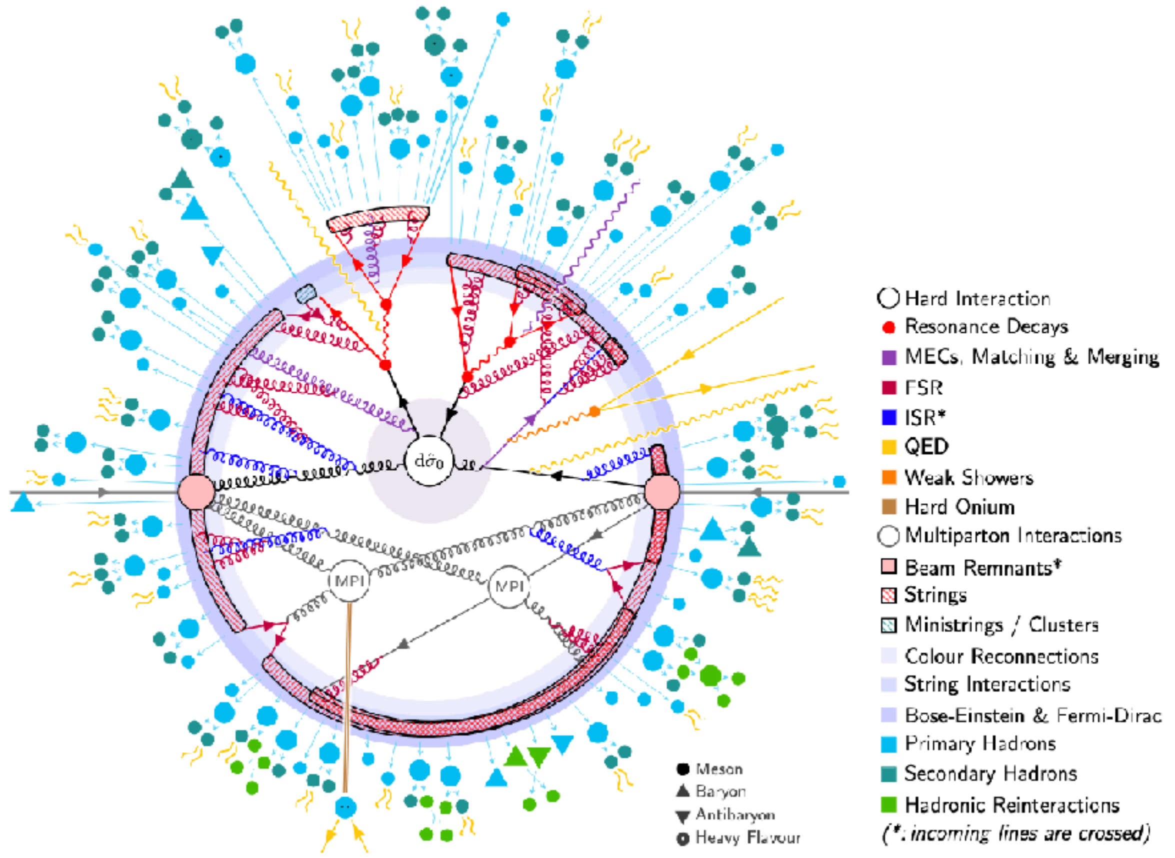
Monte Carlo generators for *Higgs / EW / Top Factories*



HELMHOLTZ

NARODOWE CENTRUM NAUKI

Opus

Universität Hamburg

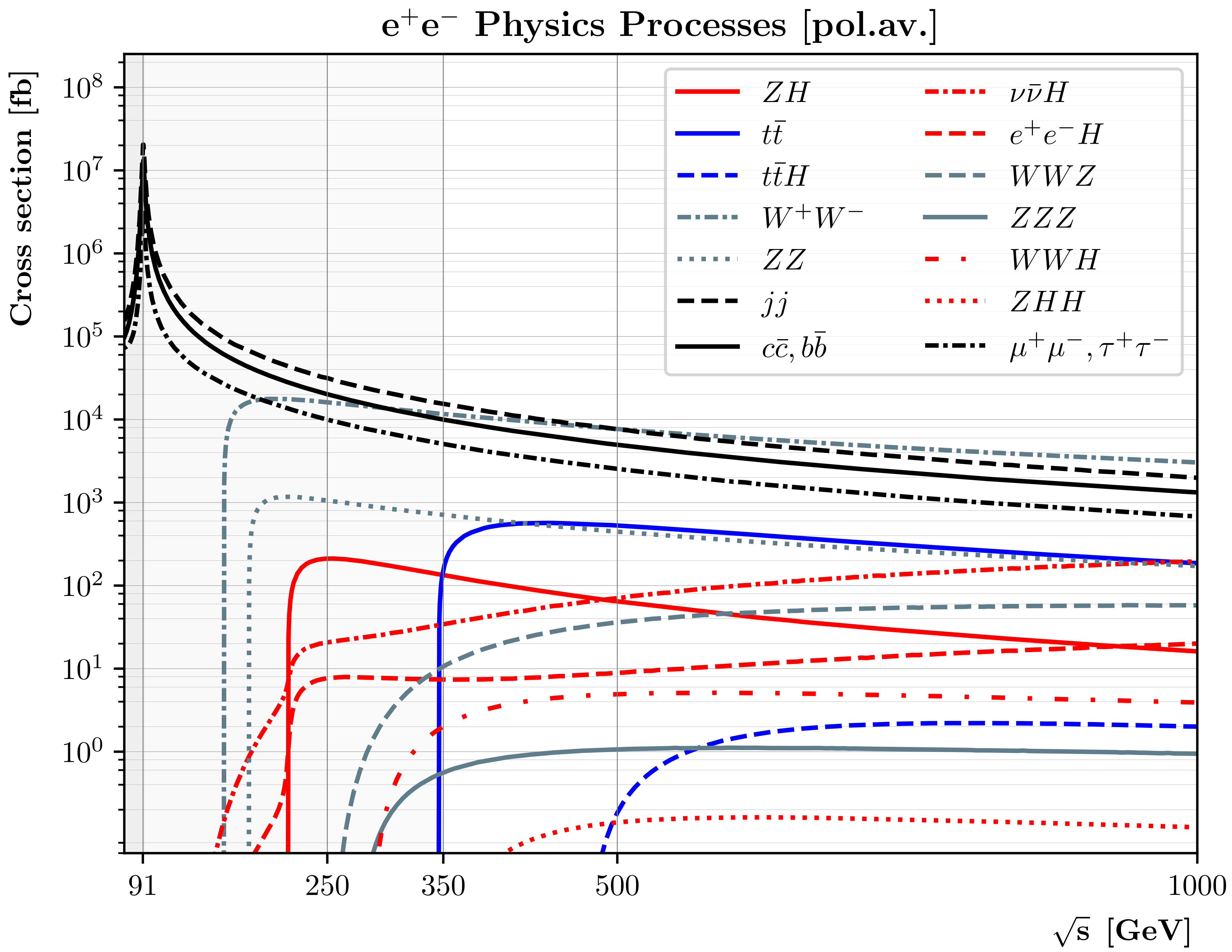
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Jürgen R. Reuter

Physics beyond the LHC

- Precision study in clean electroweak environment with triggerless operation needed: e^+e^- collider
- Highest priority in European Strategy Update for Particle Physics 2020: Higgs/top/electroweak factory
- P5 recommendation for US Particle Physics, 7.12.23: Higgs factory "off-shore" with US contribution "commensurate to LHC"



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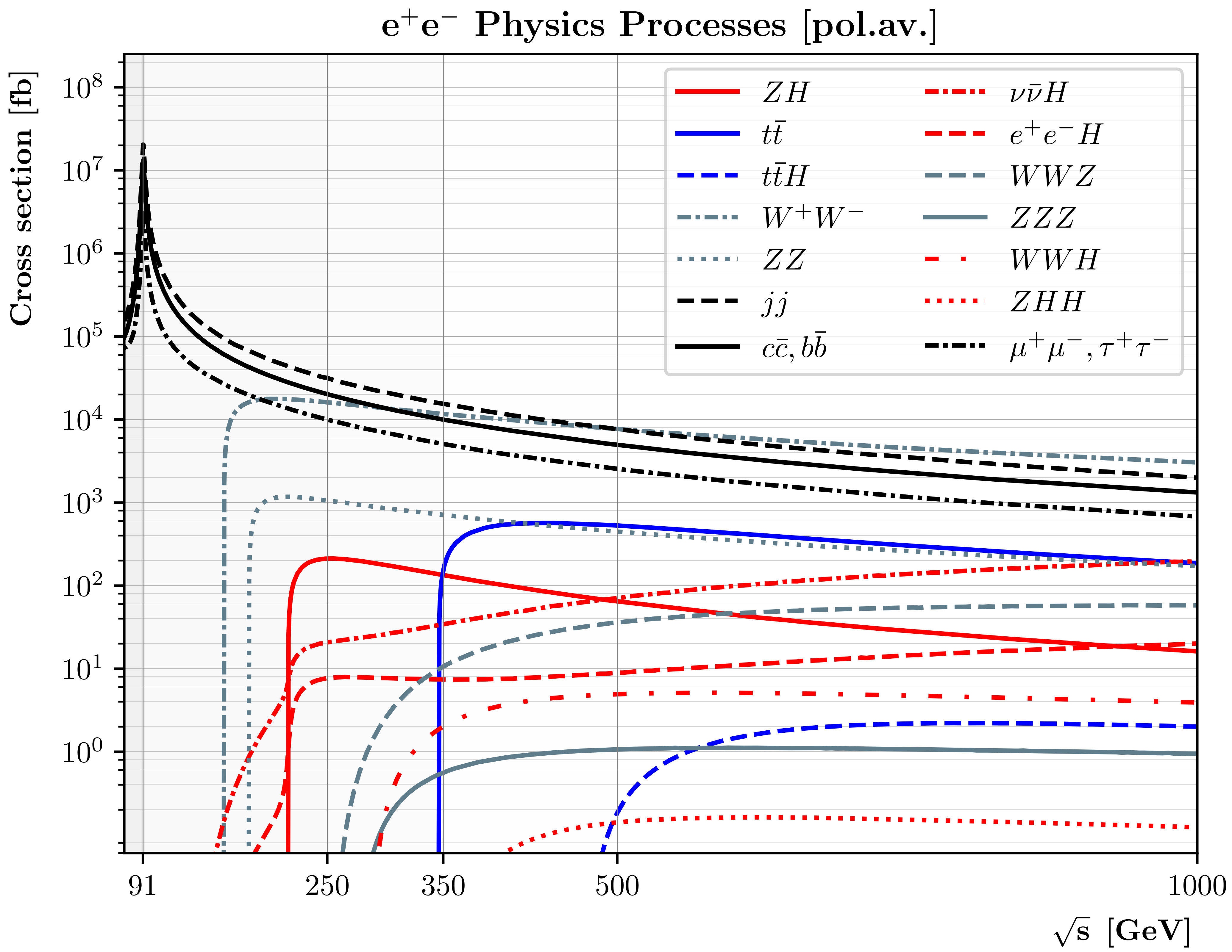
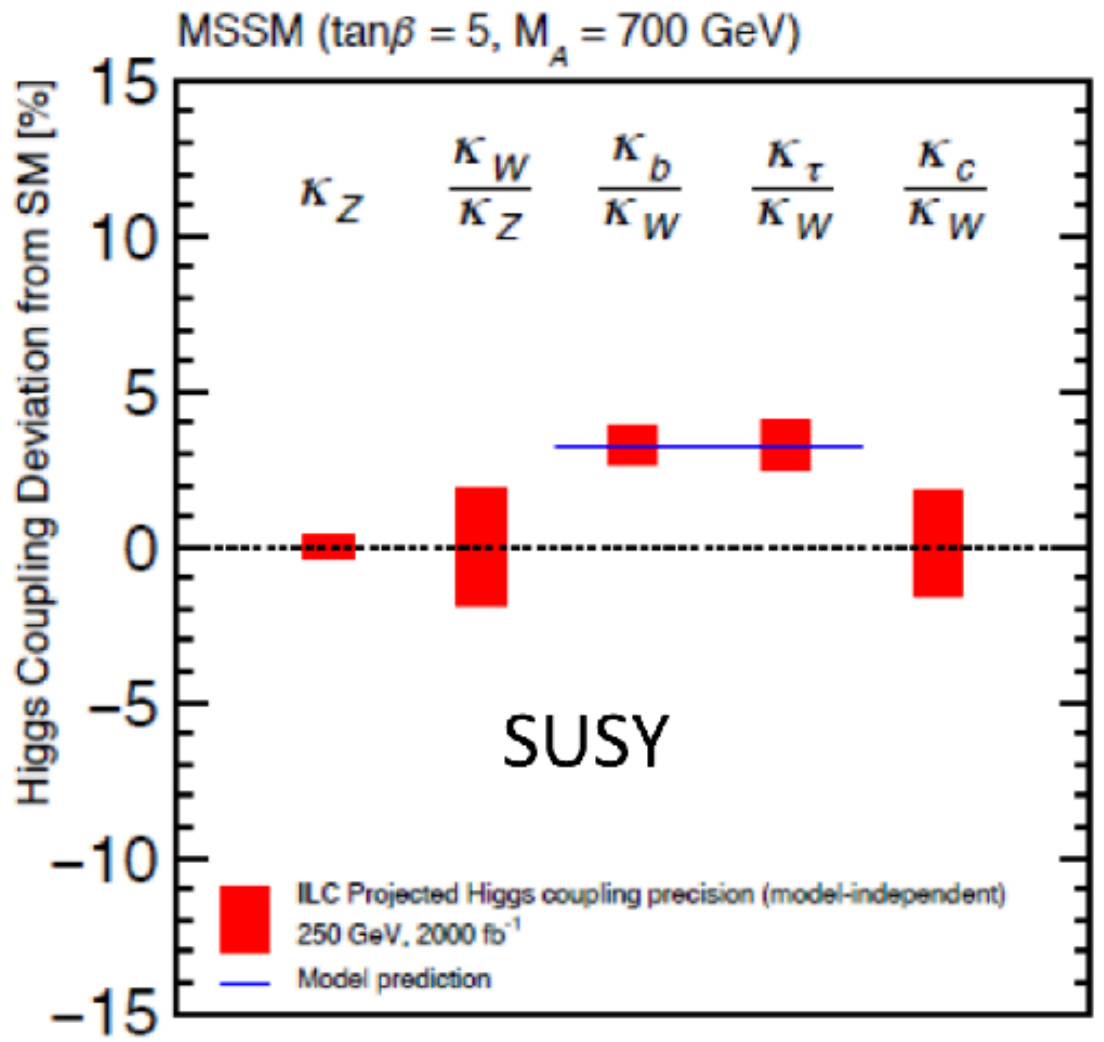
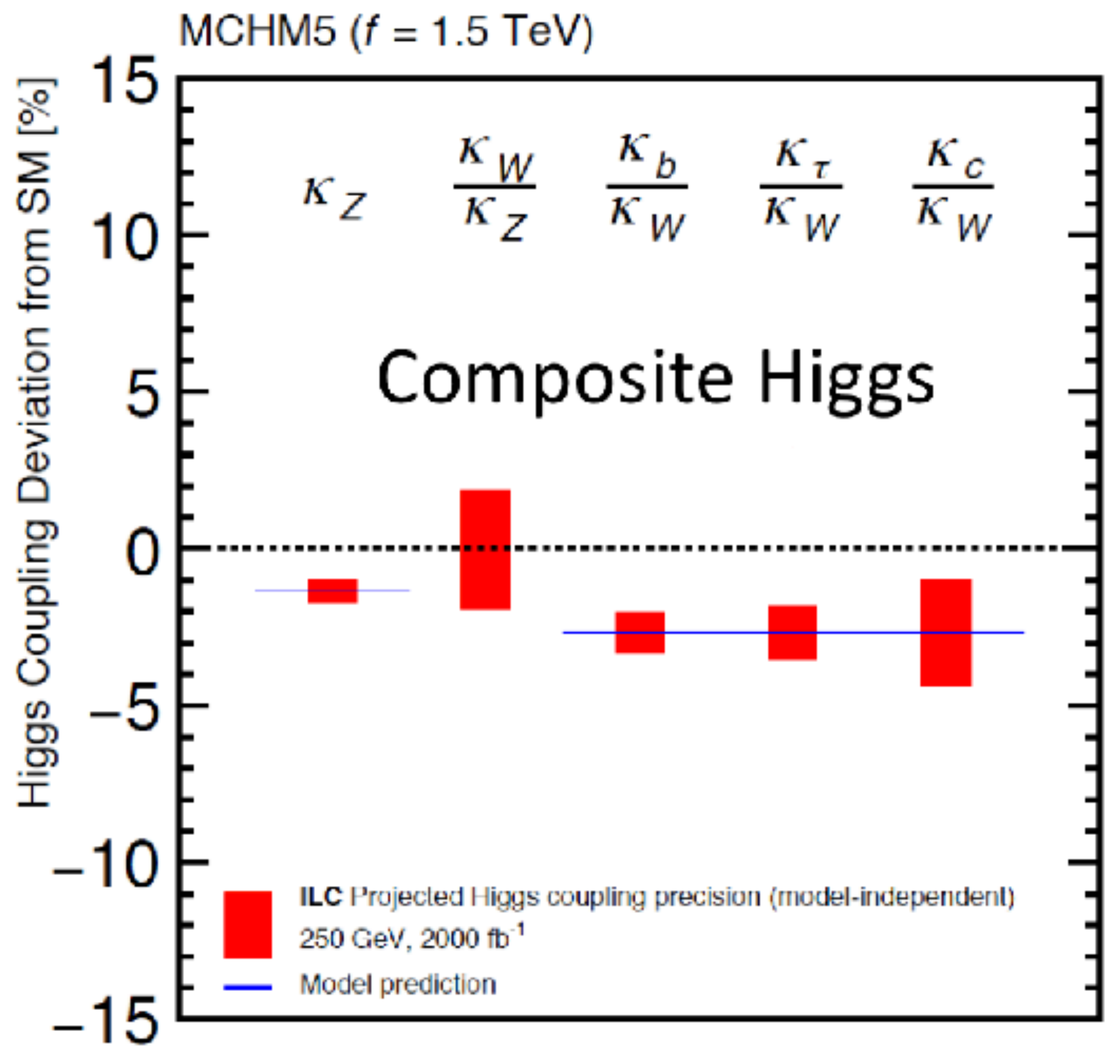
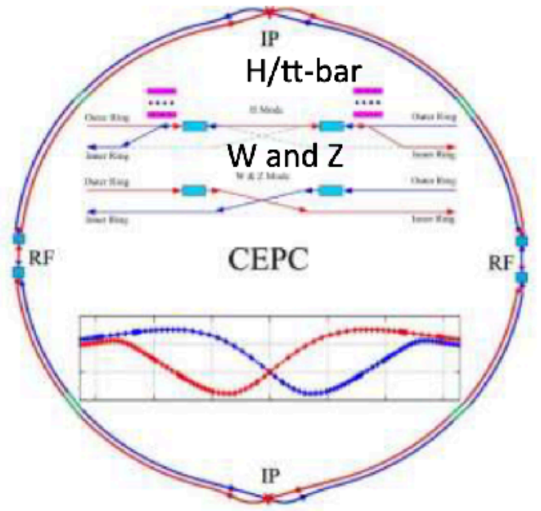


e^+e^- machine resolution power crucial for BSM model discrimination

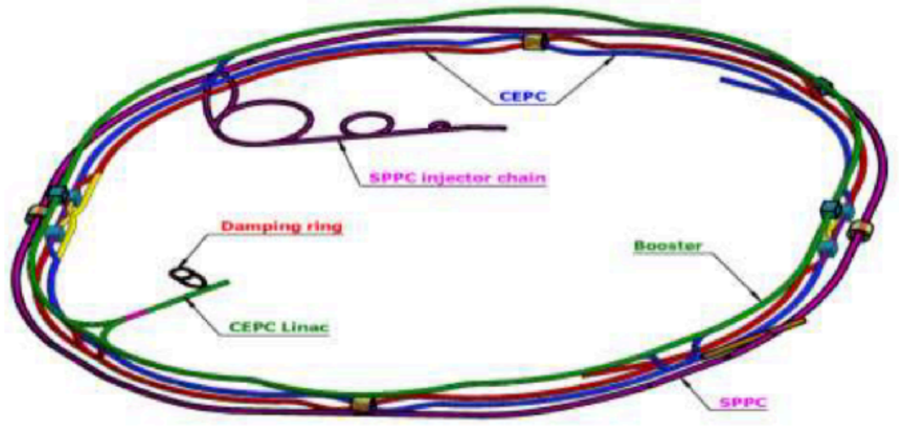




Circular and Linear Options

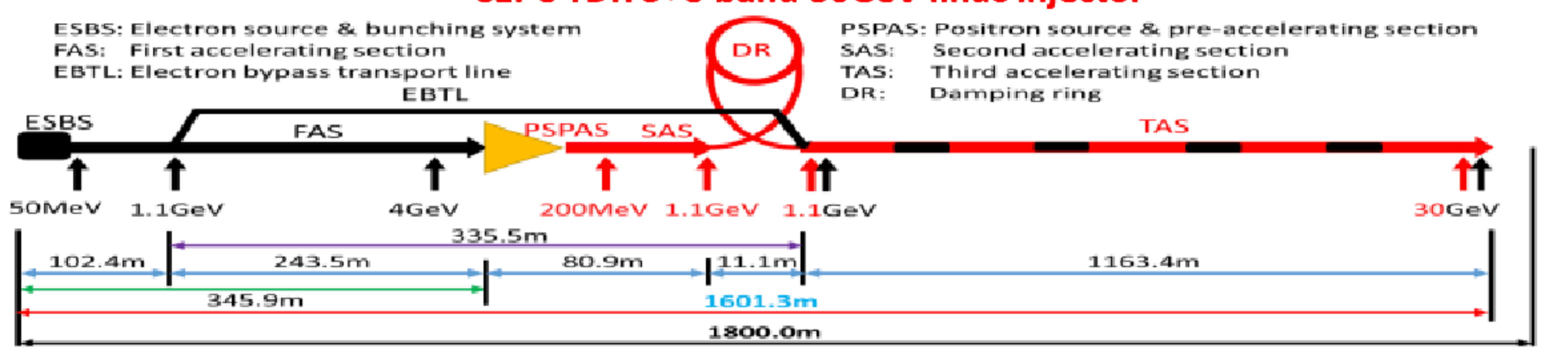


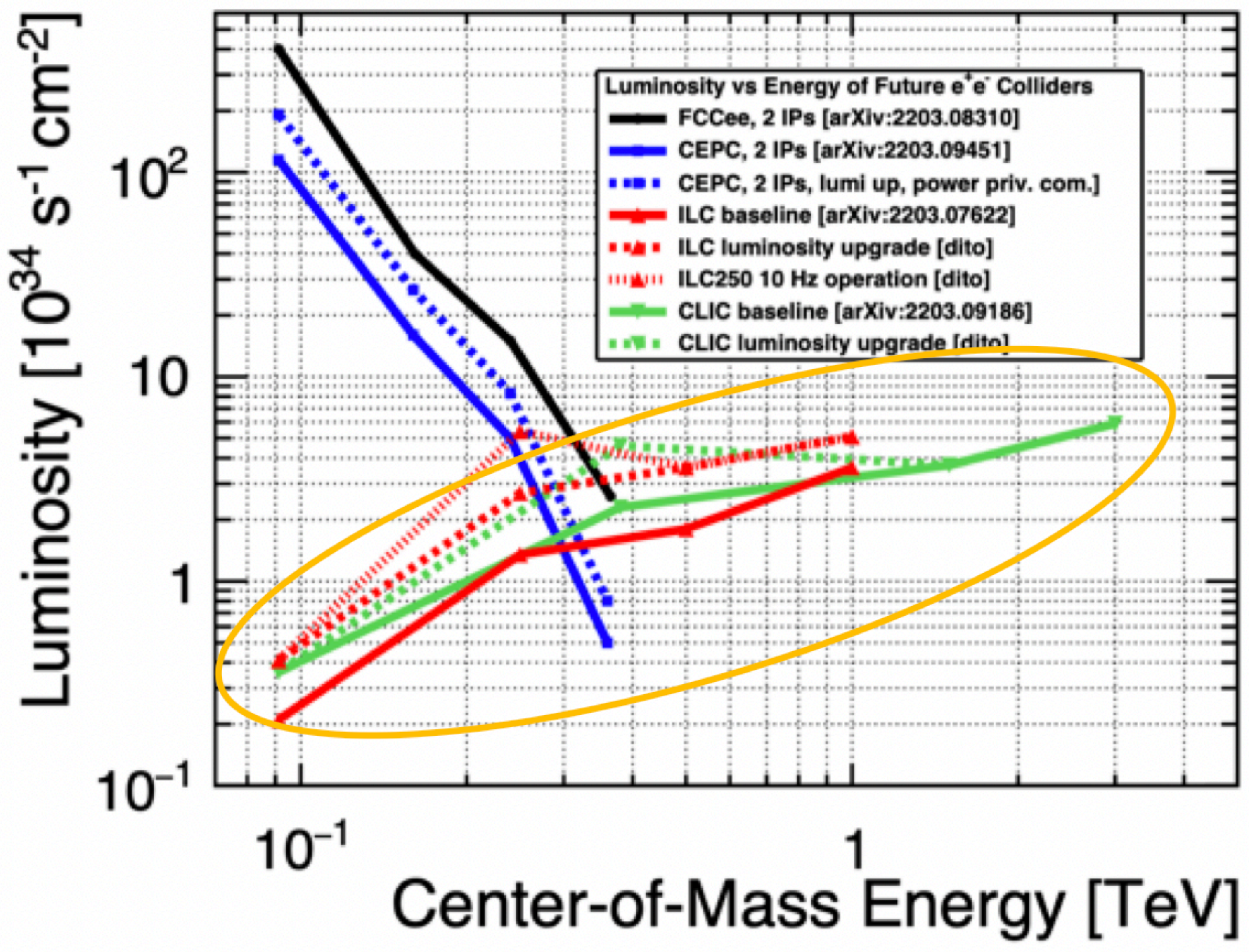
CEPC collider ring (100km)



