NSTX-U

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Resonances in drift-kinetic particle motions in perturbed tokamaks and their impact on neoclassical toroidal viscosity transport

Kimin Kim, J.-K. Park, A.H. Boozer[1]
N.C. Logan, Z.R. Wang, J.E. Menard, S.P. Gehardt

Princeton Plasma Physics Laboratory
[1]Columbia University

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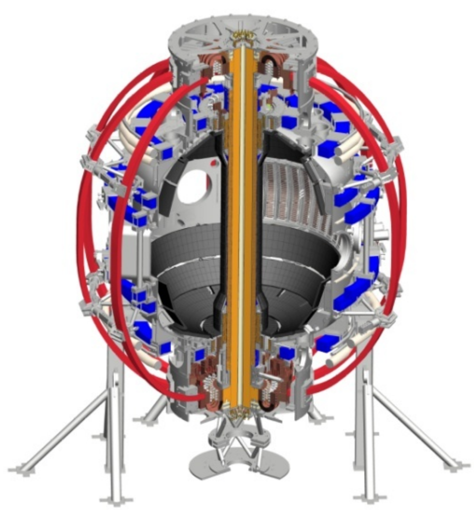


Outline

- Motivation
  - Importance of drift-kinetic δf particle simulation for NTV calculation
- Verification of NTV Physics by Guiding-Center Particle Motion
  - Banana orbit distortion, field resonance, rotational resonance
- Validation of Particle Simulation
  - Comparison with semi-analytic theory and experiment
- Summary

Motivation:
Drift-kinetic particle motion can explain fundamental NTV physics

- Non-axisymmetric magnetic fields produce toroidal rotation braking
  - Neoclassical Toroidal Viscosity (NTV) provides an additional channel for momentum transport to change toroidal plasma rotation
  - Important for control of stability and performance in perturbed tokamaks

- NTV is dominated by various resonance phenomena
  - Resonance of orbit trajectory with non-axisymmetric perturbations: *Field resonance*
  - Resonance of orbit trajectory with ExB rotation: *Rotational resonance*

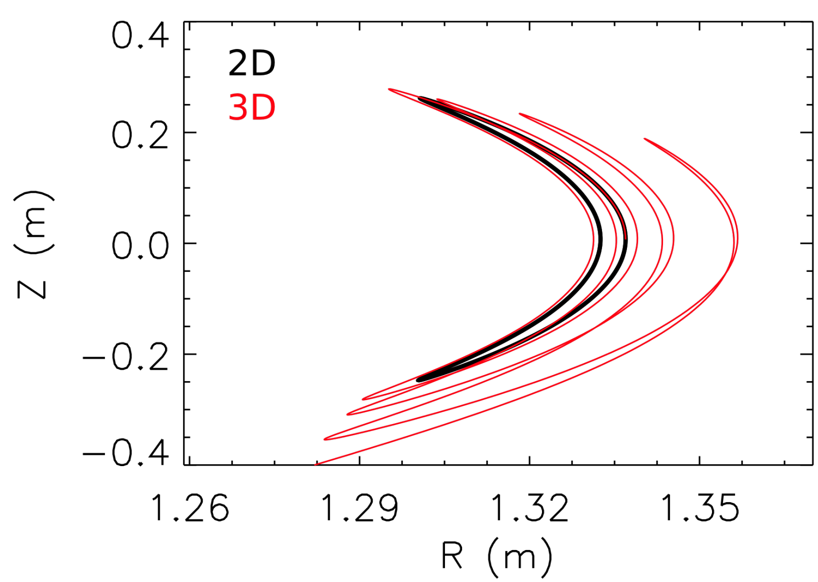
- Accurate description of guiding-center particle motions is essential for NTV study
  - Drift-kinetic δf particle code: POCA (Particle Orbit Code for Anisotropic pressures)
    - Guiding-center orbit motions on flux coordinates
    - Fokker-Plank equation with pitch-angle scattering conserving toroidal momentum
  - Verify basic NTV physics and analyze NTV torque in magnetic braking experiments

- *This talk will illustrate fundamental NTV physics with drift-kinetic particle simulations*

