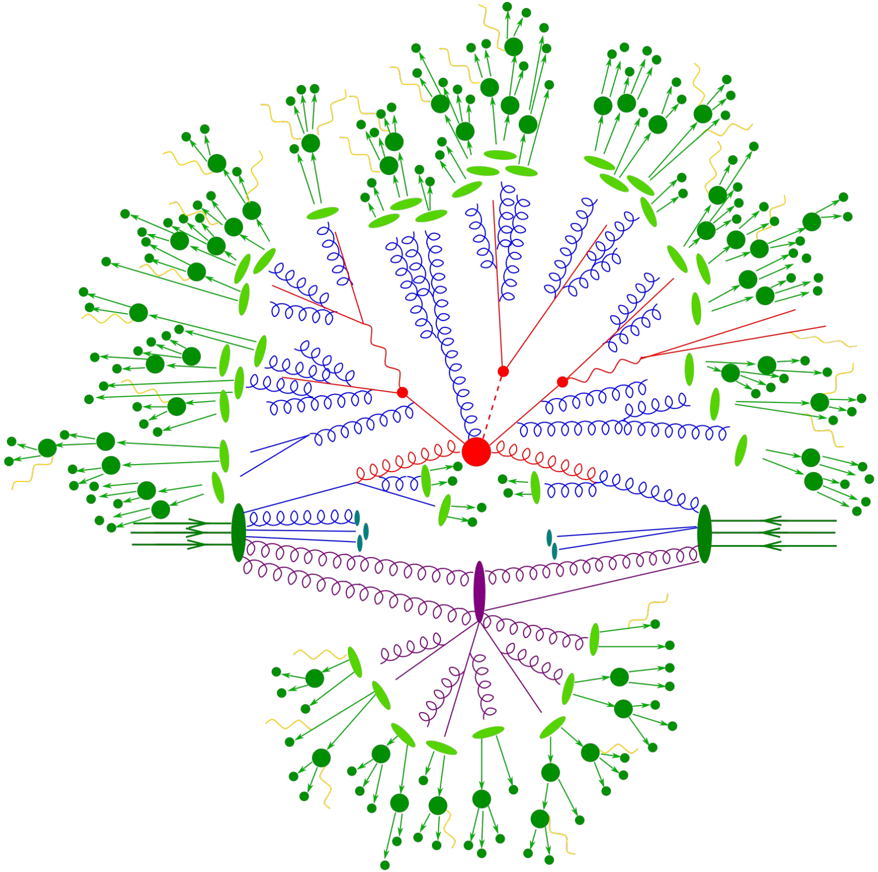
The new Sherpa 3.0 event generator

Alan Price, Frank Siegert
on behalf of the Sherpa collaboration

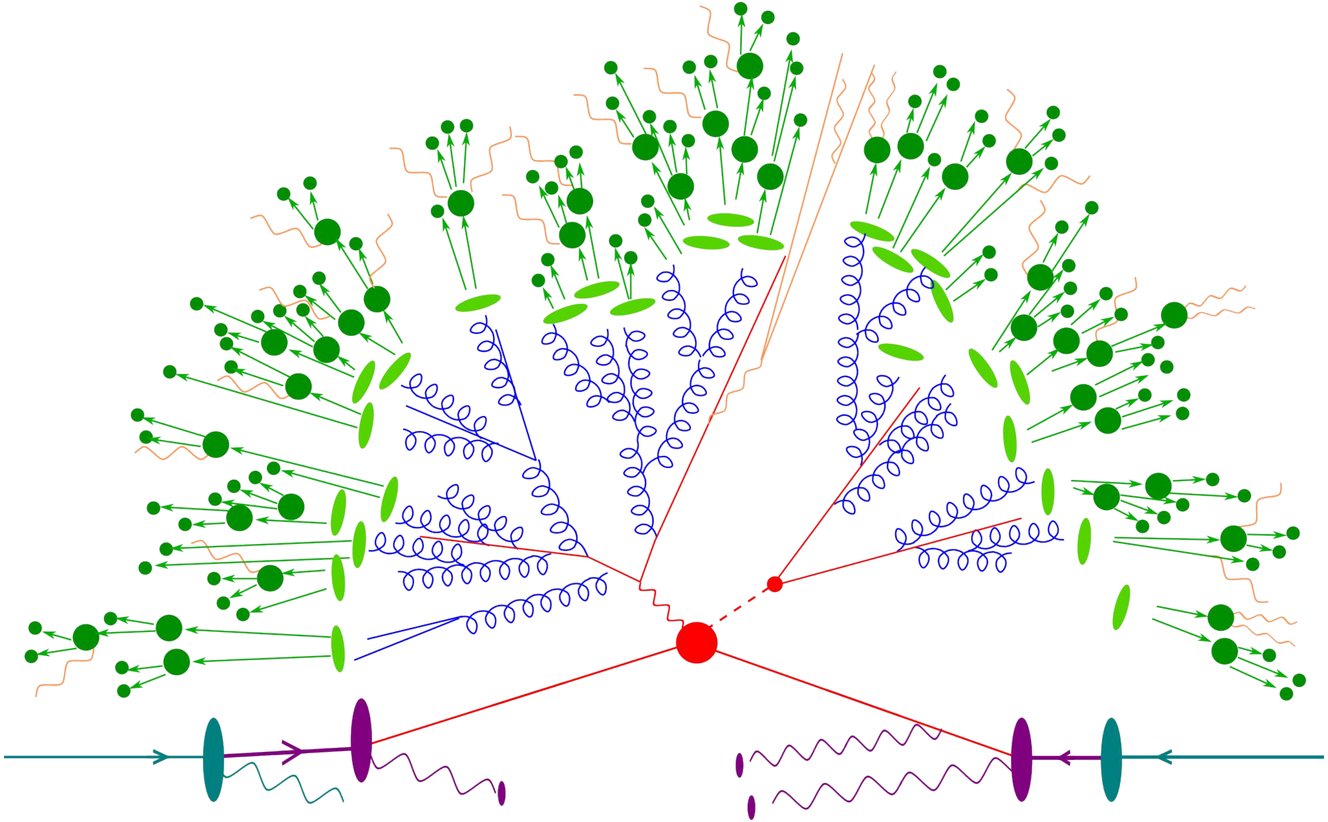
SHERPA

International Workshop on Future Linear Colliders, Tokyo, July 2024

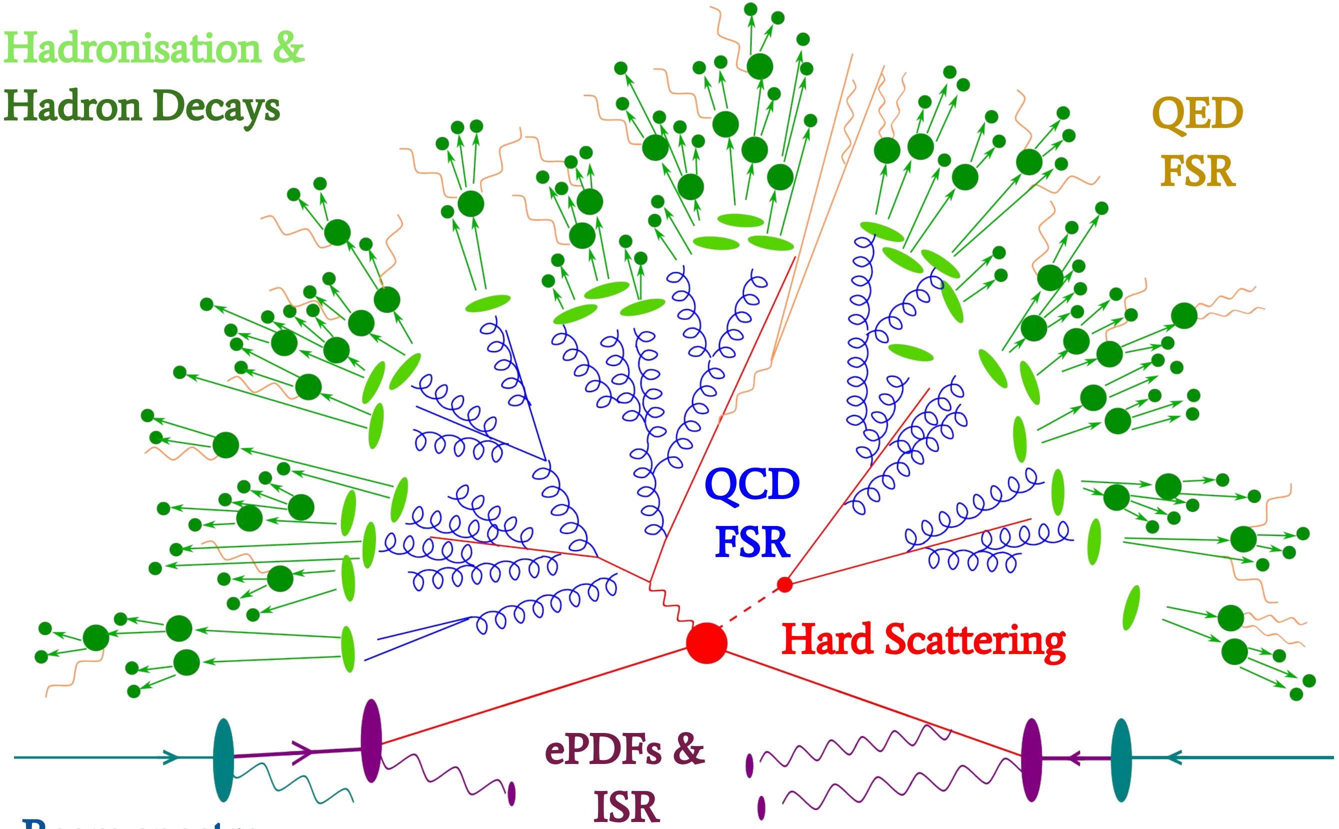
Monte Carlo event generators



Monte Carlo event generators for LC



Monte Carlo event generators for LC



Hadronisation &
Hadron Decays

QED
FSR

QCD
FSR

Hard Scattering

ePDFs &
ISR

Beam spectra

Good things come to those who wait

July 2024 :
The Sherpa collaboration
proudly presents

SHERPA 3.0.0(*)

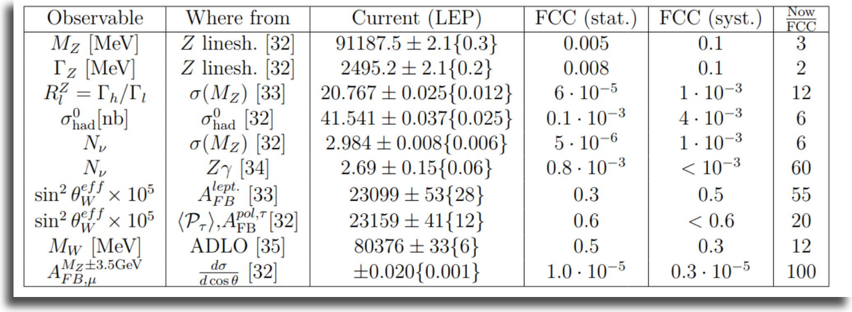
Condensing the work of the last >5 years

- new physics features
- more intuitive user interface
- more efficient CPU footprint
- modern build system
- comprehensive validation suite

* Limited warranty applies.

