Identifying Jet Observables with which to "See" the Short-Scale Structure of QGP

Krishna Rajagopal
MIT

with
Zach Hulcher (Stanford)
Dani Pablos (INFN Torino)

Quark Matter 2023
Houston, Texas; September 5, 2023

Why Jets?

- The remarkable utility of hydrodynamics, eg. in describing the dynamics of small lumps in the initial state in AA collisions, tells us that to see the inner workings of QGP, namely to see how the liquid is put together from quarks and gluons, we will need probes with fine resolution.
- Need probes that resolve scales $\ll$ size of lumps coming from the initial state that behave hydrodynamically, and scales $\ll 1/T_{\text{hydrodynamization}}$.
- Jets, as multiscale probes, provide best chance for scattering off a droplet of QGP to see its inner workings.
- Jets in heavy ion collisions *also* offer the best chance of watching how QGP hydrodynamizes. Jets leave a wake in the medium. Can we see how it hydrodynamizes, and then flows? Best shot at experimental access to this physics.
- $\rightarrow$ not easy to decode the wealth of info that jets contain! (Need high statistics LHC and sPHENIX data; and need to use today's data to build baseline of understanding.)

How you can learn from a model

- There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. (Eg, turn physical effects off and on) ...
- ... but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.
- TODAY's EXAMPLE: identifying which jet observables are more sensitive to the presence of quasiparticles — scatterers — in the QGP-soup. And, which are more sensitive to the wakes that jets make in the soup.
- Disentangling effects of jet modification from effects of jet selection. In simulations; in Z+jet or γ+jet data. 2110.13159 Brewer, Brodsky, KR
- Using jet substructure modification to probe QGP resolution length. Can QGP "see" partons within a jet shower (rather than losing energy coherently)? 1707.05245 ZH, DP, KR; 1907.11248 Casalderrey-Solana, Milhano, DP, KR. (Apparent answer: yes. Eg., 2303.13347 ALICE)
- But first, a *very* brief intro to the Hybrid Model...

Perturbative Shower … Living in Strongly Coupled QGP

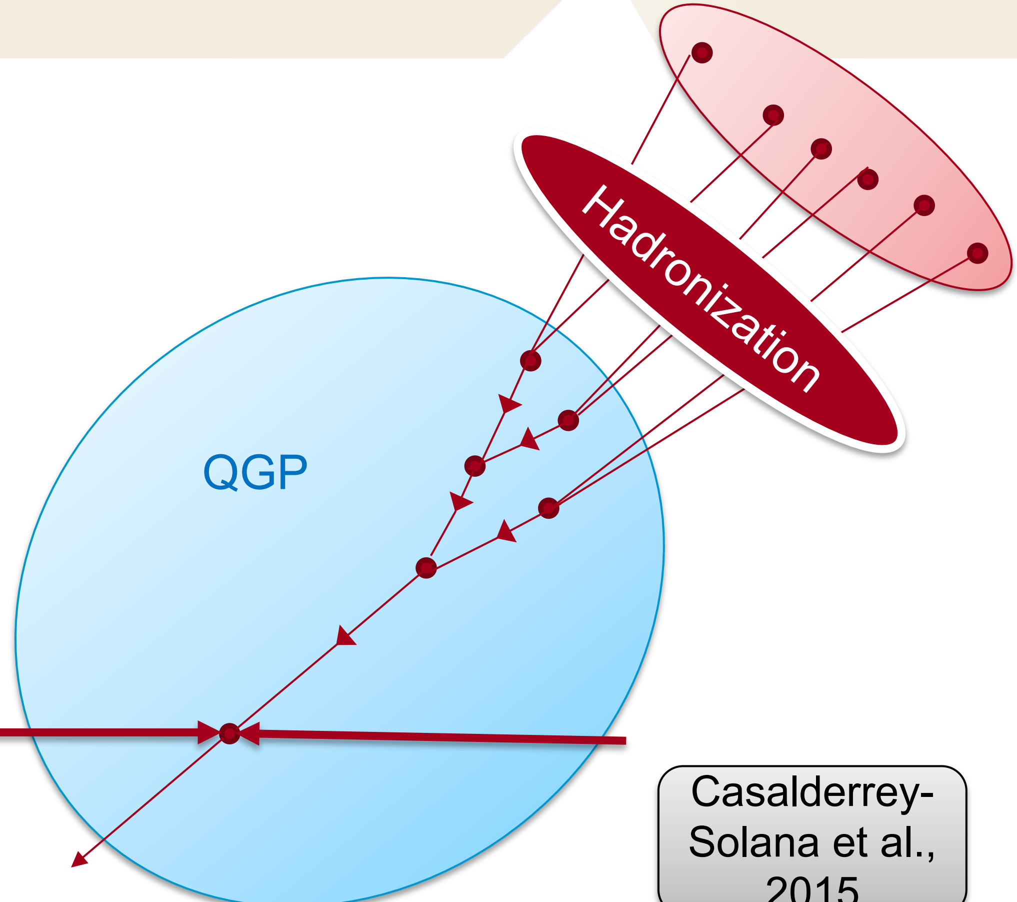
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
    - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

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

$$\tau = \frac{2E}{Q^2}$$

O(1) fit const.



Casalderrey-Solana et al., 2015

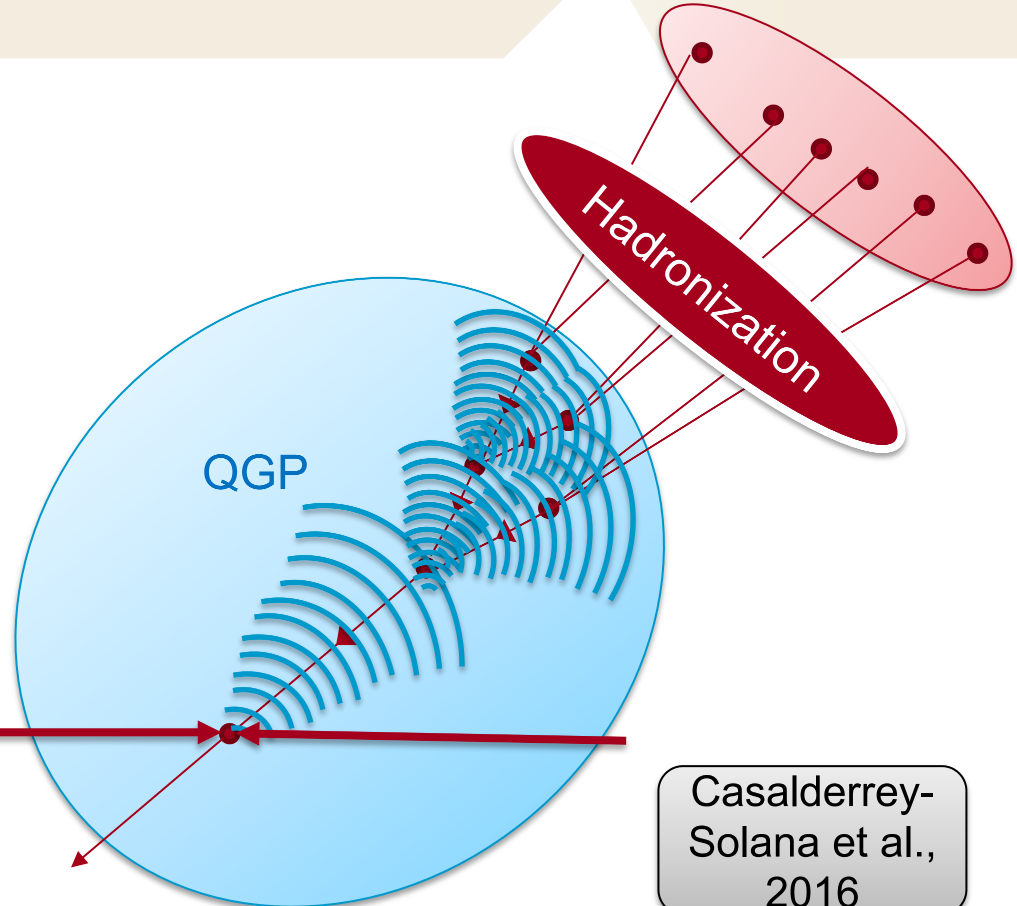
Perturbative Shower … Living in Strongly Coupled QGP

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}} \qquad \tau = \frac{2E}{Q^2}$$

O(1) fit const.



Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

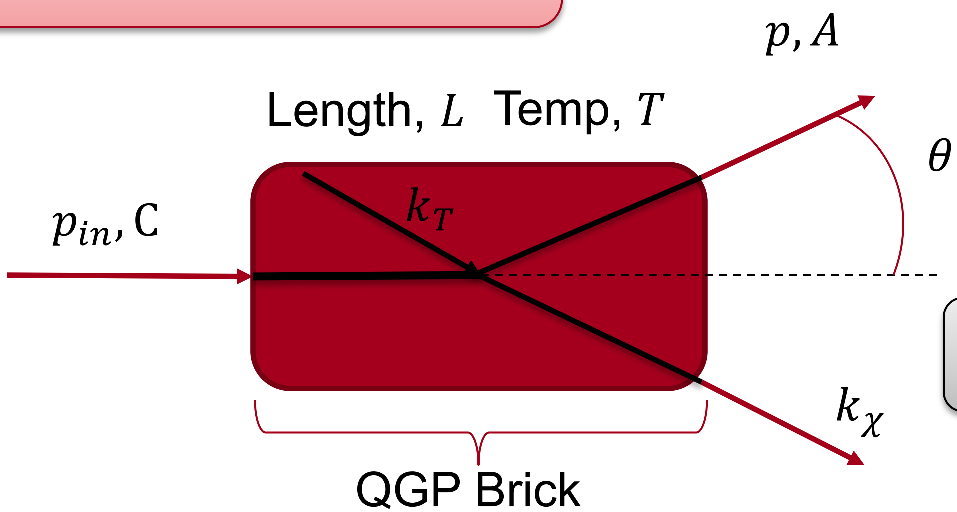
Why Molière scattering?
Why add to Hybrid Model?

- QGP, at length scales $\mathcal{O}(1/T)$, is a strongly coupled liquid. Flow, and jet observables sensitive to parton energy loss, are well-described (eg in hybrid model) in such a fluid, without quasiparticles.
- At shorter length scales, probed via large momentum-exchange, asymptotic freedom $\rightarrow$ quasiparticles matter.
- High energy partons in jet showers *can* probe particulate nature of QGP. Eg via power-law-rare, high-momentum-transfer, large-angle, Molière scattering
- "Seeing" such scattering is first step to probing microscopic structure of QGP.
- What jet observables are sensitive to effects of high-momentum-transfer scattering? To answer, need to turn it off/on.
- Start from Hybrid Model – in which any particulate effects are definitively off! Add Molière, and look at effects...

Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



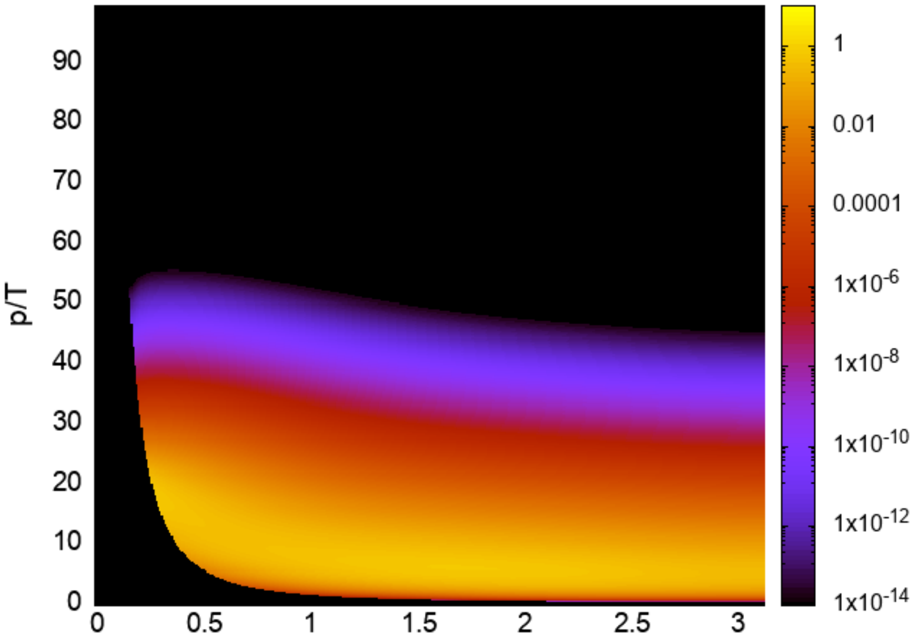
D'Eramo et al., 2019

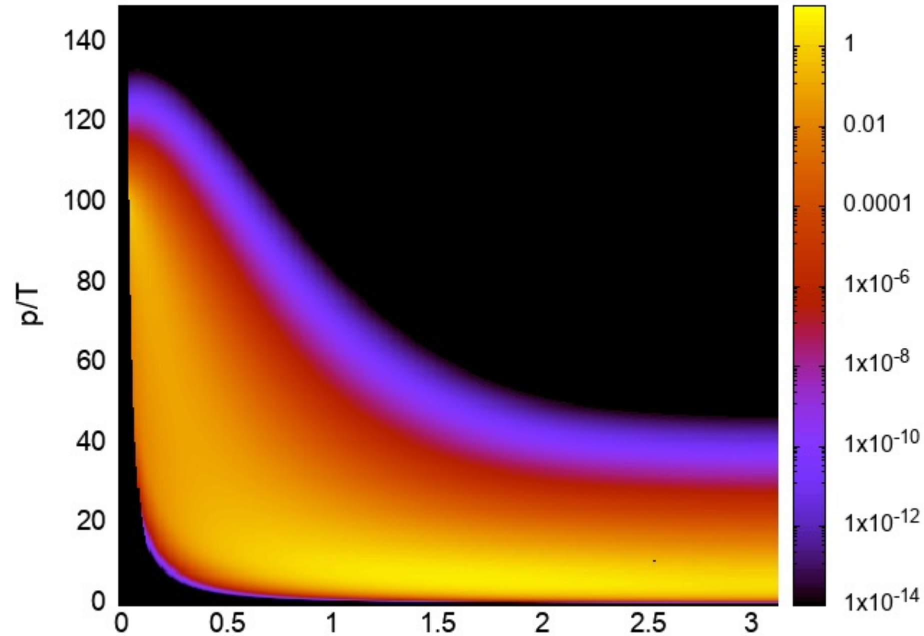
- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

Tree-Level 2-2 massless scattering amplitudes

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C\to A}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\mathbf{p}-\mathbf{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1\pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results (for a QGP brick)

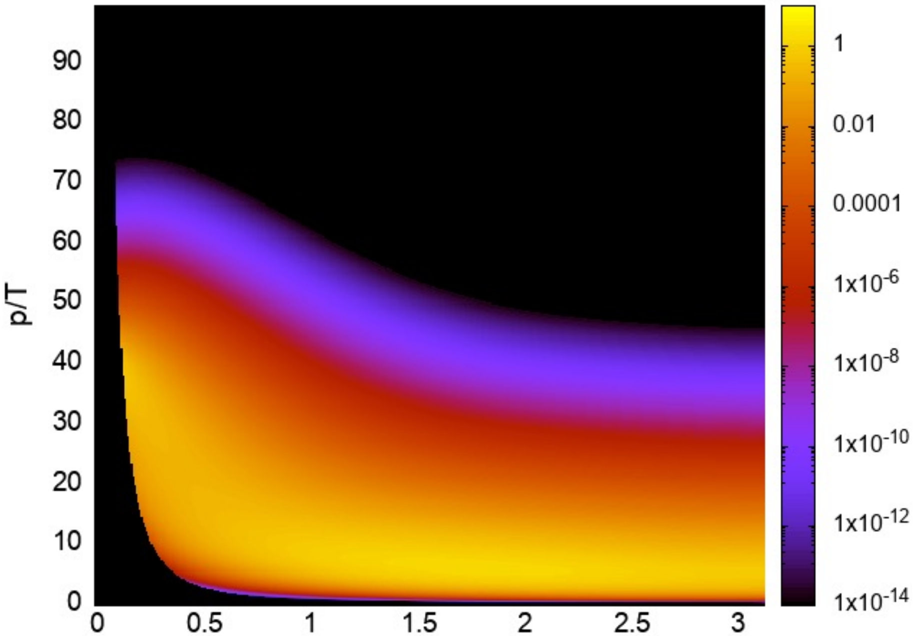


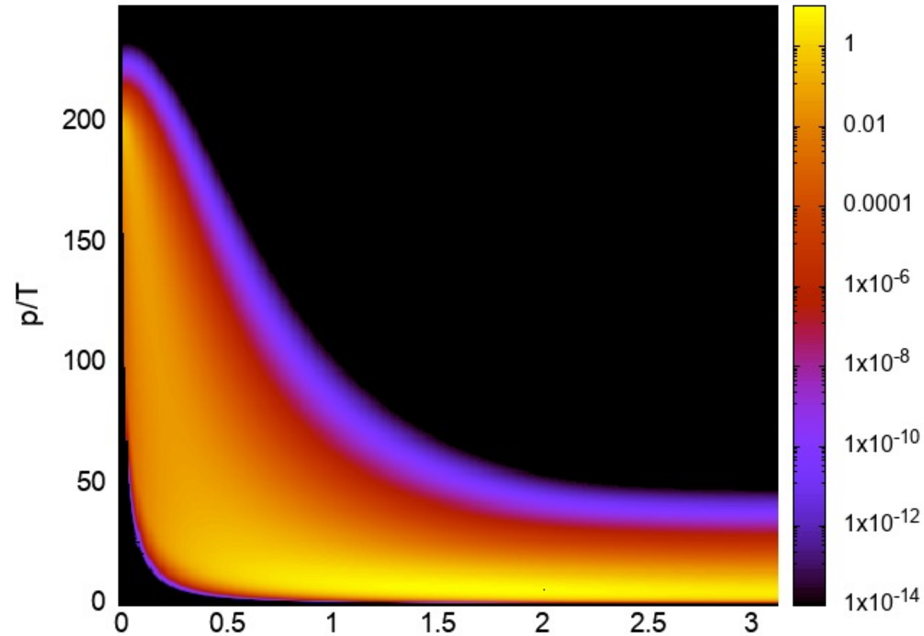


Incoming gluon, $p_{in} = 20T, \mathrm{L} = 15/T$ Incoming gluon, $p_{in} = 100T,\ \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 4\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 4\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Results (for a QGP brick)

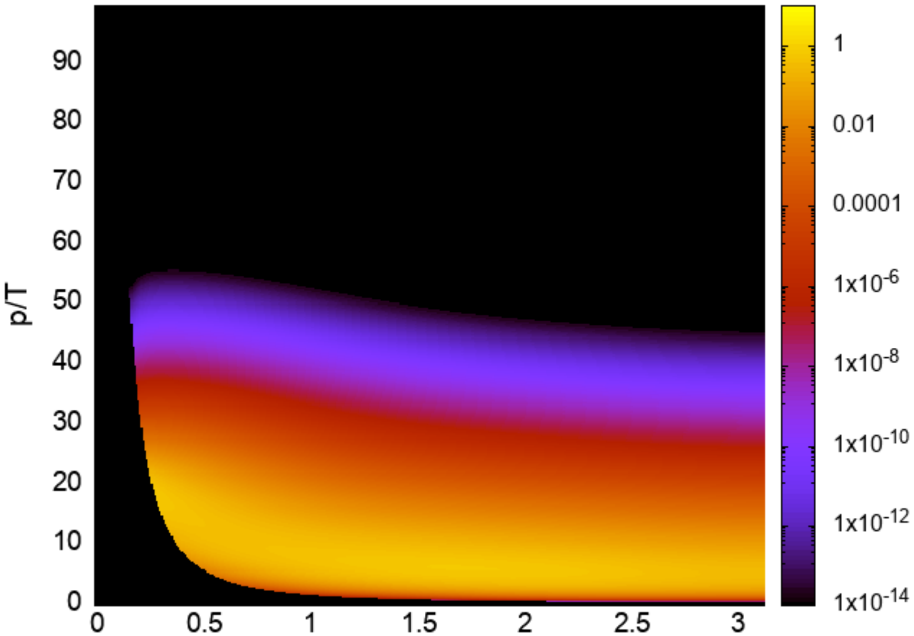


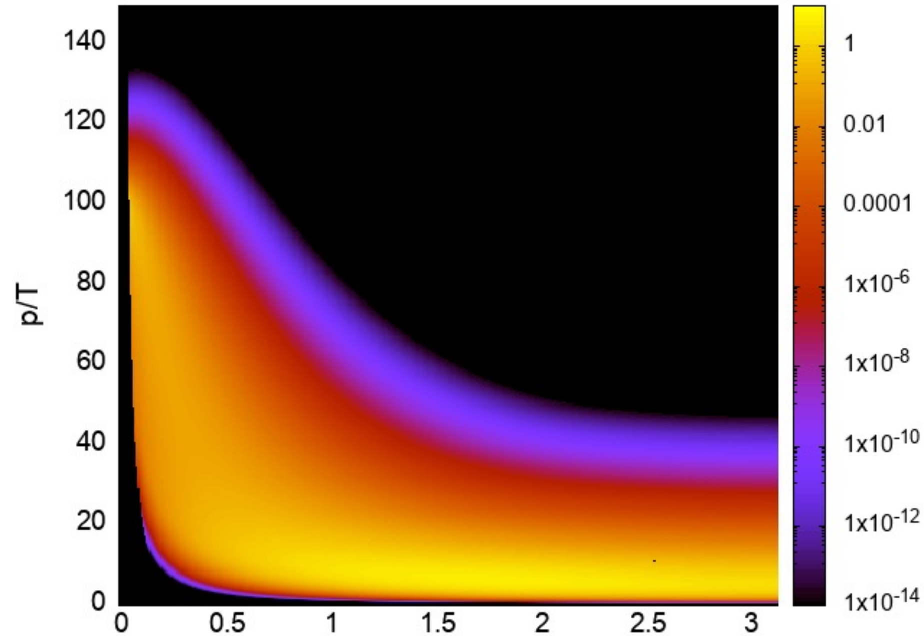


Incoming gluon, $p_{in} = 40T, \mathrm{L} = 15/T$ Incoming gluon, $p_{in} = 200T,\ \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 4\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 4\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Results (for a QGP brick)



