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Why Printed Electronics?

- Embedding computing in disposables, smart packaging, low-end healthcare items and more
- Excel in functionality and affordability
- Flexible & cost-effective manufacturing
- Point-of-use fabrication

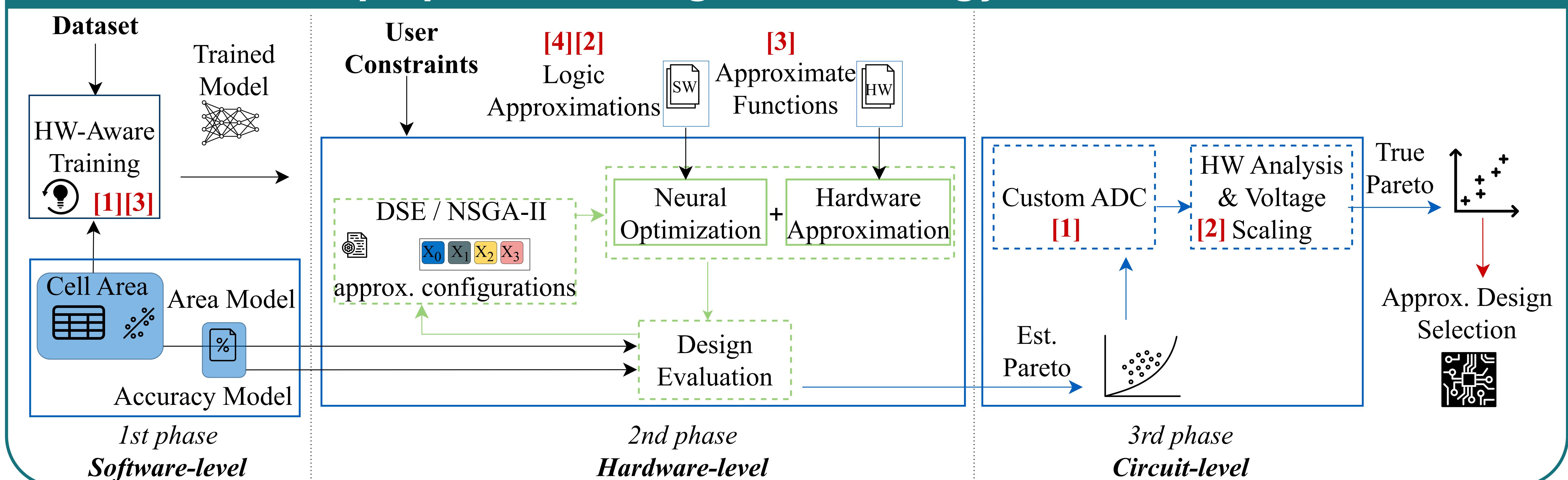
➤ Market value of US\$73B by 2027

Constraints of Printed Circuits

