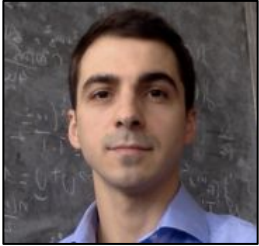


Partons²Hadrons



Pier Monni (CERN)



Simon Plätzer (University of Graz)



Andrzej Siodmok (Jagiellonian University)



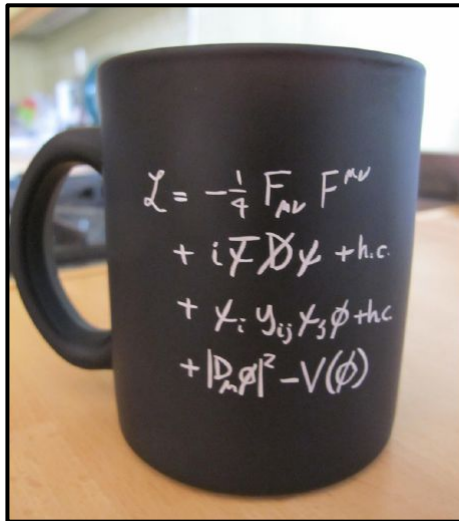
Motivation - Monte Carlo Event Generators (MCEG)

Standard Model

There is a **huge gap** between a one-line formula of a fundamental theory, like the Lagrangian of the SM, and the experimental reality that it implies

Theory

Standard Model Lagrangian



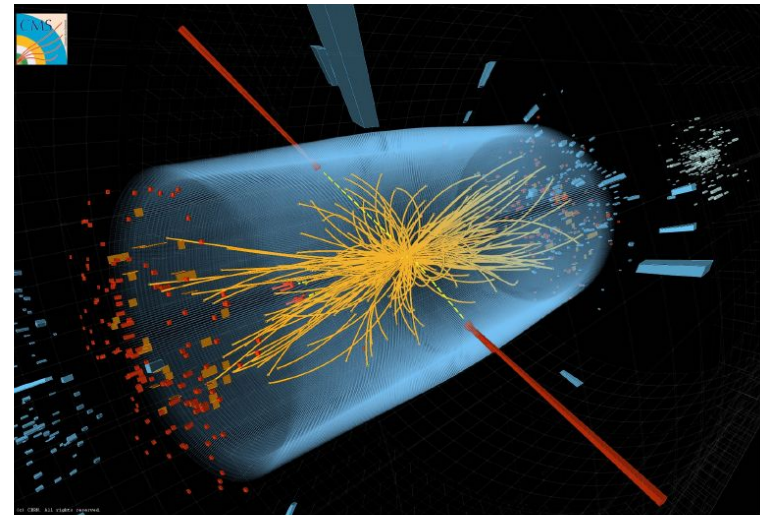
Data makes you smarter

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

Richard P. Feynman

Experiment

LHC event



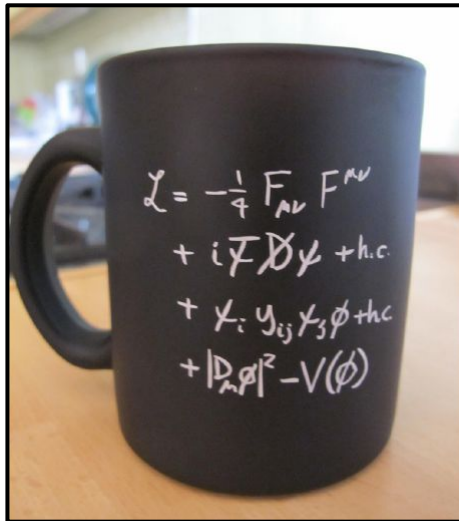
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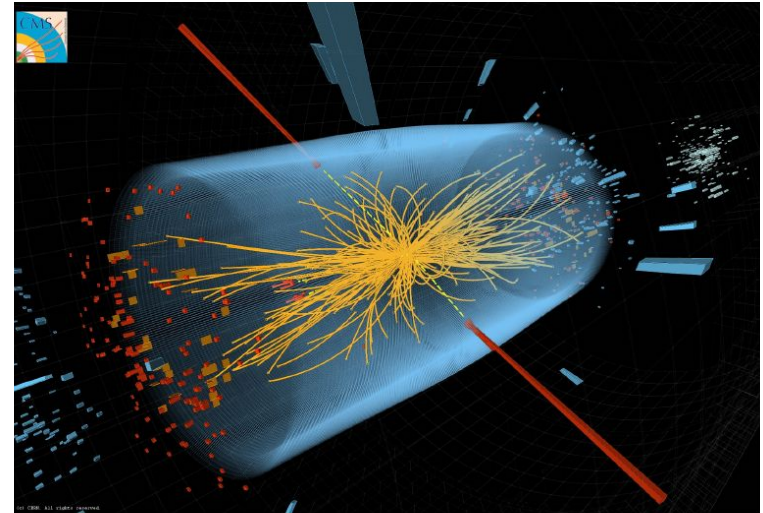
Theory