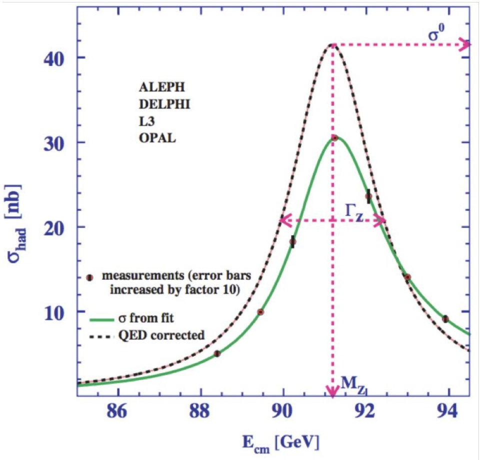
The Need For QED

- Factor 2-100 improvement in the measurement of EWPOs
- 0.1% errors which could be ignored at LEP will dominate at future e^+e^- machines
- On the theoretical side this translates into a much more sophisticated modelling
  - **Fixed Order improvements**
  - **Resummation techniques for both QCD/QED**
- Theoretical uncertainties need to be comparable (or lower!) than the experimental



Observable	Where from	Current (LEP)	FCC (stat.)	FCC (syst.)	$\frac{\text{Now}}{\text{FCC}}$
M_Z [MeV]	Z linesh. [32]	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh. [32]	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$ [33]	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
σ^0_{had}[nb]	σ^0_{had} [32]	$41.541 \pm 0.037\{0.025\}$	$0.1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$ [32]	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$ [34]	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$ [33]	$23099 \pm 53\{28\}$	0.3	0.5	55
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\text{FB}}^{pol,\tau}$[32]	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO [35]	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\text{GeV}}$	$\frac{d\sigma}{d\cos\theta}$ [32]	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

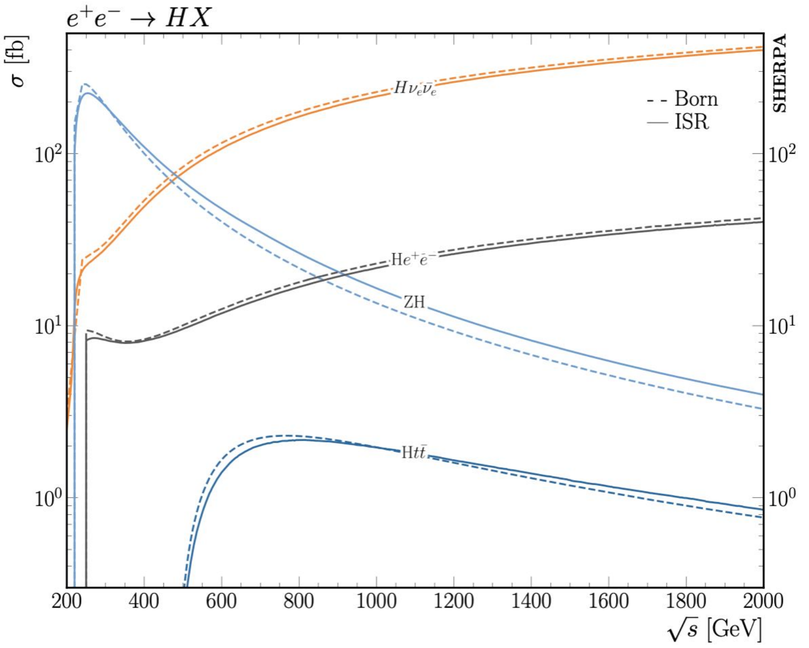
[Jadach,Skrzypek, Eur. Phys. J. C79(2019)]



QED in the initial state

New in Sherpa 3.0: Real photon emissions in the initial state! [Krauss, Schönherr, Price 2022]

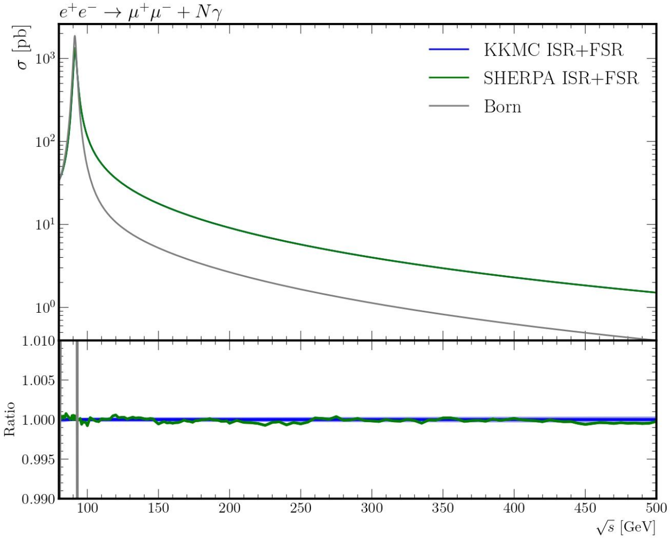
- Extension of Sherpa YFS module for soft photon resummation in final state [Krauss, Schönherr 2008]
- Supplemented with collinear logs up to O(α^3L^3)
- Complete treatment of muti-photon kinematics: Explicit photons, no simplified electron PDF
- Matching to full NLO EW underway [Price]



