

Top quark spin and CP studies with L-GATr

[MM, H. Bahl, A. Petitjean, T. Plehn (in preparation)]

ML4Jets 2026

Marco Menen

16.09.2026



Leibniz
Universität
Hannover

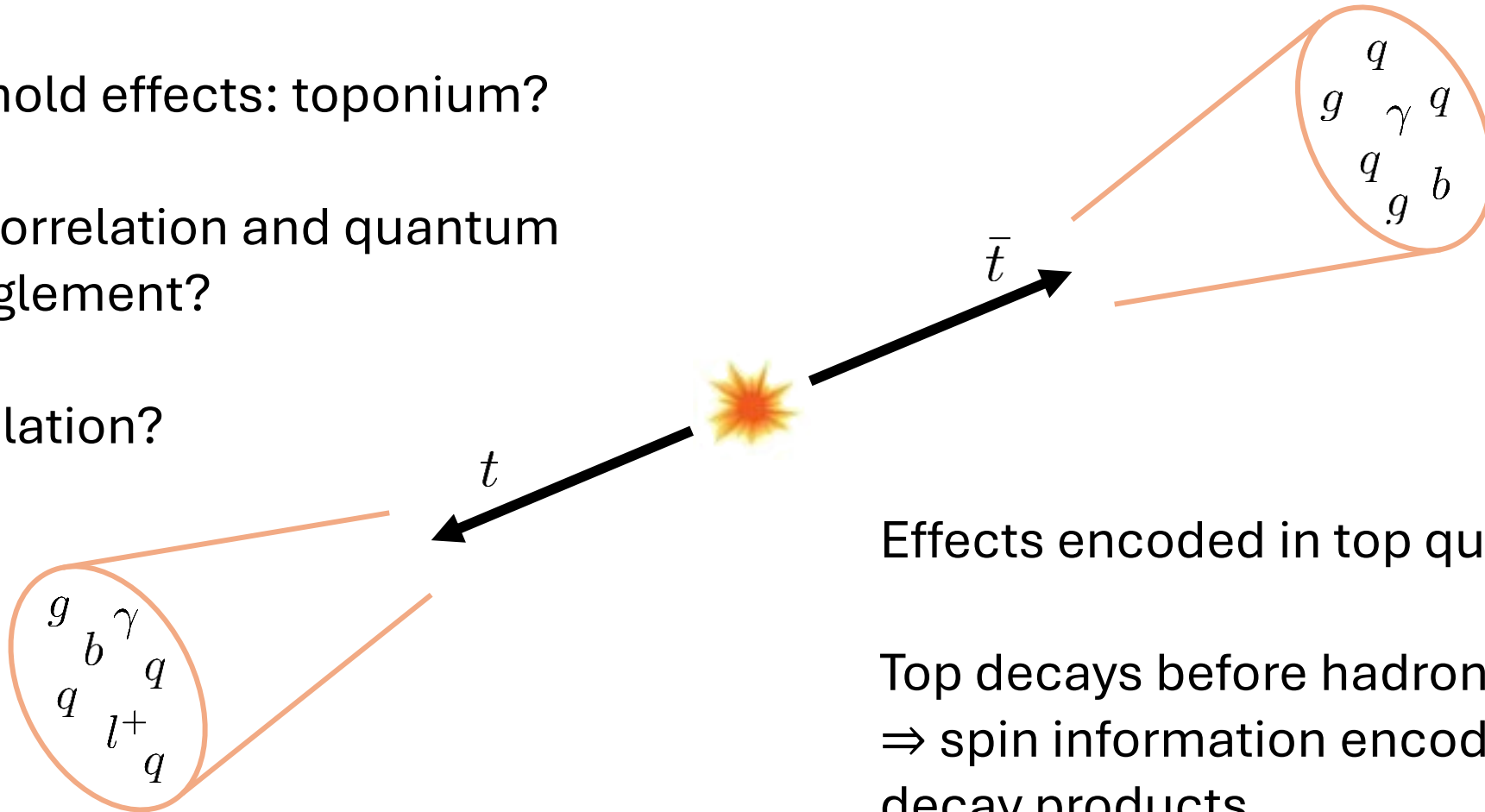


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The $t\bar{t}$ production process

Many current research projects:

- Threshold effects: toponium?
- Spin correlation and quantum entanglement?
- CP violation?



Effects encoded in top quark spin

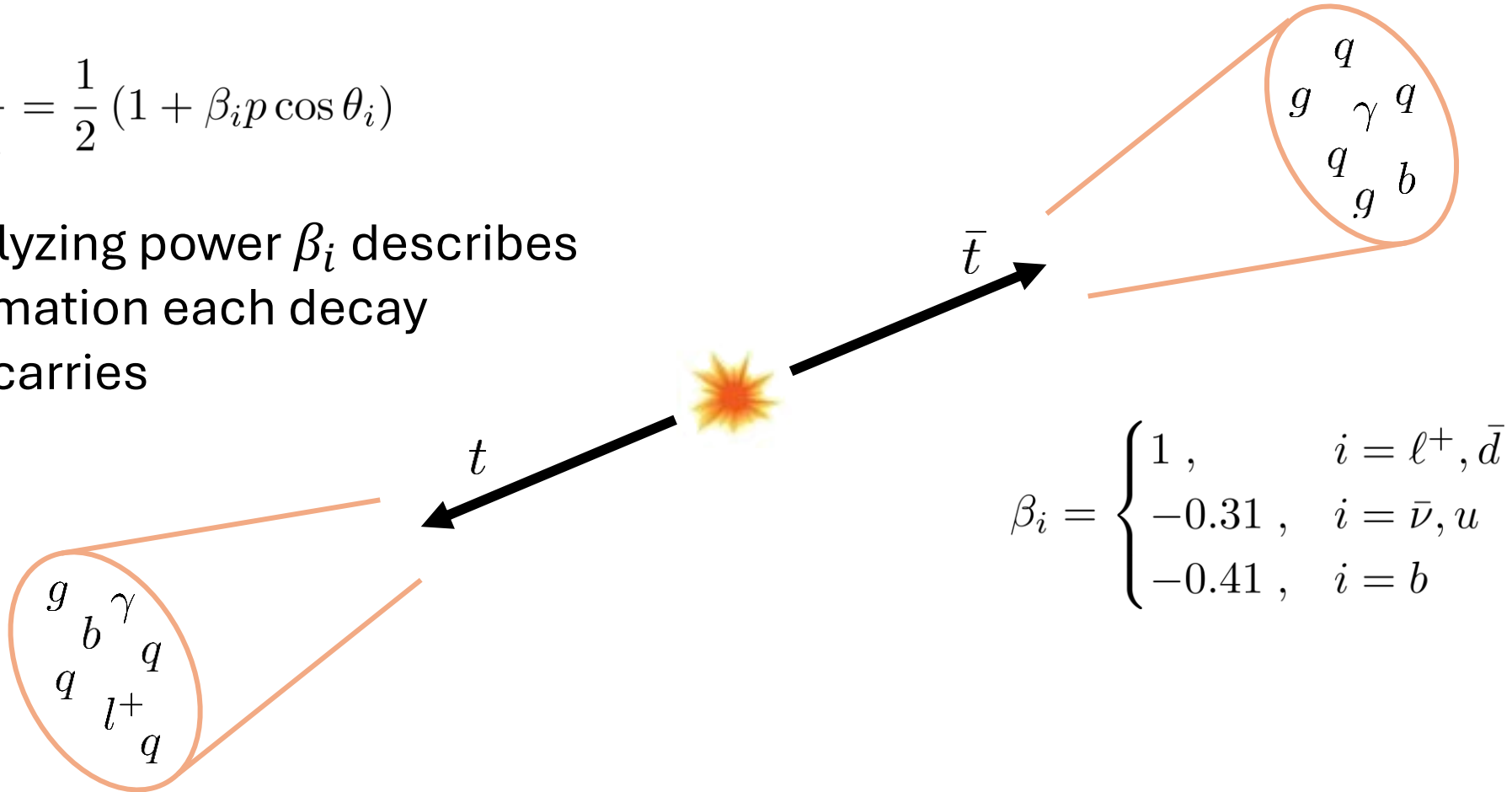
Top decays before hadronization
 $\Rightarrow$ spin information encoded in
decay products

