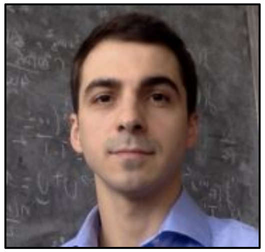
Partons2Hadrons



Pier Monni (CERN)

Simon Plätzer (University of Graz)

Andrzej Siodmok (Jagiellonian University)

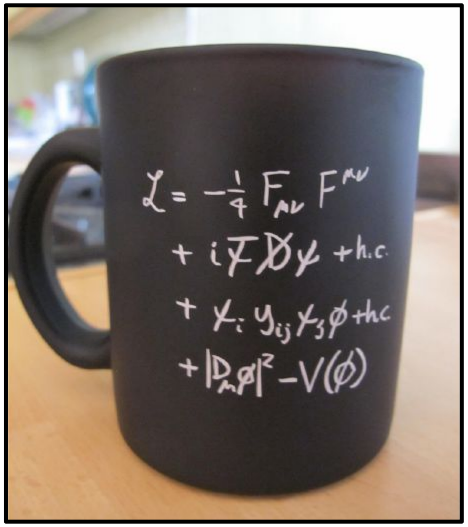
Motivation - Monte Carlo Event Generators (MCEG)

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



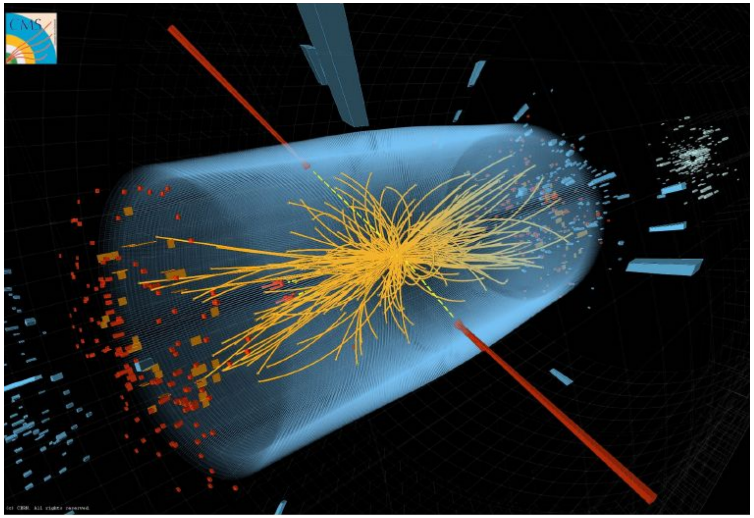
Data makes you smarter

> 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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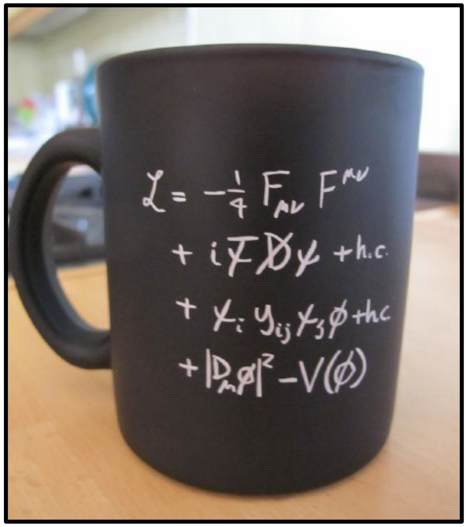

