Application of multi-lognormal distribution for characterising in-cylinder and exhaust soot generated from diesel engines

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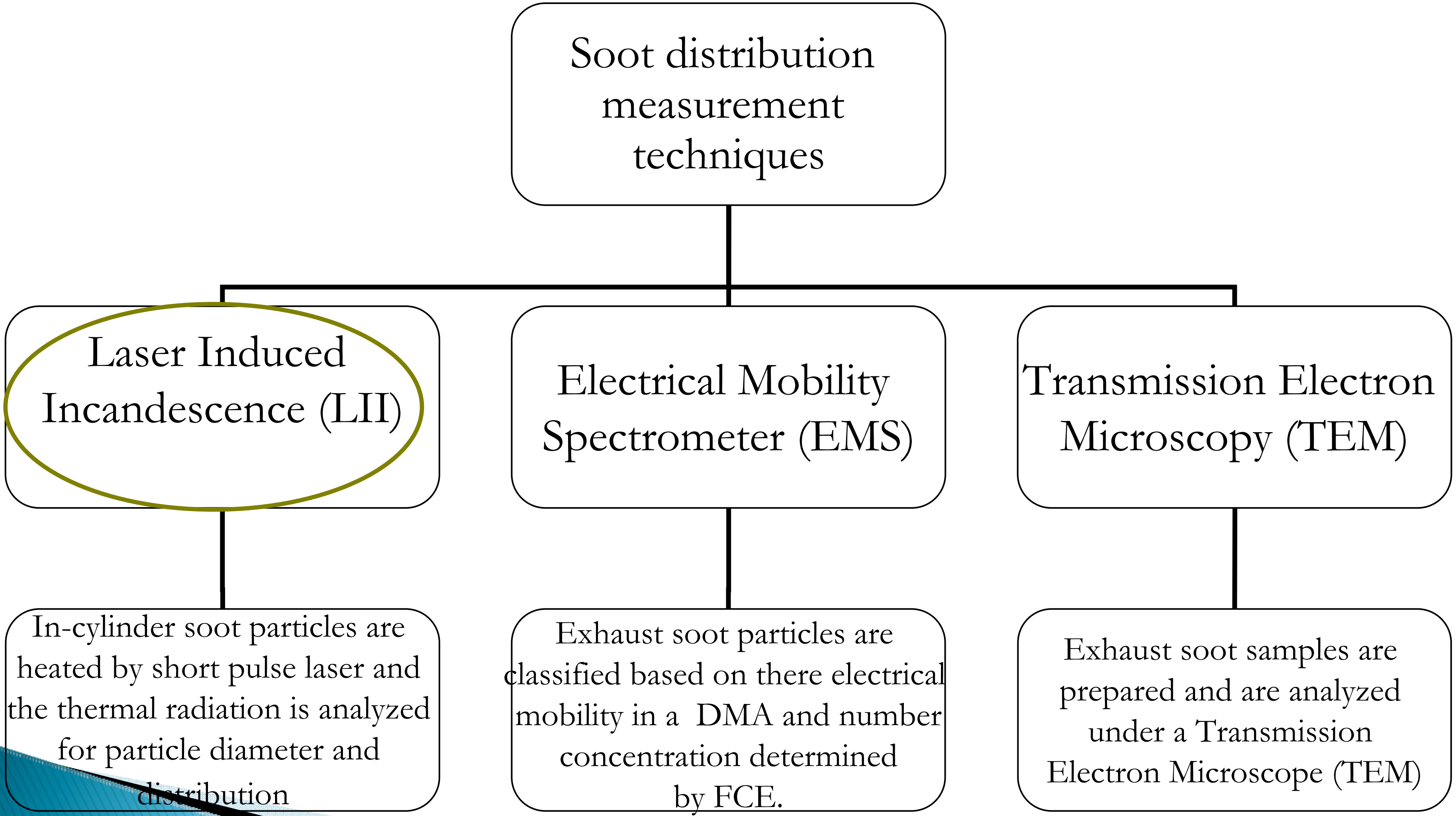
Introduction

- Diesel engines
  - Higher efficiency;
  - Less maintenance;
  - Lower fuel consumption;
  - Lower emission of carbon dioxide;
- Disadvantages (main emission products)
  - Nitrogen Oxide (NOx);
  - Particulate Matter (PM);
- Stringent vehicle emissions standards
  - Soot mass reduction;
  - Soot size distribution;
  - Airborne and transported through the respiratory tract to the lungs
  - Health hazards
- Soot size distribution is an important information

In-cylinder and exhaust soot measurement techniques



Soot distribution measurement techniques

Laser Induced Incandescence (LII)

Electrical Mobility Spectrometer (EMS)

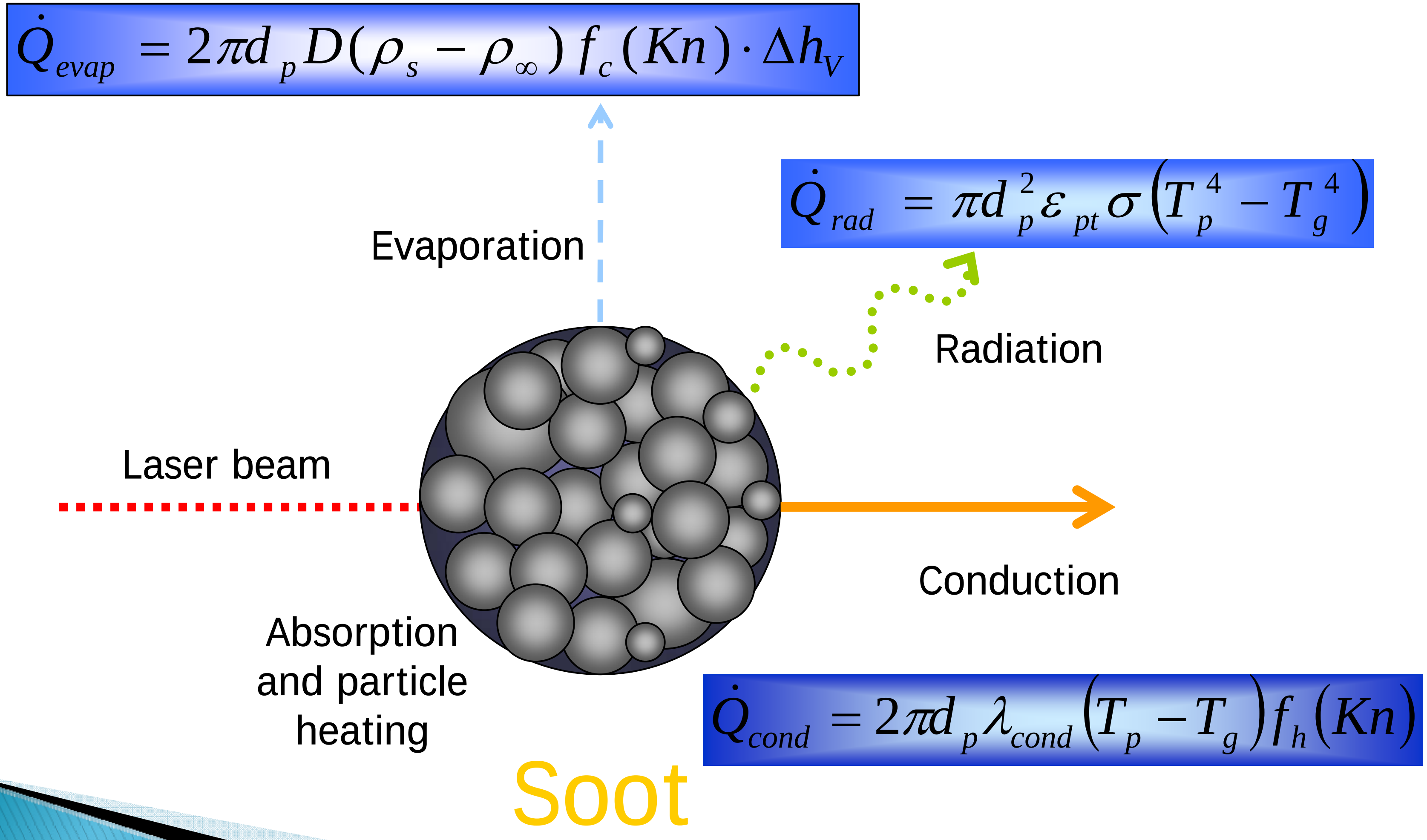
Transmission Electron Microscopy (TEM)

