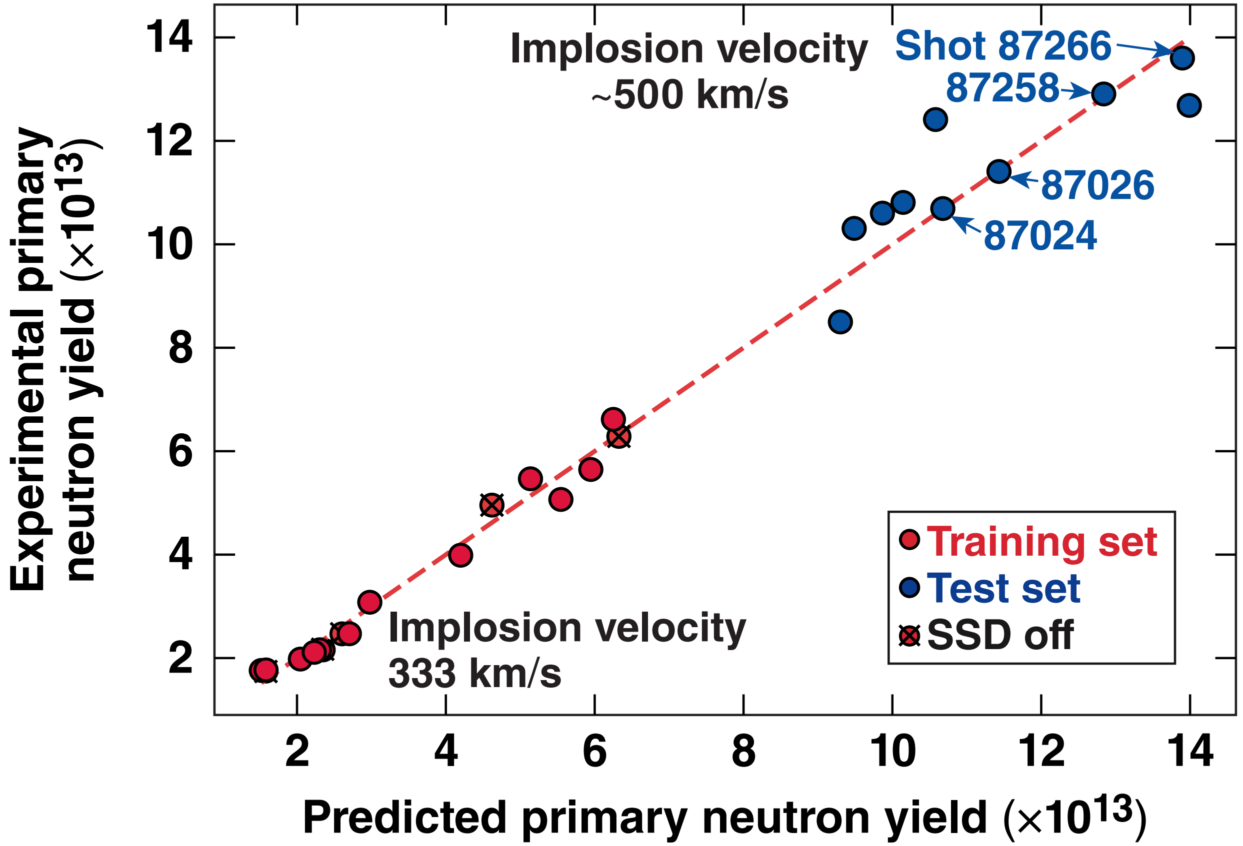
A Statistical Approach to Implosion Design on the OMEGA Laser

Prediction performance on the high-adiabat campaign (α ~ 5 to 7)



$$\text{Yield}_{\text{pred}} \sim \frac{V_{LILAC}^{4.3} M_{LILAC}}{\delta_{\text{SSD}}^{0.3}}$$

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Summary

A statistical model of OMEGA implosions has been developed to enable accurate preshot predictions and optimize implosion design

- A statistical approach is used to bridge the gap between experiments and simulations
- The statistical approach is tested on a simulation database
- Statistical predictions of yield are robust to modeling errors, while predictions of areal density are sensitive to errors in EOS*
- Predictive models are developed for the experimental neutron yield, ion temperature, and ρR by statistical mapping of the experimental database onto *LILAC* output variables

The statistical predictions enable the design of the highest primary yield cryo implosion on OMEGA ($Y = 1.34 \times 10^{14}$).