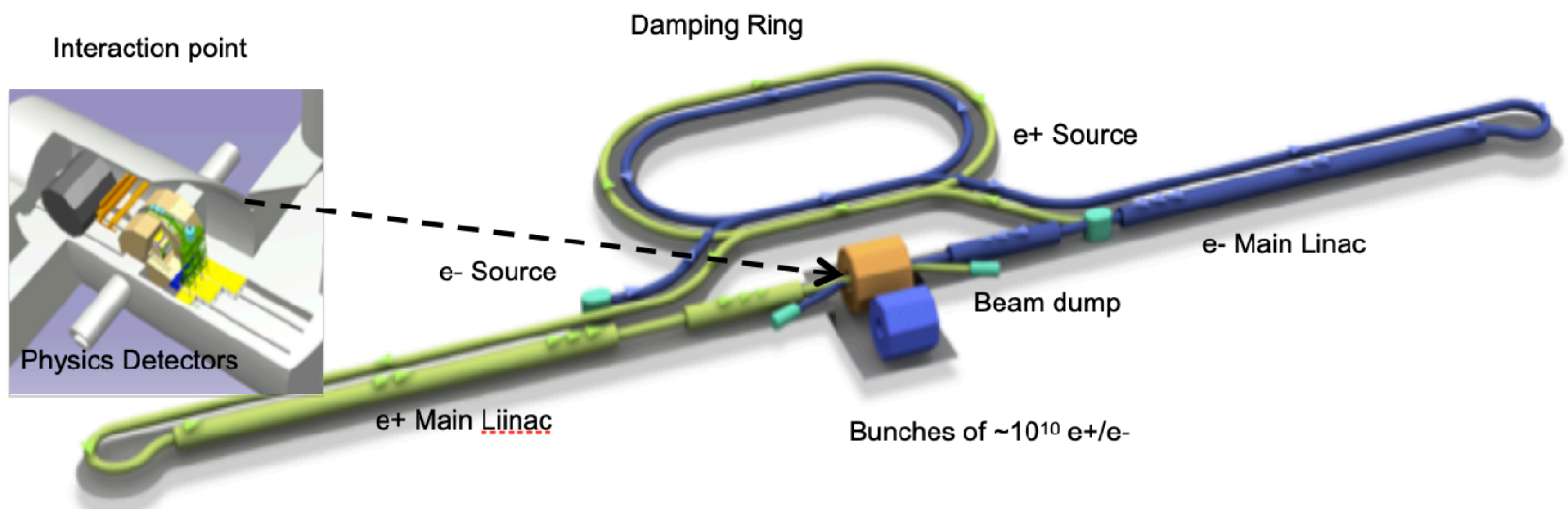
CEPC booster ring (100km)

CEPC TDR S+C-band 30GeV linac injector

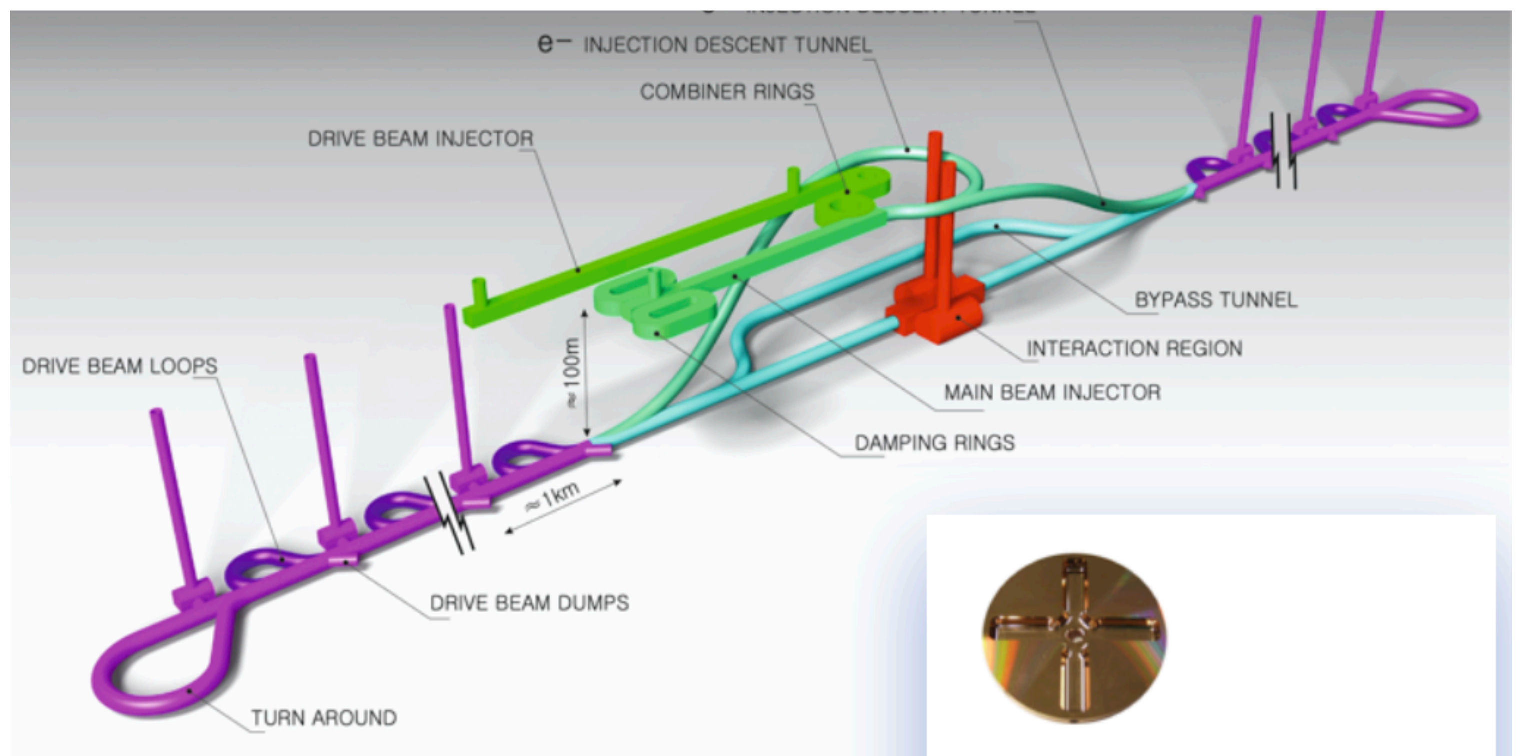


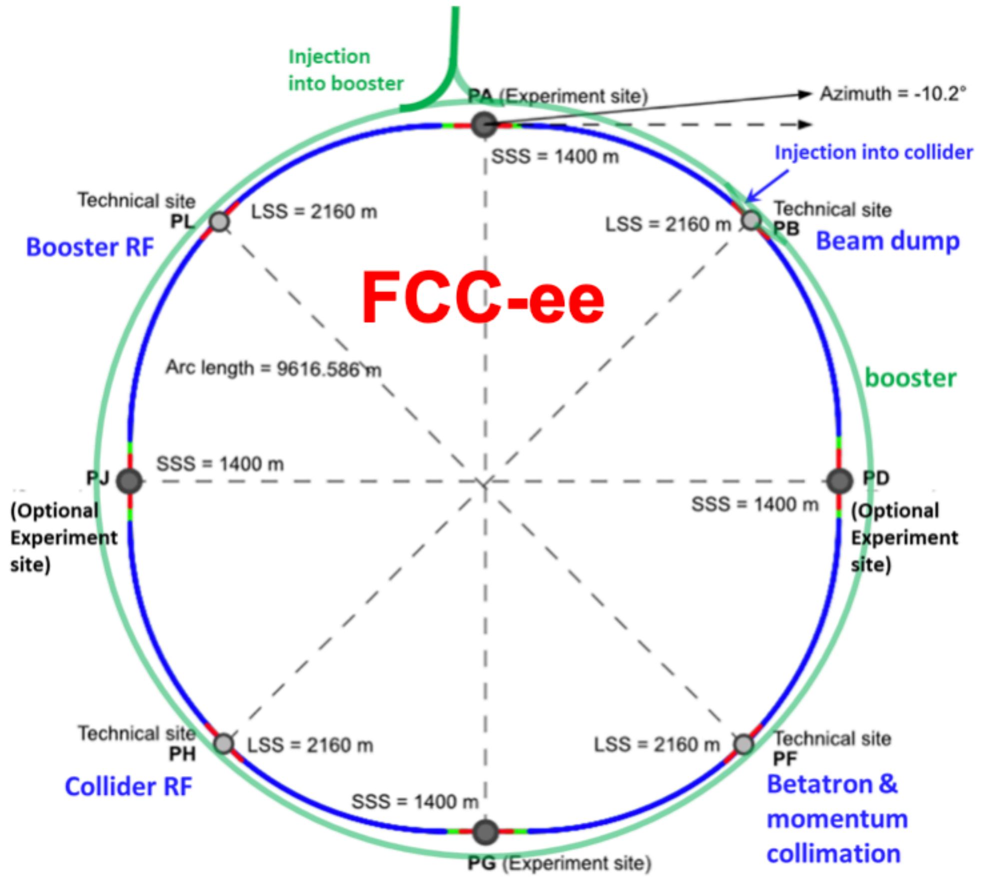


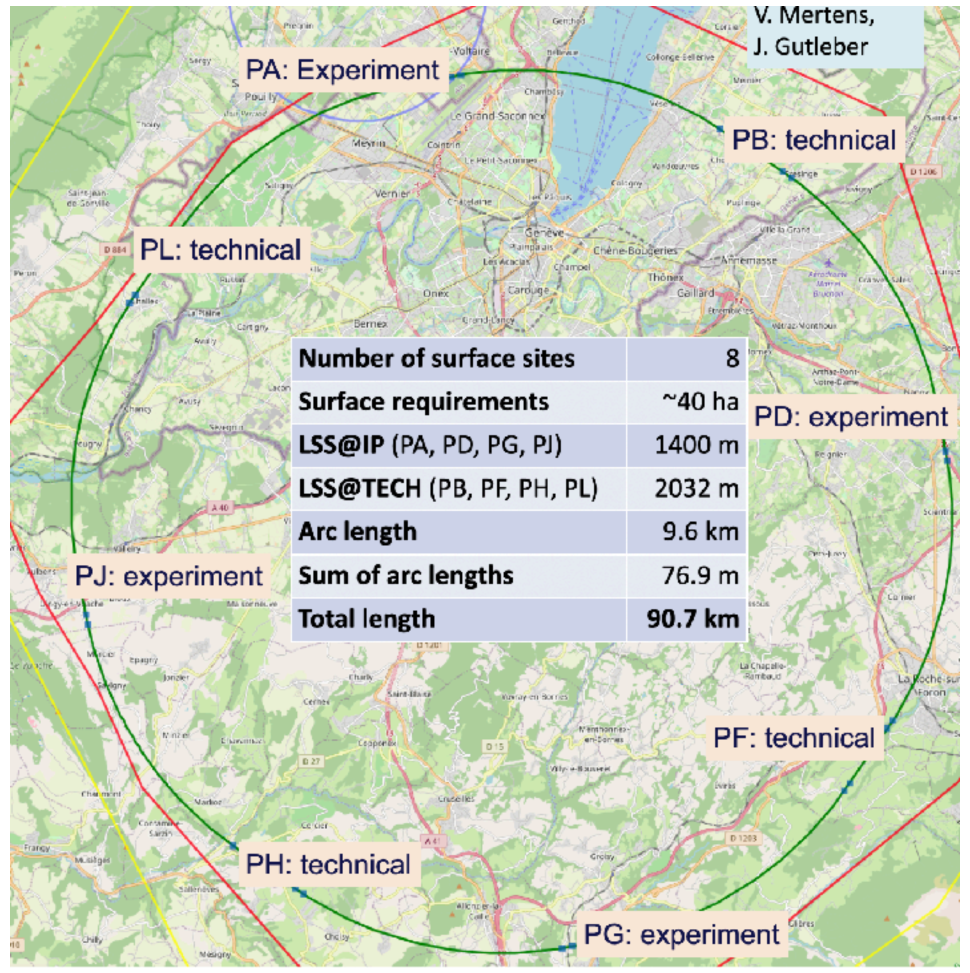
The ILC250 accelerator facility



The Compact Linear Collider (CLIC)



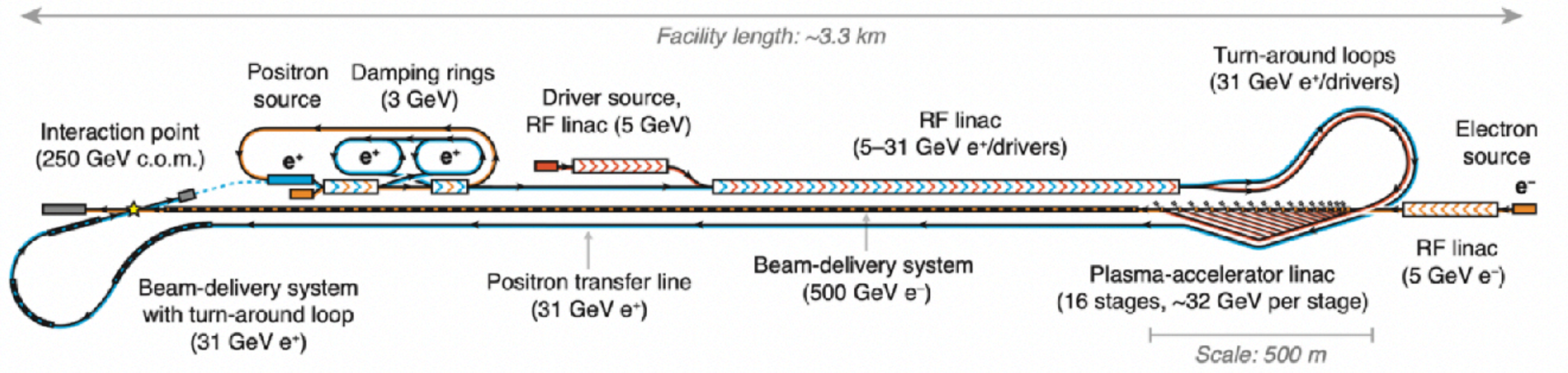




Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km

- 91 GeV — *Z* pole running
- 161 GeV — *WW* threshold
- 240 GeV — *ZH* threshold
- 365 GeV — *tt* threshold

HALHF – anywhere

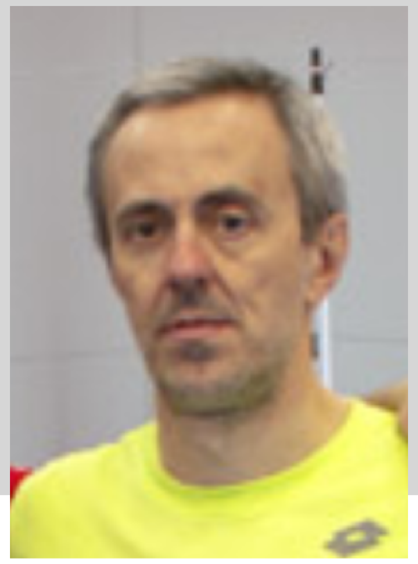


Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

> Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

ECFA H/EW/Top Factory WG3/2 MC Generators

- 1st WG2 Topical WS on Generators / Simulation, @CERN: Nov. 9-10, 2021 https://indico.cern.ch/event/1078675/
- Very efficient and effective organization ⟹ Conveners: Patrizia Azzi Fulvio Piccinini Dirk Zerwas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- Setting the stage: simulation tools, MCs, software frameworks

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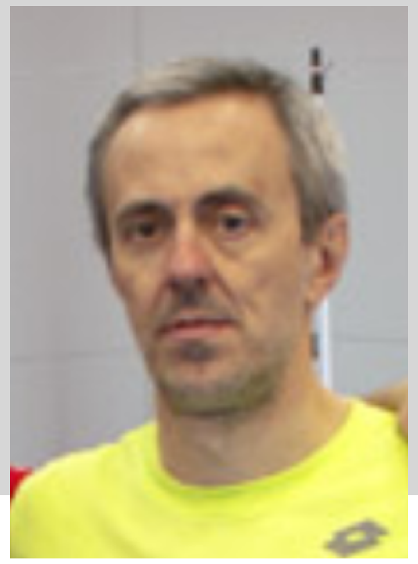

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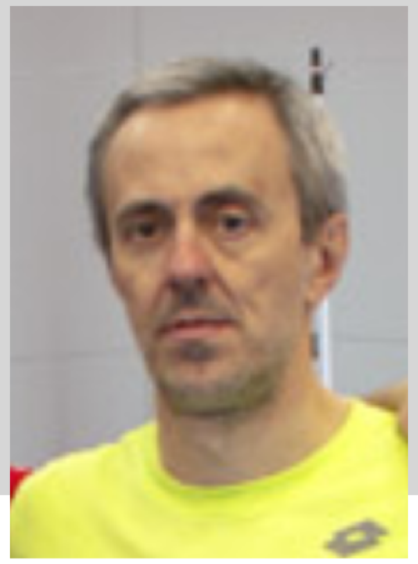


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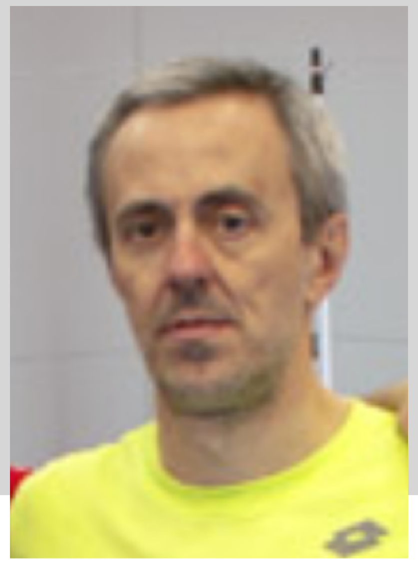


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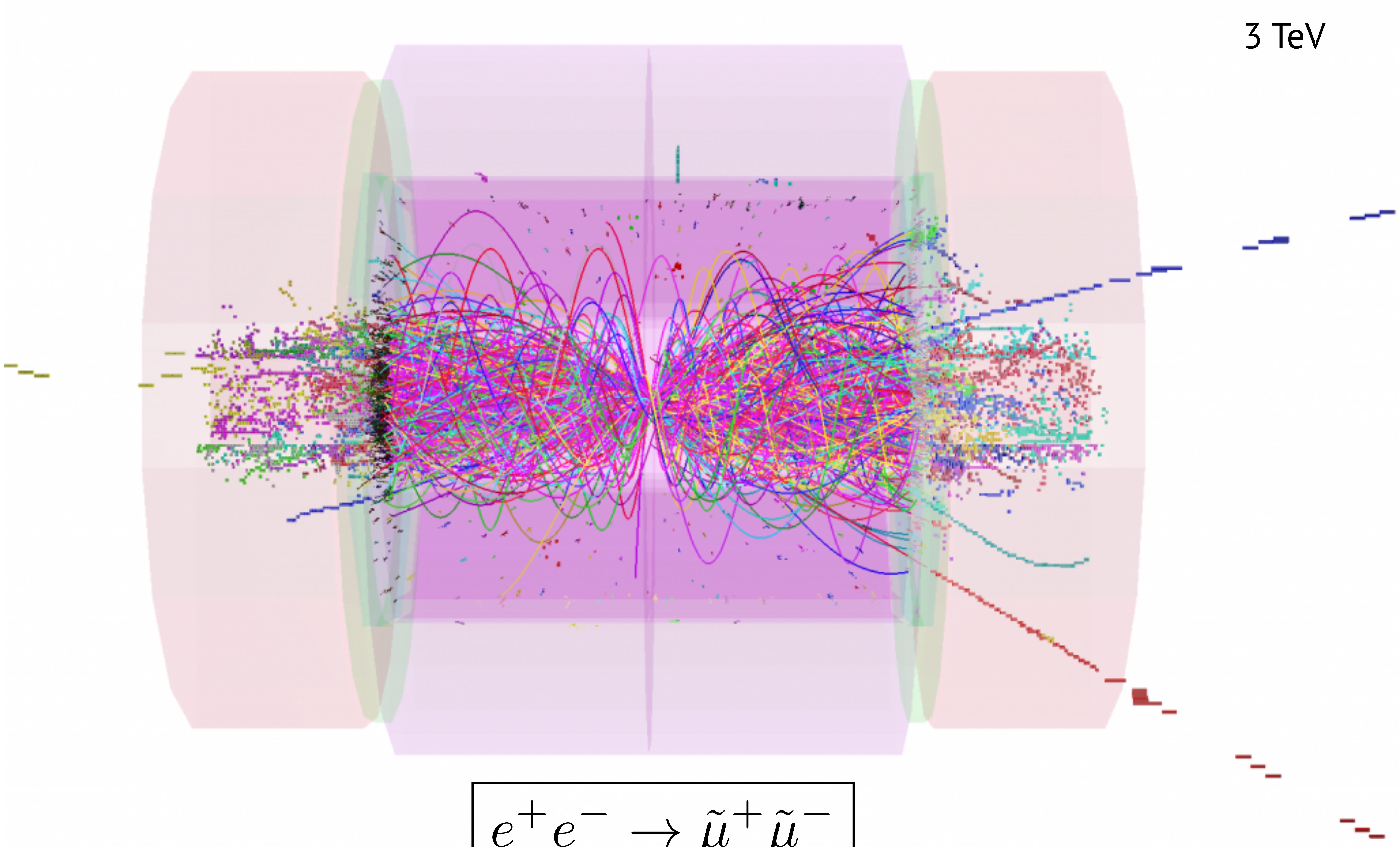
- CERN WS "Parton Showers for Future e^+e^- colliders
  Apr 24-28, 2023 https://indico.cern.ch/event/1233329
- ≳ 120 participants, roughly 80 at CERN
- Focus: perturbative and non-perturbative QCD

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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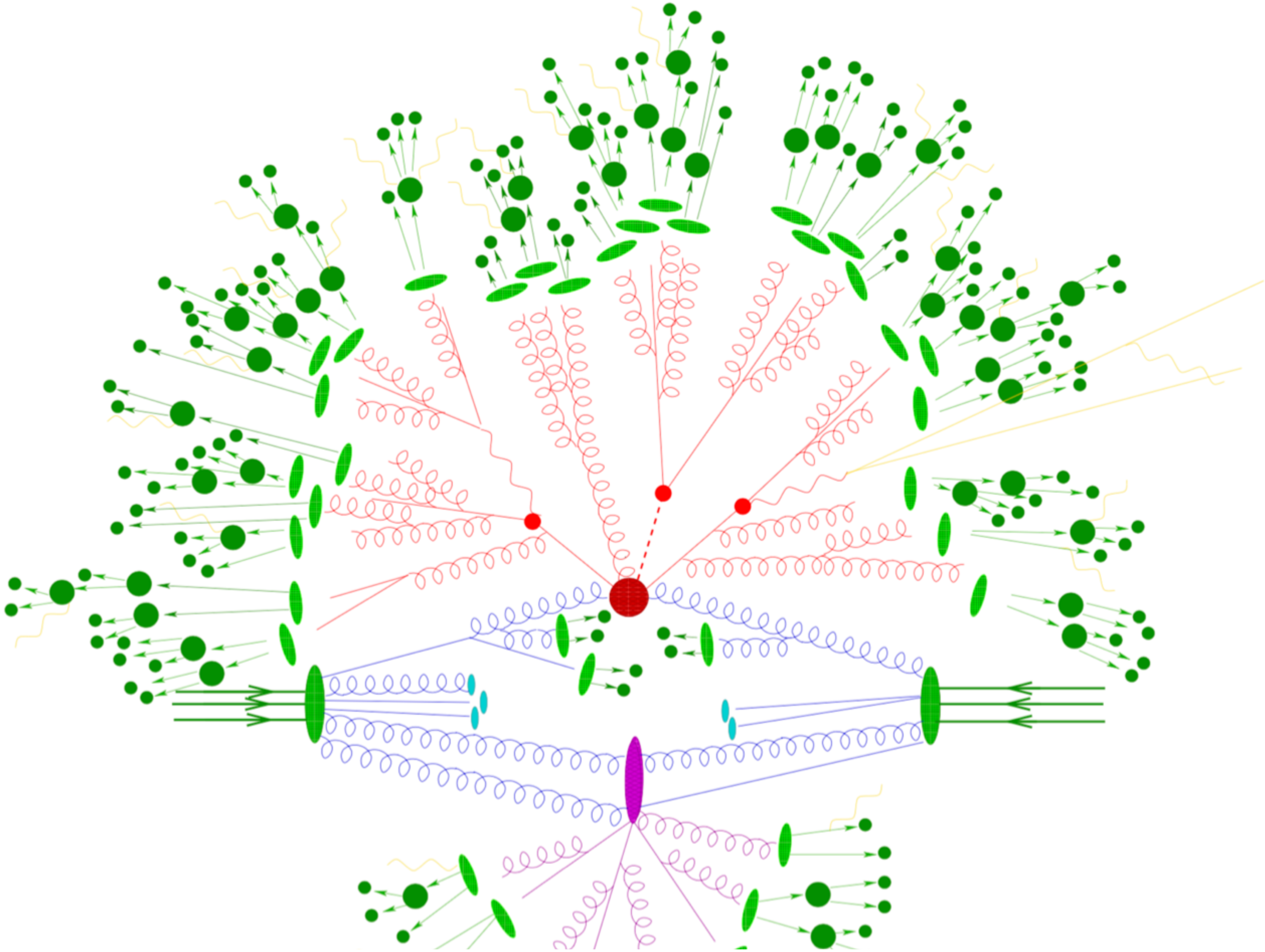

