ETH zürich

# N-Heptane Micro Pilot Ignition in Methane-Air Mixtures

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# Contents

# Large Bore Gas Engines – Why?

- Natural gas:
  - Abundant resources and low fuel price
  - High octane number of $CH_4$ (130) allows for high compression ratios and leads to high engine efficiencies
  - Substantial benefits w.r.t. particulate matter compared to Diesel
  - Reduction in $CO_2$ compared to Diesel/Gasoline due to low C/H ratio
- Large bore engines:
  - Lean-burn operation ensures low exhaust emissions, reduces knock tendency and improves cycle efficiency
  - Further measures to decrease in-cylinder temperatures (and NOx):
    - EGR
    - Miller/Atkinson valve timing

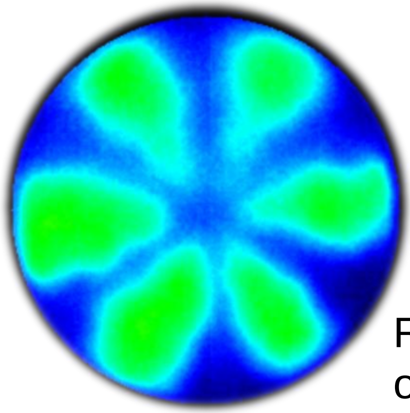
# Why do we need Enhanced Ignition Systems?

- To overcome the reduced reactivity, enhanced ignition systems are applied, which provide:
  - High ignition energies
  - Increased and stable ignition «volumes»
  - Turbulence generation

- Two ignition systems are of main interest:
  - Pilot injection (ignition of the methane/air mixture by means of auto-ignition of a directly injected «micro» liquid pilot spray)
  - Pre-chamber spark plug ignition (ignition in a separate volume, generating flame jets entering the main combustion chamber)

# Characteristics of Pilot Ignition

- Provides multiple ignition spots
- Turbulence generation due to spray
- Stable ignition source(s)
- Flexible ignition (injection) timing and ignition energy
- Two fuels needed (with different cetane numbers), **conditions must be favourable for auto-ignition of the pilot fuel to occur**



Representative OH* chemiluminescence image of pilot ignition in the RCEM (6-hole pilot nozzle)

# Motivation for this Work

- Fundamental data is sparse:
  - Most studies focus on engine performance and emission investigations
  - The energy released during ignition and early combustion is too low to draw conclusions from heat release analysis

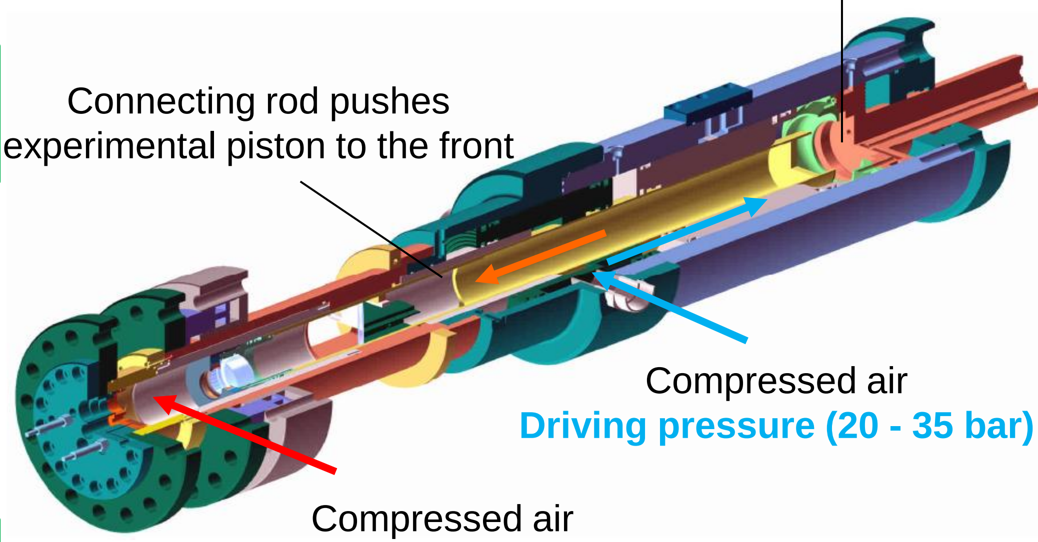
→ In-cylinder data necessary at engine relevant conditions to isolate and understand processes

- Questions addressed:
  - What are the fundamental processes of pilot ignition?
  - What are the influences of operating parameters?

