Enhancing the Sensitivity for Triple Higgs Boson Searches with Deep Learning Techniques

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MOTIVATION

PROBING THE HIGGS POTENTIAL

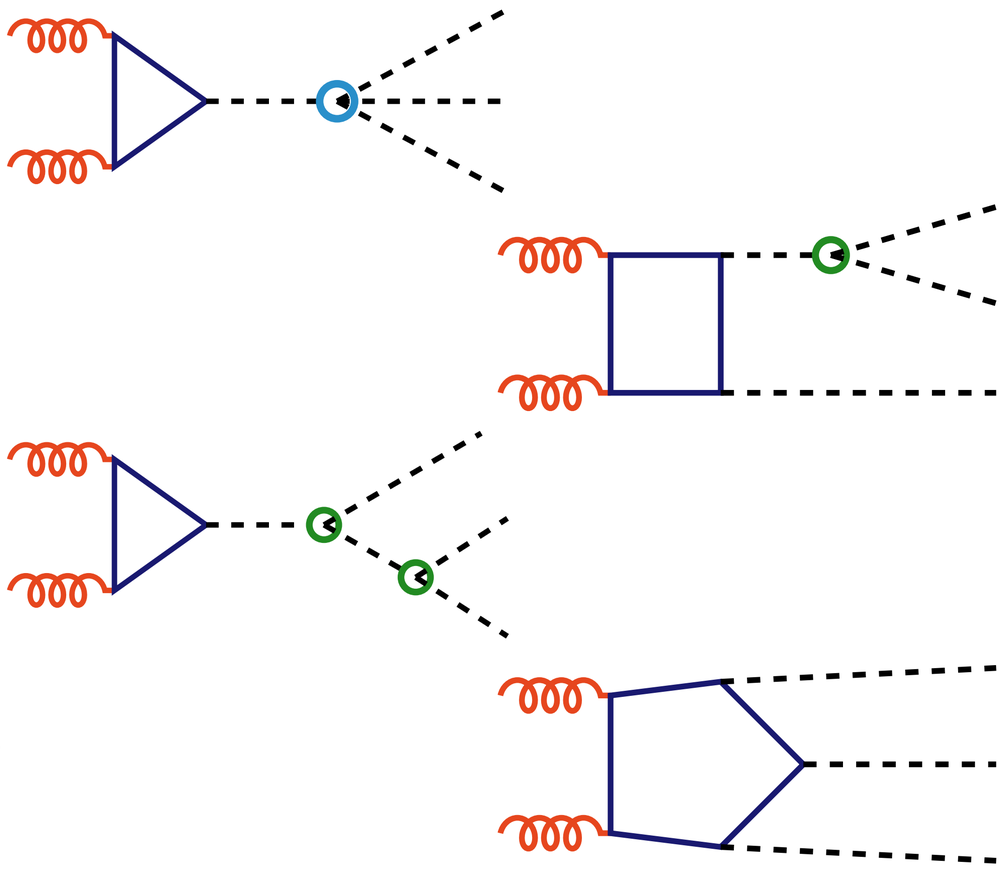
- An important task is to determine the Higgs potential and self-interactions

$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{3h} v h^3 + \lambda_{4h} h^4$$

- Determine whether the Higgs potential can facilitate a strong first-order phase transition in the early universe
- Di-Higgs: Crucial for measuring the trilinear self-coupling λ_{3h}
- Tri-Higgs: Provides additional information on this trilinear coupling and the first experimental constraints on the quartic coupling λ_{4h}

TRIPLE HIGGS PRODUCTION

- Triple Higgs production provides the only direct probe of the quartic coupling λ_{4h}
- SM tri-Higgs production cross-section is extremely small ($\sim$ 0.1 fb at 14 TeV)
- Extended scalar models (TRSM, DM-CPV) feature resonant cascade decays
- Resonant production enhances the cross-section, providing a viable discovery window ($\mathcal{O}(10)$ fb at 14 TeV)



