Coherence Effects at Strong Coupling

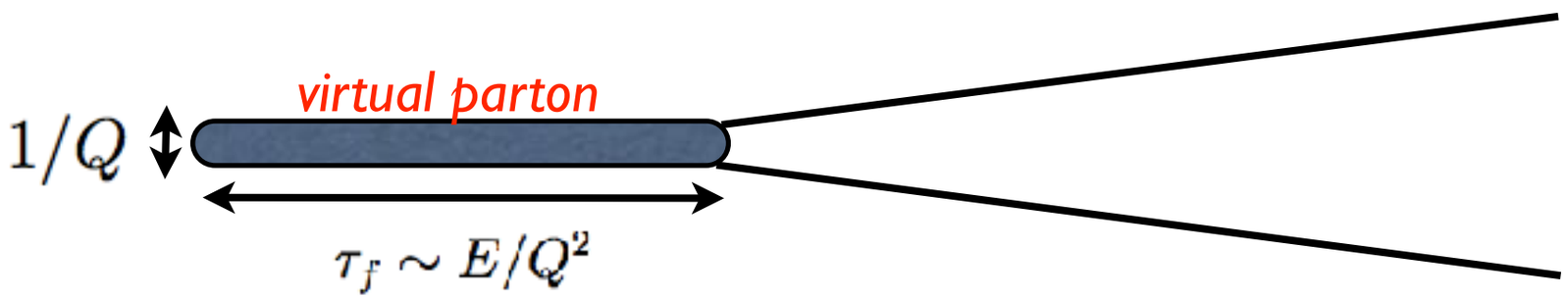
Jorge Casalderrey-Solana

Oxford Physics

THE ROYAL SOCIETY

Jets in Medium

- Jets probe different scales



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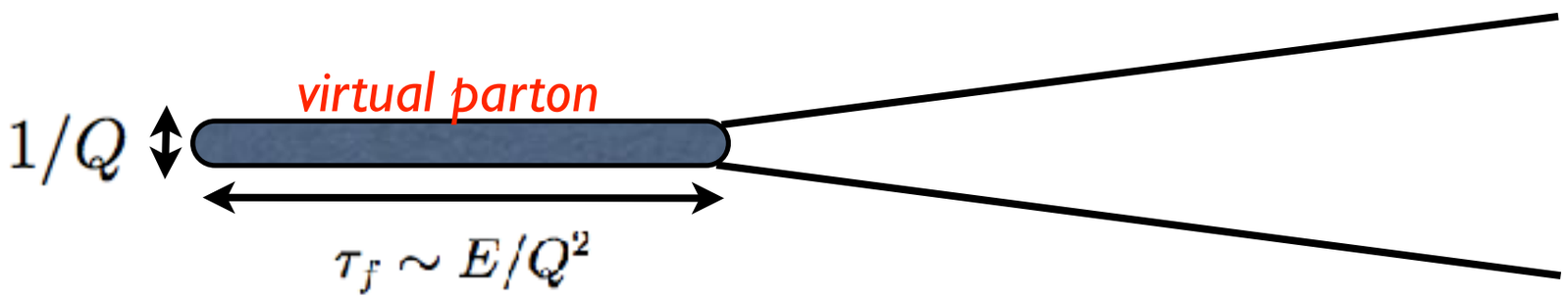

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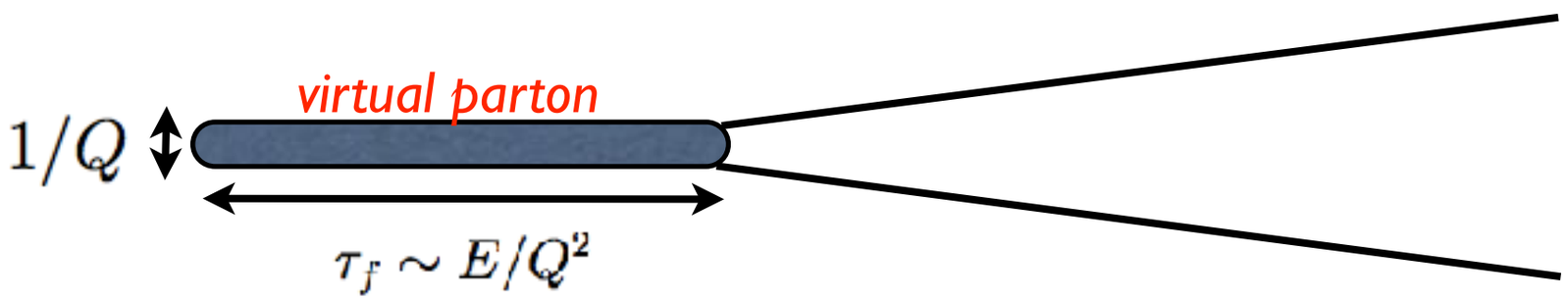

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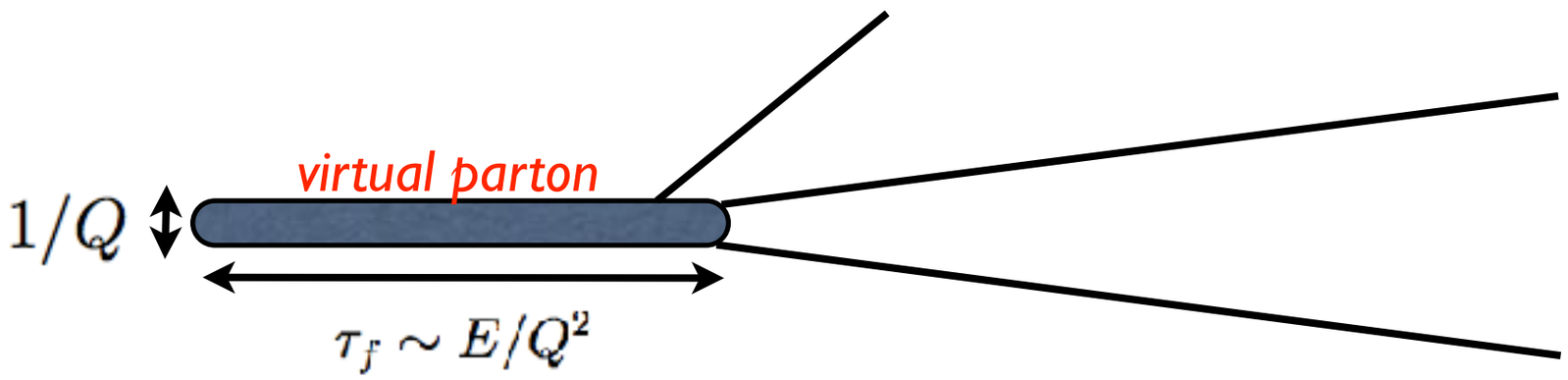

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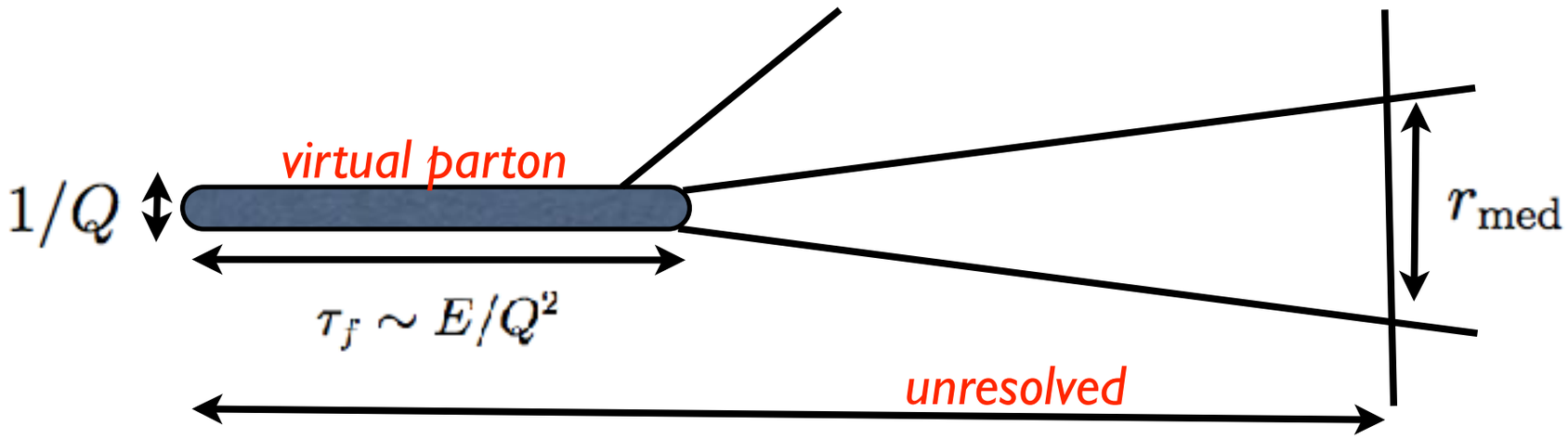

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    Radiation as single objects

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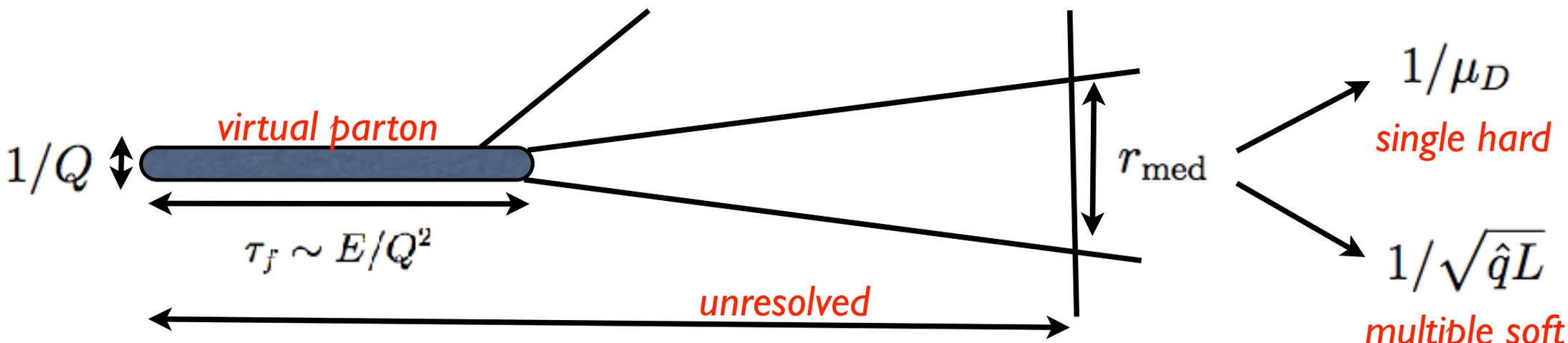

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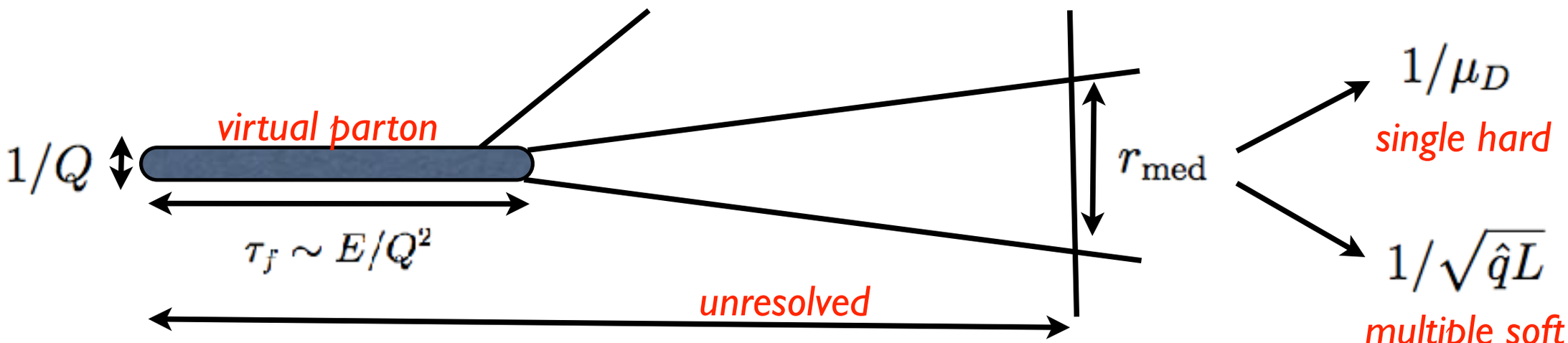

- What are the typical scales?
  - Average energy loss controlled by hardest splittings

$$Q_H \sim \sqrt{\hat{q}L} \sim 3.2\,\text{GeV}\left(\frac{\hat{q}}{2\,\text{Gev}^2/\text{fm}}\frac{L}{5\,\text{fm}}\right)^{1/2}$$

multiple soft

$$Q_H \sim \mu_D \sim 1.2\,\text{GeV}\left(\frac{g}{2}\frac{T}{0.47\text{GeV}}\right)$$

single hard

Not terribly perturbative

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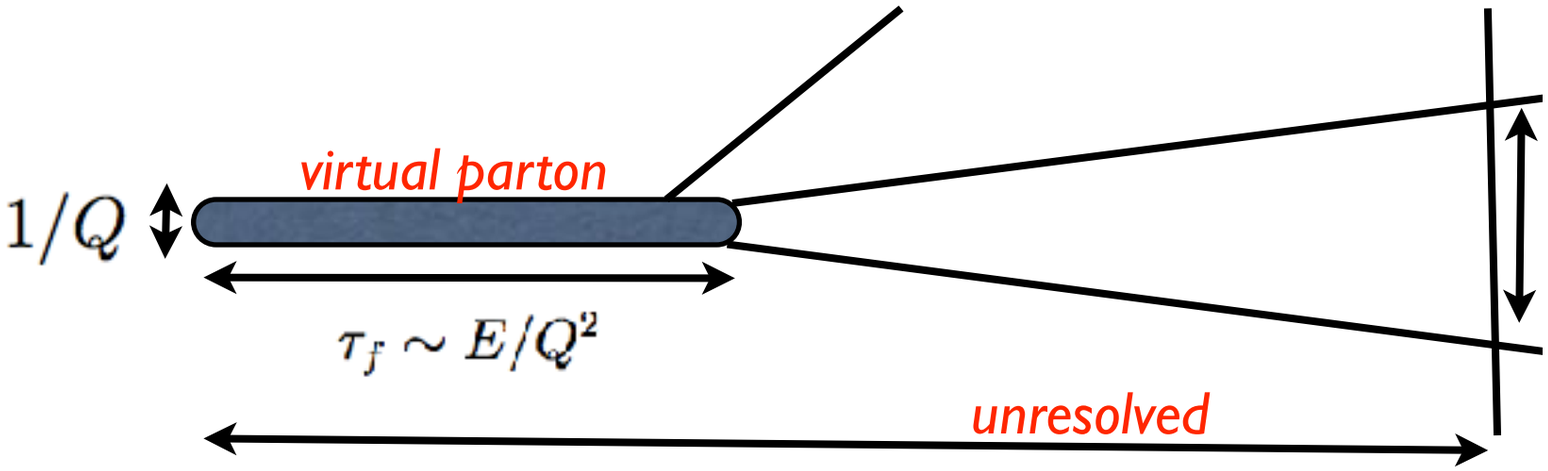
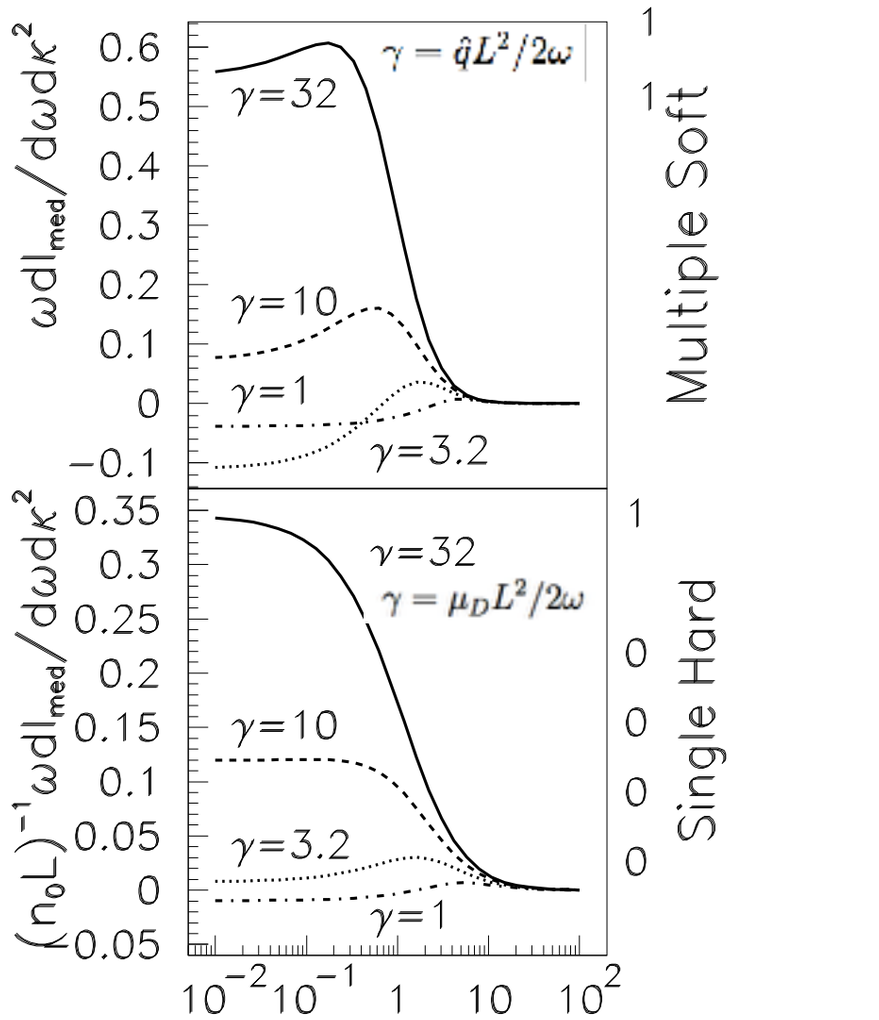


