Monte Carlo generator development

International MUON Collider Collaboration

DESY. HELMHOLTZ

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

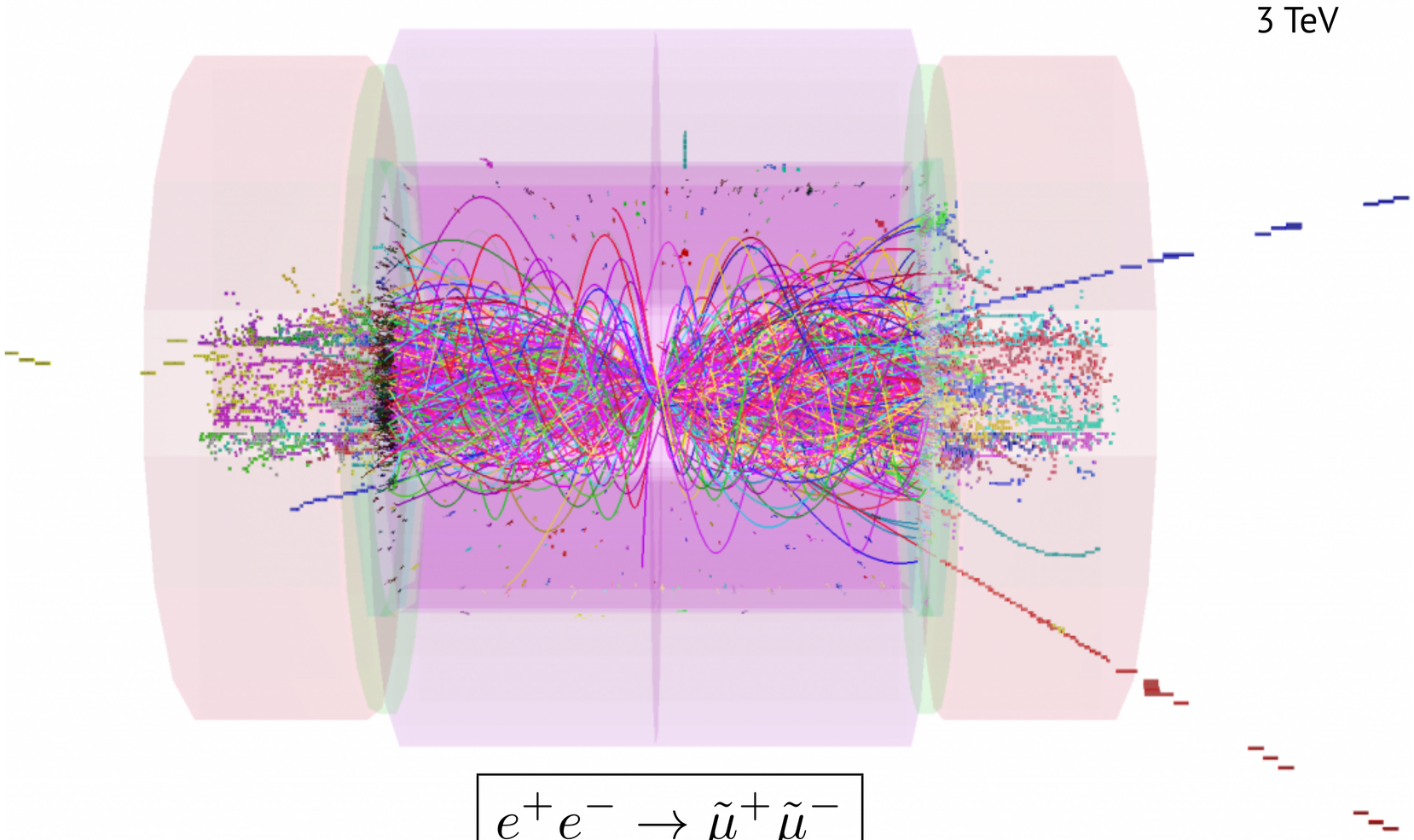
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Jürgen R. Reuter

The importance of MC event generators

Why are event generators important? Because all our forward simulation chain depends on them!

Why are event generators non-trivial? Because they contain *all* our knowledge of particle physics!



$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$$

Courtesy to Philipp Roloff

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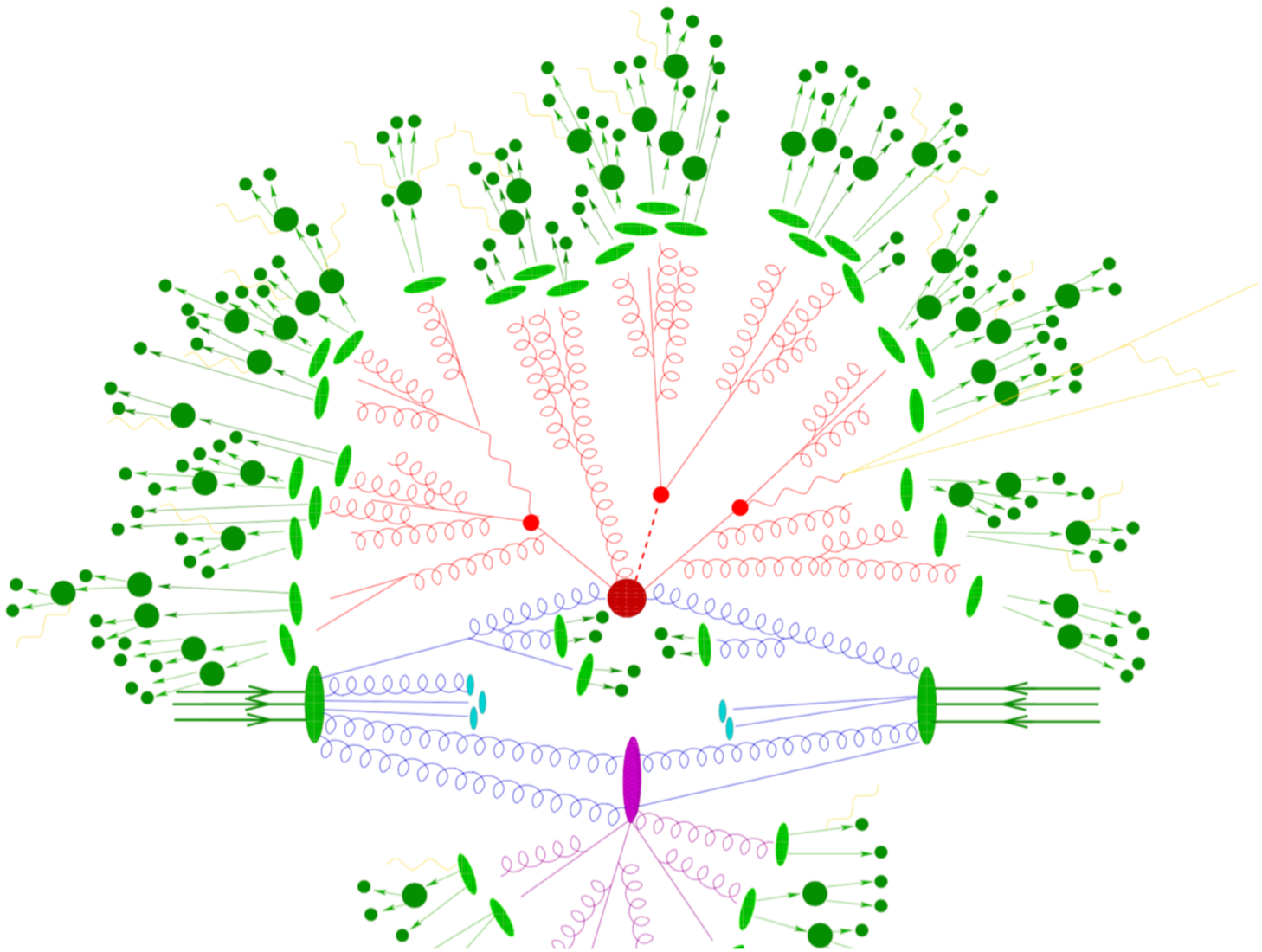

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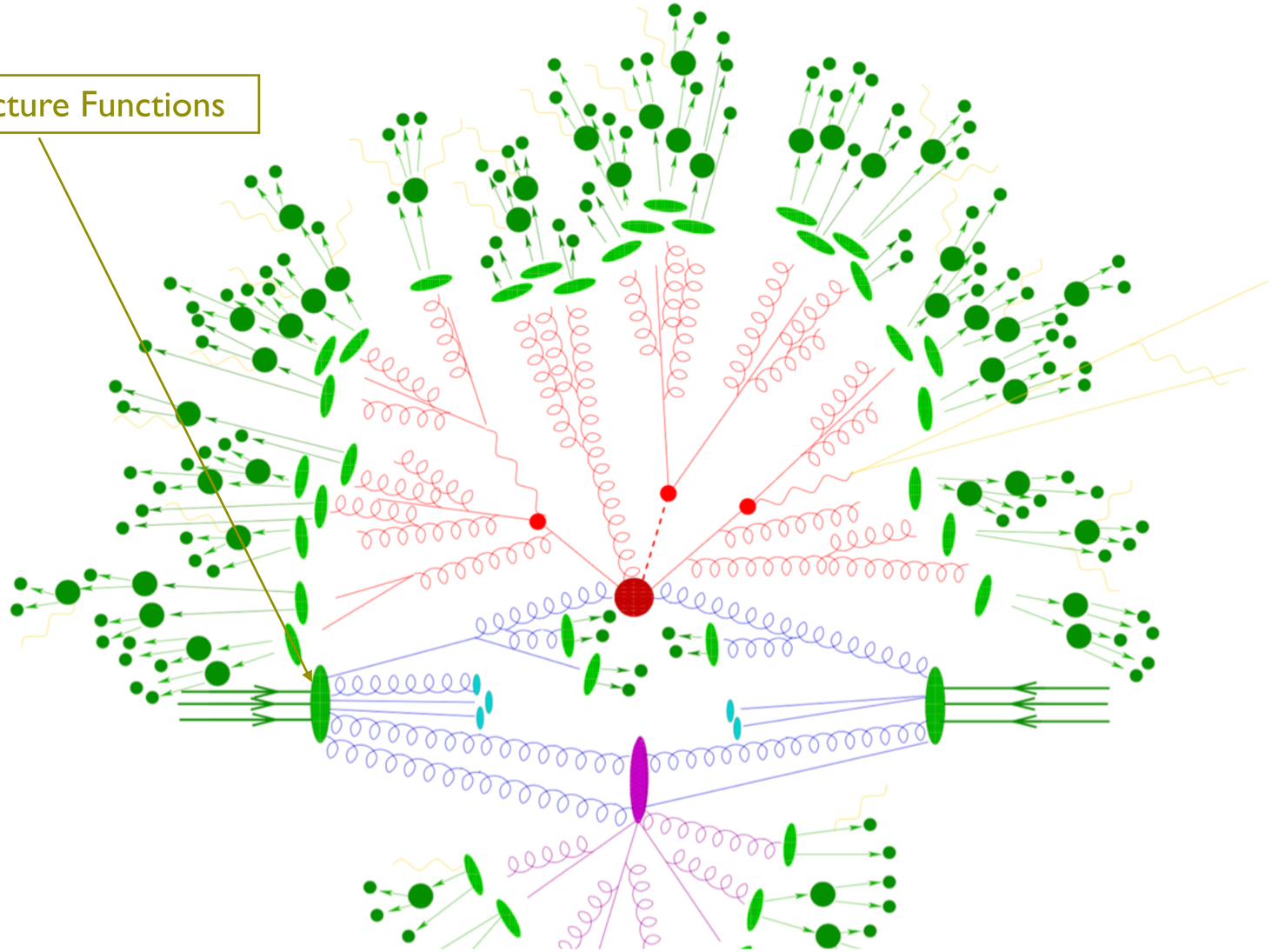
Beam spectra & ISR Structure Functions



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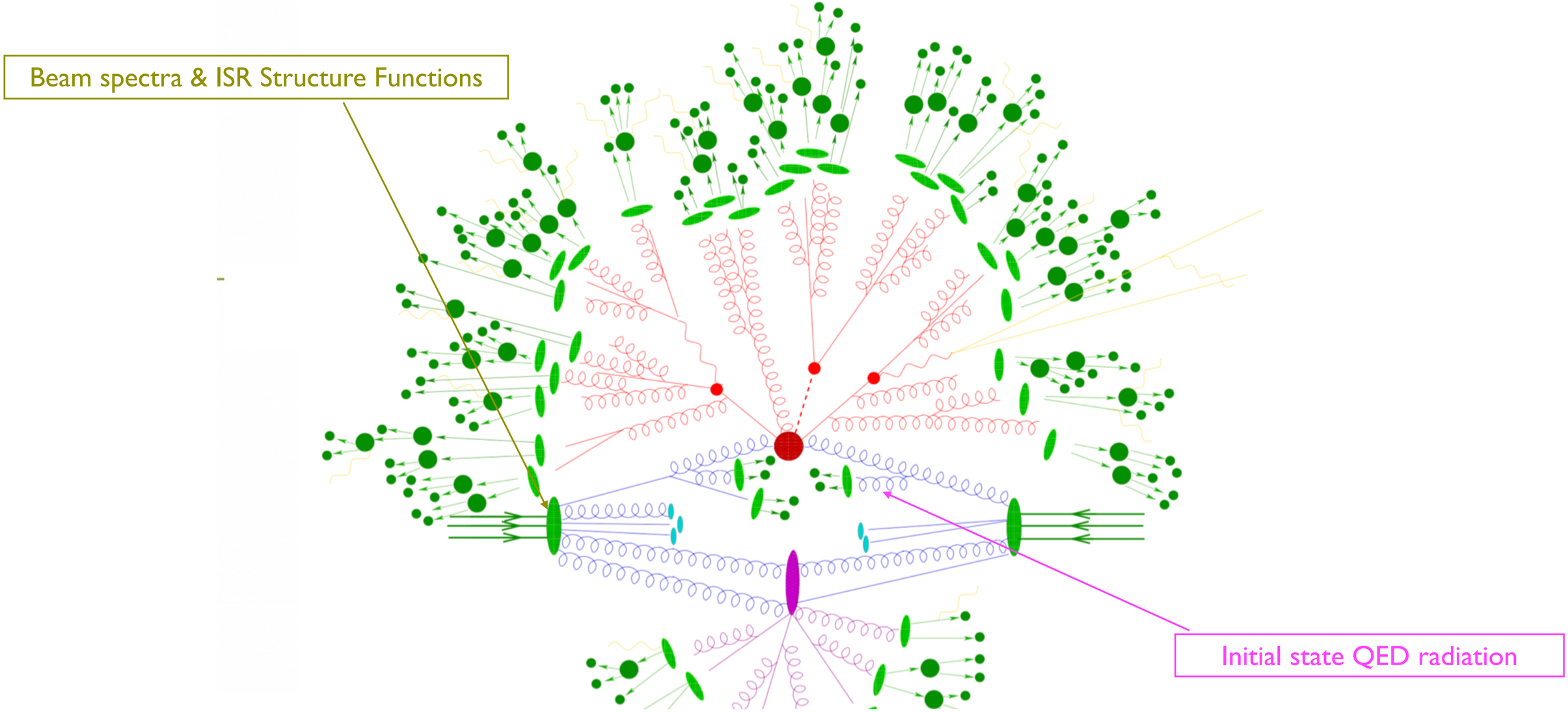

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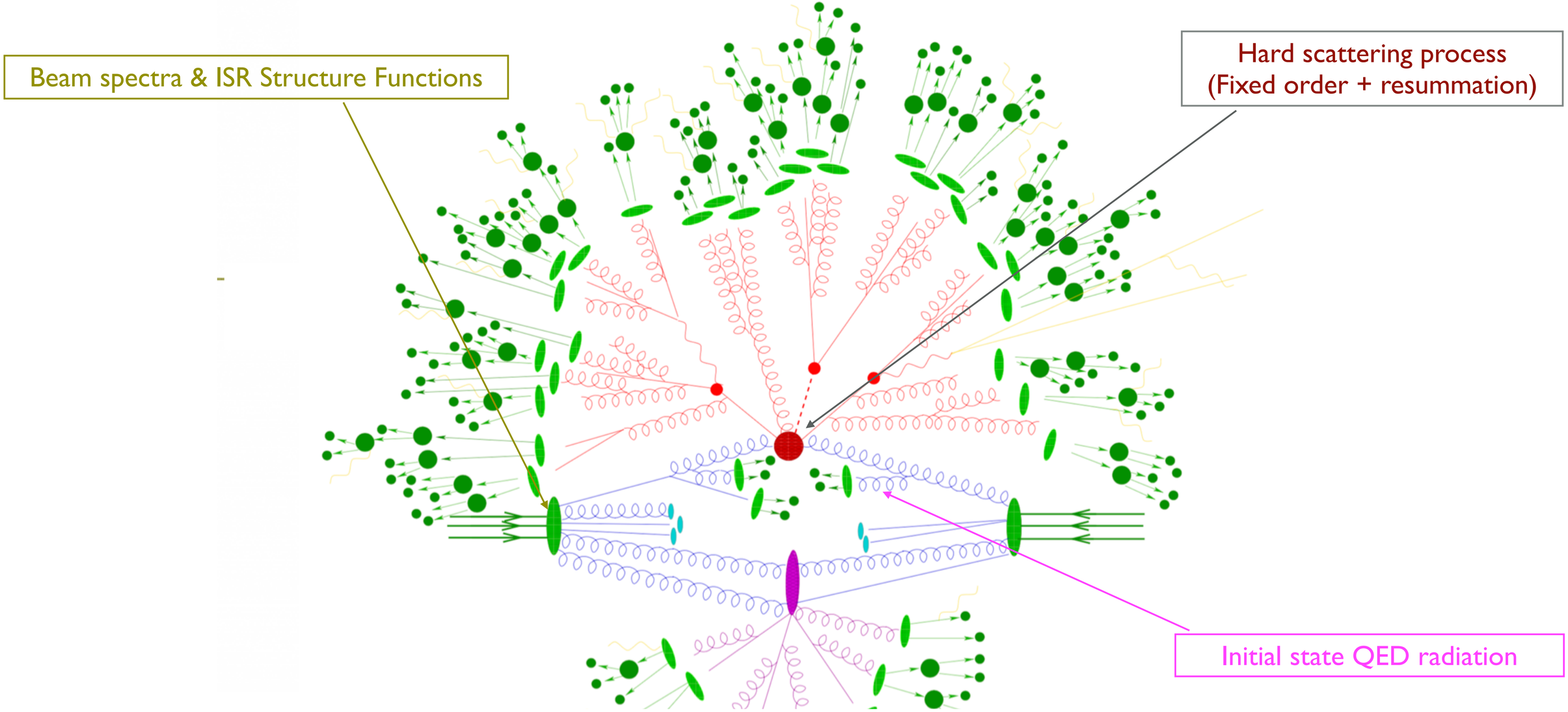