HADRONIC CHANNEL

- The $h \to b\bar{b}$ decay has the largest branching ratio, yielding maximum statistics

$$\mathrm{BR}(hhh \to 6b) \approx [\mathrm{BR}(h \to b\bar{b})]^3 \approx (0.584)^3 \approx 20\,\%$$

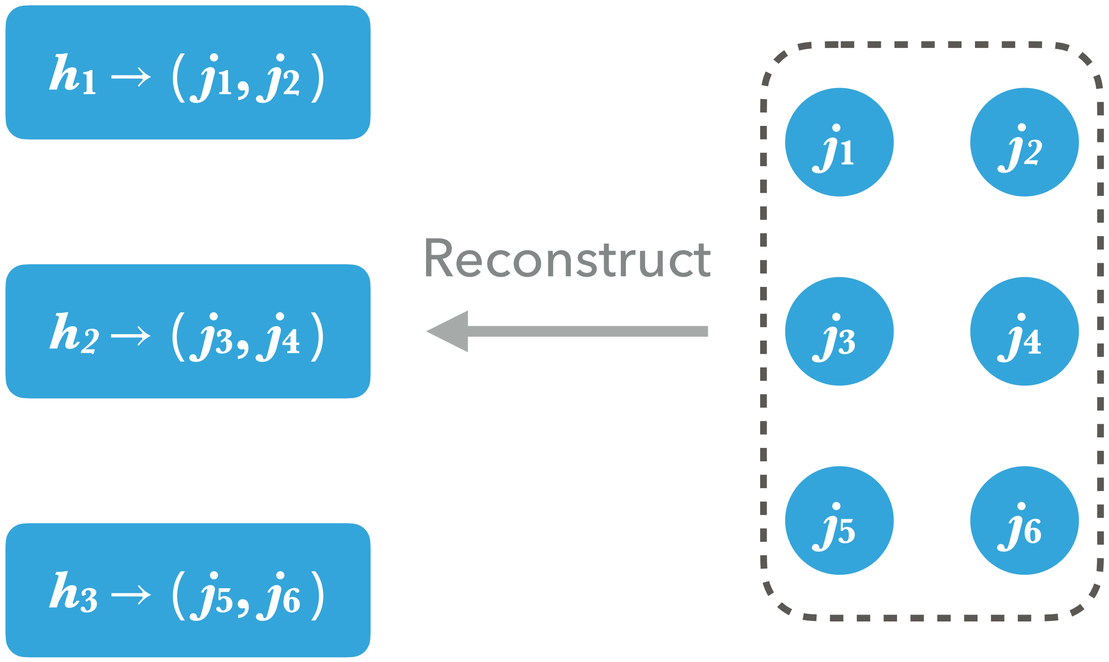
- Leptonic decay modes suffer from tiny branching ratios (< 1%) and insufficient events
- Challenge 1: Overwhelming QCD multi-jet background
  - Reconstruct 3 Higgs candidates and kinematic variables to suppress QCD events
- Challenge 2: Combinatorial explosion and mistagging in jet pairing tasks

CHALLENGE 2: COMBINATORIAL EXPLOSION

- Number of pairing combinations for 6 resolved jets:

$$\frac{6!}{2^3 \times 3!} = 15$$

- Only 1 configuration is the true signal; the other 14 are combinatorial background
- Extra radiation jets (ISR/FSR) cause permutations to escalate as $\mathcal{O}(N!)$ (e.g., 7 jets → 105, 8 jets → 420)

