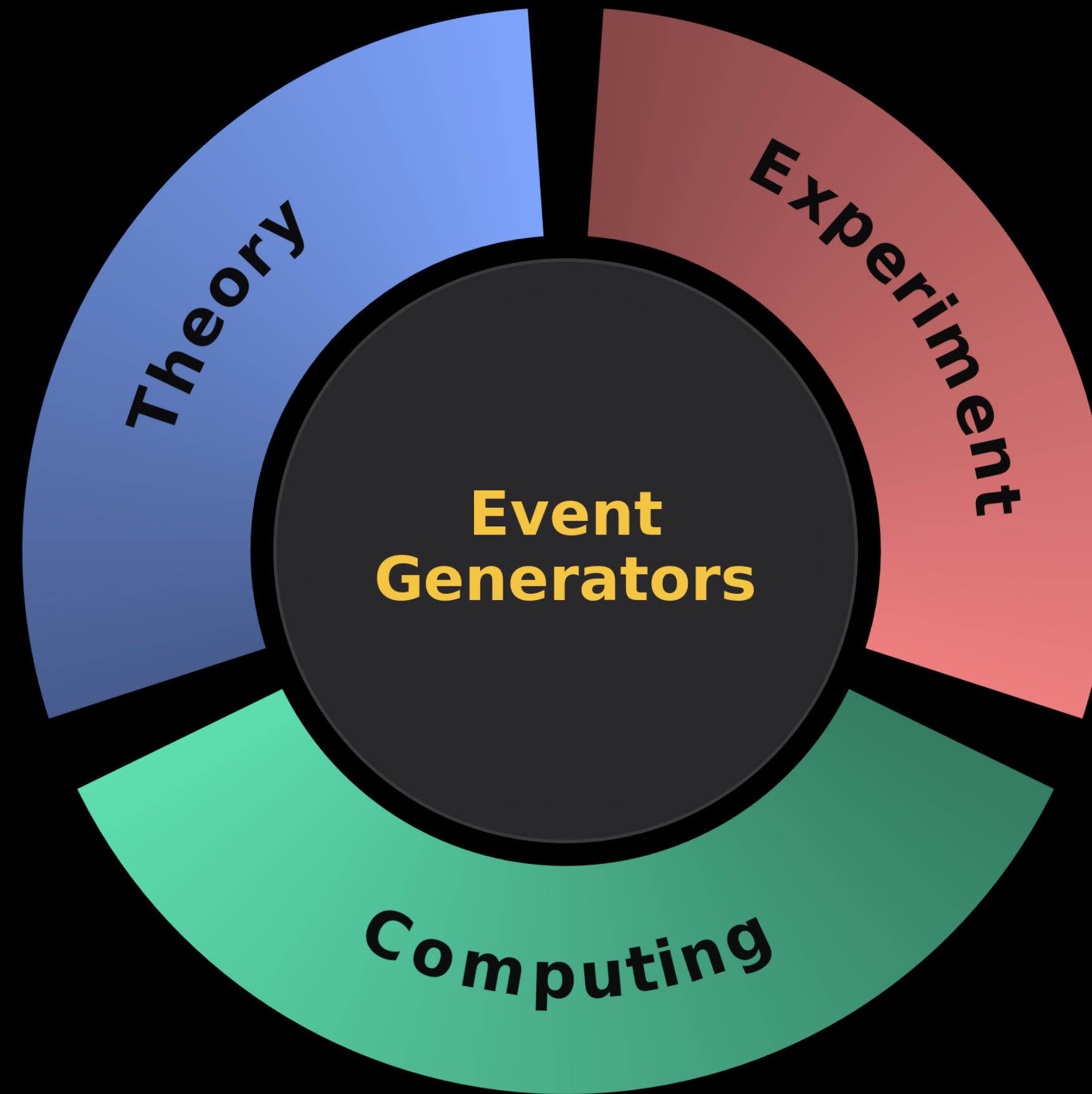


Status of event generators for FCC-ee

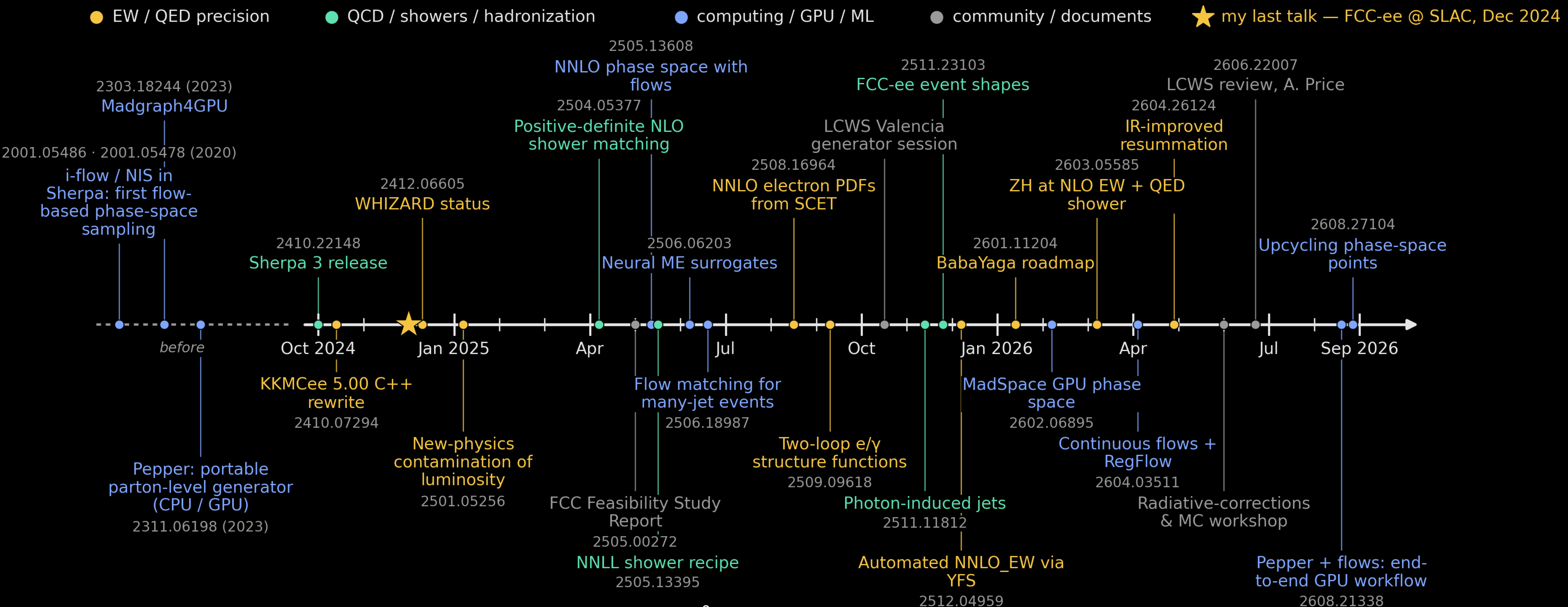


Saptaparna Bhattacharya¹, Enrico Bothmann²

Southern Methodist University¹, CERN²

Recent progress in a nutshell

- FSR (May 2025) with official targets · automated NNLO_EW via YFS · NLO-EW-matched QED shower for ZH · NNLO electron PDFs · BabaYaga roadmap to 10^{-4} · NNLL showers + positive-definite NLO matching · N³LO top threshold · GPU/ML generation mature



The FCC-ee program: quoting the Feasibility Study Report

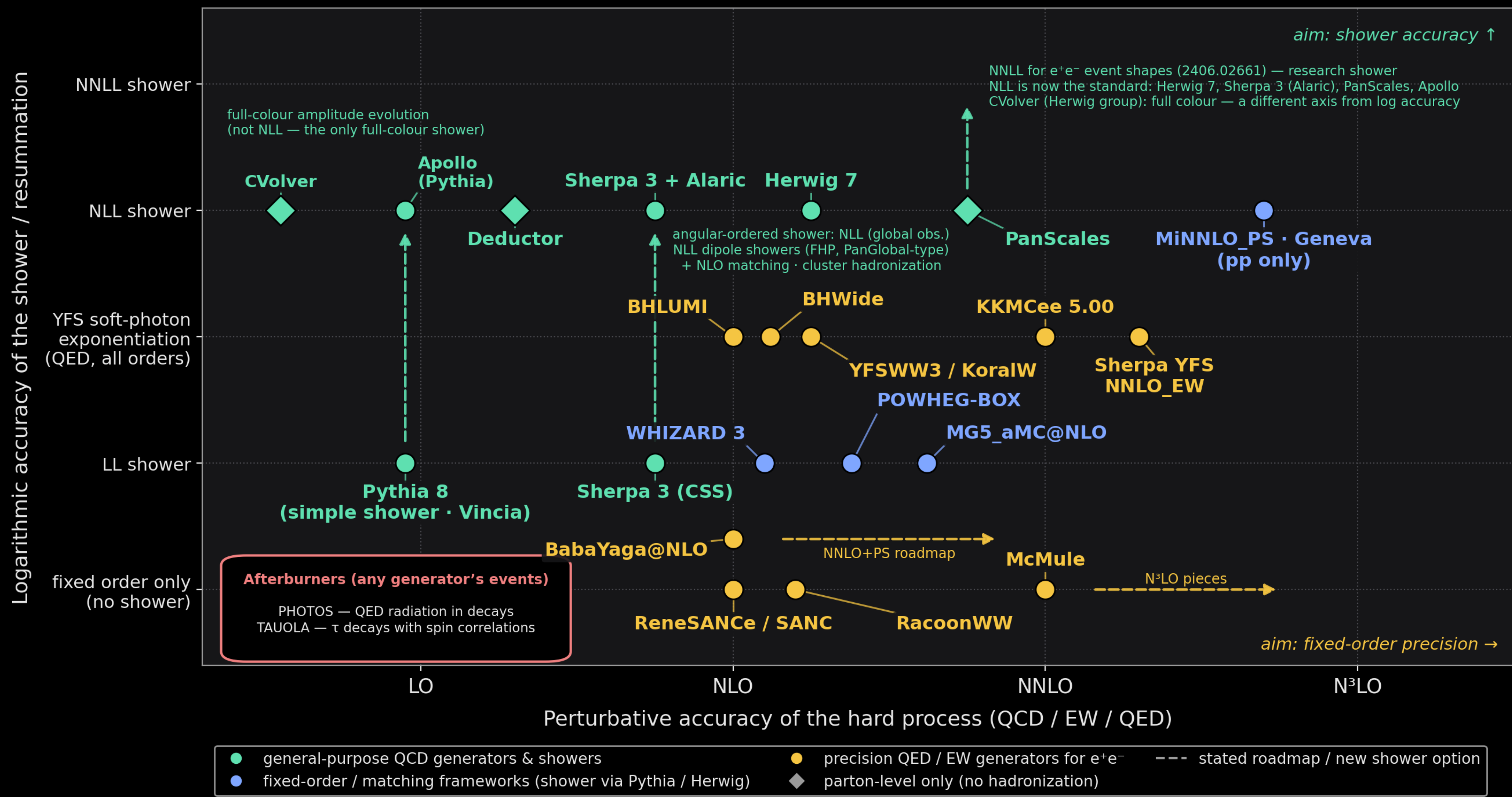
Phase	Process	$\sqrt{s}$ (GeV)	Lumi (ab ⁻¹)	Events	$\sqrt{s}$ uncertainty
FCC-ee-Z	$e^+e^- \rightarrow Z$	88–95	~205	$\sim 6 \times 10^{12}$ Z	< 50 keV
FCC-ee-W	$e^+e^- \rightarrow W^+W^-$	157–163	~19	$> 2 \times 10^8$ WW	< 200 keV
FCC-ee-H	$e^+e^- \rightarrow ZH$	240	~10.8	$> 2 \times 10^6$ ZH	2 MeV
FCC-ee-tt	$e^+e^- \rightarrow t\bar{t}$	340–365	~3	$> 2 \times 10^6$ $t\bar{t}$	5 MeV

~10⁵ Z/s

per detector at the Z pole — LEP’s entire dataset in minutes

Statistical precision this extreme places great demands on the theory & simulation

The toolsets at a glance: fixed-order precision vs shower accuracy

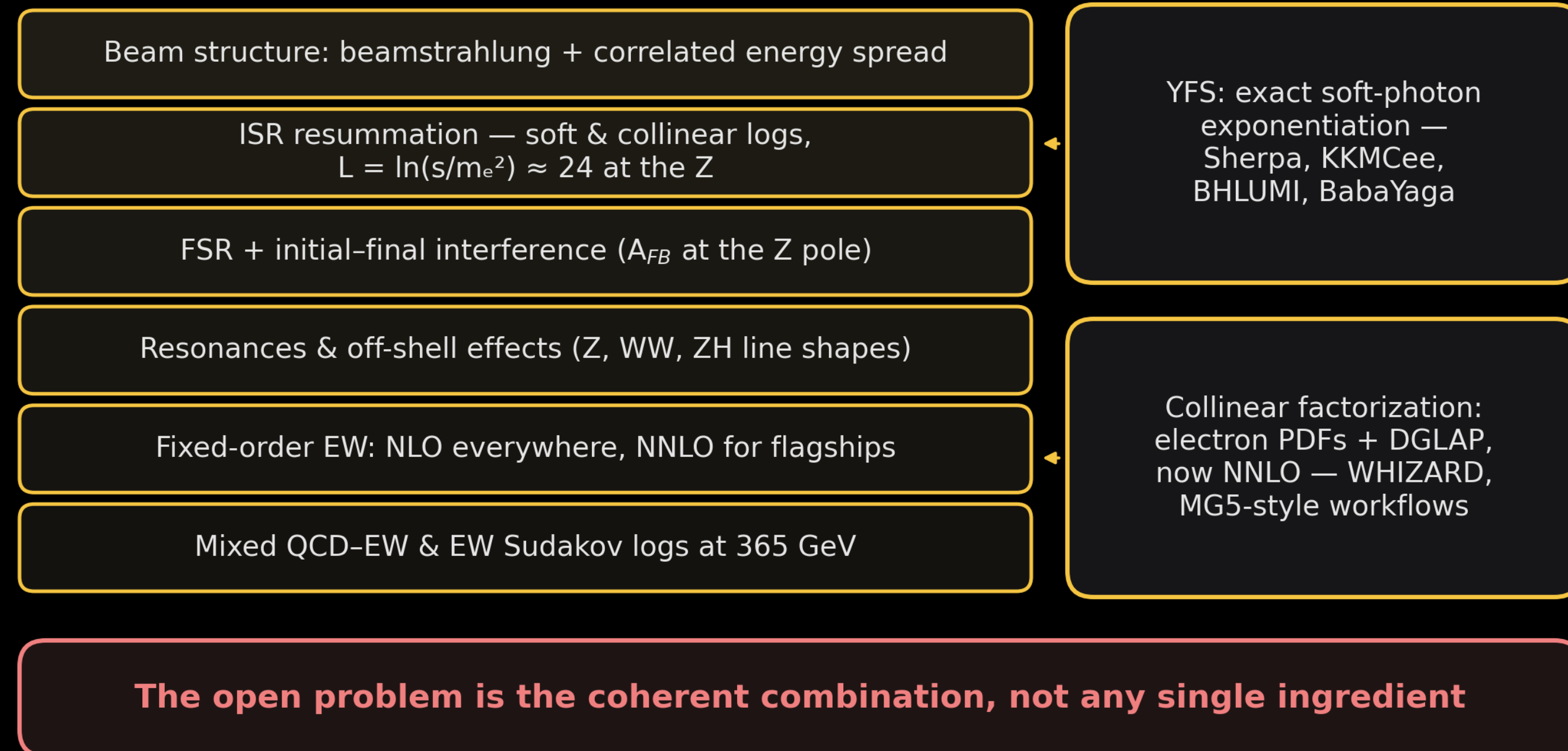


Two frontiers: general-purpose generators push logarithmic accuracy (teal, upward); the e^+e^- QED/EW codes push perturbative order (gold, rightward)

The electroweak challenge is multi-layered

- A precision e^+e^- event:
 - ISR: soft + collinear logs, $L = \ln(s/m_e^2) \approx 24$ at the Z pole
 - Resonances & off-shell effects (Z, WW, ZH line shapes)
 - Fixed-order EW: NLO everywhere, NNLO for flagship observables
 - Mixed QCD–EW corrections and EW Sudakov logs at 365 GeV
 - Beamstrahlung + correlated energy spread convolved with all of the above

The electroweak challenge is multi-layered



*A. Price, LCWS 2025 review:
[arXiv:2606.22007](https://arxiv.org/abs/2606.22007)*

New reviews & community documents (2025–2026)

MC Event Generators for Future Lepton Colliders — A. Price (LCWS 2025)

arXiv:2606.22007 · EPJ Plus 141, 711 (2026). Sharpest current map of the field: EW layers, beam spectra, NNLO+PS matching, hadronization limits, ML/GPU

Monte Carlo Event Generators — J. Reuter (Encyclopedia of Particle Physics)

arXiv:2509.21611. Generators as “digital twins” of the experiment; clean pedagogical structure (hard process → shower → hadronization → decays).

Challenges for Monte Carlo generators — LCWS 2024 proceedings

arXiv:2412.06580. Lepton-collider-specific gaps: beam simulation, polarization, higher-order EW, resummed QED.

FCC Feasibility Study Report, Vol. 1

arXiv:2505.00272. Official physics targets & detector concepts; the reference point for every generator requirement

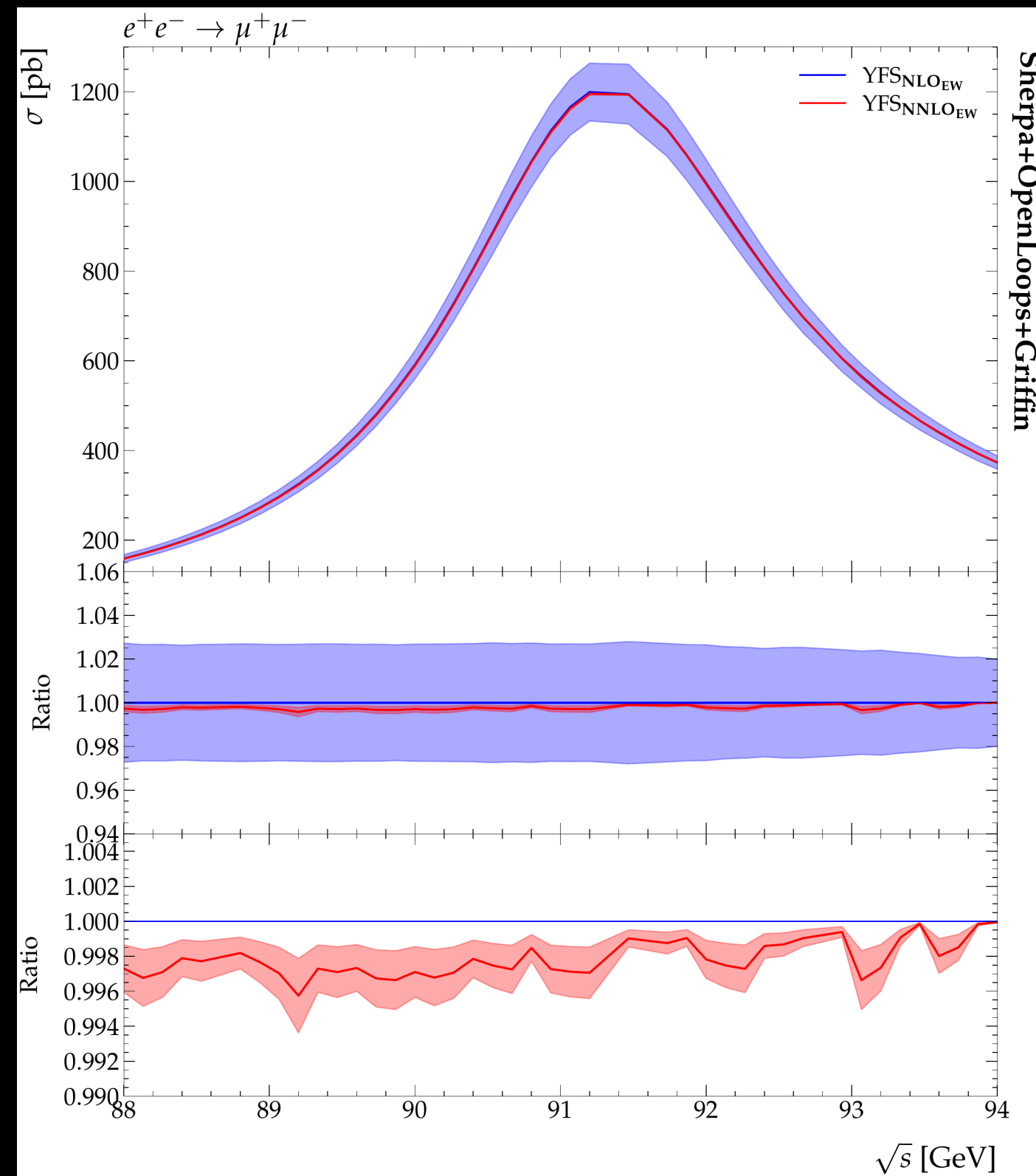
Gearing up for Future Colliders — Workshop on Radiative Corrections at Future Lepton Colliders