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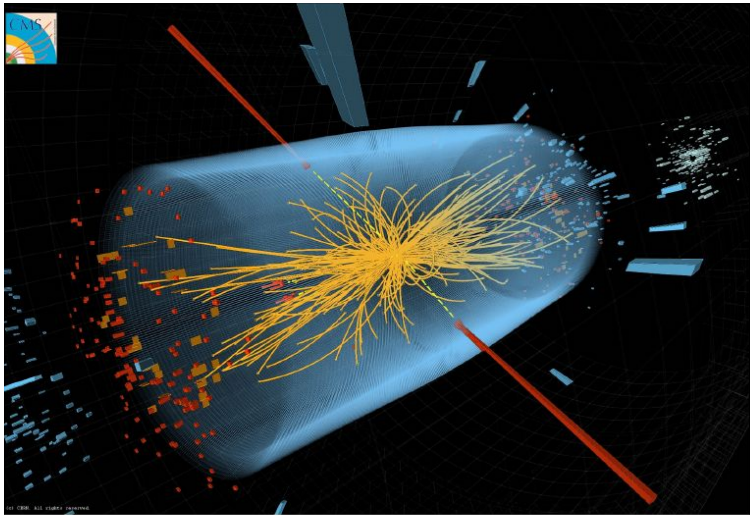


- MC event generators are designed to bridge the that **gap**
- “Virtual collider” ⇒ Direct comparison with data

⇩

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)

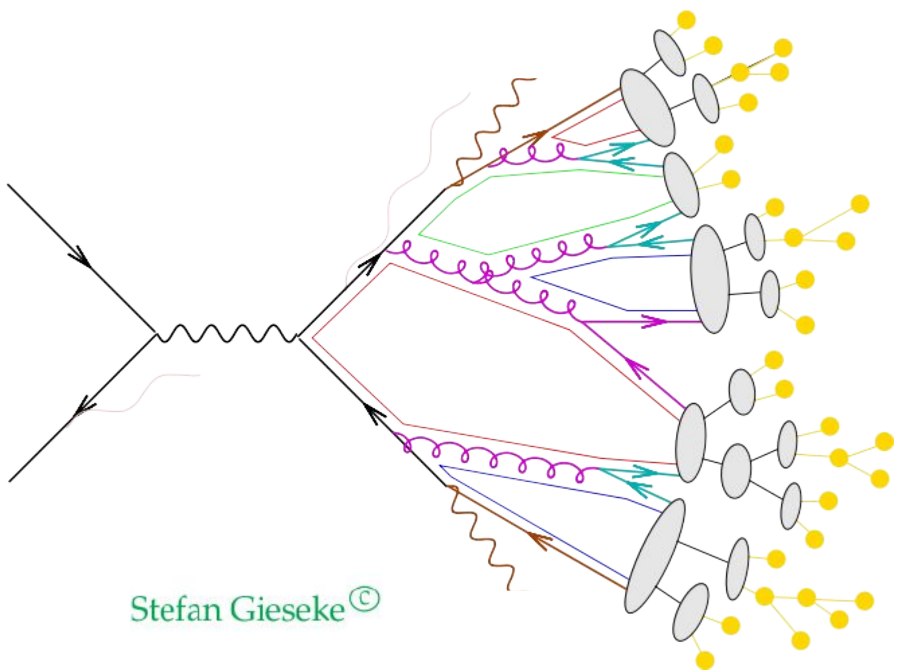
QCD correctly describes strong interactions in each energy range but its complex mathematical structure makes it very difficult to obtain precise predictions (Millennium Prize Problem $1,000,000)

