RANS-Turbulenzmodellierung für subsonische druckinduzierte Strömungsablösung

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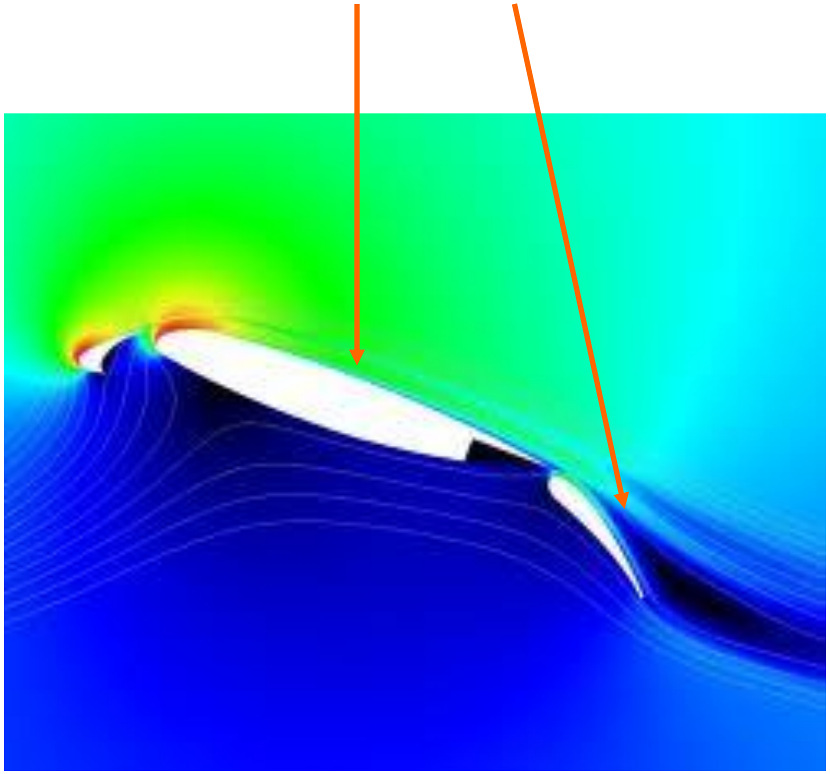
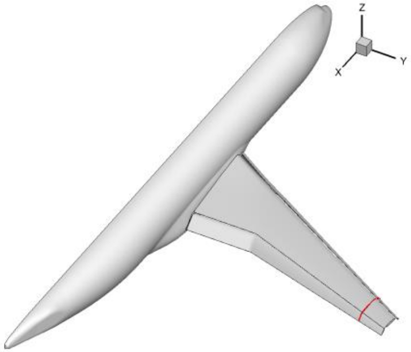
DLR

Goal: Improve RANS turbulence models to predict the onset of flow separation of low-speed flows

Significant adverse pressure gradient (APG) during take-off and landing





Outline

- Goal: Modification of the differential Reynolds stress model SSG/LRR-ω
- Method: Combination of theoretical work and experimental data
- Challenge (show stopper): Worldwide suitable test-cases and data are not available for high Re

  => VicToria experiment within the project VicToria

Strategy for RANS model improvement

Physics-based improvement of RANS + RSM

Strategy for RANS model improvement

(Empirical) laws for turbulence statistics

Physics-based improvement of RANS

Extension of the log-law for adverse pressure gradients

DLR

Strategy for RANS model improvement

High-quality data base (exp., DNS/LES)

(Empirical) laws for turbulence statistics

Physics-based improvement of RANS

Strategy for RANS model improvement

High-quality data base (exp., DNS/LES)

At high Re: only by experiments

(Empirical) laws for turbulence statistics

Physics-based improvement of RANS

Part I:

The VicToria experiment.

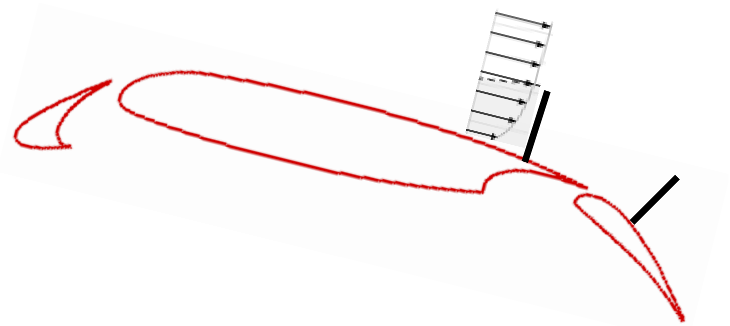
Data base for turbulent boundary layers at adverse pressure gradient with incipient separation

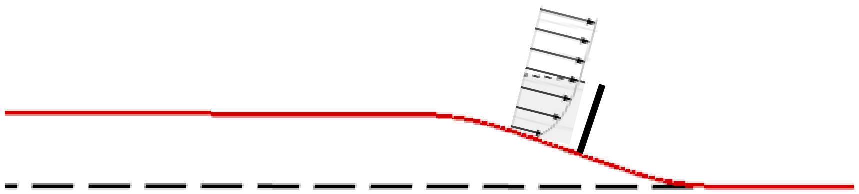
Design of the VicToria experiment

Design criteria for the VicToria experiment

- **Well defined and controlled flow conditions**
  - Use a generic contour mounted to wind tunnel wall instead of airfoil/wing at high incidence angle
- **Boundary layer characteristics similar to transport aircrafts at high-lift**
  - Large Reynolds numbers
  - Strong adverse pressure gradients leading to separation
  - Thin separation bubble
- **Highly resolved experimental data using particle-imaging/tracking methods**
  - Mean velocity, Reynolds stresses, wall-shear stress

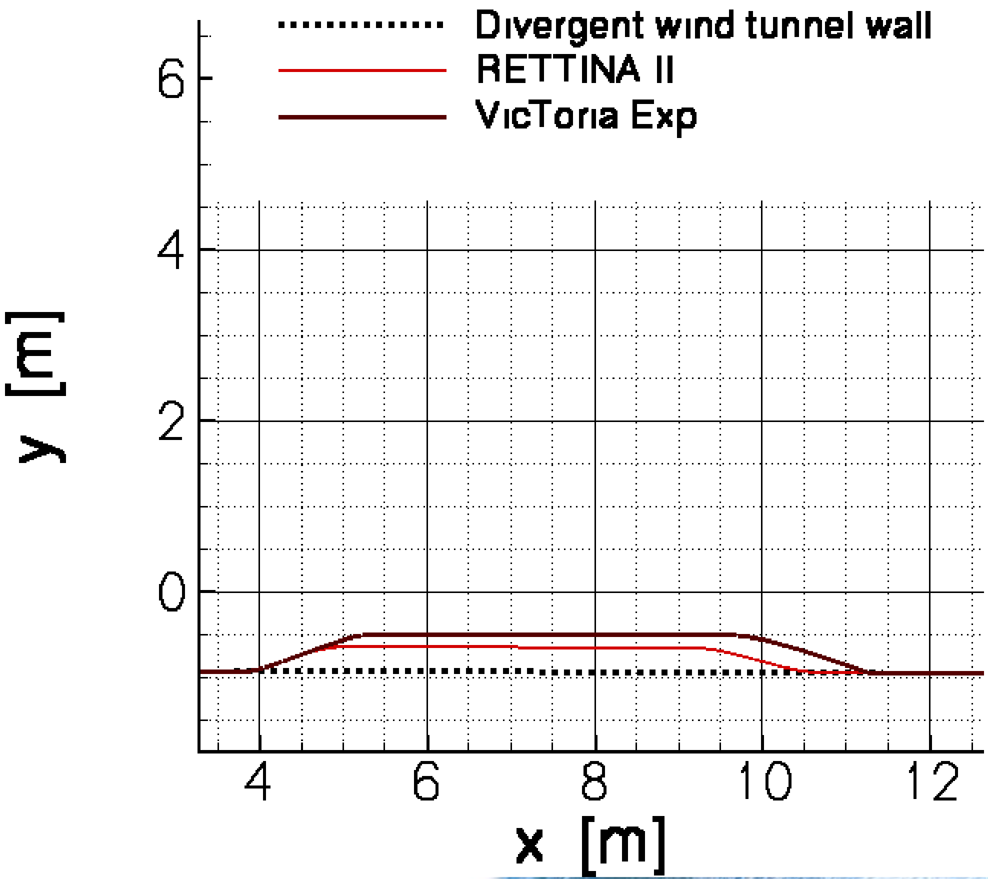
  ⇒ **Thick boundary layers** to enable measurement in the near-wall region

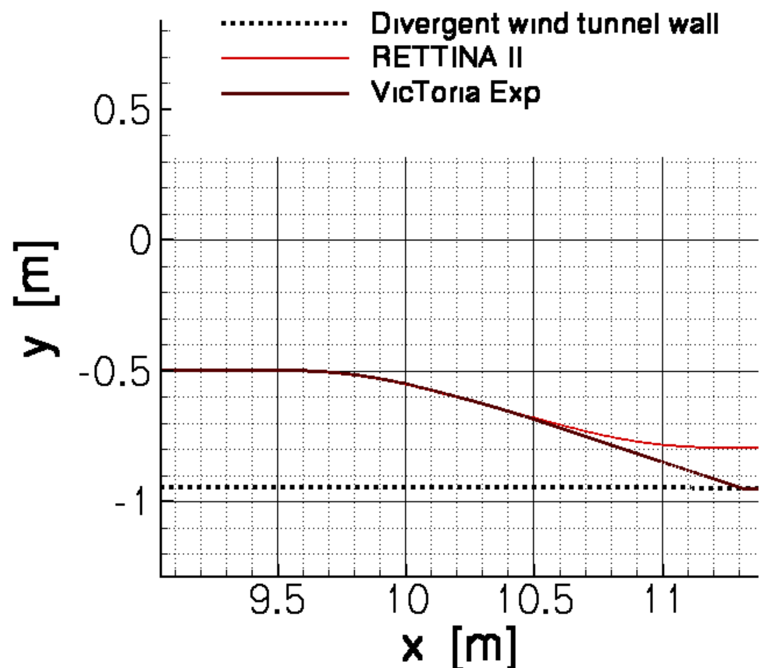




Design criteria for the VicToria experiment

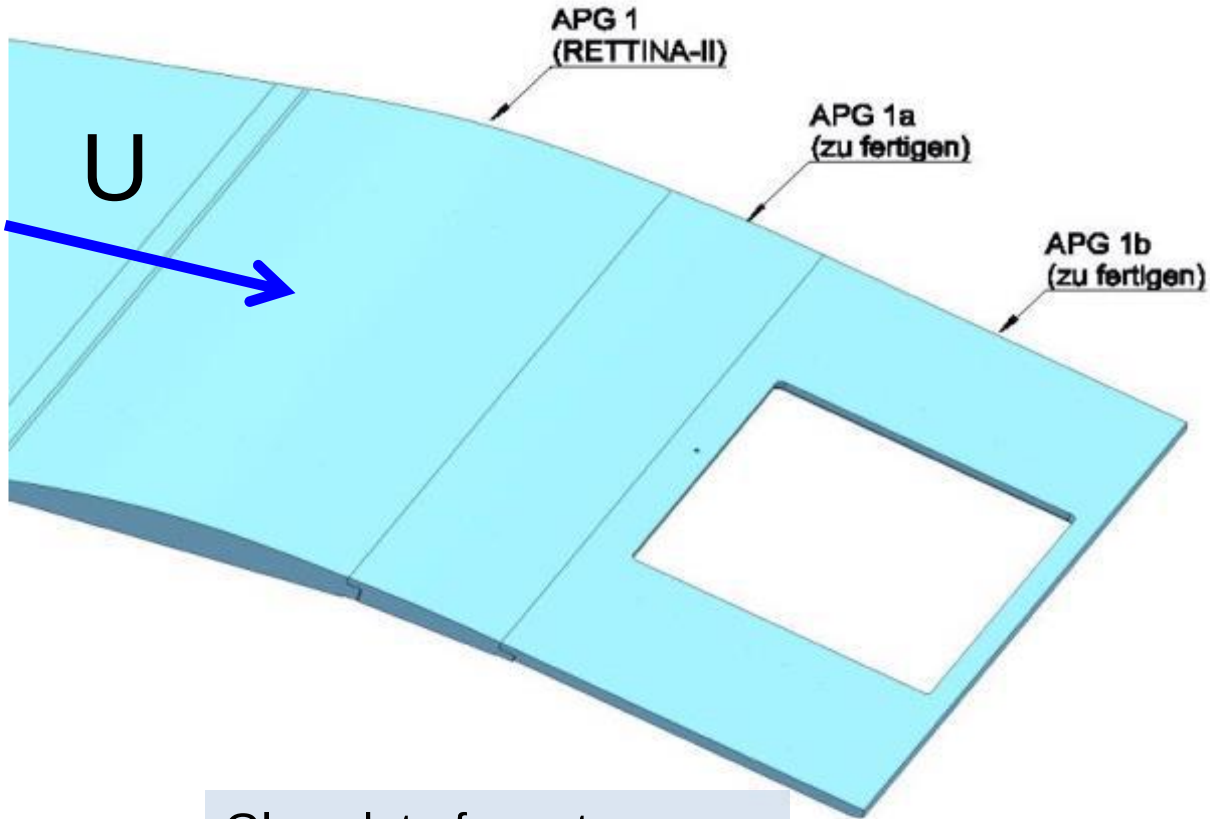
- Re-use of parts of so-called RETTINA II geometry (precursor DFG/DLR exp.)
  - RETTINA II experiment: Moderate APG, flow remains attached
  - VicToria experiment: Strong APG leading to mild separation





Design of the VicToria geometry model

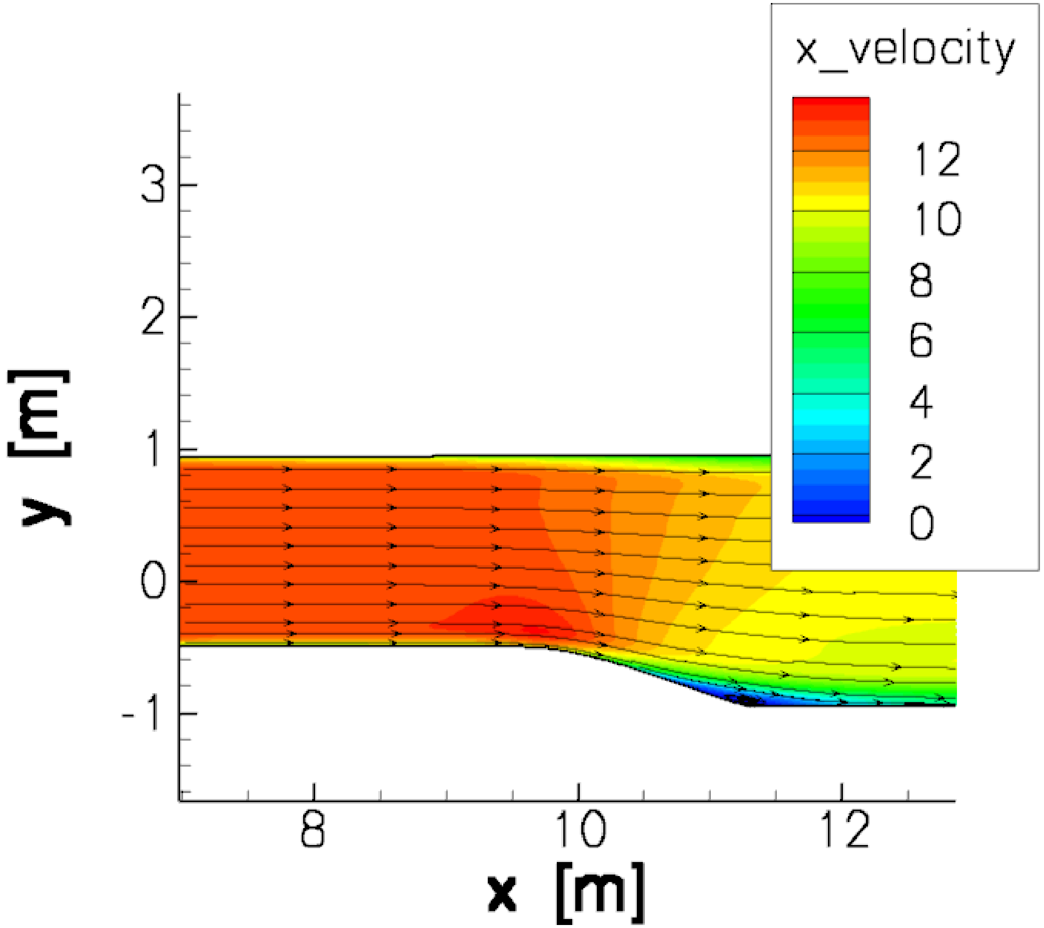
- Requirement by measurement technique: onset of separation on an inclined flat plate
- This enables measurements through the geometry from behind



Glas plate for opt. access

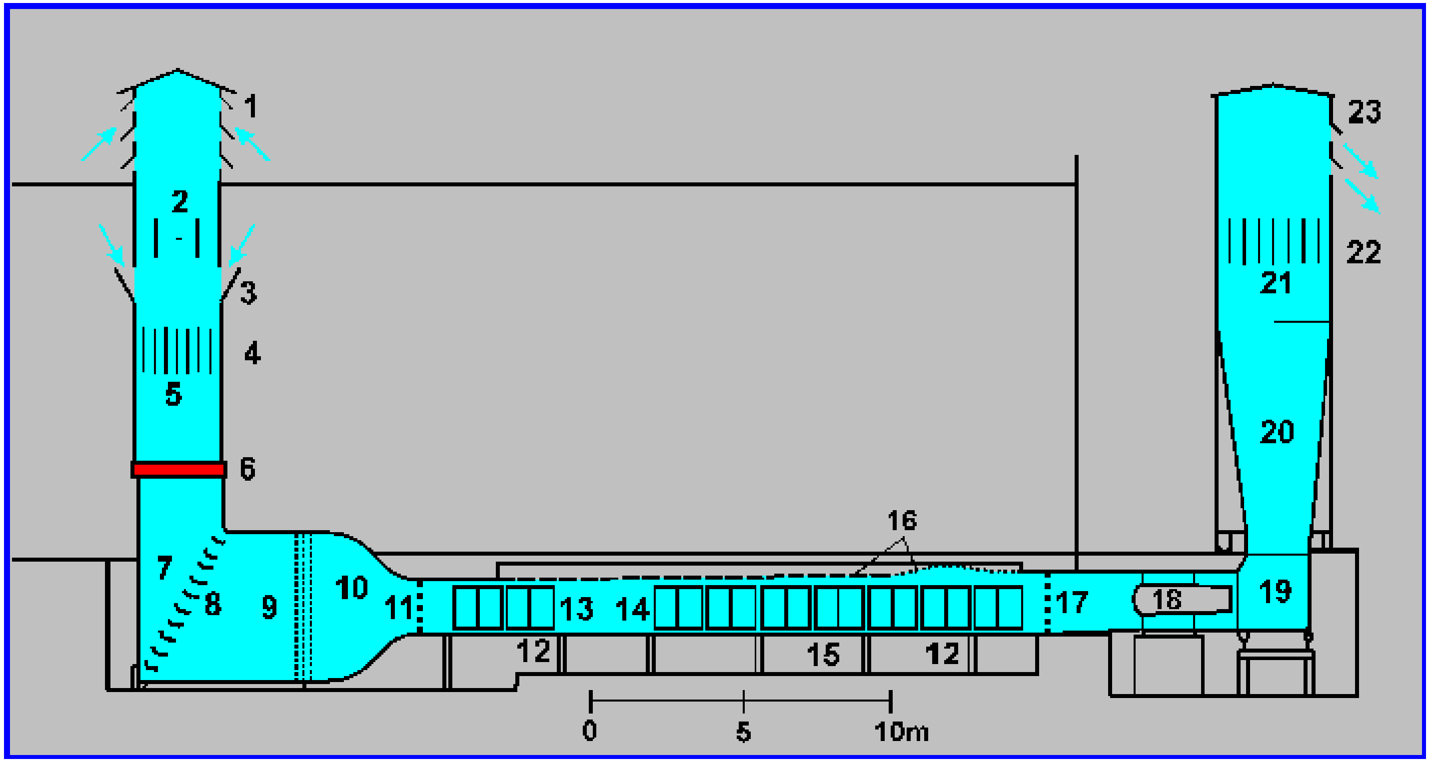
Design criteria for the VicToria experiment

Precursor RANS simulations for the design of the experiment



Atmospheric wind-tunnel AWM at UniBw München

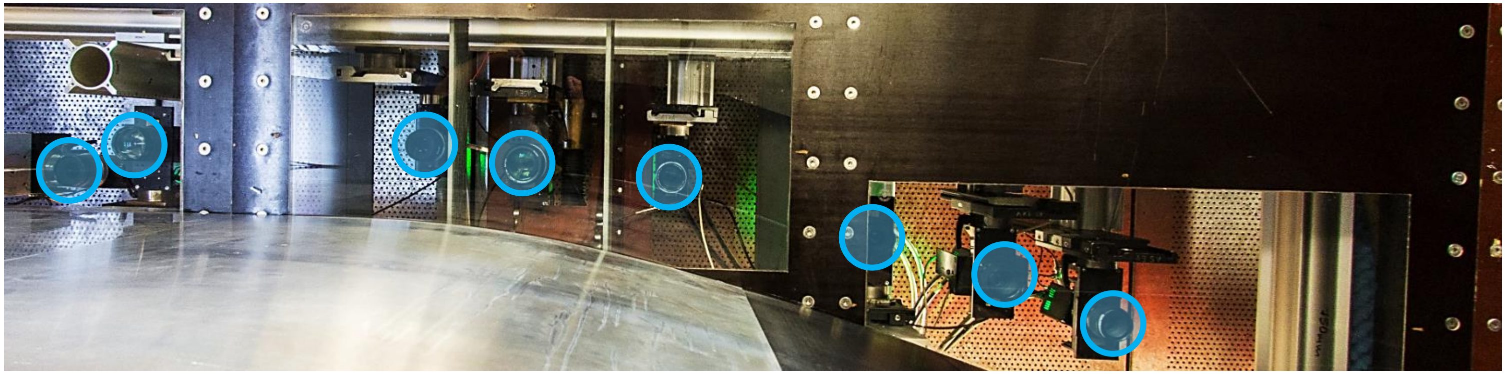
- Experiments where performed in the AWM at UniBw München at the Institute of Fluid Mechnics and Aerodynamics headed by Prof. Christian Kähler



