Outer region structures in a turbulent boundary layer under a strong adverse pressure gradient

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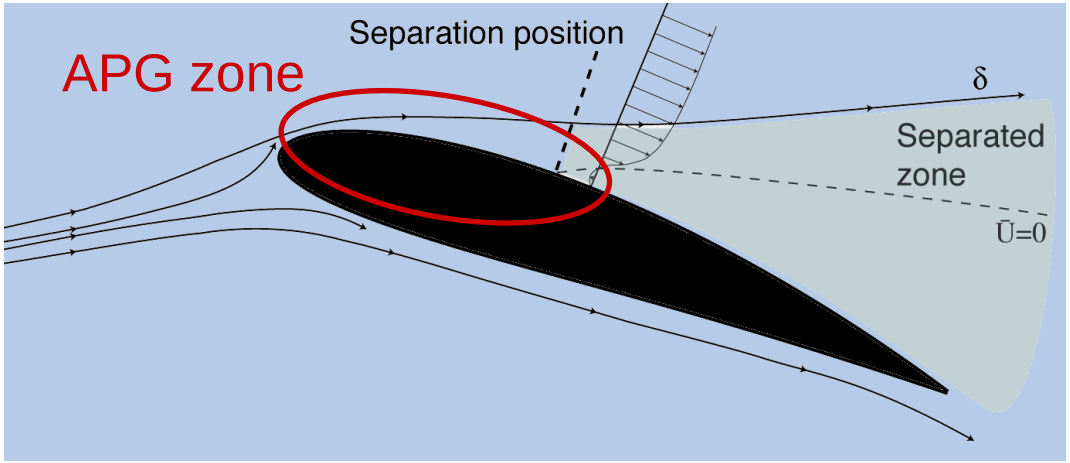
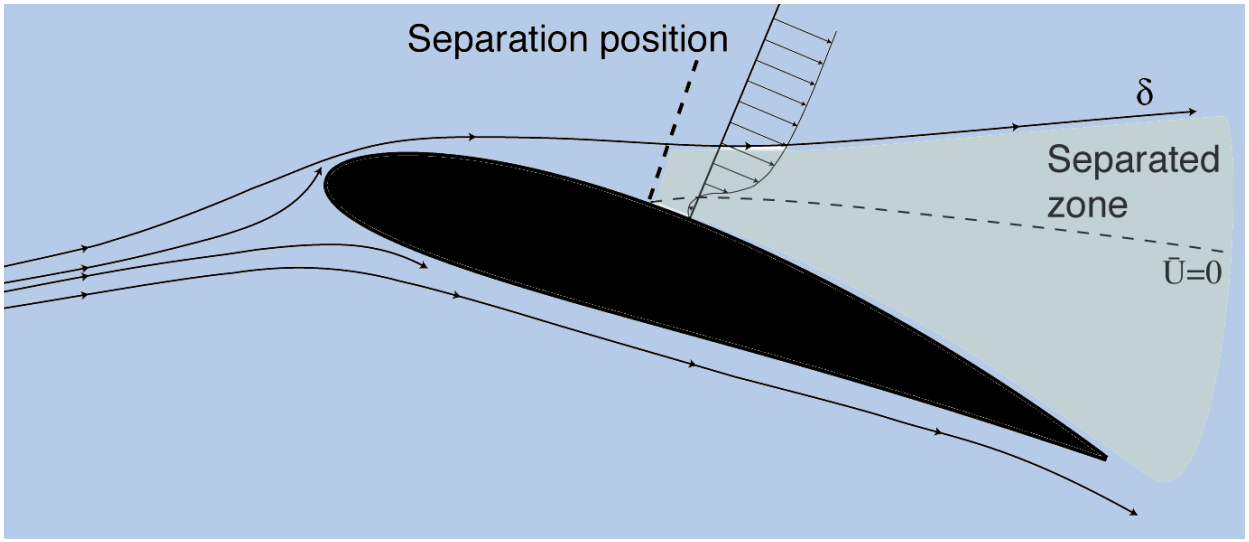
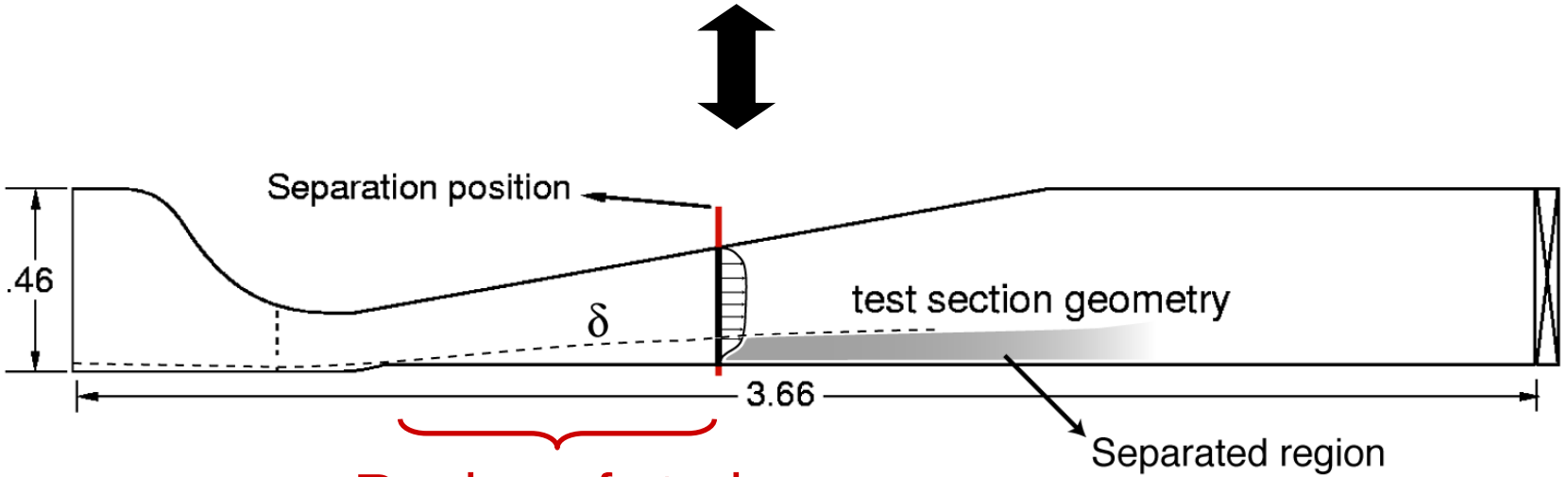
Outer region of adverse-pressure-gradient turbulent boundary layers

- Are the large-scale dynamics the same as in ZPG TBL?
- Analyze a flow with strong non-equilibrium conditions from a fundamental perspective

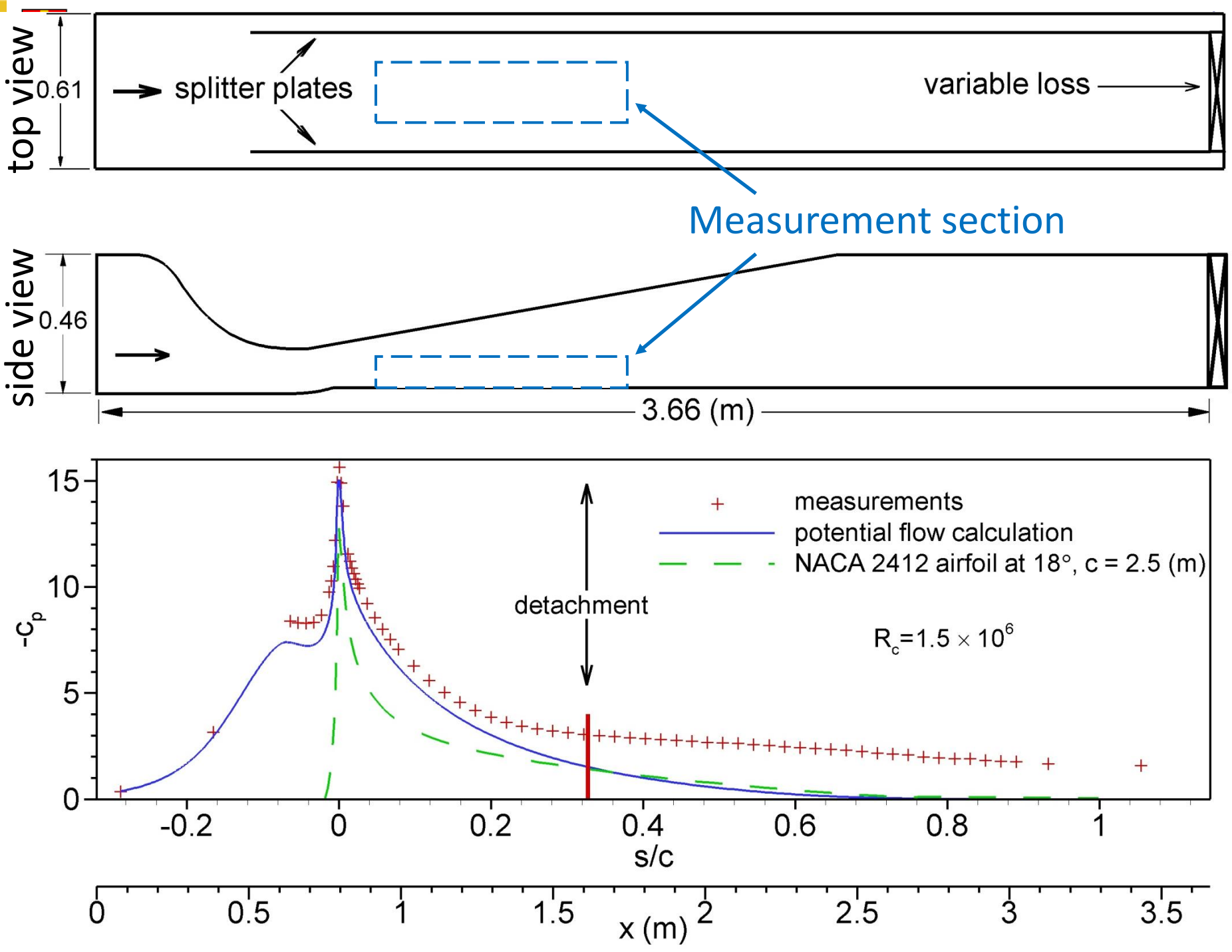


Strong adverse-pressure gradient flow



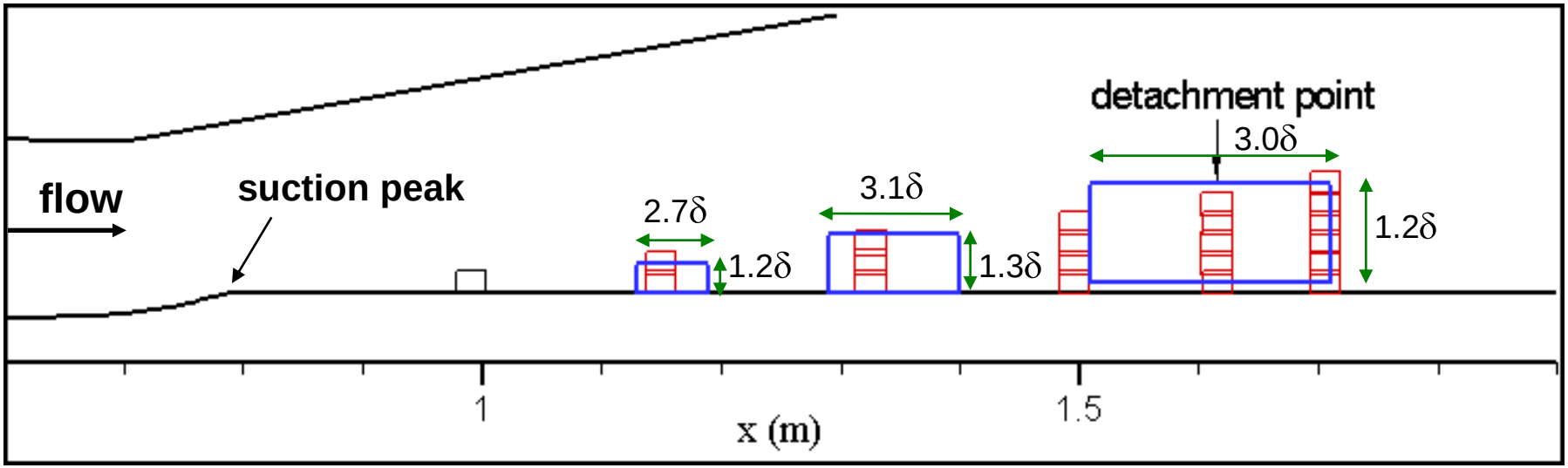


Region of study
APG region

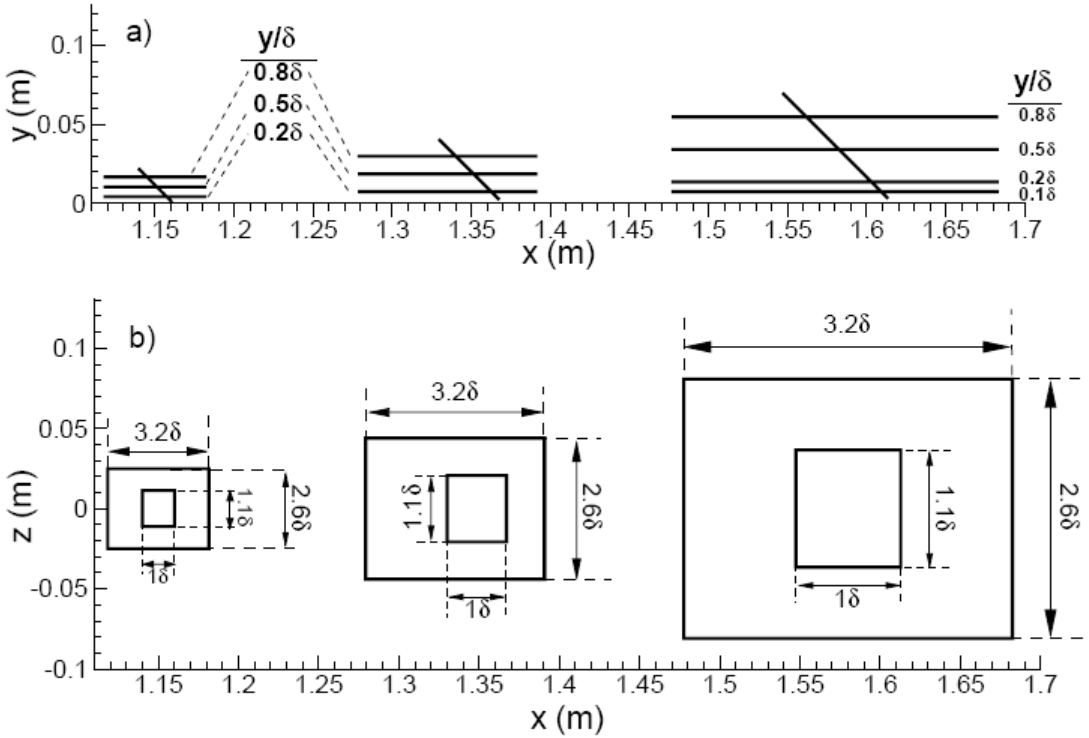

top view
0.61
splitter plates
variable loss
Measurement section
side view
0.46
3.66 (m)
15
10
5
0
-c_p
detachment
measurements
potential flow calculation
NACA 2412 airfoil at 18°, c = 2.5 (m)
R_c=1.5 × 10^6
-0.2
0
0.2
0.4
0.6
0.8
1
s/c
0
0.5
1
1.5
2
2.5
3
3.5
x (m)

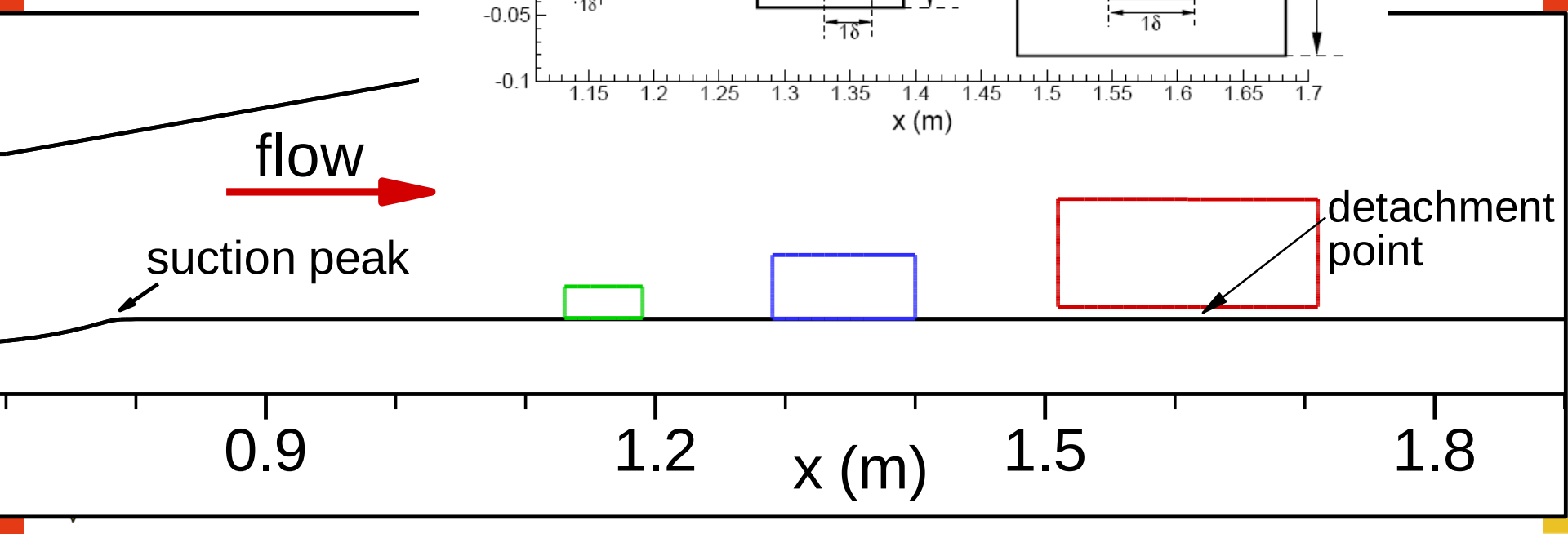
PIV: xy, horizontal and inclined planes

- Small *xy* planes: Flow statistics
- Large *xy* planes: Coherent structures



Inclined and horizontal planes





xy planes (3δx1.2δ)

x (mm)	Re_θ	$\Delta x/\delta$, $\Delta y/\delta$	Δx^+, Δy^+
ZPG Adrian et al. 2000	6845	0.028	62.0
1156	5329	0.018	13.2
1392	8638	0.018	15.2
1600	12095	0.018	≈0

inclined planes (1.3δx1.1δ)

x (mm)	Re_θ	$\Delta x/\delta$, $\Delta z/\delta$	Δx^+, Δz^+
ZPG Hutchins et al. 2005	7440	0.025	69.0
1156	5329	0.018	13.2
1392	8638	0.018	15.2
1600	12095	0.018	≈0

Note: δ varies by more than 20% in one plane in APG case

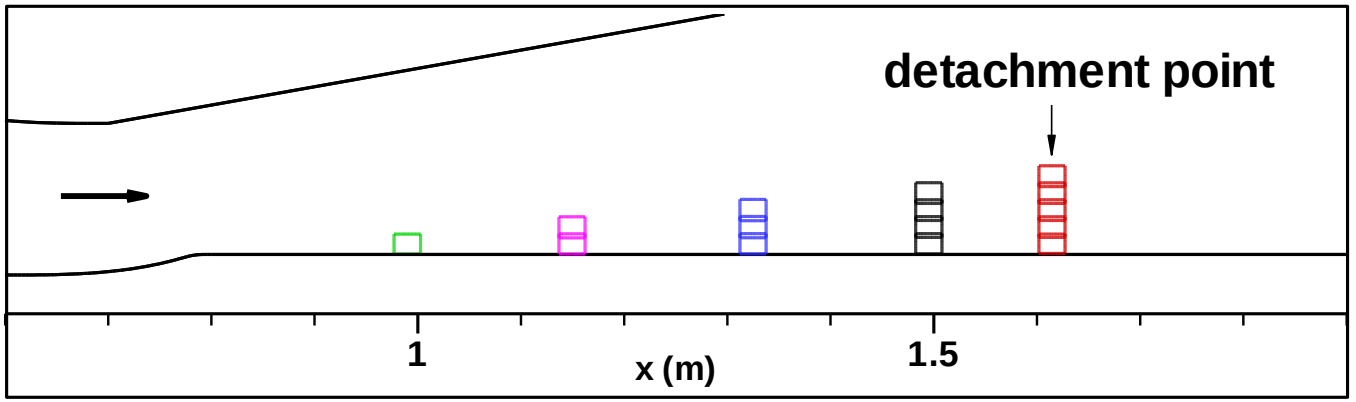
horizontal planes

x (mm)	Re_θ	$\Delta x/\delta$, $\Delta z/\delta$	Δx^+, Δz^+	Plane size L_x/δ x L_z/δ
ZPG Tomkins and Adrian 2003	7705	0.027x0.022 0.024	29.1	1.4 x 2.8 2.5 x 3.1
1156	5329	0.075	54.7	3.2 x 2.6
1392	8638	0.075	63.3	3.2 x 2.6
1600	12095	0.075	≈0	3.2 x 2.6

Note: δ varies by more than 20% in one plane in APG case

Measurements for statistical description of flow

Maciel, Rossignol and Lemay (2006)



- 2000 fields per measurement plane
- Interrogation zone: ≤ 0.64 x 0.64 mm^2

  $\Delta x = 0.008\delta$ to 0.05δ

  $\Delta y = 0.008\delta$ to 0.025δ

APG: Outer velocity scale

Friction velocity: $$u_\tau = \left(\frac{\tau_w}{\rho} \right)^{1/2}$$

Zagarola-Smits velocity: $$U_{ZS} = U_e \frac{\delta^*}{\delta}$$

Zagarola and Smits (1998)

Pressure-gradient velocity: $$U_{po} = \left(\frac{\delta^*}{\rho} \frac{dp}{dx} \right)^{1/2}$$

Mellor and Gibson (1966)

Other suggestions: $$U_e, (u_\tau U_e)^{1/2},$$

$$U_{PS} = \left[k \ -\overline{u'v'}_{\max} \ U_e \, \delta^* / L \right]^{1/3}$$

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Not a scale for strong APG TBL

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Not a scale for ZPG TBL

Other suggestions:

$$U_e, (u_\tau U_e)^{1/2},$$

$$U_{PS} = \left[k \; -\overline{u'v'}_{\max} \; U_e \delta^* / L \right]^{1/3}$$

TBL structure and scaling
(not to scale)

$y = \delta$

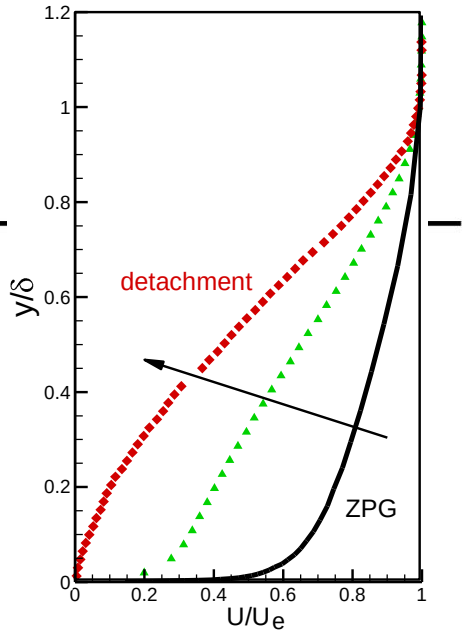
outer region

wake region

$U_o = u_\tau$ or U_{ZS}
$L_o = \delta$ or Δ

$U_o = U_{ZS}$ or U_{po}
$L_o = \delta$ or Δ

$$\beta_o = \frac{T_o}{T_e} = -\frac{L_o}{U_o}\frac{\partial U_e}{\partial x}$$



structure?