In-cylinder soot particles are heated by short pulse laser and the thermal radiation is analyzed for particle diameter and distribution

Exhaust soot particles are classified based on there electrical mobility in a DMA and number concentration determined by FCE.

Exhaust soot samples are prepared and are analyzed under a Transmission Electron Microscope (TEM)

Principle of Laser Induced Incandescence



$$\dot{Q}_{evap} = 2\pi d_p D(\rho_s - \rho_\infty) f_c(Kn) \cdot \Delta h_V$$

Evaporation

$$\dot{Q}_{rad} = \pi d_p^2 \varepsilon_{pt} \sigma \left(T_p^4 - T_g^4\right)$$

Radiation

Laser beam

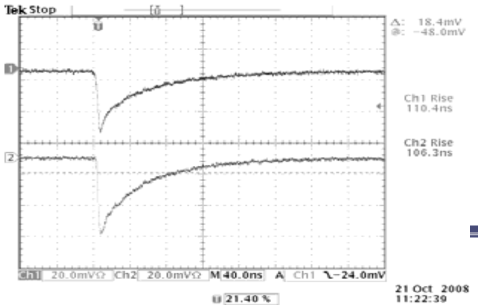
Conduction

Absorption
and particle
heating

$$\dot{Q}_{cond} = 2\pi d_p \lambda_{cond} \left(T_p - T_g\right) f_h(Kn)$$

Soot

Time-resolved Laser Induced Incandescence process flow



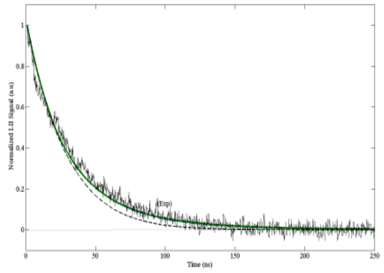
Experimental Signal Decay

Theoretical Signal Decay

Compare for min χ2

If Yes

Stop and Display



If No

Change particle size

Energy and Mass Balance Equations

$$\frac{dm_p}{dt} = 4\pi r_p^2 \varrho_v u_v$$

$$\frac{dU}{dt} = \dot{Q}_{abs} - \dot{Q}_{vap} - \dot{Q}_{con} - \dot{Q}_{rad} ,$$

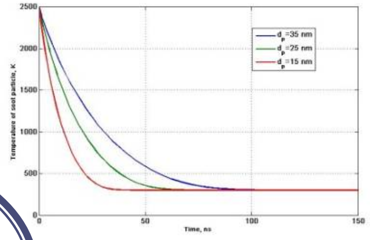
Numerical Integration And Signal Generation

MATLAB

Mono or Lognormal Size Distribution

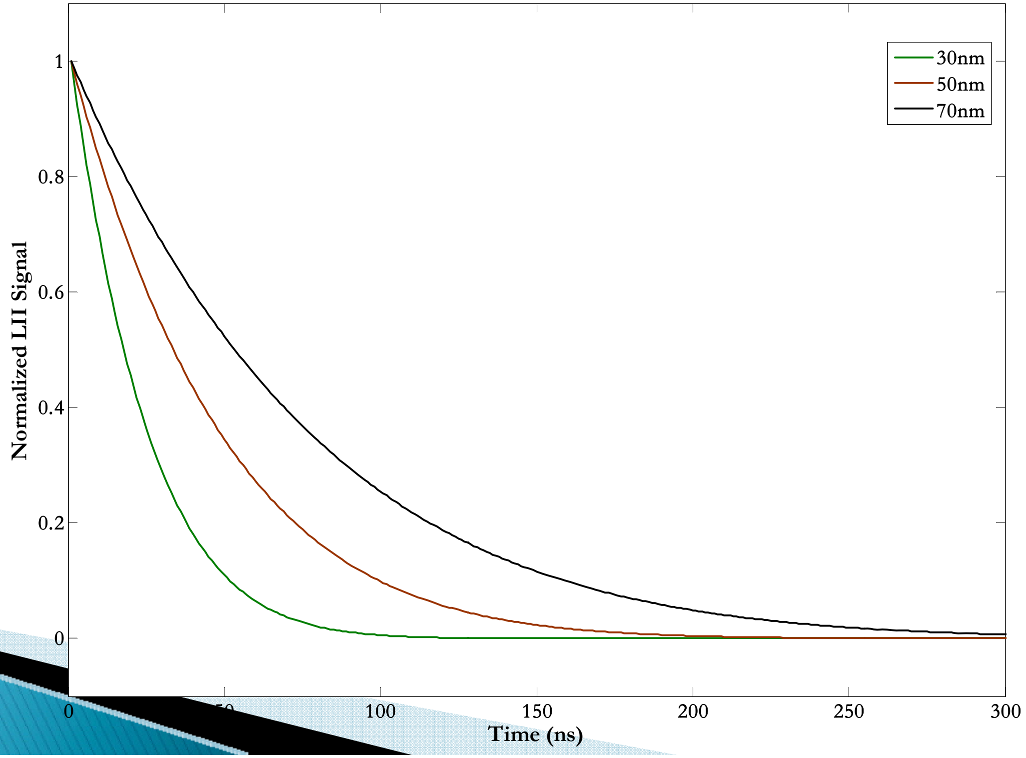
$$P(r_{cmd}) = \frac{1}{\sqrt{2\pi} r_p \sigma} \exp\left[-\frac{(\ln(r_p) - \ln(r_{cmd}))^2}{2\sigma^2}\right]$$

$$P(r_{i,cmd\_multi}) = \sum_{i=1}^{n} \frac{1}{\sqrt{2\pi} r_p \sigma_i} \exp\left\{-\frac{[\ln(r_p) - \ln(r_{i,cmd\_multi})]^2}{2\sigma_i^2}\right\}$$



