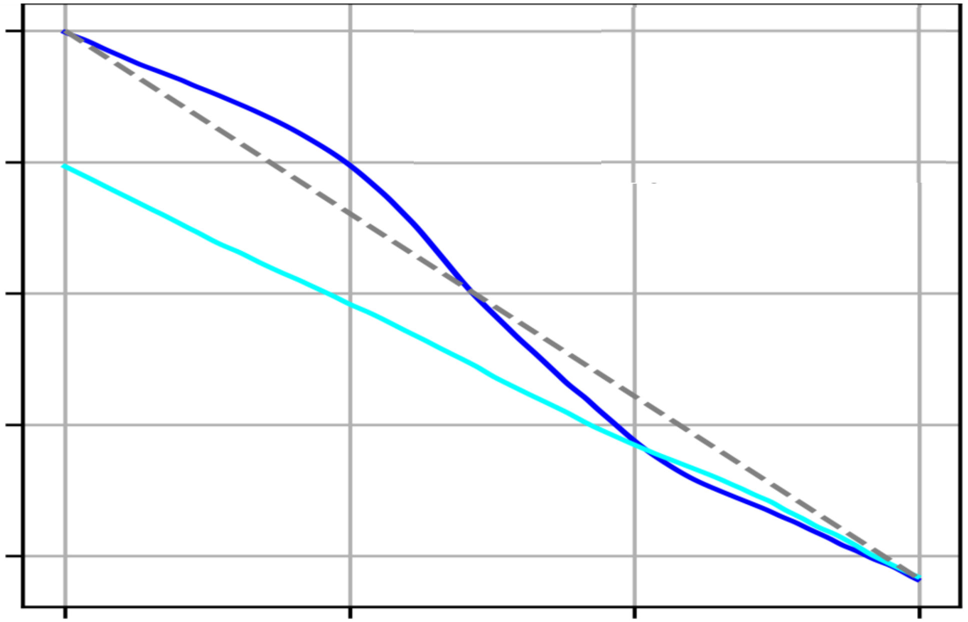
Investigation of Triggering of Internal Transport Barriers in Tokamaks with Flux Tube Simulations



TSVV1 Workshop 2023

Arnas Volčokas, Justin Ball, Stephan Brunner

27/06/2022

Swiss Plasma Center

Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

EPFL

Outline

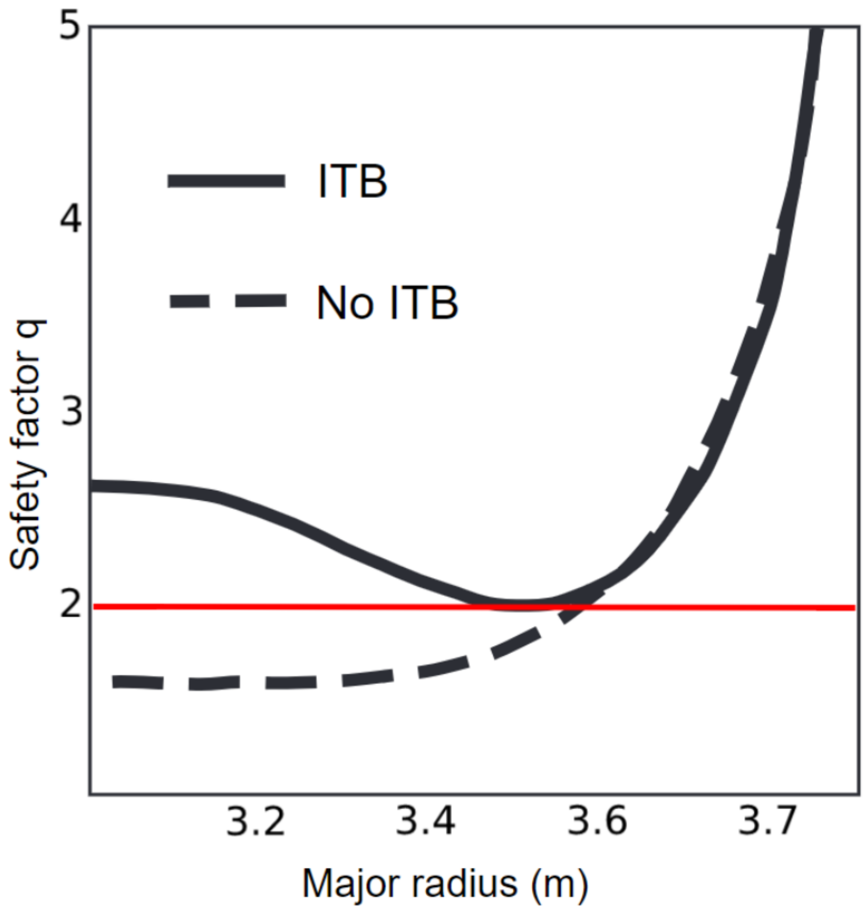
- **Motivation and background**
- Methods
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

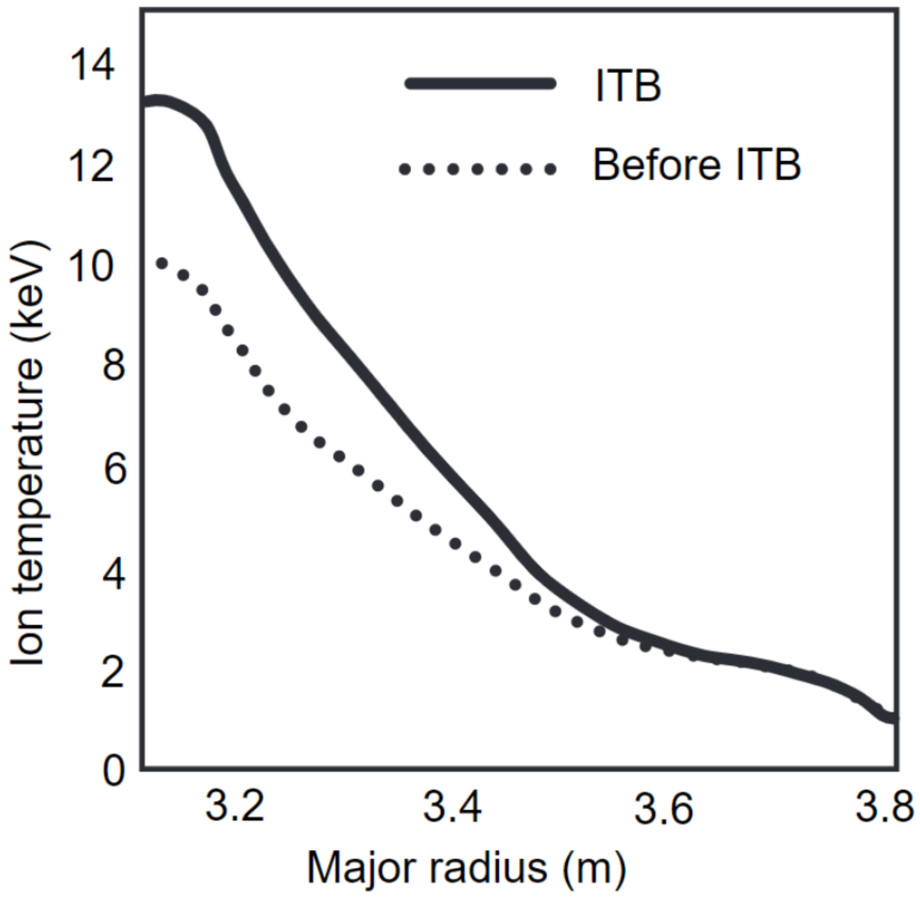
Swiss Plasma Center

ITBs from at minimum q

ITBs are formed when:

- A power threshold is exceeded
- Low magnetic shear $\hat{s} \approx 0$ is present
- Facilitated by integer or low order rational $q = M/N$ with $\hat{s} \approx 0$





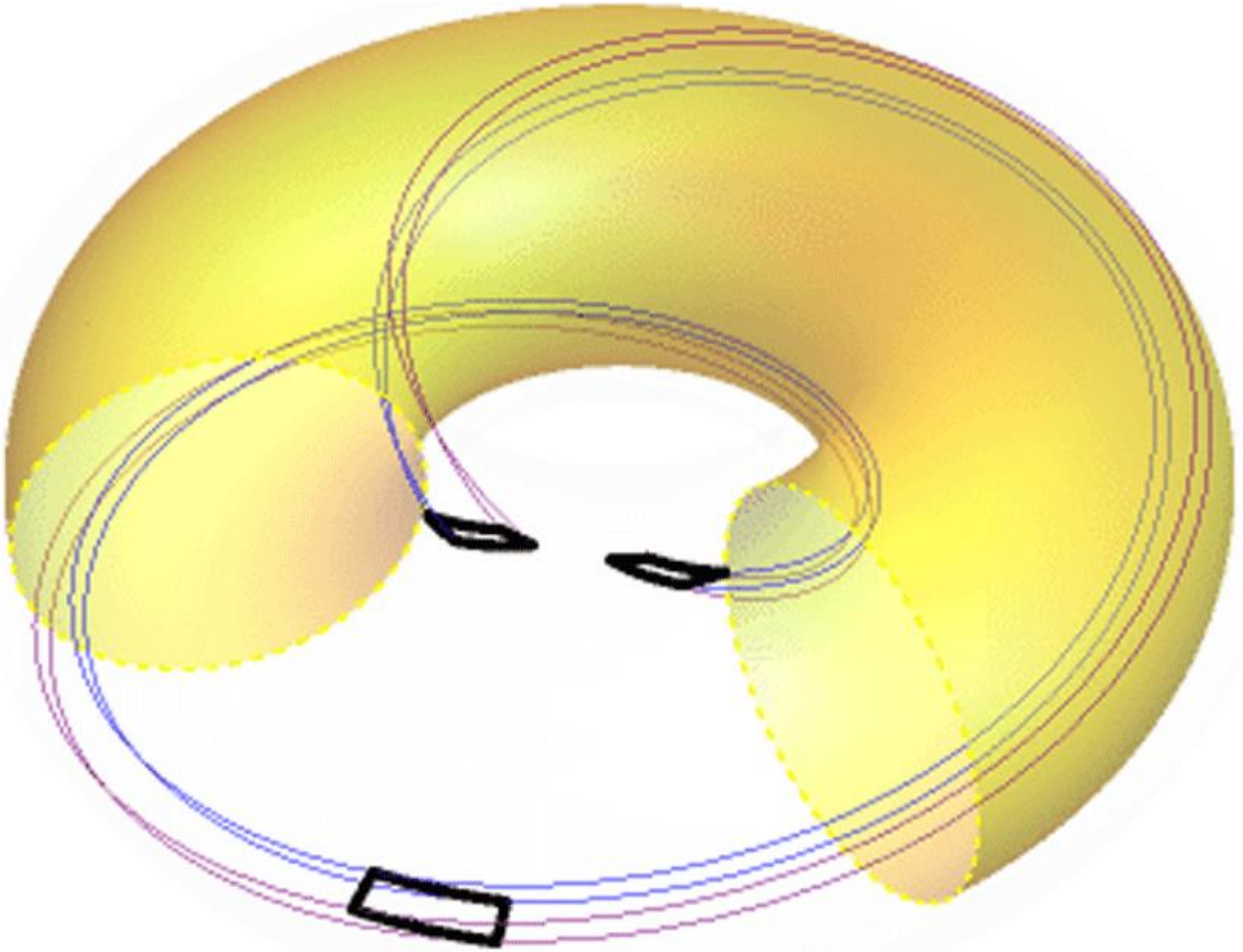
- L.-G. Eriksson et al., Phys. Rev. Lett. 88, 145001 (2002)
- K Ida and T Fujita 2018 Plasma Phys. Control. Fusion 60 033001

Outline

- Motivation and background
- **Methods**
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

Swiss Plasma Center

GENE flux-tube simulations



- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

Swiss Plasma Center

Usual simulation parameters

- Electrostatic* ($\beta = 10^{-5}$)
- Simulations with **kinetic electrons**
- Two cases – Cyclone Base Case (CBC) or pure ITG drive

Cyclone Base Case (CBC):

- $T_e = T_i$
- $R/L_T = 6.96$
- $R/L_n = 2.22$
- $q = 1.4$
- $\hat{s} = 0$

Pure ITG drive:

- $T_e = T_i$
- $R/L_{T,i} = 6.96$
- $R/L_{T,e} = 0$
- $R/L_n = 0$
- $q = 1.4$
- $\hat{s} = 0$

- Dimits et al. 2000, Physics of Plasmas **7**, 969

Swiss Plasma Center

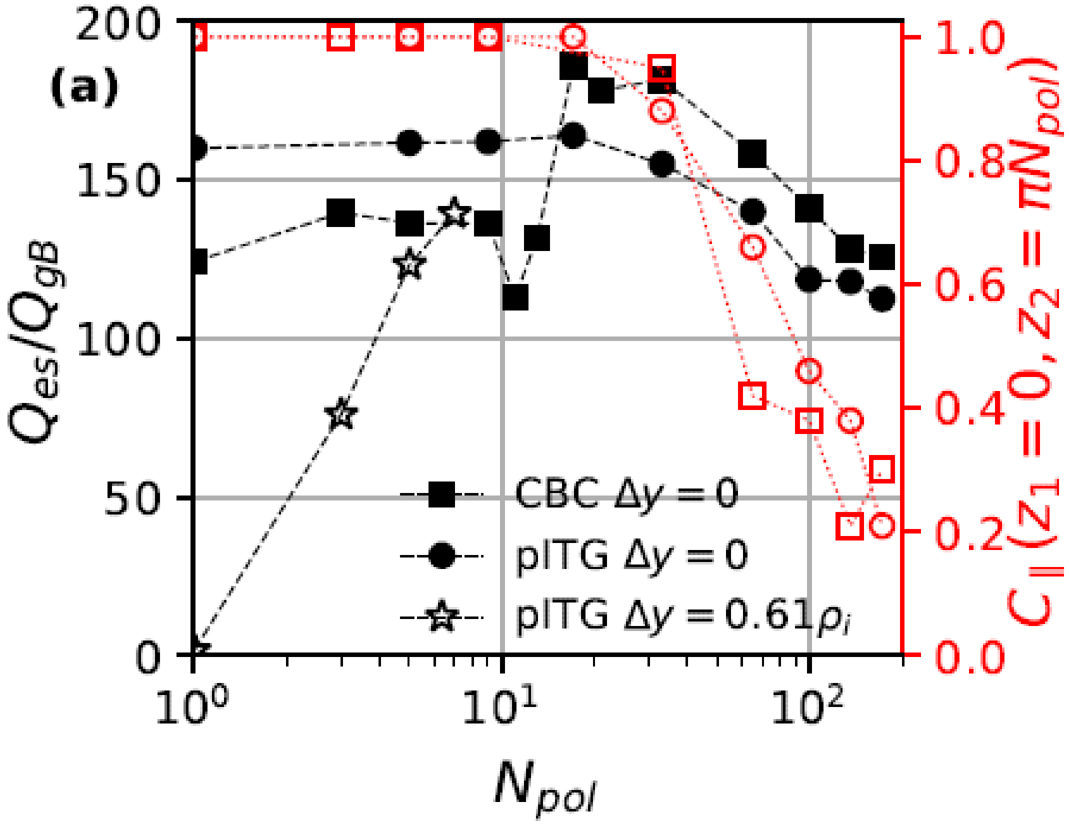
Outline

- Motivation and background
- Methods
- **Ultra-long turbulent eddies**
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

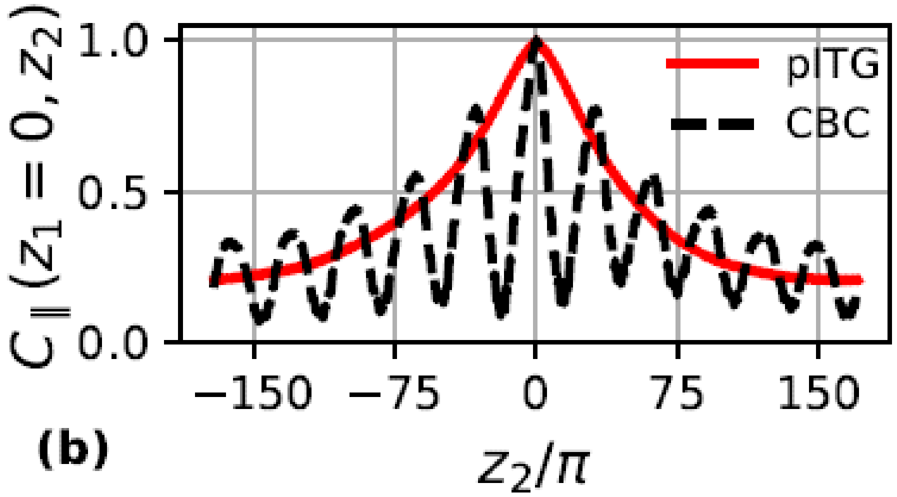
Swiss Plasma Center

Ultra-long turbulent eddies $N_{pol} > 20$

- The **total electrostatic heat flux** and **parallel correlation** with the parallel domain length N_{pol} for different simulation parameters.

