The Hybrid Framework

Jorge Casalderrey-Solana

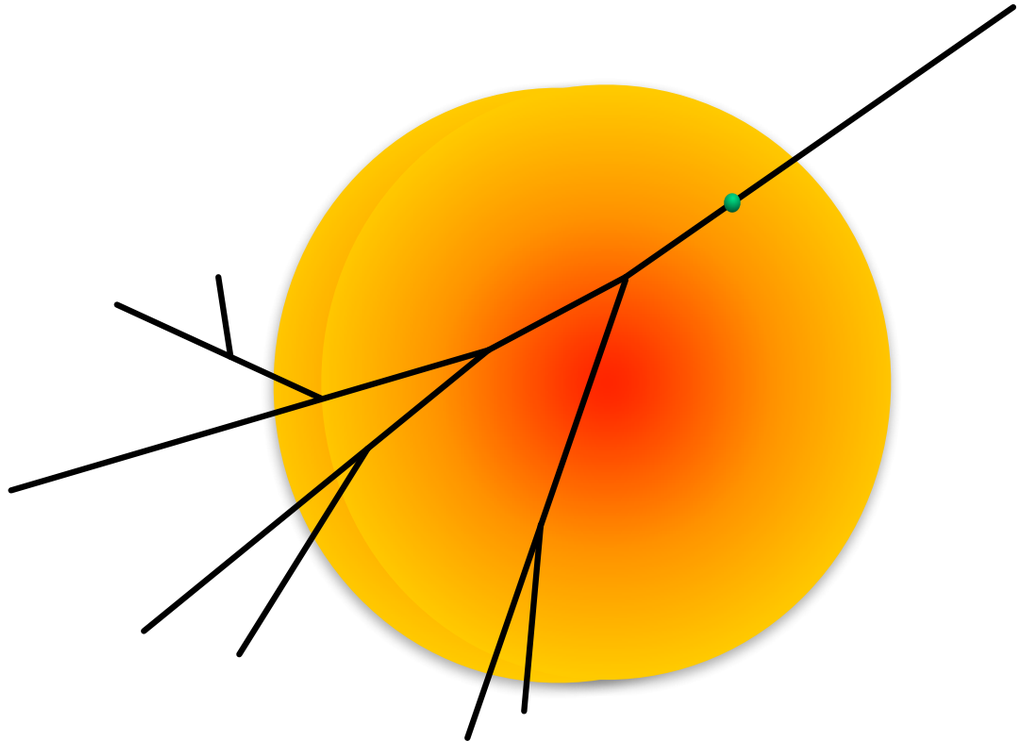
In collaboration with

G. Milhano, D. Pablos, K. Rajagopal and Xiaojun Yao

UNIVERSITAT DE BARCELONA

Hybrid Model

- Simple but predictive model
  - Ingredients



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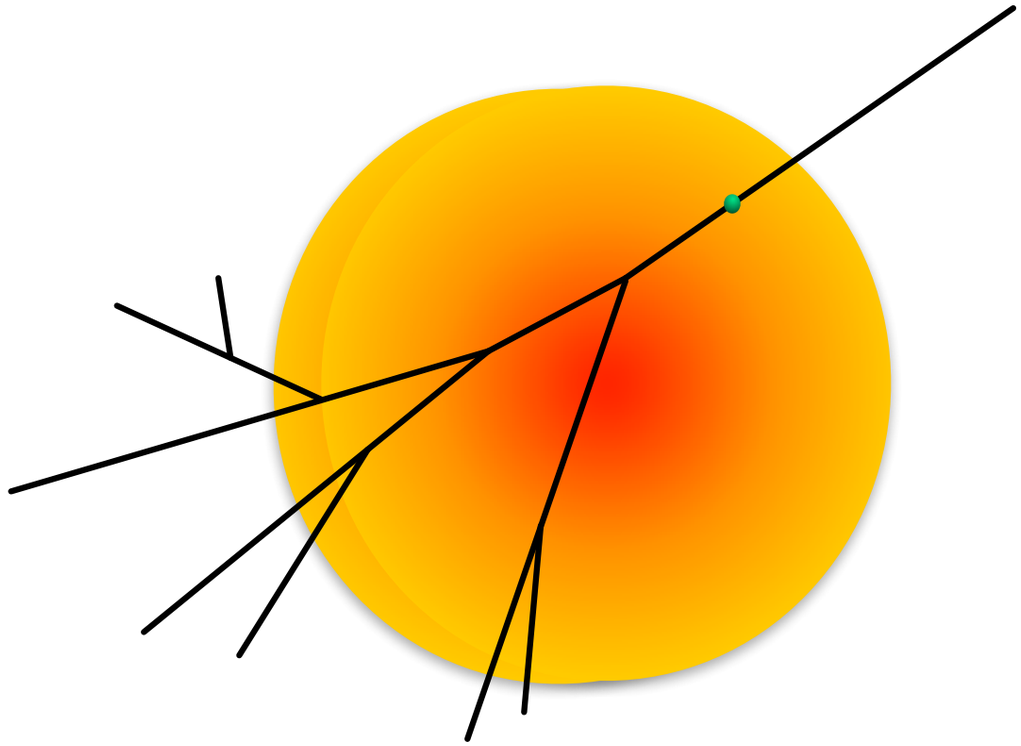

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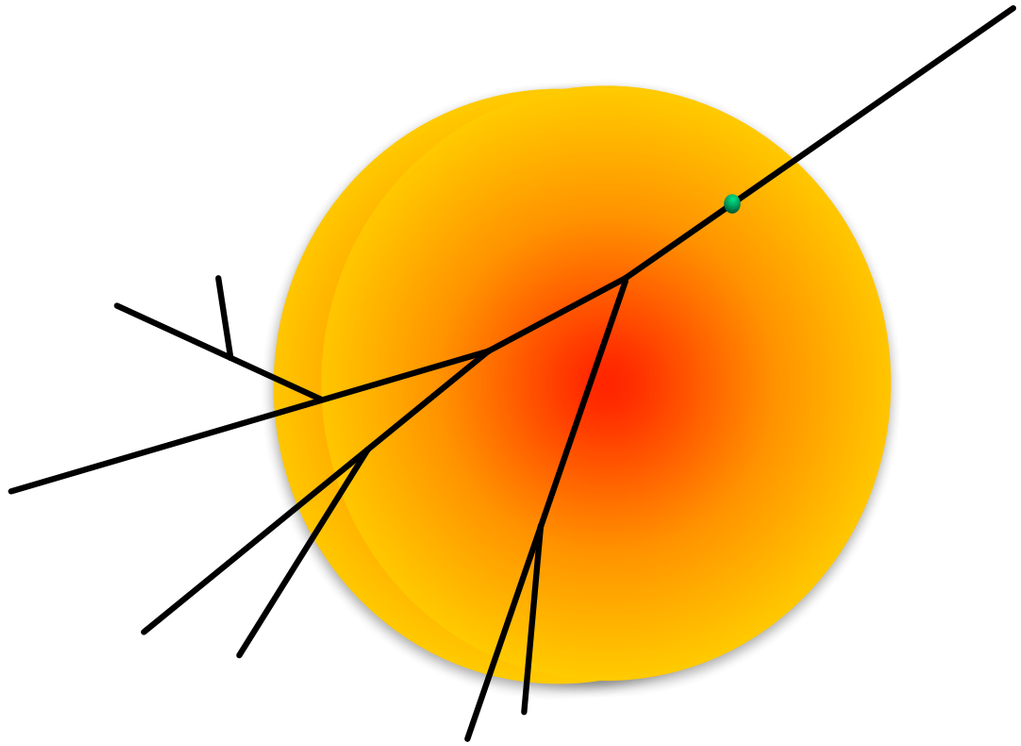
      (PYTHIA 8)



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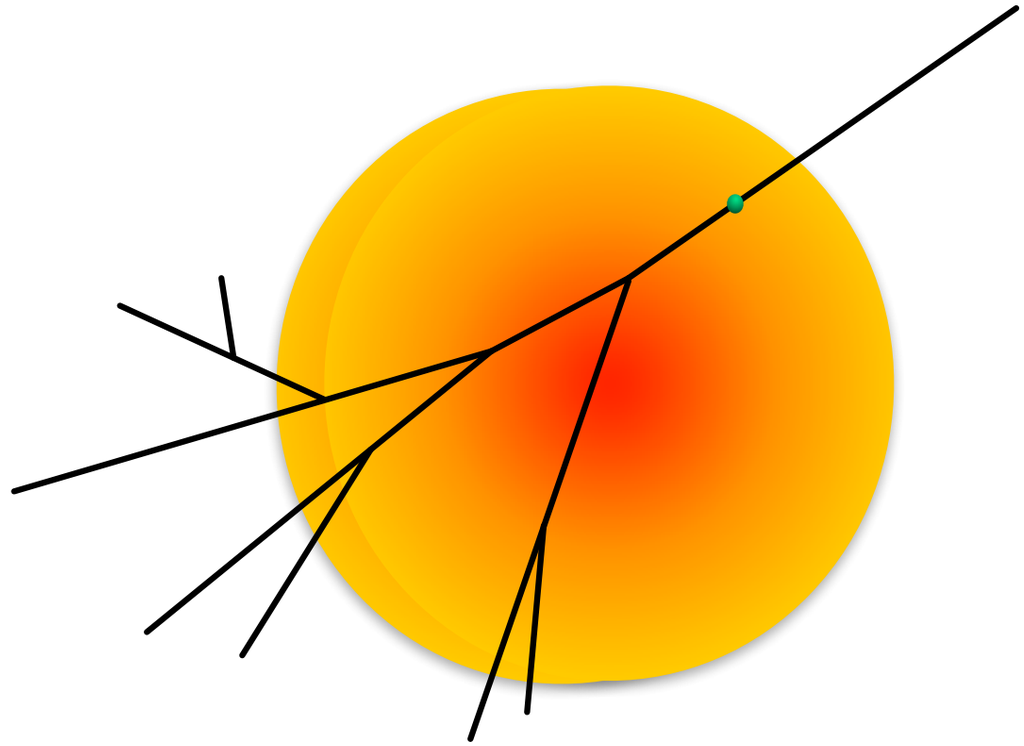

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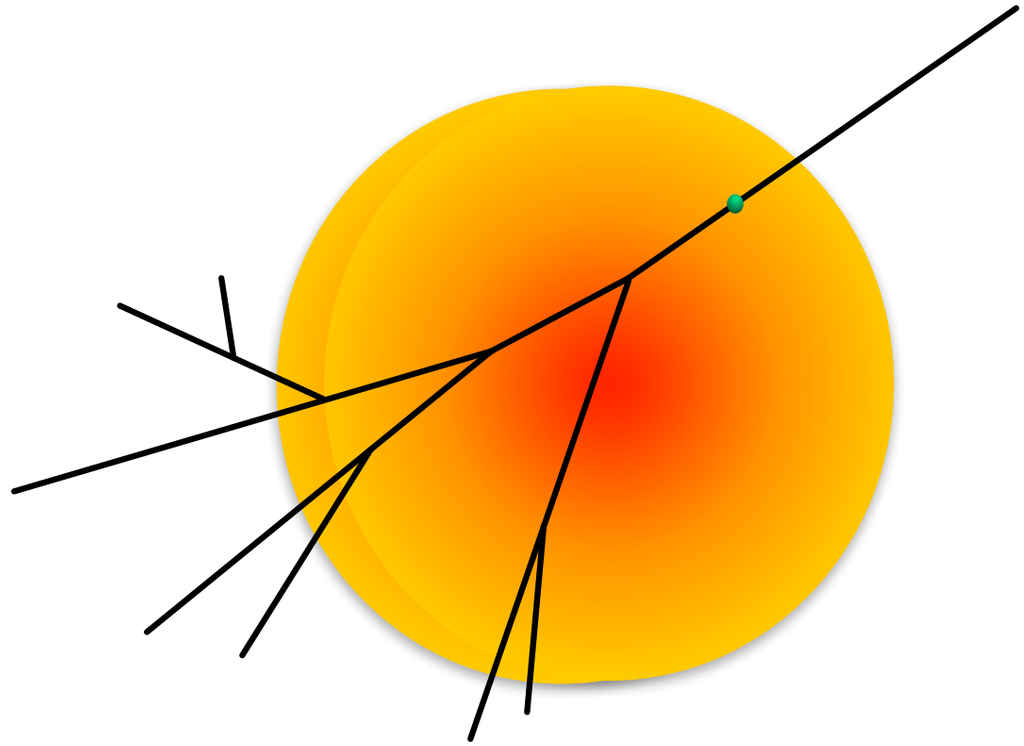

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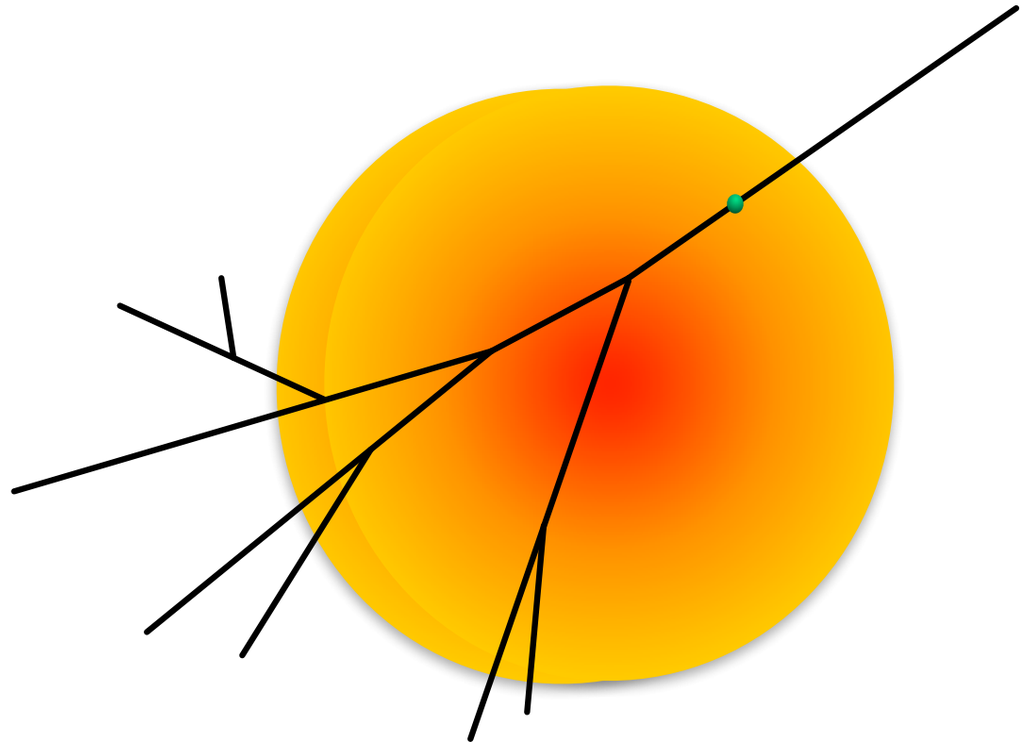

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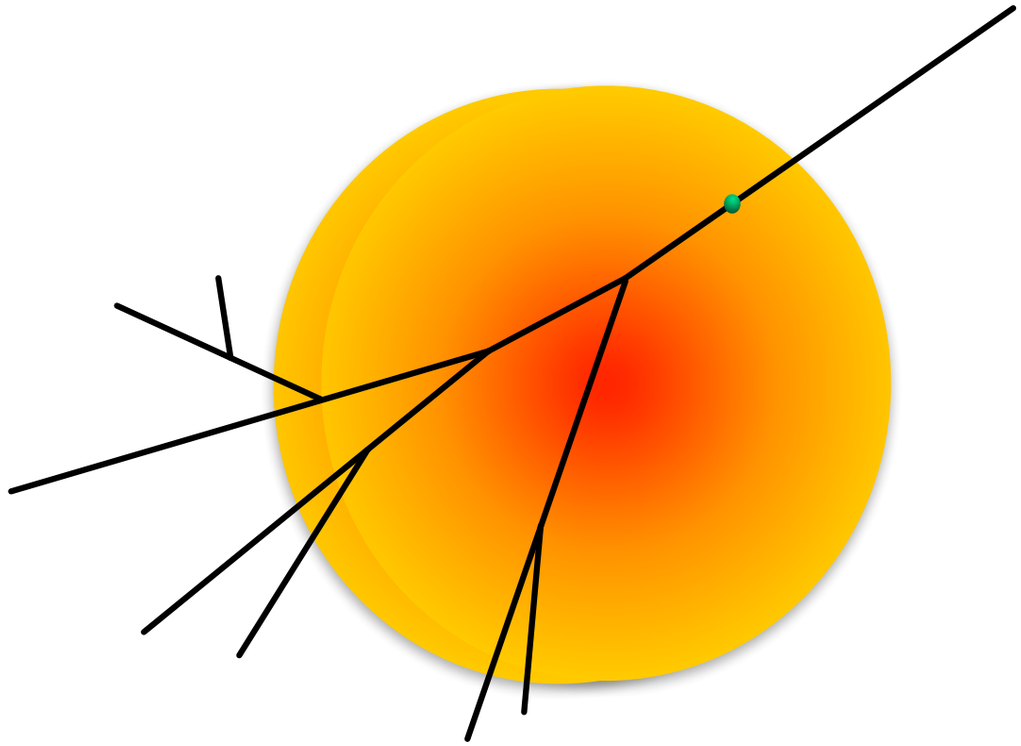

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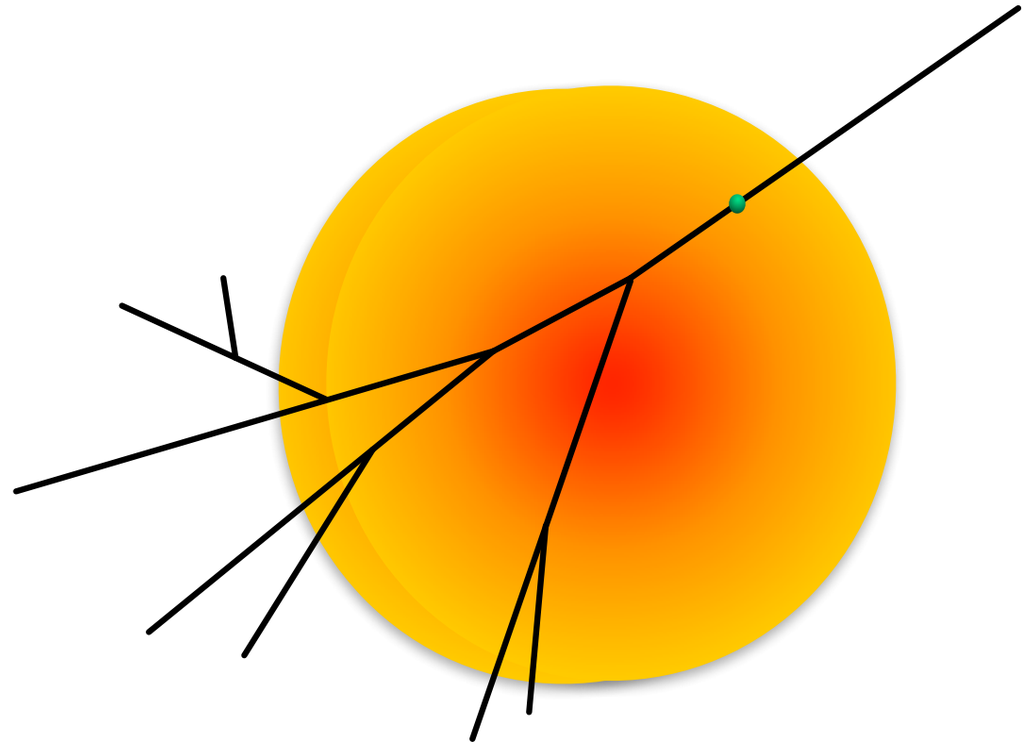

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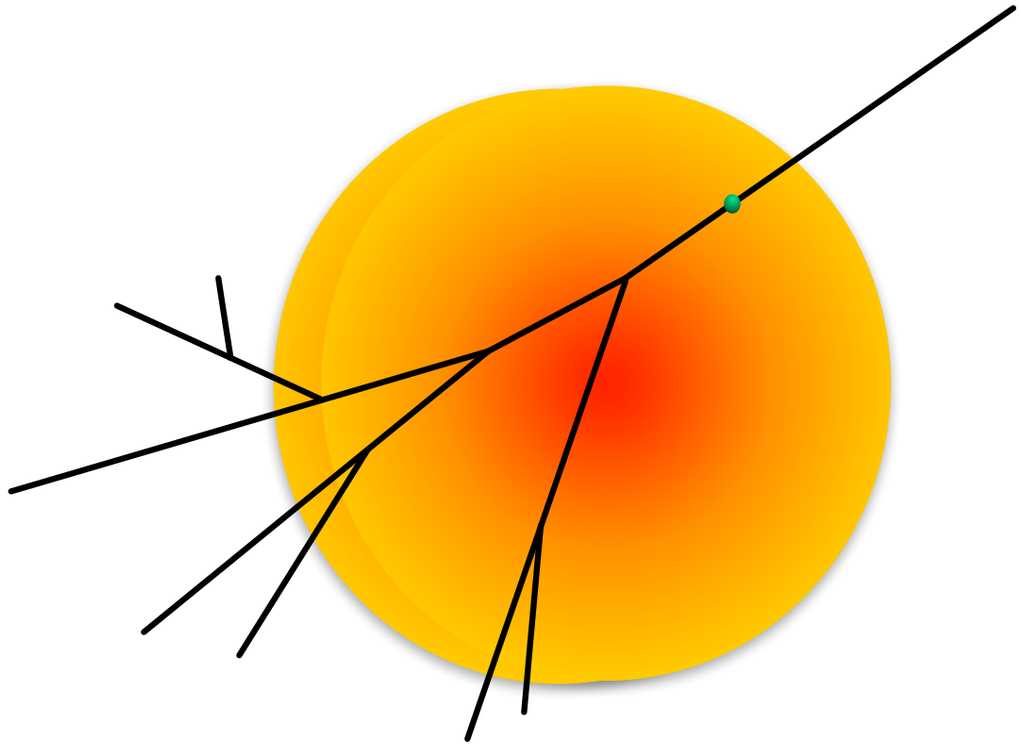

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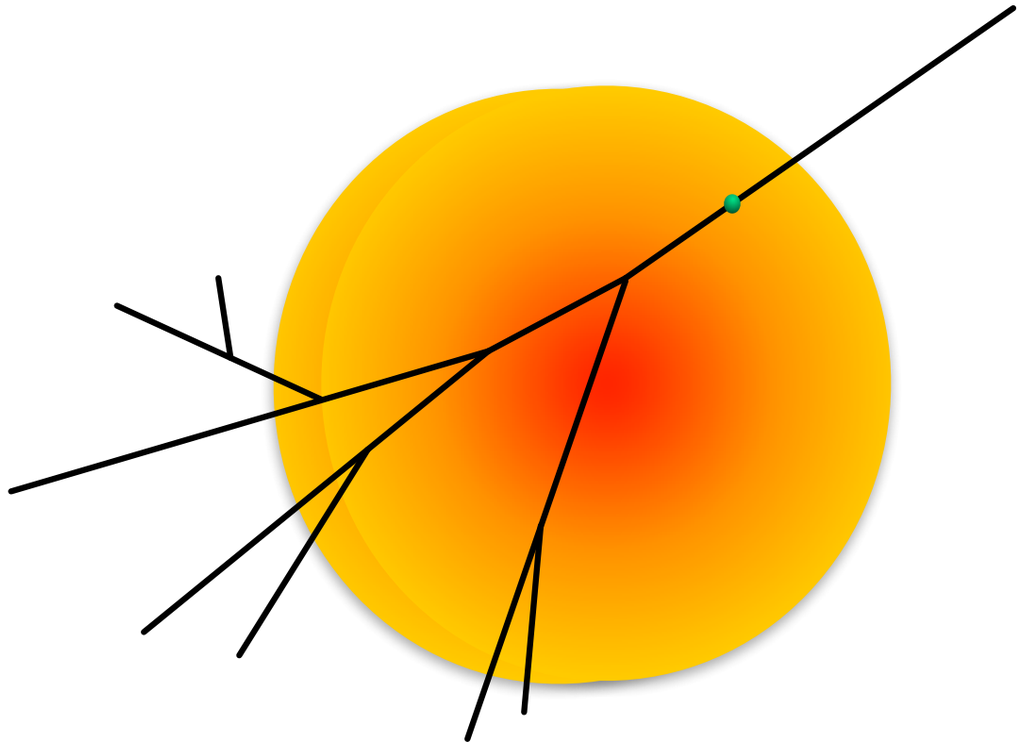

- Medium back-reaction
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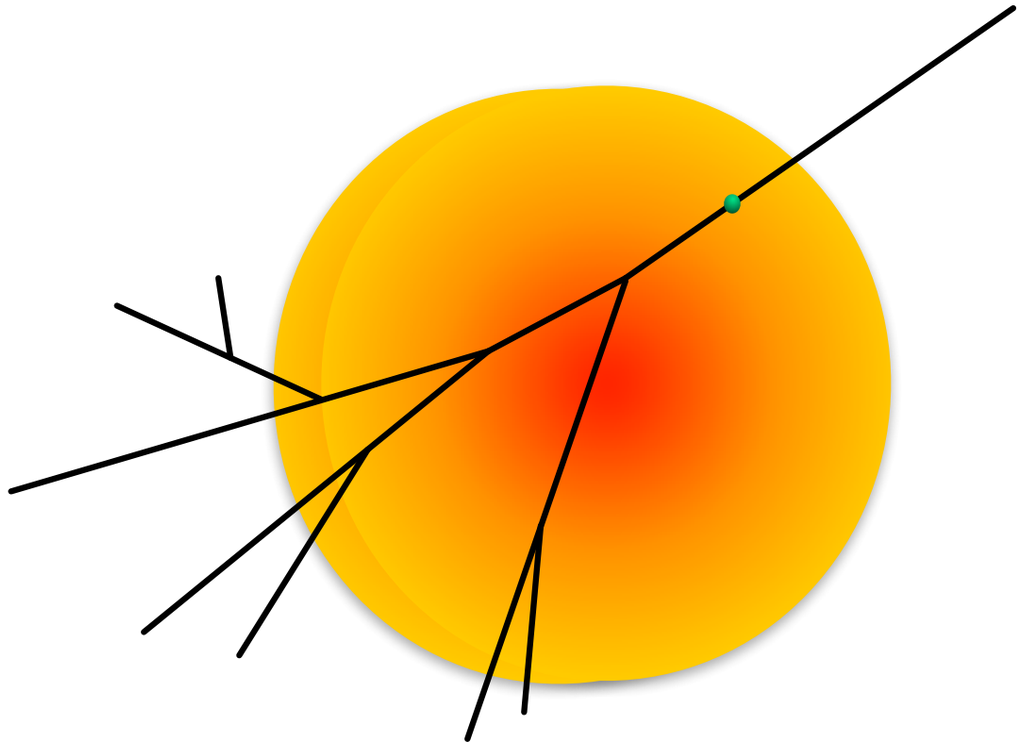
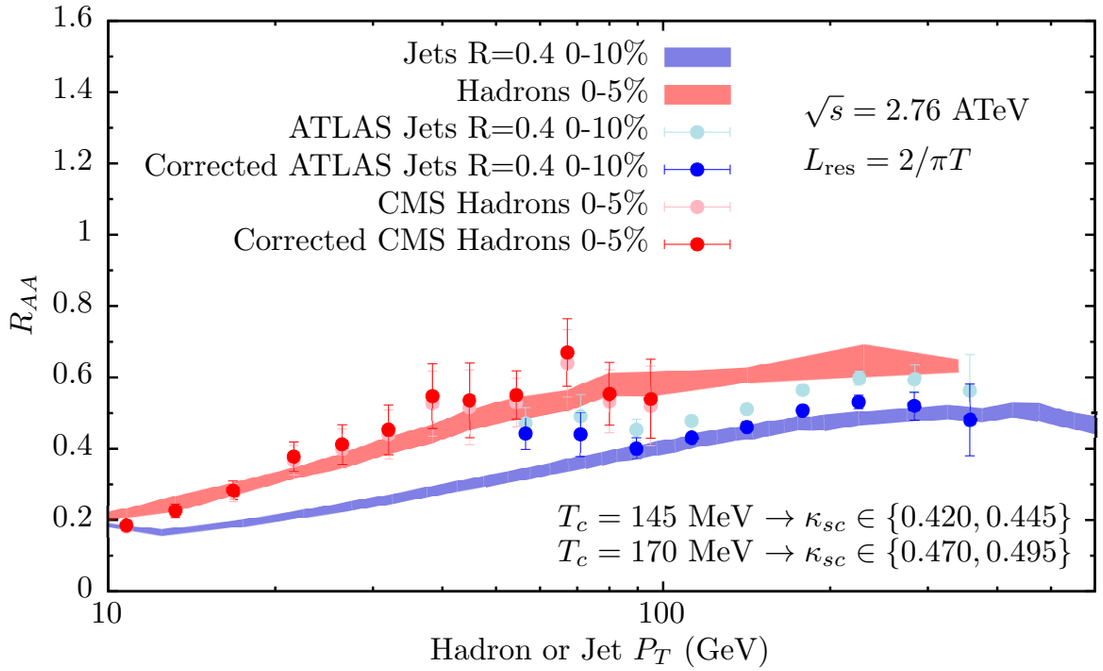
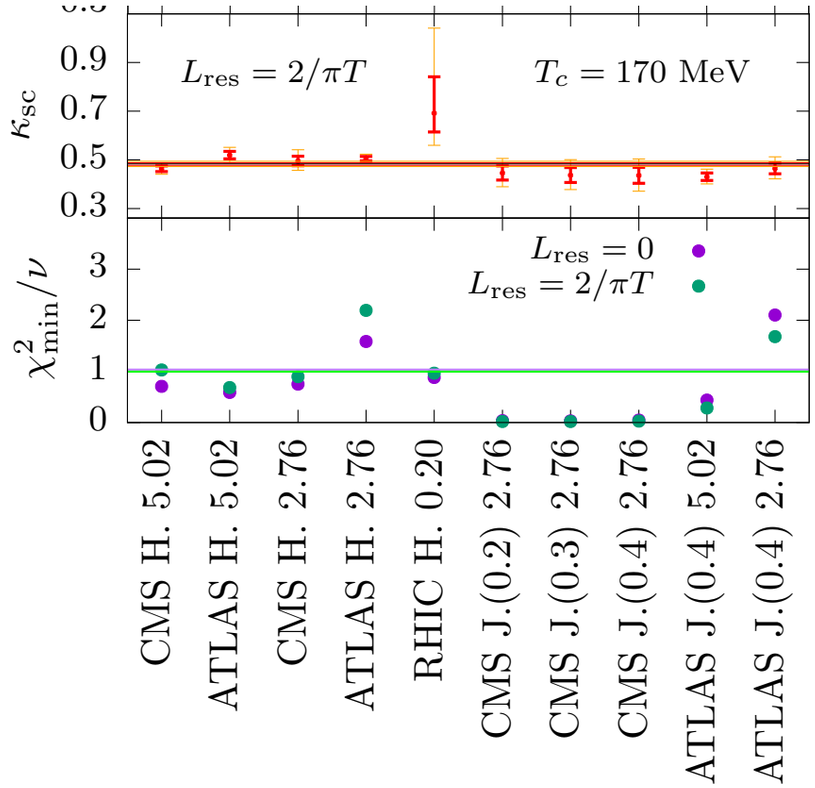
      } (Local) Equilibrium Contribution



Fixing the Model From Data





- Global fit to Jet and Hadron Data

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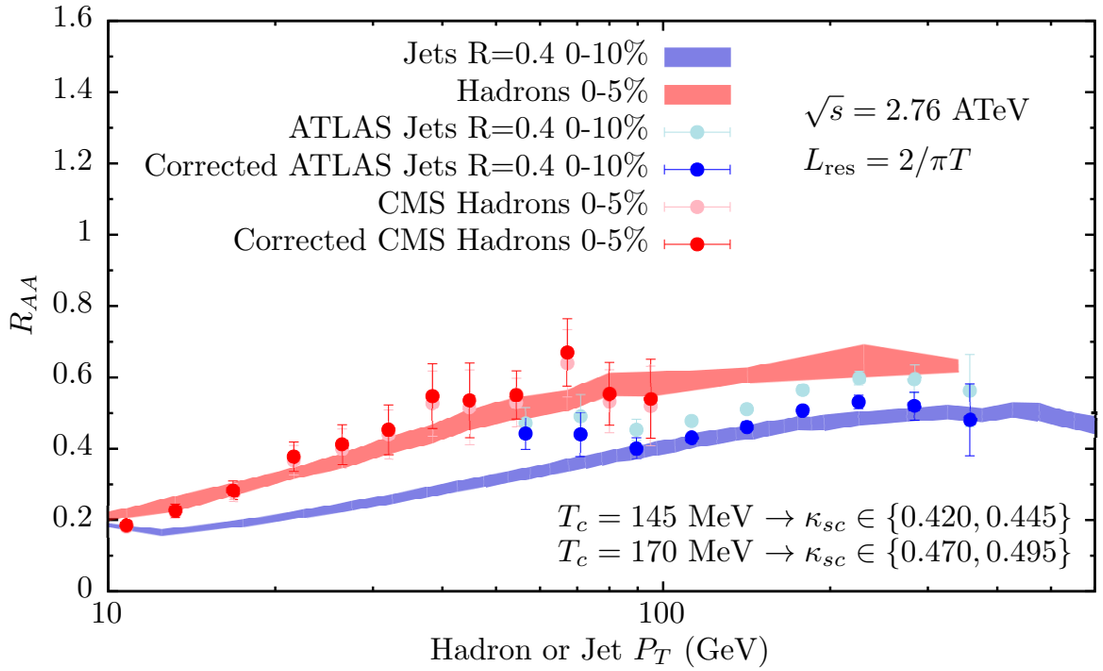

