NSTX-U

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Progress on momentum transport predictions in NSTX

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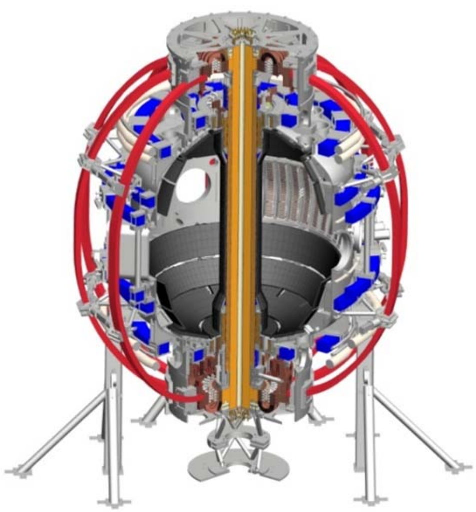


Overview & Summary

- Quasilinear predictions are unable to account for experimental observations of strong momentum pinch in high beta NSTX H-modes
- Have begun investigating additional effects (nonlinear, E$\times$B shear, finite ρ_*)
- Initially focused on a low beta L-mode unstable to ITG/TEM (easier to handle and interpret computationally):

1) Nonlinear simulations, including E$\times$B shear, give Pr and RV_φ/χ_φ similar to quasilinear analysis
   – IF this holds for H-modes, can not explain observed pinch
2) Linear, global (finite ρ_*) simulations predict residual stress contributions comparable to pinch but directed outward; both smaller than diffusive flux
3) Initial nonlinear, global simulations predict a strong inward momentum flux in the absence of flow or flow shear
   – Linear and nonlinear global simulations ongoing for high beta H-mode plasmas unstable to mix of microtearing (MT) and kinetic ballooning modes (KBM)

Background & Motivation

Interpretation of toroidal angular momentum transport often assumes diffusive and convective components

- Transport equation: $$\frac{\partial}{\partial t}\left(n_i m_i \left\langle R^2 \right\rangle \Omega\right) + \nabla \cdot \Pi_\varphi = S_\Omega \rightarrow \sum_s (\cdots)$$

- *Assumed* transport form: $$\Pi_\varphi = -nmR\chi_\varphi (R\nabla\Omega) + nmV_\varphi (R\Omega)$$

Prandtl number $\boxed{\Pr = \frac{\chi_\varphi}{\chi_i}}$

Pinch parameter $\boxed{\frac{RV_\varphi}{\chi_\varphi}}$

$$\hat{\Pi}_\varphi = \hat{\chi}_\varphi \left(\hat{u}' + \frac{RV_\varphi}{\chi_\varphi} \hat{u} \right)$$

$$\hat{u}' = \frac{-R^2 \nabla\Omega}{c_s} \qquad \hat{u} = \frac{R\Omega}{c_s}$$

- Pinch expected due to Coriolis drift [Peeters, 2007], turbulent equipartition + thermoelectric force [Hahm, 2007]

Momentum transport is anomalous in NSTX, Prandtl numbers $\chi_\varphi/\chi_i < 1$ for L- and H-modes

- $Pr=\chi_\varphi/\chi_i \approx 0.3\text{-}1.0$ over many radii and discharges (assumes $V_\varphi=0$)

- $\chi_\varphi > \chi_{\varphi,NC}$ for both L and H

  In L-mode $\chi_i > \chi_{i,NC}$

$$\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i} \approx \frac{\chi_{\varphi,\mathrm{turb}}}{\chi_{i,\mathrm{turb}}}$$

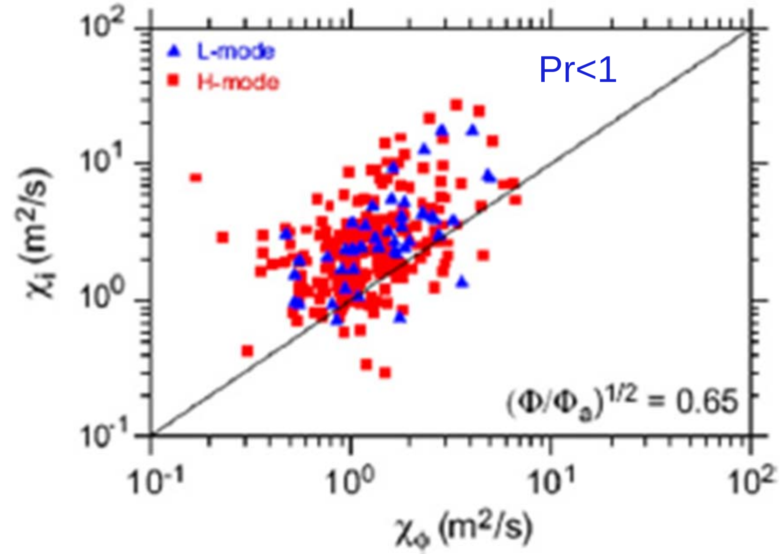
  In H-mode $\chi_i \approx \chi_{i,NC}$

$$\mathrm{Pr} = \frac{\chi_\varphi}{\chi_i} = \frac{\chi_{\varphi,\mathrm{turb}}}{(\chi_{i,\mathrm{NC}} + \cancelto{\sim 0}{\chi_{i,\mathrm{turb}}})}$$

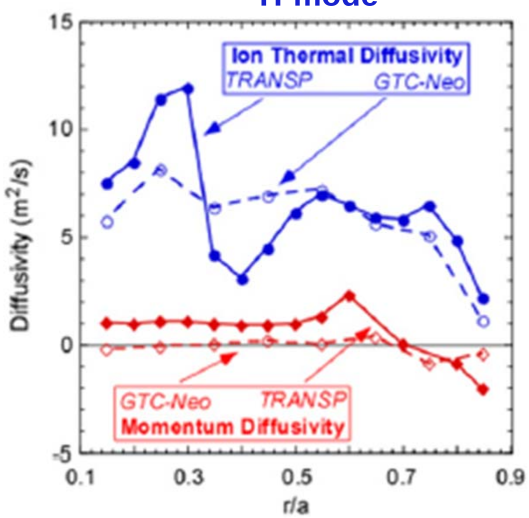
$\Rightarrow$ Pr less useful in H-mode?

- RV_φ/χ_φ less ambiguous

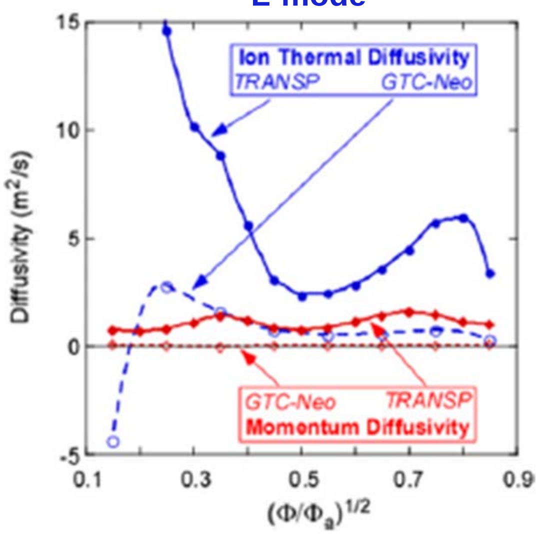
Steady state transport analysis (Kaye et al., 2009)



H-mode



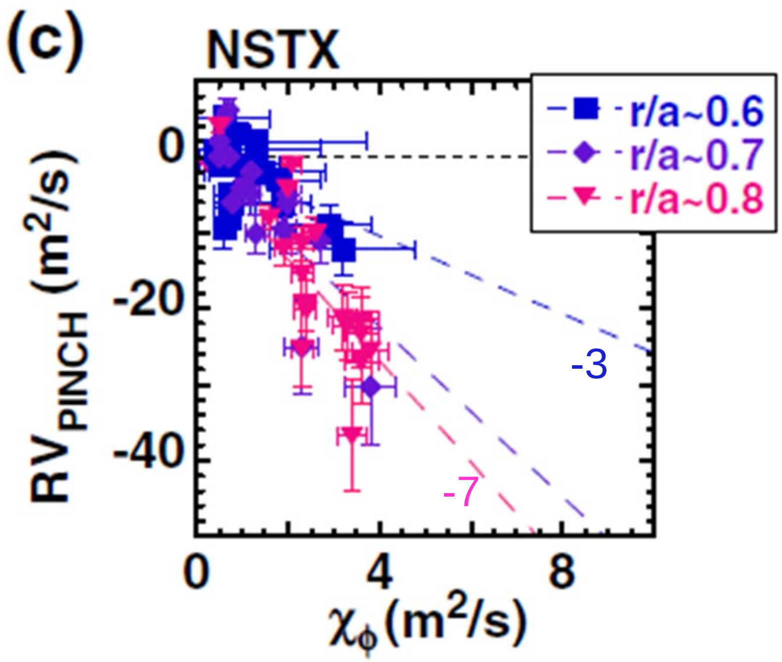
L-mode



Perturbative H-mode experiments (using n=3 magnetic braking) indicate existence of an inward momentum pinch