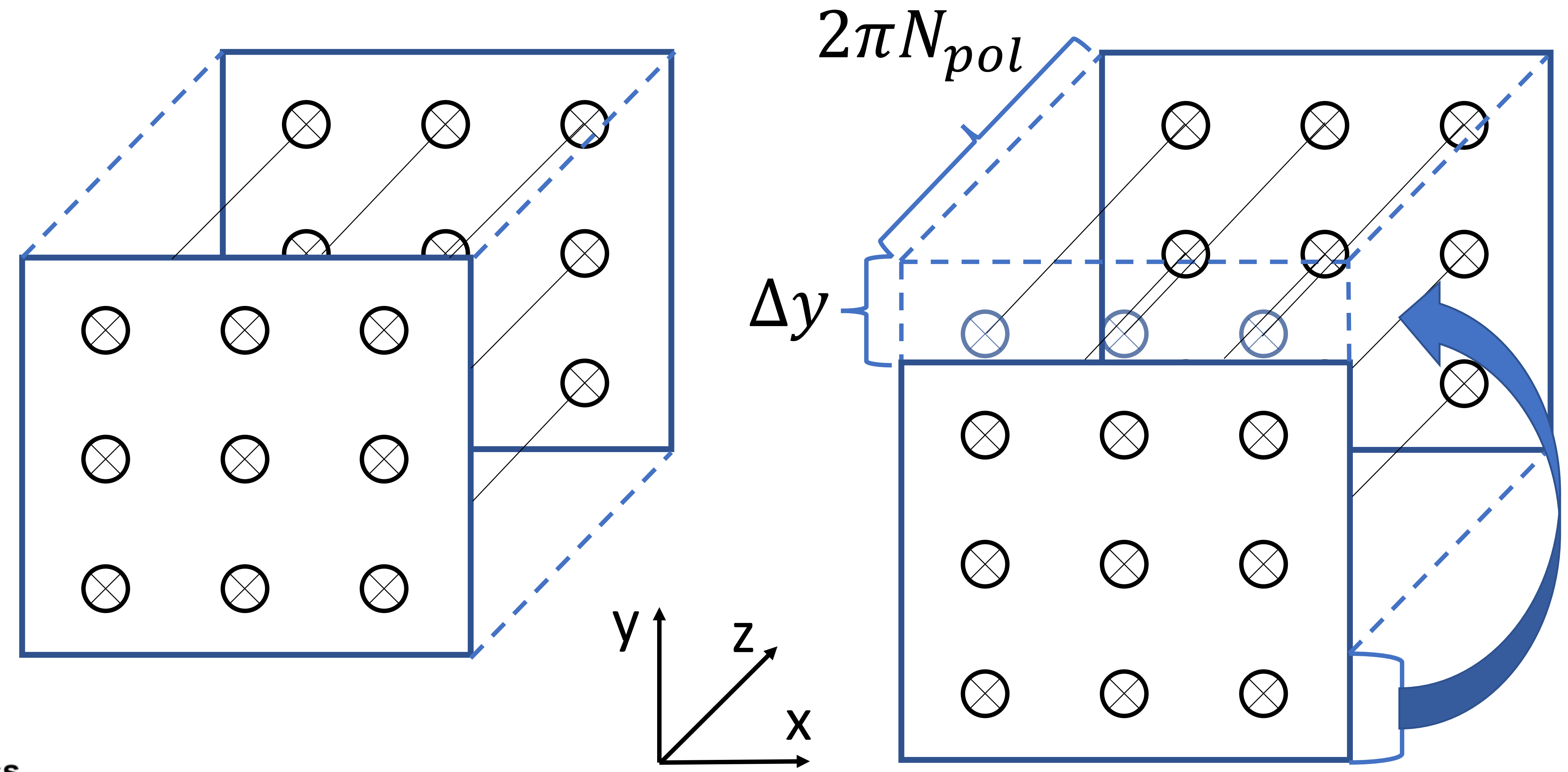


- The parallel correlation within the longest simulation domain $N_{pol} = 170$



- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

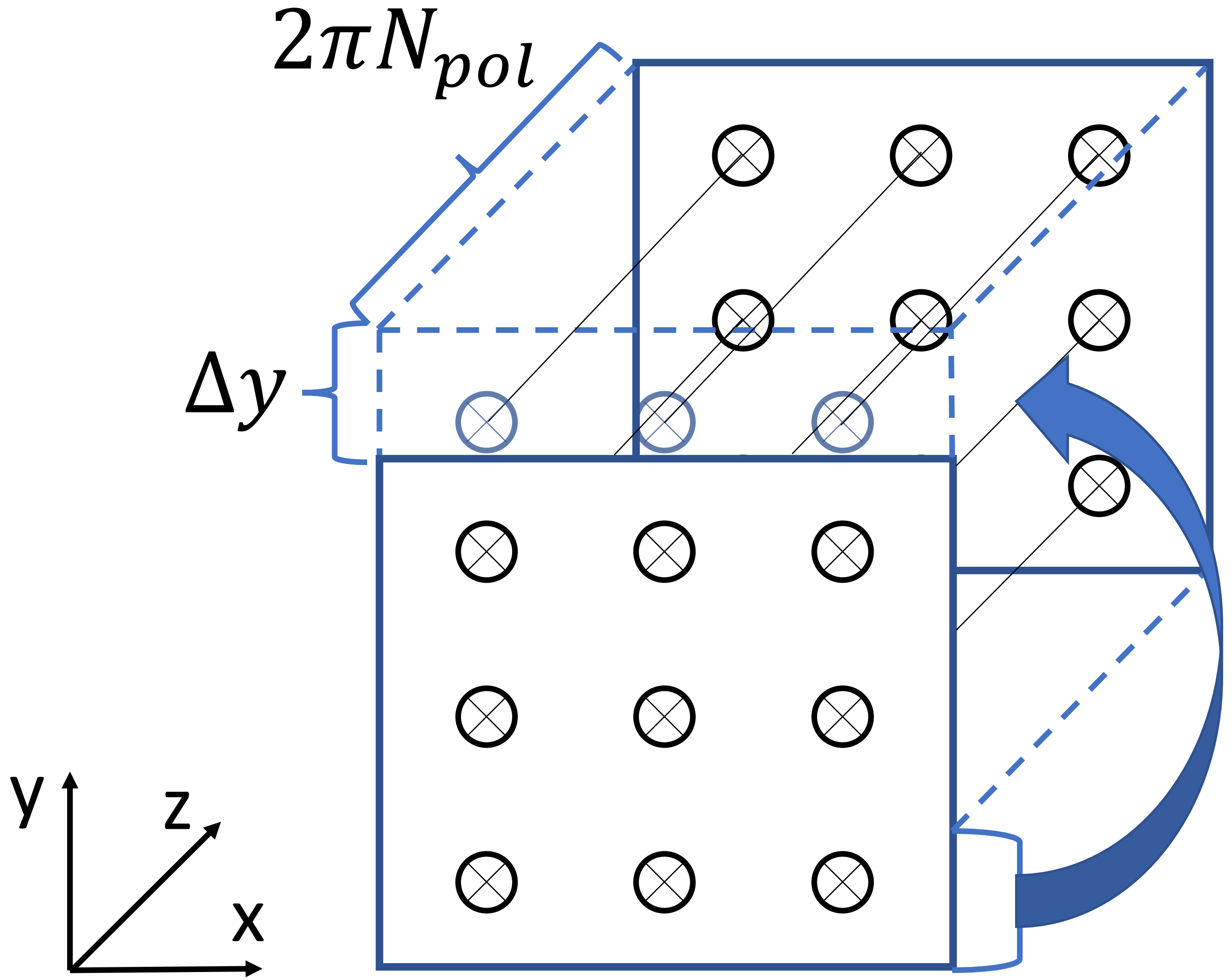
Reminder: parallel boundary shift



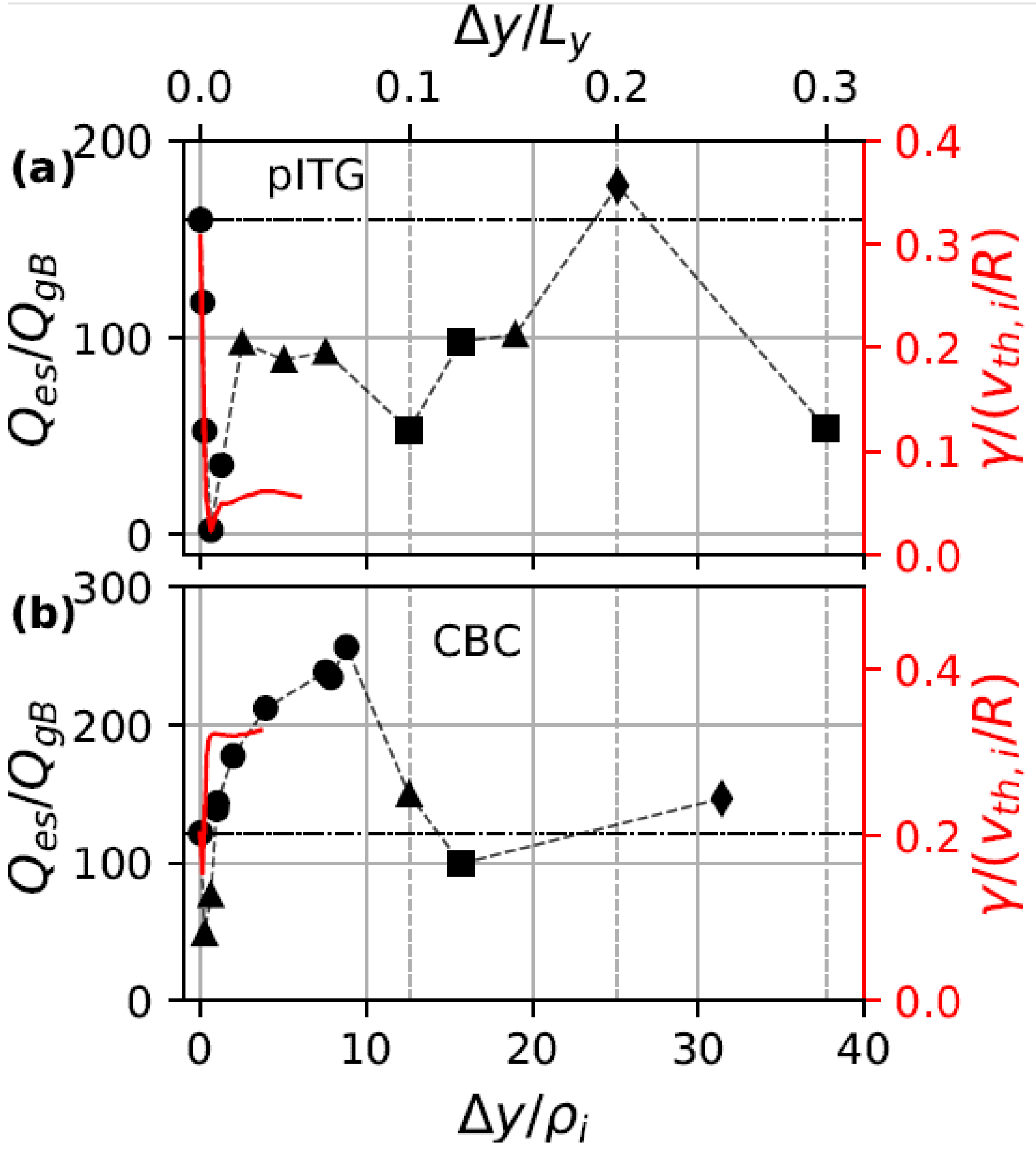
Reminder: parallel boundary shift

Phase factor:

$$\eta = \Delta y / L_y$$



Binormal shift $\Delta\, y$



- The $\Delta\, y$ simulates different ways magnetic field lines can connect (correctly accounting for safety factor value in local simulations).

- Turbulence can be strongly affected by the magnetic field topology, leading **to complete stabilization** in some cases.

- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

Turbulence self-interaction study

Eddy parallel length study

- Simulations with kinetic electrons at zero magnetic shear **require hundreds of poloidal turns** to achieve convergence
- **Kinetic electrons** set the parallel turbulence length scale
- In simulations with electron temperature gradient long parallel waves emerge

Binormal shift study

- Allows to study self-interaction in a region close to rational-q
- Proximity to a rational surface has a large impact on stability

Swiss Plasma Center

- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

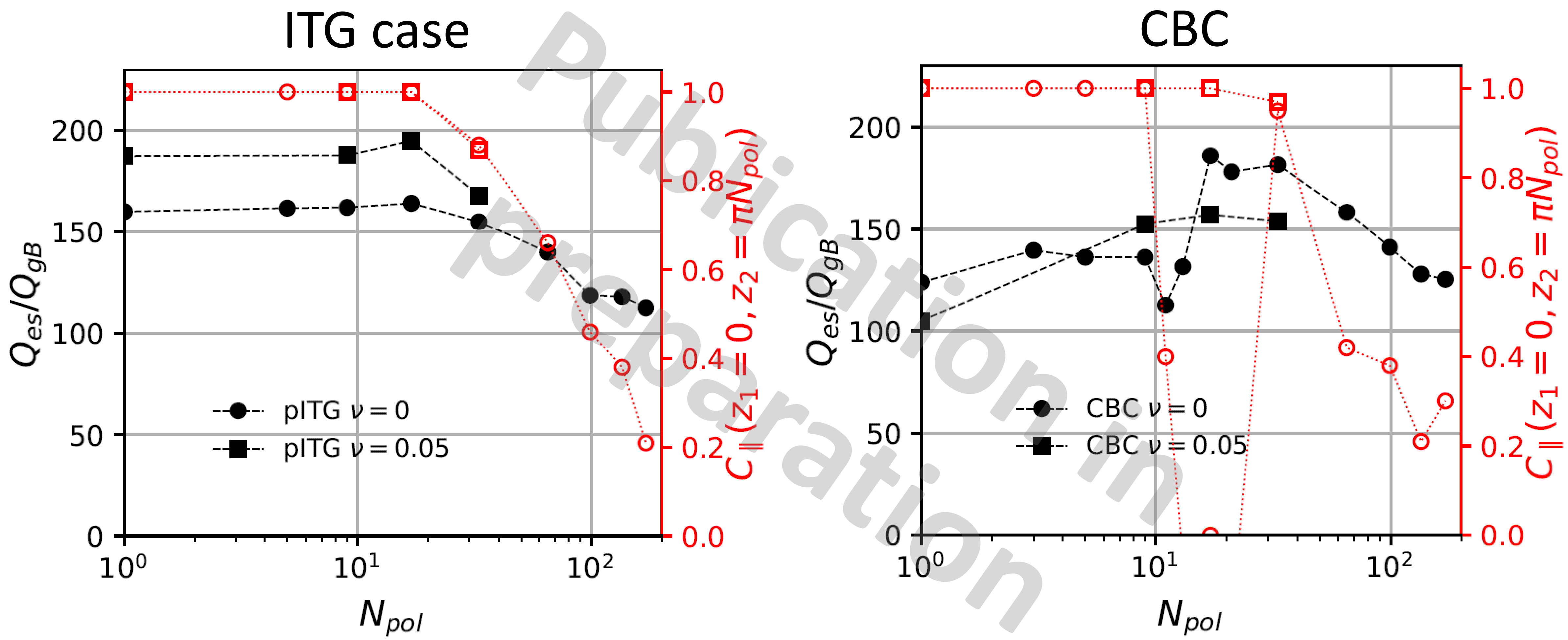
Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- **Persistence of ultra-long turbulent eddies**
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

Persistence of ultra-long turbulent eddies

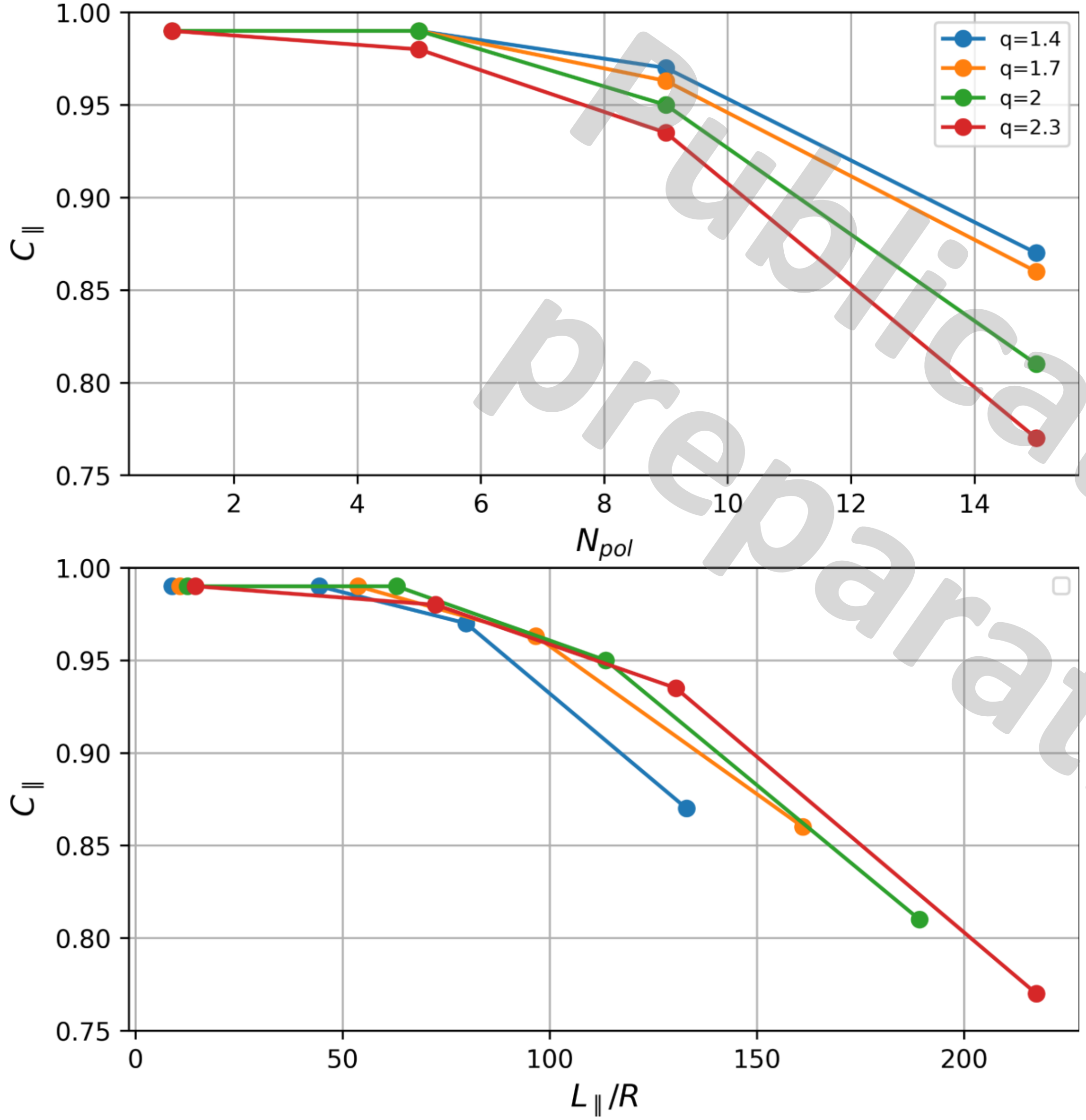
- Collisions
- Safety factor
- Triangularity and elongation

Collisions ($m_e = m_{e,real}$)



Parallel waves disappear when $\nu = 0.01$

Safety factor scan (pITG drive)



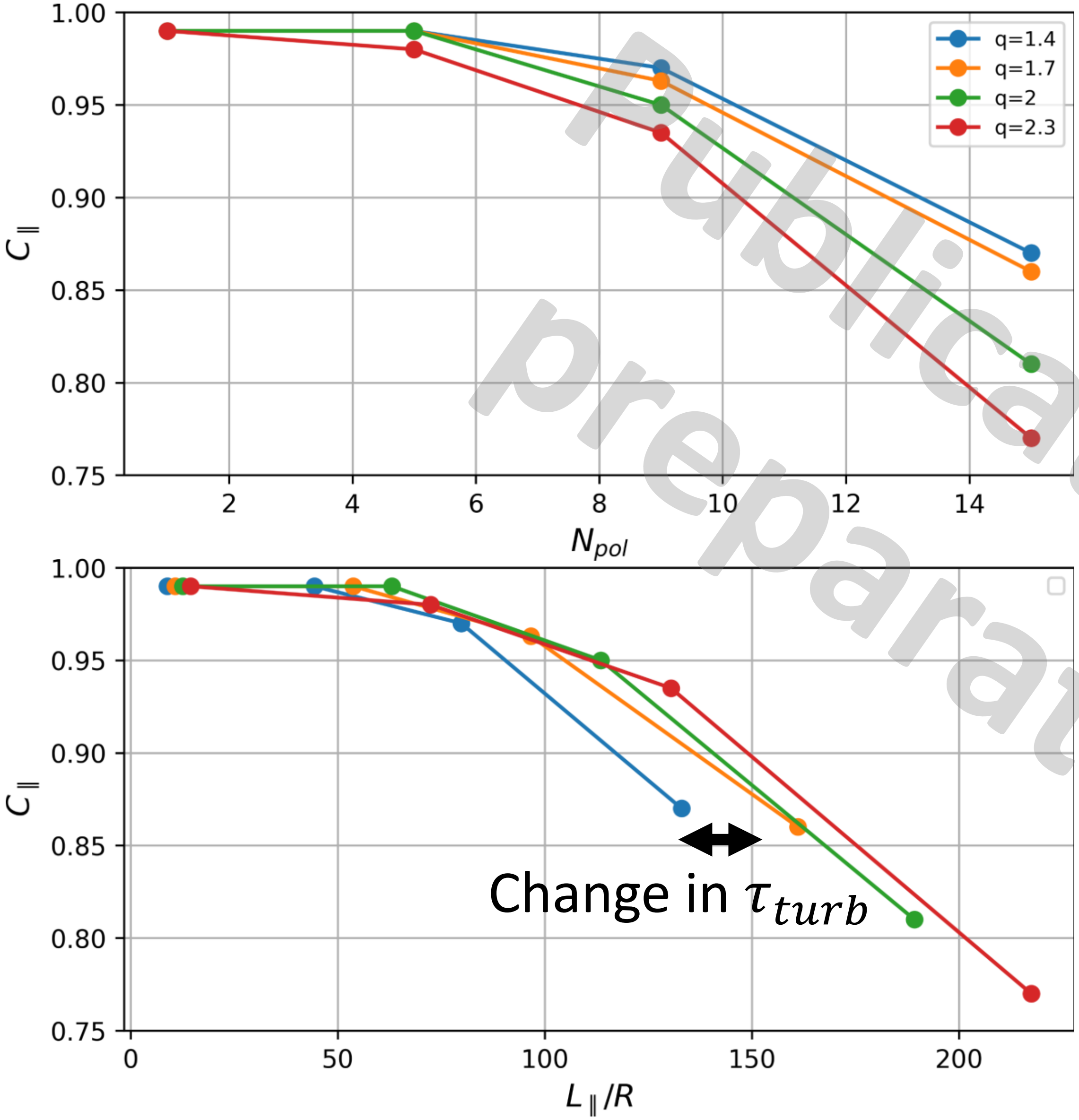
$$\frac{L_{Npol=1}}{R} \approx \frac{2\,\pi\epsilon}{\sin(\arctan\frac{\epsilon}{q})}$$

(Circular geometry)

Physical eddy length $l_{\parallel}$ does not change substantially

Swiss Plasma Center

Safety factor scan (pITG drive)



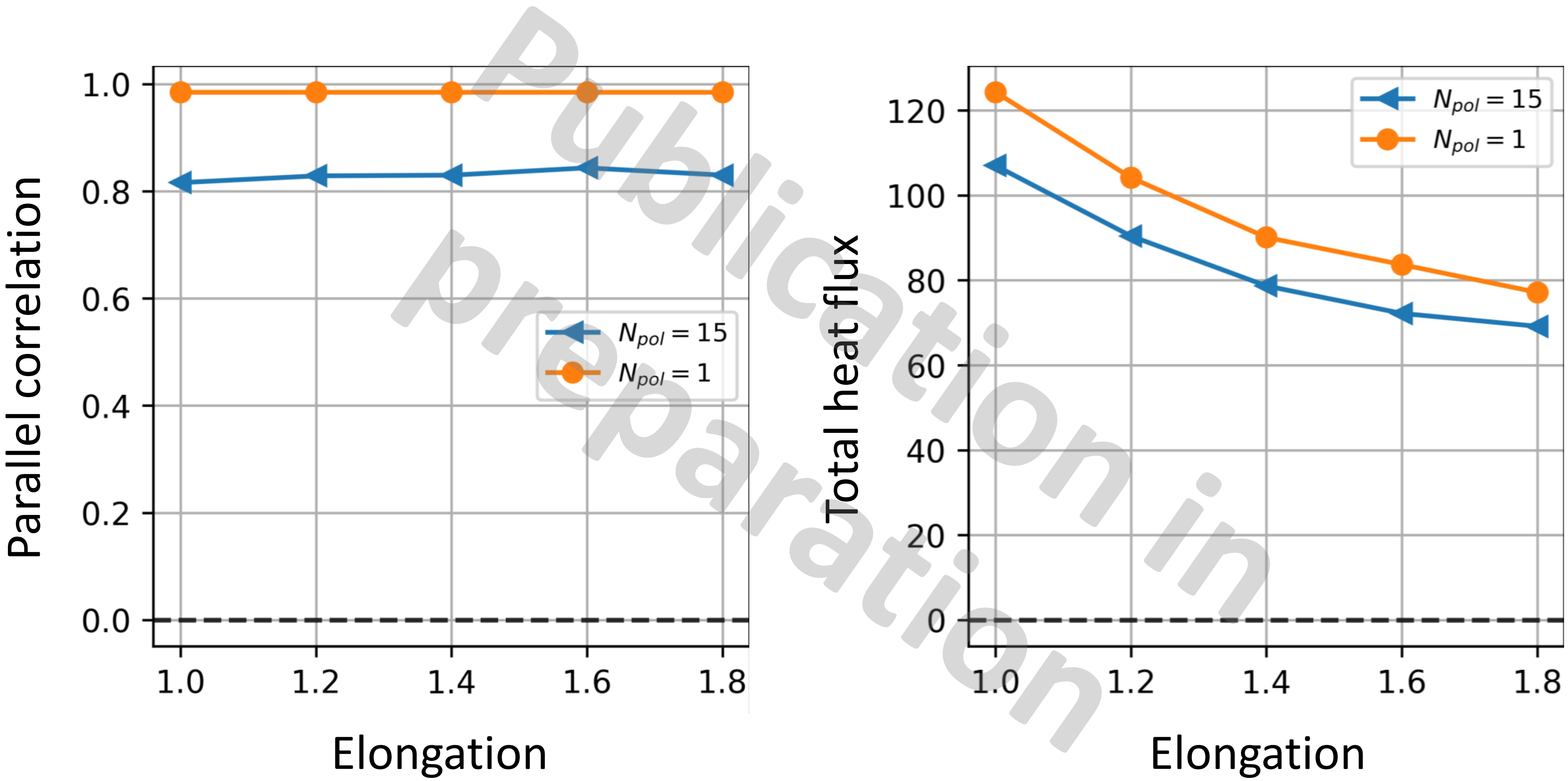
$$\frac{L_{Npol=1}}{R} \approx \frac{2\,\pi\epsilon}{\sin(\arctan\frac{\epsilon}{q})}$$

(Circular geometry)

Physical eddy length $l_\parallel$ does not change substantially

Swiss Plasma Center

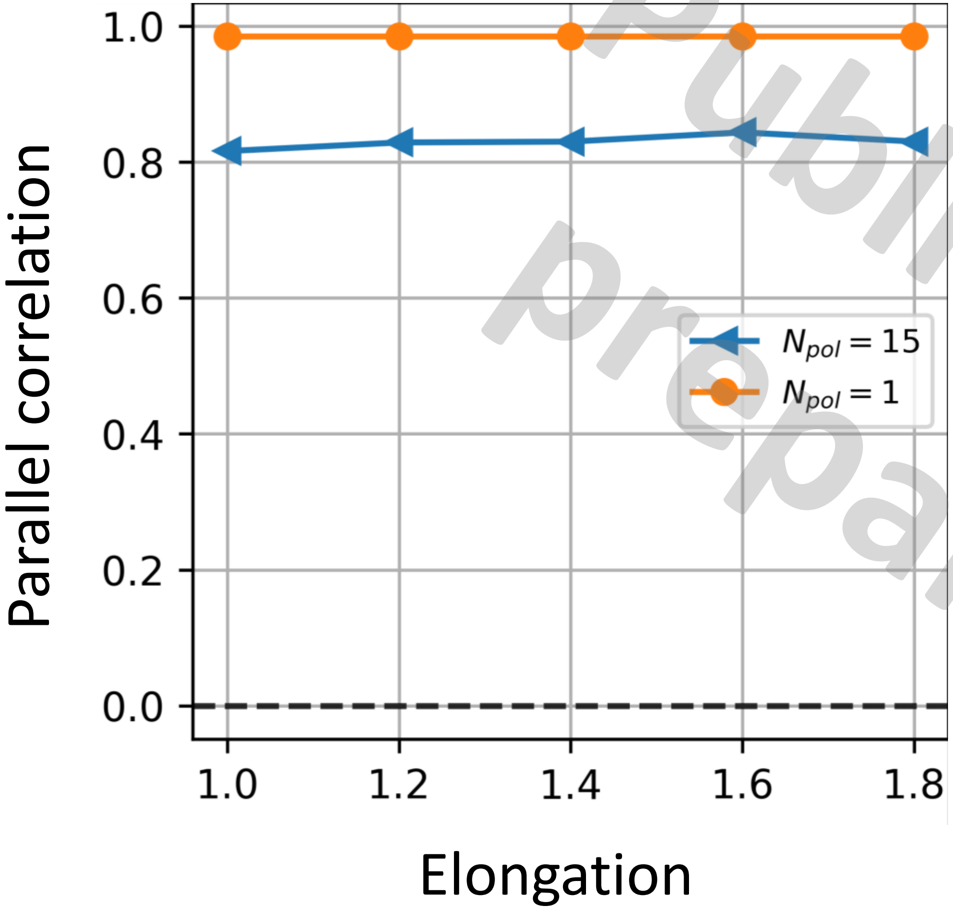
Elongation (with $\delta = 0$)



- pITG drive to avoid parallel waves

Swiss Plasma Center

Elongation (with $\delta = 0$)