Standard Model Lagrangian



Experiment

LHC event



- MC event generators are designed to bridge the that **gap**
- “Virtual collider” \Rightarrow Direct comparison with data



Almost all **HEP measurements and discoveries** in the modern era have **relied on MCEG**, most notably the discovery of the Higgs boson.

Herwig [**AS,SP**], Sherpa, Pythia

Published papers by ATLAS, CMS, LHCb: **2252**
Citing at least 1 of 3 existing MCEG: **1888 (84%)**

Motivation - Monte Carlo Event Generators (MCEG)

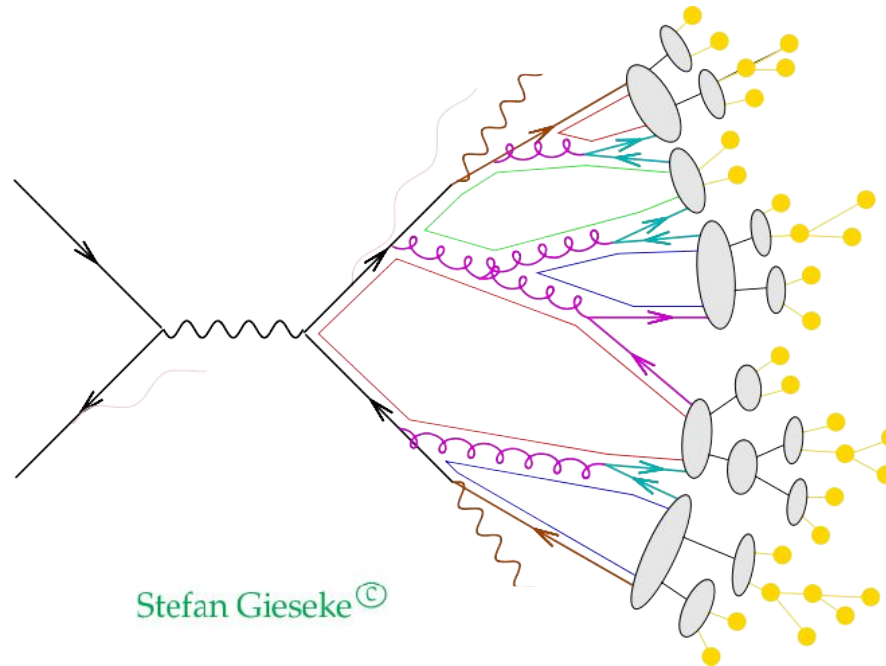
QCD correctly describes strong interactions in each energy range but its complex mathematical structure makes it very difficult to obtain precise predictions (Millennium Prize Problem \$1,000,000)

High energy

- perturbative QCD
- in theory we know what to do
- in practice very challenging

Low energy

- non-perturbative QCD
- we don't know what to do
- phenomenological models (with many free parameters)



Why hadronization?