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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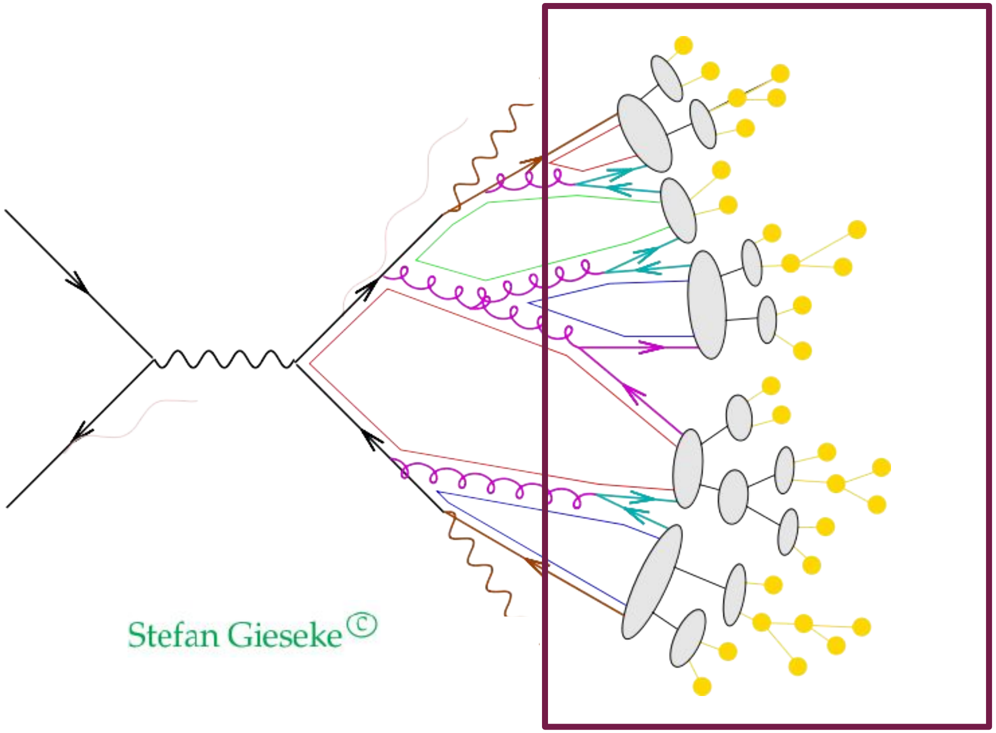


Partons2Hadrons

one of the least understood elements of MCEG

Motivation - Hadronization

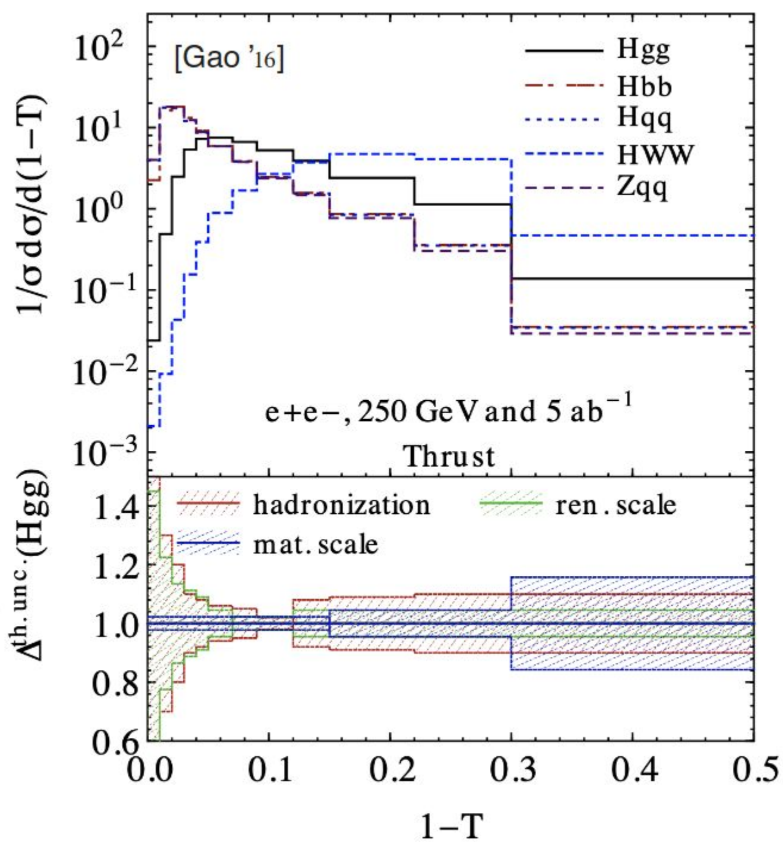
Hadronization:

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

- W mass measurement using a new method [Freytsis at 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



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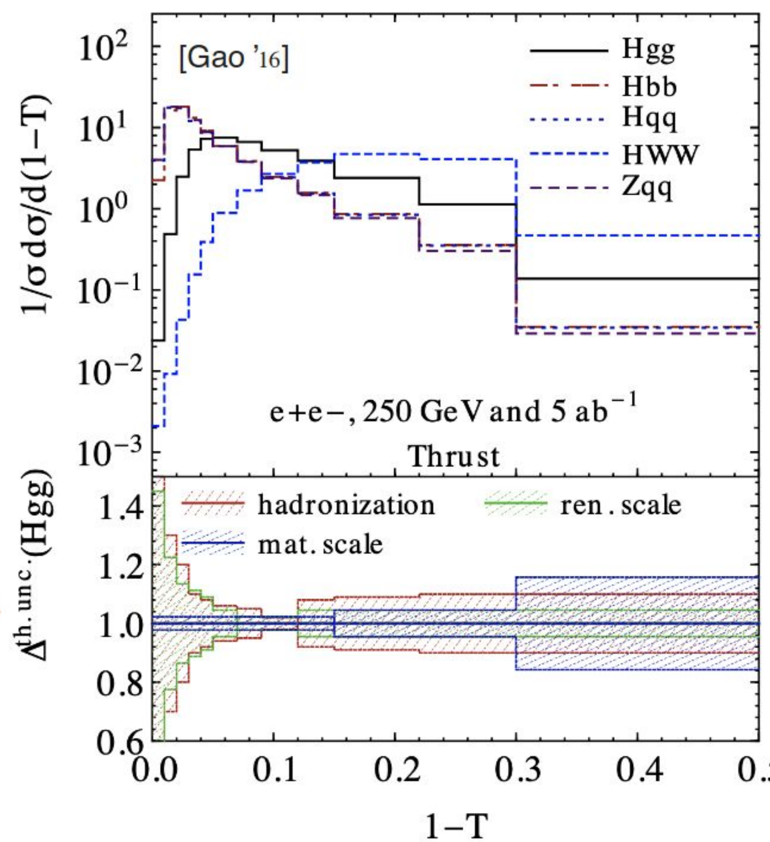

