On zonal flow dynamics and ITG turbulence saturation in NT tokamaks

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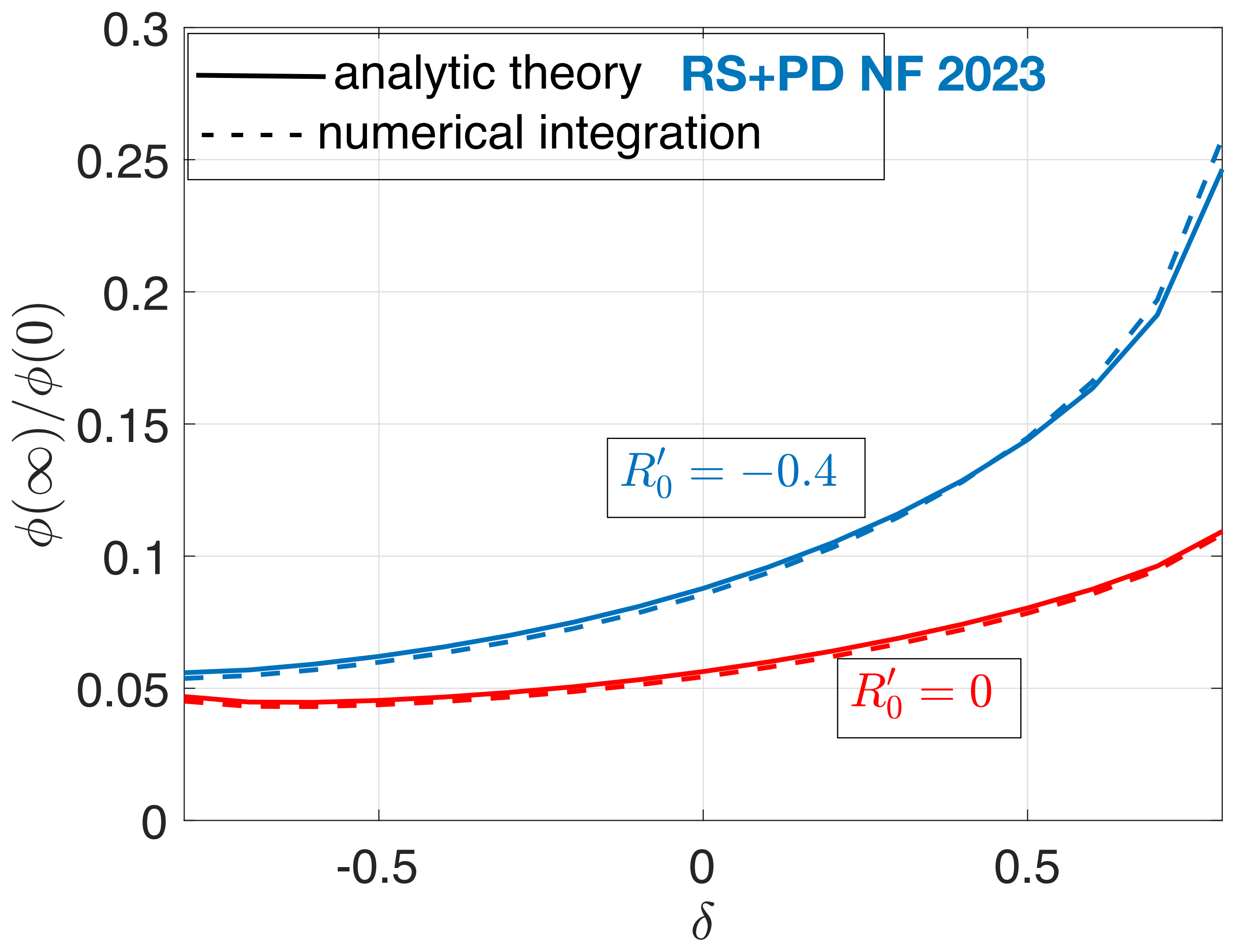
Motivation

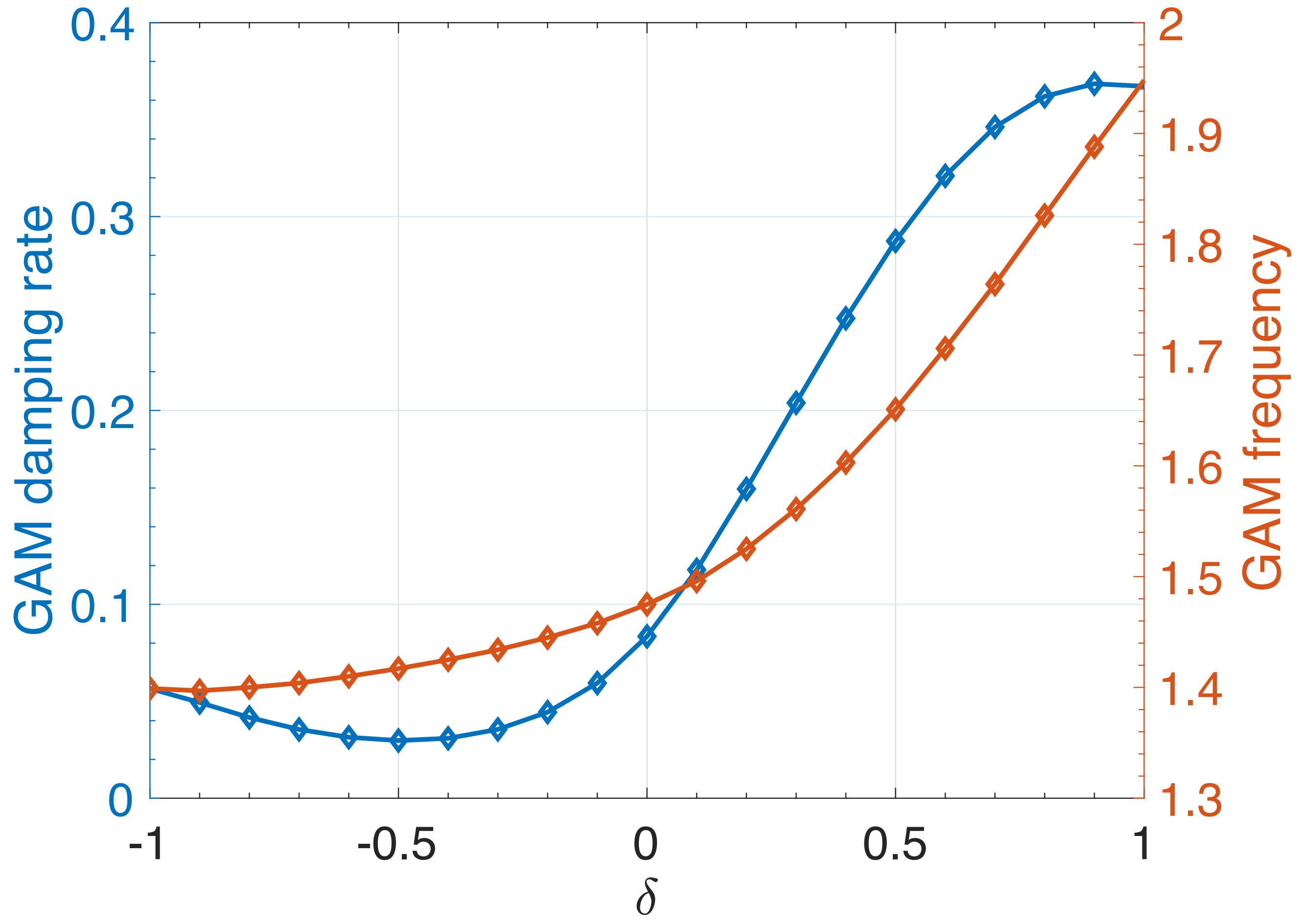
- Improved confinement in NT tokamaks experiments is now well established. [Y Camenen+ NF 2007, M Austin+ PRL 2019, A Marinoni+ 2019]

- Theoretical understanding lacking!
  - TEM stabilization by precession drift reduction [A Marinoni+ 2009]
  - ITG turbulence and transport with NT are poorly understood.

- Zonal flow residuals + GAM frequency and Landau damping rates are lower for NT than for PT. [RS+PD NF2023, FEC 2023]

- NT turbulence saturation by Zonal flow, GAM or both? Nonlinearly generated shear flow more relevant than residual !?



