MAX-PLANCK-INSTITUT
FÜR PHYSIK

Track 3 summary

Chiara Signorile-Signorile*
Robert Szafron
Francisco Antonio Villaescusa Navarro
Ramon Winterhalder

ACAT2024, Stony Brook
15/03/2024

A universe in two lines

The Standard Model: from colliders to the Universe

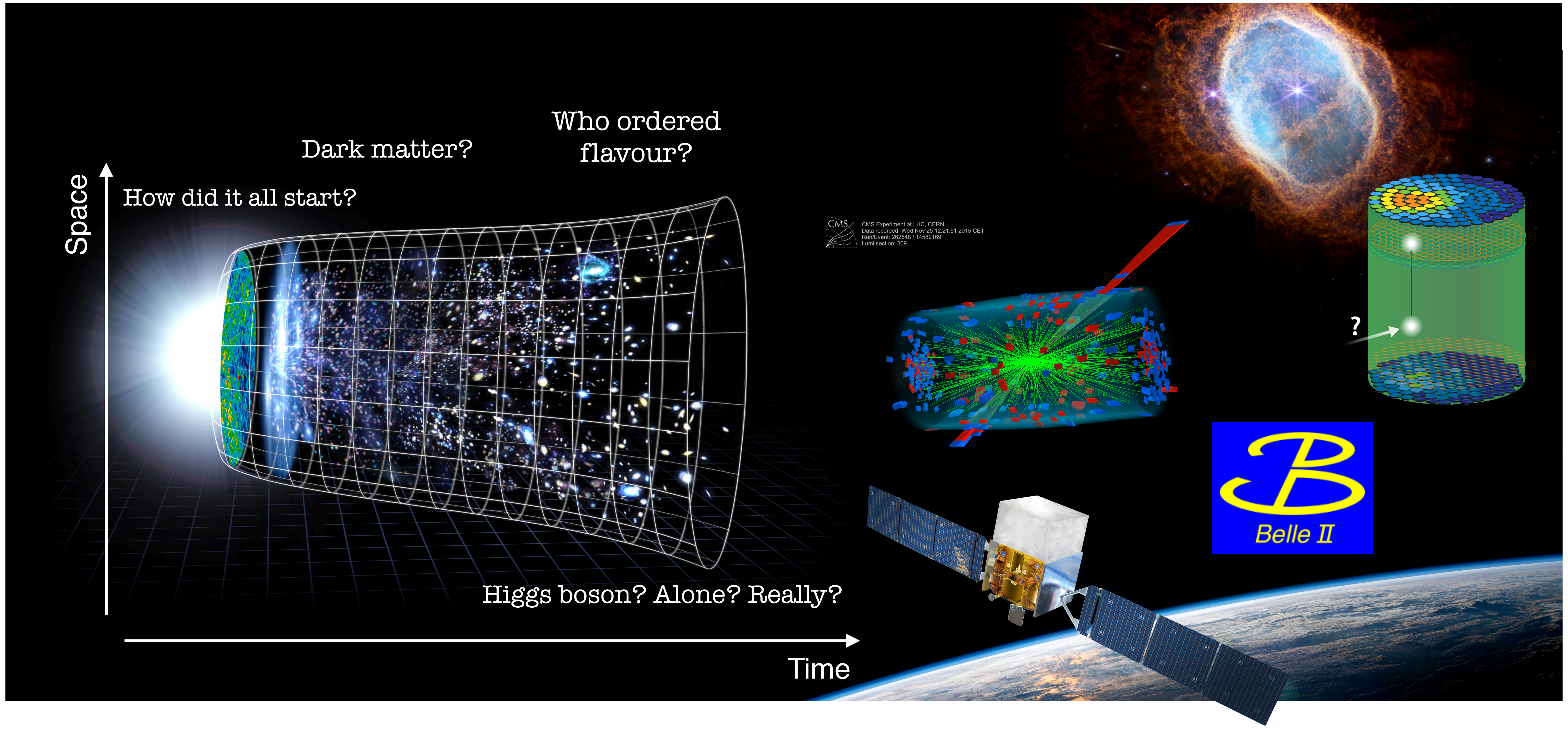
- **Standard Model** (SM) of particle physics gives us the **“code of the Universe”** through a compact formula

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}} + \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}} + \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

[CRC TRR257 poster]

- The SM explains outcomes of most current terrestrial experiments and many aspects of the evolution of the Universe from the Big Bang through today (**add a drop of General Relativity**).
- However, many questions remain unresolved.
- **The main goal of the particle physics community is to test the Standard Model as thoroughly as possible and, hopefully, find physics beyond it.**

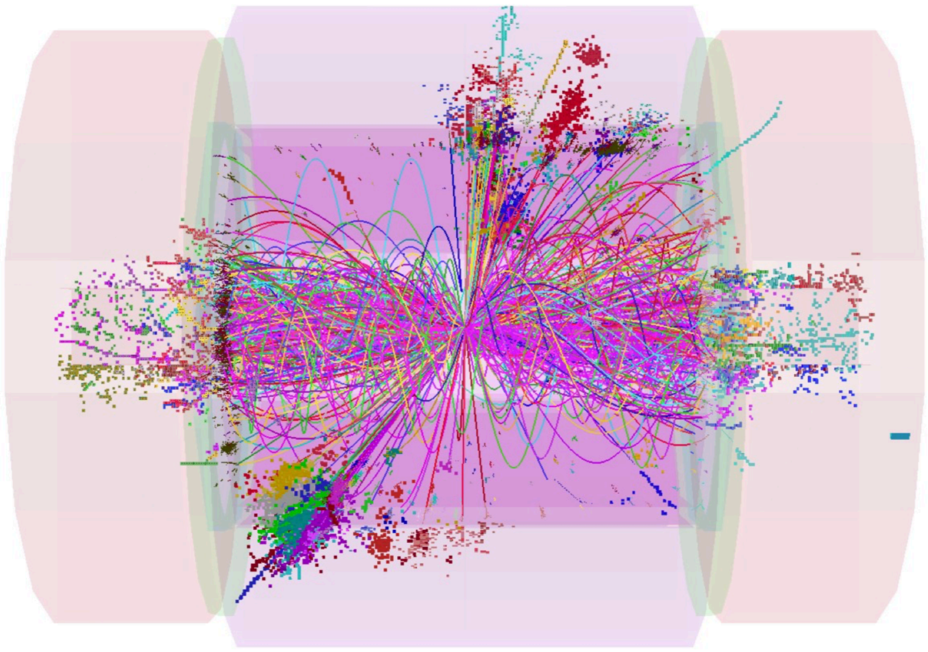


My personal perspective

❖ One key aspect of this search is related to collider physics, where **increasing precision requires experimental improvements, but also advances in our understanding of the fundamental underlying theory.**

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi + h.c \\ &+ \psi_i y_{ij}\psi_j\phi + h.c \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

Quantitative connections through a chain of experimental and theoretical links



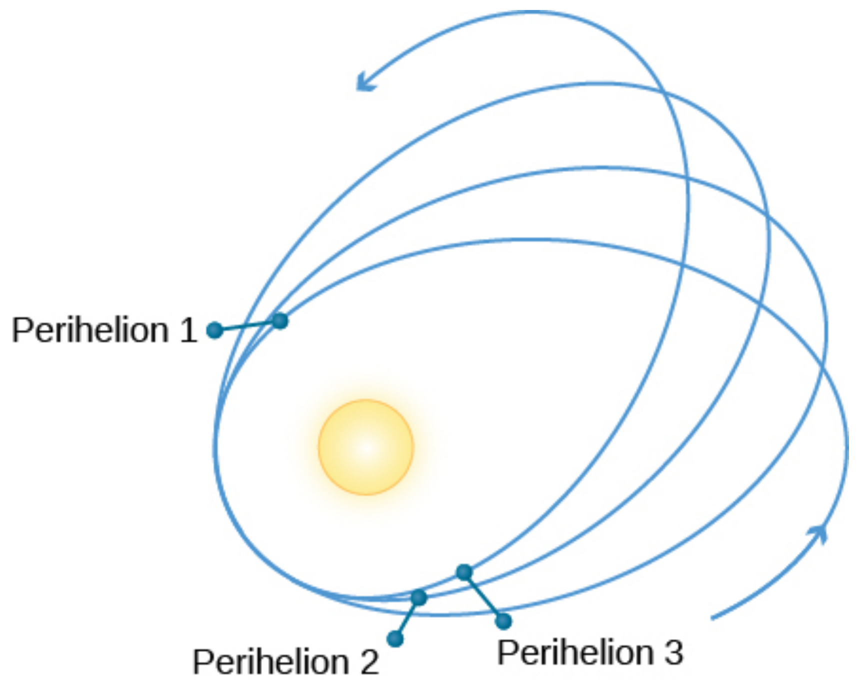
❖ **The core idea of theoretical particle research:**

- **Develop methods to obtain high precision theoretical predictions.**
- **Exploit these methods** for a wide range of **phenomenological studies** to improve our **knowledge of the SM.**

When precision changes the game

❖ **Proof of general relativity: 1% discrepancy with the Newtonian predictions**

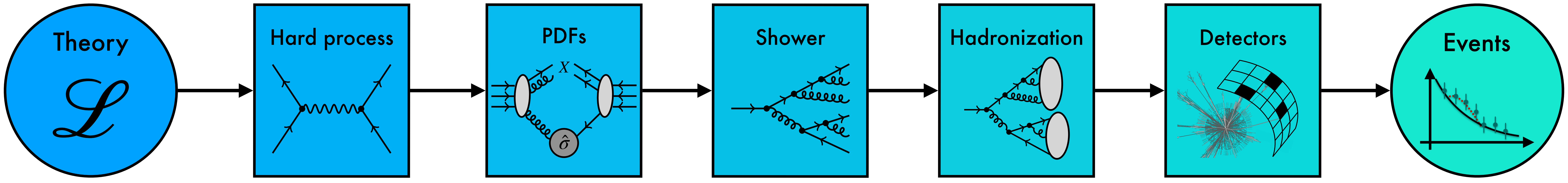
❖ **Advent of Quantum Electrodynamics: 0.1% discrepancy with predictions of QM**



Rudiments of particle physics (at colliders)

The success of a percent level phenomenology program relies on our ability to interpret and predict the outcome LHC measurement.

[Snowmass'2021 whitepaper]



[courtesy of Ramon]

→ Theoretical predictions in hep-ph require description of physics across manu different energy scales

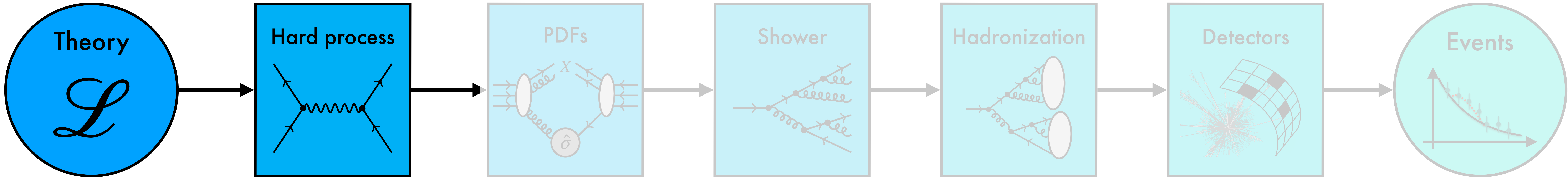
$$d\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, d\hat{\sigma}_{ij}(x_1 x_2 s) \left(1 + \mathcal{O}\left(\frac{\Lambda^n_{\rm QCD}}{Q^n}\right)\right), \quad n \geq 1$$

Parton distribution functions
$\pm(3-5)\,\%$

Hard scattering
(perturbative quantum field theory)
aim for few $\%$ level!