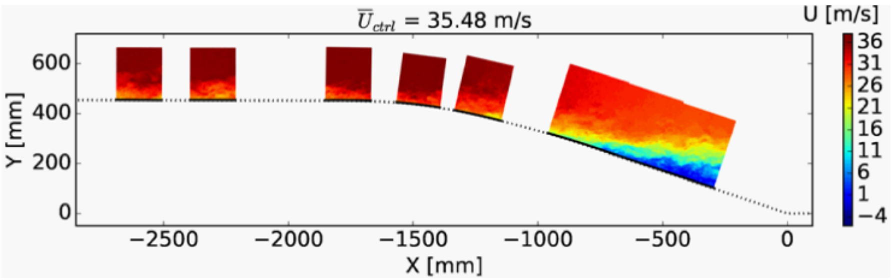
Measurement technique

Large-scale overview measurement: 2D2C PIV

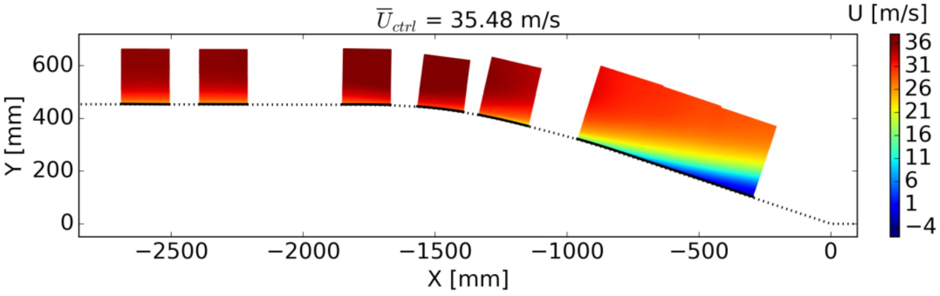
- High quality data for mean velocity from y+~150 to the outer edge of boundary layer



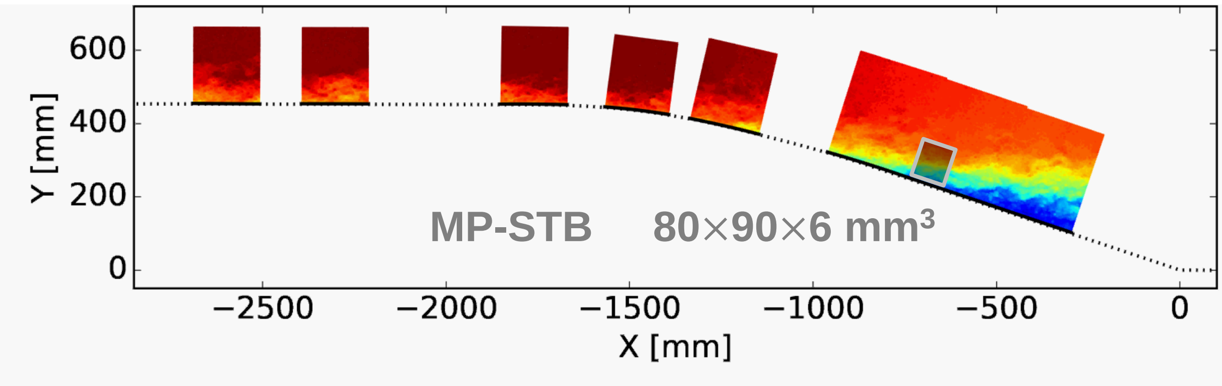
Instantaneous snapshot

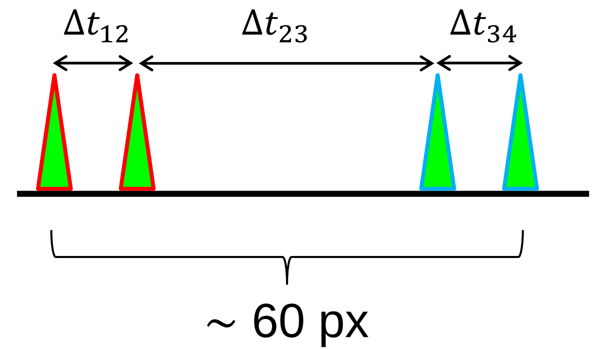


Statistically averaged flow field

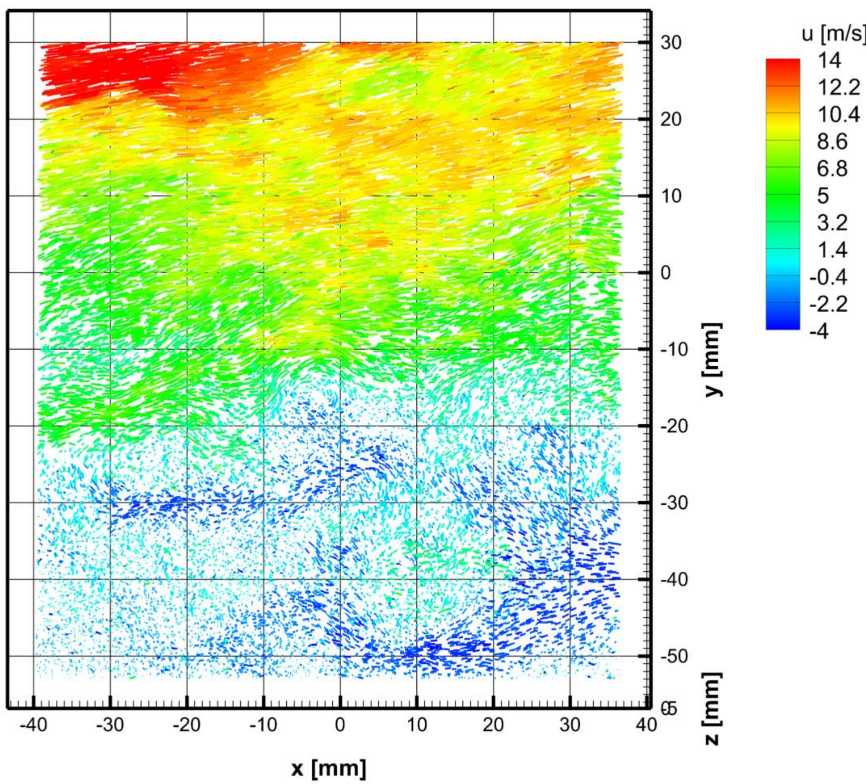


Detail measurement: 3D3C PTV STB (Multi-pulse)

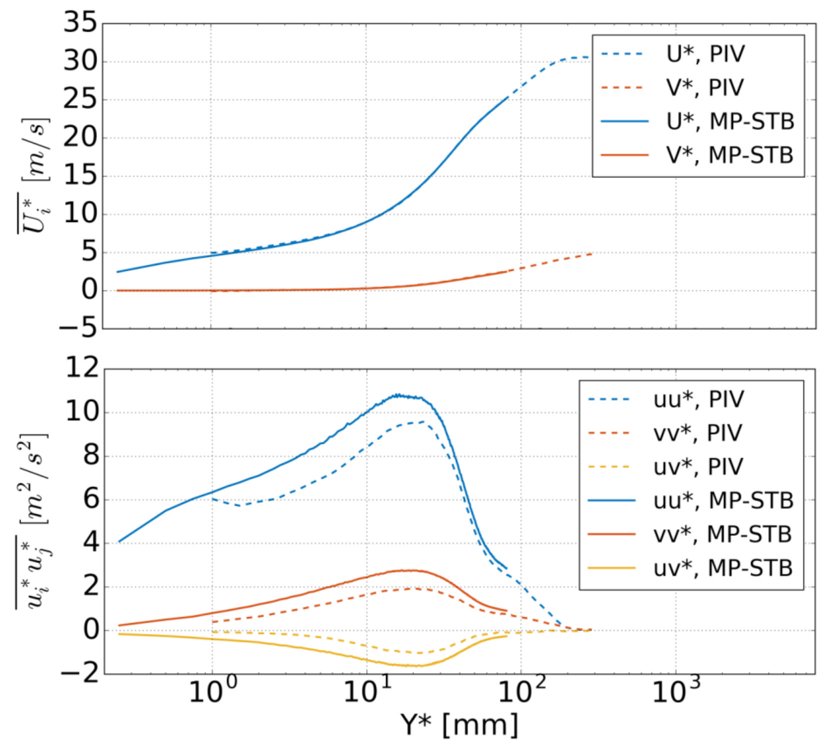




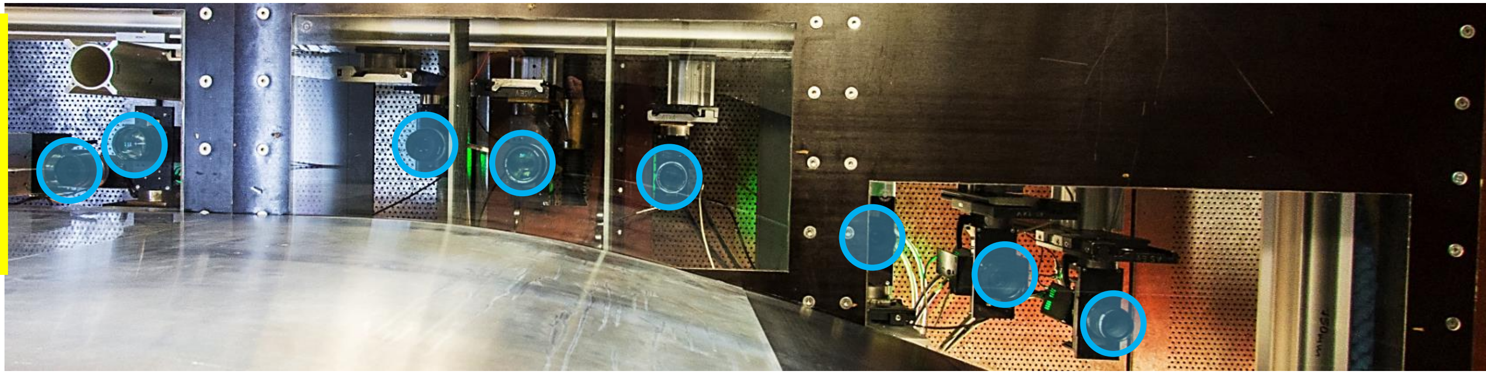
~ 20,000 instantaneous tracks



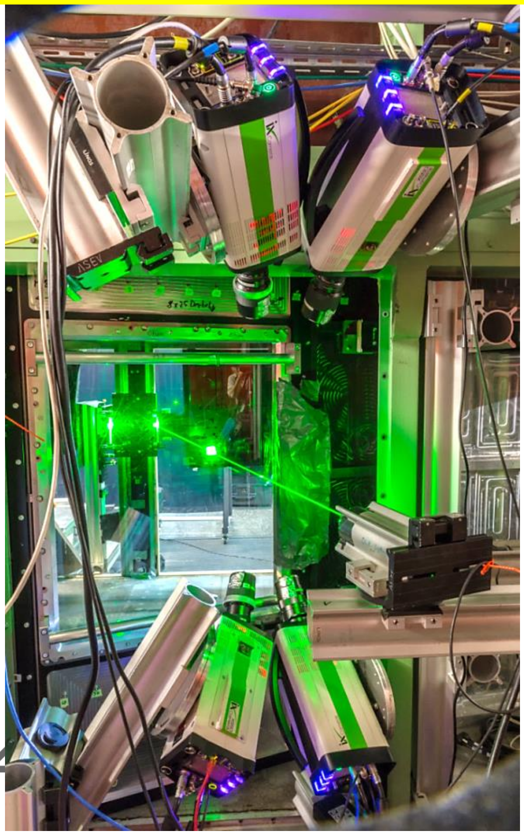
Ensemble average (bin size = 70 microns)



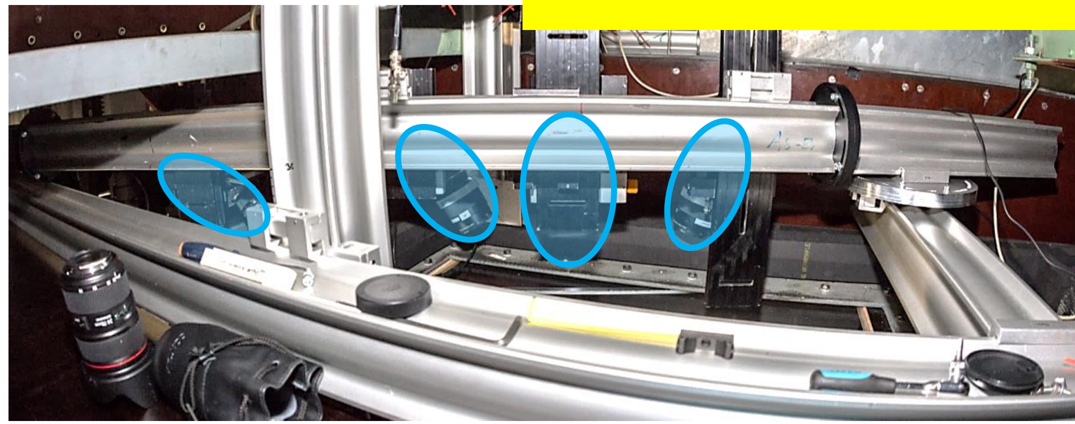
Overview large-scale 2D2C-PIV



Time resolved 3D3C PTV-STB



3D3C PTV MP-STB



Measurement techniques and cameras

2D2C-PIV

8 PCO-Edge cameras

2D-2C overview measurement

2D2C-PTV

1 SA-X2 camera

high-resolution profiles with 2D-STB

3D3C PTV

TR-STB

4 IX cameras

time-resolved 3D STB

3D3C PTV

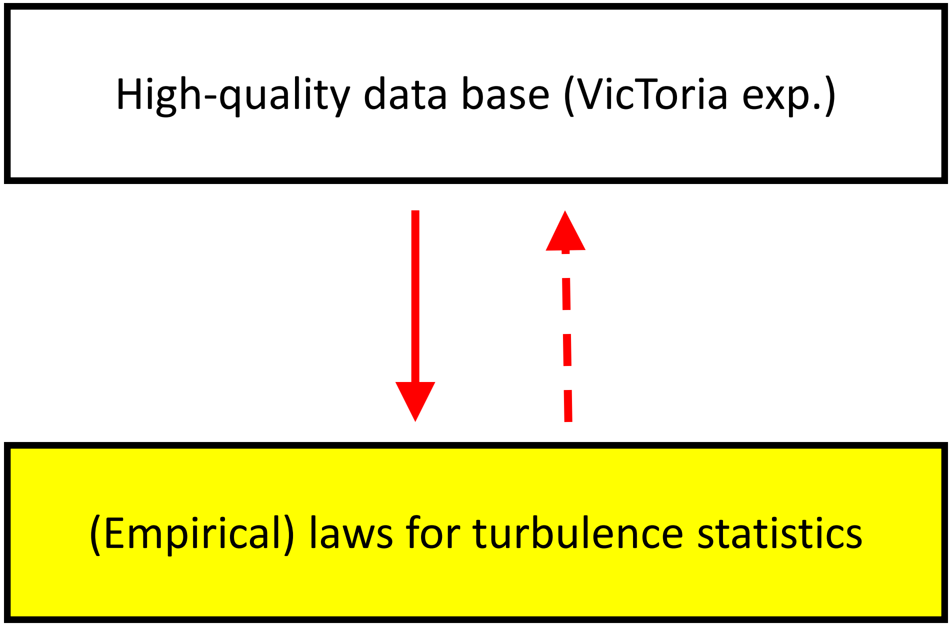
MP-STB

4 PCO Edge cameras

multi-pulse 3D-STB

Part II:
Evaluation of the results
and
extension of the log-law for adverse pressure gradients
when approaching separation

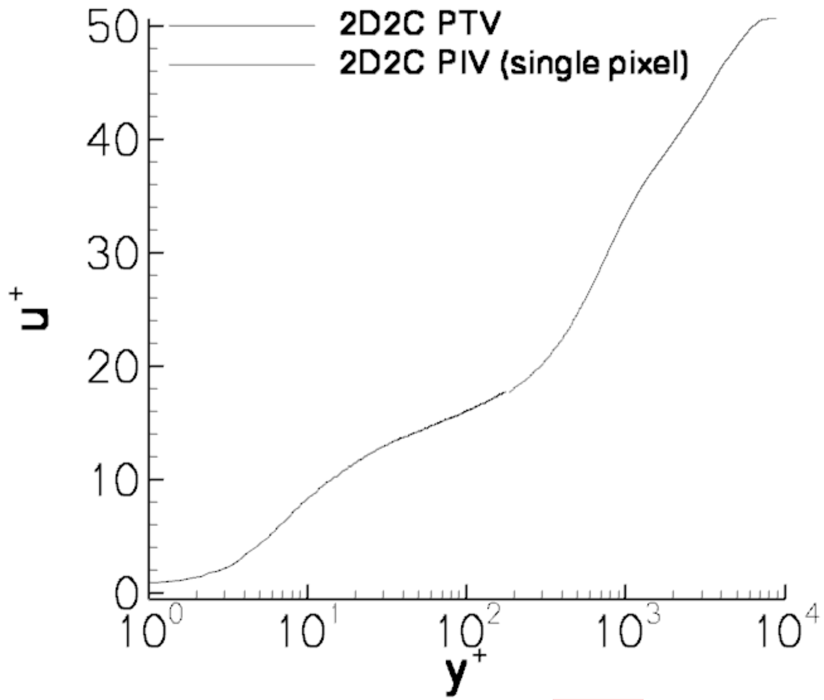
RANS model improvement



Input for wall-law scaling: Wall-shear stress

- The wall-shear stress is the central quantity for the physically meaningful non-dimensionalization ("scaling") of the data
    - scaling for the inner 15% of the boundary layer

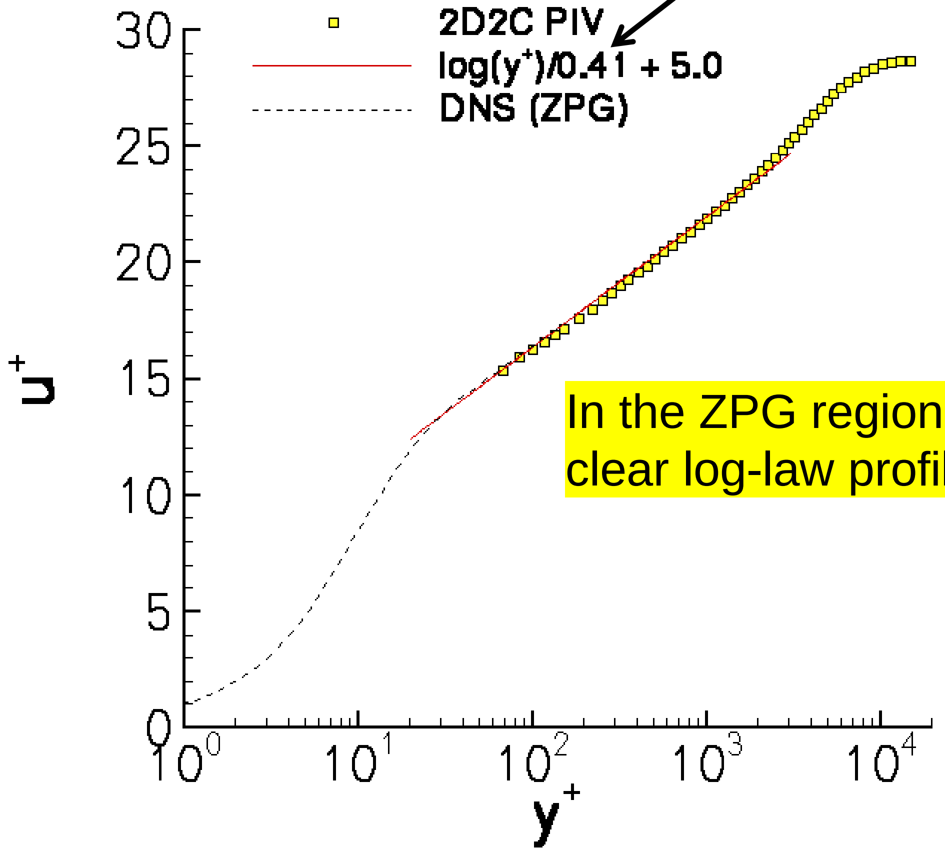
$$u^+ = \frac{U}{u_\tau}$$



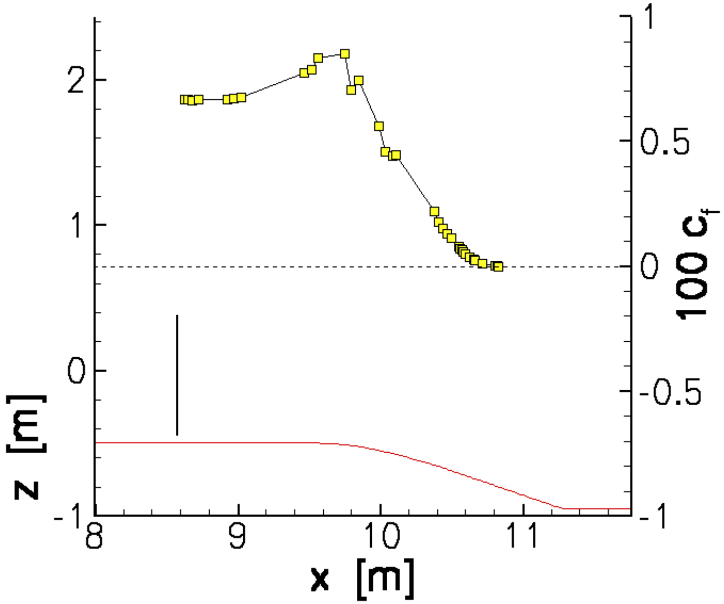
$$y^+ = \frac{y u_\tau}{\nu}$$

Mean velocity profiles

von Karman constant

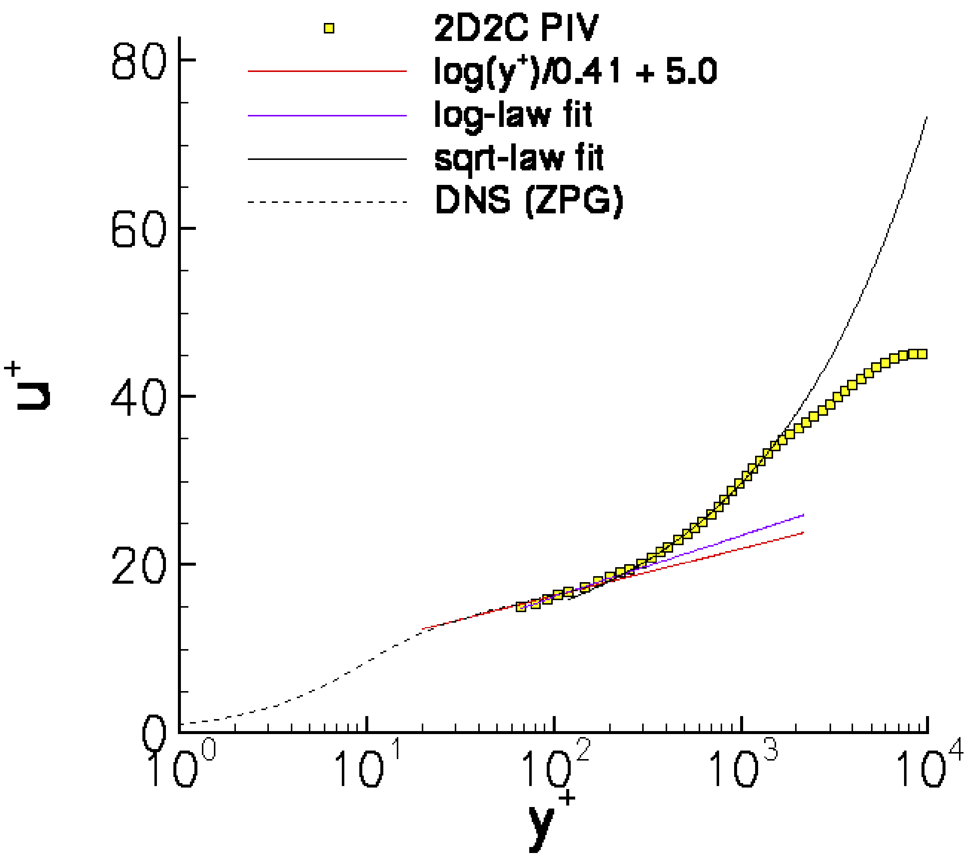


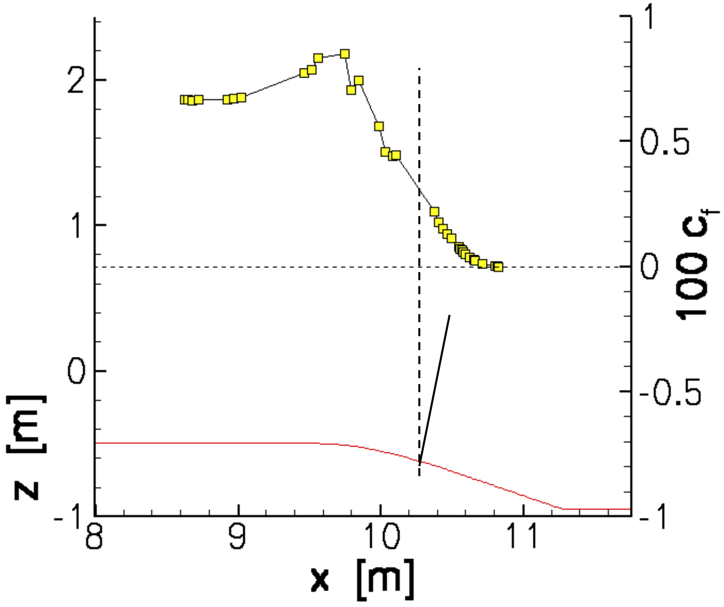
In the ZPG region: clear log-law profile



$\Delta p_x^+ = dp^+/dx^+ = 0$

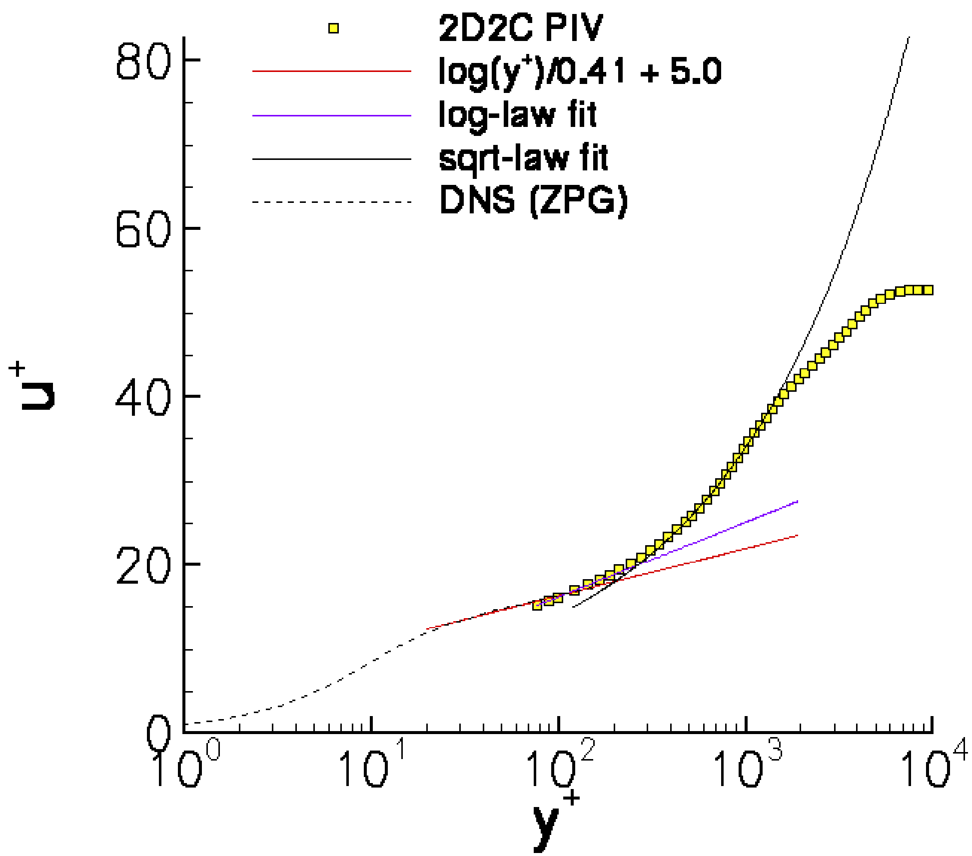
Mean velocity profiles

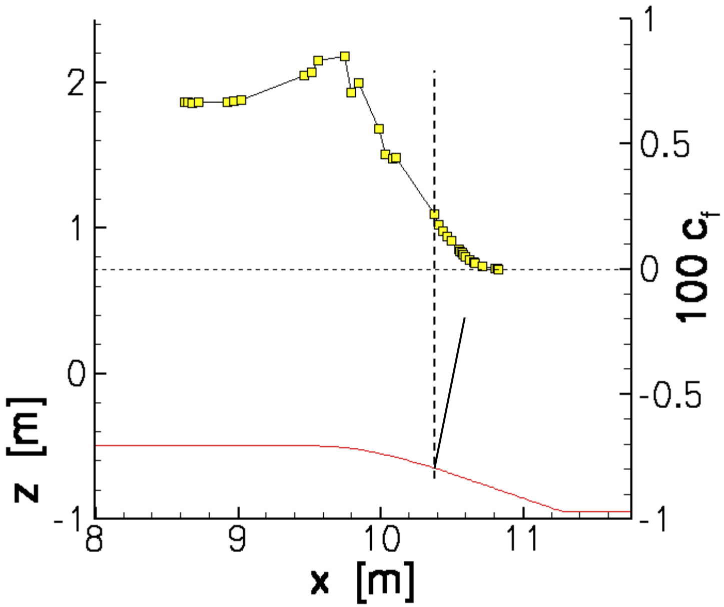




$\Delta p_x^+ = dp^+/dx^+ = 0.039$

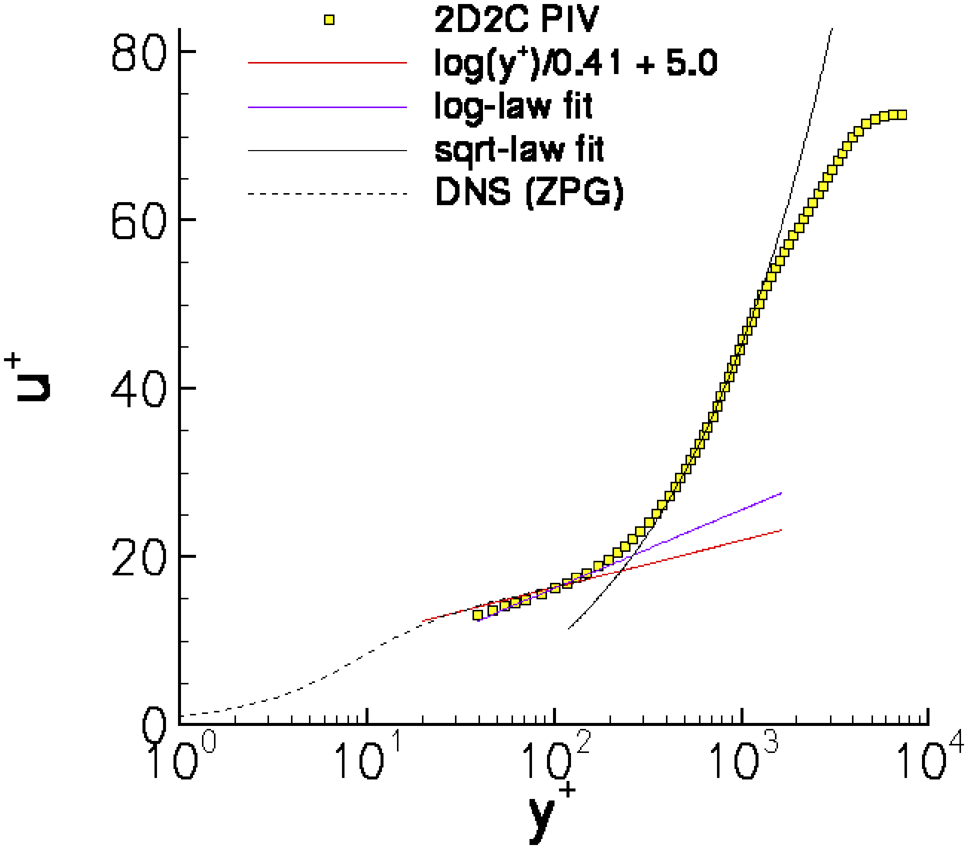
Mean velocity profiles

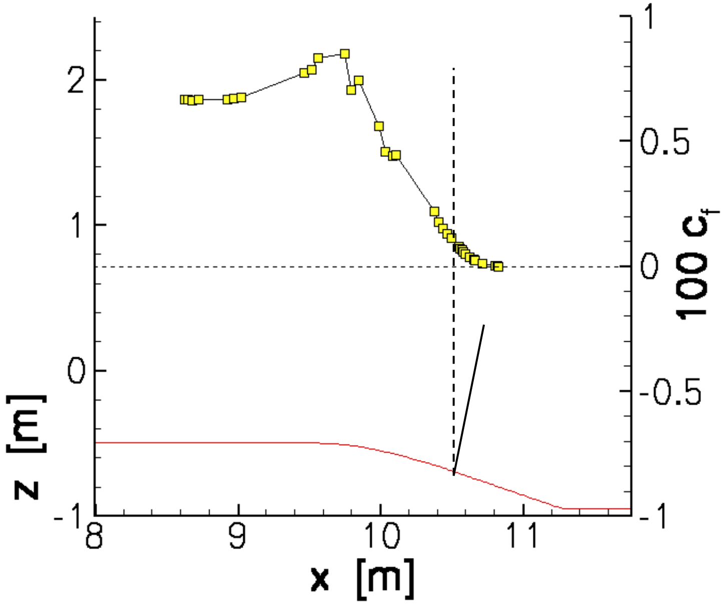




$\Delta p_x^+ = dp^+/dx^+ = 0.064$

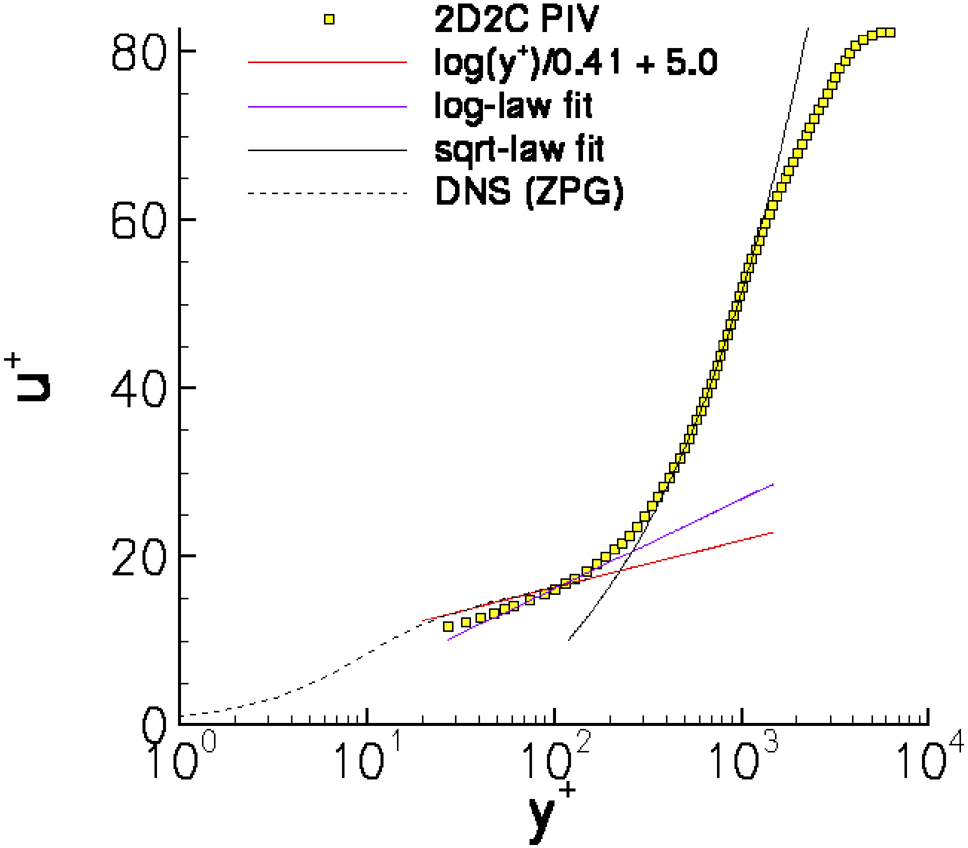
Mean velocity profiles

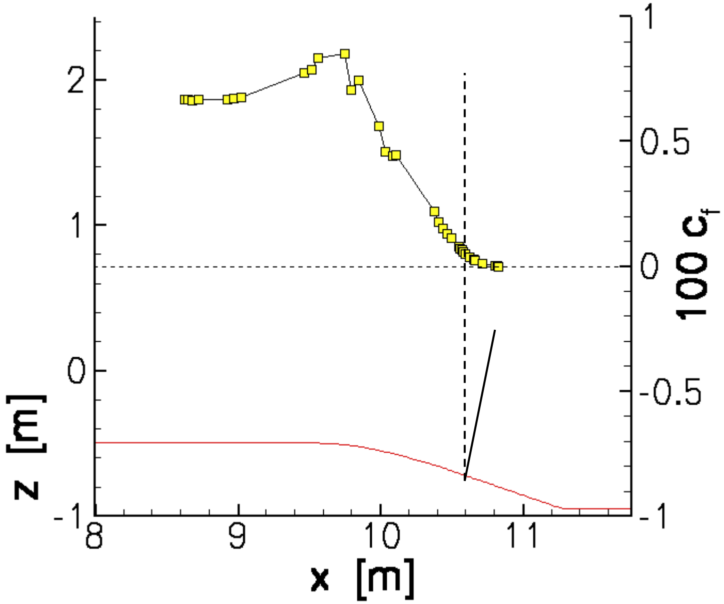




$\Delta p_x^+ = dp^+/dx^+ = 0.140$

Mean velocity profiles

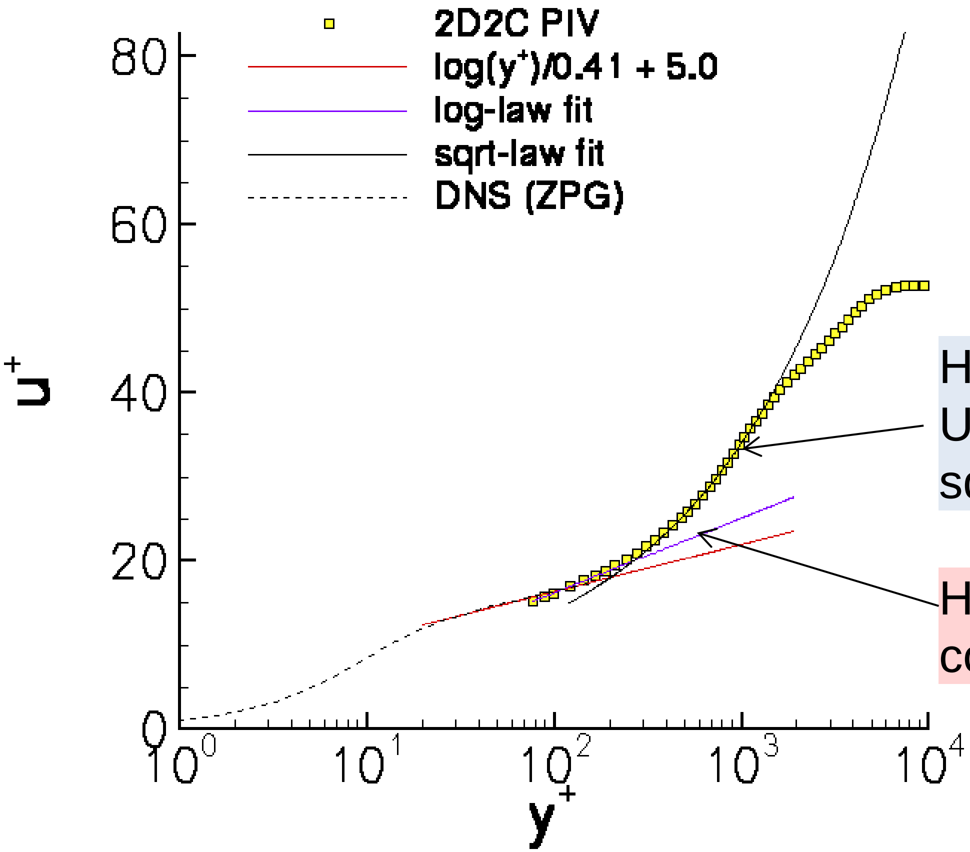




$\Delta p_x^+ = dp^+/dx^+ = 0.180$

DLR

Hypotheses for wall-law at adverse pressure gradients



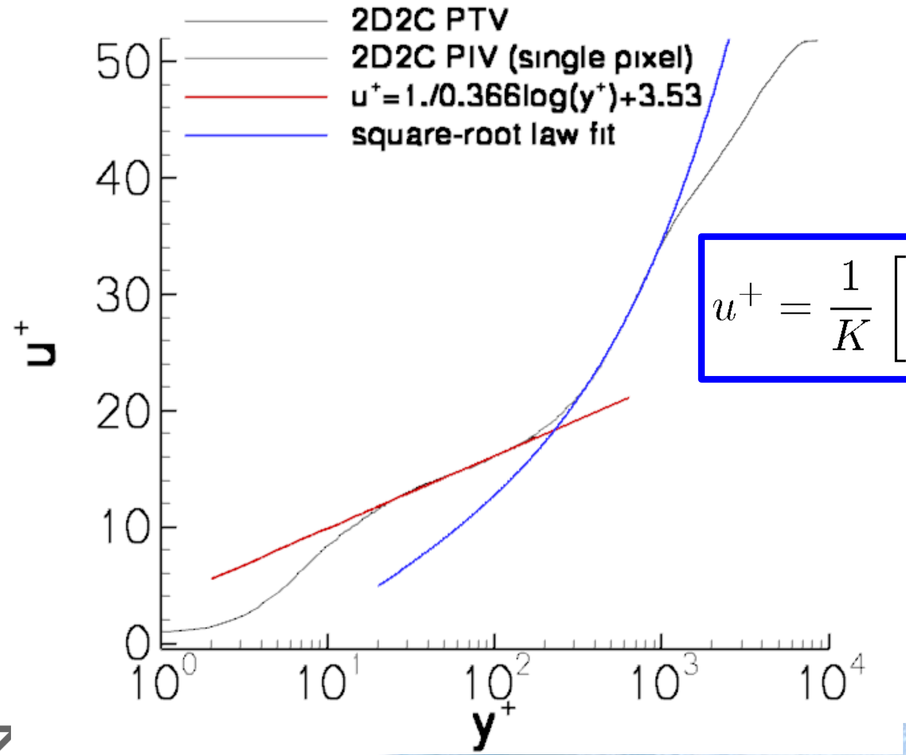
Hypothesis #1:
Upward-turn of U(y) above the log-law
sqrt-law $U \sim y^{1/2}$

Hypothesis #2: Change of slope coefficient of the log-law

$\Delta p_x^+ = dp^+/dx^+ = 0.064$

Hypothesis #1: Square-root law above the log-law

- Review of the literature of turbulent boundary layers at APG
- A square-root law is claimed by some authors in the literature
  - Szablewski (1952), Townsend (1960), Perry & Schofield (1973), van den Berg (1973), …
- Sqrt-law was found in DFG RETTINA II experiment by DLR AS and UniBw München



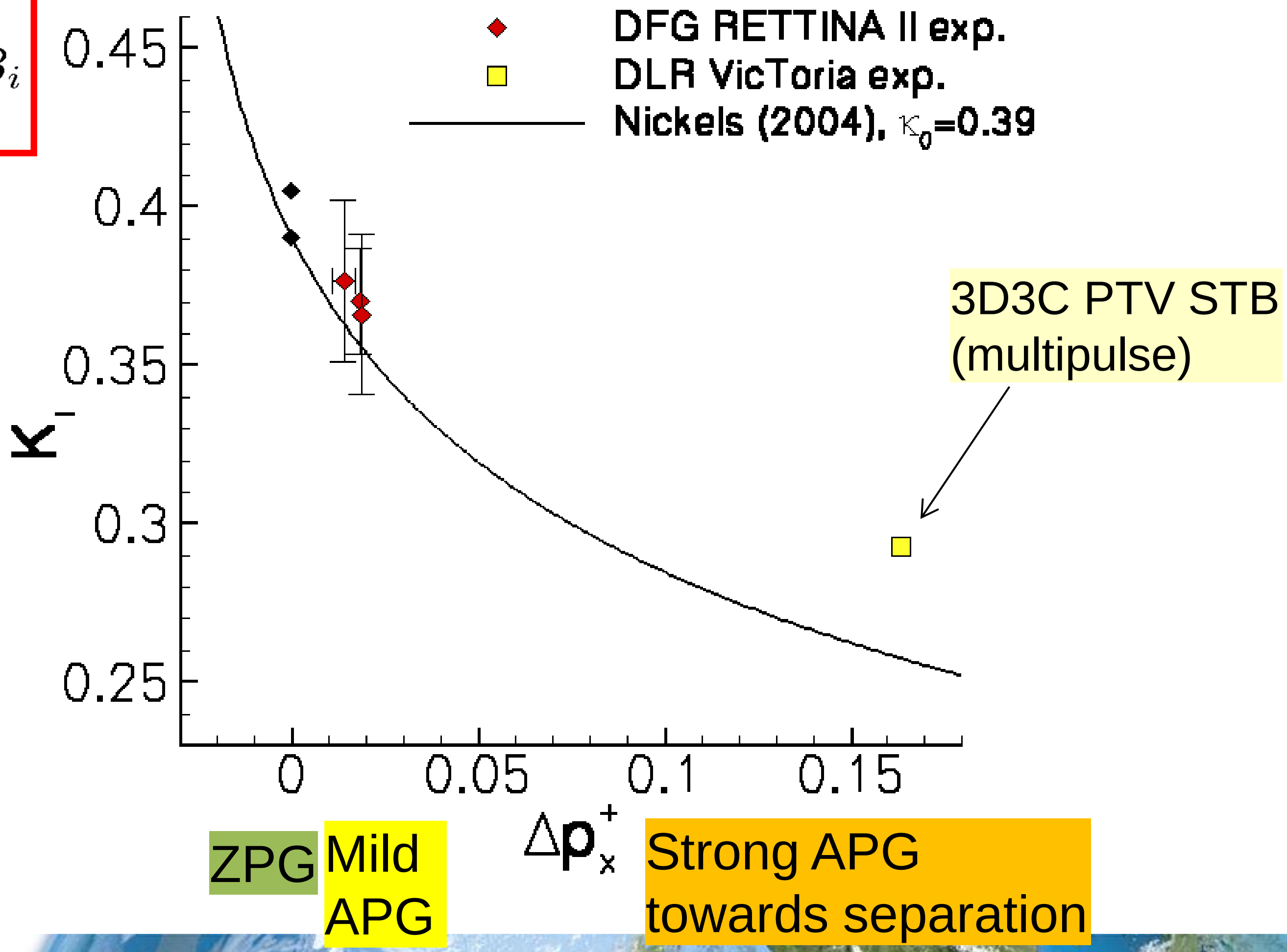
$$u^+ = \frac{1}{K}\left[\log(y^+) + 2\left(\sqrt{1 + \Delta p_x^+ y^+} - 1\right)\right] + \tilde{B}$$

