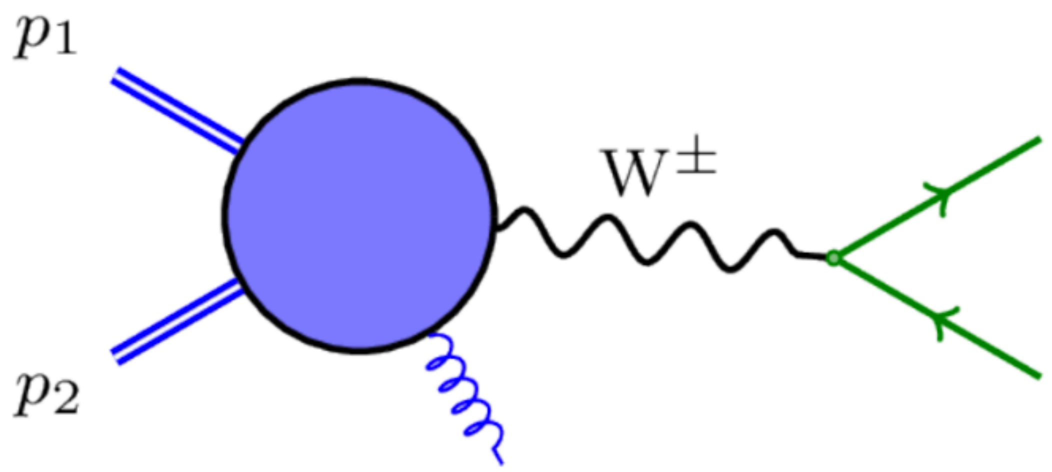
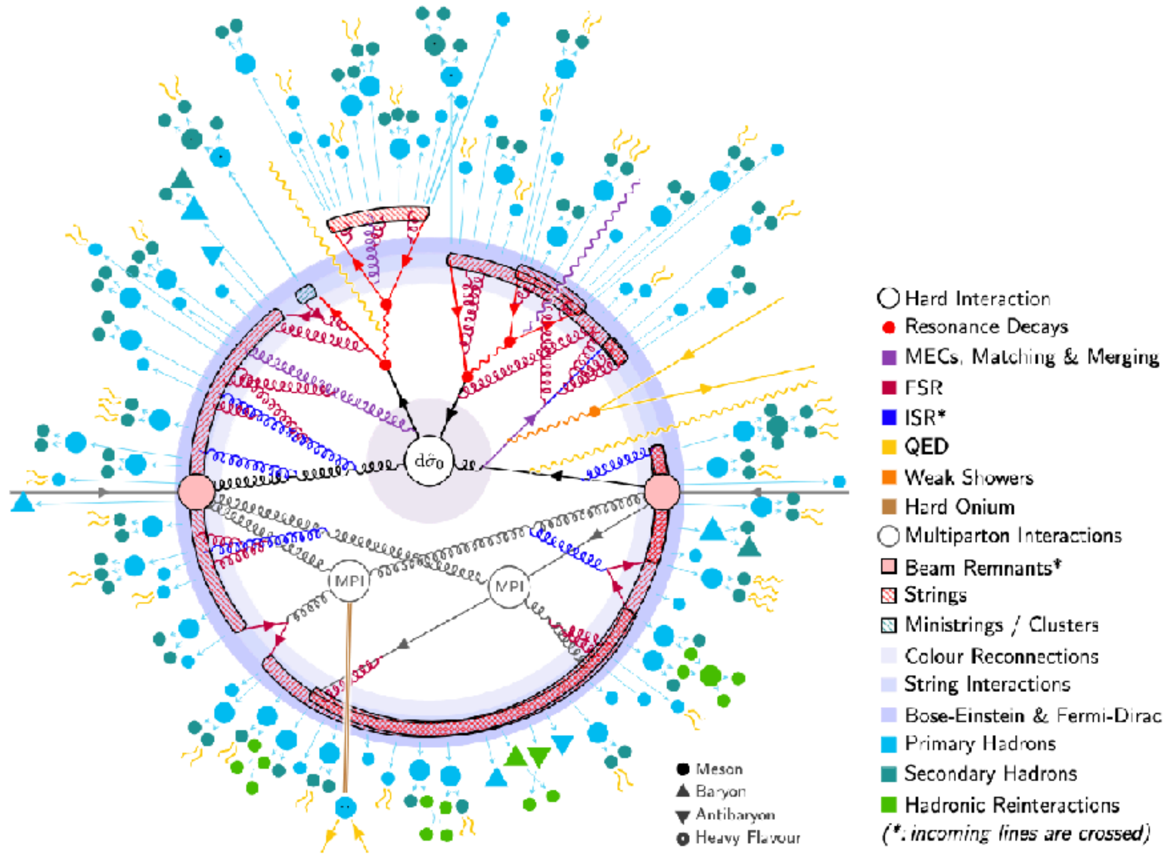
Challenges for MC generators (for e^+e^- colliders)





Jürgen R. Reuter

DESY. HELMHOLTZ

Narodowe Centrum Nauki
Opus

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
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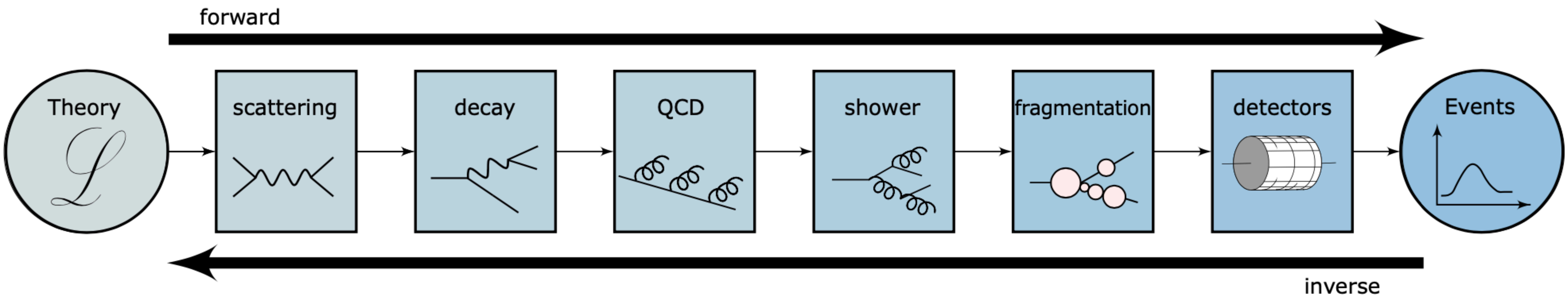
DESY.

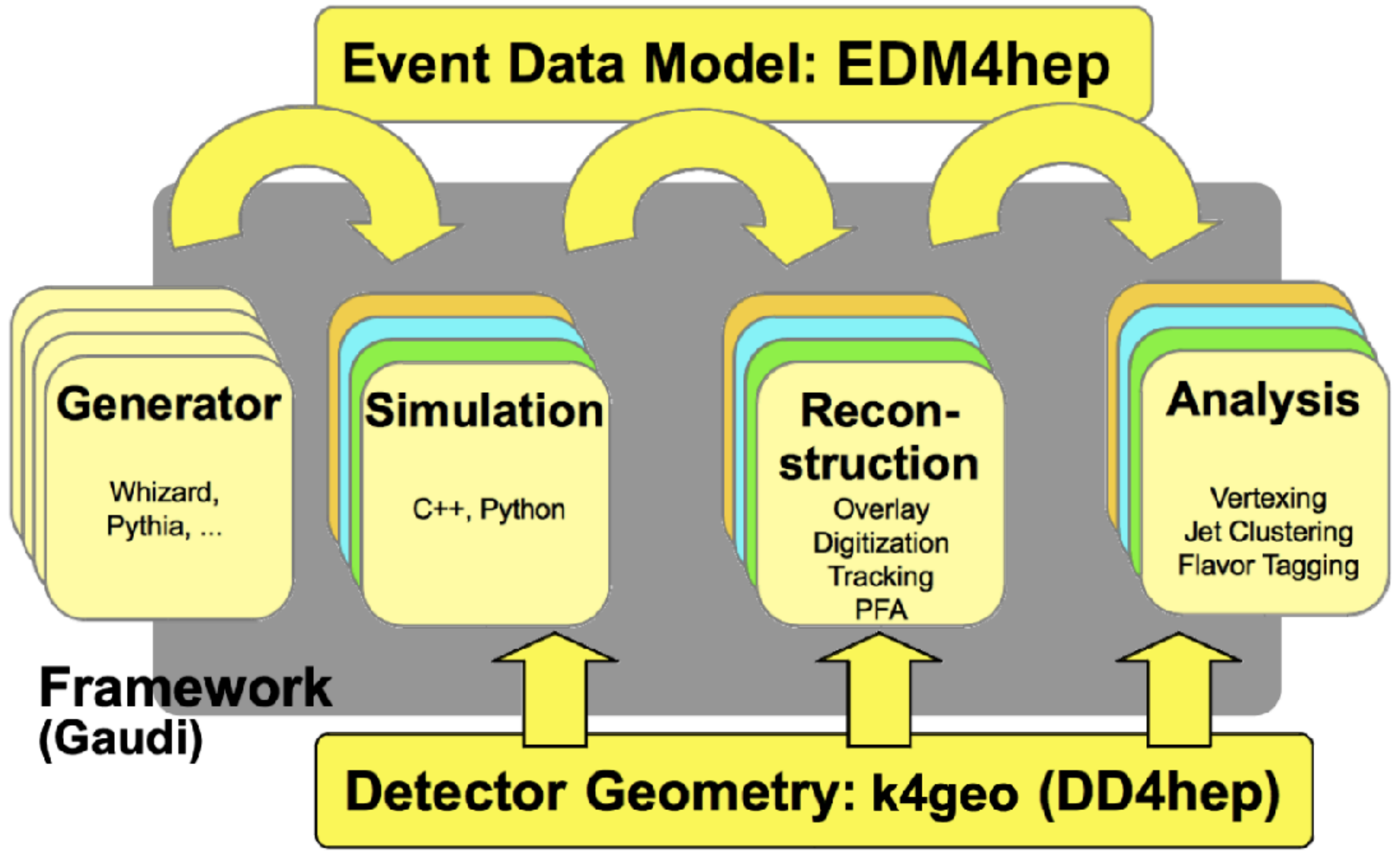
Monte Carlo Challenges

Monte Carlo Challenges

Why are MC generators important?

"Forward simulation": Monte Carlo generators

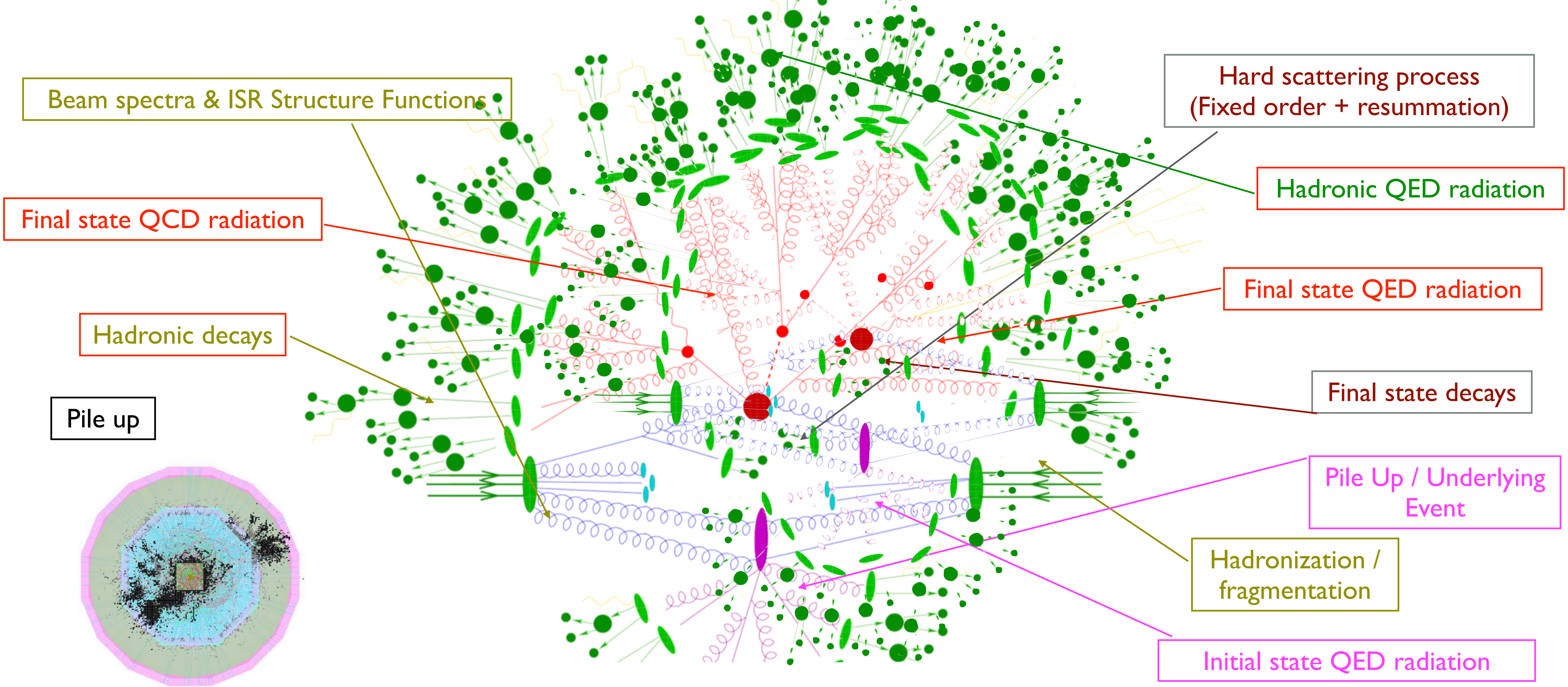




"Inverse simulation": Reconstruction

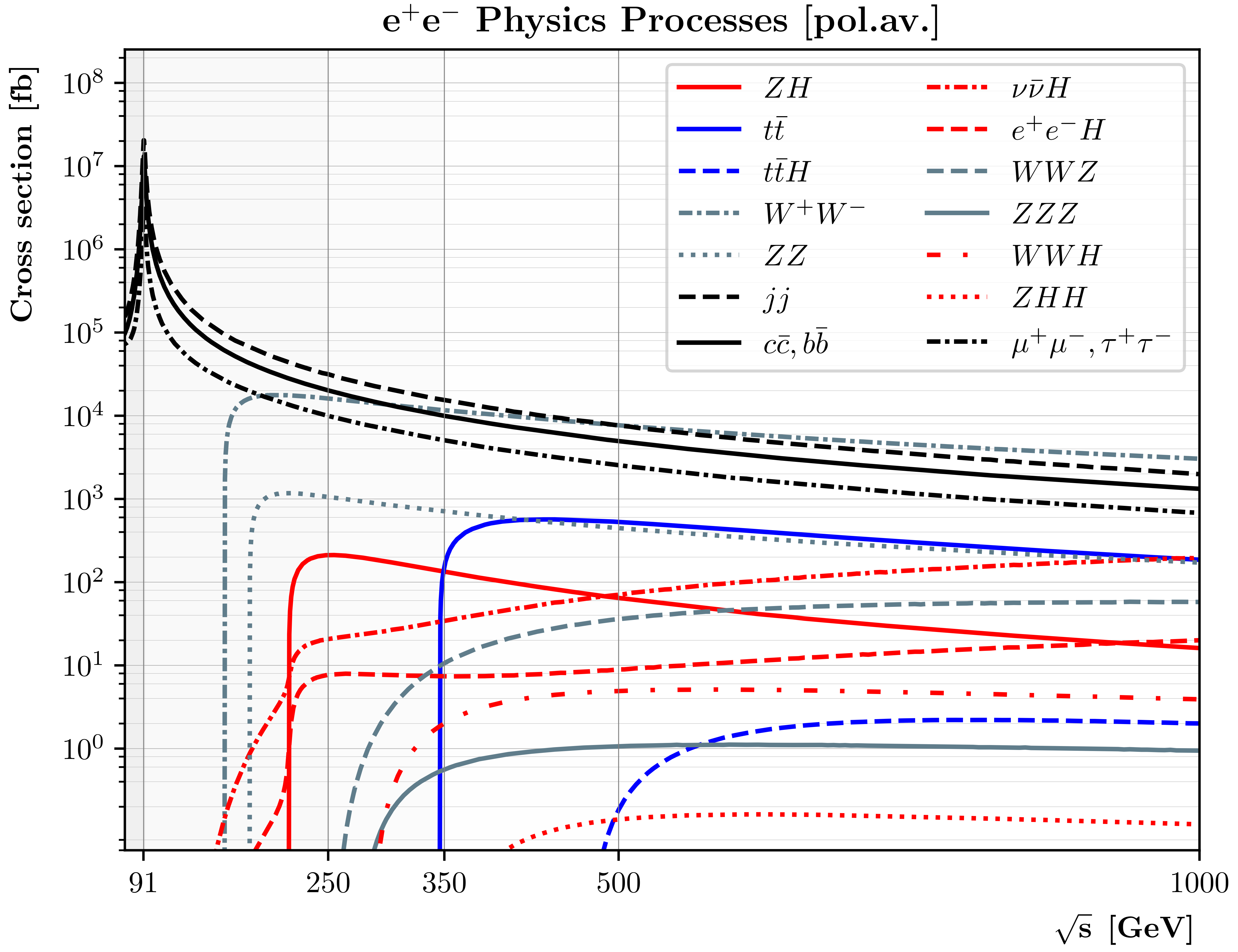
Why are MC event generators non-trivial?

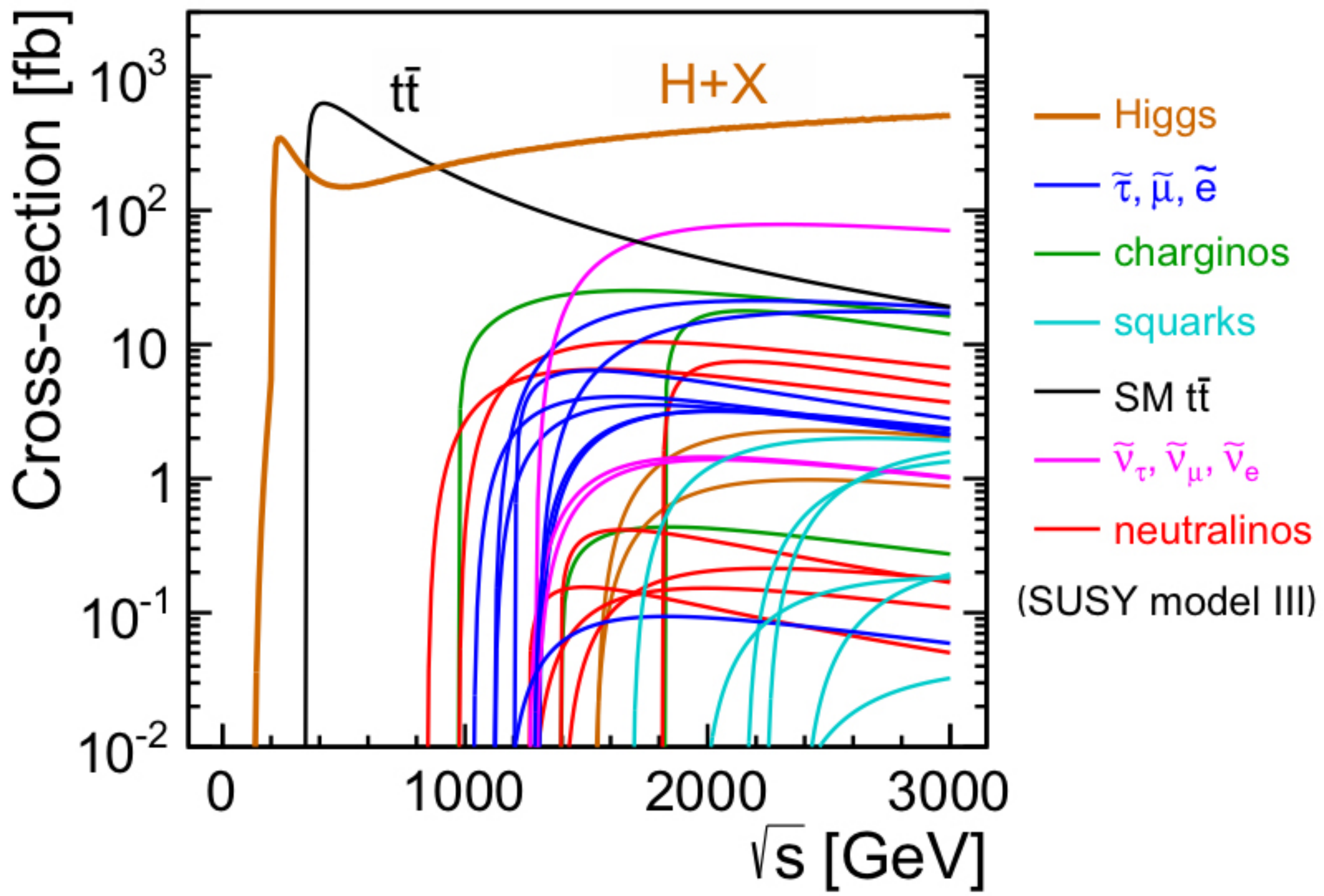
Because they contain *all* our knowledge of particle physics!