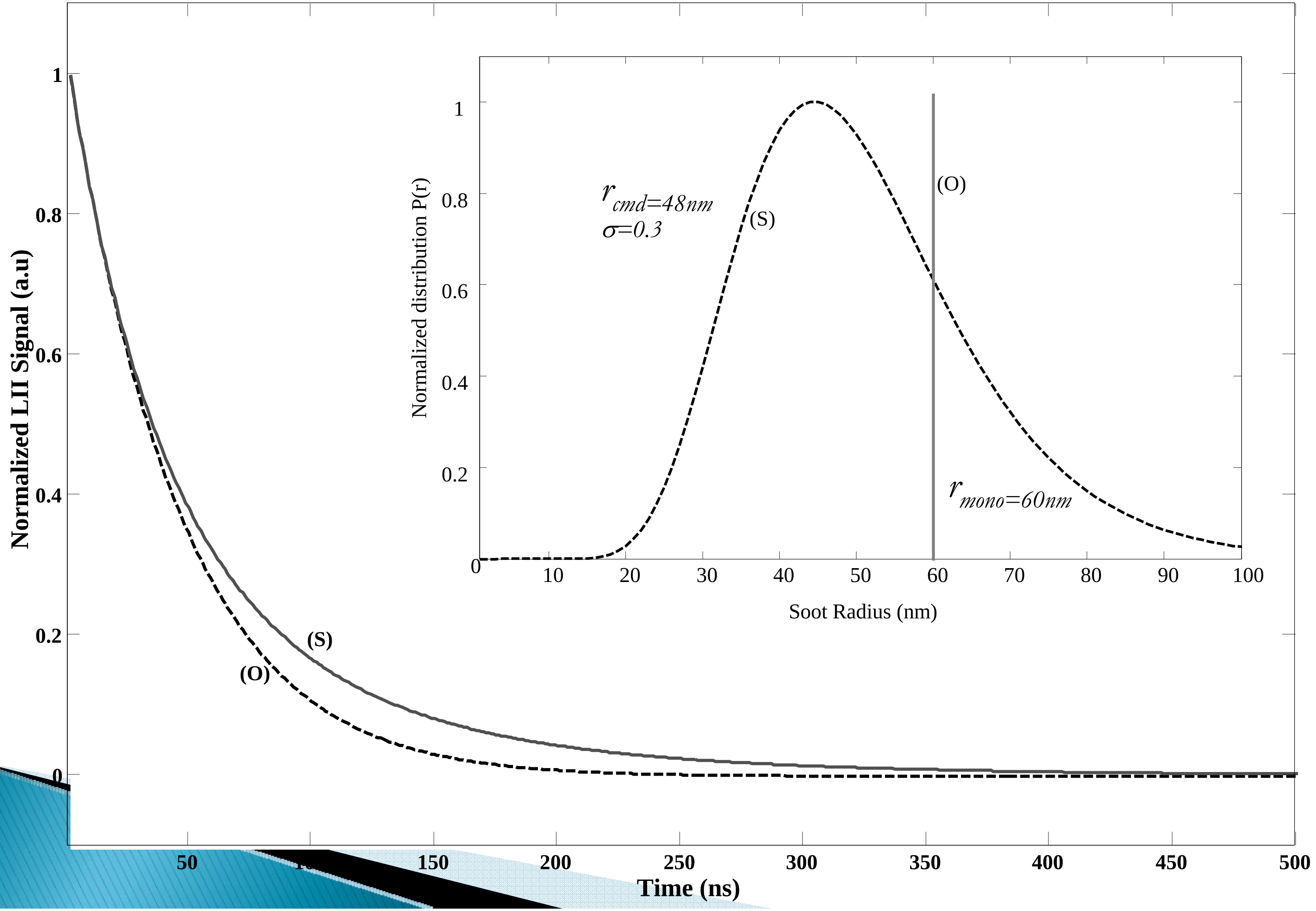
Mono-dispersive soot size distribution

- Mono-dispersive soot size distribution r_{mono} results in a pure exponential decay of the theoretical LII signal.
- Experimental LII signal is the cumulative signal from particles of various sizes and the highest contribution comes from the primary-particle size r_{mono}.
- The smaller particles decay faster and therefore have a constantly decreasing influence on the total signal of the particle distribution, which results in a deviation of the LII signal from a pure exponential decay.