*EOS: equation of state

TC13755

Collaborators

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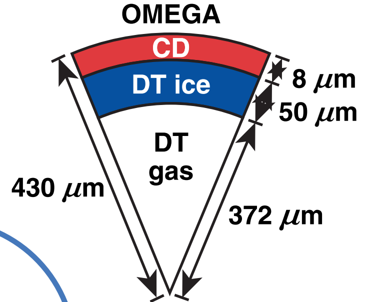
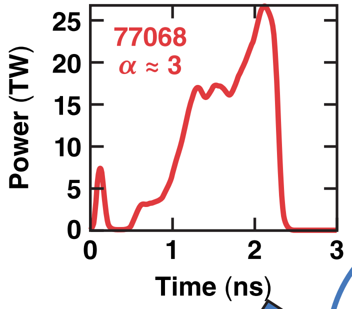
Statistical mapping of the experimental database onto *LILAC* output variables provides a predictive tool for 1-D or systematically perturbed implosions

- Current hydrocodes are not accurate enough to predict experimental outcomes from first principles
- Use statistics to bridge the gap between simulation and experiment

Laser pulse and target specifications are inputs to both the code and the experiment





Assuming 1-D implosions

1-D physics models (*LILAC*)

Implosion experiment: real physics

Code output:

Yield^{L}, V_{imp}^{LILAC}, ρR^{LILAC}, T_{i}^{LILAC}, τ^{LILAC}, R^{LILAC}

Mapping

Measurable parameters:

Yield^{Exp}, V_{imp}^{Exp}, ρR^{Exp}, T_{i}^{Exp}, τ^{Exp}, R^{Exp}

Example: Yield$^{Exp} = F\left(V_{imp}^{LILAC}, \rho R^{LILAC}, T_{i}^{LILAC}, \tau^{LILAC} \ldots\right)$