0.15-0.2 δ ? ?

inner region

overlap layer

mixed scales?
overlap: mixed log and $y^{1/2}$?

Large defect flows

30-200 ν/u_τ

buffer layer

$U_i = u_\tau$
$L_i = \nu/u_\tau$

$$\beta_i = \left(\frac{U_{pi}}{u_\tau}\right)^3 = \frac{\nu}{\rho u_\tau^3}\frac{dp}{dx}$$

$$\overset{?}{U_i} = U_{pi} = \left(\frac{\nu}{\rho}\frac{dp}{dx}\right)^{1/3}$$
$$\overset{?}{L_i} = \nu/U_{pi}$$

3-5 ν/u_τ

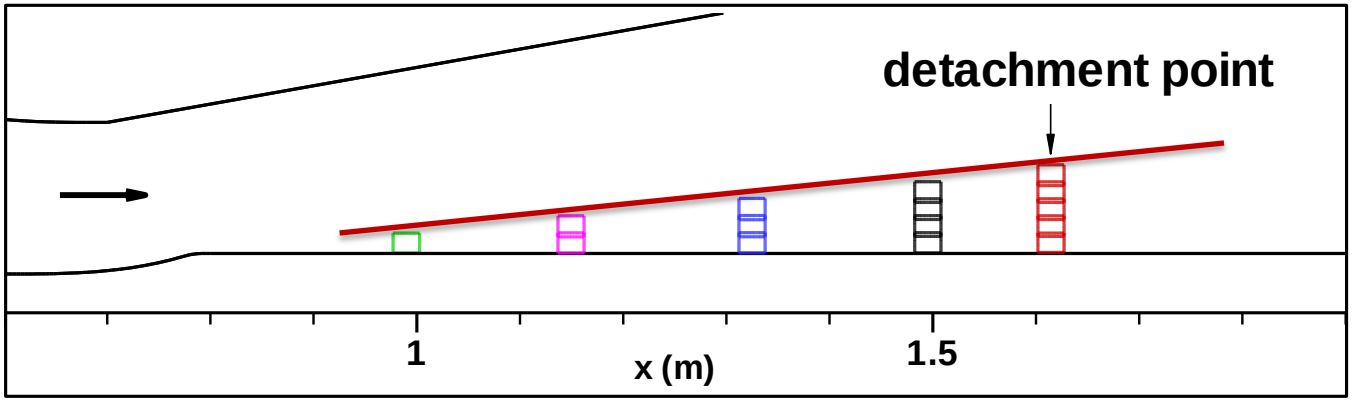
viscous sublayer

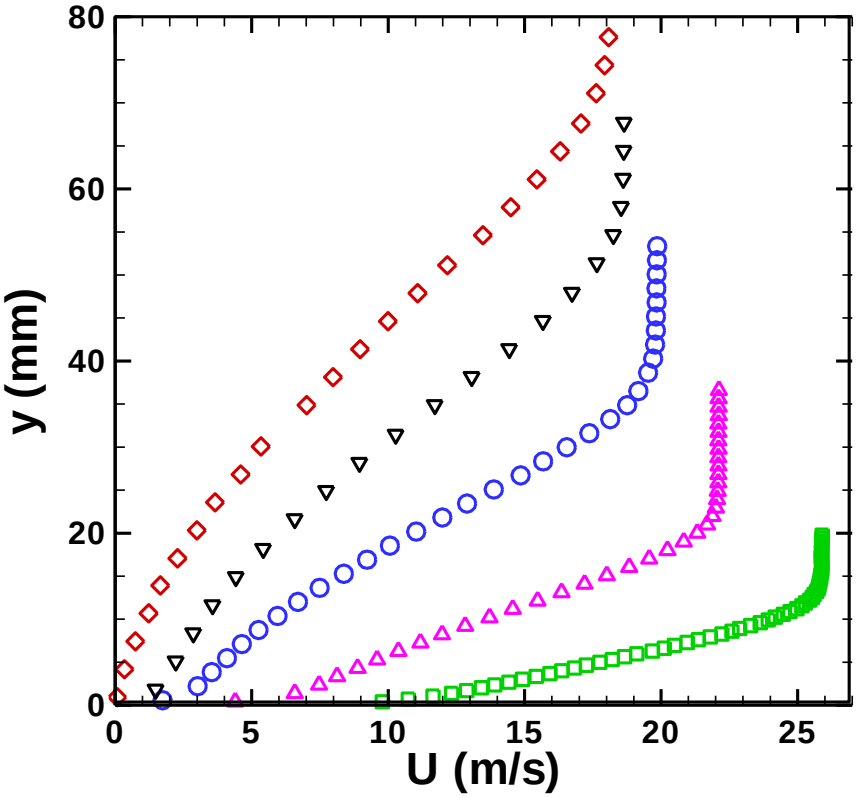
$u^+ = y^+$ $\quad$ $u^+ = y^+ + 1/2\,(U_{pi}/u_\tau)^3\,(y^+)^2$ or $u^p = 1/2\,(y^p)^2 + (u_\tau/U_{pi})^2\,y^p$ $\quad$ $u^p = 1/2\,(y^p)^2$?

ZPG → increasing ~~APG~~ defect → detachment
(increasing β_i and β_o) ($\beta_i \to \infty$ and β_o finite)

$u_\tau/U_{pi} \to \infty$ → decreasing u_τ/U_{pi} → $u_\tau/U_{pi} \to 0$

Outer region of the boundary layer





Re_θ: $3360 \rightarrow 12690$

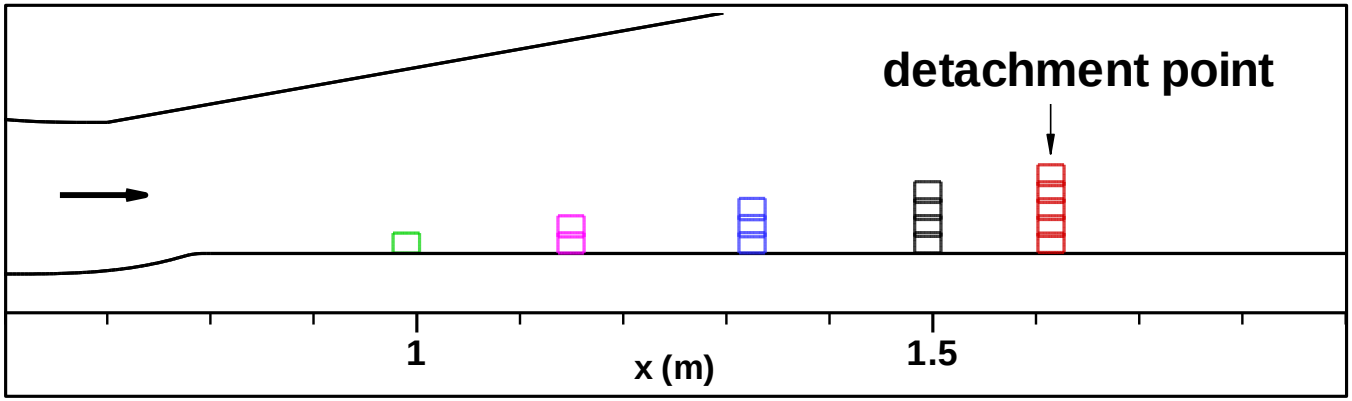
C_f: $0.0023 \rightarrow 0$

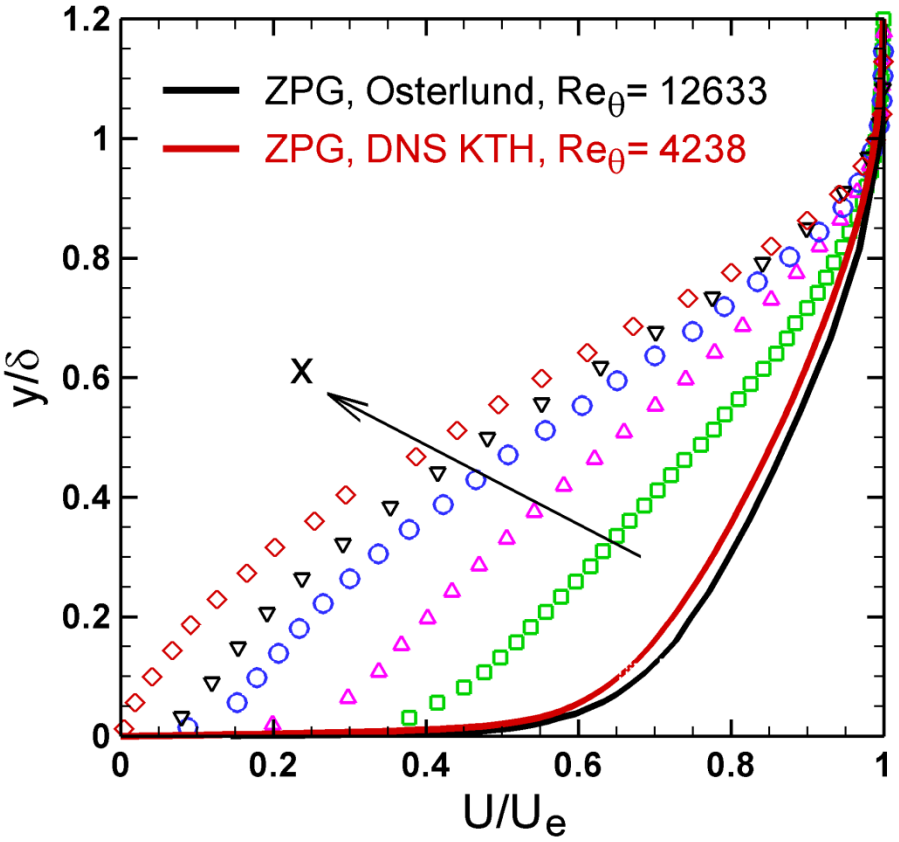
H: $1.72 \rightarrow 3.85$

$\beta = -\frac{\delta}{u_\tau}\frac{dU_e}{dx}$: $3200 \rightarrow \infty$

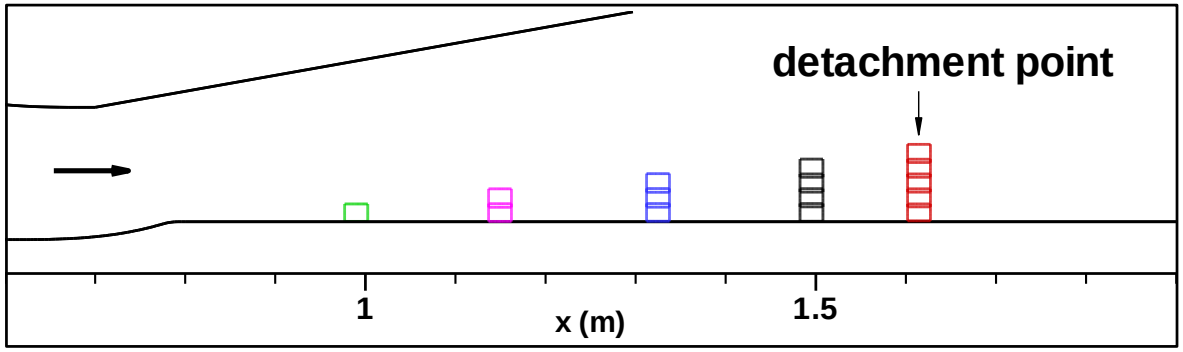
$\beta_{ZS} = -\frac{\delta}{U_{ZS}}\frac{dU_e}{dx}$: $0.052 \rightarrow 0.020$

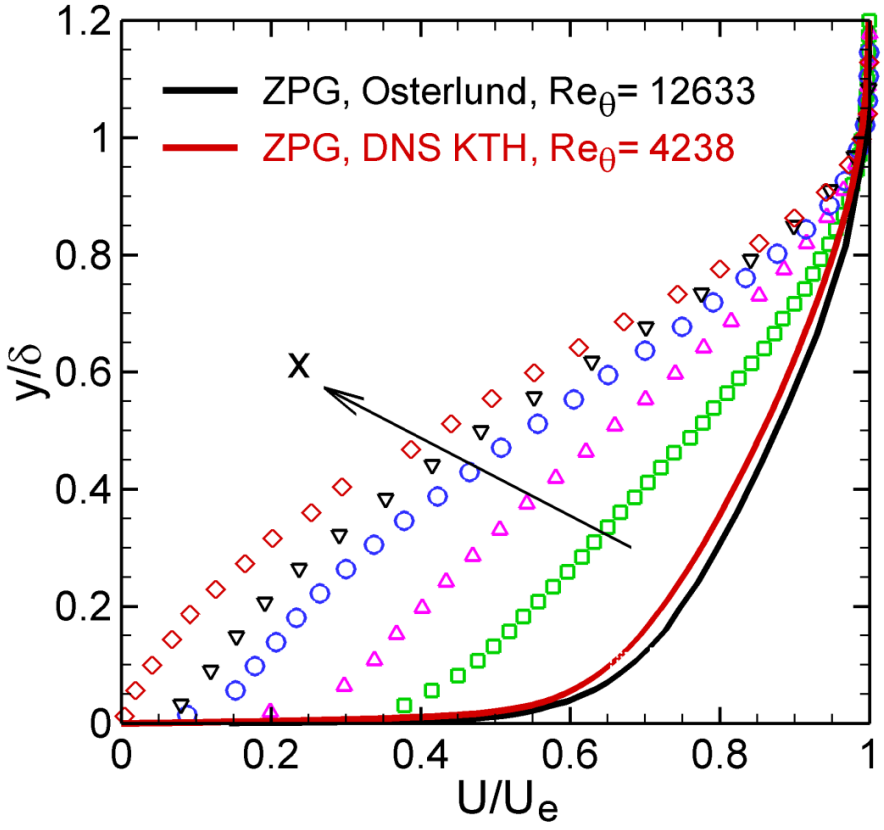
Outer region of the boundary layer

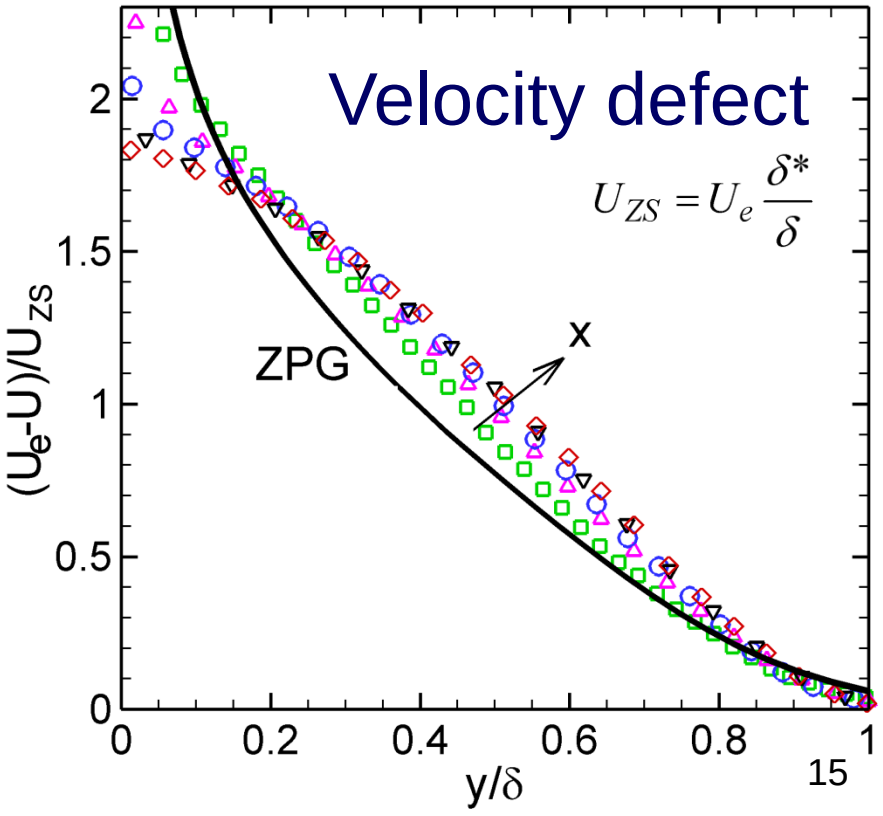




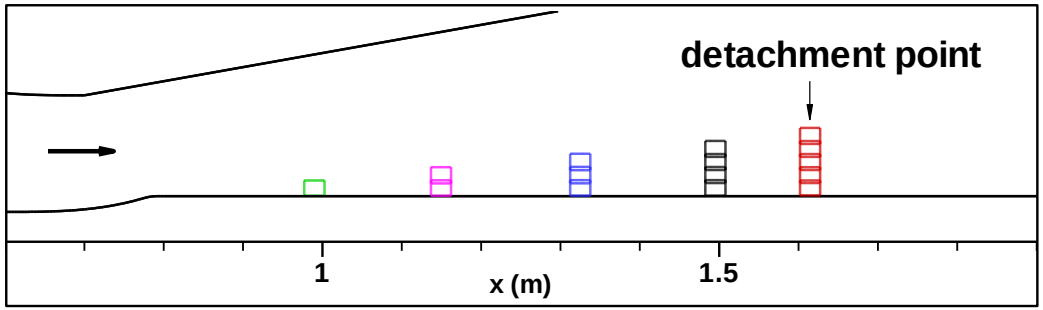
Outer region of the boundary layer

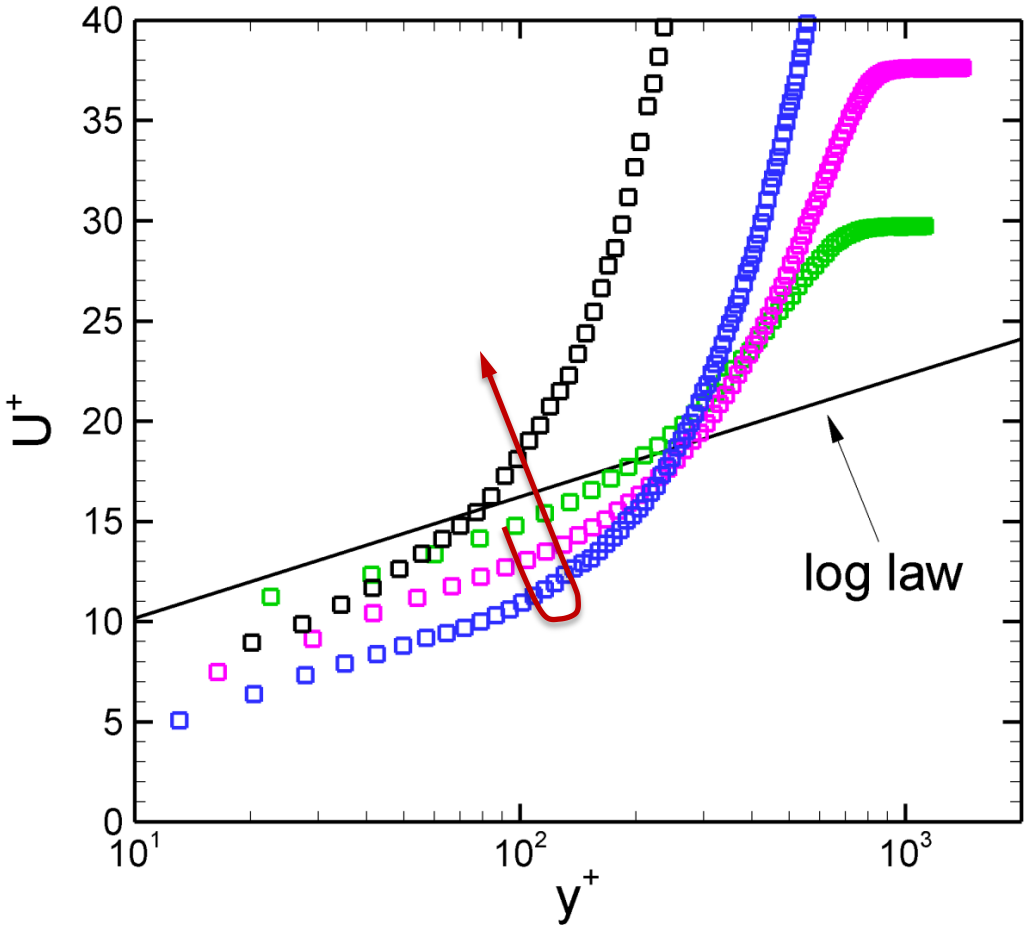




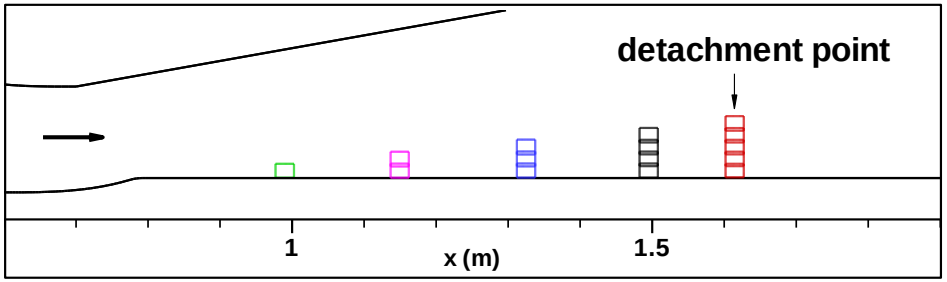


Law of the wall ?



