Overcoming Plasma-Induced Noise: Statistical Optimization of α-Particle Detection in EXL-50U p-B Reactions

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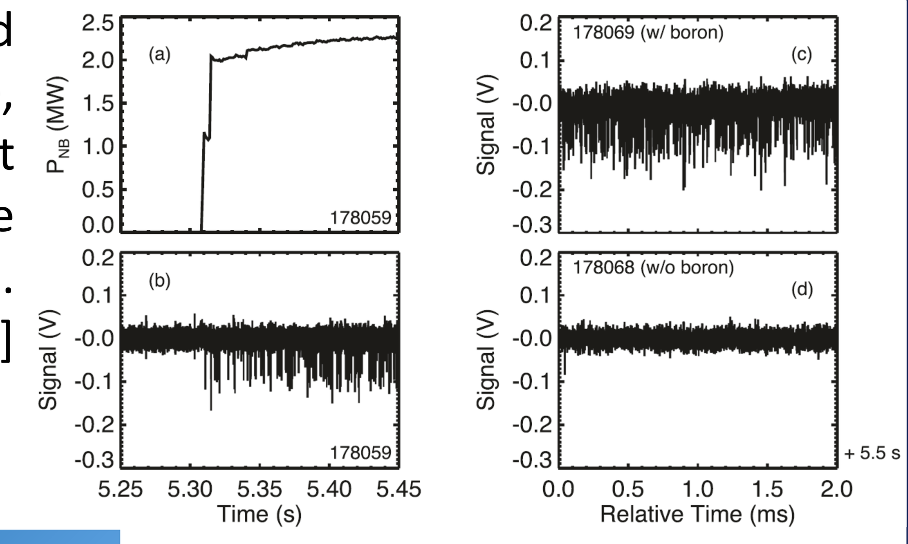
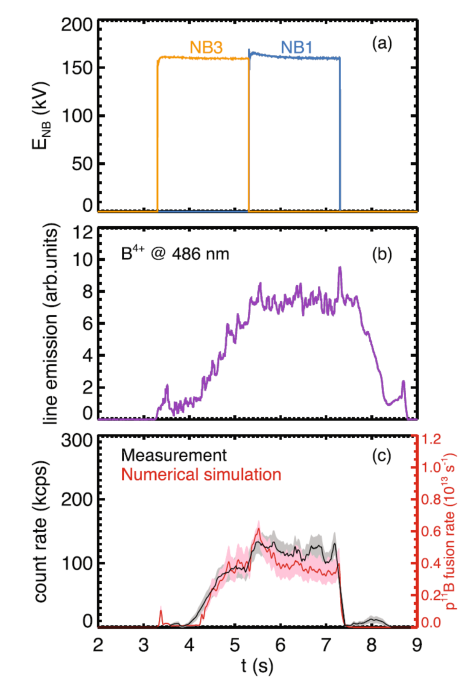
Abstract:

Accurate measurement of charged fusion products in magnetically confined plasmas (MCP) faces significant challenges due to plasma radiation exposure, electromagnetic interference, thermal loads, and background bombardment by electrons/ions, which generate substantial noise while yielding sparse signals. To address these issues, advanced solutions are required beyond conventional detector design and calibration, including signal discrimination techniques, machine learning-based noise suppression for enhanced signal-to-noise ratios, and statistical analysis to improve signal significance. This study focuses on the detection simulation of α-particles generated by proton-boron (p-B) fusion reactions in the ENN-operated ST-type device EXL-50U. By employing Monte Carlo simulations, we systematically evaluate the expected α-particle signals, reducible backgrounds (e.g., electromagnetic interference, plasma fluctuations, and energetic protons/electrons/photons), and irreducible backgrounds (e.g., high-energy proton pileup events and fortuitously energized helium impurities). The signal significance of measurable fusion products is quantified using statistical metrics, providing critical insights for optimizing α-particle diagnostics in p-B fusion experiments under high-background conditions.