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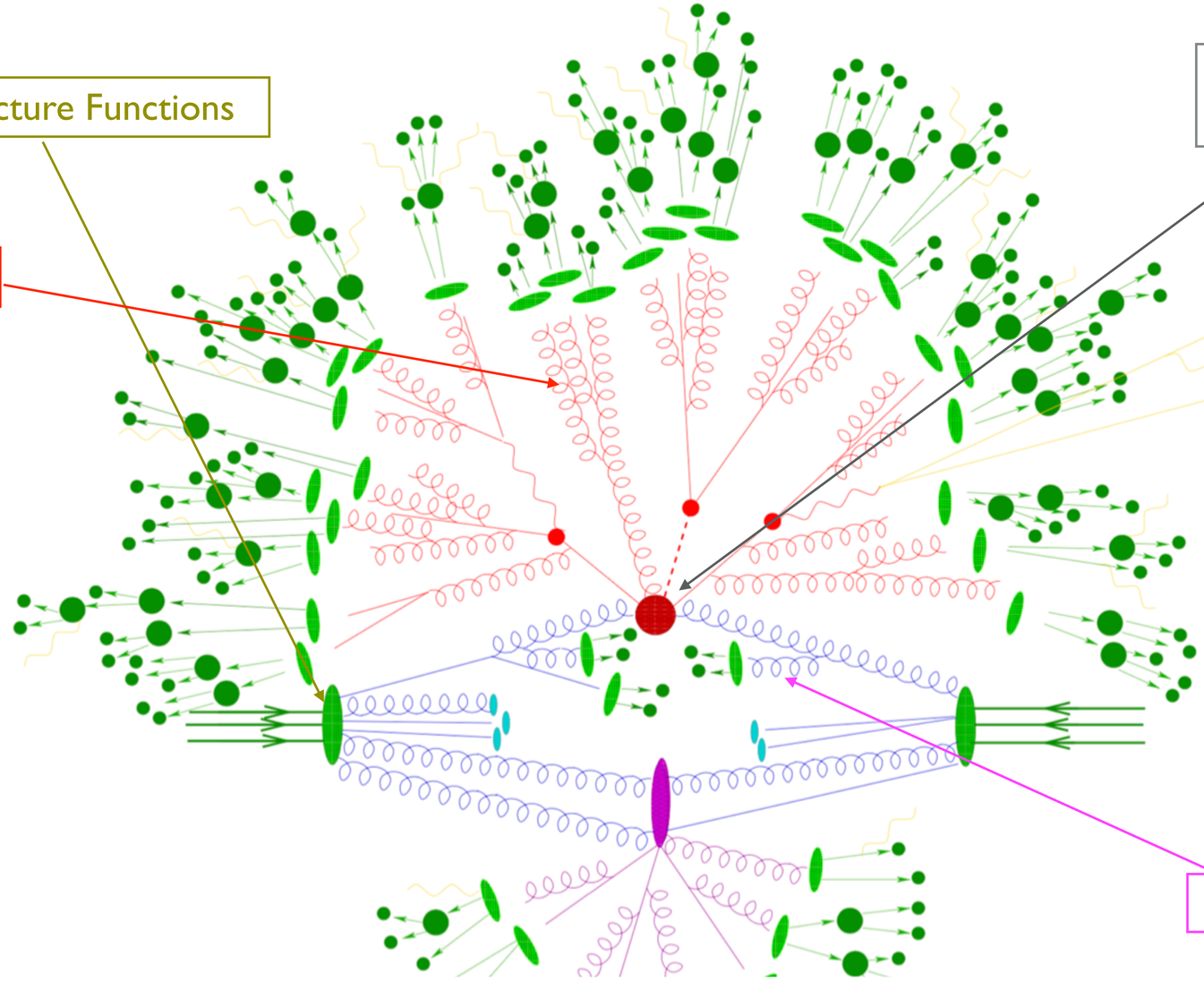

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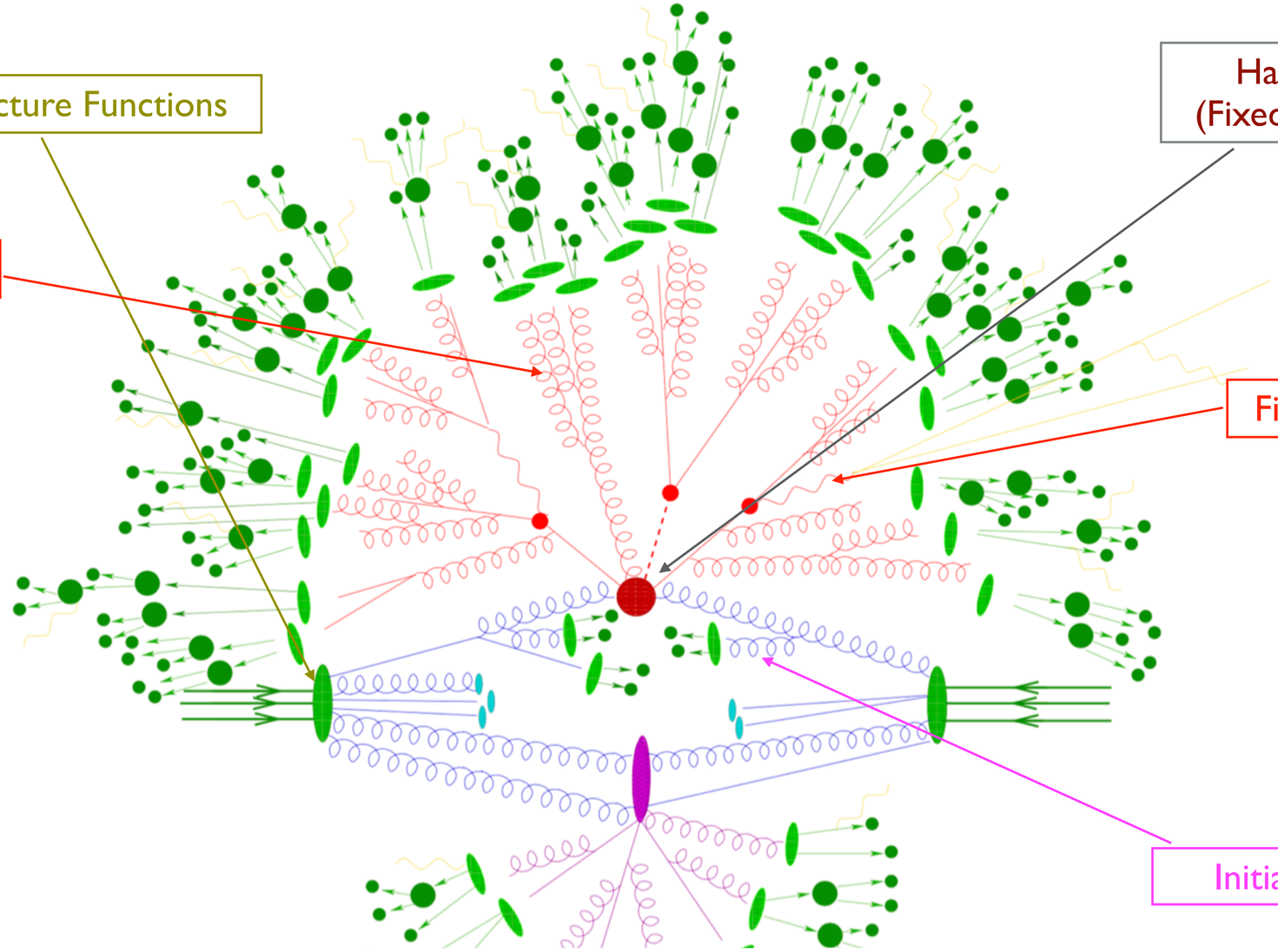

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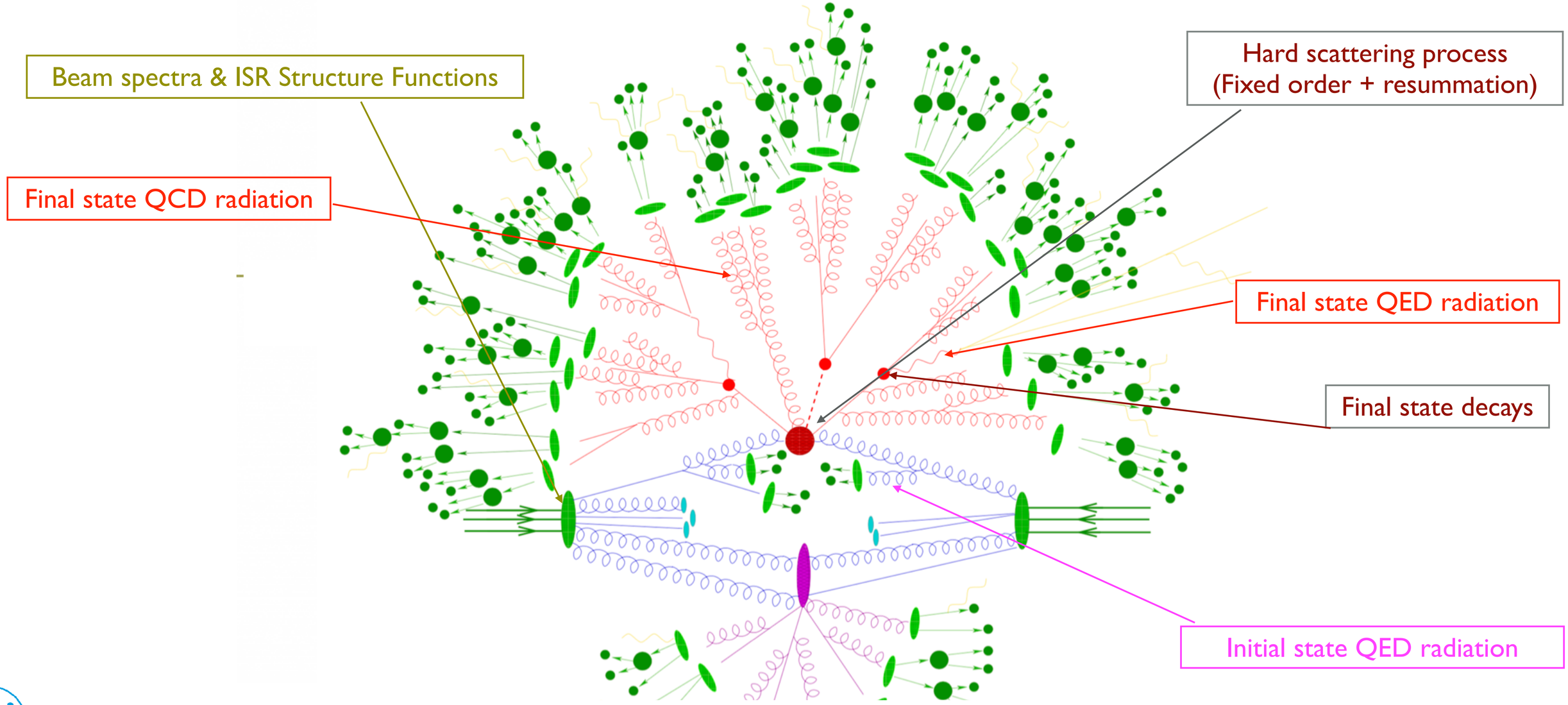

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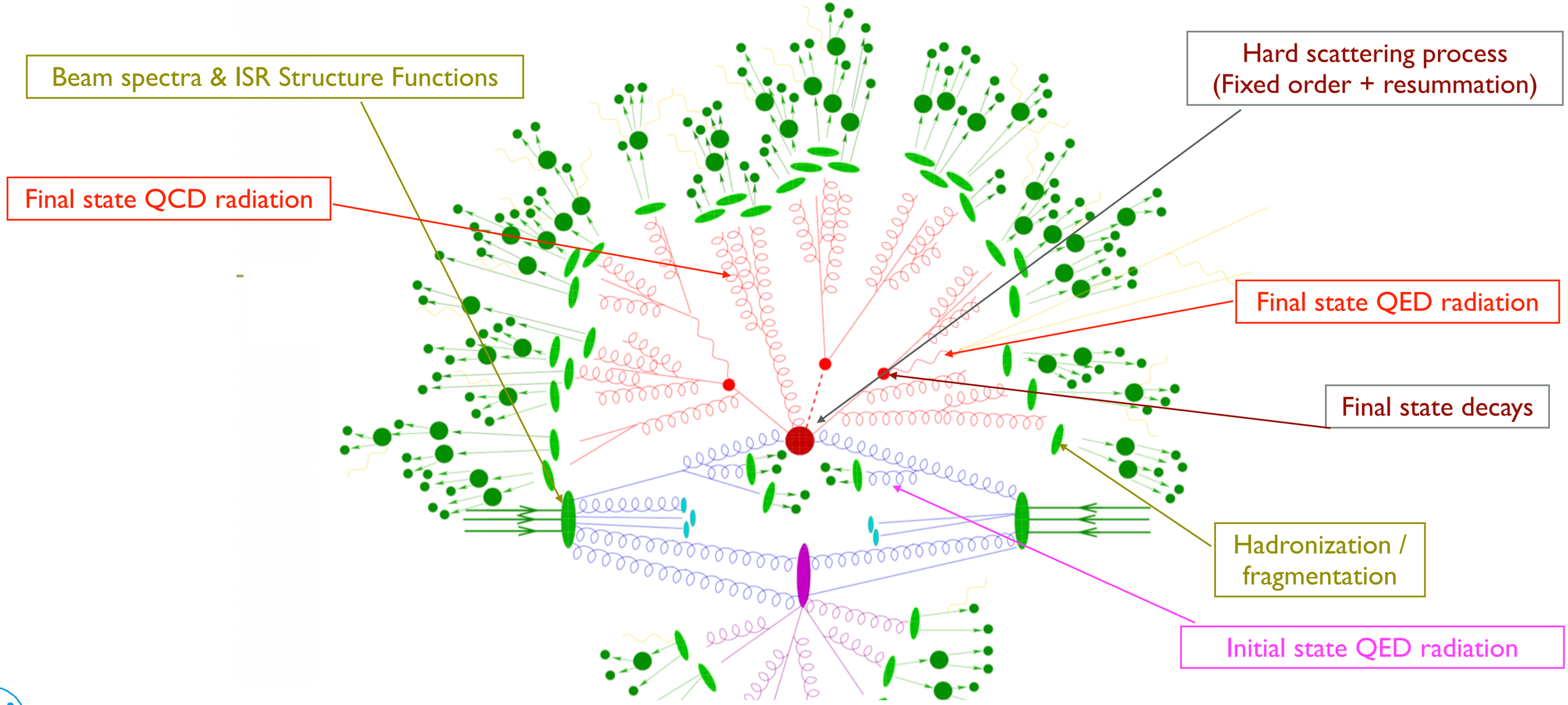

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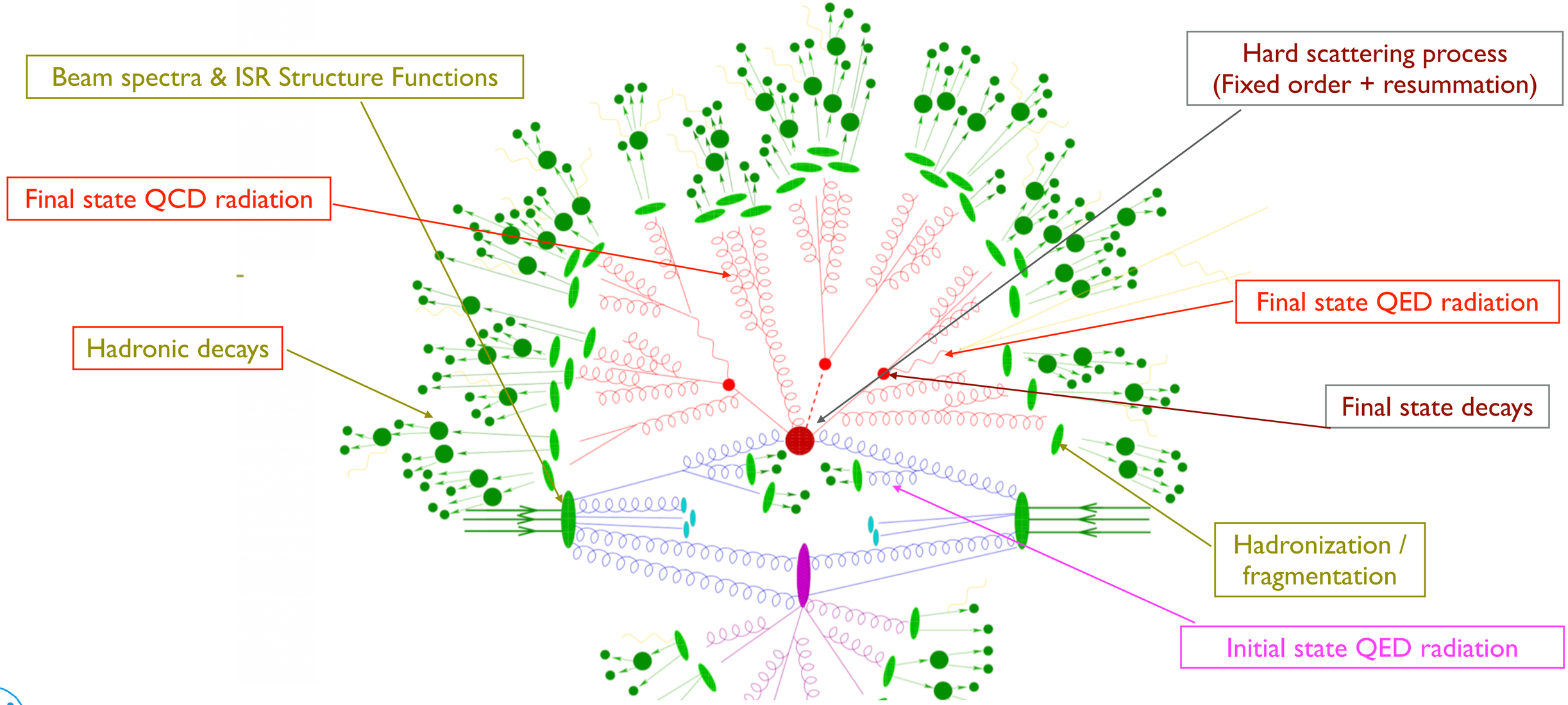

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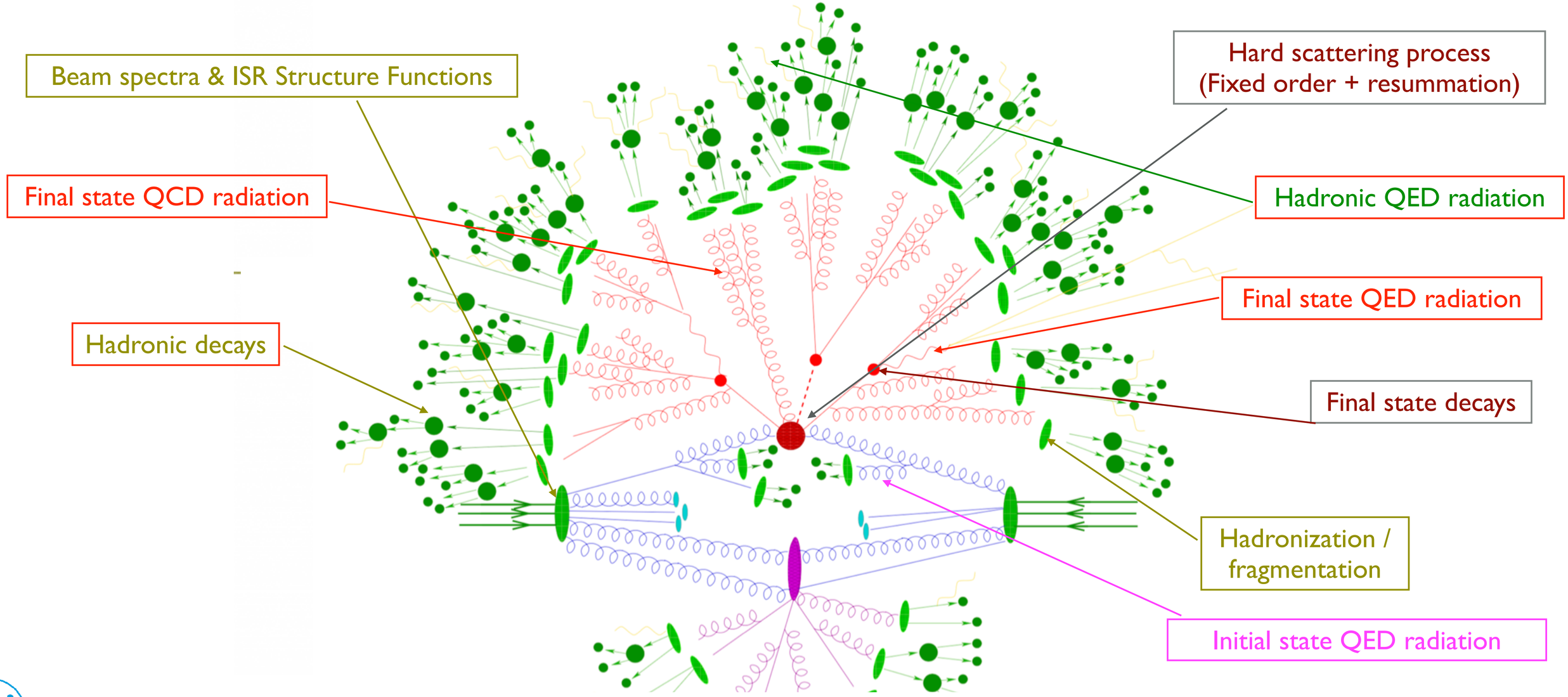

