Does equivariance make better models?

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BOOST 2024, Genova, Italy

Fundamental Science models

Minimally parametrized
Interpretable
Generalizable

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Overparametrized
Black box
Limited generalization

Machine Learning models

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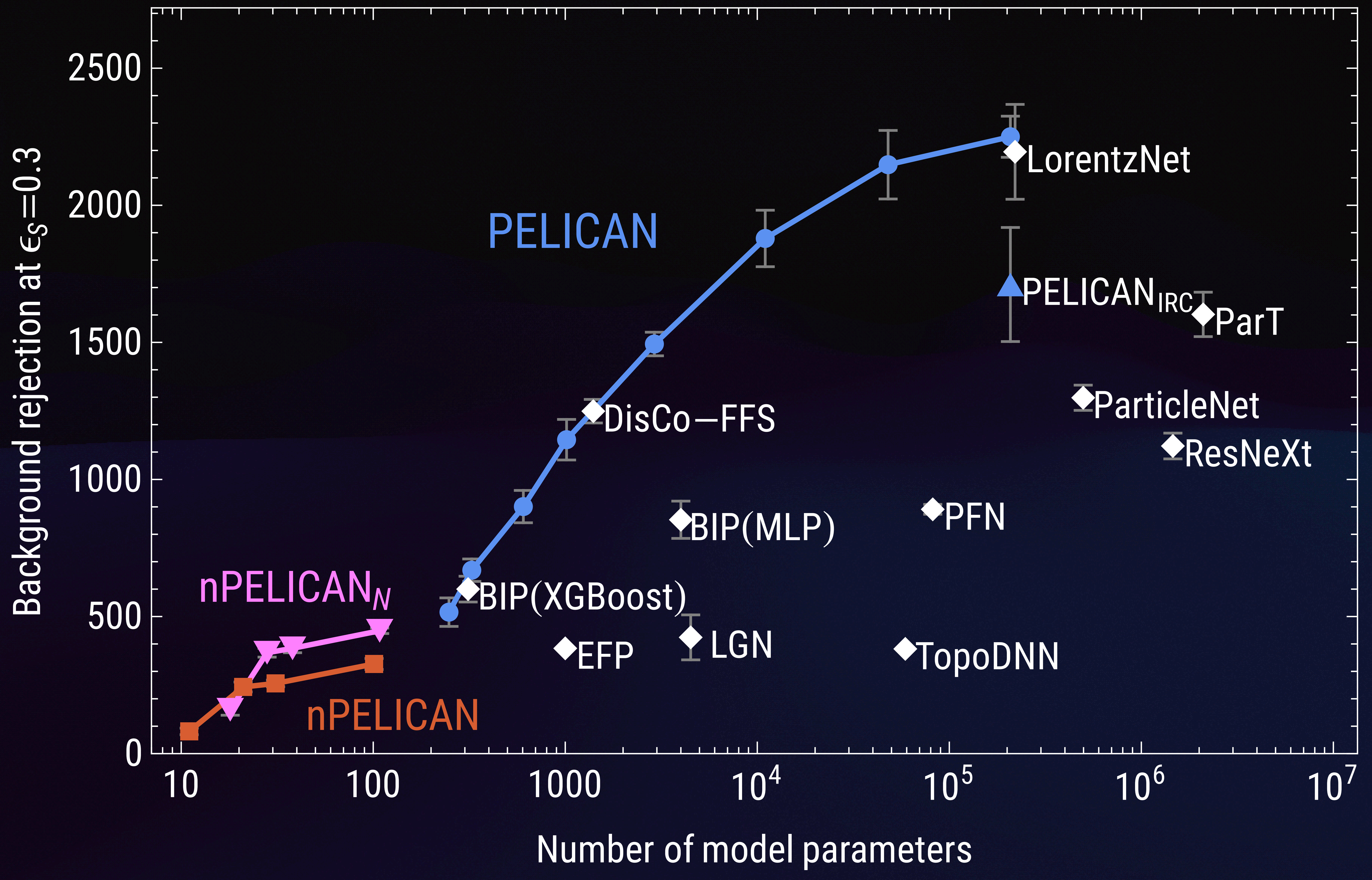
Comparison of top-taggers (binary classification of jets)



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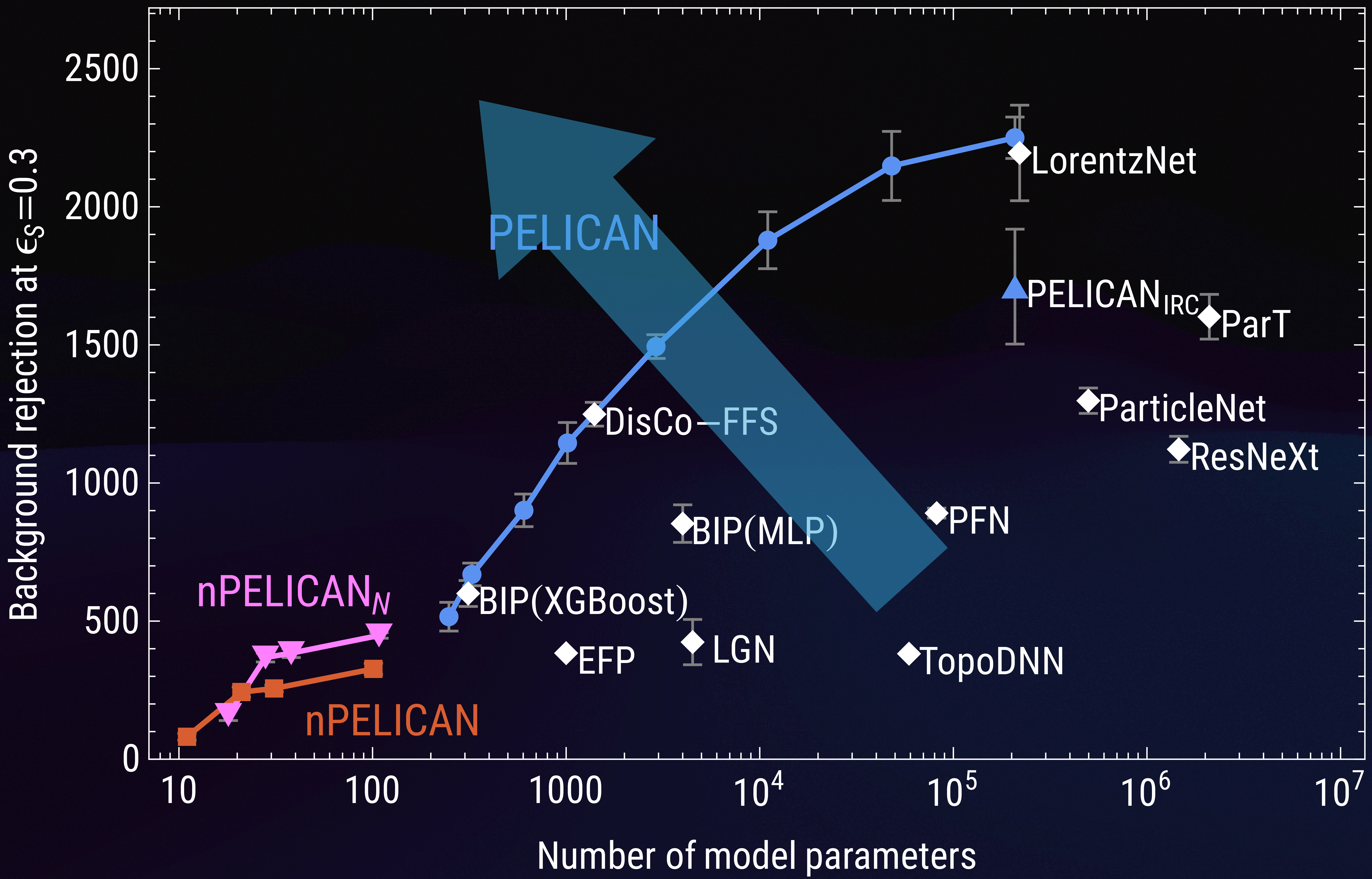

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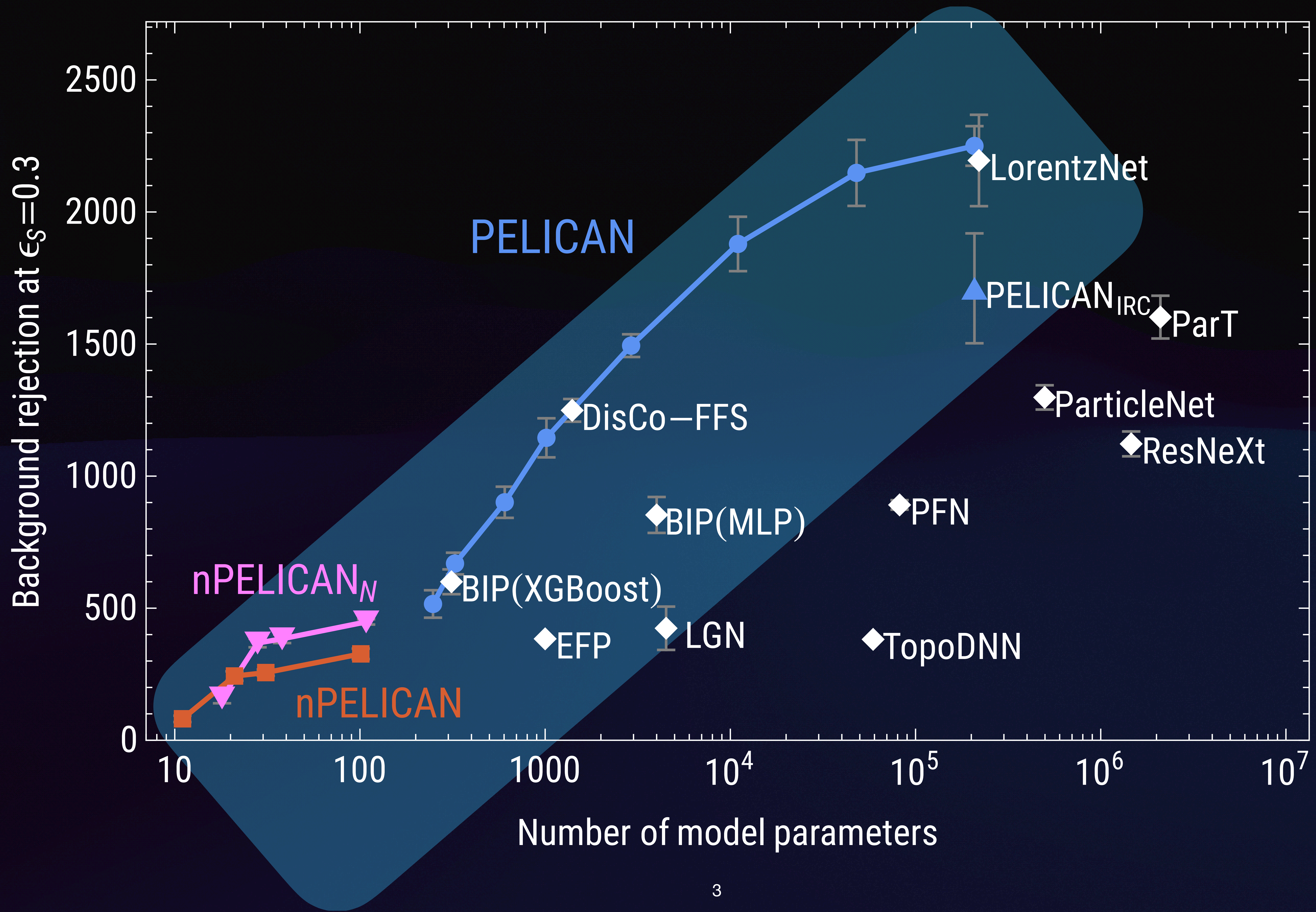

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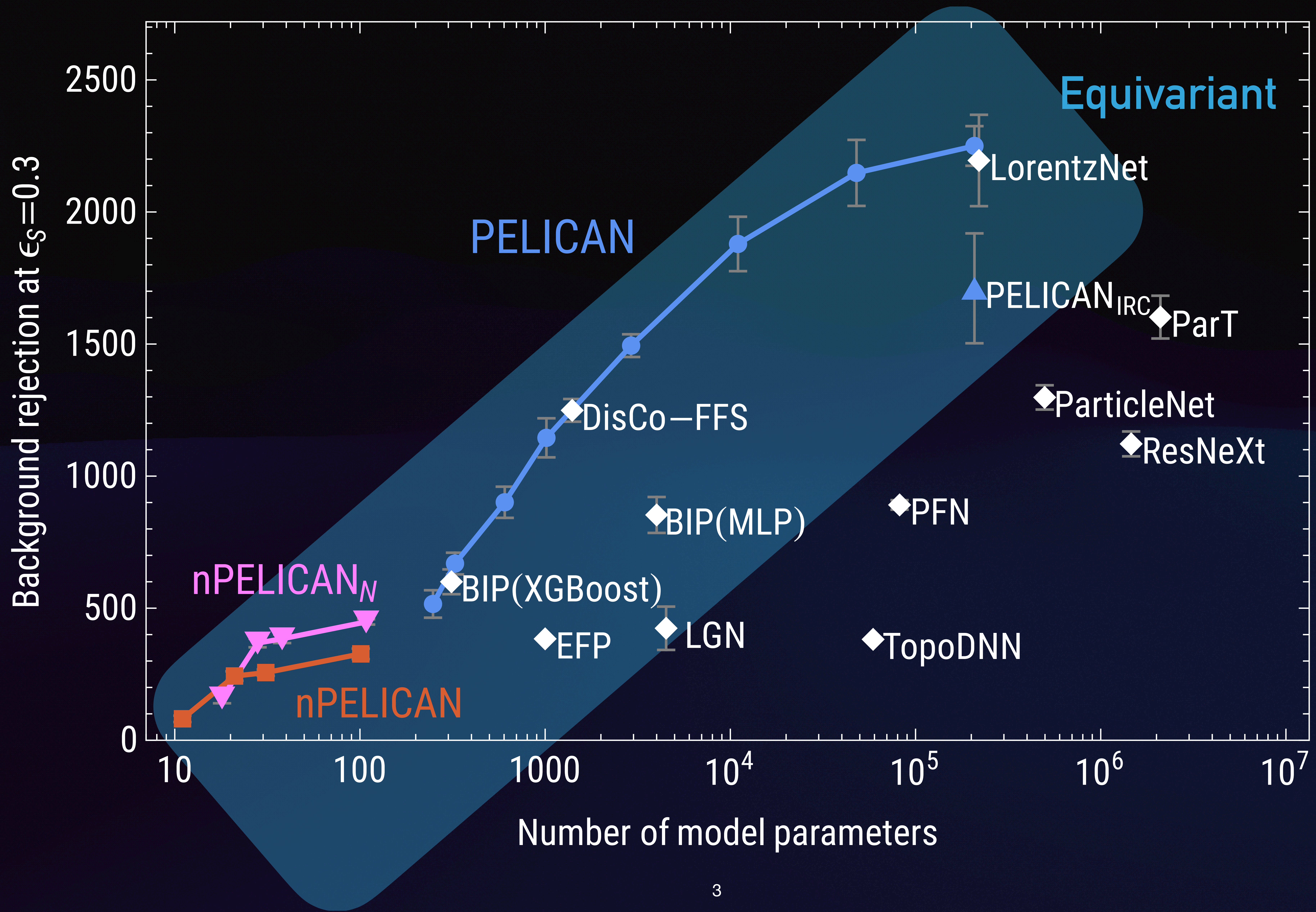
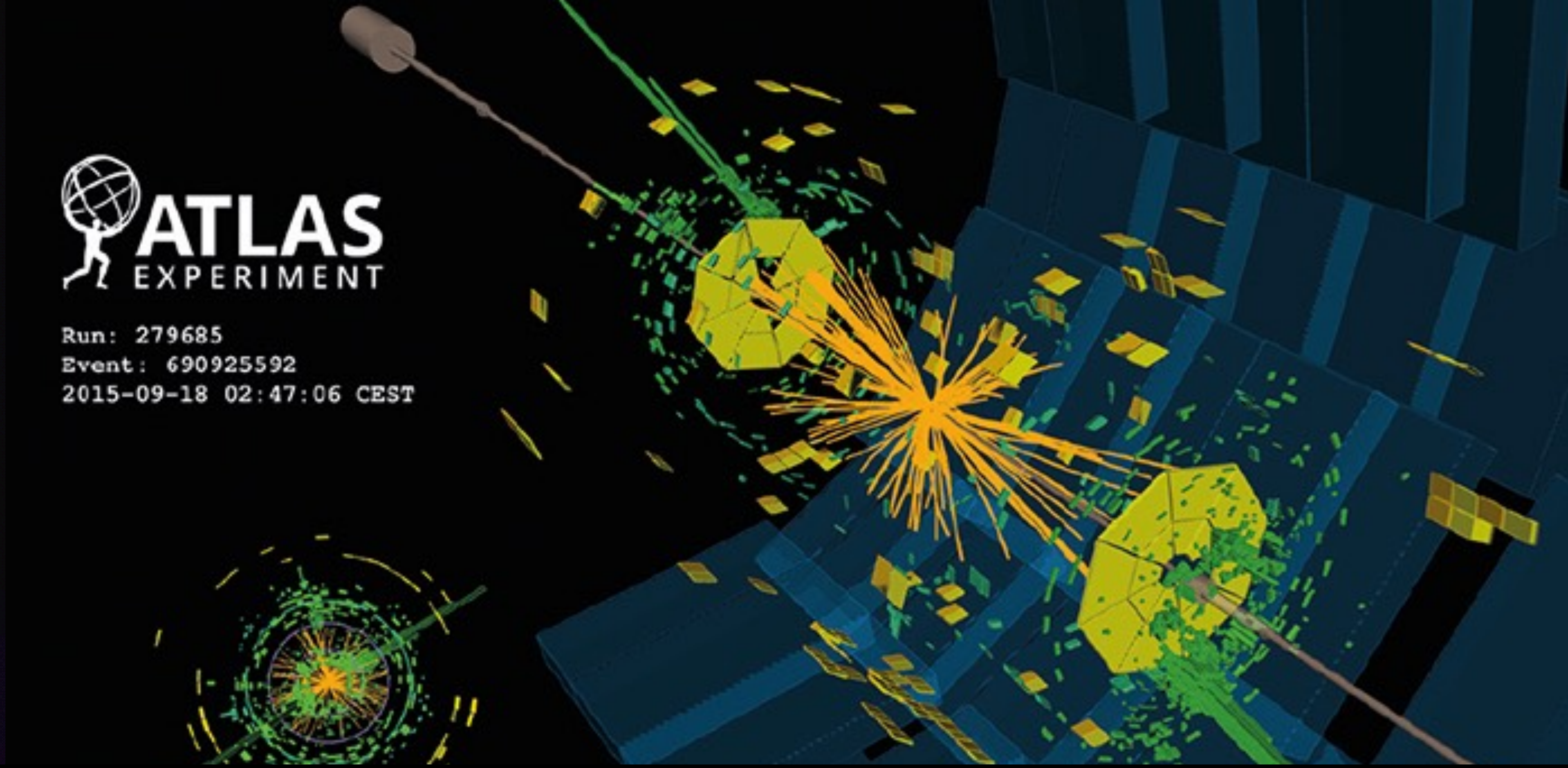
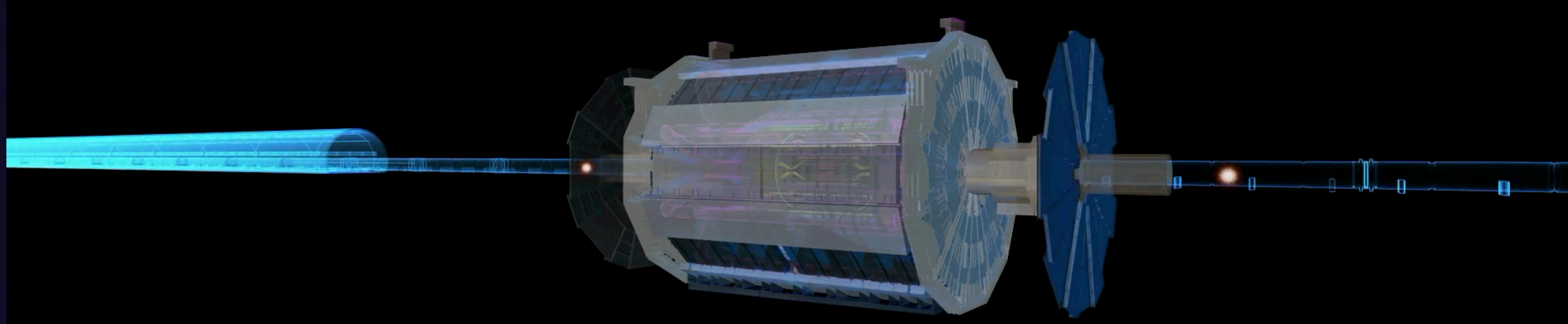


