THTLAB Internal Report

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Database of Fully Developed Channel Flow

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Contents

1 Comments

1.1 Date of Release

June 11, 2002

1.2 Computors

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1.3 Nomenclature

δ = channel half width
k = turbulent kinetic energy, $u_i u_i/2$
k_x, k_z = streamwise and spanwise wave numbers
ν = kinematic viscosity
ω_y = vorticity component in the y-direction
p = pressure
$R(ab)$ = correlation coefficient between a and b
U_c = channel center mean velocity
U_m = bulk mean velocity
u, v, w = streamwise, wall-normal and spanwise velocity fluctuations
u_τ = friction velocity
u_i = i-th component of velocity fluctuation
$u^+, v^+, w^+ = u/u_\tau, v/u_\tau, w/u_\tau$
x, y, z = streamwise, wall-normal, spanwise directions
$y^+ = y \times u_\tau/\nu$

1.4 Description of Flow Field

The flow field simulated is a fully developed two-dimensional turbulent flow between two parallel walls. Hence, the flow is homogeneous both in the streamwise and spanwise directions and the statistics are dependent only upon the distance from the wall. The data presented here are non-dimensionalized by the wall variables, i.e., u_τ and ν. The flow condition is defined by the pressure gradient imposed (or the friction velocity) and the distance between the walls (channel height).

1.5 Flow conditions

Case	$Re_\tau = \delta \cdot u_\tau/\nu$	$Re_m = 2\delta \cdot U_m/\nu$
1	109.429	3220.38
2	150.479	4586.21
3	297.899	10039.1
4	395.760	13924.9
5	642.540	24272.2

1.6 Numerical Method

Governing equations: a forth-order equation for v, a second-order equation for ω_y derived from the incompressible Navier-Stokes equations, and the continuity equation.

Discretization method: spectral method = $N_1 \times N_2$ Fourier series in the x- and z-directions, and Chebyshev polynomials up to the order N_3 in the y- direction (Chebyshev-tau method).

Re_τ	N_1	N_2	N_3
110	96	65	96
150	128	97	128
300	128	193	128
400	192	257	192
650	288	257	384

Aliasing treatment: nonlinear terms computed with collocation grids 1.5 times finer in the x- and z-directions, and 2 times finer in the y-direction.

Grid spacing: Δx and Δz viscous units in the x- and z- directions and $\Delta y_{min} \sim \Delta y_{max}$ in the y-direction.

Re_τ	Δx^+	Δy^+_{min}	Δy^+_{max}	Δz^+
110	18.0	0.13	5.4	7.20
150	18.4	0.08	4.91	7.36
300	18.4	0.04	4.91	7.36
400	16.4	0.03	4.91	6.54
650	17.7	0.049	7.98	5.32

Time integration: A forth-order Runge-Kutta scheme for the nonlinear terms and a second-order Crank-Nicolson scheme for the viscous terms.

Size of computational box: $B_x\pi\delta \times 2\delta \times B_z\pi\delta$.

Re_τ	B_x	B_z
110	5	2
150	5	2
300	2.5	1
400	2.5	1
650	2.5	1

Initial conditions: u, v and u_{mean} given in accordance with the previous numerical results.

Criterion for stationary state: linear profile of total stress and stationary behavior of mean velocity and second-order moments of the three velocity components at some distance from the wall.

Length of time integration for ensemble averaging: about $T_1\delta/u_\tau$ ($T_2\nu/u_\tau^2$) after the fully developed state is reached.

Re_τ	T_1	T_2
110	2559	279991
150	2061	310130
300	277	82384
400	129	47364
650	40	25947

Error in continuity equation = $Max \mid div(\rho \cdot v) \mid$: not applicable

Courant number = $Max(\Delta t \mid u_i/\Delta x_i \mid) :< 1.0$

Computer: HITACHI SR8000/128 (C_1 nodes (= C_2 cpus)) at the Computer Center of the University of Tokyo.

Re_τ	C_1	C_2
110	1	8
150	4	32
300	2	16
400	4	32
650	8	64

Computation time: about S_1 sec actual computational time per one time step (= four sub-time steps).

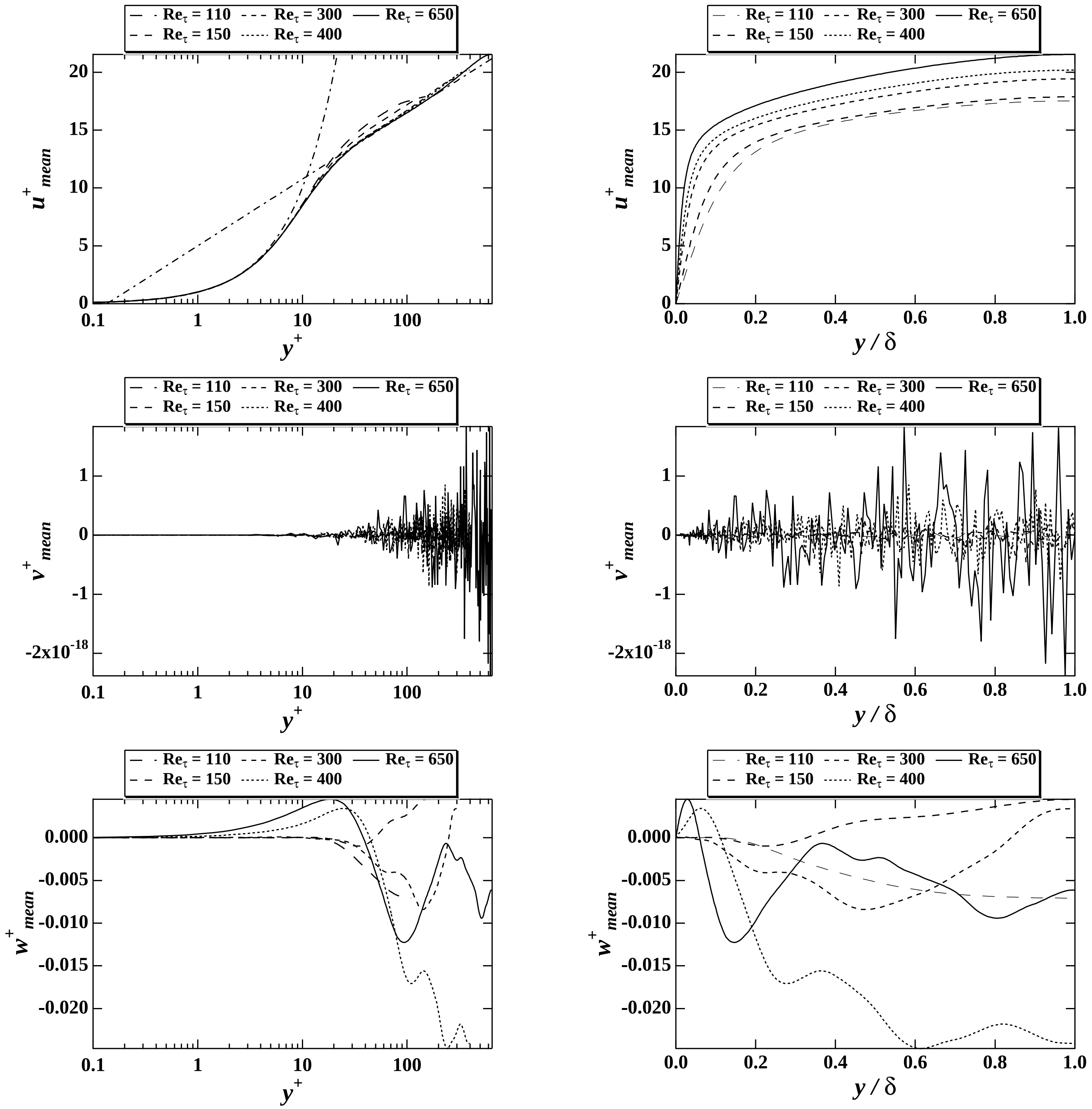
Re_τ	S_1
110	2.99
150	2.82
300	8.44
400	15.0
650	15.9

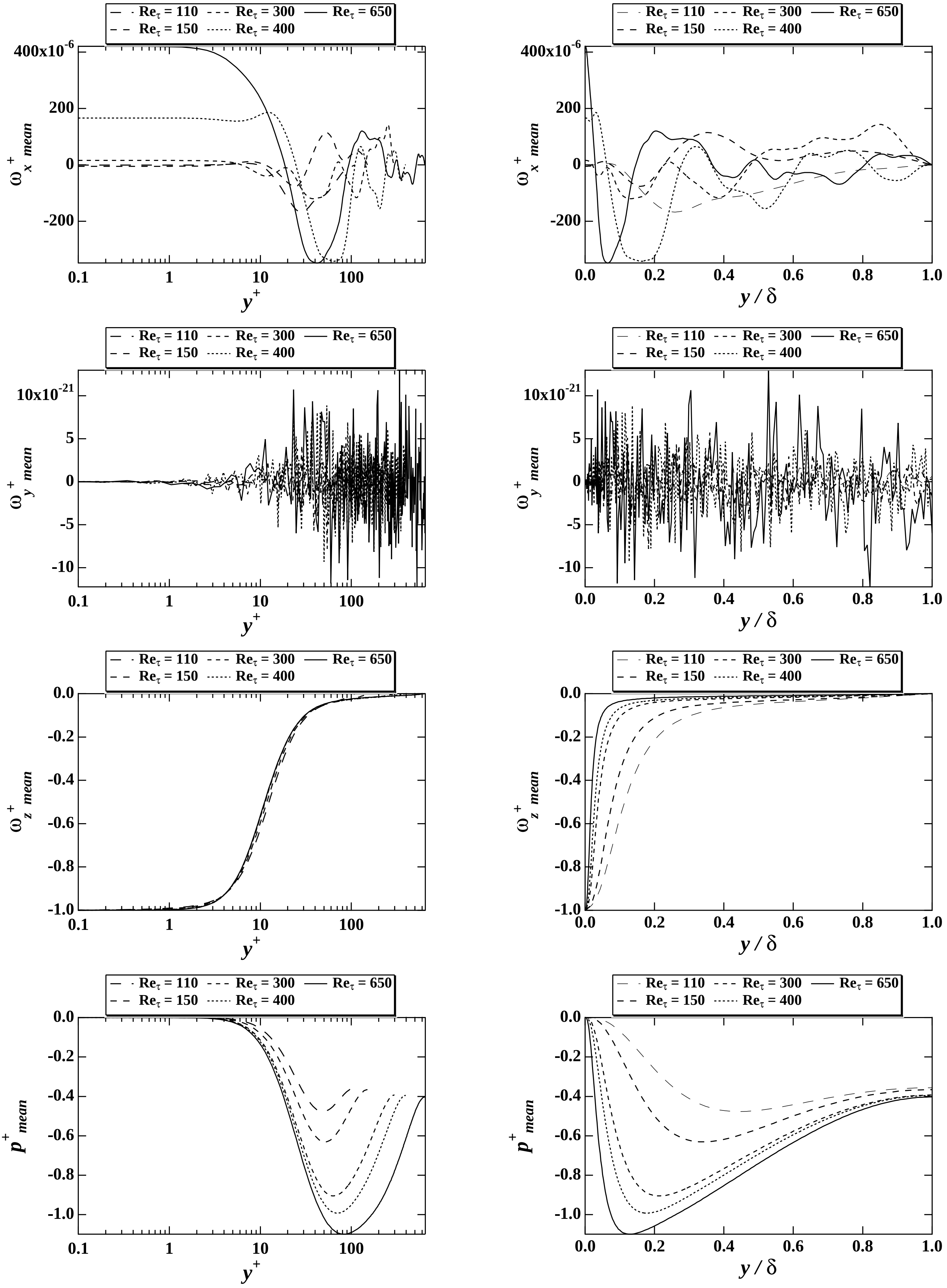
References

[1] Iwamoto, K., Suzuki, Y., and Kasagi, N., 2002. "Reynolds Number Effect on Wall Turbulence: Toward Effective Feedback Control," Int. J. Heat and Fluid Flow, Vol. 23, pp. 678-689.

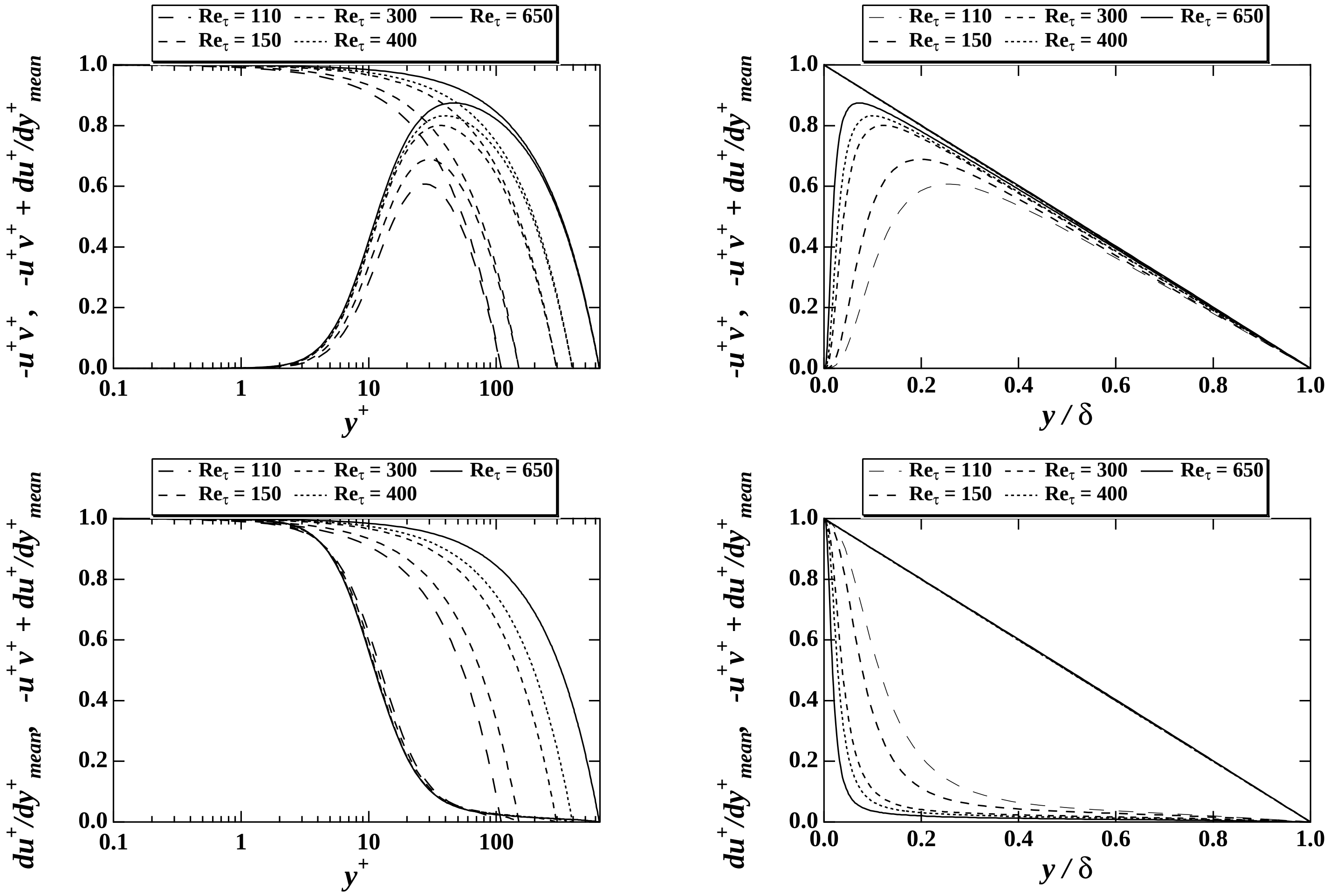
2 Turbulence statistics

2.1 Mean

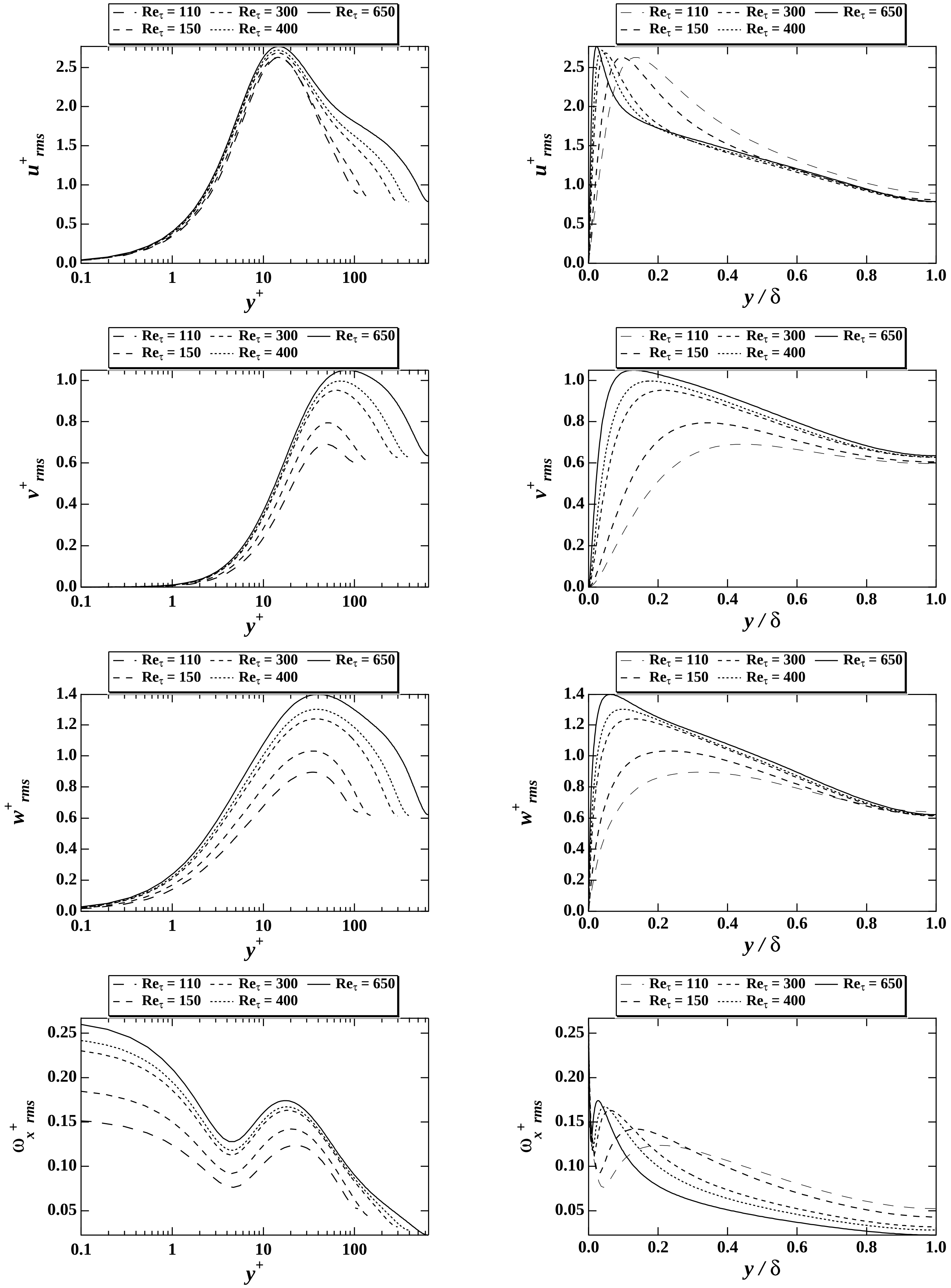




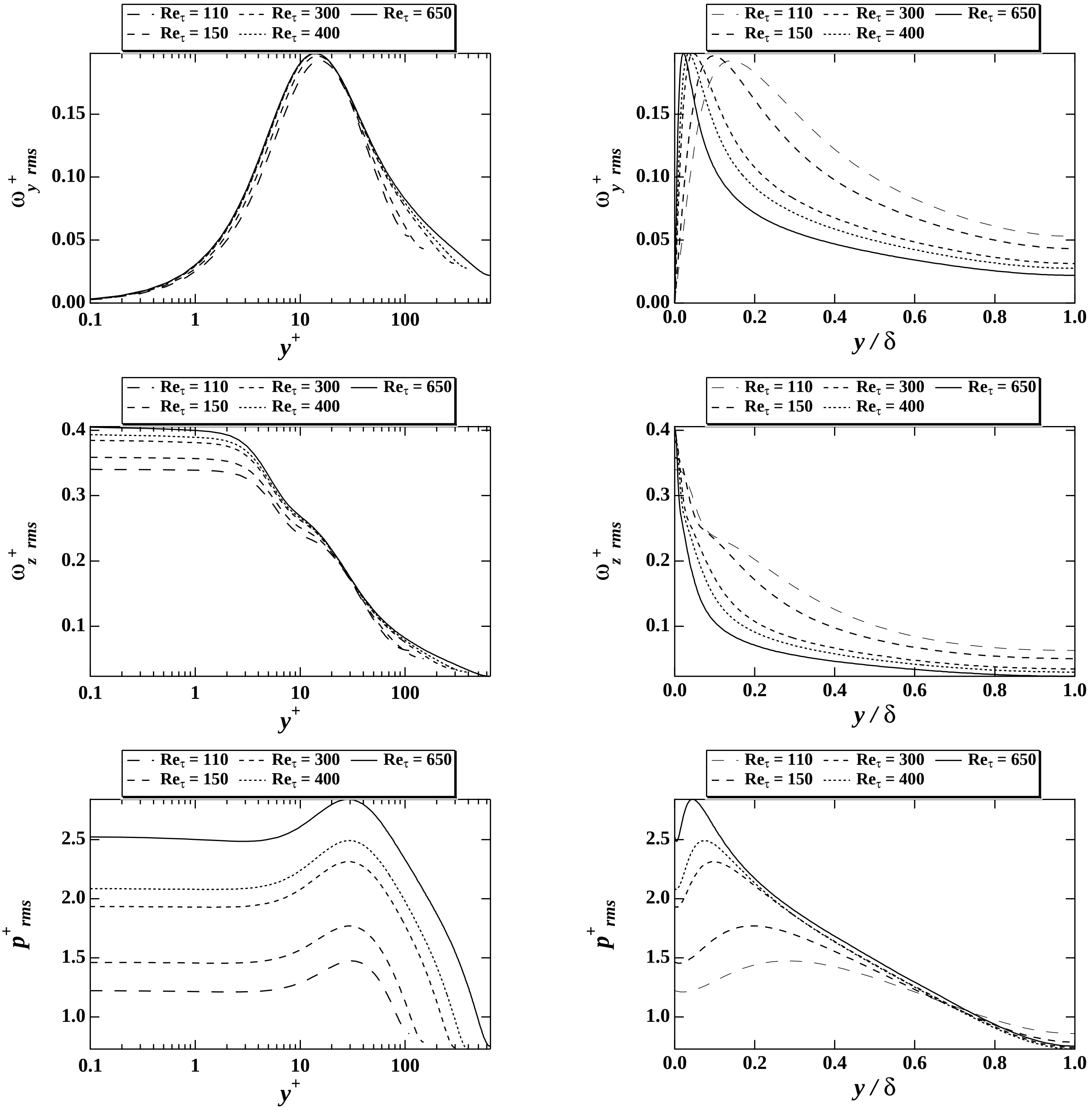
Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
ω+x mean
y+
y / δ
ω+y mean
ω+z mean
p+mean


Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
-u⁺v⁺, -u⁺v⁺ + du⁺/dy⁺_mean
du⁺/dy⁺_mean, -u⁺v⁺ + du⁺/dy⁺_mean
y⁺
y / δ
0.0
0.2
0.4
0.6
0.8
1.0
0.1
1
10
100

2.2 Rms

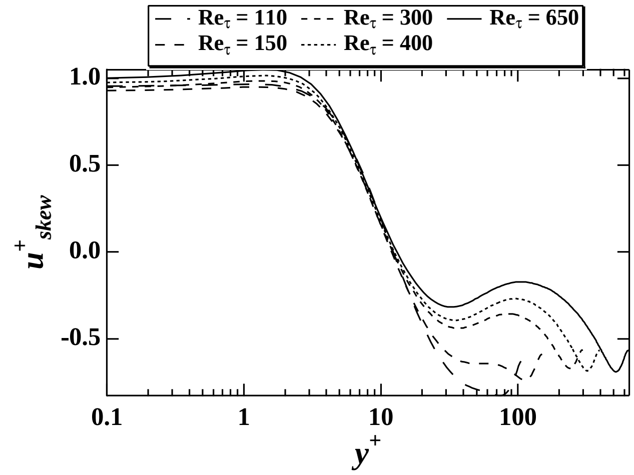


Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
u^+_{rms}
v^+_{rms}
w^+_{rms}
$\omega^+_{x\ rms}$
y^+
y/δ

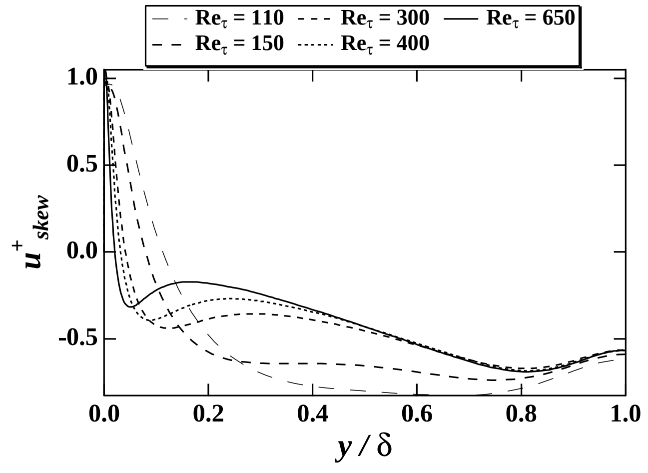


$Re_\tau = 110$
$Re_\tau = 150$
$Re_\tau = 300$
$Re_\tau = 400$
$Re_\tau = 650$
$\omega^+_{y\ rms}$
$\omega^+_{z\ rms}$
p^+_{rms}
y^+
y/δ

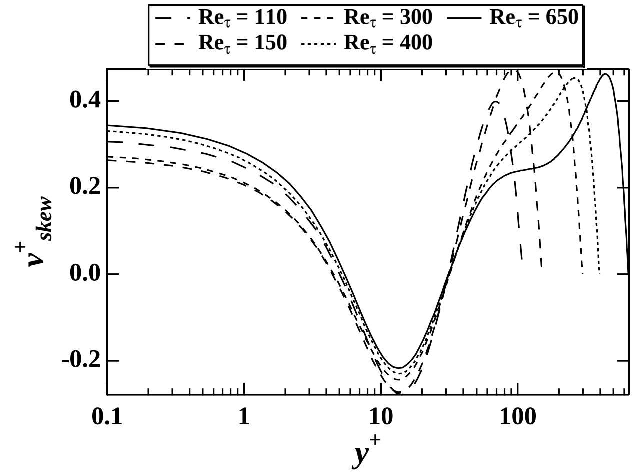
2.3 Skew



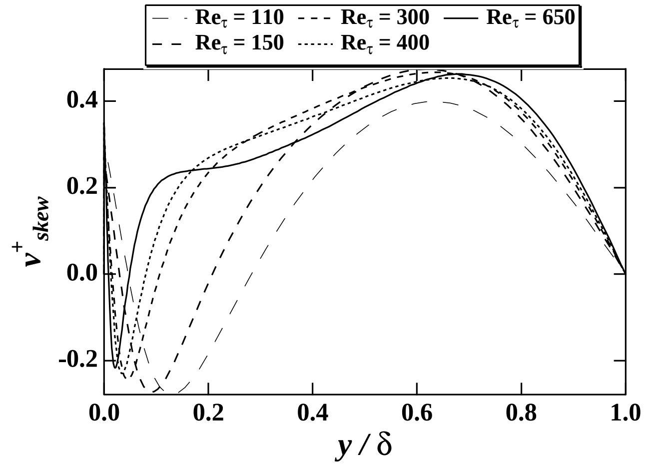
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
u^+_{skew}
y^+



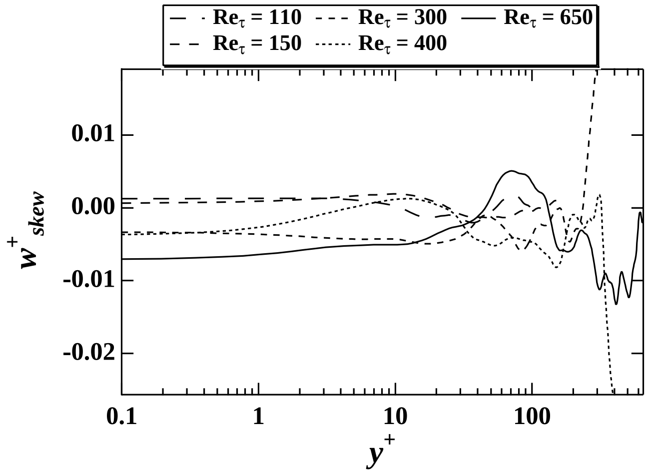
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
u^+_{skew}
$y\,/\,\delta$



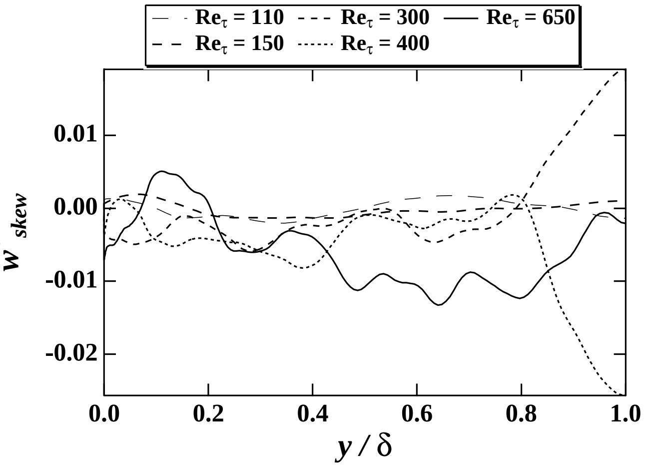
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
v^+_{skew}
y^+



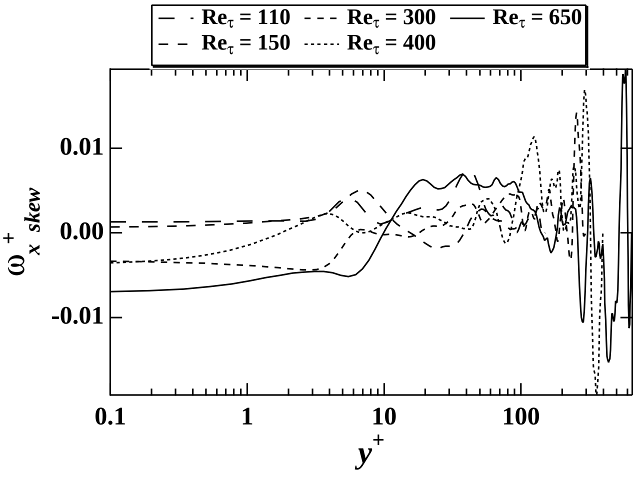
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
v^+_{skew}
$y\,/\,\delta$



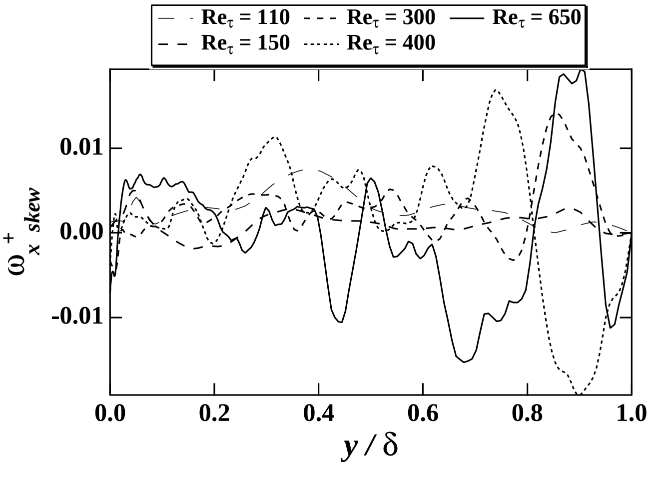
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
w^+_{skew}
y^+



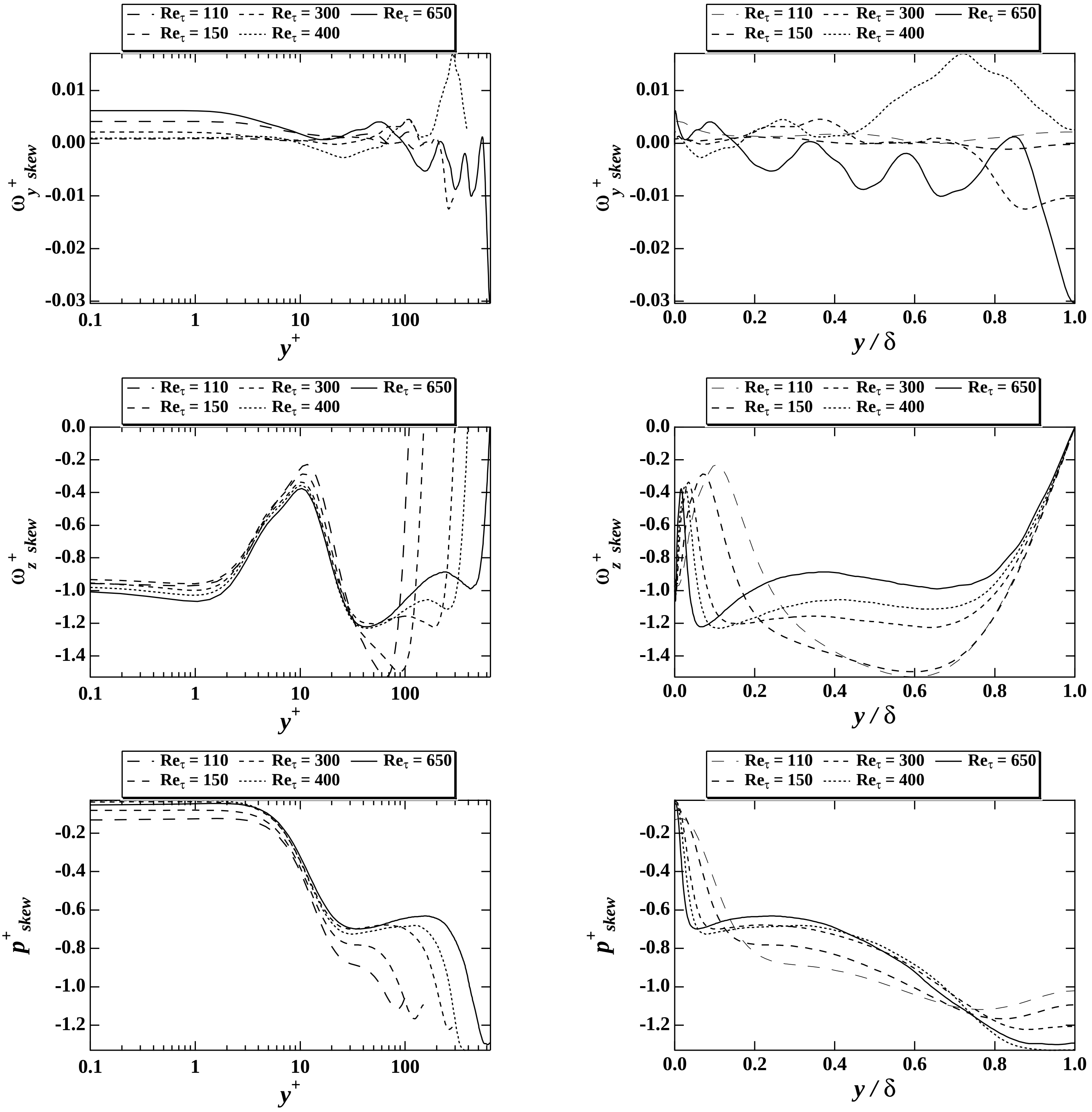
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
w^+_{skew}
$y\,/\,\delta$



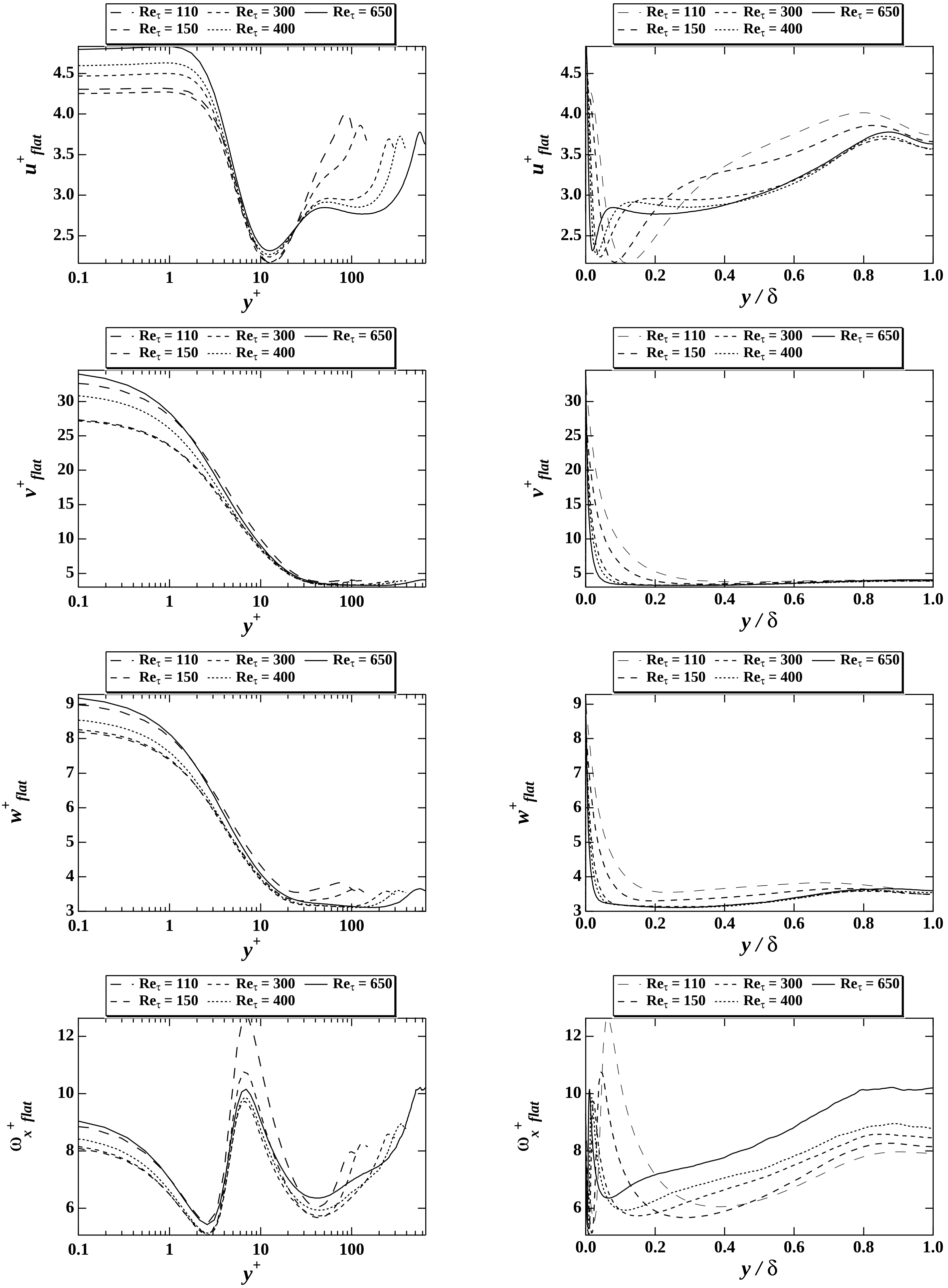
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
$\omega^+_{x\ skew}$
y^+