Non perturbative effects
(fragmentation, hadronisation)
$\sim \%\,(?)$

Higher-order corrections to hard processes: main difficulties

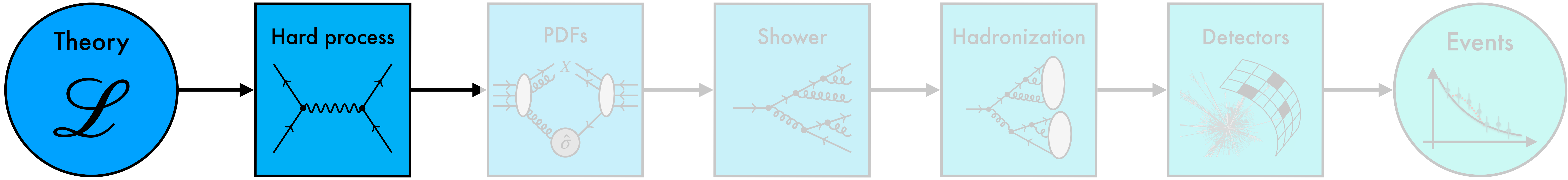


$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_s\, d\sigma_{\mathrm{NLO}} + \alpha_s^2\, d\sigma_{\mathrm{N^2LO}} + \alpha_s^3\, d\sigma_{\mathrm{N^3LO}} + \dots$$

Strong couplings:
$\alpha_s \sim 0.1$

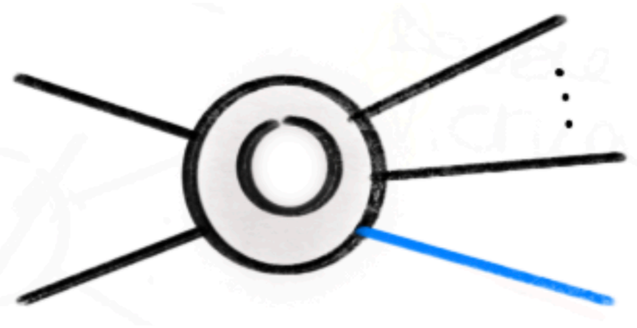
$\mathcal{O}(\alpha_s) \sim 10\,\%$ $\mathcal{O}(\alpha_s^2) \sim 1\,\%$ $\mathcal{O}(\alpha_s^3) \sim 0.1\,\%$

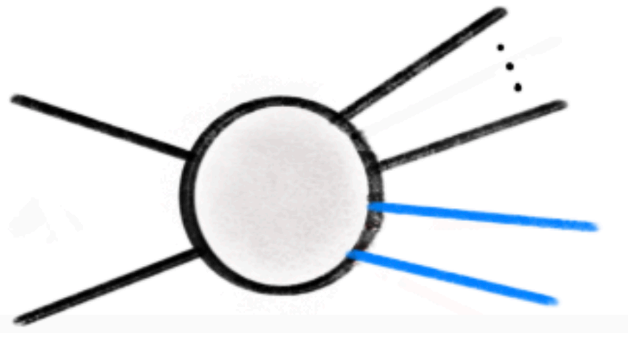
Higher-order corrections to hard processes: main difficulties



$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_s\, d\sigma_{\mathrm{NLO}} + \alpha_s^2\, d\sigma_{\mathrm{N^2LO}} + \alpha_s^3\, d\sigma_{\mathrm{N^3LO}} + \dots$$

$$d\sigma_{\mathrm{N^2LO}} = \int d\Phi_n\, VV_n + \int d\Phi_{n+1}\, RV_{n+1} + \int d\Phi_{n+2}\, RR_{n+2}$$





Each ingredient presents significant **technical challenges**.

Virtual amplitudes:

- **Multi-loop integrals** involving **multiple scales, arising from different masses and many legs**

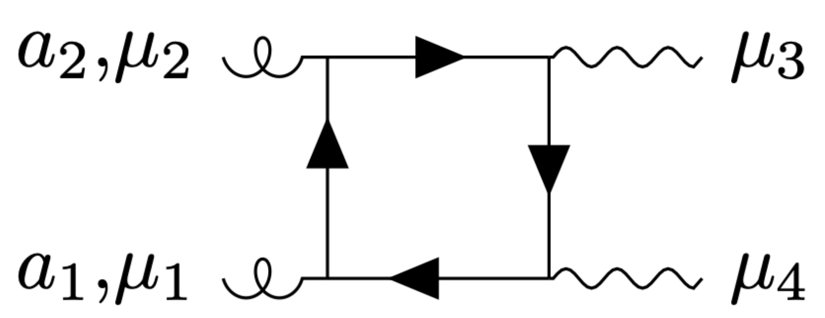
Real radiation singularities

- Extraction of **soft and collinear** singularities

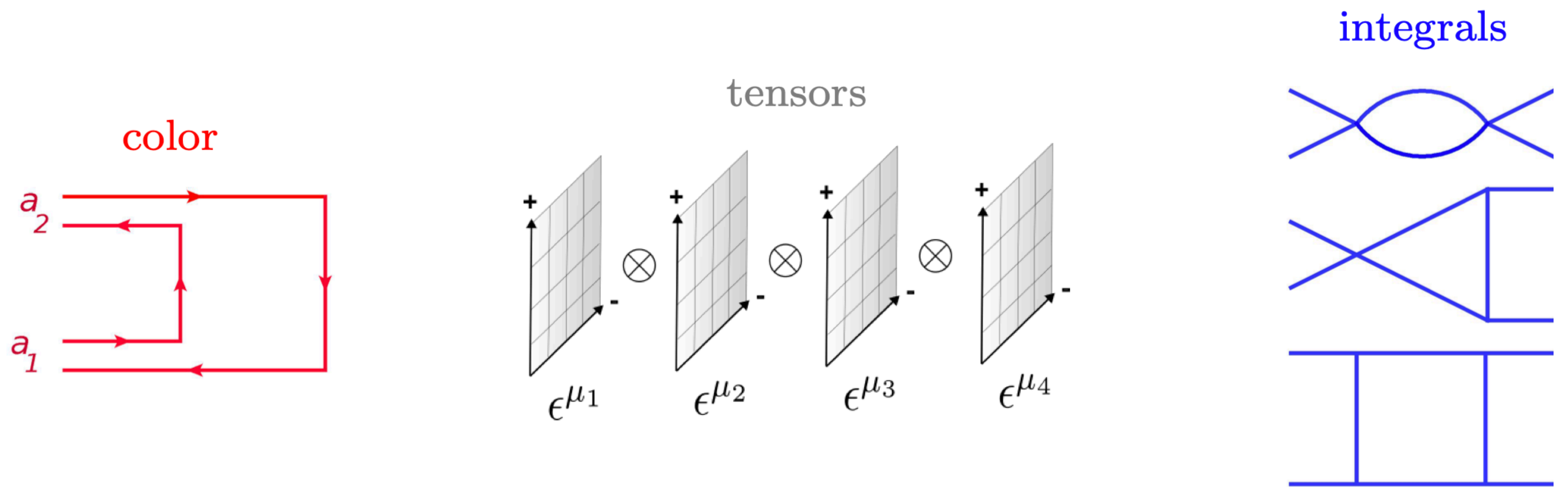
Loop amplitudes

- Increasing complexity: more legs, more loops, more masses.
- Need for a representation of the amplitudes that can be evaluated efficiently and yields numerically reliable results.

Algebraic complexity + analytic complexity



$$= g_s^4\, \mathrm{Tr}\{T^{a_1}T^{a_2}\} \int \frac{d^dk}{(2\pi)^d} \frac{\mathrm{tr}\left[(\not{k})\not{\epsilon}_1(\not{k}+\not{p}_1)\not{\epsilon}_2(\not{k}+\not{p}_{12})\not{\epsilon}_3(\not{k}+\not{p}_{123})\not{\epsilon}_4\right]}{(k)^2(k+p_1)^2(k+p_{12})^2(k+p_{123})^2}$$



[Bargiela@ICHEP22]

Astonishing improvements using different approaches:

- **Analytic**
  - Fast, precise evaluation
  - Wider applications (e.g. changing parameters)
- **Approximate**
  - Not universal
  - Non-trivial to find a good small parameter
- **Numerical**
  - Flexible
  - The challenge is to have fast and stable implementations

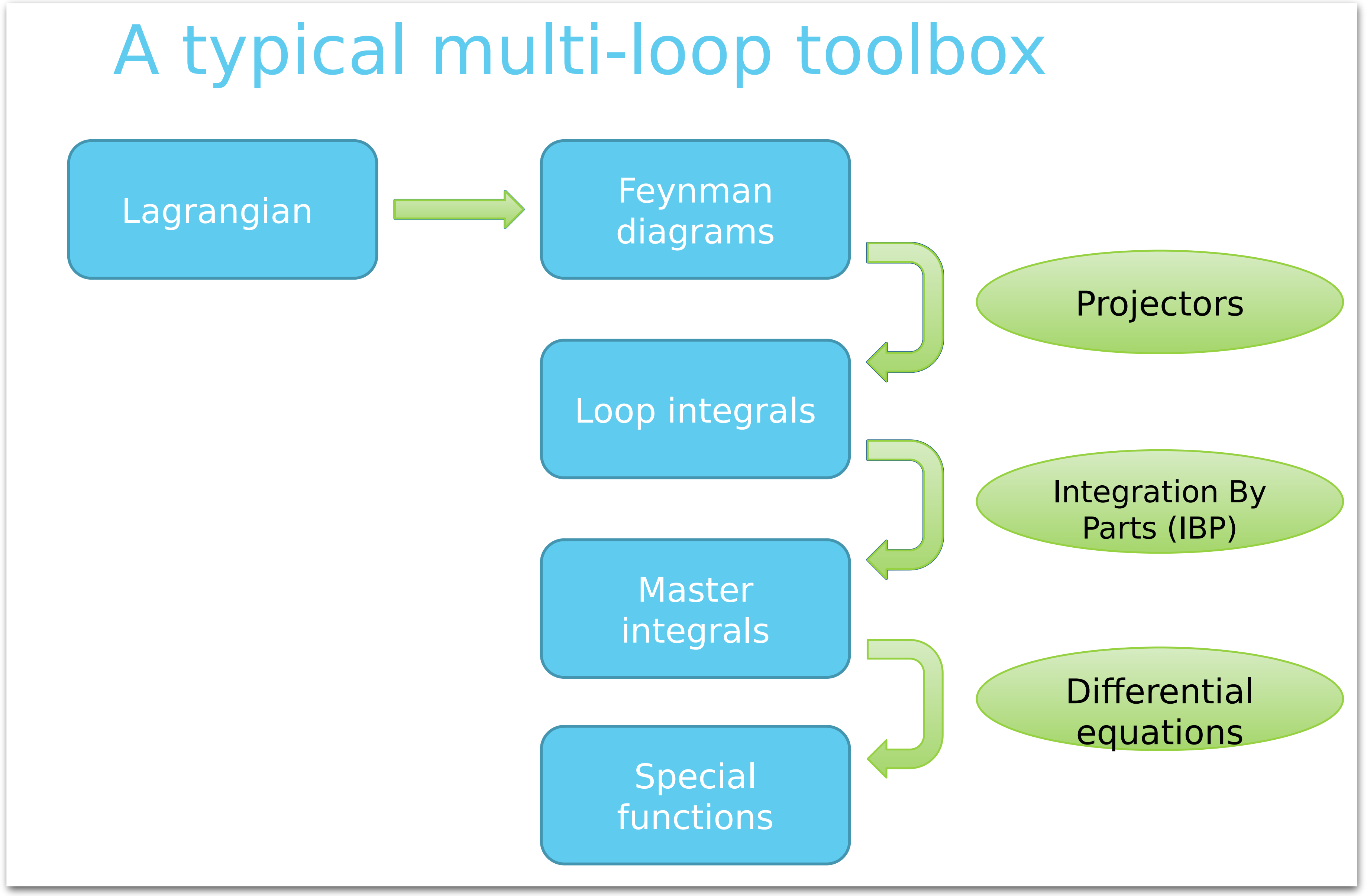
Loop amplitudes

[courtesy of Herschel]

- Increasing complexity: more legs, more loops, more masses.
- Need for a representation of the amplitudes that can be evaluated efficiently and yields numerically reliable results.