Symmetries in jet data





ATLAS Experiment © CERN

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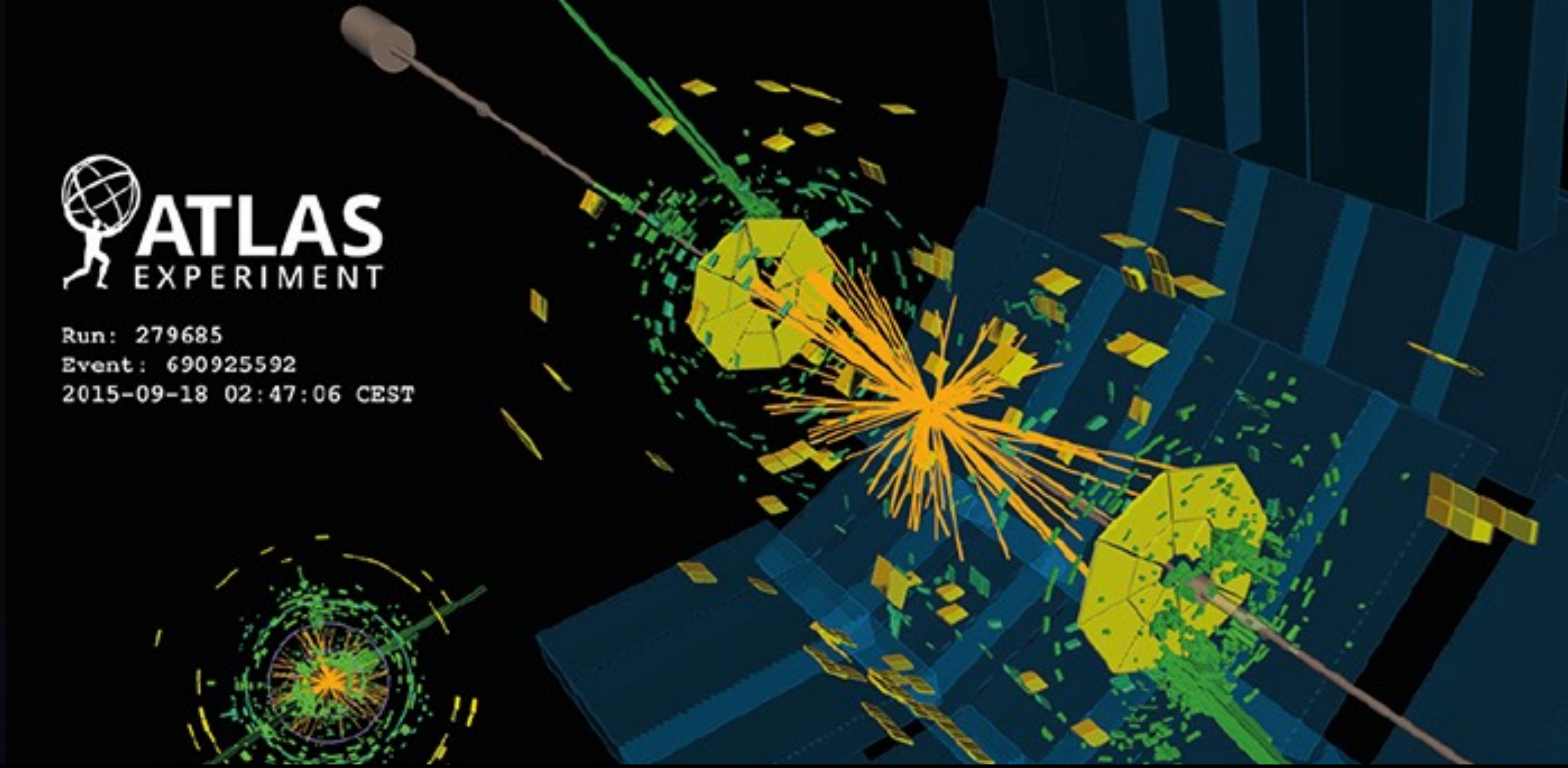

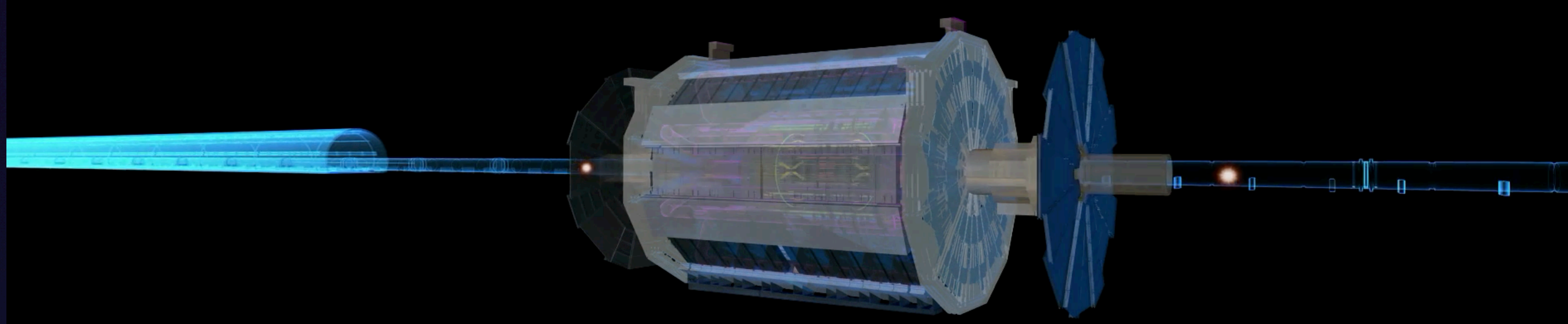

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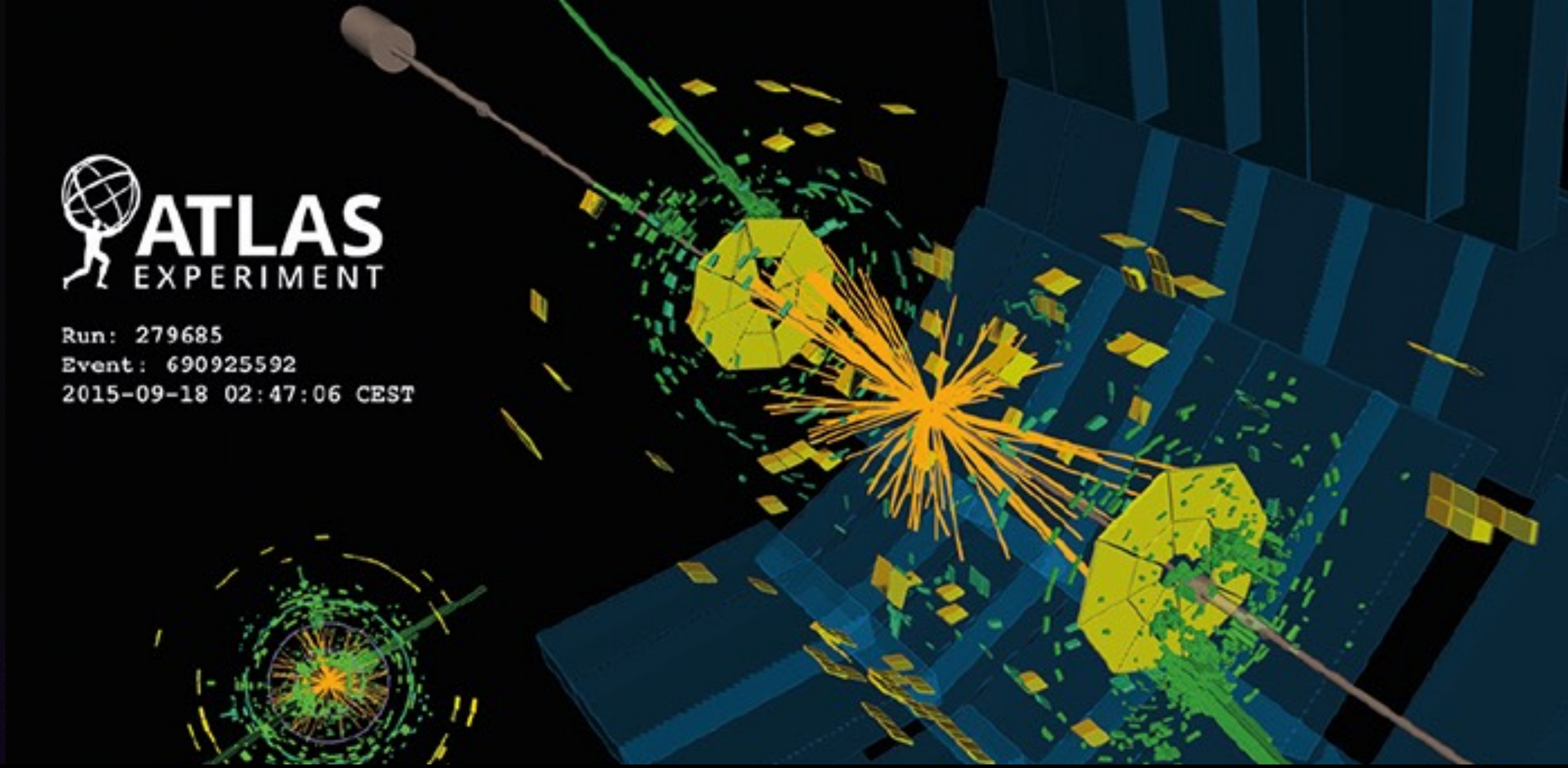
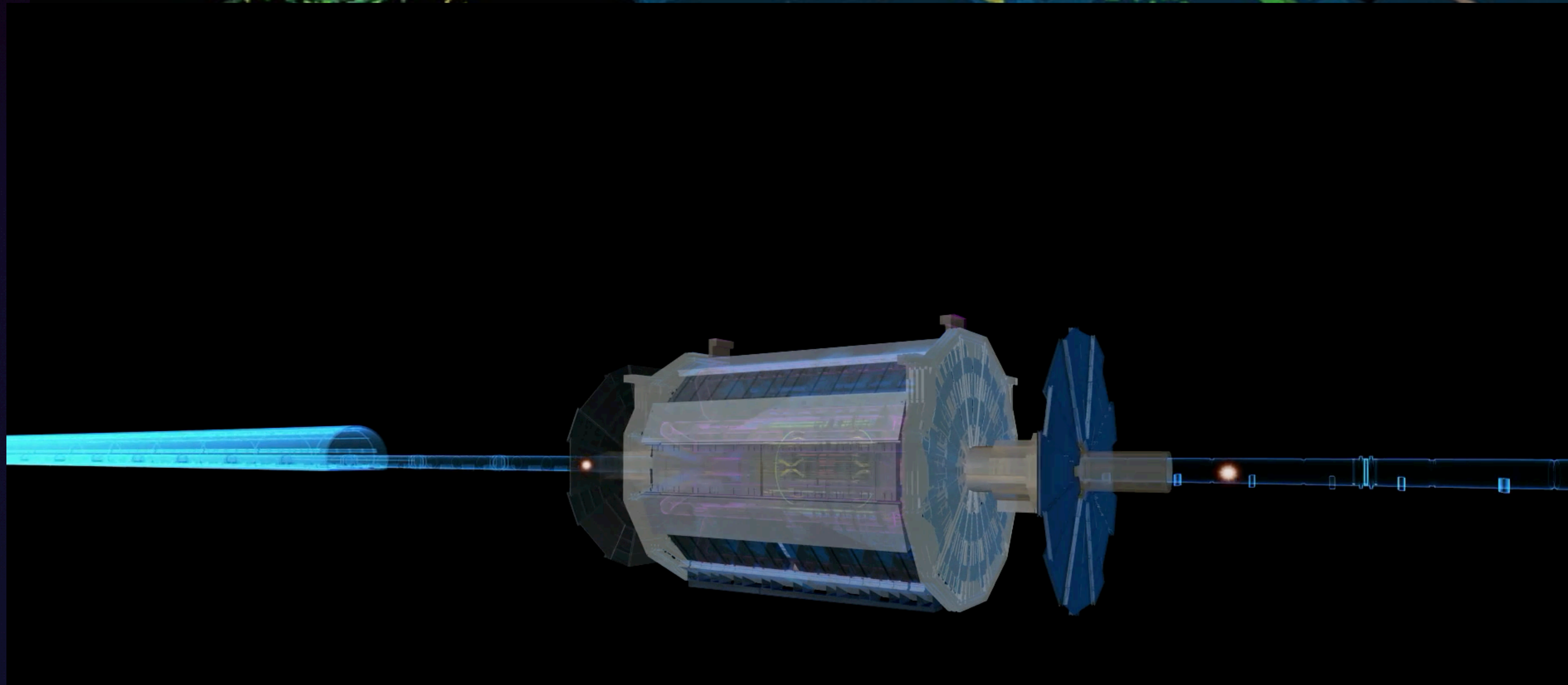
Symmetries in jet data

- Permutations of constituents





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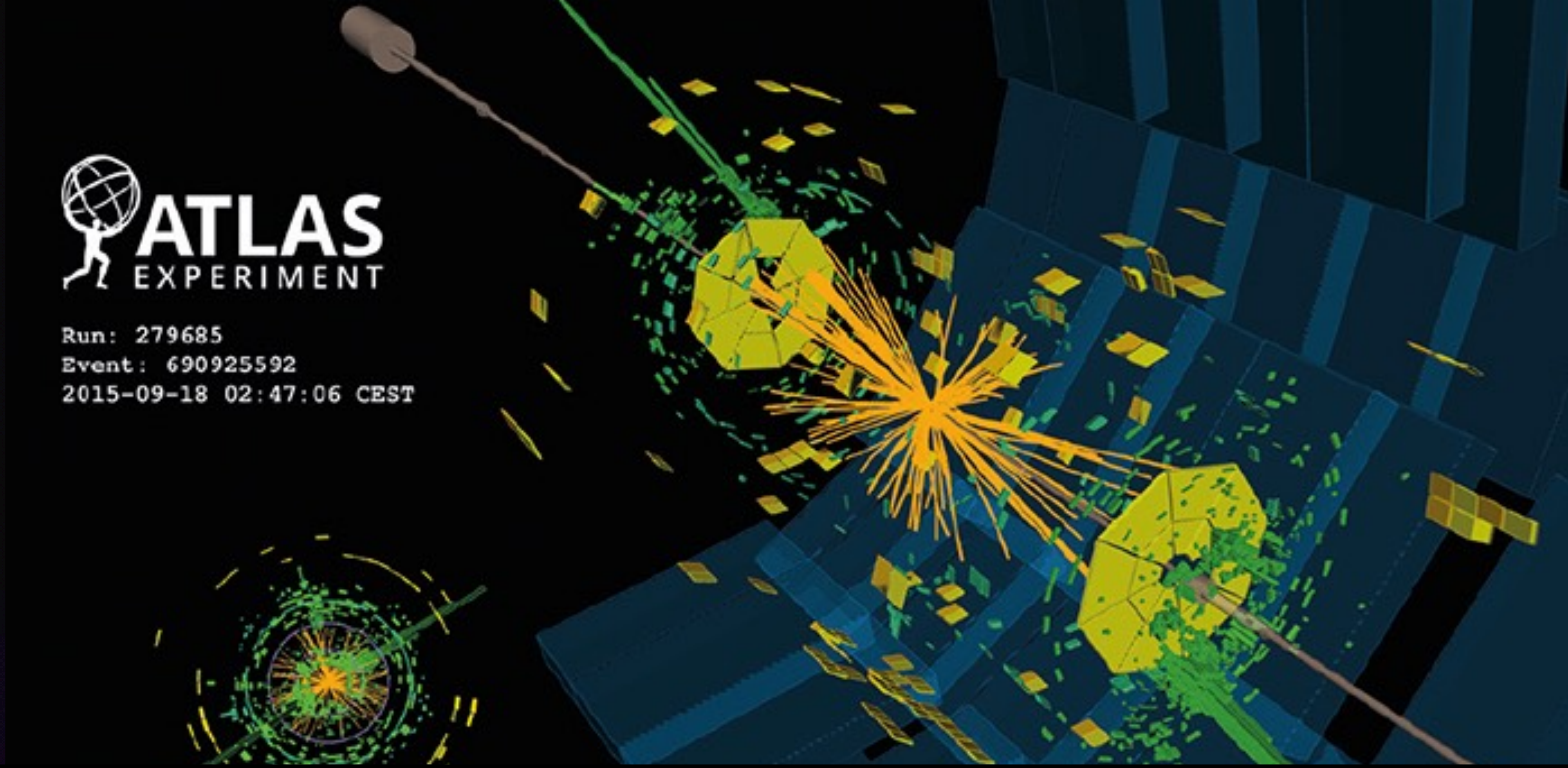
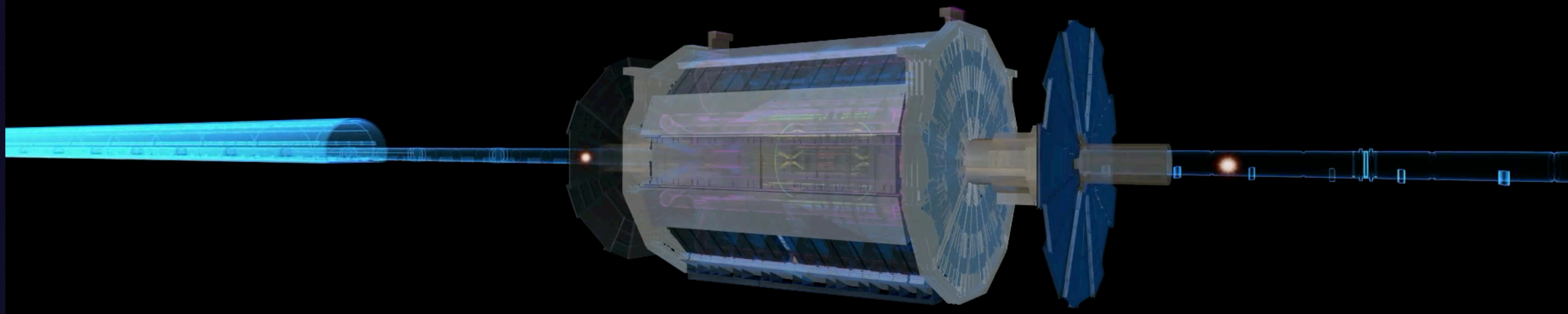


- Permutations of constituents

- Rotational, boost, Lorentz symmetries



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3. Compare to an equivariant model that accesses the same information content in the data.