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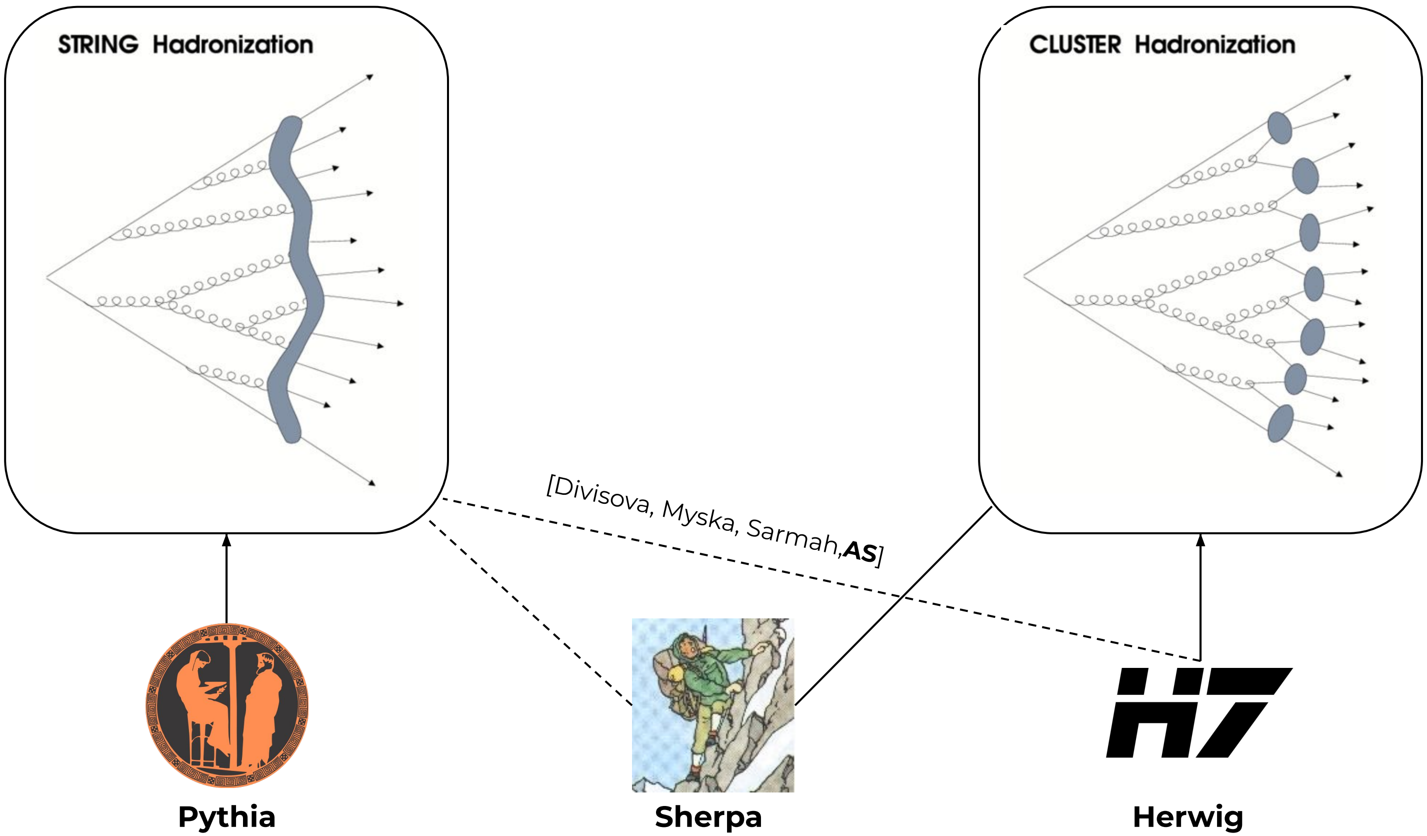
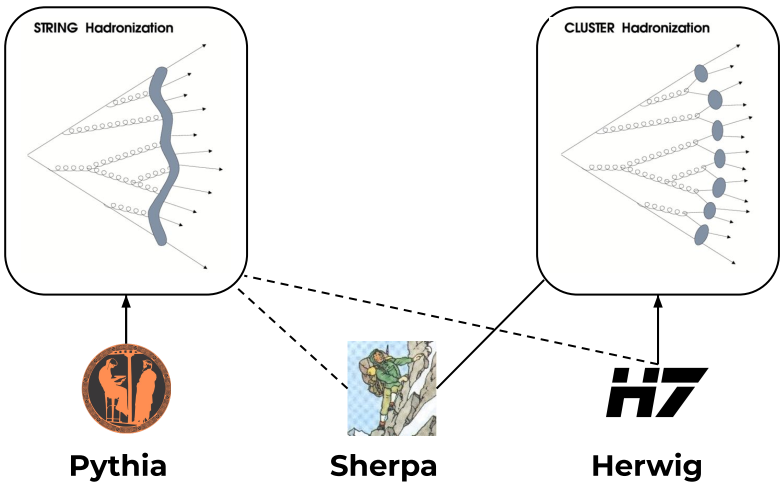


Partons2Hadrons

Early 1980's

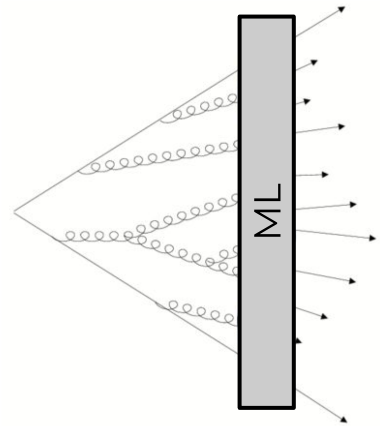


Cluster:
[Webber NPB238(1984)492]
...