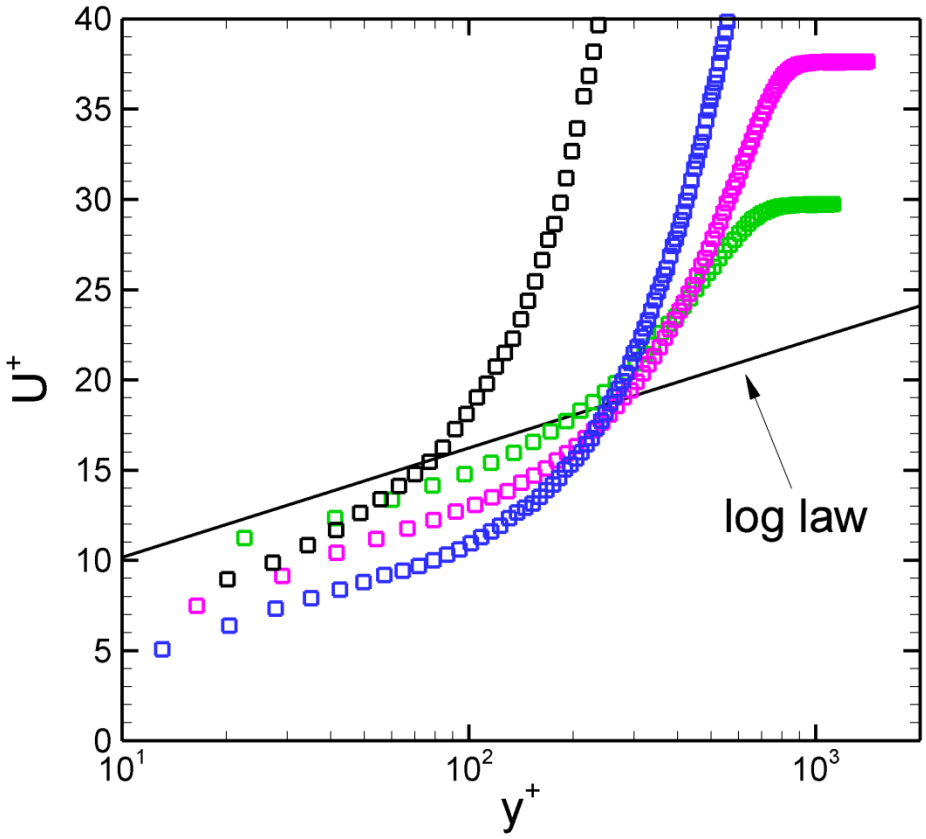


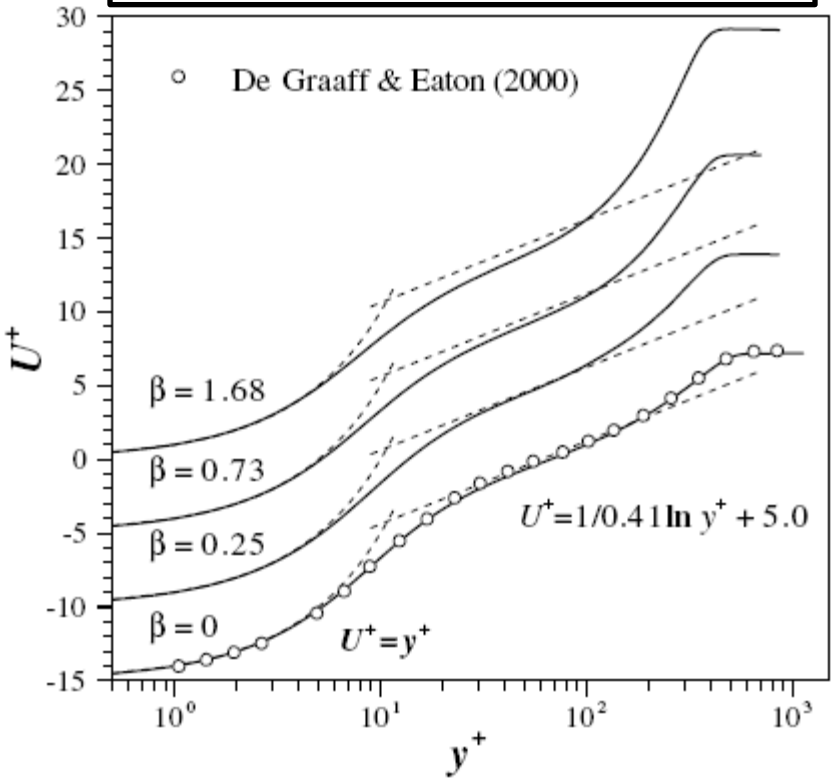
Law of the wall ?



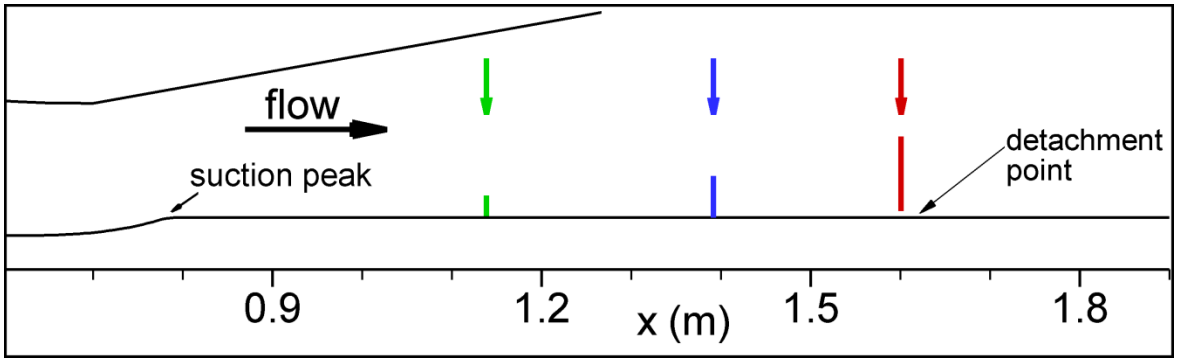
DNS,Lee and Sung (2009)

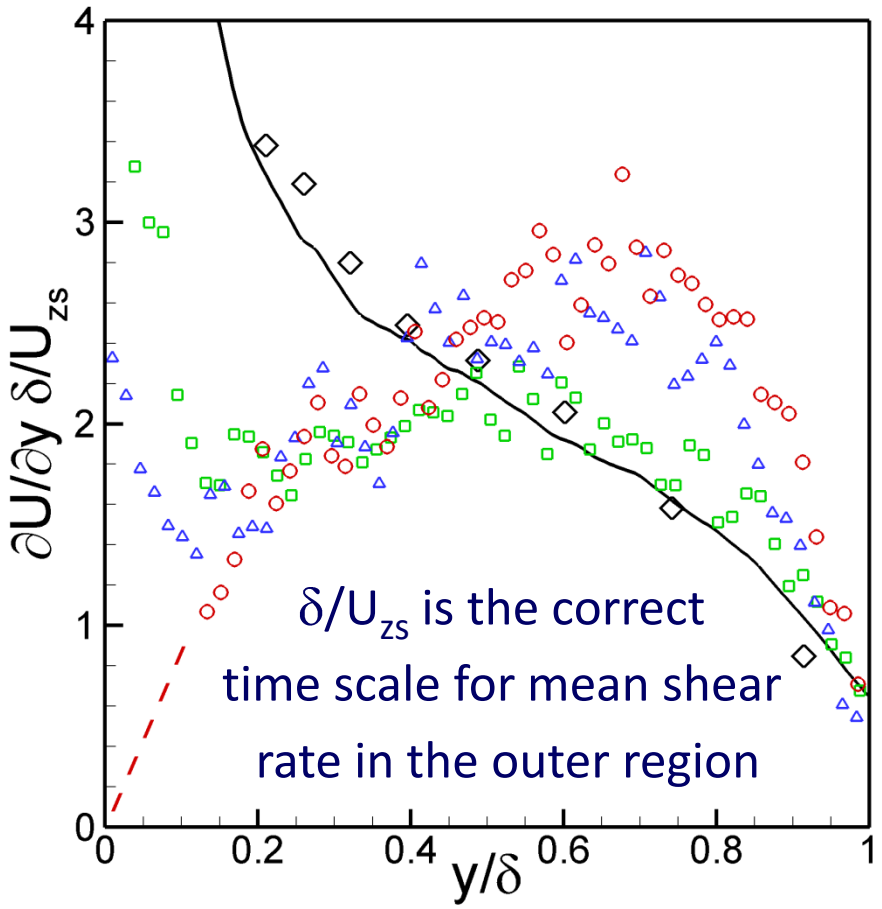
- moderate APG cases
- **Equilibrium flows**
- But low Re_θ (1000-1400)

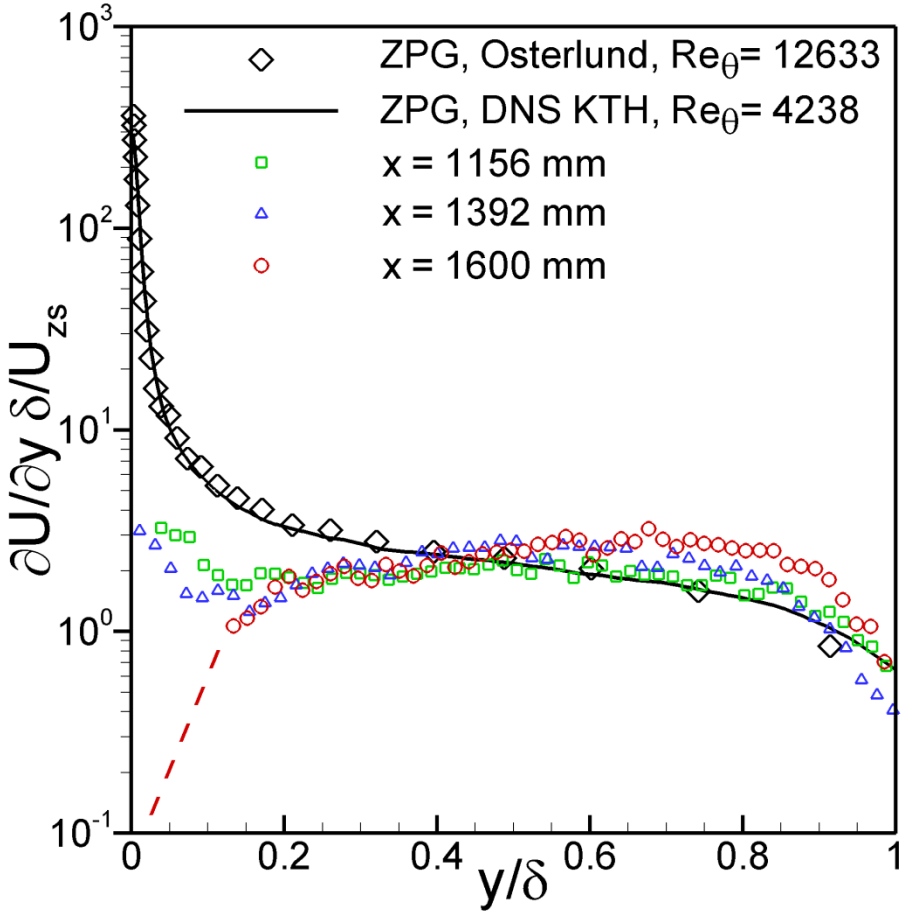




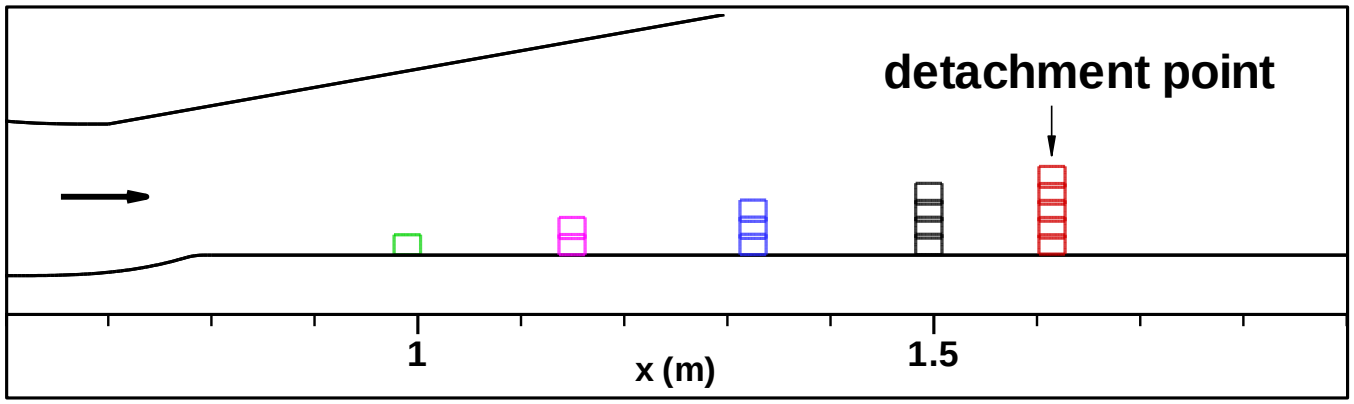
Mean shear strain rate

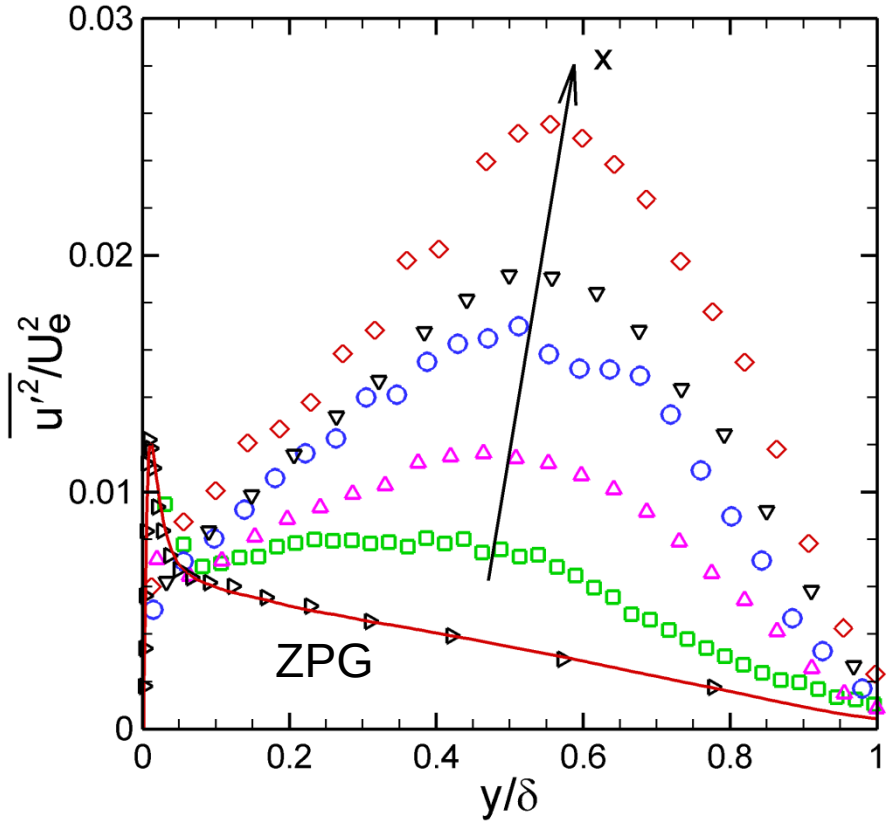


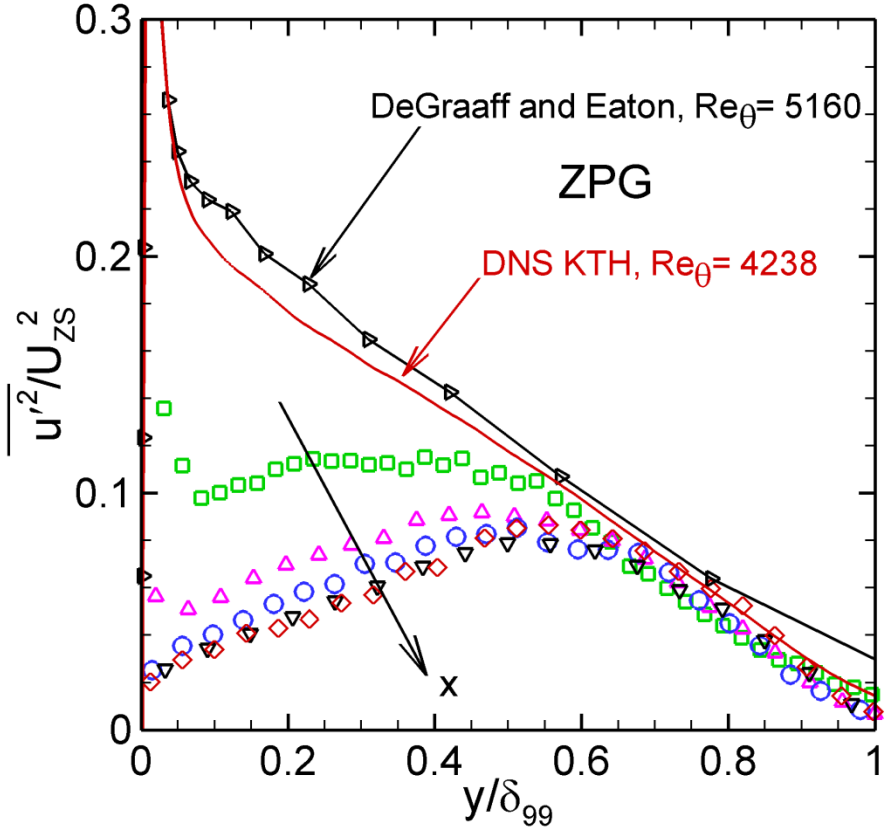




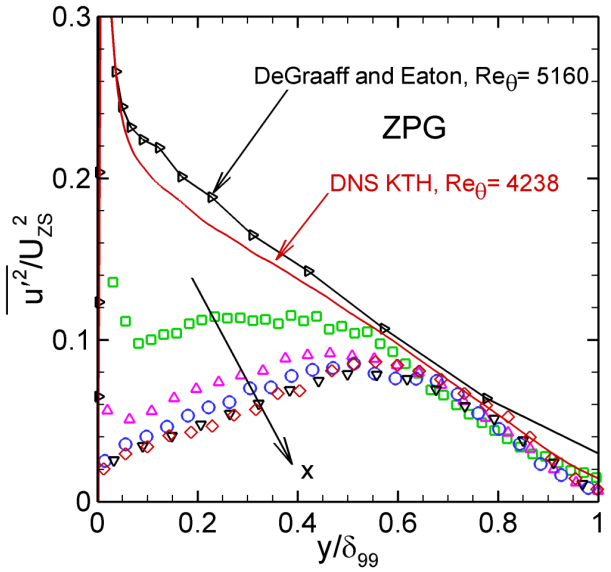
Reynolds stresses – streamwise fluctuations