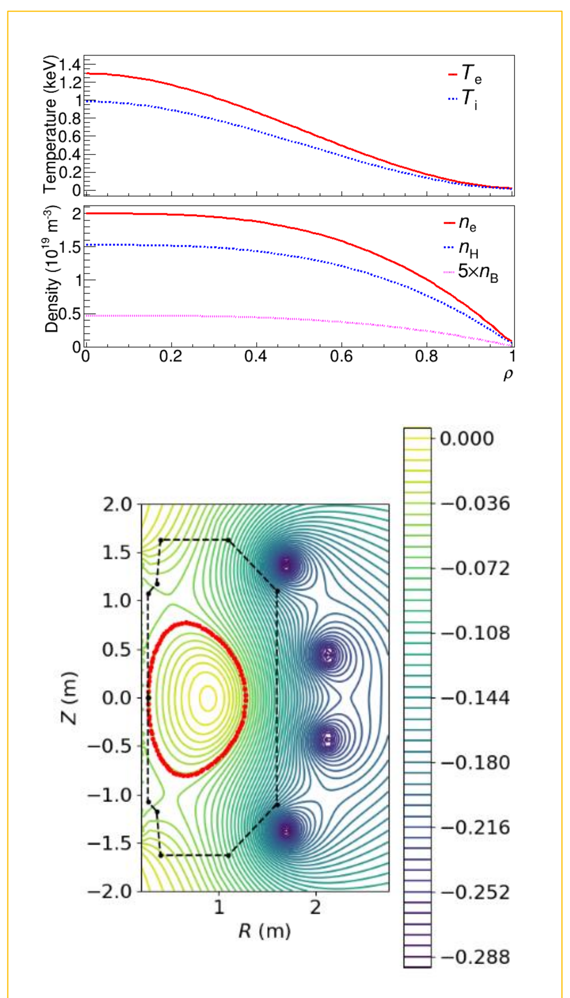
First measurement of p-B fusion with beam-MCP on LHD:

Owing to a distinct signal and minimal background interference, even basic variable management is enough to substantiate the happening of p-B fusion. [R. Magee, et al., 2023]

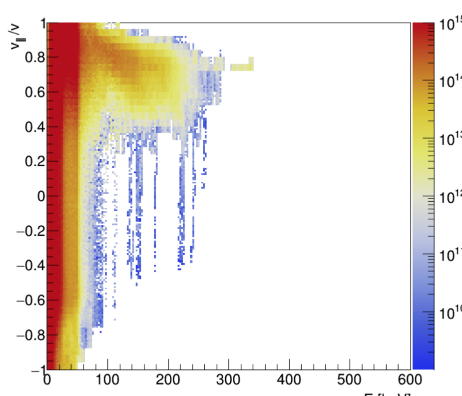




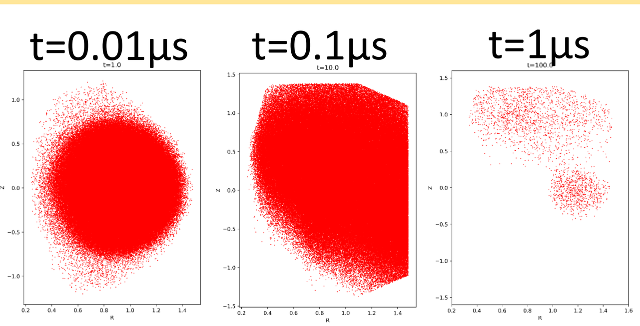
Proposing p-B fusion via NBI-ICRF synergy on EXL-50U:



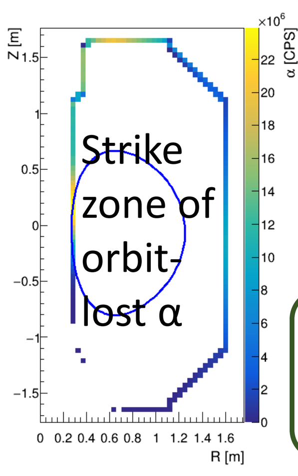
Profiles of the main plasma in the simulation



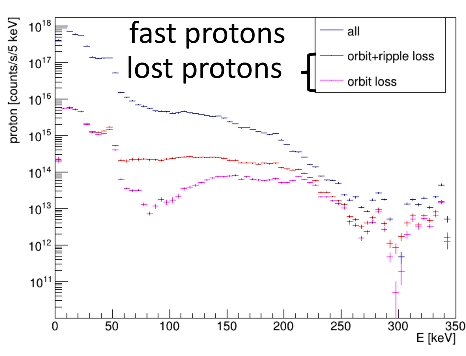
Fast protons boosted by NBI (MW)-ICRF (~300 kW) synergy.