→ Optical data generation in the RCEM of pilot ignition with emphasis on separation of effects

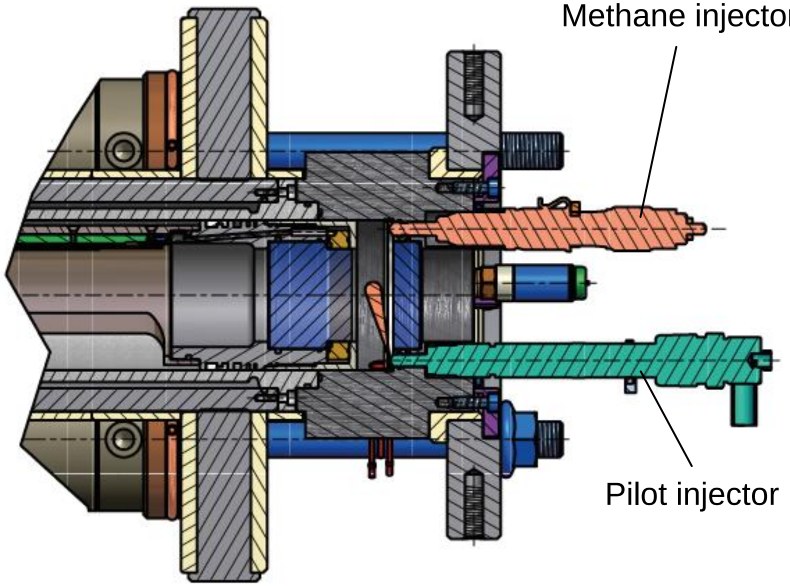
# The Rapid Compression Expansion Machine (RCEM)

| | |
|---|---|
| bore | B=84 mm |
| stroke | s=120 – 250 mm |
| compression ratio ε | 5 -30 |
| piston bowl | $d_{bowl}$=52 mm, 4 mm depth |
| piston optical access | $d_{window}$=52 mm, quartz |
| cylinder pressure | $p_{max}$ up to 200 bar |
| cylinder head | flat, highly flexible |
| pressure measurement | piezoelectric transducer, 0 - 250 bar |
| heating | head and liner up to 470 K |
| injection system | flexible, multiple injectors |
| ignition system | pre-chamber, flexible |
| # of experiments | 15-20 per hour (theoretically) |



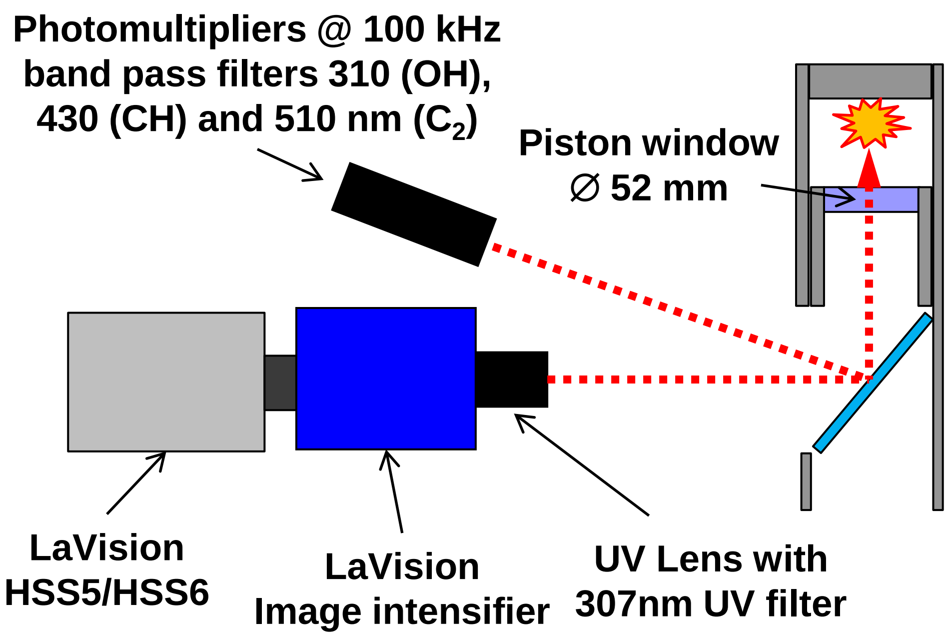
# Experimental Setup – Arrangement of Injectors and optical accesses