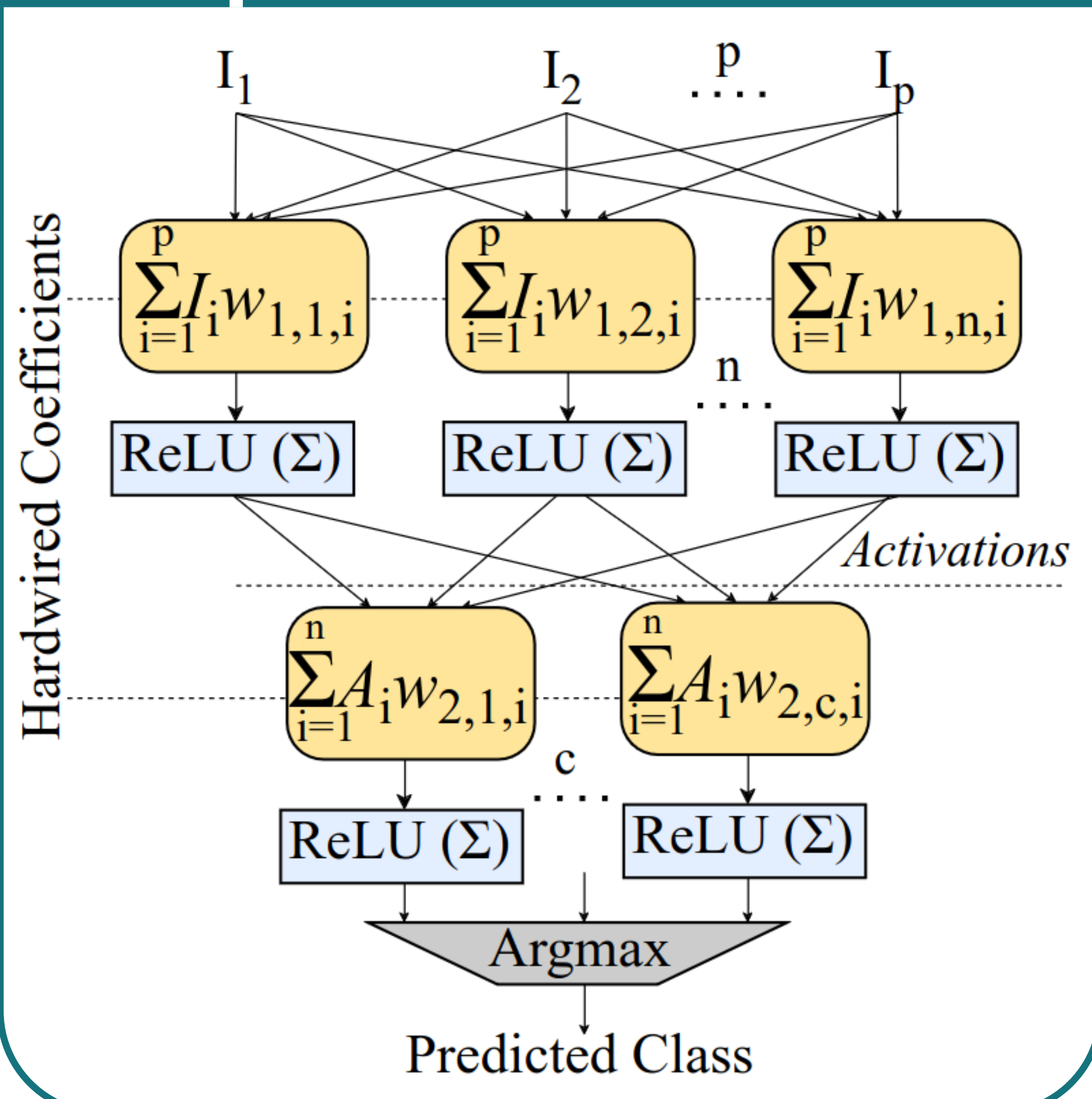
- Lack affordable computing solutions
- Large feature sizes (e.g., MAC → 6 orders of magnitude larger than CMOS)
- Infeasible hardware overheads

Challenge: Enable battery-powered printed ML classifiers through AC at both HW and SW level

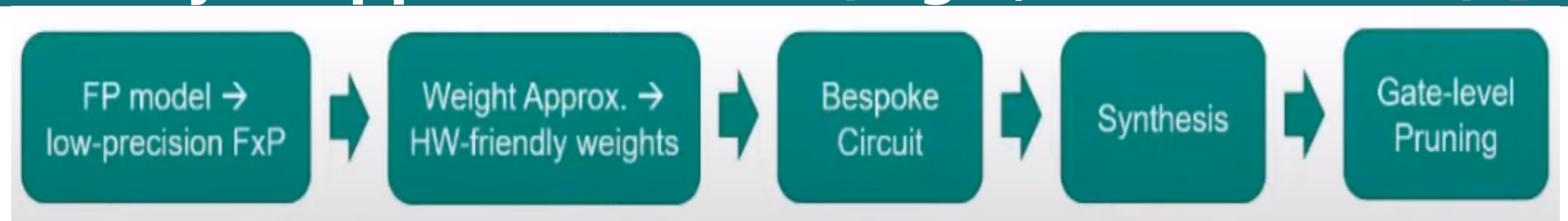
Overview of the proposed co-design methodology flow