- Most gluons radiated at smaller scale
  - In a steeply falling spectrum losses are dominated by softer emissions

$$Q_{\rm dom} < \left(\frac{p_{\rm T}}{n}\hat{q}\right)^{1/4} = 1.6\,{\rm GeV}\left(\frac{\hat{q}}{2\,{\rm Gev}^2/{\rm fm}}\frac{p_{\rm T}}{100\,{\rm GeV}}\frac{6}{n}\right)^{1/4}$$

BDMS 01

Salgado & Wiedemann 03



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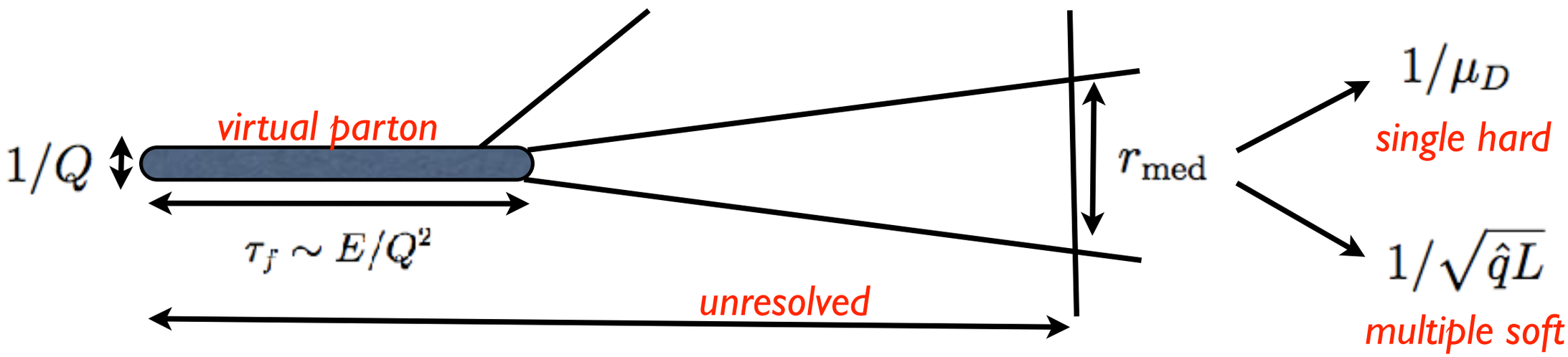

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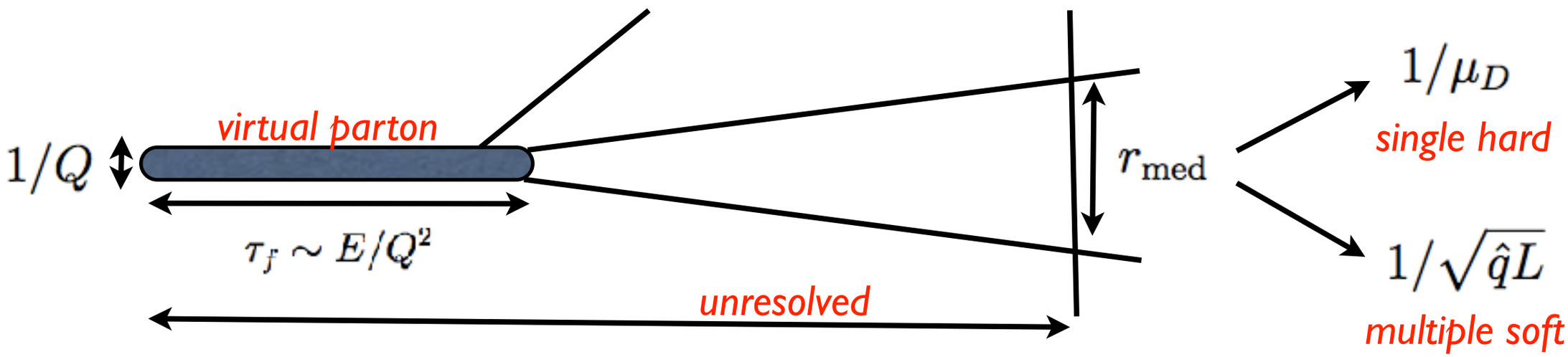

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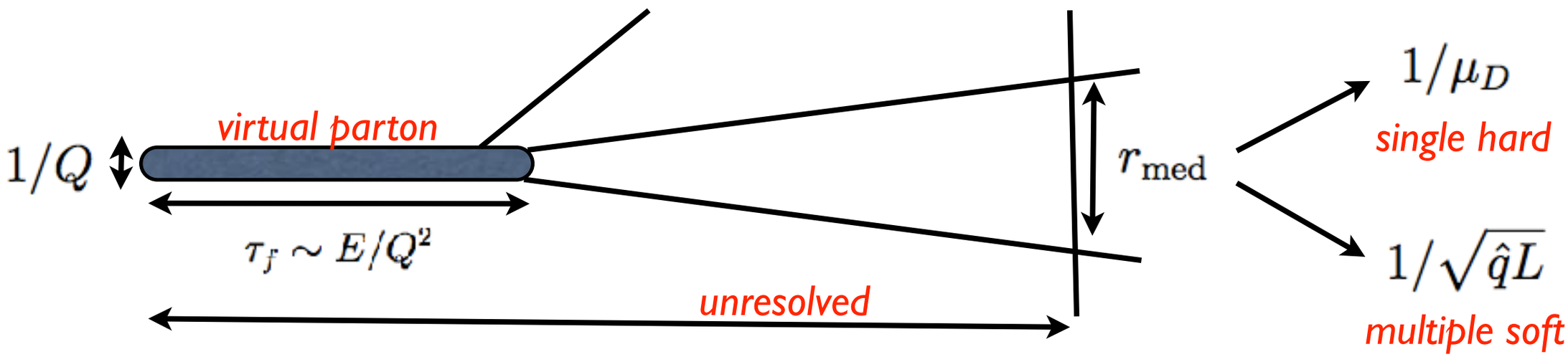

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  Infinite coupling limit (only accessible via gauge/gravity duality)

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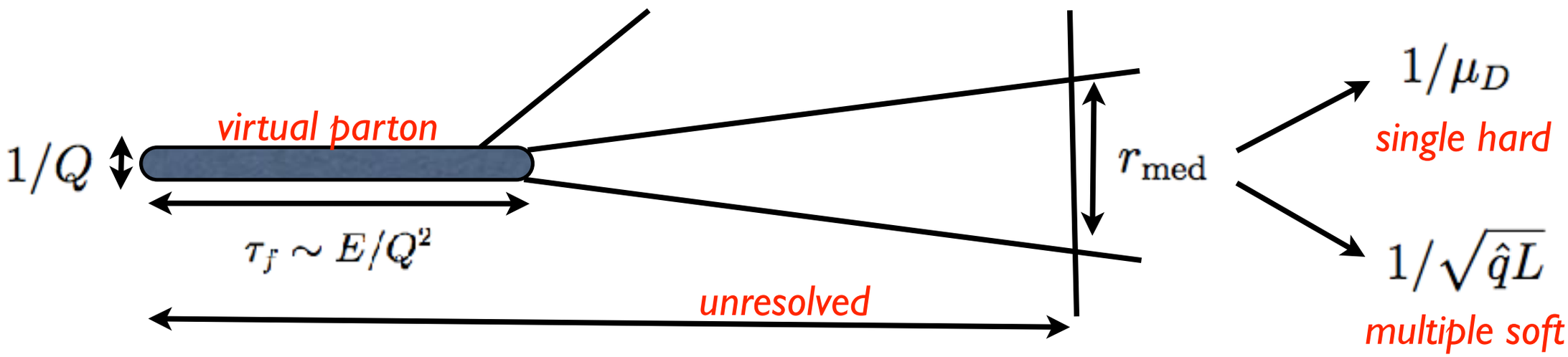

- Scales involved in quenching are not large
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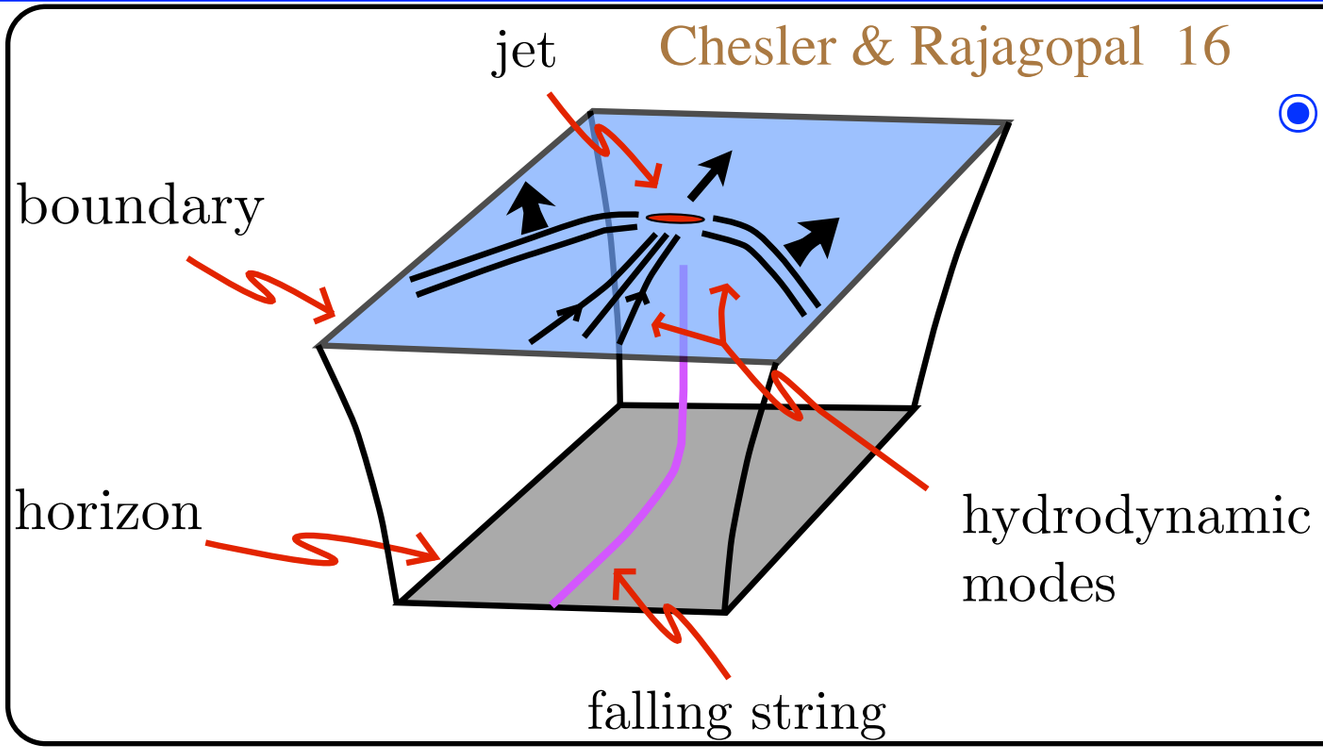
  Infinite coupling limit (only accessible via gauge/gravity duality)
  - Can we get and equally good description?
  - Can we find different characteristic features?

Energy Distribution to a Jet



- $T^{\mu\nu}$ associated to falling string
  - High energy core

    Jet
  - Hydro excitations

    Thermalised lost energy

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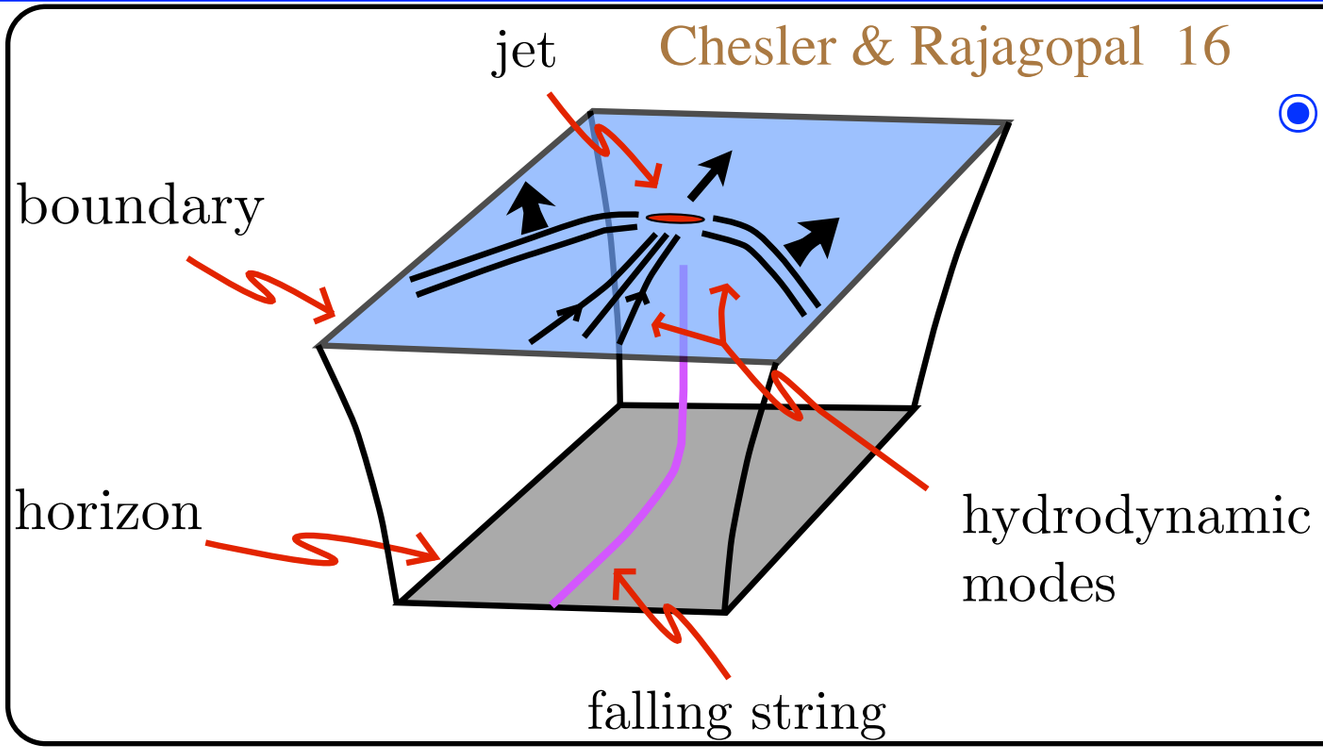

Chesler & Rajagopal 16

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- Dumping of energy into hydro modes at a rate

Gubser et al 08, Chesler et al. 08, Ficnar and Gubser 13

$$\frac{1}{E_{\rm init}}\frac{dE_{\rm jet}}{dx} = -\frac{4x^2}{\pi x_{\rm therm}^2\sqrt{x_{\rm therm}^2 - x^2}} \xrightarrow{\text{depend on jet energy}} x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}\,,$$

number

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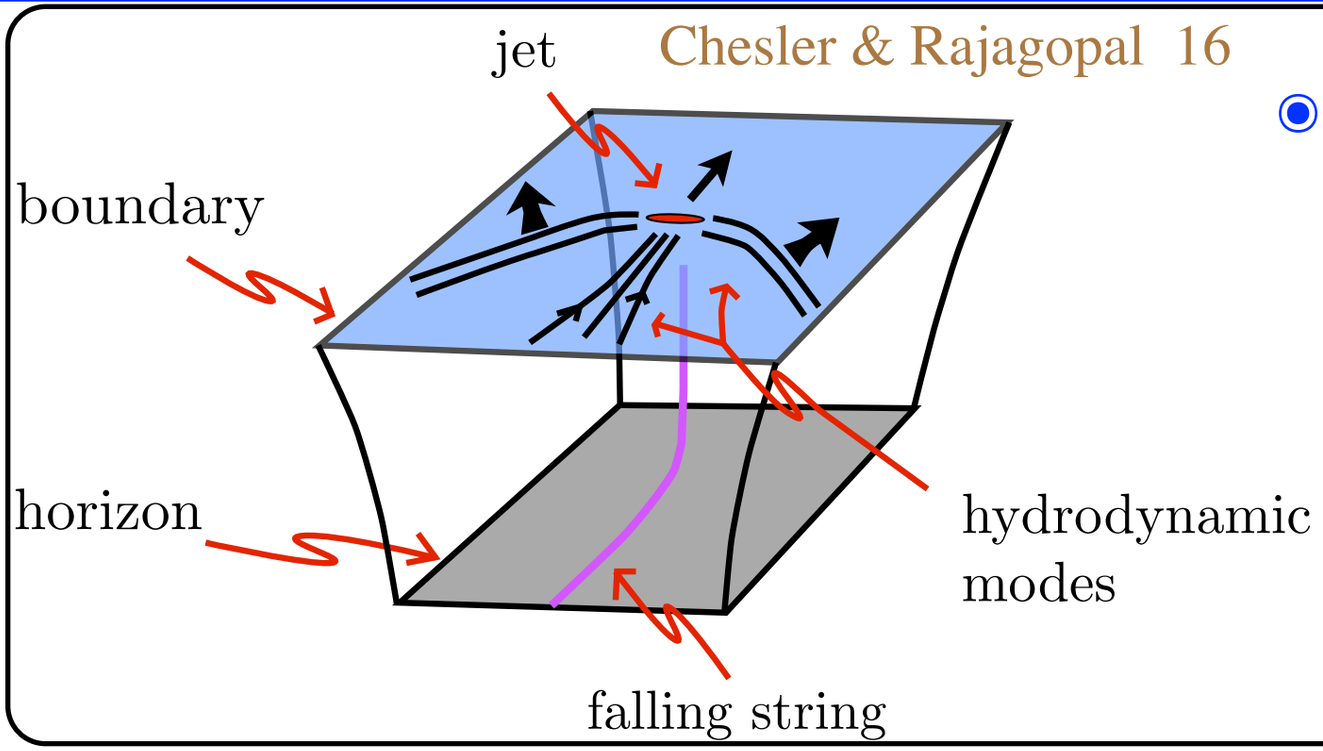