- Investigations with pilot ignition:
  - Methane is injected directly into the combustion chamber (before compression)
  - Pilot injector: single hole nozzle fueled with n-heptane (injection rates and tota injected masses measured)
  - Located off-axis
  - Second optical access in cylinderhead → schlieren imaging
  - 2D OH* chemiluminescence

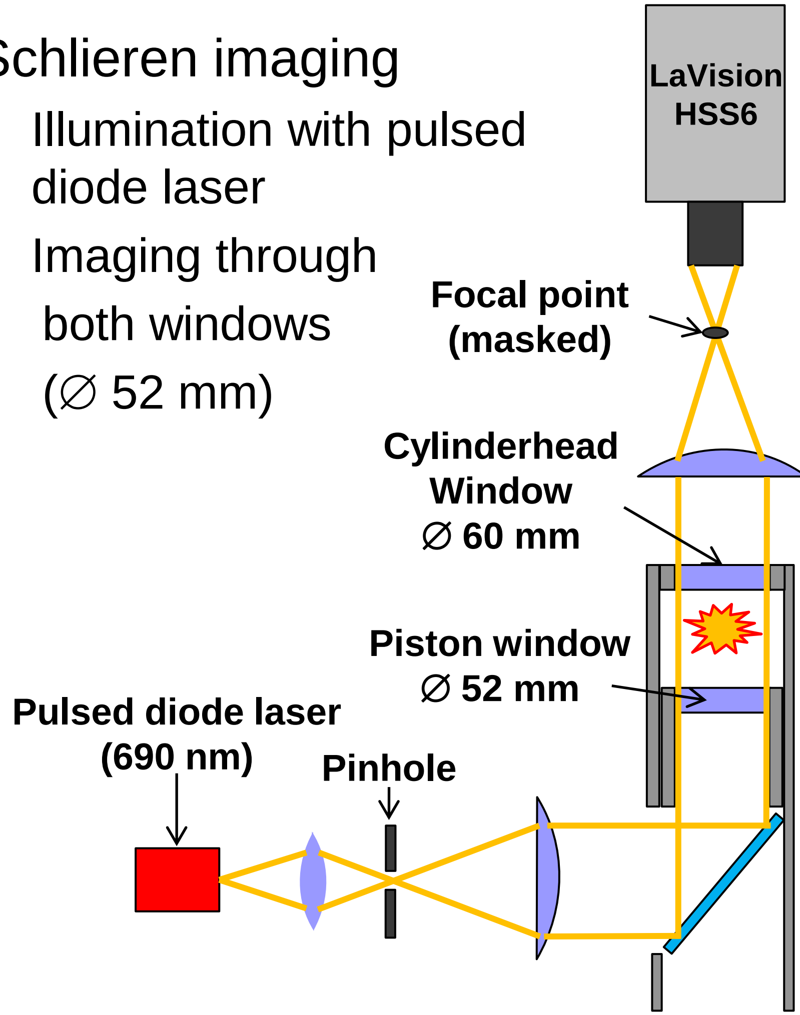


# Experimental Setup - Optical Diagnostics

- Chemiluminescence imaging
  - Photomultipliers and 2D OH* chemiluminescence
  - Imaging through piston window




- Schlieren imaging
  - Illumination with pulsed diode laser
  - Imaging through both windows (∅ 52 mm)