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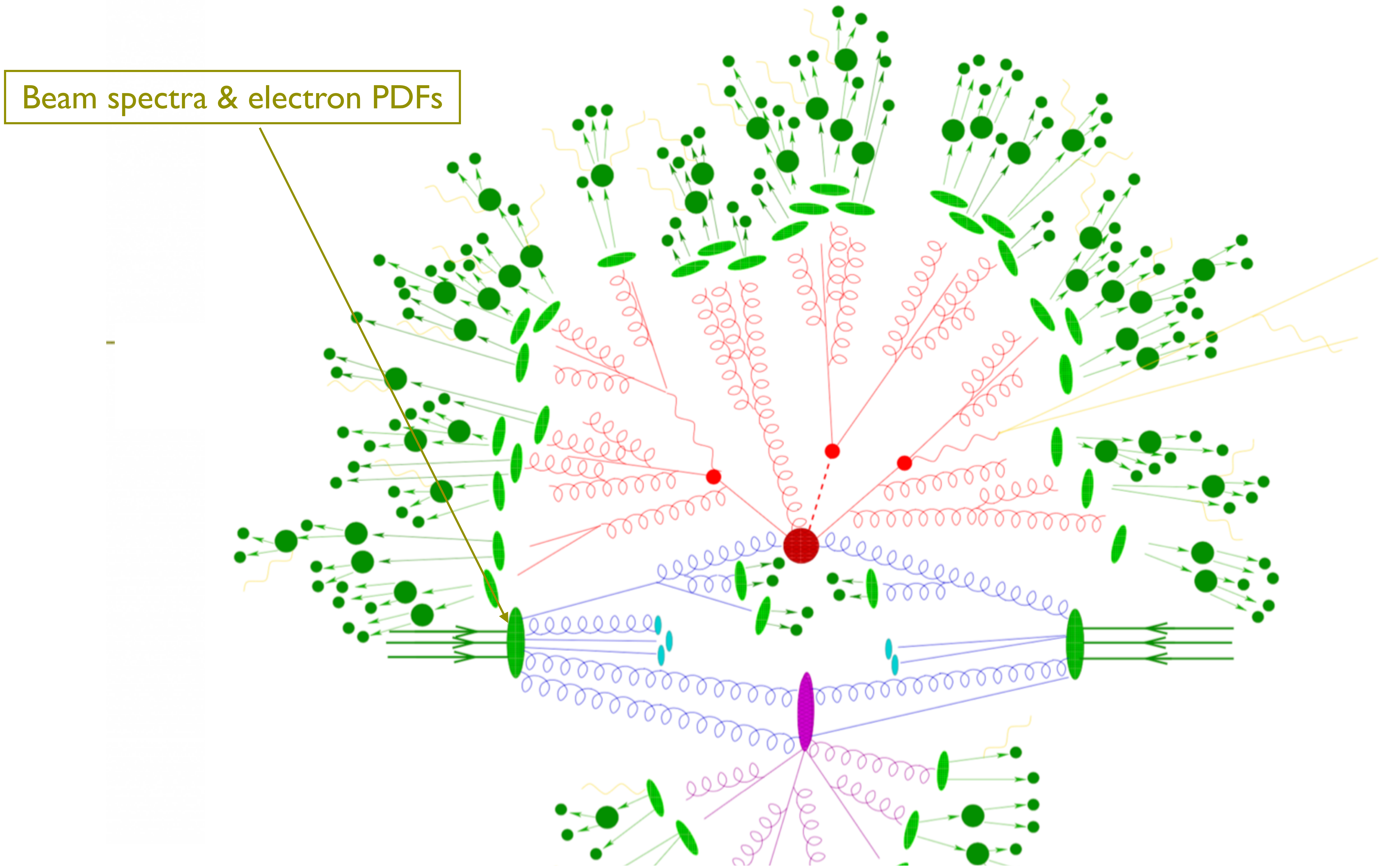

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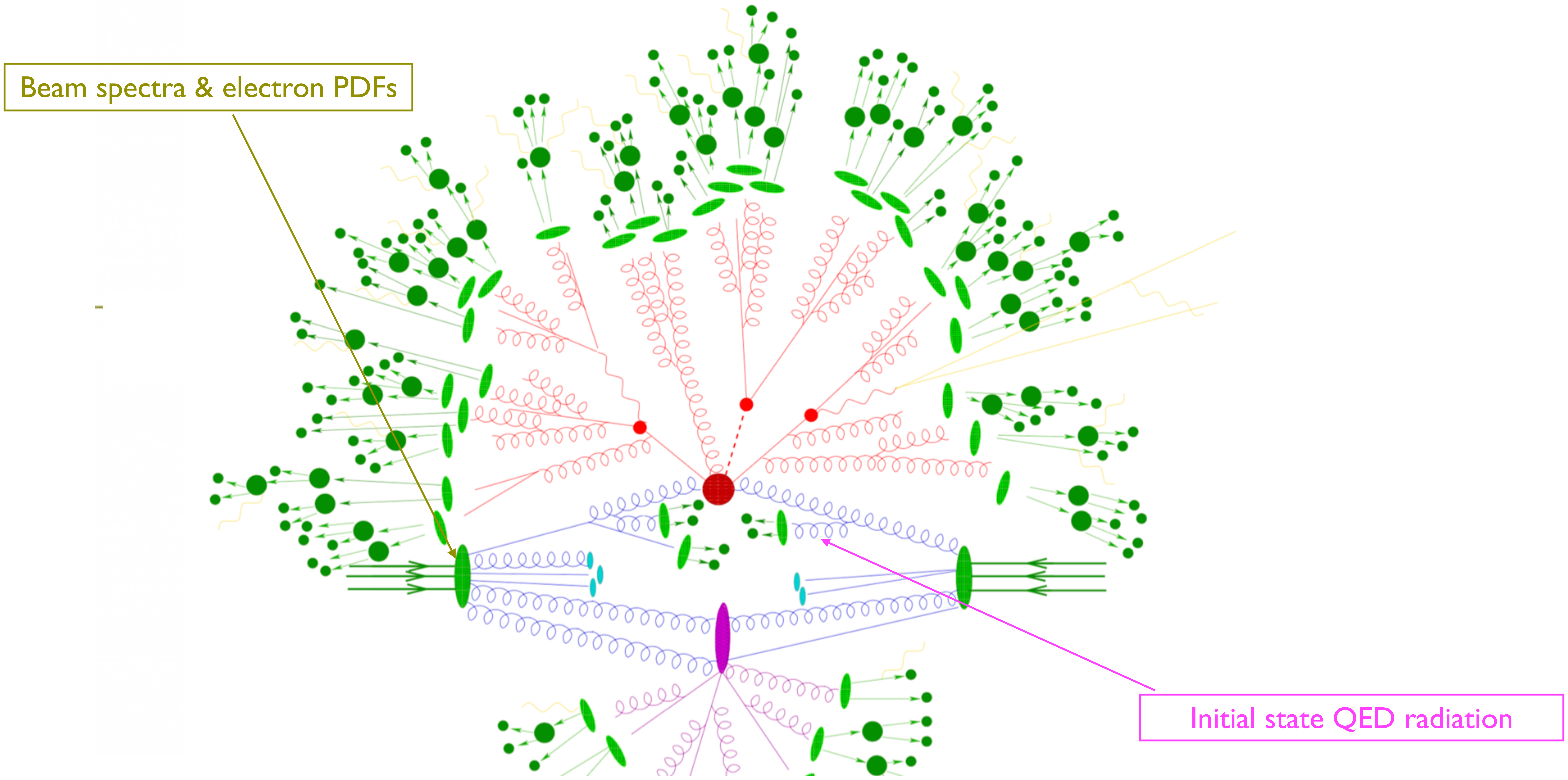

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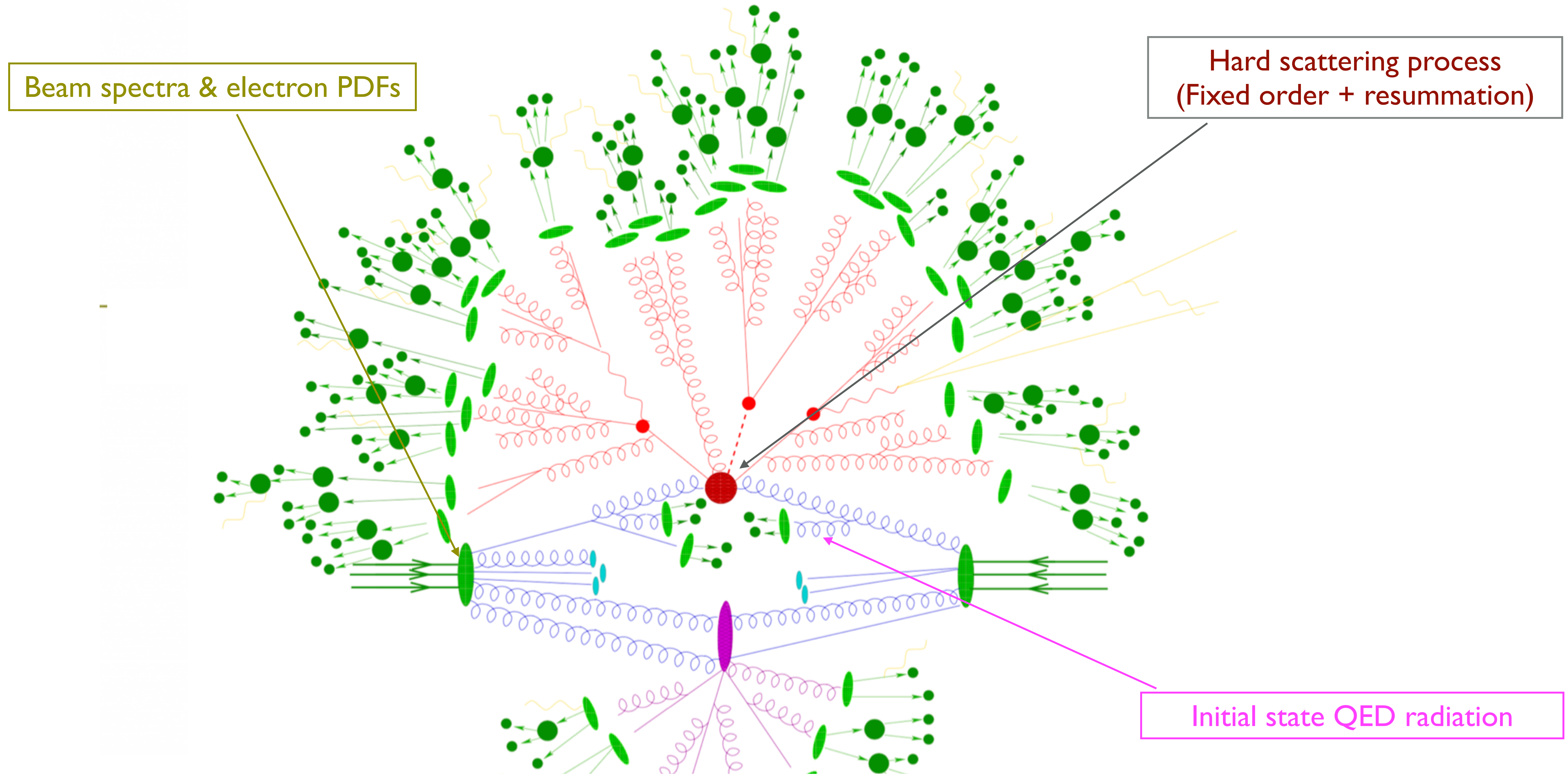

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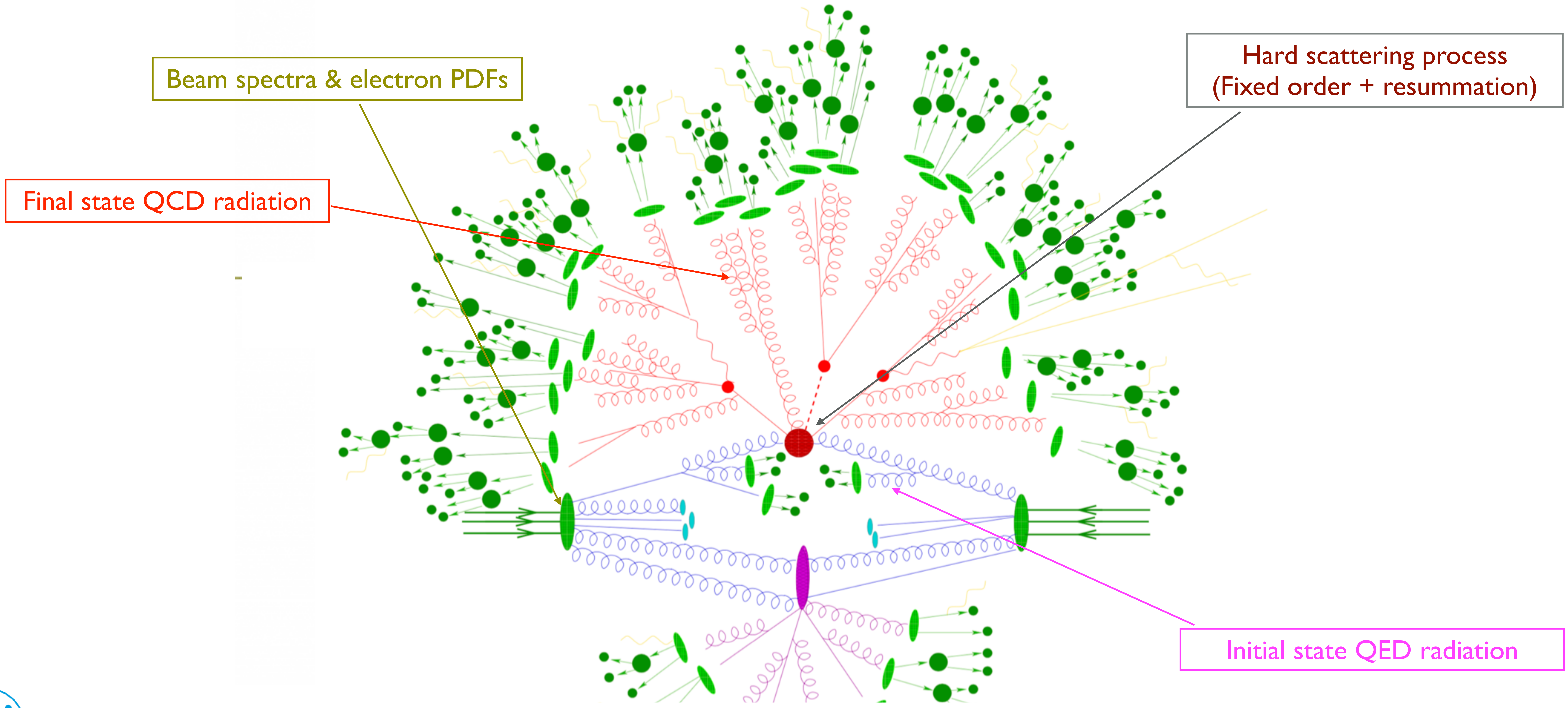

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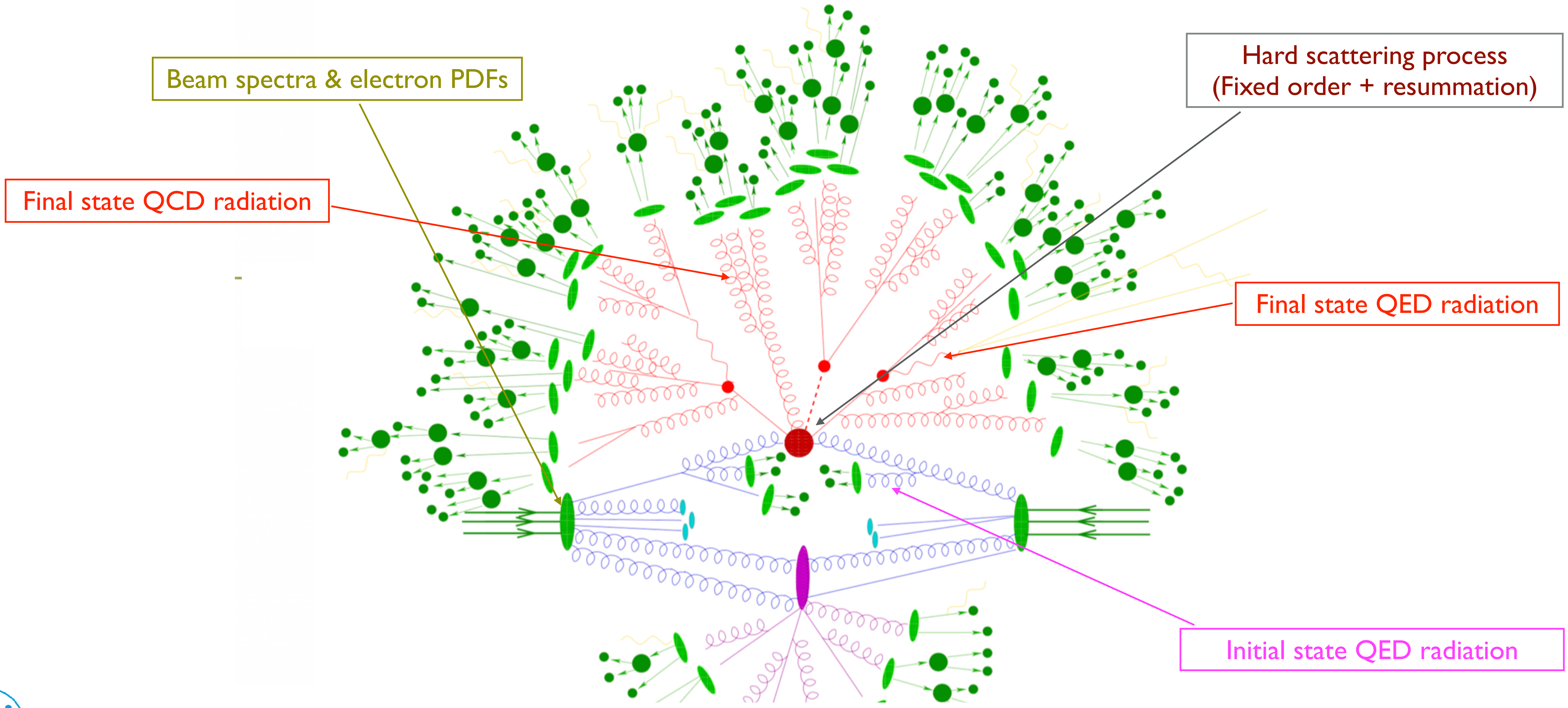

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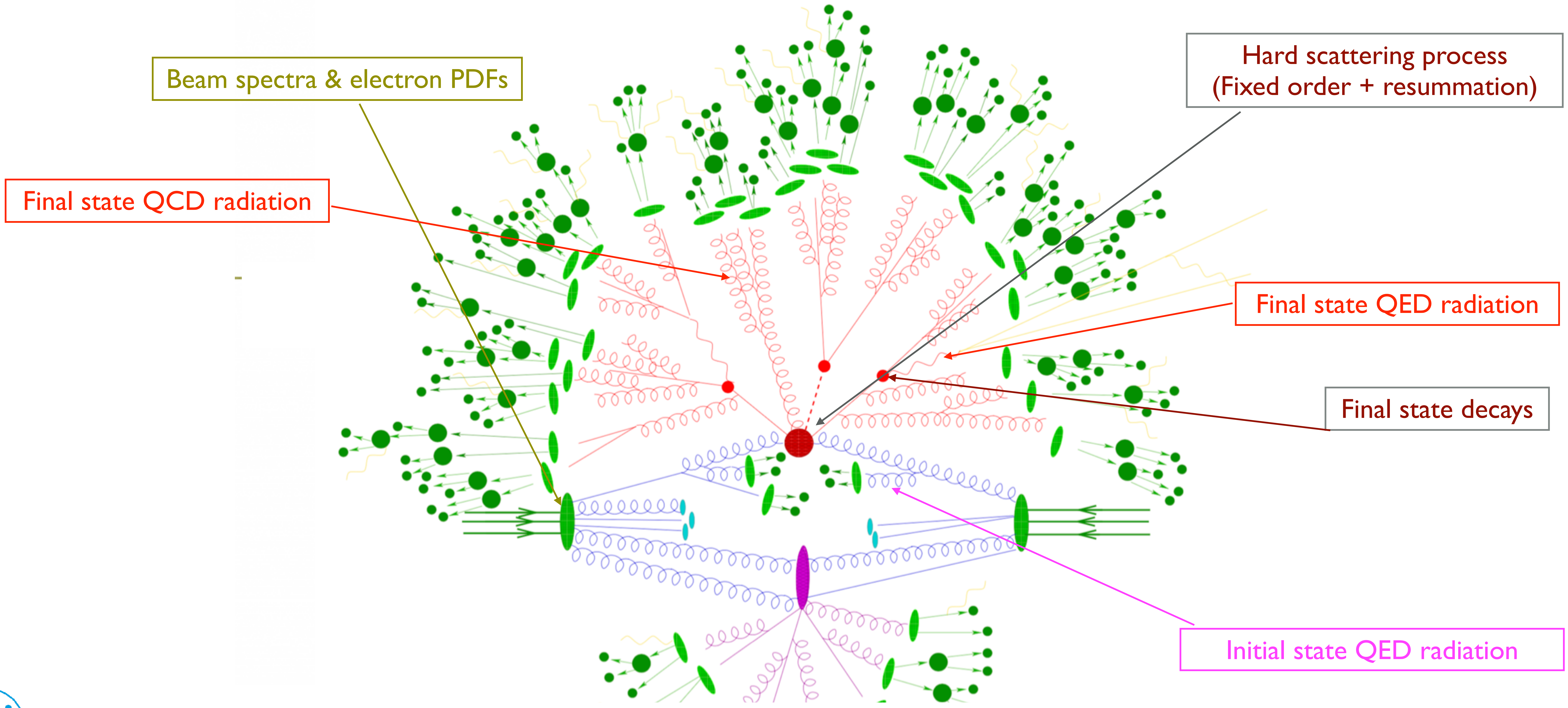

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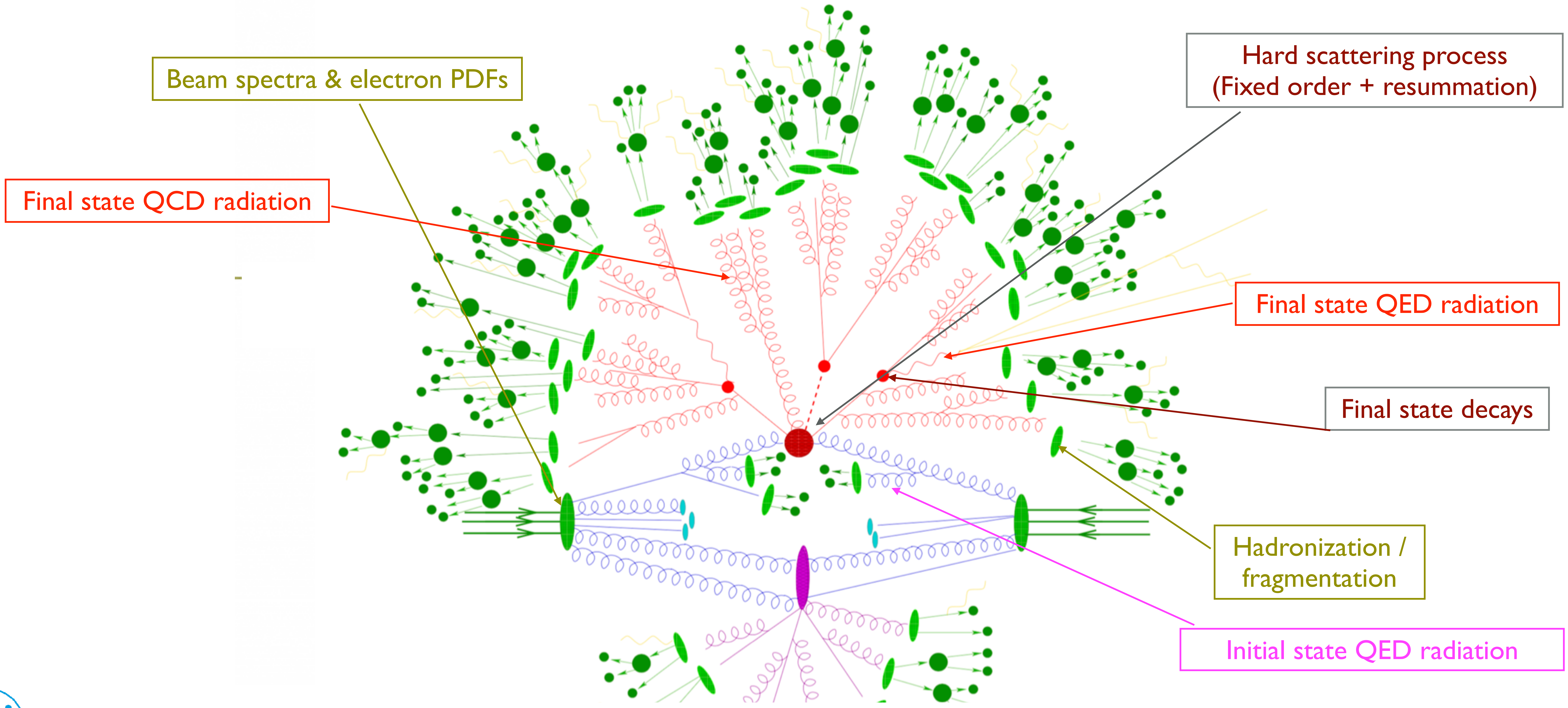