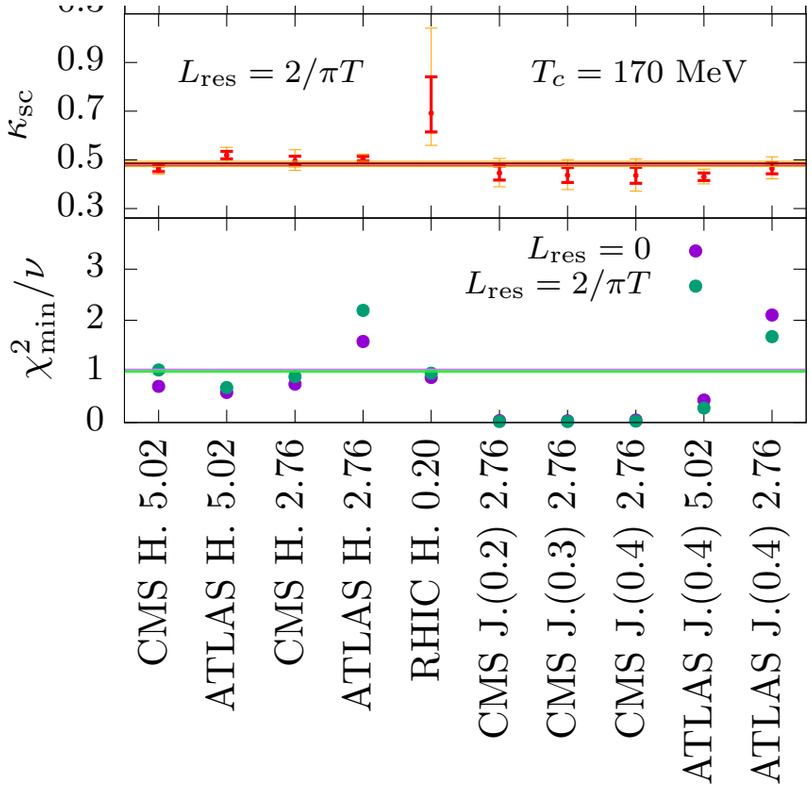

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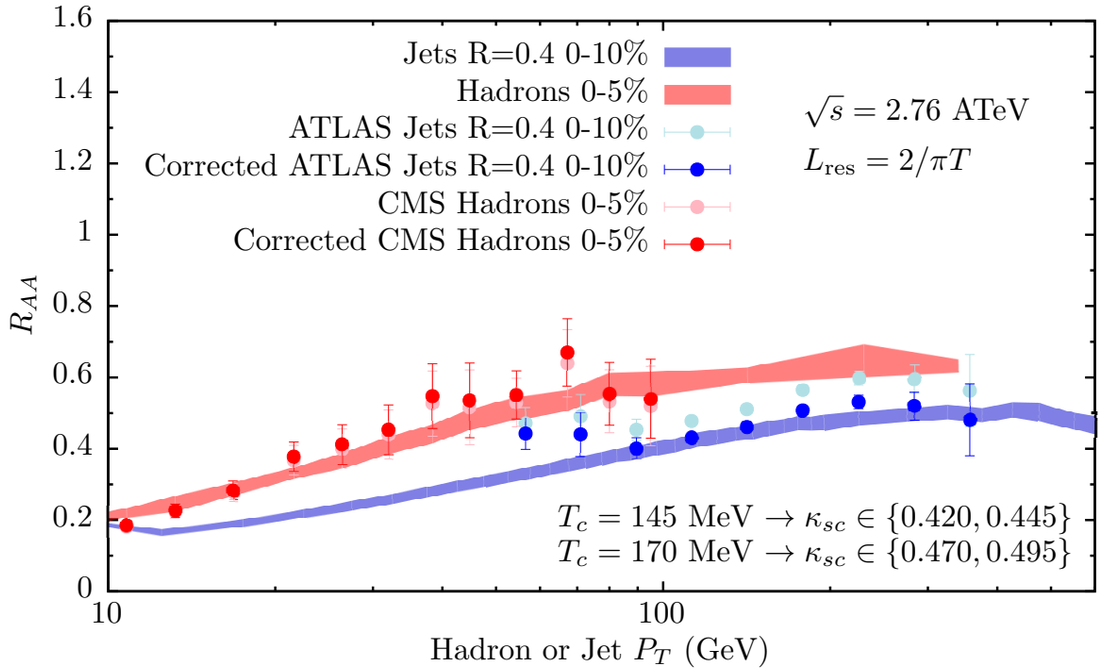

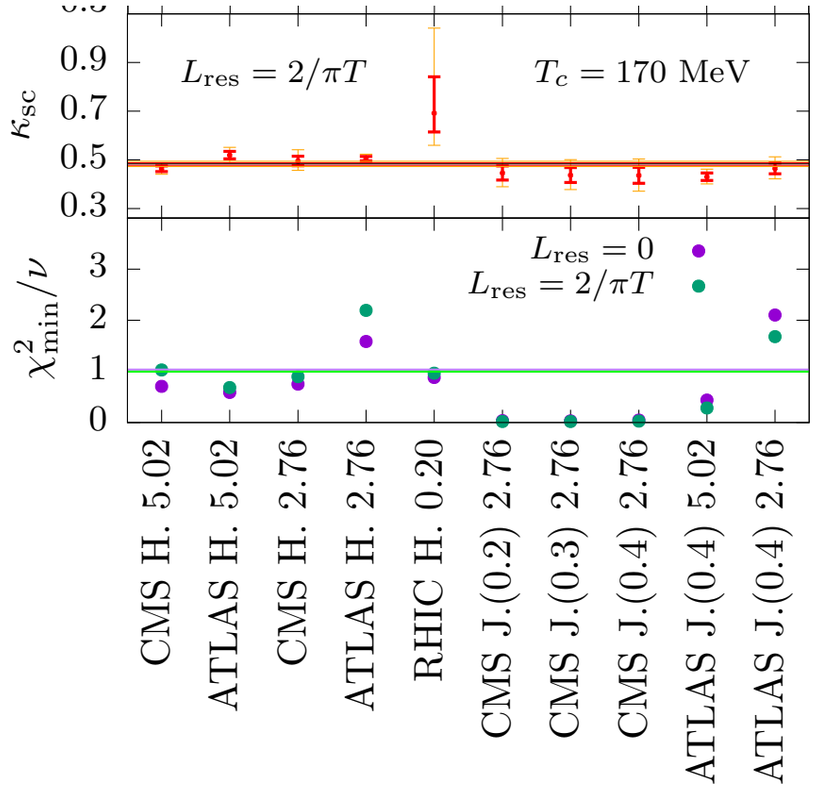

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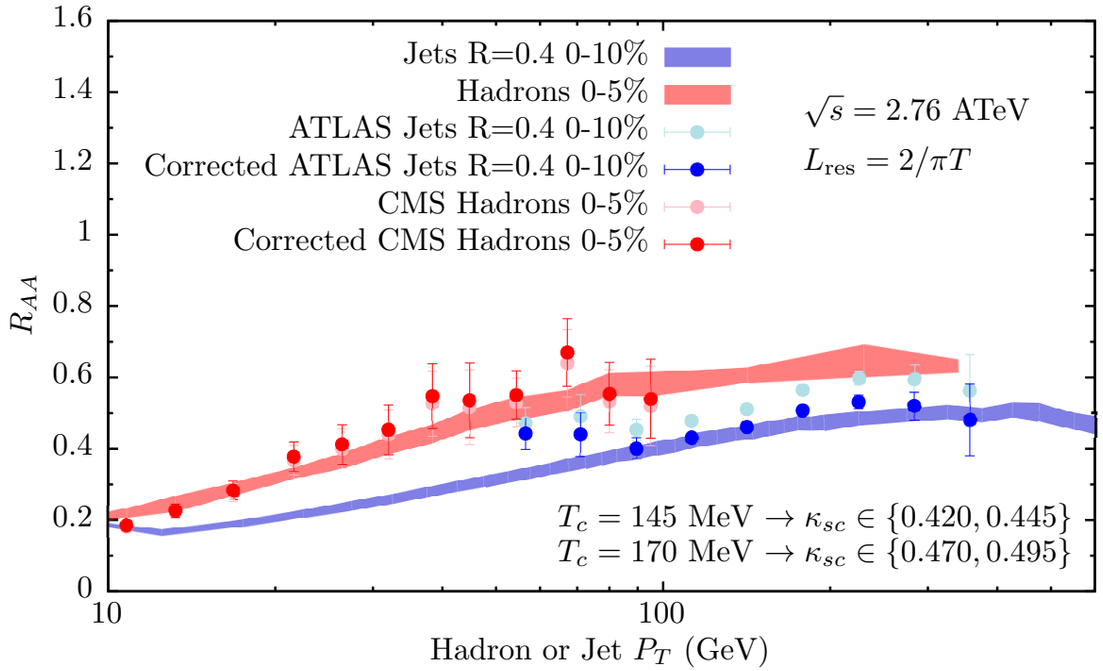

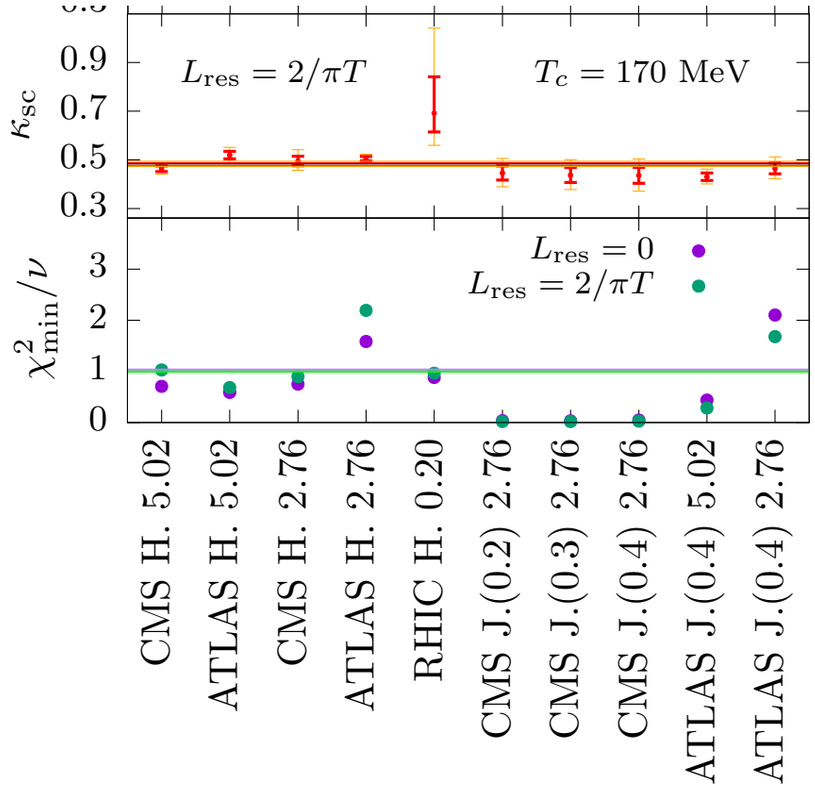

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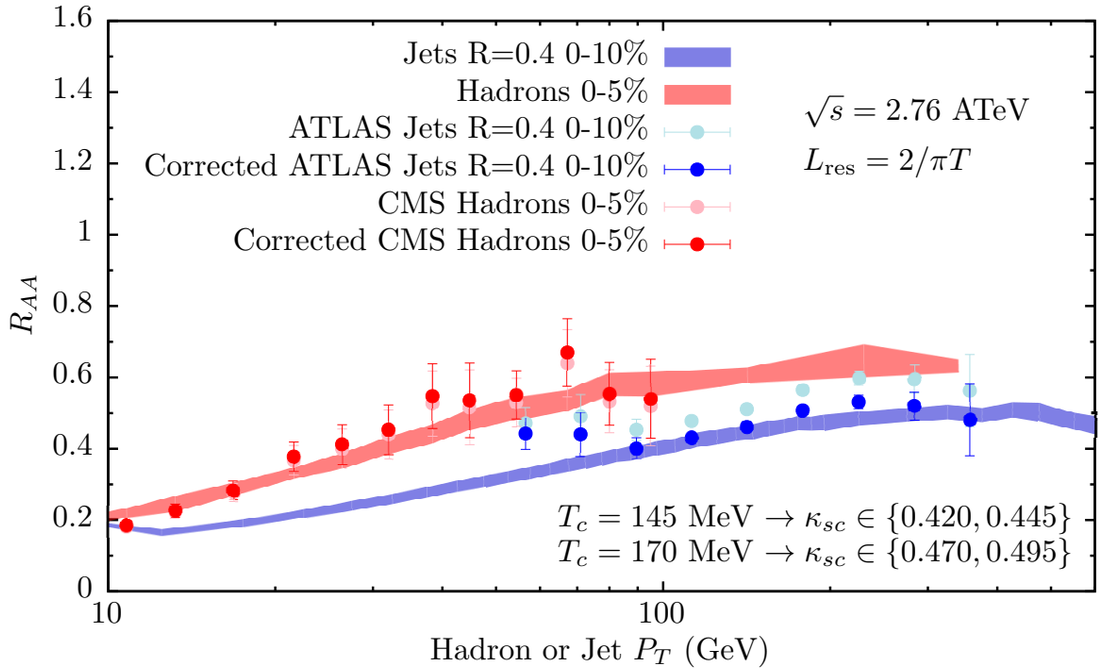

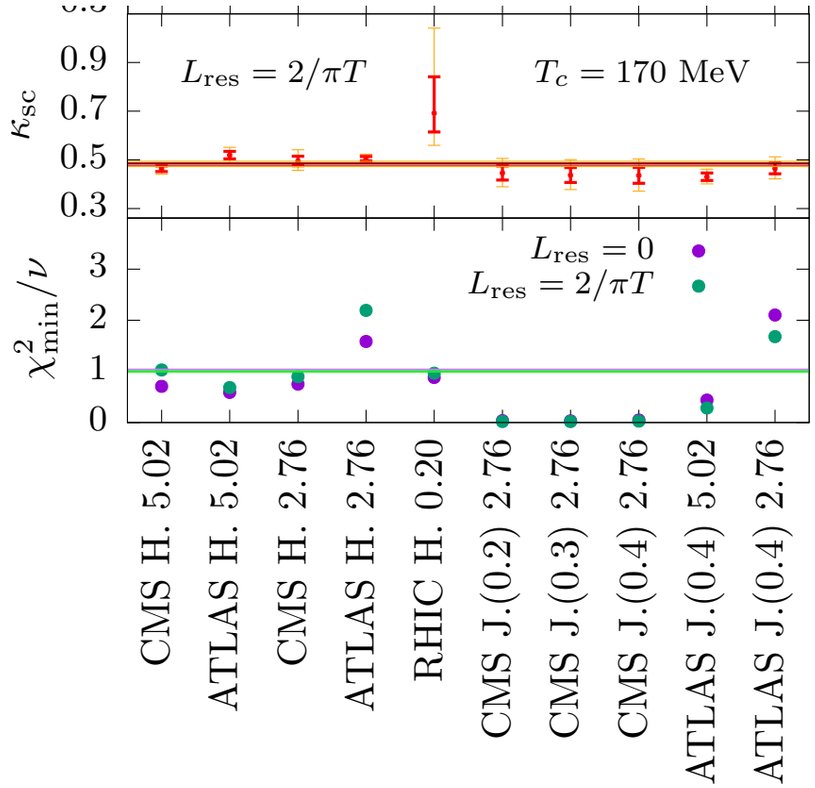

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Feal et al. ; Andres et al; Mehtar-Tani & Tykowniuk; Barata et al… ; GLV, HT, JEWEL..

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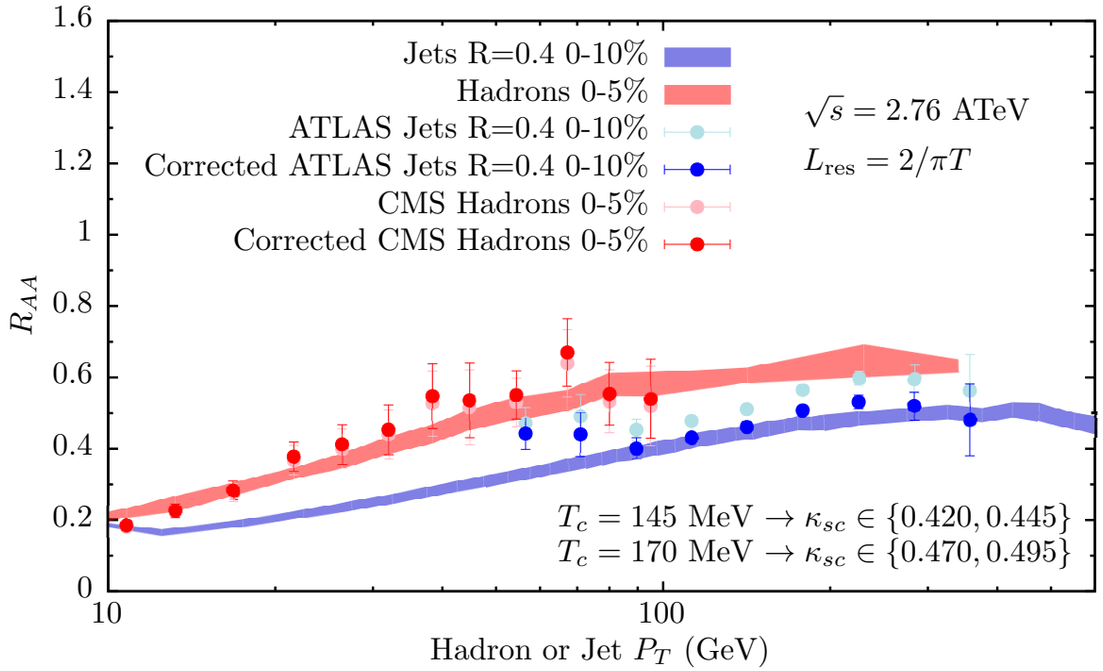

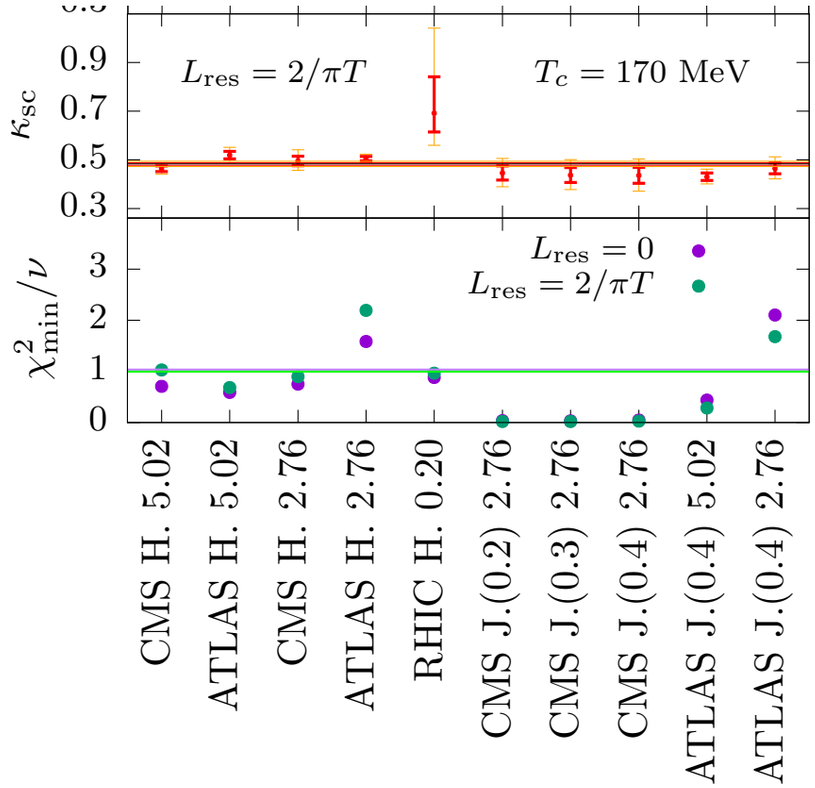

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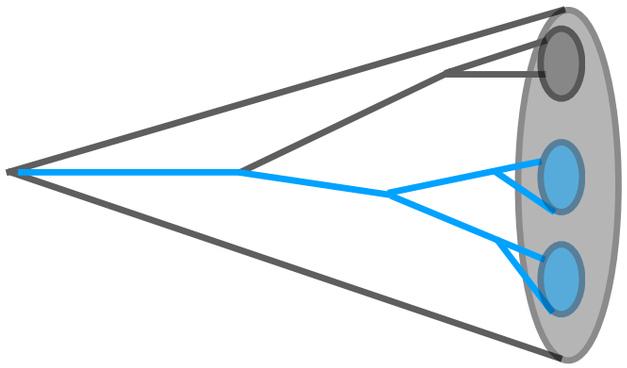
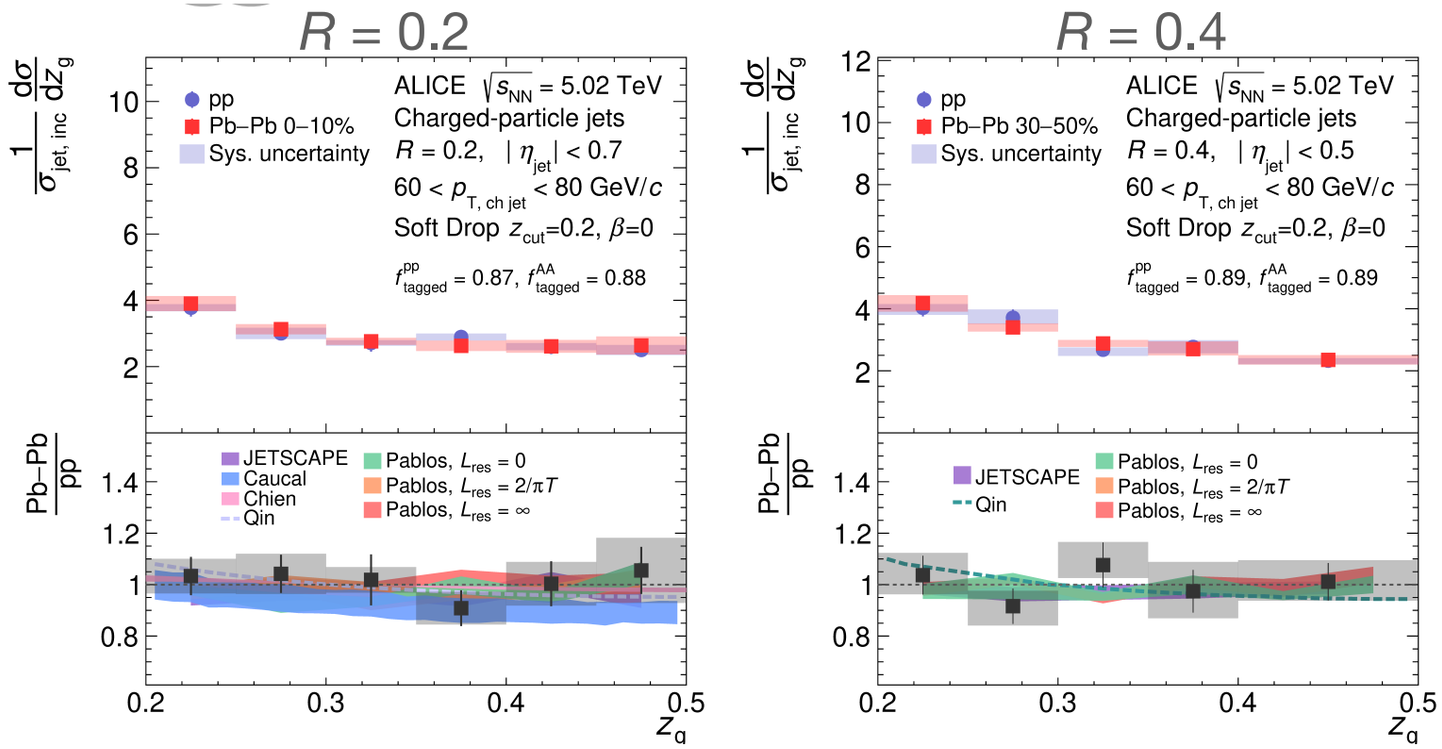
      Feal et al. ; Andres et al; Mehtar-Tani & Tykowniuk; Barata et al… ; GLV, HT, JEWEL..
    - Ongoing efforts to implement hard scatterings in hybrid

      Hulcher, Pablos, Rajagopal

Inner Jet Structure





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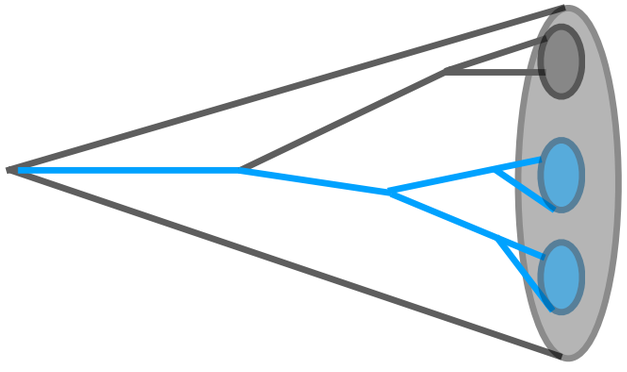

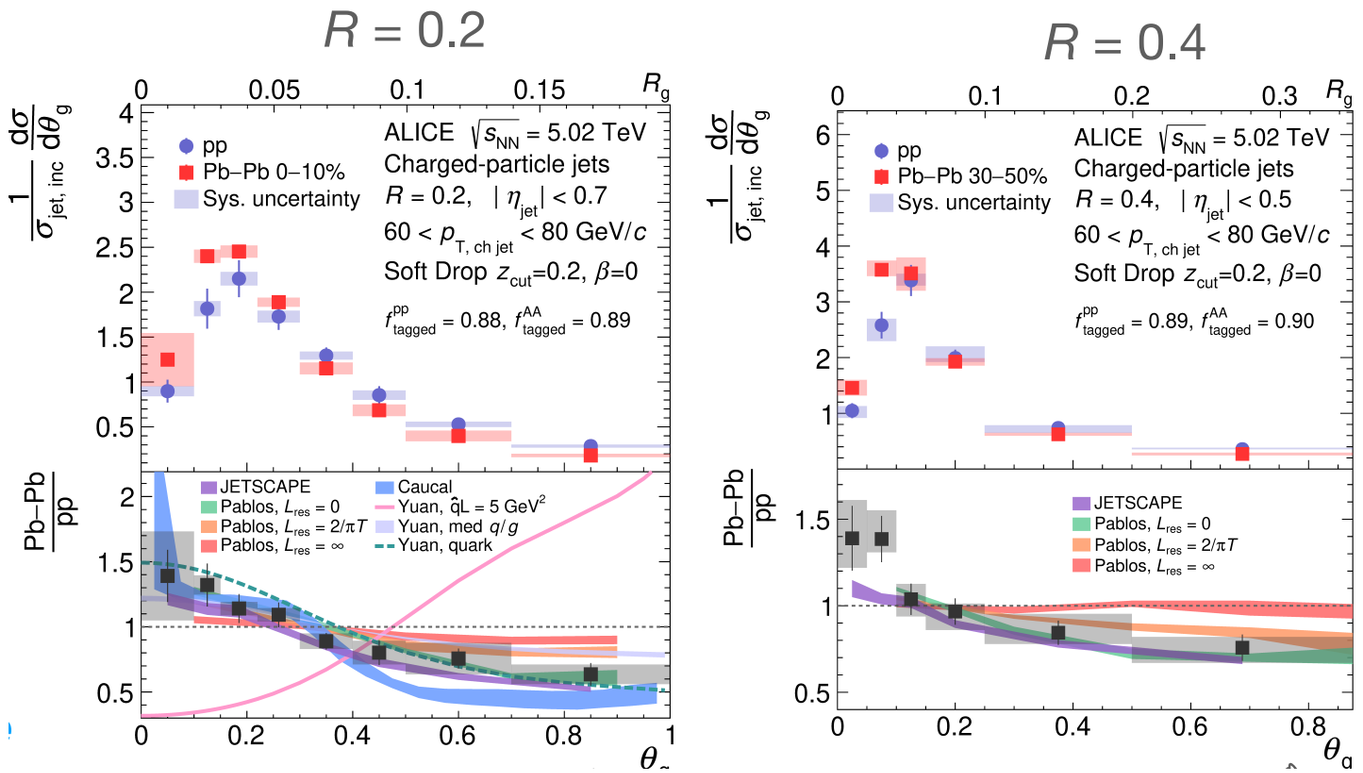

- No significant modification of the (groomed) splitting functions
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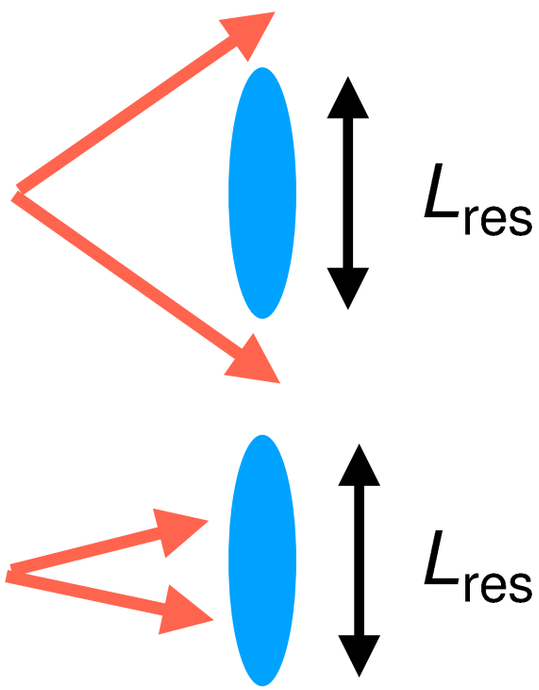
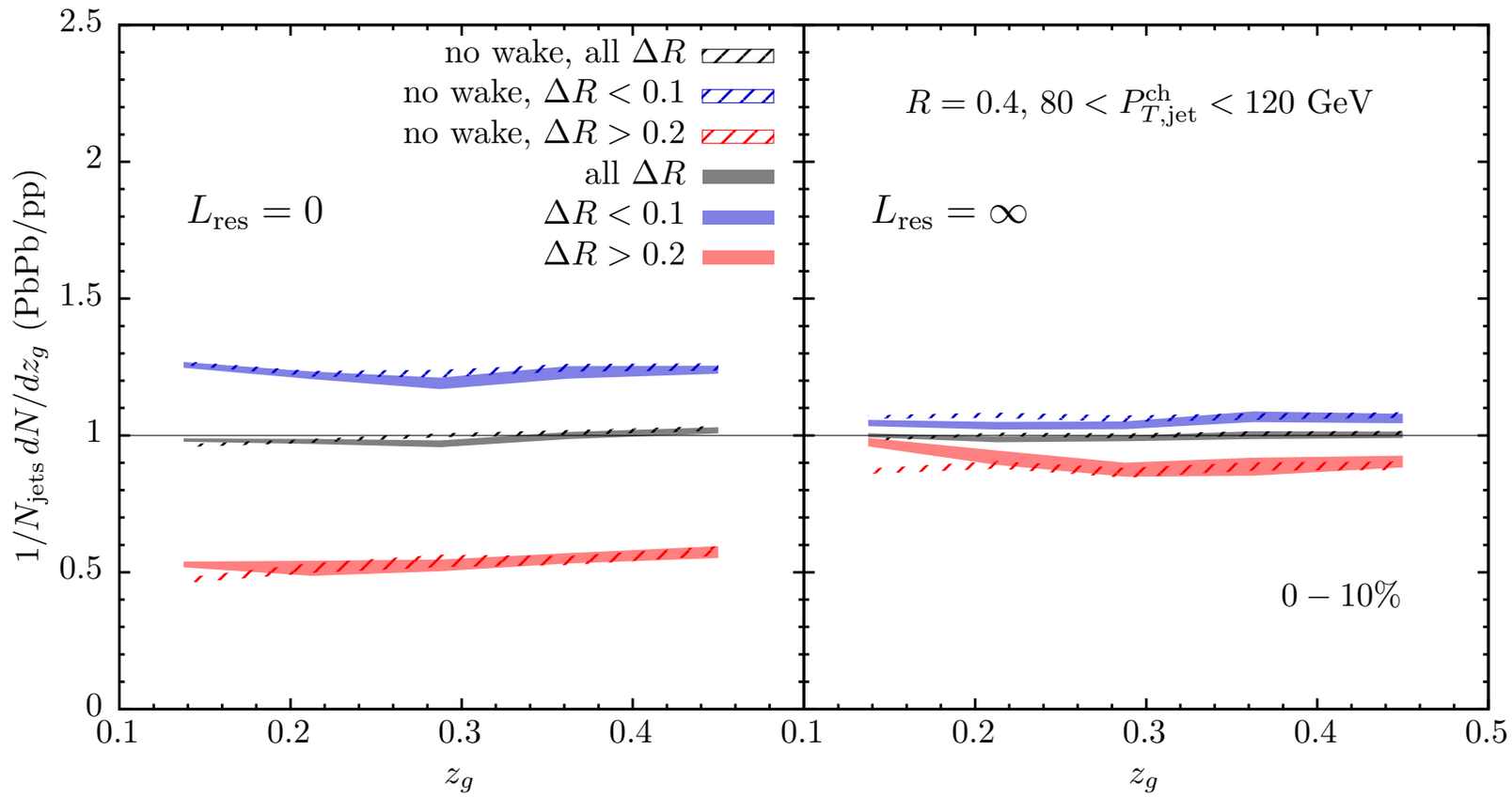
- But inner jet structure is modified
  - Wider jets lose more energy

The medium can resolve the inner jet structure

Inner-Jet in Hybrid Model





- Wider jets are made of more partons $\Longrightarrow$ more energy loss
  - How many?