Dependent on dp/dx-parameter
Slope is increasing with increasing (dp/dx)+

Hypothesis #2: Change of log-law slope coefficient

- Supported by data of DLR VicToria exp. and precursor RETTINA II experiment

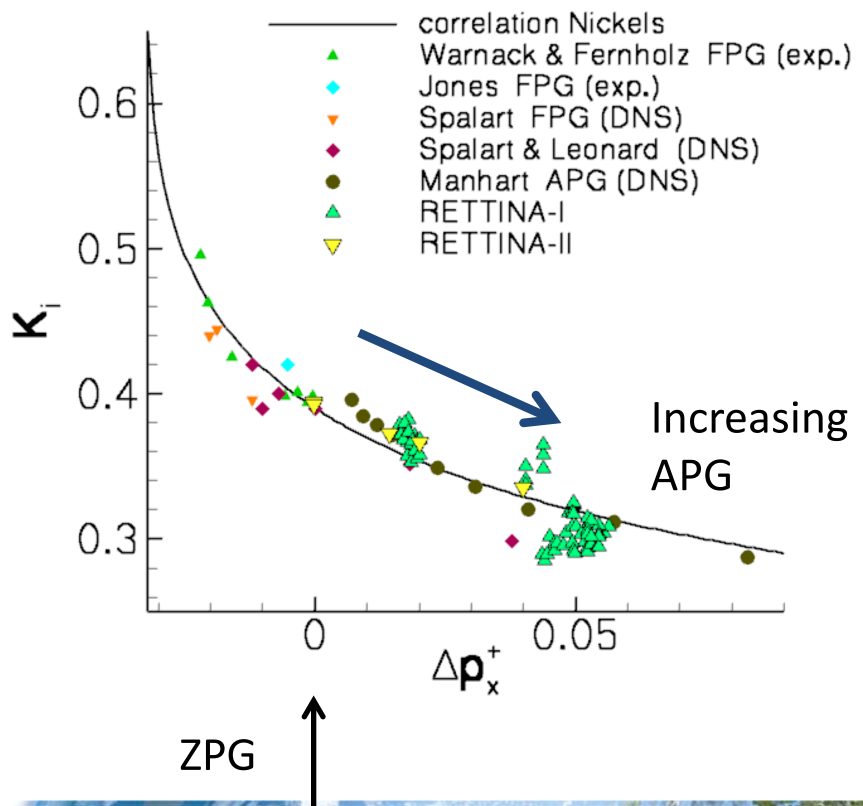
$$u^+_{\log} = \frac{1}{K_i}\log(y^+) + B_i$$



Hypothesis #2: Change of log-law slope coefficient

- Slope coefficient K

$$u^+_{\text{log}} = \frac{1}{K_i}\log(y^+) + B_i$$



Part III:
Extension of RANS turbulence models for adverse pressure gradients

RANS model improvement

High-quality data base (exp., DNS/LES)

(Empirical) laws for turbulence statistics

Physics-based improvement of RANS

RANS model augmentation

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

- Transport equation for the Reynods stress tensor

$$U_k \frac{\partial}{\partial x_k}\overline{u_i' u_j'} = \mathcal{P}_{ij} + D_{ij}^{\nu} + D_{ij}^{t} + D_{ij}^{p} + \Pi_{ij} - \epsilon_{ij}$$

- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_\omega - \epsilon_\omega + D_\omega^{\nu} + D_\omega^{t}$$

RANS model augmentation

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

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RANS model augmentation

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- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_\omega - \epsilon_\omega + D_\omega^\nu + D_\omega^t$$

„Net effect“:
The sum of all modelled terms determines <u_i‘u_j‘> and hence U

RANS model augmentation

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

- Transport equation for the Reynods stress tensor

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The sum of all modelled terms determines $\langle u_i' u_j' \rangle$ and hence U

- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_\omega - \epsilon_\omega + D_\omega^{\nu} + D_\omega^{t}$$

RANS model augmentation

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u'_i u'_j \rangle\right) = 0$$

- Transport equation for the Reynods stress tensor

$$U_k \frac{\partial}{\partial x_k}\overline{u'_i u'_j} = \mathcal{P}_{ij} + D^{\nu}_{ij} + D^{t}_{ij} + D^{p}_{ij} + \Pi_{ij} - \epsilon_{ij}$$

- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_{\omega} - \epsilon_{\omega} + D^{\nu}_{\omega} + D^{t}_{\omega}$$

Step #2: variation of kappa at APG

Step #1: sqrt-law for U(y) at APG

Step 1: Boundary layer approximation

Take into account only dominant terms and derivatives in wall-normal direction

$$U_j \frac{\partial \omega}{\partial x_j} = \gamma \left(\frac{\partial U_i}{\partial x_j} \right)^2 - \beta_\omega \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right]$$

Non-dimensionalize (= scale) the equation to inner viscous units

$$-\frac{\mathrm{d}}{\mathrm{d}y^+} \left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+} \right) = \gamma \left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+} \right)^2 - \beta_\omega \left(\omega^+ \right)^2$$

Step 2: Substitute wall-law into the ω-equation

$$-\frac{\mathrm{d}}{\mathrm{d}y^+}\left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+}\right) = \gamma \left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+}\right)^2 - \beta_\omega \left(\omega^+\right)^2$$

$$\Leftrightarrow \qquad -D_{\omega,t}^+ \quad = \quad P_\omega^+ \quad - \quad \epsilon_\omega^+$$

Step 2: Substitute wall-law into the ω-equation

Following ideas by Rao & Hassan,
Catris & Aupoix

Part 2: Wall law for dU/dy and for turbulence statistics

$\kappa y^+ \sqrt{1+\alpha y^+}$ $\quad$ $\dfrac{\sqrt{1+\alpha y^+}}{a_1 \kappa y^+}$ $\quad$ $\dfrac{\sqrt{1+\alpha y^+}}{\kappa y^+}$ $\quad$ $\dfrac{\sqrt{1+\alpha y^+}}{a_1 \kappa y^+}$

$$-\frac{\mathrm{d}}{\mathrm{d}y^+}\left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+}\right) = \gamma \left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+}\right)^2 - \beta_\omega \left(\omega^+\right)^2$$

$$\Leftrightarrow \qquad -D^+_{\omega,t} \quad = \quad P^+_\omega \quad - \quad \epsilon^+_\omega$$

Step 2: Substitute wall-law into the ω-equation

$\kappa y^+ \sqrt{1+\alpha y^+}$ $\quad \frac{\sqrt{1+\alpha y^+}}{a_1 \kappa y^+}$ $\quad \frac{\sqrt{1+\alpha y^+}}{\kappa y^+}$ $\quad \frac{\sqrt{1+\alpha y^+}}{a_1 \kappa y^+}$

$$-\frac{\mathrm{d}}{\mathrm{d}y^+}\left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+}\right) \neq \gamma \left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+}\right)^2 - \beta_\omega \left(\omega^+\right)^2$$

$$\Leftrightarrow \qquad -D^+_{\omega,t} \neq P^+_\omega - \epsilon^+_\omega$$

$$\Leftrightarrow \qquad -\frac{\sigma_\omega}{a_1}\frac{1}{\left(y^+\right)^2} \neq \frac{1}{\kappa^2}\left(\gamma - \frac{\beta_\omega}{a_1^2}\right)\frac{1+\alpha y^+}{\left(y^+\right)^2}$$

Step 3: Spatial discrepency term

$$\kappa y^+\sqrt{1+\alpha y^+} \qquad \frac{\sqrt{1+\alpha y^+}}{a_1\kappa y^+} \qquad \frac{\sqrt{1+\alpha y^+}}{\kappa y^+} \qquad \frac{\sqrt{1+\alpha y^+}}{a_1\kappa y^+}$$

$$-\frac{\mathrm{d}}{\mathrm{d}y^+}\left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+}\right) = \gamma\left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+}\right)^2 - \beta_\omega\left(\omega^+\right)^2$$

$$\Leftrightarrow \qquad -D_{\omega,t}^+ = P_\omega^+ - \epsilon_\omega^+ \quad + m^+(y^+,\Delta p_x^+)$$

$$\Leftrightarrow \qquad -\frac{\sigma_\omega}{a_1}\frac{1}{\left(y^+\right)^2} = \frac{1}{\kappa^2}\left(\gamma - \frac{\beta_\omega}{a_1^2}\right)\frac{1+\alpha y^+}{\left(y^+\right)^2} \quad + m^+(y^+,\Delta p_x^+)$$

This gives an analytical expression for m as a function of y^+ and the parameter $\alpha=\Delta p_x^+$

Spatial model discrepency term m

Step 3: Spatial discrepency term

Part 2: Wall law for dU/dy and for turbulence statistics

$\kappa y^+\sqrt{1+\alpha y^+}$ → ν_t^+, $\frac{\sqrt{1+\alpha y^+}}{a_1\kappa y^+}$ → $\frac{d\omega^+}{dy^+}$, $\frac{\sqrt{1+\alpha y^+}}{\kappa y^+}$ → $\frac{du^+}{dy^+}$, $\frac{\sqrt{1+\alpha y^+}}{a_1\kappa y^+}$ → ω^+

$$-\frac{\mathrm{d}}{\mathrm{d}y^+}\left(\sigma_\omega \nu_t^+ \frac{\mathrm{d}\omega^+}{\mathrm{d}y^+}\right) = \gamma\left(\frac{\mathrm{d}u^+}{\mathrm{d}y^+}\right)^2 - \beta_\omega\left(\omega^+\right)^2$$

$$\Leftrightarrow \quad -D^+_{\omega,t} = P^+_\omega - \epsilon^+_\omega + m^+(y^+,\Delta p_x^+)$$

$$\Leftrightarrow \quad -\frac{\sigma_\omega}{a_1}\frac{1}{\left(y^+\right)^2} = \frac{1}{\kappa^2}\left(\gamma - \frac{\beta_\omega}{a_1^2}\right)\frac{1+\alpha y^+}{\left(y^+\right)^2} + m^+(y^+,\Delta p_x^+)$$

Inverse modelling: If we add the model discrepency term m to the ω-equation, then the assumed wall-laws at APG solves the modified ω-equation

Step 4: Functional discrepency term

- **Step 4: Express the discrepency term as a function of admissible mean flow and turbulence quantities**

$$m^+(y^+) = \mathcal{M}^+ \left[\frac{\mathrm{d}u^+_{\mathrm{law}}(y^+)}{\mathrm{d}y^+}, \tau^+_{xy,\mathrm{law}}(y^+), \omega^+_{\mathrm{law}}(y^+); \Delta p^+_x \right]$$

  - For the turbulence model augmentation term to account for the sqrt-law at APG we choose the **pressure diffusion term by Rao & Hassan**

$$m = -D_{\omega,p} = -\frac{\omega}{k}\frac{\partial}{\partial y}\left[\sigma_{k,P}\nu_t \frac{-\overline{u'v'}}{k}\frac{1}{\rho}\frac{\partial P}{\partial x}\right]$$

RANS model augmentation. Summary of step #1

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

- Transport equation for the Reynods stress tensor

$$U_k \frac{\partial}{\partial x_k}\overline{u_i' u_j'} = \mathcal{P}_{ij} + D_{ij}^{\nu} + D_{ij}^{t} + D_{ij}^{p} + \Pi_{ij} - \epsilon_{ij}$$

- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_\omega - \epsilon_\omega + D_\omega^{\nu} + D_\omega^{t} + D_\omega^{p}$$

Modification #1 to account for sqrt-law at APG

Idea #2: RANS model coefficients for log-law slope sensitized to pressure gradient parameter Δp_x^+

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$$U_j \frac{\partial \omega}{\partial x_j} = \gamma \left(\frac{\partial U_i}{\partial x_j}\right)^2 - \beta_\omega \omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right]$$

Coefficient γ controls the slope of the log-law

Standard calibration is for ZPG
κ=0.41 = const

$$\gamma = \frac{\beta_\omega}{\beta_k} - \frac{\sigma_\omega \kappa^2}{\sqrt{\beta_k}}$$

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Idea #2: RANS model coefficients for log-law slope sensitized to pressure gradient parameter Δp_x^+

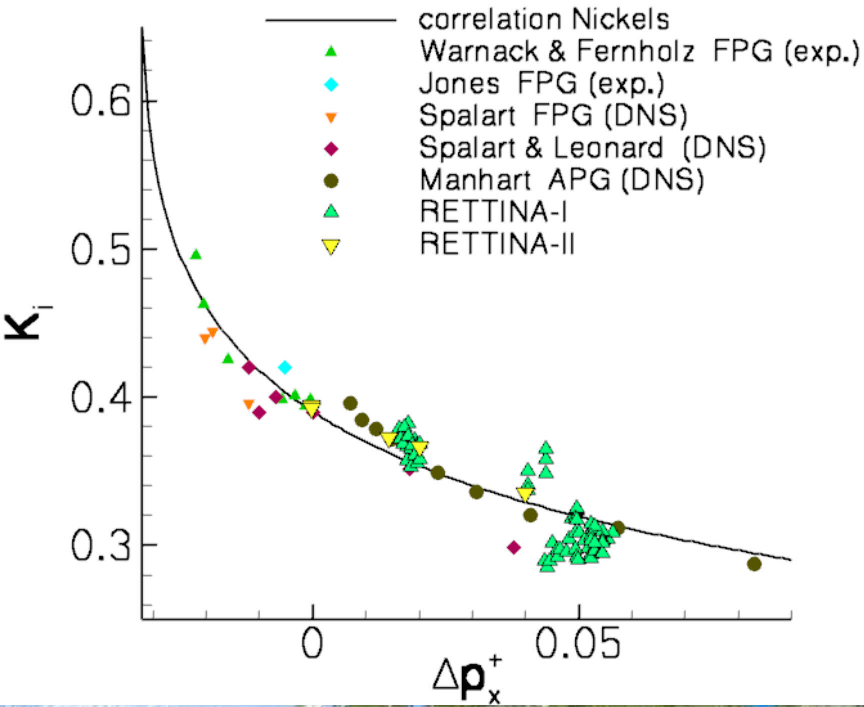
$$U_j \frac{\partial \omega}{\partial x_j} = \gamma \left(\frac{\partial U_i}{\partial x_j} \right)^2 - \beta_\omega \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_t) \frac{\partial \omega}{\partial x_j} \right]$$

Coefficient γ controls the slope of the log-law

Modification: $\kappa = \kappa(\Delta p_x^+)$

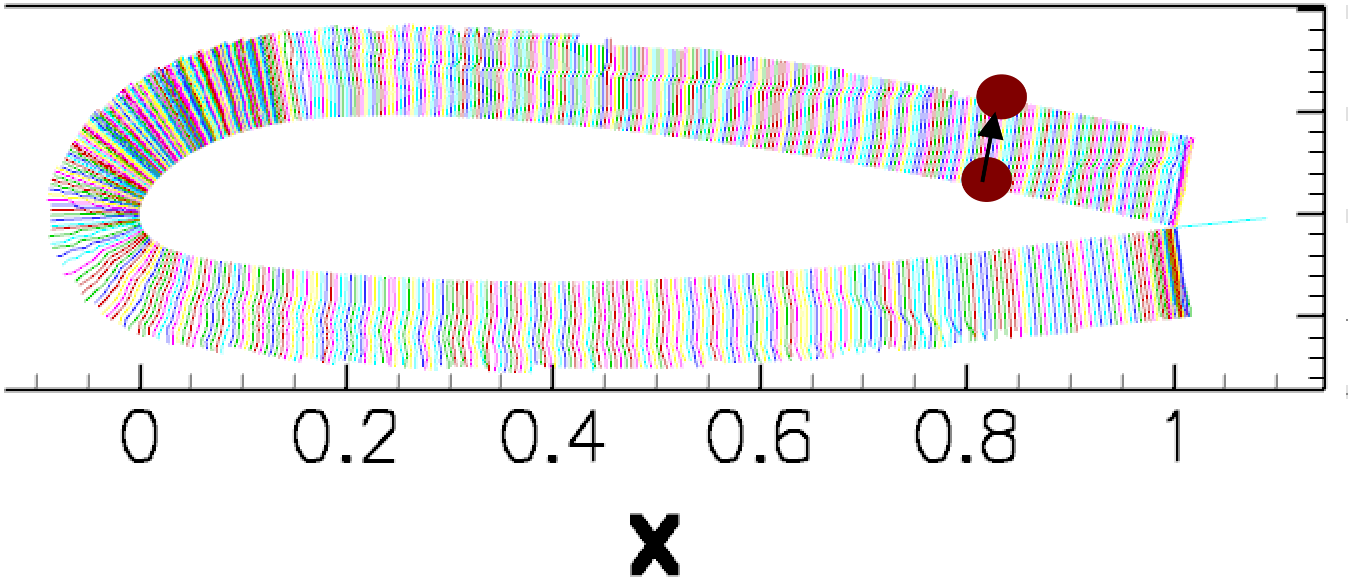
$$\gamma = \frac{\beta_\omega}{\beta_k} - \frac{\sigma_\omega \kappa^2}{\sqrt{\beta_k}}$$

Coefficients of the turbulence model become functions of the local flow conditions



Data structure of wall-normal lines for Δp_x^+

- Extension of unstructured flow solver DLR TAU code
  - Data structure for wall-normal lines
  - Method to determine δ_{99}, δ^*, θ, H_{12}



