Geometric Dependencies of Mean ExB Shearing Rate in Negative Triangularity Tokamaks

[Singh, Diamond, Nelson *NF* 2023]

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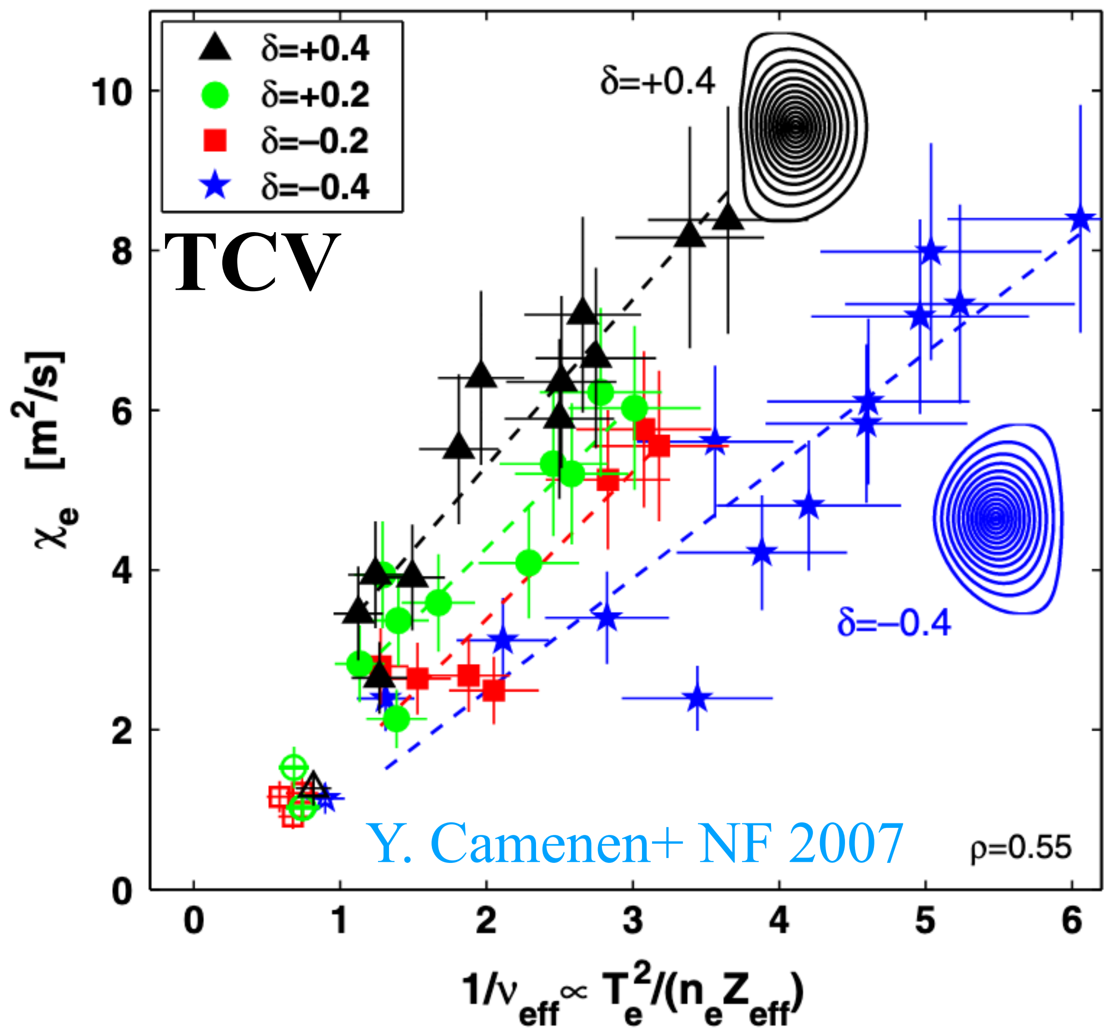
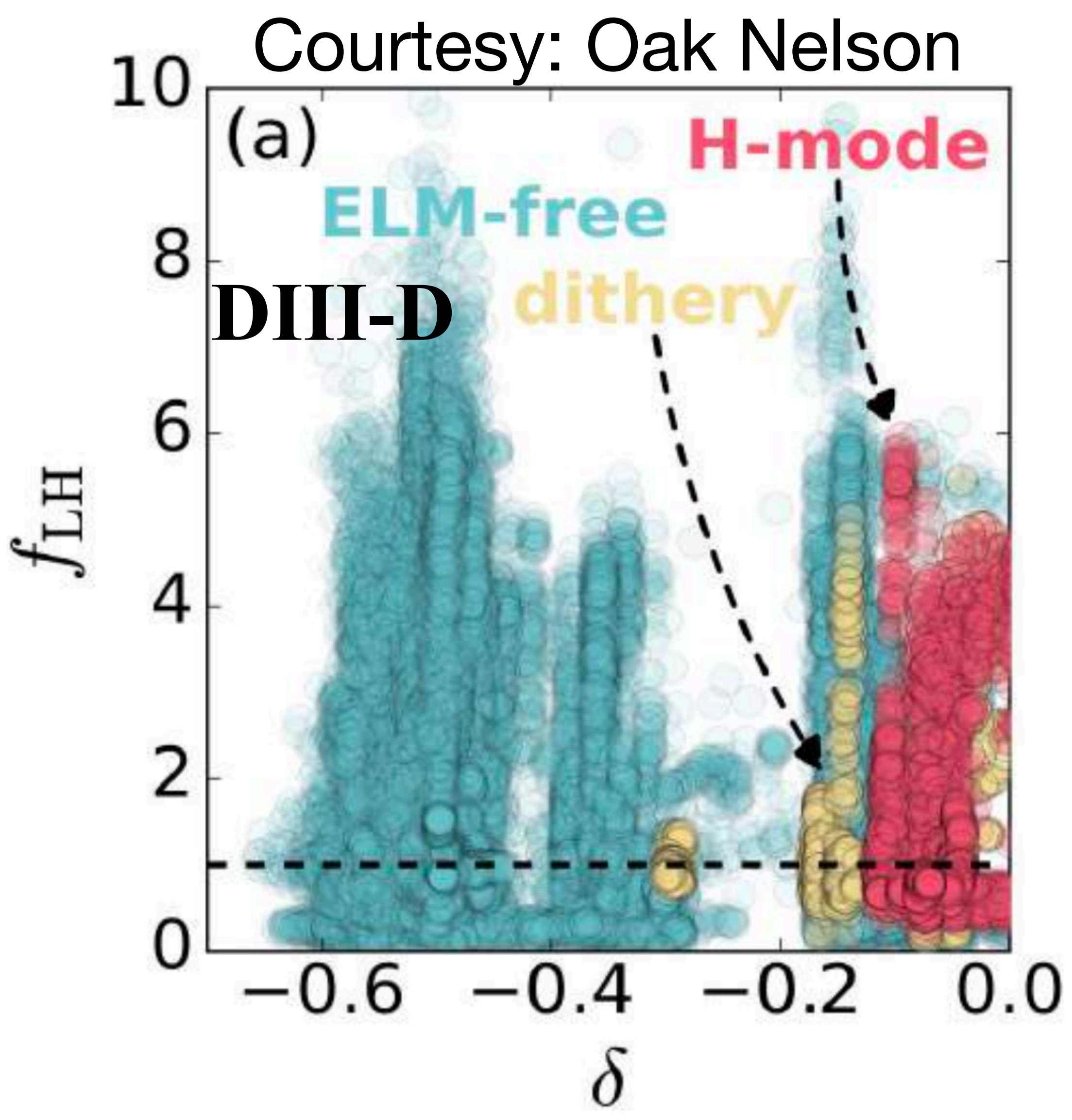
Effect of triangularity on confinement, fluctuations, and L-H transition

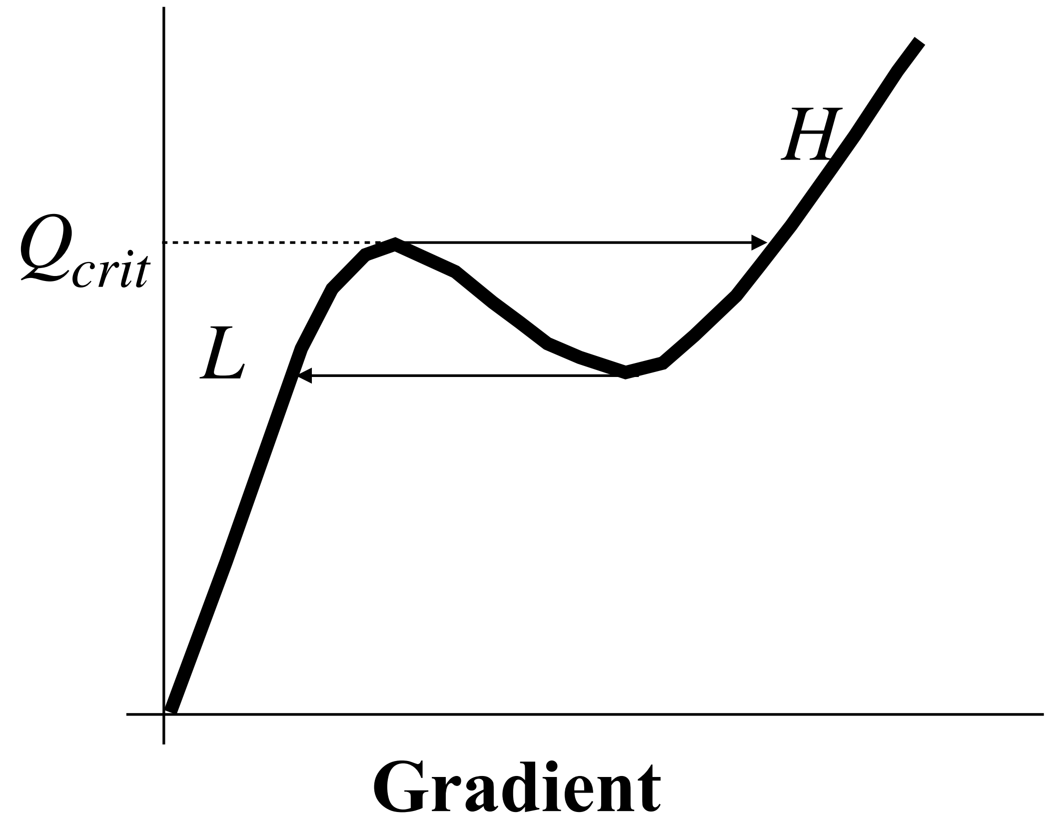
- TCV: Energy confinement time doubled, fluctuations reduced when $\delta \rightarrow -\delta$

- DIII-D: No H-mode transition for $\delta < \delta_{crit} \sim -0.18$
  - $P_{L \rightarrow H}$ diverges for $\delta < \delta_{crit}$.
  - loss of access to 2nd stability region of $n = \infty$ ideal MHD ballooning modes for $\delta < \delta_{crit}$ [Saarelma+ PPCF 2021, Nelson+ NF 2022].