    Depends on how the medium resolves transverse separation

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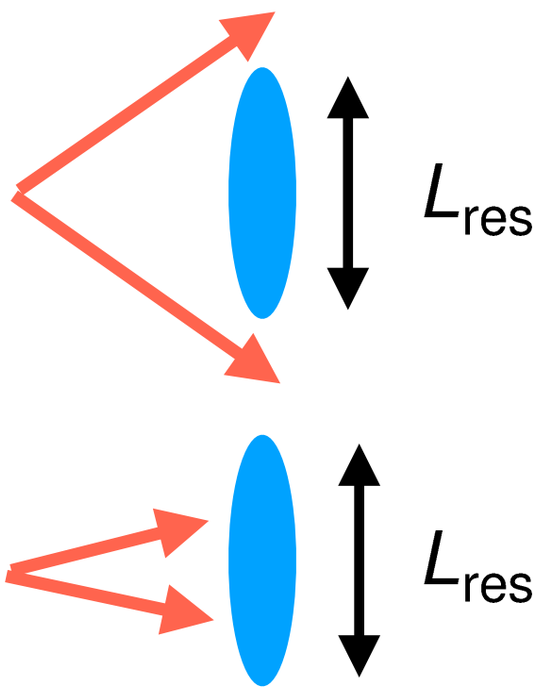

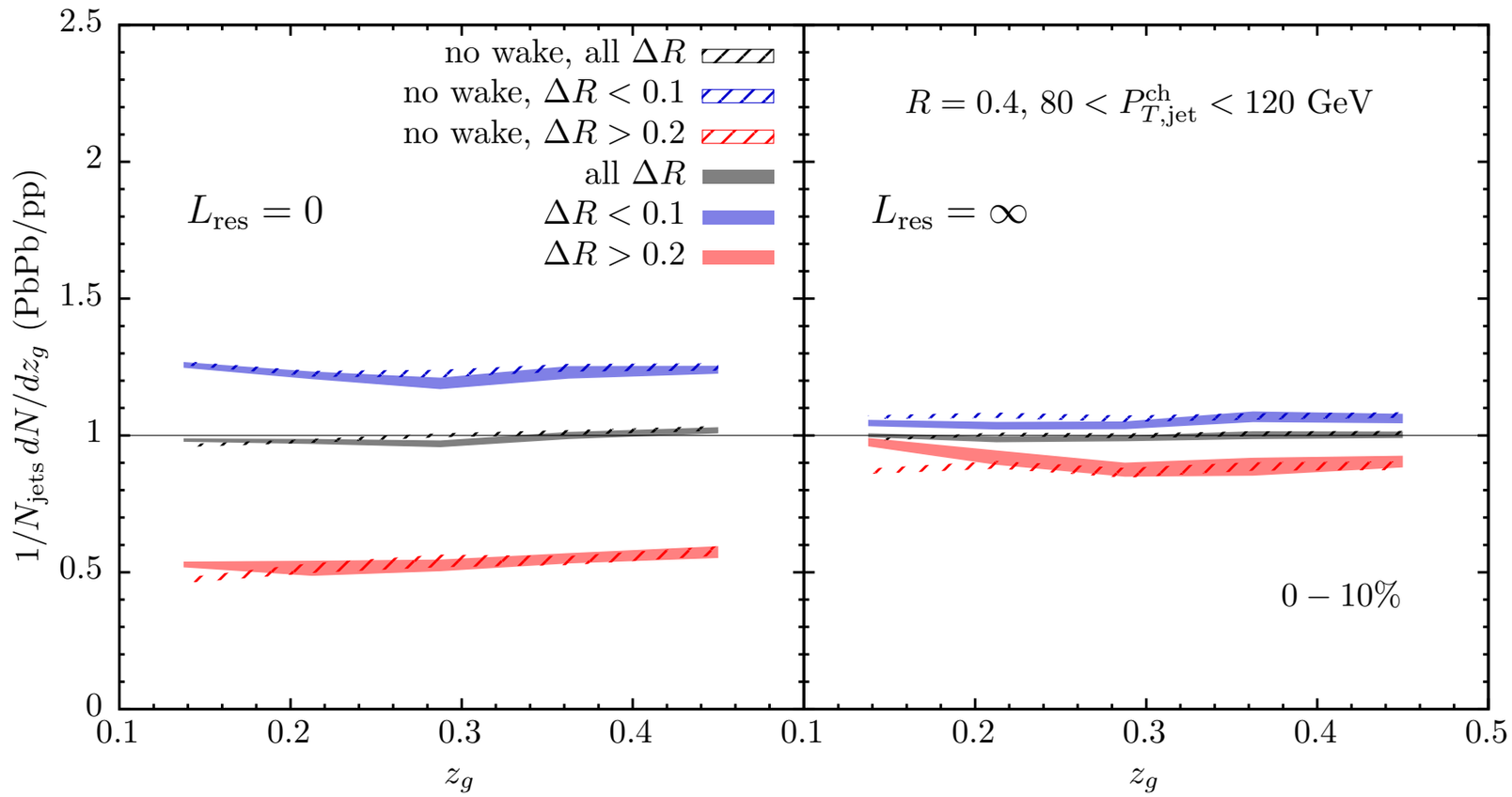

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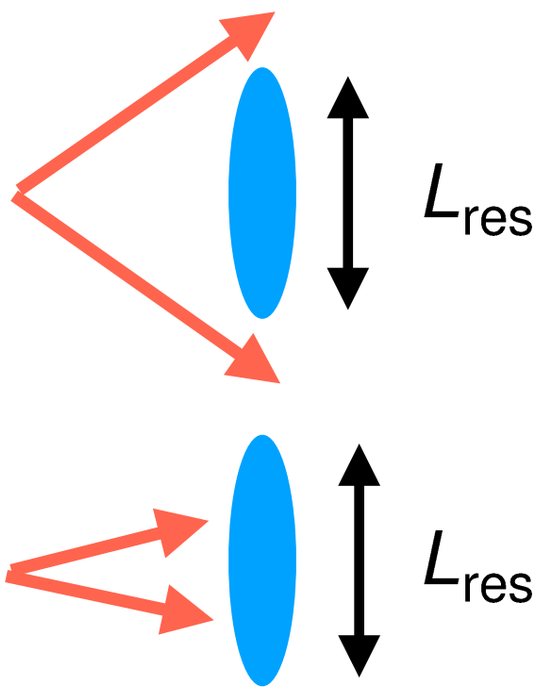

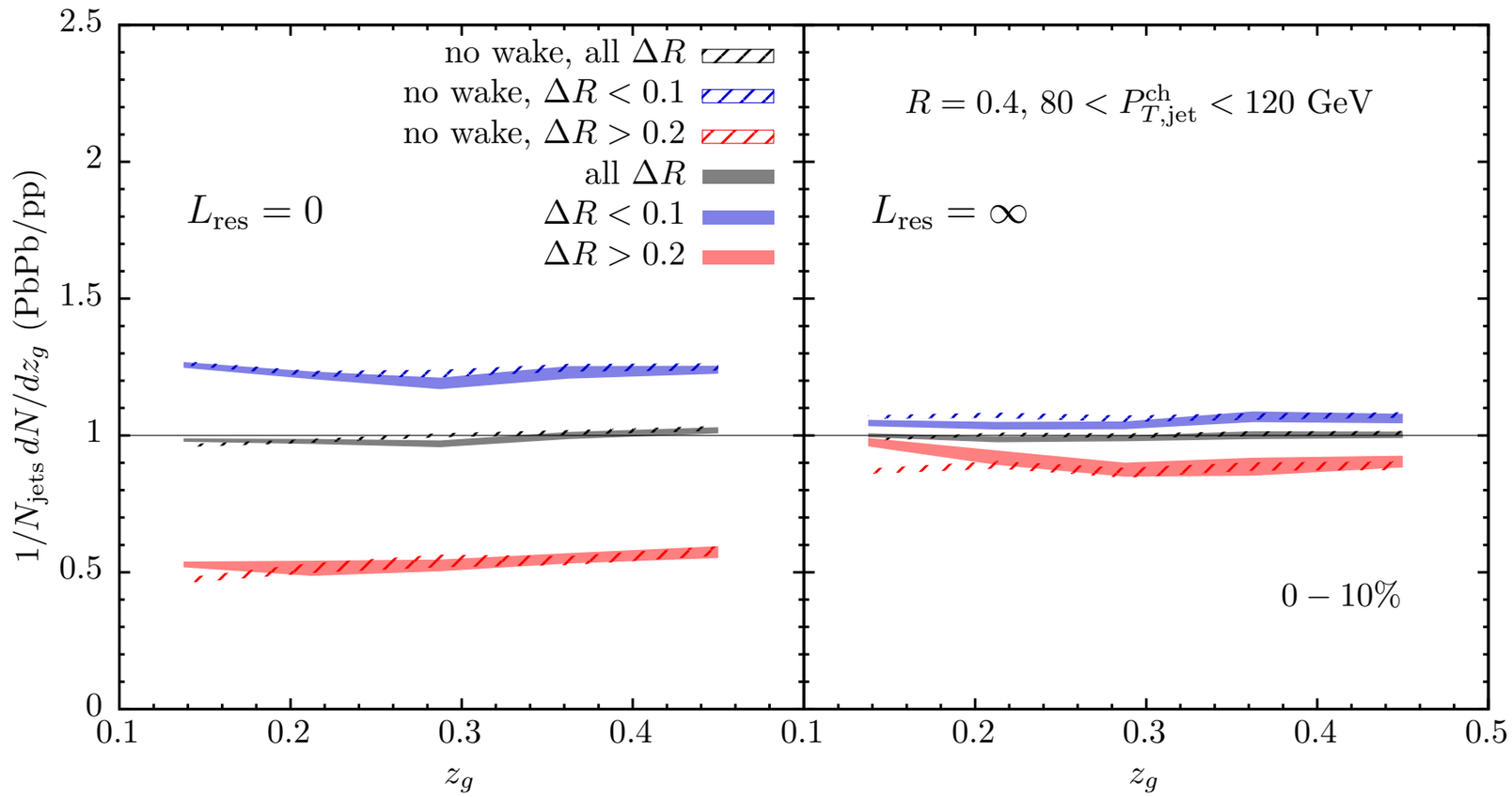

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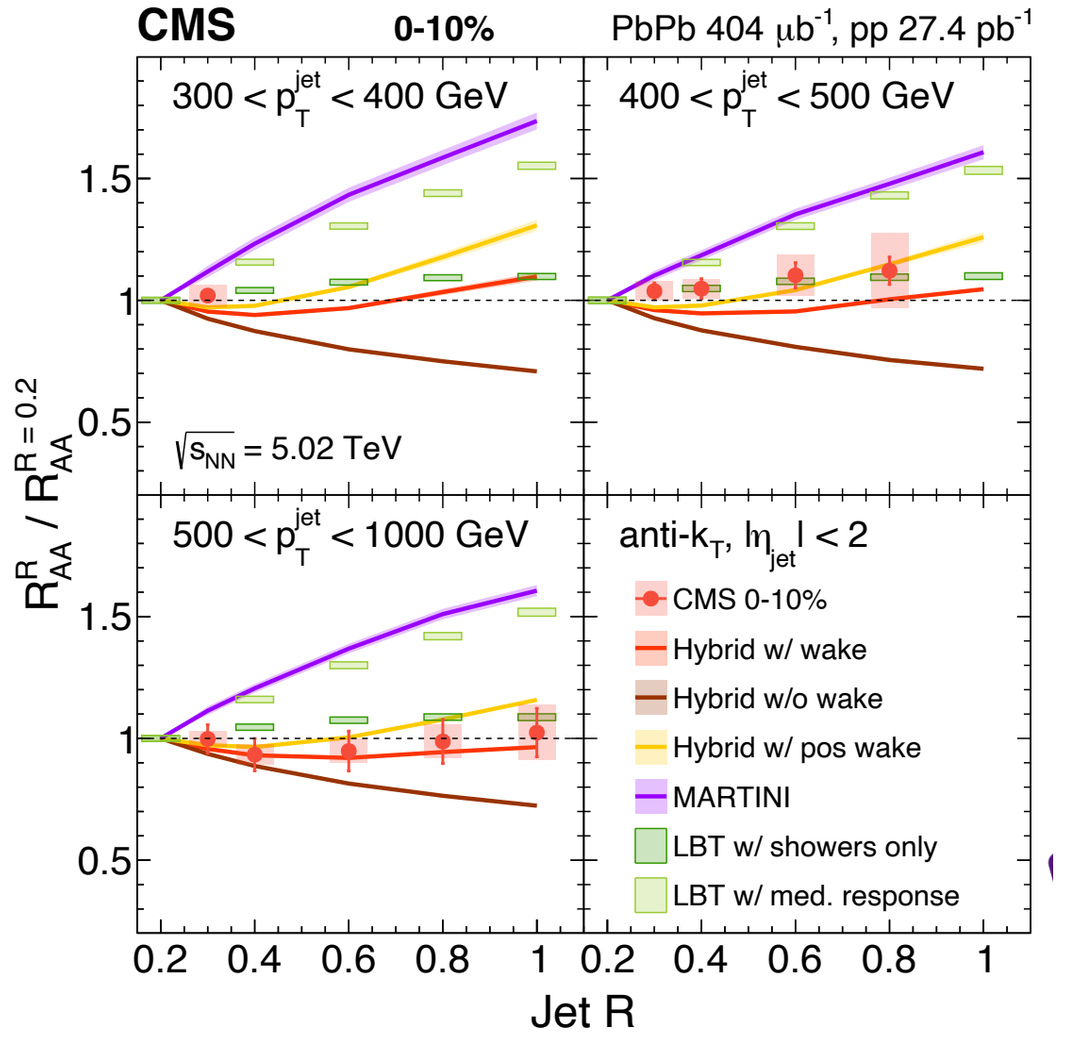
Resolution effects in many other frameworks:
Mehtar-Tani, Salgado, Tywoniuk (&JCS); JCS, Iancu; Arnold, Chang, Iqbal, Gorda; Blaizot, Dominguez et al.; Barata et al.; Caucal, Iancu and Soyez ….

RAA vs Jet Angular Size



- Jet suppression (at LHC) seems independent of R

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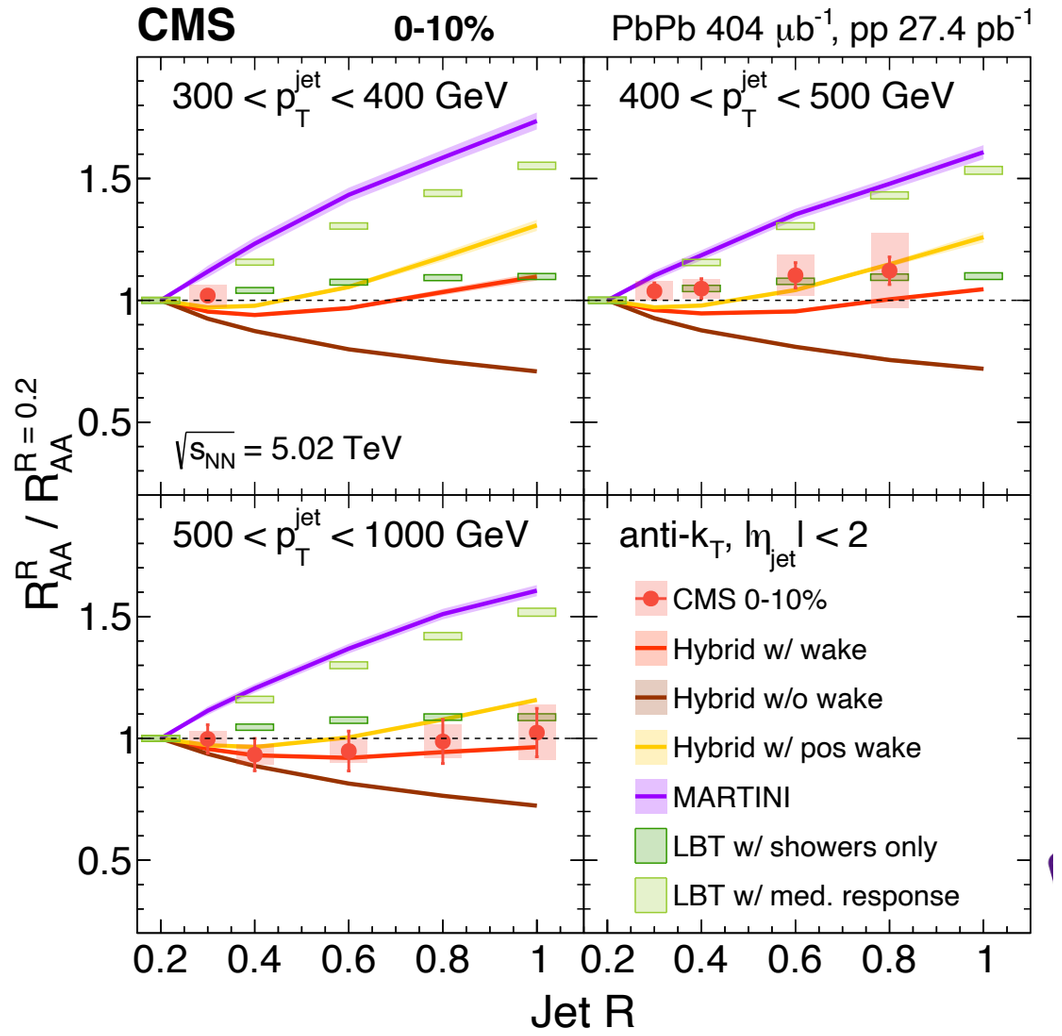

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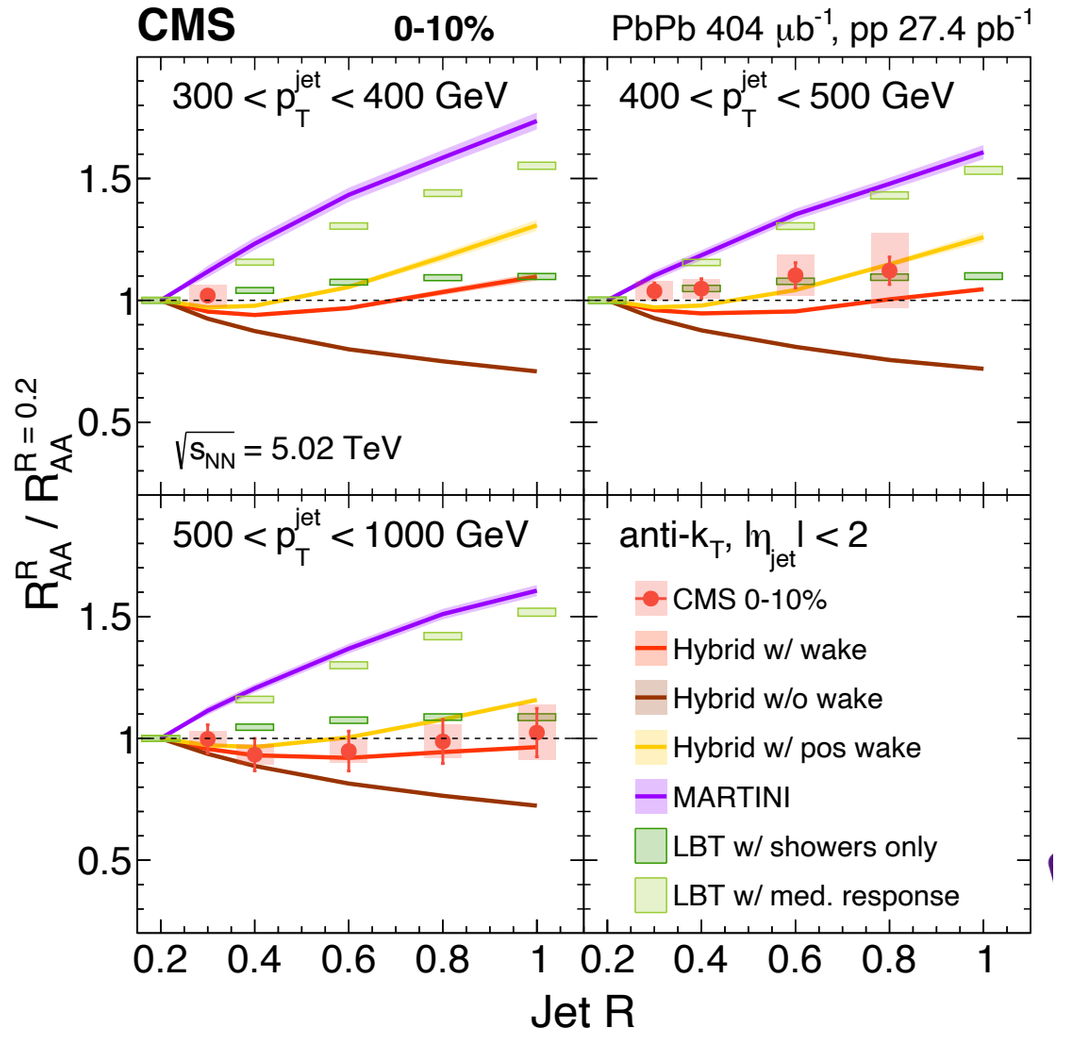

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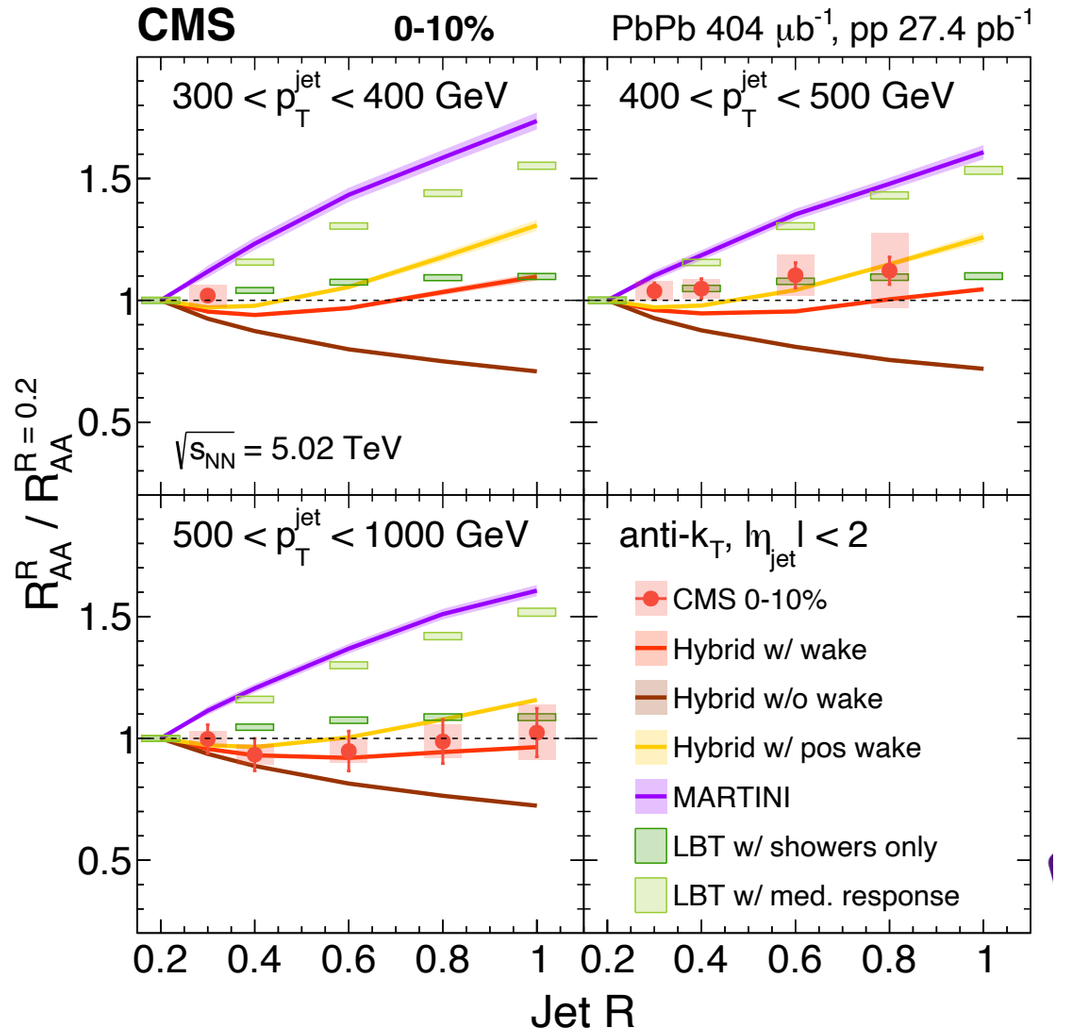

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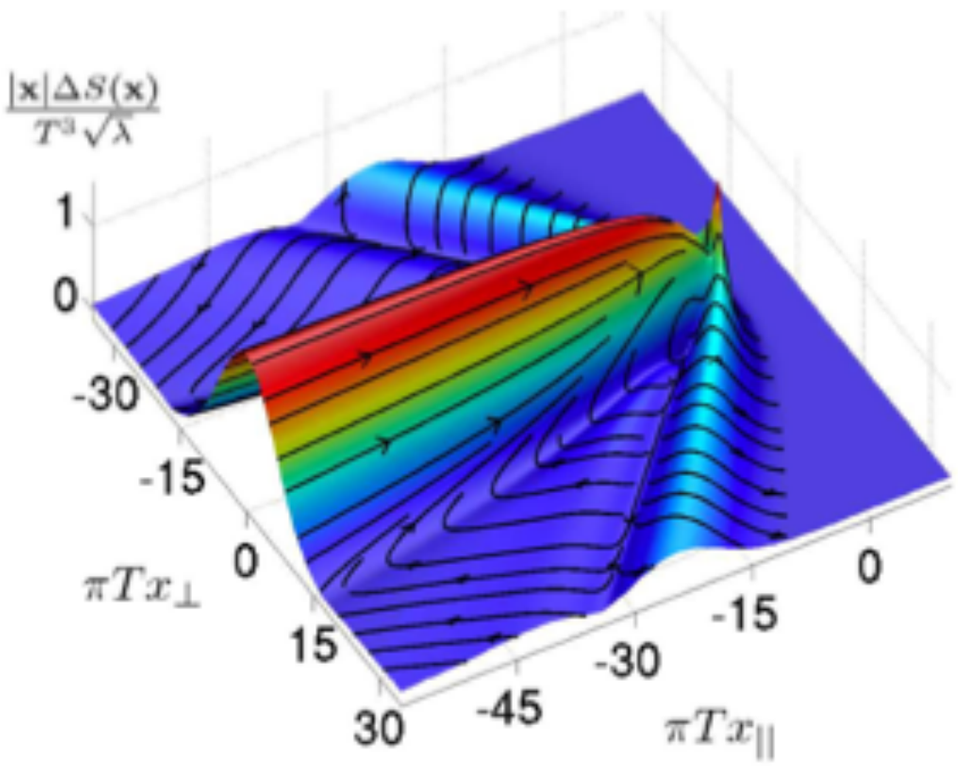
Test of the medium back-reaction

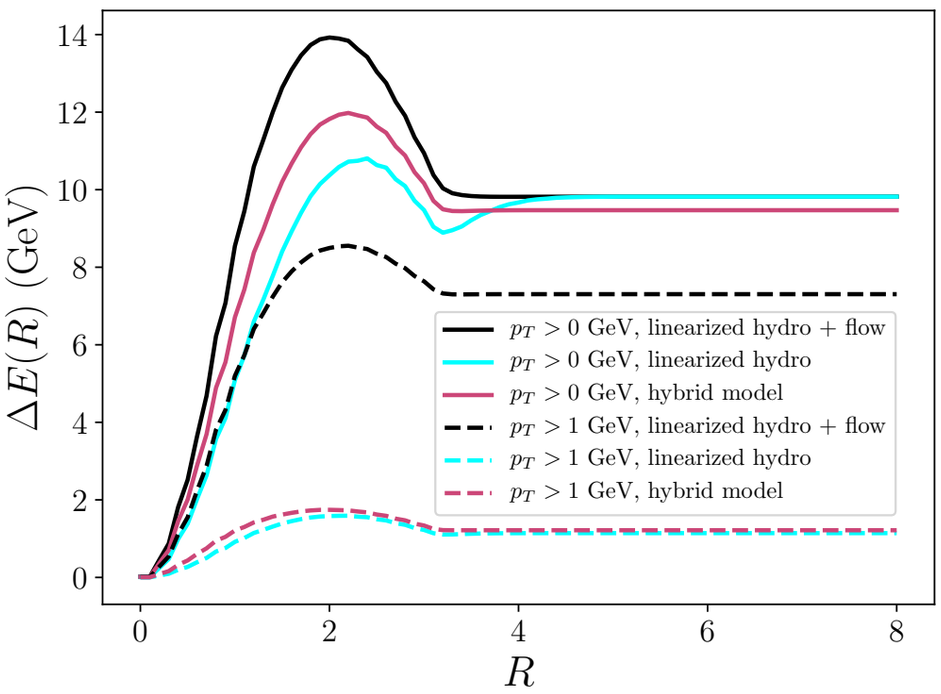
Expected Effect at Strong Coupling

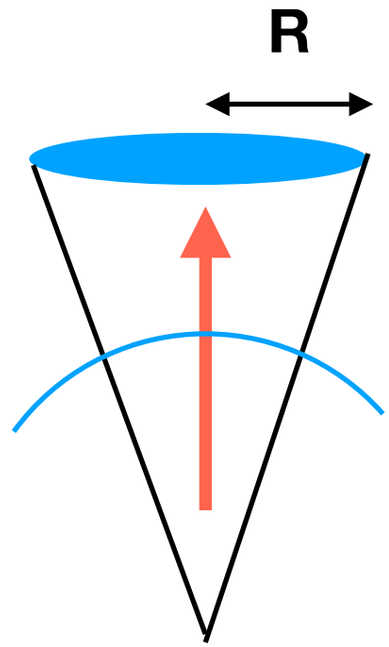
- Energy lost quickly thermalises and creates a wake

Chesler&Yaffe 07



Energy Recovered from wake





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Expected Effect at Strong Coupling

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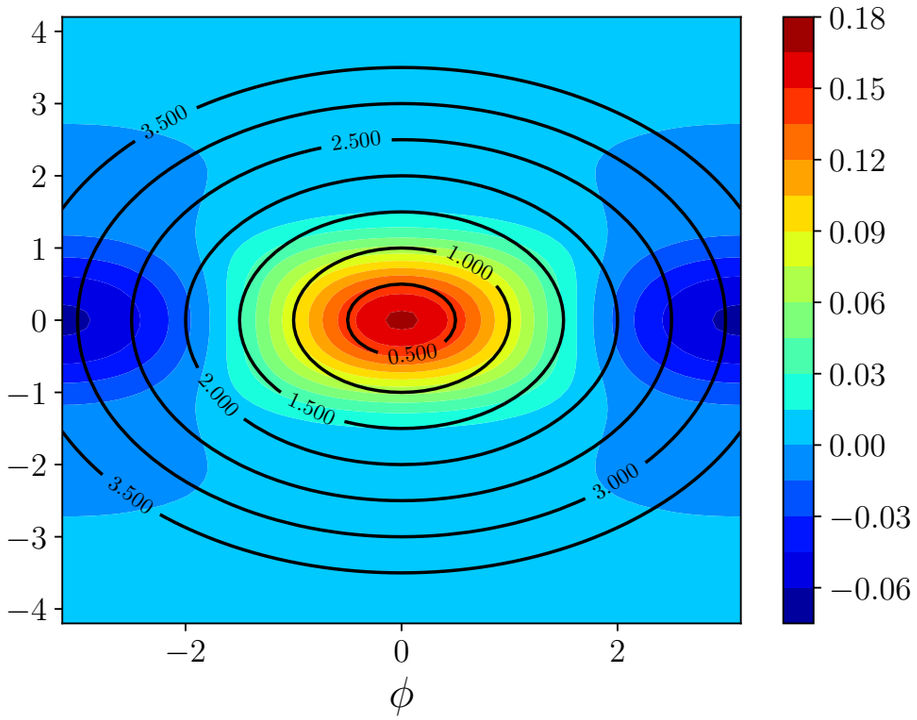
Energy density in wake particles



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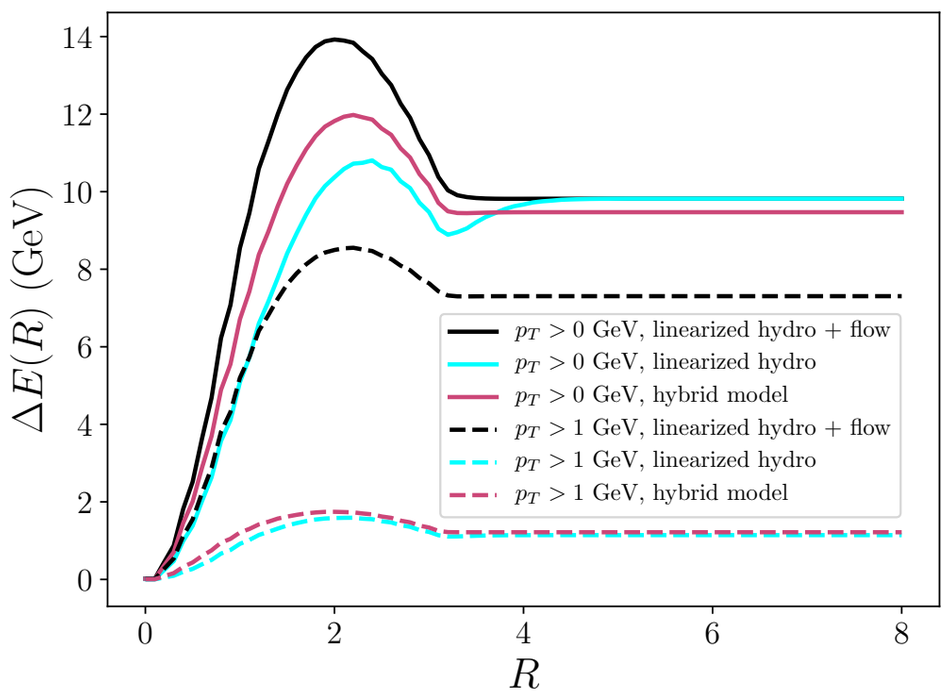