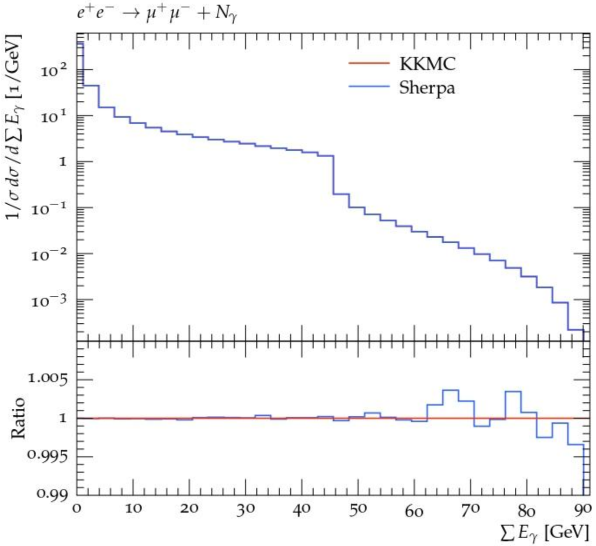
YFS Validation

KKMC: LEP Era YFS MC for e+e- -> ffbar

Comput.Phys.Commun. 130 (2000) 260-325



Superb agreement in σ over a range of √s

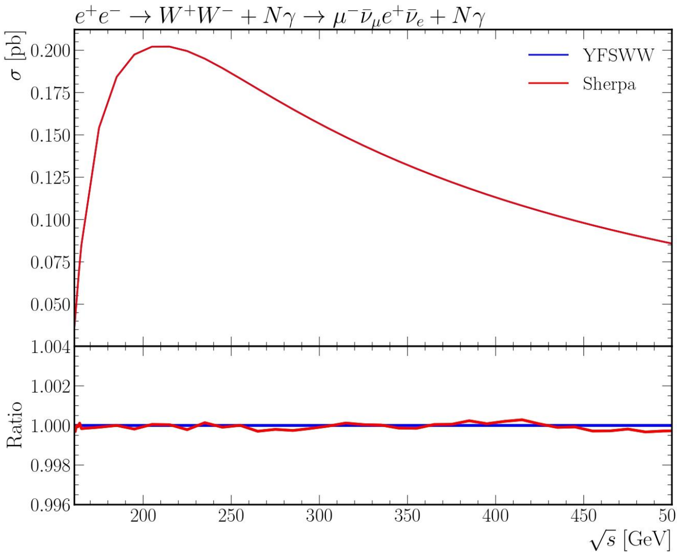


Excellent agreement in the photon kinematics

YFS Validation

YFSWW : LEP Era YFS MC for e+e- -> WW

Comput.Phys.Commun. 140 (2001) 475-512



Superb agreement in σ
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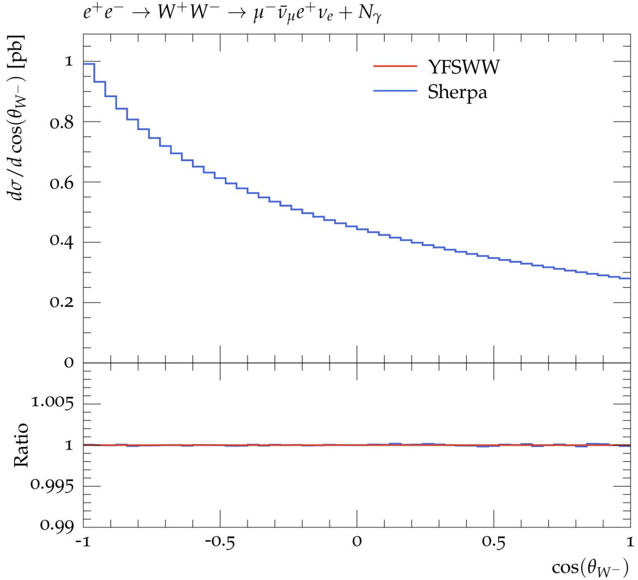
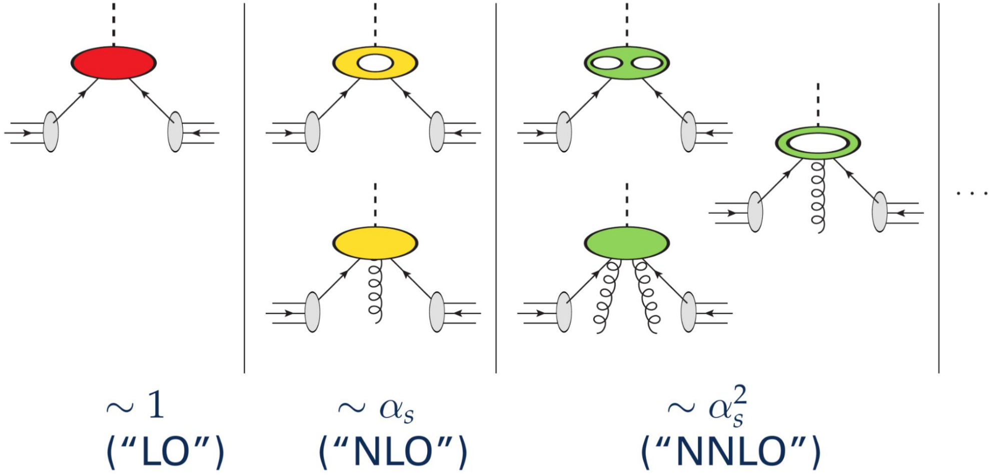


Excellent agreement in
the W kinematics

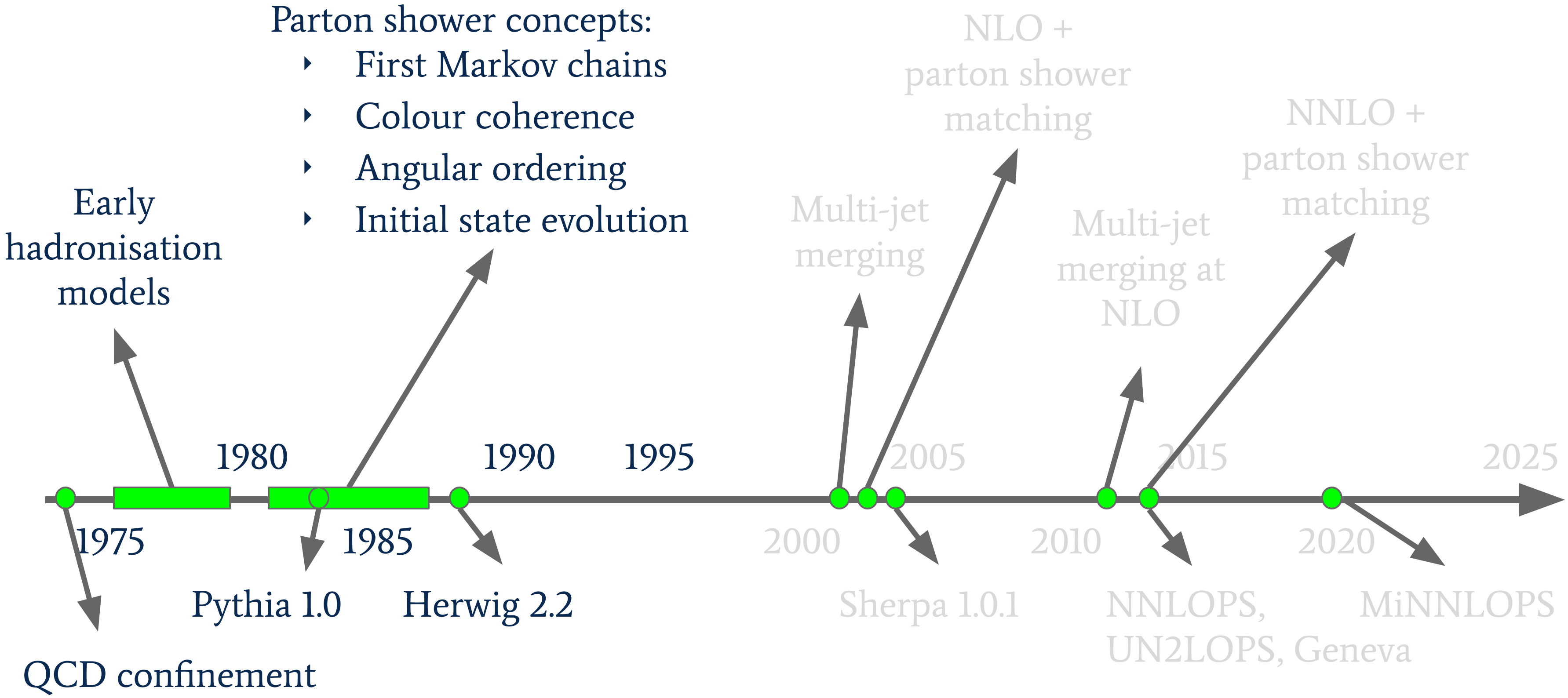
The need for (resummed) QCD

- Don’t know how to solve QCD **analytically**
- Only **perturbation series** in α_s for hard scattering



- For predictions at **fully-realistic particle level** (low energies, hadrons, …): series **diverges** !
- Resummation necessary, but only feasible in approximation:
  - Parton Showers (PS) resum the large contributions that repeat universally at each order!

QCD parton showers around for a long time!



Parton shower concepts:
- First Markov chains
- Colour coherence
- Angular ordering
- Initial state evolution

Early hadronisation models

QCD confinement

Pythia 1.0

Herwig 2.2

Multi-jet merging

NLO + parton shower matching

Sherpa 1.0.1

Multi-jet merging at NLO

NNLO + parton shower matching

NNLOPS, UN2LOPS, Geneva

MiNNLOPS

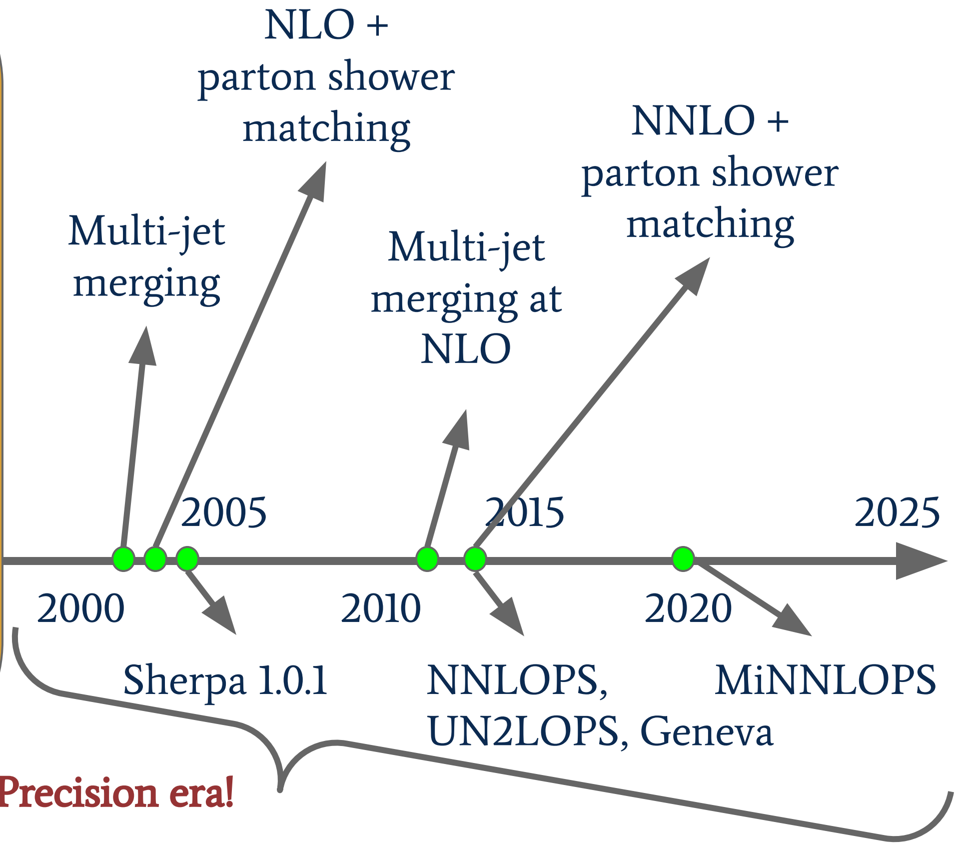
QCD parton shower corrections

Beyond the collinear approximation using higher-order calculations!

NLO matrix elements

Two families of methods, ~automated:

- MC@NLO
  - implementations in MadGraph5_aMC@NLO, **Sherpa** , Herwig7
- Powheg
  - implementation in POWHEG-Box for various processes, Whizard



NLO + parton shower matching

Multi-jet merging

Multi-jet merging at NLO

NNLO + parton shower matching

Sherpa 1.0.1

NNLOPS, UN2LOPS, Geneva

MiNNLOPS

Precision era!