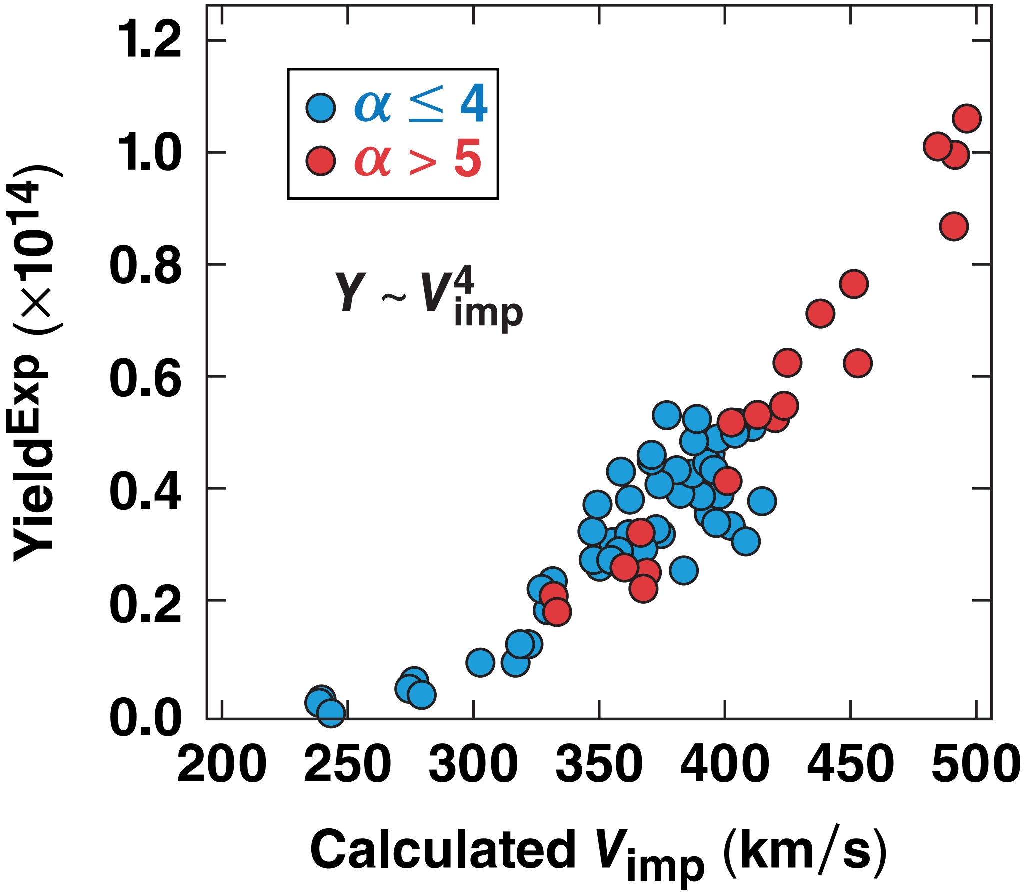
New predictive capability (also valid for 3-D systematic nonuniformities)

Instead of comparing each simulated parameter with its measured value, we map each measurement onto all simulated parameters through nonlinear correlations.

TC13680b

Predictive models from statistical mapping have been constructed in Python using simple regression analysis

- We have developed the statistical modeling and visualization tool, pyCAT, to interrogate a database of experimental and simulation results
- We assume mapping is of the form $\hat{y} = a_0 \Pi x_i^{a_i}$
- Overfitting is controlled by
  - choosing a limited quantity of physically relevant regression variables
  - cross validation
  - parameter hypothesis testing
  - choosing reasonable Bayesian prior for parameters



