Challenges in MC Simulations: pp vs e^+e^-

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Theory Seminar

MSU, 21/04/2026

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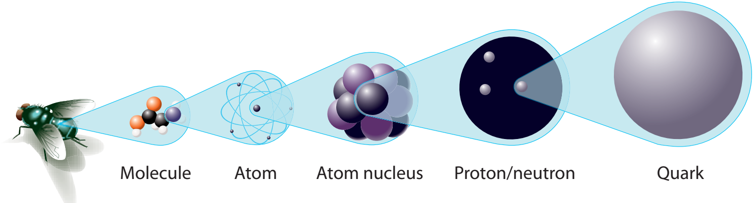
Elementary Particle Physics



10^{-2}m 10^{-9}m 10^{-10}m 10^{-14}m 10^{-15}m $< 10^{-18}$m

Dalton 1808

Thomson 1897

Rutherford 1911

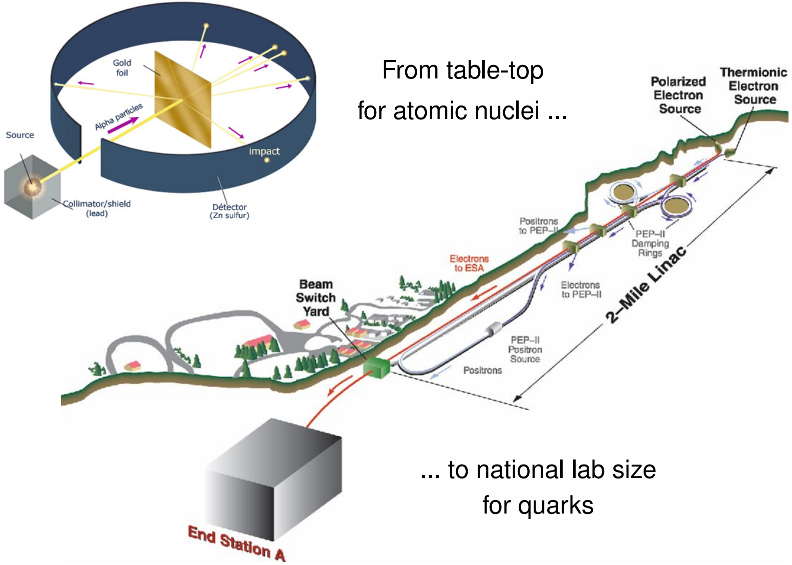
Chadwick 1932

SLAC 1968

- Analyze & categorize building blocks of matter
  - Smaller constituents?
  - Similarities/differences?
- Study their interactions
  - Attractive vs. repulsive
  - Short vs. long range

Image credit: NobelPrize.org, Nobel Prize Outreach 2025

Older “microscopes”



From table-top

for atomic nuclei ...

... to national lab size

for quarks

Image credits: https://radioactivity.eu.com, Phys.Rev.ST Accel.Beams 13 (2010) 082802

What we have learned so far

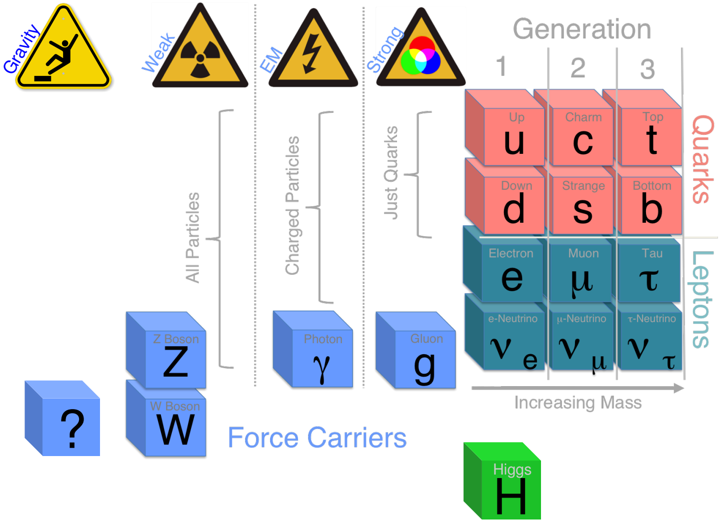
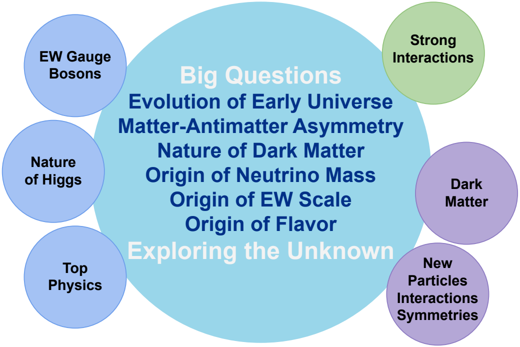


Image credit: http://neutrinoscience.blogspot.com

Open questions

[Narain et al.] arXiv:2211.11084



EW Gauge Bosons

Nature of Higgs

Top Physics

Big Questions

Evolution of Early Universe

Matter-Antimatter Asymmetry

Nature of Dark Matter

Origin of Neutrino Mass

Origin of EW Scale

Origin of Flavor

Exploring the Unknown

Strong Interactions

Dark Matter

New Particles Interactions Symmetries

- What can we learn about the origin of the electroweak scale and phase transition from an in-depth study of SM particles at colliders (HL-LHC)?
- What can we learn about the dynamics of strong interactions?
- How can we build a complete program of new physics searches which includes both model-specific and model-independent explorations?
- **Progress depends on understanding one force in particular**

Today's "microscope" – The Large Hadron Collider

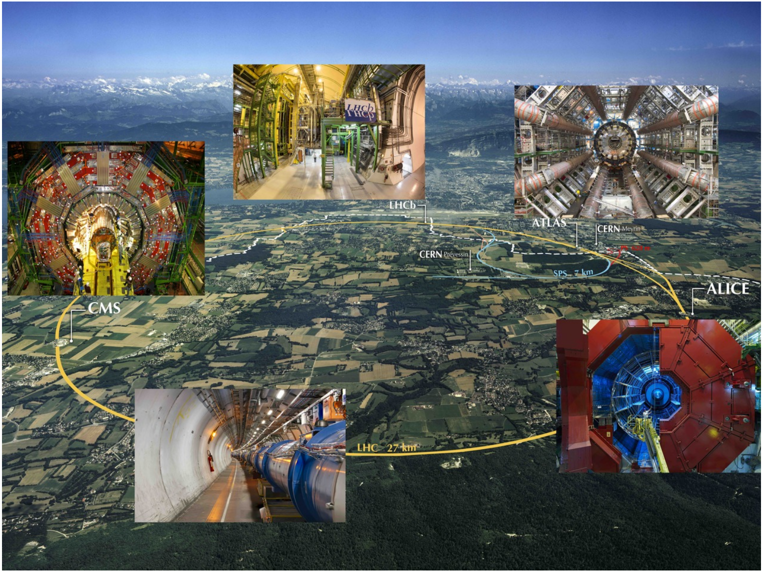


Image credit: CERN

A typical collision event at the LHC ...