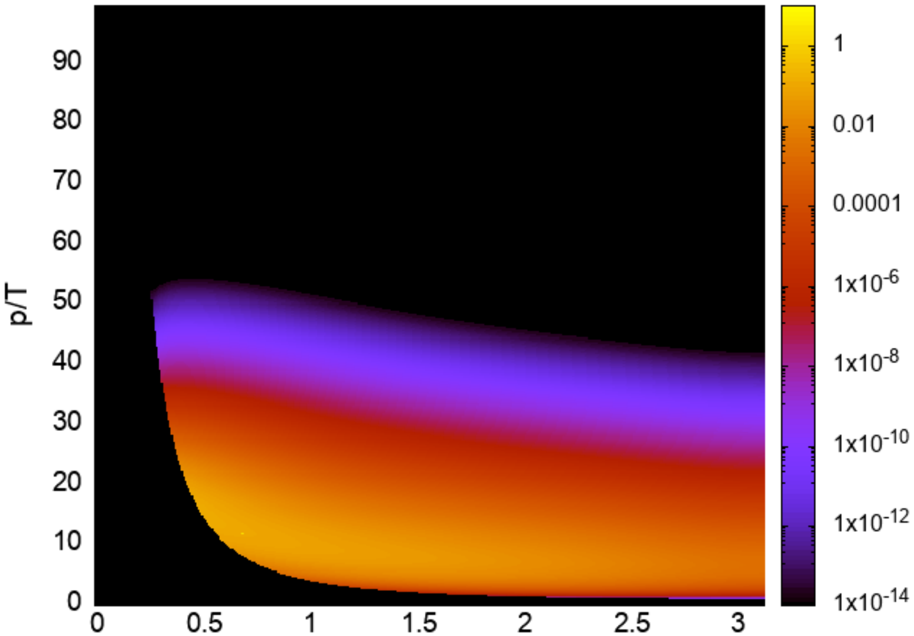


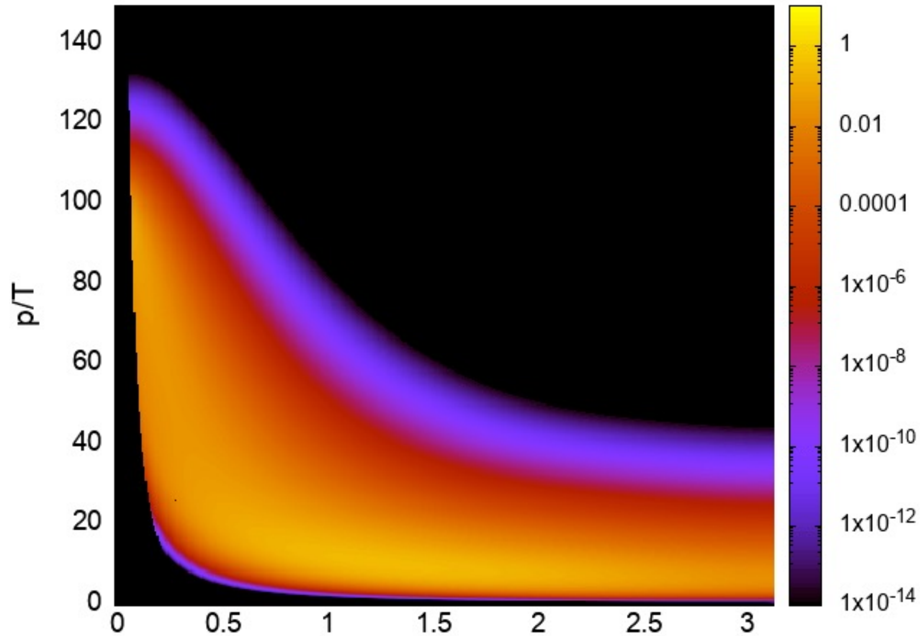
Incoming gluon, $p_{in} = 20T, \mathrm{L} = 15/T$

Incoming gluon, $p_{in} = 100T, \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 4\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 4\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Results (for a QGP brick)





Incoming gluon, $p_{in} = 20T, \mathrm{L} = 15/T$

Incoming gluon, $p_{in} = 100T, \ \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 10\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 10\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting. Can vary where to set this cut…
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

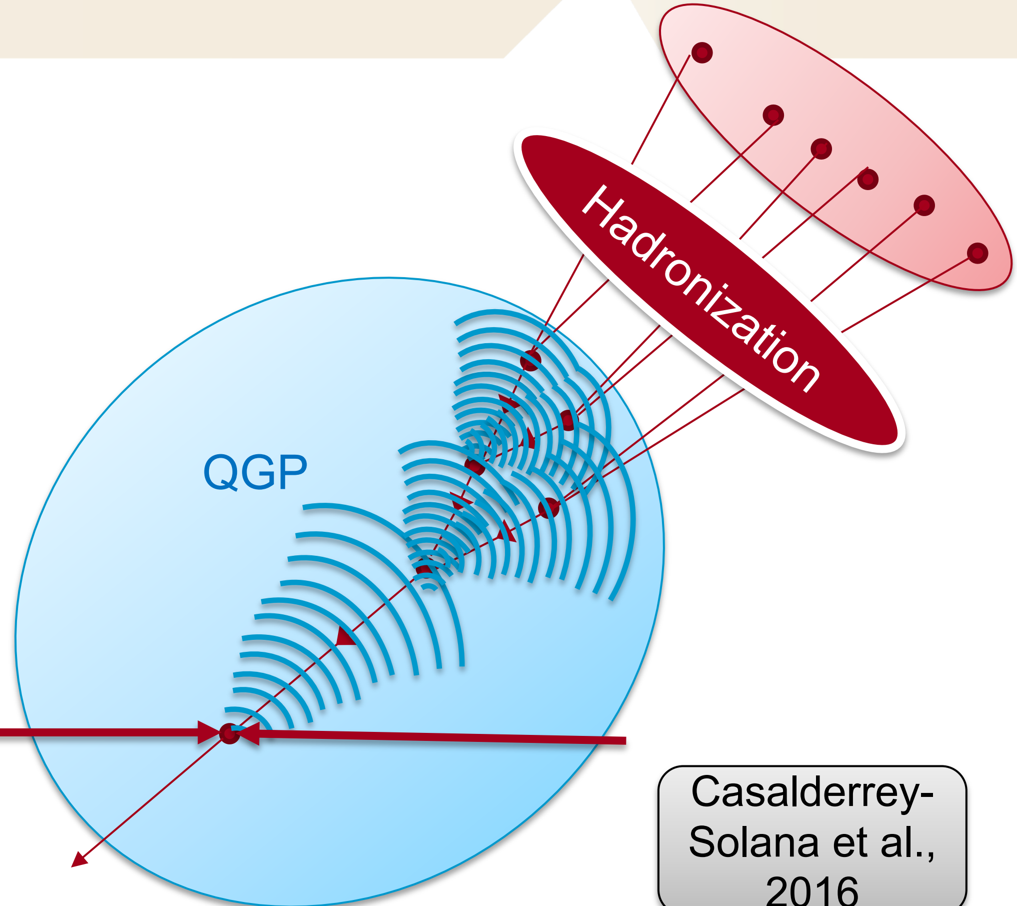
Perturbative Shower … Living in Strongly Coupled QGP

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}} \qquad \tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

Adding Moliere Scattering to Hybrid Model

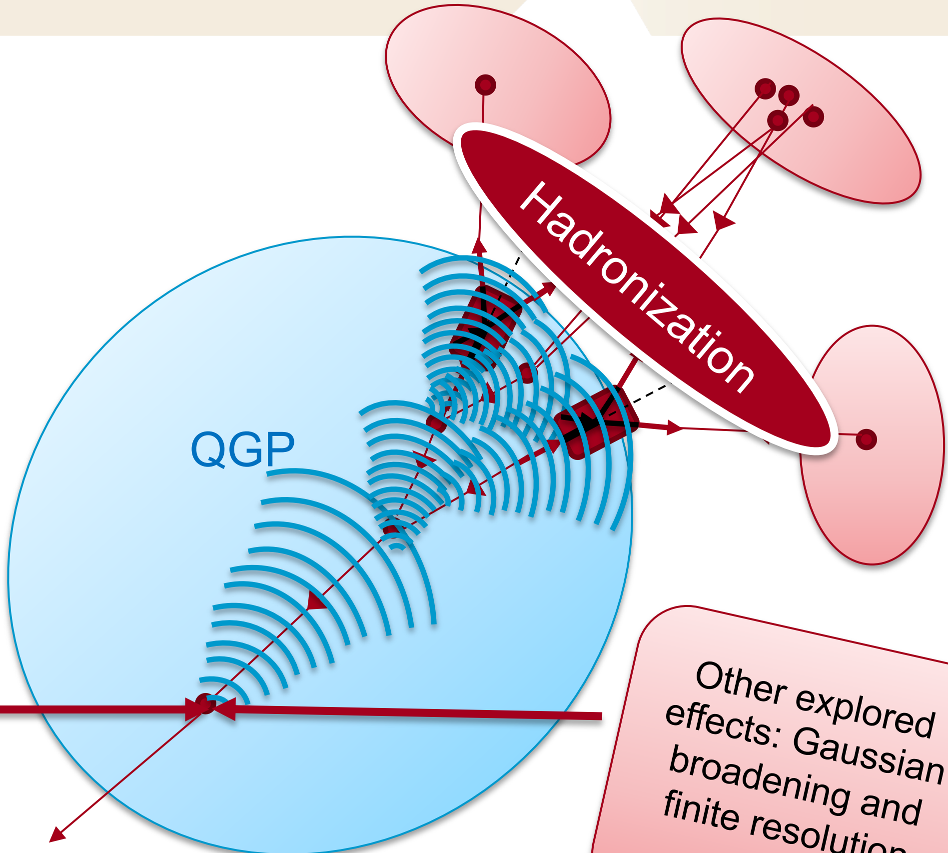
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

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

$$\tau = \frac{2E}{Q^2}$$



Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation → activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

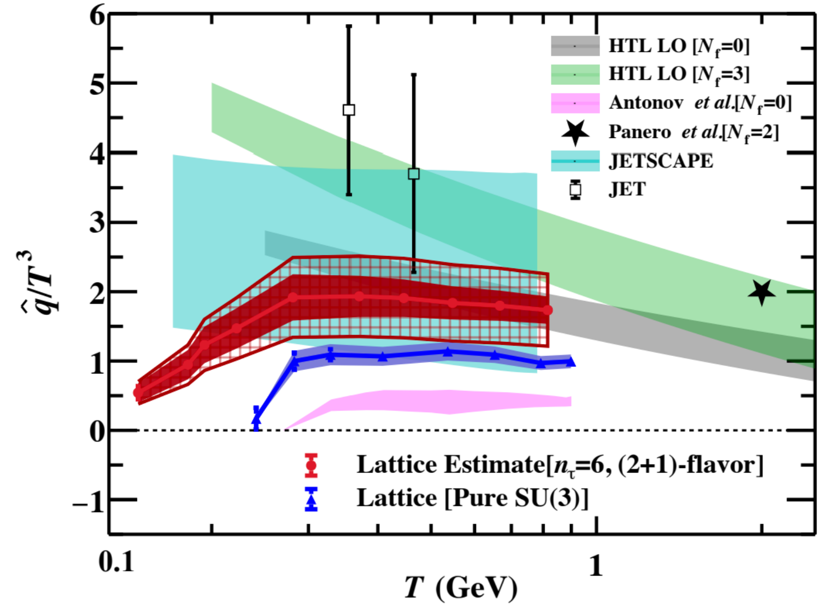
At strong coupling, holography predicts Gaussian broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\,T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; focus on perturbative regime



From Weber's HP2023 talk

D'Eramo et al., 2011, 2018
+
Mehtar-Tani et al., PRD 2021

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

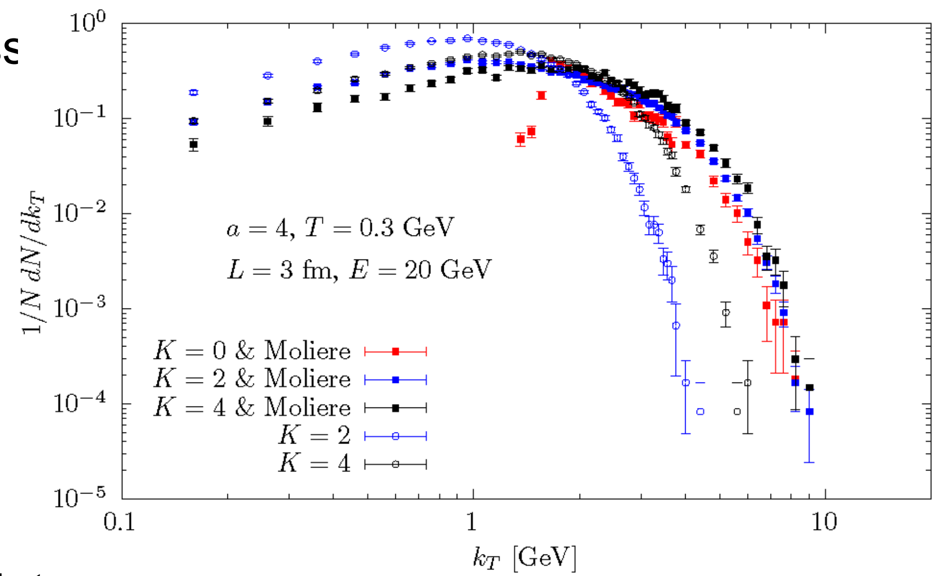
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\, T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 4$



Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

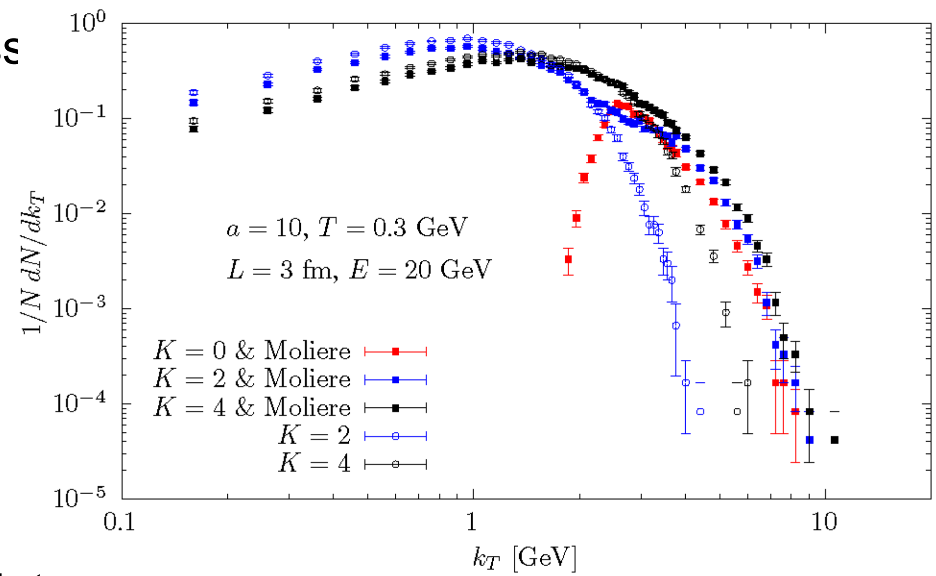
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\,T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$



Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

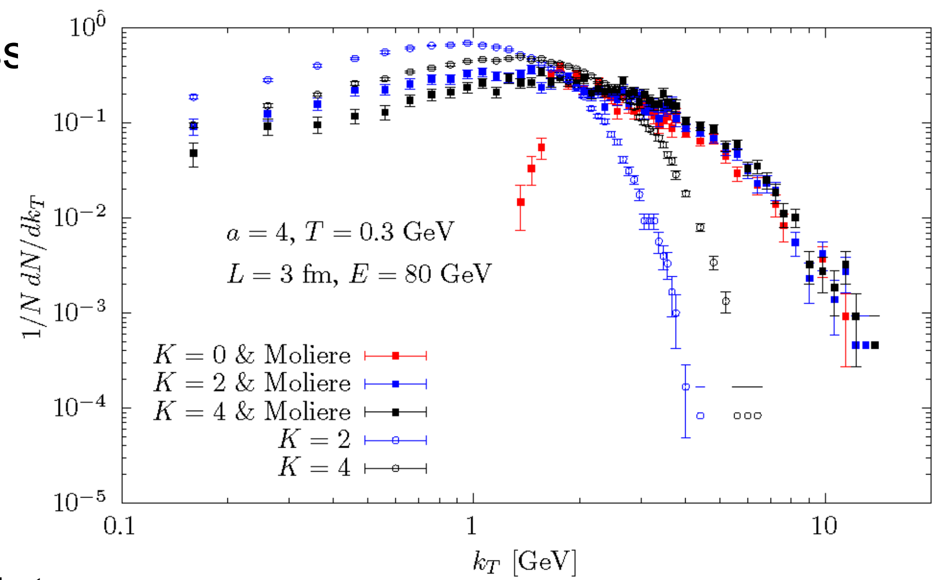
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\,T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$ and 80 GeV incident jet parton



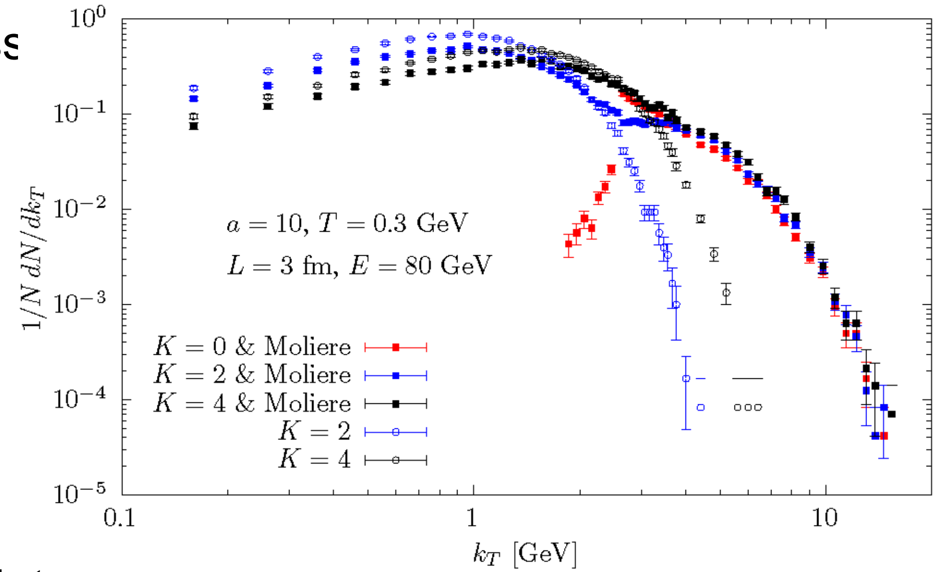
Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$



Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

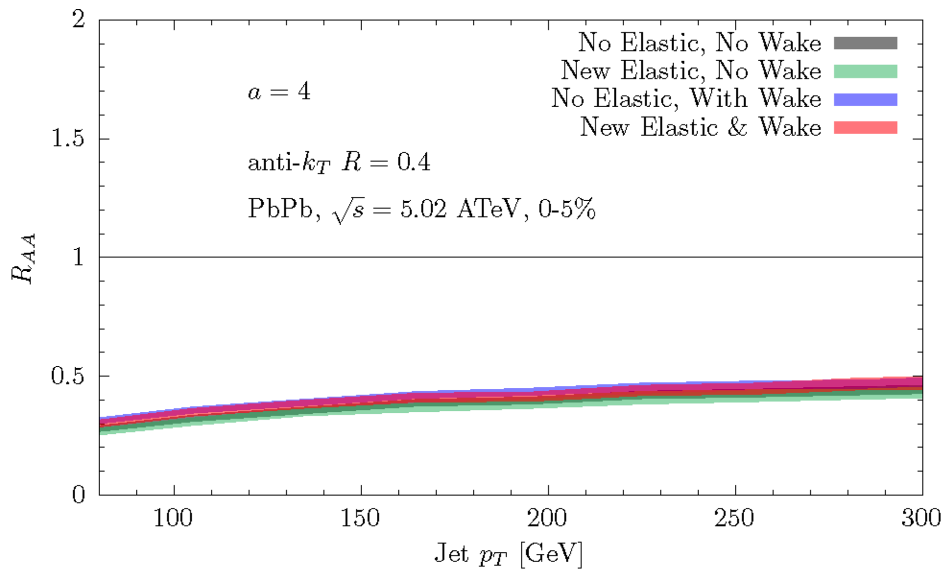
Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\, T^3$ with $K \sim 2 - 4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$ and 80 GeV incident jet parton

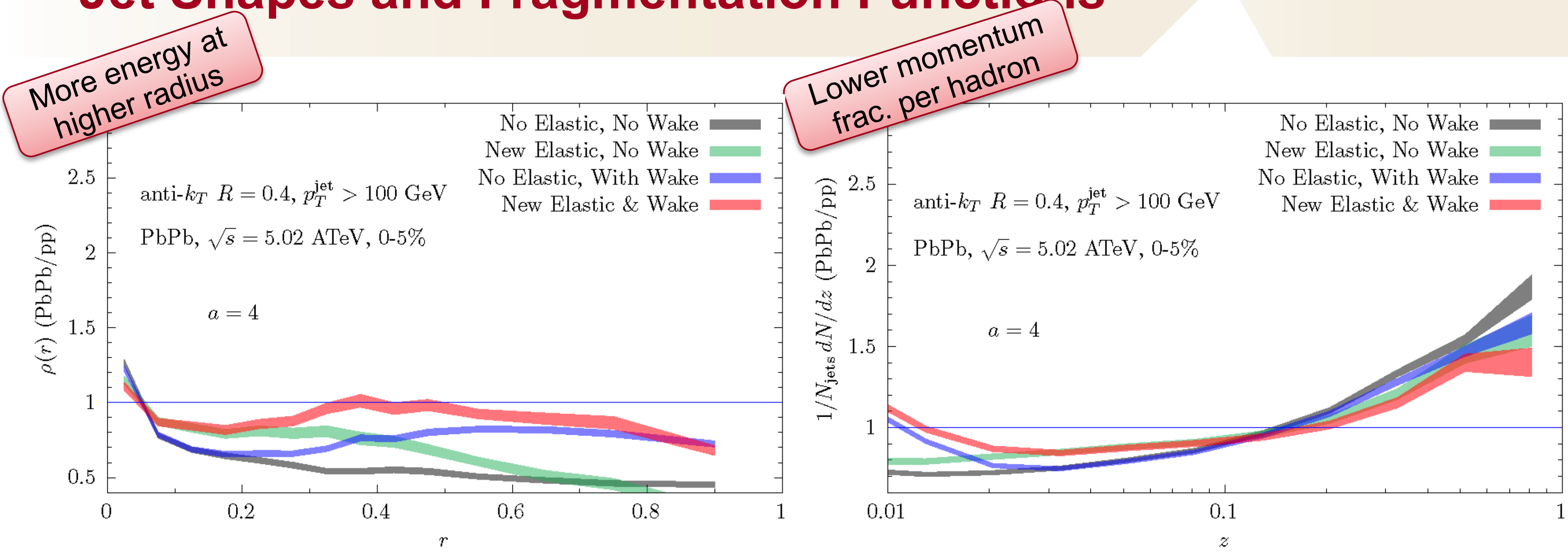
Jet R_{AA}

Casalderrey-Solana et al. 2019

- κ_{sc} previously fit with jet and hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV
- Elastic scatterings lead to slight additional suppression; refit κ_{sc} . That means red is on top of blue in this plot by construction. (Addition of the elastic scatterings yields only small change to value of κ_{sc}.)
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone; blue and green slightly below red and blue.