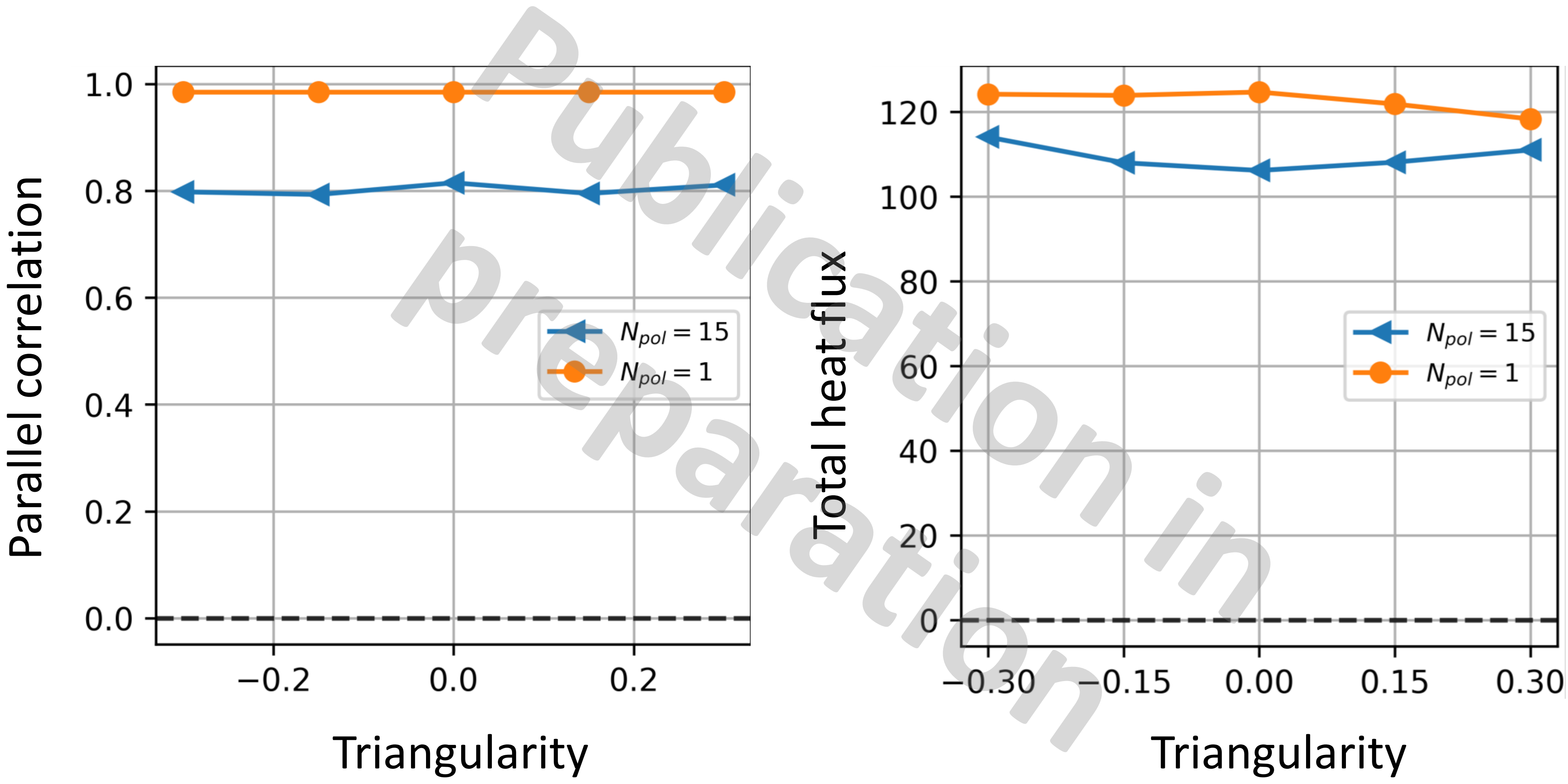
$$\frac{L_{Npol=1}}{R} \approx \frac{\pi\epsilon\sqrt{2(1+\kappa^2)}}{\sin(\arctan\frac{\sqrt{2(1+\kappa^2)}\epsilon}{2q})}$$

$$\frac{L_{Npol=1}}{R} \approx const.$$

- pITG drive to avoid parallel waves

Swiss Plasma Center

Triangularity (with $\kappa = 1.0$)



Swiss Plasma Center

Persistence of ultra-long turbulent eddies

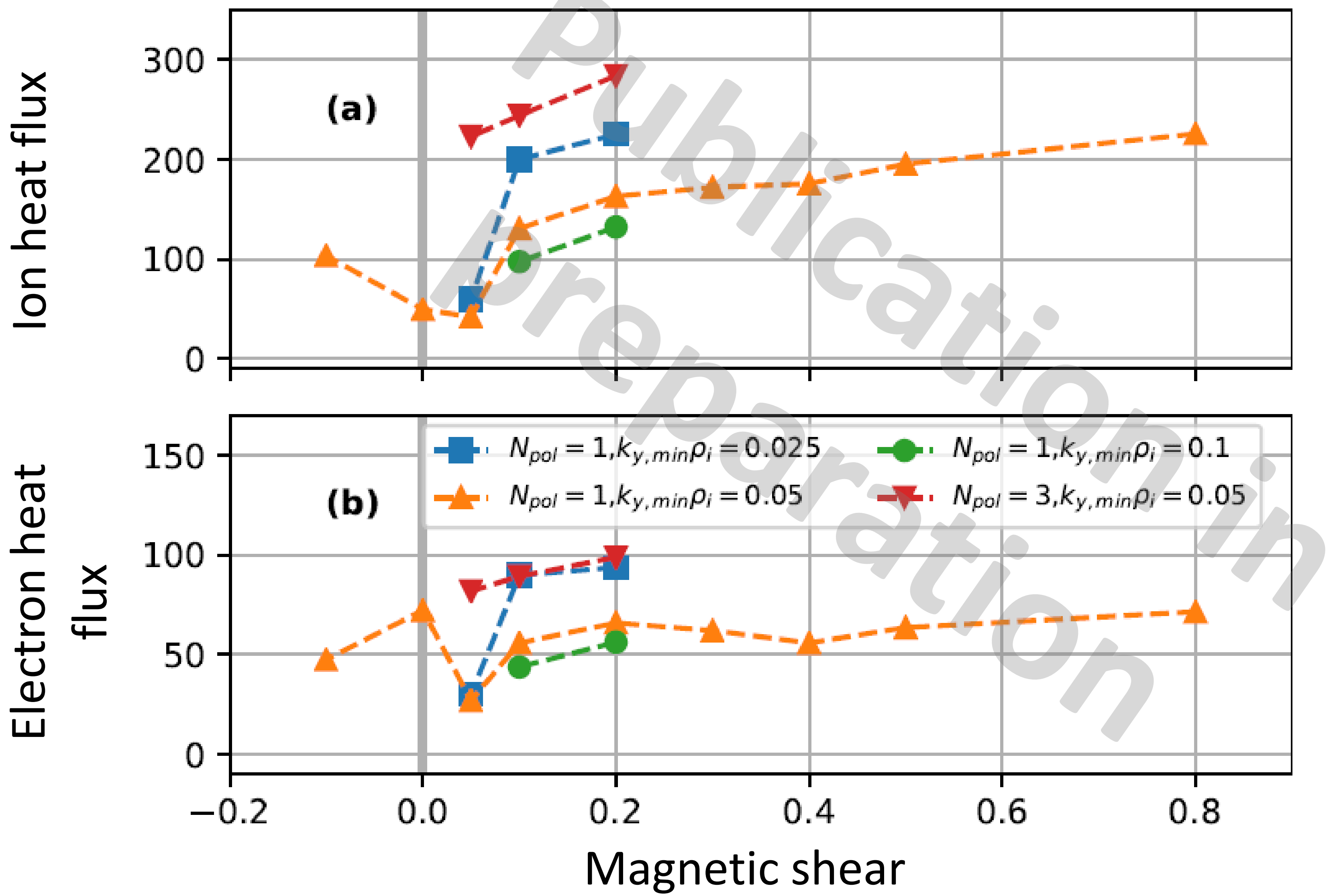
- **Collisions** do not reduce ultra-long eddy length
- No **plasma shaping** (elongation or triangularity) effects on ultra-long eddies

➢ Ultra-long eddies seem to **be a robust plasma feature** at low magnetic shear $\hat{s} \ll 1$.

Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- **Low, but finite magnetic shear simulations**
- Non-uniform magnetic shear simulations
- Conclusions

Heat flux at finite shear

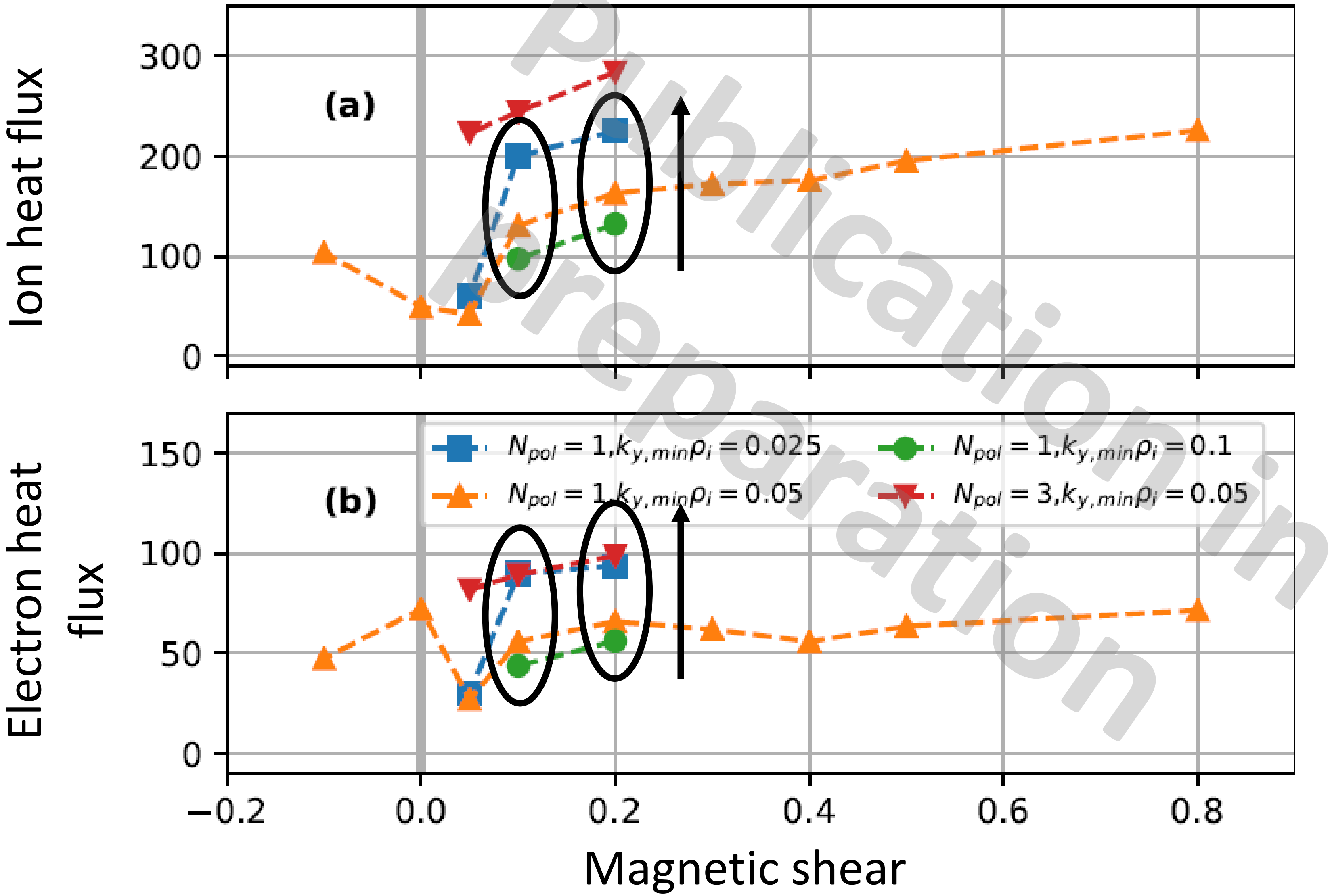


Trends at low shear agree with previous study at $\hat{s} = 0.8$

- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

Swiss Plasma Center

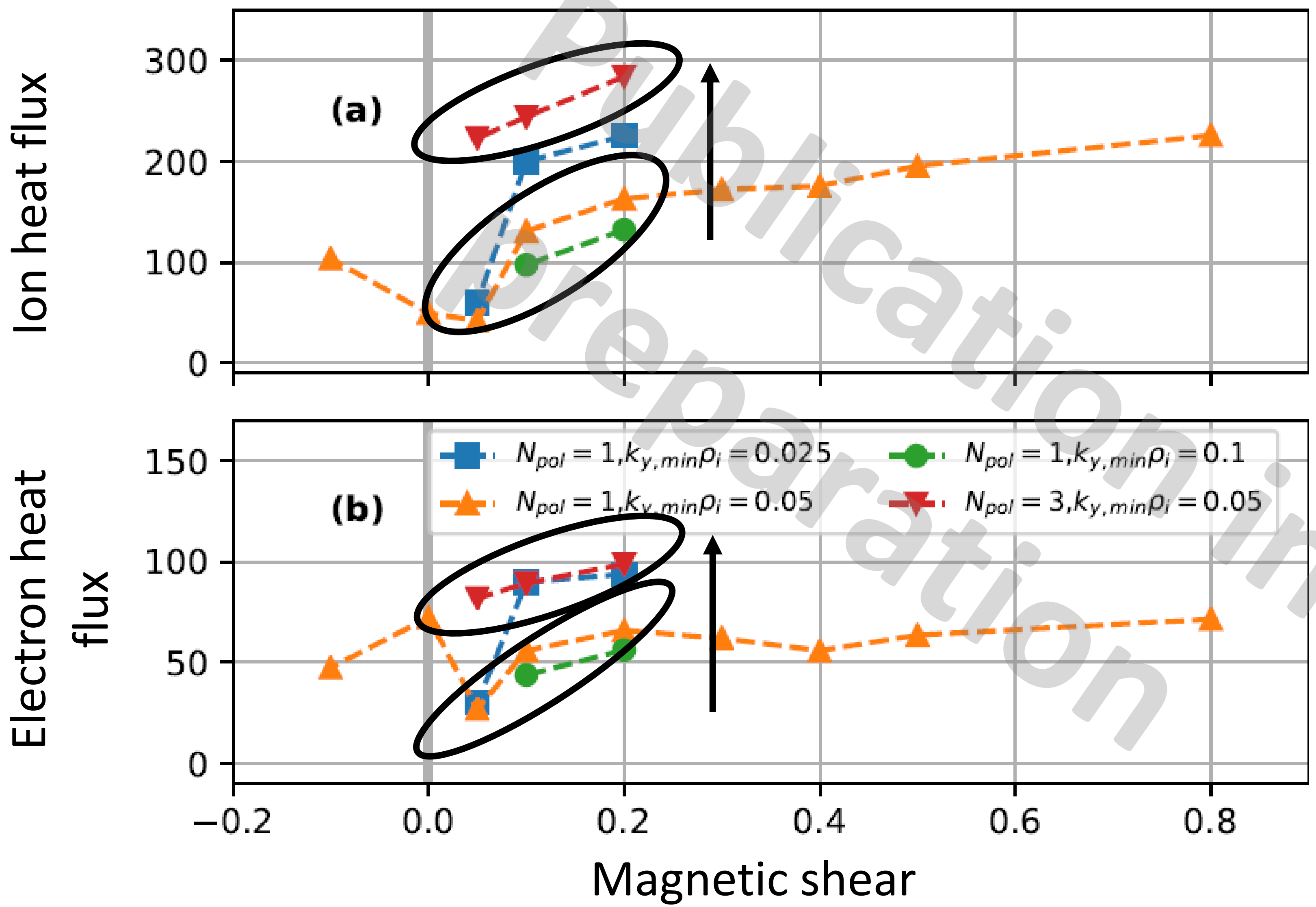
EPFL Heat flux at finite shear



Heat flux increases when effects of self-interaction are “diluted” **by spacing out integer surfaces**

Swiss Plasma Center

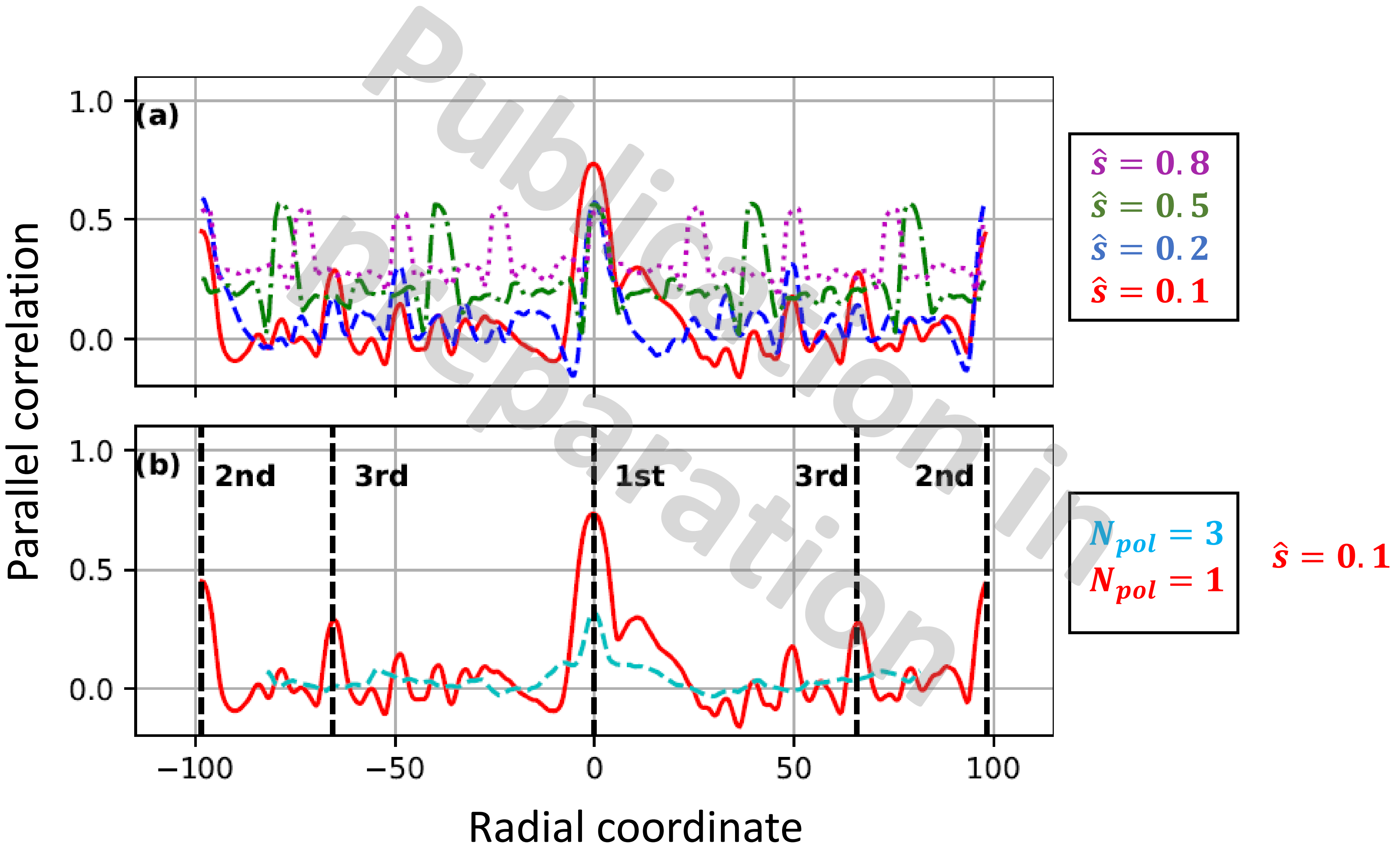
Heat flux at finite shear



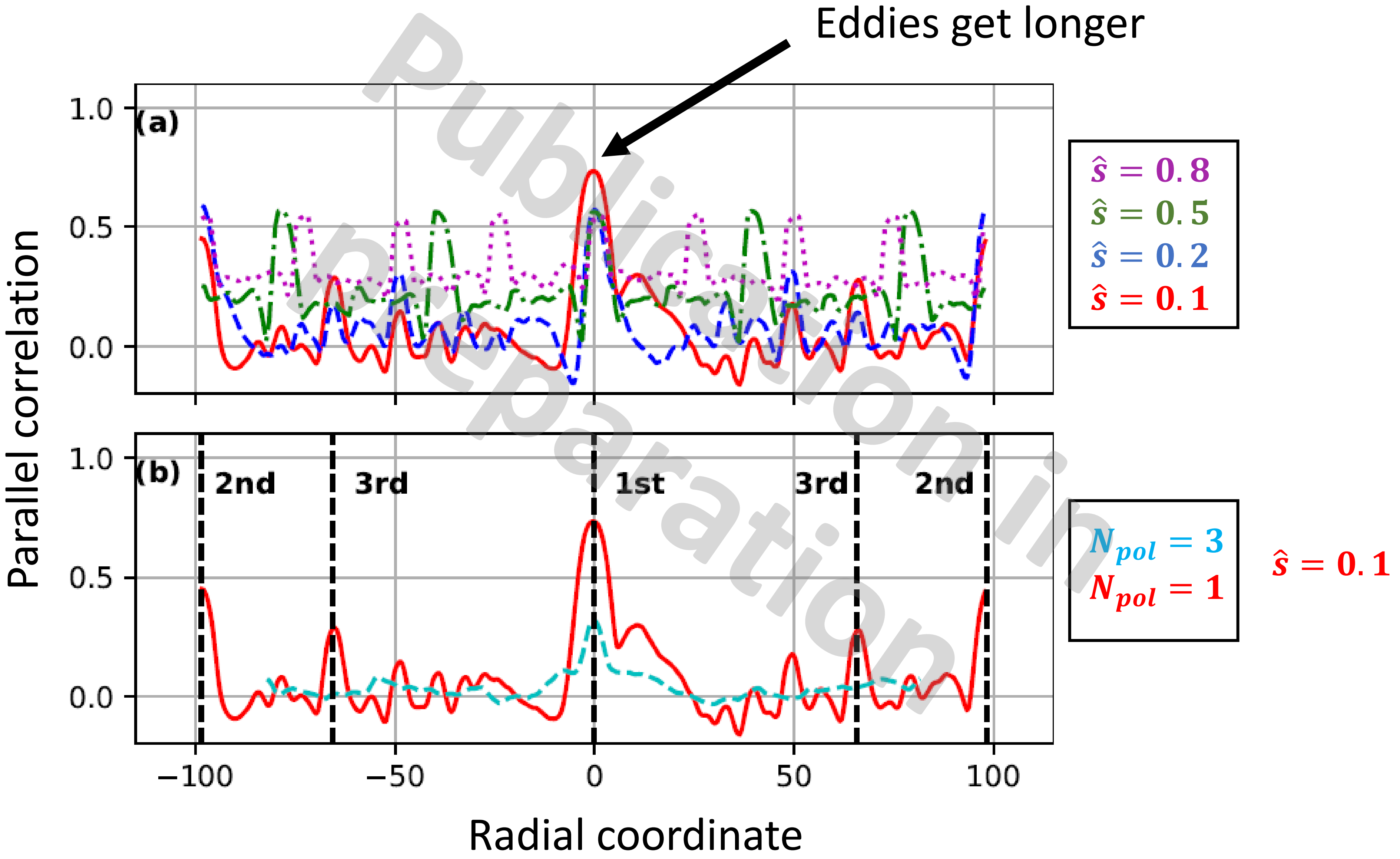
Heat flux increases when effects of self-interaction are "diluted" **by increasing domain length**