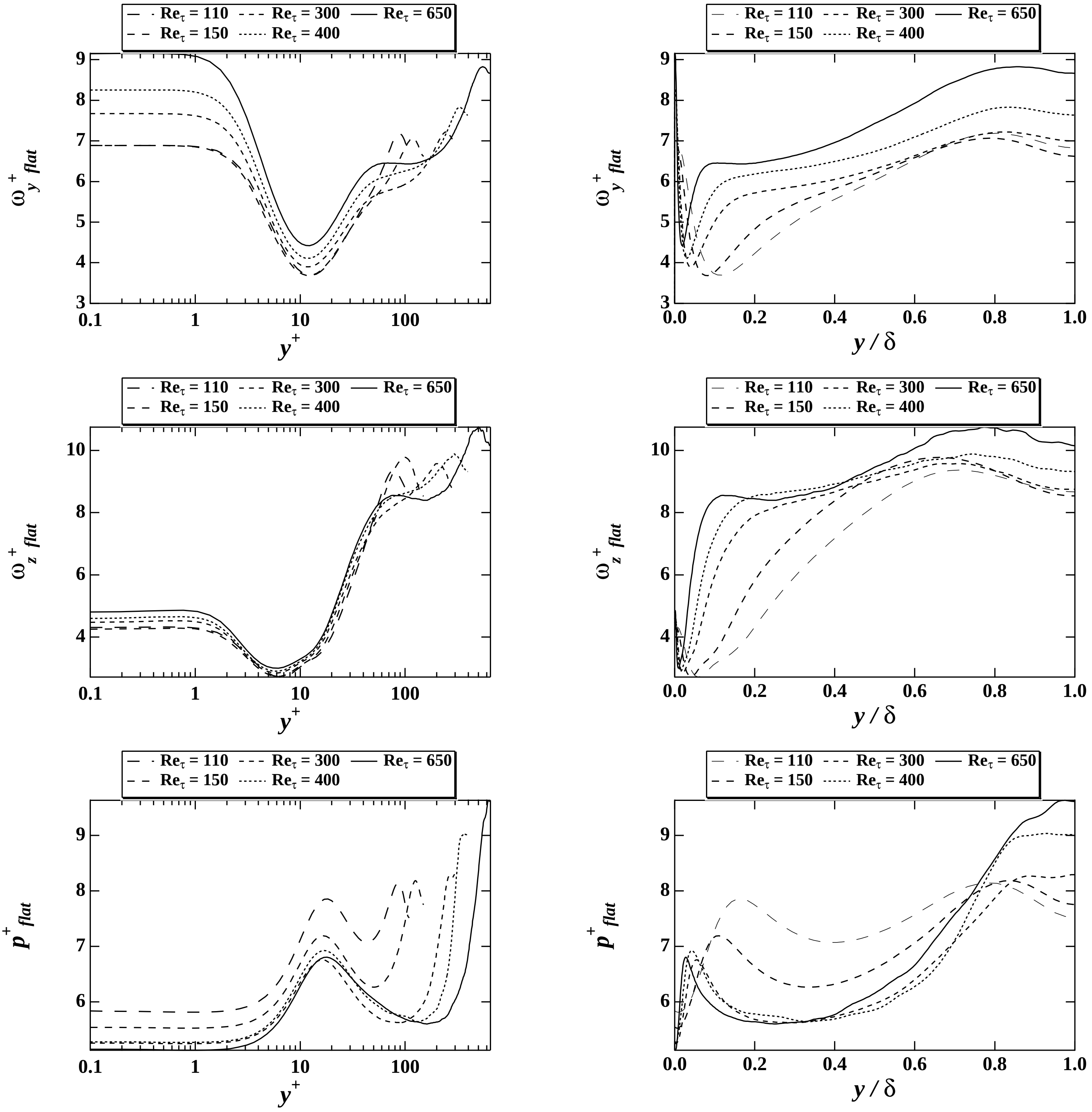
Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
$\omega^+_{x\ skew}$
$y\,/\,\delta$


Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$\omega^+_{y\ skew}$
$\omega^+_{z\ skew}$
p^+_{skew}
y^+
$y\,/\,\delta$
0.01
0.00
-0.01
-0.02
-0.03
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
0.1
1
10
100
0.2
0.4
0.6
0.8
1.0

2.4 Flat



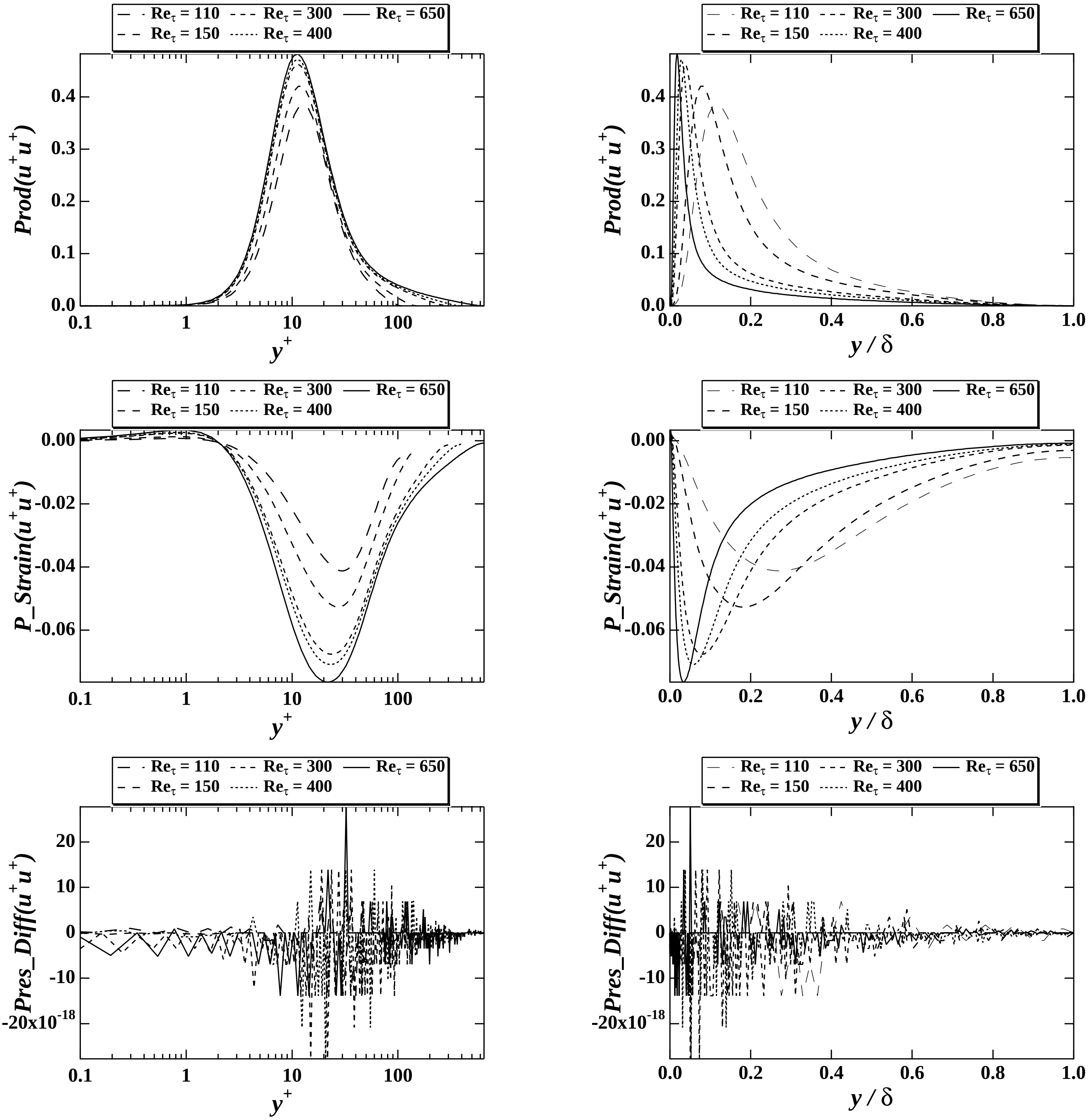
Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
u^+_{flat}
v^+_{flat}
w^+_{flat}
$\omega_x^+{}_{flat}$
y^+
y / δ
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8
1.0

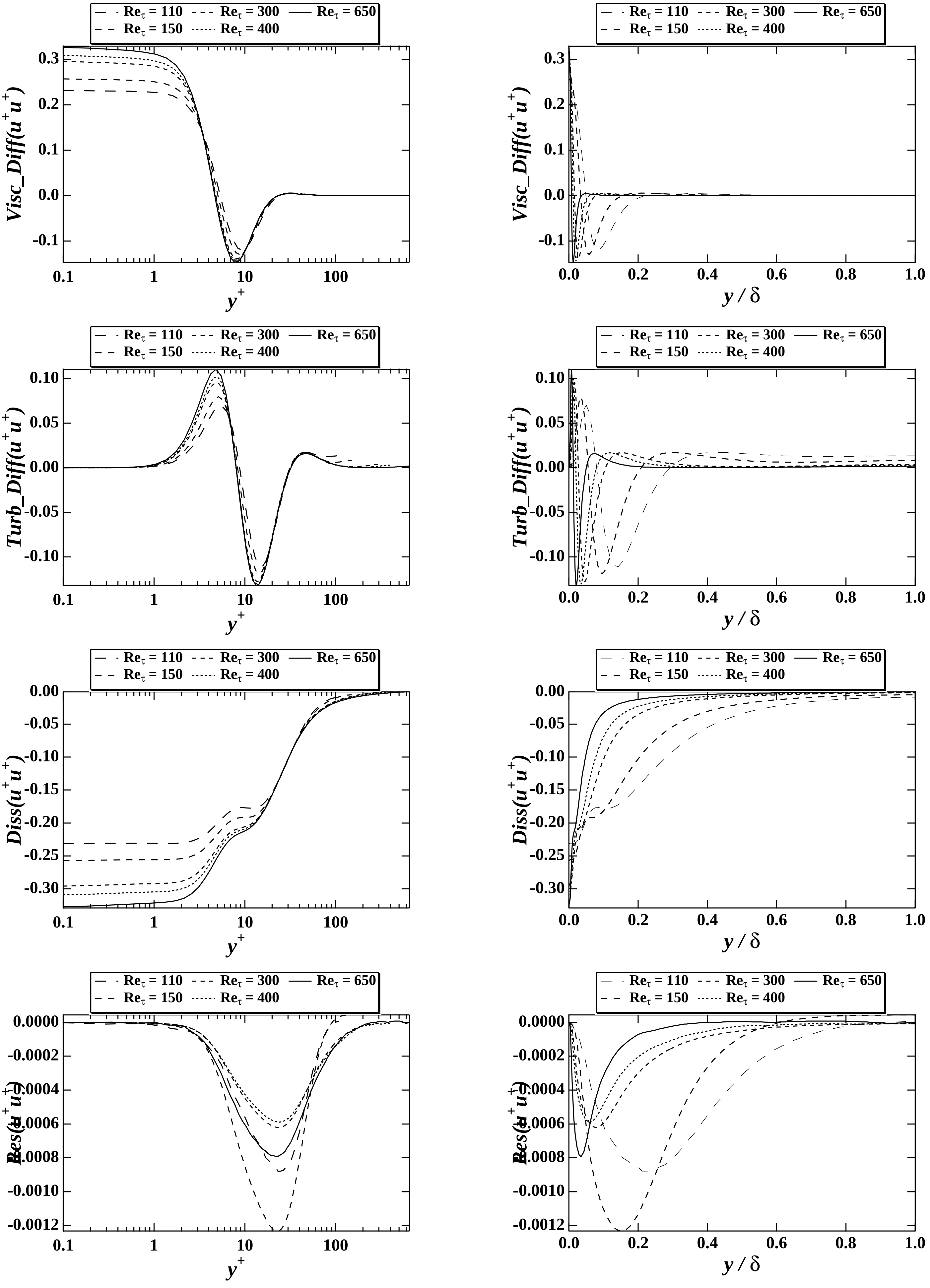


Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
ω+y flat
y+
y / δ
ω+z flat
p+flat

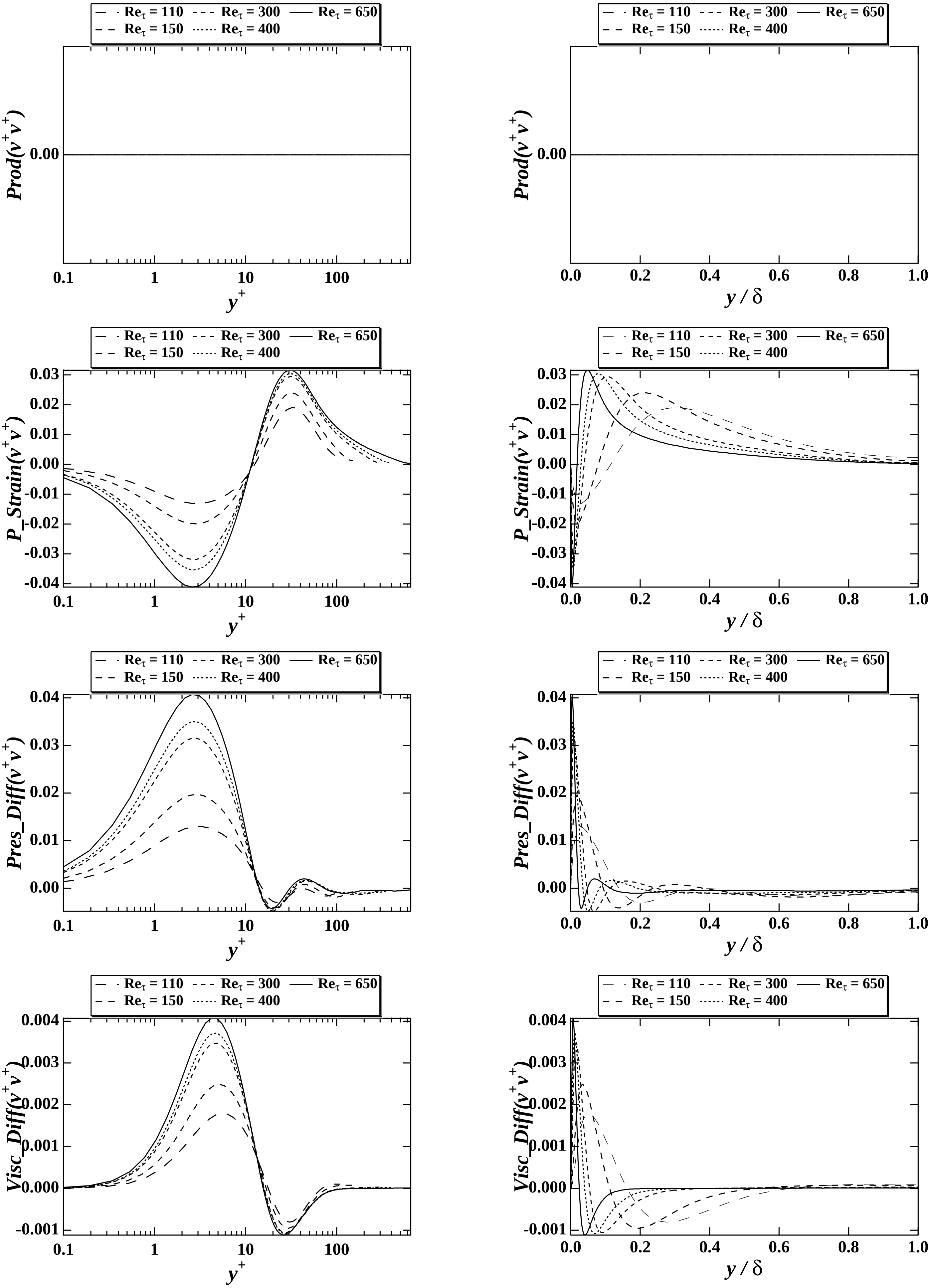
3 Budgets of Reynolds Stresses and Turbulence Energy

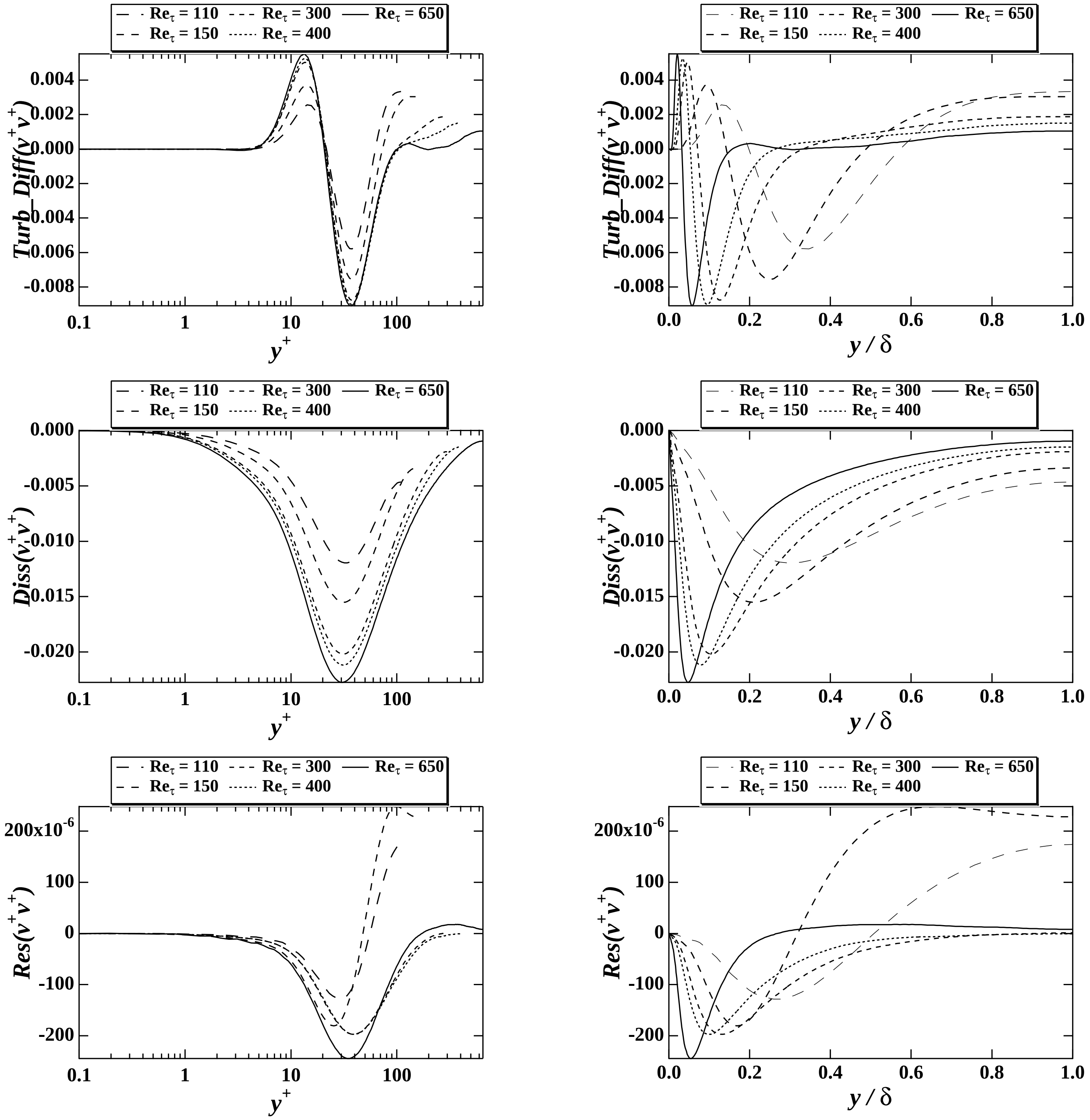
3.1 Budget for uu



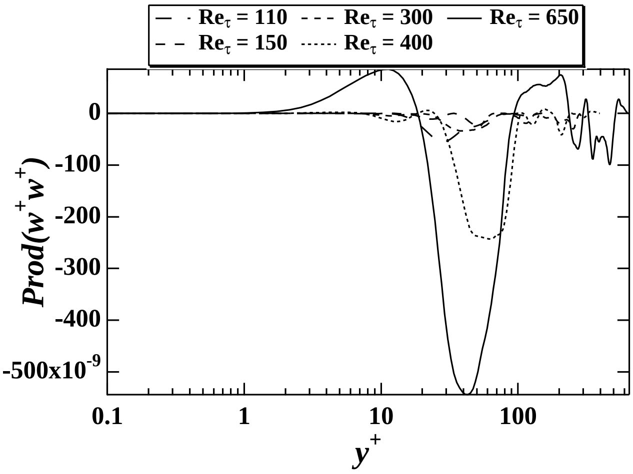

Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
Visc_Diff(u+u+)
Turb_Diff(u+u+)
Diss(u+u+)
Res(u+u+)
y+
y / δ

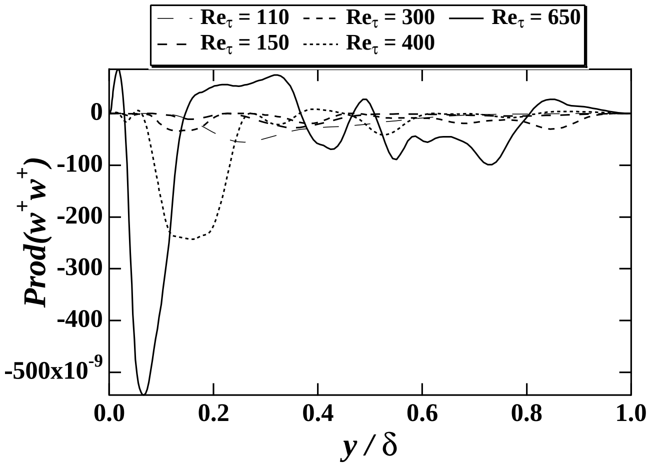
3.2 Budget for vv

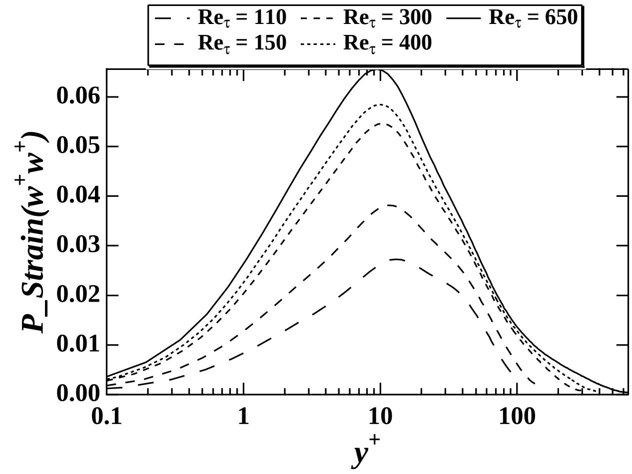


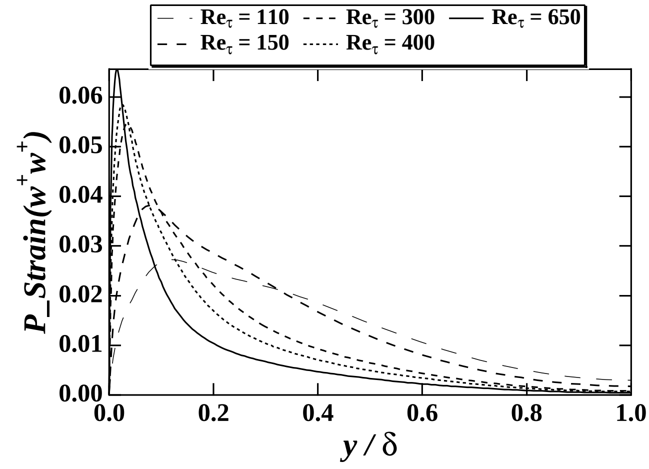

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
Turb_Diff(v^+v^+)
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
0.1
1
10
100
y^+
0.0
0.2
0.4
0.6
0.8
1.0
y/δ
Diss(v^+v^+)
0.000
-0.005
-0.010
-0.015
-0.020
Res(v^+v^+)
200x10^{-6}
100
0
-100
-200

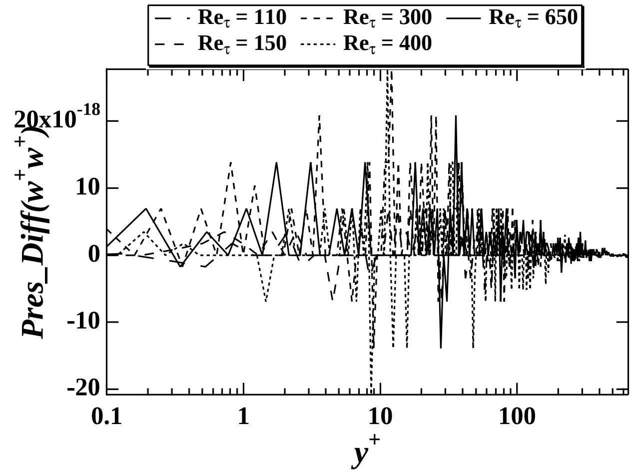
3.3 Budget for ww

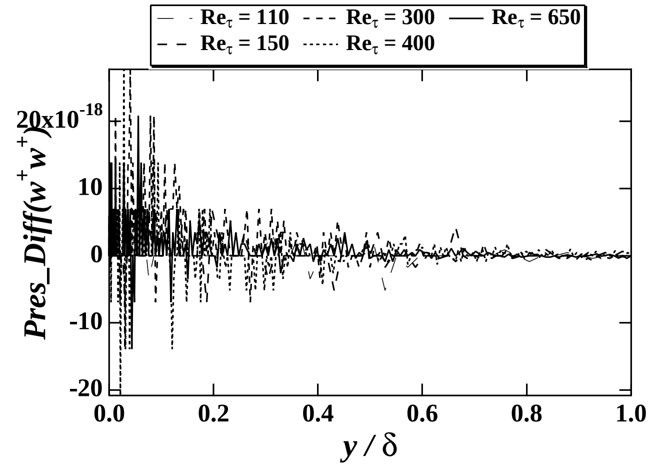


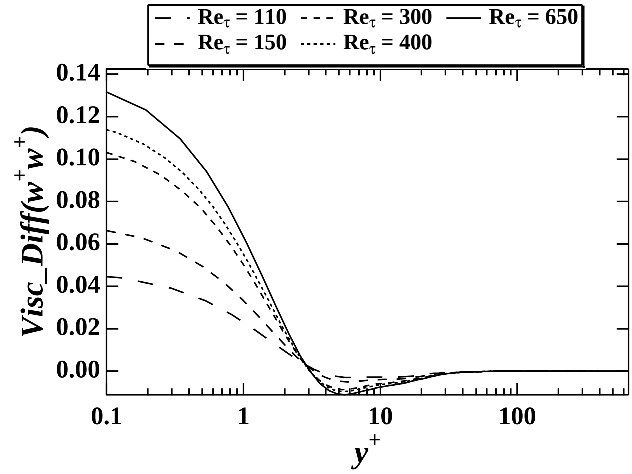


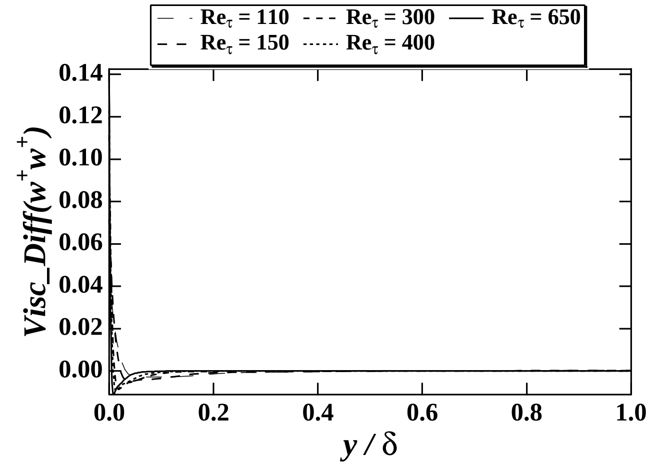


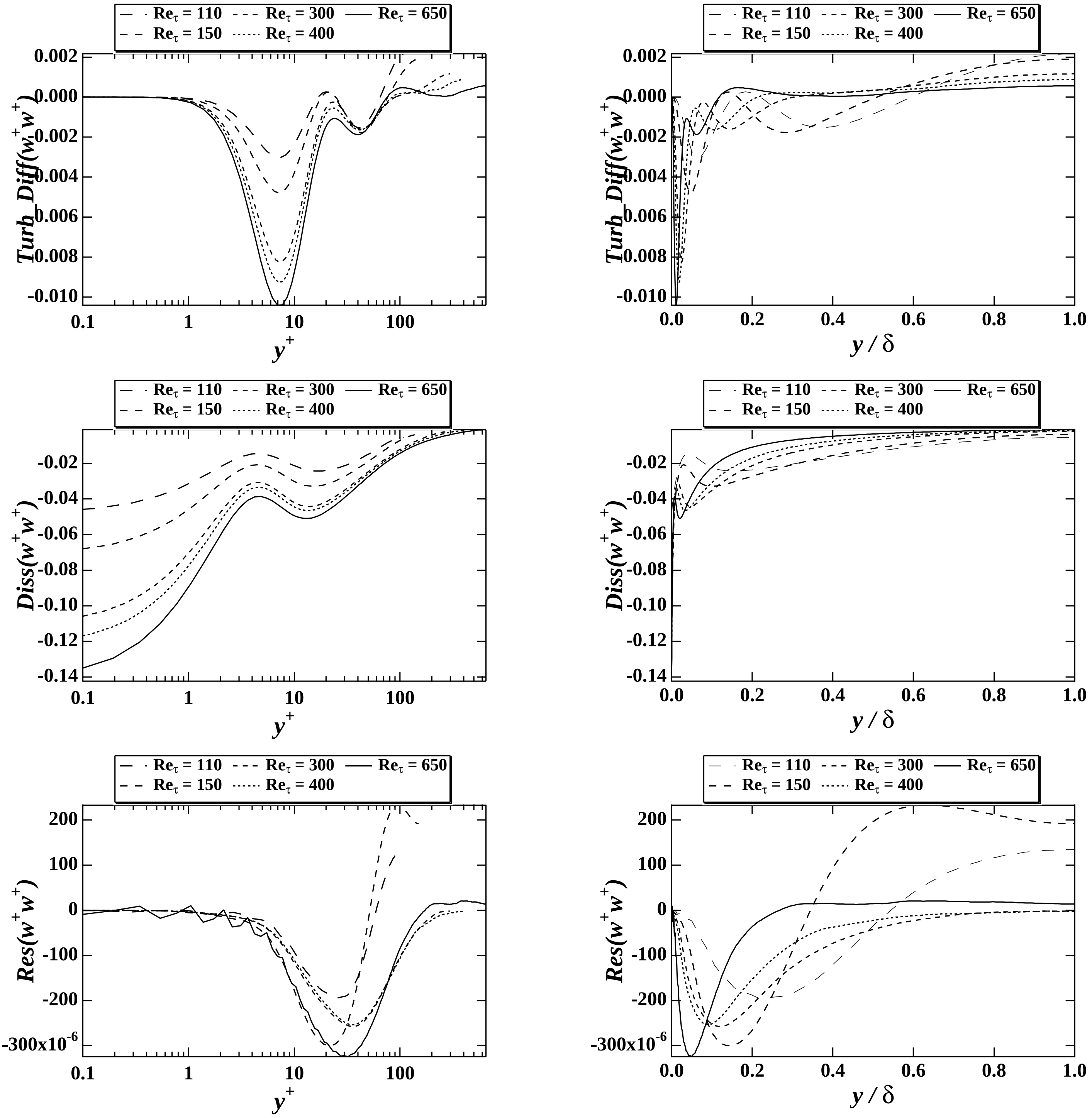






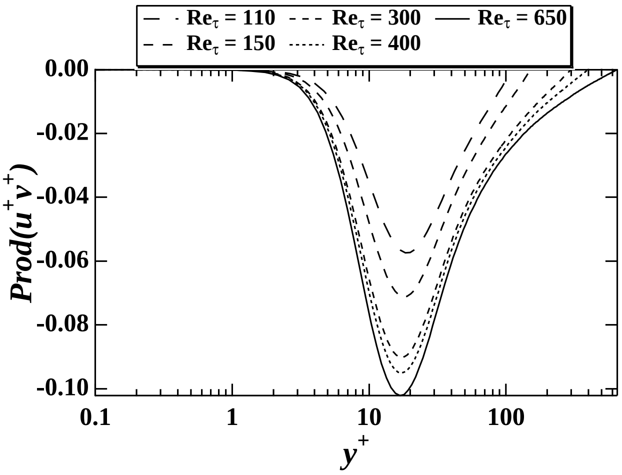


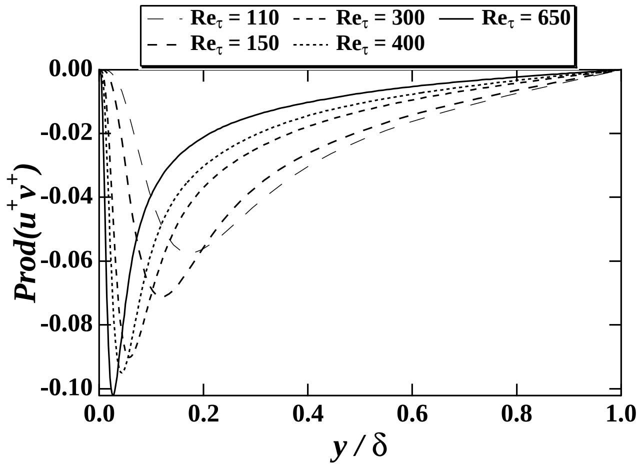


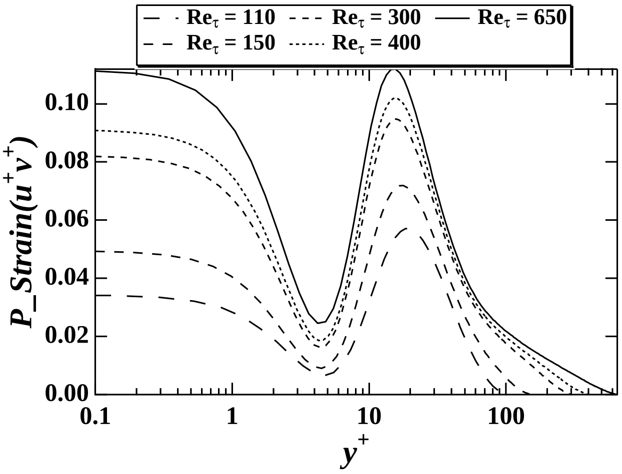


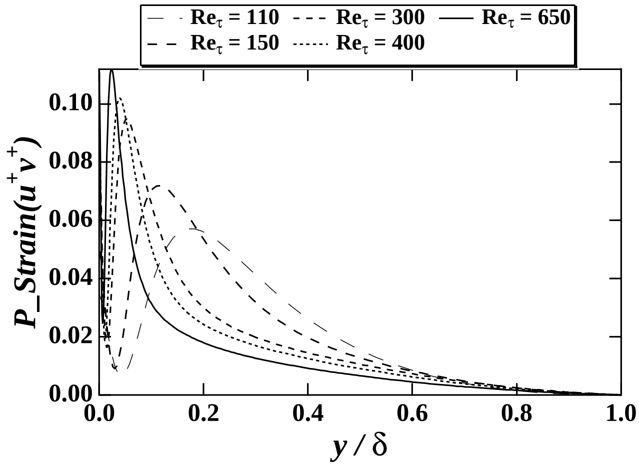
Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
Turb_Diff(w+w+)
Diss(w+w+)
Res(w+w+)
-300x10^-6
y+
y / δ

