Probing the Short-length Structure of QGP With Jet Observables

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with

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Hard Probes 2023

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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
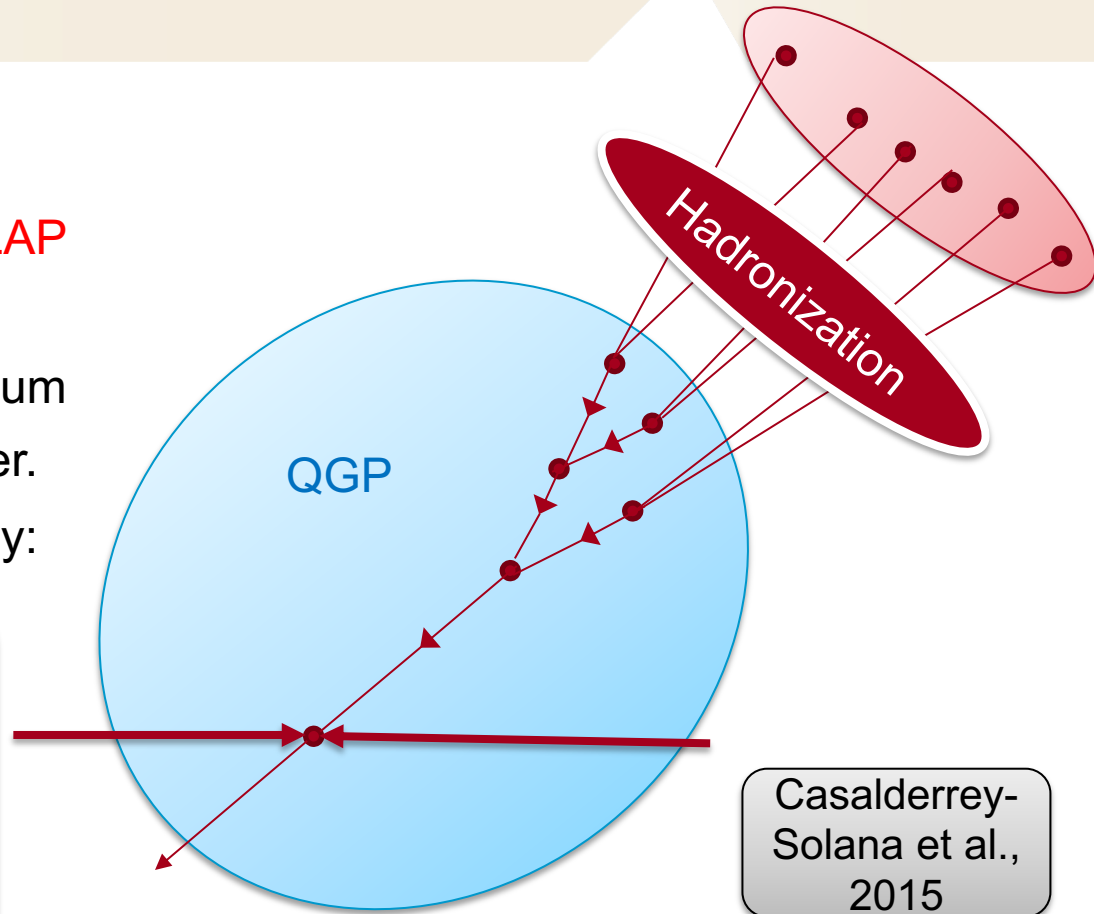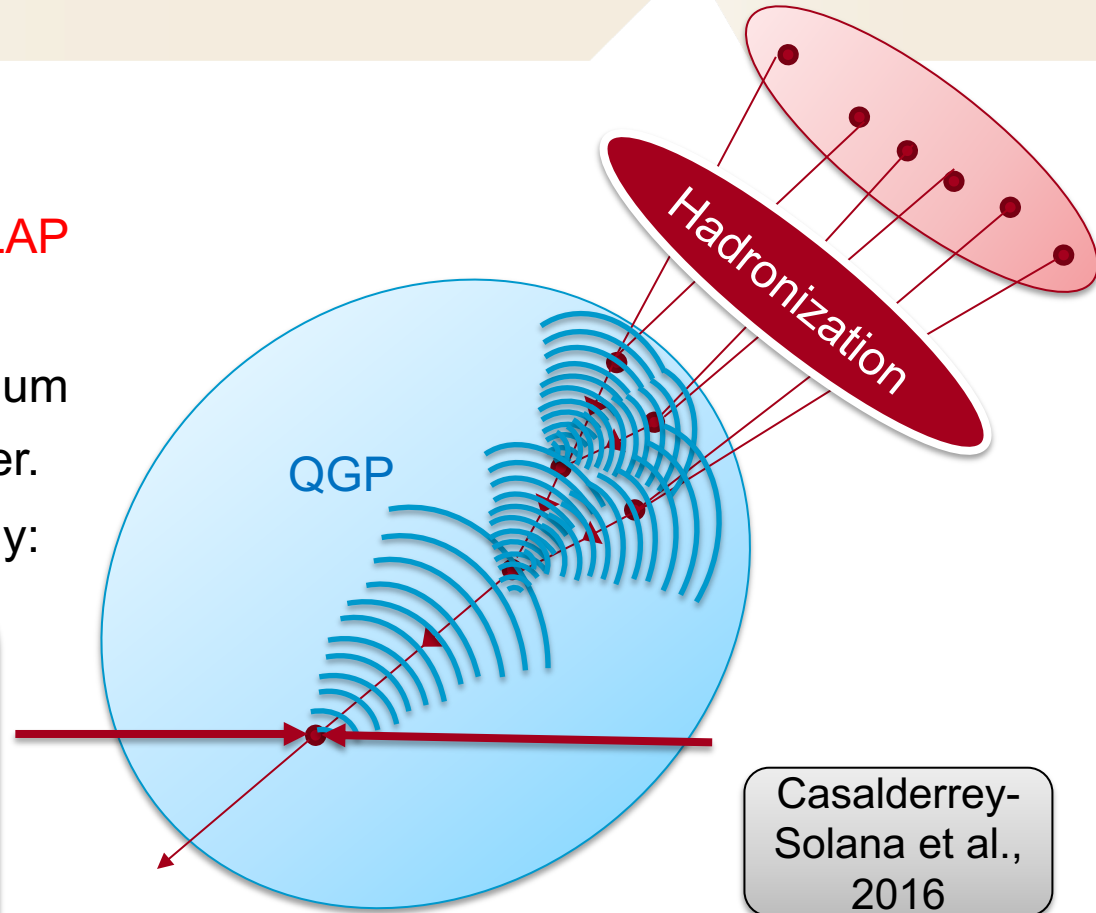
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).

- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.

  - Energy loss from holography:

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

O(1) fit const.

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

Hadronization

QGP

Casalderrey-Solana et al., 2015

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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 → 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

Length, L Temp, T

p, A

θ

k_T

p_{in}, C

k_χ

D'Eramo et al., 2019

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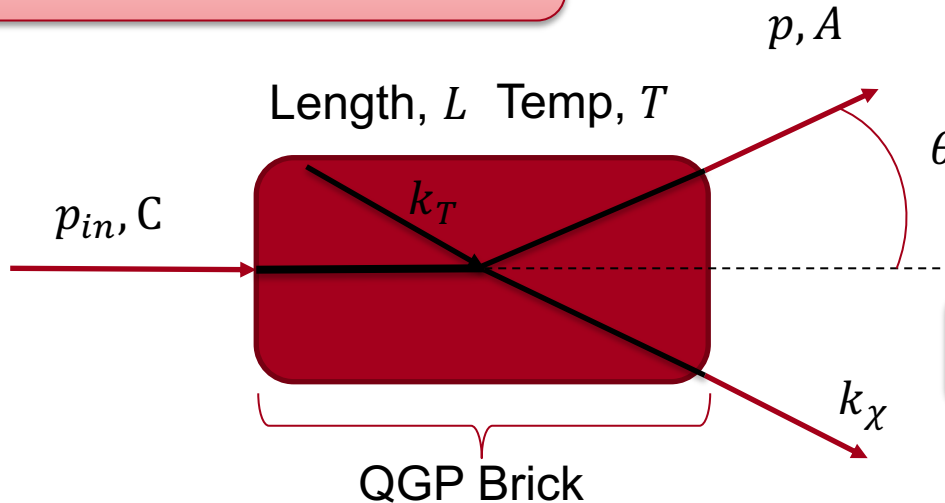
- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

Tree-Level 2-2 massless scattering amplitudes

$$F^{C \to A}(p, \theta; p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C \to A}}{2(4\pi)^3} \left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p} - \boldsymbol{p_{in}}|T} \right) \int_{k_{min}}^{\infty} dk_T \, n_D(k_T) [1 \pm n_B(k_\chi)] \int_0^{2\pi} \frac{d\phi}{2\pi} \frac{|M^{(n)}|^2}{g_s^4}$$
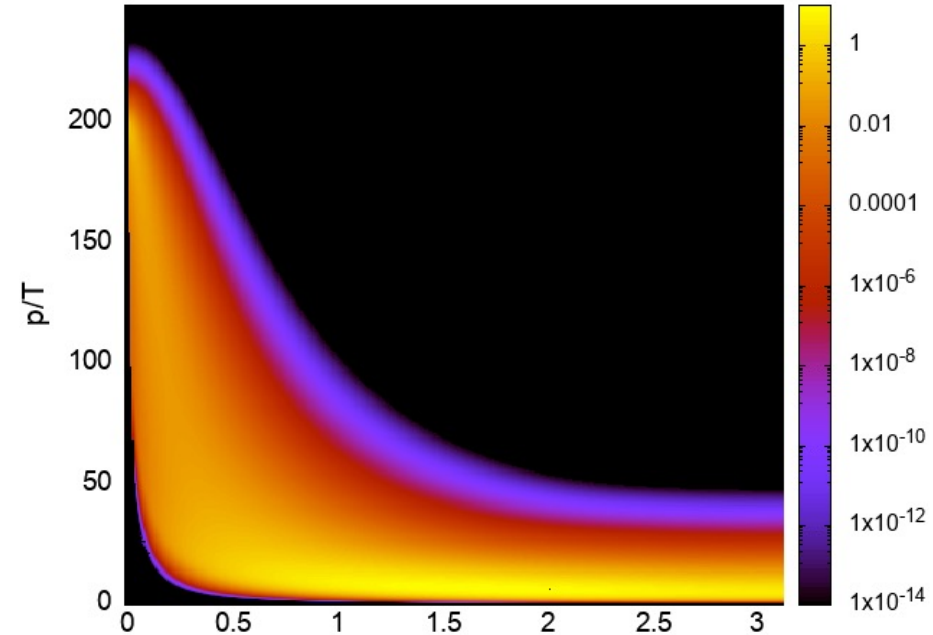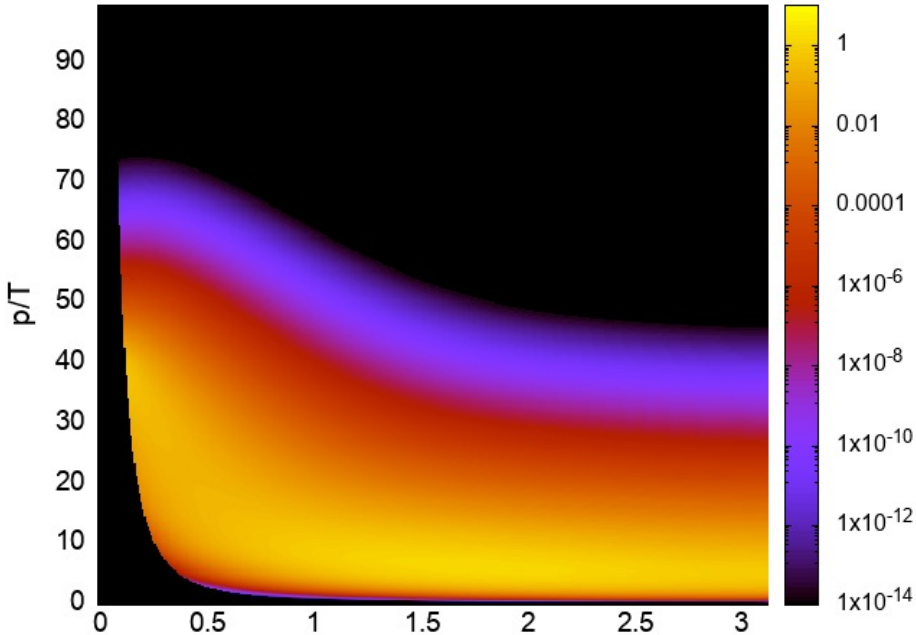
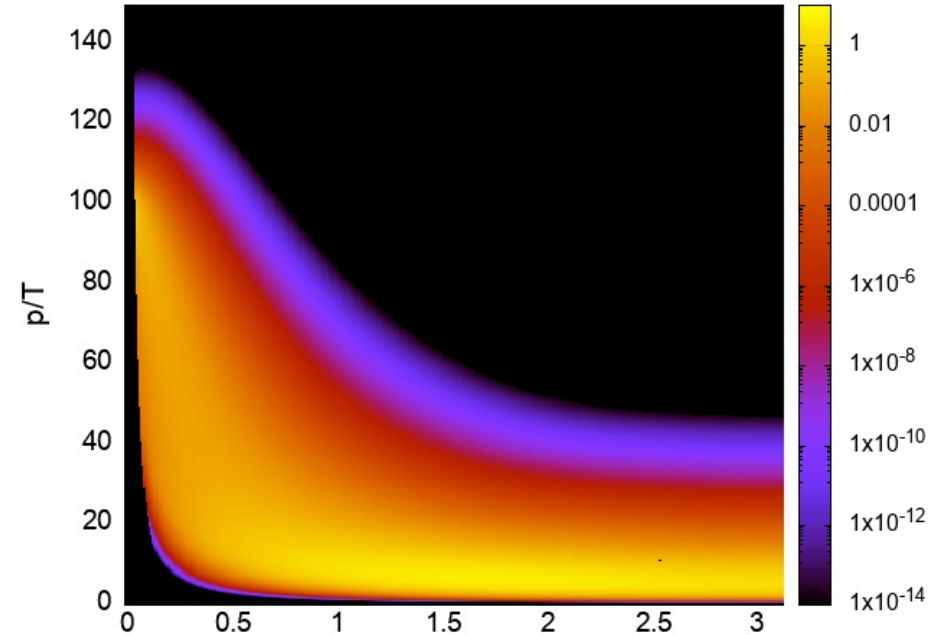# Results (for a QGP brick)
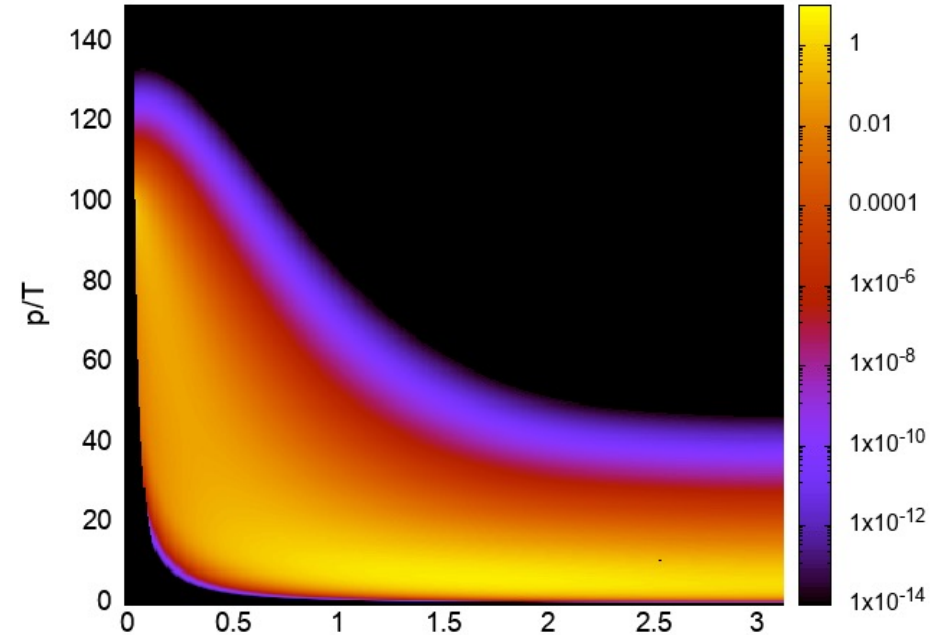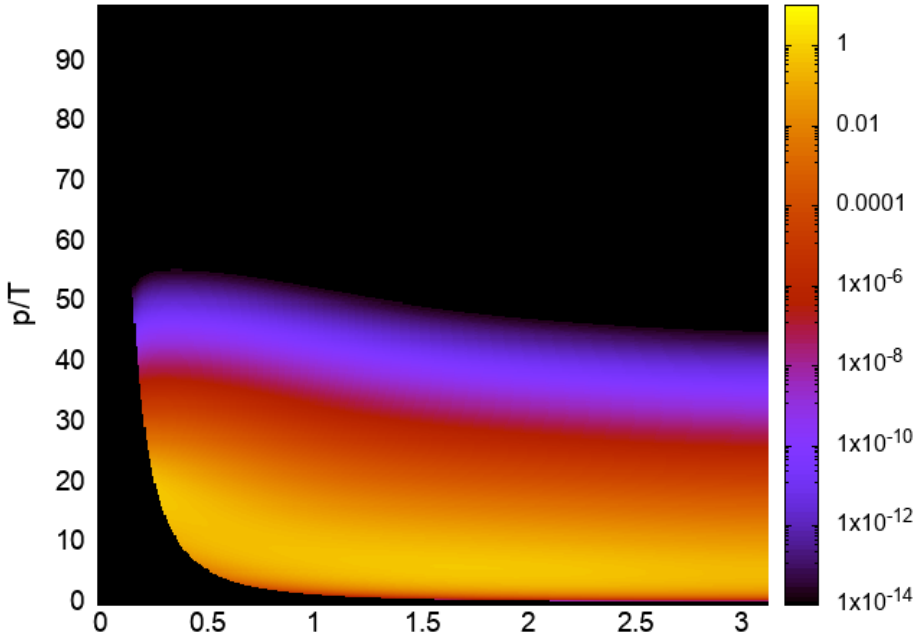
Incoming gluon, $p_{in} = 20T$, L = $15/T$ Incoming gluon, $p_{in} = 100T$, L = $15/T$