Swiss Plasma Center

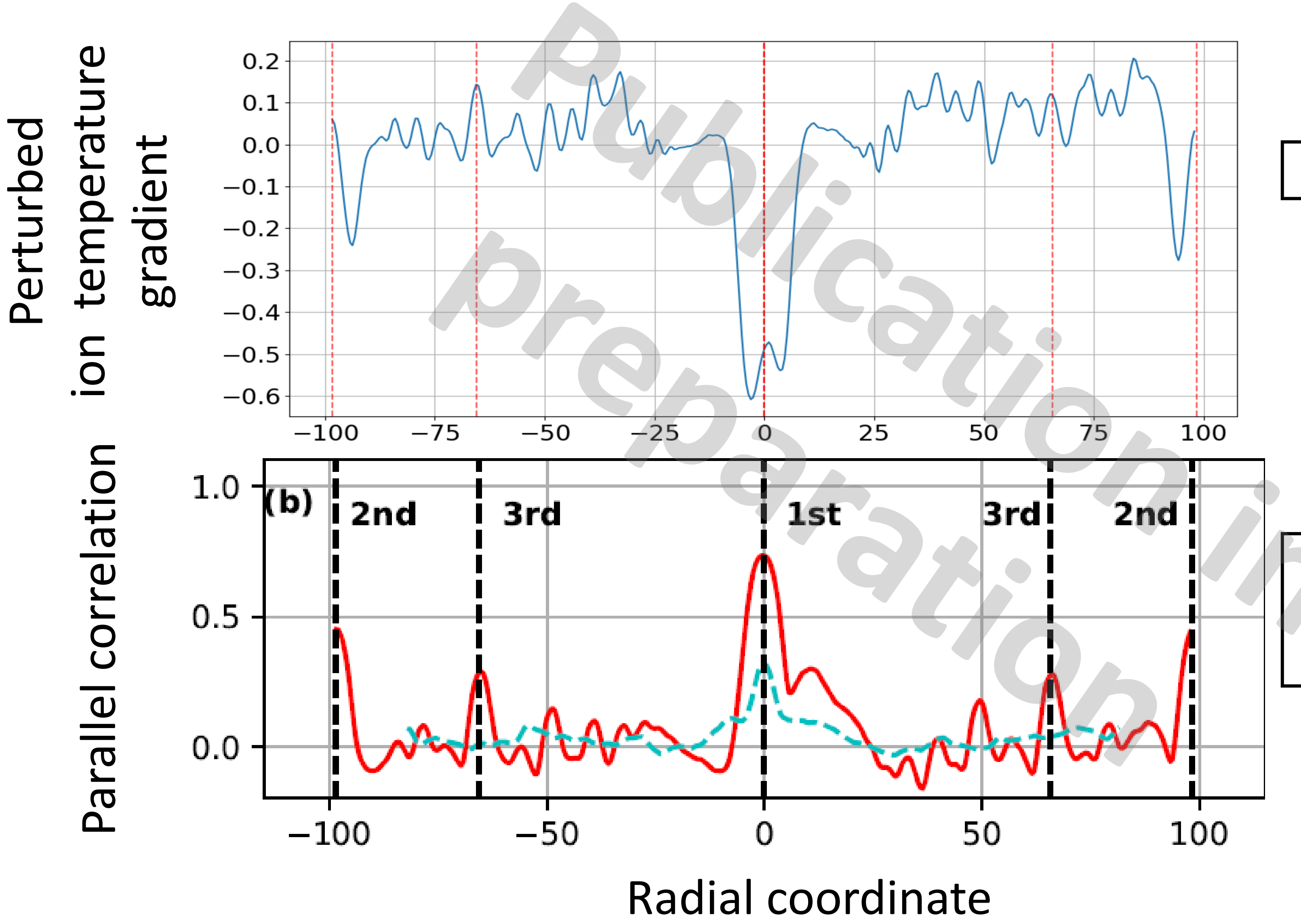
Correlation at finite shear



Correlation at finite shear



Profile steepening



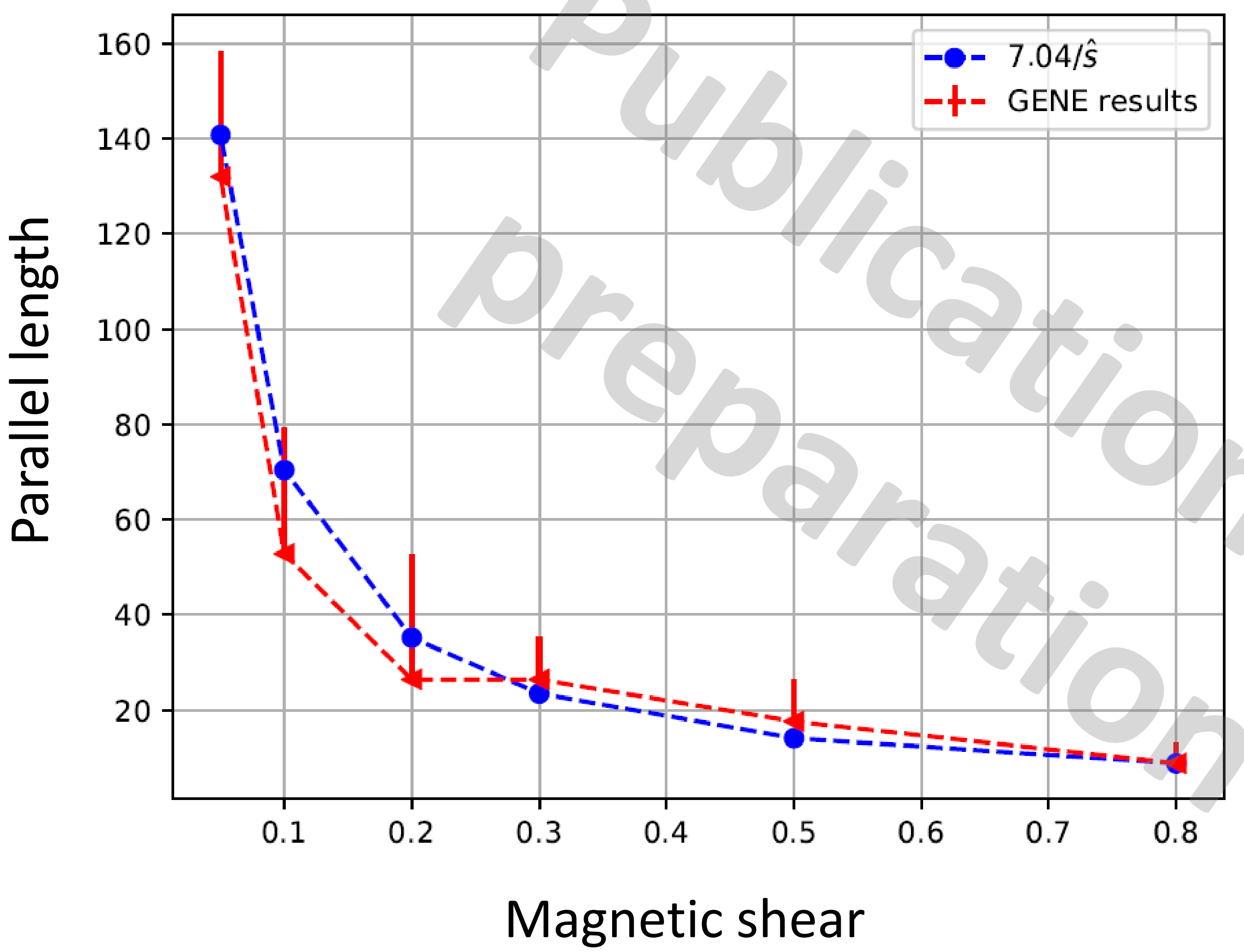
$\hat{s} = 0.1$

$N_{pol} = 3$
$N_{pol} = 1$

$\hat{s} = 0.1$

Swiss Plasma Center

Estimate of eddy length with $\hat{s}$



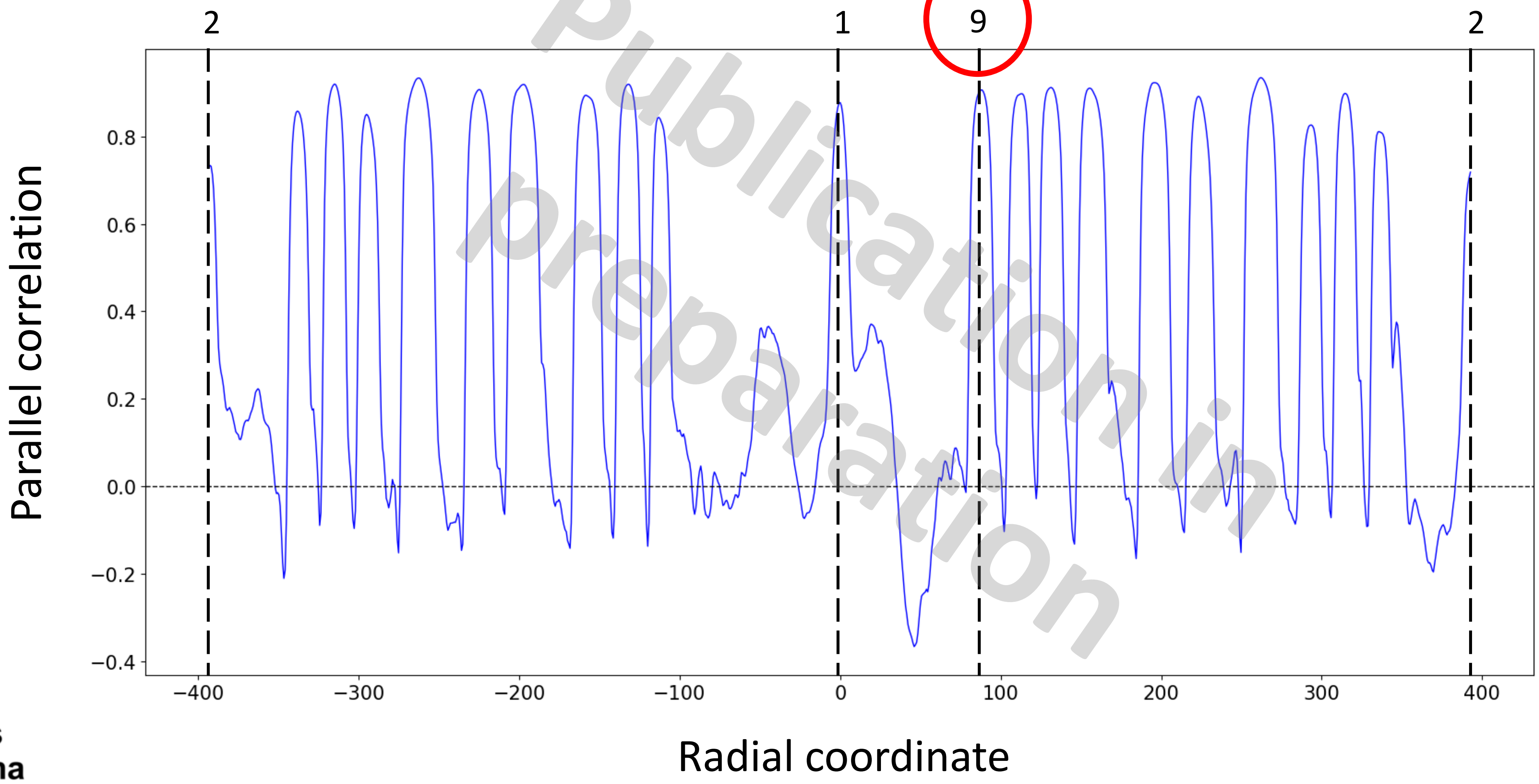
Based on the highest order rational surfaces with significant corrugations

Due to magnetic drifts and FLR effects parallel length scales like

$$\hat{s}^{-1}$$

Challenges with low shear simulations

$\hat{s} = 0.05$



Swiss Plasma Center

Finite shear study

- Effects related to self-interaction follow previously established trends
- Strong profile corrugations at rational surfaces
- Eddy parallel length scales like: $\hat{s}^{-1}$
- However, simulations computationally expensive as shear is being reduced

EPFL

Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- **Non-uniform magnetic shear simulations**
- Conclusions

Swiss Plasma Center

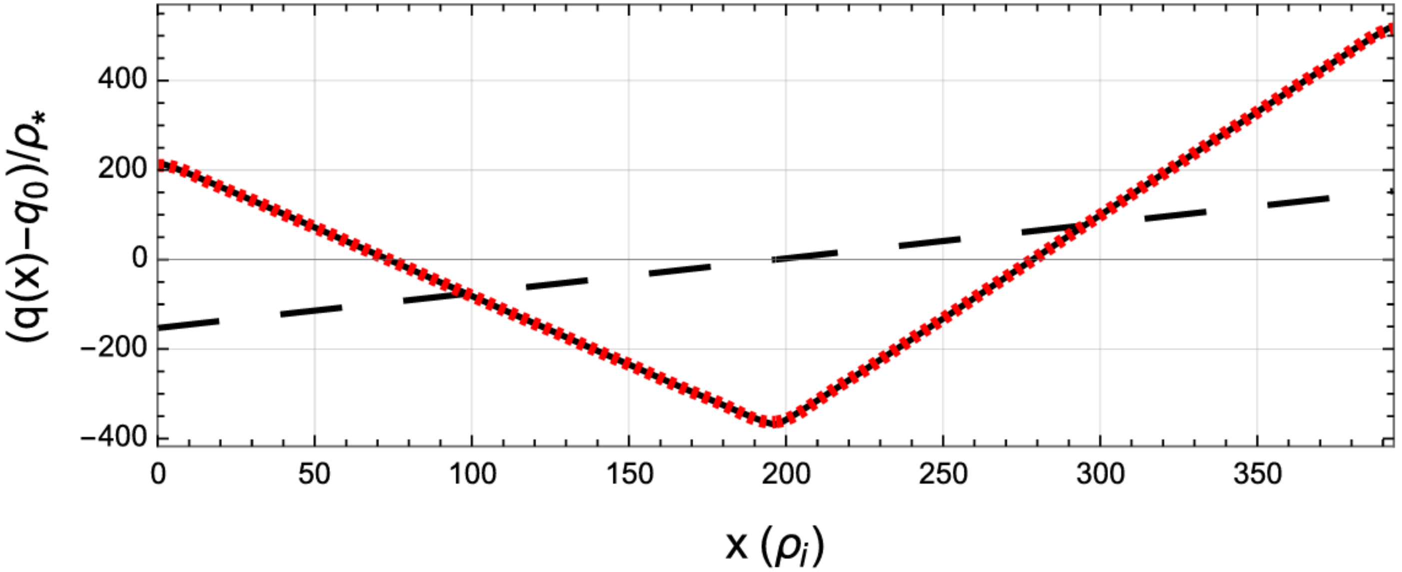
Non-uniform magnetic shear formalism

Key idea:

Create a safety factor profile that varies on the gyroradius-scale, which is rigorously derived from a current drive source inspired by ECCD

$$\tilde{q}(r) = \sum_{n=1}^{\infty} \left[\tilde{q}_n^C \cos\left(\frac{2\pi n}{L_r}(r - r_0) \right) + \tilde{q}_n^S \sin\left(\frac{2\pi n}{L_r}(r - r_0) \right) \right].$$

- The code input parameters are non-uniform magnetic shear Fourier coefficients
- The simulations are no longer "local" but still performed in a flux tube domain

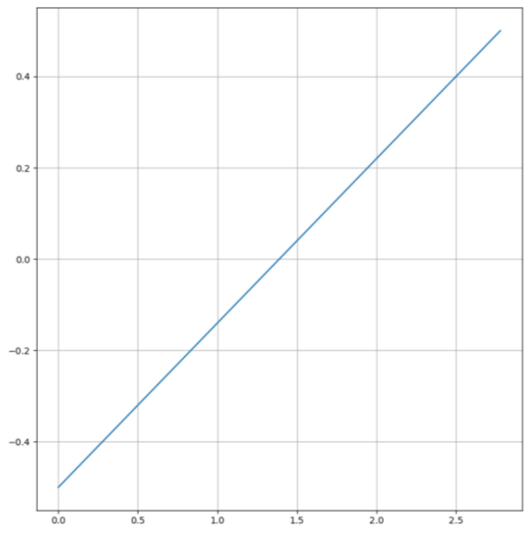


Swiss Plasma Center

- J. Ball and S. Brunner 2023 *Plasma Phys. Control. Fusion* **65** 014004

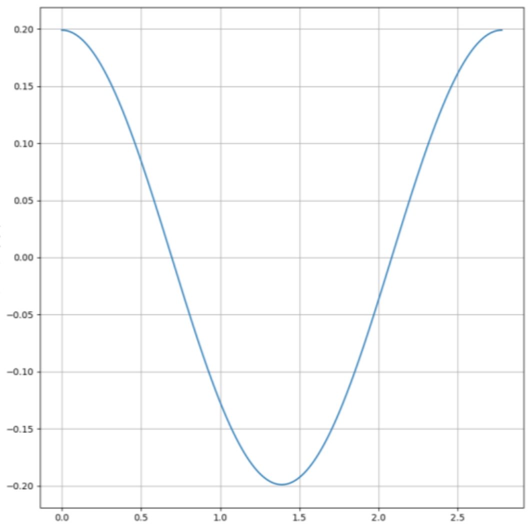
Non-uniform construction

$\hat{s} = 0.8$

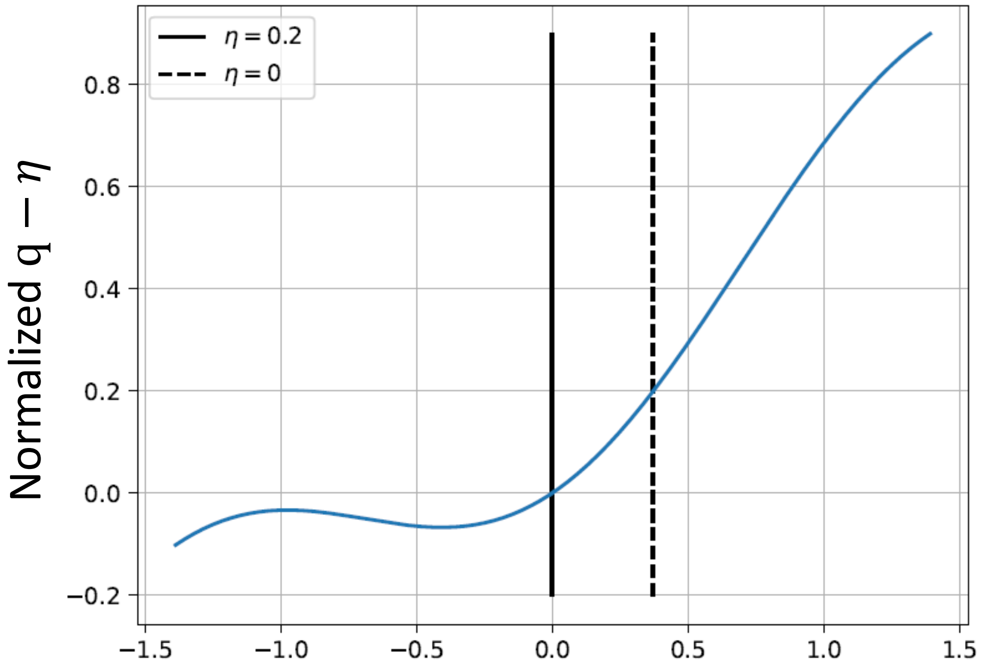


+

$s_S^1 = -1$



=



Radial coordinate

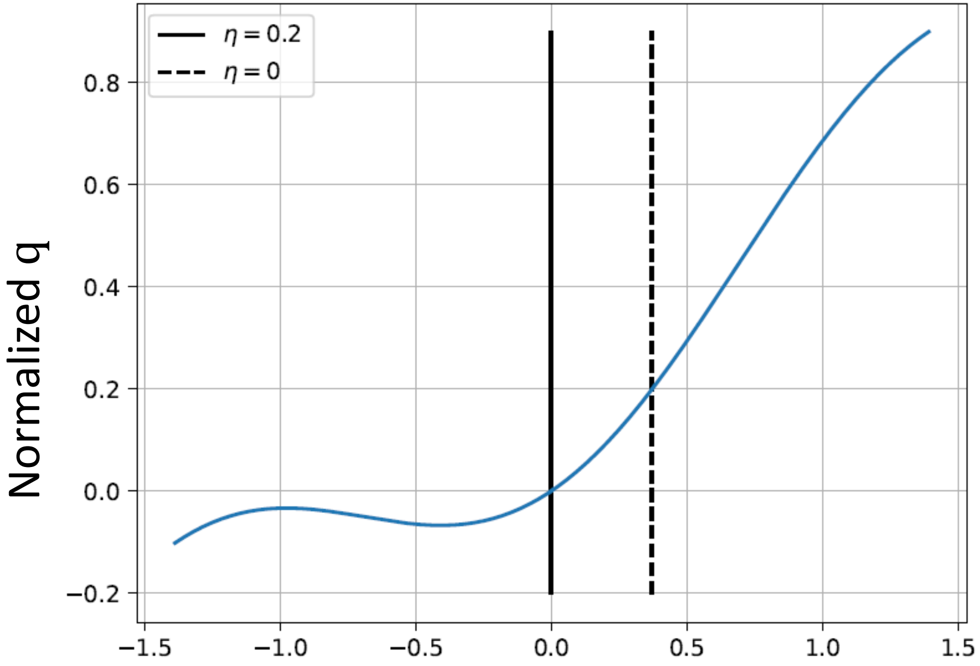
Swiss Plasma Center

EPFL Linear simulation with $\eta = \Delta y / L_y$

Linear simulations with:

$\hat{s} = 0.8$

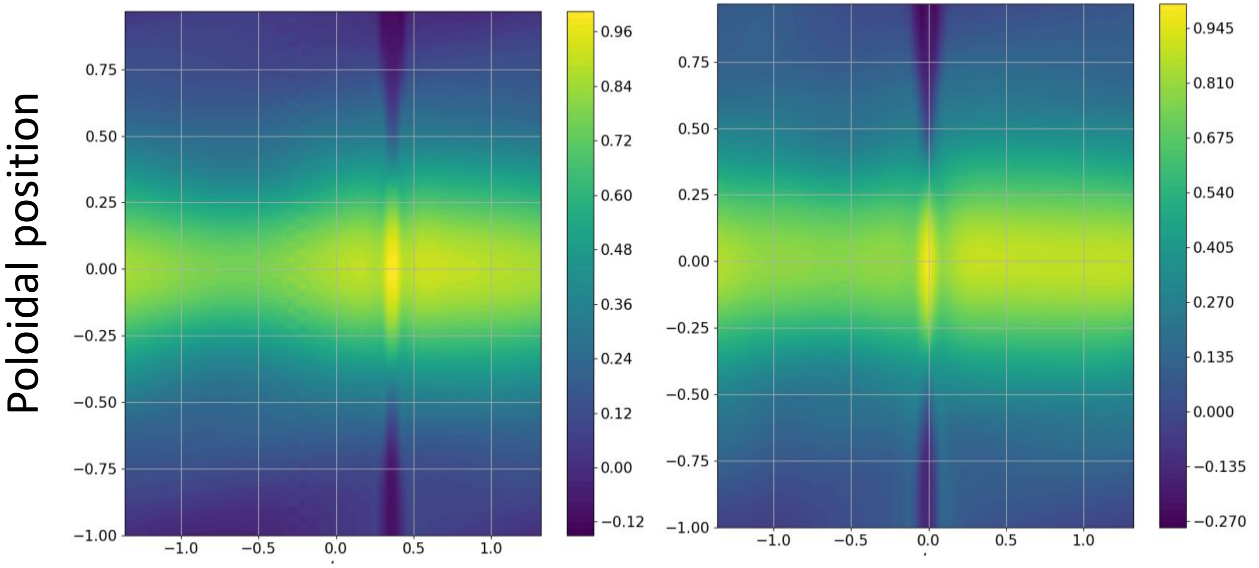
$s_S^1 = -1$



Radial coordinate

Normalized density fluctuations

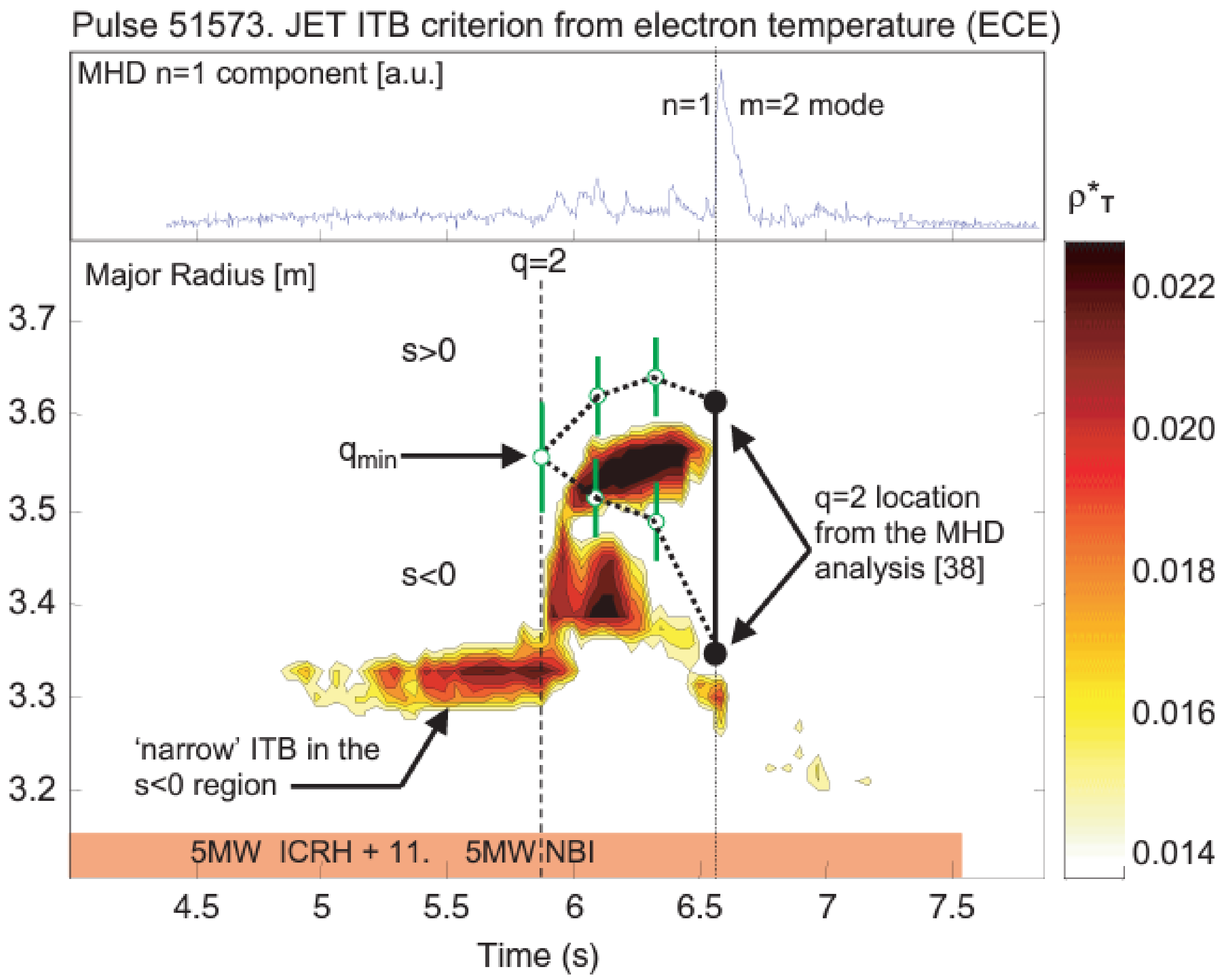
$\eta = 0$ $\eta = 0.2$



Radial coordinate

Swiss Plasma Center

Motivation (splitting ITB)