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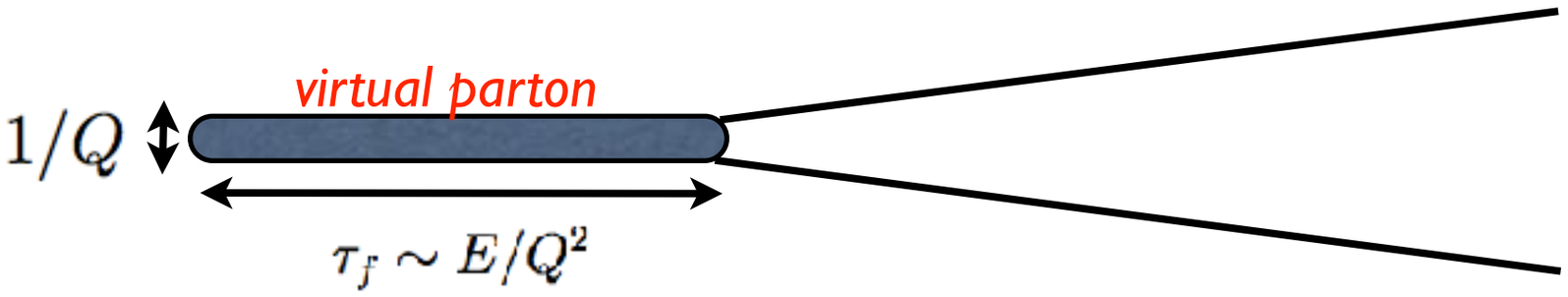
- Short distance physics remain strongly coupled

  ⇒ use as a pheno tool requires additional modelling

A Hybrid Model

JCS, Gulhan, Milhano, Pablos and Rajagopal 14,15,16



pQCD
+
Holography

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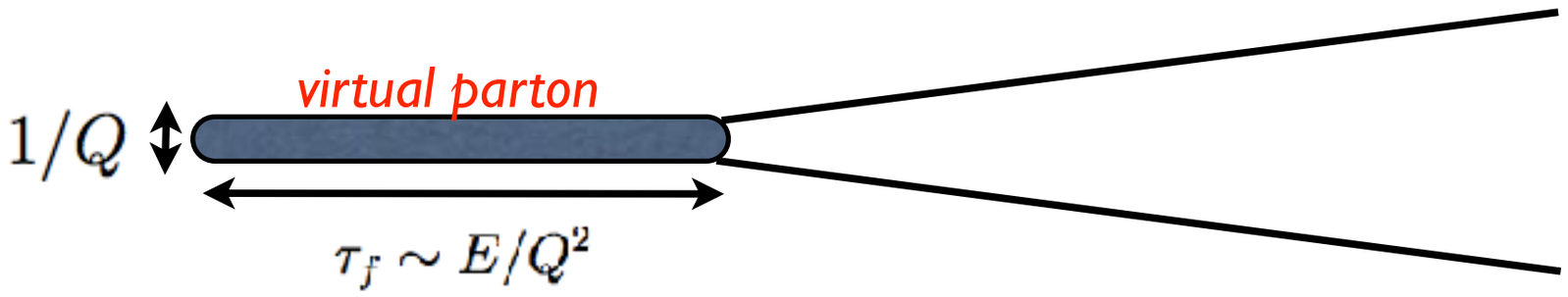

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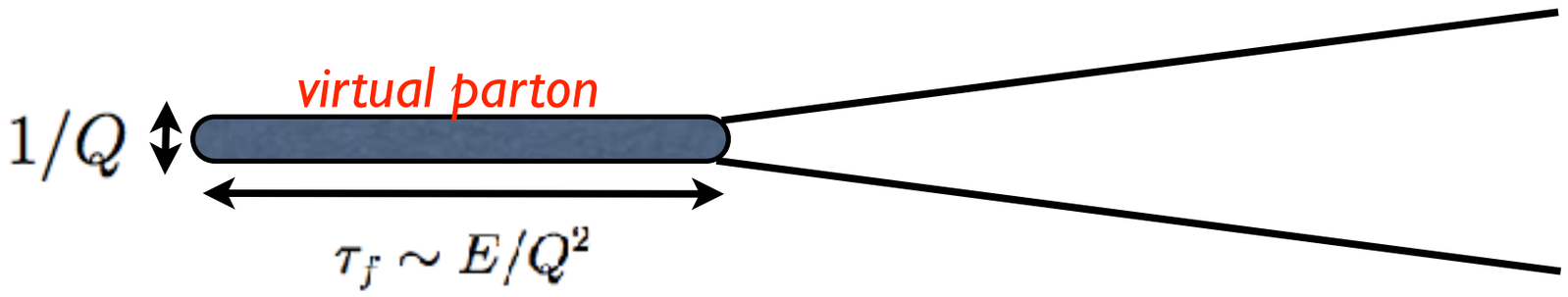

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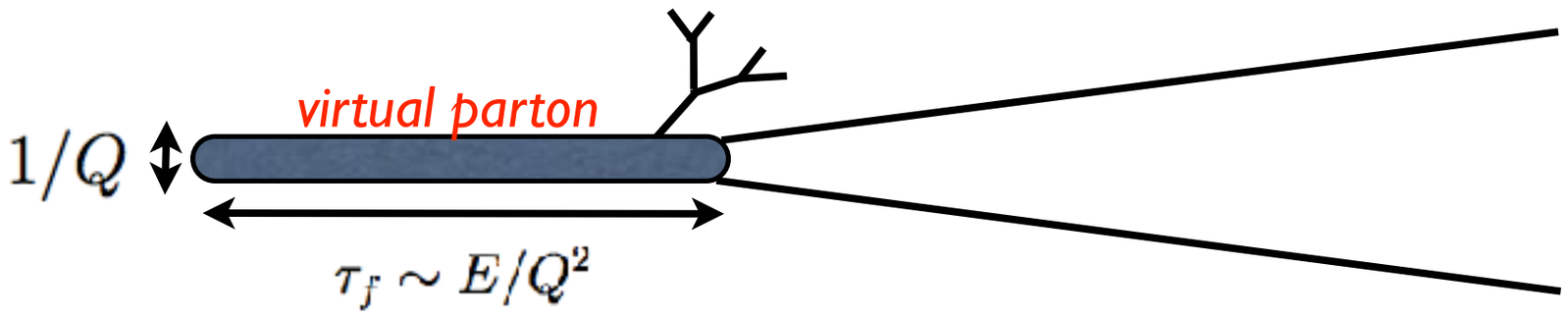

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Holography

- Keep the DGLAP structure inherited from QCD
- Neglect rare fluctuations (evolution unchanged)
- Treat small scale processes at strong coupling
  - Each parton is considered as an energetic excitation in plasma
  - Energy loss proceeds as in strong coupling

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

(unique) fitting parameter

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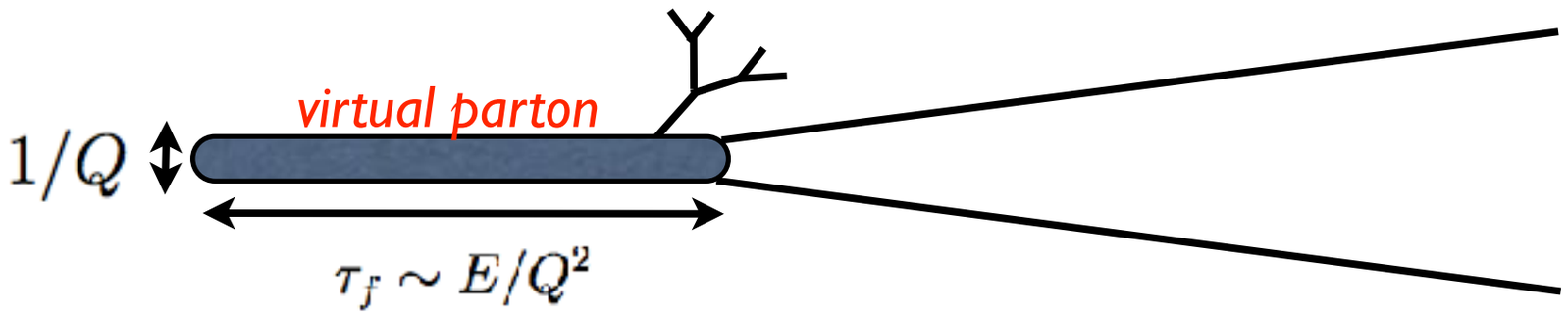

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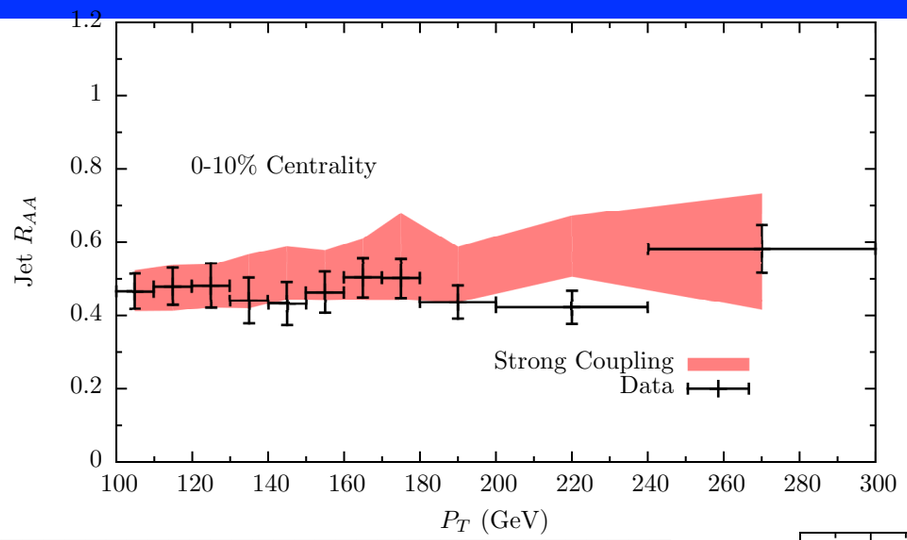
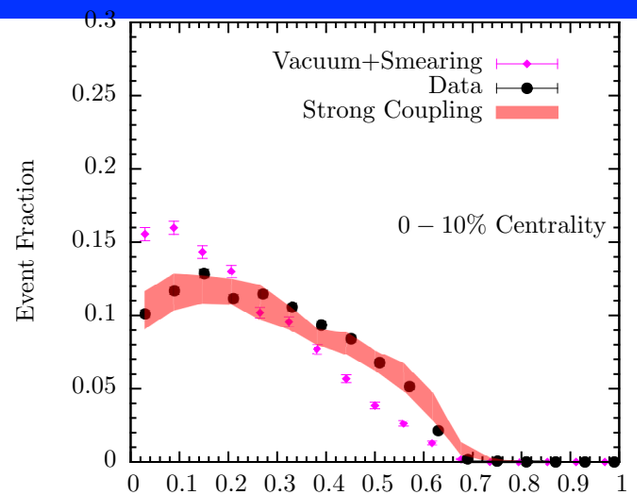
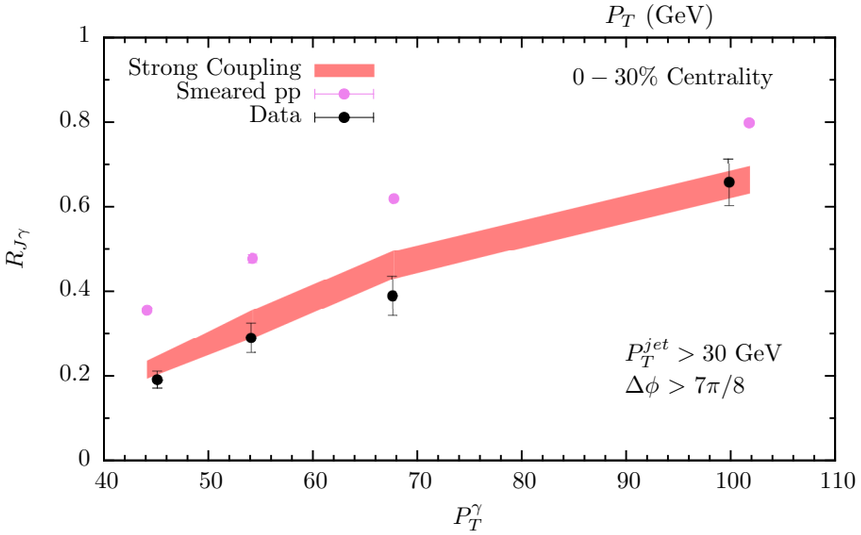
(unique) fitting parameter

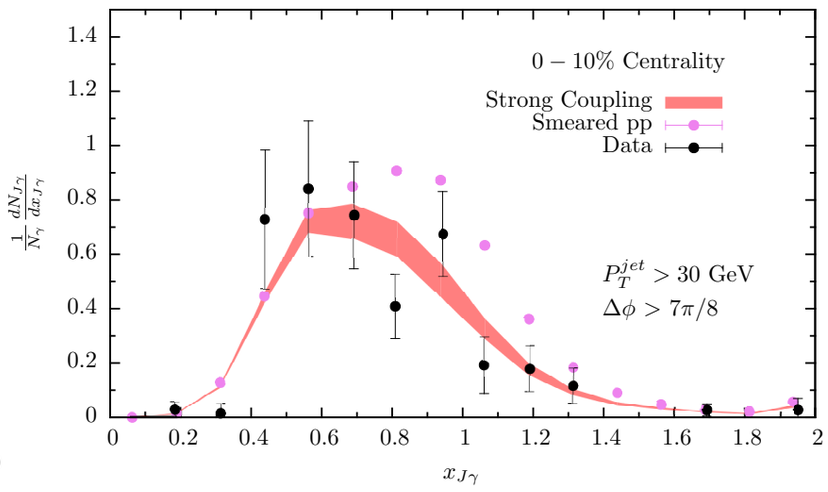
- Neglect coherence effects (for the moment)