- 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
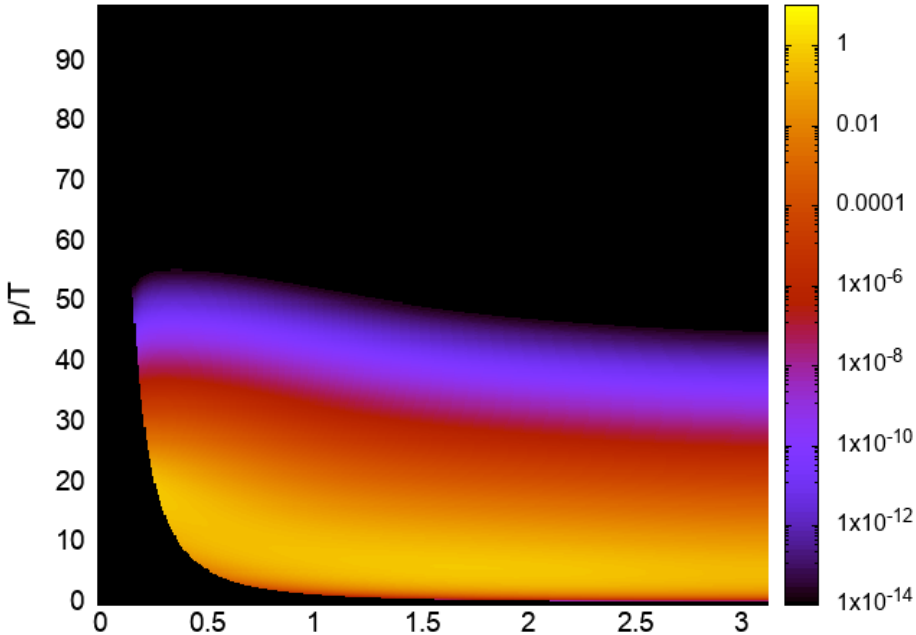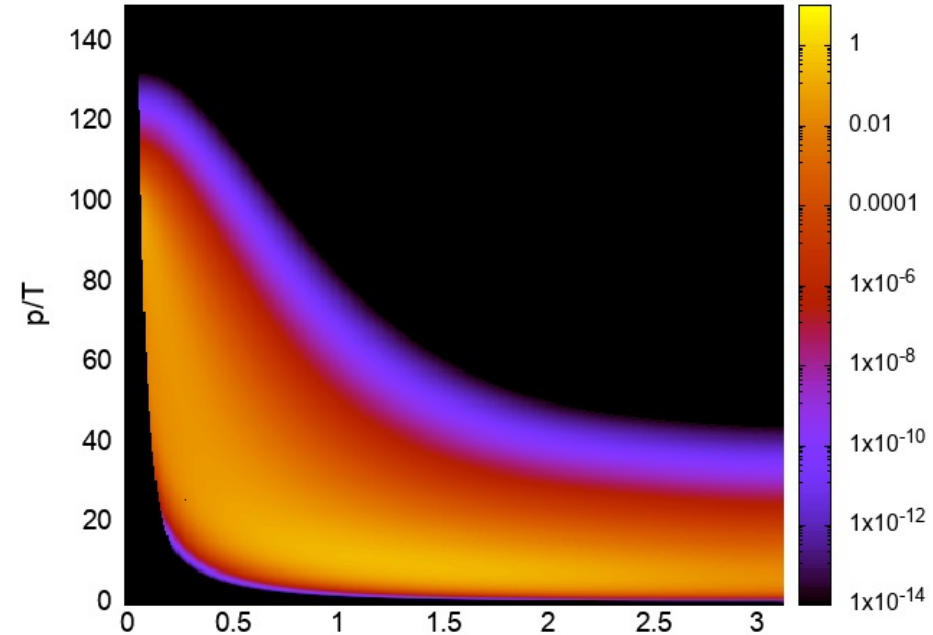
Results (for a QGP brick)

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

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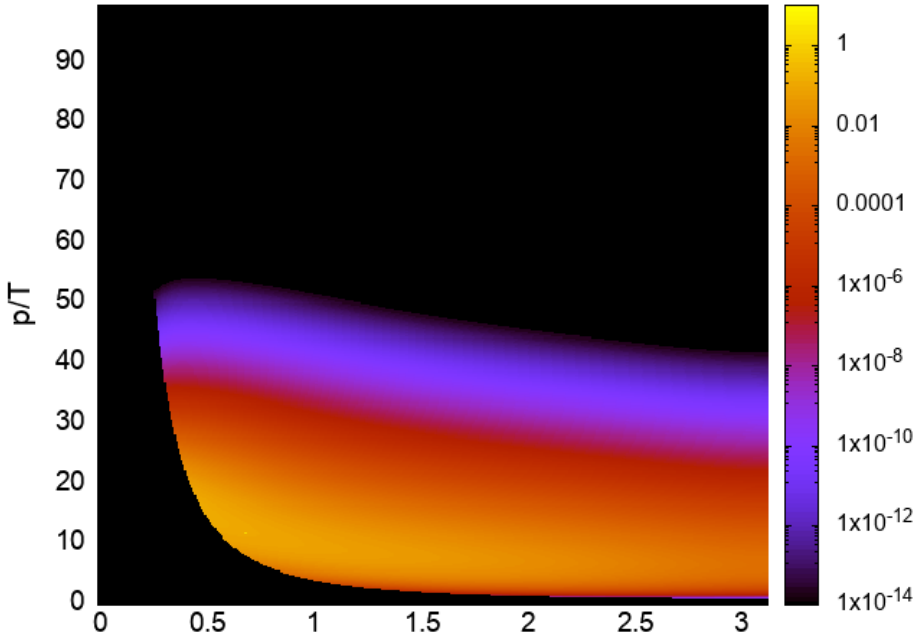
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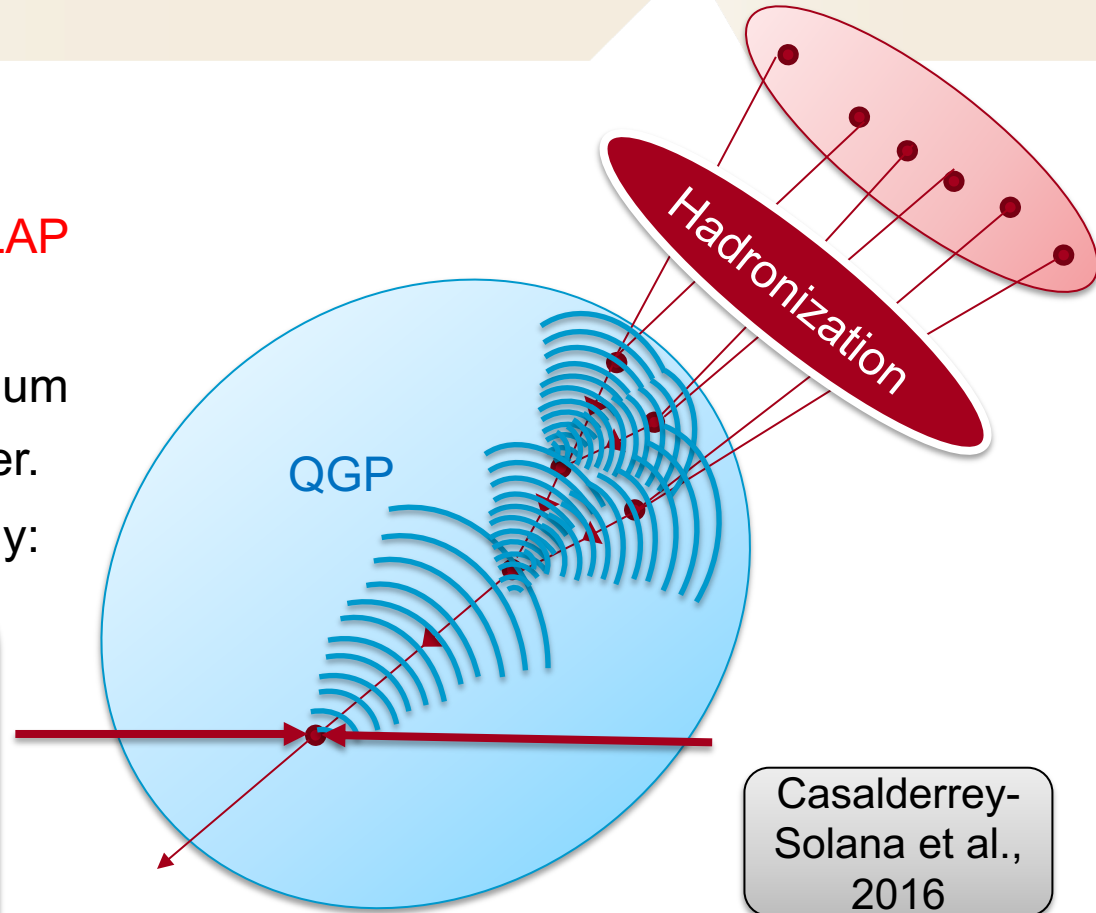
Results (for a QGP brick)

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

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- 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

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QGP

Hadronization

Casalderrey-Solana et al., 2016

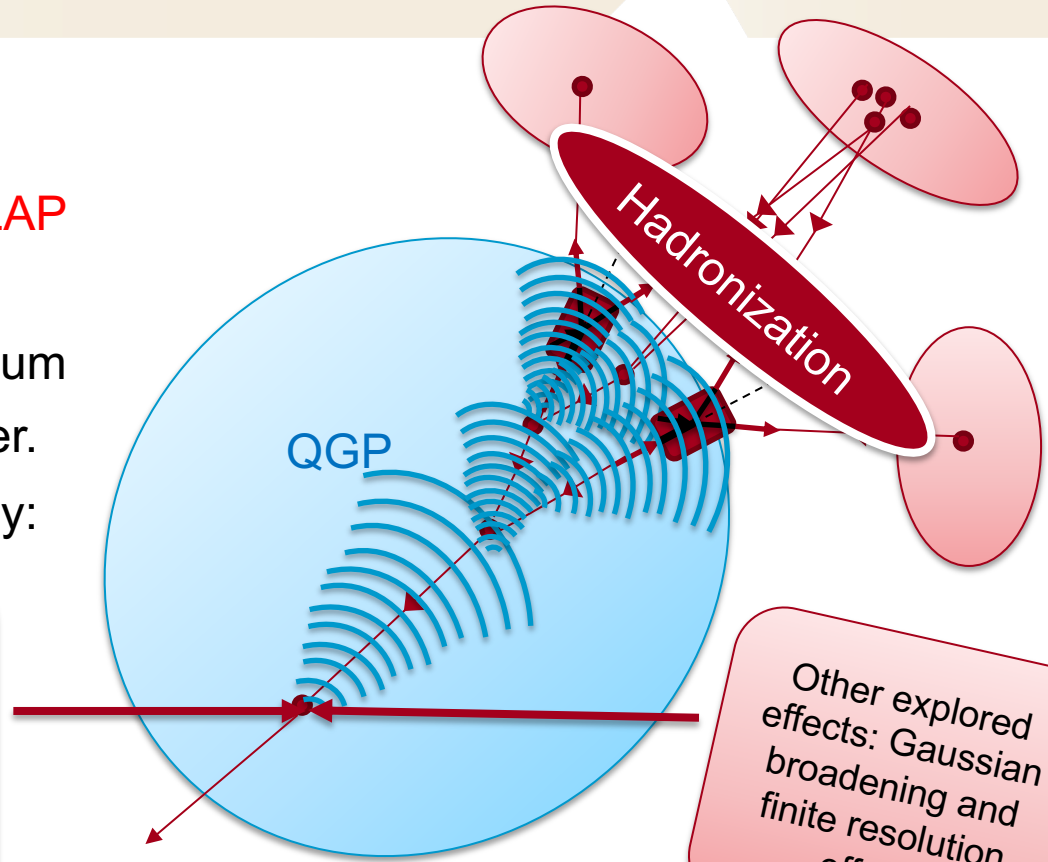Energy and momentum conservation ⟶ deposit hydrodynamic wake in QGP liquid

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Adding Moliere Scattering to Hybrid Model

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Hadronization

QGP

Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation ⟶ activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$
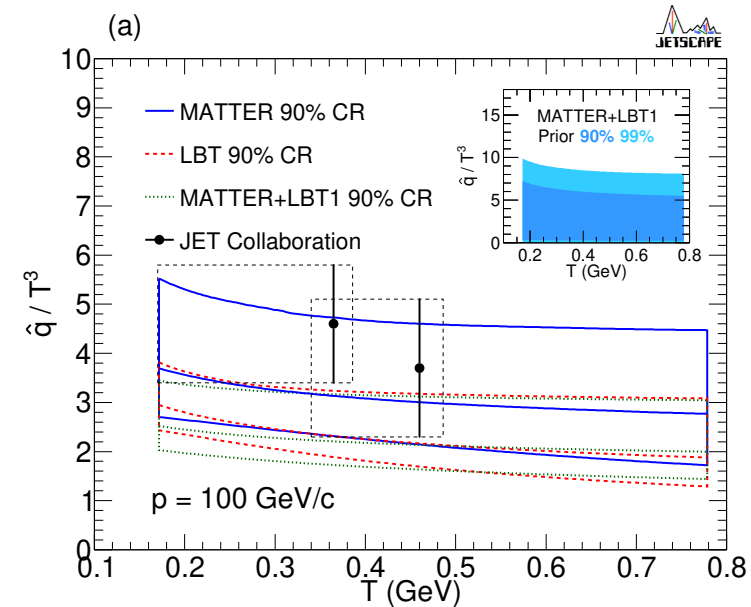
12

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) yields very little effect on jet observables

- Restrict to momentum exchanges $> m_D$

  ⟶ focus on perturbative regime with a power-law distribution

(a)

p = 100 GeV/c

MATTER 90% CR
LBT 90% CR
MATTER+LBT1 90% CR
JET Collaboration

MATTER+LBT1 Prior 90% 99%

D'Eramo et al., 2011, 2018
+
Mehtar-Tani et al., PRD 2021
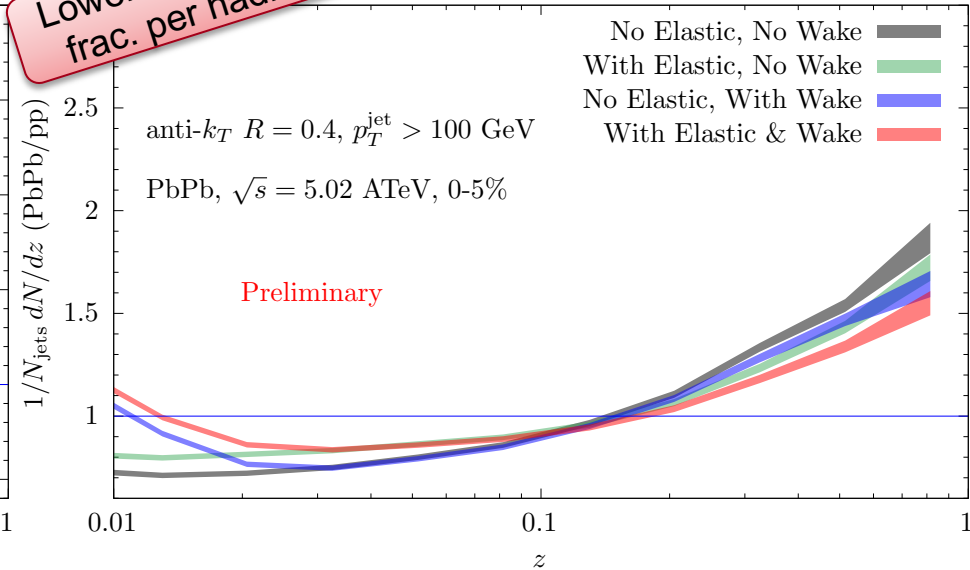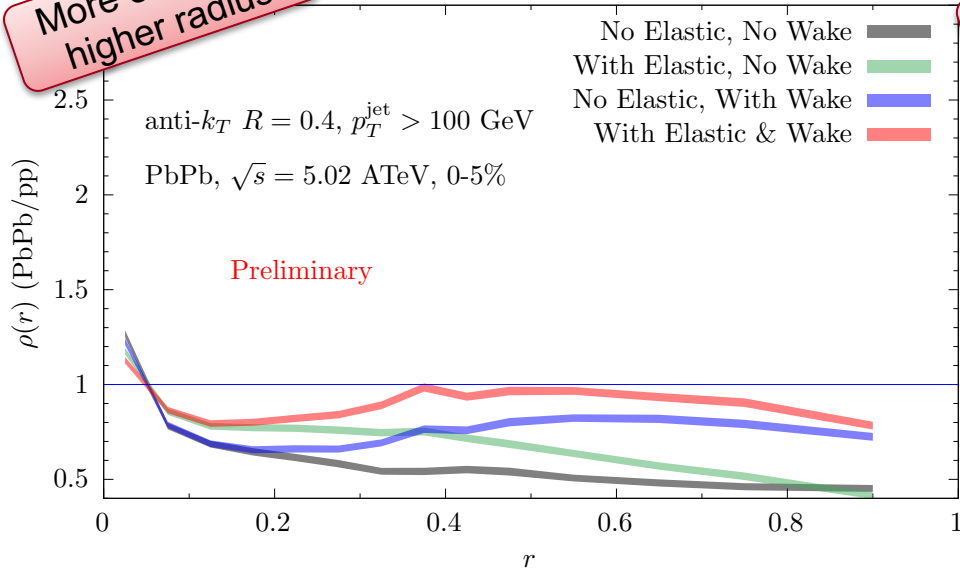
Jet R_{AA}

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.