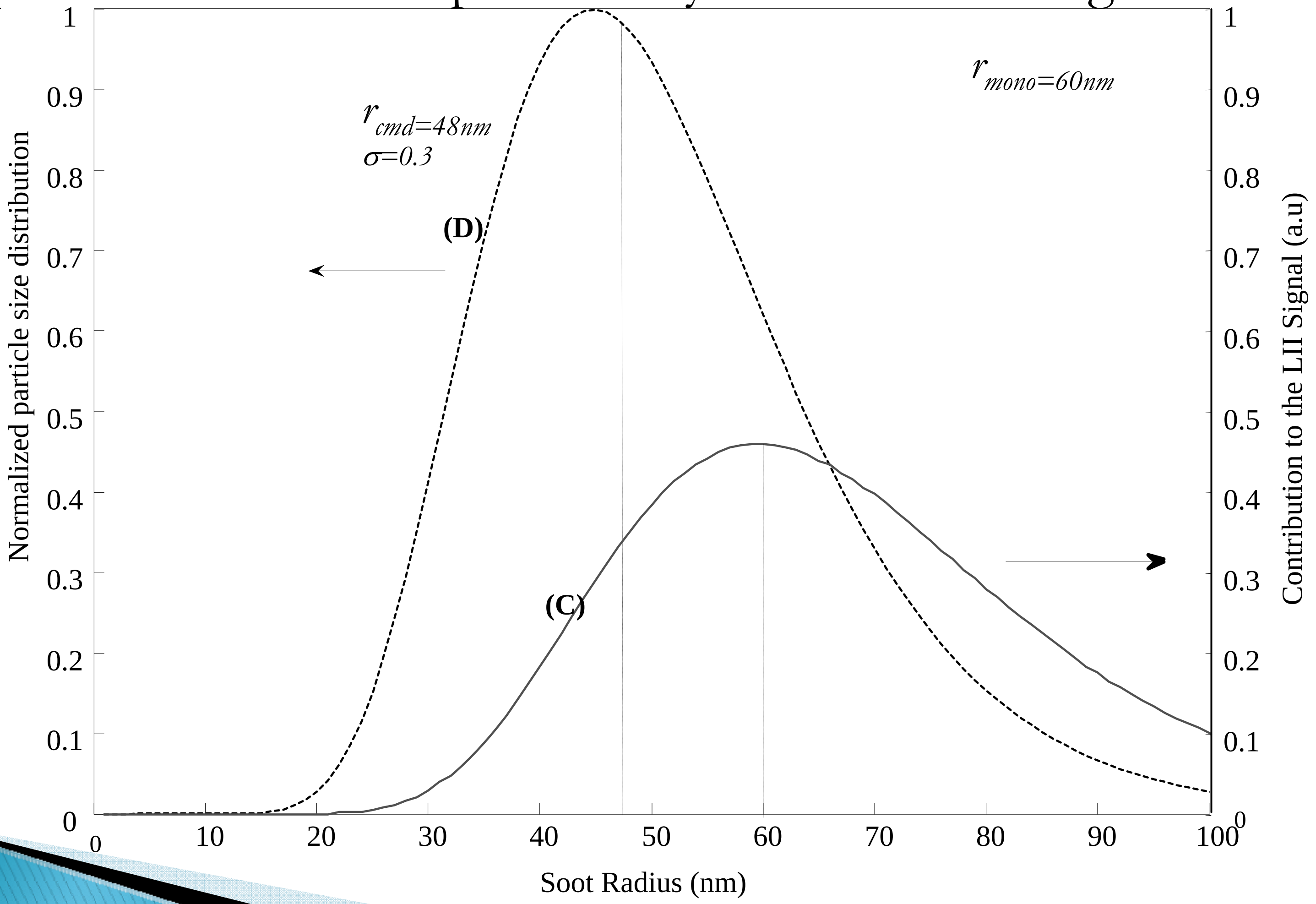
Single-lognormal soot size distribution

- Owing to a deviation from pure exponential decay, a single-lognormal size distribution is assumed in the model to reconstruct the soot size distribution.



Single-lognormal soot size distribution

- This assumption yields a count median radius $\boldsymbol{r_{cmd}}$ and erases the contribution of mono-dispersive particle size $\boldsymbol{r_{mono}}$ that is primarily responsible for the temporal decay of the TR-LII signal.



Theoretically calculated contribution to the LII signal

Multi-lognormal soot particle size distribution for TR-LII

$$P\left(r_{i,cmd\_multi}\right)=\sum_{i=1}^{n}\frac{1}{\sqrt{2\pi}r_p\sigma_i}\exp\left\{-\frac{\left[\ln\left(r_p\right)-\ln\left(r_{i,cmd\_multi}\right)\right]^2}{2\sigma_i^{\ 2}}\right\}$$

- Owing to a significant increase in the number of variables for a multi-lognormal function, a simple approach of $\sigma_i = \sigma_2$ for all $i > 2$ was employed for the purpose of reduction of variables along with the following assumption for count median radius:

$$r_{i+1,cmd\_multi}=\frac{r_{i,cmd\_multi}}{\xi}$$ where ξ is the divisible factor.

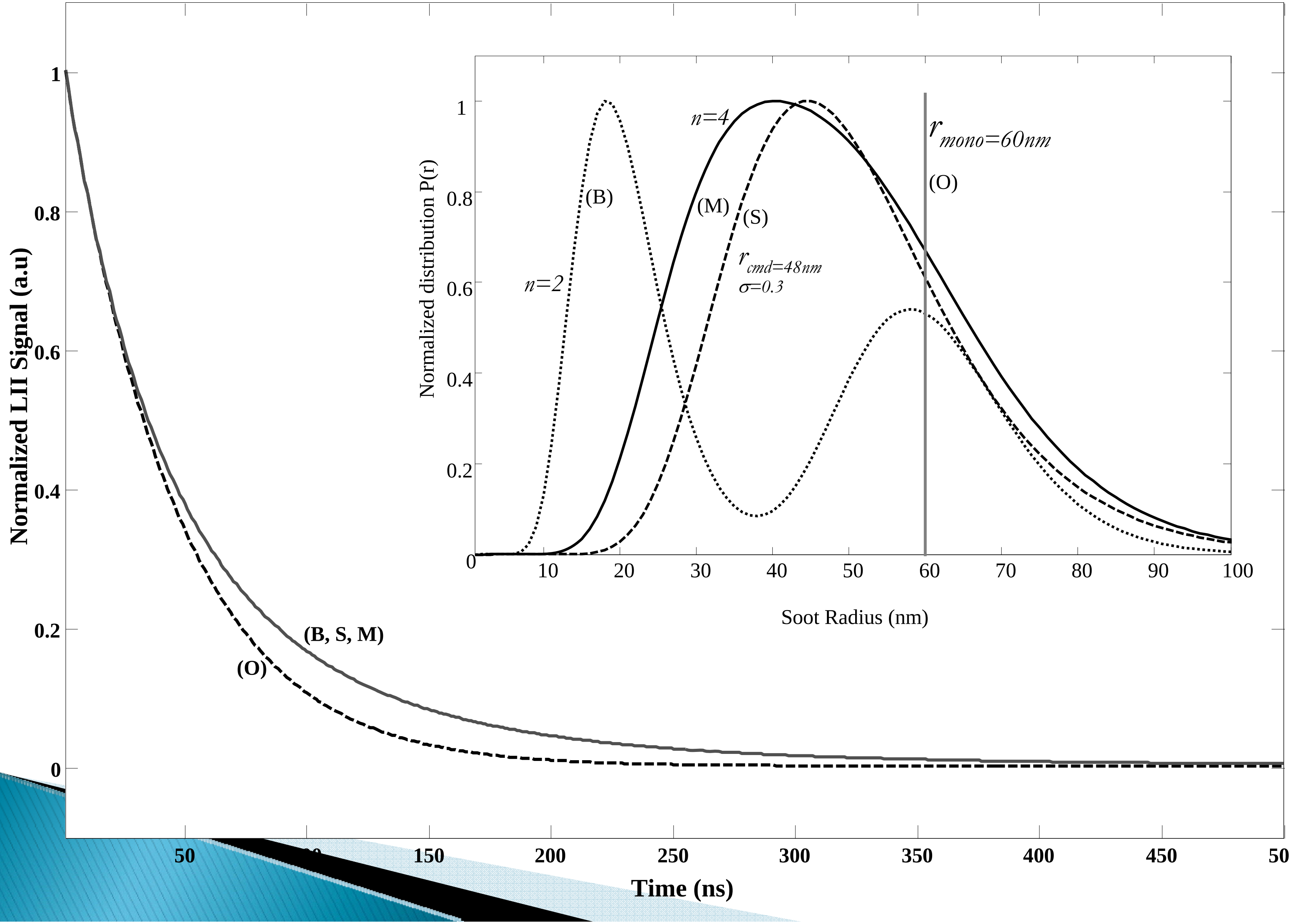
- For fitting two conditions

(a) $r_{1,cmd\_multi}=r_{mono}={}^{d_{mono}}\!/_{2}$ and

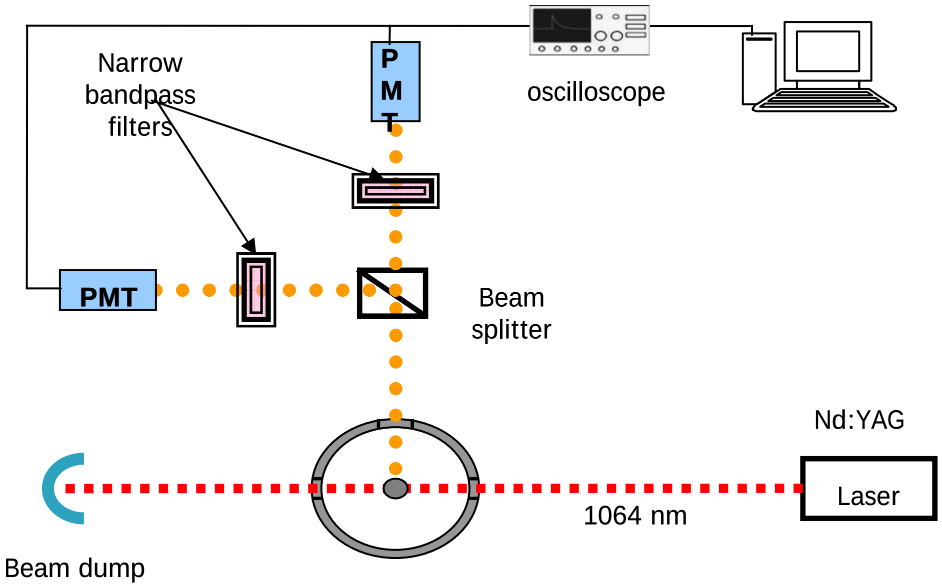
(b) minimum χ^2 for the comparison of the LII signals