"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



HADML

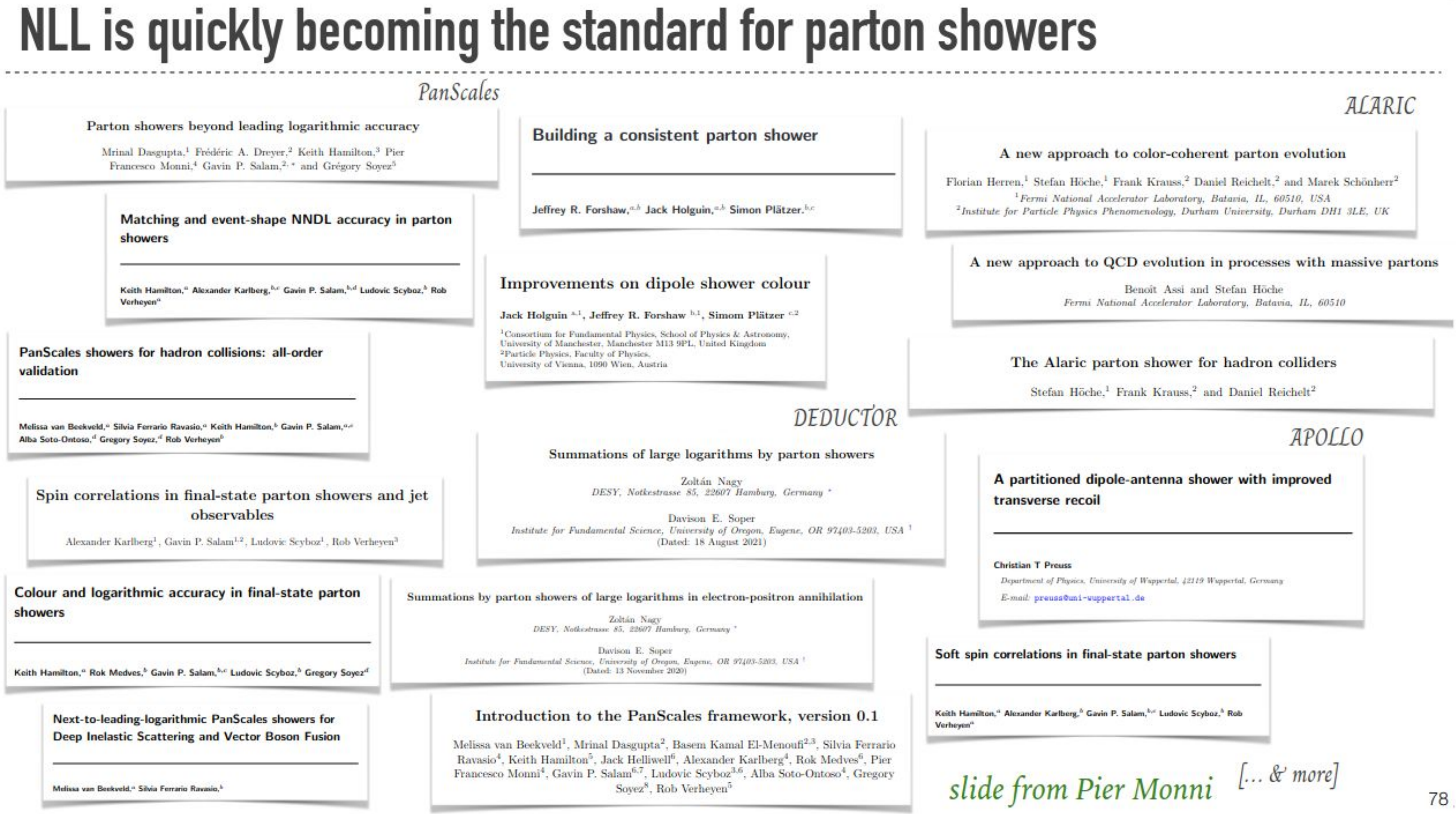
[Ghosh, Ju, Nachman **AS**, Phys.Rev.D 106 (2022) 9]
[Chan, Ju, Kania, Nachman, Sangli, **AS**, JHEP 09 (2023) 084]
[Chan, Ju, Kania, Nachman, Sangli, **AS**, Phys.Rev.D 111 (2025)]