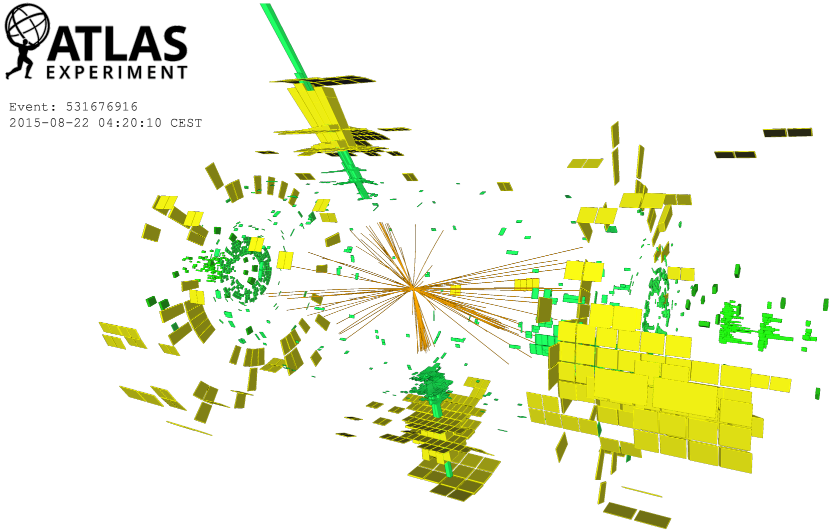
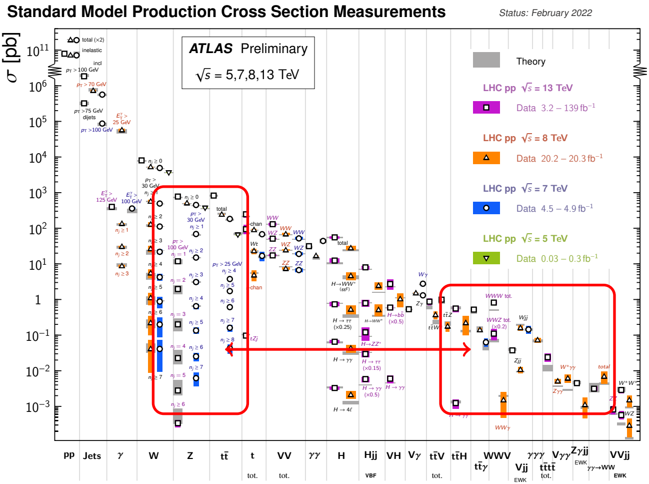


Image credit: CERN

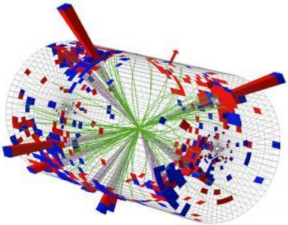
A typical event at the LHC is all about jets

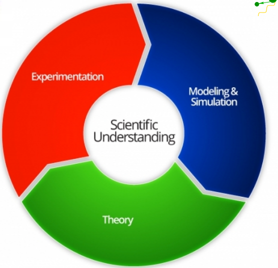


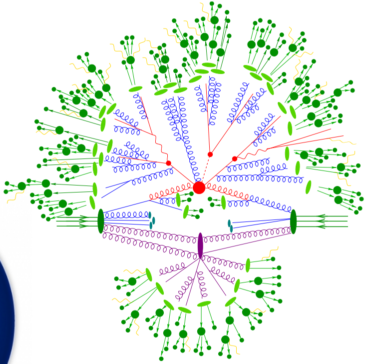
[ATLAS] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

- Signals: High multiplicity but comparably low complexity
- Main backgrounds: High multiplicity and high complexity

Connecting theory to experiment with simulation







$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c.$$

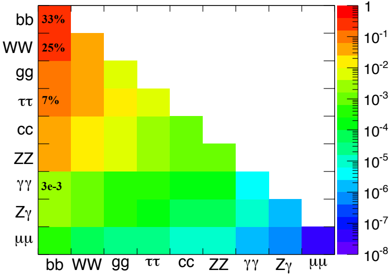
Image credits: CERN, DOE

Outline

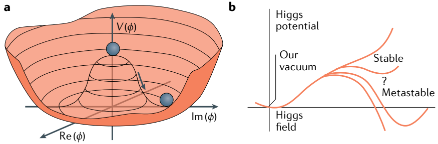
- A quick tour of LHC simulations
  - Big picture
  - Theory challenges
  - Lessons for FCC
- A tour of current FCC simulations
  - Big picture
  - Theory challenges
  - Lessons from LEP
- Towards higher precision
  - Perturbative QCD
  - QED / EW
  - Computing
- Needs and requirements

LHC – What we are preparing for

- Higgs self interaction is key to understanding of EW sector
- Measurement will require careful combination of many analyses with full HL-LHC data set
- Heavy flavor channels needed for high statistical significance



[J. Alison] LHCP ’24



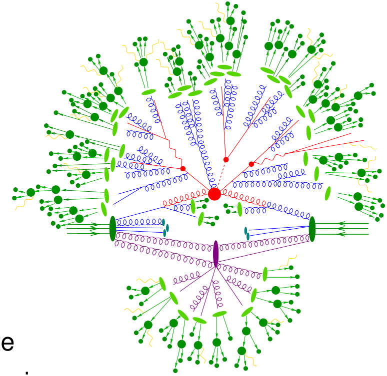
[Bass, DeRoeck, Kado] Nat. Rev. Phys. 3 (2021) 608

- Predictions for heavy quark production as part of inclusive heavy plus light flavor jets difficult to obtain at high precision
- Precise extraction of / limit setting on triple Higgs coupling depends crucially on understanding of all final states

Schematics of LHC simulations

Need to cover large dynamic range

- Short distance interactions
  - Signal process
  - Radiative corrections
- Long-distance interactions
  - Hadronization
  - Particle decays



Divide and Conquer

- Quantity of interest: Total interaction rate
- Convolution of short & long distance physics

$$\sigma_{p_1 p_2 \to X} = \sum_{i,j \in \{q,g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{f_{p_1,i}(x_1,\mu_F^2) f_{p_2,j}(x_2,\mu_F^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij\to X}(x_1 x_2,\mu_F^2)}_{\text{short distance}}$$

QCD theory as the primary tool

- $\hat{\sigma}_{ij\to n}(\mu_F^2) \to$ Collinearly factorized fixed-order result at N^{x}LO

  Implemented in fully differential form to be maximally useful

  Tree level: $\mathrm{d}\Phi_n\; B_n$
  - Automated ME generators + phase-space integrators

  1-Loop level: $\mathrm{d}\Phi_n\left(B_n + V_n + \sum C + \sum I_n\right) + \mathrm{d}\Phi_{n+1}\left(R_n - \sum S_n\right)$
  - Automated loop ME generators + integral libraries + IR subtraction

  2-Loop level: It depends ...
  - Individual solutions based on SCET, q_T subtraction, P2B

- $f_i(x, \mu_F^2) \to$ Collinearly factorized PDF at N^{y}LO

  Evaluated at $O(1\mathrm{GeV}^2)$ and expanded into a series above 1GeV^2

  DGLAP: $\displaystyle\frac{\mathrm{d}x\,x f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g}\int_0^1 \mathrm{d}\tau \int_0^1 \mathrm{d}z\,\frac{\alpha_s}{2\pi}\big[zP_{ab}(z)\big]_+\,\tau f_b(\tau,t)\,\delta(x-\tau z)$
  - Parton showers, dipole showers, antenna showers, ...

  Matching: $\mathrm{d}\Phi_n\,\dfrac{S_n}{B_n} \leftrightarrow \dfrac{\mathrm{d}t}{t}\mathrm{d}z\,\dfrac{\alpha_s}{2\pi}\,P_{ab}(z)$
  - MC@NLO, POWHEG, Geneva, MINNLO$_{\mathrm{PS}}$, ...