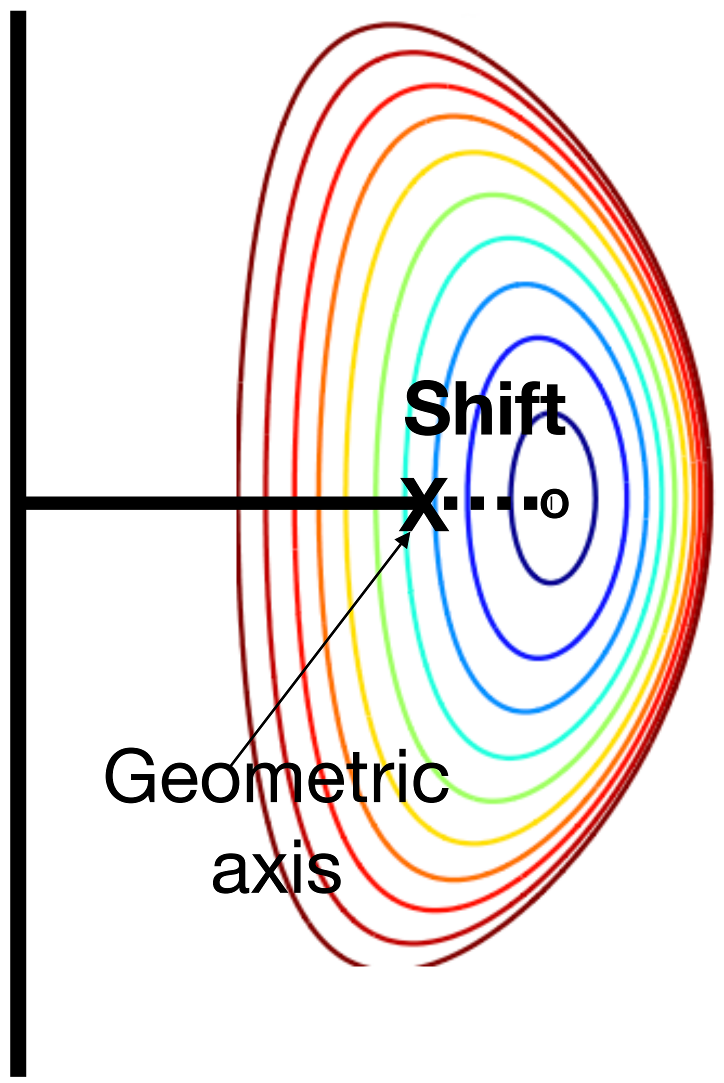


RS+PD FEC 2023

Motivation

- High dimensionality of shaping parameters space.
  - Coupled shaping parameters!
  - Important to isolate the effect of shaping parameters, one at a time.

- Here focus on **interaction of triangularity and Shafranov shift gradient on ITG turbulence saturation, transport and nonlinearly generated zonal flow shearing** using the GENE code.



- Shafranov shift gradient→ differential shift of the magnetic flux surfaces due to the plasma pressure and the hoop force from the toroidal plasma current. → flux compression.

- Shafranov shift gradient $R_0' \propto -\frac{r}{R_0}\beta_p$, thus $\alpha_{MHD} = -q^2 R \frac{d\beta}{dr}$ and R_0' are dynamically related by plasma beta but they are NOT same.
  - Stabilizing effect of α_{MHD} is well know [M Beer+ PoP 1997, S Ding+ PoP 2017, J McClenaghan+ PoP 2019, G M Staebler+ PoP 2017].
  - **Effects of interaction of R_0' and δ not well known for ITG turbulence.**

Key results

- Turbulent heat flux is lower for NT than for PT. Higher heat flux for any δ when $R_0' \neq 0$.

- All turbulent fluctuations $(n, T, v_{||})$ are lower for NT than for PT for $R_0' = 0$.

- $\omega - k$ spectra of zonal ExB shear show propagating finite frequency components. Total RMS shear dominantly from finite frequency components $0 < \omega \leq \omega_{GAM}$.

- Different δ-trends of zero frequency and total zonal shearing rates w or w/o Shafranov shift gradient!
  - $R_0' = 0$: Zero frequency shear higher for NT than for PT. Total shear decreases with $|\delta|$.
  - $R_0' \neq 0$: Both zero frequency and total shear lower for NT than for PT.

- Nonlinear shearing rates trend with δ is NOT always as expected from the residual calculations.
  - Possible Reason: Residual calculations do not account for Reynolds stress drive.
  - So, extrapolations based on residuals should be taken with caution.

Simulations set up

- GENE flux tube simulations of collisionless ITG turbulence with adiabatic electrons.

- **Shaping parameters:** aspect ratio $a/R = 1/3$, safety factor $q = 2$, magnetic shear $\hat{s}$=1, triangularity $\delta = [varied]$, triangularity gradient $S_\delta = \frac{r\frac{\partial\delta}{\partial r}}{1-\delta^2} = \frac{\delta}{1-\delta^2}$, elongation $\kappa = 1$, elongation gradient $S_\kappa = \frac{r}{\kappa}\frac{\partial\kappa}{\partial r} = 0$, squareness ζ=0, squareness gradient $S_\zeta = r\frac{\partial\zeta}{\partial r} = 0$, MHD alpha parameter $\alpha_{MHD} = -q^2R\frac{d\beta}{dr} = 0$, Shafranov shift gradient $R_0' = [0, -0.4]$.

- **Resolutions:** $n_x = 257$, $n_{k_y} = 48$, $n_z = 64$, $n_{v_\parallel} = 48$, $n_\mu = 8$, $L_{v_\parallel} = 3$, $L_\mu = 9$, $L_x = [120-140]\rho_i$, $k_{y,min}\rho_i = 0.05$, hyp_z=2, hyp_v=0.2

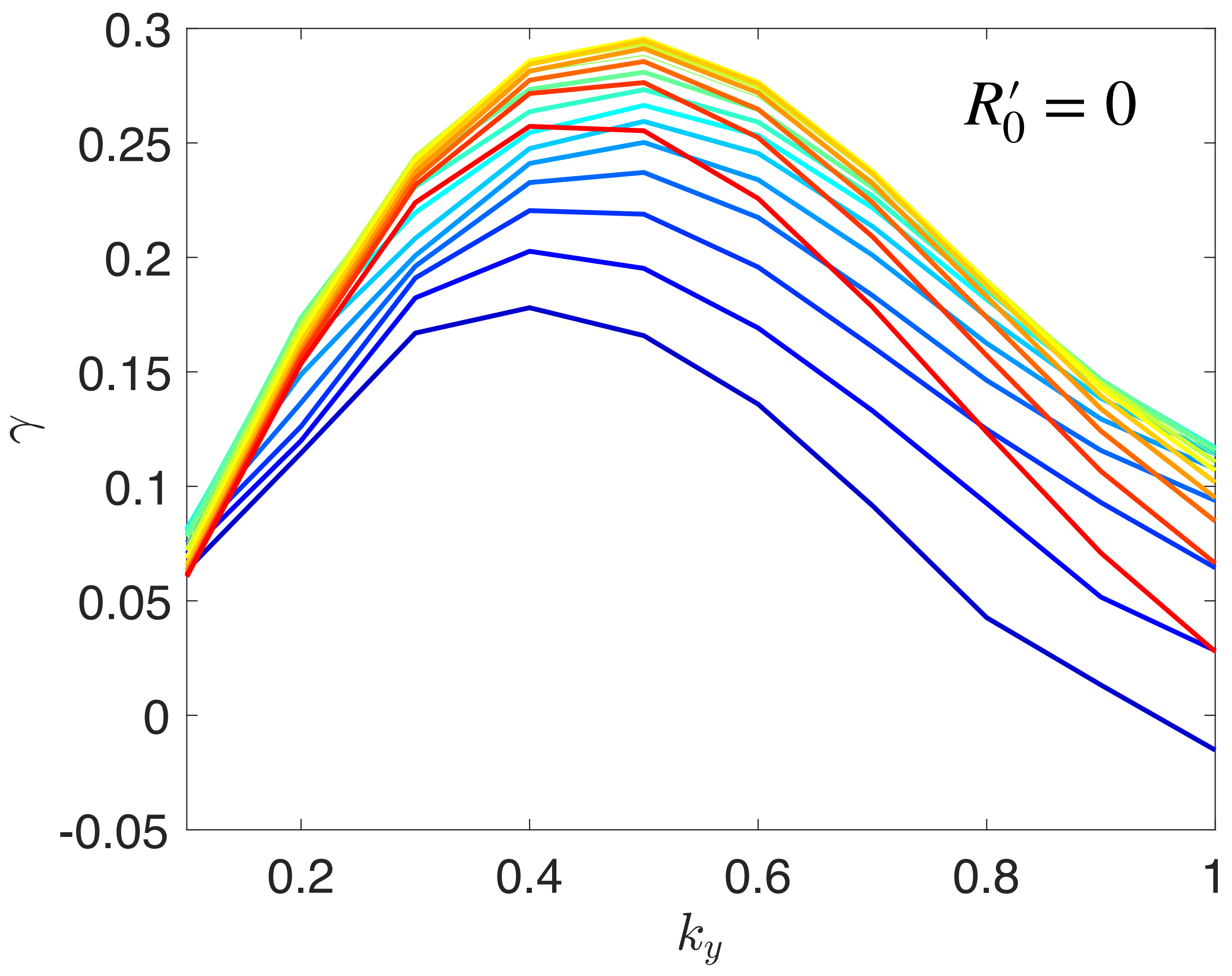
- **Gradients:** $a/L_n = 1$, $a/L_T = [4,6]$