Field point

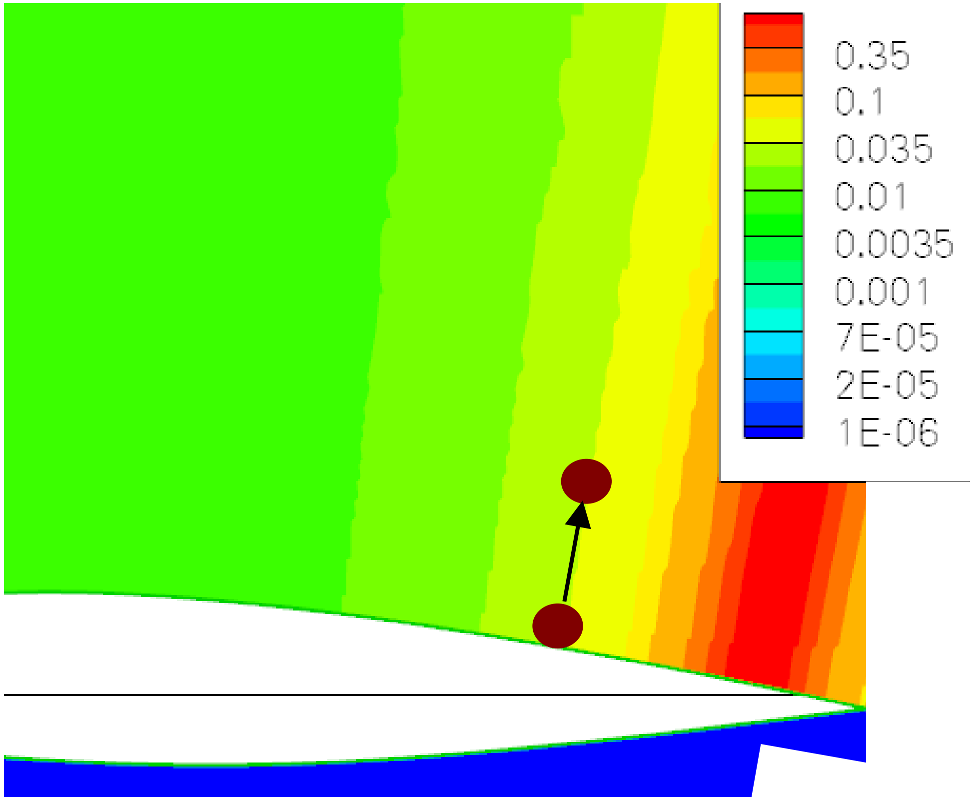
Surface point

Δp_x^+ from dp/dx and u_τ

δ_{99}, δ^*, θ, H_{12}

RANS model sensitized to pressure gradient Δp_x^+

Field distribution of Δp_x^+

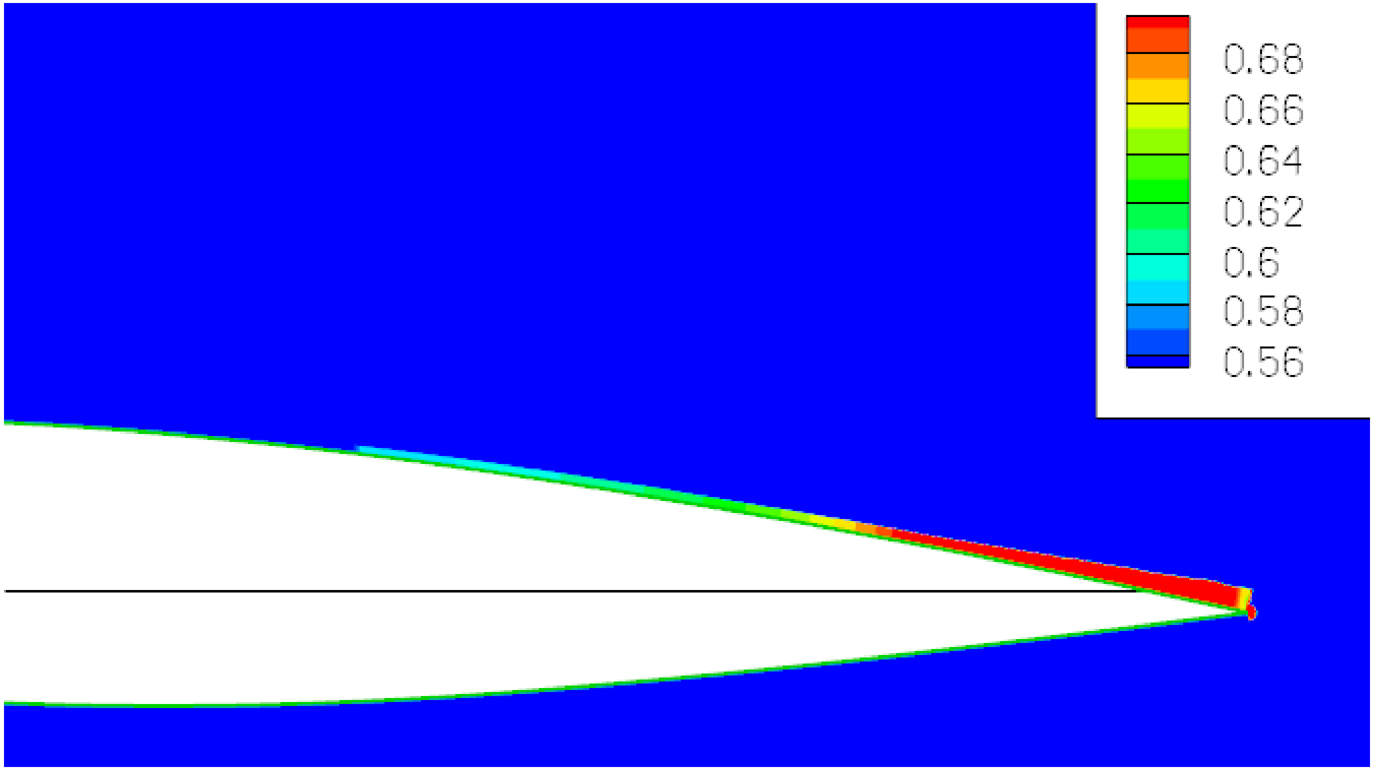


Map to corresponding field points

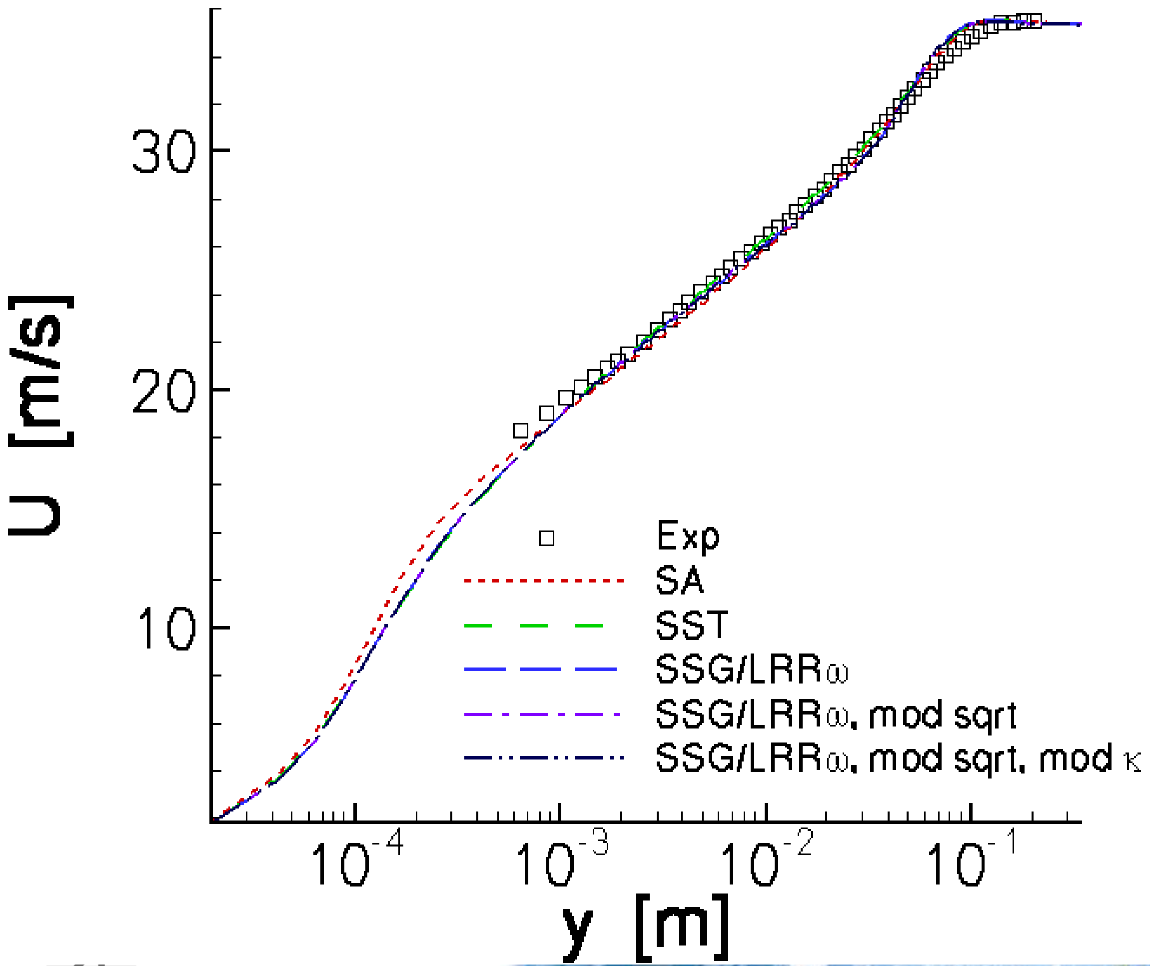
Surface quantities Δp_x^+ from dp/dx and u_τ

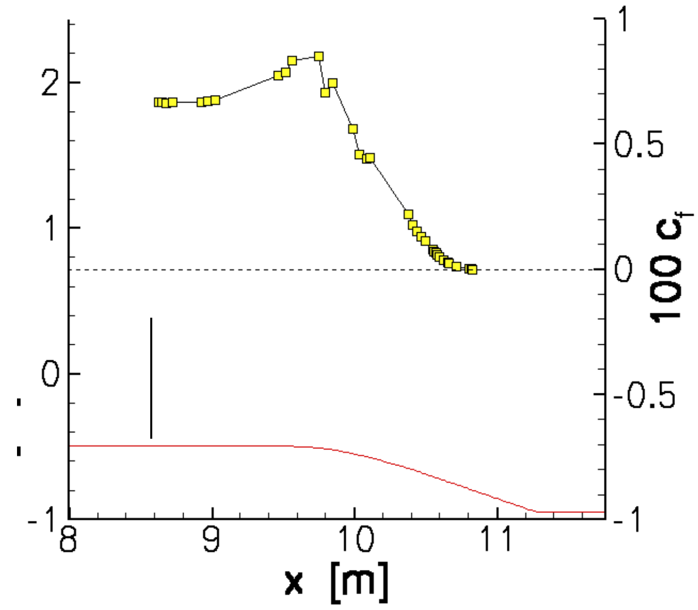
RANS model sensitized to pressure gradient Δp_x^+

RANS model coefficient **γ** becomes a function of Δp_x^+



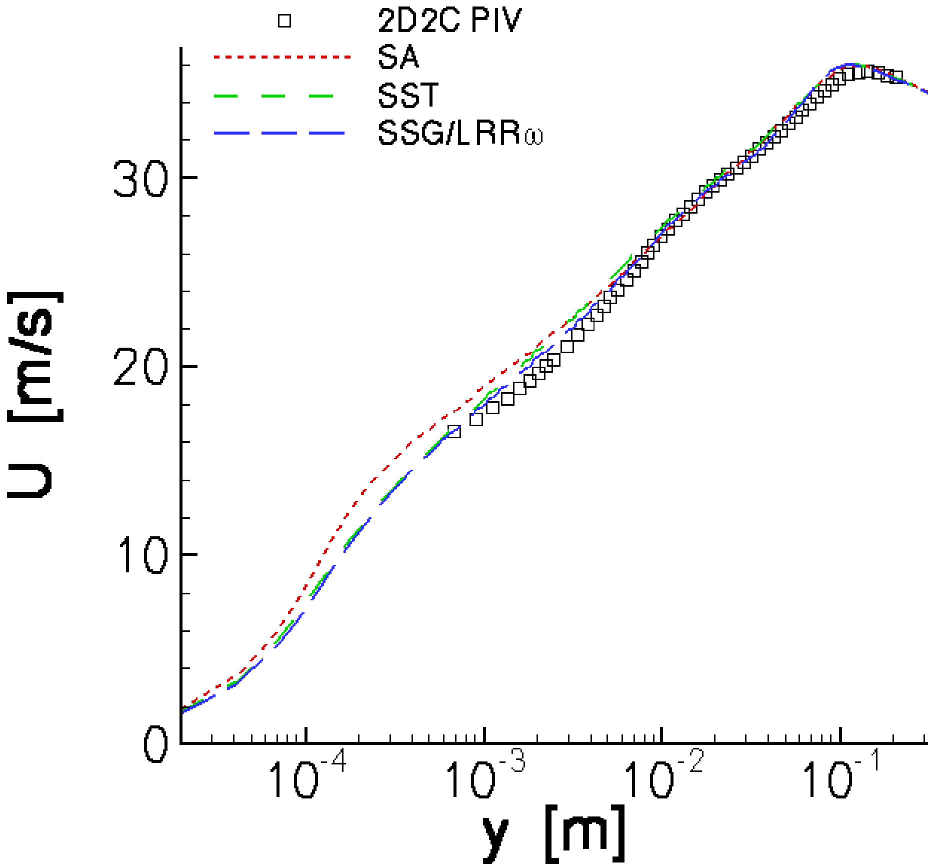
Calibration of RSM for VicToria experiment

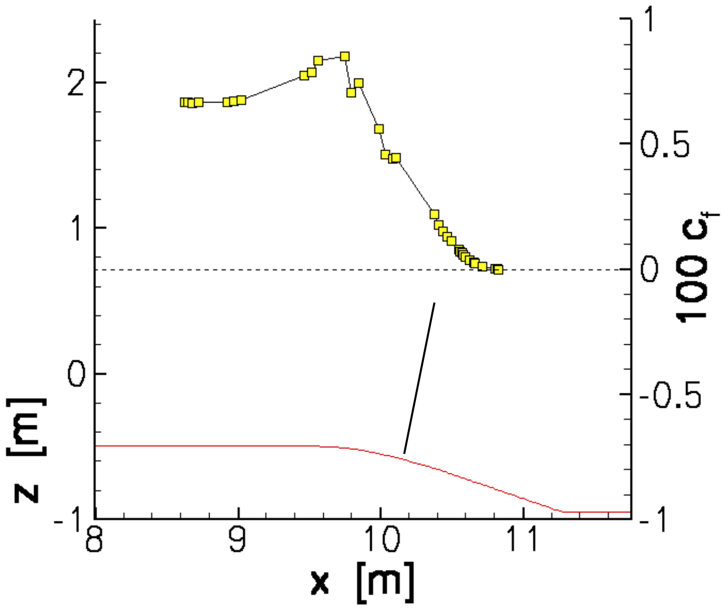




$\Delta p_x^+ = dp^+/dx^+ = 0$

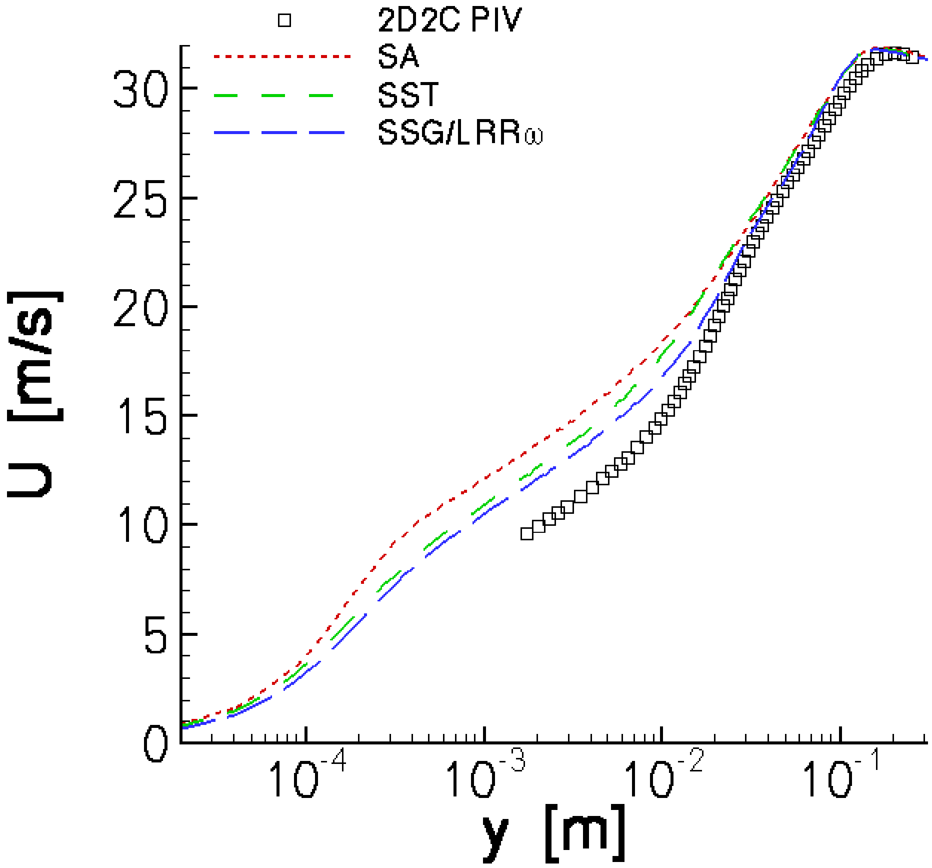
Calibration of RSM for VicToria experiment

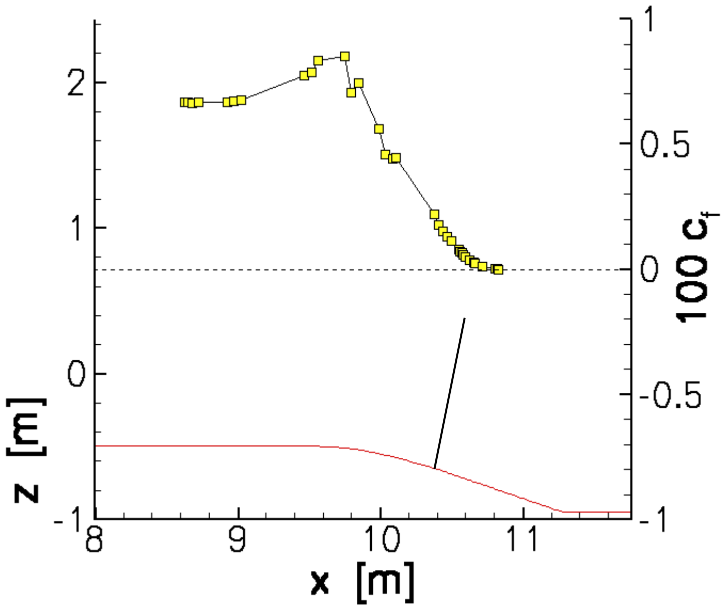




$\Delta p_x^+ = dp^+/dx^+ = 0.012$

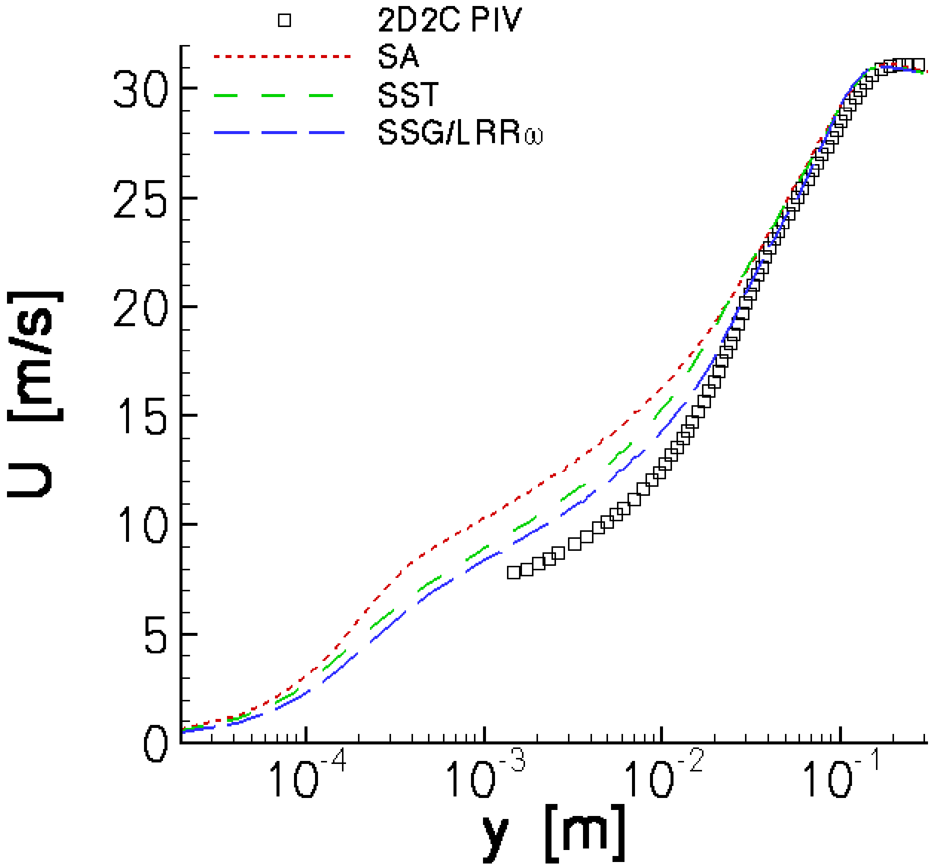
Calibration of RSM for VicToria experiment

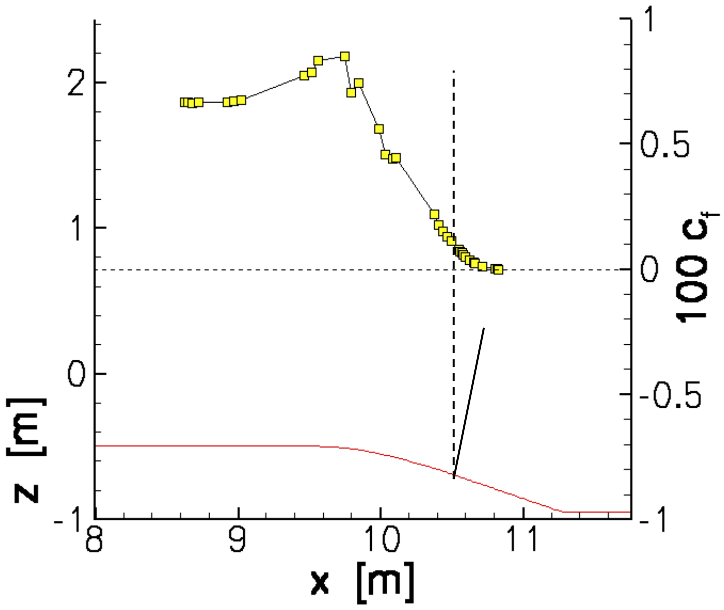




$\Delta p_x^+ = dp^+/dx^+ = 0.053$

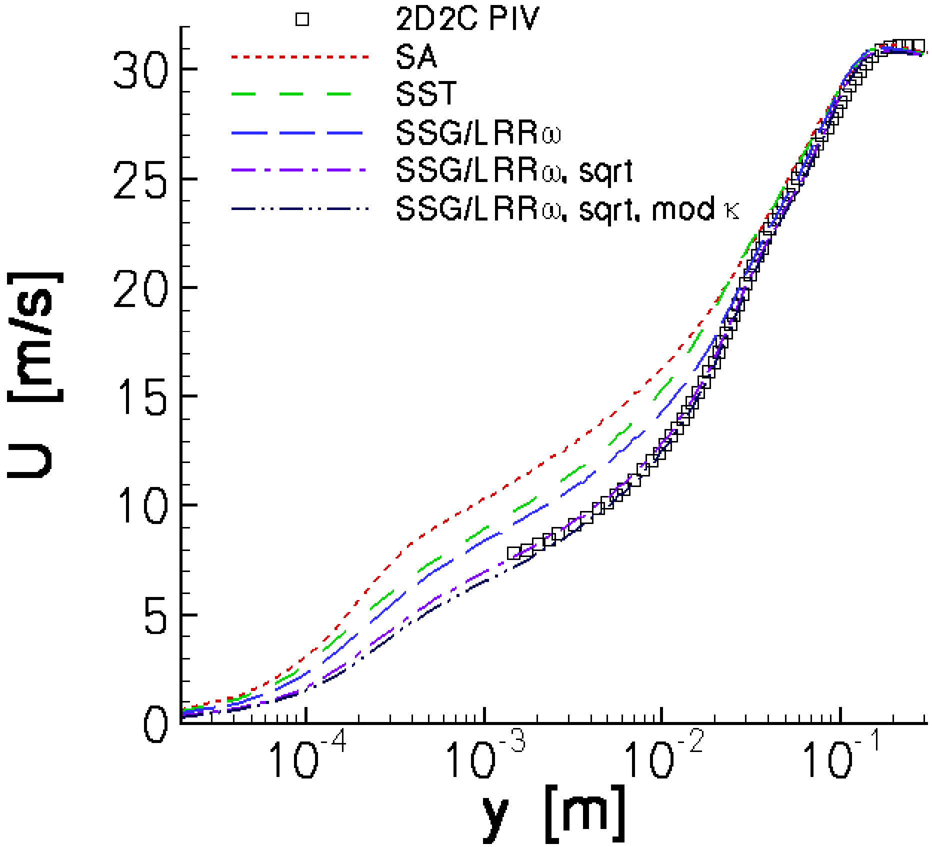
Calibration of RSM for VicToria experiment

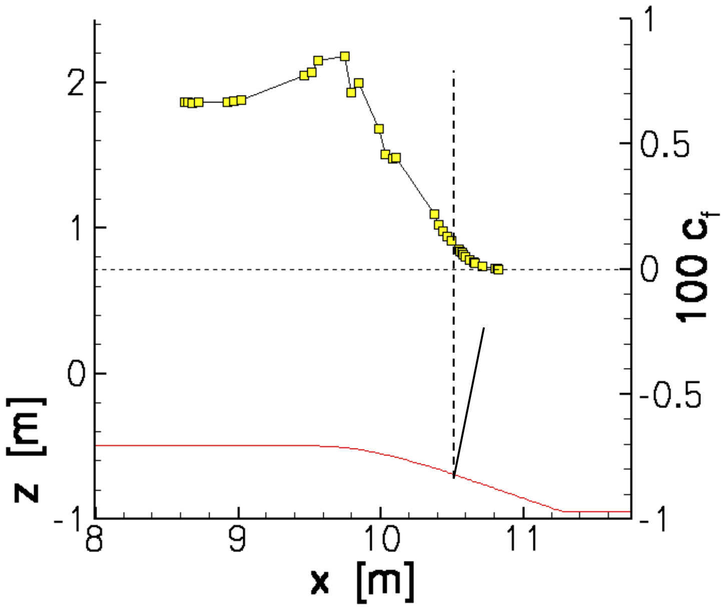




$\Delta p_x^+ = dp^+/dx^+ = 0.076$

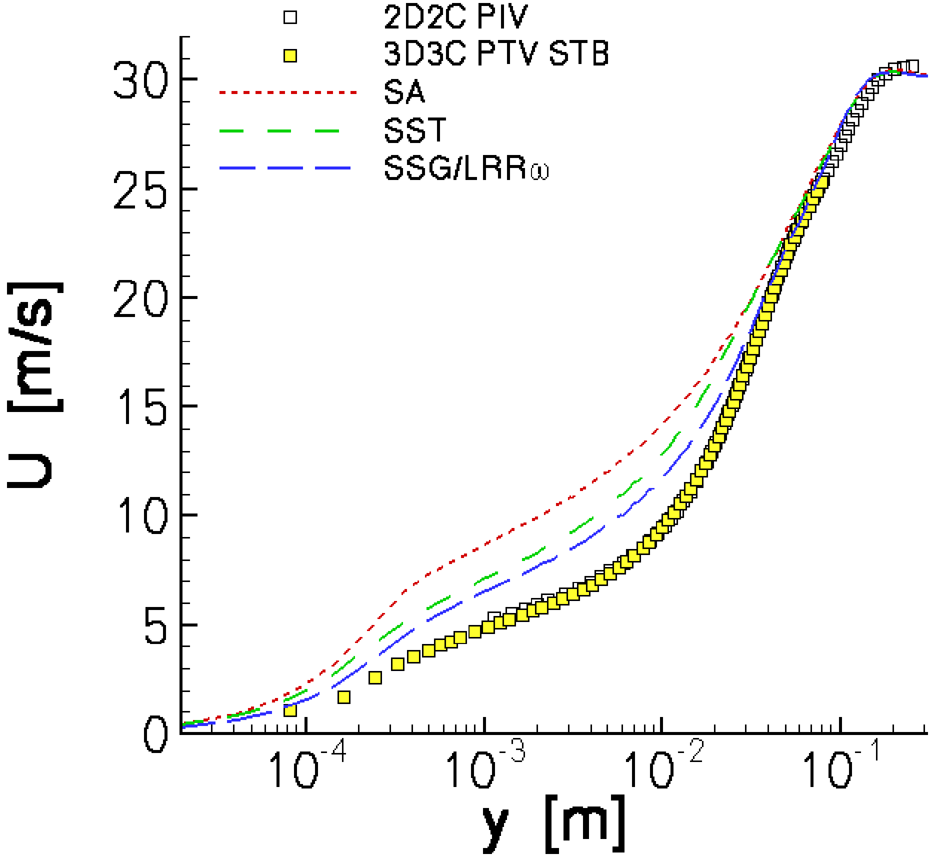
Calibration of RSM for VicToria experiment