- All results, here on, are Preliminary.
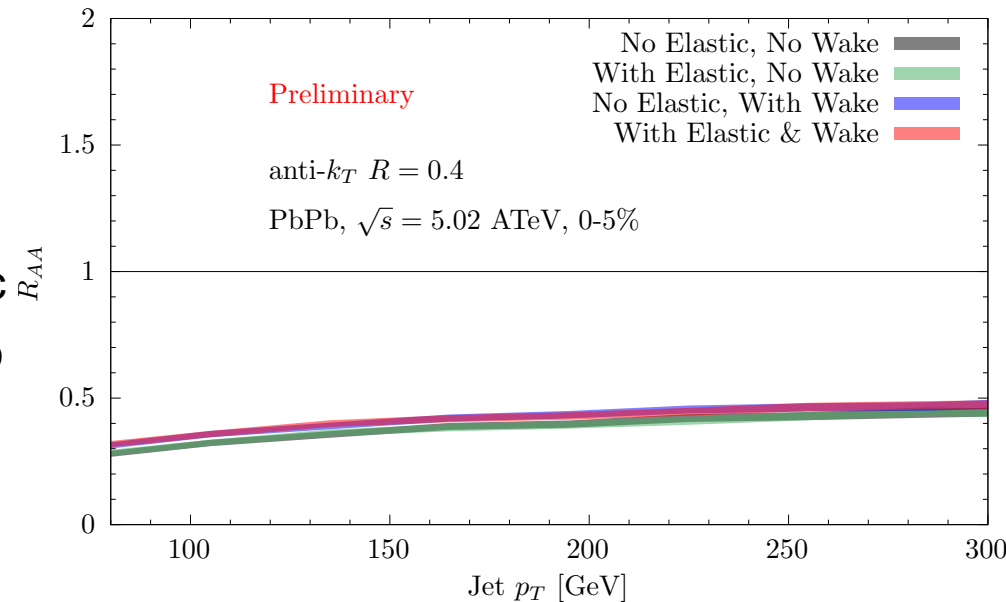
Preliminary

anti-k_T $R = 0.4$

PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

Legend:
No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic & Wake

R_{AA}

Jet p_T [GeV]

Jet Shapes and Fragmentation Functions

More energy at higher radius

Lower momentum frac. per hadron

Left plot legend:
- No Elastic, No Wake
- With Elastic, No Wake
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anti-k_T $R = 0.4$, $p_T^{\text{jet}} > 100$ GeV

PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

Preliminary

y-axis: $\rho(r)$ (PbPb/pp), x-axis: r

Right plot legend:
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Preliminary

y-axis: $1/N_{\text{jets}}\, dN/dz$ (PbPb/pp), x-axis: z

➡️ **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…

Jet Shapes and Fragmentation Functions

More energy at higher radius

Lower momentum frac. per hadron

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Preliminary

$a = 10$

Legend (left plot):
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$\rho(r)$ (PbPb/pp)

r

anti-k_T $R = 0.4$, $p_T^{\text{jet}} > 100$ GeV

PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

Preliminary

$a = 10$

Legend (right plot):
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- With Elastic No Wake
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$1/N_{\text{jets}}\, dN/dz$ (PbPb/pp)

z

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Groomed z_g and R_g
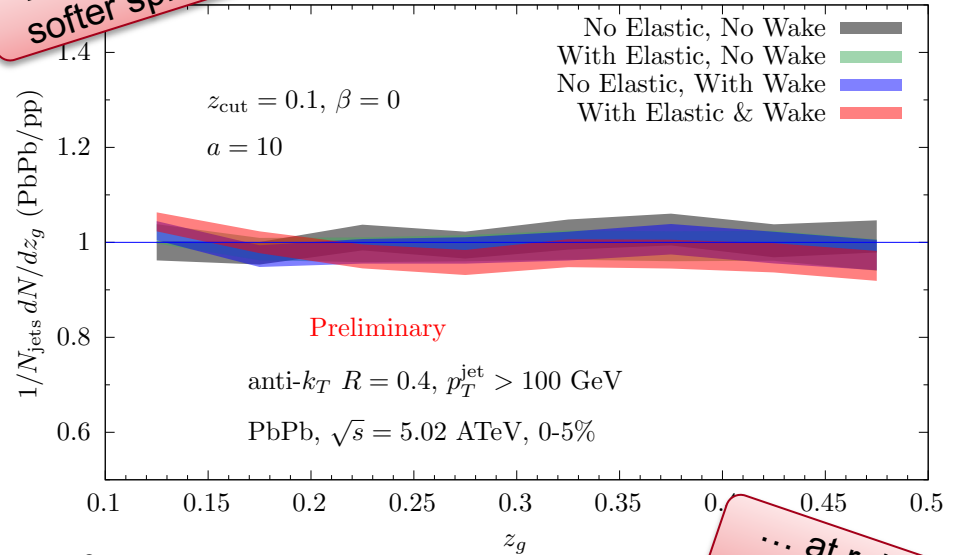
Soft Drop ($\beta = 0$)
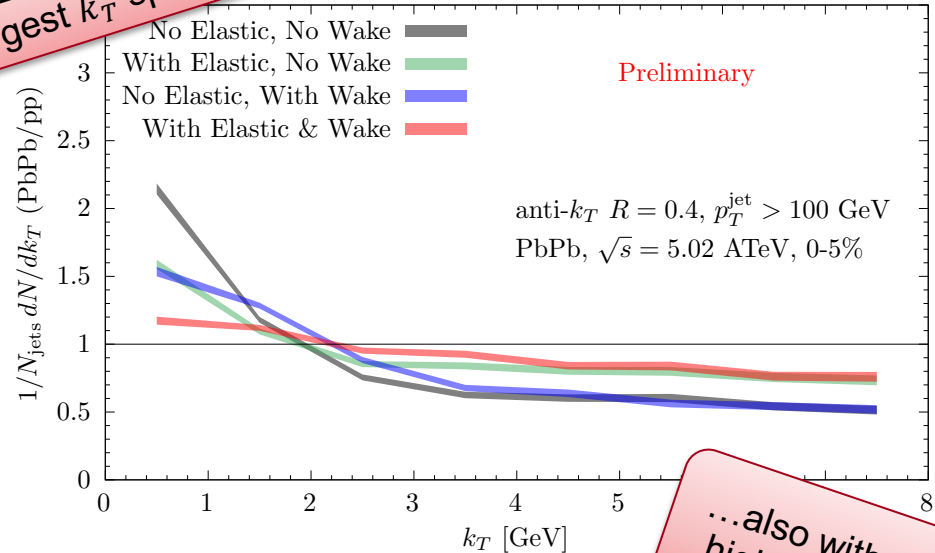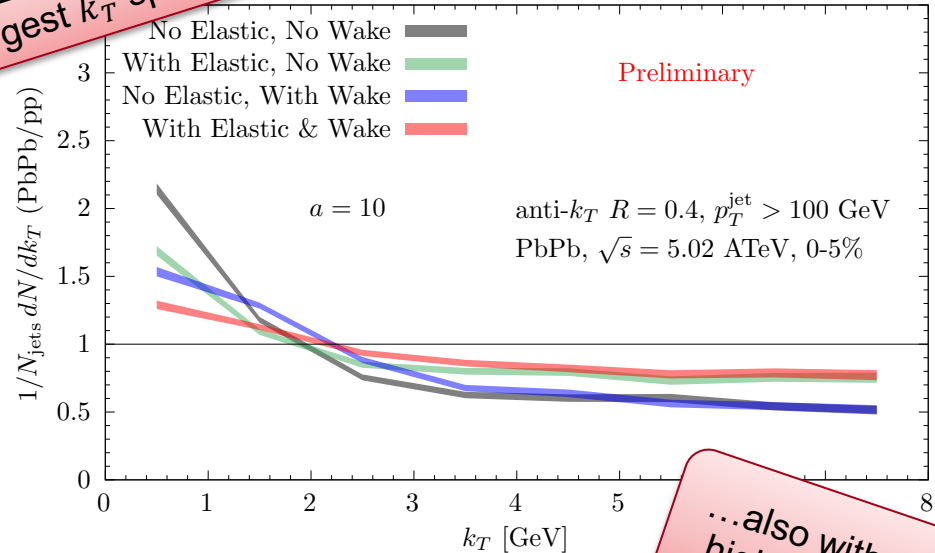
1. Reconstruct jet with anti-k_T

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 are dominant, with a=4 or 10.

Enhancement of softer splittings…
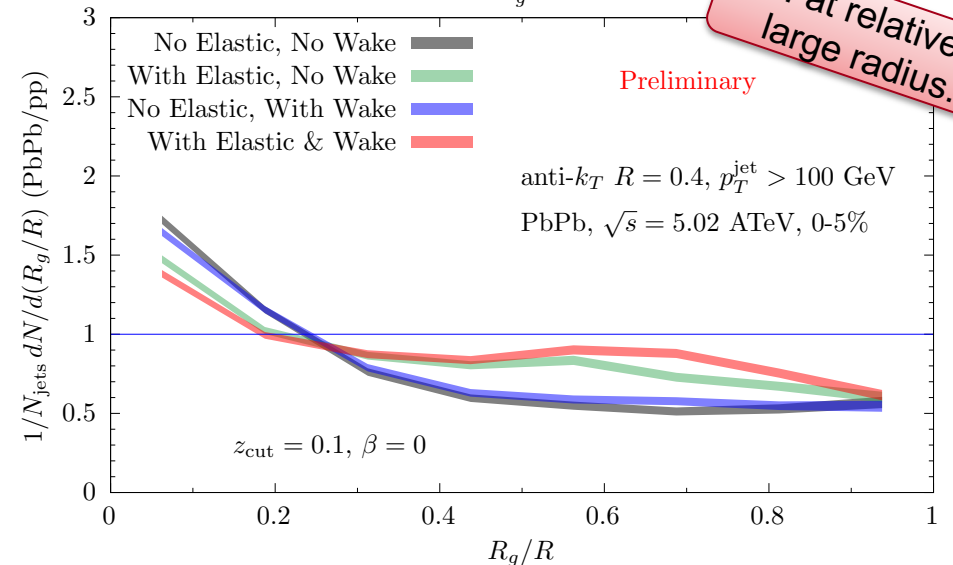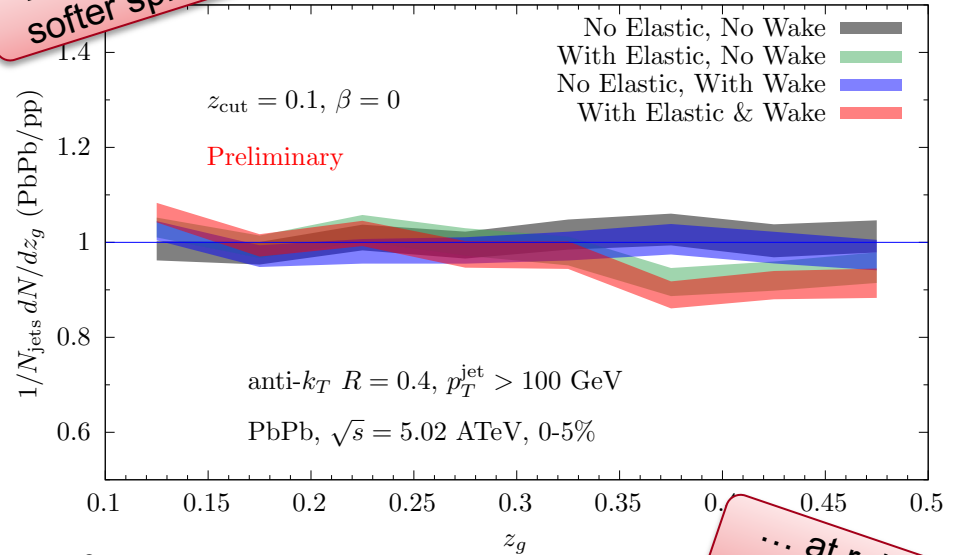
… at relatively large radius.

Groomed z_g and R_g

Soft Drop ($\beta = 0$)

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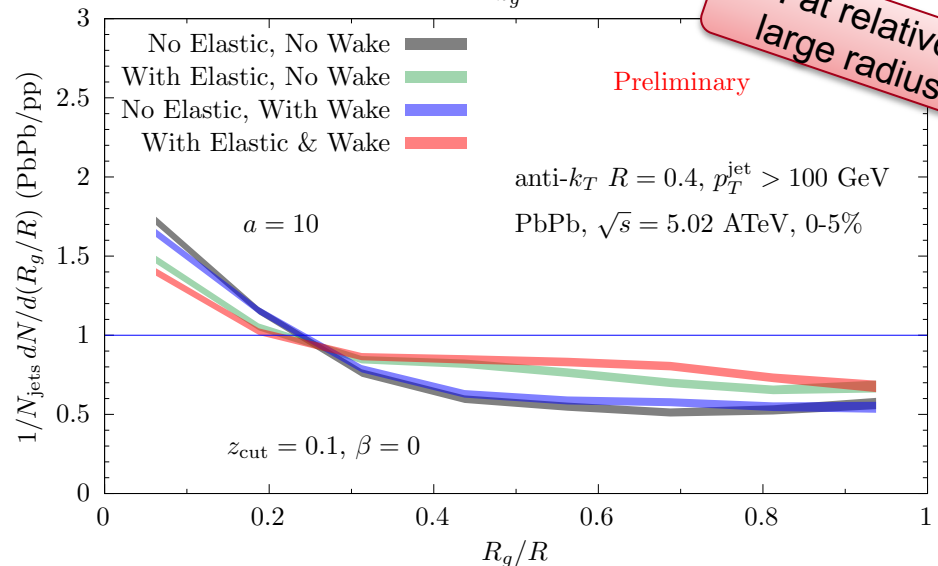
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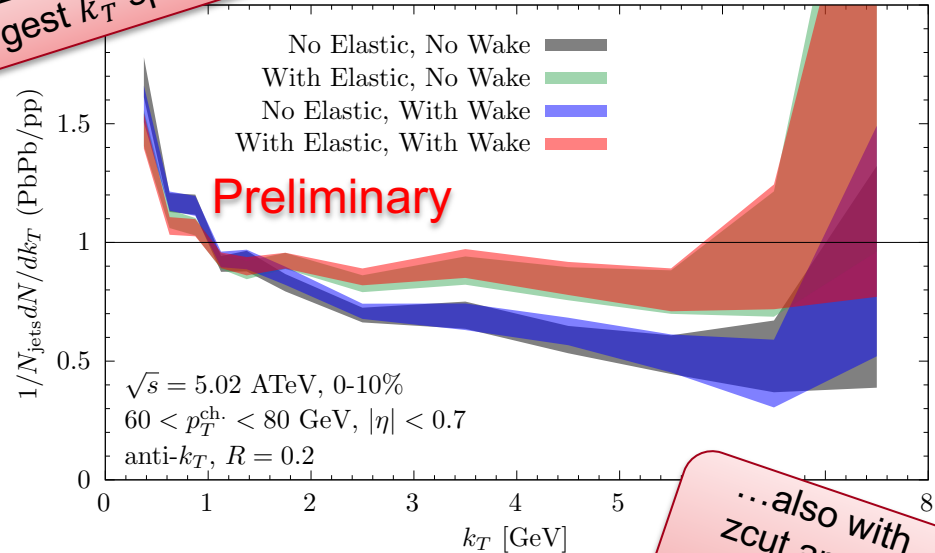# Leading k_T

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4. Note k_T of splitting

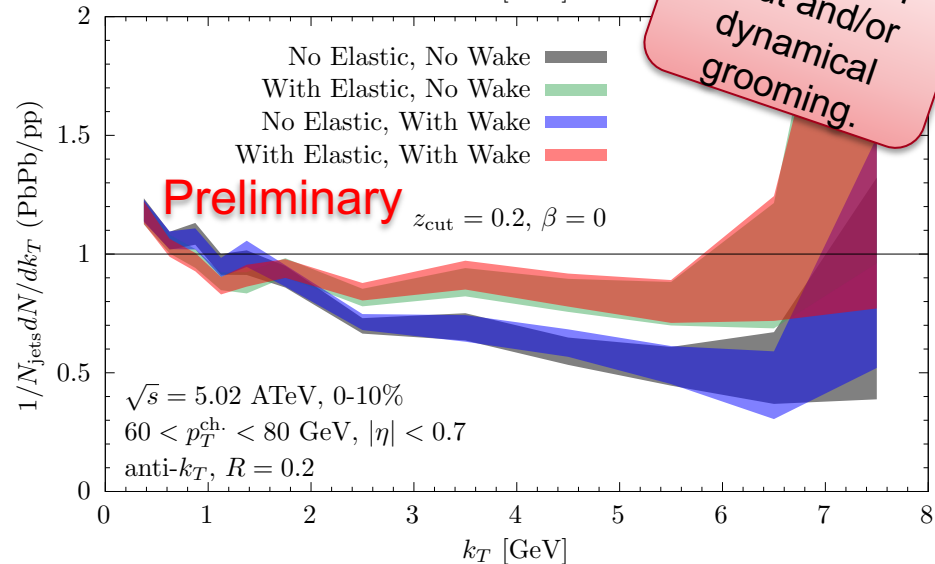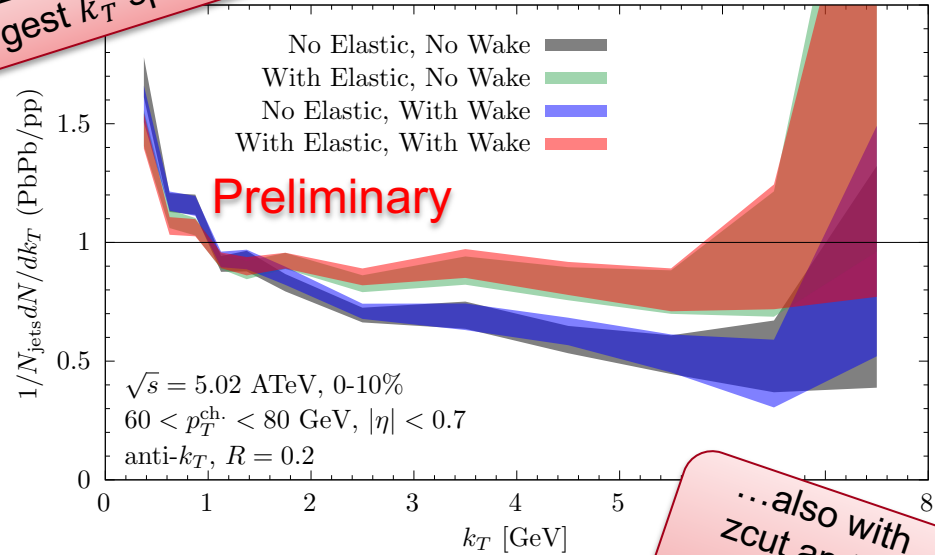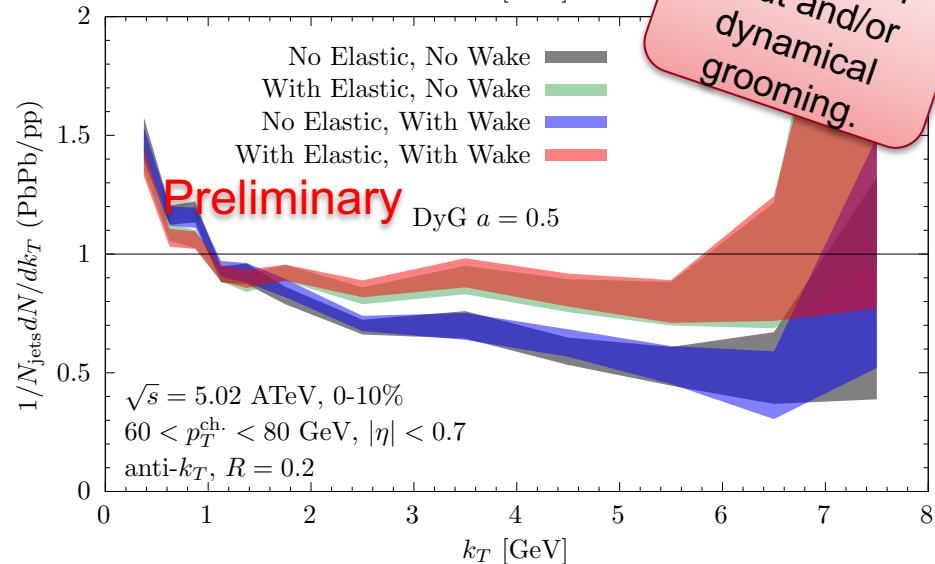5. Follow primary branch until the end.