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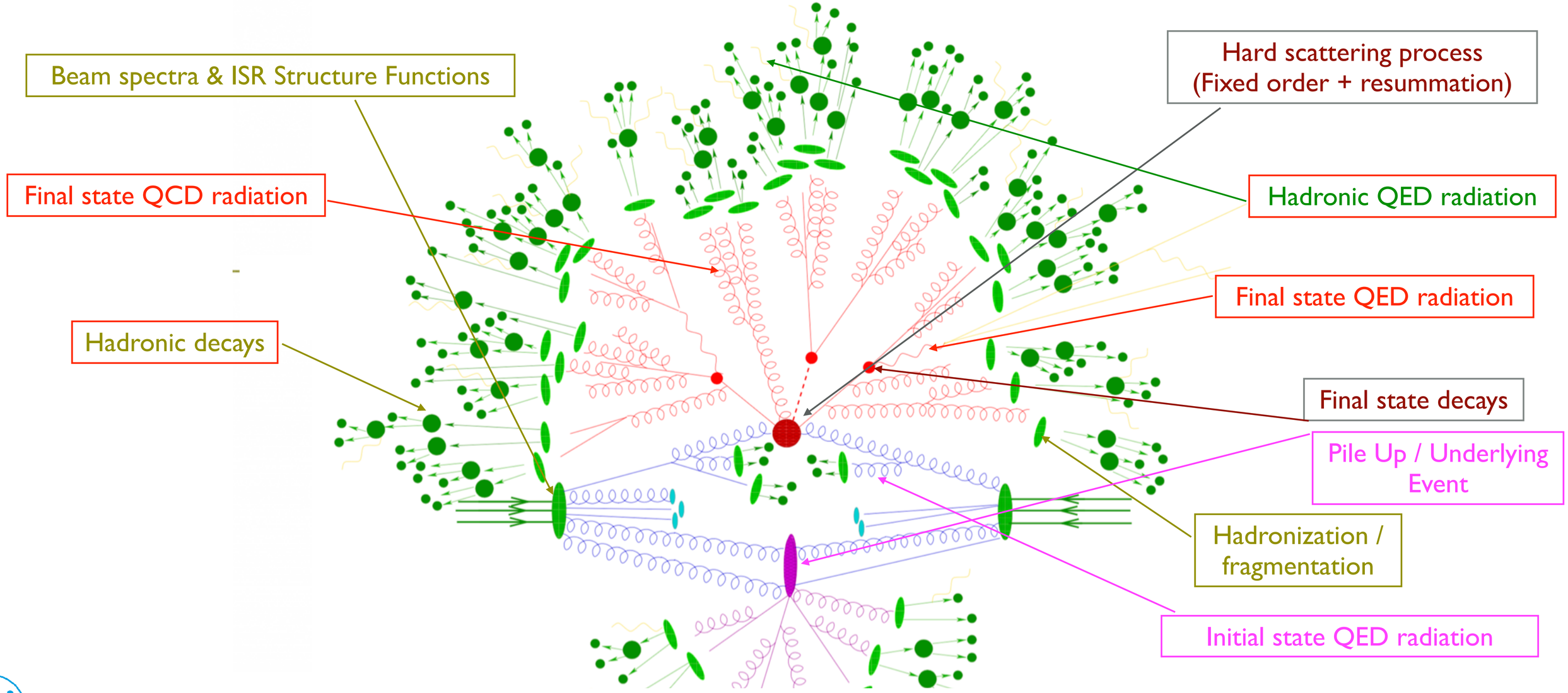

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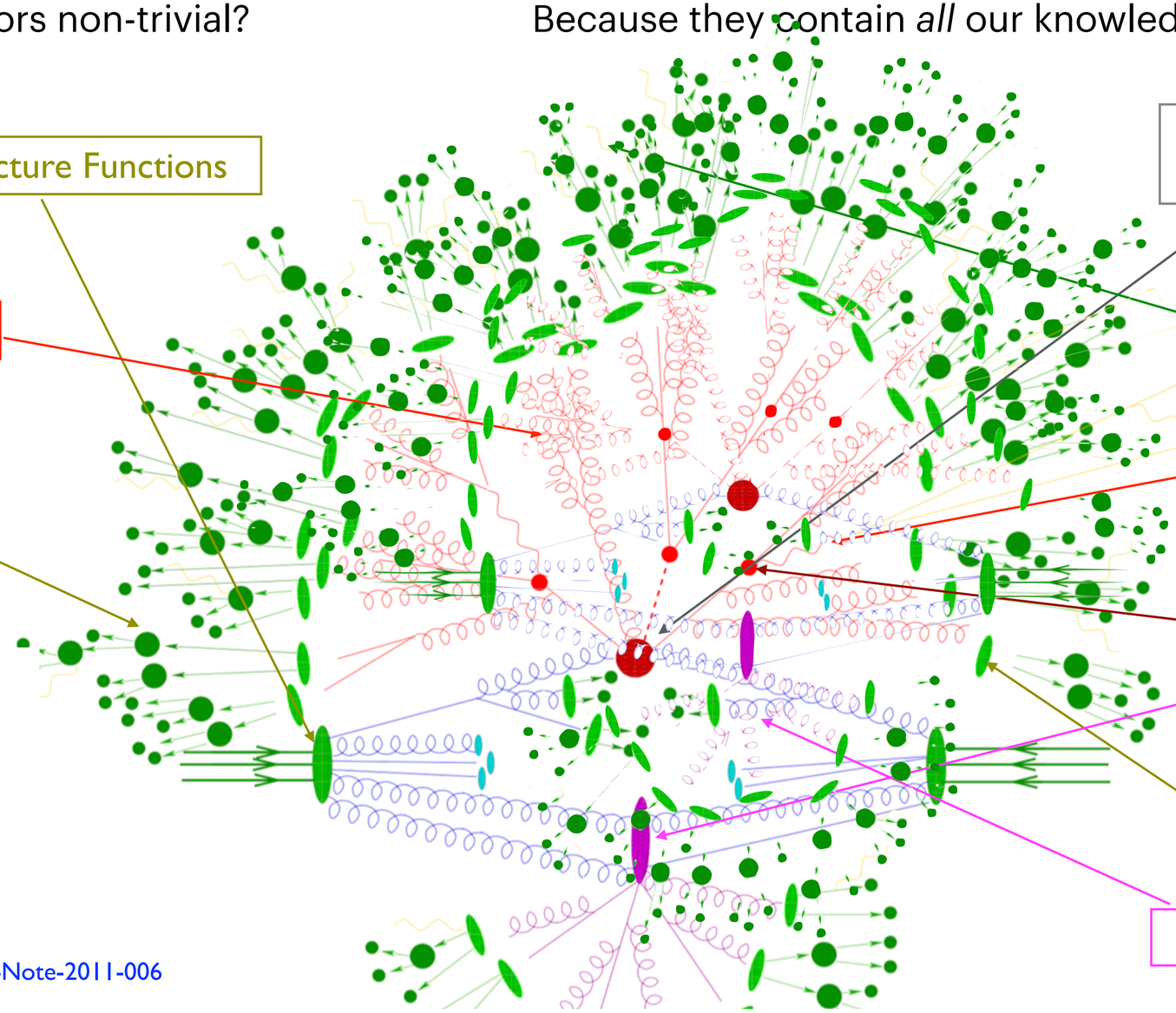
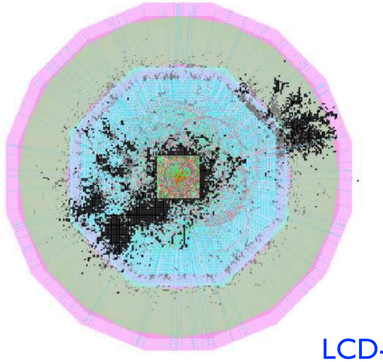




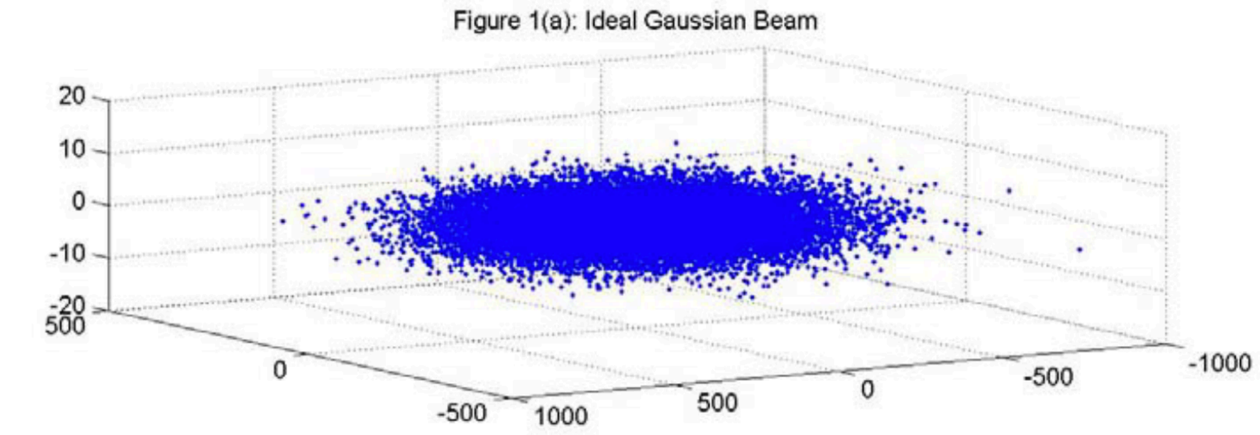
LCD-Note-2011-006

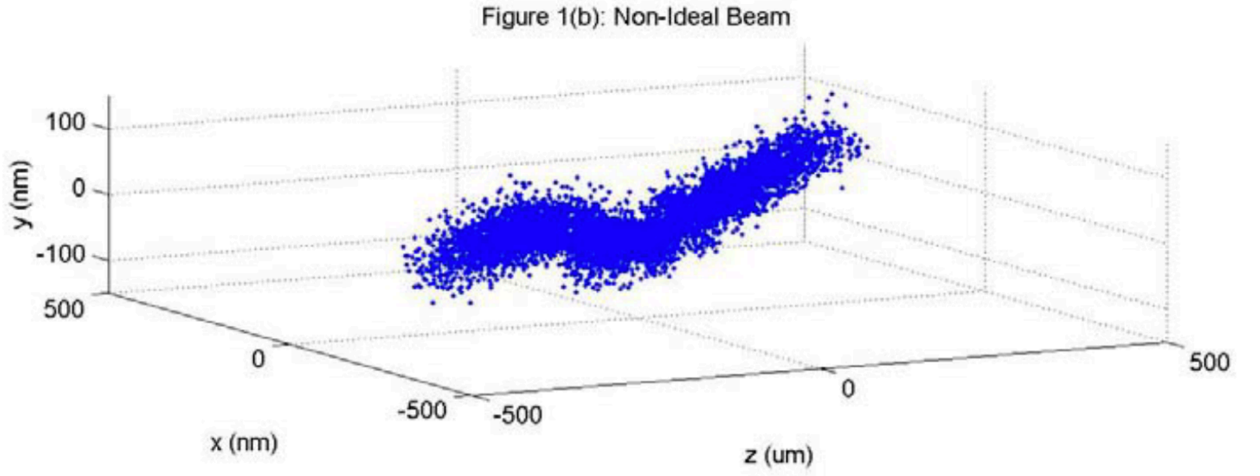
Monte Carlo generators for muon colliders

- What is different to MC event generators for the LHC?
- What is different to MC event generators for (high-energy) electron-positron colliders?
- Where do we stand and what is still needed?

1. Beam simulation
2. Initial-state structure: PDFs, collinear vs. soft resummation, cross section predictions ...
3. Hard process (SM): NLO SM automation , NNLO automation (?)
4. Hard process (BSM): any new (crazy) model? SMEFT? tweaks? which order?
5. Exclusive processes (I = QED): photons, QED showers, matching (?)
6. Exclusive processes (II = QCD): jets, QCD/interleaved/EW showers, fragmentation (!)
7. Efficiency, speed, sustainability [left out for time reasons]

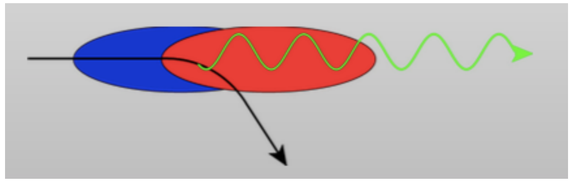
Beam simulations





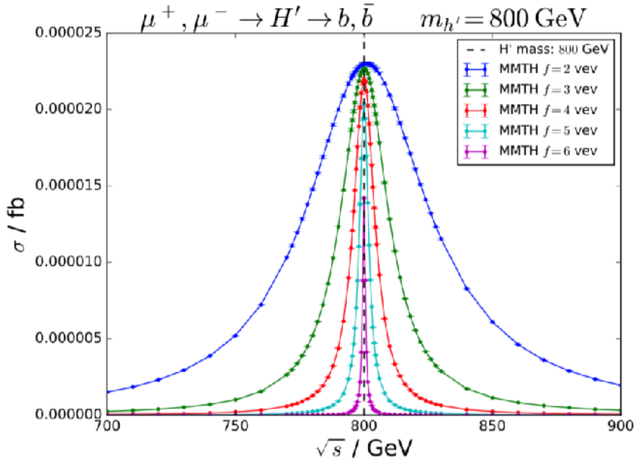
Beam simulations

- Micro-scale bunches create beam structure/-strahlung
- Mostly Gaussian shape for circular machines, but not fully
- Machine simulation with tools like `GuineaPig(++)`, `CAIN`
- 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 — Avail.: ✓
2. Parameterized (delta peak ⊕ power law) — Avail.: (✓)
3. Generator for 2D histogrammed fit — Avail.: [✓]



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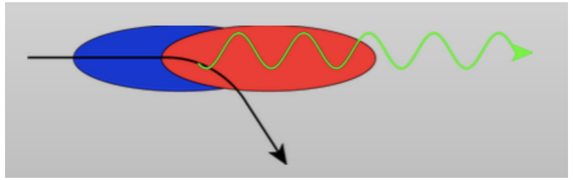

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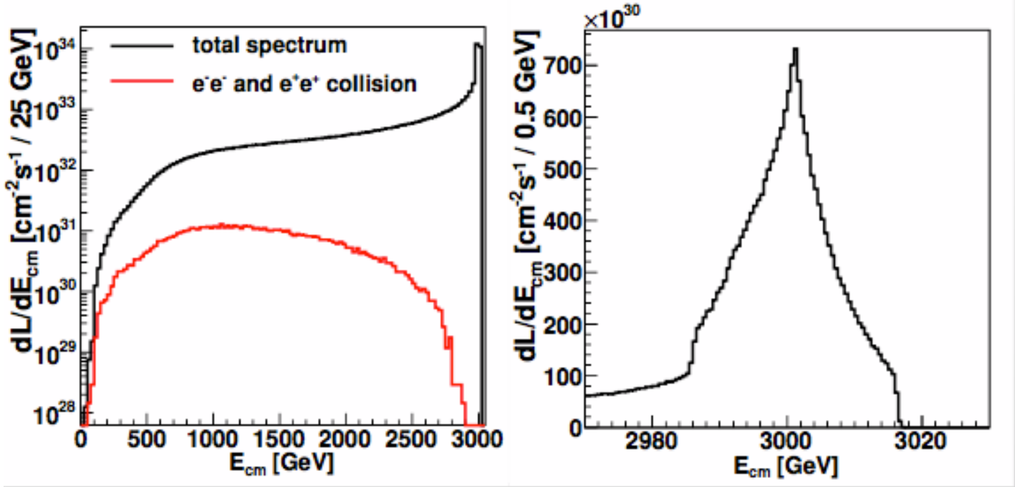

Dalena/Esbjerg/Schulte [LCWS 2011]

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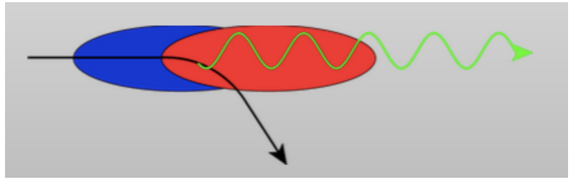

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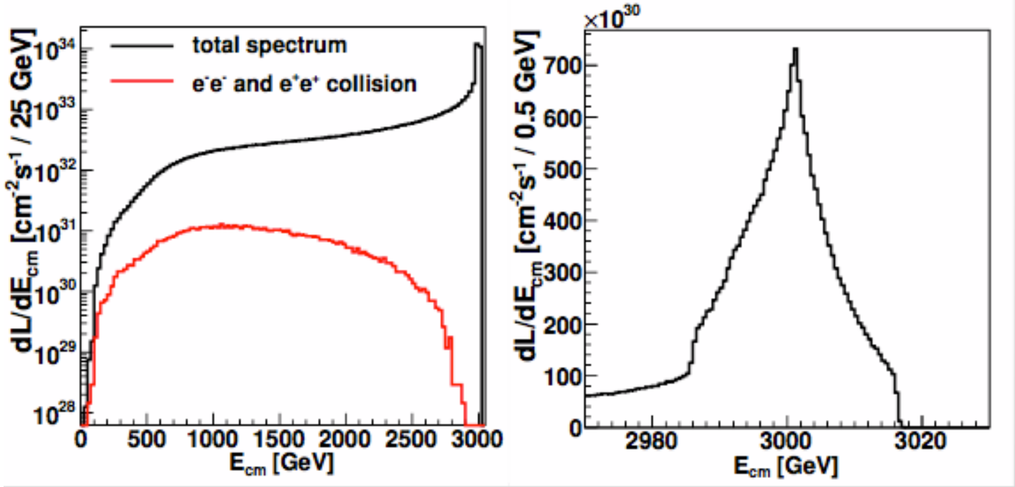

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$$D_{B_1B_2}(x_1,x_2) \neq D_{B_1}(x_1)\cdot D_{B_2}(x_2)$$
$$D_{B_1B_2}(x_1,x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1}x_2^{\alpha_2}(1-x_2)^{\beta_2}$$

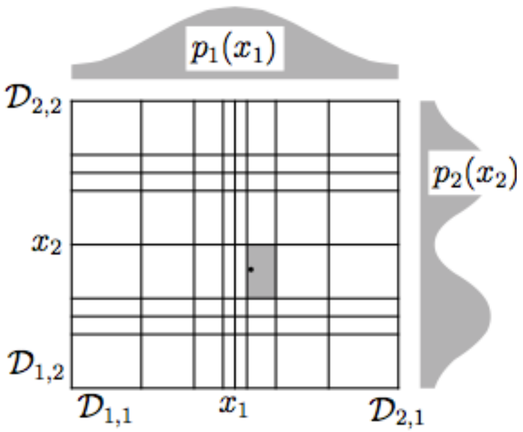
- Pro (1.): Easy implementation, covers main features
- Con (1.): Gaussian approximative, exceeds nominal collider energy
- Pro (2.): Relatively easy implementation
- Con (2.): Delta peak behaves badly in MC, beams maybe not factorizable/simple power law
- Pro (3.): most exact simulation, generator mode avoids artifacts in tails
- Con (3.): only available (yet) in dedicated tools like `LumiLinker` and `CIRCE2`

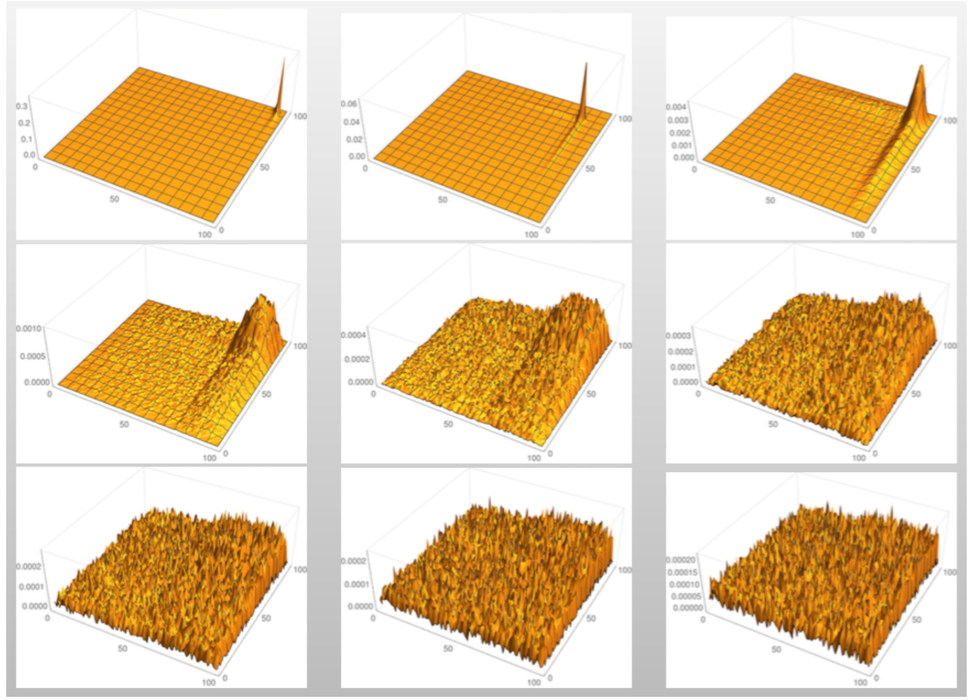
Beam simulations (technial details)