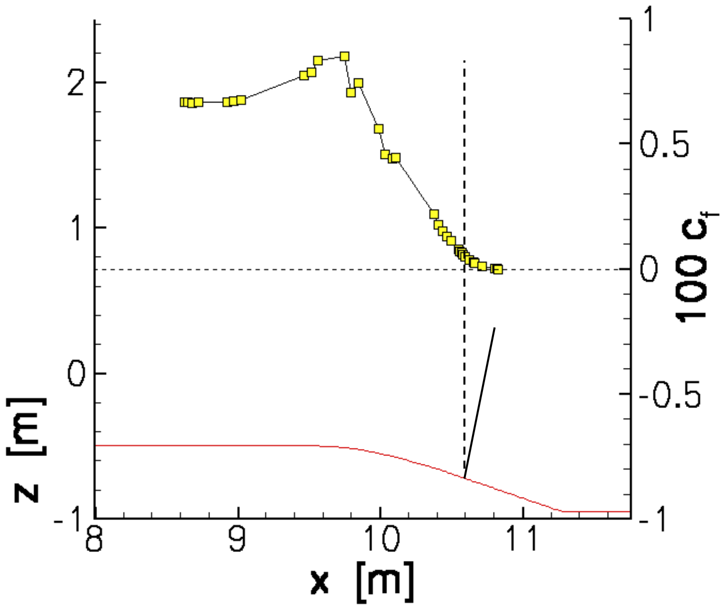




$\Delta p_x^+ = dp^+/dx^+ = 0.076$

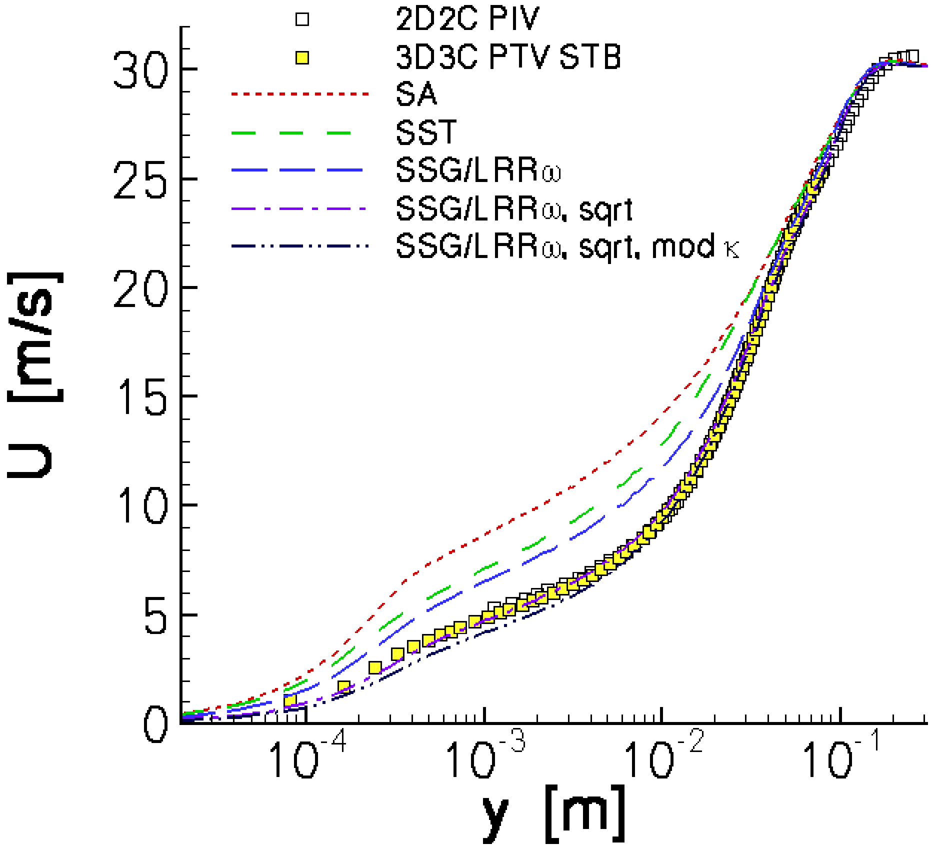
Calibration of RSM for VicToria experiment

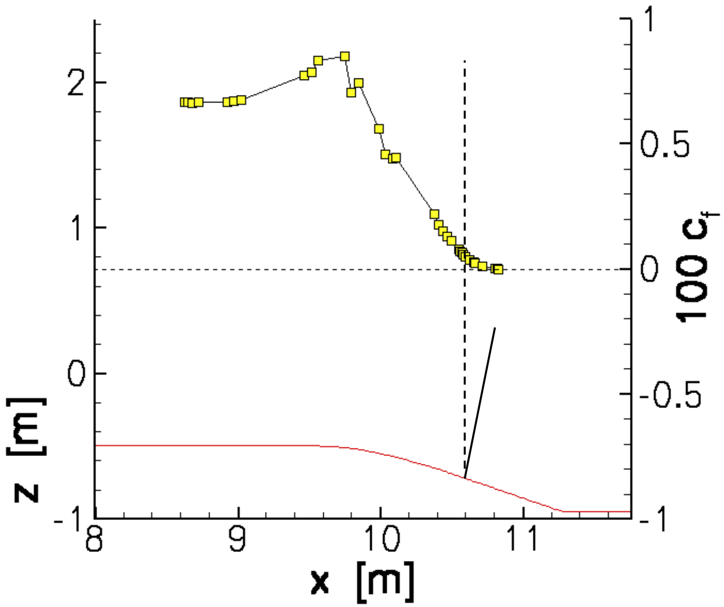




$$\Delta p_x^+ = dp^+/dx^+ = 0.140$$

Calibration of RSM for VicToria experiment





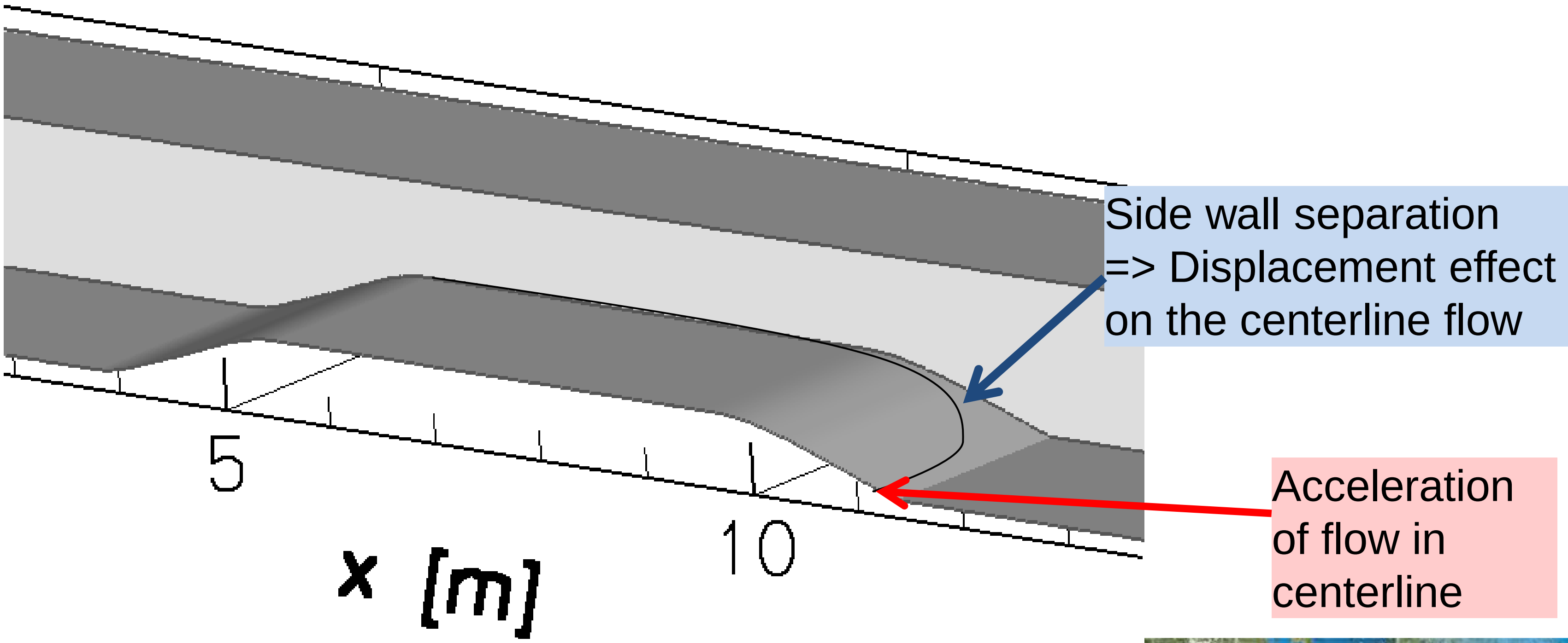
$\Delta p_x^+ = dp^+/dx^+ = 0.140$

Outlook: Next steps #1

3D effects of side walls and their measurement

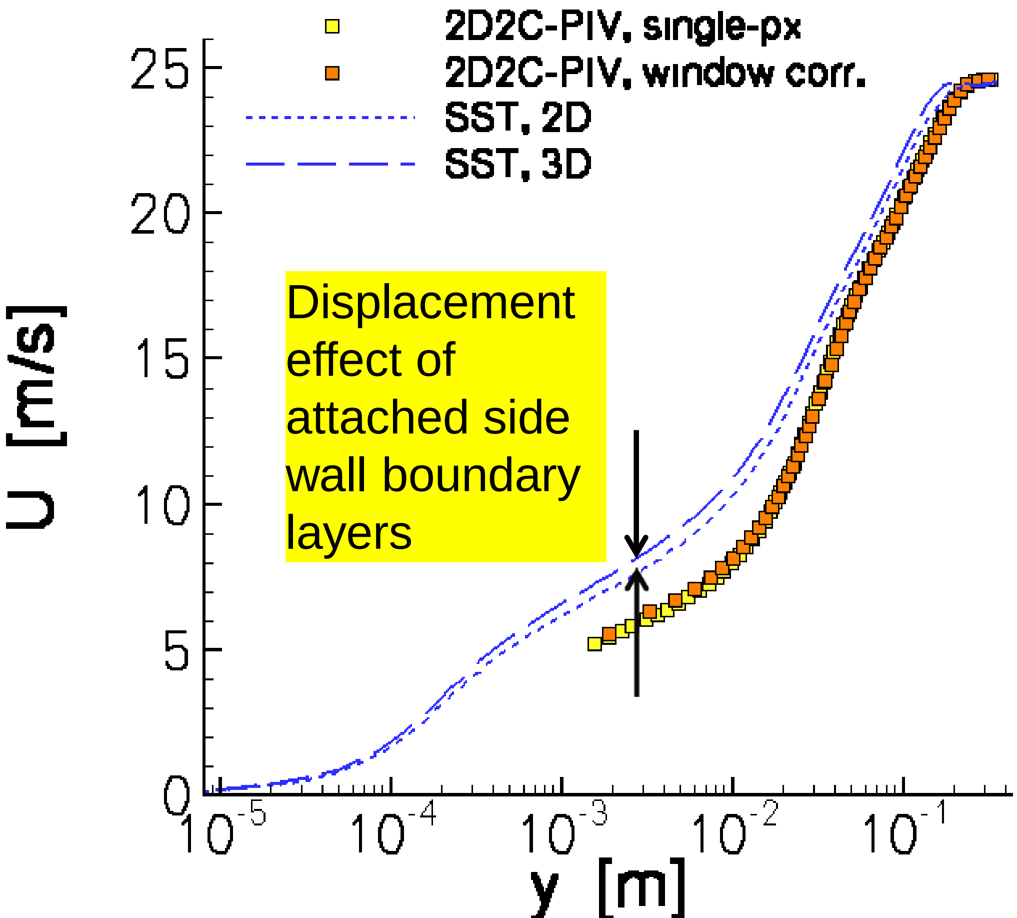
Need measurement of 3D effects (side wall separation)

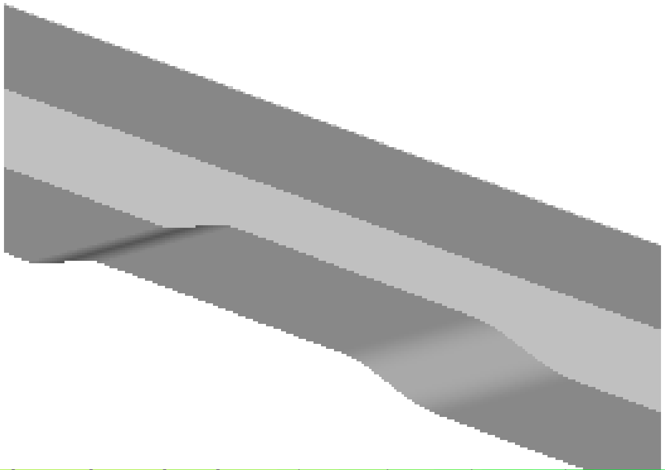
- Need qualitative and quantitative information on 3D flow field
  - **Oil flow picture of surface streamlines over the entire span (E. Schülein from AS-HGK)**

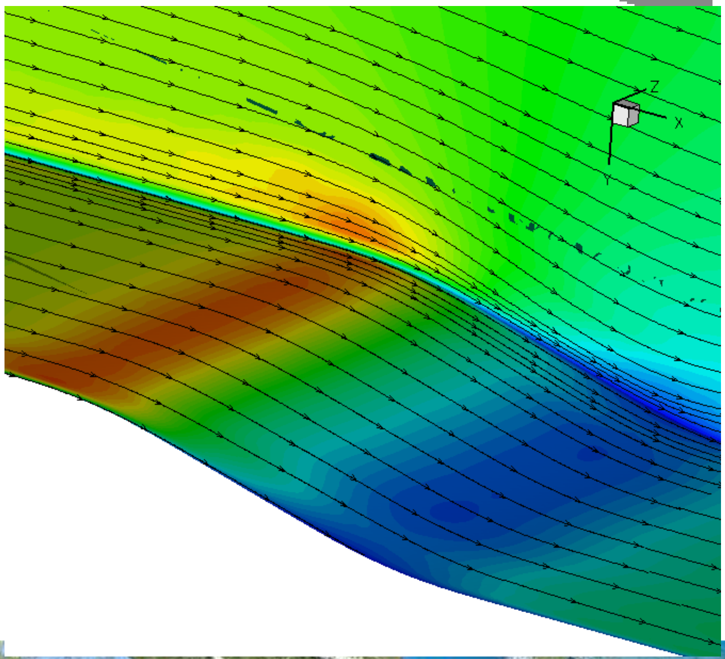


Estimate of side wall effects from RETTINA II exp

- Centerline position at mild APG, albeit side wall flow remains attached (no corner flow separation)





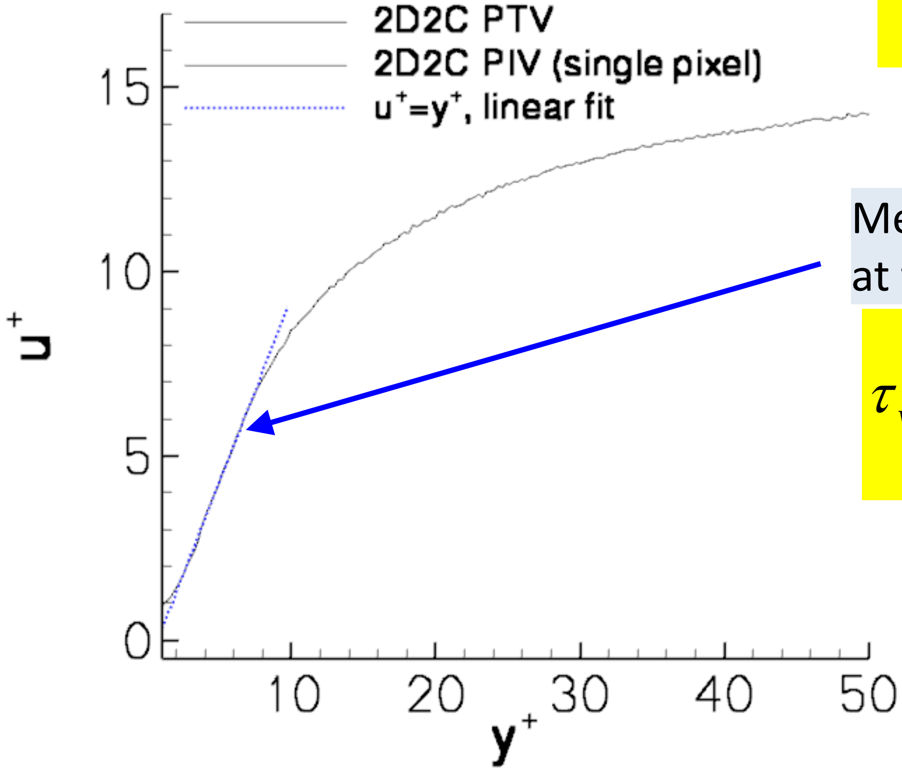


Outlook: Next steps #2

Measurement of wall shear stress

Input for wall-law scaling: Wall-shear stress

DFG RETTINA II experiment
Microscopic PTV by N. Reuther (UniBw M)

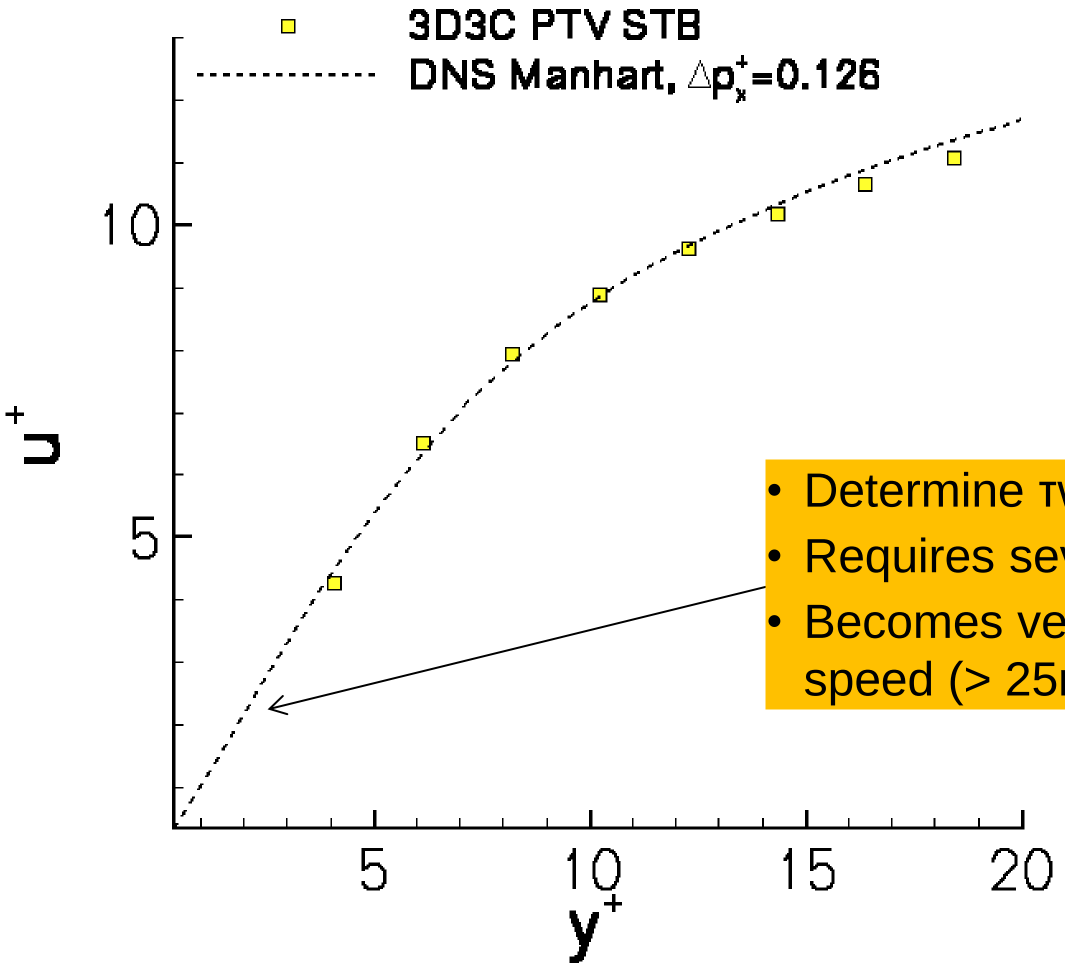


$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

Mean velocity gradient at the wall

$$\tau_w = \mu \left.\frac{\partial U}{\partial y}\right|_{y=0}$$

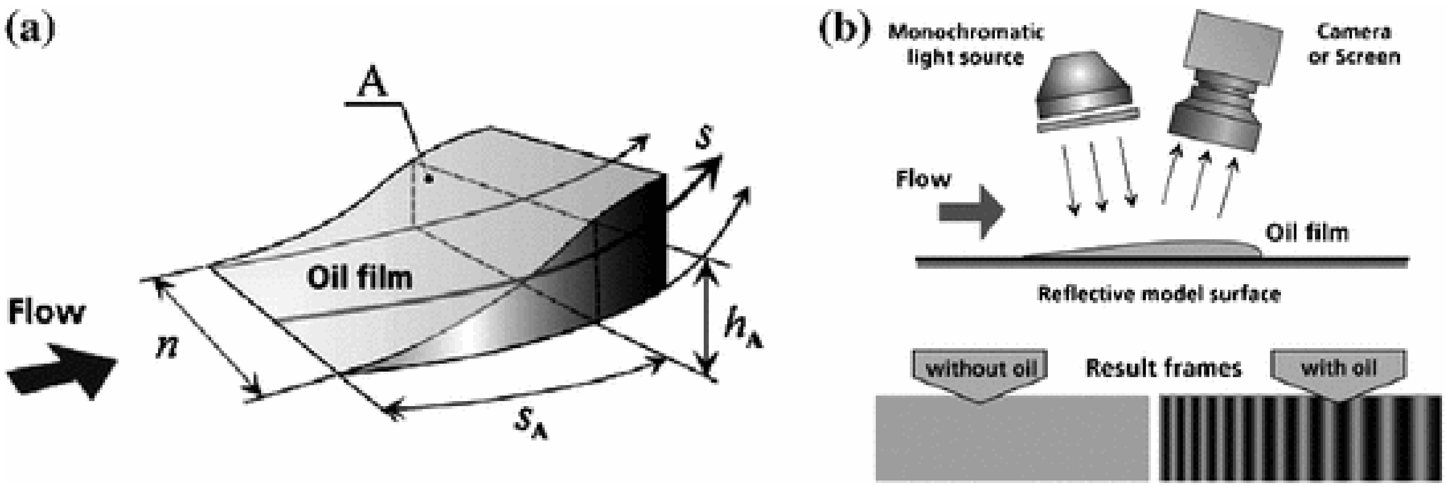
Input for wall-law scaling: Wall-shear stress