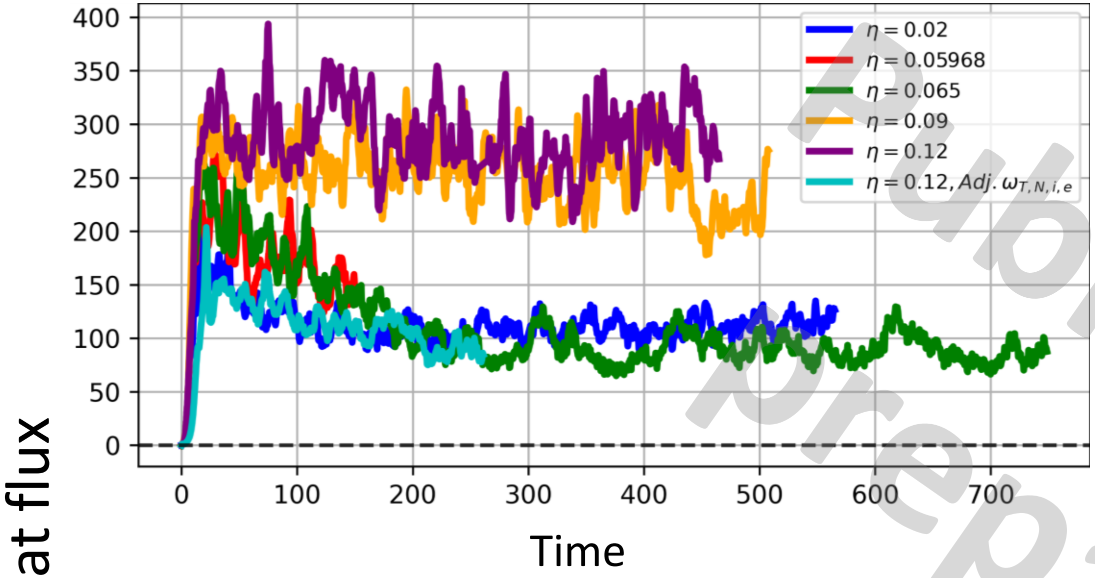


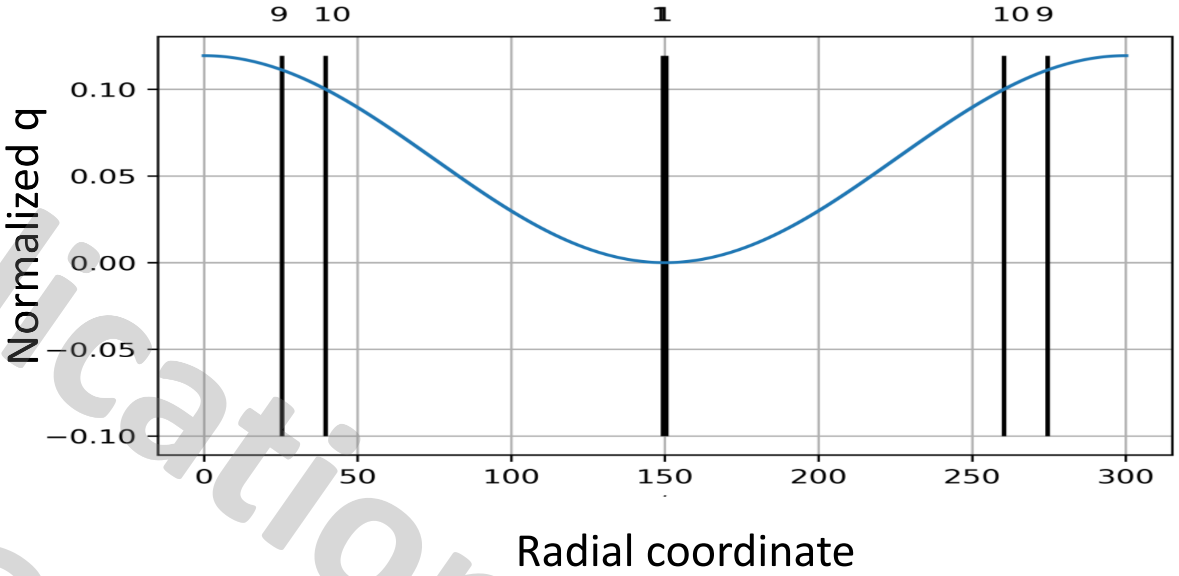
- ITB forms around $q_{min} = 2$ surface
- ITB follows $q = 2$ surfaces

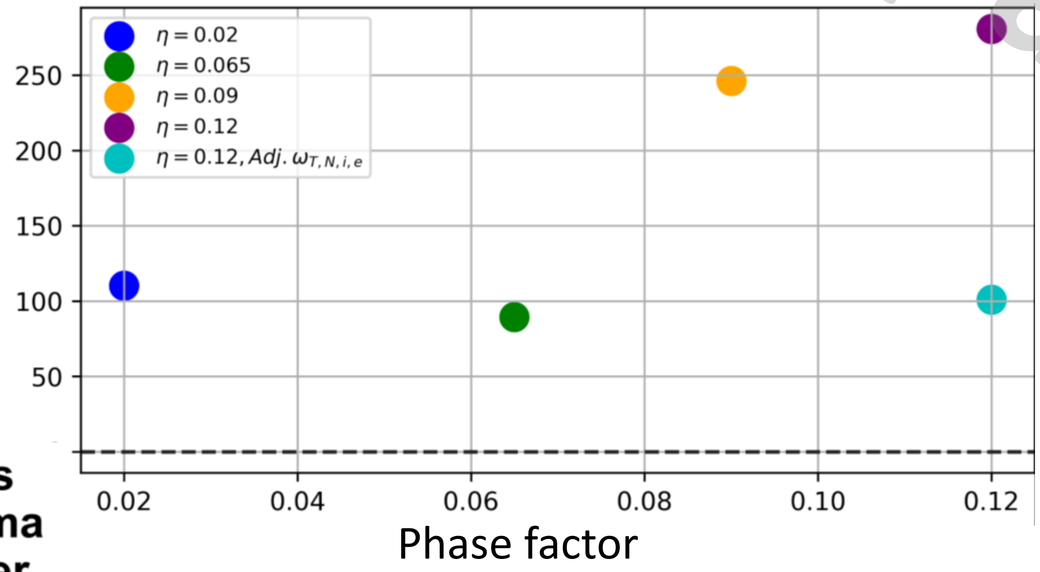
- E Joffrin et al 2002 Plasma Phys. Control. Fusion 44 1739

Swiss Plasma Center

Nonlinear simulations



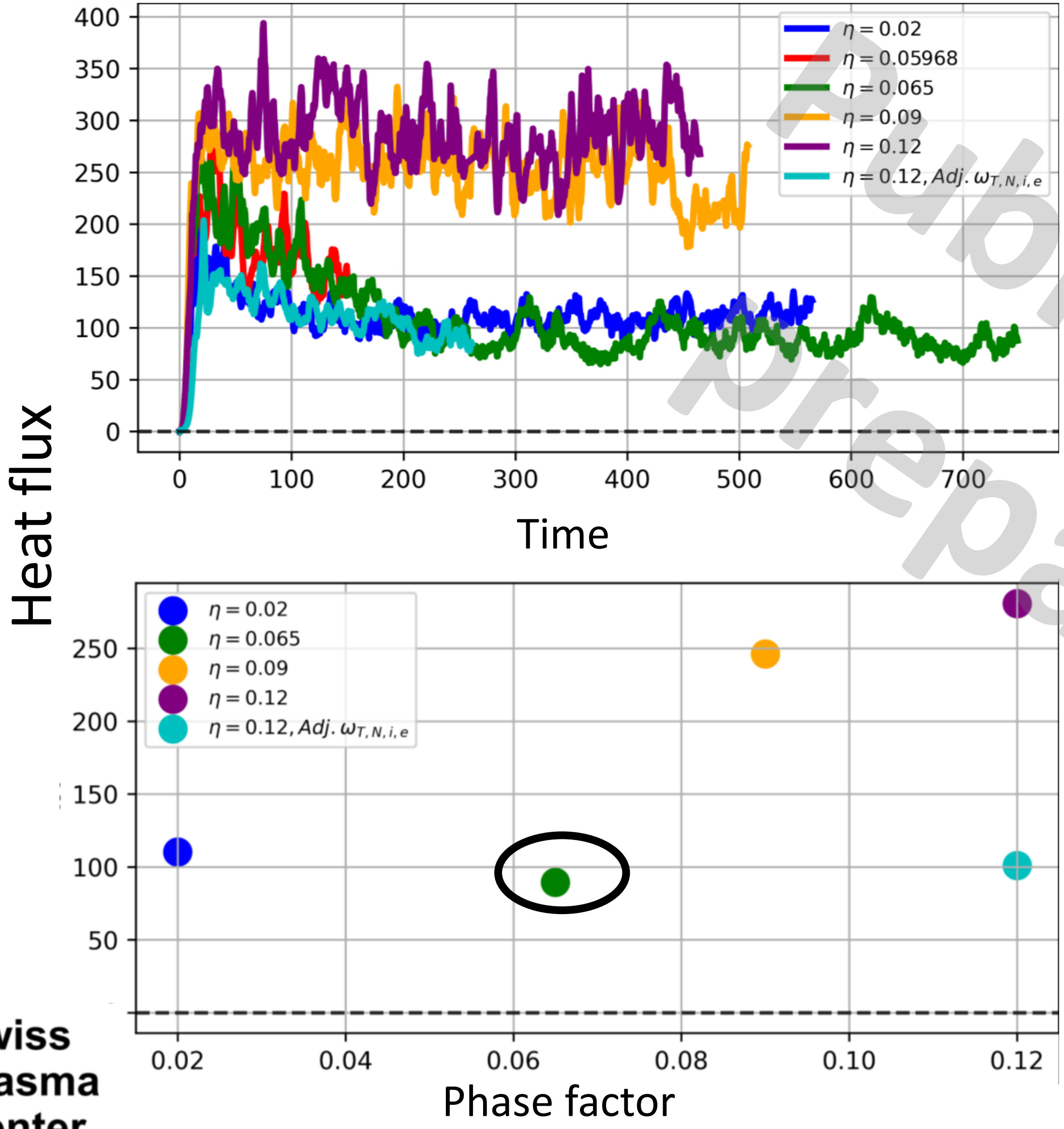


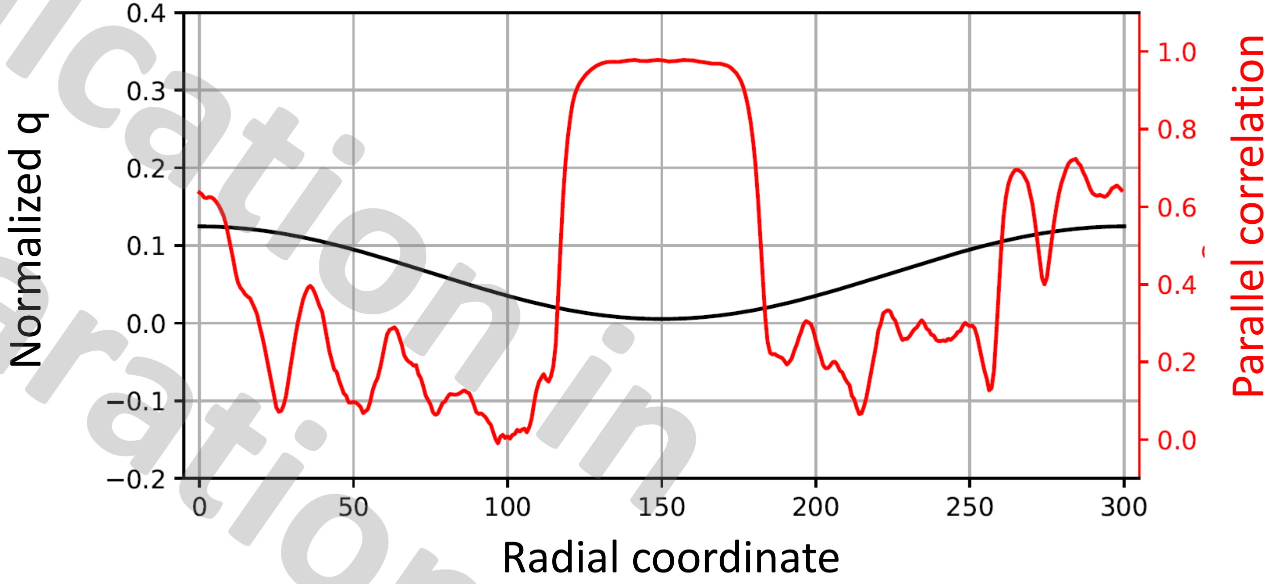


Target a q perturbation to have a minimum close to an integer surface.