- Is H mode operation always in 2nd stability region?
  - Magnetic separatrix + finite edge current → coalescence of 1st and 2nd stable region. [Bishop NF 1986]
  - H-mode persisted even after loss of 2nd stability. [L Lao + NF 1999, J R Ferron+ NF 2000]

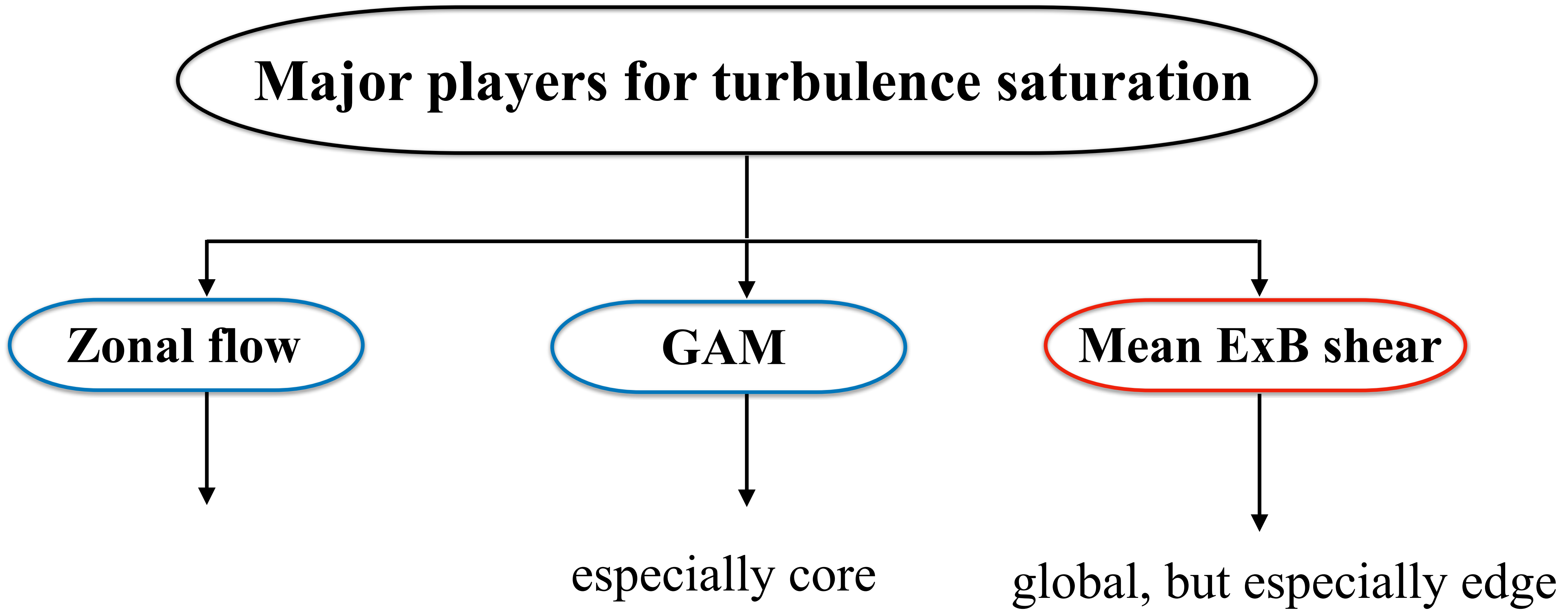


- What happens to the E_r' induced transport bifurcation picture of L-H transition in NT?

→ Role of mean ExB shear in NT pedestal formation?

How to reconcile confinement improvement in NT L-mode with diverging $P_{th,L\rightarrow H}$ for $\delta < \delta_{crit}$?

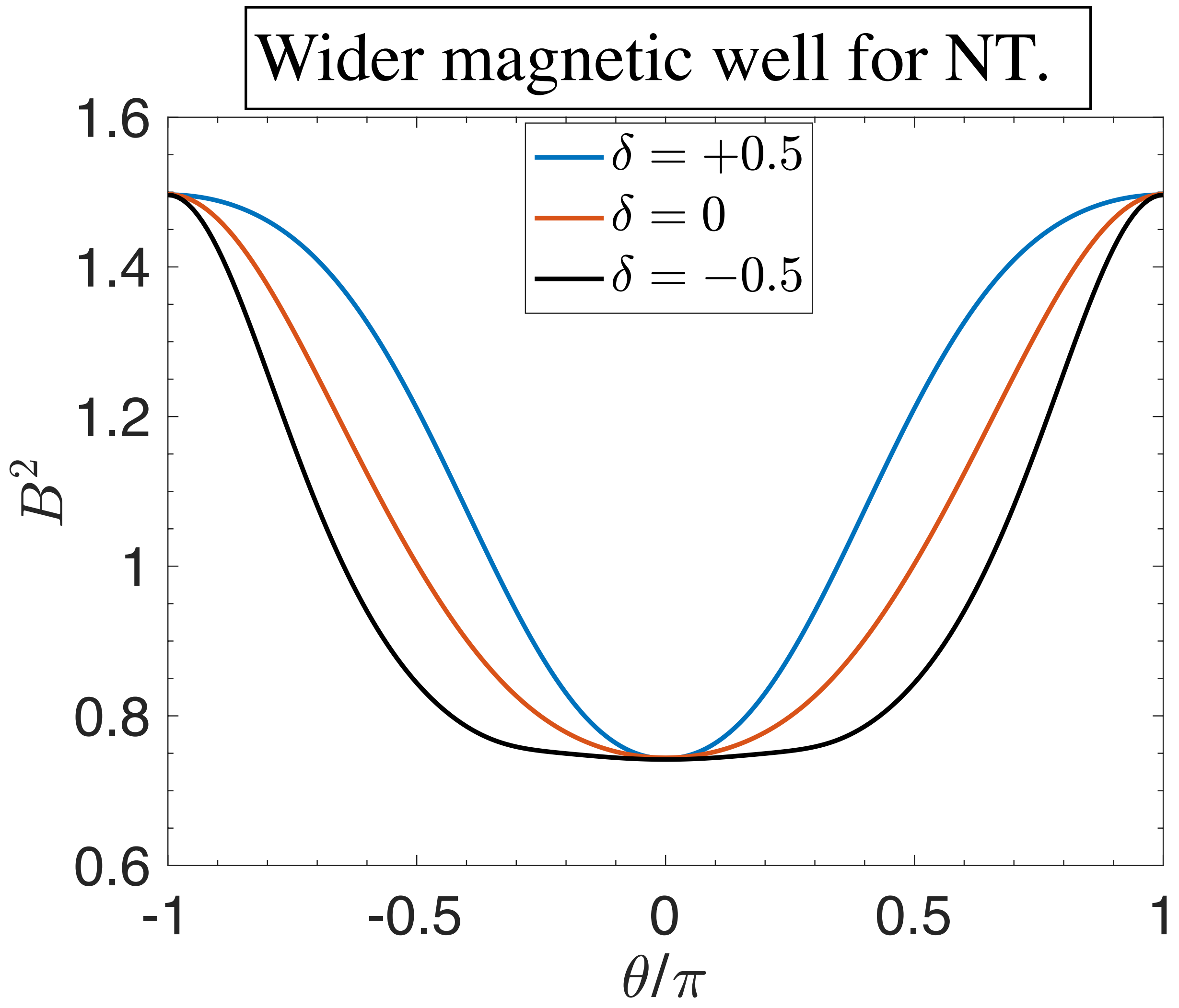
- Need think beyond linear stabilization of zoo of modes(TEM/ITG,…)!
- Understanding flux surface shaping effects on turbulence saturation mechanism is important.