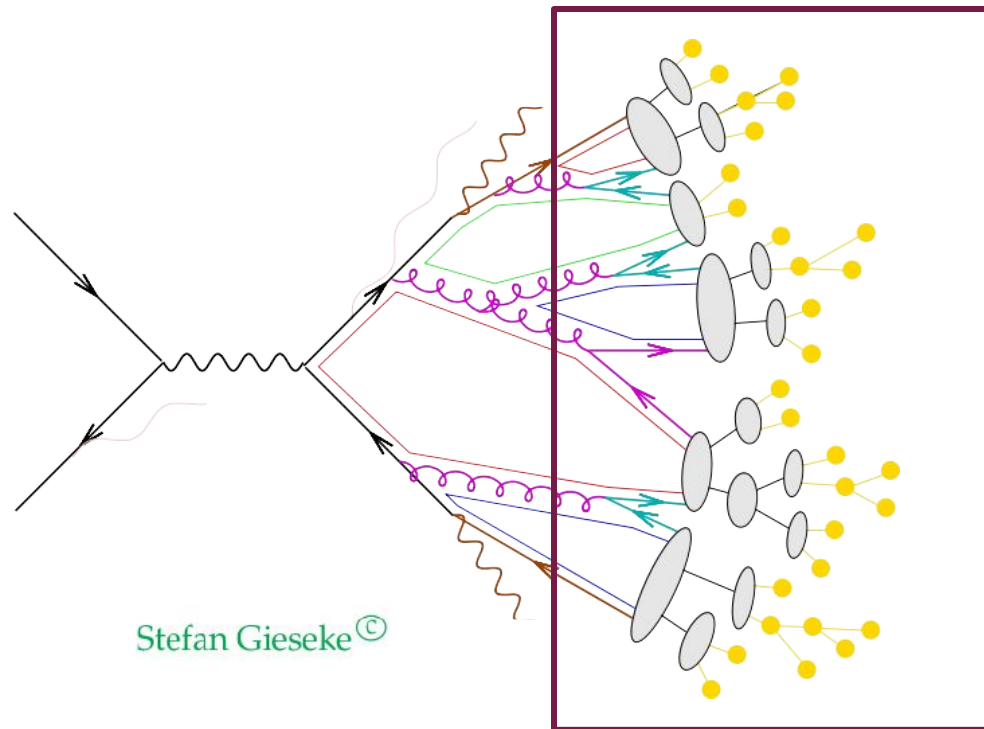
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Partons2Hadrons

one of the least understood elements of MCEG

Motivation - Hadronization

Hadronization:

→ Increased control of perturbative corrections \Rightarrow more often LHC measurements are limited by non-perturbative components, such as hadronization.

- W mass measurement using a new method [Freytsis et al. JHEP 1902 (2019) 003]
- Extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5]
- Top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
- ...

Pier Moni's talk
FCC Physics Workshop 2023

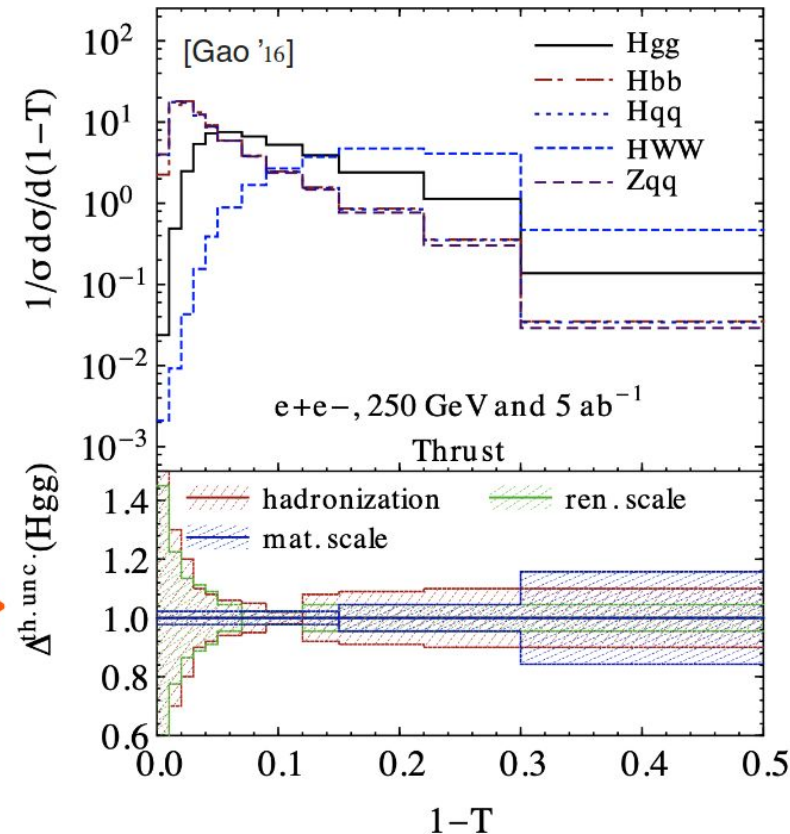
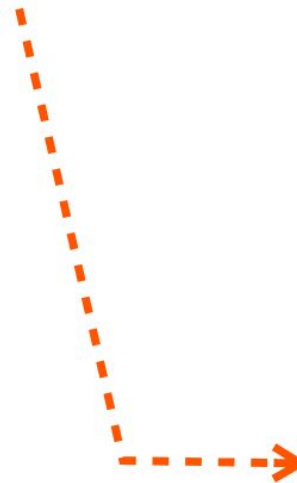
- However, hadronisation remains the main bottleneck

- e.g. thrust in Higgs decays (MC variation in plot)

- Increase in energy insufficient for suppression ($Q \sim m_H$)