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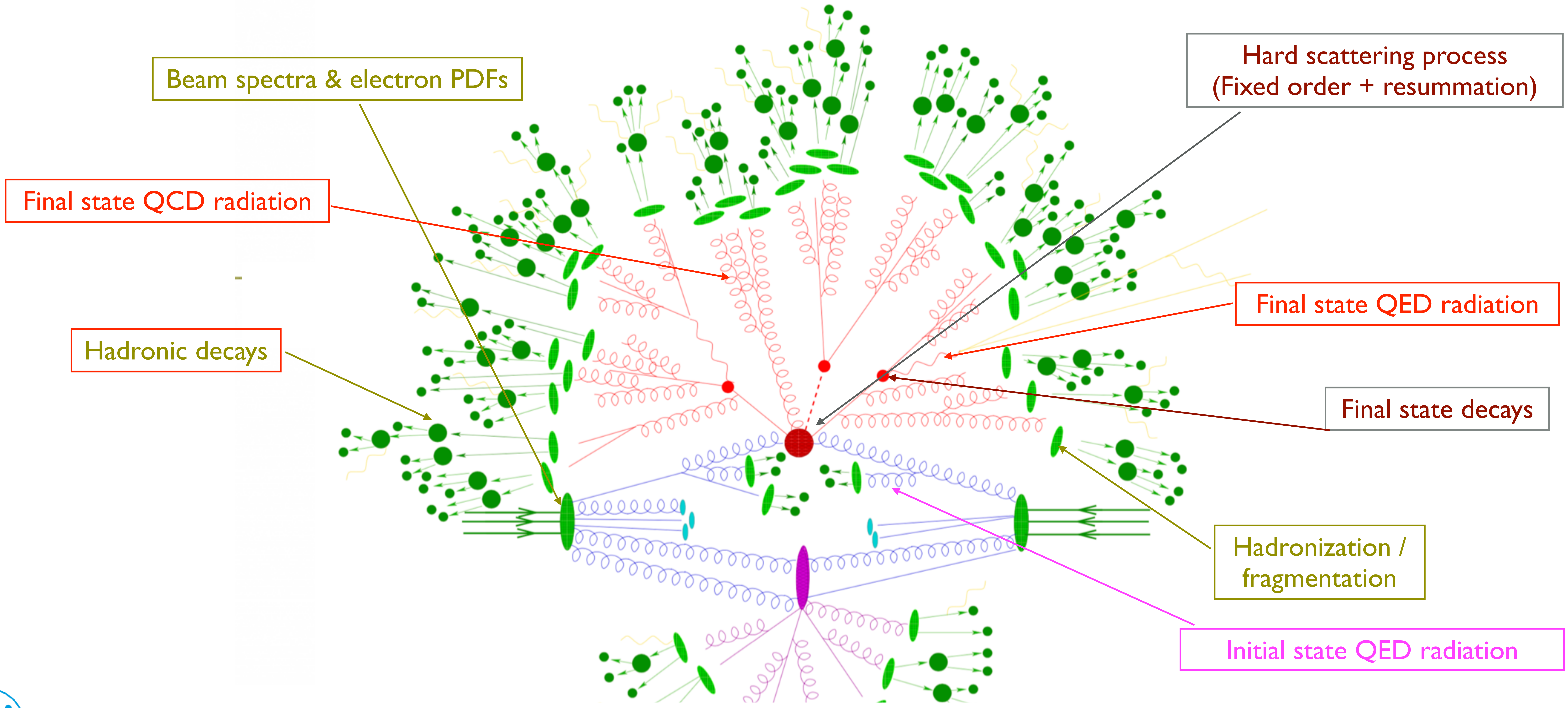

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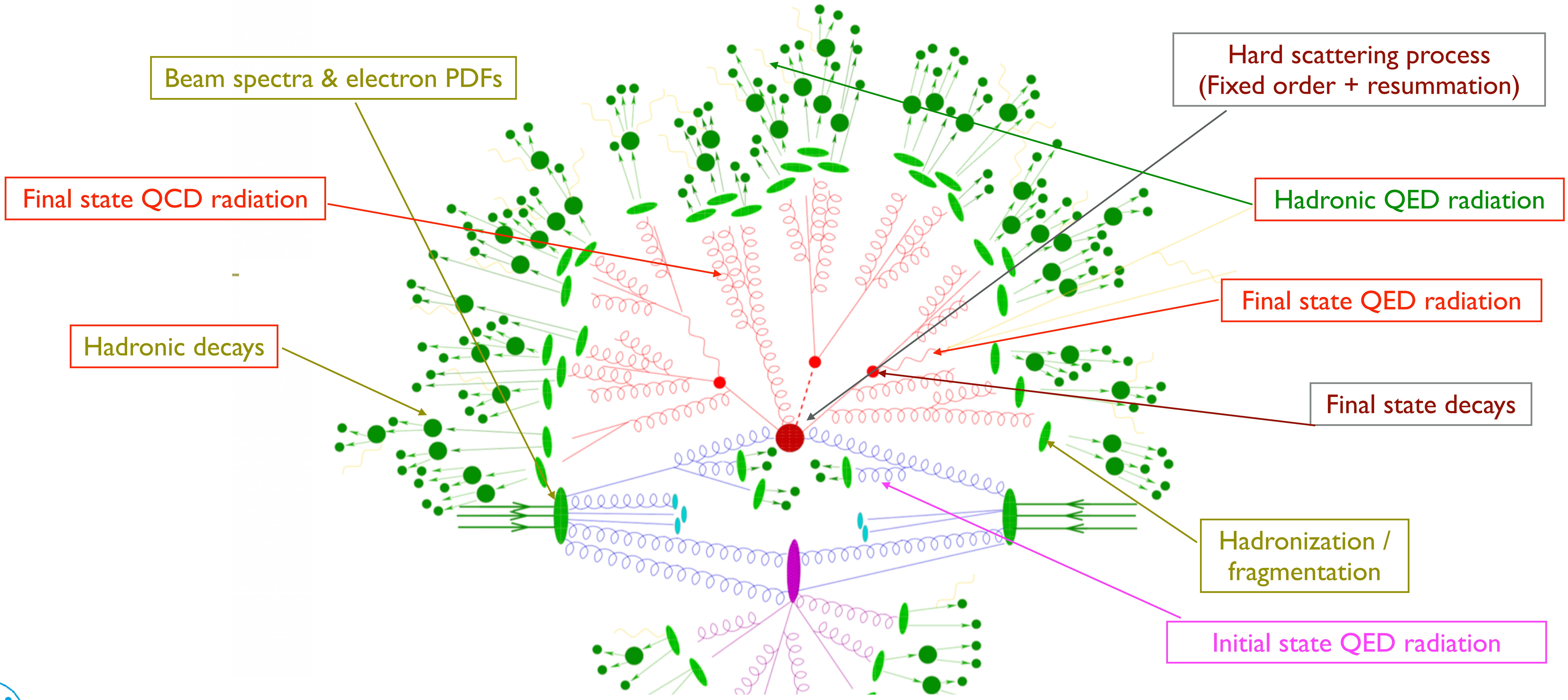

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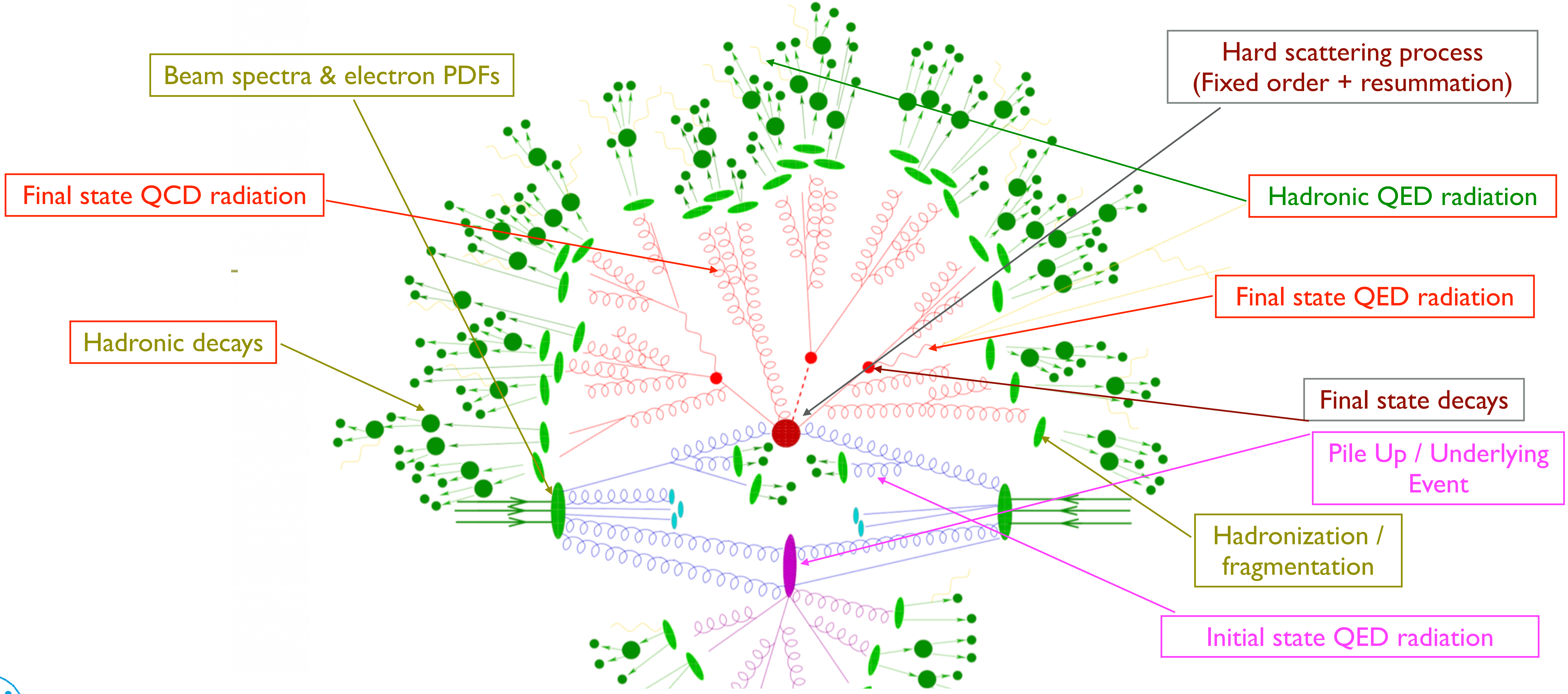

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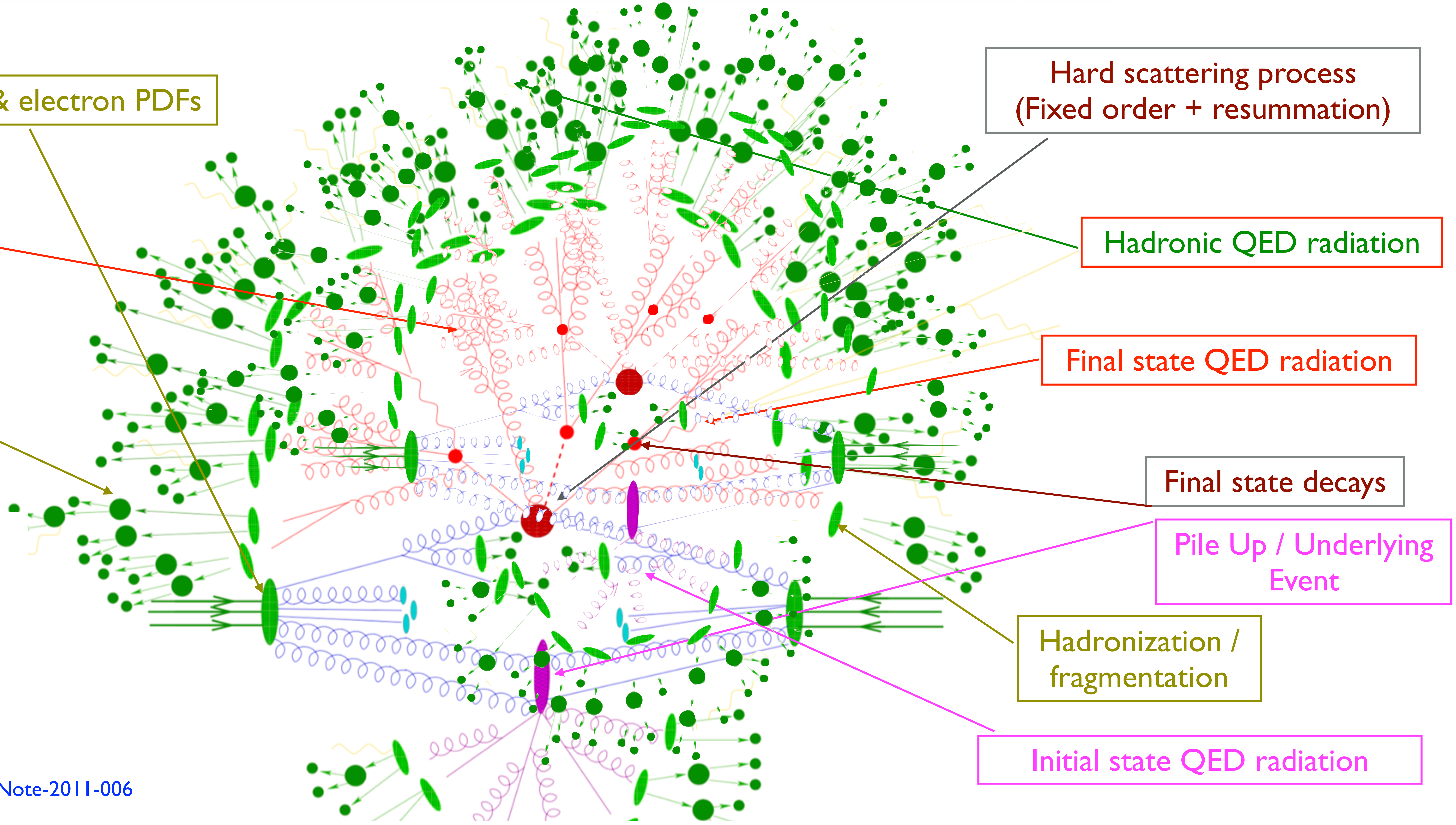

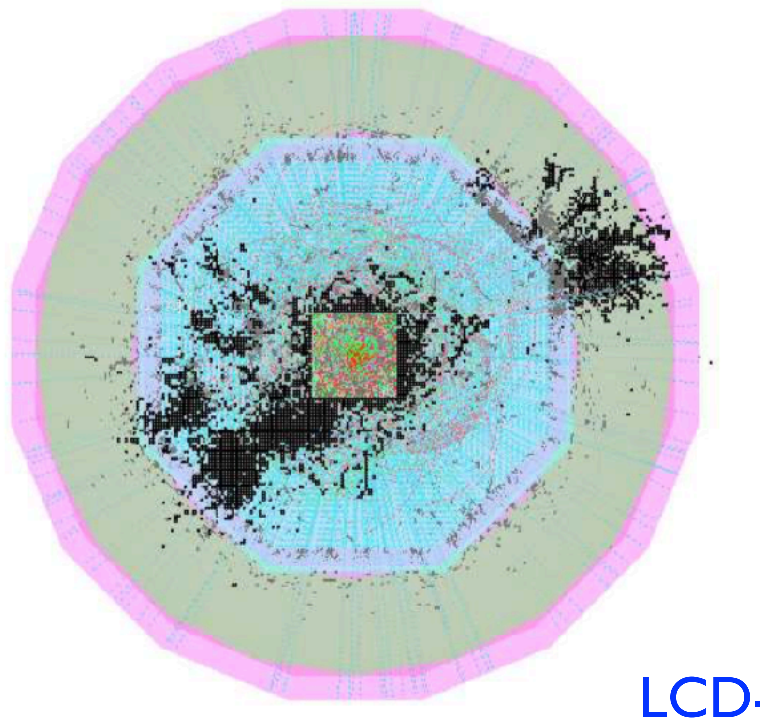

LCD-Note-2011-006

Overview over e^+e^- generators

Process Specific

- RacoonWWW
- KKCM
- YFSWW
- TAUOLA
- KoralW
- BabaYaga@NLO

General Purpose MC

- MadGraph5_aMC@NLO
- SHERPA
- PYTHIA
- HERWIG7
- WHIZARD

The scope: lessons learned and where to go

- LHC a huge success story for Monte Carlos (MCs)
- Assessment of needs for MCs event for (high-energy) e^+e^- colliders?

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4. Hard process (BSM): any new (crazy) model? SMEFT? tweaks? which order?
5. Exclusive processes (I = QED): photons, QED showers, matching
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9. Launch of MC validation effort [ECFA representative: A. Price, Krakow]

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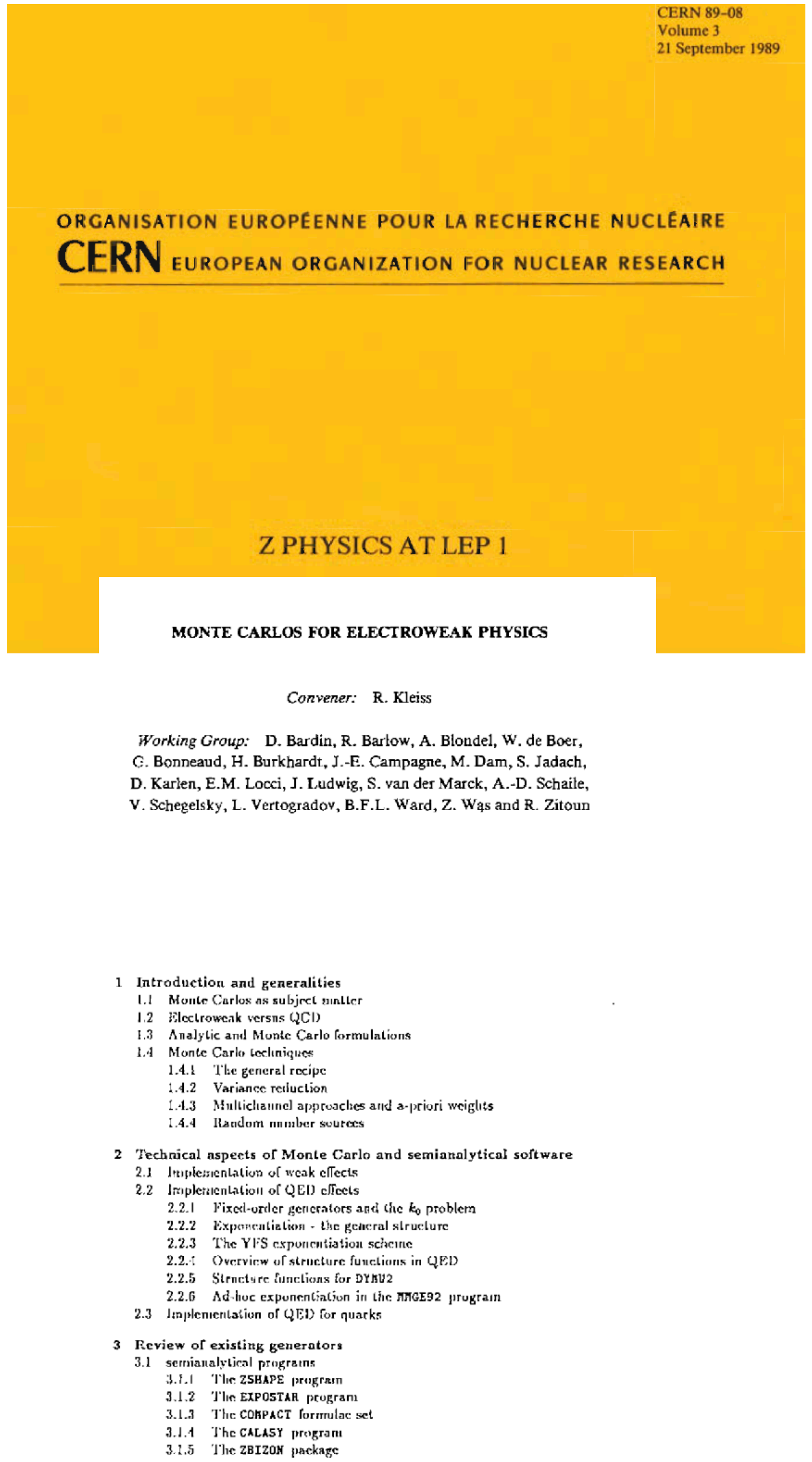

CERN 89-08
Volume 3
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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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Z PHYSICS AT LEP 1

MONTE CARLOS FOR ELECTROWEAK PHYSICS

Convener: R. Kleiss

Working Group: D. Bardin, R. Barlow, A. Blondel, W. de Boer, G. Bonneaud, H. Burkhardt, J.-E. Campagne, M. Dam, S. Jadach, D. Karlen, E.M. Locci, J. Ludwig, S. van der Marck, A.-D. Schaile, V. Schegelsky, L. Vertogradov, B.F.L. Ward, Z. Wąs and R. Zitoun

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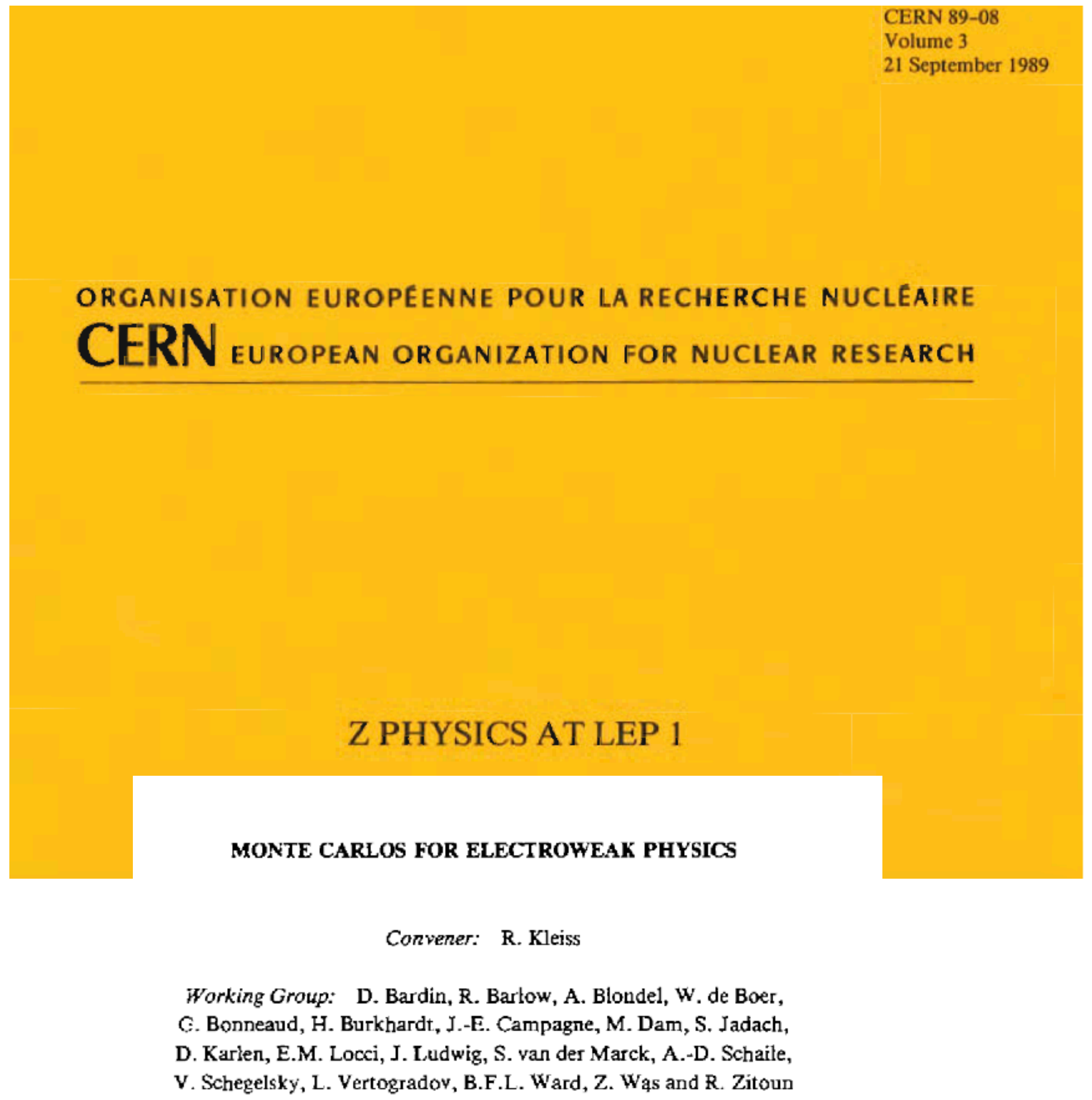
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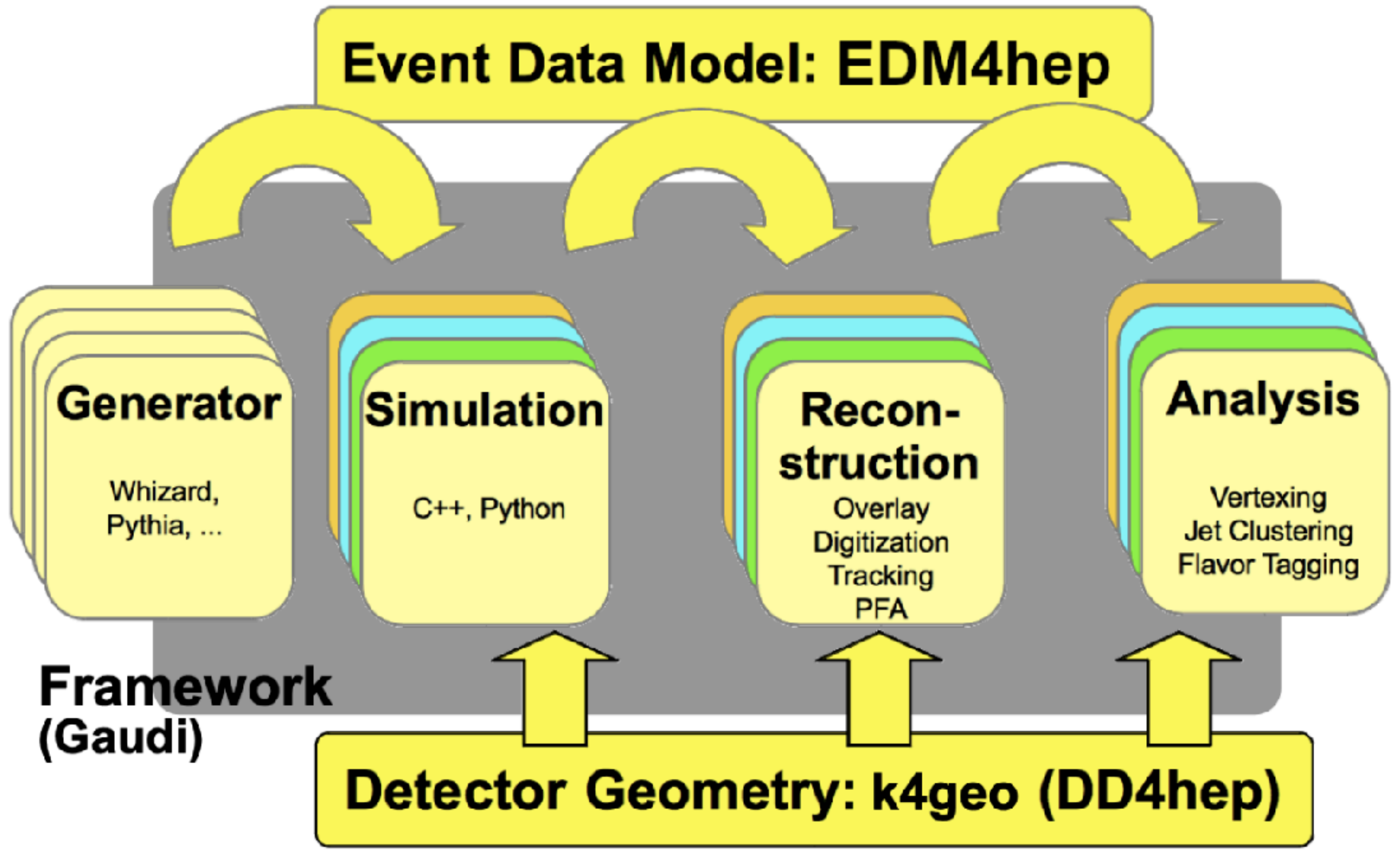
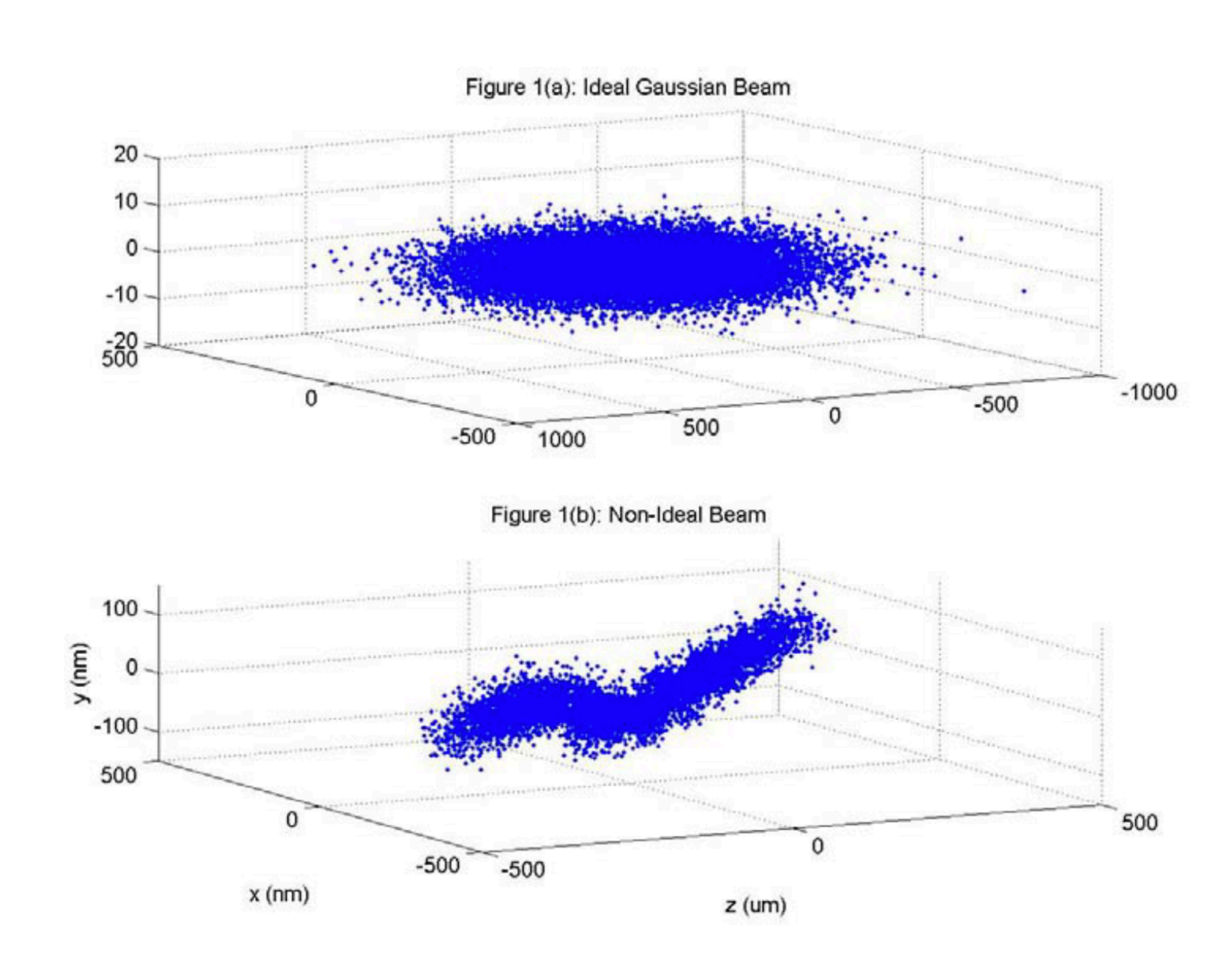
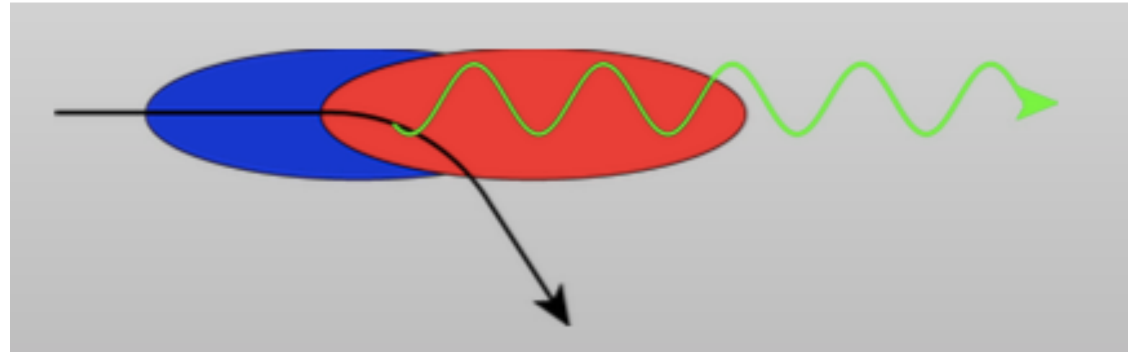