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.

Enhancement of largest k_T splittings…
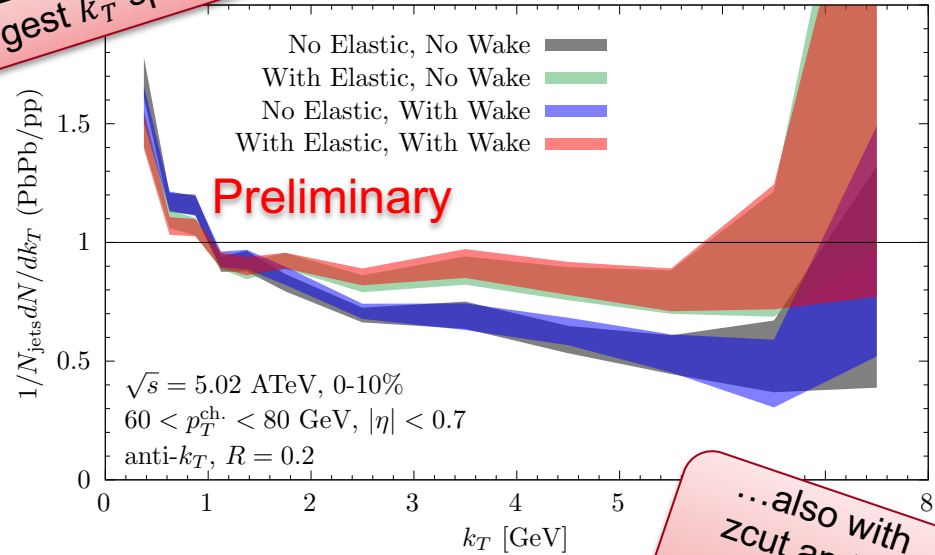

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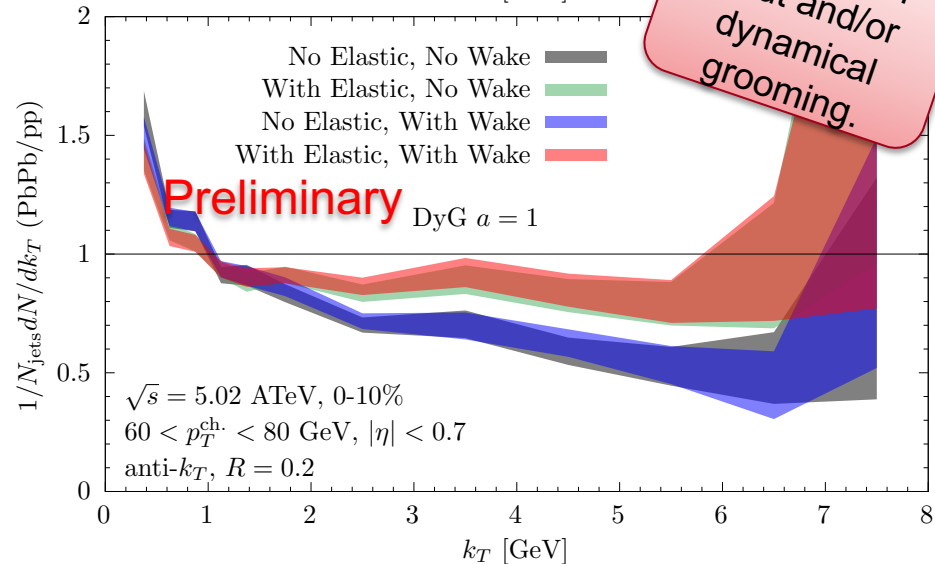5. Follow primary branch until the end.

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$1/N_{\text{jets}}\, dN/dk_T$ (PbPb/pp)

k_T [GeV]

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No Elastic, With Wake
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$z_{\text{cut}} = 0.2$

$a = 10$

Preliminary

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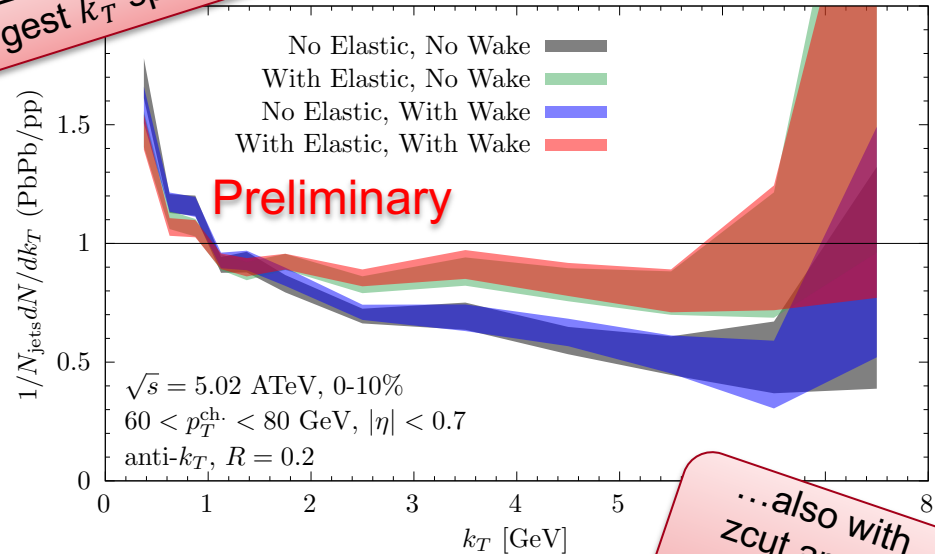
$1/N_{\text{jets}}\, dN/dk_T$ (PbPb/pp)

k_T [GeV]

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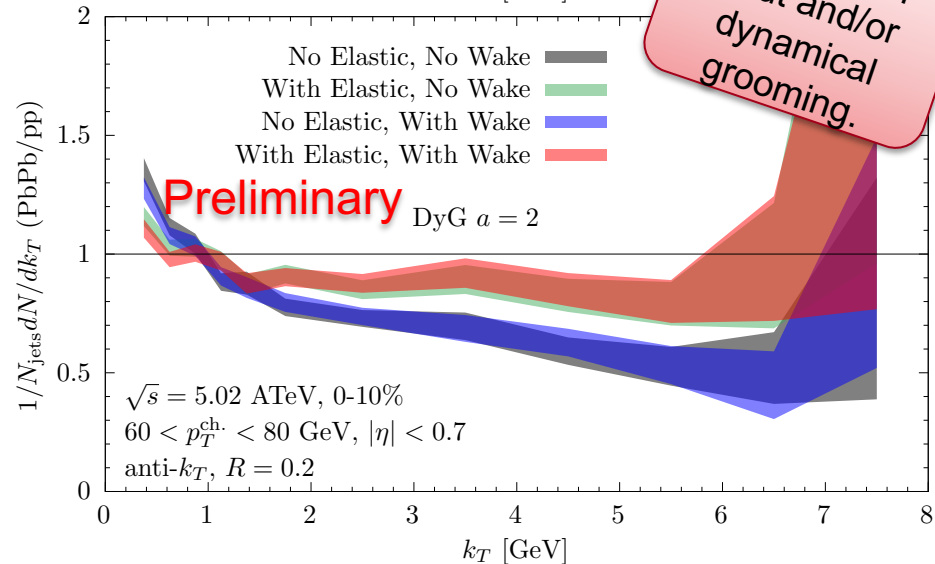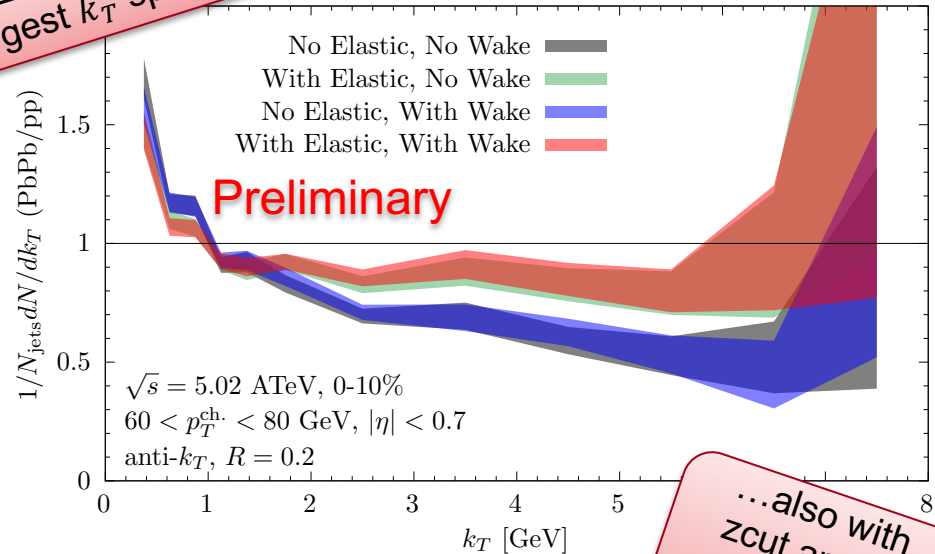5. Follow primary branch until the end.
6. Record largest k_T

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

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

Enhancement of largest k_T splittings…

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic, With Wake

Preliminary

$\sqrt{s} = 5.02$ ATeV, 0-10%
$60 < p_T^{\text{ch.}} < 80$ GeV, $|\eta| < 0.7$
anti-k_T, $R = 0.2$

$1/N_{\text{jets}} dN/dk_T$ (PbPb/pp)

k_T [GeV]

…also with zcut and/or dynamical grooming.

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic, With Wake

Preliminary
$z_{\text{cut}} = 0.2$, $\beta = 0$

$\sqrt{s} = 5.02$ ATeV, 0-10%
$60 < p_T^{\text{ch.}} < 80$ GeV, $|\eta| < 0.7$
anti-k_T, $R = 0.2$

$1/N_{\text{jets}} dN/dk_T$ (PbPb/pp)

k_T [GeV]

Leading k_T

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2. Recluster with Cambridge-Aachen
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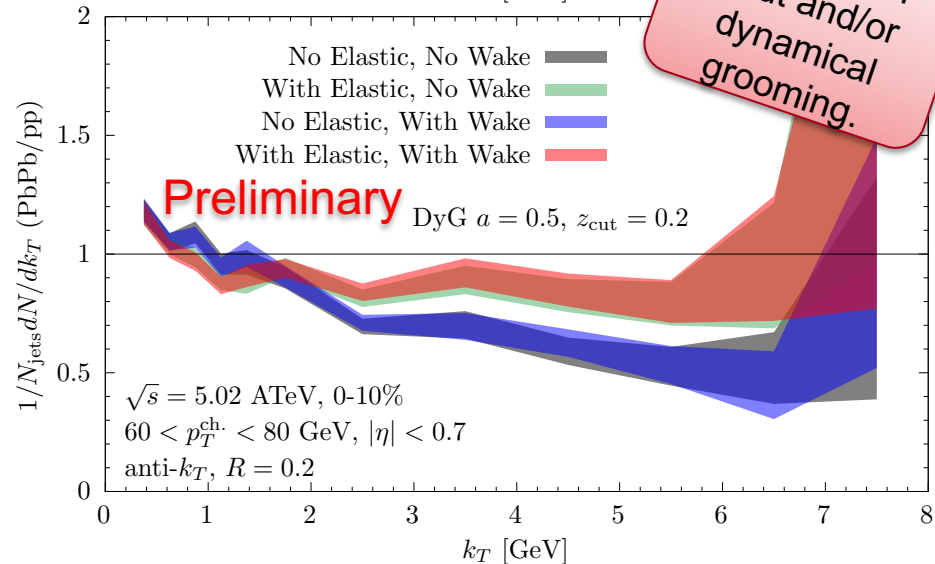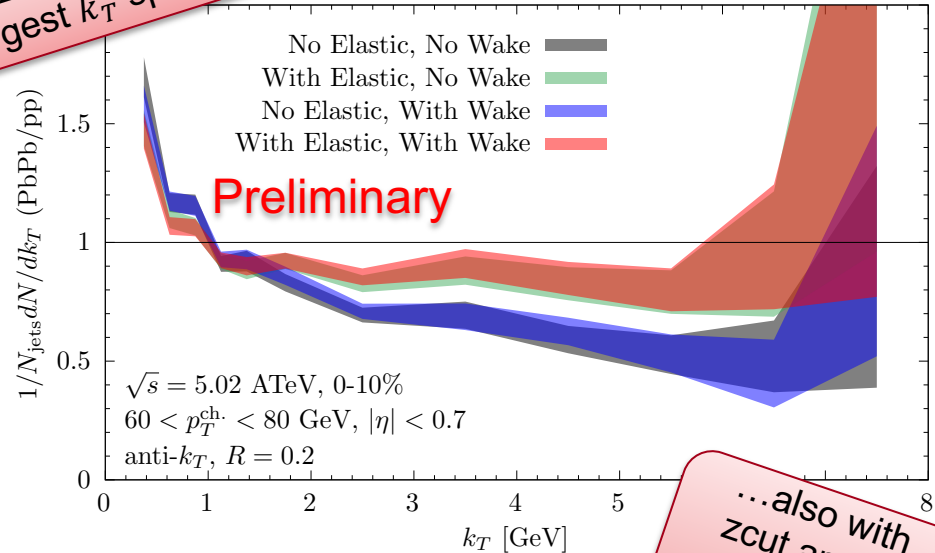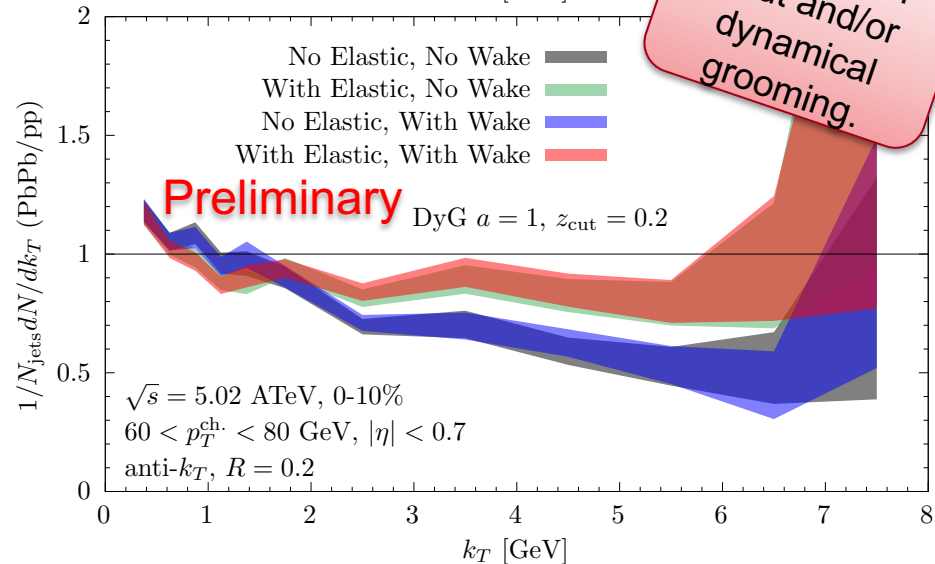5. Follow primary branch until the end.
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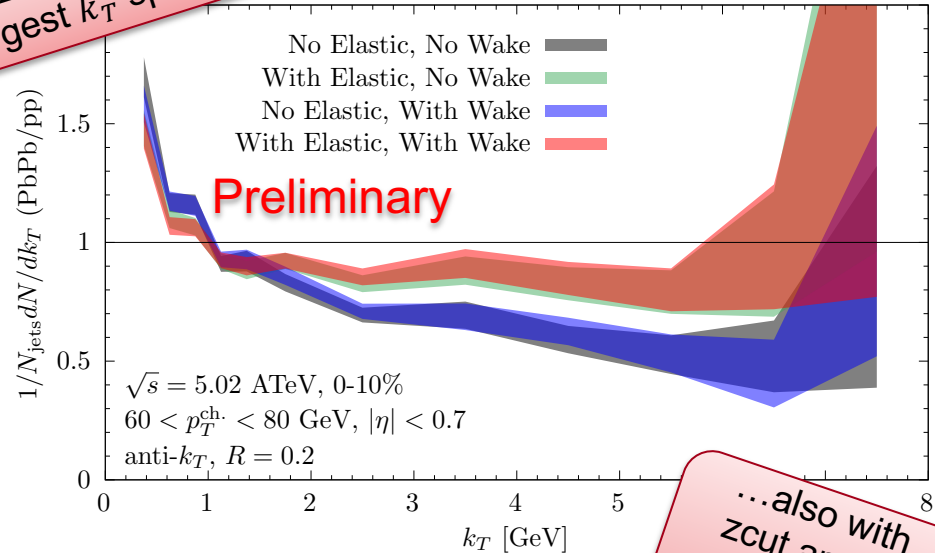
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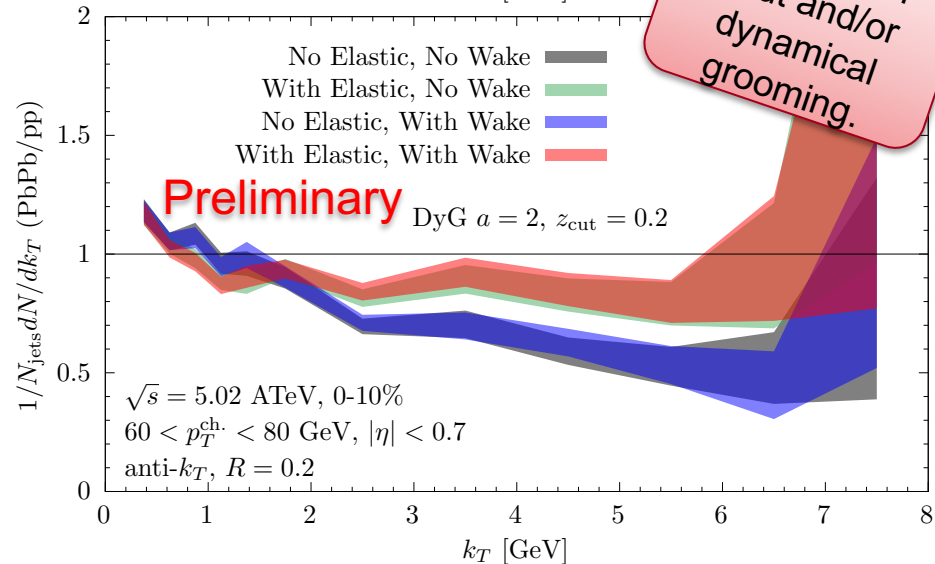5. Follow primary branch until the end.