June 29, 2026 to July 3, 2026
CERN

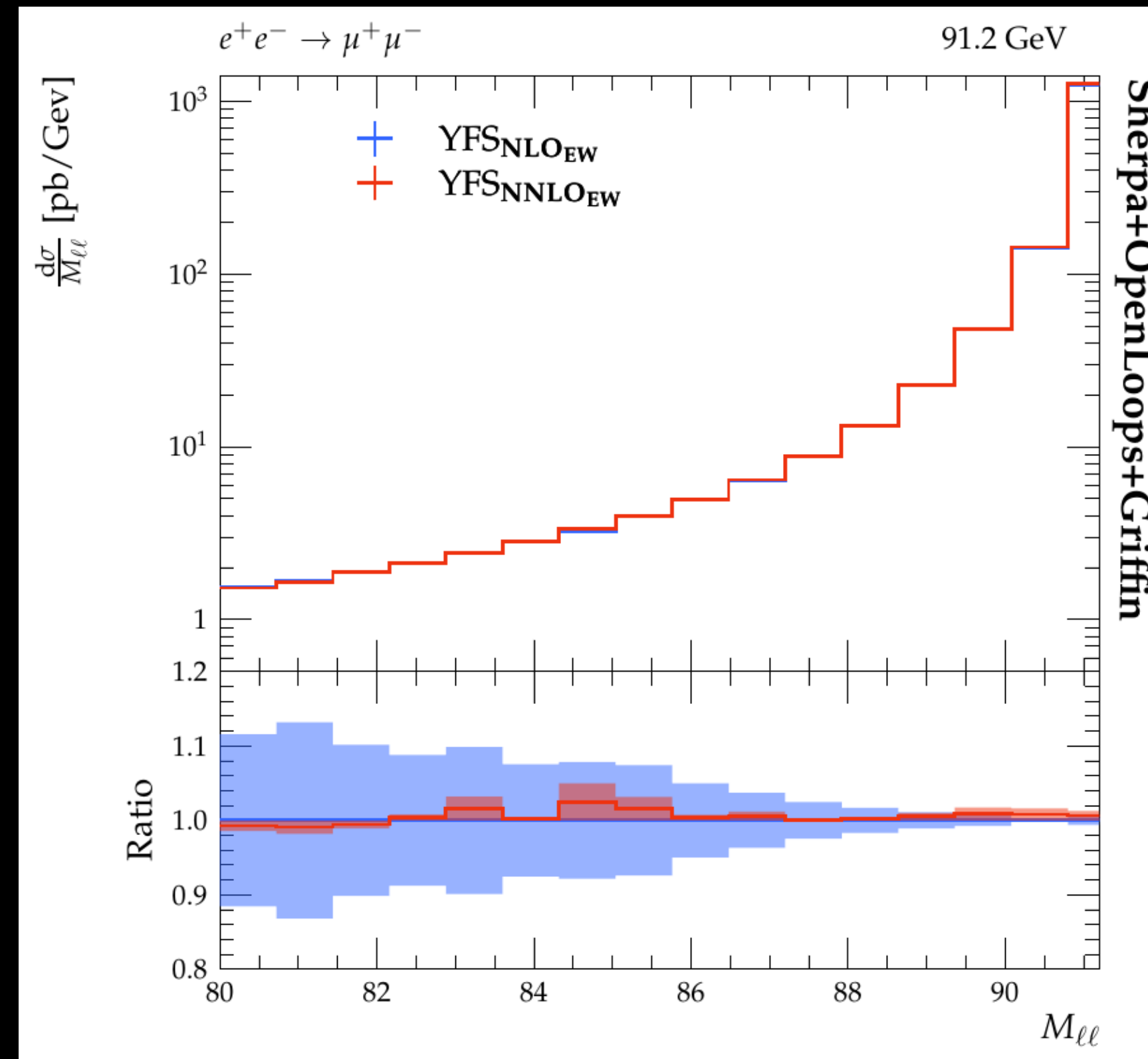
Recent precision calculations

(only a subset, non-exhaustive)

$NNLO_{EW}$ at the Z pole: first results



$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ across the Z pole: YFS_NLO_EW (blue) vs YFS_NNLO_EW (red) with perturbative uncertainty bands



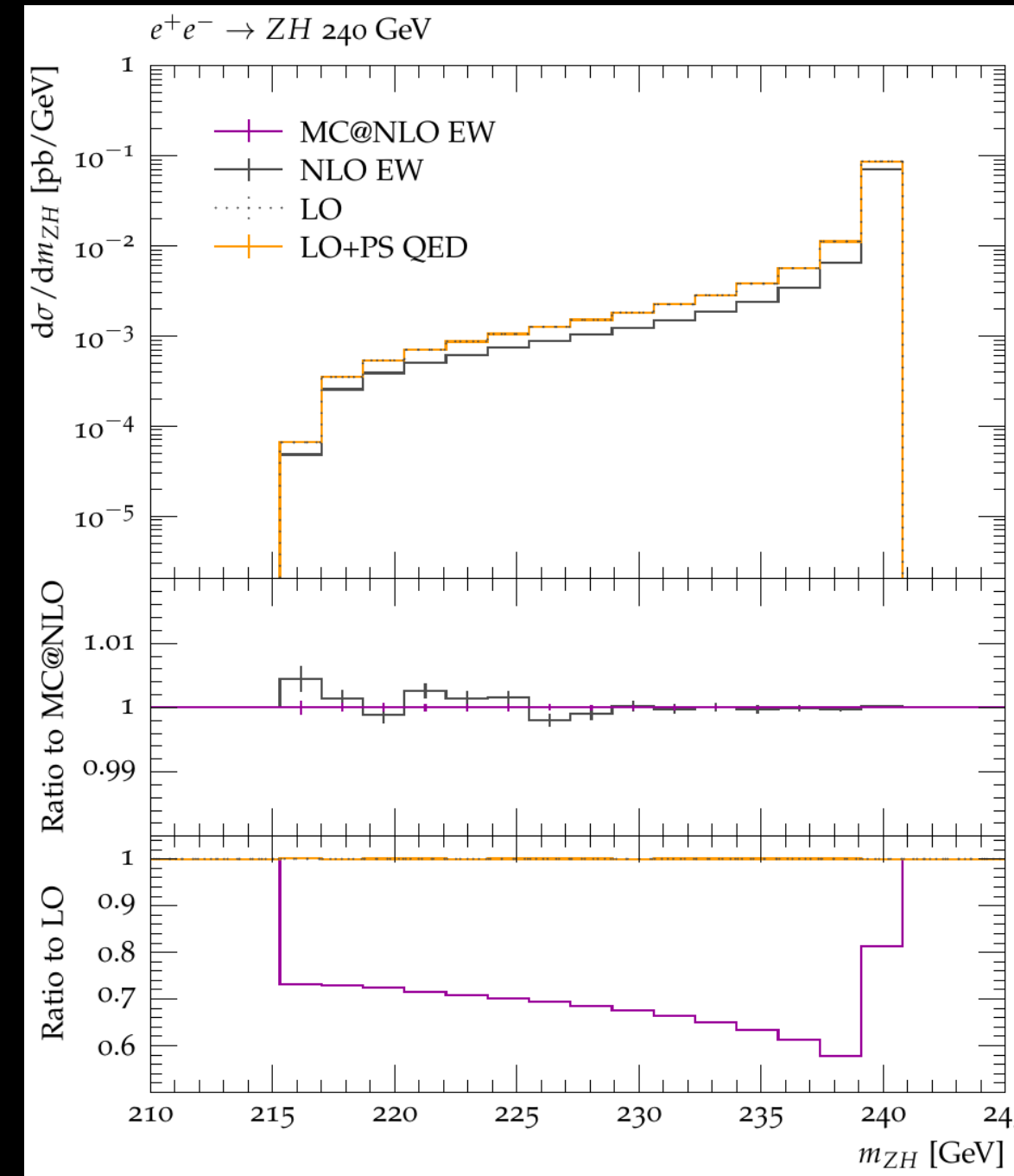
Differential $\mu^+\mu^-$ invariant mass at 91.2 GeV — band shrinks at $NNLO_{EW}$

- Benchmark: $e^+e^- \rightarrow \mu^+\mu^-$ in the Z-pole region — the Tera-Z workhorse
- $NNLO_{EW}$ -matched predictions show visibly reduced theory uncertainty vs NLO_{EW}
- Stable IR behavior across phase space; consistent with known fixed-order results
- On the road to production use:**
 - Process-by-process two-loop (double-virtual) input — the community bottleneck; automating two-loop EW amplitudes is the next frontier
 - Systematic combination with QCD corrections for hadronic final states
 - Interface to full event simulation in Key4hep workflows

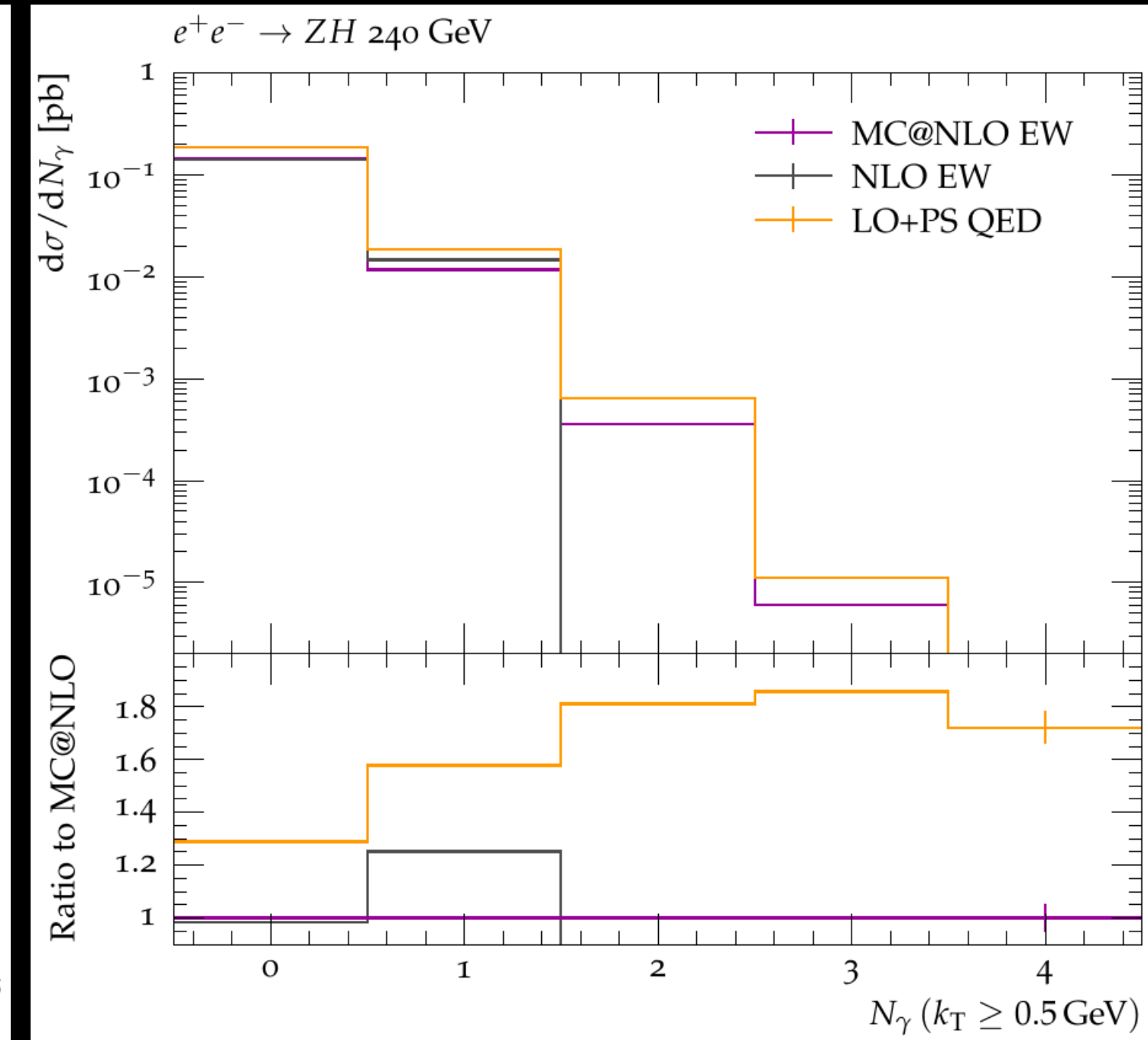
[arXiv:2512.04959](https://arxiv.org/abs/2512.04959);
two-loop status:
[arXiv:2606.22007](https://arxiv.org/abs/2606.22007)

$e^+e^- \rightarrow ZH$ at NLO EW matched to a QED parton shower

- First automated, process-independent NLO-EW-matched QED parton shower for e^+e^- colliders (2026)
- MC@NLO-style matching removes double counting between fixed-order NLO EW and shower emissions
- **Results: Higgs-strahlung with on-shell Z at both relevant FCC-ee stages**
 - $\sqrt{s} = 240$ GeV (ZH maximum) and 365 GeV — NLO EW + PS accuracy
 - Radiation modeling feeds directly into the recoil-mass method for measuring g_{HZZ}



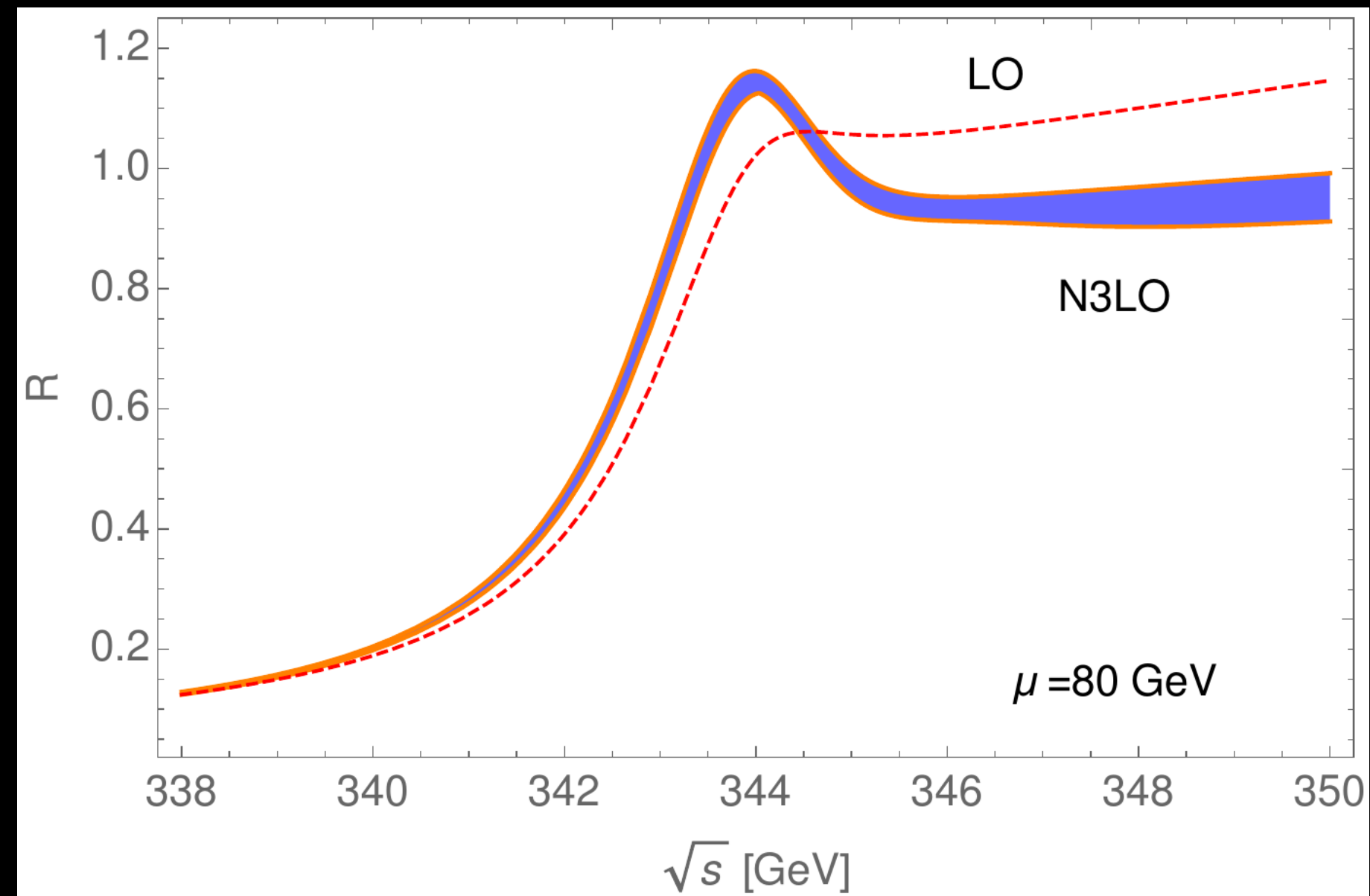
ZH invariant mass at 240 GeV: MC@NLO EW vs NLO EW vs LO(+PS)



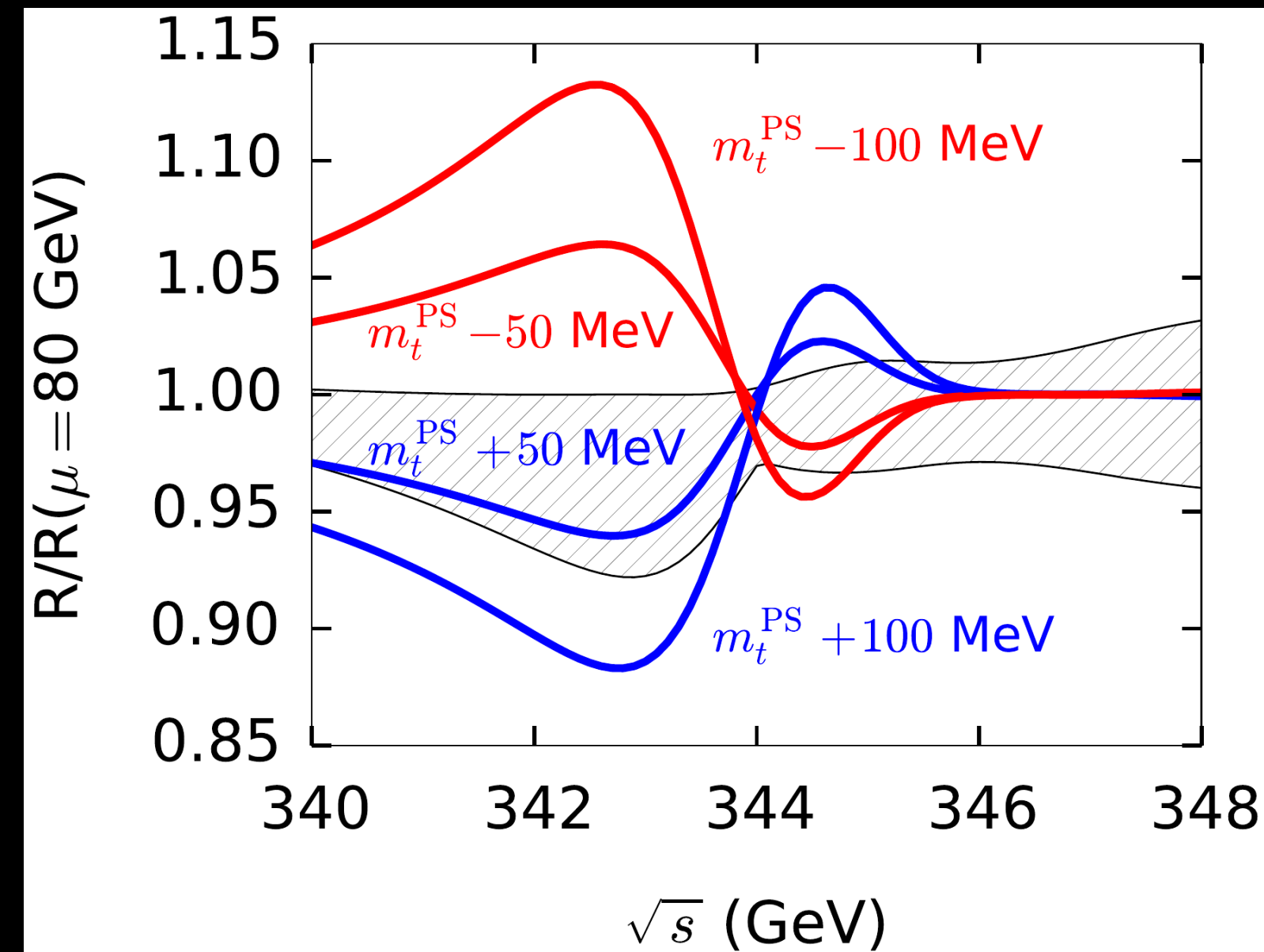
Photon multiplicity ($k_T > 0.5$ GeV) with shower

Both plots: $e^+e^- \rightarrow ZH$, $\sqrt{s} = 240$ GeV, Sherpa. The recoil-mass observable inherits its shape from exactly these radiative tails.