- ξ is a function of the total number of lognormal distribution n, unique values were obtained for ξ which is approximated by $\xi \cong 1+\frac{2.5}{n^2-2.75}$ where $2 \le n \le 6$.

Theoretical reconstruction of soot size distribution



Experimental setup



Narrow bandpass filters

PMT

P M T

oscilloscope

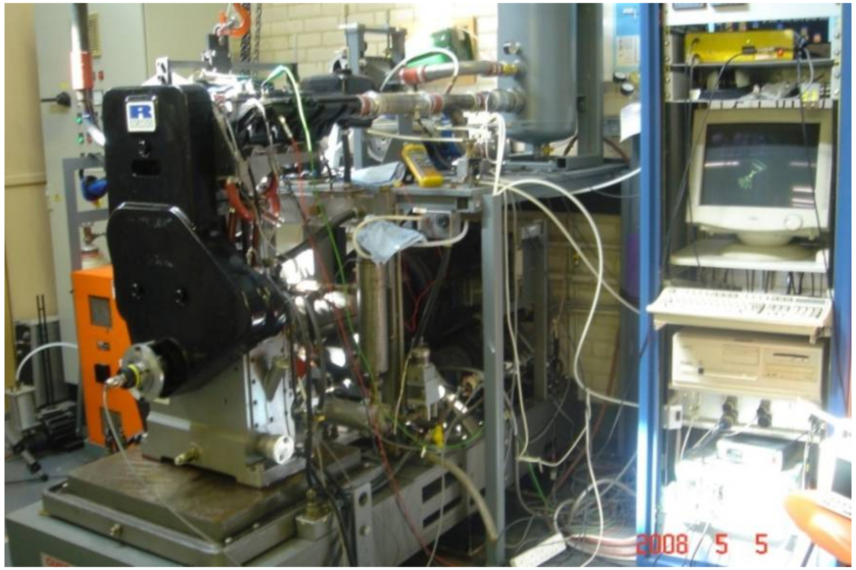
Beam splitter

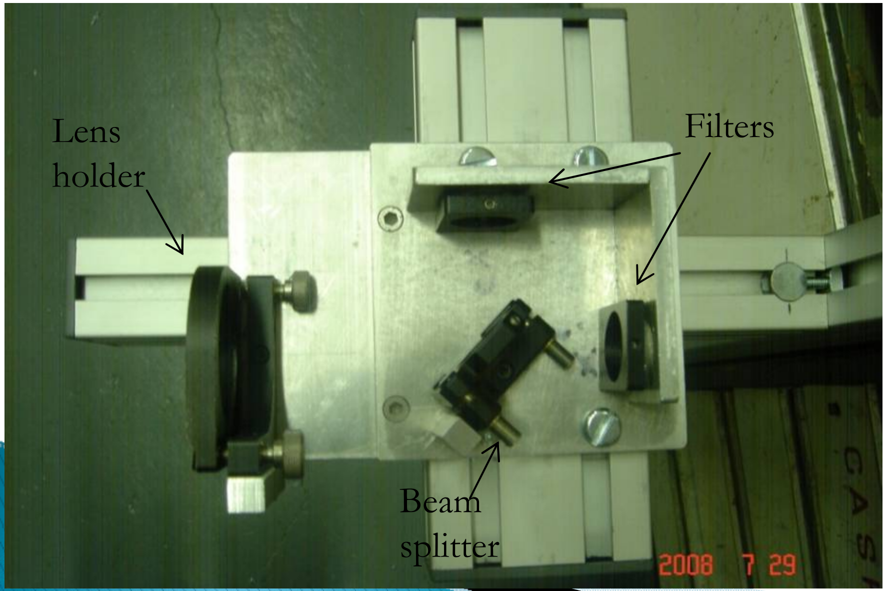
Nd:YAG

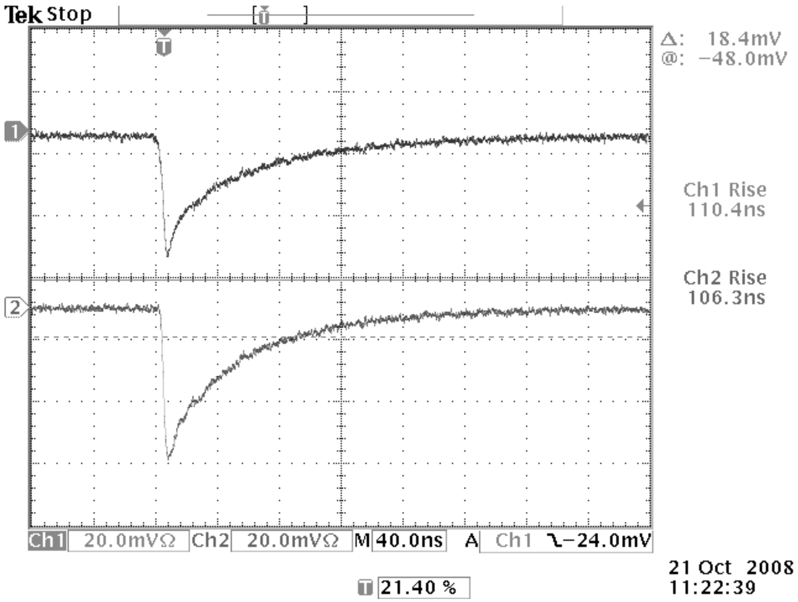
Laser

1064 nm

Beam dump







Tek Stop

Δ: 18.4mV
@: −48.0mV

Ch1 Rise
110.4ns

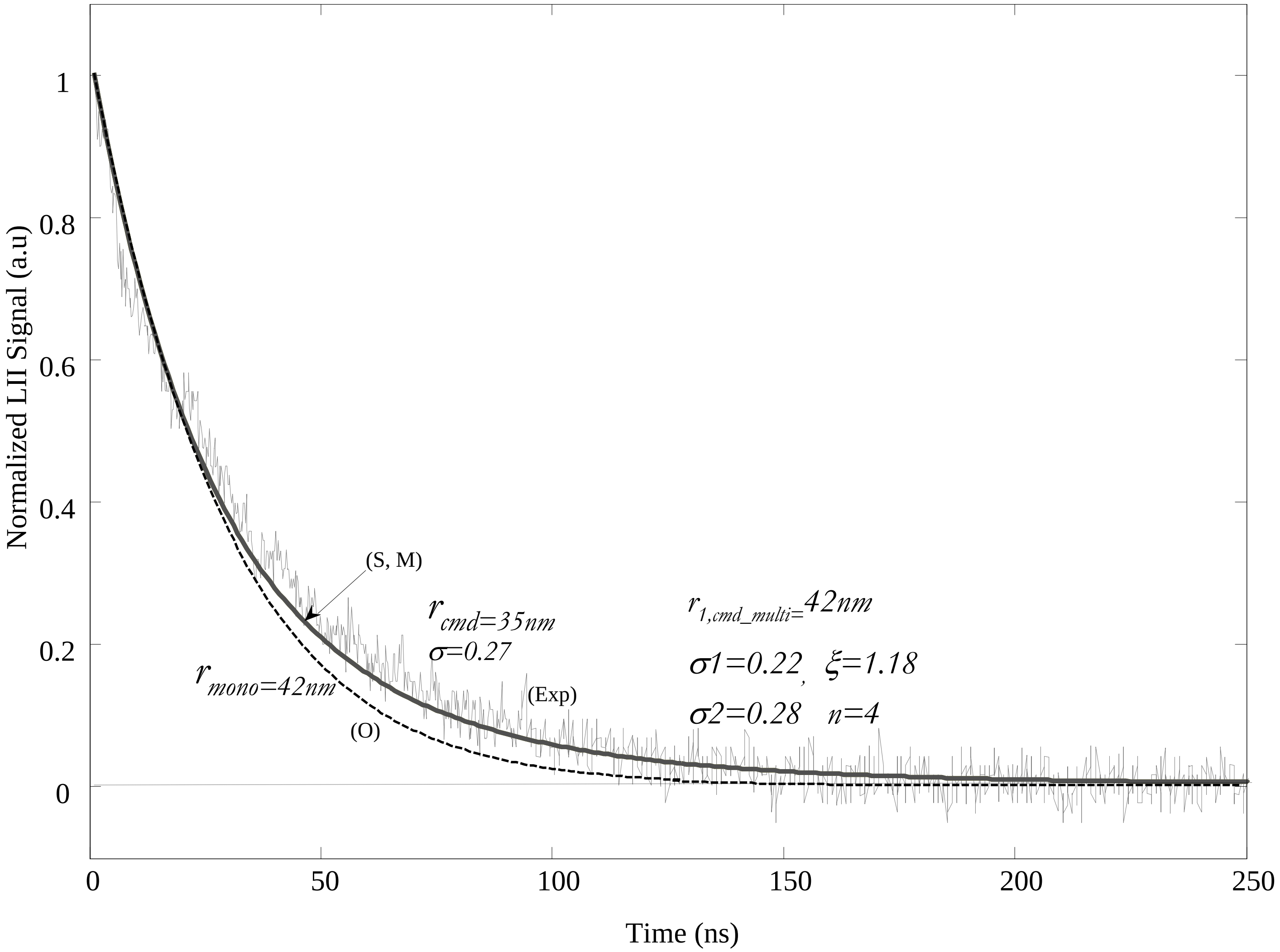
Ch2 Rise
106.3ns

