Comparison of Core Deuterium Ion Toroidal and Poloidal Rotation to Neoclassical Theory

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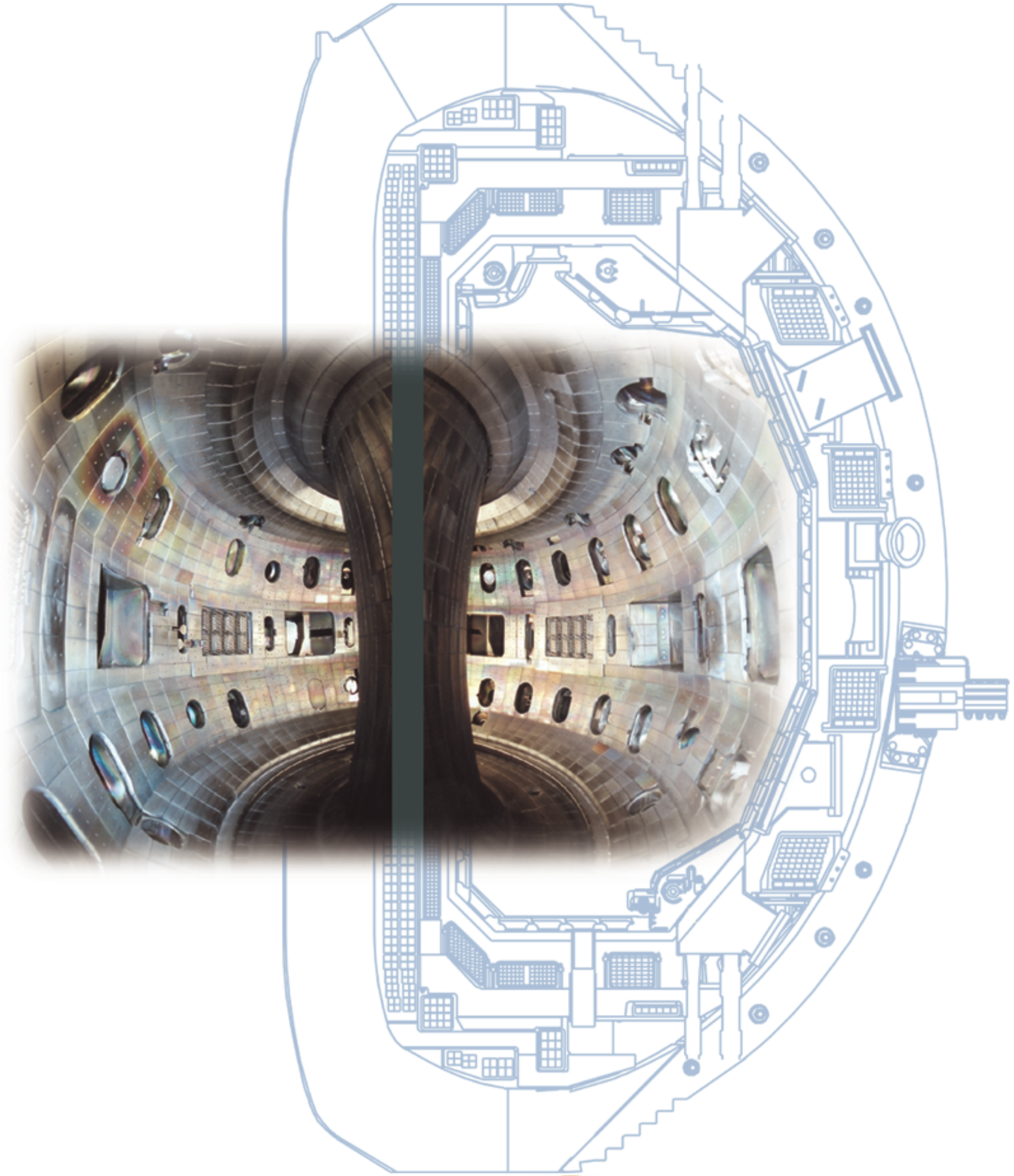


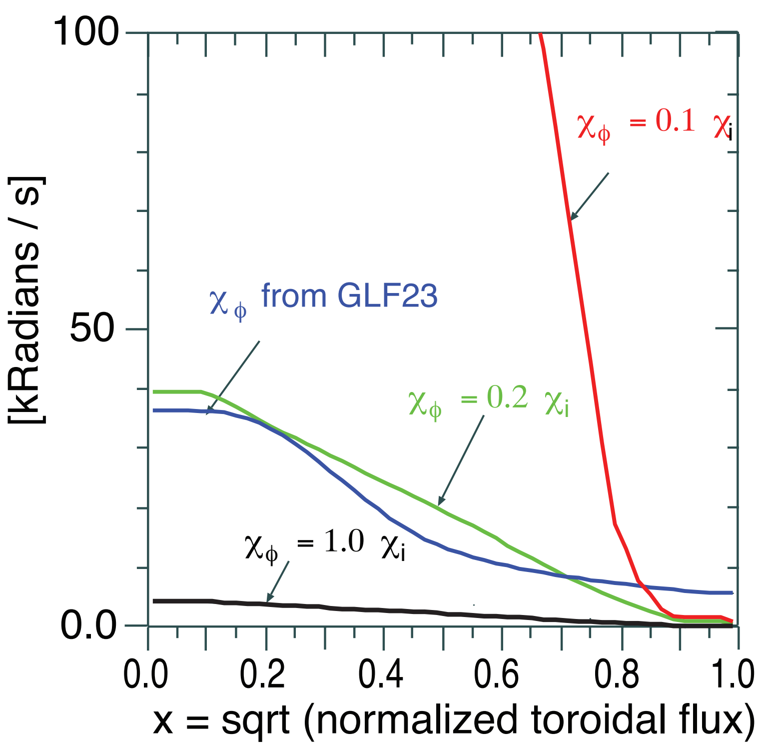
U.S. Transport Task Force Workshop
Annapolis, MD
April 10-13, 2012

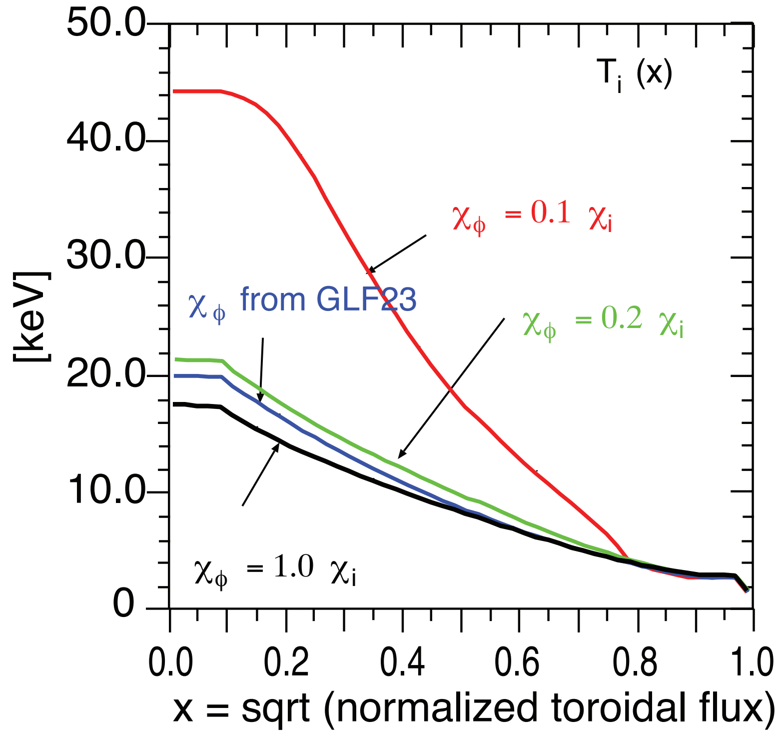
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

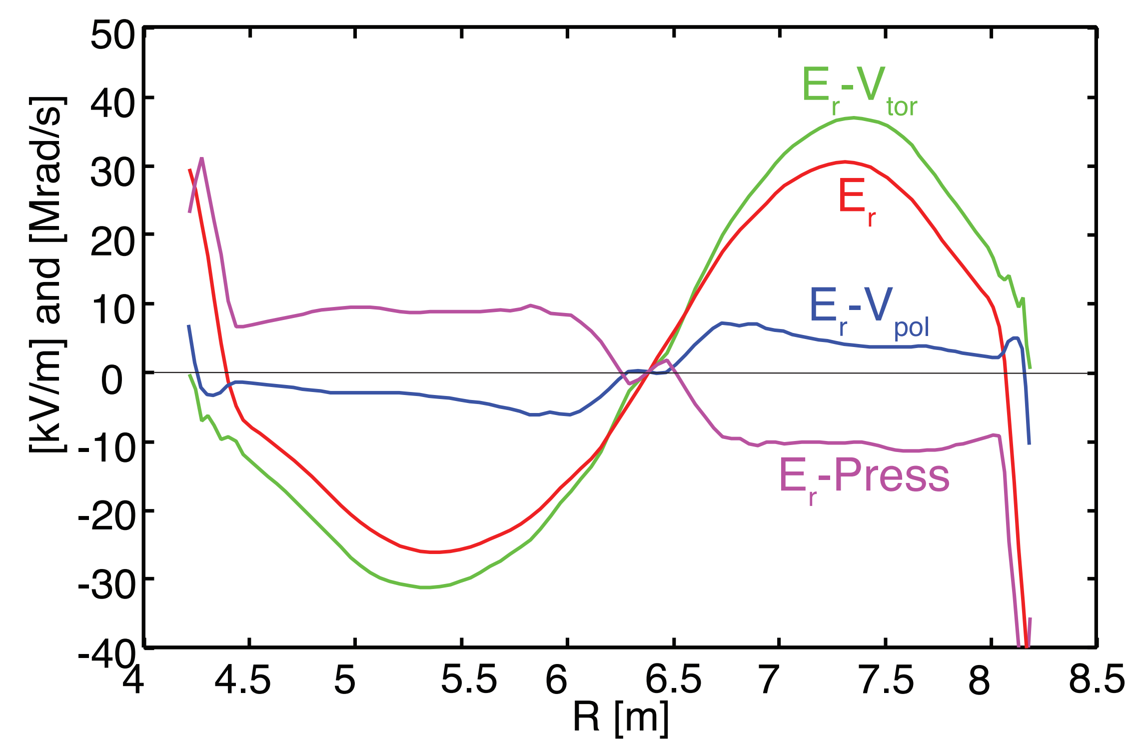
PPPL

Understanding and Predicting Toroidal and Poloidal Rotation is Critical for Projecting ITER Performance

- **Level of toroidal rotation achieved determines stability to MHD, and turbulence reduction by ExB shear[1]**
- **Predictions[2] of ITER toroidal rotation varies significantly amongst models and assumptions of χ_ϕ**
- **If core toroidal rotation is largely absent neoclassical will give no Er because poloidal and pressure contributions cancel**







[1]Politzer, Nucl. Fusion (2008)
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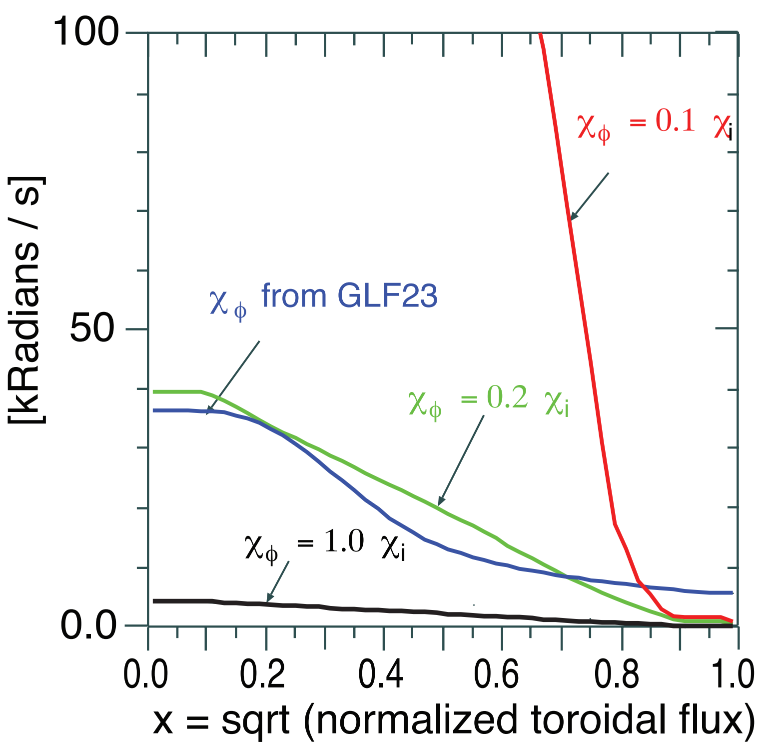