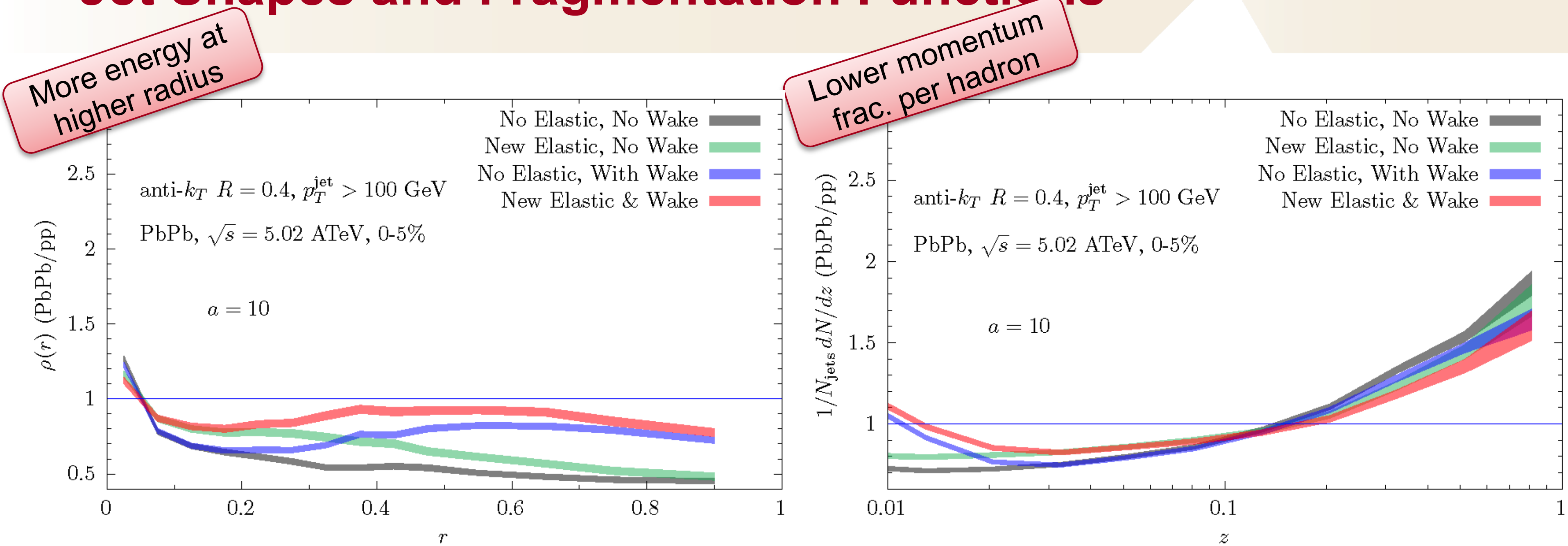
Jet Shapes and Fragmentation Functions



Elastic scattering effects look very similar to wake effects, but smaller.

- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere effects are even slightly smaller if $\tilde{u}, \tilde{t} > \mathrm{a}\, m_D^2$ with a=10.
- What if we look at groomed observables? Less sensitive to wake…

Jet Shapes and Fragmentation Functions



→ Elastic scattering effects look very similar to wake effects, but smaller.

- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere effects are even slightly smaller if $\tilde{u}, \tilde{t} > a\, m_D^2$ with a=10.
- What if we look at groomed observables? Less sensitive to wake…

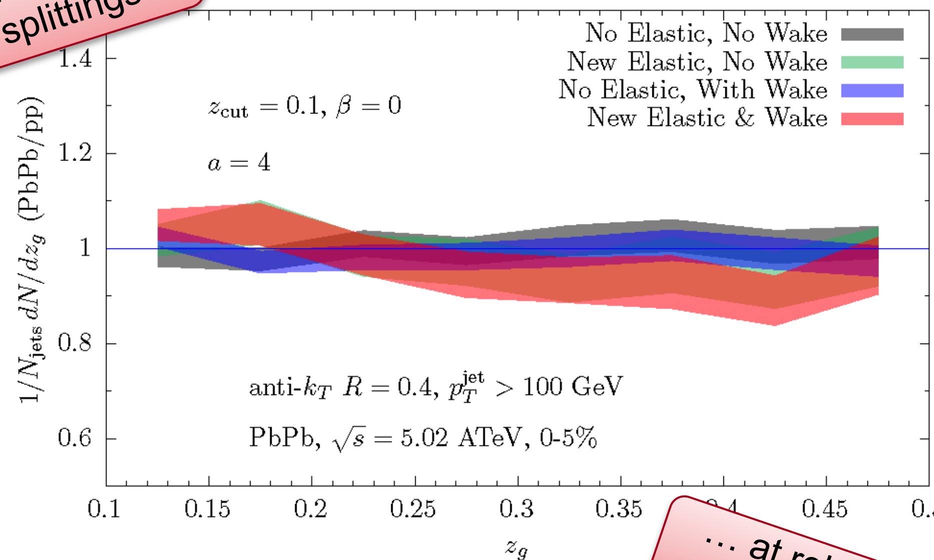
Groomed z_g and R_g

Soft Drop ($\beta = 0$)

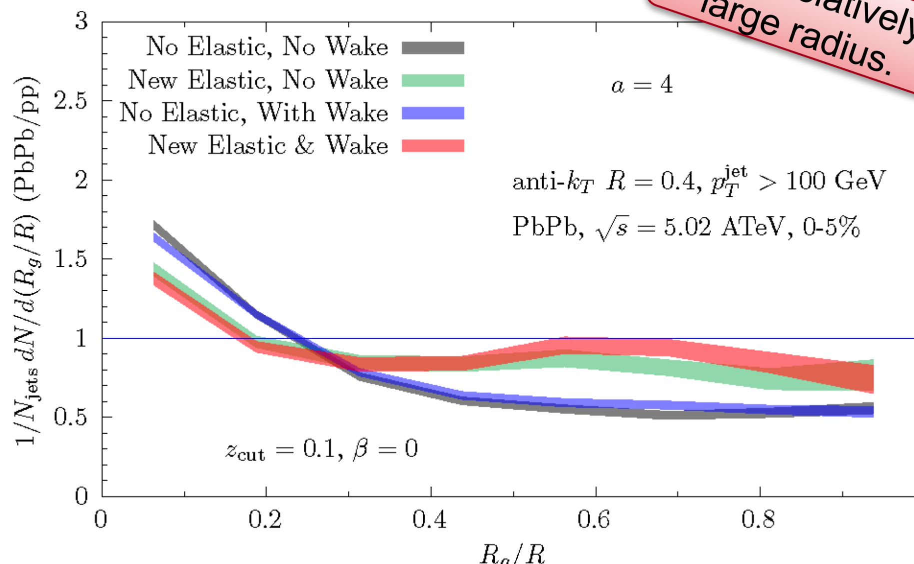
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere on R_g are dominant, with a=4 or 10.

Enhancement of softer splittings…



… at relatively large radius.



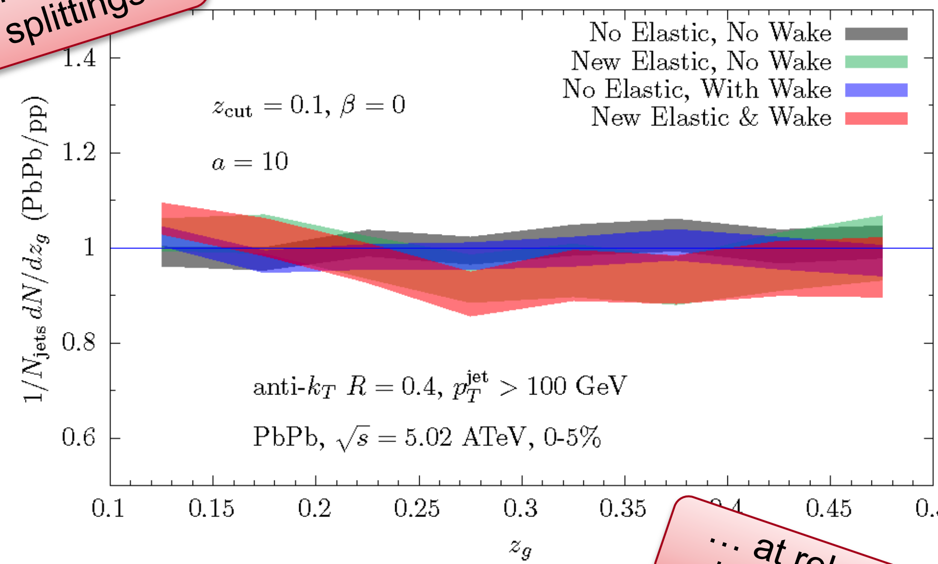
Groomed z_g and $\mathrm{R_g}$

Soft Drop ($\beta = 0$)

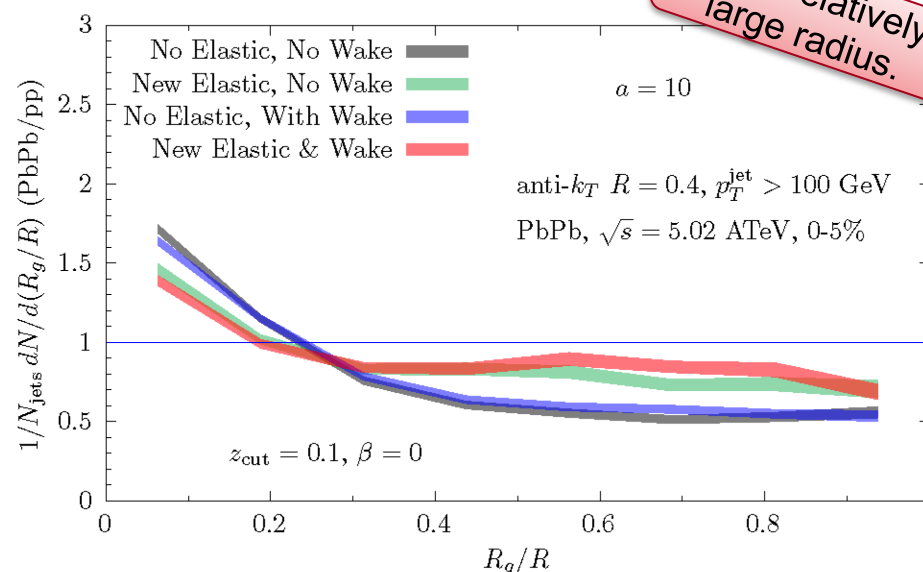
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle $\mathrm{R_g}$
4. If $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere on $\mathrm{R_g}$ are dominant, with a=4 or 10.

Enhancement of softer splittings…



… at relatively large radius.

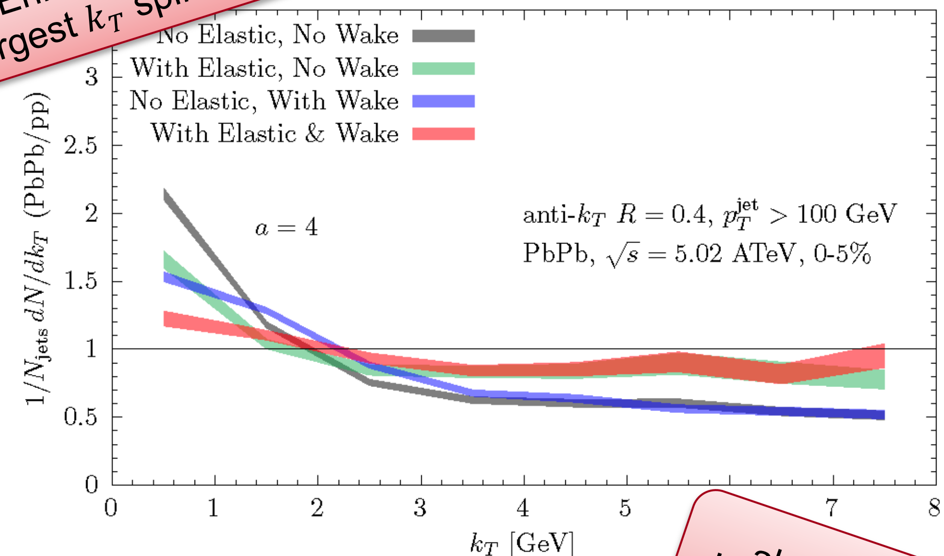


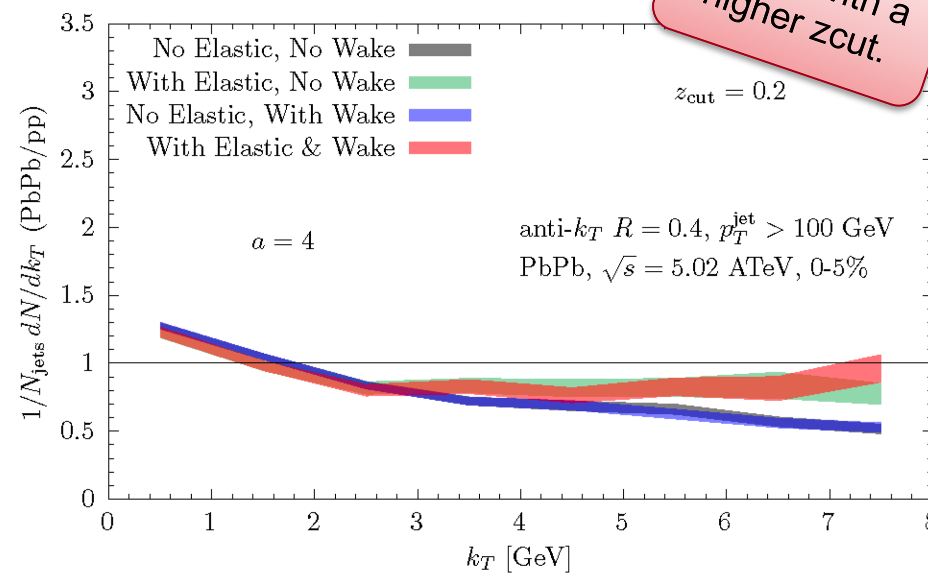
Leading k_T

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

$$k_T = \min(p_{T1}, p_{T2})\sin(R_g)$$

Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.



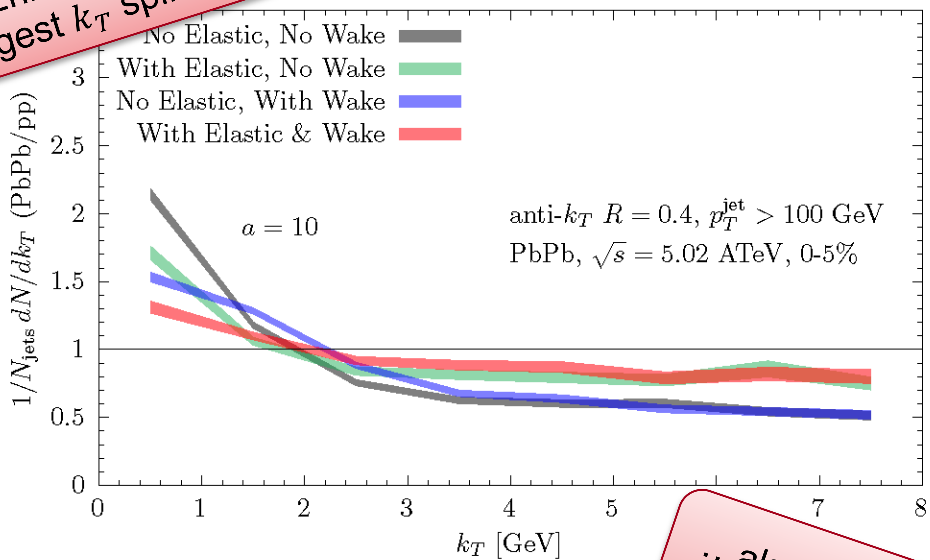


Leading k_T

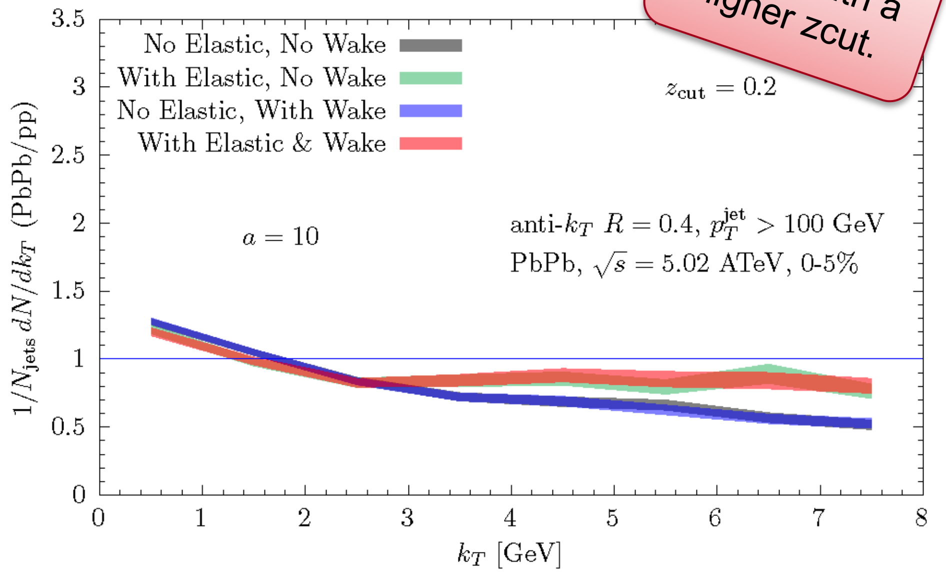
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

$$k_T = \min(p_{T1}, p_{T2}) \sin(R_g)$$

Enhancement of largest k_T splittings…

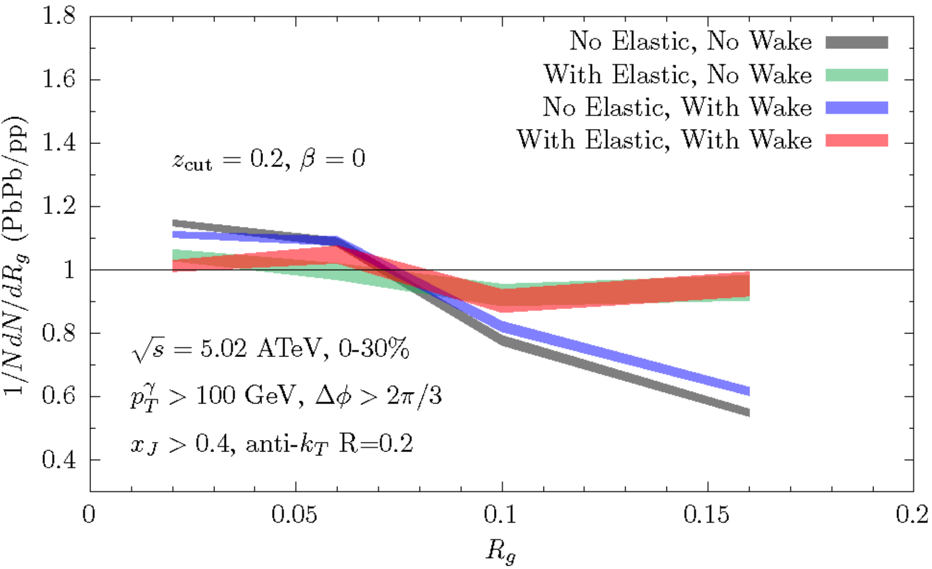


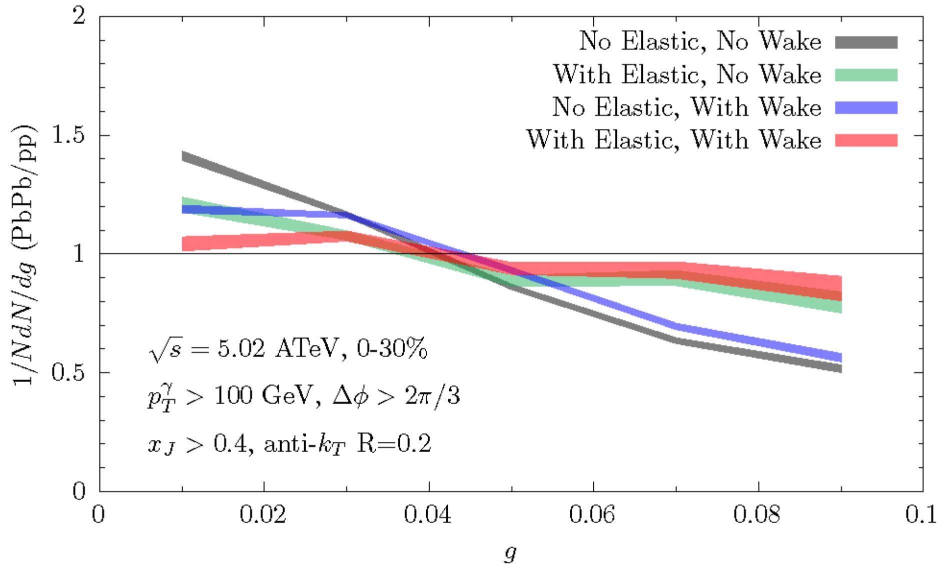
…also with a higher zcut.



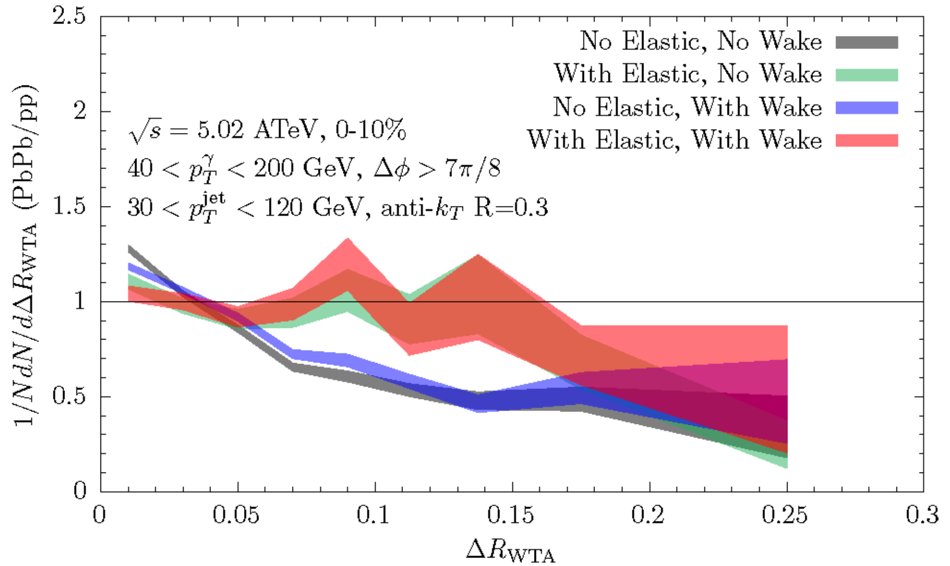
Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.