To isolate effects of equivariance:

High Energy Physics – Phenomenology

[Submitted on 16 Aug 2022 (v1), last revised 7 Mar 2024 (this version, v3)]

Does Lorentz-symmetric design boost network performance in jet physics?

Congqiao Li, Huilin Qu, Sitian Qian, Qi Meng, Shiqi Gong, Jue Zhang, Tie-Yan Liu, Qiang Li

In the deep learning era, improving the neural network performance in jet physics is a rewarding task as it directly contributes to more accurate physics measurements at the LHC. Recent research has proposed various network designs in consideration of the full Lorentz symmetry, but its benefit is still not systematically asserted, given that there remain many successful networks without taking it into account. We conduct a detailed study on the Lorentz-symmetric design. We

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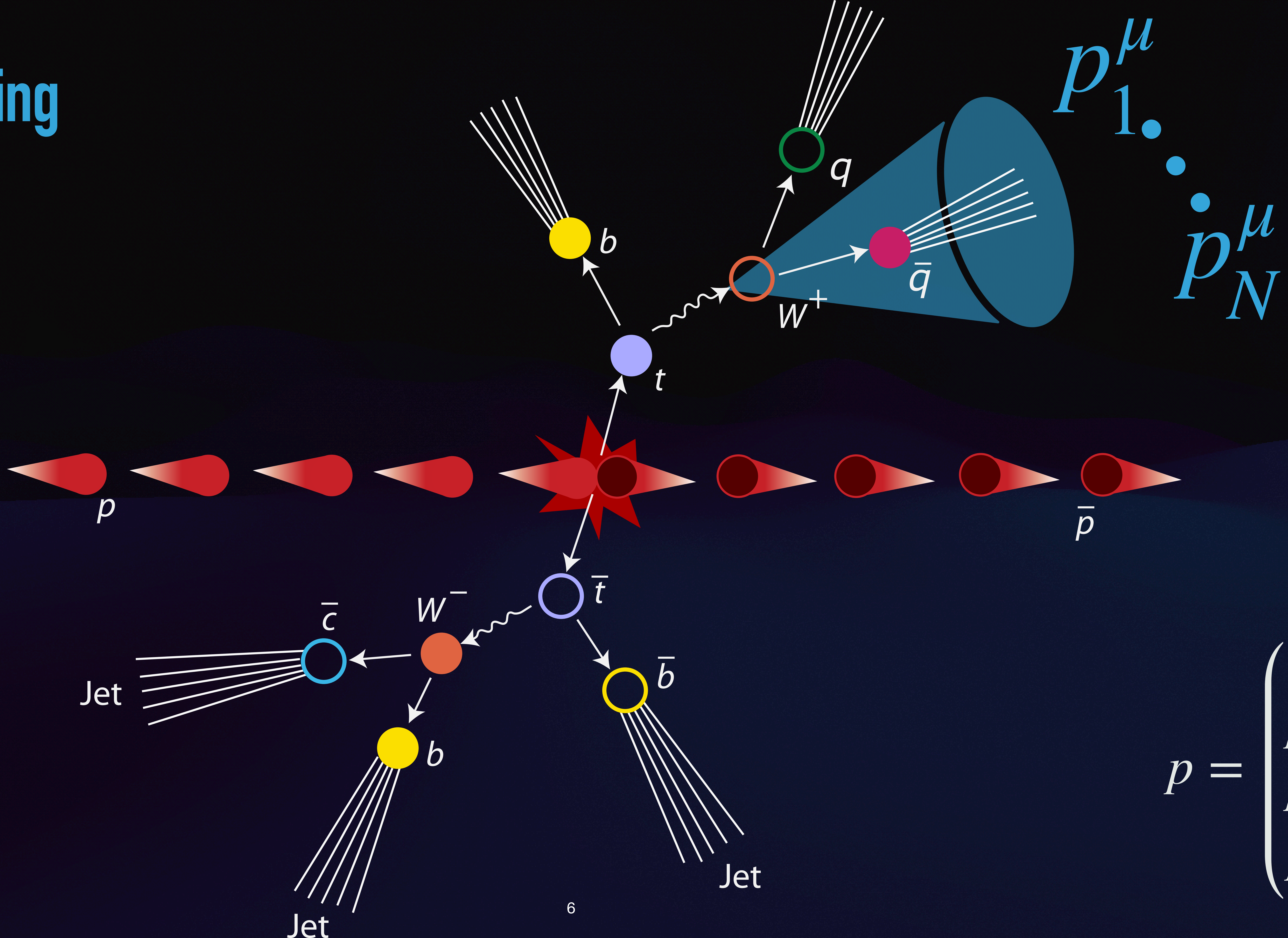
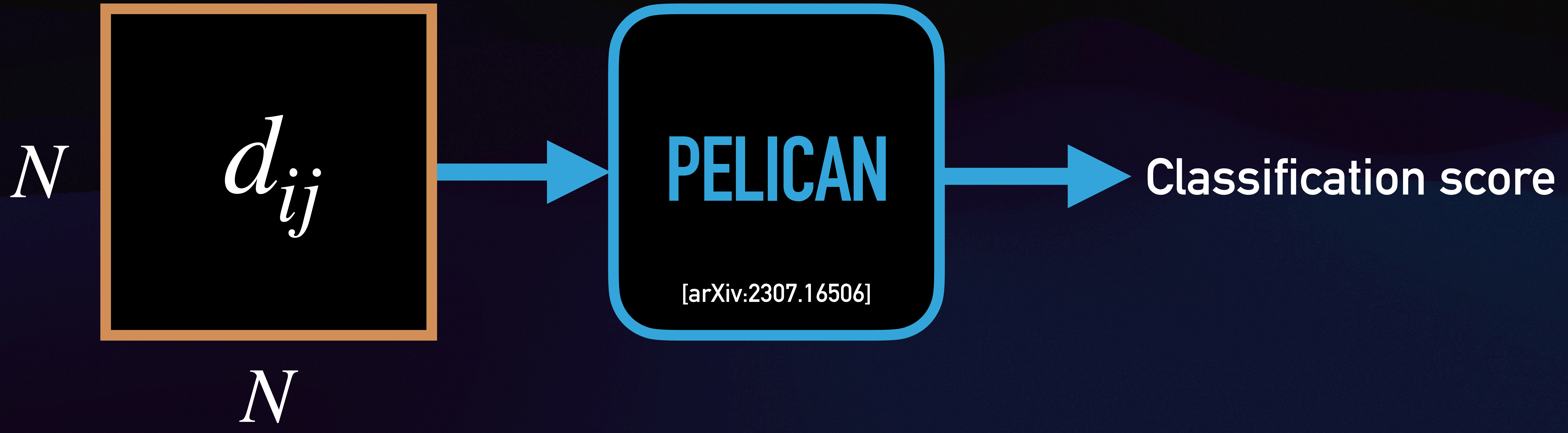
Jet tagging



$$p = \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

PELICAN

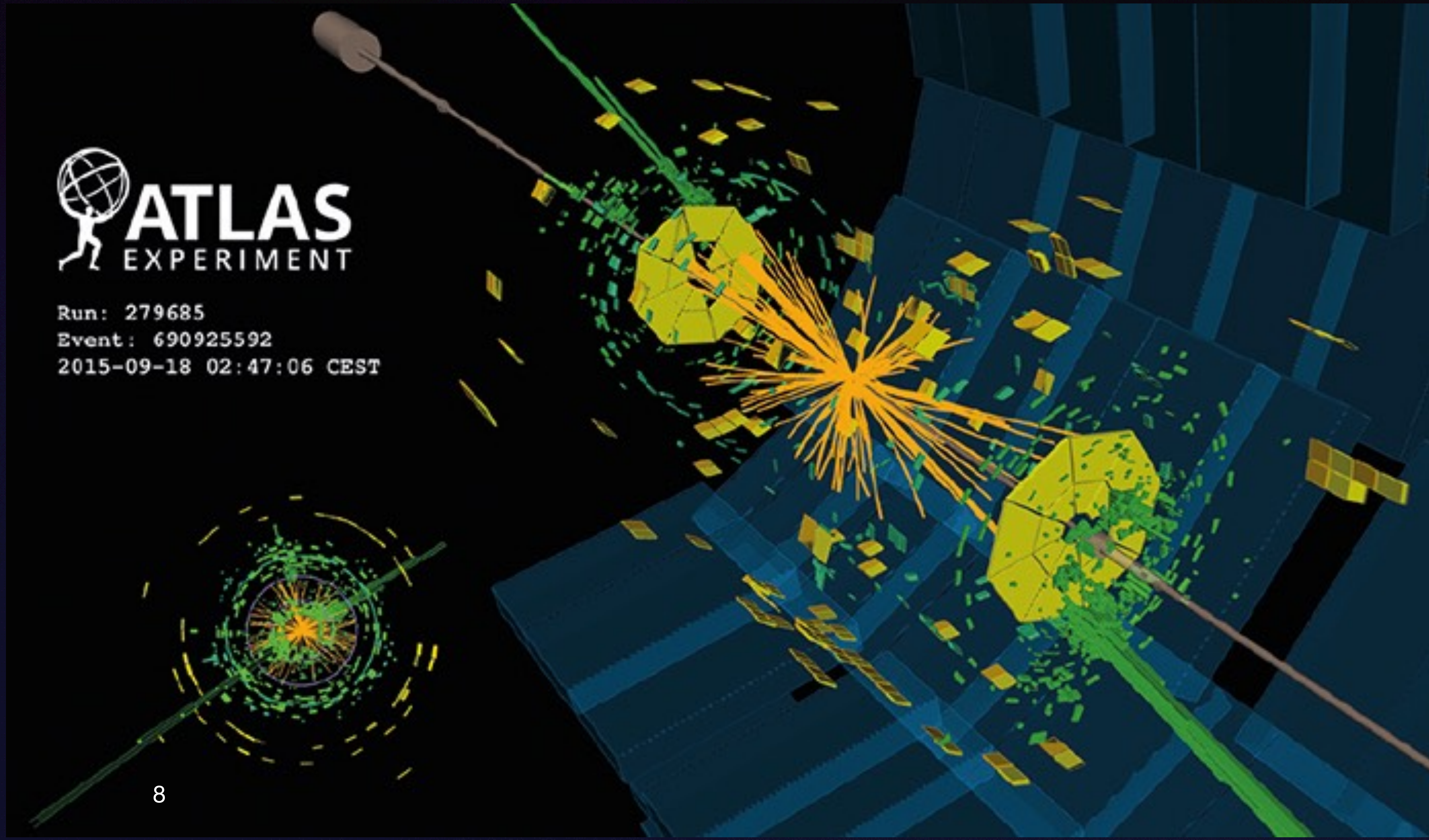
Inputs: $d_{ij} = p_i \cdot p_j = E_i E_j - \vec{p}_i \cdot \vec{p}_j$



Invariant w.r.t. the Lorentz group $\mathrm{SO}^+_{1,3}$

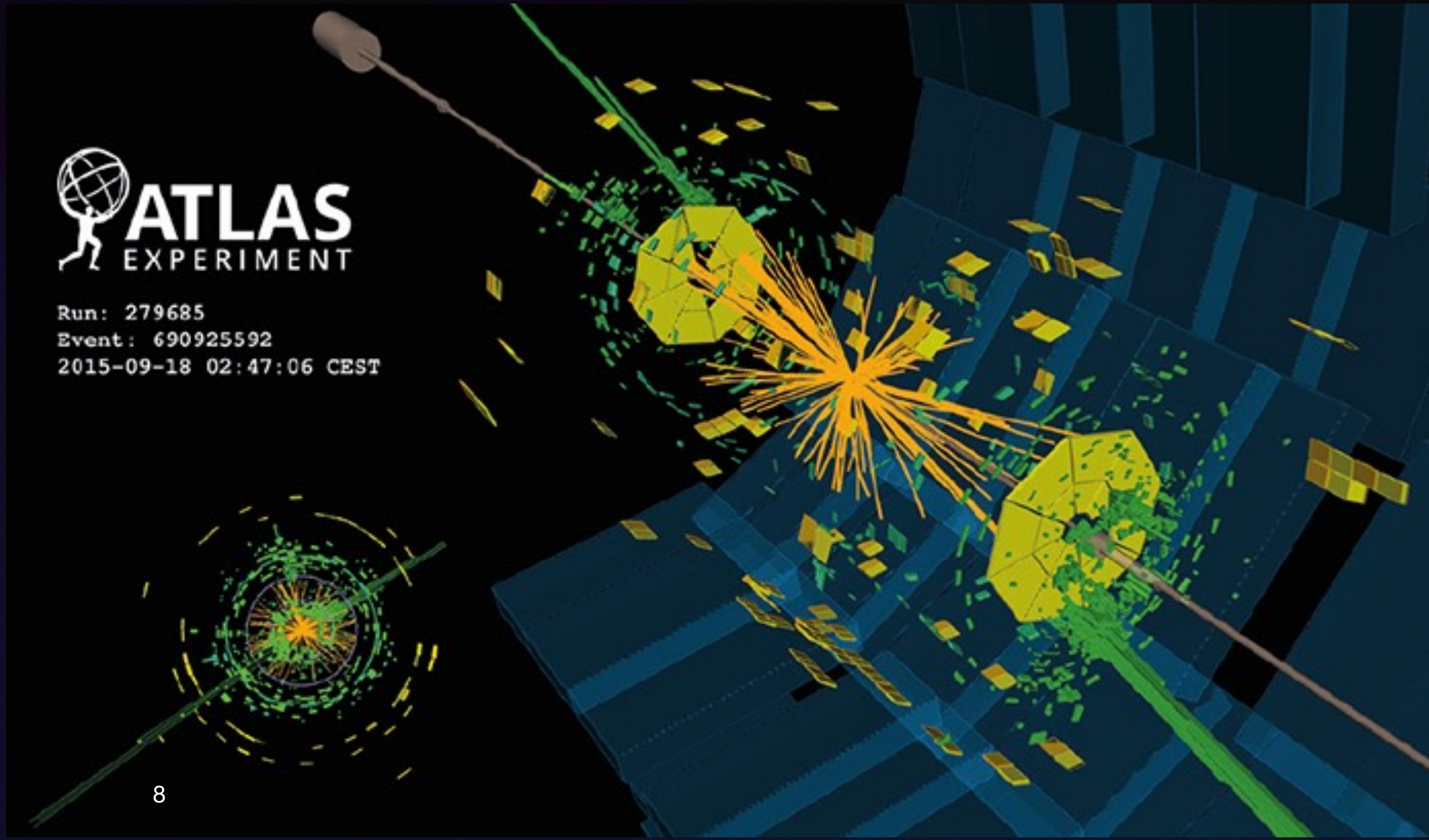
State-of-the-art across multiple tagging and regression tasks

What information is “not invariant”?



What information is "not invariant"?

1. Detector orientation: the z-axis is special. Explicit dependence on E, p_z.



What information is "not invariant"?

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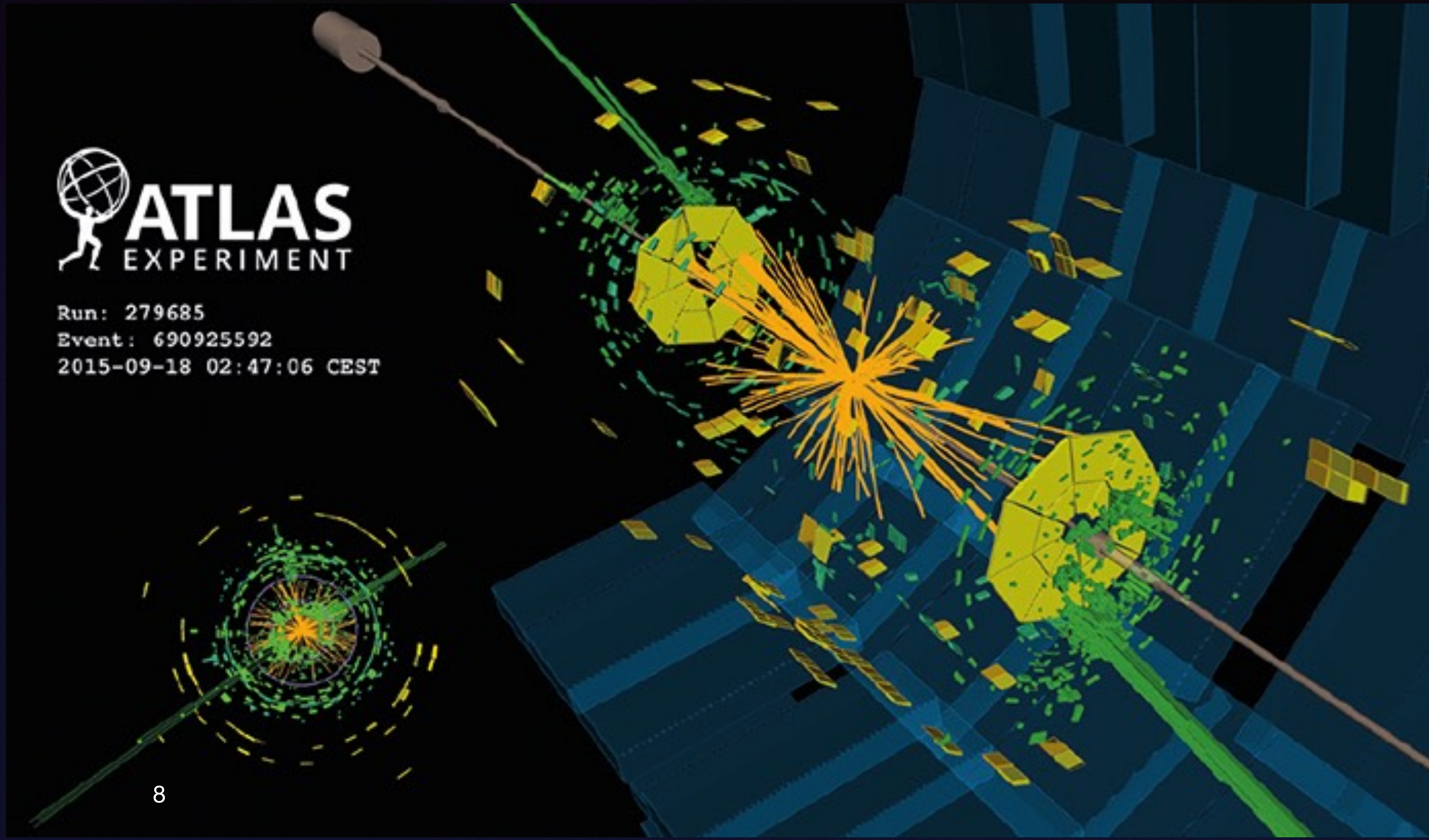
2. Finite resolution introduces potential non-isotropy w.r.t. φ-rotations.