LCD-Note-2011-006

Vast Linear Collider Facility Physics program to be simulated

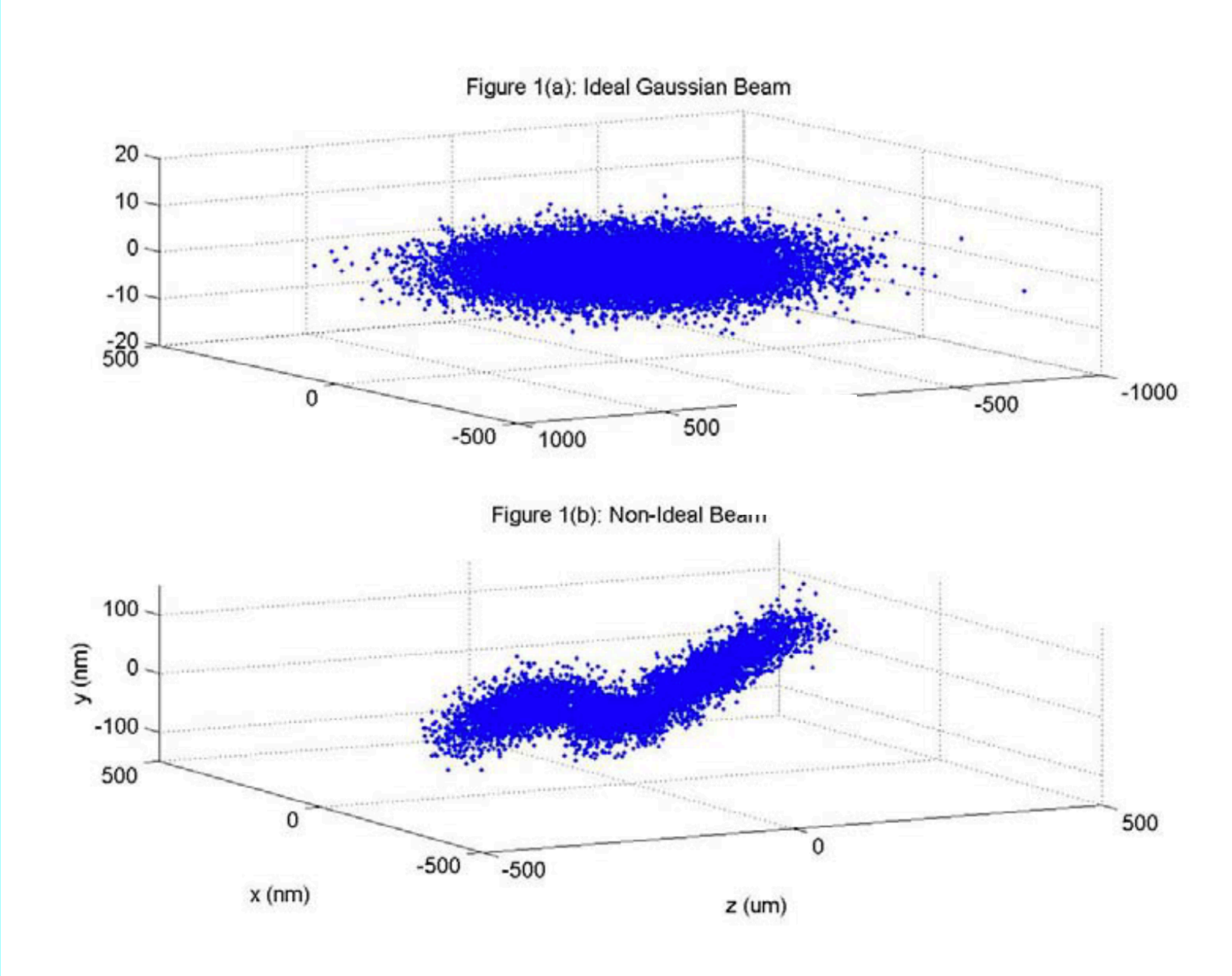


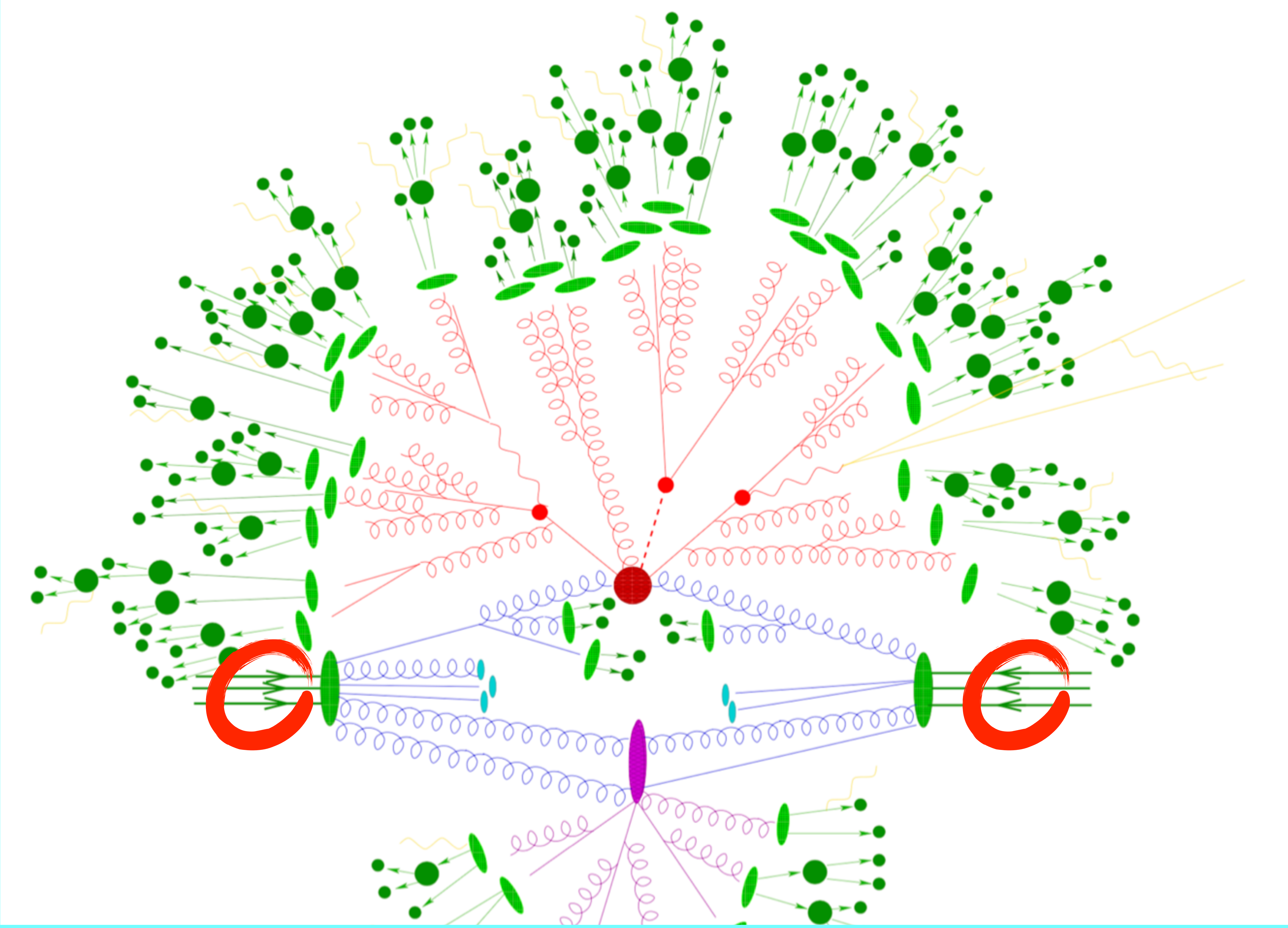


- 91 GeV — *Z* pole running
- 161 GeV — *WW* threshold
- 250 GeV — *ZH* threshold
- 350 GeV — *tt* threshold
- 550 GeV — *ttH*, *ZHH* threshold
- 1000+ GeV — Generic searches, EW physics

Full sim. ILC TDR ("DBD") + ILC-250, CEPC full sim. experience

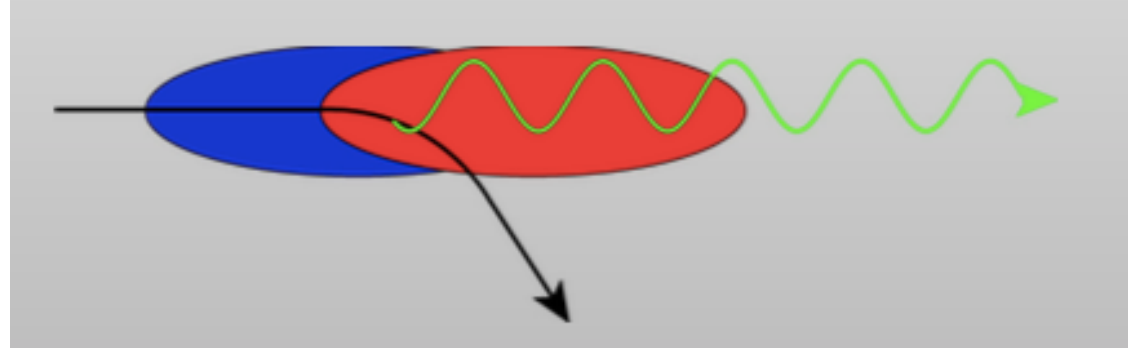
Beam simulations





Beam simulations

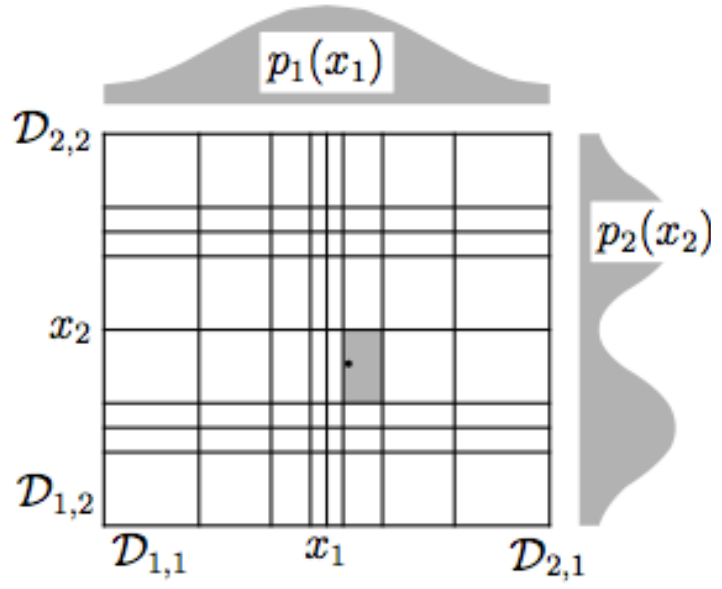
- Micro-scale bunches create beamstrahlung
- Has to be folded into realistic MC simulations



$$L \approx \frac{N}{4\pi\sigma_x\sigma_y}\frac{\eta P_{AC}}{E_{CM}}$$

1. Gaussian shape with specific spreads
2. Parameterized (delta peak ⊕ power law)
3. Generator for 2D histogrammed fit

$$\begin{aligned} D_{\ell_1\ell_2}(x_1,x_2) &= D_{\ell_1}(x_1)\cdot D_{\ell_2}(x_2) \\ D_{\ell_i}(x_i) &= \delta(1-x_i) + \gamma_i\, x_i^{\alpha_i}\cdot(1-x_i)^{\beta_i} \end{aligned}$$



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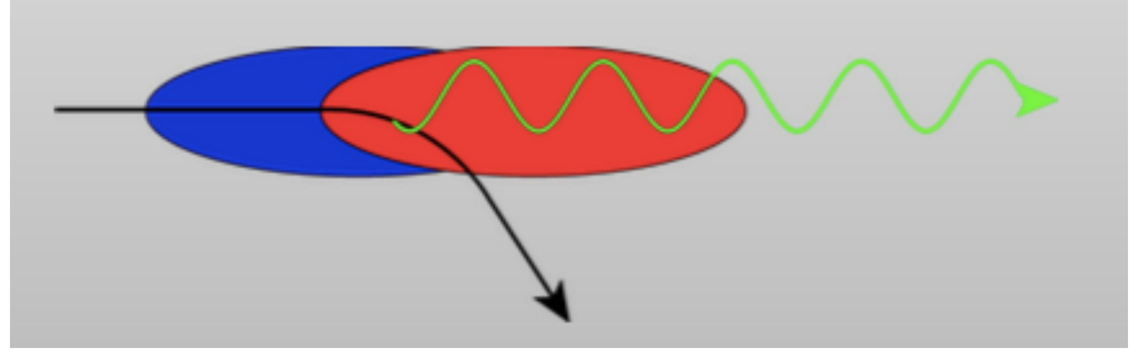

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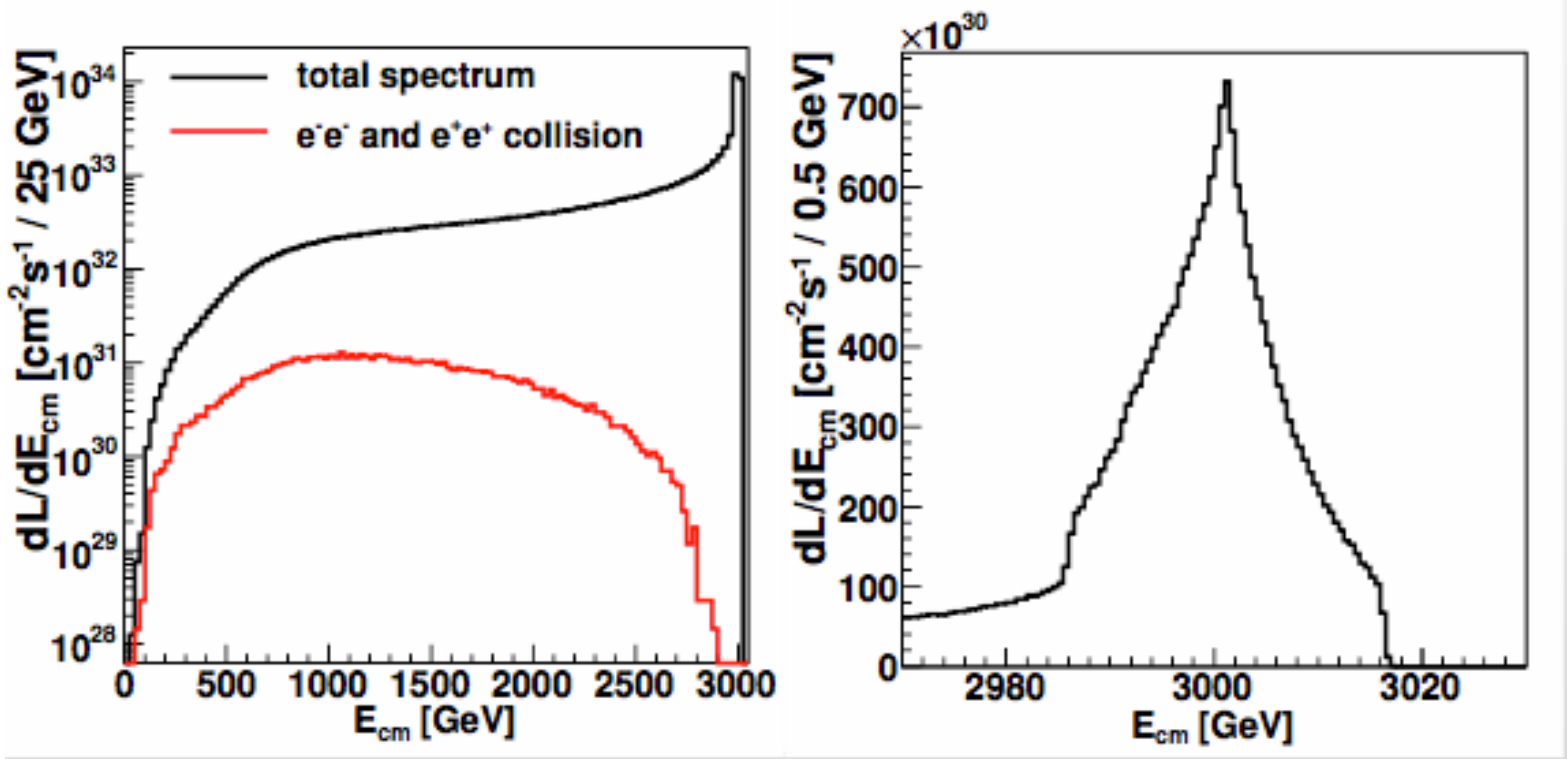
Increasing sophistication



Dalena/Esbjerg/Schulte [LCWS 2011]

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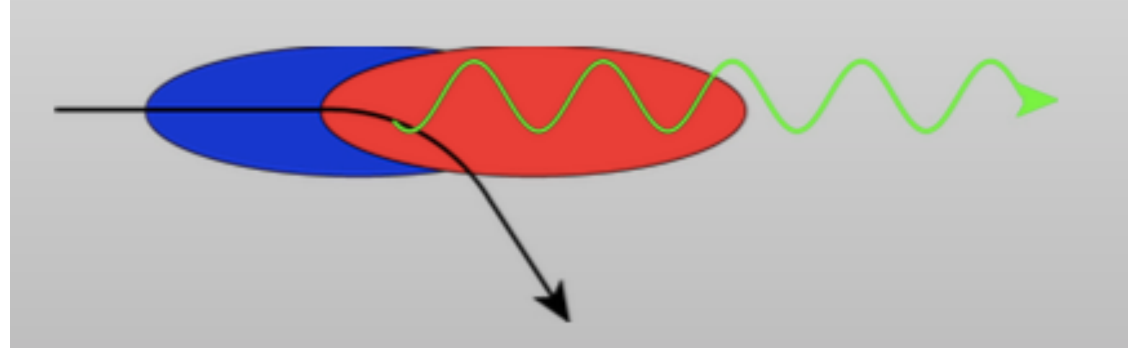

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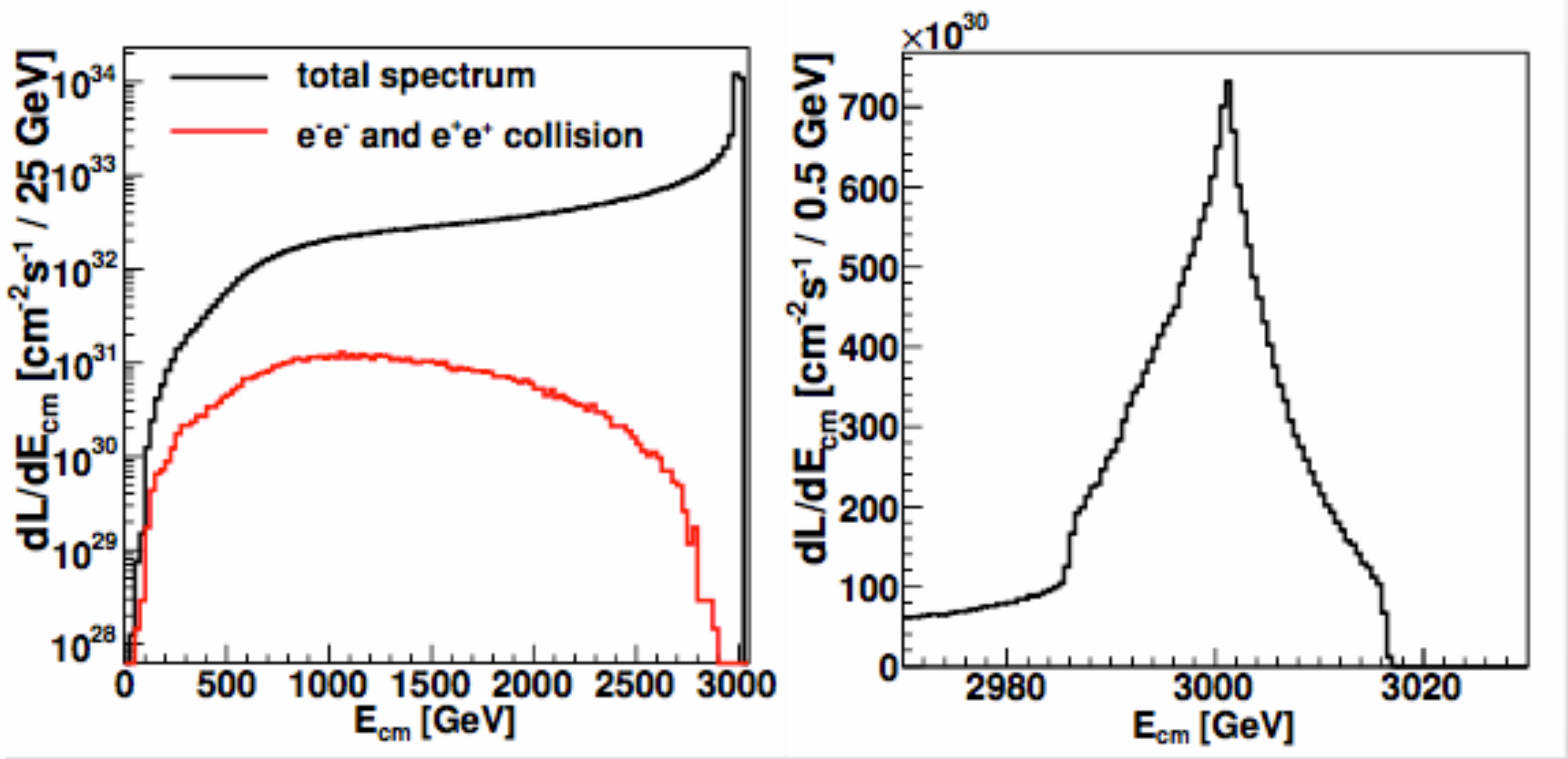
Increasing sophistication

Decreasing availability



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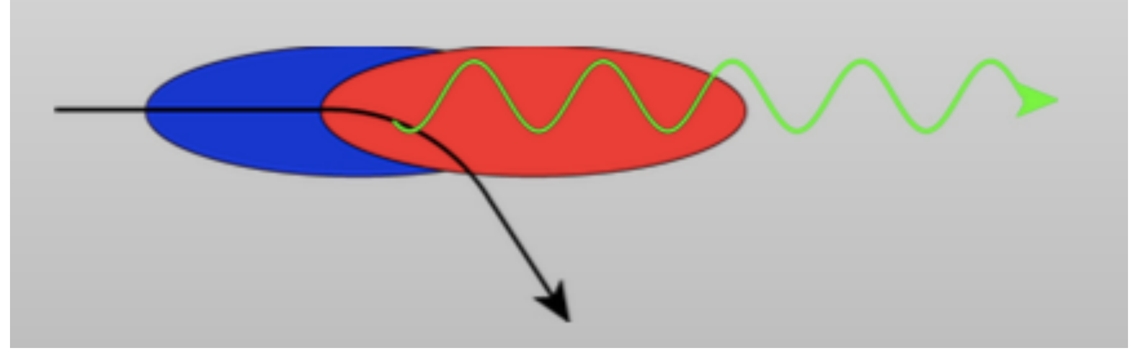