Nonaxisymmetric magnetic fields drive non-ambipolar particle transport

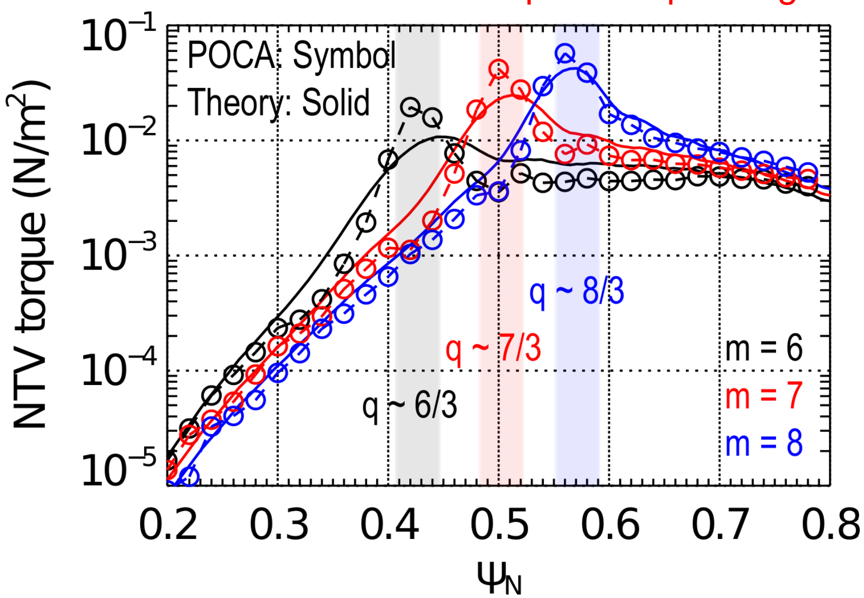
- No neoclassical transport without collisions in axisymmetry
  - Collision drives transport (cf. banana regime in 2D)
- Particles can drift out without collisions due to orbit distortion in nonaxisymmetry
  - Particles must depart from a flux surface to another in 3D fields to conserve action
  - Transport is nonambipolar as ions diffuse faster than electrons until ambipolar electric field is established
  - Toroidal rotation will be damped towards neoclassical offset rotation

Banana orbits in 2D and 3D w/o collisions



Field resonances can amplify the particle drifts

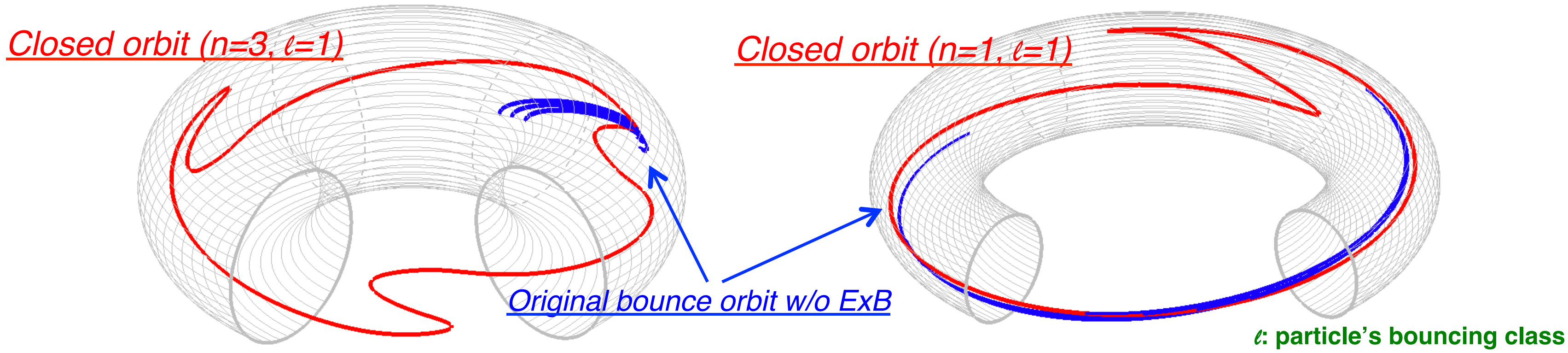
- Particle drifts and NTV can be maximized by resonant field component
  - Particle orbit can be repetitively distorted, when the field patterns are resonant with orbit trajectory
  - Field resonance can drive strong NTV on the resonant flux surface (*m-nq=0*)
  - Comparison of NTV by POCA with *semi-analytic theory* **[J.-K. Park, PRL (2009)]**
    - Single harmonic n=3 field applied to circular-shaped large aspect-ratio configuration
    - Clear field resonance effects: Shift of NTV peak responding to resonant flux surface



  - Note: Field resonance is not easily observed, as resonant field components are either too disruptive or attenuated by plasma response