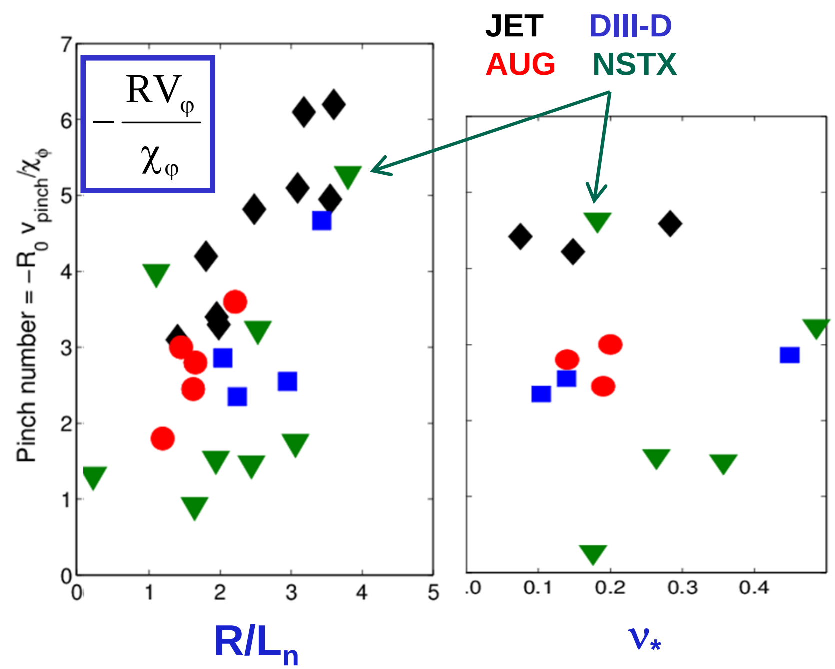
- $RV_{\varphi}/\chi_{\varphi} \approx$ -(1-7) for many NSTX discharges & radii

(Solomon et al., PRL 2008, PoP 2010; Yoshida et al., NF 2012)



- Possible dependence on density gradient (R/L_n), less clear with collisionality (ν*)

(Tala et al., IAEA 2012)



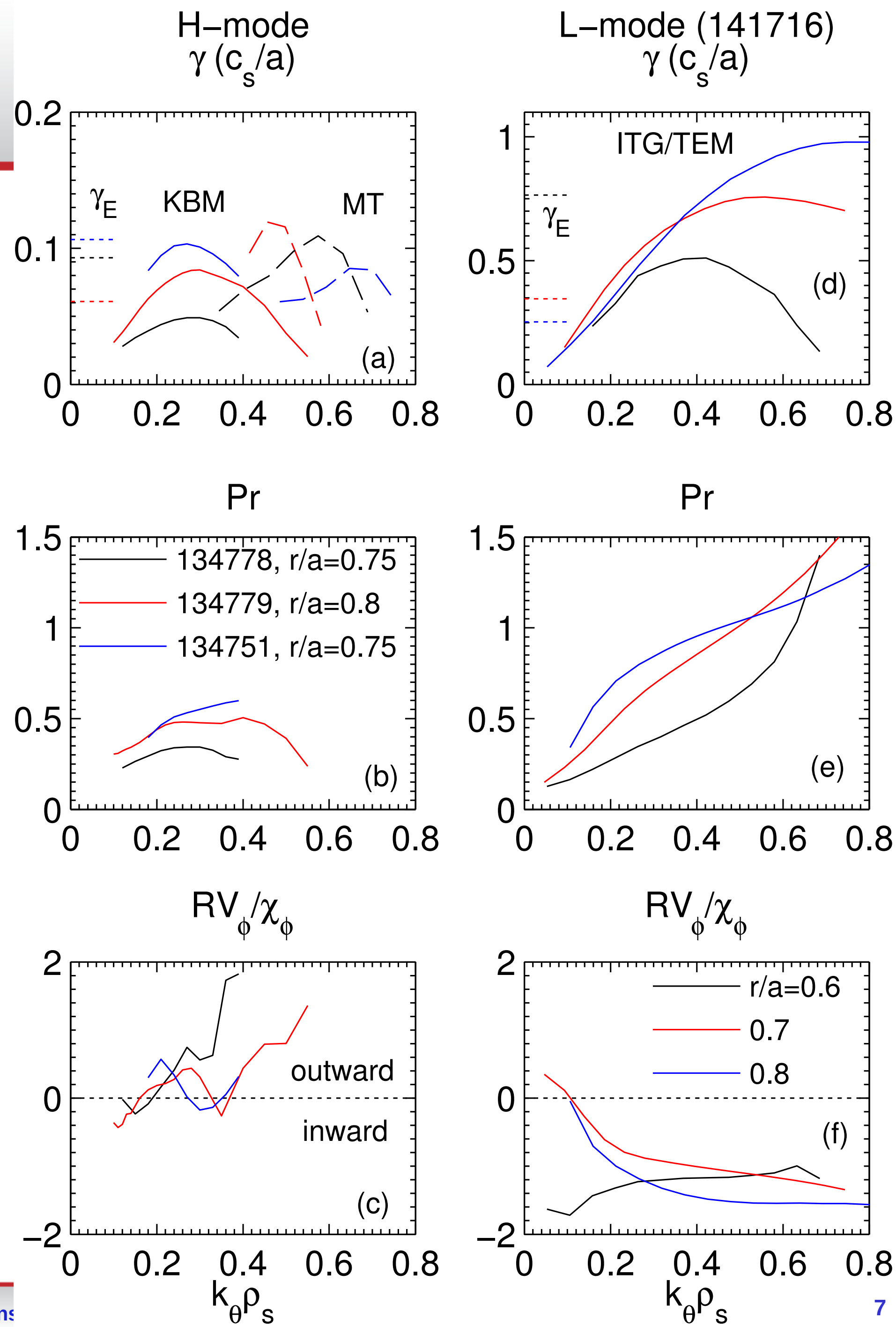
- Local, linear gyrokinetic simulations of ITG turbulence describe pinch and scaling in conventional tokamaks $\Rightarrow$ **does this hold for NSTX?**

Local, linear sims unable to explain measured pinch

- Guttenfelder (TTF, 2013) showed gyrokinetic simulations (GYRO) predicting linear stability, Pr and pinch (following Peeters, 2007)

- In H-modes, mix of microtearing (MT) and KBM predicted unstable
- No momentum transport predicted for MT but KBM predicts:
  - Small Pr~0.3-0.5
  - Small or outward convection, RV_φ/χ_φ~0-2
  - Pinch insensitive to parameter variations (R/L_n, ν_*, …)

- In L-mode, ITG/TEM unstable:
  - Larger Pr≤1
  - Small inward pinch, RV_φ/χ_φ ~ -2-0
  - Pinch insensitive to parameter variations (R/L_n, ν_*, …)



Many theoretical mechanisms to consider for momentum transport

$$\Pi_\varphi = nmR(\chi_\varphi u' + \chi_{\varphi\perp}\gamma_E) + (nmRV_\varphi + mR\Gamma_p)u + C_{UD} + C_{\rho*} + \ldots$$

- More general expression for momentum transport (e.g., Peeters, NF 2011) includes contributions due to:
  - Perpendicular (E×B) flow shear [Casson, 2010; Dominguez, 1993]
  - Particle convection (usually expected to be small)
  - Up-down asymmetry [Camenen, 2009]
  - Finite ρ_*/nonlocal effects (profile shearing, …) [Camenen, 2011]
- Also, important to consider all mechanisms in fully developed nonlinear turbulence (i.e. not just quasi-linear)
- In the core of NSTX NBI plasmas, toroidal flow dominates radial force balance so that $u'=(qR/r)\cdot\gamma_E$ (i.e. negligible v_{pol}, ∇p_i contributions)
  - In theory and codes we can vary u', γ_E, u, ρ_* independently to identify various physical mechanisms