Three "groomed" gamma-Jet Observables: R_g , Girth, and angle between standard and WTA axes

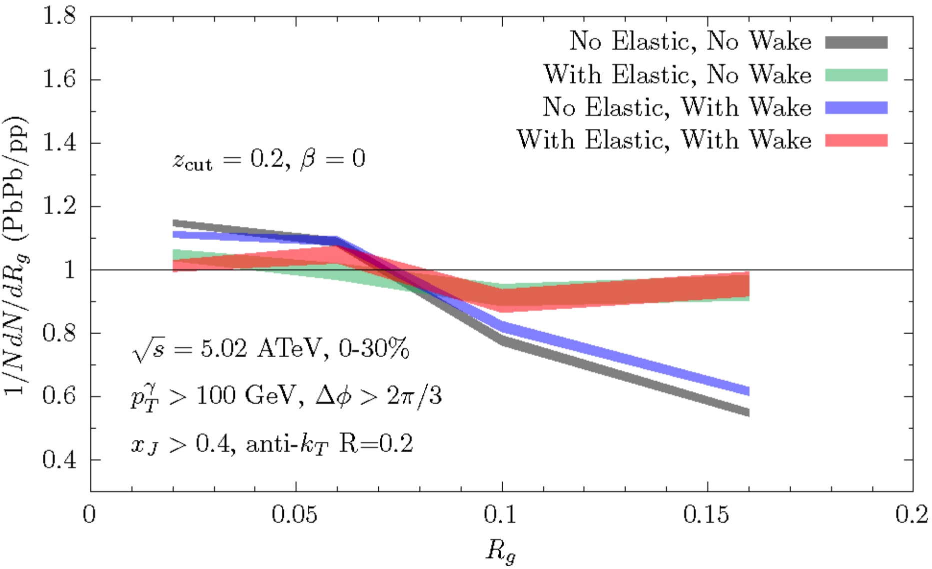


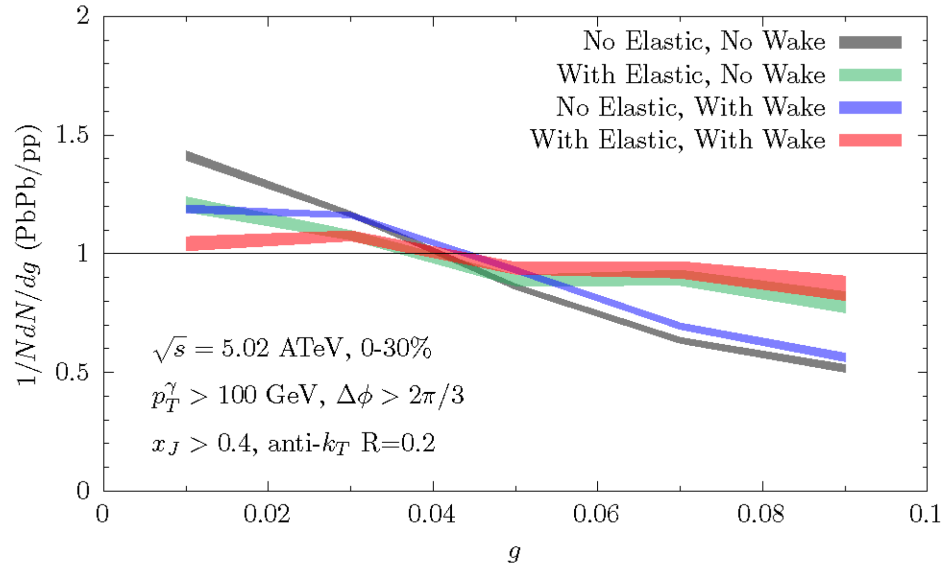


All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



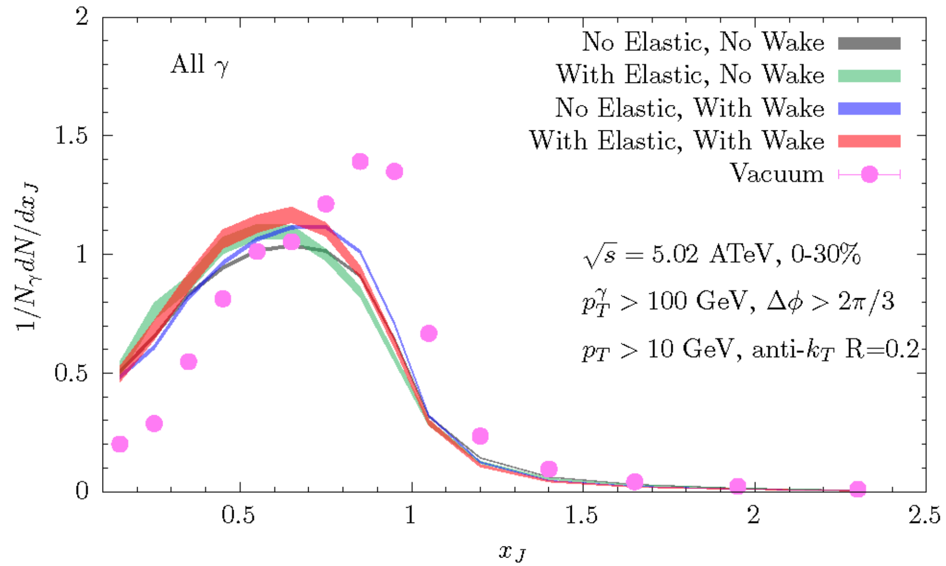
Gamma-Jet Observables: R_g and Girth



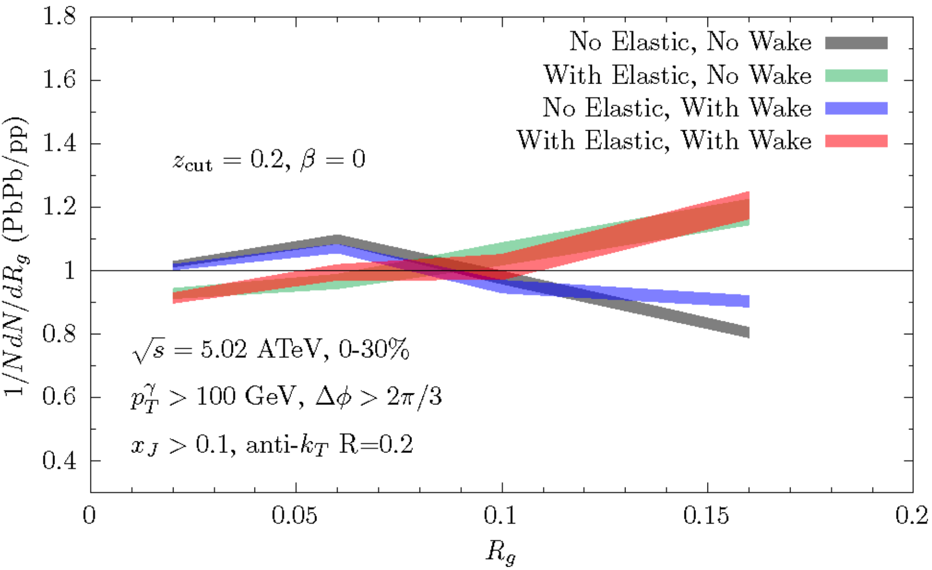


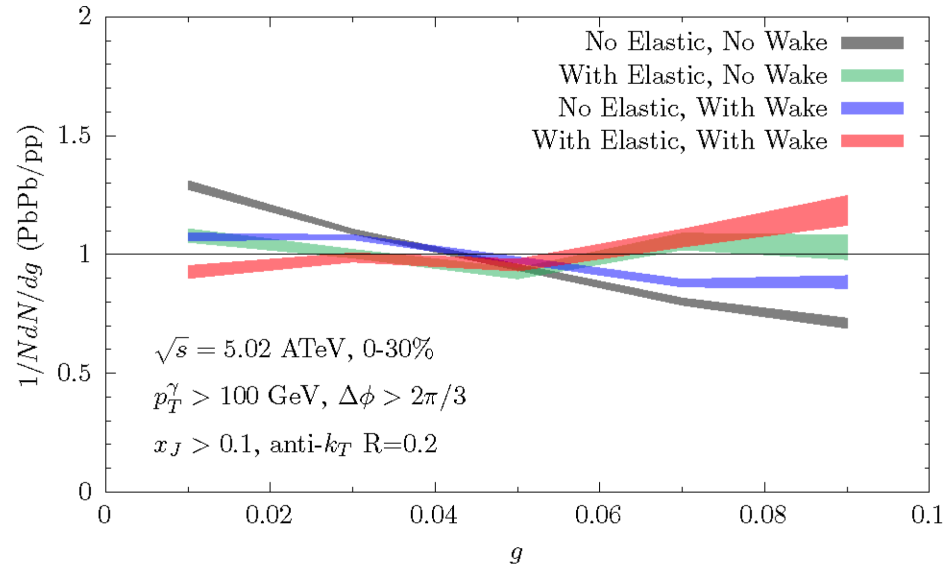
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is R_{AA} below 1? Selection bias! With x_J>0.4 selection, missing too many of the most modified jets.



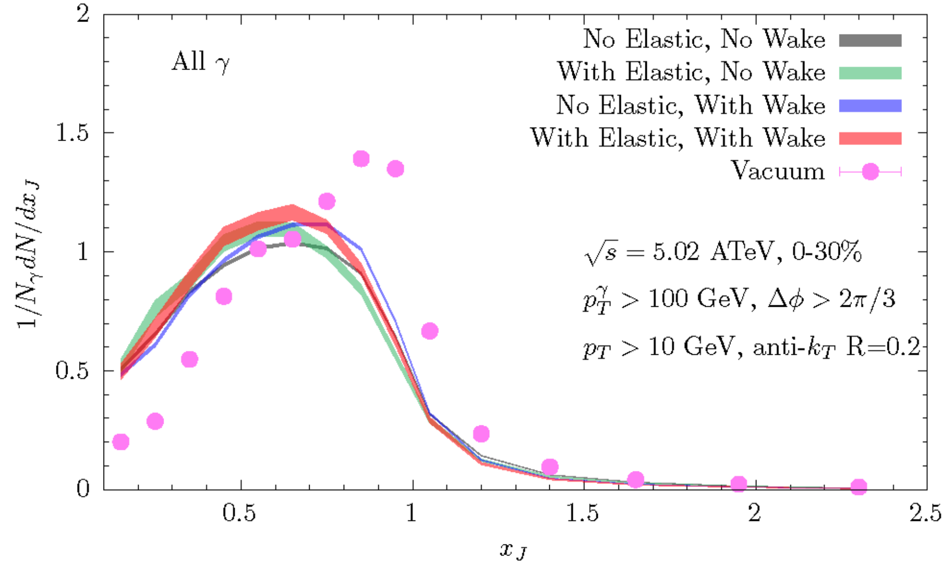
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



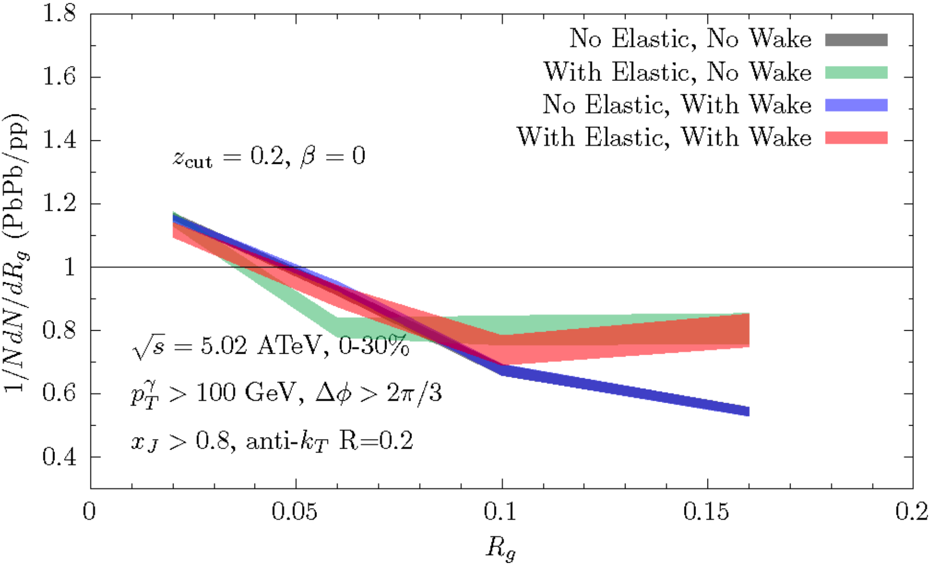


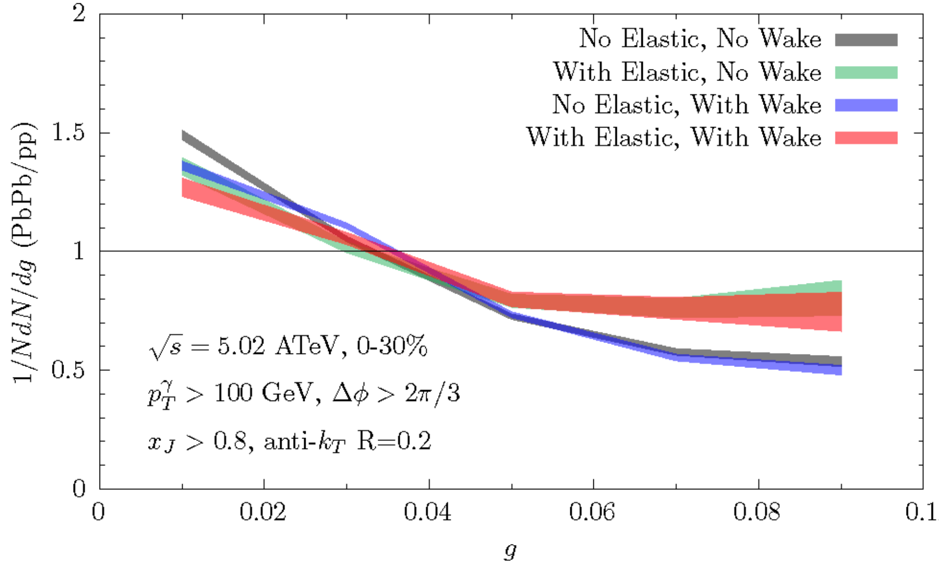
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



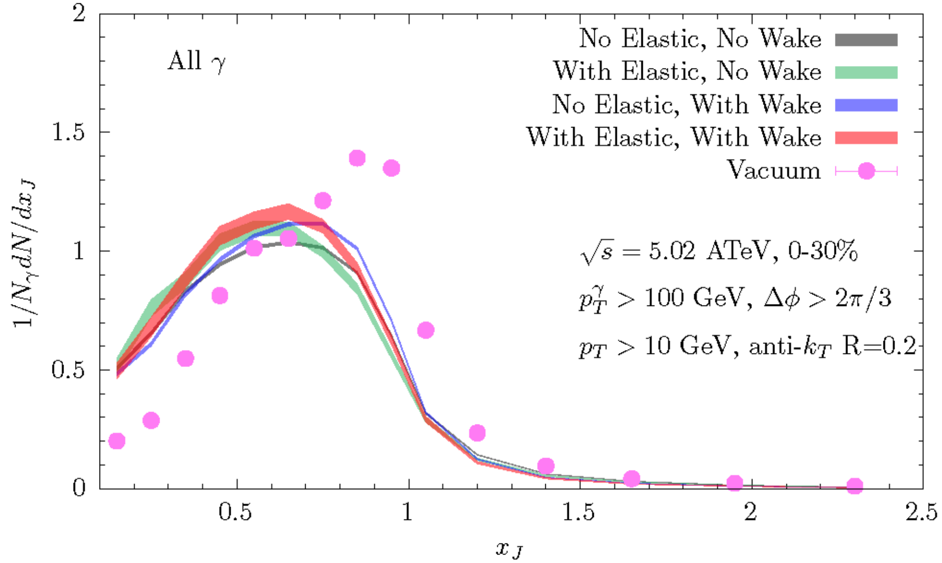
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



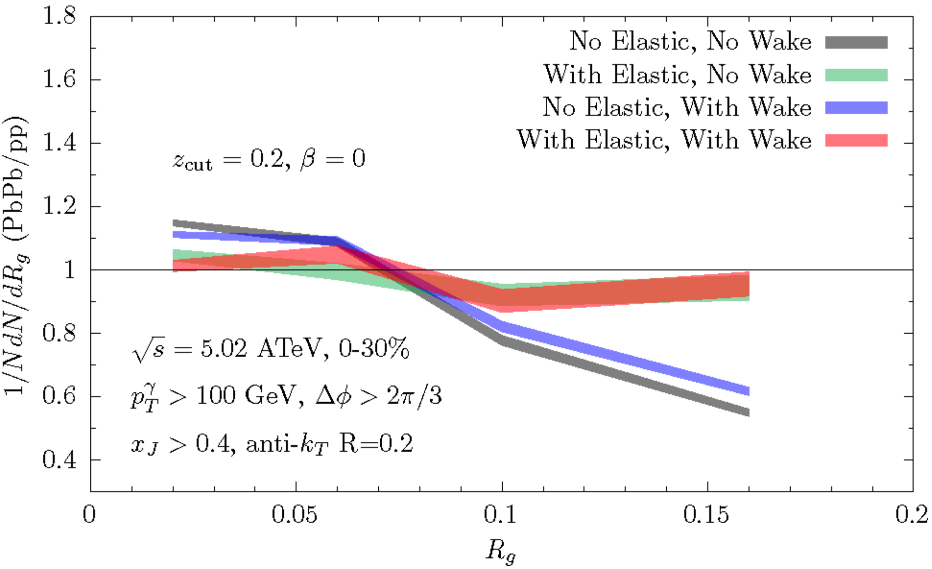


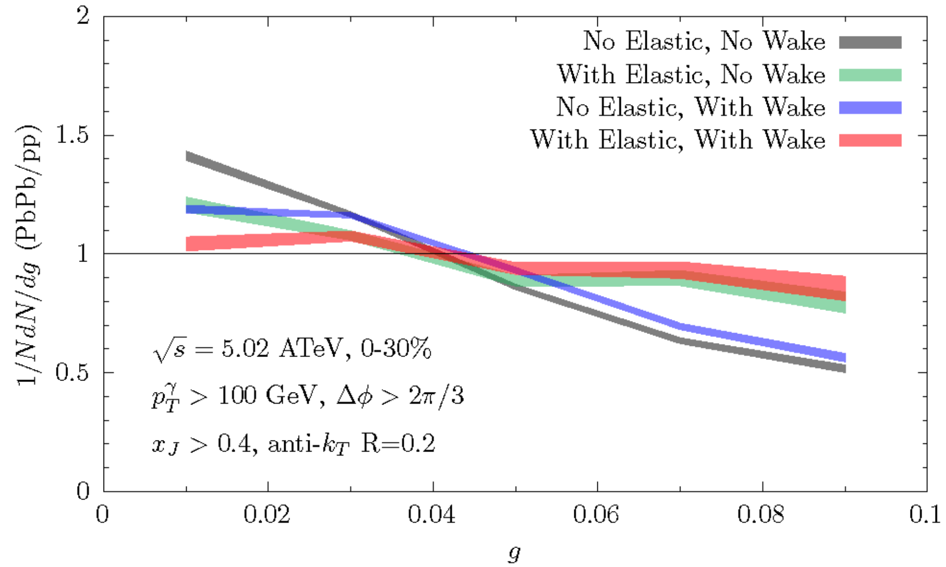
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

Moliere scattering still important, and but selection bias so strong that it does not yield R_{AA} >1.



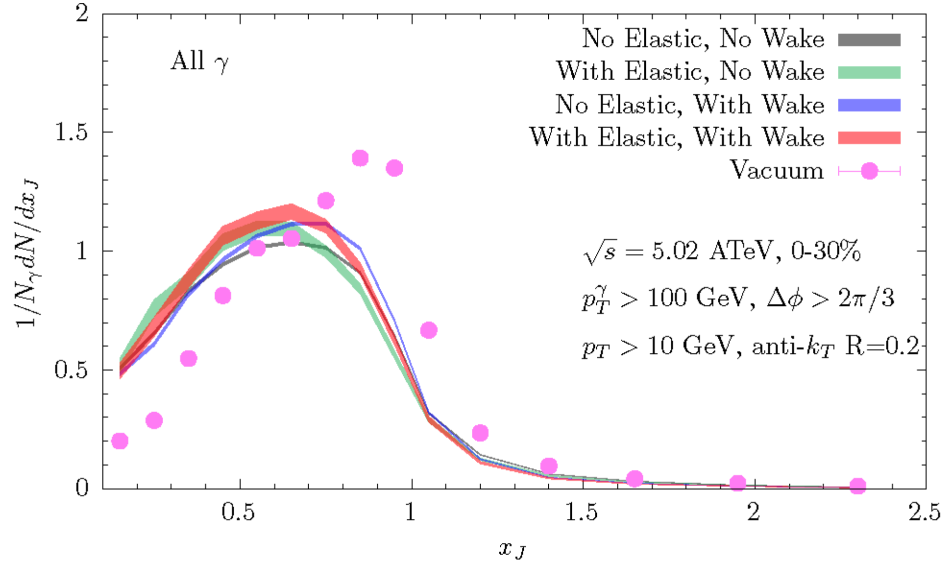
Gamma-Jet Observables: R_g and Girth, with x_J>0.4



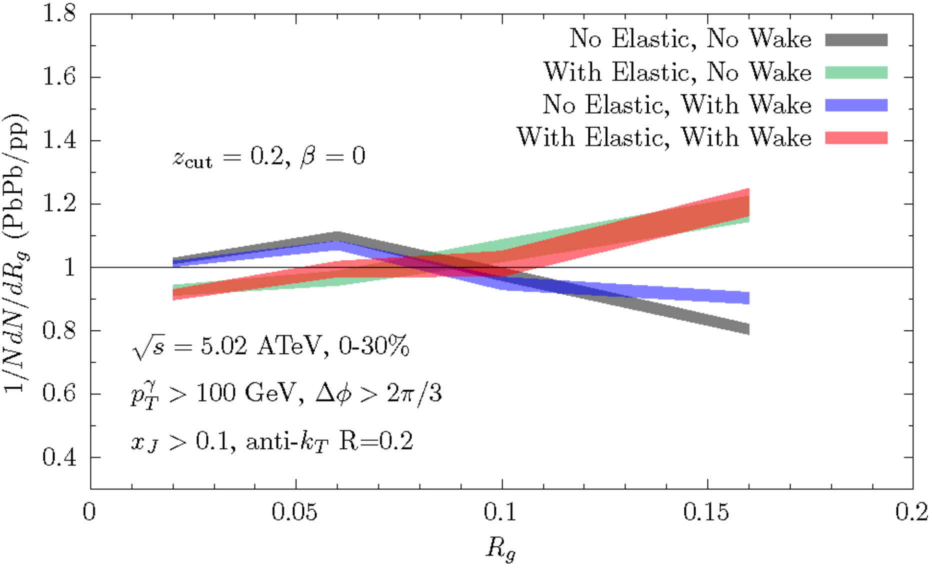


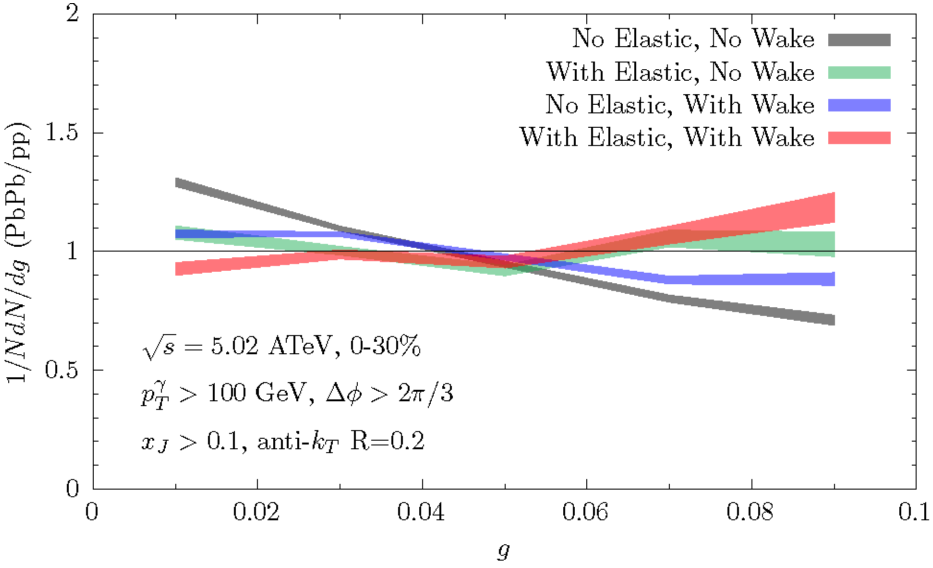
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is R_{AA} below 1? Selection bias! With x_J>0.4 selection, missing too many of the most modified jets.