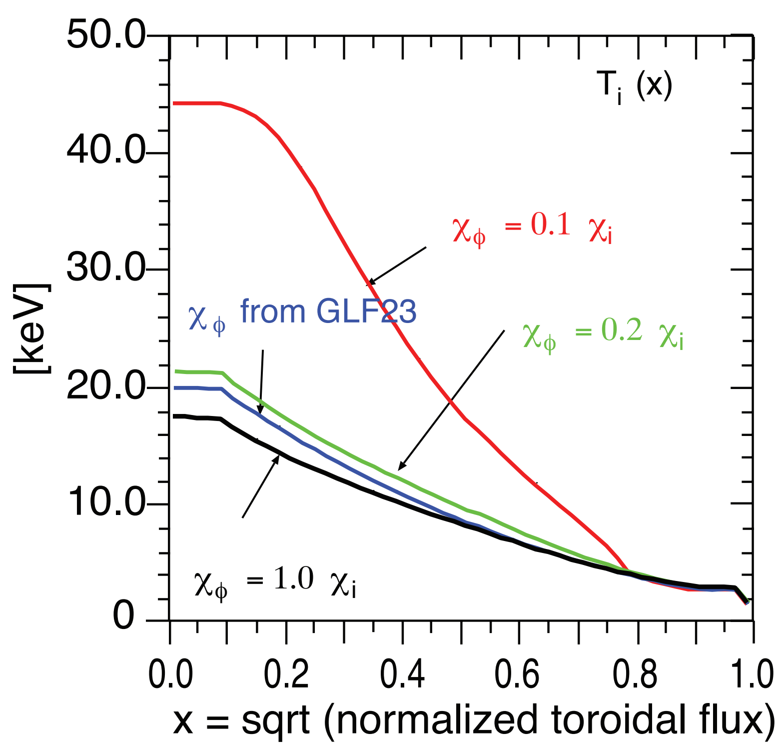

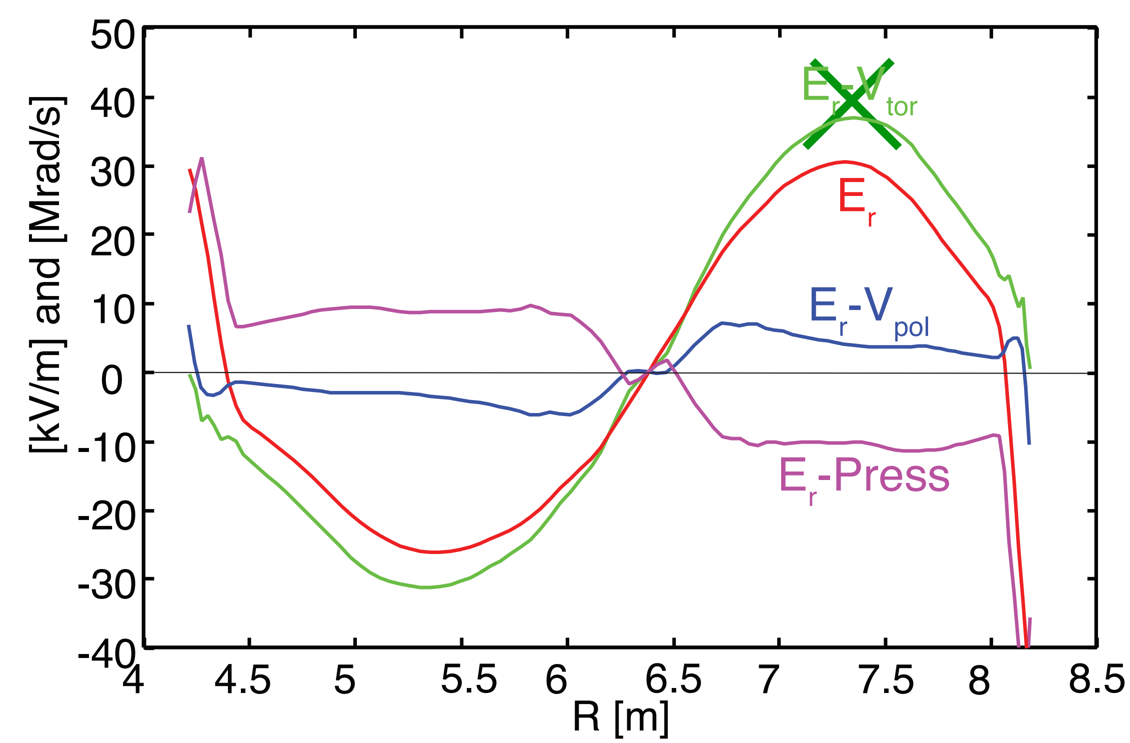

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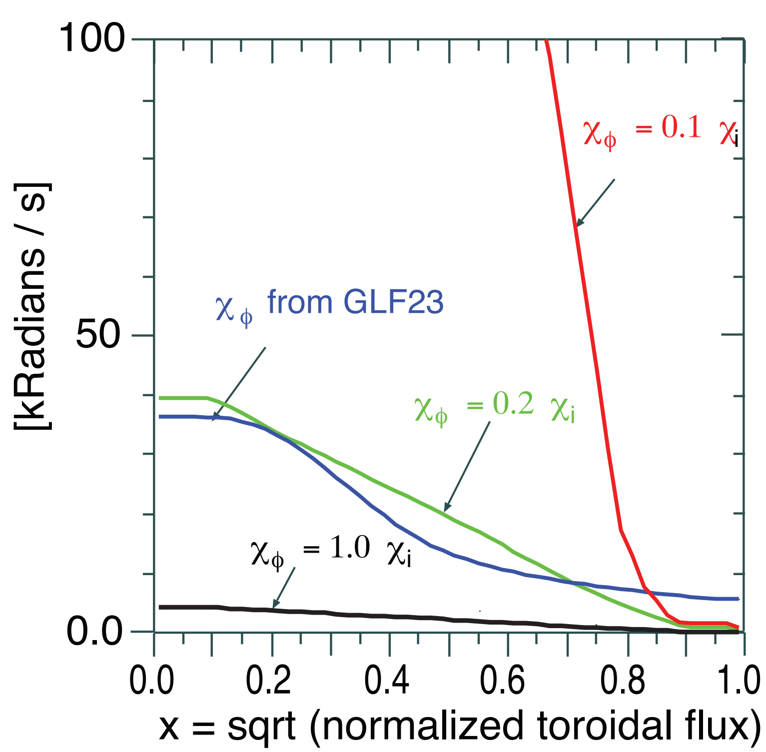

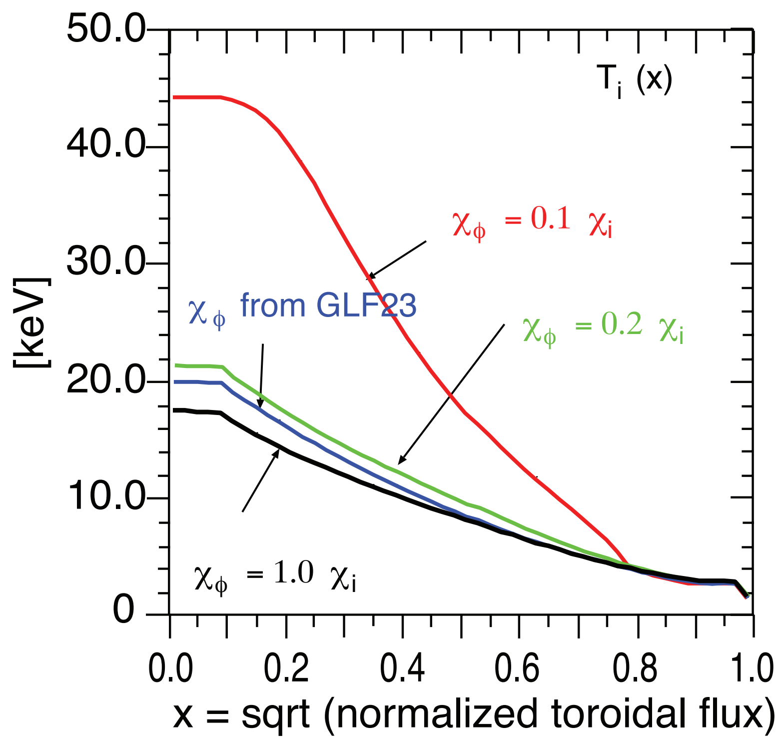

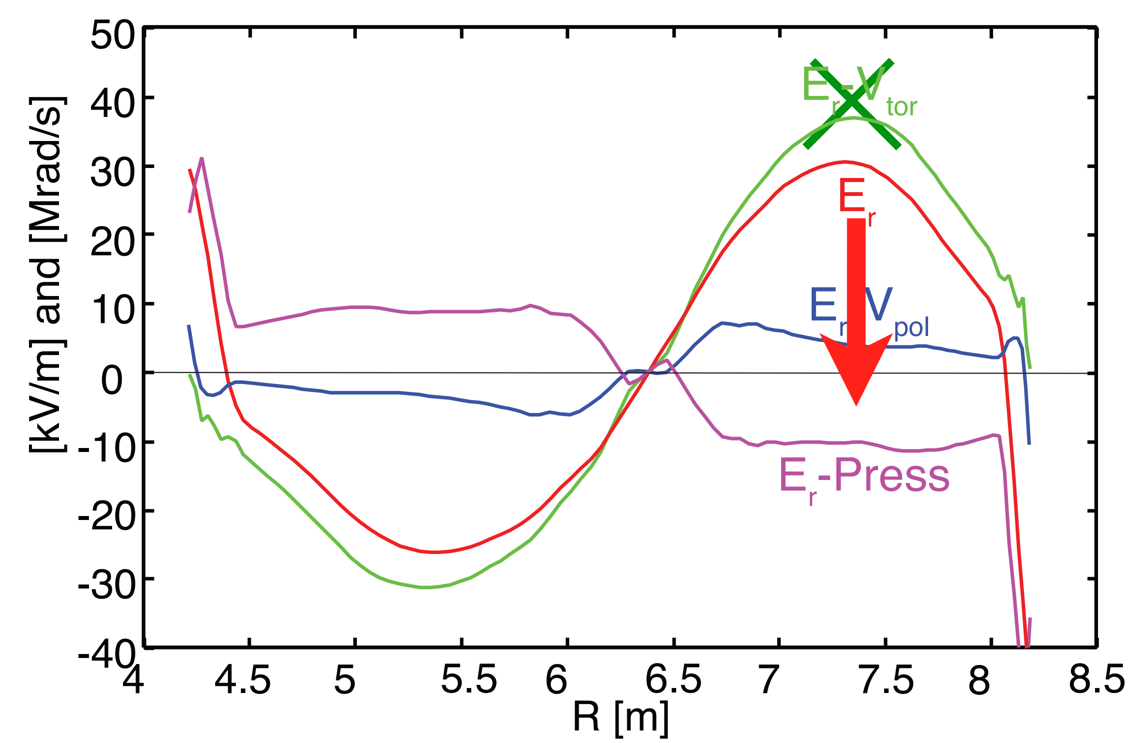

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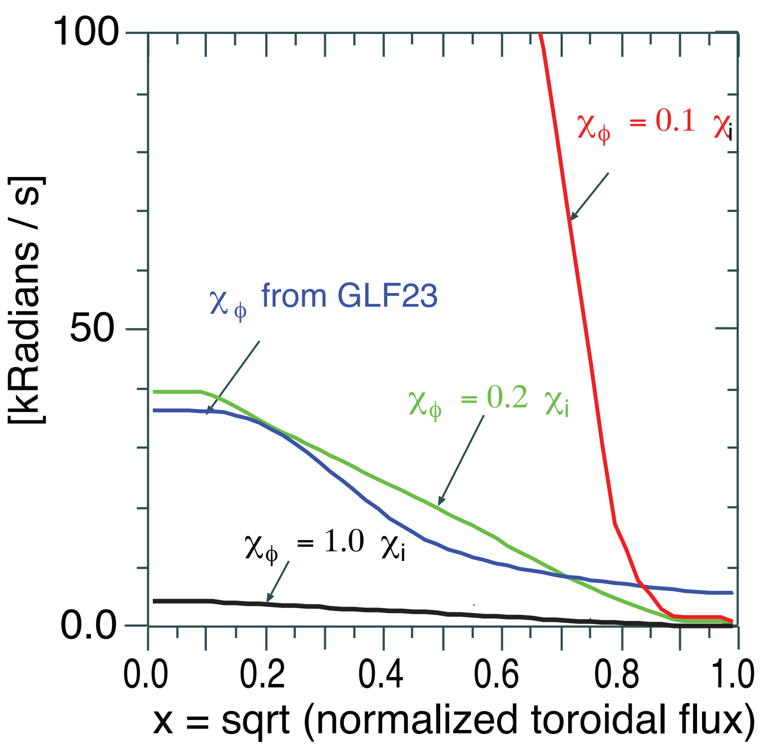

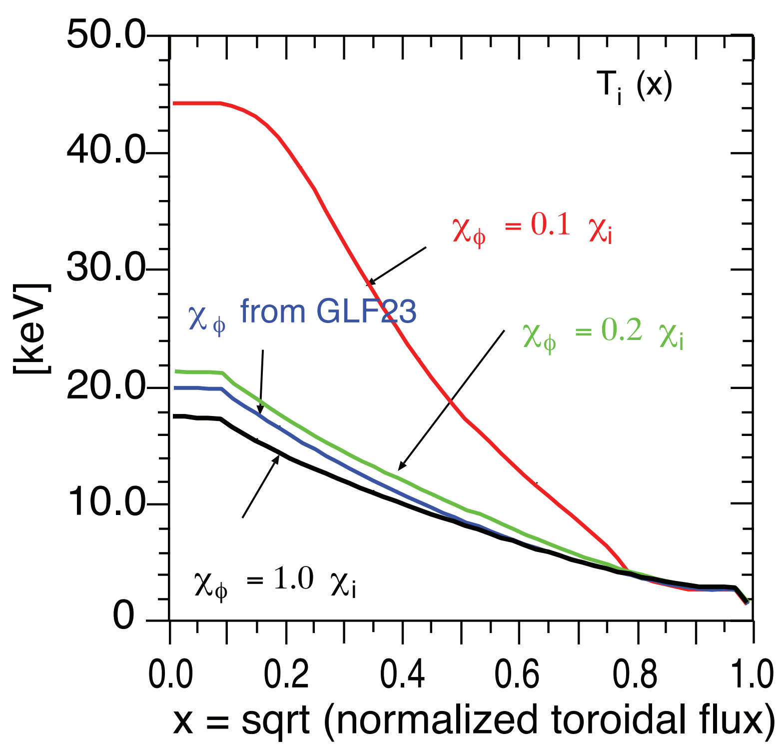

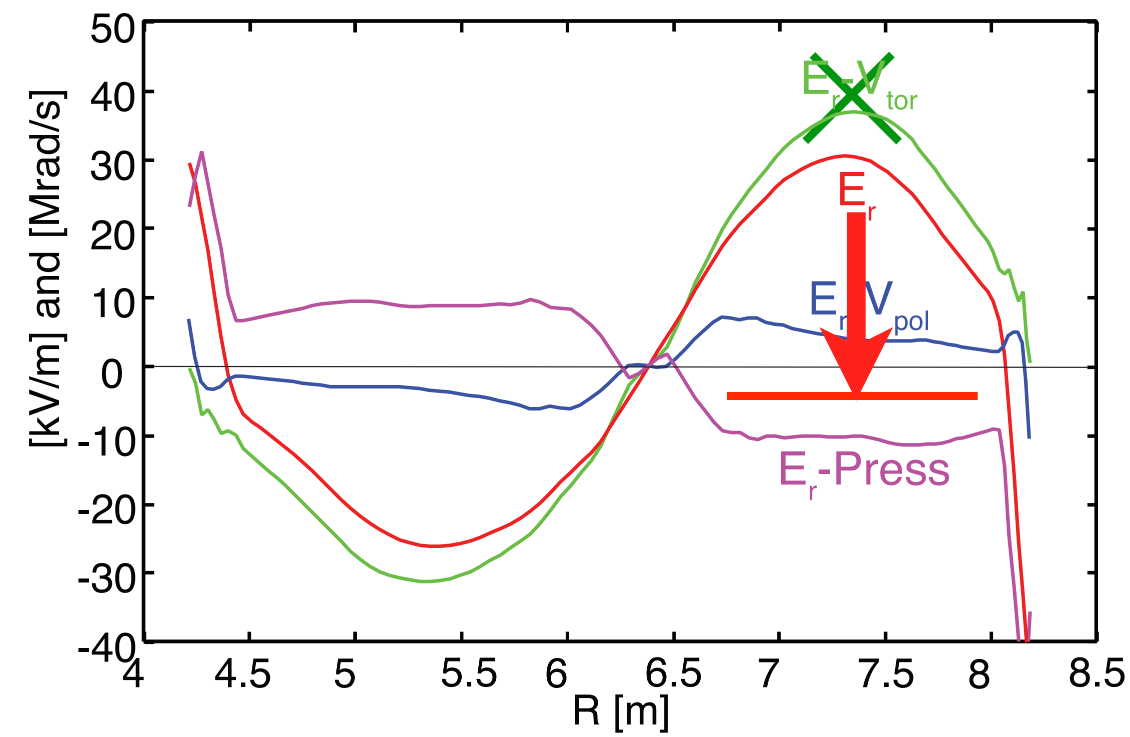

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For Negligible Toroidal Rotation the Pressure and Poloidal Rotation Contributions Determine E_r

- **Current understanding of toroidal rotation relies on χ_ϕ/χ_i scalings[1] or projections of intrinsic rotation[2]**
- Scalings of χ_ϕ/χ_i largely determined in NBI heated plasmas
- Intrinsic rotation in BP conditions unknown

$$E_r = \frac{\nabla P_i}{Zen_i} + V_\varphi B_\theta - V_\theta B_\varphi$$

1 deGrassie, Nucl. Fusion (2003)
2 Rice, Nucl. Fusion (2007)

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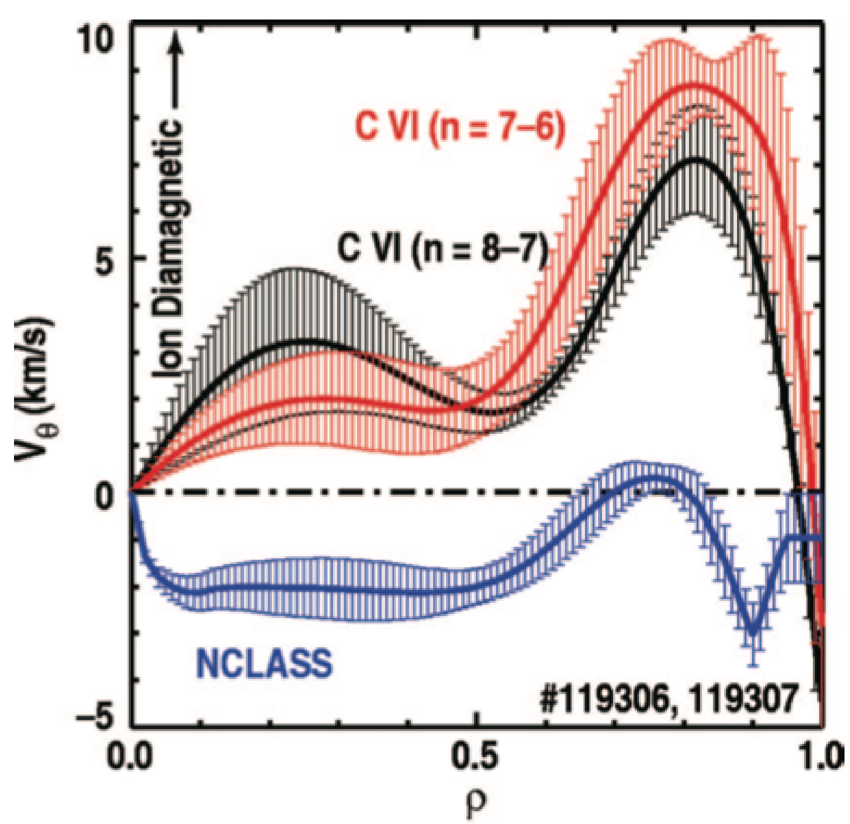
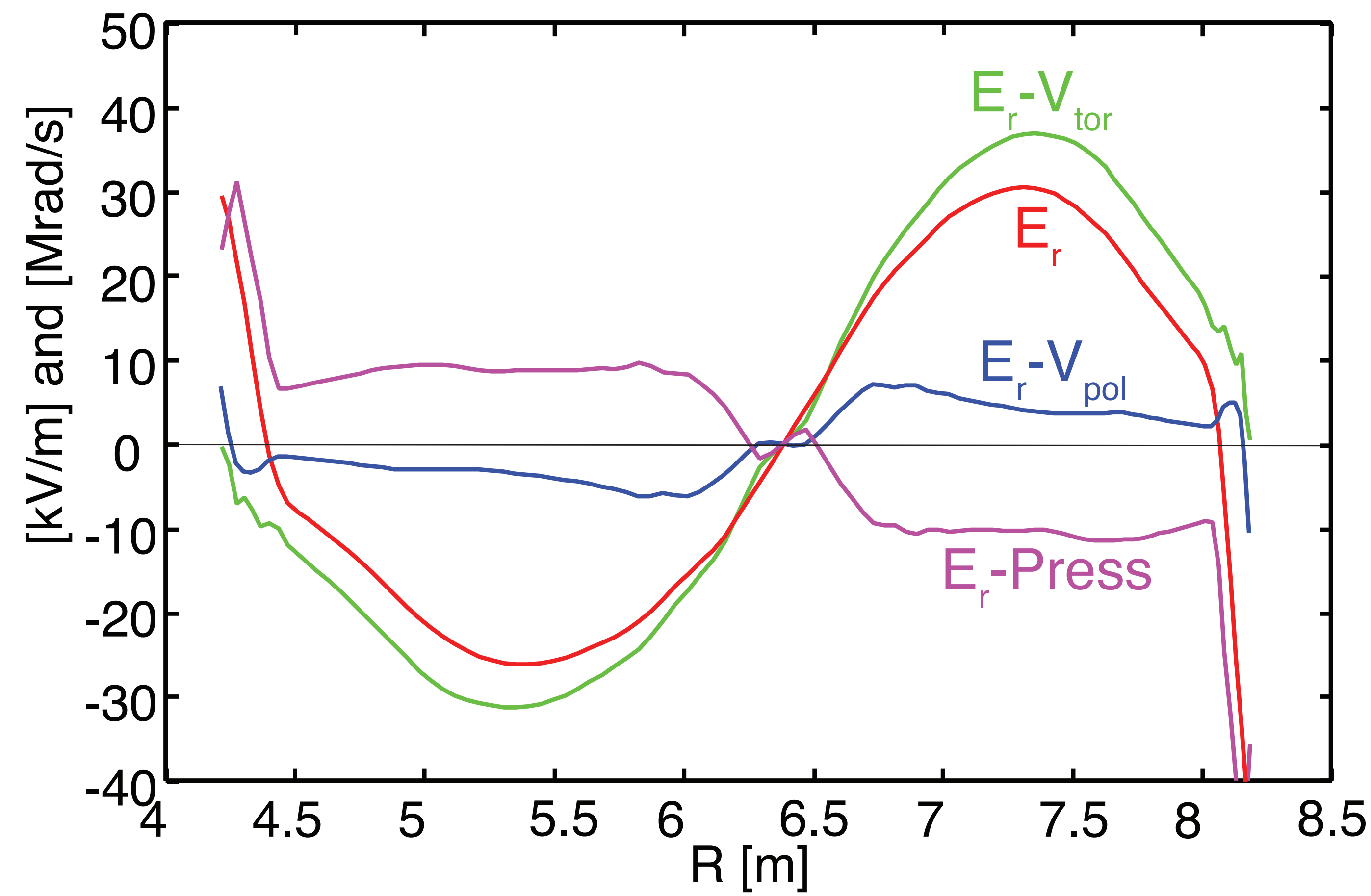
Understanding Poloidal Rotation will be Critical in the Burning Plasma Regime

- **Neoclassical codes (NCLASS) employed to compute poloidal rotation in ITER conditions**
- **Neoclassical codes appear to fail in getting magnitude and sign of poloidal flow**





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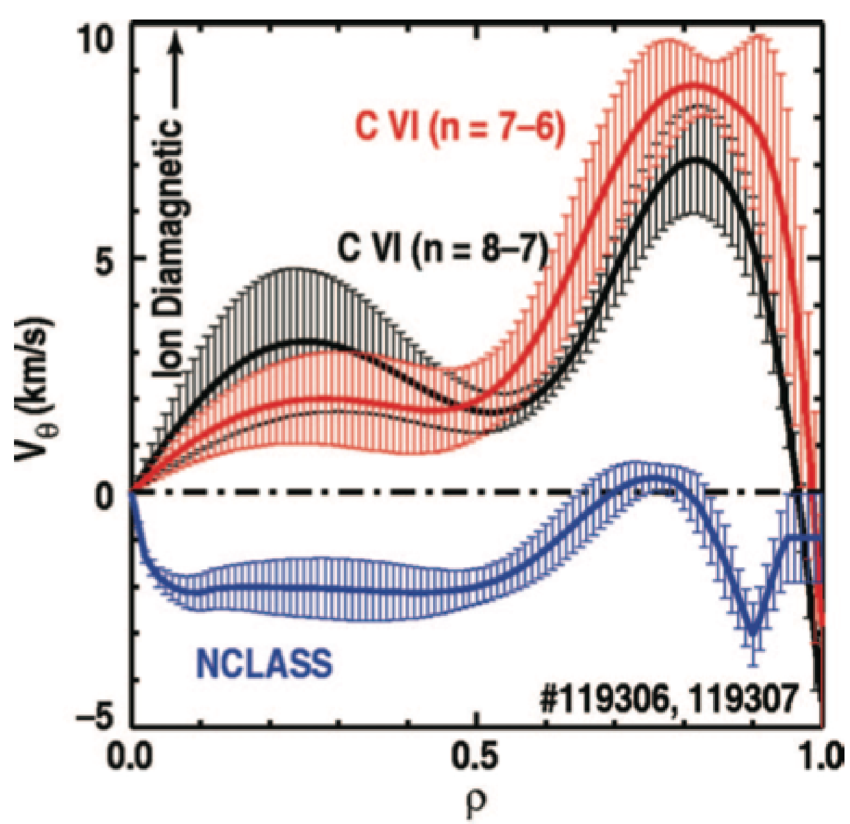

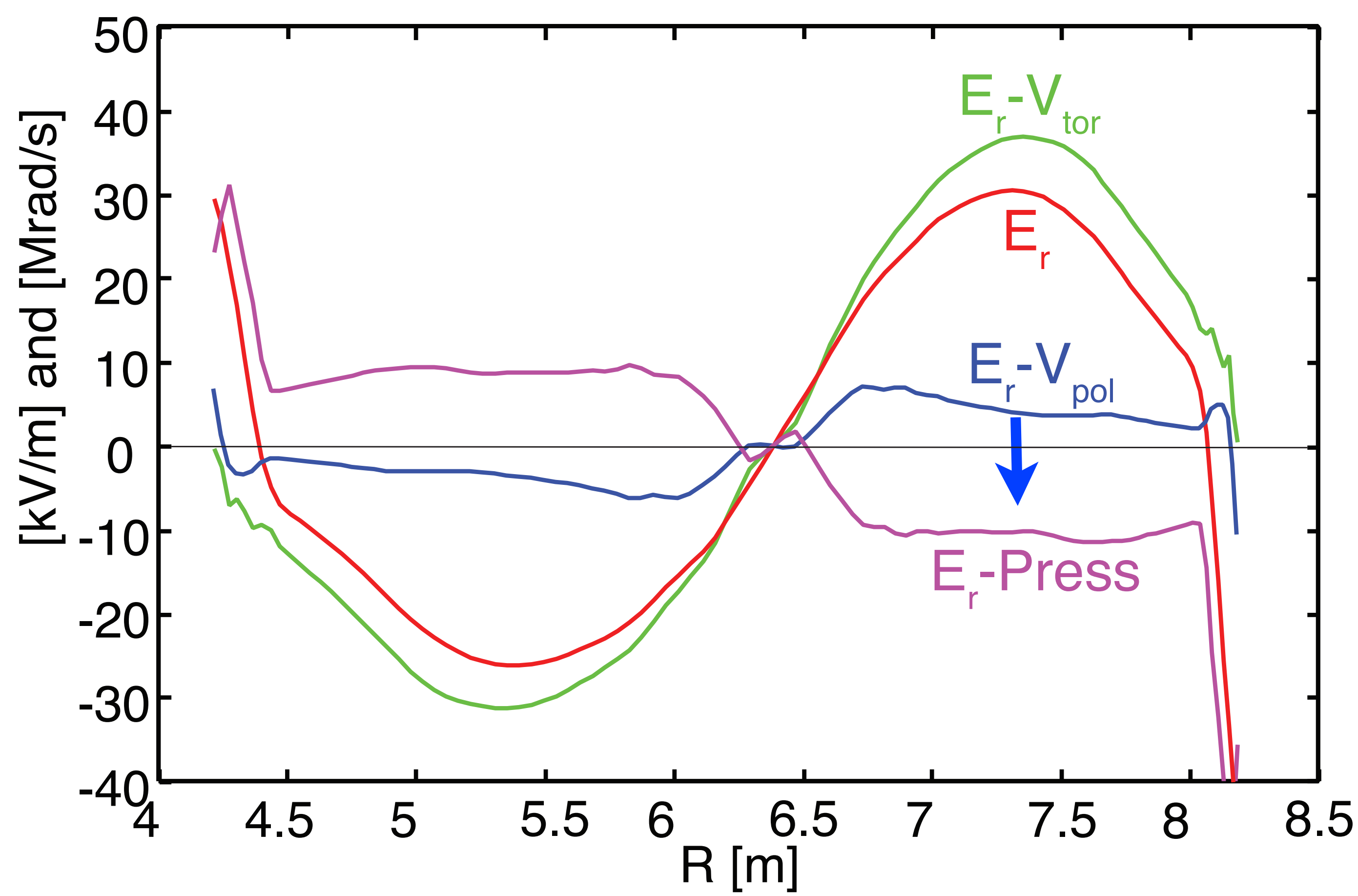

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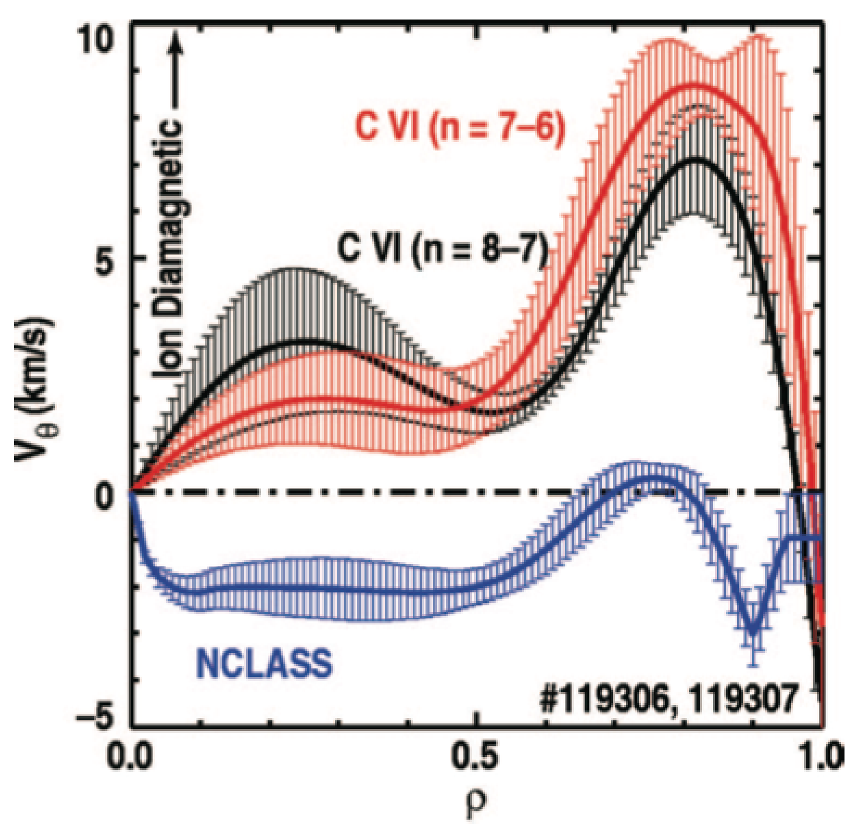

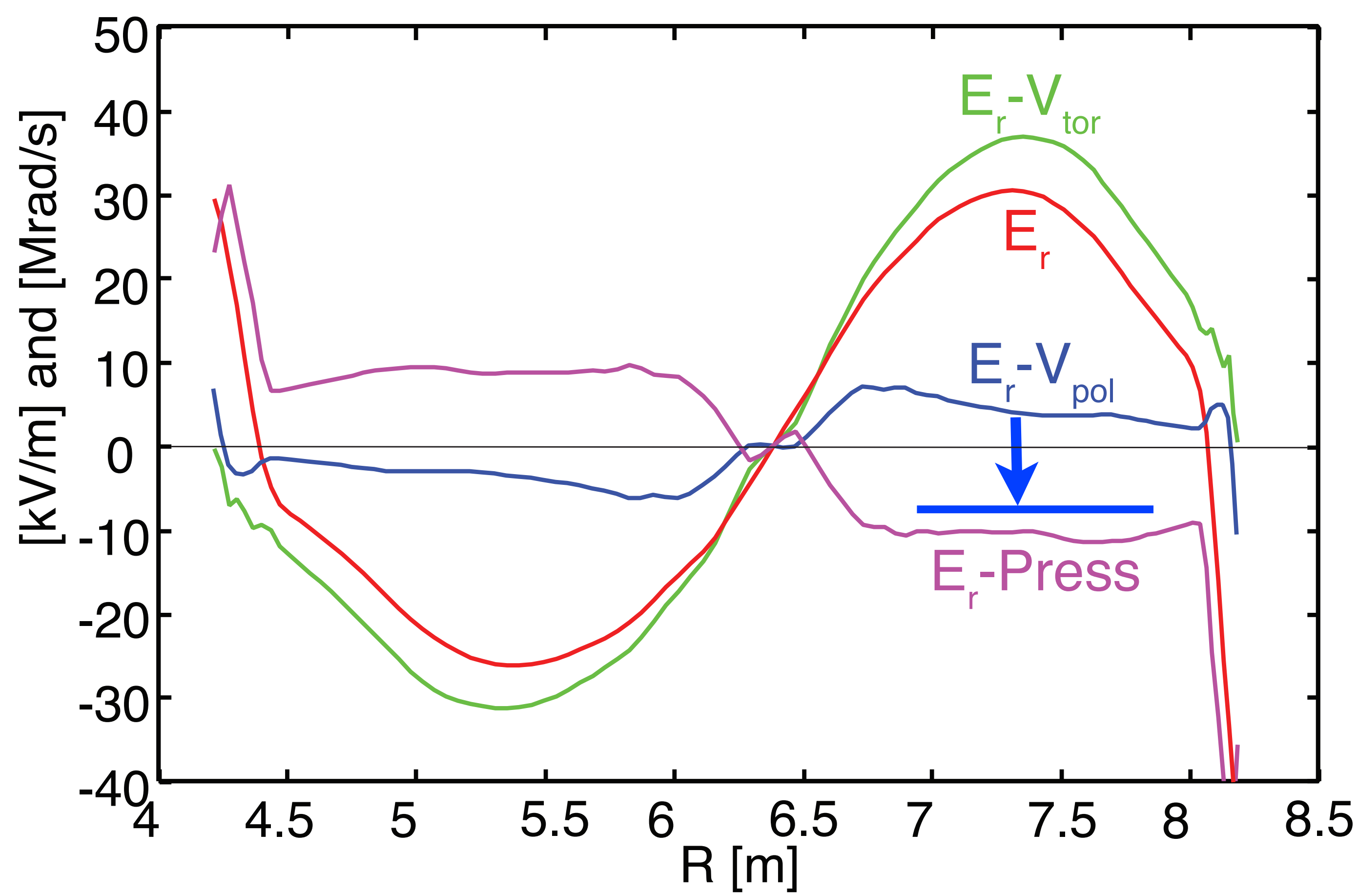

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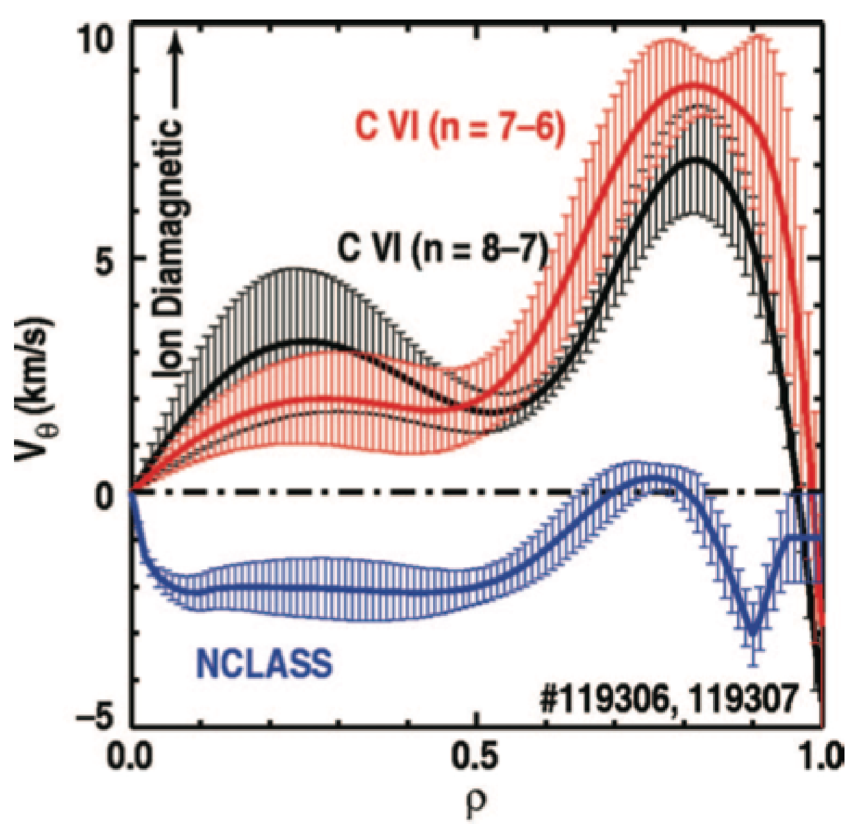
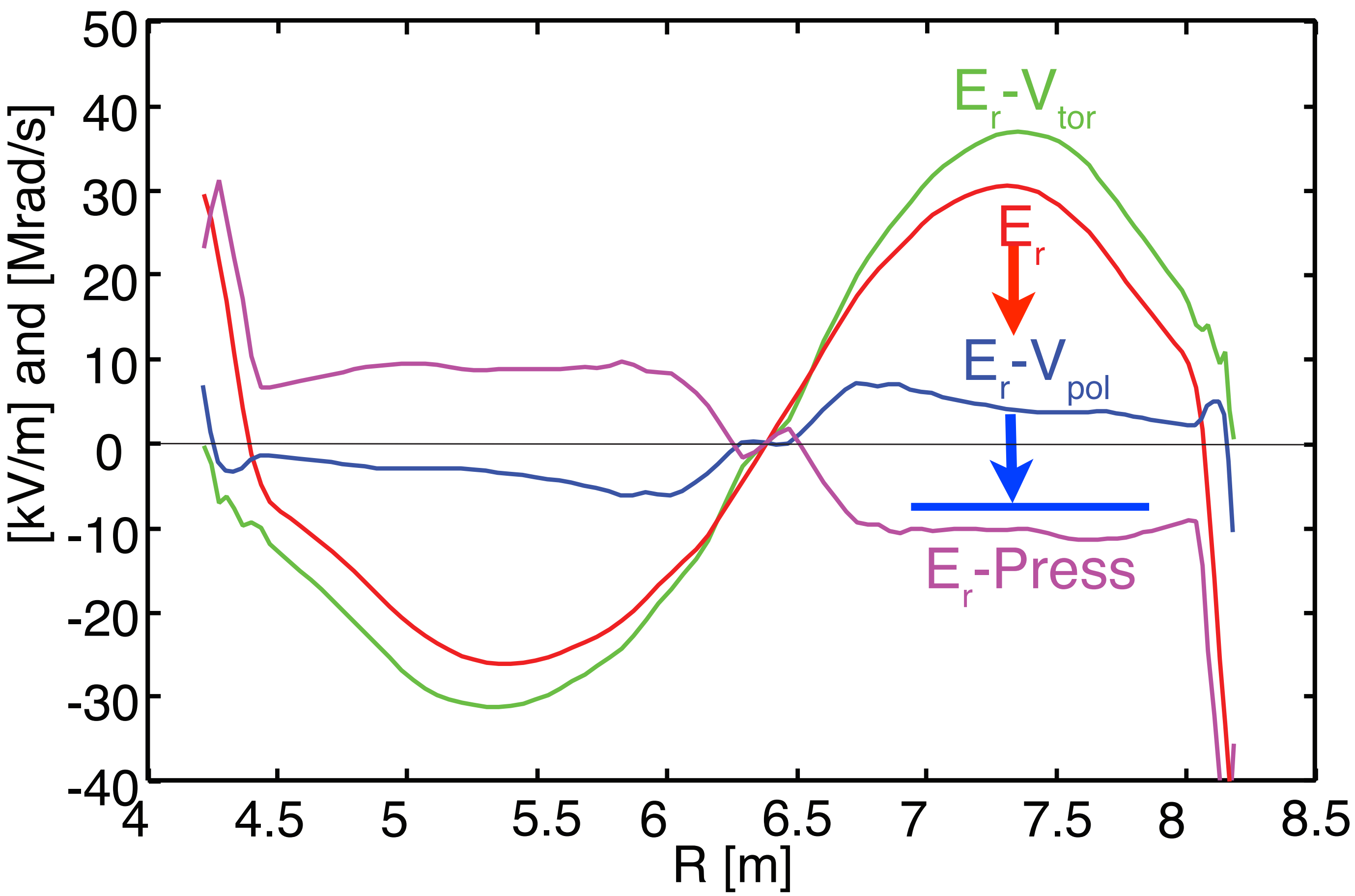




Here's what I'm going to tell you

- We can now measured the bulk ion toroidal rotation in a deuterium plasma in DIII-D
- The bulk ion toroidal rotation does not match the NCLASS predicted toroidal rotation
- Measurement of main-ion toroidal rotation and pressure allows inference of main-ion poloidal rotation via radial force balance
- The fundamental neoclassical quantity, poloidal rotation, is not consistent with observation

New Main-ion CER Capability on DIII-D Used to Investigate Deuterium Toroidal & Poloidal Rotation

- Diagnostic overcomes a number of atomic physics issues with active spectroscopy using D beams into D plasmas
- Provides radial profile of T_i^D, V_{tor}^D and inferred thermal n_D from magnetic axis to near pedestal
- Use NCLASS to compute predicted deuterium ion toroidal rotation with experimental measurements

Mechanics of the neoclassical prediction

n_e, T_e
n_C, T_i, V_φ^C
+
n_b (NUBEAM)

→ $n_D = n_e - Z_C n_C - n_b$ → n_D, T_i^D
n_C, T_i^C, V_φ^C

NCLASS → V_θ^D
V_θ^C

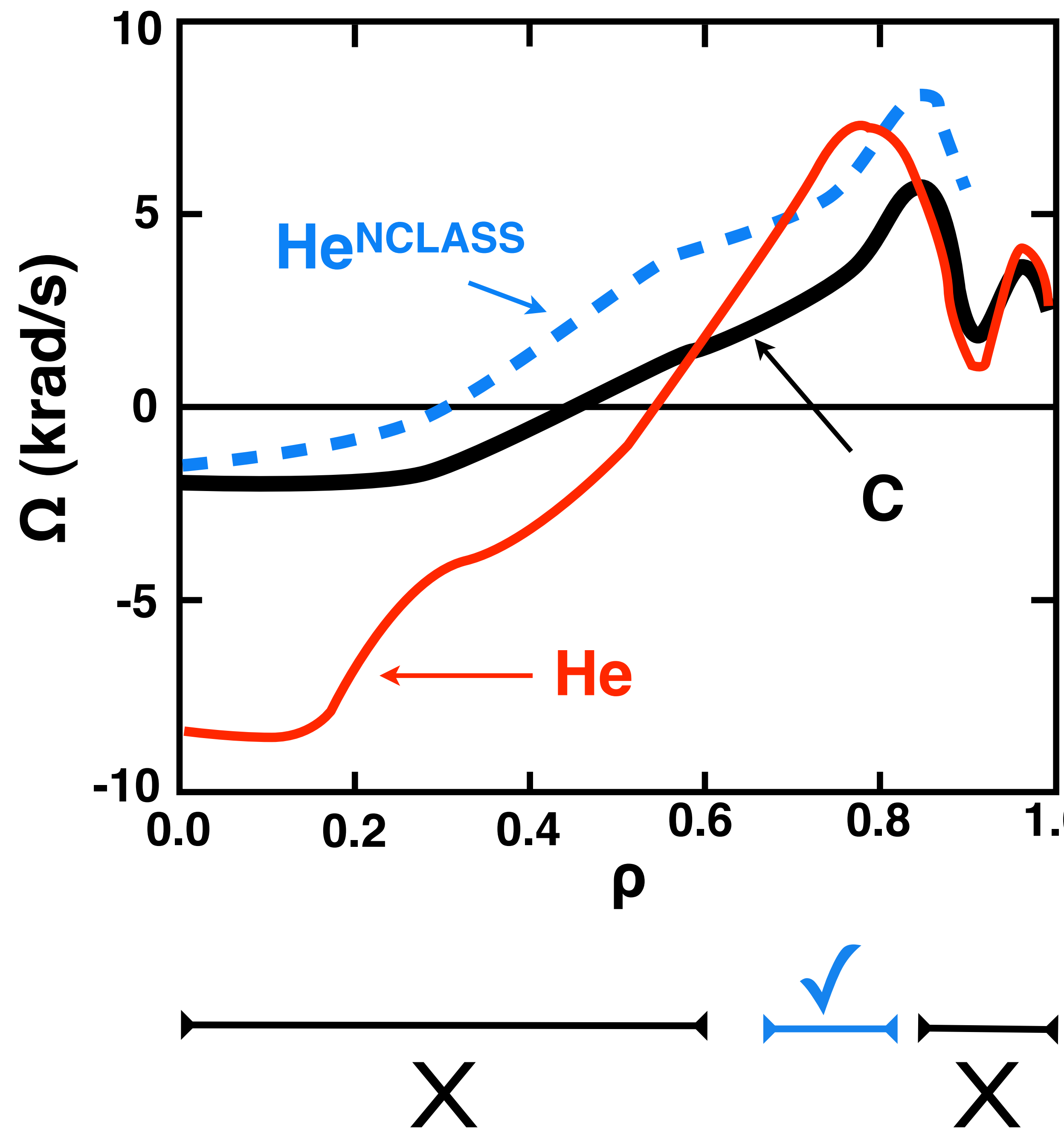
Force Balance →

$$E_r = \frac{\nabla P_i}{Zen_i} + V_\varphi B_\theta - V_\theta B_\varphi$$

$$V_\varphi^D = V_\varphi^C + \frac{1}{B_\theta}\left(\frac{\nabla P_C}{Z_C e n_C} - \frac{\nabla P_D}{e n_D}\right) - \frac{B_\varphi}{B_\theta}(V_\theta^C - V_\theta^D)$$

Previous Toroidal Rotation Studies in Helium Plasmas Displayed Significant Difference from Neoclassical

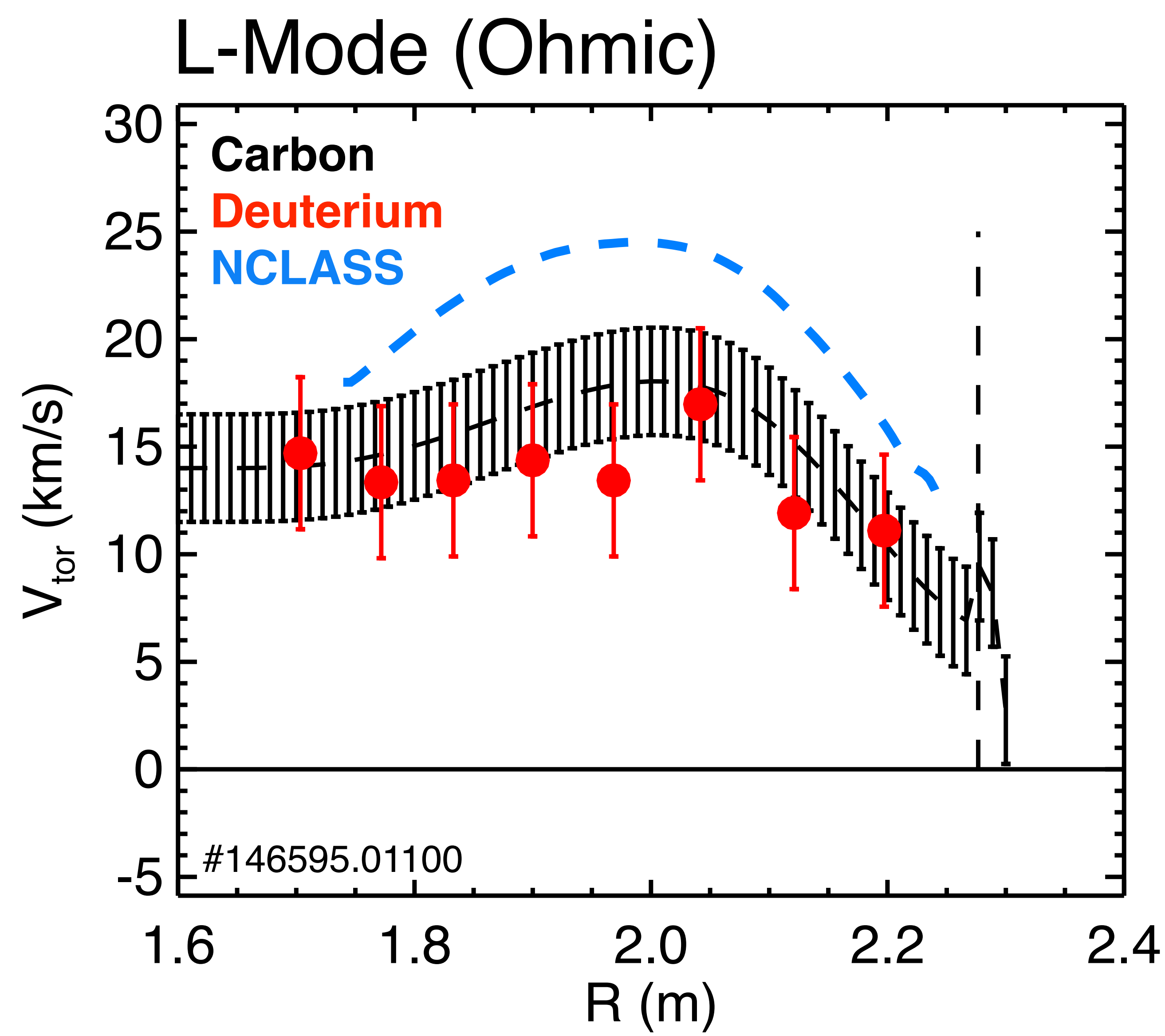
- Intrinsic rotation in ECH H-mode to determine impurity and bulk ion rotation[1]
- Measured helium profile indicates NCLASS predicts inconsistent sign of $(V_{tor}^{C} - V_{tor}^{He})$
- General result?



[1]J. S. de Grassie Phys. Plasmas **14** (2007)

New Measurements of Deuterium Toroidal Rotation also Inconsistent with NCLASS Neoclassical

- **L-mode (ohmic) main-ion rotation profile similar profile to carbon**
- ELM-free phase ECH H-mode displays measured V_{tor}^{D} more ctr-Ip in the core compared to NCLASS
- Core rotation rise of deuterium and carbon are similar as edge momentum pinched into the core, but
  - Deuterium persistently ctr-Ip compared to carbon



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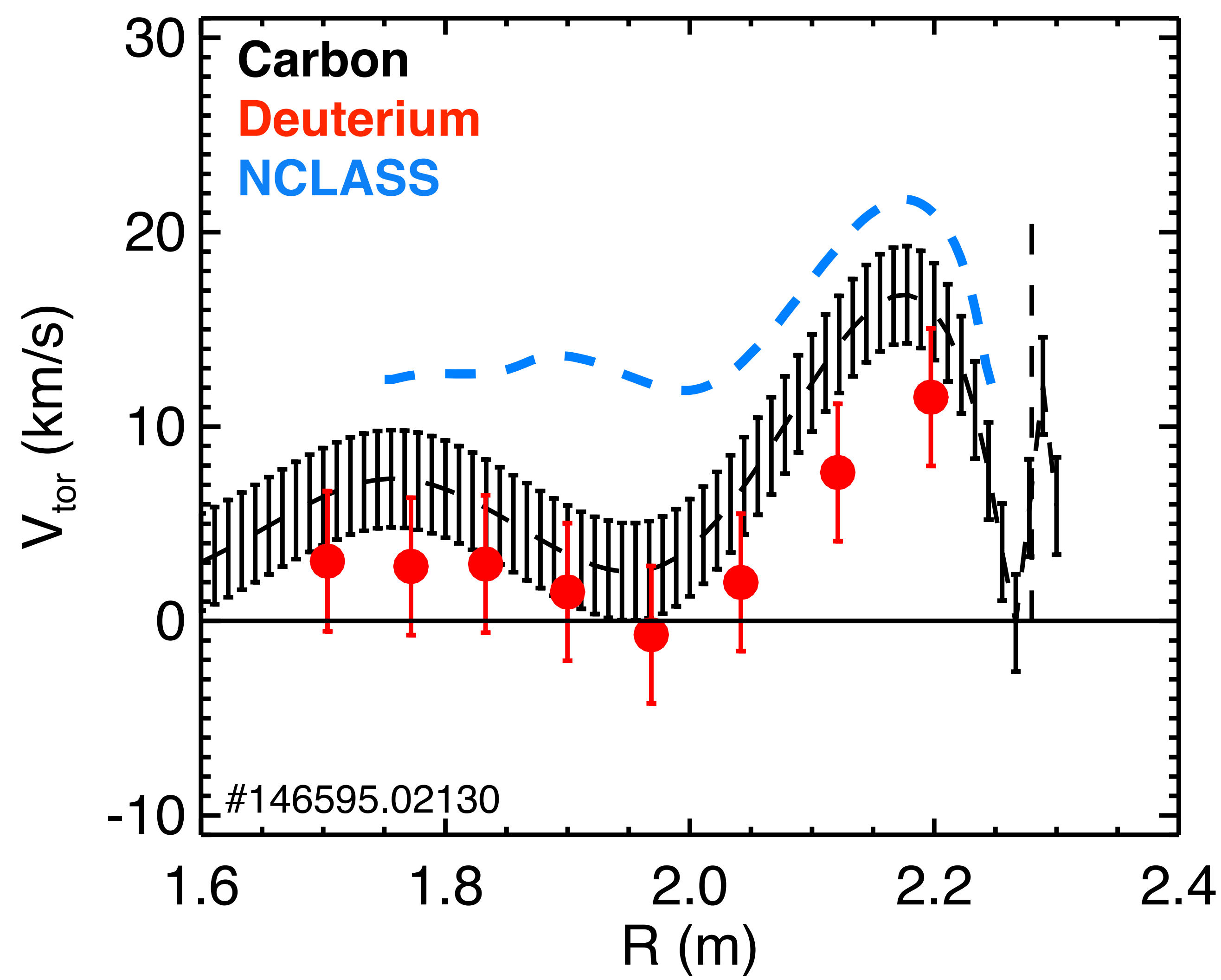
ECH H-Mode



B.A. Grierson Phys. Plasmas **19** (2012)

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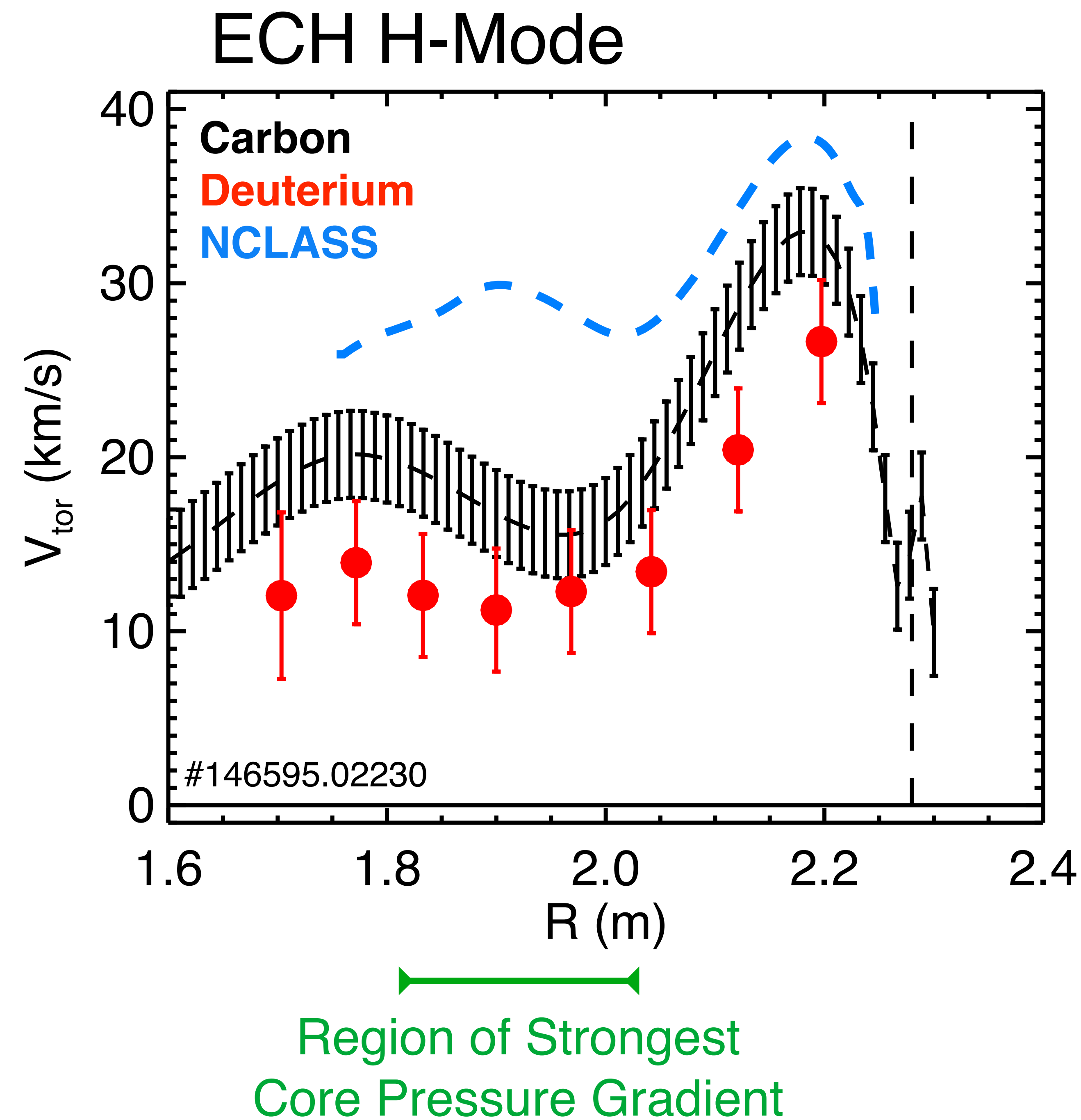
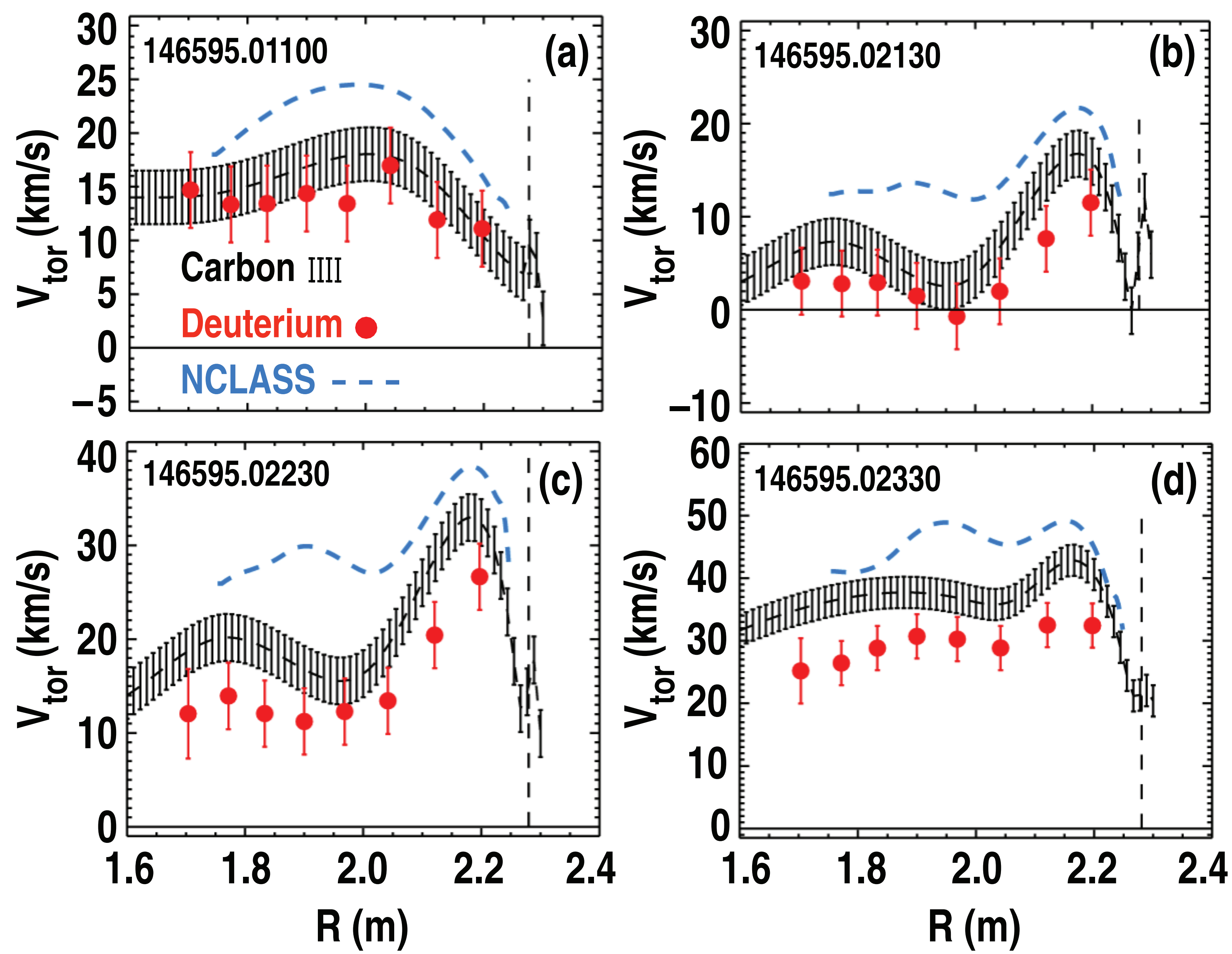


B.A. Grierson Phys. Plasmas **19** (2012)

Both Deuterium and Carbon Rotation Increase in time in ECH H-Mode

- **In ELM-free H-Mode core rotation ~0 , ~10, ~30 km/s over 300 ms**
- **Edge co-rotation stronger than core in ELM-free H-Mode**
- **NCLASS does not predict magnitude or profile shape of main-ion toroidal rotation**

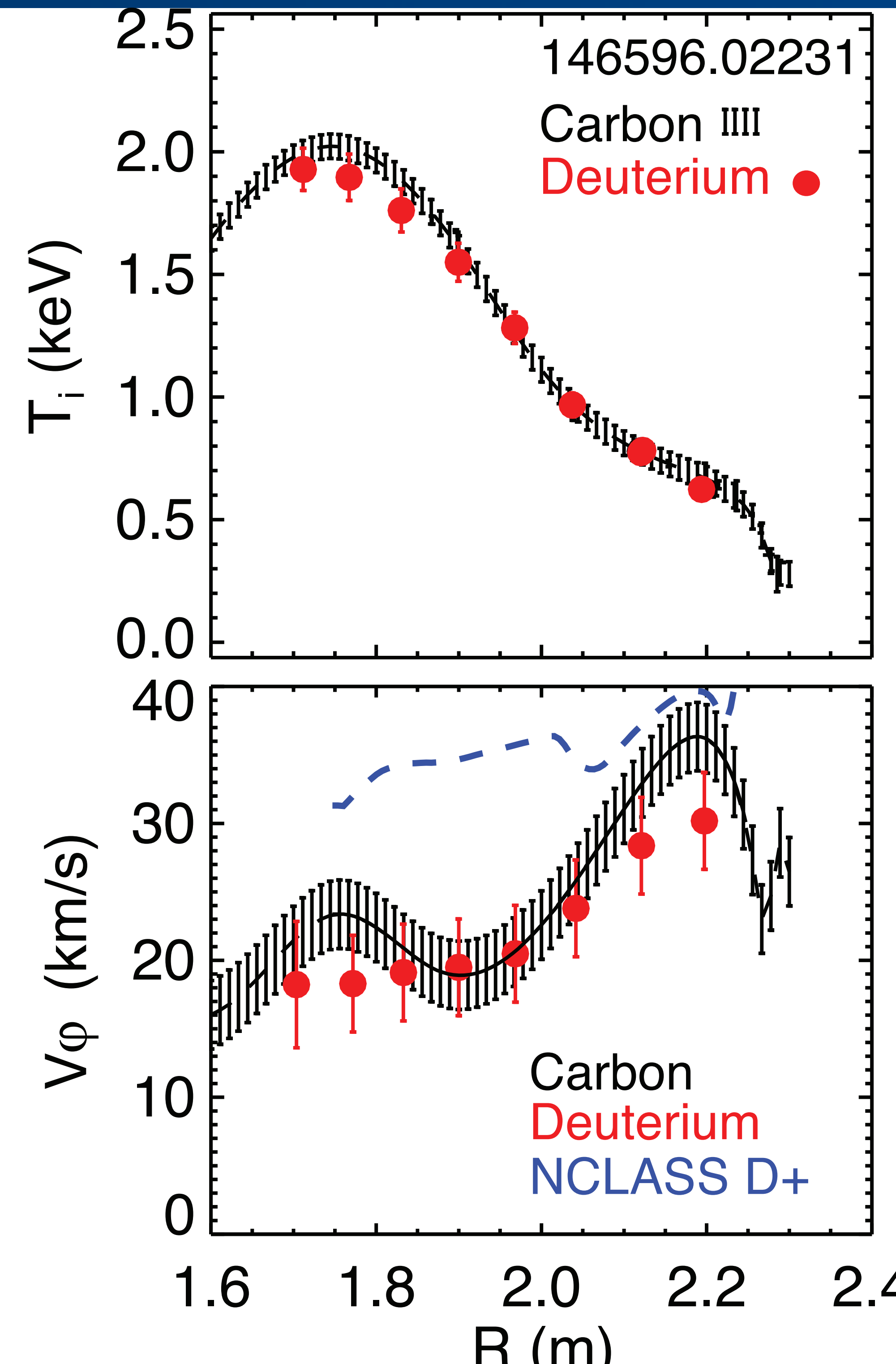


B.A. Grierson Phys. Plasmas **19** (2012)

Test Neoclassical by Inferring Poloidal Flow

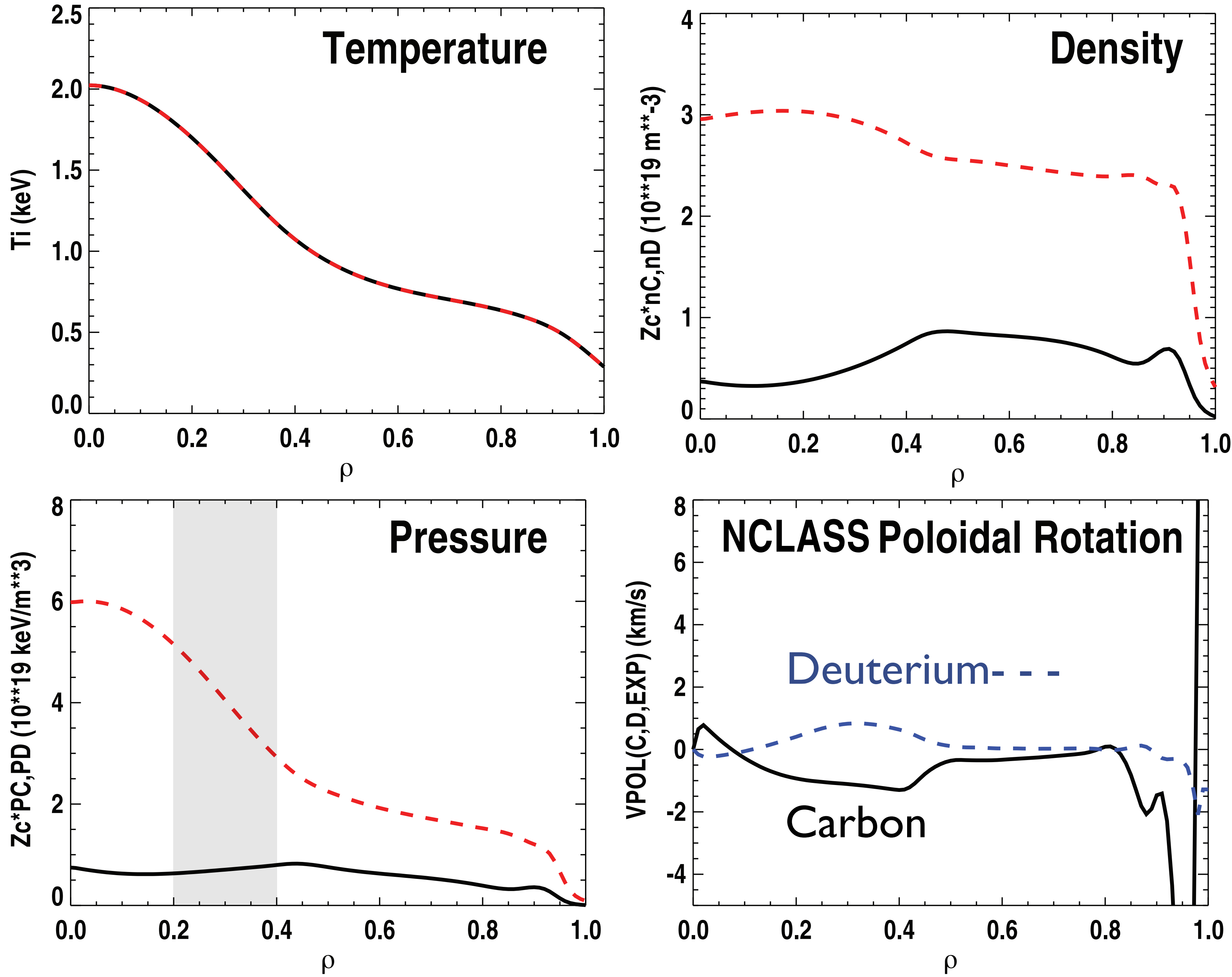
- **Reduced Current (0.74 MA vs. previous 0.93 MA) ECH H-Mode displayed strong core pressure gradient and large NCLASS predicted main-ion toroidal rotation**

- **Use measured toroidal rotation and pressure profiles and carbon V_{pol} to infer the main-ion poloidal flow**



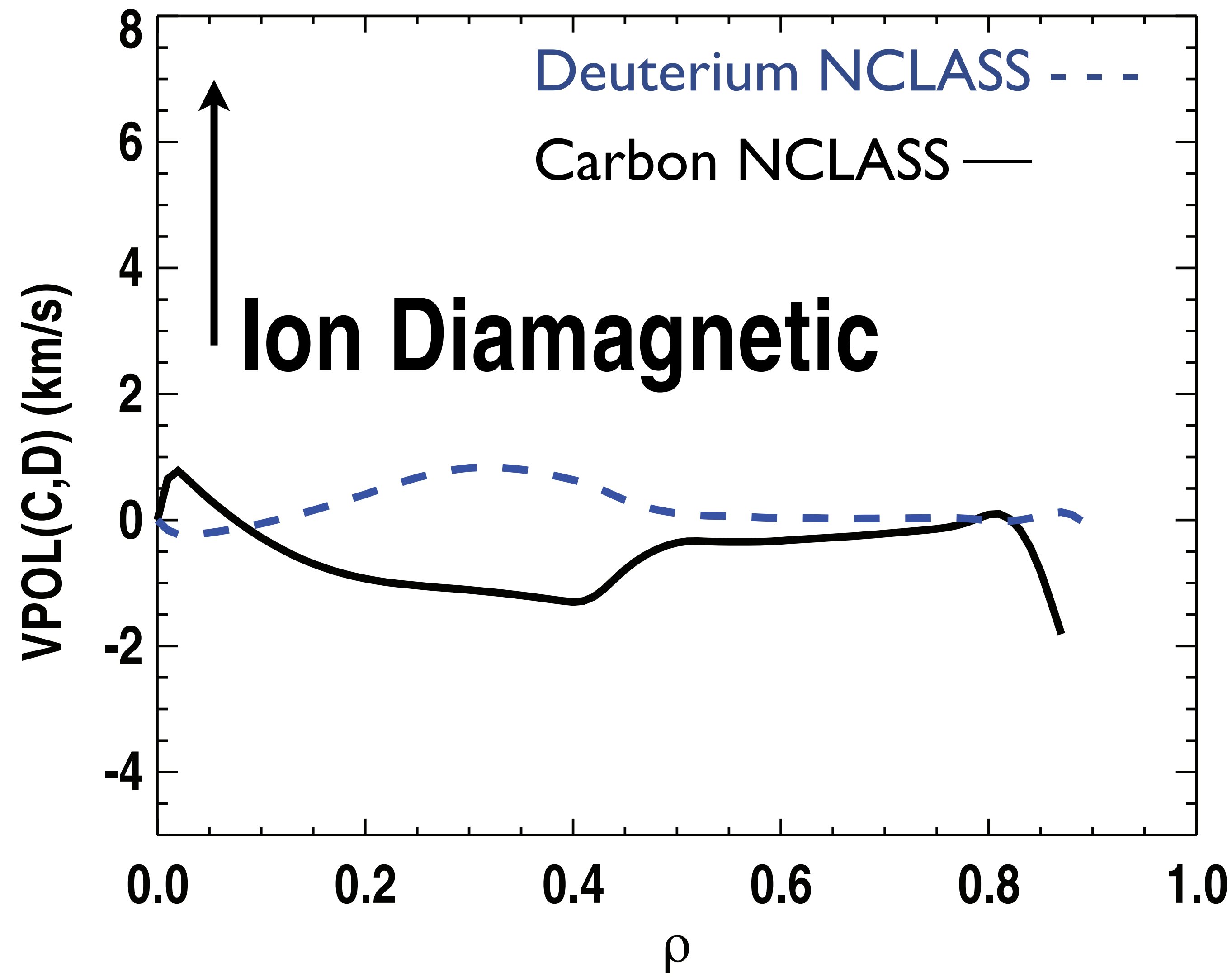
Test Neoclassical by Measuring Poloidal Flow

- Strongest core pressure gradient localized to ρ=[0.2,0.4]
- Weak reversal in q-profile (NCS) near ρ=0.3



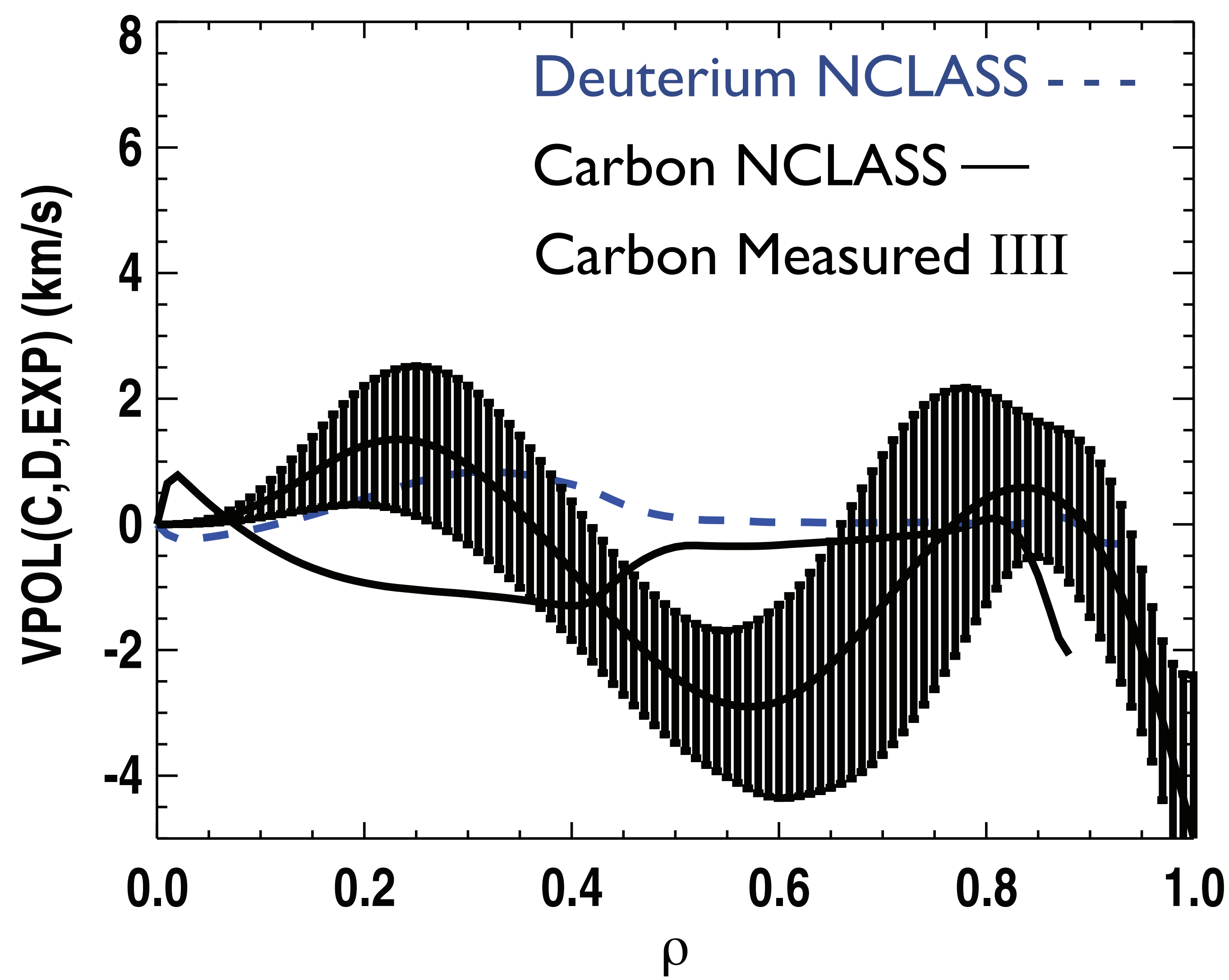
Test Neoclassical by Measuring Poloidal Flow

- **NCLASS indicates core poloidal rotation of deuterium and carbon in opposite direction (deuterium ion diamag.)**
- **Ion diamagnetic deuterium flow is consistent with banana regime**



Test Neoclassical by Measuring Poloidal Flow

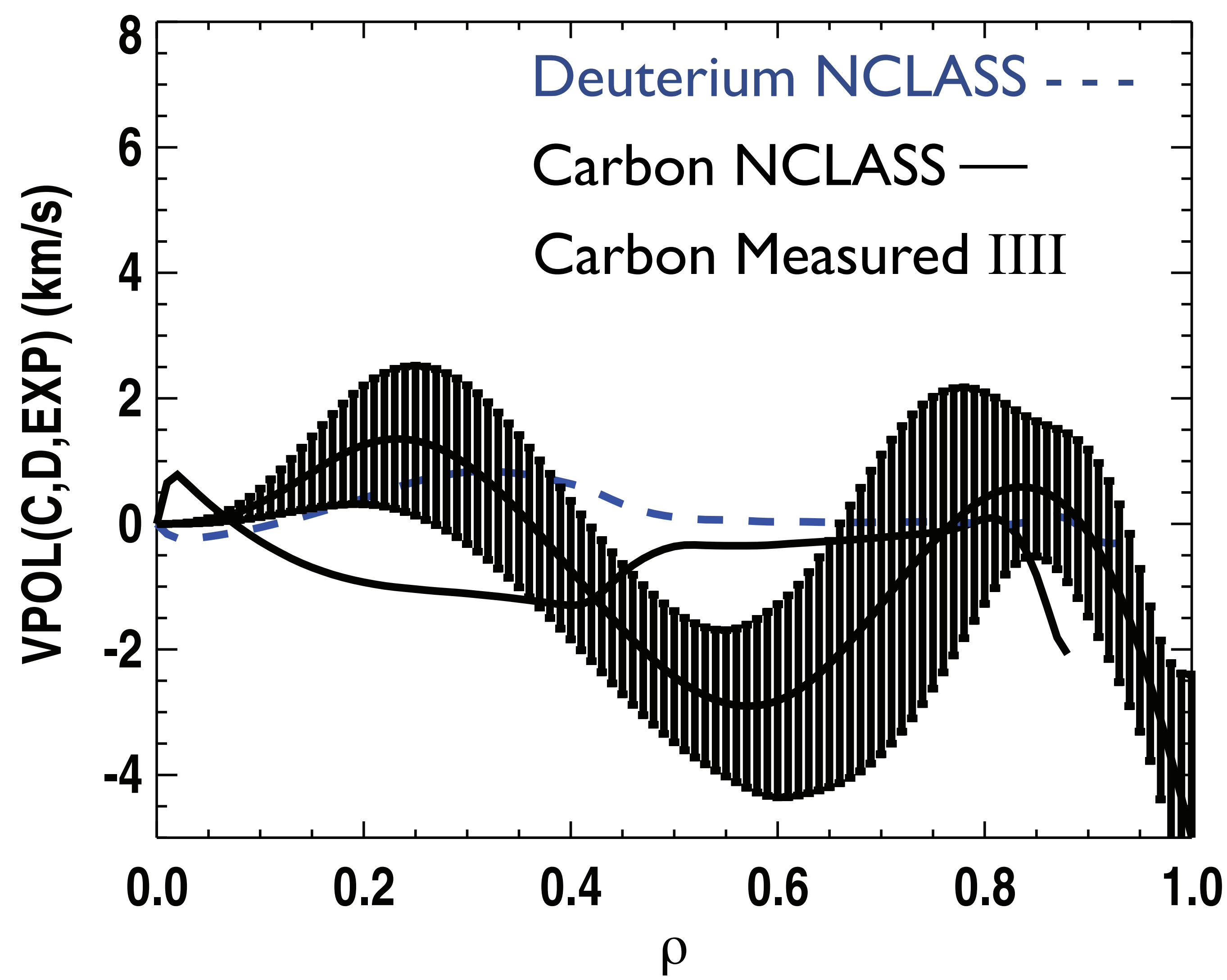
- **Carbon poloidal flow measured to be more ion diamagnetic than NCLASS in region of strong pressure**



Test Neoclassical by Measuring Poloidal Flow

- **Infer deuterium ion poloidal flow using force balance**

$$V_\theta^D = V_\theta^C - \frac{1}{B_\varphi}\left(\frac{\nabla P_C}{Z_C e n_C} - \frac{\nabla P_D}{e n_D}\right) + \frac{B_\theta}{B_\varphi}(V_\varphi^D - V_\varphi^C)$$



Test Neoclassical by Measuring Poloidal Flow

- **Infer deuterium ion poloidal flow using force balance**
- **Deuterium ion poloidal flow much faster in ion diamagnetic direction where ∇P large**

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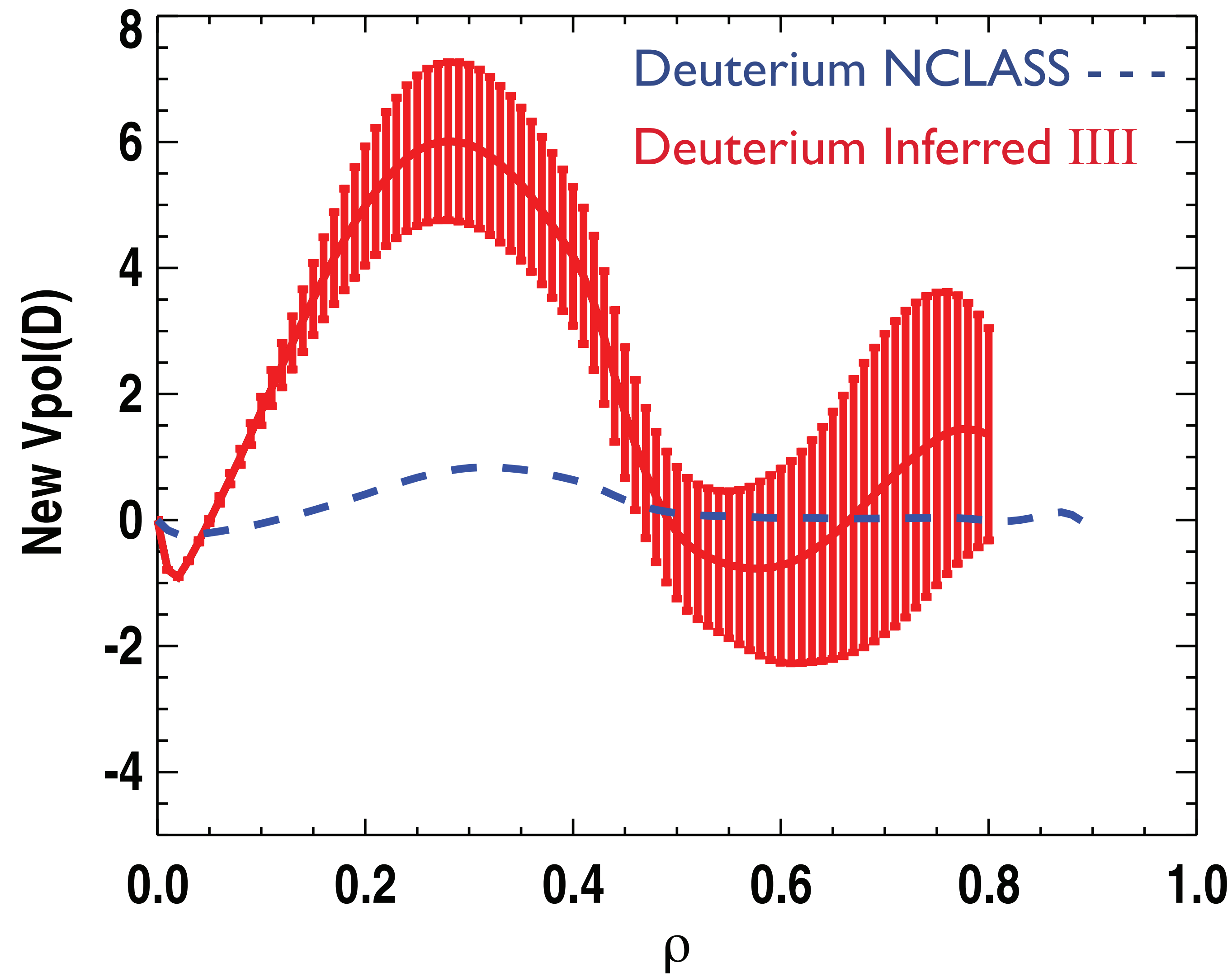
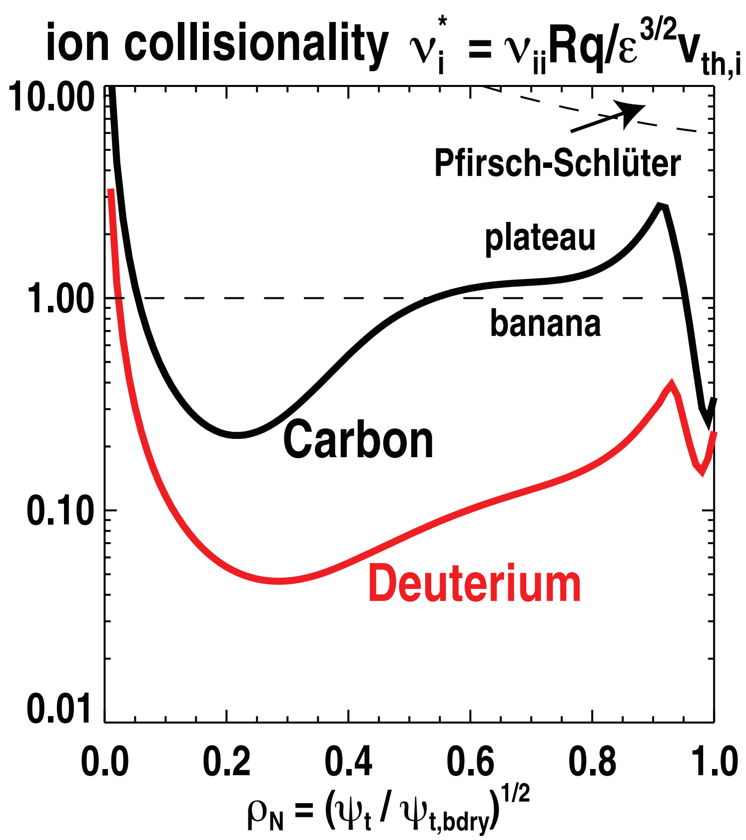


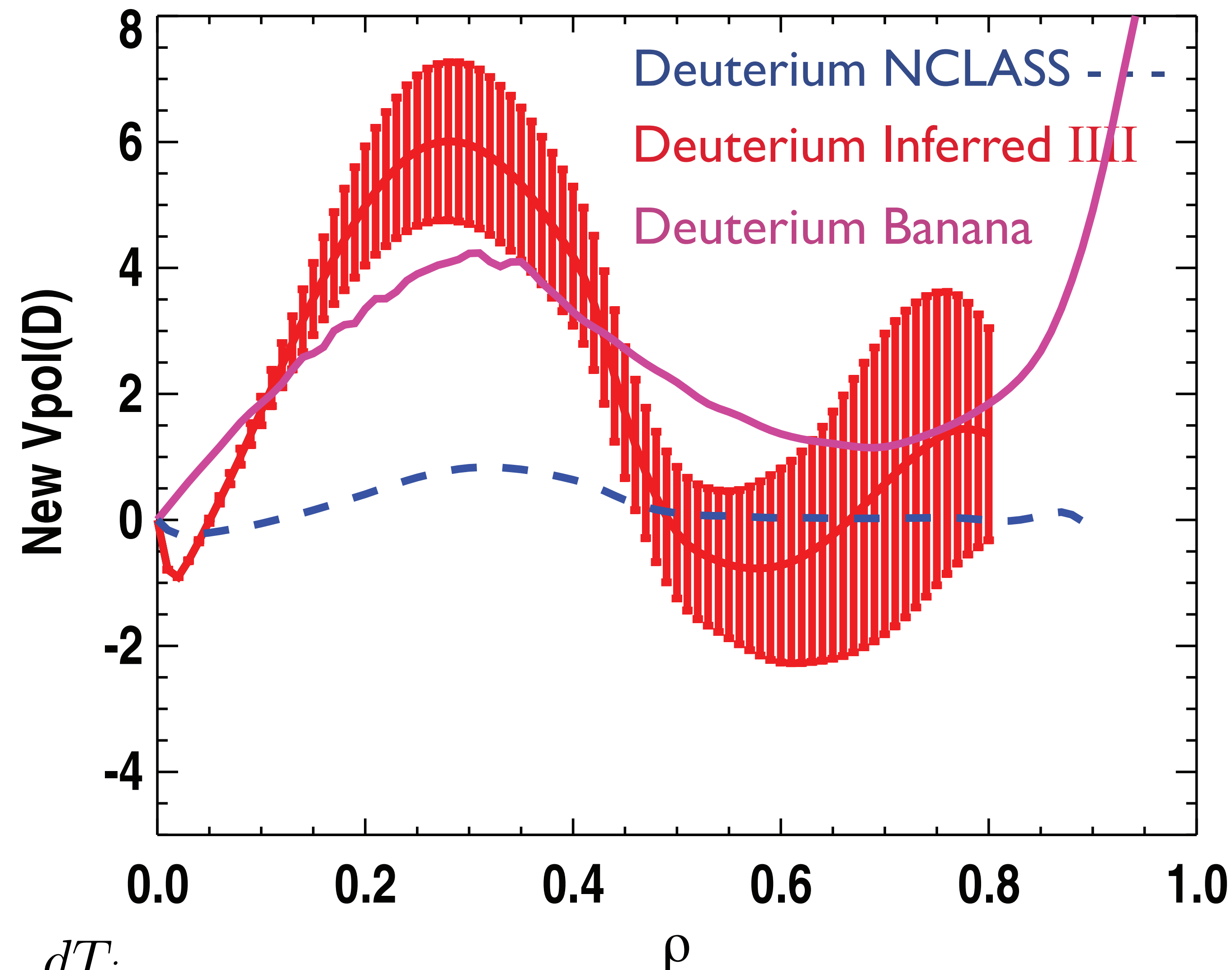
Test Neoclassical by Measuring Poloidal Flow

- **Deuterium in banana collisionality regime**
- **Use analytic formula[1]**
- **Much better agreement**



$$V_{\theta,banana} = \frac{k}{m_i \Omega_i} \frac{dT_i}{dr}$$

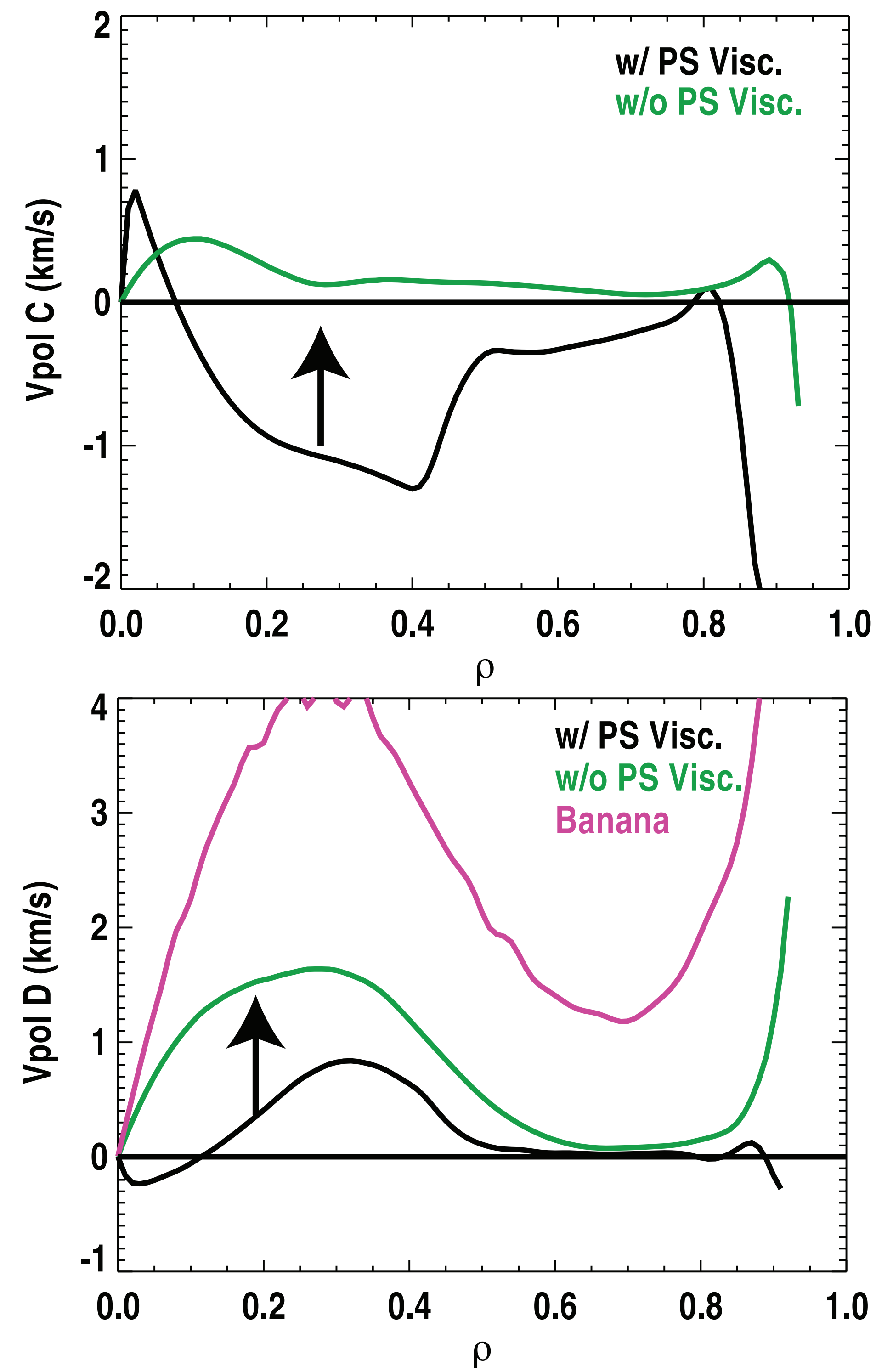
$$k = 1.17$$



[1]Helander and Sigmar, "Collisional Transport in Magnetized Plasmas", Cambridge Monographs on Plasma Physics

Neglecting Pfirsch-Schluter Viscocity Produces Better Agreement with Measurements

- **NCLASS can optionally include or neglect various pieces of physics**
- **Core collisionality is largely banana regime**
  - Run code neglecting any Pfirsch-Schlüter viscosity contributions
- **NCLASS gets closer to experiment in the steep pressure region**
- **Still insufficient to capture deuterium toroidal rotation because *differential* poloidal flow not large enough**



Banana Regime Analytic Poloidal Flow Produces Better Agreement with Measured Toroidal Flow

- **Assume banana regime poloidal flow for toroidal flow calculation**
- **Agreement over large region except near magnetic axis**

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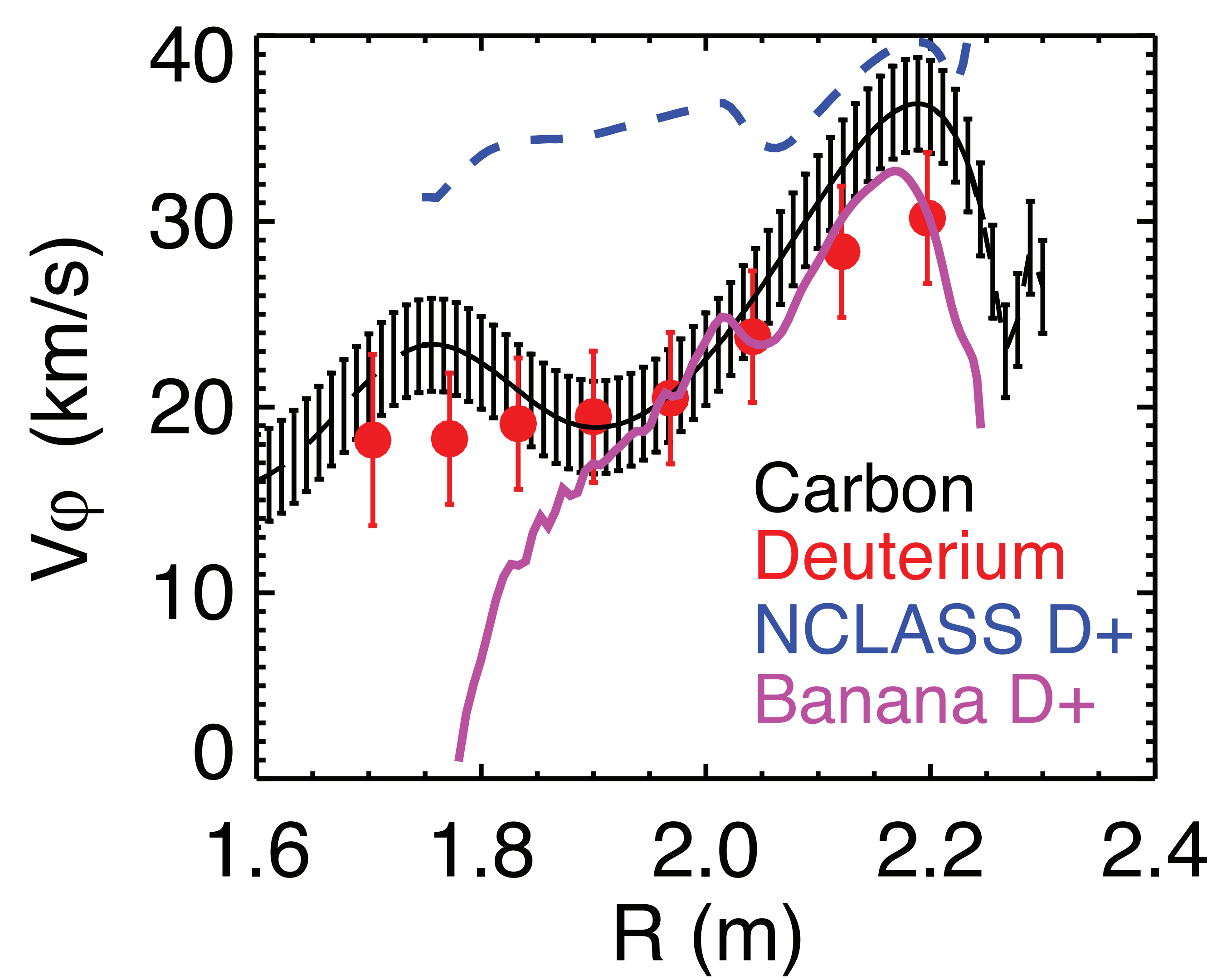
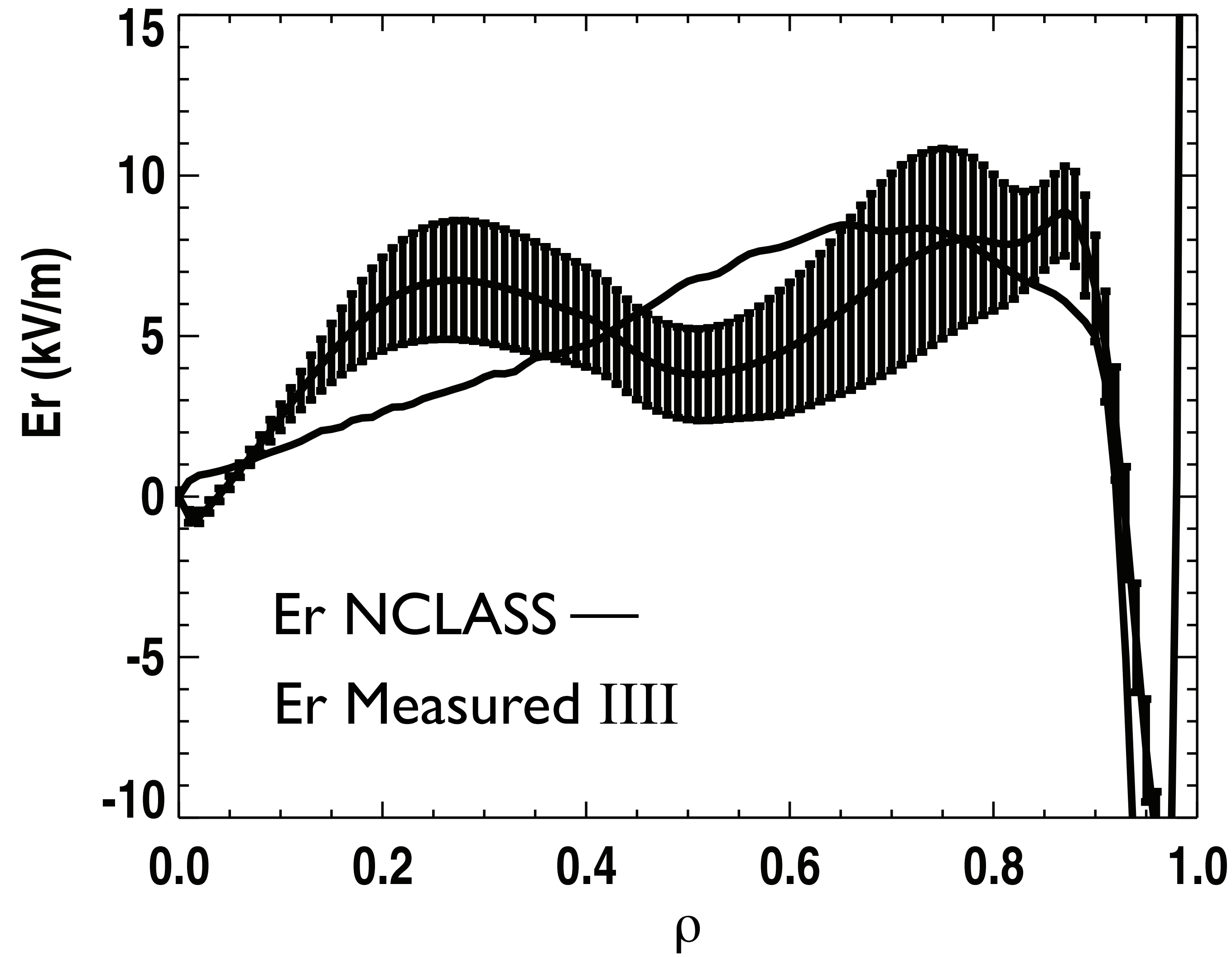


Test Neoclassical by Measuring Poloidal Flow

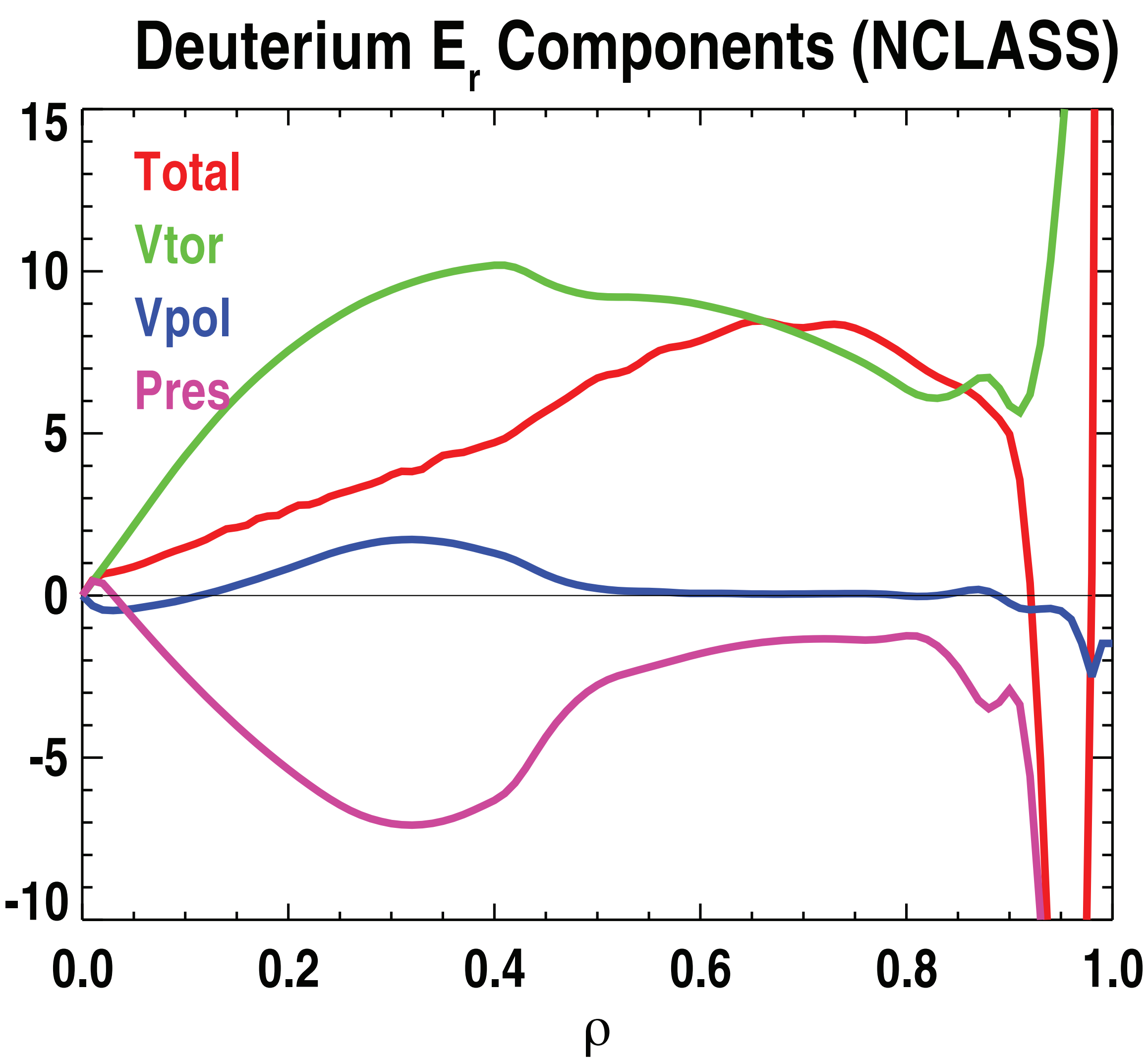
- **E_r from experiment and NCLASS different**
- **Associated shear ω_{ExB} ~$d(E_r/RB_p)/d\psi$ also clearly different**

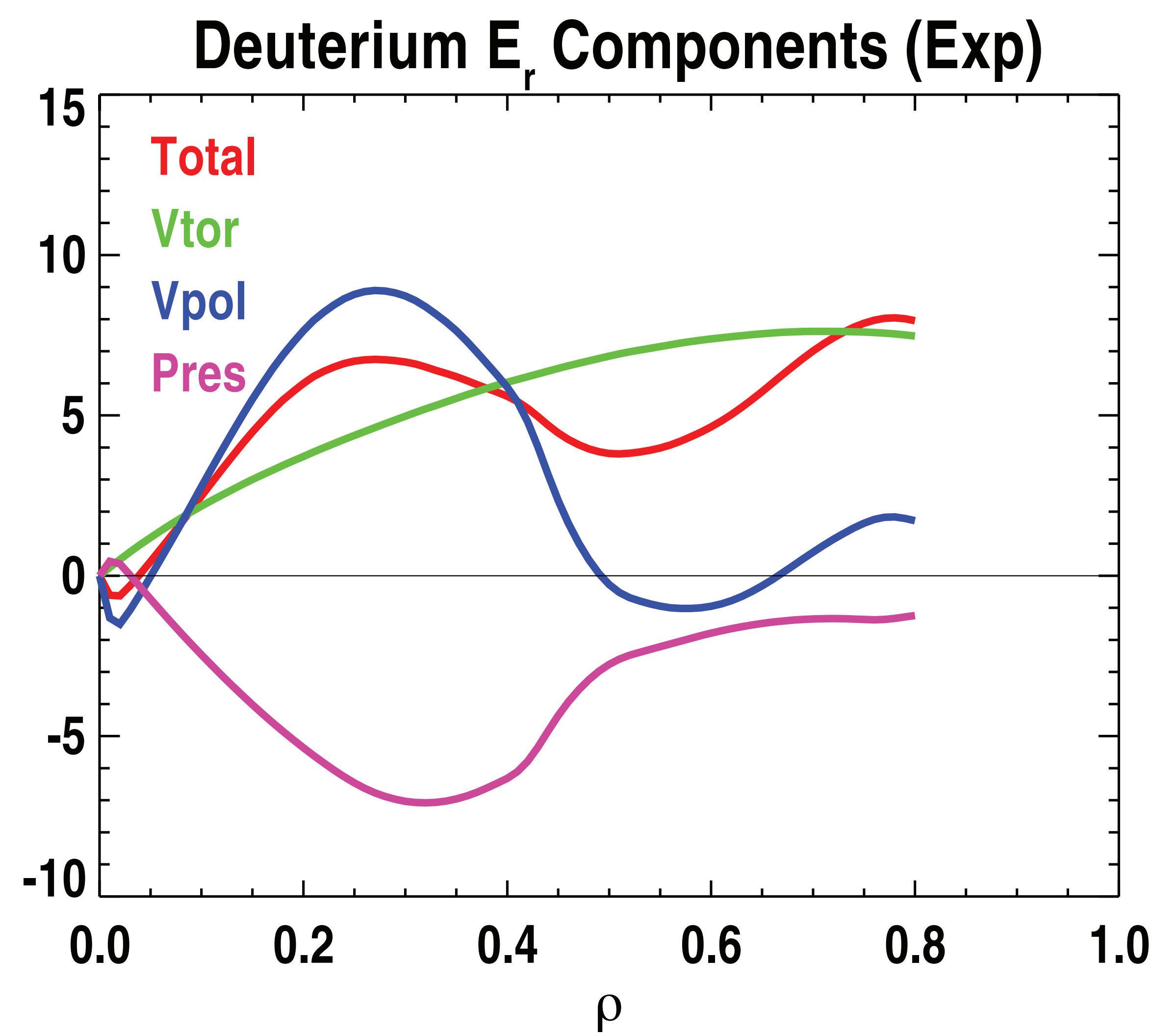
$$E_r = \frac{\nabla P_i}{Zen_i} + V_\varphi B_\theta - V_\theta B_\varphi$$



Poloidal Velocity Contribution to E_r Larger than V_{tor} for Main-Ions, Much Larger than NCLASS Predicts

- **DIII-D intrinsic rotation scenario displays large sensitivity to main-ion V_{pol} when computing E_r from main-ion pressure, V_{tor} and V_{pol}**





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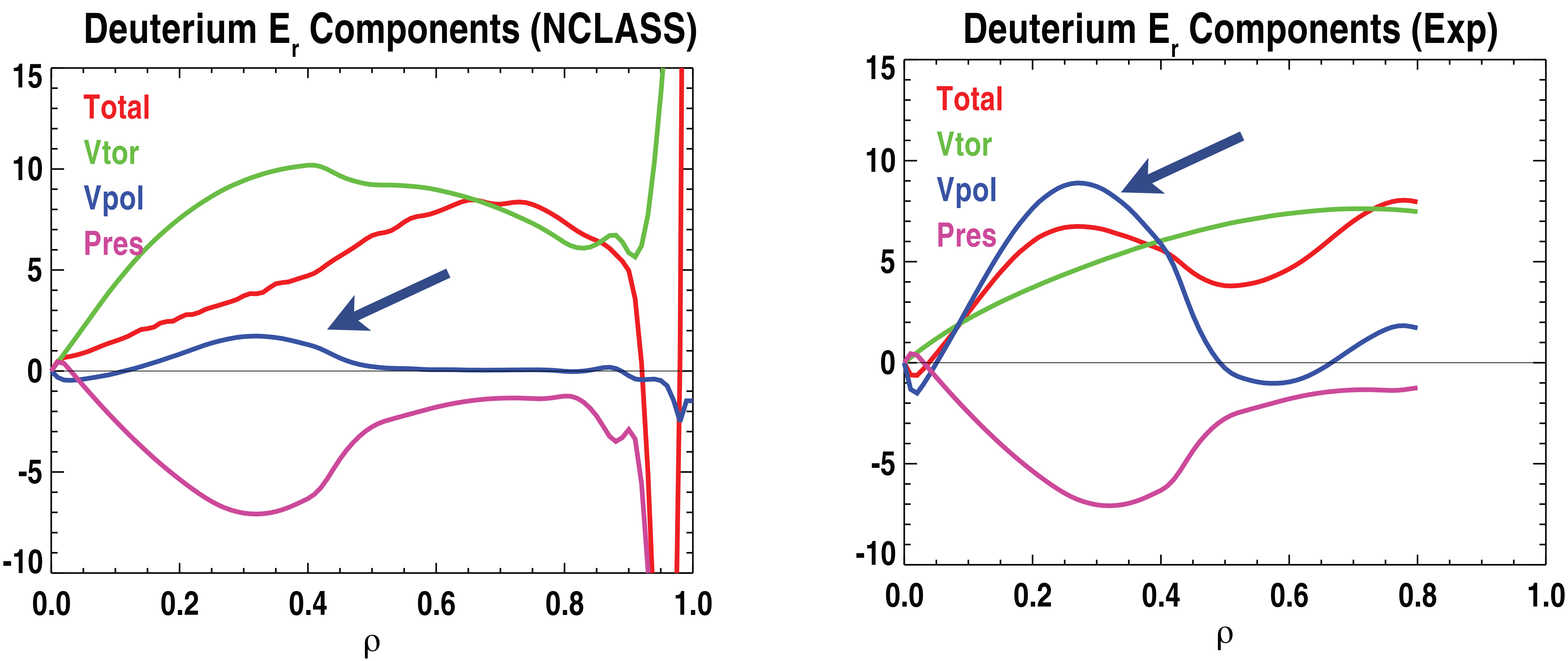

Conclusions / Future Work

- In low rotation scenarios expected in ITER, uncertainty of core Er is large due to unknown V_{tor} (hope its large)
- If toroidal rotation is small or nearly zero then Er determined by two similar magnitude terms ∇P and V_{pol}, of which V_{pol} could be large/small, positive/negative?
- Database of V_{pol} across scenarios non-existent, so we need both empirical scalings and fundamental understanding of poloidal flow physics