Beam simulations



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.: (✓)
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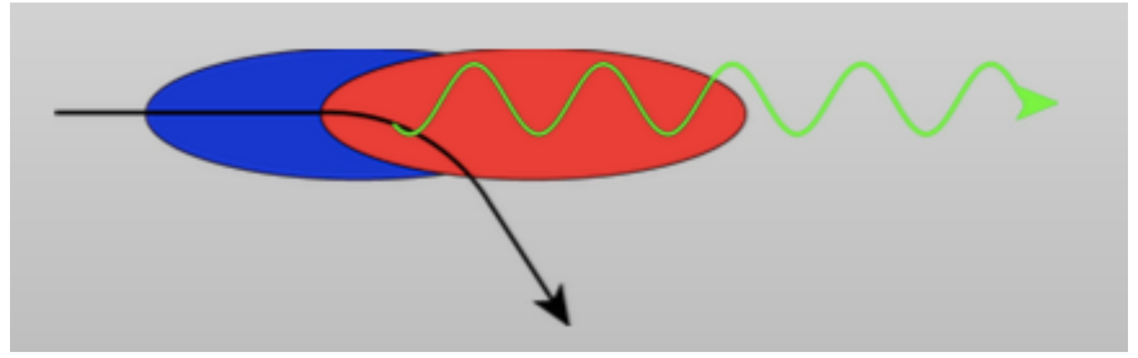

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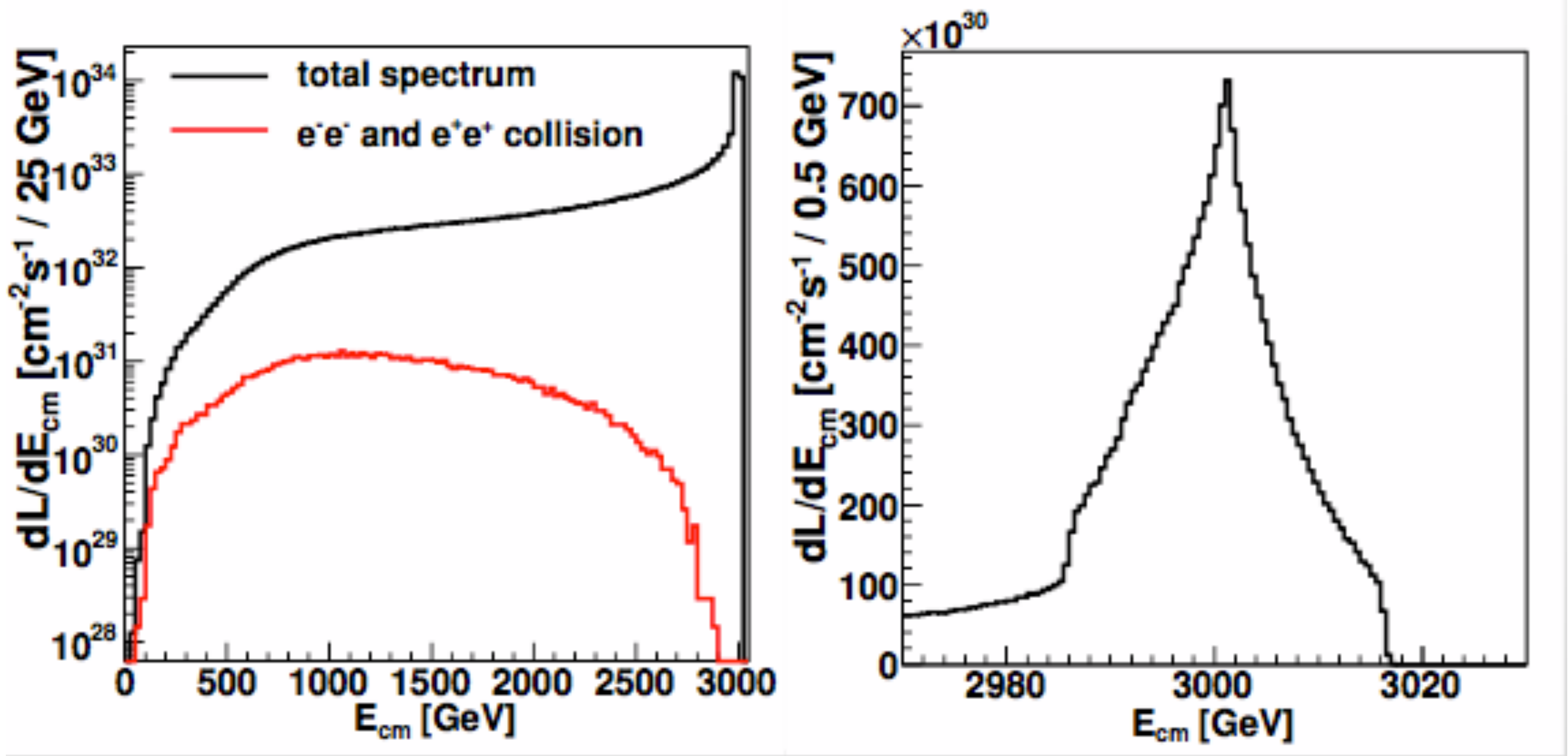

Dalena/Esbjerg/Schulte [LCWS 2011]

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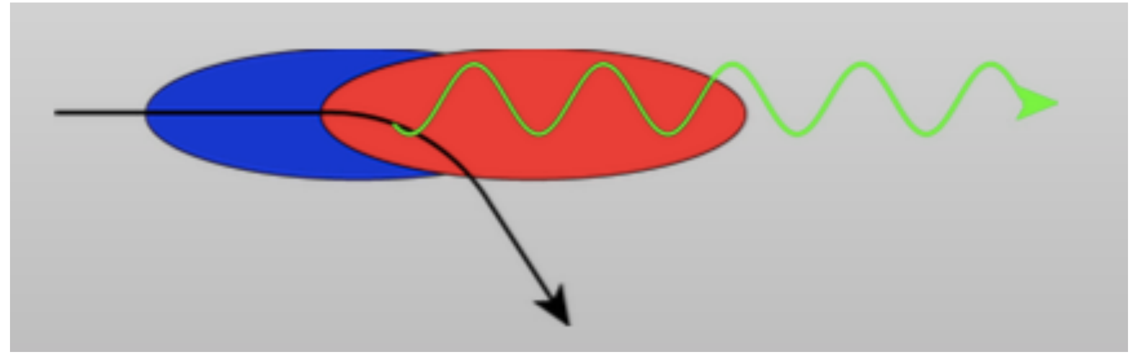

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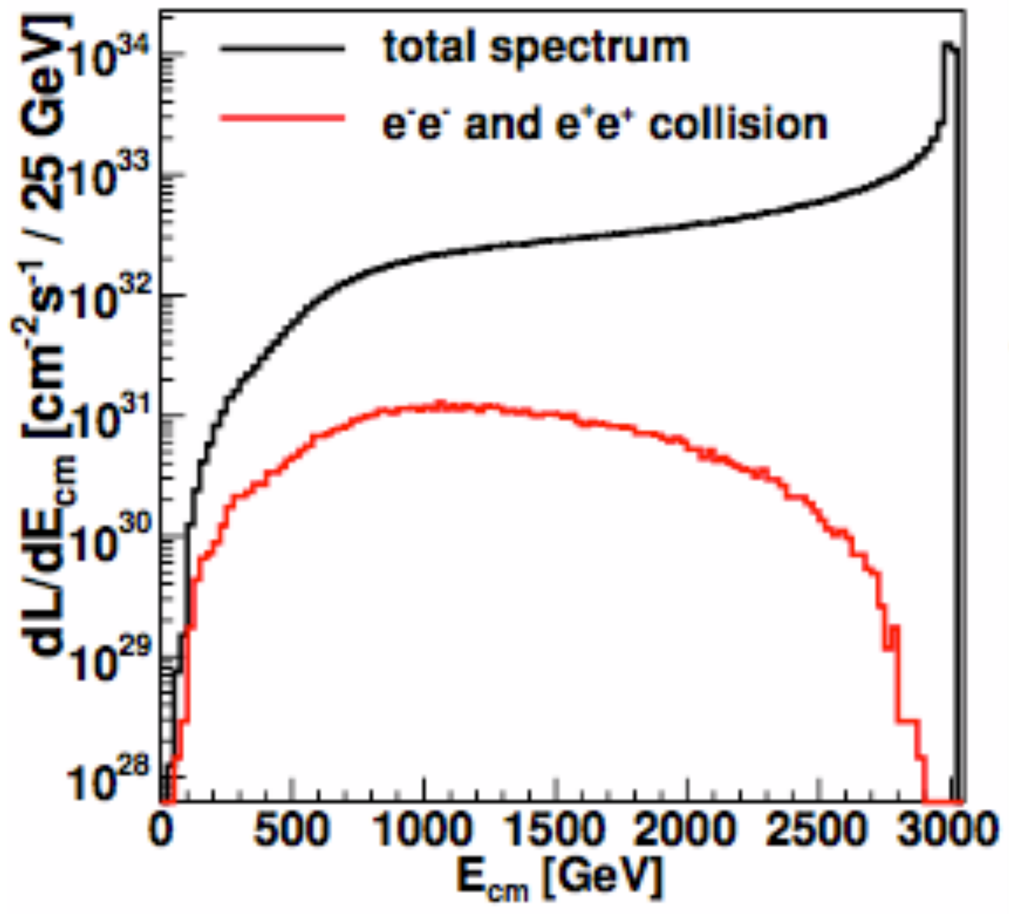
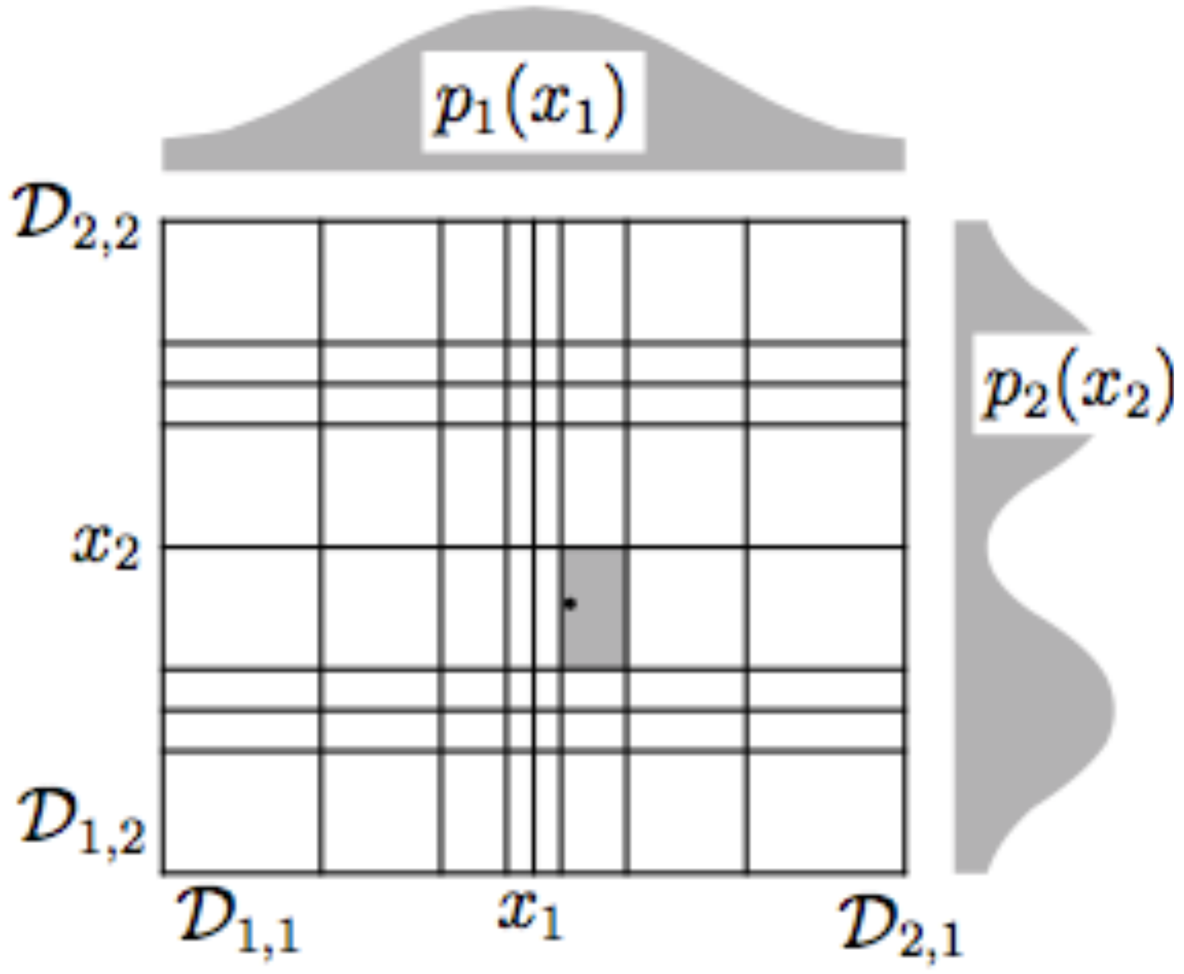
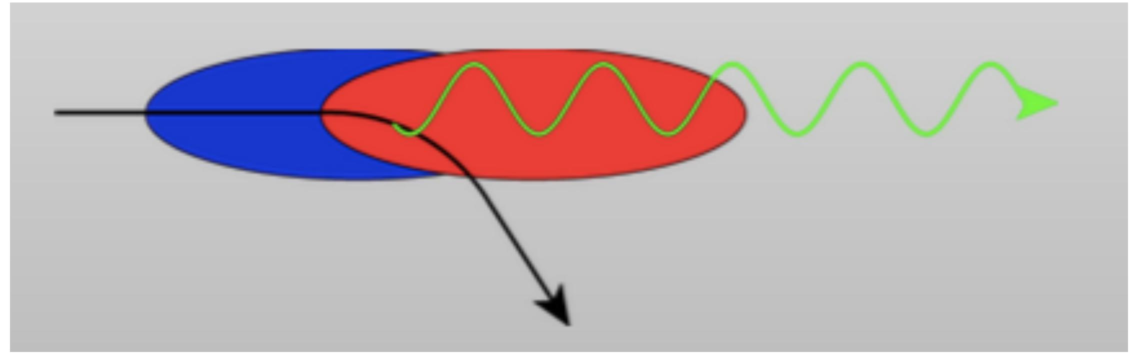




Dalena/Esbjerg/Schulte [LCWS 2011]

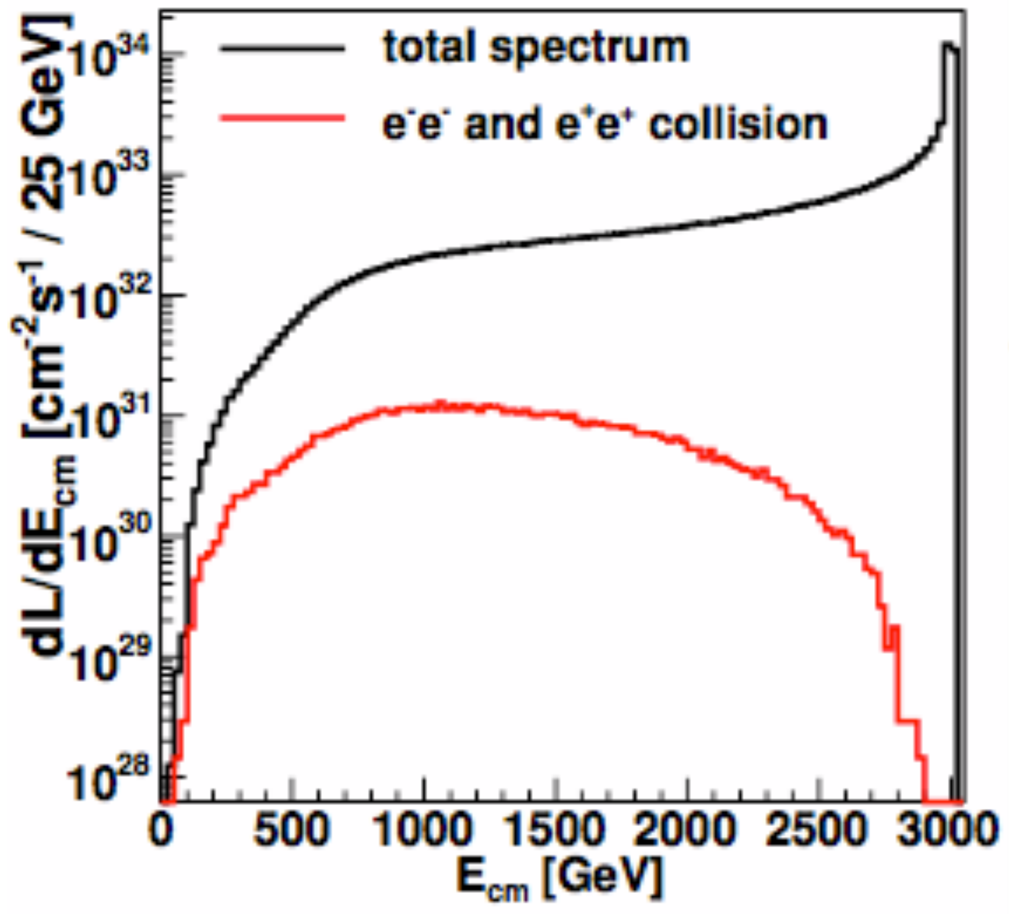
Beam simulations

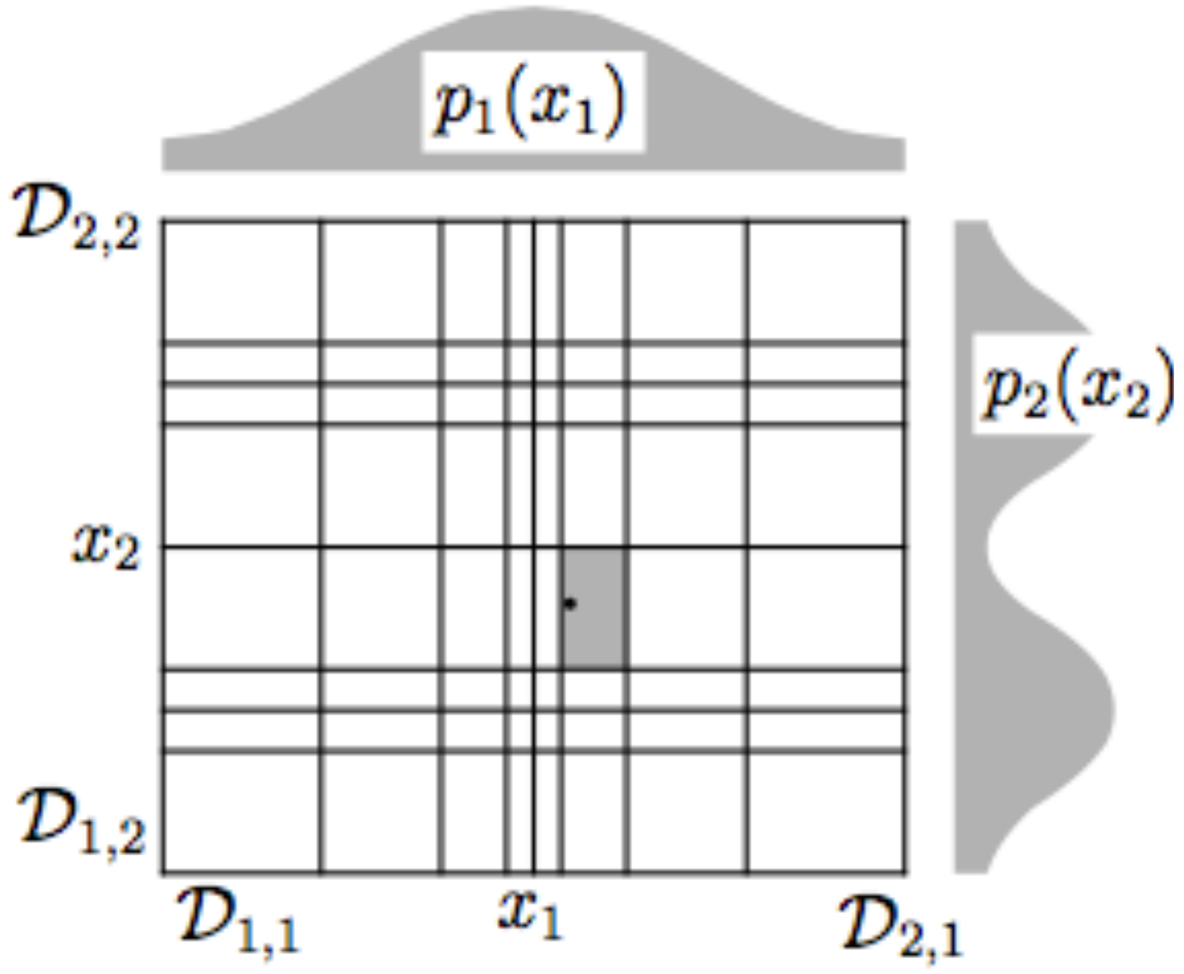
- Micro-scale bunches create beam structure/-strahlung
- Mostly Gaussian shape for circular machines, but not fully
- Machine simulation with tools like `GuineaPig(++)`, `CAIN`
- Has to be folded into realistic MC simulations