Two methods

Promote non-invariant data to an input of an invariant architecture

"Spurion method"

(thanks to Jesse Thaler)

Add non-invariant data as a direct "scalar" input

"Input method"

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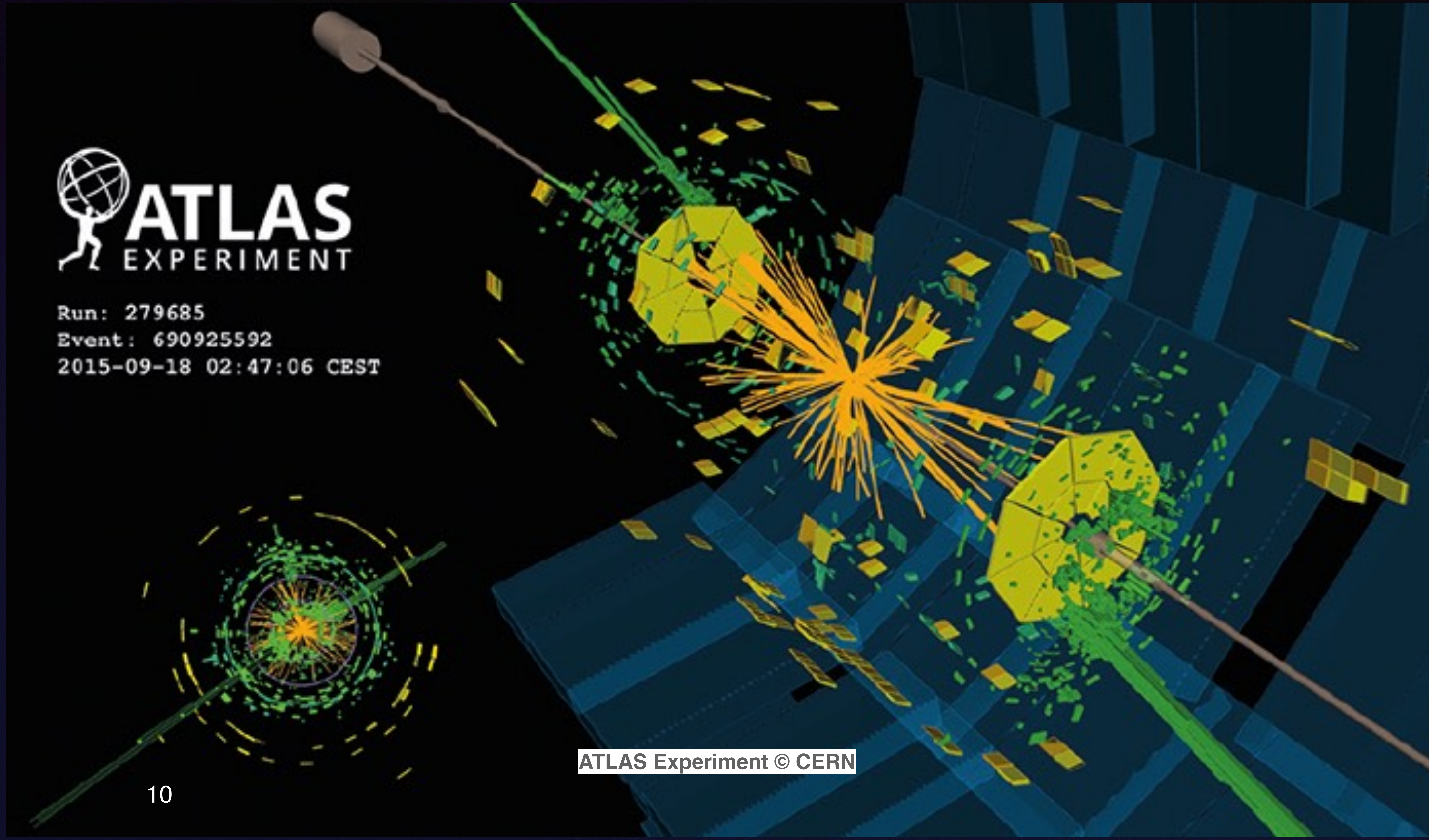
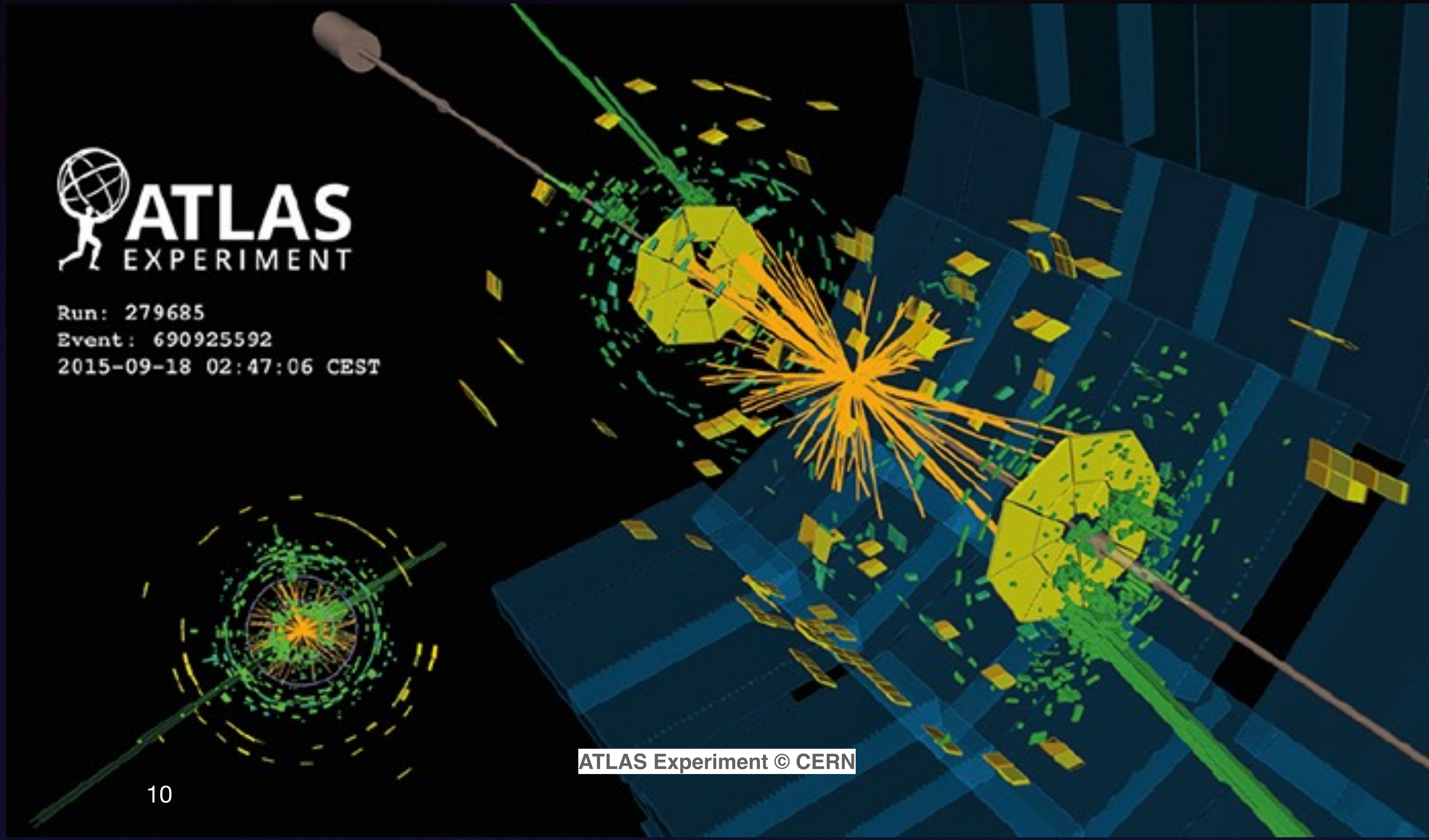
If the spurion method produces better models, equivariance can be claimed to be a source of a performance boost.

Workaround: spurions



Workaround: spurions

1. Treat detector geometry as part of input



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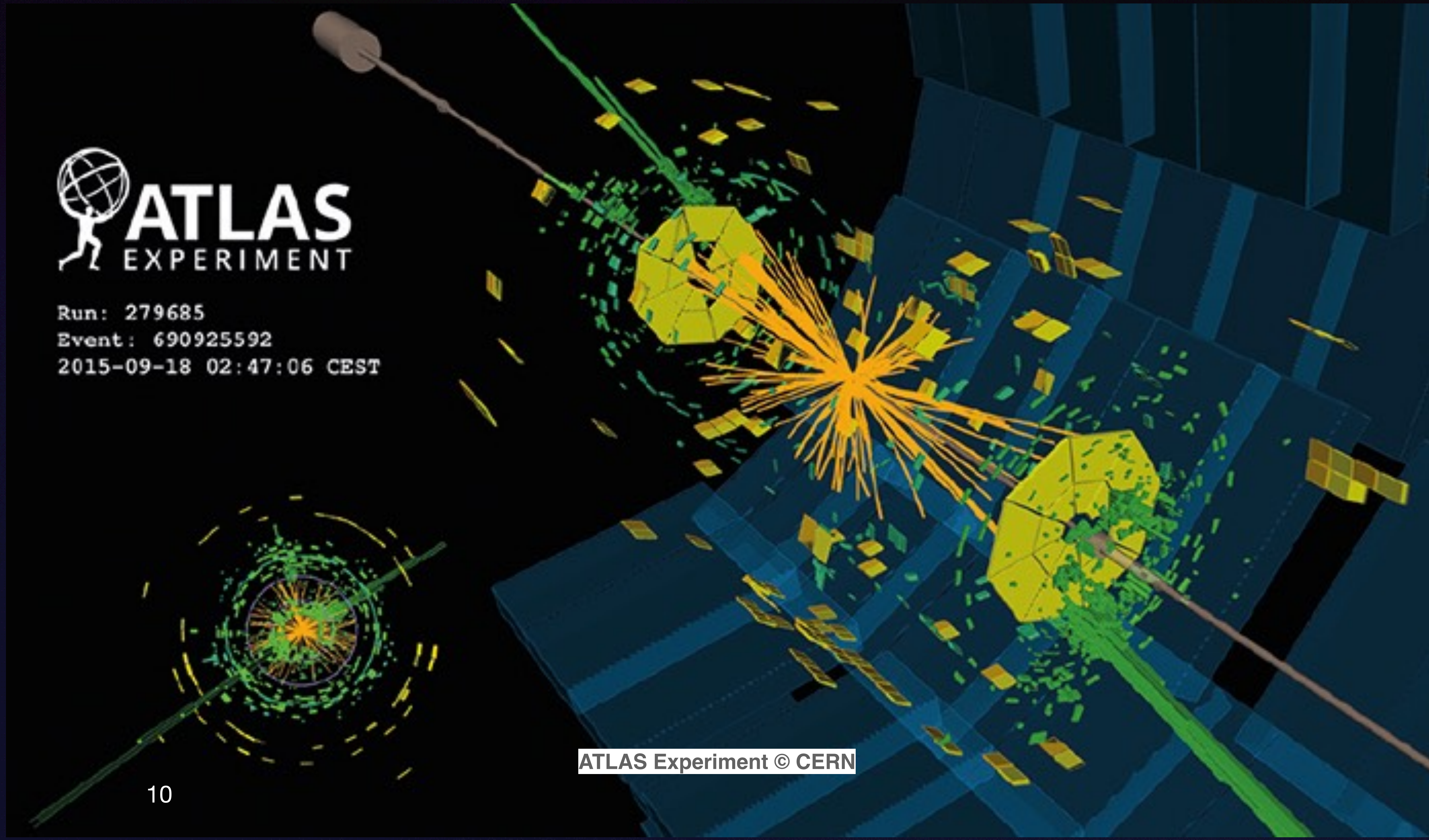

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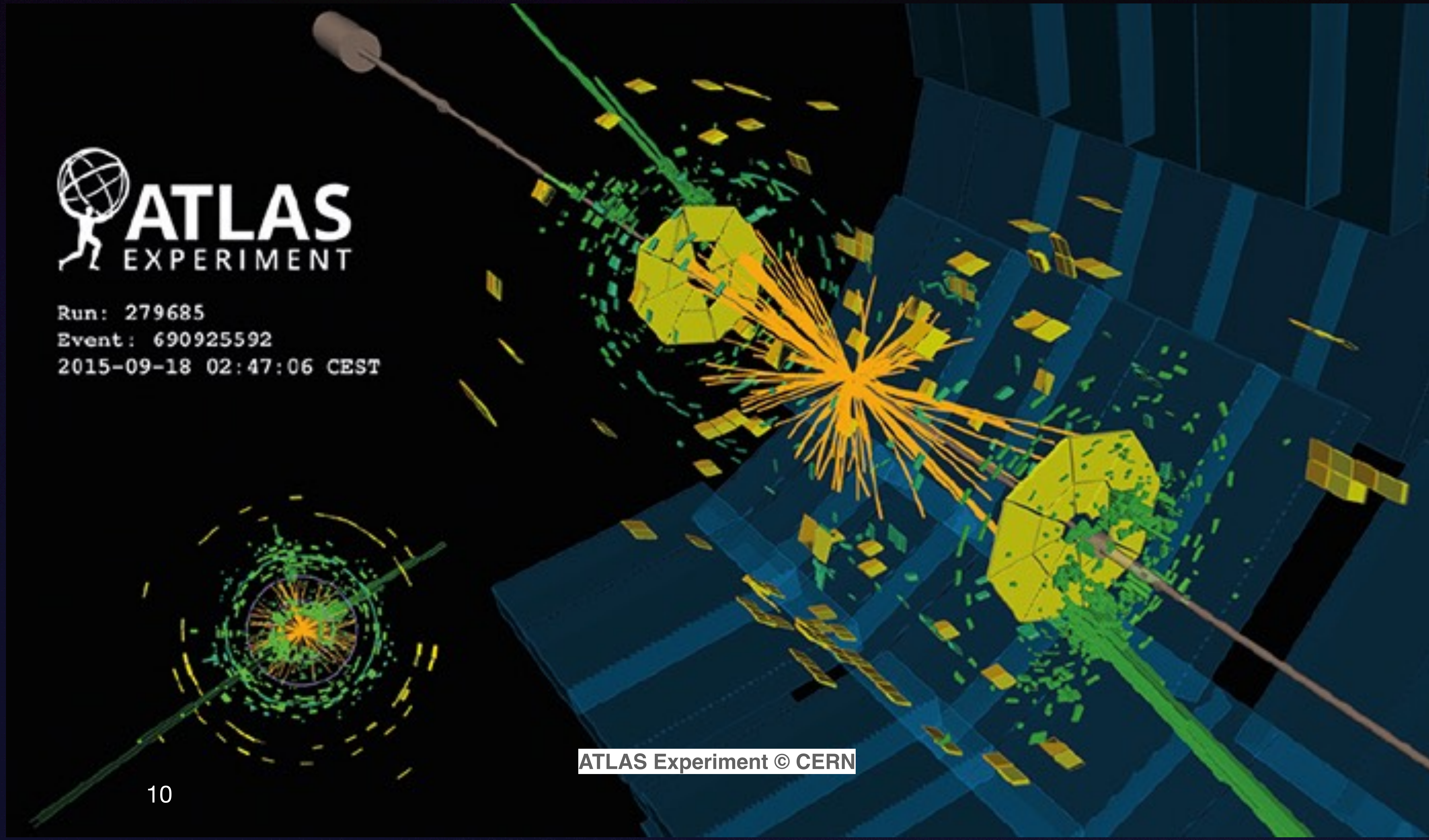

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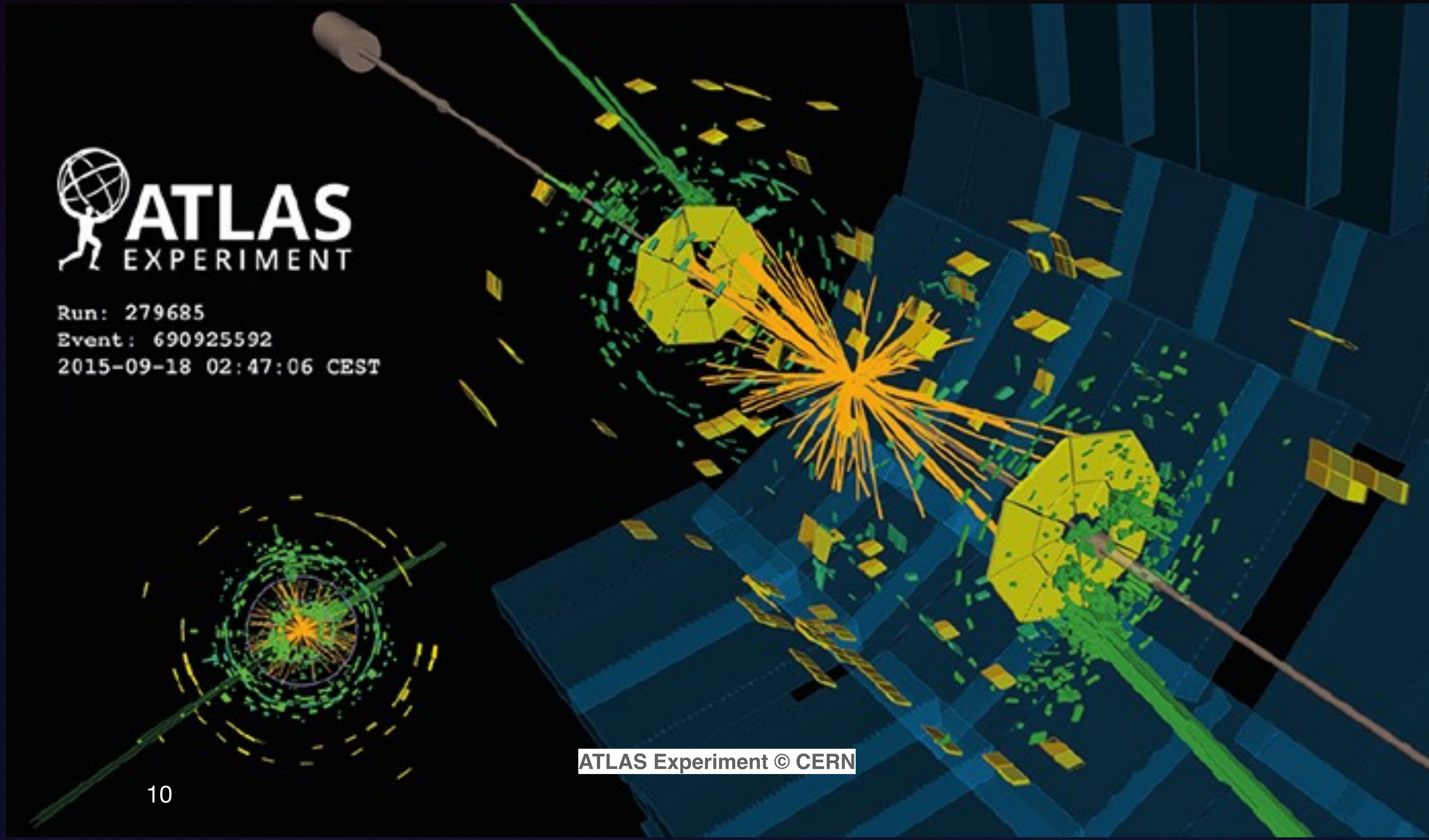
Global Lorentz is preserved, while on the jet only SO_2 remains.