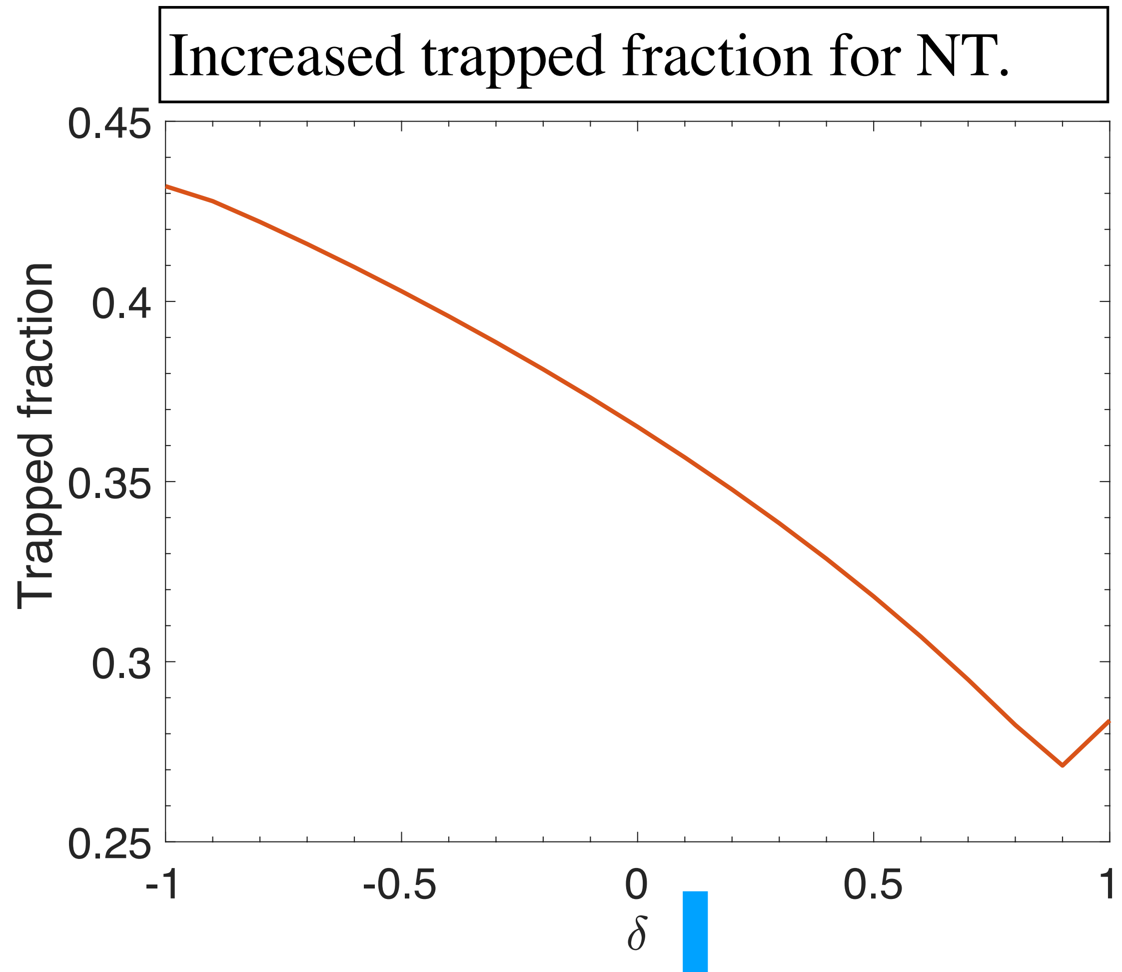


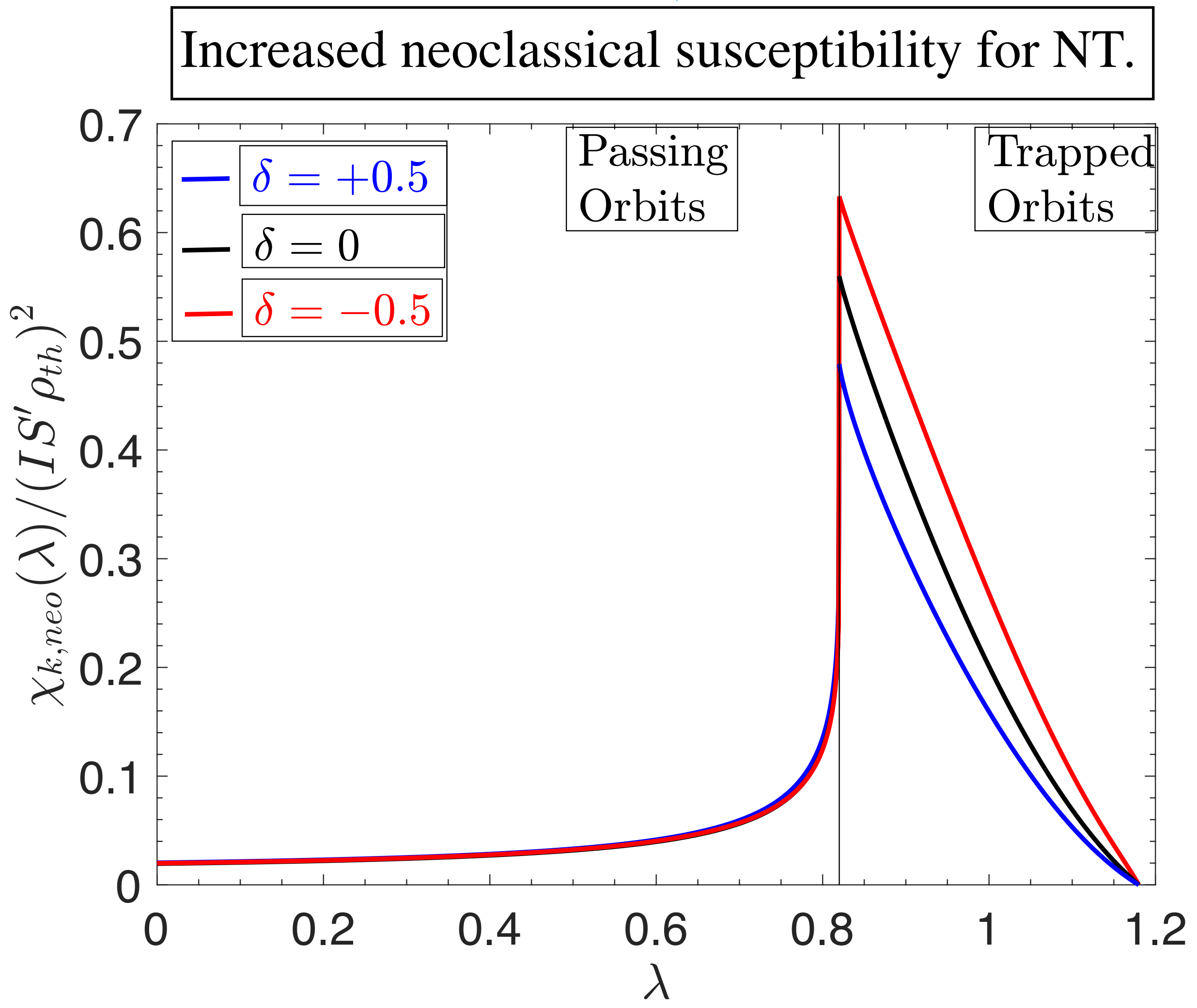
- *Interplay of NT configuration with secondary modes feedback and shearing*?

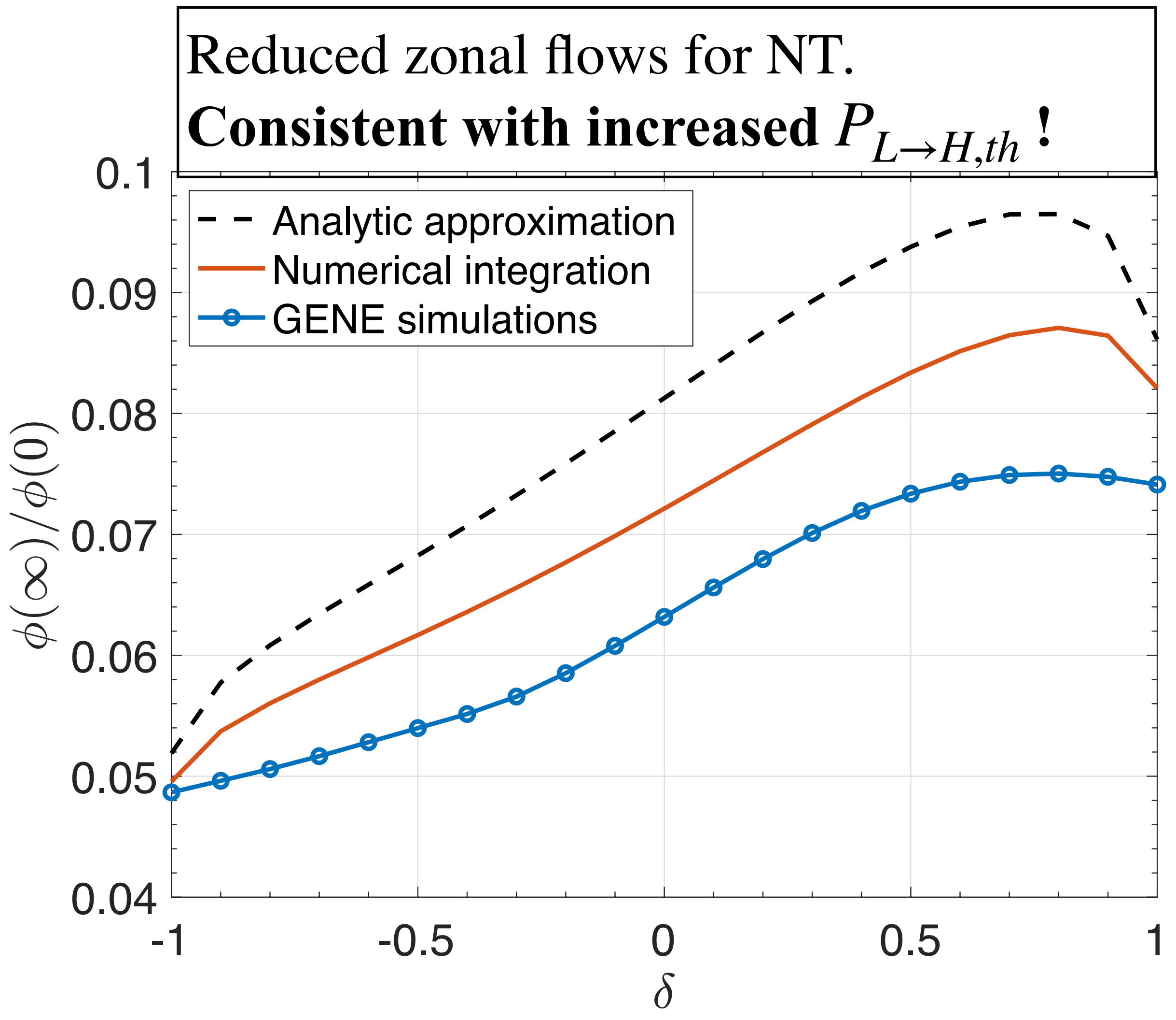
Zonal flows are reduced in NT

[Singh and Diamond NF 2022]









Wider magnetic well → increased trapped fraction → Stronger neoclassical screening → reduced zonal flows

Geometry dependence of mean ExB shearing rate ω_E

ExB shearing rate in general axisymmetric toroidal geometry obtained from a 2-point correlation calculation:

[Hahm & Burrell PoP 1995]

$$\omega_E = \left(\frac{\Delta\psi_0}{\Delta\zeta}\right)\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi),$$

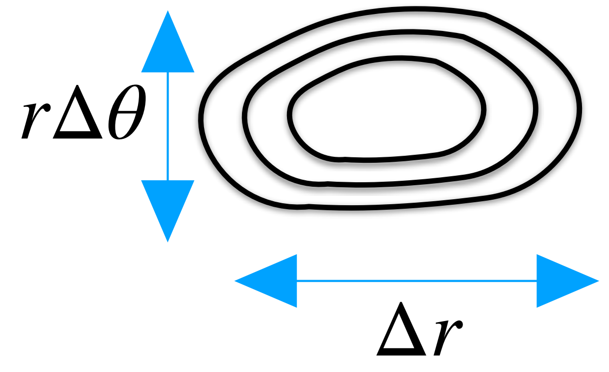
ψ:= poloidal flux $\quad$ ζ:= toroidal angle

Φ_0:= Mean electrostatic potential

$\Delta\psi_0$:=Turbulence correlation length in ψ

$\Delta\zeta$:=Turbulence correlation in toroidal angle ζ

- $\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi)$ is set by the radial force balance of ions - as usual!
- $\Delta\psi$ is related to turbulence radial correlation length Δr: $\Delta\psi = \Delta r\frac{\partial\psi}{\partial r}$, where ψ' is obtained from the definition of global safety factor q: $\psi' = \frac{I(\psi)}{2\pi q(\psi)}\oint d\theta\frac{\mathcal{J}}{R^2}$
- $\Delta\zeta$ is related to poloidal correlation angle $\Delta\zeta = \nu\Delta\theta$, where the local safety factor $\nu = \frac{I\mathcal{J}}{R^2\psi'}$
- Thus, $\omega_E = \frac{\Delta r}{\Delta\theta}\boxed{\frac{R^2\psi'^2}{I\mathcal{J}}}\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi),$