Phase factor η adjusted to change field line connection properties

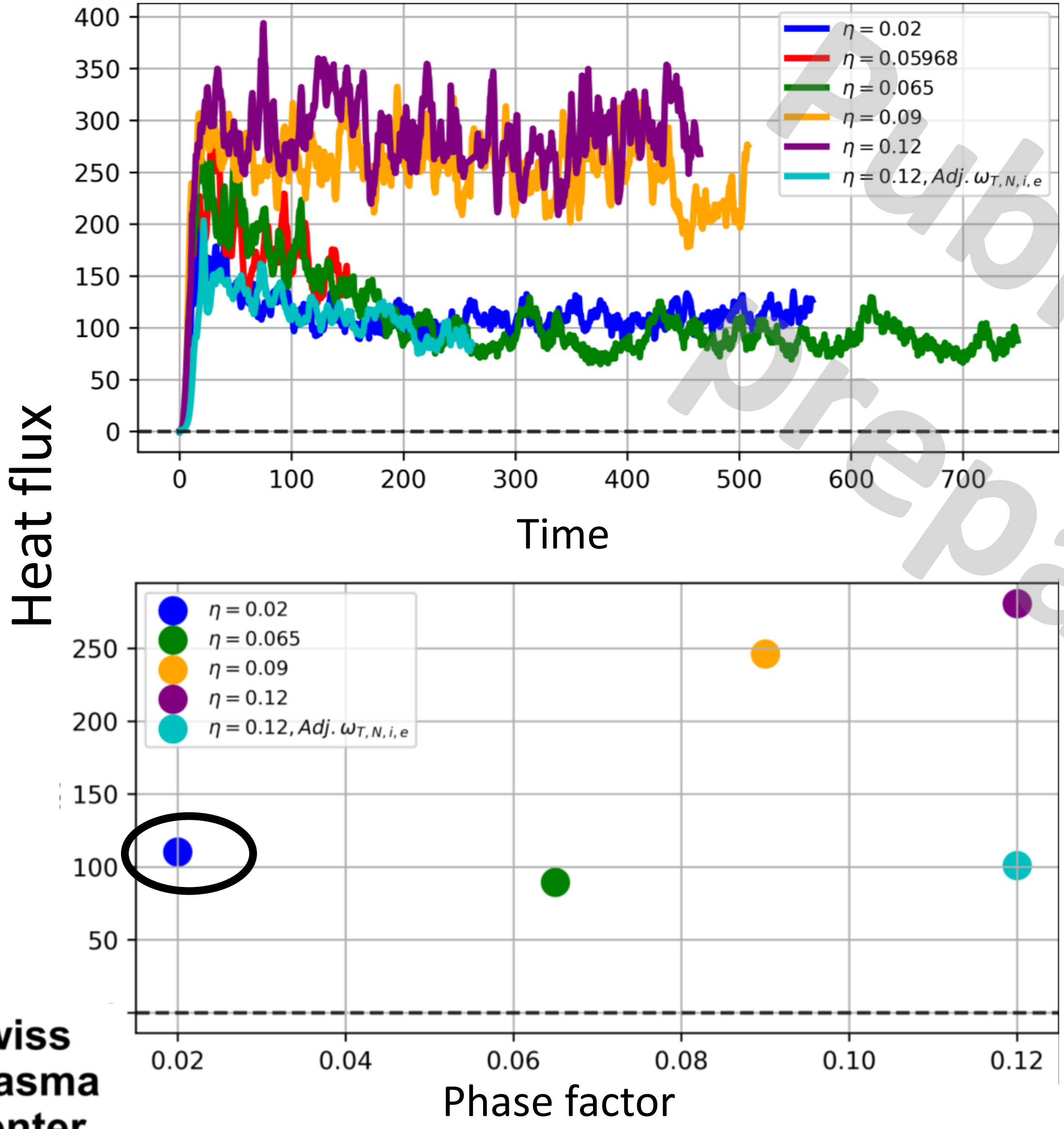
Close to integer

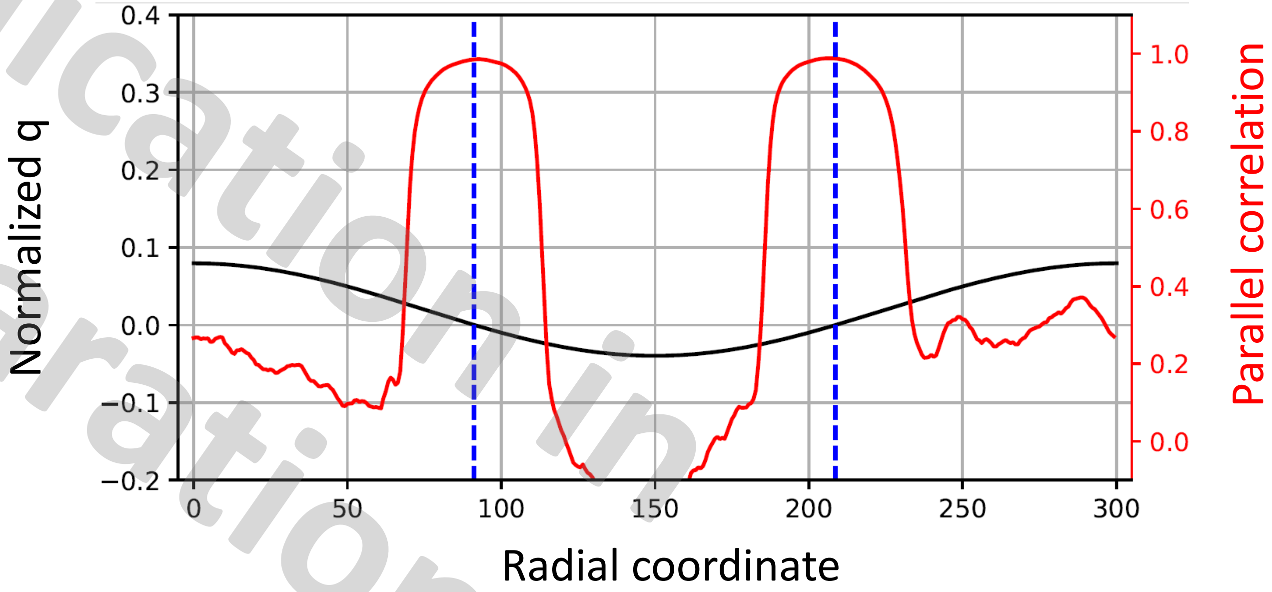




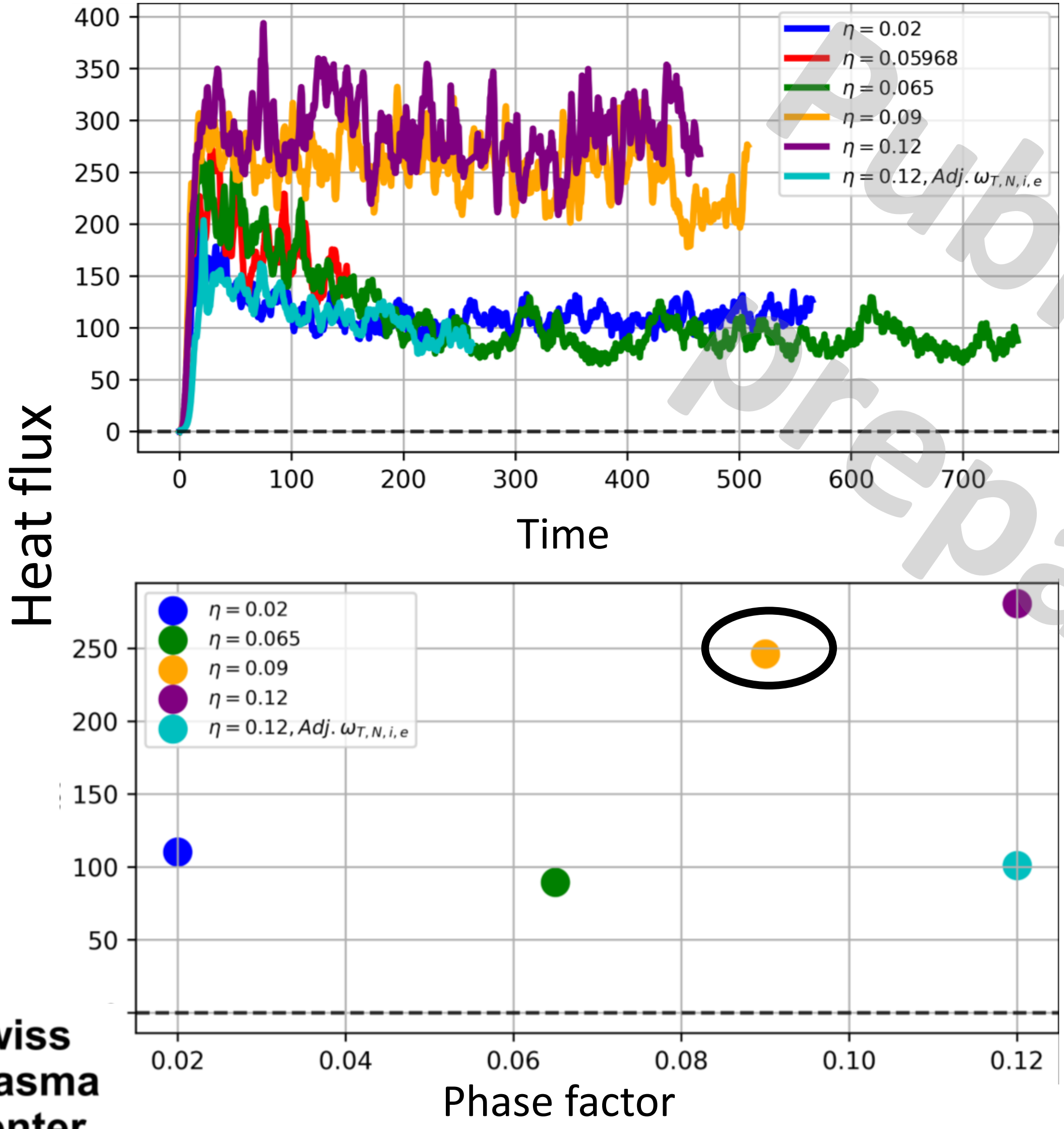
Swiss Plasma Center

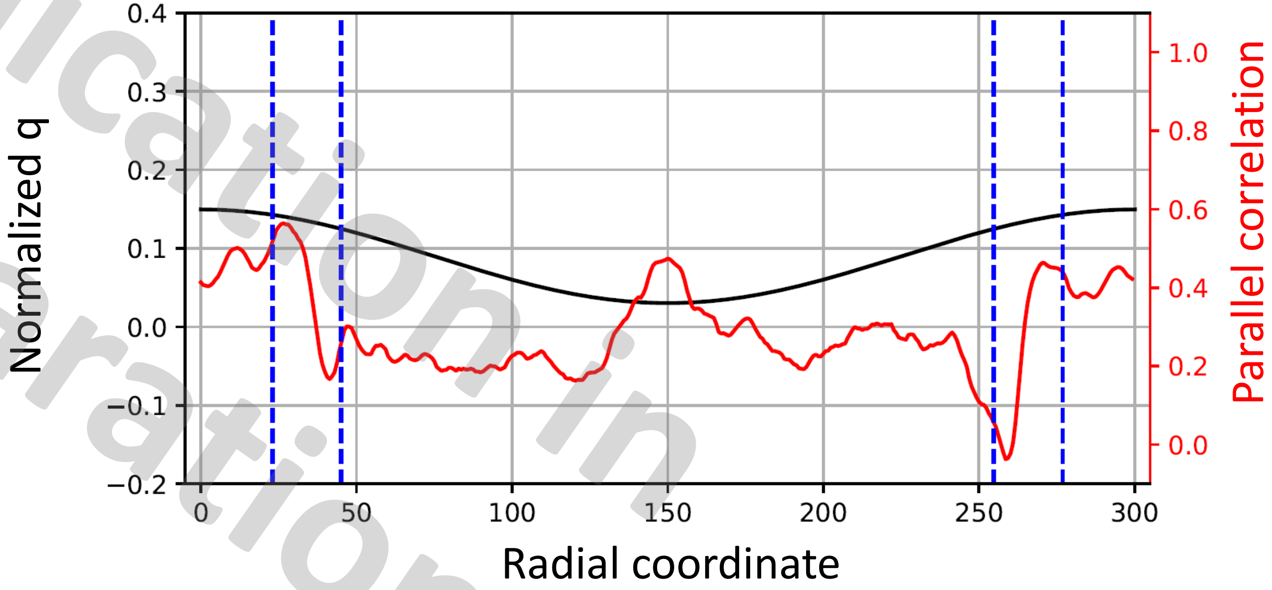
Splitting integer surface





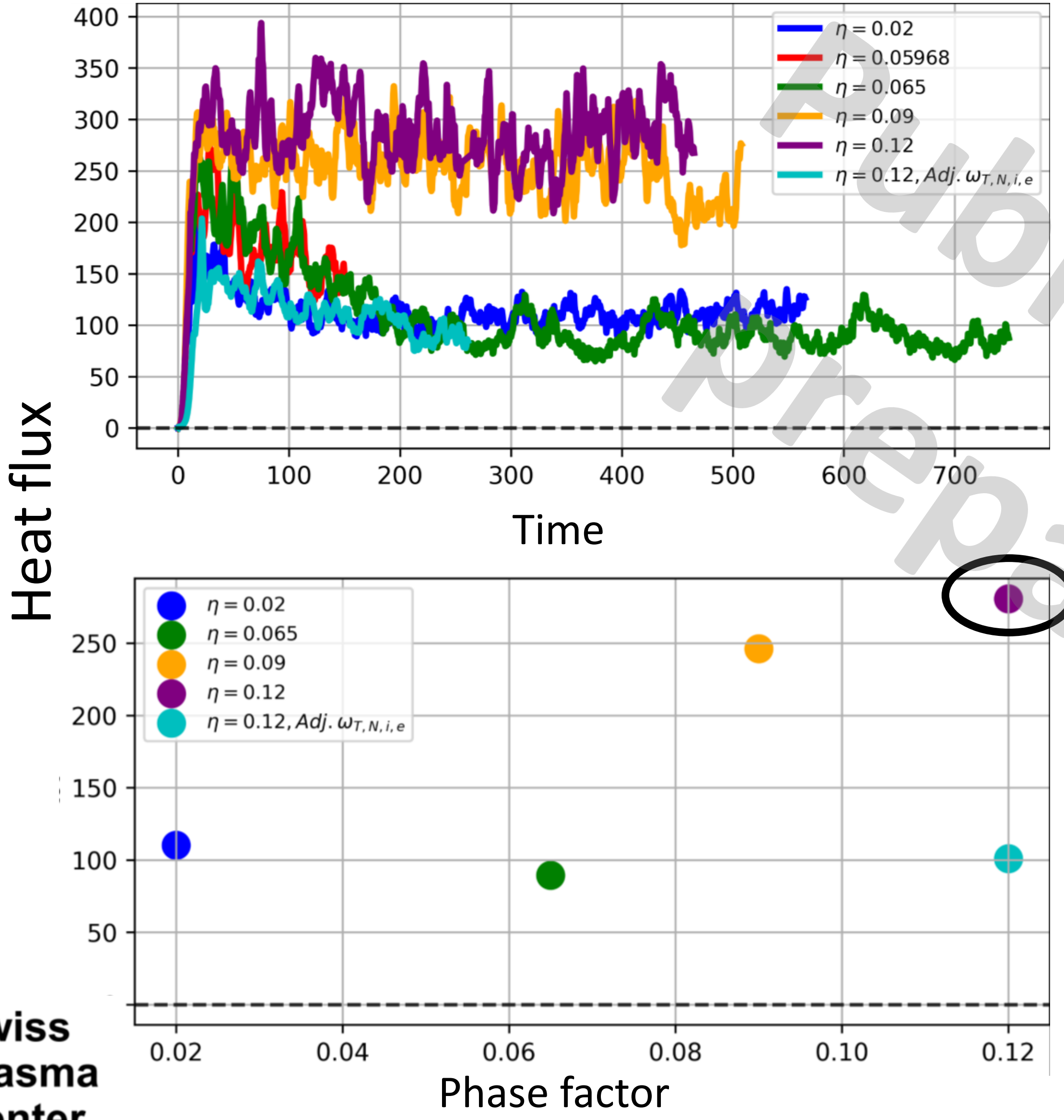
Moving away from integer

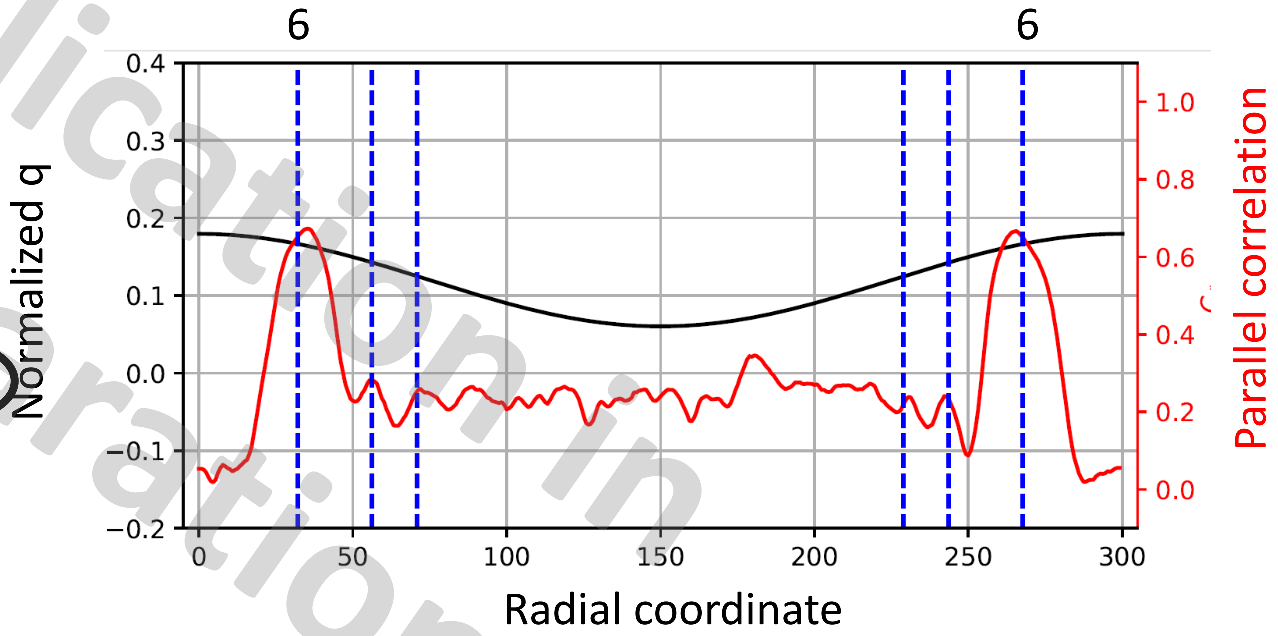




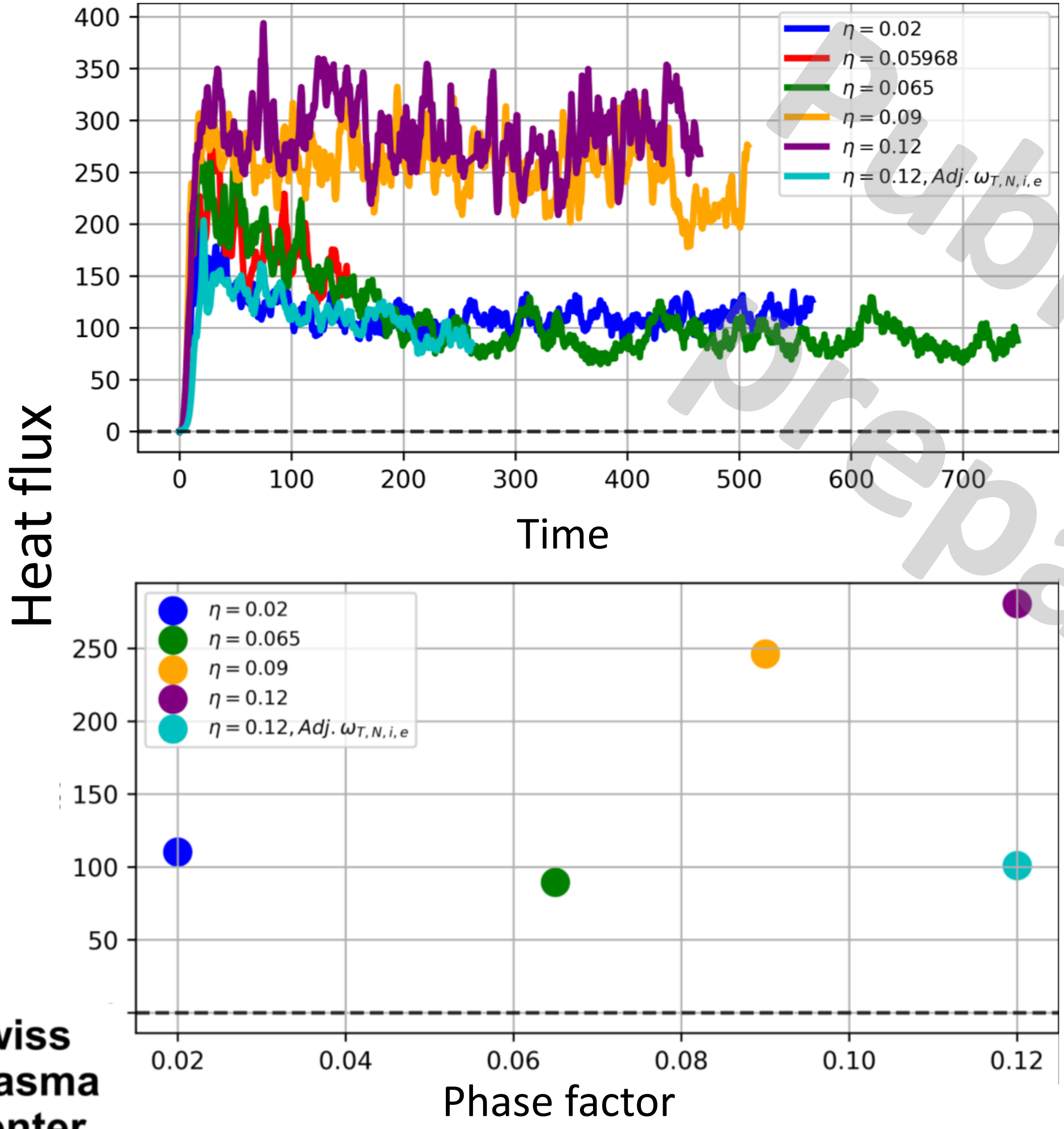
Swiss Plasma Center

Moving away from integer



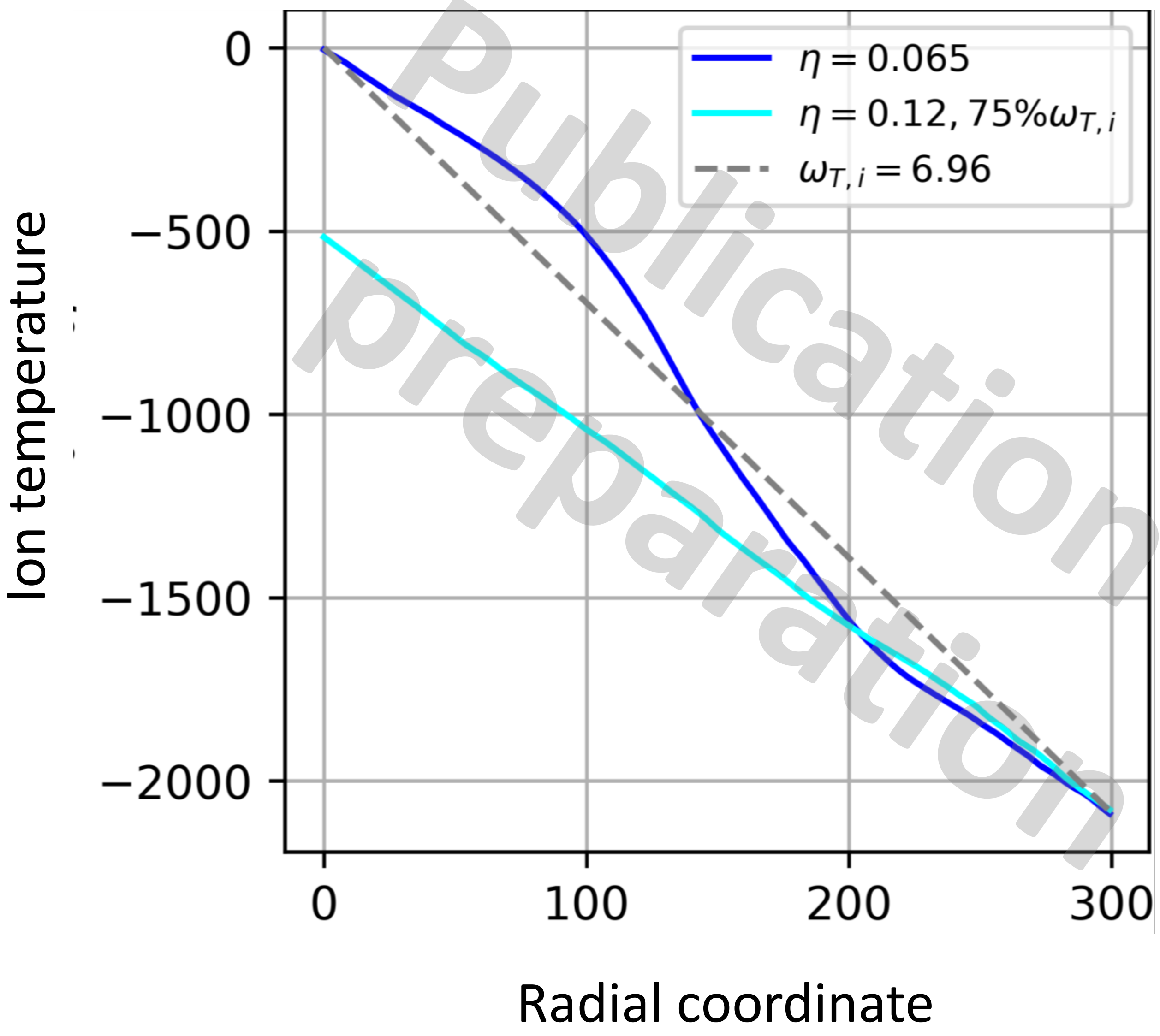


Real device – heat flux constant



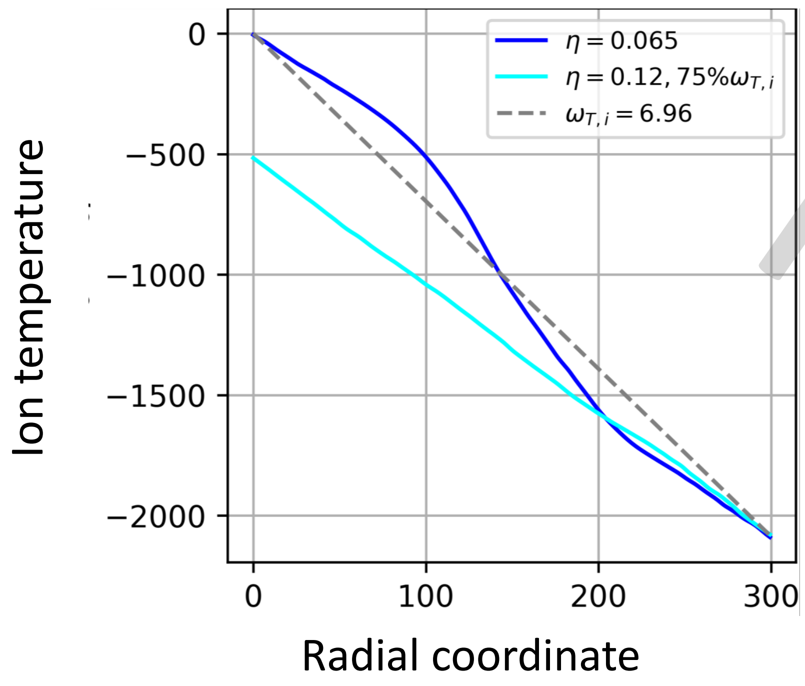
Reduce all gradients by 75 % to have similar heat flux between purple and green simulations

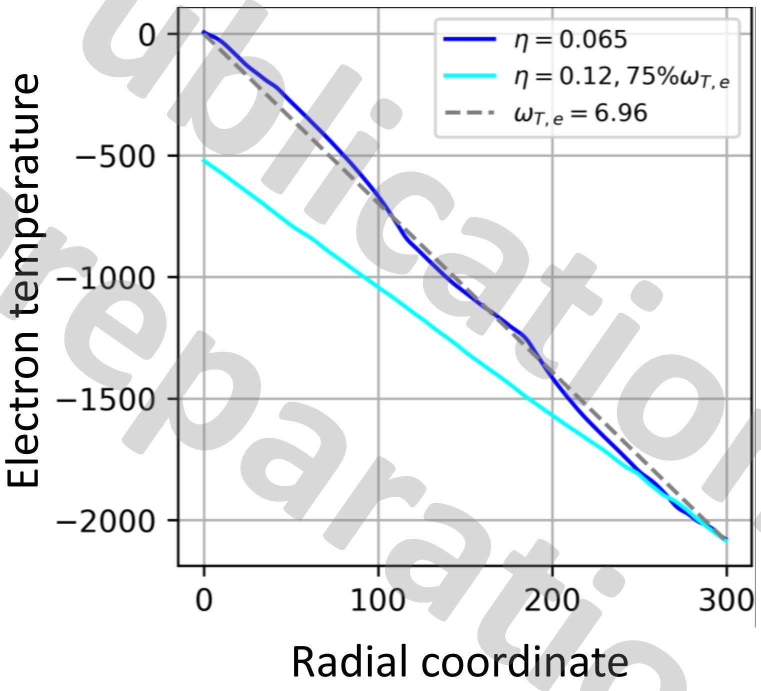
Profile corrugations

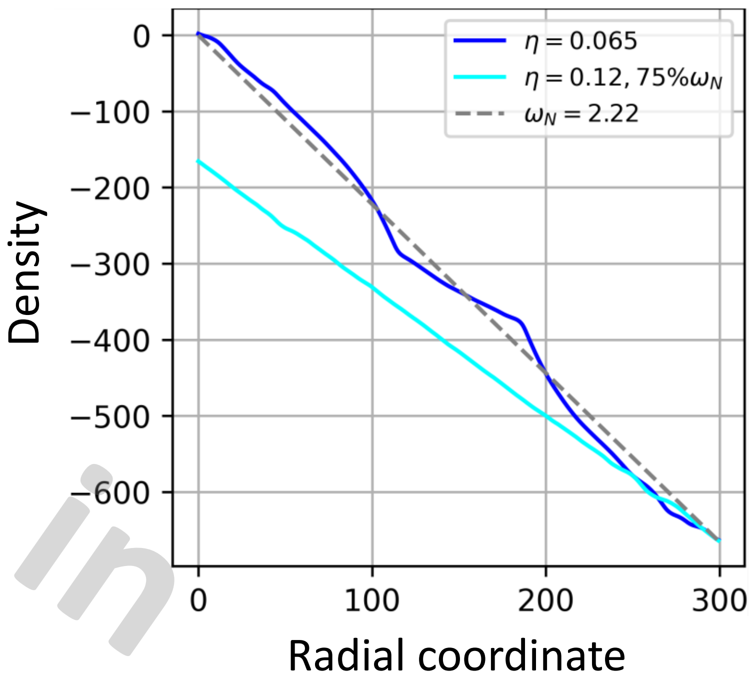


Ion ITB forming at the minimum, close to integer surface

Profile corrugations







EM corrections to safety factor

Total safety factor value: $$q_{total} = \frac{(\mathbf{B} + \delta\mathbf{B}) \cdot \nabla\zeta}{(\mathbf{B} + \delta\mathbf{B}) \cdot \nabla z}$$

Evaluation of magnetic field perturbation: $$\delta\mathbf{B} = \nabla \times \delta\mathbf{A}_{||}$$

Flux surface averaged stationary corrugations in magnetic potential lead to corrugations in safety factor profile:

$$\delta q = \frac{\partial \delta A_{||}}{\partial x} \frac{J\sqrt{\gamma_1}}{CC_y}$$