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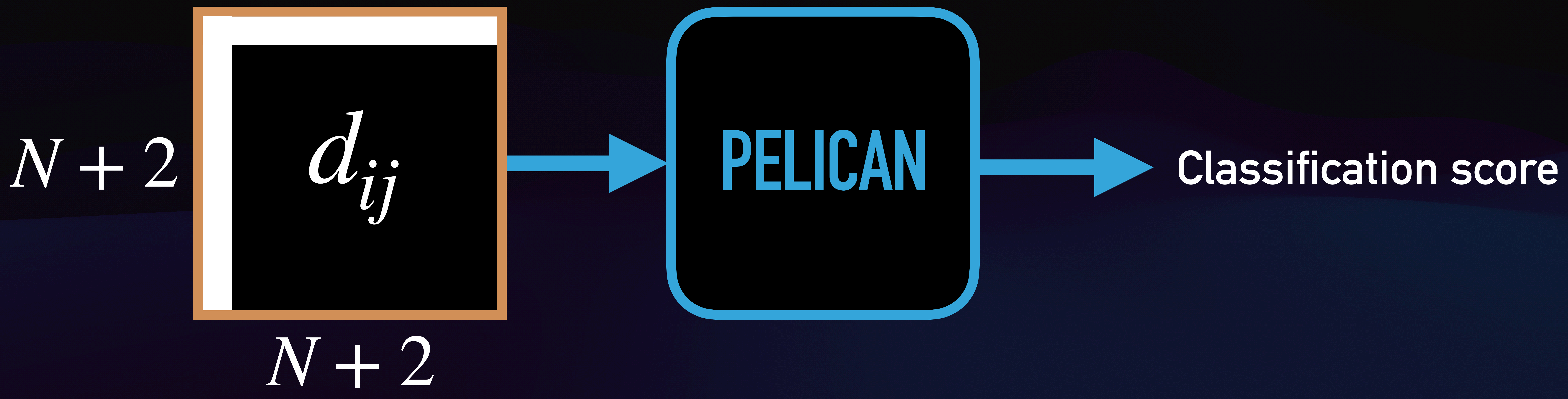

The architecture remains exactly the same and globally Lorentz invariant!

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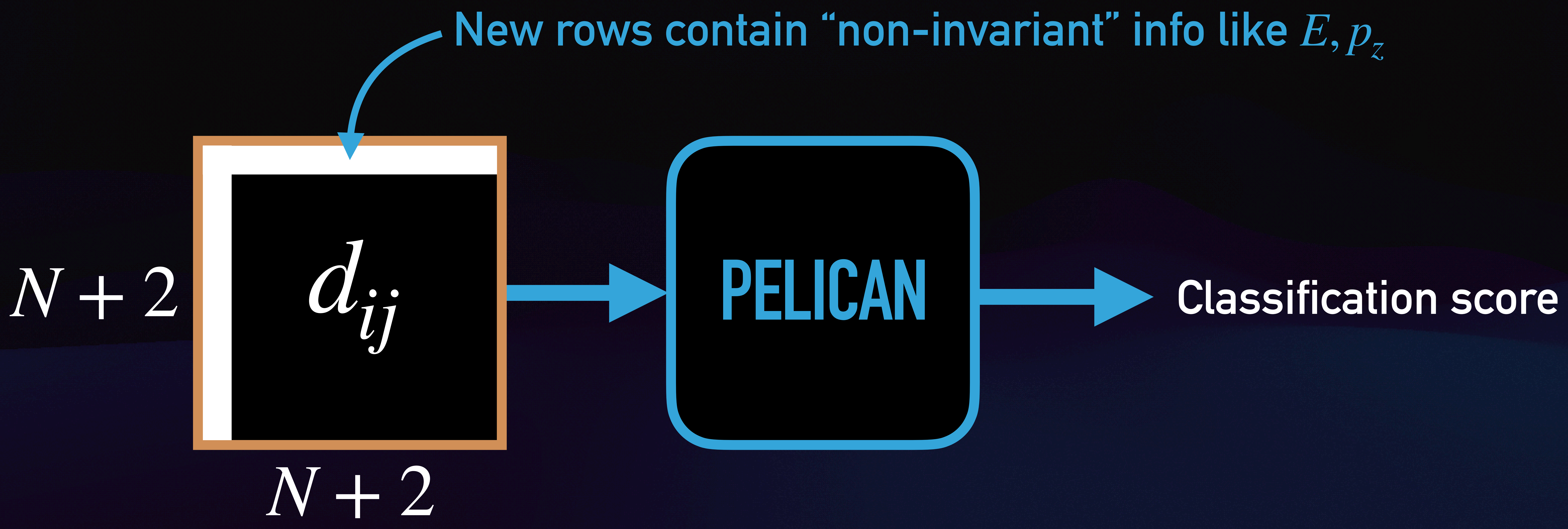

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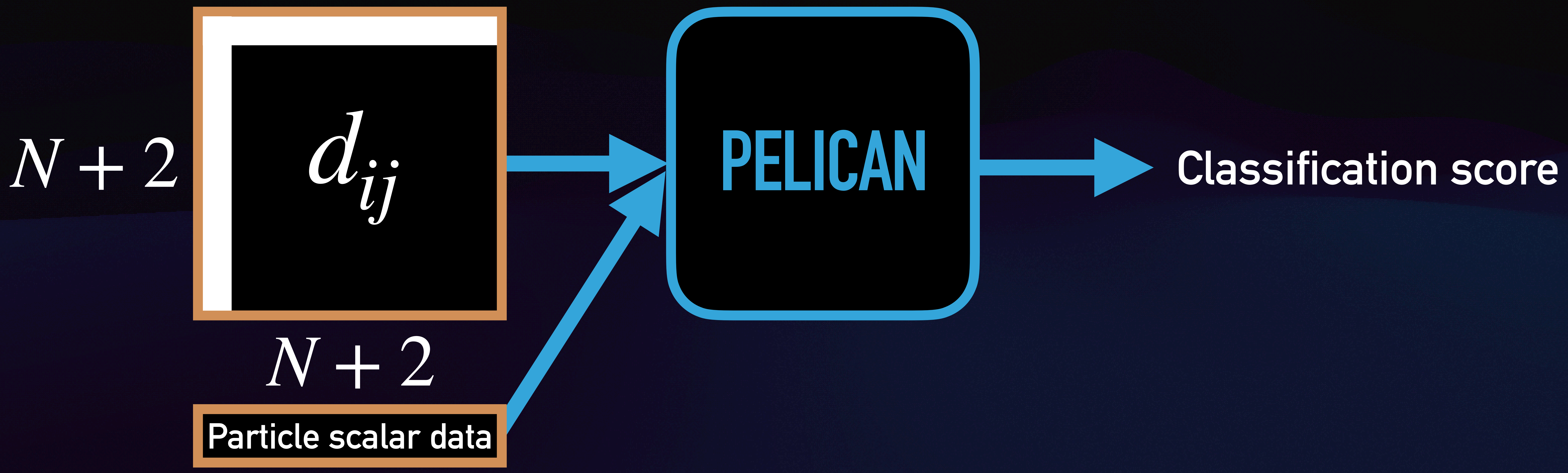

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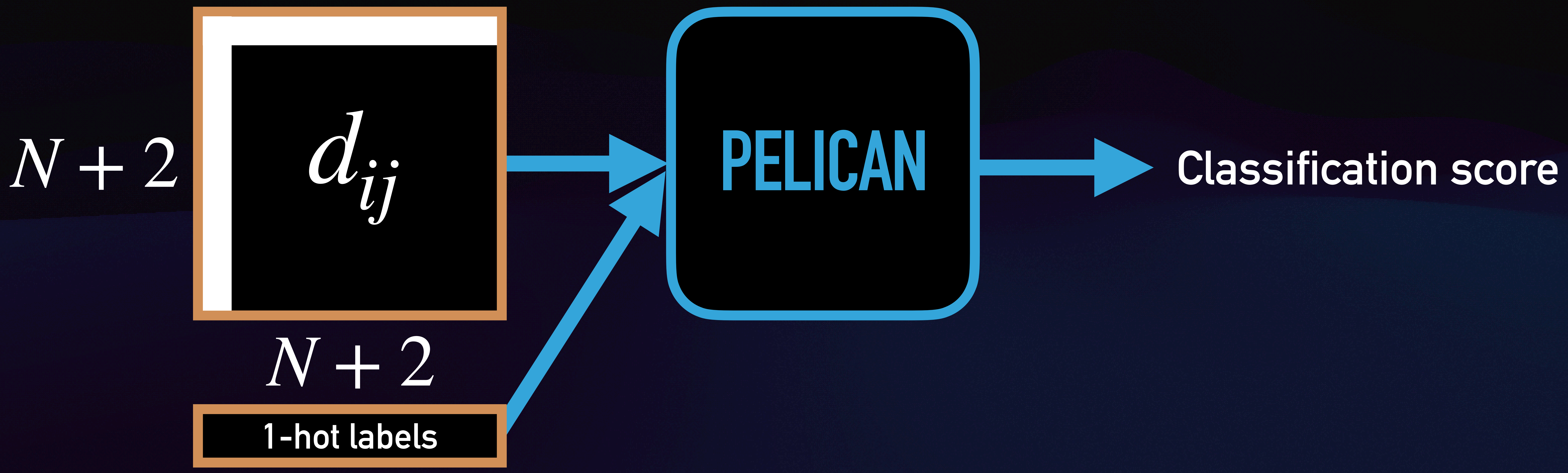
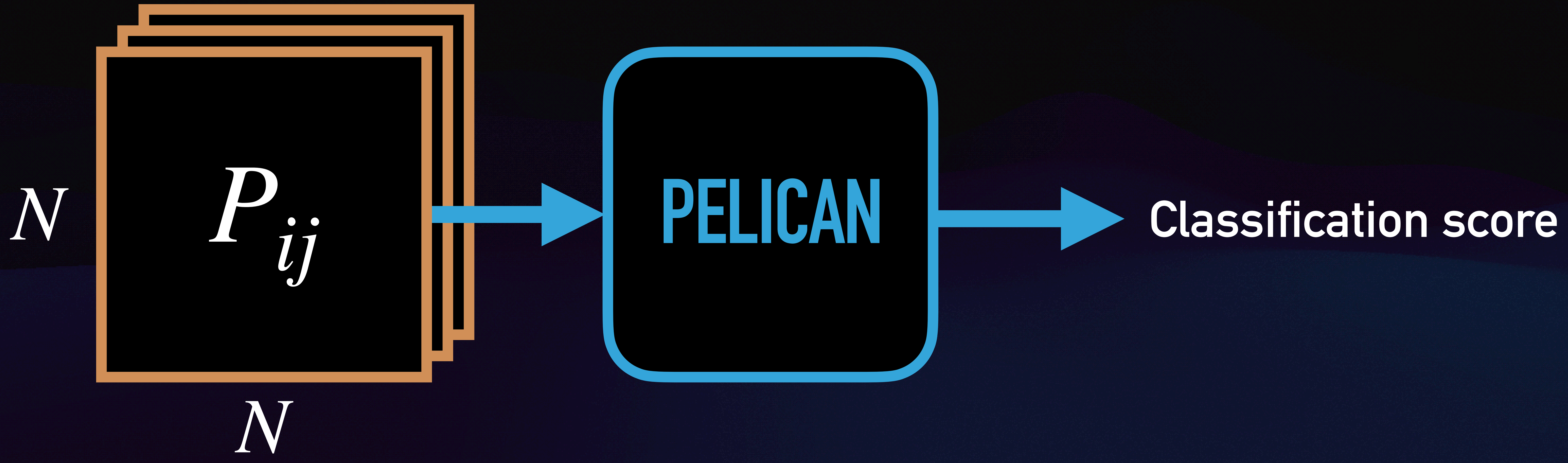


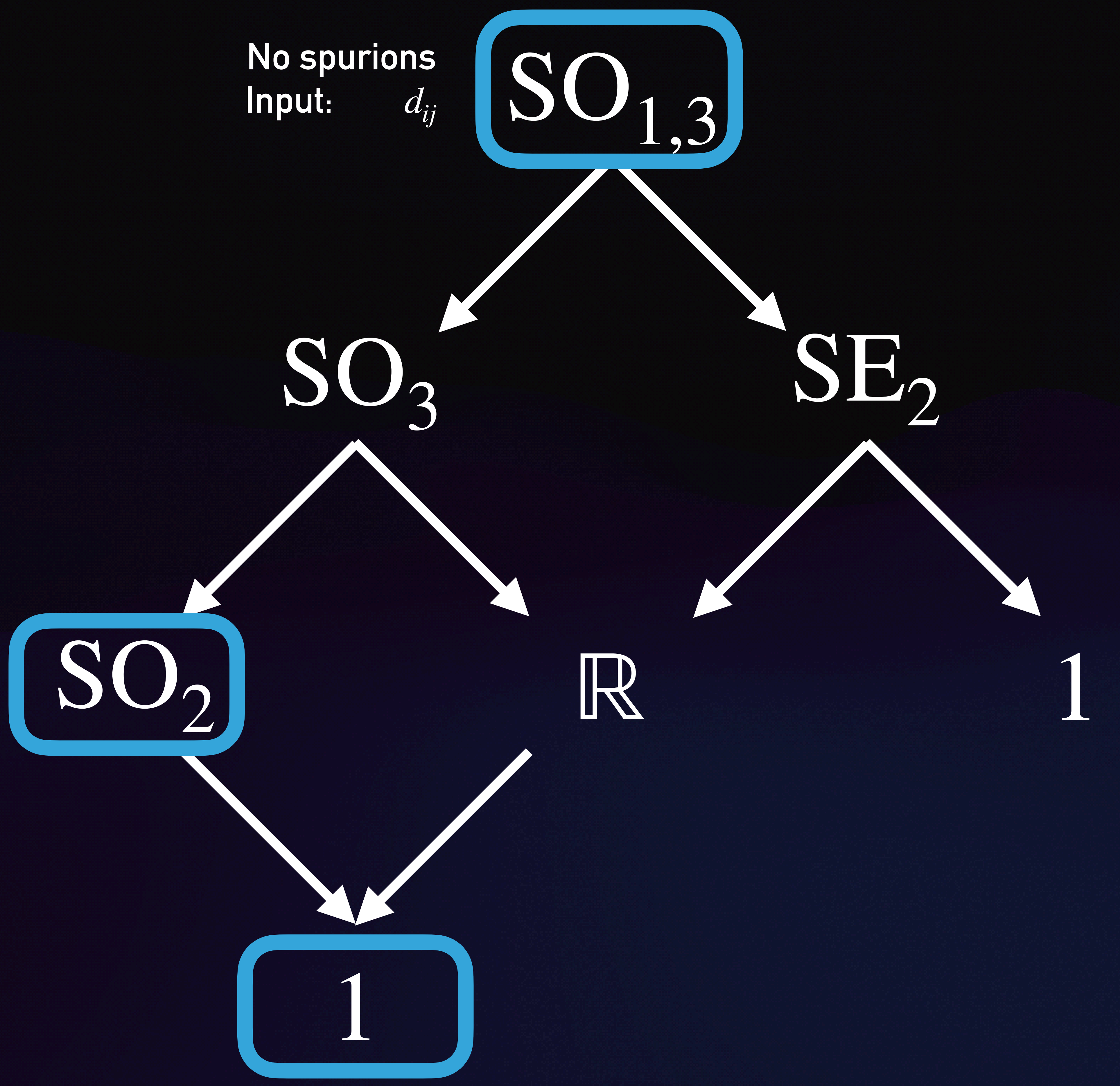
Each spurion gets a unique label, different from the common label of a jet constituent.

Alternative: extra inputs



P_{ij} a reduction of (p_i, p_j) to the relevant symmetry group

Hierarchy of symmetries



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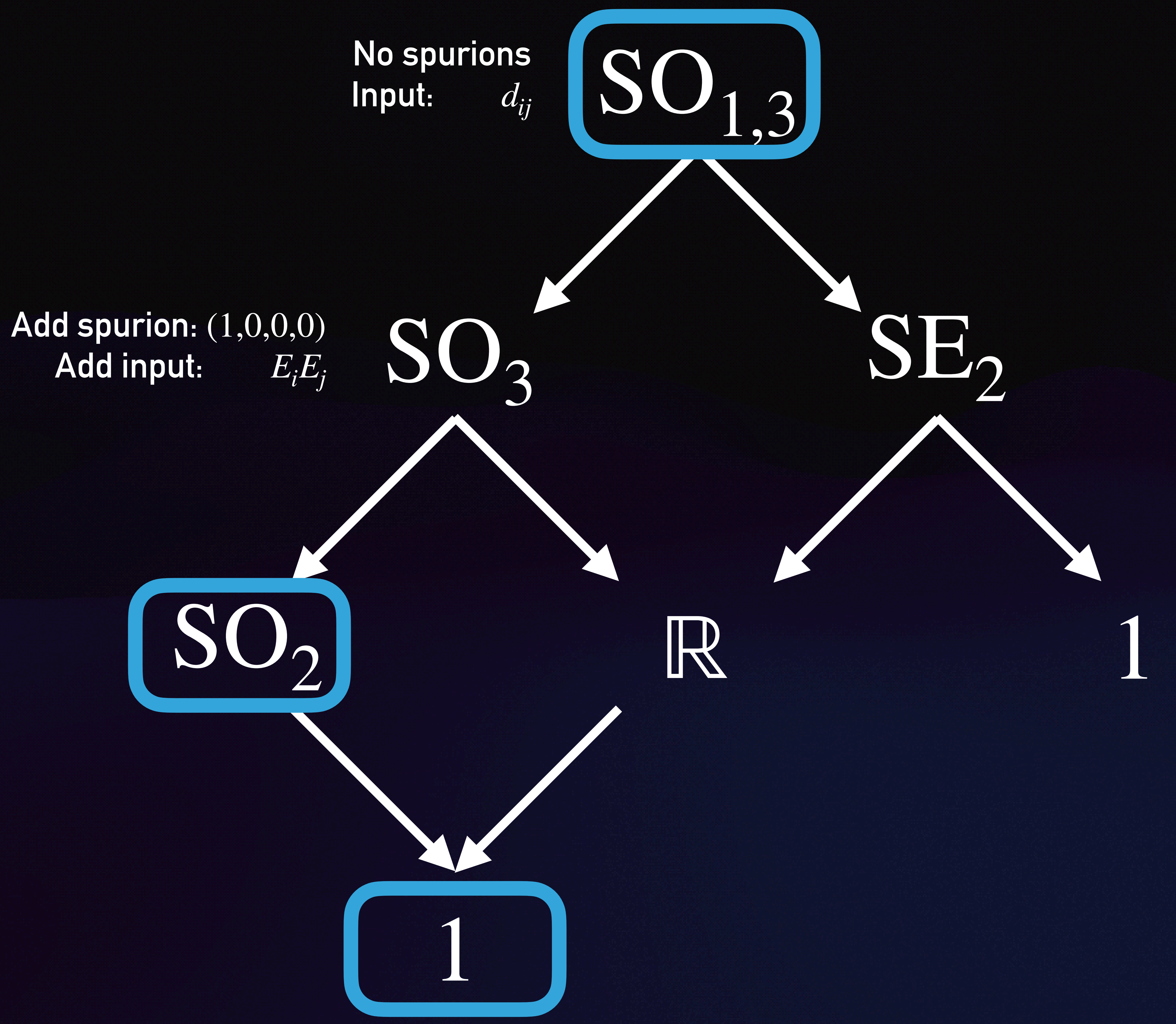