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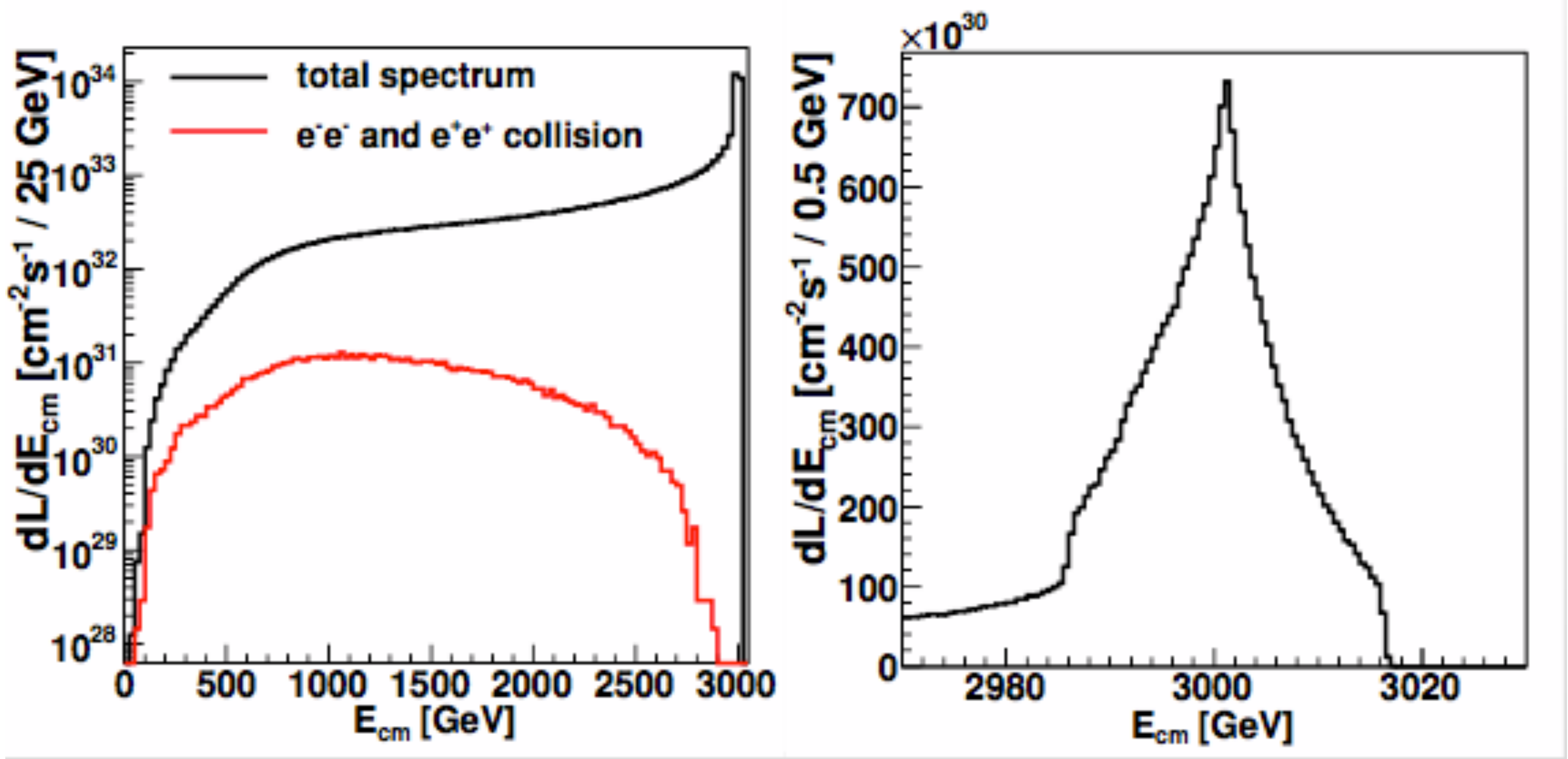

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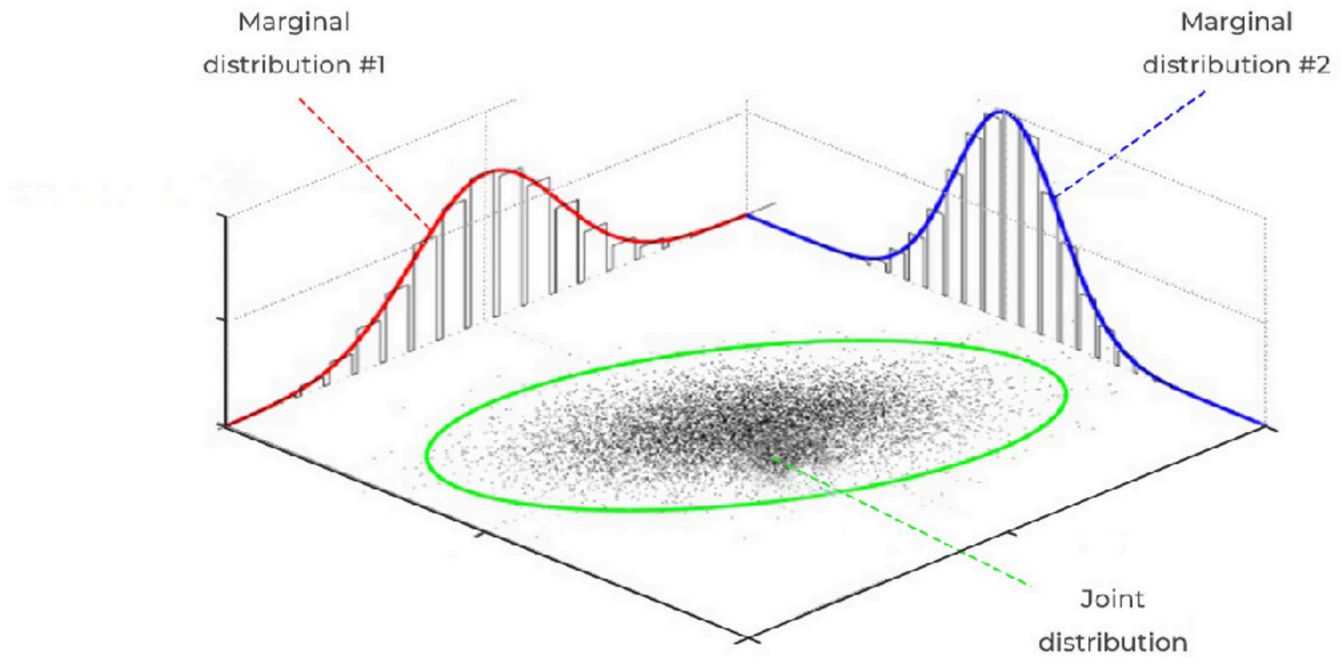
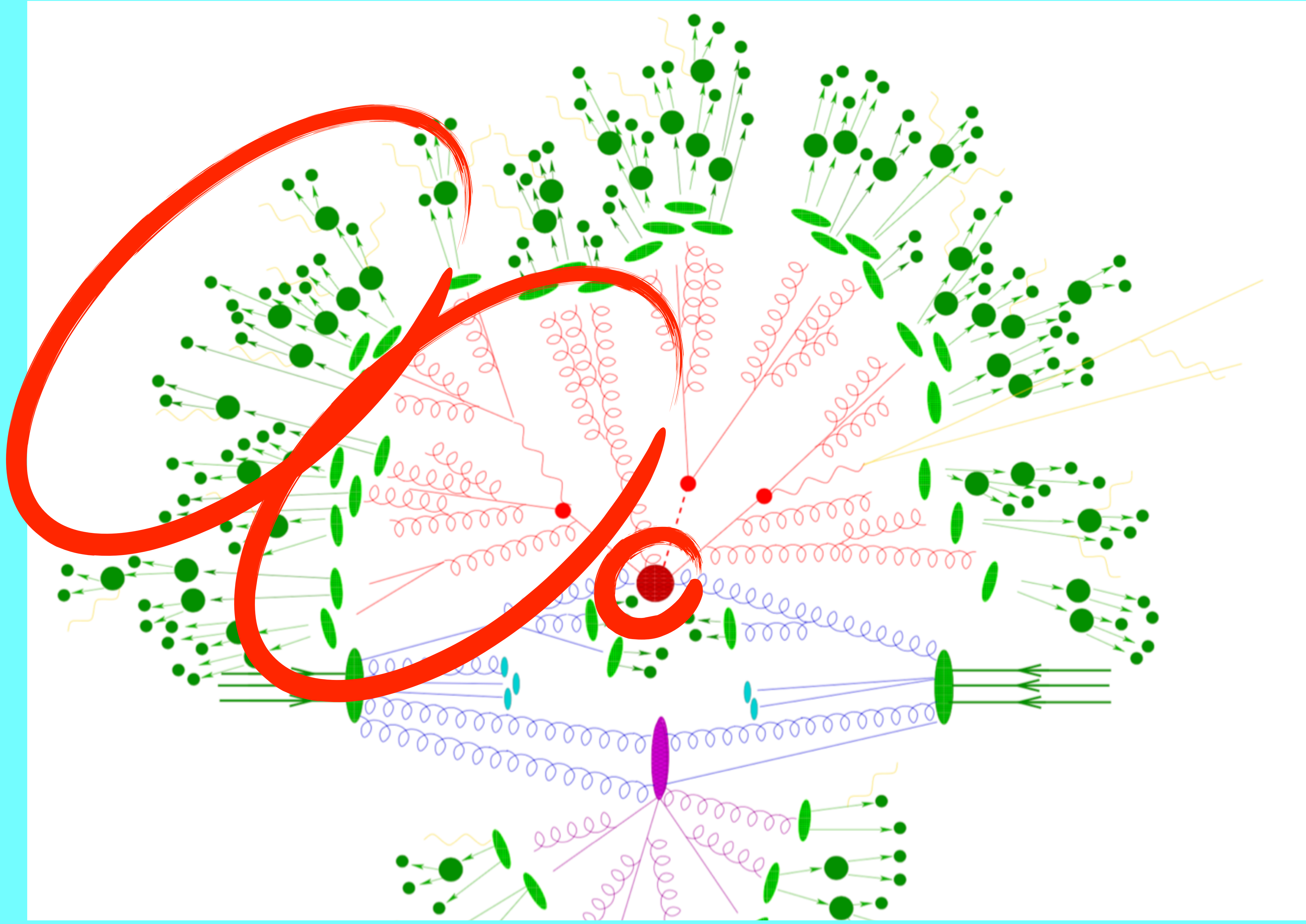
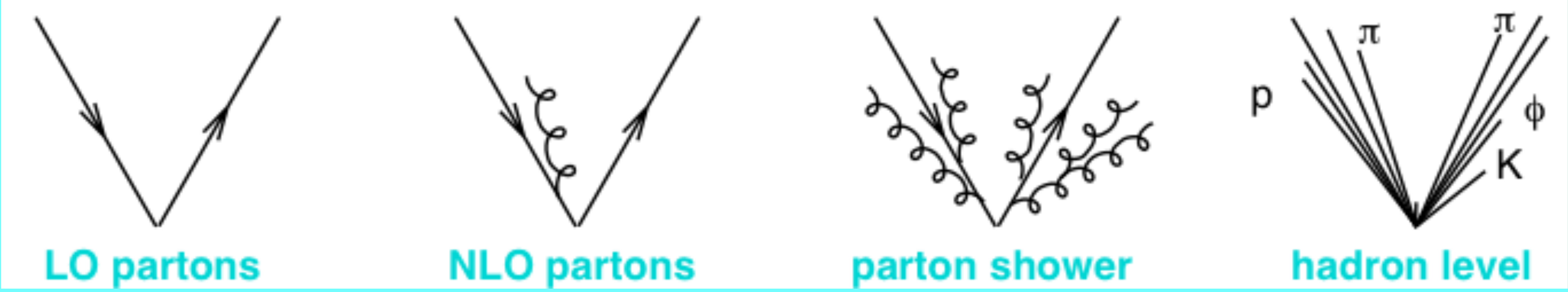
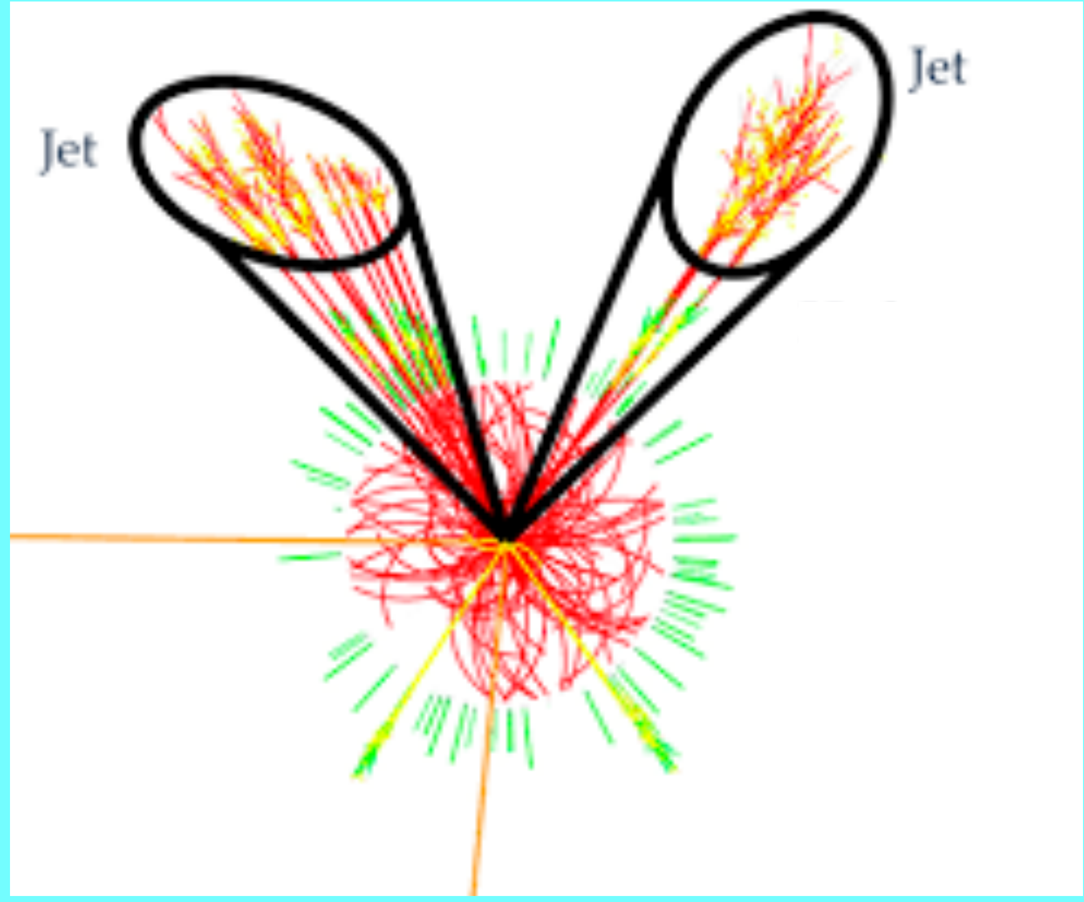


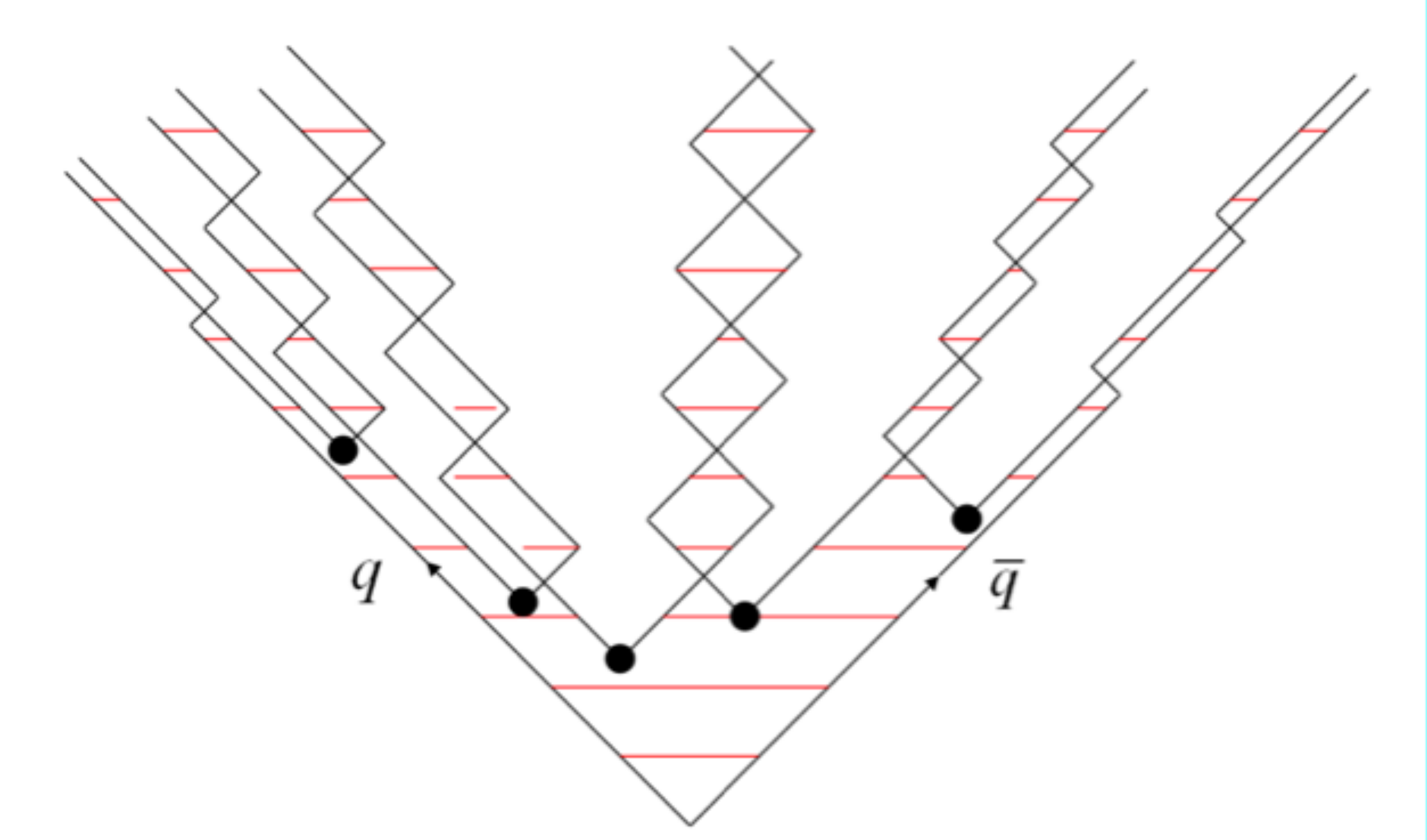
- Multi-Dim fits only viable option for photon colliders/CLIC/PWFA! (ERL?)
- Parameterized spectra still be useful: fast evaluation, unfolding
- 3D-structure of beam spectra (z-dependence)

SM precision: fixed-order, resummed, hadronized

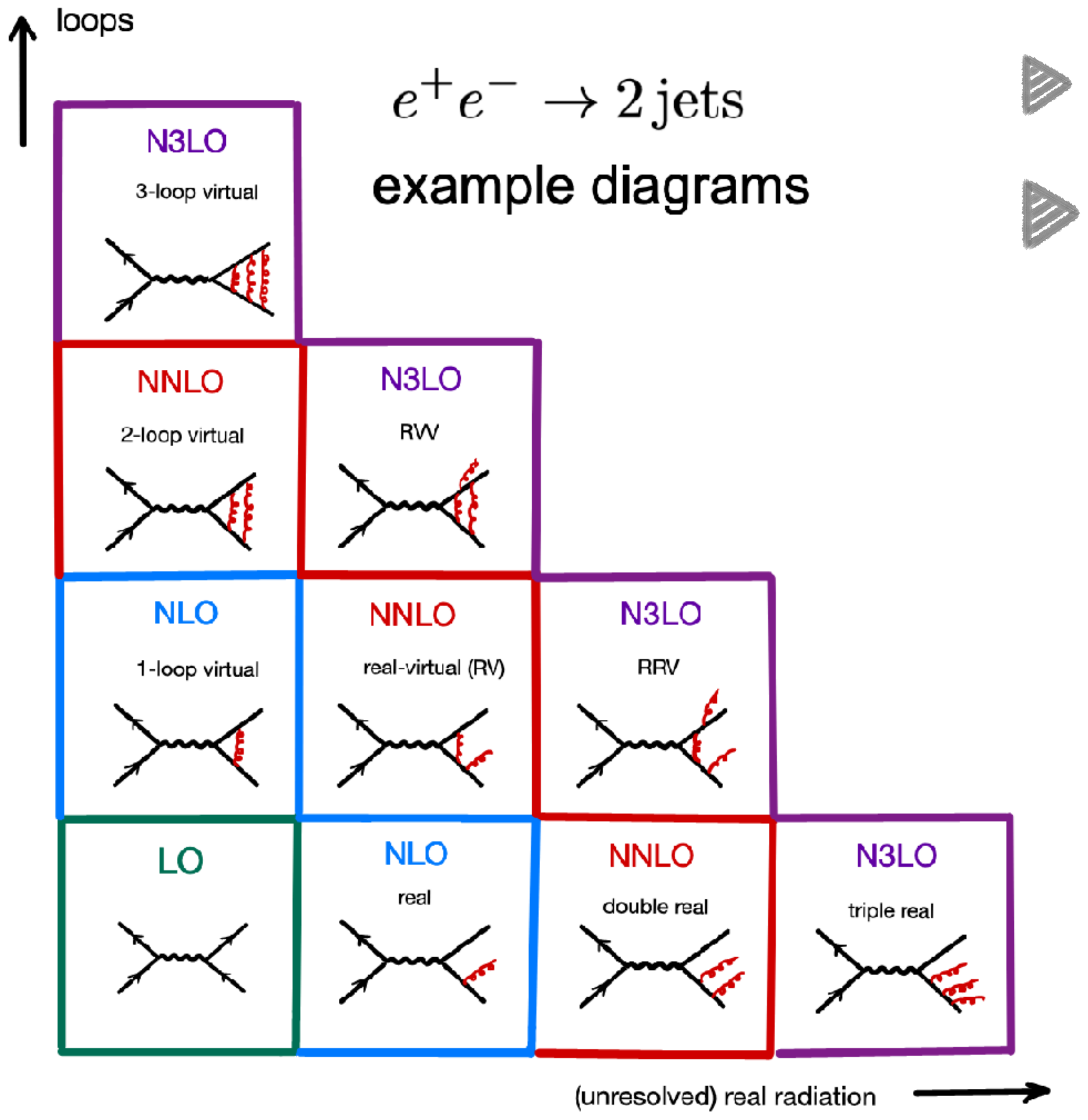








The “Exclusive” Frontier — fN(N)LO, Automation in MCs



- NLO QCD ⊕ EW automated: `Sherpa, MadGraph5_aMC@NLO, Whizard` (NLO EW caveats)
- Signal & bkgd. samples at full SM QFT interference level @ NLO QCD ⊕ EW