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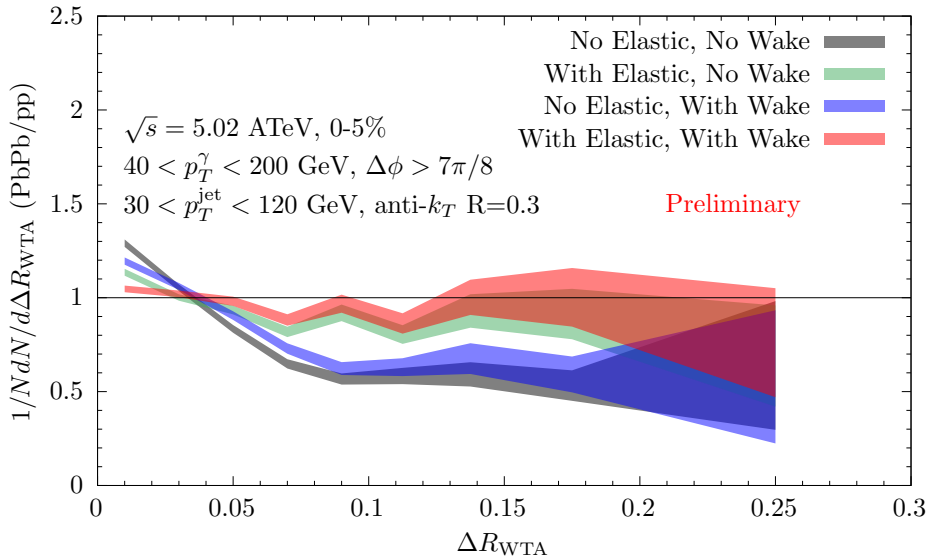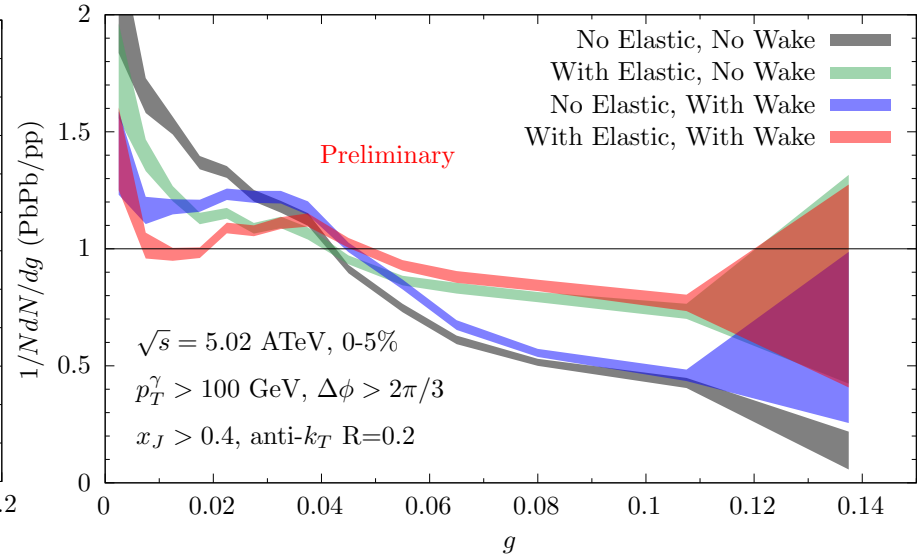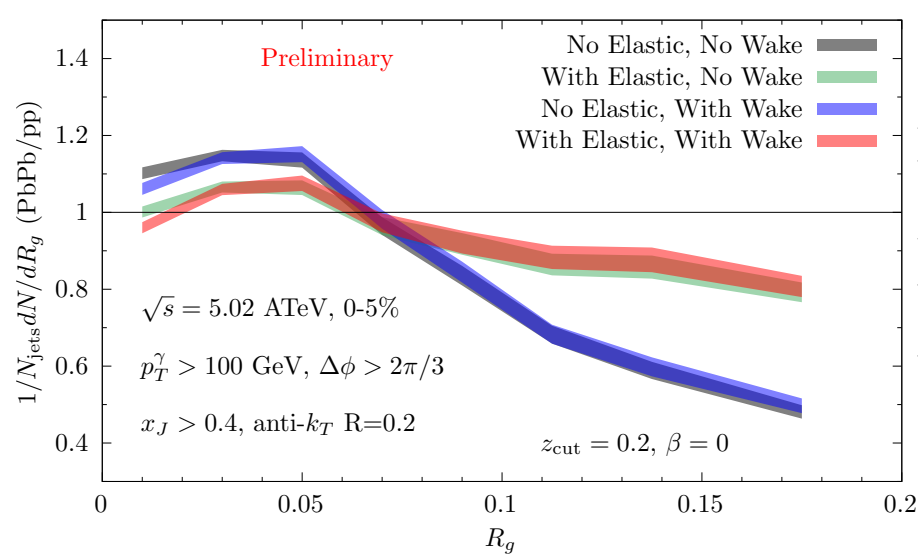Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.

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k_T [GeV]

…also with zcut and/or dynamical grooming.

No Elastic, No Wake
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With Elastic, With Wake

Preliminary   DyG $a = 2$

$\sqrt{s} = 5.02$ ATeV, 0-10%
$60 < p_T^{\text{ch.}} < 80$ GeV, $|\eta| < 0.7$
anti-k_T, $R = 0.2$

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Preliminary

No Elastic, No Wake
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k_T [GeV]

Preliminary

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic, With Wake

DyG $a = 0.5$, $z_{\text{cut}} = 0.2$

$1/N_{\text{jets}} dN/dk_T$ (PbPb/pp)

$\sqrt{s} = 5.02$ ATeV, 0-10%
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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.

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Gamma-Jet Observables: R_g and Girth, with xJ>0.1
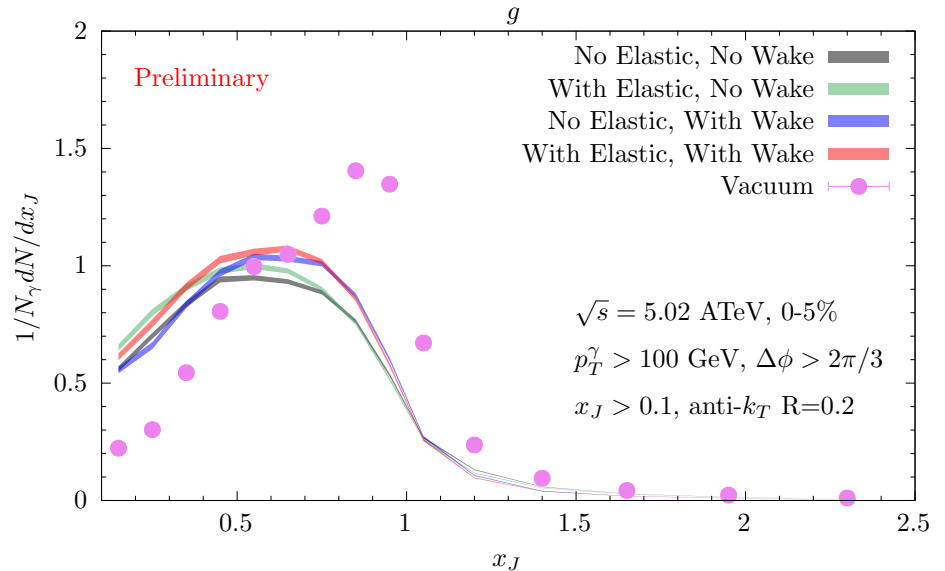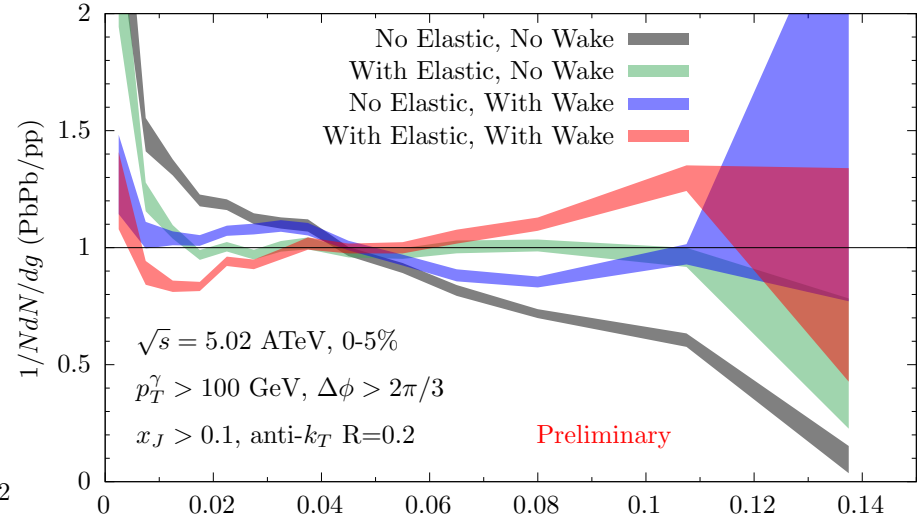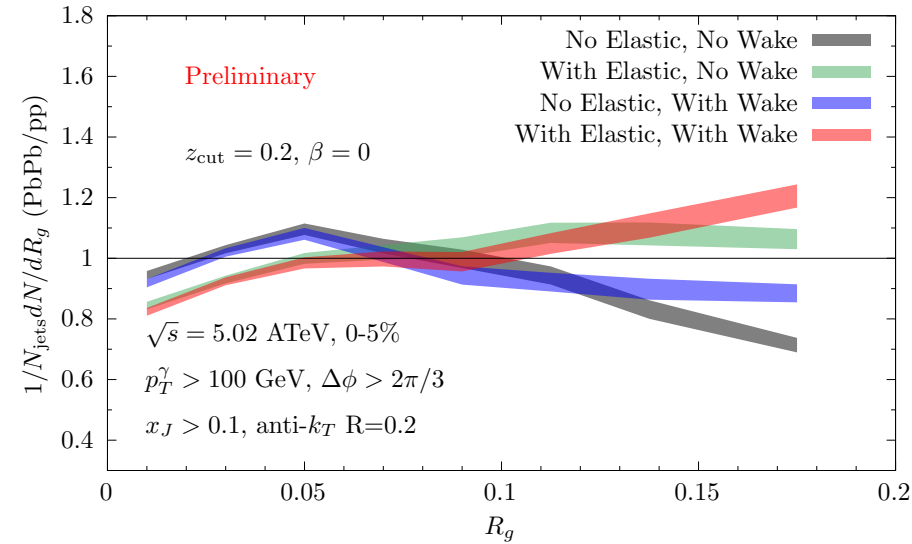
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important. Some effects of wake.

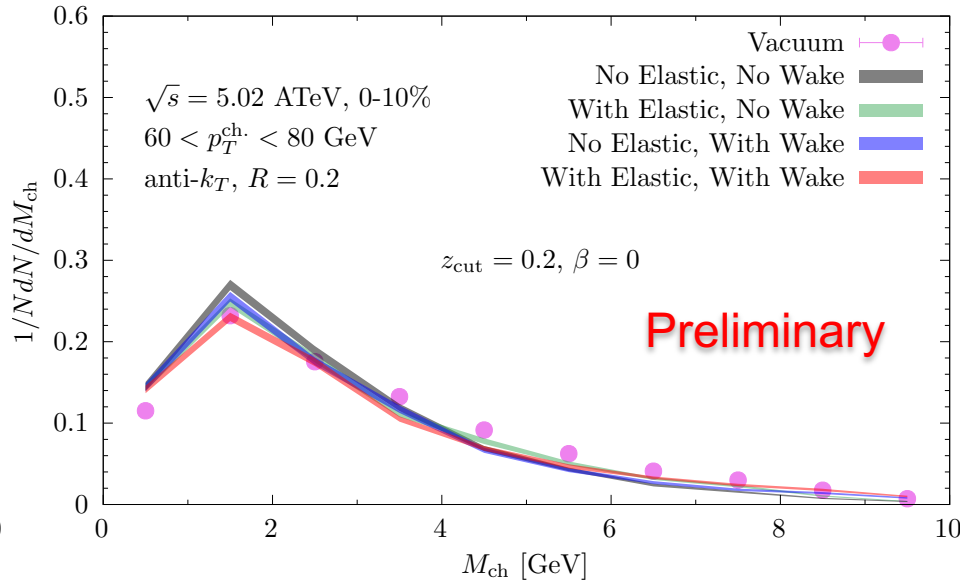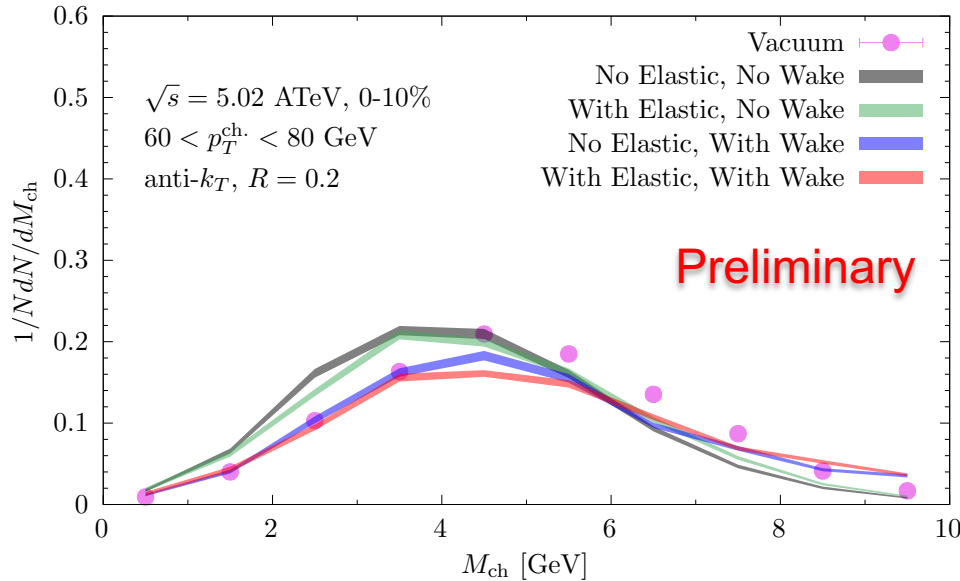Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.

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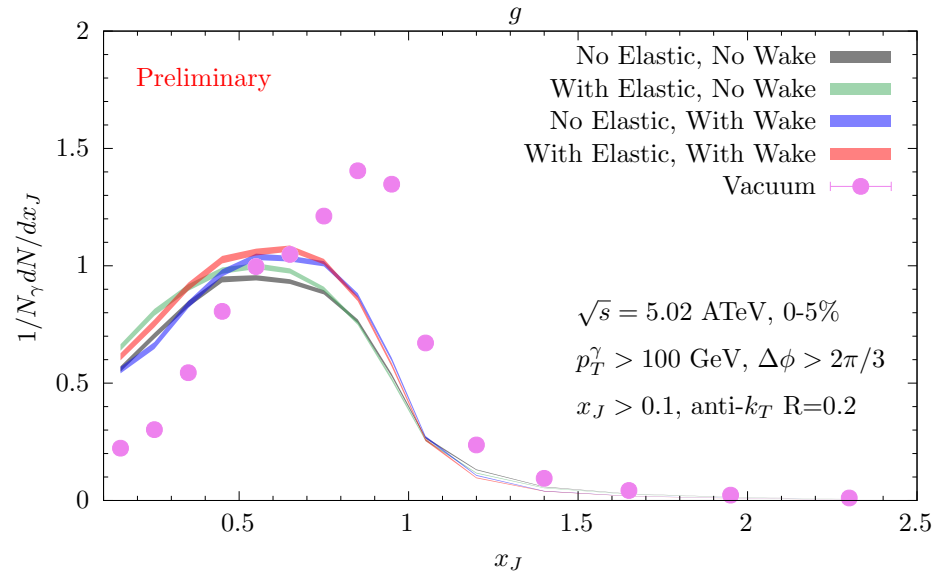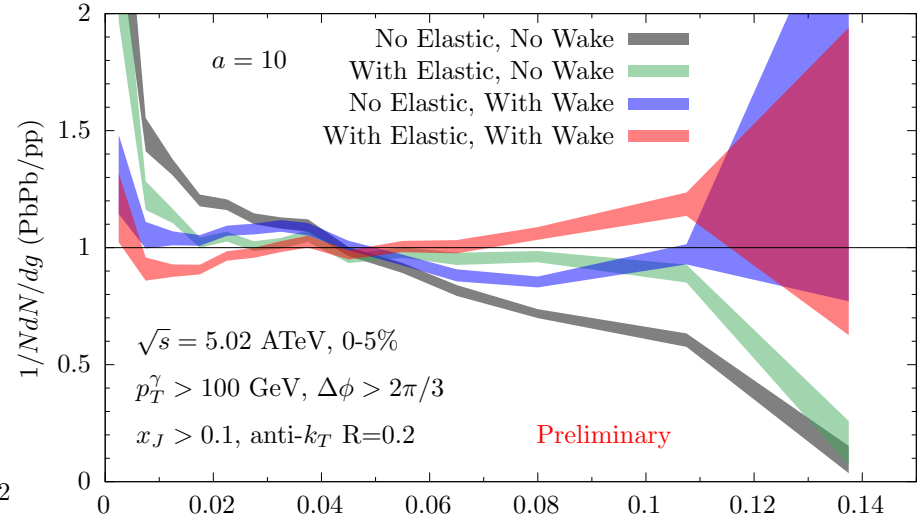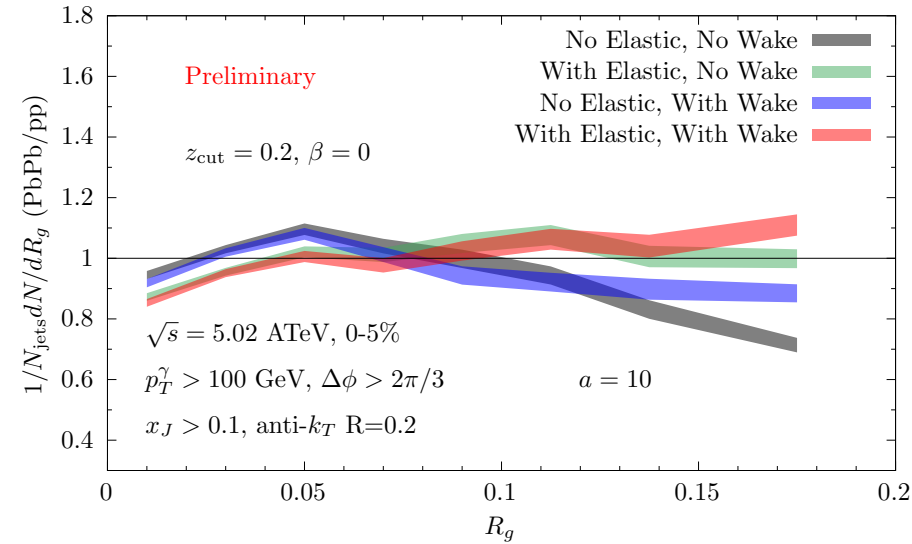
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Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.