CIRCE2 algorithm T. Ohl, 1996, 2005

↪ Talk by Thorsten Ohl 06/2023: https://indico.cern.ch/event/1266492/

- Adapt 2D factorized variable width histogram to steep part of distribution
- Smooth correlated fluctuations with moderate Gaussian filter [suppresses artifacts from limited GuineaPig statistics
- Smooth continuum/boundary bins separately [avoid artificial beam energy spread]





(171.306 GuineaPig events in 10.000 bins)

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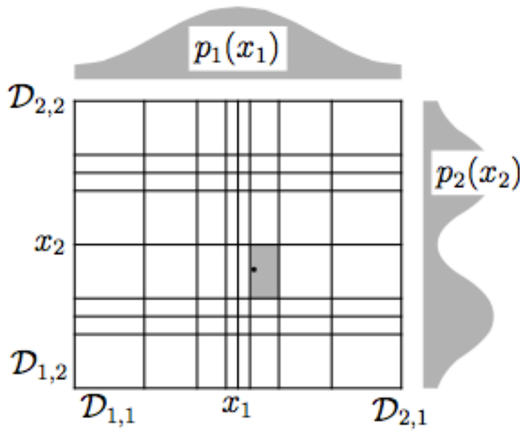

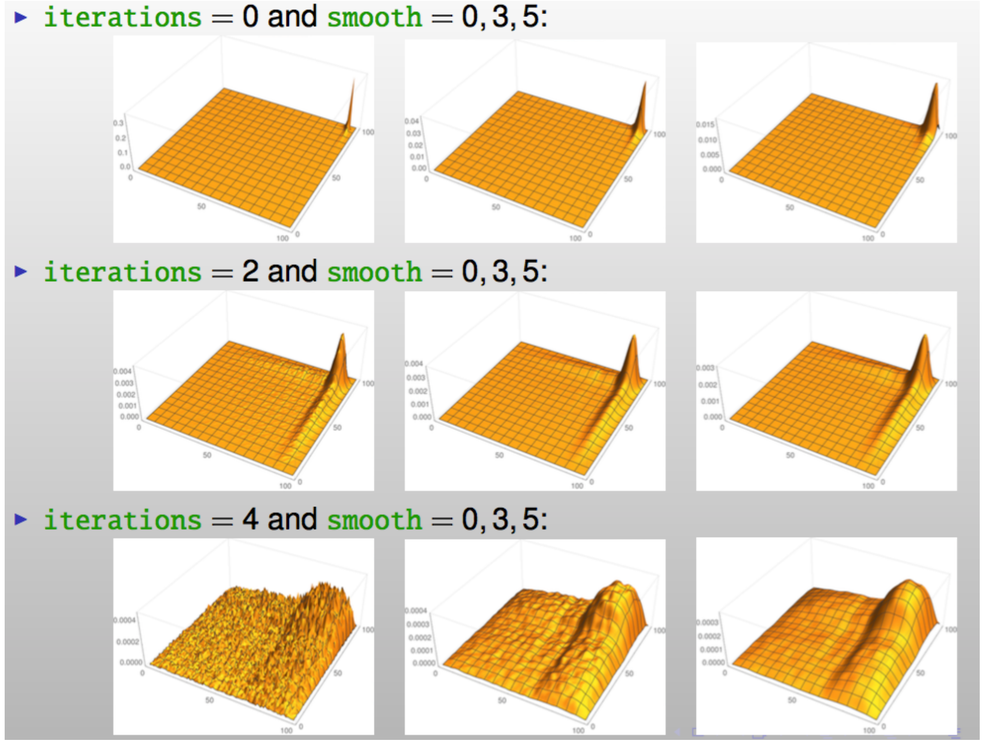

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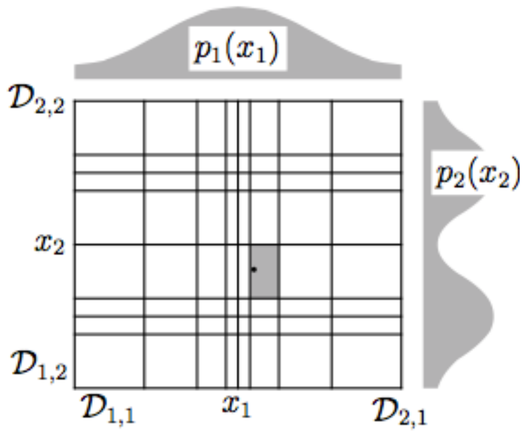

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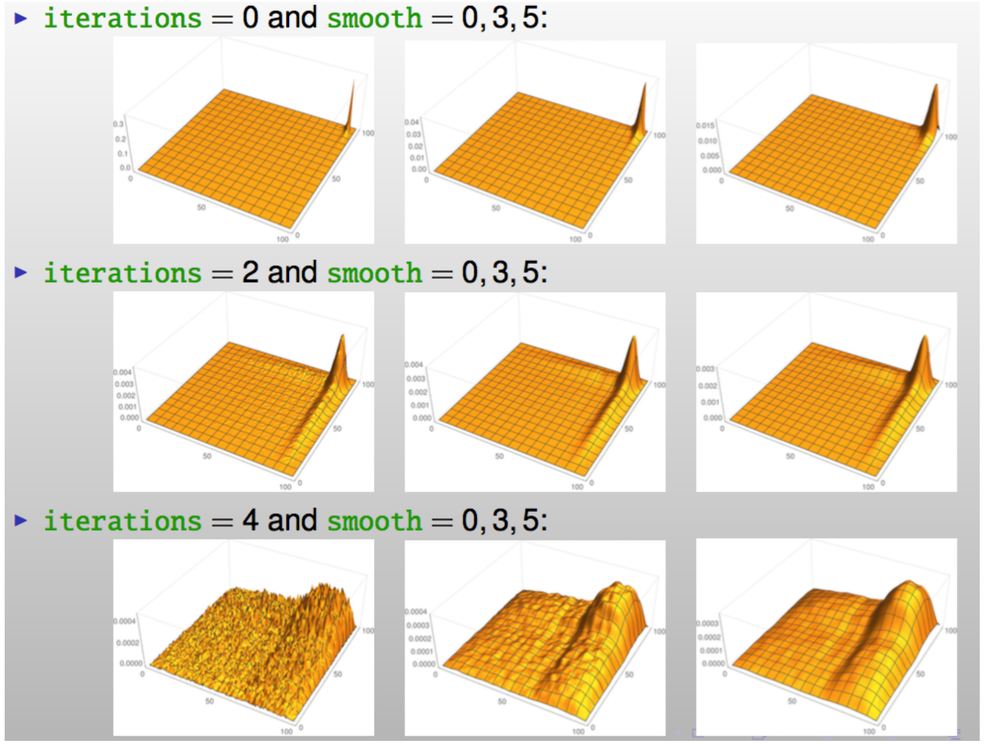


1. Run `Guinea-Pig++` with

```
do_lumi=7;num_lumi=100000000;num_lumi_eg=100000000;num_lumi_gg=100000000;
```

to produce `lumi.[eg][eg].out` with (E_1, E_2) pairs.

[Large event numbers, as `Guinea-Pig++` will produce only a small fraction!]

2. Run `circe2_tool.opt` with steering file

```
{ file="ilc500/beams.circe"                        # to be loaded by WHIZARD
  { design="ILC" roots=500 bins=100 scale=250 # E in [0,1]
    { pid/1=electron pid/2=positron pol=0      # unpolarized e-/e+
      events="ilc500/lumi.ee.out" columns=2    # <= Guinea-Pig
      lumi = 1564.763360                       # <= Guinea-Pig
      iterations = 10                          # adapting bins
      smooth = 5 [0,1) [0,1)                   # Gaussian filter 5 bins
      smooth = 5 [1] [0,1) smooth = 5 [0,1) [1] } } }
```

to produce correlated beam description

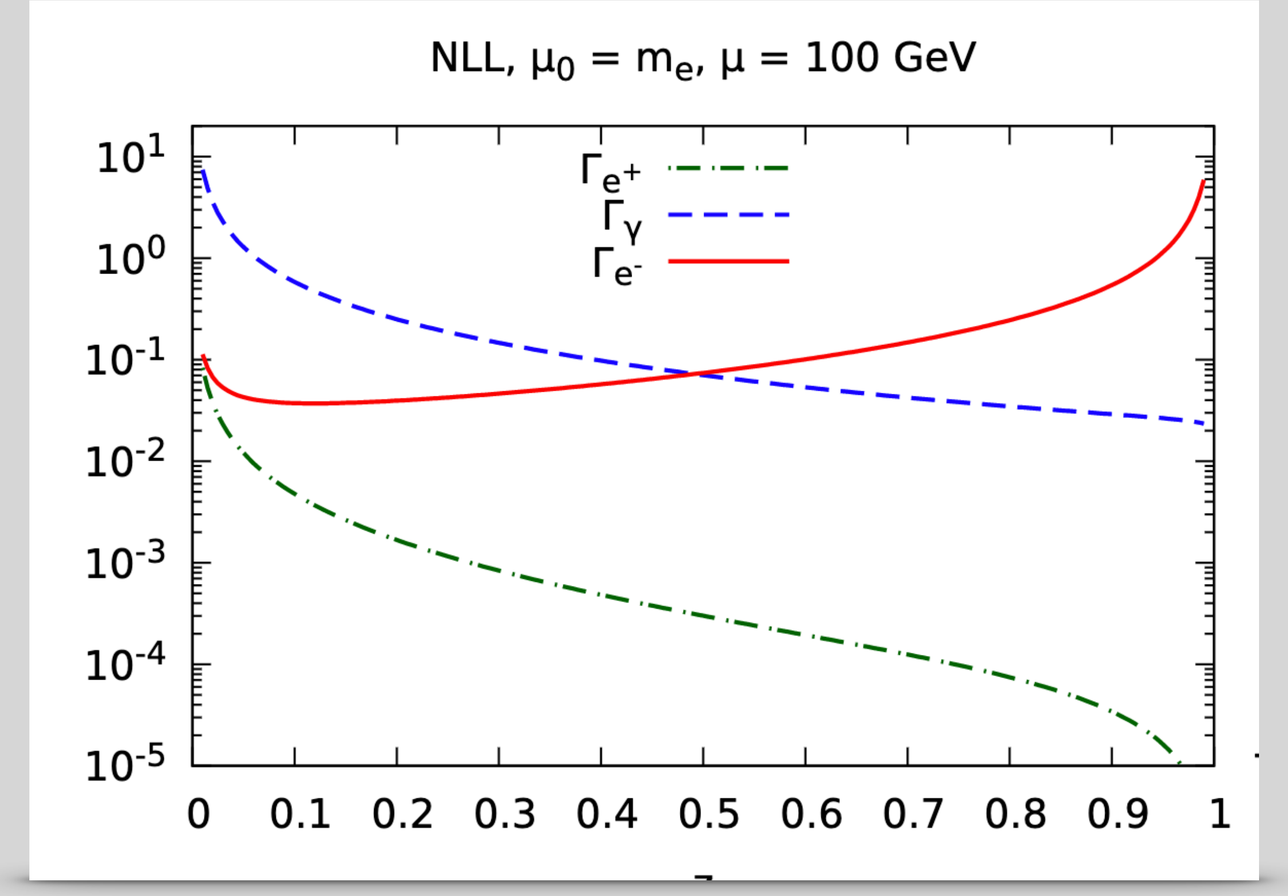
3. Run `WHIZARD` with `SINDARIN` input:

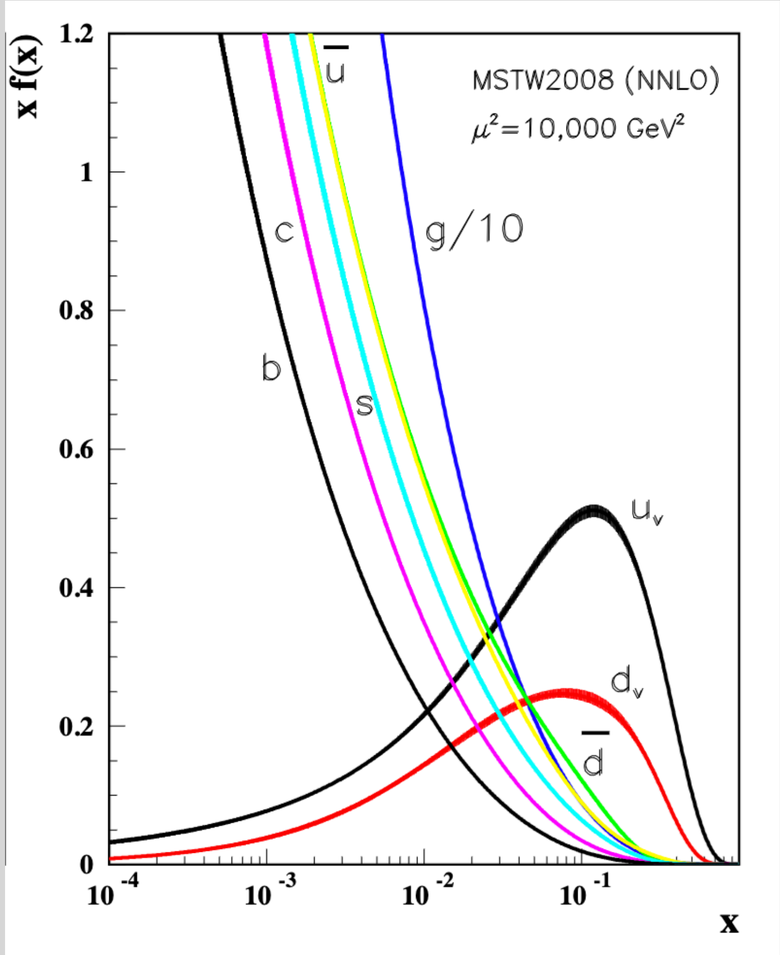
```
beams = e1, E1 => circe2
$circe2_file = "ilc500.circe"
$circe2_design = "ILC"
?circe_polarized = false
```

3 simulation options

1. Unpolarized simulation with unpol. spectra
2. Pol. simulation: unpol. spectra + pol. beams
3. Polarized spectrum with helicity luminosities

Initial State Radiation — Lepton PDFs





QED PDFs — QED Initial State Resummation

- Different factorization schemes: focus on collinear logs, $\log \frac{Q^2}{m_\mu^2}$, vs. soft logs, $\log \frac{Q^2}{E_\gamma^2}$, cf. 2203.12557

- YFS (Yennie-Frautschi-Suura), cf. e.g. 2203.10948 $d\sigma = \sum_{n_\gamma}^{\infty} \frac{\exp[Y_{res.}]}{n_\gamma!} \prod_{j=1}^{n_\gamma} \left[d\mathrm{LIPS}_j^\gamma S_{res.}(k_j) \right] \left[\sigma_0 + \mathrm{corrections} \right]$

  - Universal soft exponentiation factor, provides n_γ exclusive resolved photons with (almost) exact kinematics
  - Exponentiation at amplitude level (CEEX) oder squared ME level (EEX)
  - Implemented in LEP legacy MCs (`BHLUMI/BHWIDE`, `KORAL(W/Z)`, `KKMC-ee`, `YFS(WW/ZZ)`, also: `Sherpa`, w.i.p.: `Whizard`
  - Can be systematically improved at fixed-order level by higher-order corrections

- Collinear factorization: universal lepton QED PDFs, LL: $(\alpha L)^k$, NLL: $\alpha(\alpha L)^{k-1}$

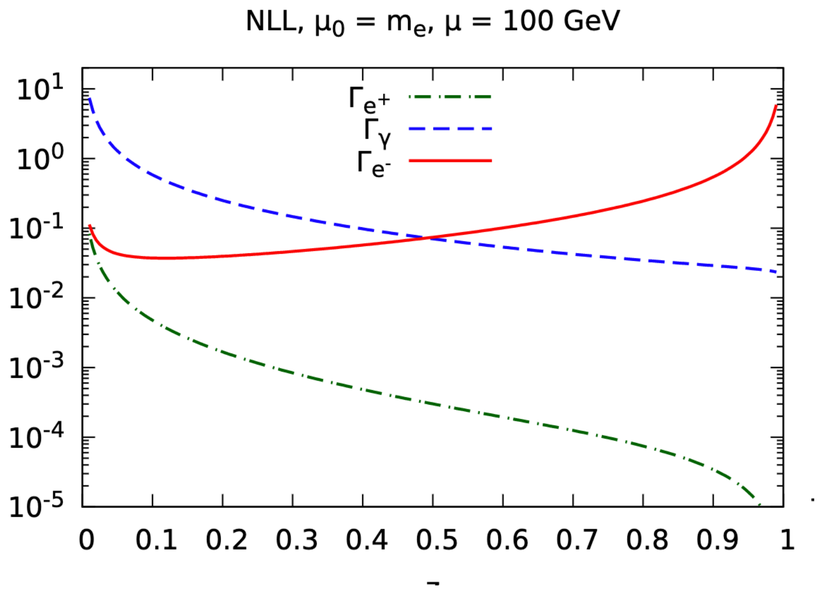
$$d\sigma_{kl}(p_k, p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \, \Gamma_{i/k}(z_+, \mu^2, m^2) \, \Gamma_{j/l}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s} \right)^p \right)$$

$$\mathbb{P}_S = \begin{pmatrix} P_{\Sigma\Sigma} & P_{\Sigma\gamma} \\ P_{\gamma\Sigma} & P_{\gamma\gamma} \end{pmatrix},$$

$$P_{NS} = P_{e^\pm e^\pm} - P_{e^\pm e^\mp} \equiv P_{ee}^V - P_{e\bar{e}}^V .$$

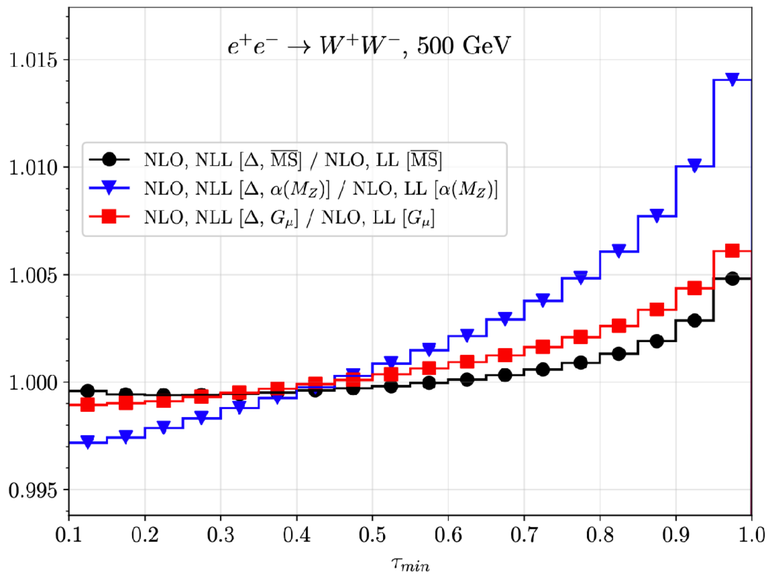
Integrable power-like singularity 1/(1-z) for $z \to 1$

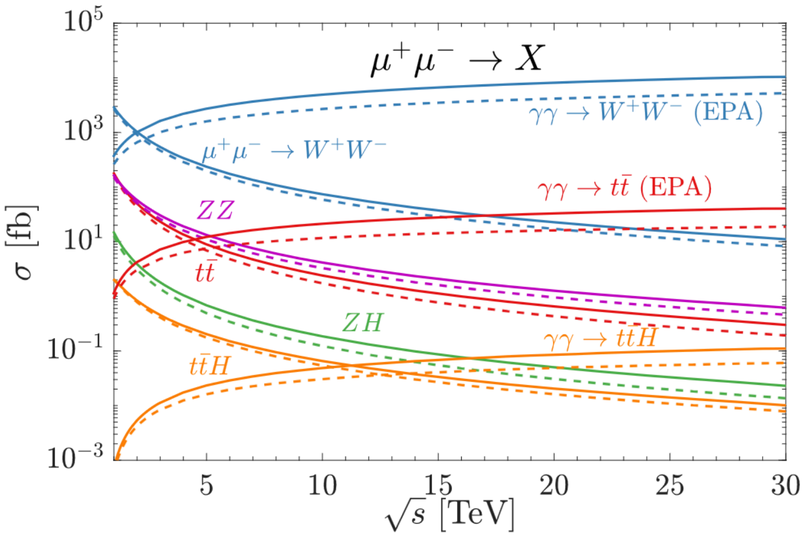
ePDFs for polarized leptons !?