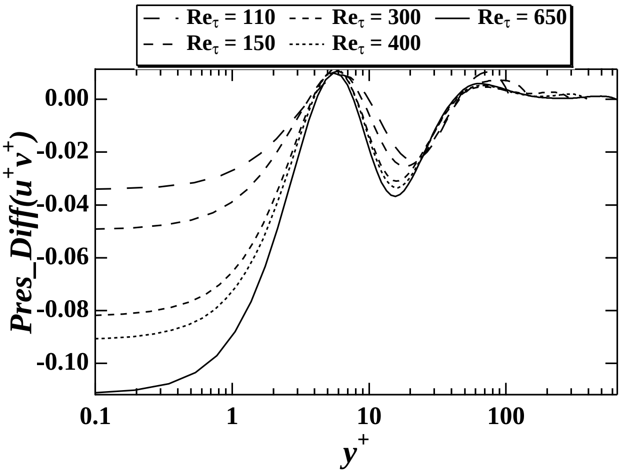
3.4 Budget for uv

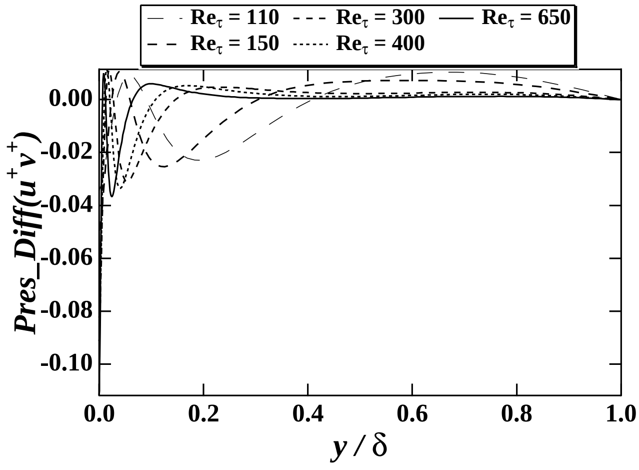


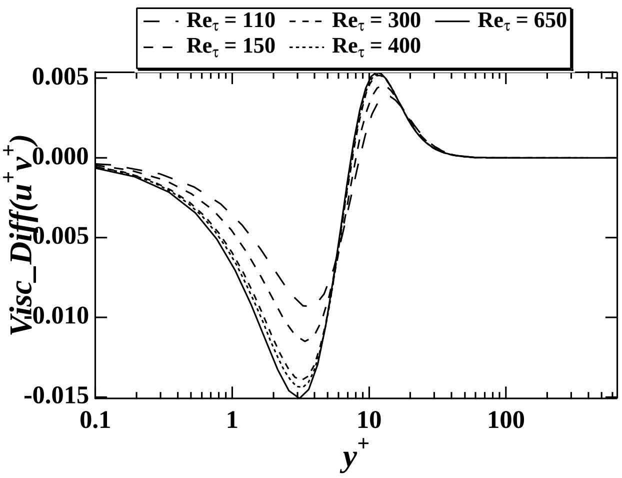


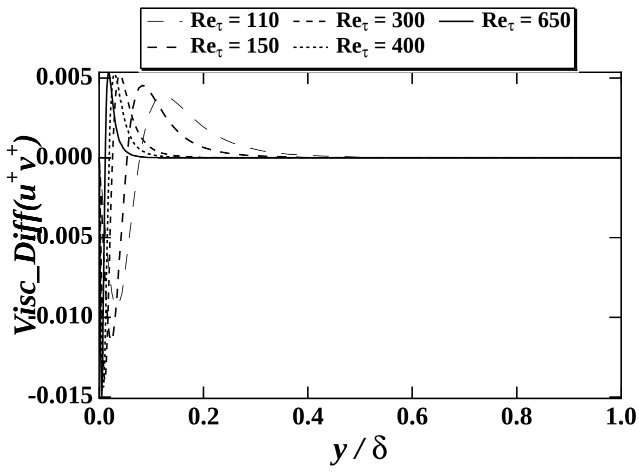


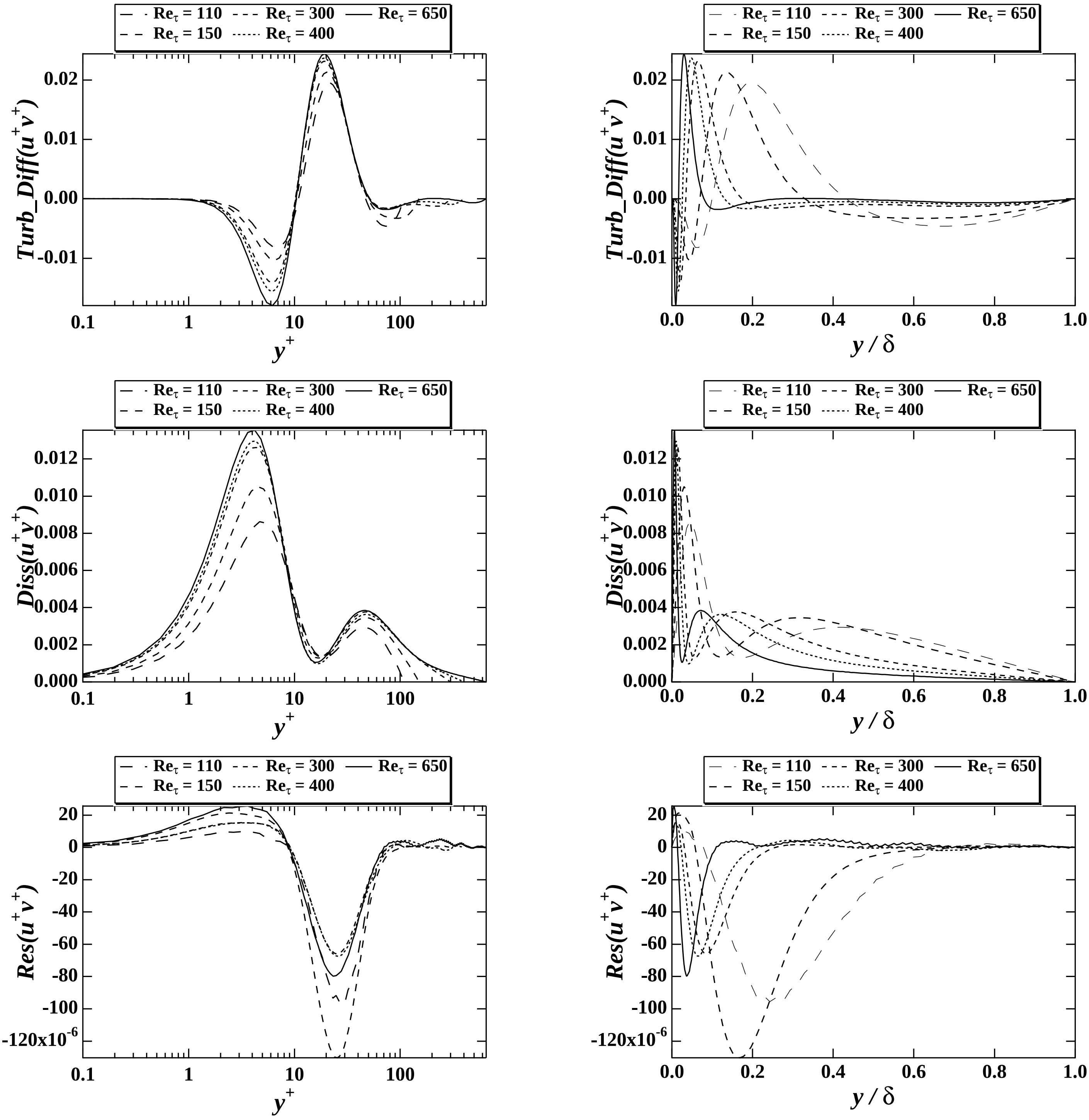




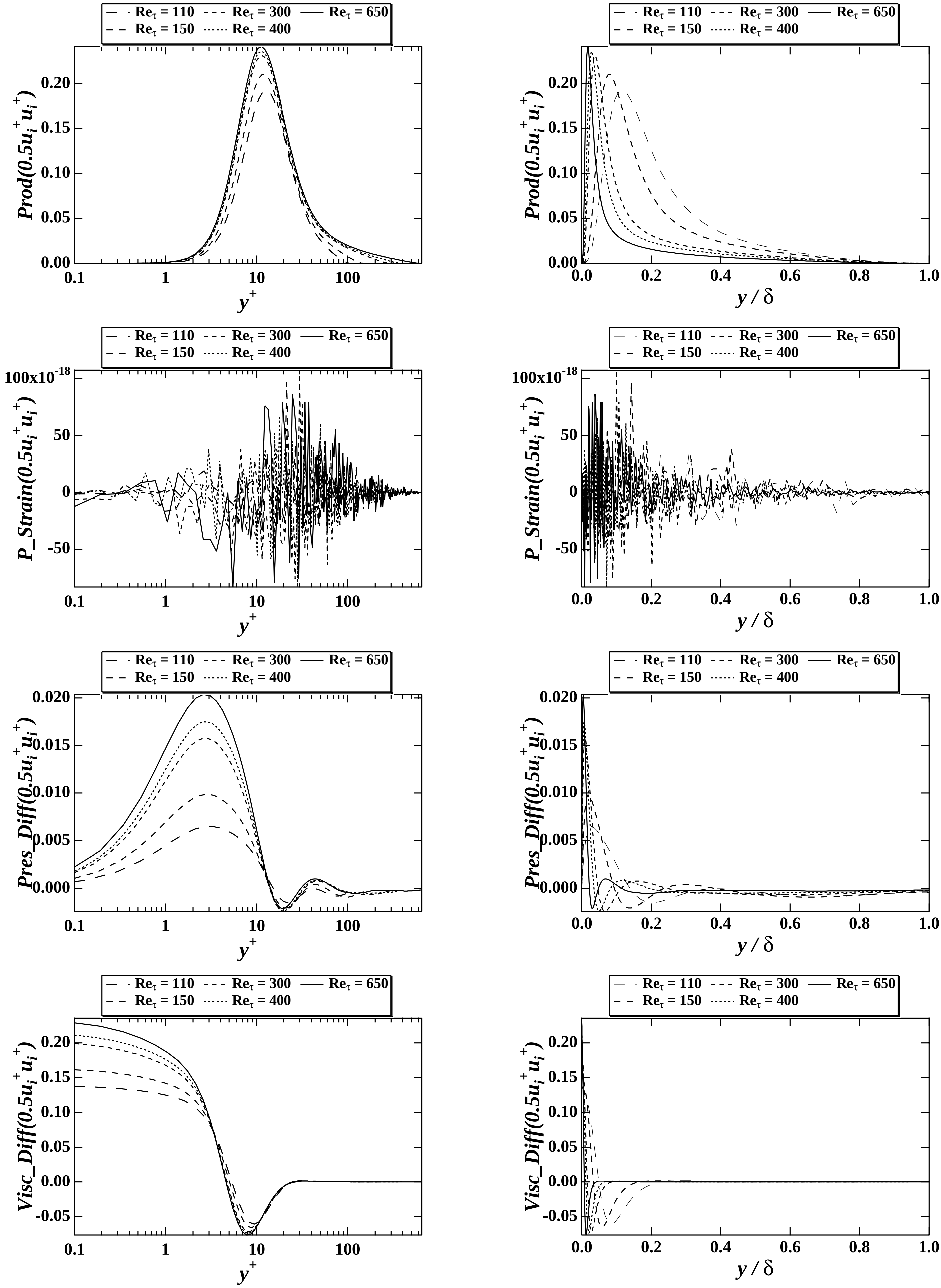


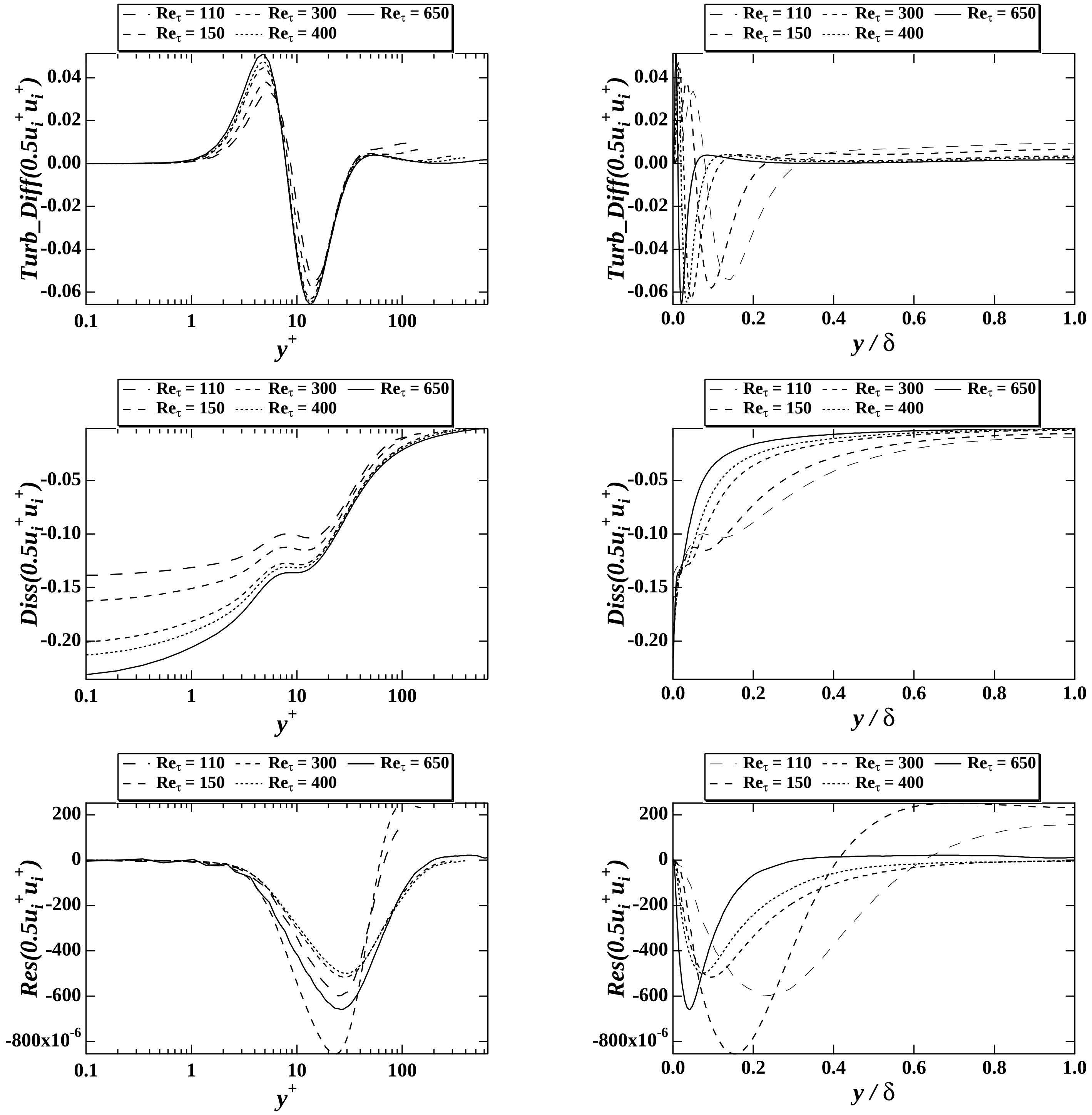





Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
Turb_Diff(u+v+)
Diss(u+v+)
Res(u+v+)
-120x10-6
y+
y / δ

3.5 Budget for k

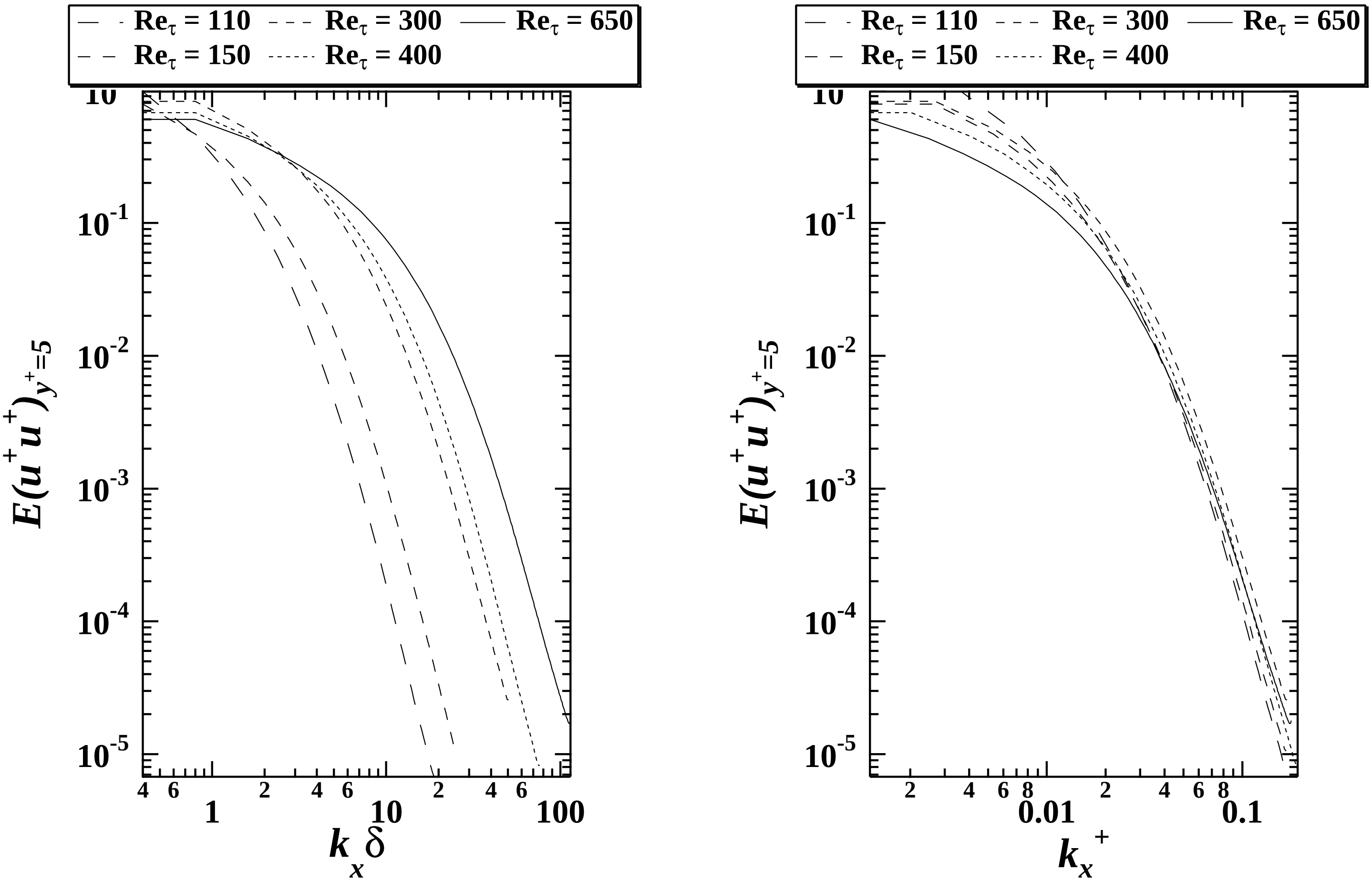


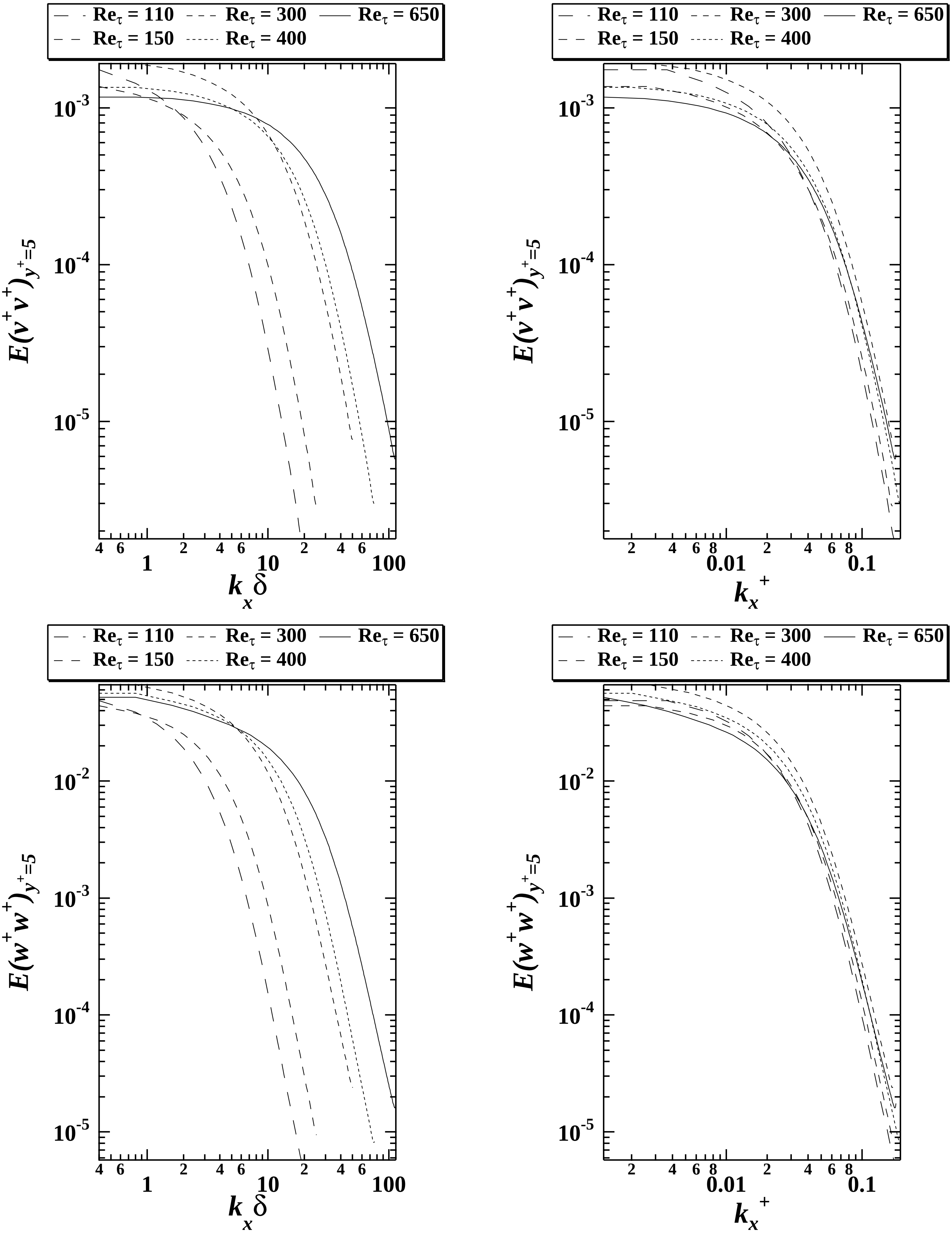

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
Turb_Diff(0.5u$_i^+$u$_i^+$)
Diss(0.5u$_i^+$u$_i^+$)
Res(0.5u$_i^+$u$_i^+$)
y$^+$
y / δ
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.05
-0.10
-0.15
-0.20
200
0
-200
-400
-600
-800x10^{-6}
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8
1.0

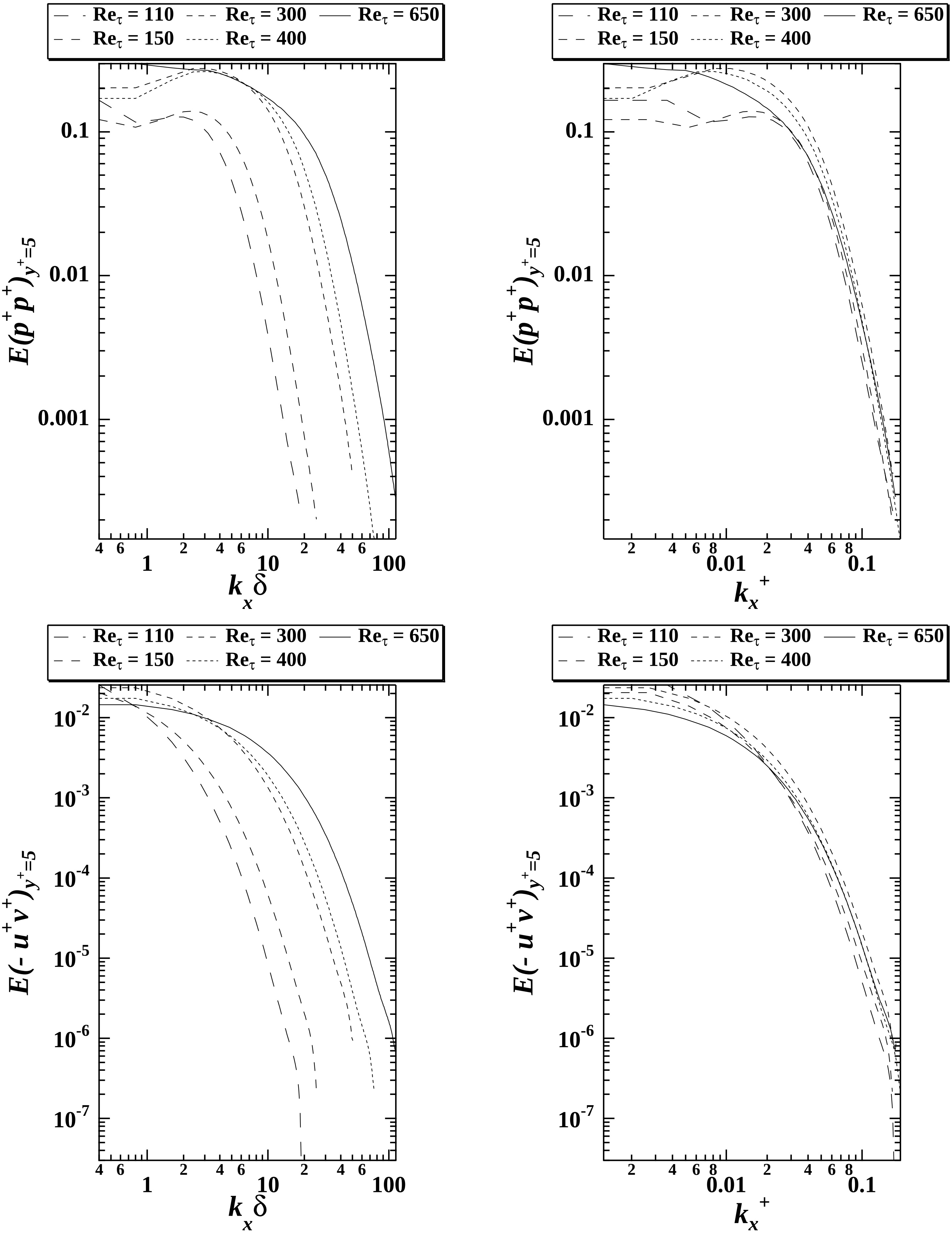
4 One-dimensional Energy Spectra at several points

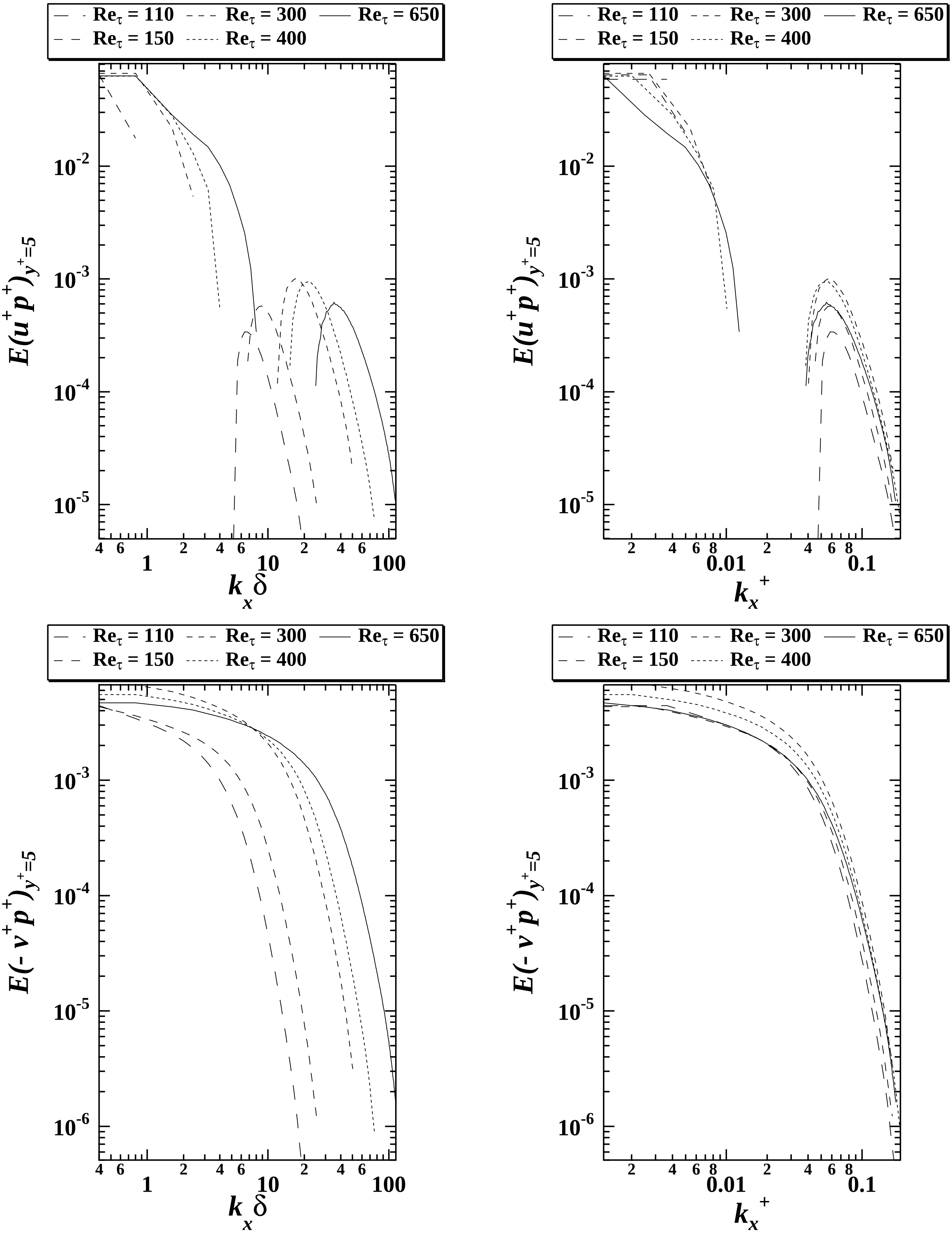
4.1 Streamwise Power Spectra

4.1.1 at $y^+ = 5$

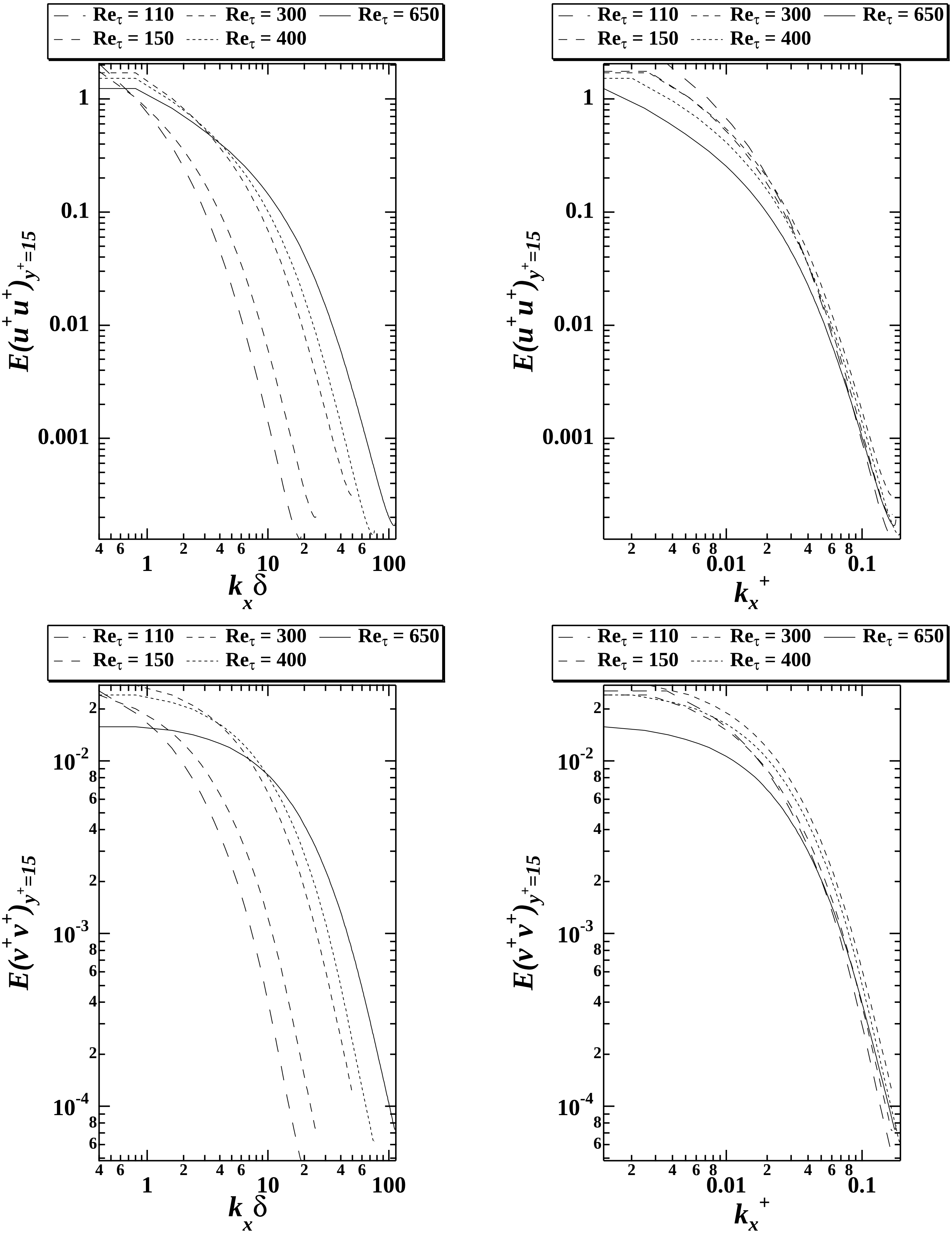



Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
$E(v^+v^+)_{y^+=5}$
$k_x\delta$
k_x^+
$E(w^+w^+)_{y^+=5}$

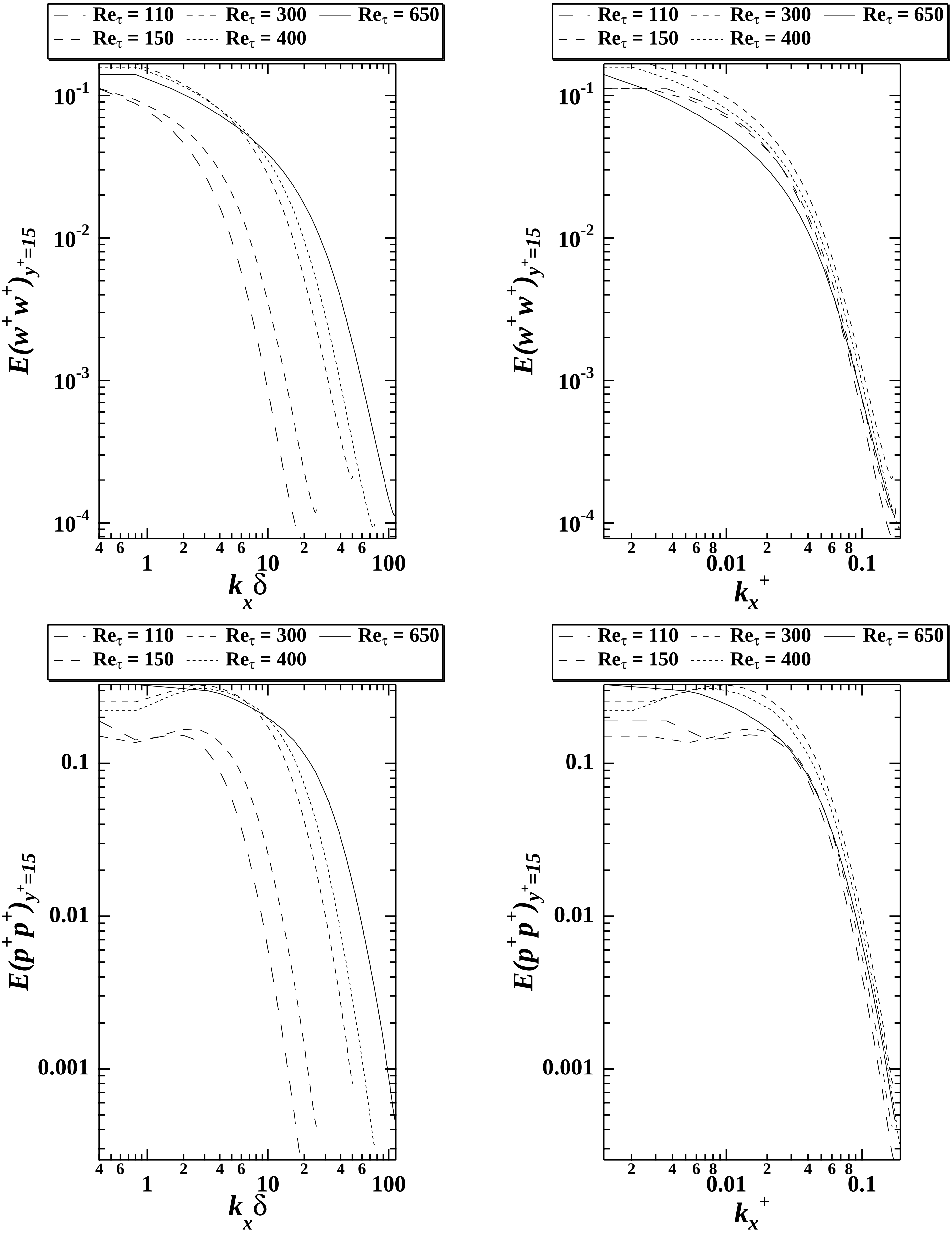

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(p^+p^+)_{y^+=5}$
$E(-u^+v^+)_{y^+=5}$
$k_x\delta$
k_x^+

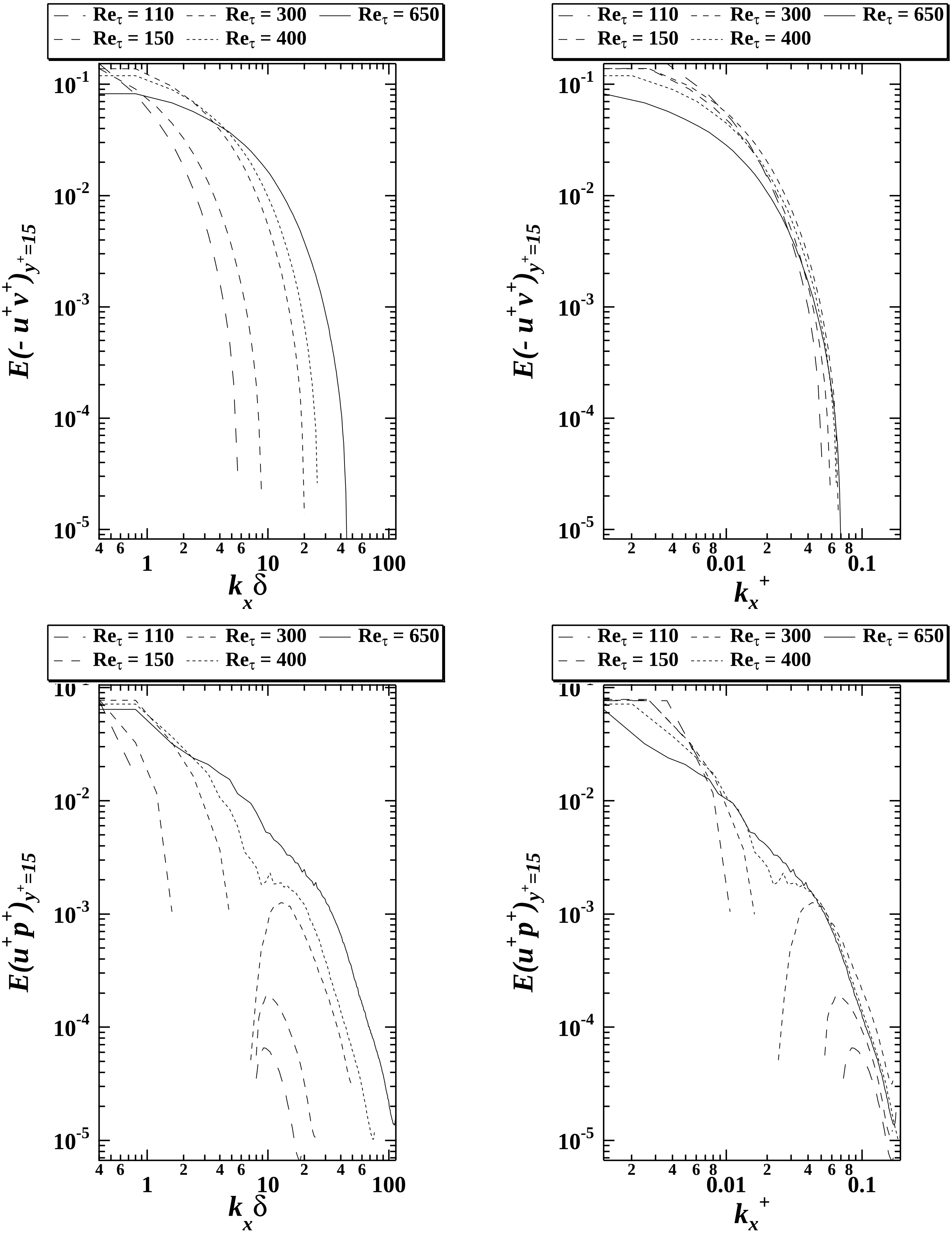

Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
$E(u^+p^+)_{y^+=5}$
$E(-v^+p^+)_{y^+=5}$
$k_x\delta$
k_x^+
10^-2
10^-3
10^-4
10^-5
10^-6
1
10
100
0.01
0.1

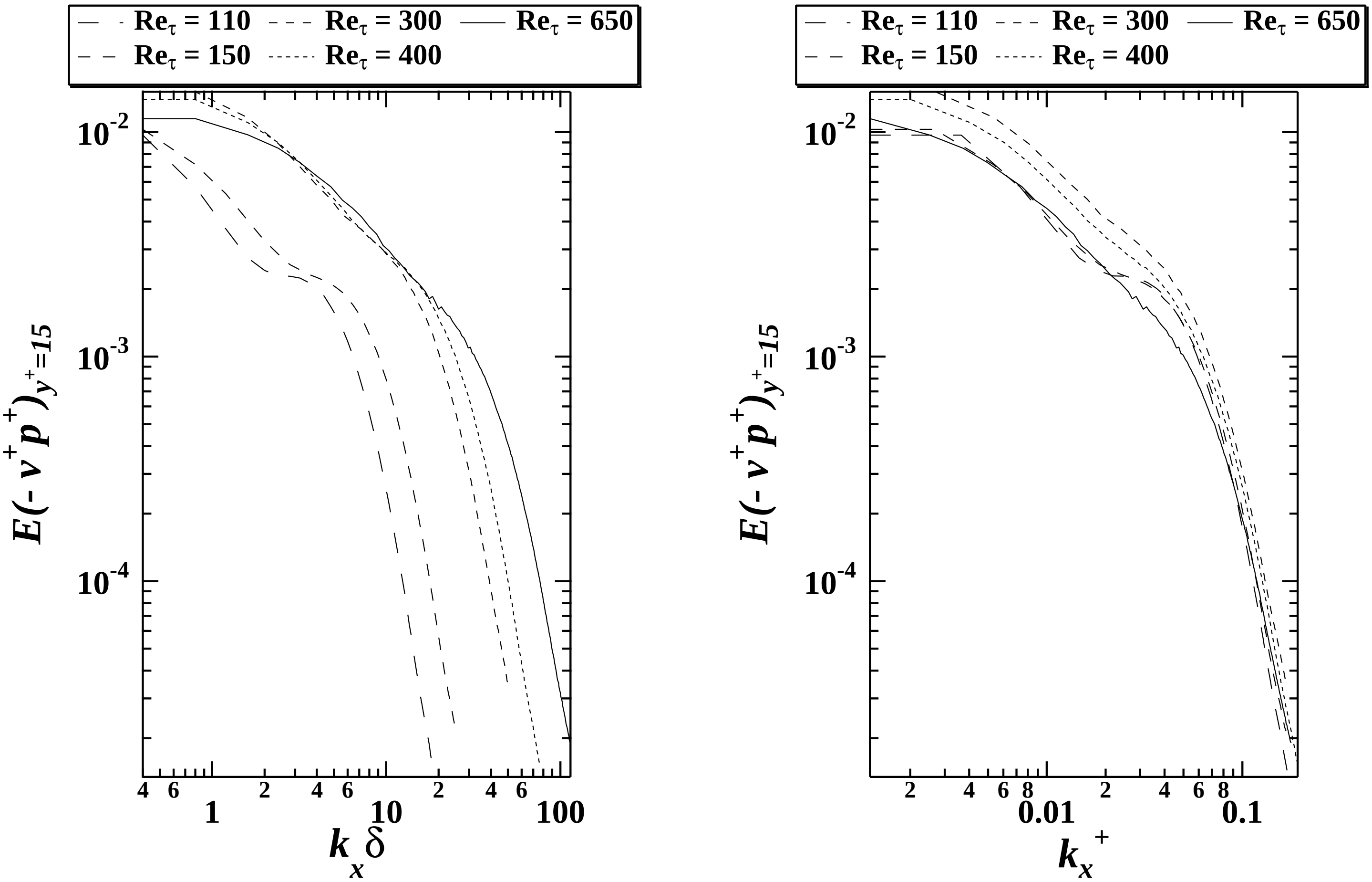
4.1.2 at $y^+ = 15$



Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(u⁺u⁺)_{y⁺=15}
k_x δ
k_x⁺
E(v⁺v⁺)_{y⁺=15}
1
0.1
0.01
0.001
10
100
10^-2
10^-3
10^-4