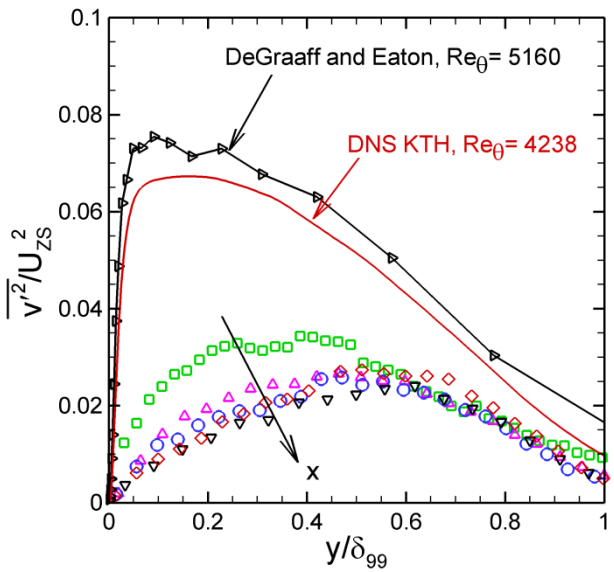


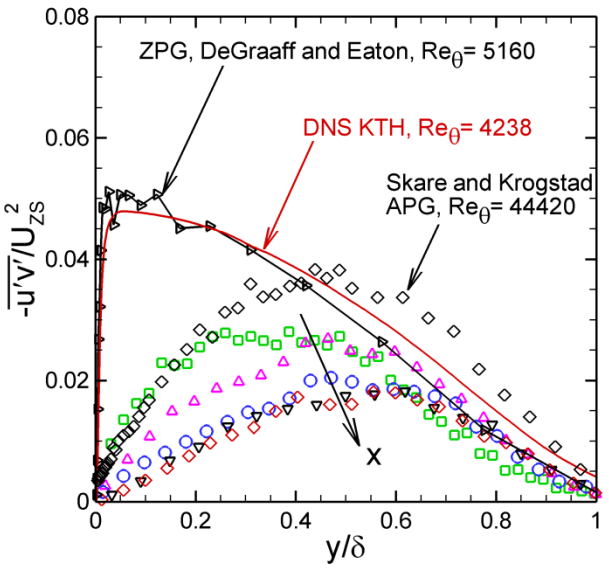




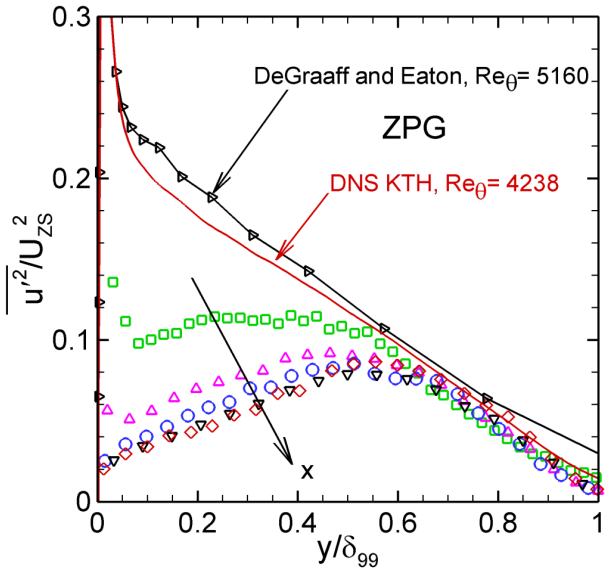
Reynolds stresses

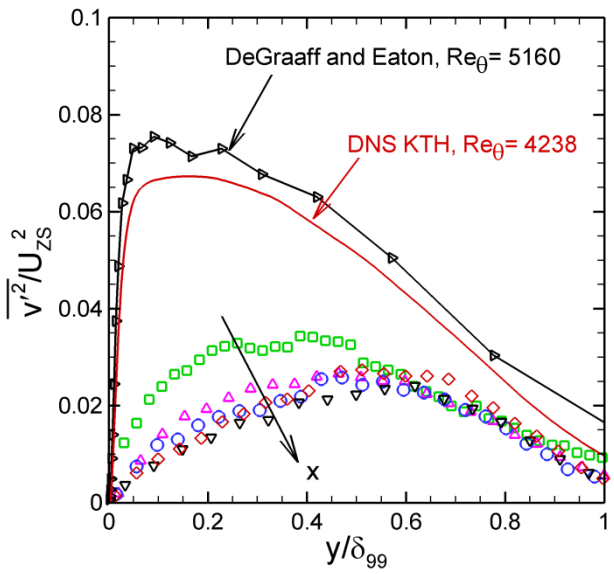


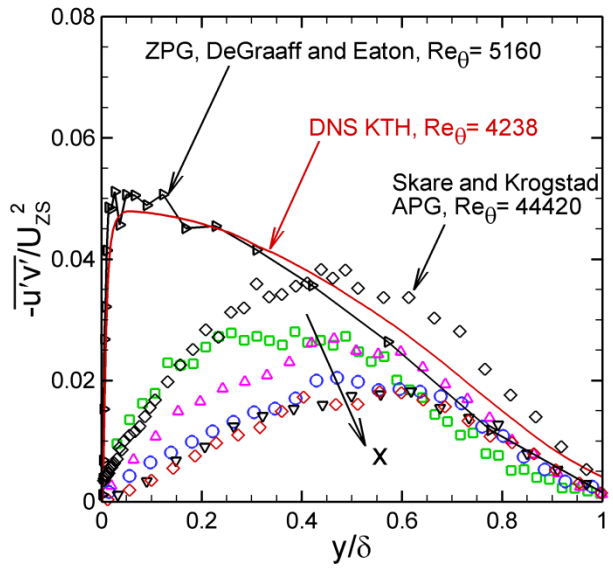


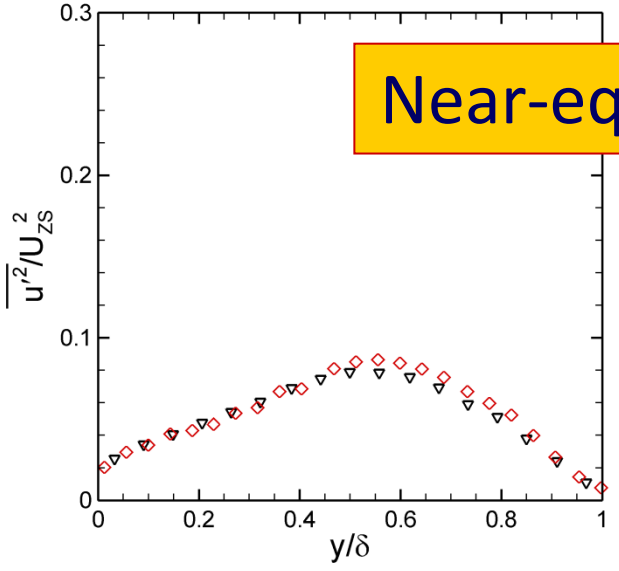


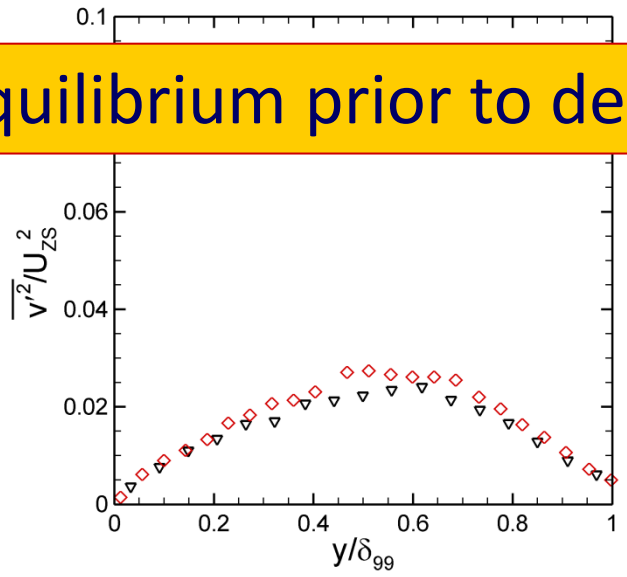
Reynolds stresses

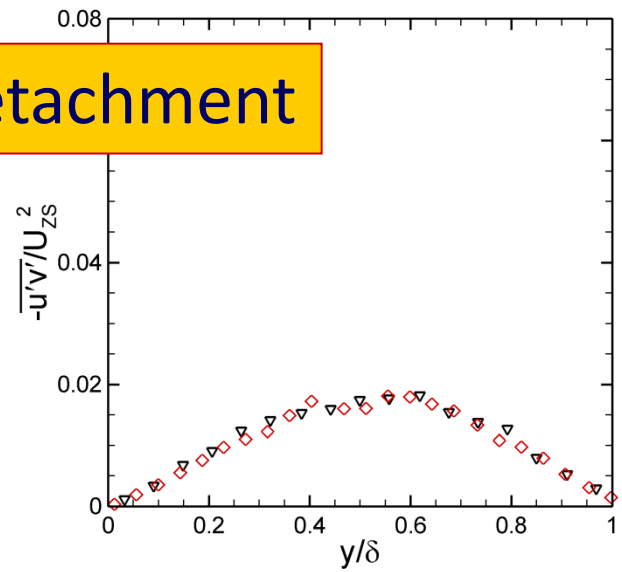






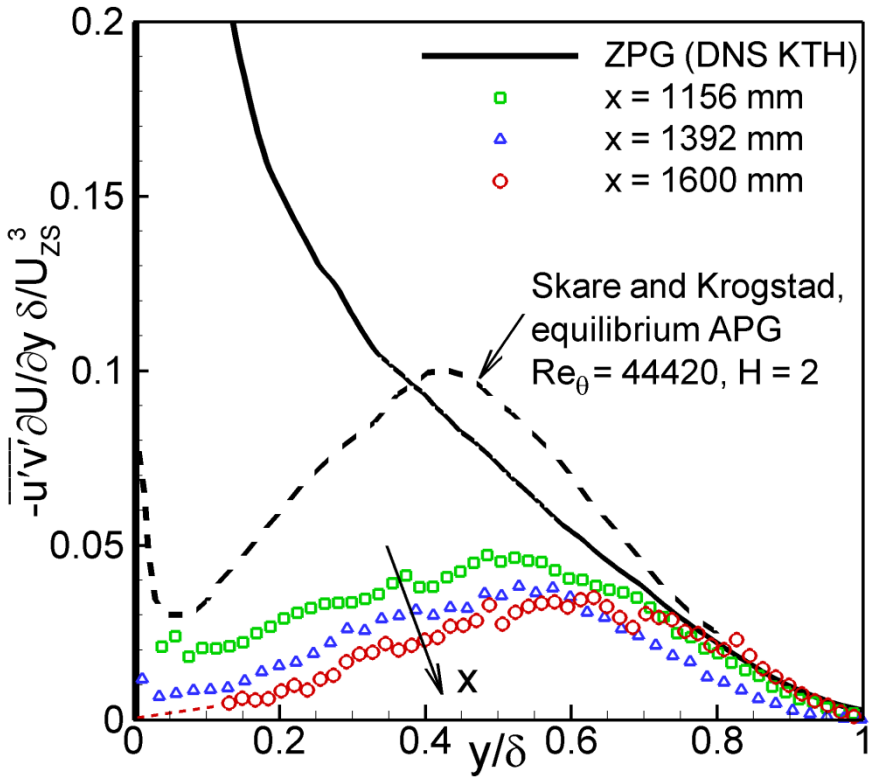


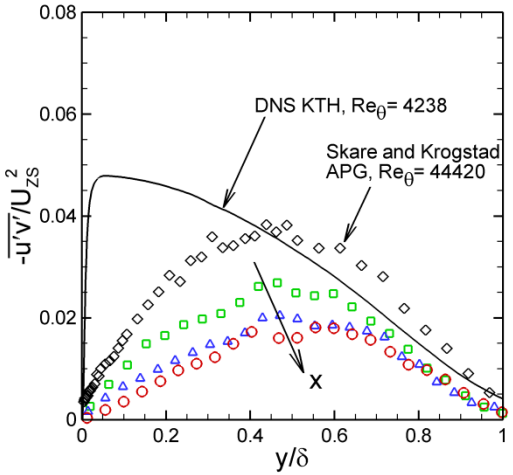


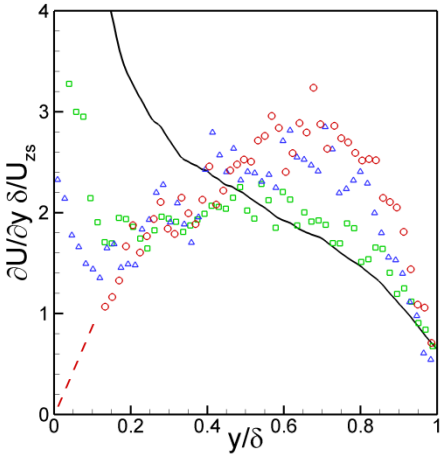


Near-equilibrium prior to detachment

Turbulence production

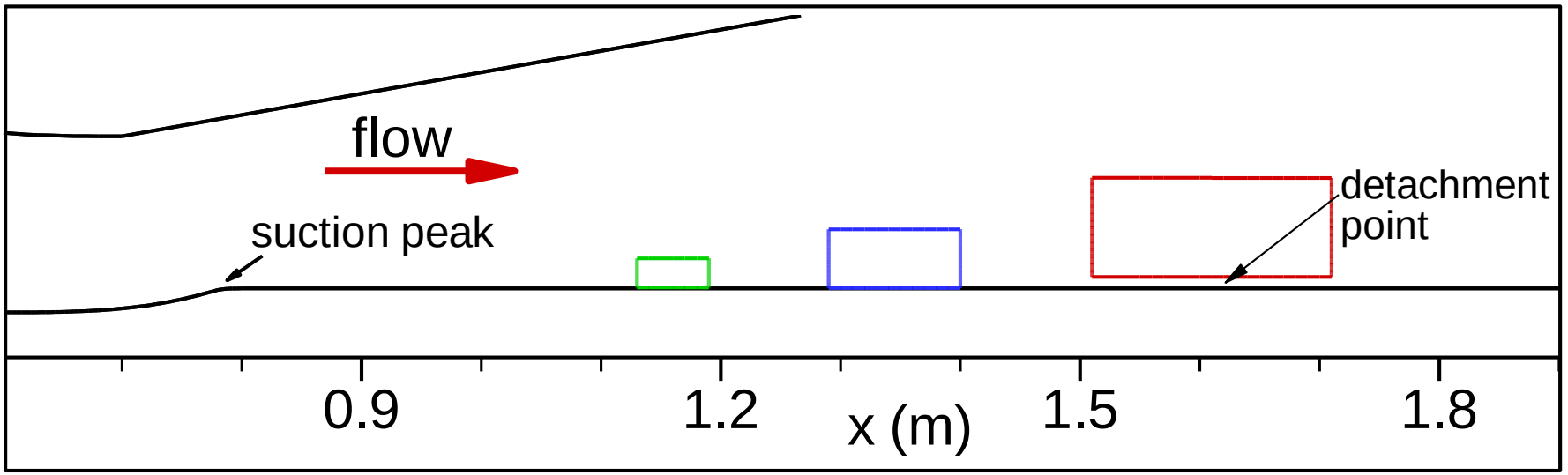






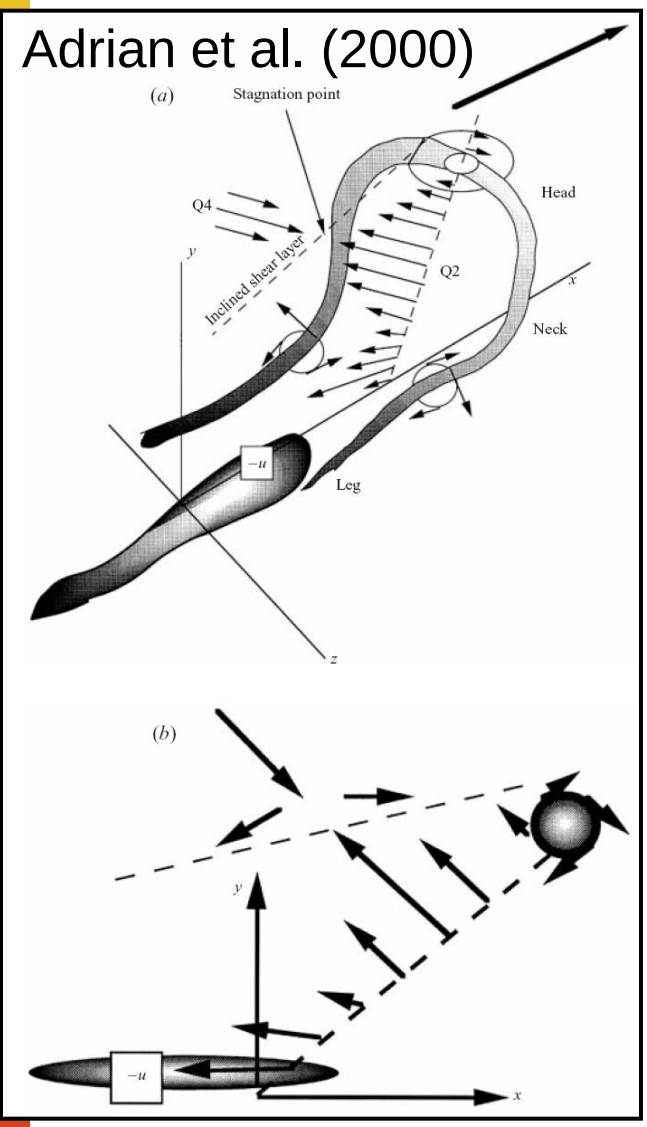
Coherent structures in APG TBL (outer region)

xy planes



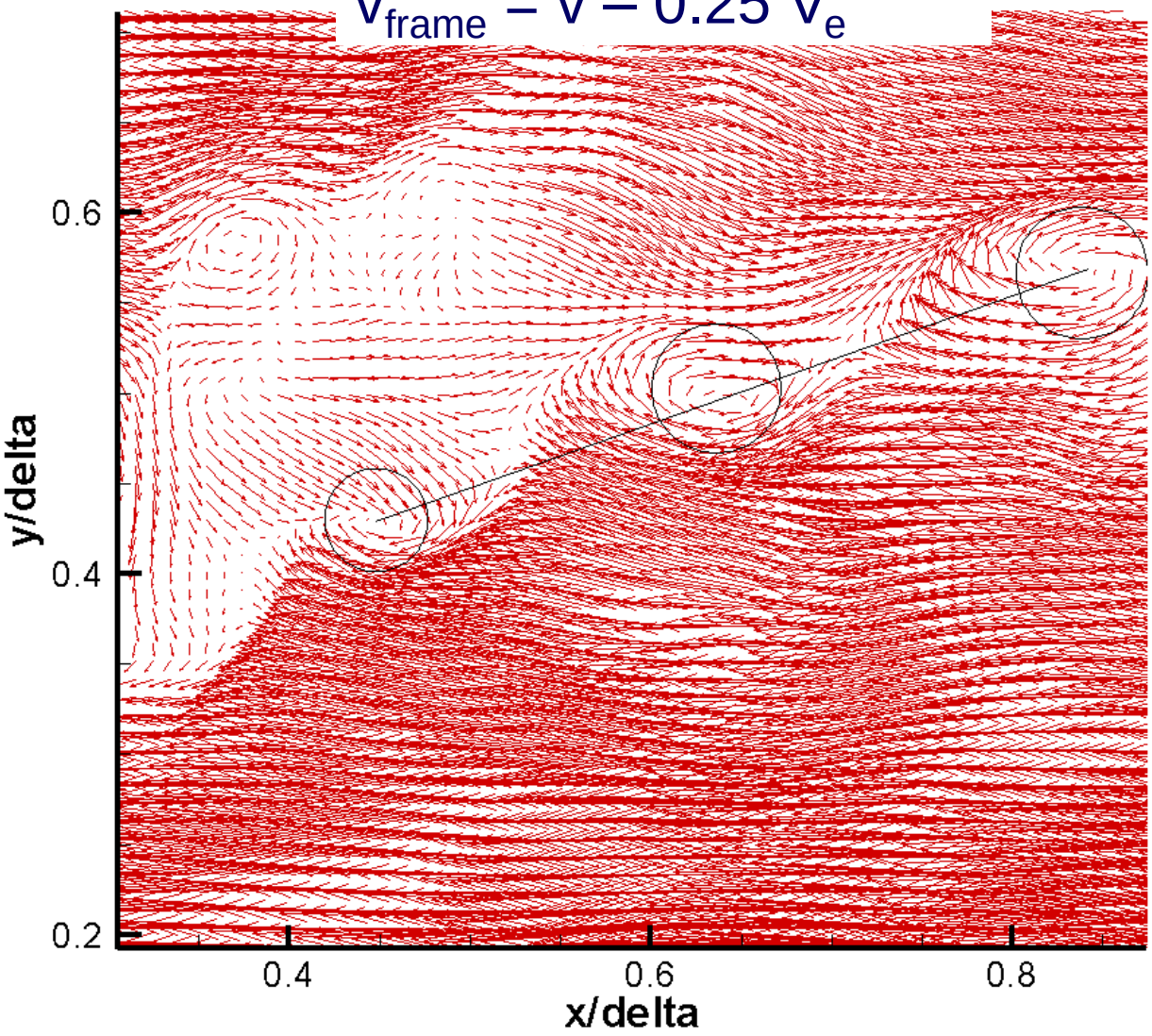
xy planes

Adrian et al. (2000)