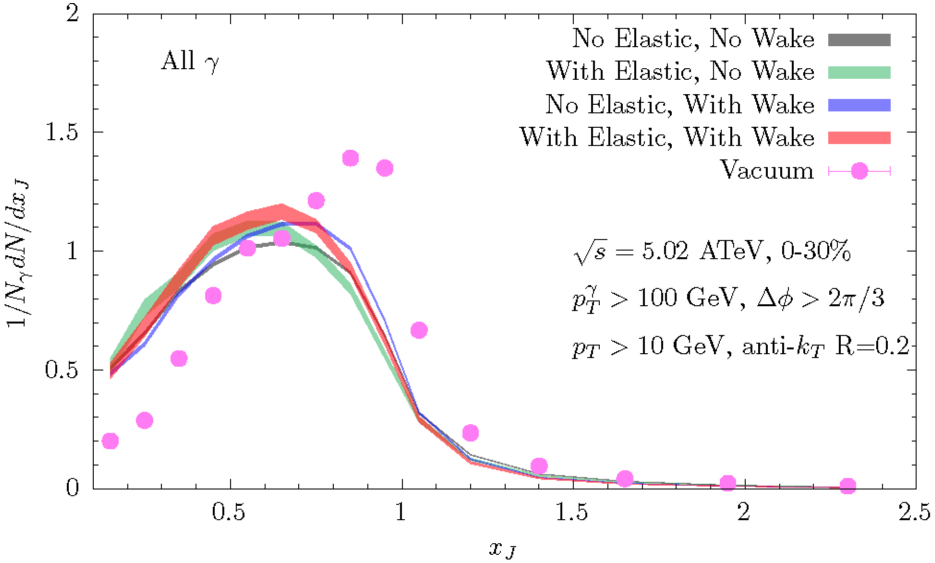
Gamma-Jet Observables: R_g and Girth, with x_J>0.1



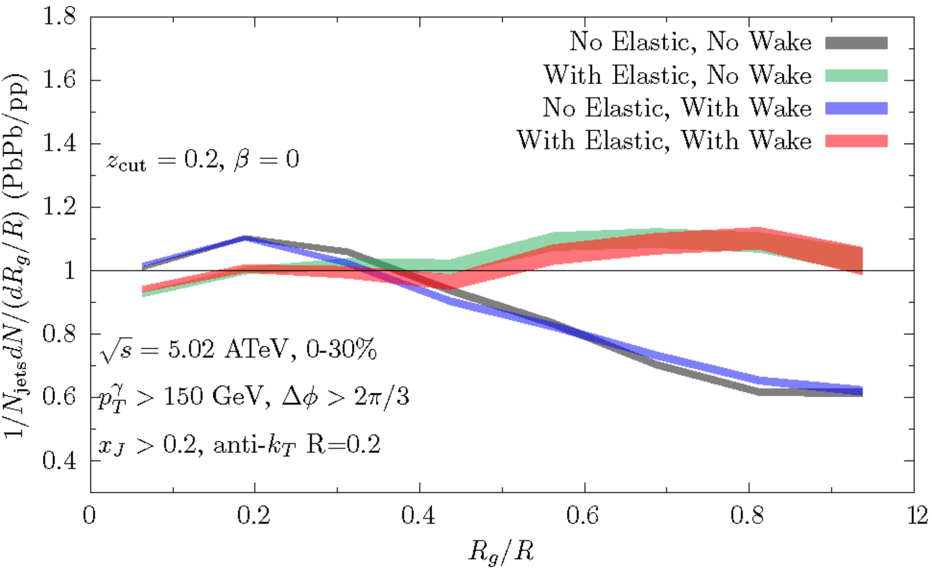


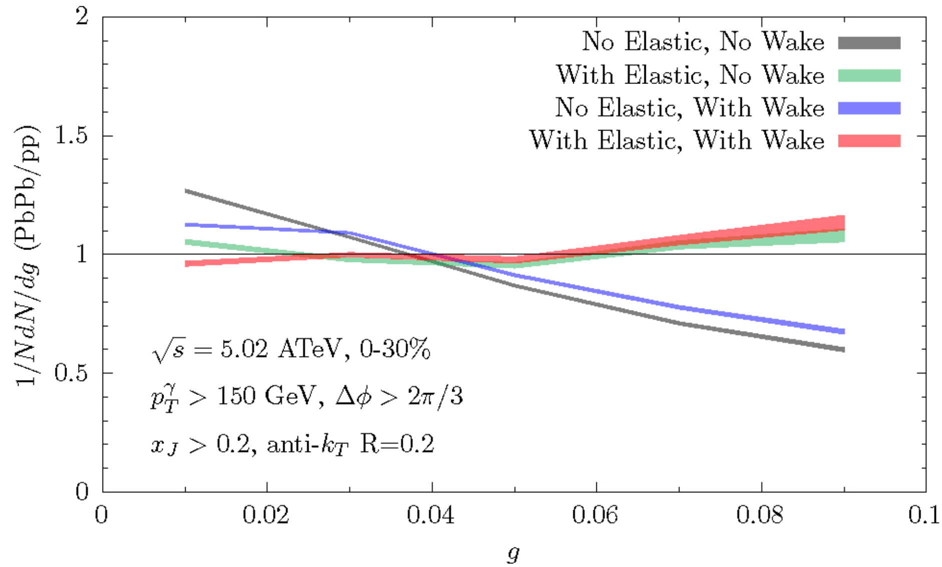
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



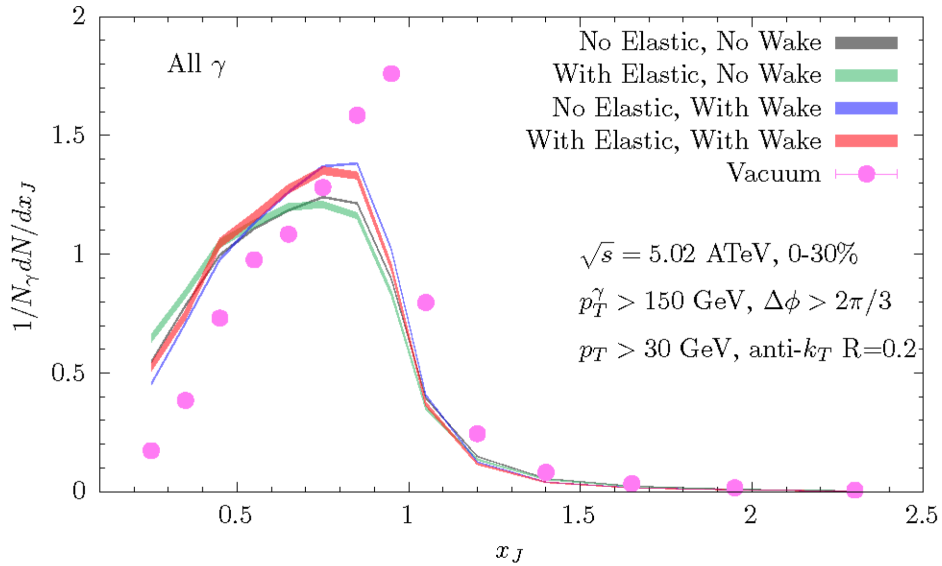
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2



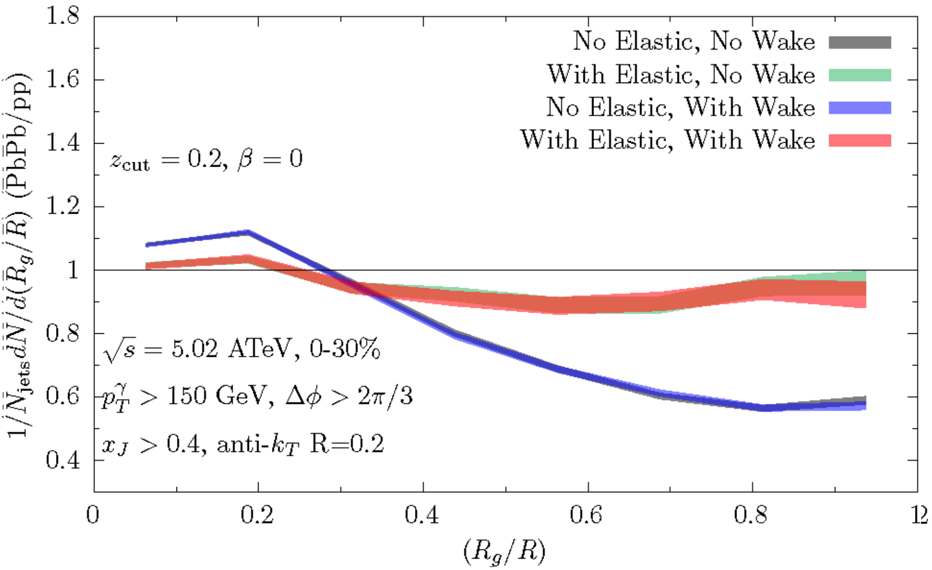


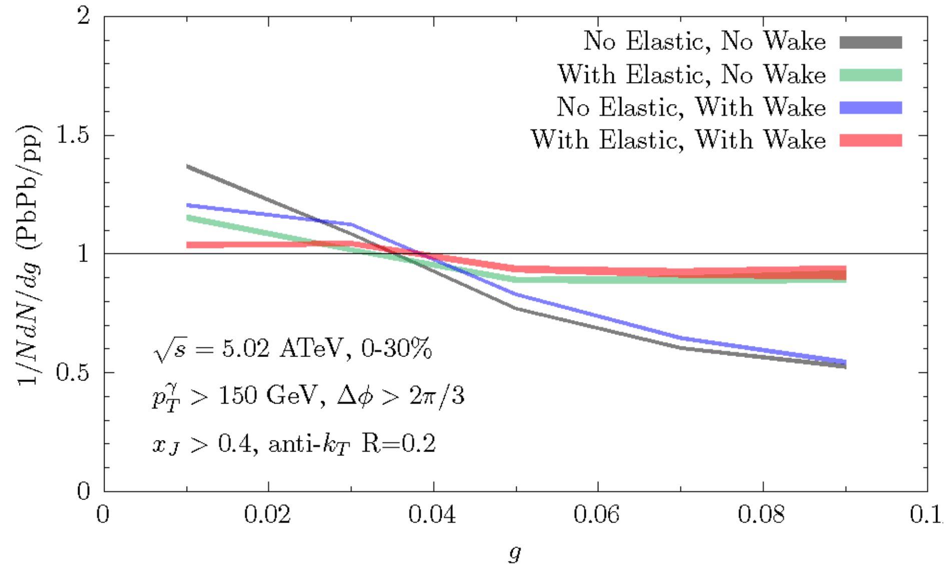
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV. Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

Moliere effects substantial; selection bias reduced; wake effects negligible.



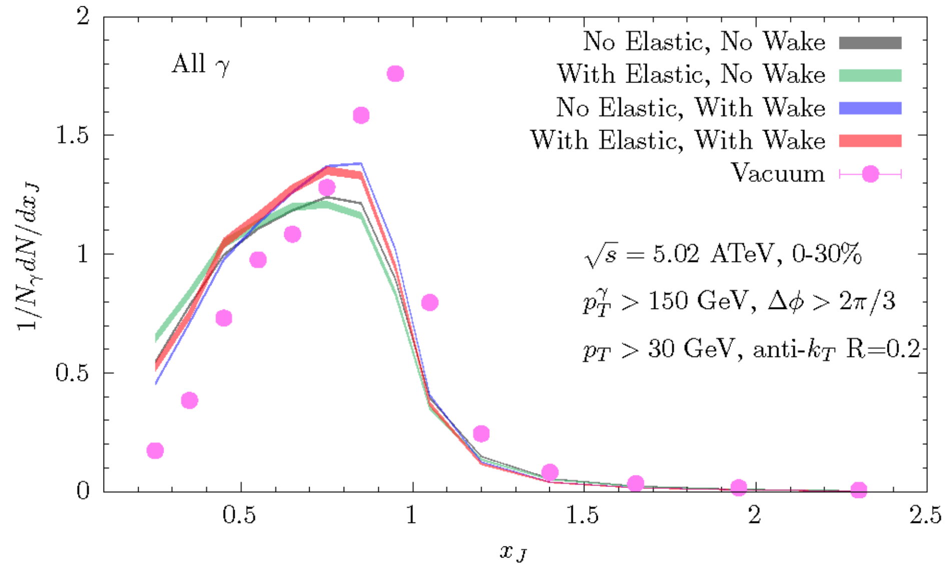
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.4



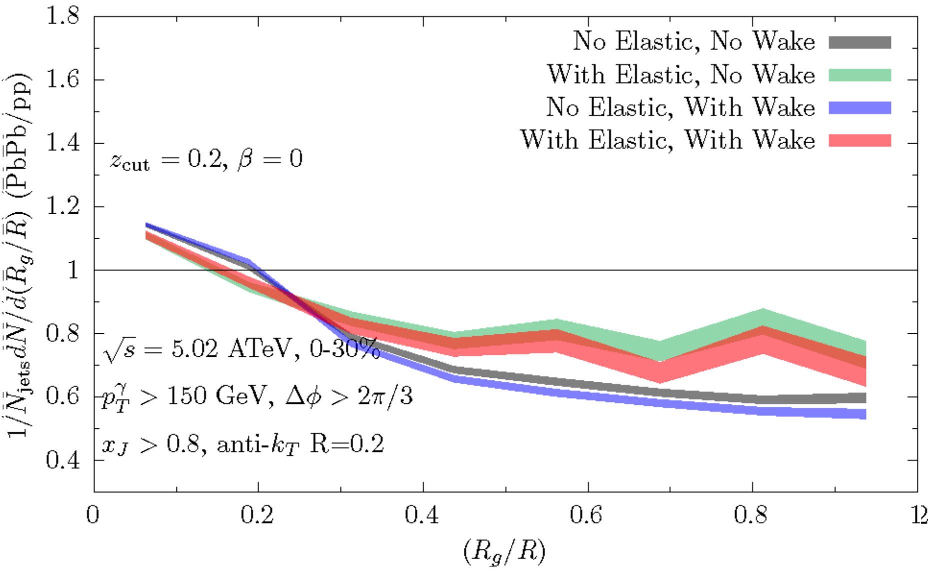


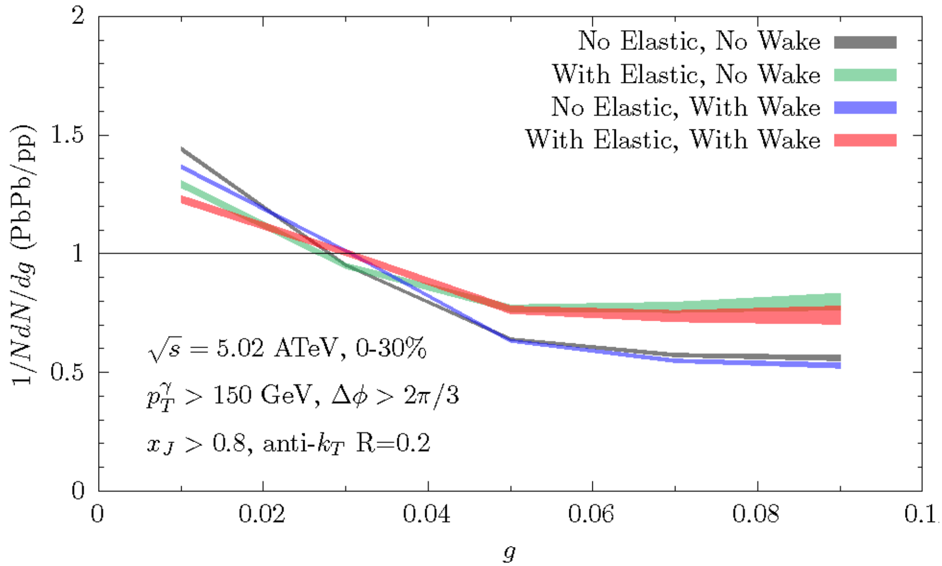
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV.
Means x_J>0.4 corresponds to p_T^{jet}>60 GeV.

Moliere effects substantial; selection bias significant; wake effects negligible.



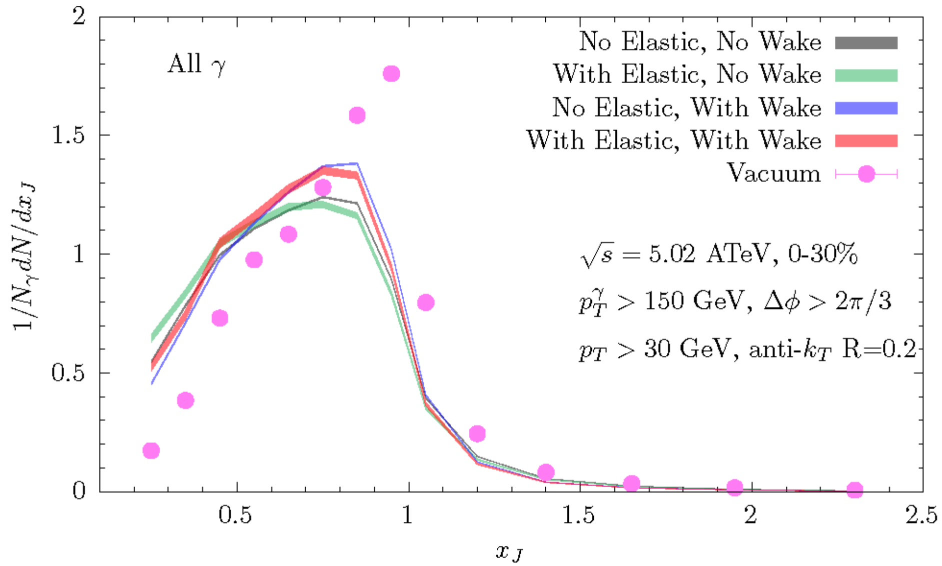
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.8



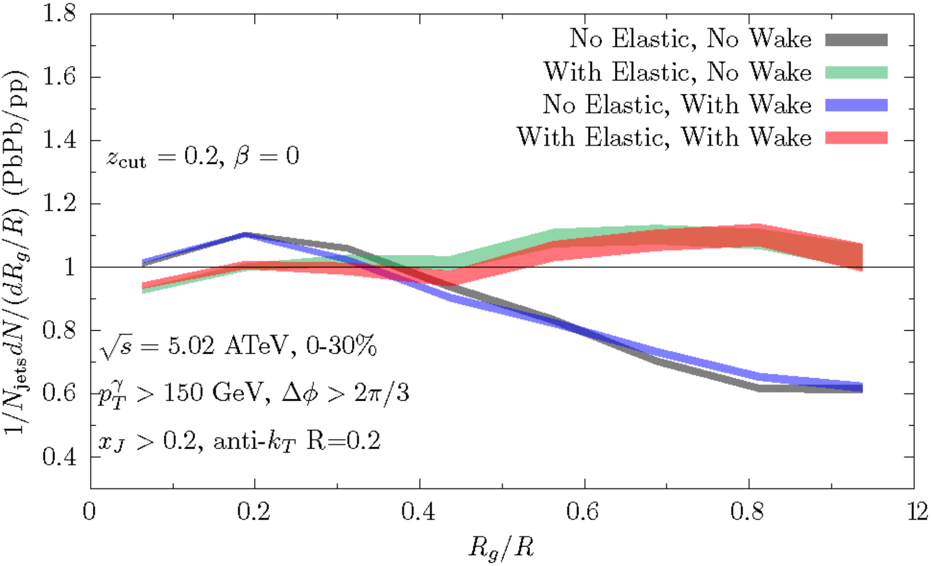


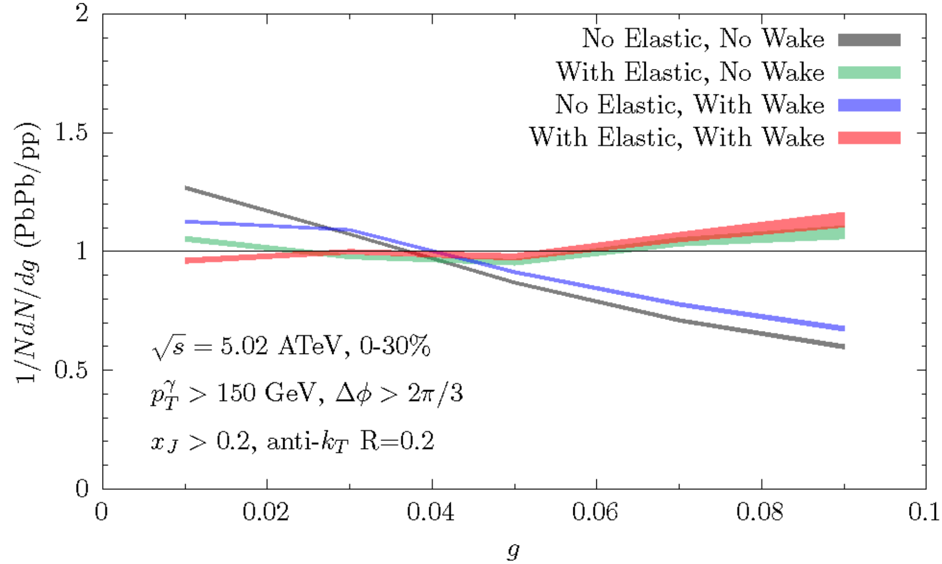
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.8 corresponds to p_T^{jet}>120 GeV.

Moliere effects substantial; selection bias dominant; wake effects negligible.