MLHAD

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

Parton Showers (recent developments):

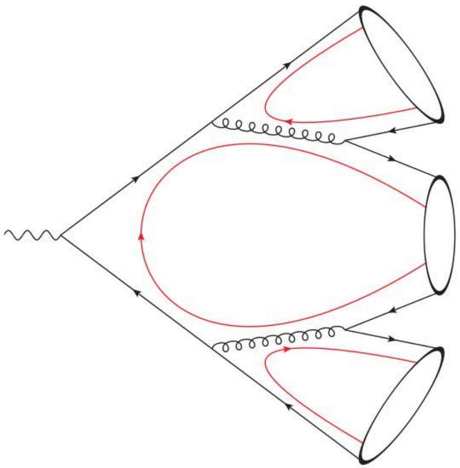
Possibly in the future NNLL becoming the next state-of-the-art



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]:



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- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters

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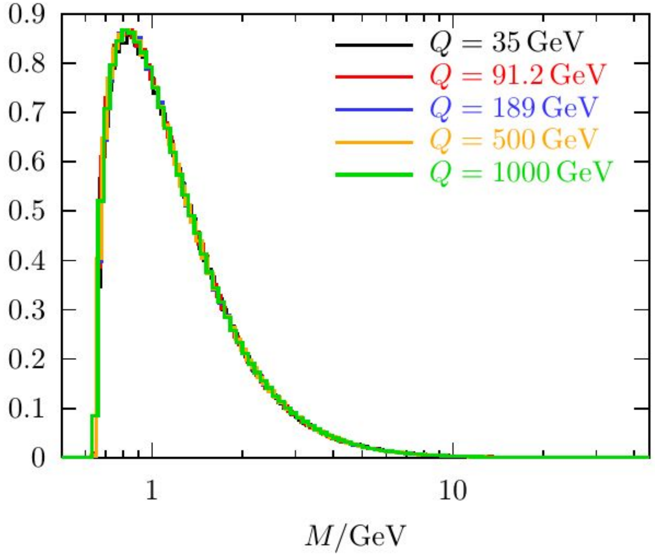
[S. Gieseke, A. Ribon, MH Seymour, P Stephens, B Webber JHEP 0402 (2004) 005]



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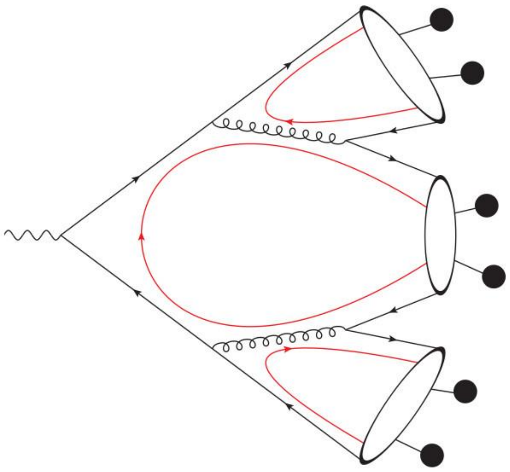

- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters
- Pre-confinement states that the spectra of clusters are independent of the hard process and energy of the collision
- Peaked at low mass (1-10 GeV) typically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