Directions of development

Much effort focused on perturbative QCD

- Phenomenologically interesting: Drives jet production, b-tagging, ...
- Experimentally relevant: Often source of largest uncertainty

Fixed-order aspects

- (N)NLO fixed order QCD
- Matching to parton shower
- Combination with QED (YFS)
- ... and NLO EW corrections

All-order aspects

- (N)NLL precision
- Heavy quark effects
- Sub-leading color & spin
- Threshold effects

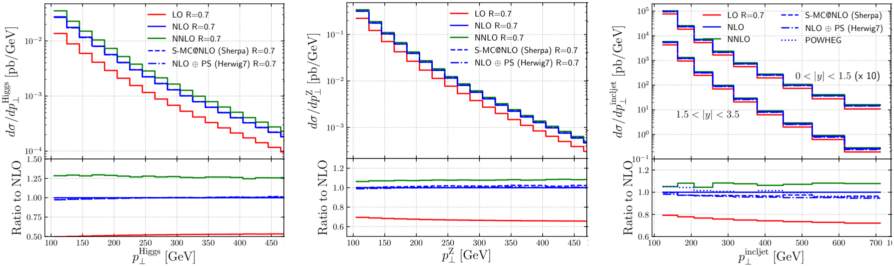
Understanding uncertainties & limitations

- Multi-year projects in context of LesHouches workshops to compare different generators on equal footing
- Growing community of MC devs & expert users in experiments with ties to MC groups & knowledge of common pitfalls in MC usage

Uncertainties in QCD NLO+PS matching

[Bellm at al.] arXiv:1903.12563

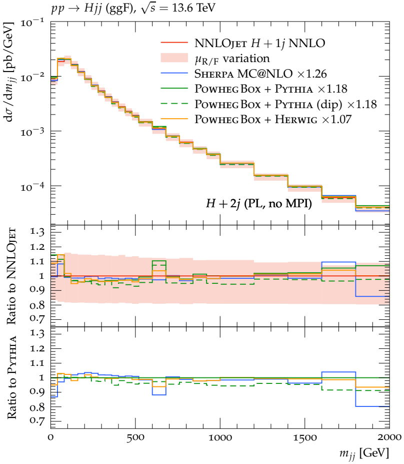
- Ratio of inclusive jet-$p_\perp$ cross sections for different radii in $pp \to jets$
- Excellent agreement of very different simulations → small uncertainties

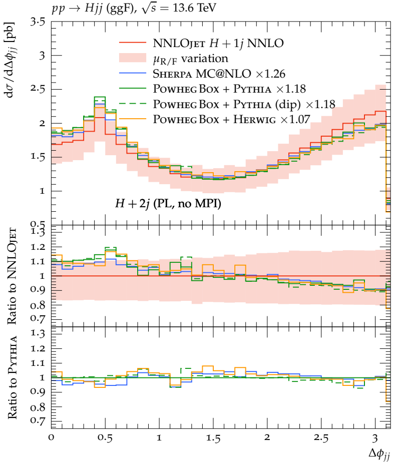


Uncertainties in fixed-order + resummed simulations

[Chen et al.] arXiv:2509.10368

- Irreducible background to VBF Higgs boson production from gluon fusion
- Much smaller theoretical uncertainties ($\mathcal{O}(10\%)$) than estimated ($> 20\%$)





Heavy quark production

- Two different approaches to dealing with heavy-quark masses:
  - 4-flavor scheme (4FS): Decoupling scheme - (no b-quarks in PDF)
  - 5-flavor scheme (5FS): Minimal subtraction scheme
- Calculations can be matched by
  - Re-expressing both in same renormalization scheme
  - Subtracting the overlap

$$\sigma^{\mathsf{FONLL}} = \sigma^{\mathrm{massive}} + (\sigma^{\mathrm{massless}} - \sigma^{\mathrm{massive},\,0})$$

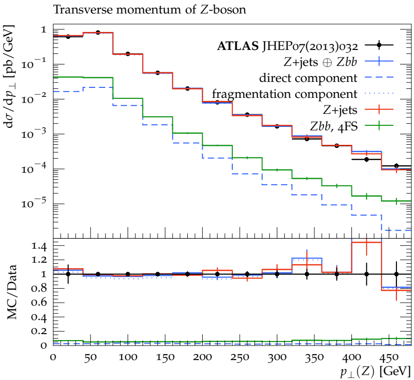
- This has been applied extensively to inclusive observables and is know as fixed-order next-to-leading log (FONLL) scheme

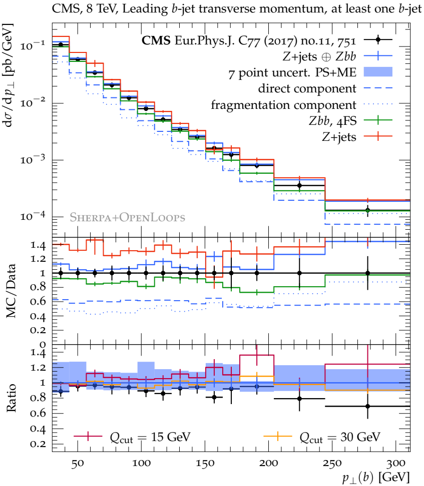
  [Cacciari,Frixione,Mangano,Nason,Ridolfi] hep-ph/0312132,
  [Forte,Napoletano,Ubiali] arXiv:1508.01529, arXiv:1607.00389, . . .
- Extension to differential observables is needed for MC simulations → fully differential “fusing” algorithm [Krause,Siegert,SH] arXiv:1904.09382

Heavy quark production

- Z+jets vs $Zb\bar{b}$ at LHC

[Krause,Siegert,SH] arXiv:1904.09382





	Data [pb]	**Fusing** [pb]
$Z+\geq 1b$	$3.55 \pm 0.24_{\text{comb}}$	$3.80(5) \pm^{0.83}_{0.33}$
$Z+\geq 2b$	$0.331 \pm 0.037_{\text{comb}}$	$0.282(4) \pm^{0.027}_{0.022}$

Improvements needed for FCC

Fully differential high precision calculations

- NNLO QCD subtraction formalism
- Mixed QCD/EW corrections

Resummation and matching to fixed order

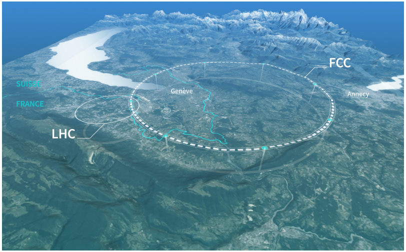
- Parton showers at NNLL precision
- Reduction of matching scheme uncertainty

Incorporation of quark mass effects

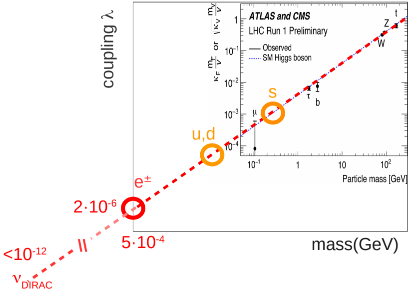
- Formal accuracy beyond FONLL-A
- Interplay with fragmentation functions

Where do we go from here?

- Unprecedented luminosity at Tera-Z option of a potential FCC-ee will leave no room for mis-modeling of non-perturbative QCD effects



[CERN] https://www.home.cern/science/accelerators

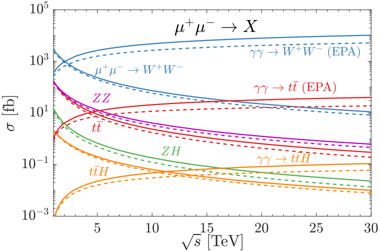


[D. d'Enterria] FCC week '24

- Extraction of Higgs Yukawa couplings will depend on precise modeling of light / heavy flavor jet production and flavor dynamics

Where do we go from here?