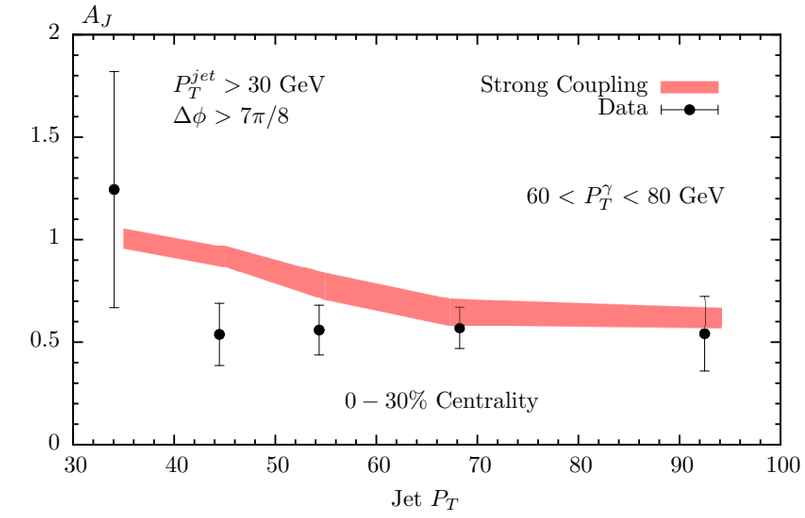
Success of the Hybrid Model

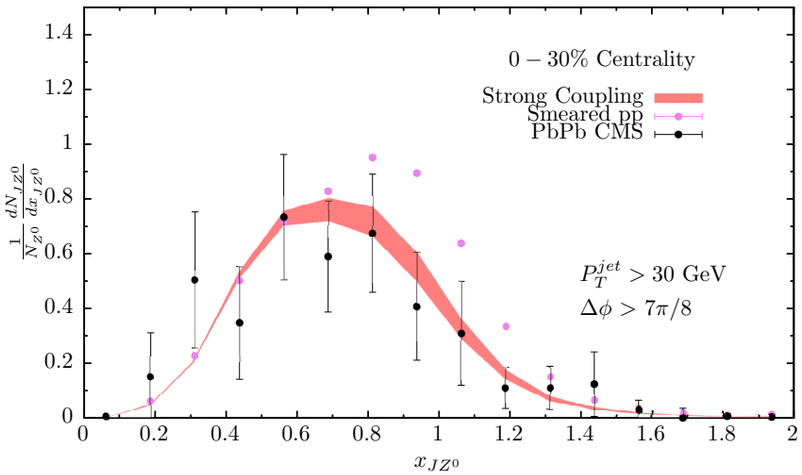


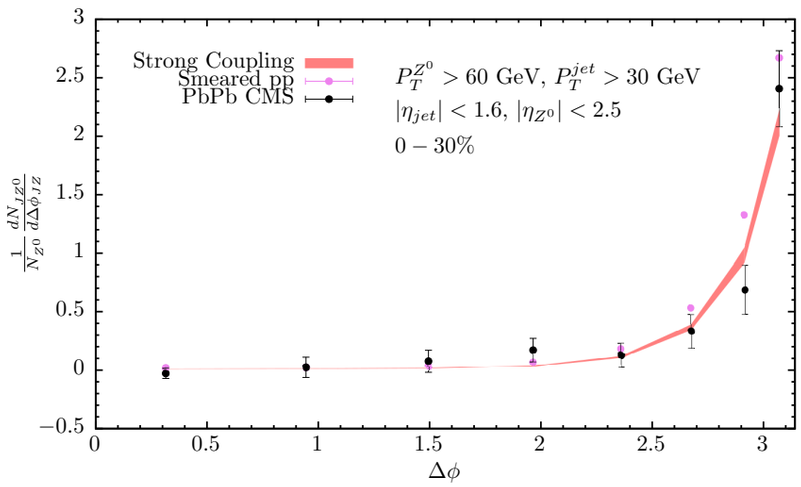












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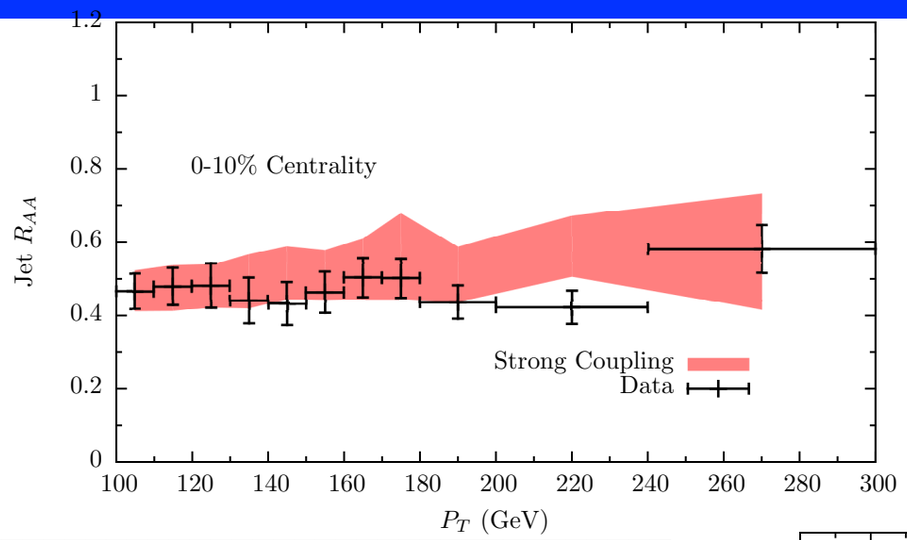
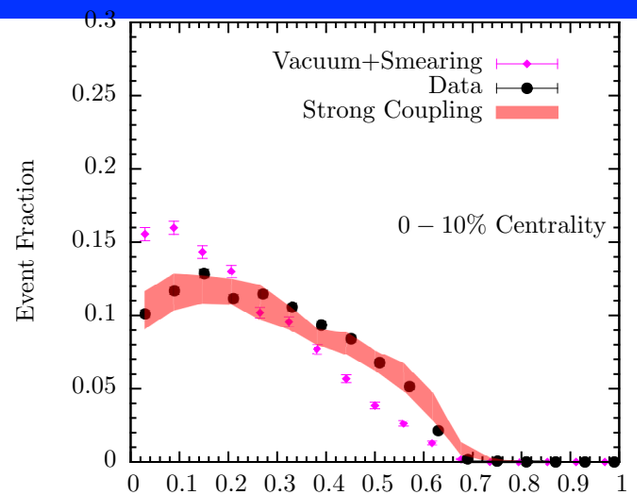
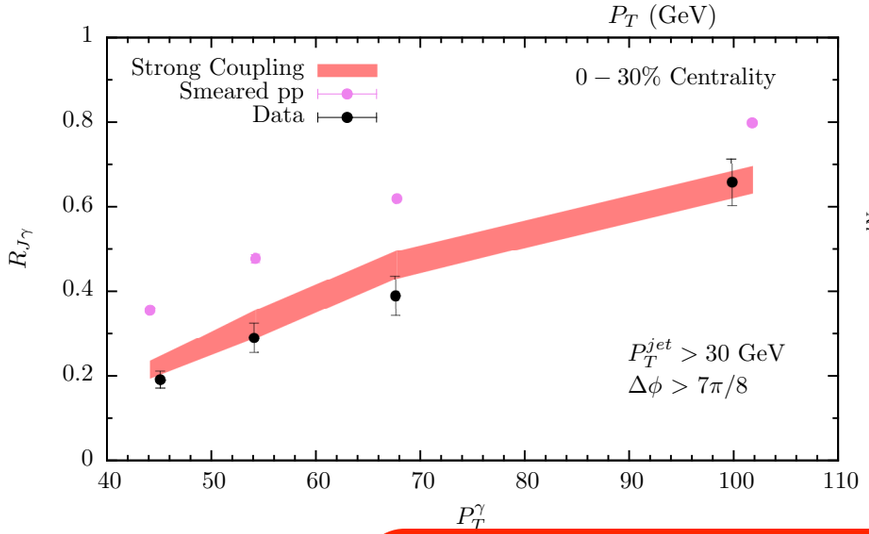
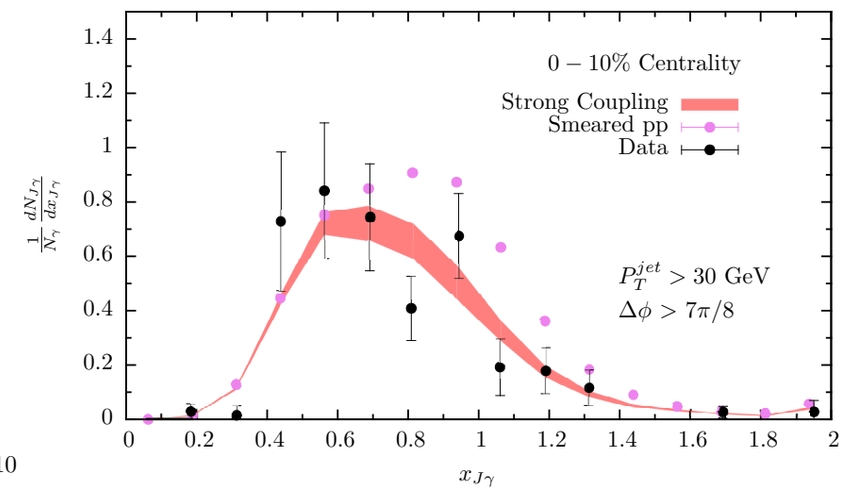
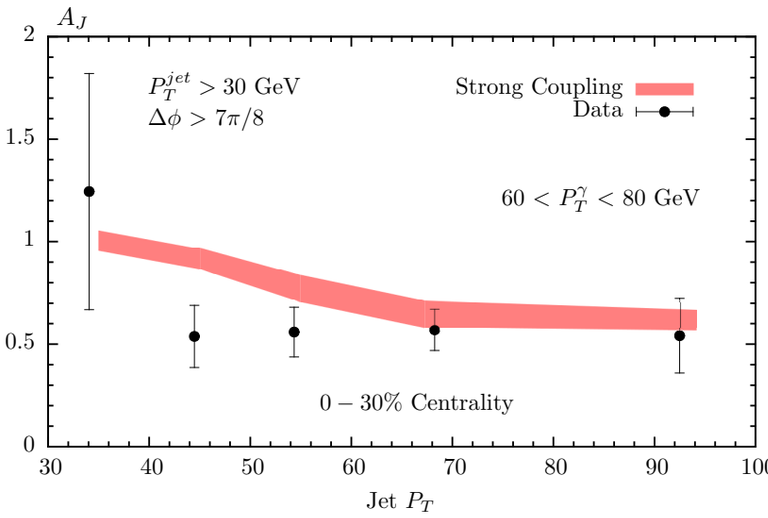
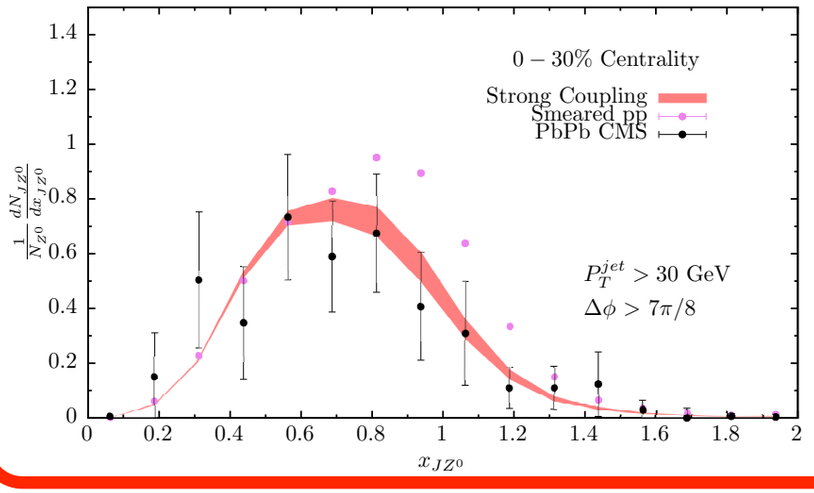


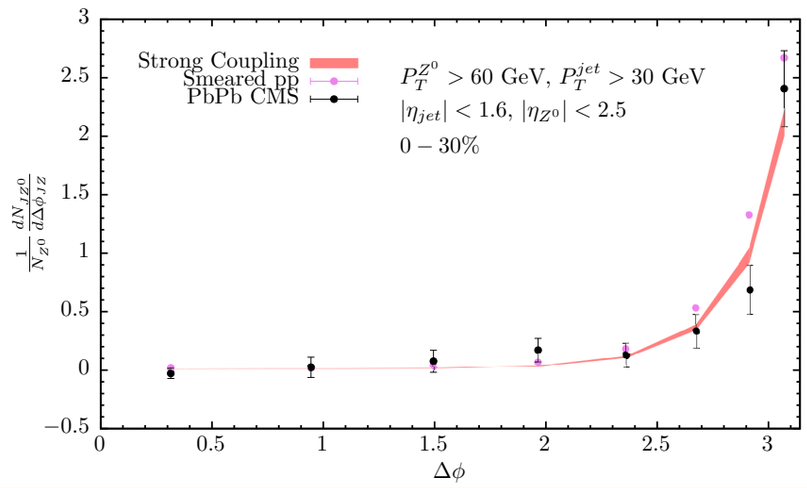




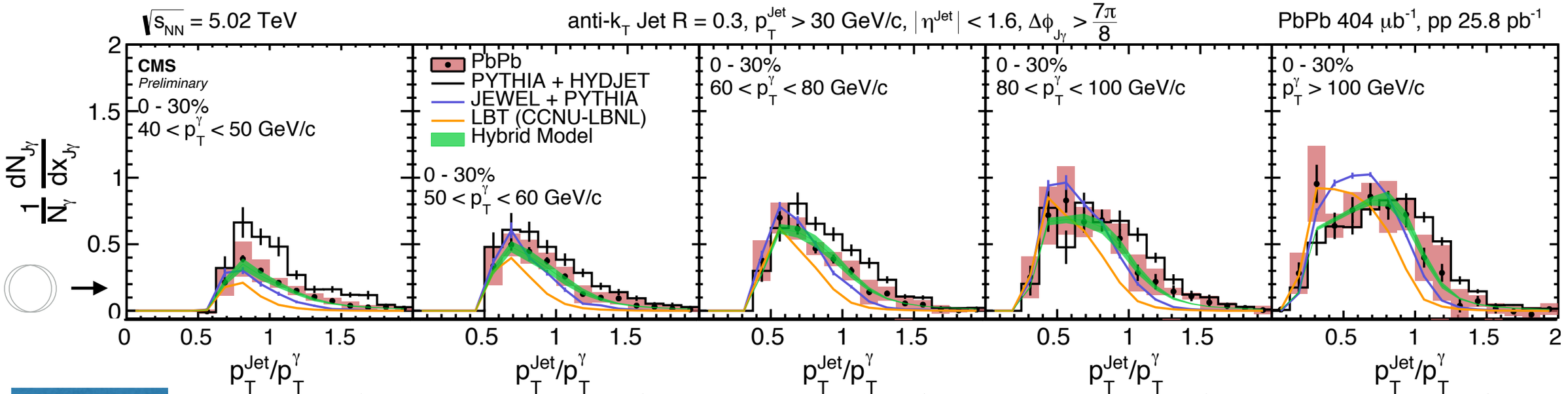






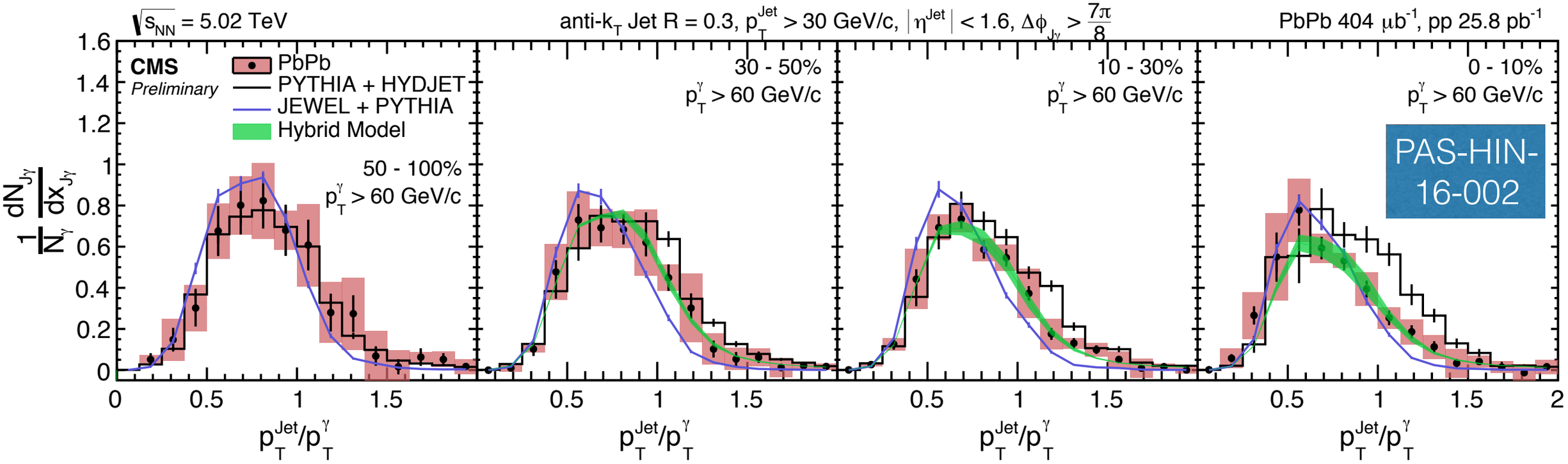


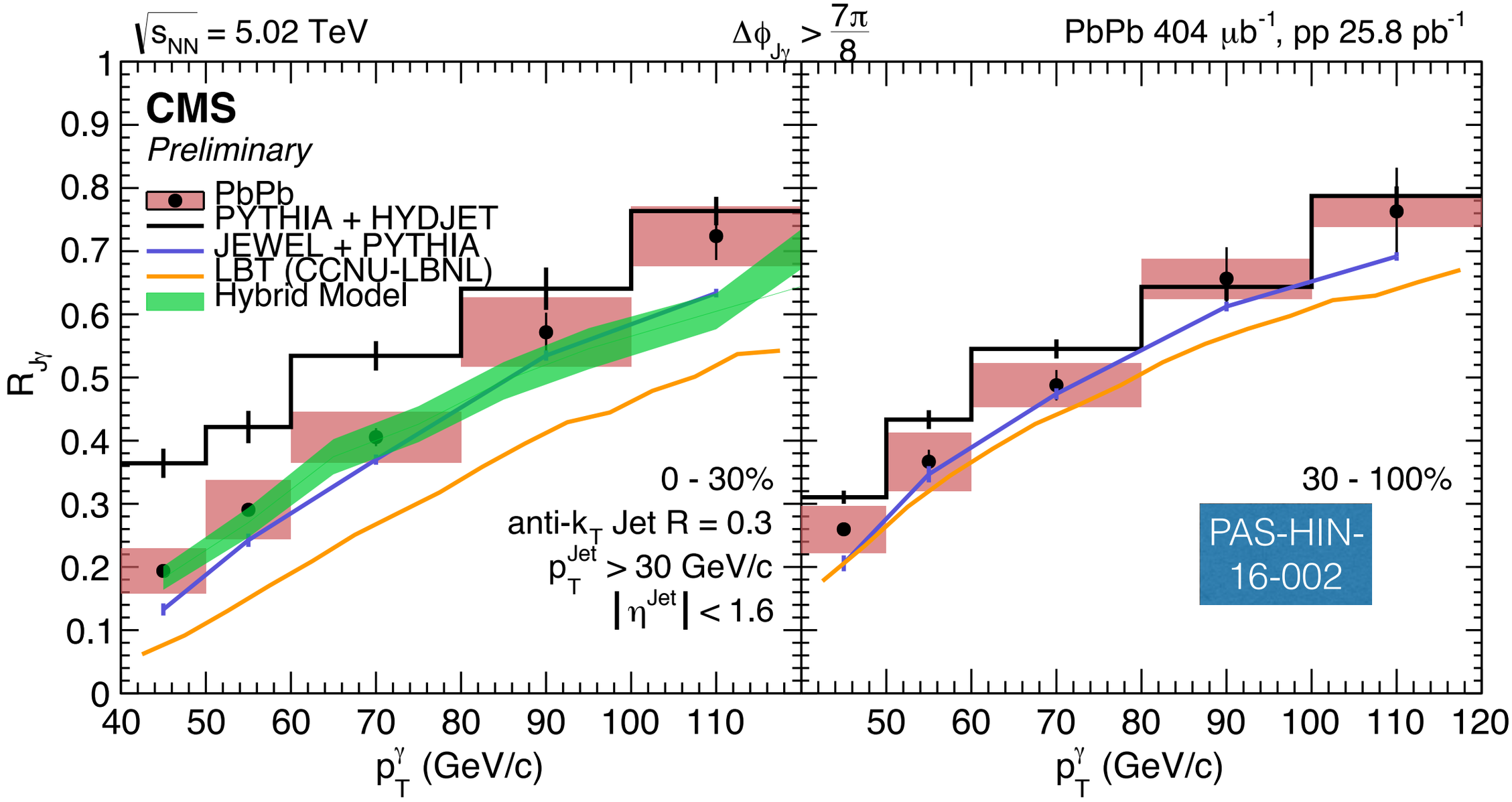
Predictions!



