Computational methods for precision collider physics

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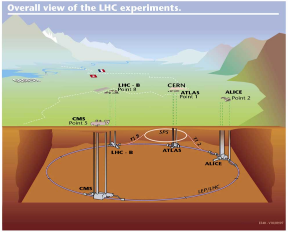
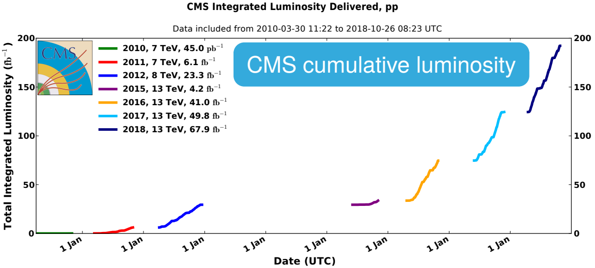
RESEARCH ACTIVITIES

Physics at the high energy frontier

- LHC offers access to a whole qualitatively new set of interactions, Yukawas couplings, which can be probed at precision over a wide range of momenta.
- Extremely broadband new-physics search machine, with ∼1k channels across several orders of magnitude in momentum scales.
- Accurate predictions and optimized algorithms are required to make sense of noisy data spanning orders of magnitude in energy.





CMS cumulative luminosity

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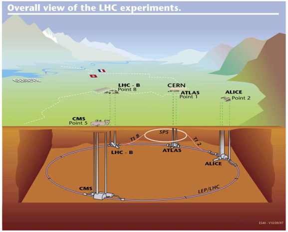
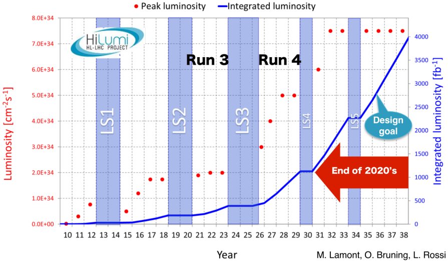




M. Lamont, O. Bruning, L. Rossi

ATLAS and CMS

Run 3	Run4	HL-LHC total
300 fb^{-1}	1 ab^{-1}	3 – 4 ab^{-1}

LHCb

Run 3	Run 4	HL-LHC total
23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

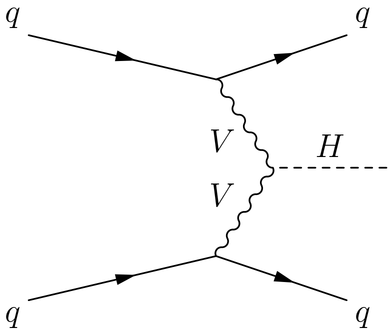
Higgs physics with high precision

Studies of H and HH production can offer clues into electroweak symmetry breaking, notably on the Higgs potential and Yukawa couplings.

VBF-induced Higgs production is accompanied by two high rapidity jets.

$$qq \to qq + (V^*V^* \to)H$$

To distinguish these events from $gg \to H$, impose kinematics cuts on the jets, which requires precise predictions of the jet fragmentation.



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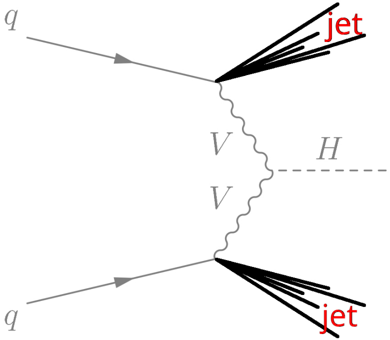
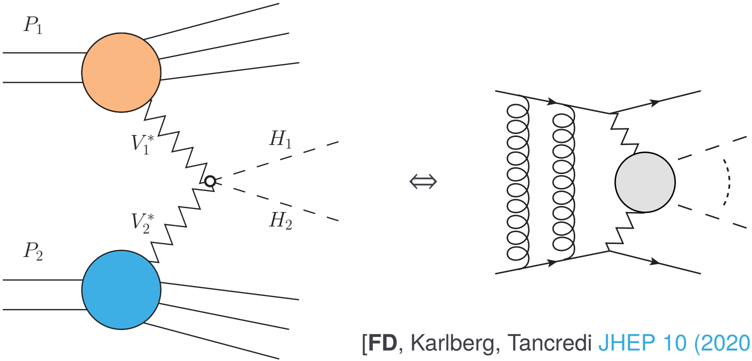


Non-factorisable effects in VBF Higgs production

- Higher order corrections typically computed in structure function approximation, where interference between quark lines is neglected.
- Understanding limitations of these approximations is necessary to study Higgs sector at few percent-level accuracy.
- Non-factorisable QCD corrections can have large impact on di-Higgs production.