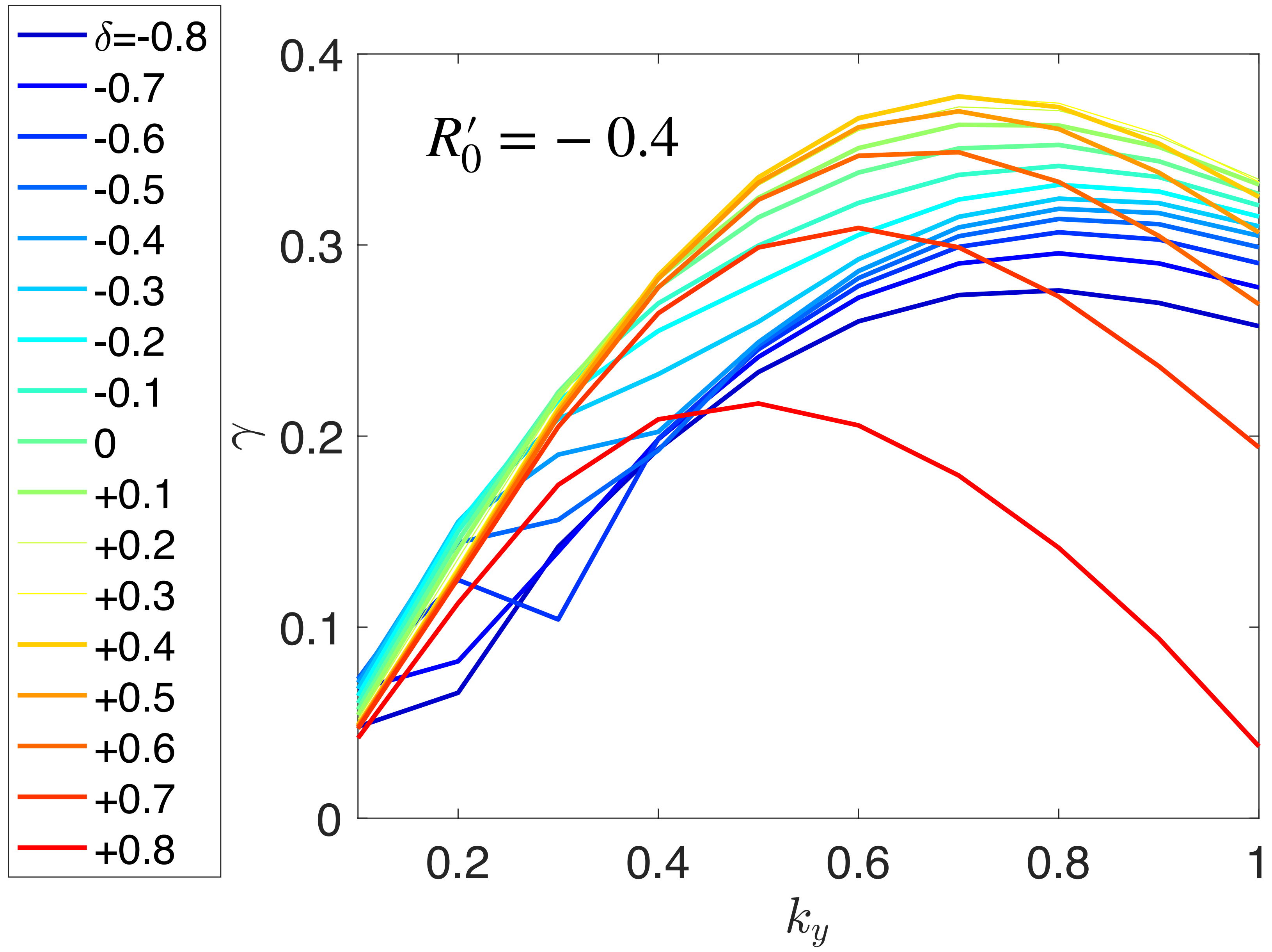
Linear results

- Growth rate spectra:

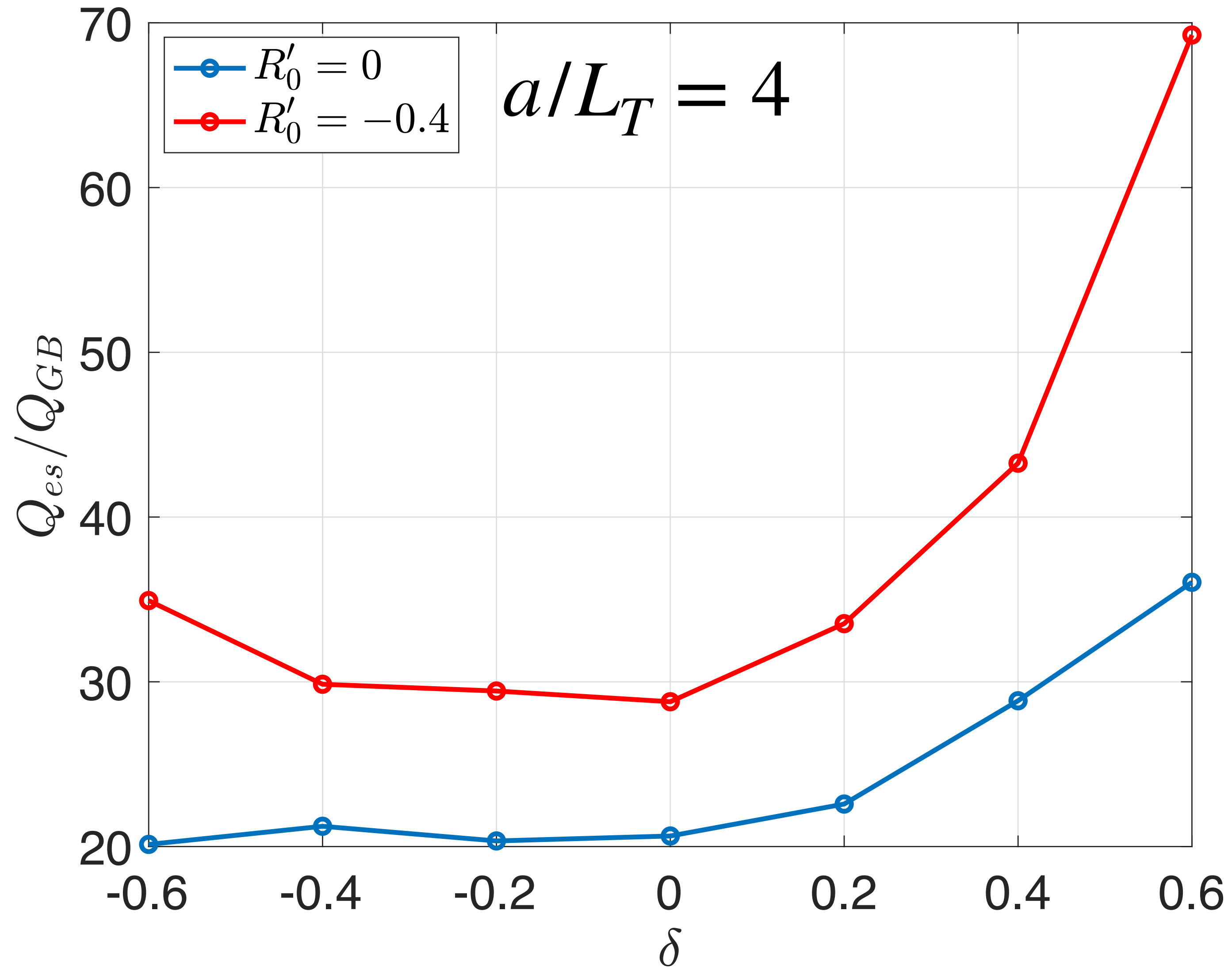
- **Zero Shafranov shift gradient:** Growth rates are lower for NT than for PT.