Top-quark threshold: fixed order reaches N³LO



$t\bar{t}$ threshold cross section (R -ratio) at N³LO in PNRQCD; band = scale variation $\mu \in [50, 350]$ GeV; LO dashed — Beneke et al.



Sensitivity: relative change for $m_t^{PS} \pm 50, \pm 100$ MeV vs N³LO scale band

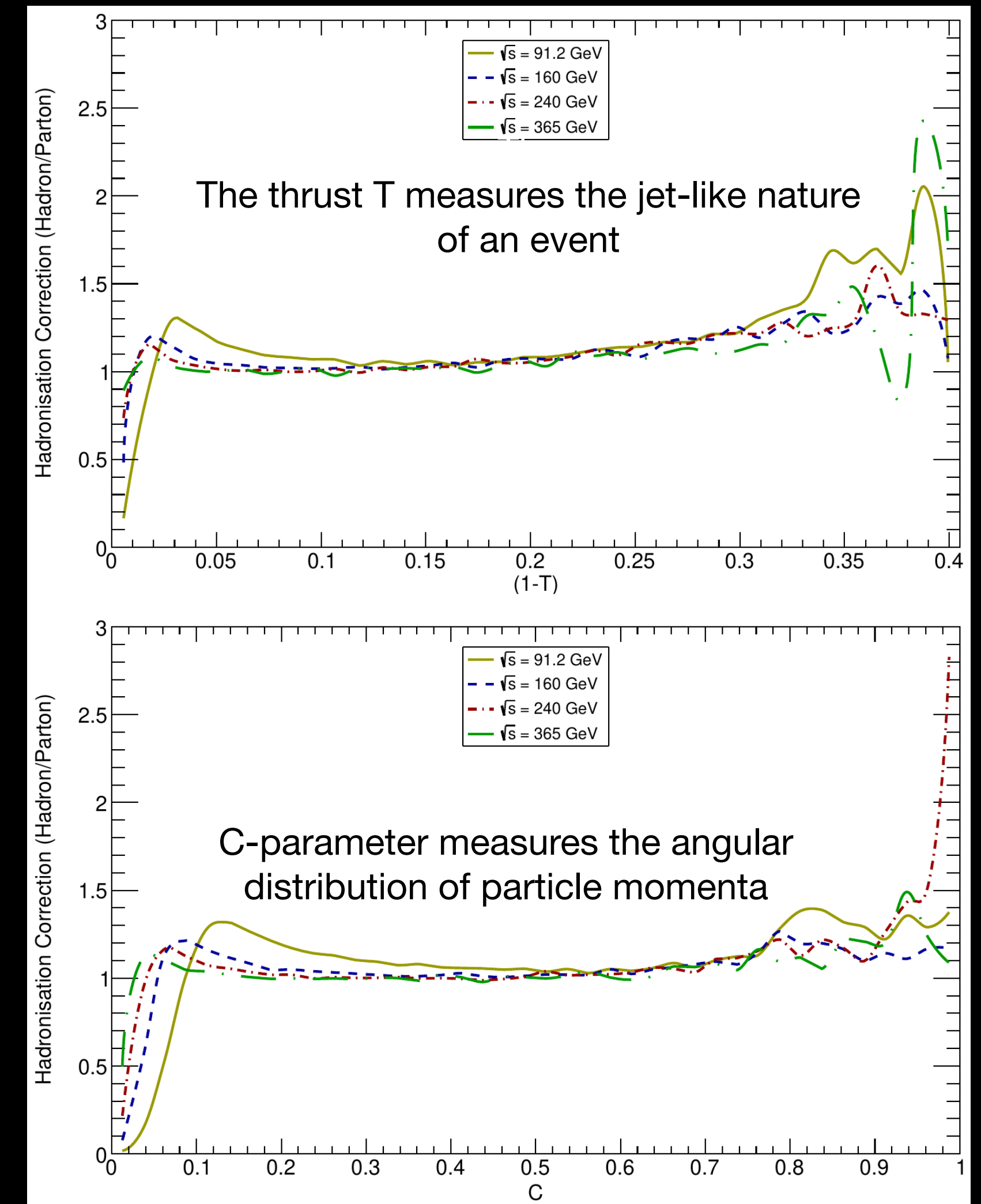
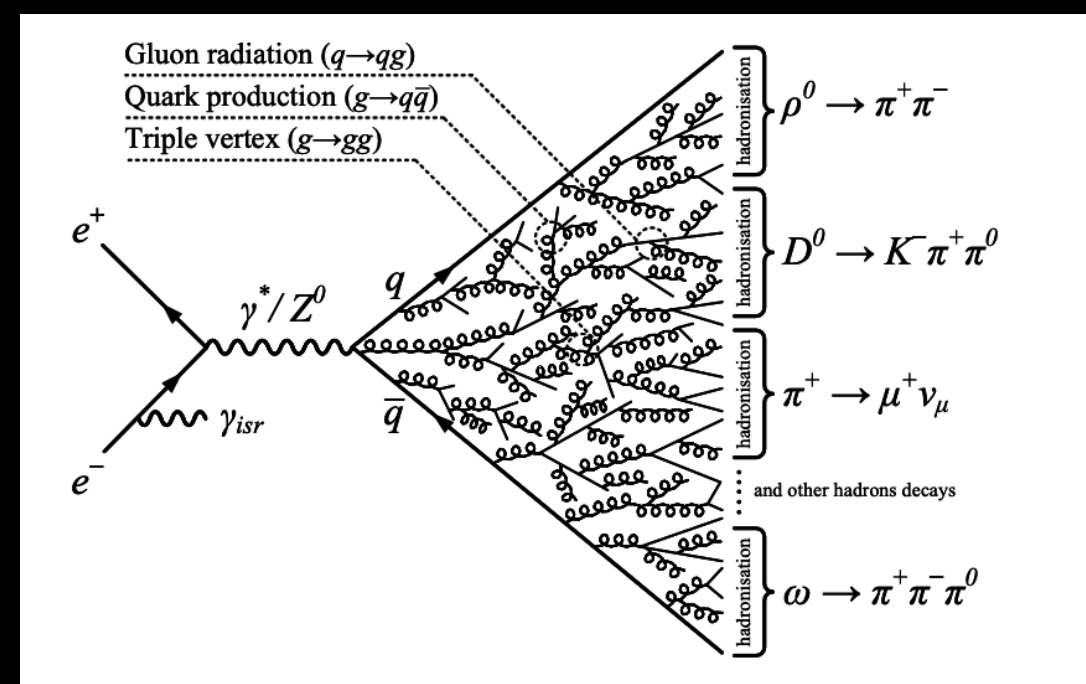
- FCC-ee- $t\bar{t}$: threshold scan targets m_{top} to O(10–20 MeV) — needs the $t\bar{t}$ excitation curve at matching precision
- N³LO threshold production in PNRQCD — effective-theory setup + matching coefficients; resums Coulomb (α_s/v) physics
- Apr 2026: resonance- & width-aware NLO+PS for $e^+e^- \rightarrow W^+W^-b\bar{b}$ near threshold (Alaric/Sherpa, 2604.13978)

- ISR + beamstrahlung convolution (dominant shape distortion of the turn-on)
- EW / non-resonant corrections and full 6-fermion final states

Beneke et al., JHEP 2025
([arXiv:2409.05960](https://arxiv.org/abs/2409.05960)); [arXiv:1506.06864](https://arxiv.org/abs/1506.06864);
generator status: [arXiv:2412.06605](https://arxiv.org/abs/2412.06605),
[2606.22007](https://arxiv.org/abs/2606.22007)

Hadronization & color reconnection — the non-perturbative wall

- All mainstream hadronization models (string, cluster) anchored to LEP-era tunes — extrapolation across FCC-ee
- **Color reconnection**
 - Dominant theory systematic for m_W from W^+W^- at threshold (the LEP story, at $\times 10^3$ the statistics)
 - New CR model shipped in Sherpa 3; CR remains phenomenological
- Heavy-flavor fragmentation: b/c spectra critical for the flavor program and $H \rightarrow b\bar{b}, c\bar{c}$
- Top-mass interpretation: CR effects couple hadronization to the threshold-scan systematics
- What FCC-ee itself provides: Tera-Z = the ultimate tuning dataset (identified spectra, flavor-tagged event shapes, multiplicities)



Hadronisation correction factors to $(1-T)$ and C at the FCC-ee energies (Pythia 8.313) — the size of what the model must get right — arXiv:2511.23103

[arXiv:2410.22148](https://arxiv.org/abs/2410.22148); [arXiv:2606.22007](https://arxiv.org/abs/2606.22007) and refs. therein

Recent event generator developments

(only a subset, non-exhaustive)

KKMCee 5.00 — the LEP flagship, rebuilt for FCC-ee

- Version 5.00: complete rewrite in C++
- HepMC3 event record → Key4hep-friendly; KkeeFoam companion for semi-analytical validation
- Physics: coherent exclusive exponentiation (CEEX) of multi-photon emission, $O(\alpha^2)$ precision established at LEP2 ($\sim 0.2\%$)
- Ongoing: IR-improved amplitude-based resummation (Ward et al. 2026)

$v_{\max}$	$\sigma(v_{\max})$ (pb)		$A_{\text{FB}}(v_{\max})$	
	KKMC 4.13	KKMCee 5.00	KKMC 4.13	KKMCee 5.00
0.10	2.5967 ± 0.0027	2.6015 ± 0.0001	0.5922 ± 0.0012	0.5931 ± 0.0001
0.30	3.1190 ± 0.0029	3.1236 ± 0.0001	0.5856 ± 0.0011	0.5864 ± 0.0001
0.50	3.4203 ± 0.0029	3.4250 ± 0.0001	0.5863 ± 0.0010	0.5970 ± 0.0000
0.70	3.7596 ± 0.0030	3.7641 ± 0.0001	0.5947 ± 0.0009	0.5953 ± 0.0000
0.90	7.1780 ± 0.0030	7.1849 ± 0.0001	0.3170 ± 0.0005	0.3174 ± 0.0000
0.99	7.6542 ± 0.0029	7.6596 ± 0.0001	0.2912 ± 0.0004	0.2917 ± 0.0000

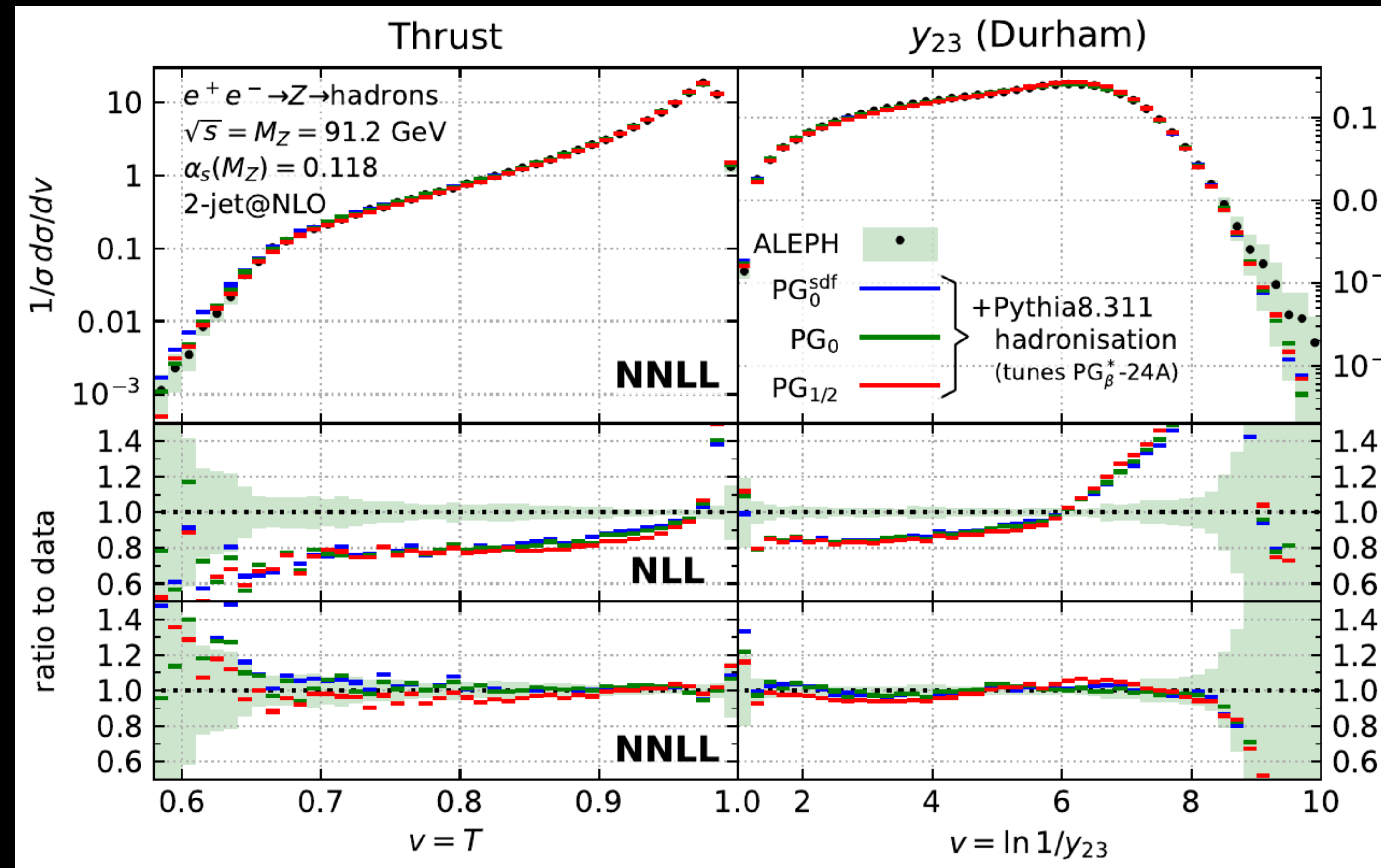
Total Cross Section (σ) and charge asymmetry (A_{FB}) as a function of photon energy fractions ($v_{\max}$). The C++ rewrite reproduces the legacy code — [arXiv:2410.07294](https://arxiv.org/abs/2410.07294)

[arXiv:2410.07294](https://arxiv.org/abs/2410.07294); resummation status: [arXiv:2604.26124](https://arxiv.org/abs/2604.26124)

Parton showers: increase logarithmic accuracy

14

- PanScales targets NNLL-accurate parton showers — a new standard for the field
- May 2025: the systematic recipe — NLO-accurate 3-jet + NNLO-accurate 2-jet structure embedded in the shower; consistent recoil & color
- April 2025: logarithmically-accurate and positive-definite NLO matching



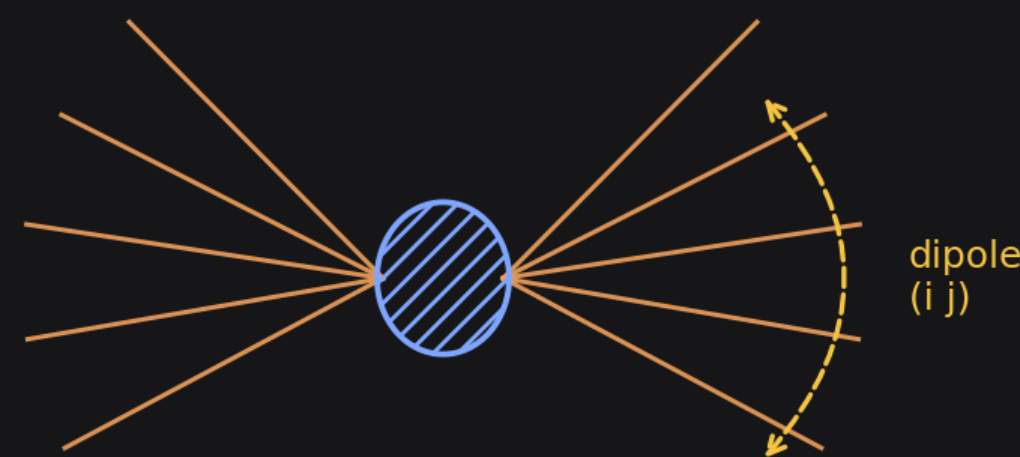
PanGlobal NNLL vs NLL showers (+ Pythia 8 hadronisation) against ALEPH thrust and Durham y_{23} (three-jet resolution)

[arXiv:2406.02661](https://arxiv.org/abs/2406.02661); [arXiv:2505.13395](https://arxiv.org/abs/2505.13395); [arXiv:2504.05377](https://arxiv.org/abs/2504.05377)

Beyond leading color: amplitude evolution (CVolver)

- **CVolver evolves amplitudes, not probabilities: cross sections → density operators, kernels → “Hamiltonians”; soft-gluon evolution at full color, real and virtual**
- Real emission beyond dipoles (“strings”, “rings”); virtual colour mixing (N^{-2} , N^{-1} colour swaps) — not obtainable from probabilistic unitarity
- **Color reconnection $\approx$ perturbative colour mixing (our m_W systematic from $W^+W^- \rightarrow 4q$) · shower $\leftrightarrow$ hadronization boundary (same interplay 2605.02622 found decisive) · non-global logs & jet vetoes**

Dipole shower (leading colour)

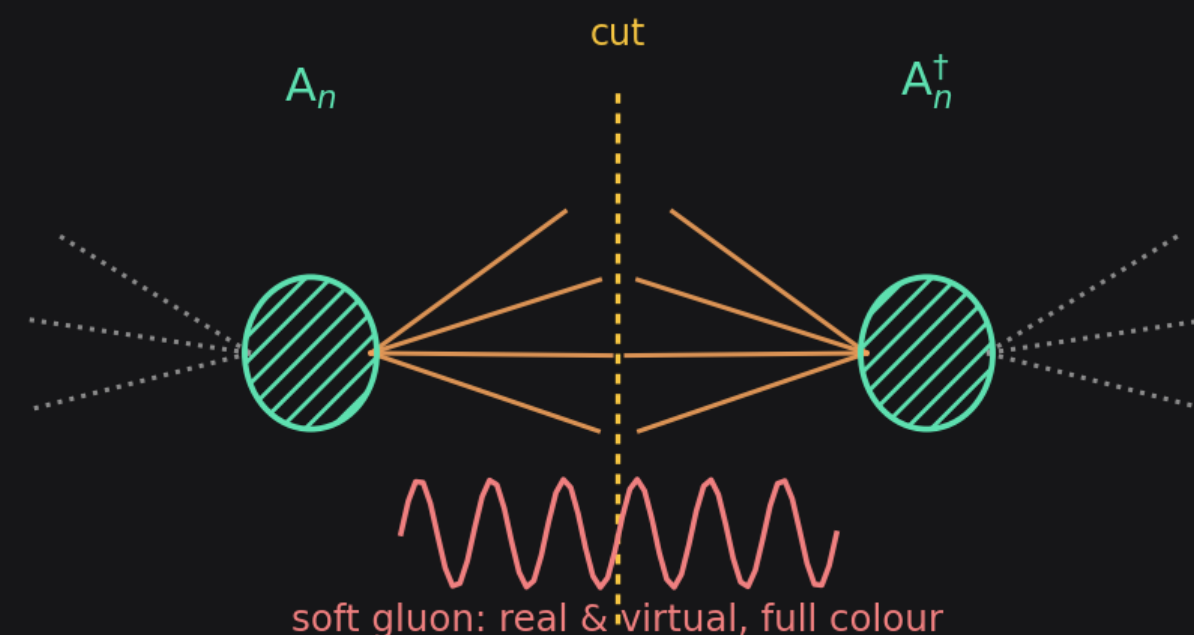


each emission from one colour dipole (i j)
probability $\propto \omega_{ij}$

interferences outside colour-connected
dipoles dropped: suppressed by $1/N^2$...
but $\alpha_s N^2 \sim \alpha_s L \sim 1$ when logs are large

Pythia · Herwig · Sherpa · PanScales (LC / NODS)

CVolver: amplitude evolution



$$\sigma \sim \sum_n \alpha_s^n \int \text{Tr}[\mathbf{A}_n(\mu_S) \mathbf{S}_n(\mu_S)] d\phi_n$$

$$\mathbf{A}_n(q) = \int_q^Q \frac{dk}{k} \mathbf{P} e^{-\int_q^k \frac{dk'}{k'} \Gamma(k')} \times$$

$$\mathbf{D}_n(k) \mathbf{A}_{n-1}(k) \mathbf{D}_n^\dagger(k) \bar{\mathbf{P}} e^{-\int_q^k \frac{dk'}{k'} \Gamma(k')}$$

cross sections → density operators · kernels → “Hamiltonians”
virtual Γ = dipole + N^{-2} + N^{-1} colour swaps
real emission beyond dipoles: “strings”, “rings”

Forshaw, Holguin, Plätzer, De Angelis, Torre Gonzalez et al.