Ch1 20.0mVΩ Ch2 20.0mVΩ M 40.0ns A Ch1 ↘ −24.0mV

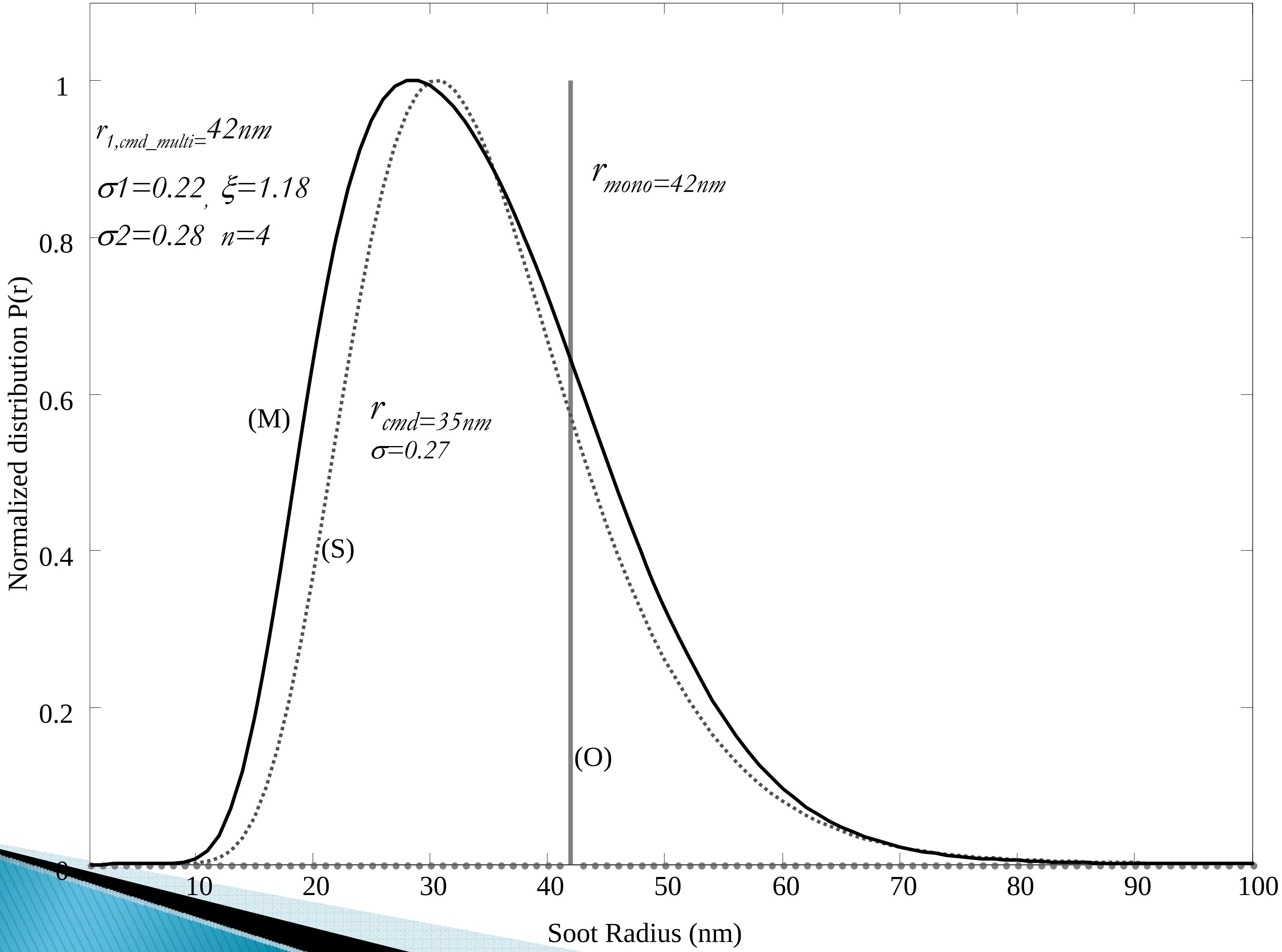
21.40 %

21 Oct 2008
11:22:39

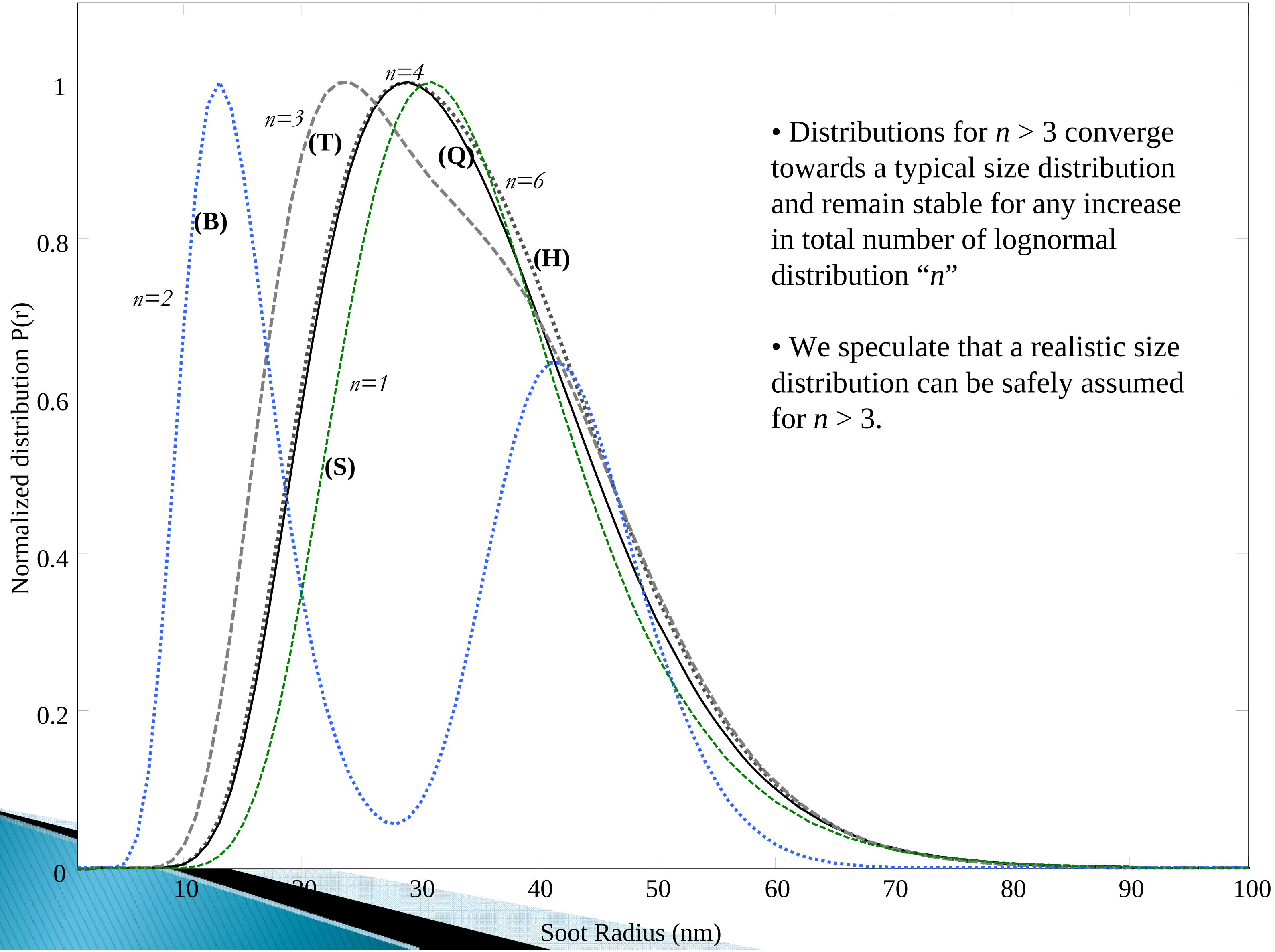
Experimental Results



Experimental Soot size distribution



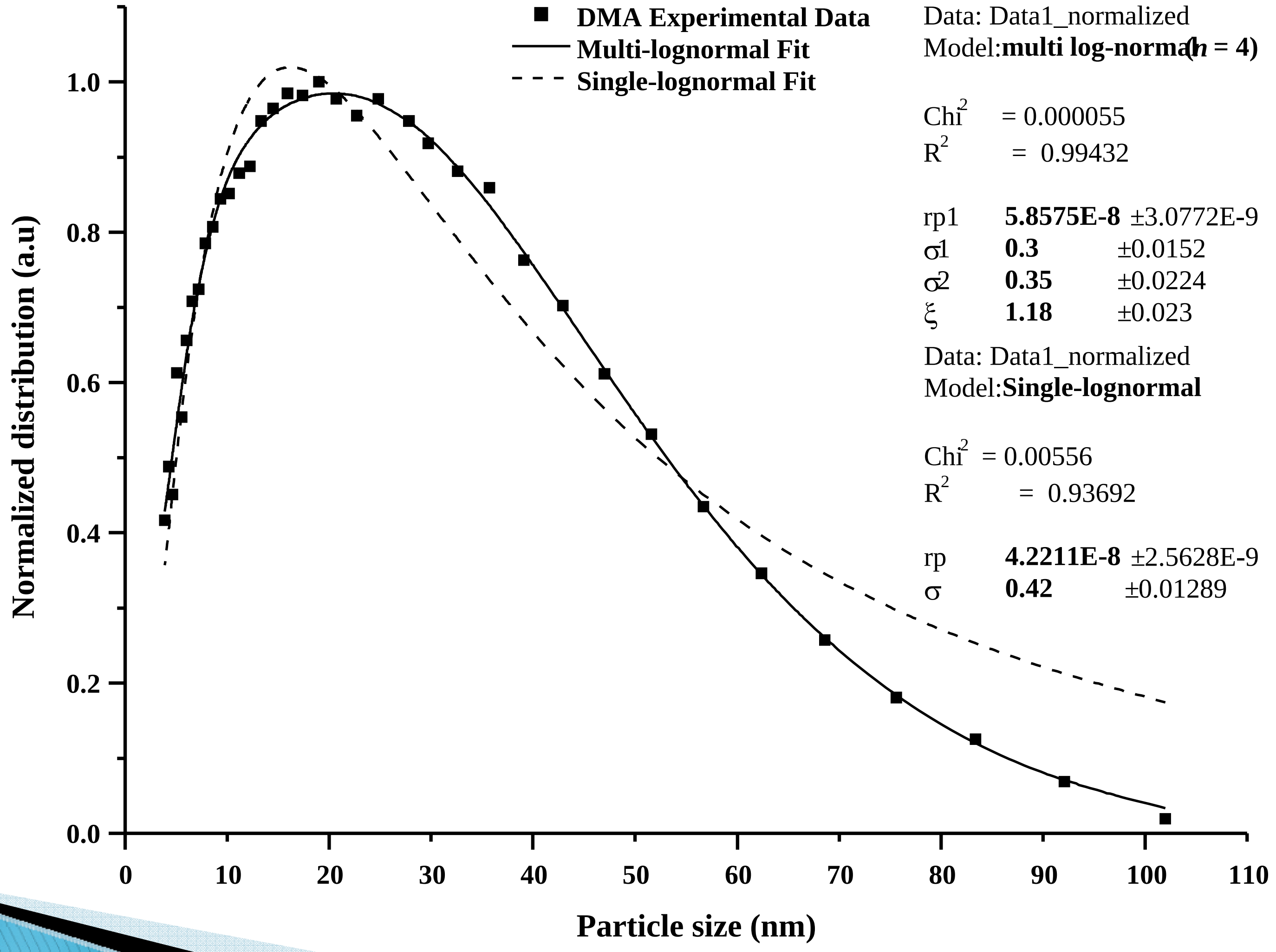
Validation of the multi-lognormal size distribution