- Have begun to investigate nonlinear, E×B shear and finite ρ_* effects

Local nonlinear L-mode predictions

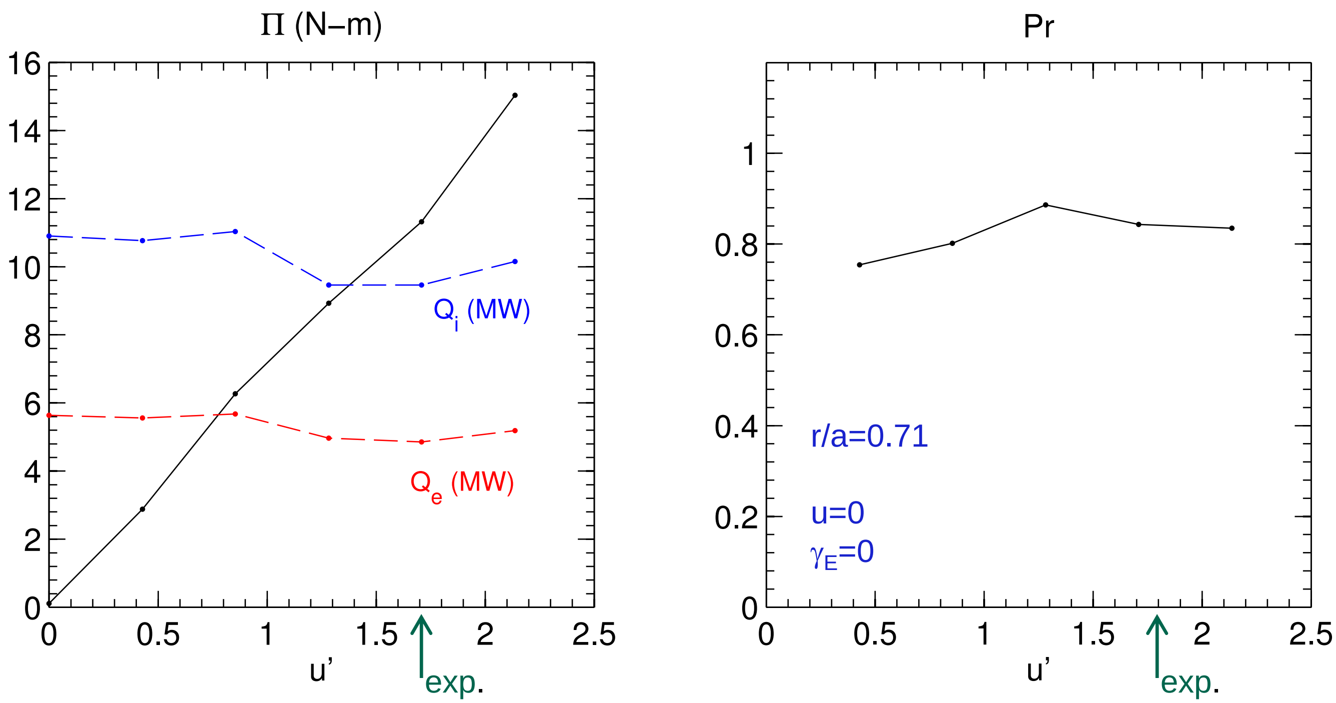
- Using L-mode analyzed extensively in [Ren, NF 2013]
- Nonlinear simulations run with varying E×B shear, parallel flow shear and toroidal flow (following [Casson, 2009])

- Summary: Nonlinear results with E×B shear largely consistent with quasilinear results

Increasing u′ drives diffusive transport

- Linear dependence Π~u’ as expected
- Pr~0.8, consistent with quasilinear analysis using $k_\theta\rho_s$~0.35 (nonlinear peak)
- Heat fluxes ~constant, unaffected by parallel gradient drive

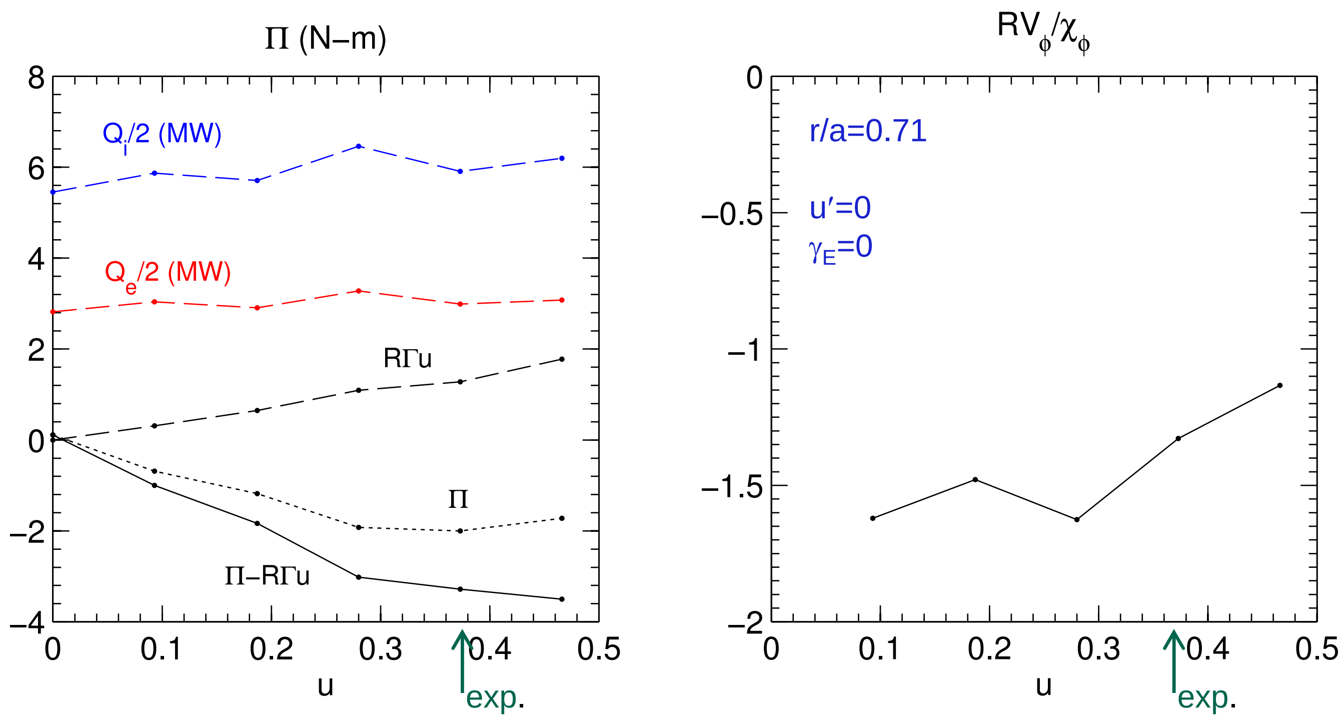
$$\Pi_\varphi = nmR(\underline{\chi_\varphi u'} + \chi_{\varphi\perp}\cancel{\gamma_E}) + (nmRV_\varphi + mR\Gamma_p)\cancel{u} + \cancel{C_{UD}} + \cancel{C_{\rho*}} + \ldots$$



Increasing u gives convective pinch

- Near linear dependence $\Pi \sim u$
- $RV_\varphi/\chi_\varphi \sim -1$, consistent with quasilinear analysis using $k_\theta\rho_s \sim 0.35$
  - Subtracting contribution from particle flux, $mR\Gamma_p u$
- Heat fluxes ~constant, unaffected by toroidal rotation

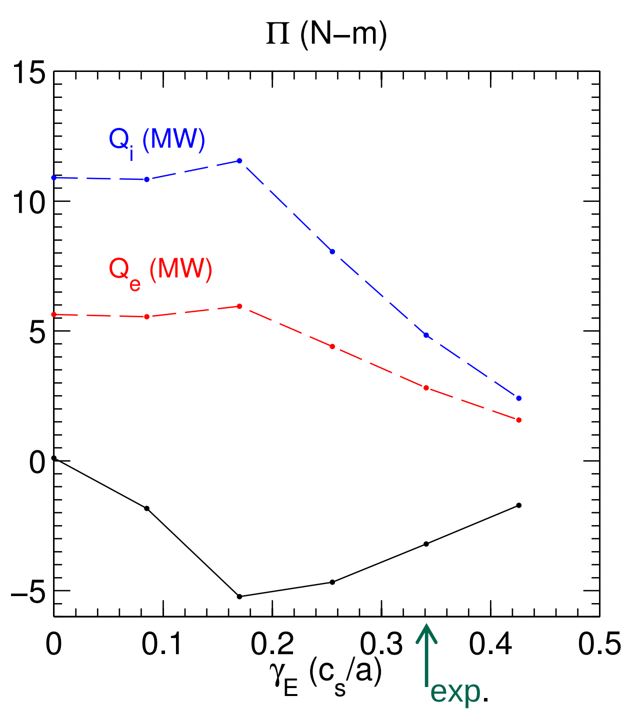
$$\Pi_\varphi = nmR(\cancel{\chi_\varphi u'} + \cancel{\chi_{\varphi\perp}\gamma_E}) + \underline{(nmRV_\varphi + mR\Gamma_p)u} + \cancel{C_{UD}} + \cancel{C_{\rho*}} + \ldots$$