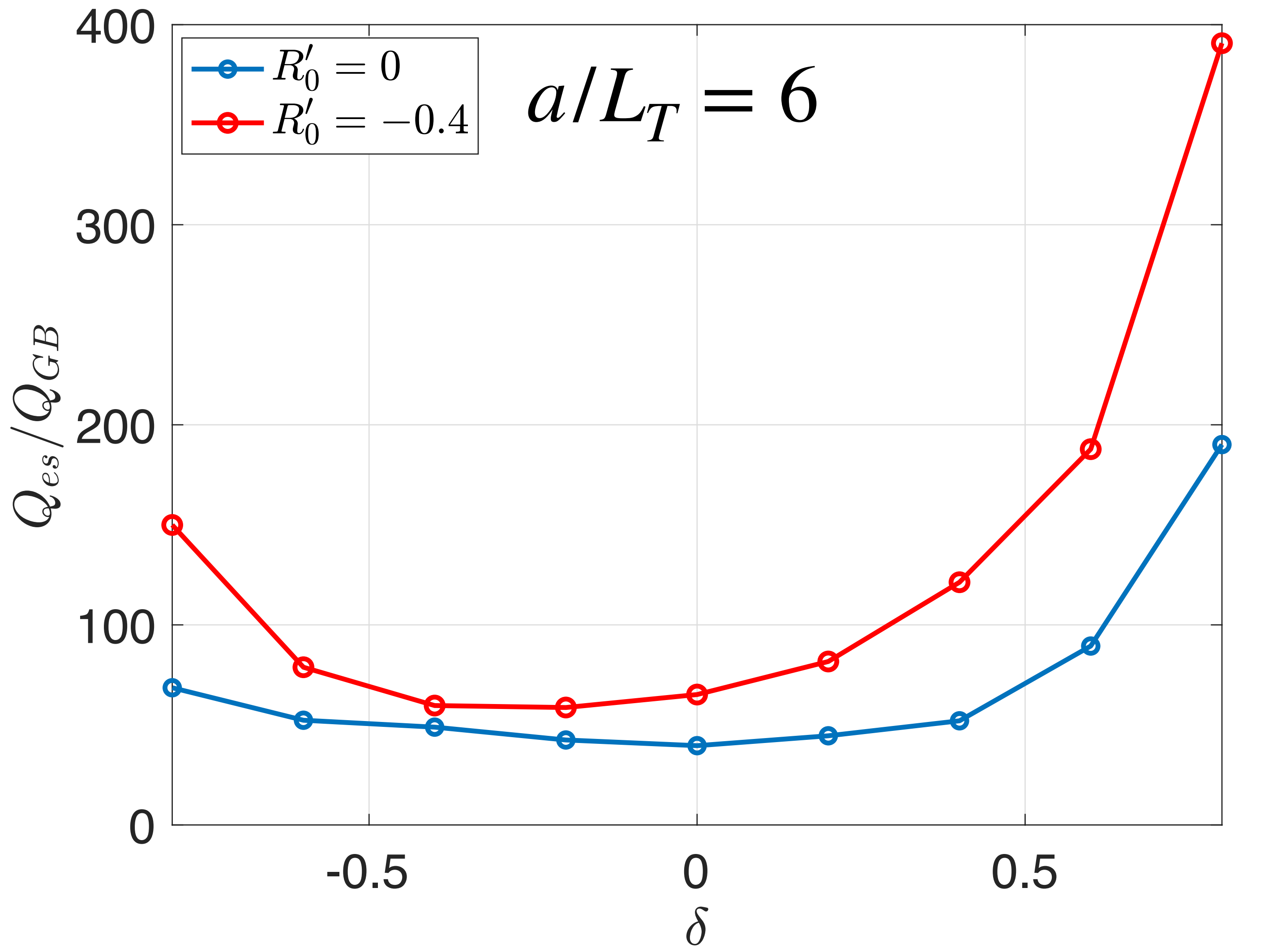
- **Finite Shafranov shift gradient:**
  - At small $|\delta|$,
    - growth rates are smaller for NT than for PT.
    - Growth rate peak moves towards high k_y.
    - Instability window expands to sub-larmor radius scales i.e., $k_y\rho_i > 1$.
  - At large $|\delta|$,
    - low k_y growths are smaller for NT than for PT; high k_y growths are higher for NT than for PT.



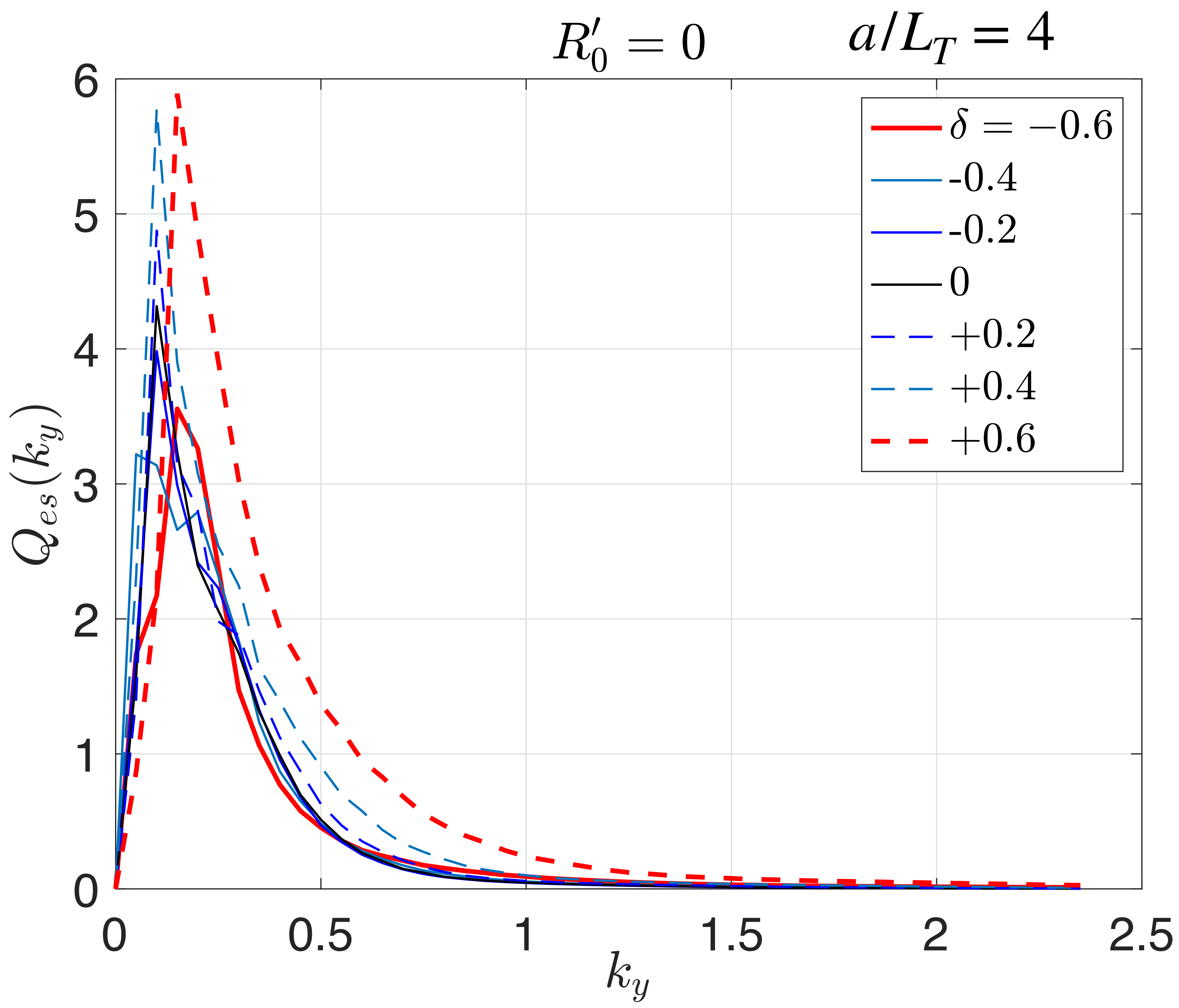


Nonlinear Heat flux vs Triangularity





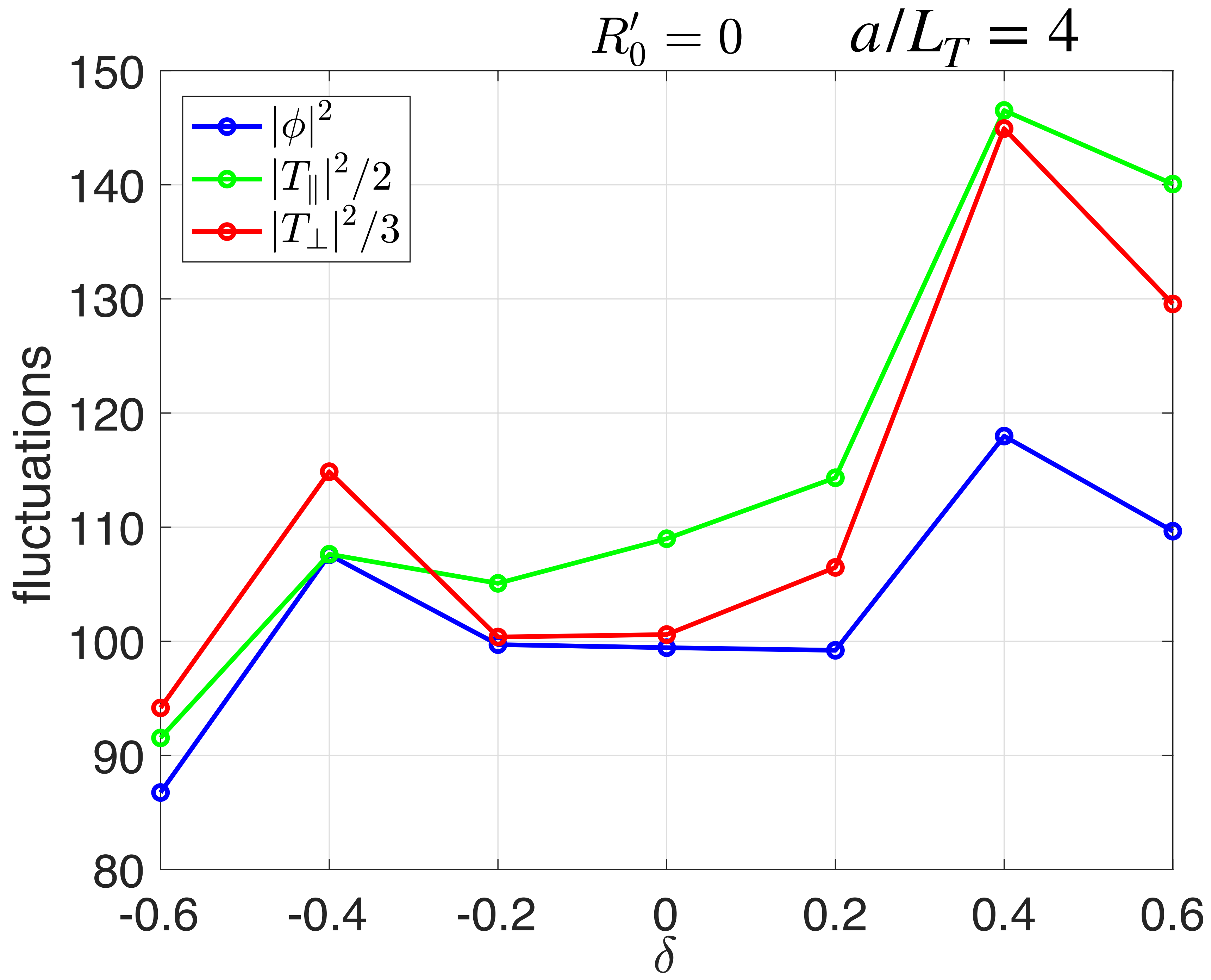
- Heat flux increases with $|\delta|$ but generally heat flux is lower for NT than for PT.
- Heat flux is higher at finite shafranov shift gradient R_0' for any triangularity.
- High k_y contributions to heat flux is higher for PT than for NT.