Jet Mass, and Groomed Jet Mass

Left panel: $\sqrt{s} = 5.02$ ATeV, 0-10%; $40 < p_T^{\text{ch.}} < 60$ GeV; anti-k_T, $R = 0.2$. Legend: Vacuum; No Elastic, No Wake; With Elastic, No Wake; No Elastic, With Wake; With Elastic, With Wake. **Preliminary**. Axes: $1/N dN/dM_{\text{ch}}$ vs M_{ch} [GeV].

Right panel: $\sqrt{s} = 5.02$ ATeV, 0-10%; $40 < p_T^{\text{ch.}} < 60$ GeV; anti-k_T, $R = 0.2$; $z_{\text{cut}} = 0.2$, $\beta = 0$. Legend: Vacuum; No Elastic, No Wake; With Elastic, No Wake; No Elastic, With Wake; With Elastic, With Wake. **Preliminary**. Axes: $1/N dN/dM_{\text{ch}}^g$ vs M_{ch}^g [GeV].
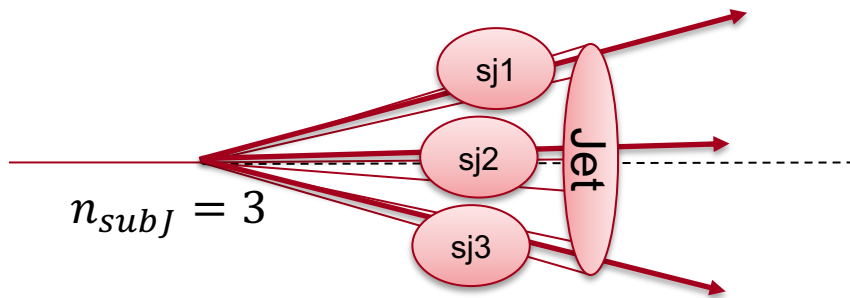
Ungroomed observable is sensitive to the wake; not to Moliere scattering.
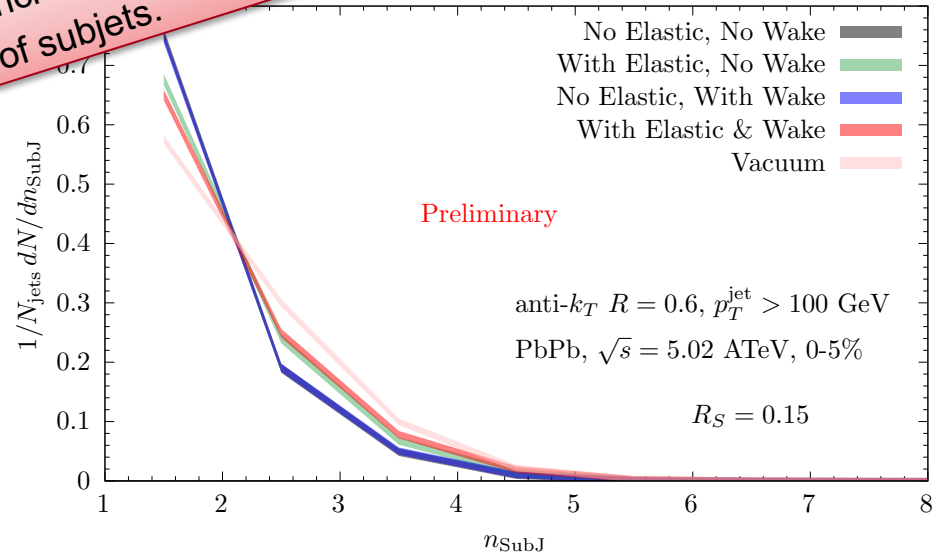**Grooming removes wake, but still little sensitivity to Moliere scattering.**

- 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

Left panel: $\sqrt{s} = 5.02$ ATeV, 0-10%; $60 < p_T^{\text{ch.}} < 80$ GeV; anti-k_T, $R = 0.2$. Legend: Vacuum; No Elastic, No Wake; With Elastic, No Wake; No Elastic, With Wake; With Elastic, With Wake. **Preliminary**

Right panel: $\sqrt{s} = 5.02$ ATeV, 0-10%; $60 < p_T^{\text{ch.}} < 80$ GeV; anti-k_T, $R = 0.2$; $z_{\text{cut}} = 0.2$, $\beta = 0$. **Preliminary**

Ungroomed observable is sensitive to the wake; not to Moliere scattering. Grooming removes wake, but still little sensitivity to Moliere scattering.

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Jet Mass, and Groomed Jet Mass

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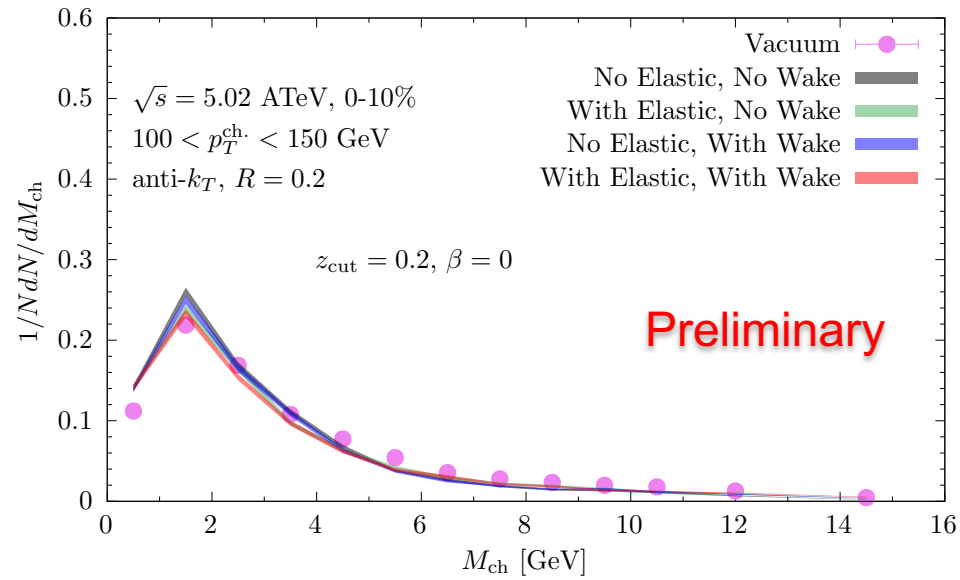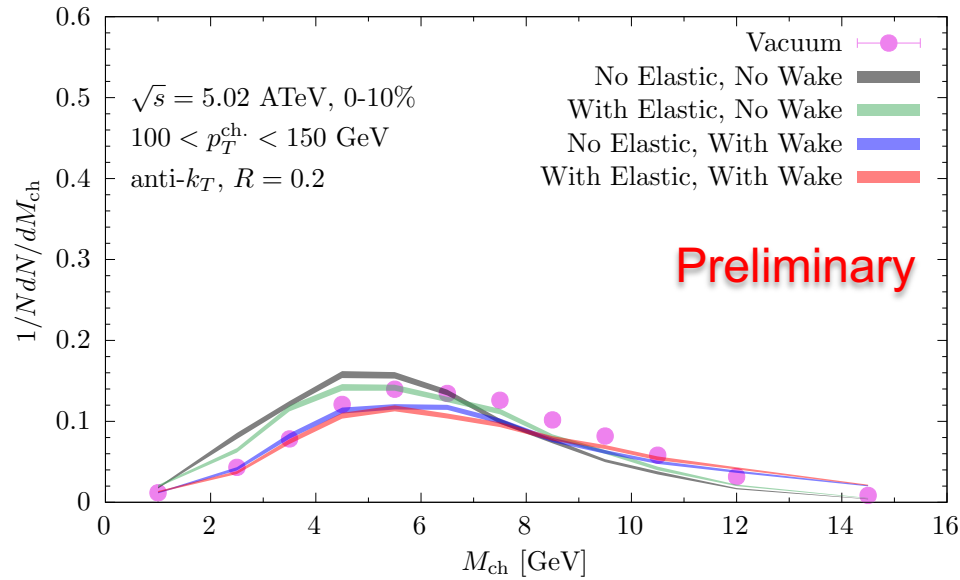
- What if we look at groomed observables? Less sensitive to wake...
- Yes, but not every groomed observable is sensitive to hard scattering...

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
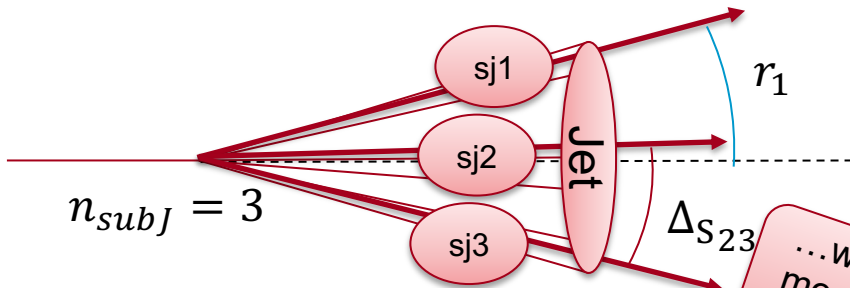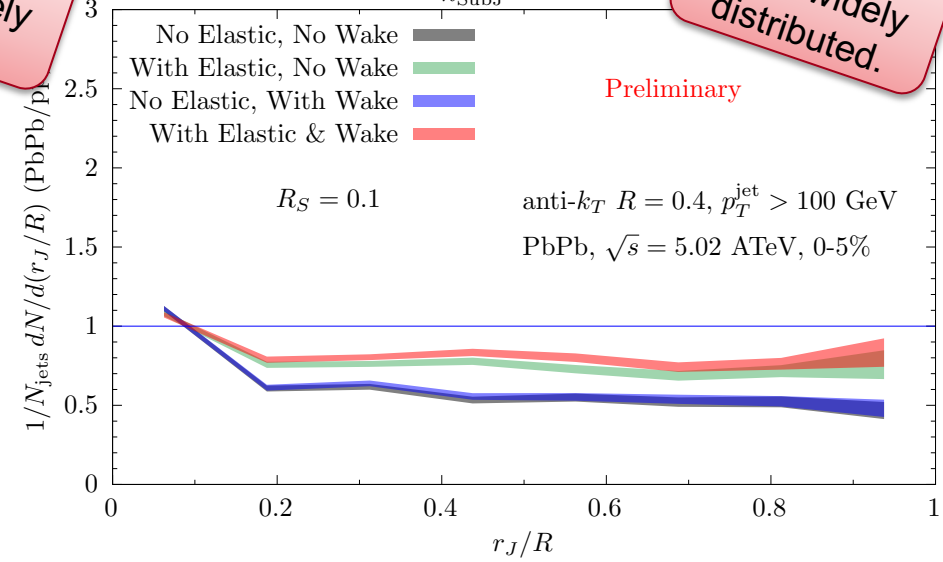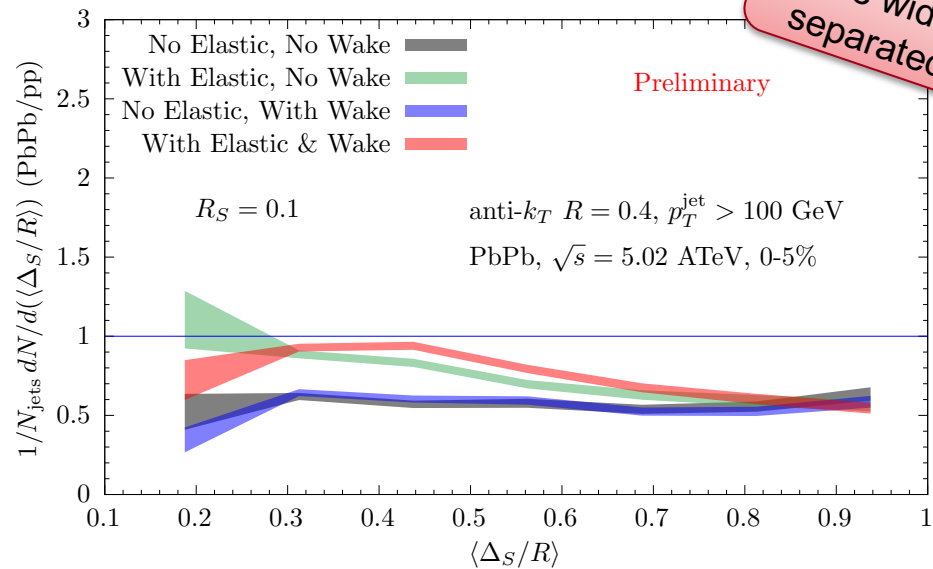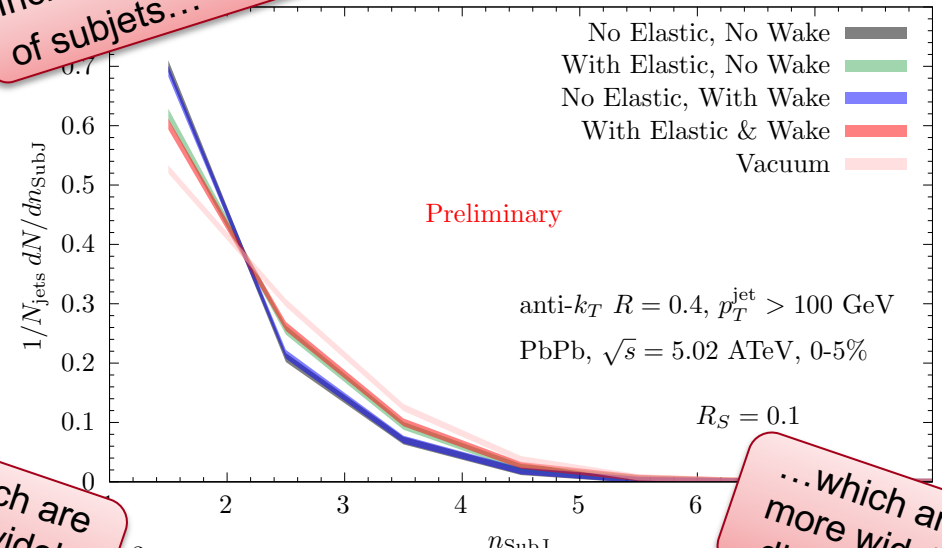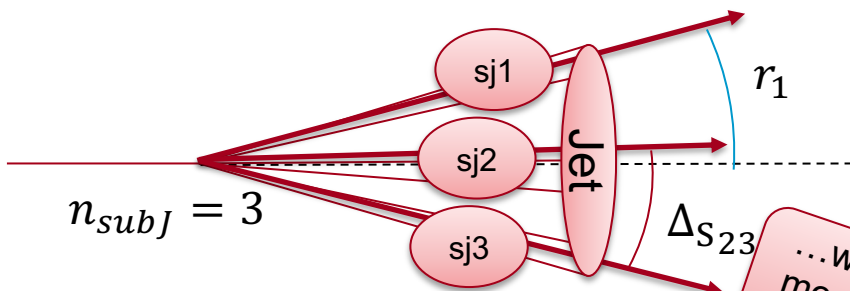
$n_{subJ} = 3$

Increase in number of subjets.