QED PDFs — Collinear Factorization

- Collinear resummation LO/LL Gribov/Lipatov, 1972; Kuraev/Fadin, 1985; Skrzypek/Jadach, 1992; Cacciari/Deandrea/Montagna/Nicrosini, 1992
- NLO QED PDFs, collinear evolution @ NLL
  Frixione, 1909.0388; Bertone/Cacciari/Frixione/Stagnitto, 1911.12040 + 2207.03265
- Inclusive in all initial-state photons
- Gives most precise normalization of total cross section
- Numerical stability differs in different QED renormalization schemes, DIS vs. $\overline{\text{MS}}$
- *Also:* fast interpolation (CTEQ-like) grids available
- Implementations available in `MG5` and `Whizard`
- Different levels of precision possible: NLL+NLO, LL+NLO, LL+NLO, LL+LO
- Different names in literature: electron structure functions, ISR structure functions
- "Photon PDF" (a.k.a. EPA, Weizsäcker-Williams) Γ_γ, peaked at small z
- Very well known from ILC/CLIC simulations: "virtual photon"-induced processes
- At very high energies lepton colliders become $\gamma\gamma$ colliders (like LHC is gg)





Han/Ma/Xie, 2007.14300

EW PDFs — EW Collinear Factorization

- Collinear factorization not in QED, but in full SM
  Han/Ma/Xie, 2007.14300, 2103.09844
- Ancient name (from SSC times!): EWA ("Effective *W* approximation)
- Fully inclusive in collinear/forward/beam direction
- *Also:* fast interpolation (CTEQ-like) grids available

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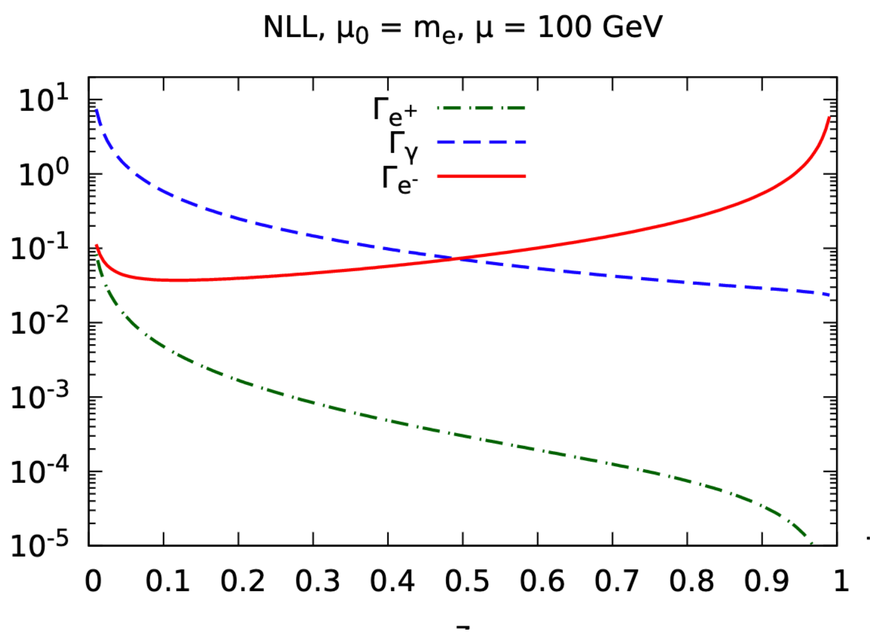

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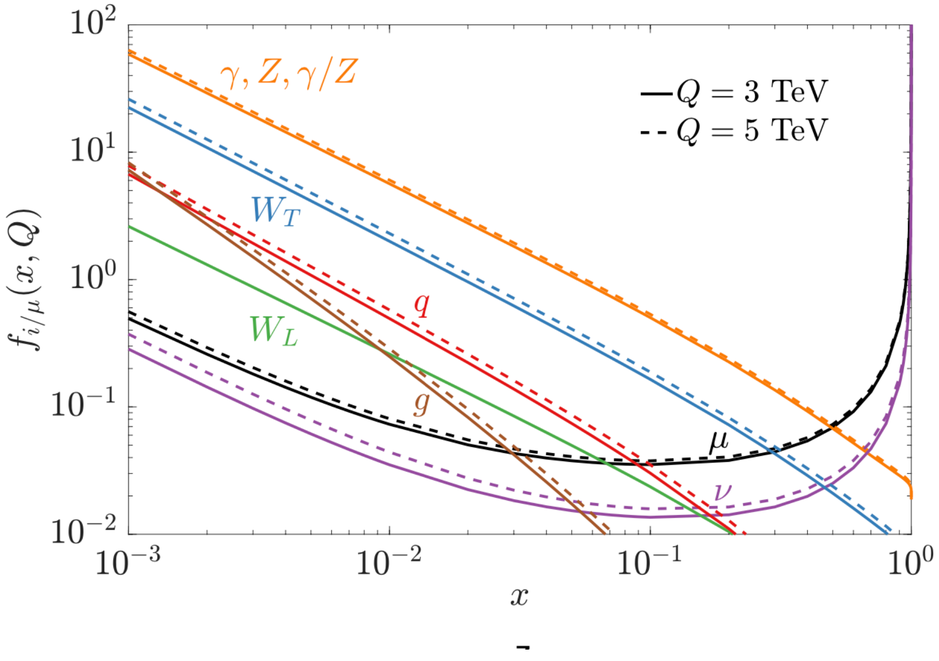

↪ talk by David Marzocca

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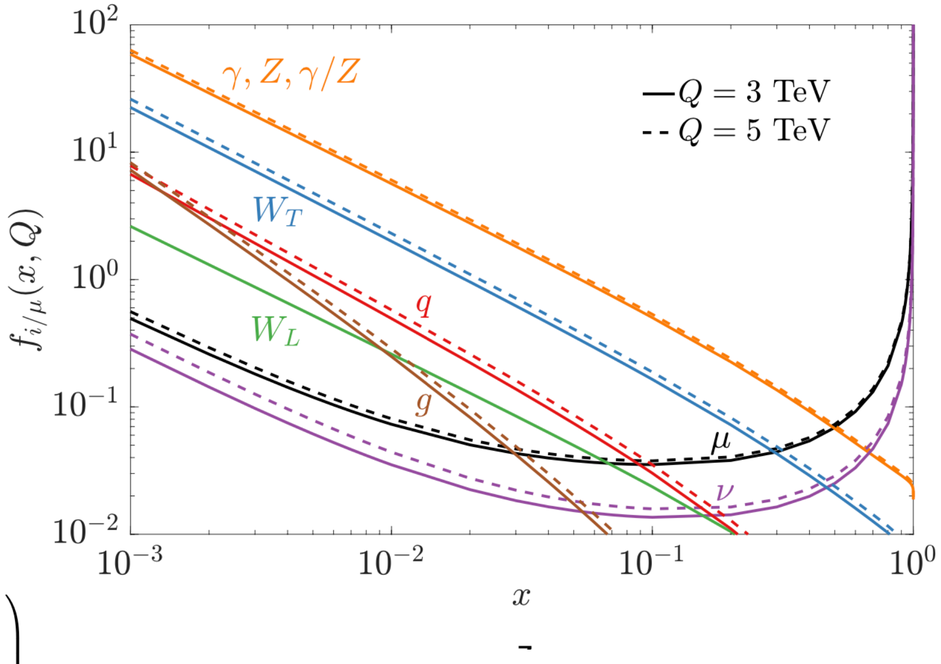
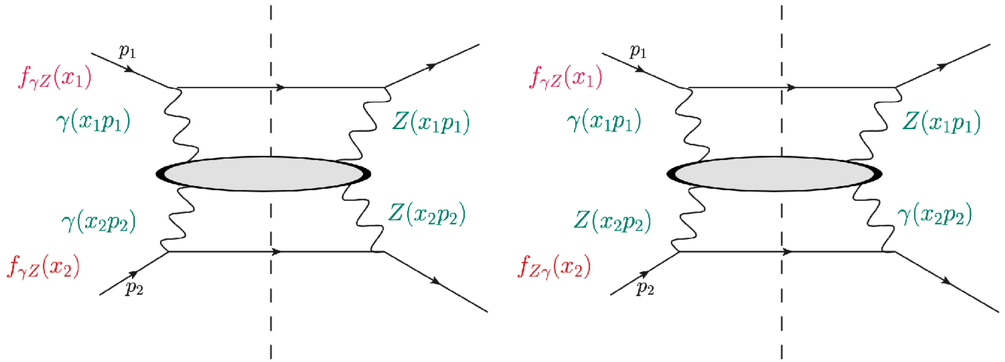
- Collinear factorization not in QED, but in full SM
  Han/Ma/Xie, 2007.14300, 2103.09844
- Ancient name (from SSC times!): EWA ("Effective *W* approximation)
- Fully inclusive in collinear/forward/beam direction
- *Also:* fast interpolation (CTEQ-like) grids available





$$\begin{array}{c} \\ \gamma \\ Z \\ \gamma/Z \end{array} \begin{array}{c} \begin{array}{ccc} \gamma & Z & \gamma/Z \end{array} \\ \begin{pmatrix} \hat\sigma(\gamma,\gamma) & \hat\sigma(\gamma,Z) & \hat\sigma(\gamma,\gamma/Z) \\ \hat\sigma(Z,\gamma) & \hat\sigma(Z,Z) & \hat\sigma(Z,\gamma/Z) \\ \hat\sigma(\gamma/Z,\gamma) & \hat\sigma(\gamma/Z,Z) & \hat\sigma(\gamma/Z,\gamma/Z) \end{pmatrix} \end{array}$$

- $\gamma\gamma$ part (quasi-) identical to collinear QED lepton PDFs
- Factorization has coherent interference $\gamma\gamma/\gamma Z/ZZ$
- Trivial on the PDF infrastructure side, complication for ME generation
- Work in progress in `MG5` and `Whizard`
- Has to be accompanied by EW fragmentation functions (event selection!)

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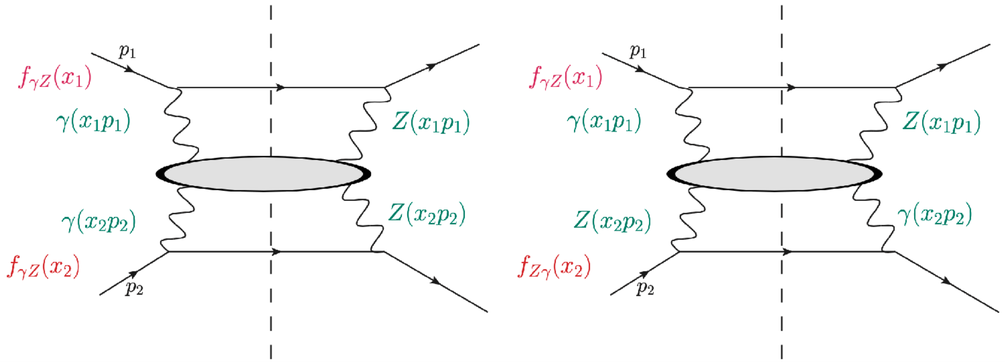

$$
\begin{array}{c}
 \\ \gamma \\ Z \\ \gamma/Z
\end{array}
\begin{array}{c}
\begin{array}{ccc} \gamma & Z & \gamma/Z \end{array} \\
\begin{pmatrix}
\hat\sigma(\gamma,\gamma) & \hat\sigma(\gamma,Z) & \hat\sigma(\gamma,\gamma/Z) \\
\hat\sigma(Z,\gamma) & \hat\sigma(Z,Z) & \hat\sigma(Z,\gamma/Z) \\
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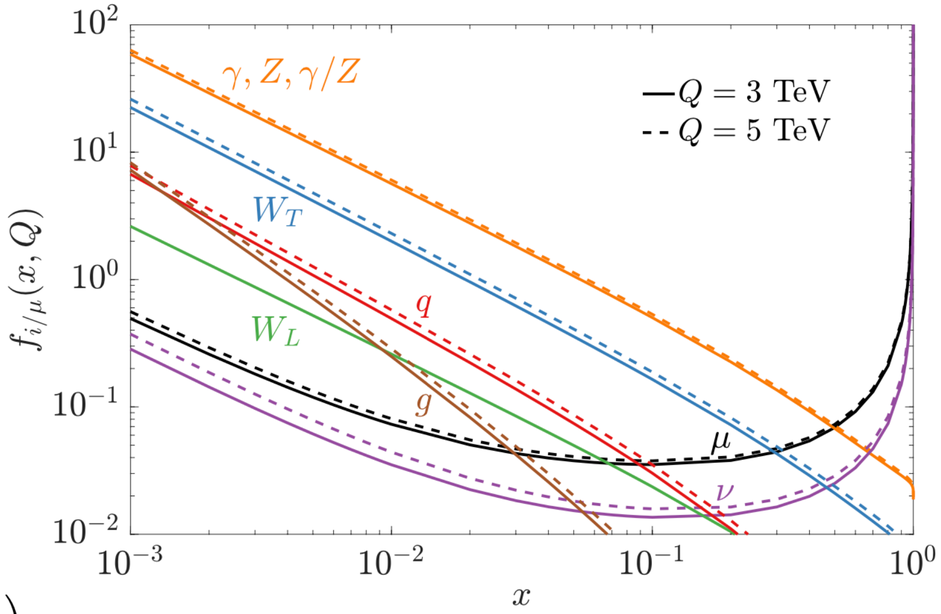
\end{pmatrix}
\end{array}
$$



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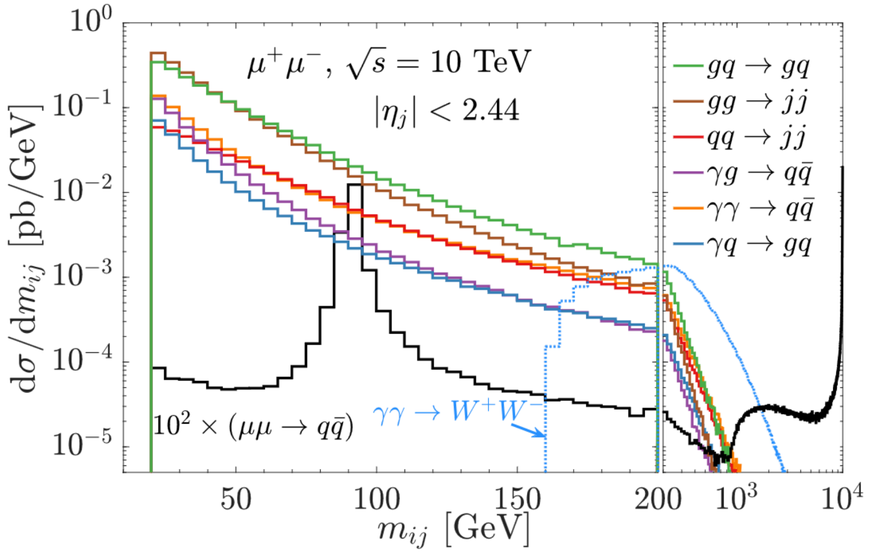
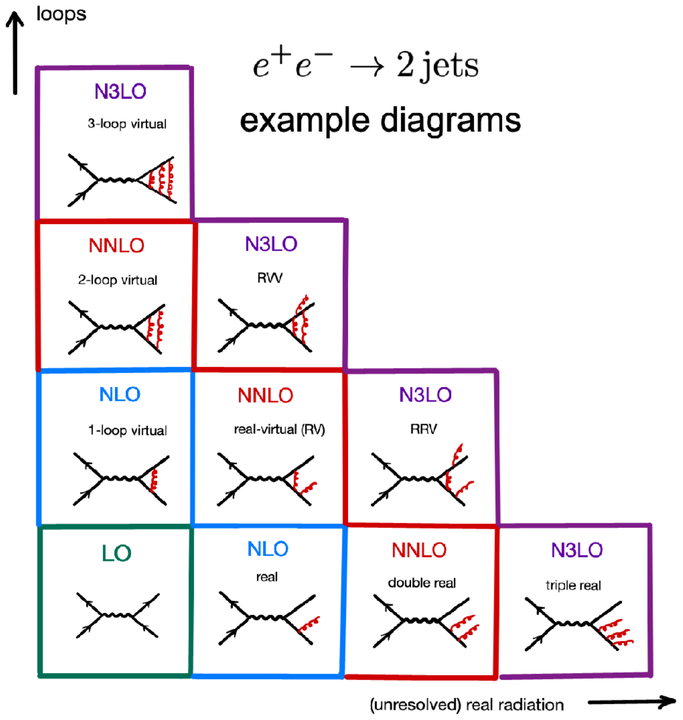


SM precision in hard processes — Loops and Legs

Getty Villa, Pacific Palisades, Etruscan, 525 BC

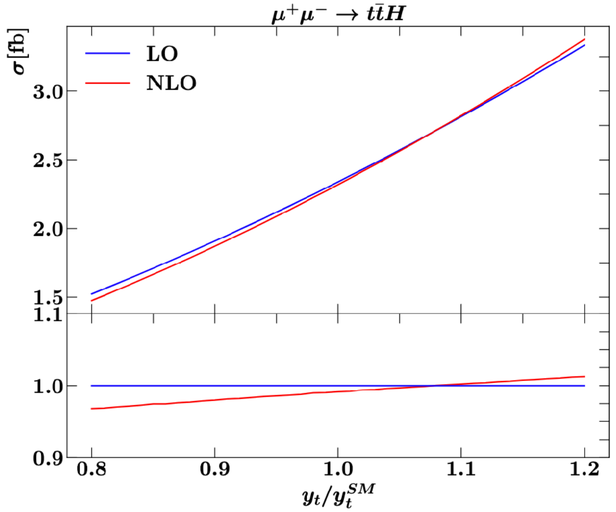
The "Exclusive" Frontier — fN(N)LO, Automation in MCs



	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

- Fixed-order N(N)LO, resummation and matching in MCs
- Determination of efficiencies and systematic uncertainties
- Signal and background samples at full SM QFT interference level
- Need $e^+e^- \to$ *2f, 3f, 4f, 5f, 6f, [7-10f]* @ *NLO QCD ⊕ EW* (arbitrary cuts, fully differential)

- NLO QCD ⊕ EW automated: Sherpa, MG5, Whizard
- Caveats and fine-prints



NLO QCD

$\mu^+\mu^- \to t\bar{t}H$

$\sqrt{s}$[GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K
500	0.272	$0.435^{+3.82\%}_{-3.13\%}$	1.601
800	2.339	$2.319^{+0.01\%}_{-0.09\%}$	0.991
1000	2.008	$1.893^{+0.49\%}_{-0.62\%}$	0.942
1400	1.323	$1.192^{+0.81\%}_{-1.08\%}$	0.900
1000	2.009	$1.894^{+0.45\%}_{-0.65\%}$	0.942
3000	0.406	$0.342^{+1.54\%}_{-1.84\%}$	0.842
6000	0.128	$0.102^{+2.22\%}_{-2.55\%}$	0.794
10000	0.053	$0.040^{+3.01\%}_{-3.11\%}$	0.759
14000	0.030	$0.0221^{+3.33\%}_{-3.13\%}$	0.735

NLO EW

$\mu^+\mu^- \to t\bar{t}H$

$\sqrt{s}$[GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K
500	0.271	0.091	0.335
800	2.339	1.533	0.655
1000	2.008	1.402	0.698
1400	1.323	0.967	0.731
1000	2.008	1.322	0.658
3000	0.407	0.296	0.728
6000	0.128	0.086	0.669
10000	0.053	0.027	0.516
14000	0.030	0.017	0.579

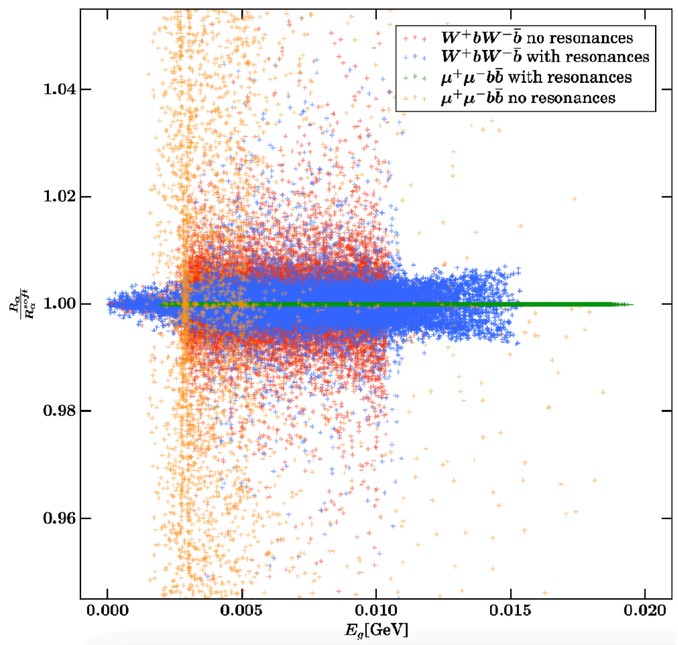
Francesco Ucci, DESY summer student report, 2022

	MCSANCee[37]		WHIZARD+RECOLA			
$\sqrt{s}$ [GeV]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	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

Pia Bredt, Phd thesis, DESY, 2022

N(N)LO Automation in MC — Some technical details

- MC NLO implementation relies on 2 building blocks: Subtraction (Catani-Seymour or Frixione/Kunszt/Soper)
- also: resonance-aware FKS subtraction cf. Ježo/Nason, 1509.09071; Chokoufé, 2017
- Automatic differential fixed-order results (histogrammed distributions) in MCs
- Photon isolation, photon recombination, light-, b-, c-jet selection
- Covers also loop-induced processes ("LO", virtual-squared)



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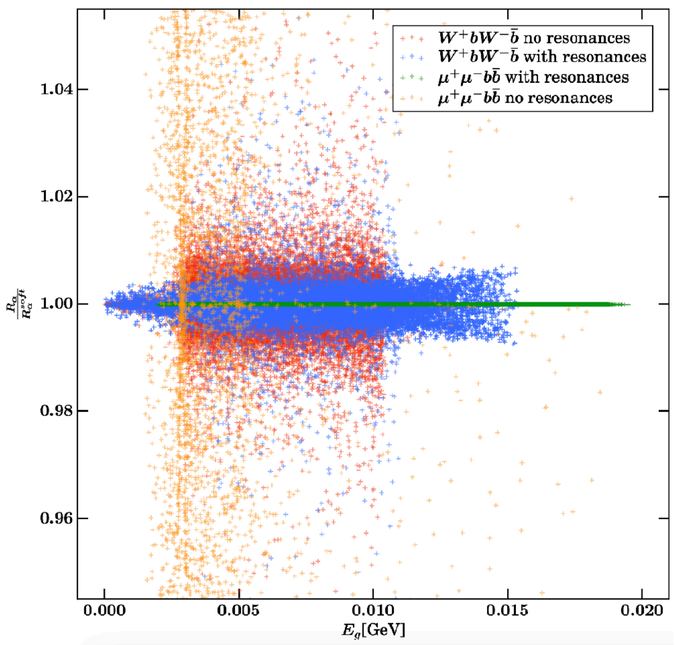

Two major bottlenecks

- Virtual integrals with many mass scales / off-shell legs
  Abreu ea., Badger ea., Baglio ea., Brønnum-Hansen ea.
- IR pole treatment / subtraction CS, FKS, NS, Stripper, qT/sub-jettiness etc.