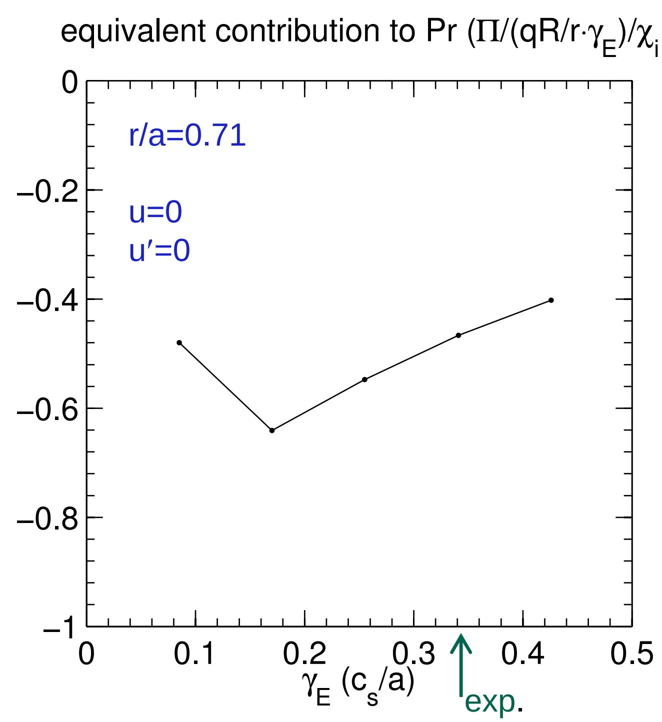


E×B (perpendicular) shear drives strong inward convection but nonmonotonic

- Near linear dependence for small enough E×B shear
- Decreases above γ_E>0.15 as E×B shear begins to suppress turbulence
  - Seen in all transport channels - Γ, Q, Π

$$\Pi_\varphi = nmR(\cancel{\chi_\varphi u'} + \underline{\chi_{\varphi\perp}\gamma_E}) + (nmR\cancel{V_\varphi} + mR\Gamma_p)u + \cancel{C_{UD}} + \cancel{C_{\rho*}} + \ldots$$



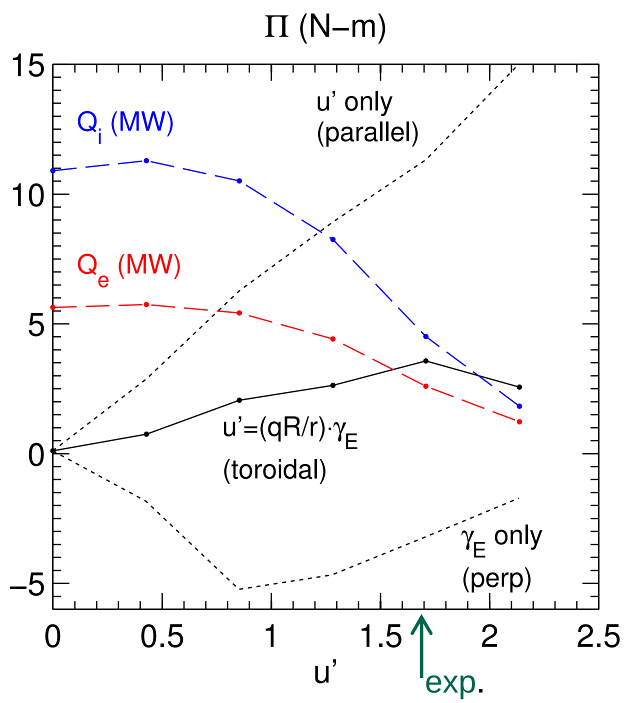


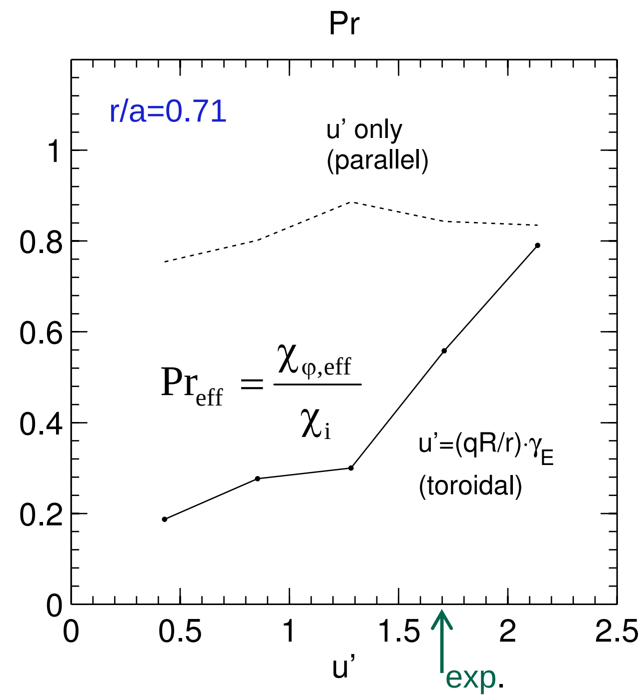
Using purely toroidal flow gives less transport, Pr approaches diffusive-only value at large flow shear

- Can define an effective momentum diffusion using purely toroidal flow, $\gamma_E=(r/qR)\cdot u'$ (appropriate for NBI driven core plasma in NSTX)

$$\Pi_\varphi = nmR(\underline{\chi_\varphi u' + \chi_{\varphi\perp}\gamma_E}) + (nmR\cancel{V_\varphi + } mR\Gamma_p)u + \cancel{C_{UD}} + \cancel{C_{p*}} + \ldots$$

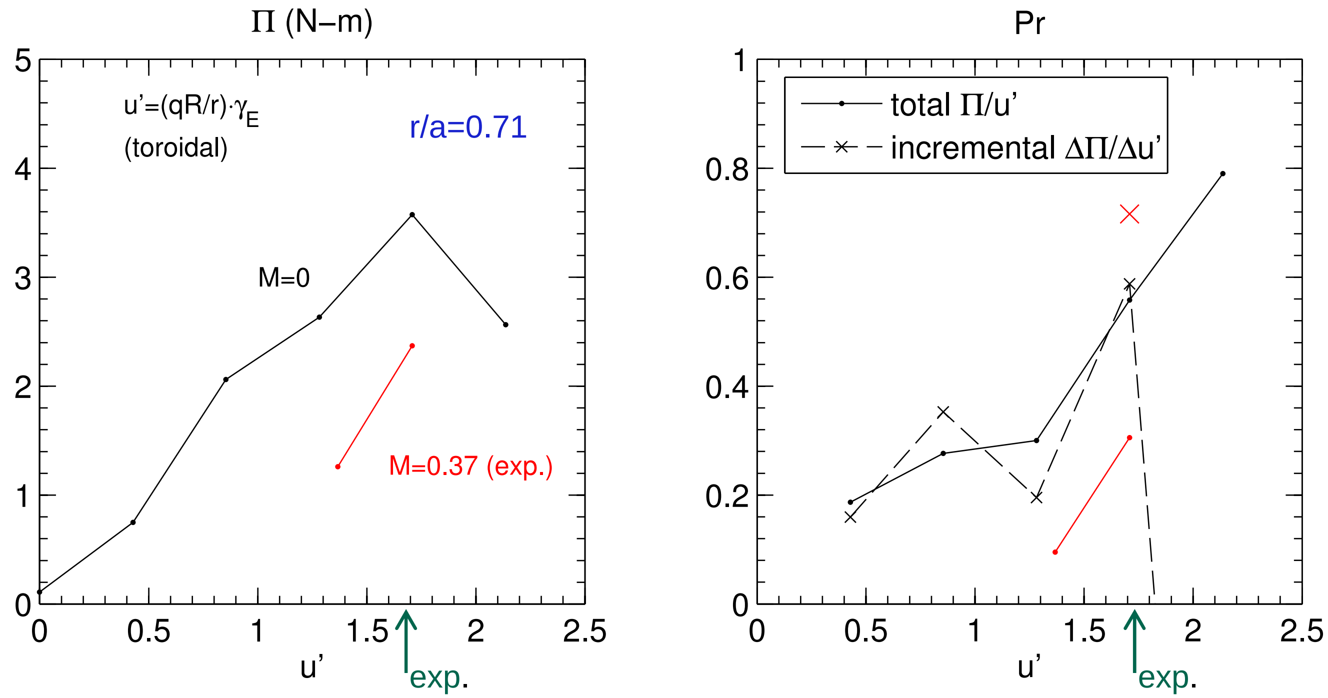
$$(\chi_\varphi + \chi_{\varphi\perp}\frac{r}{qR})u' = \chi_{\varphi,\mathrm{eff}}\, u'$$