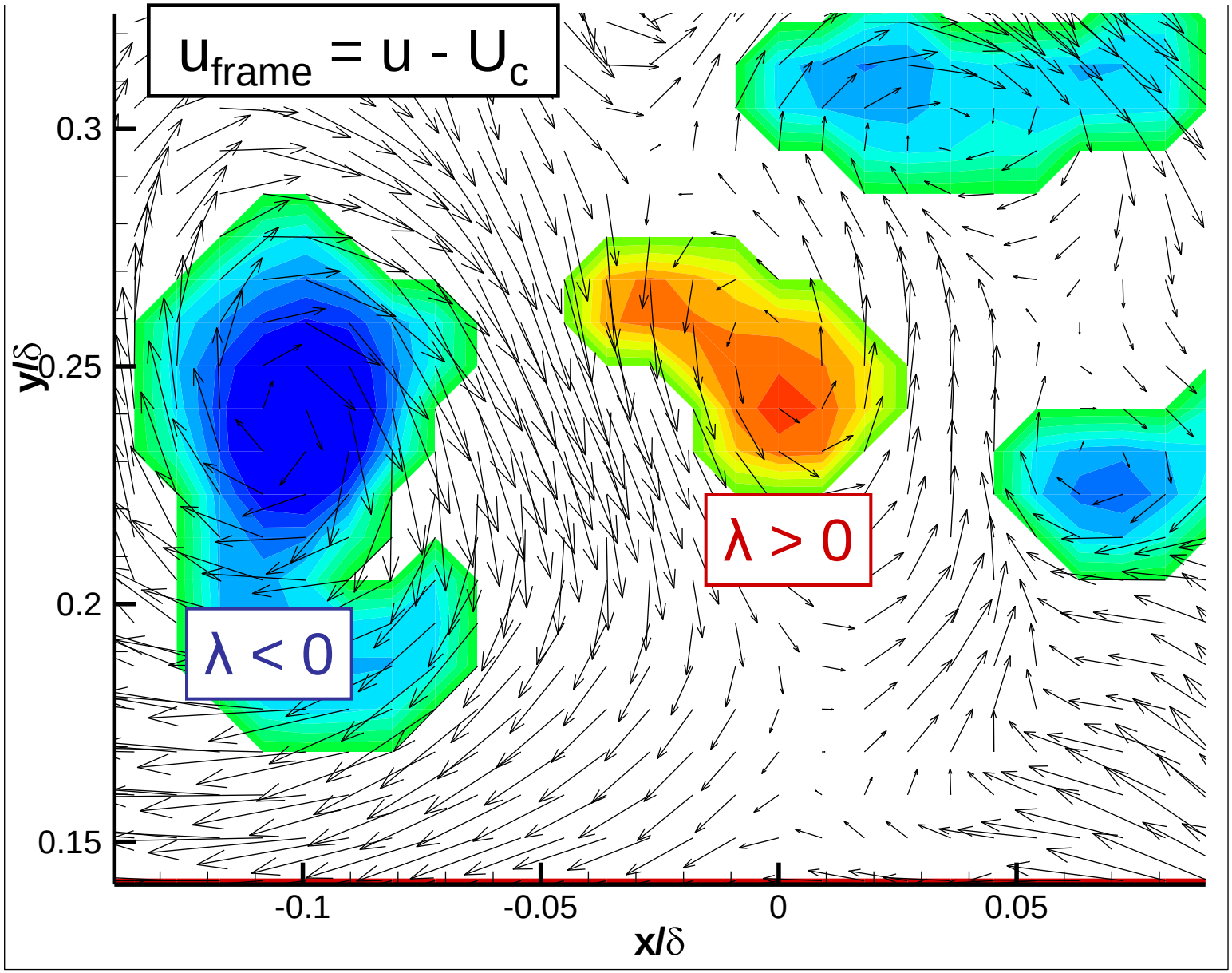


$u_{frame} = u - 0.70\ U_e$

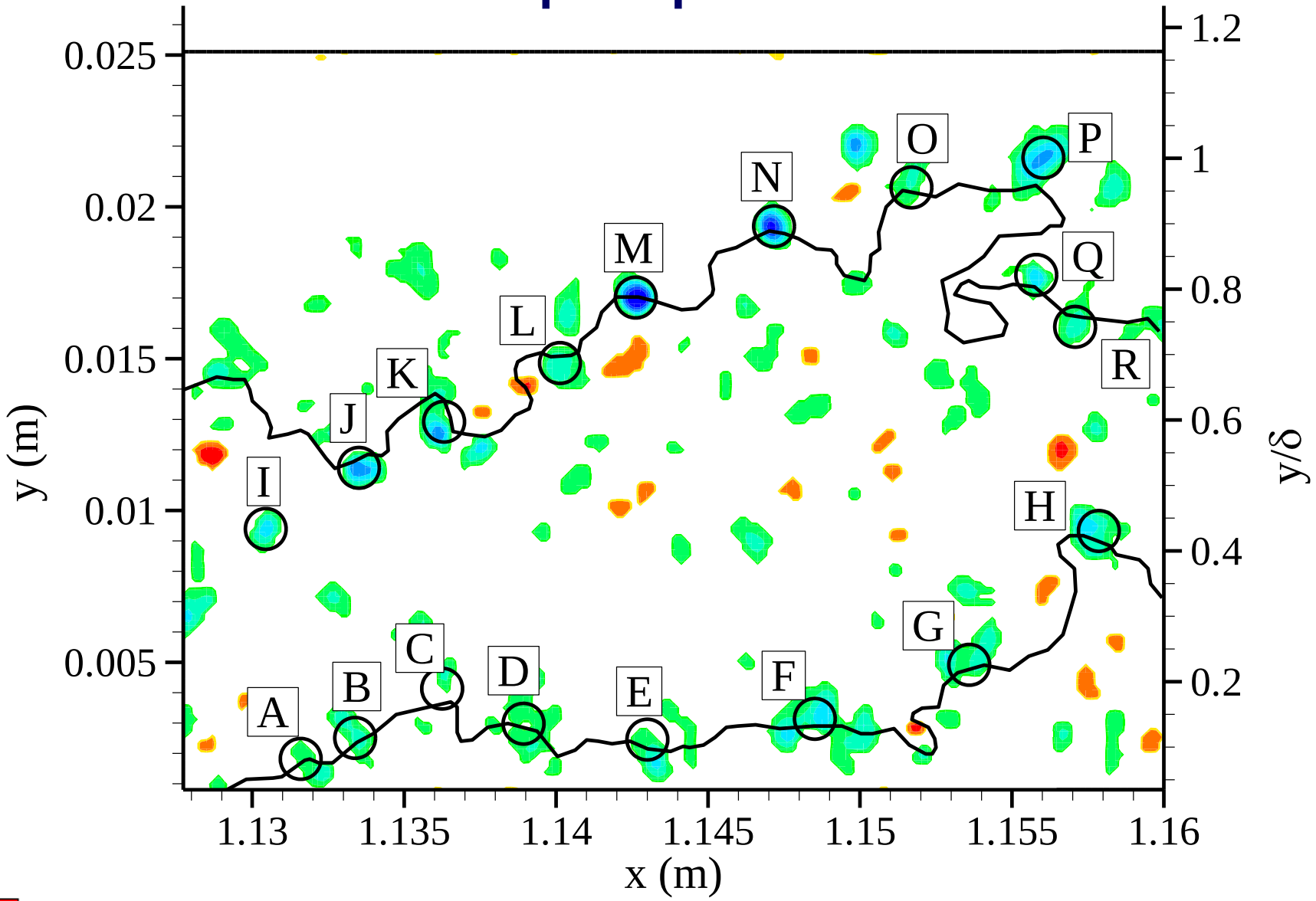
$v_{frame} = v - 0.25\ V_e$

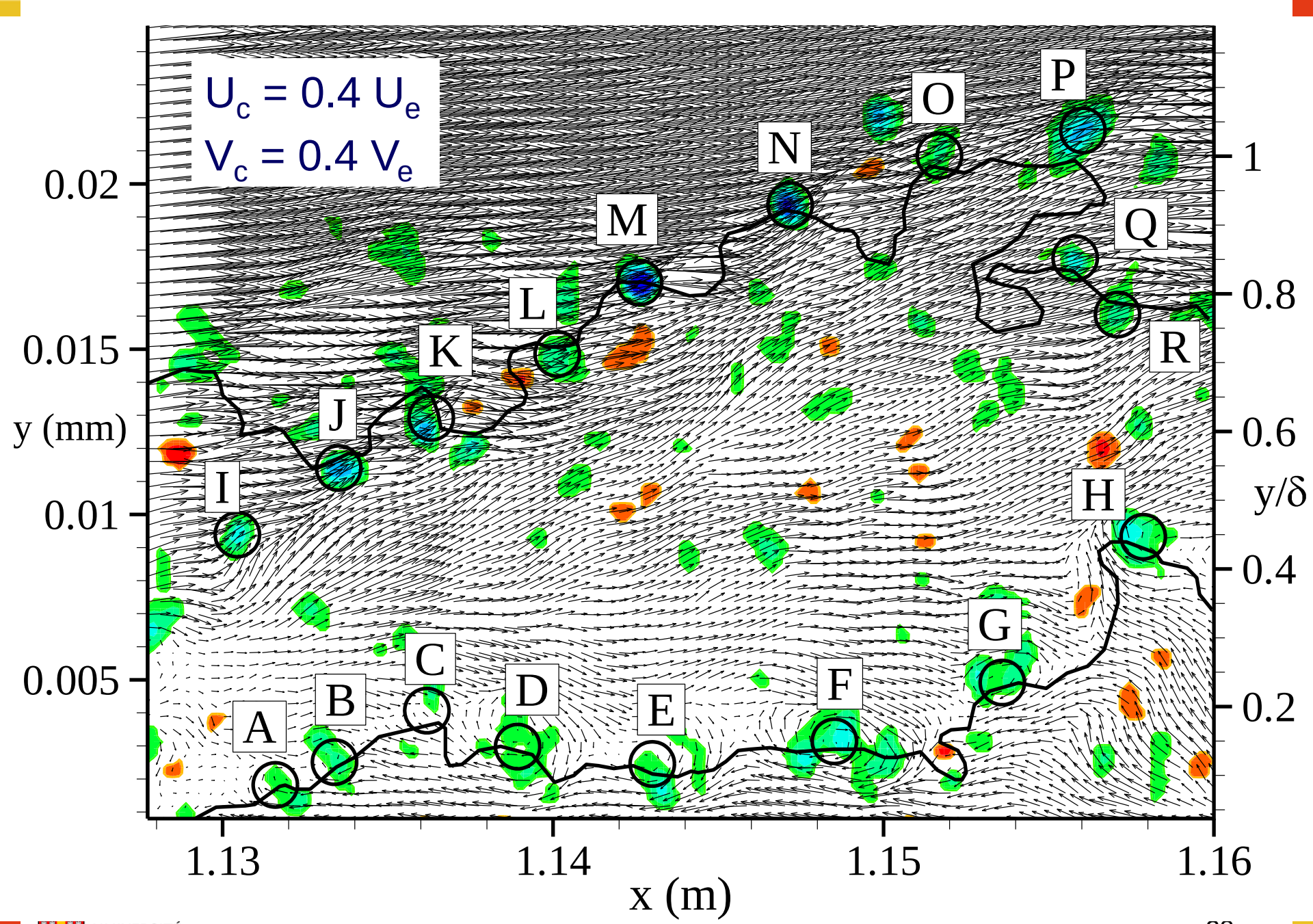


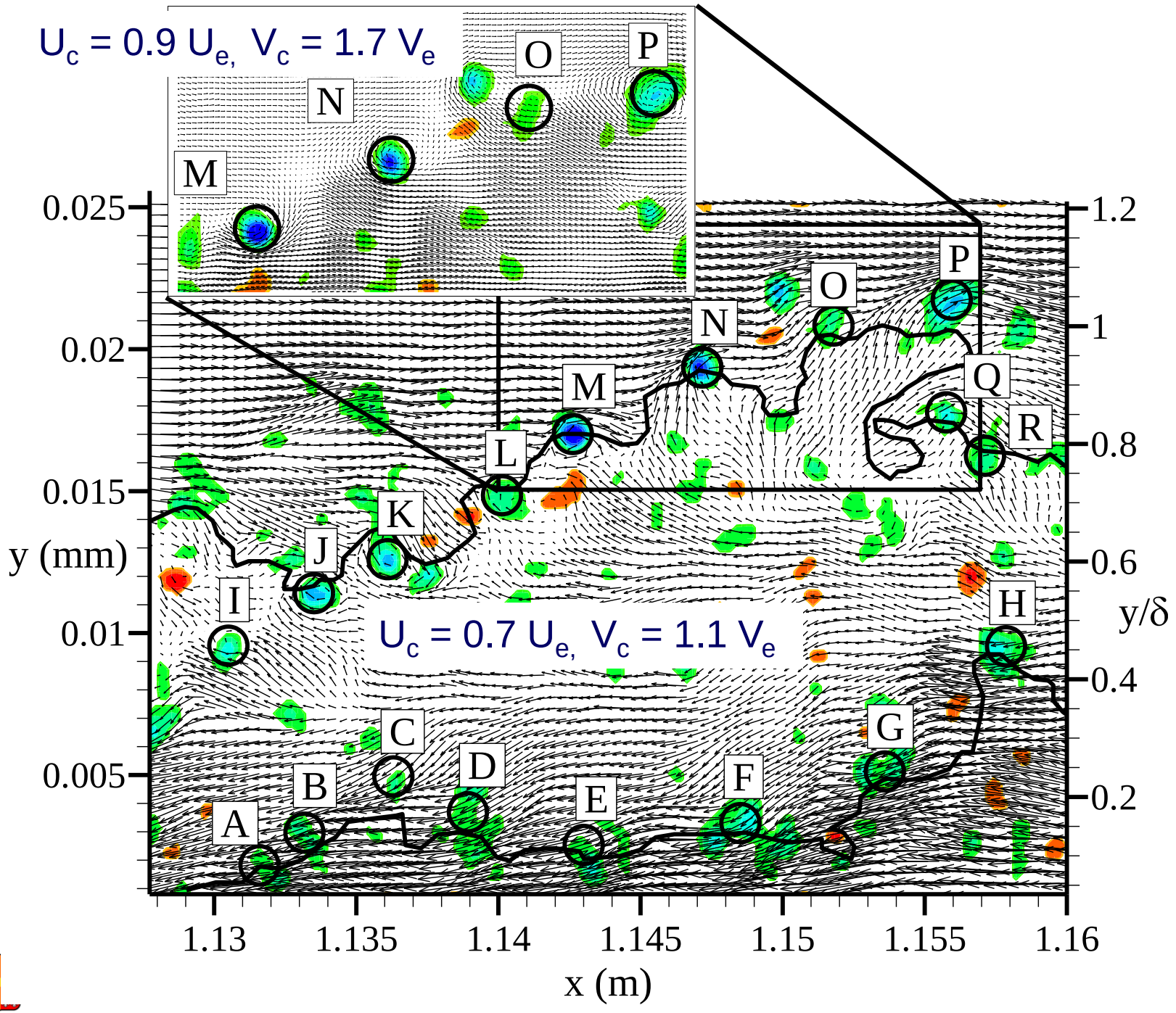
Swirling rate λ with threshold



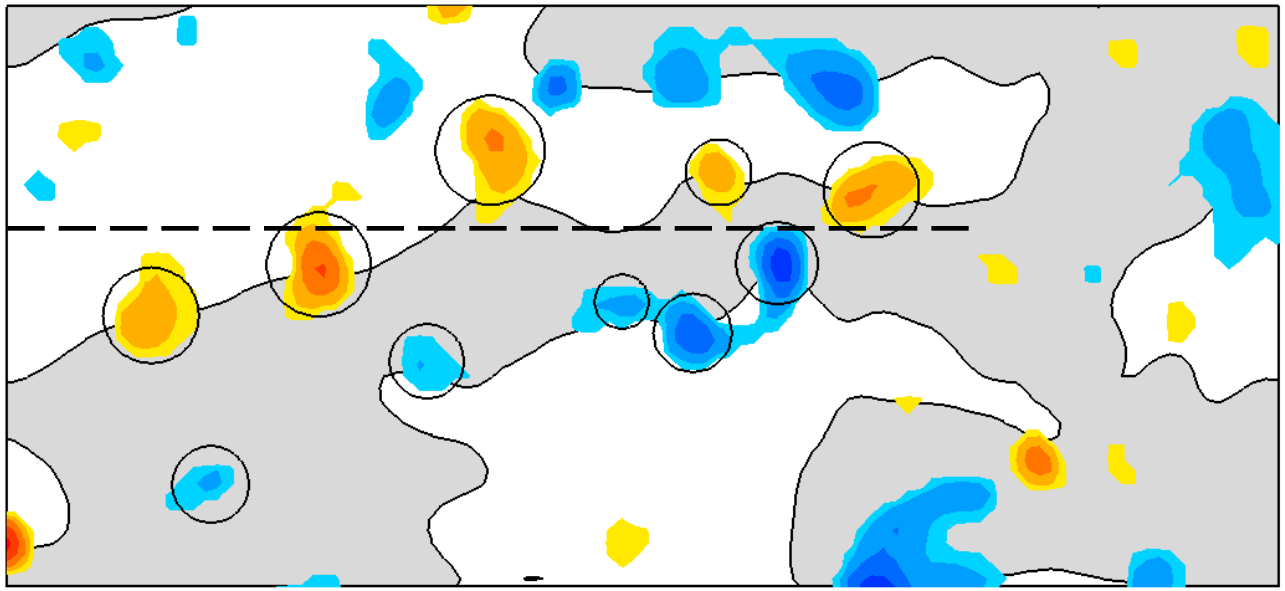
2 “Hairpin packets”

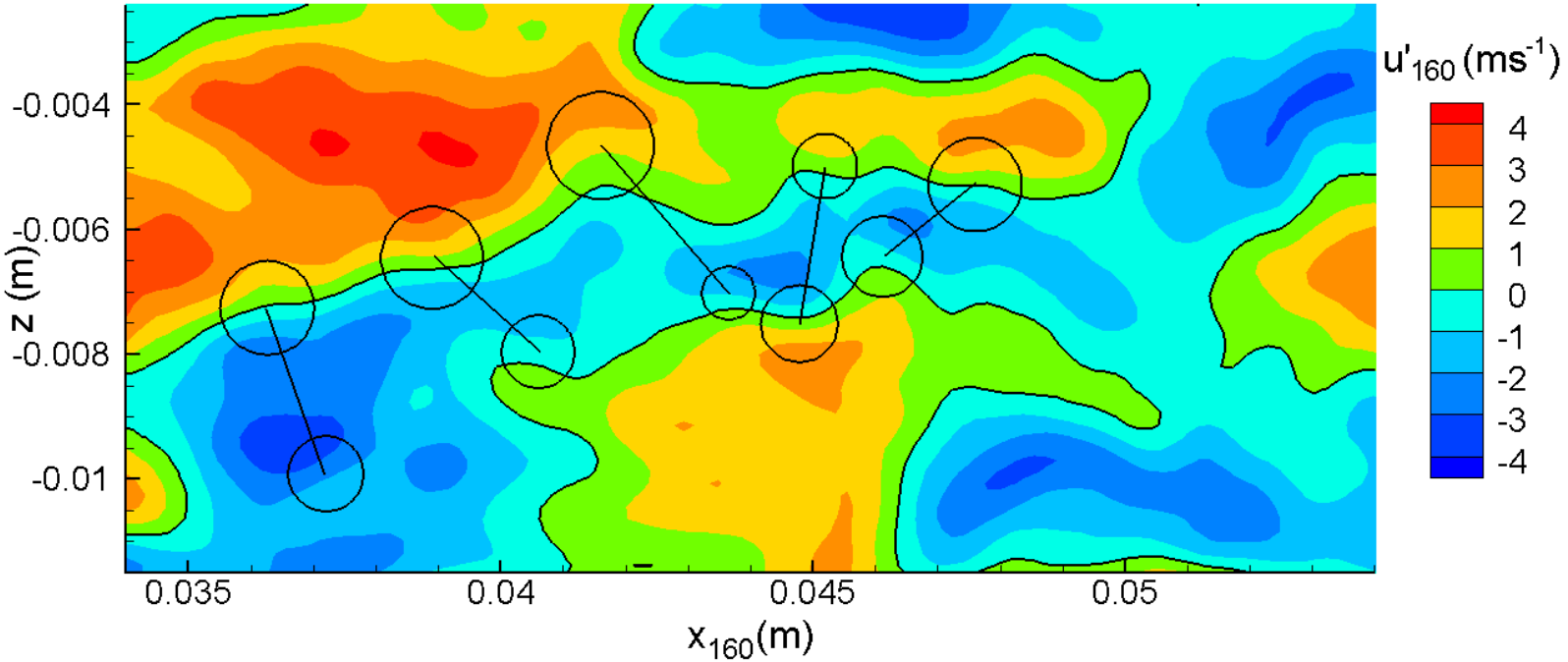



$U_c = 0.4\ U_e$
$V_c = 0.4\ V_e$
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
0.02
0.015
0.01
0.005
y (mm)
1
0.8
0.6
0.4
0.2
y/δ
1.13
1.14
1.15
1.16
x (m)