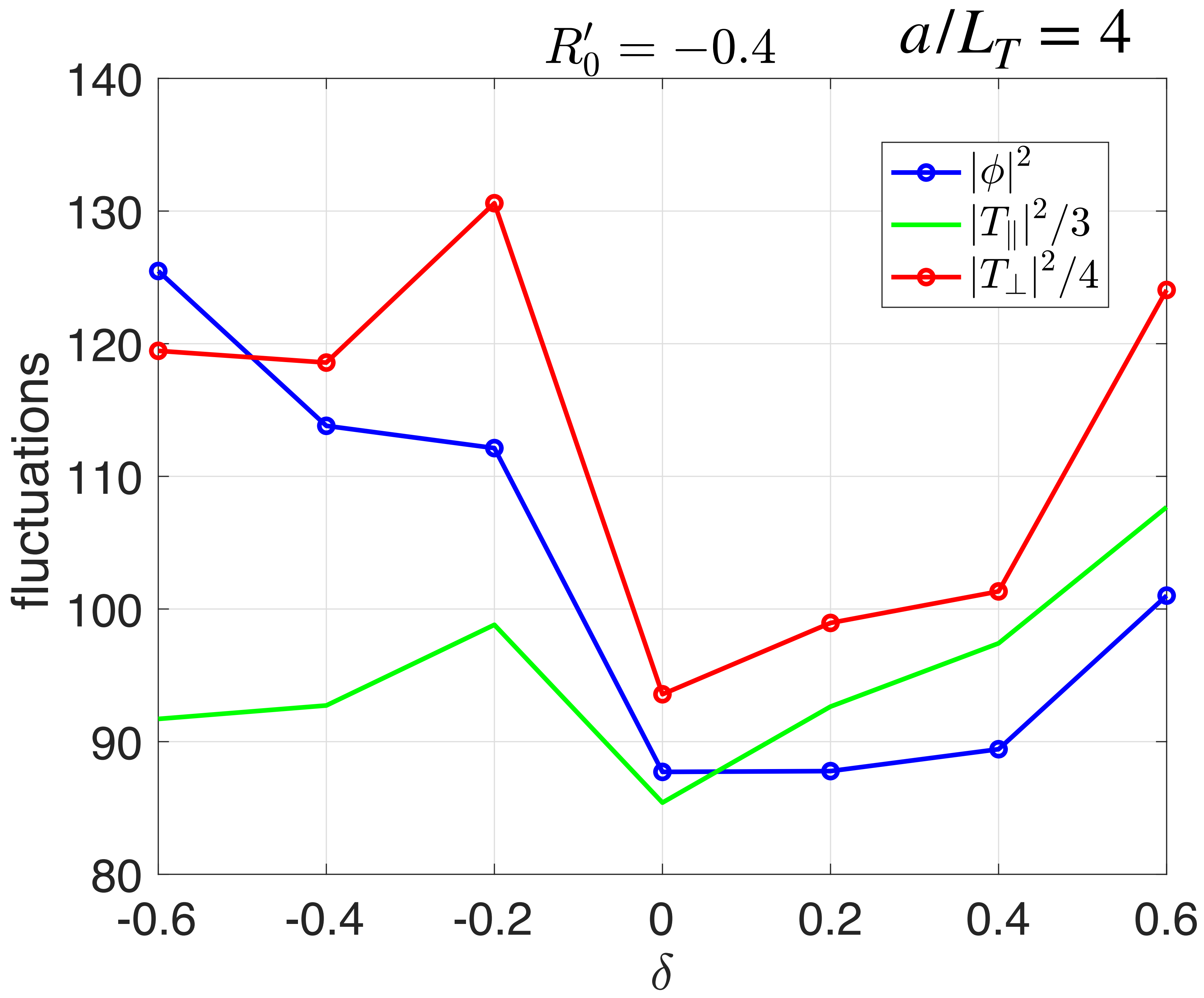


Saturated fluctuation intensity vs Triangularity

- Fluctuations are lower for NT than for PT for $R_0' = 0$. Cross phase dependency on δ weaker.

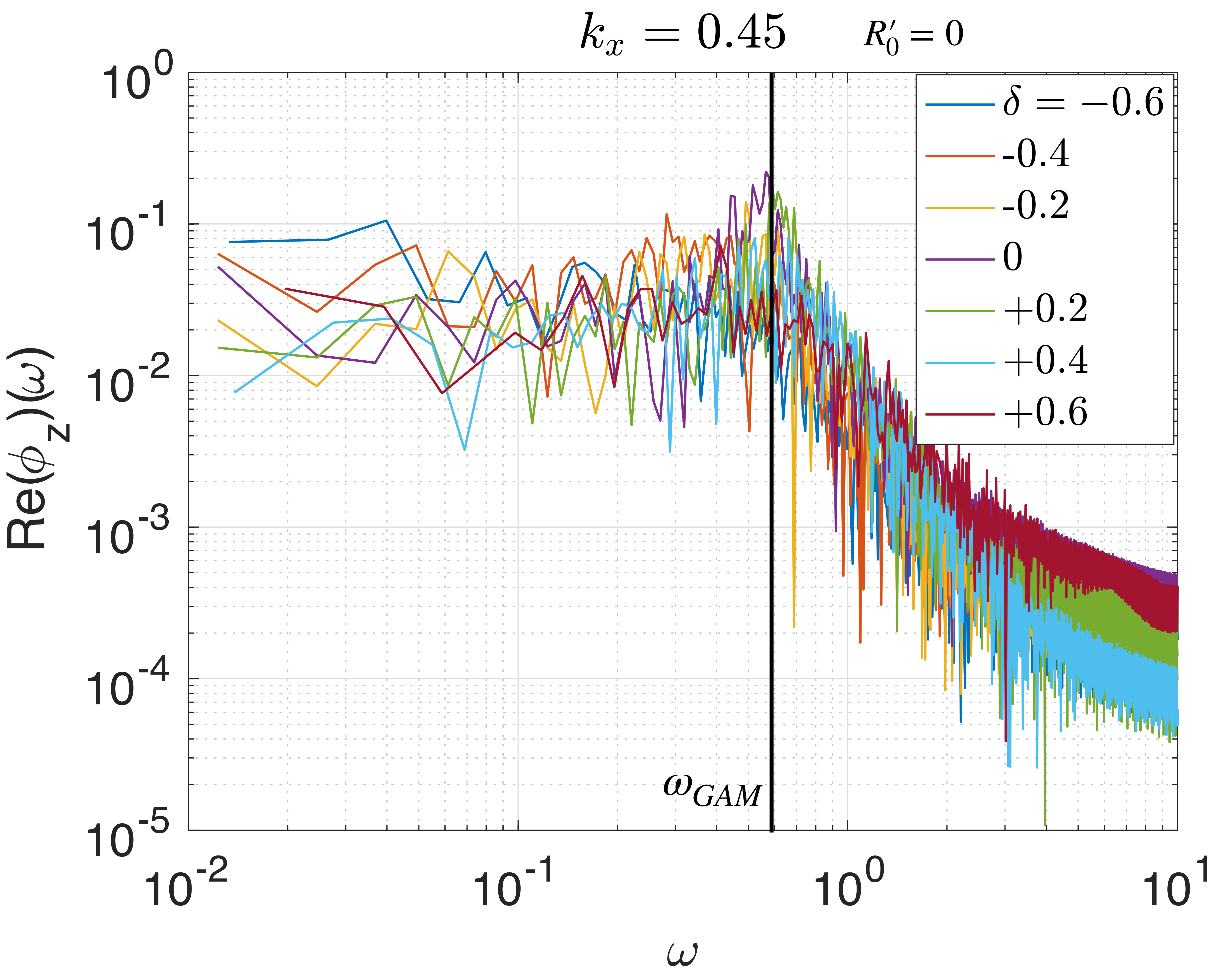
- Fluctuations are higher for NT than for PT for $R_0' = -0.4$. Yet heat flux is lower for NT than for PT. —>Effect of δ on cross phase must be stronger at finite $R_0' \neq 0$.