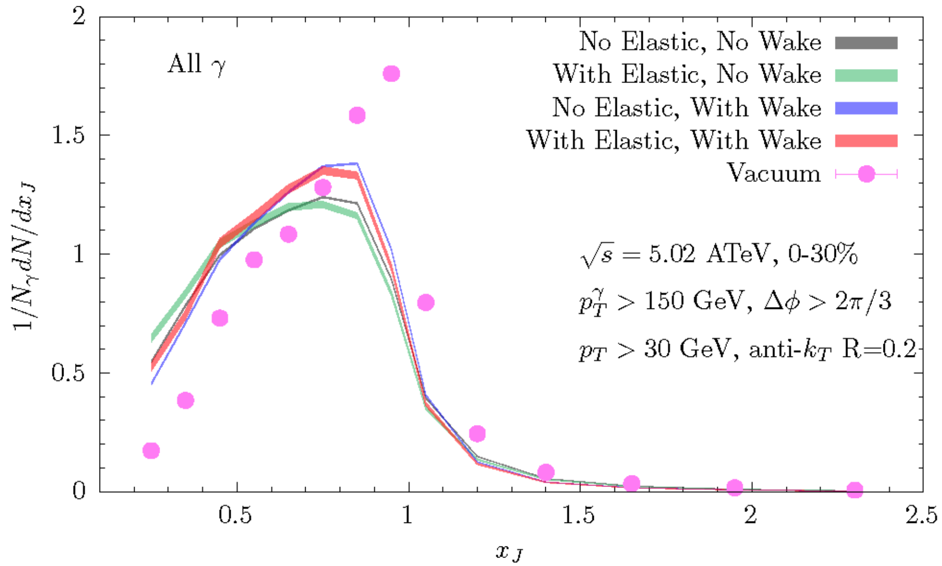
Gamma-Jet Observables with p_T^γ >150 GeV: R_g and Girth, with x_J>0.2



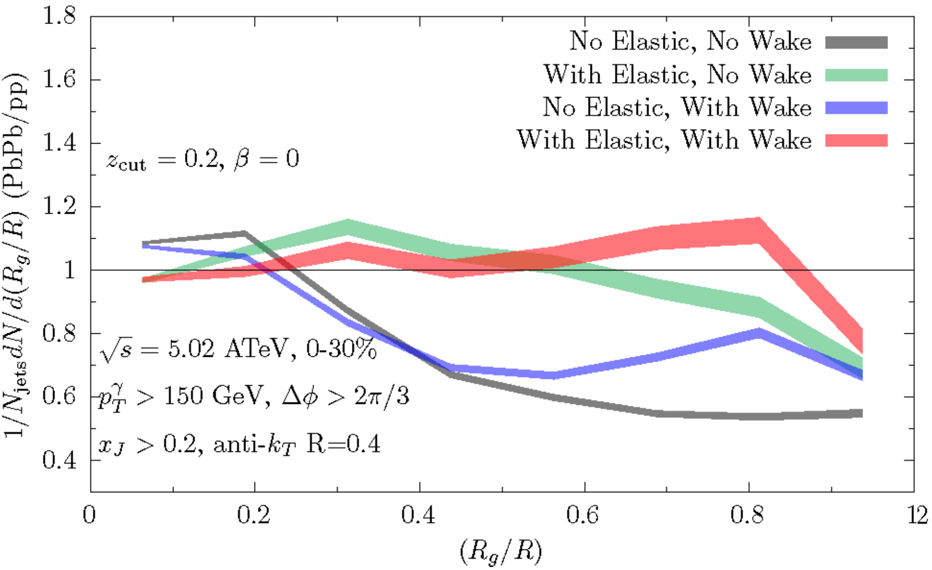


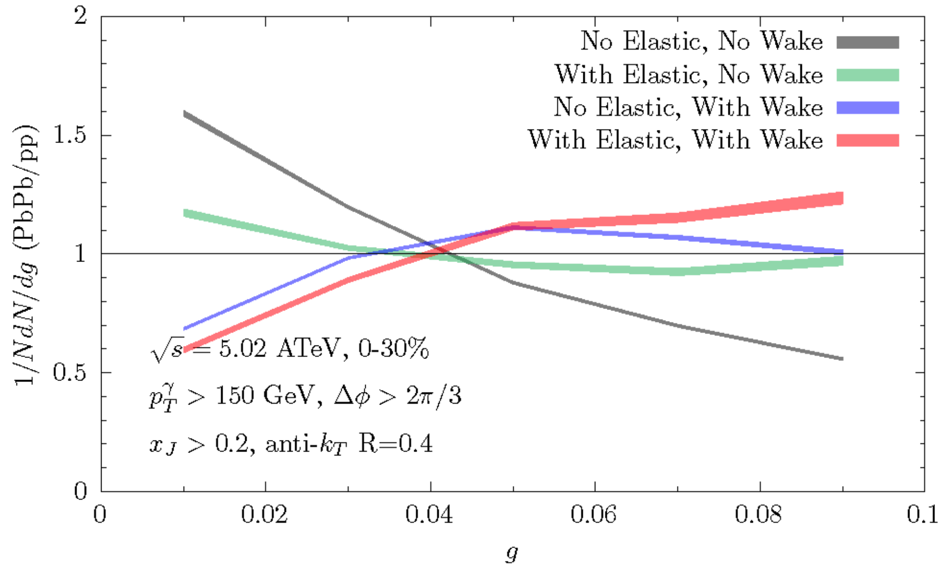
On previous slides, p_T^γ >100 GeV; here, p_T^γ >150 GeV. Means x_J>0.2 corresponds to p_T^{jet}>30 GeV. And, no need to go down to x_J>0.1.

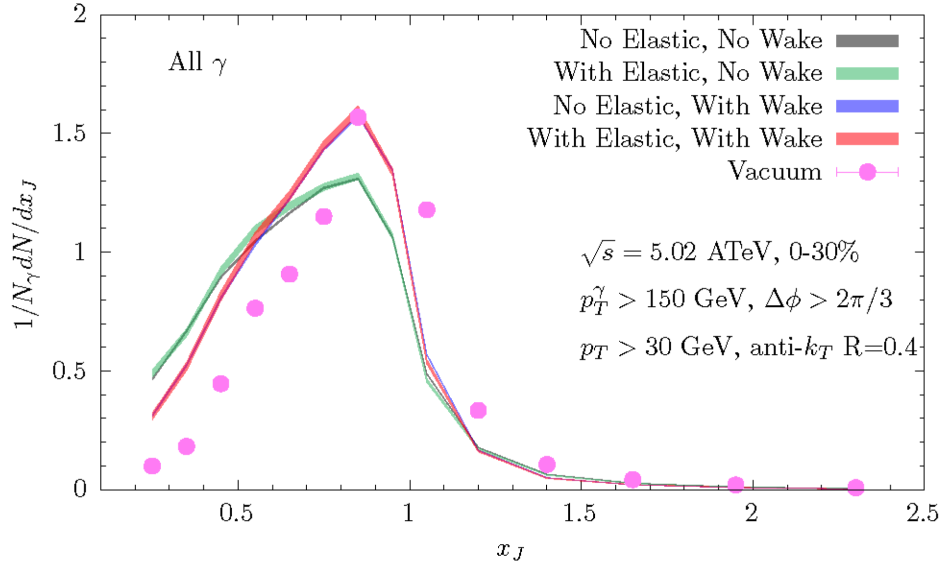
Moliere effects substantial; selection bias reduced; wake effects negligible.



Gamma-Jet Observables with p_T^{γ} >150 GeV and R=0.4: R_g and Girth, with x_J>0.2



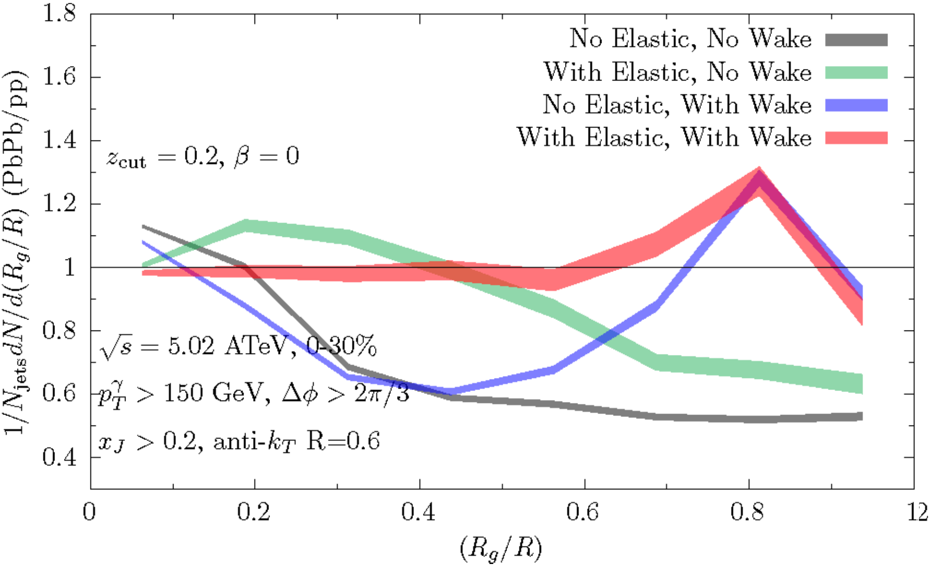


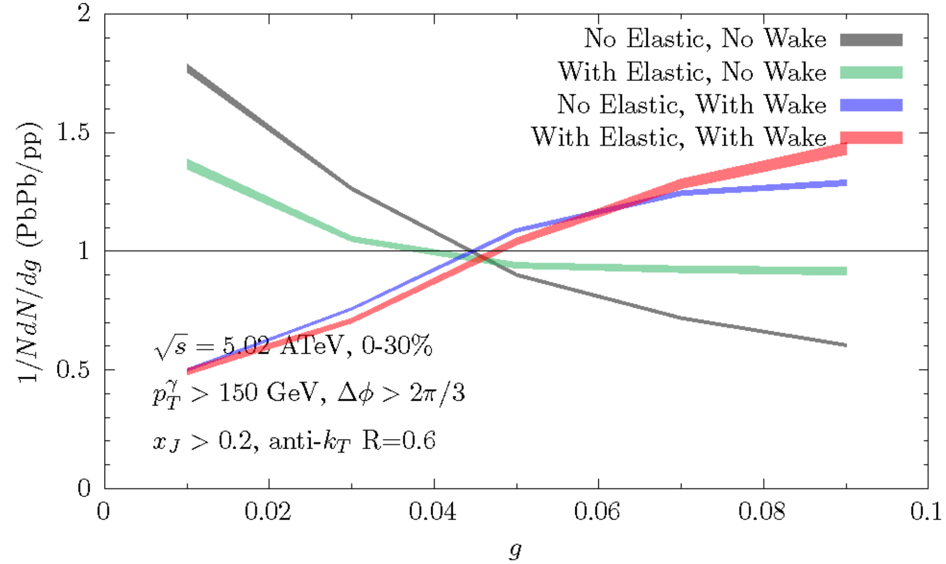


On previous slides, p_T^{γ} >150 GeV with R=0.2. Here, R=0.4, so that we can "catch" more wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects significant.

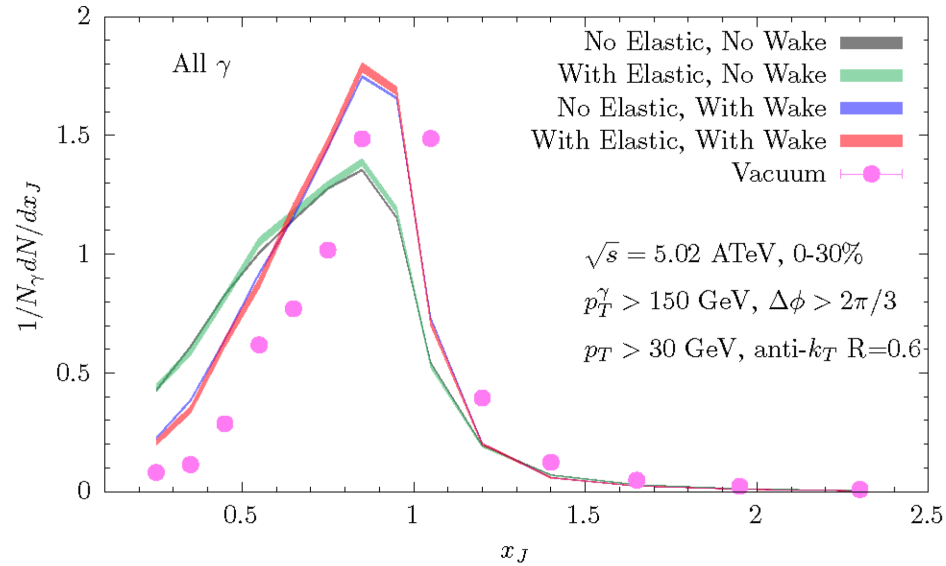
Gamma-Jet Observables with p_T^{γ} >150 GeV and R=0.6: R_g and Girth, with x_J>0.2



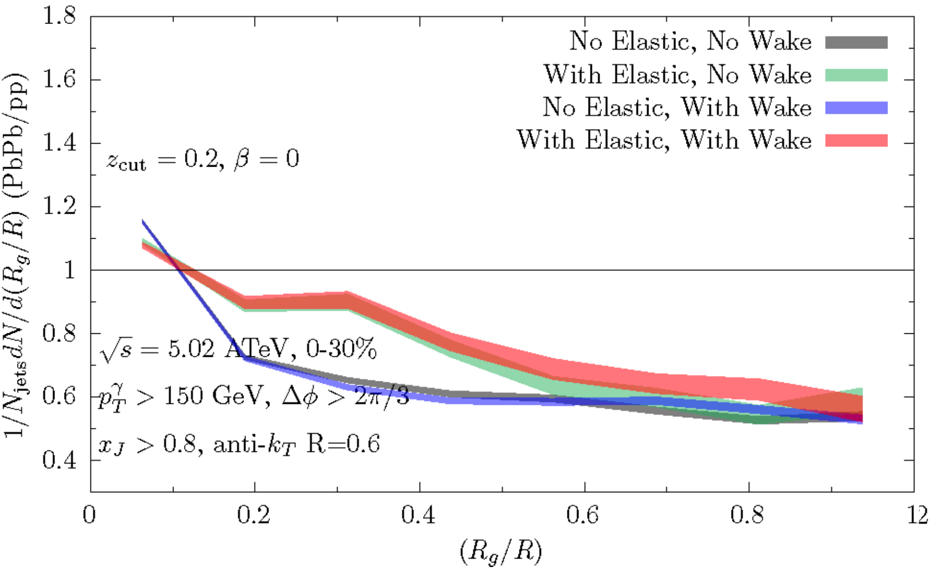


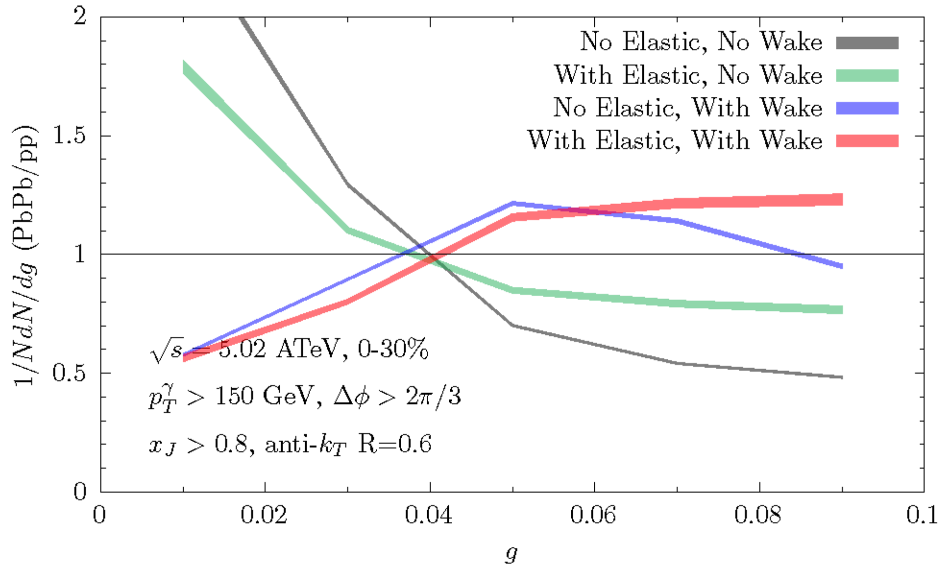
On previous slides, p_T^{γ} >150 GeV with R=0.2. Here, R=0.6, so that we can "catch" *even more* wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects enormous, and as in Brewer+Brodsky+KR.



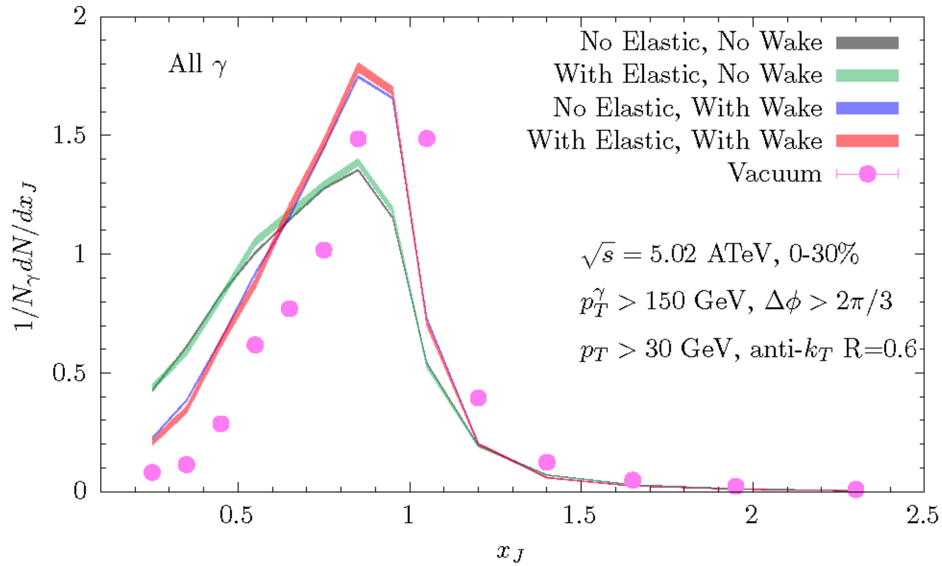
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.8





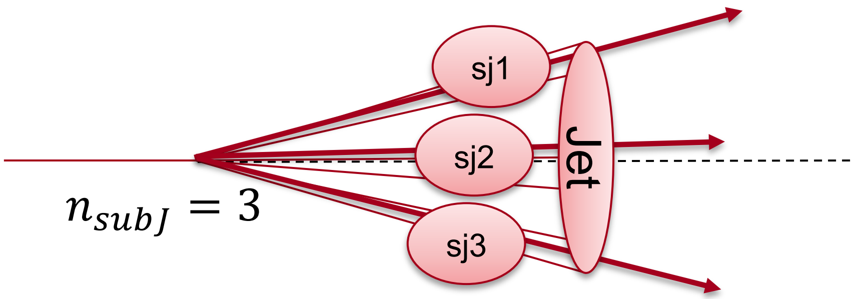
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6. But, we've turned the selection bias back ON.

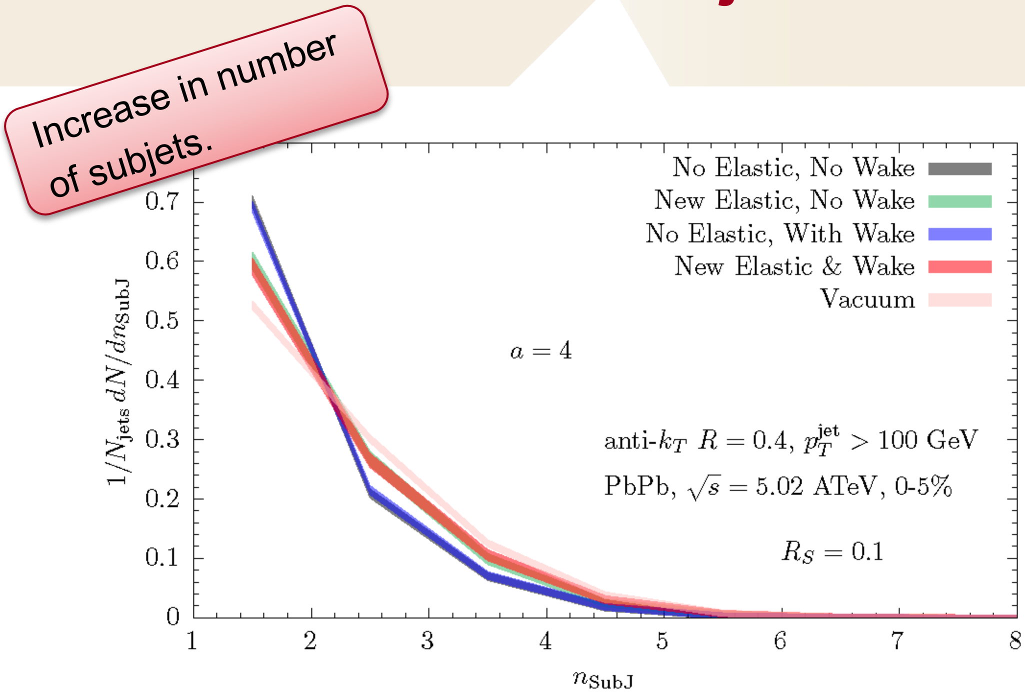
Moliere effects still substantial; selection bias dominant; wake effects *greatly reduced*, as in Brewer+Brodsky+KR.



Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15





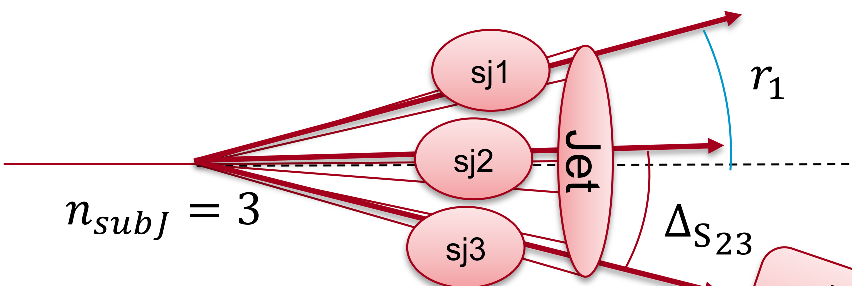
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

Moliere scattering also yields more separated subjets…

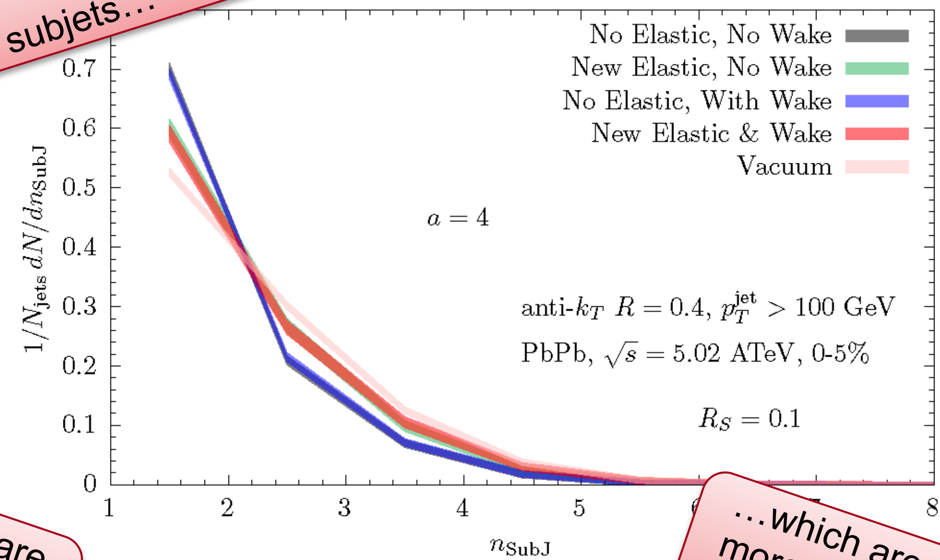
These observables are directly sensitive to "sprouting a new subjet" the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

Inclusive Subjets

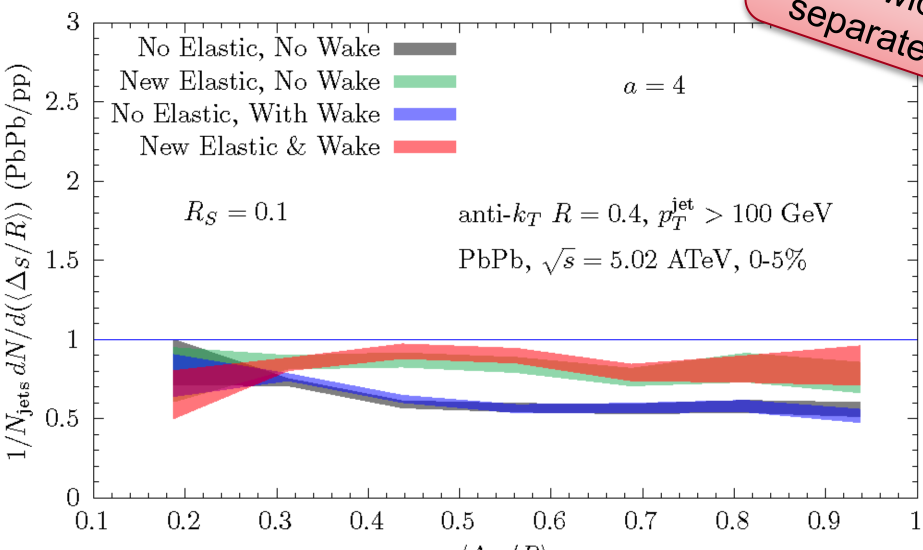
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



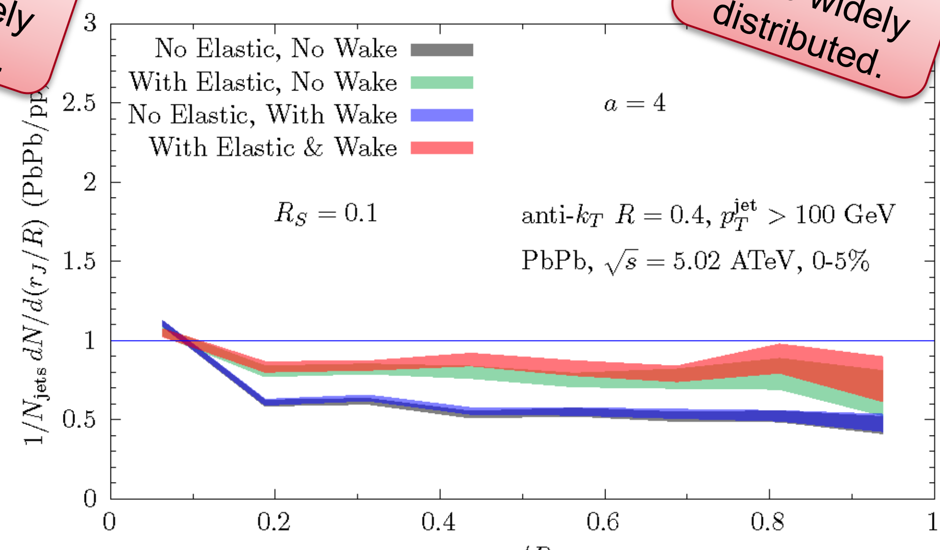
Increase in number of subjets…



…which are more widely separated.