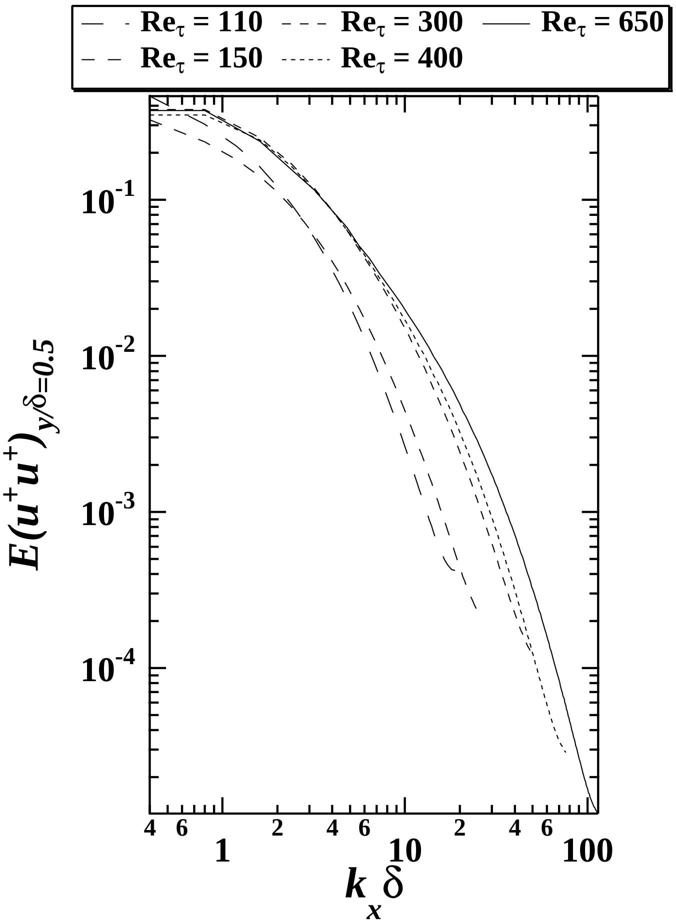

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(w^+w^+)_{y^+=15}$
$k_x\delta$
k_x^+
$E(p^+p^+)_{y^+=15}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
0.01
0.001
1
10
100

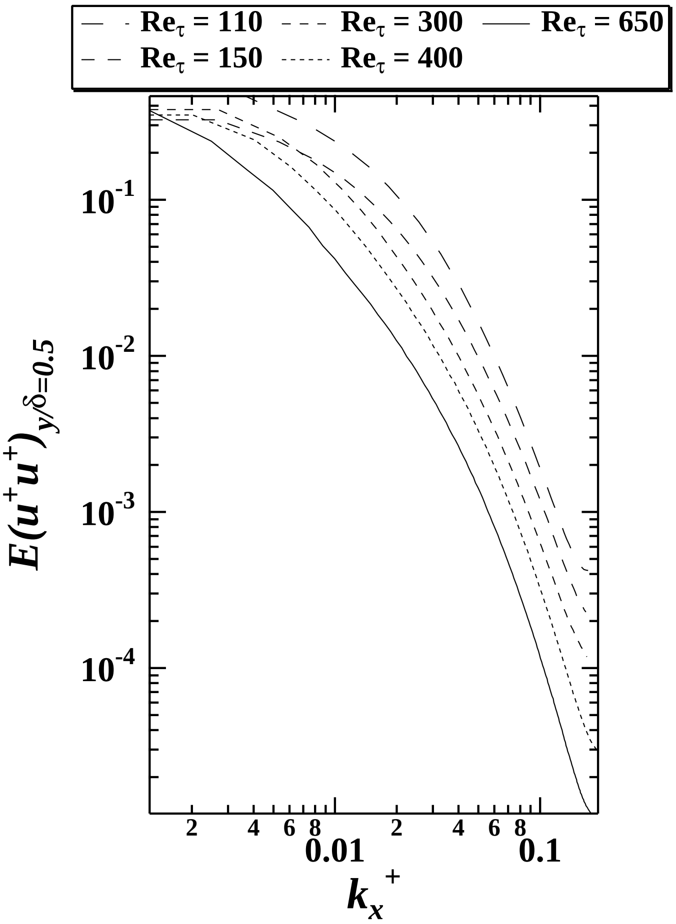

Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
E(- u+v+)y+=15
kxδ
kx+
E(u+p+)y+=15
10-1
10-2
10-3
10-4
10-5
1
10
100
0.01
0.1

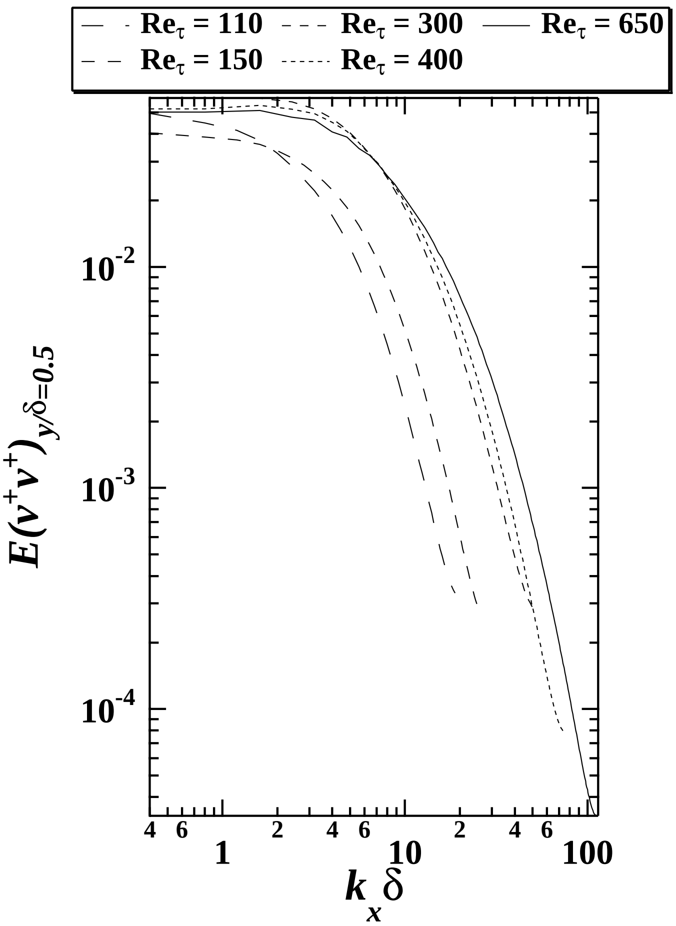


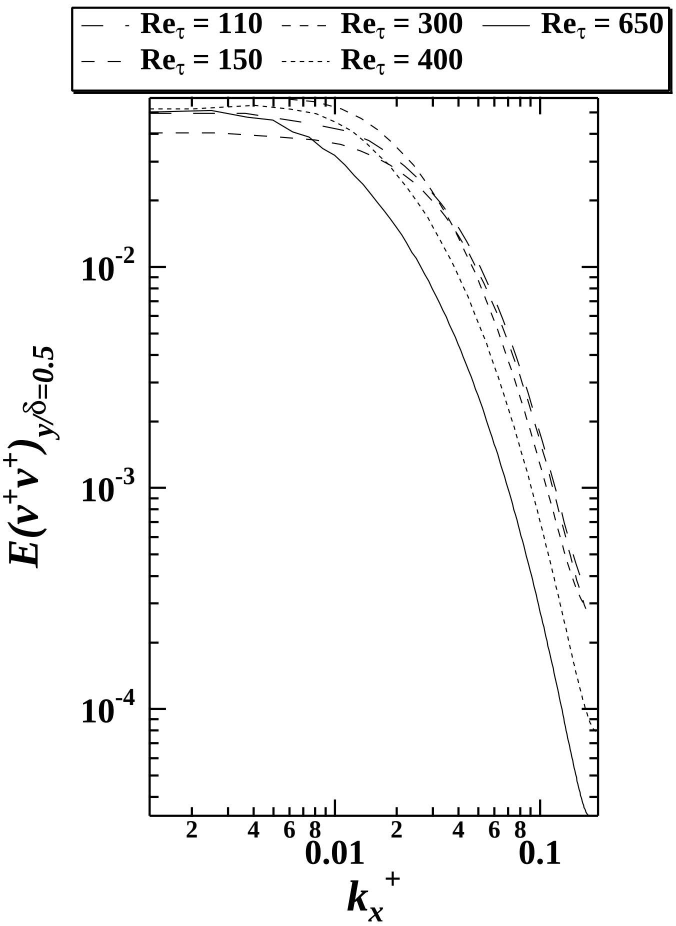
Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
$E(-v^+p^+)_{y^+=15}$
$k_x\delta$
k_x^+

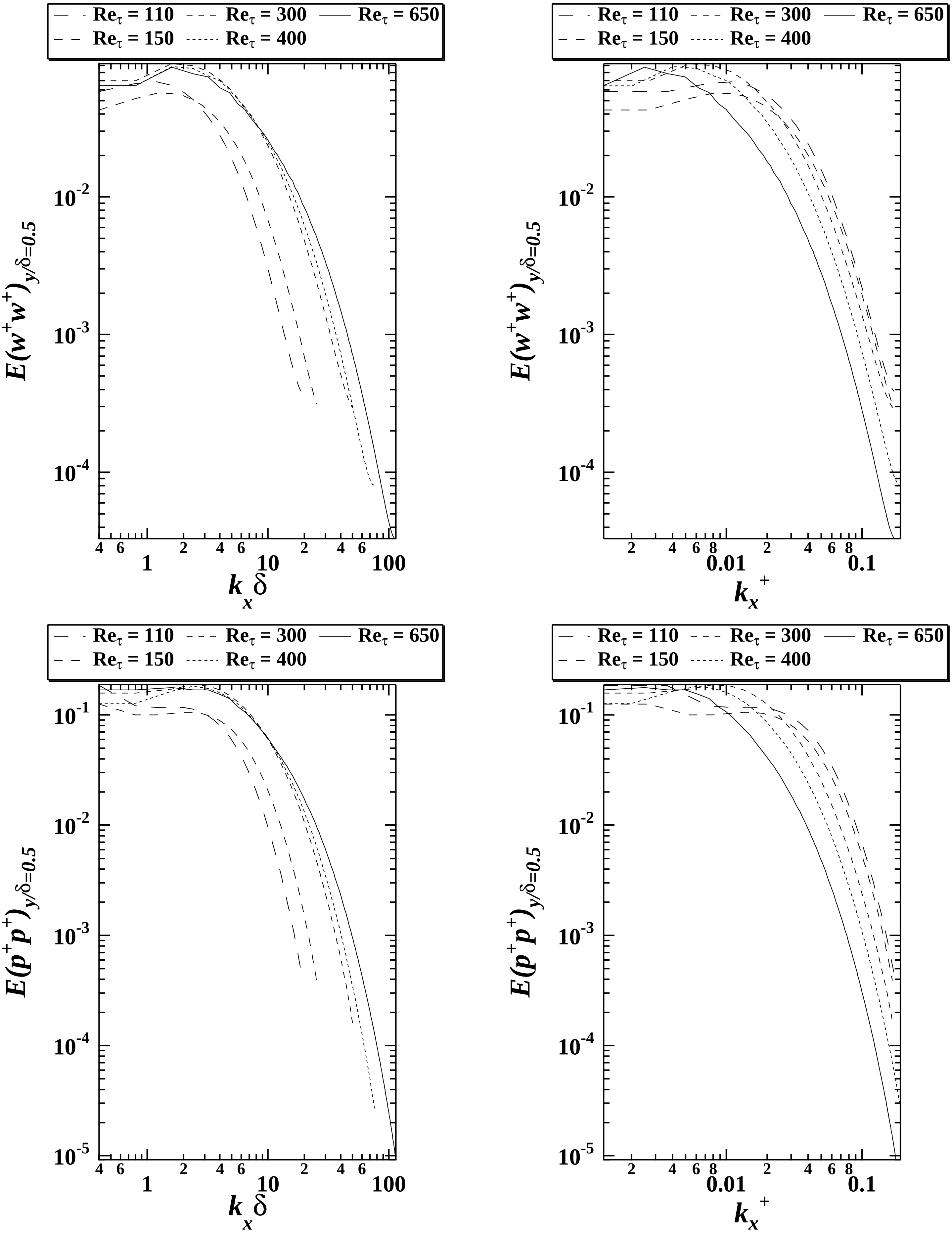
4.1.3 at $y/\delta = 0.5$



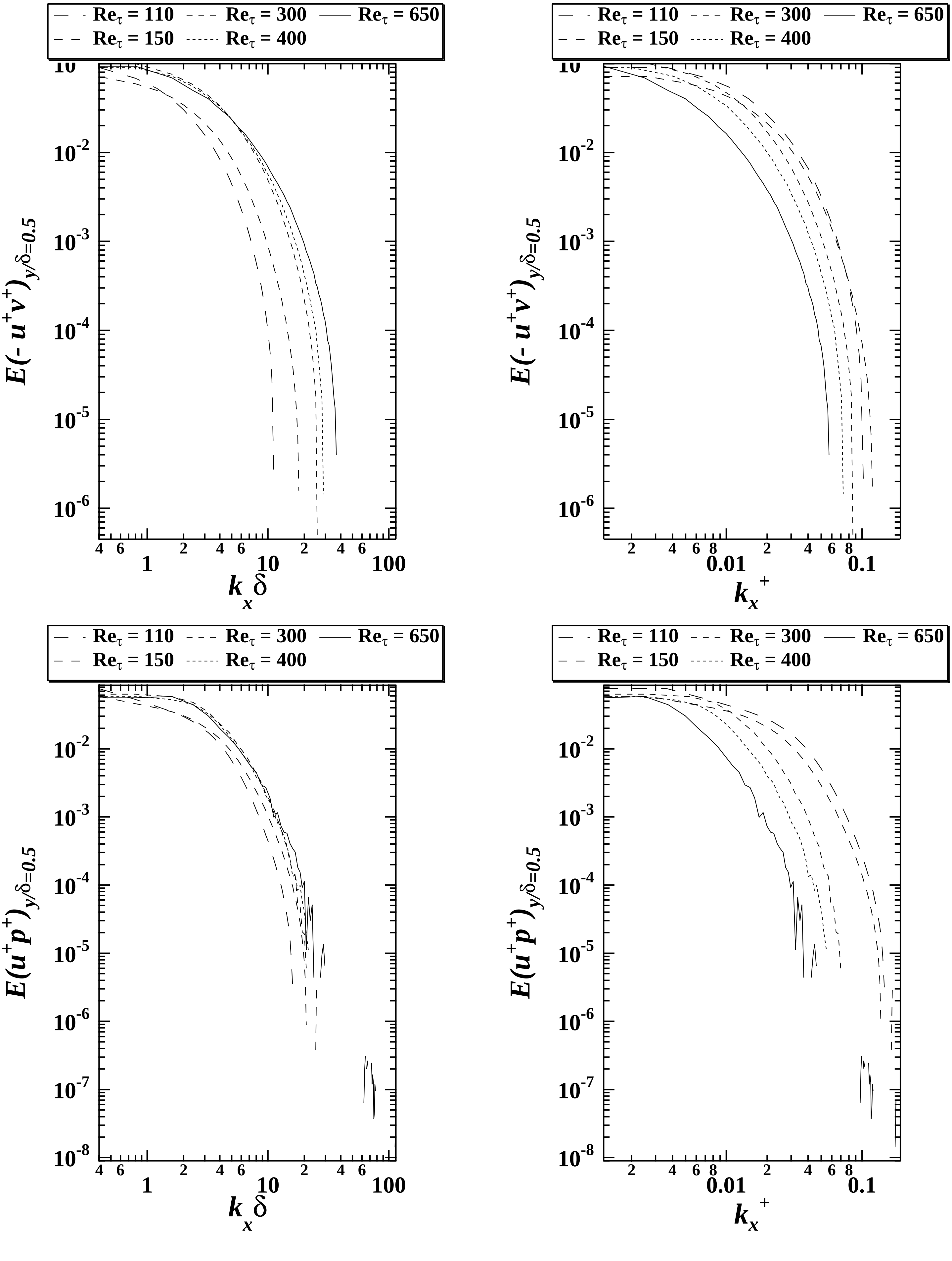




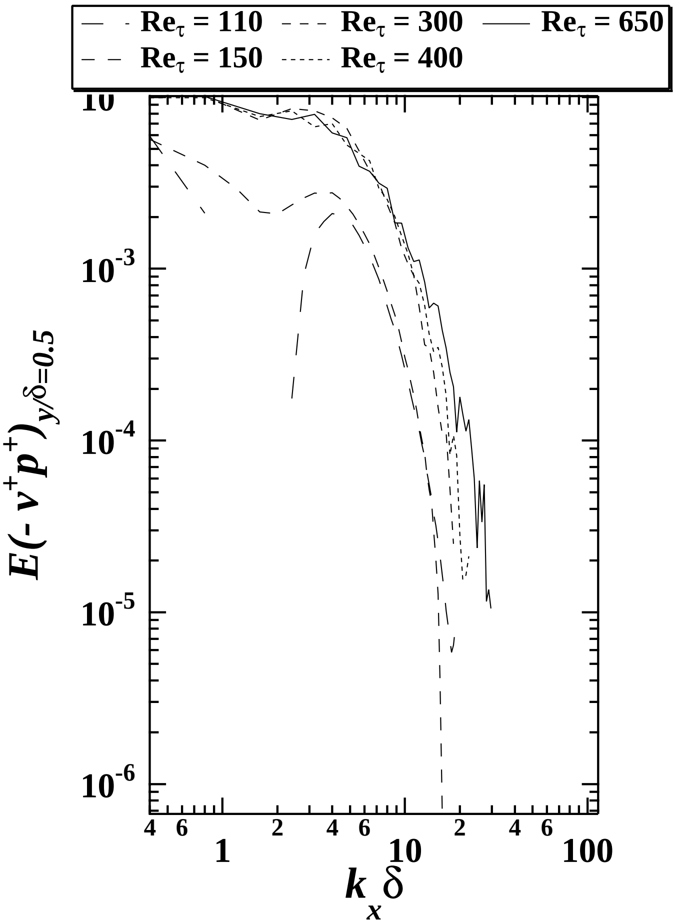




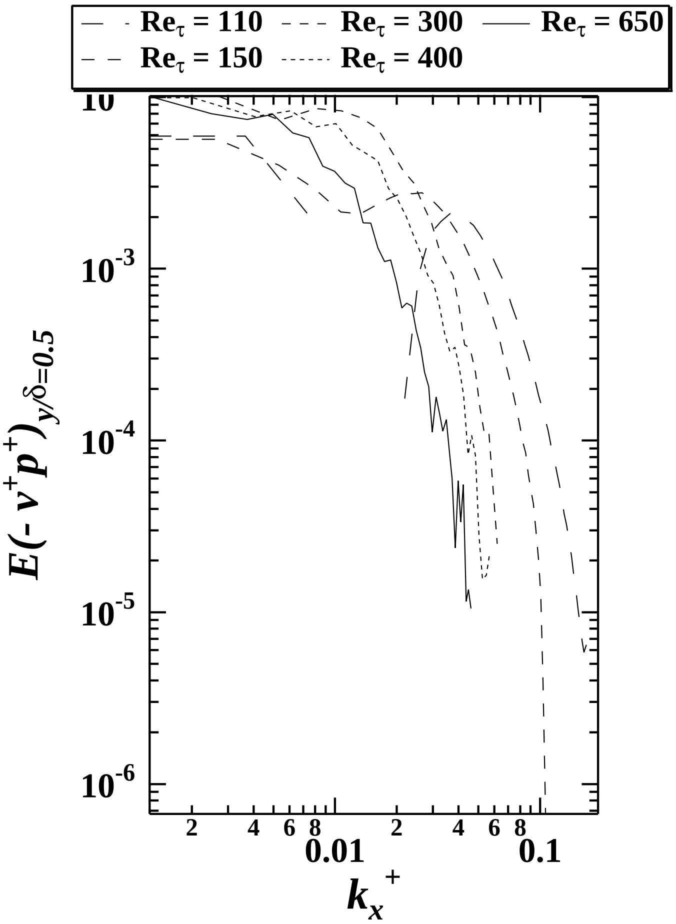
Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
E(w+w+)y/δ=0.5
kxδ
kx+
E(p+p+)y/δ=0.5



Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
E(- u⁺v⁺)_{y/δ=0.5}
E(u⁺p⁺)_{y/δ=0.5}
k_x δ
k_x⁺

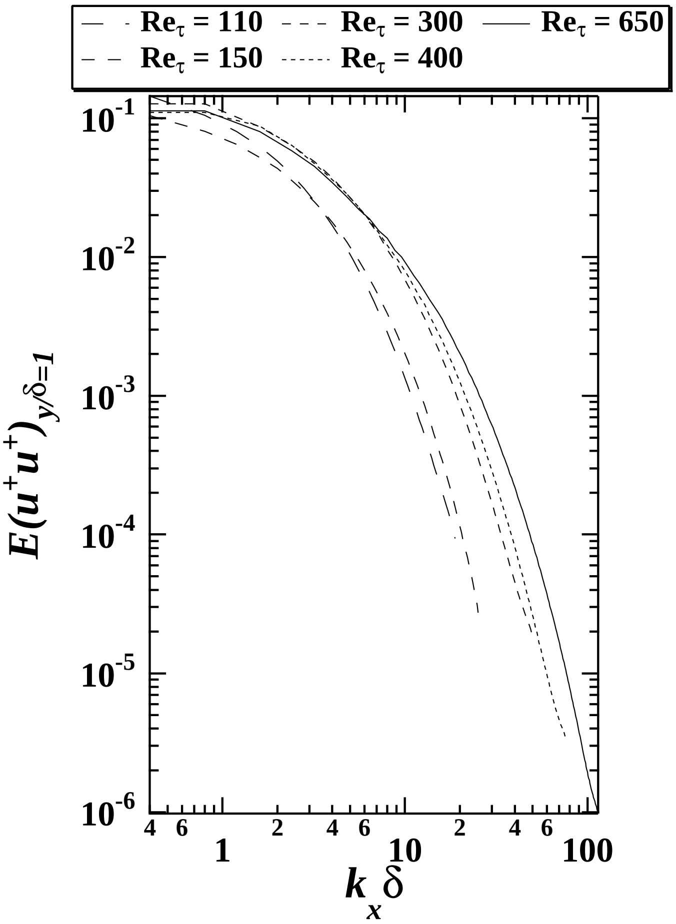


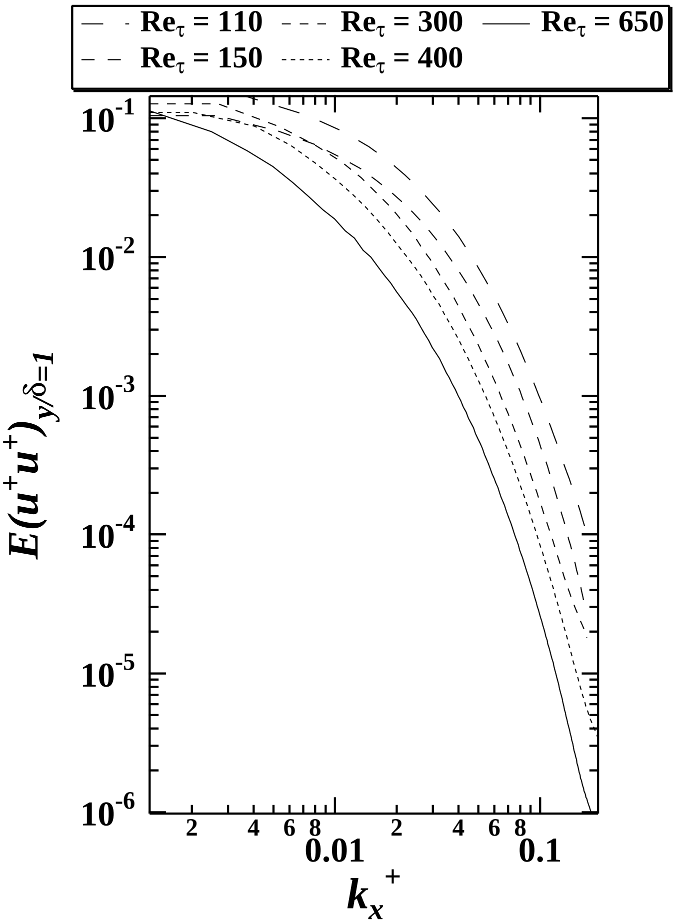
Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
10
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$E(-v^+p^+)_{y/\delta=0.5}$
4 6 1 2 4 6 10 2 4 6 100
$k_x\delta$

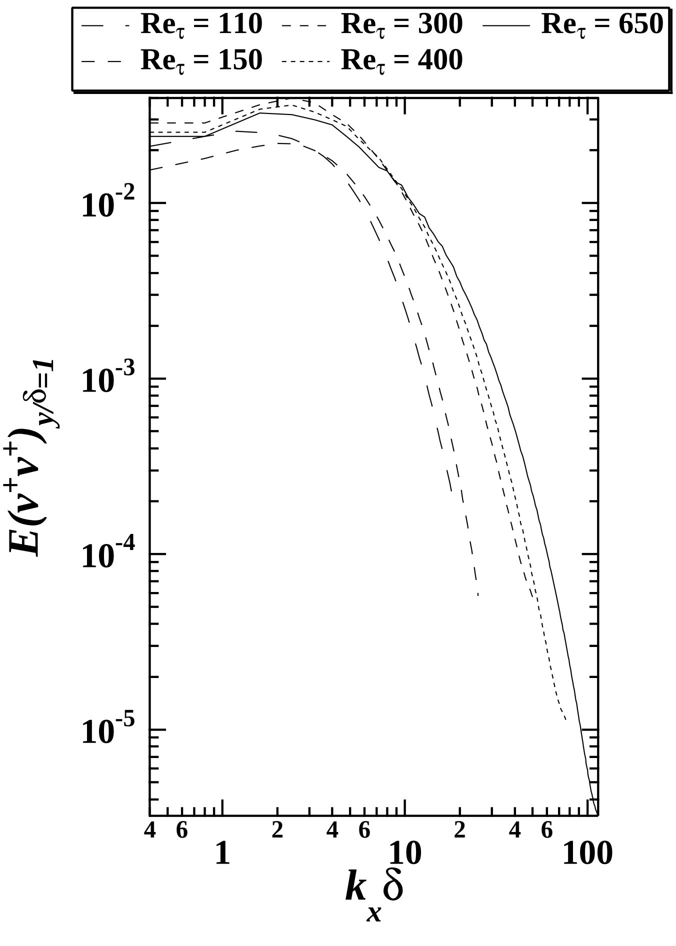


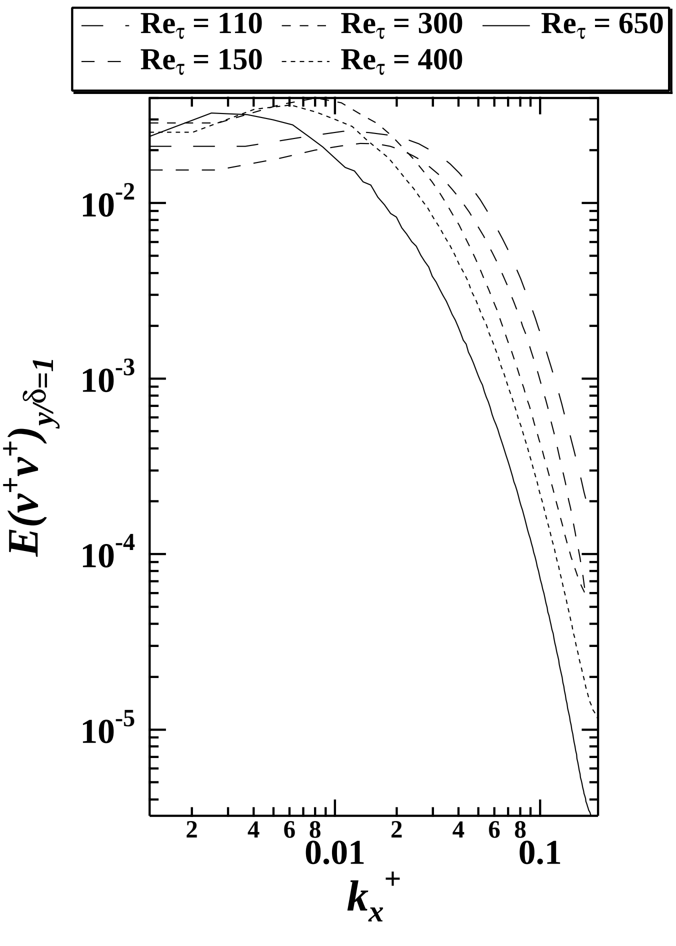
Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
10
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$E(-v^+p^+)_{y/\delta=0.5}$
2 4 6 8 0.01 2 4 6 8 0.1
k_x^+

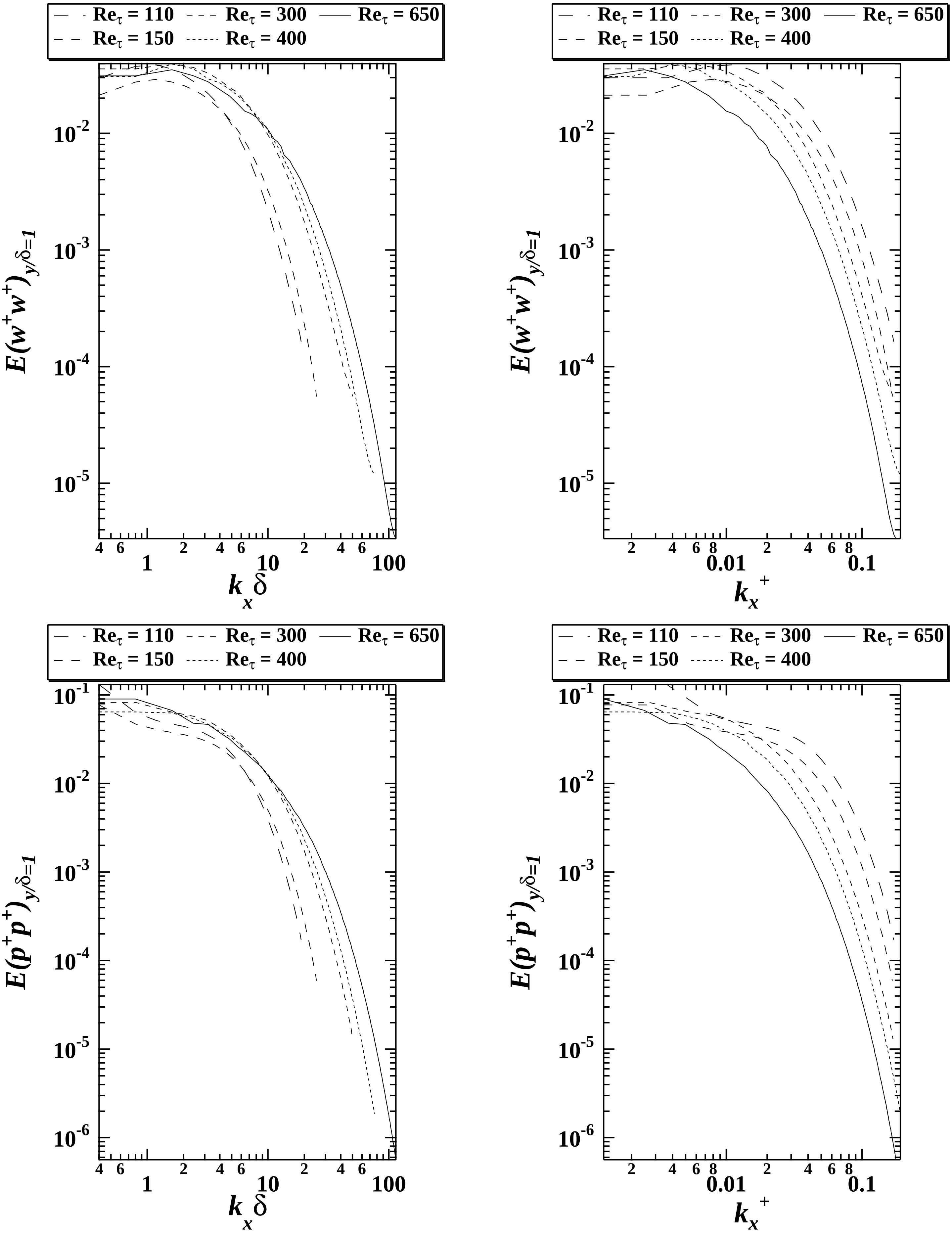
4.1.4 at $y/\delta = 1$

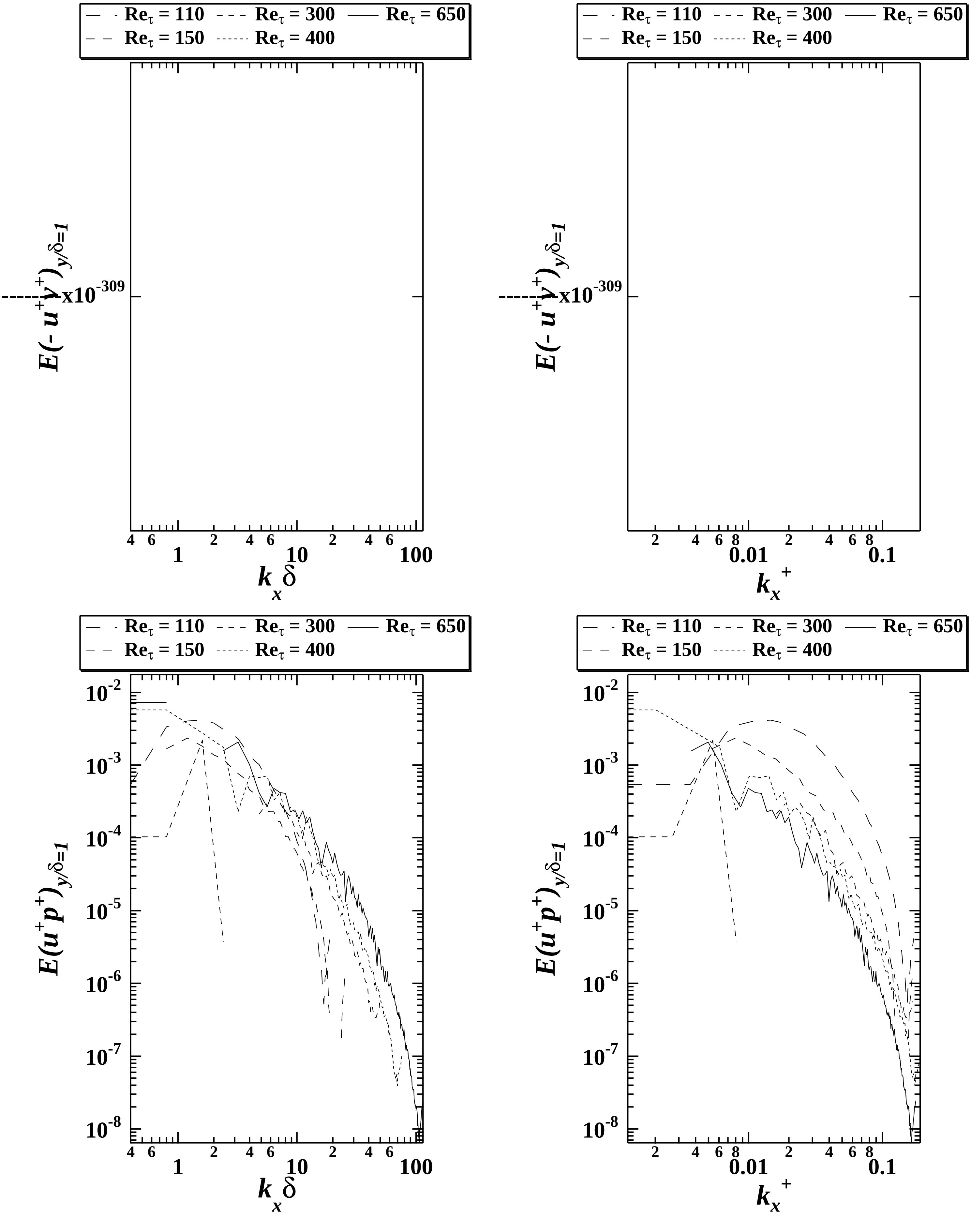




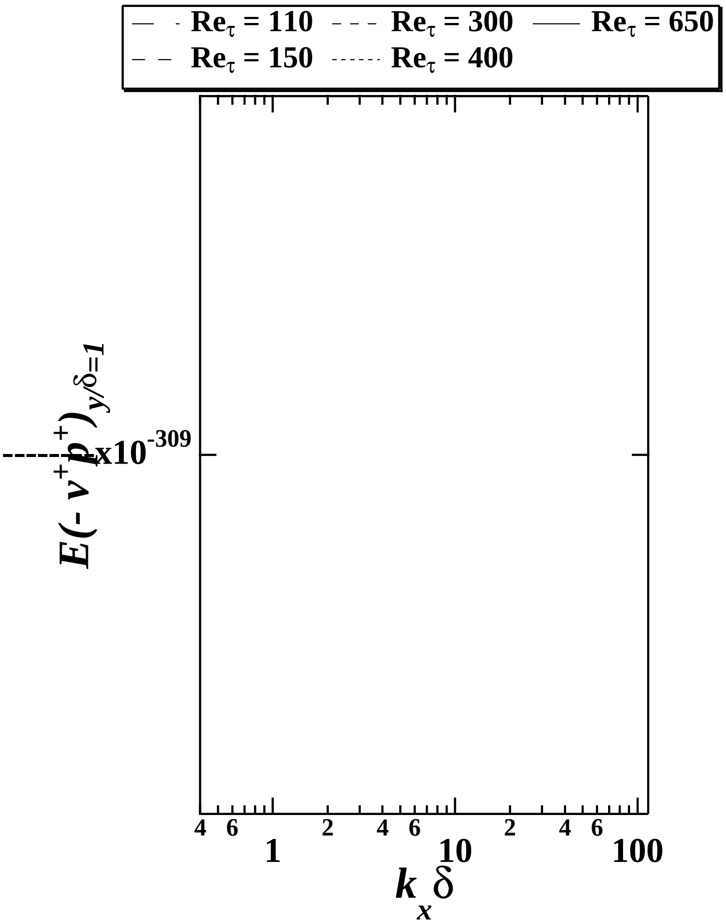


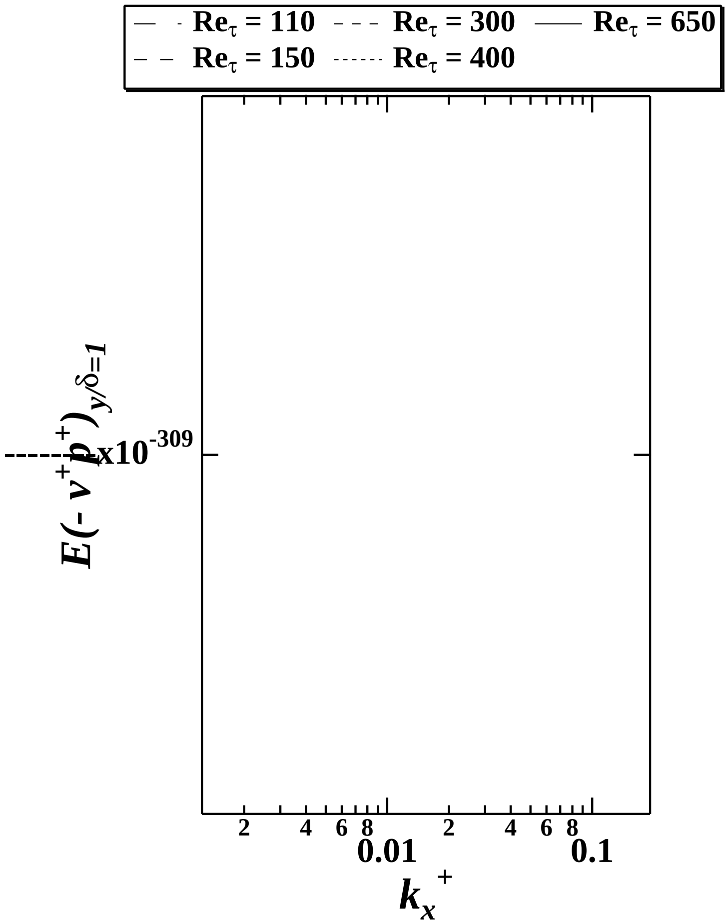



Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
E(w+w+)y/δ=1
10-2
10-3
10-4
10-5
1
10
100
kxδ
0.01
0.1
kx+
E(p+p+)y/δ=1
10-1
10-6



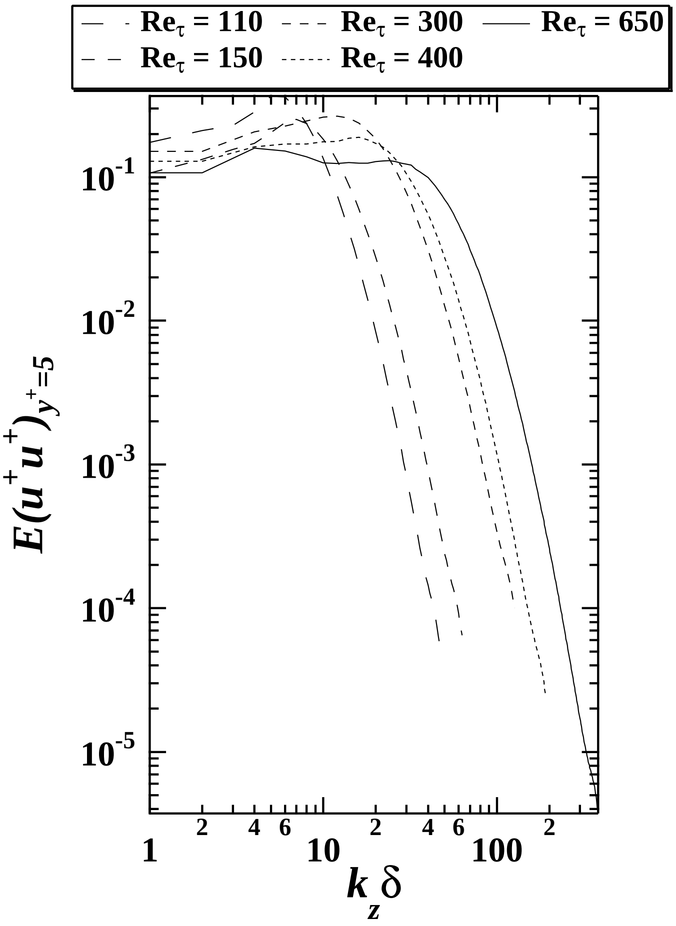
Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-u^+v^+)_{y/\delta=1}$
x10^{-309}
$E(u^+p^+)_{y/\delta=1}$
$k_x\delta$
k_x^+
1
10
100
0.01
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

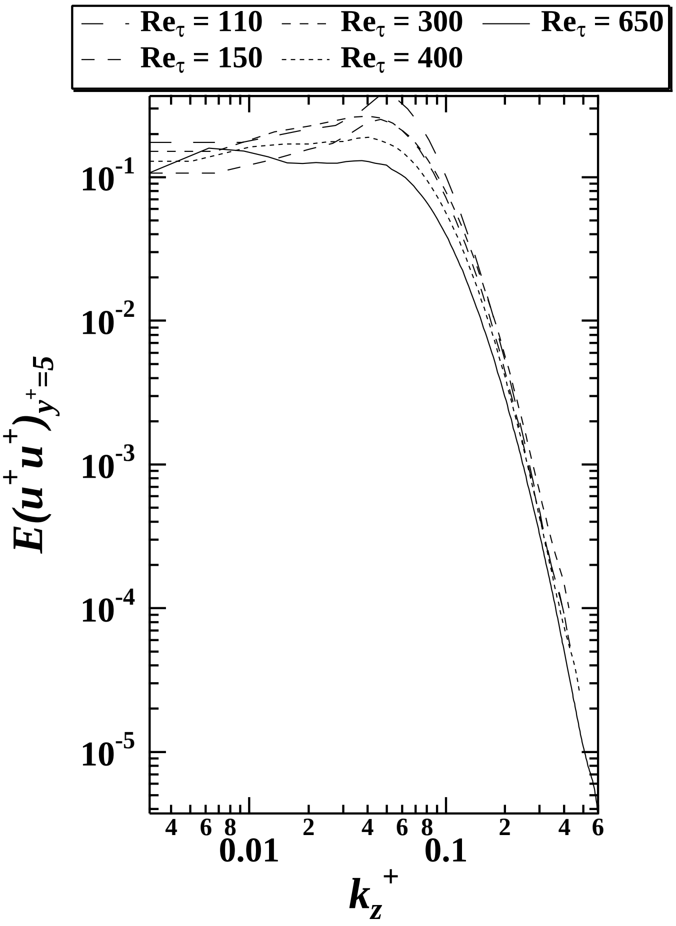

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-v^+p^+)_{y/\delta=1}$
x10^{-309}
4 6 1 2 4 6 10 2 4 6 100
$k_x\delta$

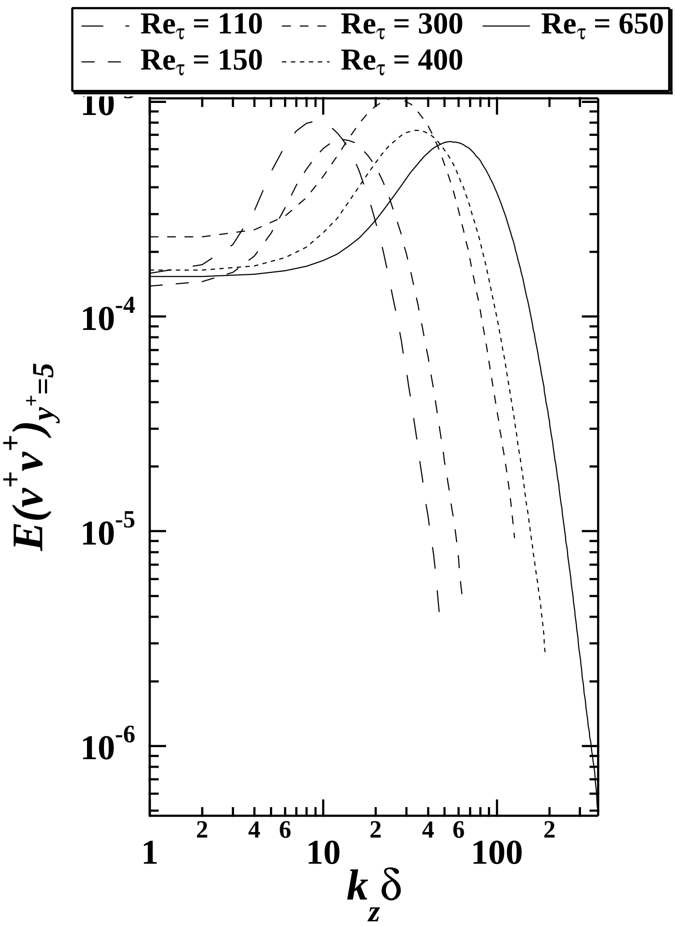

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-v^+p^+)_{y/\delta=1}$
x10^{-309}
2 4 6 8 0.01 2 4 6 8 0.1
k_x^+

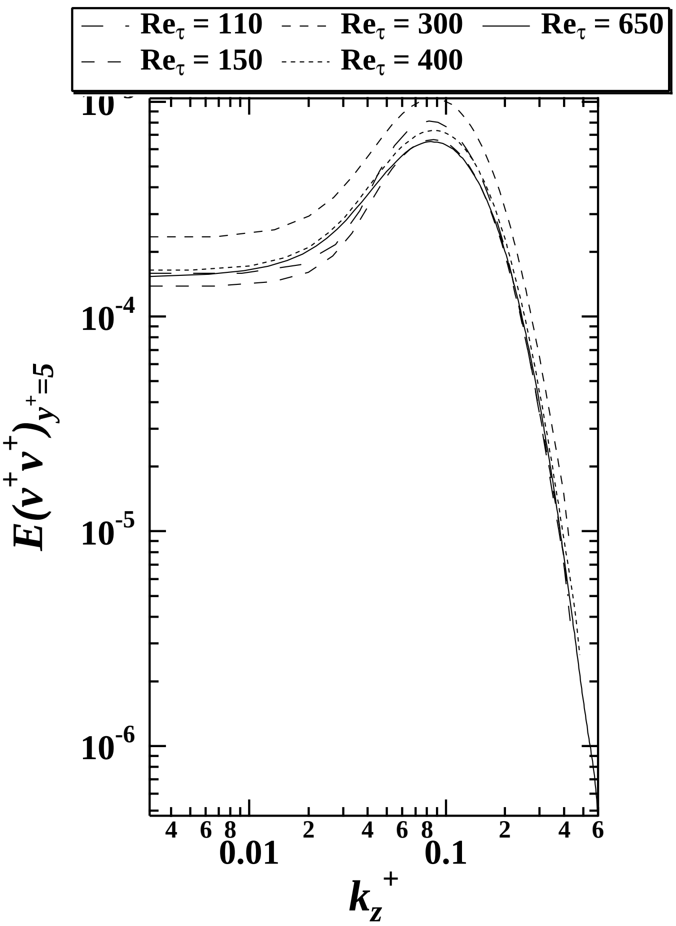
4.2 Spanwise Power Spectra

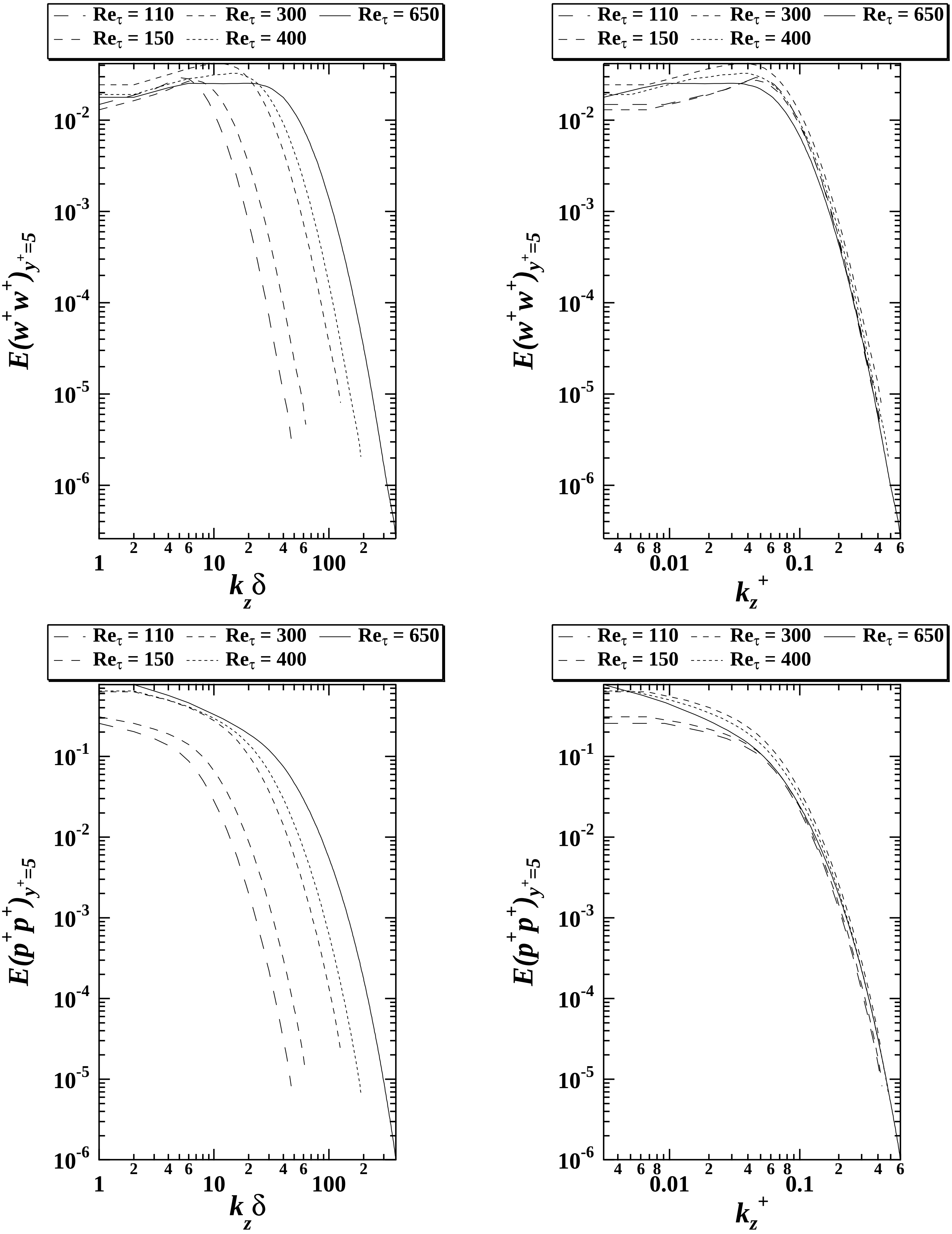
4.2.1 at $y^+ = 5$

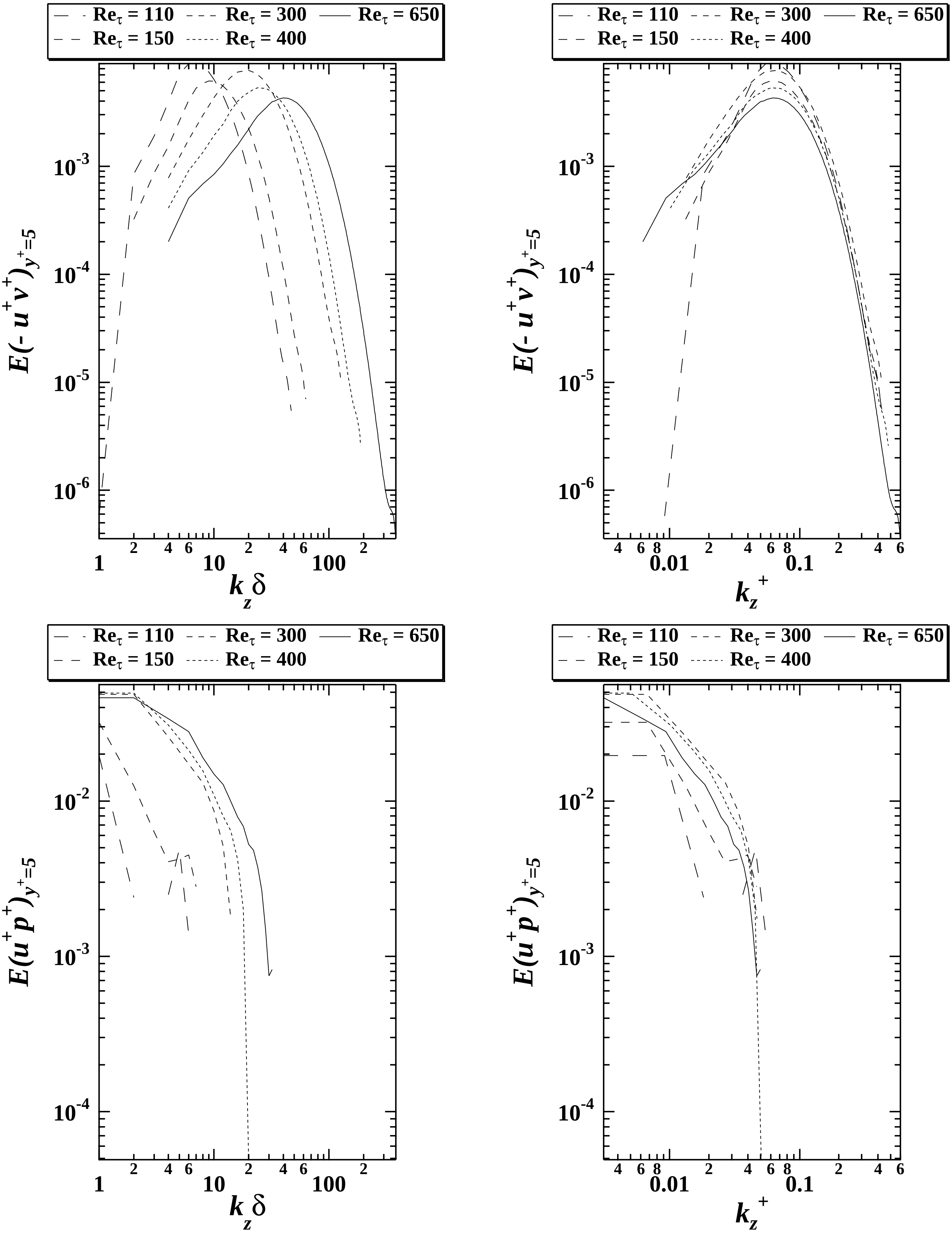




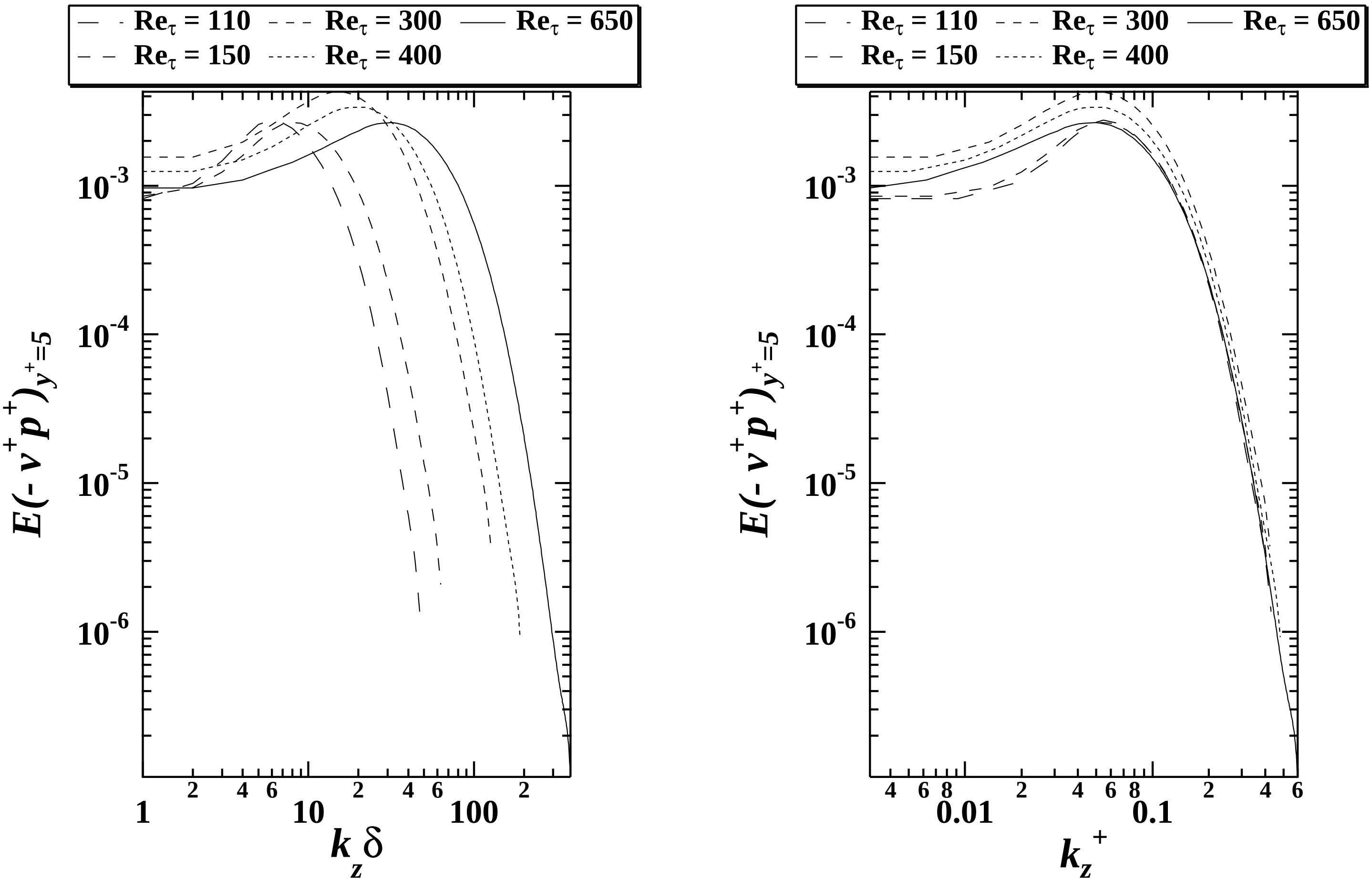





Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
$E(w^+w^+)_{y^+=5}$
$k_z\delta$
k_z^+
$E(p^+p^+)_{y^+=5}$

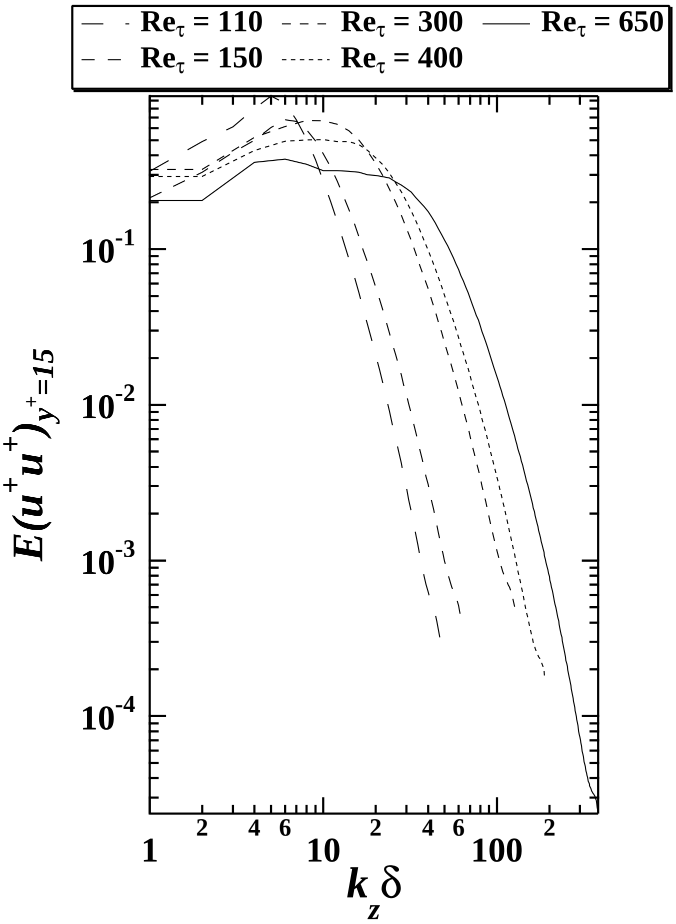


Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-u^+v^+)_{y^+=5}$
$k_z\delta$
k_z^+
$E(u^+p^+)_{y^+=5}$

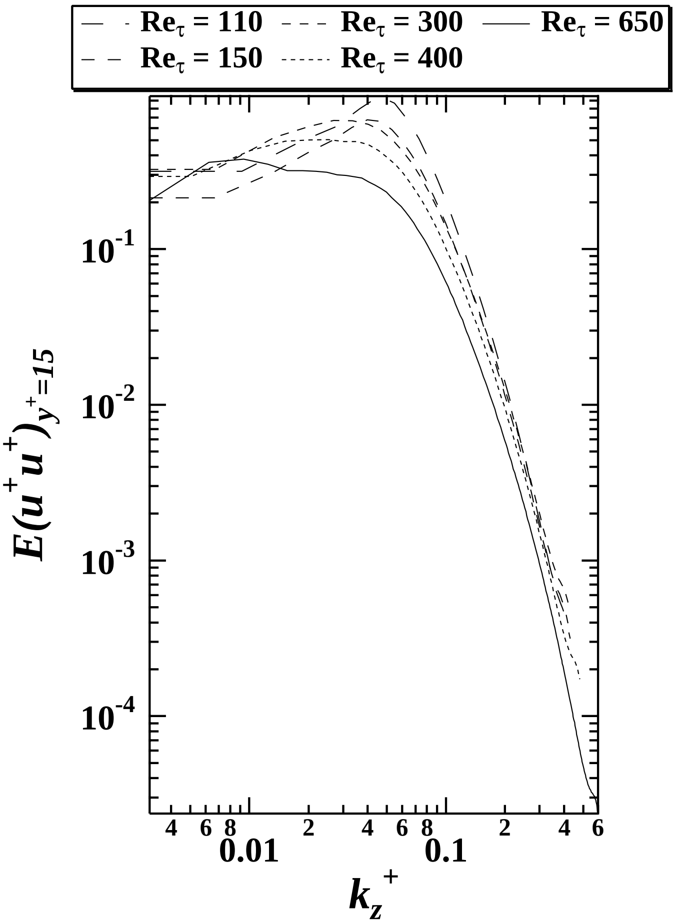


Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-v^+p^+)_{y^+=5}$
$k_z\delta$
k_z^+

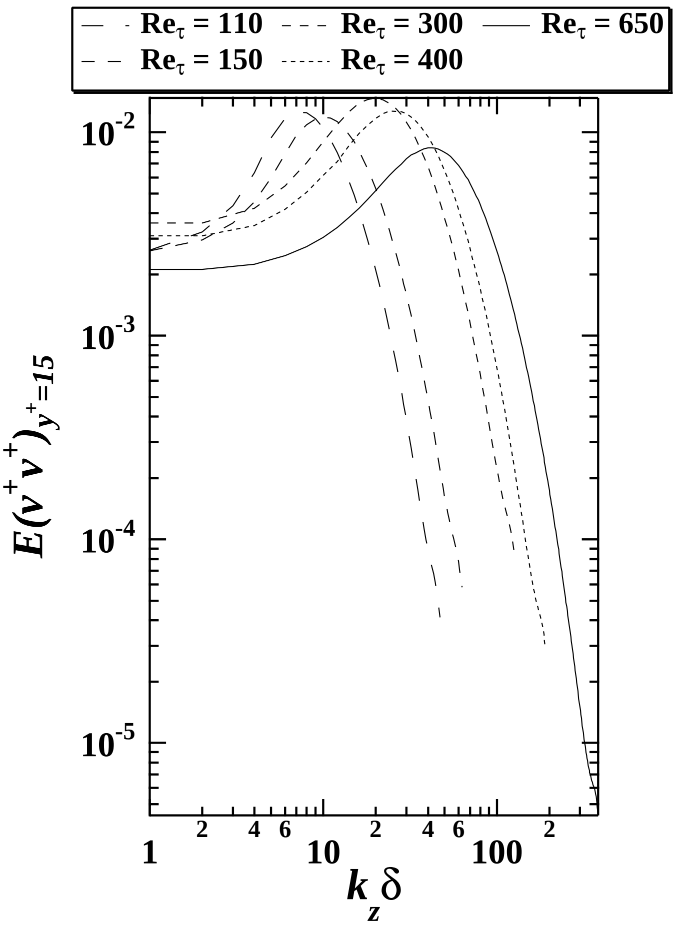
4.2.2 at $y^+ = 15$



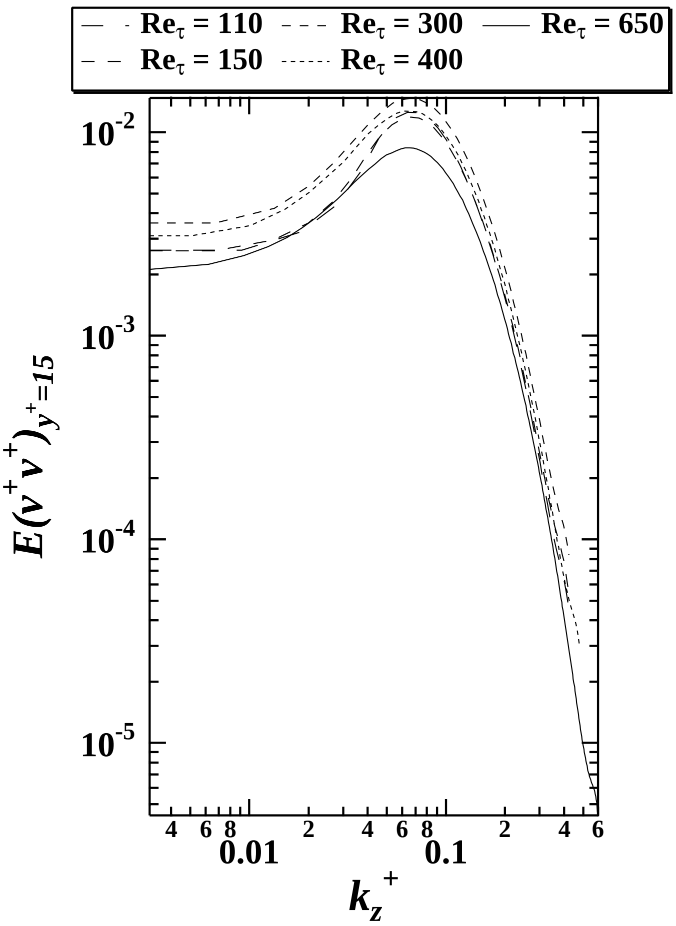
Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(u⁺u⁺)_{y⁺=15}
k_z δ



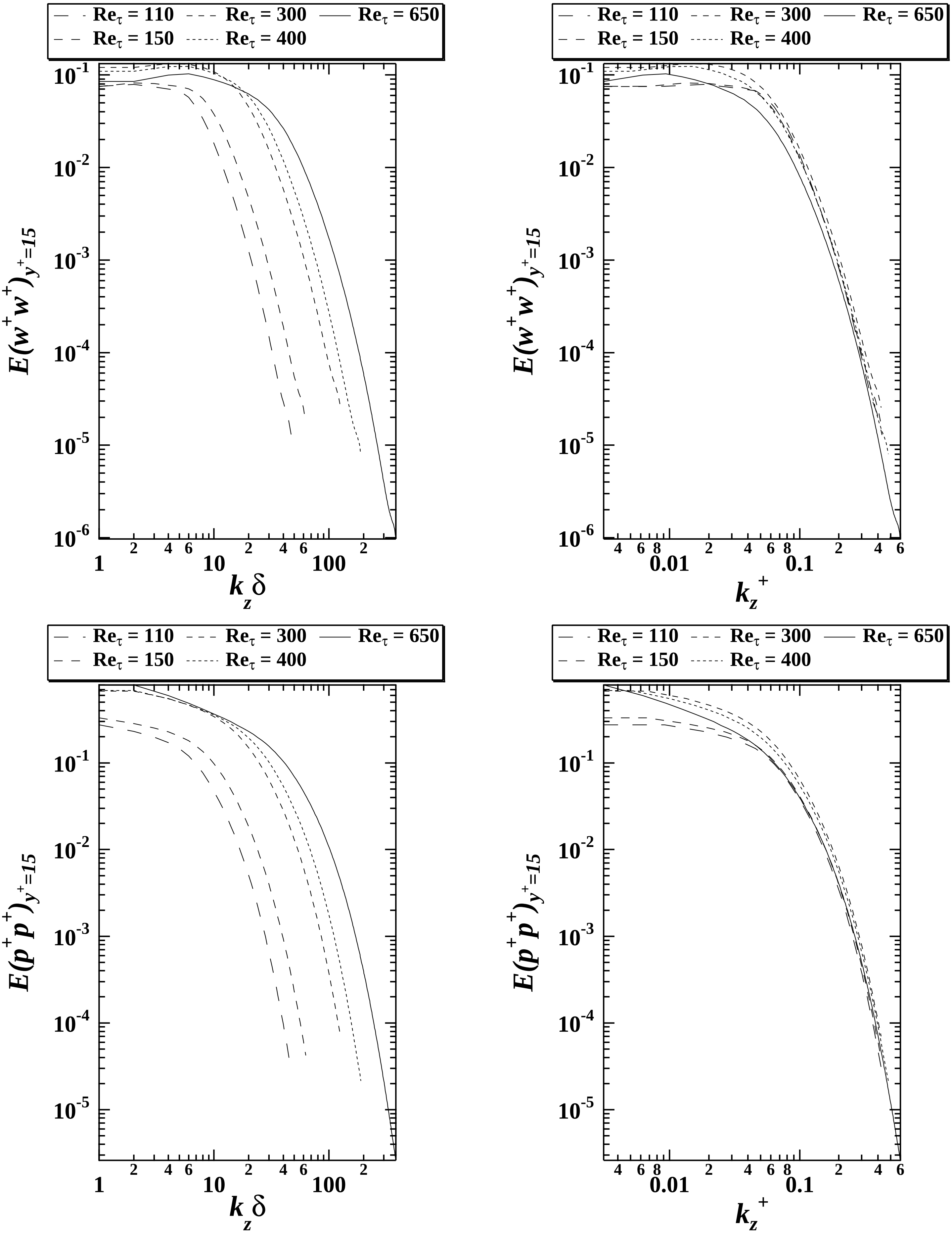
Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(u⁺u⁺)_{y⁺=15}
k_z⁺



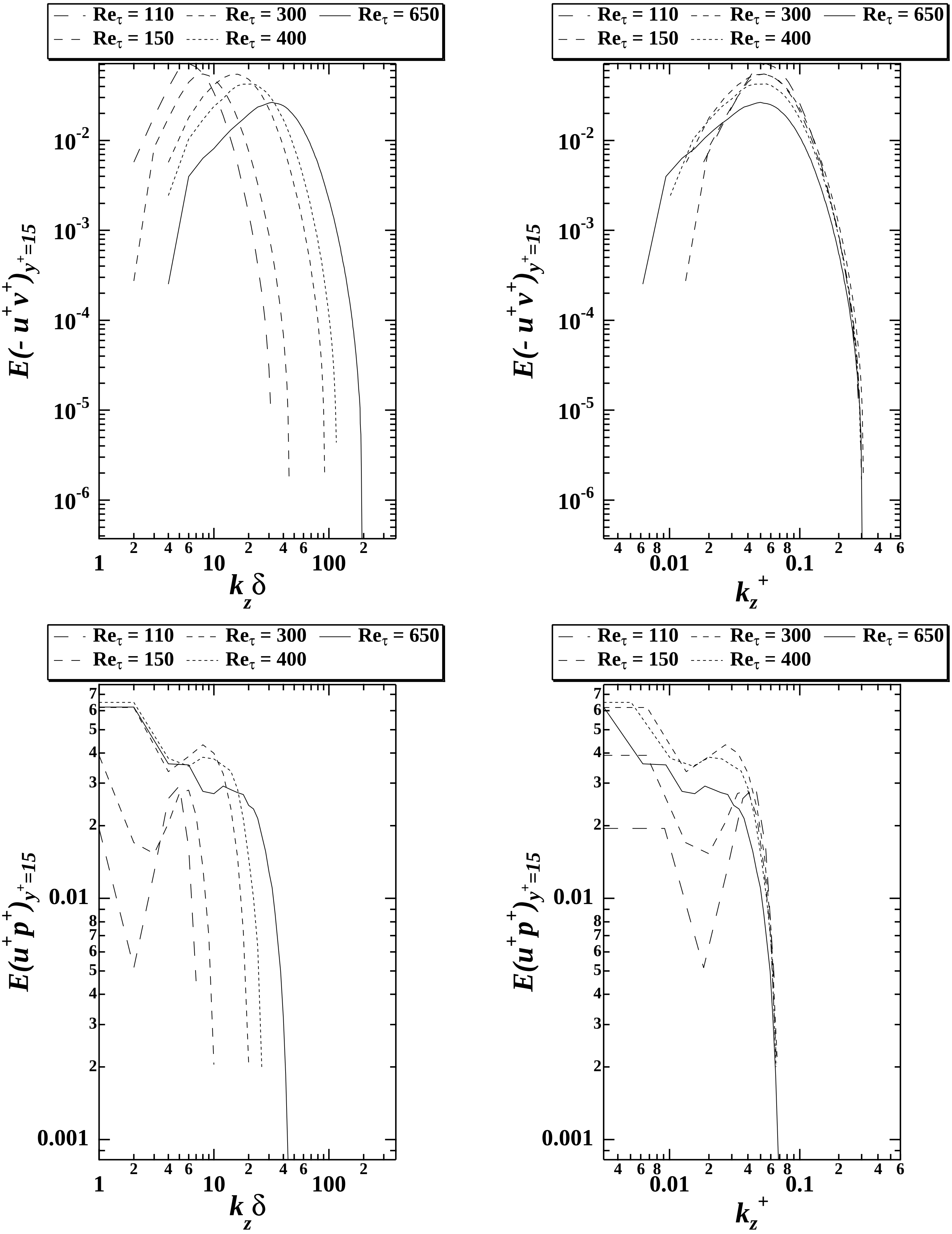
Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(v⁺v⁺)_{y⁺=15}
k_z δ

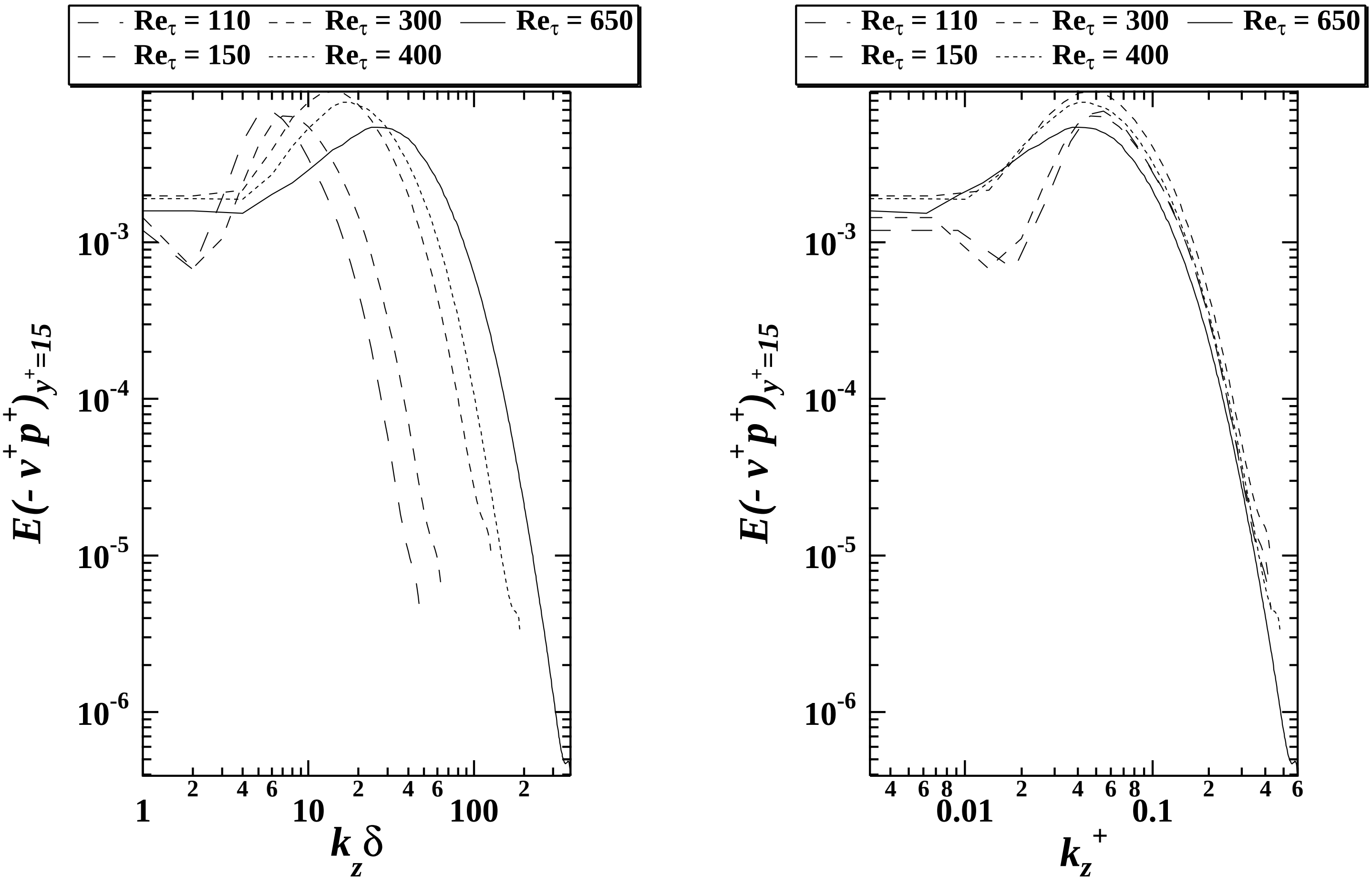


Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(v⁺v⁺)_{y⁺=15}
k_z⁺



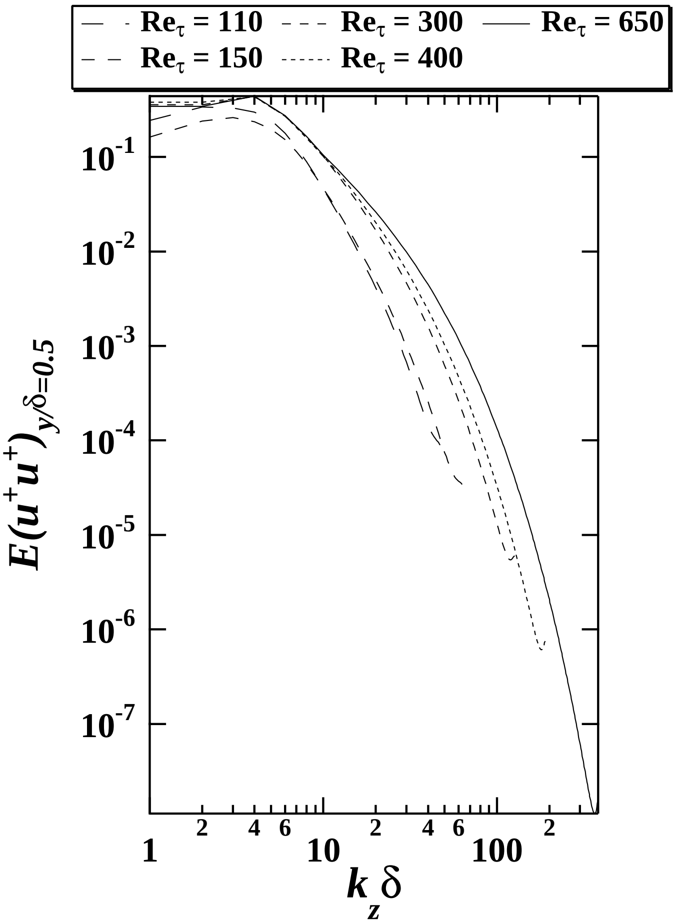
Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
E(w+w+)y+=15
kzδ
kz+
E(p+p+)y+=15