The $t\bar{t}$ production process

Helicity angle probes top quark polarization:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2} (1 + \beta_i p \cos\theta_i)$$

Spin analyzing power β_i describes the information each decay product carries



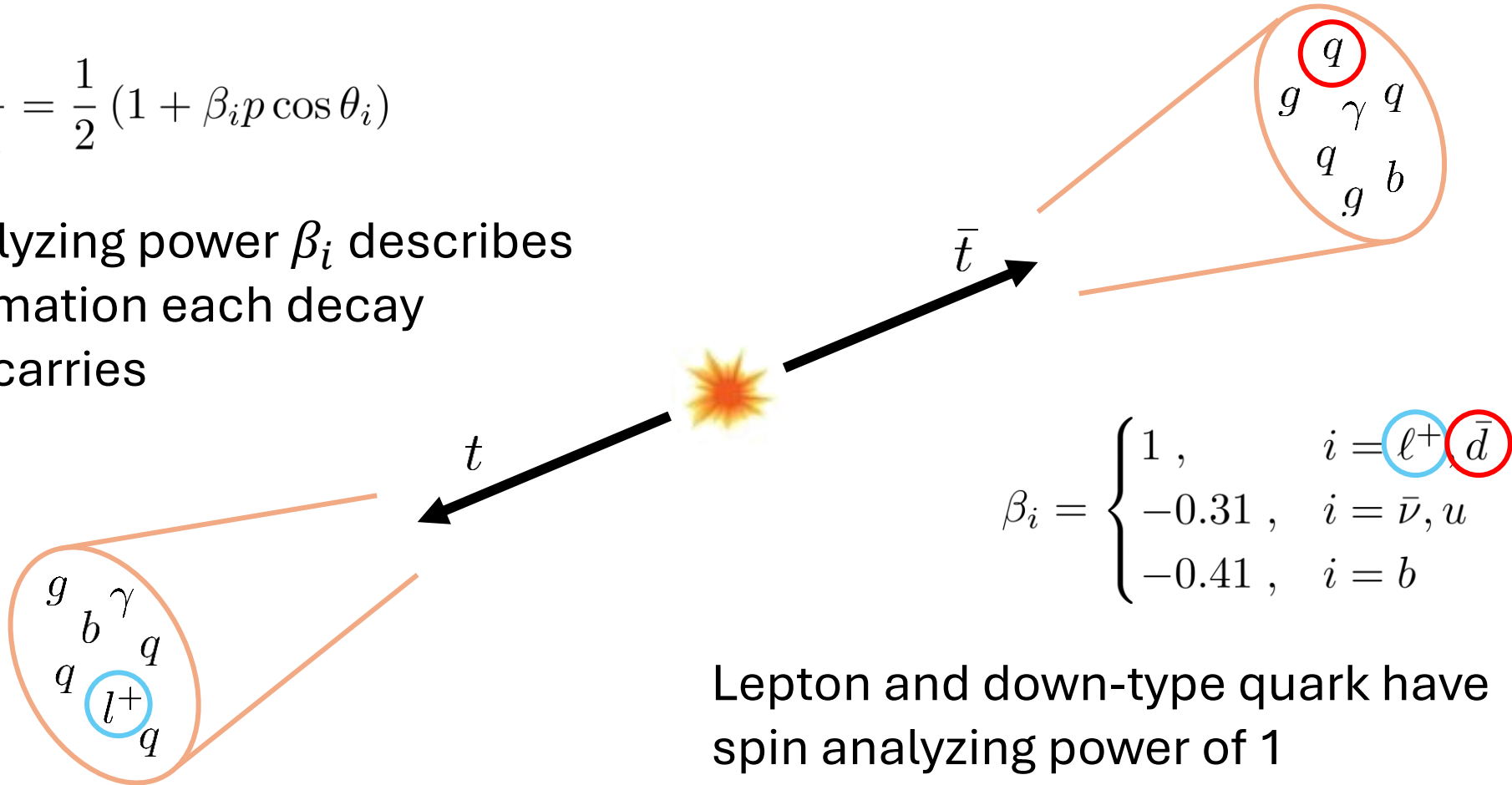
$$\beta_i = \begin{cases} 1, & i = \ell^+, \bar{d} \\ -0.31, & i = \bar{\nu}, u \\ -0.41, & i = b \end{cases}$$

The $t\bar{t}$ production process

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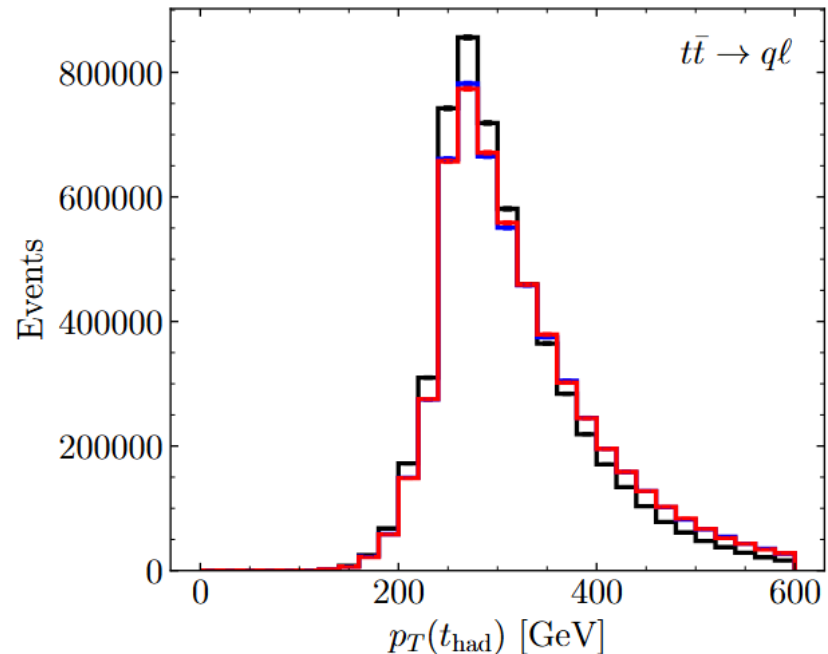