Bespoke Architectures



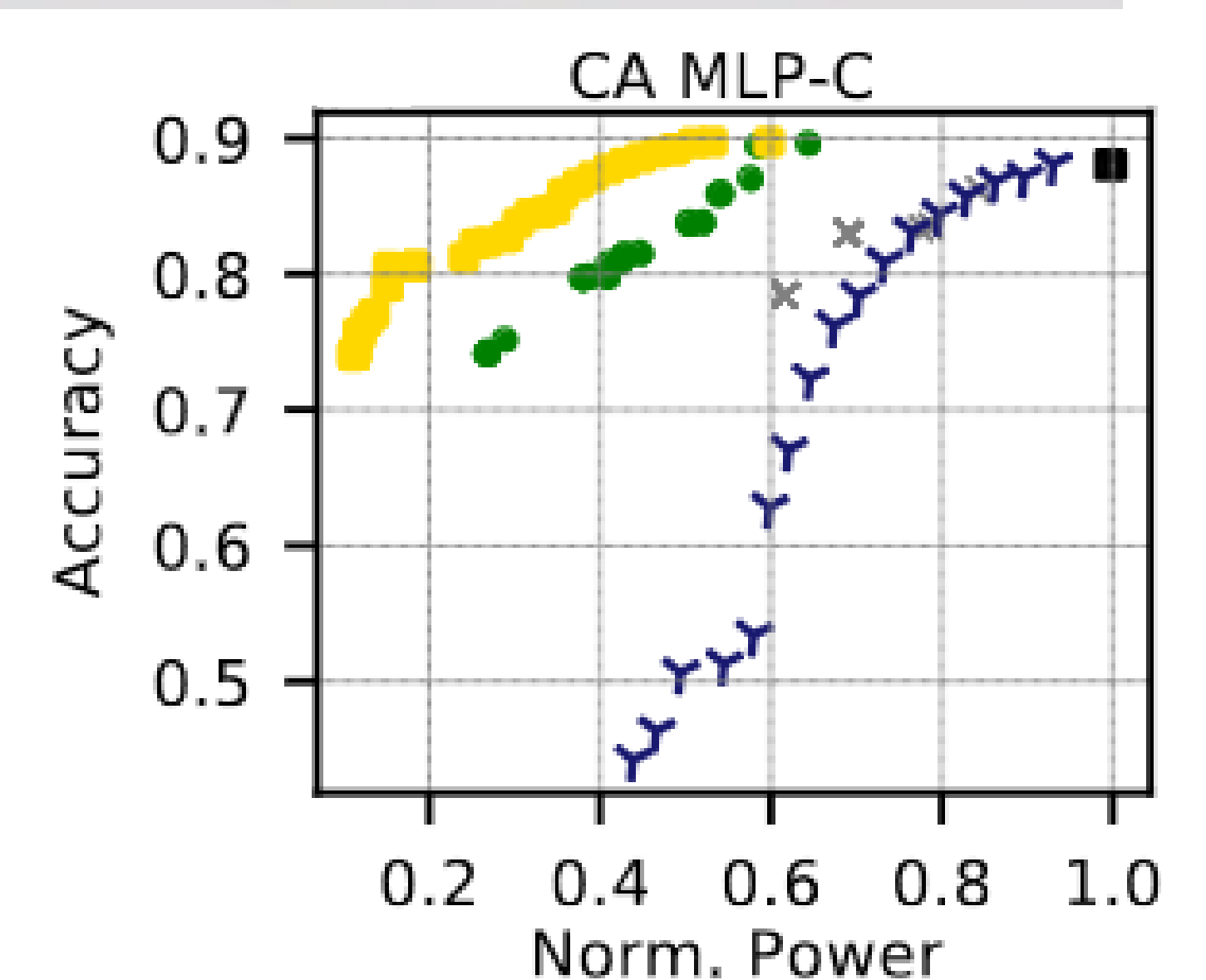
Cross-layer approximations (logic, HW & circuit) [2,4]



Experimental setup:

- MLPs and SVMs classifiers
- Fully parallel bespoke architectures
- 8-bits weights & 4-bit inputs

➤ **logic&HW:** 47% (44%) area (power) gains for <1% acc loss
 ➤ **&circuit (VOS):** additional 22% power gains



■ Exact Bespoke x Only Pr. approx ● CoA&Pr approx. y Only VOS ■ Proposed Cross

Retraining & HW approximation [3]

Key ideas:

- **Coefficient clustering** based on their constant multiplication **area**
- Approximate **neuron** discarding LSBs based on their **significance**

➤ **x6, x9, x19** less area (~power) for 1%, 2%, 5% acc loss
 ➤ **8/10** MLPs can now be battery powered

Unary Decision Tree classifiers [1]

Why Unary arithmetic:

- Comparisons are performed by checking **1 bit**

$$I \geq .1011_2 \xrightarrow{\text{Unary}} I \geq .0000111111111111_U \equiv I[11]$$

- Suitable for Decision Tree classifiers
- Fitting to **custom ADCs**

➤ **3x (6x)** area (power) w/ **0%** acc
 ➤ HW-aware training → **8x (12x)** area (power) for **1%** acc loss

References:

- [1] G. Armeniakos, P. L. Duarte, P. Pal, G. Zervakis, M. B. Tahoori, and D. Soudris. "On-sensor Printed Machine Learning Classification via Bespoke ADC and Decision Tree Co-Design". In: 2024 Design, Automation & Test in Europe Conference & Exhibition (DATE). 2024.
 [2] G. Armeniakos, G. Zervakis, D. Soudris, M. B. Tahoori, and J. Henkel. "Model-to-Circuit Cross-Approximation For Printed Machine Learning Classifiers". In: IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 42.11 (2023), pp. 3532–3544.
 [3] G. Armeniakos, G. Zervakis, D. Soudris, M. B. Tahoori, and J. Henkel. "Co-Design of Approximate Multilayer Perceptron for Ultra-Resource Constrained Printed Circuits". In: IEEE Transactions on Computers (2023)
 [4] G. Armeniakos, G. Zervakis, D. Soudris, M. B. Tahoori, and J. Henkel. "Cross-Layer Approximation For Printed Machine Learning Circuits". Design, Automation & Test in Europe Conference & Exhibition (DATE). 2022