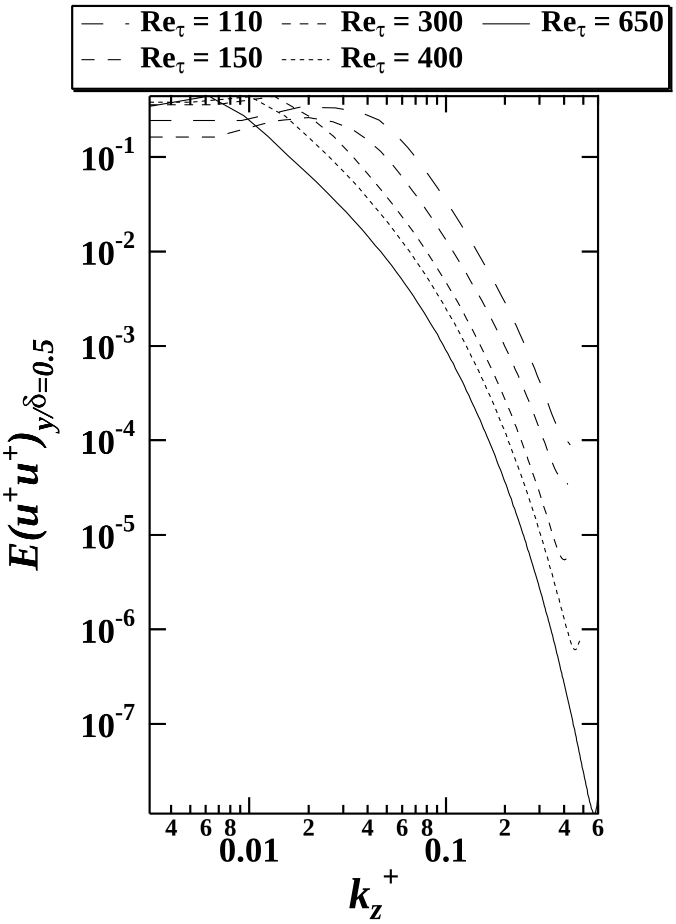

Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-u^+v^+)_{y^+=15}$
$k_z\delta$
k_z^+
$E(u^+p^+)_{y^+=15}$

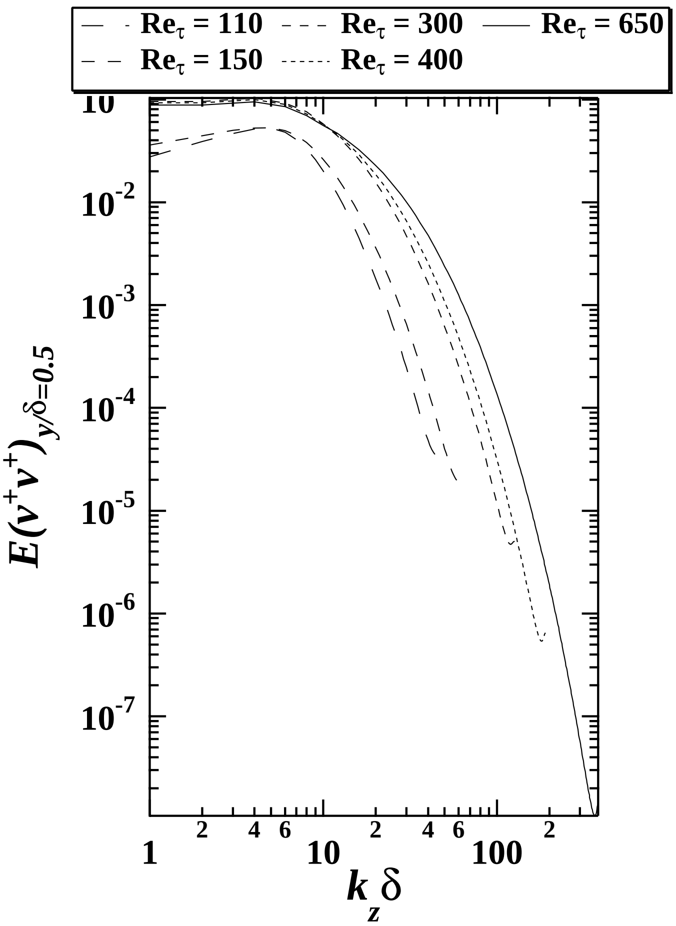


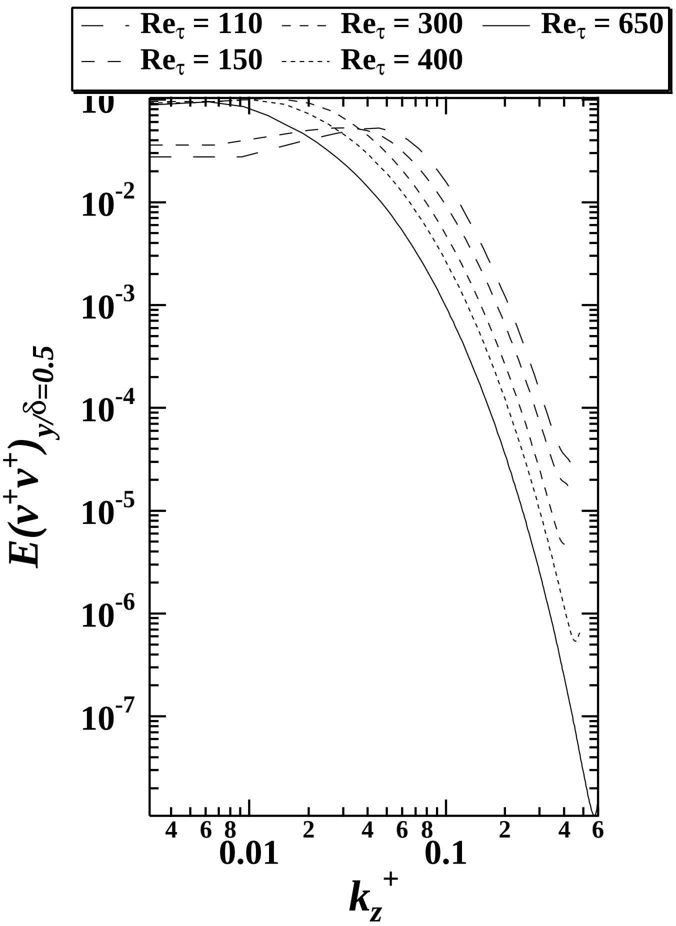
Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
E(- v+p+)y+=15
10-3
10-4
10-5
10-6
1
10
100
kzδ
0.01
0.1
kz+

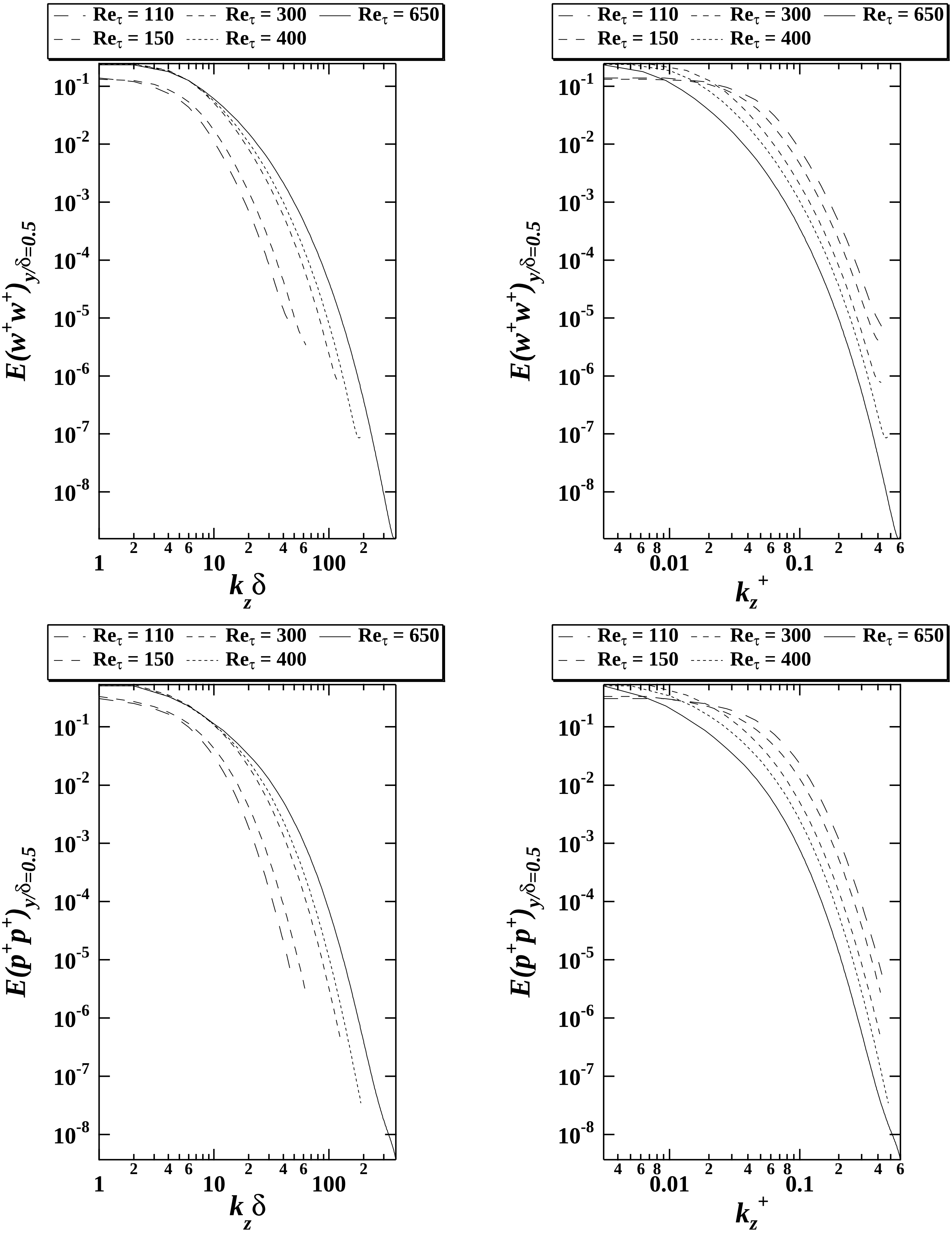
4.2.3 at $y/\delta = 0.5$

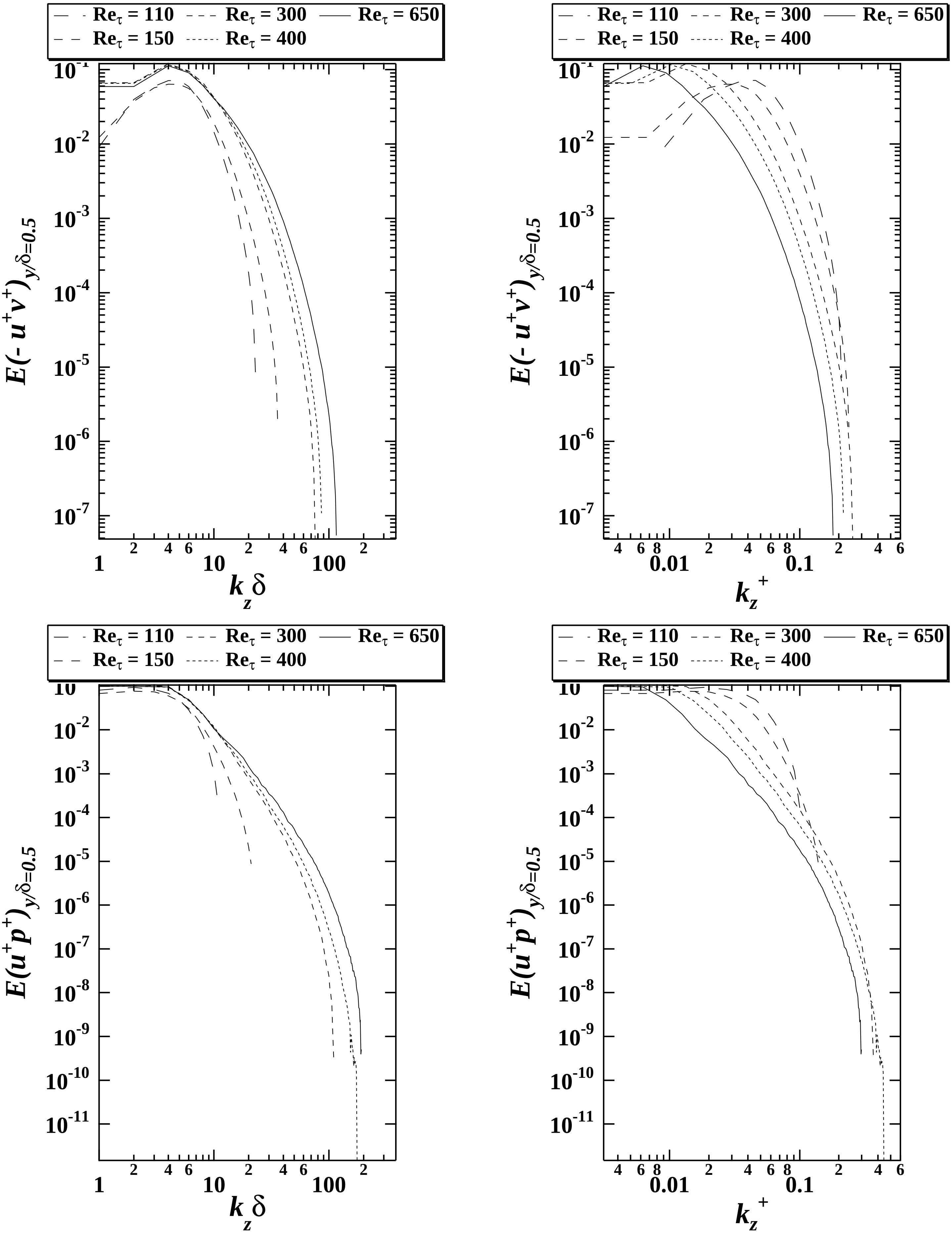




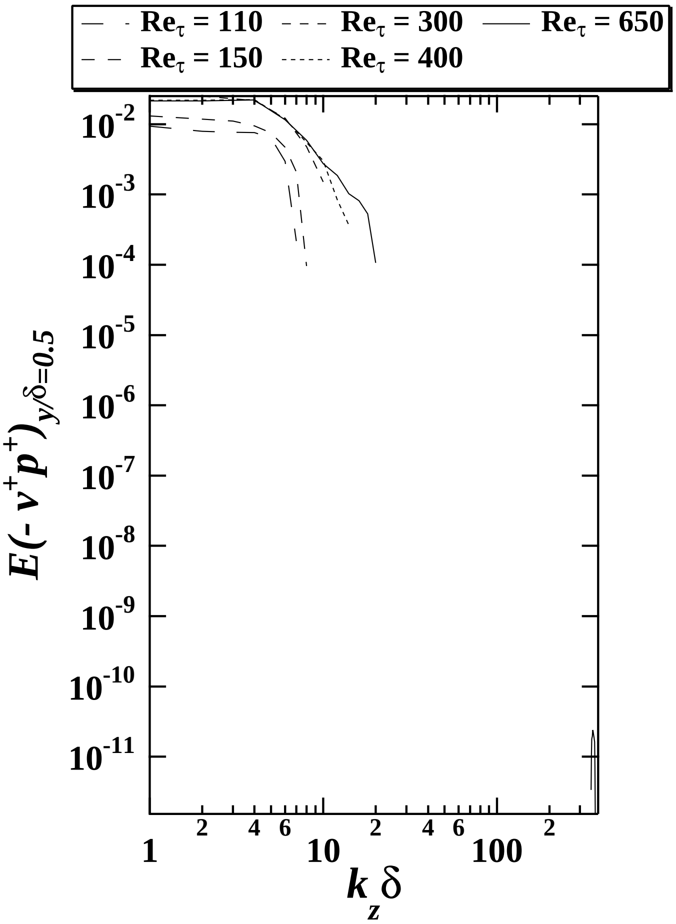




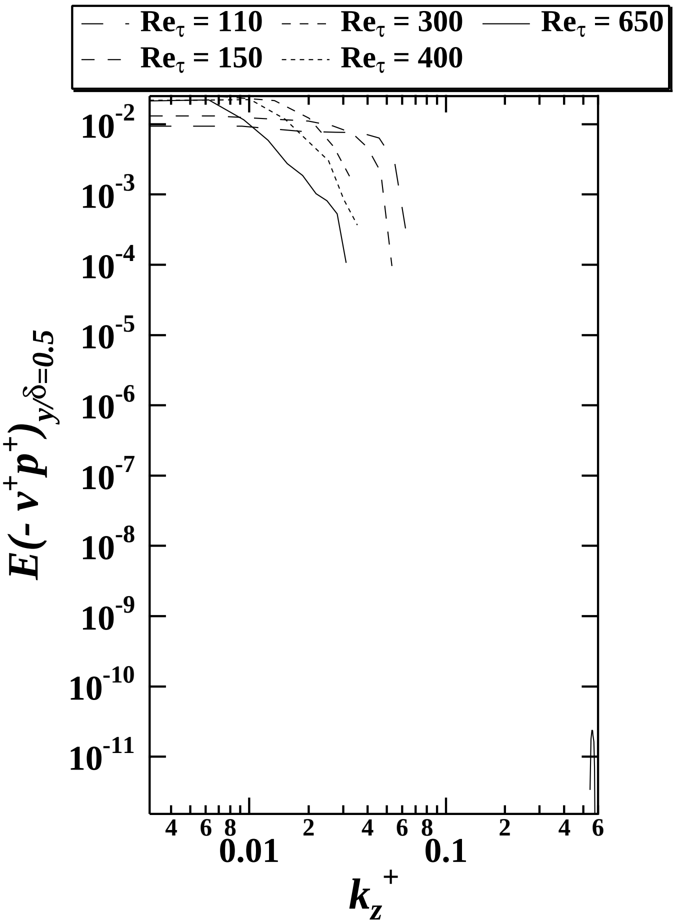

Re_τ = 110
Re_τ = 300
Re_τ = 650
Re_τ = 150
Re_τ = 400
E(w+w+)y/δ=0.5
k_z δ
k_z+
E(p+p+)y/δ=0.5
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
1
10
100
0.01
0.1



Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
$E(-u^+v^+)_{y/\delta=0.5}$
$k_z\delta$
k_z^+
$E(u^+p^+)_{y/\delta=0.5}$

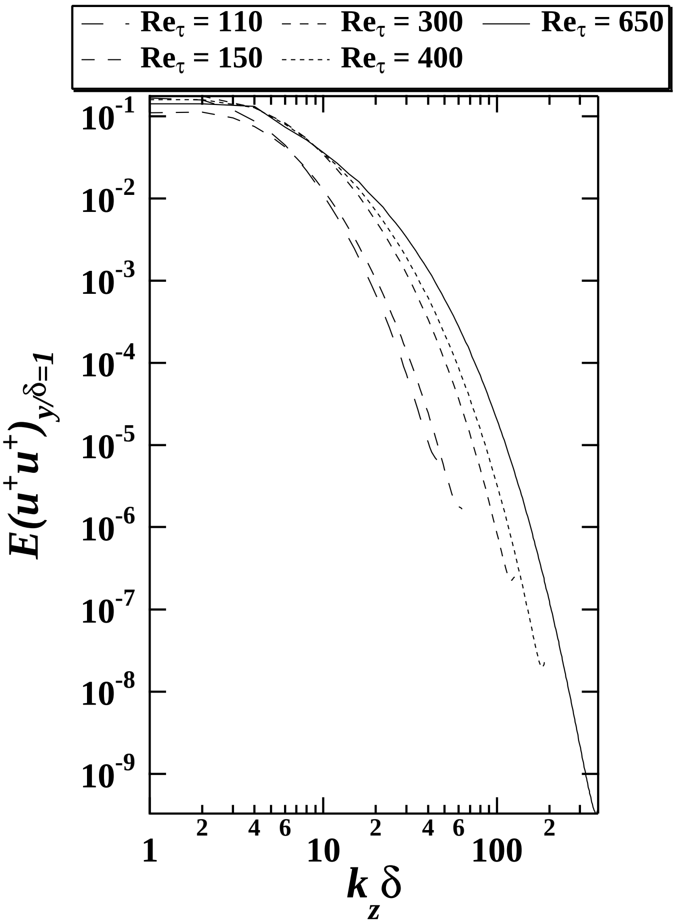


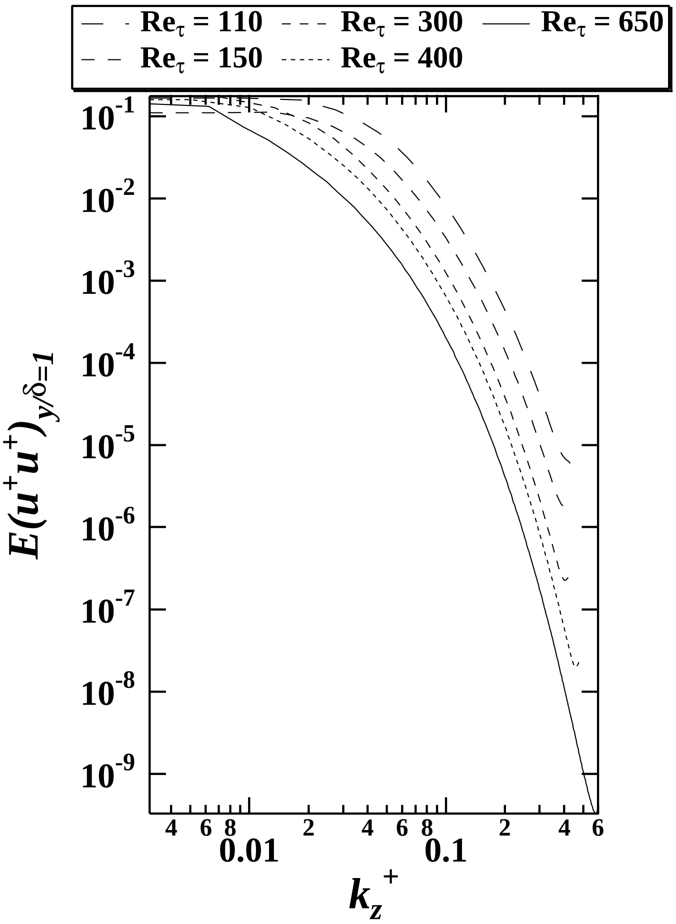
Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
$E(-v^+p^+)_{y/\delta=0.5}$
$k_z\delta$

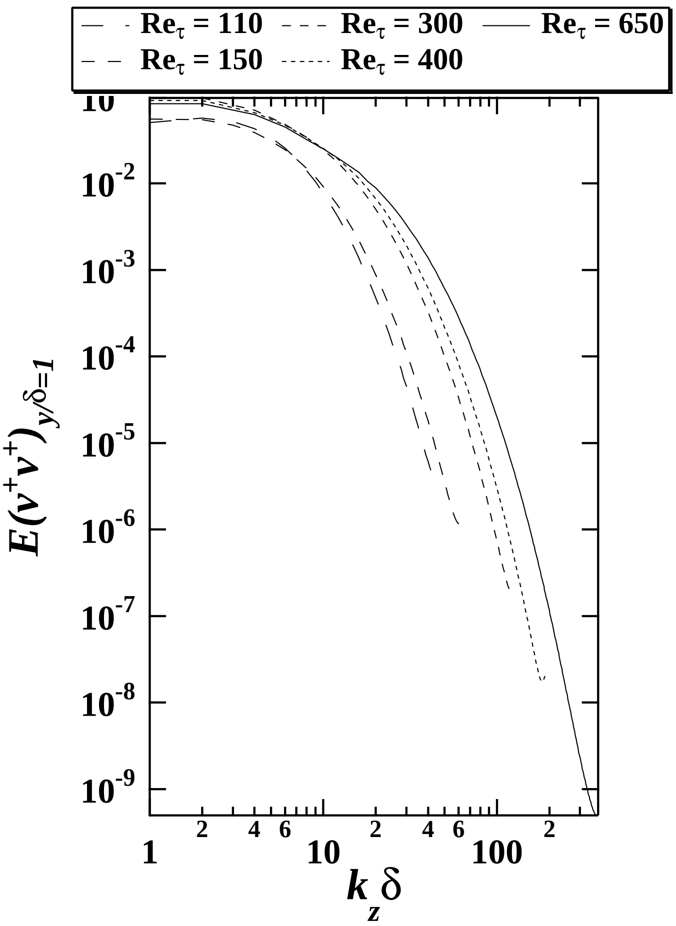


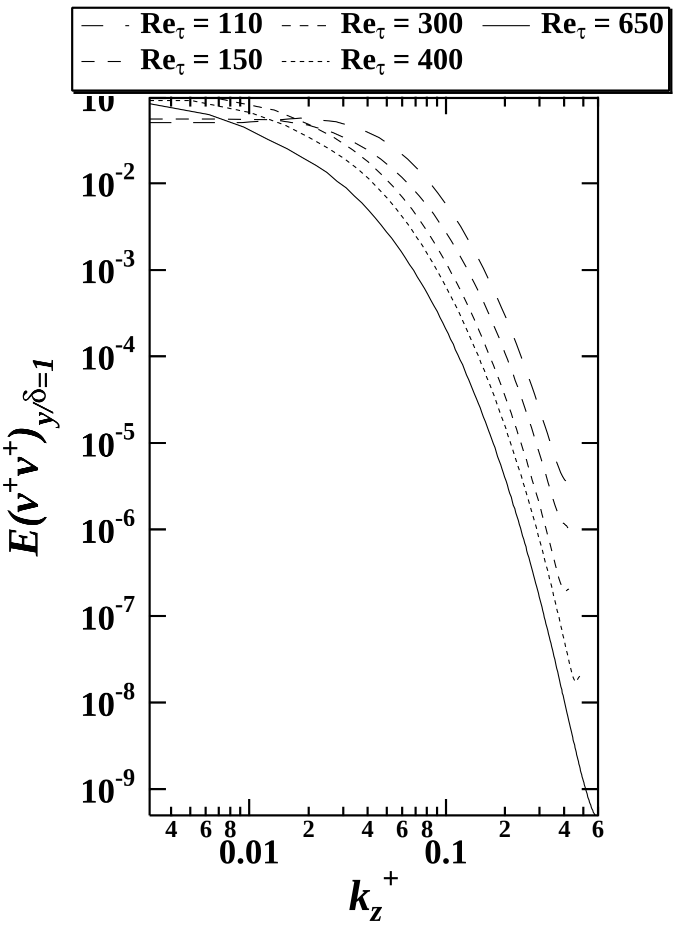
Re$_\tau$ = 110
Re$_\tau$ = 300
Re$_\tau$ = 650
Re$_\tau$ = 150
Re$_\tau$ = 400
$E(-v^+p^+)_{y/\delta=0.5}$
k_z^+

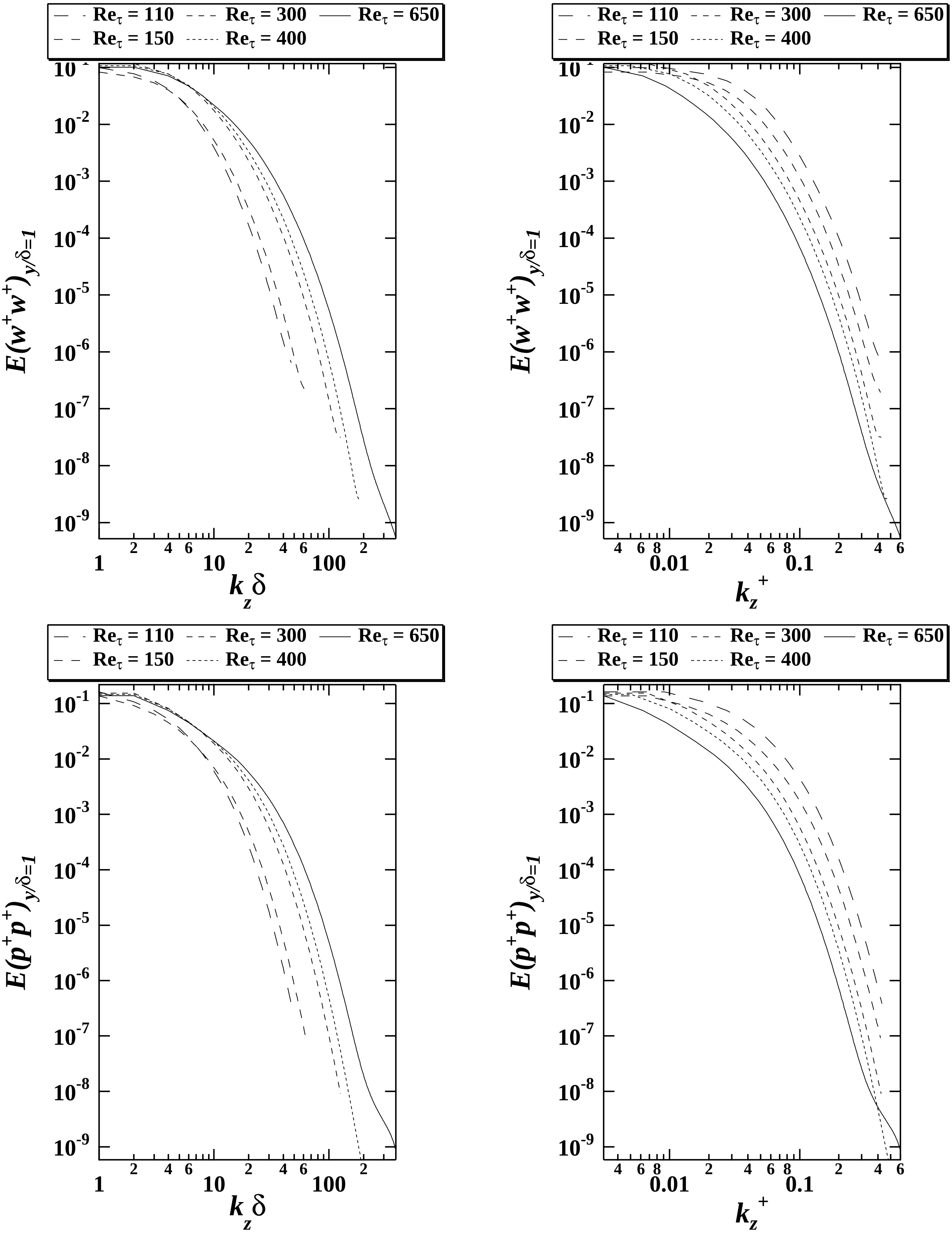
4.2.4 at $y/\delta = 1$

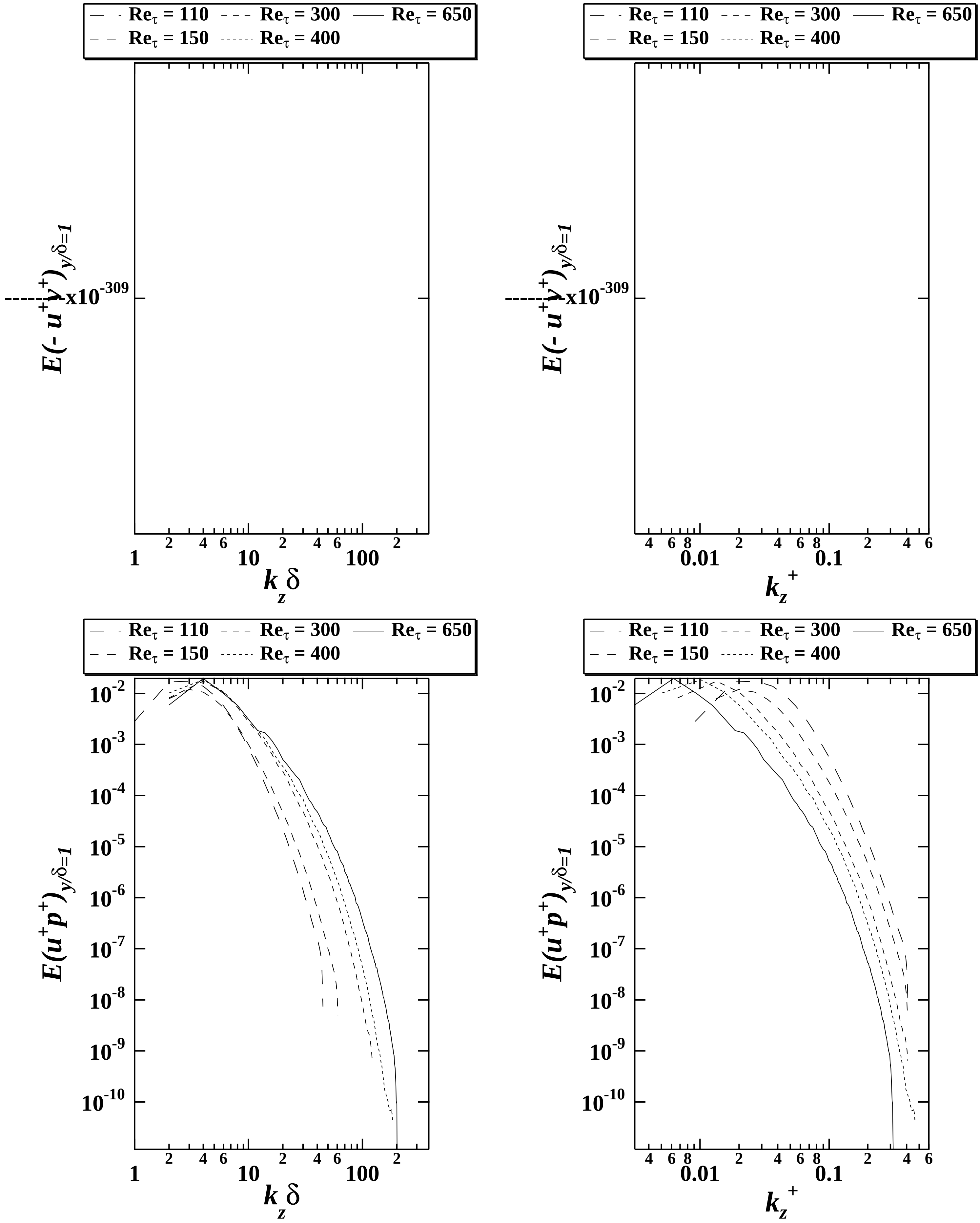




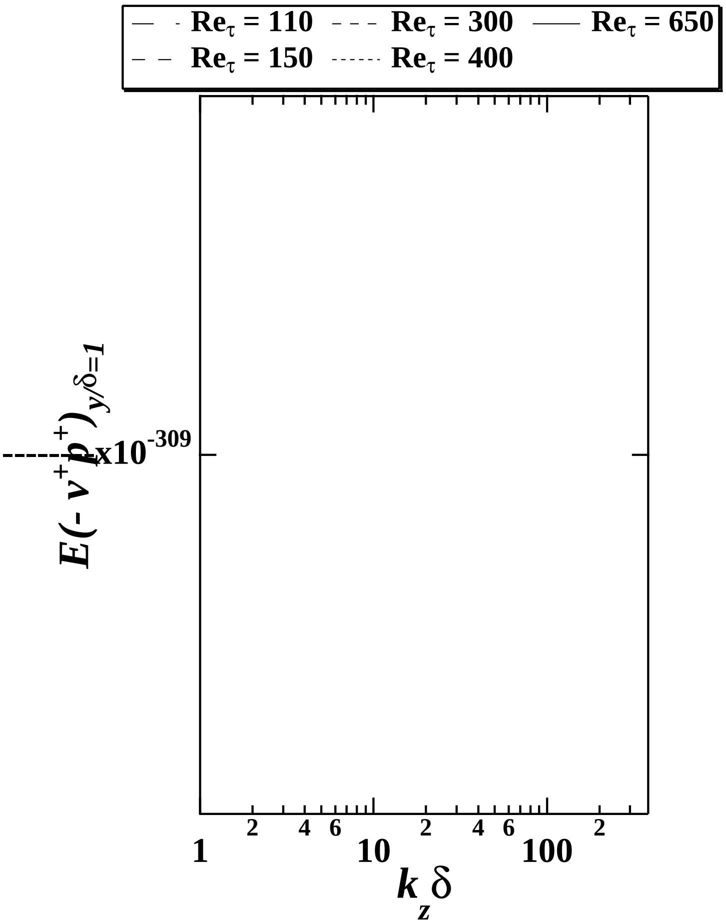


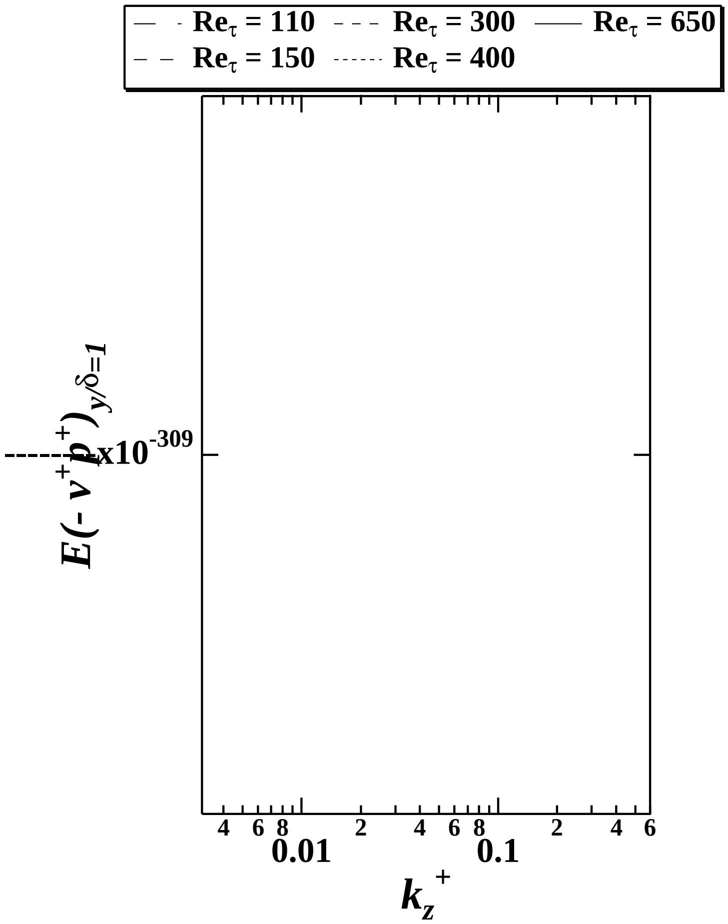



Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(w^+w^+)_{y/\delta=1}$
$E(p^+p^+)_{y/\delta=1}$
$k_z\delta$
k_z^+
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1
10
100
0.01
0.1



Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$E(-u^+v^+)_{y/\delta=1}$
x10^{-309}
$k_z\delta$
k_z^+
$E(u^+p^+)_{y/\delta=1}$

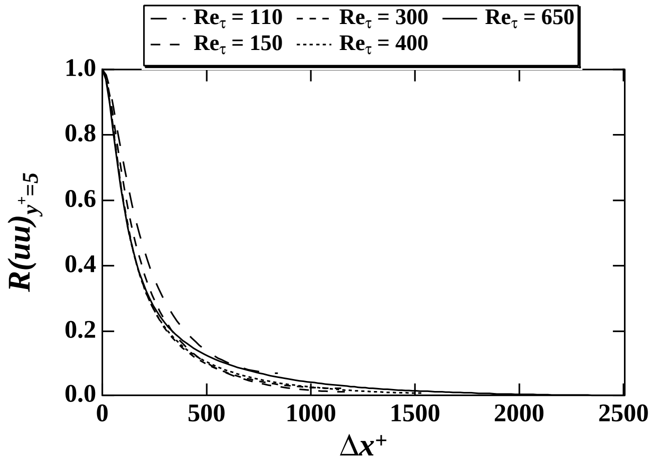

Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
E(- v+p+)y/δ=1
x10-309
1
2
4
6
10
2
4
6
100
2
kzδ

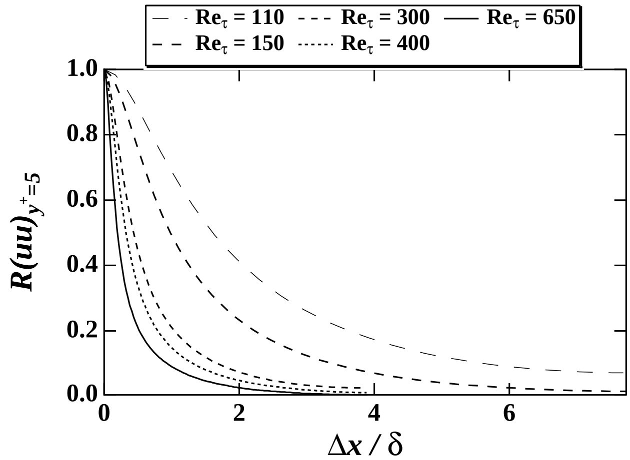

Reτ = 110
Reτ = 300
Reτ = 650
Reτ = 150
Reτ = 400
E(- v+p+)y/δ=1
x10-309
4
6
8
0.01
2
4
6
8
0.1
2
4
6
kz+