- New collider concepts require different theoretical and computational strategies
- At highest energies targeted by muon collider concepts, electroweak sector of Standard Model requires resummation



[Han,Ma,Xie] arXiv:2007.14300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Science

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AAAS

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MUON SHOT

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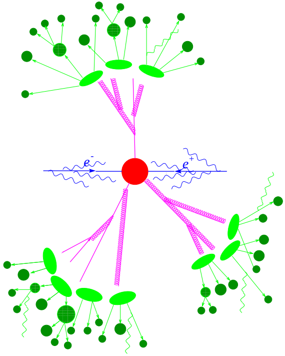
[Science] March ’24

Schematics of FCC simulations

Need to cover modest dynamic range

- Short distance interactions
  - Signal process
  - QCD radiative corrections
  - QED radiative corrections
- Long-distance interactions
  - Hadronization
  - Particle decays



Divide and Conquer

- Quantity of interest: Interaction rate
- If hadrons involved, convolution of short & long distance physics, e.g.

$$\sigma_{p_1p_2\to X} = \sum_{i,j\in\{q,g\}} \int \mathrm{d}x_1\mathrm{d}x_2 \underbrace{\hat{\sigma}_{ij+X}(x_1,x_2,\mu_F^2)}_{\text{short distance}} \underbrace{D_{h_1,i}(x_1,\mu_F^2)D_{h_2,j}(x_2,\mu_F^2)}_{\text{long distance}} \ldots$$

Aspects of pQCD at FCC

Things to consider

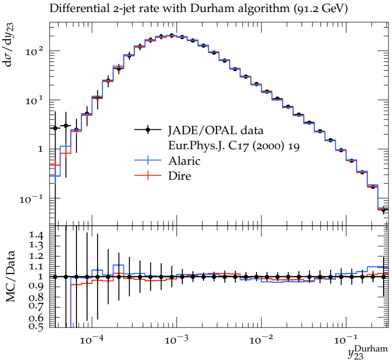
- At Tera-Z, the dynamic range is modest: $\sqrt{s} \approx 20 \times m_b$
  QCD radiative effects are important, but still limited
  We get about 7 gluons on average before hadronization
- This implies that understanding sub-leading powers is more important for precision than controlling higher logs
- Parton showers include some of those effects through exact phase-space & scalar splitting functions ($\nearrow$ later)

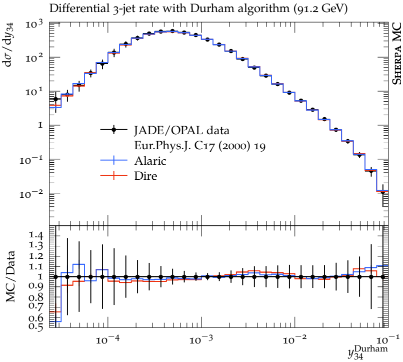
Consequences for MC development

- Parton-showers have to satisfy boundary conditions from analytic resummation, but we need to go beyond
- Much can be done by matching to fixed order, because the average number of emissions between $\sqrt{s}$ and $\Lambda_{\rm QCD}$ is small

Typical performance of parton-showers

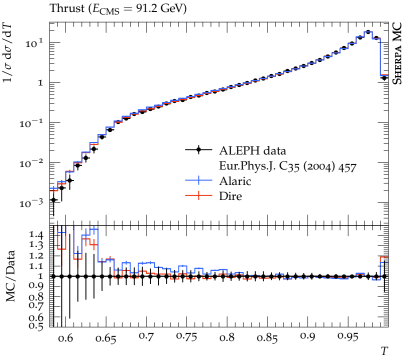
[Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057

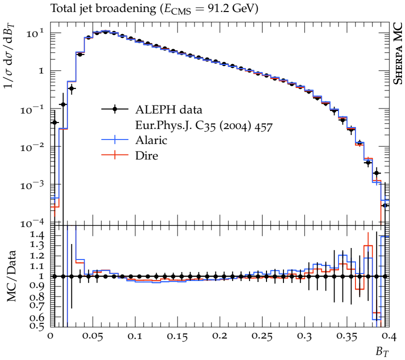

Differential 2-jet rate with Durham algorithm (91.2 GeV)


Differential 3-jet rate with Durham algorithm (91.2 GeV)

Typical performance of parton-showers

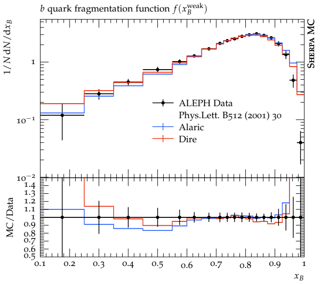
[Herren,Krauss,Reichelt,Schönherr,SH] arXiv:2208.06057

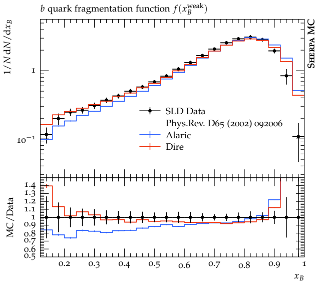


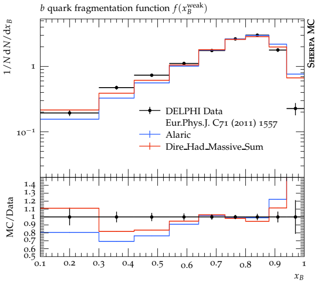


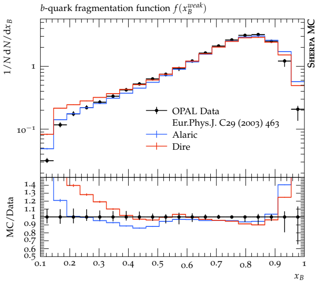
Typical performance in heavy quark evolution

[Assi,SH] arXiv:2307.00728





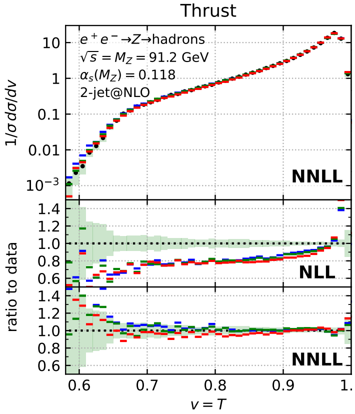


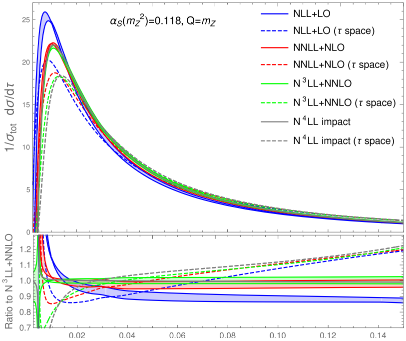


NNLL evolution for event shapes

[vanBeekveld et al.] arXiv:2406.02661

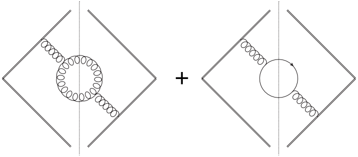
- NNLL for global event shapes achieved recently
- Found differences of $\mathcal{O}(20\%)$ between NLL and NNLL
  Compare to analytic computation [Aglietti,Ferrera,Ju,Miao] arXiv:2502.01570
- Better understanding needed to achieve target precision for FCC-ee
  $\rightarrow$ Is there a need for N^{3}LL, or rather sub-leading power?