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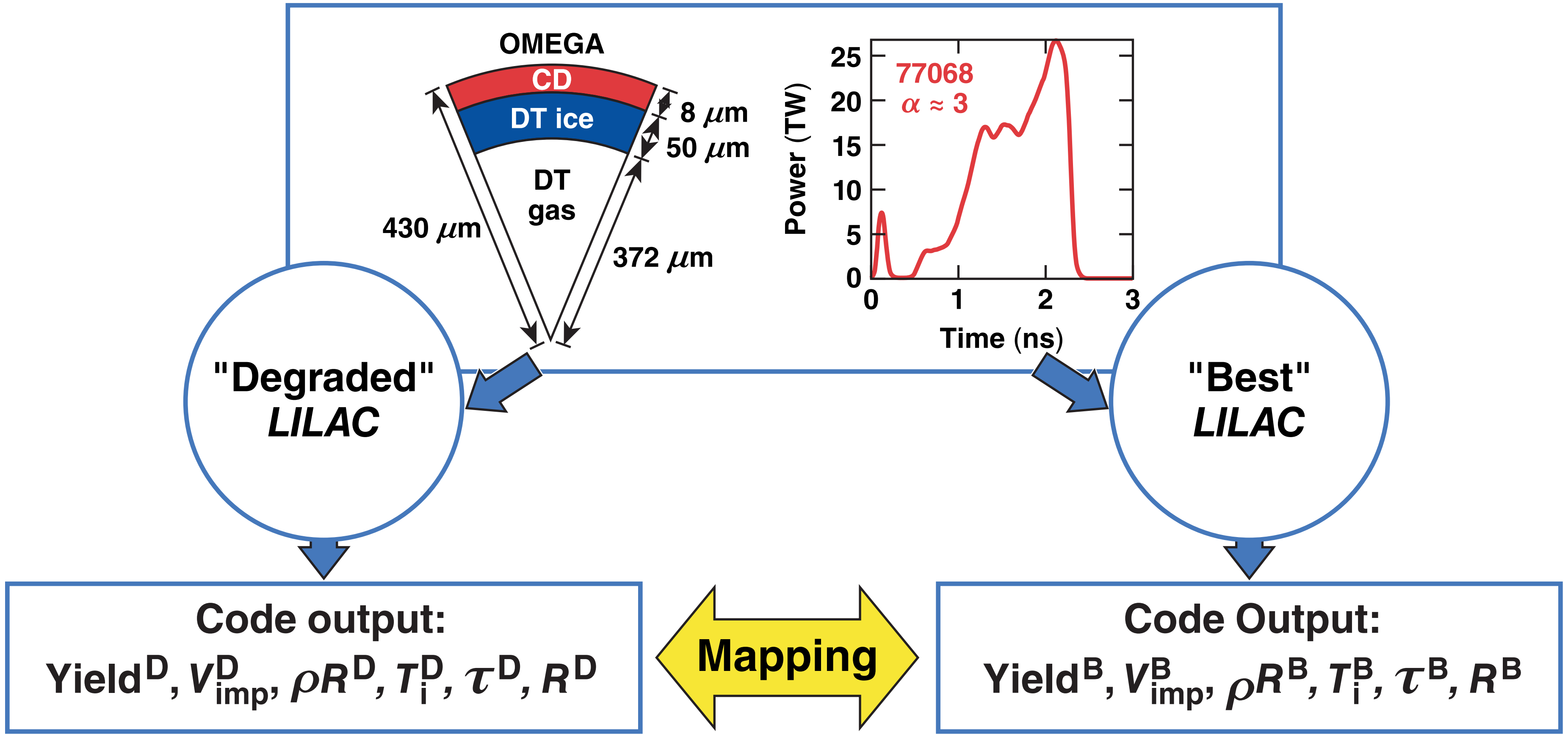
The validity of the statistical mapping is tested by deliberately choosing suboptimal models in *LILAC*

- "*Best*" *LILAC* includes: CBET,* nonlocal electron transport, FPEOS,** radiation transport
- "*Degraded*" *LILAC*
  - – turn off radiation transport
  - – change EOS to ideal gas/Thomas–Fermi (shock-timing physics)
  - – turn off CBET and nonlocal thermal transport [laser–plasma interaction (LPI) and transport physics]

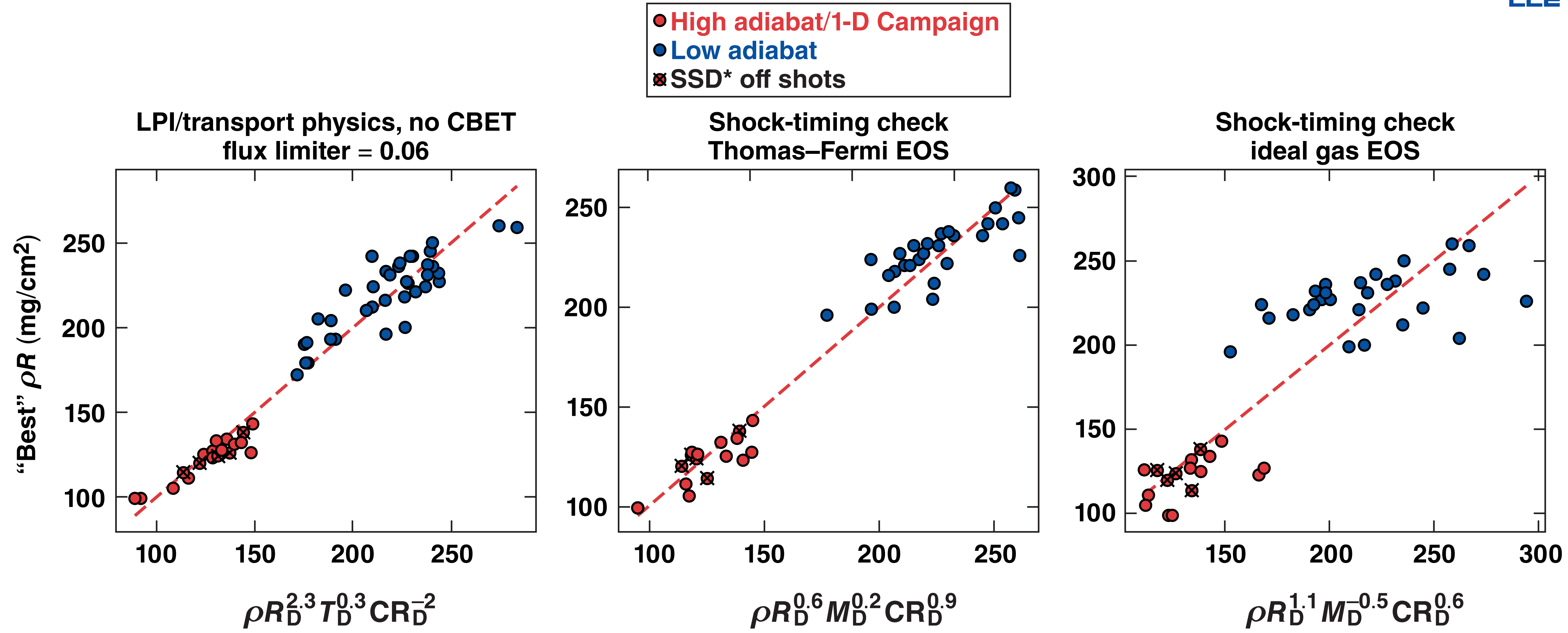


Can we use the "degraded" *LILAC* to predict the "best" *LILAC* using statistical mapping?

*CBET: cross-beam energy transfer
**FPEOS: first-principle equation of state

TC13680c

Statistical predictions of areal density require accurate enough EOS



Where ρR_D, T_D, CR_D, and M_D are the areal densities, ion temperatures, inner convergence ratios, and stagnating masses of the degraded *LILAC* simulations.