Rotational resonances can enhance radial particle transport by suppressing random phase-mixing

- Parallel/perpendicular ExB drifts close an orbit by resonances with orbit patterns



  - Resonant field condition shifted to follow path of closed orbit: $m-nq\pm\ell=0$
  - Resonance frequency condition: $n\omega_E\approx\ell\omega_b$

[K. Kim, PRL (2013)]

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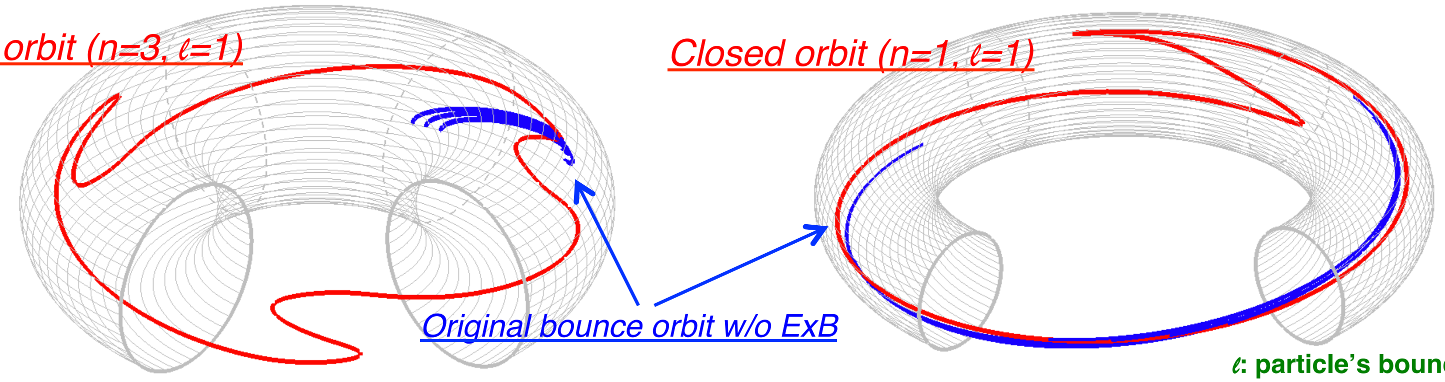

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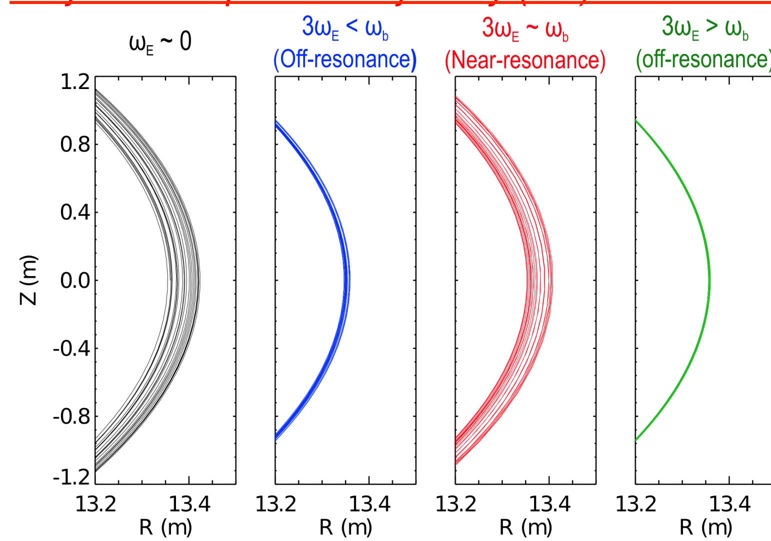
- 3D particle transport can be dominated by rotational resonances
  - Enhanced transport by precession resonance at ω_E~0, and bounce-harmonic resonance at $3\omega_E$~ω_b
  - Off-resonance rotations reduce the particle transport by random phase-mixing