Towards NLO QCD evolution: Soft limit

- Approximate soft-gluon emission times collinear decay in $q(i)\bar{q}(j)g(1)g(2)$ using semi-classical limit and gluon splitting function



$$+ \quad = \sum_{b=q,g} j_{ij,\mu}(p_{12}) j_{ij,\nu}(p_{12}) \frac{P^{\mu\nu}_{gb}(z_1)}{s_{12}}$$

$$P^{\mu\nu}_{gq}(z) = T_R \left(-g^{\mu\nu} + 4\, z(1-z)\, \frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2} \right)$$

$$P^{\mu\nu}_{gg}(z) = C_A \left(-g^{\mu\nu} \left(\frac{z}{1-z} + \frac{1-z}{z} \right) - 2\,(1-\varepsilon) z(1-z)\, \frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2} \right)$$

- Combine with phase space for one parton emission in collinear limit $D = 4 - 2\varepsilon$, $y = s_{12}/Q^2$, see for example [Catani,Seymour] hep-ph/9605323

$$\mathrm{d}\Phi_{+1} = \frac{Q^{2-2\varepsilon}}{16\pi^2} \frac{(4\pi)^\varepsilon}{\Gamma(1-\varepsilon)}\, \mathrm{d}y\, \mathrm{d}z\, \big[y\, z(1-z) \big]^{-\varepsilon}$$

- Perform Laurent series expansion

$$\frac{1}{y^{1+\varepsilon}} = -\frac{\delta(y)}{\varepsilon} + \sum_{n=0}^{\infty} \frac{\varepsilon^n}{n!} \left(\frac{\ln^n y}{y} \right)_+$$

Towards NLO QCD evolution: Soft limit

- $\mathcal{O}(\varepsilon^0)$ differential remainder terms have contributions proportional to

$$g \to q\bar{q}: \quad T_R \Big[2z(1-z) + \big(1-2z(1-z)\big) \ln(z(1-z)) \Big]$$

$$g \to gg: \quad 2C_A \left[\frac{\ln z}{1-z} + \frac{\ln(1-z)}{z} + \big(-2+z(1-z)\big) \ln(z(1-z)) \right]$$

- Integration over z, addition of some semi-classical terms & one-loop soft current gives two-loop cusp anomalous dimension

$$K = \left(\frac{67}{18} - \frac{\pi^2}{6} \right) C_A - \frac{10}{9} T_R n_f$$

  - Local K-factor for soft-gluon emission
  - Scheme dependent: originates in dim. reg. and $\overline{\mathrm{MS}}$
  - **Can be absorbed in effective coupling** [Catani,Marchesini,Webber] NPB349(1991)635

- Similarly, we find $\mathcal{O}(\varepsilon^0)$ contributions proportional to

$$\frac{\alpha_s}{2\pi} \beta_0 \log \frac{(p_i p_{12})(p_{12} p_j)}{(p_i p_j)\mu^2}$$

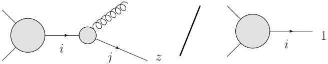
  - Can be eliminated by setting scale to transverse mass of soft pair
  - **Leading NLO correction** [Amati, et al.] NPB173(1980)429

Towards NLO QCD evolution: Collinear limit

- Higher-order DGLAP evolution kernels from factorization
  [Curci,Furmanski,Petronzio] NPB175(1980)27, [Floratos,Kounnas,Lacaze] NPB192(1981)417

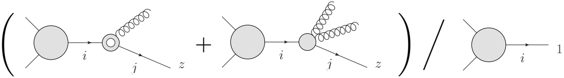
$$D_{ji}^{(0)}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$



$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$\leftrightarrow$



- In NLO parton shower, perform computation of $P_{ji}^{(1)}$ fully differentially using modified dipole subtraction [Catani,Seymour] hep-ph/9605323

Towards NLO QCD evolution: Collinear limit

[Prestel,SH] arXiv:1705.00742

- Schematically very similar to Catani-Seymour dipole subtraction
  e.g. simplest case of flavor-changing quark splitting

$$P^{(1)}_{qq'}(z) = \mathrm{C}_{qq'}(z) + \mathrm{I}_{qq'}(z) + \int \mathrm{d}\Phi_{+1}\Big[\mathrm{R}_{qq'}(z,\Phi_{+1}) - \mathrm{S}_{qq'}(z,\Phi_{+1})\Big]$$

  - Real correction $R_{qq'}$ and subtraction terms $S_{qq'}$
    given by $1 \to 3$ splitting and factorized expression
  - Integrated subtraction term and factorization counterterm

$$\mathrm{I}_{qq'}(z) = \int \mathrm{d}\Phi_{+1} S_{qq'}(z,\Phi_{+1})$$

$$\mathrm{C}_{qq'}(z) = \int_z \frac{\mathrm{d}x}{x}\left(P^{(0)}_{qg}(x) + \varepsilon\mathcal{J}^{(1)}_{qg}(x)\right)\frac{1}{\varepsilon}P^{(0)}_{gq}(z/x)$$

$$\mathcal{J}^{(1)}_{qg}(z) = 2C_F\left(\frac{1+(1-x)^2}{x}\ln(x(1-x)) + x\right)$$

- All components of $P^{(1)}_{ij}$ eventually finite in 4 dimensions
  Can be simulated fully differentially in parton shower

Combination of soft and collinear expressions

Problems with existing splitting functions

- **Kinematical limits obscure underlying structure**
  Matching soft functions to collinear limit not straightforward
- **Different pQCD techniques for different limits**
  Soft limits in Feynman gauge, collinear ones in axial gauge

To understand the structure, we have to go back to basics
→ recompute in common gauge and w/o taking limits

Say that again ... How can we NOT take limits?
It's the one thing we know how to do!

Combination of ~~soft~~ scalar and ~~collinear~~ splitting expressions

[Campbell,Knobbe,Preuss,Reichelt,SH] arXiv:2505.10408

- Gordon decomposition [Gordon] ZeitPhys140(1928)630

$$\frac{\not p + \not q}{(p+q)^2}\, T^a_{ij}\gamma^\mu = T^a_{ij}\left[\, S^\mu(p,q) + \frac{i\sigma^{\nu\mu}q_\nu}{(p+q)^2} - \frac{\gamma^\mu \not p}{(p+q)^2}\,\right]$$

  - Leading and sub-leading (**LBK!**) soft behavior given by scalar current
    [Gell-Mann,Goldberger] PR96(1954)1433, [Brown,Goble] PR173(1968)1505

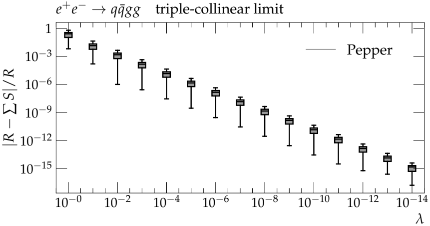
$$S^\mu(p,q) = \frac{(2p+q)^\mu}{(p+q)^2}$$

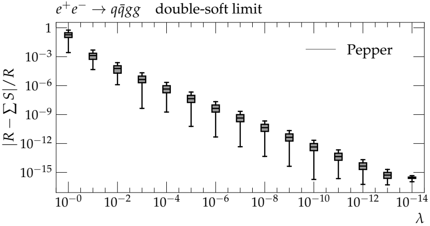
  - Magnetic term $\sigma^{\nu\mu} = i/2[\gamma^\nu, \gamma^\mu]$ due to quark spin
    $\gamma^\mu \not p$ generates seagull interactions of scalar theory
- Decomposition of triple & quartic gluon vertex even simpler
- Both decompositions hold at amplitude squared level [Chen et al.] arXiv:1404.5963
- **Separate scalar splitting functions & spin-dependent remainders**
  Clean identification of overlap beyond kinematical limits
- At 1-loop level, Background Field Method allows to derive
  Scalar radiators that satisfy the naive Ward identities
  → Extension of soft current [Catani,Grazzini] hep-ph/0007142