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

1. Gaussian shape with specific spreads — Avail.: ✔
2. Parameterized (delta peak ⊕ power law) — Avail.: (✔)
3. Generator for 2D histogrammed fit — Avail.: [✔]





Dalena/Esbjerg/Schulte [LCWS 2011]

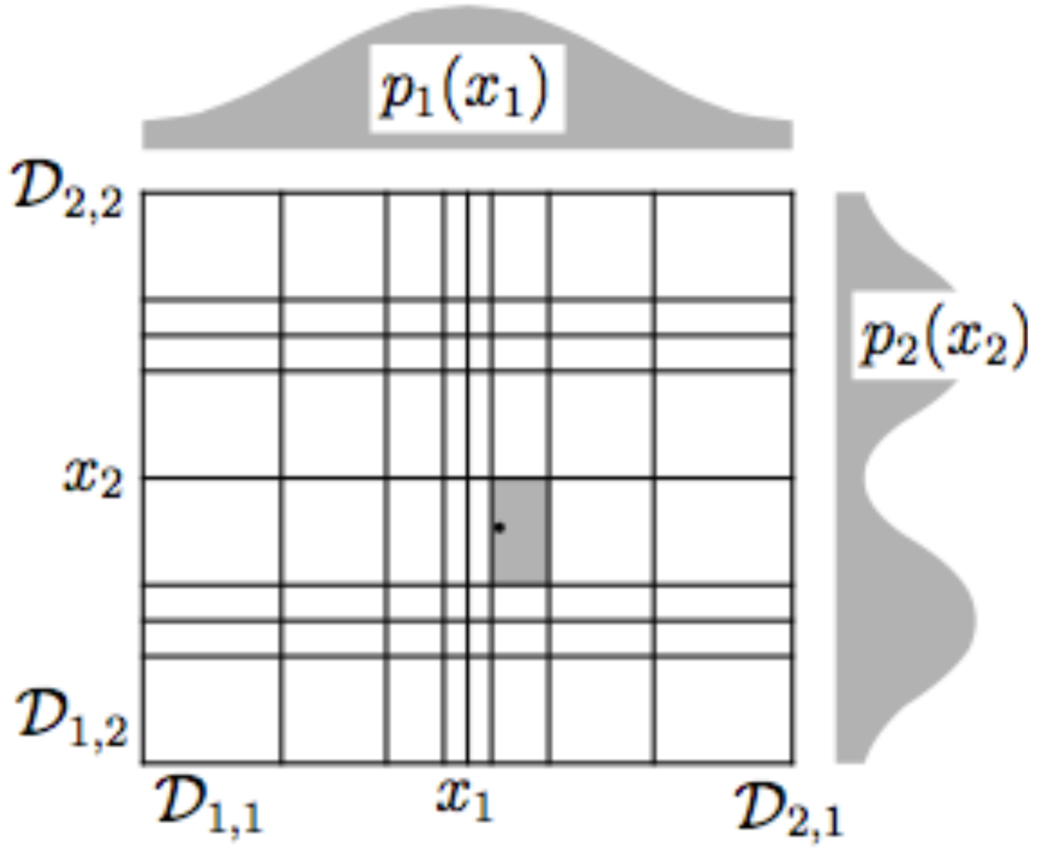
- Pro (1.): Easy implementation, covers main features
- Con (1.): Gaussian approximative, exceeds nominal collider energy
- Pro (2.): Relatively easy implementation
- Con (2.): Delta peak behaves badly in MC, beams maybe not factorizable/simple power law
- Pro (3.): most exact simulation, generator mode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

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

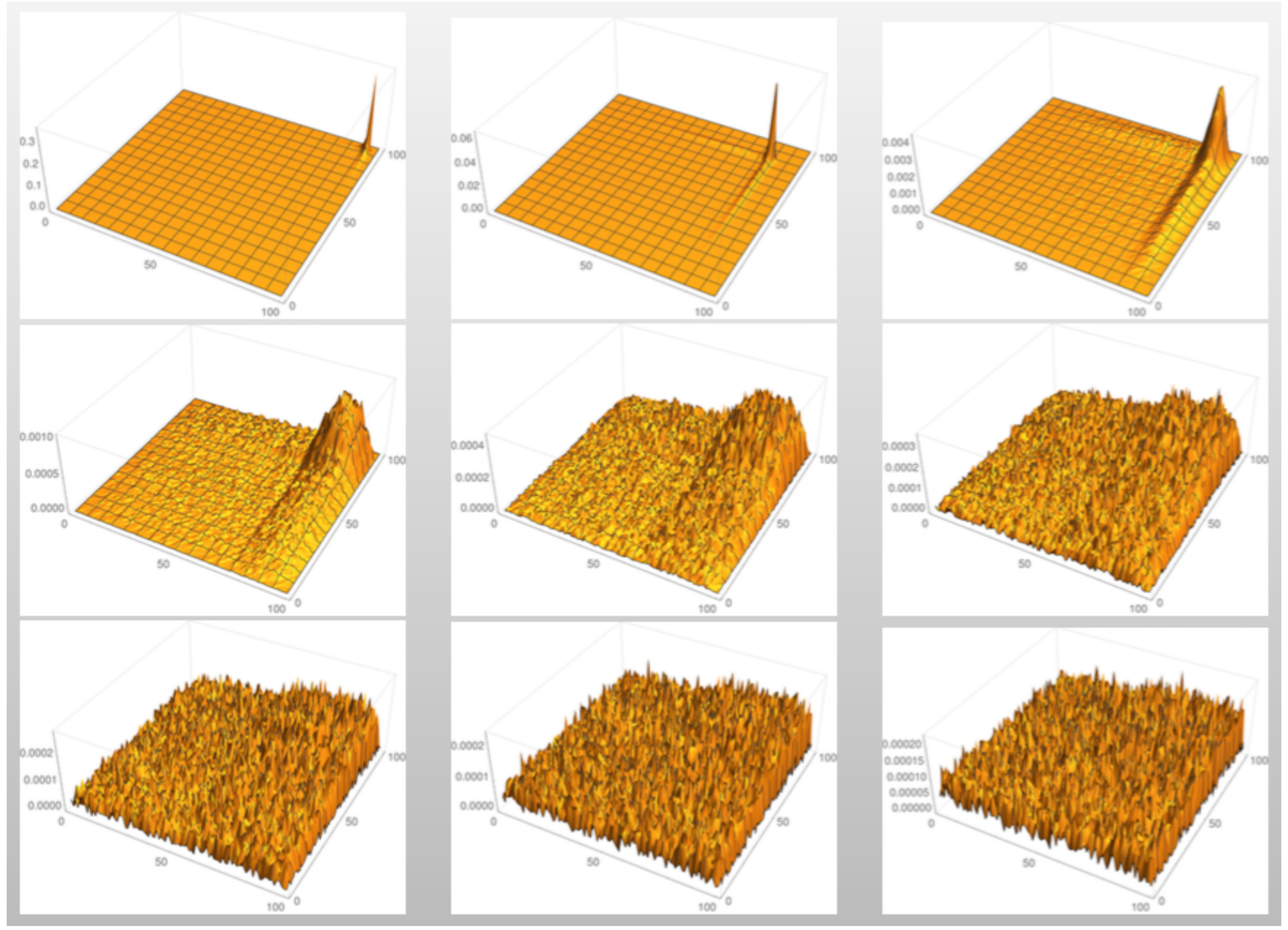
Beam simulations (technial details)

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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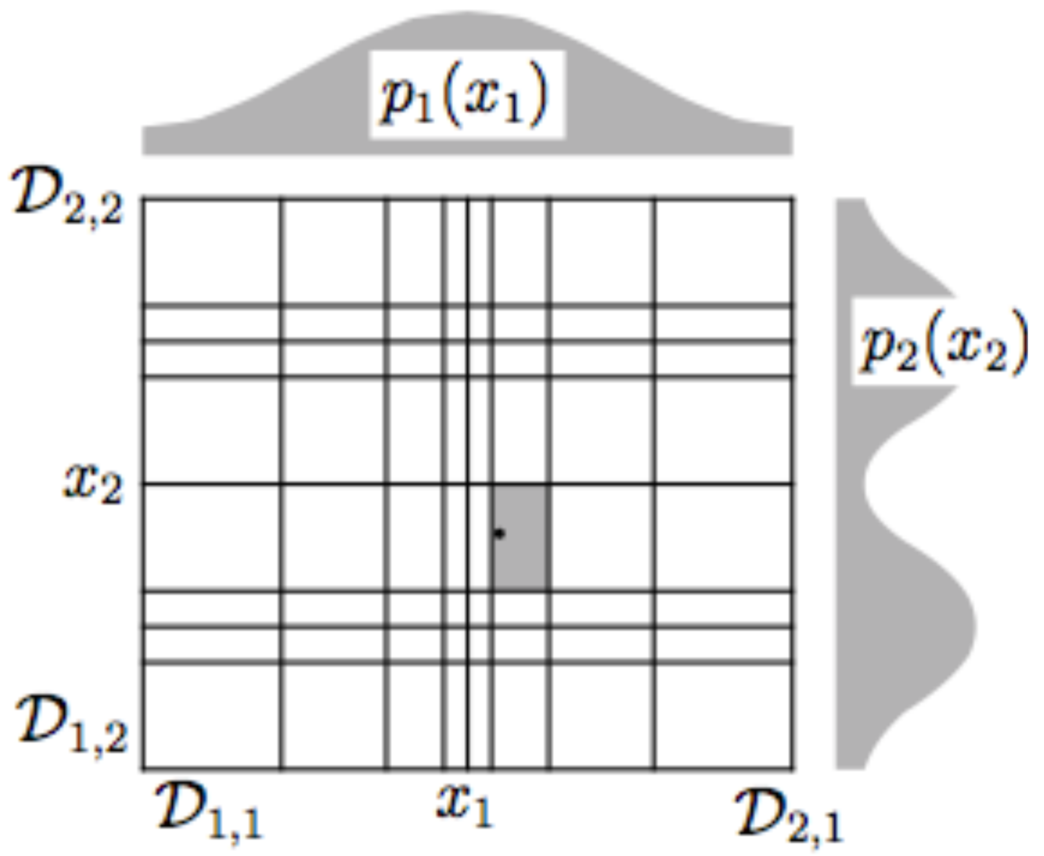

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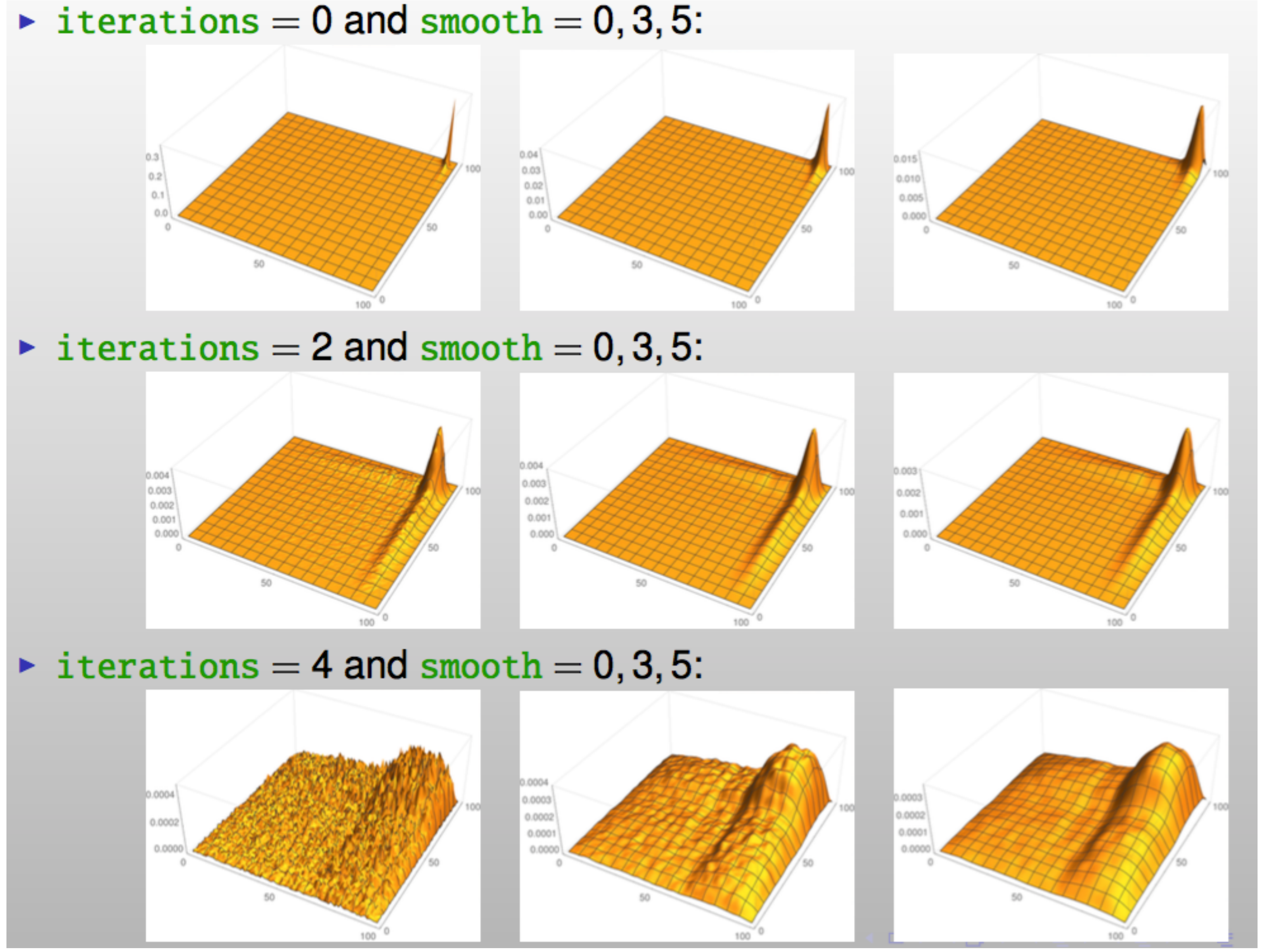

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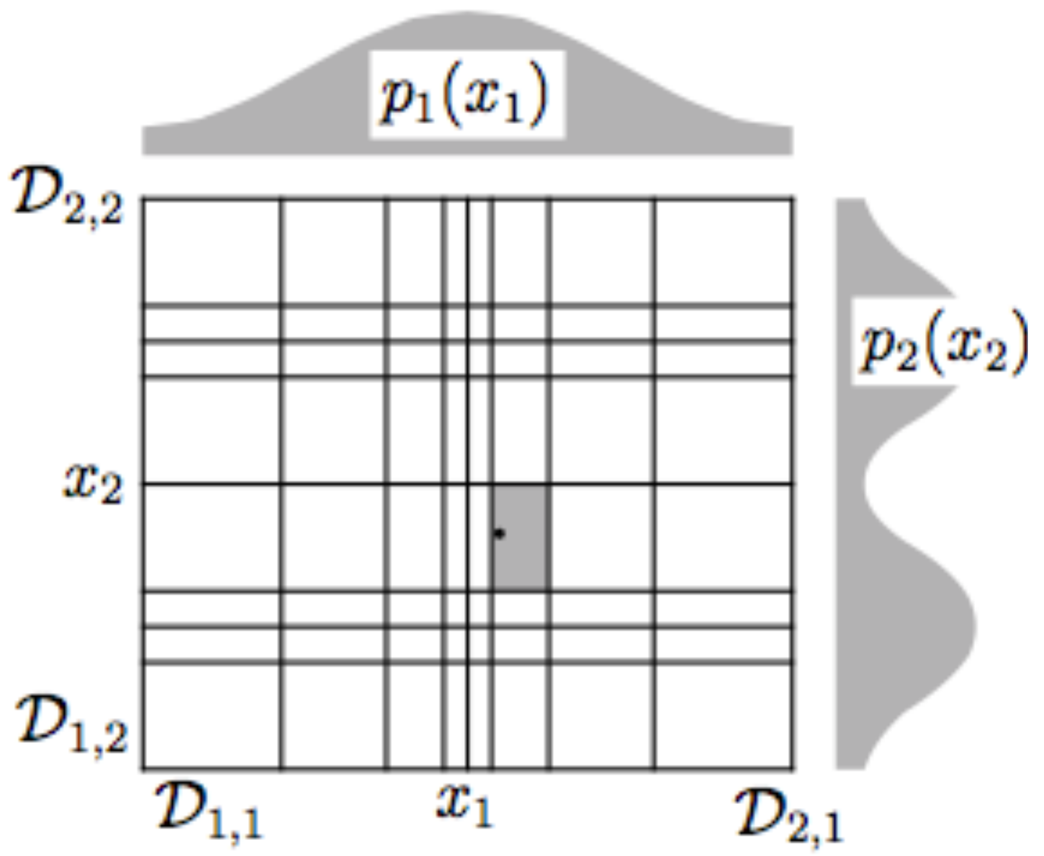

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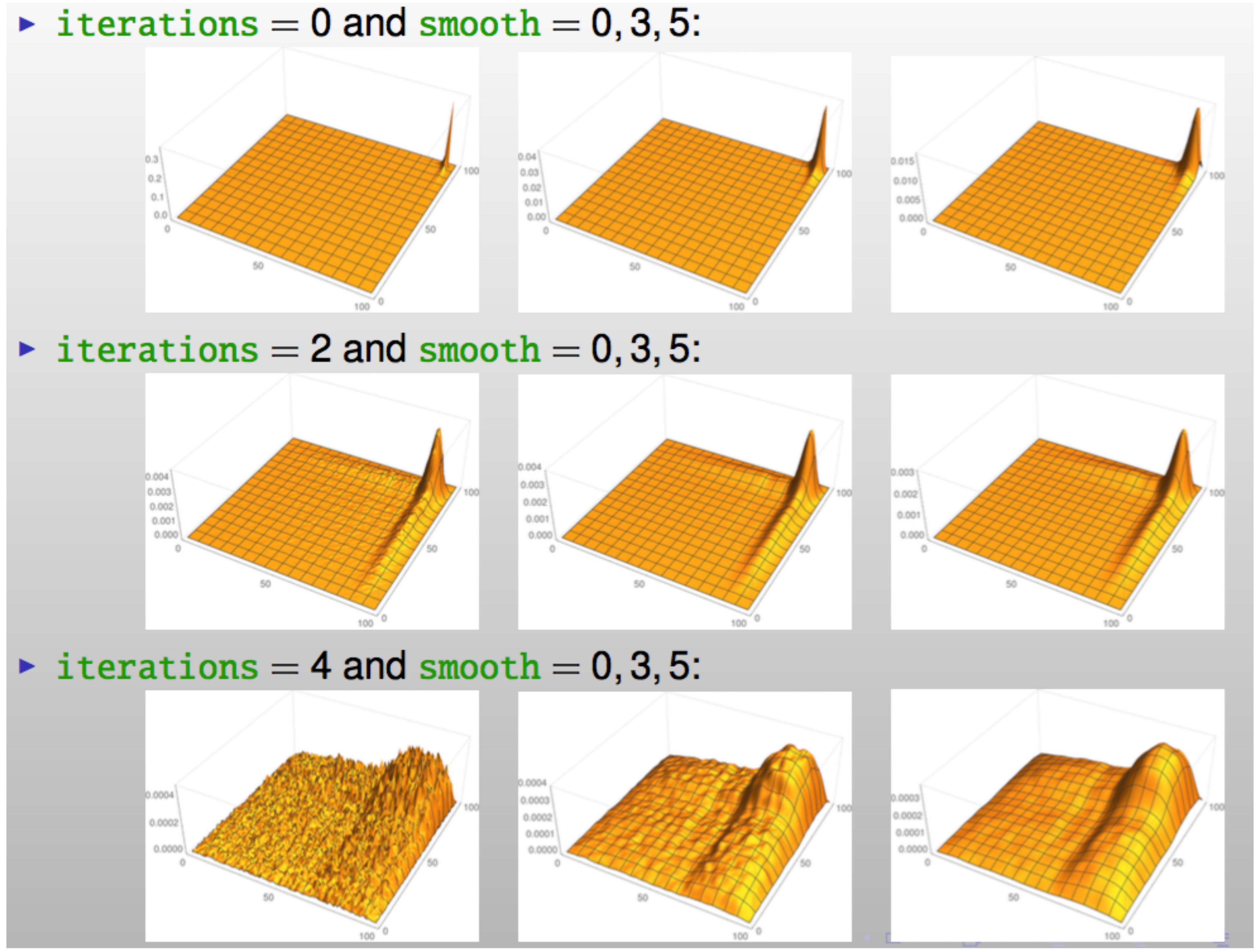