- Runs at lower energies are essential for a robust tuning of NP models in MCs

- Also crucial for training of ML algorithms for jet tagging, instrumental in extraction of Higgs couplings



Motivation - Hadronization

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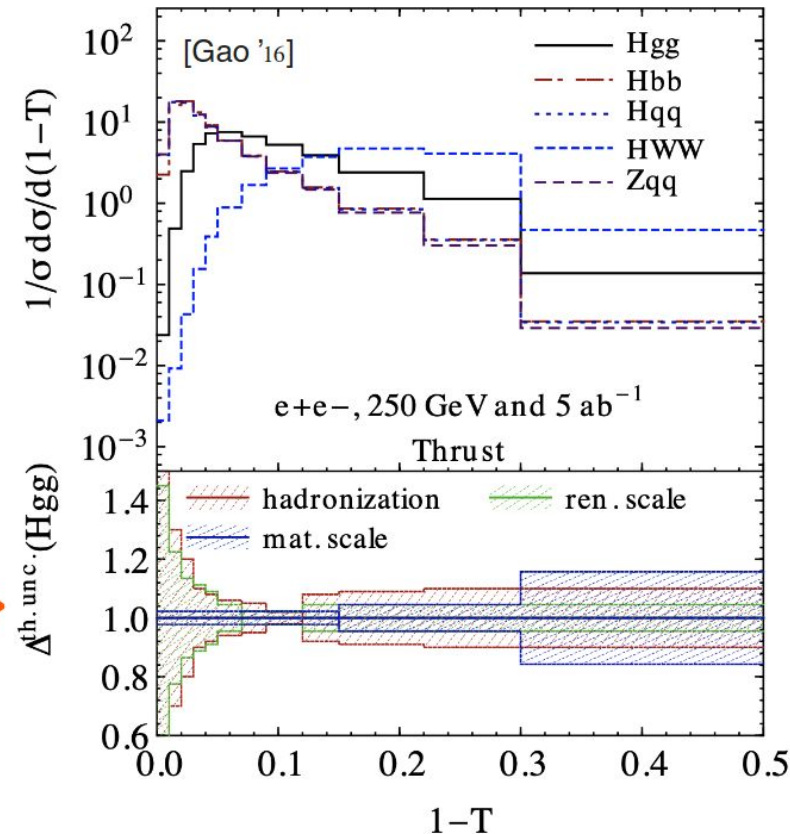
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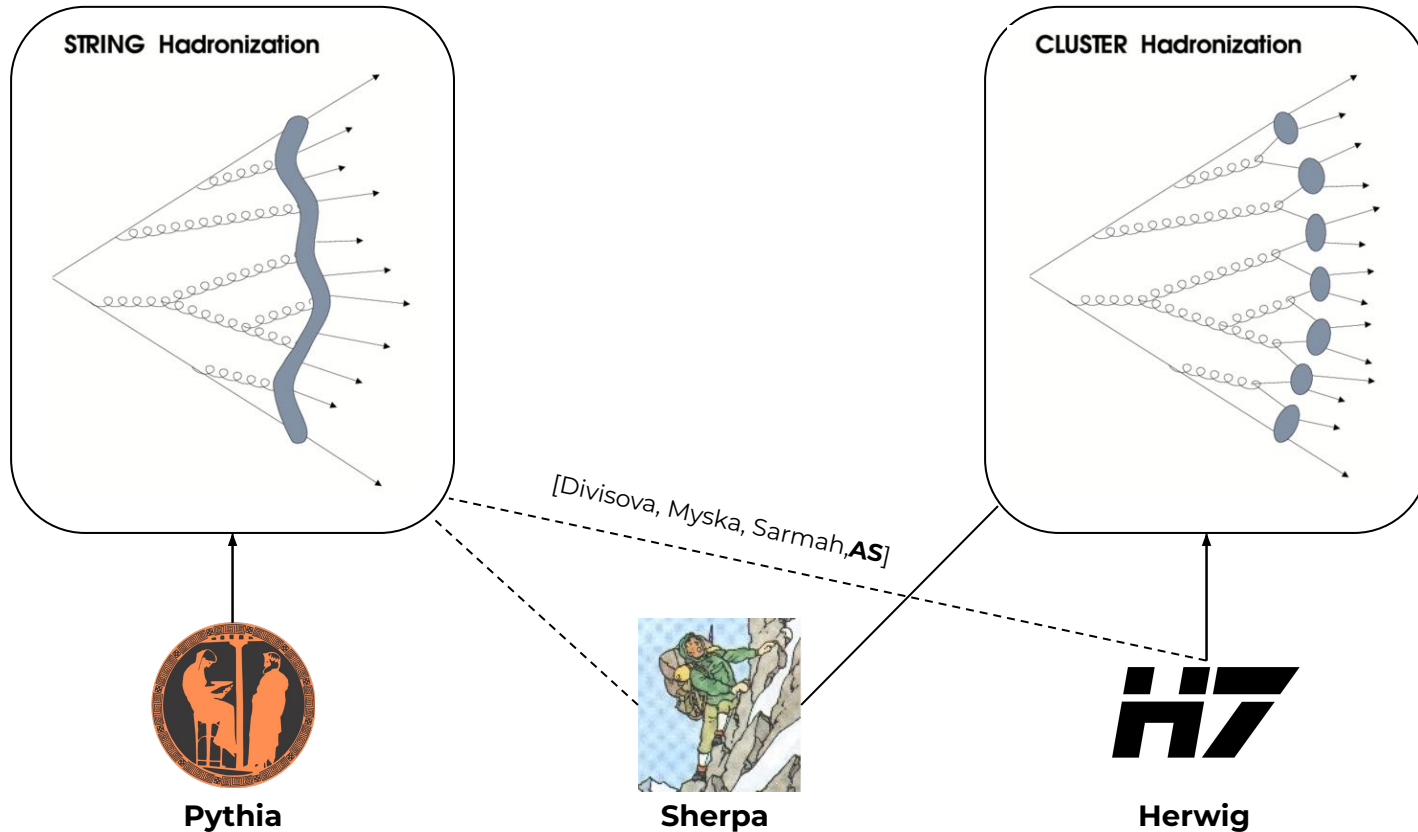