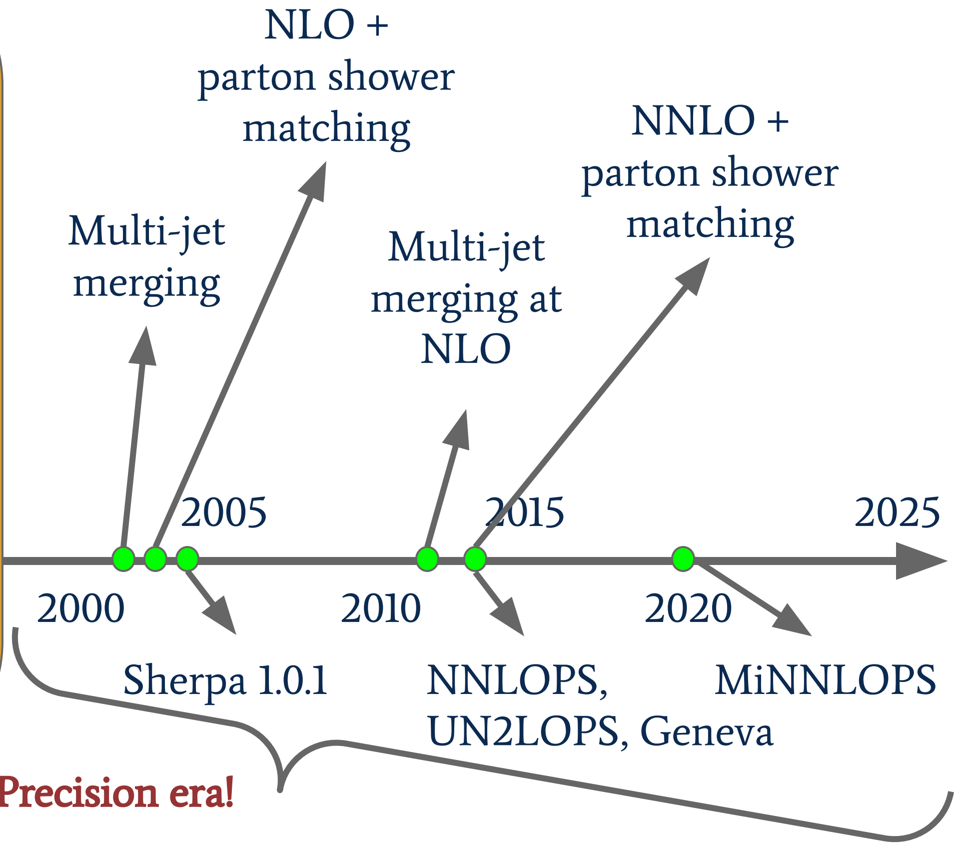
QCD parton shower corrections

Beyond the collinear approximation using higher-order calculations!

NNLO matrix elements

Not automated, individual implementations for several processes (typically colour-singlet, ttbar)

- NNLOPS/MiNNLOPS
- UN2LOPS (**Sherpa**)
- Geneva



Multi-jet merging

NLO + parton shower matching

Multi-jet merging at NLO

NNLO + parton shower matching

2000

2005

2010

2015

2020

2025

Sherpa 1.0.1

NNLOPS, UN2LOPS, Geneva

MiNNLOPS

Precision era!

QCD parton shower corrections

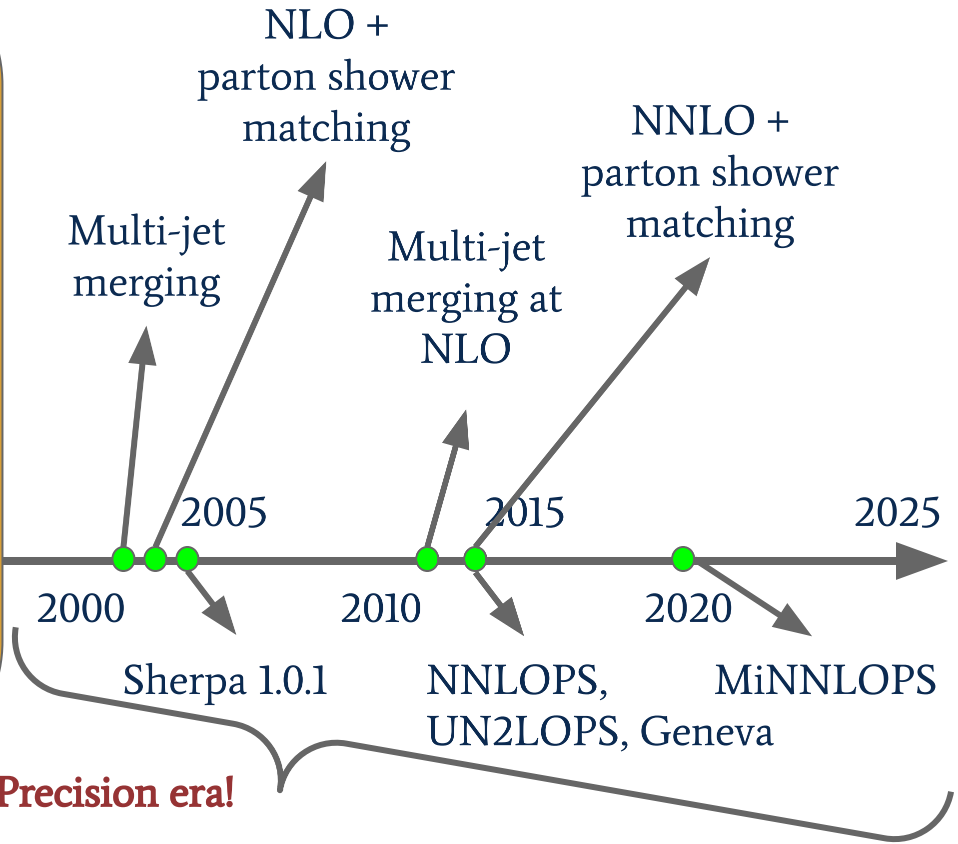
Beyond the collinear approximation using higher-order calculations!

Multi-jet matrix elements

Automated for arbitrary processes/models

- **Sherpa** (with state-of-the-art ME generator built-in)
- Herwig7 and Pythia8 (with external ME generators, e.g. MG5_aMC, Sherpa)

Q



NLO + parton shower matching

NNLO + parton shower matching

Multi-jet merging

Multi-jet merging at NLO

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Sherpa 1.0.1

NNLOPS, UN2LOPS, Geneva

MiNNLOPS

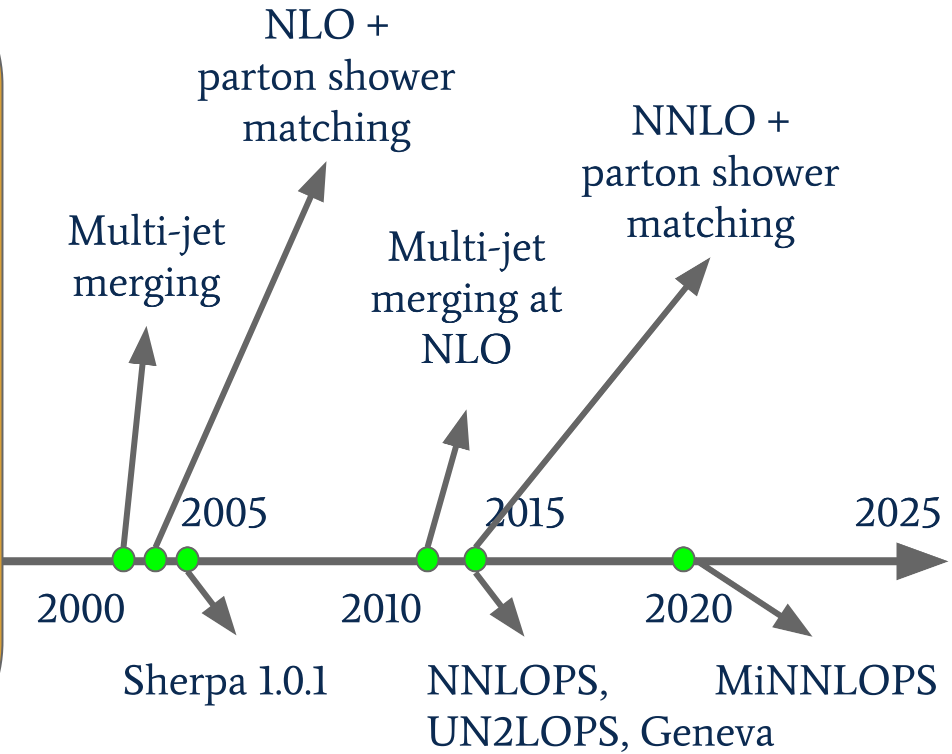
Precision era!

QCD parton shower corrections

In parallel: Improving the collinear approximation to all orders

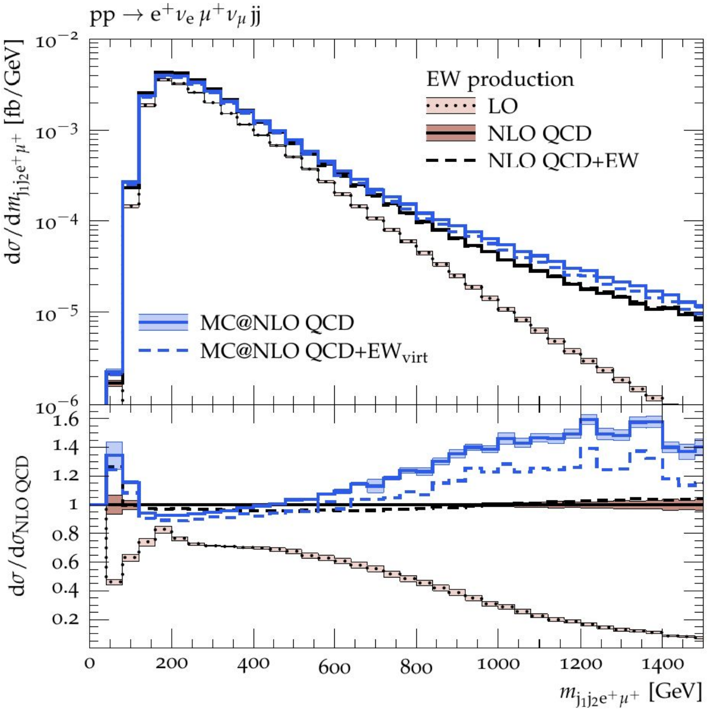
- Large efforts on new parton shower algorithms in recent years