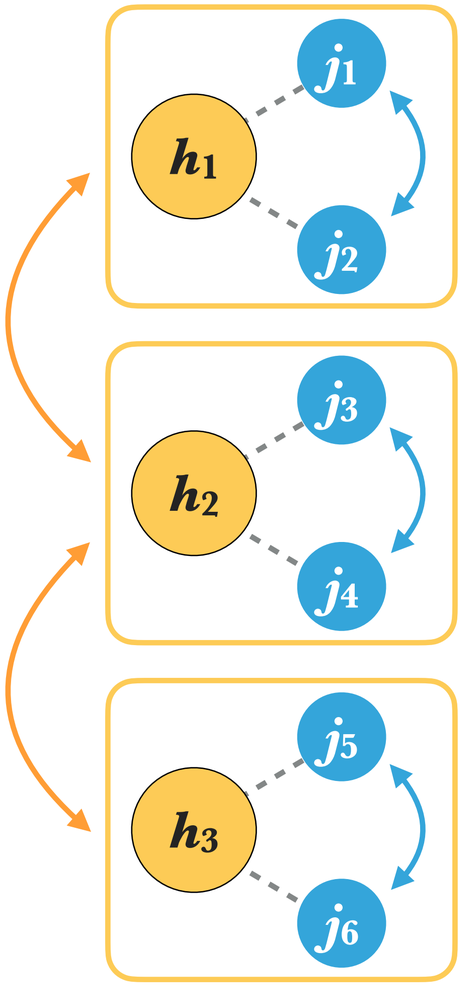


EXPERIMENTAL CHALLENGES

- Detectors cannot distinguish a b-jet from a $\overline{b}$-jet, introducing inherent ambiguity
- b-tagging is not perfect, leading to incomplete events with missing true b-jets
- Mistagged light and charm jets introduce fake background objects
  - Reconstruction algorithms must be robust against both jet combinatorics and experimental noise

PERMUTATION SYMMETRIES

- Particle decay cascades possess exact permutation symmetries
  - Exchanging daughter jets within each Higgs
  - Exchanging intermediate Higgs bosons
- Some algorithms do not preserve these symmetries, losing geometric structure
- Motivates algorithms that incorporate permutation symmetries



CHALLENGE 1: ERROR PROPAGATION

- Traditional workflows separate analysis into distinct steps
- Each stage can propagate errors, ultimately leading to weaker cross-section upper limits

Jet Pairing

Uses minimum mass difference algorithm

→

Feature Eng.

Constructs kinematic variables based on the assumed pairings

→

Classification

Cut-based/Dense-NN. Ignores permutation symmetry

→

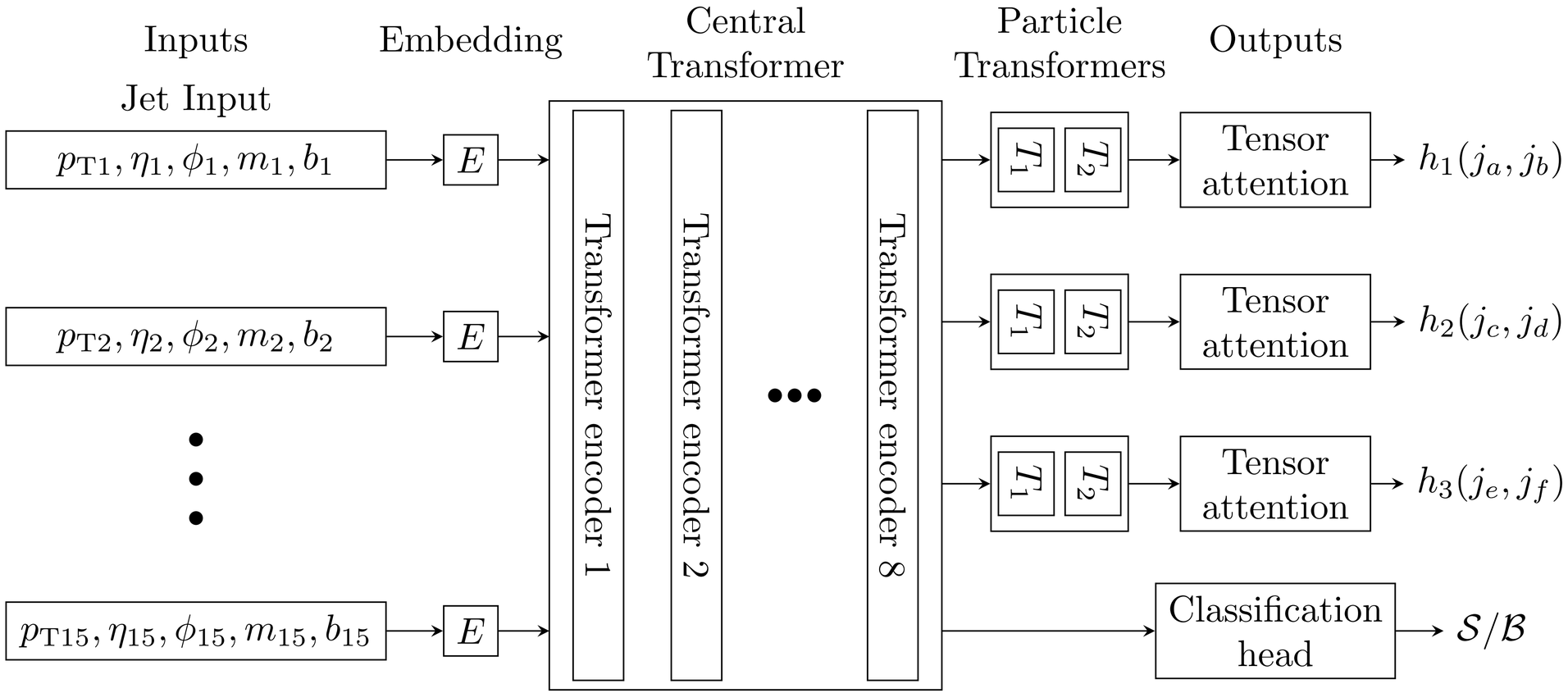
Limit Setting

Uses kinematic variables or NN scores

SPA-NET

SPA-NET ARCHITECTURE

- Symmetry Preserving Attention Network (SPA-NET) is a novel architecture specifically designed for the jet assignment task



SPA-NET CORE MECHANISMS

- Full Kinematic Attention: Inputs all jet four-momenta simultaneously without manual pre-selection
- Exact Symmetry Preservation: Employs permutation-equivariant operations to enforce exchange invariance
- Handling Mistagging: Since SPA-NET considers all jets in the final state, it can make a correct prediction even if mistagging happened
- Multi-task training: SPA-NET combined the loss in the jet pairing and classification head to implement the multi-task learning

SPA-NET WORKFLOW

- By unifying the pipeline, SPA-NET prevents the error propagation
- Benefiting from the well-constructed structure, SPA-NET achieves better classification performance, thereby constraining the cross-section upper limits much more tightly

Raw Inputs

Low-level jet info.
(p_T, η, φ, m, b)