Application to NNLO fixed-order calculations

[M. Knobbe] PSR'25, QCD@LHC'25, [Knobbe,SH] WIP

- *Novel infrared subtraction for NNLO calculations* currently under development
- No overlap between scalar and splitting components → straightforward assembly of complete IR counterterms
- Suitable for matching to a fully differential resummation at NLO QCD precision (first components of which in [Prestel,SH] arXiv:1705.00742 & [Dulat,Prestel,SH] arXiv:1805.03757)

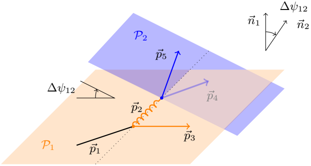




Application to parton showers

[Hoppe,Reichelt,SH] arXiv:2508.19018

- Conventional wisdom: Gluon spin correlations are a quantum effect



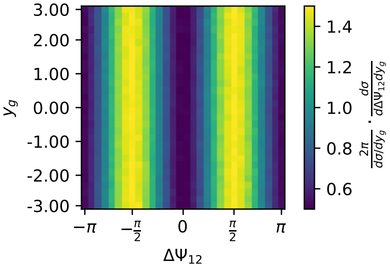
[Chen,Moult,Zhu] arXiv:2011.02492

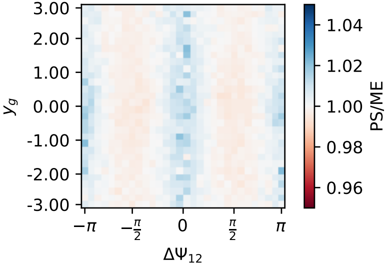
[Karlberg,Salam,Scyboz,Verheyen] arXiv:2103.15526

- Re-analyze using new formalism
  $\rightarrow$ Most correlations are classical

[Staelin,Morgenthaler,Kong] *Electromagnetic Waves*, Pearson (1993)

- Reproduced perfectly in simulation using simple and robust algorithm

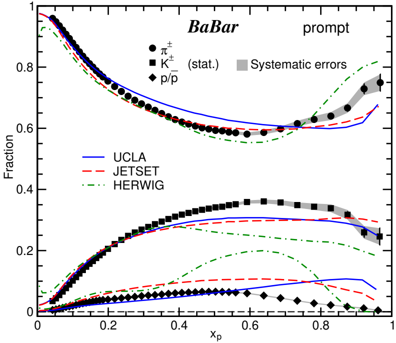




The Need for improved Hadronization Models

- Modeling of non-perturbative parton-to-hadron transition important for detector response, especially at low particle multiplicity
- Flavor composition of jets and identified hadron production typically challenging to model, especially at low energy
- Must be addressed in order to reach precision goals of FCC-ee

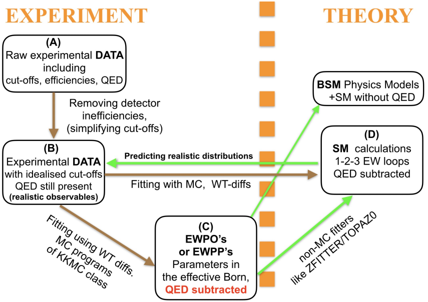
[Lees et al.] arXiv:1306.2895



The Need for Precise QED Simulations

- Projected 2-100× improvement in measurement of EWPOs
- Permille-level uncertainties could be ignored at LEP but not at FCC-ee, particularly Tera-Z option
- QED radiative effects must be modeled as precisely as possible

[Jadach,Skrzypek] arXiv:1903.09895



EXPERIMENT

THEORY

(A)
Raw experimental **DATA**
including
cut-offs, efficiencies, QED

Removing detector inefficiencies, (simplifying cut-offs)

(B)
Experimental **DATA**
with idealised cut-offs
QED still present
(realistic observables)

Predicting realistic distributions

Fitting with MC, WT-diffs

BSM Physics Models
+SM without QED

(D)
SM calculations
1-2-3 EW loops
QED subtracted

Fitting using WT diffs. MC programs of KKMC class

(C)
EWPO's
or EWPP's
Parameters in
the effective Born,
QED subtracted

non-MC fitters like ZFITTER/TOPAZ0

Observable	Where from	Present (LEP)	FCC stat.	FCC syst	$\frac{\text{Now}}{\text{FCC}}$
M_Z [MeV]	Z linesh.	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh.	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
$\sigma^0_{\rm had}$[nb]	$\sigma^0_{\rm had}$	$41.541 \pm 0.037\{0.025\}$	$0.1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$	$23099 \pm 53\{28\}$	0.3	0.5	55
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\rm FB}^{pol,\tau}$	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z\pm 3.5\rm GeV}$	$\frac{d\sigma}{d\cos\theta}$	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

QED Resummation

Collinear Resummation

[Frixione et al.] JHEP03(2020)135

- Collinear logs are resummed with universal PDF
- Matched to $\mathrm{NLO}_{\mathrm{EW}}$
- Combined with Parton Shower to generate photon emissions
- Beyond NLO becomes tricky

Soft Resummation

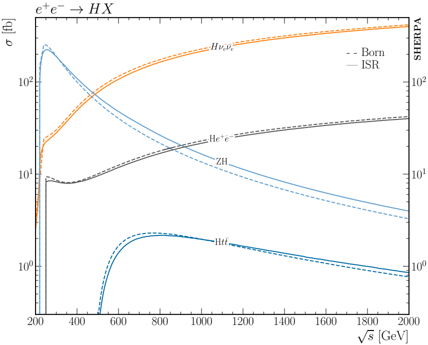
[Jadach et.al] ZPC49(1991)577, EPL17(1992)123

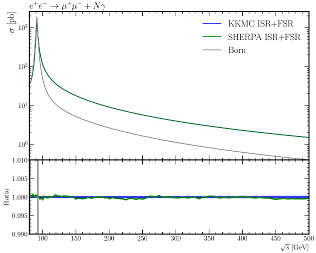
- Soft logs resummed to infinite order using the YFS method

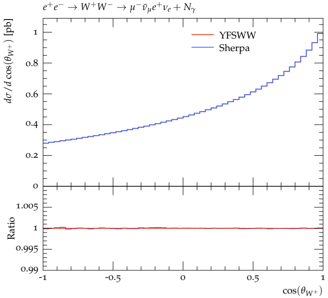
  [Yennie,Frautschi,Suura] Ann.Phys.13(1961)379
- Provides a robust scheme for the inclusion of real and virtual corrections at any order.
- Collinear terms can be added

QED Resummation

- Modern YFS tools validated carefully against state-of-the art from LEP, e.g. KKMC [Jadach,Ward,Was] hep-ph/9912214, YFSWW [Jadach et al.] hep-ph/0104049







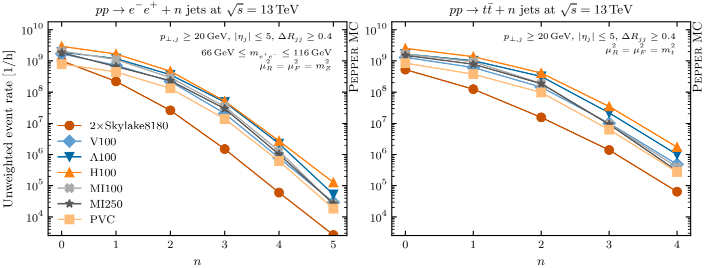
Addressing the computing bottleneck

- Modern computing → many vendors & heterogeneous architectures
- (Pre-)Exascale computing systems intentionally diverse