NLO EW

Pia Bredt, Phd thesis, DESY, 2022, arXiv:2212.04393

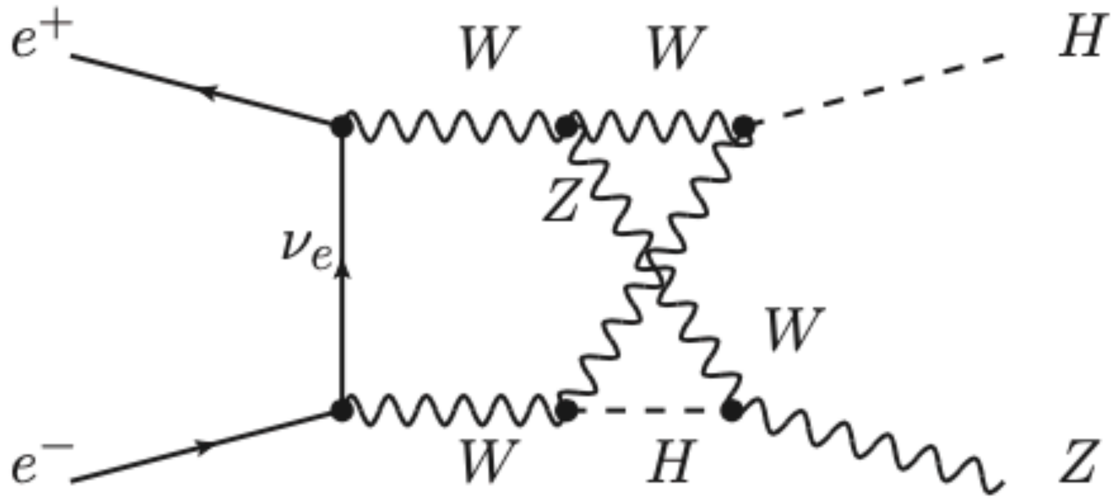
$\sqrt{s}$ [GeV]	MCSANCee[37] $\sigma^{\text{tot}}_{\text{LO}}$ [fb]	MCSANCee[37] $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	WHIZARD+RECOLA $\sigma^{\text{tot}}_{\text{LO}}$ [fb]	WHIZARD+RECOLA $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	WHIZARD+RECOLA δ_{EW} [%]	σ^{sig} (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	62.42(1)	53.74(3)	62.41(2)	+16.14	0.2/0.3
1000	12.05(1)	14.56(1)	12.0549(6)	14.57(1)	+20.84	0.5/0.5

NLO QCD

	σ_{LO}[fb]	σ_{NLO}[fb]	K
$e^+e^- \to jj$	622.737(8)	639.39(5)	1.027
$e^+e^- \to jjj$	340.6(5)	317.8(5)	0.933
$e^+e^- \to jjjj$	105.0(3)	104.2(4)	0.992
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)	1.100
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)	1.245
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)	1.049
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)	1.110
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)	1.225
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)	1.357

Three major bottlenecks to go to NNLO

- Virtual integrals with many mass scales / off-shell legs
- Process-independent (generic) automated NNLO subtraction
- Negative weights in NLO simulations deteriorate at NNLO

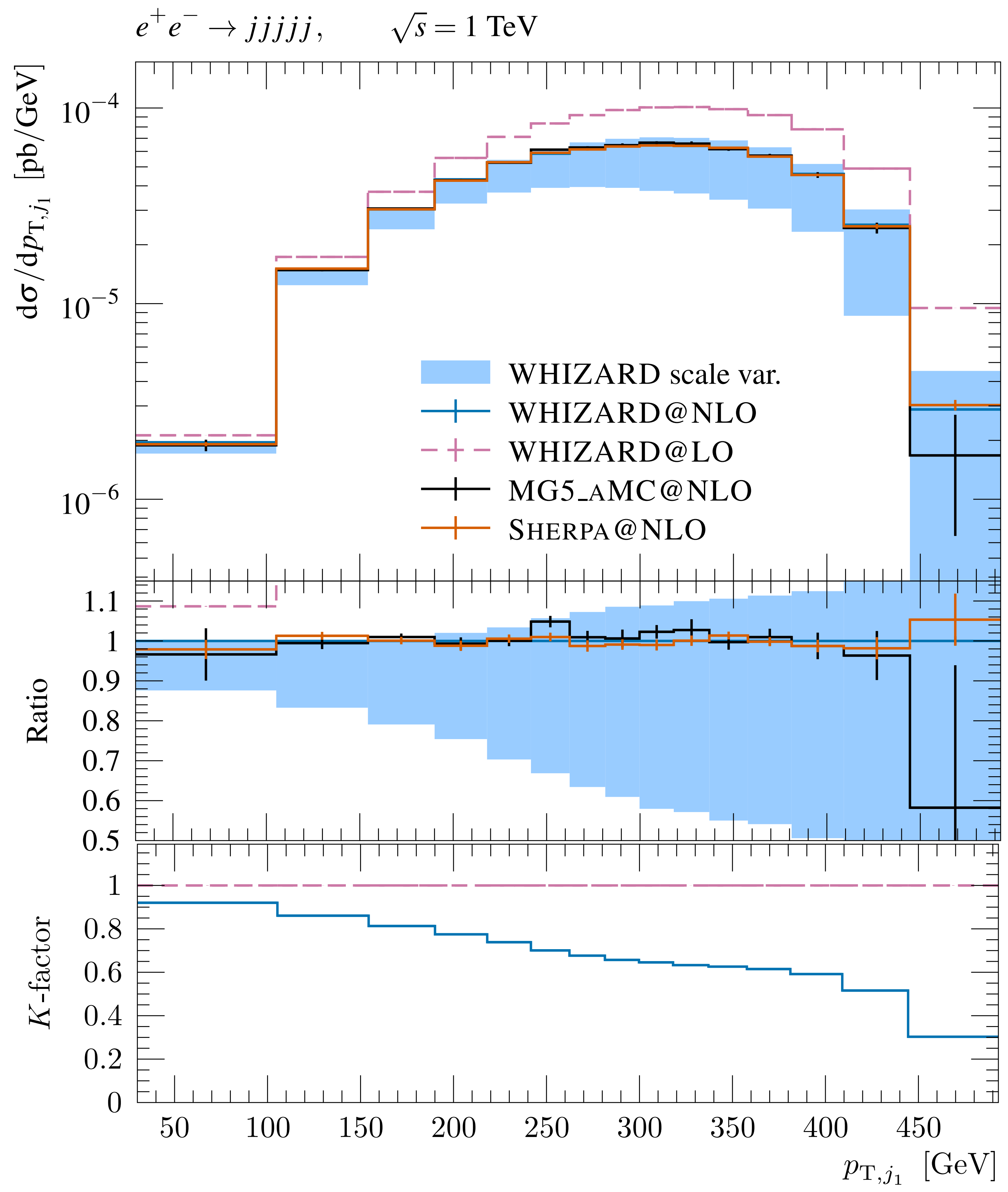


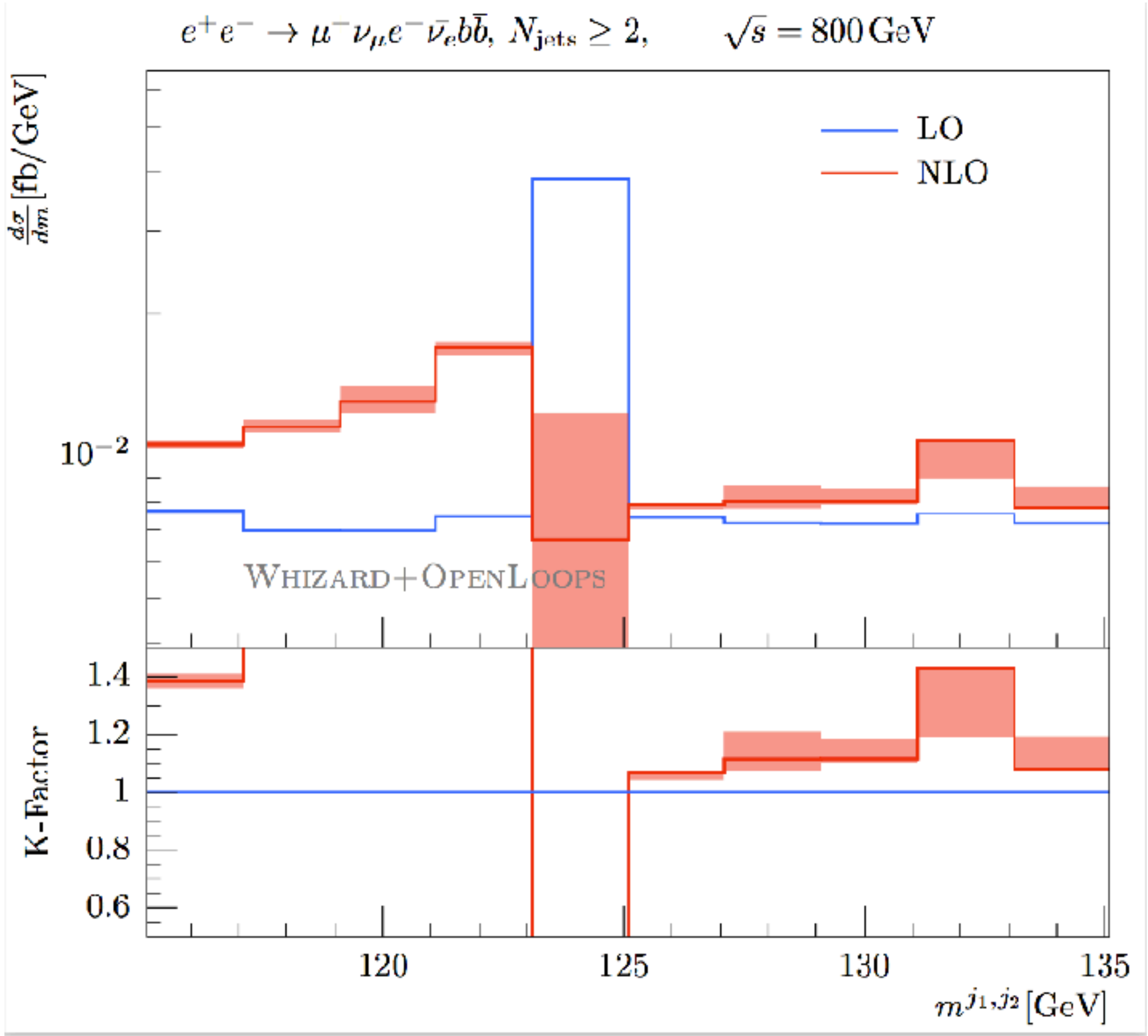
The “Exclusive” Frontier — fN(N)LO Automation in MCs

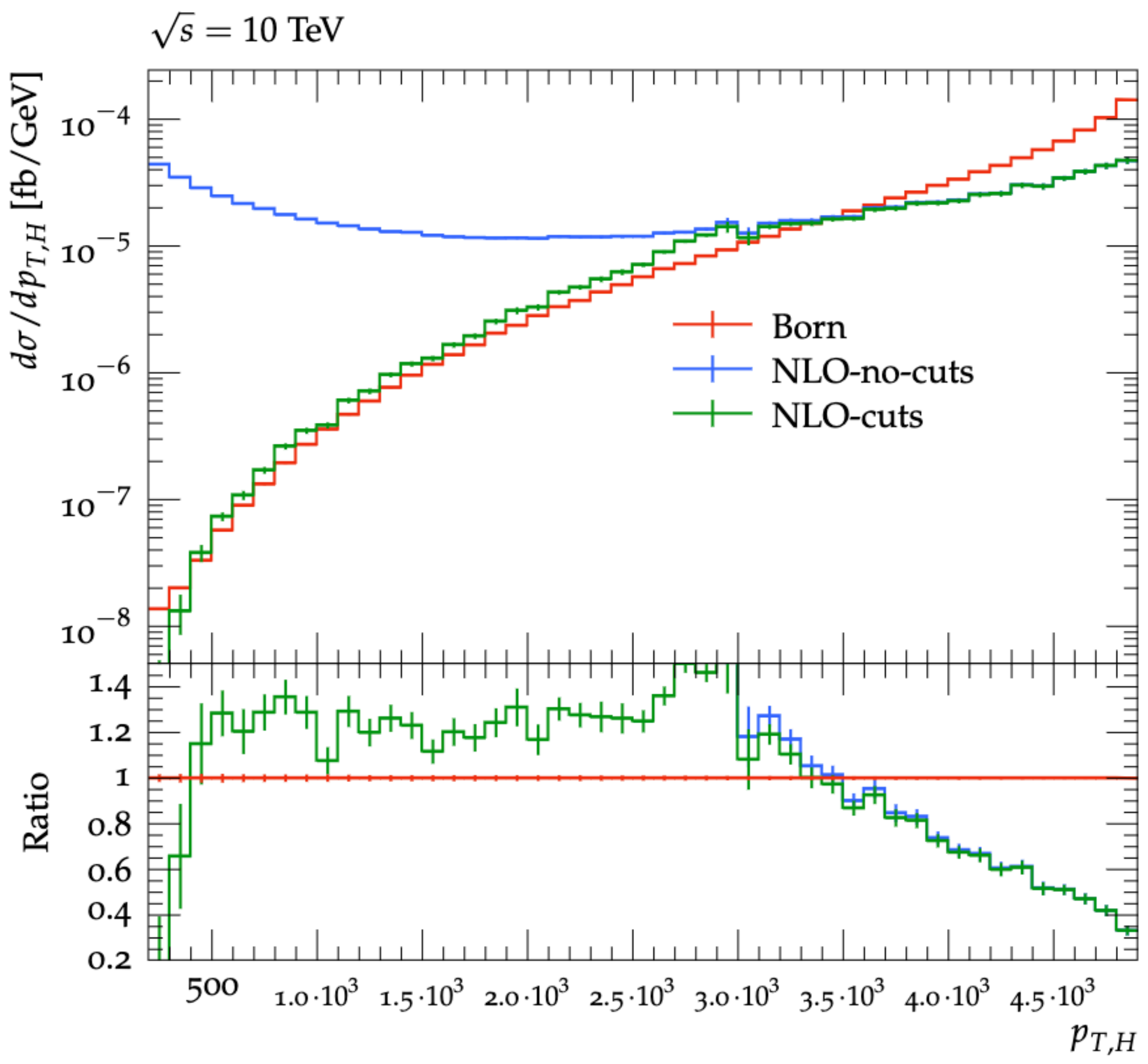
$e^+e^- \to jjjjj$ @ 1 TeV, NLO QCD

$e^+e^- \to \ell_1^+\nu_1\ell_1^-\bar{\nu}_2 b\bar{b}$ @ 0.8 TeV, NLO QCD

$\mu^+\mu^- \to ZH$ @ 10 TeV, NLO EW



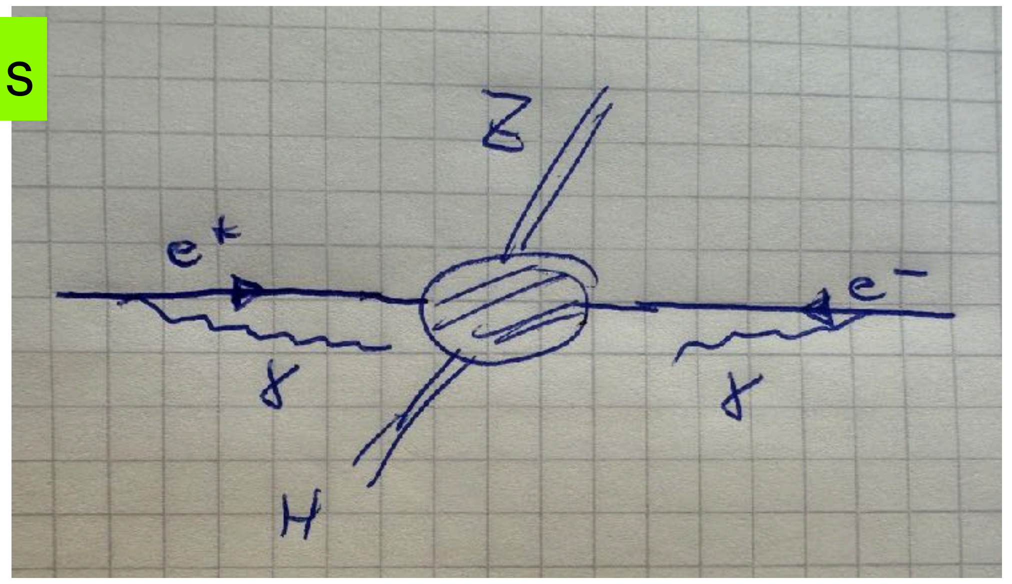




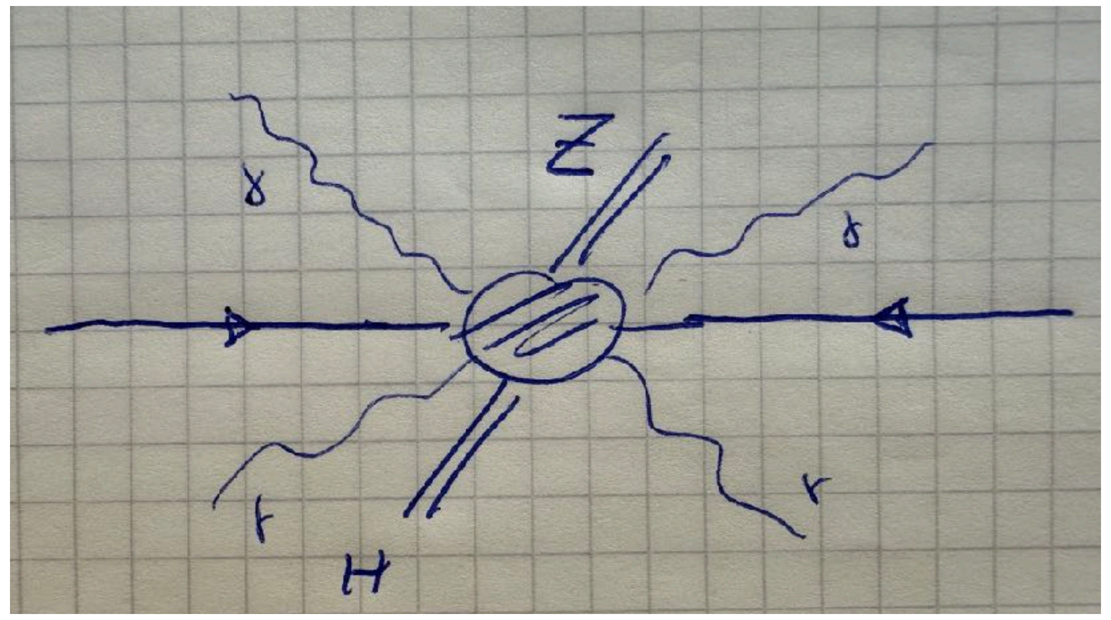
QED PDFs — QED Inclusive Photons

Collinear logarithms

$$L = \log \frac{Q^2}{m^2}$$

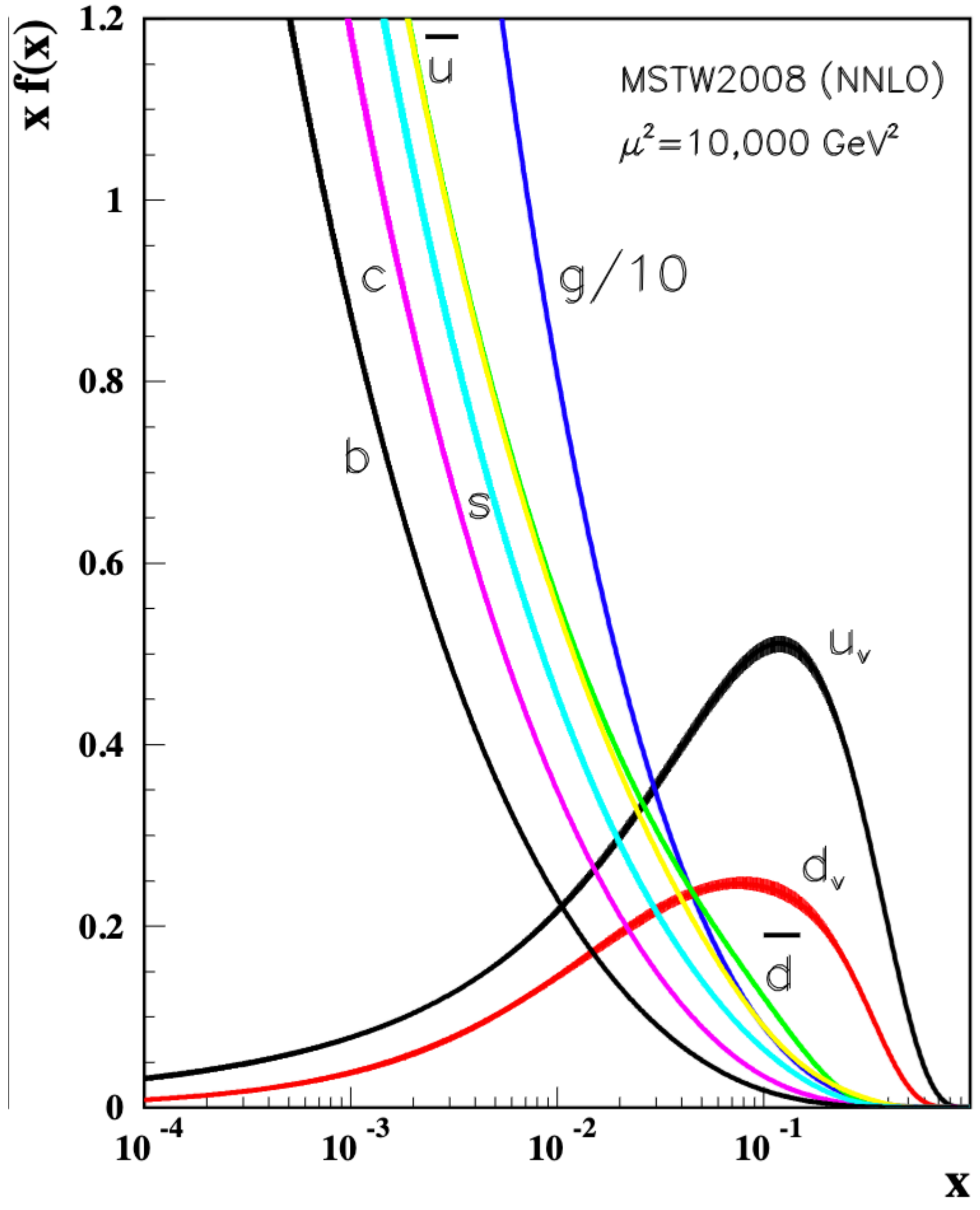


$$\sigma = \alpha^b \sum_{n=0}^{\infty} \alpha^n \sum_{i=0}^{n} \sum_{j=0}^{n} \varsigma_{n,i,j} L^i \ell^j$$