What full color gives us

Non-global logs

soft wide-angle radiation between jets at full colour, including interferences

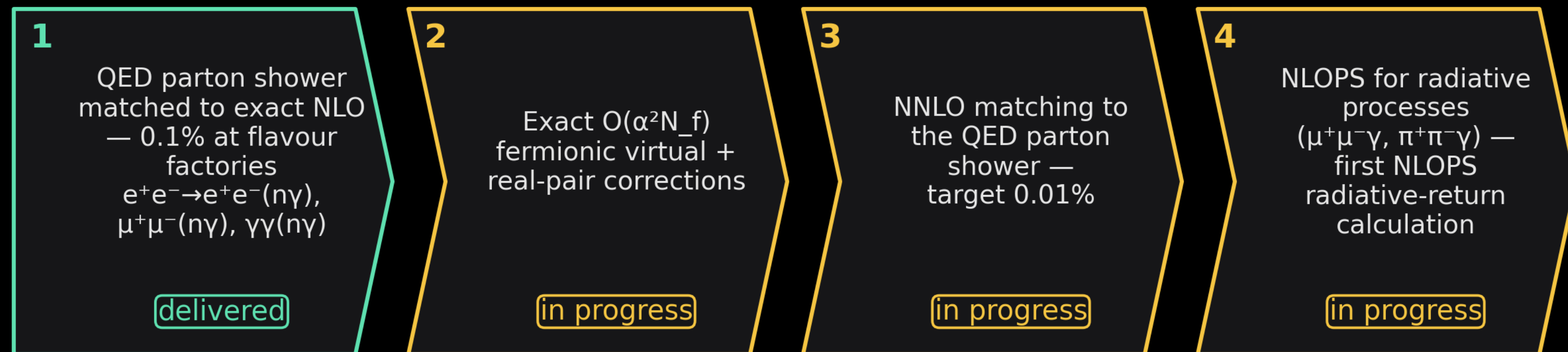
Color reconnection

Geometric CR models $\approx$ perturbative colour mixing → CVolver can predict CR-sensitive observables

BabaYaga@NLO: 25 years, and a roadmap to 10^{-4}

- QED parton shower matched to exact NLO — 0.1% theoretical accuracy at flavor factories; $e^+e^- \rightarrow e^+e^-(n\gamma)$, $\mu^+\mu^-(n\gamma)$, $\gamma\gamma(n\gamma)$ — both luminosity channels covered
- At FCC-ee: radiative corrections $O(1-2\%)$ in the $\gamma\gamma$ angular distributions must be controlled to 10^{-4} relative
- In progress toward the FCC-ee target: NNLO matching to the QED shower (0.01%); exact $O(\alpha^2 N_f)$ fermionic virtual + real-pair corrections; NLOPS for radiative processes ($\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$) — first NLOPS-accurate radiative-return calculation
- **BabaYaga (PS-matched) (for comparison: BHLUMI (YFS) and McMule (fixed-order NNLO))**

BabaYaga@NLO — road to 10^{-4} (F. P. Ucci, arXiv:2601.11204)



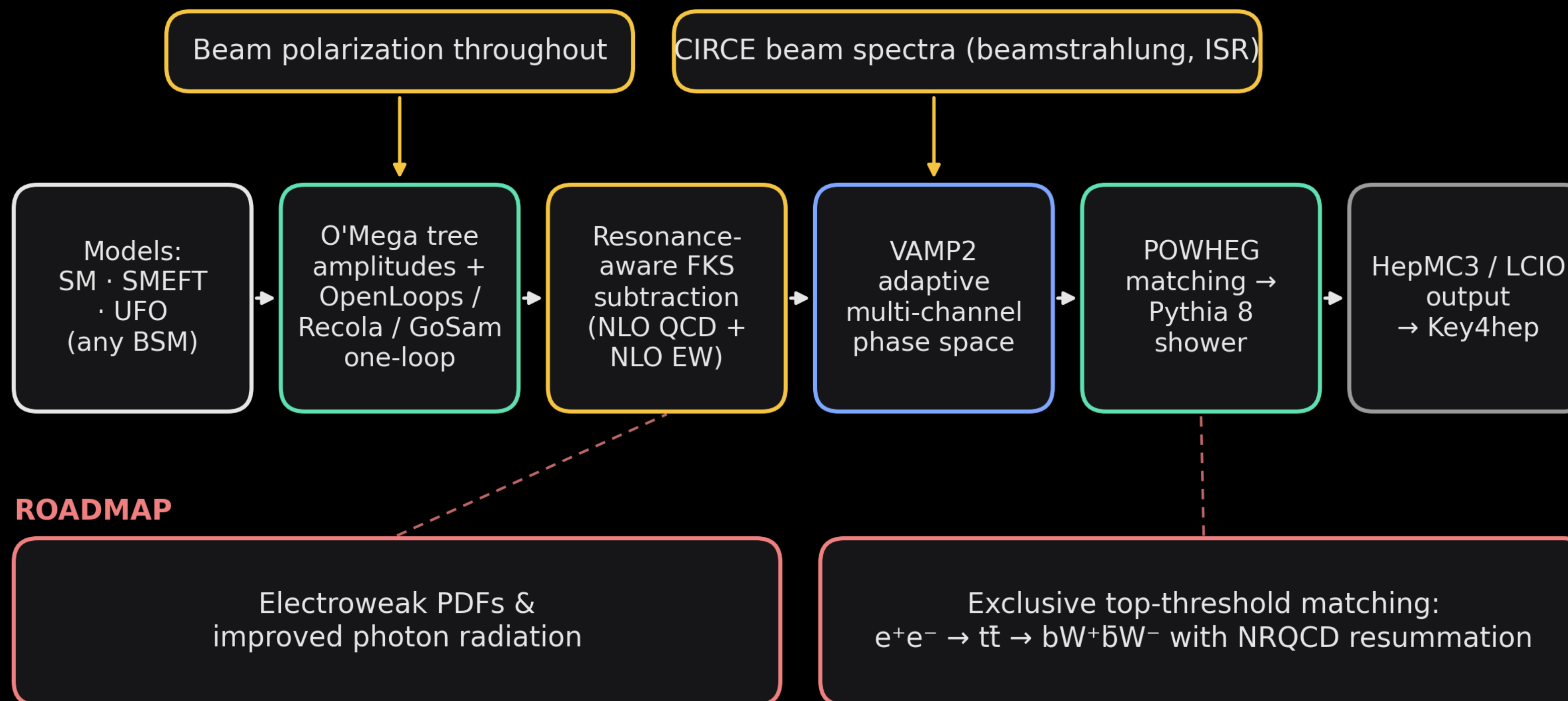
Complementary handles on the same 10^{-4} budget:
BabaYaga (PS-matched) · BHLUMI (YFS) · McMule (fixed-order NNLO)

WHIZARD: NLO EW automation, SMEFT, and the top threshold

- NLO EW automation for lepton-collider processes — extended to BSM, including SMEFT; loop-induced processes; modernized UFO interface
- Resonance-aware FKS subtraction; one-loop amplitudes from OpenLoops / Recola / GoSam; POWHEG matching
- Beam spectra via CIRCE; polarization support throughout — long-standing lepton-collider strengths
- Roadmap items aimed directly at FCC-ee: electroweak PDFs + improved photon radiation; exclusive top-threshold matching ($e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$ with threshold resummation in the full process)
- Fixed-order $N^3\text{LO}$ threshold input now exists

WHIZARD generator stack

Reuter et al., arXiv:2412.06605

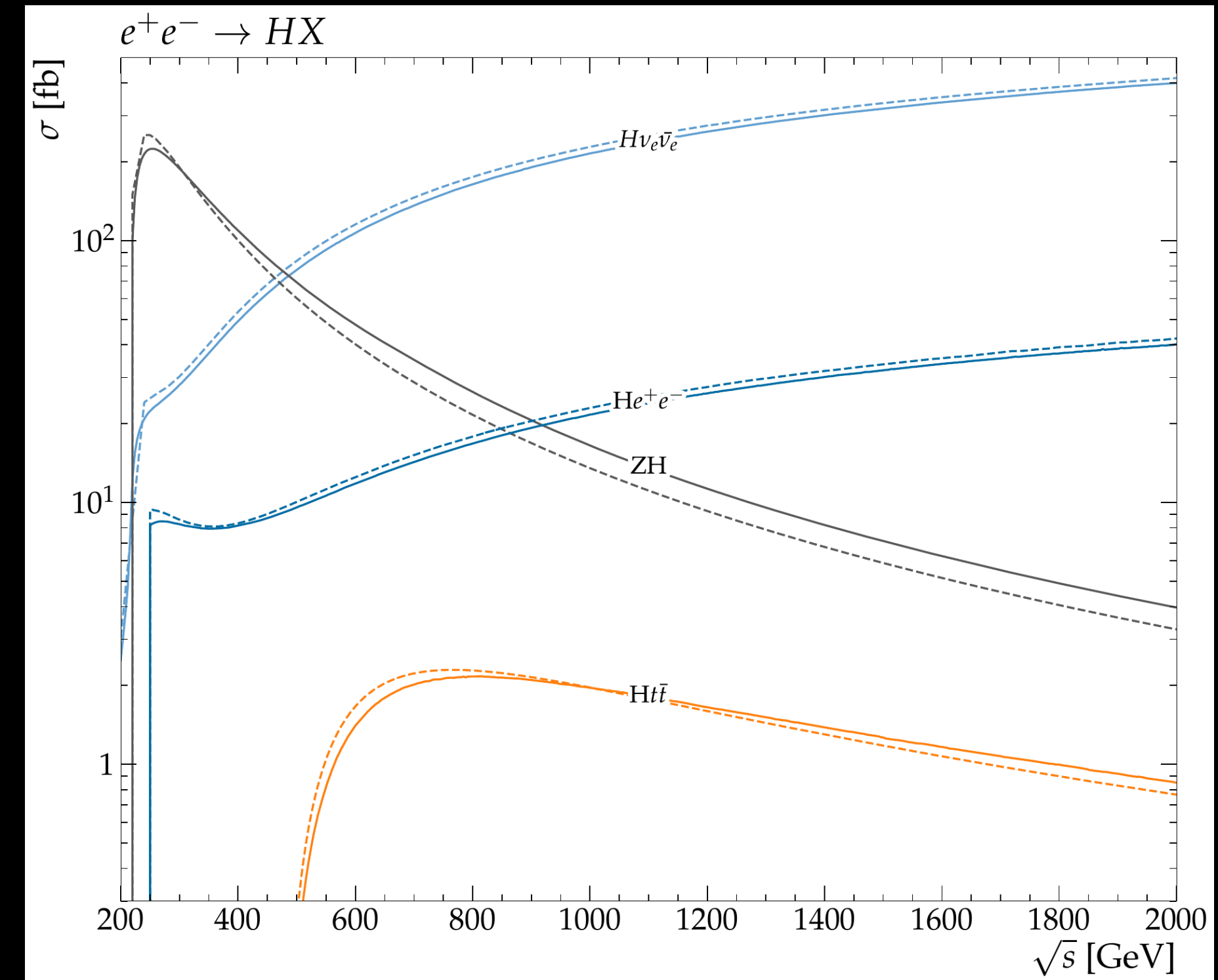


Sherpa 3

- Sherpa 3 release series (Oct 2024) — the platform on which the YFS NNLO_EW automation now runs
- **Physics additions most relevant to e^+e^-**
 - Higher-order EW: EW virtual approximation, full NLO EW workflows
 - Spin-polarized cross sections — bookkeeping for polarization-aware studies
 - New color-reconnection model + refined hadronization: impacts m_W -at-threshold systematic
 - Improved YFS QED radiation in production and decay; photoproduction; NLO multijet merging with heavy-flavor matching
- **General-purpose base (Sherpa 3) + precision layer (YFS $NNLO_{EW}$, NLO_{EW} -matched QED shower) in place**



LHC Workhorse

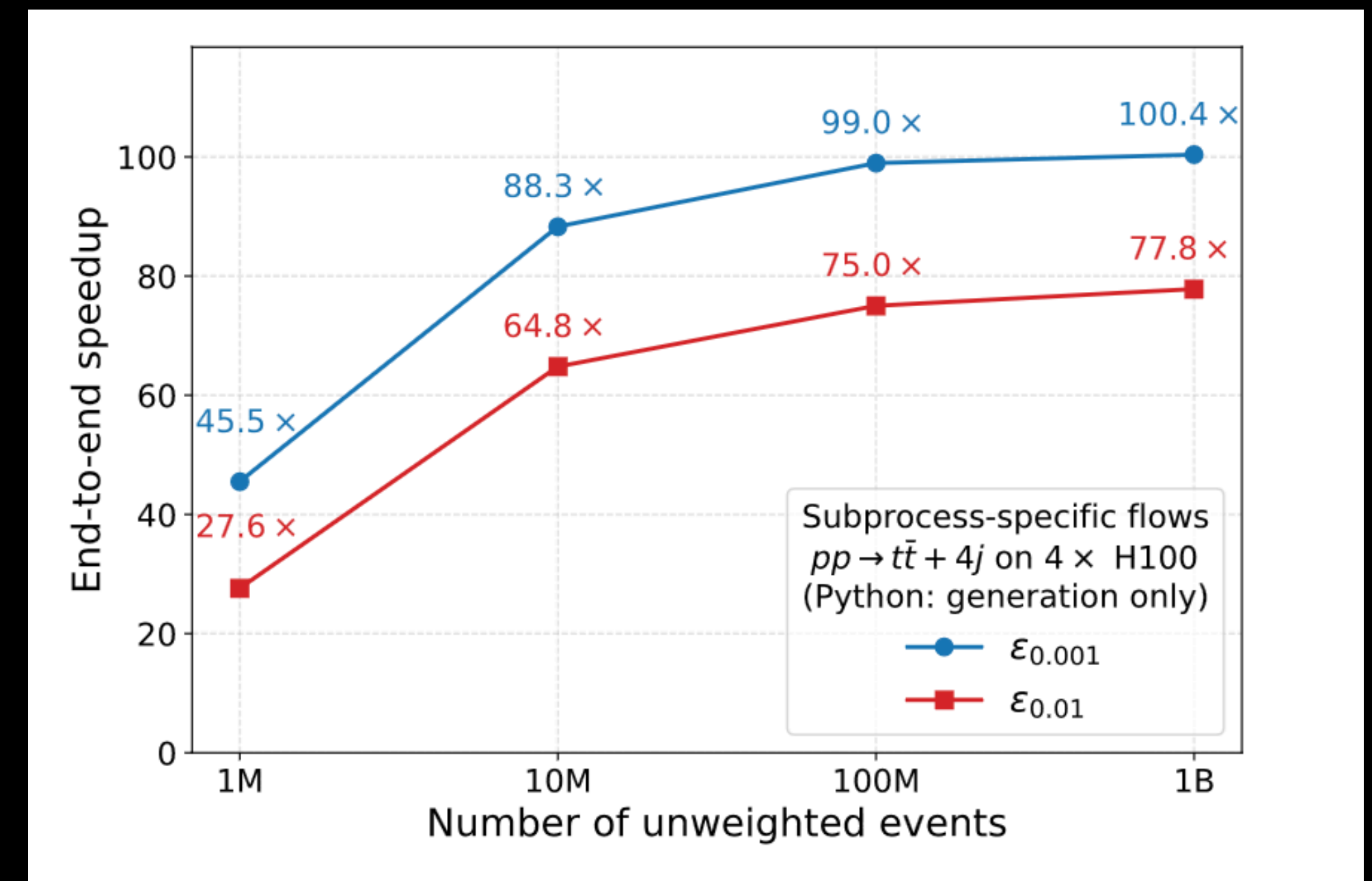


$e^+e^- \rightarrow HX$ cross sections vs $\sqrt{s}$: Born (dashed) vs with YFS ISR (solid) — Sherpa 3

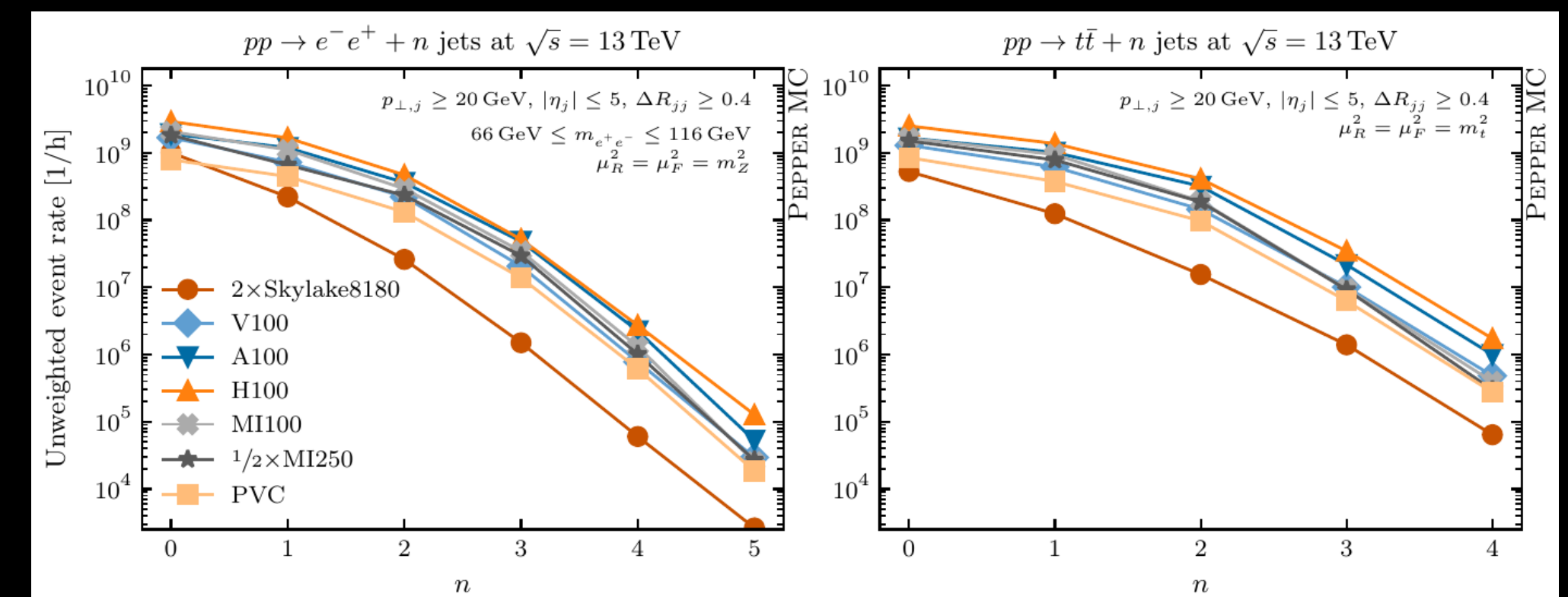
Radiation moves cross sections by tens of percent before any detector sees anything.