# Operating Conditions Investigations with Pilot Ignition (I)

- Previous investigations related to engine experiments
  - EGR consists of 20% $CO_2$ and 80% $N_2$
  - Multi-hole nozzle
  - Pilot fuel Diesel
  - Simultaneous change in p/T condition
  - Chemiluminescence (but no spray data)

*SAE 2012-01-0825, SAE 2013-24-0112*
*FVV projects «Piloteinspritzung», «Miller/Atkinson Gasmotoren» & «AGR bei Magerkonzept-Gasmotoren*

- Extended Investigations with pilot ignition
  - Dilution with 100% $N_2$ (isolate the effect of $O_2$ concentration)
  - Single hole nozzle
  - N-heptane pilot fuel
  - Variation in charge temperature only
  - Second optical access allows for schlieren imaging to generate spray data

*«N-Heptane Micro Pilot Assisted Methane Combustion in a Rapid Compression Expansion Machine»*
*Submitted for publication*

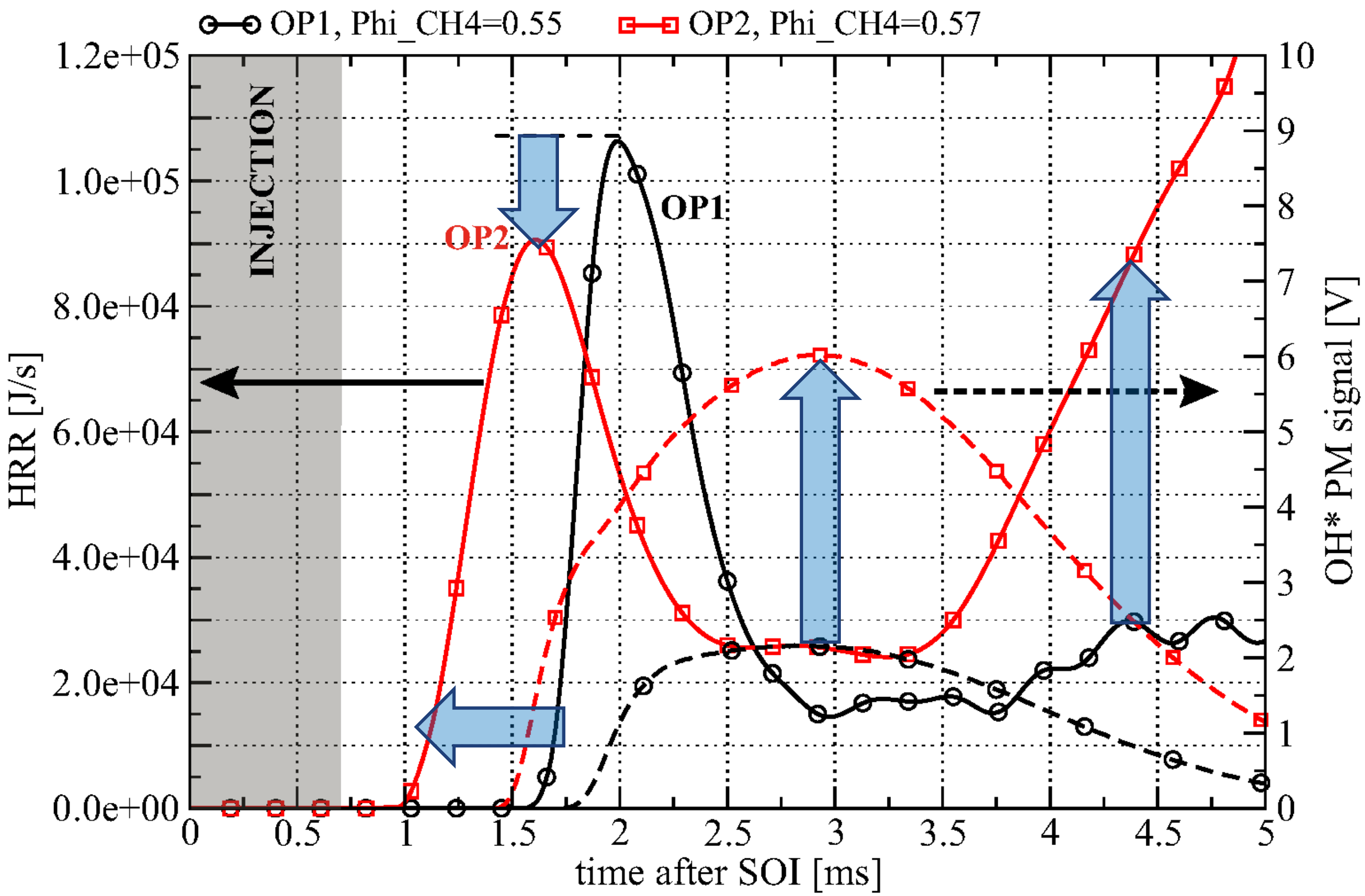
# Operating Conditions
# Investigations with Pilot injection (II)

- Three p/T combinations assessed: constant pressure evolution, only variation in T
- Same pressure at the respective SOI
- Variations in $\Phi_{CH4}$ and $O_2$ content (dilution with 100% $N_2$)
- Variation in pilot mass (injection duration)

| | OP1 | OP2 | OP3 |
|---|---|---|---|
| **T [K] at SOI** | 732 | 776 | 823 |
| **p [bar] at SOI** | | **17.8** | |
| **$\Phi_{CH4}$** | 0.0-0.66 | 0.0-1.0 | 0.0-0.6 |
| **$O_2$ [%]** | 21 | 16.8-21 | 21 |

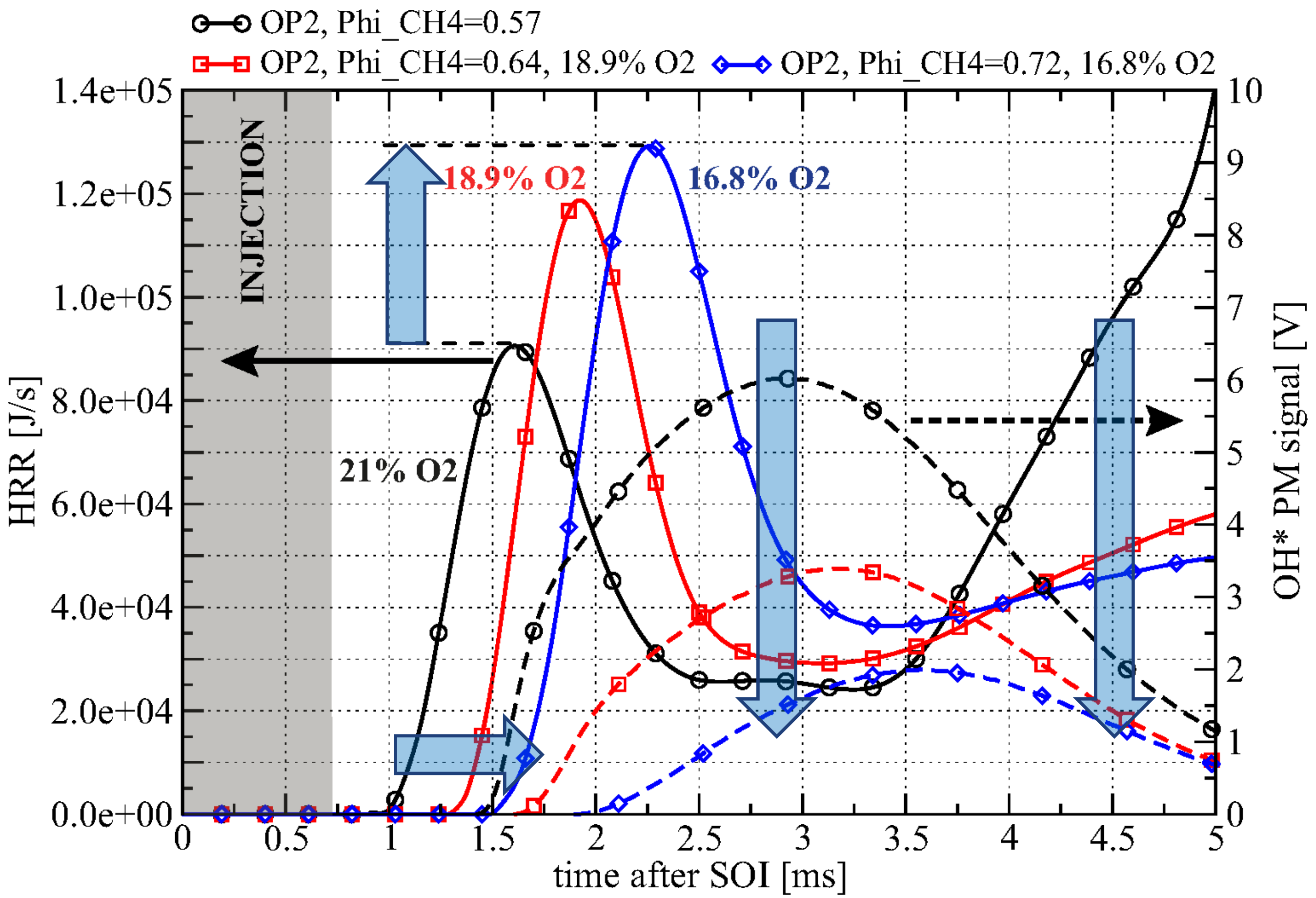
# Experimental Results
# Investigations with Pilot injection (I)

Influence of increasing ambient temperature (OP1 vs. OP2)



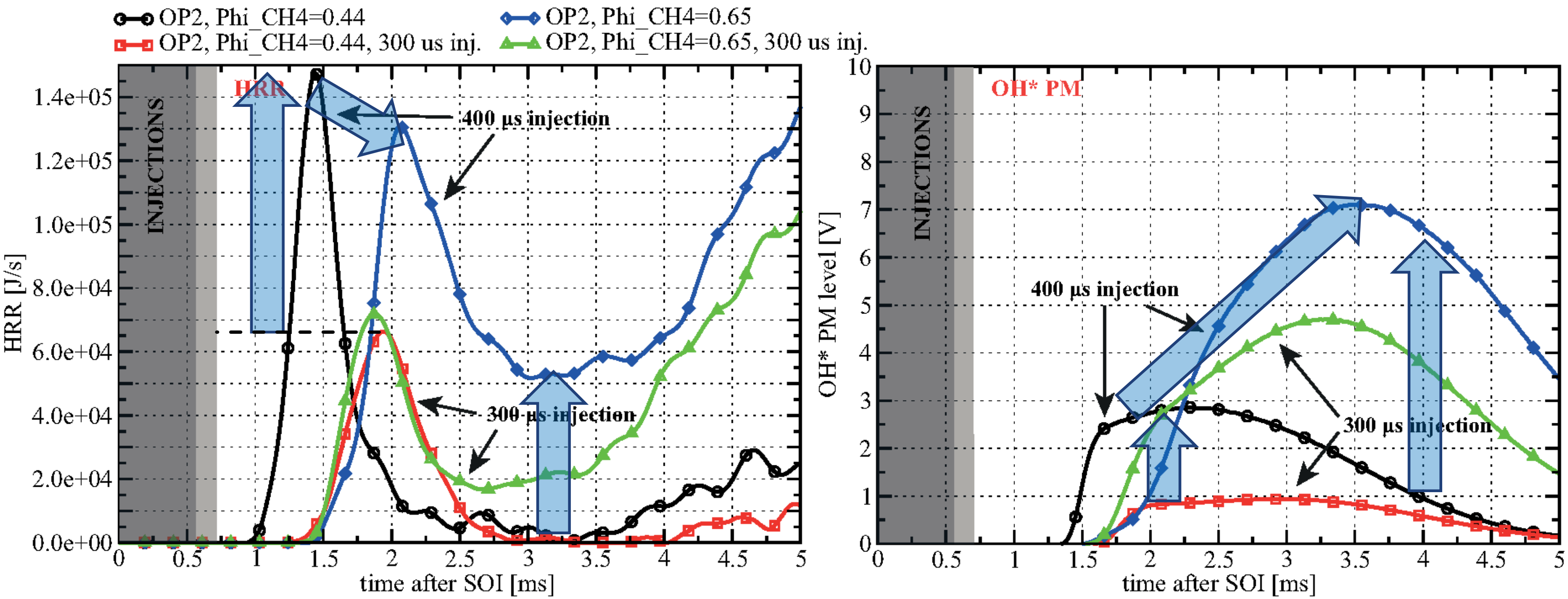
# Experimental Results
# Investigations with Pilot injection (II)