1. Run Guinea-Pig++ with

```
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:

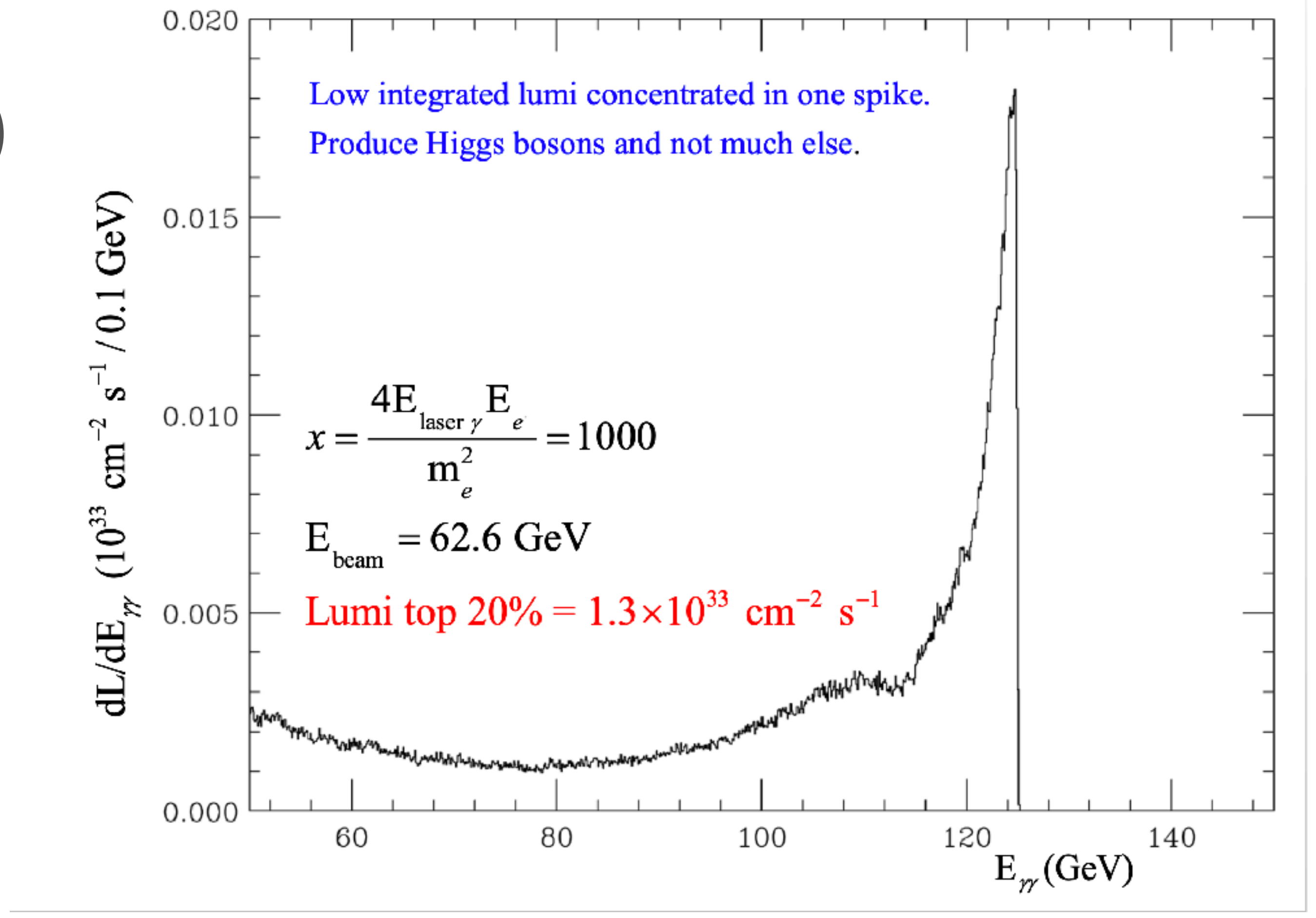
```
beams = e1, E1 => circe2
$circe2_file = "ilc500.circe"
$circe2_design = "ILC"
?circe_polarized = false
```

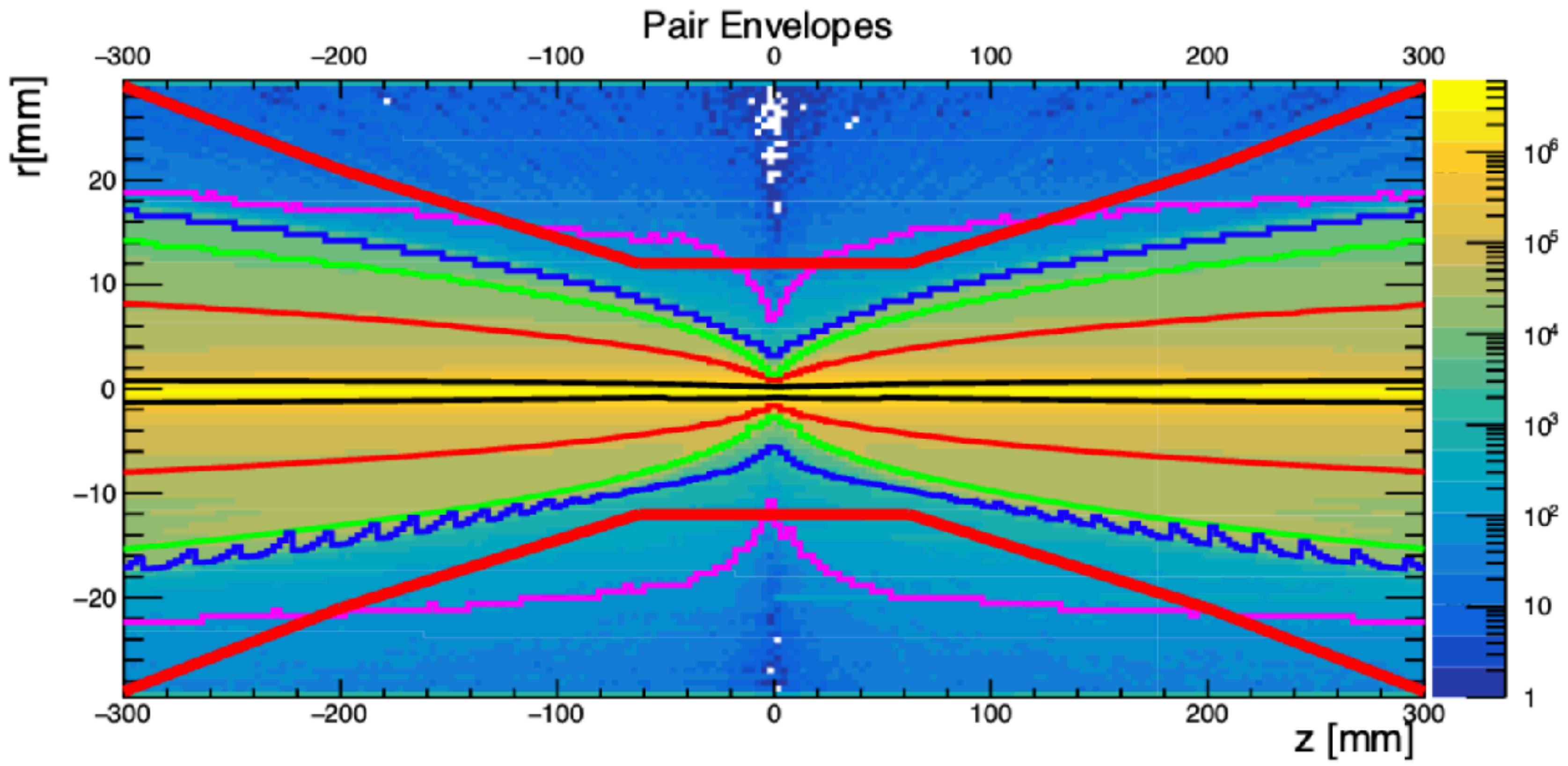
3 simulation options

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

Beam simulations

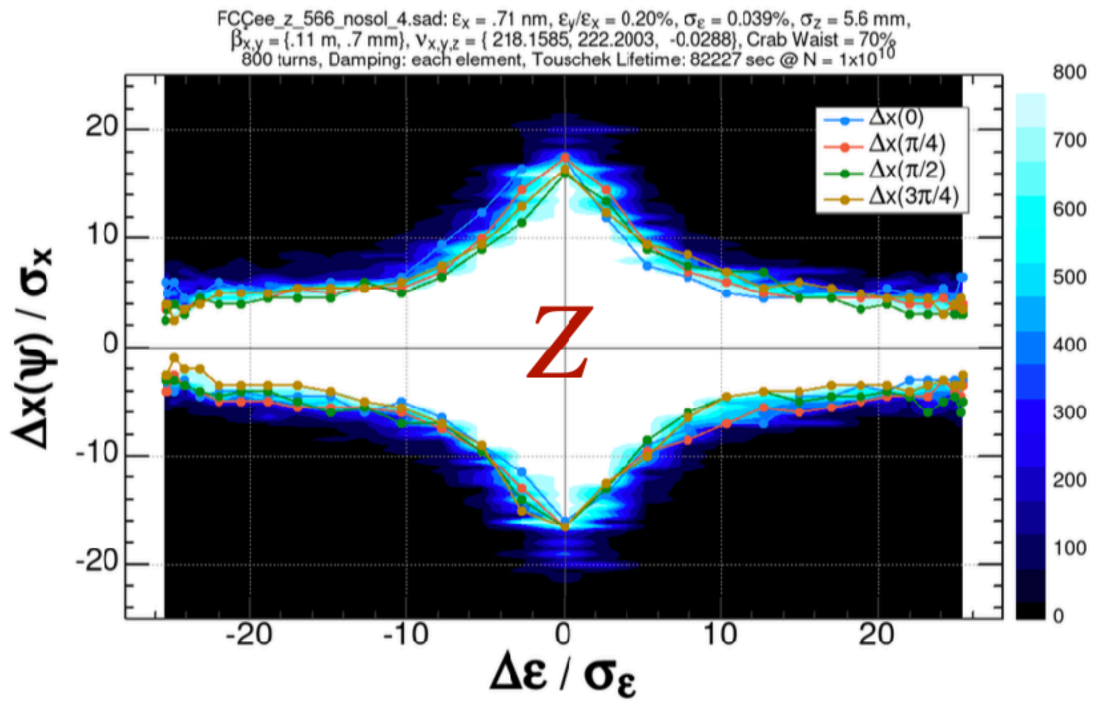
- New beam simulations for FCC-ee: 4 IPs ⇒ 1.7x lumi (91 GeV) / 1.8x lumi (161/250 GeV)
- New beam simulations for CCC and XCC (photon collider simulations)
- Photon collider simulations *not* possible with parameterized spectra
- Conclusion: `CIRCE2`-like sampling most versatile/general approach



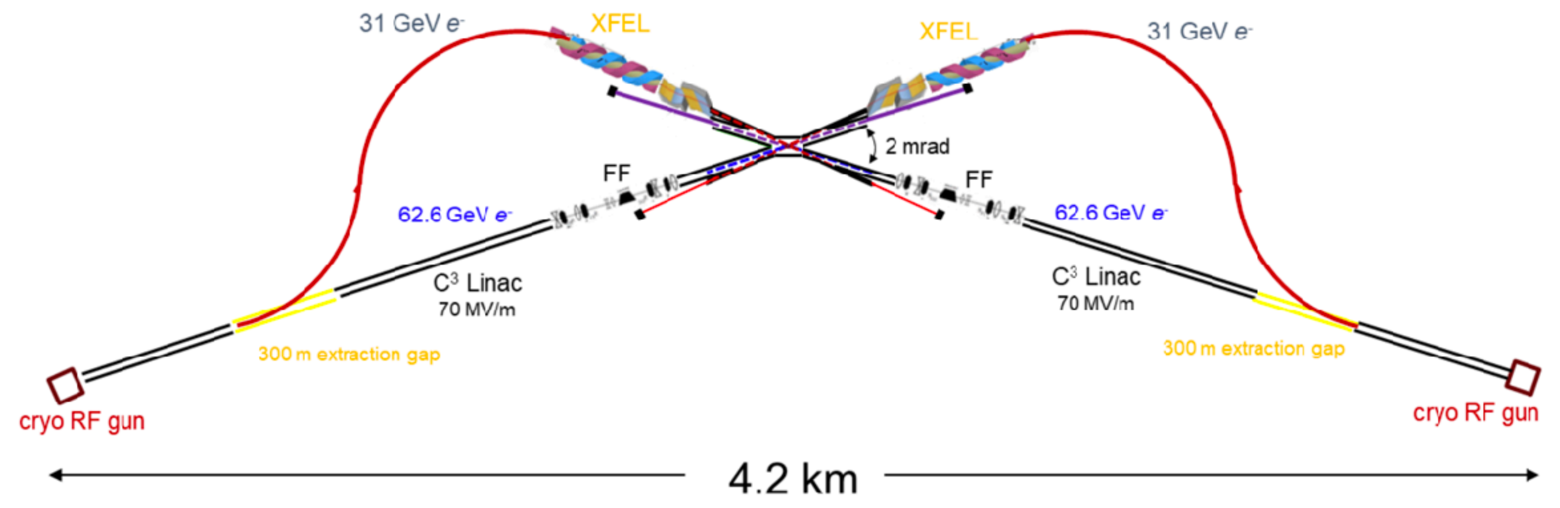


[Katsunobu Oide, FCC week]

Dynamic aperture (*z*-*x*)



XCC s-channel $\gamma\gamma \to H$ @ $\sqrt{s} = 125$ GeV



[Thorsten Ohl, 2nd ECFA (MC) WS]

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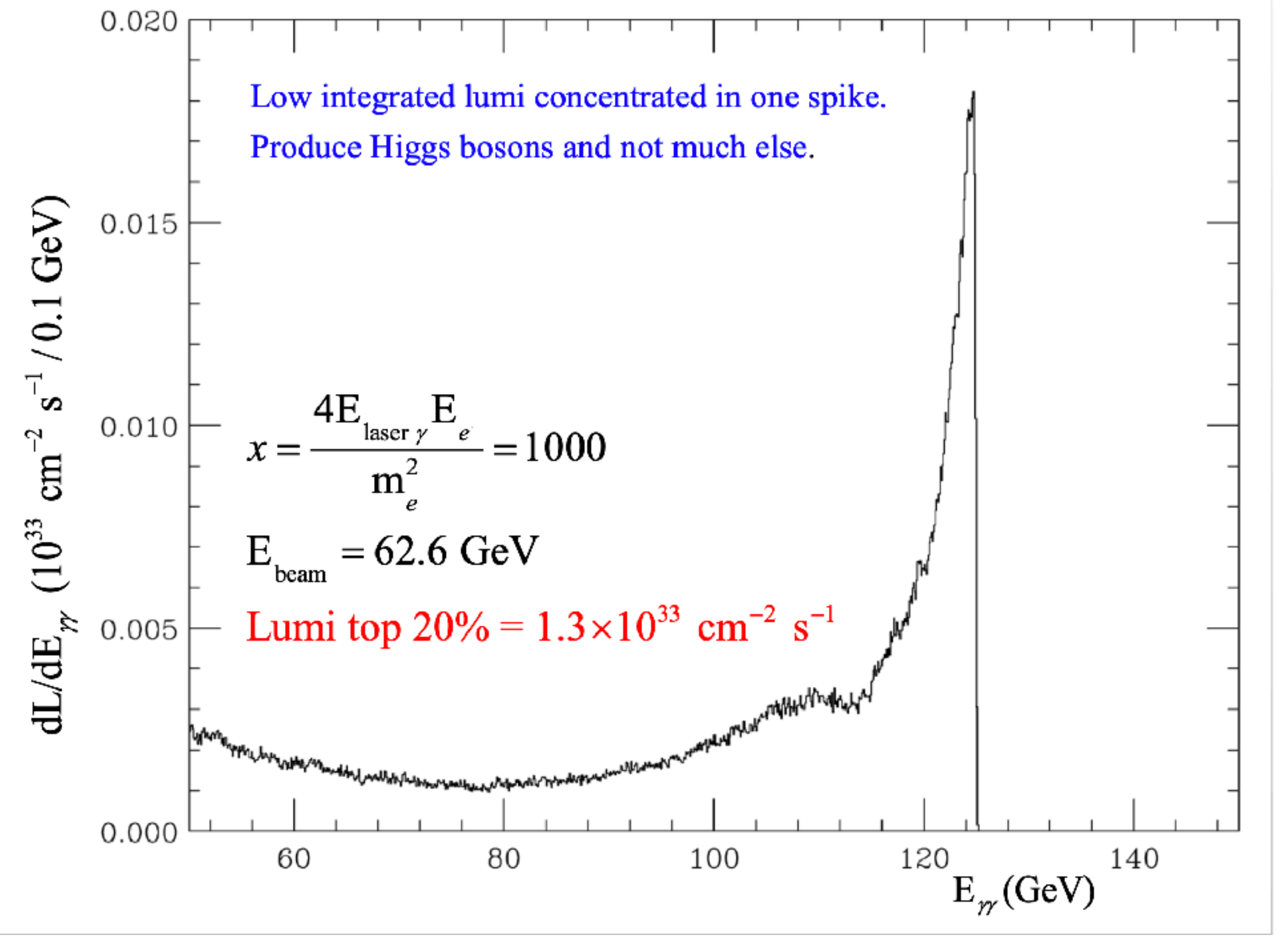

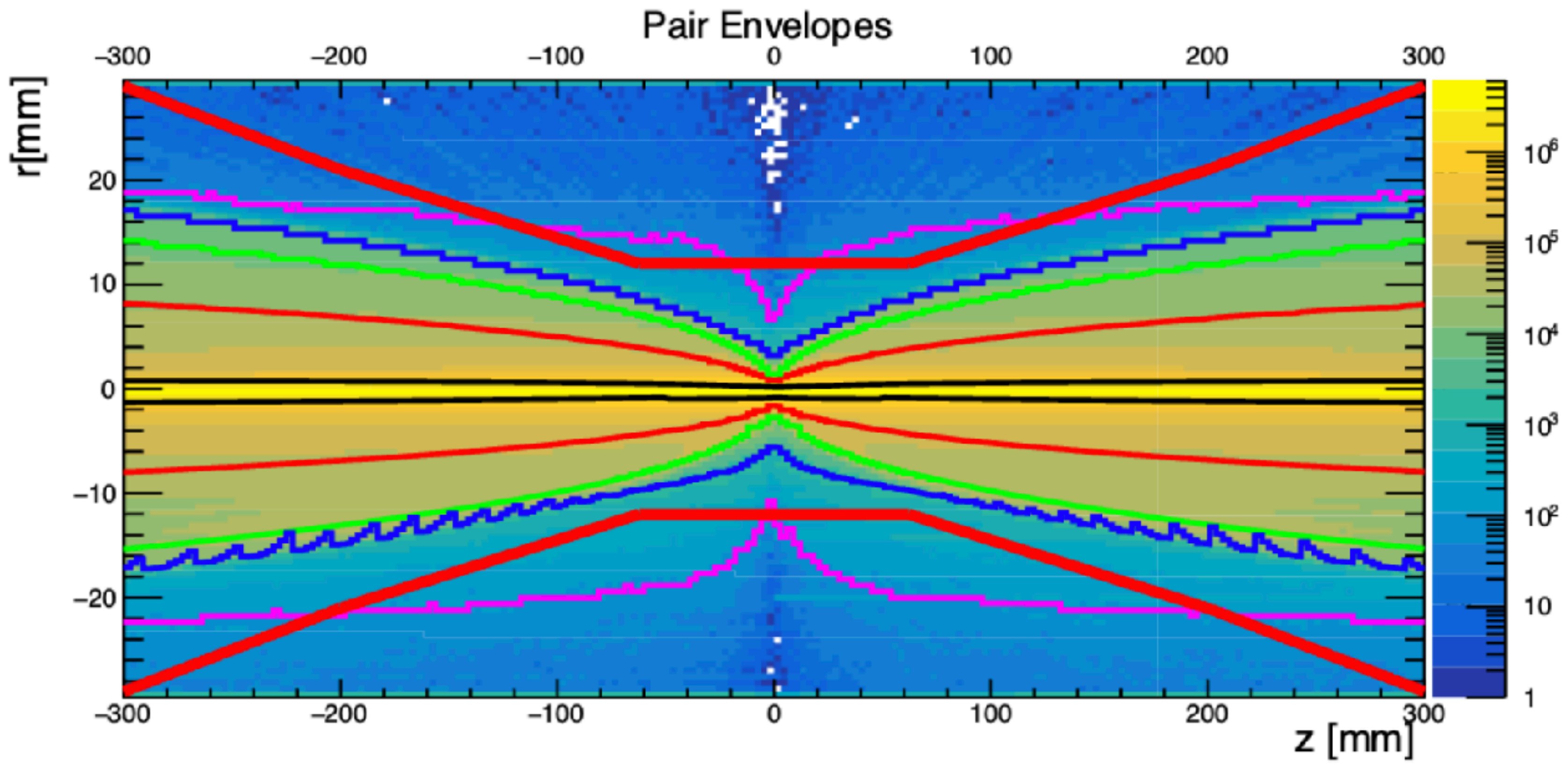

[Katsunobu Oide, FCC week]

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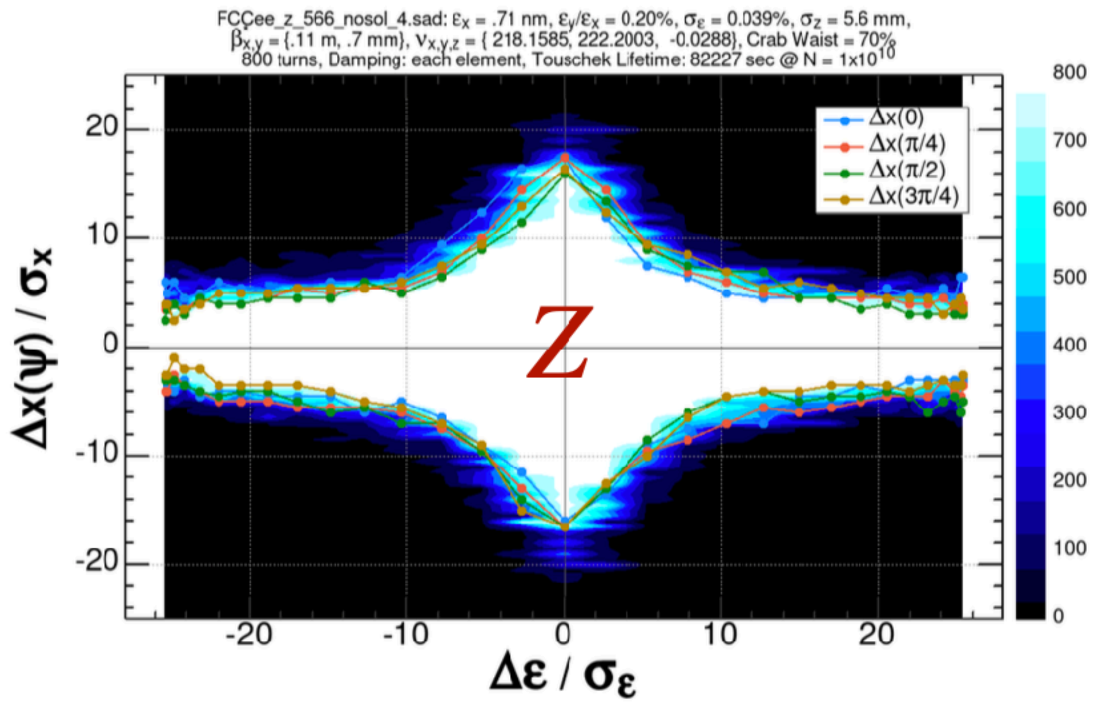

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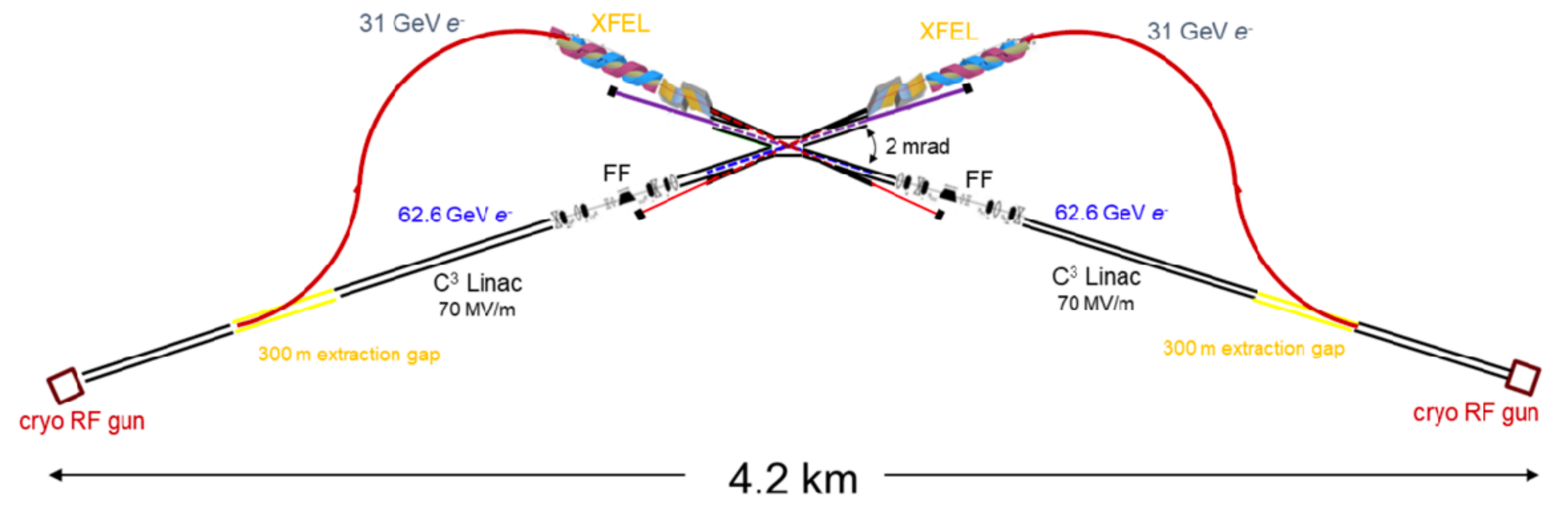
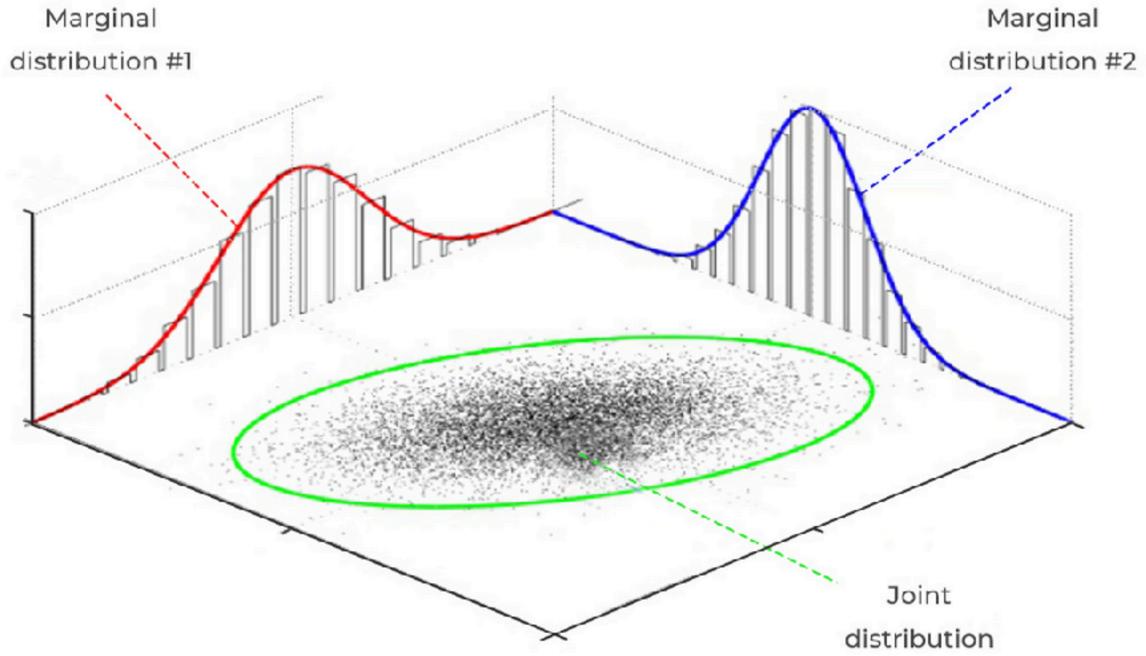
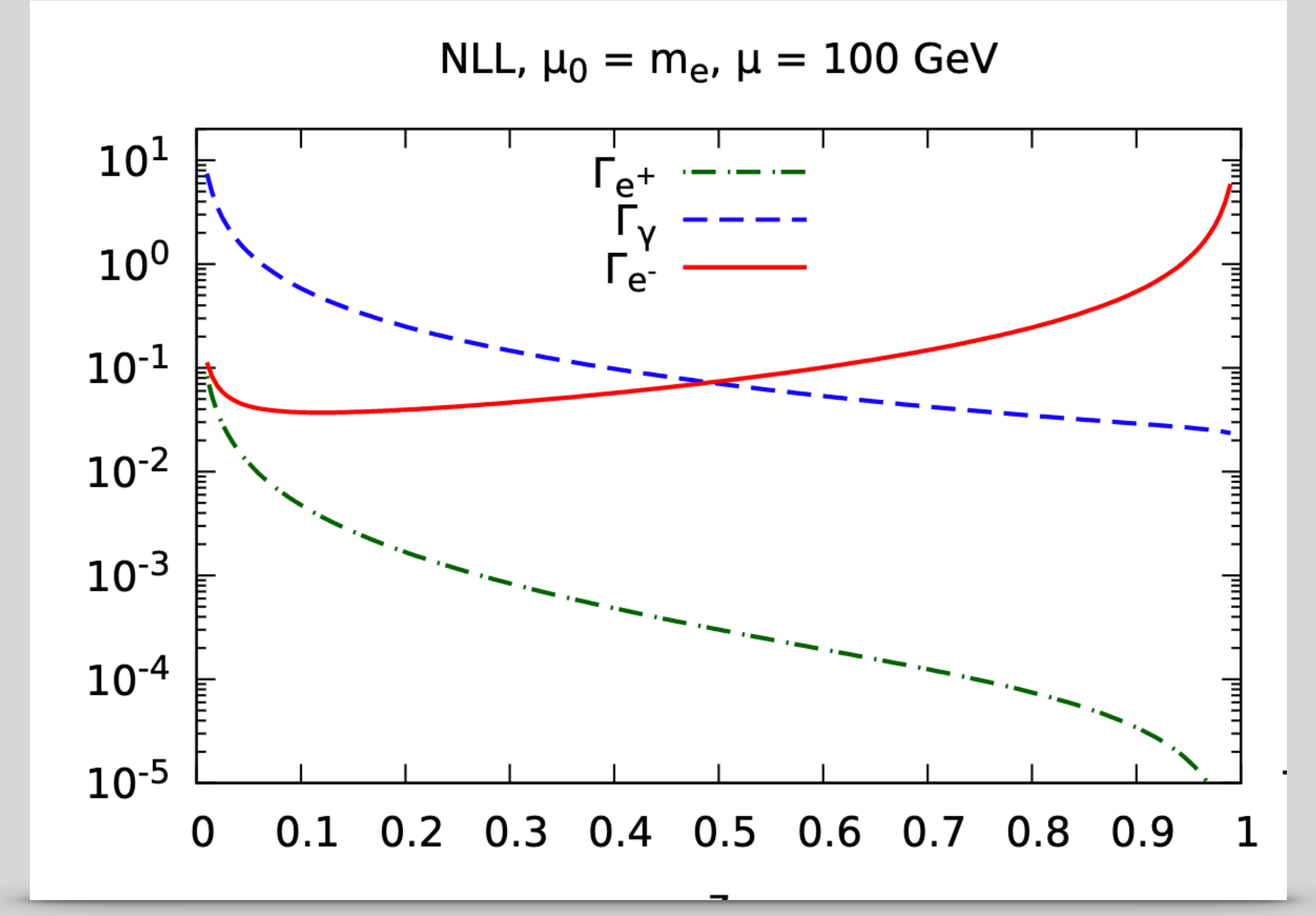


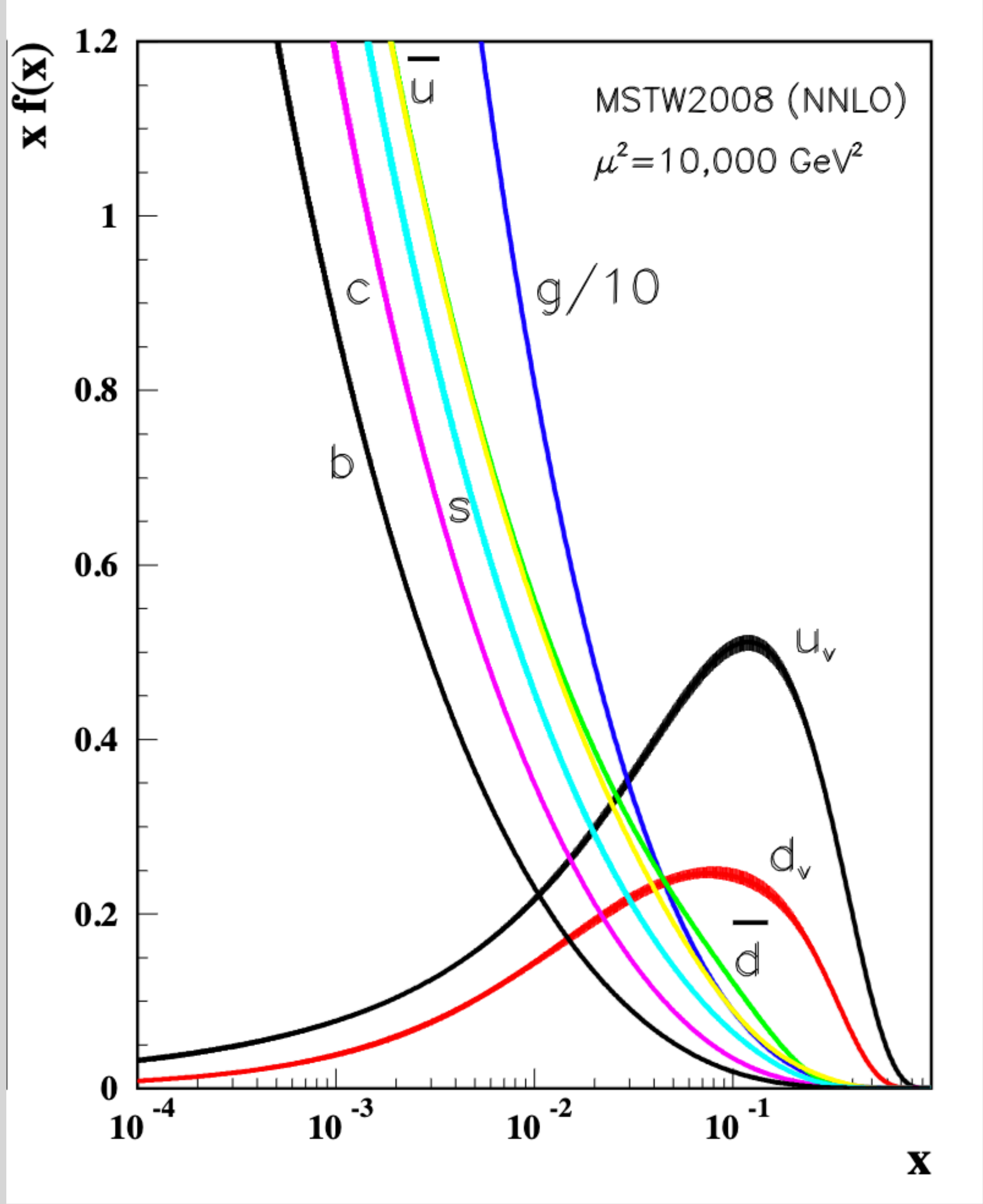
Open Issues

- Still several Higgs factories missing in general beam spectrum repository
- Machine learning for sampling beam spectra not yet started (expected performance?)
- 2D-/3D-structure of beam spectra (*z*-dependence, copulas)



Initial State Radiation — Lepton PDFs

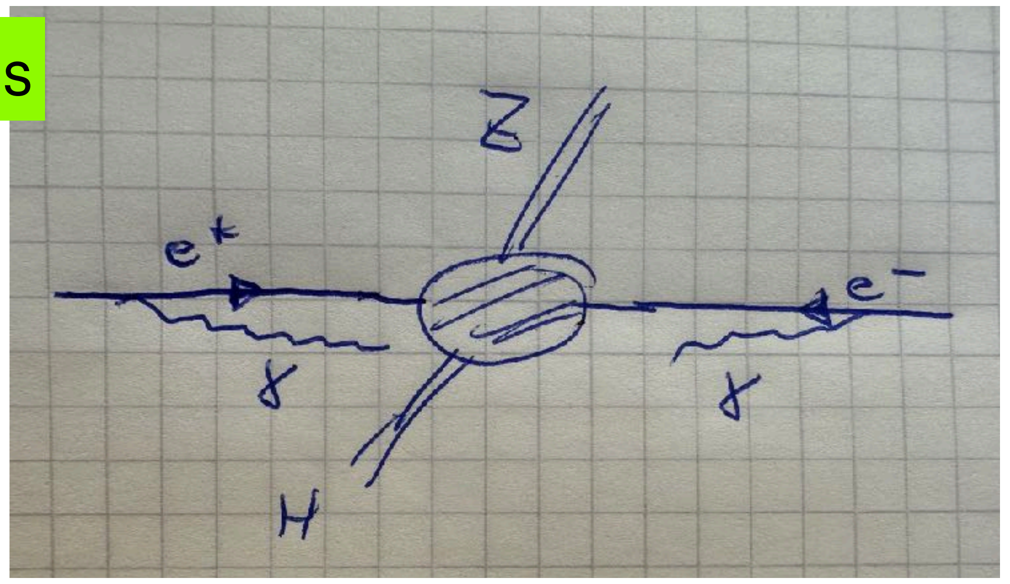




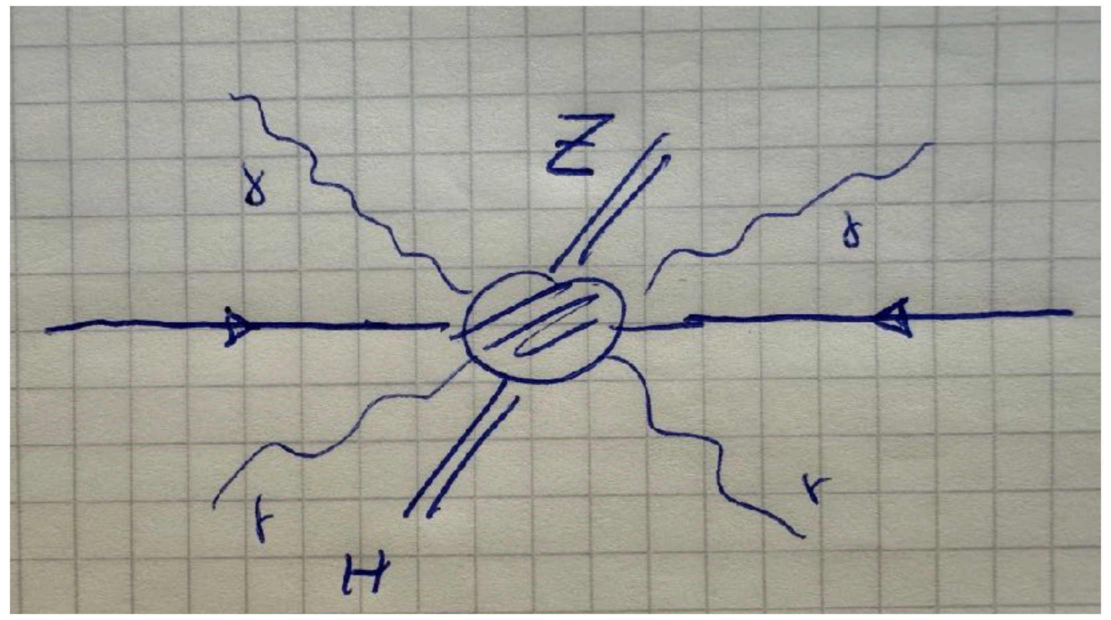
QED PDFs — QED Initial State Resummation

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