Motivation - Hadronization

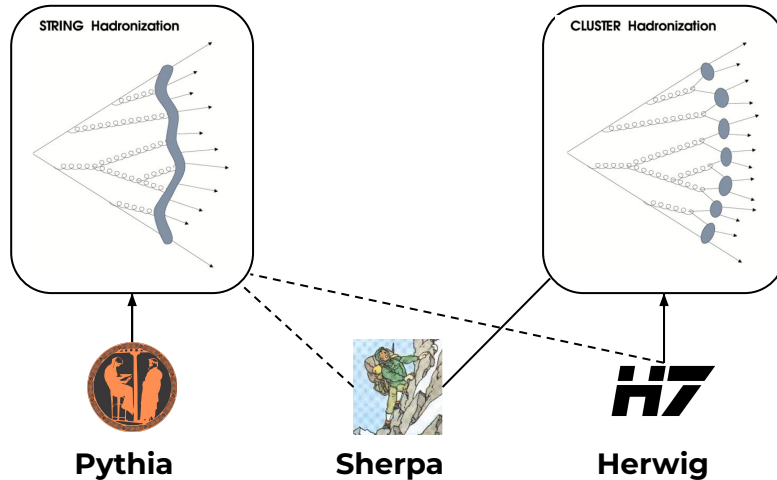
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- ...



Early 1980's



Cluster:

[Webber NPB238(1984)492]

...

“Phenomenological constraints of the building blocks of the cluster hadronization model”

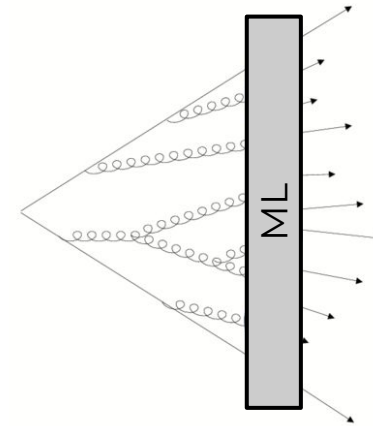
[Gieseke, Kiebacher, **SP**, Priedigkeit 2505.14542]

String:

[Andersson, Gustafson, Ingelman, Sjostrand, Phys.Rept.97(1983)31]

...

Early 2020's



H A E D M L

[Ghosh, Ju, Nachman **AS**, Phys.Rev.D 106 (2022) 9]

[Chan, Ju, Kania, Nachman, Sangli, **AS**, JHEP 09 (2023) 084]

[Chan, Ju, Kania, Nachman, Sangli, **AS**, Phys.Rev.D 111 (2025)]

MLHAD

[Ilten, Menzo, Youssef, Zupan, SciPost Phys. 14, 027 (2023)]

...