Influence of decreasing $O_2$ content (OP2)



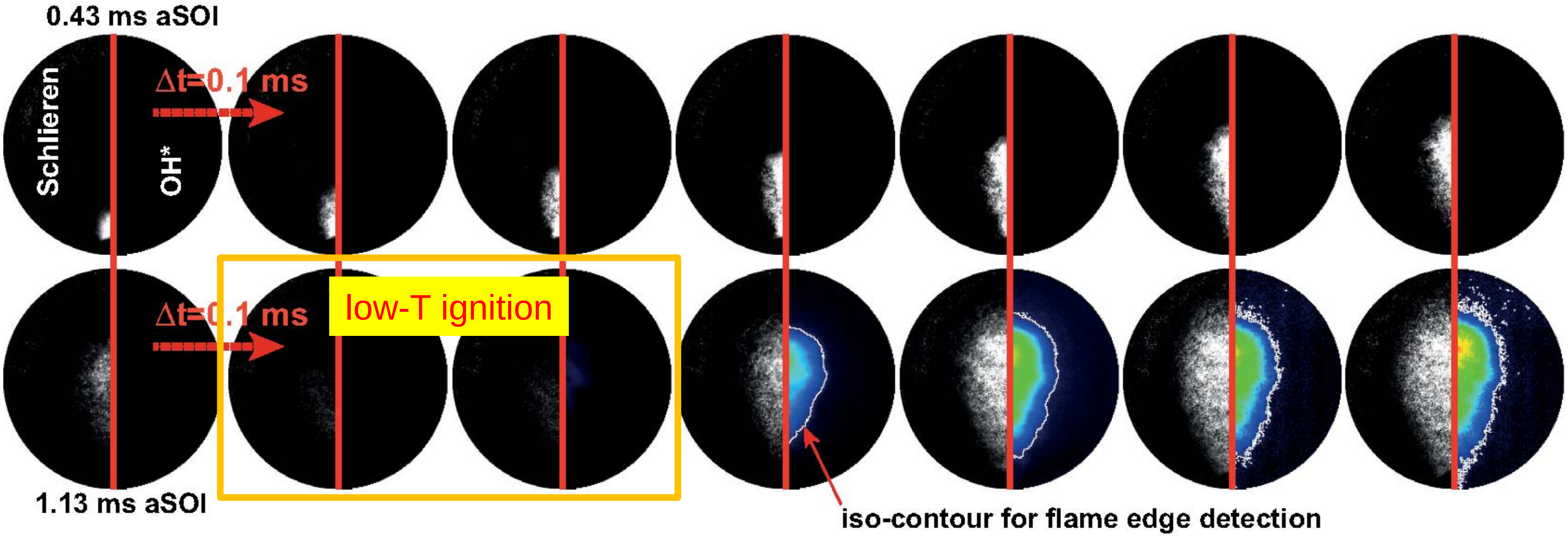
# Experimental Results
# Investigations with Pilot injection (III)

Influence of increasing $CH_4$ content and pilot mass (OP2)