[**FD**, Karlberg, Tancredi JHEP 10 (2020) 131]

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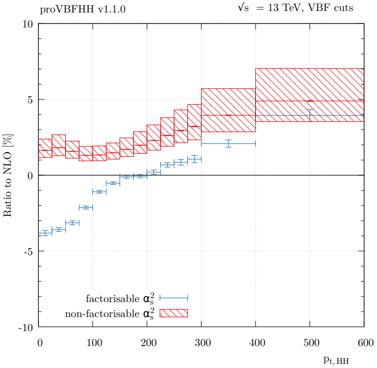
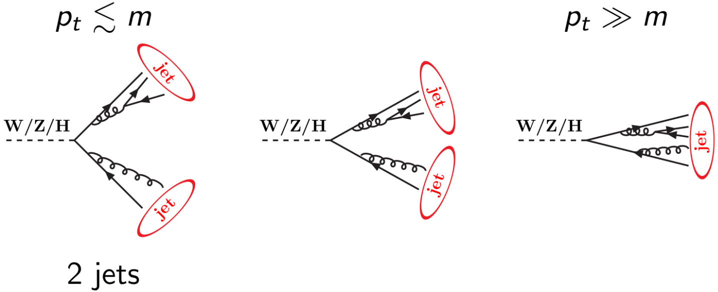
$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{HH,\mathrm{nf}} \sim \Big(\frac{N_c^2-1}{4N_c^2}\Big)\alpha_s^2\Big[\left(\frac{5}{4}-\frac{\pi^2}{3}\right)\mathrm{d}\sigma^{\mathrm{LO}}_{BB} + \left(1-\frac{\pi^2}{3}\right)\left(\mathrm{d}\sigma^{\mathrm{LO}}_{TT}+\mathrm{d}\sigma^{\mathrm{LO}}_{TB}\right)\Big]$$

[**FD**, Karlberg, Tancredi JHEP 10 (2020) 131]



Boosted objects at the LHC

- At LHC energies, EW-scale particles (W/Z/t…) are often produced with $p_t \gg m$, leading to collimated decays.
- Hadronic decay products are thus often reconstructed into single jets.



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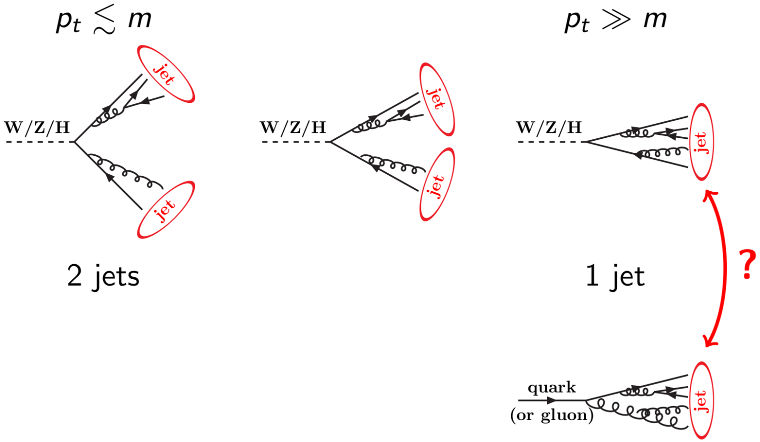


$p_t \lesssim m$

$p_t \gg m$

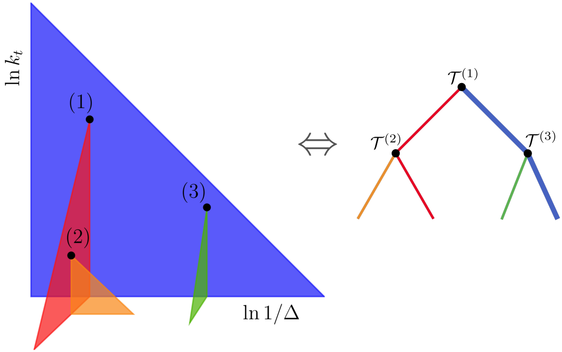
2 jets

1 jet

Lund plane representation of jets

Lund diagrams are a useful way of representing emissions in the $(\ln\Delta, \ln k_t)$-plane.