Swiss Plasma Center

Full safety factor profile

Non-uniform shear perturbation

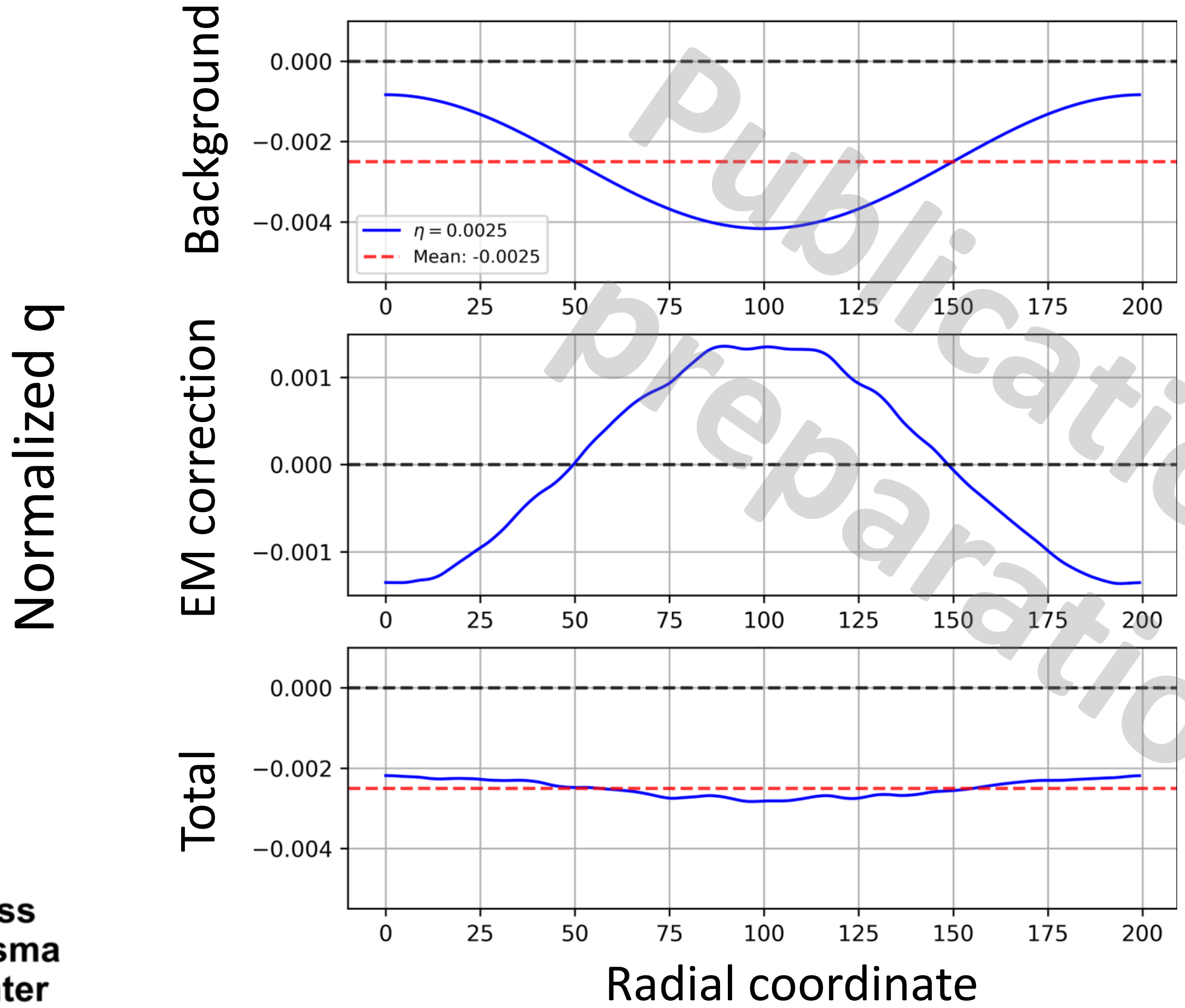
$$\frac{\bar{q} - q_0}{\rho^*} = \frac{q_0}{r_{G,0}} \hat{s} x_G + \tilde{q}_G(x_G) + \boxed{\frac{\partial \delta A_{\parallel,G}}{\partial x_G} \frac{J_G \sqrt{\gamma_{1,G}}}{C_{xy,G} C_{y,G}}}$$

Linear shear perturbation

Correction due to corrugations in magnetic potential

Swiss Plasma Center

Small non-uniform shear



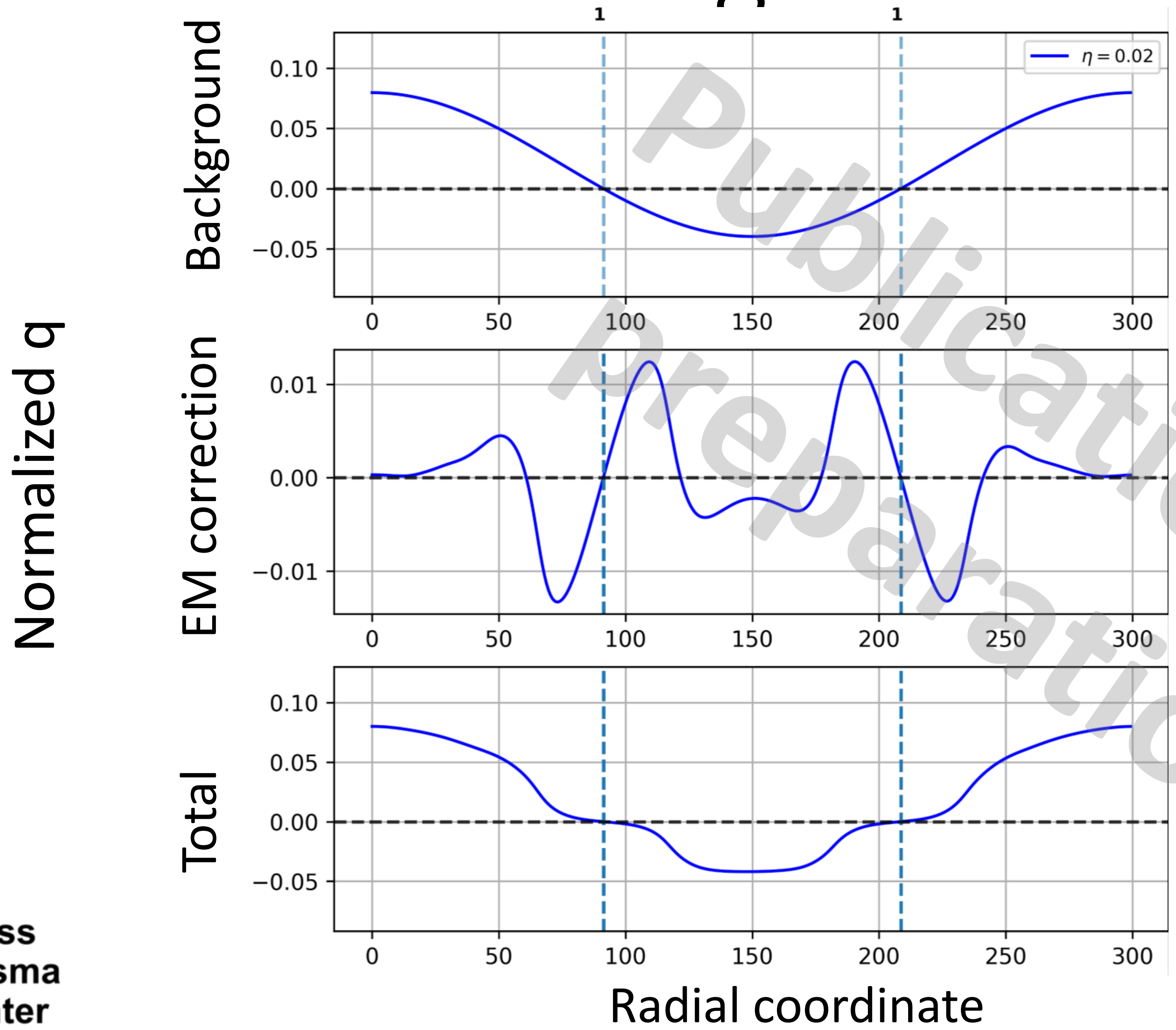
pITG case with

- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.001$

The imposed perturbation to the safety factor profile is **corrected** by the stationary electromagnetic perturbations

Swiss Plasma Center

Electromagnetic effects $\eta = 0.02$



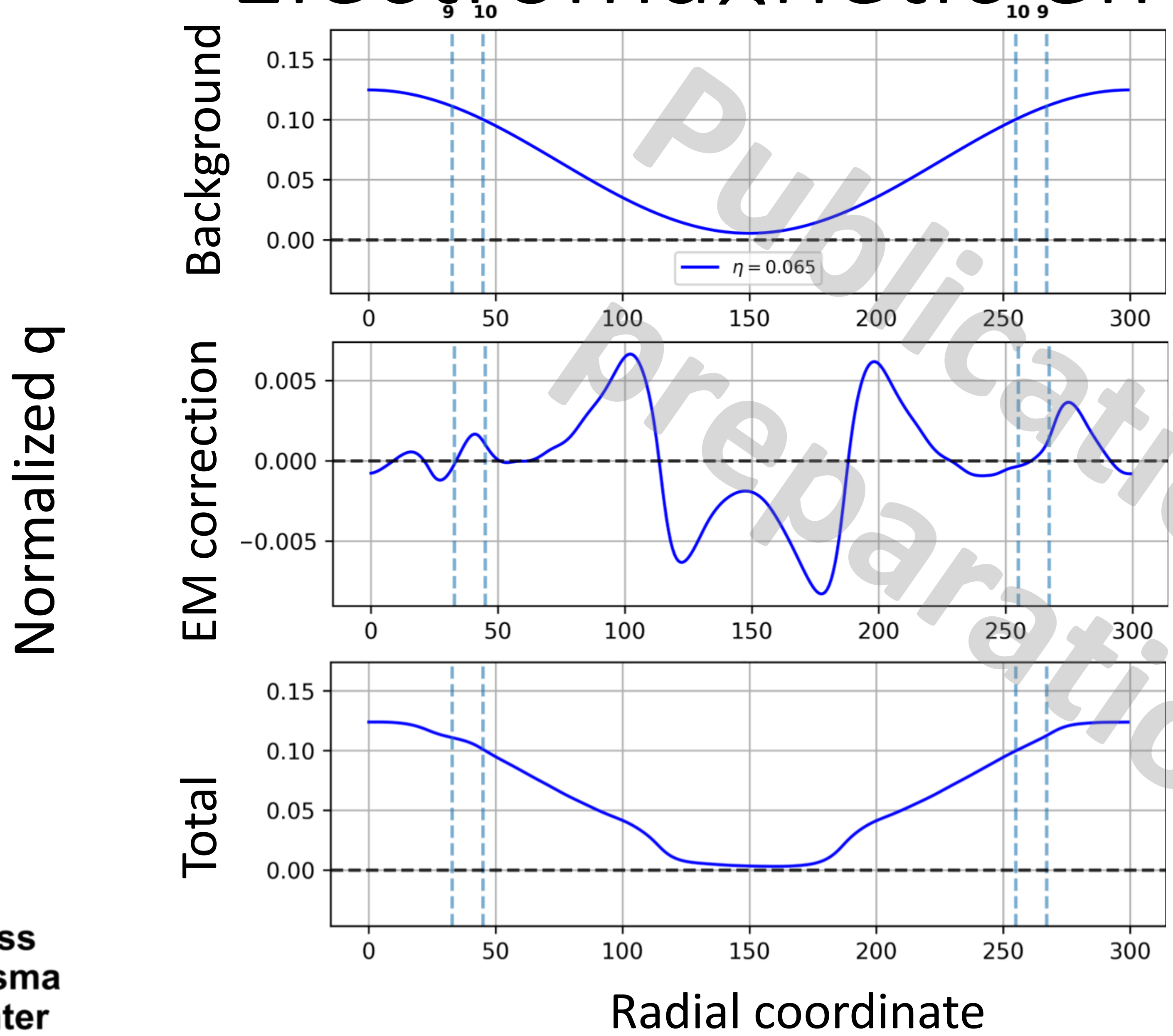
CBC case with

- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.025$

The imposed perturbation to the safety factor profile is **flattened** at integer surfaces, extending "region of rationality"

Swiss Plasma Center

Electromagnetic effects $\eta = 0.065$

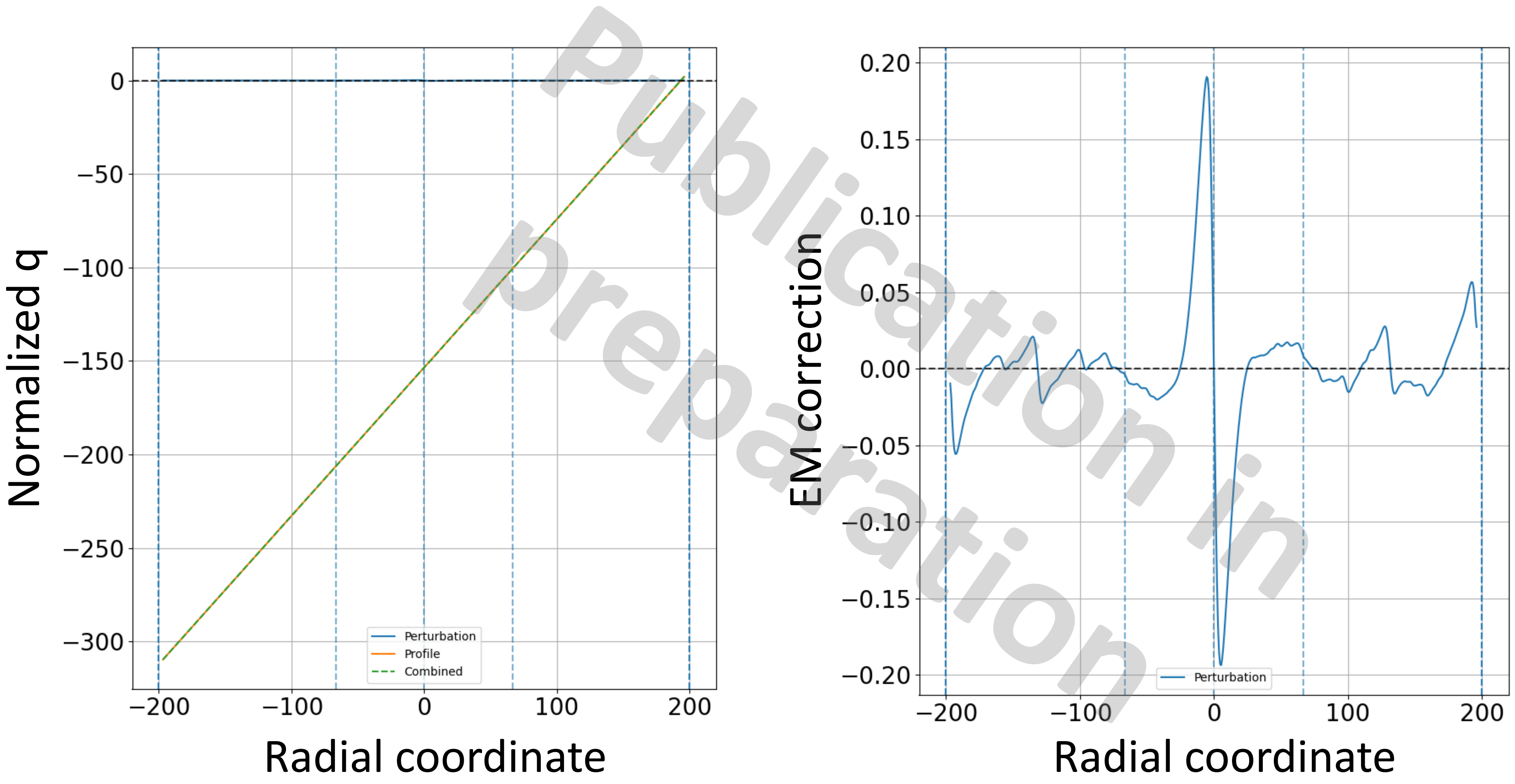


CBC case with

- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.025$

The imposed perturbation to the safety factor profile is **flattened and reduced** at integer surfaces, extending the "region of rationality"

Standard GENE simulations at low shear



$$\hat{s} = 0.1$$

Role of plasma β in ITB formation?

ITBs need extra heating power

⬇

$\beta \propto T$

⬇

Larger EM corrections to safety factor

⬇

Widening of the "region of rationality" around low order rational surfaces

⬇

Large region of strong turbulence self-interaction

Non-uniform shear study

- **Strong profile corrugations and reduction in transport** when minimum q is close to low order rational
- Corrugations follow low order rational surfaces
- Electromagnetic effects cancel imposed perturbation and **widen the "region of rationality"**

Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- Persistence of ultra-long turbulent eddies
- Low, but finite magnetic shear simulations
- Non-uniform magnetic shear simulations
- Conclusions

Conclusions

- **Kinetic electrons are critical** for accurately modelling low magnetic shear simulations
- Extreme profile corrugations appear in simulations as magnetic shear is reduced and turbulent eddies become more than poloidal turn long
- Ultra-long turbulent eddy length is not affected by collisions or plasma equilibrium shaping
- Electromagnetic effects correct imposed safety factor profile and extend the “region of rationality”.

EPFL

Future work

- An in-depth electromagnetic study to clarify the role of electromagnetic effects in ITB formation

- Extend this work to stellarators where global shear tends to be very small
- Possibility of deriving **reduced self-interaction models**
- Attempt to **measure ultra long eddies** in experiments

Swiss Plasma Center

Deliverables and milestones

Conference contribution and a paper:

- Poster at Varenna Conference (2022): Ultra Long Turbulent Eddies, Magnetic Topology, and the Triggering of Internal Transport Barriers in Tokamaks
- Invited talk at Warwick University (2022)
- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003
- First draft of a longer paper is complete

• M1.6 As a simple intermediate step towards the L-H transition, investigate the ability of standard, existing flux-tube simulations to model ITBs; if successful, validate against experiment as a proof of principle.	Target date 06/2022
• D1.2 ITB physics studied and key elements that could be transferred to edge transport barriers identified	Target date 09/2022
• M4.1 Quantify momentum drive from rational vs irrational surfaces in ITBs and compare to momentum drive at plasma edge and determine relationship of parallel correlation length with magnetic shear.	Target date 12/2021
• D4.1 Quantification of ITB momentum drive from rational vs. irrational surfaces and comparisons to plasma edge	Target date 02/2022

Swiss Plasma Center

Thank you for your attention

Theory, Simulation, Verification and Validation

Research is being caried out in the framework of TSVV1:

Physics of the L-H Transition and Pedestals

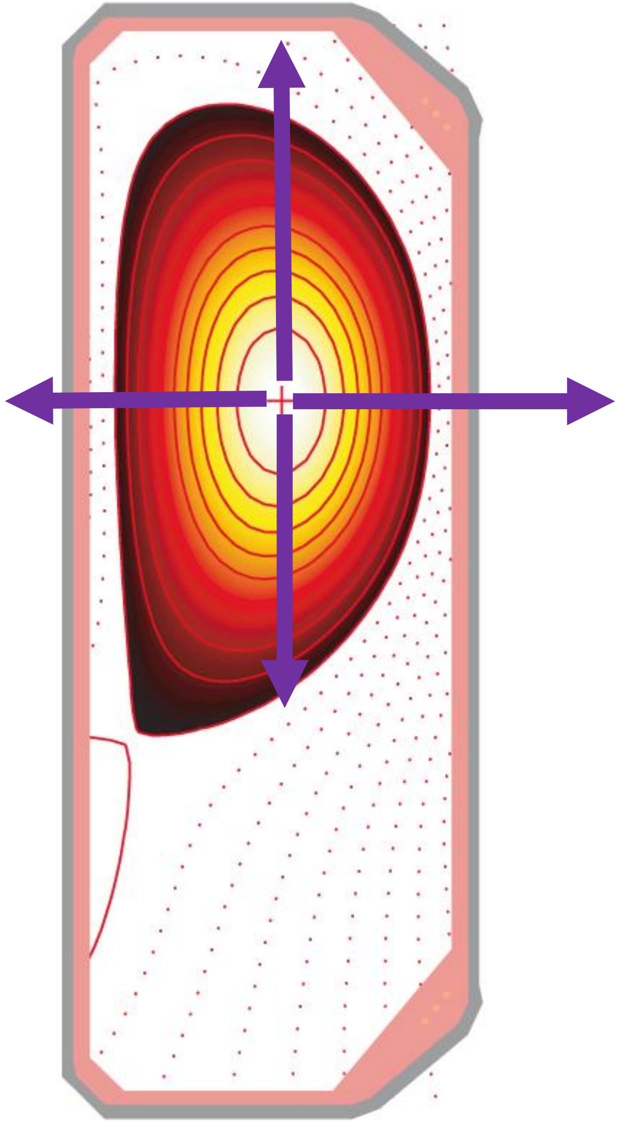
EUROfusion

Swiss Plasma Center

Additional slides

Turbulence transport problem

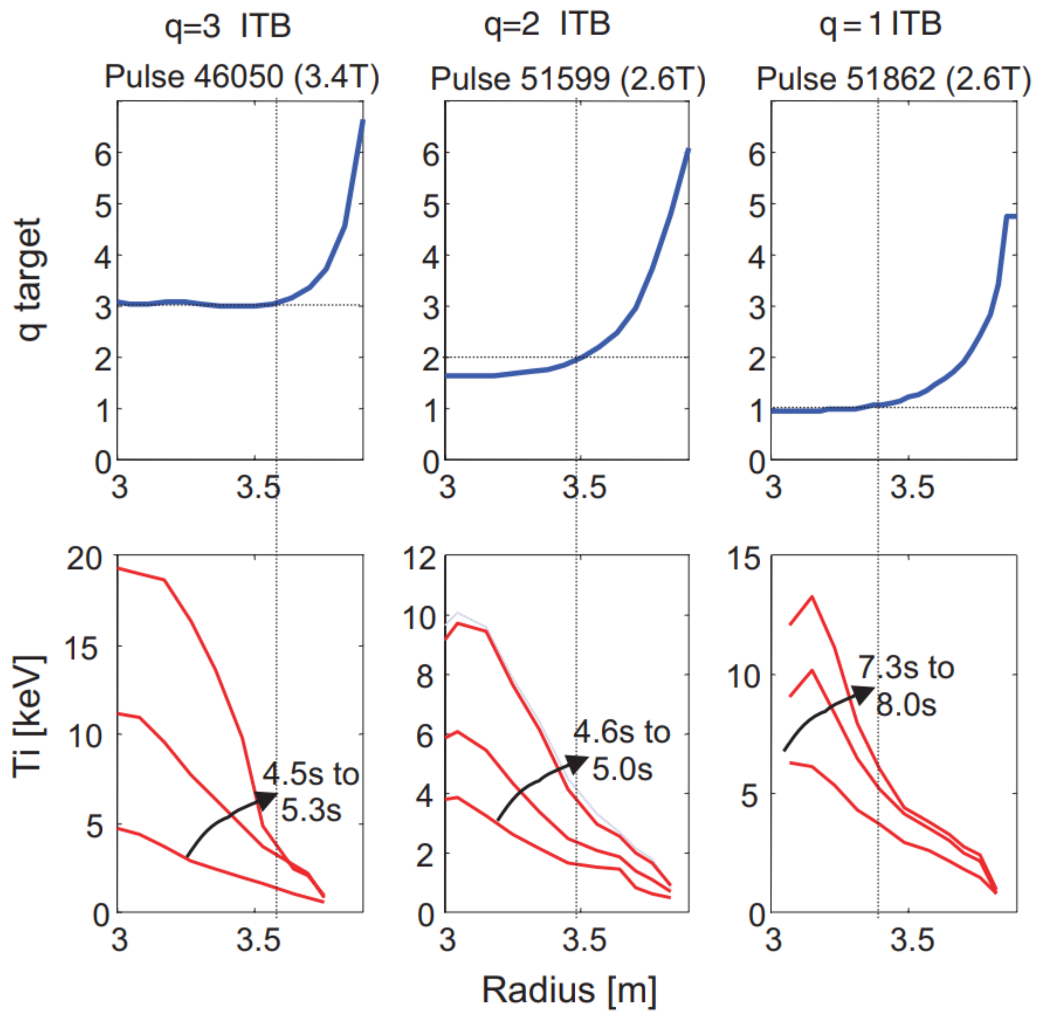
- Transport is dominated by turbulent transport
- Reducing cross-field energy/particle transport is critical in achieving fusion
- One way to reduce turbulent transport is with **internal transport barriers (ITBs)**