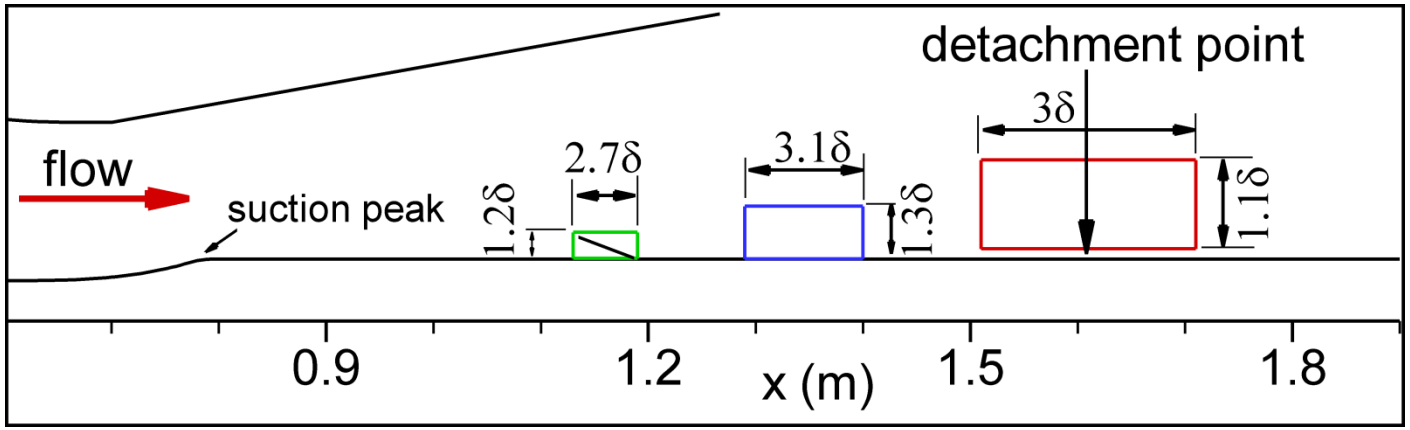

$U_c = 0.9\ U_e$, $V_c = 1.7\ V_e$
$U_c = 0.7\ U_e$, $V_c = 1.1\ V_e$
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
0.025
0.02
0.015
0.01
0.005
y (mm)
1.2
1
0.8
0.6
0.4
0.2
y/δ
1.13
1.135
1.14
1.145
1.15
1.155
1.16
x (m)

xy plane

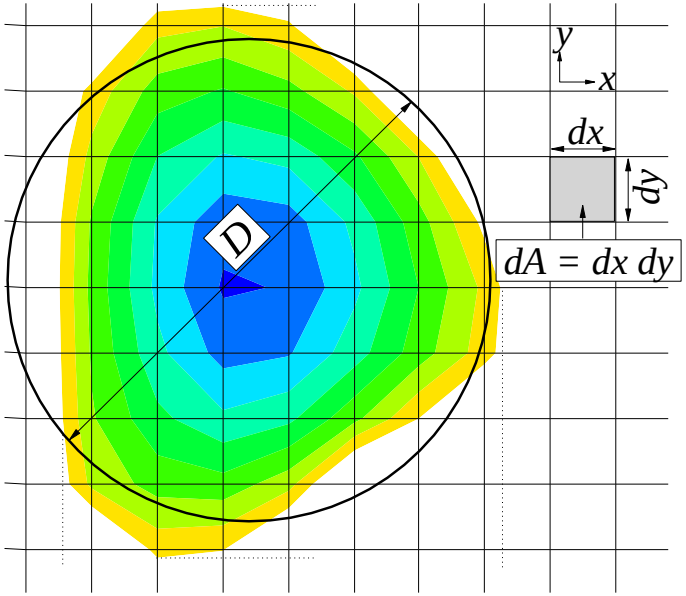

λ (s-1)
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000

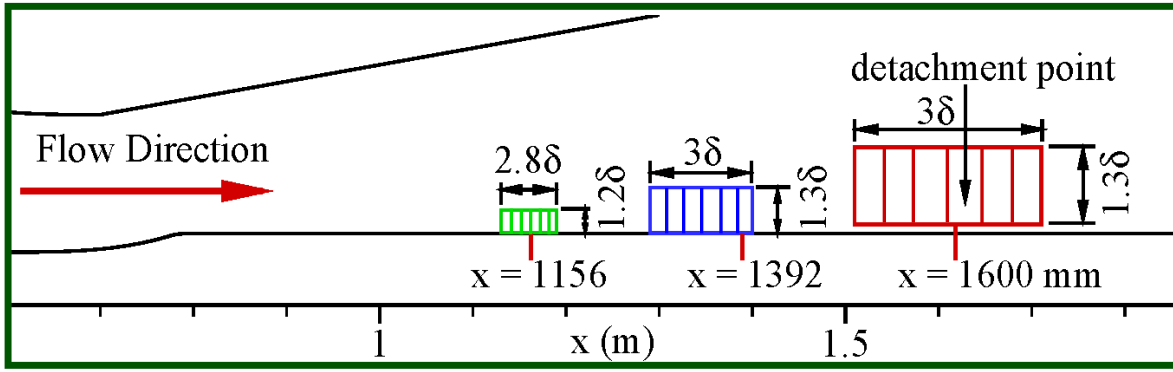

u'160 (ms-1)
4
3
2
1
0
-1
-2
-3
-4
-0.004
-0.006
-0.008
-0.01
z (m)
0.035
0.04
0.045
0.05
x160(m)

	x (mm)	No. of hairpins per packet	No. of packets per 3δ x 1.3δ field
xy planes	ZPG TBL Adrian et al. (2000)	4	2-3
	x = 1128-1125	4	3
	x = 1285-1397	4	3
	x = 1509-1680	4	3
inclined	ZPG TBL Hutchins et al. (2005)	6	
	x = 1128-1125	6	

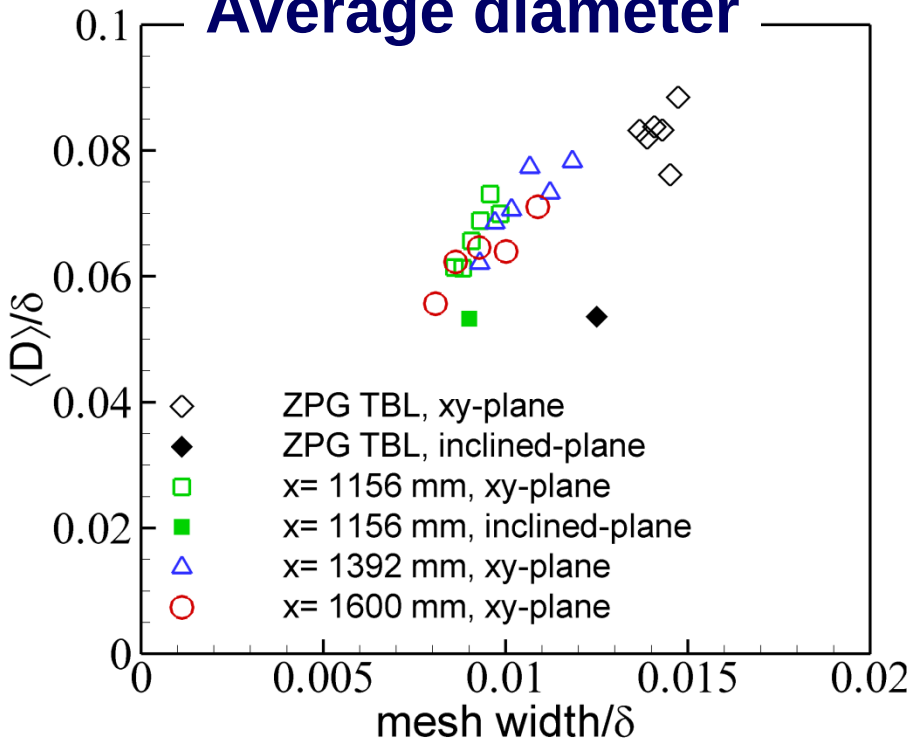


Upper region: y > 0.2δ

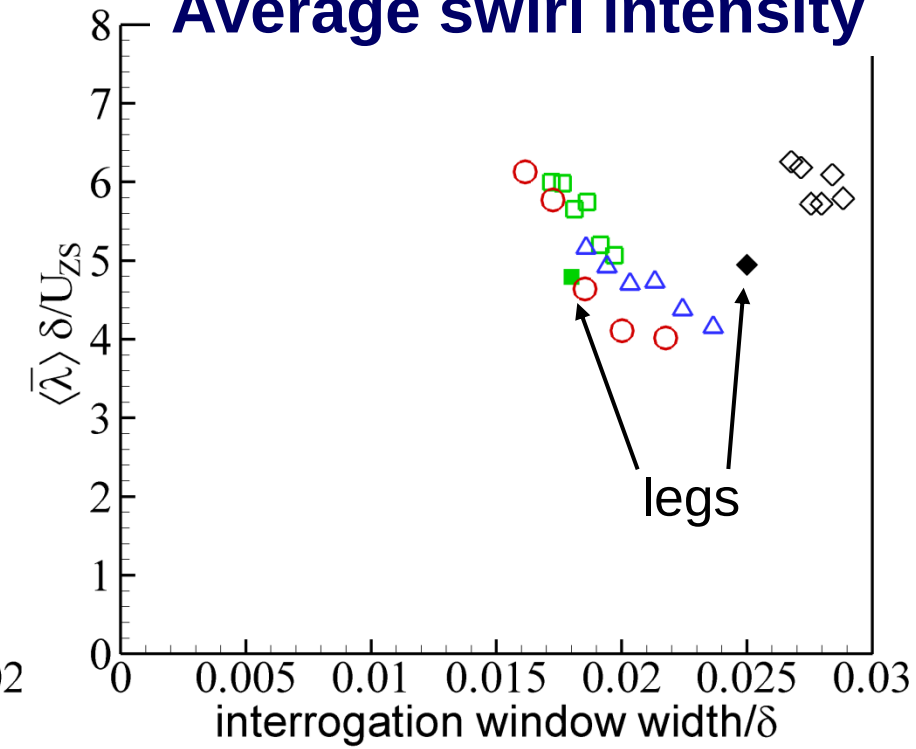




Average diameter

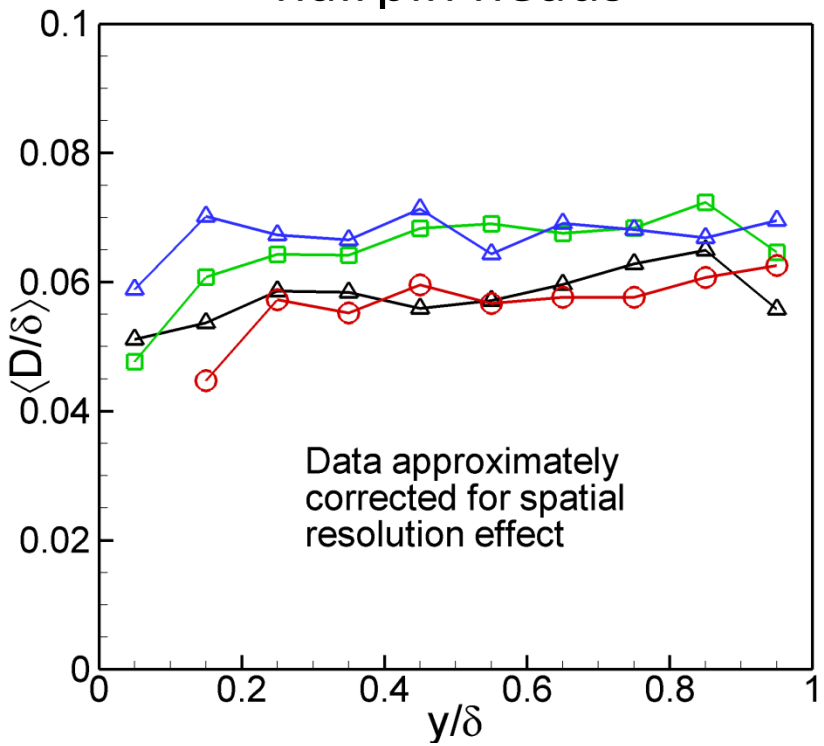


Average swirl intensity

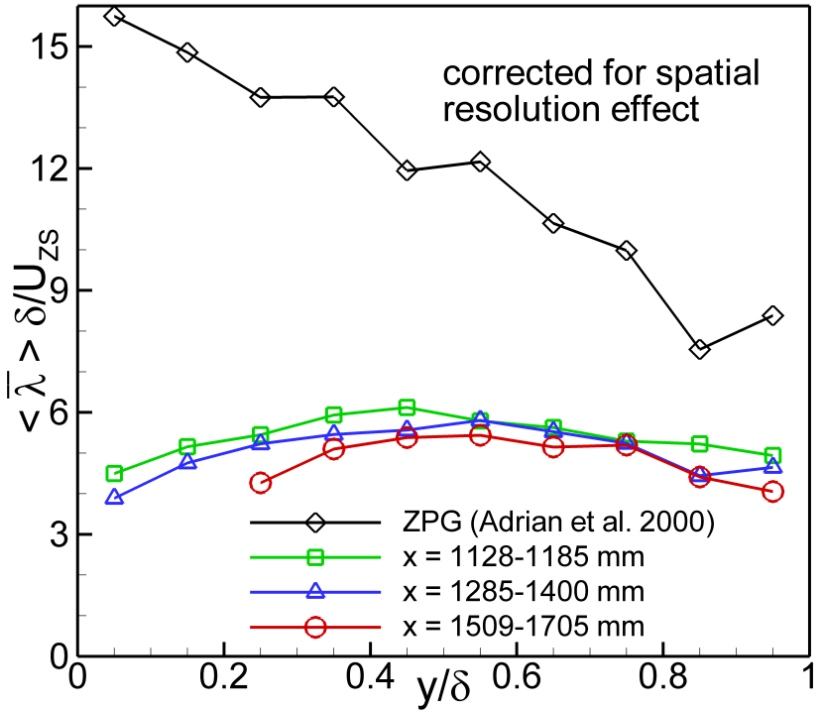


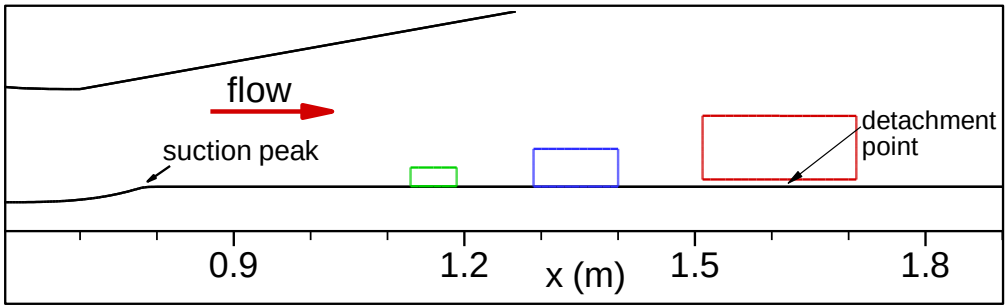
Persistent flow properties

Average diameter of hairpin heads

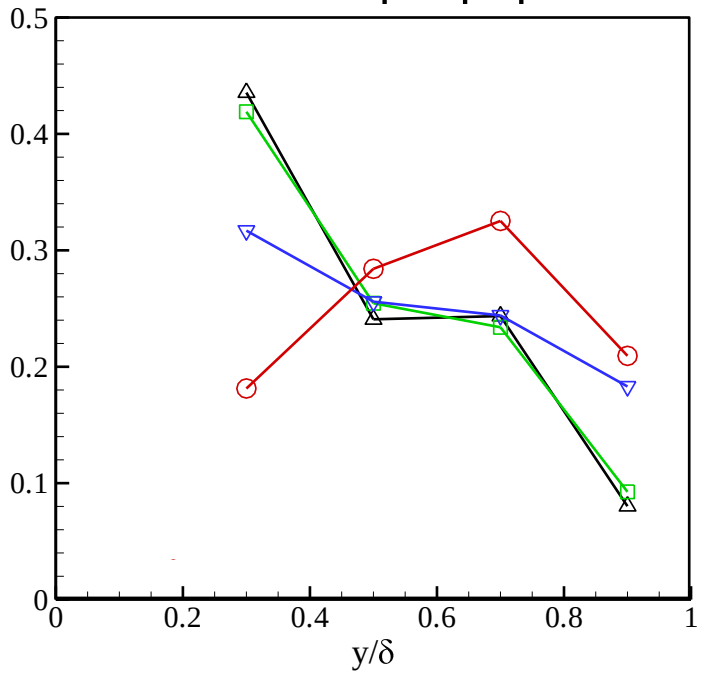


Average swirl intensity of hairpin heads



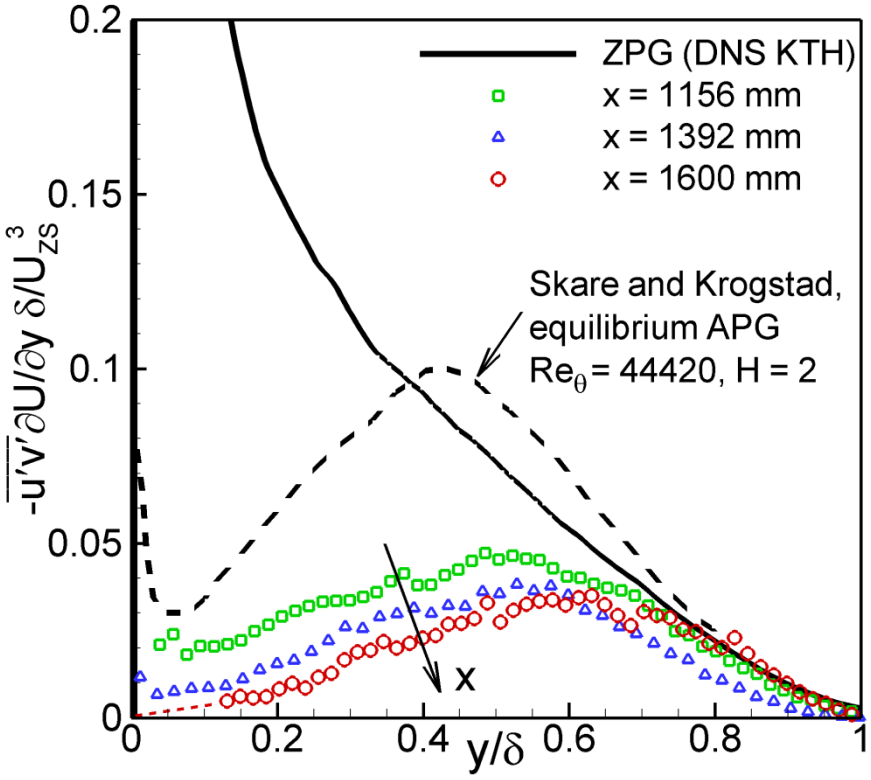


Fraction of hairpin population

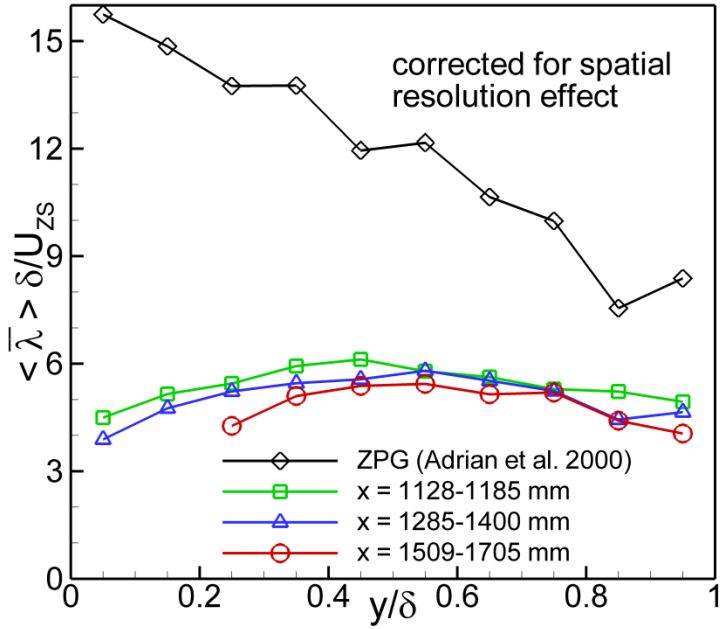


Hairpin dynamics?