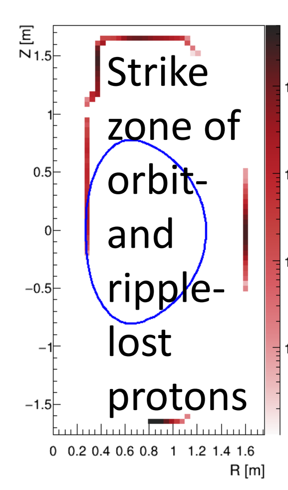


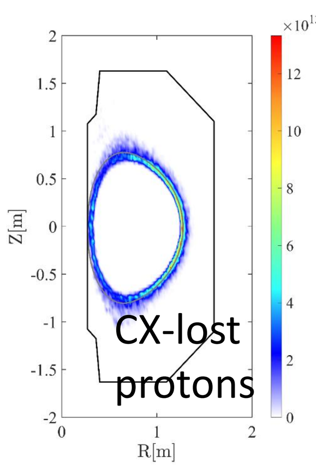
~8.6×10[11] α/s generated and escape the plasma within 1 μs of production.



Signal: **α** (1~6 MeV)







Steady-state fast proton distribution losses from orbit/ripple: 9.2%, (>100 keV), 15.0% (>150 keV), 32.4% (>200 keV); plus ~50% from charge exchange.

Signal-to-noise ratios (SNR) against key backgrounds.

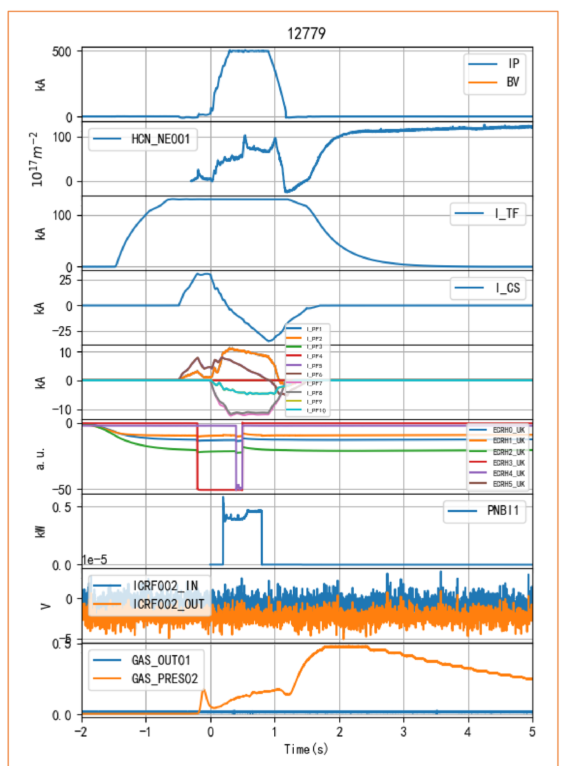
N(signal α)/N(background)		
fast proton	Hard X-ray/γ	fast electron
~10^{-4}	~10^{-5}	<<10^{-5}

Some reducible by shielding, collimation, or signal ID, yet significant background remains on EXL-50U.

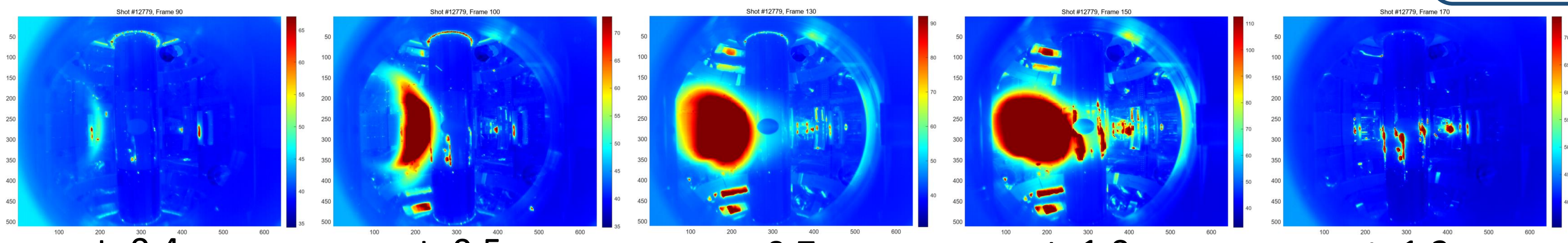
Background: **fast proton** (0.1~0.3 MeV)