- Distributions for $n > 3$ converge towards a typical size distribution and remain stable for any increase in total number of lognormal distribution “*n*”

- We speculate that a realistic size distribution can be safely assumed for $n > 3$.

Experimental results for Electrical Mobility Spectrometer (EMS)



Data: Data1_normalized
Model:**multi log-normal (*n* = 4)**

Chi^2 = 0.000055
R^2 = 0.99432

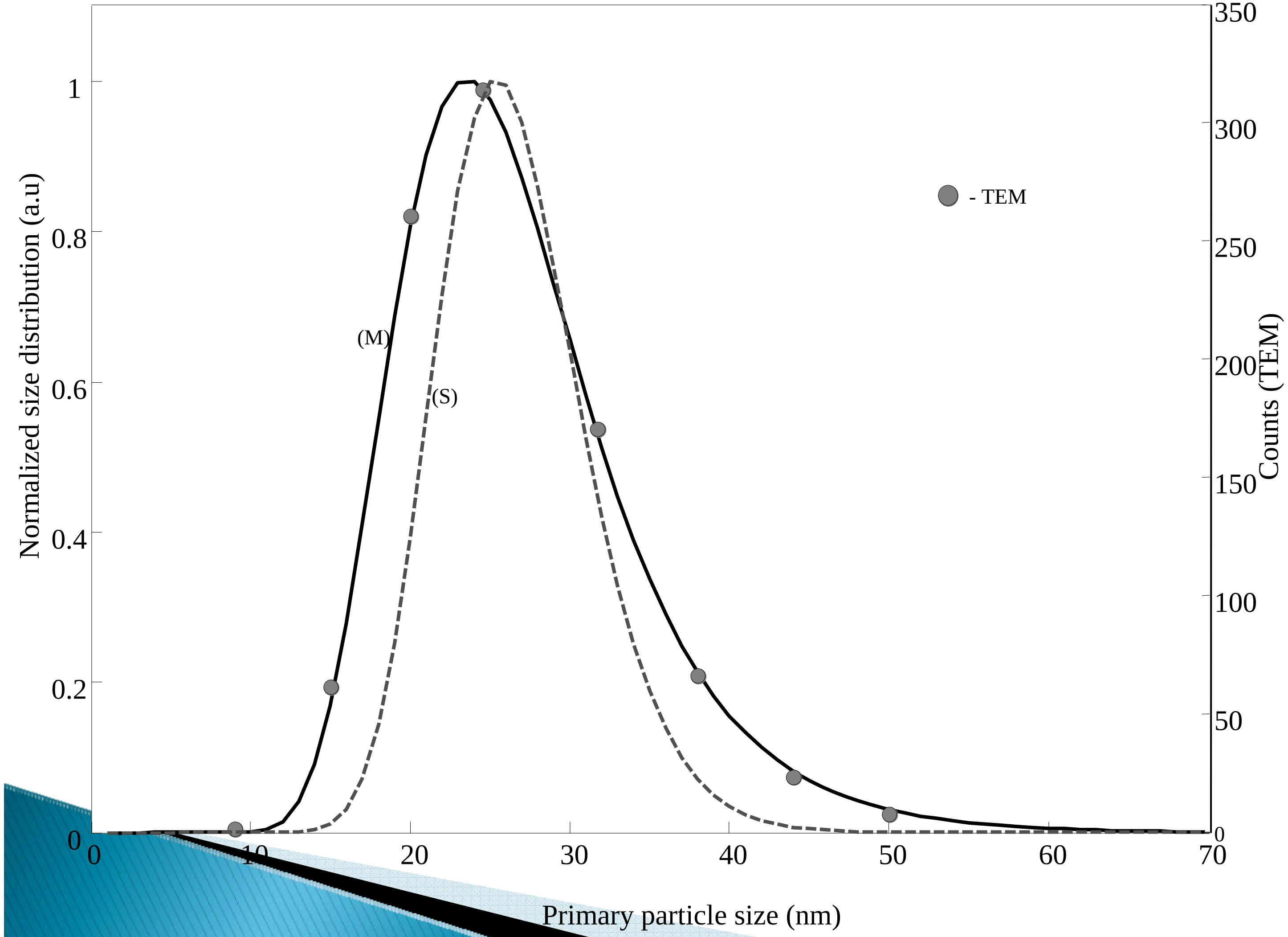
rp1	**5.8575E-8**	±3.0772E-9
σ1	**0.3**	±0.0152
σ2	**0.35**	±0.0224
ξ	**1.18**	±0.023

Data: Data1_normalized
Model:**Single-lognormal**

Chi^2 = 0.00556
R^2 = 0.93692

rp	**4.2211E-8**	±2.5628E-9
σ	**0.42**	±0.01289

Comparison of Published TEM data with proposed multi-lognormal size distribution



- S. Dankers and A. Leipertz, Appl. Opt. 43, 3726 (2004).
- Single log-normal size distribution σ = 0.175 and $\boldsymbol{d_{cmd}}$ = 27.2 nm as published
- Multi log-normal *(n = 4)* size distribution σ_1 = 0.26, σ_2 = 0.2 and ξ=1.16 $\boldsymbol{d_{1,multi\_cmd}}$ = 32 nm
- $\boldsymbol{d_{1,multi\_cmd} = d_{mono}}$ =32 nm is good agreement with the published value for single lognormal size distribution $\boldsymbol{d_{cmd}}$..
- The average count median particle diameter for (M) (*n*=4) is ~1.5 nm less than the count median particle diameter for a (S) as published $\boldsymbol{d_{cmd\_TEM}}$ = 25.6 nm

Conclusion

- In-cylinder TR-LII, Electrical mobility spectrometer (EMS) and Transmission electron microscopy (TEM) results show that the soot size distribution in engines is better represented by a multi-lognormal size distribution compared to a mono-dispersive or a single-lognormal size distribution.

- We speculate that a multi-lognormal particle size distribution with $n>3$ reconstructs a realistic soot size distribution instead of a single-lognormal distribution.

- The mono-dispersive size was preserved while reconstructing the particle size distribution assuming a multi-lognormal size distribution .

- Thank You