Addressing the computing bottleneck

[Bothmann et al.] arXiv:2311.06198

- Performance portability a major topic for simulation developers
  Driven by computing industry & large computing facilities



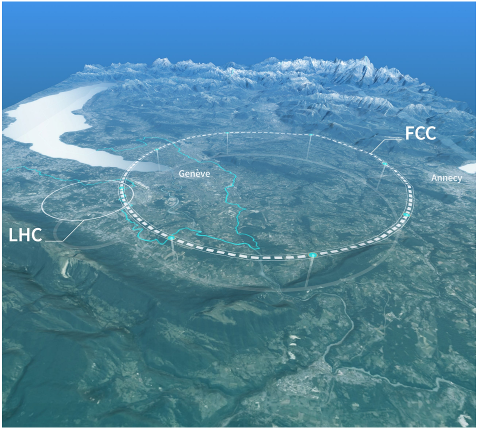
MEvents / hour	2×Skylake8180	V100	A100	H100	MI100	MI250	PVC
$pp \to t\bar{t} + 4j$	0.06	0.5	1.0	1.7	0.4	0.3	0.3
$pp \to e^-e^+ + 5j$	0.003	0.03	0.05	0.1	0.03	0.03	0.02

- Scalability highly non-trivial to achieve on large machines
  Latest result from Frontier at Oak Ridge Leadership Computing Facility
  → Scaling up to 8000 AMD MI250 GPUs (≈0.4EF) [Gainaru,Knobbe]

Summary & Discussion

- Perturbative QCD on track to deliver sufficient precision for FCC-ee
  Physics performance likely limited by understanding of hadronization
- Tera-Z will require highest MC statistics of any experiment so far
  May only be achievable with the help of HPC, possibly LCFS
- EWPOs will require multi-loop QED / EW calculations
  Must be implemented in MCs, at least partially
- Some of these developments overlap with LHC, some do not
  Mechanism needed for WFD and retention of talented developers

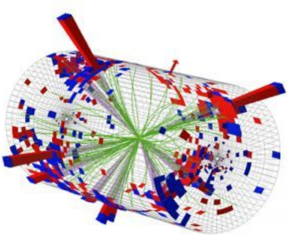
Whatever the collider concept of the future ...

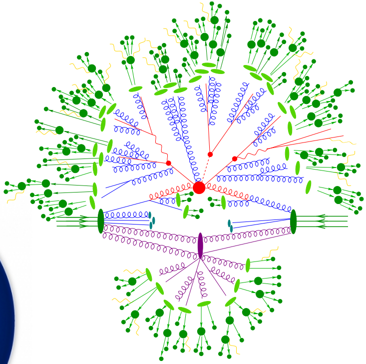


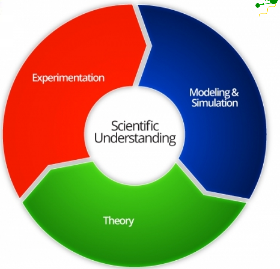
[CERN] https://www.home.cern/science/accelerators

[Science] March ’24

… precise simulations will be essential …







Experimentation

Modeling & Simulation

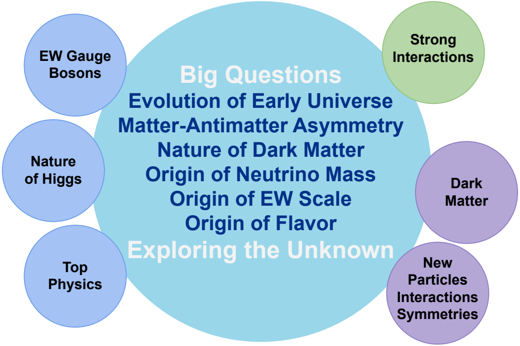
Theory

Scientific Understanding

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c.$$

Image credits: CERN, DOE

... to understand the fundamental laws of nature



Big Questions

Evolution of Early Universe

Matter-Antimatter Asymmetry

Nature of Dark Matter

Origin of Neutrino Mass

Origin of EW Scale

Origin of Flavor

Exploring the Unknown

EW Gauge Bosons

Nature of Higgs

Top Physics

Strong Interactions

Dark Matter

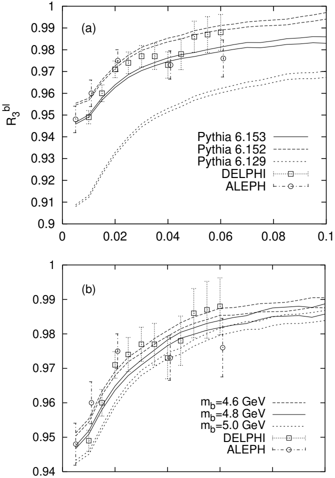
New Particles Interactions Symmetries

[Narain et al.] arXiv:2211.11084

Thank you for your attention

Heavy quark production

- Both high-energy limit and threshold region should be modeled as well as possible, but
- Infrared finite prediction for $g \to Q\bar{Q}$ leaves splitting functions somewhat arbitrary
- Soft gluon emission off light/heavy quarks associated with $\alpha_s(k_T^2)$, i.e. “correct” scale is k_T^2 [Amati et al.] NPB173(1980)429, but no such argument to set scale for $g \to Q\bar{Q}$
  $\to$ HQ production rate not very stable w.r.t. parton shower variations
- A number of different prescriptions, e.g.
  [Norrbin,Sjöstrand], hep-ph/0010012,
  [Gieseke,Stephens,Webber] hep-ph/0310083,
  [Schumann,Krauss] arXiv:0709.1027,
  [Gehrmann-deRidder,Ritzmann,Skands] arXiv:1108.6172
  varying success in describing expt. data



[Norrbin,Sjöstrand] hep-ph/0010021

Impact of the momentum mapping

[Dasgupta,Dreyer,Hamilton,Monni,Salam] arXiv:1805.09327

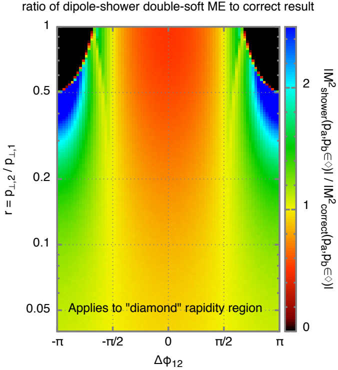
- Some dipole-like momentum mappings violate strong ordering approximation

$$p_k^\mu = \left(1 - \frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\right)\tilde{p}_k^\mu$$

$$p_i^\mu = \tilde{z}\,\tilde{p}_{ij}^\mu + (1-\tilde{z})\frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\tilde{p}_k^\mu + k_\perp^\mu$$

$$p_j^\mu = (1-\tilde{z})\,\tilde{p}_{ij}^\mu + \tilde{z}\frac{p_{ij}^2}{2\tilde{p}_{ij}\tilde{p}_k}\tilde{p}_k^\mu - k_\perp^\mu$$

- Angular correlations across multiple emissions due to recoil on splitter in anti-collinear region
- Spoils $\alpha_s \to 0$ consistency check $\leftrightarrow$ NLL accuracy cannot be achieved