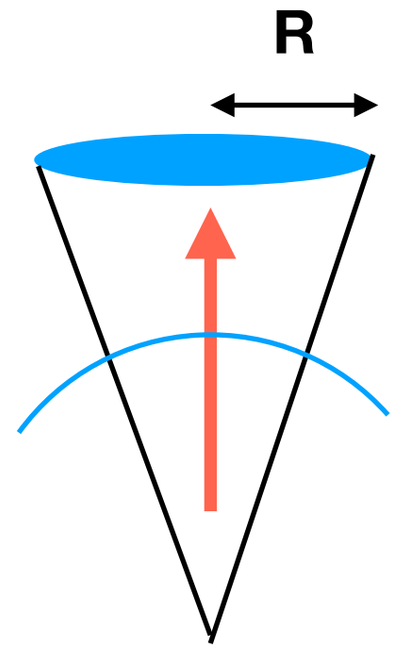

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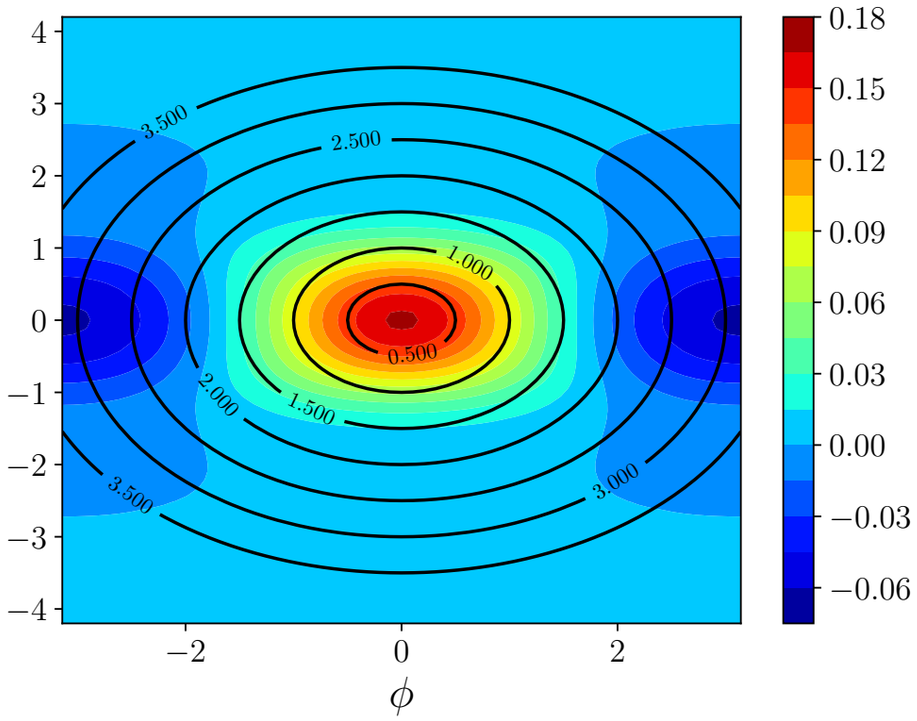

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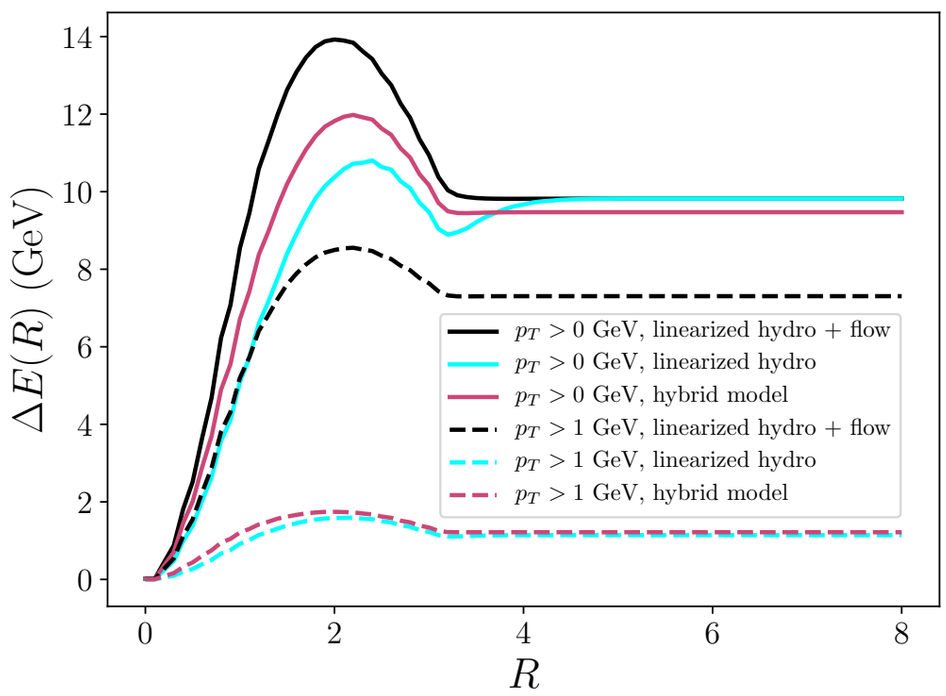

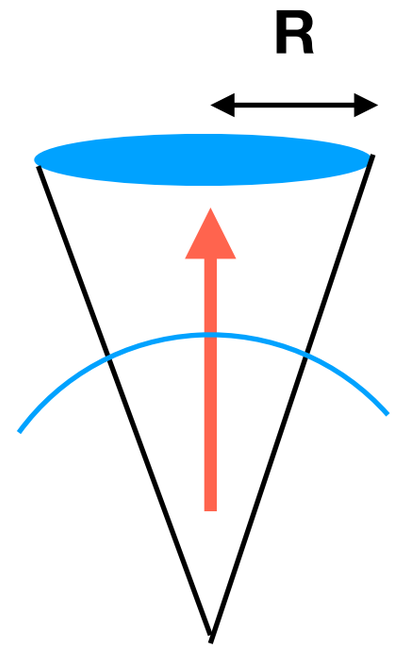

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$\Longrightarrow$depletion of particles in the direction opposite to the jet

"Negative particles"

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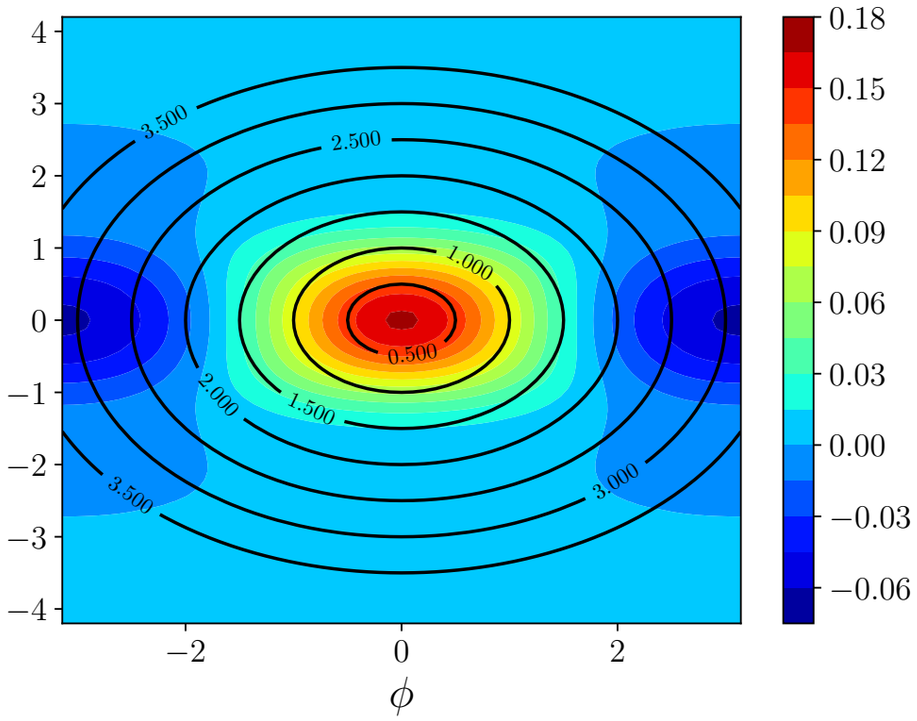
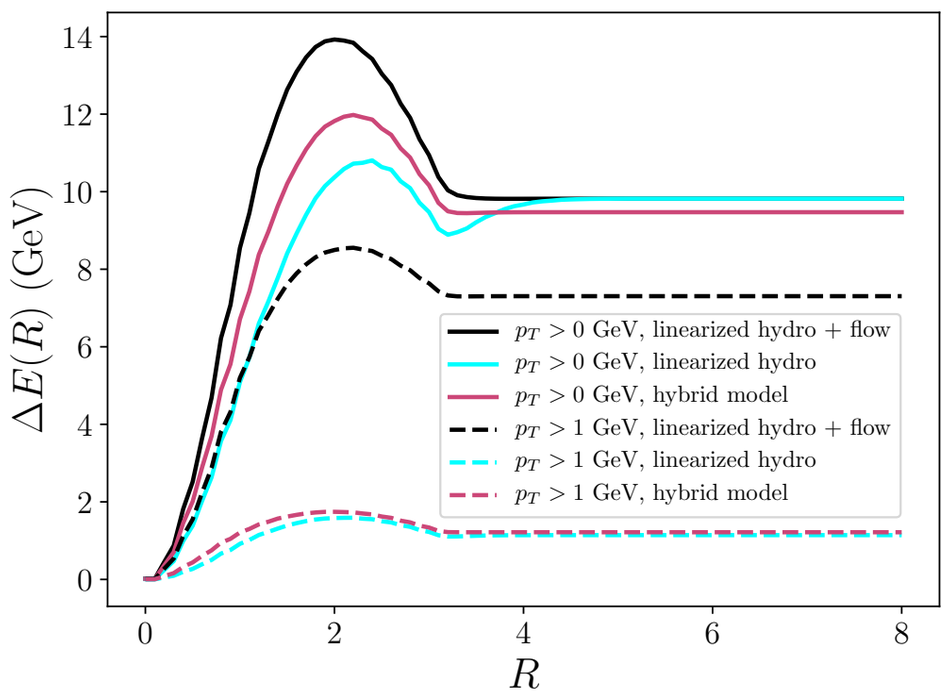
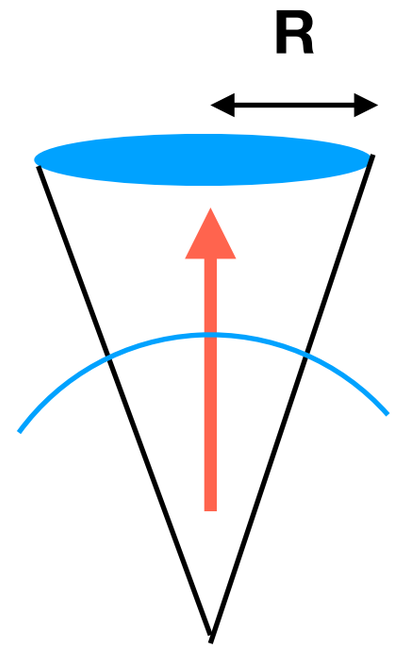


Energy Recovered from wake





- Lost energy is recovered in thermalized particles along the jet
  - The fluid is pushed along the jet direction

$\Longrightarrow$depletion of particles in the direction opposite to the jet

"Negative particles"

Also observed within the LBT framework

Expected Effect at Strong Coupling

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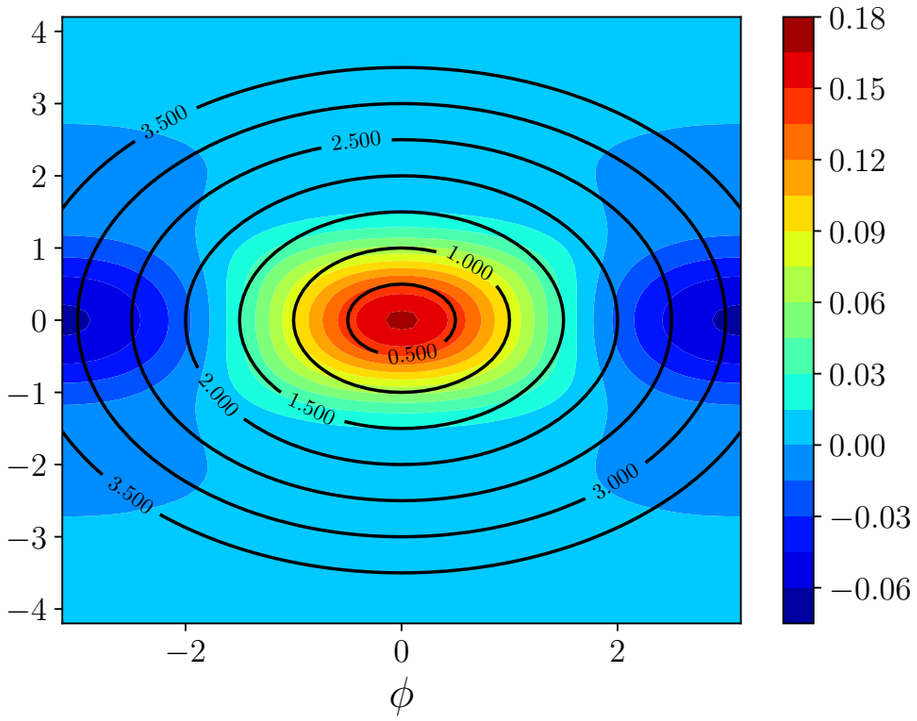

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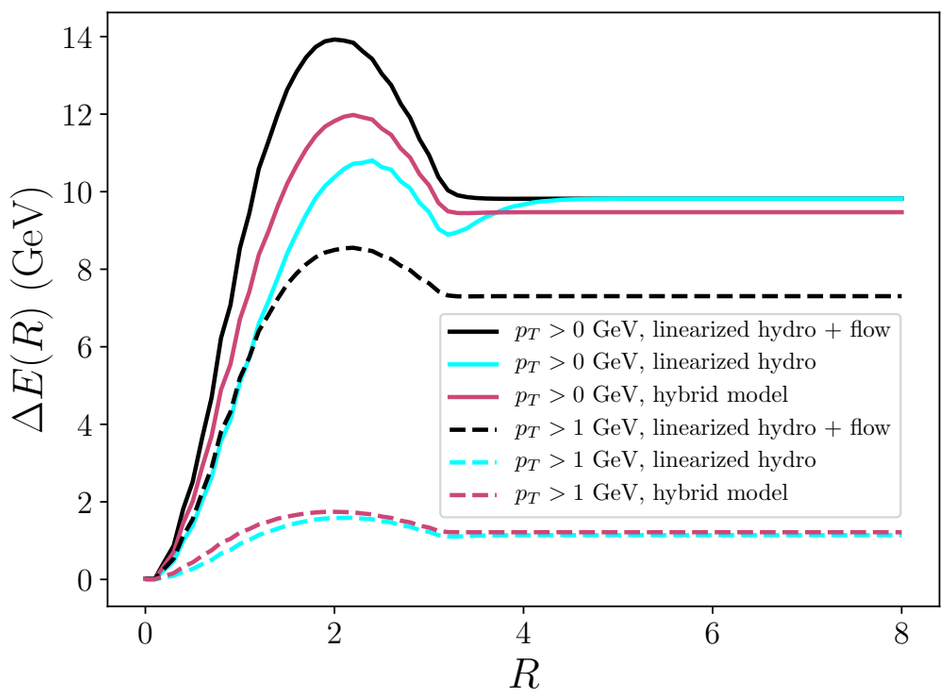

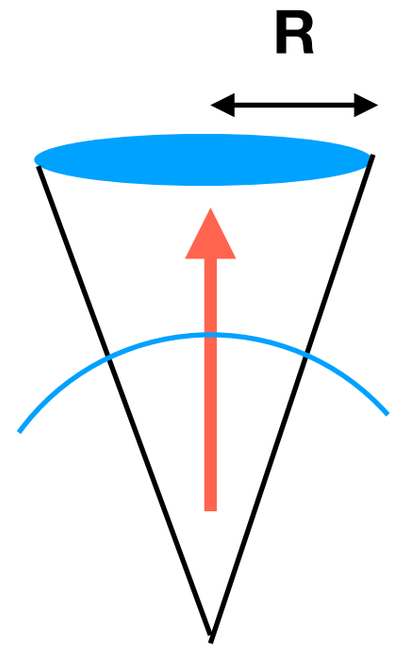

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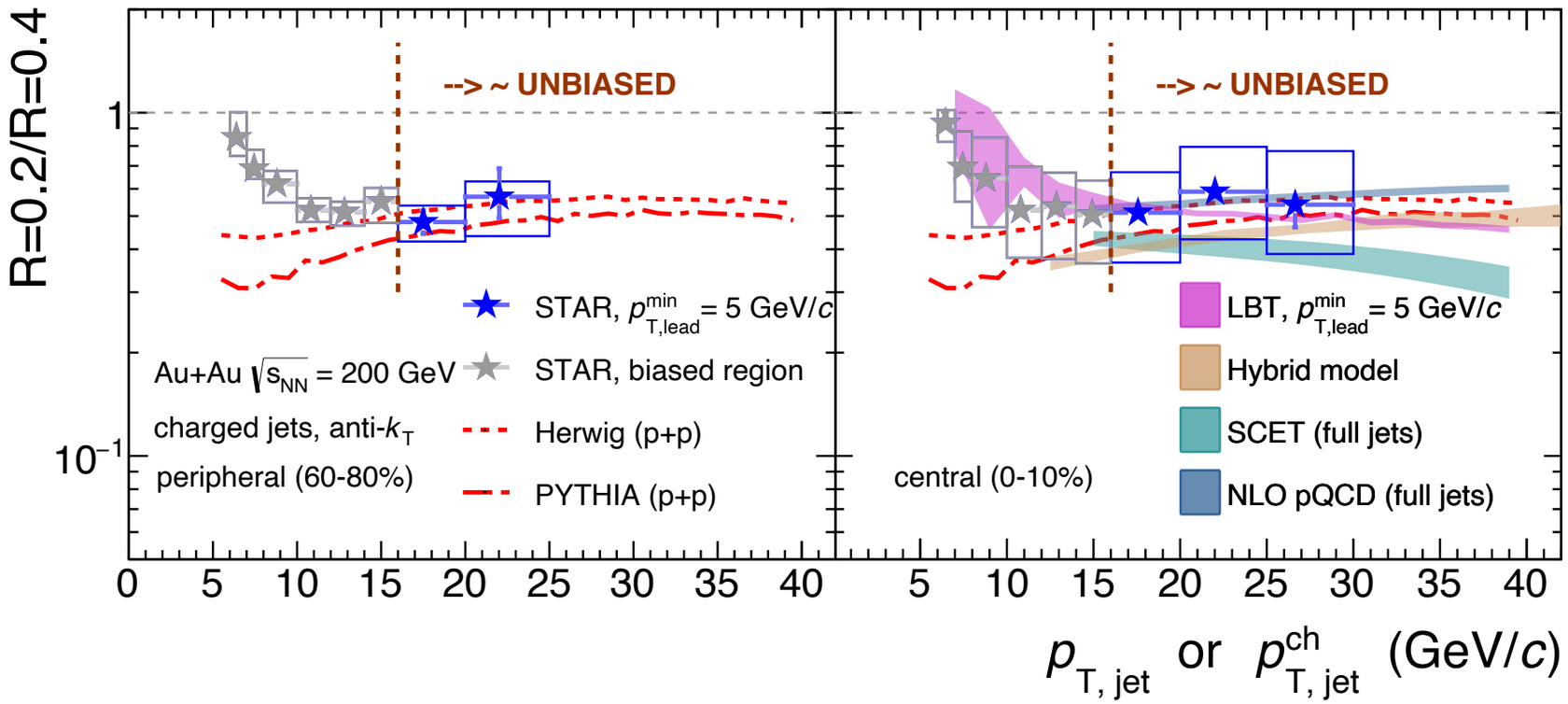
Generic expectation from hydro response

R-Dependence at RHIC

- Apparent inconsistency with LHC results



- Narrow jets are more suppressed

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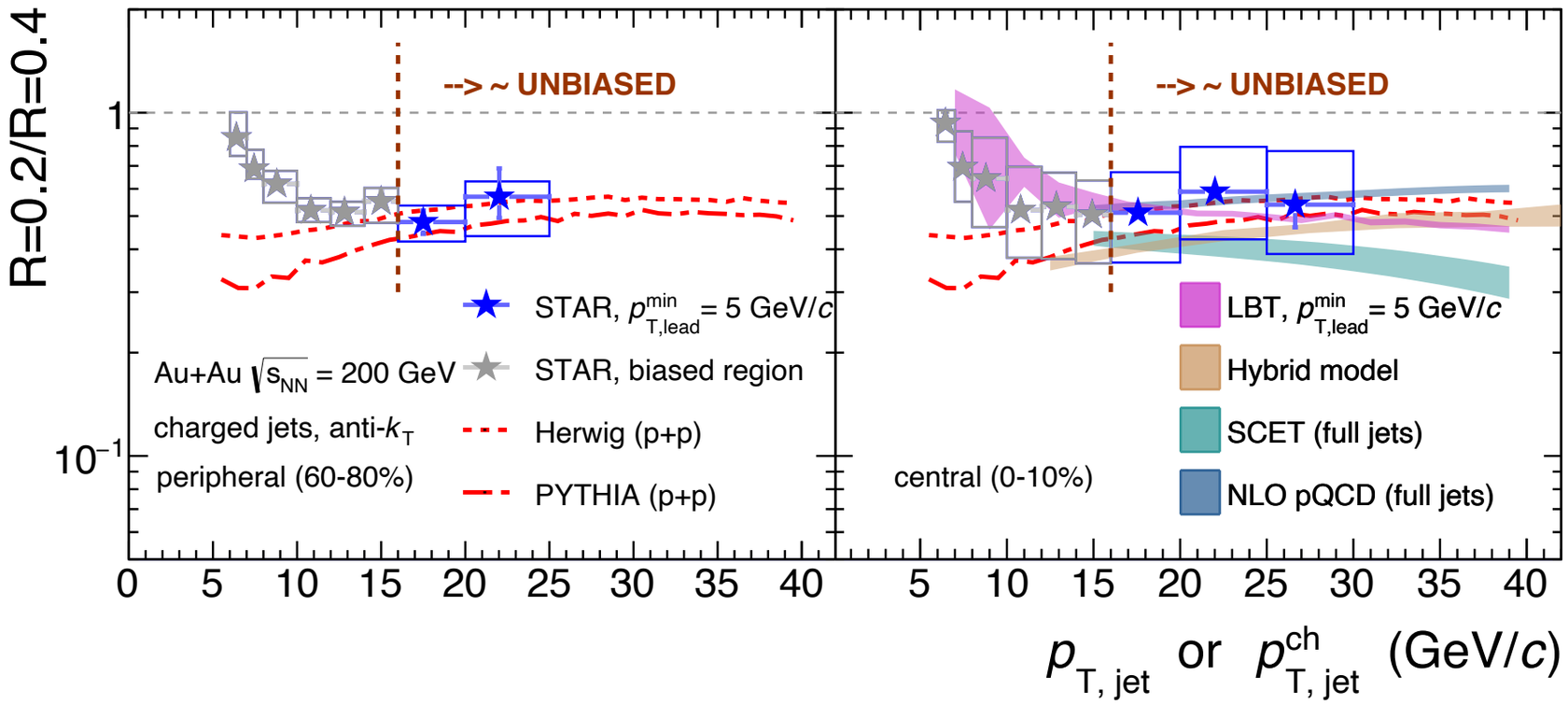

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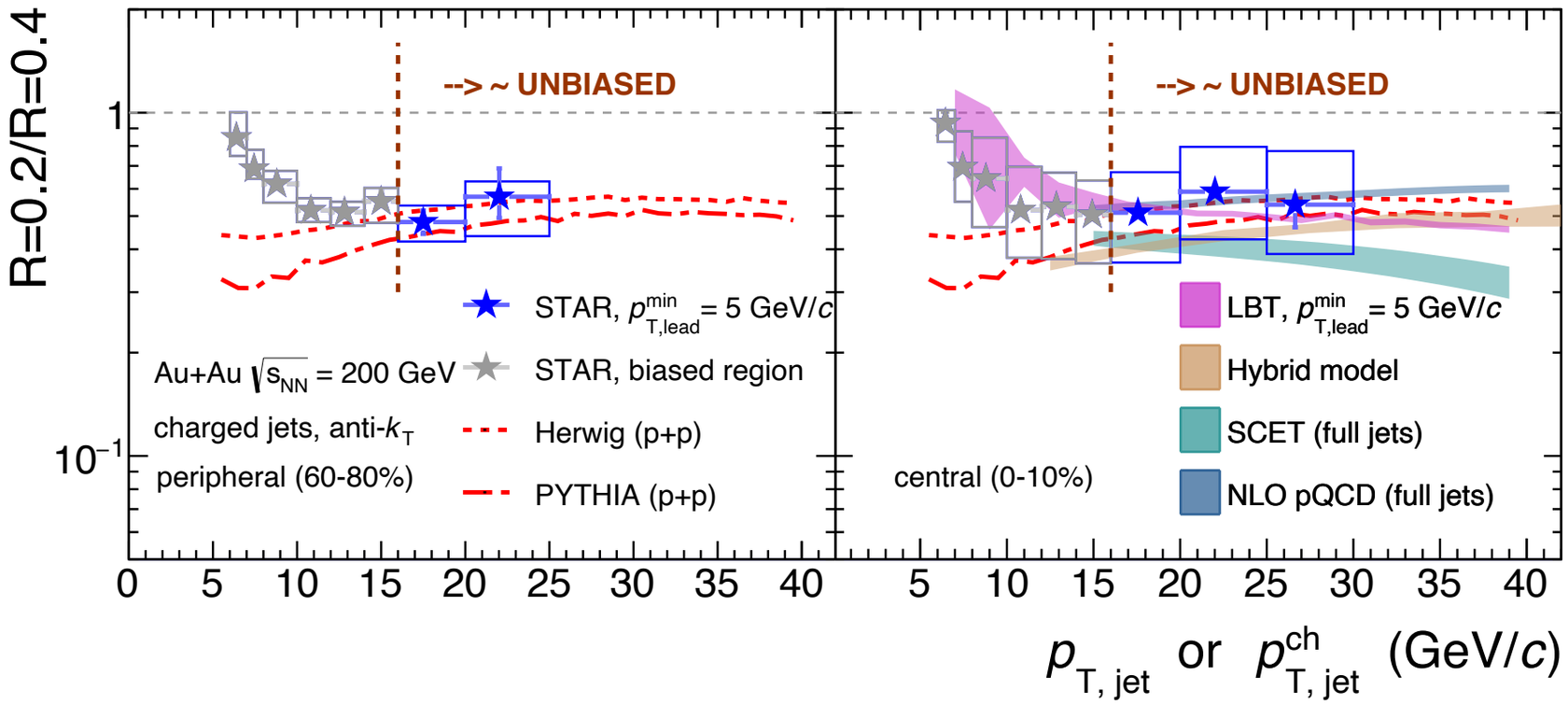

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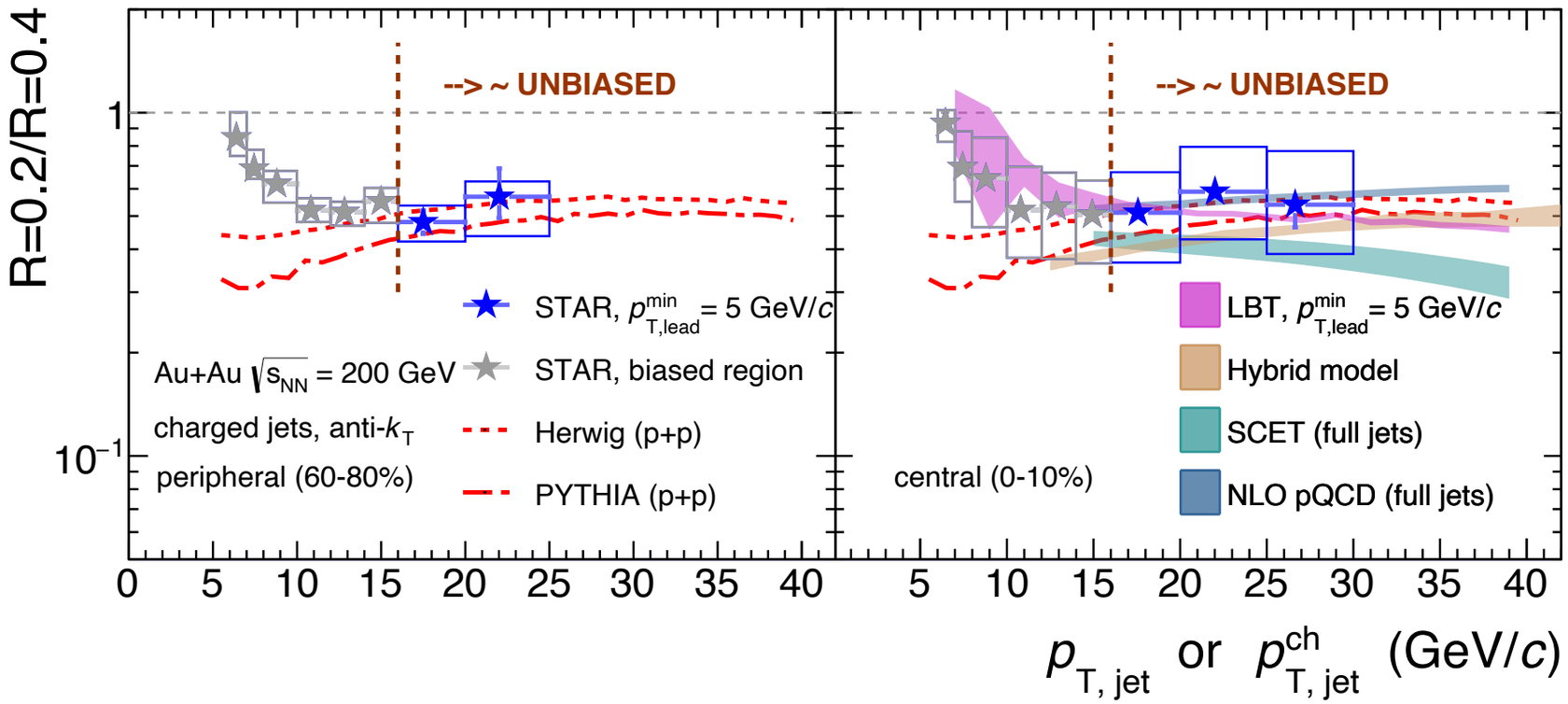

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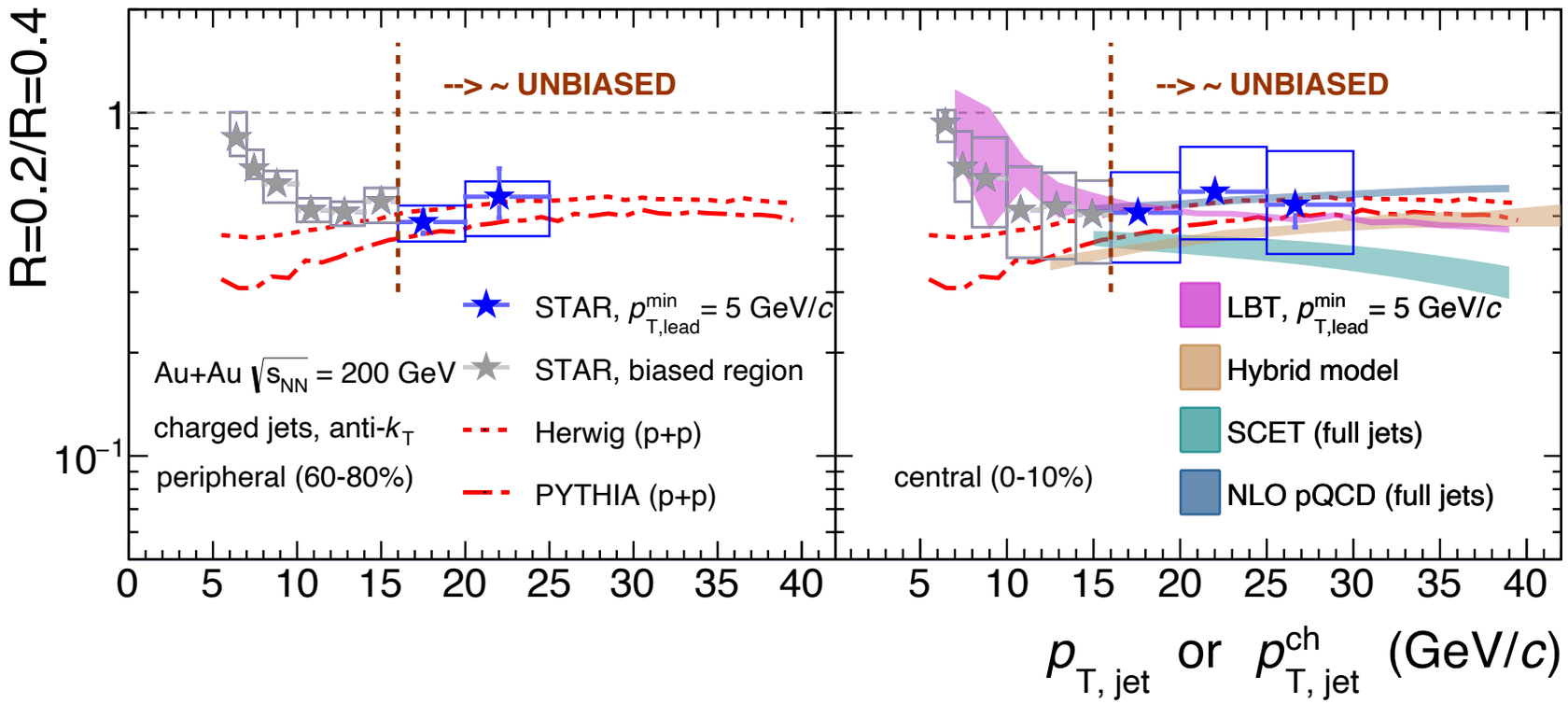