To better mimic experiment, calculating Pr and RV_φ/χ_φ using only 20% variation in u, $u'\sim\gamma_E$ around experimental values

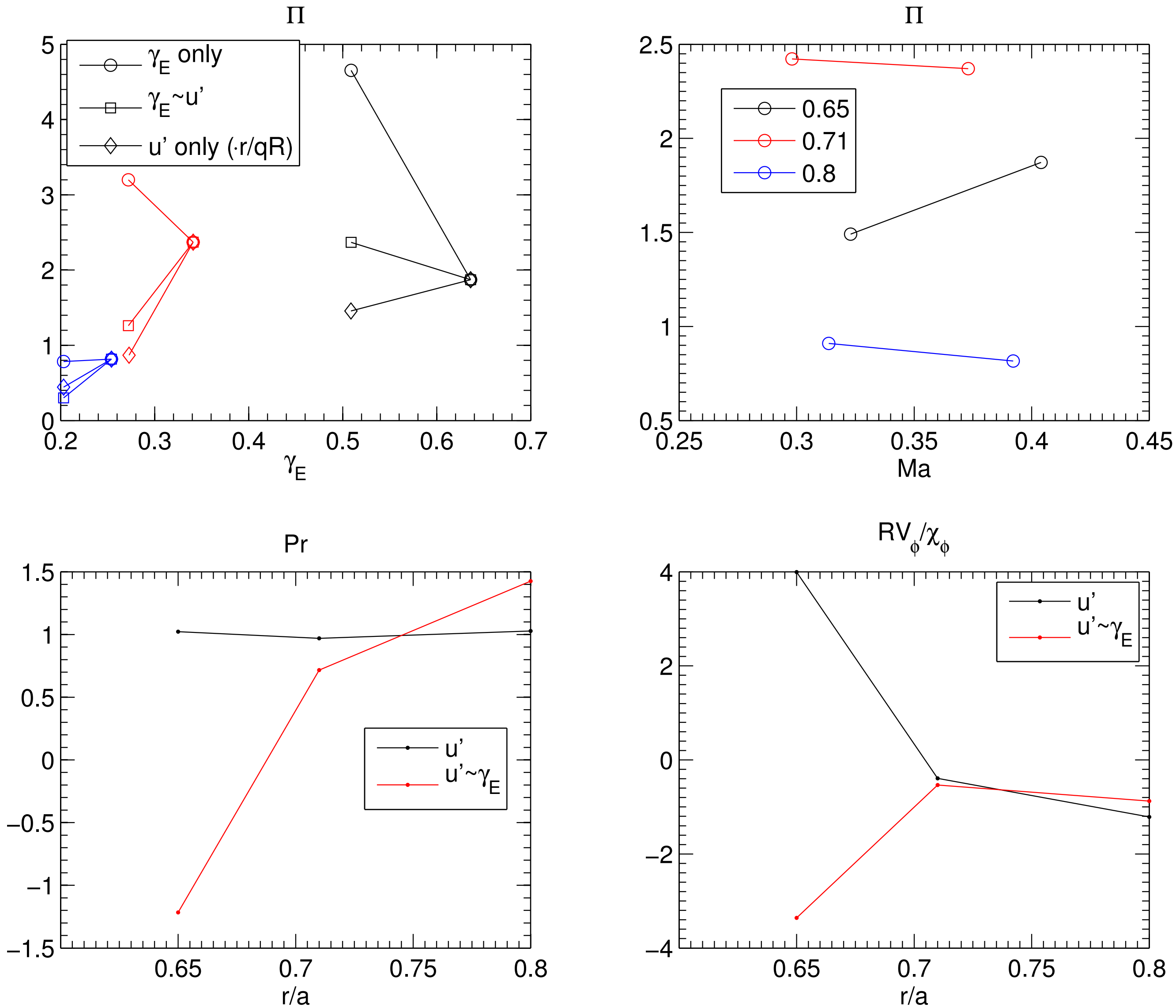
- Inferred Pr and RV_φ/χ_φ vary because of nonlinear dependencies
- Calculated two ways:
  - Using reference point at u′=0 (as above), e.g. $\Pi(u'_{exp}) - \Pi(0)$
  - Using incremental change $\Delta u'$=20%, e.g. $\Pi(u'_{exp}) - \Pi(0.8*u'_{exp})$
- Incremental values (Pr~0.7, RV_φ/χ_φ~-0.5) similar to values above



Similar Pr, RV_φ/χ_φ found at r/a=0.8

- Odd results at r/a=0.65 because of much stronger E×B shear

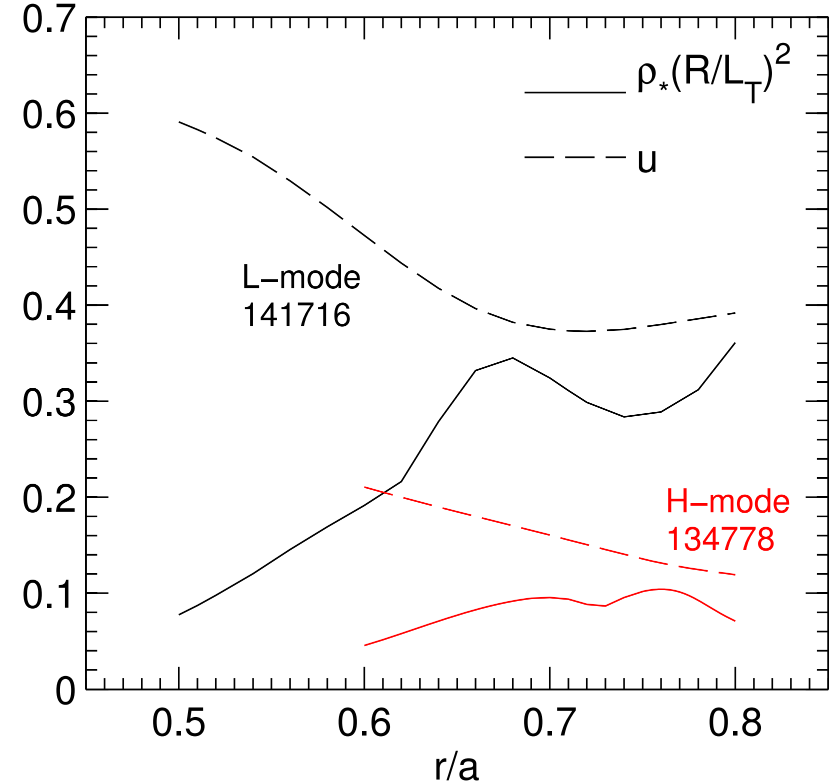
r/a	γ_E/γ_{lin}
0.65	0.8
0.71	0.45
0.8	0.25