Lepton and down-type quark have spin analyzing power of 1
 $\Rightarrow$ Need to tag in respective decay

CP observables in $t\bar{t}$

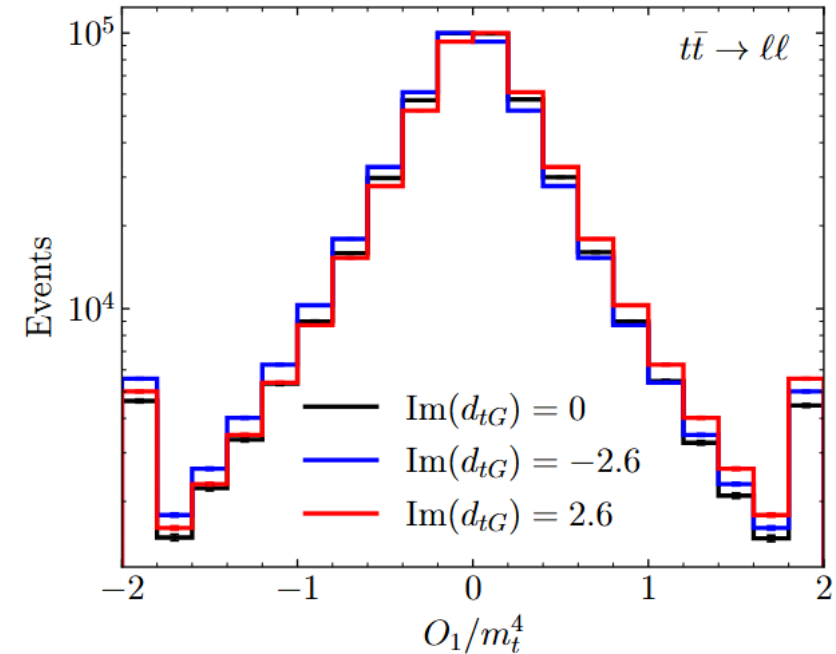
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2d_{tG}\text{Re}\left(\mathcal{M}_{\text{SM}}^\dagger \mathcal{M}_{\text{BSM}}\right) + d_{tG}^2 |\mathcal{M}_{\text{BSM}}|^2$$

CP-even observables:



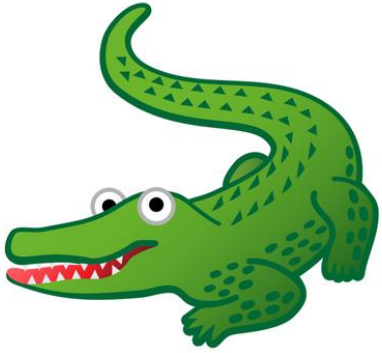
p_T is CP-sensitive but contains no information about sign of coupling

CP-odd observables:



Levi-Civita $\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$
needs top momenta and polarization

L-GATr



Lorentz-Equivariant Geometric Algebra Transformer

[Bresó-Pla, Favaro, Petitjean, Spinner]

$$f(\Lambda x) = \Lambda f(x)$$



Each network layer
is equivariant

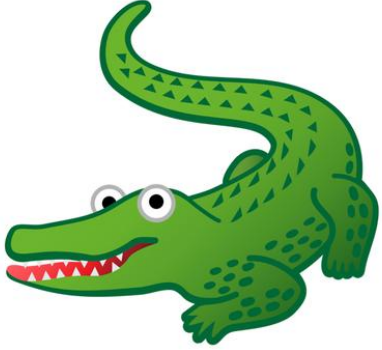
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Sitzungslegende					
Parallel Talks Parallel Talks Plenary Presentations					
09:00					
Foundation Models for High Energy Physics Anna Hallin					
C1, Hörsaalzentrum University of Vienna 09:00 - 09:30					
From Prompts to Publications: Agentic AI for Collider Analysis Eric Anton Moreno					
C1, Hörsaalzentrum University of Vienna 09:30 - 10:00					
10:00					
Coffee Break					
Hörsaalzentrum University of Vienna 10:00 - 10:30					
11:00					
LI-JEPA: Self-supervised pretraining of Lorentz Invariant ... Andreas Hermansen					
Simulating the CMS High-Granularity Calorimeter with G... Sitian Qian					
To Mask, Predict, or Classify? Comparative Analysis of Pr... Anuranjan Sarkar					
Fast Calorimeter Simulation in ATLAS with Modern Gene... Florian Ernst					
Performance of Tabular Foundation Models for analysis o... David Rousseau					
AllShowers: One model for all calorimeter showers Thorsten Buss					
What can representation geometry reveal about collider f... Tianyi Cai					
Fast Point Cloud Generation via Latent Diffusion Martina Mozzanica					
12:00					
Top quark spin and CP studies with L-GATr Marco Menen					
C1, Hörsaalzentrum University of Vienna 11:50 - 12:10					
step2point: Optimizing Point Cloud Representations for ... Peter McKeown					
FASTColor - Full-color Amplitude Surrogate Toolkit for QCD ... Javier Mariño Villadamiro					
C1, Hörsaalzentrum University of Vienna 12:10 - 12:30					

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09:00					
GPU-Accelerated Online Reconstruction in ALICE Felix Weiglhofer					
C1, Hörsaalzentrum University of Vienna 09:00 - 09:30					
Machine Learning for Hadronization Manuel Szwec					
C1, Hörsaalzentrum University of Vienna 09:30 - 10:00					
10:00					
Coffee Break					
Hörsaalzentrum University of Vienna 10:00 - 10:30					
11:00					
Neural-network quantum states for exotic hadrons and nu... weilin wu					
Virtues and Vices of Equivariant Transformers Jonas Spinner					
(ZOOM) Variational Quantum Classification Head Nadia Sharna					
Economical Jet Taggers -- Equivariant, Slim and Quantized Antoine Petitjean					
Normalising Flow-Assisted Neural Quantum States for Gr... Timur Sytchenko					
Group equivariance in infrared and collinear safe graph ... Vishal Singh Ngairangbam					
Continuous-Variable Photonic Quantum Machine Learnin... Louis Choron					
Enforcing IRC Safety and Lipschitz-Constrained Insensiti... Umar Sohail Qureshi					
12:00					
Information-theoretic quantum-informed approaches ... Aritra Bal					
One Generator, Any Process: LLM-Conditioning for the L... Thanush Sivagnanalingam					
Lund Plane to Bloch (LP2B) encoding for object and polarization tagging with quantum jet substructure Luca Della Penna					
C1, Hörsaalzentrum University of Vienna 12:10 - 12:30					