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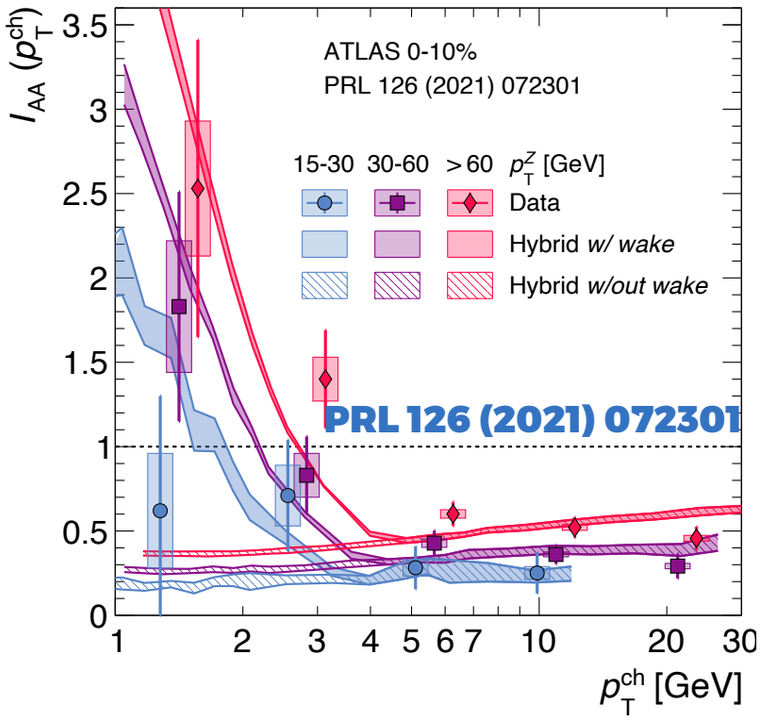
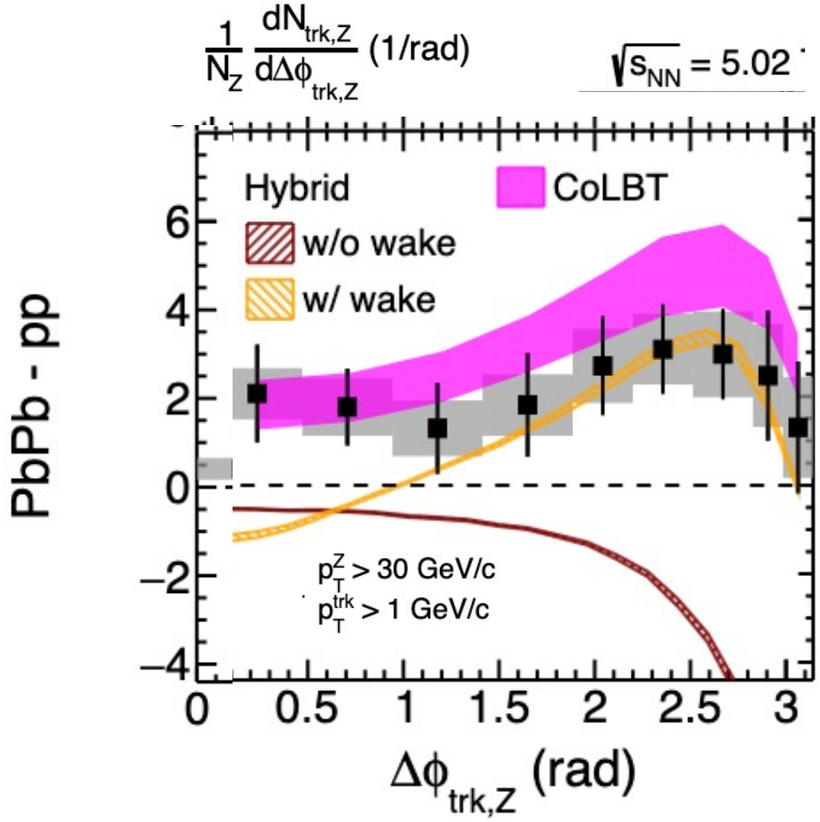
      $\Longrightarrow$over-subtraction in the leading jet

Z-hadron Correlations

- A complementary test of medium response





Phys. Rev. Lett. 128 (2022) 122301

- Jet wake: soft particles at large angles

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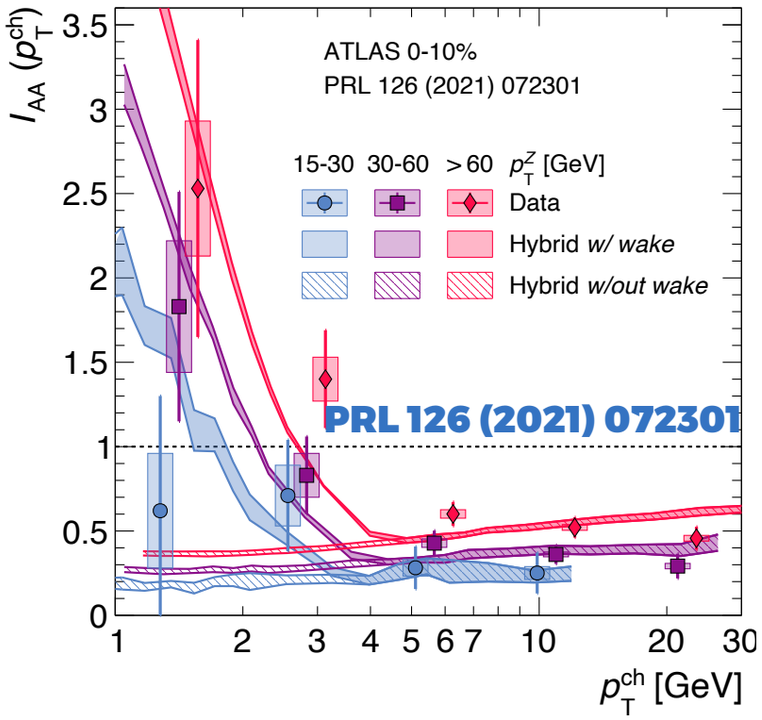

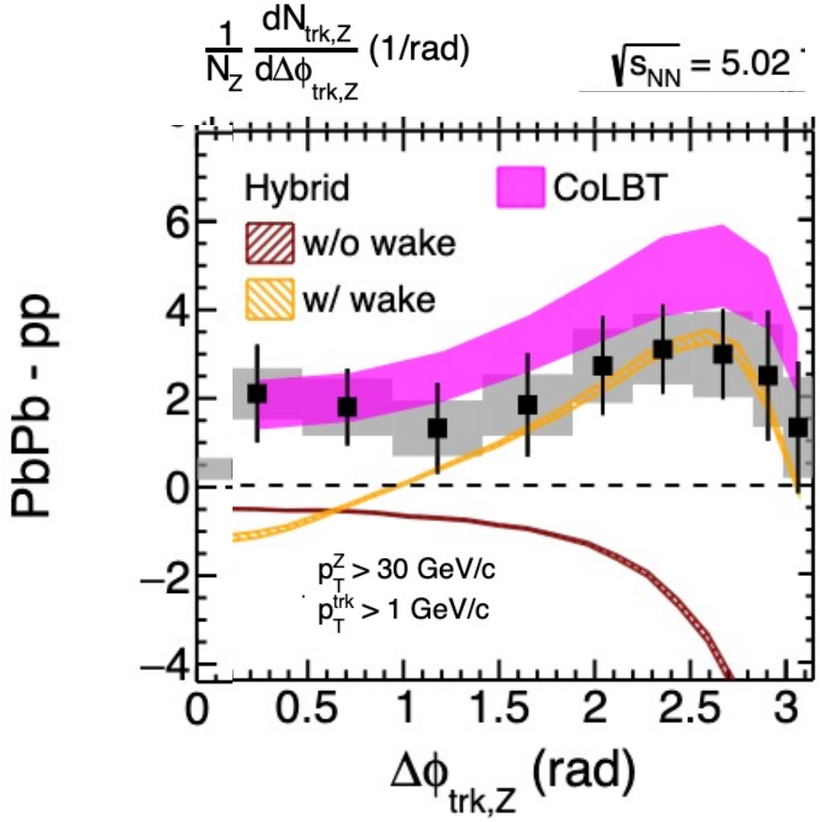

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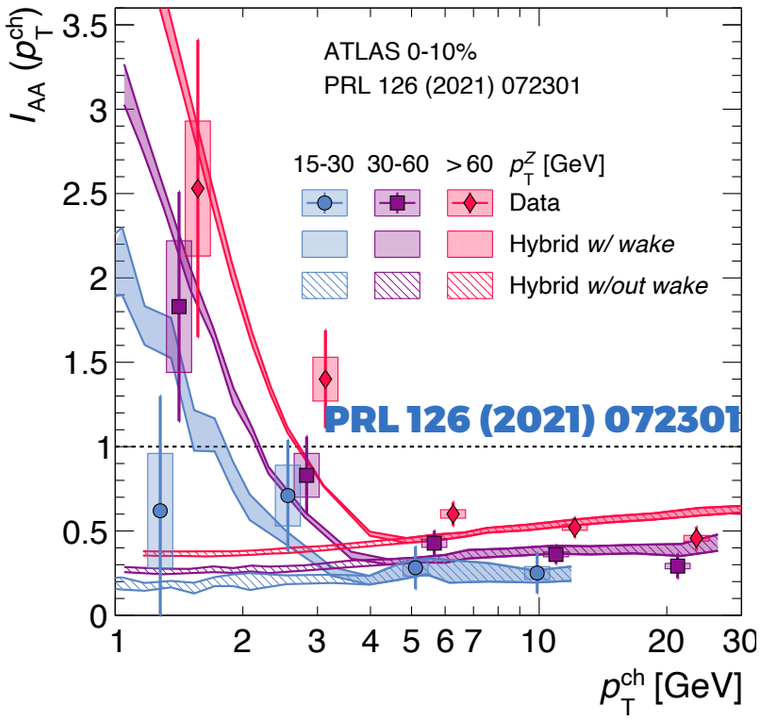

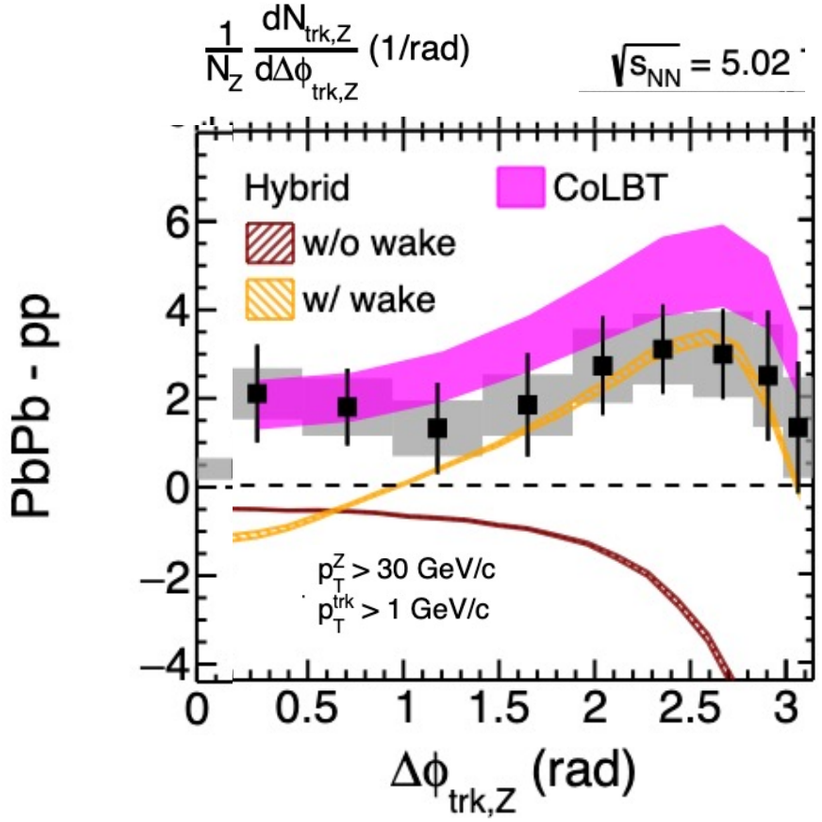

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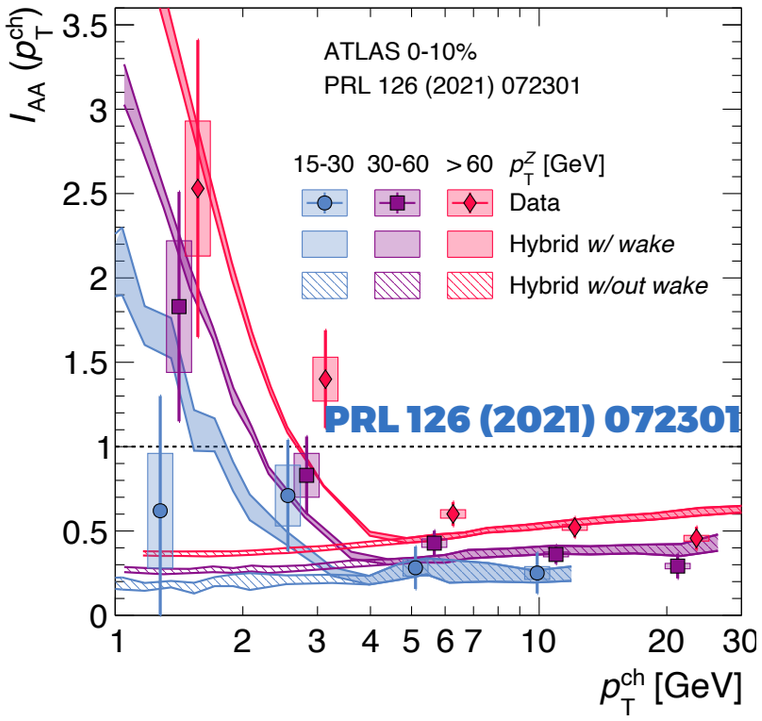

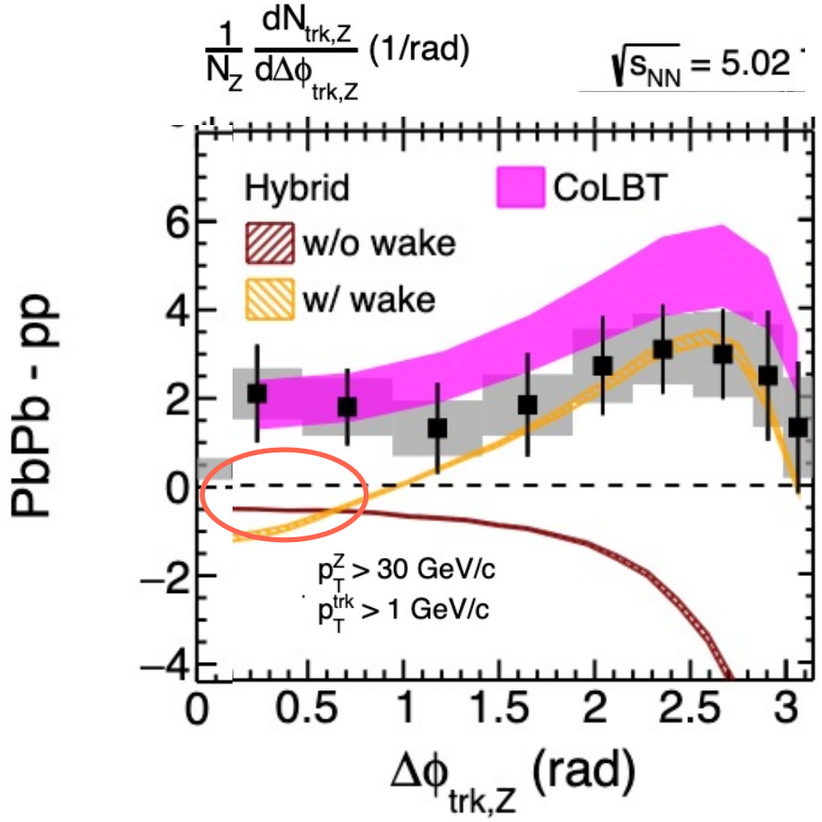

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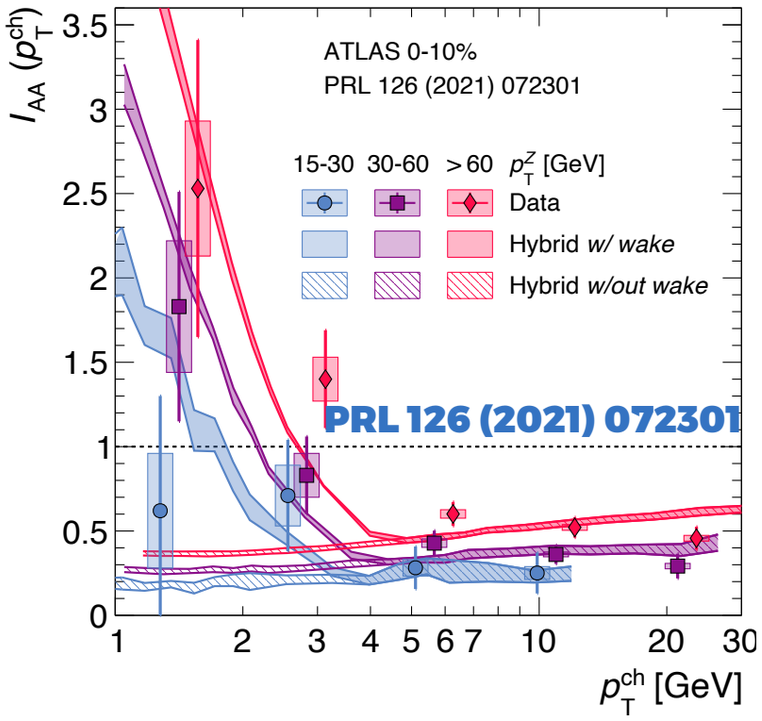

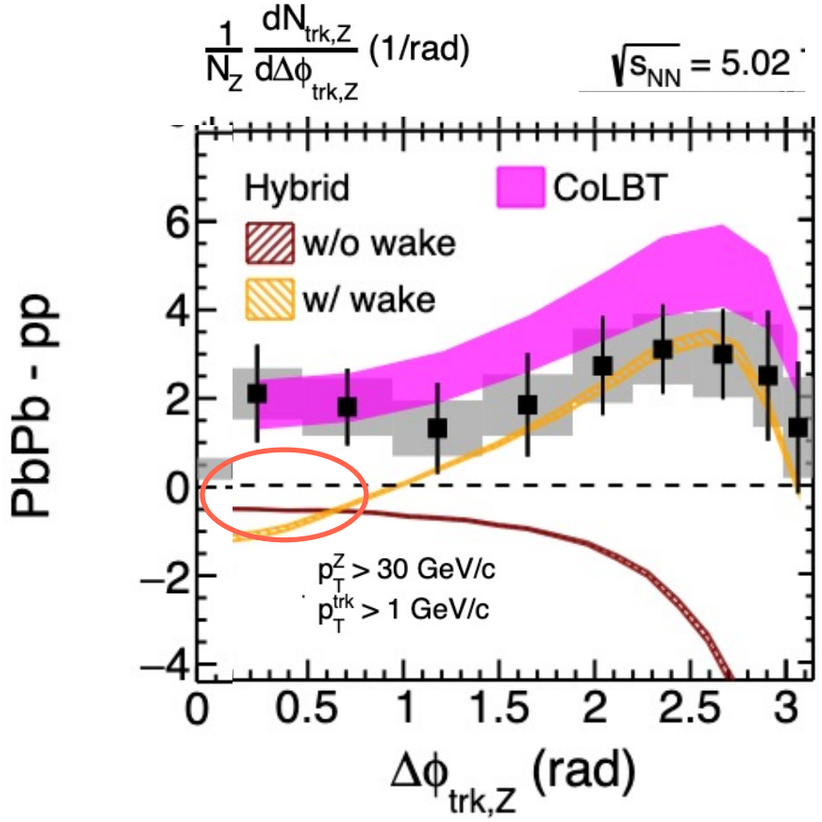

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"Too many negatives"

An Implementation Problem

- Monte Carlo analysis: millions of events
- Full hydro analysis of back-reaction:

  Simulating an event is very time consuming

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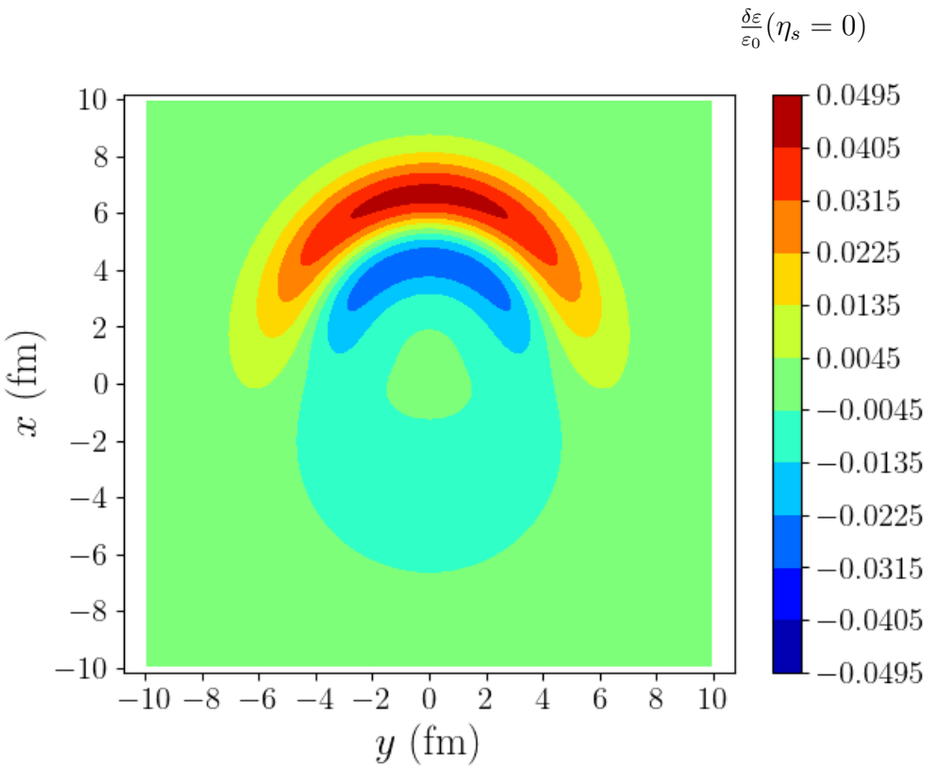
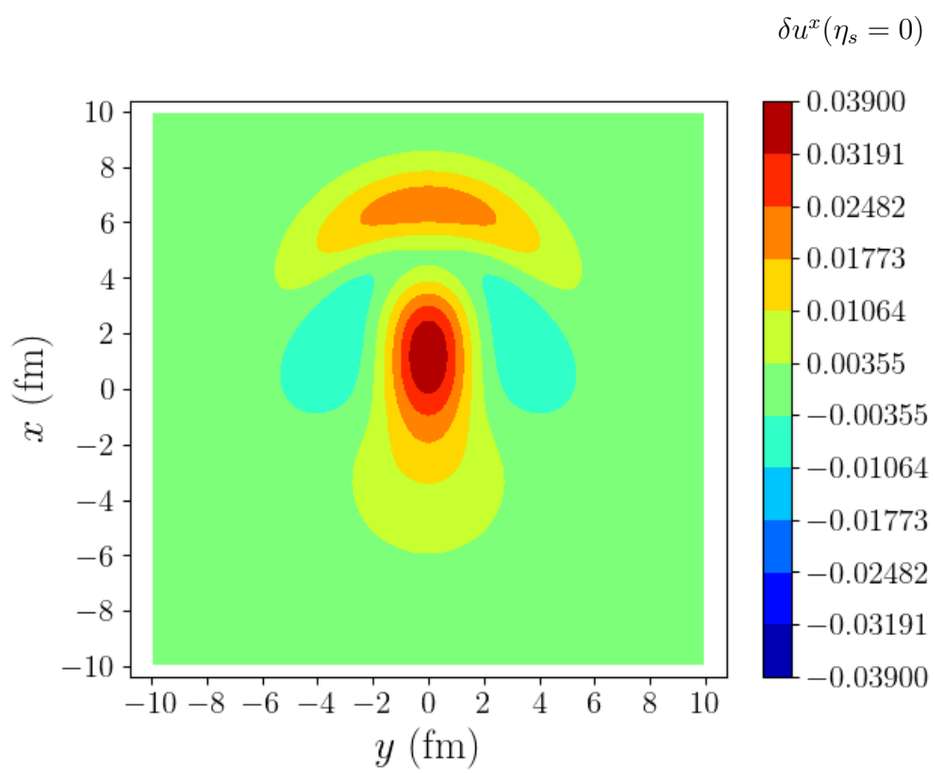
We need to do better

Step 1: Hydro Solutions

- Linearized hydrodynamic perturbation on-top of Bjorken flow





Advantages:

Valid semi-hard momenta

Hydro fields from lin. superposition

(Only depends on deposition time)

Disadvantages:

No transverse flow

Incorporating Transverse Flow

- An “approximate” procedure

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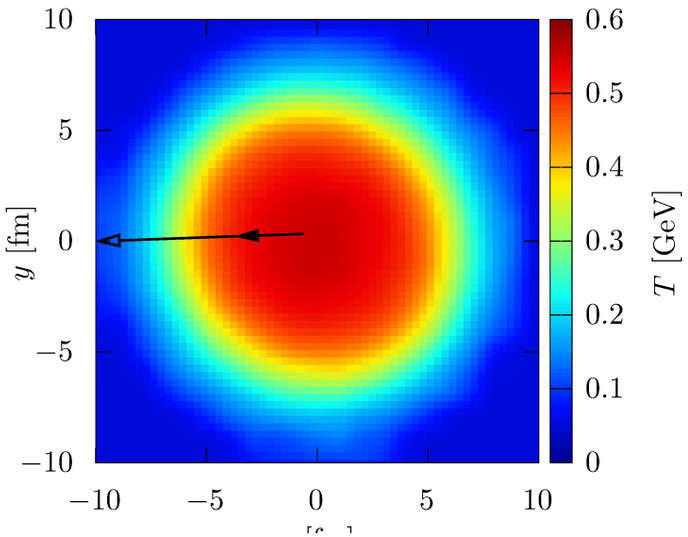
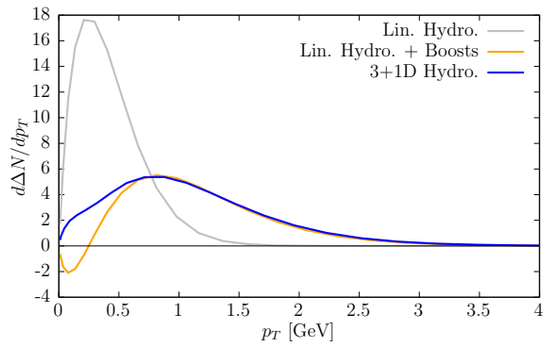
- Flow fields are generated fast
  - Library of cases for each deposition time + linear superposition

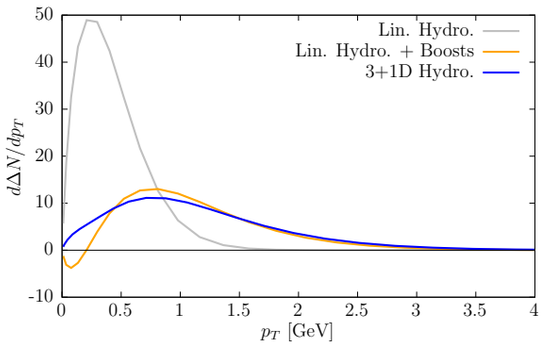
Calibration Against Full Hydro



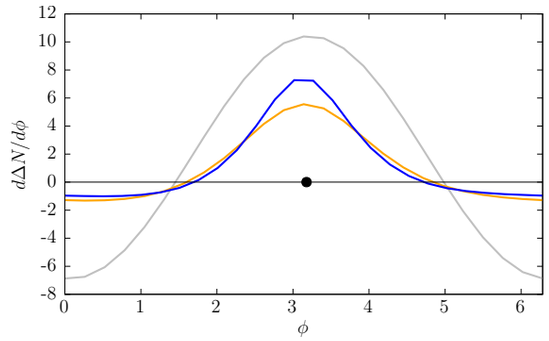
- Excellent agreement with non-linear hydro
- Spectrum is harder and more narrow than before
- Reduction of “negatives”



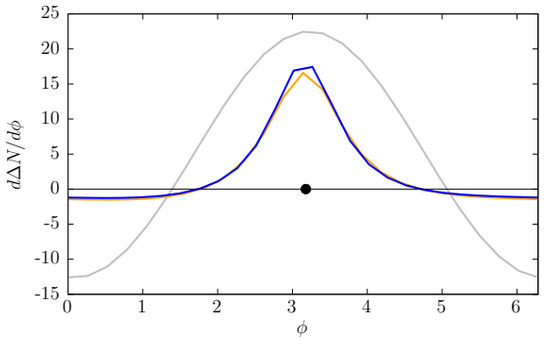
(b) p_T distribution for $E_i = 10$ GeV.



(c) p_T distribution for $E_i = 50$ GeV.



(d) ϕ distribution for $E_i = 10$ GeV.



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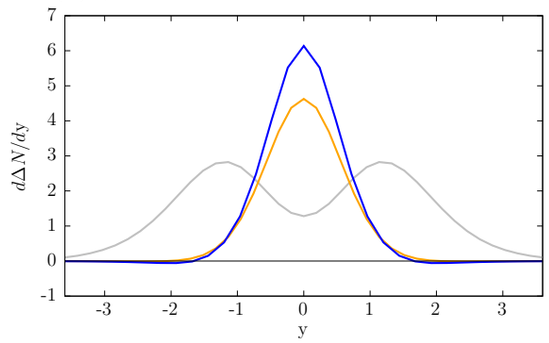
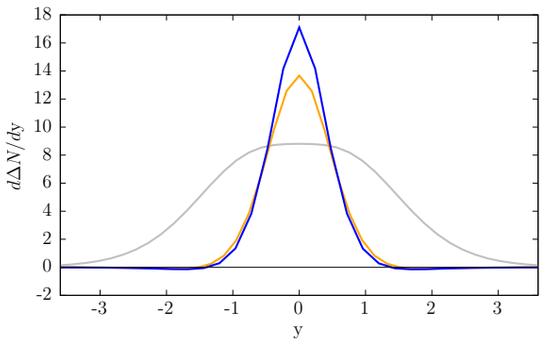


(f) y distribution for $E_i = 10$ GeV.

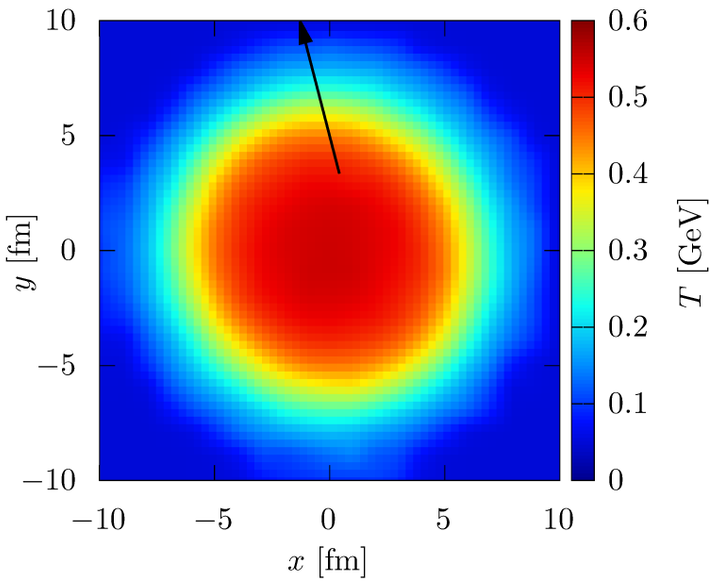


(g) y distribution for $E_i = 50$ GeV.