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic & Wake
Vacuum

Preliminary

anti-k_T $R = 0.6$, $p_T^{\rm jet} > 100$ GeV

PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

$R_S = 0.15$

$1/N_{\rm jets}\, dN/dn_{\rm SubJ}$

$n_{\rm SubJ}$

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=0.6

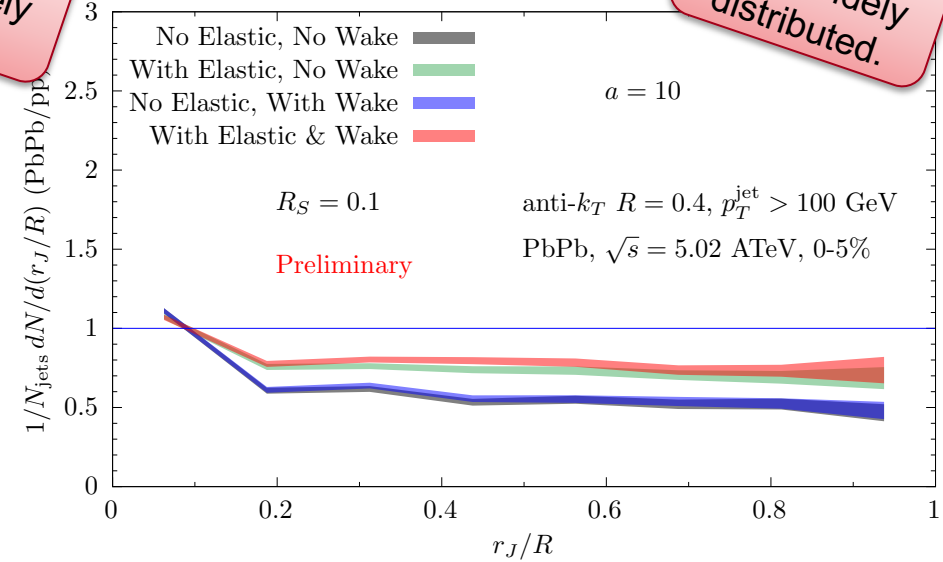2. Recluster each jet's particle content into subjets with R=0.15

Inclusive Subjets

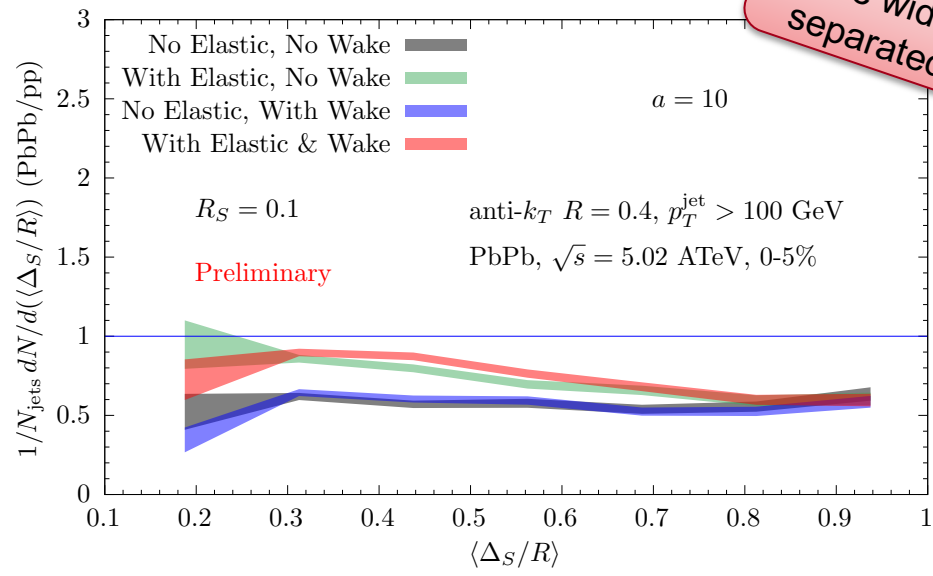1. Reconstruct jet with R=0.4

2. Recluster each jet's particle content into subjets with R=0.1
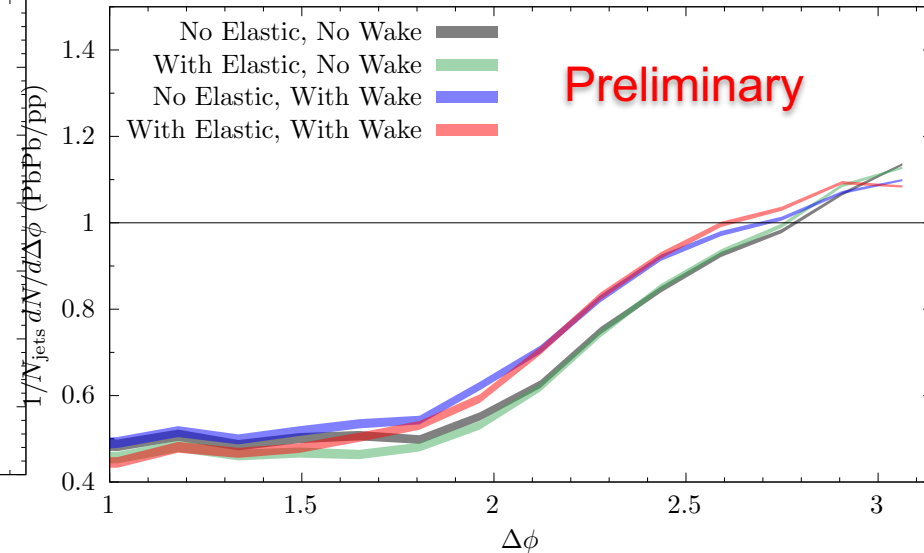
$n_{subJ} = 3$

sj1 sj2 sj3 Jet r_1 Δ_{S23}
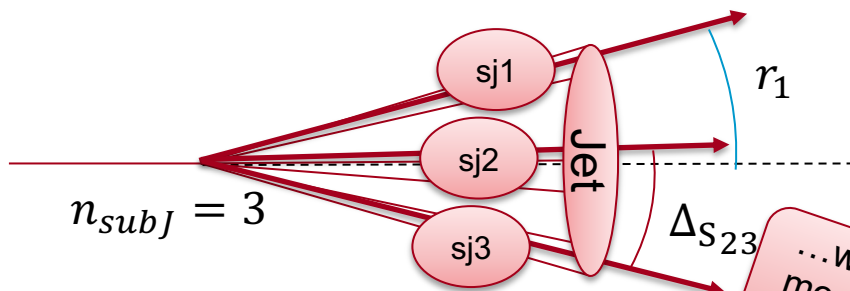
Increase in number of subjets…

…which are more widely separated.

…which are more widely distributed.

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic & Wake
Vacuum

Preliminary

anti-k_T $R = 0.4$, $p_T^{\text{jet}} > 100$ GeV
PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

$R_S = 0.1$

$1/N_{\text{jets}}\, dN/dn_{\text{SubJ}}$

n_{SubJ}

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic & Wake

Preliminary

$R_S = 0.1$

anti-k_T $R = 0.4$, $p_T^{\text{jet}} > 100$ GeV
PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

$1/N_{\text{jets}}\, dN/d(\langle\Delta_S/R\rangle)$ (PbPb/pp)

$\langle\Delta_S/R\rangle$

No Elastic, No Wake
With Elastic, No Wake
No Elastic, With Wake
With Elastic & Wake

Preliminary

$R_S = 0.1$

anti-k_T $R = 0.4$, $p_T^{\text{jet}} > 100$ GeV
PbPb, $\sqrt{s} = 5.02$ ATeV, 0-5%

$1/N_{\text{jets}}\, dN/d(r_J/R)$ (PbPb/pp)

r_J/R

Inclusive Subjets

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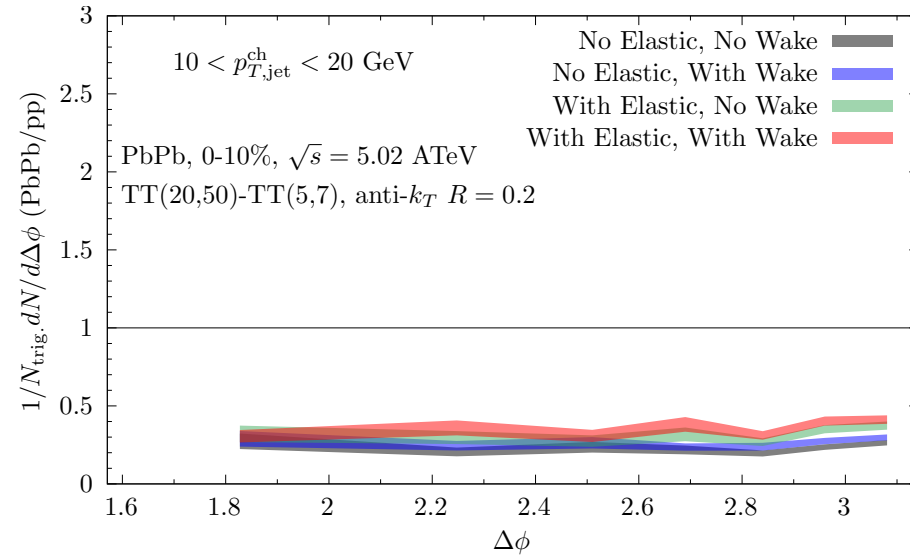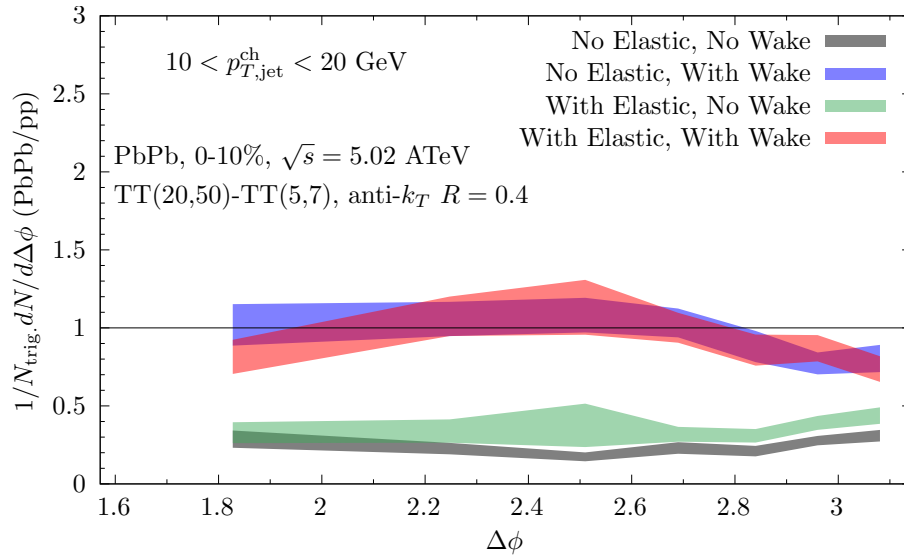2. Recluster each jet's particle content into subjets with R=0.1

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
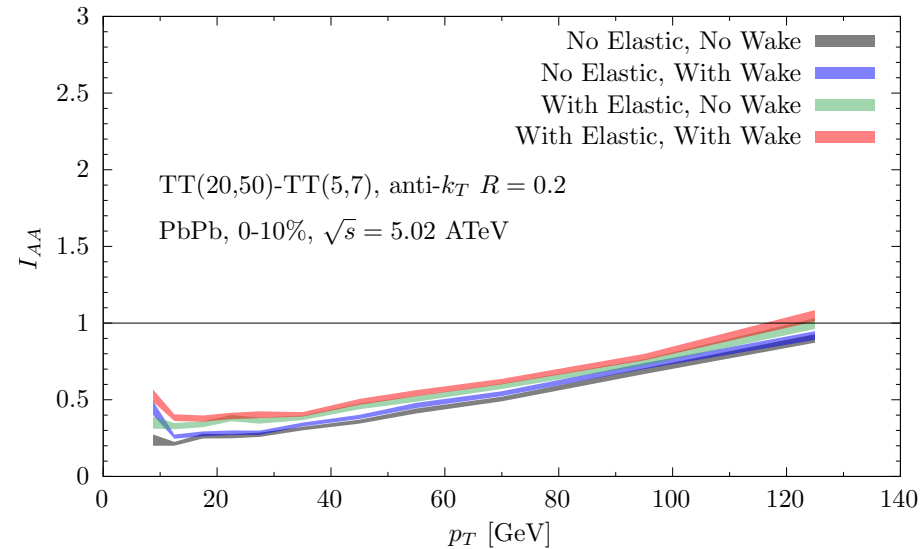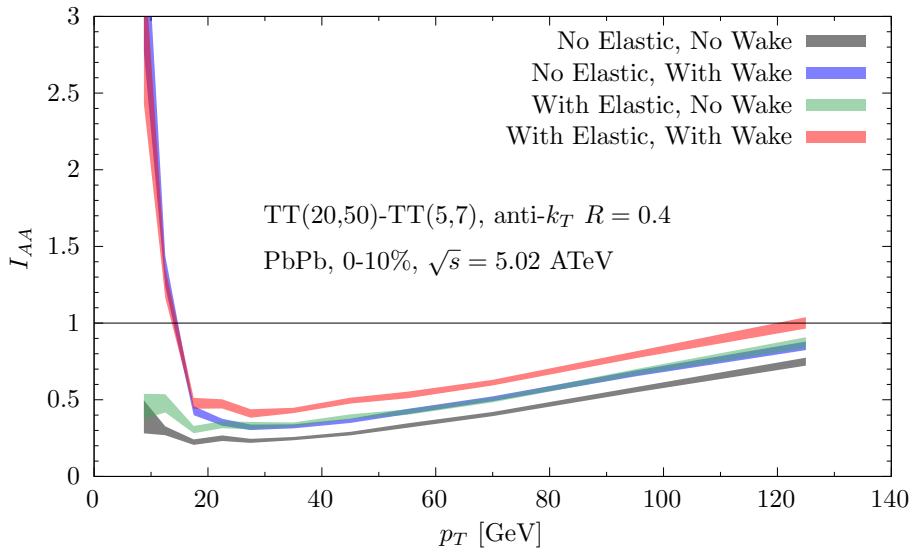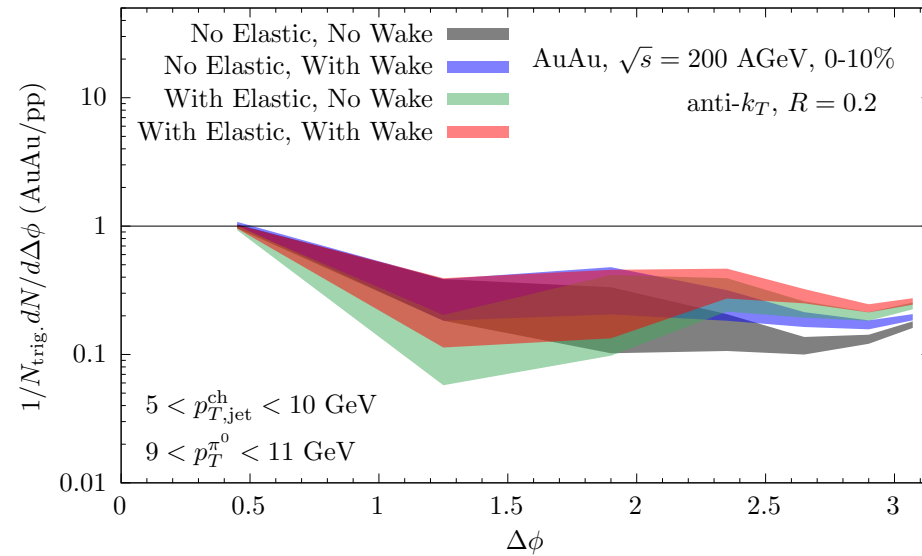
Hadron--Charge-Jet Acoplanarity, LHC energy

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

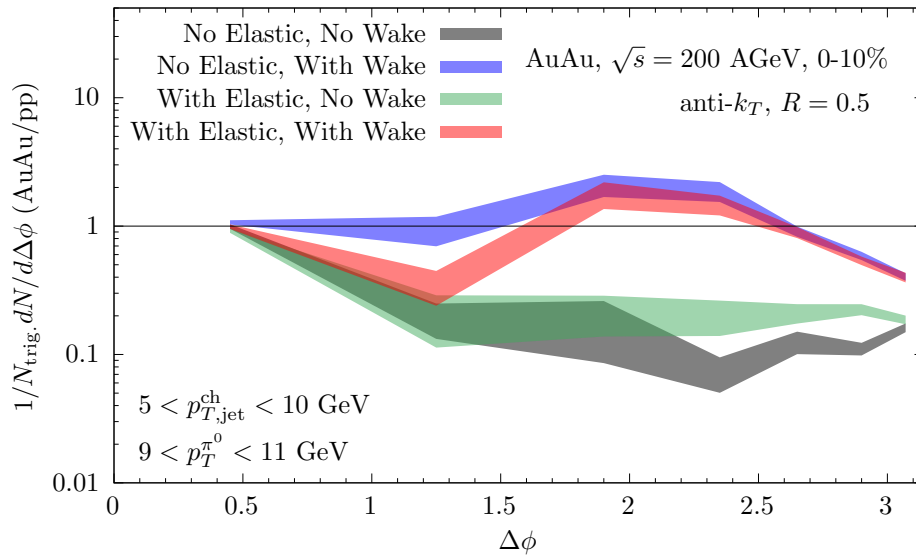# Hadron—Charge-Jet Acoplanarity, LHC energy

Preliminary

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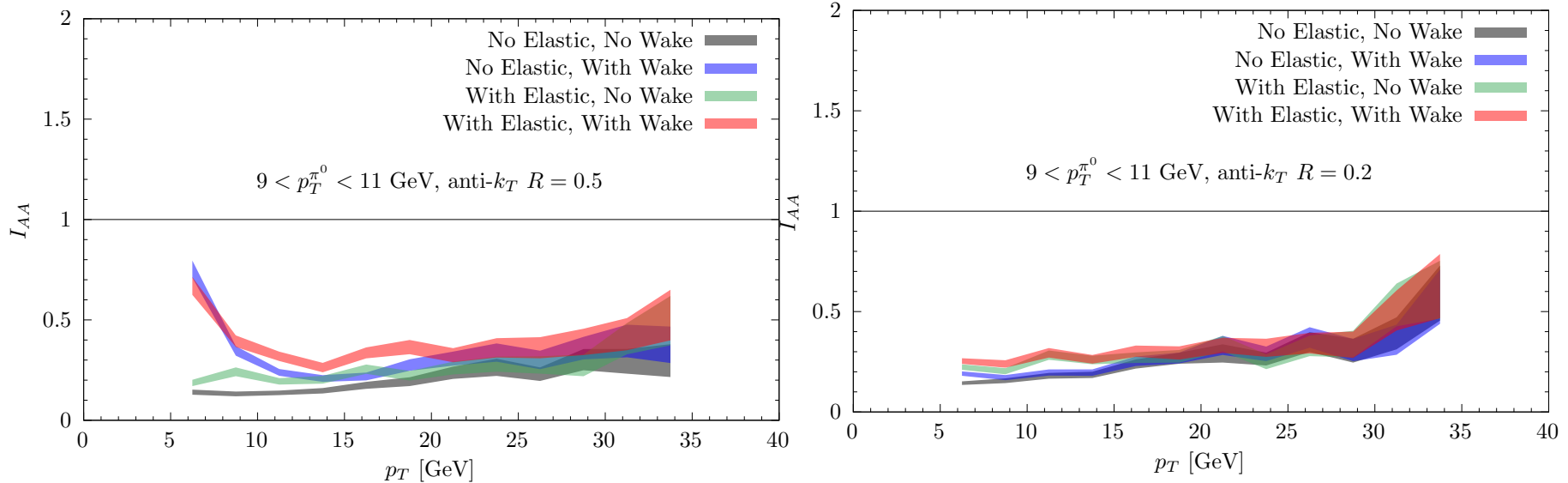
# Hadron--Charge-Jet Acoplanarity, RHIC energy

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

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Hadron--Charge-Jet Acoplanarity, RHIC energy

- Study acoplanarity in pi0 - charged jet system.
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- 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

Conclusions

- Studied the effect of power-law-rare, large-angle, scattering on jet observables in the perturbative regime.