- Each jet can be mapped onto a tree of Lund declusterings from its (Cambridge/Aachen) clustering sequence.
- Primary sequence of hardest transverse momentum branch is of particular interest for measurements and visualisation.



[**FD**, Salam, Soyez, JHEP 1812 (2018) 064]

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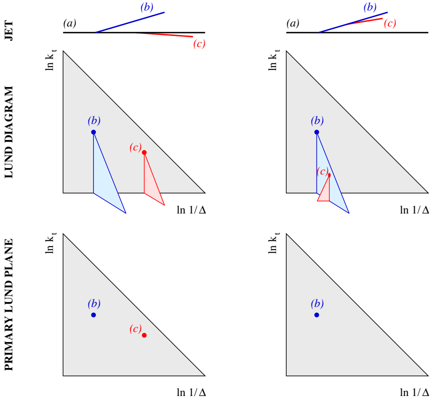
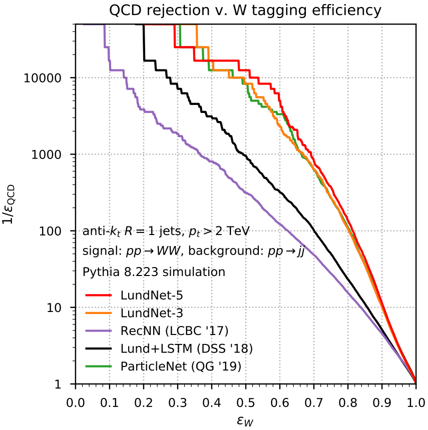
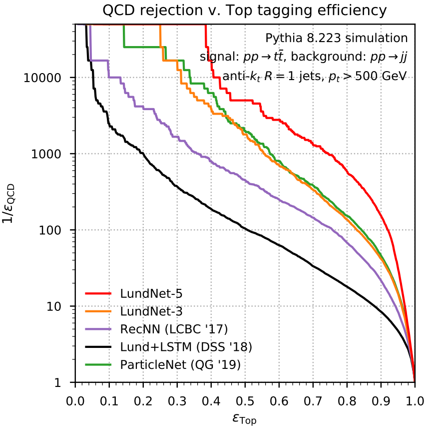


[**FD**, Salam, Soyez, JHEP 1812 (2018) 064]

Boosted object tagging with graph networks

- Use Lund plane as an input to graph neural network, treating each declustering as a node on the graph.
- LundNet model provides substantial improvement over ParticleNet (current SOTA) and is an order of magnitude faster to train/deploy.

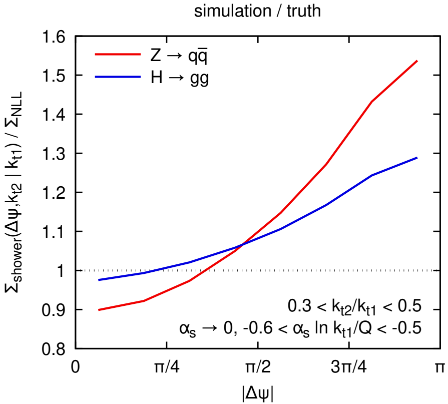

QCD rejection v. W tagging efficiency

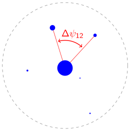

QCD rejection v. Top tagging efficiency

[**FD**, Qu, arXiv:2012.08526, to appear in JHEP]

But what does the machine learn?

- Important limitation stems from the fact that labelled training data is usually obtained from Monte Carlo event generators.
- But parton shower simulations are not perfect tools!