Event generation on GPUs

- MadSpace: phase-space generation re-designed for the GPU/ML era — sampling, mappings and unweighting built GPU-native from the start
- Lessons flowing directly from LHC production to e^+e^- workflows
- Why FCC-ee needs it: $\sim 6 \times 10^{12}$ Z events $\rightarrow$ simulated samples at unprecedented scale; generator CPU budget becomes a physics limitation (“MC statistics” as a systematic)
- Precision $\times$ volume is the real challenge: NNLO-level weights, negative-weight fractions and unweighting efficiency all interact with throughput
- HPC synergy: parton-level generation is parallel — a natural fit for DOE/NSF facilities



Pepper+Flow: end-to-end unweighted event generation $t\bar{t} + 4$ jets)
Extends to 5 initial state particles. Improvements with respect to VEGAS



Pepper: unweighted event generation + storage rates across CPU and GPU architectures ($e^+e^- + n$ jets left, $t\bar{t} + n$ jets right)

Pepper+Flow: [arXiv:2608.21338](https://arxiv.org/abs/2608.21338)

Pepper: [arXiv:2311.06198](https://arxiv.org/abs/2311.06198)

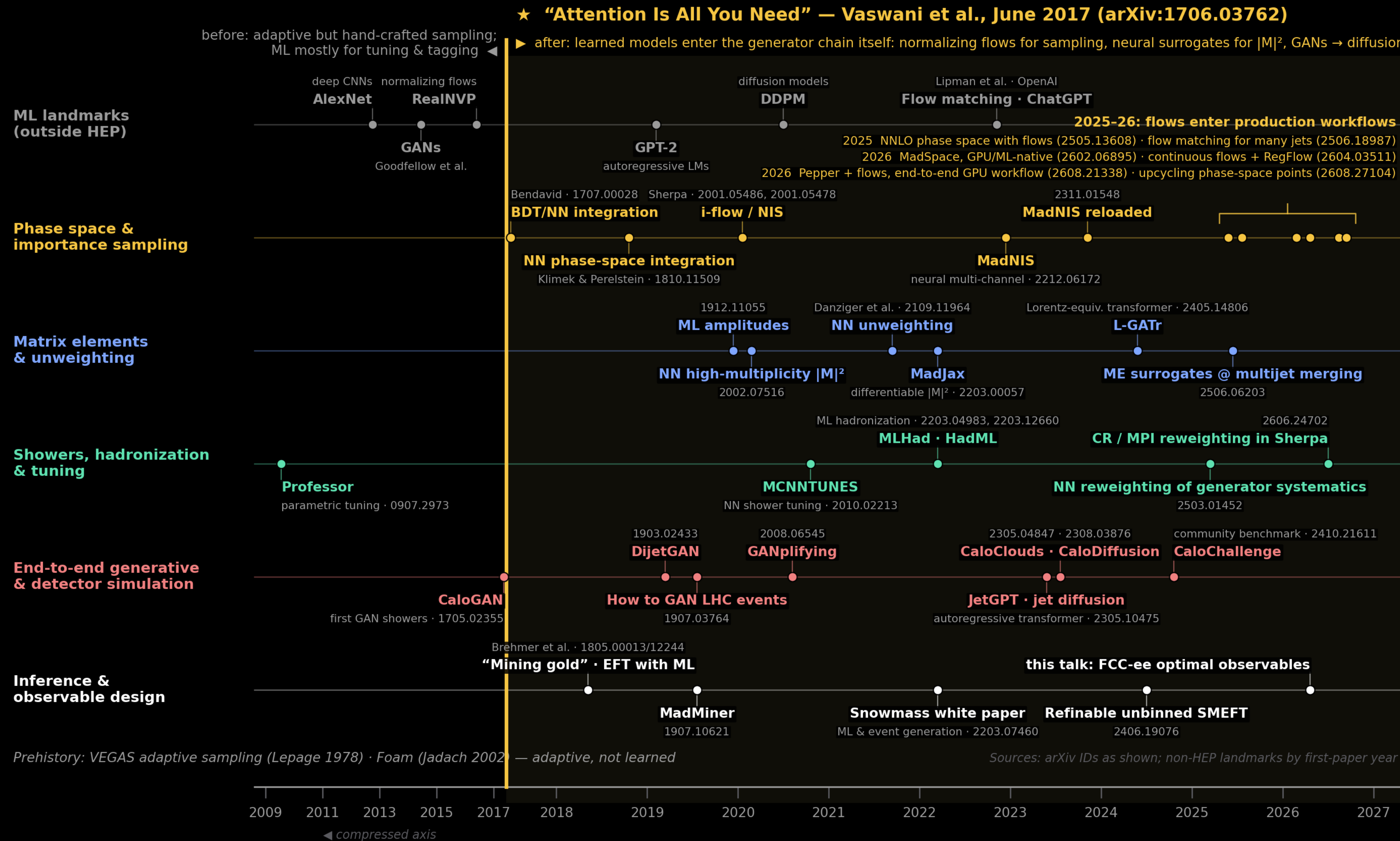
Madgraph4GPU: [arXiv:2303.1824](https://arxiv.org/abs/2303.1824)

MadSpace: [arXiv:2602.06895](https://arxiv.org/abs/2602.06895)



LHC Workhorse

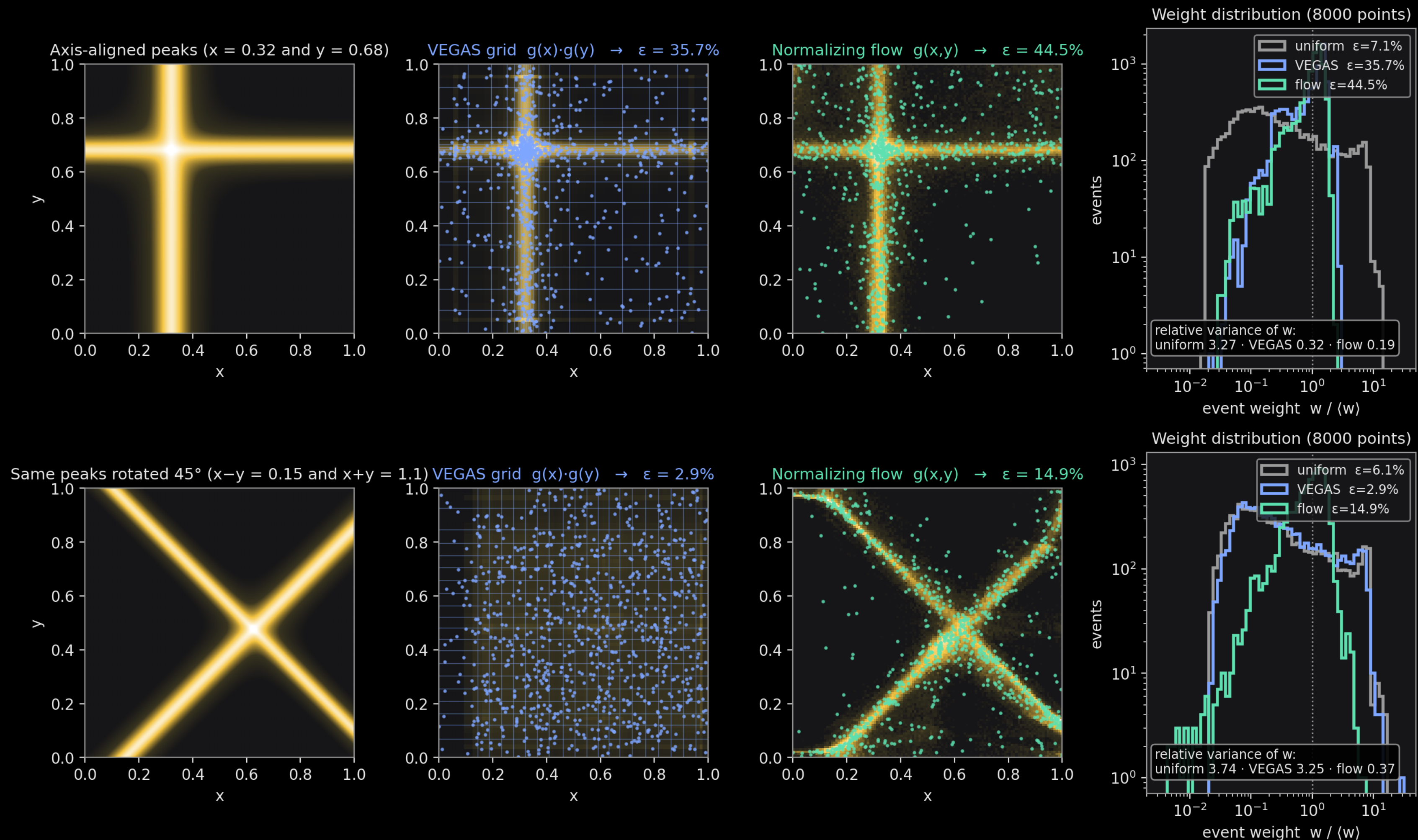
AI/ML in event generators — a timeline



★ Pepper + flow results shown on previous slide

Reading the picture: before June 2017, adaptive but hand-crafted sampling and ML only for tuning; after it, learned models entered every stage of the chain — each lane trailing its ML landmark by ~2–3 years. Pre-2017 axis compressed.

Phase-space sampling: VEGAS vs. a normalizing flow



VEGAS (1978)

Adapts a 1D grid per coordinate $\rightarrow$ density is a product $g_1(x) \cdot g_2(y)$. Robust, needs no training — but blind to correlations; multi-channel VEGAS fixes this only with hand-built channels.

Normalizing flow (2019 $\rightarrow$)

A chain of invertible coupling layers; each coordinate's map is a small network conditioned on the others, so $g(x,y)$ can follow any shape. Exact density from the Jacobian; trained by minimizing the weight variance. i-flow, Pepper flow, MadNIS, MadSpace.

Same peaks, rotated 45°

Uniform 6% $\rightarrow$ VEGAS 3% $\rightarrow$ flow 15% unweighting efficiency; weight variance 3.3 $\rightarrow$ 0.37. For FCC-ee: resonances in 4- and 6-fermion final states are exactly such off-axis structures.

Toy computed for this talk

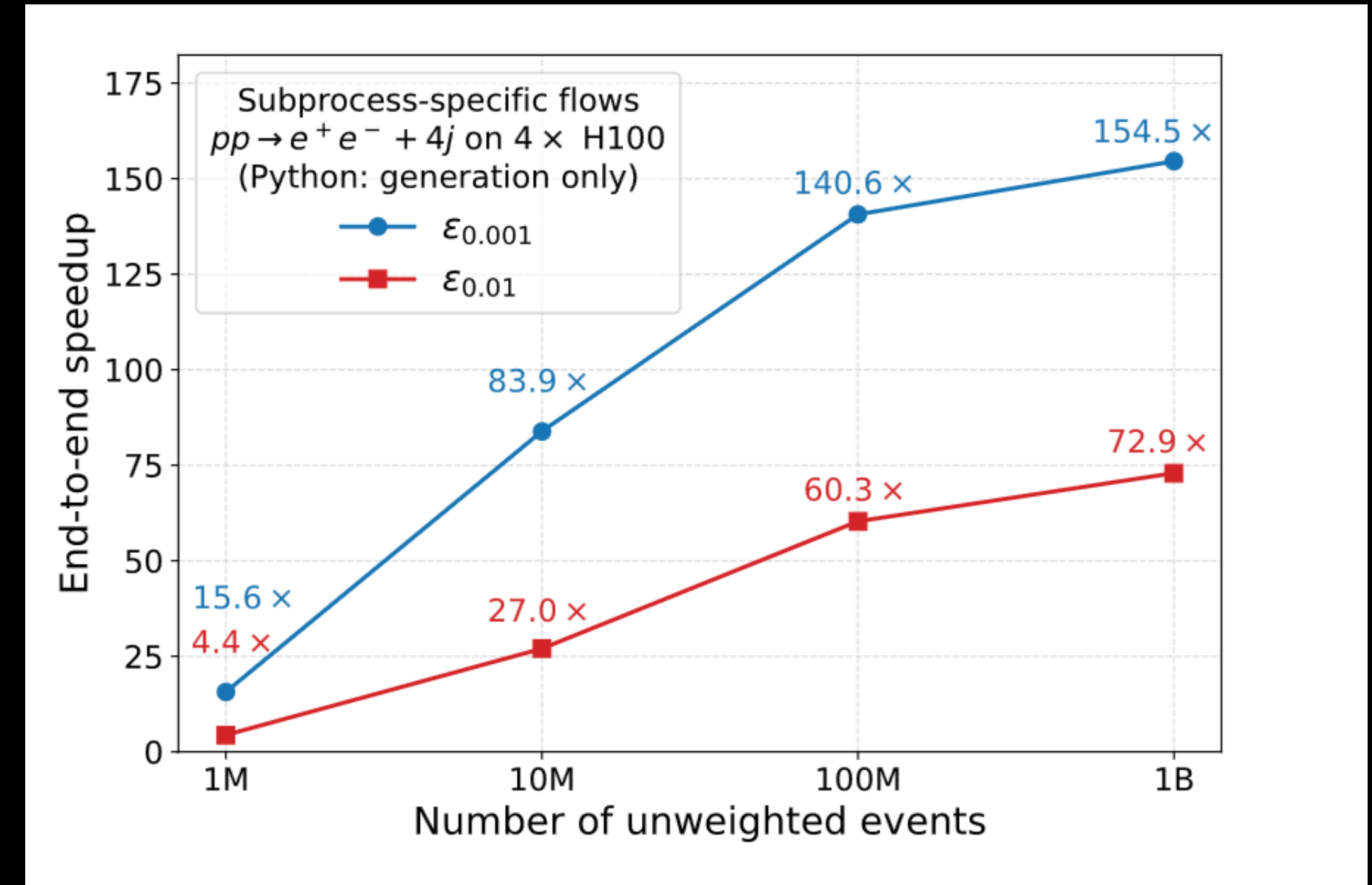
Lepage 1978; Müller et al. 2019

Pepper+Flow: [arXiv:2608.21338](https://arxiv.org/abs/2608.21338)

i-flow [2001.05486](https://arxiv.org/abs/2001.05486); MadNIS [2212.06172](https://arxiv.org/abs/2212.06172)

ML inside the generator

- Neural importance sampling mature
- Flow matching for many-jet events (2025): generative networks propose phase-space points for high-multiplicity processes — where classical sampling degrades fastest
- Neural matrix-element surrogates: fast, accuracy-controlled stand-ins for expensive amplitudes, with correction to exact results — relevant wherever two-loop-level evaluations are the cost driver
- The pattern: ML replaces the expensive inner loops (sampling, amplitude evaluation), exact physics restored by reweighting — precision is preserved, not traded away
- For FCC-ee central production: evaluate these now, in the Key4hep context, so the 2030s workflows are designed around them rather than retrofitted

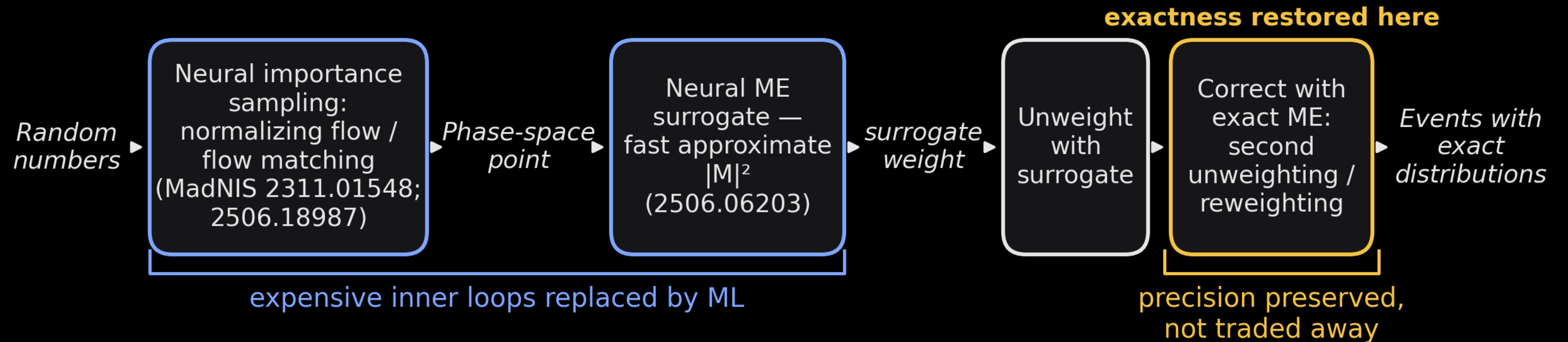


Unweighting efficiency for $pp \rightarrow e^+ e^- + 4$ gluons

Where classical sampling degrades fastest ($n \geq 3$), learned mappings recover orders of magnitude in efficiency.

[arXiv:2608.21338](https://arxiv.org/abs/2608.21338); [arXiv:2311.01548](https://arxiv.org/abs/2311.01548);
[arXiv:2506.18987](https://arxiv.org/abs/2506.18987); [arXiv:2506.06203](https://arxiv.org/abs/2506.06203)

ML inside the generator

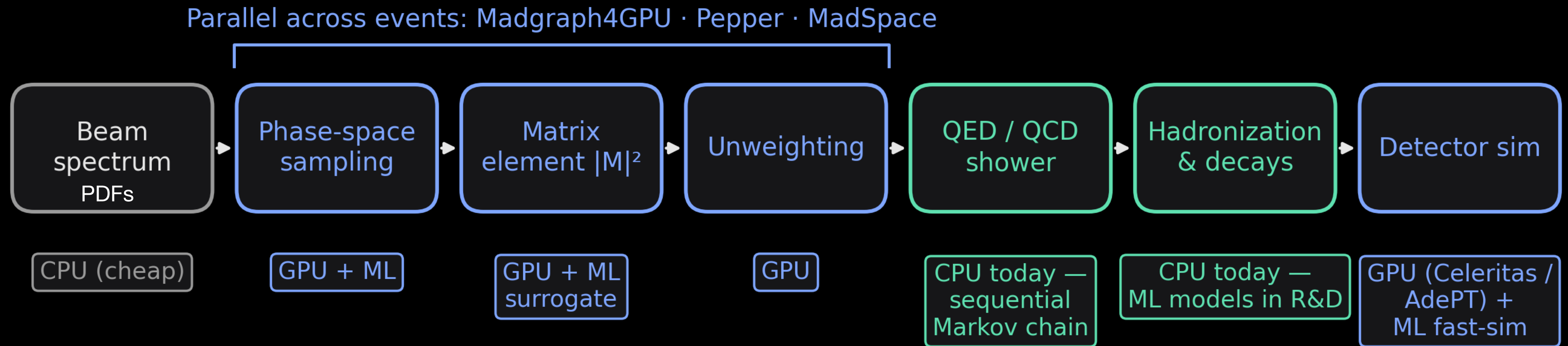


Where it matters: high-multiplicity final states,
two-loop-level amplitudes

- Blue boxes: the expensive inner loops (phase-space proposals, $|M|^2$ evaluation) are replaced by learned models
- Gold box: a second unweighting / reweighting against the exact matrix element restores exactness — precision is preserved, not traded away ([arXiv:2109.11964](#))
- Highest computational gains: High-multiplicity final states (6-fermion + photons + jets) and two-loop-level amplitudes, where the amplitude cost dominates

Pepper+Flow: [arXiv:2608.21338](#), Continuous normalizing flows: [2604.03511](#)
MadNIS: [arXiv:2311.01548](#); flow matching: [arXiv:2506.18987](#);
ME surrogates: [arXiv:2506.06203](#)

Where the chain can be offloaded



GPU: parton level

Phase-space sampling, $|M|^2$ evaluation and unweighting are independent per point — Madgraph4GPU, Pepper, MadSpace. Throughput gains of 10–100× per device; HPC allocations are the natural venue.

ML: sampling & surrogates

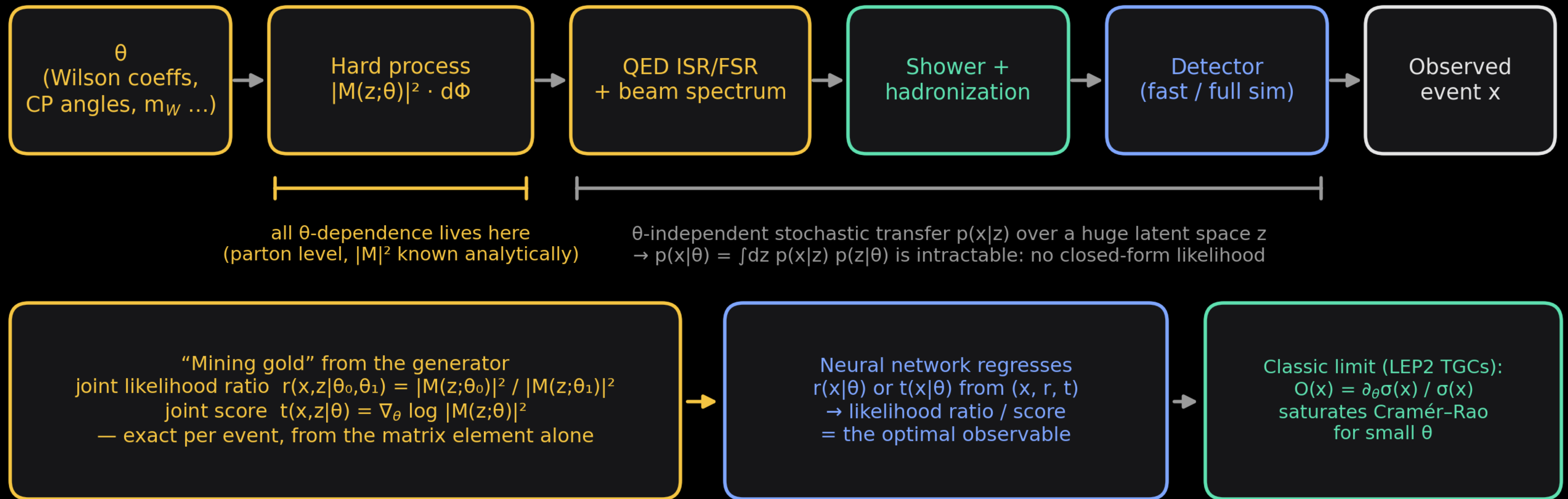
Normalizing flows / flow matching raise unweighting efficiency at high multiplicity; neural ME surrogates cut amplitude cost. Exactness restored by a second unweighting or reweighting.

CPU today: shower & hadronization

Sequential Markov chains with data-dependent branching; small per-event work. Gains come from accuracy (NNLL) and tunes, not from GPUs. ML hadronization models are R&D.

[arXiv:2303.18244](https://arxiv.org/abs/2303.18244), [2311.06198](https://arxiv.org/abs/2311.06198), [2602.06895](https://arxiv.org/abs/2602.06895),
[arXiv:2506.18987](https://arxiv.org/abs/2506.18987), [2506.06203](https://arxiv.org/abs/2506.06203), [2608.21338](https://arxiv.org/abs/2608.21338)

Optimal observables



- θ enters through $|M(z;\theta)|^2$: the joint likelihood ratio $r(x,z|\theta_0,\theta_1)$ and joint score $t(x,z|\theta)$ are exact per event and free to compute; ML turns them into the intractable $r(x|\theta)$, $t(x|\theta)$ at detector level (“mining gold”, MadMiner)
- Consequence for generators: every event must carry its parameter dependence — $|M|^2$ at reference points (or the SMEFT quadratic-form coefficients) as event weights, at the same perturbative order as the nominal sample**

Brehmer, Cranmer, Louppe, Pavez: [arXiv:1805.12244](https://arxiv.org/abs/1805.12244); MadMiner: [arXiv:1907.10621](https://arxiv.org/abs/1907.10621)

From tools to samples: central production readiness

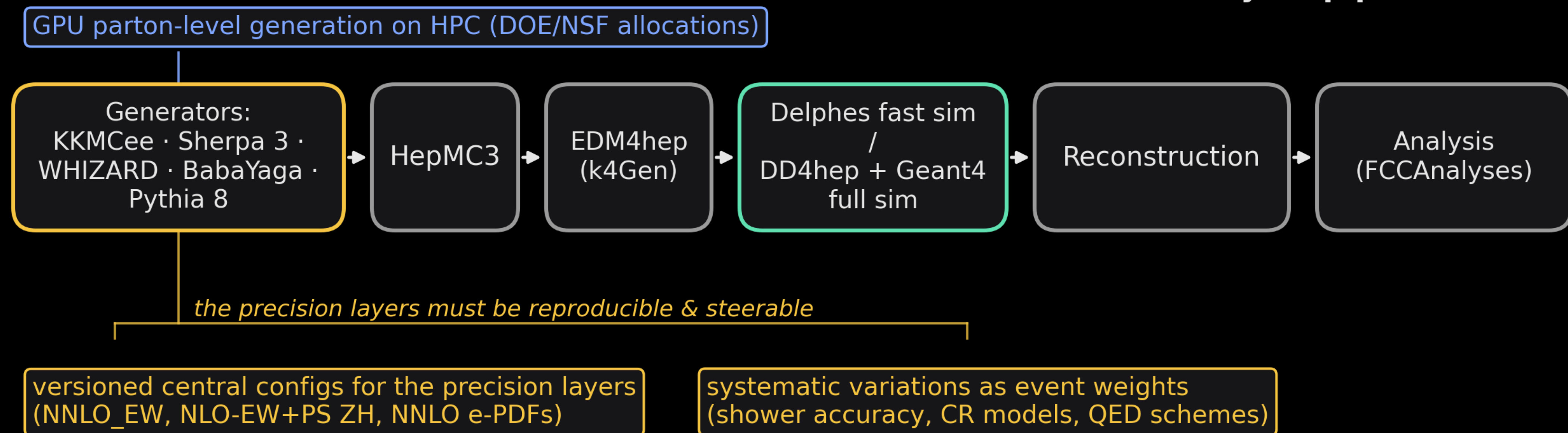
- **Ecosystem status:**

- Key4hep provides the common stack (EDM4hep, k4run, Delphes & full-sim chains); HepMC3 generator interfaces now standard across new releases (KKMCee, Sherpa 3, WHIZARD)
- FCC sample campaigns + tutorials exist and are maintained (hep-fcc tutorials, winter production campaigns)

- **What the new physics developments *could* change for production**

- Precision layers (NNLO_EW, NLO-EW+PS ZH, NNLO e-PDFs) must be captured in reproducible, versioned central configurations
- Systematic variations (shower accuracy, CR models, QED schemes) should ship as event weights where possible — the LHC lesson

Key4hep production chain



Partnership with the generator theory community

- Implement state-of-the-art workflows with the most precise predictions available — as they appear
- Design the centralized MC production workflow jointly: theory (accuracy, schemes), experiment (samples, systematics), computing (throughput, facilities)

Concrete near-term asks

1 · Benchmarking campaign

Same processes, all generators (KKMCee / Sherpa / WHIZARD / BabaYaga / McMule), agreed observables — a LEP-workshop-style tuned comparison for the FCC era.

2 · Common schemes & uncertainties

Shared QED/EW scheme definitions and uncertainty prescriptions across codes, so that “NNLO_EW” means the same thing in every sample.

3 · Sustained career paths

Generator developers — the field’s perennial risk; several flagship codes depend on very few people. Precision is a people problem too.

Venue for event generator discussions

- Software and Computing group at the USHFCC
- Monte Carlo Group at the FCC
 - I serve as a convener in both groups



Andrzej
Siódmok



Simon
Plätzer



Louis
Portales



Alan
Price

Conclusions

- Event generators are central to the FCC physics program
- Lots of progress in the last few years with regard to
 - precision calculations
 - event generators
- AI/ML based computational improvements are beginning to emerge
- In the process of building an MC community focused on FCC-ee physics

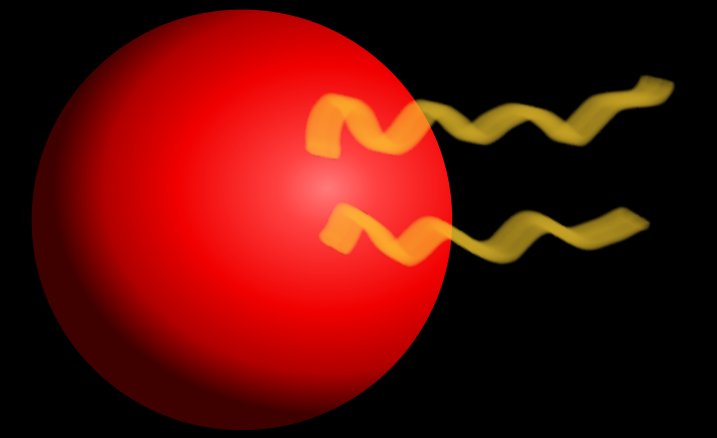
Additional Material

Which generators from this talk are in Key4hep?

k4Gen = Gaudi generator components · Key4hep stack = key4hep-stack spack meta-package · k4GeneratorsConfig = common run-card layer (ECFA Higgs-factory studies)

	k4Gen native interface	Key4hep stack (installed in release)	k4GeneratorsConfig (FCC run-cards)	How events get into EDM4hep / notes
GENERAL-PURPOSE QCD / MATCHING				
Pythia 8 (+ Vincia)				PythiaInterface (Gaudi)
Herwig 7				HepMC3 · config module pending
Sherpa 3 (+ Alaric, YFS)				HepMC3
WHIZARD 3				HepMC3 / LCIO · OpenLoops+GoSam
MG5_aMC@NLO				LHE → Pythia 8 · HepMC3
POWHEG-BOX				standalone → LHE
PRECISION QED / EW FOR E+E-				
KKMCee 5				HepMC3 · pinned 5.01
BabaYaga@NLO				LHE (Linux build only)
BHLUMI				standalone output
BHWide				standalone
McMule				fixed order — not an event generator
YFSWW3 / KoralW				standalone (LEP-era)
RacoonWW				standalone (LEP-era)
ReneSANCe / SANC				standalone
RESEARCH SHOWERS				
PanScales				research shower
Deductor				research shower
Apollo				Pythia-based, not in a release yet
GPU / ML PROTOTYPES				
Pepper (+ flows)				HepMC3 · standalone
Madgraph4GPU (CUDACPP)				plugin in MG5 ≥ 3.6; not built for GPU
MadSpace · MadNIS				standalone / MG7 (unreleased)
AFTERBURNERS & BEAMS				
EvtGen + PHOTOS + TAUOLA				via PythiaInterface · KKMC template
GuineaPig (beam-beam)				MDIReader for backgrounds
CIRCE2 beam spectra				inside WHIZARD · CirceHelper
1 generator 8 generators 6 generators				
yes partial / inside another package no — run standalone, import as HepMC3 / LHE				

Electron PDFs?



- Electron → elementary particle
- Collinear emission of initial state radiation (ISR) with $p_T < \text{energy of the hard scattering}$
 - Factorized like PDFs (as is done for parton content of the proton in proton colliders)
 - Collinear photon emission from an electron using effective photon approximation:
 - $f_\gamma(x) = \frac{\alpha_\gamma}{2\pi} P_{\gamma e}(x) \log \frac{E^2}{m_e^2}$, $E = \text{energy of initial electron}$ and $P_{\gamma e}(x) = \frac{1 + (1 - x)^2}{x}$ is the splitting function (probability of an electron emitting a photon with a fraction x of the energy)
 - $E \gg m_e$, large logs resummed to improve perturbative expansion and introduce factorization scale Q
 - Physics invariant under factorization scale → DGLAP equations
- Non-perturbative nature of proton → initial conditions fitted from collider data
 - For leptons, initial conditions computed perturbatively → solved from first principles
- NLO corrections to initial conditions become relevant when next-to-leading log evolution is considered

Initial State Radiation (ISR)

- Looking closely, large logarithms due to collinear and/or soft photon emissions

$$X \simeq \alpha^b \sum_{n=0}^{\infty} \alpha^n \sum_{i=0}^n \sum_{j=0}^n c_{n,i,j} \ell^i L^j$$

Soft
 $\ell = \log \frac{Q^2}{\langle E_\gamma^2 \rangle}$

Collinear
 $L = \log \frac{Q^2}{m_e^2}$

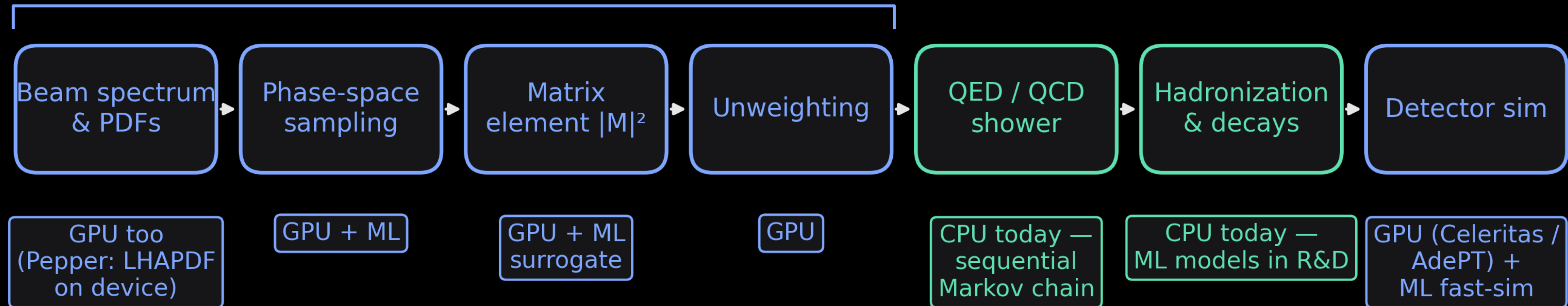
- b : power of the α in the Born process, m_e =electron mass
- Q^2 : typical hard scale of the processes ($\sqrt{s}$)

All precision observables at e^+e^- collider affected by ISR

- Yennie-Frautschi-Suura (YFS): prioritizes soft logarithms
- Collinear factorization: prioritizes collinear logarithms

Where the chain can be offloaded

Parallel across events — Pepper: PDFs + phase space + $|M|^2$ + unweighting, all GPU-resident
MG5 + CUDACPP: $|M|^2$ only · MadGraph 7 + MadSpace: full parton level (once released)



GPU: parton level

Phase-space sampling, $|M|^2$ evaluation and unweighting are independent per point. Pepper keeps PDFs, phase space, $|M|^2$ and unweighting all on the GPU; MG5 + CUDACPP offloads $|M|^2$ only; MadGraph 7 + MadSpace will offload the full parton level. Gains of 10–100× per device.

ML: sampling & surrogates

Normalizing flows raise unweighting efficiency at high multiplicity (coupling-layer flows already competitive, no costly continuous flows needed); neural ME surrogates cut amplitude cost. Exactness restored by a second unweighting or reweighting.

CPU today: shower & hadronization

Sequential Markov chains with data-dependent branching; small per-event work. Gains come from accuracy (NNLL) and tunes, not from GPUs. ML hadronization models are R&D.

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arXiv:2303.18244, 2311.06198, 2602.06895, 2608.21338, 2604.03511, 2506.06203

General-purpose generators & showers

Generator	Hard process	Shower / resummation	Primary aim	e^+e^- / FCC-ee status
Pythia 8.3	LO internal; NLO via POWHEG-BOX / MG5 interfaces; e^+e^- ISR via structure functions	Simple shower & Vincia: LL (recoil-improved); Apollo: partitioned dipole-antenna shower targeting NLL (2403.19452)	Full simulation — hadronization, decays, tunes	Key4hep baseline; LEP-tuned; FCC-ee event-shape study (2511.23103); Pythia Facility roadmap (2603.01744)
Herwig 7.3	NLO QCD via Matchbox (MC@NLO / POWHEG); NLO EW partial	Angular-ordered shower NLL for global observables (1904.11866); dipole shower with NLL fixes (2003.06400)	Full simulation — cluster hadronization	LEP-tuned; used for tune/hadronization cross-checks; no FCC-ee-specific QED layer
Sherpa 3	NLO QCD + NLO EW automated (OpenLoops / Recola); MEPS@NLO merging; YFS NLO_EW $\rightarrow$ NNLO_EW (2512.04959)	CSS dipole shower LL; Alaric NLL (2407.12977); resonance- & width-aware NLO+PS for $e^+e^- \rightarrow W^+W^-b\bar{b}$ (2604.13978)	Both: fixed-order precision and shower accuracy in one framework	Emerging FCC-ee precision stack: NLO EW + QED shower ZH (2603.05585), NNLO_EW 2f, top-threshold $WWb\bar{b}$
PanScales	NLO, positive-definite matching (2504.05377)	NLL (2020) $\rightarrow$ NNLL for global event shapes, proven (2406.02661, 2505.13395)	Shower accuracy as a design goal	Parton level; hadronization via Pythia; α_s / event-shape program
Deductor	LO	Full colour & spin evolution; NLL programme	Shower accuracy (colour/spin)	Parton level; research code
WHIZARD 3	LO any process (O'Mega); NLO QCD + NLO EW (FKS; OpenLoops / Recola / GoSam); SMEFT / UFO	Pythia 8 shower (LL) + POWHEG matching; NRQCD threshold resummation for $t\bar{t}$	Fixed-order precision at lepton colliders; beams (CIRCE), polarization	Lepton-collider specialist; roadmap: EW PDFs, exclusive $t\bar{t}$ threshold matching (2412.06605)
MG5_aMC@NLO	NLO QCD + NLO EW automated; SMEFT@NLO; reweighting; GPU (Madgraph4GPU)	Via Pythia / Herwig (MC@NLO matching)	Fixed-order precision + model flexibility	e^+e^- via e-PDFs (LL/NLL); phenomenology; MadMiner / SBI workflows
MiNNLO_PS · Geneva	NNLO QCD for colour singlets (Geneva: N ³ LL' 0-jettiness resummation)	Matched to Pythia / Sherpa showers	NNLO+PS accuracy	Hadron colliders only so far — an e^+e^- analogue is missing

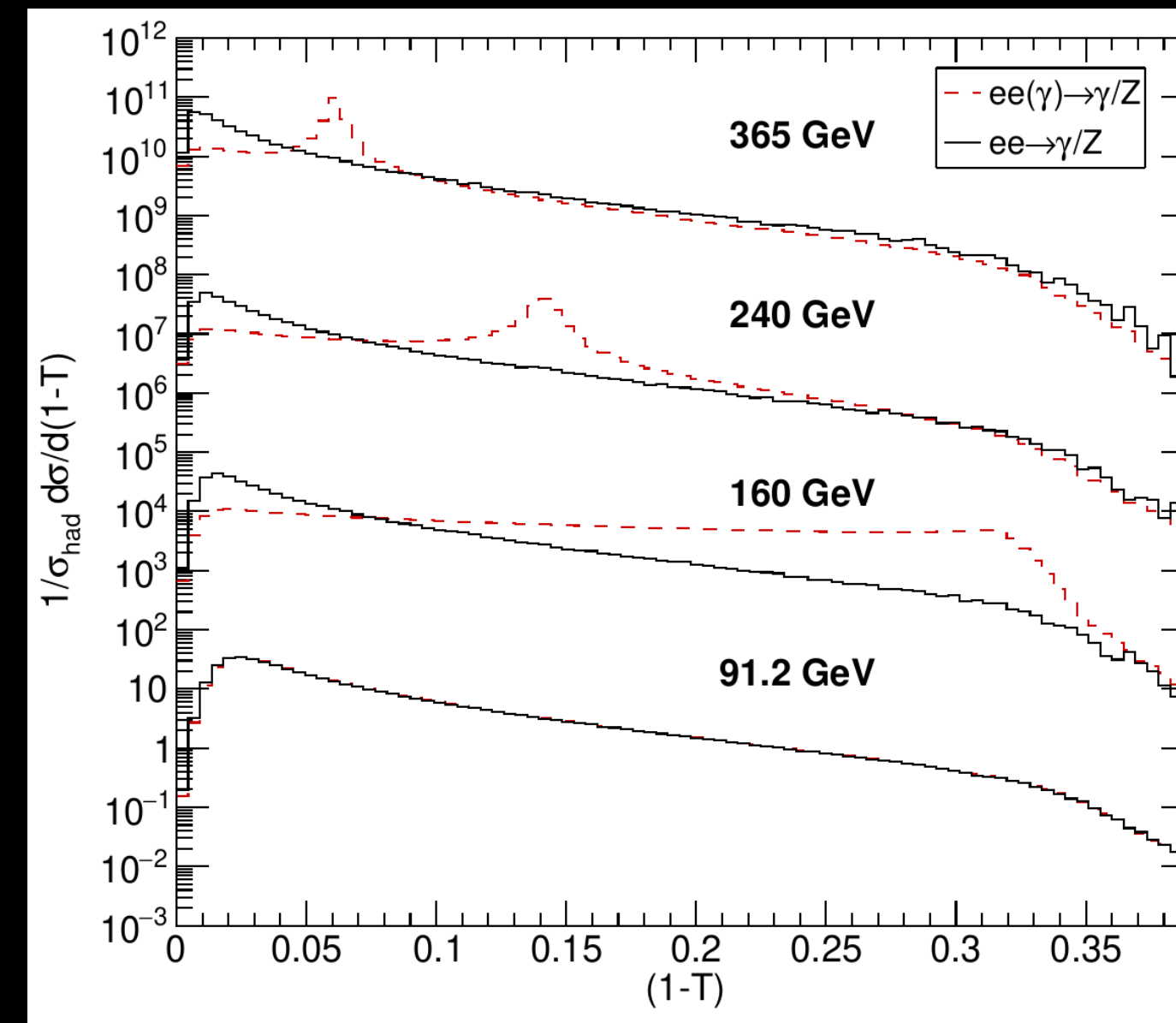
Precision QED / EW generators for e^+e^-