Non-linear hydro response from Music

Other non-linear response: Tachibana et al.; CoLBT

Calibration Against Full Hydro



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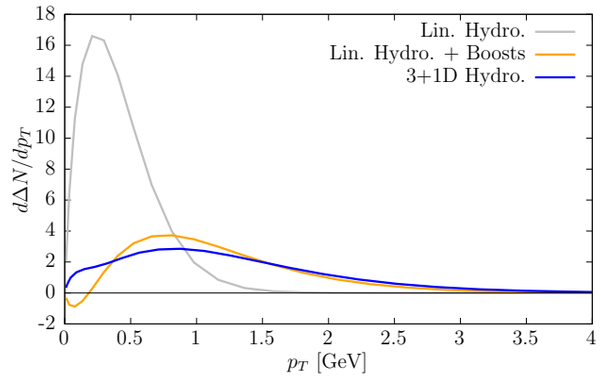

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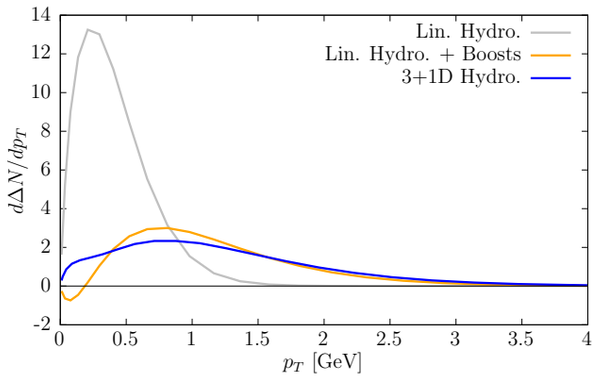

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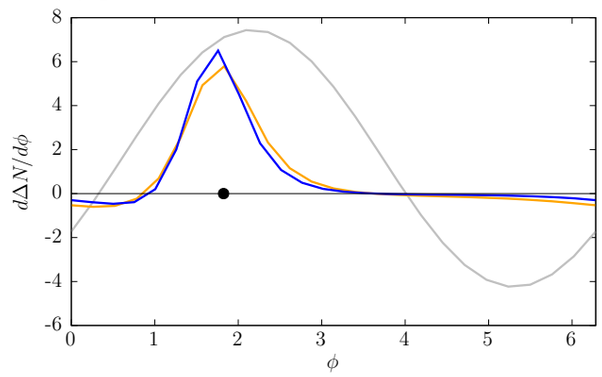

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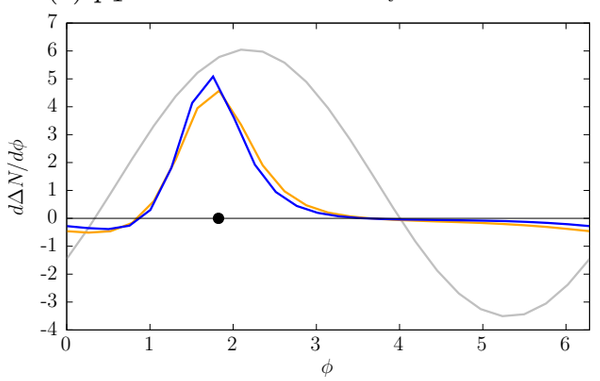

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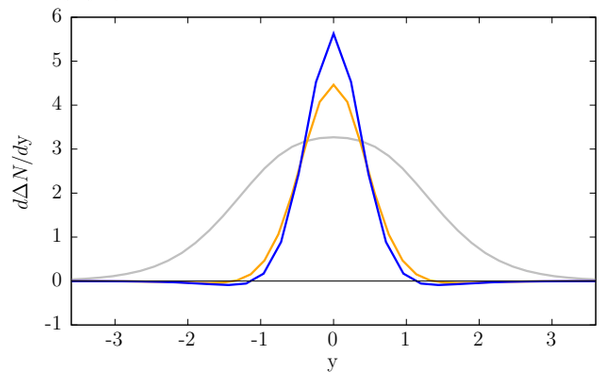
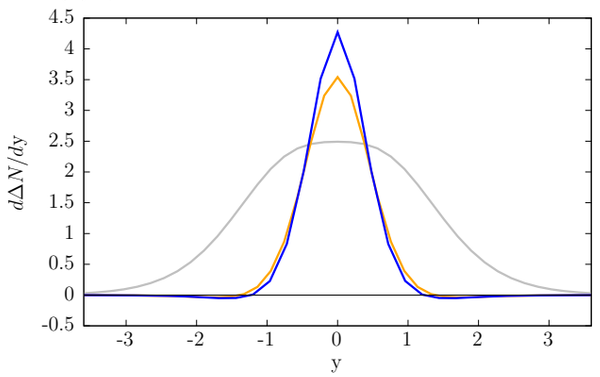
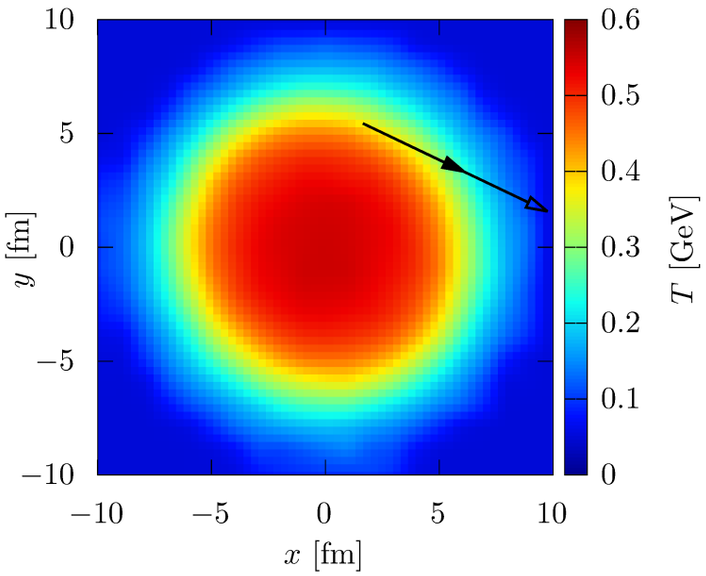




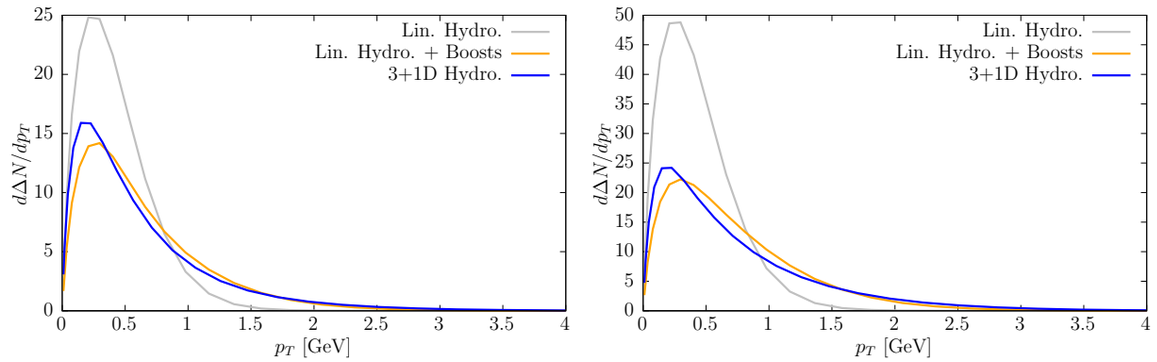
Non-linear hydro response from MUSIC

Other non-linear response: Tachibana et al.; CoLBT

Calibration Against Full Hydro



- Good agreement with non-linear hydro
- Spectrum is harder than before
- Intricate angular structure



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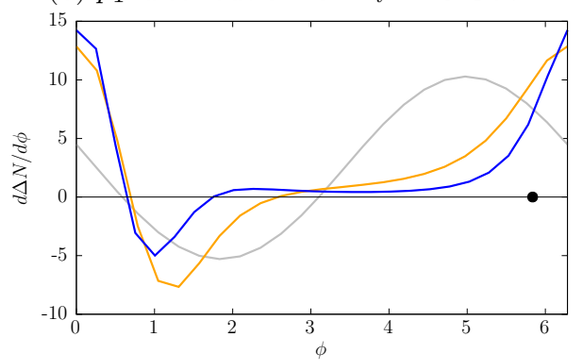

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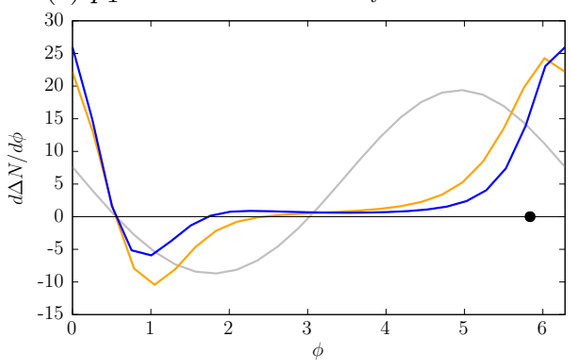

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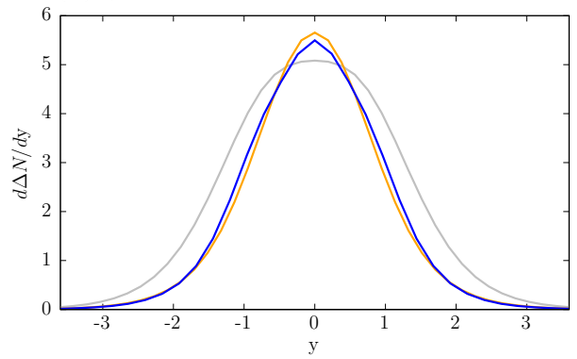

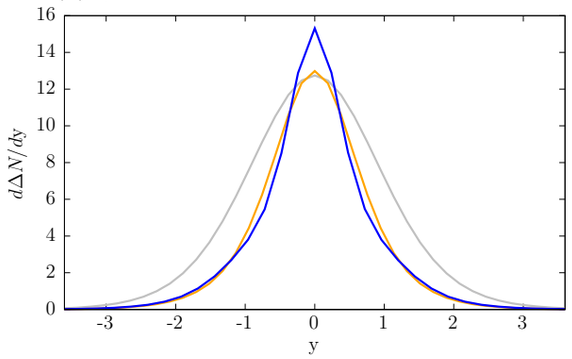

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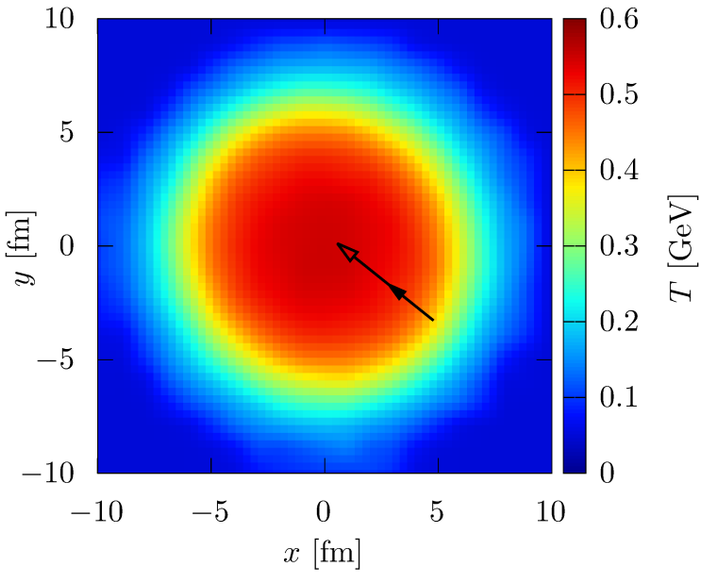
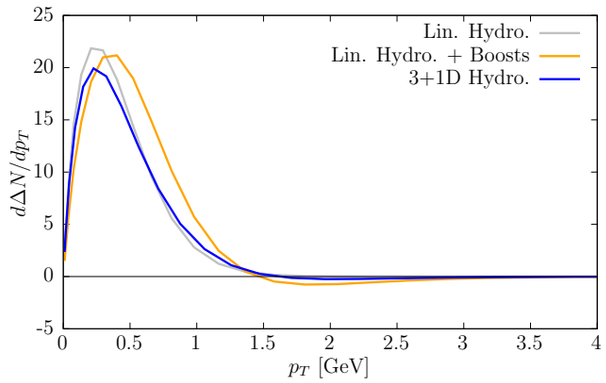
Other non-linear response: Tachibana et al.; CoLBT

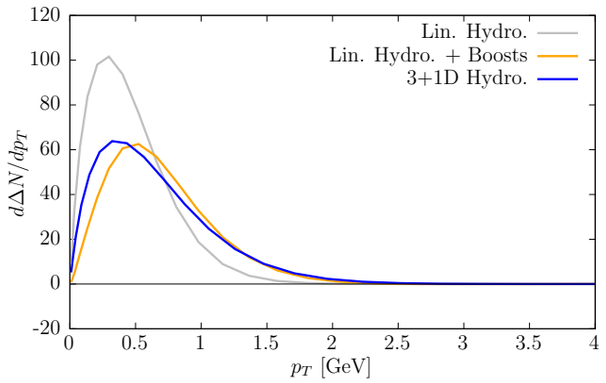
Calibration Against Full Hydro



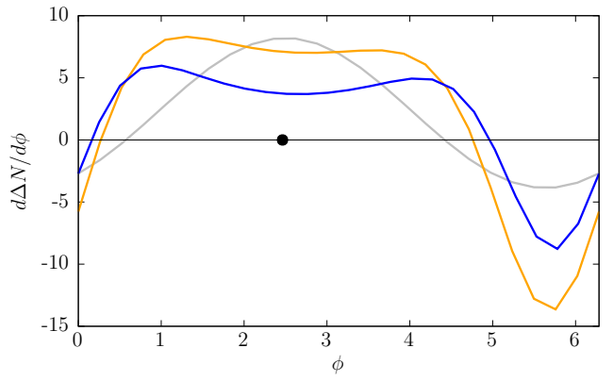
- Semi-quantitative agreement with non-linear hydro
- Spectrum is harder than before
- Intricate angular structure



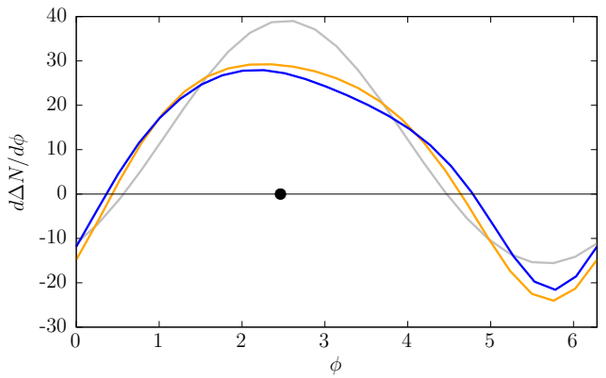
(b) p_T distribution for $E_i = 10$ GeV.



(c) p_T distribution for $E_i = 50$ GeV.



(d) ϕ distribution for $E_i = 10$ GeV.



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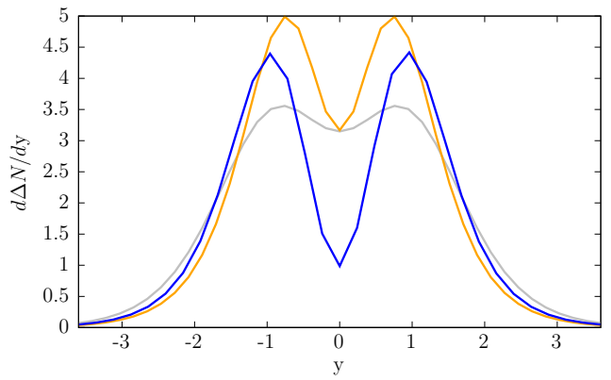
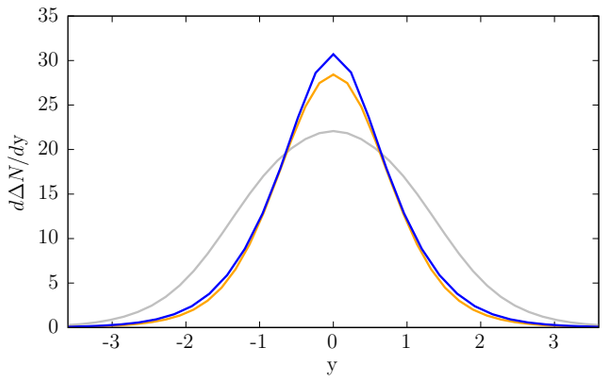
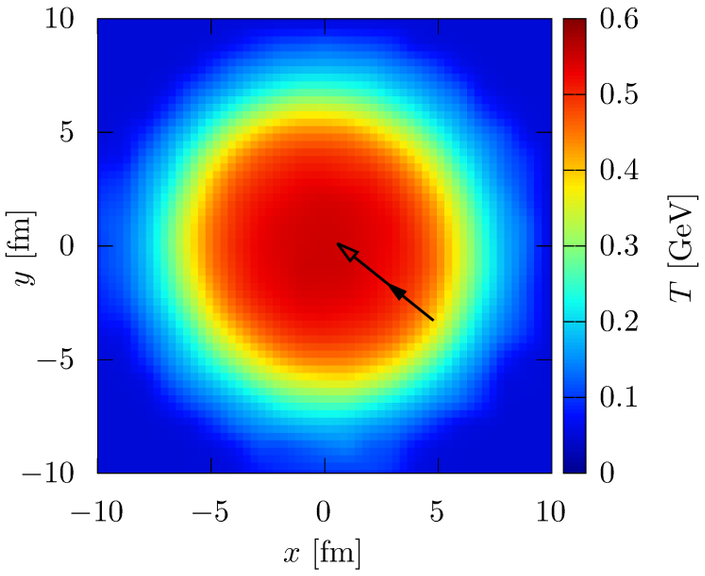




Non-linear hydro response from MUSIC

Calibration Against Full Hydro



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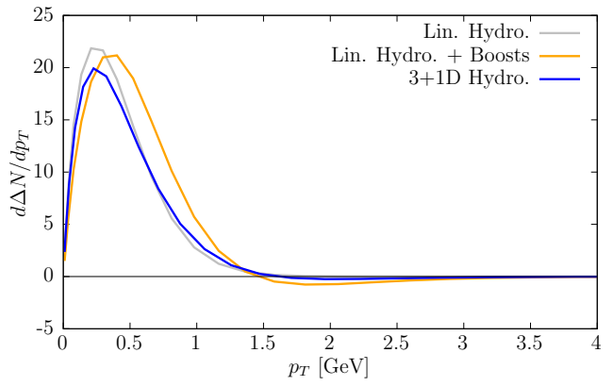

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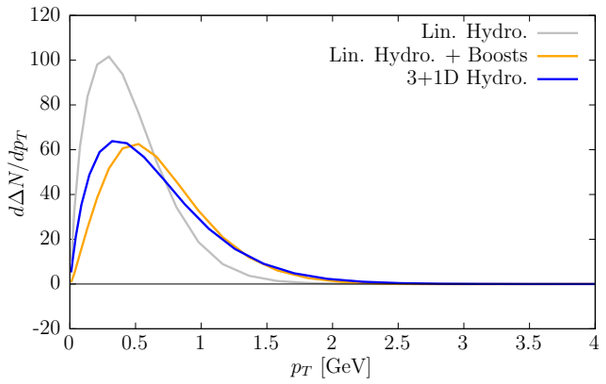

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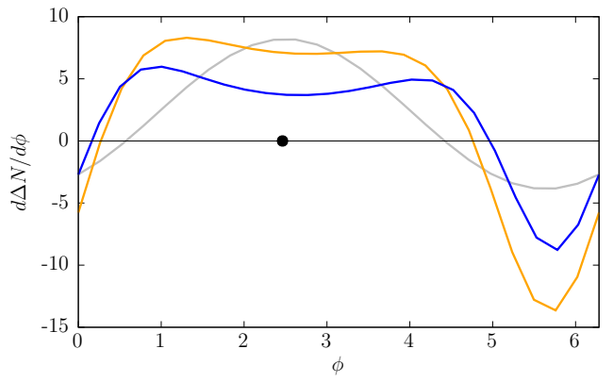

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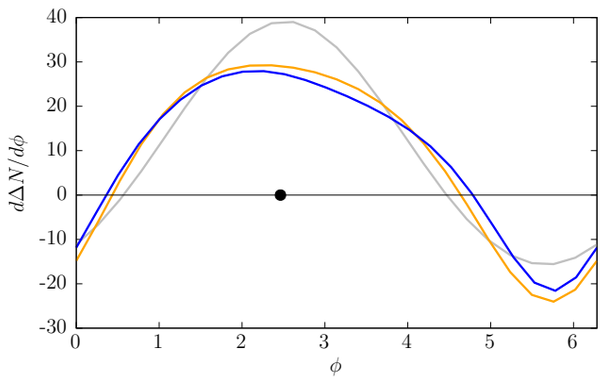

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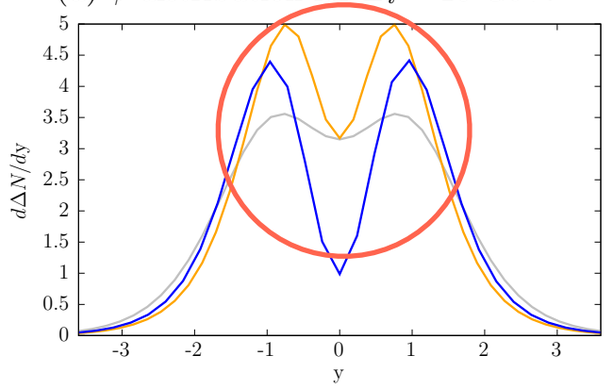
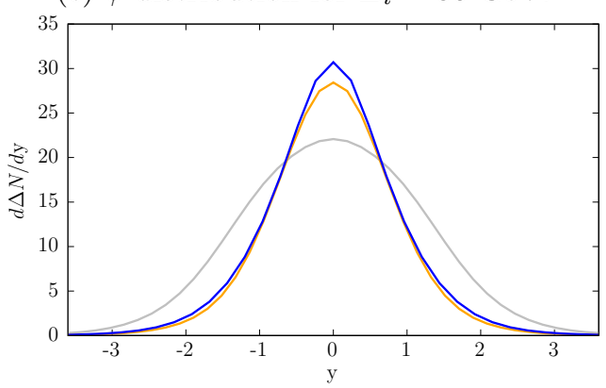
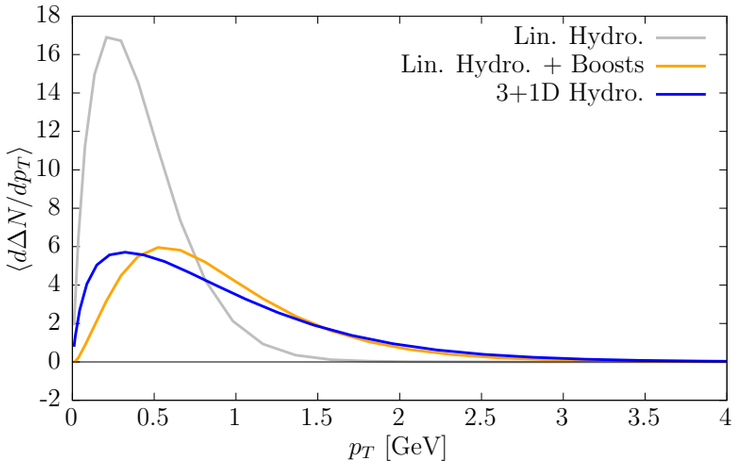


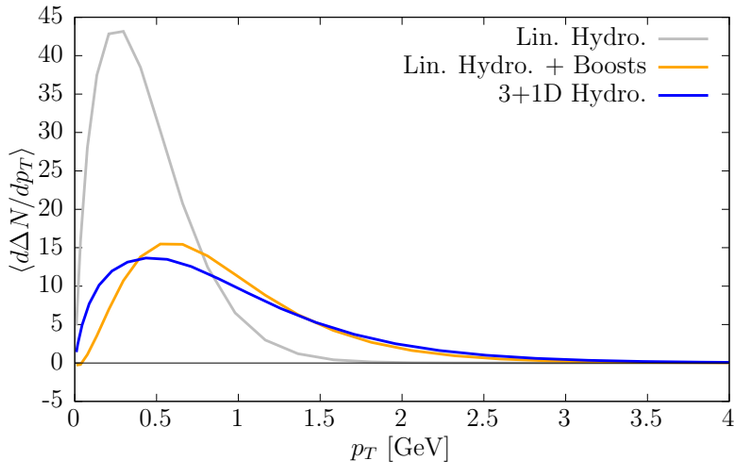


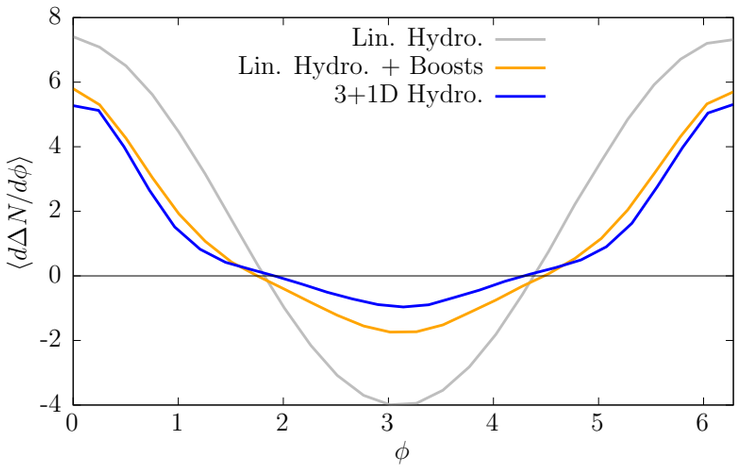
Non-linear hydro response from MUSIC

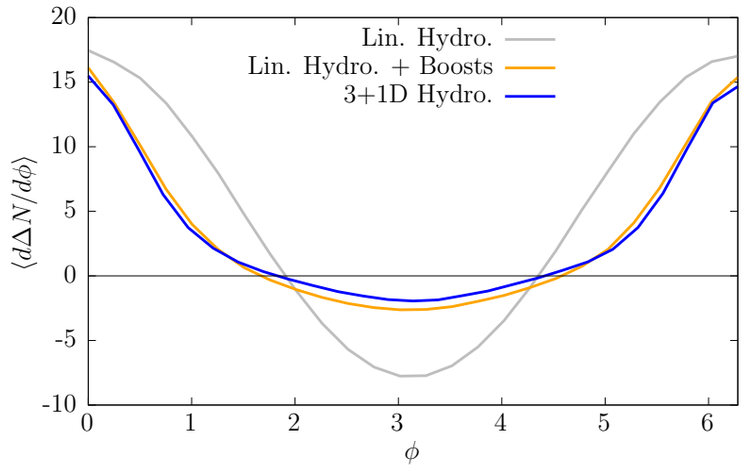
Manifestation of sound waves in rapidity (for certain configuration)

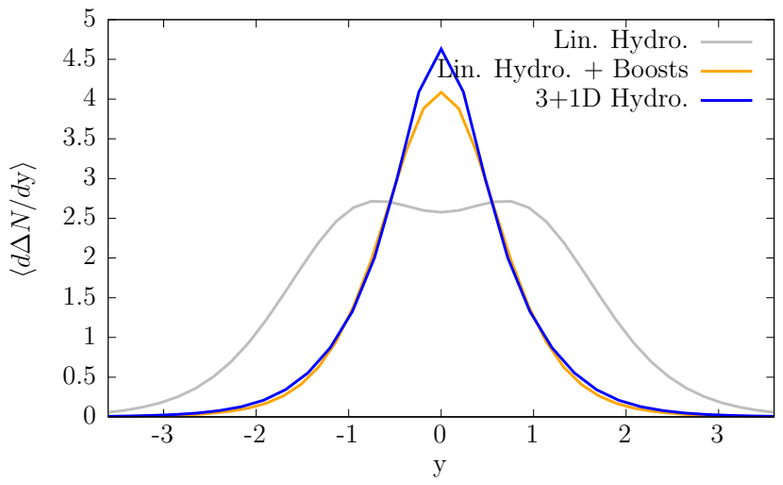
Average over events

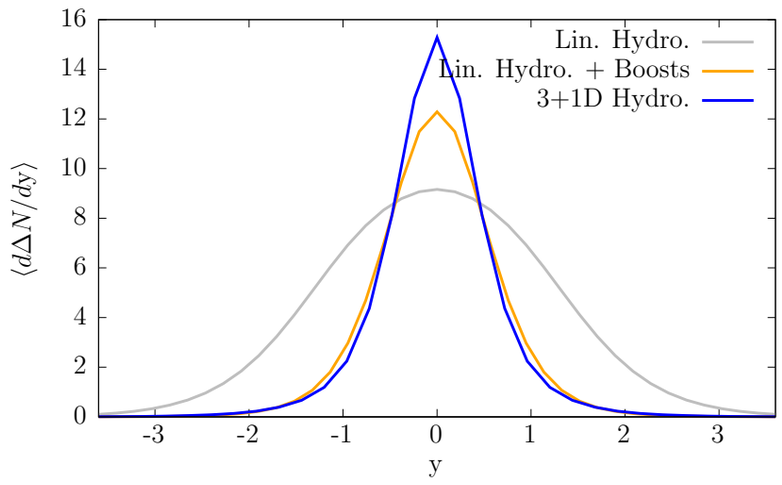












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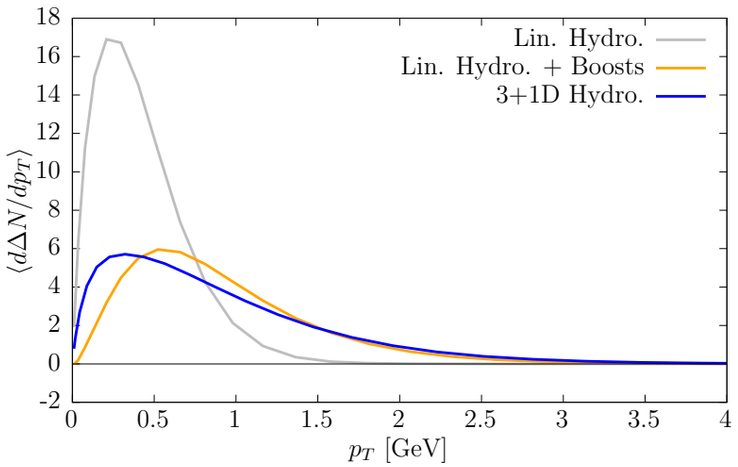
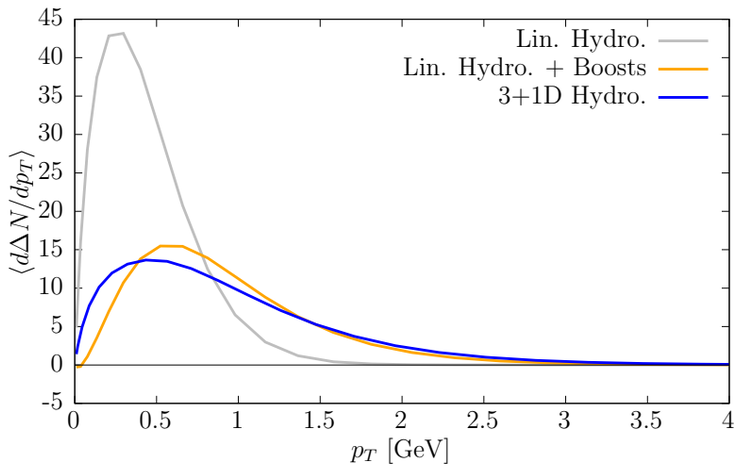
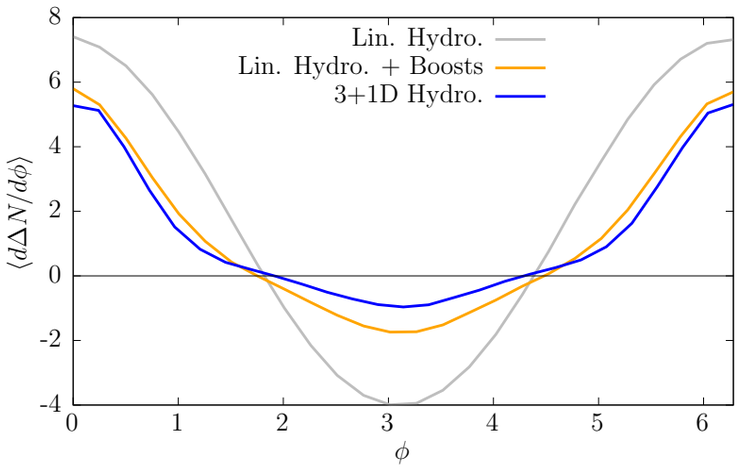
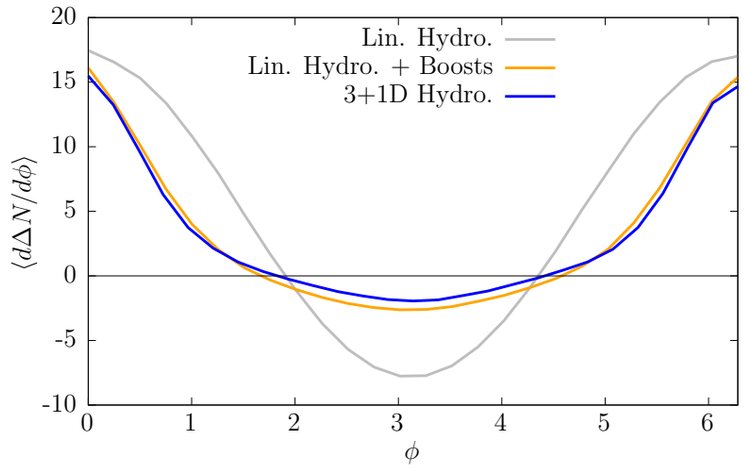
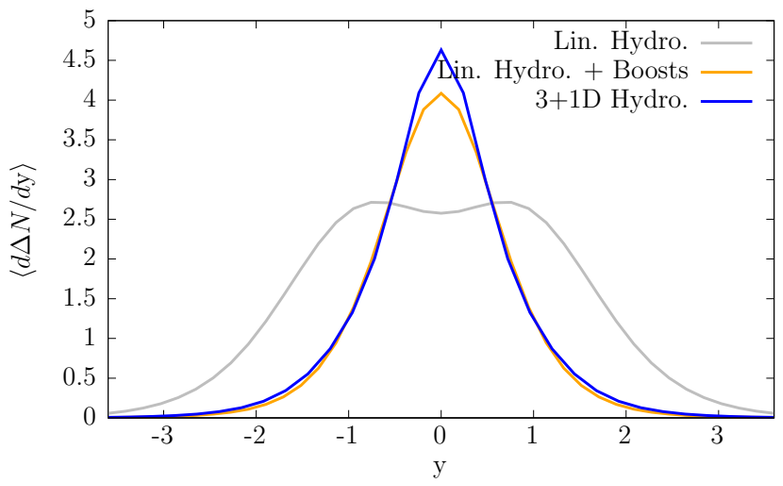


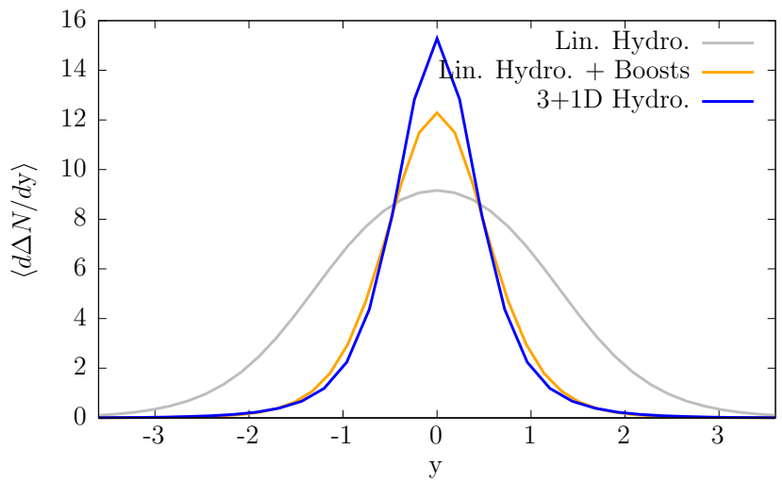


Good agreement with non-linear hydro









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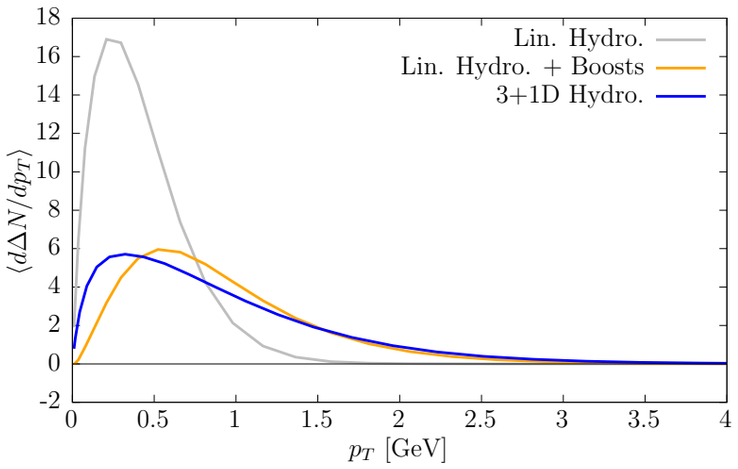
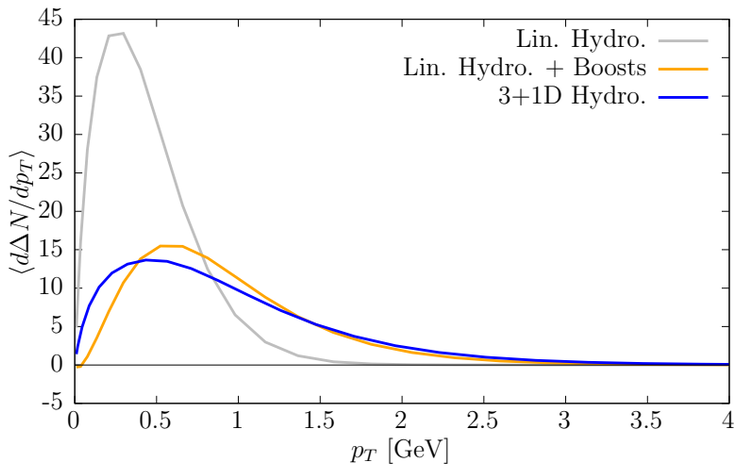
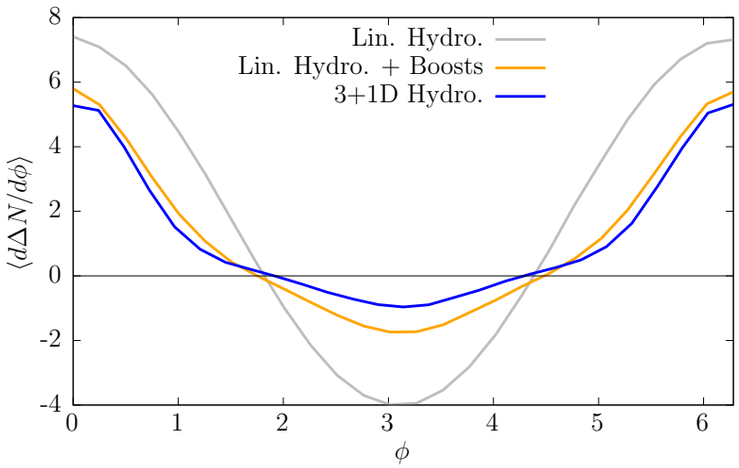
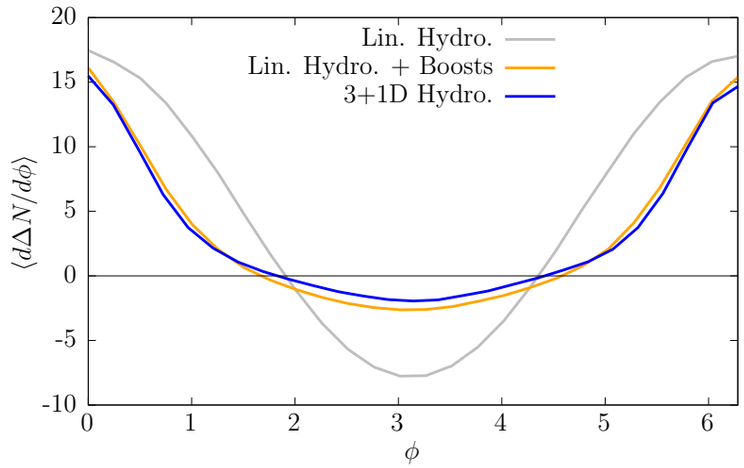
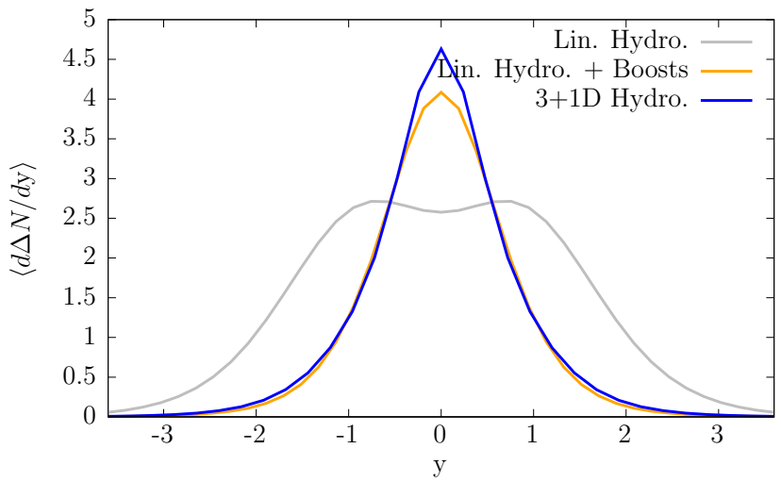
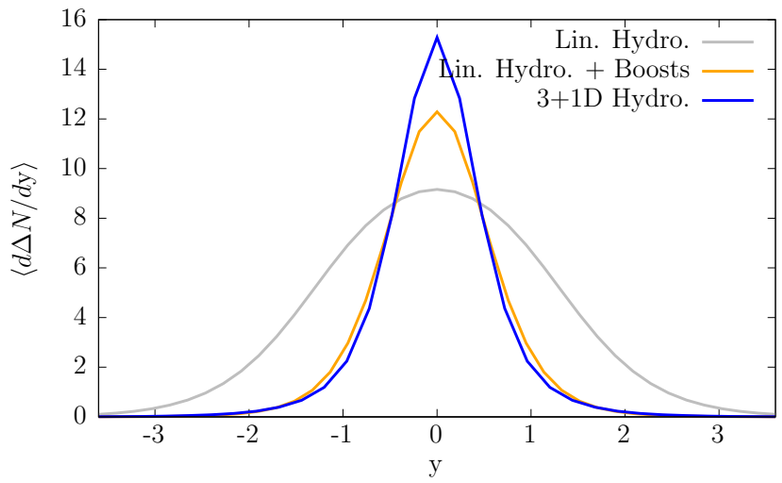








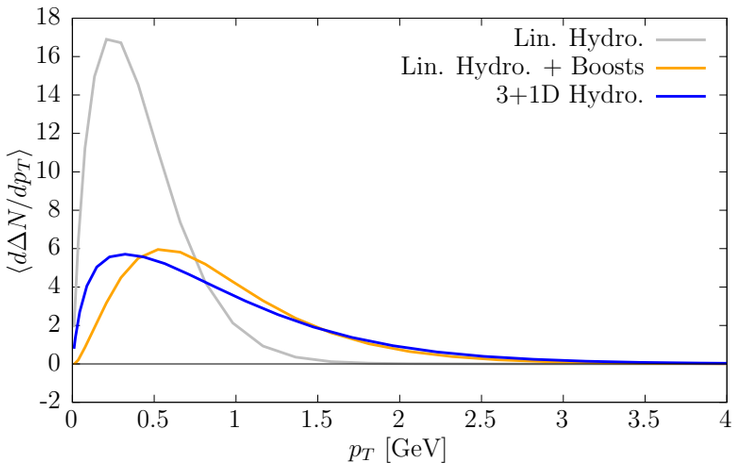


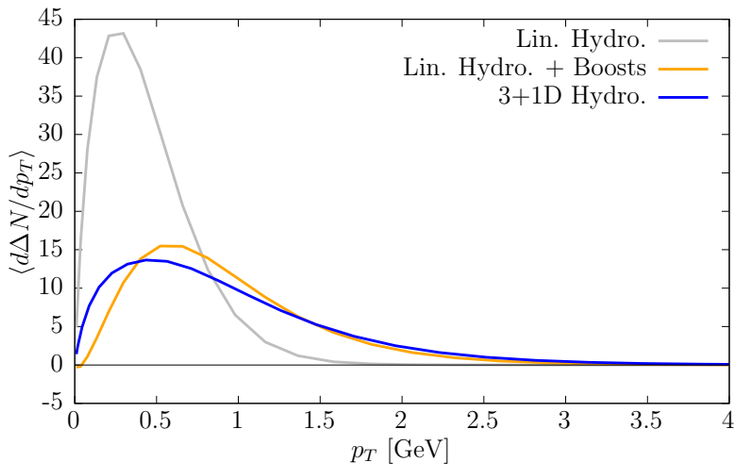


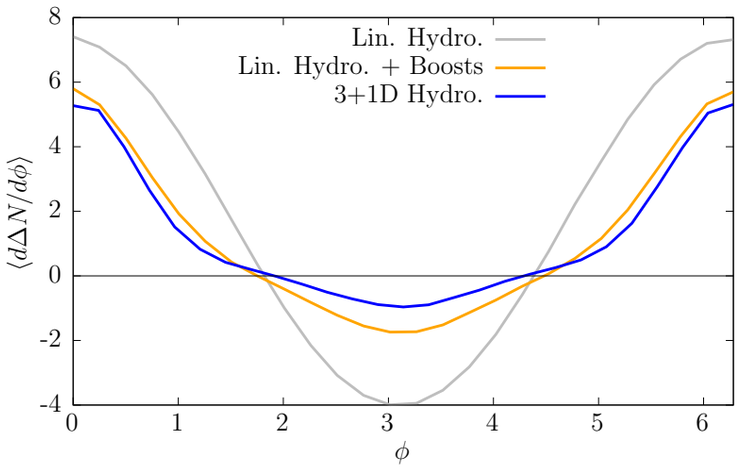
Good agreement with non-linear hydro

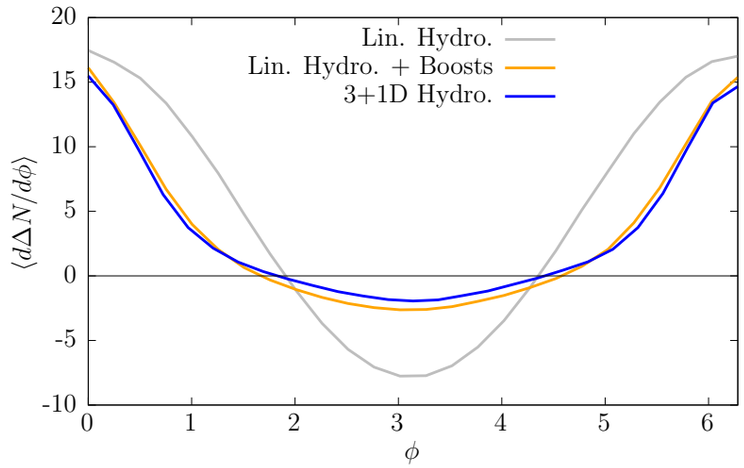
Spectrum becomes
- Harder
- Narrower
- With fewer negatives than in previous approx.

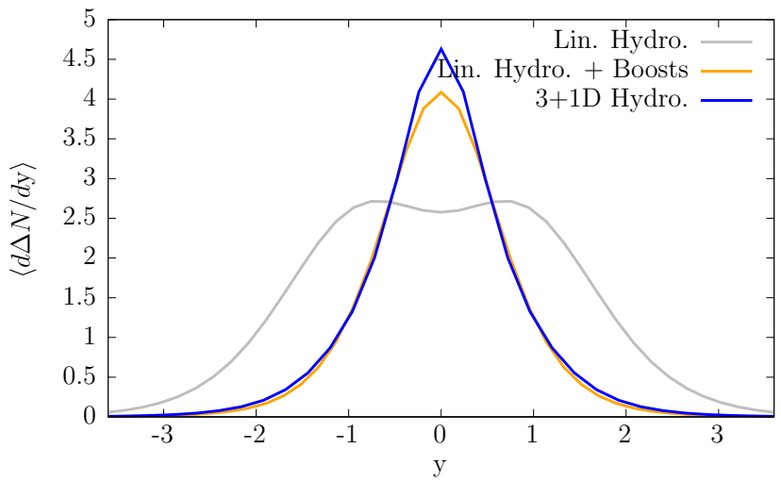
Average over events

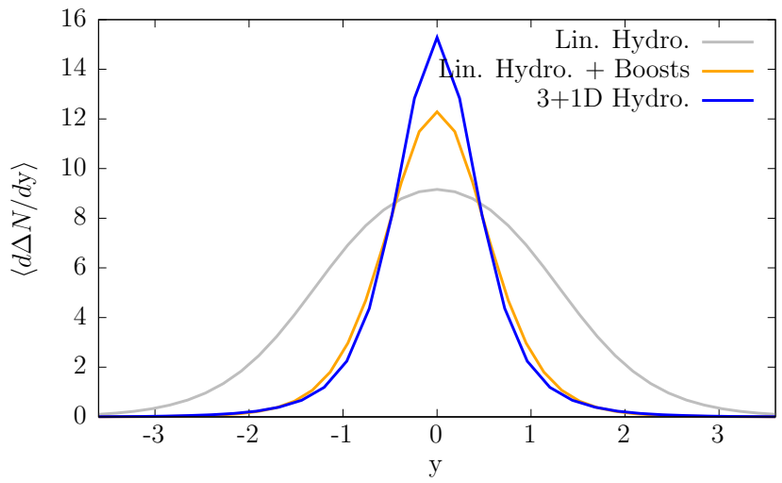












Good agreement with non-linear hydro

Spectrum becomes
- Harder
- Narrower
- With fewer negatives than in previous approx.

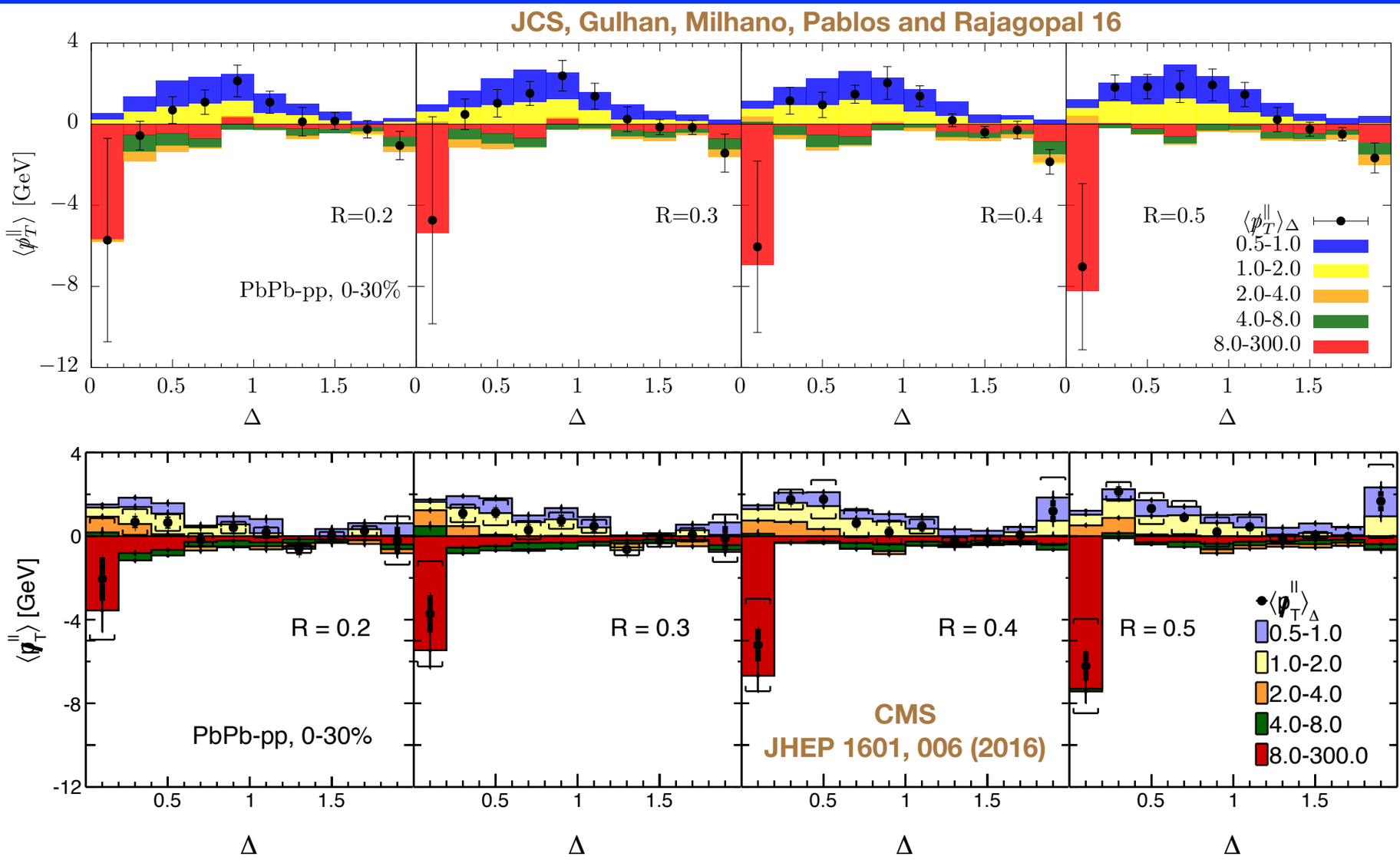
At least 1000 X faster than non-linear solution

Conclusions

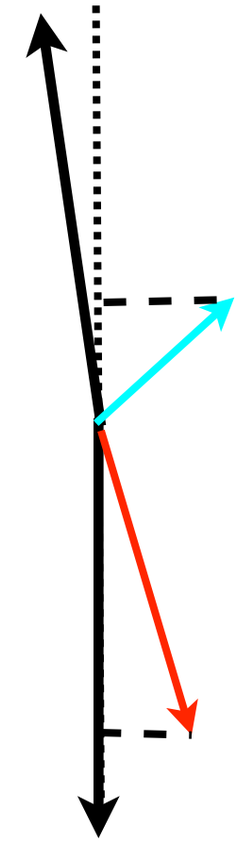
- The Hybrid model is a simple but predictive model
  - Its few ingredients can be constrained by different measurements
- An important piece of the framework is medium response
  - Soft medium particles affect many jet observables
  - This is a complementary way to study thermalization
  - However, full hydro response is computational expensive
- We have found a set of “approximations” that capture the main physics of the non-linear response
  - We are now ready for a Monte Carlo implementation

And for a more stringent comparison with RHIC and LHC data

Too simple⇒Too Soft & Too Wide



Associated Jet



Leading Jet

- The simple back-reaction implemented in hybrid model:
  - Captures the general features of the energy-degradation
  - Produces too many soft particles at large angles
- In this talk: first steps towards a better description of back-reaction

Approximation in the Hybrid Model

- Particle production via Cooper Fry at fixed proper time

$$\frac{\mathrm{d}\Delta N}{p_T\,\mathrm{d}p_T\,\mathrm{d}\phi\,\mathrm{d}y} = \frac{1}{(2\pi)^3}\int \mathrm{d}^2x_\perp \tau\,\mathrm{d}\eta\, m_T\cosh(y-\eta)$$
$$\times\left\{\exp\left[-\frac{u^\mu p_\mu}{T+\delta T}\right]-\exp\left[-\frac{m_T\cosh(y-\eta)}{T}\right]\right\}.$$

Unperturbed spectrum

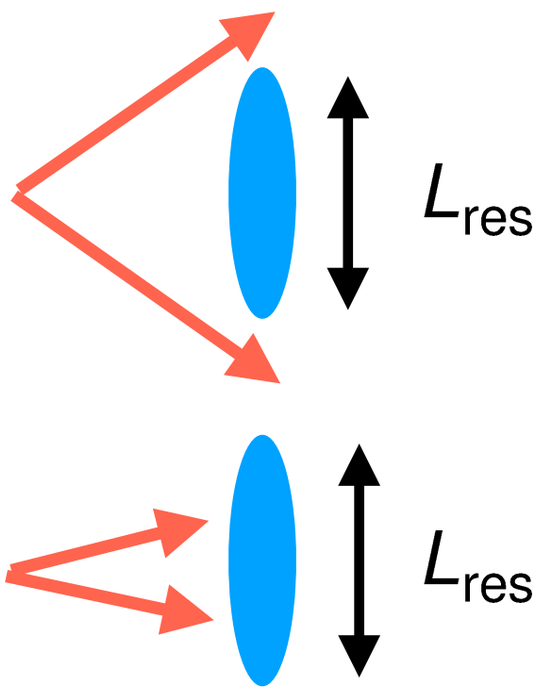
$u^\mu = (1,\delta u^x,\delta u^y,\delta u^\eta)$ **=perturbed velocity**

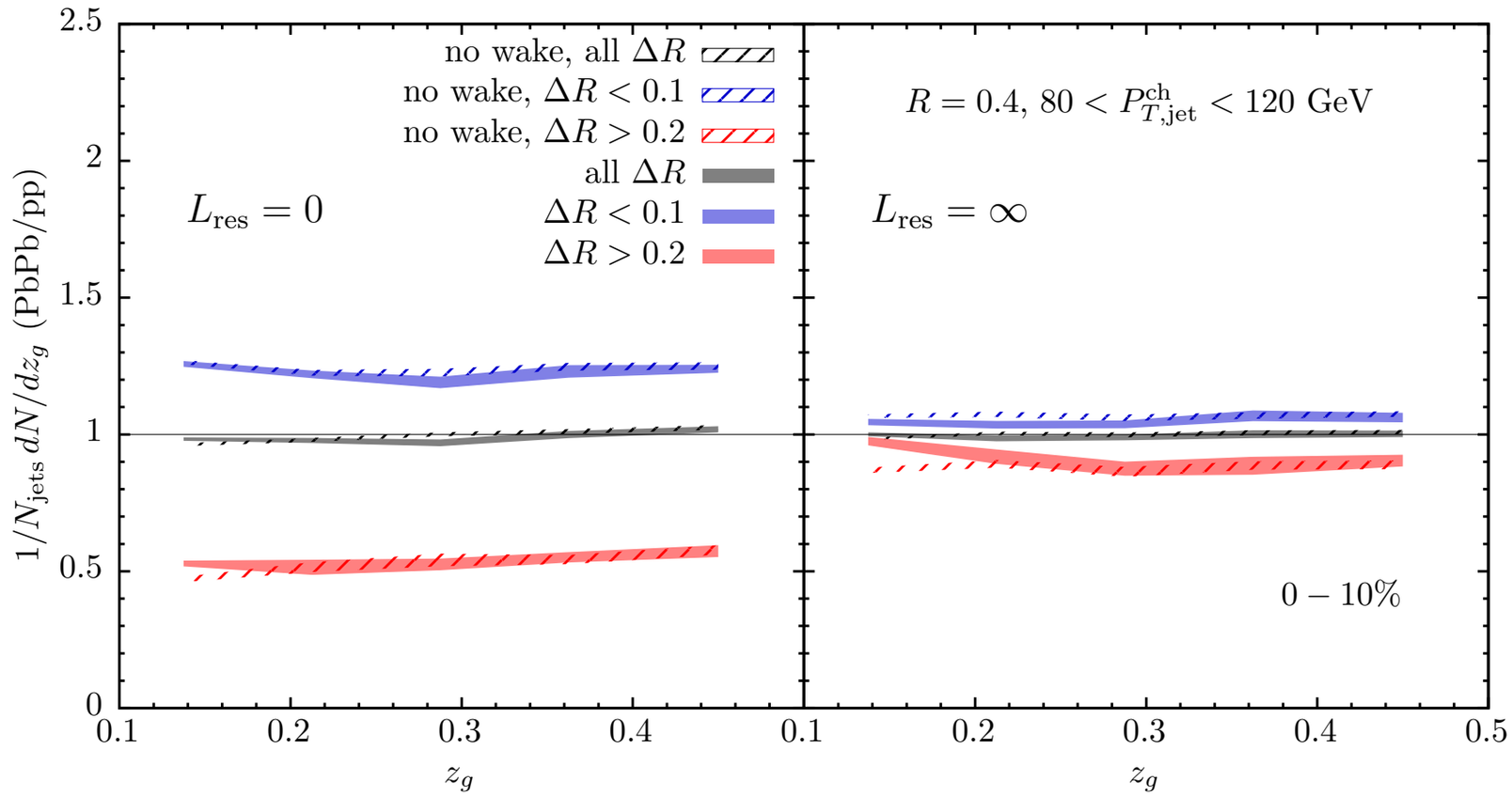
- Valid for small perturbations as long as thermalisation is achieved

- Approximation in the hybrid model: $e^{\frac{\delta u\cdot p}{T}} \approx 1+\frac{\delta u\cdot p}{T}$
  - No need to know the perturbed flow, only Eloss.
  - Strictly valid for soft particles
  - We expect modifications for $p_T \gg T$

- Here we use the expression without expanding in momentum
  - It requires the explicit form of the flow fields

Inner-Jet in Hybrid Model

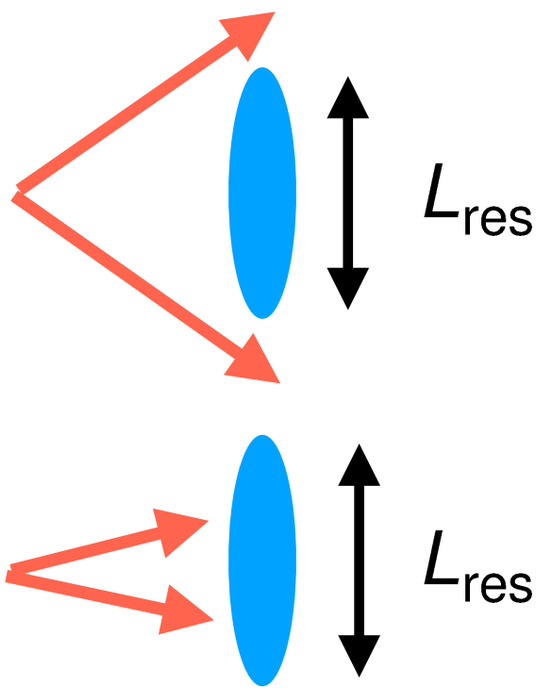


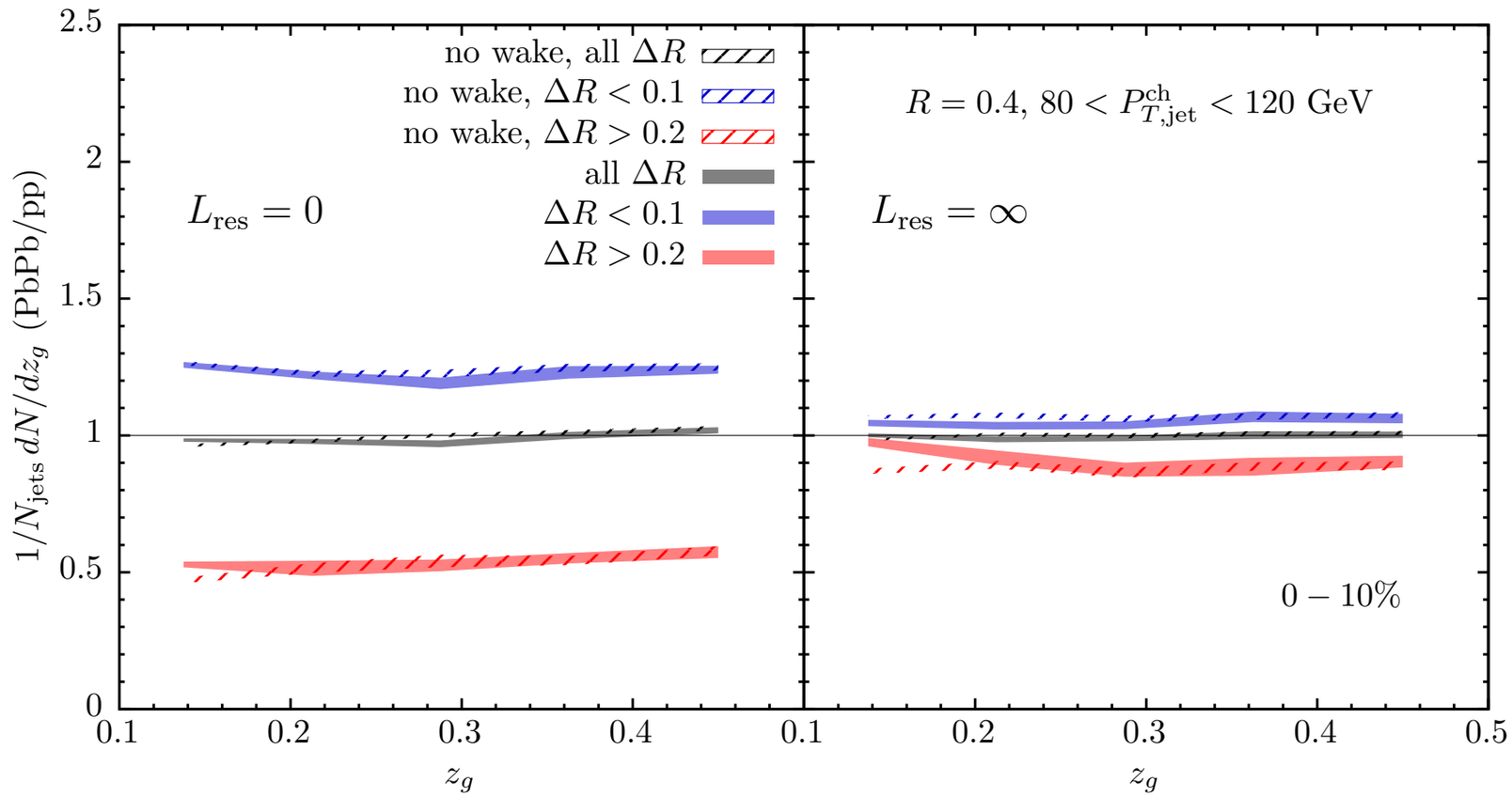


- Wider jets are made of more partons $\Longrightarrow$ more energy loss
  - How many?