Soft logarithms

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



QED PDFs — QED Inclusive Photons

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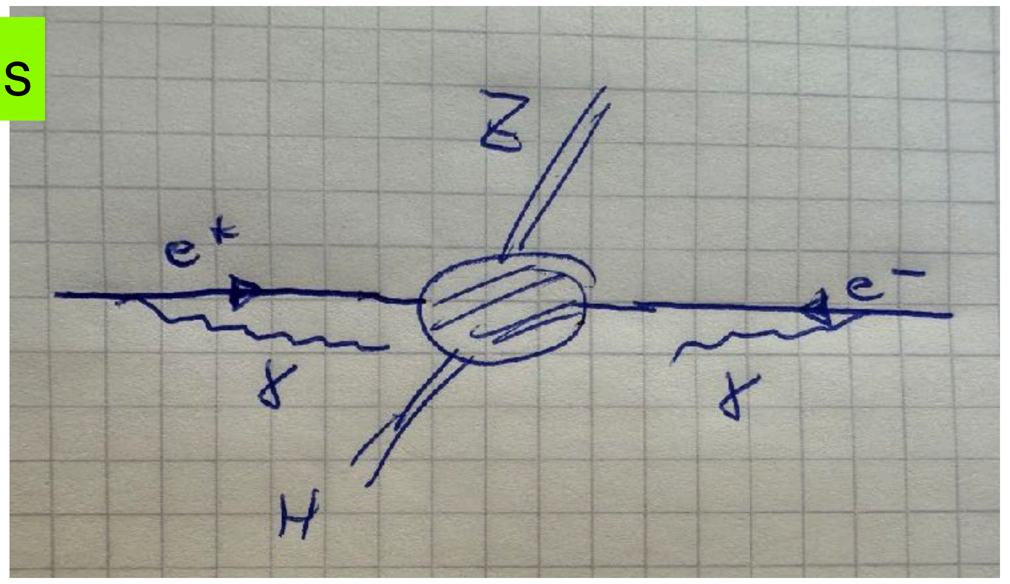

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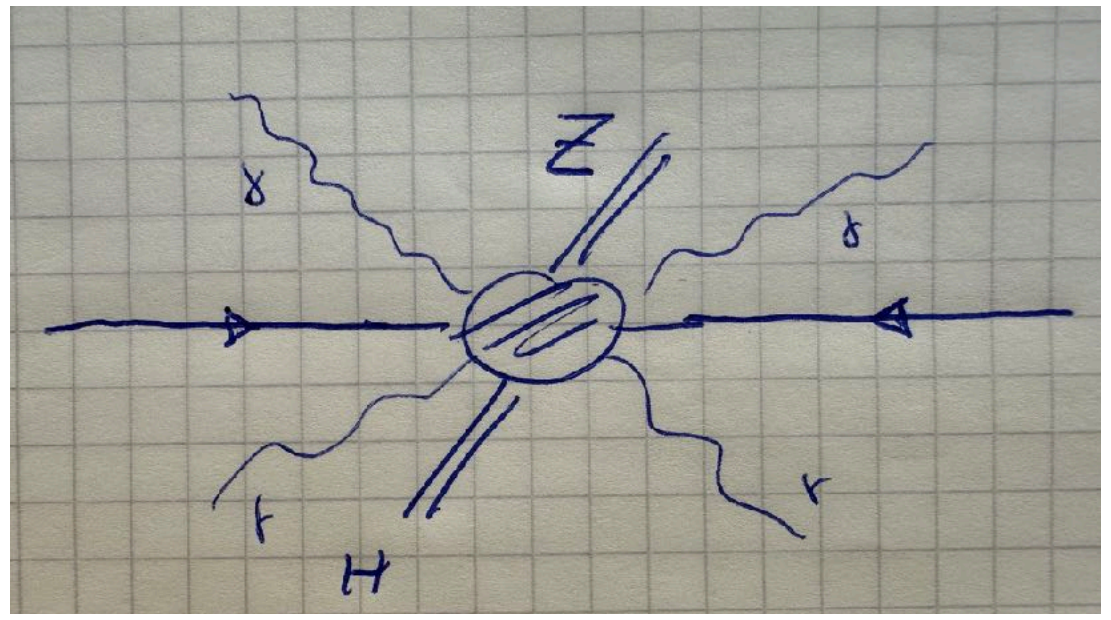
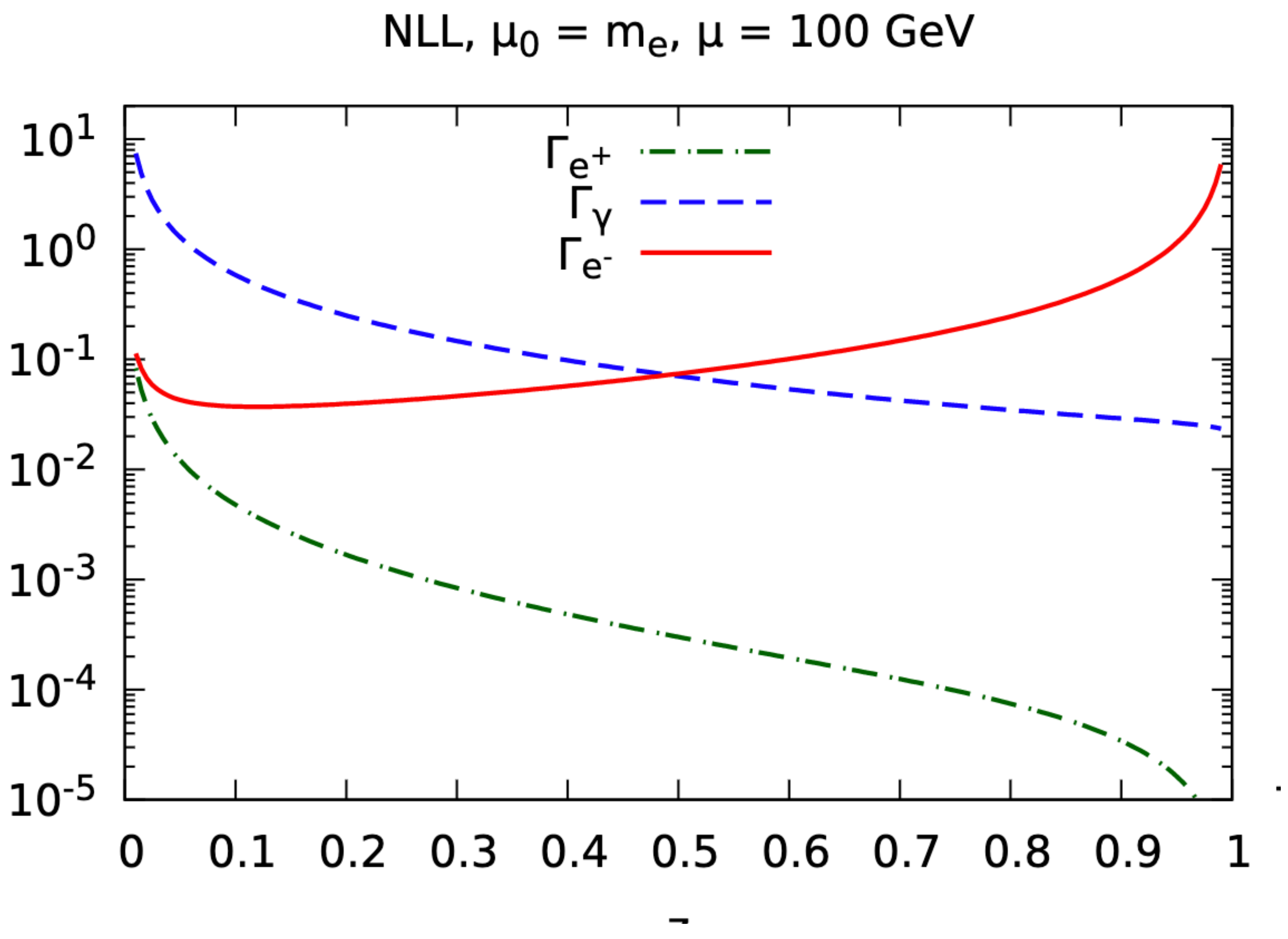


Soft logarithms

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

- Collinear factorization: universal QED ePDFs, LL: $(\alpha L)^k$, NLL: $\alpha(\alpha L)^{k-1}$
- NLO EW: fixed order with massive electrons vs. massless with NLL ePDFs
- 2nd option: most precise normalization of total cross section [2-4 per mille]
- Numerical stability intricate: integrable singularity for $z \to 1$
- Implementations available in `MG5` and `Whizard`

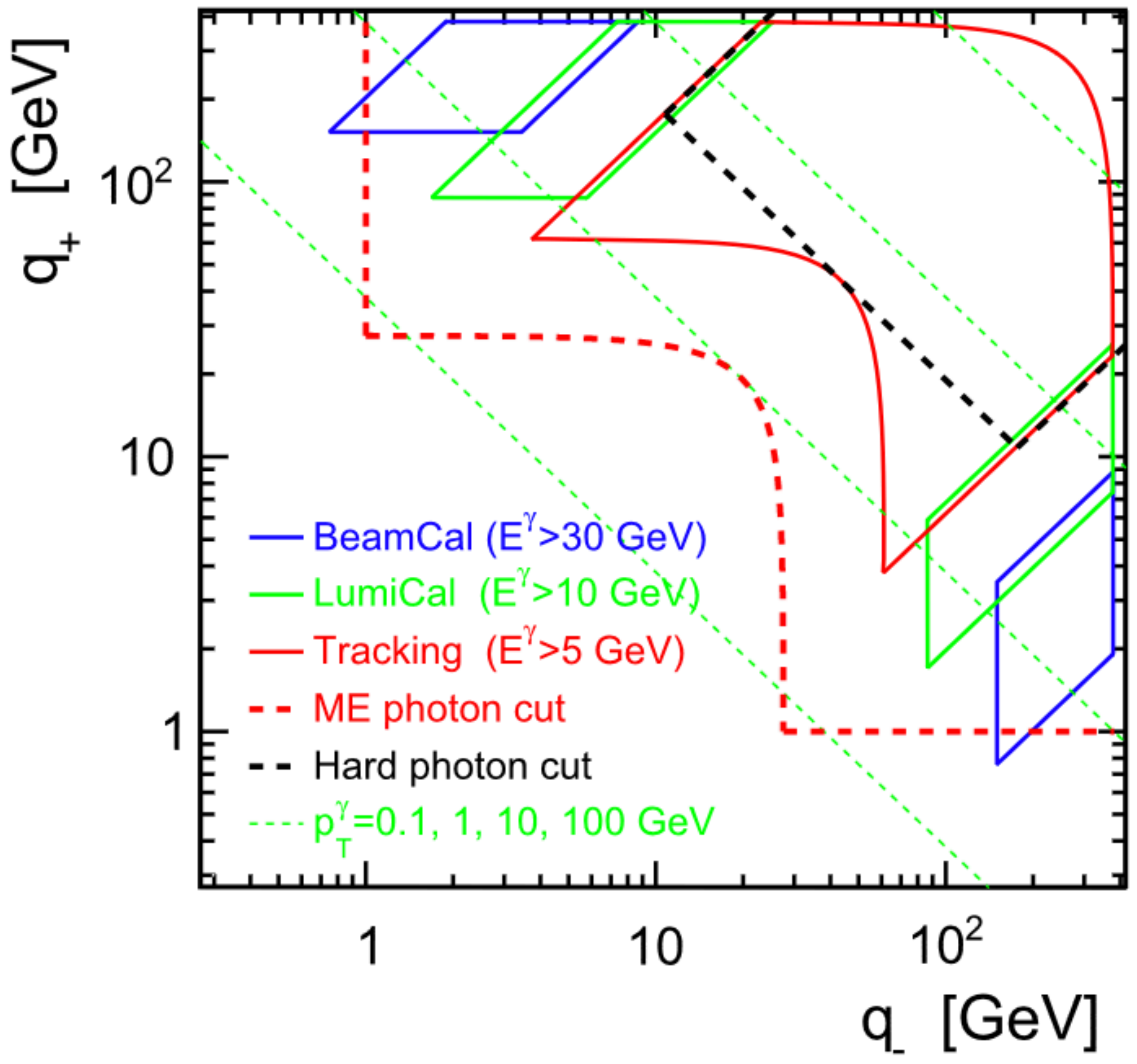


ePDFs for polarized leptons !?

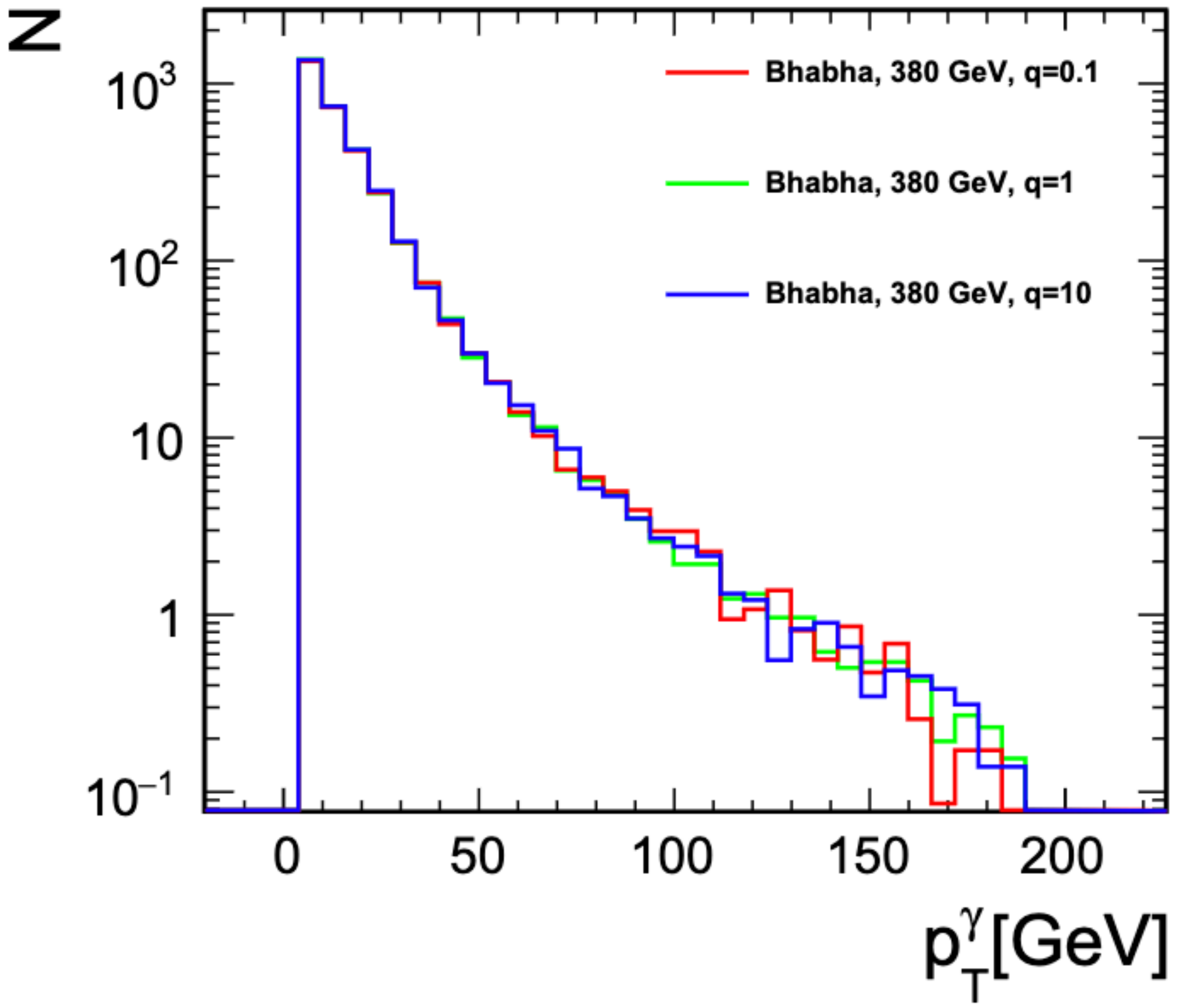
Exclusive Photon Simulation

- Exclusive photon distribution important for detector optimization / mono-photon searches etc.
- Different algorithms: QED shower, soft/eikonal resummation (YFS), recursive algorithms
- Challenges: Proper transverse momentum distributions, QED/EW matching algorithms

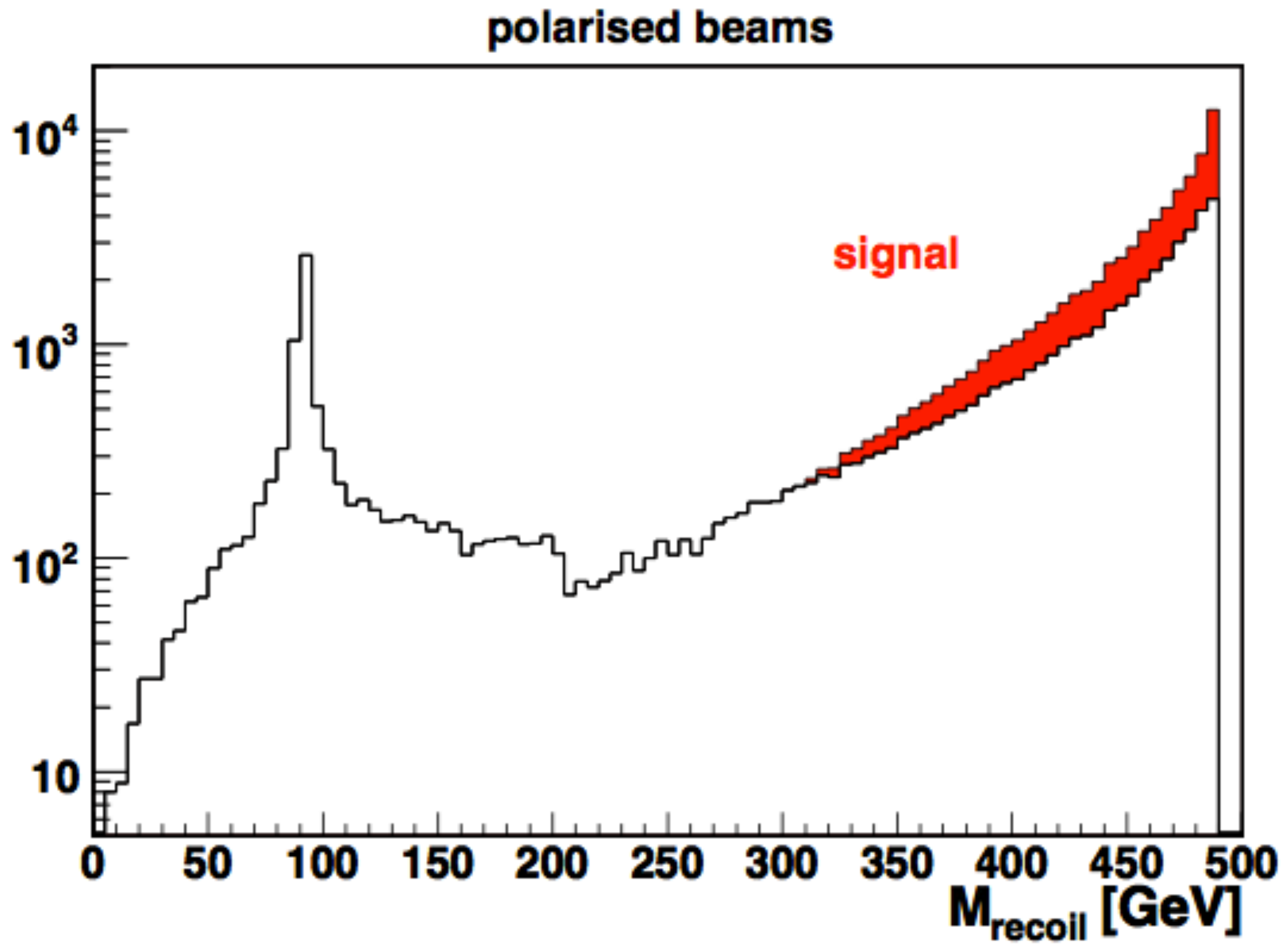
Photon matching in detector components



Photon matching in Bhabha scattering

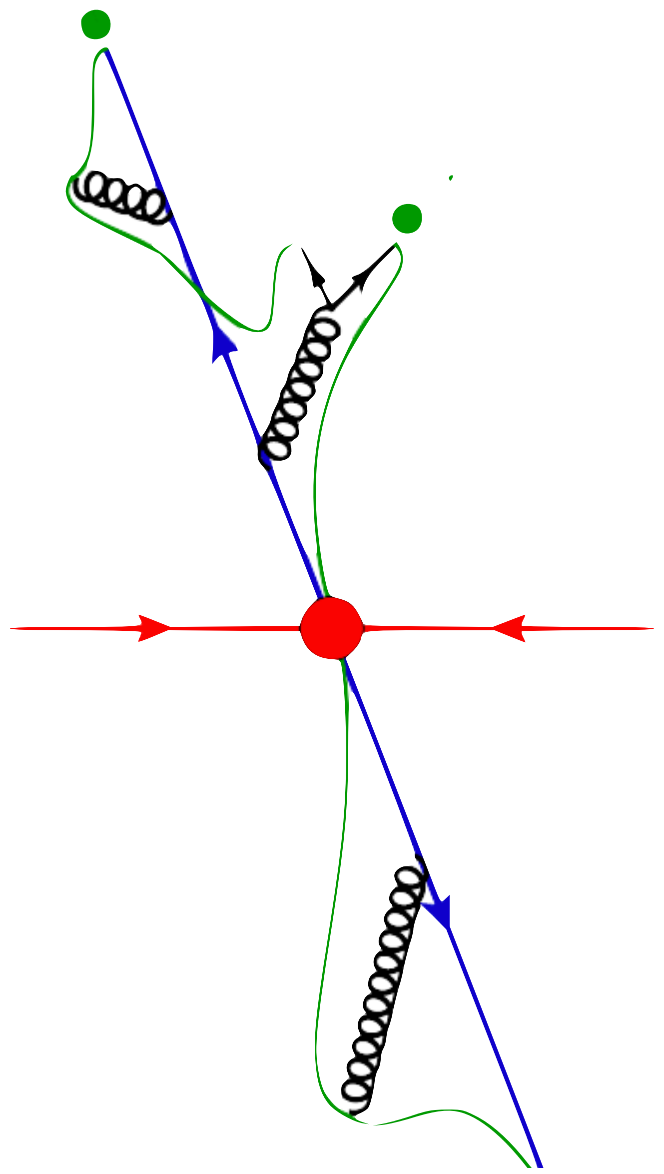


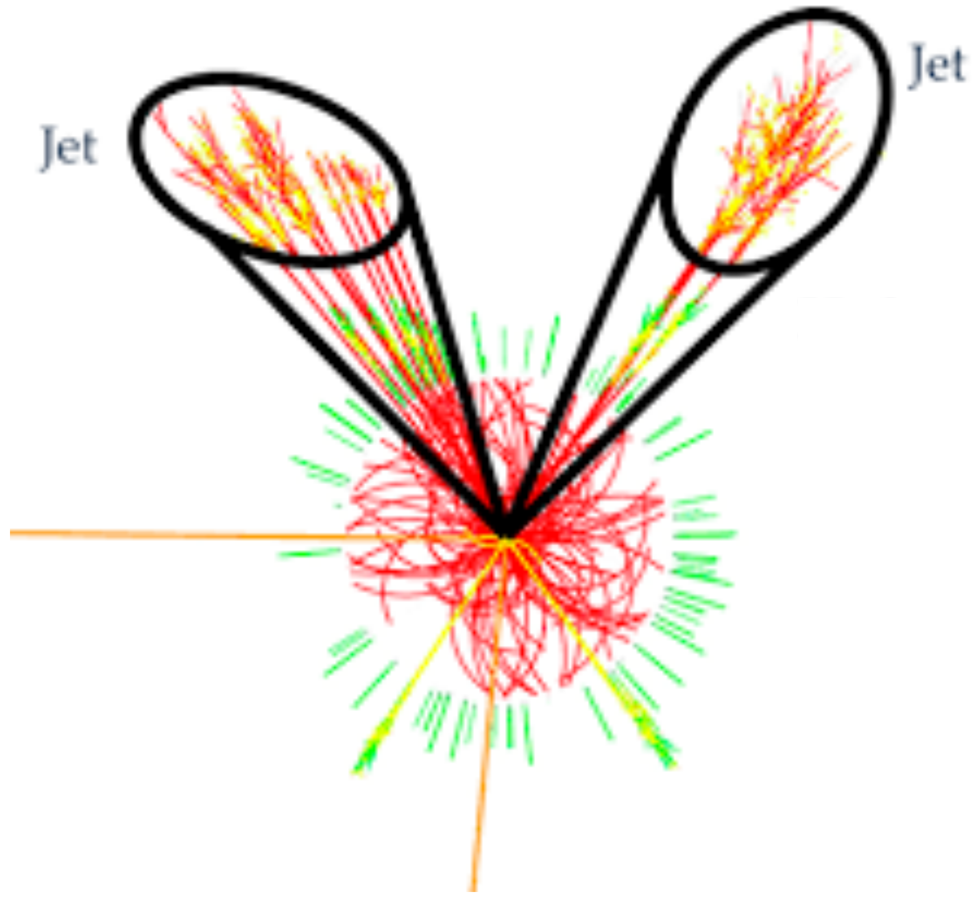
Mono-photon recoil spectrum in DM search