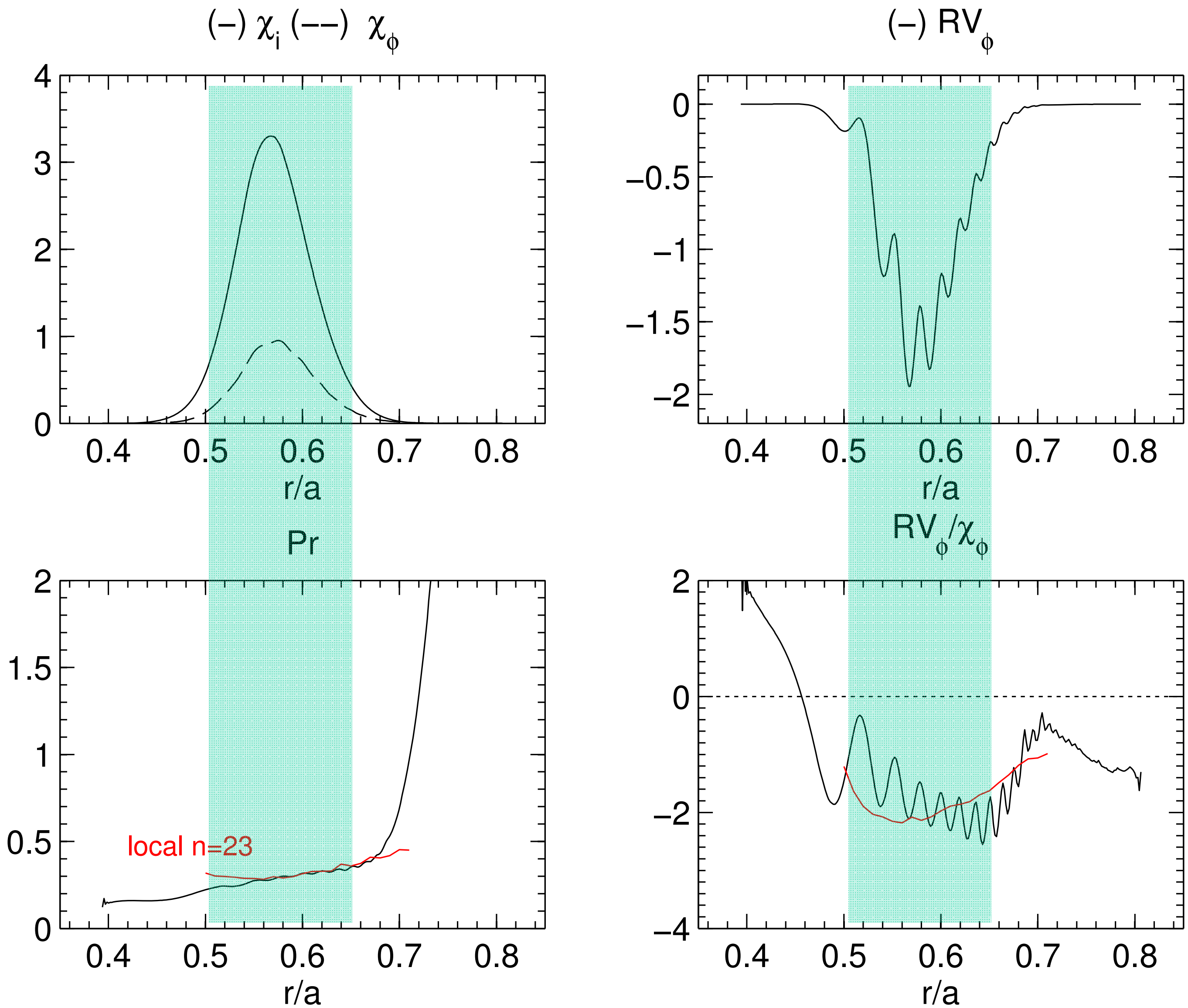
Global linear L-mode predictions

- Investigating Pr, RV_φ/χ_φ and residual stress ($C_{\rho*}/\chi_\varphi$) for linear, *global* simulation (n=23, $k_\theta\rho_s$=0.3 at r/a=0.6) (following Camenen, 2011)

- Rough criteria (Peeters, 201) - expect residual stress from profile shearing to be comparable to pinch if: $\rho_*(R/L_T)^2>u$
  - Close for both L-mode and H-mode

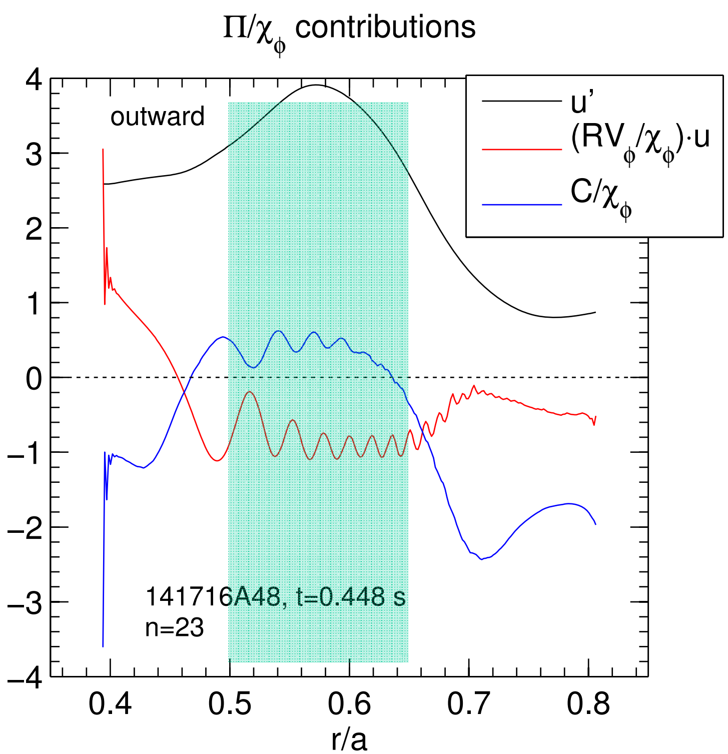


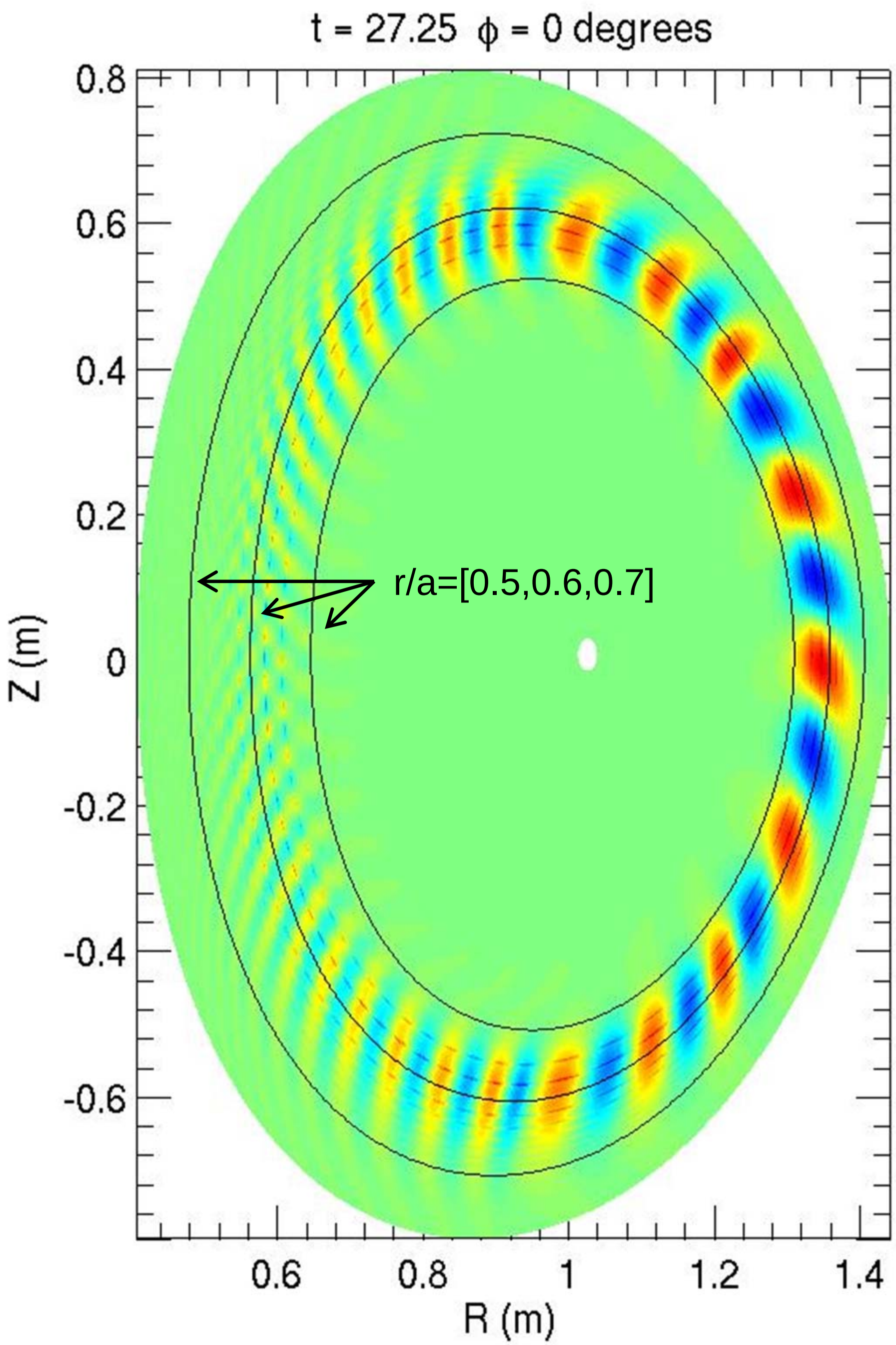
Quasilinear Pr and RV_φ/χ_φ from linear, global simulations in good agreement with local simulations



