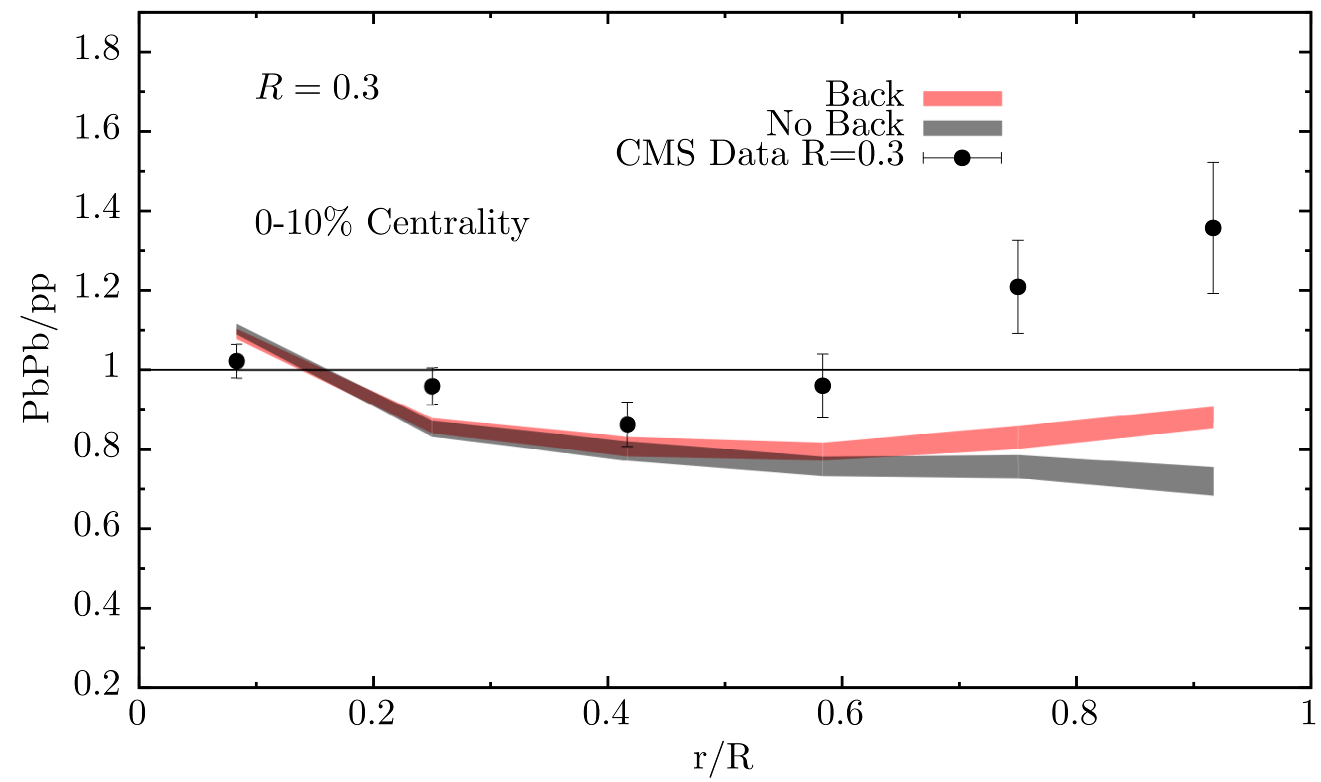


(w/ novel simplified background subtraction)