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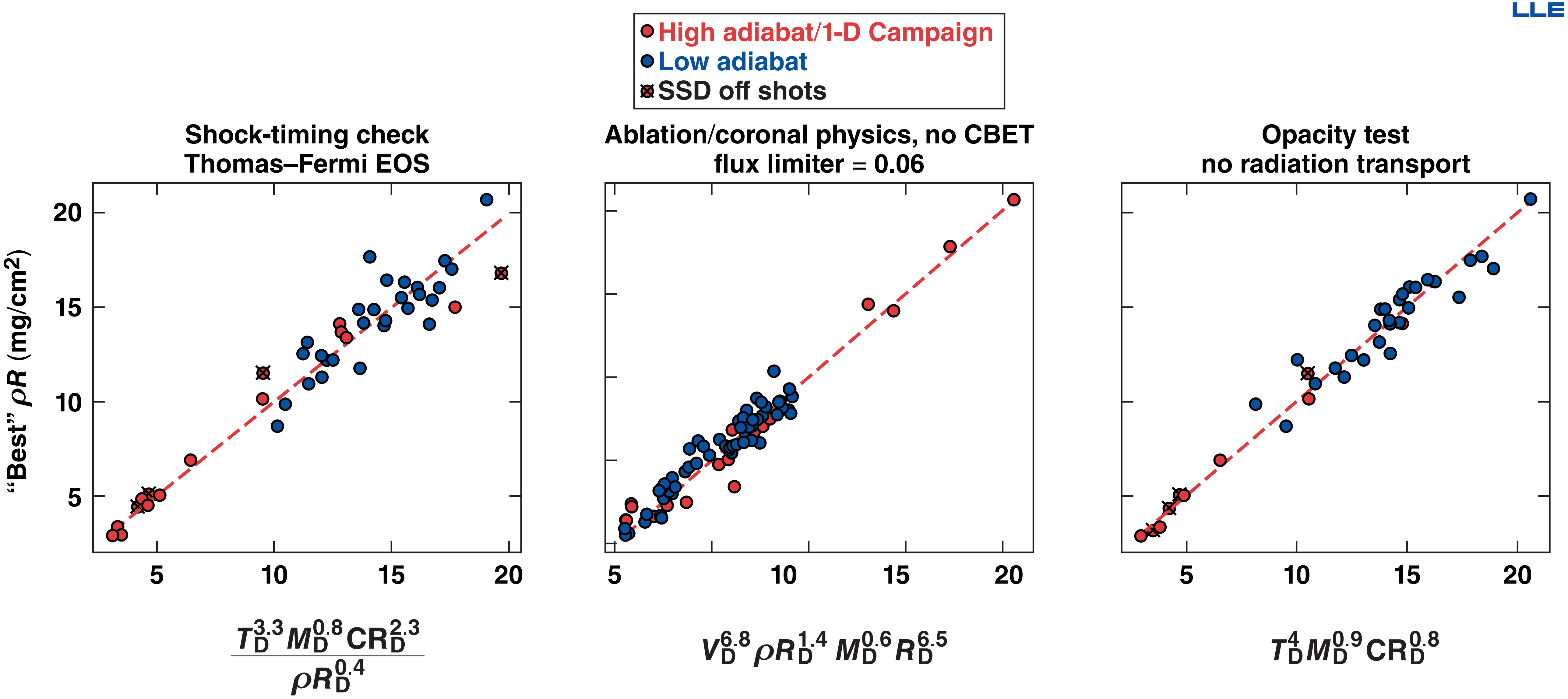
*SSD: smoothing by spectral dispersion

Predictions of the primary neutron yield are relatively robust to modeling errors