Geometry dependent factor

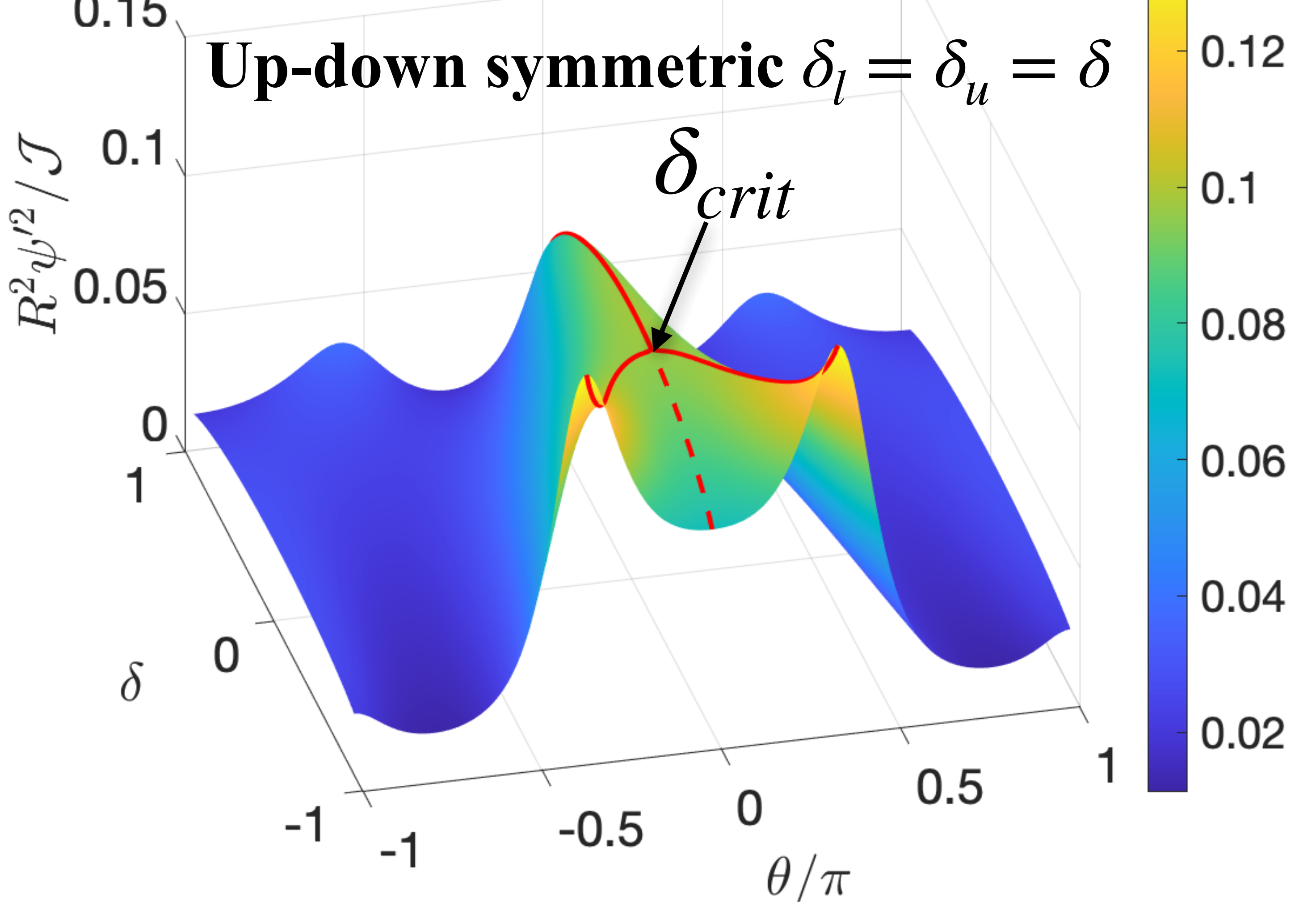
Calculated for Miller's equilibrium for **fixed** $\frac{\Delta r}{\Delta\theta}$ and $\frac{\partial^2}{\partial\psi^2}\Phi_0(\psi)$.

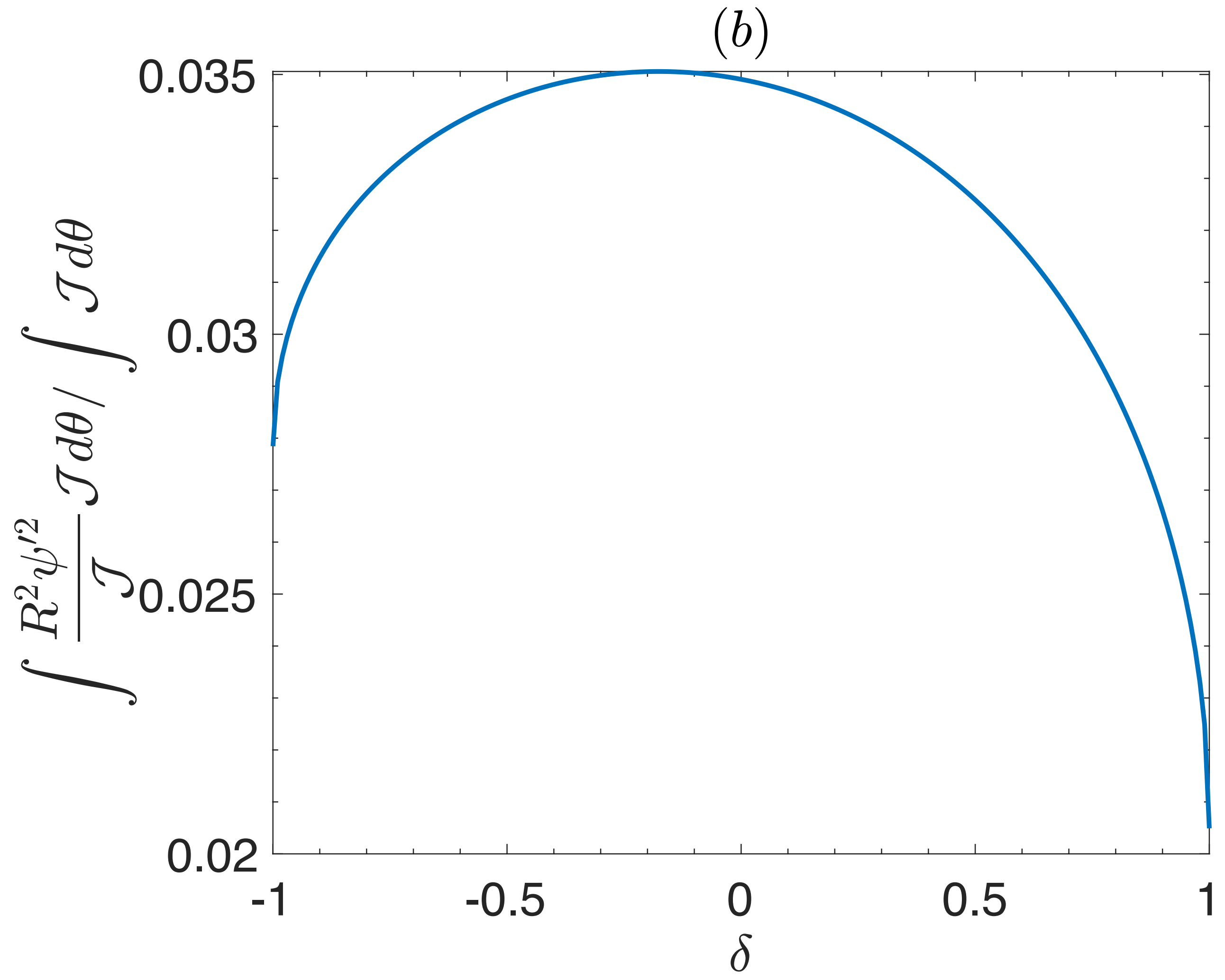
Variation of mean ExB shearing rate with triangularity δ

- **Maximum shear off the outboard mid-plane for for $\delta < \delta_{crit}$ (~NT)→** Shearing is less effective for $k_x = 0$ modes i.e, the modes ballooning at $\theta = 0$.

- **Shear at $\theta = 0$:**
  - $\downarrow$ with increasing NT.
  - Weaker for NT than for PT. Note that fluctuations balloon at $\theta = 0$. Thus, shearing efficiency $\downarrow \implies P_{L\rightarrow H,th} \uparrow$ (!?).

Geometric 'bifurcation' of shearing rate

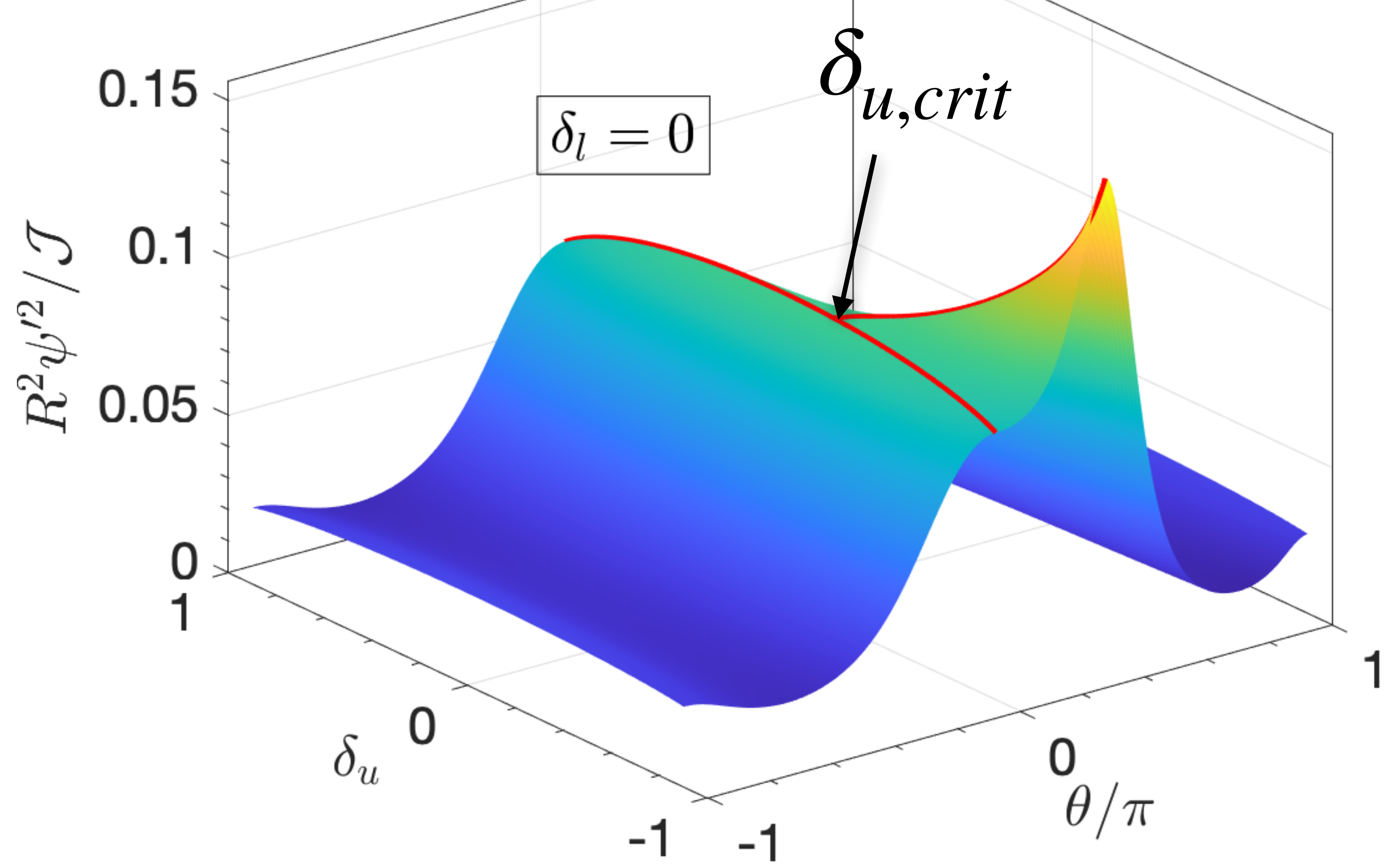




- Flux surface averaged shearing rate is higher for NT than for PT. -Global confinement ?!