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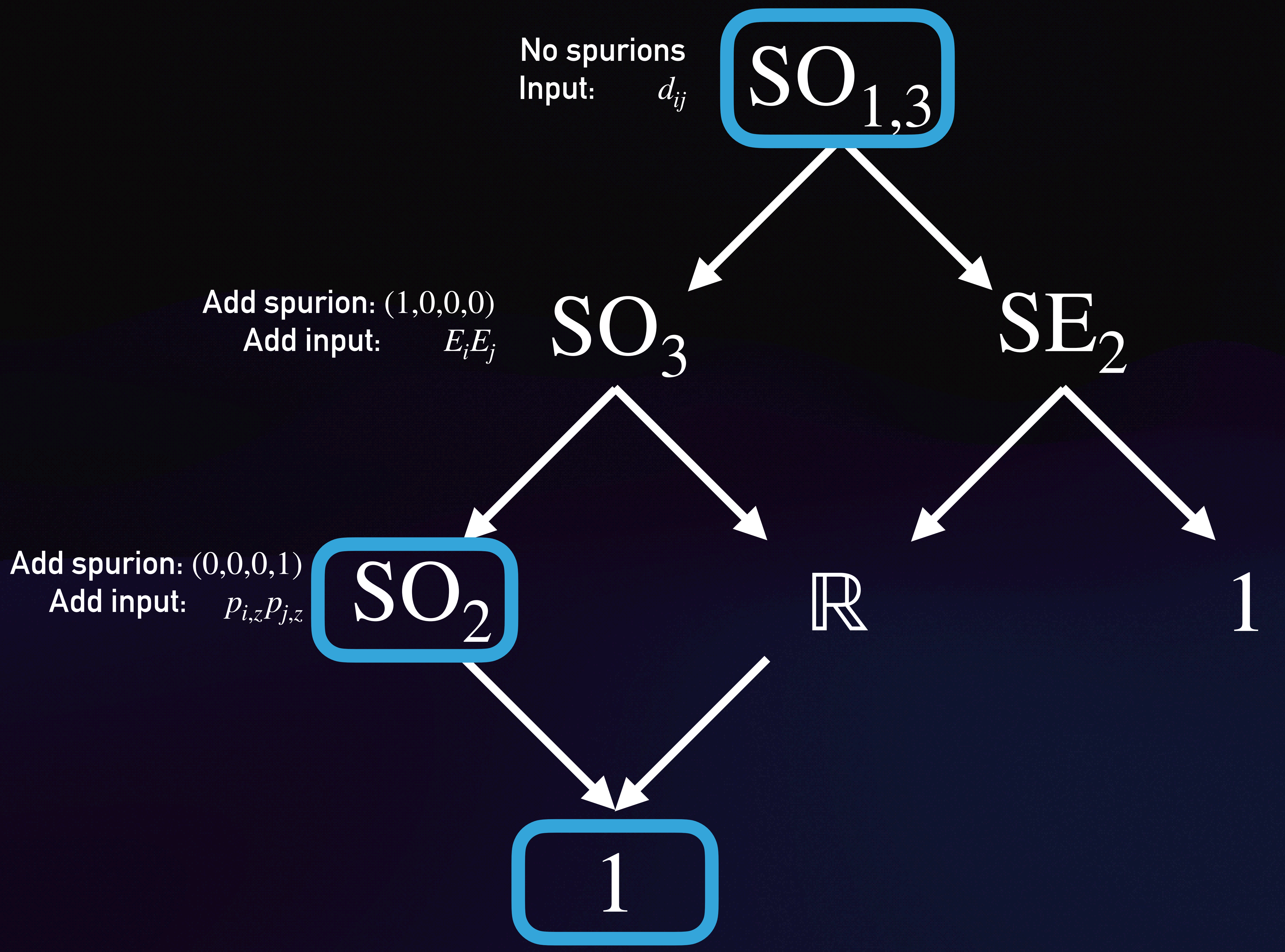

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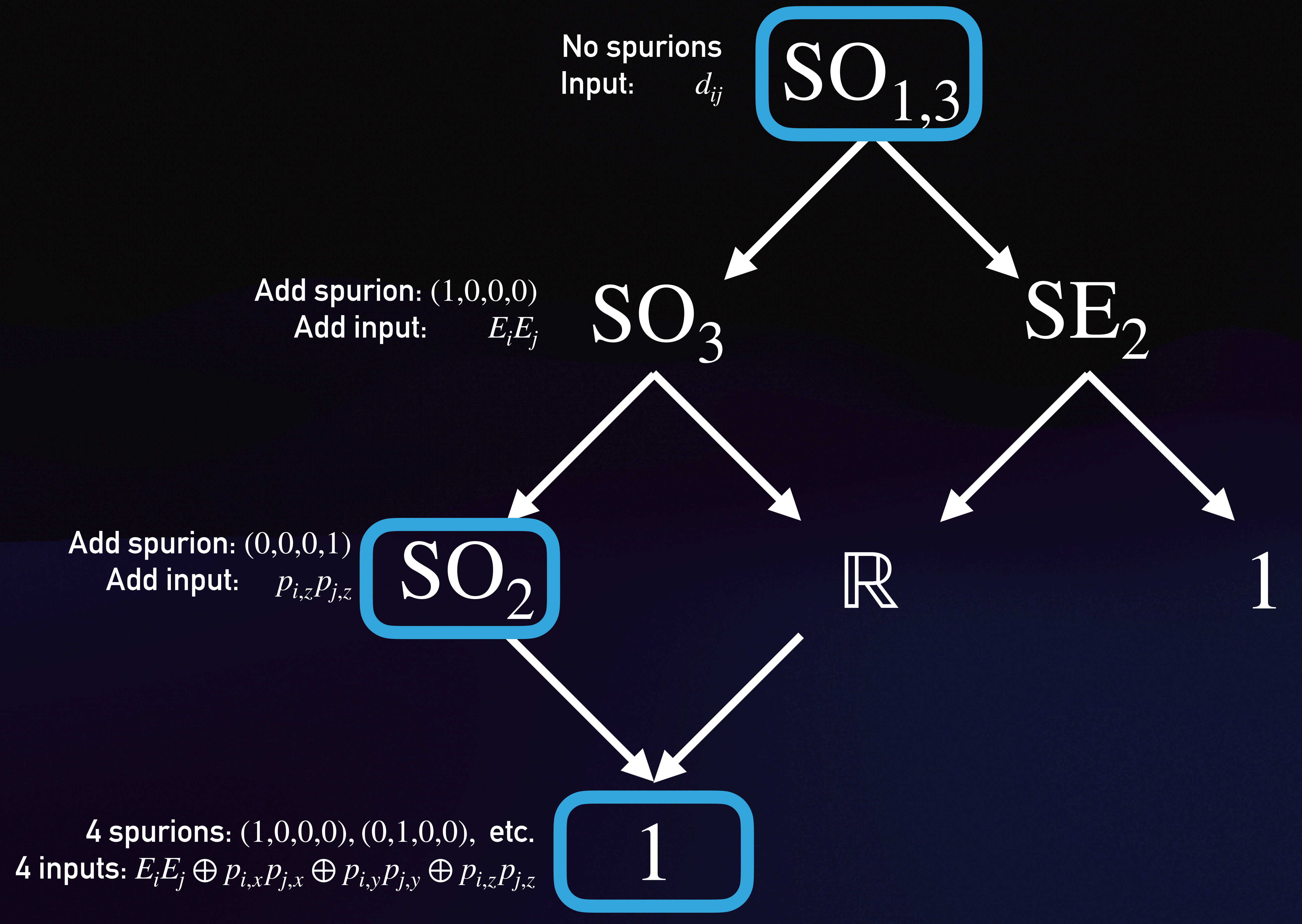

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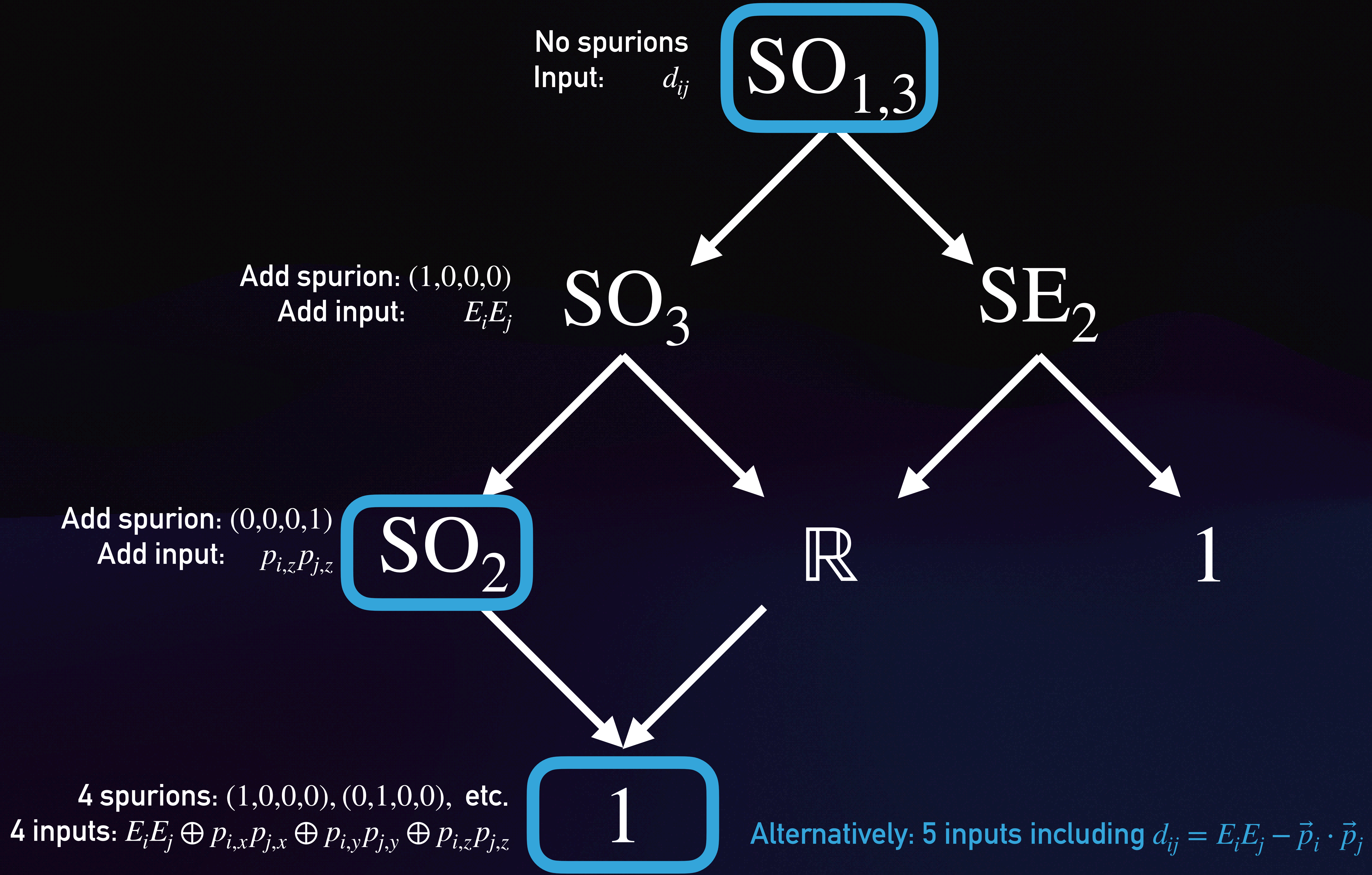

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k spurions, full Lorentz symmetry

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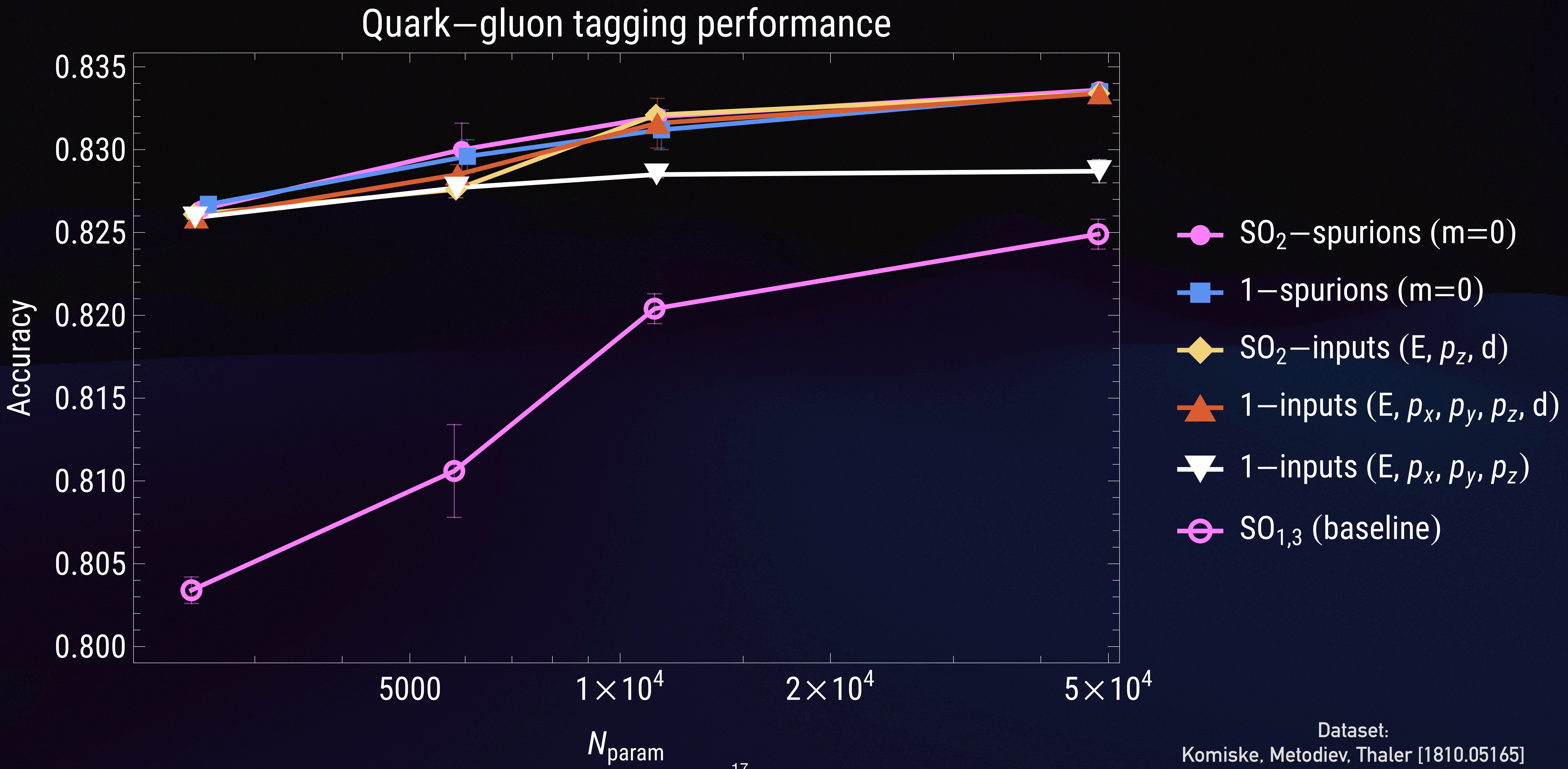
- Input method has extra dimensions to optimize in.

Quark/gluon tagging



Dataset:
Komiske, Metodiev, Thaler [1810.05165]

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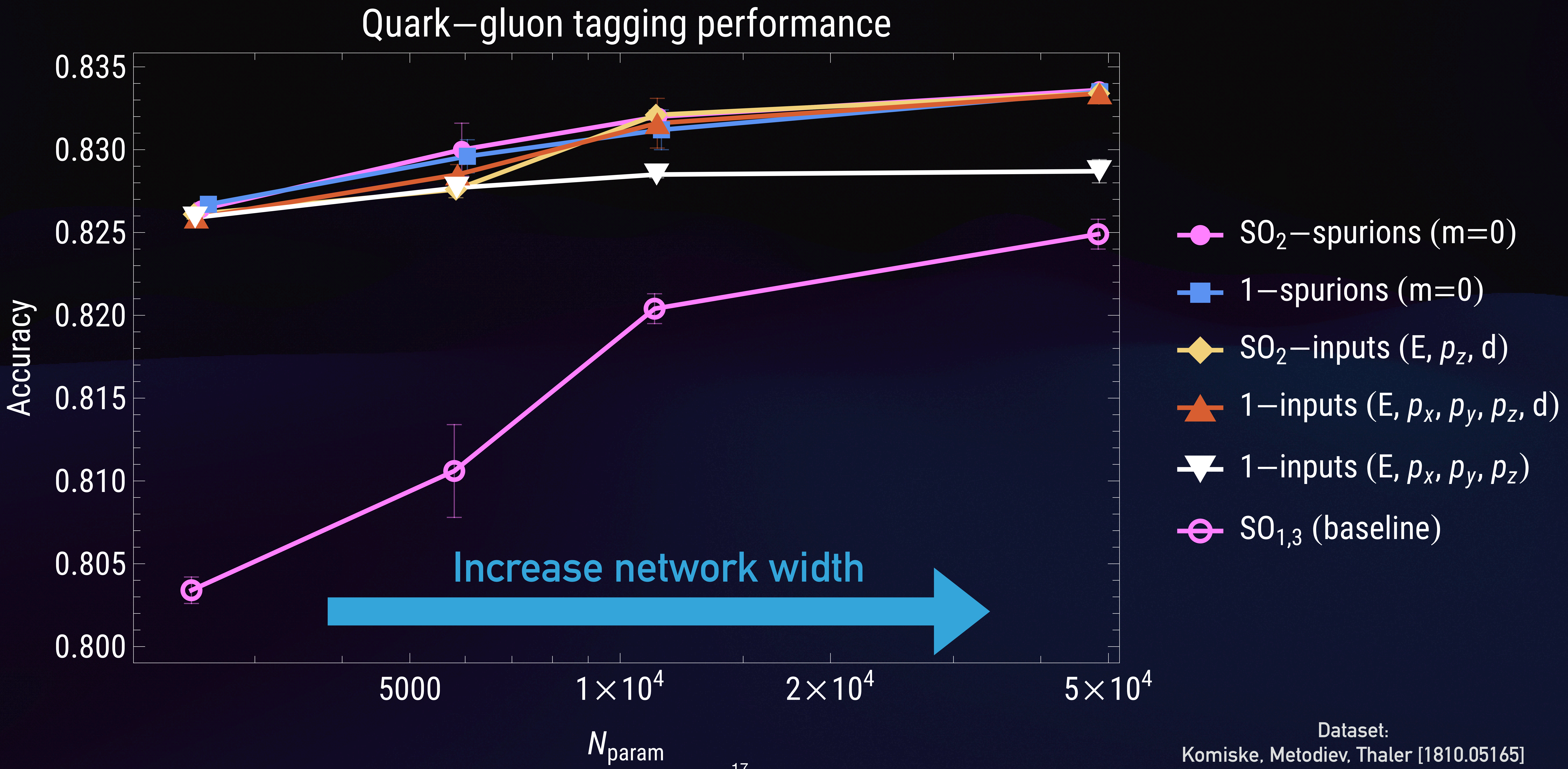