Zonal ExB shearing rates: $\omega - k$ spectra

- The spectra roll over at ~GAM frequency → all frequencies up to the GAM frequency matters for total shearing effect!



Relative contributions of zero frequency and finite frequency zonal components

- Most of the spectrum is dominated by finite frequency components.

- Zero frequency zonal components are dominant only towards the low k_x side of the spectrum.
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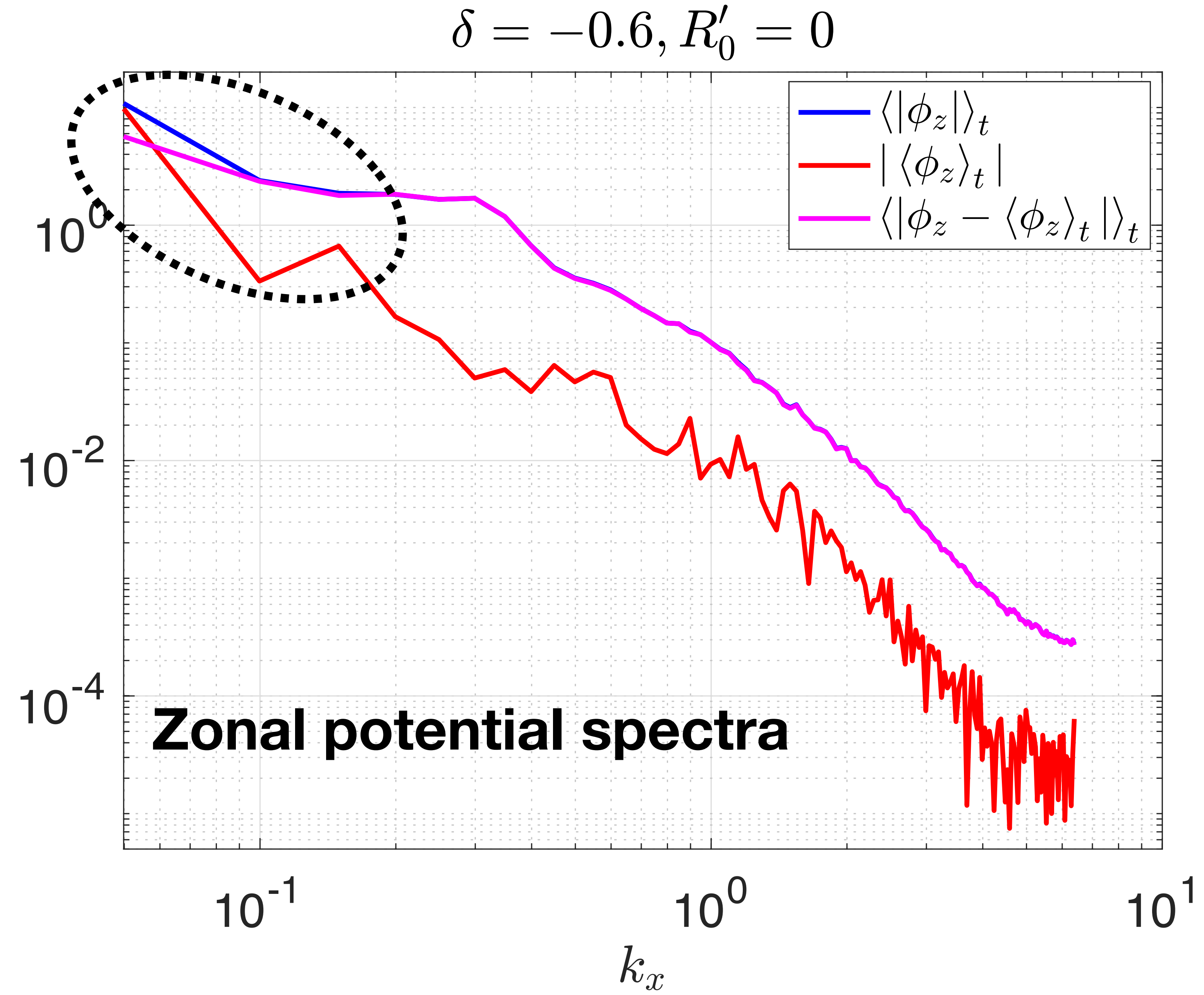
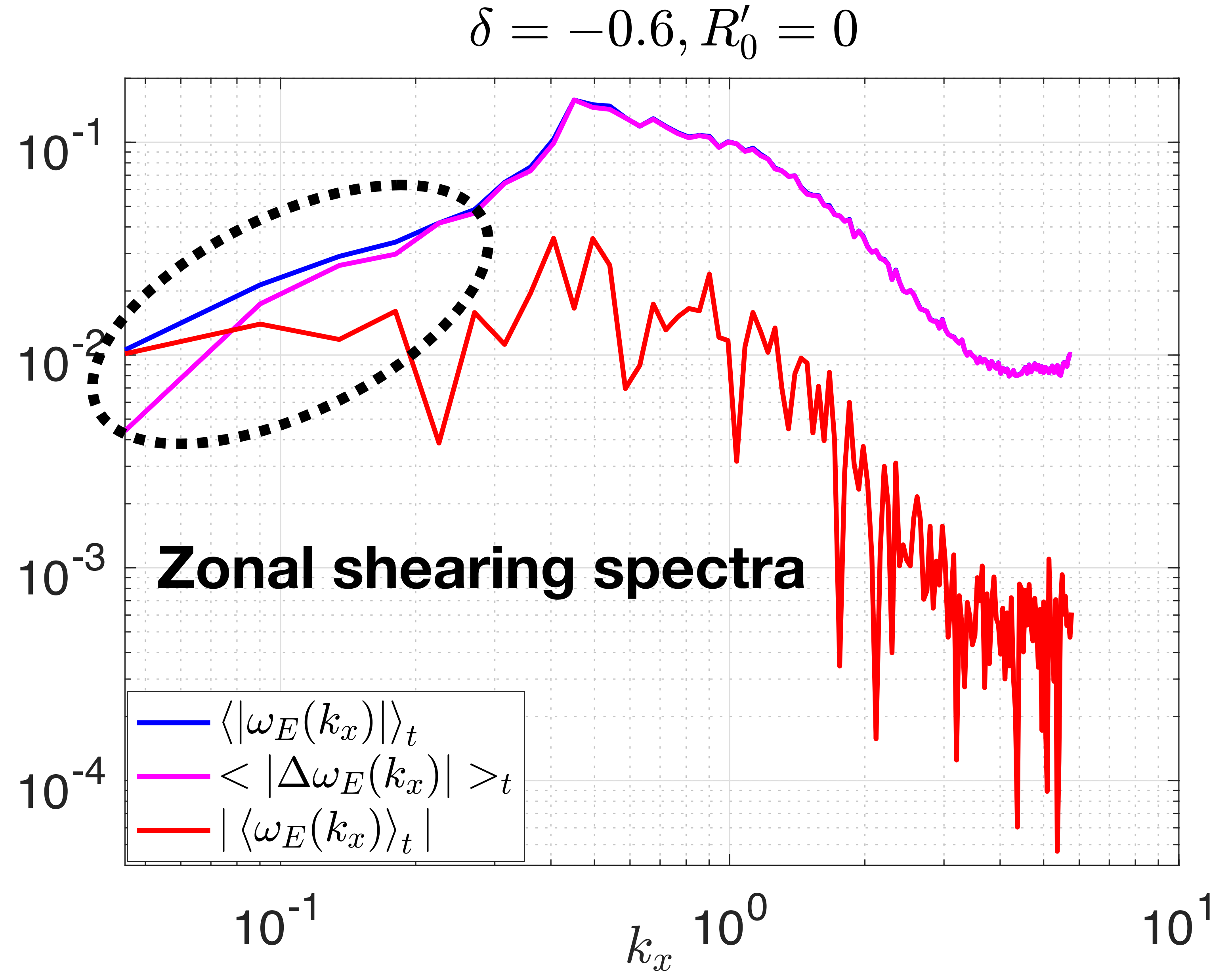
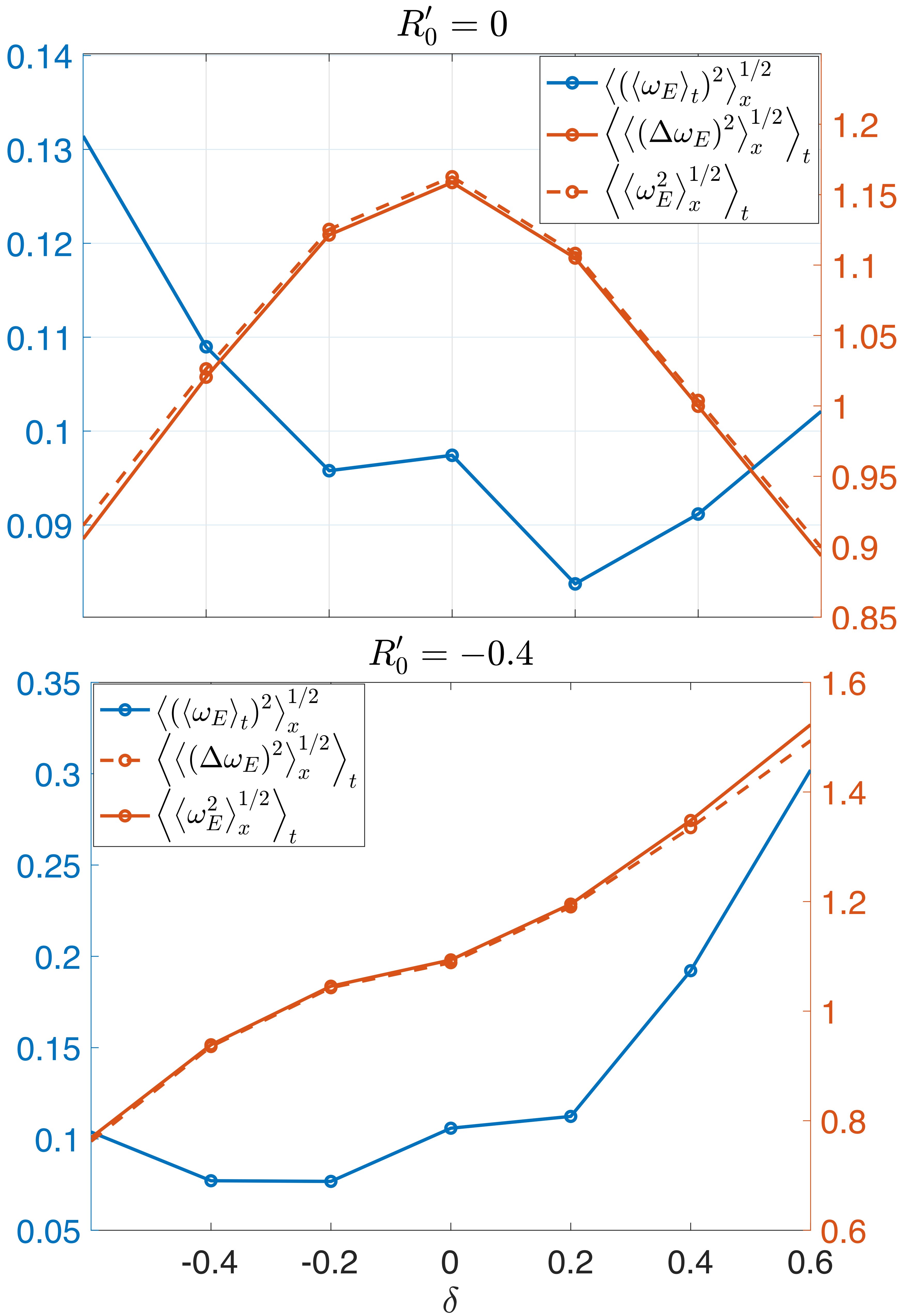