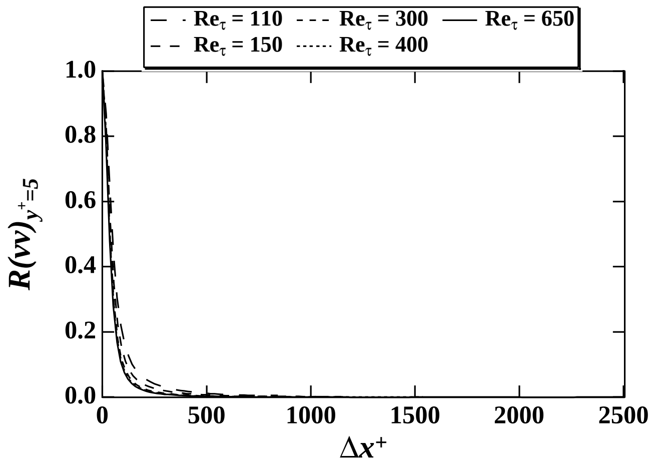
5 Two-point Correlations at several points

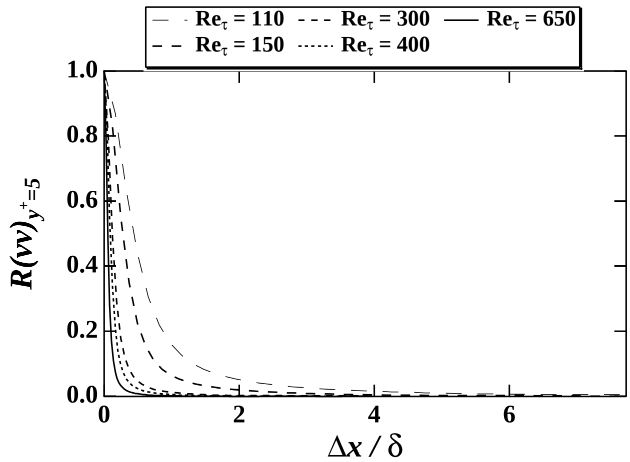
5.1 Streamwise Separations

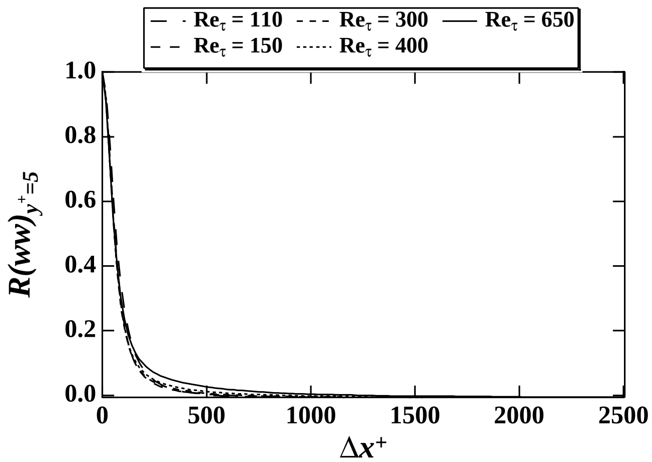
5.1.1 at $y^+ = 5$

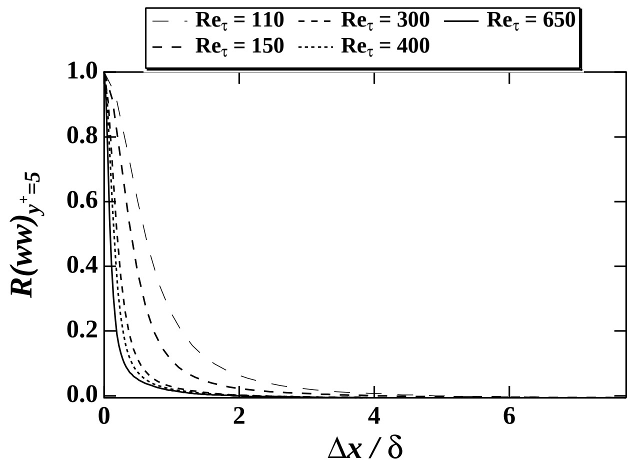


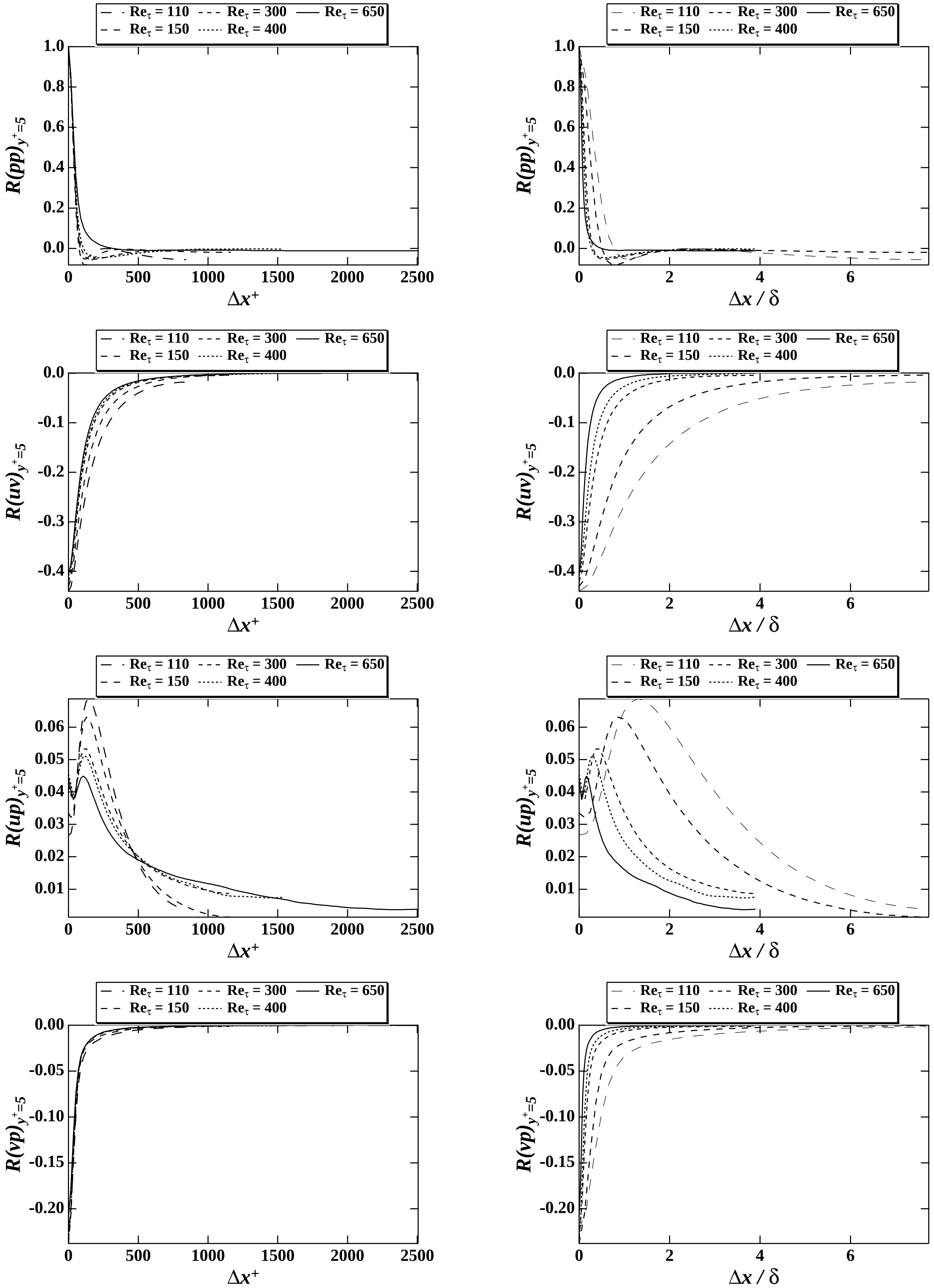






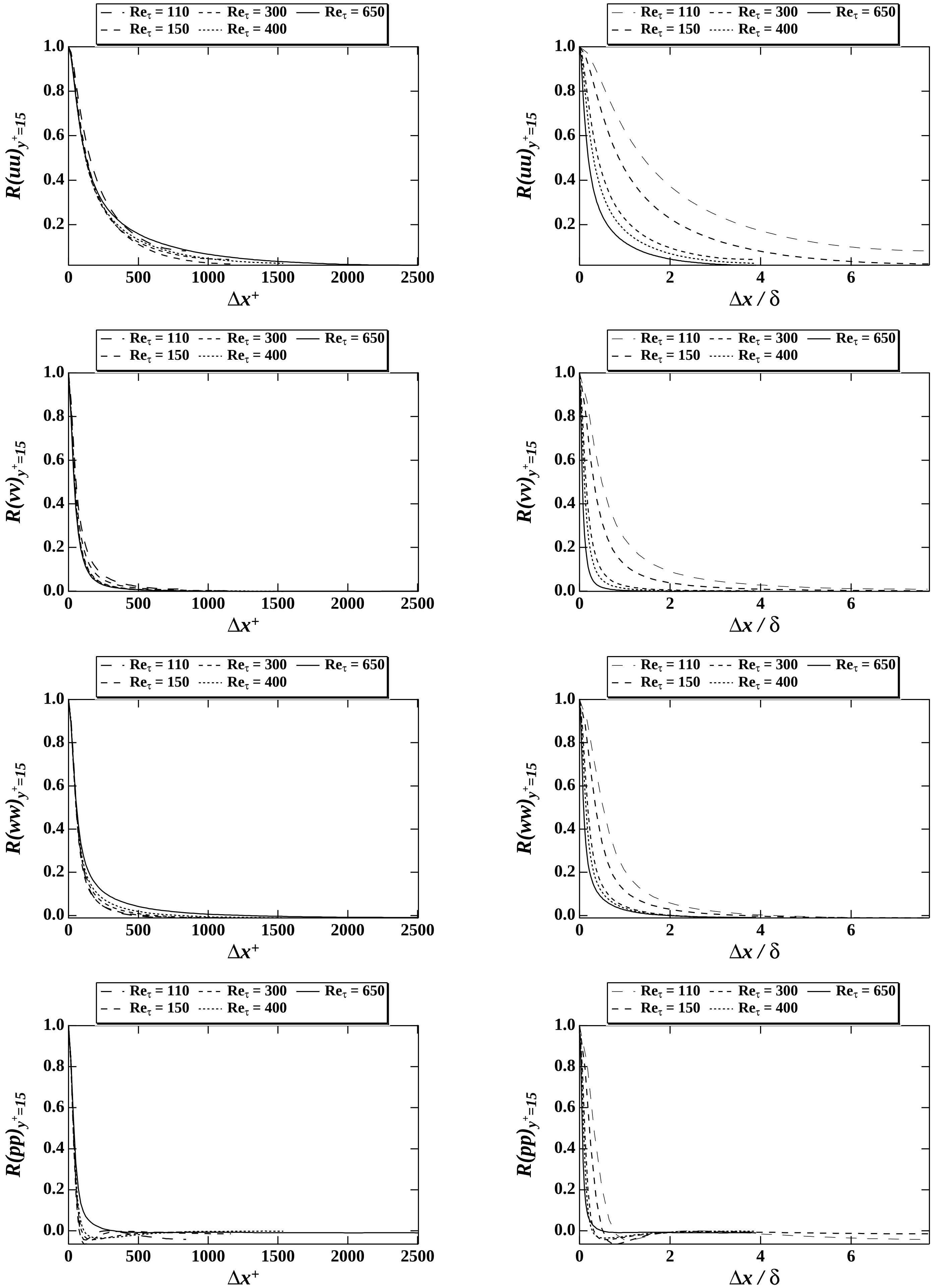




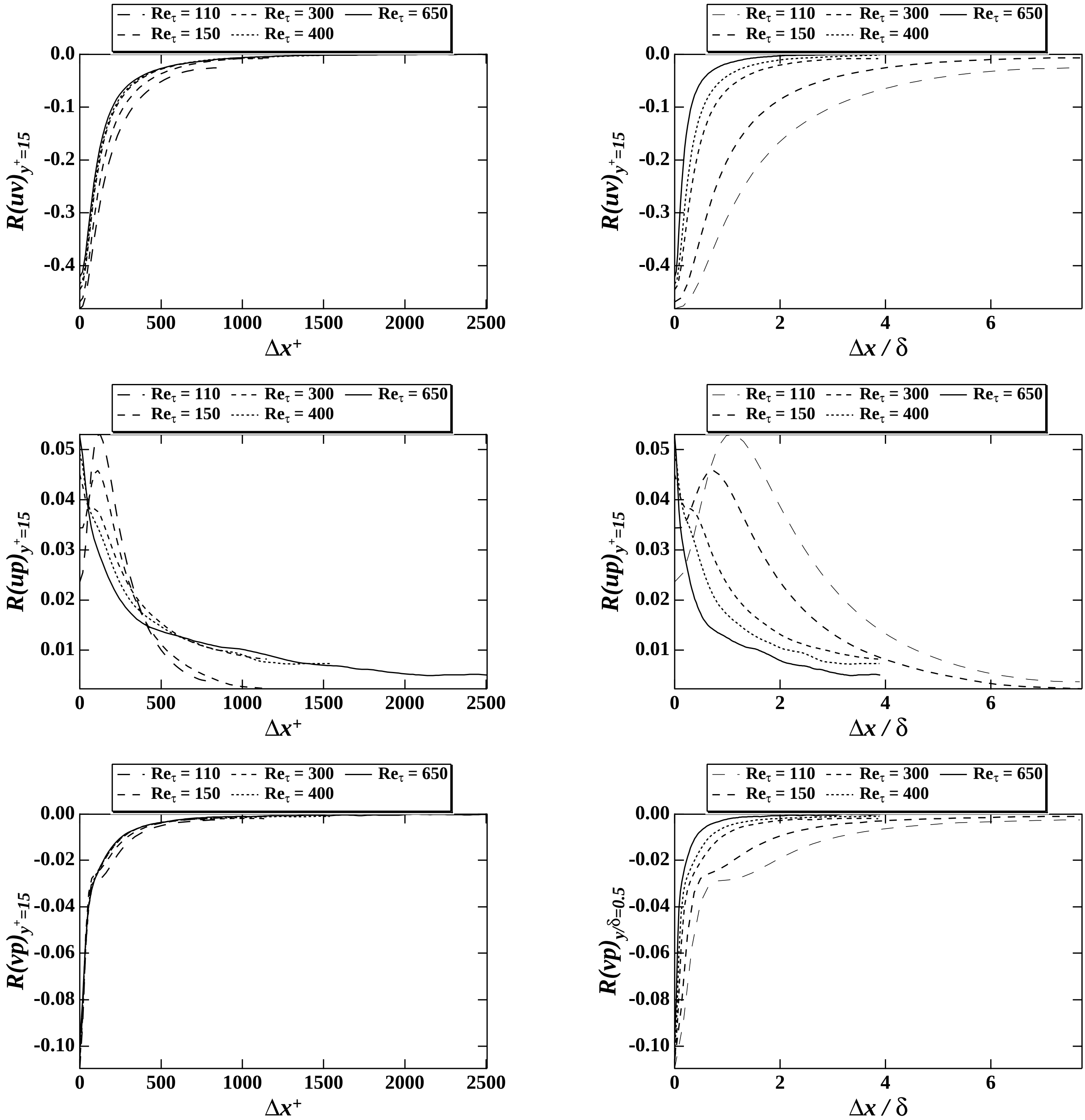


Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
$R(pp)_{y^+=5}$
$R(uv)_{y^+=5}$
$R(up)_{y^+=5}$
$R(vp)_{y^+=5}$
Δx^+
$\Delta x / \delta$

5.1.2 at $y^+ = 15$

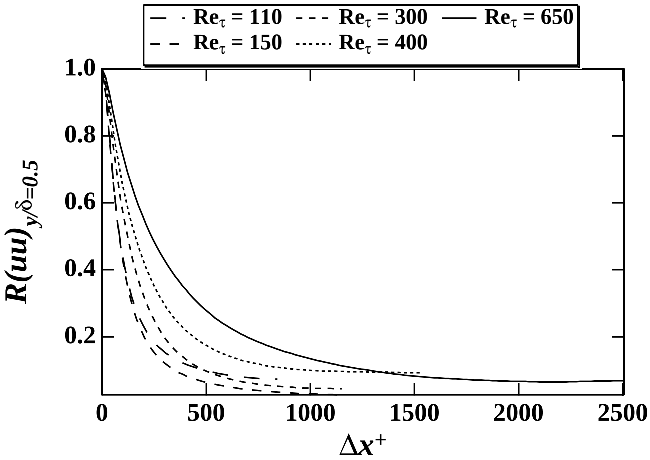


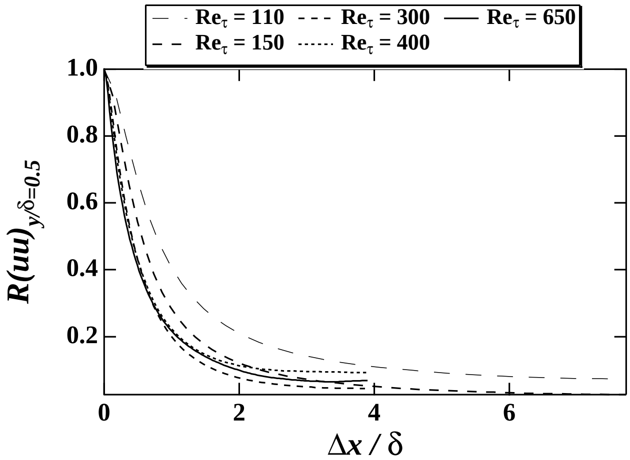
Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
R(uu)_y+=15
R(vv)_y+=15
R(ww)_y+=15
R(pp)_y+=15
Δx+
Δx / δ
0.0
0.2
0.4
0.6
0.8
1.0
0
500
1000
1500
2000
2500
2
4
6

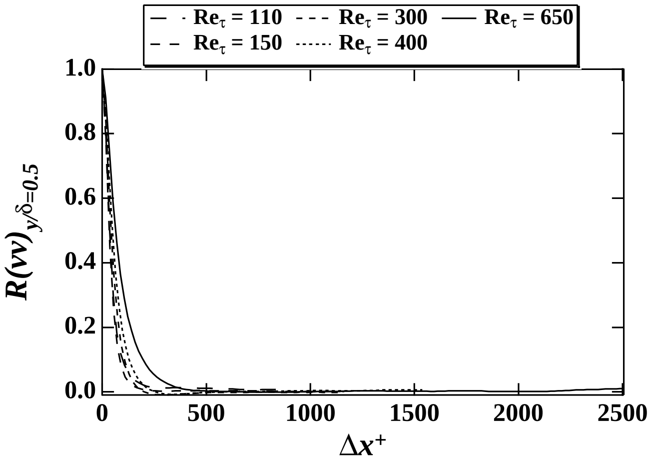


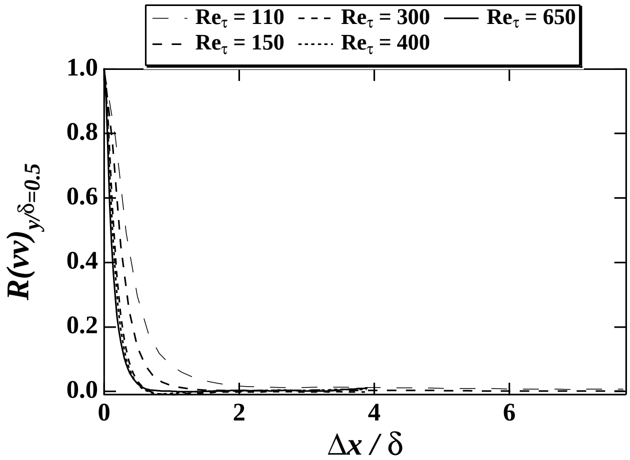
Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$R(uv)_{y^+=15}$
$R(up)_{y^+=15}$
$R(vp)_{y^+=15}$
$R(vp)_{y/\delta=0.5}$
Δx^+
$\Delta x / \delta$
0
500
1000
1500
2000
2500
2
4
6
0.0
-0.1
-0.2
-0.3
-0.4
0.05
0.04
0.03
0.02
0.01
0.00
-0.02
-0.04
-0.06
-0.08
-0.10

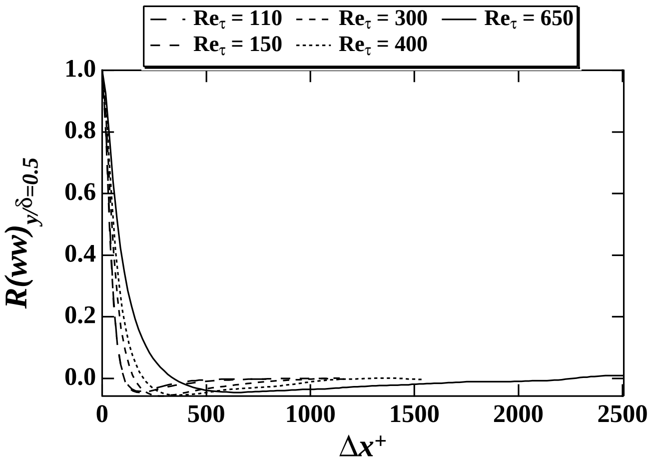
5.1.3 at $y/\delta = 0.5$

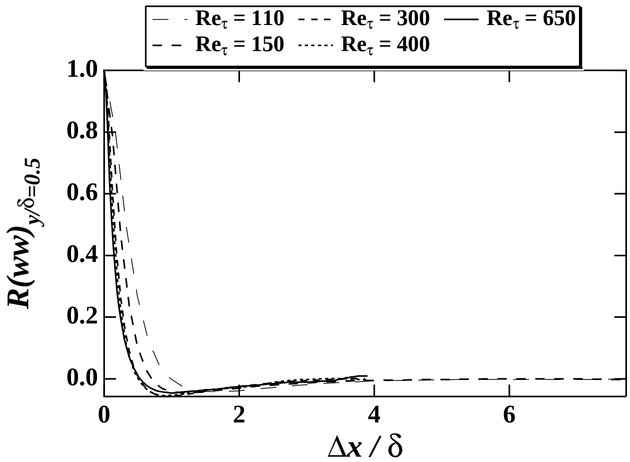


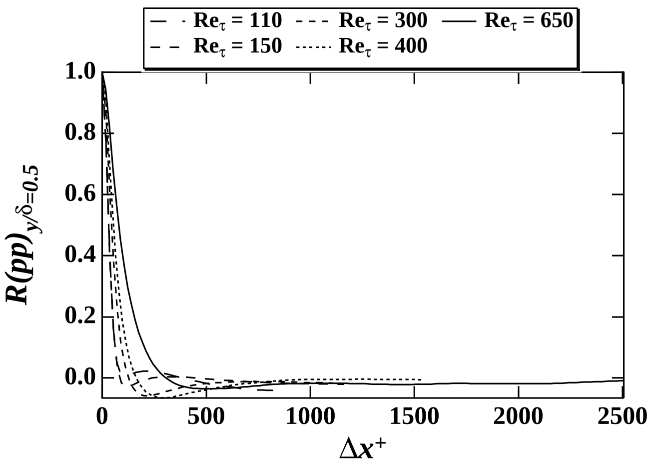


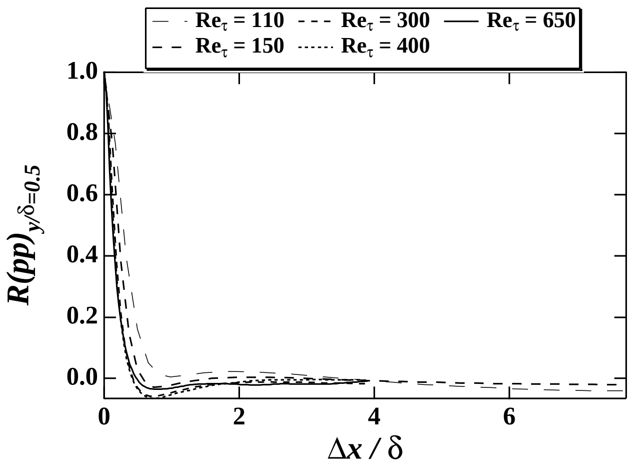


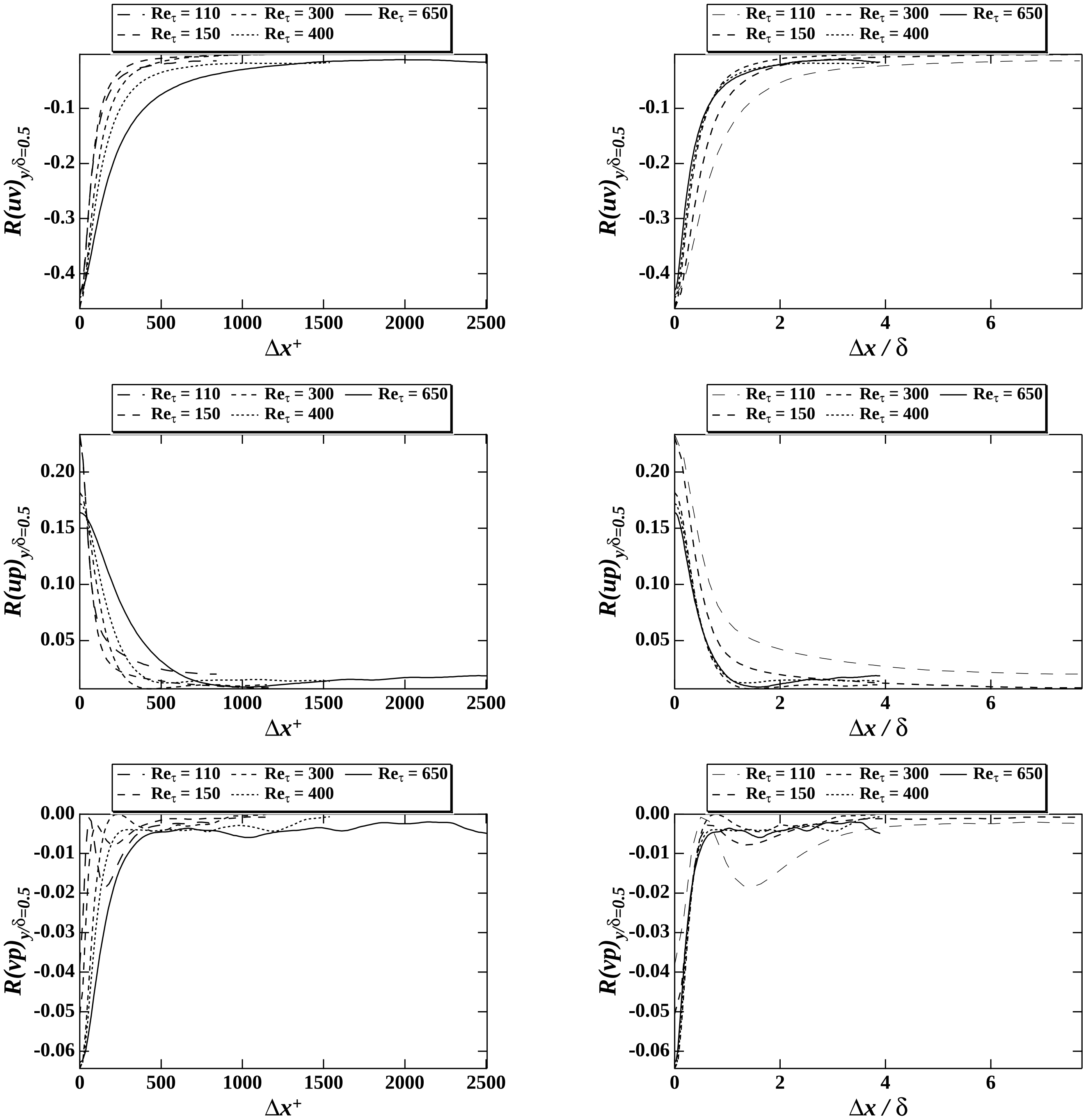




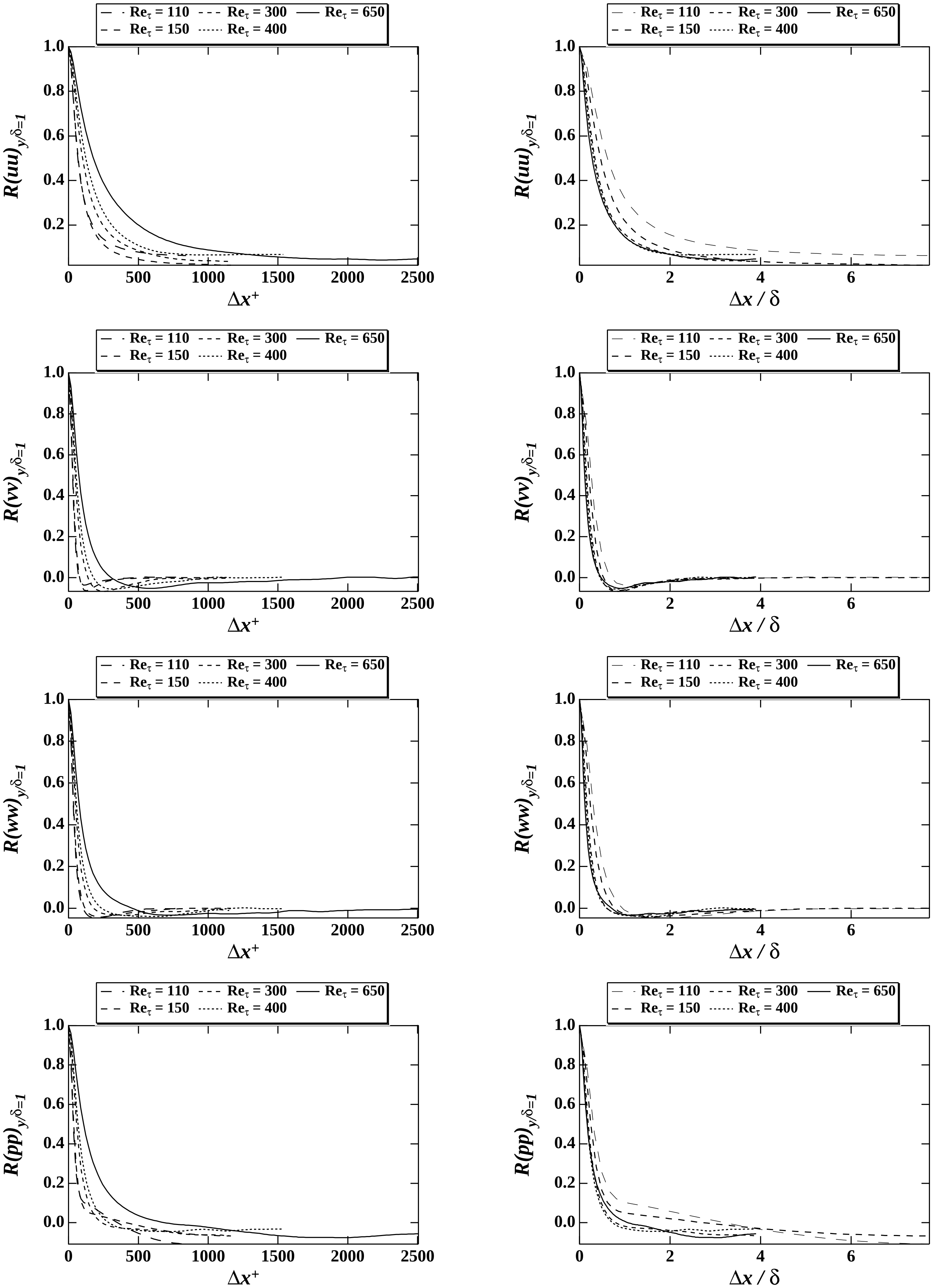


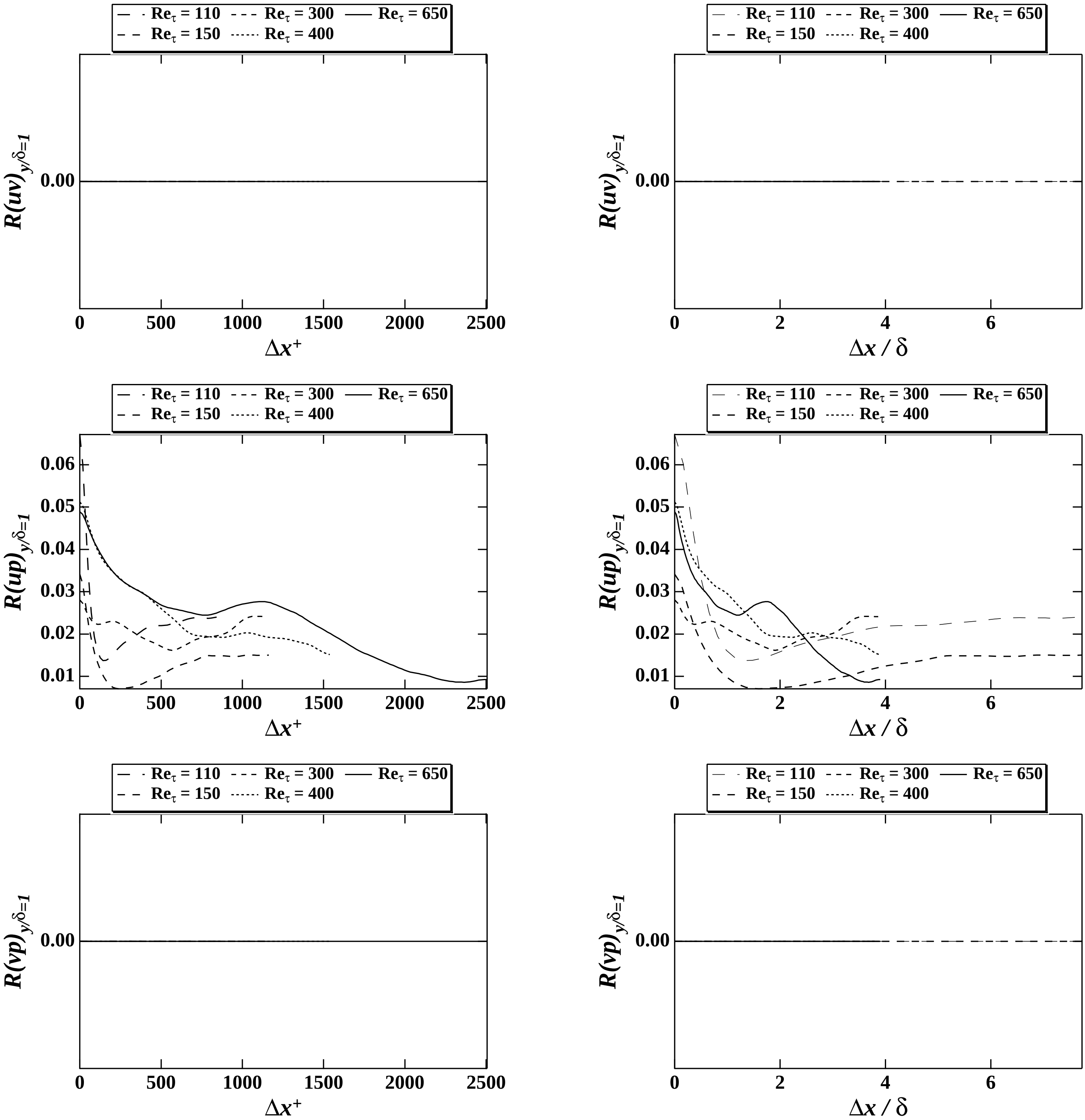





Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
R(uv)y/δ=0.5
R(up)y/δ=0.5
R(vp)y/δ=0.5
Δx+
Δx / δ

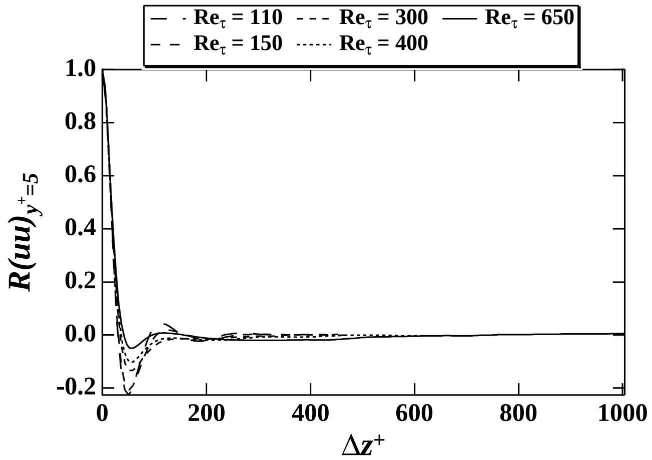
5.1.4 at $y/\delta = 1$

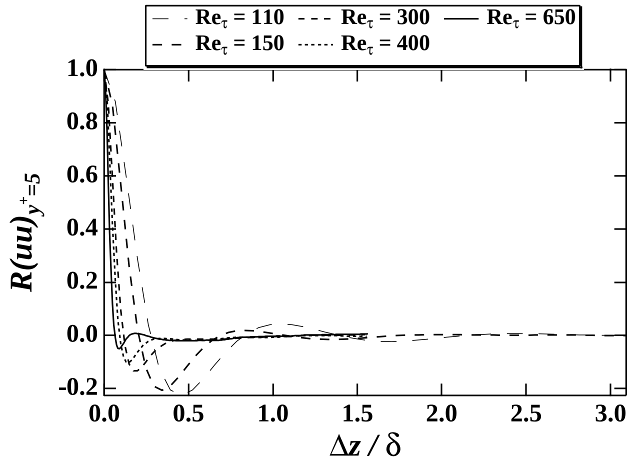


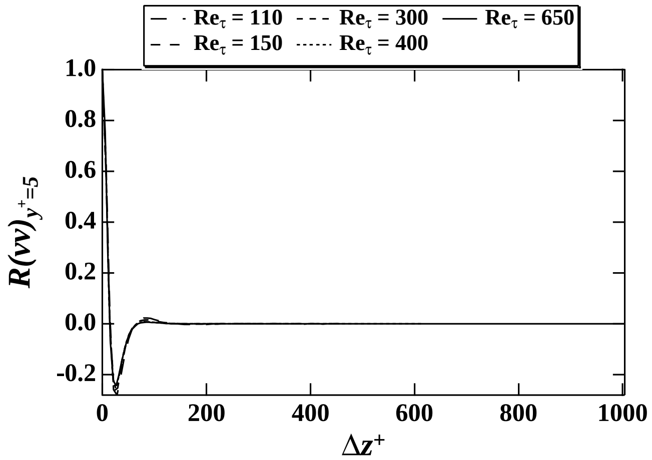

Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
R(uv)_y/δ=1
0.00
0
500
1000
1500
2000
2500
Δx⁺
0
2
4
6
Δx / δ
R(up)_y/δ=1
0.06
0.05
0.04
0.03
0.02
0.01
R(vp)_y/δ=1