    Depends on how the medium resolves transverse separation

Inner-Jet in Hybrid Model





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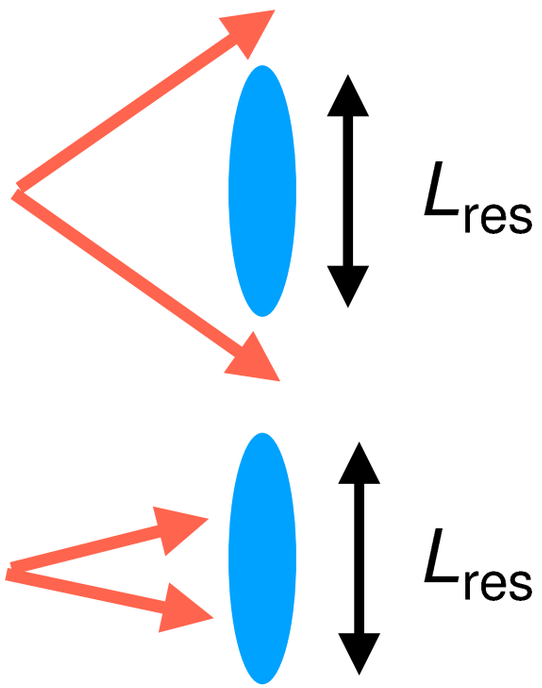
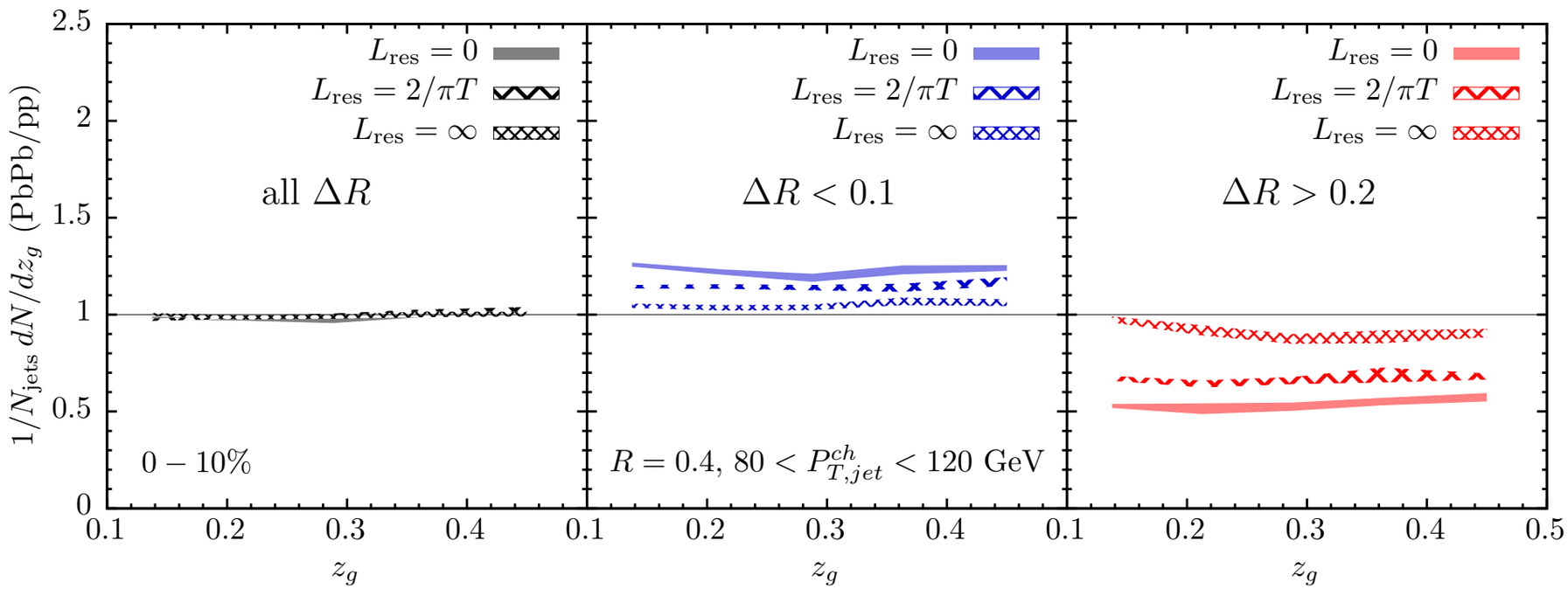
Inner-Jet in Hybrid Model





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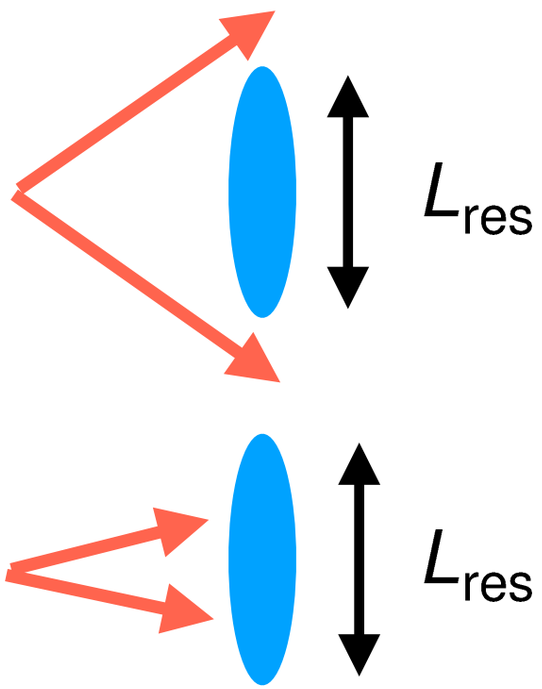

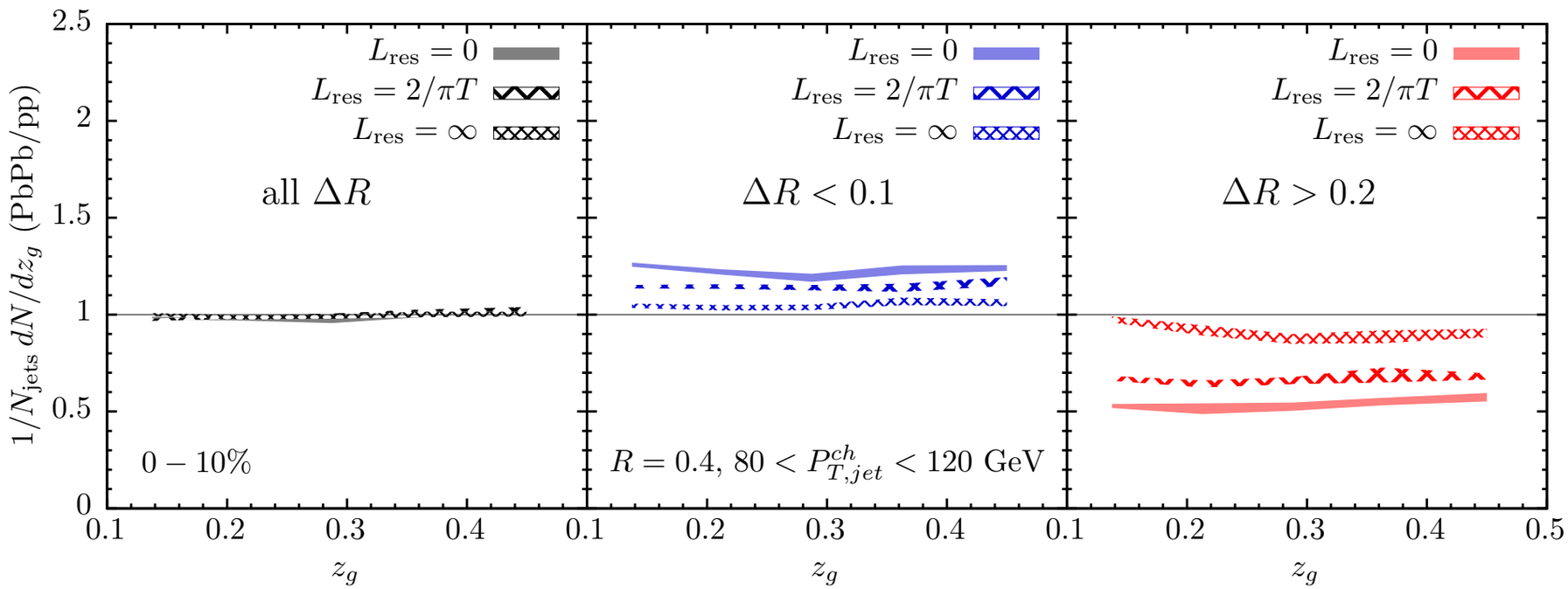

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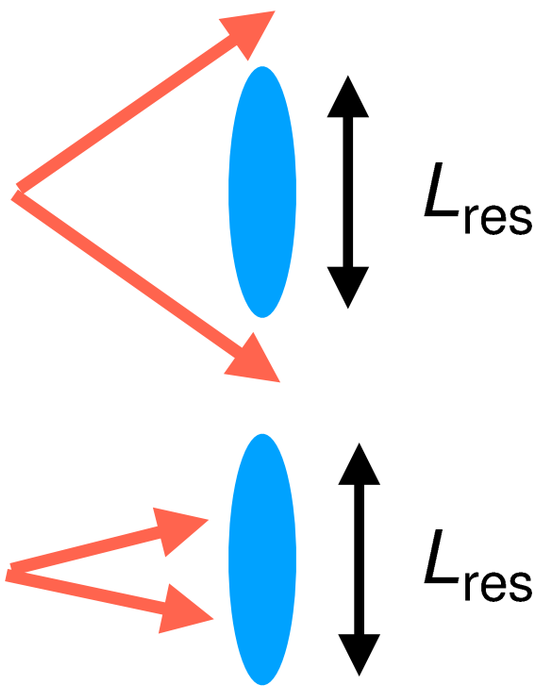
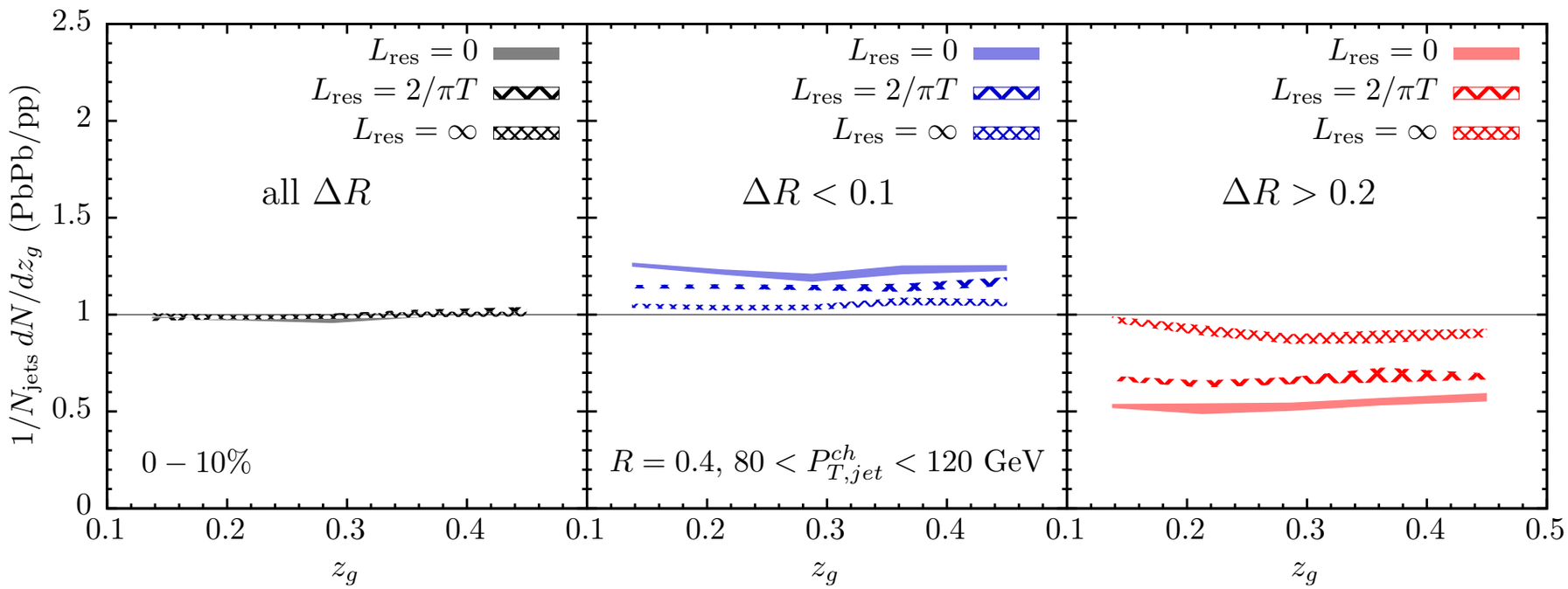
  But it is sensitive to medium properties: In particular L_{res}

Inner-Jet in Hybrid Model





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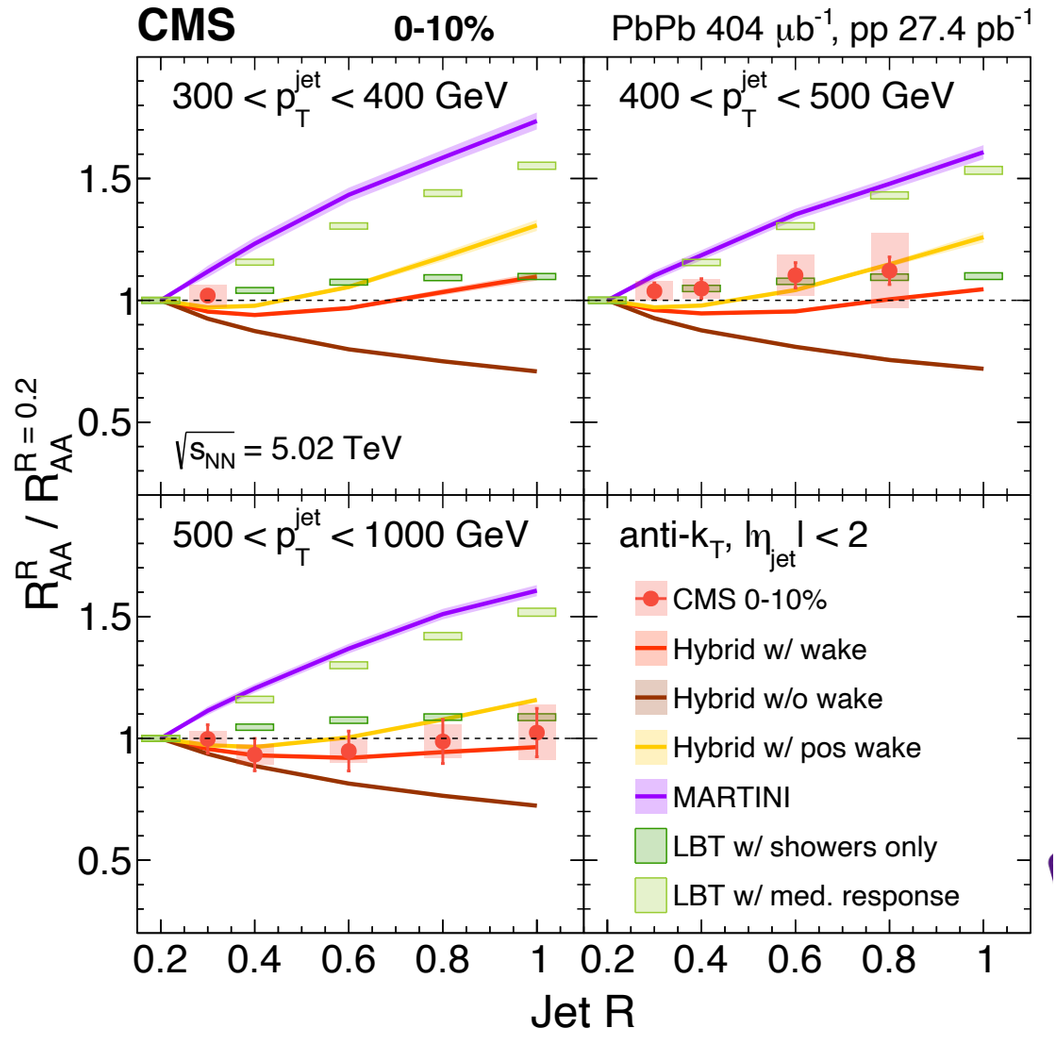
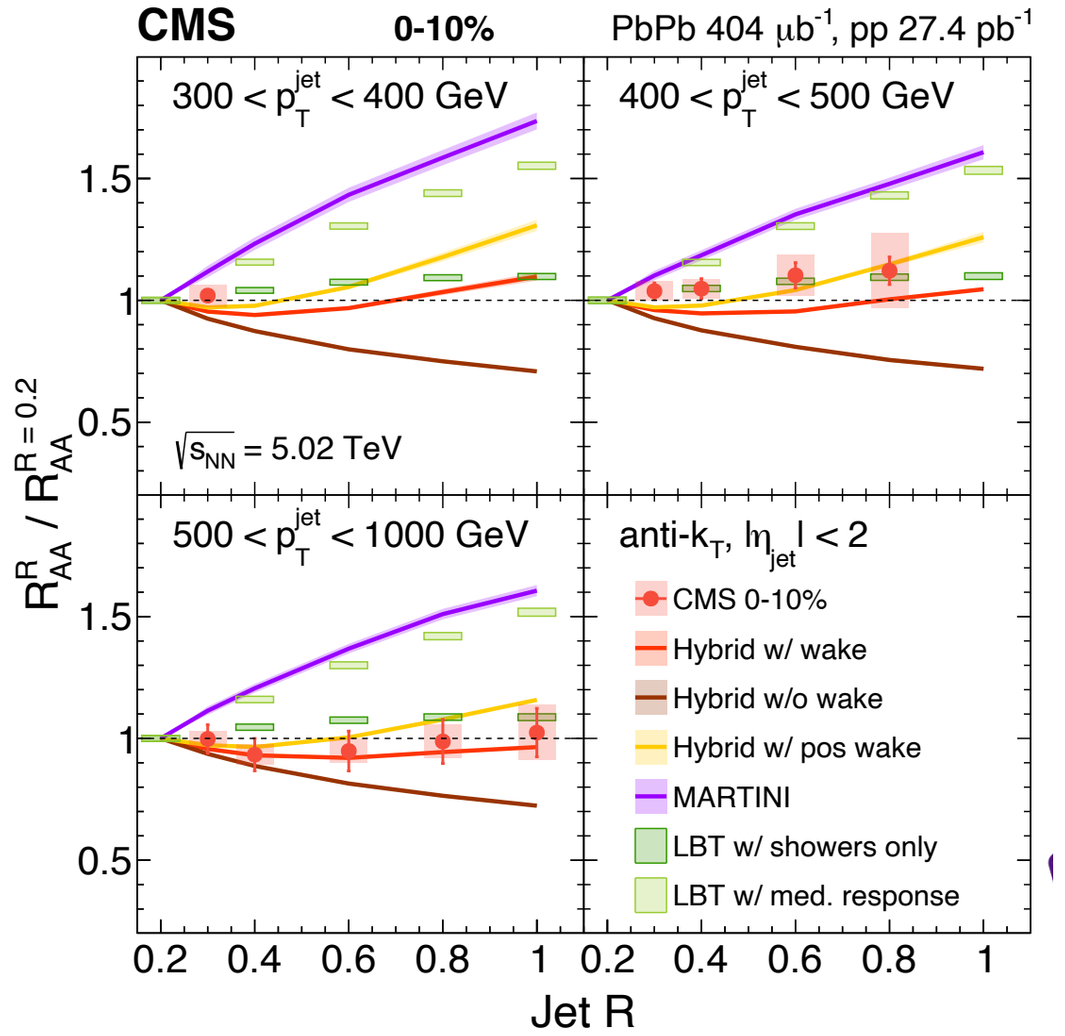
Resolution effects in many other frameworks:
Mehtar-Tani, Salgado, Tywoniuk (&JCS); JCS, Iancu; Arnold, Chang, Iqbal, Gorda; Blaizot, Dominguez et al.; Barata et al.; Caucal, Iancu and Soyez ….

RAA vs Jet Angular Size



- Jet suppression (at LHC) seems independent of R

RAA vs Jet Angular Size



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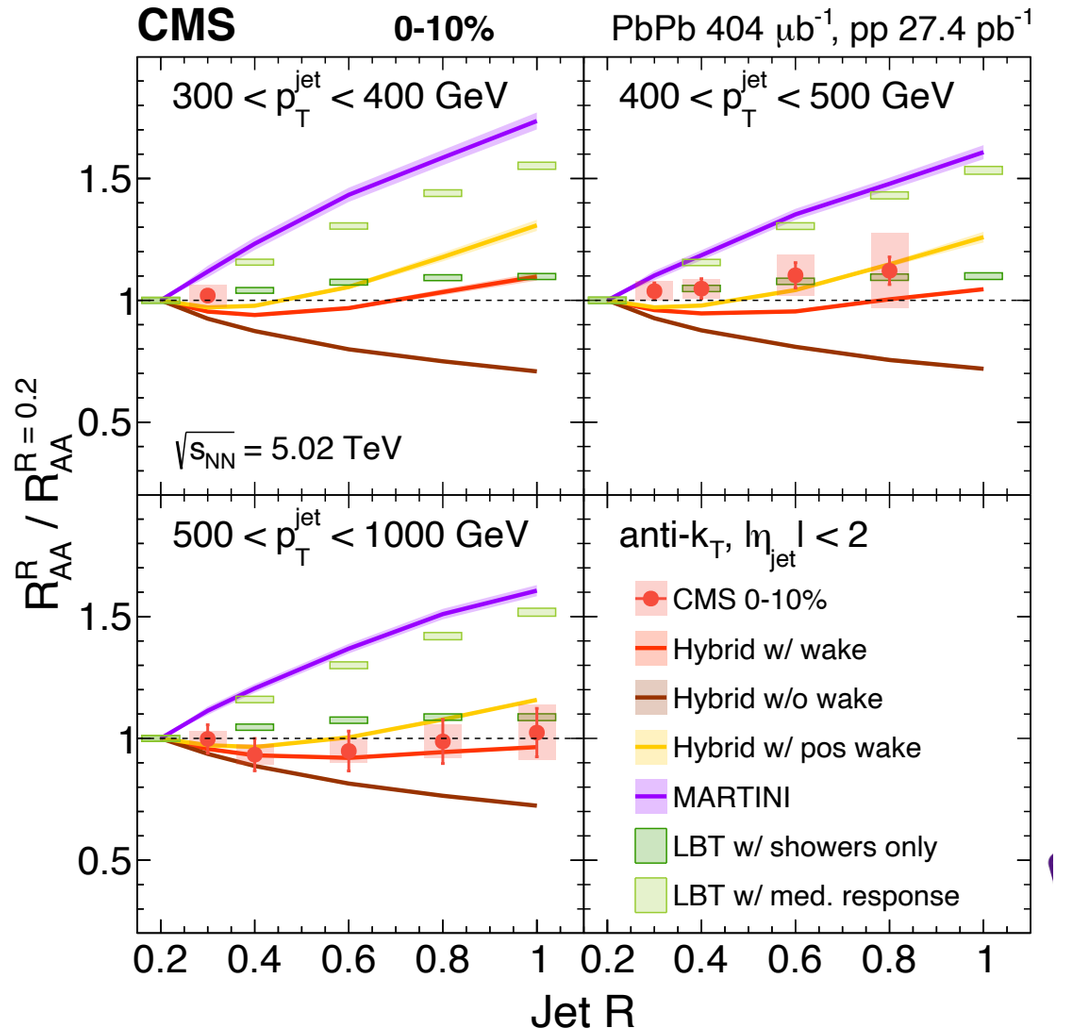

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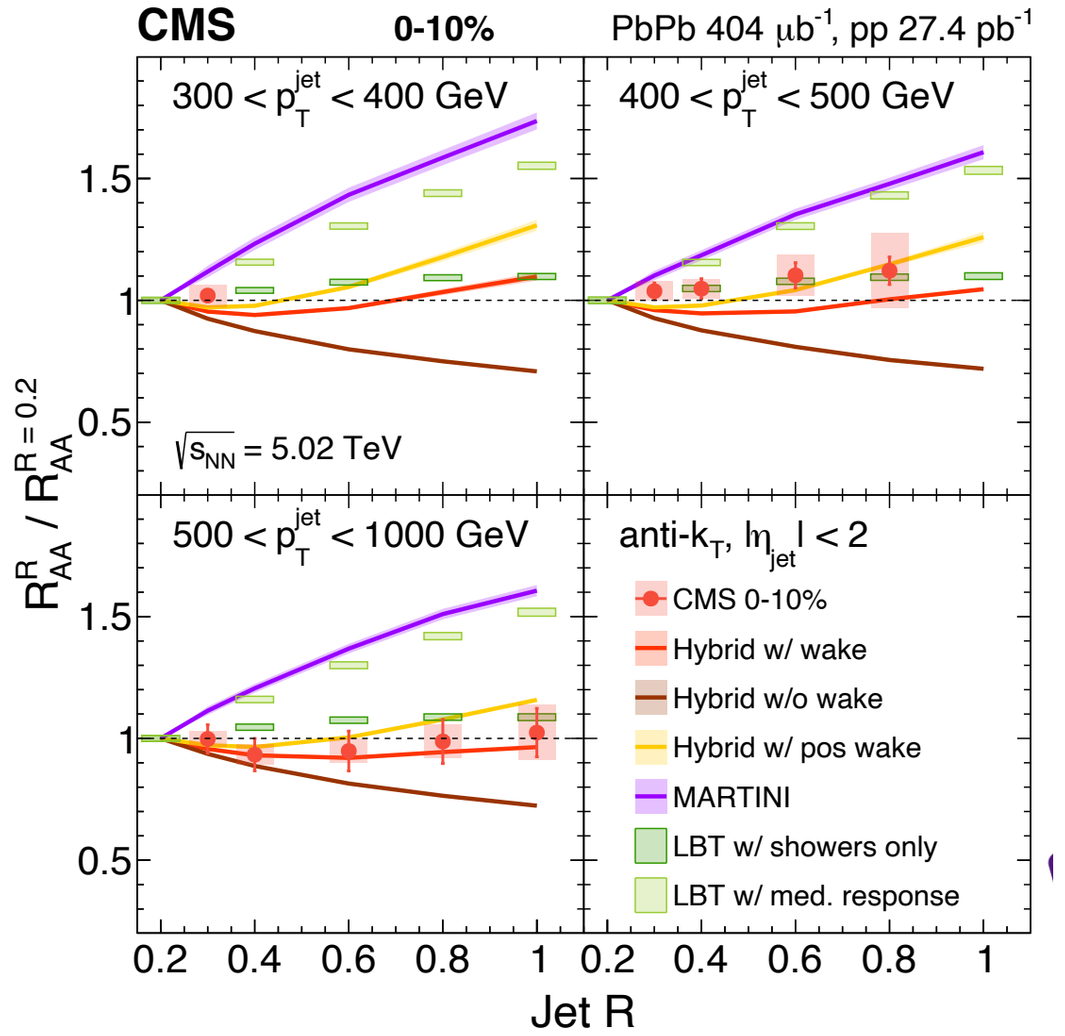

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Test of the medium back-reaction

RAA vs Jet Angular Size

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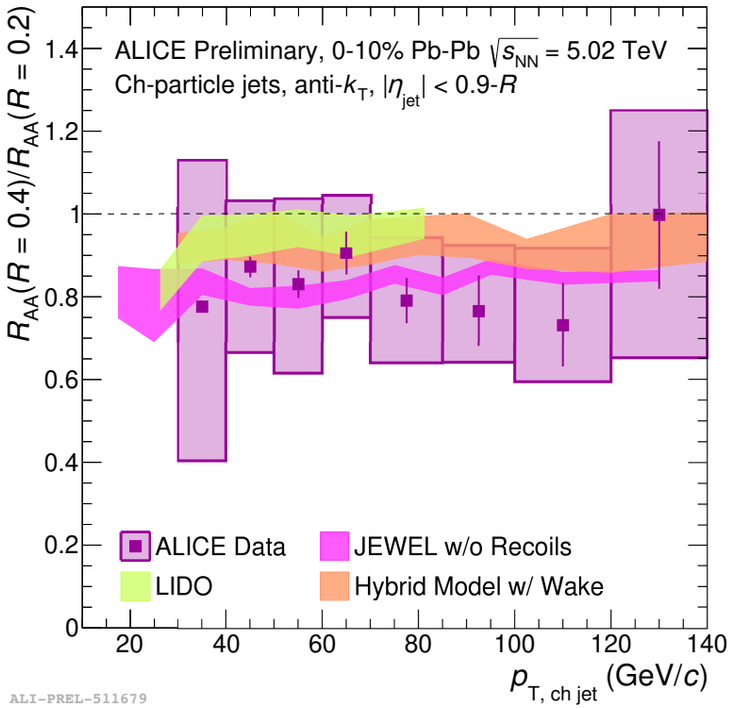
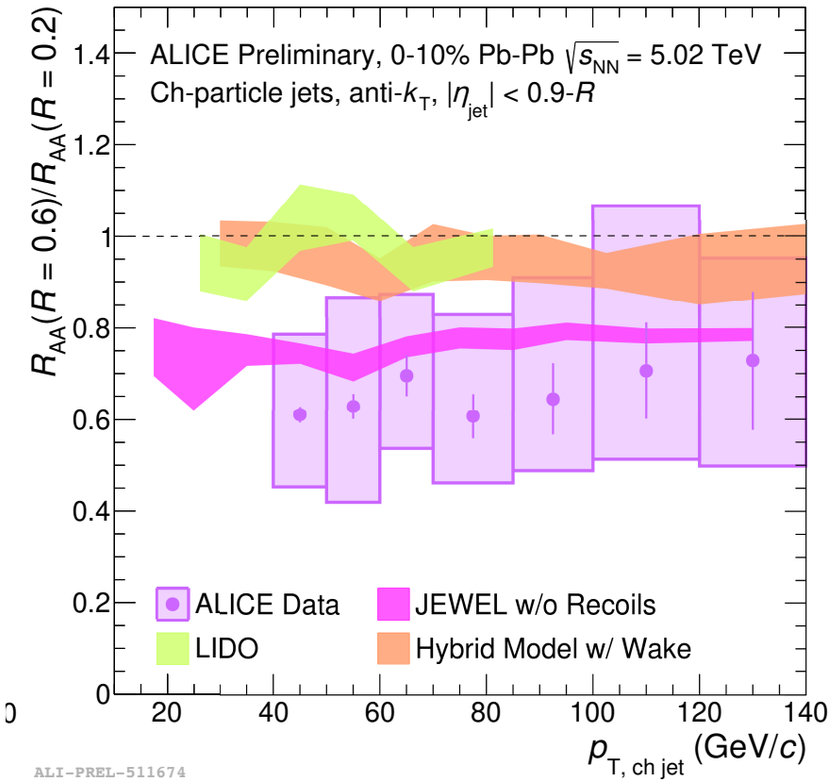


$R = 0.6 / R = 0.2$



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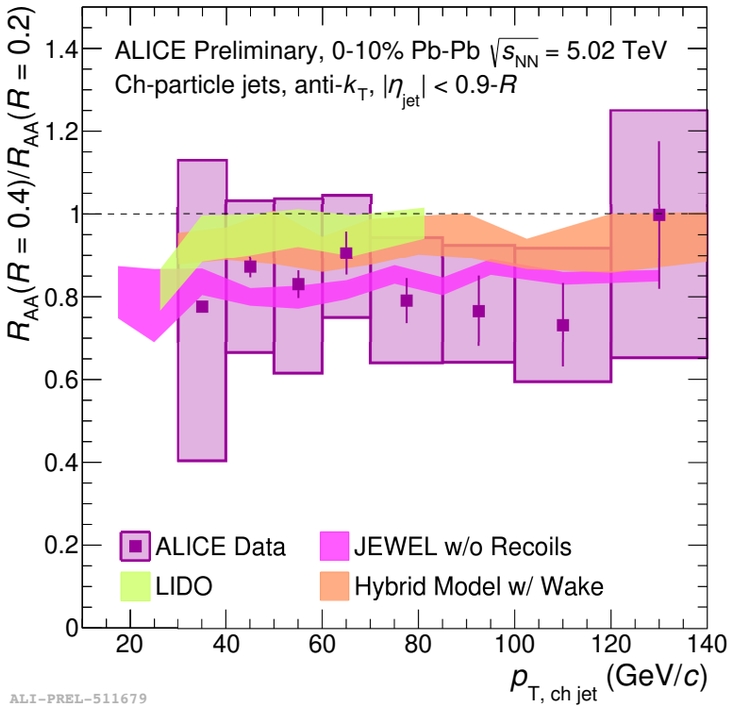

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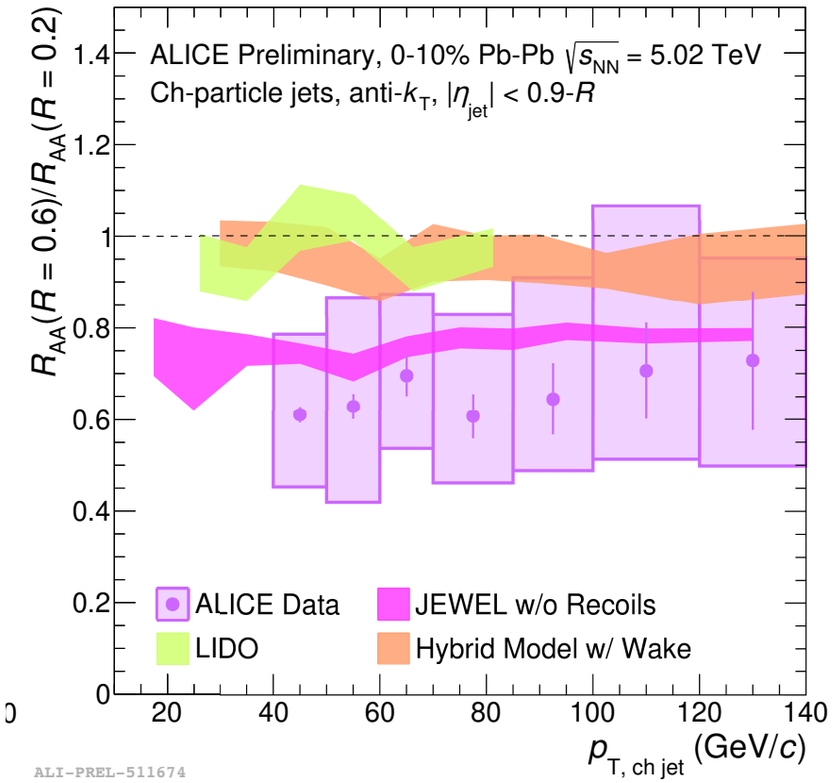

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