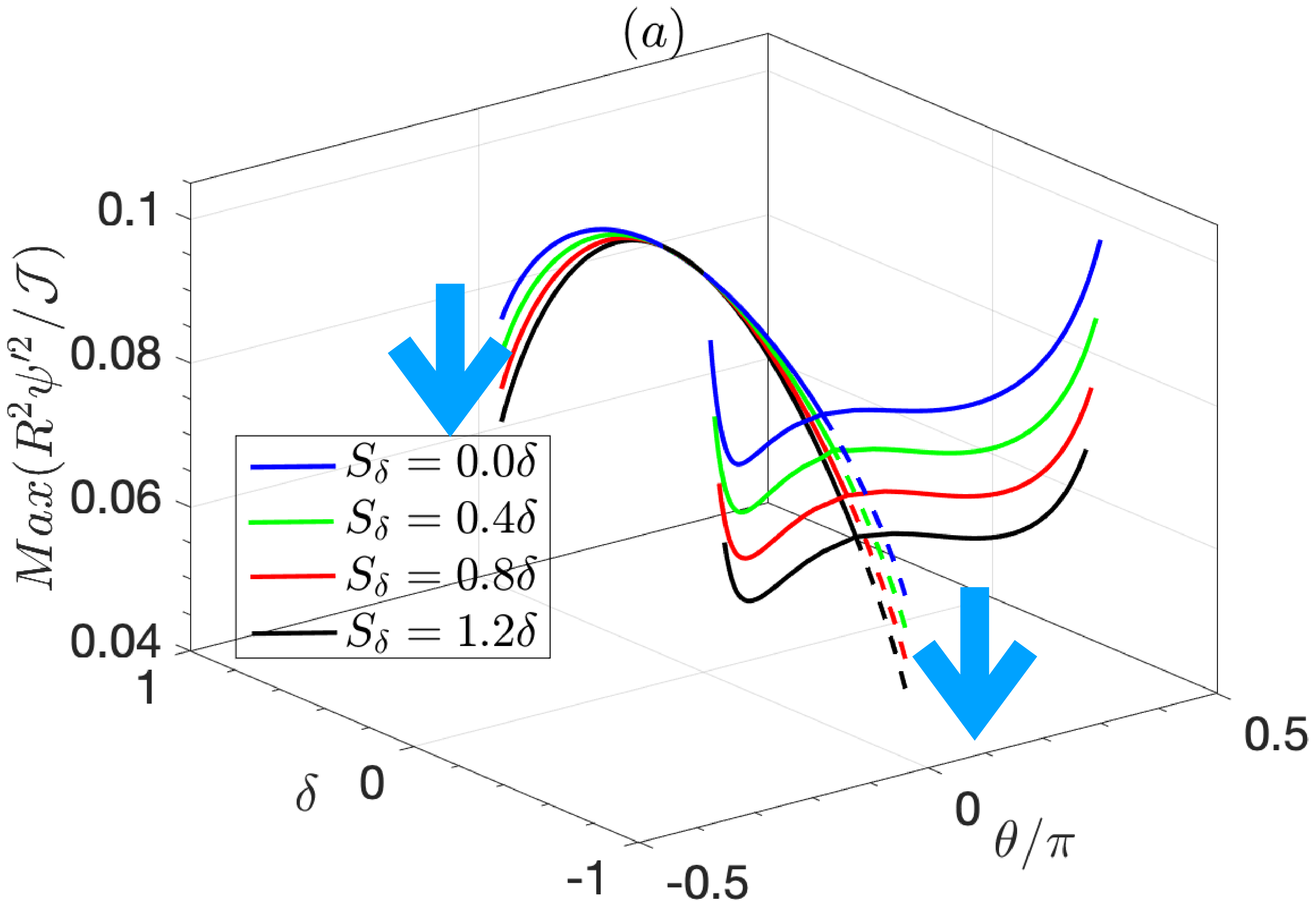
(b)

Up-down asymmetric $\delta_l \neq \delta_u$



- Maximum shear above the outboard mid-plane for for $\delta_u < \delta_{u,crit}$ & $\delta_l > \delta_u$

ExB shearing rate variations with triangularity gradient S_δ, elongation κ and elongation gradient S_κ

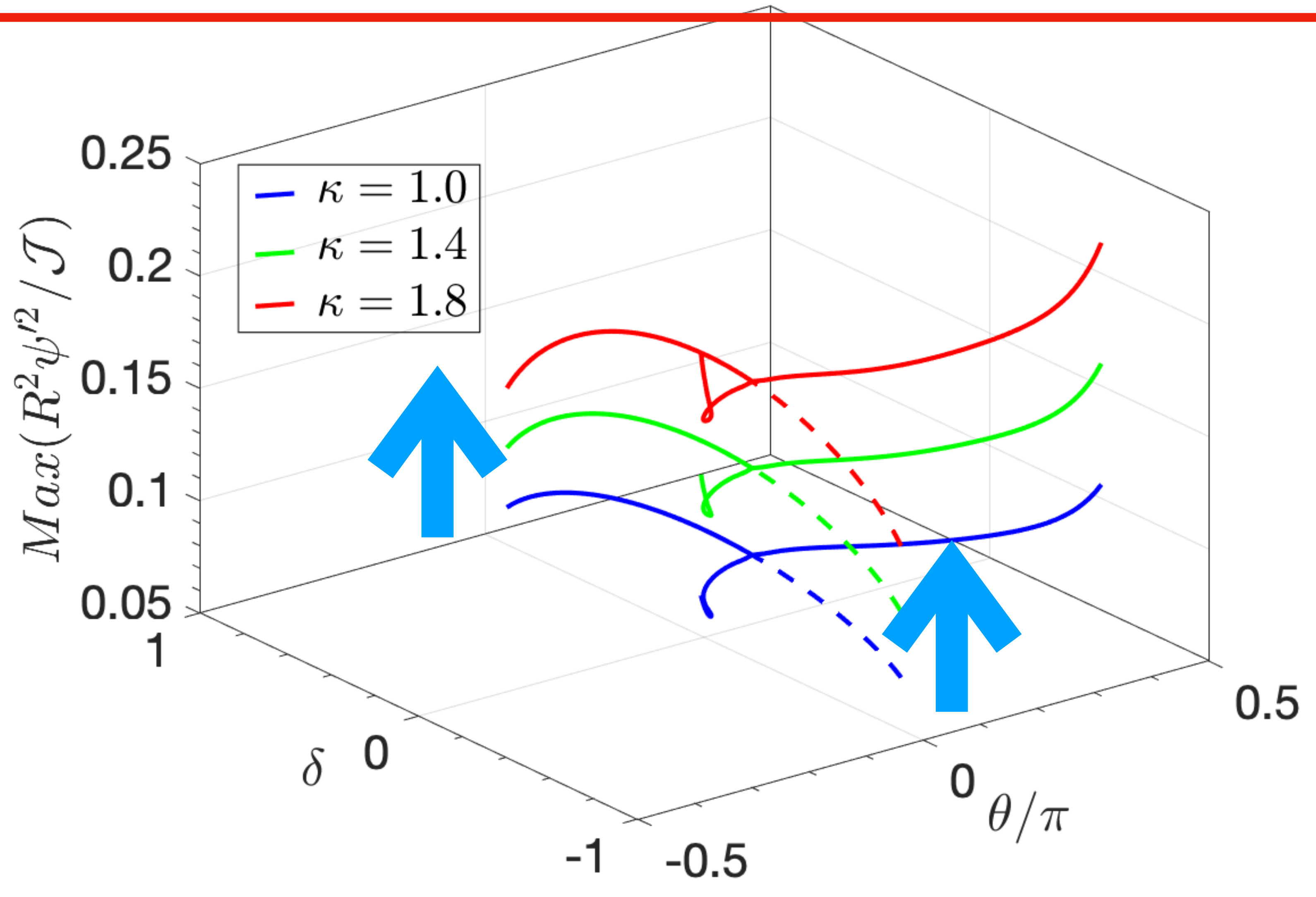


On increasing $|S_\delta|$:

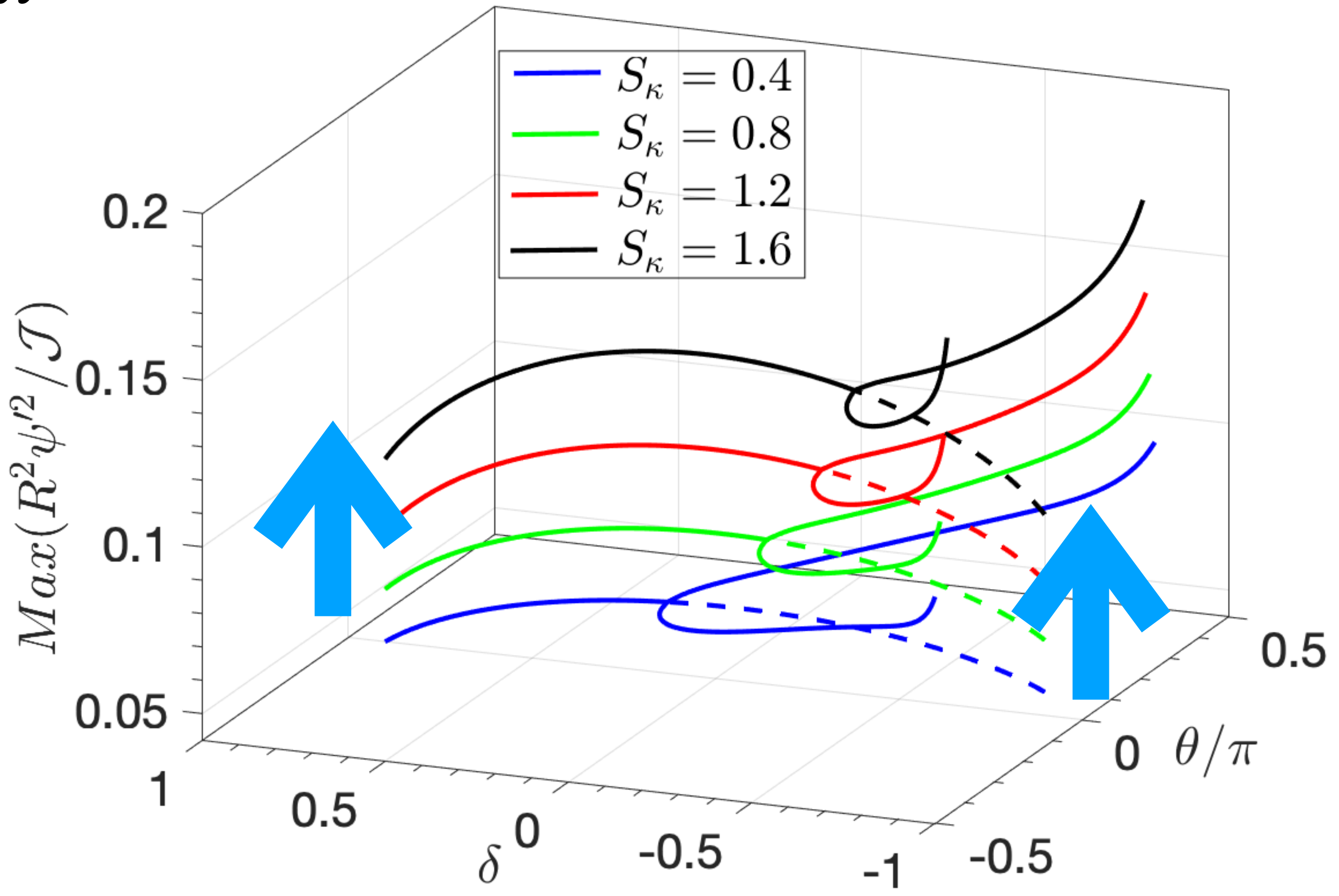
- Shearing rate decreases.
- δ_{crit} moves toward δ^-.

➡Radial profile of triangularity matters!

➡Can triangularity profile can be tailored to boost mean ExB shear?



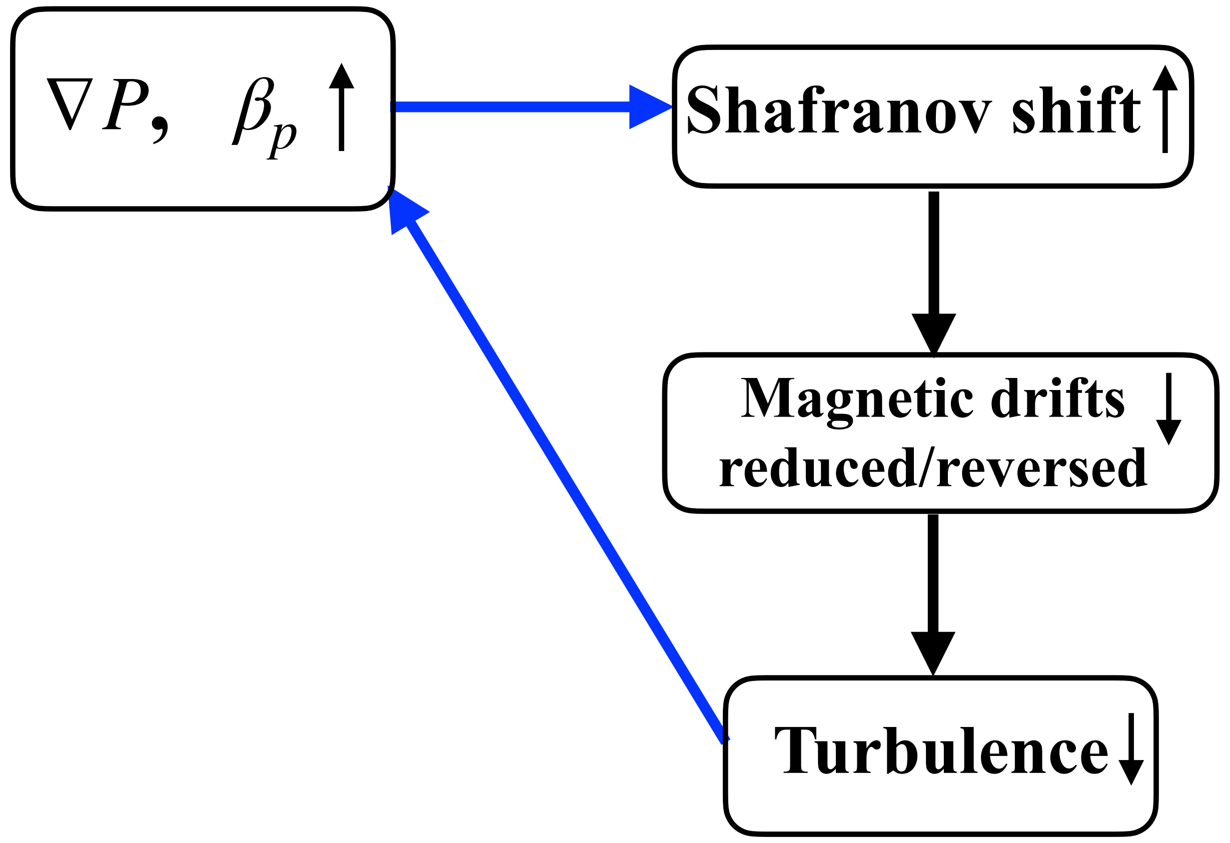
- Shearing rate increases with κ
- δ_{crit} is independent of κ.



- Shearing rate increases with S_k.
- δ_{crit} moves along δ^-.

Shafranov shift induced transport bifurcation

- ITB formation in high-β_p regime is often linked to transport bifurcation due to turbulence stabilization by Shafranov shift due to mag drift reduction/reversal, *ignoring* the mean ExB shear effect. [M Beer+ PoP 1997, S Ding+ PoP 2017, J McClenaghan+ PoP 2019, G M Staebler+ PoP 2017]



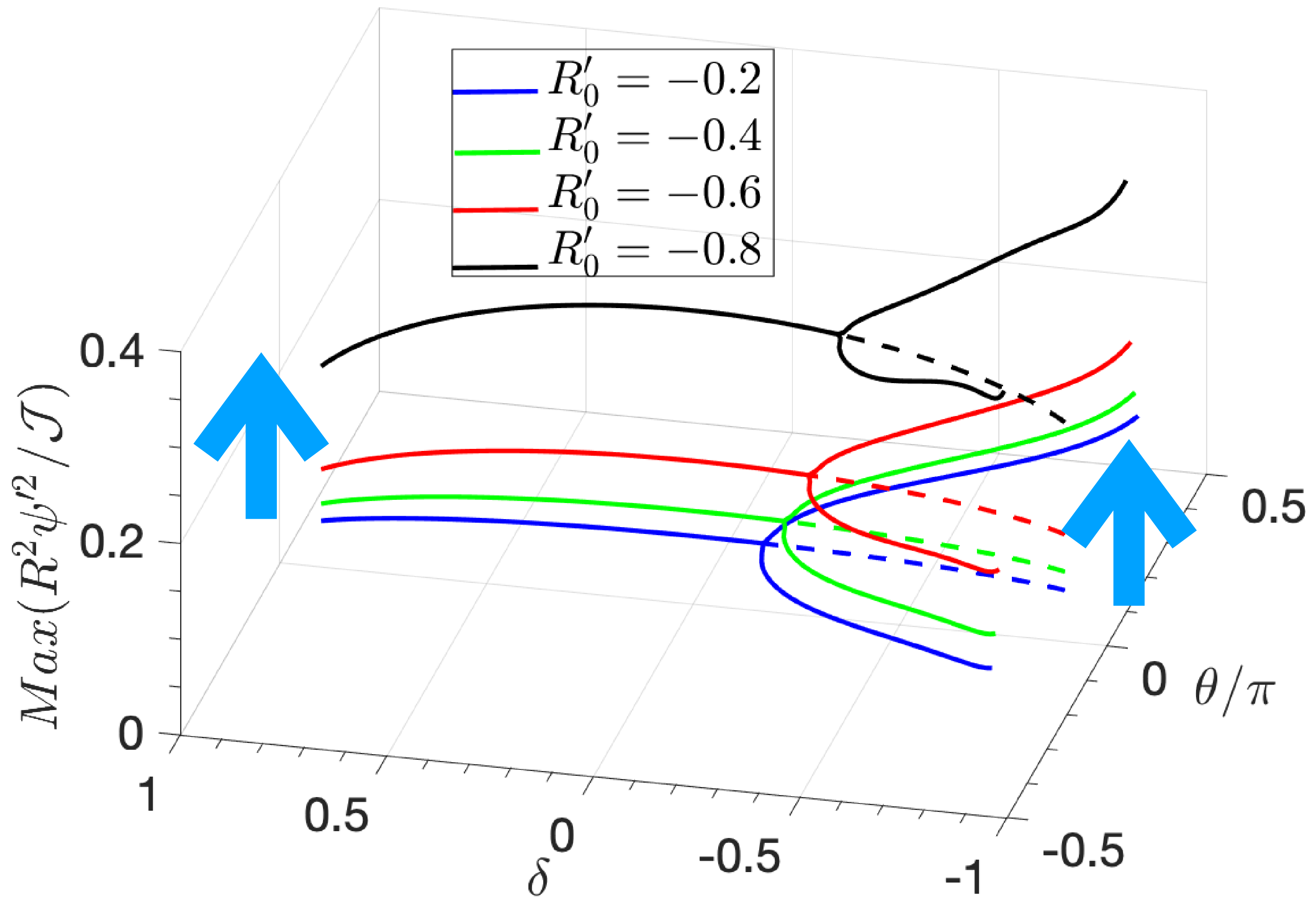
Feedback loop for Shafranov shift induced transport bifurcation

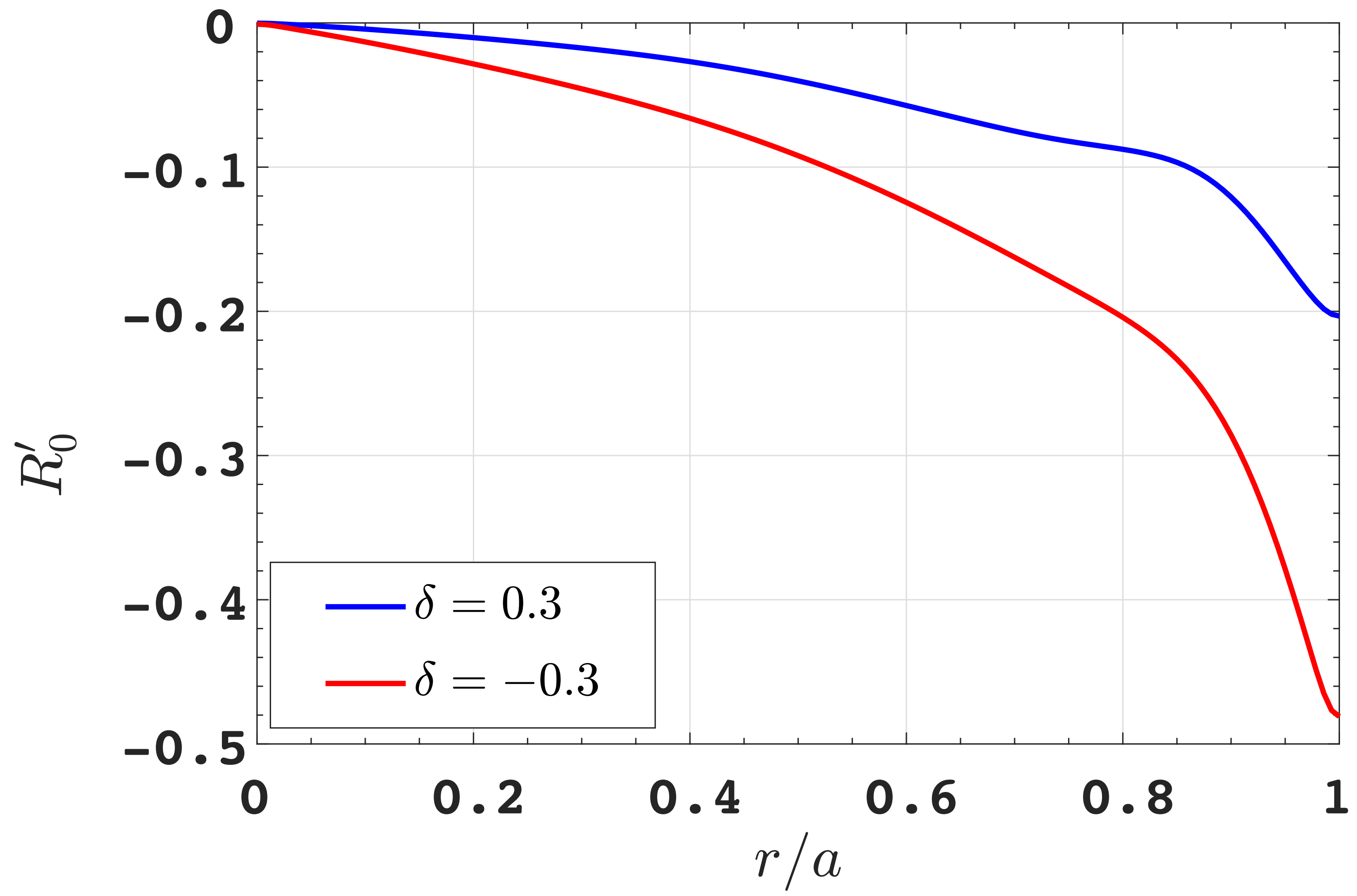
- But… like it or not - mean shear *exist* in high-β_p discharges!
- So, how does mean shear and Shafranov shift interact ?
- Interplay of mean ExB shear, Shafranov shift and NT?

Variation of mean ExB shearing rate with Shafranov shift gradient R_0'

On increasing $-R_0'$:

- Shearing rate increases for all δ.
- δ_c moves toward δ^- on increasing $-R_0'$.
- Key reason→flux compression.





Shafranov shift gradient obtained using CHEASE code

Significant for:

- high β_p regime (i.e, RS ITB) as $R_0' \propto \frac{r}{R_0}\beta_p$
- NT shapes
  - as $\beta_p(\delta^-) > \beta_p(\delta^+)$
  - Numerical MHD equilibrium study shows $R_0'(\delta^-) > R_0'(\delta^+)$ even for fixed β_p.

➡ Even more significant for future NT+ITB discharges

Implications of Shafranov shift effect on ExB shear

- Shafranov shift affects turbulence in 2 distinct ways:

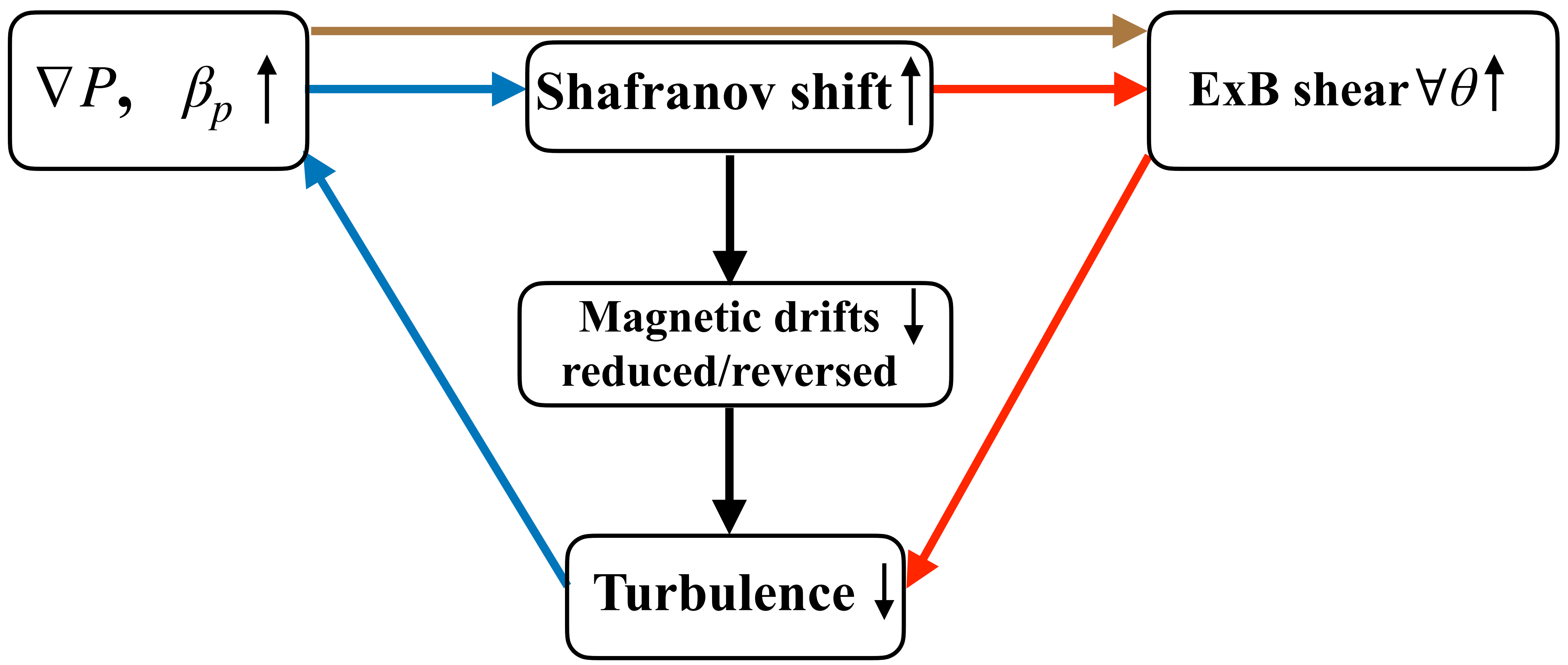
(I) Stabilizes turbulence by reduction/reversal of magnetic drifts

(II) Directly enhances the mean shear, → additional turbulence suppression

Bifurcation by (I) is often invoked as a mechanism of confinement improvement in high-β_p regime, *ignoring* the mean shear effect.

Mean ExB shear ↑ by Shafranov shift → +ve feedback on the feedback loop of the Shafranov shift induced transport bifurcation.

Shafranov shift has a +ve effect on the mean ExB shear induced transport bifurcation, through: (a) $\gamma_{lin}\downarrow$, and (b) ExB shear ↑.



Both (I) and (II) can work in tandem to reduce the ∇P_{crit} for the onset of ITB in reversed shear PT shape

Conclusions

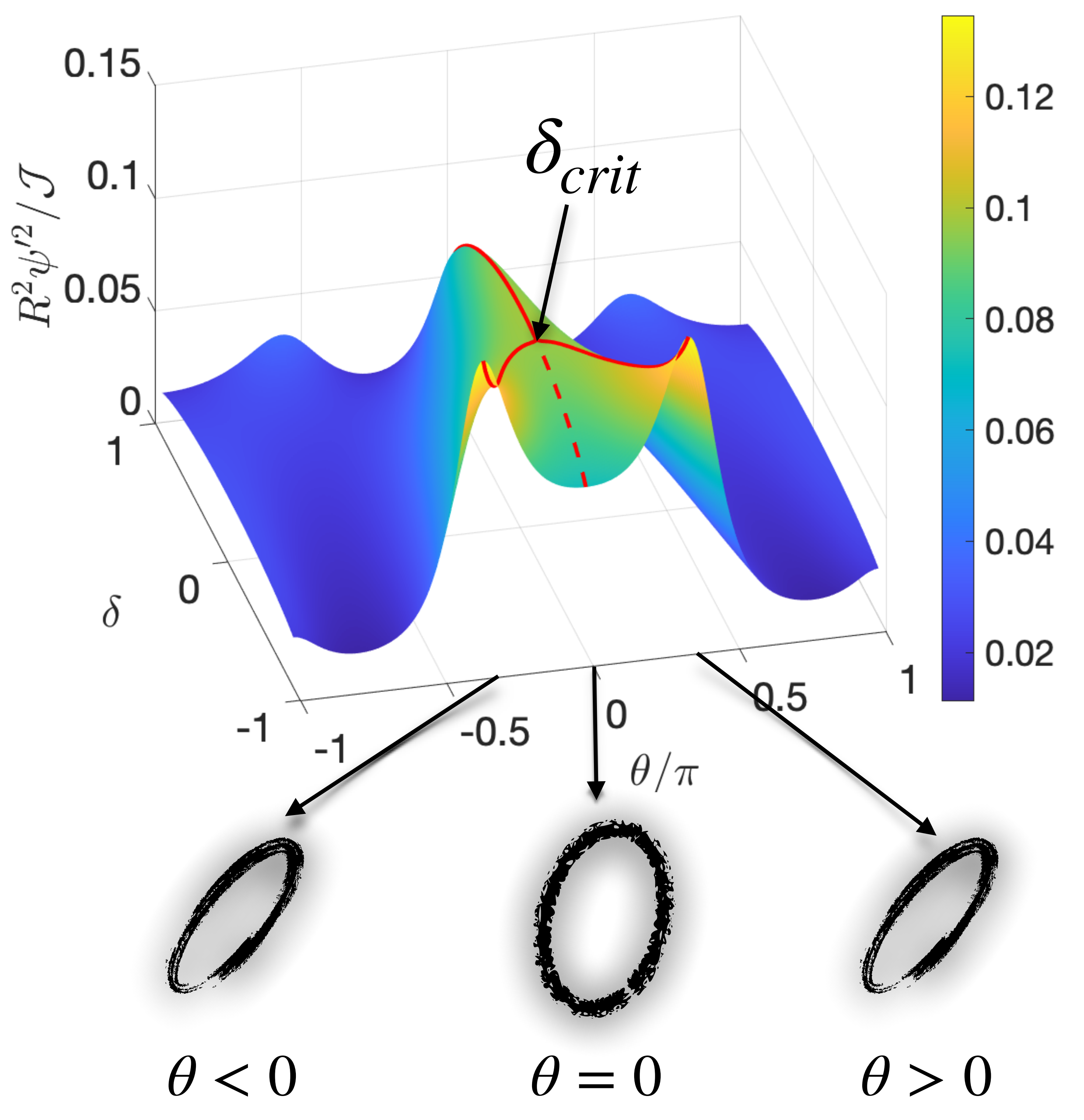
- **Maximum shear off the outboard mid-plane for $\delta < \delta_{crit}(\leq 0)$**
  - ➡ Up-down symmetry: Max shear located symmetrically above and below the outboard mid-plane for $\delta_u = \delta_l = \delta < \delta_{crit}$
  - ➡ Up-down asymmetry: Max shear located above the outboard mid-plane for $\delta_u < \delta_{crit}$ & $\delta_l > \delta_u$. Max shear located below the outboard mid-plane for $\delta_l < \delta_{crit}$ & $\delta_u > \delta_l$.
  - ➡ Shear at $\theta = 0$ decreases with increasing NT. Fluctuations balloon at $\theta = 0$. Thus, shearing efficiency $\downarrow \Longrightarrow P_{L\rightarrow H,th} \uparrow$(!?). Is this sufficient ?