Background: **fast electron** (up to 10 MeV)

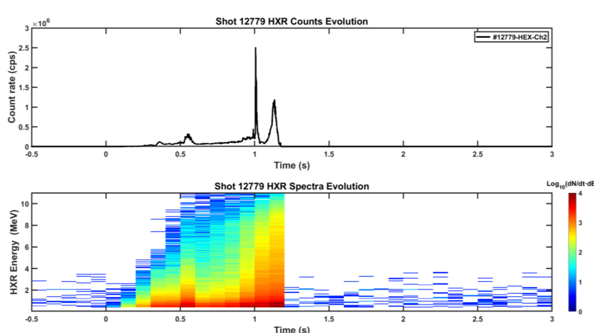
Background: **hard X-ray** (up to 10 MeV)



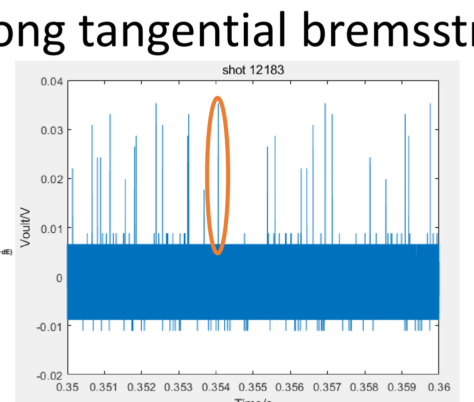
Discharge parameters of shot EHL-50U #12799.

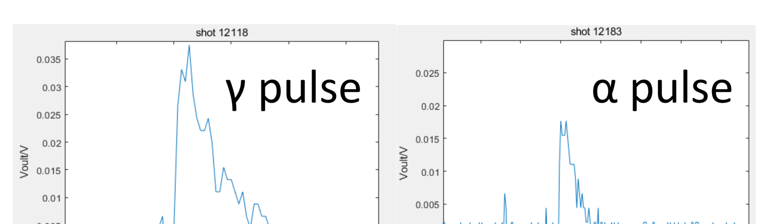


Images of Infrared Radiation: CS+ECRH initiated/sustained. At 0.5 seconds, additional ECRH power generated fast electrons, producing strong tangential bremsstrahlung. These electrons persisted after ECRH termination.



Energy of hard X-ray in #12799.