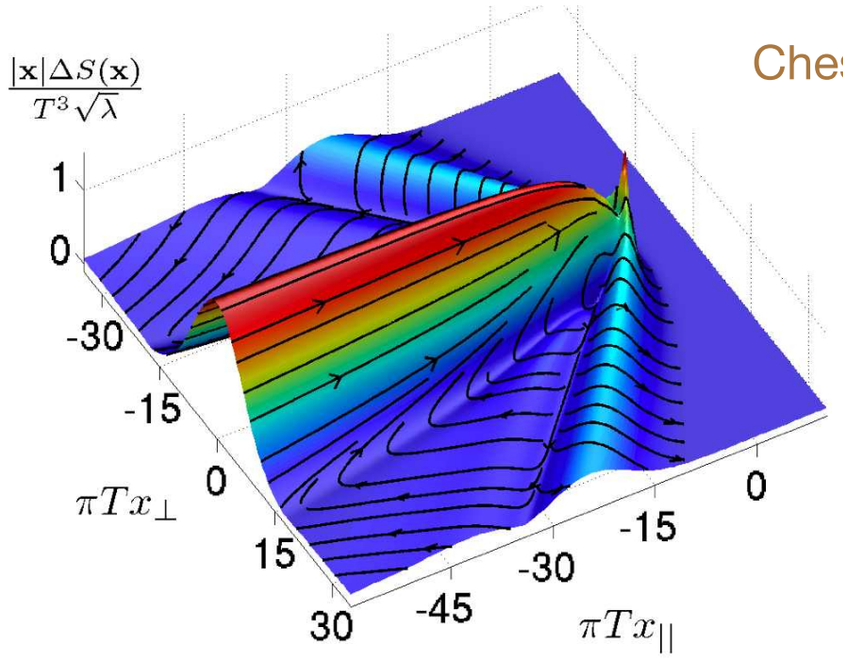
PAS-HIN-16-002

40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**




$\sqrt{s_{NN}}$ = 5.02 TeV
$\Delta\phi_{J\gamma} > \frac{7\pi}{8}$
PbPb 404 μb^{-1}, pp 25.8 pb^{-1}
CMS
Preliminary
PbPb
PYTHIA + HYDJET
JEWEL + PYTHIA
LBT (CCNU-LBNL)
Hybrid Model
$R_{J\gamma}$
0 - 30%
anti-k_T Jet R = 0.3
$p_T^{Jet} > 30$ GeV/c
$|\eta^{Jet}| < 1.6$
30 - 100%
PAS-HIN-16-002
p_T^{γ} (GeV/c)
p_T^{γ} (GeV/c)

Back-Reaction and Wake



Chesler &Yaffe 06

- The QGP is an extremely good fluid

JCS, Shuryak & Teaney 06

  - ➤ Medium response to Eloss must be collective
  - ➤ Strong coupling computations provide an explicit example
    - ➤ Collectivity starts at short distance 1/T from the jet
    - ➤ There is a strong momentum flux along the jet direction

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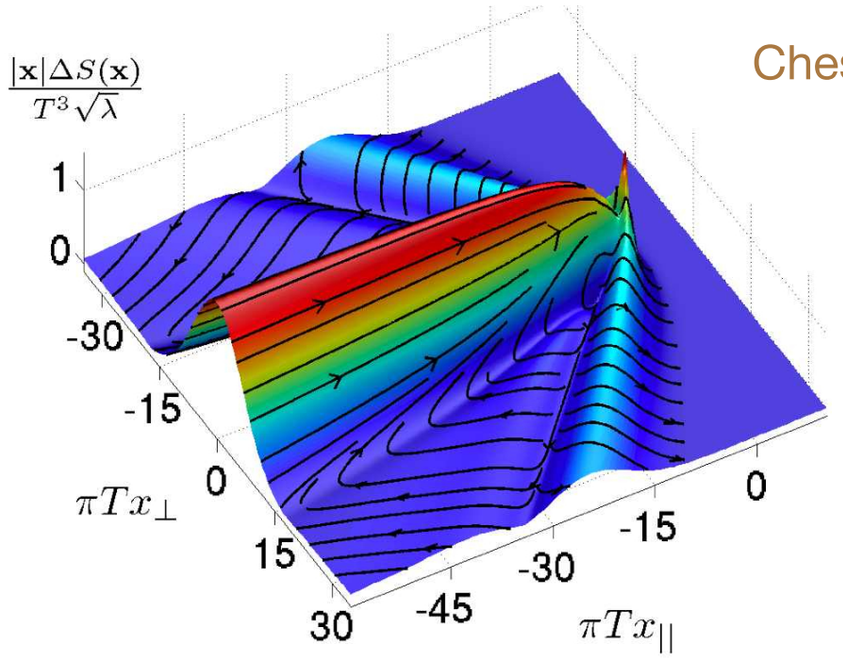

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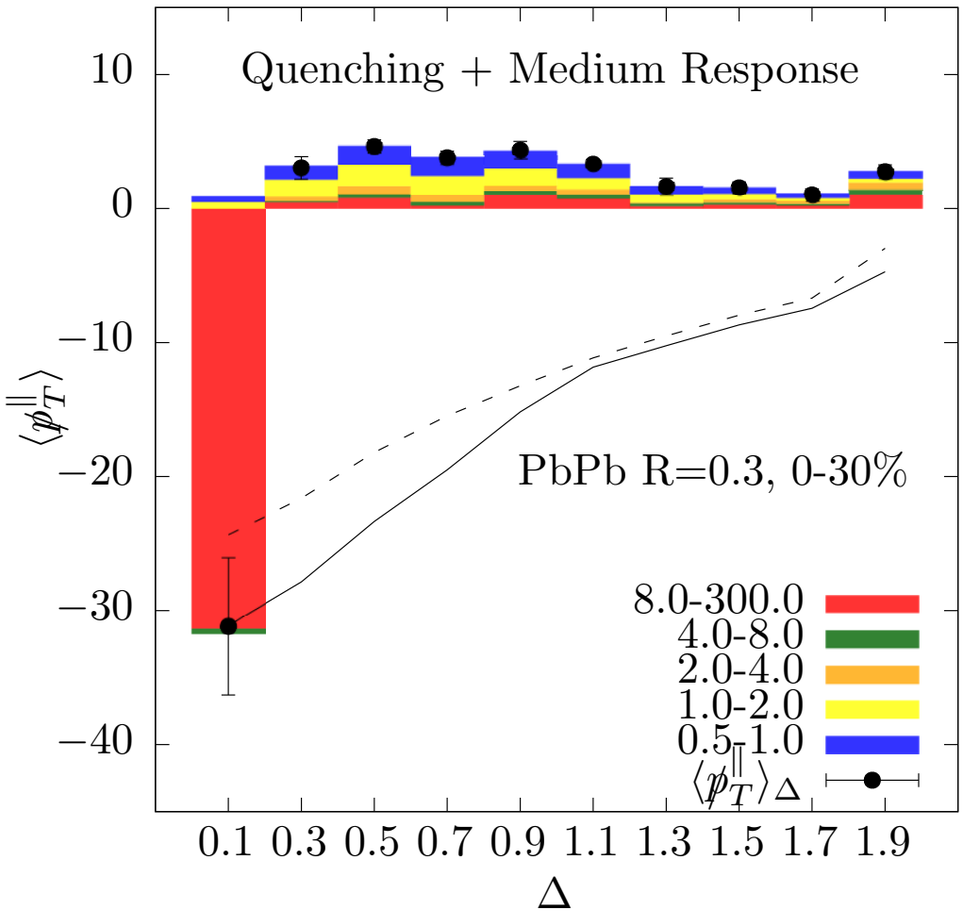
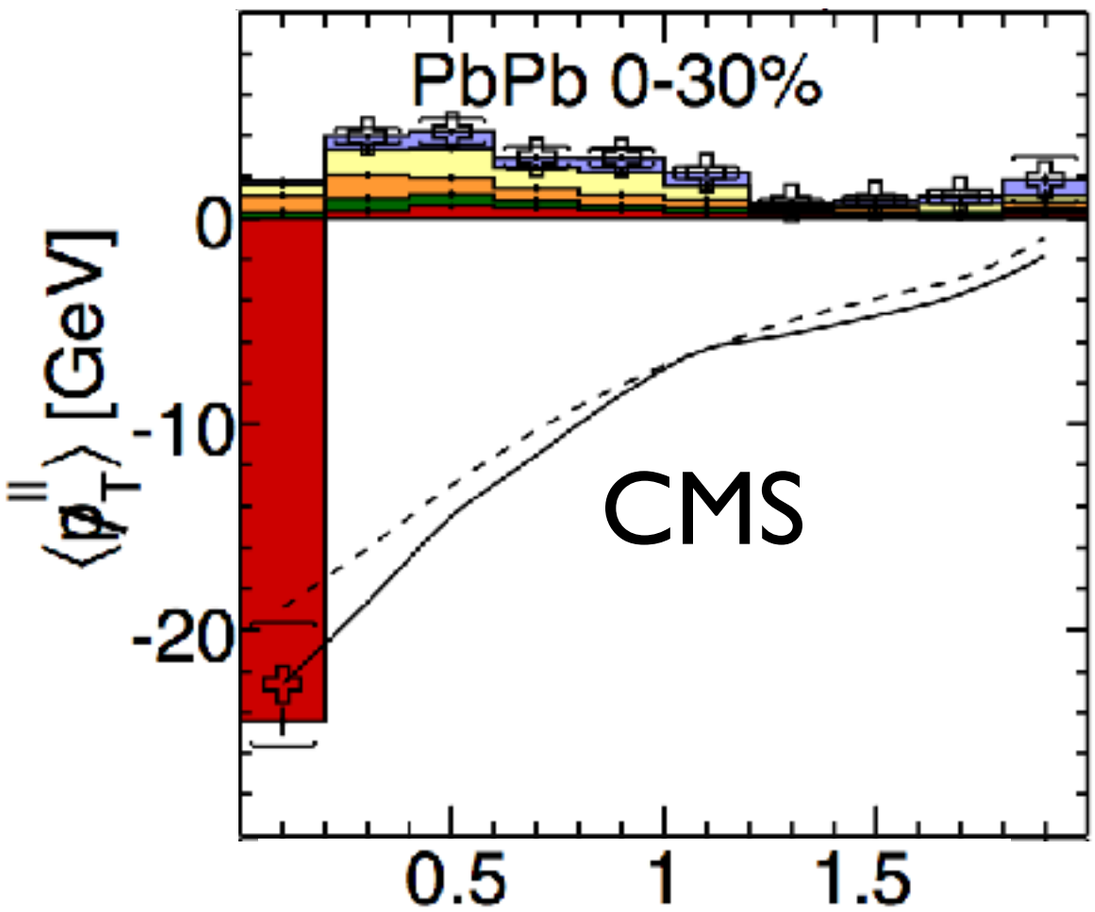
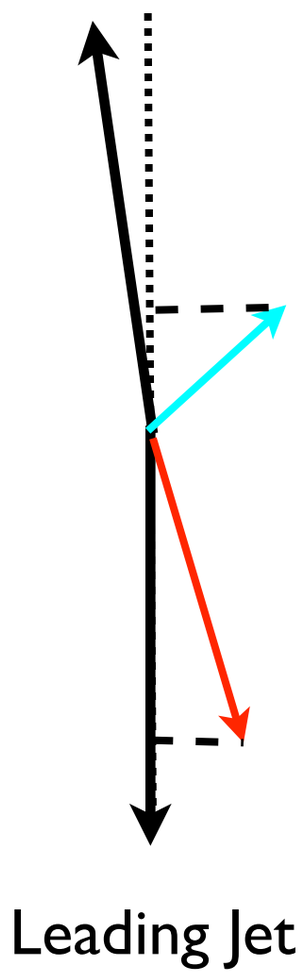
    - ➤ Collectivity starts at short distance 1/T from the jet
    - ➤ There is a strong momentum flux along the jet direction
- We only model the generic contribution to (soft) particles from E&M conservation
    - ➤ Underestimates production at pT>>T (model dependent)

Recovering Jet Energy

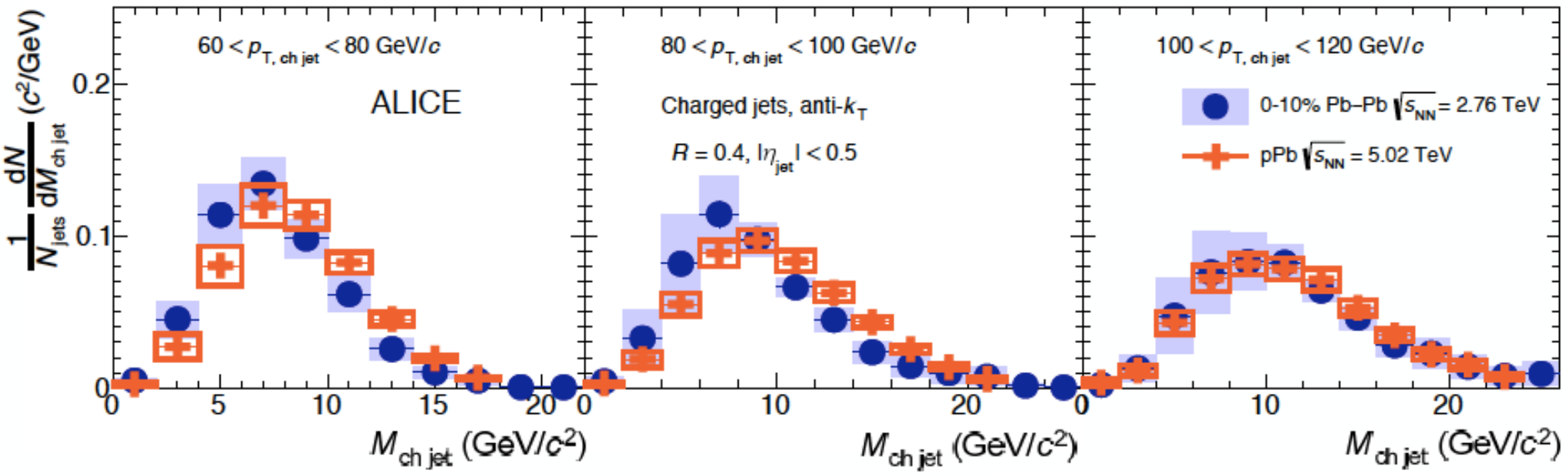






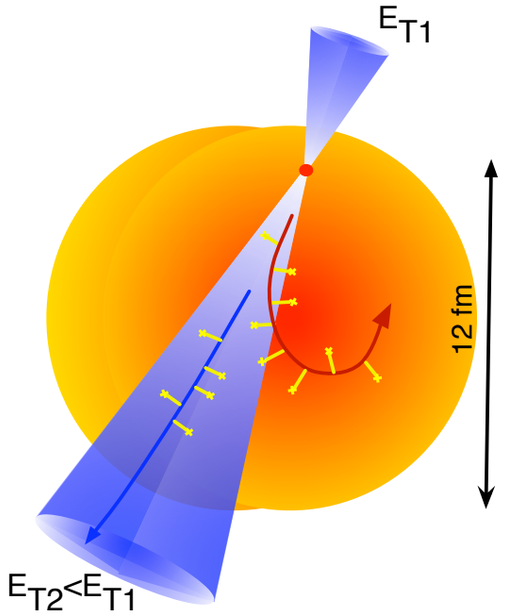
- Medium response completely fixed by Eloss
  - ➤ No additional parameters

Jet Masses



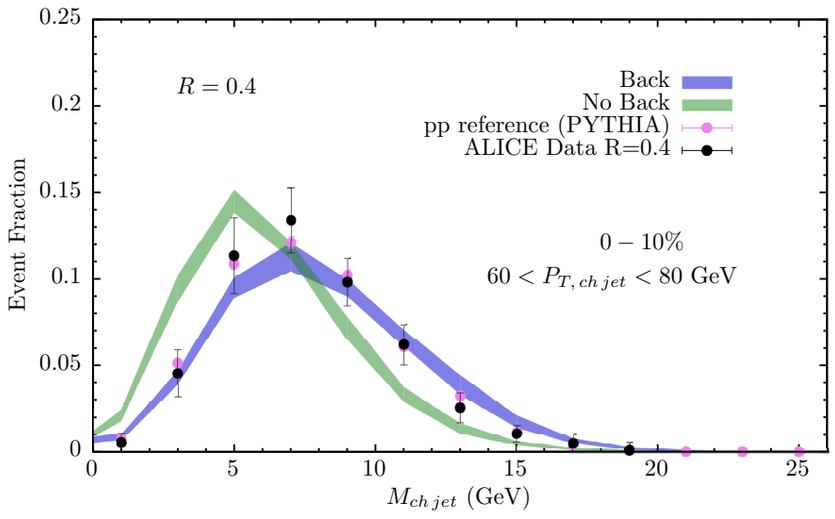
- Little sensitivity to strong quenching!
  - ➤ Puzzling result
  - ➤ Removing soft fragments ⇒