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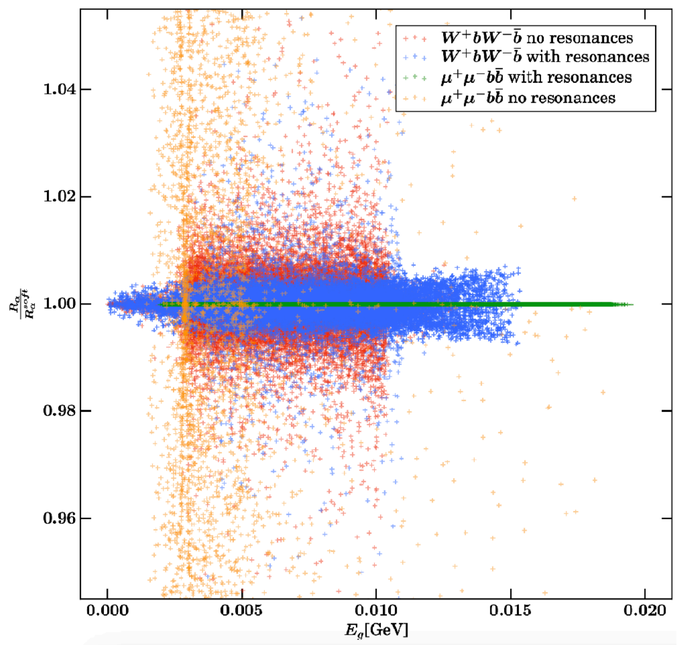

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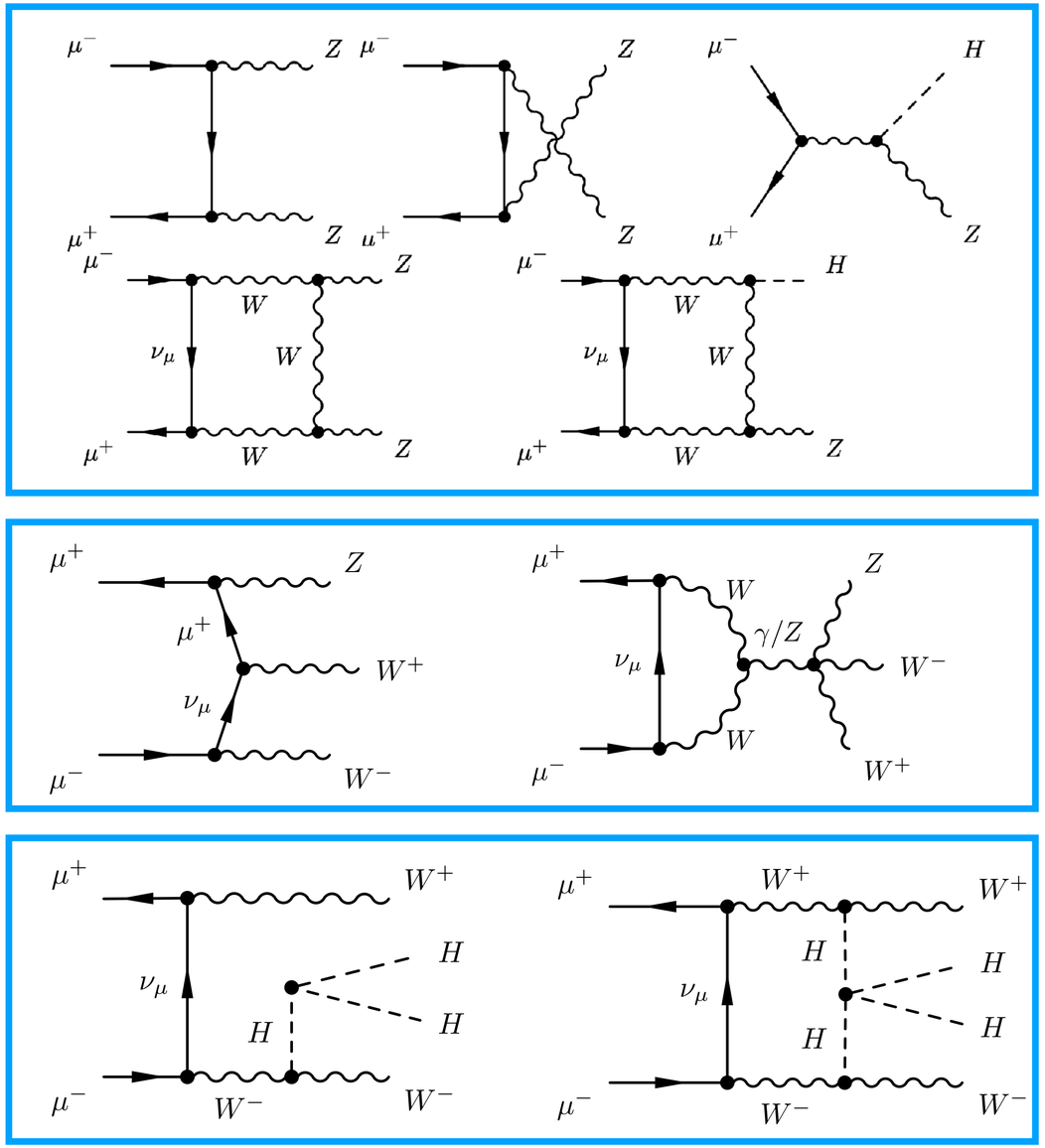
- ☑ FKS soft/eikonal subtraction sufficient for low-energy machines
- ☑ NNLO QED (massive, virtuals pending): `McMule` Signer ea. [Whizard]
- ☑ Baby steps to NNLO automation: `Griffin` Chen/Freitas, 2023
- ☑ for NNLO EW need for full-fledged soft+collinear NNLO subtraction

SM EW Corrections to Multi-Bosons

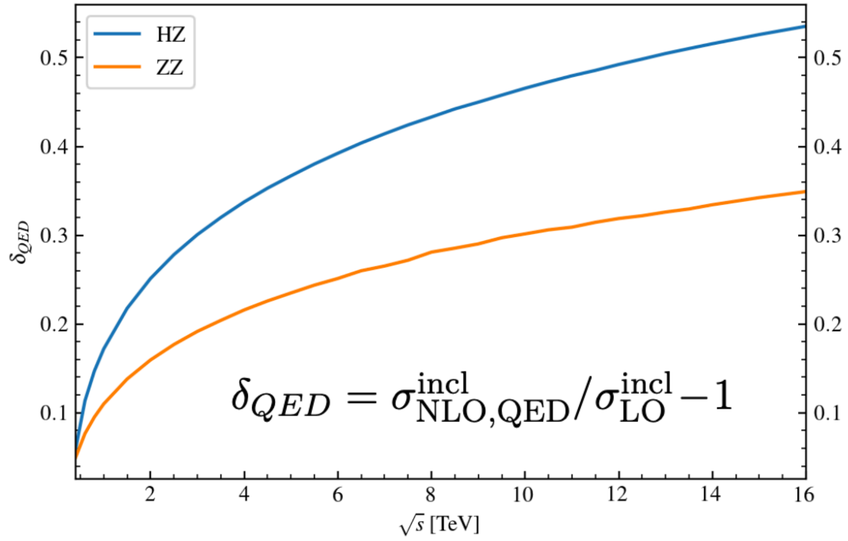
arXiv: 2208.09438



$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma_{\rm LO}^{\rm incl}$ [fb]	$\sigma_{\rm NLO}^{\rm incl}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$4.6591(2)\cdot 10^2$	$4.847(7)\cdot 10^2$	$+4.0(2)$
ZZ	$2.5988(1)\cdot 10^1$	$2.656(2)\cdot 10^1$	$+2.19(6)$
HZ	$1.3719(1)\cdot 10^0$	$1.3512(5)\cdot 10^0$	$-1.51(4)$
HH	$1.60216(7)\cdot 10^{-7}$	$5.66(1)\cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2)\cdot 10^1$	$2.568(8)\cdot 10^1$	$-22.9(2)$
W^+W^-H	$1.1253(5)\cdot 10^0$	$0.895(2)\cdot 10^0$	$-20.5(2)$
ZZZ	$3.598(2)\cdot 10^{-1}$	$2.68(1)\cdot 10^{-1}$	$-25.5(3)$
HZZ	$8.199(4)\cdot 10^{-2}$	$6.60(3)\cdot 10^{-2}$	$-19.6(3)$
HHZ	$3.277(1)\cdot 10^{-2}$	$2.451(5)\cdot 10^{-2}$	$-25.2(1)$
HHH	$2.9699(6)\cdot 10^{-8}$	$0.86(7)\cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1)\cdot 10^0$	$0.993(6)\cdot 10^0$	$-33.1(4)$
W^+W^-ZZ	$1.209(1)\cdot 10^0$	$0.699(7)\cdot 10^0$	$-42.2(6)$
W^+W^-HZ	$8.754(8)\cdot 10^{-2}$	$6.05(4)\cdot 10^{-2}$	$-30.9(5)$
W^+W^-HH	$1.058(1)\cdot 10^{-2}$	$0.655(5)\cdot 10^{-2}$	$-38.1(4)$
$ZZZZ$	$3.114(2)\cdot 10^{-3}$	$1.799(7)\cdot 10^{-3}$	$-42.2(2)$
$HZZZ$	$2.693(2)\cdot 10^{-3}$	$1.766(6)\cdot 10^{-3}$	$-34.4(2)$
$HHZZ$	$9.828(7)\cdot 10^{-4}$	$6.24(2)\cdot 10^{-4}$	$-36.5(2)$
$HHHZ$	$1.568(1)\cdot 10^{-4}$	$1.165(4)\cdot 10^{-4}$	$-25.7(2)$

- EW corrections for massive initial state muons
- Massive eikonals need special treatment at high energies

Validation of the QED & Sudakov regime



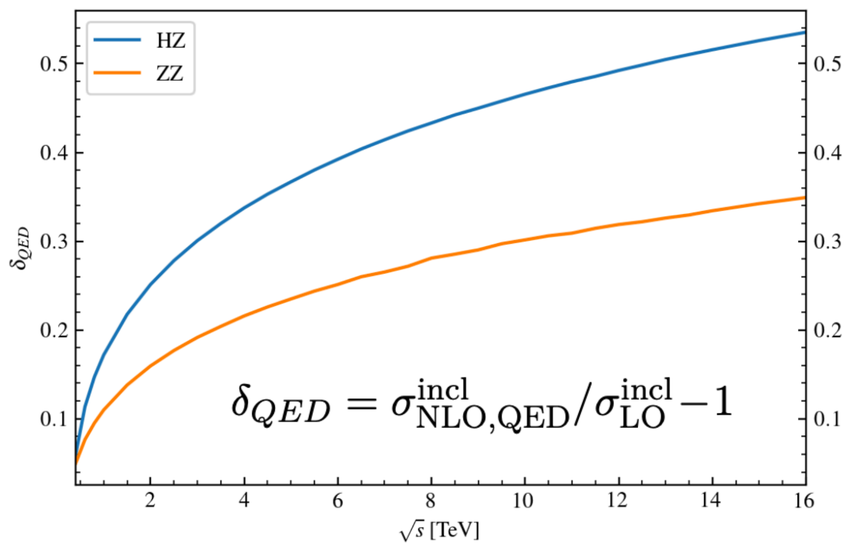
$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm LO+ISR}$ [fb]	$\delta_{\rm ISR}$ [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$7.295(7) \cdot 10^1$	$+24.0(1)$
ZZ	$3.2730(4) \cdot 10^0$	$4.119(4) \cdot 10^0$	$+25.8(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.8278(5) \cdot 10^{-1}$	$+48.69(4)$
W^+W^-Z	$9.609(5) \cdot 10^0$	$10.367(8) \cdot 10^0$	$+7.9(1)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$2.410(2) \cdot 10^{-1}$	$+13.3(1)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$9.431(7) \cdot 10^{-2}$	$+10.1(1)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$1.677(1) \cdot 10^{-2}$	$+14.62(8)$
HHZ	$6.083(2) \cdot 10^{-3}$	$6.916(3) \cdot 10^{-3}$	$+13.68(6)$

arXiv: 2208.09438

Validation of the QED & Sudakov regime

$$L(s, M_W^2) = \frac{\alpha}{4\pi} \log^2 \frac{s}{M_W^2} \overset{10\,\text{TeV}}{\sim} 6\%$$

$$l(s, M_W^2) = \frac{\alpha}{4\pi} \log \frac{s}{M_W^2} \overset{10\,\text{TeV}}{\sim} 0.6\%$$



- EW corrections at high energies dominated by EW double & single Sudakov logs
- Relevant in kinematic region of Sudakov limit $r_{kl} = (p_k + p_l)^2 \sim s \gg M_W^2$
- IR quasi-divergencies of virtual corrections not cancelled by real EW radiation
- Both initial and final states no EW "color" singlets

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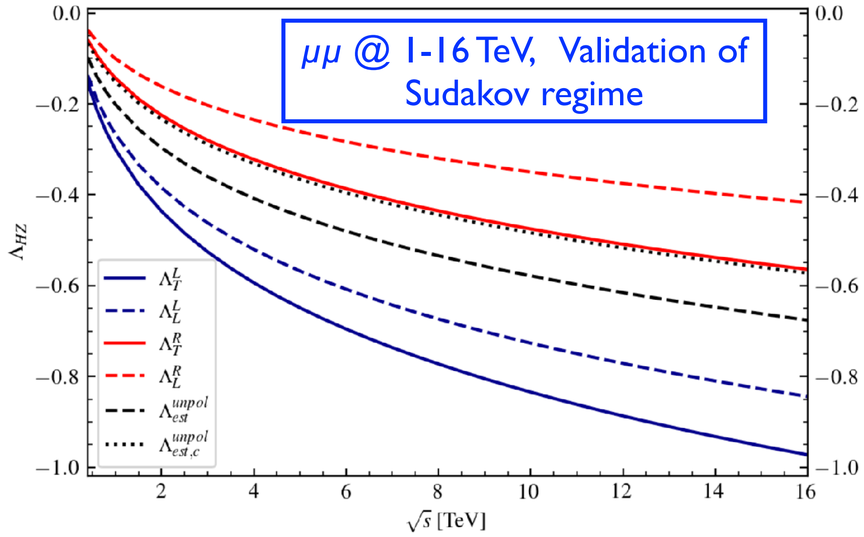


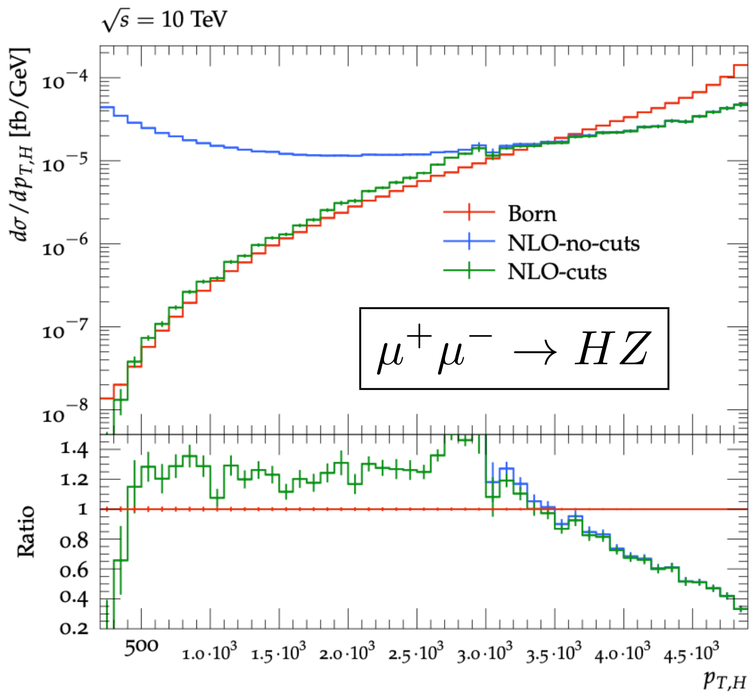
↪ talks by Davide Pagani, Alfredo Glioti