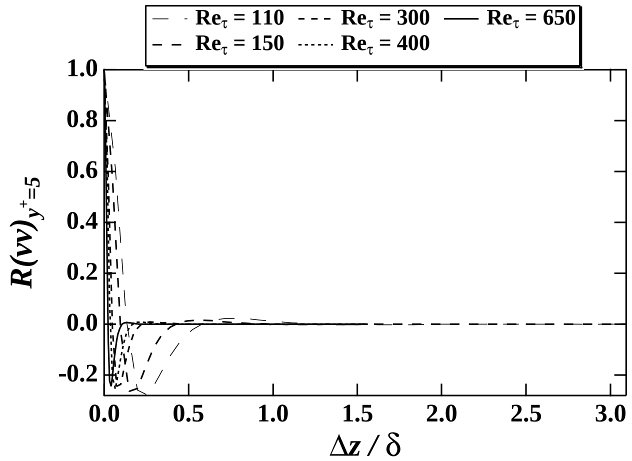
5.2 Spanwise Separations

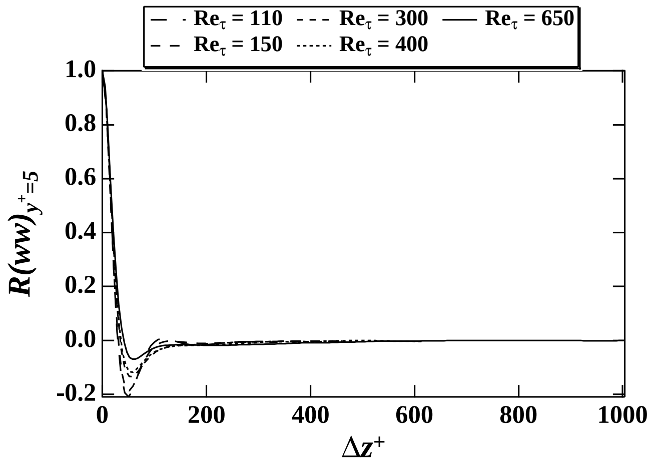
5.2.1 at $y^+ = 5$

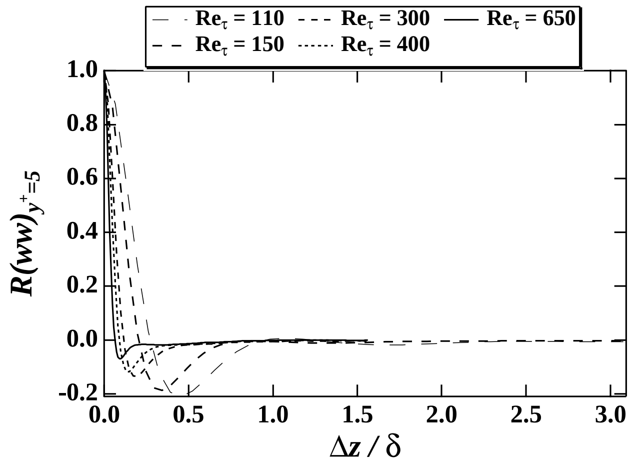


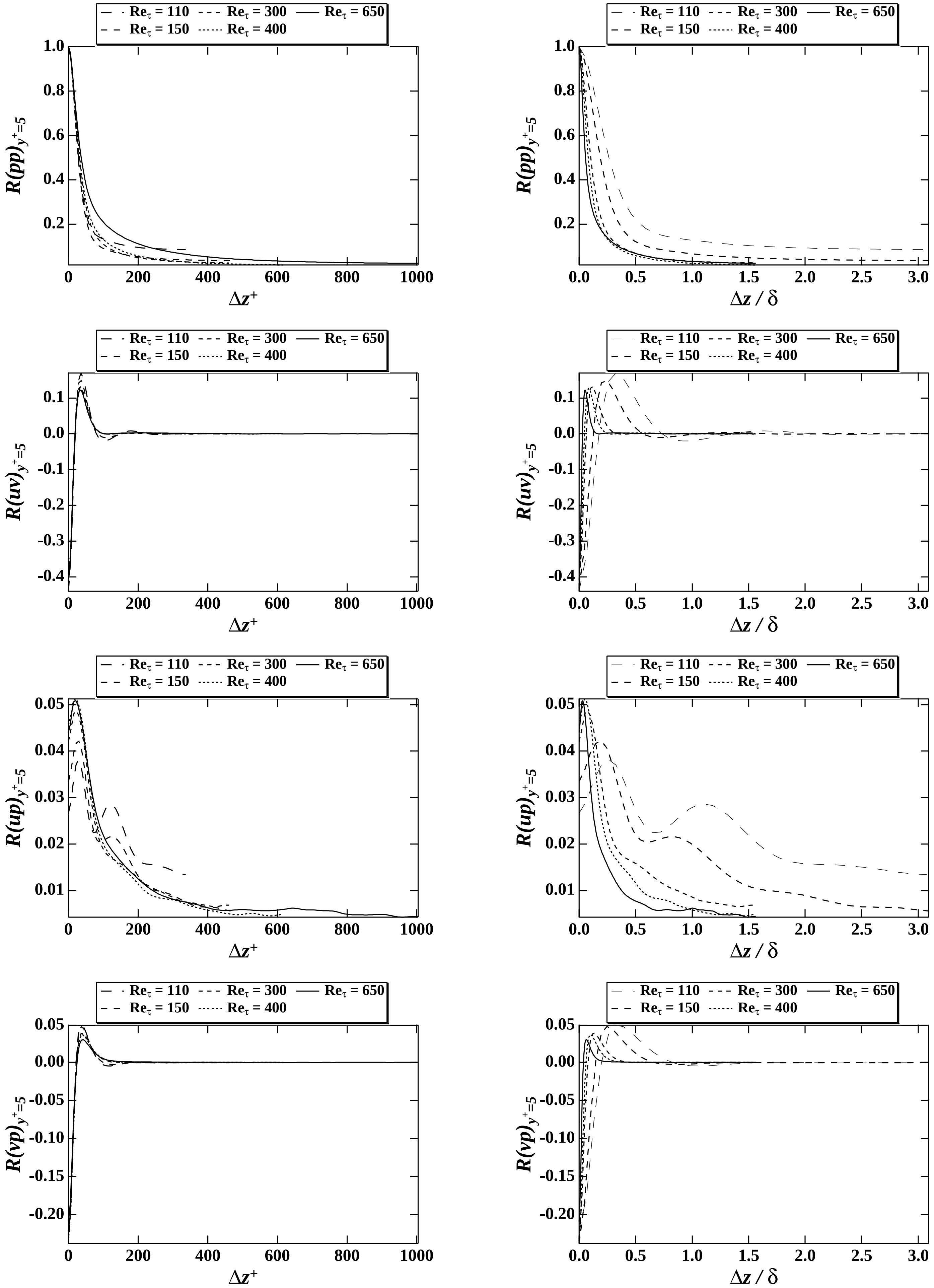




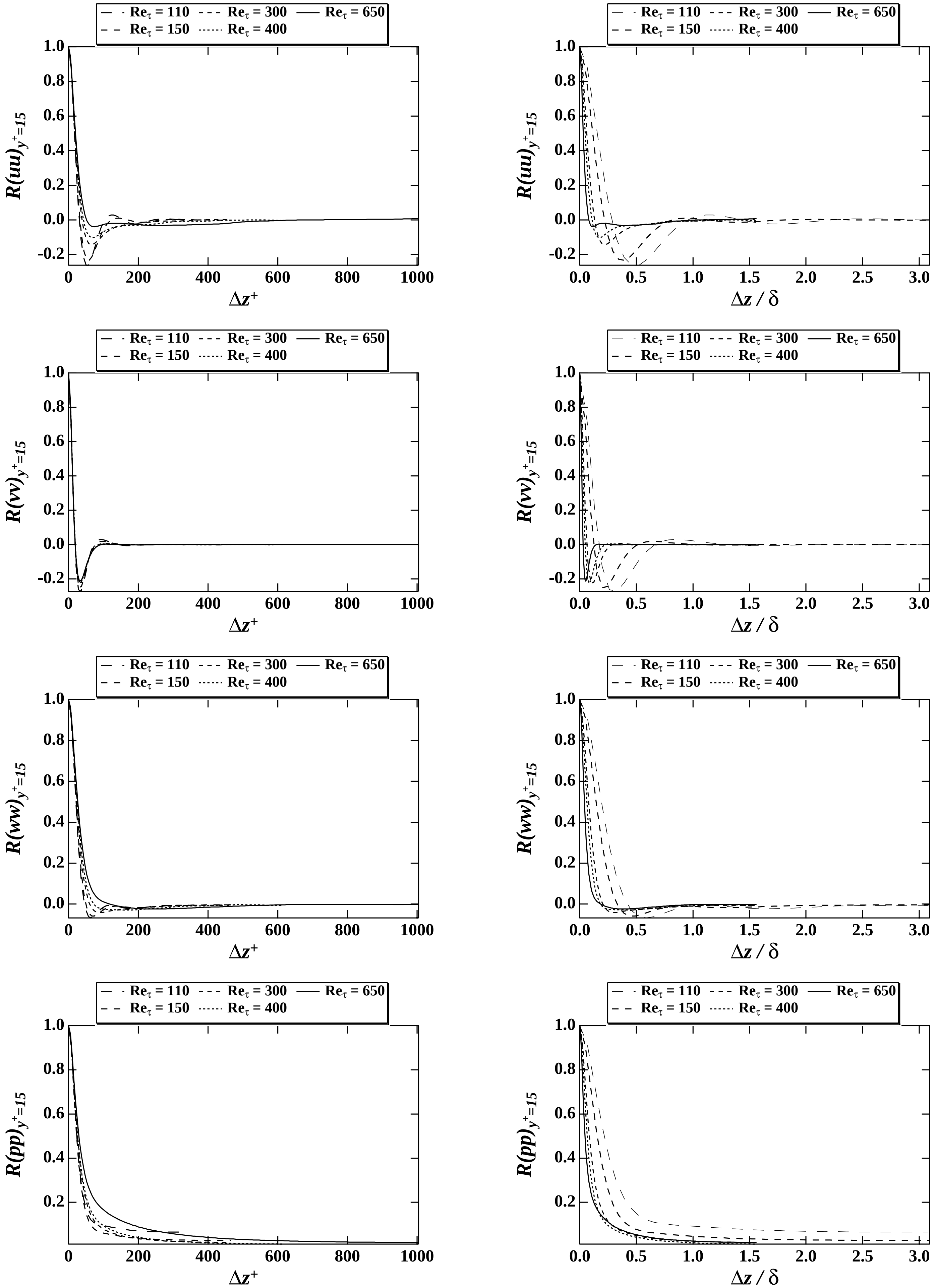


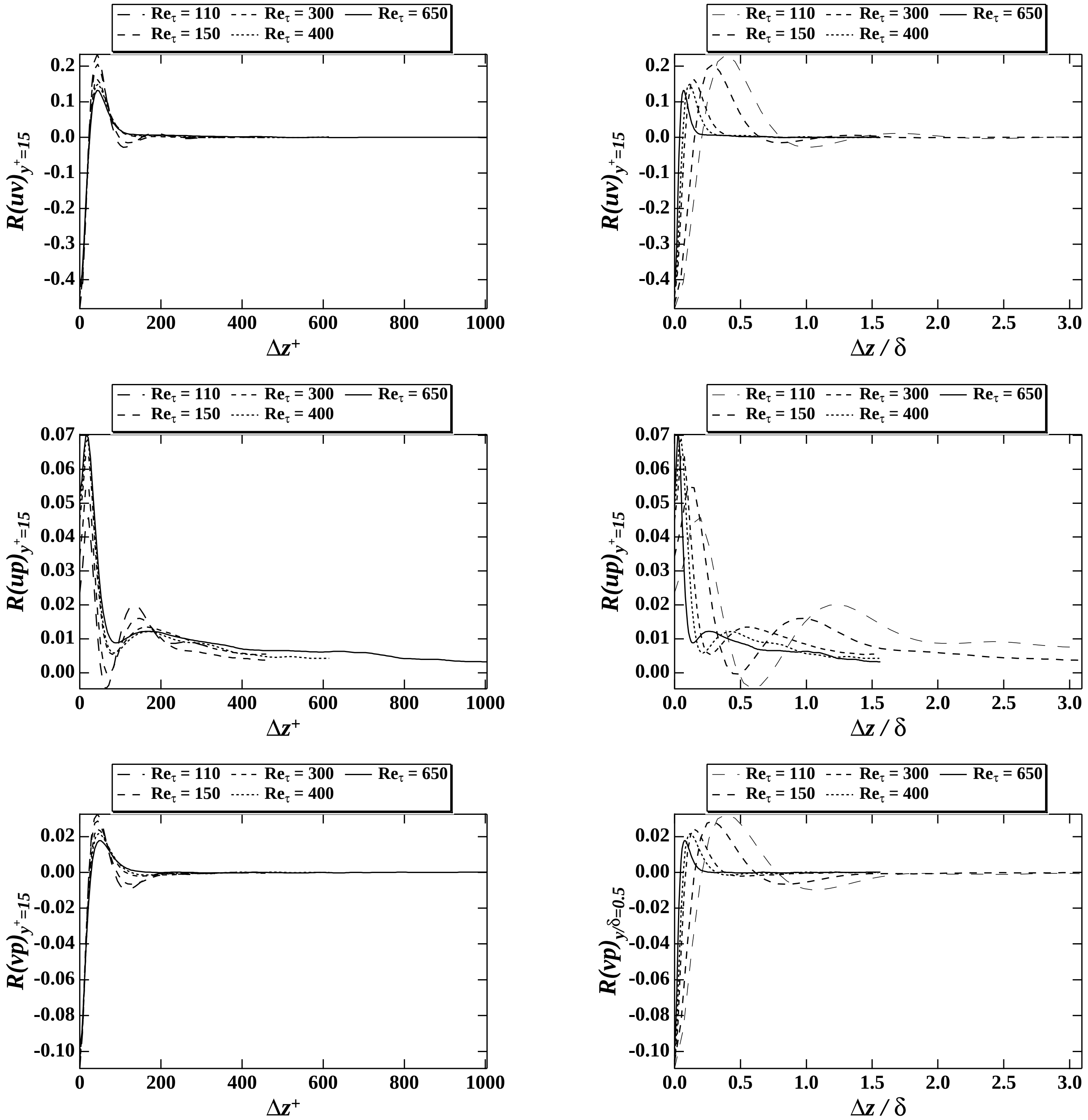





Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$R(pp)_{y^+=5}$
$R(uv)_{y^+=5}$
$R(up)_{y^+=5}$
$R(vp)_{y^+=5}$
Δz^+
Δz / δ

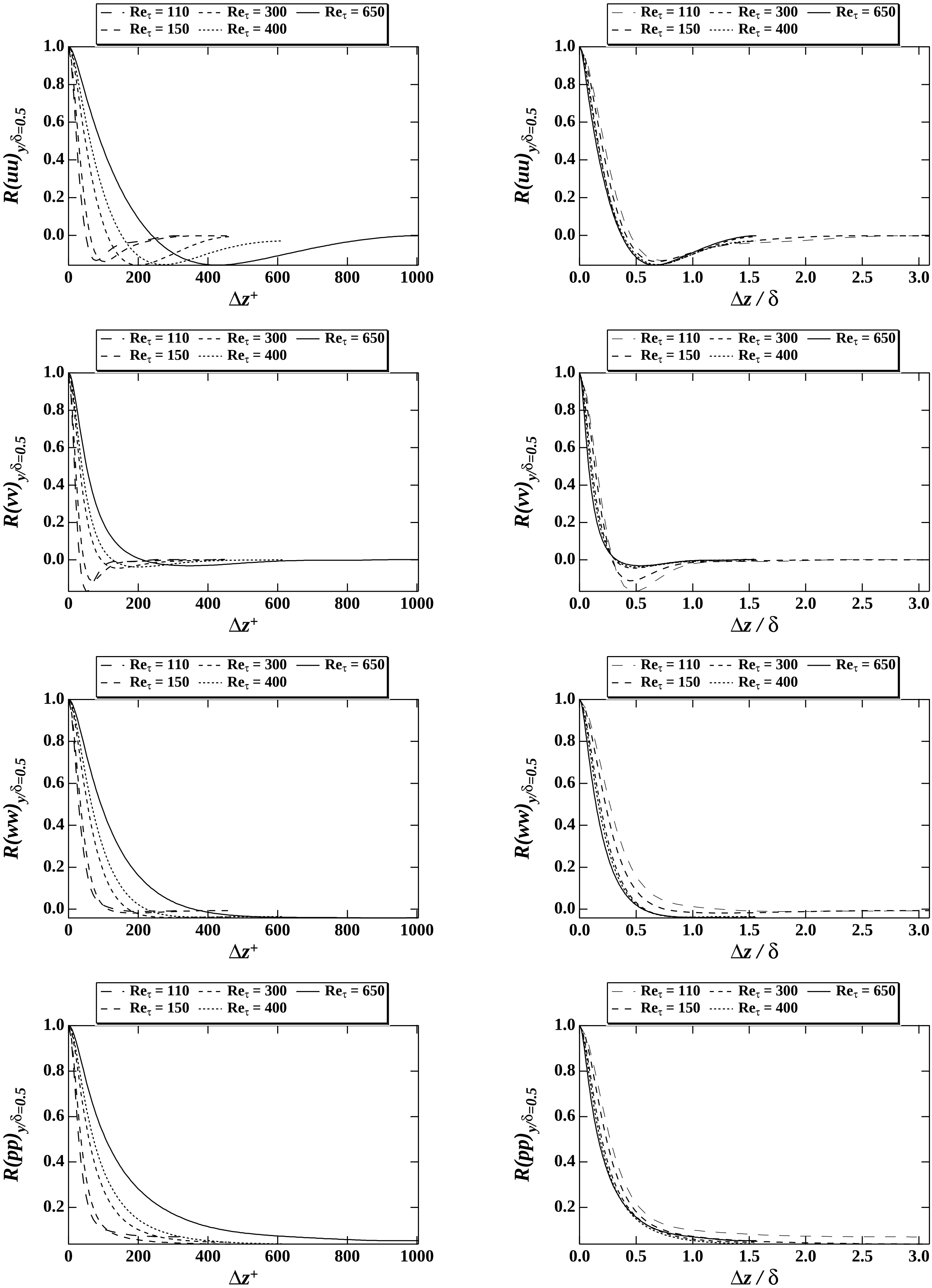
5.2.2 at $y^+ = 15$

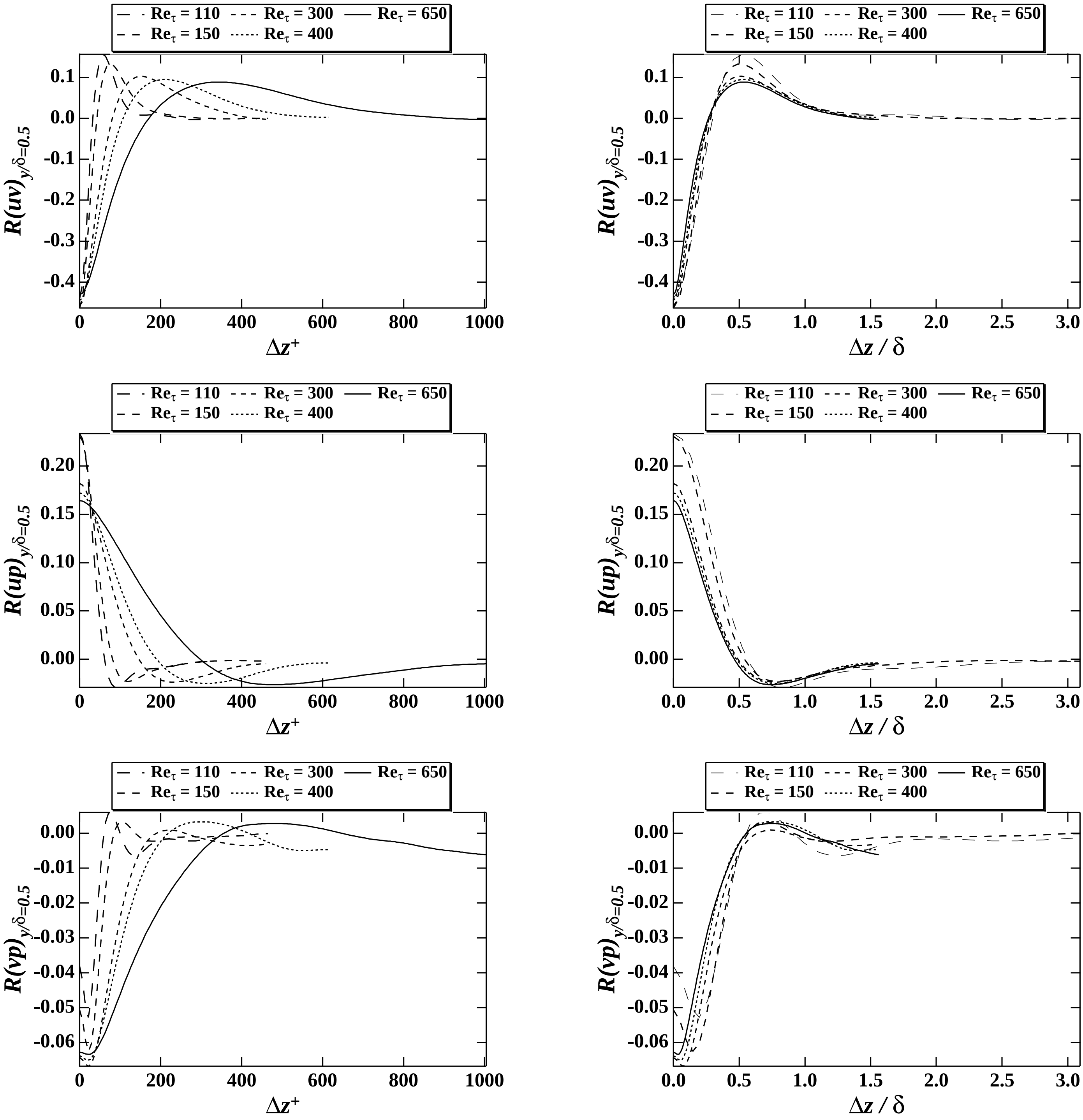

Re$_\tau$ = 110 Re$_\tau$ = 300 Re$_\tau$ = 650
Re$_\tau$ = 150 Re$_\tau$ = 400
$R(uu)_{y^+=15}$
$R(vv)_{y^+=15}$
$R(ww)_{y^+=15}$
$R(pp)_{y^+=15}$
Δz^+
$\Delta z / \delta$



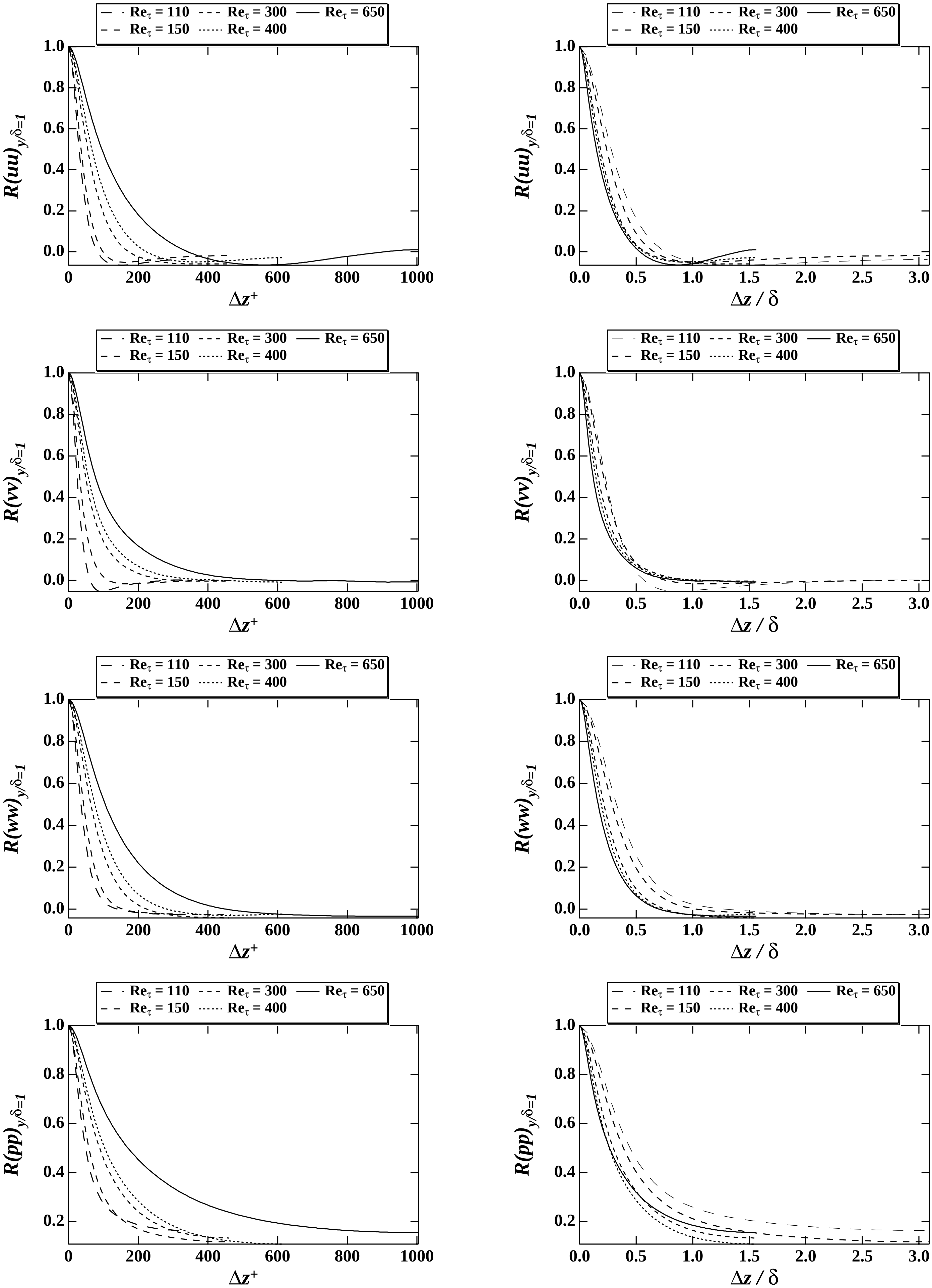
Re$_\tau$ = 110
Re$_\tau$ = 150
Re$_\tau$ = 300
Re$_\tau$ = 400
Re$_\tau$ = 650
$R(uv)_{y^+=15}$
$R(up)_{y^+=15}$
$R(vp)_{y^+=15}$
$R(vp)_{y/\delta=0.5}$
Δz^+
$\Delta z / \delta$

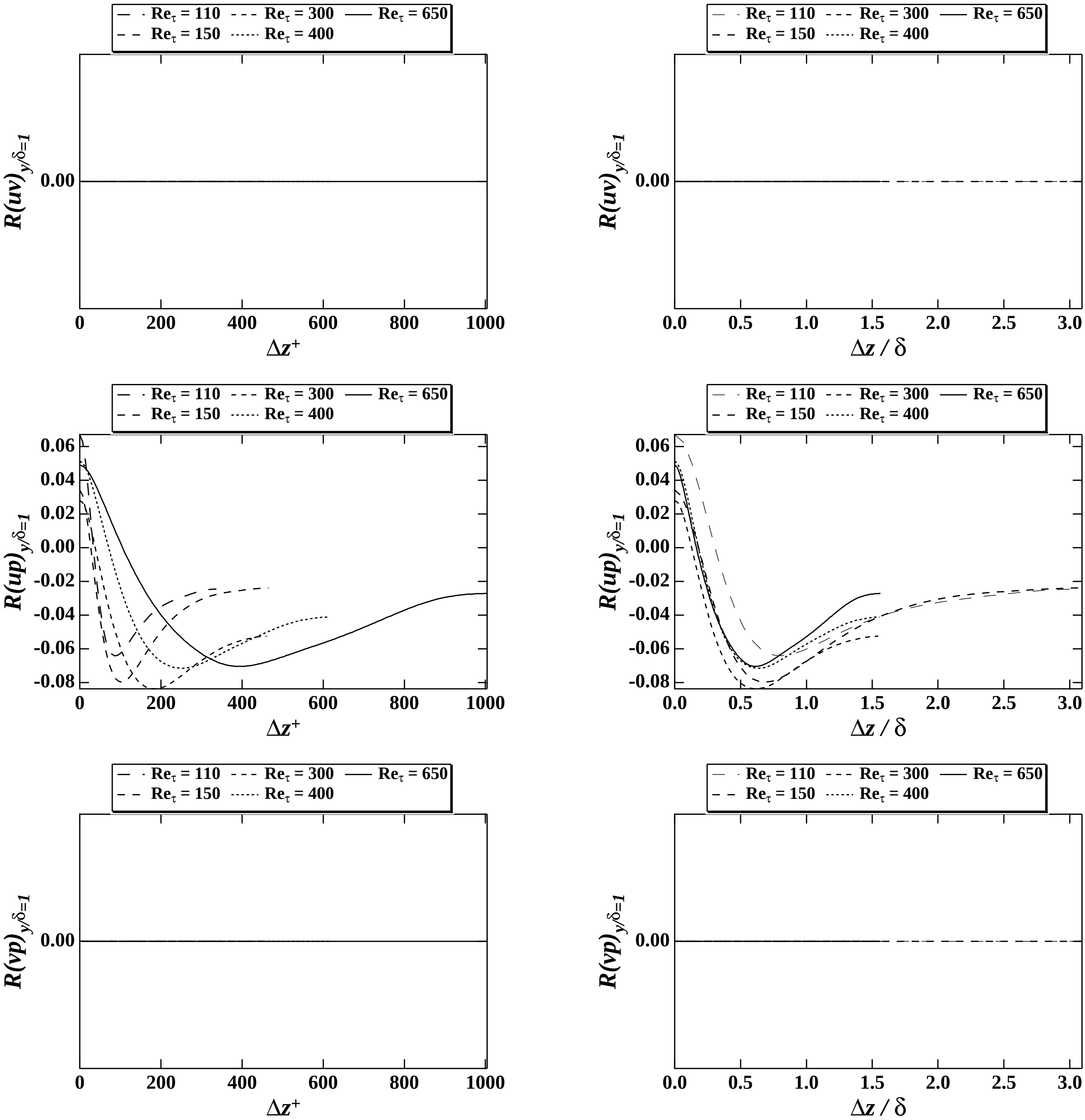
5.2.3 at $y/\delta = 0.5$



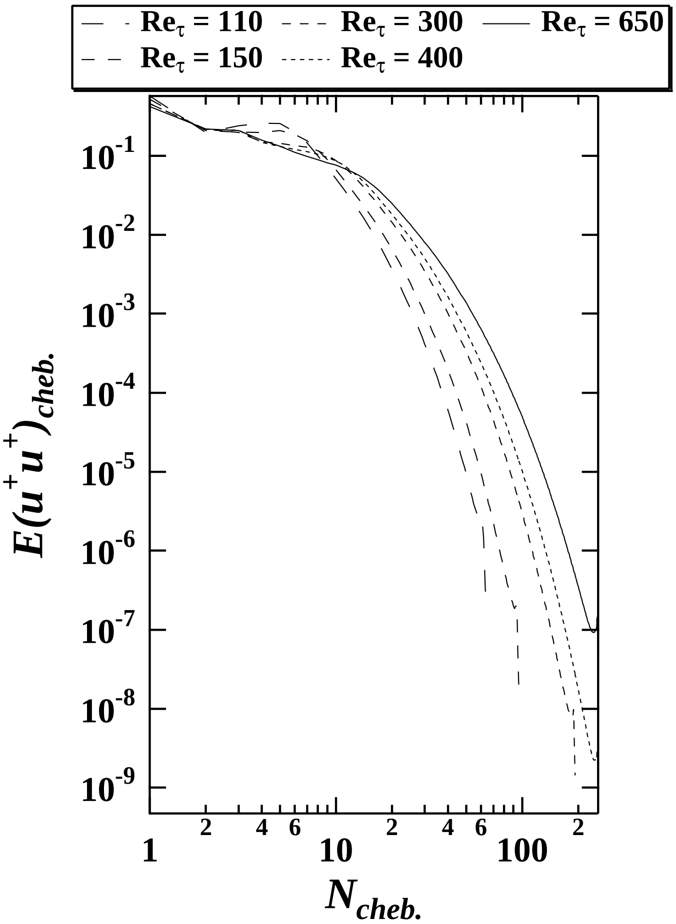

Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
$R(uv)_{y/\delta=0.5}$
$R(up)_{y/\delta=0.5}$
$R(vp)_{y/\delta=0.5}$
Δz^+
$\Delta z / \delta$

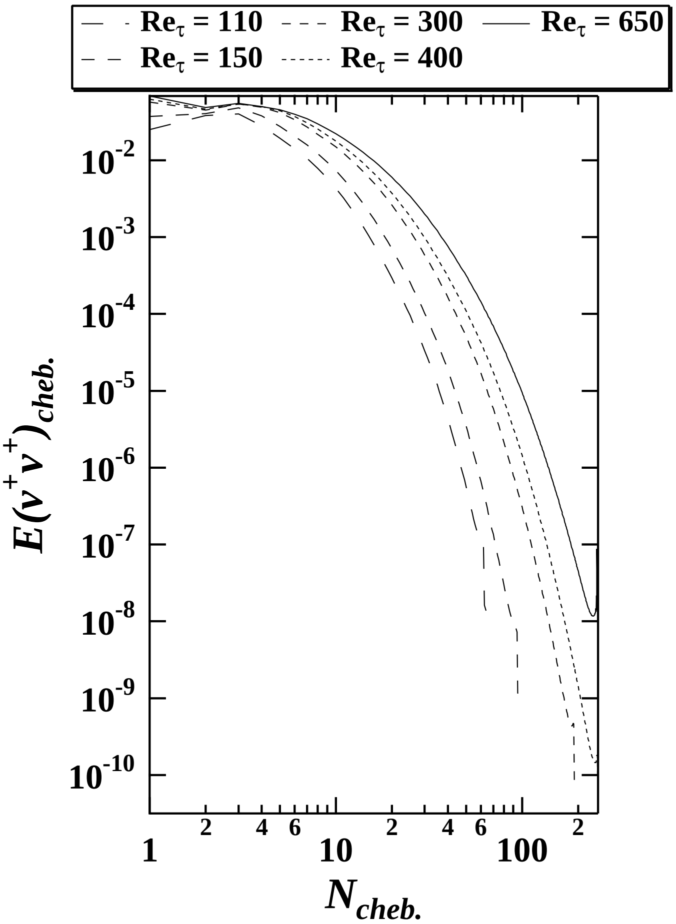
5.2.4 at $y/\delta = 1$

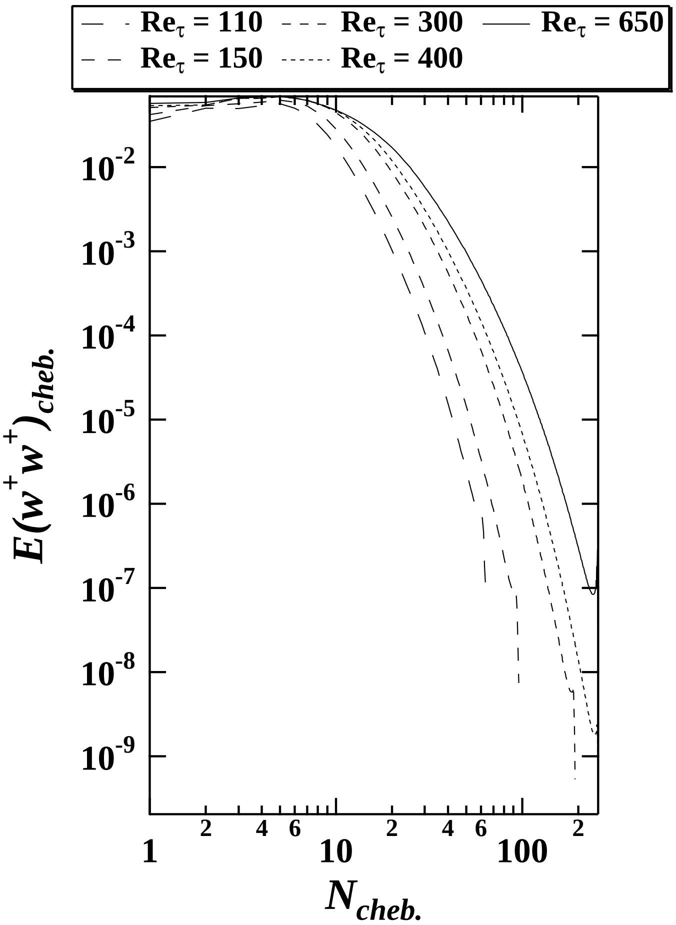


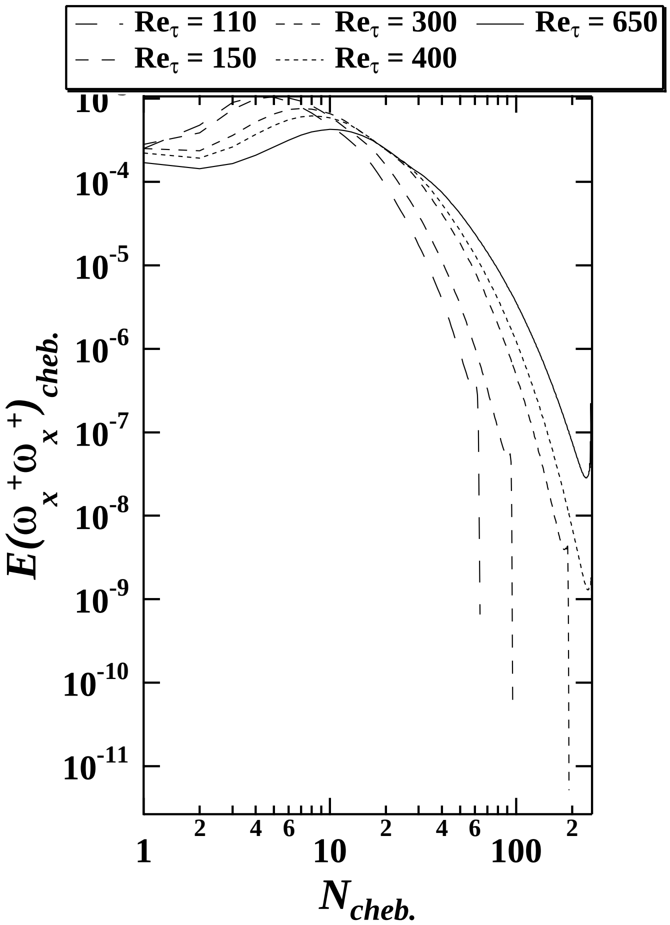

Reτ = 110
Reτ = 150
Reτ = 300
Reτ = 400
Reτ = 650
R(uv)y/δ=1
R(up)y/δ=1
R(vp)y/δ=1
Δz+
Δz / δ
0.00
0.06
0.04
0.02
-0.02
-0.04
-0.06
-0.08
0
200
400
600
800
1000
0.0
0.5
1.0
1.5
2.0
2.5
3.0

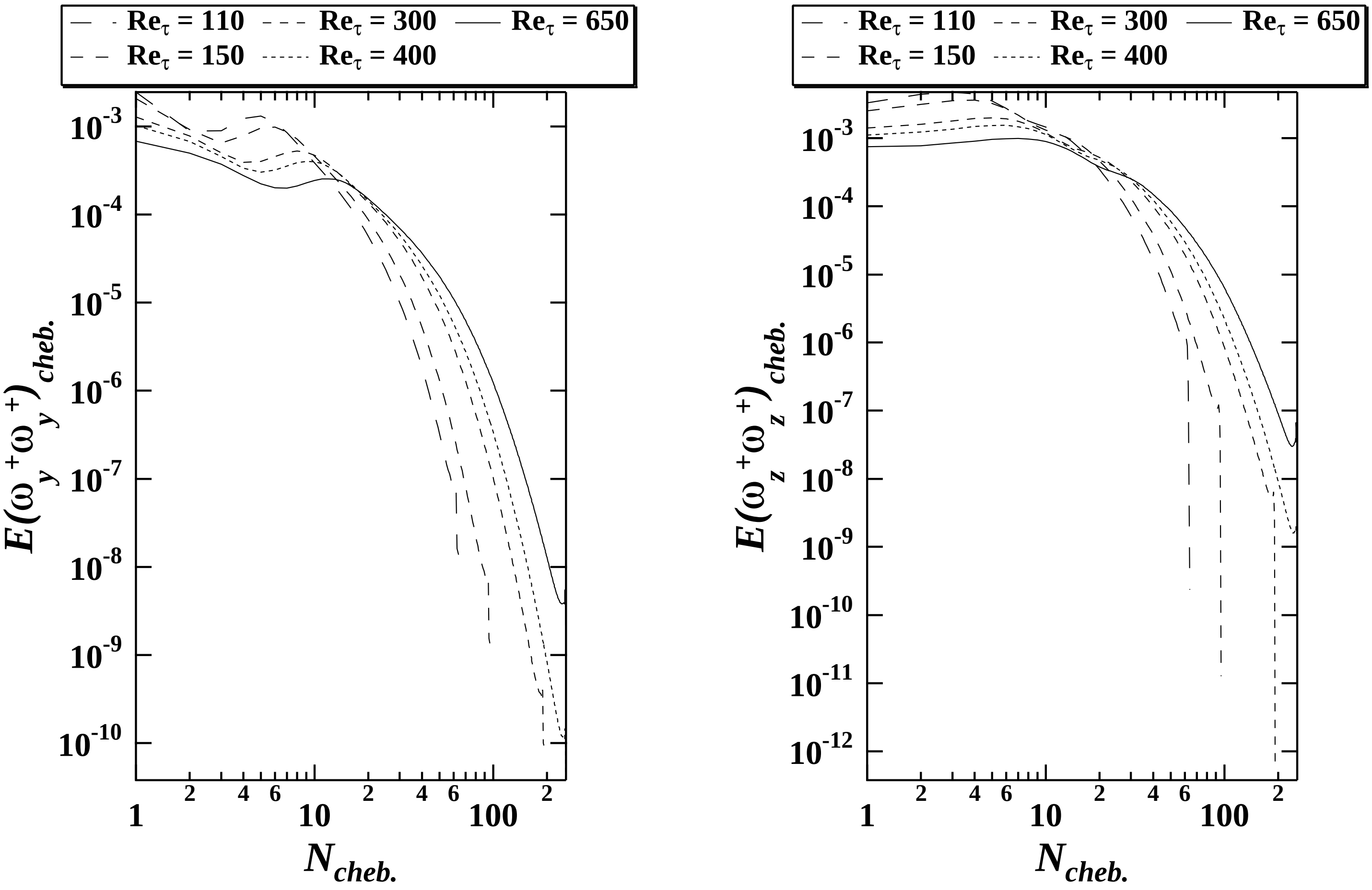
6 Chebyshev Power Spectra











Re_τ = 110
Re_τ = 150
Re_τ = 300
Re_τ = 400
Re_τ = 650
E(ω_y^+ω_y^+)_cheb.
E(ω_z^+ω_z^+)_cheb.
N_cheb.