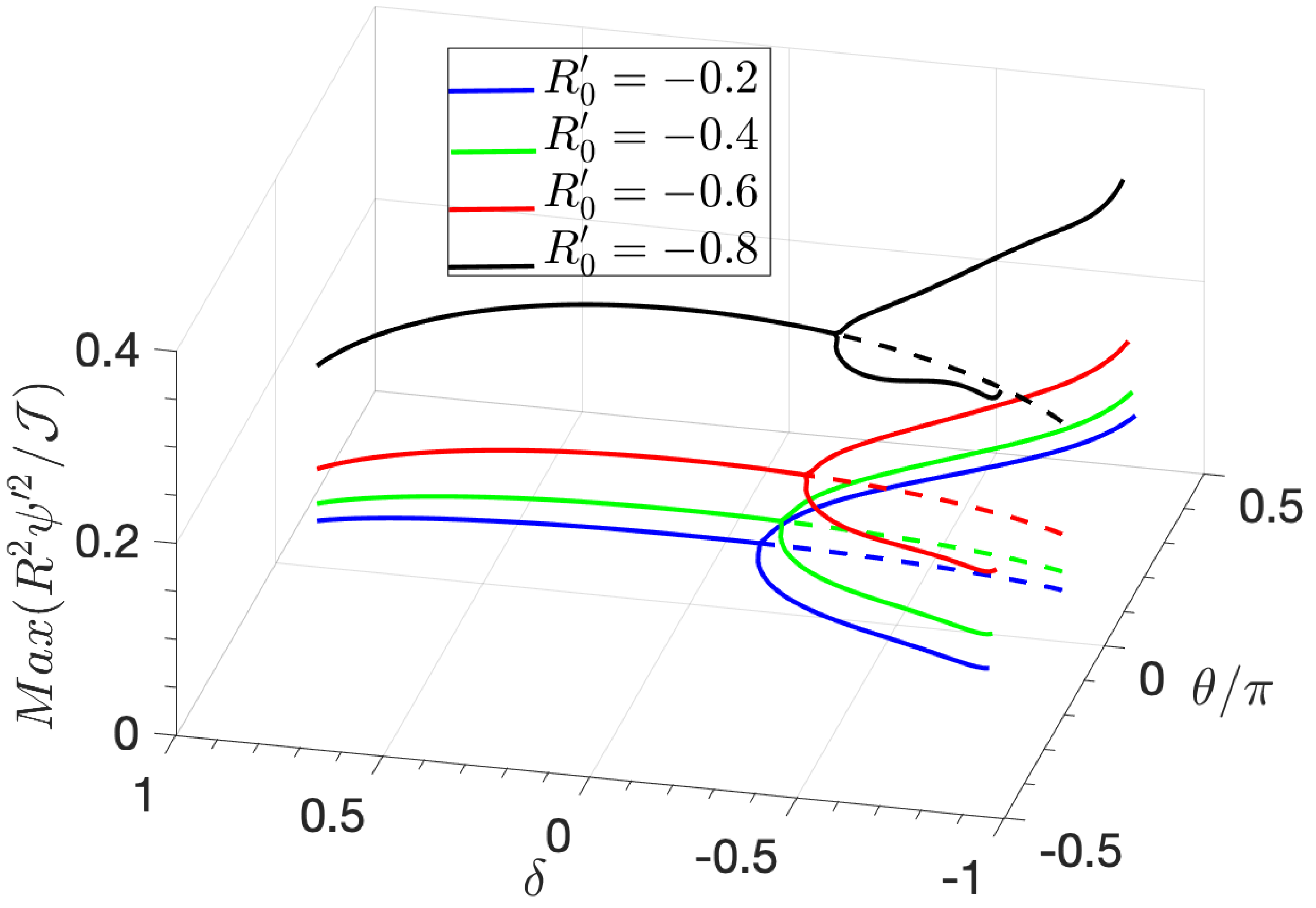
- **Direct effect of Shafranov shift gradient $-R_0'$ on shearing rate:** Shearing rate increases with increasing $-R_0'$ for all δ. Key reason→flux compression. Significant for high β_p regime and NT shapes.

These results has implications not just for confinement & L-H transition for NT but also for ITB discharges in PT and NT(proposed), and NT core and and pedestal.

For the experimentalists

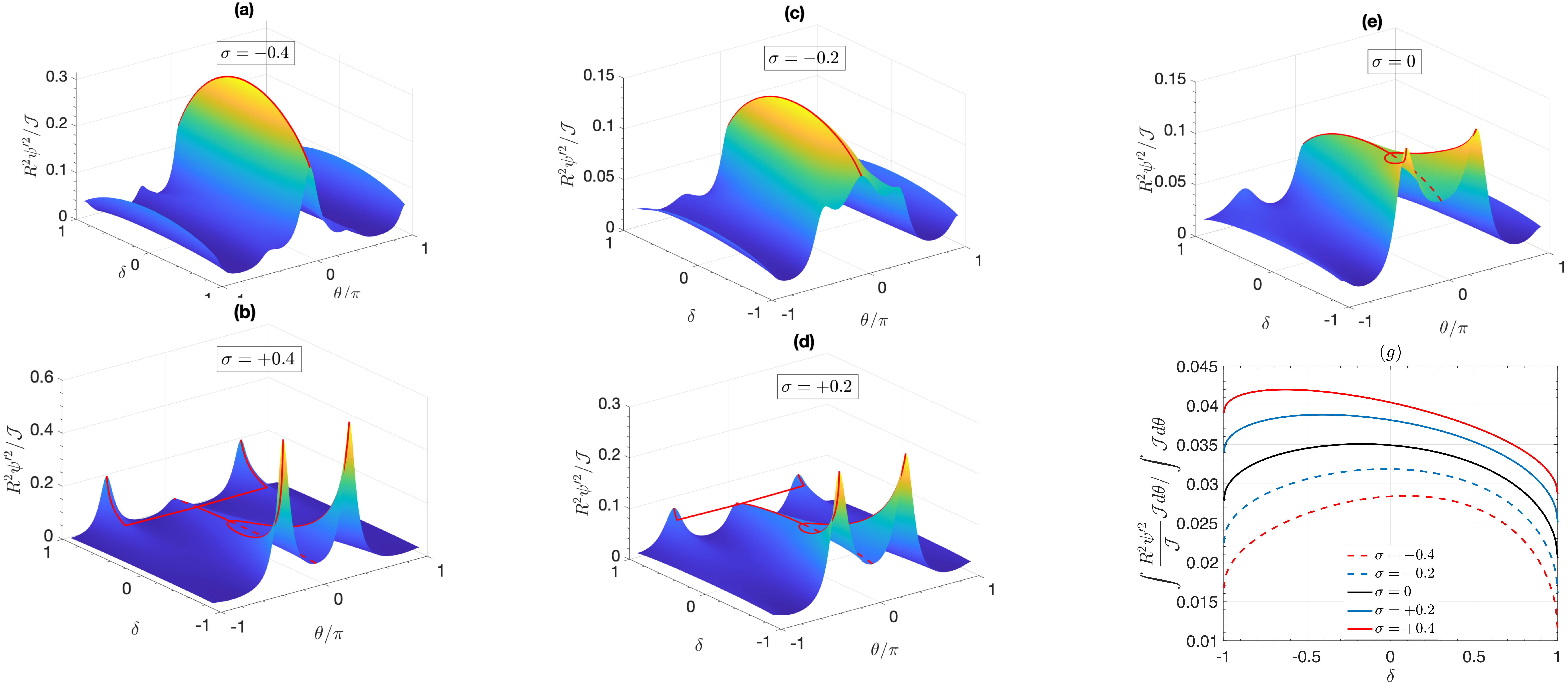
- **Mean ExB Shearing is maximal off the mid-pane for NT:** $\Longrightarrow$ Eddy tilting should be strongest off the mid-plane.
  - Direct imaging using gas-puffing.
  - Joint pdf of radial and poloidal velocity fluctuations (i.e., $\tilde{v}_r$ & $\tilde{v}_\theta$) should show max tilting (most-correlated) off the mid-plane for NT.
  - Up-down asymmetric tilting distribution for $\delta_u \neq \delta_l$





- **Shafranov shift gradient R_0' directly boosts the mean ExB shear:**
  - Re-assess the role of mean ExB shear in high-β_p reverse shear discharges.

Back-up: ExB shearing rate variations with squareness σ



- The flux surface averaged shearing rate increases with increasing σ
- Shearing at $\theta = 0$ decreases with increasing σ.
- For $\sigma < 0$ the the geometric bifurcation disappears, the poloidal width of shear gets narrow and the shearing at $\theta = 0$ increases.