Algebraic complexity + analytic complexity

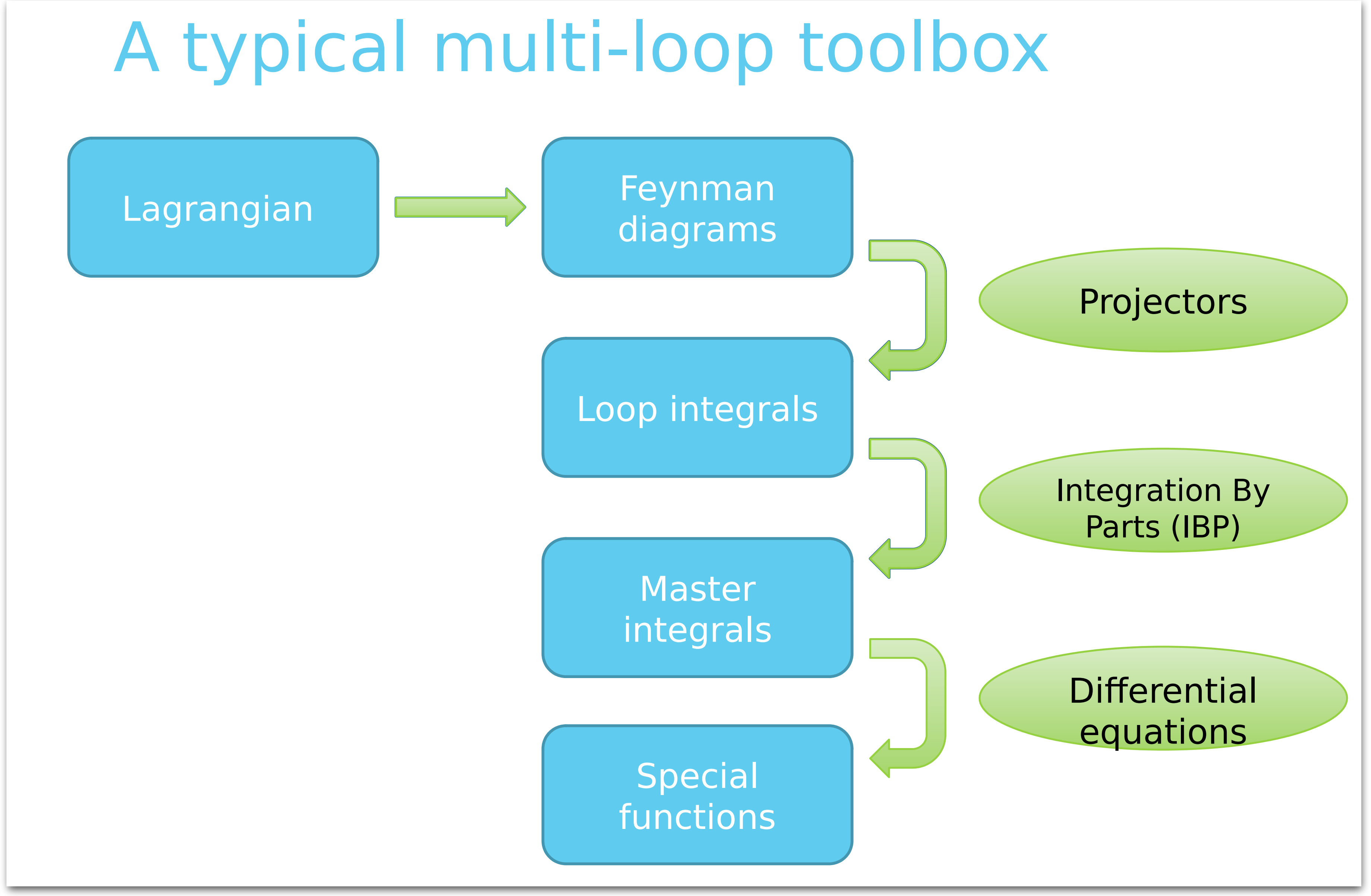
Analytic → standard workflow, but crucial "tricks" in different steps



Loop amplitudes

[courtesy of Herschel]

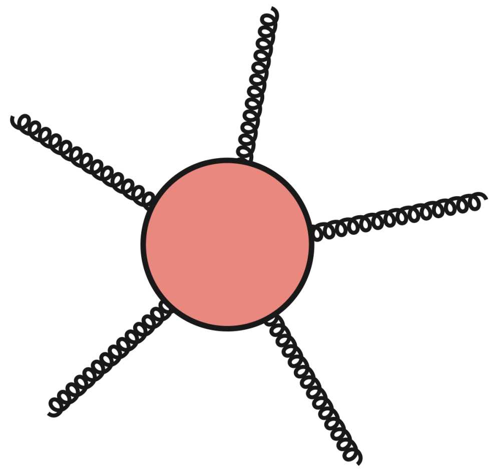
- Increasing complexity: more legs, more loops, more masses.
- Need for a representation of the amplitudes that can be evaluated efficiently and yields numerically reliable results.



Algebraic complexity + analytic complexity

Analytic → standard workflow, but crucial "tricks" in different steps

- Simplify large rational functions arising from IBP by means of partial fractioning:
  - Singular+MultivariateApart



5-point 2-loop full-color

GCD 3GB —Singular / MultivariateApart→ **Partial Fractioned** 24MB

See F. Devoto's talk

  - p-adic numbers

5-point 2-loop $\gamma\gamma j$ production

Expression	Size	Parameters to fit
Original	605 MB	1,369,559
Reconstructed	4.5 MB	52,527 (*of which 15,403 non-zero*)

See H. Chawdhry's talk

Loop amplitudes

- Increasing complexity: more legs, more loops, more masses.
- Need for a representation of the amplitudes that can be evaluated efficiently and yields numerically reliable results.

Algebraic complexity + analytic complexity

Numeric

- Automatic adaptive integration of loop integrals
- Efficiency based on GPUs, iterated integration and double extrapolation

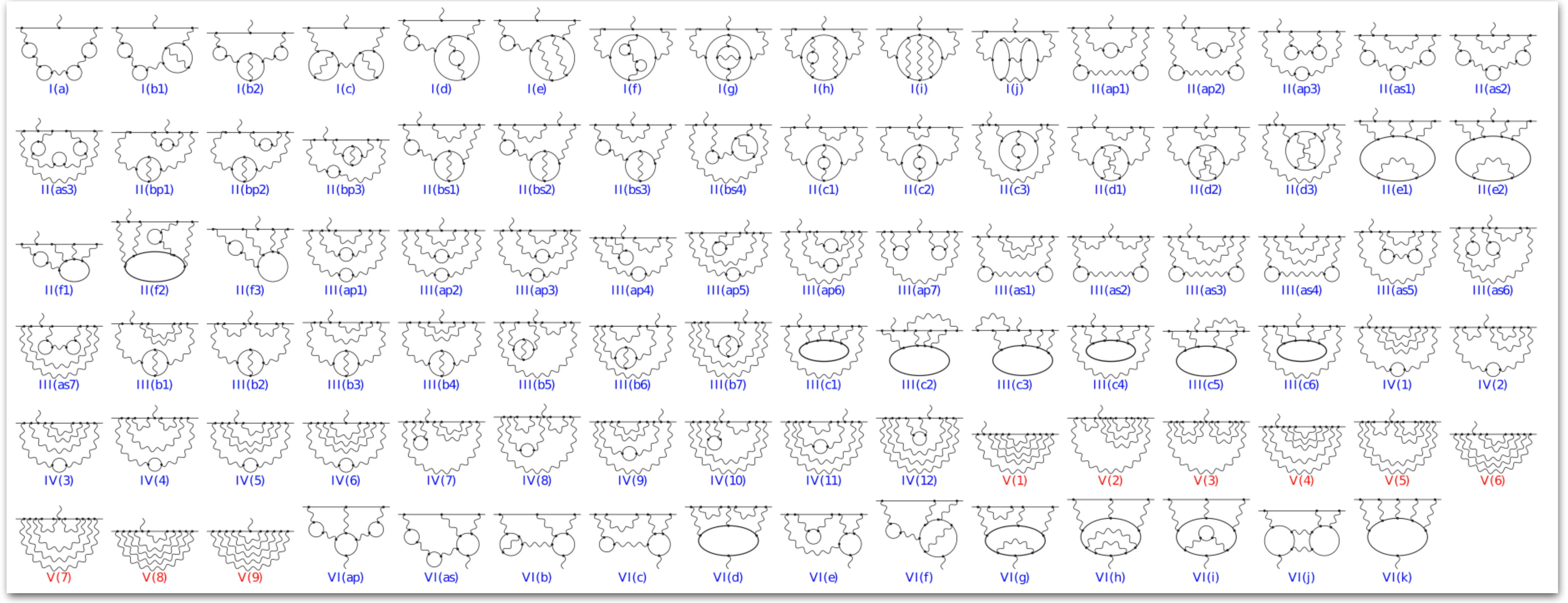
3-loop Feynman integrals in the Euclidean or physical kinematical region

See E. De Doncker's talk

- Reduction to finite integrals (no MI)
- MC integration (non-adaptive)
- Parallel realisation

See S. Volkov's talk

Total 10-th order QED electron anomalous magnetic moment calculation

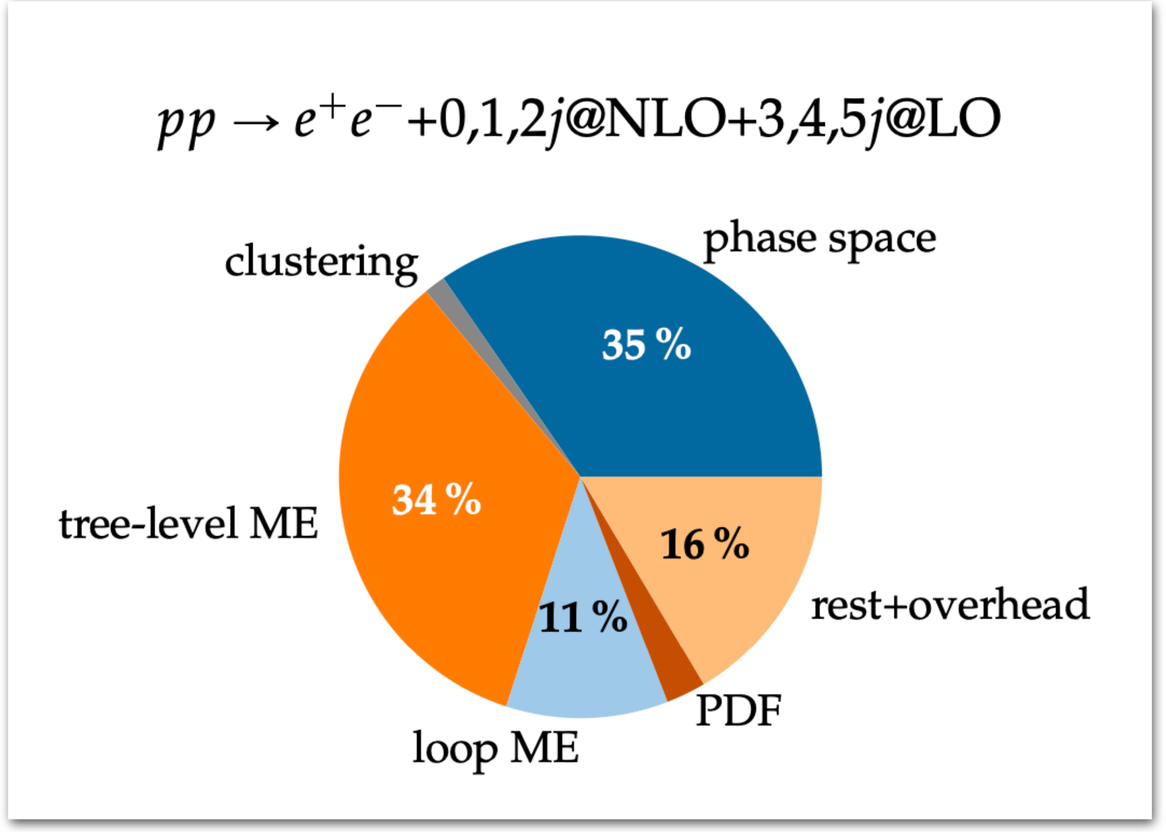


Computing amplitudes/matrix elements with Machine Learning techniques

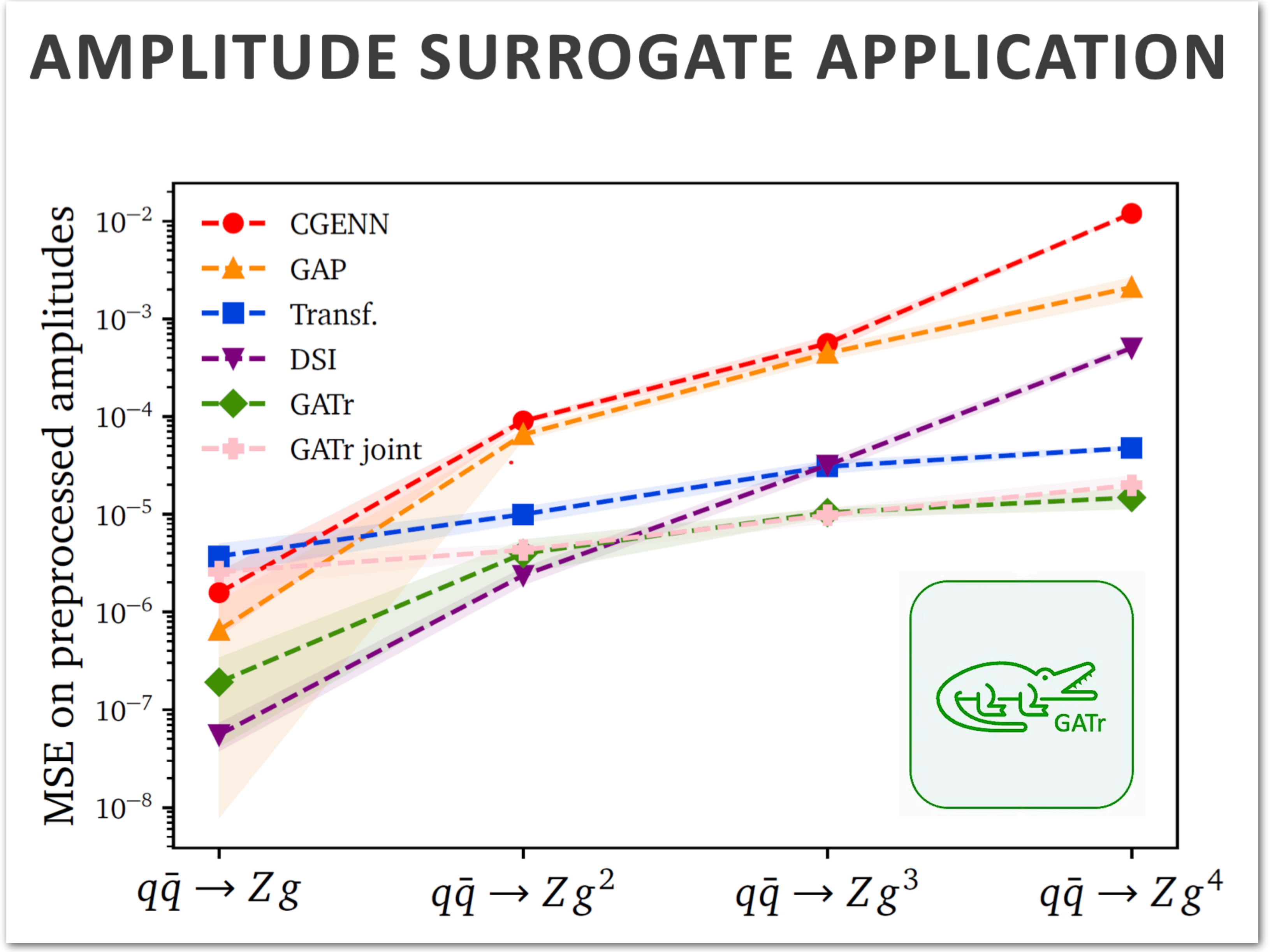
❖ Largest portion of MC time spent on MEs (by far)

See E. Bothmann's talk

Can ML step in and help?



- Problem: Build an algorithm that can predict interaction amplitudes from phase space points for multiple processes
- Machine learning approaches struggle for 2 reasons:
  1. The output range covers a very large interval
  2. There exists a scaling problem. The more particles, the more complicated it is to estimate the amplitude

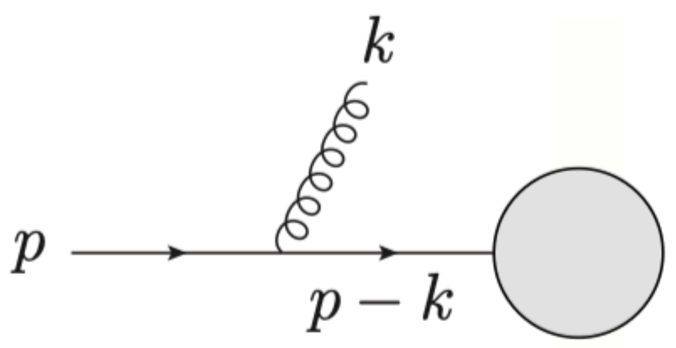


Bayesian and Symmetry Preserving Networks

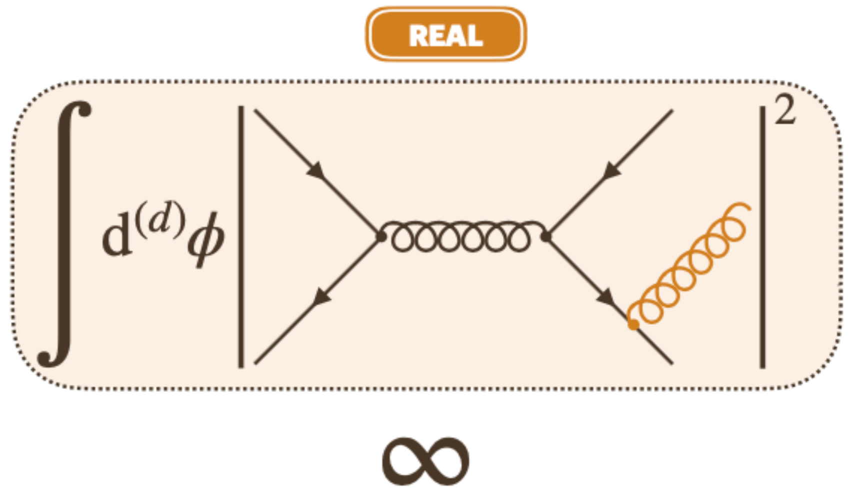
See V. Bresó Pla's talk

Real corrections

- Affected by singularities that arise after integrating over the phase space



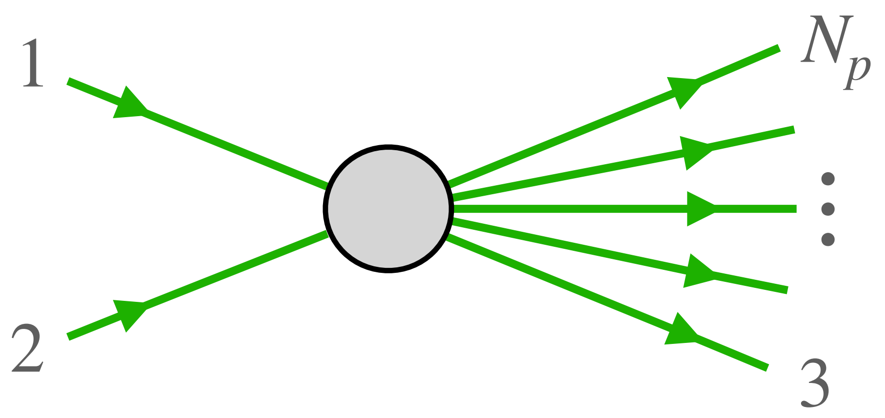
$$\sim \frac{1}{(p-k)^2} = \frac{1}{2E_pE_k(1-\cos\theta)} \xrightarrow[E_k \to 0 \text{ or } \theta \to 0]{} \infty .$$



- Goal: **extract IR singularities preserving fully differential prediction**

The frontier: NNLO for arbitrary partonic process [local and analytic]

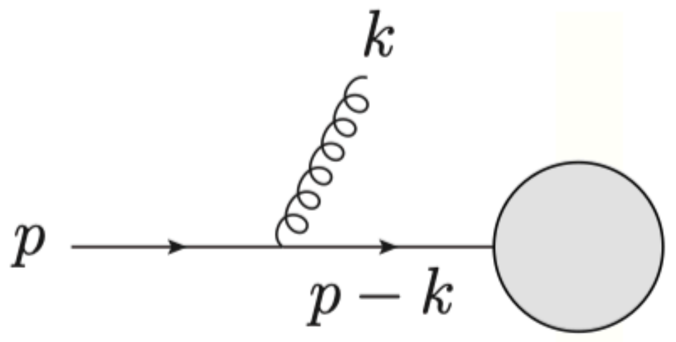
Conceptual + technical complexity



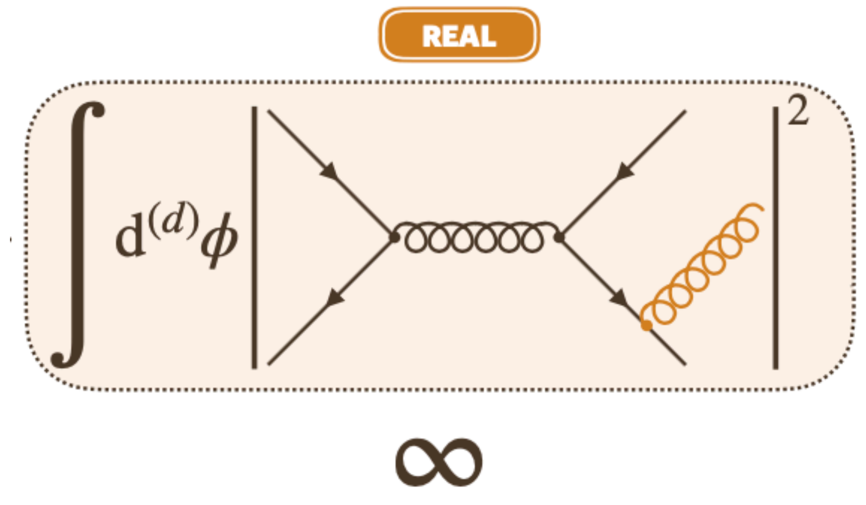
- Overlapping singularities,
- **Integration of intricate functions analytically** in d-dimensions.
- **Bookkeeping** becomes immediately **cumbersome** → large number of subtraction terms.
- Standard approaches may **hide a number of simplifications** that can occur **before explicit evaluation**.

Real corrections

- Affected by singularities that arise after integrating over the phase space



$$\sim \frac{1}{(p-k)^2} = \frac{1}{2E_pE_k(1-\cos\theta)} \xrightarrow[E_k \to 0 \text{ or } \theta \to 0]{} \infty .$$



- Goal: **extract IR singularities preserving fully differential prediction**

The frontier: NNLO for arbitrary partonic process [local and analytic]

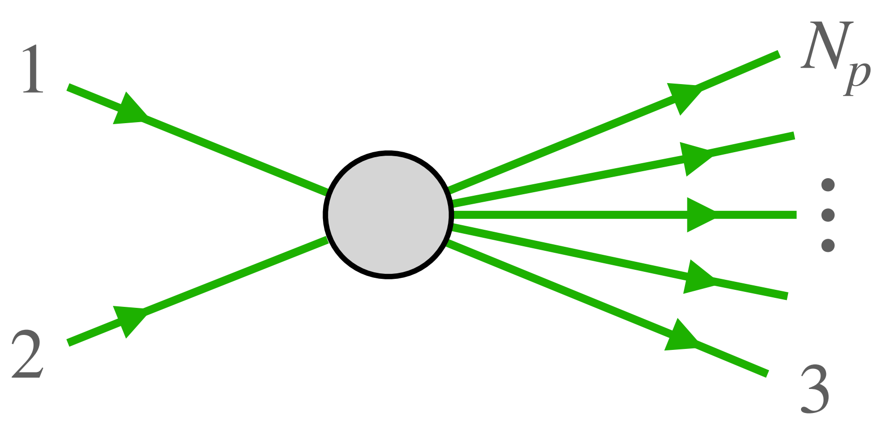
Conceptual + technical complexity

Searching for recurring structure seems to be the key…

See D. M. Tagliabue's talk

Virtual component · **Soft component** · **Collinear component**

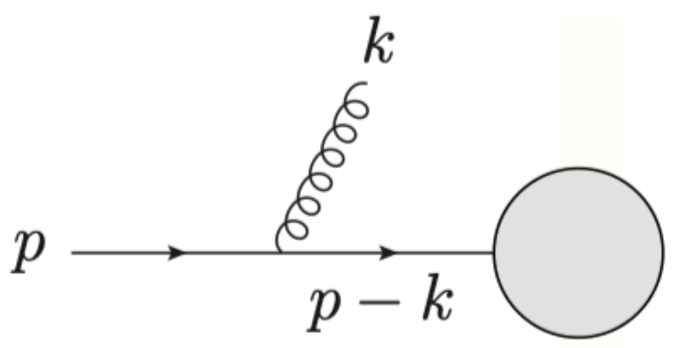
$$I_T(\epsilon) = I_V(\epsilon) + I_S(\epsilon) + I_C(\epsilon)$$



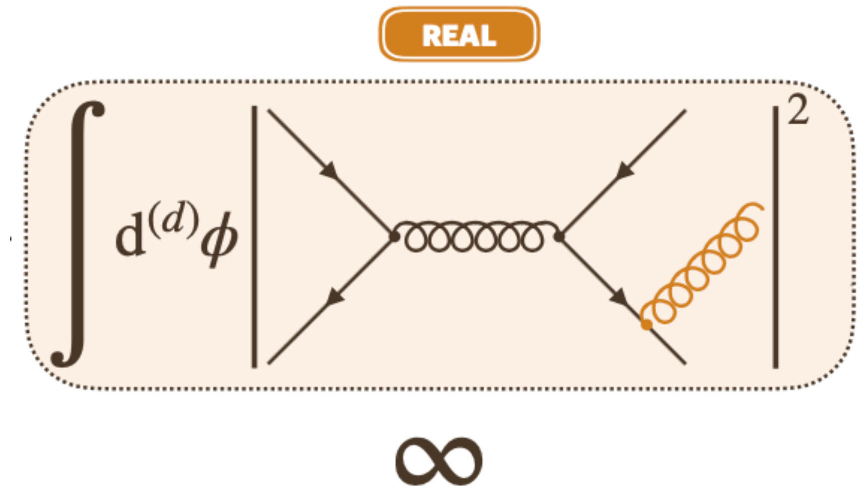
Free of poles
Fully general in the number of partons

Real corrections

- Affected by singularities that arise after integrating over the phase space



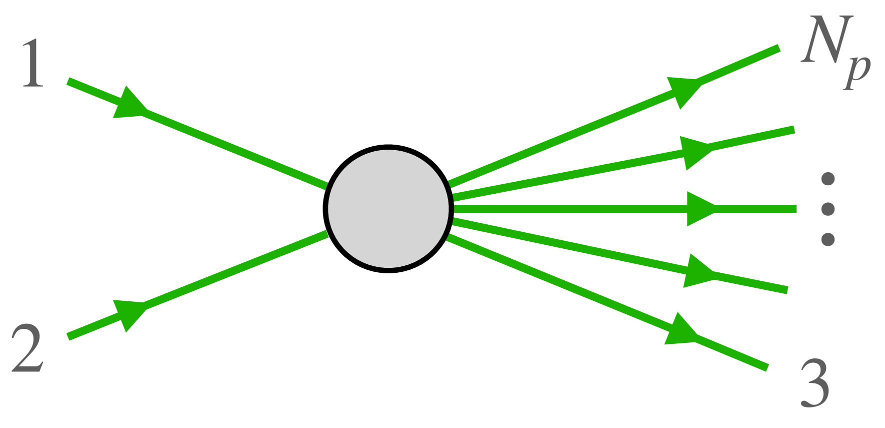
$$\sim \frac{1}{(p-k)^2} = \frac{1}{2E_pE_k(1-\cos\theta)} \xrightarrow[E_k \to 0 \text{ or } \theta \to 0]{} \infty .$$



- Goal: **extract IR singularities preserving fully differential prediction**

The frontier: NNLO for arbitrary partonic process [local and analytic]

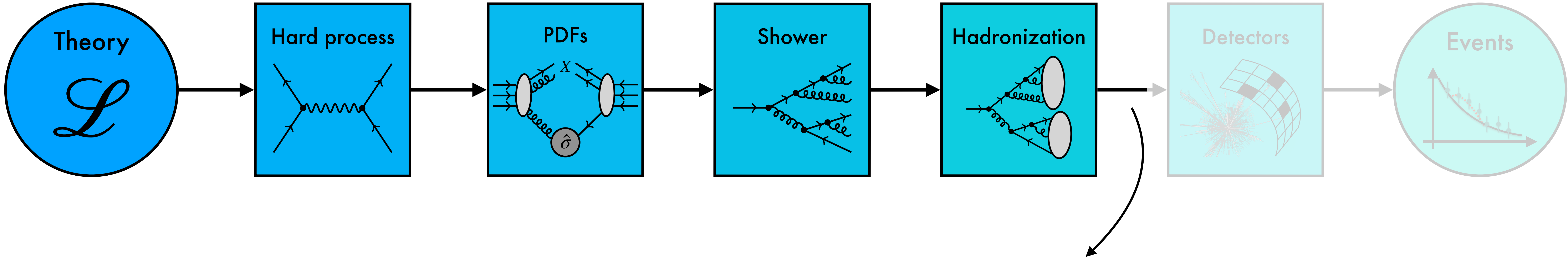
Conceptual + technical complexity



Searching for recurring structure seems to be the key…

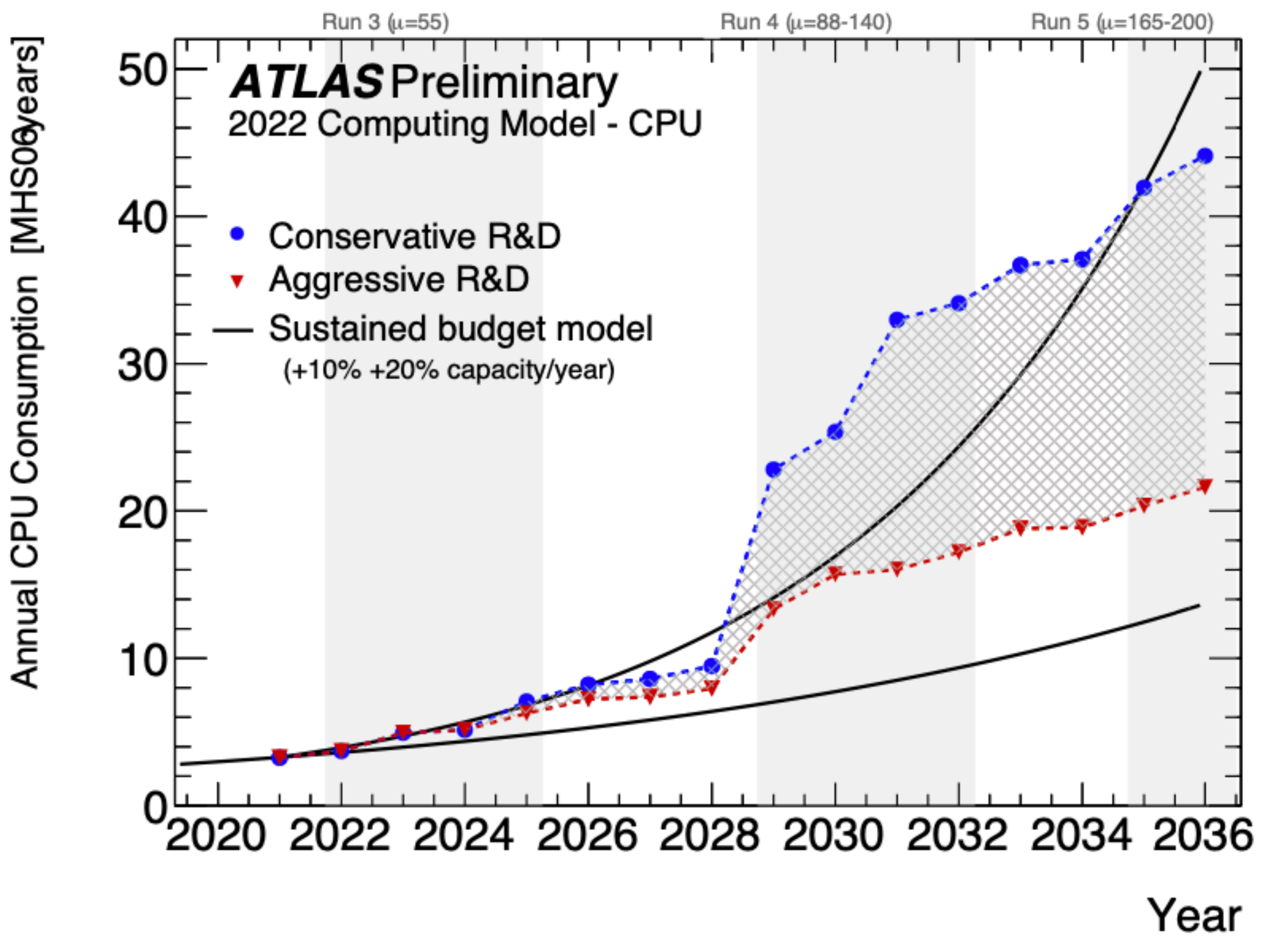
Can AI help us recognise such recurring structures?

From paper to nature: Monte Carlo event generator



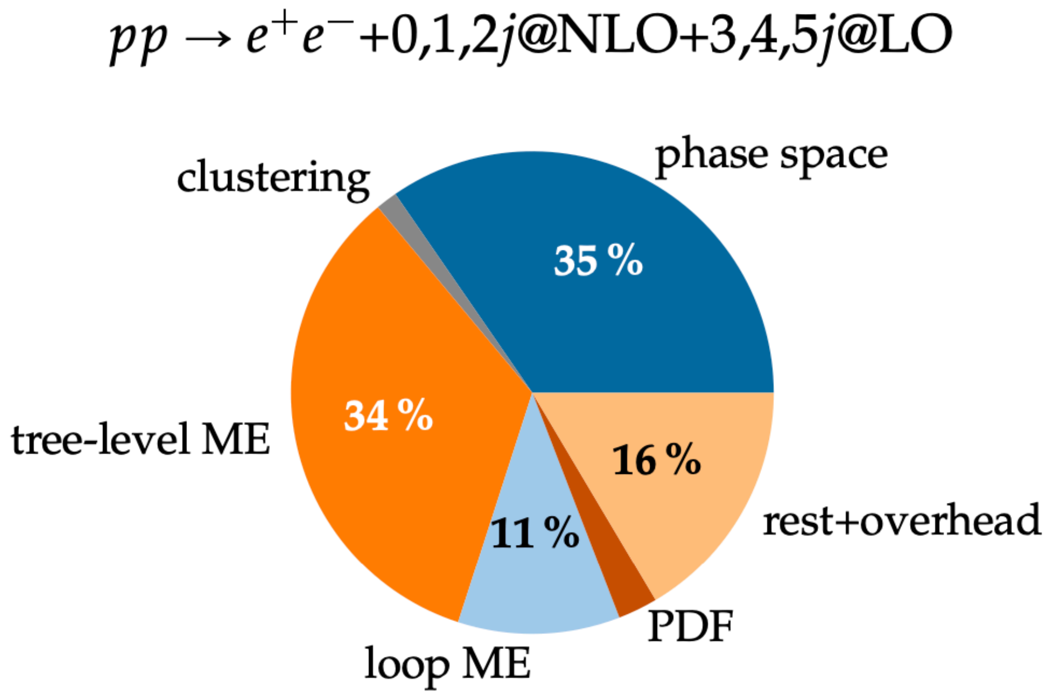
MC event generator's desirable features:
speed + portability + scalability

See C. Gütschow and E. Bothmann's talk

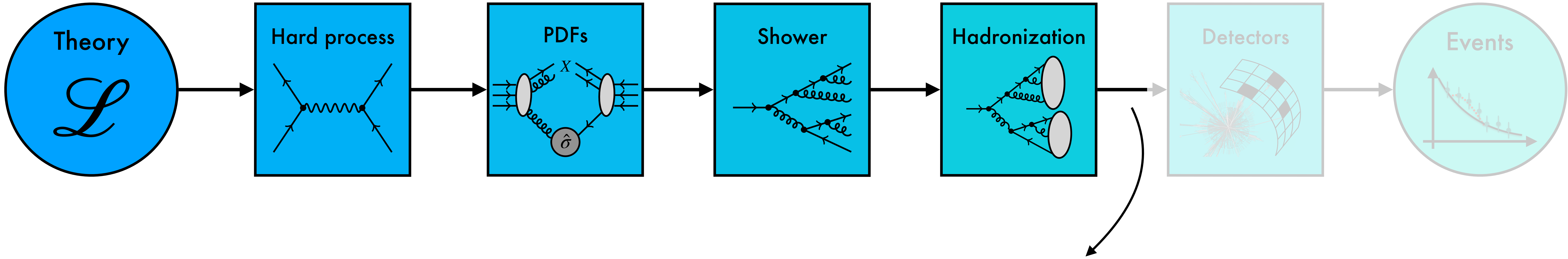


Components we need to consider:

- Tree-level Matrix elements
- Phase space generation
- PDF's



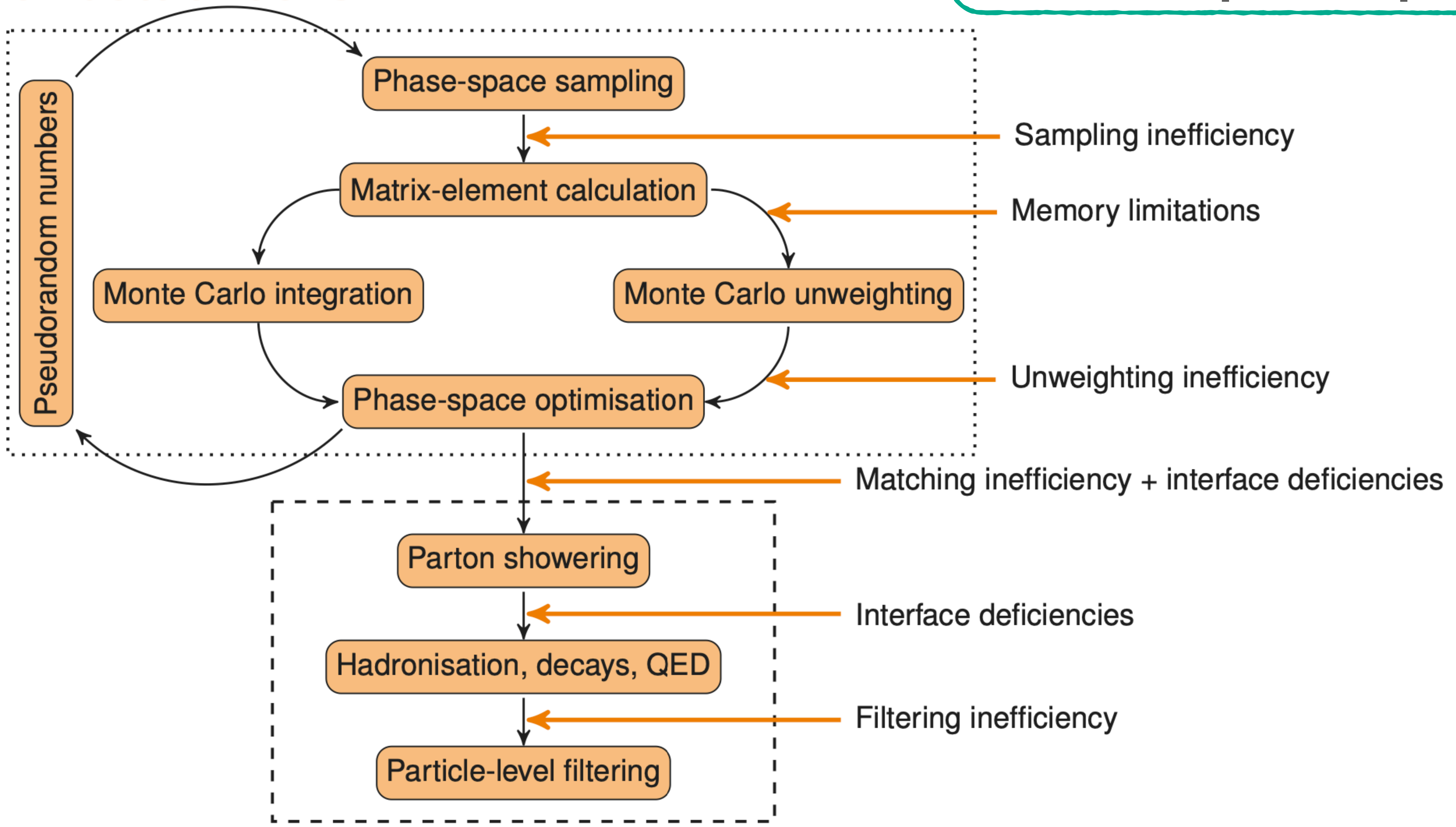
From paper to nature: Monte Carlo event generator



See C. Gütschow's talk

MC event generator's desirable features:
speed + portability + scalability

Other bottlenecks

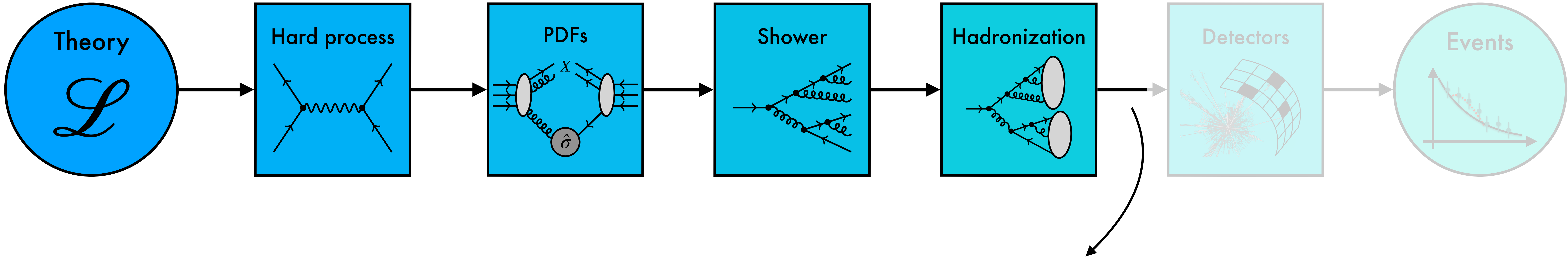


Very diverse and composite layers of complexity…

…the problem seems hopeless.

However…

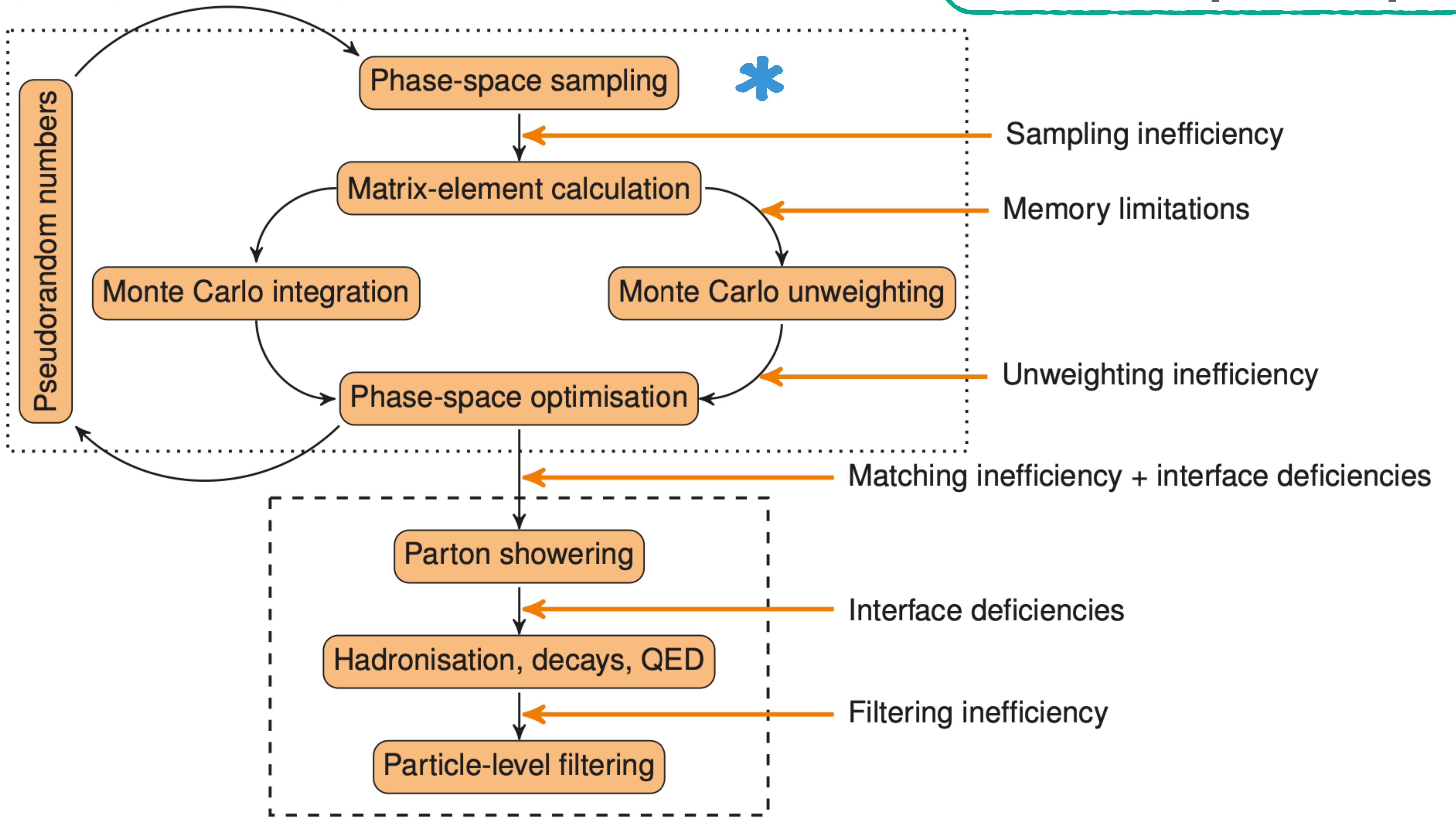
From paper to nature: Monte Carlo event generator



MC event generator's desirable features:
speed + portability + scalability

See C. Gütschow's talk

Other bottlenecks



* Neural Importance Sampling

MadNIS

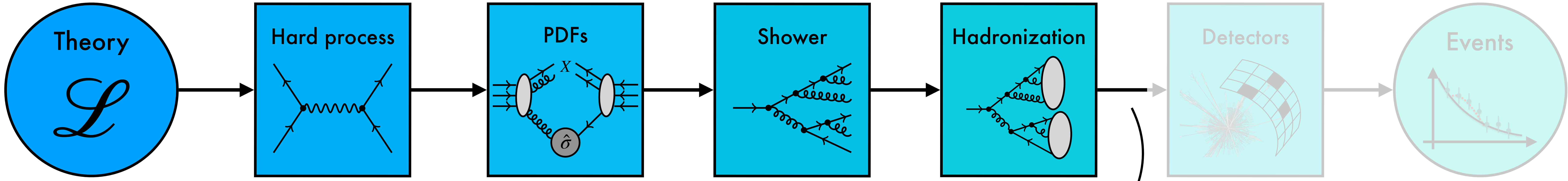
See T. Heimel's talk

The MadNIS Reloaded

Large improvements,
even for high multiplicities
and complicated processes!

[2311.01548]

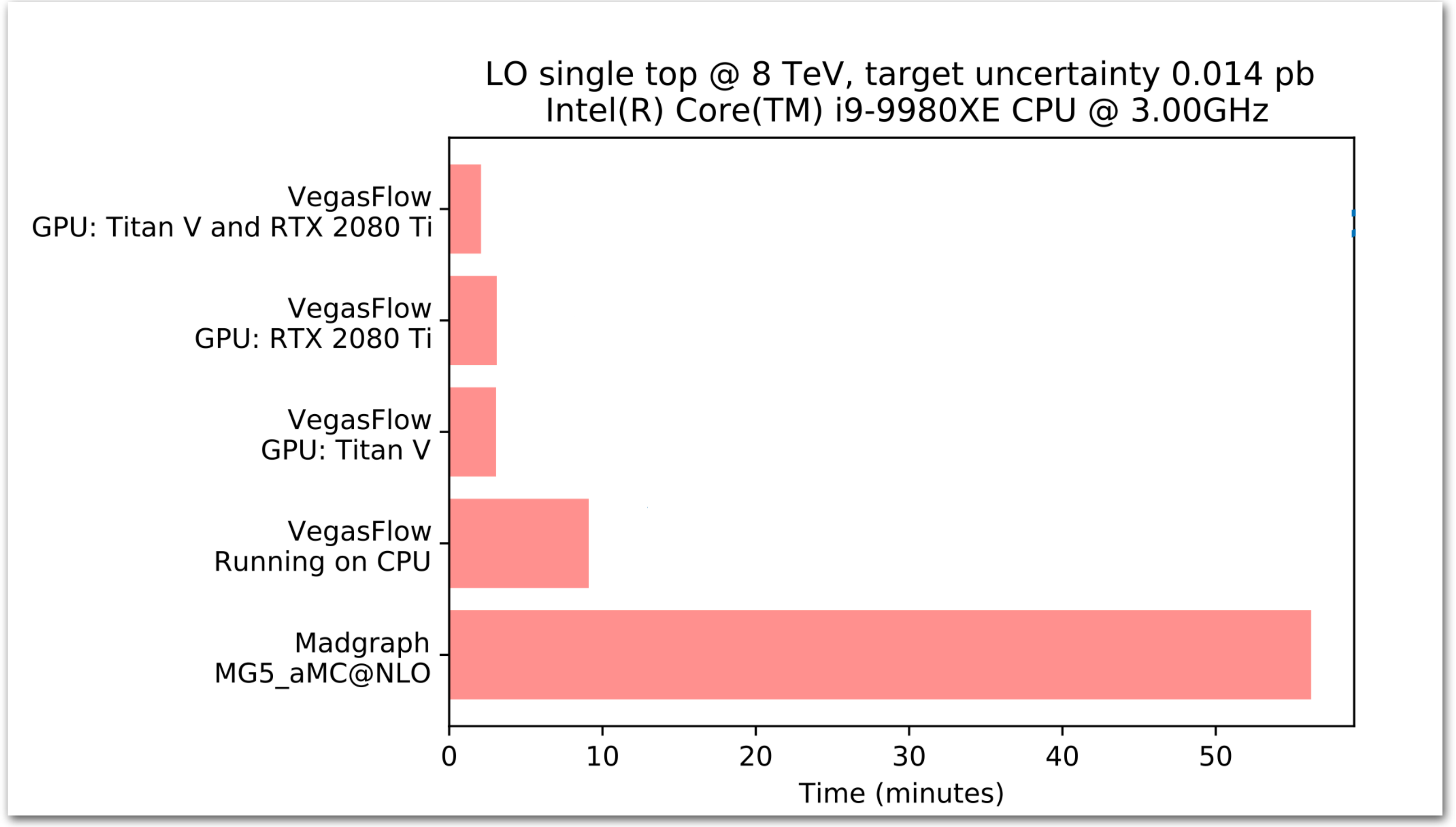
From paper to nature: Monte Carlo event generator



MC event generator's desirable features:
speed + portability + scalability

TensorFlow

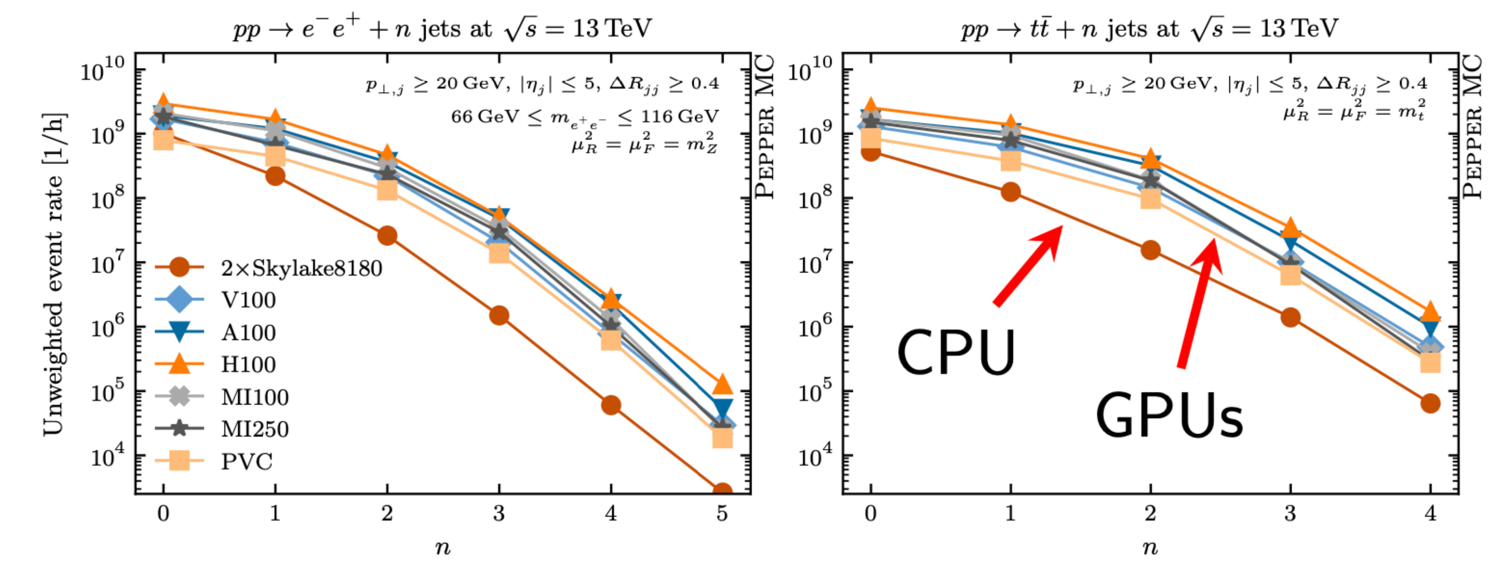
See S. Carrazza's talk



- ❖ **portable event generator** that incorporates GPU resources into high-precision simulations
- ❖ **Parallelisation desired**
- ❖ **Scalability from a laptop to a Computing Facility.**

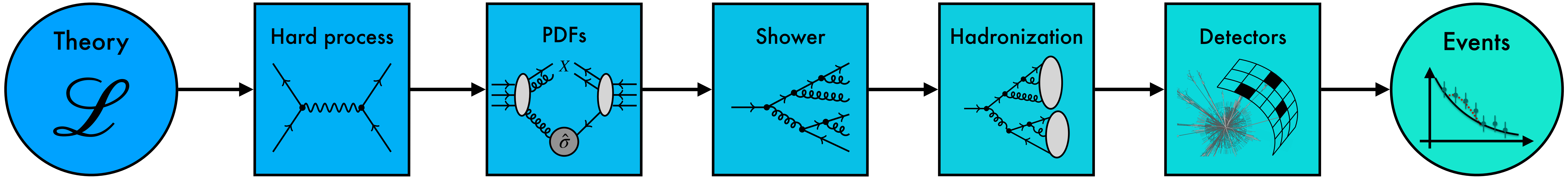
PEPPER

See E. Bothmann's talk



MEvents / hour	2×Skylake8180	V100	A100	H100	MI100	MI250	PVC
$pp \to t\bar{t} + 4j$	0.06	0.5	1.0	1.7	0.4	0.3	0.3
$pp \to e^- e^+ + 5j$	0.003	0.03	0.05	0.1	0.03	0.03	0.02

Going for the likelihood



$$\int dx_{hard} \quad p(x_{hard}|\alpha) \quad p(x_{reco}|x_{hard},\alpha)\,\epsilon(x_{hard},\alpha) = p(x_{reco}|\alpha)$$

Three network setup makes the **MEM tractable**

1) **Transfer-Network** encoding the transfer probability $p(x_{reco}|x_{hard})$
2) **Acceptance-Network** encoding the efficiency $\epsilon(x_{hard})$
3) **Sampling-Network** encoding the proposal distribution $q(x_{hard})$

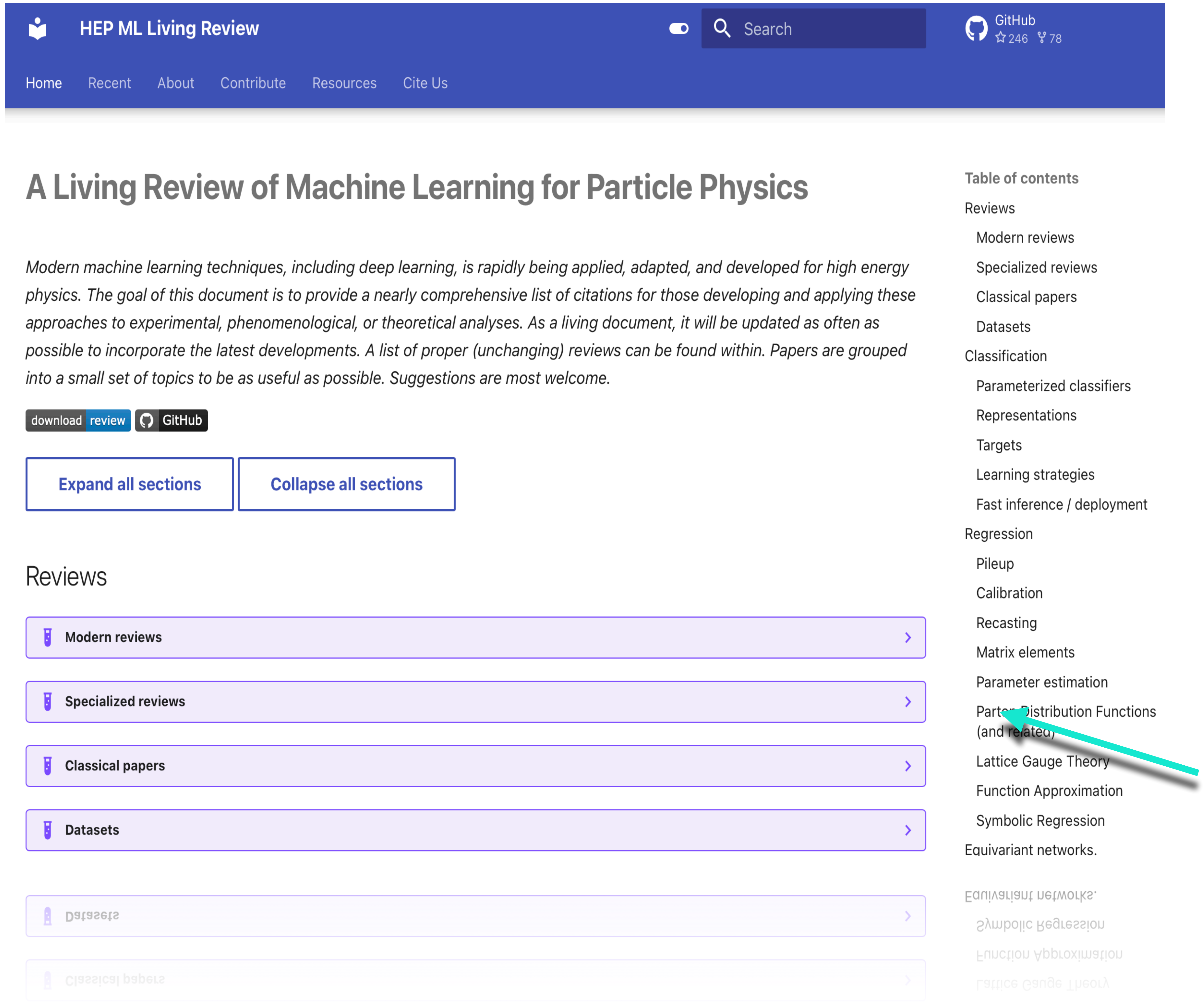
See N. Huetsch's talk

* if you are not interested in the full likelihood you can also just do **unfolding from detector to particle level**

See J. Mariño Villadamigo's talk

- Unfolding to parton-level is not only inverting detector effects, but rather inverting the entire forward simulation chain
- Faithful modeling of complex correlations at parton-level, i.e., W boson and top mass resonances
- Non-trivial combinatorics between physics objects at both levels

Advertisement



❖ Do you have an idea that relies on ML techniques?

❖ Do you want to apply ML to your favorite problem?

❖ **Take a look at the literature first!**

Stay tuned for many other **ML4HEP applications**

HEPML

The world is not only LHC…

Low-energy QED scattering

See Y. Ulrich's talk

fixed-order NNLO QED framework

- provided: matrix elements by us or others
- output: physical cross section for any physical observable
- McMule: phase space generation, subtraction, stabilisation, integration, etc.

- all leptonic $2 \to 2$ processes in QED at NNLO (+ a few others)
- integrator & generator
- user defines cuts through arbitrary function that is loaded at run time

Get the code here: `https://mule-tools.gitlab.io`
Read the docs here: `https://mcmule.readthedocs.io`

McMule

Multiscale Lattice Gauge Theory algorithms

See P. Boyle's talk

Software: https://www.github.com/paboyle/Grid

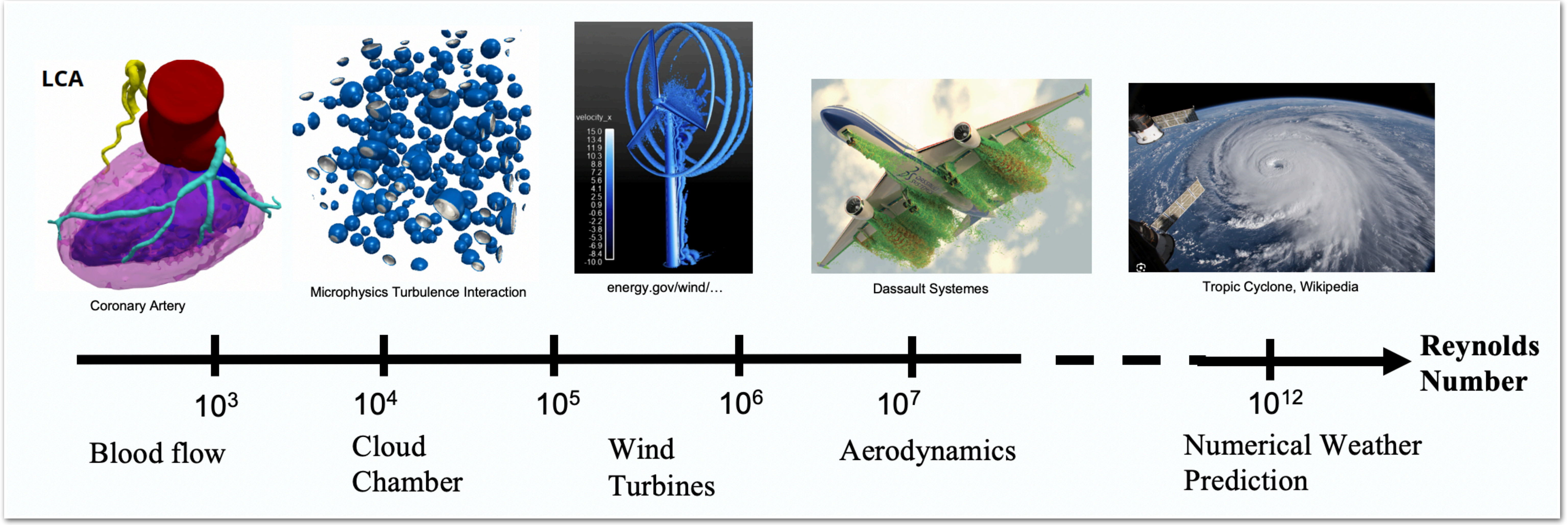
- Lattice QCD and muon g-2
- Grid code for structured Lattice Gauge theory calculations, developed under ECP
  - Parallelization & portability: *covariant programming*
  - Performance

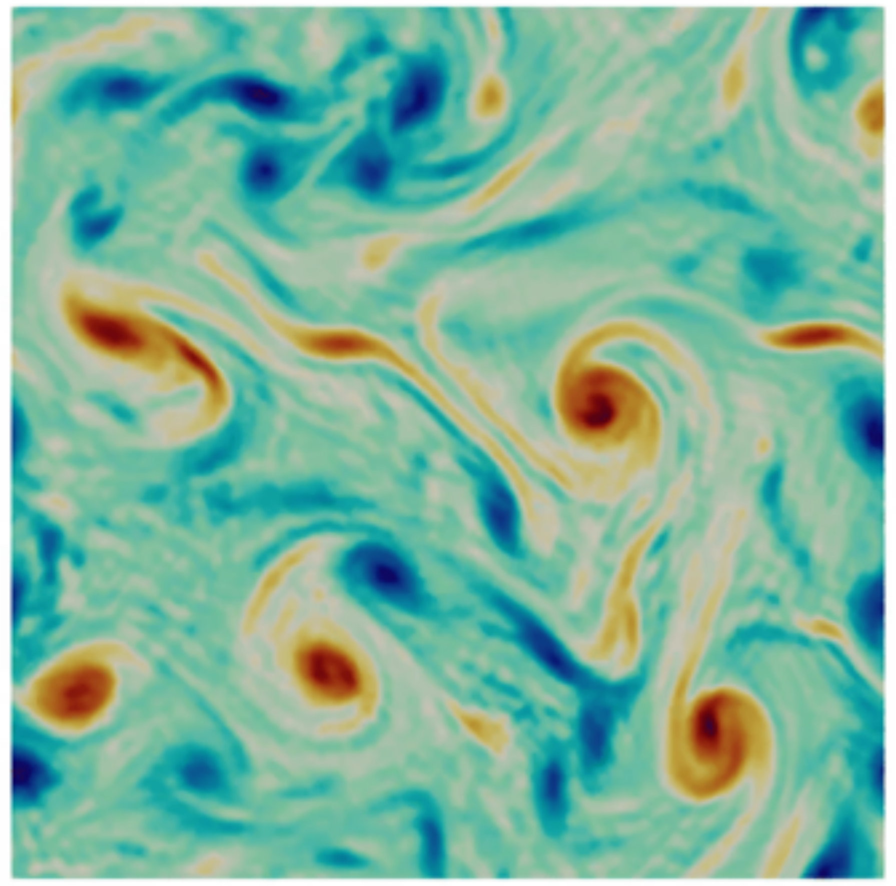
- Exascale algorithms and SciDAC-5
  - Multiple right-hand-side multigrid and GPU tensor units

The world is not only LHC…

…and it is not only colliders…

Study of **turbulence: computational challenge** with a variety of declinations:





See M. Atif's talk

Fourier Neural Operator as a surrogate for Navier-Stokes solver

Interconnection between different field and complementary expertise can unlock the doors of an exciting wonderland…

Thank you for your attention!

E. Golzio