Turbulence production

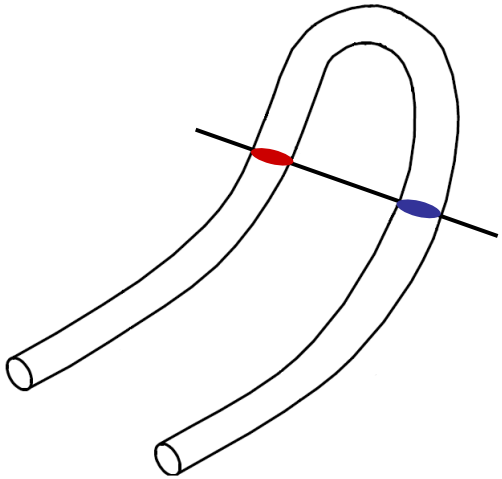


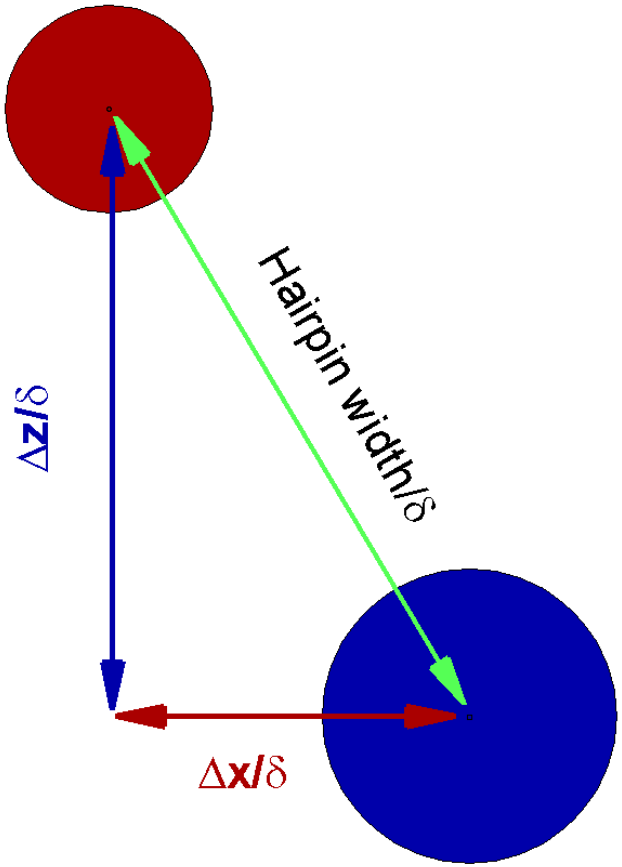
Av. swirl intensity of hairpin heads

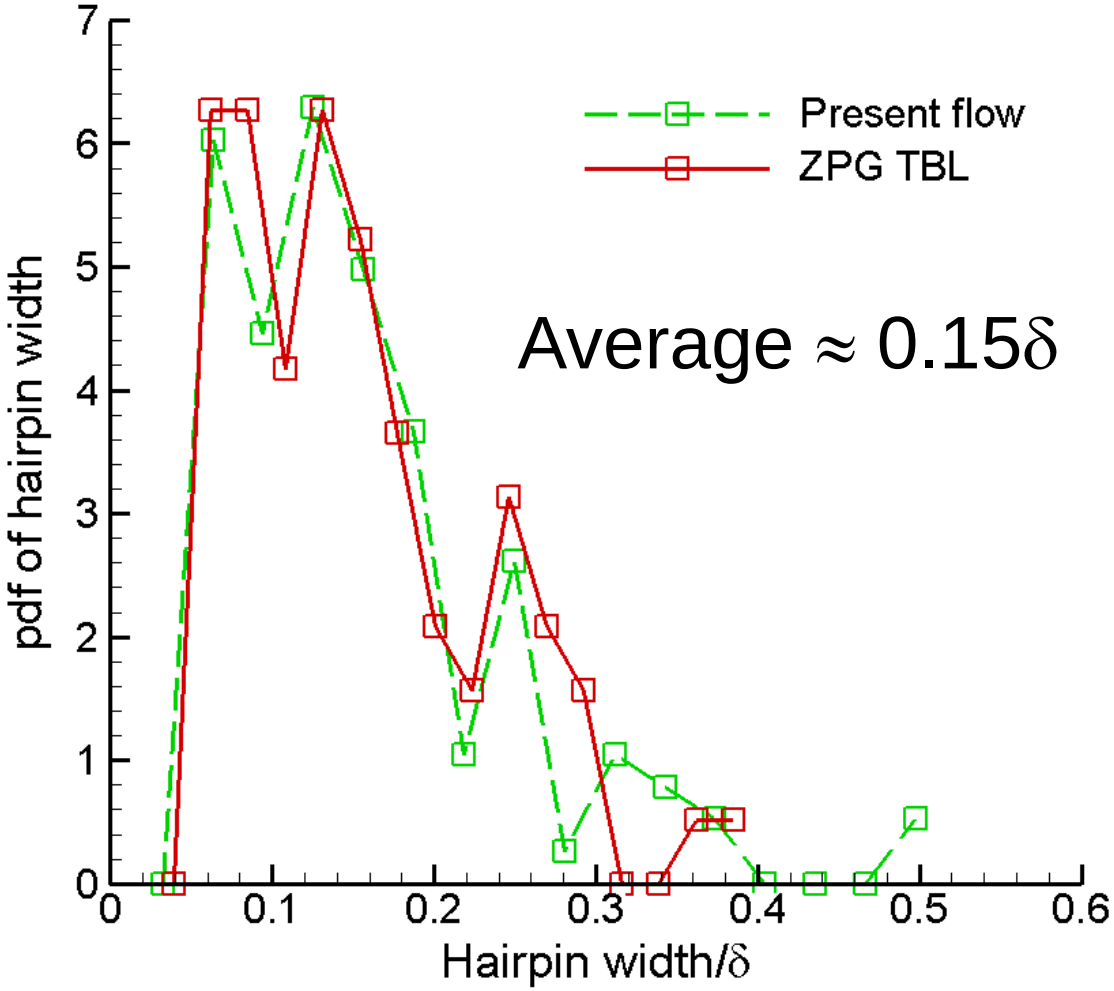


“Hairpin” width

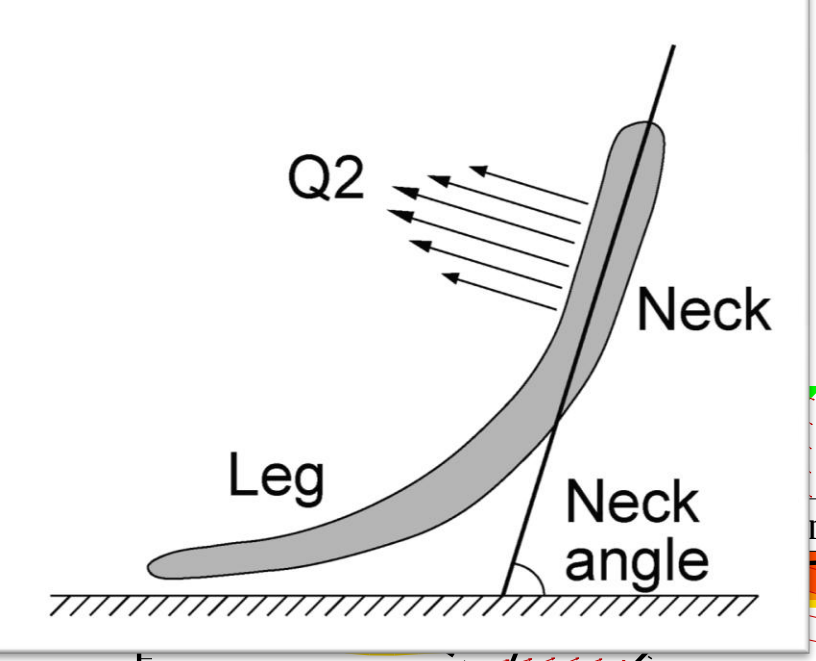
($y > 0.2\delta$)



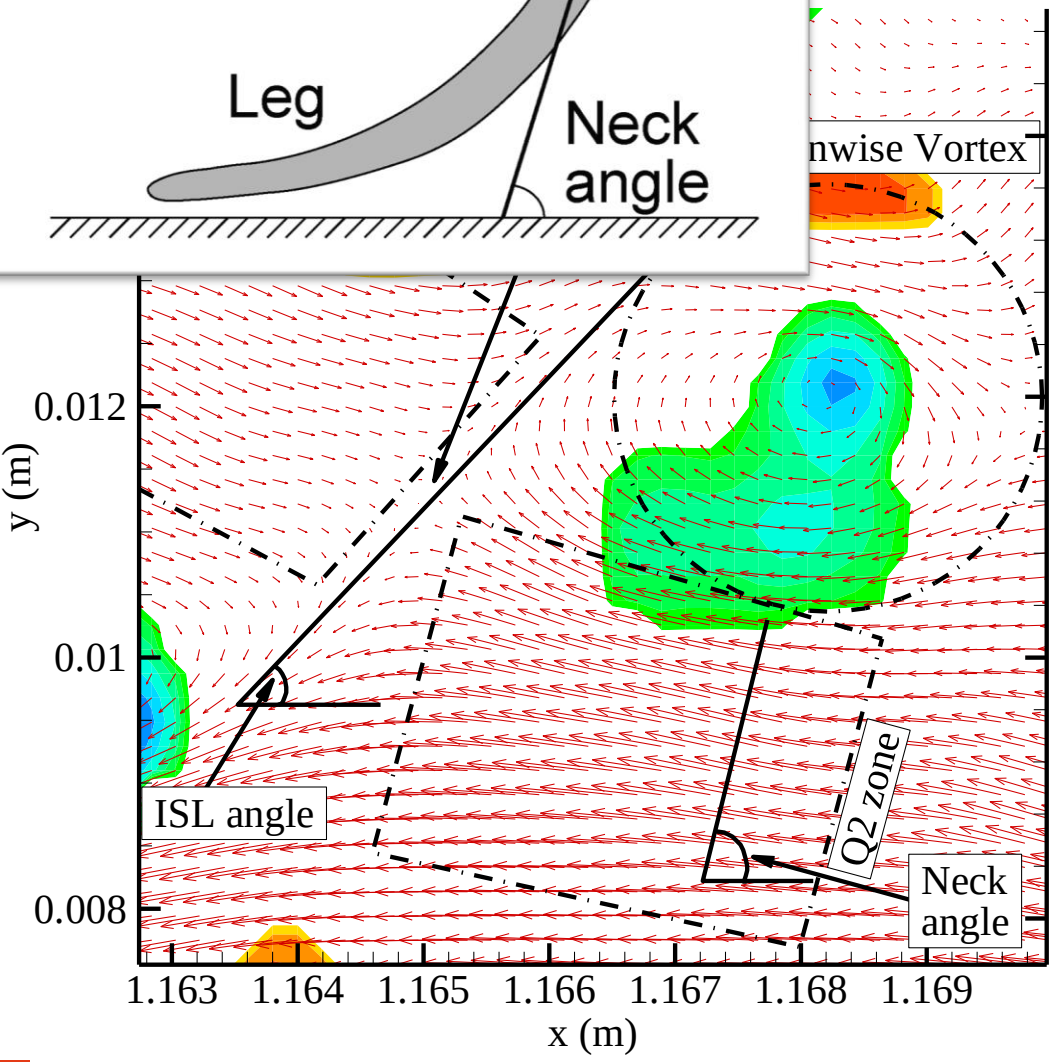


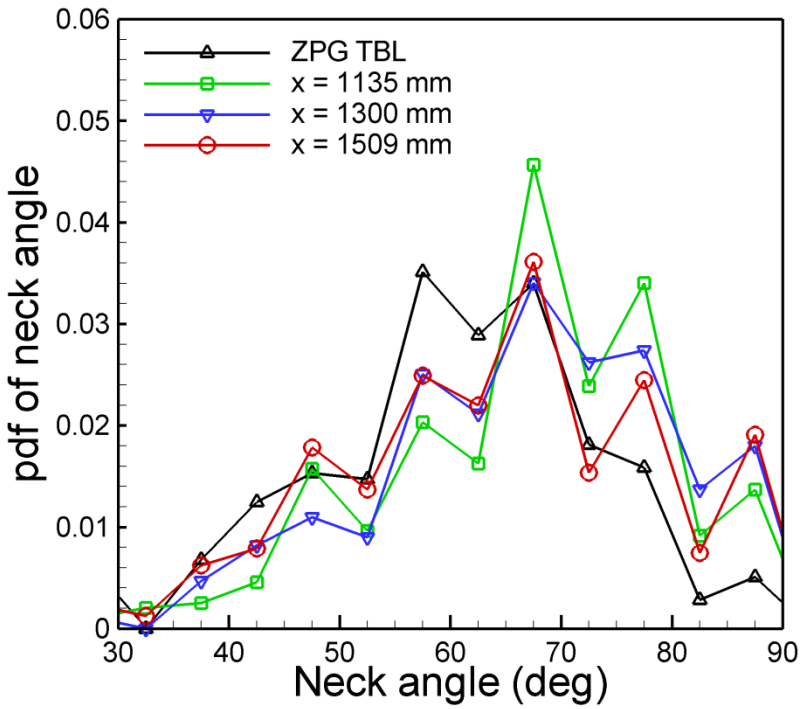


Upper neck inclination ($y > 0.2\delta$)



	Average upper neck angle
ZPG TBL data of Adrian et al.	**62° ± 2°**
APG TBL all positions	**67-70° ± 2°**



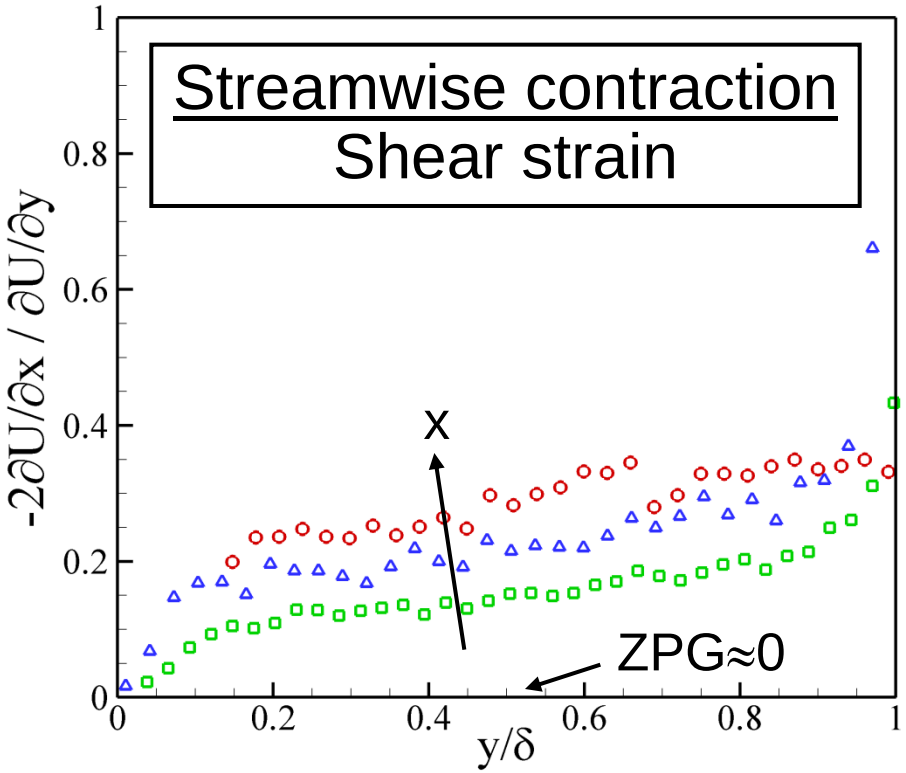


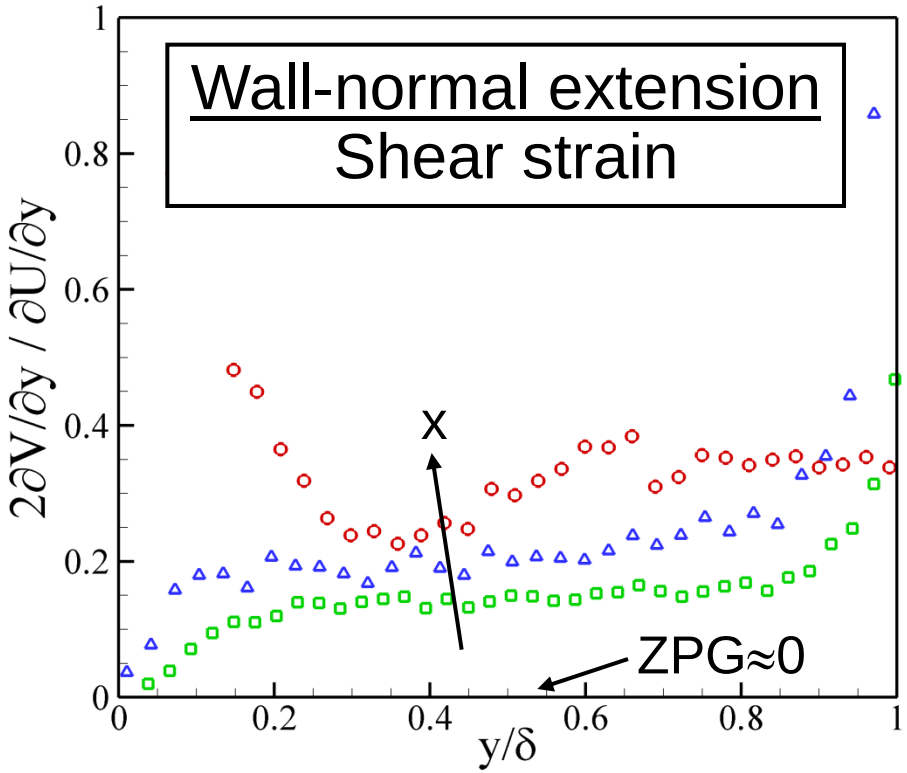
Mean strain rates

Vorticity equations

Simplified 2D inviscid analysis

$$\begin{cases} \dfrac{D\omega_x}{Dt} \approx \omega_x \dfrac{\partial U}{\partial x} + \omega_y \left(\dfrac{1}{2} \dfrac{\partial U}{\partial y} \right) \\ \dfrac{D\omega_y}{Dt} \approx \omega_x \left(\dfrac{1}{2} \dfrac{\partial U}{\partial y} \right) + \omega_y \dfrac{\partial V}{\partial y} \end{cases}$$



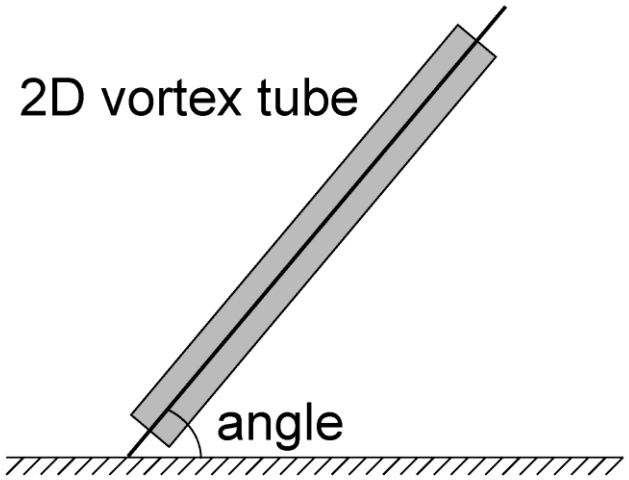


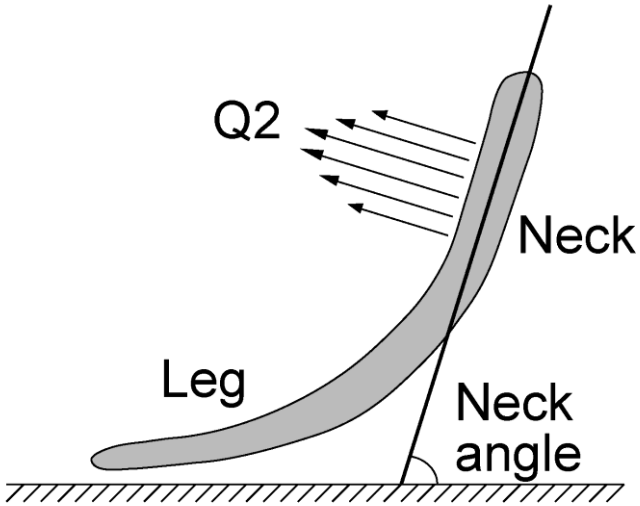
Simplified 2D inviscid analysis

	2D vortex tube angle
ZPG TBL	45°
APG TBL	50-53°

Measurements

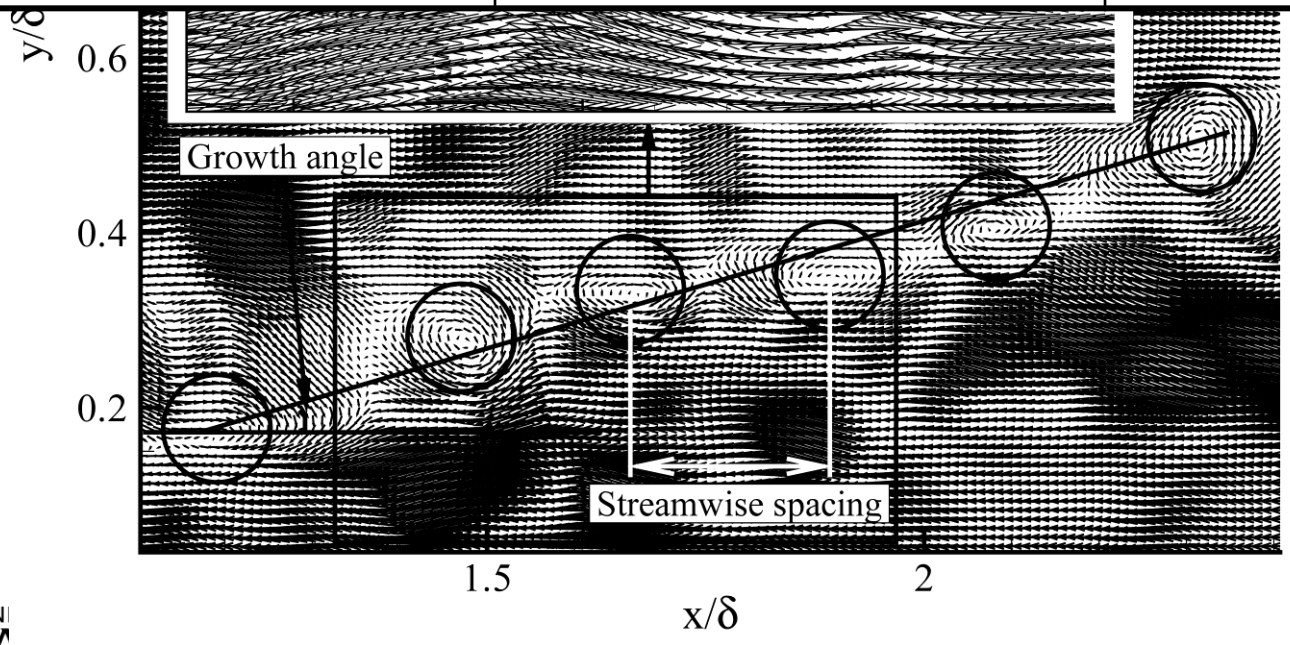
	Average upper neck angle
ZPG TBL data of Adrian et al.	62°
APG TBL all positions	67-70°