- Determine τw from the mean velocity profiles
- Requires several data points for y+ < 1.5
- Becomes very complicated for high flow speed (> 25m/s)

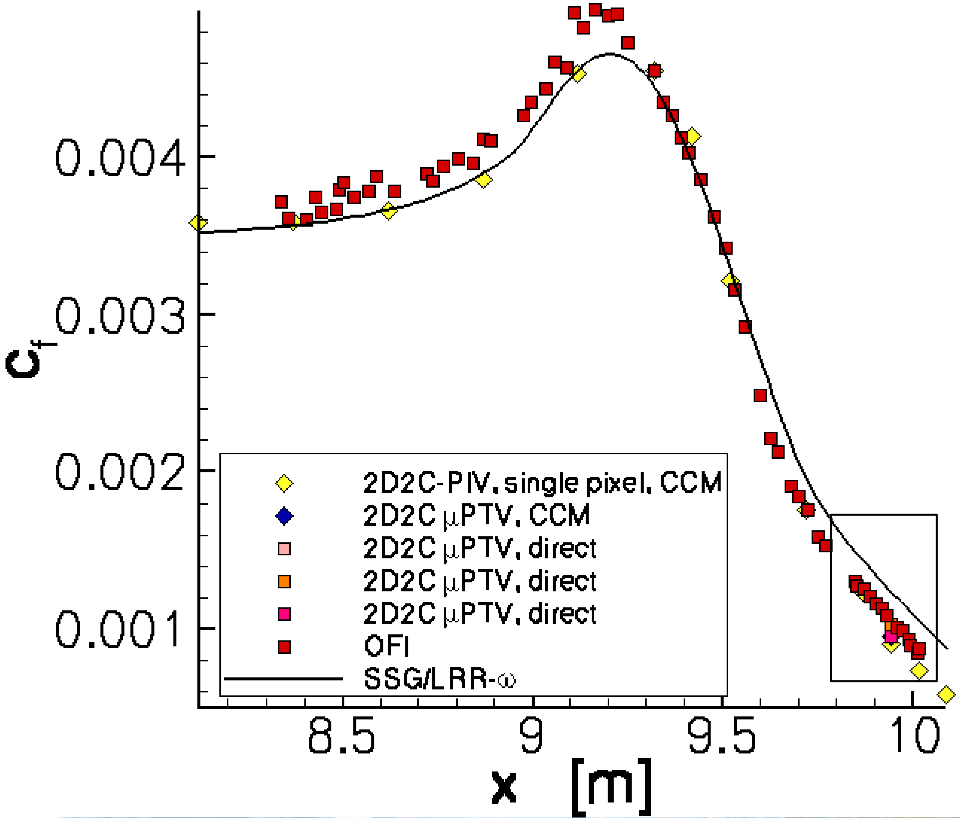
Need for additional (complementary) measurements

- Highly accurate measurement of wall shear stress τ_w
- Oil film interferometry
- Gave excellent data for RETTINA II experiment by Erich Schülein (DLR AS HGK)



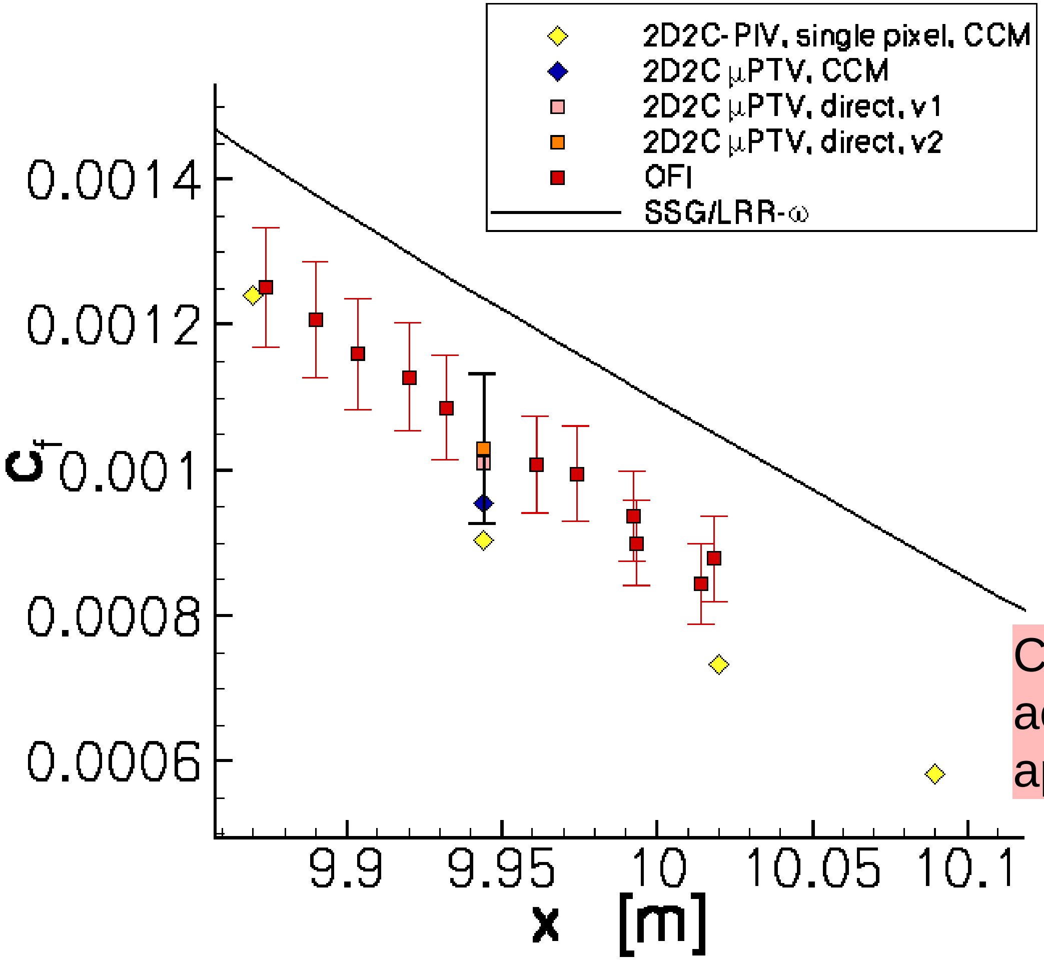
Comparison of PTV-direct versus Oil-film interferometry

- Evaluation of data for RETTINA II experiment was part of VicToria project
- Oil-film interferometry by Erich Schülein (DLR AS HGK), assisted by Nico Reuther (Uni Bw M)



Comparison of PTV-direct versus Oil-film interferometry

- Estimate of error bars for case U=23m/s



Clauser-chart not accurate enough when approaching separation

Summary & conclusion

Summary and conclusion

- We presented the work for the DLR VicToria experiment and the improvement of RANS turbulence models for adverse pressure gradients and the onset of separation
- Status of the work
  - ✓ Design of a high Re turbulent boundary layer exp with mild separation
  - ✓ Overview & detail PIV/PTV measurements performed and evaluated
  - ✓ Evaluation of a new wall law for adverse pressure gradient
  - ✓ Validation of modified SSG/LRR-ω RSM for the VicToria experiment

- A second measurement campaign is tentatively planned and would deliver important, missing complementary measurements
  - Information of 3D surface flow field and side wall separation (**oil film surface picture**)
  - **Oil film interferometry** (OFI) measurements for wall-shear stress
    => Needed for calibration of wall-law at APG towards separation
  - Measurement of details of the Reynolds stress transport equation (turbulent transport, dissipation) using recent improvements of the **3D3C PTV STB** method achieved during the VicToria project

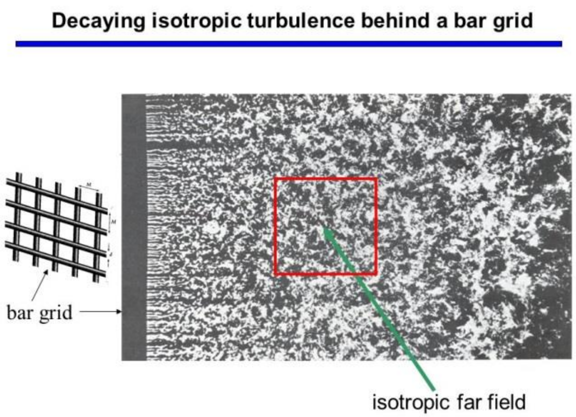
Acknowledgement

- The experimental microscopic PTV data for the RETTINA II were meaured by **Nico Reuther** and **Christian Kähler** (Uni Bw München)
- The OFI data for the RETTINA II experiment were measured by **Erich Schülein** (AS HGK) and assisted by Nico Reuther
- The funding of measurement campaign by **DFG** within „Investigation of turbulent boundary layers with pressure gradient at high Reynolds numbers with high resolution multi-camera techniques“ is gratefully acknowledged
- The funding of the geometry model of the RETTINA II experiment by **DLR AS-BS** is gratefully acknowledge
- Thanks to **Mike Zippert (DLR SHT)** for excellent cooperation in design and construction of the VicToria experiment

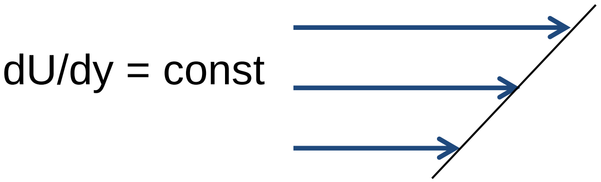
Thank you for your attention!

Questions …?

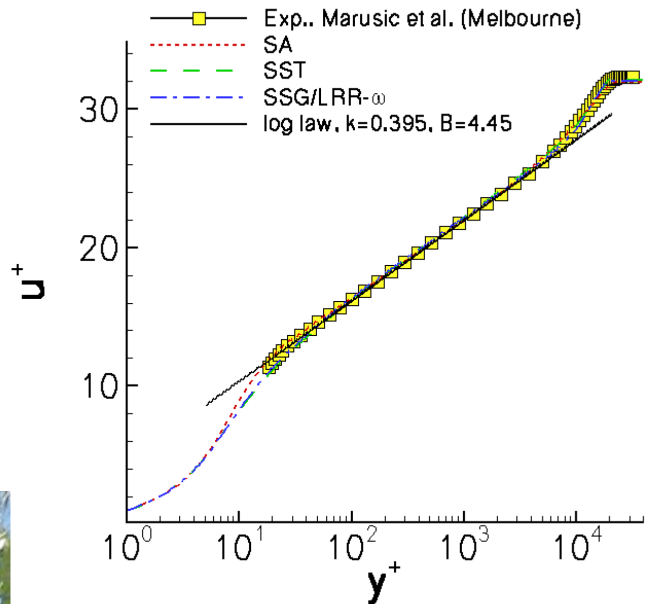
State-of-the-art calibration of RANS models



- Decaying isotropic turbulence (=turbulence downstream of a grid)



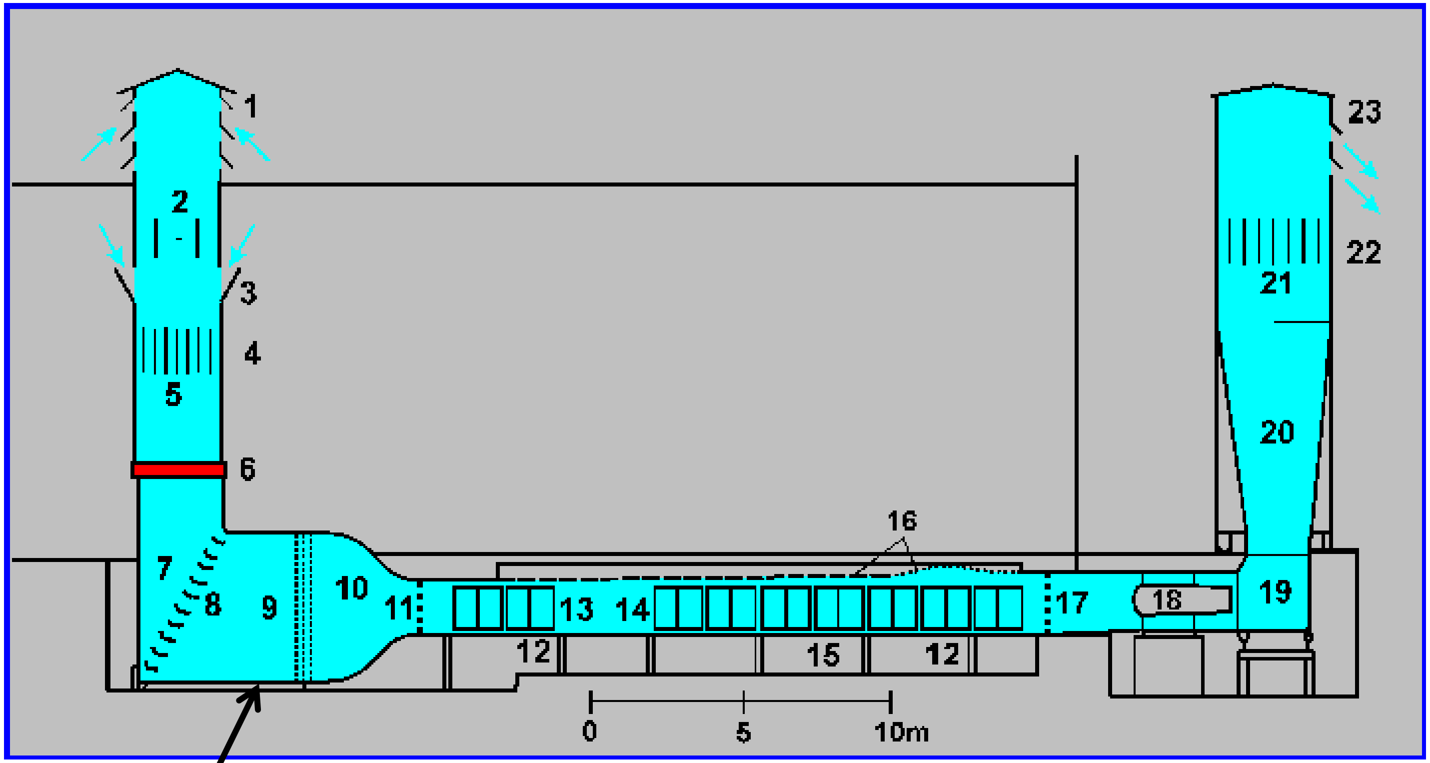
- Homogeneous shear flows (=flow with constant mean shear rate dU/dy remote from viscous walls)



- Turbulent boundary layer flow over a flat plate at zero pressure gradient: The log-law

Simulation of wind-tunnel characteristics of AWM

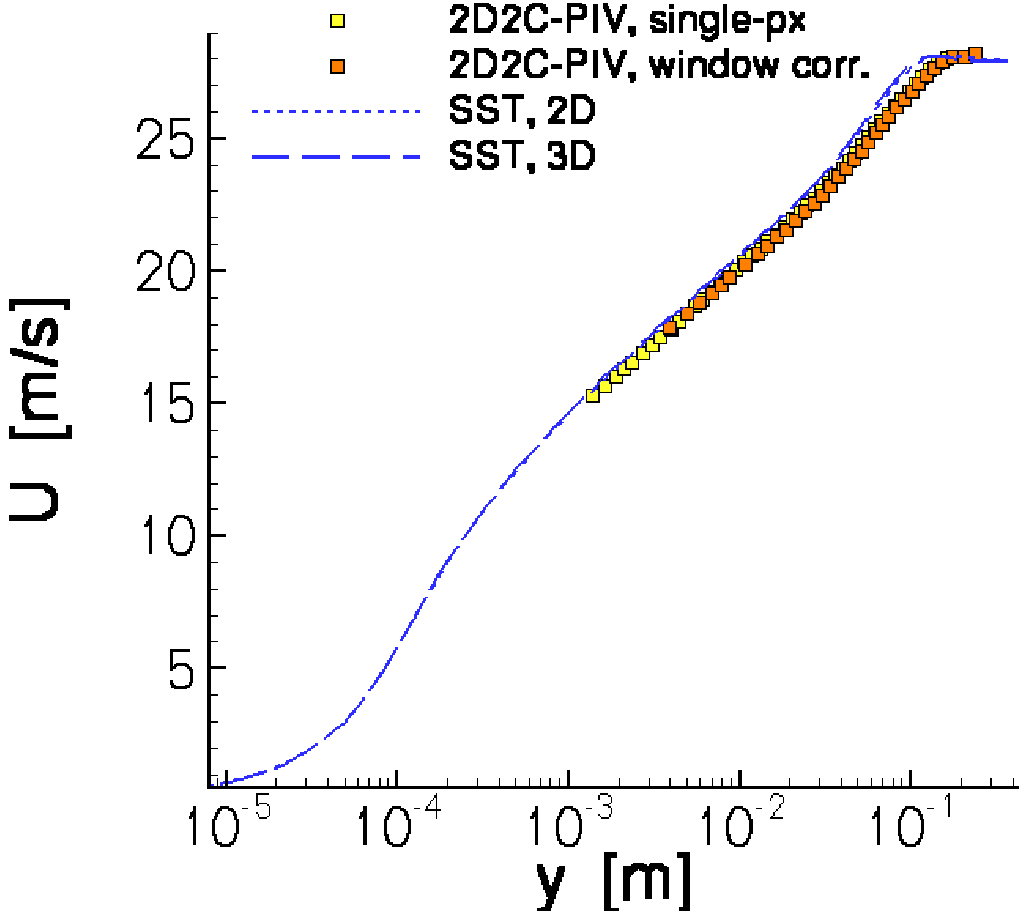
- Need correct boundary layer thickness in the test section
- Complicated flow history in open Eiffel wind tunnel

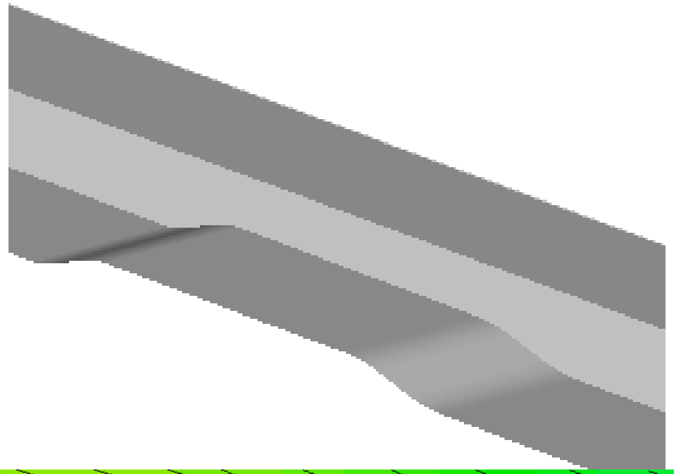


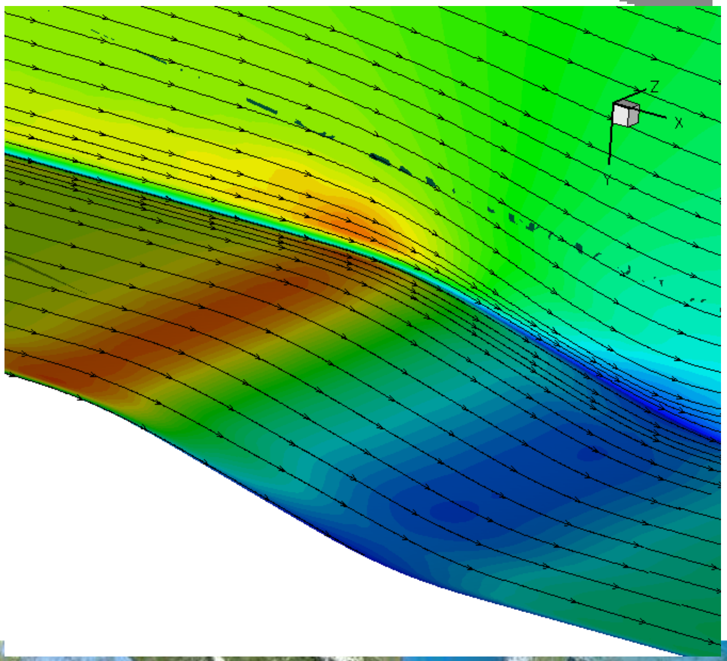
Complicated evolution of boundary layer thickness on wind tunnel walls