Parton Showers (recent developments):

Possibly in the future NNLL becoming the next state-of-the-art

NNLL is quickly becoming the standard for parton showers

PanScales

Parton showers beyond leading logarithmic accuracy

Mrinal Dasgupta,¹ Frédéric A. Dreyer,² Keith Hamilton,³ Pier Francesco Monni,⁴ Gavin P. Salam,^{2,*} and Grégory Soyez⁵

Matching and event-shape NNLL accuracy in parton showers

Keith Hamilton,^a Alexander Karlberg,^{b,c} Gavin P. Salam,^{b,d} Ludovic Scyboz,^b Rob Verheyen^a

PanScales showers for hadron collisions: all-order validation

Melissa van Beekveld,^a Silvia Ferrario Ravasio,^a Keith Hamilton,^b Gavin P. Salam,^{a,c} Alba Soto-Ontoso,^d Grégory Soyez,^d Rob Verheyen^b

Spin correlations in final-state parton showers and jet observables

Alexander Karlberg¹, Gavin P. Salam^{1,2}, Ludovic Scyboz¹, Rob Verheyen³

Colour and logarithmic accuracy in final-state parton showers

Keith Hamilton,^a Rok Medves,^b Gavin P. Salam,^{b,c} Ludovic Scyboz,^b Grégory Soyez^d

Next-to-leading-logarithmic PanScales showers for Deep Inelastic Scattering and Vector Boson Fusion

Melissa van Beekveld,^a Silvia Ferrario Ravasio,^b

Building a consistent parton shower

Jeffrey R. Forshaw,^{a,b} Jack Holguin,^{a,b} Simon Plätzer,^{b,c}

Improvements on dipole shower colour

Jack Holguin^{a,1}, Jeffrey R. Forshaw^{b,1}, Simon Plätzer^{c,2}

¹ Consortium for Fundamental Physics, School of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom
² Particle Physics, Faculty of Physics, University of Vienna, 1080 Wien, Austria

DEDUCTOR

Summations of large logarithms by parton showers

Zoltán Nagy
DESY, Notkestrasse 85, 22607 Hamburg, Germany *

Davison E. Soper
Institute for Fundamental Science, University of Oregon, Eugene, OR 97403-5203, USA¹
(Dated: 18 August 2021)

Summations by parton showers of large logarithms in electron-positron annihilation

Zoltán Nagy
DESY, Notkestrasse 85, 22607 Hamburg, Germany *

Davison E. Soper
Institute for Fundamental Science, University of Oregon, Eugene, OR 97403-5203, USA¹
(Dated: 13 November 2020)

Introduction to the PanScales framework, version 0.1

Melissa van Beekveld¹, Mrinal Dasgupta², Basem Kamal El-Menoufi^{2,3}, Silvia Ferrario Ravasio⁴, Keith Hamilton⁵, Jack Helliwell⁶, Alexander Karlberg⁴, Rok Medves⁶, Pier Francesco Monni⁴, Gavin P. Salam^{6,7}, Ludovic Scyboz^{3,6}, Alba Soto-Ontoso⁴, Grégory Soyez⁸, Rob Verheyen³

ALARIC

A new approach to color-coherent parton evolution

Florian Herren,¹ Stefan Höche,¹ Frank Krauss,² Daniel Reichelt,² and Marek Schönherr²

¹ Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA
² Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

A new approach to QCD evolution in processes with massive partons

Benoît Assi and Stefan Höche
Fermi National Accelerator Laboratory, Batavia, IL, 60510

The Alaric parton shower for hadron colliders

Stefan Höche,¹ Frank Krauss,² and Daniel Reichelt²

APOLLO

A partitioned dipole-antenna shower with improved transverse recoil

Christian T. Preuss

Department of Physics, University of Wuppertal, 42119 Wuppertal, Germany
E-mail: preuss@uni-wuppertal.de

Soft spin correlations in final-state parton showers

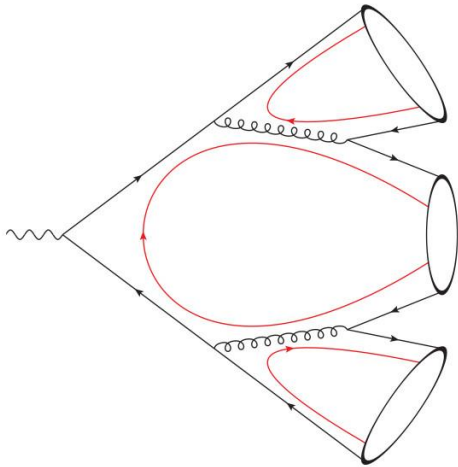
Keith Hamilton,^a Alexander Karlberg,^b Gavin P. Salam,^{b,c} Ludovic Scyboz,^b Rob Verheyen^a

slide from Pier Monni [... & more]

N(N)LL PS (will be) available for standard MCEG (PY8, HERWIG, SHERPA):
Hadronization parameters need to be retuned to match the improved perturbative shower.