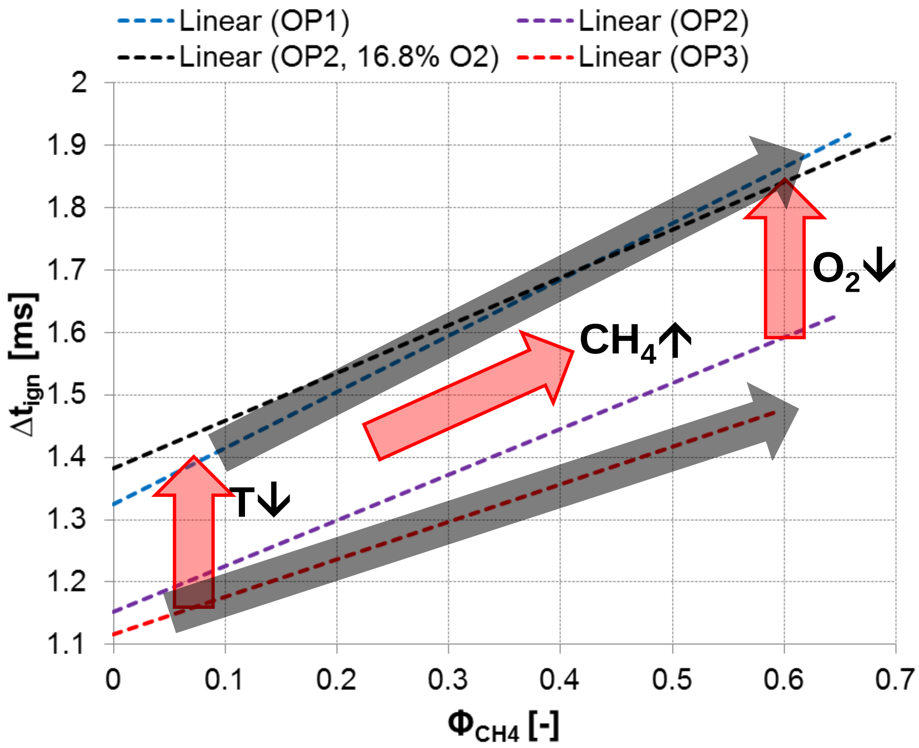
# Experimental Results
# Investigations with Pilot injection (III)

- Optical data, Schlieren vs. OH* chemiluminescence images:
  - Low-T ignition causes «weakening» of the schlieren effect (due to small local temperature rise)
  - "Reappearance" of schlieren signal at high-T ignition onset



# Experimental Results Ignition Delay Investigations with Pilot injection (IV)

- High temperature ignition delays over all operating conditions increase for:
  - Increasing methane content
  - Decreasing temperature
  - Decreasing $O_2$ content




- Higher sensitivity of ignition delay w.r.t. Methane content for OP1 than OP3 (steeper linear trendline)

# Conclusions (I)

- Two distinct phases in HRR are observed, characterizing pilot ignition/combustion and premixed combustion phase
- Schlieren imaging delivers information about the penetration and location of the pilot spray vapor phase and ignition timing/location
- Additionally, low temperature ignition in the pilot spray was observed, characterized by a weakening or disappearance of the refractive indices

➡ **Supporting observations made in spray flames**

- Increasing high-temperature ignition delays with increasing amounts of premixed methane, increasing methane equivalence ratios show a higher impact on ignition delay for “cold” conditions than for higher temperatures

➡ **Inhibiting effect of $CH_4$ on auto-ignition reactions of n-heptane influenced by temperature and mixture**

# Conclusions (II)

- Contribution of the presented work:
  - Results from pilot ignited gas engine investigations without optical access don't allow for model formulation and proper validation thereof

    → **Optical in-cylinder data from the RCEM, including spray data to reduce modeling uncertainties**

  - Literature on ignition behaviour of the pilot spray is sparse and often not in agreement (investigations show different trends depending on setup)

    → **Separation of the influences of changing T, equivalence ratio, dilution and multi-component pilot fuel in the RCEM (as opposed to engine investigations)**

# Outlook and Future Work

- Pilot injection and ignition characterization:
  - Ignition and combustion behaviour of micro pilot sprays largely unknown, but with increasing importance also to Diesel engine applications
  - Specific design of experiment needed for optical investigations of pilot sprays in reacting atmospheres and limited choices of generic test rigs

- Auto-ignition phenomena in dual fuel mixtures:
  - No shock-tube data available for n-heptane/methane mixtures (or other PRF's for dual fuel) and hence no validated reaction mechanisms

# Acknowledgements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  - FVV Projects «Piloteinspritzung», «Miller/Atkinson Gasmotoren» & «AGR bei Magerkonzept-Gasmotoren»
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# Thank you for your attention