→

SPA-NET Joint Learning

Jet Pairing + Event Classification

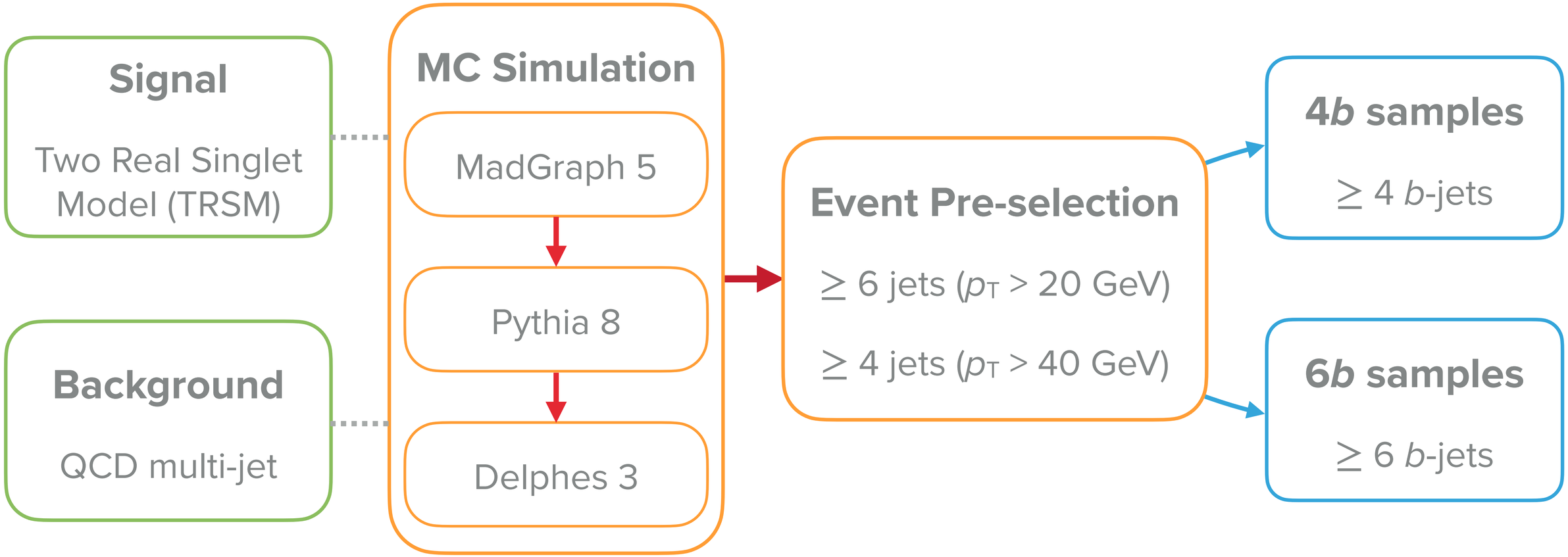
→

Limit Setting

Uses kinematic variables or NN scores

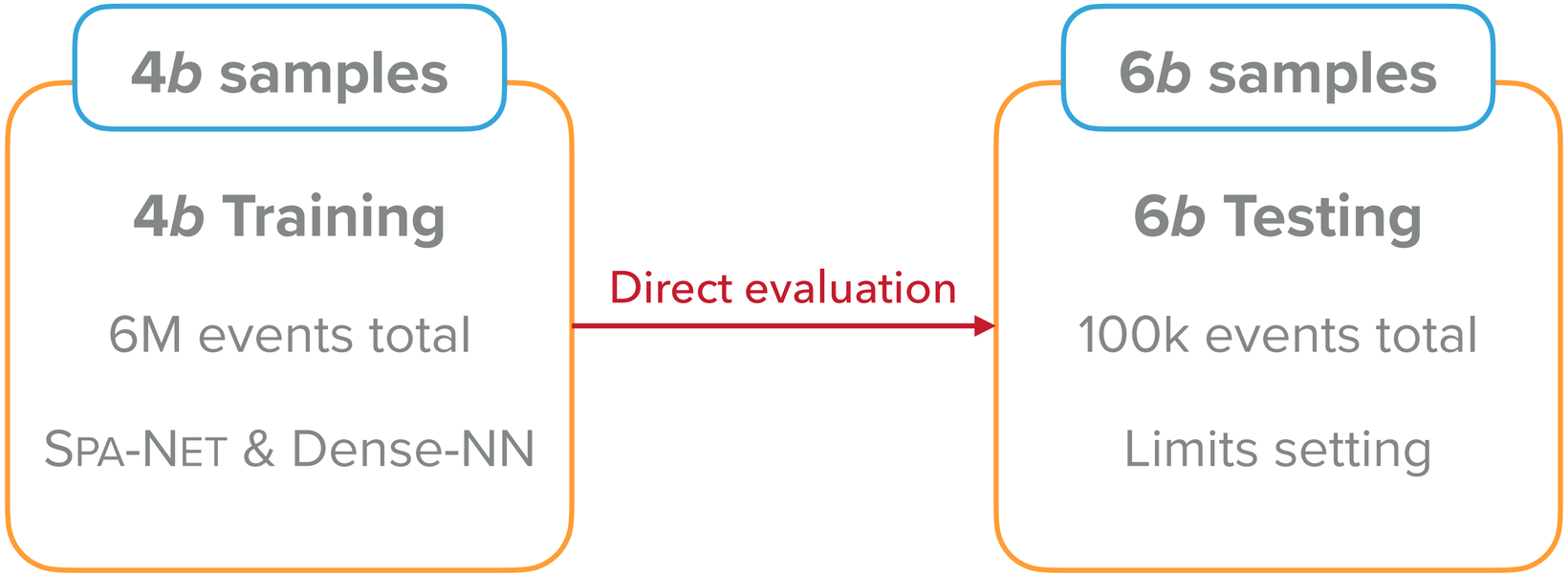
ANALYSIS

SIMULATION PIPELINE & SAMPLES