Build on insights originating from Perturbative Evolution

The philosophy of cluster m.: use information from perturbative QCD as an input for hadronization. QCD **pre-confinement** discovered by Amati & Veneziano [*Phys.Lett.B* 83 (1979) 87-92]:

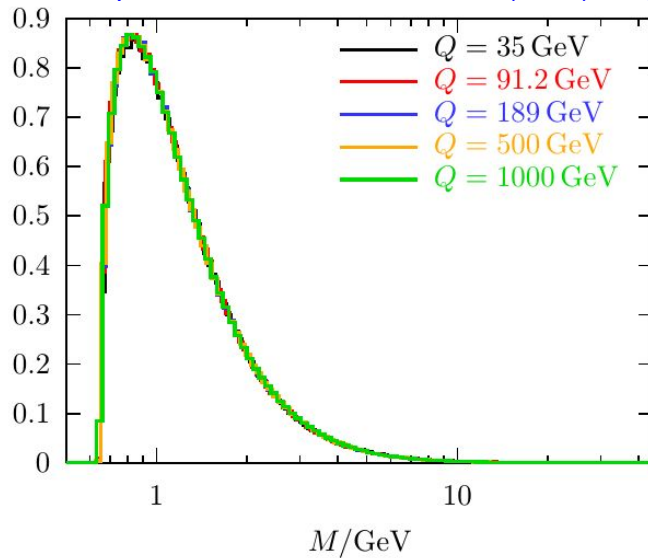


- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters

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[S. Gieseke, A. Ribon, MH Seymour,
P Stephens, B Webber JHEP 0402 (2004) 005]

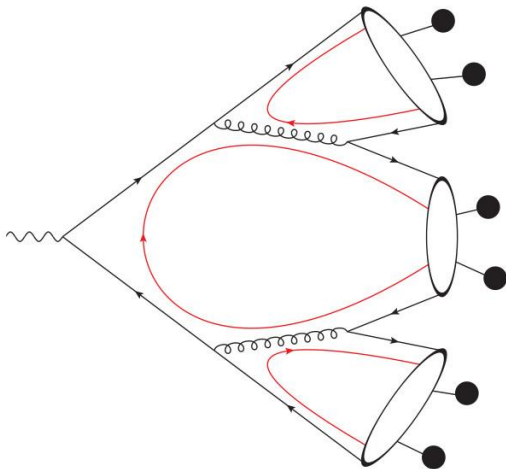


- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters
- Pre-confinement states that the spectra of clusters are independent of the hard process and energy of the collision

Build on insights originating from Perturbative Evolution

The philosophy of the model: use information from perturbative QCD as an input for hadronization.

QCD **pre-confinement** discovered by Amati & Veneziano:



- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters
- Pre-confinement states that the spectra of clusters are independent of the hard process and energy of the collision
- Peaked at low mass (1-10 GeV) typically decay into 2 hadrons

Other example:

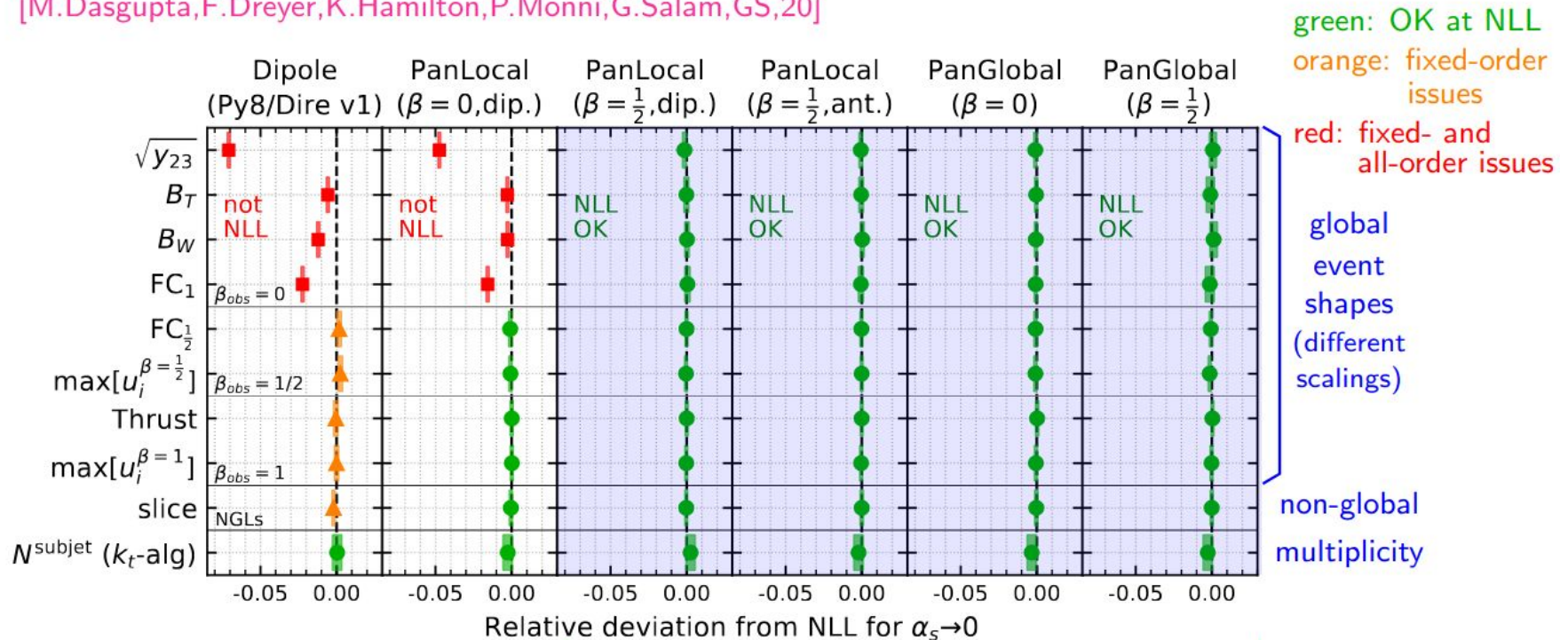
- “Colour Reconnection from Soft Gluon Evolution” [Gieseke, Kirchgaßer, **SP, AS**, JHEP 11 (2018)]
- “Matching Hadronization and Perturbative Evolution: The Cluster Model in Light of Infrared Shower Cutoff Dependence” [Hoang, Jin, **SM**, Samitz, 2404.09856]

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[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]



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Plan

1. Foster collaborations and discussions across the theoretical and experimental community on the state-of-the-art modelling of non-perturbative aspects in MCPS (everyone is welcome!). [\[PM, CERN natural location\]](#)
2. Development and implementation of novel hadronization models
 - a. Build on insights originating from the development of PS with higher logarithmic accuracy
see for example: “New Standard for the Logarithmic Accuracy of Parton Showers”
[\[PanScales including PM, Phys.Rev.Lett. 134 \(2025\) 1\]](#)
 - b. Exploitation of ML techniques
see for example: HADML
[\[Chan, Ju, Kania, Nachman, Sangli, AS, Phys.Rev.D 111 \(2025\)\]](#)
3. Analysis of publicly available LEP and Belle-II measurements
 - a. Construction of new observables (reanalysis of archived LEP)
see for example: “Measurement of parton shower observables with OPAL”
[\[Fischer, Gieseke, Kluth, SP, P. Skands, Eur. Phys. J. C75, 571 \(2015\)\]](#) also
[\[Thaler et al., Phys.Lett.B 856 \(2024\) 138957 and 2505.11828\]](#)
 - b. Using of unbinned data for tuning
see for example: “Fitting a deep generative hadronization model”
[\[Chan, Ju, Kania, Nachman, Sangli, AS, JHEP 09 \(2023\) 084\]](#)
4. Tuning of the hadronization models interfaced with public NLL and NNLL PS algorithms. [\[AS and SP a lot of experience\]](#)

Budget

Total: 330 kEUR

(accounting also for administrative overheads and conversion rate to CHF)

Personnel:

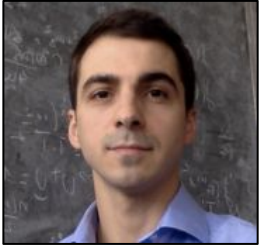
260 kCHF for a two-years postdoc position (TH or EXP fellowship) at CERN

Others:

50 kCHF to fund:

- the visit of EXP/TH users at CERN for collaboration meetings and studies on-site,
- topical workshops relevant to the development of the proposal
- stays at CERN of the project leaders Simon Plätzer and Andrzej Siodmok, needed to ensure a smooth execution of the proposal.

Partons²Hadrons



Pier Monni (CERN)



Simon Plätzer (University of Graz)



Andrzej Siodmok (Jagiellonian University)

Thank you for your attention!