Differential results

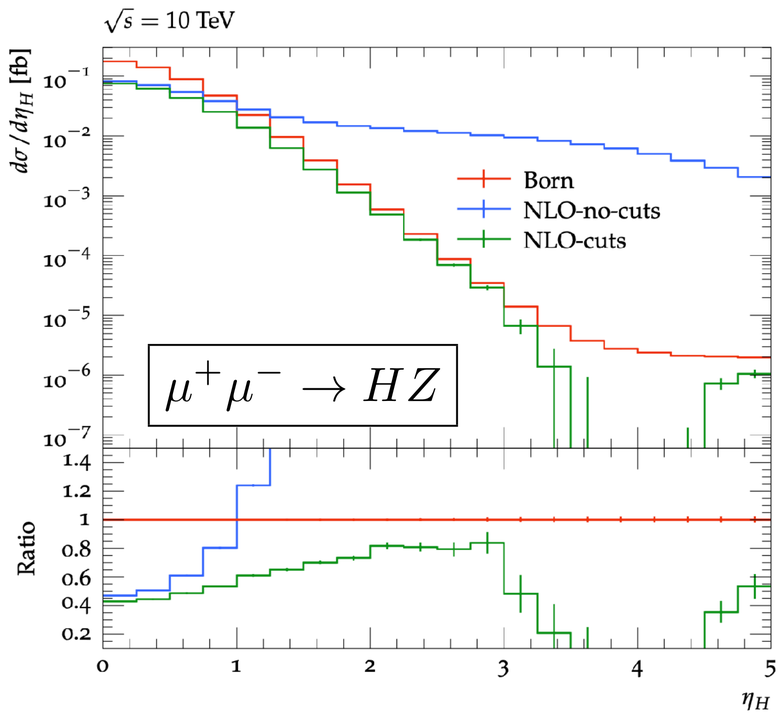
Experimentally motivated photon veto in hard radiation: $E_\gamma < 0.7 \cdot \sqrt{s}/2$

arXiv: 2208.09438

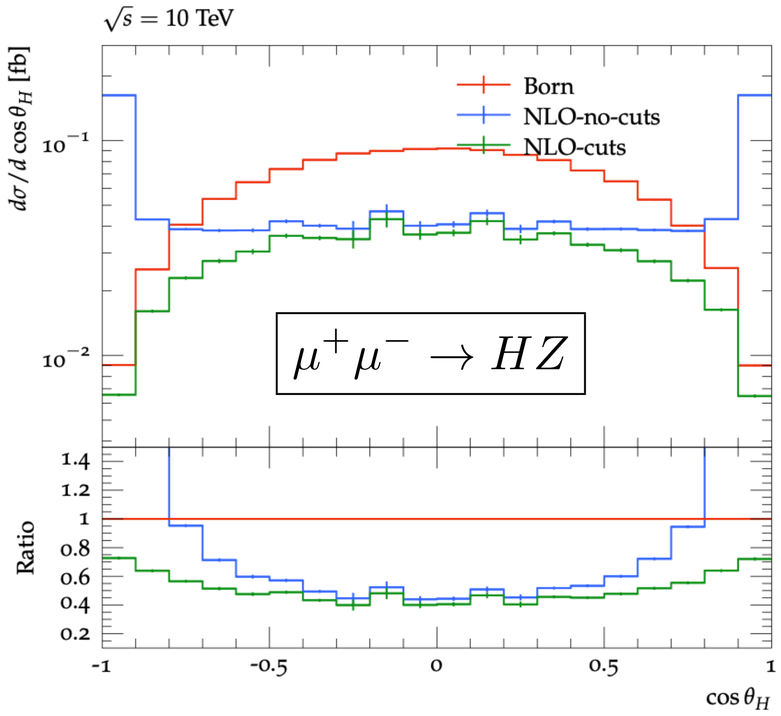
Higgs Transverse Momentum



Higgs rapidity

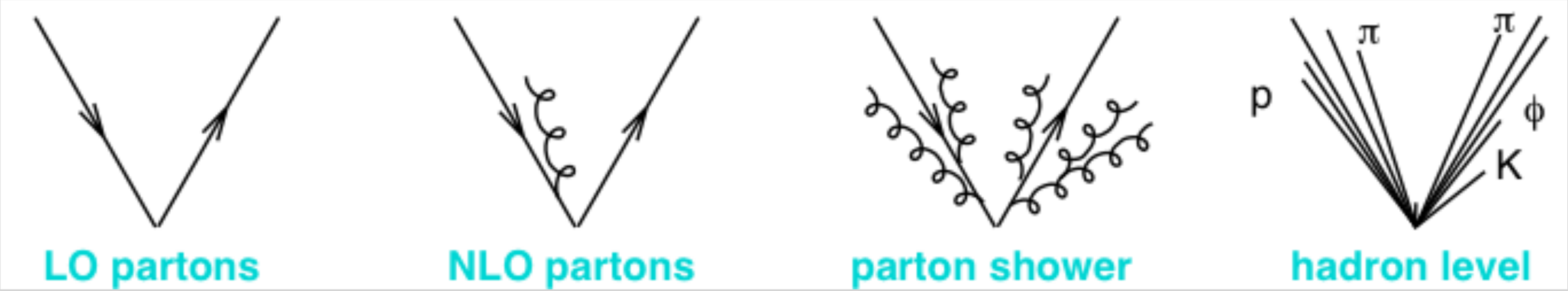


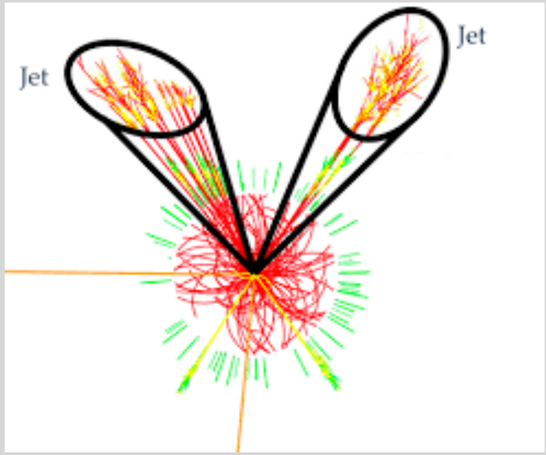
Higgs scattering angle

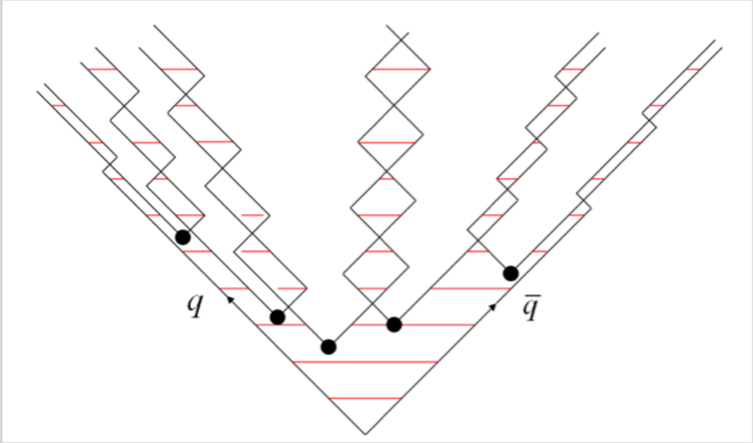


More tasks for even more realistic predictions: exclusive events w/ matching to QED/weak showers, resummation, off-shell processes, separate VBF from VBS

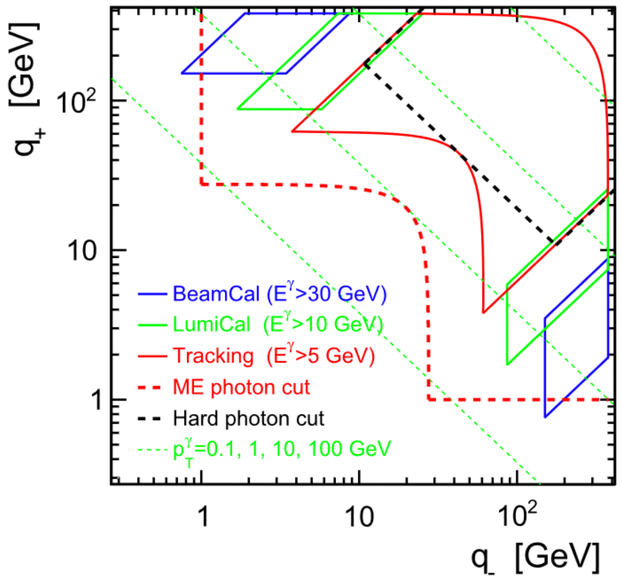
Parton Showers and Hadronization

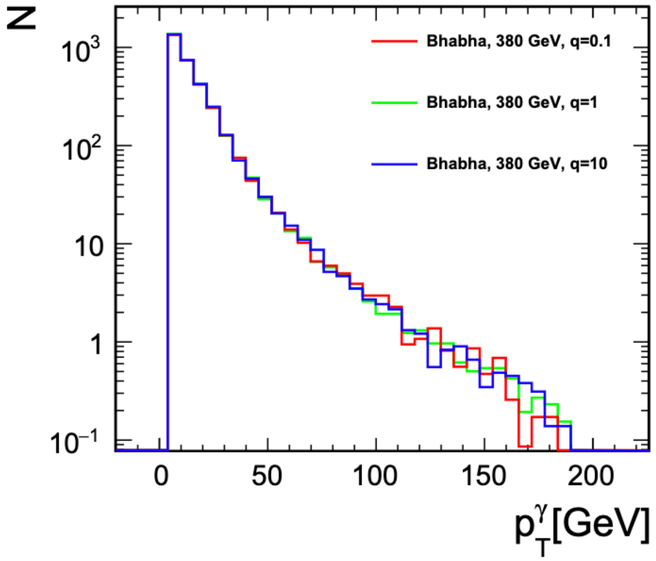






Exclusive photons



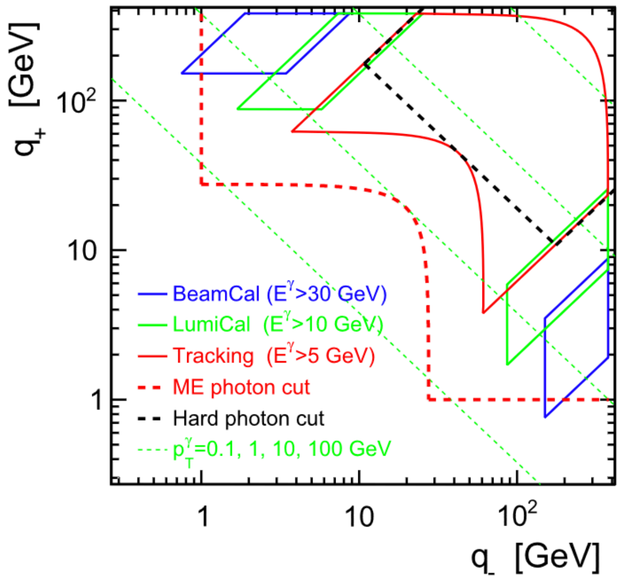


J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

QED ISR [+FSR], matching

- Explicit photon from fix-order (LO/NLO/NNLO) matrix element (best description)
- "Shower-recoil approach": generate $p_\perp$ according to $\frac{\alpha}{\pi} \cdot \log \frac{p_\perp^2}{m_e^2}$
- Boost according to the generated $p_\perp$ (avail. for for ISR, EPA or ISR+EPA)
- Algorithm applied recursively (similar to massive NLO EW ISR PS construction)
- Recursive algorithm resembles a photon shower with *n* exclusive photons

Exclusive photons



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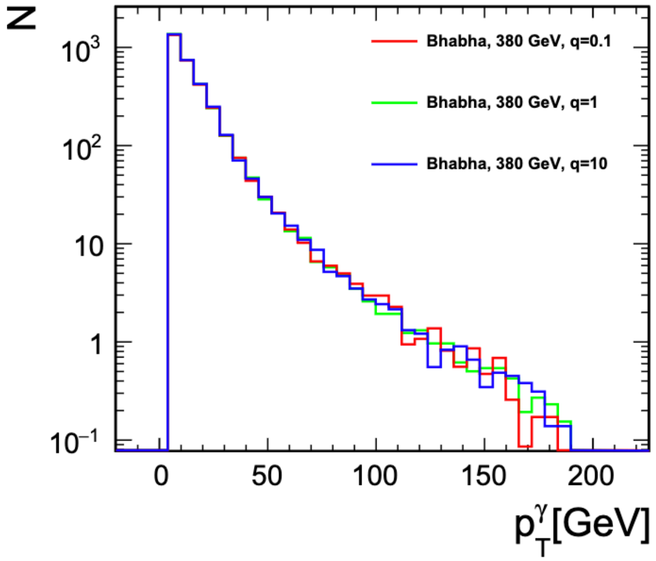


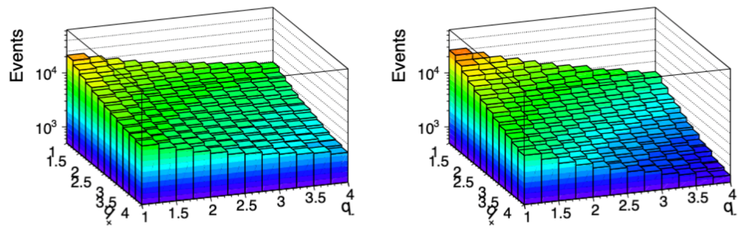
J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

Full QED shower

- Based either on dipoles or antennae, for ISR separate, for FSR interleaved [?]
- Can then be combined with POWHEG/MC@NLO/XXX-type matching
- Can be combined with resummation in (semi-)automated ways ... w.i.p.