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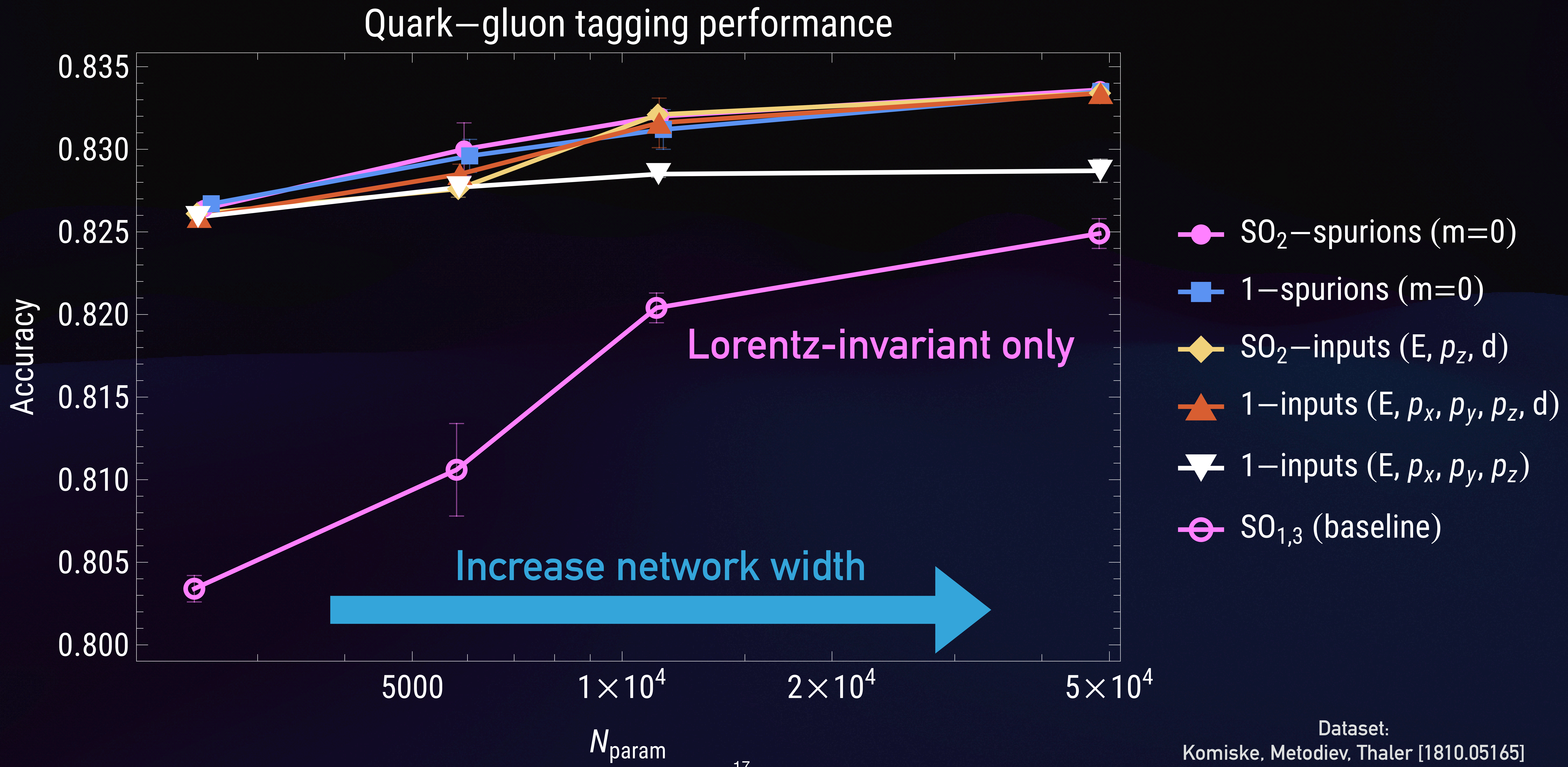

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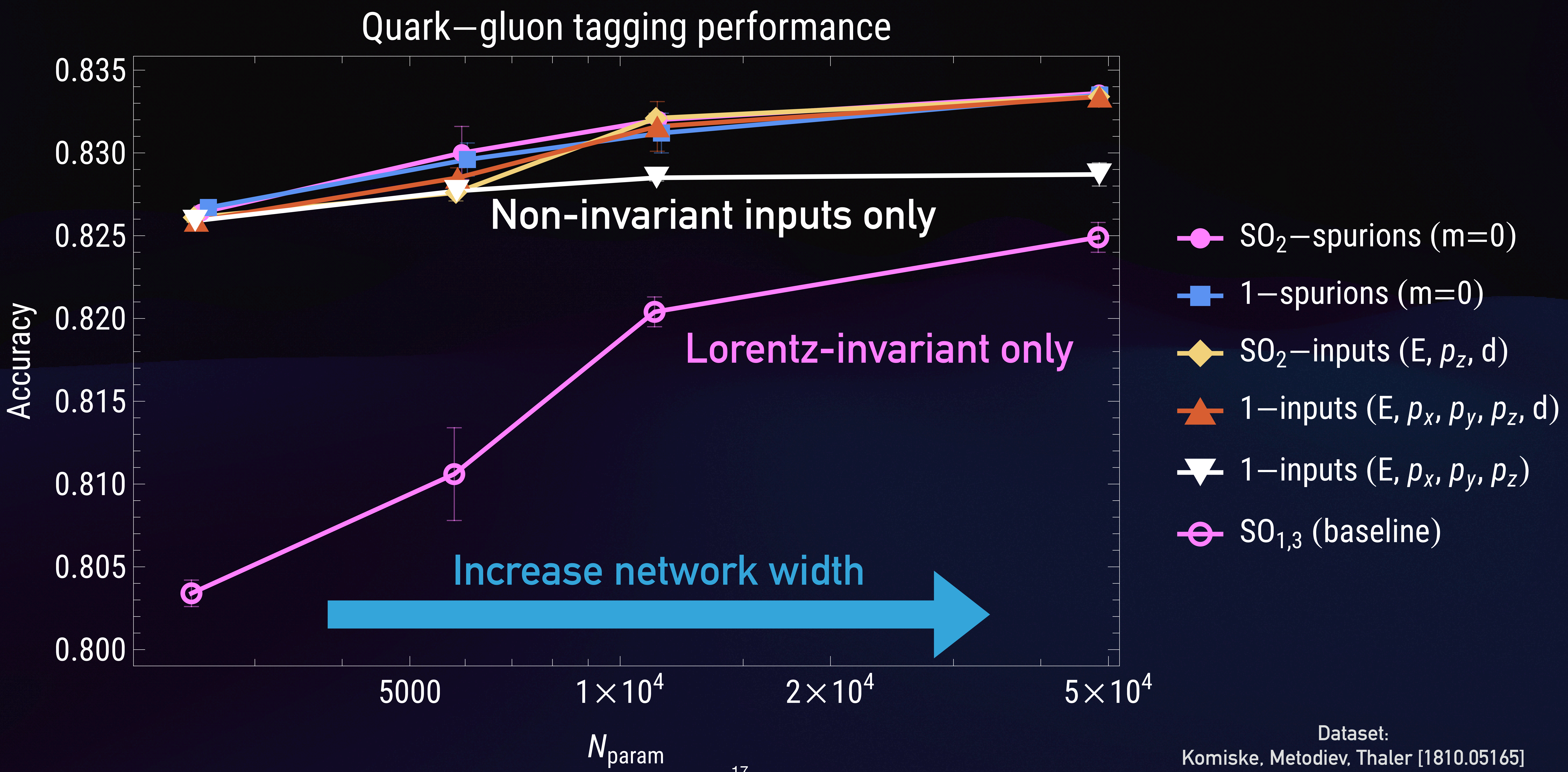

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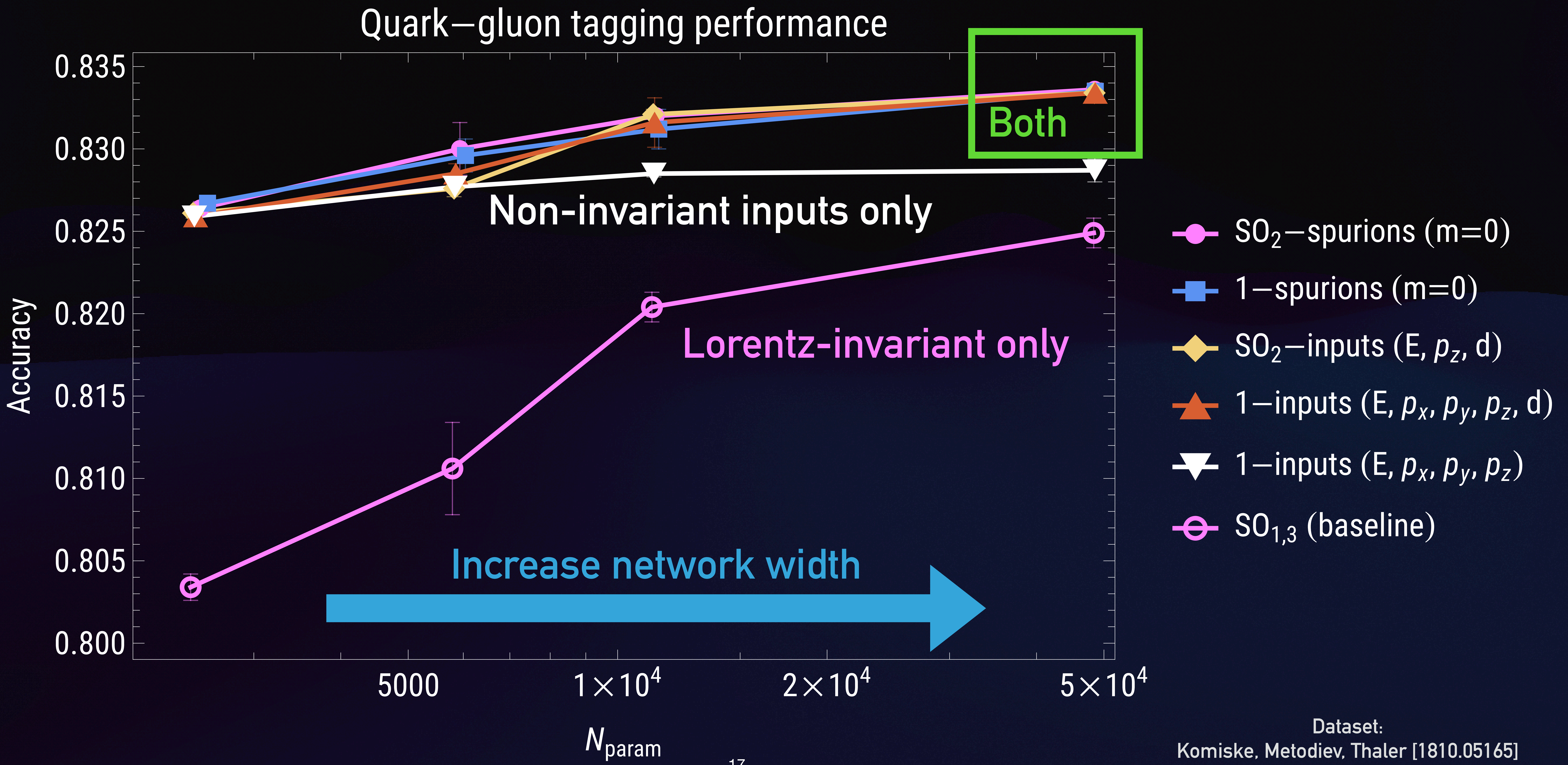

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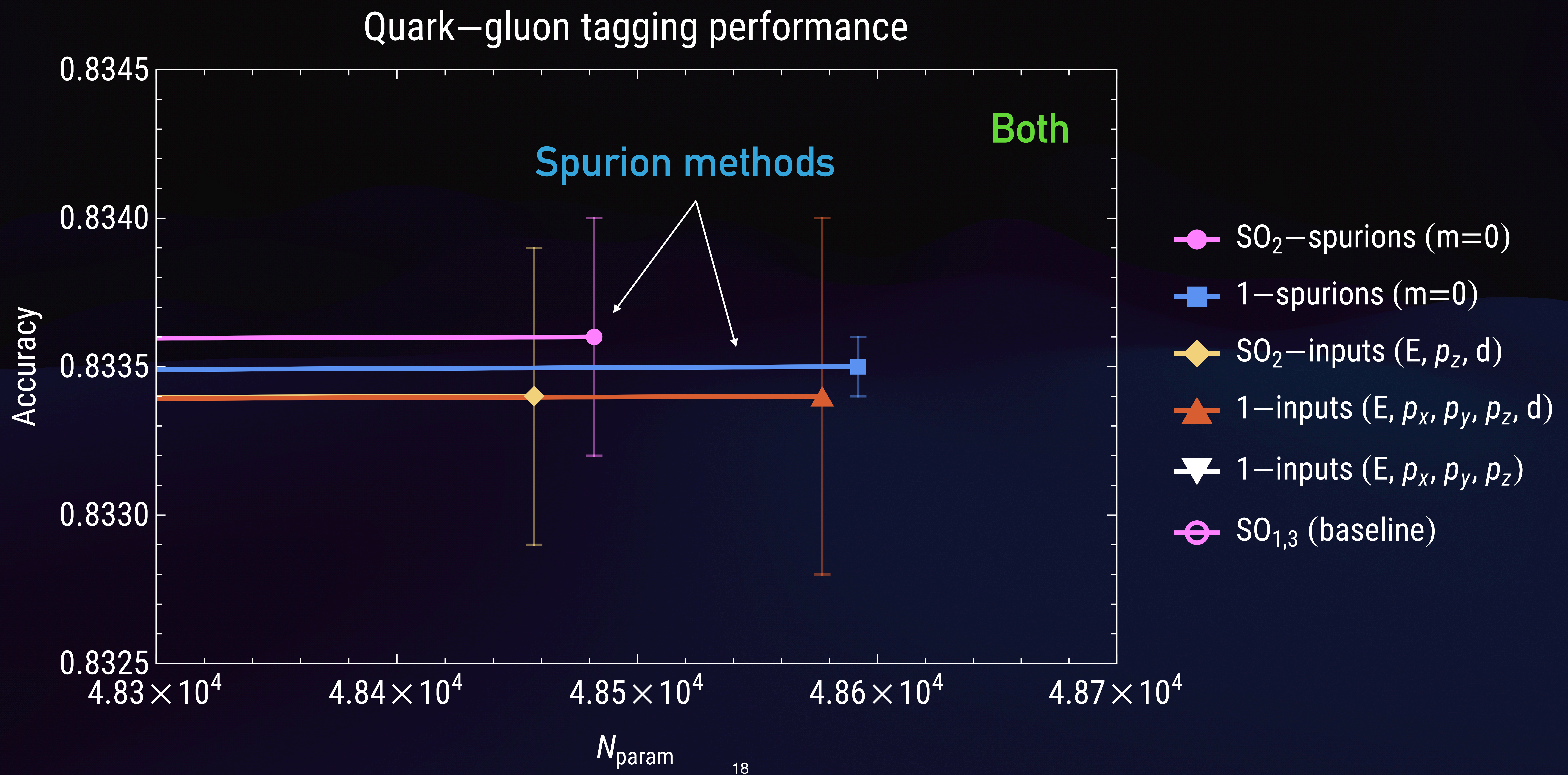

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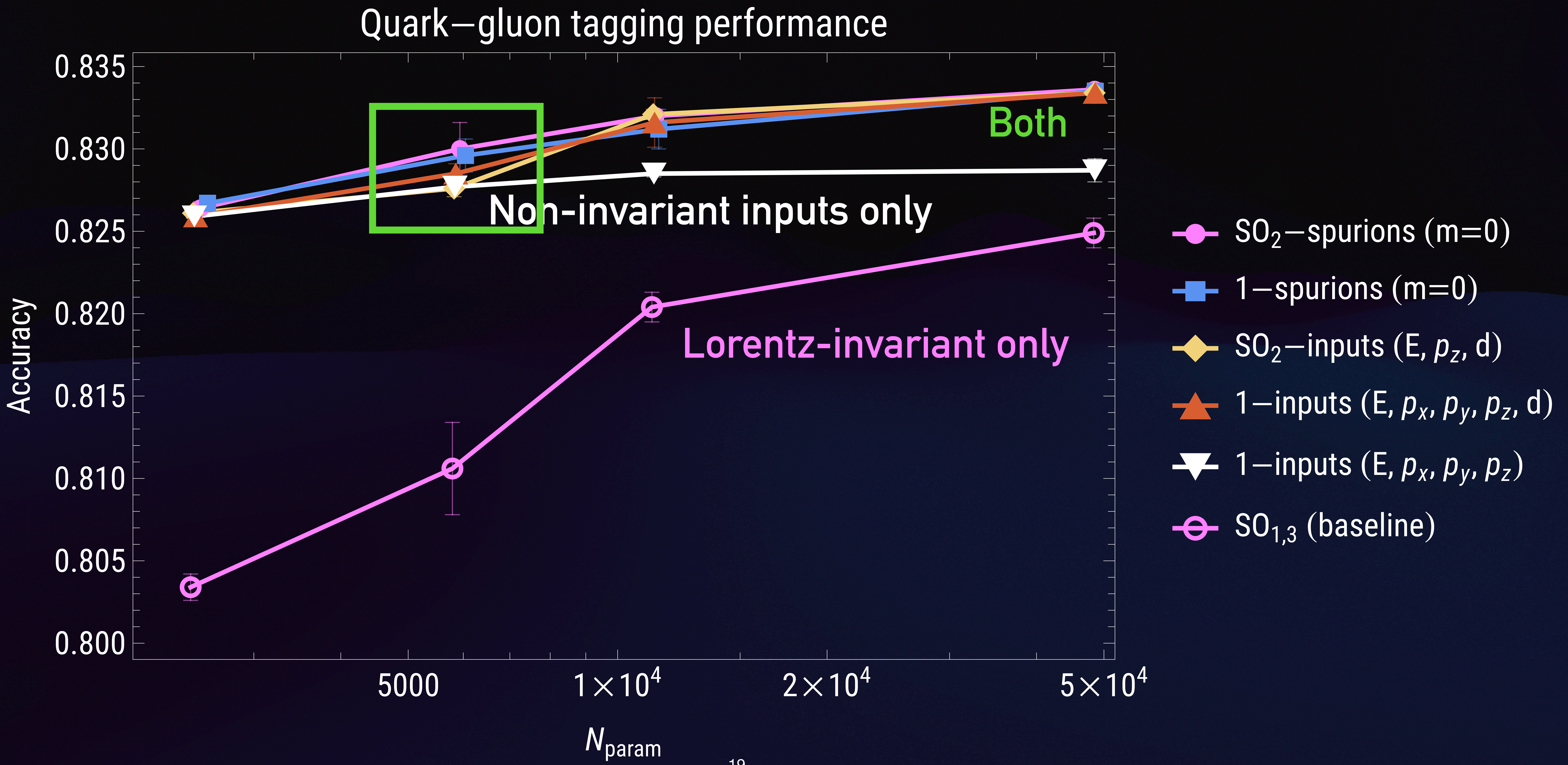