TRAINING WORKFLOW

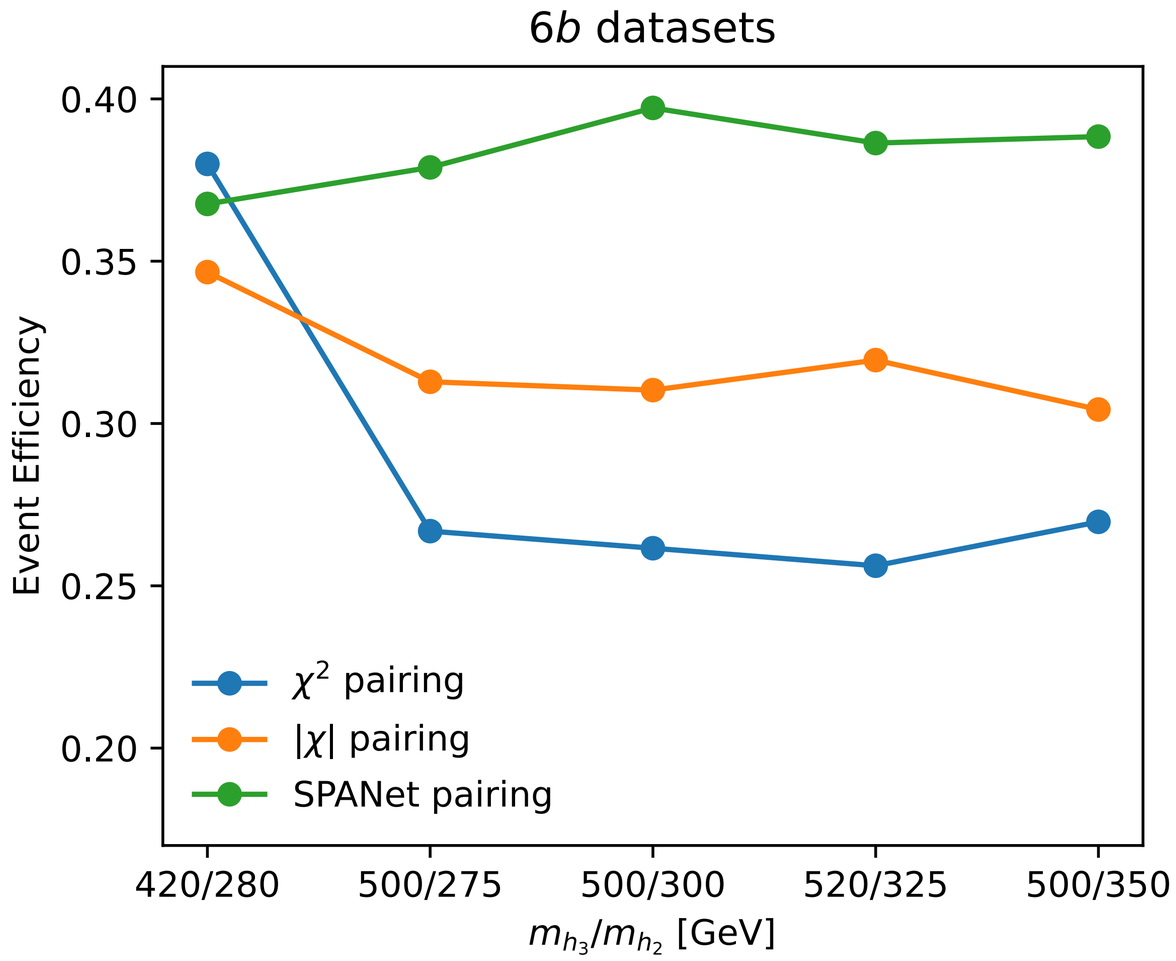
- Train on a large-statistics 4*b* dataset and evaluate on the 6*b* signal region
- The 4*b* and 6*b* samples are completely disjoint and statistically independent



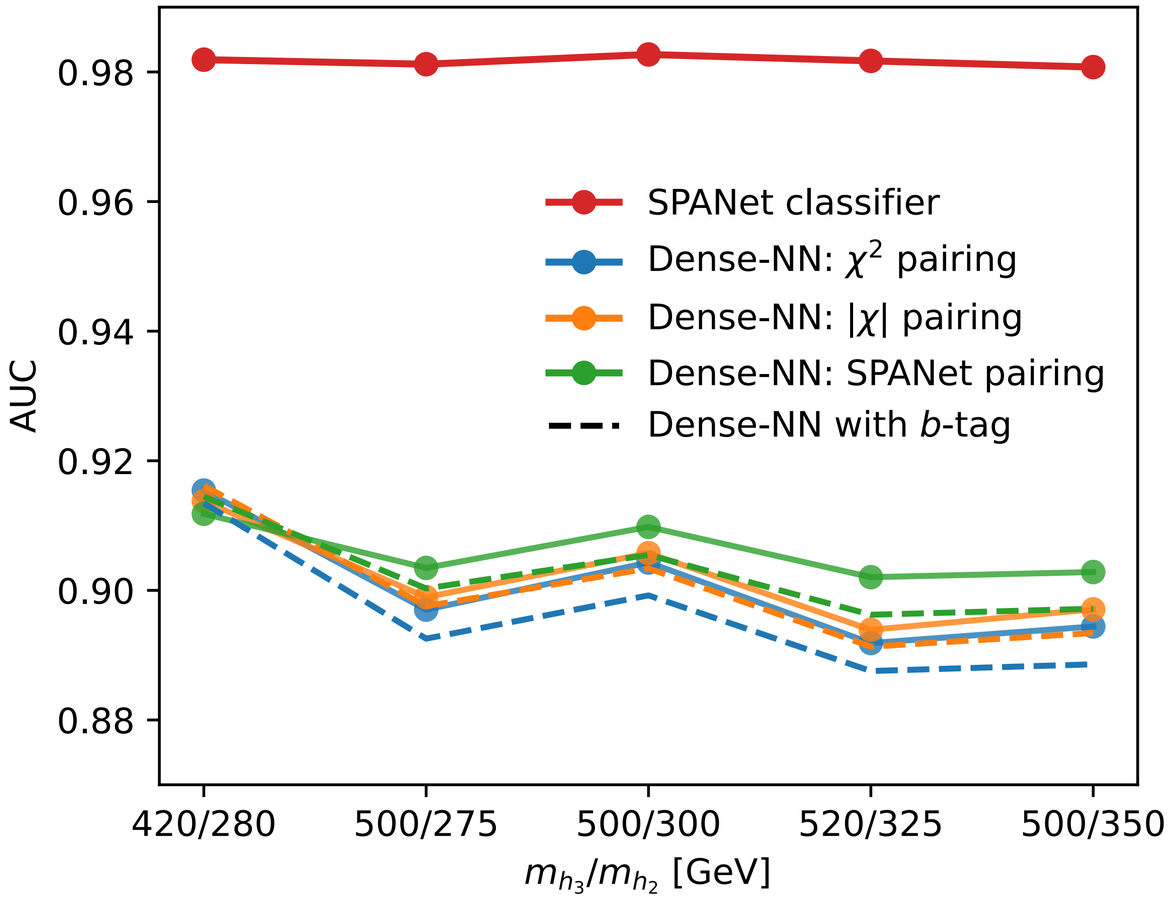
RESULTS

TRI-HIGGS PAIRING EFFICIENCY

- SPA-NET achieves higher pairing efficiency across most benchmarks
- SPA-NET effectively resolves multi-jet combinatorics in high-mass decays