Conference dinner

From L-GATr to L-GATr-slim



Lorentz-Equivariant
Geometric **A**lgebra
Transformer

[Bresó-Pla, Favaro, Petitjean, Spinner]

$$f(\Lambda x) = \Lambda f(x)$$



Each network layer
is equivariant

Input to L-GATr is multivector
of spacetime algebra:

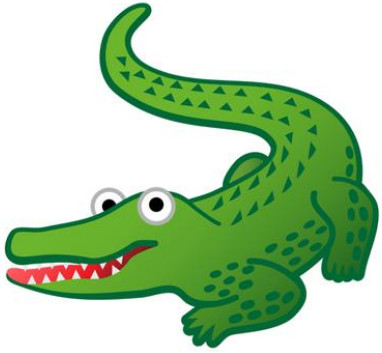
$$\begin{aligned} x^S &= \text{PID} \\ x_\mu^V &= p_\mu \\ &\vdots \end{aligned}$$

$$\begin{pmatrix} x^S \\ x_\mu^V \\ x_{\mu\nu}^B \\ x_\mu^A \\ x^P \end{pmatrix} \in \mathbb{R}^{16}$$

[Brehmer et al. '24]

⇒ Can predict e.g. matrix element of P-odd
transition via scalar + pseudoscalar outputs

From L-GATr to L-GATr-slim



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L-GATr-slim:

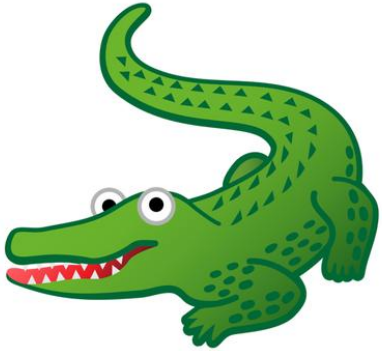
Reduce to scalar + vector

$$\begin{pmatrix} x^S \\ x_\mu^V \end{pmatrix} \in \mathbb{R}^5$$

[Petitjean et al. '25]

⇒ Sufficient for most applications, but
much less computationally expensive

Recovering pseudoscalars in L-GATr-slim



Lorentz-Equivariant
Geometric Algebra
Transformer

[Bresó-Pla, Favaro, Petitjean, Spinner]

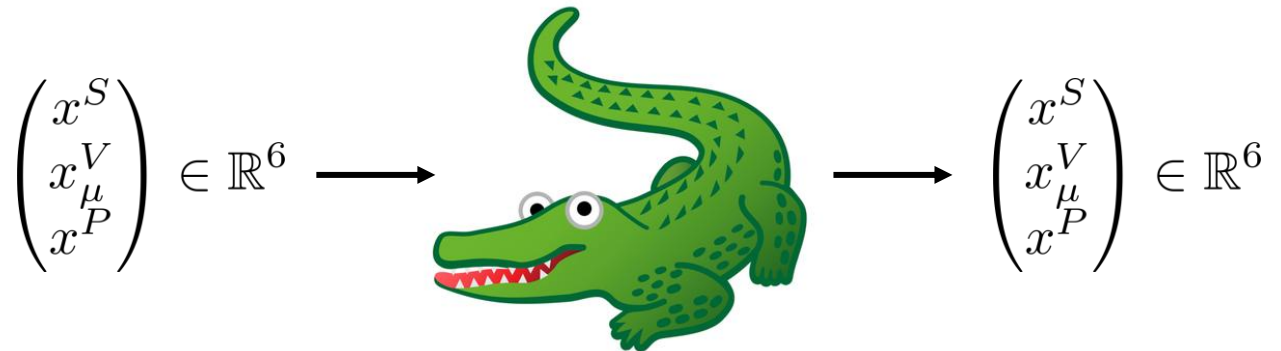
$$f(\Lambda x) = \Lambda f(x)$$



Each network layer
is equivariant

We are interested in CP-odd observables:
Give pseudoscalar back to L-GATr-slim

⇒ contains all information needed for $t\bar{t}$
spin and CP studies with a fraction of the
cost for the full L-GATr

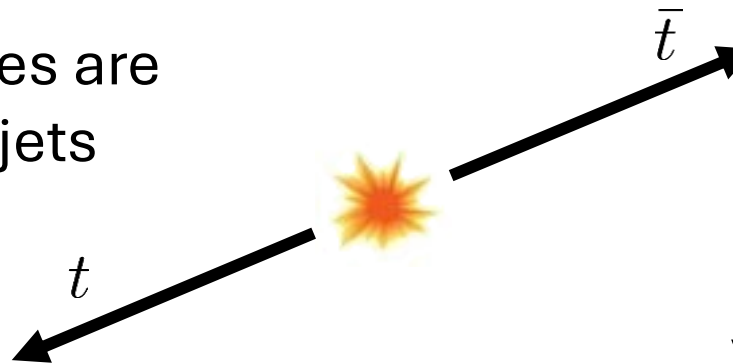
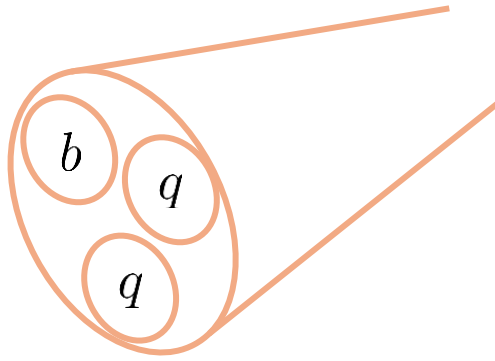


⇒ We can access the scalar and
pseudoscalar information independently

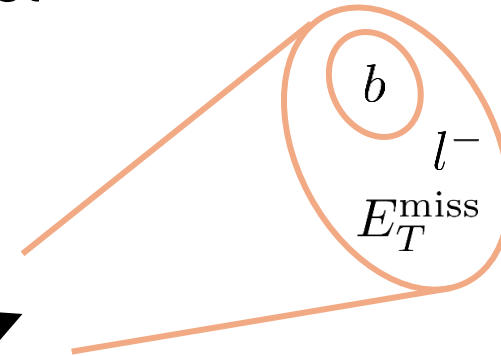
Input data

We simulate $t\bar{t}$ data in semileptonic decay channel

Hadronic top candidates are declustered into three jets (one is b-tagged)



Leptonic top candidates are reconstructed from E_T^{miss} via W-mass requirement



We save the four-momenta of all particles and all information about the jet substructure

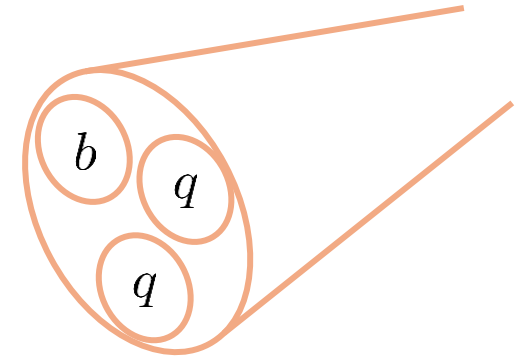
Task 1: Hadronic spin reconstruction

Break down data into binary classification problem:
Identifying the down-type quarks from the two light quark jets

Hadronic spin proxy vector from weighted average:

$$q_d = p(d \rightarrow q_{\text{hard}} | \mathcal{O}) \hat{q}_{\text{hard}} + p(d \rightarrow q_{\text{soft}} | \mathcal{O}) \hat{q}_{\text{soft}}$$

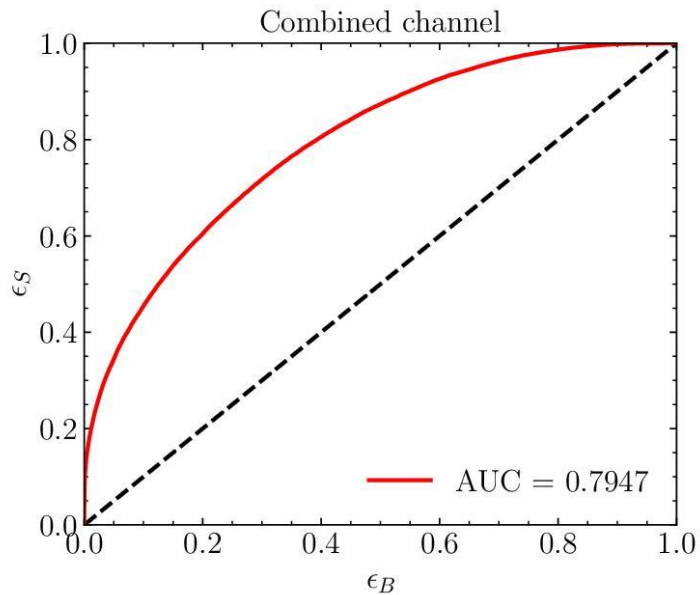
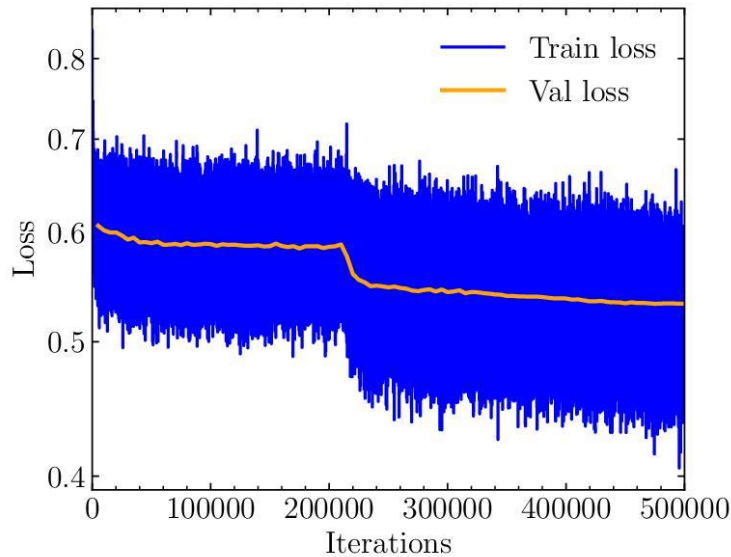
Spin analyzing power: $\beta_d = \langle |q_d| \rangle$



Previous approaches:

- [B. Tweedie '14] based on angular observables $\beta_d = 0.64$
- [Z. Dong et al. '24] based on ParticleNet $\beta_d = 0.68$
[Qu, Gouskos '19]

Task 1: Hadronic spin reconstruction

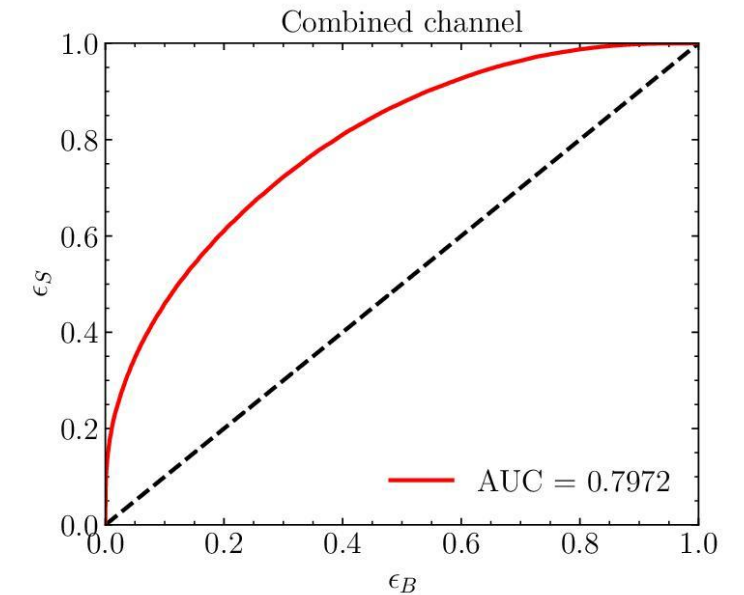
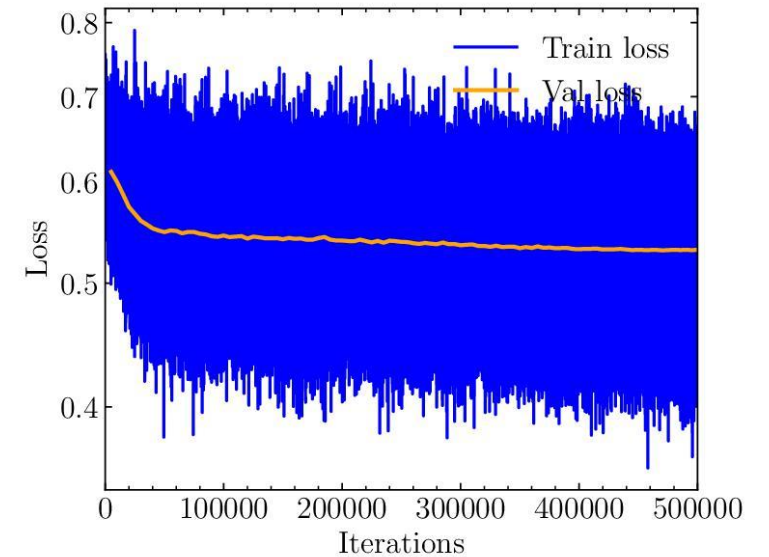