Diamagnetic profile shear tilts eddies, breaks symmetry

- Transport due to residual stress (C/χ_φ) is comparable to pinch transport ($RV_\varphi/\chi_\varphi \cdot u$), but directed outward (opposite pinch)
- Both small compared to diffusive component (u')

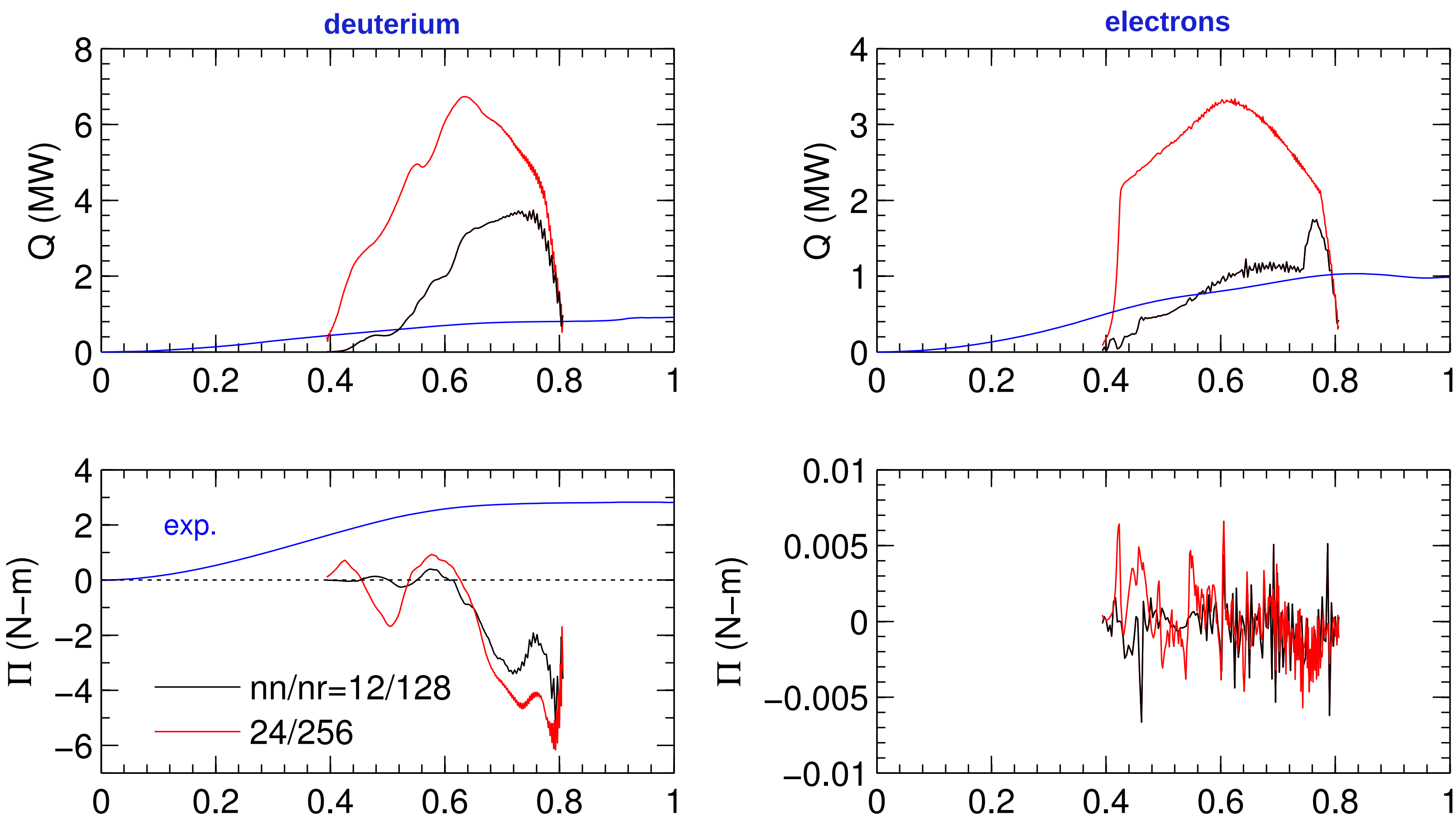




Global nonlinear L-mode predictions

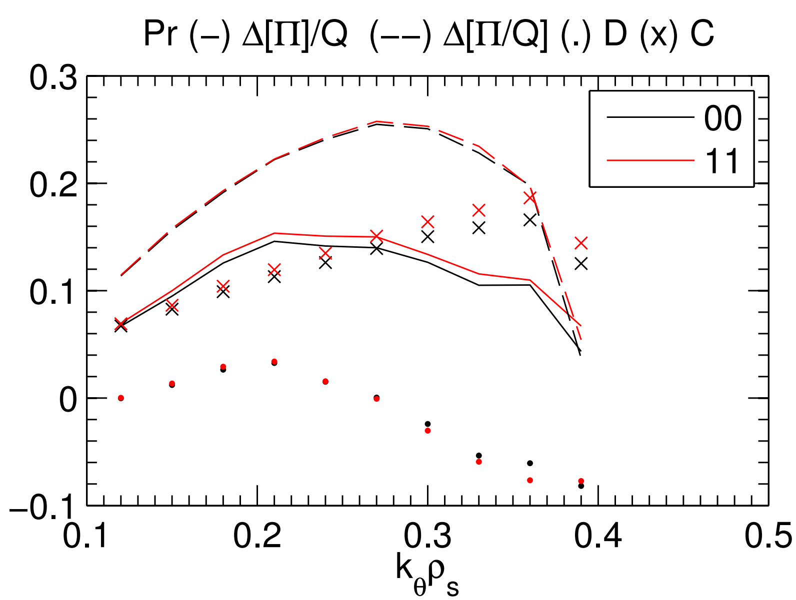
Global nonlinear simulation (no flow or flow shear)

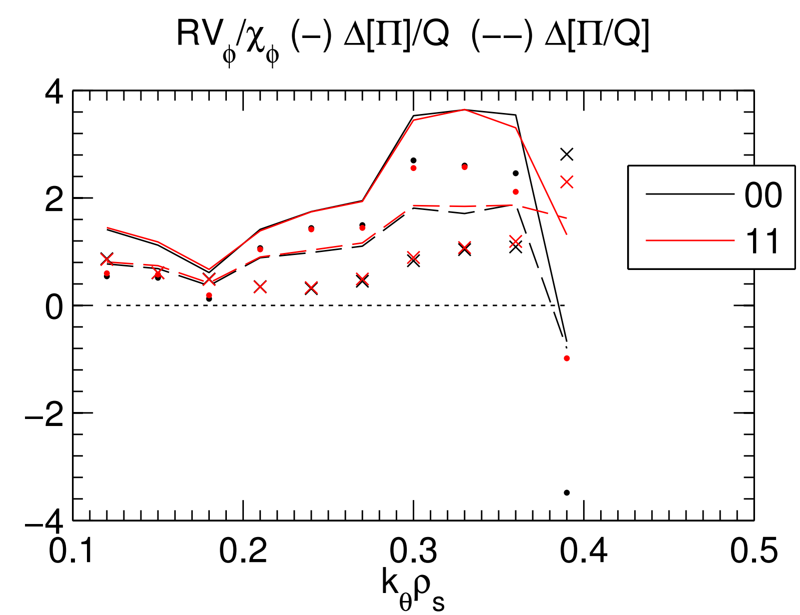
- Significant inward directed momentum flux (no flow or flow shear)
- Transport peaks further out (r/a~0.8) than linear n=23 eigenmode
  - More work required to investigate resolution and boundary conditions



Other considerations

- Up-down asymmetry weak in these plasmas (far from separatrix)
- Investigating influence of centrifugal effects using GKW (Buchholz, Hornsby, Peeters)
- Will investigate uncertainty in profiles and equilibrium reconstructions
- Interesting aside: D, C contribute differently to Pr and RV_φ/χ_φ (significant carbon impurity fraction in H-modes, Z_{eff}~3)





Extra slides

Three flow terms in the strong flow limit
(e.g., from GYRO Technical Guide, https://fusion.gat.com/theory/Gyro)

$$\frac{\partial h_a}{\partial t} + (v_\parallel \mathbf{b} + \mathbf{v}_d) \cdot \nabla H_a + \mathbf{v}_{E0} \cdot \nabla h_a + \delta \mathbf{v}_a \cdot \nabla h_a + \delta \mathbf{v}_a \cdot \left(\nabla f_{a0} + \frac{m_a v_\parallel f_{a0}}{T_a} \frac{I}{B} \nabla \omega_0 \right) = C_a^{GL}[H_a] \ . \quad (3.29)$$