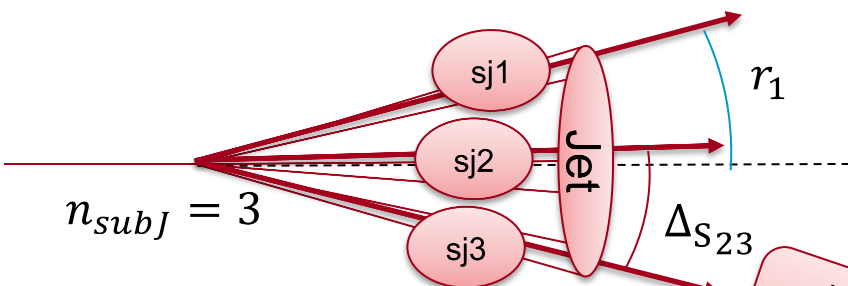


…which are more widely distributed.

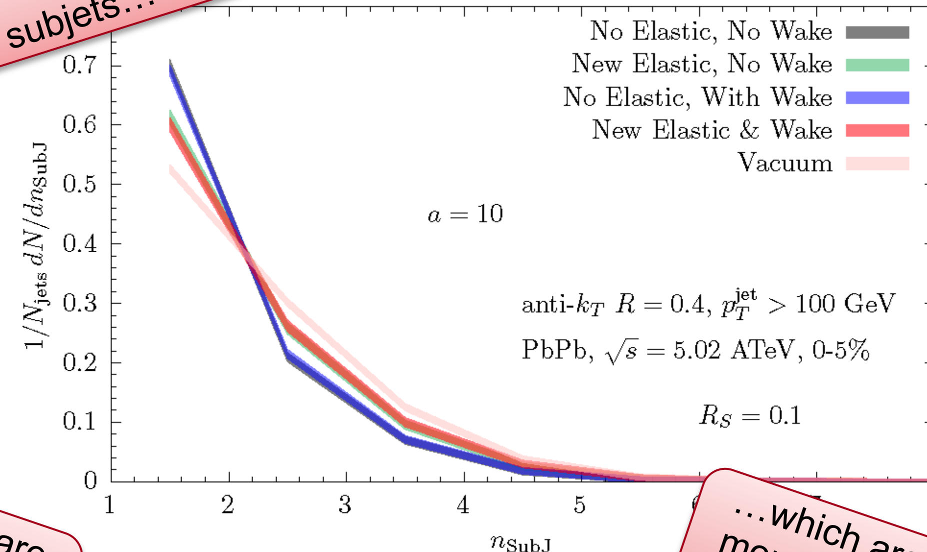


Inclusive Subjets

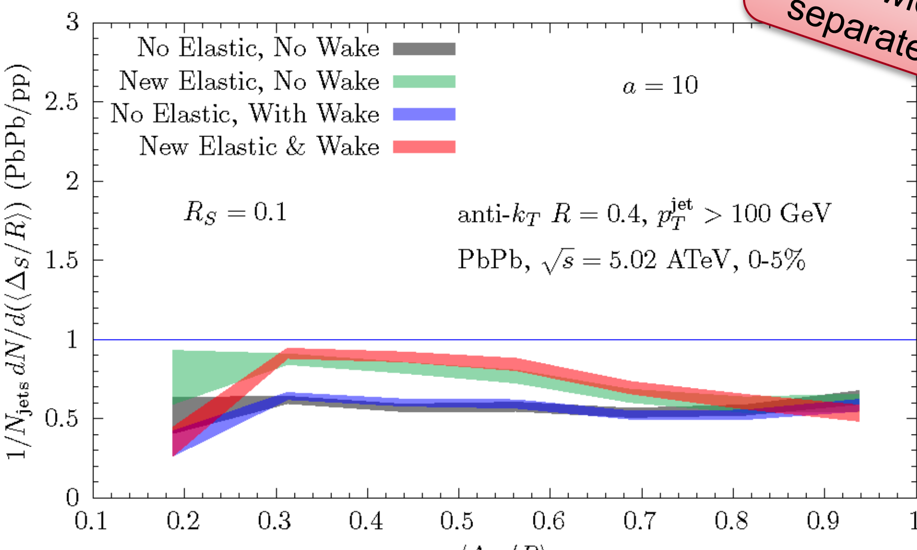
1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1



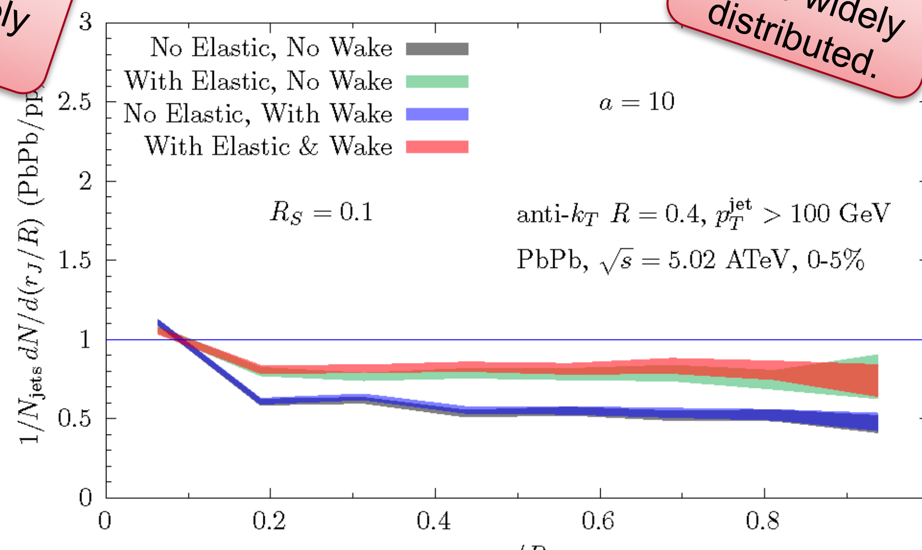
Increase in number of subjets…



…which are more widely separated.



…which are more widely distributed.



R=1.0 Jets made of R=0.2 Jets

- Another interesting observable, introduced by ATLAS at QM19 in Wuhan. See ATLAS publication 2301.05606.
- First reconstruct anti-k_t-$R = 0.2$ jets, call them subjets, with $p_T^{\text{subjet}} > 35$ GeV; then reconstruct anti-k_t-$R = 1.0$ jets (p_T's from ~ 90 to ~ 900 GeV) from these objects.
- Find R_{AA} for $R = 1.0$ jets with 1 (≥ 2) subjets is less (more) suppressed. For those with 2 subjets, look at distributions of angular separation and splitting parameter.
- A way to find pairs of $R = 0.2$ jets with a chosen ΔR_{12}.
- Arjun Kudinoor, Dani Pablos and KR are investigating this observable using the hybrid model, turning Moliere off and on, turning wake off and on.
- Moliere effects seem to be small in magnitude; motivates repeating this study with somewhat lower-p_T subjets.
- Can pick two $R = 0.2$ jets with a specified separation up to $\Delta R_{12} = 1.0$ and look at the wake between and around them. An interesting arena in which to test how well models describe the dynamics of jet wakes.

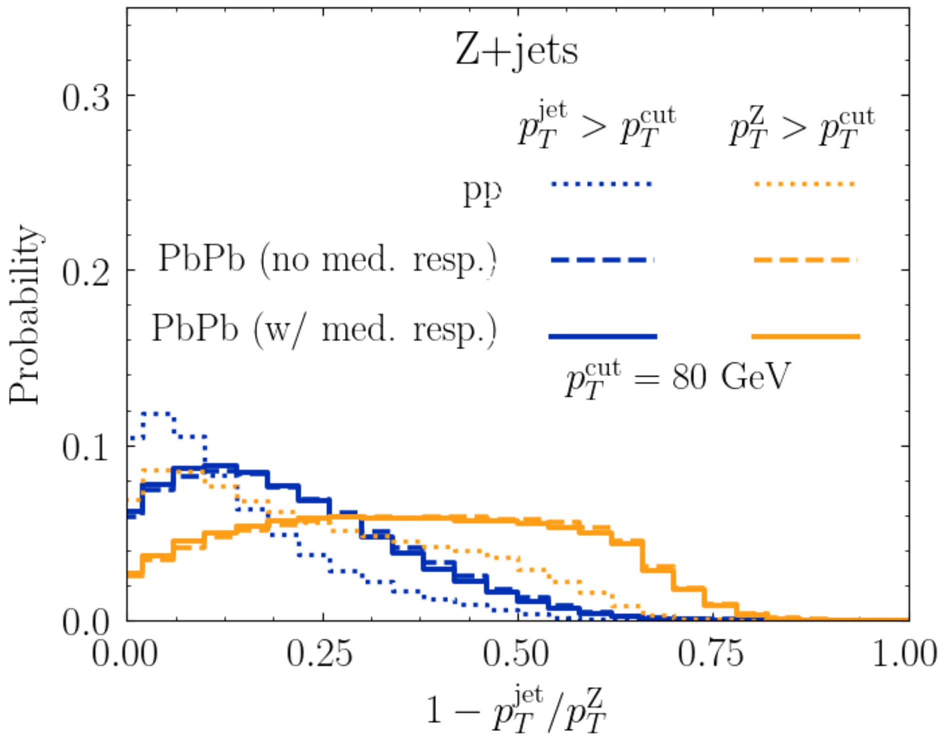
Conclusions

- Studied the effect of elastic Moliere scattering of jet partons off medium partons on jet observables in the perturbative regime.
- For "overall shape observables" (jet shapes; FF) effects of Moliere scattering are similar to, and smaller than, effects of wake.
- Grooming helps, by grooming away the soft particles from the wake. Effects of Moliere scattering dominate the modification of several groomed observables (R_g, Leading k_T, Girth, WTA axis angle.)
- R_g and girth observables in γ+jet events can be "engineered" to reduce (or enhance) selection bias by selecting with x_J > a low (or high) threshold. When selection bias is reduced, Moliere scattering yields R_{AA}>1.
- R_g and girth observables in γ+jet events can be "engineered" to remove (or highlight) effects of the wake by choosing small R (or large R with x_J > a low threshold).
- Modification of inclusive subjet observables (number, and angular spread, of subjets) are especially sensitive to the presence of Moliere scatterings. These observables are unaffected by the wake. They reflect what it is that makes the effects of scattering different from those of the wake.
- Subjet and γ+jet observables may also be influenced by other ways in which jet shower partons "see" particulate aspects of the QGP. That's great!
- Acoplanarity observables that we have investigated to date show little sensitivity to Moliere scattering; significant sensitivity to the wake in many cases.

Jets as Probes of QGP

- **Theorists taking key steps...**
- **Disentangling jet modification from jet selection.**
- **Showing that QGP *can* resolve structure within jet shower.**
- **Jet wakes in droplets of QGP.**
- **Selecting those jet substructure observables that *are* sensitive to scattering of jet partons off QGP partons, and are *not* sensitive to particles coming from the wake: 2208.13593 and in progress, Hulcher, Pablos, KR.**
  - **Builds upon theoretical framework for computing Molière scattering in QGP, and finding point-like scatterers in a liquid developed in: 1808.03250 D'Eramo, KR, Yin**
- **Next several years will be the golden age of HIC jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theory advances, here and elsewhere, whet our appetite for the feast to come. We shall learn about the microscopic structure of QGP, and the dynamics of rippling QGP.**

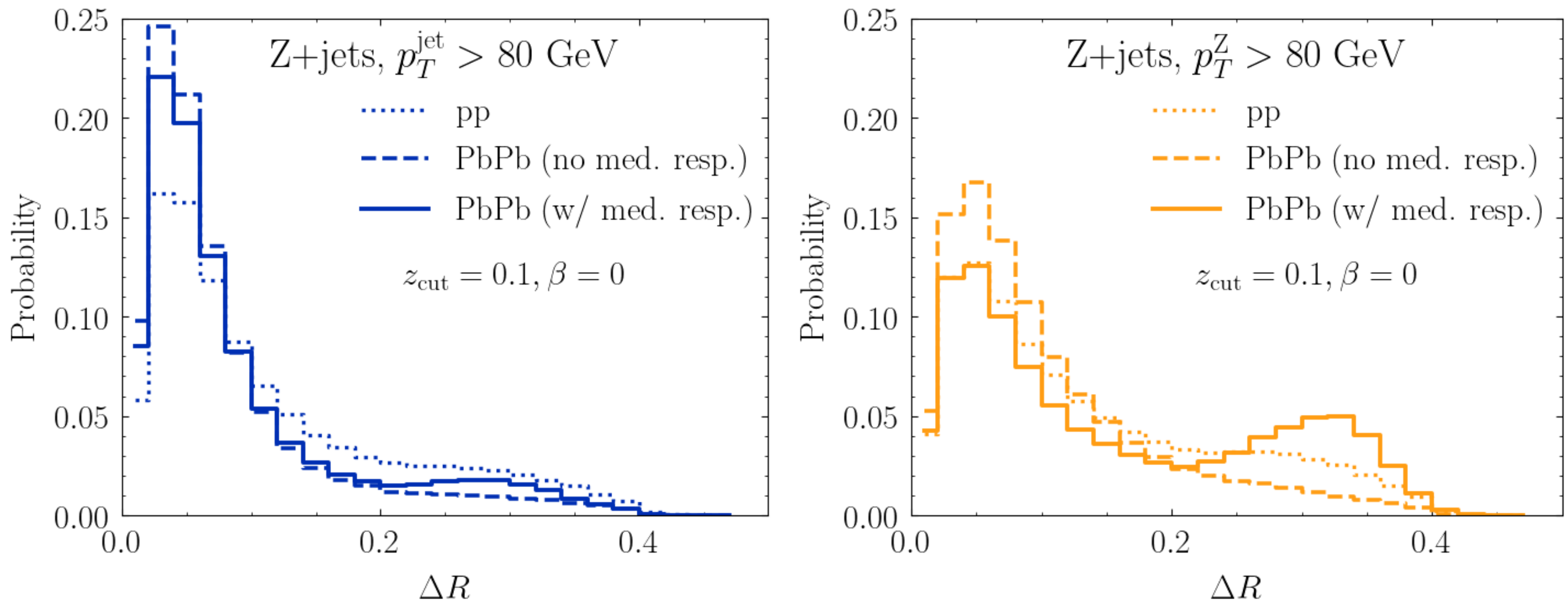
Disentangling Jet Modification from Selection



Orange: $p_T^Z > 80$ GeV; $p_T^{\text{jet}} > 30$ GeV

Blue: $p_T^{\text{jet}} > 80$ GeV; $p_T^Z > 30$ GeV — jet selection biases toward those jets that lose less energy

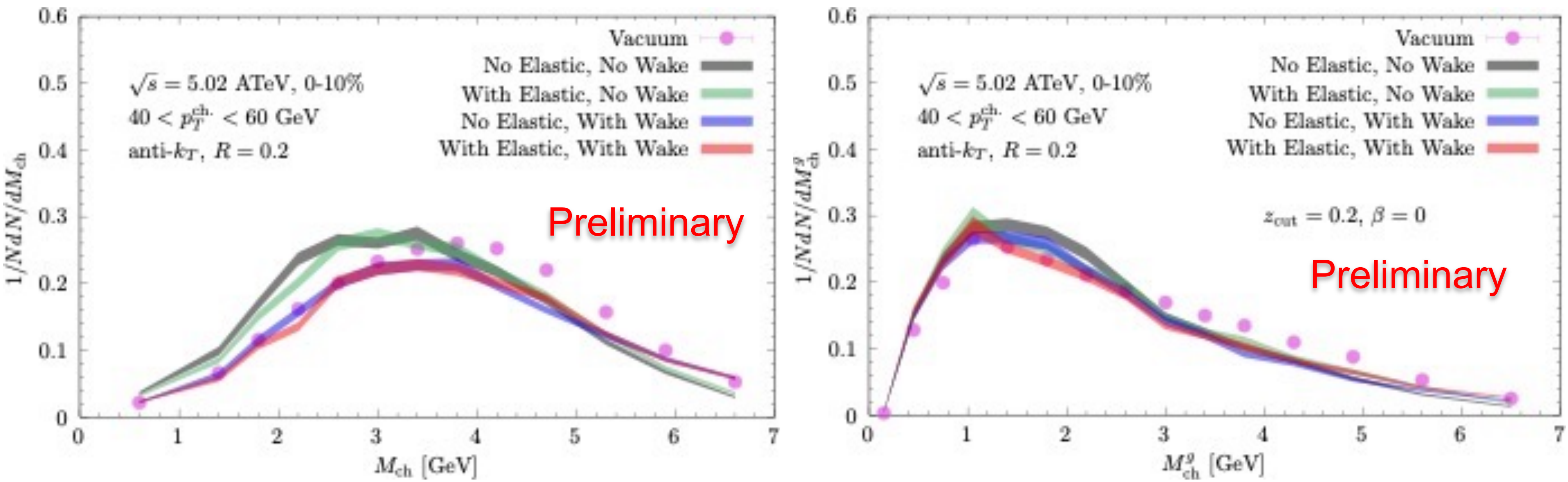
Disentangling Jet Modification from Selection



Orange: $p_T^Z > 80$ GeV; $p_T^{\text{jet}} > 30$ GeV. See jet modification.

Blue: $p_T^{\text{jet}} > 80$ GeV; $p_T^Z > 30$ GeV — jet selection biases toward those jets that lose less energy. These jets are skinnier. And the bias is toward less jet modification.

Jet Mass, and Groomed Jet Mass

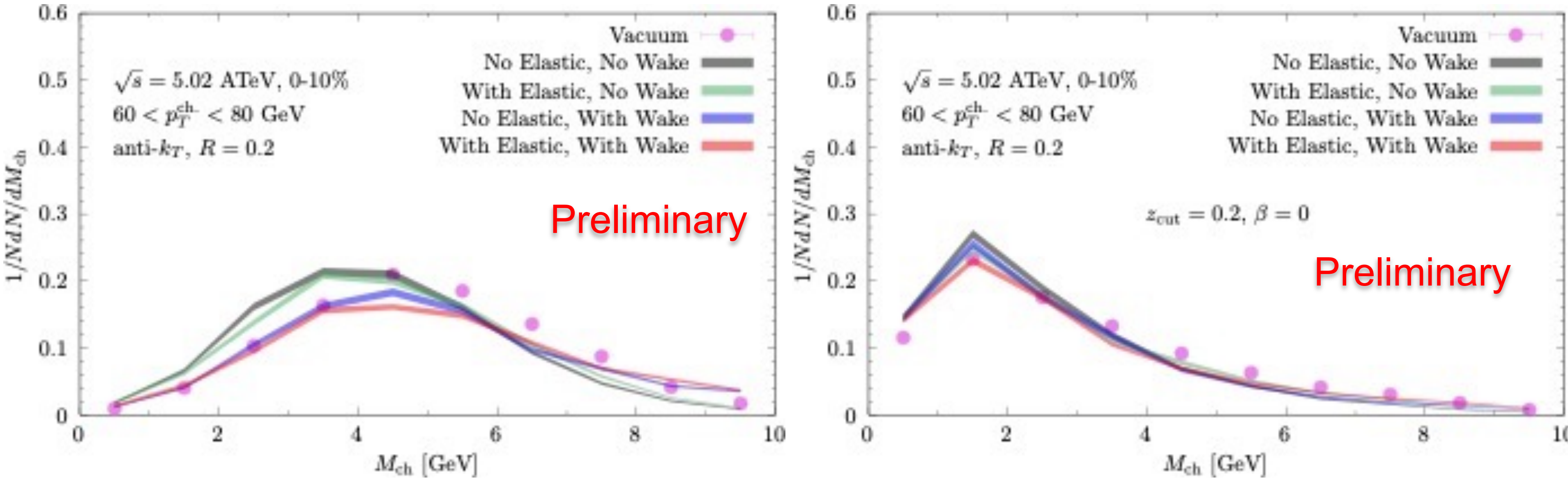


→ Ungroomed observable is sensitive to the wake; not to Moliere scattering.

Grooming removes wake, but still little sensitivity to Moliere scattering.

- What if we look at groomed observables? Less sensitive to wake…
- Yes, but not every groomed observable is sensitive to hard scattering…

Jet Mass, and Groomed Jet Mass

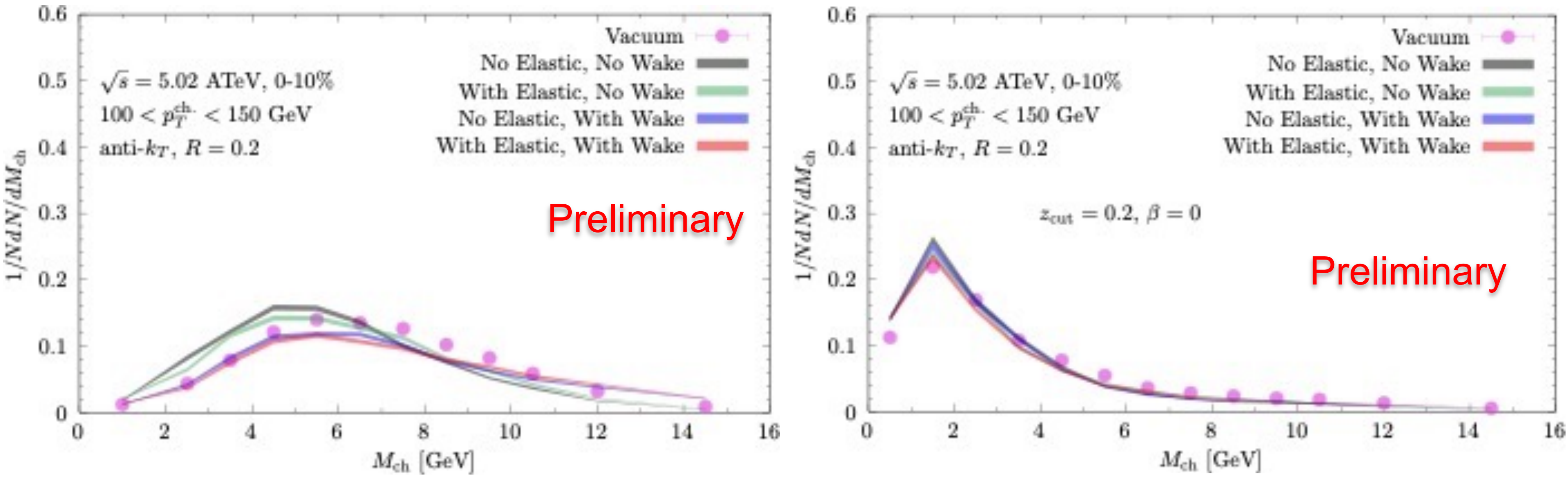


→ Ungroomed observable is sensitive to the wake; not to Moliere scattering.