RMS Zonal ExB shearing rates at saturated state

- **Zero Shafranov shift gradient:**
  - Zero frequency shearing higher NT than for PT
  - Total and finite frequency shearing decreases with $|\delta|$.

- **Finite Shafranov shift gradient:**
  - Higher shearing than w/o Shafranov shift gradient !
  - Zero frequency shearing lower for NT than for PT
  - Total and finite frequency shearing increases with δ. Lower shearing for NT than for PT.



Summary

- Turbulent heat flux is lower for NT than for PT. Higher heat flux for any δ when $R_0' \neq 0$.

- Different δ-trends of turbulent fluctuations:
  - $R_0' = 0$: All fluctuations are lower for NT than for PT.
  - $R_0' \neq 0$: All fluctuations are higher for NT than for PT, and yet the heat flux is lower for NT.

- $\omega - k$ spectra of zonal ExB shear show propagating finite frequency components. Total shear dominantly from finite frequency components $0 < \omega \leq \omega_{GAM}$. Dispersive effects akin GAM seen.

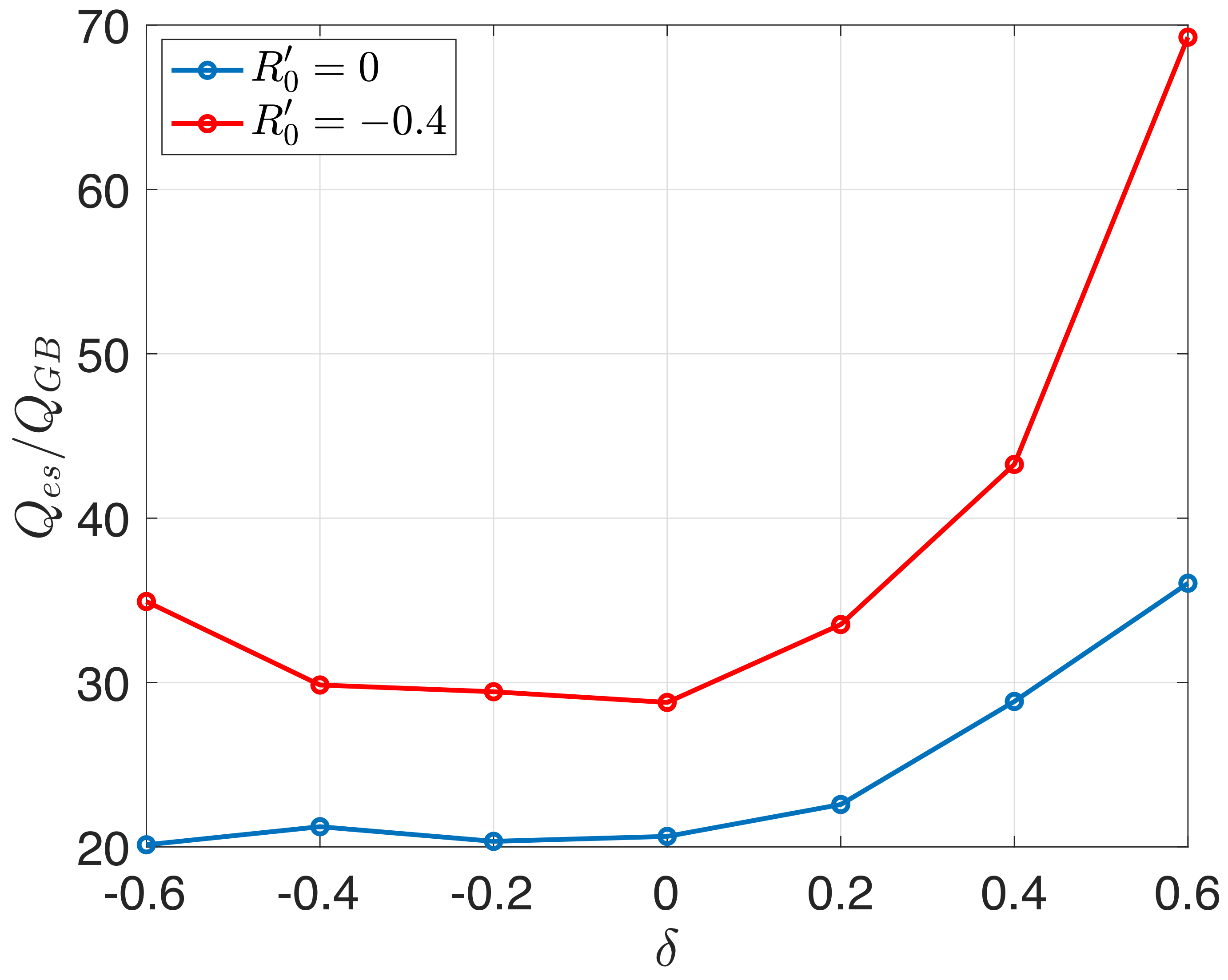
- Higher total shear for all δ when $R_0' \neq 0$.