- X. Garbet et al. 2010 Nucl. Fusion 50 043002
- M. Kikuchi, M. Azumi. Frontiers in Fusion Research II. 2015

Swiss Plasma Center

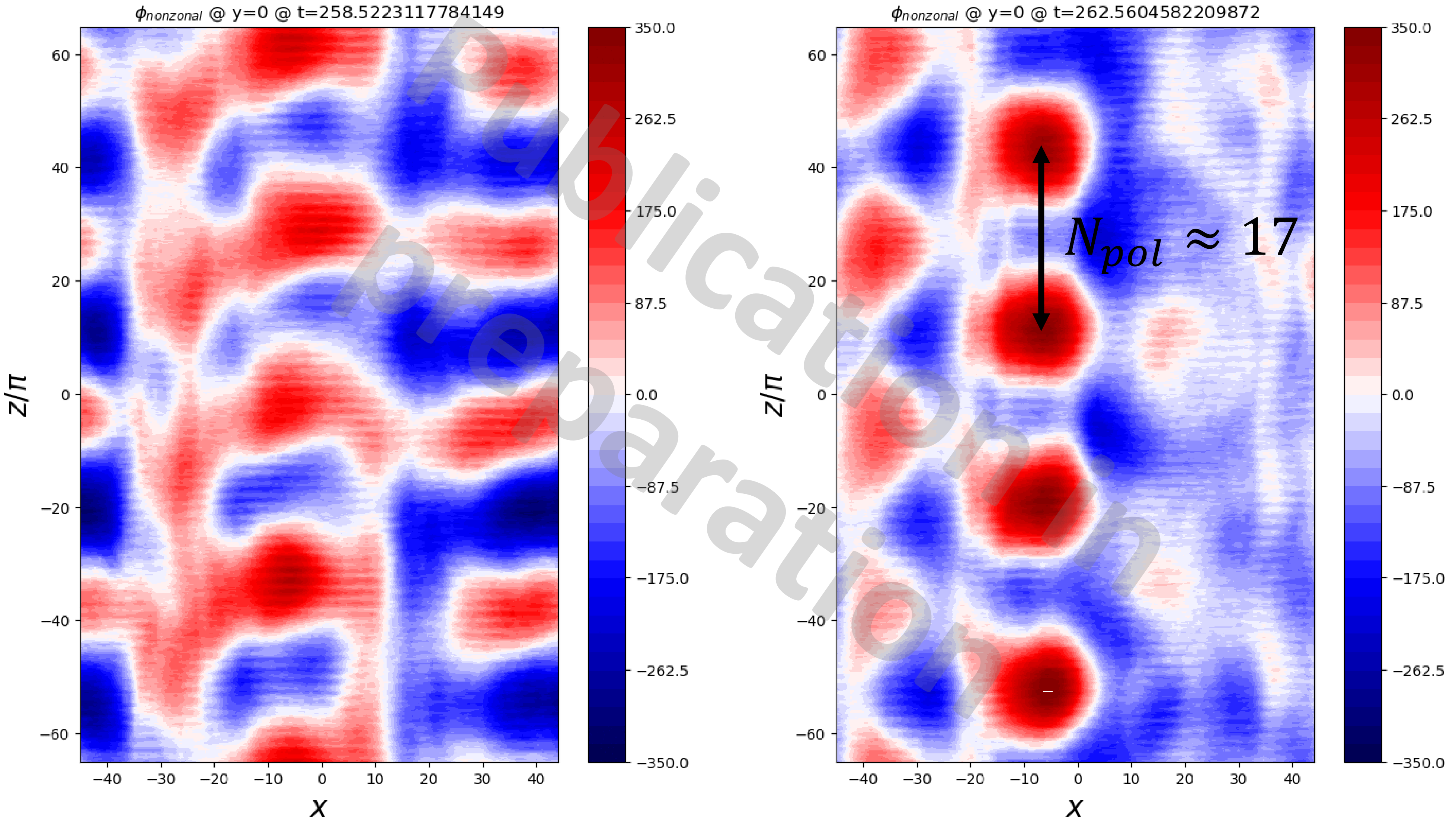
Example of strong ITBs at JET



- E Joffrin et al 2002 Plasma Phys. Control. Fusion 44 1739

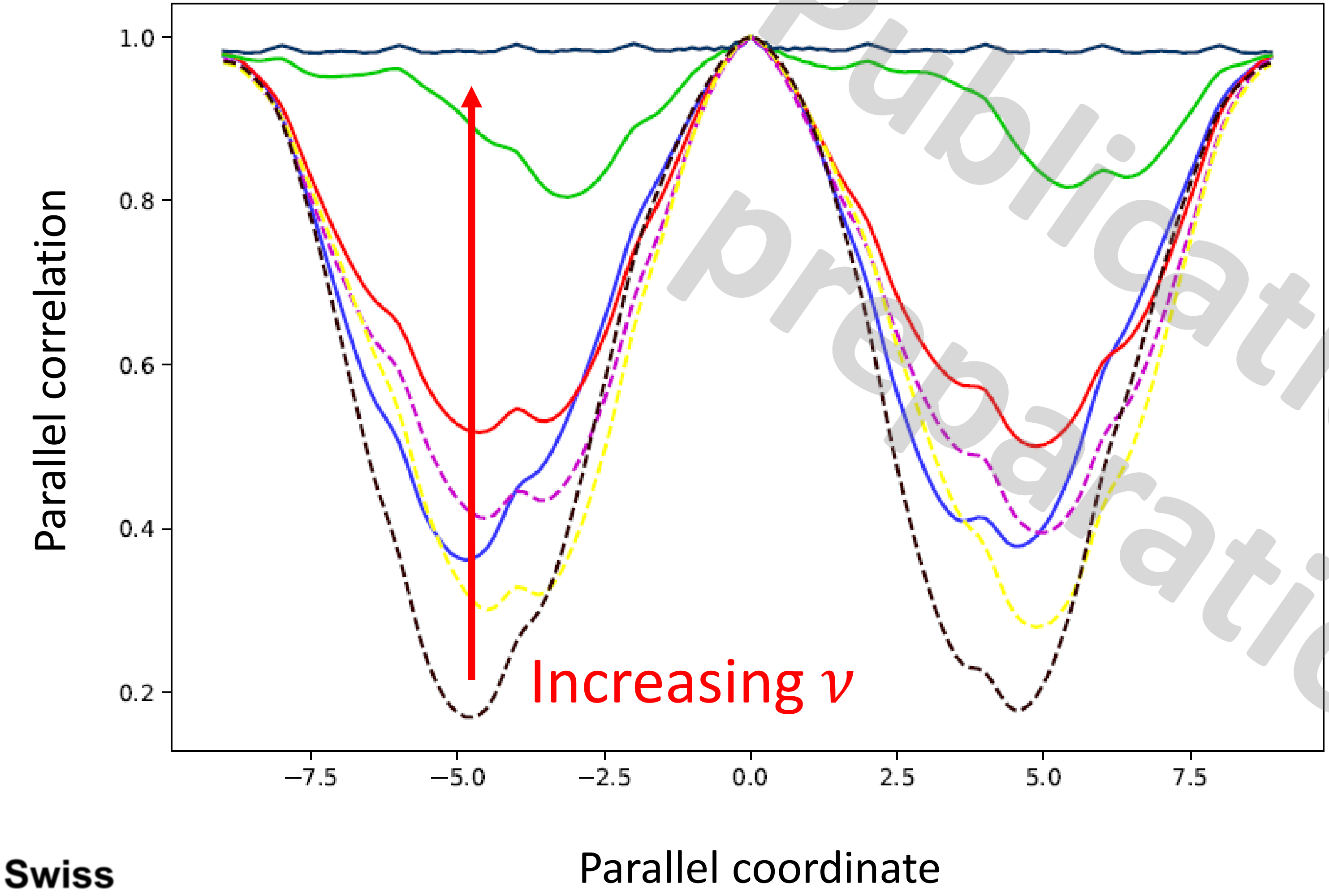
Long parallel wave-like structures

$N_{pol} = 65$



Swiss Plasma Center

EPFL Collisions ($m_e = 10m_{e,nominal}$)

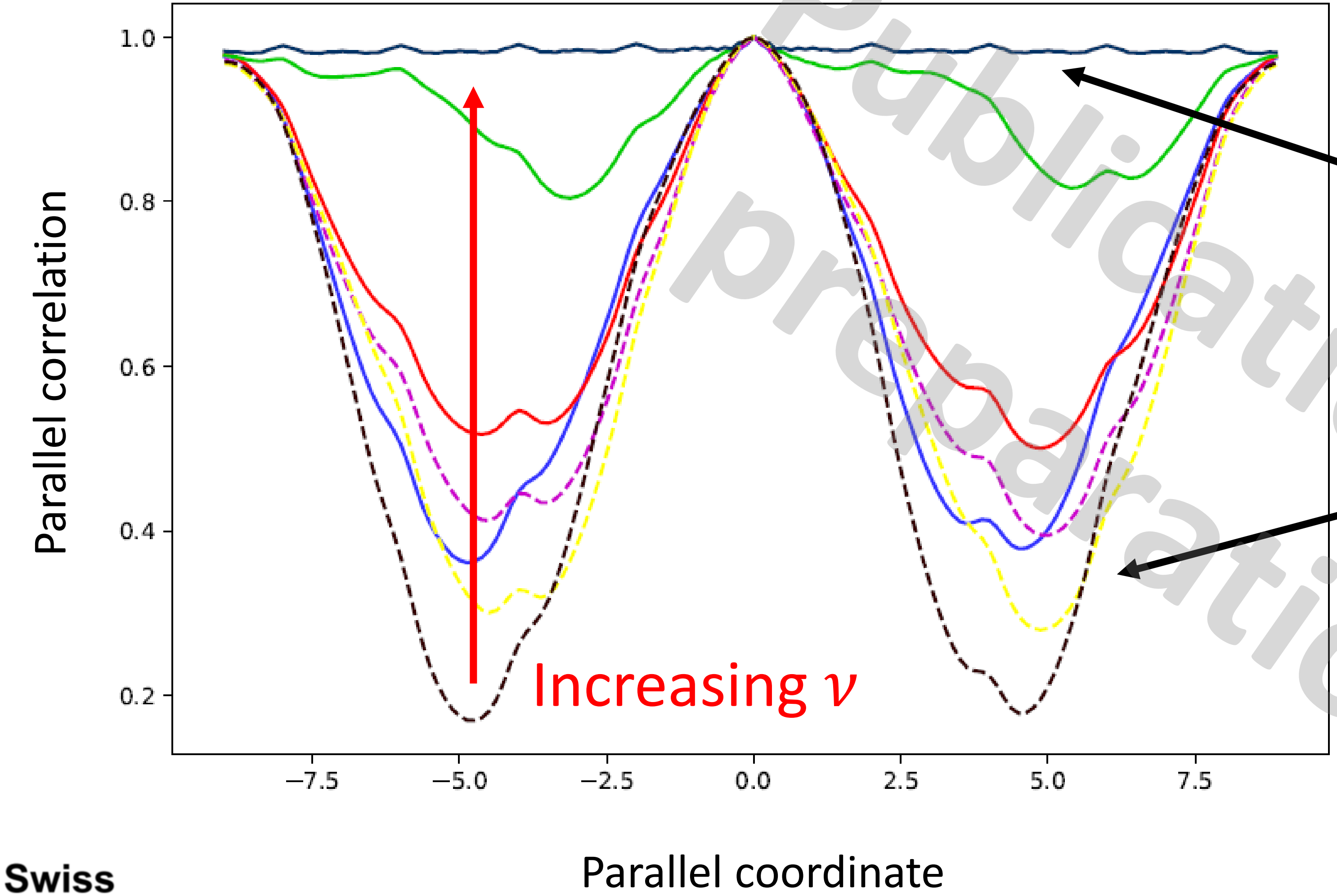


$$l_{\parallel,turb} \approx v_{th,e} t_{turb}$$

$$t_{turb} \approx const. \quad T_e = const. \Rightarrow l_{\parallel,turb} \propto (m_e)^{-\frac{1}{2}}$$

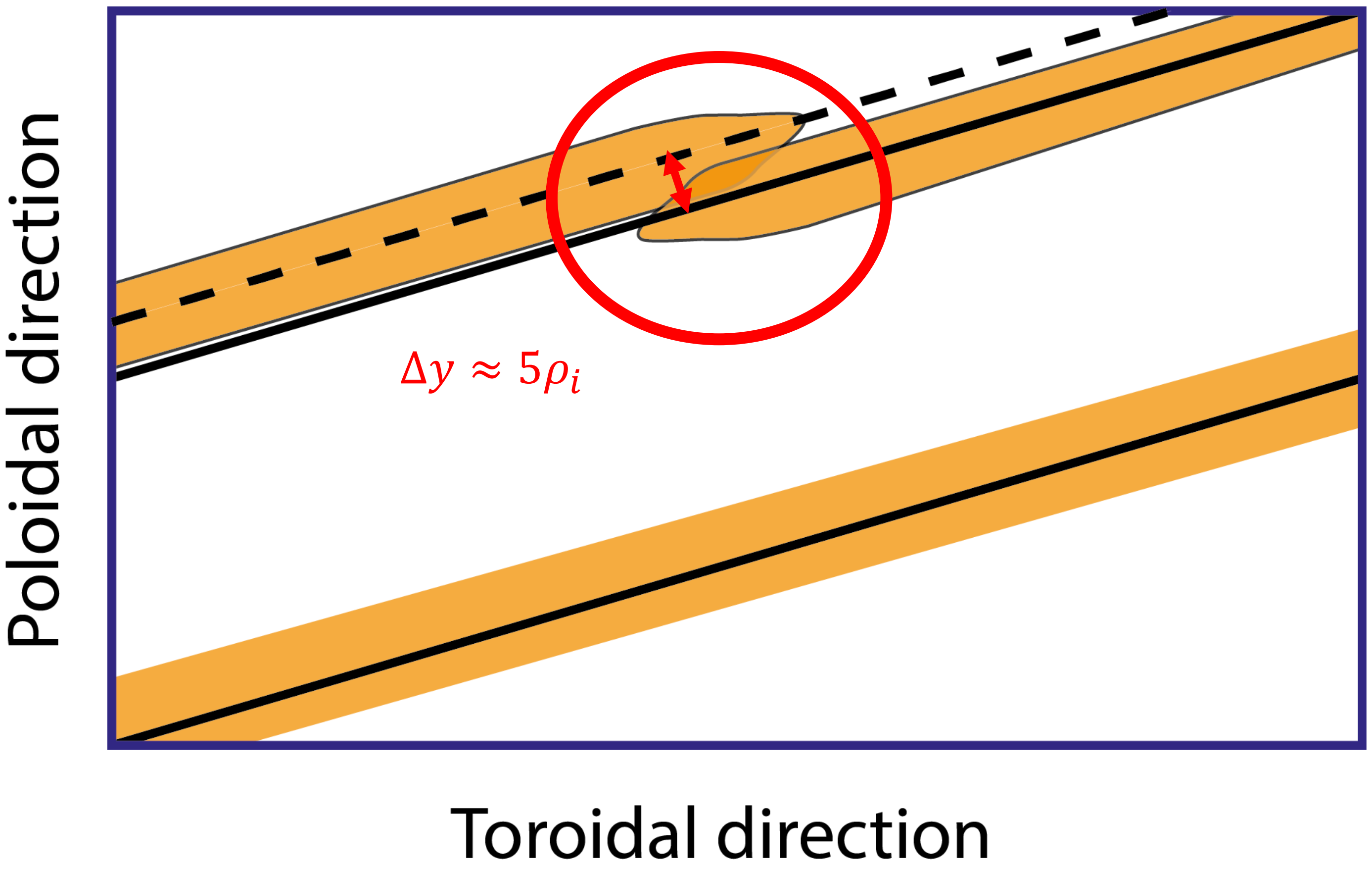
Swiss Plasma Center

Collisions ($m_e = 10m_{e,nominal}$)



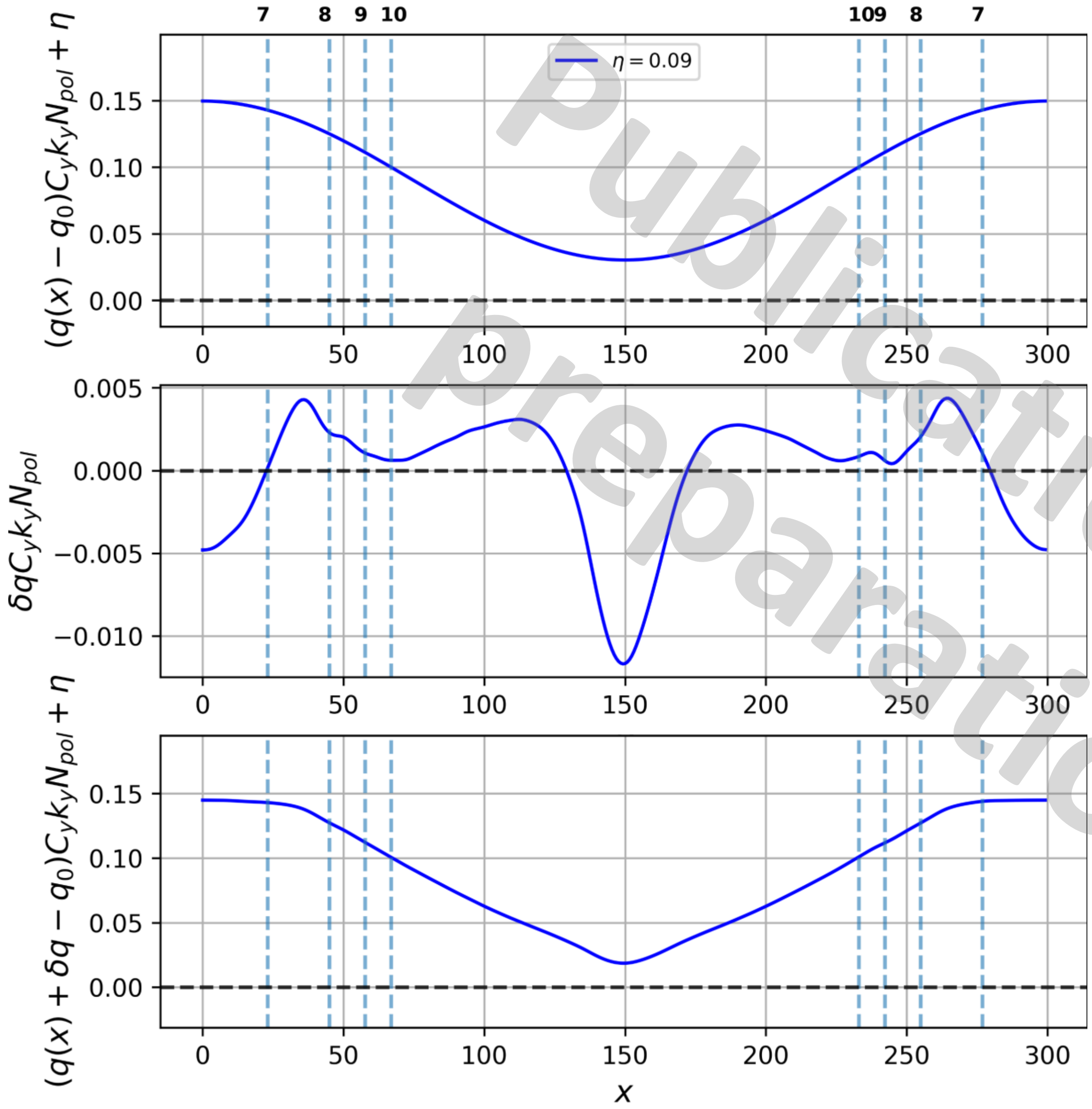
- CBC –> parallel waves disappear when $\nu = 0.01$
- CBC –> parallel waves present when $\nu = 0$

Parallel boundary shift



$q = 2.01$

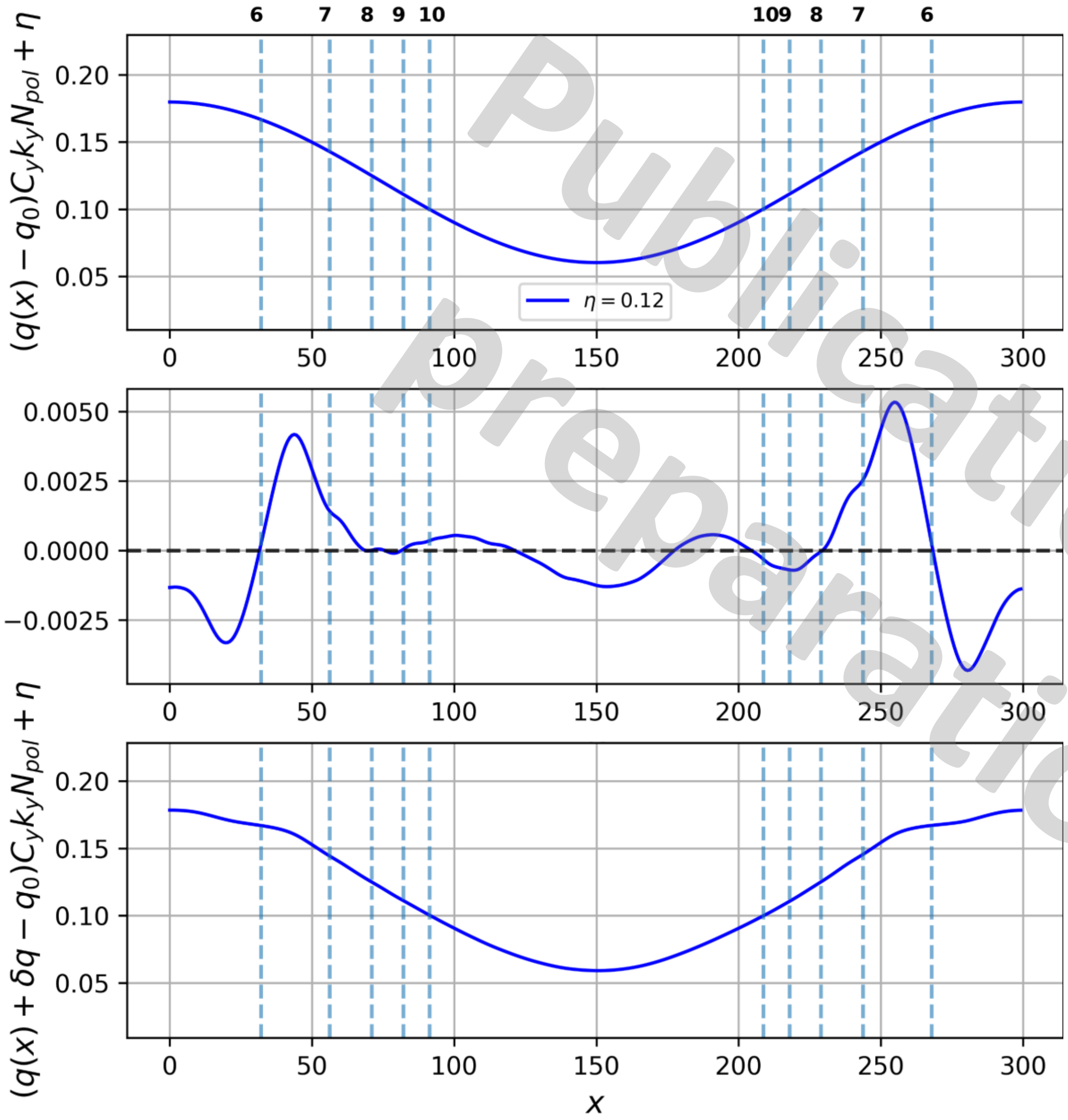
Electromagnetic effects $\eta = 0.09$



CBC case with

- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.025$

Electromagnetic effects $\eta = 0.12$



CBC case with

- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.025$