Grooming removes wake, but still little sensitivity to Moliere scattering.

- What if we look at groomed observables? Less sensitive to wake…
- Yes, but not every groomed observable is sensitive to hard scattering…

Jet Mass, and Groomed Jet Mass

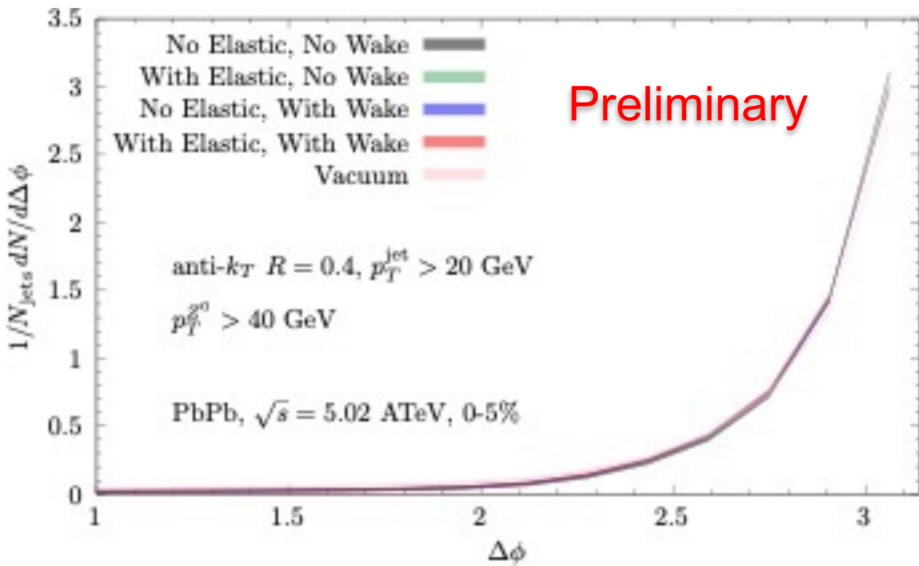


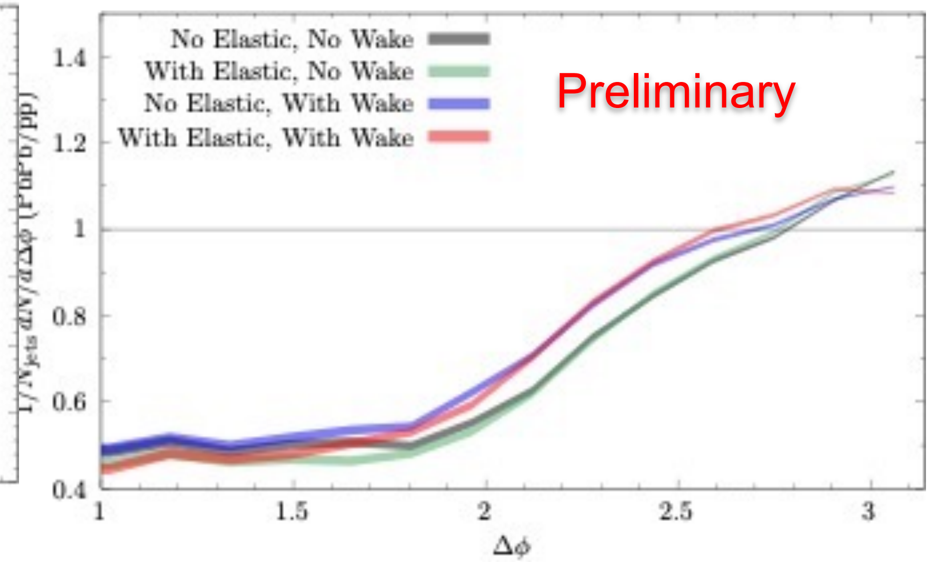
→ Ungroomed observable is sensitive to the wake; not to Moliere scattering.

Grooming removes wake, but still little sensitivity to Moliere scattering.

- What if we look at groomed observables? Less sensitive to wake…
- Yes, but not every groomed observable is sensitive to hard scattering…

Z-Jet Acoplanarity

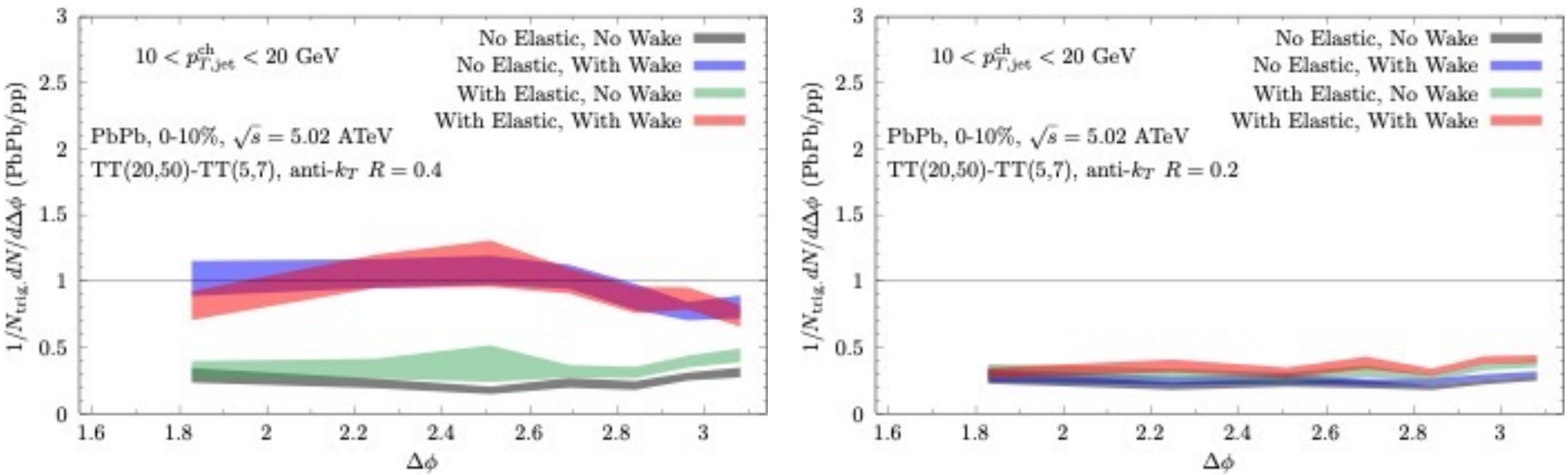




- Study acoplanarity in boson-jet system: Z-jet.
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Similar conclusions for acoplanarities at even lower p_T , via hadron—charged-jet correlations. Should look also Gamma-D, $D\bar{D}$ correlations….
- Groomed z_g and R_g , leading kT, and in particular inclusive subjet observables all more sensitive to Moliere scattering.
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, LHC energy

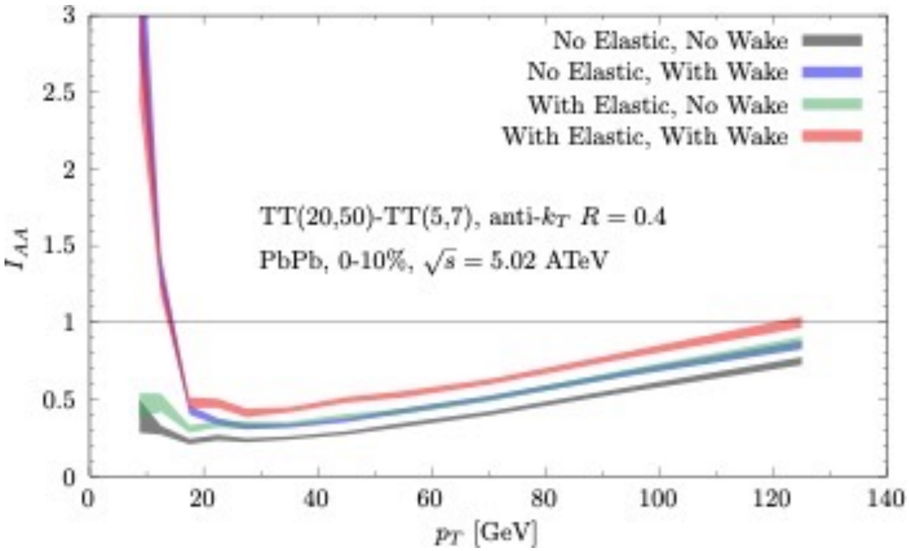
Preliminary

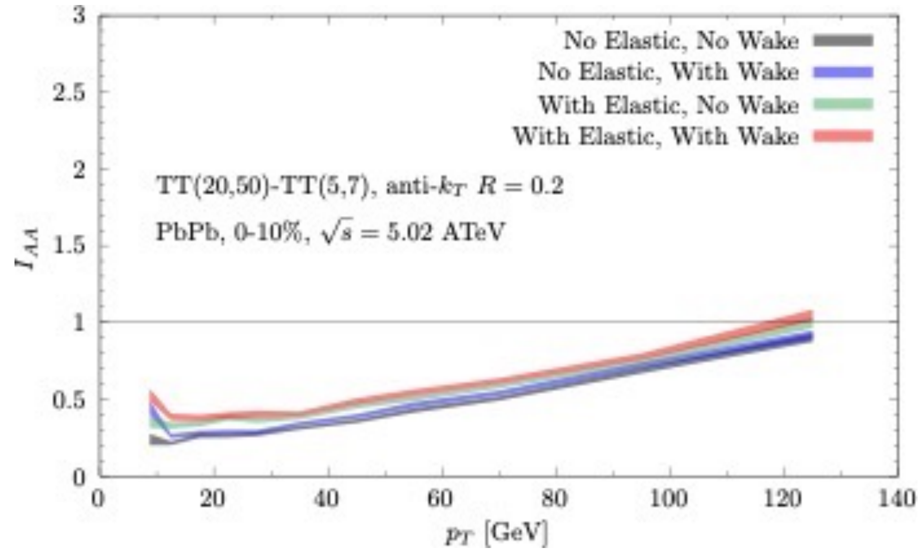


- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron—Charge-Jet Acoplanarity, LHC energy

Preliminary

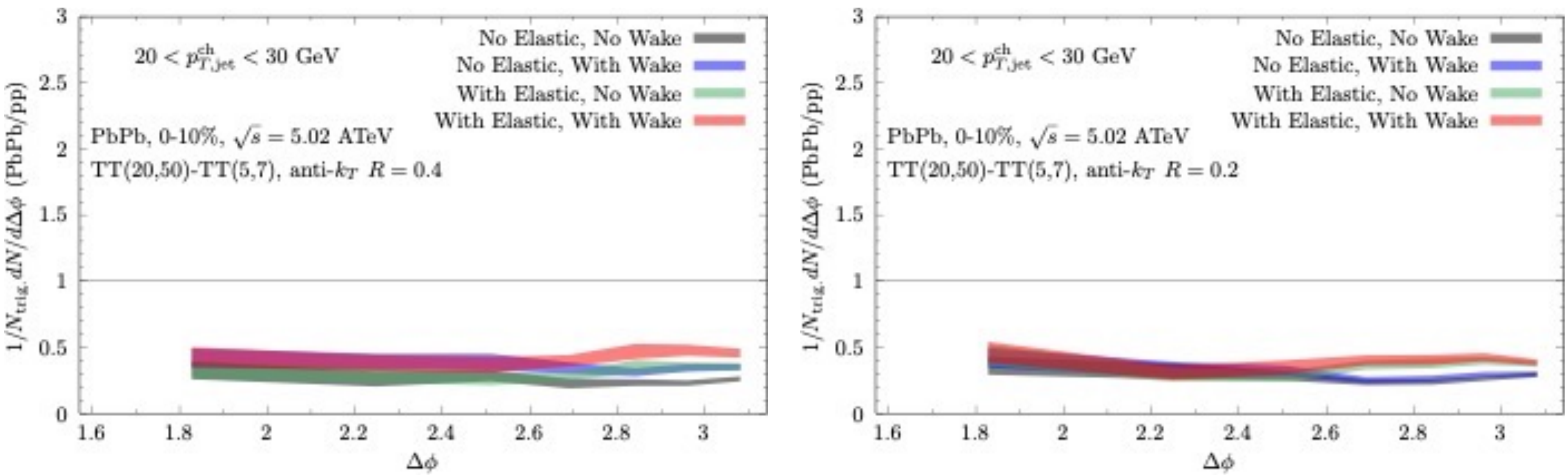




- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

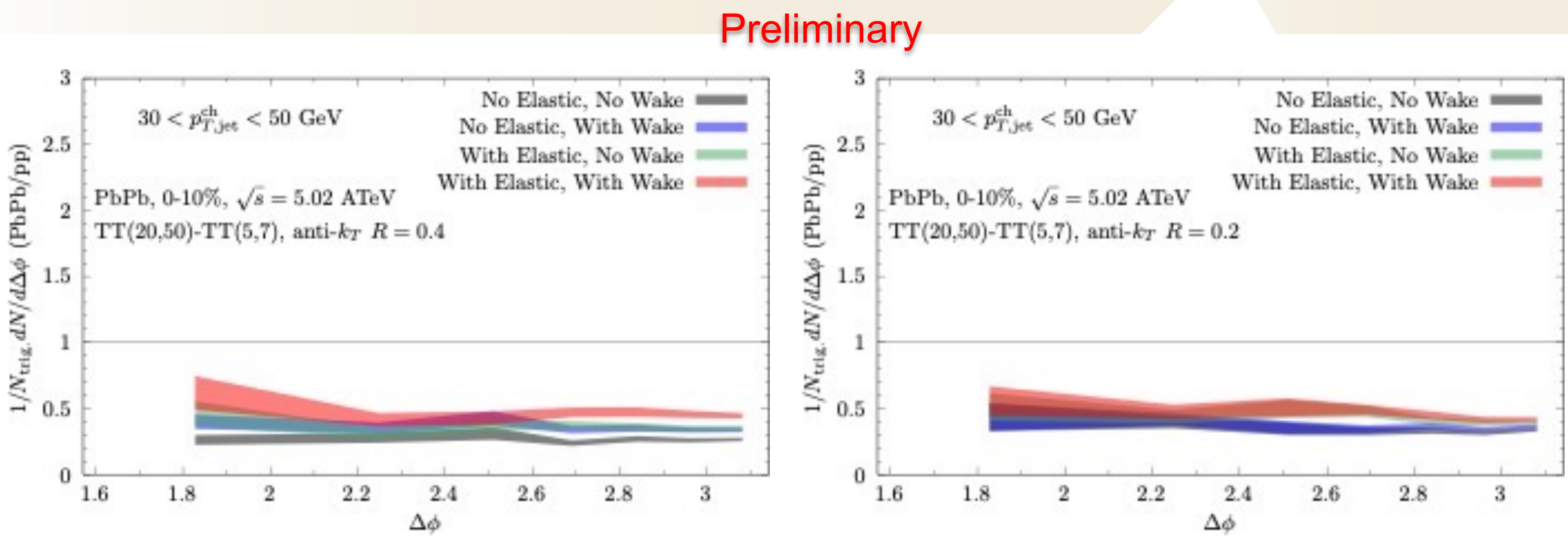
Hadron--Charge-Jet Acoplanarity, LHC energy

Preliminary



- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

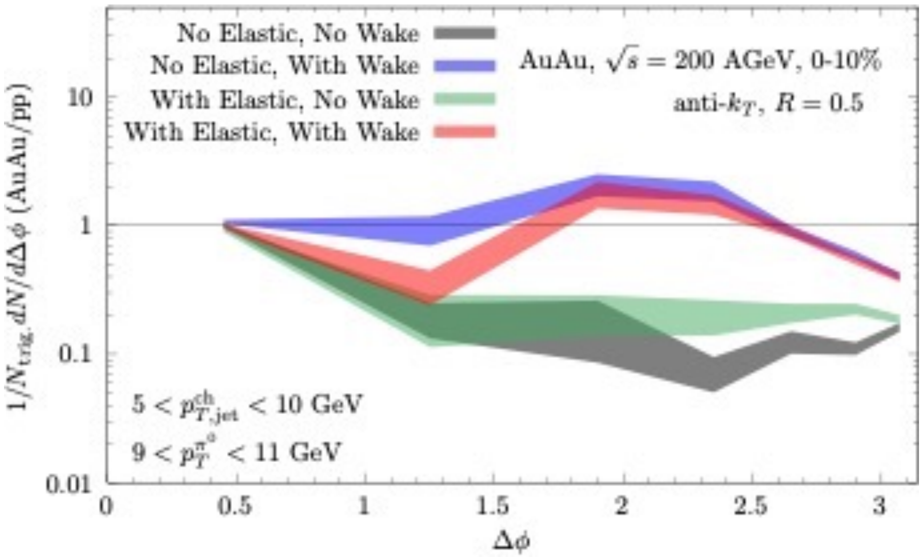
Hadron--Charge-Jet Acoplanarity, LHC energy

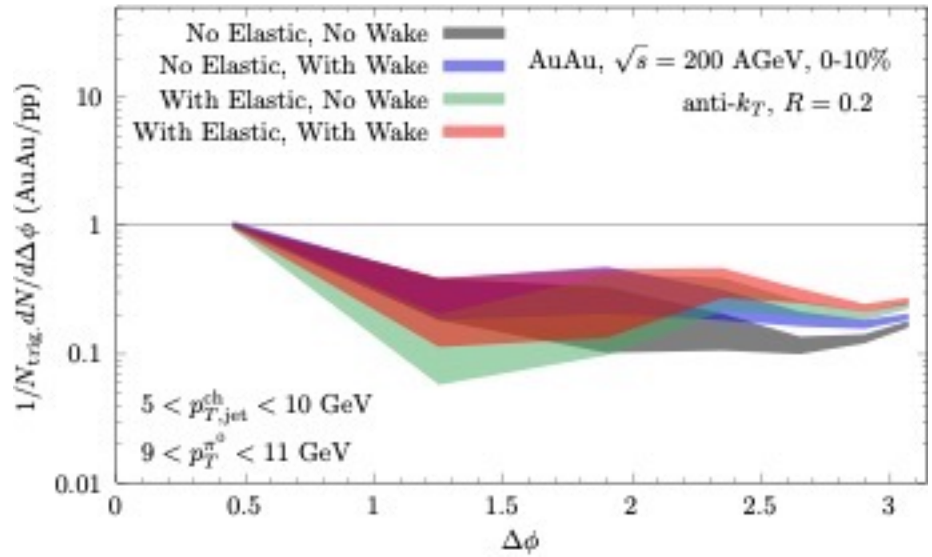


- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, RHIC energy

Preliminary

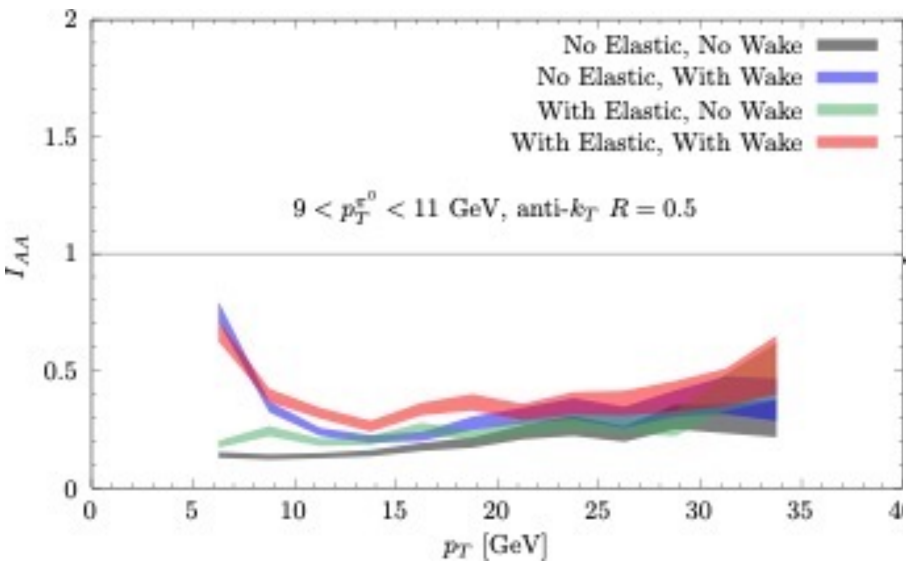


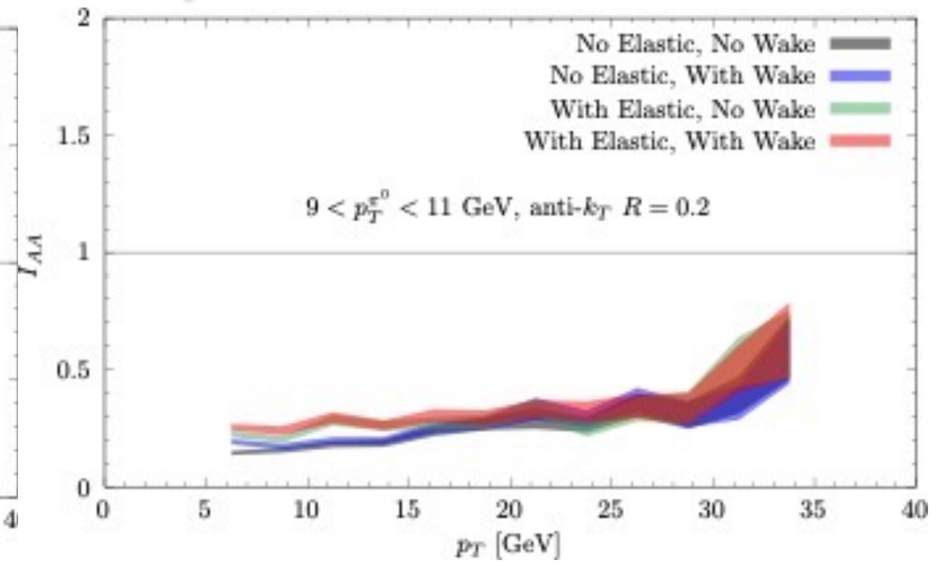


- Study acoplanarity in pi0 - charged jet system.
- Parameters similar to but not same as STAR
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.5 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, RHIC energy

Preliminary





- Study acoplanarity in pi0 - charged jet system.
- Parameters similar to but not same as STAR
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.5 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- Moliere scattering: jet sprouts added prongs, not much overall deflection