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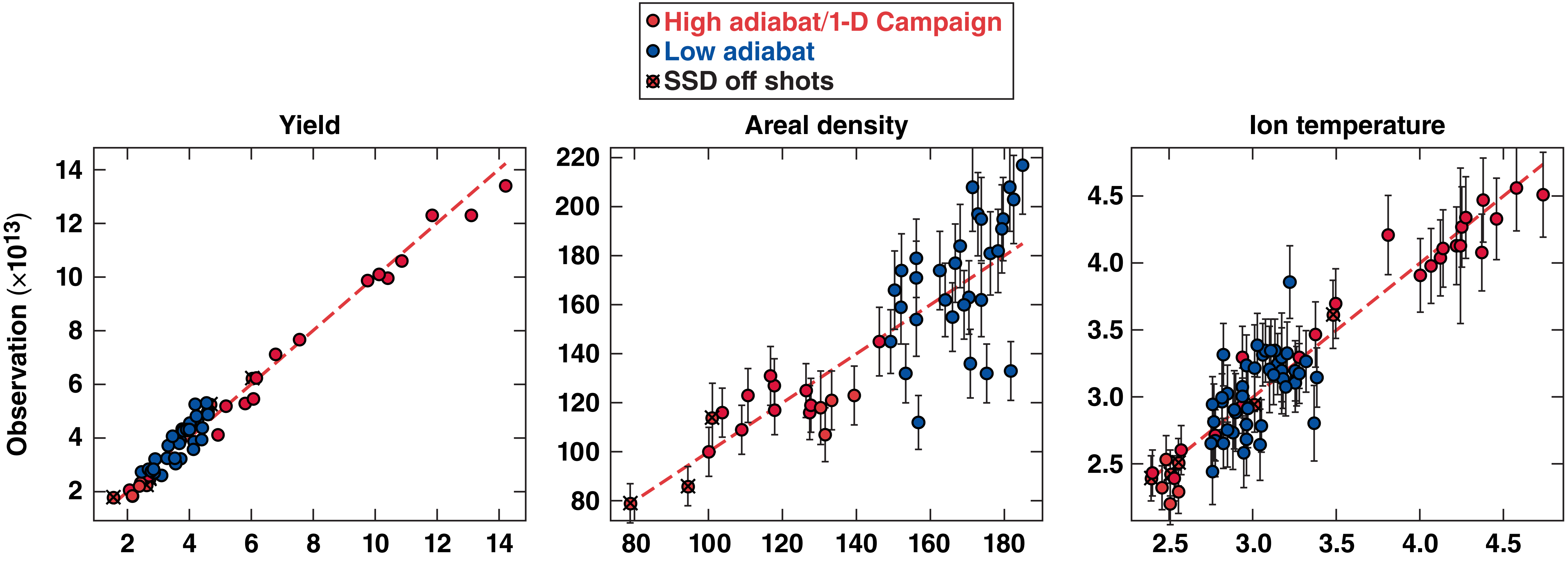
Predictive models are developed for the experimental primary neutron yield, ion temperature, and ρR, using only *LILAC* quantities