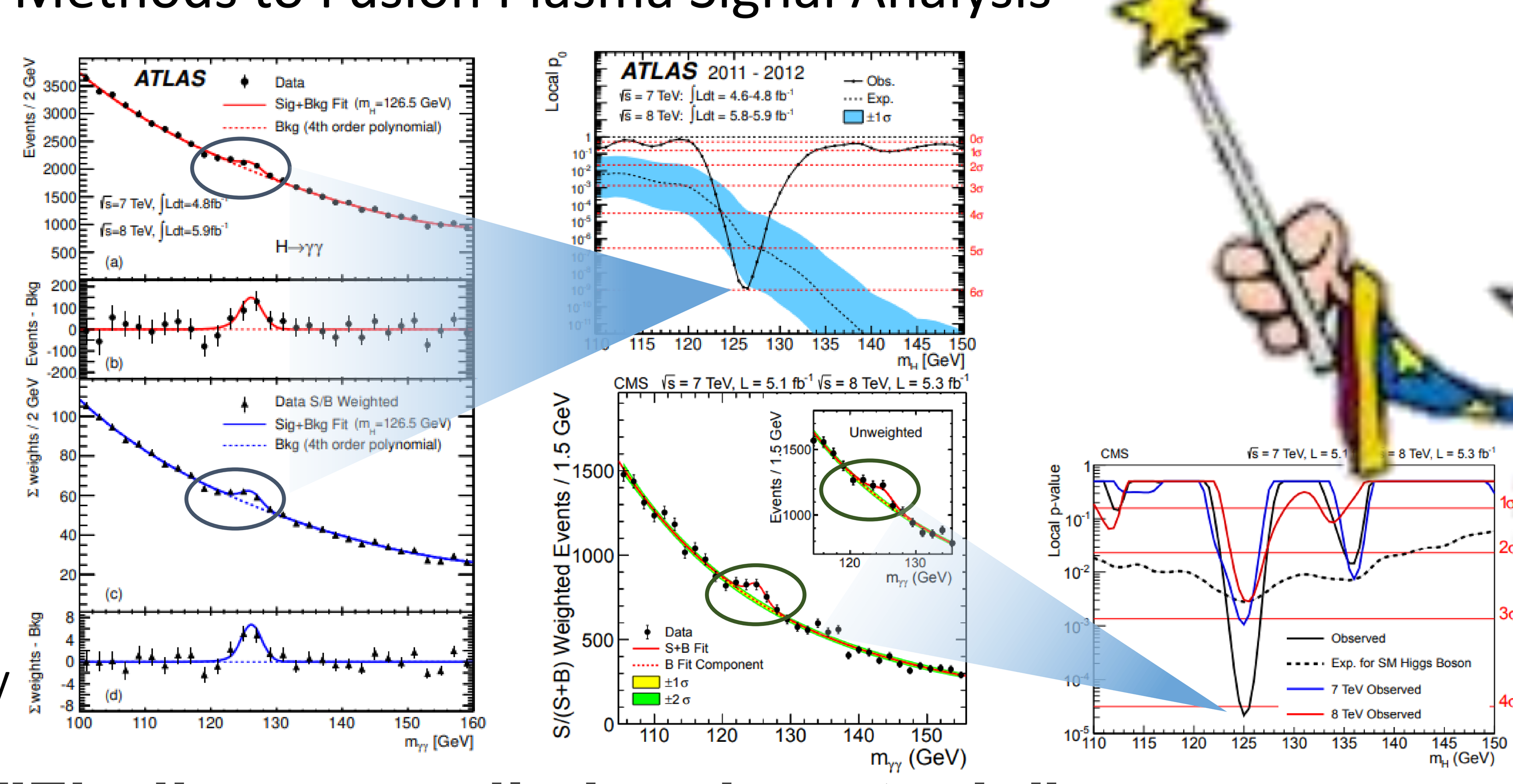


The α pulse signal is buried in noise. Detection was carried out using a system configured with LYSO+SiPM.