J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

Parton Showers, Matching, Merging, Hadronization

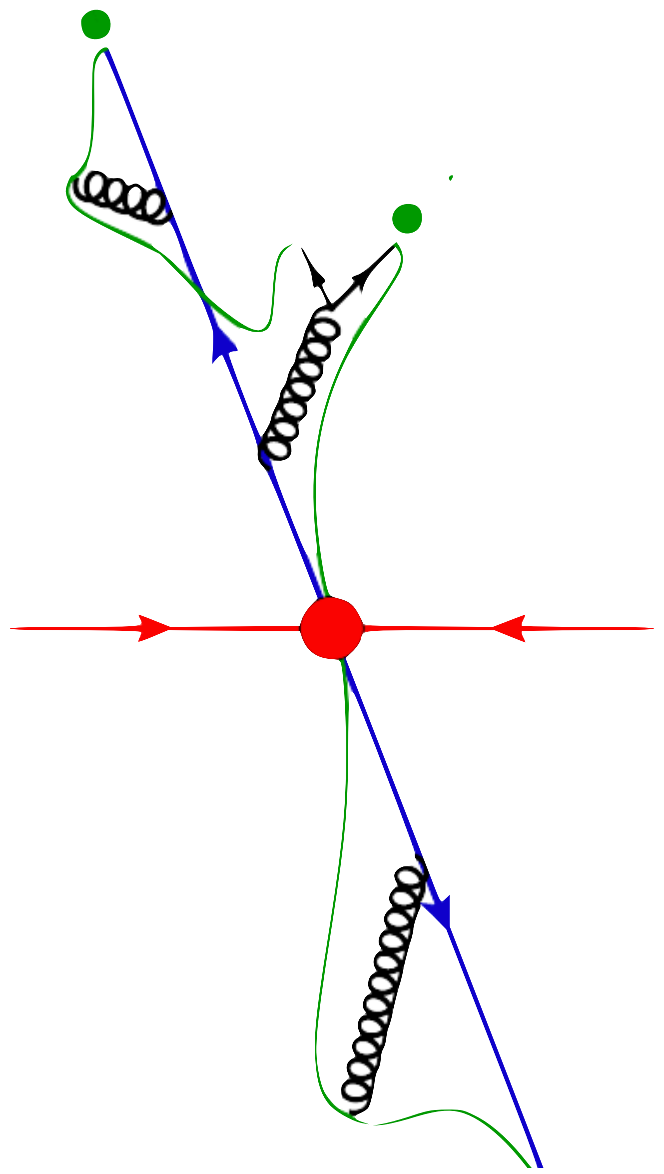


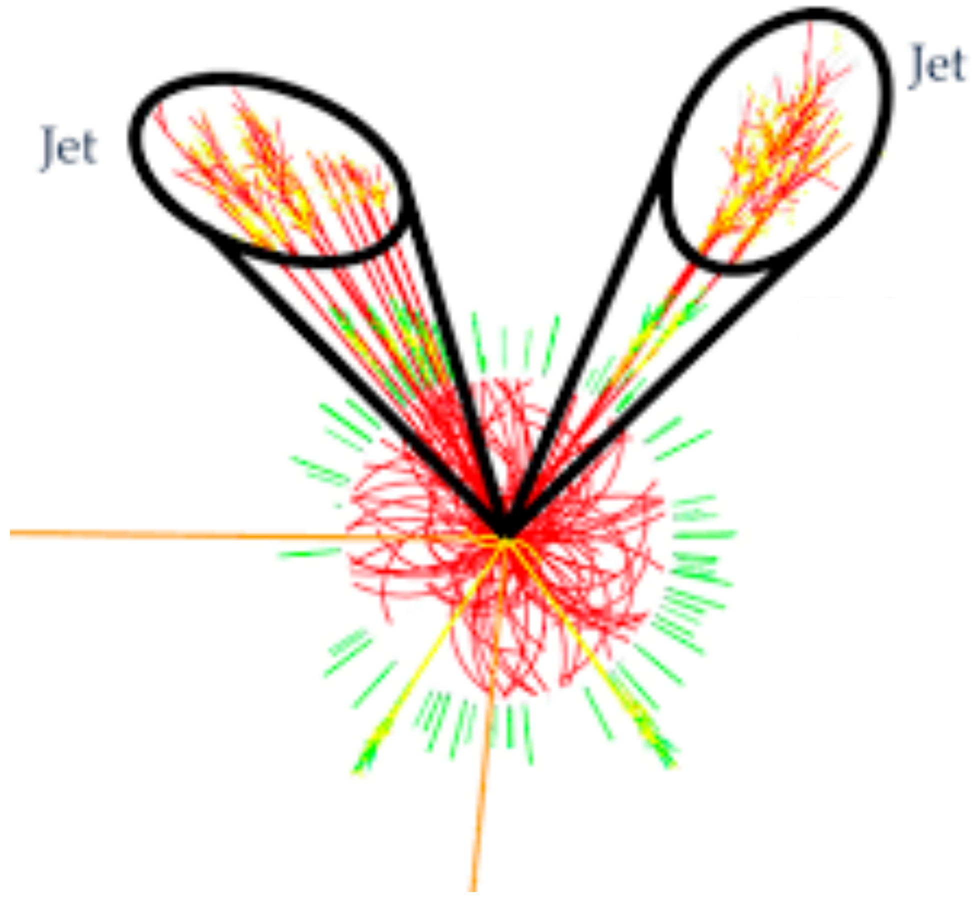


- Parton showers resums large logarithms; provide exclusive multi-jet events
- A lot of progress driven by LHC: final-state showers already accurate at NLL, NNLL w.i.p.
- "Interleaved" showers: QCD / QED / EW emissions $\alpha_s/\alpha \sim 15$ (sampled with veto algorithm)
- Matching: consistently combine fixed-order emissions with resummed shower emissions

Shower	Ordering	NLL Validation
PanScales [2002.11114]	[1] $0 \leq \beta < 1$	Fixed and all order numerical tests for a range of observables
Alaric [2208.06057]	k_t $(\beta = 0)$	Analytical, numerical tests for global event shapes
Deductor [2011.04777]	k_t, Λ $(\beta = 0, 1)$	Analytical and numerical tests for thrust
Manchester-Vienna [2003.06400]	k_t $(\beta = 0)$	Analytical for thrust and multiplicity

Parton Showers, Matching, Merging, Hadronization





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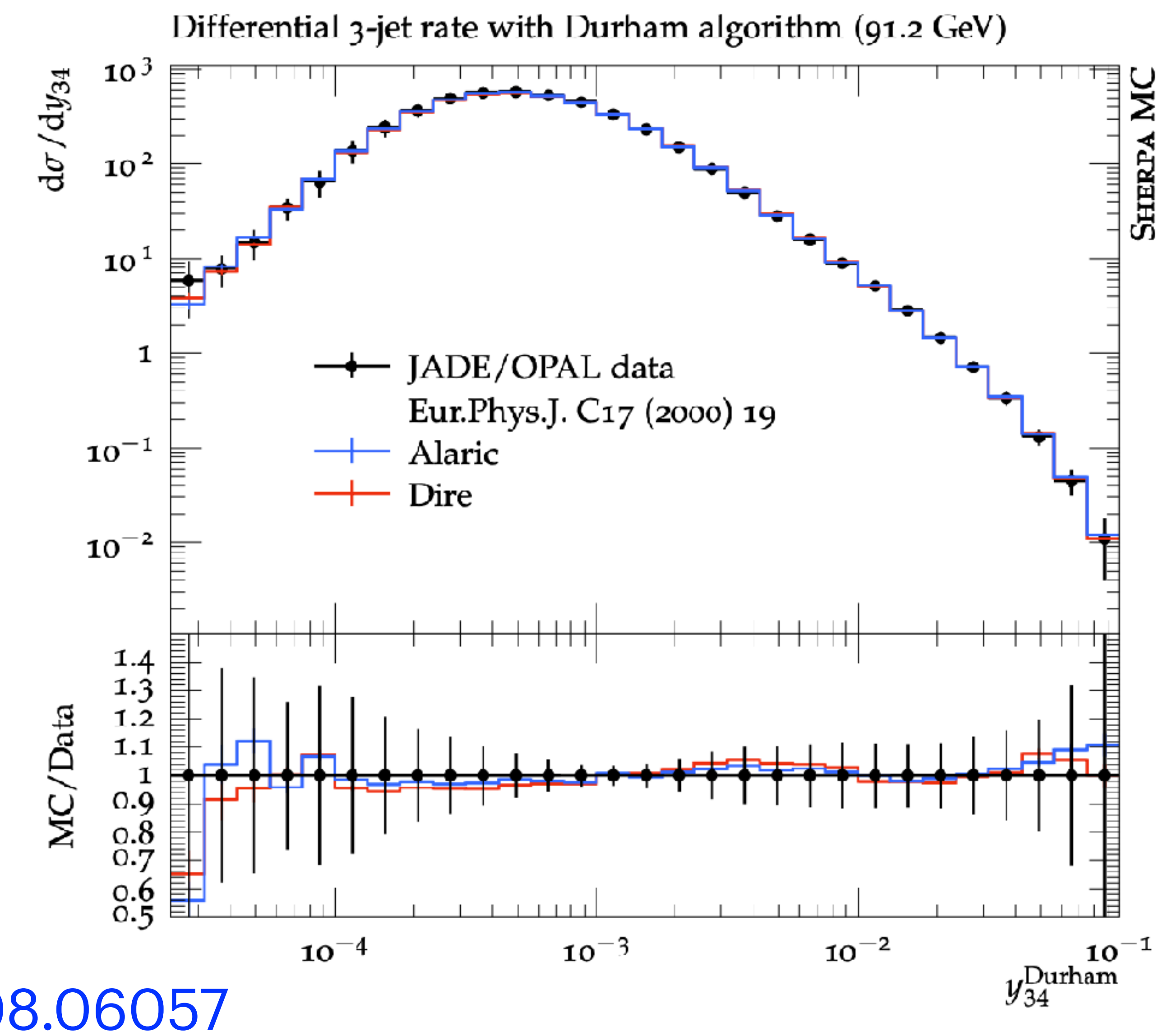

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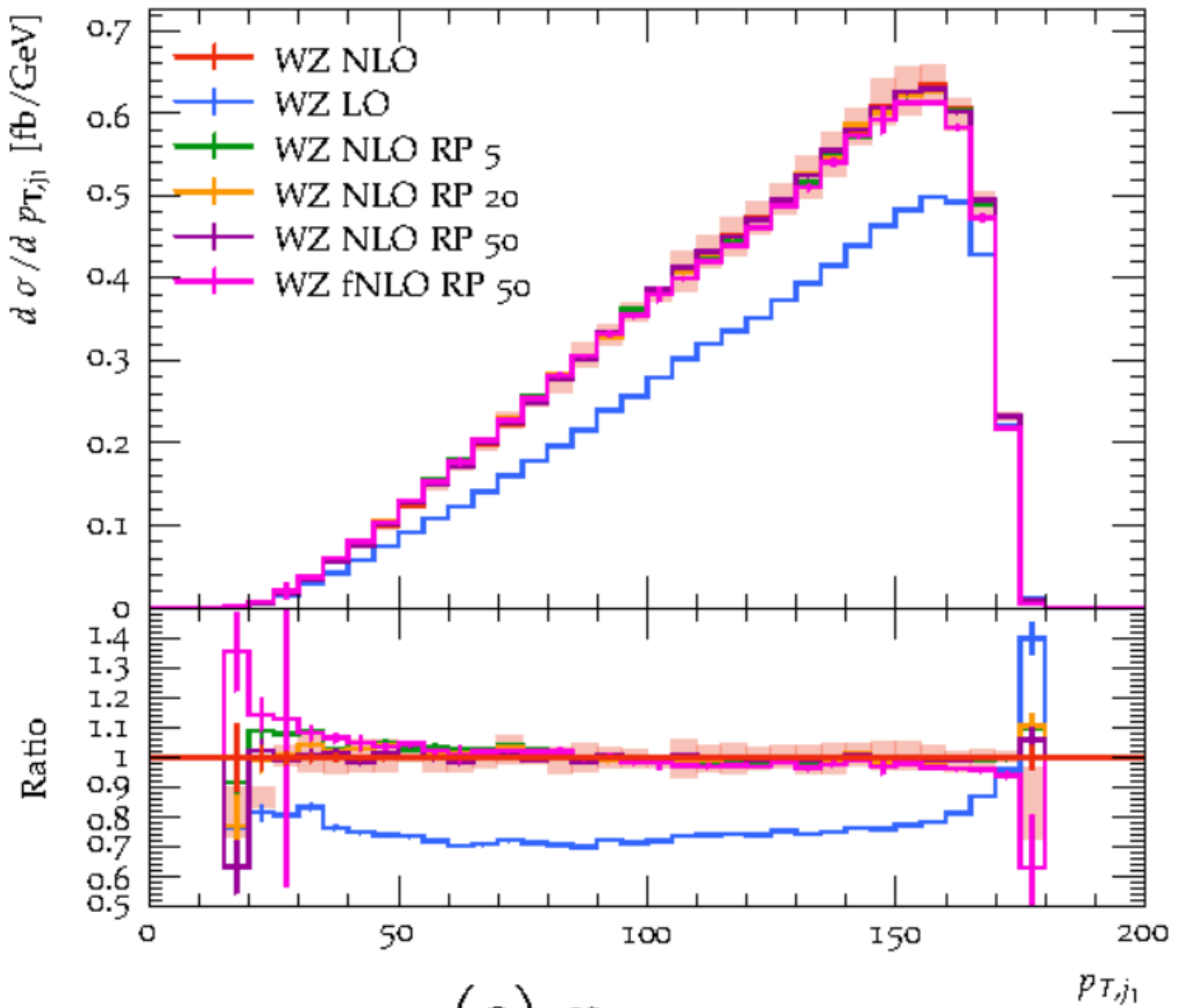
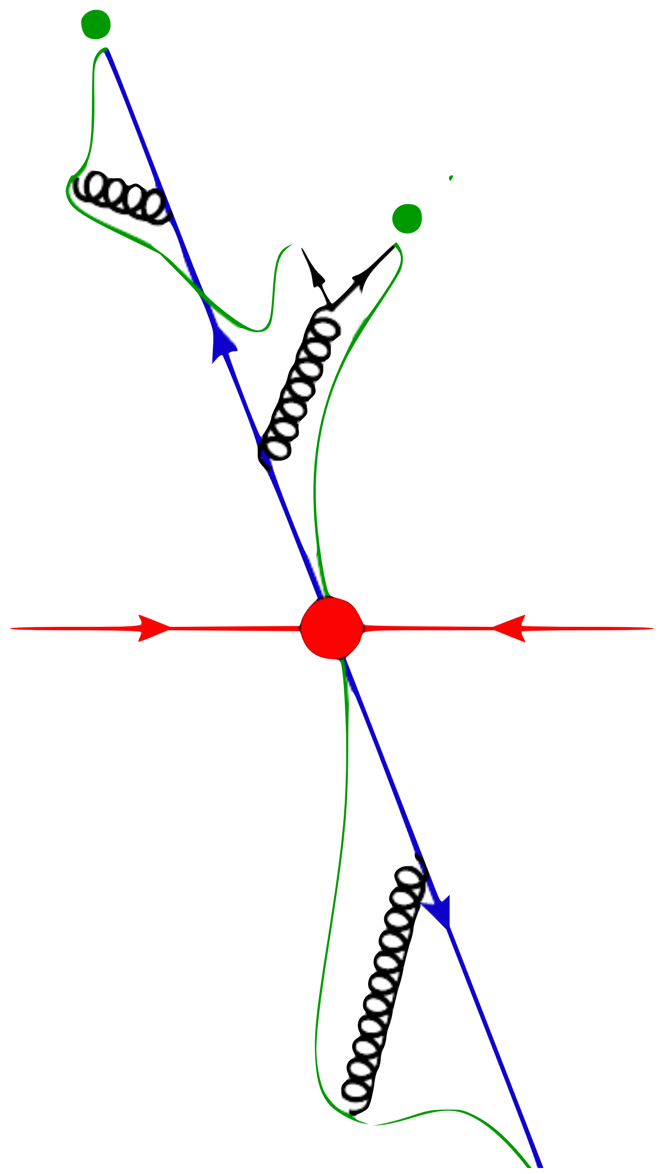
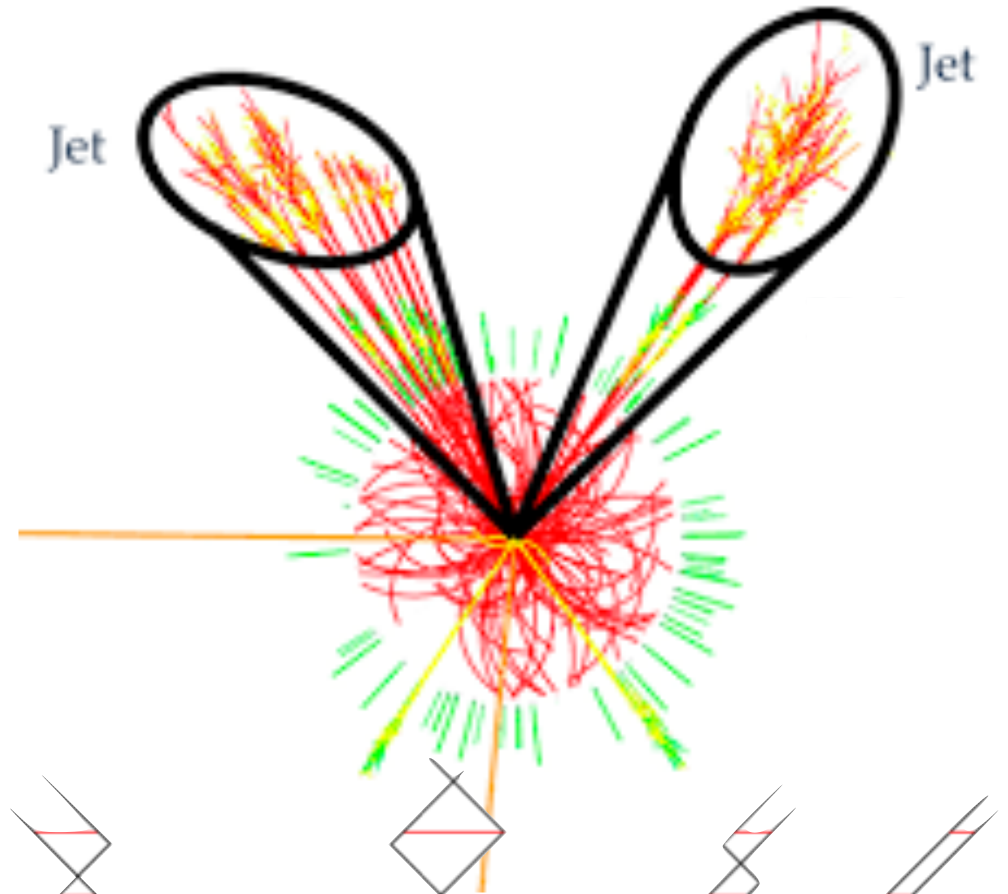
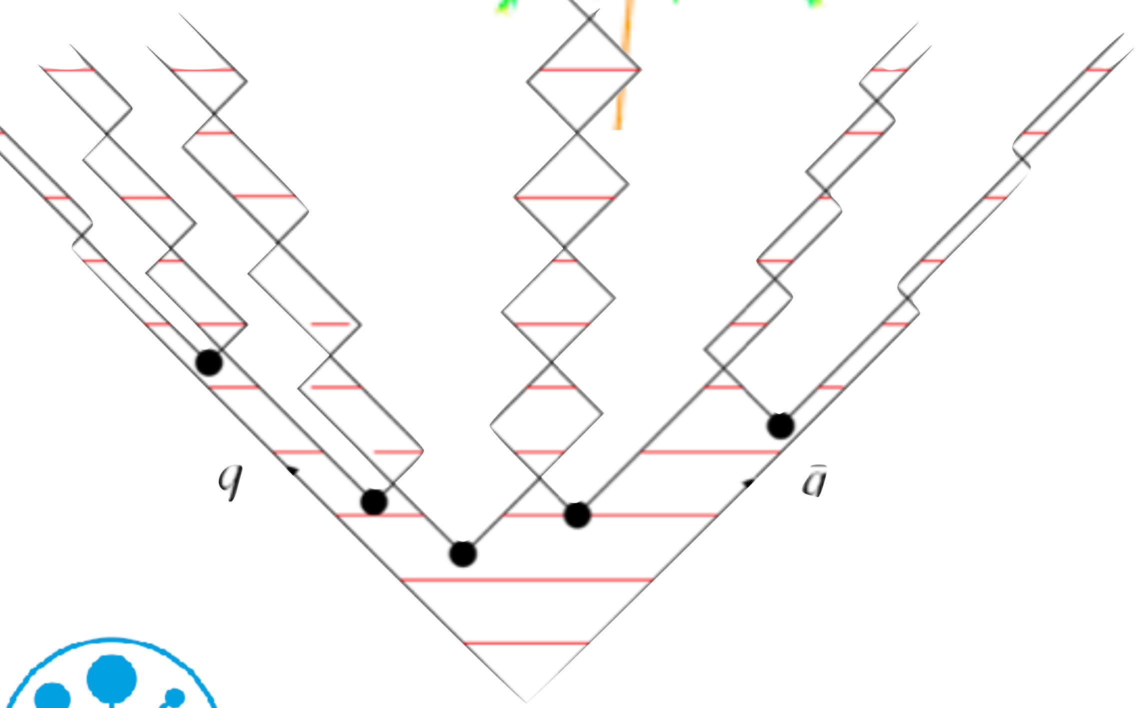