$$Y_{\mathrm{exp}} \propto \frac{V_{LILAC}^{3.8}\,\rho R_{LILAC}^{0.2}\,M_{LILAC}^{0.45}\,E_{\mathrm{L}}^{0.7}}{\delta_{\mathrm{SSD}}^{0.3}}$$

$$\rho R_{\mathrm{exp}} \propto \frac{1}{V_{LILAC}^{0.95}\,R_{LILAC}^{0.85}\,\delta_{\mathrm{SSD}}^{0.4}}$$

$$T_{\mathrm{exp}} = 0.85\,T_{LILAC}$$

TC13761

The statistical model was used to design the highest-yield implosions on OMEGA

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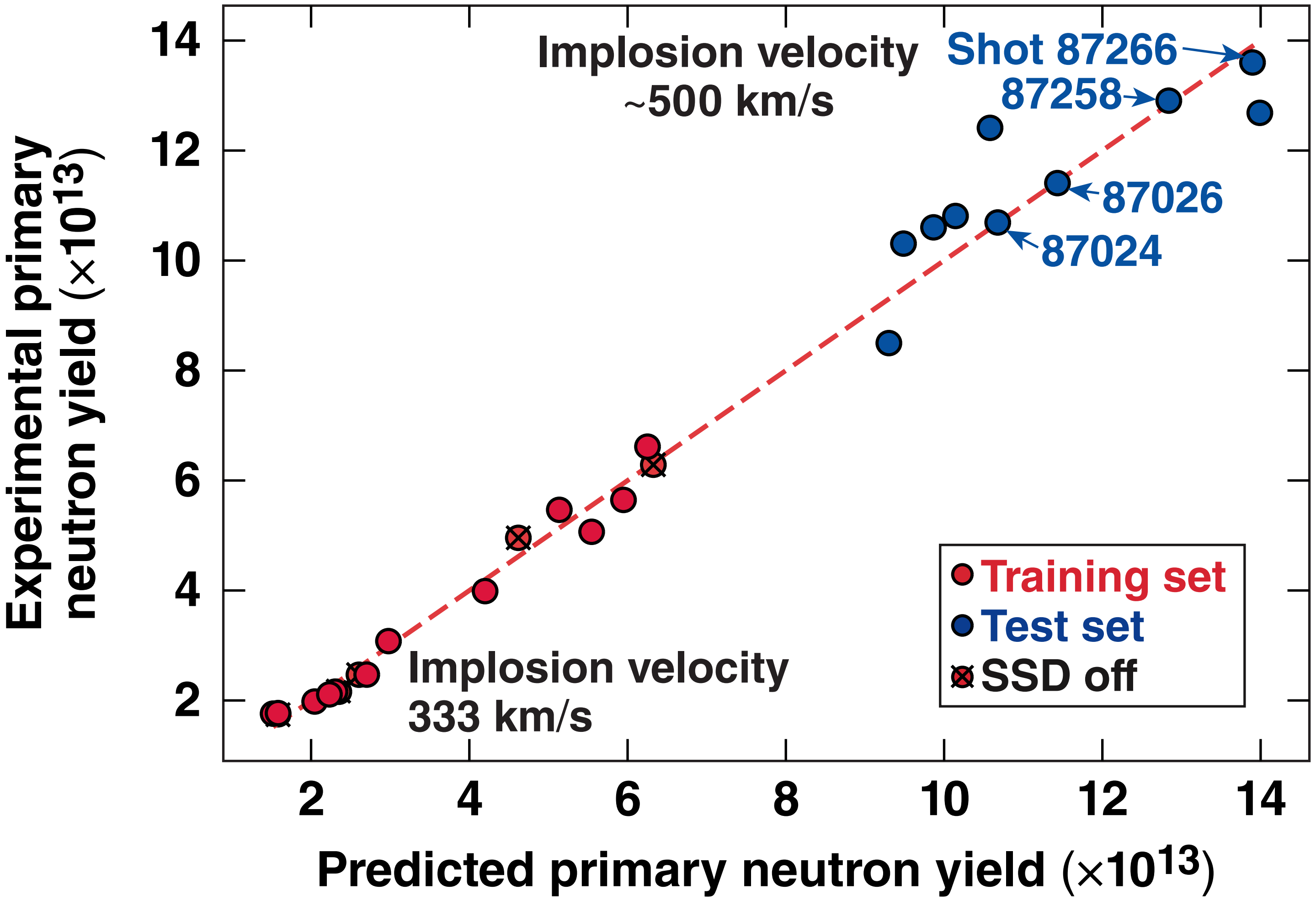

$$\text{Yield}_{\text{pred}} \sim \frac{V_{LILAC}^{4.3} M_{LILAC}}{\delta_{\text{SSD}}^{0.3}}$$

TC13762

A statistical model of OMEGA implosions has been developed to enable accurate preshot predictions and optimize implosion design

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The dependence of the experimental yield on 1-D parameters will persist if the 3-D effects are dominated by systematic nonuniformities

- $\boxed{Y_{exp} = Y_{1\text{-}D}\,(\text{1-D parameters})\,\text{YOC*}\,(\text{distortion})}$
- A_0 = initial nonuniformities (target and/or laser)
- f (1-D) = amplifications of distortion caused by implosion (RT,** RM,† BP‡)
- $\text{YOC} = \text{YOC}\left[\tilde{A}_0^{\text{systematic}} f_s\,(\text{1-D}) + \tilde{A}_0^{\text{random}} f_r\,(\text{1-D})\right]$
- If systematic nonuniformities are dominant: $\tilde{A}_0^{\text{systematic}} \gg \tilde{A}_0^{\text{random}}$
- $Y_{exp} = Y_{1\text{-}D}\,(\text{1-D parameters})\,\text{YOC}\left[\tilde{A}_0^{\text{systematic}} f_s\,(\text{1-D parameters})\right]$
- If $\tilde{A}_0^{\text{systematic}}$ = constant, the yield depends only on 1-D parameters even in distorted implosions

$\boxed{Y_{exp} = Y_{1\text{-}D}\,(\text{1-D parameters})}$

For 1-D implosions or 3-D with dominant systematic nonuniformities

*YOC: yield over clean
**RT: Rayleigh–Taylor
†RM: Richtmyer–Meshkov
‡BP: Bell–Plesset

TC13683b