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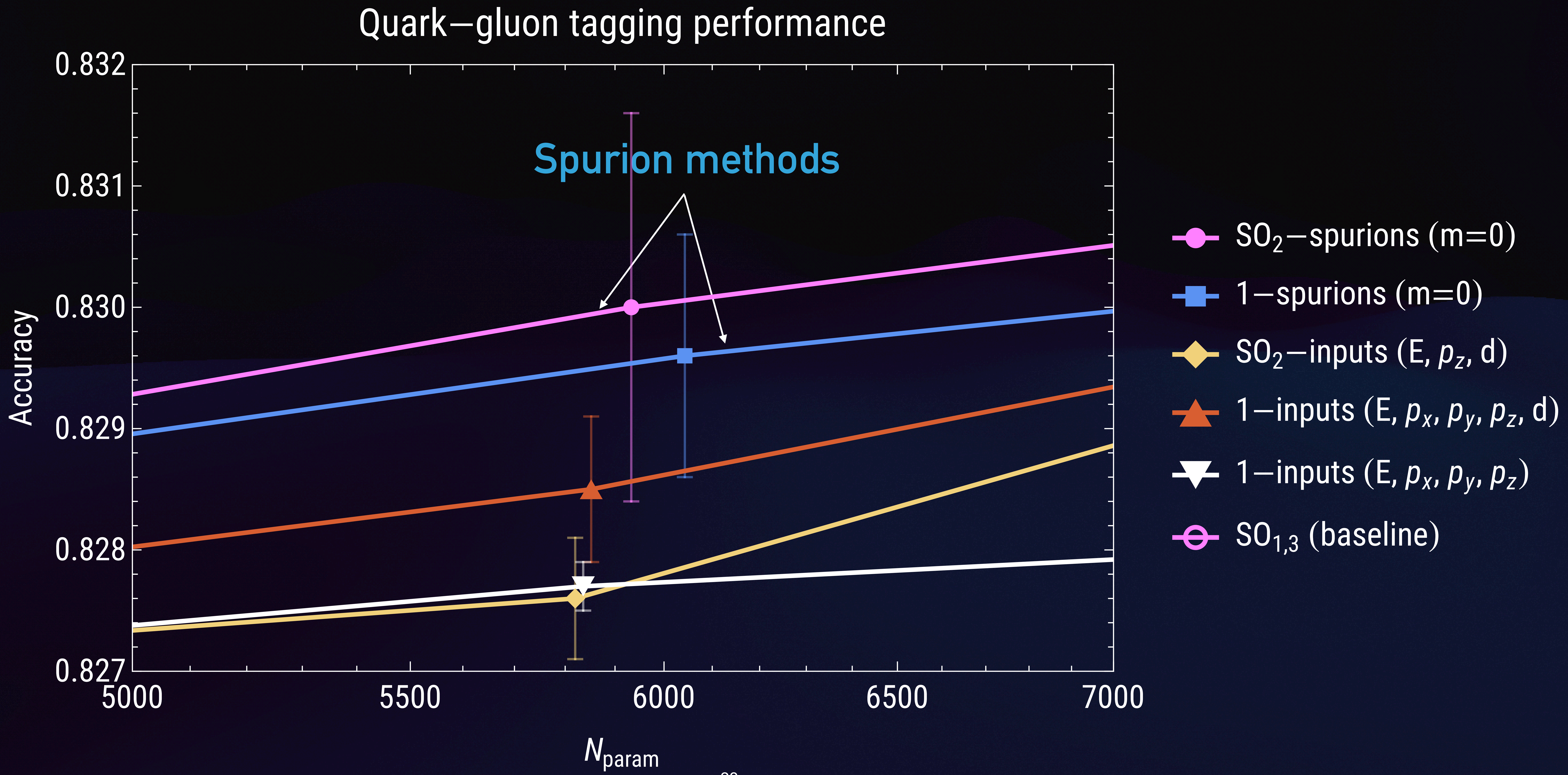
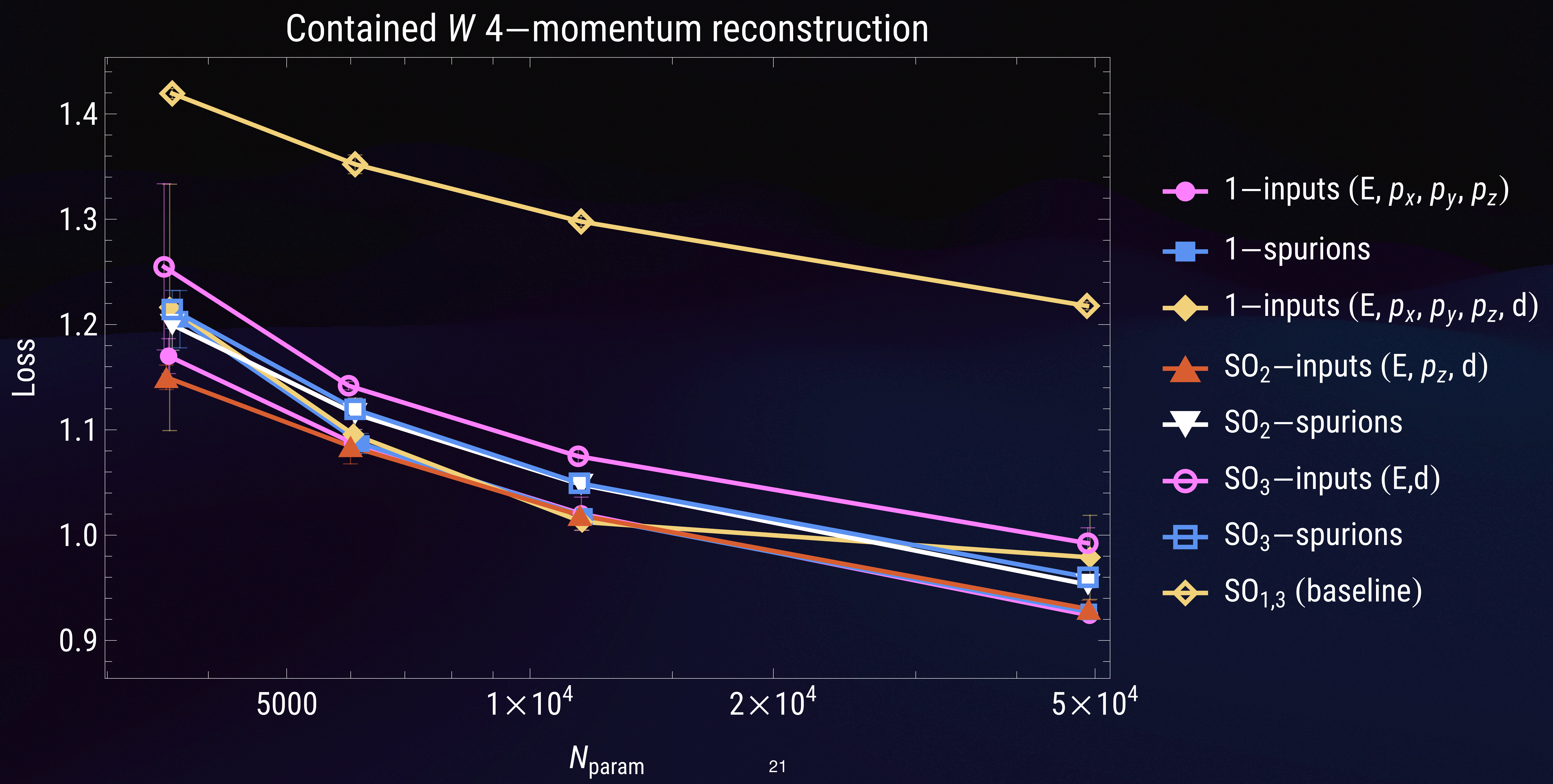


W momentum reconstruction



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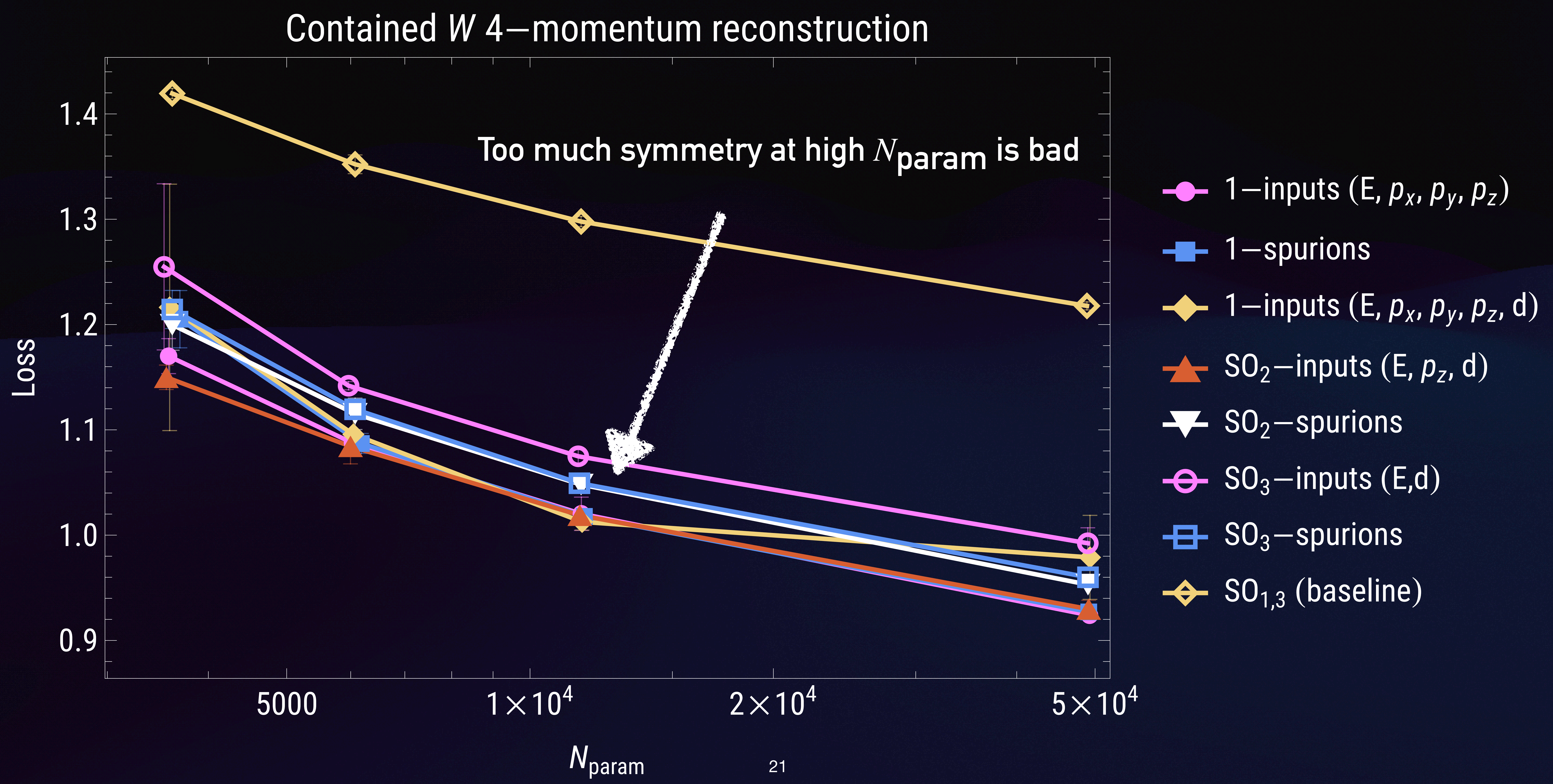

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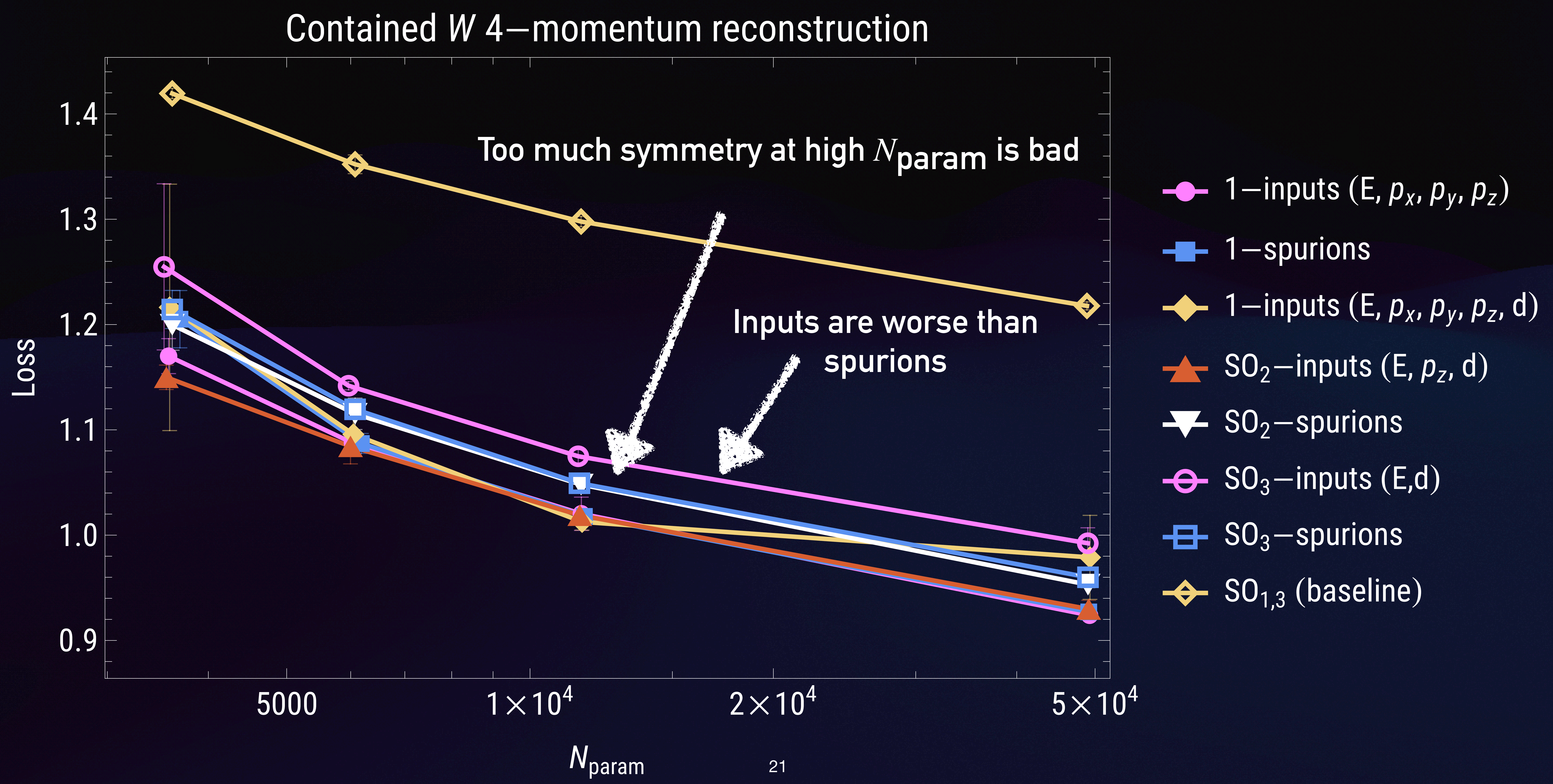

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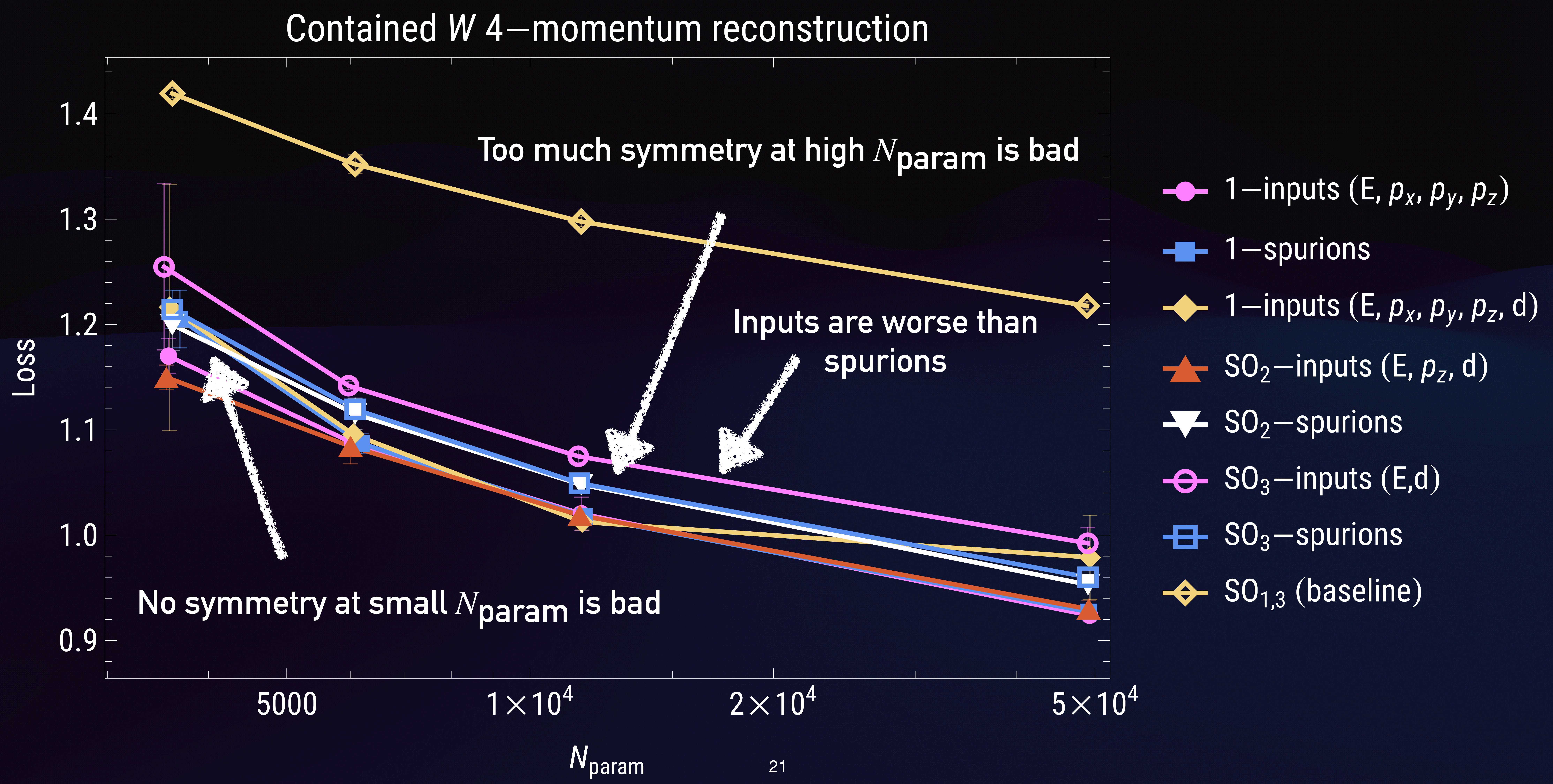

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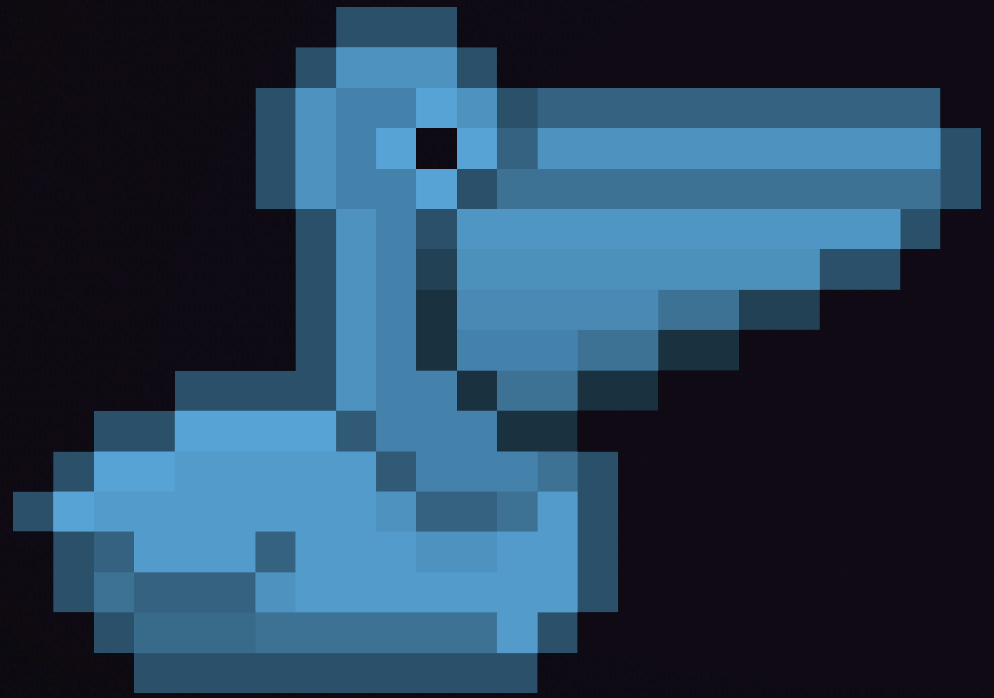
4. At small model size, more symmetry is better.



arXiv

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2307.16506

2310.16121