L-GATr vs. L-GATr-slim

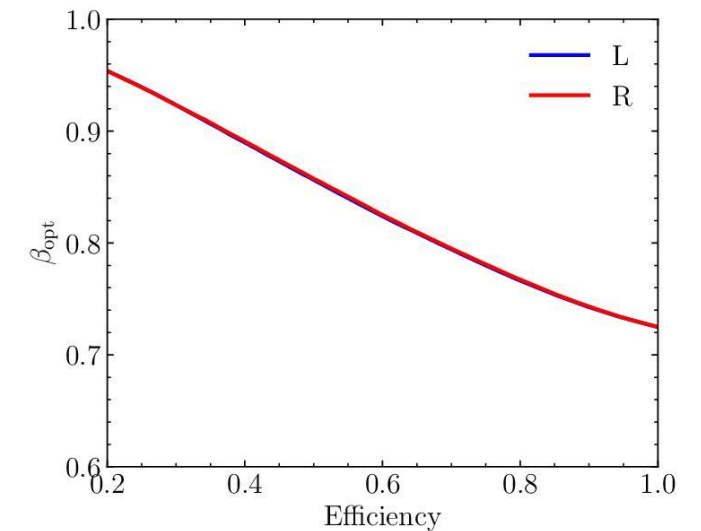
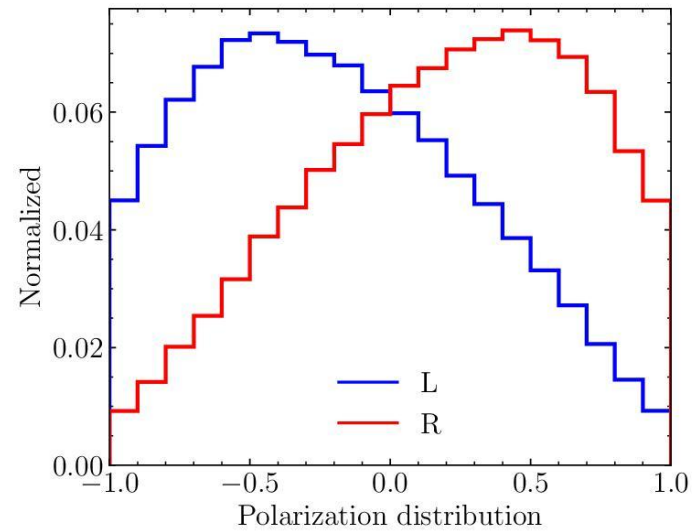
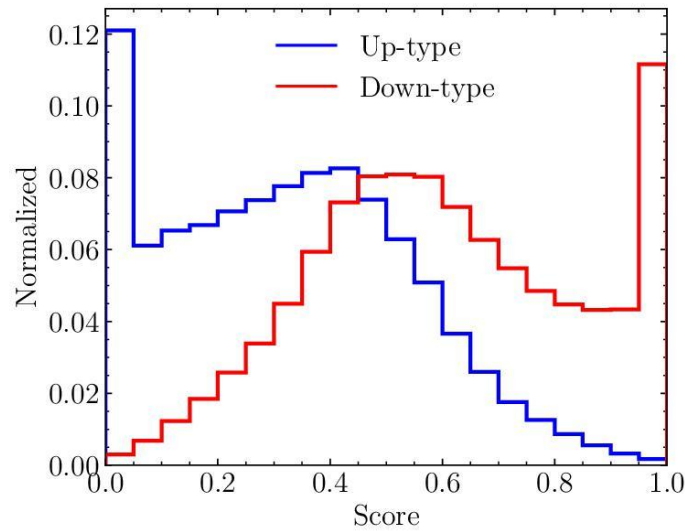
Both models show similar performance

L-GATr-slim learns more smoothly

⇒ Only L-GATr-slim results shown from now on



Task 1: Hadronic spin reconstruction



Use score to build hadronic spin proxy $q_d = p(d \rightarrow q_{\text{hard}}|\mathcal{O})\hat{q}_{\text{hard}} + p(d \rightarrow q_{\text{soft}}|\mathcal{O})\hat{q}_{\text{soft}}$

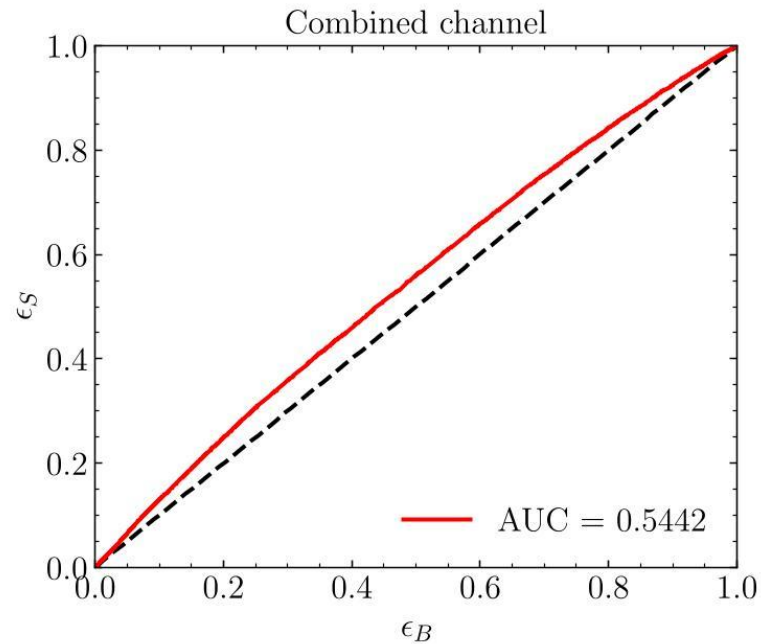
⇒ Improve spin analyzing power to $\beta_d = 0.72$ ($\beta_d = 0.95$ for 20% best events)

Task 2: CP classification

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2d_{tG}\text{Re}\left(\mathcal{M}_{\text{SM}}^\dagger \mathcal{M}_{\text{BSM}}\right) + d_{tG}^2 |\mathcal{M}_{\text{BSM}}|^2$$