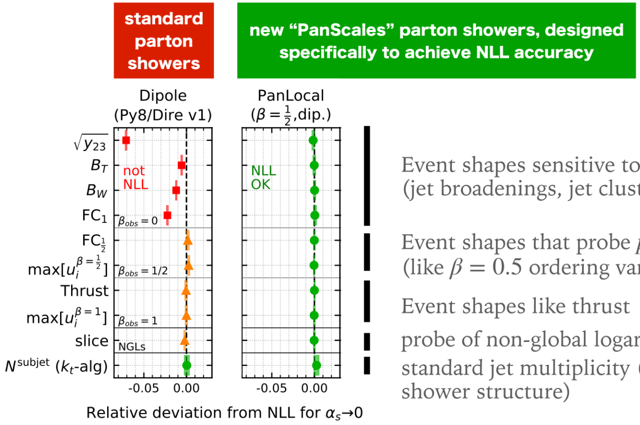


Common dipole showers display quark/gluon differences that should not be there.

- How to be sure ML models are not overfitting unphysical features?

[Dasgupta, **FD**, Hamilton, Monni, Salam, Soyez, Phys.Rev.Lett. 125 (2020) 5, 052002]

Designing new showers for precision physics



Event shapes sensitive to transverse momentum (jet broadenings, jet clustering transitions)

Event shapes that probe $p_t e^{-0.5|\eta|}$ (like $\beta = 0.5$ ordering variable)

Event shapes like thrust

probe of non-global logarithms

standard jet multiplicity (probe of full recursive shower structure)

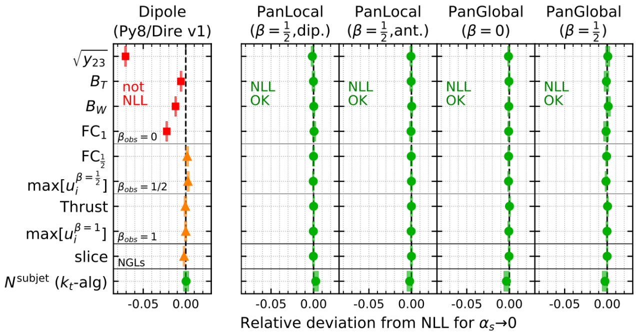
[Dasgupta, **FD**, Hamilton, Monni, Salam, Soyez, Phys.Rev.Lett. 125 (2020) 5, 052002]

Paves the way for improved simulations with more accurate physical description of perturbative radiation.

Designing new showers for precision physics

standard parton showers

new “PanScales” parton showers, designed specifically to achieve NLL accuracy



All PanScales shower that are expected to agree with NLL pass these tests

(Standard dipole showers don’t)

[Dasgupta, **FD**, Hamilton, Monni, Salam, Soyez, Phys.Rev.Lett. 125 (2020) 5, 052002]

Paves the way for improved simulations with more accurate physical description of perturbative radiation.

SOFTWARE AND COMPUTING

Notable software contributions

Fixed order programs:

- proVBFH & proVBFHH: NNLO QCD corrections to VBF single and di-Higgs production.
- proVBFH-incl: inclusive N^3LO QCD corrections to the same processes.

Resummation and parton showers:

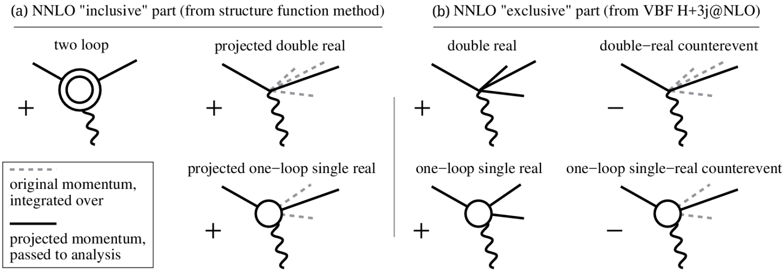
- MicroJets: Resummation of small-radius jets and interactive web interface.
- PanScales: New generation of parton showers with higher accuracy.

Jet substructure and machine learning:

- LundPlane & RecursiveTools plugins: FastJet implementation of novel substructure methods.
- GroomRL: Reinforcement learning framework for jet grooming.
- gLund & CycleJet: Generative and image-to-image translation models for jets.
- LundNet: Framework for jet tagging with graph networks.

proVBFH: QCD corrections in VBF Higgs production

- Fortran 90 program performing state-of-the-art calculation of higher order QCD corrections in VBF single and di-Higgs production
  - proVBFH: fully differential VBF Higgs production at NNLO using project-to-Born method.
  - proVBFHH: fully differential VBF Higgs pair production at NNLO.
  - proVBFH-incl: inclusive N^{3}LO corrections to single and di-Higgs VBF.
- Non-factorisable corrections in the eikonal approximation can be included in proVBFH & proVBFHH.