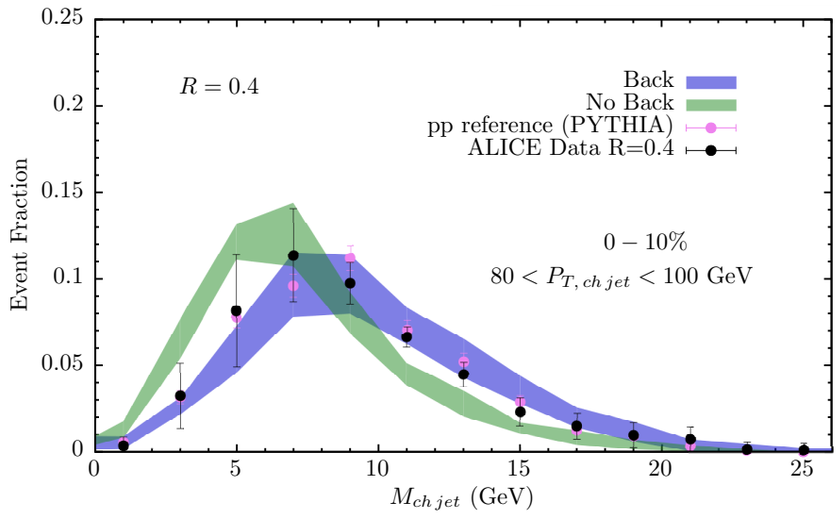
    Jet mass narrowing

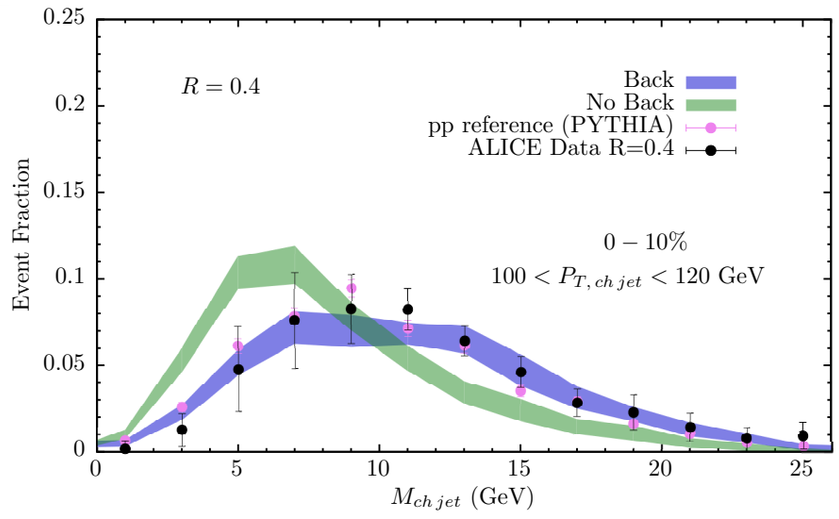


Jet Masses

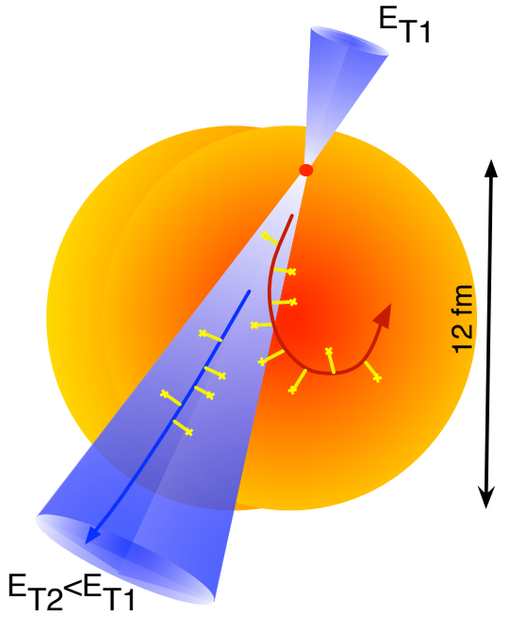
JCS, Pablos, Hulcher, Milano, Rajagopal (in preparation)





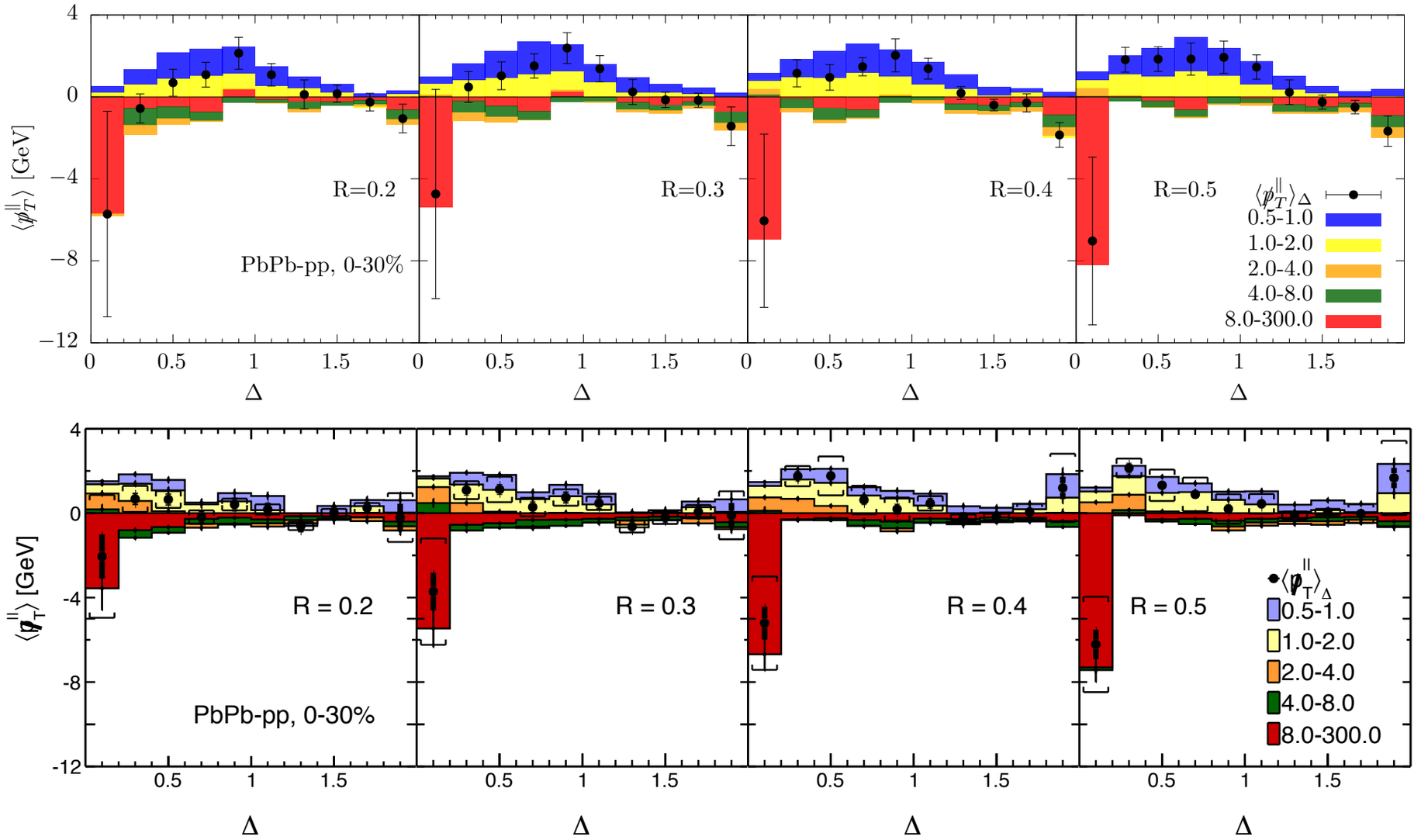


- Little sensitivity to strong quenching!
  - ➤ Puzzling result
  - ➤ Removing soft fragments ⇒ Jet mass narrowing



- Medium response regenerates the missing mass

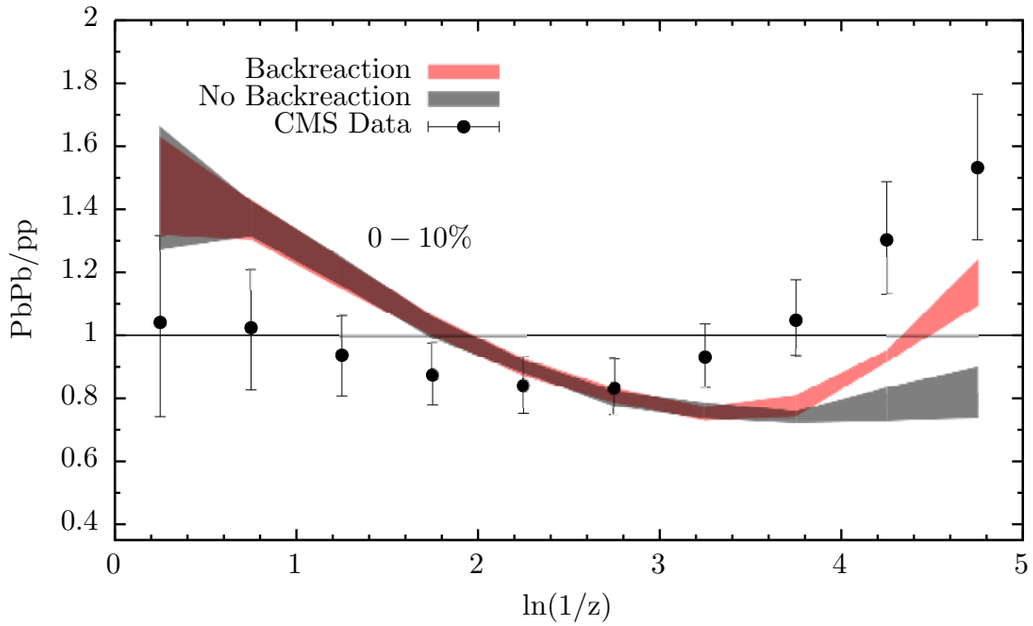
Soft Back-reaction



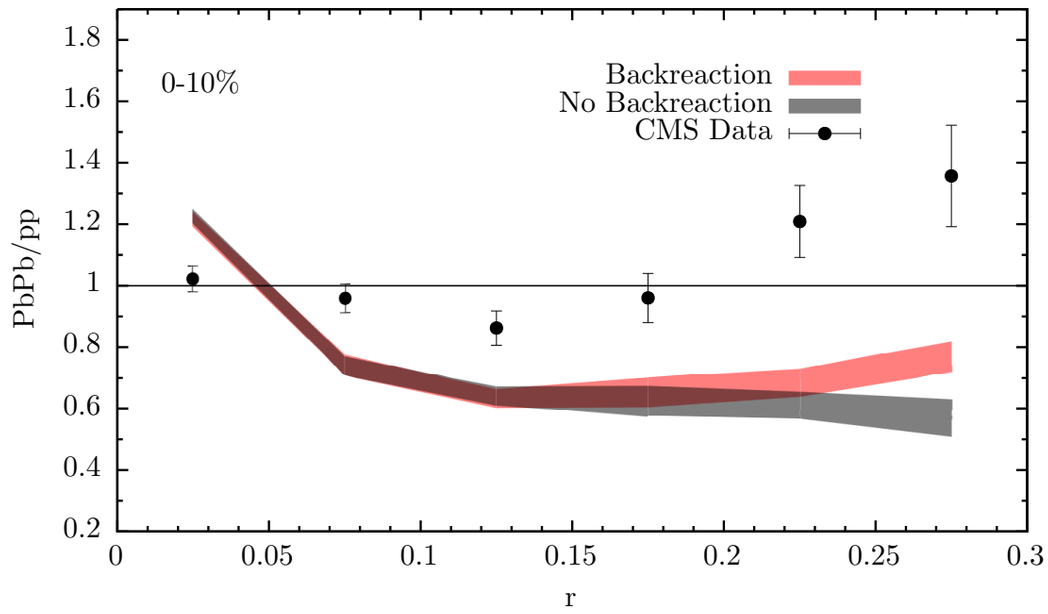
- Energy is recovered in soft (~ T) particles
  - ➤ Expected deficiency of the treatment
  - ➤ But also in the region where incomplete thermalisation should appear (e.g. radiative processes)

Not Everything Works

Ratio of FF



Ratio of jet shapes



- What is the origin of the discrepancy?
  - Shape modification may be sensitive to perturbative emissions
  - Treatment of back-reaction may be too crude
    - Other model implementations show sensitivity to recoil/back-reaction in these and other observables

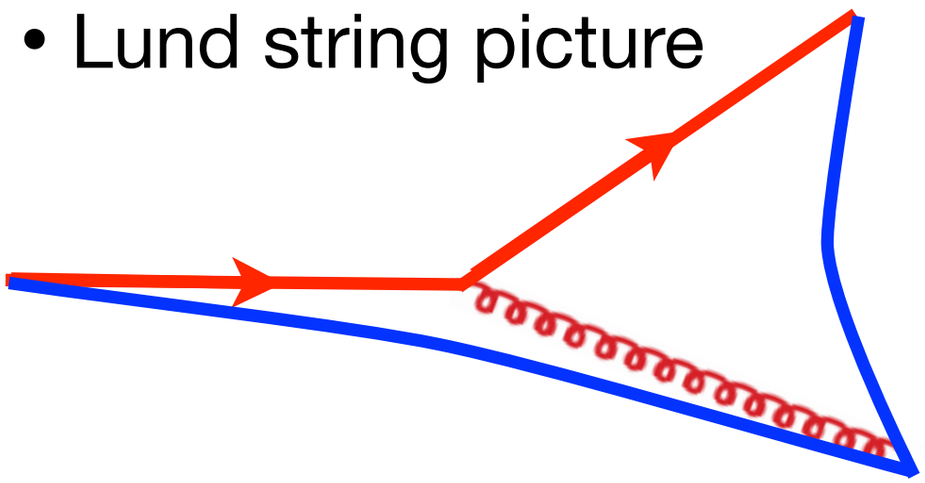
Tachibana, Chang and Quin, 17, Kunnawalkam, Elayavalli and Zapp 17, Milhano, Wiedemann and Zapp 17