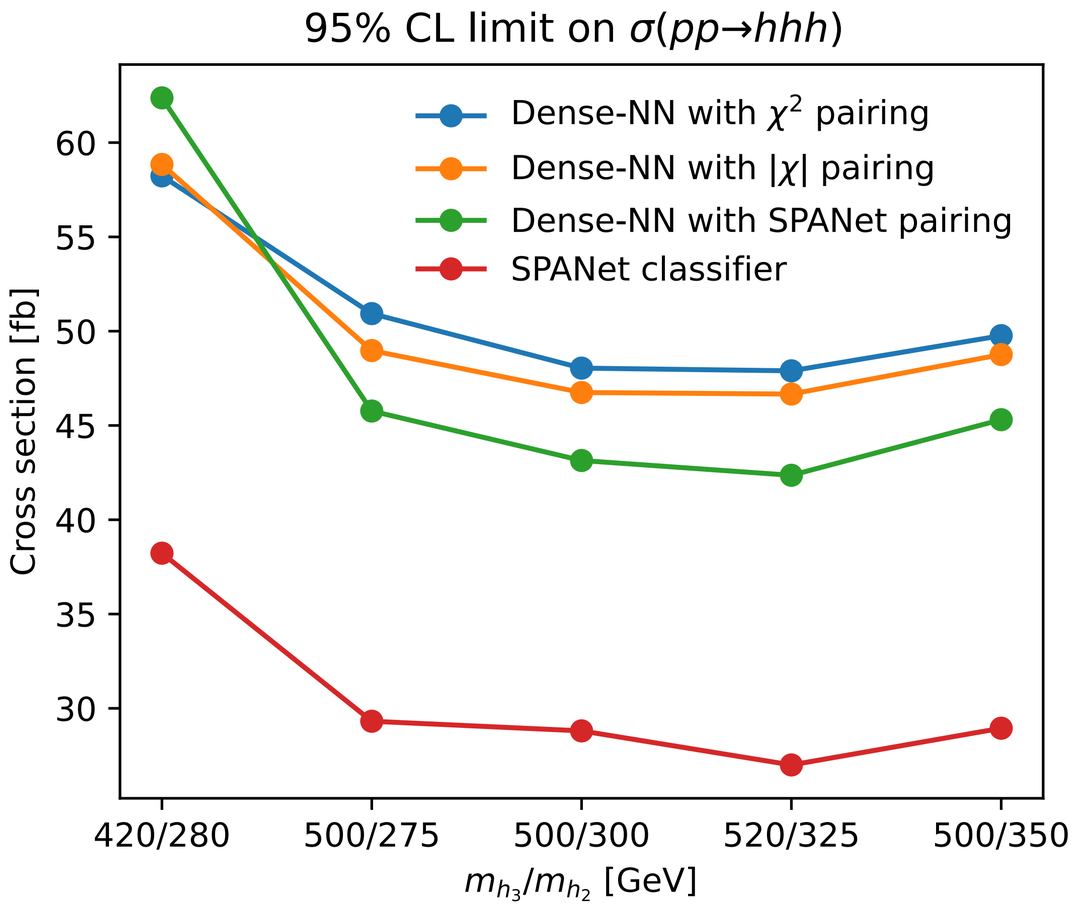
TRI-HIGGS CLASSIFICATION



- Dense-NN baseline classifiers achieve AUC around 0.89–0.92
- SPA-NET classifier consistently achieves AUC > 0.98 across all benchmark points
- SPA-NET effectively suppresses QCD multi-jet background

TRI-HIGGS CONSTRAINTS

- Evaluated at 14 TeV and L = 300 fb^{-1}
- SPA-NET improves cross-section upper limits by up to 40% relative to Dense-NN workflows
- Consistent ~ 40% improvement is also maintained under L = 3000 fb^{-1}
- SPA-NET architectures can unlock significant potential in tri-Higgs searches



SUMMARY

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- SPA-NET is designed to incorporate permutation symmetry and can be trained on the pairing and classification tasks simultaneously
- SPA-NET outperforms Dense-NN in separating signal from background
- SPA-NET workflow provides the strongest cross-section upper limits, demonstrating its ability to exploit complex event structures and enhance analysis sensitivity
- These works demonstrate the remarkable potential of SPA-NET in tri-Higgs analysis. Its superior performance in both jet pairing and classification tasks holds significant promise for enhancing physics research