Generator	Processes	Accuracy reached	Perturbative order vs shower	FCC-ee target / status
KKMCee 5.00	$e^+e^- \rightarrow f\bar{f}$ (+ $n\gamma$): μ , τ , ν , quarks; Z pole to LEP2	CEEX $O(\alpha^2)$ coherent exclusive exponentiation; EW via DIZET; $\sim 0.2\%$ at LEP2	Fixed order ($O(\alpha^2)$) inside all-orders YFS exponentiation; QCD via Pythia interface	C++ rewrite (2410.07294); beam spread + beamstrahlung built in; 10^{-4} via IR-improved resummation (2604.26124)
BHLUMI 4.04	Small-angle Bhabha (luminosity)	YFS $O(\alpha)$ exponentiation + $O(\alpha^2 L^2)$; total theory error 0.061% at LEP (1999)	Fixed order within YFS exponentiation	Forecast 10^{-4} with $O(\alpha^2 L)$, $O(\alpha^3 L^3)$, pairs, VP updates (1812.01004); needs implementation
BabaYaga@NLO	$e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\gamma\gamma$ (+ $n\gamma$); radiative return	NLO QED matched to a QED parton shower; 0.1% at flavour factories	Fixed order (NLO) matched to a LL QED shower	NNLO+PS matching and $O(\alpha^2 N_f)$ pairs in progress $\rightarrow 0.01\%$ (2601.11204)
McMule	Bhabha, $\mu e \rightarrow \mu e$, $e^+e^- \rightarrow \mu^+\mu^-$, muon decay	Fully differential NNLO QED; N ³ LO pieces (photonic, muon decay)	Pure fixed order — no shower, no exponentiation	Independent NNLO reference for the luminosity budget; $e^+e^- \rightarrow \gamma\gamma$, wide-angle Bhabha
Sherpa YFS	Arbitrary e^+e^- processes (2f, 4f, ZH, $\pi\pi$...)	NLO_EW automated; NNLO_EW with process-specific two-loop input; IR cancellation to machine precision	Fixed order (NNLO_EW) matched to YFS soft-photon resummation; QCD shower available	Framework exists (2512.04959); scaling across the program = two-loop amplitudes + Key4hep integration
ReneSANCe / SANC	$e^+e^- \rightarrow f\bar{f}$, ZH, W^+W^- , γZ ... with beam polarization	Complete one-loop EW; some higher-order terms	Fixed order (NLO EW) — no shower	Cross-check generator for FCC-ee / CEPC / ILC EW observables
YFSWW3 / KoralW · RacoonWW	$e^+e^- \rightarrow W^+W^- \rightarrow 4f$ (+ γ)	$O(\alpha)$ EW in leading-pole / double-pole approximation + YFS ($\sim 0.4\%$ at LEP2)	Fixed order (NLO EW, pole approximations) with YFS	No modern successor — m_W at threshold needs NNLO EW 4f generation

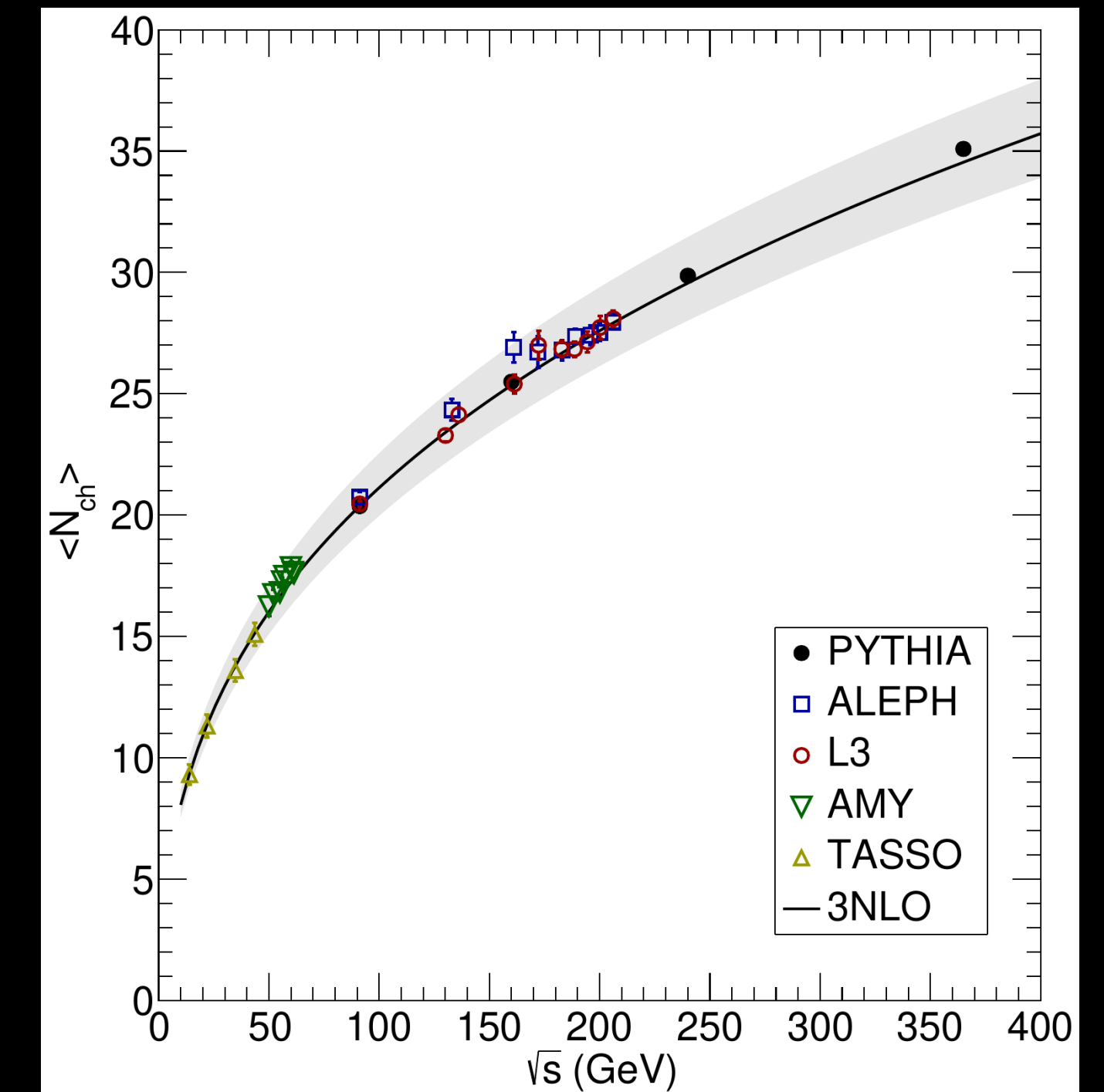
Pattern: the e^+e^- precision codes compete on perturbative order and exact QED exponentiation, not on QCD showers — which is why the FCC-ee stack has to be a combination, not a single tool.

Event shapes & hadron spectra across the FCC-ee stages

- New phenomenology study spanning all four energies — 91.2, 160, 240, 365 GeV (Pythia 8.313)
- Thrust and C-parameter; inclusive charged-hadron spectra; charged multiplicities
- Explicit treatment of ISR distortion and EW backgrounds on the QCD observables — the real-life FCC-ee analysis situation
- α_s extracted via NNLO QCD fits to the simulated event shapes
- Validation against LEP: ALEPH & L3 data at 161–200 GeV; multiplicities reproduced to $\sim 0.5\%$
- **Takeaways for the generator program**
 - Baseline Pythia describes LEP-era hadronic final states well — but FCC-ee statistics will expose the model at a level LEP never could
 - Power corrections $\sim \Lambda_{\text{QCD}}/Q$ compete with $N^3\text{LL}/\text{NNLO}$ terms — hadronization modeling becomes the α_s systematic
 - Motivates the NNLL-shower + modern-tune program, and dedicated FCC-ee tuning campaigns



Impact of ISR on $(1-T)$, 91.2–365 GeV

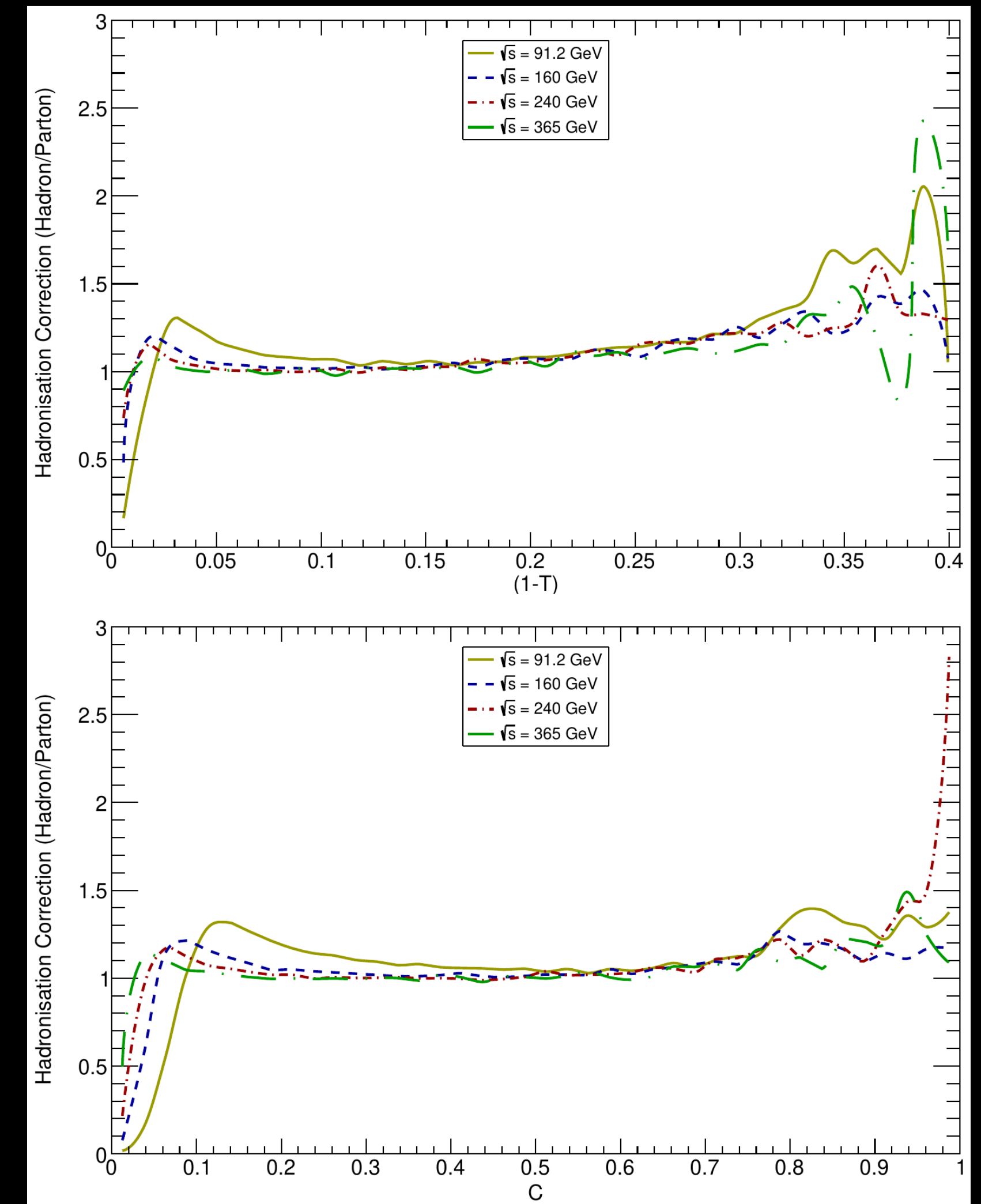


$\langle N_{ch} \rangle$ vs $\sqrt{s}$: Pythia vs data and the 3NLO QCD band

Left: ISR (dashed) vs no-ISR (solid) thrust distributions at all four stages — radiative return to the Z pole is the dominant distortion above 91 GeV. **Right:** $\langle N_{ch} \rangle$ vs $\sqrt{s}$ — the model interpolates data well, but FCC-ee statistics will test it at 0.1%, not 0.5%.

Hadronization & colour reconnection — the non-perturbative wall

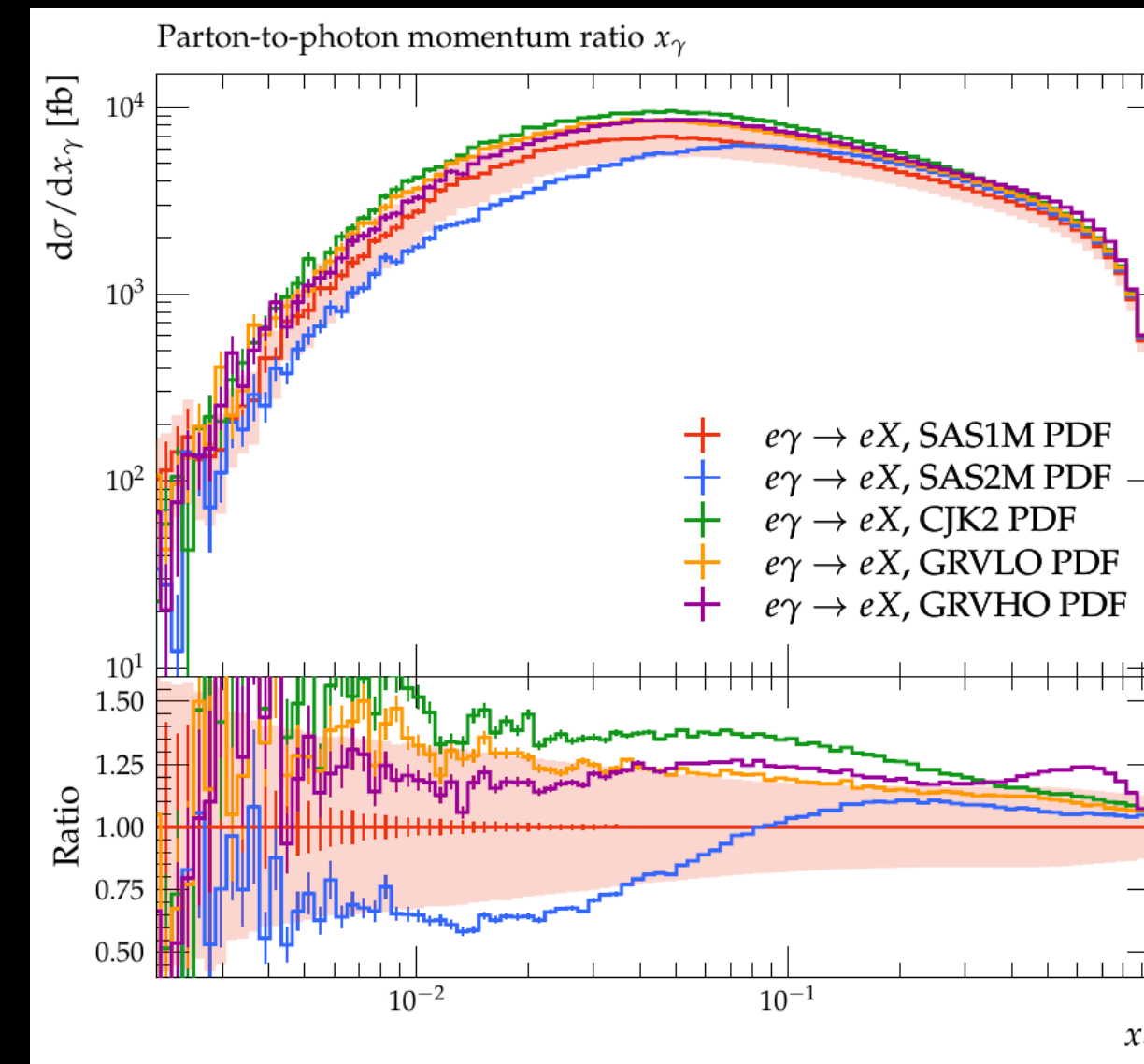
- All mainstream hadronization models (string, cluster) still anchored to LEP-era tunes — extrapolation across FCC-ee stages is an assumption, not a measurement
- **Colour reconnection**
 - Dominant theory systematic for m_W from W^+W^- at threshold (the LEP story, at $\times 10^3$ the statistics)
 - New CR model shipped in Sherpa 3; CR remains phenomenological — no first-principles framework yet
- Heavy-flavour fragmentation: endpoint behaviour & b/c spectra critical for the flavour program and $H \rightarrow b\bar{b}/c\bar{c}$ templates
- Top-mass interpretation: renormalon ambiguities + CR effects couple hadronization to the threshold-scan systematics
- What FCC-ee itself provides: Tera-Z = the ultimate tuning dataset (identified spectra, flavour-tagged event shapes, multiplicities)
- **Program need: tuning infrastructure ready on day one — modern showers + tuned models validated stage-by-stage, not LEP tunes reused for 20 more years**



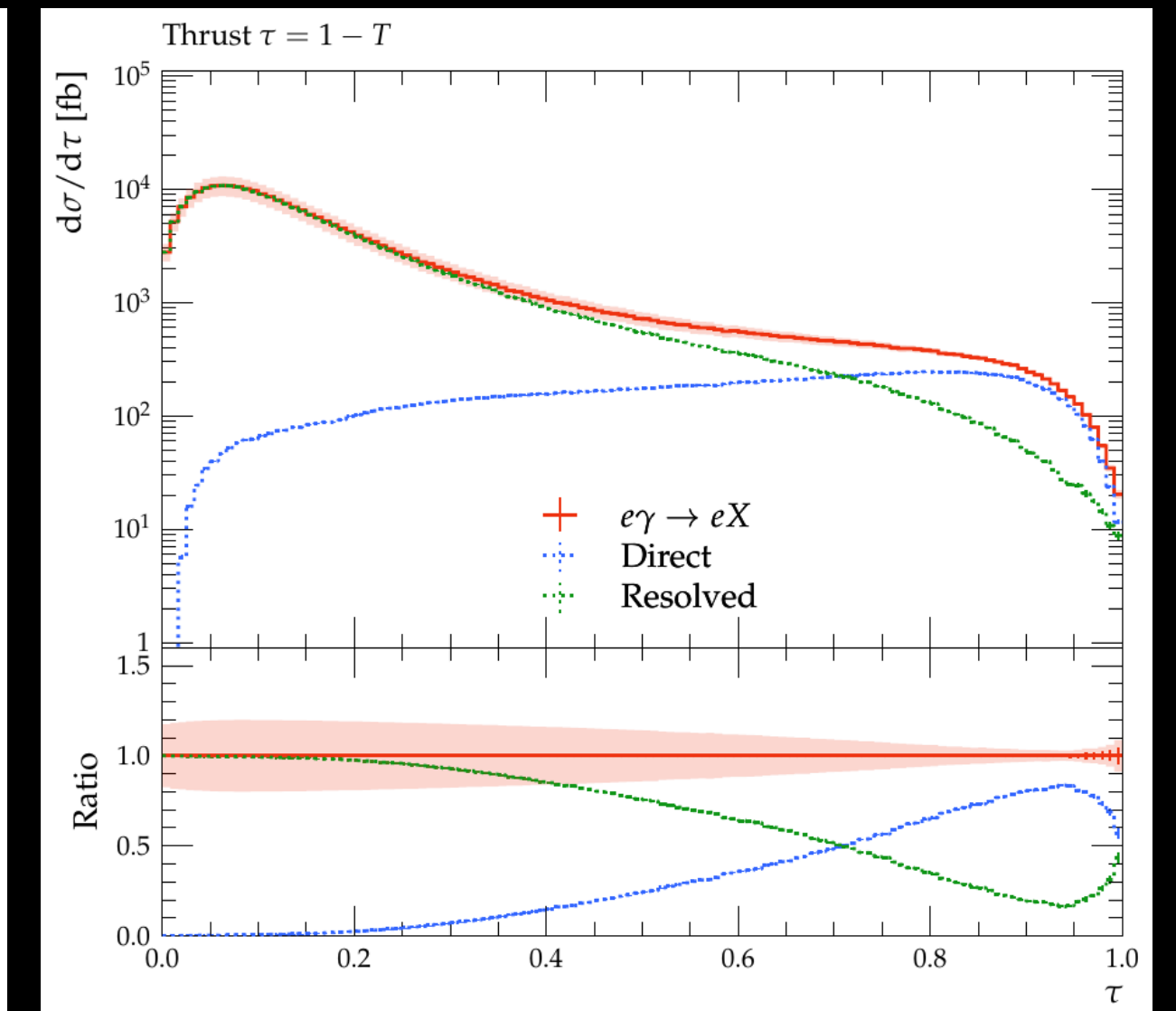
Hadronisation correction factors to $(1-T)$ and C at the FCC-ee energies (Pythia 8.313) — the size of what the model must get right — [arXiv:2511.23103](#)

Photon-induced processes: a background coming into focus

- New (2025): jet production from photon-induced channels at future lepton colliders
- $\gamma\gamma$ and resolved-photon contributions computed for lepton-collider kinematics
- Resolved photons need a photon PDF — connects to the two-loop photon-in-electron structure functions (e-PDF slide)
- **Why it matters at FCC-ee / high-energy stages**
 - $\gamma\gamma \rightarrow$ hadrons pile-up-like backgrounds contaminate hadronic observables and jet clustering
 - Backgrounds to invisible-Higgs, dark-sector and low-mass searches are often γ -induced
 - Beam modeling enters again: photon flux depends on the beamstrahlung spectrum — generator + machine inseparable
- **Generator status: historically a weak spot in e^+e^- simulation chains; systematic NLO-level treatment is new and should be integrated into central production**



x_γ distribution for $e\gamma \rightarrow eX$ with different photon-PDF sets

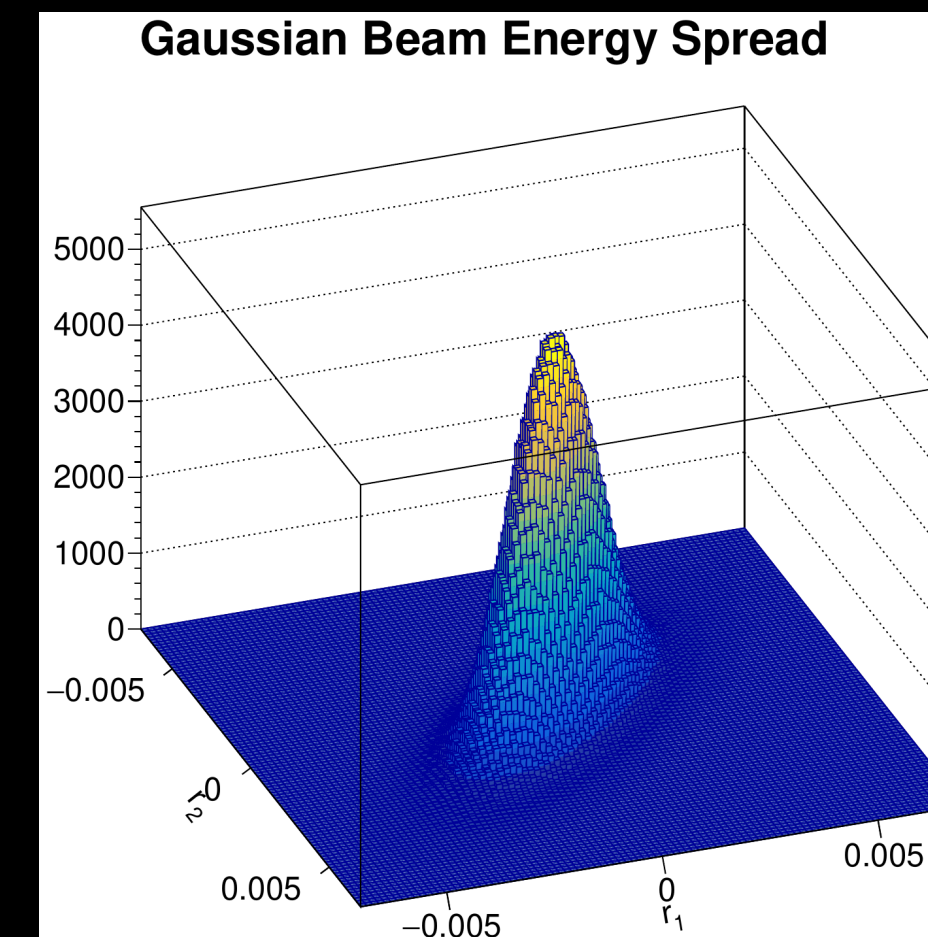


Thrust for $e\gamma \rightarrow eX$: direct vs resolved contributions

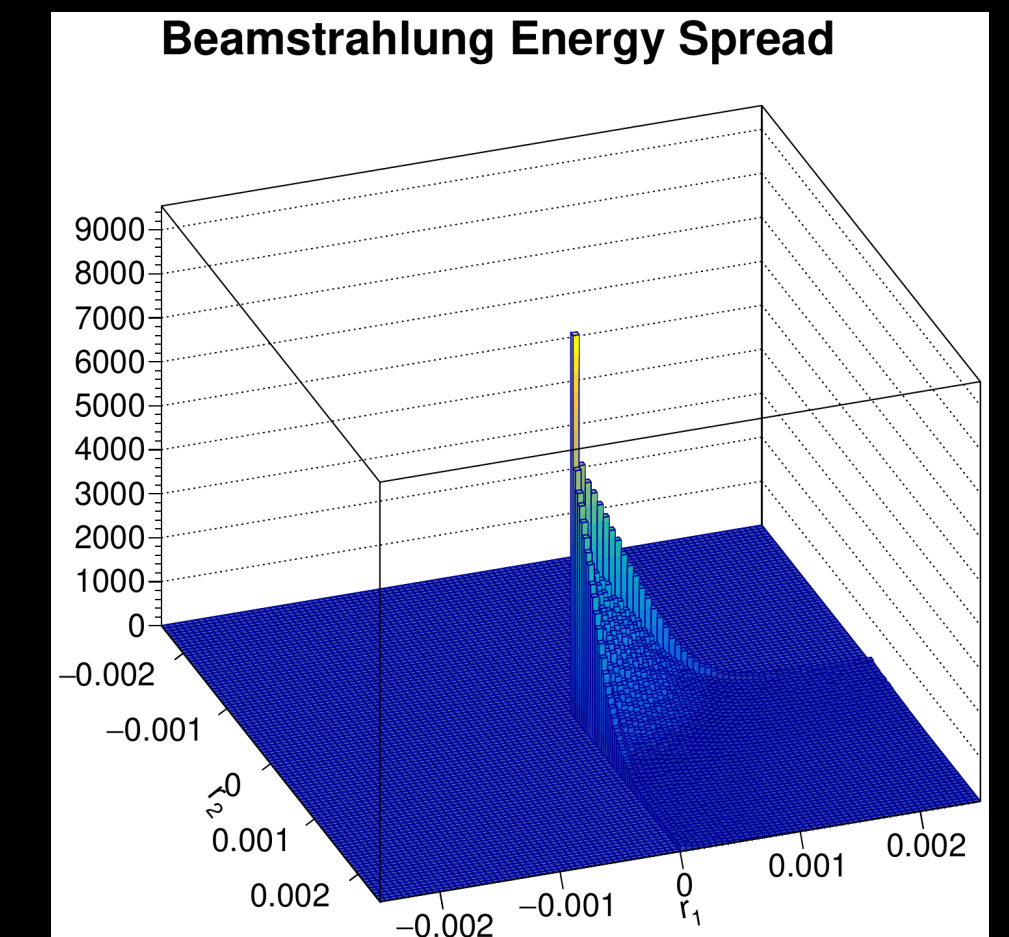
Spread between photon-PDF parametrizations (left) is itself a systematic $\rightarrow$ NNLO photon-in-electron content closes the loop with the e-PDF program.

Beam dynamics × generators: the luminosity spectrum

- Every precision observable is convolved with the machine: beamstrahlung tail + intrinsic energy spread + crossing angle
- FCC-ee: modest beamstrahlung vs linear colliders, but sub-permille shape knowledge required at the Z pole and WW threshold ($\sqrt{s}$ calibration at 10^{-6} !)
- Current practice: parametrized spectra (Circe-style) fitted to GuineaPig simulations — adequate for LEP-era targets, not for these
- **What the 2025–26 generator releases brought**
 - KKMCEE 5.00: correlated Gaussian beam-energy spread + beamstrahlung natively in the generator (right)
 - Community push (LCWS 2025 review): fully differential, machine-specific spectra with non-Gaussian tails, delivered as a standard interface to all generators
- **Needed: joint MDI-generator validation — the same spectrum object used by the machine group, the luminometer simulation, and the physics generators**
- Resonant depolarization gives $\sqrt{s}$ — but the spectrum shape stays a simulation deliverable



Correlated Gaussian beam-energy spread of the two beams



Beamstrahlung energy-loss distribution

Both from KKMCEE 5.00 (arXiv:2410.07294), in terms of $r_i = (E_i - \bar{E}_i)/\bar{E}_i$. The Gaussian core is a few 10^{-4} wide; the beamstrahlung tail is one-sided and non-Gaussian — precisely the shape that must be shared, versioned and validated between MDI and generators.

Thank you! — key references (2024 → 2026)

Reviews & reports

- Price, MC generators for future lepton colliders — arXiv:2606.22007
- Reuter, Monte Carlo Event Generators — arXiv:2509.21611
- Challenges for MC generators (LCWS 2024) — arXiv:2412.06580
- FCC Feasibility Study Report Vol. 1 — arXiv:2505.00272

QED / EW precision

- Price & Krauss, automated NNLO_EW — arXiv:2512.04959
- ZH at NLO EW + QED PS — arXiv:2603.05585
- NNLO e-PDFs (SCET) — arXiv:2508.16964
- Two-loop e/ γ structure functions — arXiv:2509.09618
- IR-improved resummation status — arXiv:2604.26124

Generators & luminosity

- KKMSee 5.00 — arXiv:2410.07294
- Sherpa 3 — arXiv:2410.22148
- WHIZARD developments — arXiv:2412.06605
- BabaYaga at future colliders — arXiv:2601.11204
- Bhabha luminosity to 0.01% — arXiv:1812.01004
- NP contamination of luminosity — arXiv:2501.05256

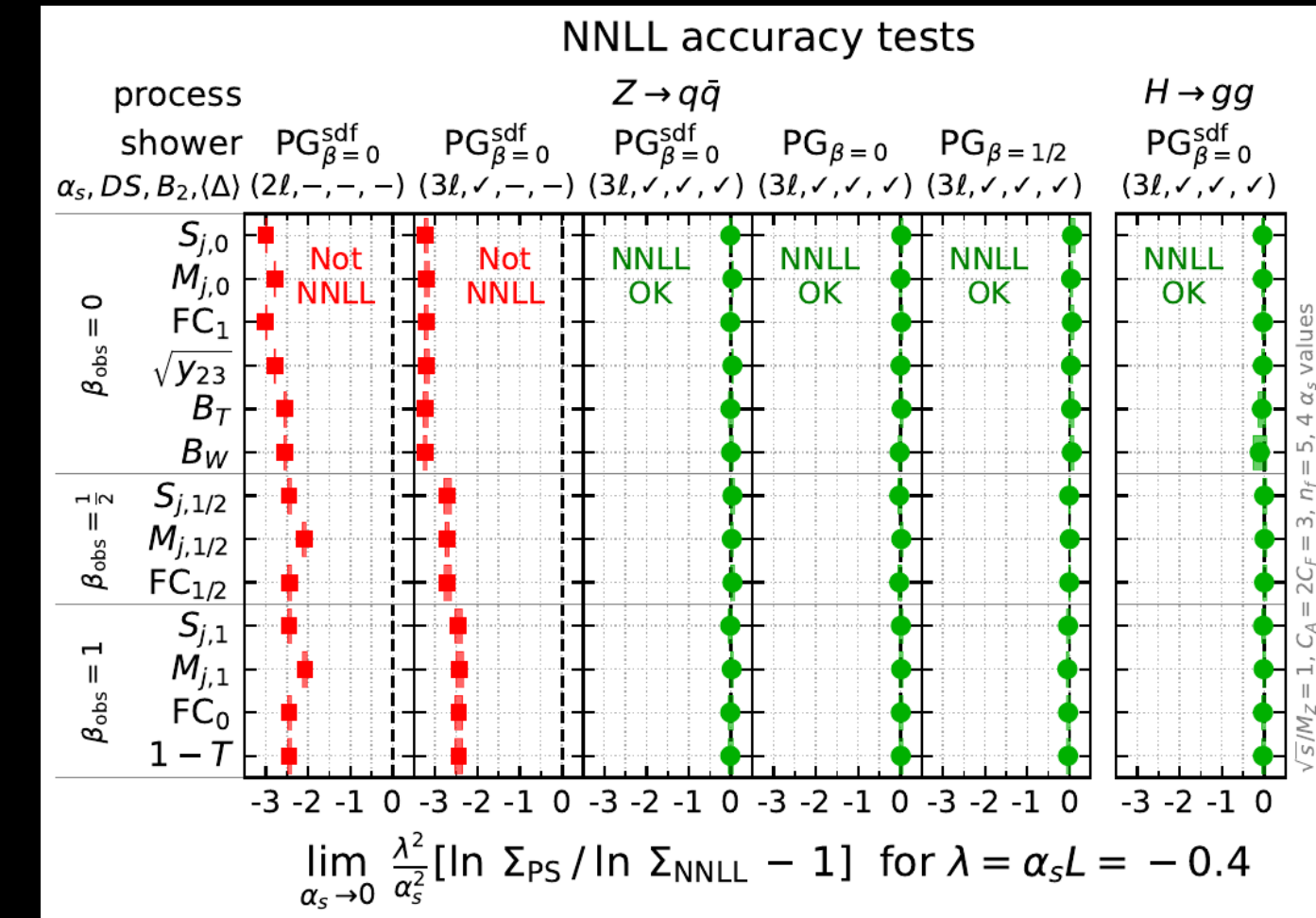
QCD, showers, computing

- NNLL showers + recipe + NLO matching — arXiv:2406.02661, 2505.13395, 2504.05377
- FCC-ee event shapes — arXiv:2511.23103
- Photon-induced jets — arXiv:2511.11812
- N³LO top threshold — arXiv:2409.05960; JHEP 07 (2025) 273
- Madgraph4GPU / Pepper / MadSpace — arXiv:2303.18244, 2311.06198, 2602.06895
- Flows / surrogates — arXiv:2506.18987, 2506.06203

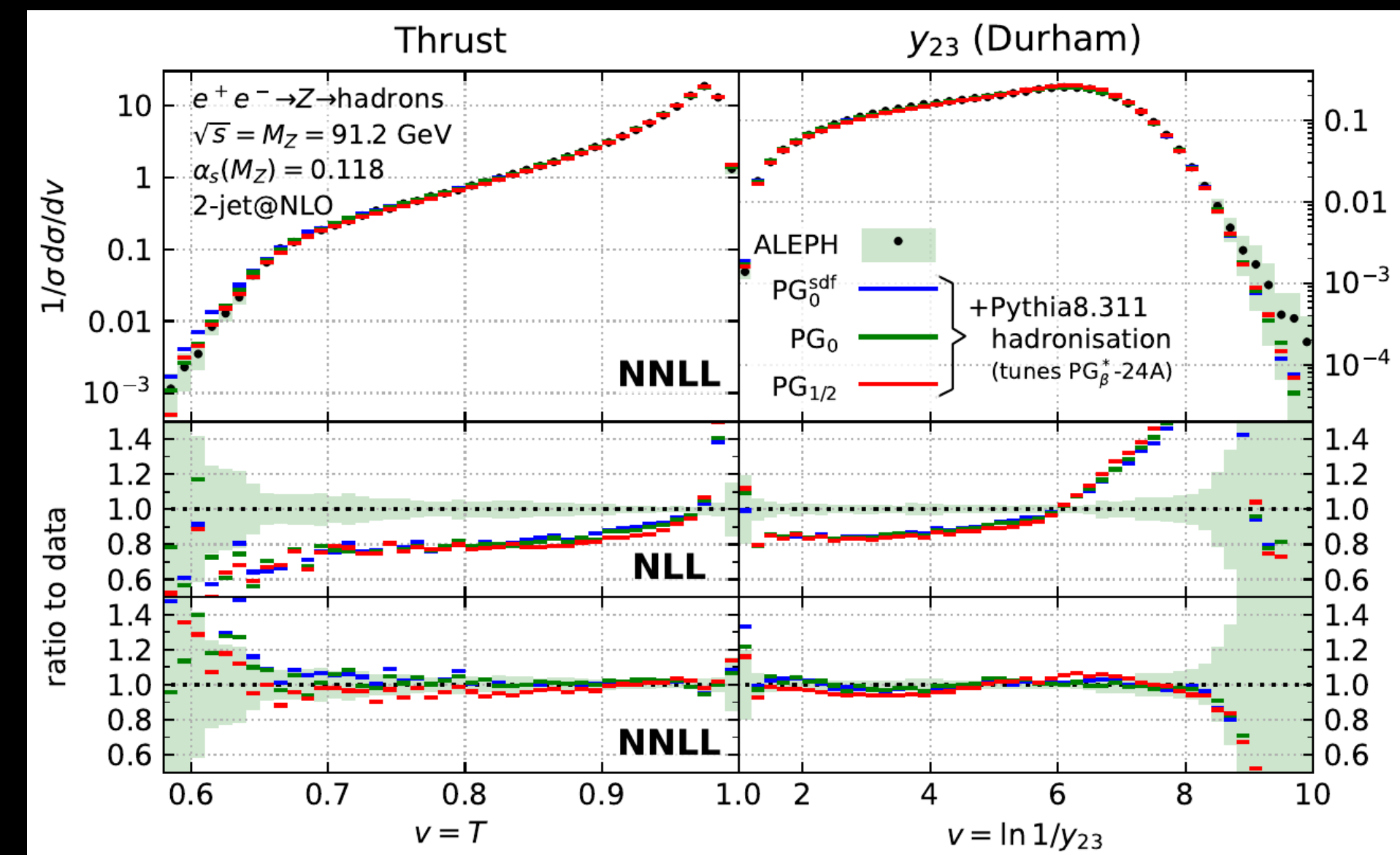
Parton showers: increase logarithmic accuracy

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- First demonstrably NNLL-accurate parton showers (PanScales) — a new standard for the field
- May 2025: the systematic recipe — NLO-accurate 3-jet + NNLO-accurate 2-jet structure embedded in the shower; consistent recoil & colour
- April 2025: logarithmically-accurate and positive-definite NLO matching — no negative weights, accuracy preserved on both sides
- α_s from event shapes: shower accuracy $\leftrightarrow$ hadronization corrections disentangled only if the perturbative side is under control



NNLL accuracy tests across event shapes: green = agrees with NNLL — arXiv:2406.02661



PanGlobal NNLL vs NLL showers (+ Pythia 8 hadronisation) against ALEPH thrust and Durham y_{23}

arXiv:2406.02661; arXiv:2505.13395; arXiv:2504.05377