→ Daniel Reichelt's talk later in this session

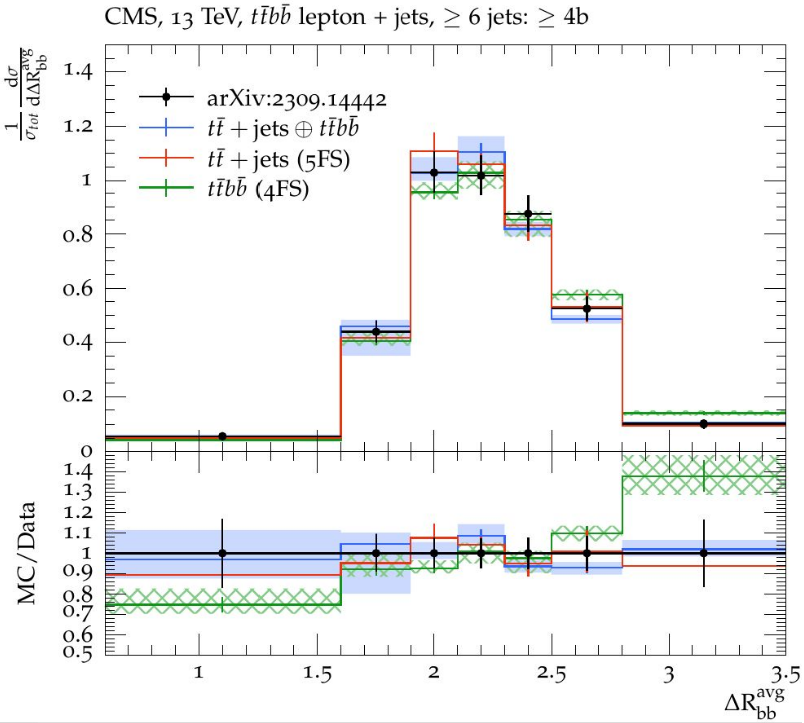


Recent state-of-the-art QCD predictions

At pp colliders …



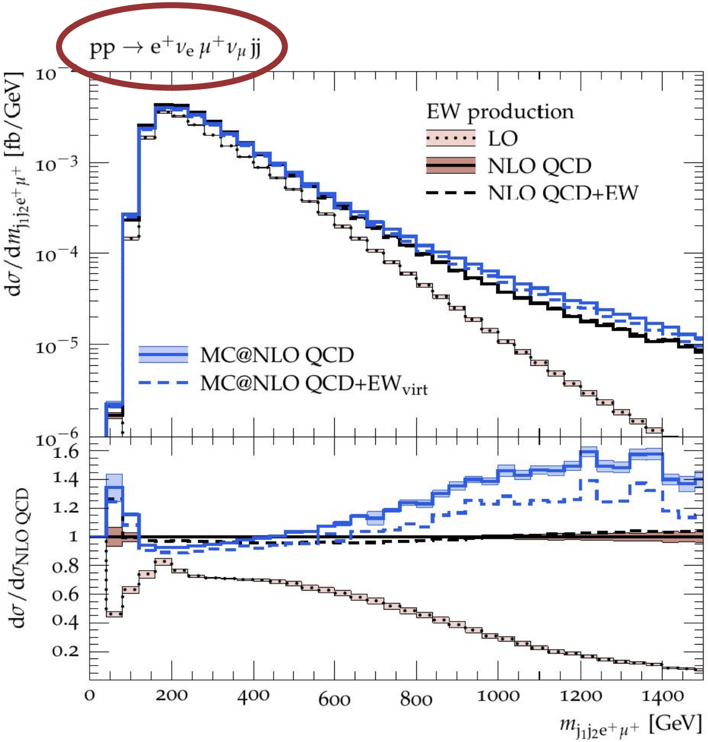
[Denner, Pellen, Schönherr, Schumann 2024]



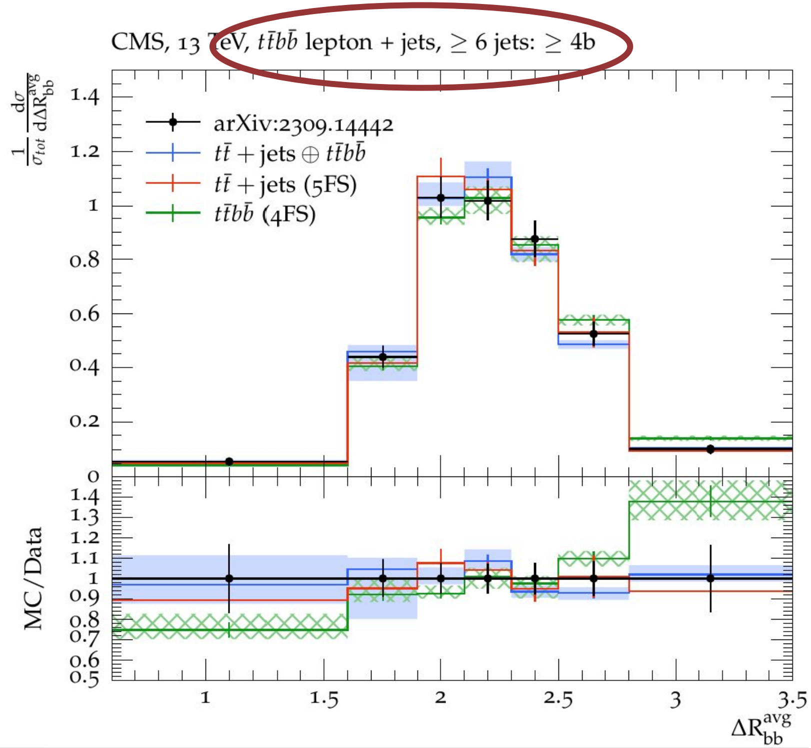
[Ferencz, Katzy, Höche, FS 2024]

Recent state-of-the-art QCD predictions

At pp colliders …



[Denner, Pellen, Schönherr, Schumann 2024]

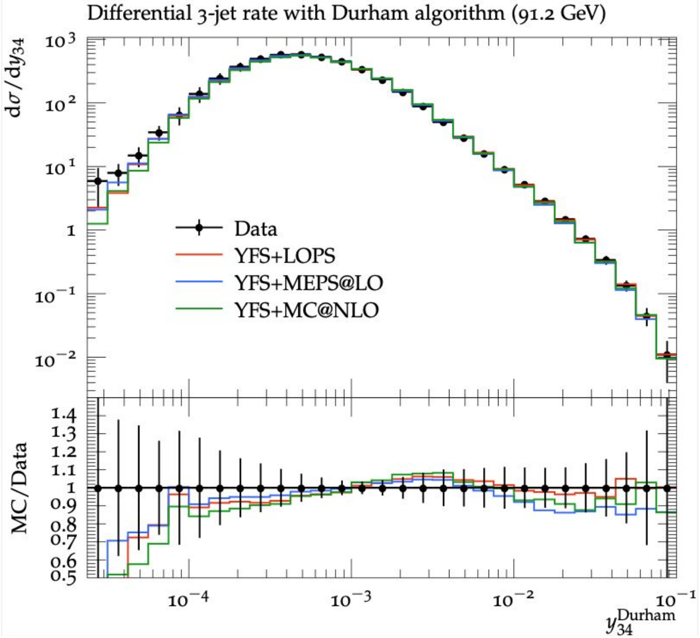


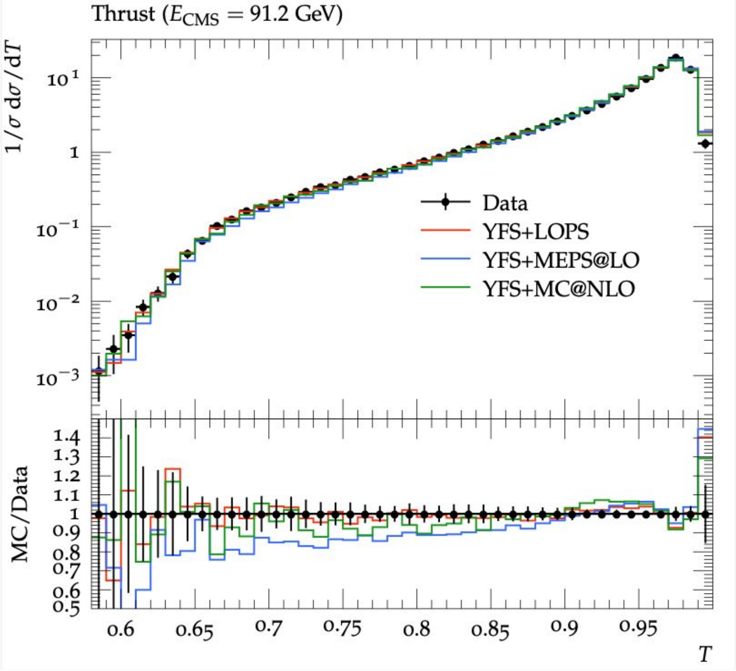
[Ferencz, Katzy, Höche, FS 2024]

Recent state-of-the-art QCD predictions

… and at e^+e^- colliders for hadronic final states:

$e^+e^- \rightarrow$ jets





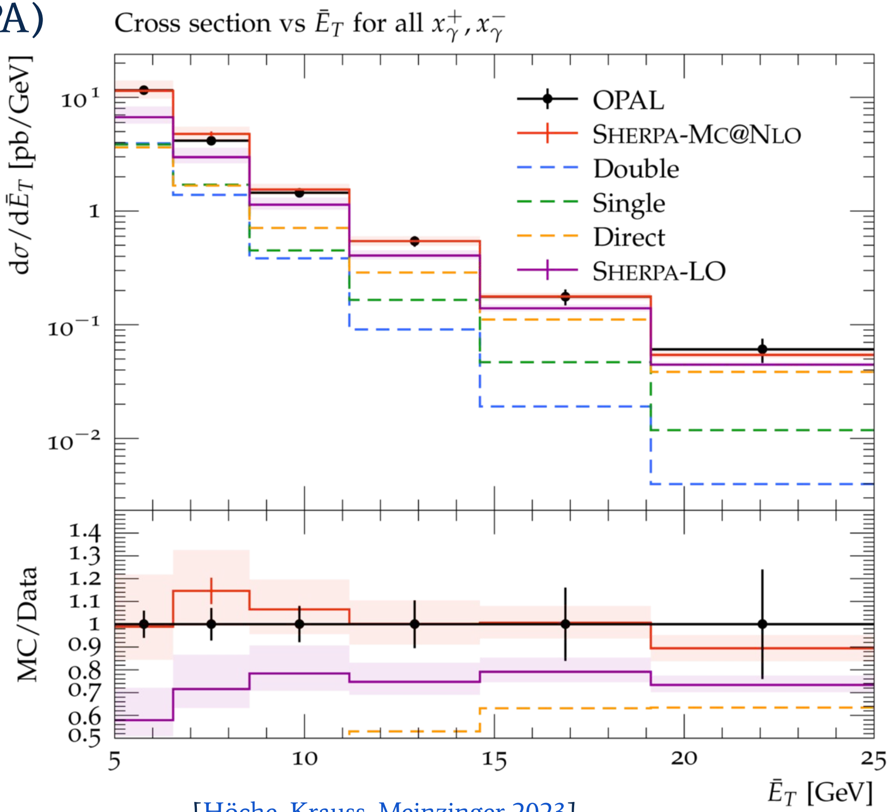
We can combine Sherpa's state of the art QED ISR and QCD FSR.