(c) p_{T,j_1}

Parton Showers, Matching, Merging, Hadronization







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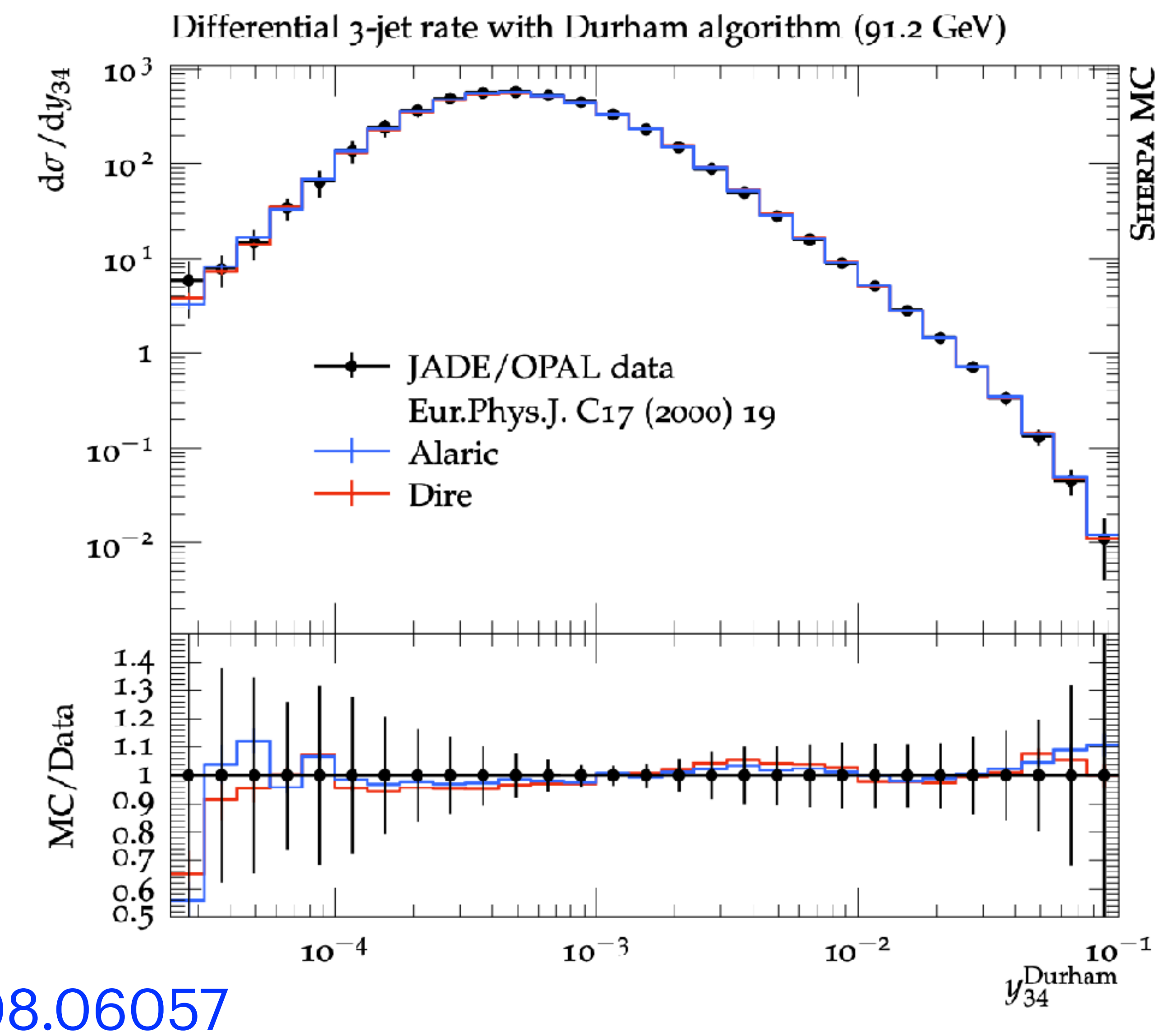

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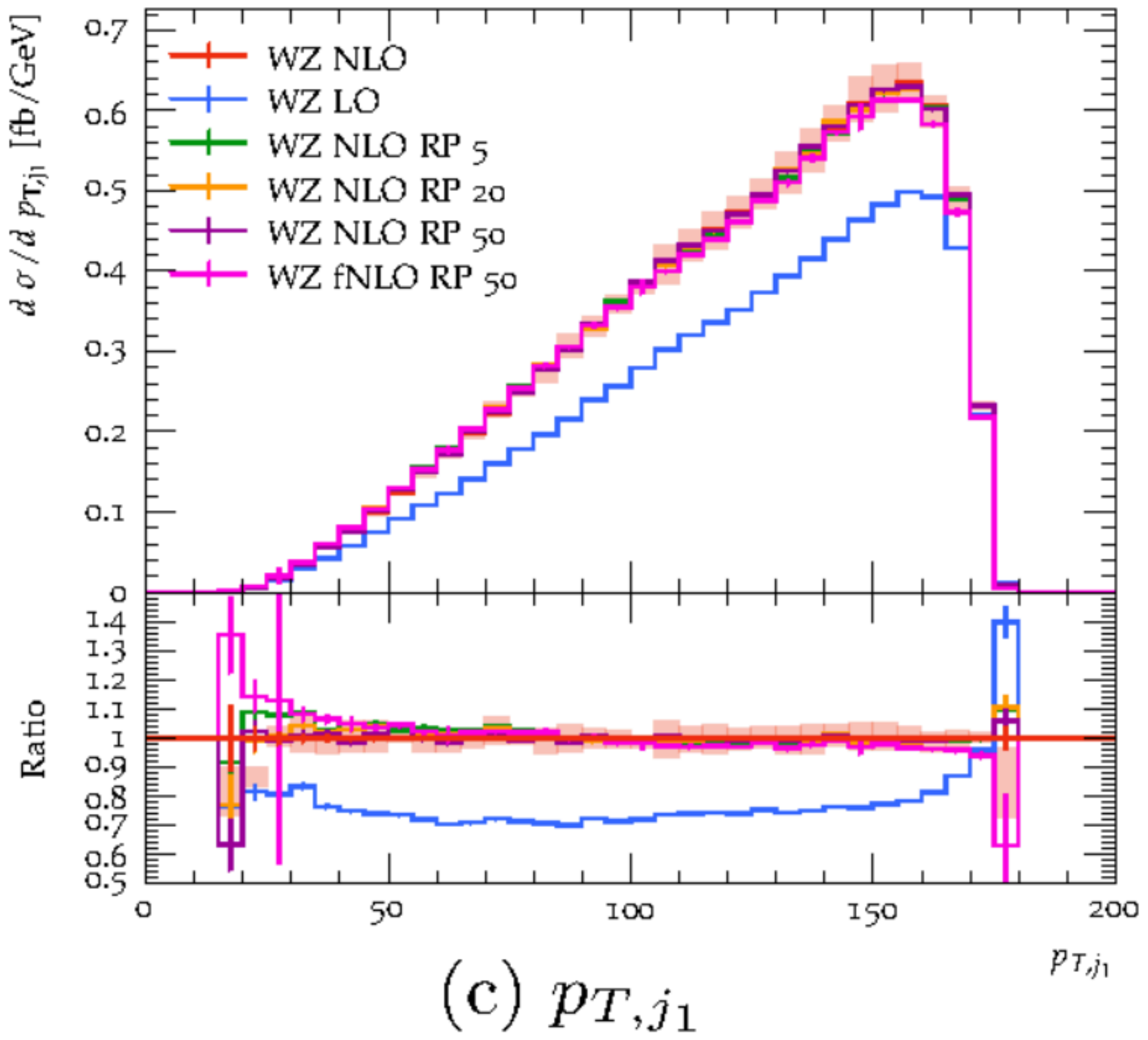
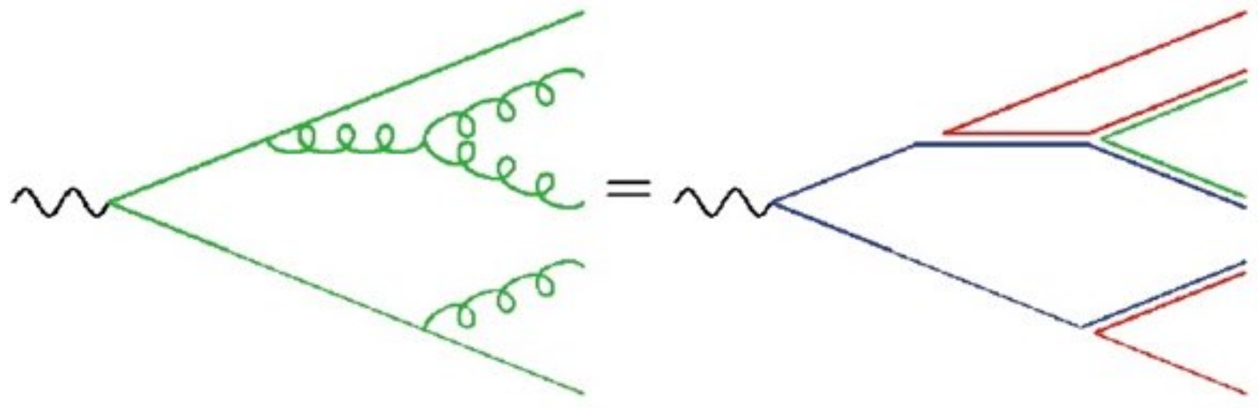
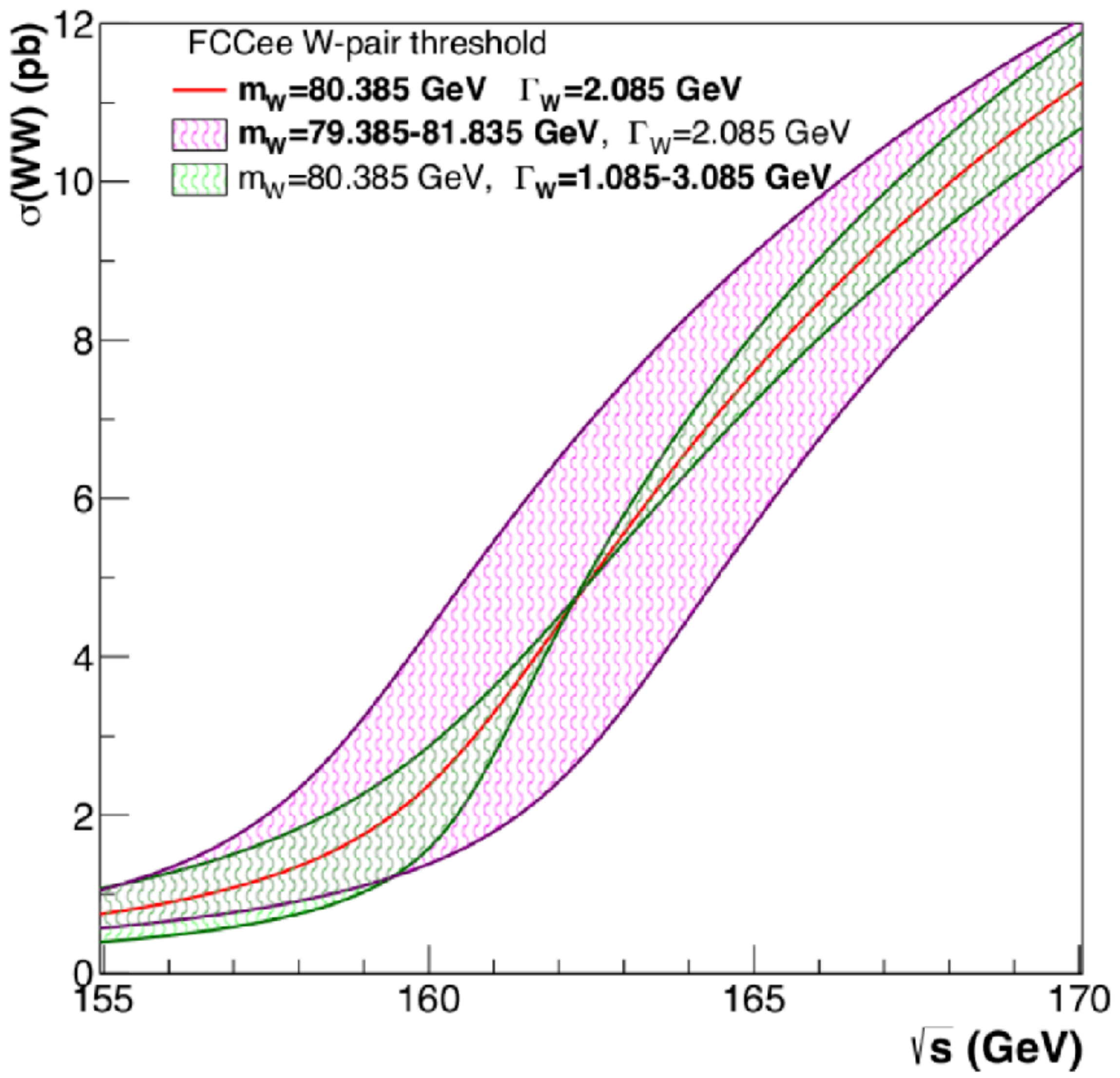


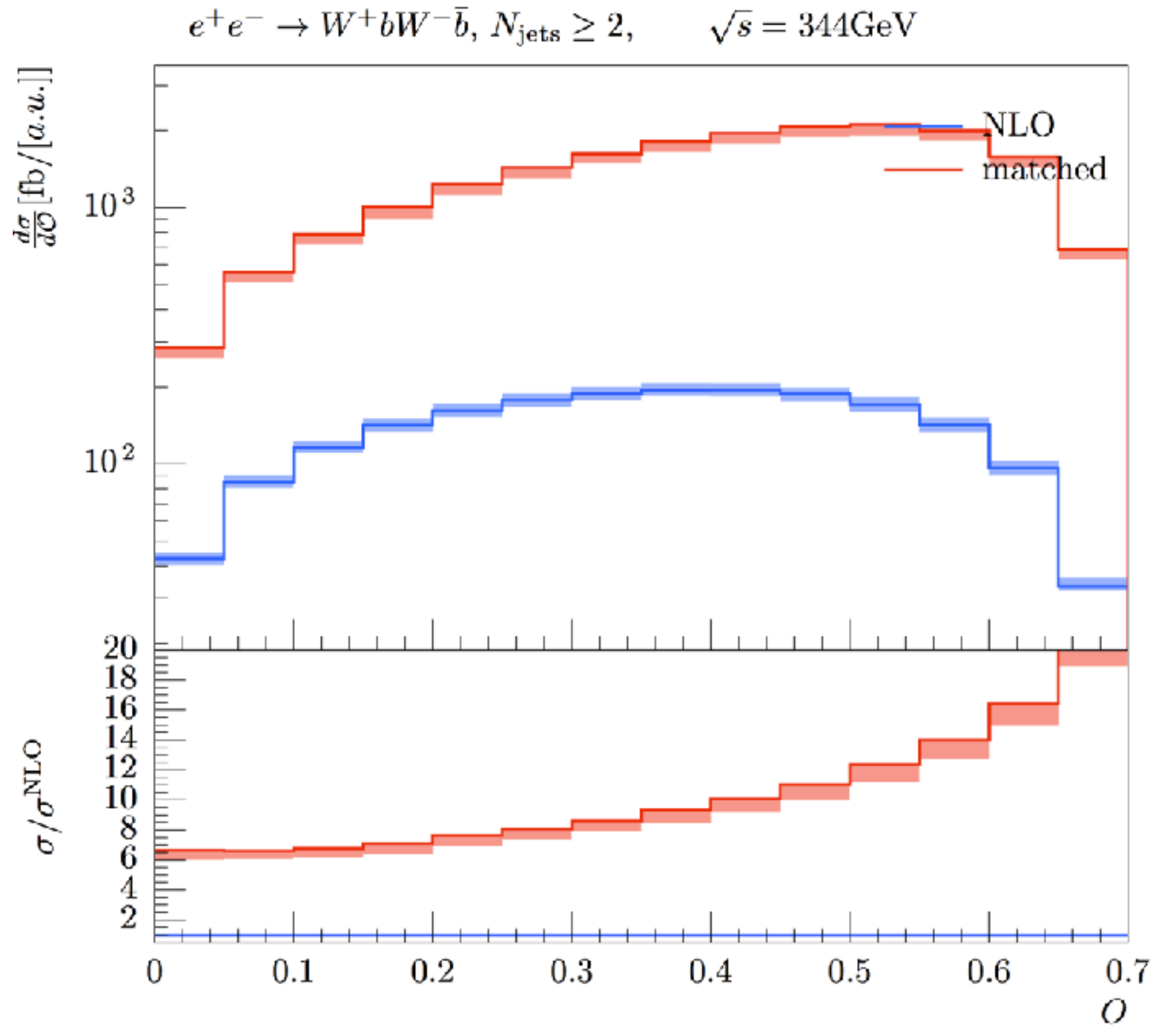
- Higgs/Top/EW Factory will provide pure sample of hadron data
- *Need* for much improved fragmentation formalism (?)

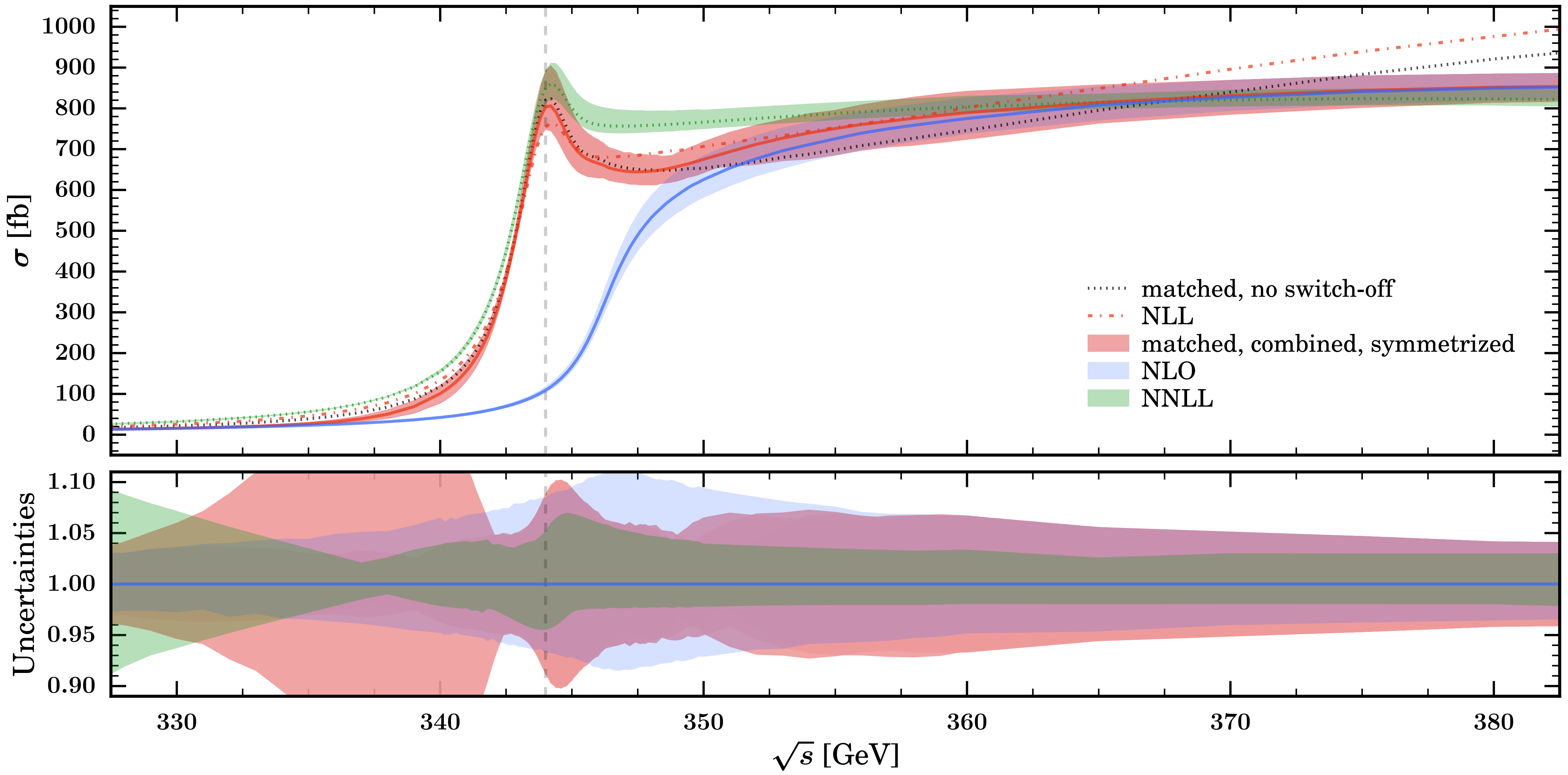


Thresholds and “dedicated processes”

- Special luminometry codes: Bhabha scattering ($\ell^+\ell^- \to \ell^+\ell^-$) and diphotons ($\ell^+\ell^- \to \gamma\gamma$) $[10^{-4} - 10^{-5}$ precision]
- Special treatment: *t* and *W* mass measurements at threshold with precisions at $10^{-4} - 10^{-5}$ precision
- Exclusive Monte Carlo need to take into account QED and QCD threshold effects
- Improvements needed: e.g. shower matching, NLO EW corrections, etc.