E×B (perpendicular) flow shear

$$\gamma_E \doteq -\frac{r}{q}\frac{\partial \omega_0}{\partial r} \ ,$$

Parallel/toroidal flow shear

$$\gamma_p \doteq -R_0 \frac{\partial \omega_0}{\partial r} \ .$$

$$\mathbf{v}_d \doteq \frac{v_\parallel^2 + \mu B}{\Omega_{ca} B} \mathbf{b} \times \nabla B + \frac{2 v_\parallel \omega_0}{\Omega_{ca}} \mathbf{b} \times \mathbf{s} + \frac{4\pi v_\parallel^2}{\Omega_{ca} B^2} \mathbf{b} \times \nabla p$$

Toroidal flow

$$\omega_0 \doteq -c \frac{\partial \phi_{-1}}{\partial \psi}$$

$$M \doteq \frac{\omega_0 R_0}{c_s} \ ,$$

- Toroidal flow can lead to momentum pinch (e.g., Coriolis [1], TEP+thermoelectric [2])
- Parallel flow shear is a thermodynamic drive gradient, can cause/enhance instability [3] and drive momentum transport [4]
- E×B (perpendicular) flow shear can suppress instability and turbulent transport, can also cause momentum transport [5].
- For theoretical insight, can vary each term independently, although in the core of NSTX NBI plasmas, toroidal flow dominates radial force balance so that: $\gamma_E = \frac{r}{qR} \gamma_p$

Method for predicting quasi-linear Prandtl (χ_φ/χ_i) and Pinch numbers (RV_φ/χ_φ)

- Local linear GYRO simulations run between r/a=0.6-0.8 ($\rho_{tor}\approx$0.5-0.7), with
  - deuterium, carbon, electrons
  - φ, $A_{||}$, $B_{||}$
  - numerical equilibrium (EFIT/LRDFIT)
  - n_e profiles from averaged inboard/outboard measurements (no centrifugal effects in GYRO)

- Pr and RV_φ/χ_φ determined using momentum flux from different combinations of u, u′ $\hat{\Pi}_\varphi = \hat{\chi}_\varphi \hat{u}' + (\hat{R}\hat{V}_\varphi + \hat{R}\hat{\Gamma}_p)\hat{u} + \hat{\Pi}_{\varphi,RS}$

$$\mathrm{Pr} = \frac{\hat{\chi}_\varphi}{\hat{\chi}_i} = \frac{\hat{\Pi}_\varphi(0,u') - \hat{\Pi}_\varphi(0,0)}{\hat{u}'} \cdot \frac{a/L_{Ti}}{\hat{Q}_i}$$

$$\left(\frac{RV_\varphi}{\chi_\varphi}\right) = \left[\frac{\hat{\Pi}_\varphi(u,0) - \hat{\Pi}_\varphi(0,0)}{\hat{u}} - \underline{\hat{m}\hat{R}\hat{\Gamma}_p(u,0)}\right] \cdot \frac{\hat{u}'}{\hat{\Pi}_\varphi(0,u') - \hat{\Pi}_\varphi(0,0)}$$

Following Peeters et al.
PRL (2007)
Nucl. Fusion (2011)

- Subtracting particle convection contribution

Transport of toroidal angular momentum calculated from delta-f gyrokinetics (GYRO*)

- Transport calculated for toroidal momentum from correlation of perturbed distribution function and effective radial drifts from all EM fields

$$\delta f_s(\vec{x}) = -\frac{e\delta\varphi(\vec{x})}{T_s}F_{s0} + H_s(\vec{R}) \qquad (3.22)$$

$$\Pi_s = \underbrace{\oint}_{\text{flux surface average}} \int d^3v \underbrace{H_s^*(\vec{R})}\left\langle \underbrace{[m_s R(\vec{V}_0+\vec{v})\cdot\vec{e}_\varphi]}\, \underbrace{\frac{c}{B}\vec{b}\times\nabla\left[\delta\varphi(\vec{x}) - \frac{1}{c}(\vec{V}_0+\vec{v})\cdot\delta\vec{A}(\vec{x})\right]\cdot\nabla r} \right\rangle_{\text{gyro average}} \qquad (3.55)$$

Electrostatic E×B drift

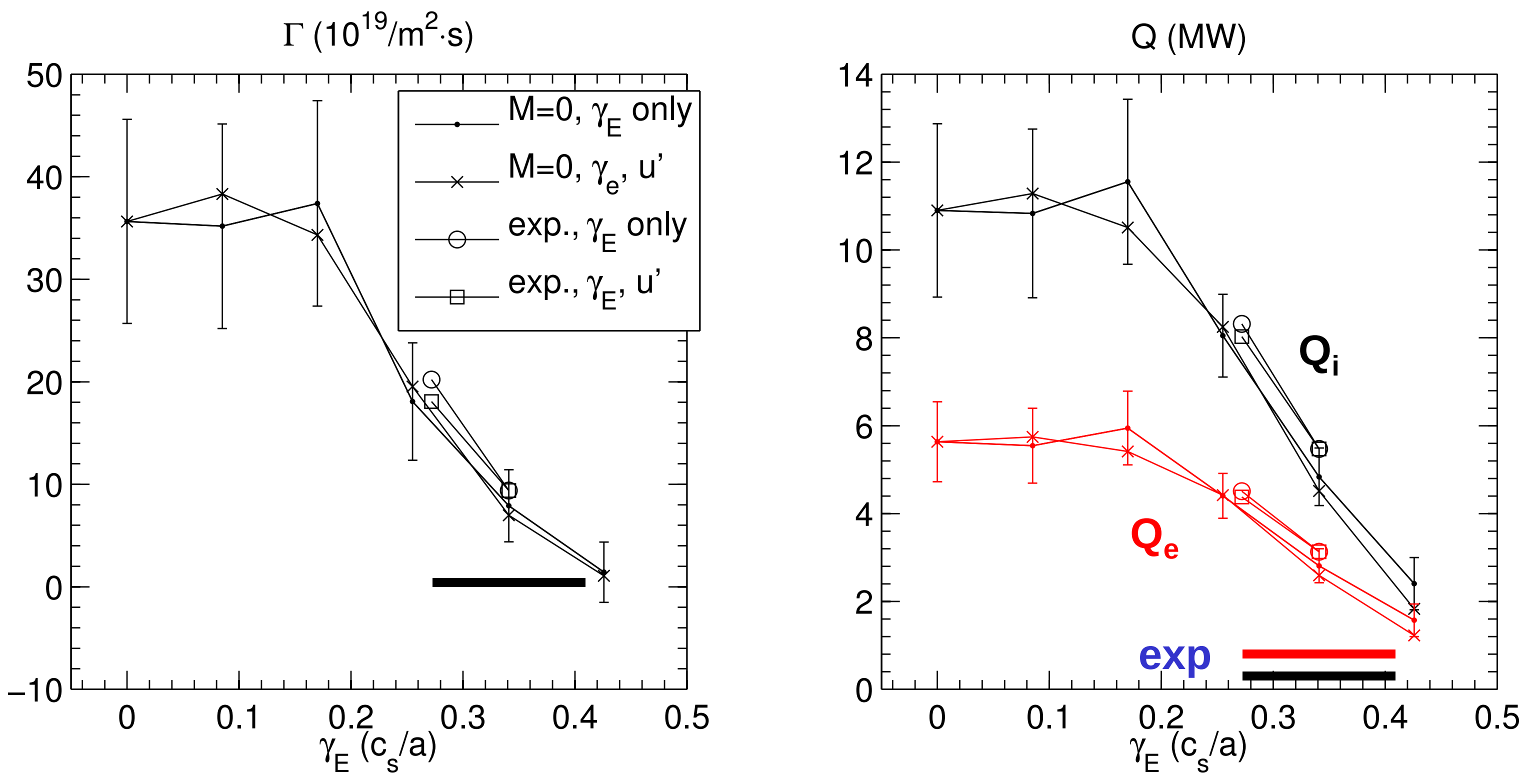
Drifts from shear ($v_{||}\nabla A_{||}\sim v_{||}B_r$) and compressional ($v_\perp\nabla A_\perp\sim v_\perp B_{||}$) magnetic perturbations

- *EM contributions are important in NSTX H-modes*

*Candy & Belli, GYRO Technical Guide, https://fusion.gat.com/theory/Gyro

E×B shear significantly reduces predicted transport

- Predicted fluxes are larger than experiment, opposite ratio of heat fluxes (Q_e/Q_i)
- Including parallel flow shear and toroidal flow have negligible impact on particle and heat flux



Residual stress (Π/Q) compared to real frequency variation