Estimate of side wall effects from RETTINA II exp

- Centerline position in ZPG region

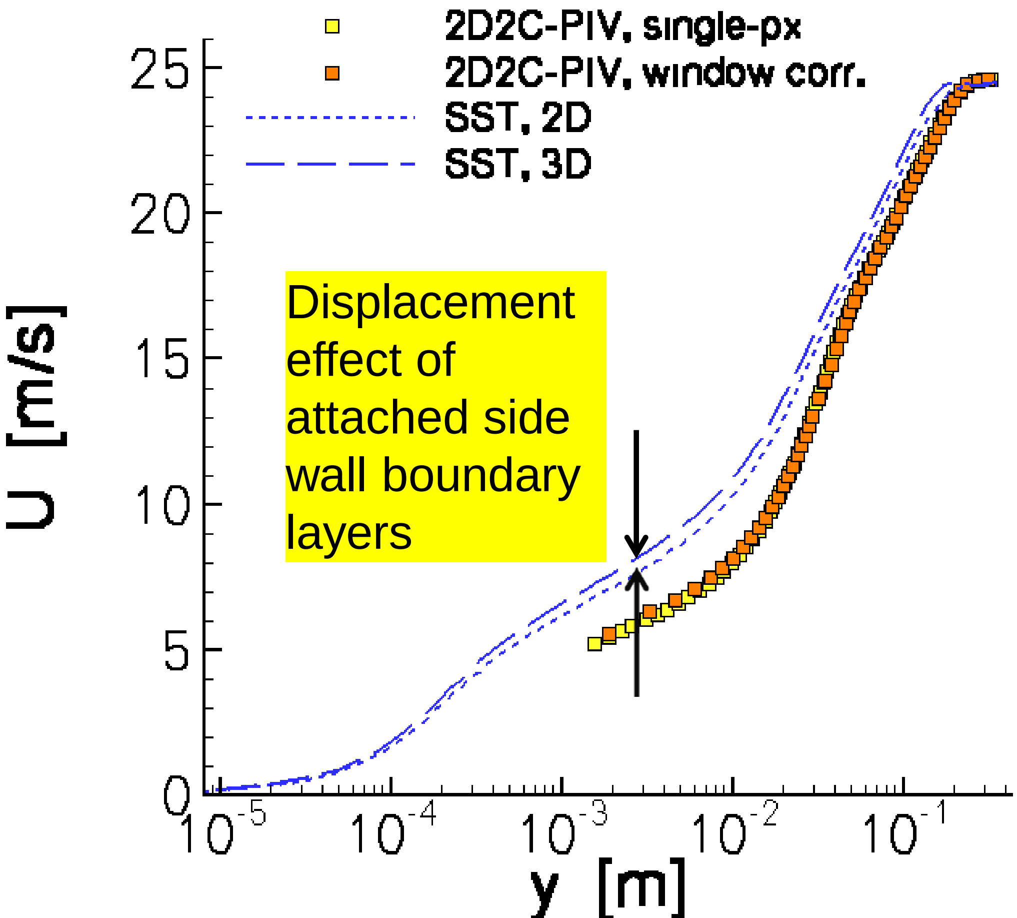


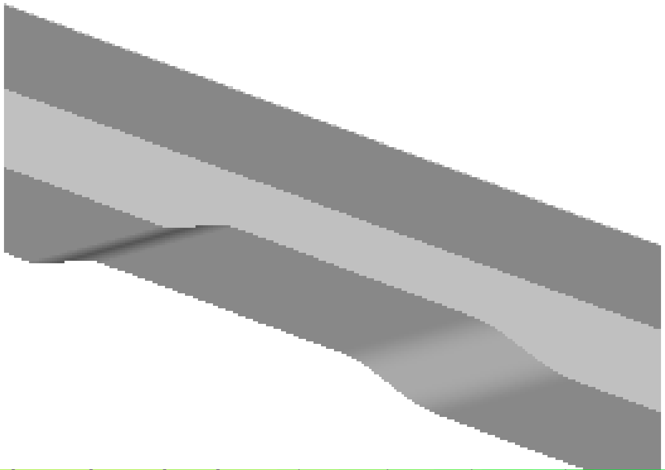


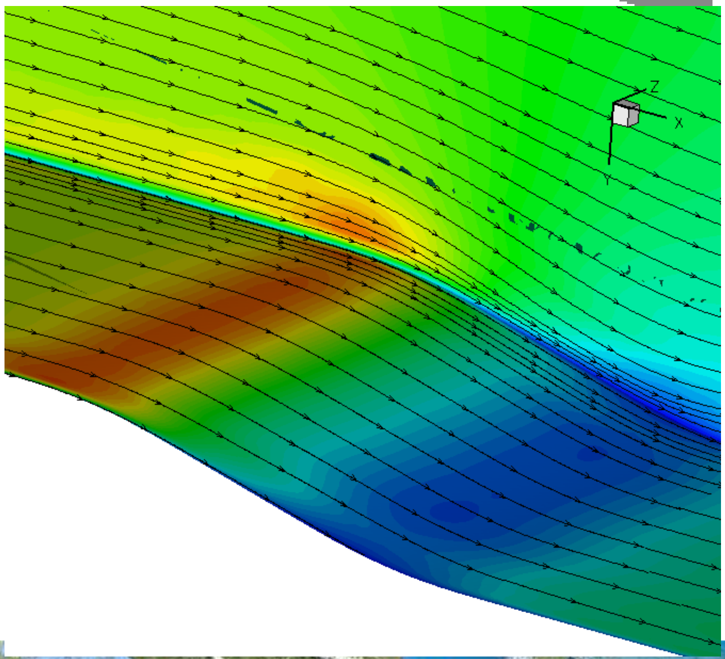


Estimate of side wall effects from RETTINA II exp

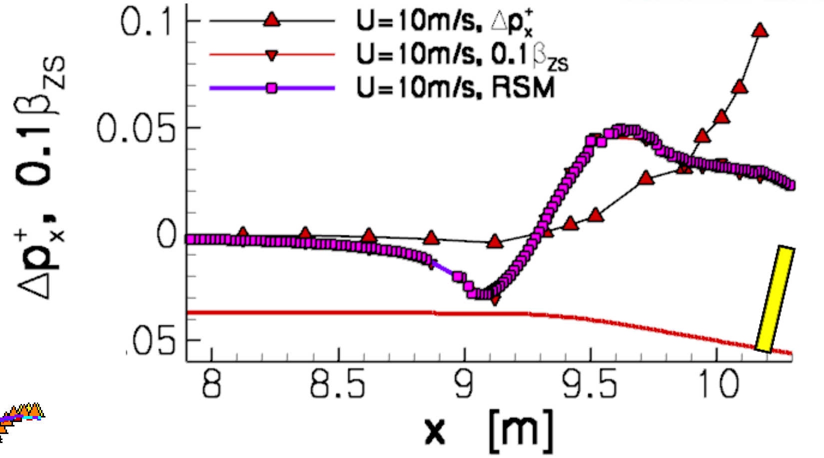
- Centerline position at mild APG, albeit side wall flow remains attached (no corner flow separation)

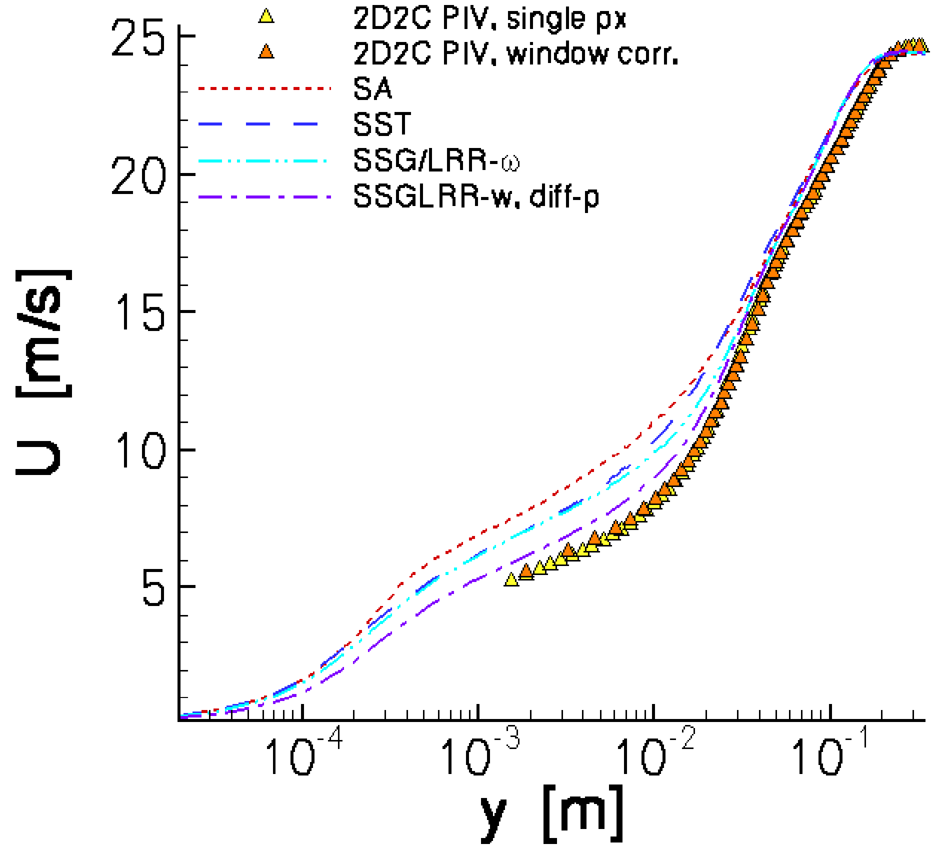




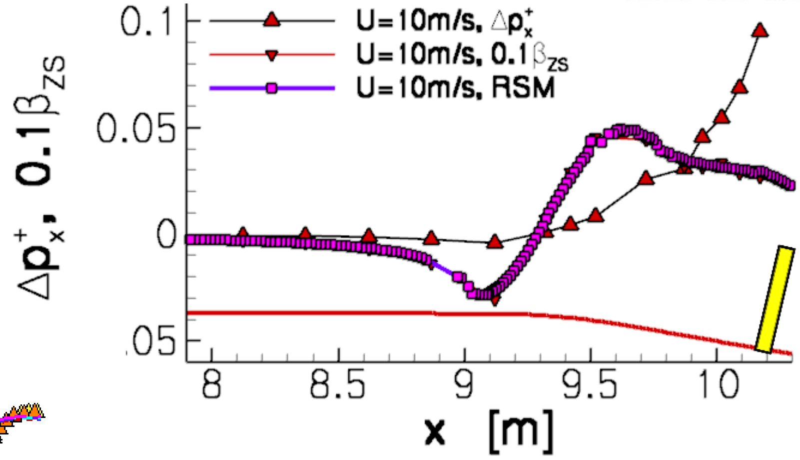


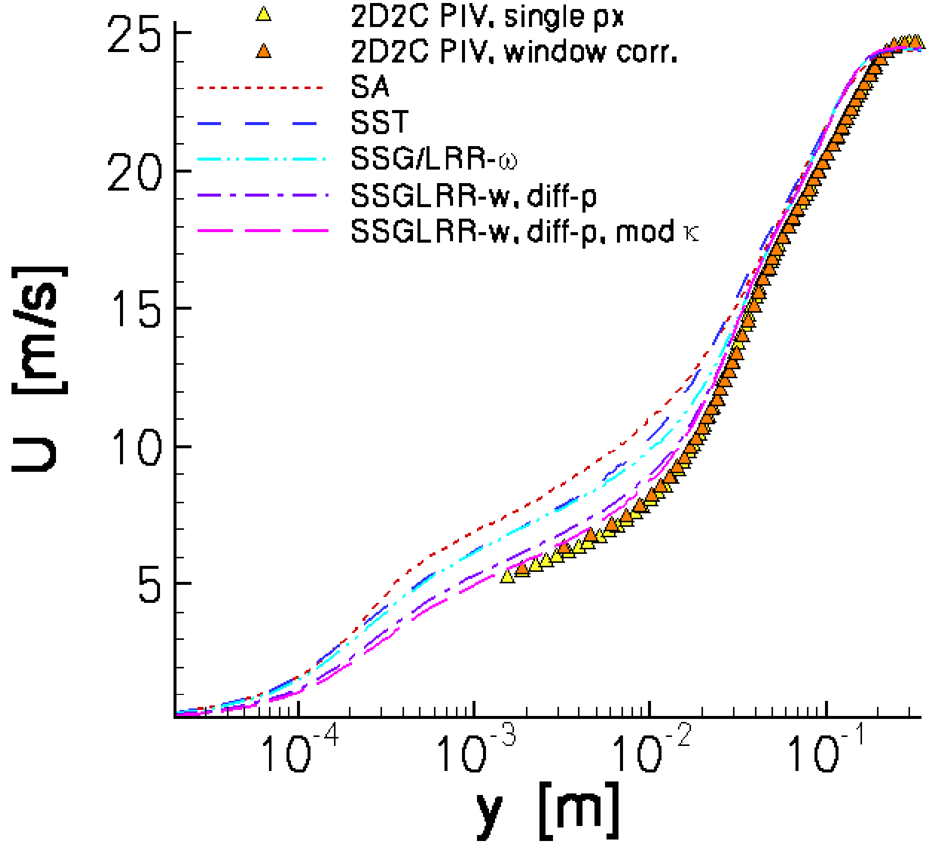
Results for RETTINA II experiment





Results for RETTINA II experiment





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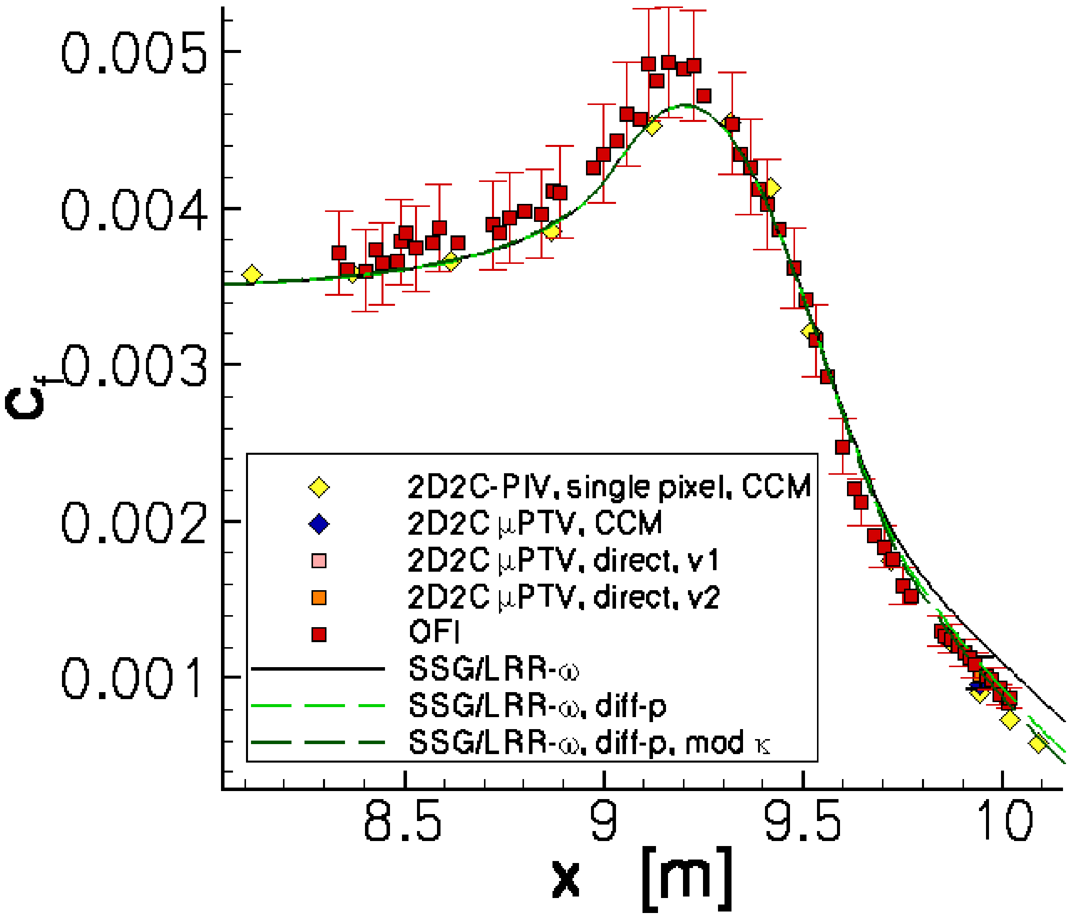
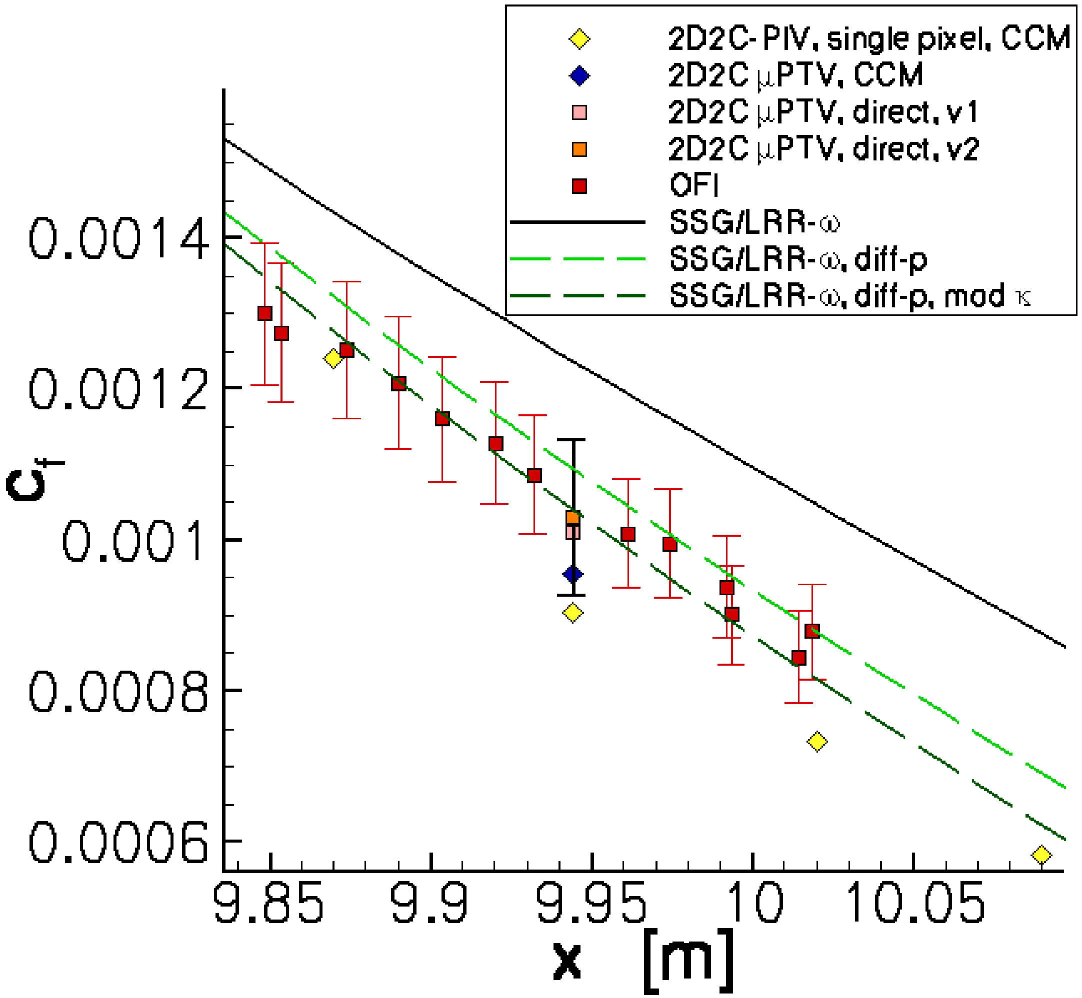
Results for RETTINA II experiment

- Case U=23m/s

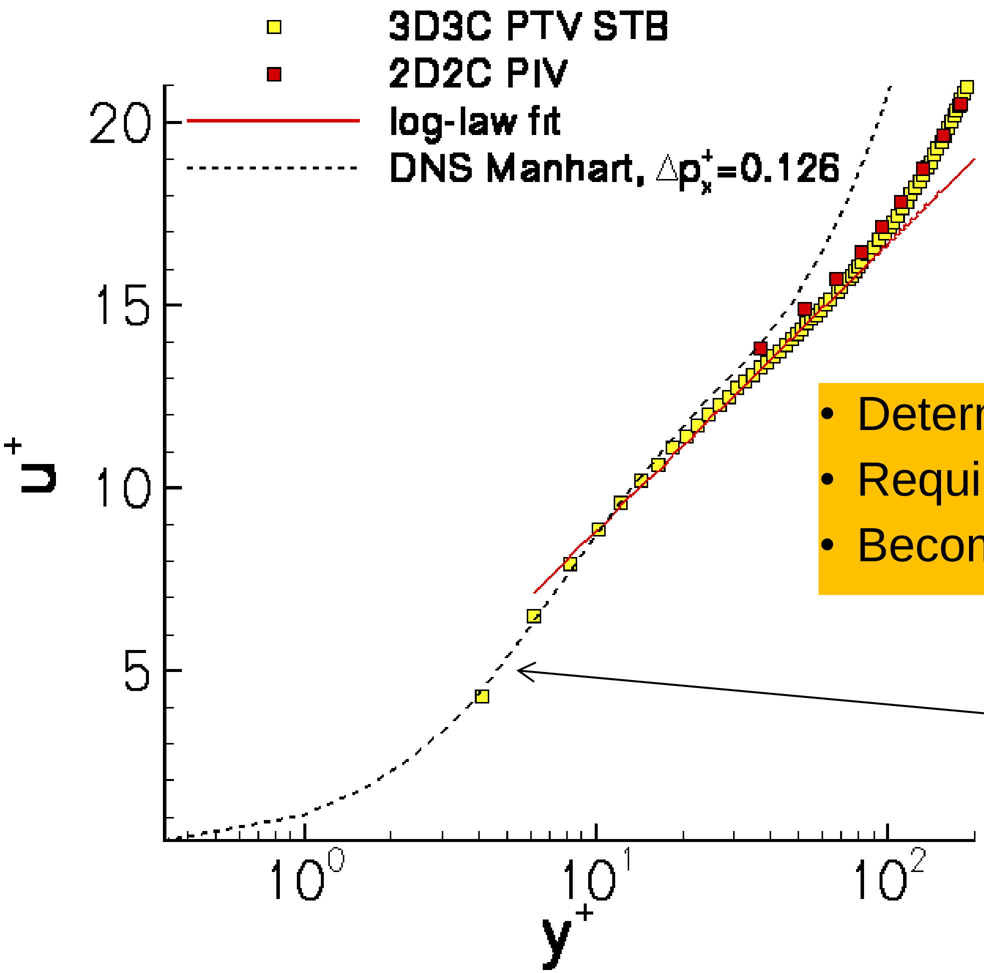


Results for RETTINA II experiment

- Case U=23m/s



Improved indirect method to determine wall-shear stress



- Determine τw from the mean velocity profiles
- Requires several data points for y+ < 1.5
- Becomes very complicated for high Re flows

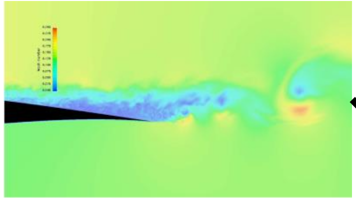
Determine uτ using a least-square fit to DNS data at similar (dp/dx)+ for y+<20

RANS turbulence modelling

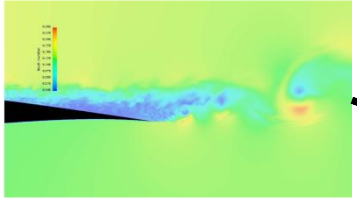
Laws of turbulence for statistically averaged data

Experiment number

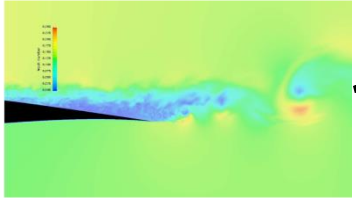
i=1



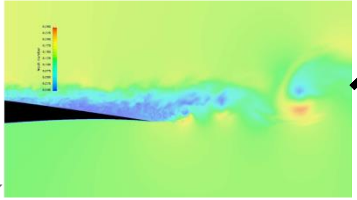
i=2



i=3



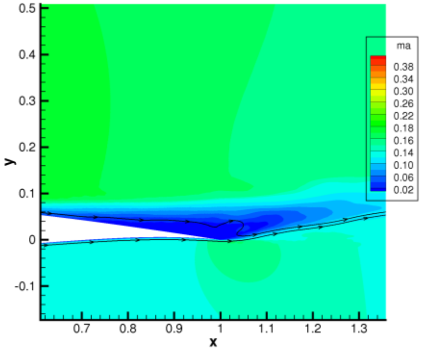
i=4



Average over an ensemble of N snapshots

$$\langle \vec{u}(\vec{x},t) \rangle_N = \frac{1}{N} \sum_{i=1}^{N} \vec{u}^{(i)}(\vec{x},t)$$

Averaged solution (=mean flow solution) looks smooth



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Bilder von Geurts, Meinke & Schröder, AIA, RWTH Aachen Personal communication

Reynolds-averaged Navier-Stokes (RANS)

- Application of a statistical averaging operator to the Navier-Stokes equations gives the transport equation for the mean flow (RANS equations)

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

Reynolds-stress tensor

- averaged effect of velocity fluctuations

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Summary: RANS equations

- Transport equation for the mean velocity

$$\frac{\partial}{\partial x_j}(U_i U_j) + \frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \langle u_i' u_j' \rangle\right) = 0$$

- Transport equation for the Reynods stress tensor

$$U_k \frac{\partial}{\partial x_k}\overline{u_i' u_j'} = \mathcal{P}_{ij} + D^{\nu}_{ij} + D^{t}_{ij} + D^{p}_{ij} + \Pi_{ij} - \epsilon_{ij}$$

- Transport equation for the dissipation rate ω

$$U_j \frac{\partial \omega}{\partial x_j} = P_\omega - \epsilon_\omega + D^{\nu}_{\omega} + D^{t}_{\omega}$$