Support for most generic BSM

- Layer between "Lagrangian tools" (`LanHEP`/`SARAH`/`FeynRules`) and MC generators: **Universal Feynman Format (UFO)** v1 1108.2040 v2: 2304.09883

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

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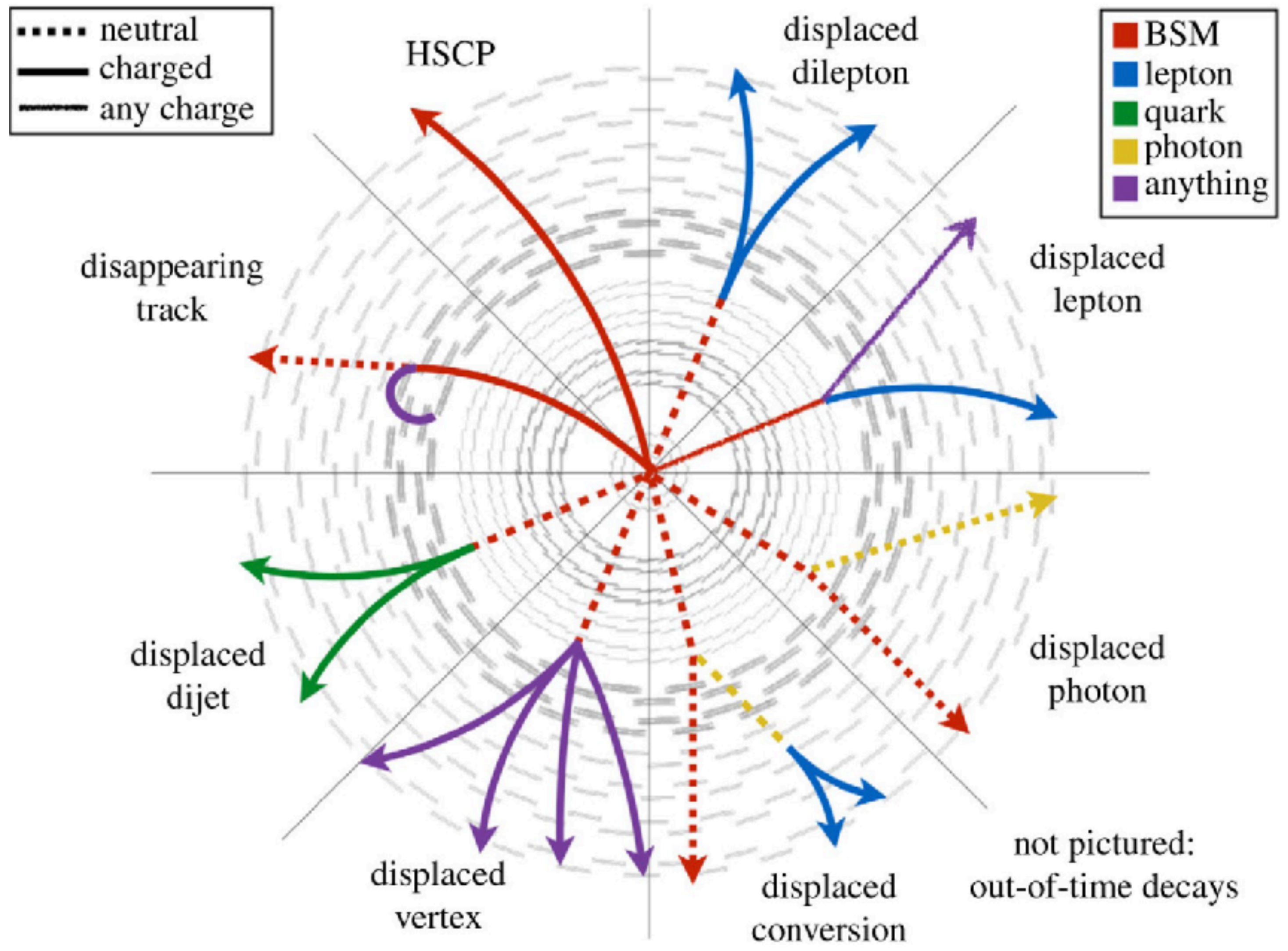

LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- Dark photons
- ALPs
- Dark sector models

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

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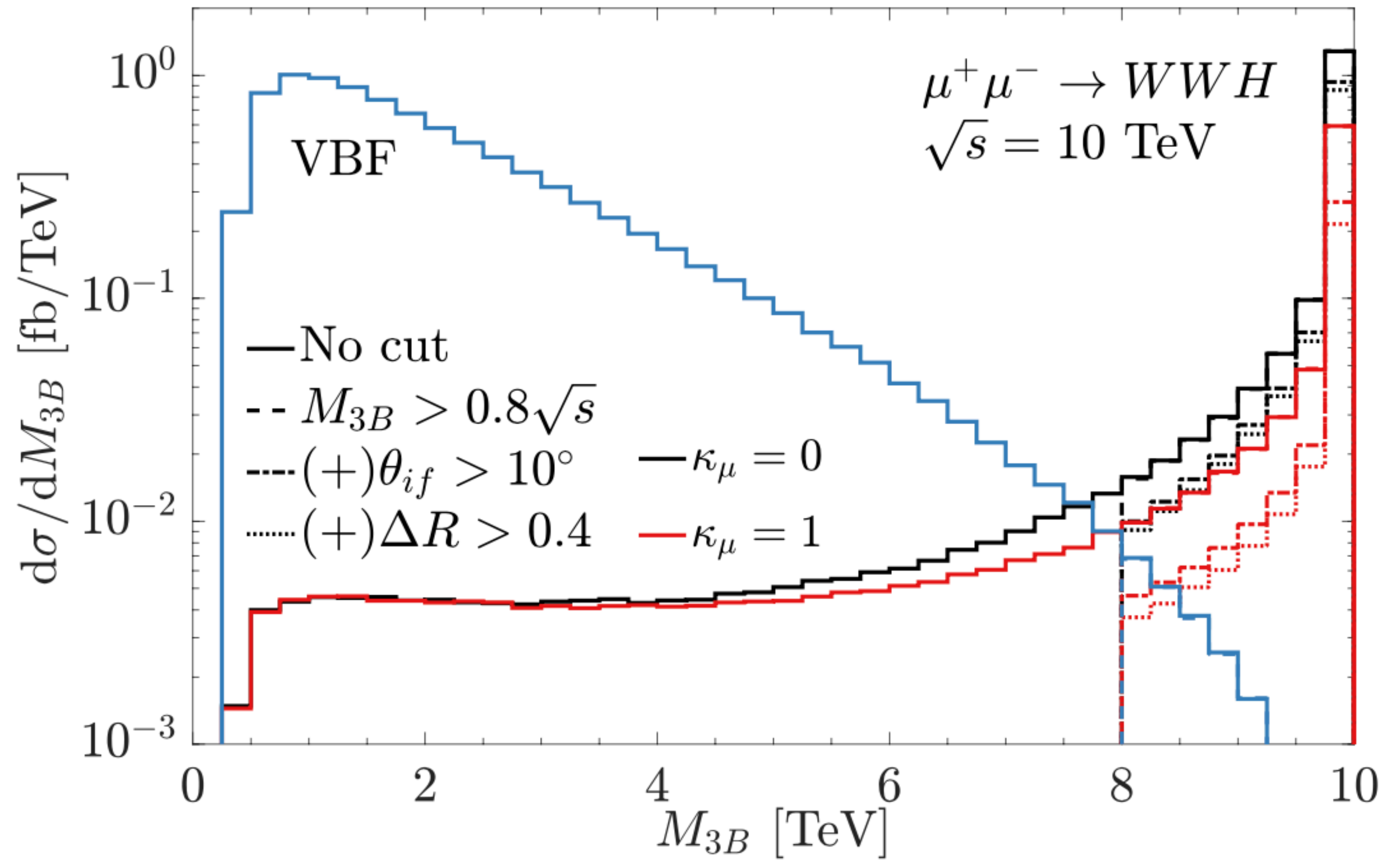
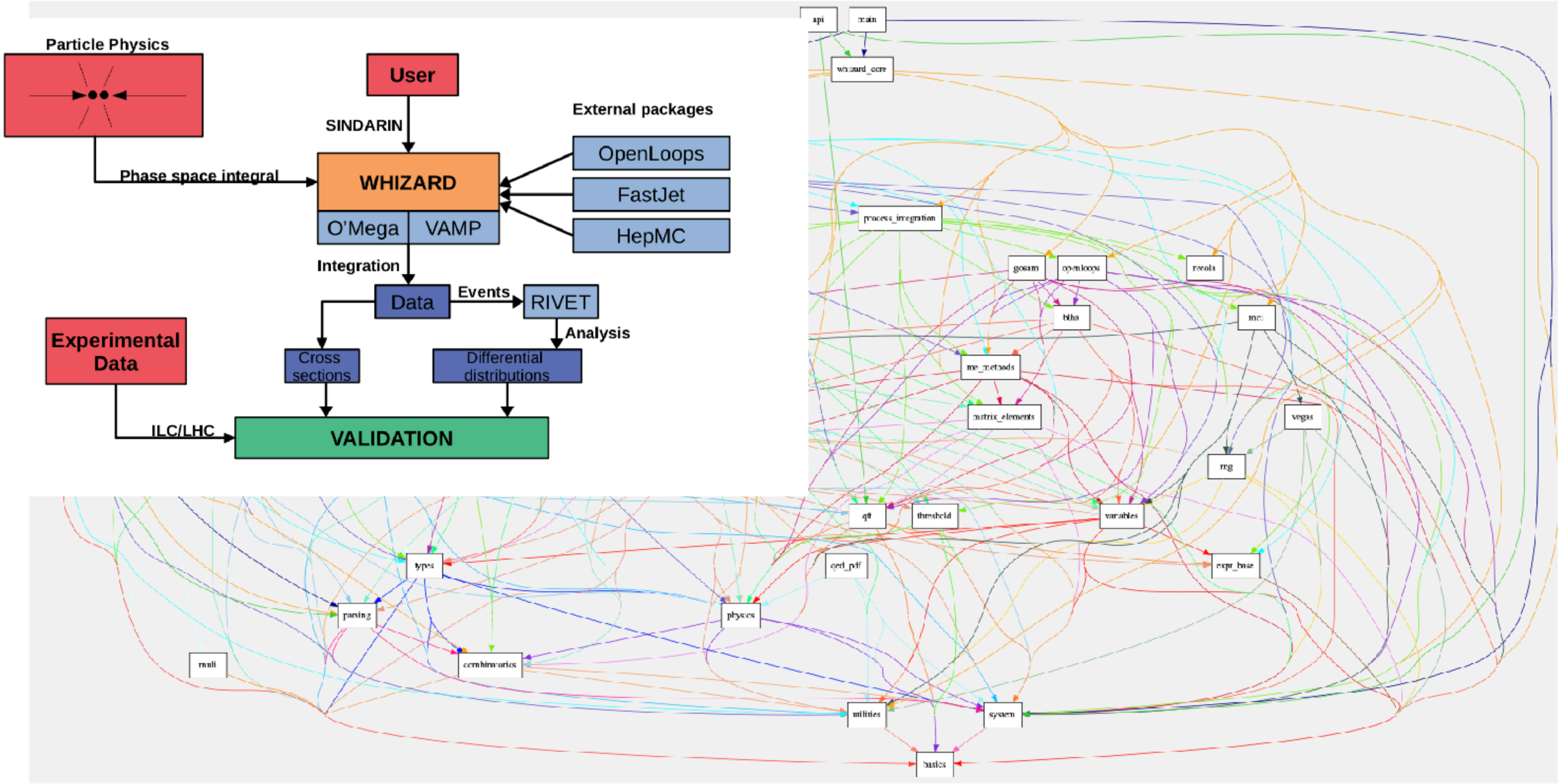
Exotic Higgs decays

MuC example for SMEFT/HEFT UFO, from: T. Han et al. arXiv:2108.05362

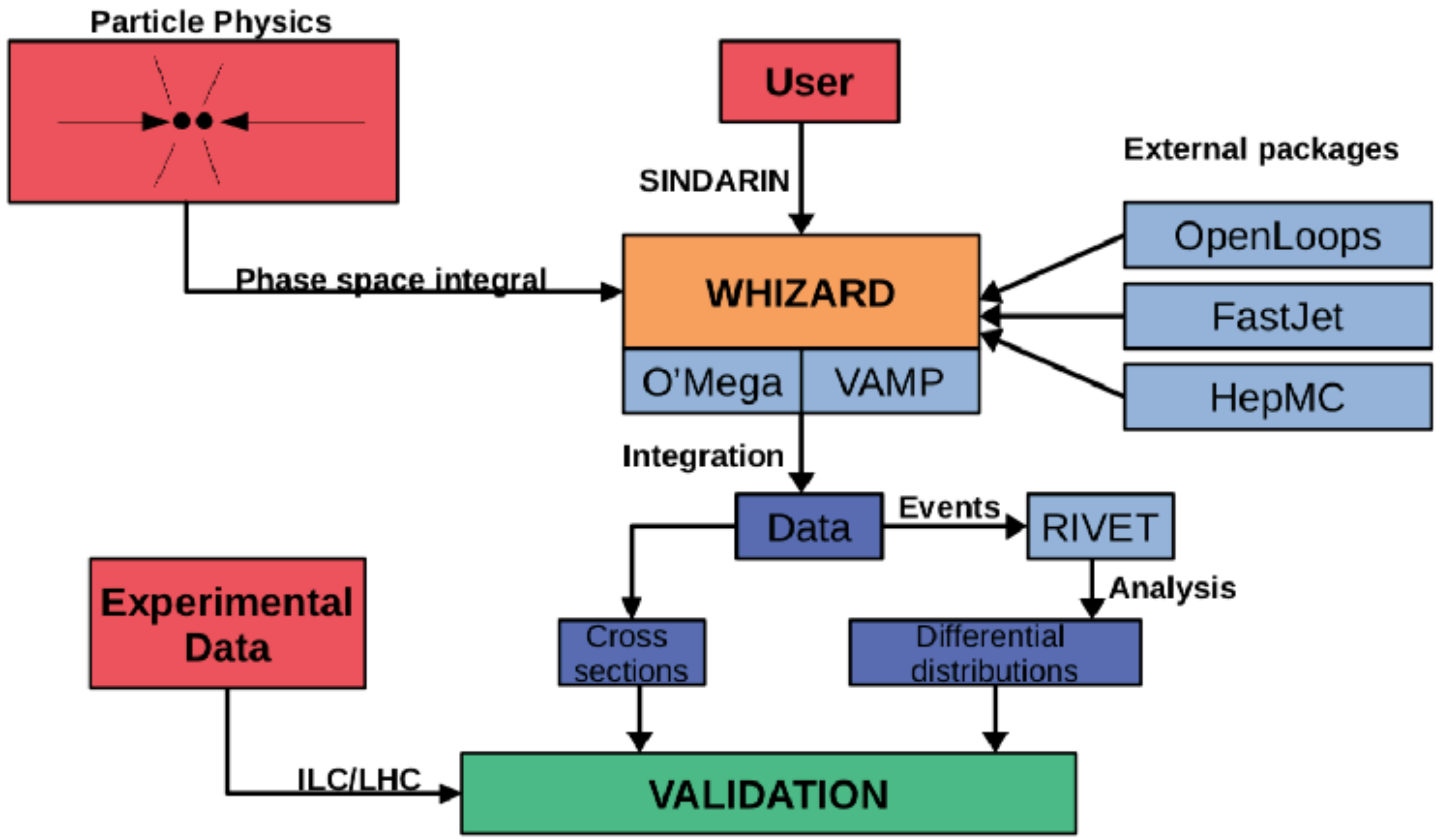


- Big challenge: NLO EW for BSM models (e.g. renormalization scheme!)

More Challenges of MC Event Generators



More Challenges of MC Event Generators



- Typical MC generator $\gtrsim$ 0.5M lines of code
- Many physics parts: necessity of a team/collaboration
- No tool implements all physics (and probably never will)
- Modularity and interchangeability is a must
- e.g. typically interfaces to ca. 15 external libraries
- Unit testing & Continuous integration

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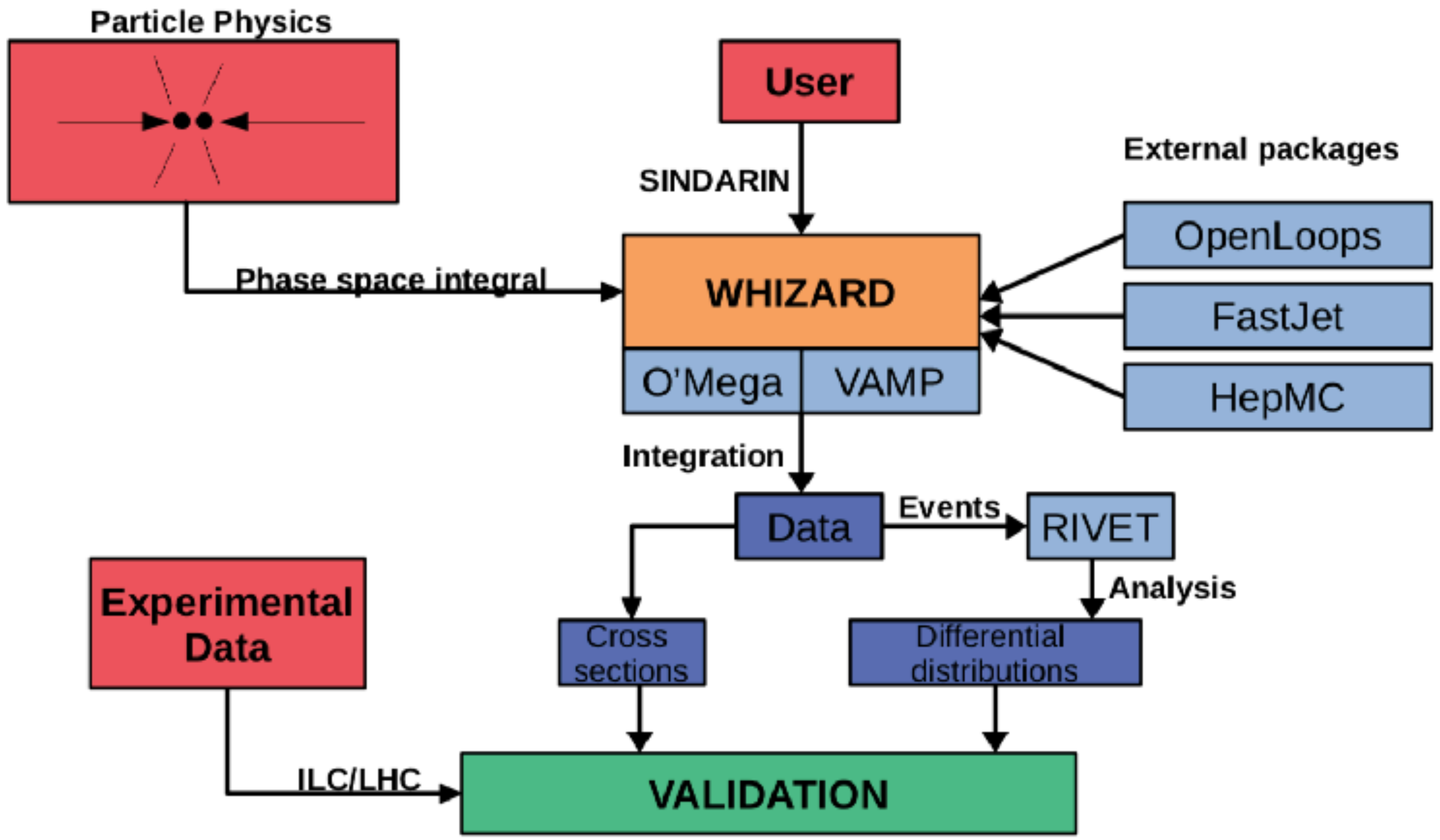

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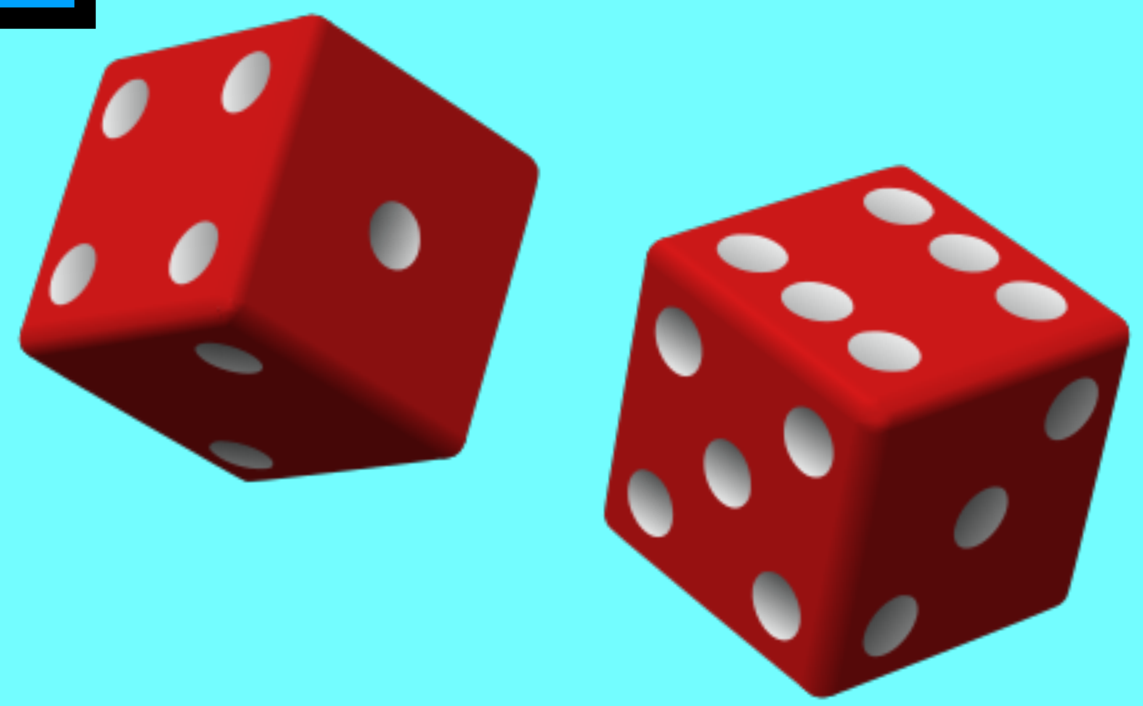
- 3—5 major MC event generators
- Most of these MC members will retire around 2040-45
- Need for ca. MC 8—10 staff positions world-wide
  in the next ca. 20 years
- Already many example of "zombie codes" in experiments

Conclusions & Outlook



- Monte-Carlo generators almighty workhorses of particle physics!!
- MCs implement *all* necessary SM and BSM physics
- Tedious work for MC collaboration members: difficult long-term planning of MC collaborations
- NLO QCD+EW for SM and NLO QCD BSM (almost) under control, attempts for NNLO automation
- Precision in initial-state QED radiation resummation and exclusive photons crucial
- Parton Showers for QCD and QED radiation much matured (now up to NLL for FSR)
- Hadronization will be probed with much enhanced precision at future e^+e^- colliders (improvements?)
- Computing bottlenecks: parallelization & optimization of phase space integration, negative weights
- Sustainability of codes big issue (sustainability of code and Nature)

MC Event generators: Accuracy vs. Precision

Visit the Generator session Wednesday 14:00 hrs Koshiba Hall !