Projection of particle trajectory (ℓ=1) with n=3 fields

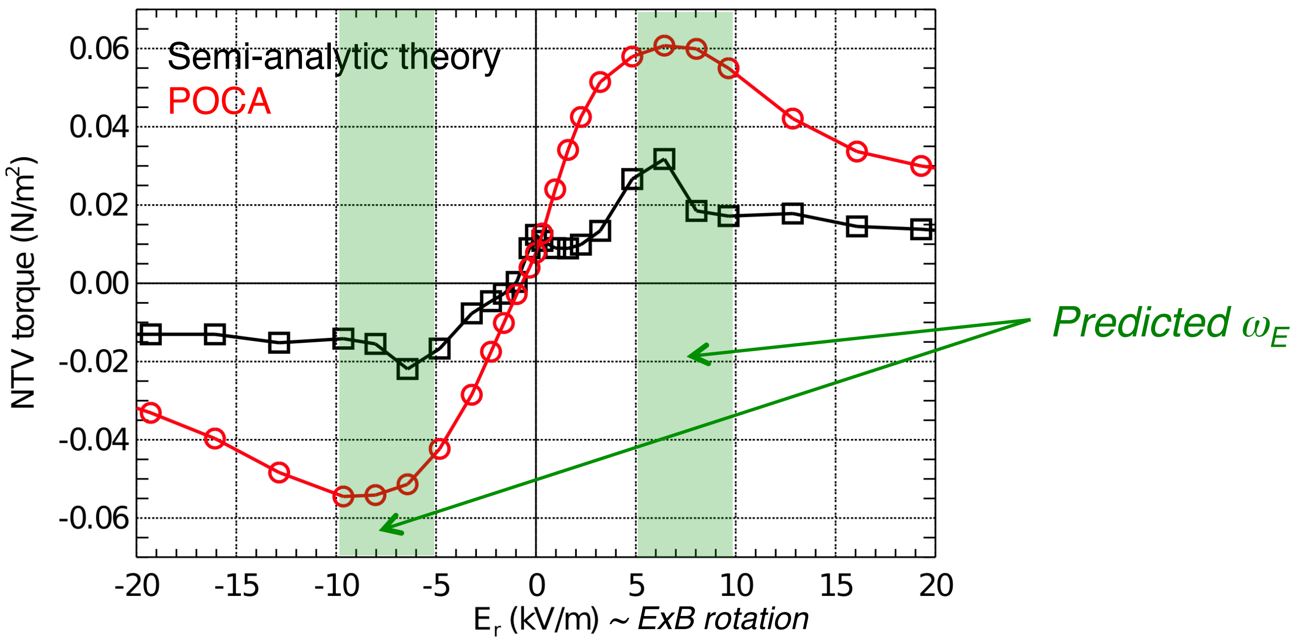


[K. Kim, PRL (2013)]

Implication of Bounce-Harmonic Resonance for NTV

- ExB scan in the simplified configuration shows an enhancement of NTV by bounce-harmonic resonances
  - Resonant ExB frequency for peak NTV agrees with theory prediction
  - Important driving mechanism of NTV in the fast rotating plasmas
  - BH resonances always exist in the finite ExB due to Maxwellian energy distribution, and on every surface due to multi-harmonic magnetic perturbations

Peak NTV appears at the predicted resonant ω_E



[K. Kim, PRL (2013)]