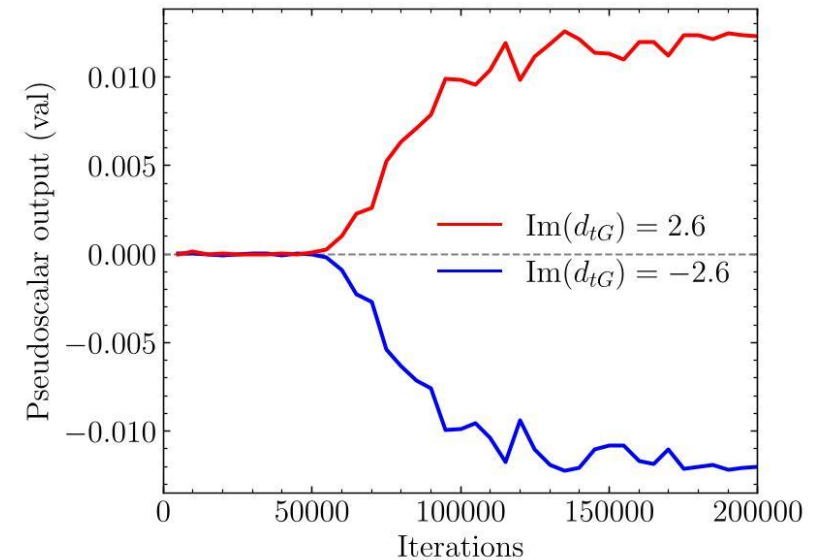
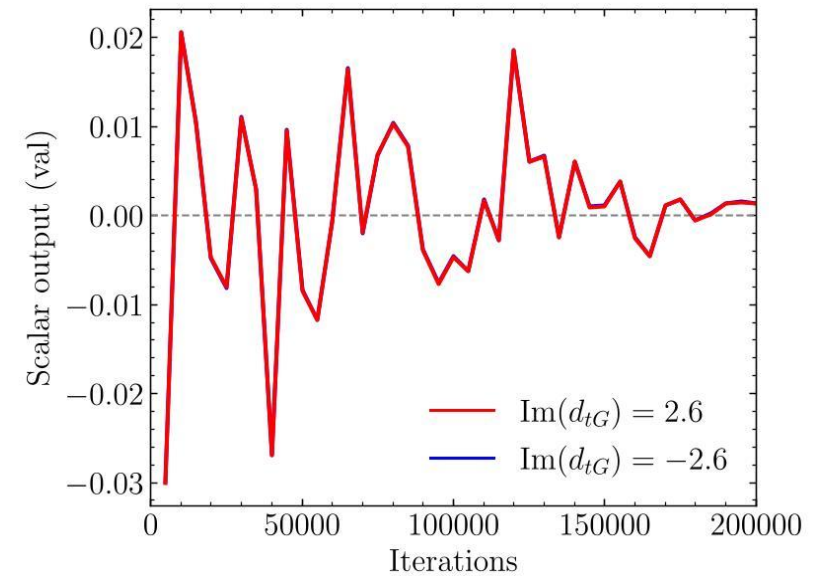
- Training to differentiate events with positive and negative interference produces an optimal CP-odd observable
- Training to differentiate the SM from a non-zero d_{tG} contains both CP-even and CP-odd information
- Training is performed with full down quark information
- Evaluation is performed with the output from the down-tagging network

Task 2: CP classification: neg. vs. pos.



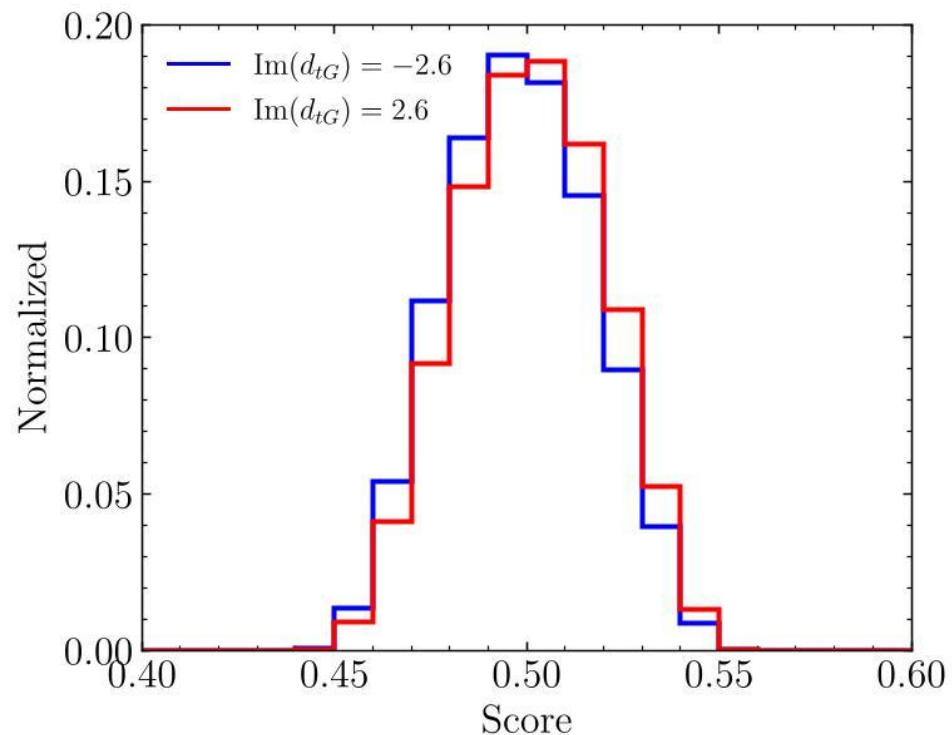
For the positive vs. negative training, all the separation power sits in the pseudoscalar channel

⇒ L-GATr-slim learns in the pseudoscalar channel and drives the scalar output to zero