PRELIMINARY

Jet Shapes vs R





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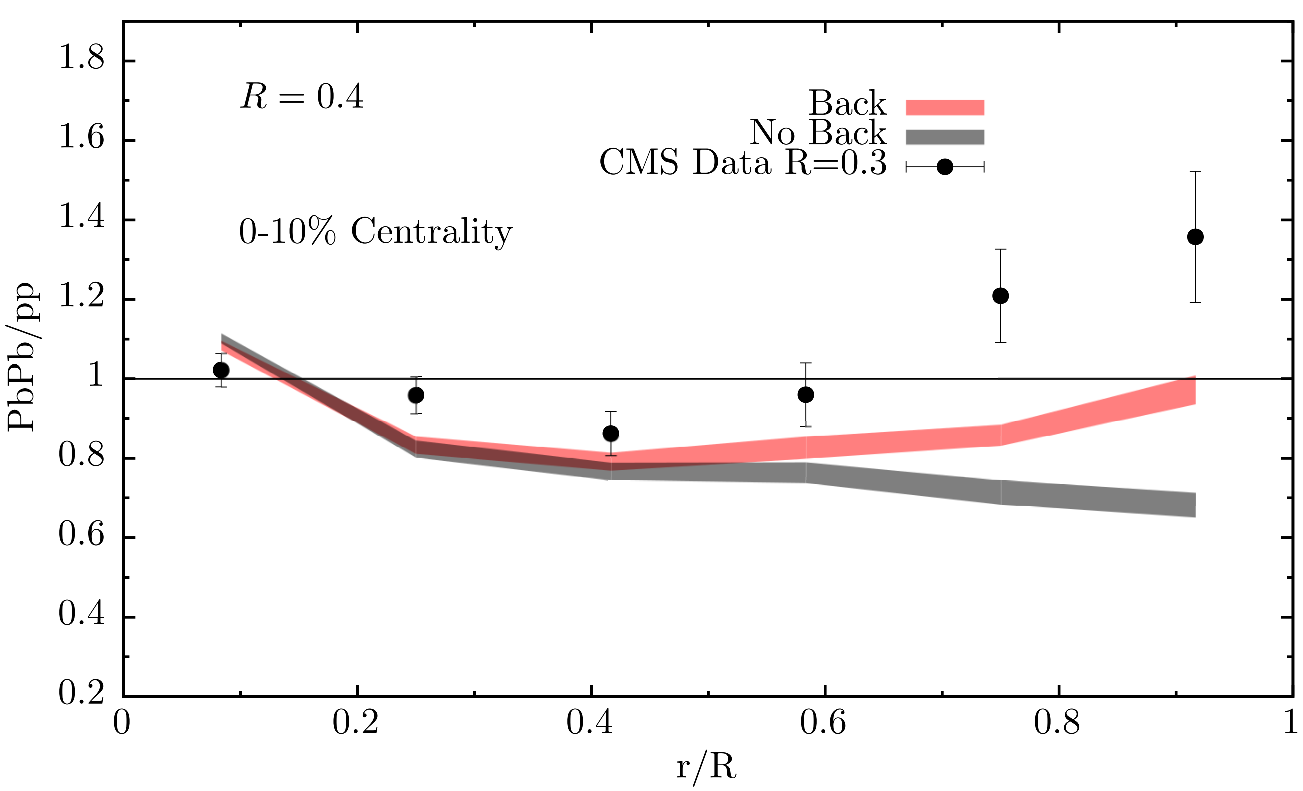
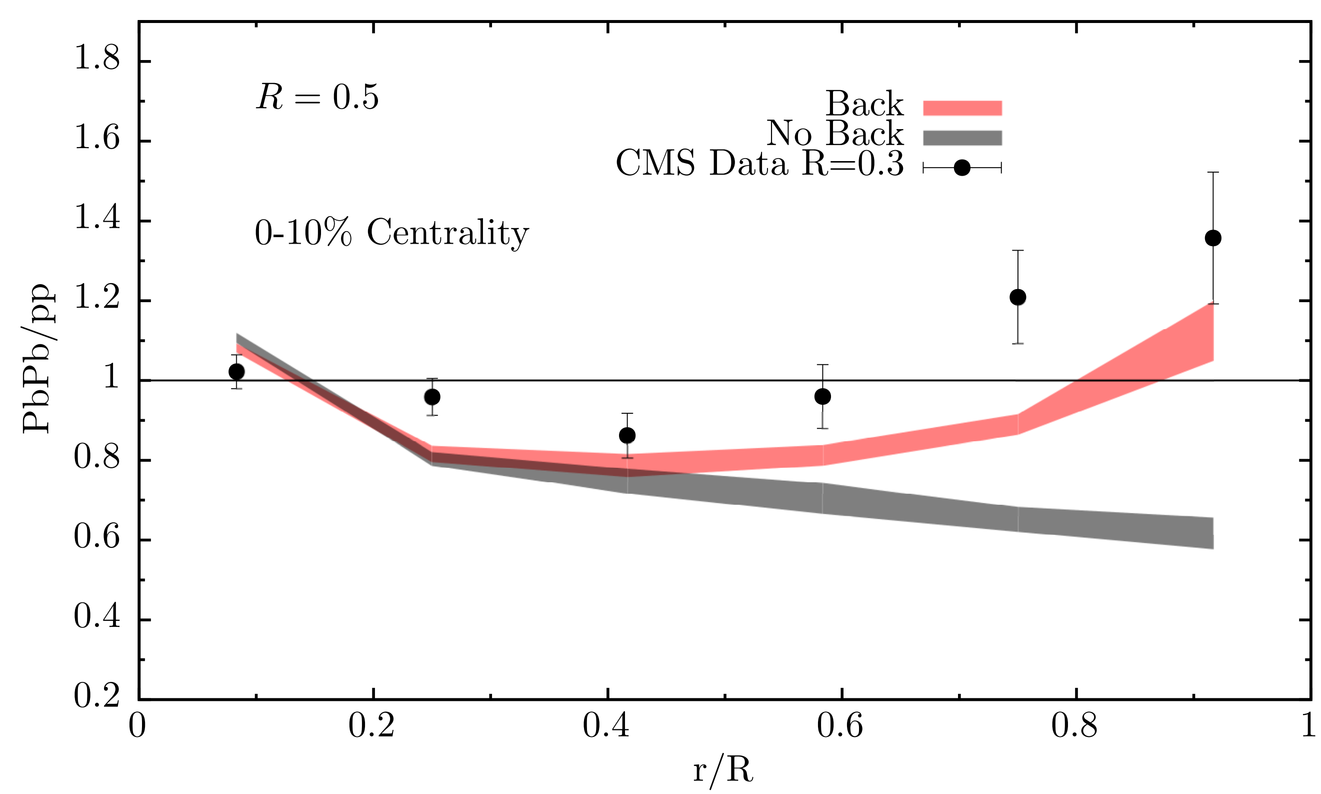
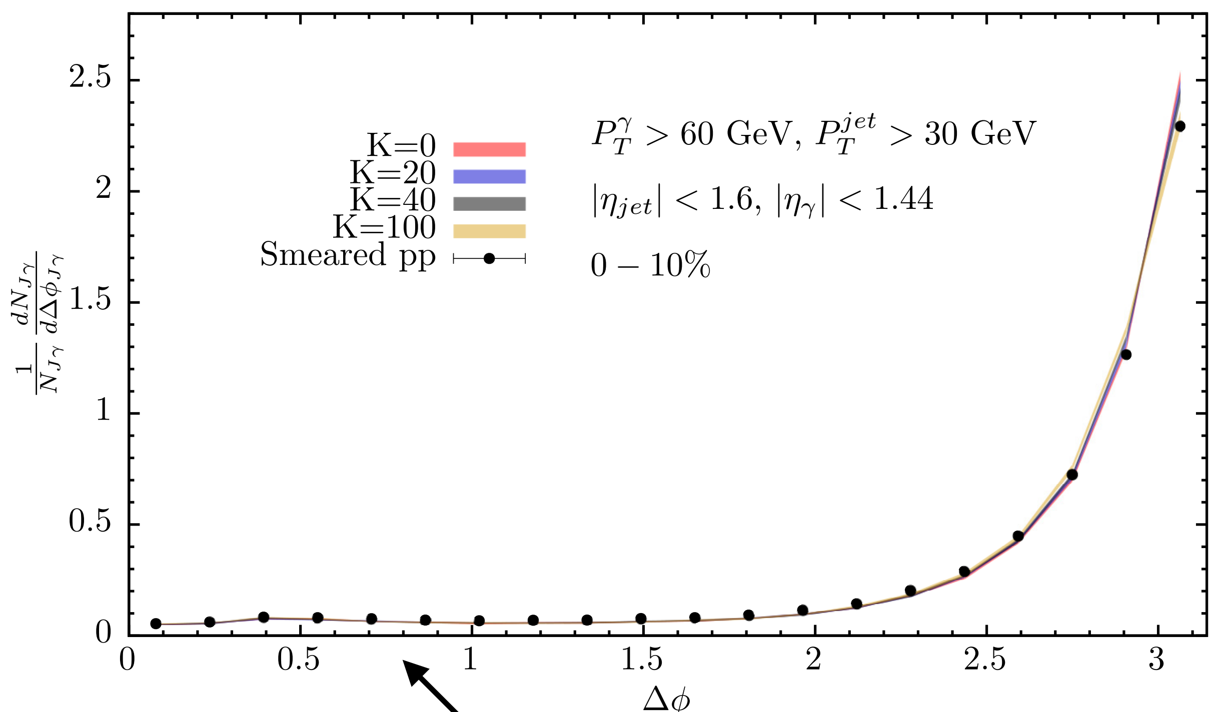