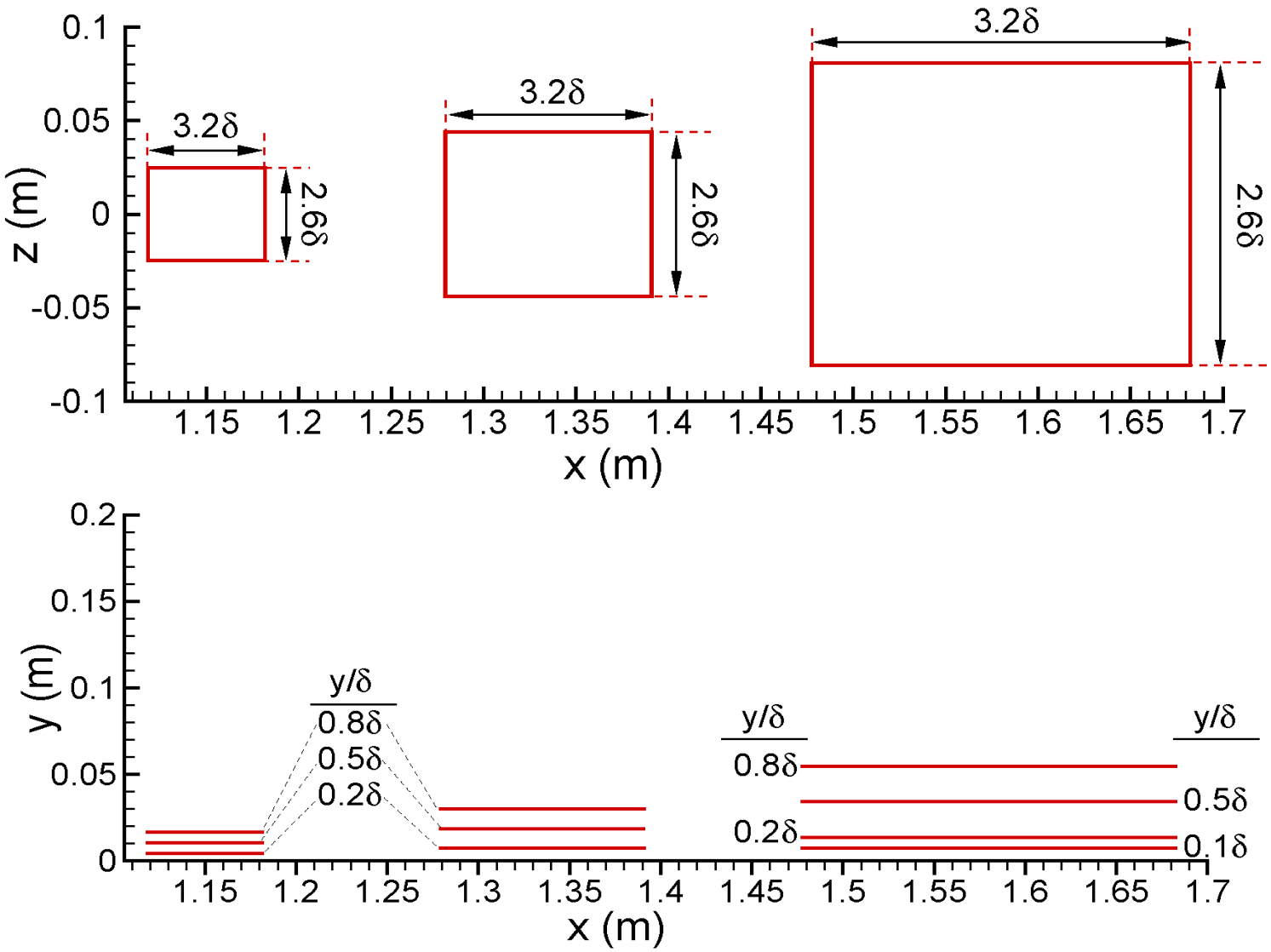
Hairpin packet parameters (y > 0.2δ)

x (mm)	Growth angle (°)	Xsep/δ
ZPG TBL	5 ± 2	0.204 ± 0.019
x = 1128-1185	12 ± 2	0.145 ± 0.013
x = 1285-1400	11 ± 2	0.150 ± 0.014
x = 1509-1705	11 ± 2	0.126 ± 0.010

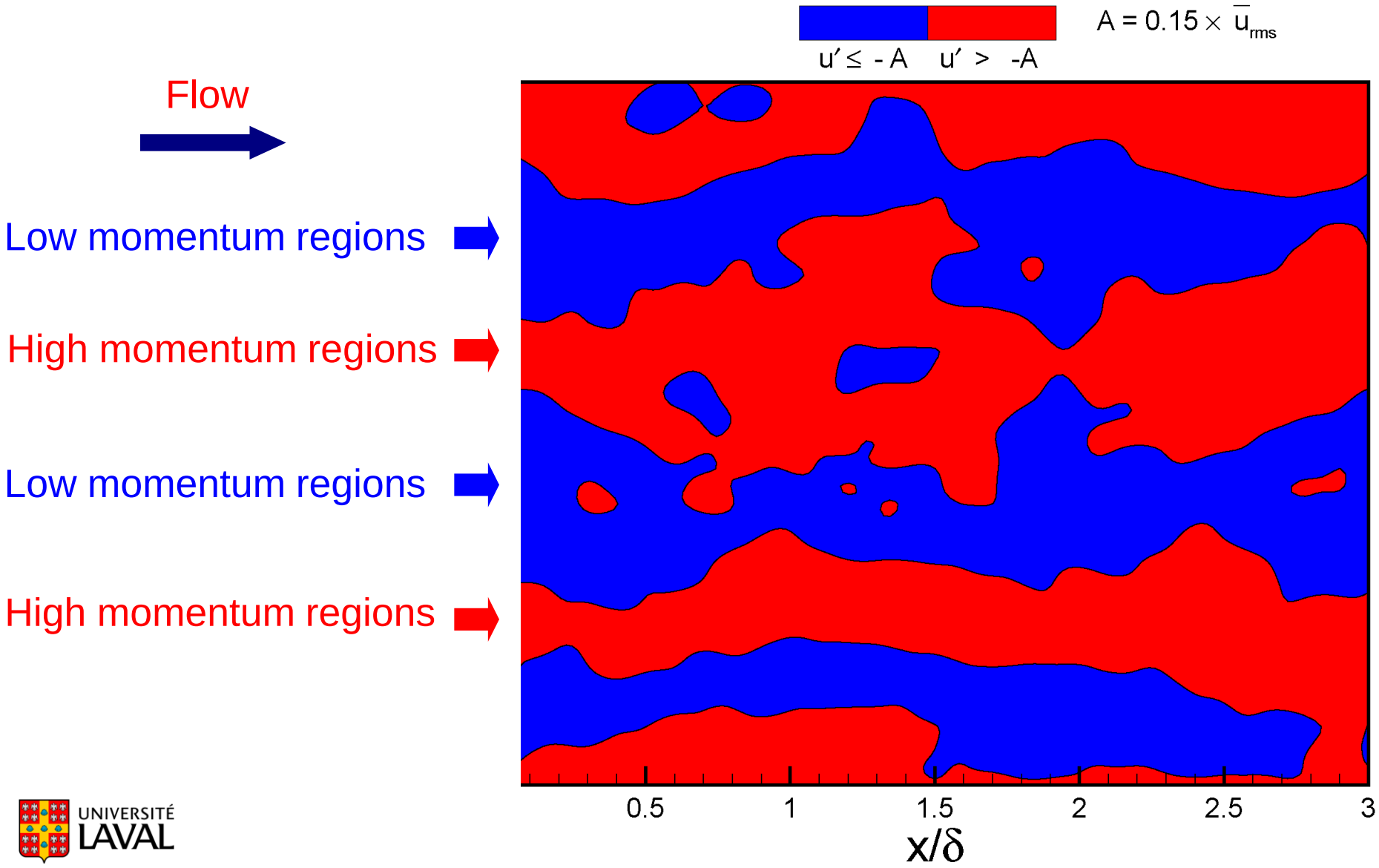


Does not vary with y!

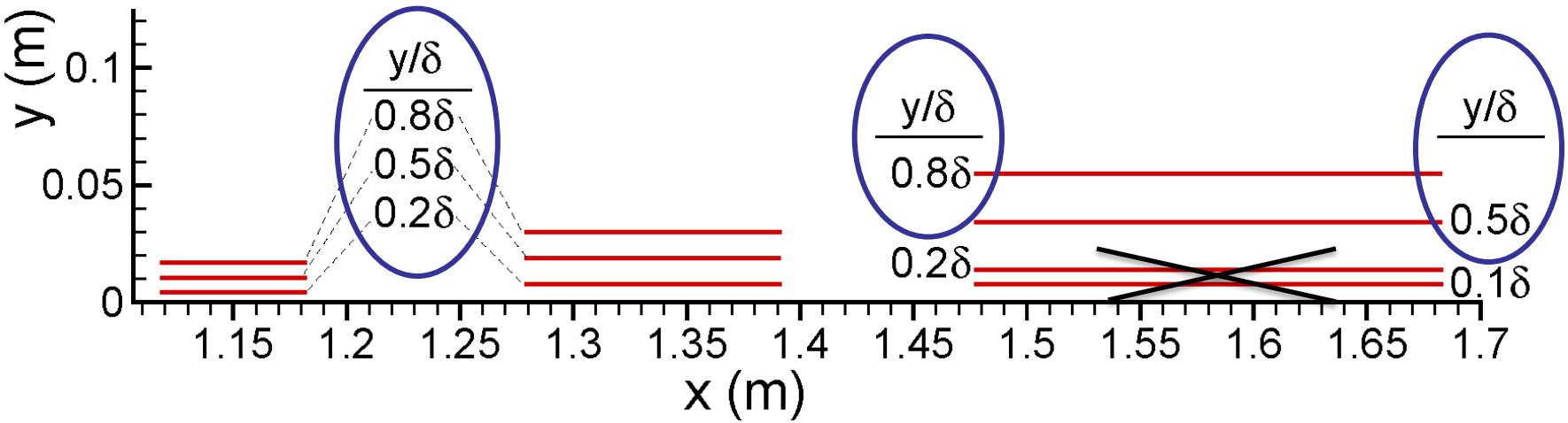
Large-scale motions – horizontal planes



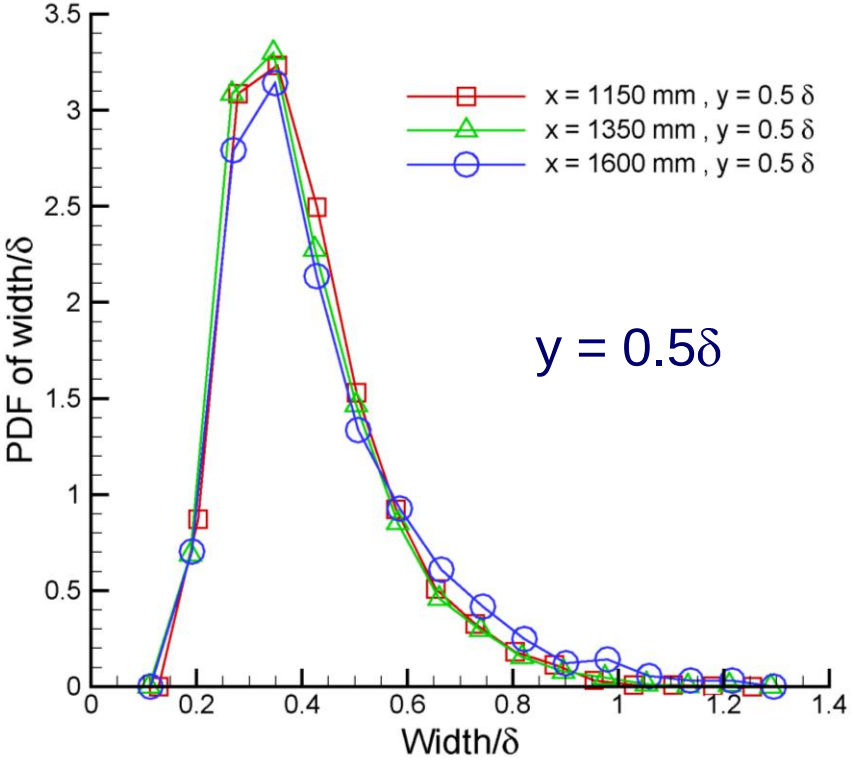
Low and high momentum regions

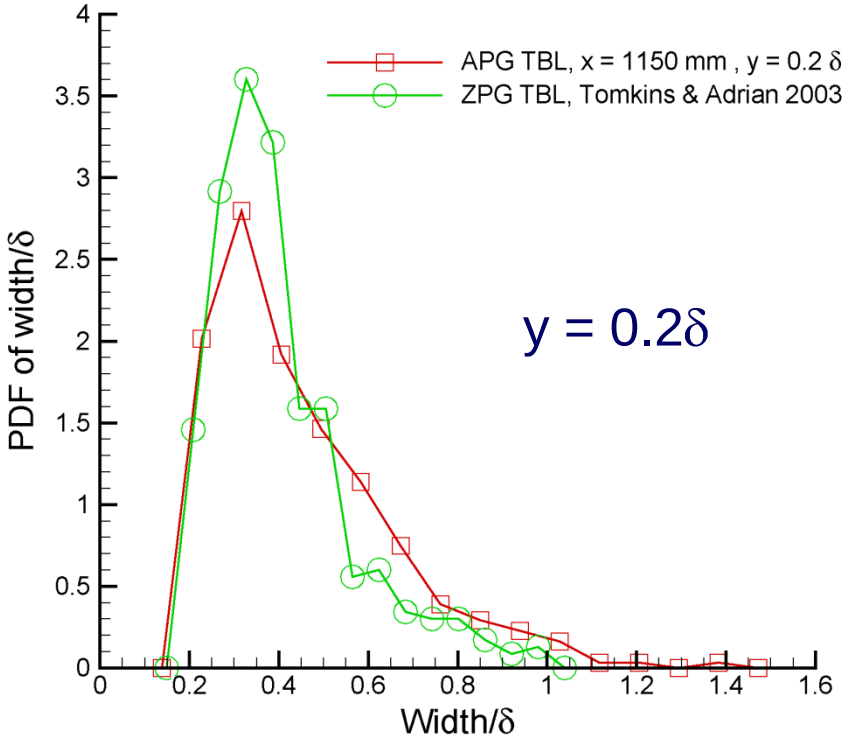


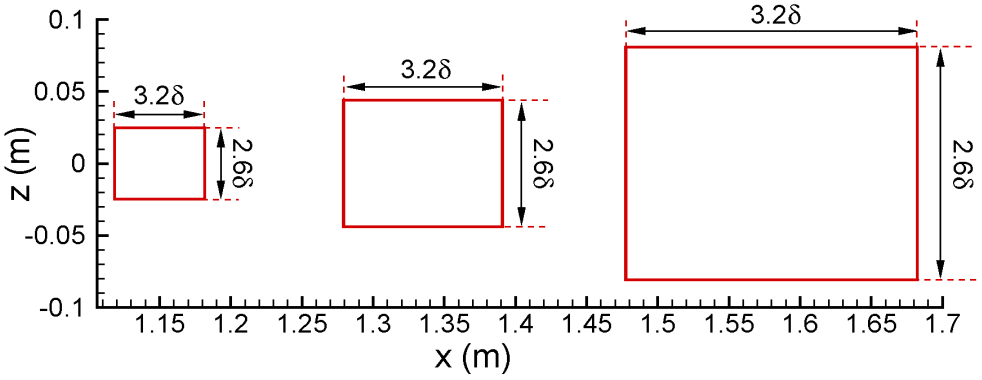
Excluding near-wall zone near separation



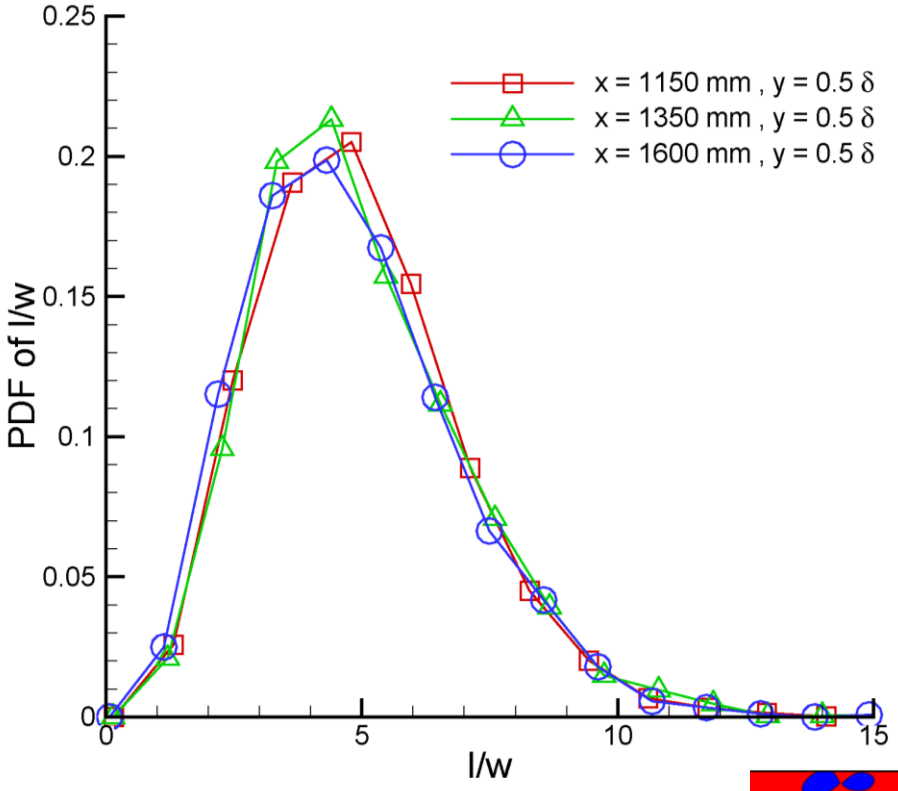
Width of low-momentum regions



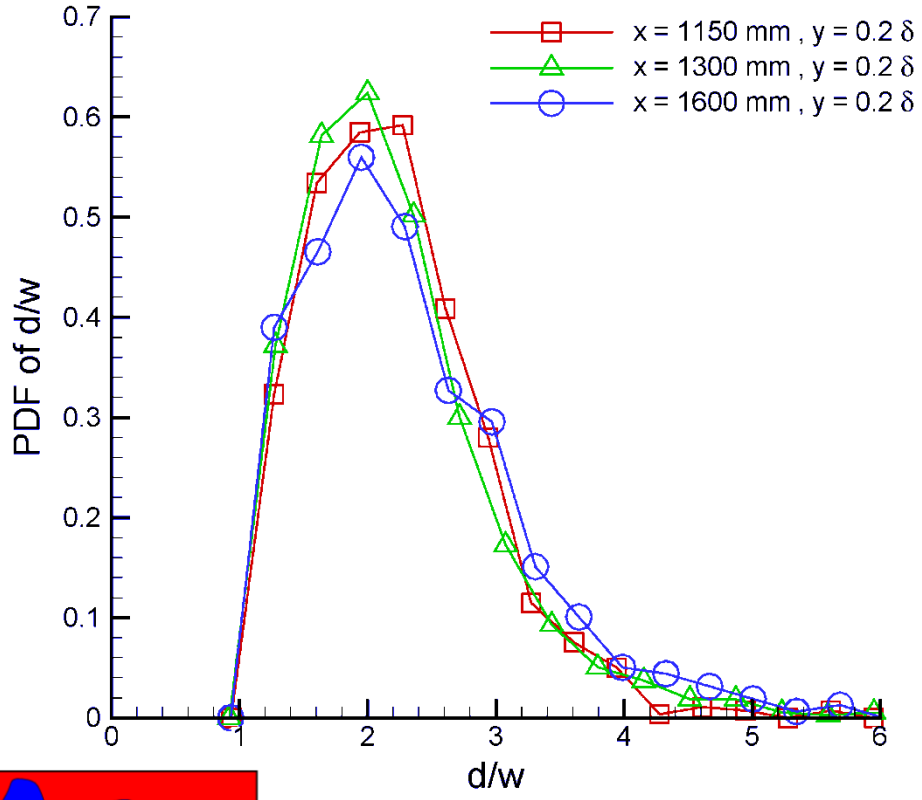


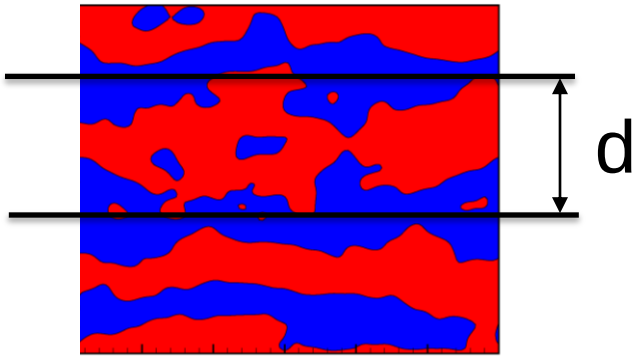


Aspect ratio: length/width (structures shorter than 3.2δ)



Spanwise distance/width





Main conclusions – outer region

Scaling with U_{zs} and δ for flow statistics **and** all large-scale structures

Many features of hairpin vortices, hairpin packets and low-momentum regions remain similar:

- between ZPG and APG TBL
- throughout APG flow (even if non-equilibrium)

But in APG TBL:

- less swirl intensity *with respect to mean shear*
- Hairpins and packets are more inclined
- Streamwise separation between hairpins smaller

The latter two differences are consistent with the variations of the mean strain rates.

No obvious link between hairpin characteristics and turbulence production