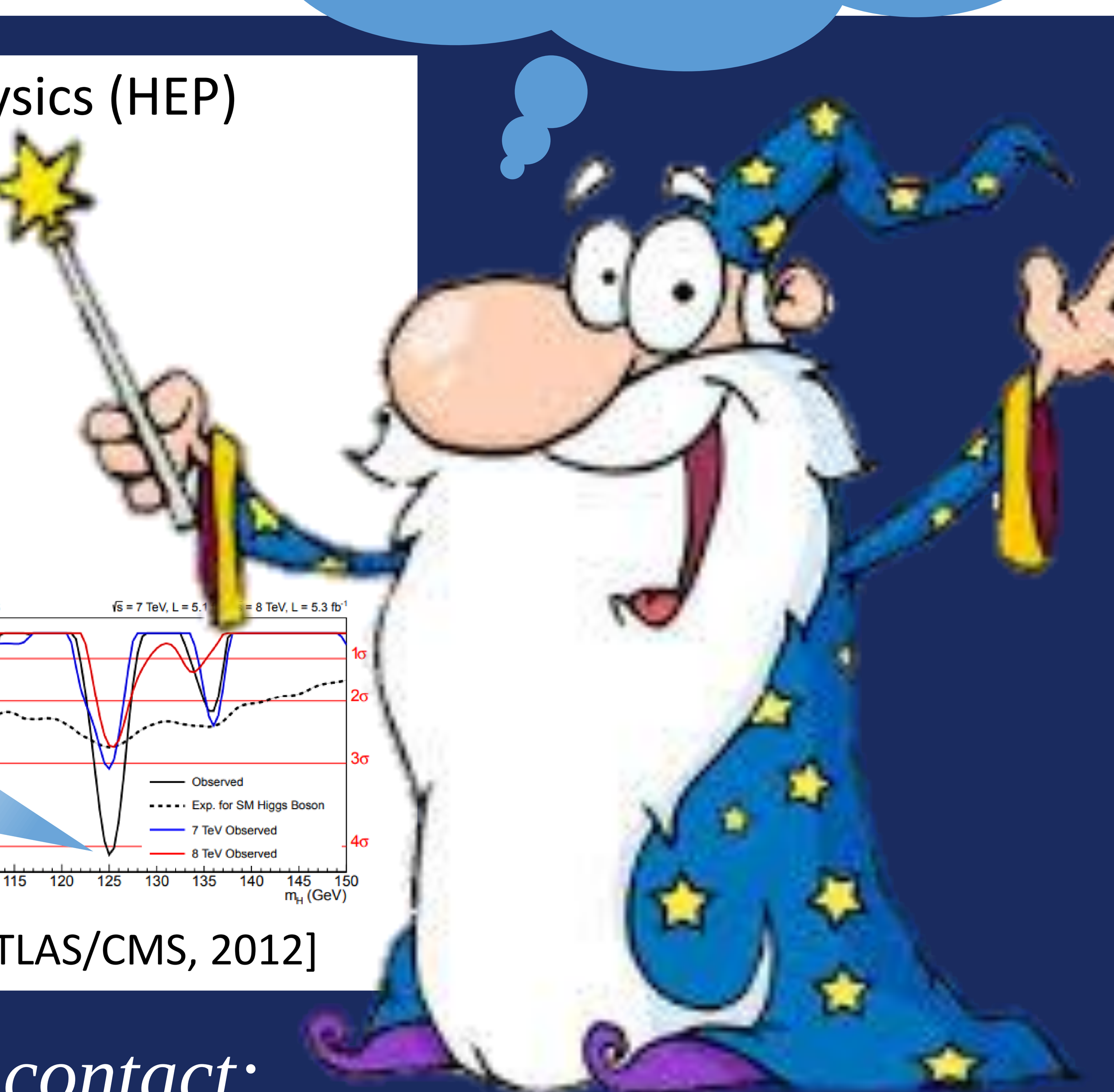
Statistical analysis

Advantages and Feasibility of Applying High-Energy Physics (HEP) Statistical Methods to Fusion Plasma Signal Analysis

- **Enhanced signal extraction:** Statistical tools from HEP (e.g., likelihood fitting, multivariate analysis, and machine learning-based denoising) improve the detection of weak signals—such as those from α particles—even under high background noise.
- **Robust hypothesis testing:** Techniques like significance estimation and anomaly detection allow for reliable identification of transient events with low false-positive rates.
- **Cross-disciplinary efficacy:** These methods have been validated in extreme noise environments (e.g., LHC experiments), ensuring their adaptability to fusion challenges and offering new pathways toward real-time monitoring and control.



"Finding a needle in a haystack." [ATLAS/CMS, 2012]



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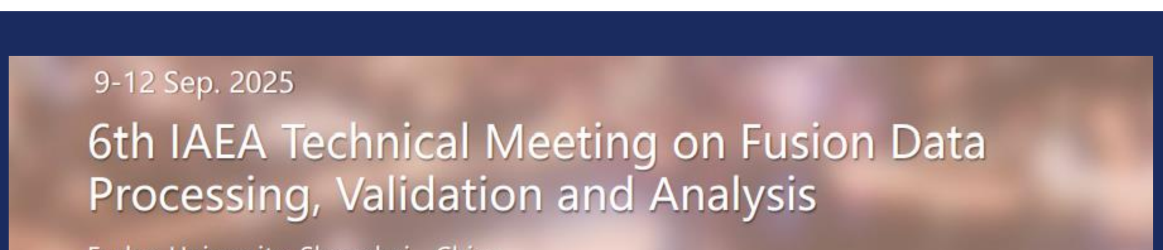

Please contact:
lizhiz@enn.cn *for further interests!*