  - Additional physics processes may be required

Coherence at Strong Coupling

- Preparing “multi partonic” excitations in holography

  - Lund string picture

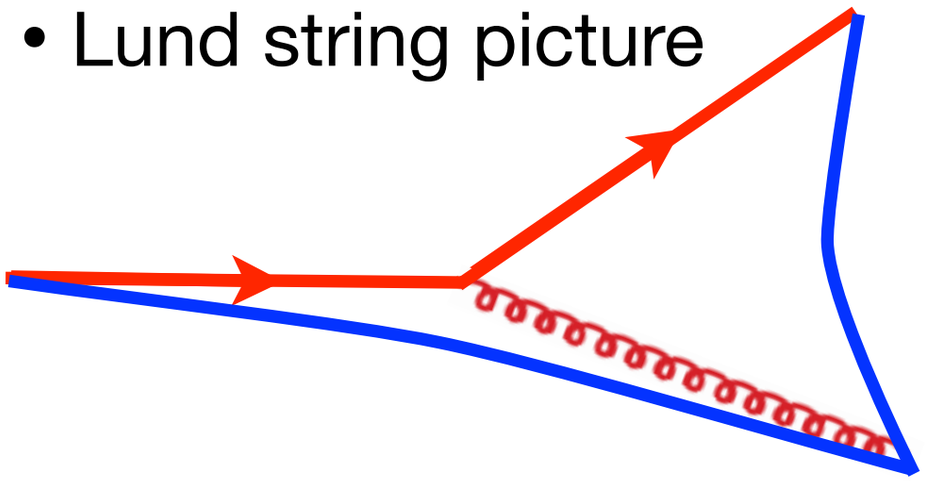


gluons ⇒ string with kinks

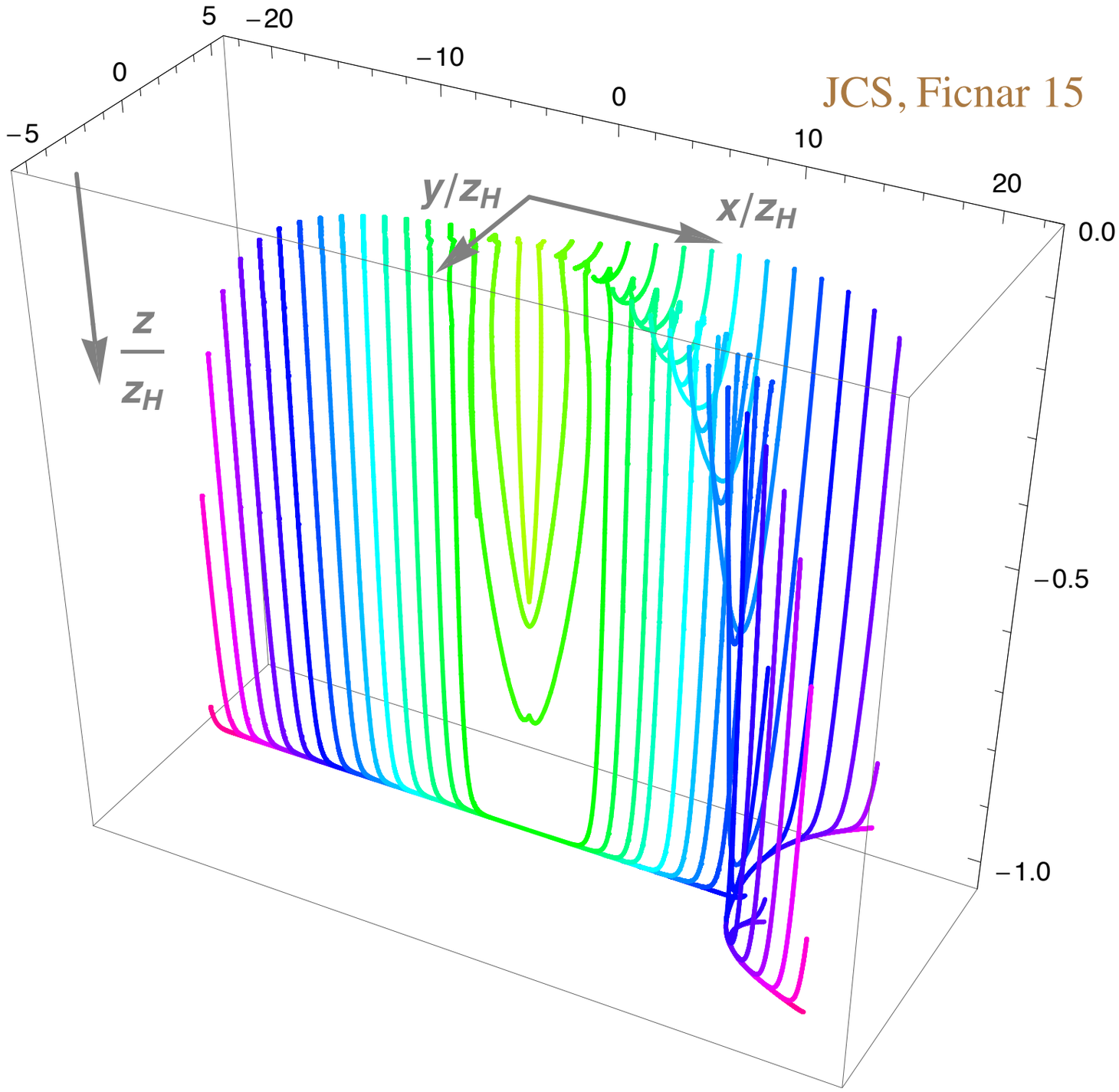
Coherence at Strong Coupling

- Preparing “multi partonic” excitations in holography

  - Lund string picture



gluons ⇒ string with kinks

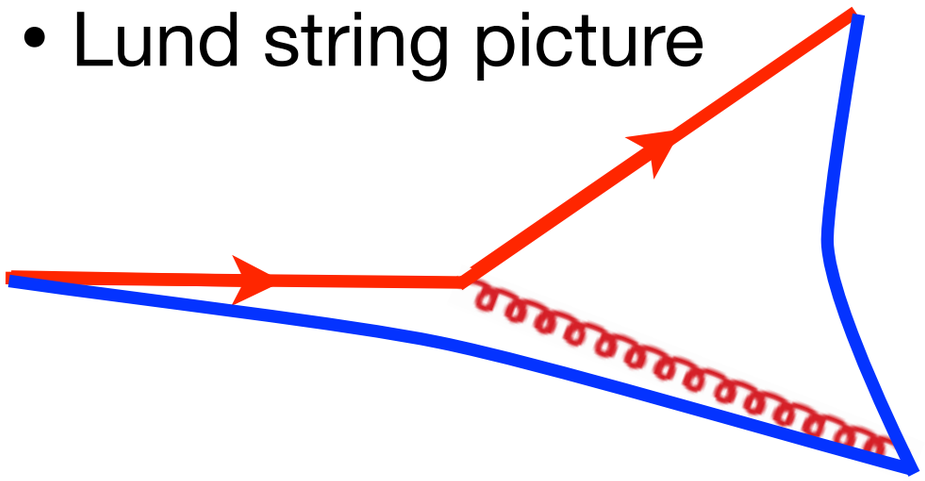


JCS, Ficnar 15

Coherence at Strong Coupling

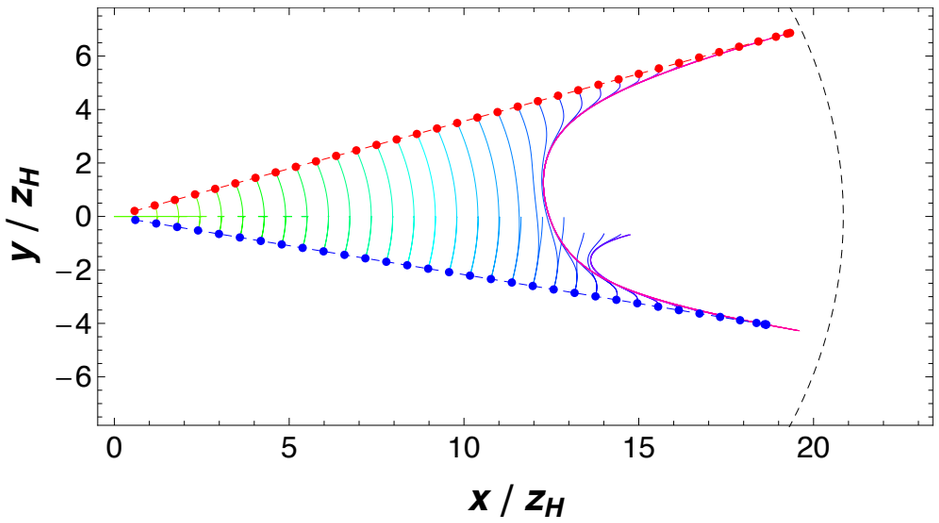
- Preparing “multi partonic” excitations in holography

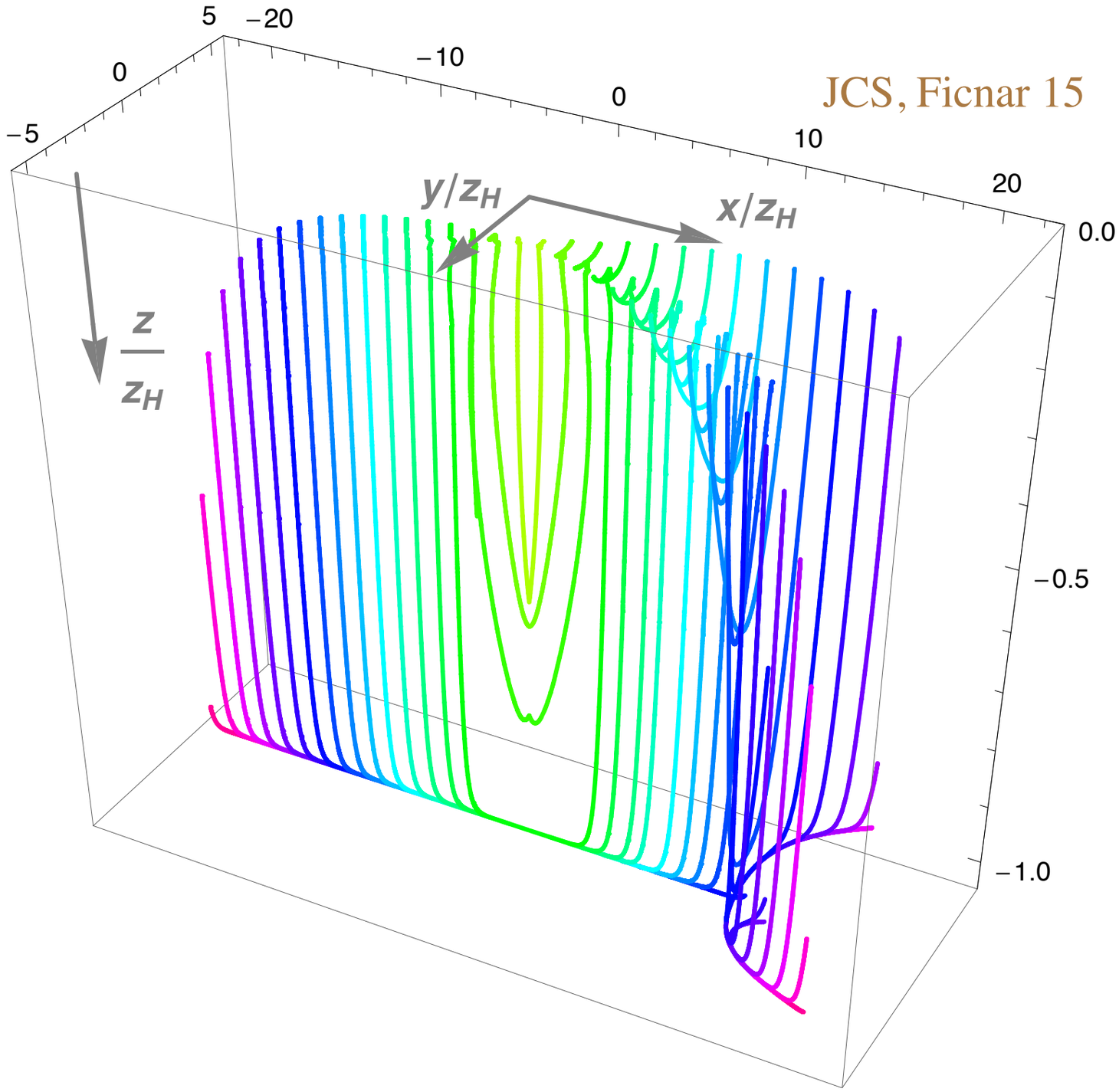
  - Lund string picture



gluons ⇒ string with kinks

resolved jets





JCS, Ficnar 15

Coherence at Strong Coupling

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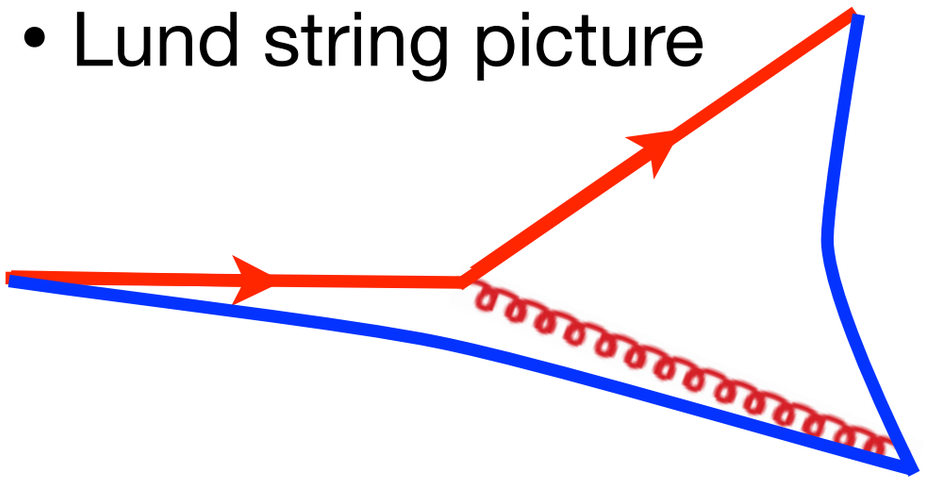
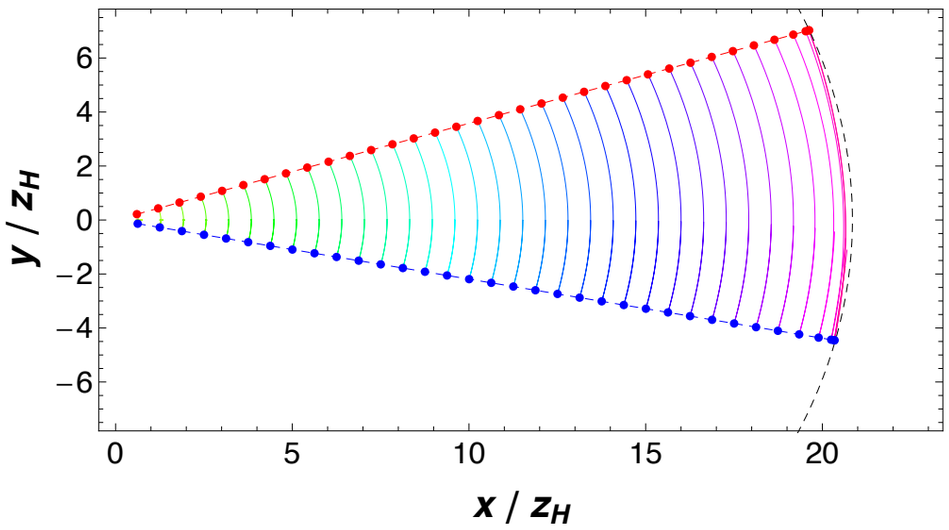
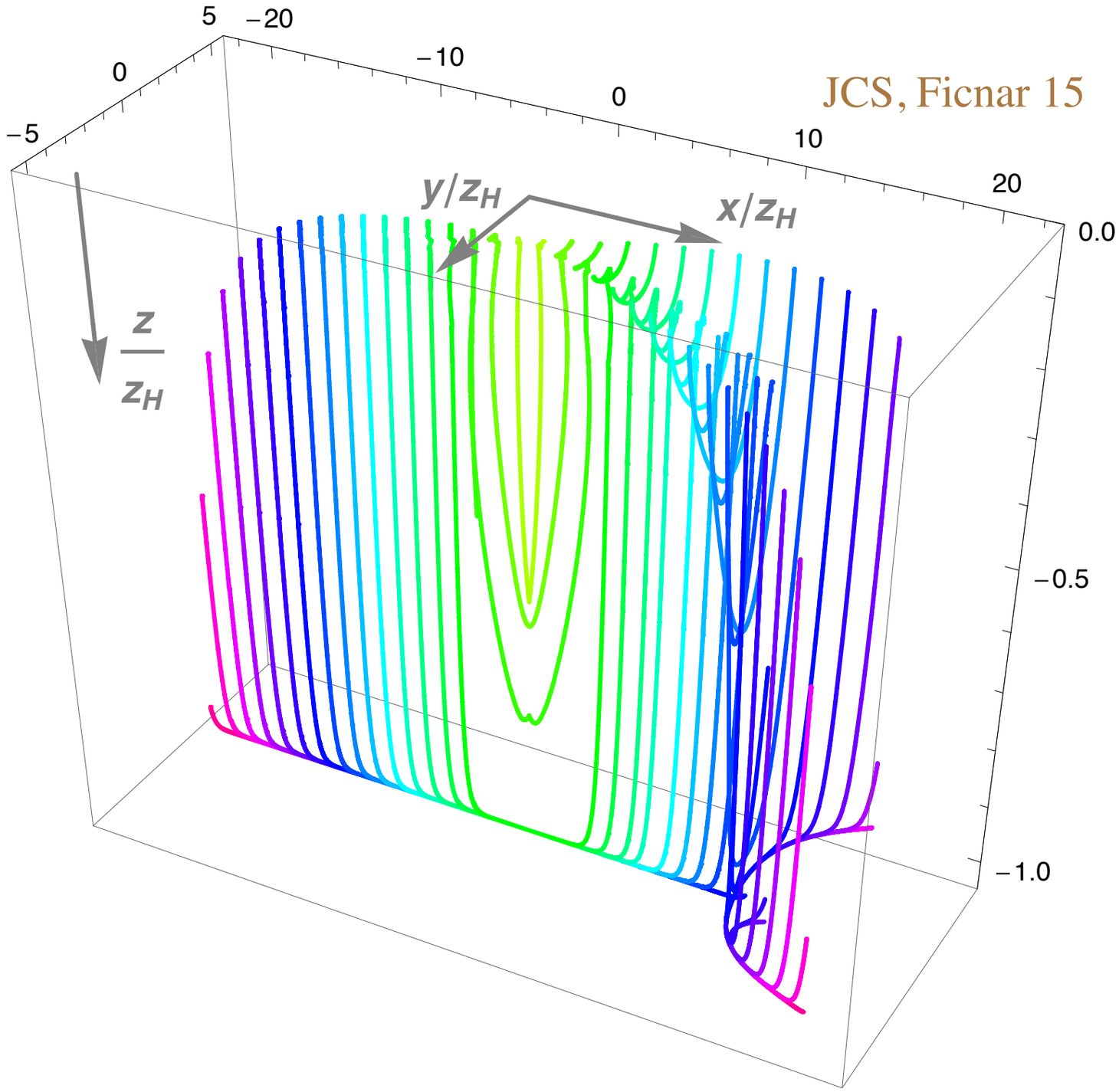