New YFS seamlessly combines with all of Sherpa's native features!

More QCD at Lepton Colliders: Photoproduction

Photon radiation from electron beams (e.g. via EPA)
→ photon induced scattering processes

- Photoproduction dominant channel for ee → jets at LEP (inclusive)!
- Photons can be direct or resolved
- First MC@NLO calculation of photoproduction in Sherpa, incl. multiple interactions, hadronisation, etc.
- Very good agreement with data from LEP and HERA
- Allows for study of hadronic structure of the photon
- BSM searches via photon fusion?



[Höche, Krauss, Meinzinger 2023]

QED FSR: Photons splitting into fermions

Yennie-Frautschi-Suura soft-photon resummation does not include $\gamma \to f^+f^-$ corrections which enter at $\mathcal{O}(\alpha^2)$

Yennie, Frautschi, Suura '61; Krauss, Schönherr '08

Collinear QED evolution:

- reconstruct starting scale of every photon
- evolve in parton shower picture until every photon virtuality drops below $4m_e^2$

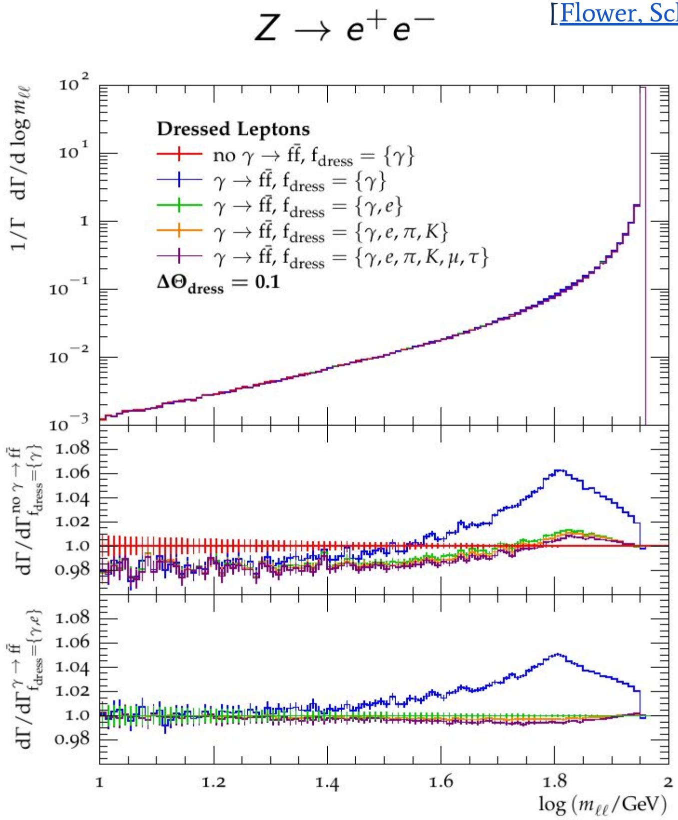
⇒ effect only corrections beyond YFS resummation

Dressing algorithm:

- lepton dressing ambiguous beyond photon FSR

→ include secondary flavours?
if yes, some, or all?

- depending on dressing algorithm, more or less energy may be recombined into dressed lepton

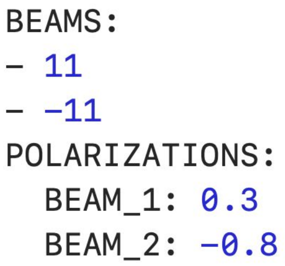


[Flower, Schönherr 2023]

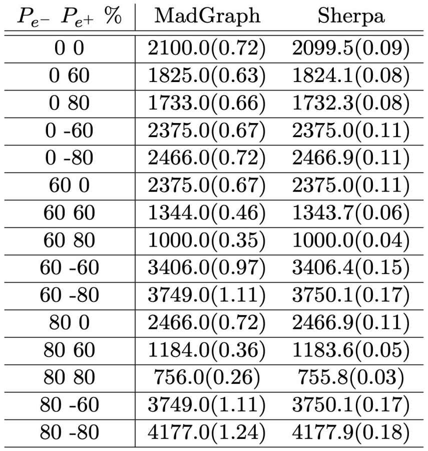
**Connection with QED ISR underway!
[Flower, Price]**

IS polarisation

- Available in one of Sherpa's ME generators (AMEGIC)
  - Recently resurrected for Sherpa 3
- Reweight the ME with pol factor (1+P),(1-P)
- Validated against Madgraph/Whizard
- Automatically included in YFS: Soft photons blind to spin!

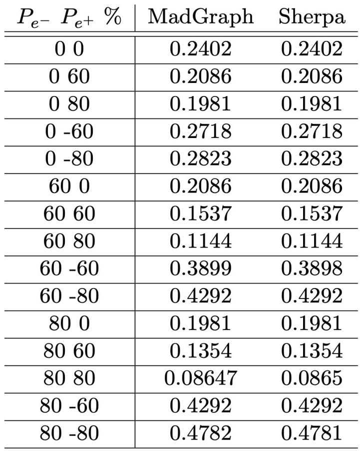


```
BEAMS:
- 11
- -11
POLARIZATIONS:
  BEAM_1: 0.3
  BEAM_2: -0.8
```



P_{e^-} P_{e^+} %	MadGraph	Sherpa
0 0	2100.0(0.72)	2099.5(0.09)
0 60	1825.0(0.63)	1824.1(0.08)
0 80	1733.0(0.66)	1732.3(0.08)
0 -60	2375.0(0.67)	2375.0(0.11)
0 -80	2466.0(0.72)	2466.9(0.11)
60 0	2375.0(0.67)	2375.0(0.11)
60 60	1344.0(0.46)	1343.7(0.06)
60 80	1000.0(0.35)	1000.0(0.04)
60 -60	3406.0(0.97)	3406.4(0.15)
60 -80	3749.0(1.11)	3750.1(0.17)
80 0	2466.0(0.72)	2466.9(0.11)
80 60	1184.0(0.36)	1183.6(0.05)
80 80	756.0(0.26)	755.8(0.03)
80 -60	3749.0(1.11)	3750.1(0.17)
80 -80	4177.0(1.24)	4177.9(0.18)

Table 1: Polarized cross-section for $e^+e^- \to \mu^+\mu^-$ at 91.2 GeV. The results are quoted in fb.

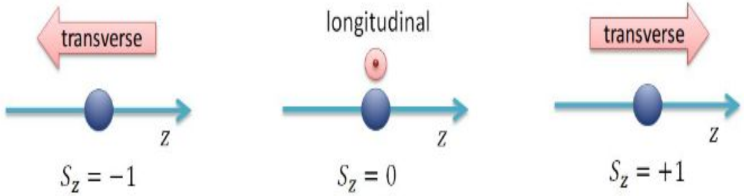


P_{e^-} P_{e^+} %	MadGraph	Sherpa
0 0	0.2402	0.2402
0 60	0.2086	0.2086
0 80	0.1981	0.1981
0 -60	0.2718	0.2718
0 -80	0.2823	0.2823
60 0	0.2086	0.2086
60 60	0.1537	0.1537
60 80	0.1144	0.1144
60 -60	0.3899	0.3898
60 -80	0.4292	0.4292
80 0	0.1981	0.1981
80 60	0.1354	0.1354
80 80	0.08647	0.0865
80 -60	0.4292	0.4292
80 -80	0.4782	0.4781

Table 1: Polarized cross-section for $e^+e^- \to HZ$ at 250 GeV. The results are quoted in fb.

Polarised intermediate particles

- Not only beams can be polarised!
  - Is LC physics sensitive to the polarisation of intermediate vector bosons?



- Idea:
  Use polarised MC predictions as templates for analyses based on realistic final states

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

→ Exploit longitudinal polarisation for EWSB studies
→ Exploit SM-suppressed polarisation configurations for BSM studies

- Lessons from LHC:
  - Analytical projections not applicable in the presence of lepton cuts
  - Exclusive predictions in MC event generators possible, ideally with higher order corrections

Polarised intermediate particles

- Caveats for polarised predictions:

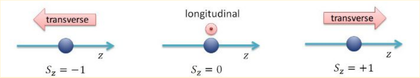
Polarization for intermediate particles

- completeness relation

$$\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2}\right) = \sum_{\lambda=1}^{4} \varepsilon^\mu(q,\,\lambda)\varepsilon^{*\nu}(q,\,\lambda)$$

- leads to interferences between different polarizations

Polarization basis



Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf

- helicity basis

$$\varepsilon^\mu_\pm(q) = \frac{e^{\mp i\phi}}{\sqrt{2}}(0,\ -\cos\theta\cos\phi \pm i\sin\phi,\ -\cos\theta\sin\phi \mp i\cos\phi, \sin\theta)$$

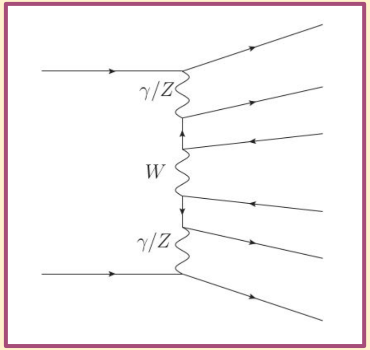
$$\varepsilon^\mu_0(q) = \frac{q^0}{m}\left(\frac{|\vec{q}|}{q^0}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right)$$

- frame dependent!