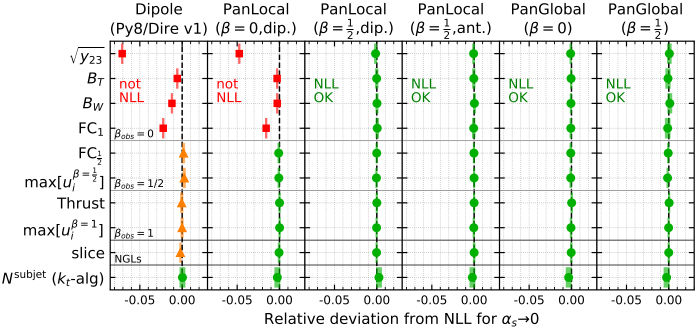
Impact of the momentum mapping

[Dasgupta,Dreyer,Hamilton,Monni,Salam,Soyez] arXiv:2002.11114

- Problem can be solved e.g. by partitioning of antenna radiation pattern and choosing a suitable evolution variable ($\beta \sim 1/2$)

$$k_T = \rho v e^{\beta|\bar{\eta}|} \qquad \rho = \left(\frac{s_i s_j}{Q^2 s_{ij}}\right)^{\beta/2}$$

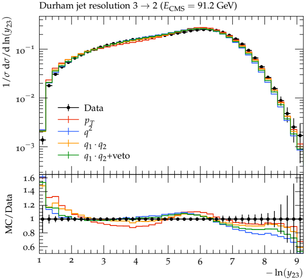
- NLL correct for global and non-global observables in $e^+e^- \to$hadrons

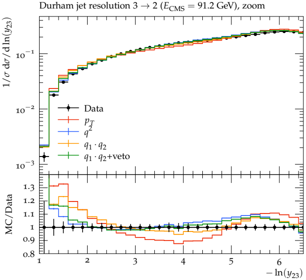


Impact of the momentum mapping

[Bewick,Ferrario-Ravasio,Richardson,Seymour] arXiv:1904.11866

- Note: Recoil schemes affect logarithmic accuracy but impact also phase-space coverage & sub-leading power effects
- In context of angular ordered Herwig 7 (NLL accurate for global observables)
  - q_T preserving scheme:
    Maintains logarithmic accuracy
    Overpopulates hard region
  - q^2 preserving scheme:
    Breaks logarithmic accuracy
    Good description of hard region
  - Dot product preserving scheme (new):
    Maintains logarithmic accuracy
    Good description of hard radiation

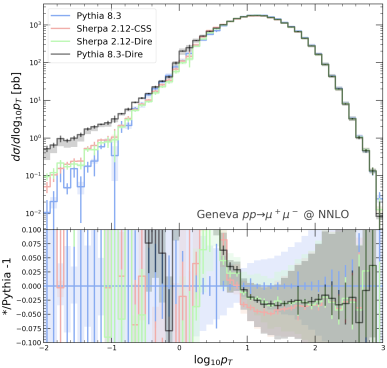


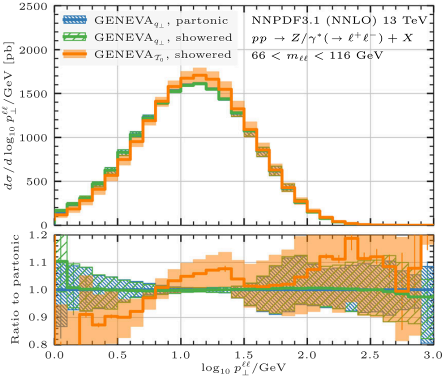


Uncertainties in QCD NNLO+PS matching

[D. Napoletano, HP2 2022], [Alioli et al.] arXiv:2102.08390

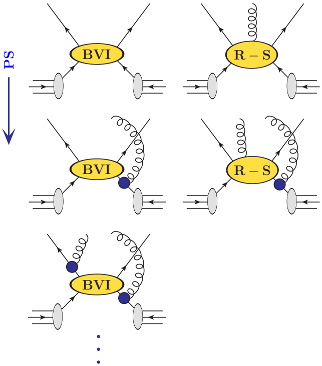
- NNLO+PS precise predictions for $pp \to Z$ from Geneva
- Matched to shower by vetoing events with $r_N(\Phi_{N+M}) > r_N$
- Significant residual uncertainties, even though NNLO





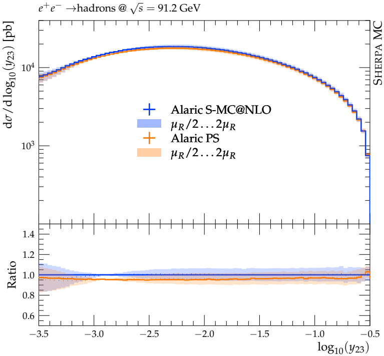
- Parton shower scheme uncertainty
- Choice of resolution variable

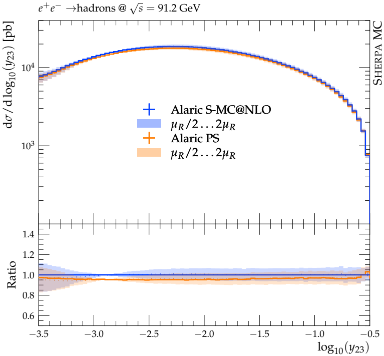
MC@NLO matching



Typical performance of MC@NLO matching

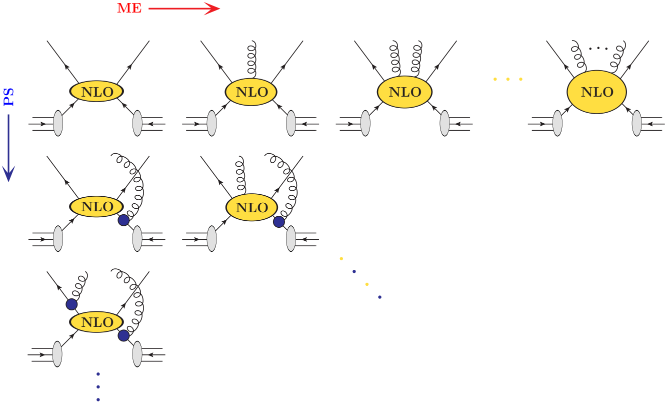
[Krauss,Meinzinger,Reichelt,SH] arXiv:2507.22837





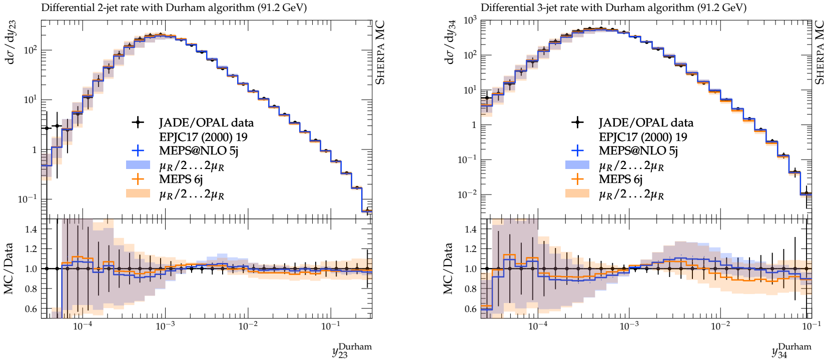
- Jet rates in Durham algorithm
- Radiation pattern determined almost exclusively by PS

Multi-jet merging



Typical performance of matching & merging

[Krauss,Meinzinger,Reichelt,SH] arXiv:2507.22837



Typical performance of matching & merging

[Krauss,Meinzinger,Reichelt,SH] arXiv:2507.22837