gluons ⇒ string with kinks

un-resolved jets

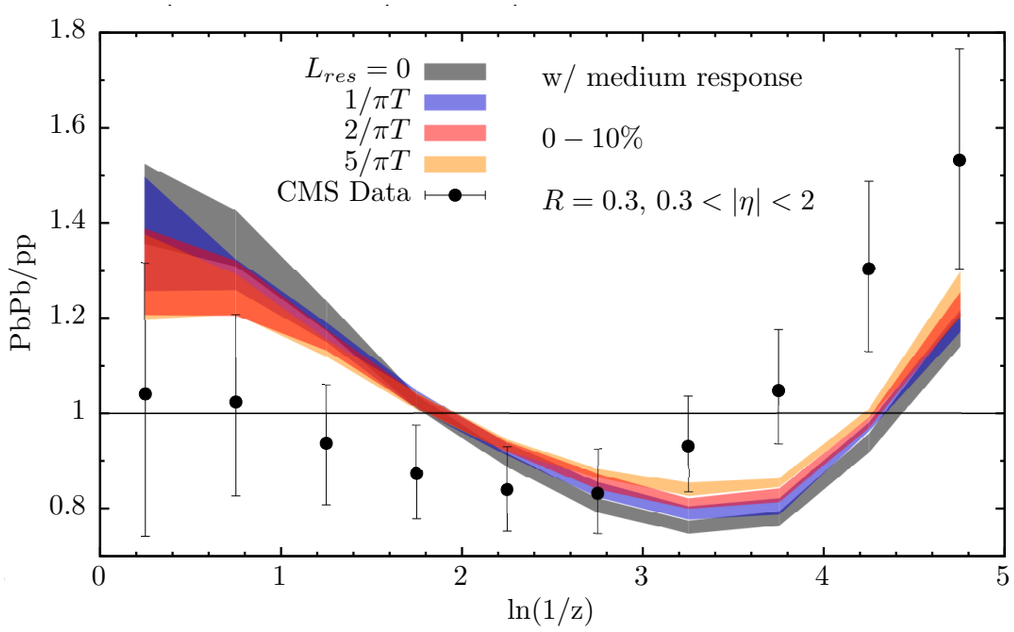


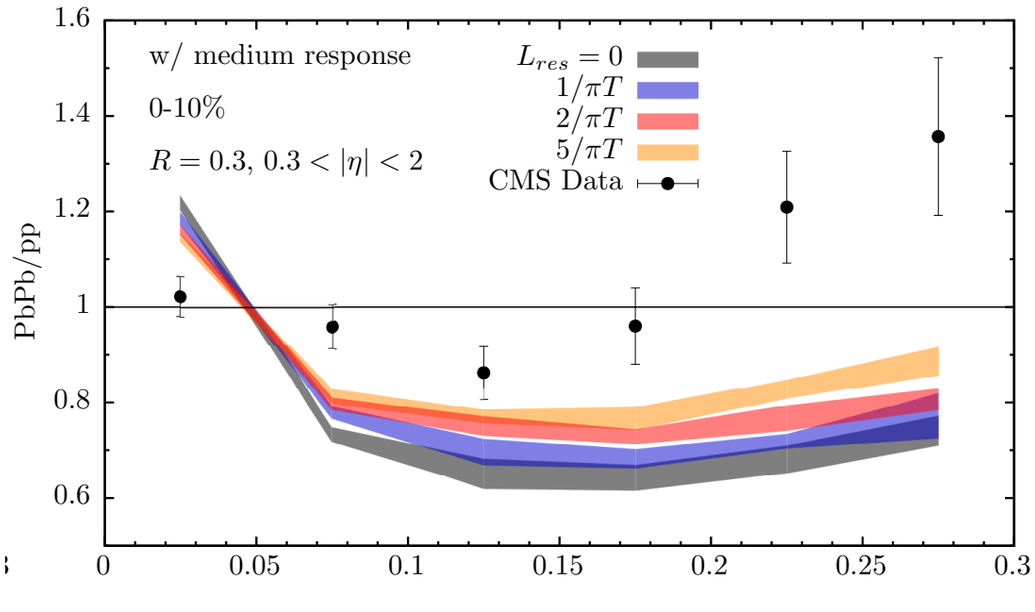


JCS, Ficnar 15

Resolution effects

Pablos, Hulcher, Rajagopal 17

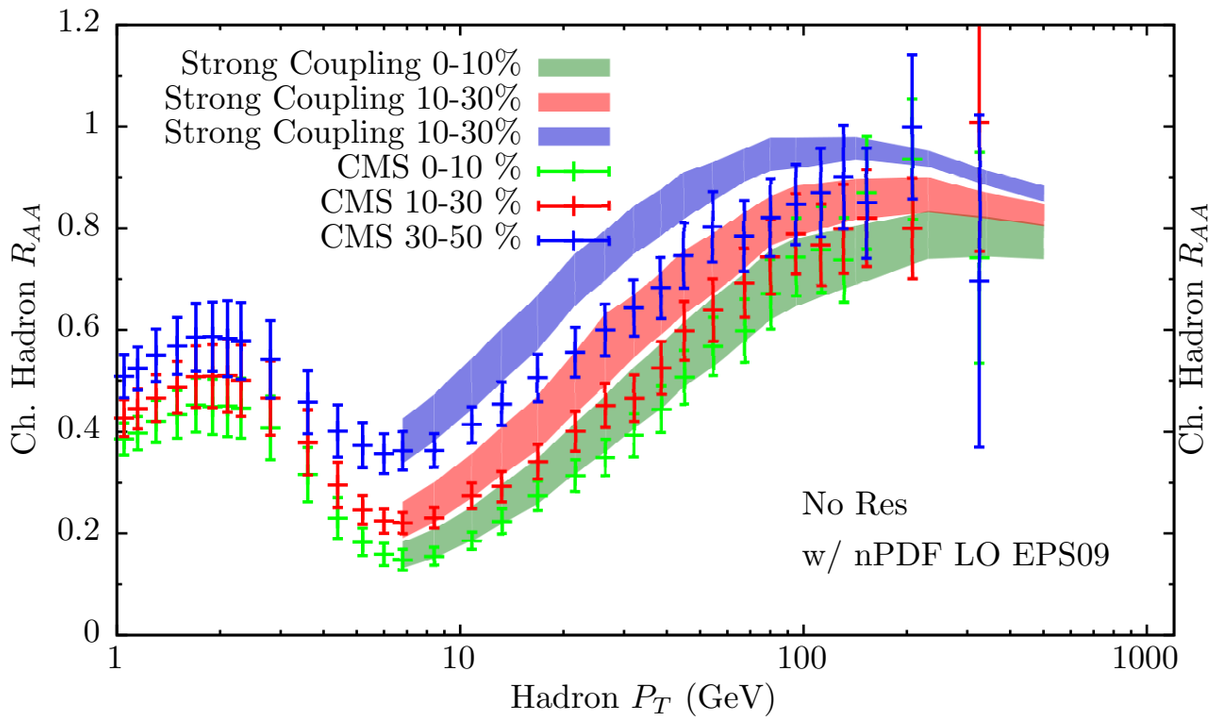


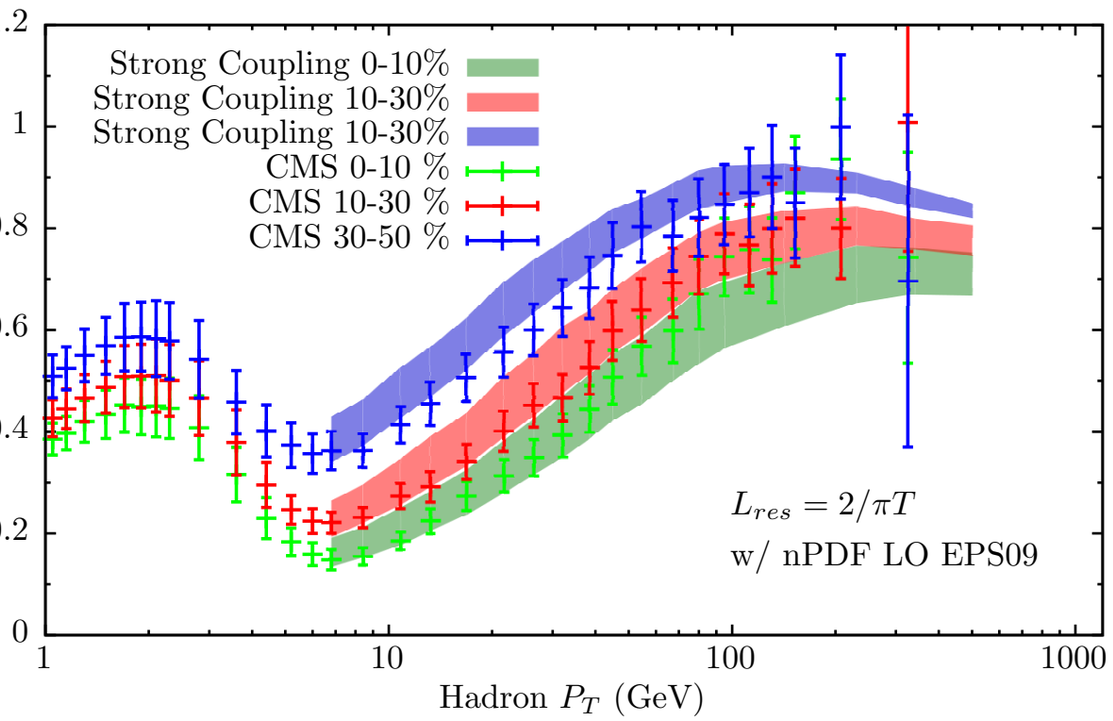


- Phenomenological implementation
  - Introduce a transverse resolution parameter π T L_{res} ~$\mathcal{O}$(1)
  - Partons in shower loose independently if L> L_{res}
- Combination of resolution and back-reaction
  - Pushes distributions in the right direction
  - But still not enough…

Hadron Raa

JCS, Pablos, Hulcher, Milano, Rajagopal (in preparation)





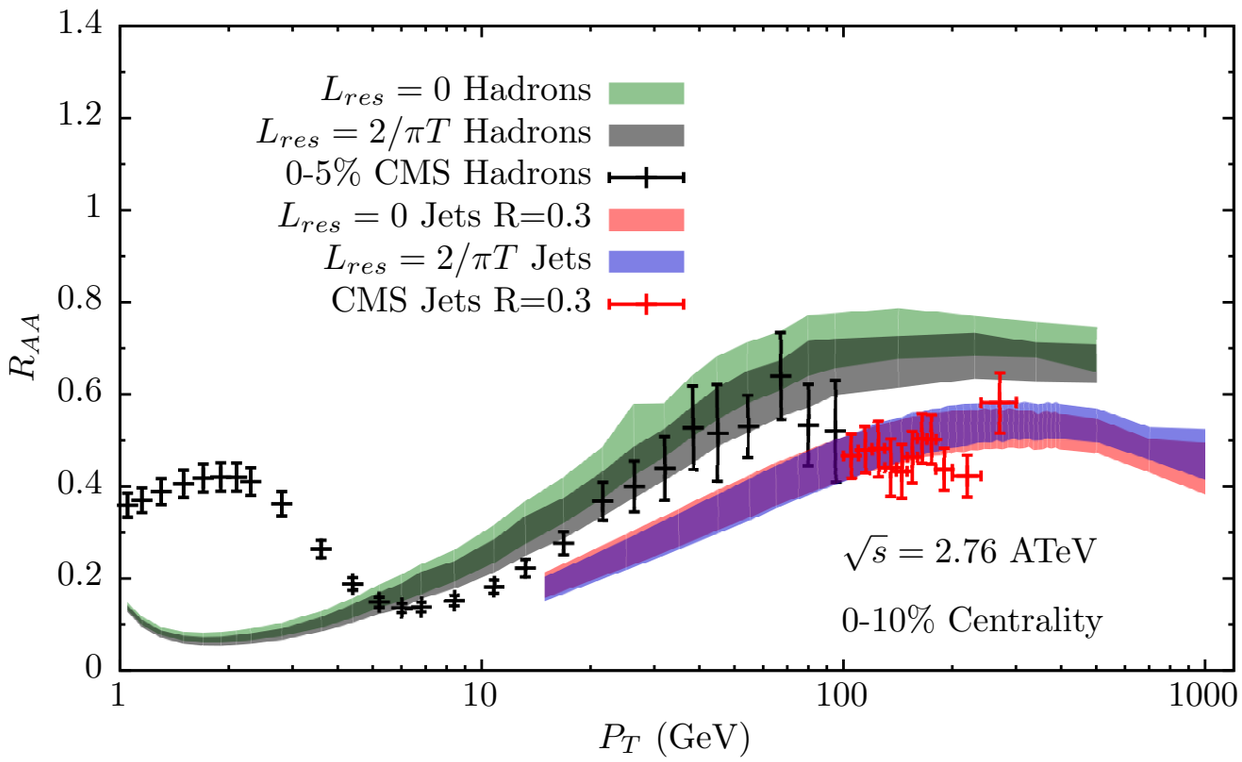
- Resolution effects have an impact in the description of charged particle R_{AA}

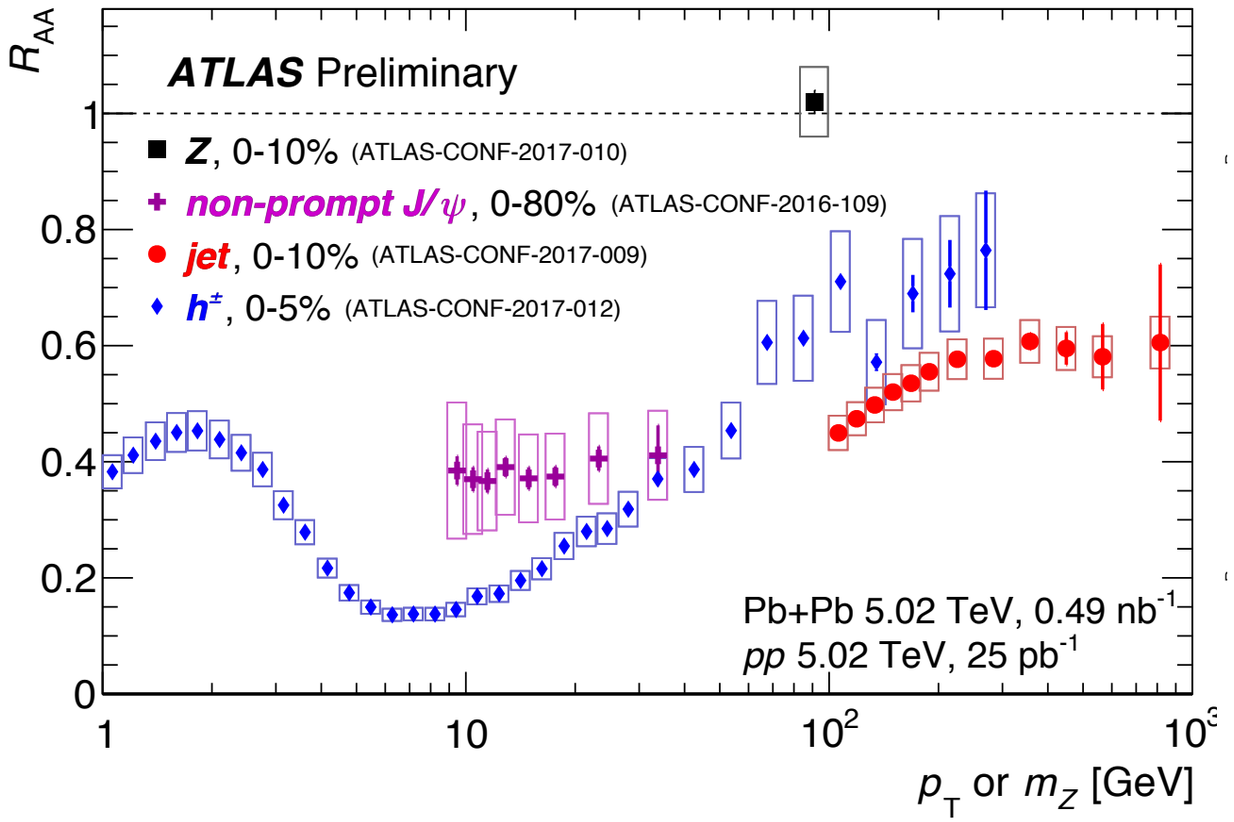
- Jet and charged particle R_{AA} show different sensitivity to resolution

also noted in Mehtar-Tani, Tywoniuk, 17

Particle vs Jets

JCS, Pablos, Hulcher, Milano, Rajagopal (in preparation)





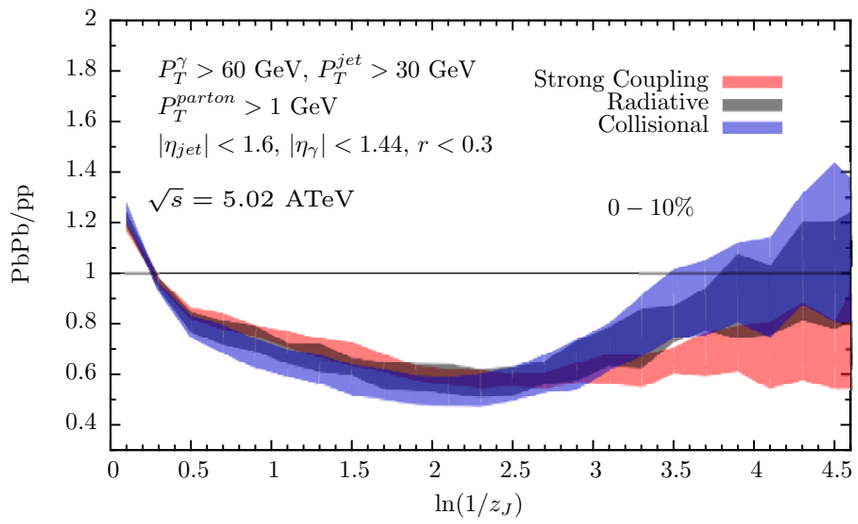
- Simultaneous description of Jet and hadron RAA
  - Including correct spectrum and flavour
  - NPDF
  - Fluctuation in jet structure (i.e. not all jets loose the same energy)

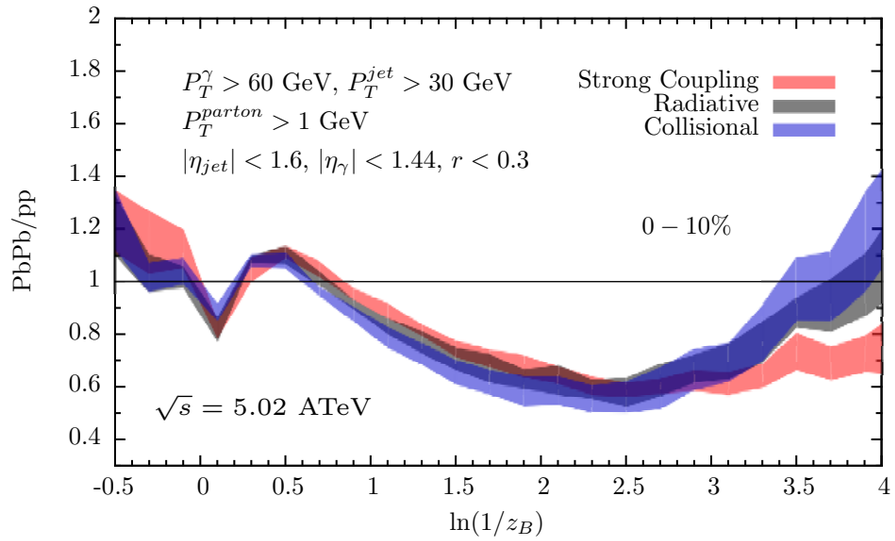
Conclusion

- How can we discern the nature of the d.o.f from hard probes?
  - Not clear yet
  - We are exploring the consequences of a strongly coupled physics.
- A simple model
  - Incorporates relevant physics from strong coupling
  - We can implement new physics processes
  - Is testable and predictive

Photon Fragmentation Functions

- Parton level





Insensitivity to Broadening