Polarization only defined in production ⊗ propagator ⊗ decay factorizable amplitudes

- problem: non-resonant diagrams
  → no polarisation definition, but necessary for gauge invariance

- solution: appropriate approximations - gauge invariant options:
  - Pole Approximation ((D)PA)
  - Narrow-Width Approximation (NWA)

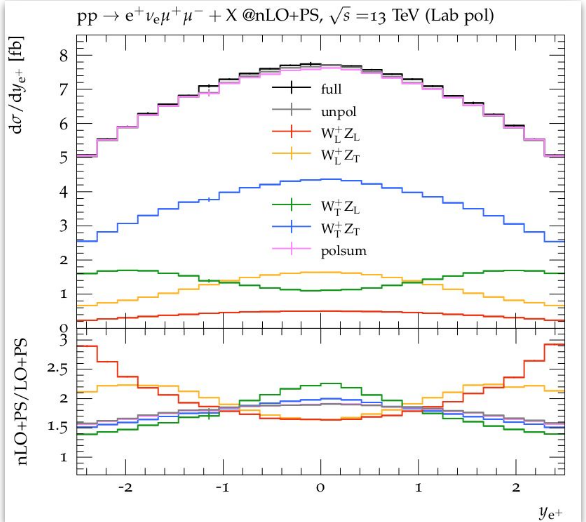


Sherpa's new polarisation framework beyond LO

Methodology:

[Hoppe, Schönherr, FS, 2023]

- Unpolarised simulation run, polarised XS as event weights
- All polarisation combinations, interferences, reference frames in one simulation run
- Accuracy options:
  - nLO QCD+PS matching



Born polarisation (ultra-collinear/-soft virtual corrections unpolarised)

S-event

Polarisation of real correction

H-event

$$\begin{aligned}\langle O\rangle^{(\mathrm{NLOMC})} =& \sum_{\{\vec{f}\}}\int \mathrm{d}\Phi_B(\{\vec{p}\})\,\bar{\mathrm{B}}^{(\mathrm{A})}(\{\vec{a}\})\Bigg[\underbrace{\bar{\Delta}^{(\mathrm{A})}(t_0;\{\vec{a}\})}_{\text{unresolved}}\,O(\{\vec{p}\})\\ &+\sum_{\{\widetilde{ij},\tilde{k}\}}\sum_{F_i=q,g}\int \mathrm{d}\Phi^{ij,k}_{R|B}\,\Theta(t(\Phi^{ij,k}_{R|B})-t_0)\;O(r_{\widetilde{ij},\tilde{k}}(\{\vec{p}\}))\\ &\times\underbrace{\frac{1}{S_{ij}}\,\frac{S(r_{\widetilde{ij},\tilde{k}}(F_i;\{\vec{f}\}))}{S(\{\vec{f}\})}\,\frac{\mathrm{D}^{(\mathrm{A})}_{ij,k}(r_{\widetilde{ij},\tilde{k}}(F_i,\Phi^{ij,k}_{R|B};\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})}\,\bar{\Delta}^{(\mathrm{A})}(t;\{\vec{a}\})}_{\text{resolved, singular}}\Bigg]\\ &+\sum_{\{\vec{F}\}}\int \mathrm{d}\Phi_R(\{\vec{P}\})\underbrace{\left[\mathrm{R}(\{\vec{A}\})-\sum_{ij,k}\mathrm{D}^{(\mathrm{A})}_{ij,k}(\{\vec{A}\})\right]}_{\text{resolved, non-singular}}O(\{\vec{P}\})\,.\end{aligned}$$

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Born polarisation (ultra-collinear/-soft virtual corrections unpolarised)

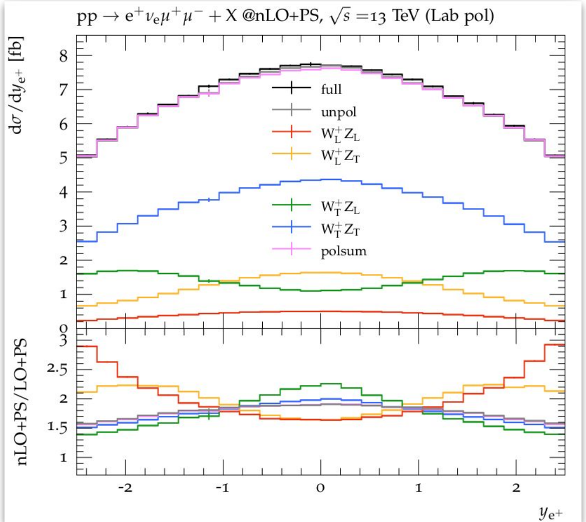
S-event

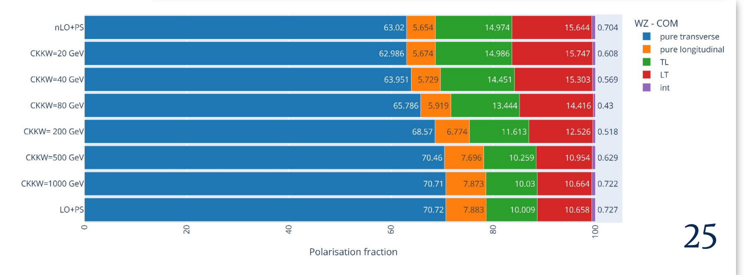
Polarisation of real correction

H-event

$$
\begin{aligned}
\langle O\rangle^{(\mathrm{NLOMC})} = \sum_{\{\vec{f}\}} \int \mathrm{d}\Phi_B(\{\vec{p}\})\, \bar{\mathrm{B}}^{(\mathrm{A})}(\{\vec{a}\}) \Bigg[& \underbrace{\bar{\Delta}^{(\mathrm{A})}(t_0;\{\vec{a}\})}_{\text{unresolved}}\, O(\{\vec{p}\}) \\
& + \sum_{\{\widetilde{\imath\jmath},\tilde{k}\}} \sum_{F_i=q,g} \int \mathrm{d}\Phi_{R|B}^{ij,k}\, \Theta\big(t(\Phi_{R|B}^{ij,k}) - t_0\big)\; O(r_{\widetilde{\imath\jmath},\tilde{k}}(\{\vec{p}\})) \\
& \times \underbrace{\frac{1}{S_{ij}} \frac{S(r_{\widetilde{\imath\jmath},\tilde{k}}(F_i;\{\vec{f}\}))}{S(\{\vec{f}\})} \frac{\mathrm{D}_{ij,k}^{(\mathrm{A})}(r_{\widetilde{\imath\jmath},\tilde{k}}(F_i,\Phi_{R|B}^{ij,k};\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})}\, \bar{\Delta}^{(\mathrm{A})}(t;\{\vec{a}\})}_{\text{resolved, singular}} \Bigg] \\
+ \sum_{\{\vec{F}\}} \int \mathrm{d}\Phi_R(\{\vec{P}\}) & \underbrace{\Bigg[\mathrm{R}(\{\vec{A}\}) - \sum_{ij,k} \mathrm{D}_{ij,k}^{(\mathrm{A})}(\{\vec{A}\}) \Bigg]}_{\text{resolved, non-singular}} O(\{\vec{P}\})\,.
\end{aligned}
$$

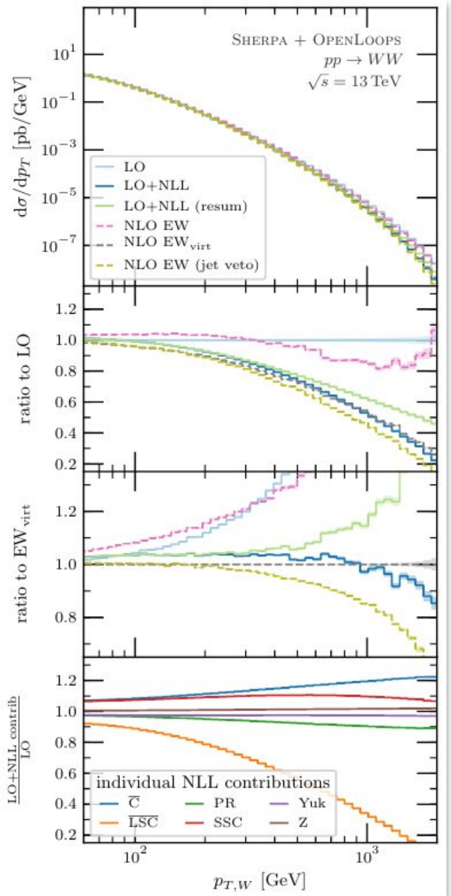
  - Multi-jet merging, e.g. W(ev)Z(mm)+jets





Electroweak corrections in Sudakov approximation

- NLO EW corrections more & more important to reach precision targets for √s > 1 TeV
- Complete NLO EW calculation possible, but not always feasible
- Possible approximation: EW Sudakov logarithms
  [A. Denner & S. Pozzorini 2000, 2001]
  - NLO EW logarithmically enhanced for energies above EW scale
  - Large contributions in tails of kinematic distributions
  - Can be universally applied to any Sherpa calculation
    (in particular, in matched multi-jet matrix element calculations)
- Automated in SHERPA [Bothmann, Napoletano 2020, Bothmann et al. 2021]

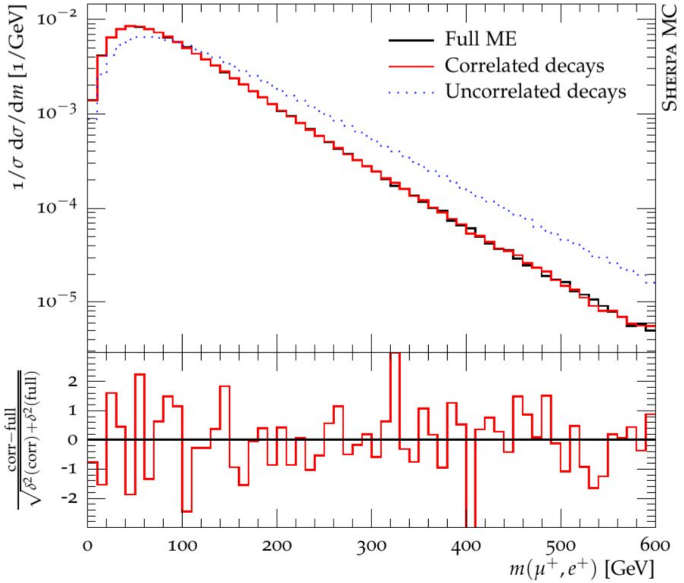


BSM models: UFO interface

- Dream of phenomenologists or experimentalists:
  From a model's Lagrangian L → simulated event samples
- Important ingredient: UFO standard to automatically transfer Feynman rules (from FeynRules, SARAH, ...) into event generators

- Sherpa interface available for a while
  [Höche, Kuttimalai, Schumann, FS 2014]
  - New in Sherpa 3.0.0: UFO 2.0 interface with more flexibility, e.g. with form factors
  - Automatic decay tables/chains
  - Spin correlations
  - Effective field theories (SMEFT, HEFT) via UFO model

Squark pair production in MSSM



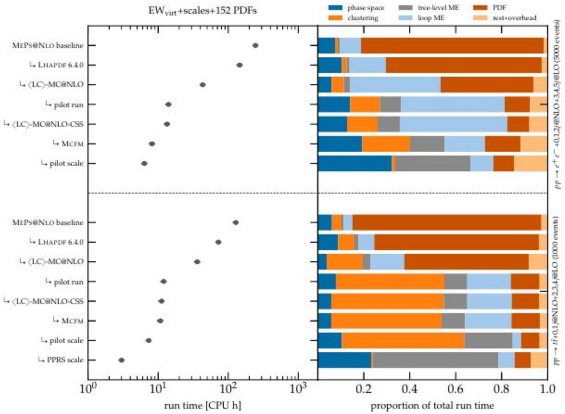
Significant CPU performance improvements

- Motivation: Poor event generation performance can limit experimental success of HL-LHC and future colliders

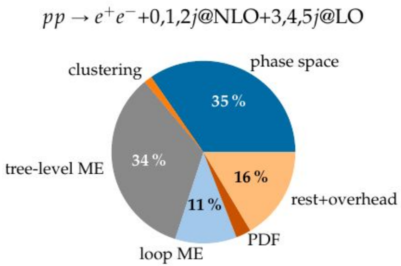
  [HSF Physics Event Generator WG] arXiv:2004.13687, arXiv:2109.14938

FCC-ee! ILC250?

- E.g. pilot run: Only run full simulation for unweighted events



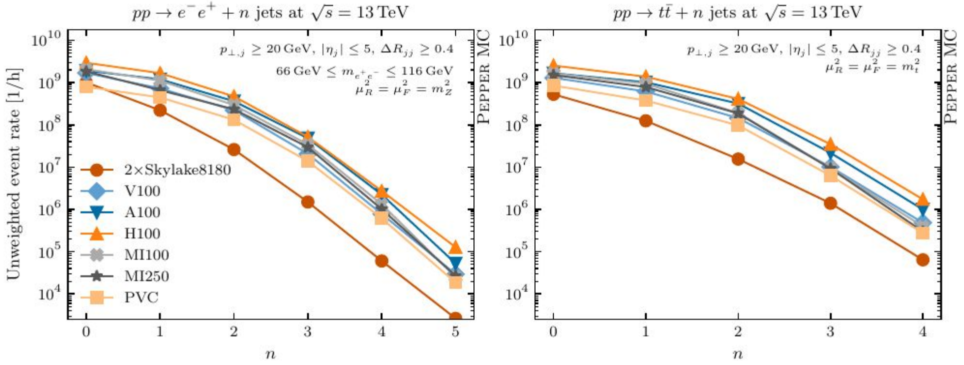
Case study: ATLAS production setups for Z+jets and $t\bar{t}$+jets



- CPU consumption overall improved by factors of $\times\mathbf{39}$ and $\times\mathbf{43}$ for V+jets and $t\bar{t}$+jets [Bothmann et al.] arXiv:2209.00843
- After optimisation, more than two thirds of CPU time spent in phase space sampling and (tree-level) matrix elements

Portable GPU-accelerated event generation

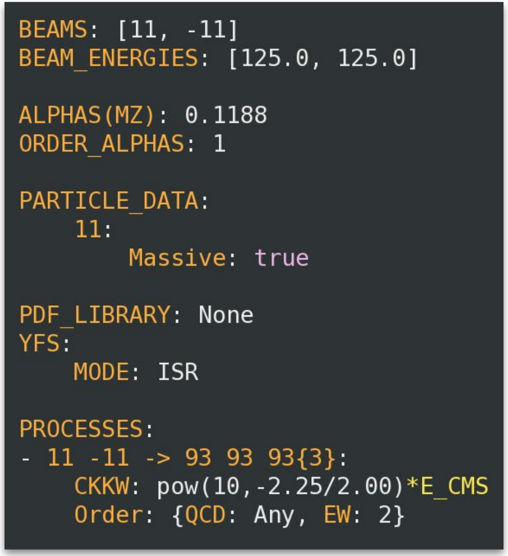
- Motivation: Strong AI-driven HPC trend towards heterogeneous computing resources (i.e. CPU+GPU)
- Novel portable tree-level parton-level event generator PEPPER
  [Bothmann et al.] arXiv:2311.06198
- Use SHERPA's & PYTHIA's existing LHEH5 interfaces to add particle-level simulation steps [Bothmann et al.] arXiv:2309.13154
- Ideal provider of on-device jet training data for ML applications
- Strongly improved numerical stability for (N)NLO applications
  [Bothmann, Campbell, Höche, Knobbe] arXiv:2406.07671



Conclusions

- Hot off the press: Sherpa 3.0.0 released!
  - Download and information on Sherpa homepage: https://sherpa-team.gitlab.io/
  - New user interface (YAML language)
    Give it a try!
  - Availability in Key4Hep software stack:
    - » Both Sherpa2 and Sherpa3 will be available in the nightlies
    - » source /cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh
    - » Sherpa3-0-0 MyFavouriteProcess.yaml

  [Key4Hep => Thomas Madlener’s talk]



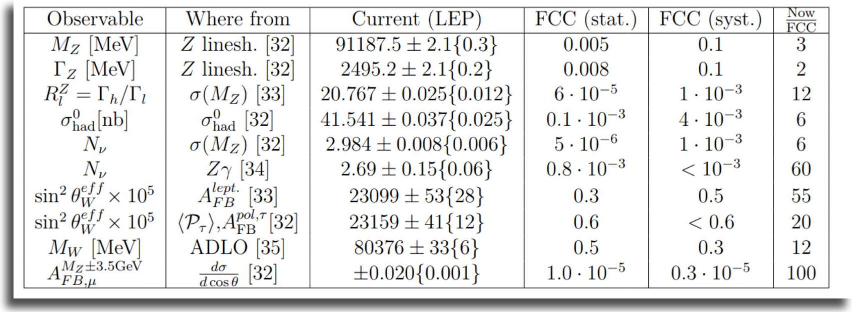
```
BEAMS: [11, -11]
BEAM_ENERGIES: [125.0, 125.0]

ALPHAS(MZ): 0.1188
ORDER_ALPHAS: 1

PARTICLE_DATA:
  11:
    Massive: true

PDF_LIBRARY: None
YFS:
  MODE: ISR

PROCESSES:
- 11 -11 -> 93 93 93{3}:
  CKKW: pow(10,-2.25/2.00)*E_CMS
  Order: {QCD: Any, EW: 2}
```

- Sherpa’s LHC expertise carries over to LC
  - Additionally dedicated developments for Linear Collider physics!
- NEW: automated YFS for state-of-the-art QED corrections in the initial state [Alan Price]
- NEW: photon → lepton splittings in YFS [Lois Flower]
- NEW: state-of-the-art photo-production of ee → jets [Peter Meinziger]

Backup

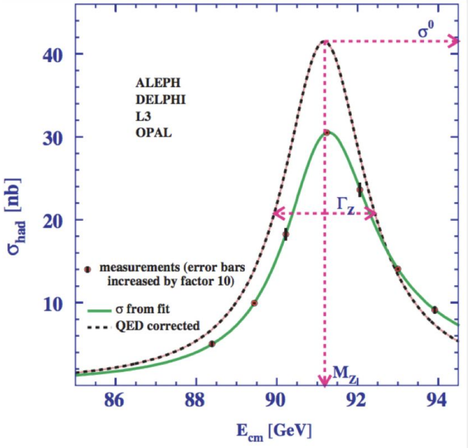
The Need For QED

- Factor 2-100 improvement in the measurement of EWPOs
- 0.1% errors which could be ignored at LEP will be dominant at future e+e- machines
- On the theoretical side this translates into a much more sophisticated modelling
  - **Fixed Order Improvements**



Observable	Where from	Current (LEP)	FCC (stat.)	FCC (syst.)	$\frac{\text{Now}}{\text{FCC}}$
M_Z [MeV]	Z linesh. [32]	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh. [32]	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$ [33]	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
σ^0_{had}[nb]	σ^0_{had} [32]	$41.541 \pm 0.037\{0.025\}$	$0.1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$ [32]	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$ [34]	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$ [33]	$23099 \pm 53\{28\}$	0.3	0.5	55
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\text{FB}}^{pol,\tau}$ [32]	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO [35]	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\text{GeV}}$	$\frac{d\sigma}{d\cos\theta}$ [32]	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

[Jadach,Skrzypek, Eur. Phys. J. C79(2019)]



$$d\sigma(L,\hat{L}) = \alpha^k \sum_n^\infty \alpha^n \sum_{i=0}^\infty \sum_{j=0}^\infty \hat{\sigma}_{n,i,j} L^i \hat{L}^j$$

$$\hat{L} = \log\left(\frac{Q^2}{E_\gamma^2}\right) \qquad L = \log\left(\frac{Q^2}{m_e^2}\right)$$

Soft Log **Collinear Log**