Matching between EPA/γPDF + beam γ

M. Berggren/W. Kilian/K. Mękała/JRR

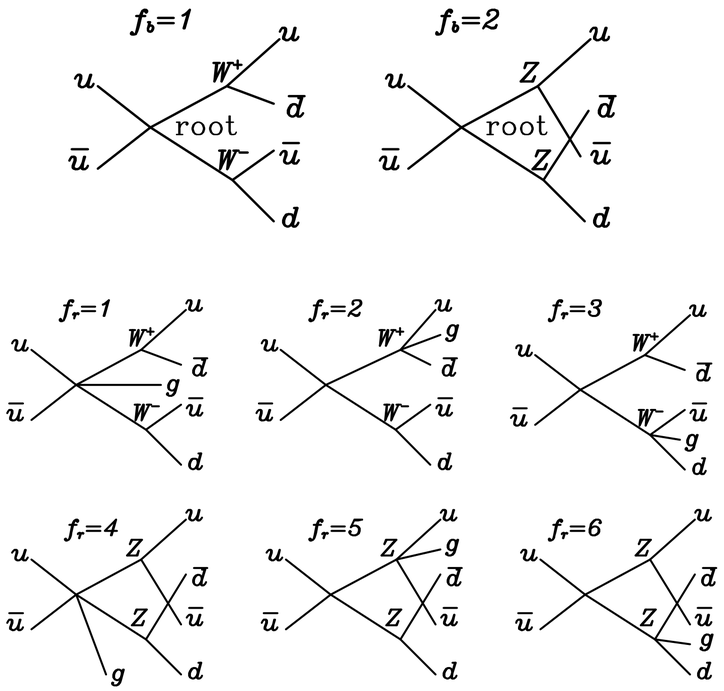


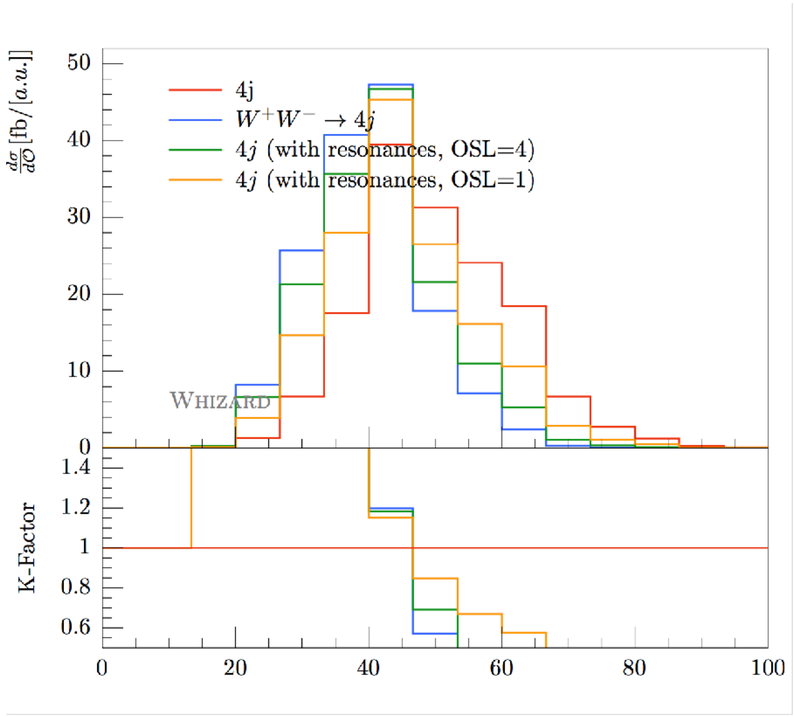
(a) Double EPA (b) Full matrix elements

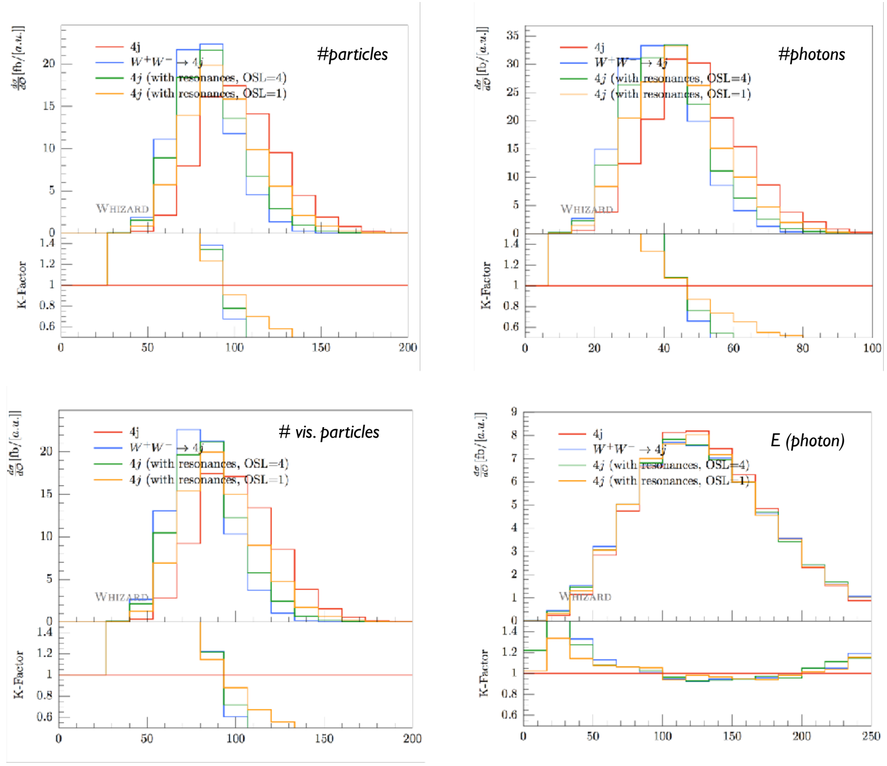
(Resonance) Matching to shower / hadronization


```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power, but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging w/ resonant subprocesses by resonance histories
- MC generators allow to pass resonance history to SMC



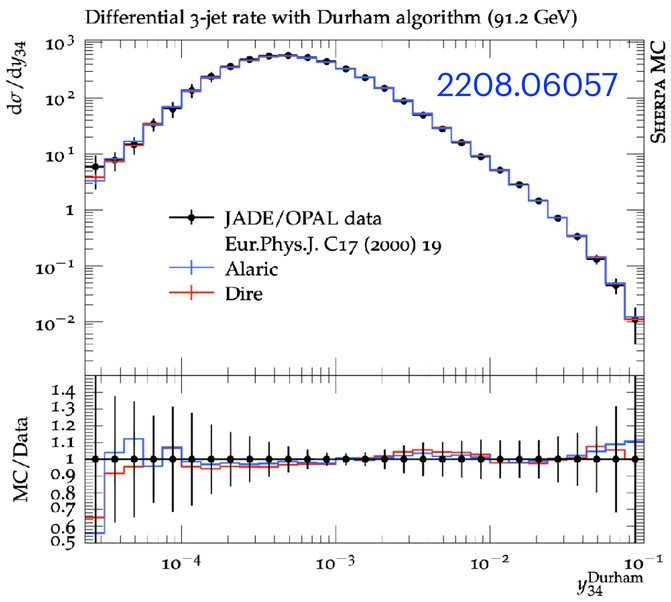




LO + NLO QCD (+EW?) matching and fragmentation

- A lot of development for parton showers, towards NLL and next-to-leading color

  (DIRE, ALARIC, Deductor, HERWIG, PanScales, VINCIA, PYTHIA)
- Matching between NLO real emission from hard ME and parton shower (PS)
- Different MCs have different schemes: MC@NLO, POWHEG, [NNLO+N³LO schemes]
- Special cases: Massive/massless emitters, back-to-pack kinematics, running α_s
- Real partitioning of phase space into singular and finite regions
- Resonance-aware subtraction: Intermediate resonances handled
- At the moment mostly: NLO QCD; straightforward (?) QED/EW generalization

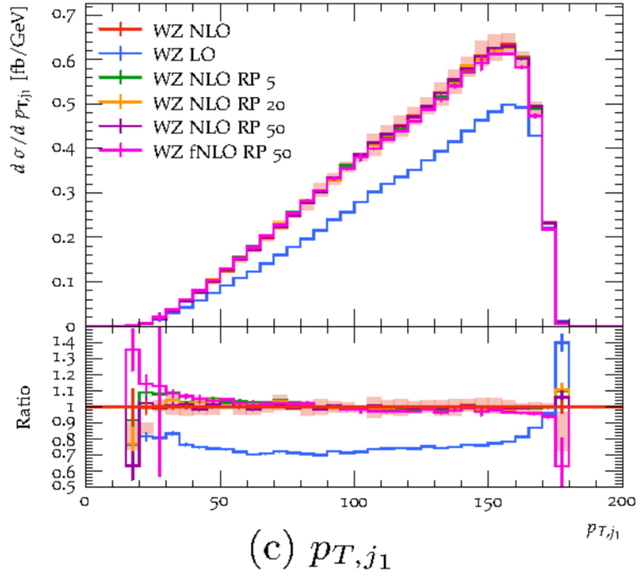


- Apply specific NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\mathrm{rad}} R(\Phi_{n+1})$$

- Modified Sudakov form factor:

$$\Delta_R^{\mathrm{NLO}}(k_T) = \exp\left[-\int d\Phi_{\mathrm{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T)\right]$$



(c) p_{T,j_1}

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

ILC 500: $e^+e^- \to t\bar{t}j$

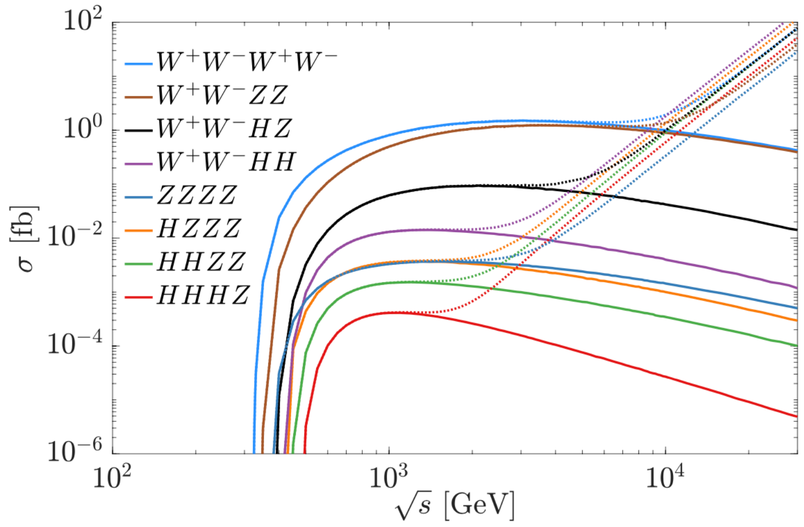
$\mu_R = H_T/2$ with $H_T := \sum_i \sqrt{p_{T,i}^2 +}$

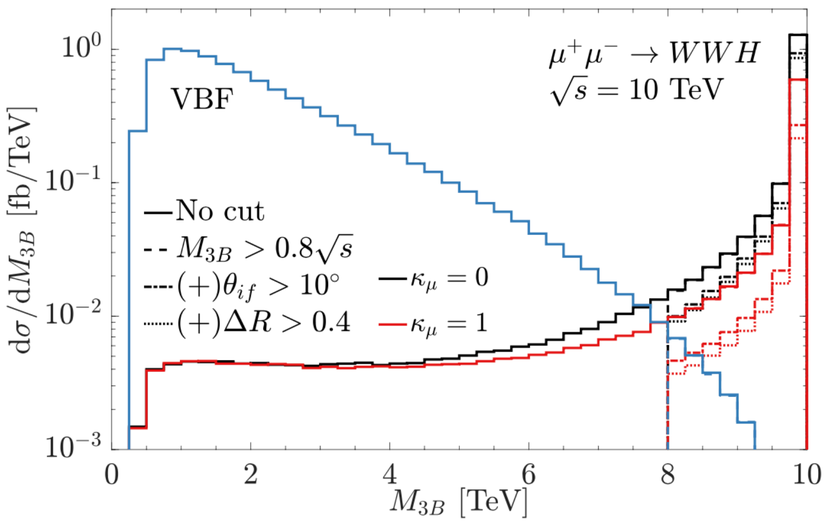
BSM Modelling in Simulation

BSM Models: UFO magic

- BSM models available from Lagrangian level tools (`LanHEP`, `SARAH`, `FeynRules`)
- Transferred to MC generator via UFO format: v1 1108.2040 v2:2304.09883
- Allows for all Lagrangian-based BSM models

- ☑ Spin 0, 1/2, 1, 3/2, 2 supported (some 3/2, 2 features missing in some MC)
- ☑ Majorana fermions and fermion-number violating vertices
- ☑ 5-, 6-, 7-, 8-, ... point vertices (optimization for code generation pending)
- ☑ Arbitrary Lorentz structures in vertices
- ☑ Keeping track of the order of insertions
- ☑ Customized propators
- ☑ Exotic colored objects (sextets, decuplets, epsilon structures)
- ☑ (S)LHA-style input files from spectrum generators to MC generators (scans!)
- ☑ Automated calculations of widths (UFO side vs. MC generator side)
- ☐ Long-lived particles, displaced vertices, oscillations in decays (not all MCs yet)
- ☑ Lots of bug reports and constructive feedback from many different users
- ☐ LO fully supported, NLO (QCD) available on UFO side, but not all MCs





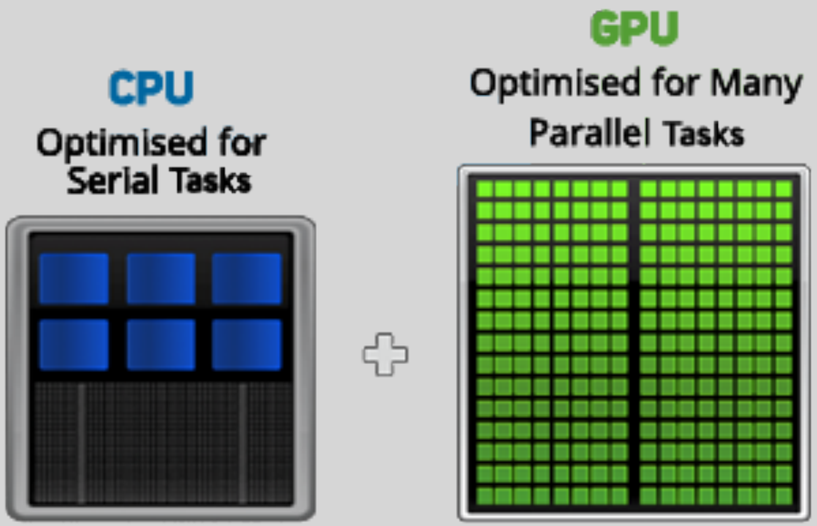
MuC example for SMEFT/HEFT UFO, from: T. Han et al. arXiv:2108.05362

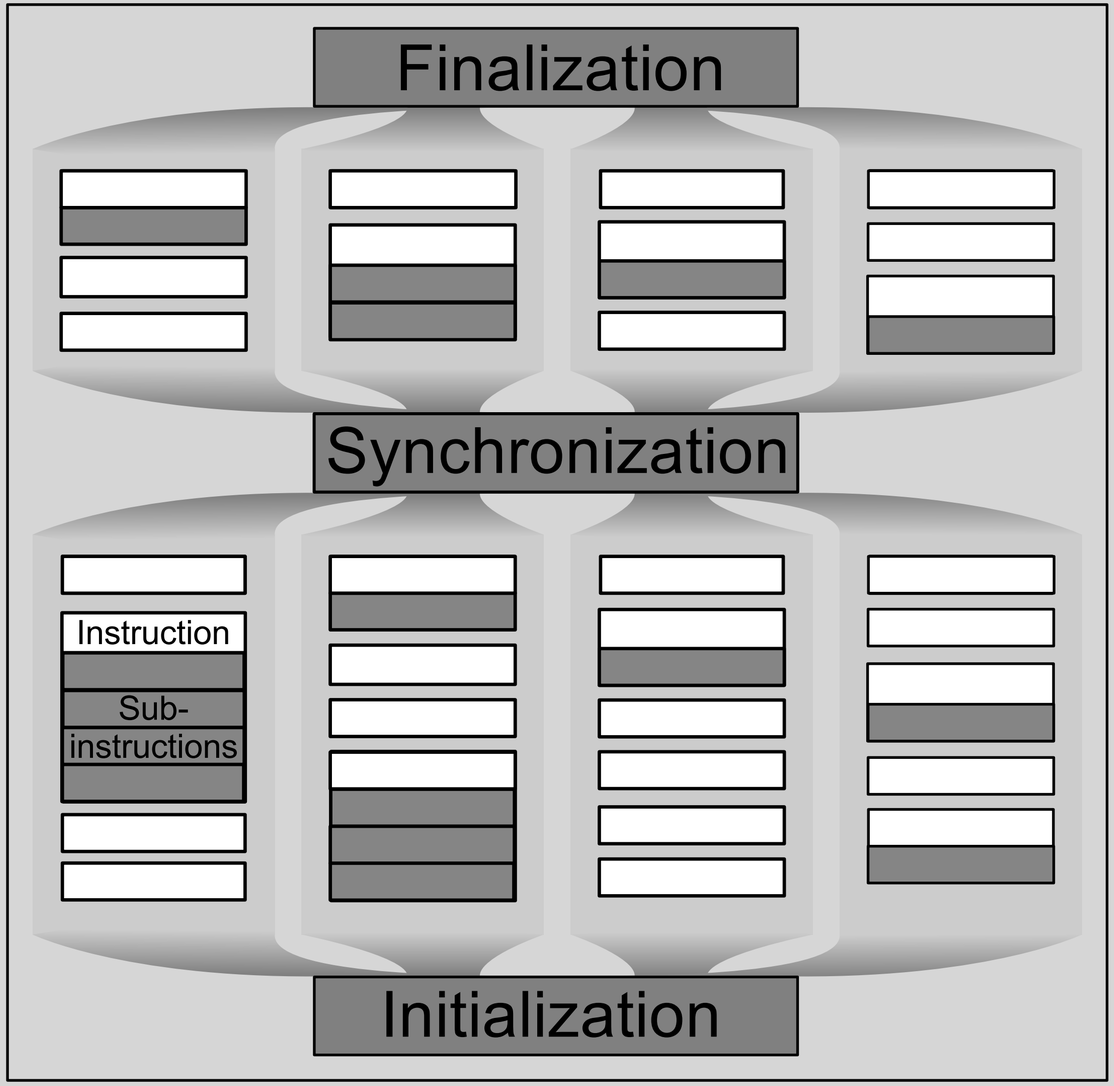
Conclusions & Outlook

- Monte-Carlo event generators implement *all* necessary SM and BSM physics
- Fixed-order NLO QCD+EW for SM and NLO QCD BSM under control (mostly)
- Attempts to go to NNLO for QED (with certain assumptions)
- LL/NLL μPDF in collinear factorization vs. YFS soft/eikonal factorization
- Matching prescriptions for exclusive photon radiation
- Important (but still in infancy) work in QED + EW parton showers with matching
- Different focus in different generators: no *a priori* best strategy for QED (and EW) corrections
- More studies, test cases and benchmarks needed: also 2nd and 3rd implementations important!
- Also need for dedicated MCs, e.g. for luminosity measurement ($\mu\mu \to \mu\mu, \gamma\gamma$)
- Not to forget: QCD showers + factorization [Higgs factories will boost this to new precision!]

BACKUP

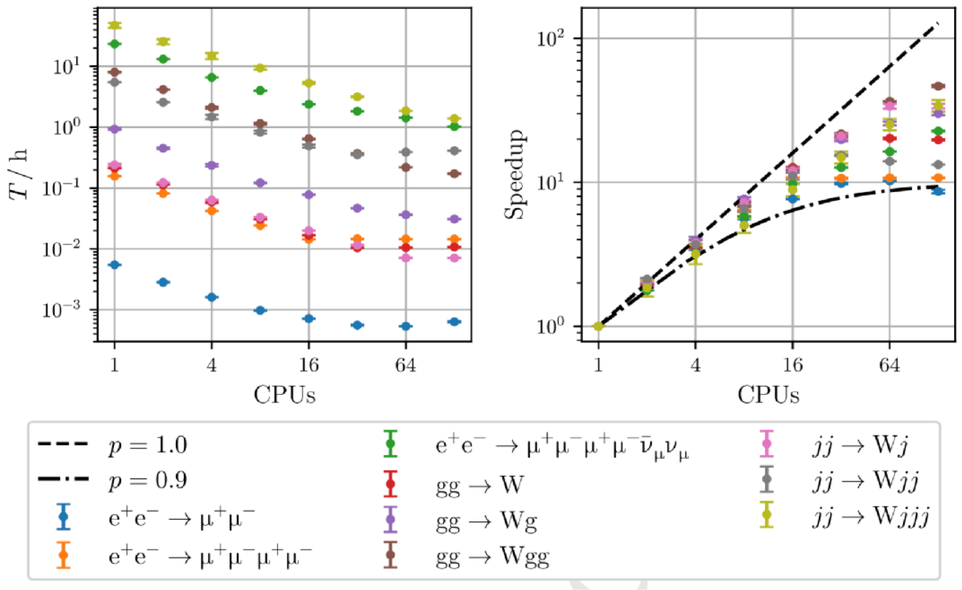
Monte Carlo Efficiency / Speed Up





Flash through working algorithms

- Parallelization of integration: OMP multi-threading for different helicities / PS channels [can do also parallel event generation]
- MPI parallelization (using OpenMPI or MPICH) Braß/Kilian/JRR, 1811.09711
- Distributes workers over multiple cores
- Grid adaption needs non-trivial communication
- Speedups of 10 to 30, saturation at O(100) tasks
- Load balancer / non-blocking communication
- Offloading of MEs / parts of infrastructure code to GPU



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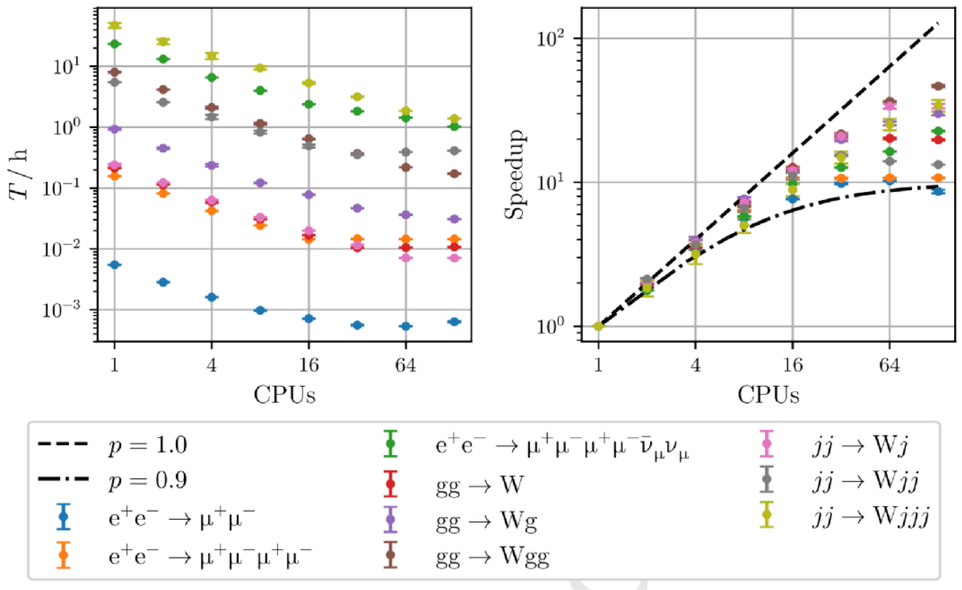

- Offloading of MEs / parts of infrastructure code to GPU
- Semi-automatized ME generation for GPU in `MG5` and `Whizard`
- Bottleneck: cache of GPU allows only for small-ish code chunks transferred
- Still a lot of work needed to make it fully competitive

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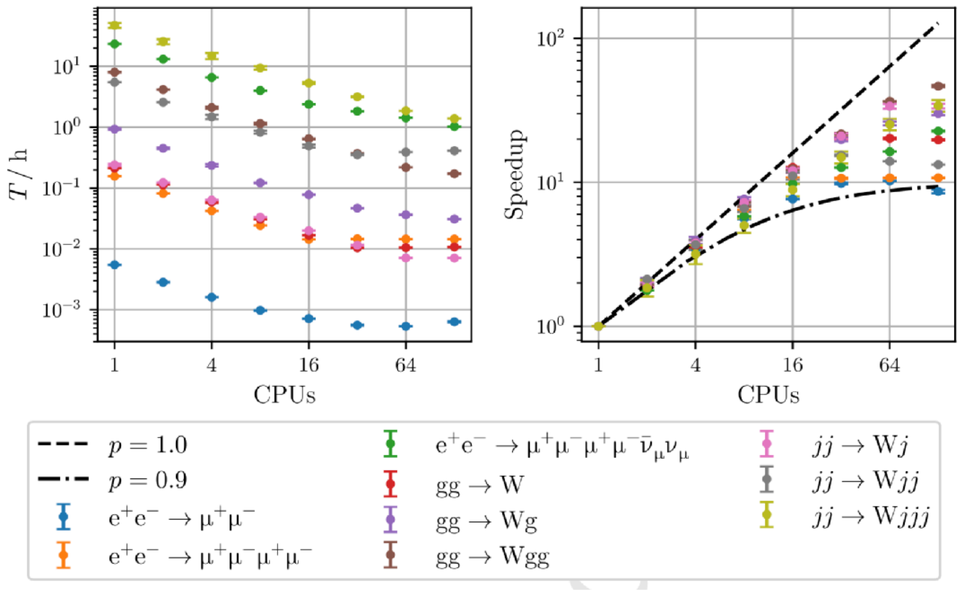

Very preliminary:

Process	$t^{CPU}[s]$	$t^{GPU}[s]$
$e^+e^- \to t\bar{t}$	0.98	4.28
$e^+e^- \to bW^+\bar{b}W^-$	28.8	23.1
$e^+e^- \to bW^+\bar{b}W^-H$	57.5	37.8
$e^+e^- \to b\bar{b}\bar{\nu}_e e^-\bar{\nu}_\mu\mu^+$	154	124
$e^+e^- \to 2j$	1.9	5.4
$e^+e^- \to 3j$	45	65
$e^+e^- \to 4j$	870	608
$e^+e^- \to 5j$	4106	978
$pp \to jj$	42	86
$pp \to W^+W^-W^+W^-$	670	192

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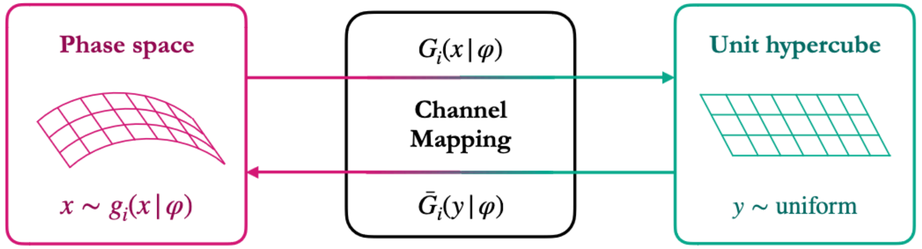
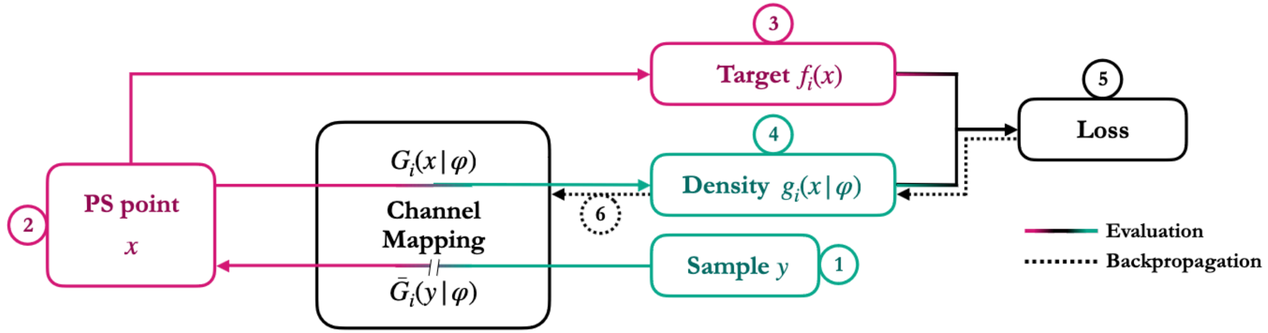
Machine Learning: MC for integration and simulation

- Phase space integration / adaptation by Invertible Neural Networks (INNs) / normalizing flows
- Define divergence-based loss function
- Use of buffered losses and training

Hoeche ea., 2001.10028, Heimel/ Winterhalder ea., 2212.06172



Online training:



Buffered training: