MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

Experimental validation of momentum transport theory in the core of a tokamak plasma

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EUROfusion

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Motivation

- Understanding of momentum transport **crucial to predict toroidal plasma rotation**, which
  - impacts impurity transport (see talks from F. Reimold and D. Fajardo)
  - stabilizes turbulence via $E \times B$ shear $\rightarrow$ **influences confinement**
  - **provides stability** against MHD events $\rightarrow$ **avoids disruptions**

- **No fully validated theoretical model** for momentum transport available
  $\rightarrow$ no predictive capability for rotation profiles of a future reactor

- **Momentum transport studies are challenging** due to a third transport mechanism
  $\rightarrow$ Strong assumptions or **simplifications usually made** in previous exp. works

- To be presented: method to **assess** the momentum **transport coefficients purely from experimental data** and **validate theoretical predictions**

Outline

- Introduction

- **Background** of the Methodology: Equations and Modeling

- Comparison of **Gyrokinetic Predictions and Experimental Results**
- **Parameter and Isotope Dependence** of Momentum Transport

- Summary and Outlook

Momentum Transport Equation

Flux, NBI

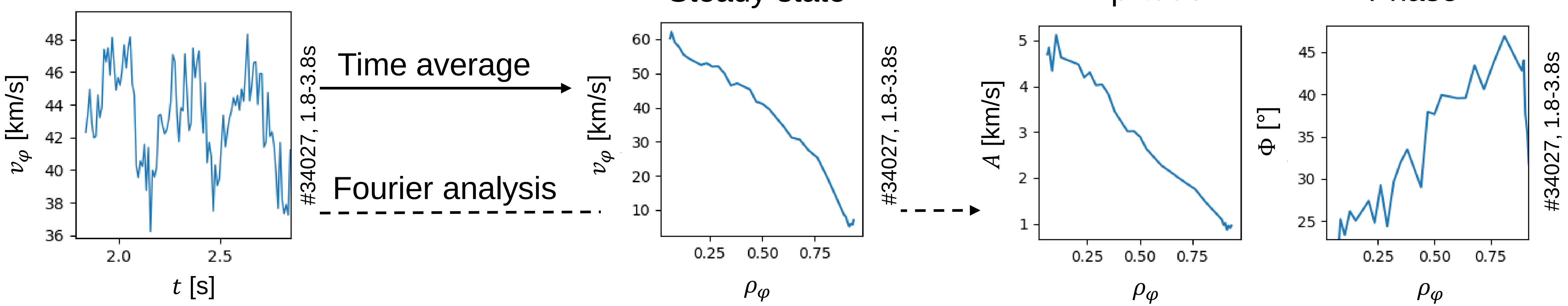
$$m \frac{\partial}{\partial t} nRv_\varphi = -\frac{1}{V'}\frac{\partial}{\partial \rho} V' \Gamma_\varphi + S_{NBI}$$

Diffusion, Conv., Res. stress

$$\Gamma_\varphi = -mnR\left(\chi_\varphi \frac{\partial v_\varphi}{\partial \rho} - V_c\, v_\varphi\right) + \Pi_{Rs}$$

→ Problem underconstrained in a steady-state analysis

NBI modulation



→ Problem constrained if modulation of turbulence can be compensated

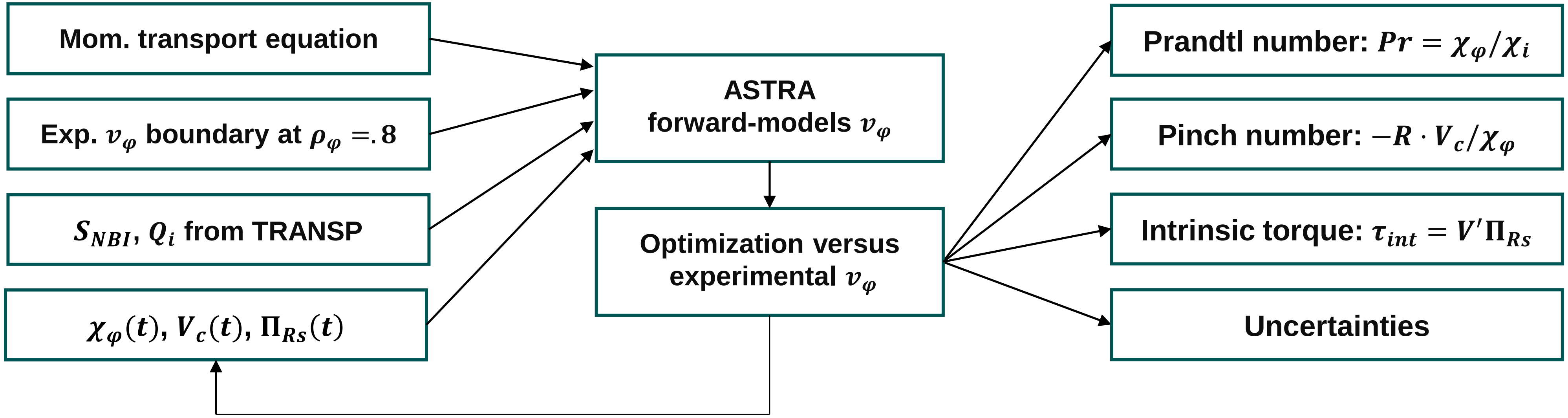
Momentum Transport Modeling

Flux NBI

$$m\frac{\partial}{\partial t} nRv_\varphi = -\frac{1}{V'}\frac{\partial}{\partial\rho}V'\,\Gamma_\varphi + S_{NBI}$$

Diffusion Conv. Res. stress

$$\Gamma_\varphi = -mnR\left(\chi_\varphi \frac{\partial v_\varphi}{\partial\rho} - V_c\, v_\varphi\right) + \Pi_{Rs}$$

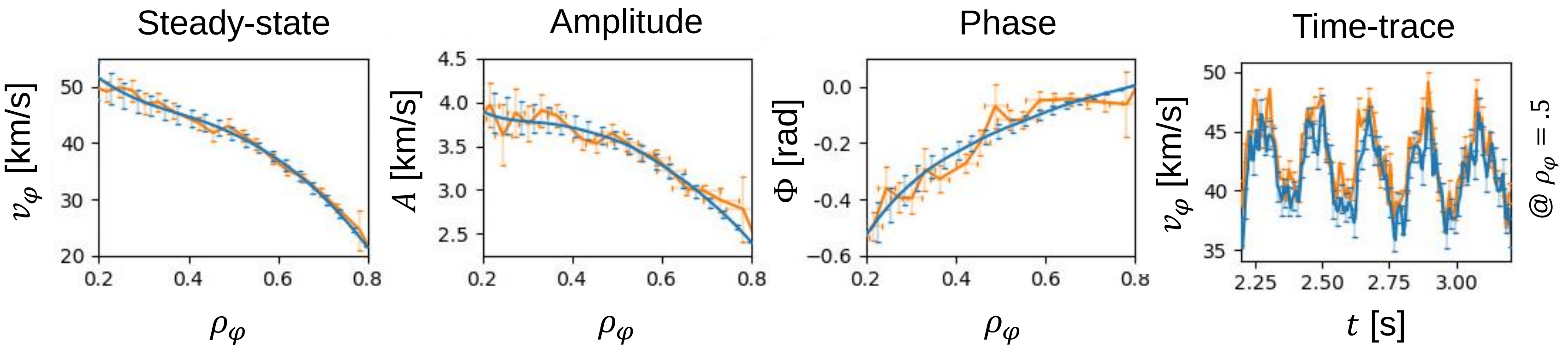


→ First model to retain time dependencies (via χ_i) in all transport coefficients and channels

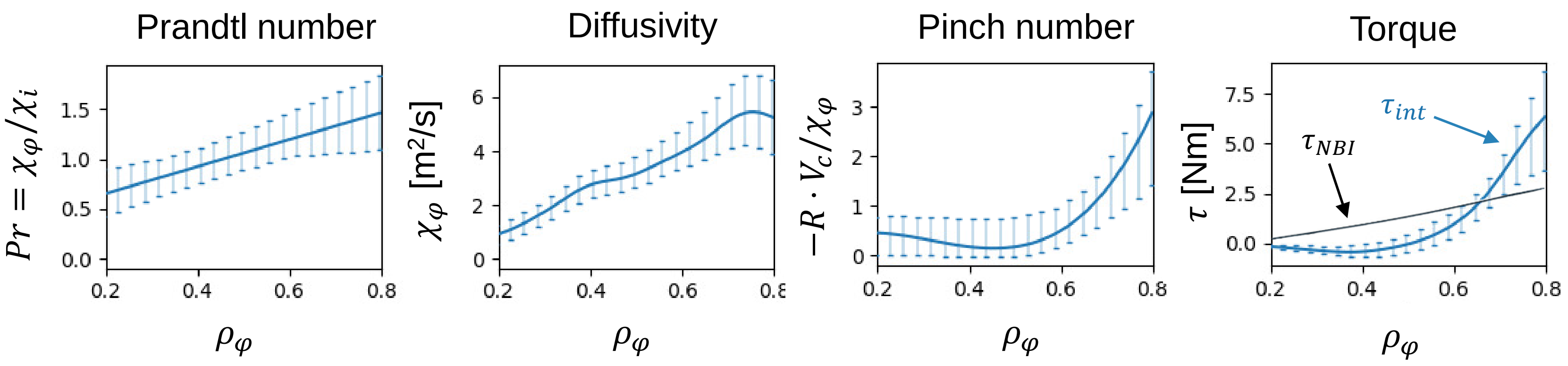
→ Concept has been validated on a broad set of discharges [Zimmermann et al. PPCF. 64. 2022]

Fitting of the reference case #40076 at 1.8-4.2s (ELMy H-mode)

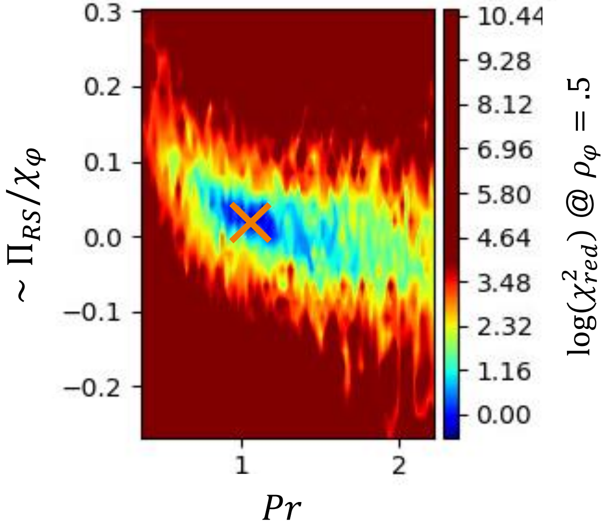
Experimental data vs. successful ASTRA modelling



Transport Coefficients:



Colormap of the parameter space



→ unique solution obtained

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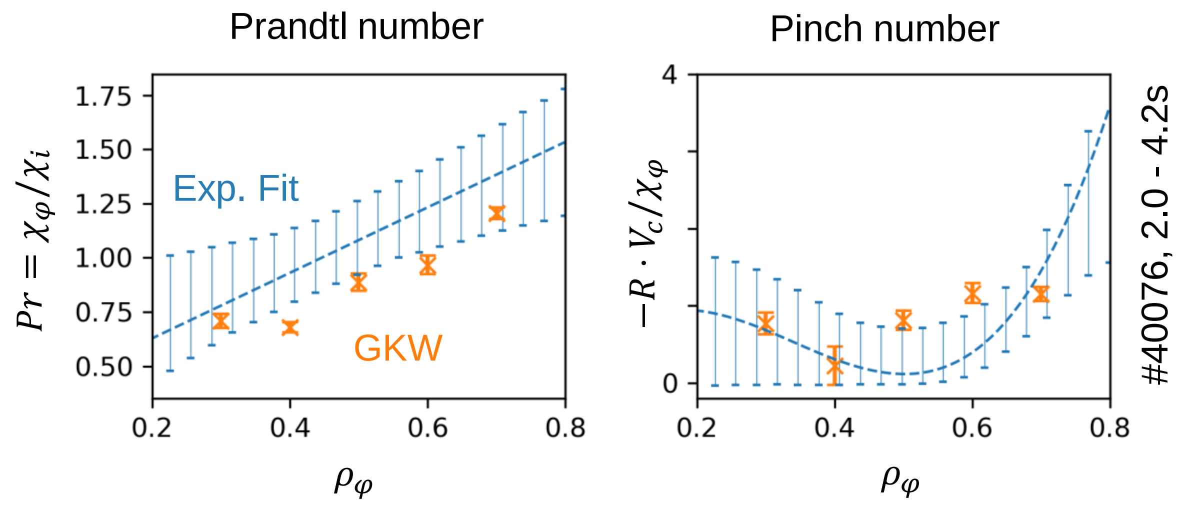
Validation of Gyrokinetic Predictions

- Performed quasi-linear, local gyrokinetic calculations via GKW



- Coefficients are predicted to be stable despite modulation, χ_i time dependence valid
- Good agreement of Gyrokinetic Predictions and Experimental Results for ITG dominated plasma

  → First time to quantitatively validate this kind of theoretical predictions

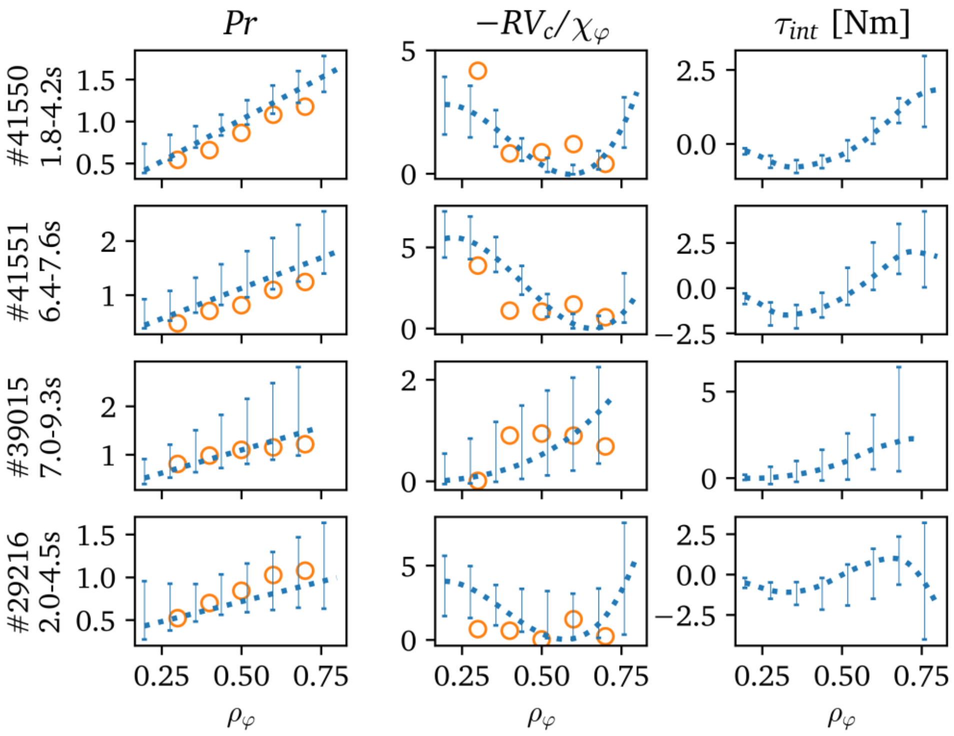
  → Retaining time dependencies is crucial to obtain best solution

Parameter Dependence of Momentum Transport

[Zimmermann et al. NF Letter. 2023. Submitted.]

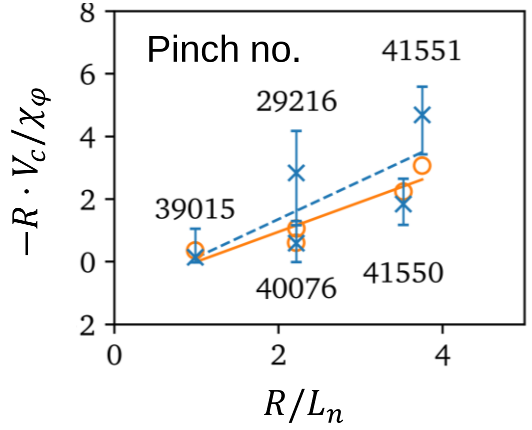
Compared ITG dominated discharges with variation in plasma current, density, and density gradient:

Experiment vs. GKW prediction



Experiment at $\rho_\varphi = .35$

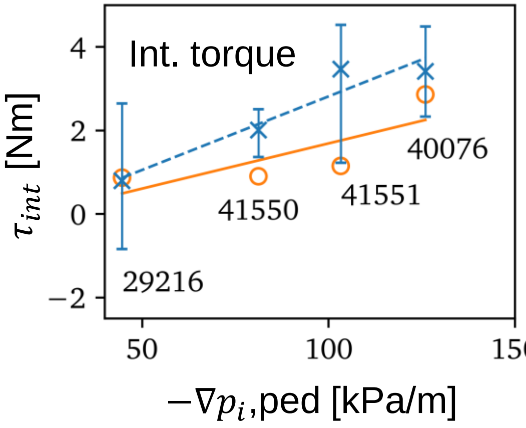
vs. GKW prediction



→ Coriolis pinch, deformation of the eigenfunction & $k_\parallel$

Experiment at $\rho_\varphi = .7$

vs. Stolzfus-Dueck model



→ deeper E_r well, smaller turbulence decay length?

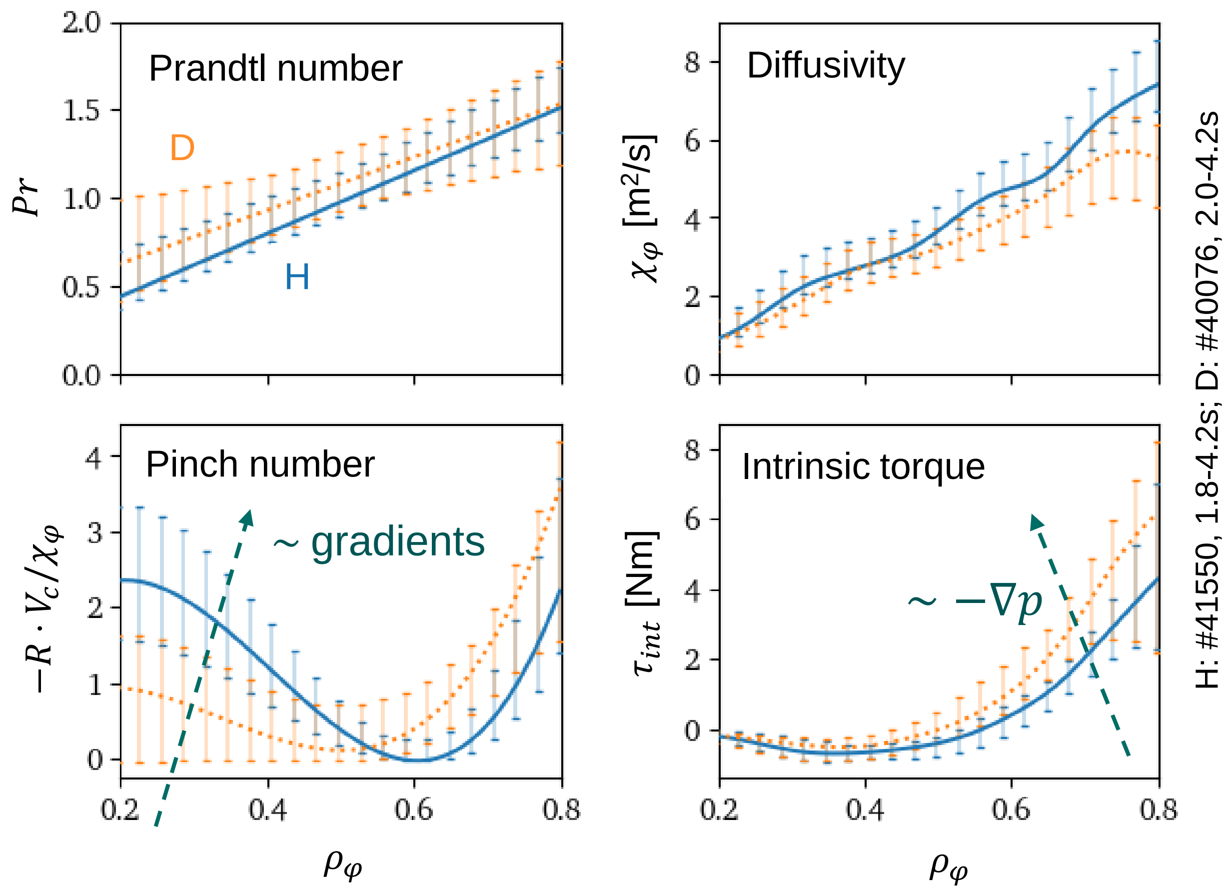
→ Technique opens the door to further theory validation and physics-based parameter scalings

Isotope Dependence of Momentum Transport

[Zimmermann et al. NF. 63. 2023]

- Comparison of hydrogen and deuterium plasma
- Matched fluxes, dimensionless parameters, and heat transport to isolate isotope dependence
- Theory predicts negligible isotope dependence
- Very similar transport coefficients assessed: no isotope dependence observed
- Variation of $\tau_{int} \sim -\nabla p$ at edge,

  $\frac{-RV_c}{\chi_\varphi} \sim$ gradients in core



→ Increases confidence when applying theory to other main ion species and mixtures

Summary and Outlook

- Developed a code framework to extract momentum transport
  coefficients purely from experimental data
- First methodology to disentangle all three momentum fluxes simultaneously,
  key requirement is retaining the time dependencies
- Validated gyrokinetic predictions for ITG dominated plasmas,
  studied theory scalings on convection, intrinsic torque, and isotope dependence

- Expand this validation to more discharges ($\rightarrow$ TEM), compare to a GKW data base
- Apply this technique to other tokamaks as JET and KSTAR to analyze ρ_* dependence (A. Kirjasuo)
- Develop physics-based scaling laws, to be used for example in integrated modeling approaches

References

- Momentum transport equation: [Fable. PPCF. 2017]
- GKW code: [Peeters. CPC. 2009]
- ASTRA code: [Pereverzev. MPI. 2002]
- Coriolis pinch: [Peeters. PRL. 2007]
- NUBEAM/TRANSP code: [Beslau. PPPL. 2018] [Pankin. CPC. 2004]
- Prandtl number: [Strintzi. PoP. 2008]
- Stoltzfus-Dueck model: [Stoltzfus-Dueck. PRL. 2012]
- IMEP: [Luda. NF. 2021]