Precision theory for high-energy colliders

Rene Poncelet

37th Rencontres de Blois on "Particle Physics and Cosmology"

10^{th} – 15^{th} May 2026

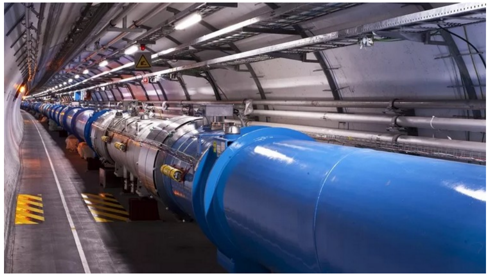
THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Funded by the European Union
European Research Council Established by the European Commission
NARODOWE CENTRUM NAUKI

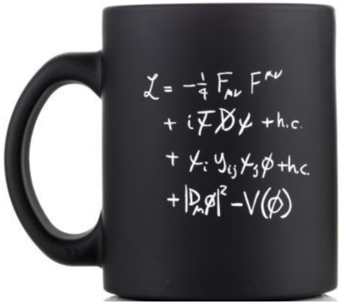
What are the fundamental building blocks of matter?

Scattering experiments

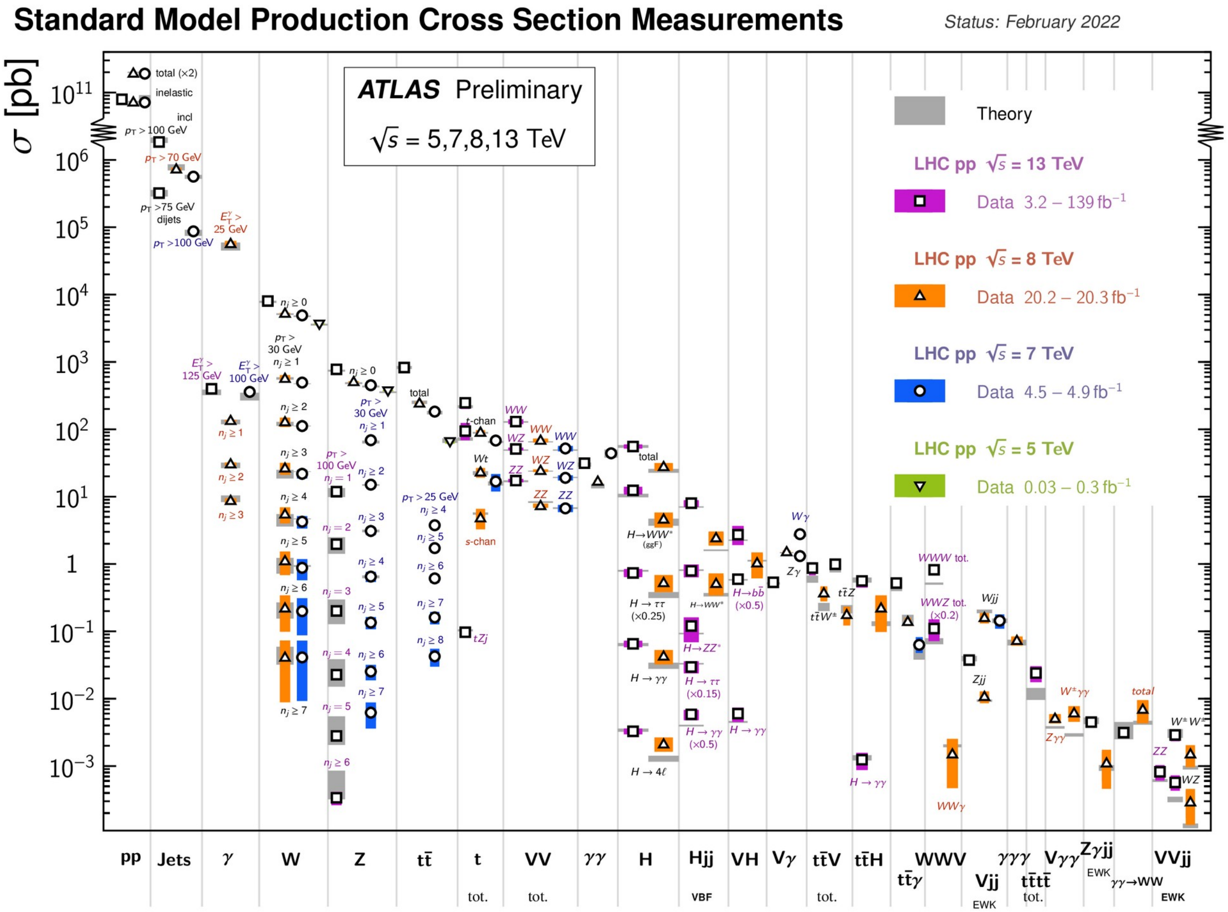
Large Hadron Collider (LHC)



Credit: CERN

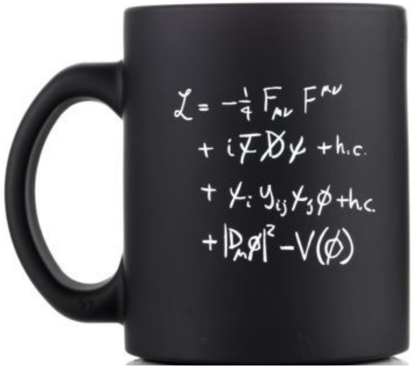


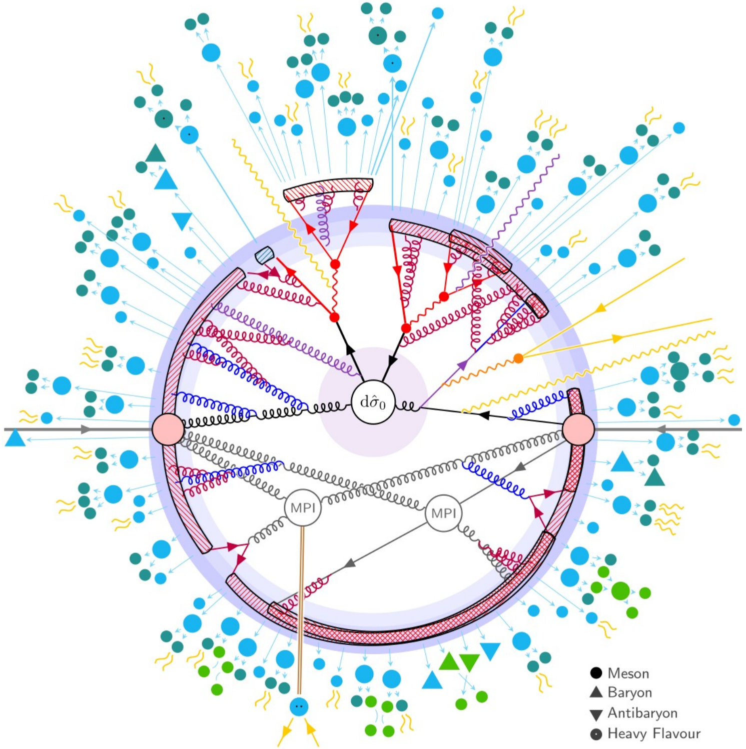
Theory/ Standard Model

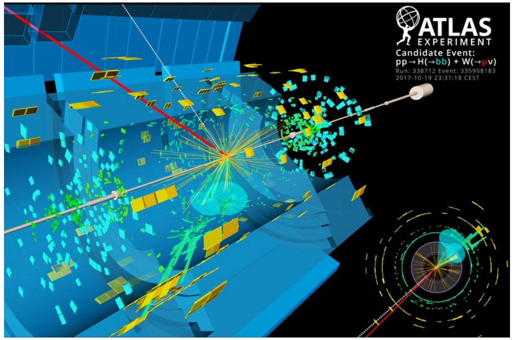


Monte Carlo Event Simulations

… the **bridge** between “theory world” and “real world”







[Pythia 8.3]

Scale factorization in collision events

Guiding physics principle
"What you see depends on the resolution"

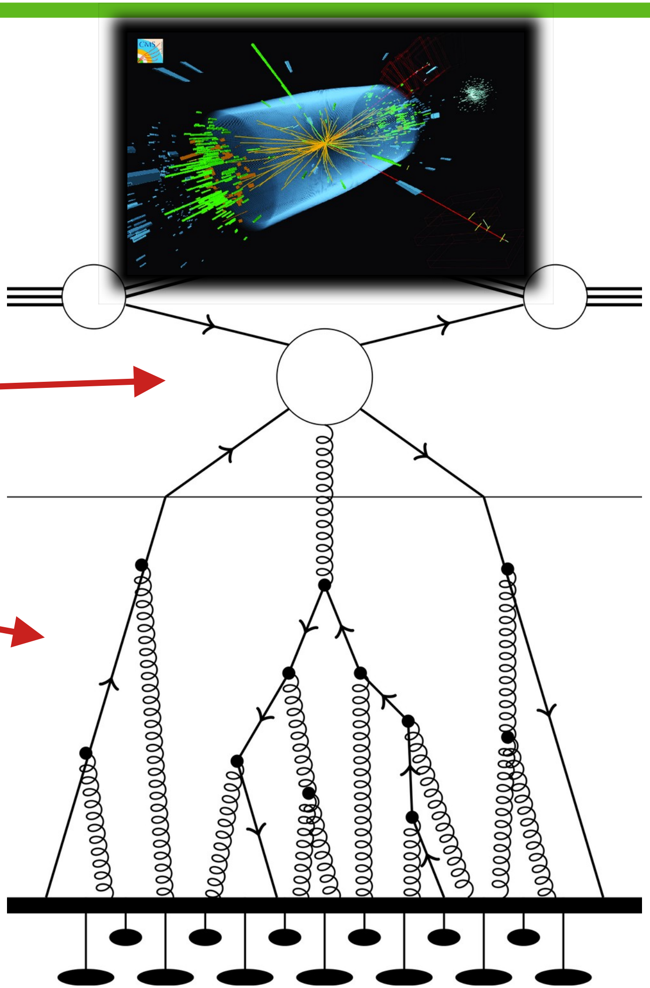
Example: Quantum Chromodynamics (QCD)

$Q \gg \Lambda_{\mathrm{QCD}}$ **Fixed-order perturbation theory**

$Q \gtrsim \Lambda_{\mathrm{QCD}}$ **Parton-shower/Resummation**

$Q \sim \Lambda_{\mathrm{QCD}}$ **"Hadronization"/MPI/...**

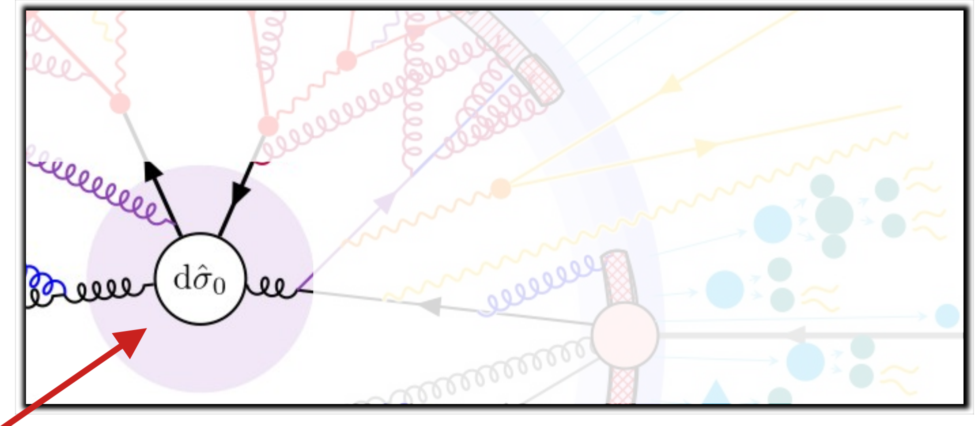
Energy



The tasks of Monte Carlo Event Generators

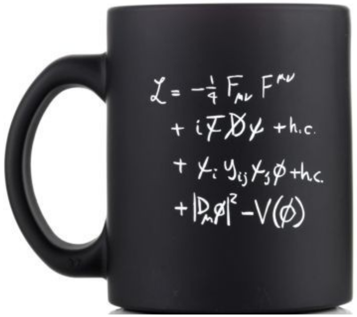
Energy

$Q \gg \Lambda_{\mathrm{QCD}}$

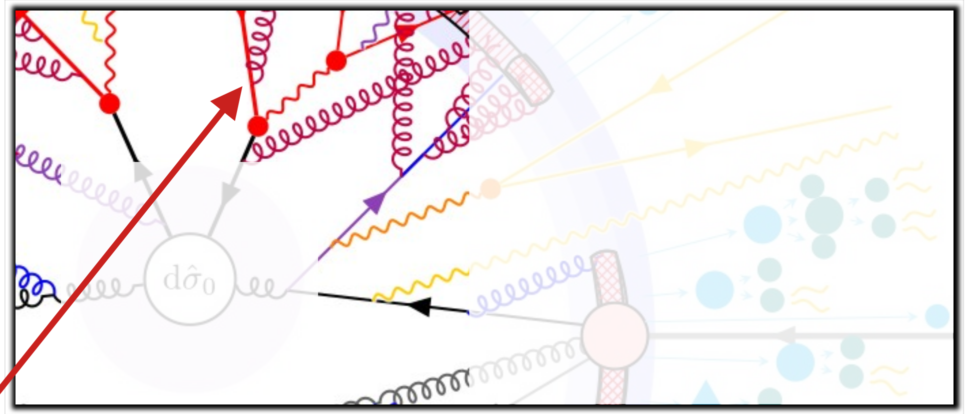


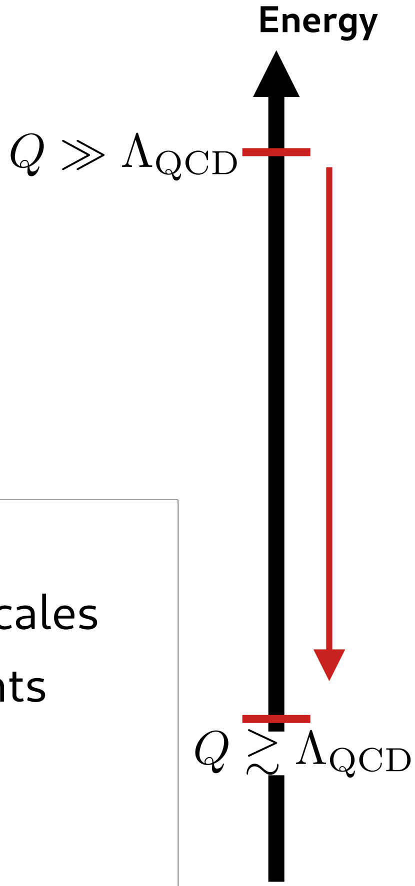
Hard scattering process

- Individual partons scatter at high momentum transfer
- Matrix elements directly from Lagrangian
- Fixed-order perturbation theory controls precision
  → expansions in orders of QCD and EW couplings



The tasks of Monte Carlo Event Generators

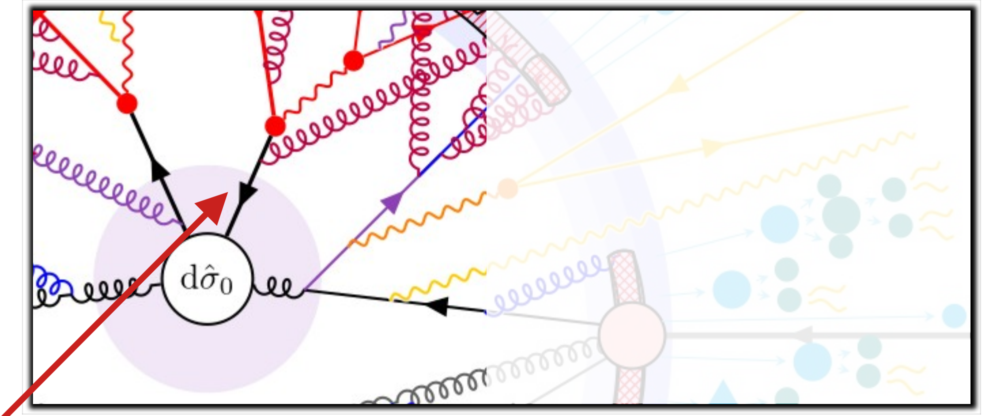


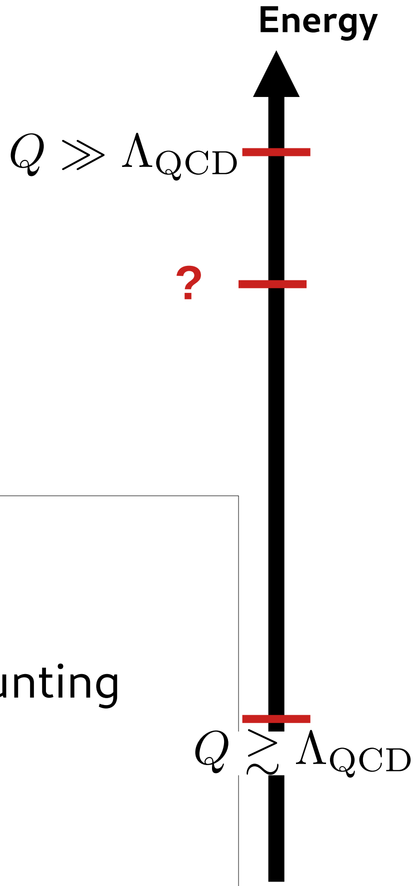


Parton-shower evolution

- Particle radiation: sequence of parton splittings at successively lower scales
- Splitting probabilities → soft/collinear approximations of matrix elements
- all-order resummation, accuracy measured in resummed logarithms
- Accuracy controlled by:
  splitting functions, kinematics, treatment of color & spin

The tasks of Monte Carlo Event Generators

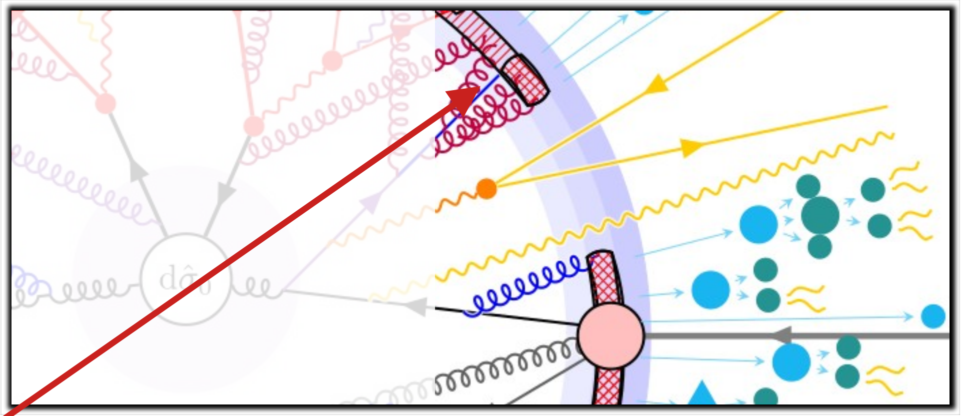


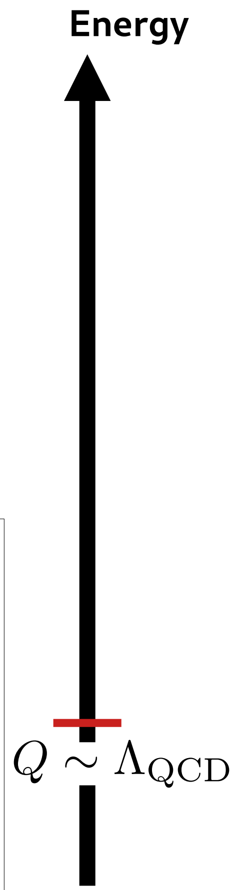


Matching/Merging

- combine hard scattering and parton-shower
- tricky bit: how to preserve the **precision/accuracy** and avoid double counting
- solve pathologies of higher fixed-order computations

The tasks of Monte Carlo Event Generators





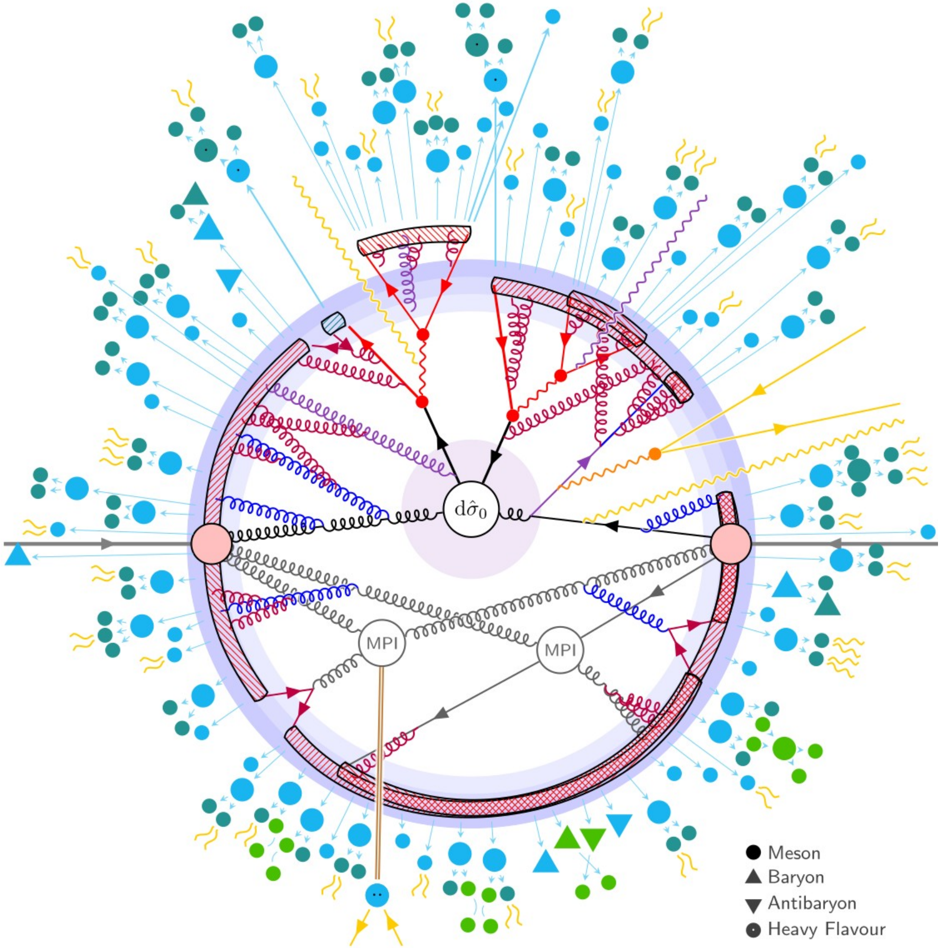
Hadronization

- Formation and decay of observable particles
- Intrinsically non perturbative physics
  → driven by phenomenological models
  → input from experiments

The tasks of Monte Carlo Event Generators

Global event considerations
- underlying event
- color reconnection
- multi parton interactions (MPI)
- beam remnants
- ...

Technical aspects
- Performance
- Tuning
- Uncertainties



LHC Era Monte Carlo Generators

[table shamelessly copied from S. Plätzer]

	Hard matrix elements	Shower algorithms	NLO Matching	Multi-jet merging	MPI	Hadronization	Shower variations
Herwig 7 [Eur.Phys.J.C 84 (2024)]	Internal, libraries, event-files	Qtilde, Dipoles	Internally automated	Internally automated	Eikonal	Cluster, (Strings)	Yes
Pythia 8 [SciPost Phys.Codeb. (2022)]	Internal, event-files	PT ordered, VINCIA	External	Internal, ME via event files	Interleaved	Strings	Yes
Sherpa 3 [JHEP 12(2024)]	Internal, libraries	CSShower, Alaric (future)	Internally automated	Internally automated	Eikonal	Clusters, Strings	Yes

The physics to describe is complicated: **methodological diversity is key** to **understand systematics** and to **validate** → relying on a single MC is asking for trouble…

Current precision efforts

$Q \gg \Lambda_{\mathrm{QCD}}$

Fixed-order perturbation theory
→ automatise state-of-the-art (N)NNLO QCD
→ EW and mixed QCD-EW corrections
→ matching to parton-shower (NNLO+PS)

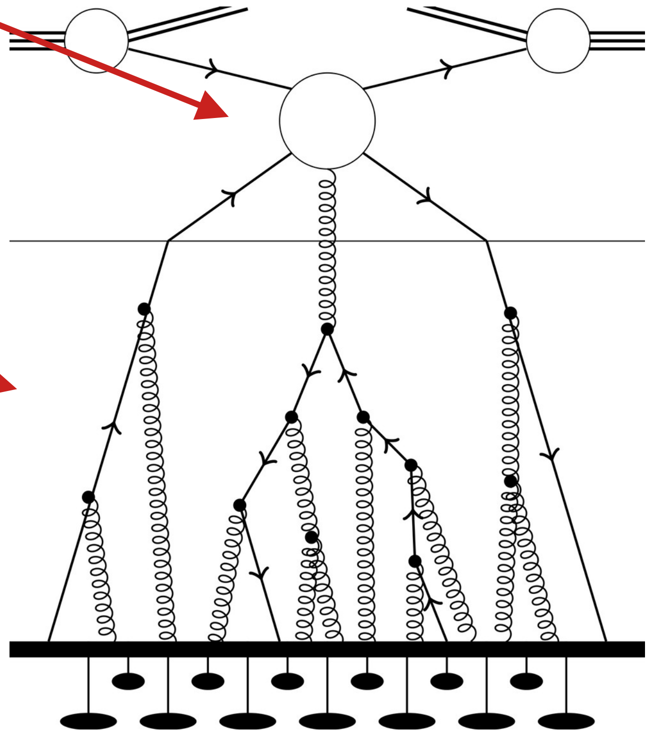
$Q \gtrsim \Lambda_{\mathrm{QCD}}$

Parton-shower/Resummation
→ increasing parton-shower accuracy
→ (N)NLL accurate showers
→ sub-leading color effects

$Q \sim \Lambda_{\mathrm{QCD}}$

"Hadronization"/MPI/…
→ refinement of models
→ improving constraints

Energy



Current precision efforts

not covered here...

$Q \gg \Lambda_{\text{QCD}}$

Fixed-order perturbation theory
→ automatise state-of-the-art (N)NNLO QCD
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→ increasing parton-shower accuracy
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→ **sub-leading color effects**

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"Hadronization"/MPI/…
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→ **improving constraints**

Energy

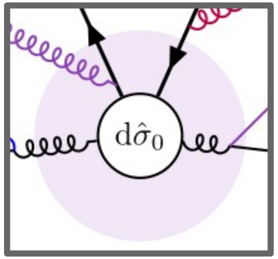
NLO EW (DY)
[Baur, Brein, Hollik, Schappacher, Wackeroth'01] [Dittmaier, Kramer'01][Baur,Wackeroth'04]

QCD-EW mixed (DY)
[Bonciani, Buonocore, Grazzini, Kallweit, Rana, Tramontano, Vicini'21][Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melnikov, Röntsch,Signorile-Signorile'22][Armadillo, Bonciani, Buonocore, Devoto, Grazzini, Kallweit, Rana Vicini'24]

Subleading color effects
[Hatta, Ueda'13'20] [Nagy, Soper'07-15][De Angelis, Forshaw, Holguin, Plaetzer, Torre,'13-'25]

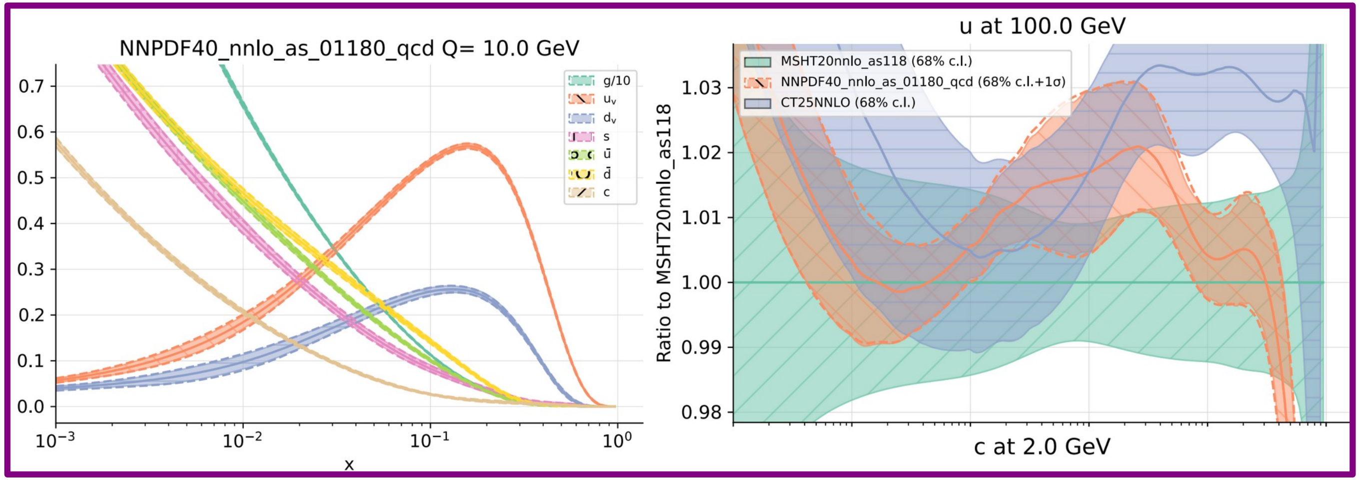
Hadronization
Herwig [Eur.Phys.J.C 84 (2024)] Pythia [SciPost Phys.Codeb. (2022)] SHERPA [JHEP 12(2024)] + some recent developments: [Altmann, Bernardinis, Skands, Zaccolo'25][Gieseke, Kiebacher, Plaetzer, Priedigkeit'25]

Fixed-order QCD in collinear factorization

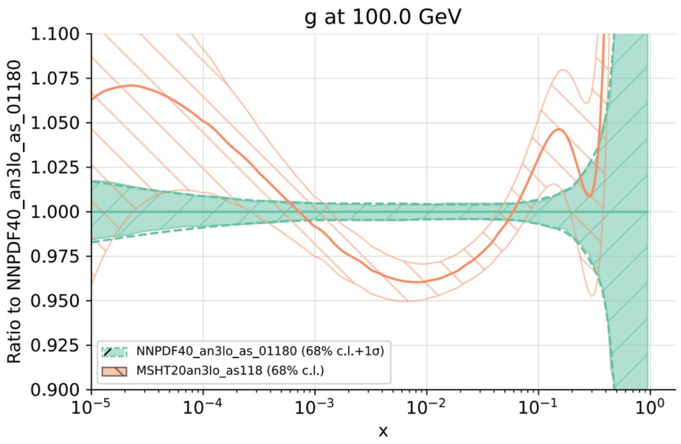


$$\sigma_{h_1 h_2 \to X} = \sum_{ij} \int_0^1 \int_0^1 \underline{\mathrm{d}x_1 \mathrm{d}x_2 \phi_{i,h_1}(x_1, \mu_F^2)} \phi_{j,h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \to X}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

Collinear (unpolarised) parton distribution functions



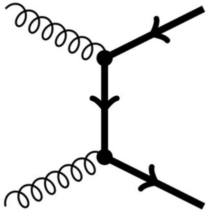
First steps towards N3LO ...

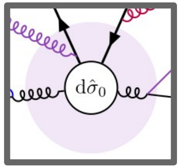


[from Juan's DIS talk last week]

Fixed-order QCD in collinear factorization

LO



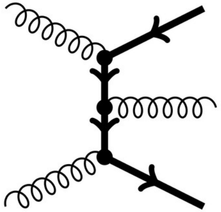


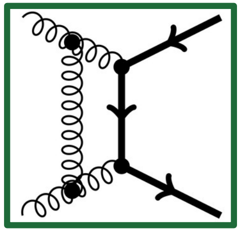
$$\sigma_{h_1 h_2 \to X} = \sum_{ij} \int_0^1 \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \phi_{i,h_1}(x_1, \mu_F^2) \phi_{j,h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \to X}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

partonic cross section

$$\hat{\sigma}_{ab \to X} = \hat{\sigma}^{(0)}_{ab \to X} + \hat{\sigma}^{(1)}_{ab \to X} + \hat{\sigma}^{(2)}_{ab \to X} + \mathcal{O}(\alpha_s^3)$$

NLO





$$\hat{\sigma}^{(i)} \ni \frac{1}{\mathcal{F}} \int |\mathcal{M}_n|^2 \mathrm{d}\Phi_n$$

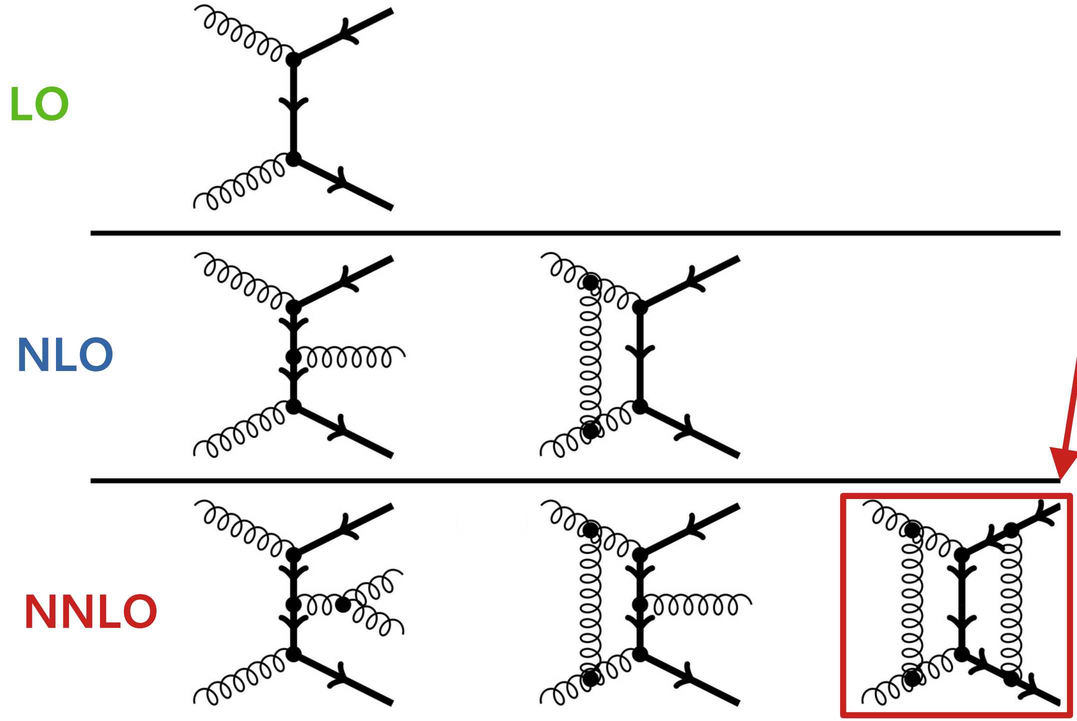
IR-finite cross section

NNLO

Automated fixed-order @ NLO

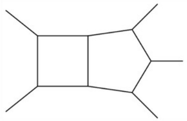
- oneloop-matrix elements
  - Openloops, Recola, Helac, MadGraph, GoSam
- local QCD/EW subtraction
  - FKS: MadGraph5_aMC@NLO, Powheg
  - CS dipoles: Sherpa, Herwig

NNLO QCD challenges: two-loop amplitudes

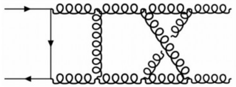


How to compute
multi-scale two-loop QCD amplitudes?
→ **fast growing complexity:**
rational coef. and **special functions**
→ deeper understanding of the analytical properties
→ refinement of computational tools

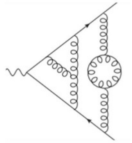
Two-loop 5-point
[Abreu, Agarwal, Badger, Buccioni, Chawdhry, Chicherin,Czakon, de Laurenties, Febres-Cordero, Gambuti, Gehrmann, Henn, Lo Presti, Manteuffel, Ma, Mitov, Page, Peraro, Poncelet, Schabiner Sotnikov, Tancredi, Zhang,...]



Three-loop 4-point
[Bargiela, Dobadilla, Canko, Caola, Jakubcik, Gambuti, Gehrmann, Henn, Lim, Mella, Mistleberger, Wasser, Manteuffel, Syrrakow, Smirnov, Trancredi, ...]

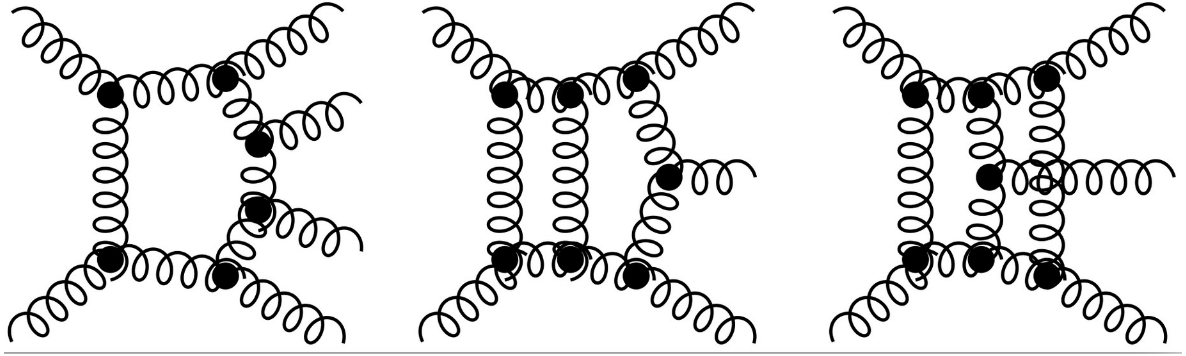


Four-loop 3-point
[Henn, Lee, Manteuffel, Schabinger, Smirnov, Steinhauser,...]



Approach to multi-loop amplitudes

Feynman diagrams



→ many graphs contribute to a given process, O($10^3 - 10^4$) typical at the moment

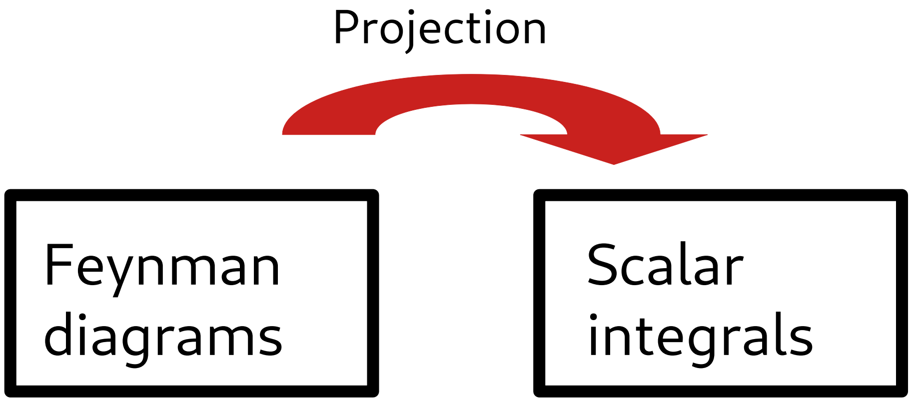
→ however fully automated techniques available: **QGraph**, **DiaGen**, ...

→ direct evaluation not possible:

→ (tensor-)loop integrals need regularisation (IR & UV) $\rightarrow d = 4 - 2\epsilon$

→ dimensional regularisation obscures spin& Lorentz structure

Color & Spin projection



color & spin decomposition:

color structure

$$\mathcal{M} = \sum_{c,s} \mathcal{M}_{c,s} \mathbf{C}_c \mathbf{T}_c$$

spin structure

scalar partial amplitudes

$$\mathcal{M}_{s,c} = \sum_j c_j(\{p\}, \epsilon) \mathcal{I}_j(\{p\}, \epsilon)$$

rational functions
(kinematics and ϵ)

(scalar) Feynman Integrals

Integration by Part Identities

Projection

Feynman diagrams → Scalar integrals → Master integrals

Feynman Integrals

propagators

$$\mathcal{I}_i(\{p\},\epsilon) = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d}\prod_{k=1} D_k^{-n_{i,k}}$$

Integration-by-parts identities:
[Chetyrkin, Tkachov '81, Laporta '00]

$$0 = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d} l_\mu \frac{\partial}{\partial l^\mu}\prod_{k=1} D_k^{-n_{i,k}}$$

→ matrices to be solved for basis of "**Master Integrals**" M_i

Modern solvers: **Reduze** [von Manteuffel, Studerus], **Fire** [Smirnov, Zeng], **Kira** [Lange, Usovitsch, Wu], **LiteRed** [Lee], **FiniteFlow** [Peraro]
Simplified systems: **NeatIBP** [Z. Wu, J. Boehm, R. Ma, H. Xu, Y. Zhang], **Blade** [Guan,Liu,Ma,Wu], **CALICO** [Bertolini, Fontana, Peraro]

Differential equations for Master Integrals

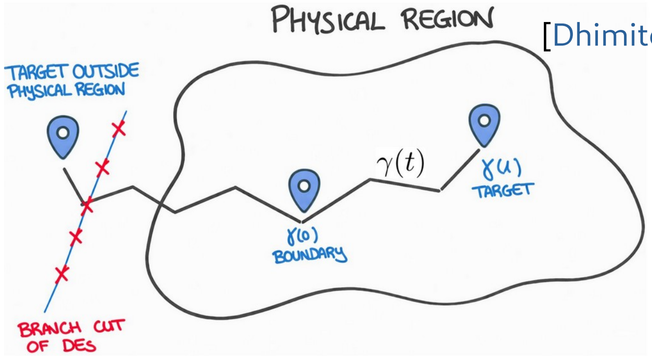
Projection — Integration-by-parts

Feynman diagrams → Scalar integrals → Master integrals → 'Analytic' functions

Master integrals fulfil DEQs [Kotikov'91, Gehrmann, Remiddi'00]

$$\partial_x \mathbf{M}_i = \sum_j A_{ij}(\{p\}, \epsilon)\mathbf{M}_j$$

- requires boundary conditions
→ 'analytic' solution if simple otherwise numerics

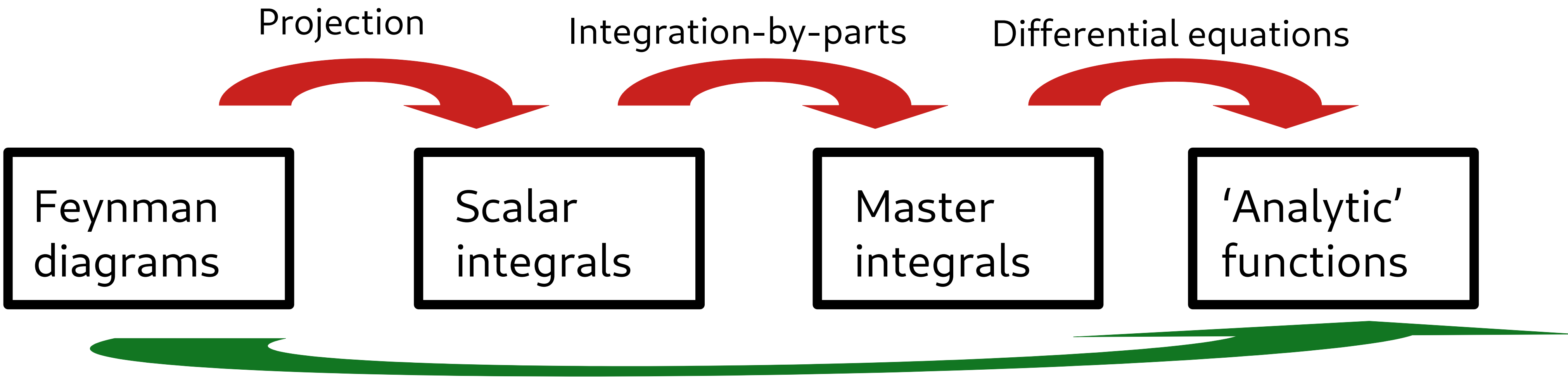


[Dhimiter Canko]

Systematic approach: canonical form [Henn, 13]
→ solutions are iterated integrals

Alternative direct numerical evaluation, e.g. sector decomposition [T. Binoth, G. Heinrich] with **PySecDec** [G. Heinrich, S. P. Jones, M. Kerner, V. Magerya, A. Olsson, J. Schlenk, et al.]

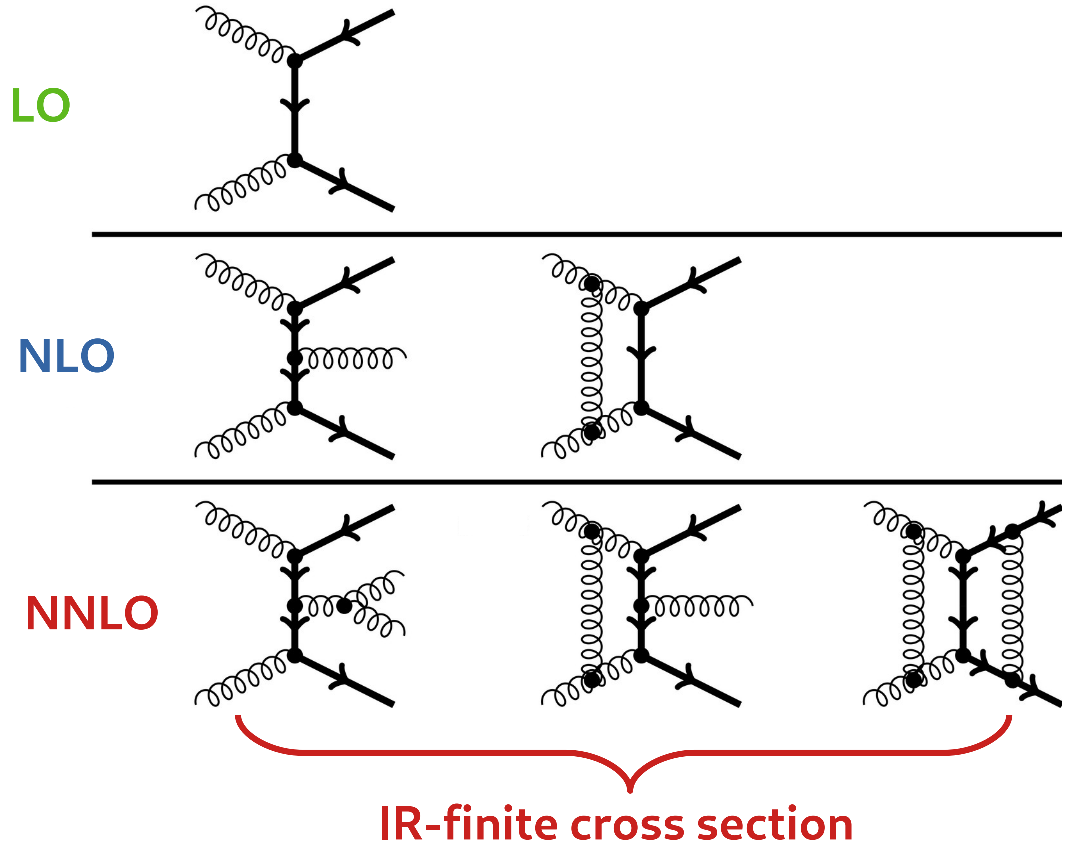
Approach to multi-loop amplitudes



Using **finite field reconstruction** to avoid expression swell:
→ numerical evaluations over finite fields to evaluate at rational points
→ rational interpolation over many points to recover exact analytic expression

[Kant'14, von Manteuffel, Schabinger'14, Peraro'16]
tools: **FiniteFlow**, **FireFly+Kira**, **Fire**, **Caravel**

NNLO QCD challenges: subtraction



How to achieve **infrared (IR) finite differential** cross sections at NNLO QCD?

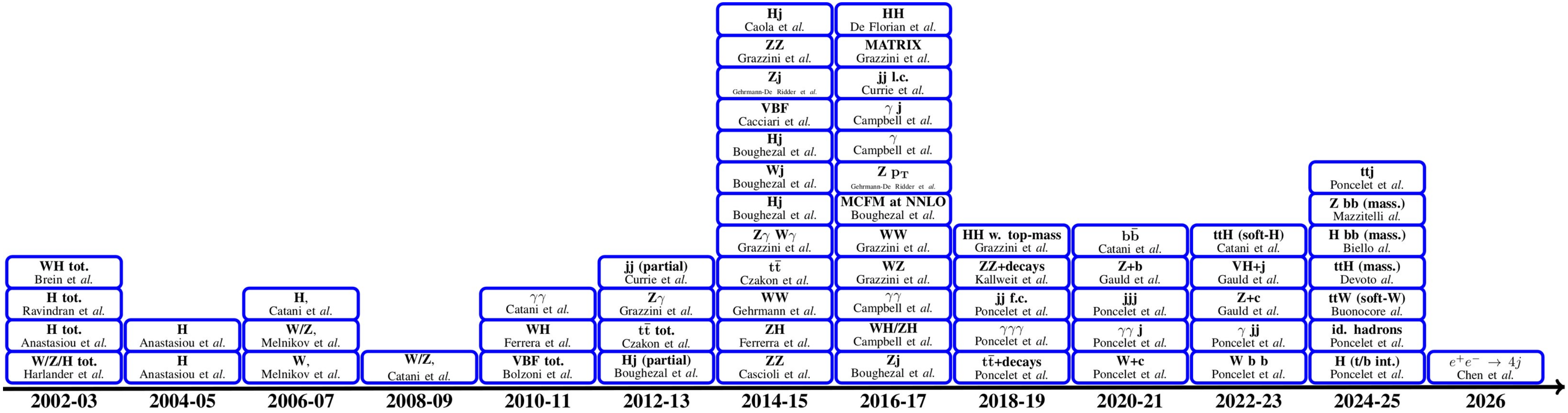
~20 years to solve this problem

qT-slicing [Catani'07], N-jettiness slicing [Gaunt'15/Boughezal'15], Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15], Projetction [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Local Analytic [Magnea'18] Sector-improved residue subtraction [Czakon'10-'14,'19]

Automation of NNLO QCD subtraction:

- qT-slicing (massive/color singlet) in **MATRIX** & **MCFM** (public)
- Antenna subtraction in **NNLOJet** (public)
- Sector-improved residue subtraction in **Stripper** (private impl.)
- color singlets with nested-collinear in **history** (public)

Status of NNLO QCD cross section computations

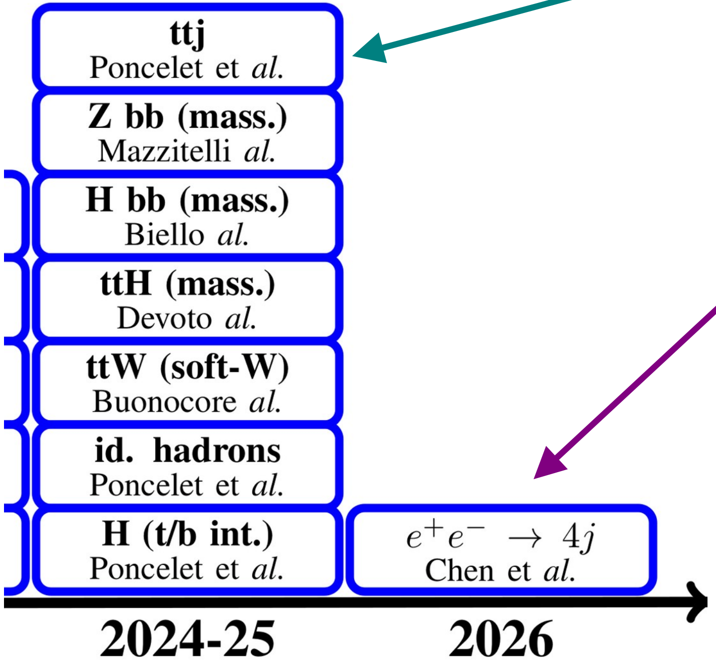


All 2 → 2 SM processes, 2 → 3+ only **limited by**

→ **the available two-loop matrix elements**

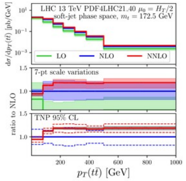
→ **numerical/computational challenges**

Status of NNLO QCD cross section computations

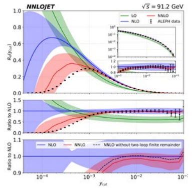


related talks here at Blois (all Thursday afternoon)

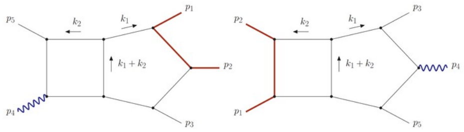
NNLO QCD corrections to top quark pair production in association with a jet
- Matteo Becchetti



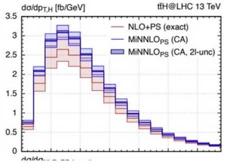
The four-Jet Rate in e+e- at Order α_s^4
- Elliot Fox



Towards NNLO QCD corrections ttW production
- Dhimiter Canko



Toward NNLO-accurate ttH event generation with approximate two-loop contributions
- Chiara Signorile-Signorile



Ultimate precision for HL-LHC → towards N3LO QCD

Semi-inclusive computations:

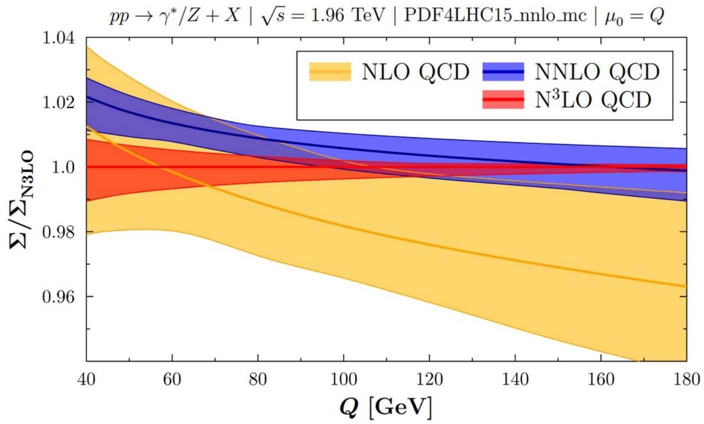
- Higgs/DY [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, '15-'20]
- VH [Baglio, Duhr, Mistlberger, Szafron '22]
- (Di-)Higgs in VBF [Dreyer Karlberg'16'18]

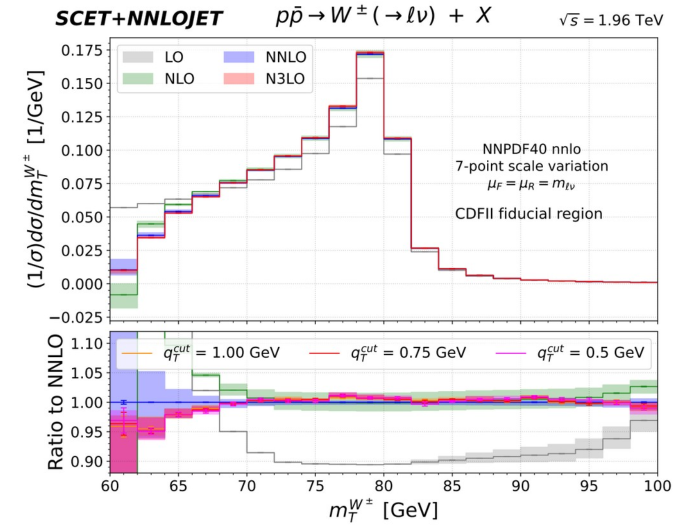
Fully differential cross sections

- Local e+e-→ jets with Antenna [Chen, Jakubčík, Marcoli, Stagnitto'25]
- Projection-to-Born for Higgs in pp [Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni]
- Local NNLO + qT slicing for hadron-hadron [Chen, Gehrmann, Glover, Huss, Yang, Zhu'21-'22] [Czakon, Eschment, Generet, Poncelet'26]
- Double slicing in DIS [Dong, Fang, Gao,Li,Shao,Zhu,Zhu'26]

Three loop amplitudes:

- 2→ 2 partons/photons [Bargiela, Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi '20-'23]
- 2 → 2 with one massive leg (planar):
  - H+jet [Chen, Guan, Mistlberger'25]
  - V+jet [Gehrmann,Jakubčík,Mella,Syrrakos,Tancredi'23]





N3LO QCD photon pair production

[Czakon, Eschment, Generet, Poncelet'26]

Combination of local subtraction
+ qT-slicing [Grazzini, Catani'07]

$$\sigma^{pp\to\gamma\gamma}_{\mathrm{N^3LO}} = \int_0^{q_T^{\mathrm{cut}}} \mathrm{d}q_T \frac{\mathrm{d}\sigma^{pp\to\gamma\gamma}_{\mathrm{N^3LO}}}{\mathrm{d}q_T} + \int_{q_T^{\mathrm{cut}}}^{\infty} \mathrm{d}q_T \frac{\mathrm{d}\sigma^{pp\to\gamma\gamma j}_{\mathrm{NNLO}}}{\mathrm{d}q_T}$$

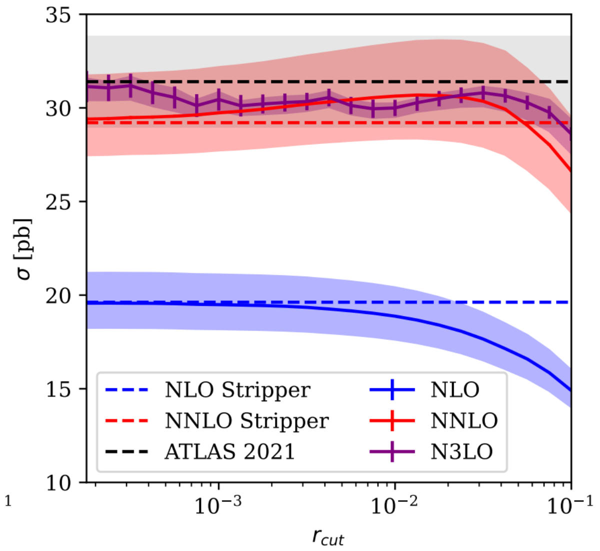
qT-factorization:

Sector-improved residue subtraction
[Czakon'10' et al 14'19]

$$\frac{\mathrm{d}\sigma^{pp\to\gamma\gamma}}{\mathrm{d}\boldsymbol{q}_T^2\,\mathrm{d}m_{\gamma\gamma}\,\mathrm{d}y} = \sum_{a,b} H_{ab}(m_{\gamma\gamma}) \int \frac{\mathrm{d}^2\boldsymbol{b}_T}{(2\pi)^2} e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}\ \tilde{f}_a(x_1,\boldsymbol{b}_T)\tilde{f}_b(x_2,\boldsymbol{b}_T) + \mathcal{O}(q_T/m_{\gamma\gamma})$$

$$\tilde{f}_i(x,\boldsymbol{b}_T) = \sum_j \int_x^1 \frac{\mathrm{d}z}{z} \tilde{\mathcal{I}}^{\mathrm{TMD}}_{ij}(z,\boldsymbol{b}_T) f_j\left(\frac{x}{z}\right) + \mathcal{O}(\boldsymbol{b}_T\Lambda_{\mathrm{QCD}})$$

N3LO TMDs [Ebert, Mistlberger, Vita '20] [Luo, Yang, Zhu, Zhu '20]



Fiducial cross sections:

$$\sigma^{pp\to\gamma\gamma}_{\mathrm{N^3LO}} = 31.2(6)^{+0.5}_{-0.7}\ \mathrm{pb}$$

$$\sigma^{pp\to\gamma\gamma}_{\mathrm{ATLAS}} = 31.4 \pm 0.1\ (\mathrm{stat.}) \pm 2.4\ (\mathrm{syst.})\ \ \mathrm{pb}$$

Phase space from [ATLAS 2107.09330]
with hybrid-cone photon-isolation
[Siegert'16 Chen et al '19]

N3LO QCD photon pair production

[Czakon, Eschment, Generet, Poncelet'26]

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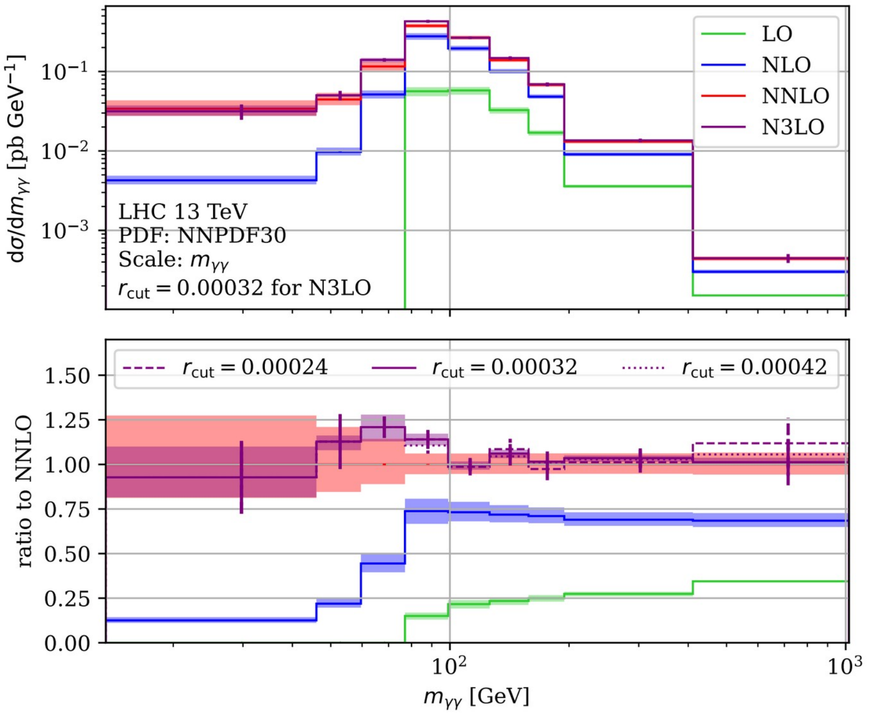
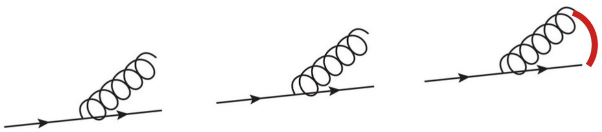


Beyond Leading Order: The Need for Matching

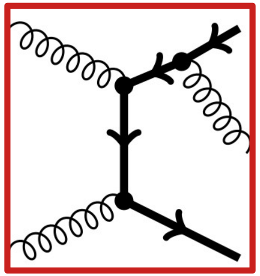
The challenge

Combine fixed-order with parton shower evolution
while **preserving** the precision/accuracy of both!



v ← shower scale

"Hard" scattering scale Q



parton shower approximation: $\alpha_S^i(v)\ln^j(v)$
but to all orders!

accuracy: LL, NLL, NNLL, ...

Fixed-order: expansion in $\alpha_S(Q)$

→ cross section ~ $\underbrace{e^{\sum_{ij}\alpha_S^i(v)\ln^j(v)} \times (\mathrm{LO} + \mathrm{NLO} + \mathrm{NNLO} + \ldots)}$

A matching scheme needs to avoid double counting
of the logarithmic contributions!

Beyond Leading Order: The Need for Matching

NLO + Parton Shower Matching

- Standard tools: **POWHEG** and **MC@NLO**
- Implemented in all major frameworks: Herwig, SHERPA, Madgraph, Powheg-box,...
- Standard for most LHC analyses today.

Current state-of-the-art: NNLO+PS

target to preserve LL accuracy so far

→ MiNNLOPS [Hamilton, Nason, Re, Zanderighi'13] [Monni, Nason, Re, Wiesemann, Zanderighi'20],

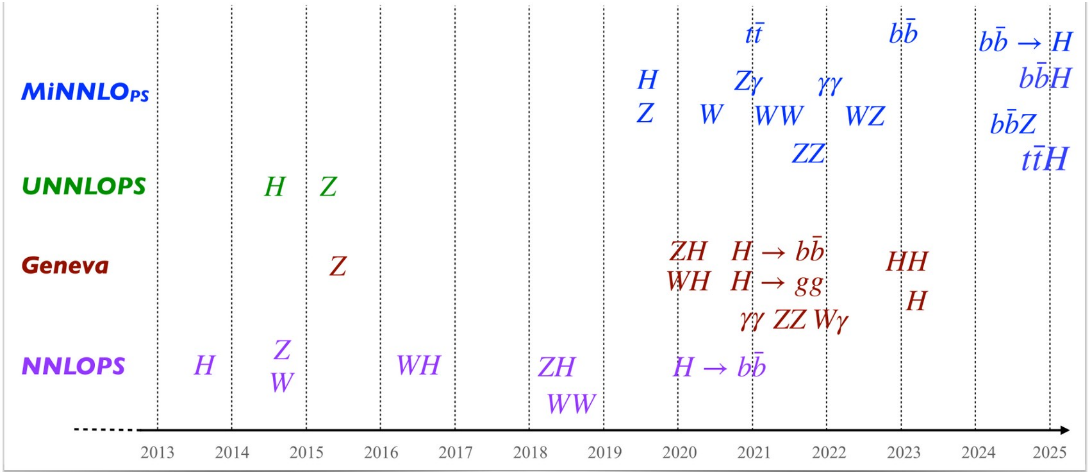
→ Geneva [Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi'13-'25]

→ UN2LOPS [Hoche, Prestel'14]

→ Vincia [El-Menoufi,Preuss,Scyboz,Skands'24]

Other ideas to incorporate higher-orders:

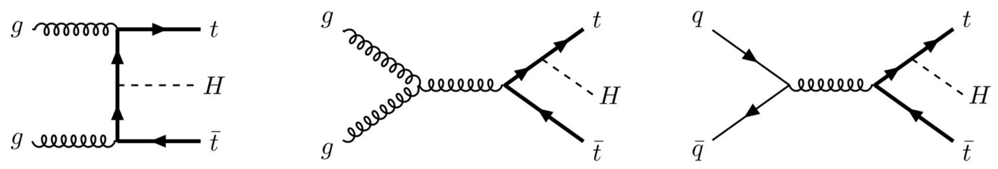
→ reweighting with energy-flow polynomials [Assi, Lee, Thaler'26]



[talk by Wiesemann'25]

NNLO PS with MiNNLOPS

Next-to-next-to-leading order event generation for $t\bar{t}H$ production with approximate two-loop amplitude
[Biello, Savoini, Signorile-Signorile, Wiesemann 2603.06143]
→ public event generator in Powheg framework



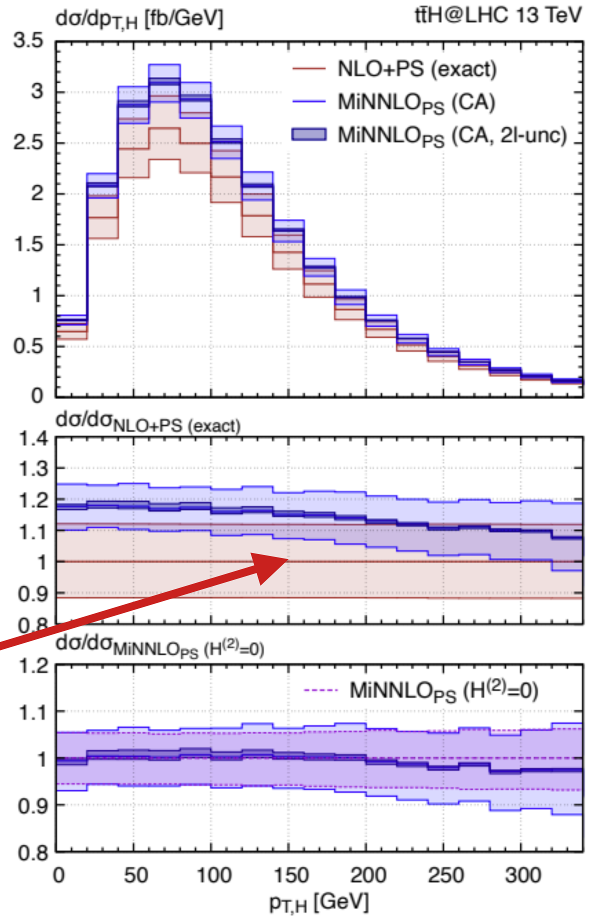
(a) t-channel gg diagram (b) s-channel gg diagram (c) s-channel $q\bar{q}$ diagram

Why NNLO PS matching matters

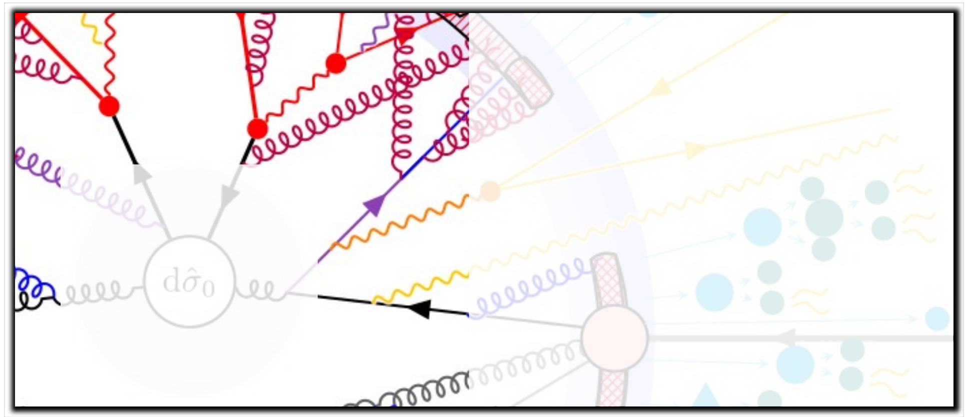
→ propagation of **NNLO QCD effects on the shape**

→ **global NNLO/NLO k-factors are not sufficient**

→ consistent propagation to particle level is needed!



Higher accuracy parton showers



Steps towards better controlled accuracy in the parton shower

→ **NLL showers**

Not covered here:

→ Higher-order splitting kernels

→ Sub-leading color effects

→ Treatment of spin-correlation

→ Electroweak effects

PanScales [van Beekveld, Dasgupta, Dreyer, Ferrario Ravasio, Hamilton, Karlberg, Medves, Monni, Salam, Scyboz, Soto Ontoso, Soyez,Verheyen'18-'25]

Alaric [Assi,Herren, Höche, Krauss, Reichelt, Schönherr'22-'24]

Apollo [Preuss'24]

Deductor [Nagy, Soper'20]

Herwig [Forshaw, Holguin, Plätzer Bewick, Ferrario Ravasio, Richardson, Seymour'19-'21]

Jet substructure: why logarithmic accuracy matters

Jet sub-structure

- Example: Lund plane multiplicity by ATLAS
- comparison of different showers
  and analytic resummed predictions
- Data is sensitive to the shower model
  → how to **estimate shower uncertainties**?
  → why are the shower so different from the analytic resummation?

Outlook

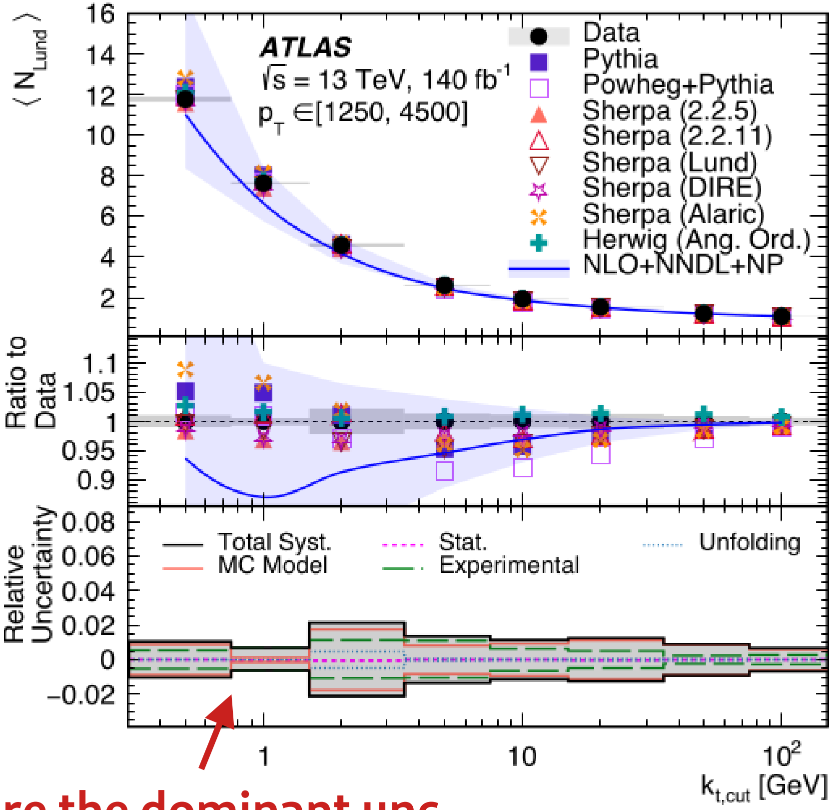
→ Implications for jet substructure measurements

→ everything that uses jet substructure techniques

→ flavour tagging

→ quark/gluon jet discrimination

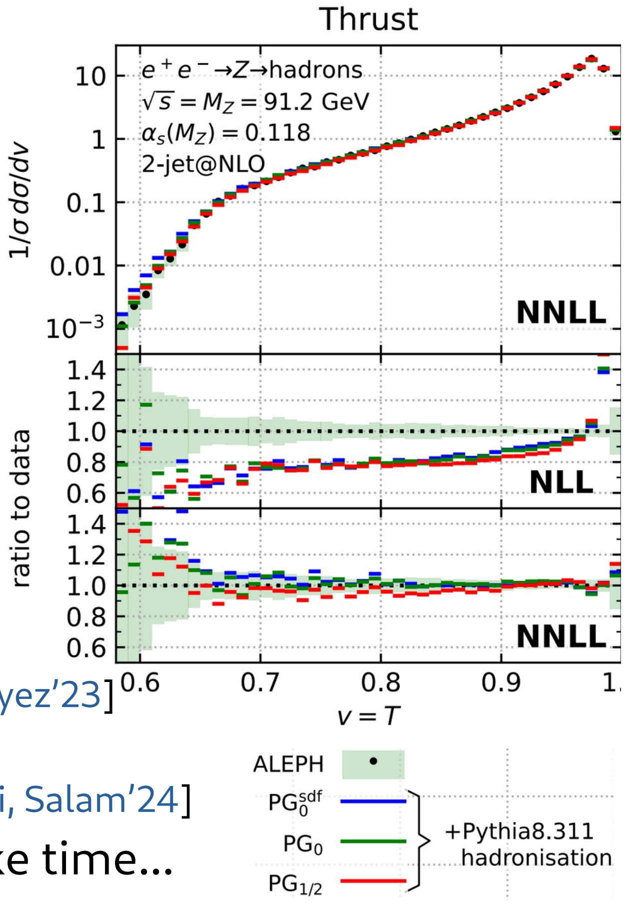
→ jet calibration



MCs are the dominant unc.

Towards NNLL showers

- For some e+e- event shapes already feasible
  → PanScales showers + Pythia
  → understood with $\alpha_S = 0.118$ at NLL → NNLL spot on
  → other showers might behave differently
- Take-home message:
  → high log accuracy can resolves modelling issues
  → increased consistency



Step-by-step towards NNLL showers come up

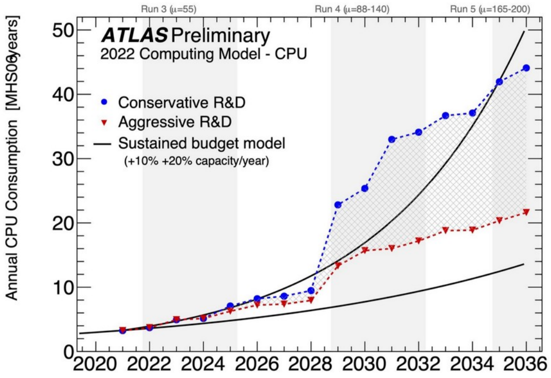
- Double soft-corrections [Ferrario Ravasio, Hamliton, Karlberg, Salam, Scyboz, Soyez'23]
- Soft-collinear emissions [PanScales'24]
- Triple-collinear emissions [van Beekveld, Dasgupta, el-Menoufi, Helliwell, Monni, Salam'24]

→ so far limited to special cases in e+e-, transfer to pp/DIS will take time…

Computational challenges

The HL-LHC Problem
Generating enough events is/will be computationally expensive
1) **negative events**
2) **expensive higher point ME unweighting**

[CERN-LHCC-2022-005]



Ensure positivity of event weights

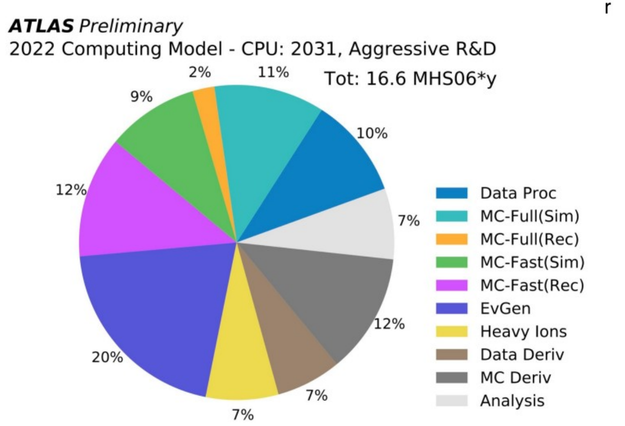
- Positive matching: ESME [PanScales'25], KrK [Pratixan, Siodmok, Whitehead '24]
- Reweighting methods: cell-resampling [J. Andersen, A. Maier'21+Maître'23] Arcane [Shyamsundar'25]

Exploit modern architectures → CPU + GPU

- MEs: PEPPER [Bothmann, Childers, Giele, Höche, Isaacson Knobbe'23]
- Madgraph on GPUs [Valassi, Childers, Hageböck, Massaro, Mattelaer, Nichols, Optolo Roiser, Teig, Wettersten'25]

Machine Learning Methods
[De Crescenzo, Mariño, Elmer, Heimel, Plehn, Winterhalder, Zaro '26][Bothmann, Janßen, K Schmitzer, Sinz'26][Jansen, Poncelet, Schumann '25]

- Neural Importance Sampling
- Surrogates to emulating MEs



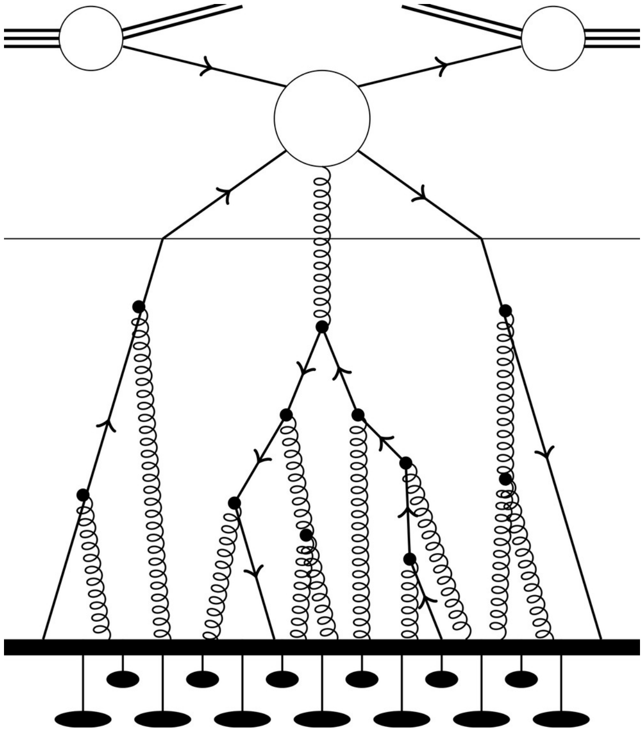
Take-home messages

- **Higher-order predictions in QCD and EW** are key for the LHC "precision era"

- Theory predictions and Monte Carlos evolved in the last decades from **"order-of-magnitude"** to **precision instruments**

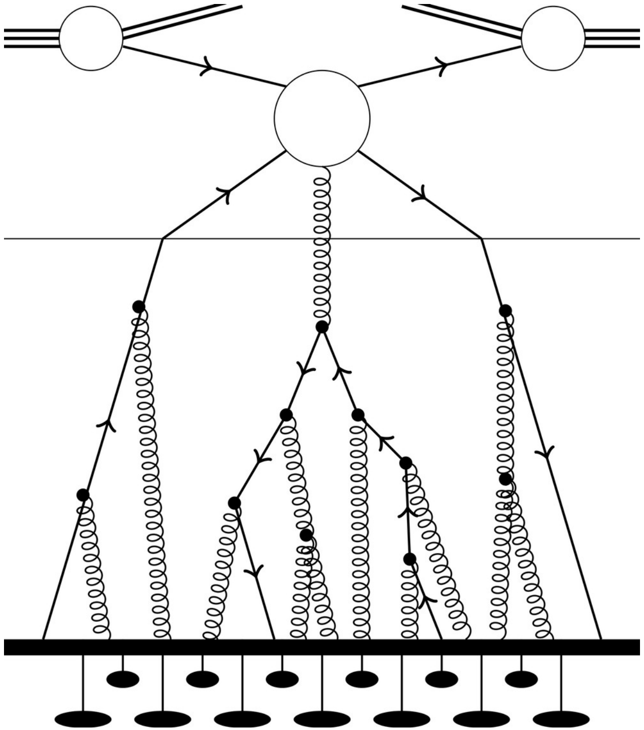
- **N3LO, NNLO+PS** and **(N)NLL showers** are (will be) the new standard for the 2020s.

- Success of the LHC physics program **depends on the continued evolution** of these tools.



Challenges = Outlook

- Towards **automated (numerical) two-loop** matrix element
- **Generalizations of new developments** to arbitrary processes:
  → public fully-automated NNLO QCD codes
  → showers beyond NLL
  → (local) NNLO+PS matching
  → sub-leading color
  → QCDxEW mixed for precision observables (Drell-Yan for example)
  → deeper understand of **theory uncertainties**
- Better understanding of **performance bottlenecks**:
  → negative weights
  → hybrid architectures

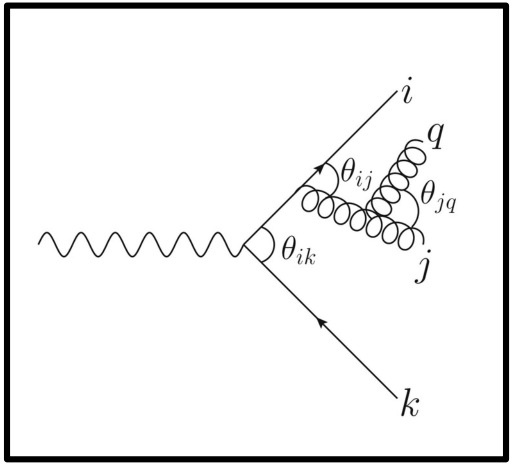


Backup

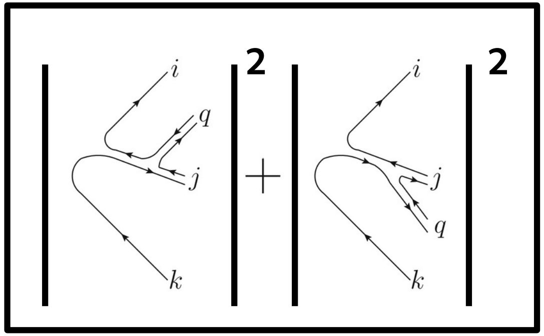
Sub-leading color evolution

[Diagrams from Holguin, Forshaw, Plaetzer'21]

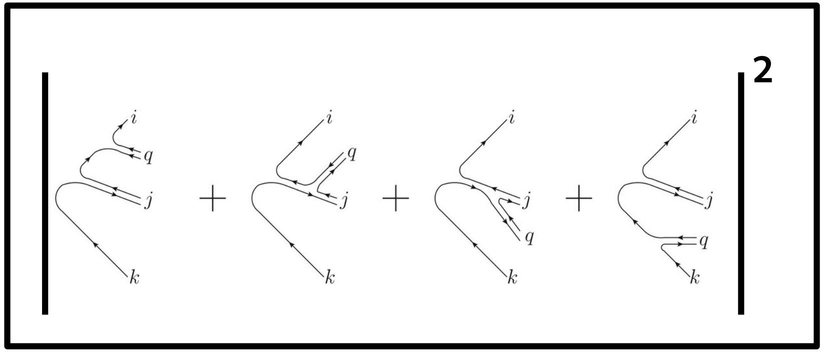
Most showers work in leading color approximation: $N_c \to \infty$



Leading color

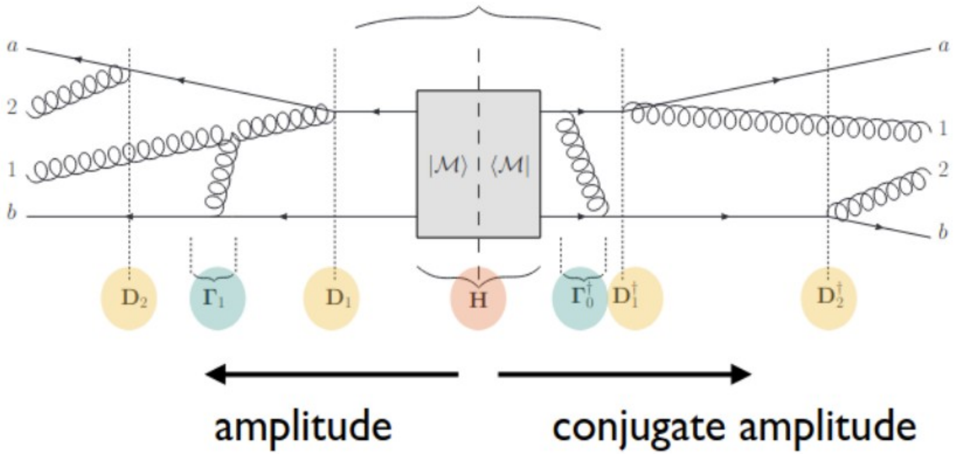


Full color

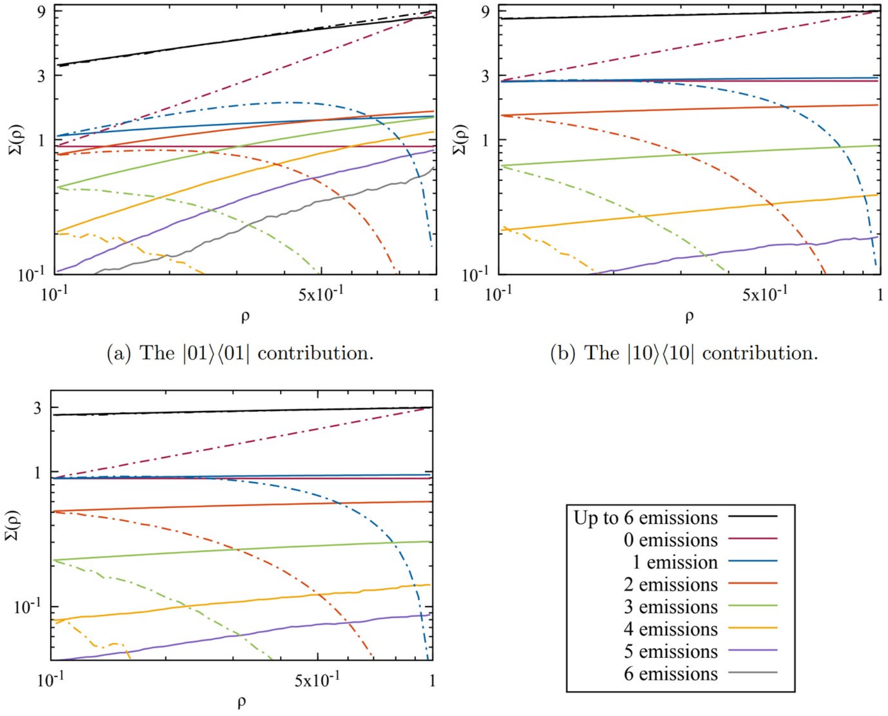


Sub-leading color evolution

In general events have complicated color structure:



[Forshaw, Plaetzer, Torre'25]



(a) The $|01\rangle\langle 01|$ contribution.

(b) The $|10\rangle\langle 10|$ contribution.

(c) The $|10\rangle\langle 01|$ (interference) contribution.

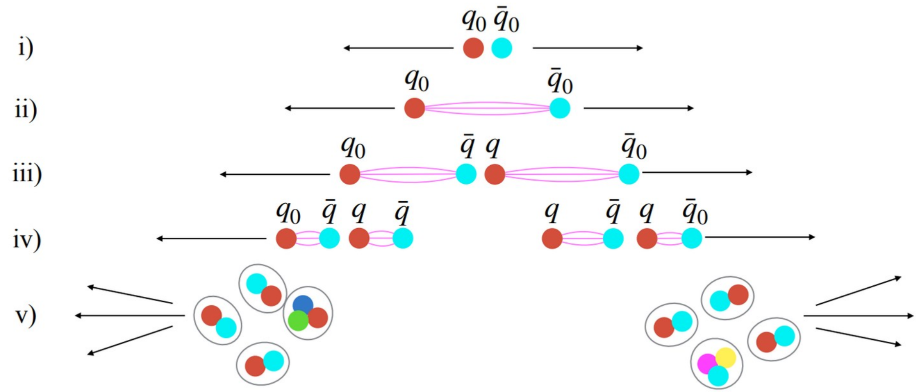
Methods implementing sub-leading color evolution

- subleading color effects in soft gluon emissions [Hatta, Ueda'13'20]
- Deductor [Nagy, Soper'07-15]
- Cvolver [De Angelis, Forshaw, Holguin, Plaetzer, Torre,'13-'25]

Hadronization

String Model (Pythia)

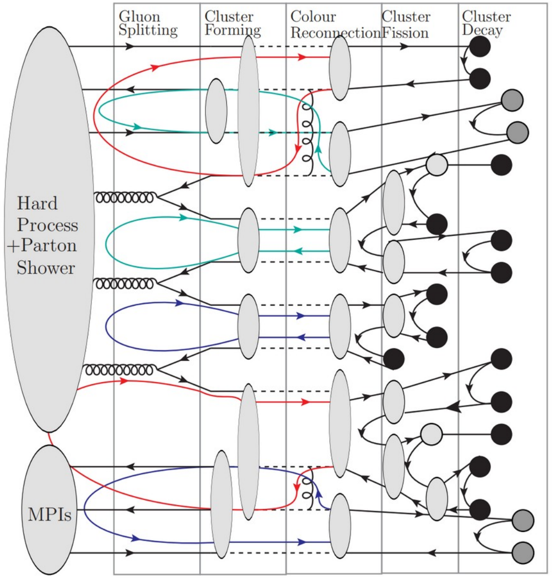
→ dynamics of a 1d color field (string)



[pic from Altmann, Bernardinis, Skands, Zaccolo'25]

The Cluster Model (Herwig/Sherpa)

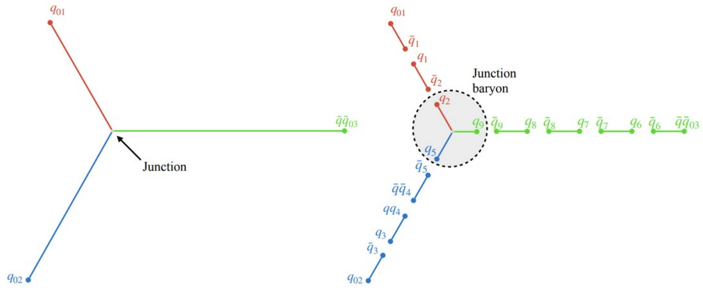
→ partons form color-singlet clusters which decay to hadrons

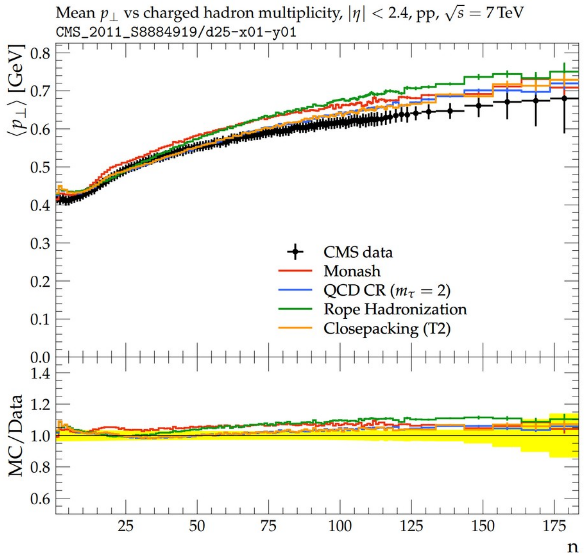


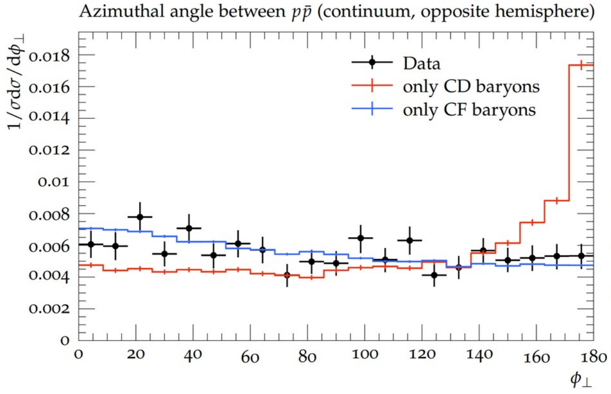
[Herwig 7]

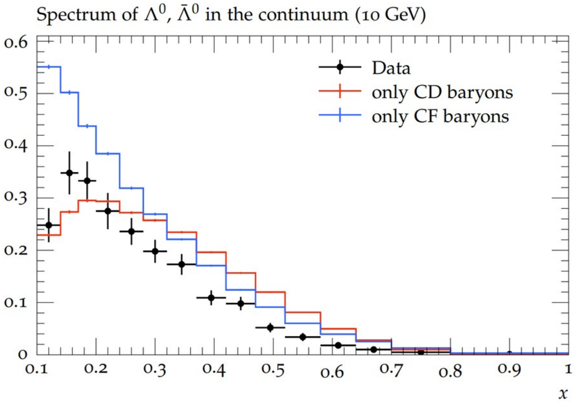
Hadronization – new developments

New developments Closepacking effects on strangeness and baryon production at the LHC
[Altmann, Bernardinis, Skands, Zaccolo'25]









Phenomenological constraints of the building blocks of the cluster hadronization model
[Gieseke, Kiebacher, Plaetzer, Priedigkeit'25]

Neural importance sampling & surrogates

Variance reduction through importance sampling:

$$\hat{I} = \frac{1}{N}\sum_{i=1}^{N} f(\mathbf{x}_i)\,, \quad \delta\hat{I} = \sqrt{\frac{1}{N-1}\left(\frac{1}{N}\sum_{i=1}^{N} f^2(\mathbf{x}_i) - \hat{I}^2\right)}$$

$$I = \int_{\mathbf{H}(\mathbf{x})\in\Omega} \mathrm{d}\mathbf{H}\,\frac{f(\mathbf{x})}{h(\mathbf{x})} \qquad h(\mathbf{x}) = \left|\det\left(\frac{\partial\mathbf{H}(\mathbf{x})}{\partial\mathbf{x}}\right)\right|$$

Task: find $h(\mathbf{x})$adaptive MC techniques: VEGAS [Lepage'78], Parni [Hameren'14]

Neural importance sampling

Normalising Flows in Sherpa [Bothmann'20], Madgraph [Heimel'22'25],STRIPPER [Jansen'25]

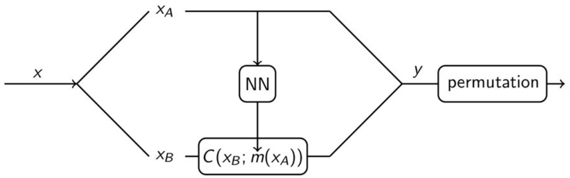
Surrogates

If f(x) is very expensive → finding a surrogate improves performance
→ can be unbiased by unweighting against real f(x)

- QCD factorization aware NN ME emulators [Maitre'21] [Janssen'23]
- two-stage unweighting to correct surrogates [Danziger'22]
- one-loop emulators [Aylett-Bullock'21][Badger'23] [Maitre'23]

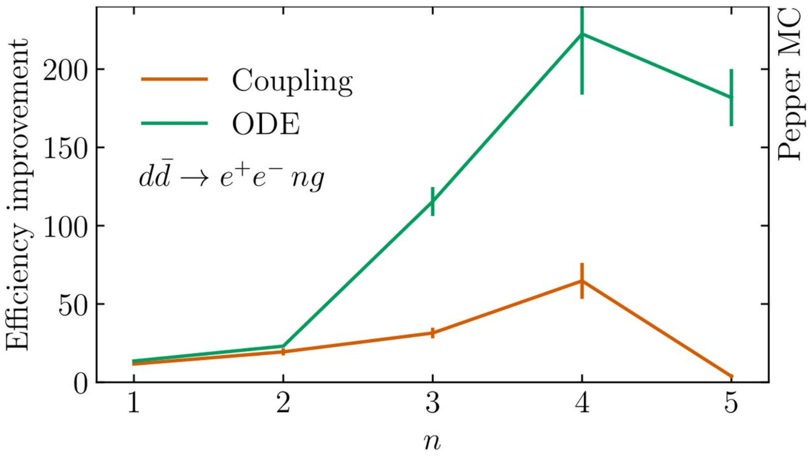
Unweighting with Normalizing Flows

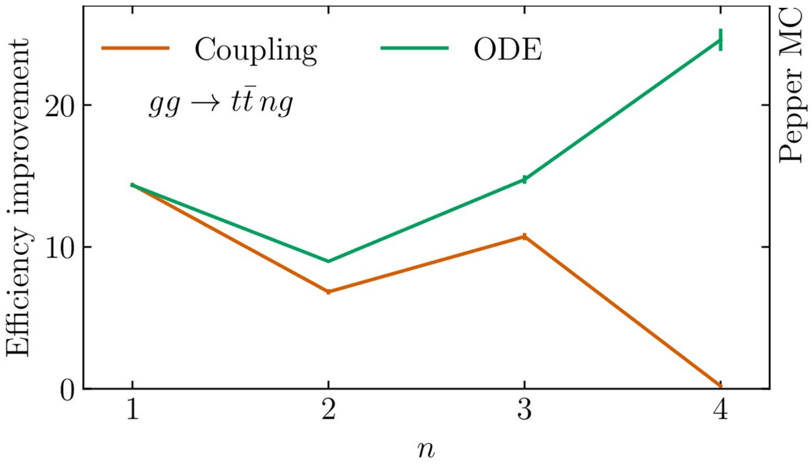
Coupling Layer Flows → series of simple bijections



Continuos Normalising Flows $\frac{\mathrm{d}\psi_t(x)}{\mathrm{d}t} = v_t(\psi_t(x))$

Substantial unweighting efficiency improvements $$\epsilon_\theta = \frac{\langle w_\theta \rangle}{w_{\max,\theta}} \quad \text{with} \quad w_\theta(x) := \frac{p_0(x)}{q_\theta(x)} \,.$$



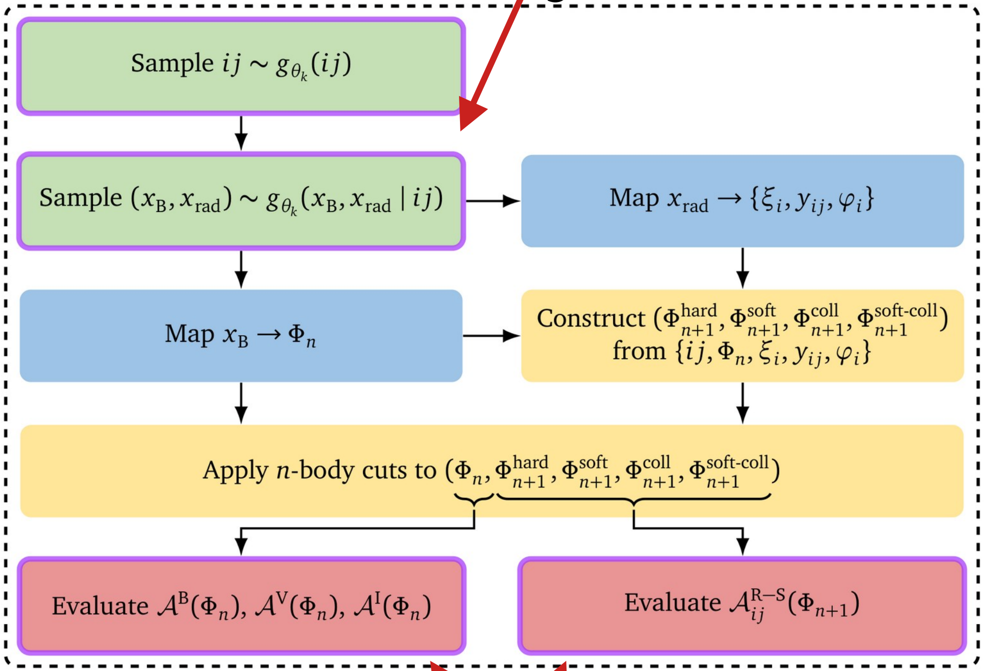


[Bothmann, Janßen, Knobbe, Schmitzer, Sinz, 2604.03511]

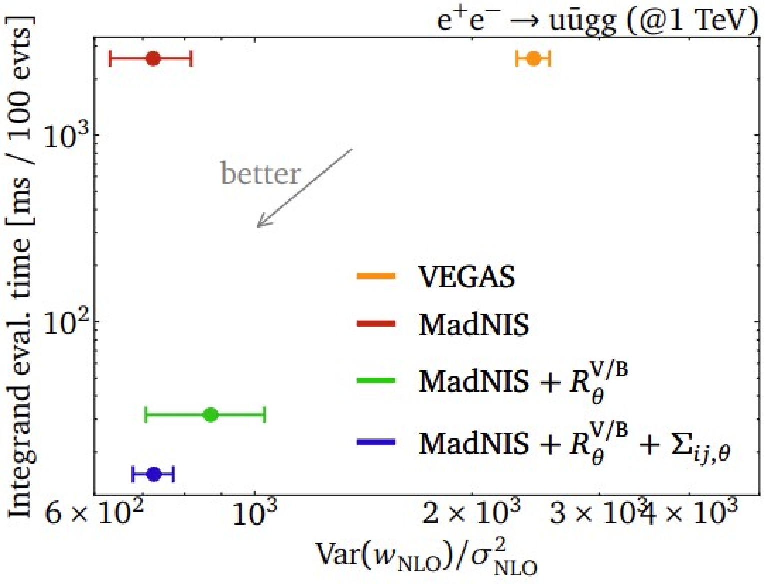
Surrogates + Normalising flows

Madnis@NLO [De Crescenzo, Mariño, Elmer, Heimel, Plehn, Winterhalder, Zaro 2603.22407]

Normalizing Flows



Surrogates



Matching and merging of NLL showers

Examples (plots from left-to-right):

- Alaric LO merging in Z+jets [Hoeche, Krauss, Reichelt’24]
- PanScales NLO for DY [PanScales’25]
- Alaric NLO merging at LEP [Hoeche, Krauss, Meinzinger, Reichelt’25]