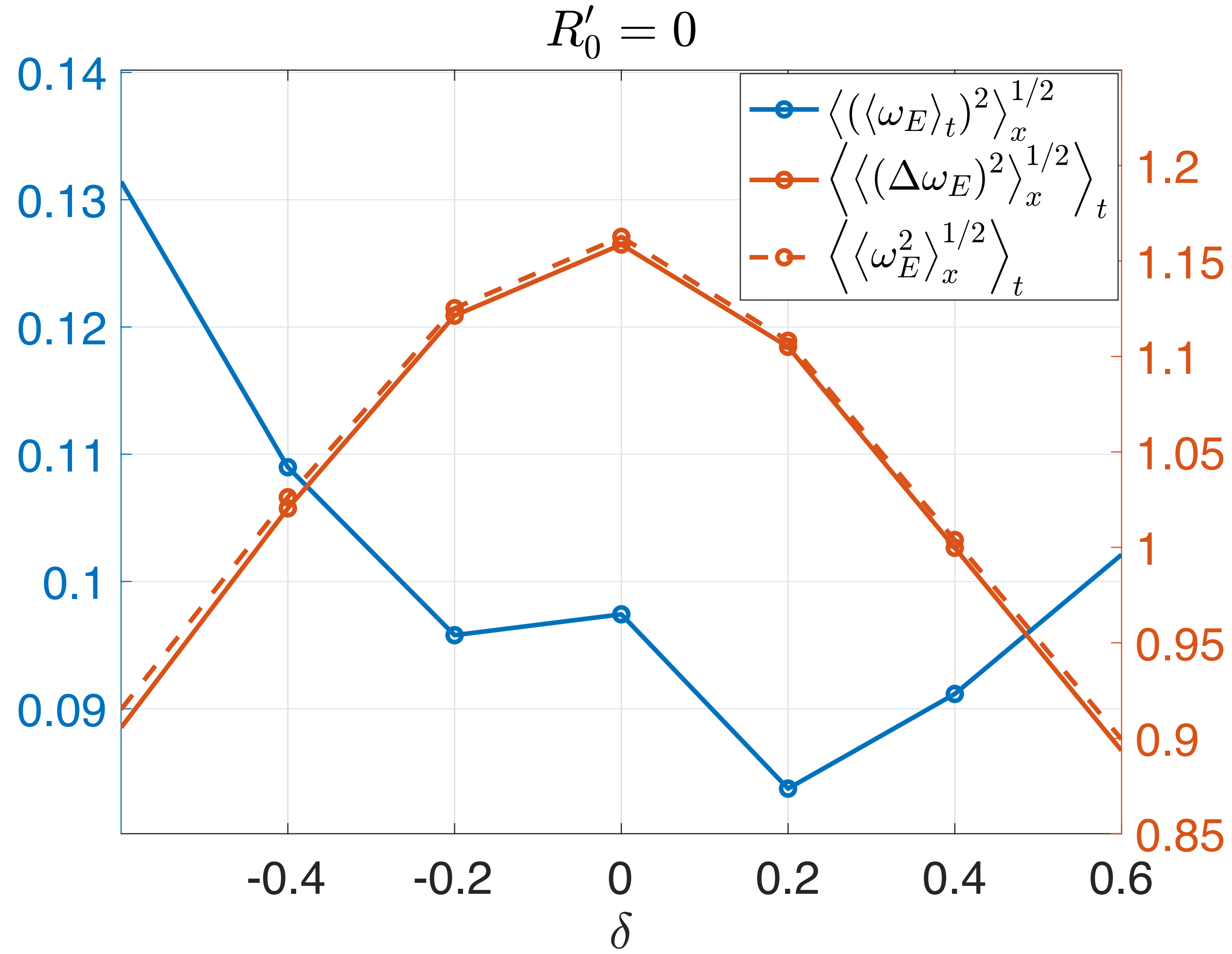
- Different δ-trends of zero frequency and total zonal shearing rates w or w/o Shafranov shift gradient!
  - $R_0' = 0$: Zero frequency shear higher for NT than for PT. Total shear decreases with $|\delta|$.
  - $R_0' \neq 0$: Both zero frequency and total shear lower for NT than for PT.

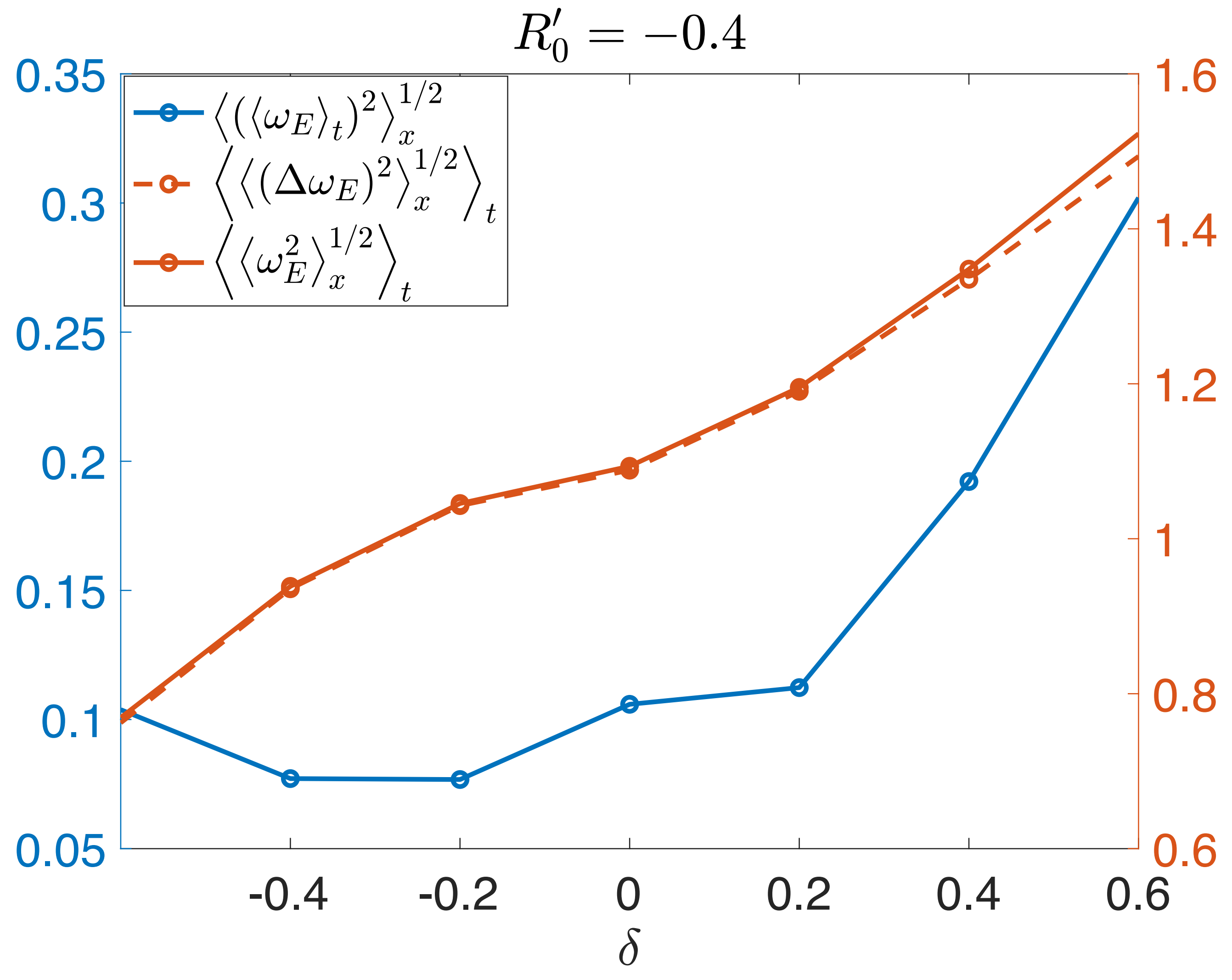
- Non-linear shearing rates trend with δ is NOT always as expected from the residual calculations.
  - Residual calculations do not account for Reynolds drive! So, extrapolations based on residuals should be taken with caution.

Future work

- **What we do not understand:**
  - Why is total shearing rate decreasing with $|\delta|$ when $R_0' = 0$ whereas, monotonically increasing from NT to PT when $R_0' \neq 0$? →requires analysis of Reynolds power $\frac{\partial \langle v_\theta \rangle}{\partial r} \langle \tilde{v}_r \tilde{v}_\theta \rangle$.
  - Why both heat flux and zonal shearing are increasing for PT with $R_0' \neq 0$? What happens to the feedback loop with $R_0' \neq 0$?
  - Why are fluctuations higher for NT than for PT when $R_0' \neq 0$ and yet heat flux is lower for NT? How is the transport transport cross-phase affected by combination of δ and R_0' ?







For experiments

- Should calculate $\omega - k$ spectra of the zonal flow. Identify finite frequency components? →BES velocimetry
- Reynolds power $\frac{\partial \left\langle v_\theta \right\rangle}{\partial r} \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$ vs triangularity comparison? →BES velocimetry
- Bi-spectra analysis to identify how dominant interactions change with triangularity ?

Back-up slides

- What is different from Duff and others?
  - New effect of Shafranov shift gradient.
  - Detailed zonal ExB shearing rate spectra analysis.
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