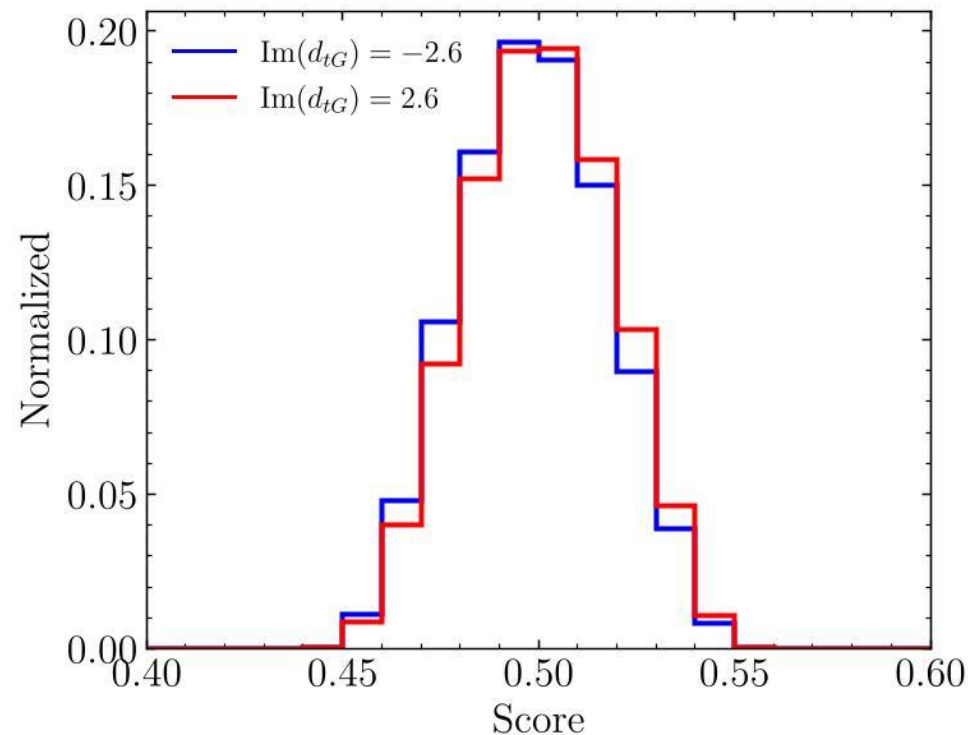


Task 2: CP classification: neg. vs. pos.

Dileptonic channel (full spin information)

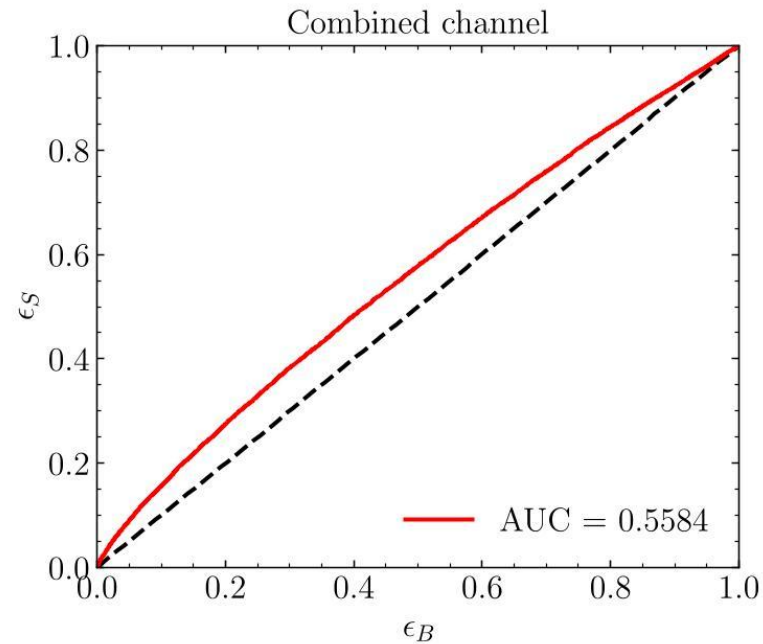


Semileptonic channel (down-tagging information)



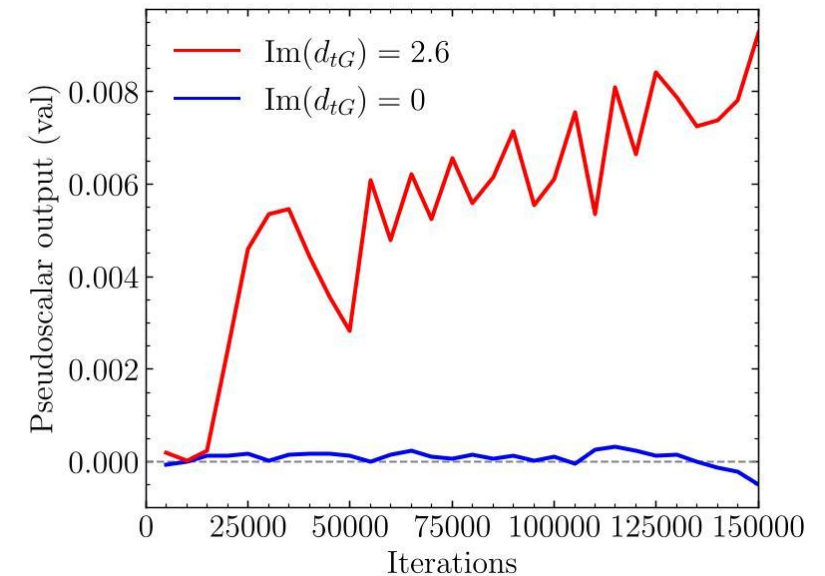
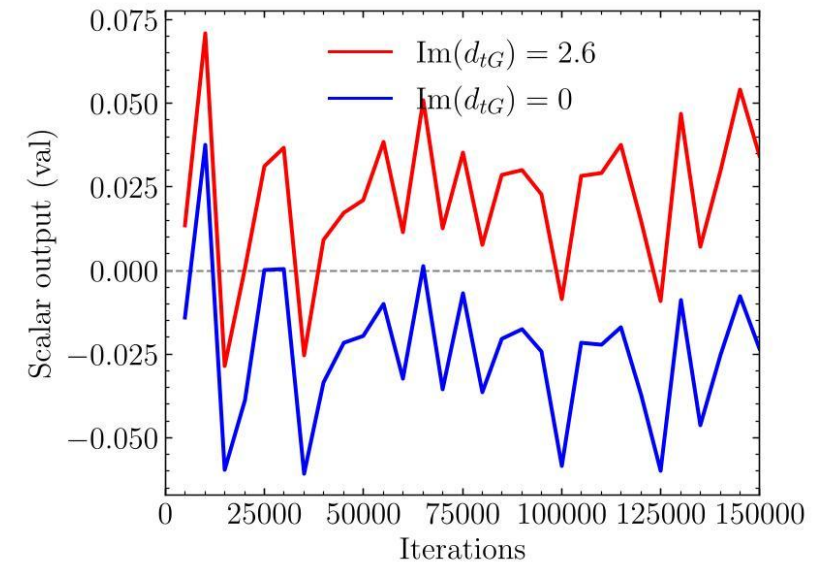
Clear separation also in the semileptonic channel
Experimental sensitivity to be studied (number of events, backgrounds)

Task 2: CP classification: SM vs. pos.



Slightly better AUC due to the additional scalar separation power

The SM data stays at a pseudoscalar output of zero



Conclusions & Outlook

- L-GATr reaches state-of-the-art performance for hadronic top quark spin reconstruction via light quark tagging
- L-GATr-slim performs at least as well as the full architecture
- The Lorentz-equivariant design offers a clear separation of CP-violating data into its CP-even and CP-odd components for increased interpretability

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- Outlook: Lunch