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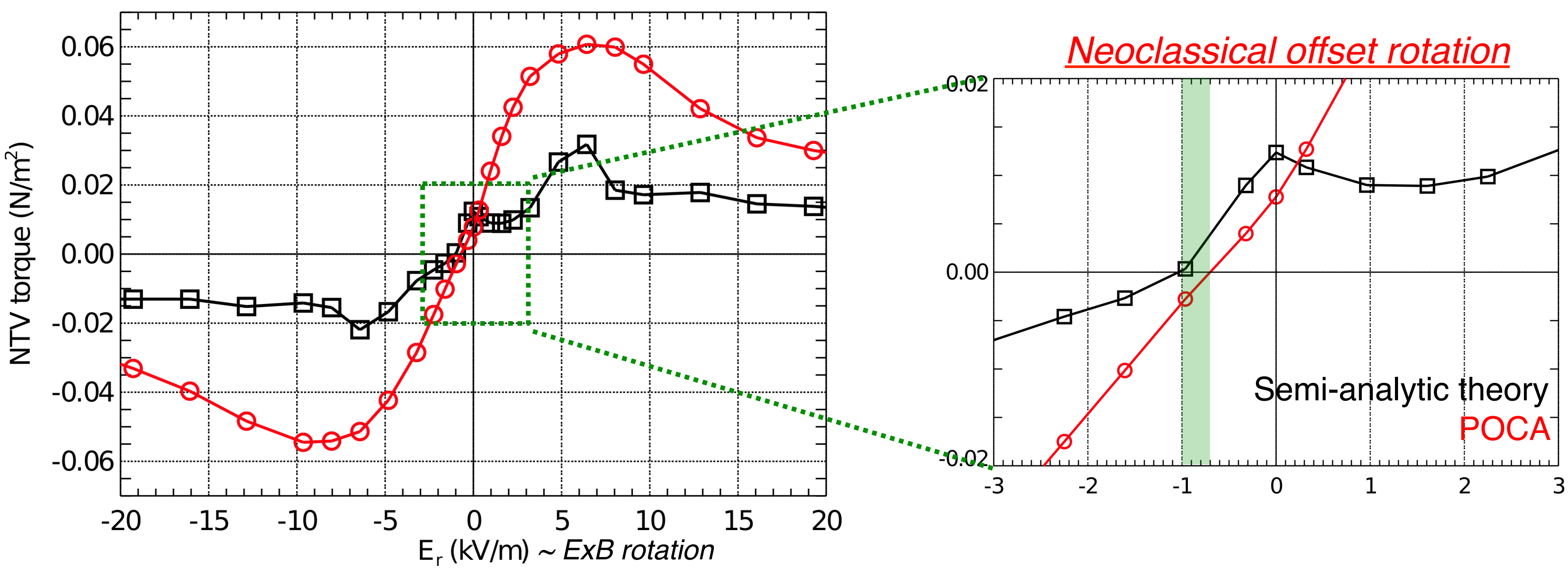
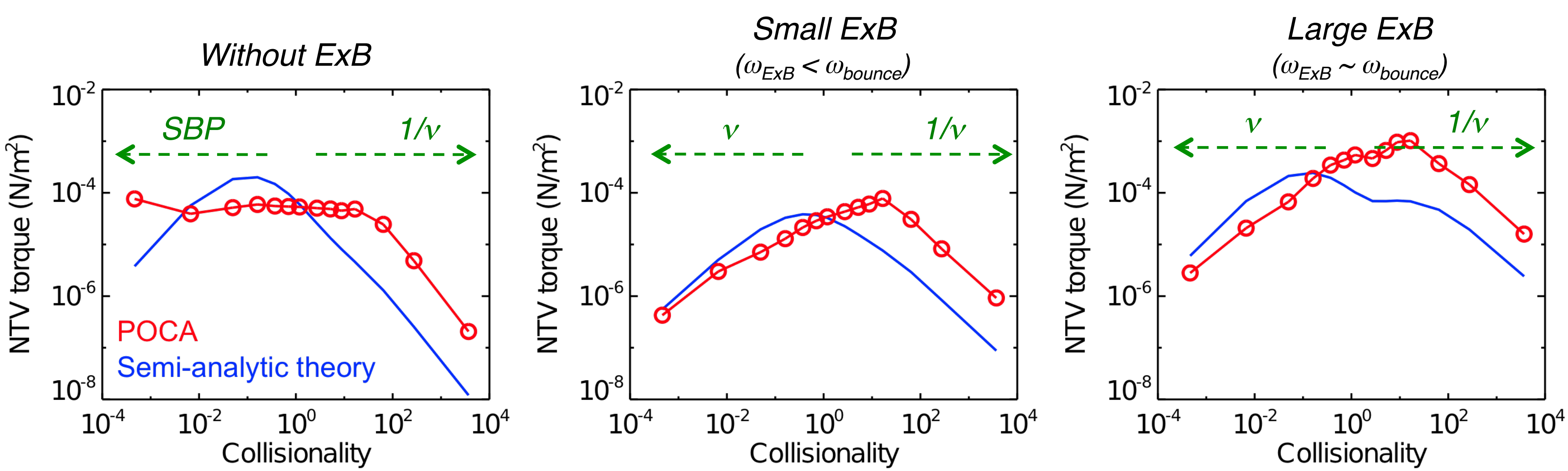
  - BH resonances always exist in the finite ExB due to Maxwellian energy distribution, and on every surface due to multi-harmonic magnetic perturbations
- Neoclassical offset can be identified when NTV crosses zero



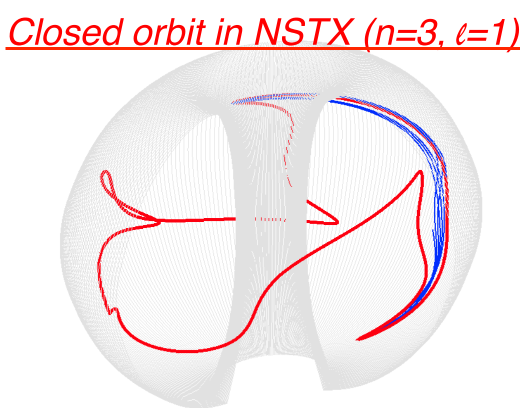
Particle simulation reproduces predicted NTV physics