Other example:

- *"Colour Reconnection from Soft Gluon Evolution"* [Gieseke, Kirchgaeßer, **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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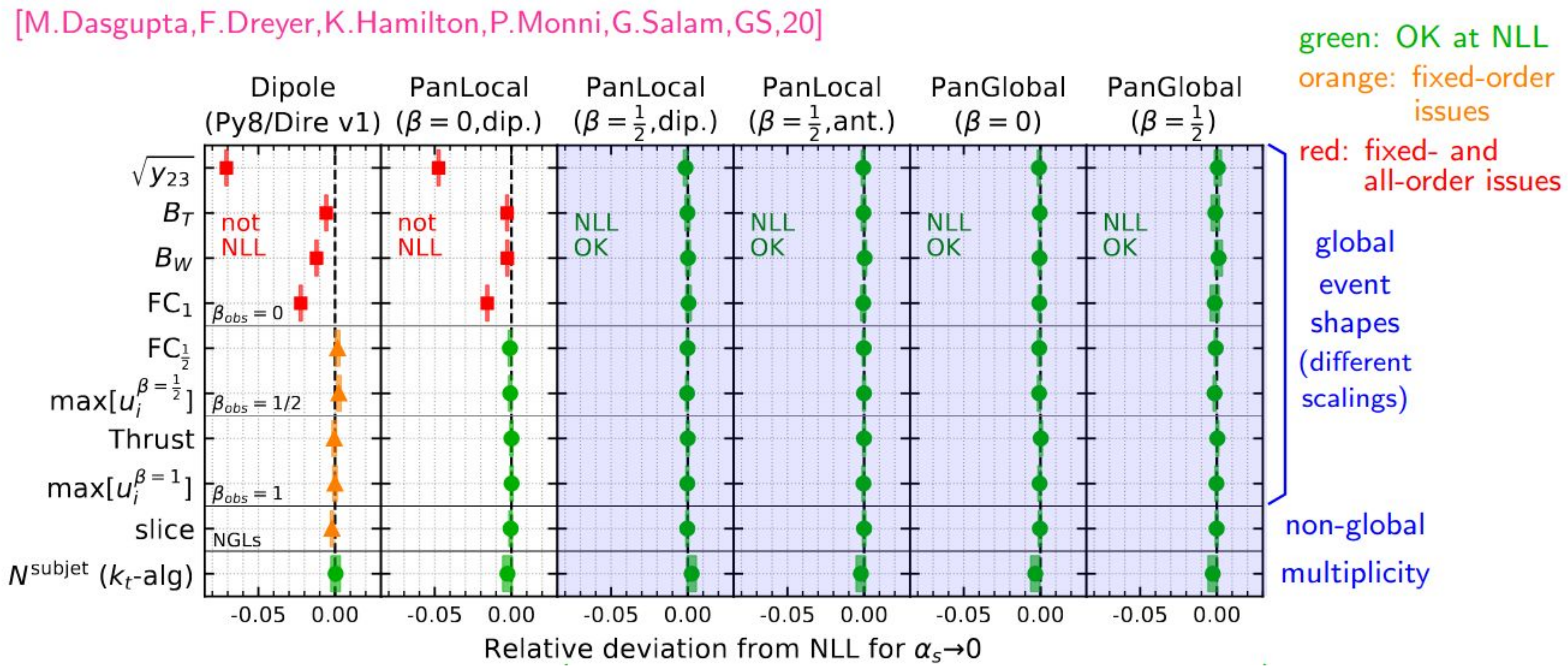

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Plan

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 at 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]

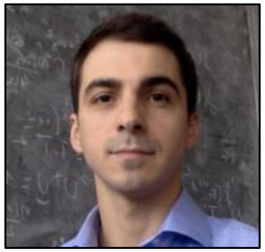
Budget

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



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Thank you for your attention!