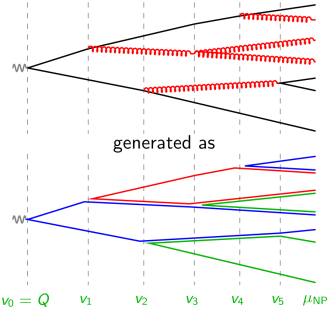
Code available at provbfh.hepforge.org

PanScales: Parton showers with higher logarithmic accuracy

- C++ framework for new generation of parton showers.
- Provides NLL accurate parton shower with systematic checks.
- Achieves stable results in extreme kinematic limits.

Evolution from state with n particles to state with $n+1$ is described by

$$\frac{d\mathcal{P}_{n\to n+1}}{d\ln v} = \sum_{\text{dipoles }\{\tilde{i},\tilde{j}\}} \int d\bar{\eta}\frac{d\phi}{2\pi}\frac{\alpha_s(k_t)+K\alpha_s^2(k_t)}{\pi} \times \left[g(\bar{\eta})a_k P_{\tilde{i}\to ik}(a_k) + g(-\bar{\eta})b_k P_{\tilde{j}\to jk}(b_k)\right],$$

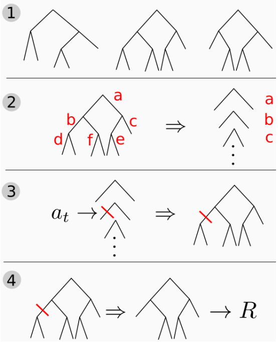


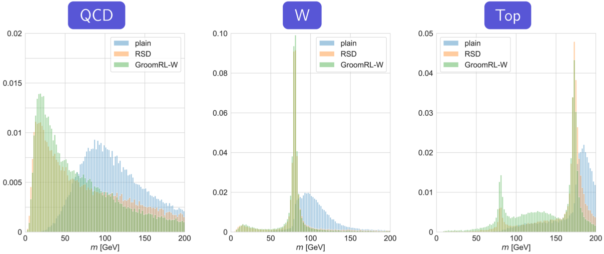
Key ingredients:

- Kinematic mapping $S_n \longrightarrow S_{n+1}$.
- Choice of volution variable v.

GroomRL: Jet grooming with reinforcement learning

- Optimisation of jet grooming strategy using Deep-Q-Network.
- Python 3 code using Keras-RL, TensorFlow, OpenAI gym & Hyperopt.
- First application of reinforcement learning in HEP, leads to improvement in mass resolution.



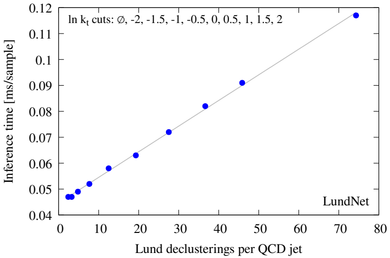


$n_{\text{epochs}} = 500k$

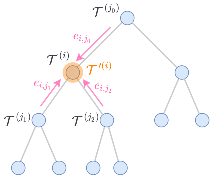
Code available at:
github.com/JetsGame/GroomRL

LundNet: Jet tagging in the Lund plane with graph networks

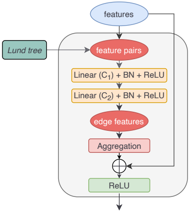
- Python 3 code using dgl and torch for jet tagging with graph networks.
- Order of magnitude speed gain over previous graph-based models.
- Outperforms state-of-the-art for top tagging by factor $\sim 2-3$.



Code available at:
github.com/fdreyer/LundNet



(a)



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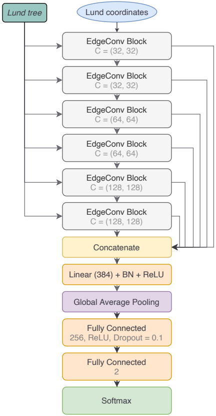

(c)