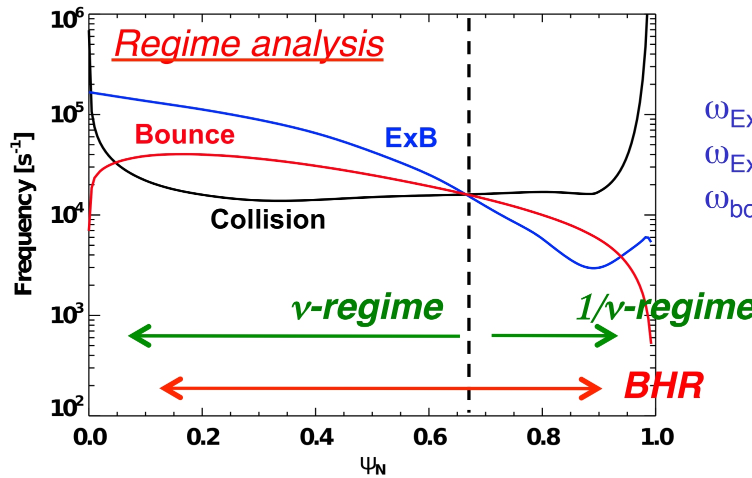
- Consistent features of NTV dependency on the collisionality are reproduced with drift-kinetic particle simulations
  - Clear $1/\nu$-regime in the high collisionality with passing particle effects
  - Superbanana-plateau (SBP) resonance in the low collisionality without ExB
  - ν−regime in the low collisionality with small ExB
  - Enhanced NTV by bounce-harmonic resonance in the large ExB



NTV prediction can be improved with particle simulation

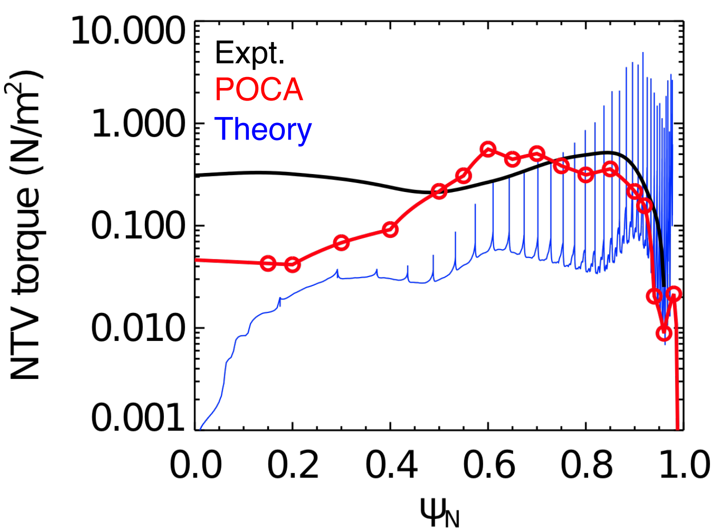
- Complicated closed orbit and overlapping of regimes in NSTX (#124439)





$\omega_{ExB} > \omega_{col} \rightarrow \nu$
$\omega_{ExB} < \omega_{col} \rightarrow 1/\nu$
$\omega_{bounce} \sim \omega_{ExB} \rightarrow$ BHR

- BH resonances can dominate NTV transport in the fast rotating plasmas



– Comparison between experiment, particle simulation, and semi-analytic theory
  - Dominant BH resonance with POCA (finite orbit width)
  - NTV prediction improved with particle simulation (Expt. ~3.5Nm / POCA ~2.7Nm / Theory ~0.5Nm)
  - Nonphysical peaks in theory due to perturbed field from ideal plasma response

Summary

- Particle orbit motion is a essential element to explain the toroidal momentum transport in the perturbed tokamaks
  - Distortion of banana orbits, interaction with collision and precession

- Guiding-center particle simulation is a useful tool
  - Verify and validate theories, analyze and predict experiments, investigate new physics

- Field and Rotational resonances can significantly enhance the NTV
  - Orbit closing reduces phase-mixing effect to enhance transport
  - Essential to achieve an improved predictability in magnetic braking experiment

Theoretical progress in NTV will be presented by
Z.R. Wang (NO6.00002) *and* ***N.C. Logan (NO6.00003)*** *in this session!*