- Moliere scattering affects many "shape observables". But, for "overall shape observables" (jet shapes; FF) effects 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 (Rg, Leading kT, Girth, WTA axis angle. Inclusive jets, and gamma-jets; for the latter, selection biases can be reduced.)

- Not all groomed observables are sensitive to Moliere scattering; cf groomed jet mass.

- 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 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.

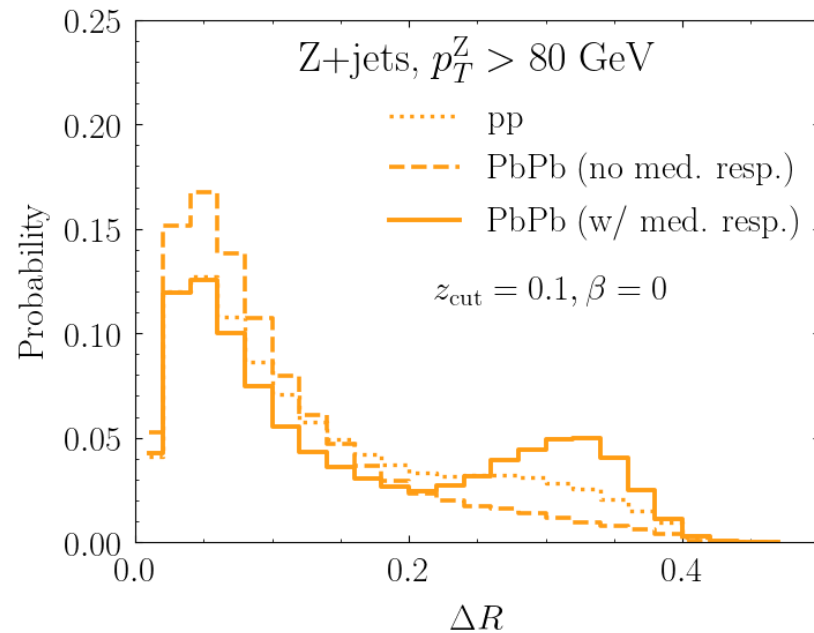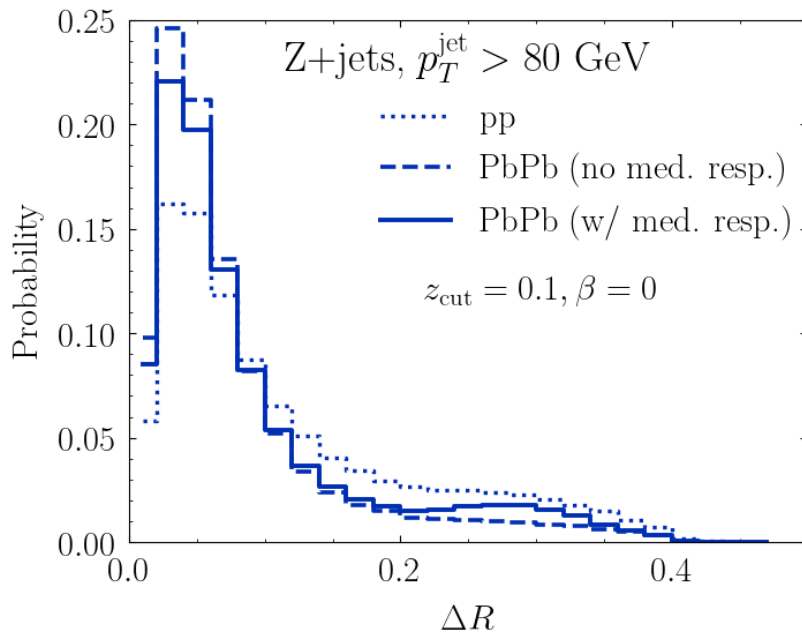- Future: studying charm observables (gamma-D, $D\bar{D}$, D within jets …)

# Disentangling Jet Modification from Selection
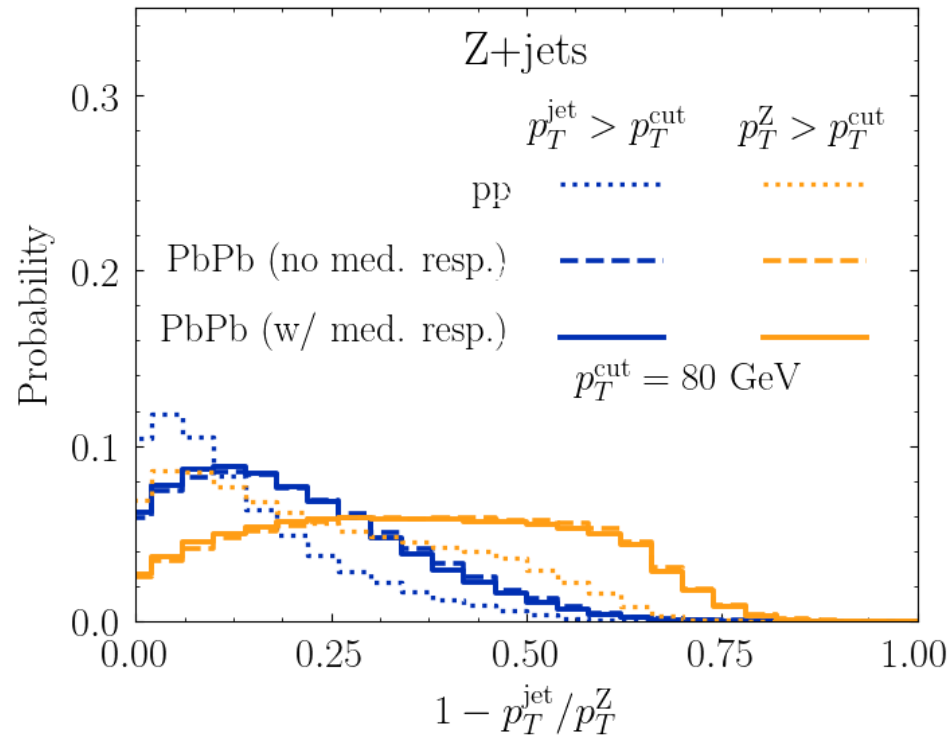
Orange: $p_T^Z > 80$ **GeV;** $p_T^{\text{jet}} > 30$ **GeV**

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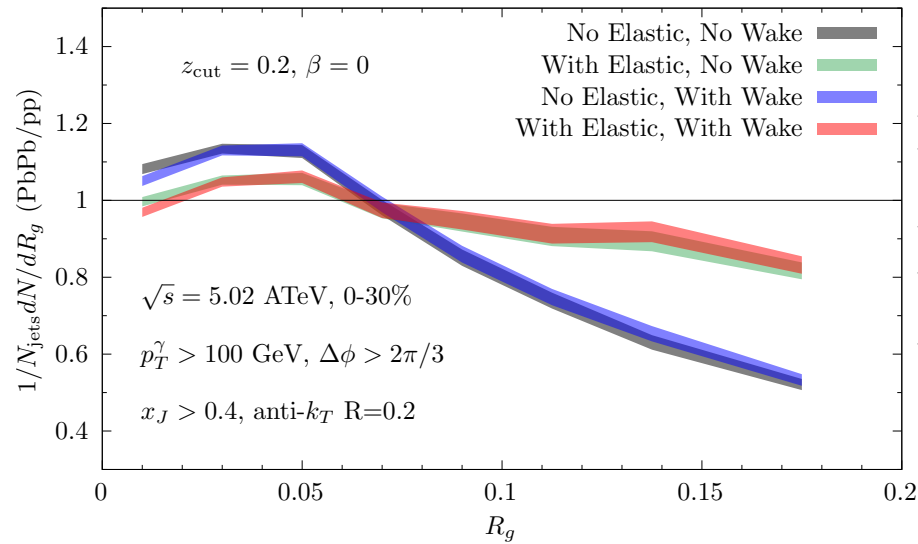
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Orange: $p_T^Z > 80$ **GeV;** $p_T^{\text{jet}} > 30$ **GeV. See jet modification.**

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.**
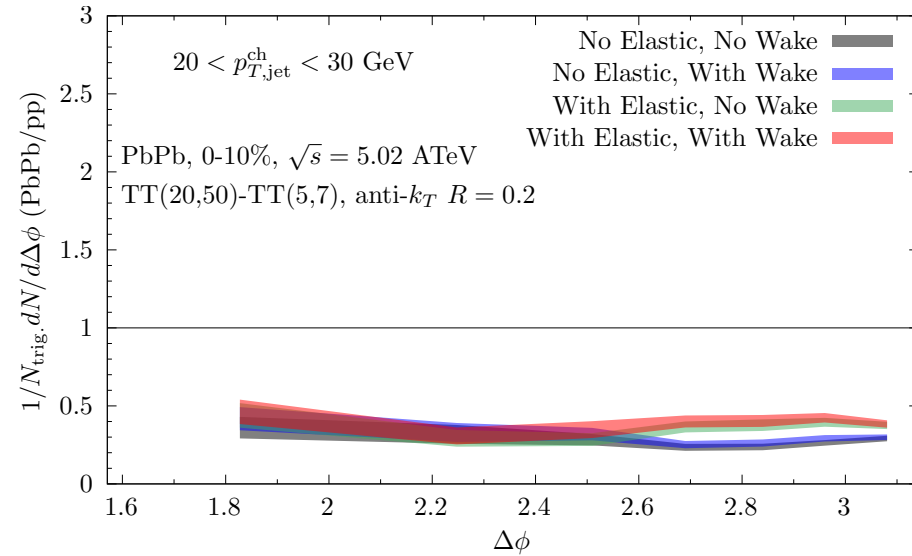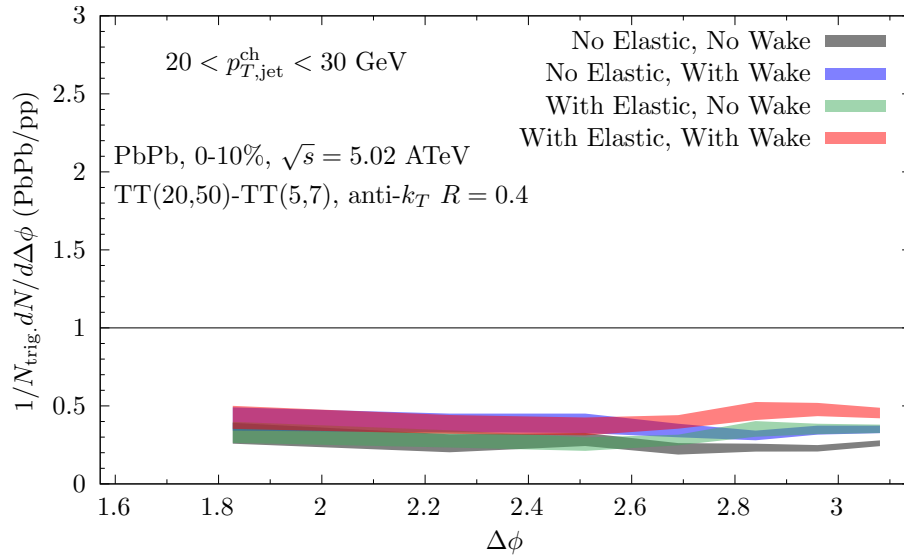
Three "groomed" gamma-Jet Observables: R_g, Girth, and angle between standard and WTA axes
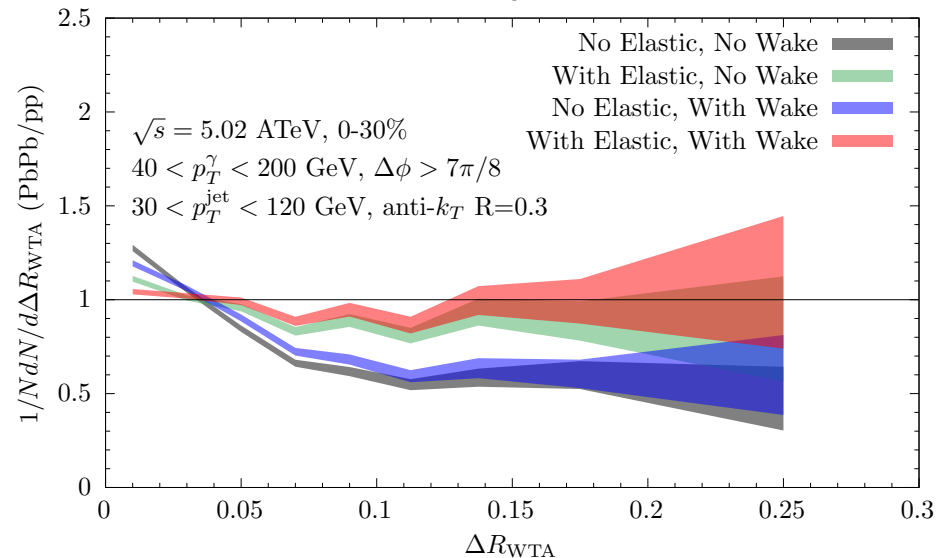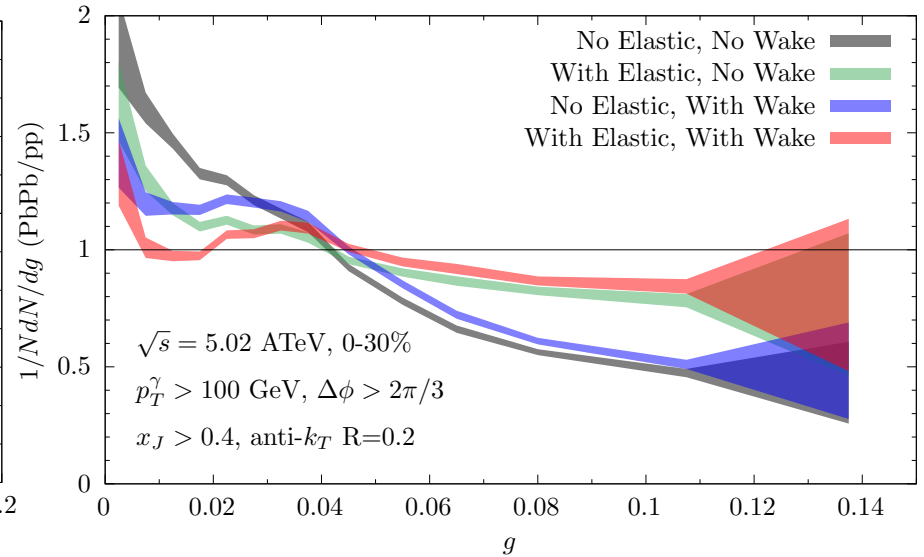
All show much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.
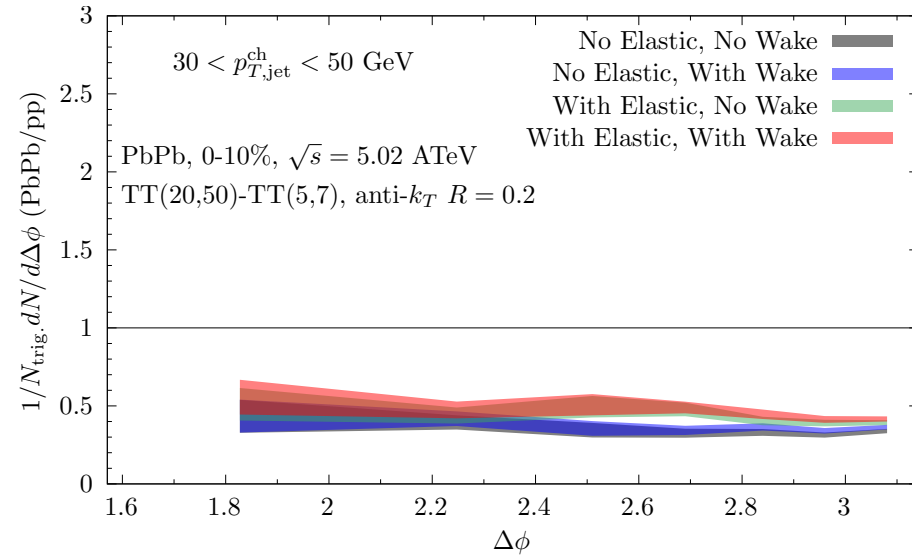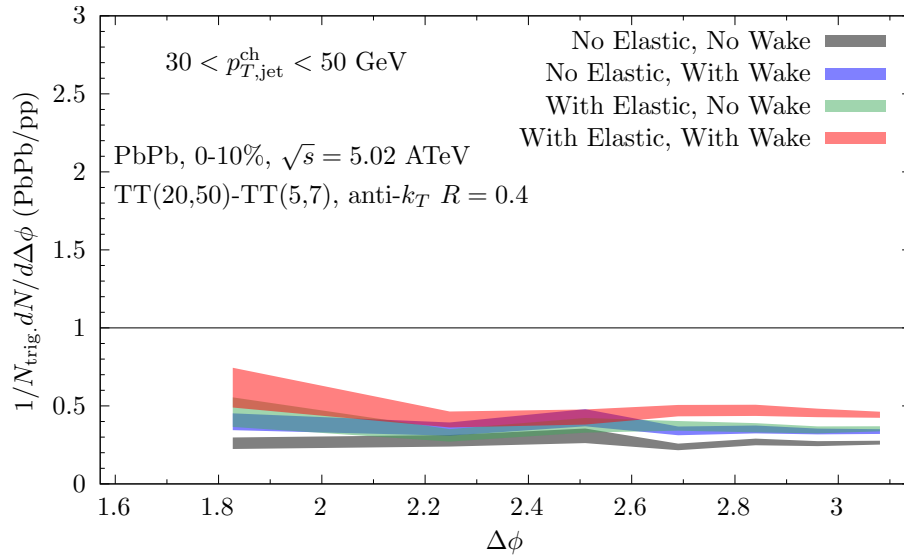
Hadron--Charge-Jet Acoplanarity, LHC energy

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

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