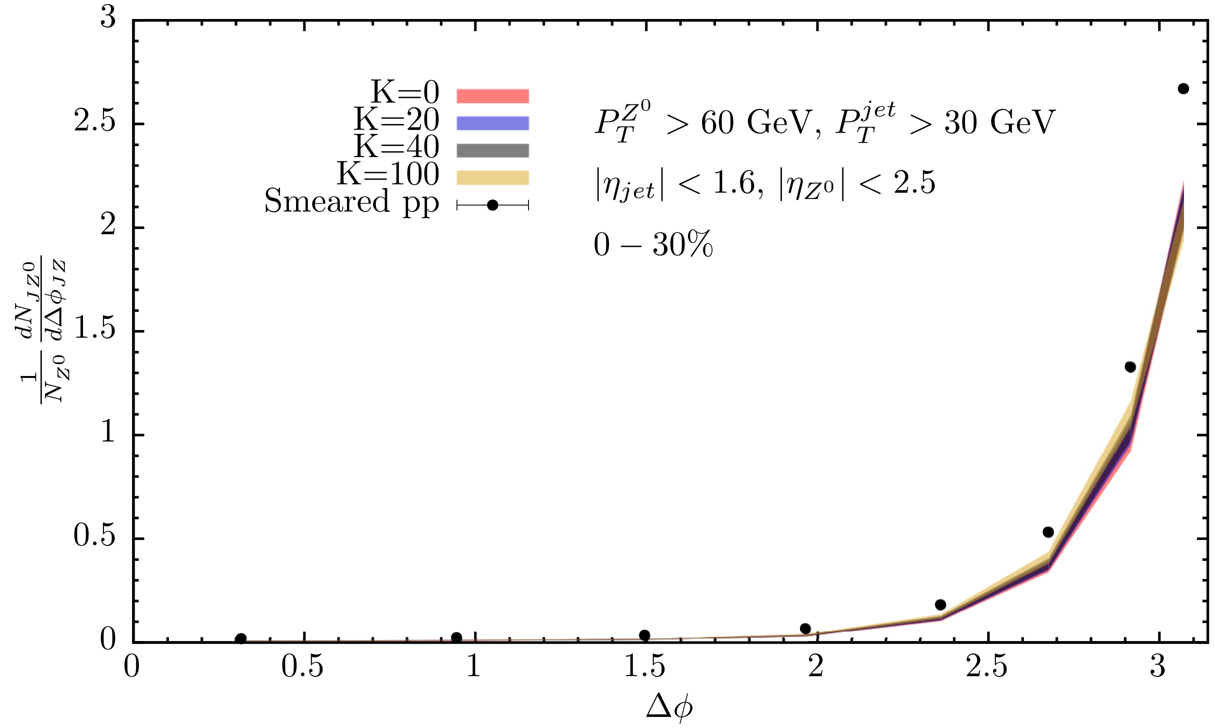


Boson Jet Acoplanarities

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

Hadron suppression at RHIC