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

- 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

$$d\sigma = \sum_{n_\gamma}^{\infty} \frac{\exp[Y_{res.}]}{n_\gamma!} \prod_{j=1}^{n_\gamma} \left[d\mathrm{LIPS}_j^\gamma S_{res.}(k_j) \right] [\sigma_0 + \text{corrections}]$$

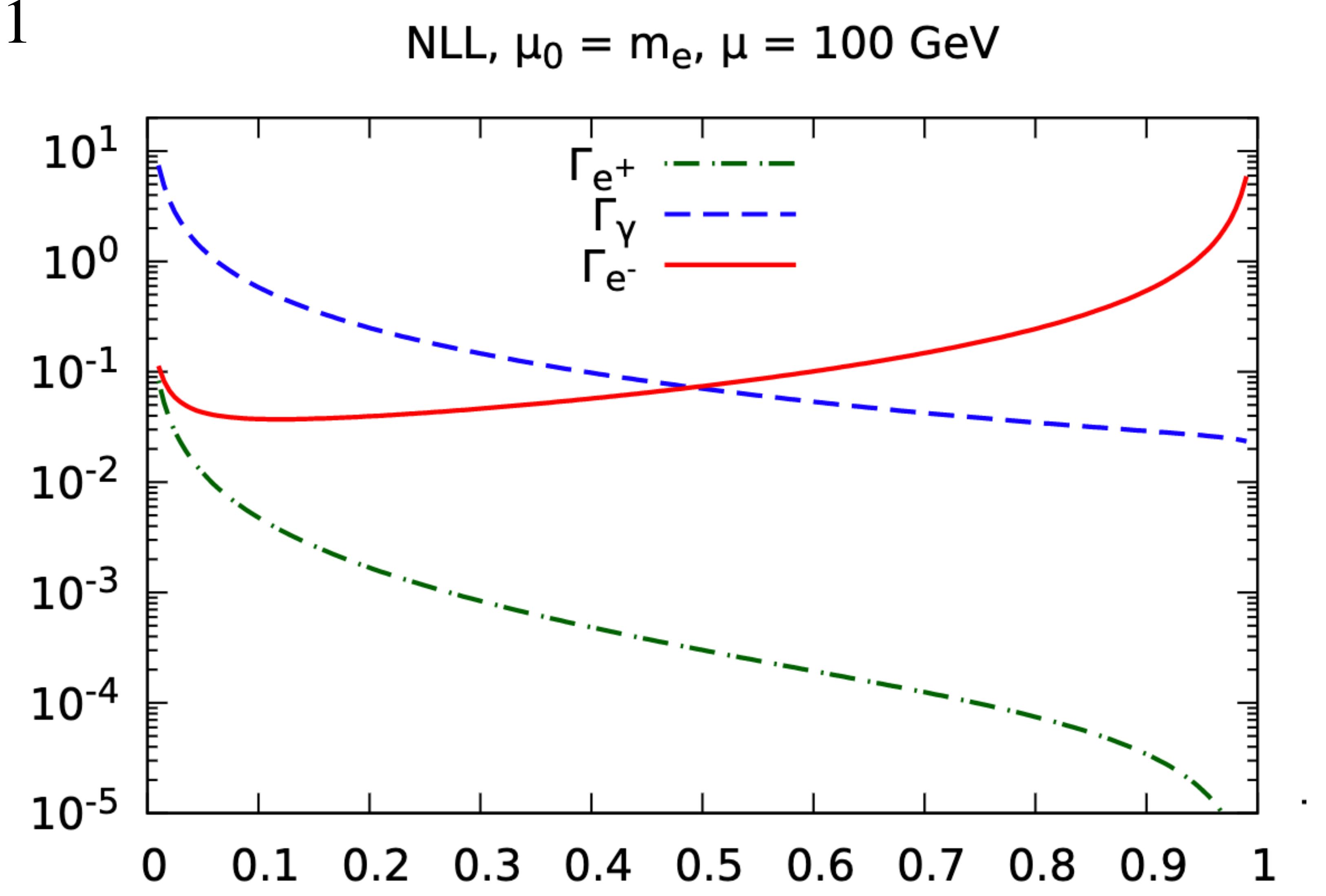
  - Universal soft exponentiation factor, provides n_γ exclusive resolved photons with (almost) exact kinematics
  - Exponentiation at amplitude level (CEEX) oder squared ME level (EEX)
  - Implemented in LEP legacy MCs (`BHLUMI/BHWIDE`, `KORAL(W/Z)`, `KKMC-ee`, `YFS(WW/ZZ)`, also: `Sherpa`, w.i.p.: `Whizard`
  - Can be systematically improved at fixed-order level by higher-order corrections
- Collinear factorization: universal QED ePDFs,
  LL: $(\alpha L)^k$, NLL: $\alpha(\alpha L)^{k-1}$

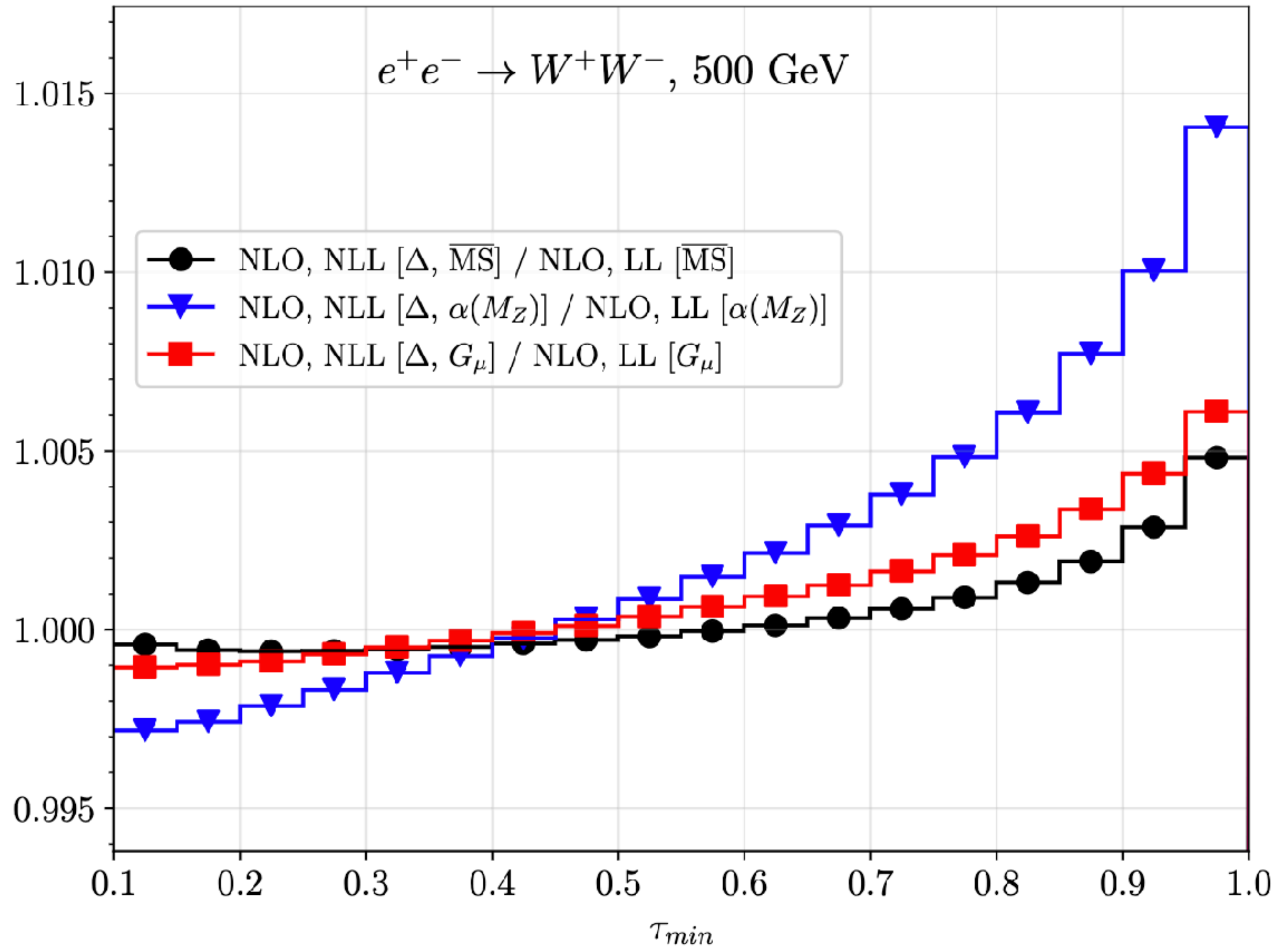
$$d\sigma_{kl}(p_k, p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \, \Gamma_{i/k}(z_+, \mu^2, m^2) \, \Gamma_{j/l}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$$

QED PDFs — Collinear Factorization

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

- 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: 2-4 per mille
- 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



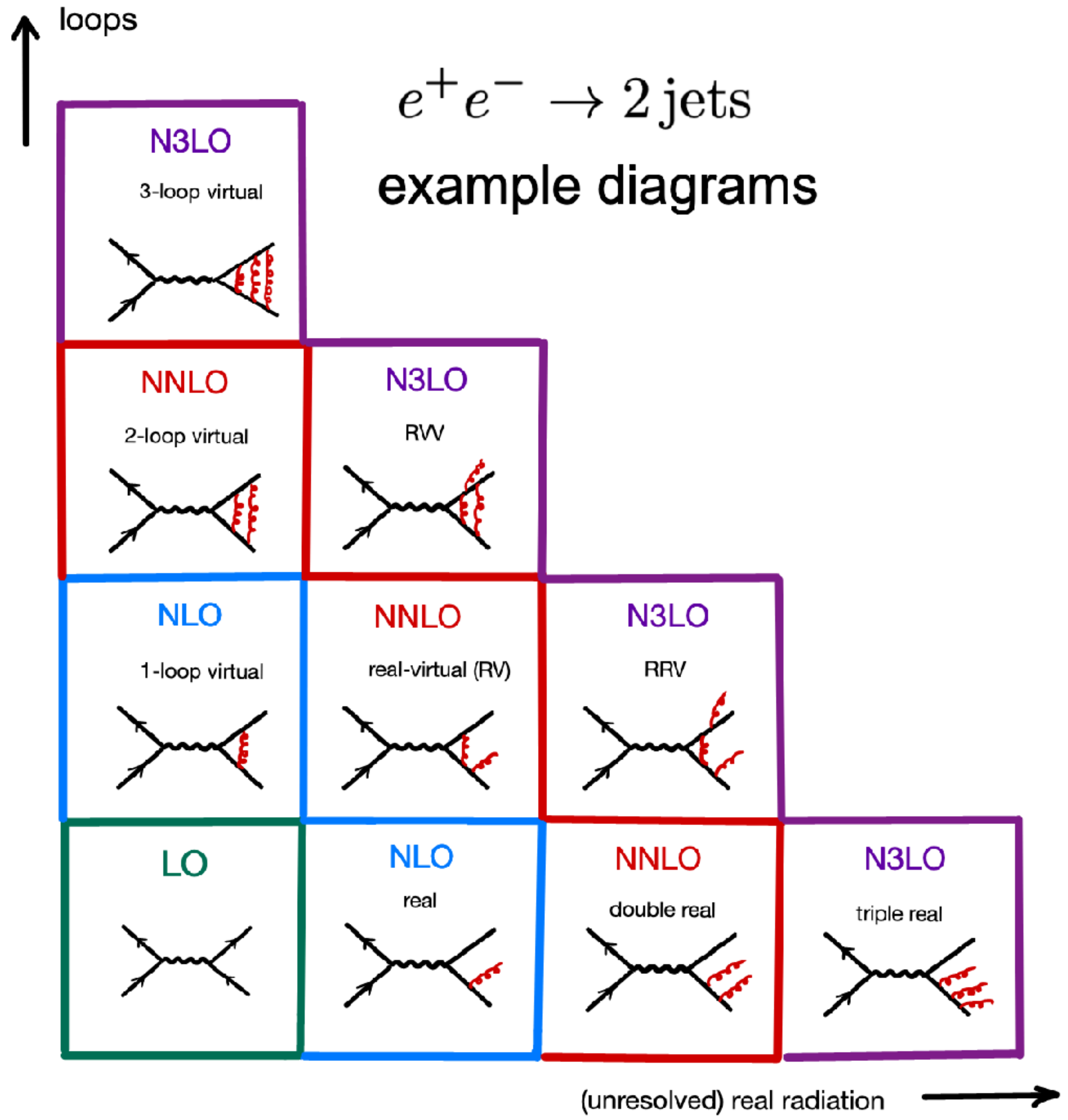


ePDFs for polarized leptons !?

SM precision in hard processes — Loops and Legs

Getty Villa, Pacific Palisades, Etruscan, 525 BC

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



- LO + NLO QCD ⊕ EW automated: Sherpa, MG5, Whizard
- Note the fine-prints

- 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

	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[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

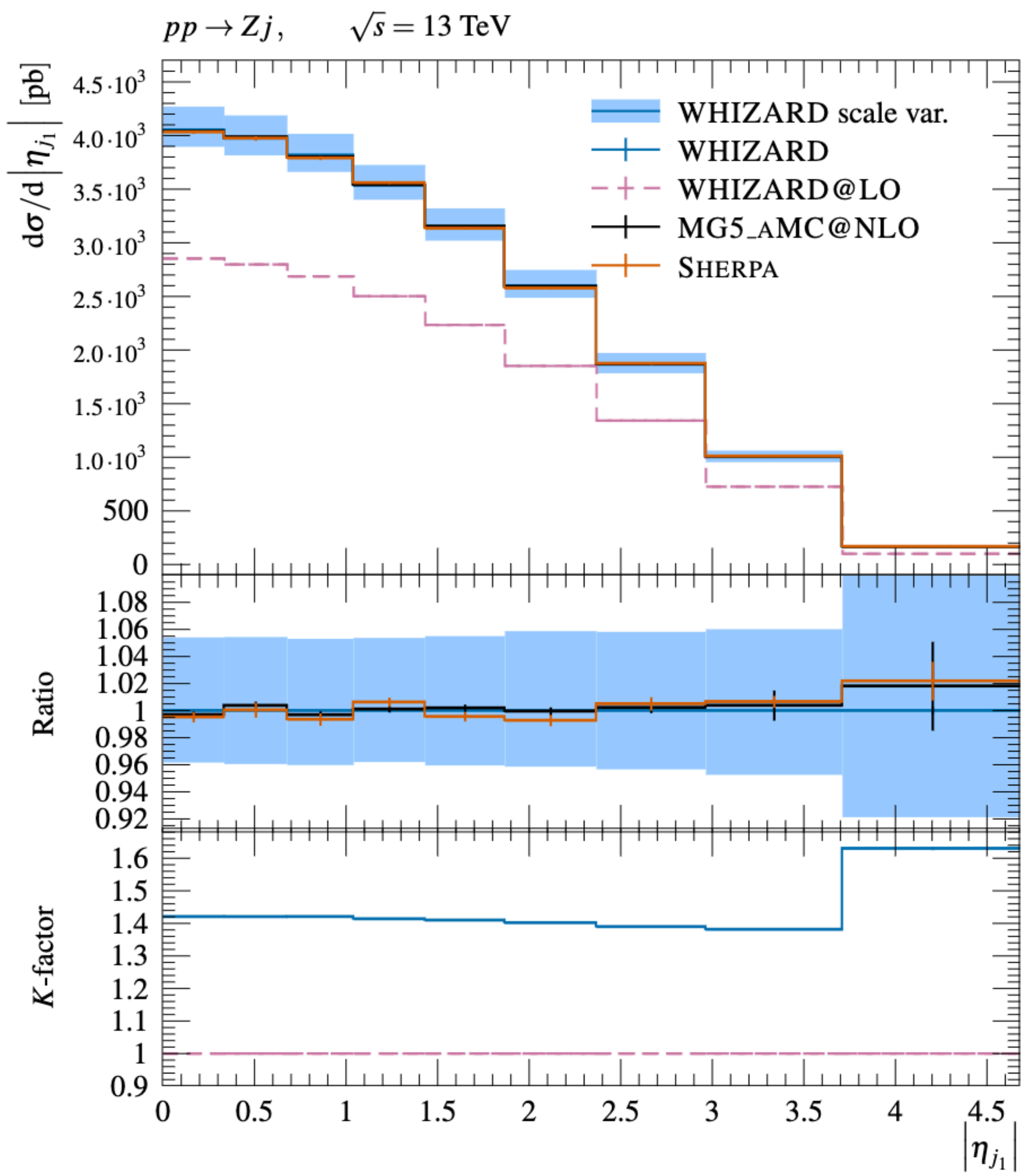
NLO EW

Pia Bredt, Phd thesis, DESY, 2022

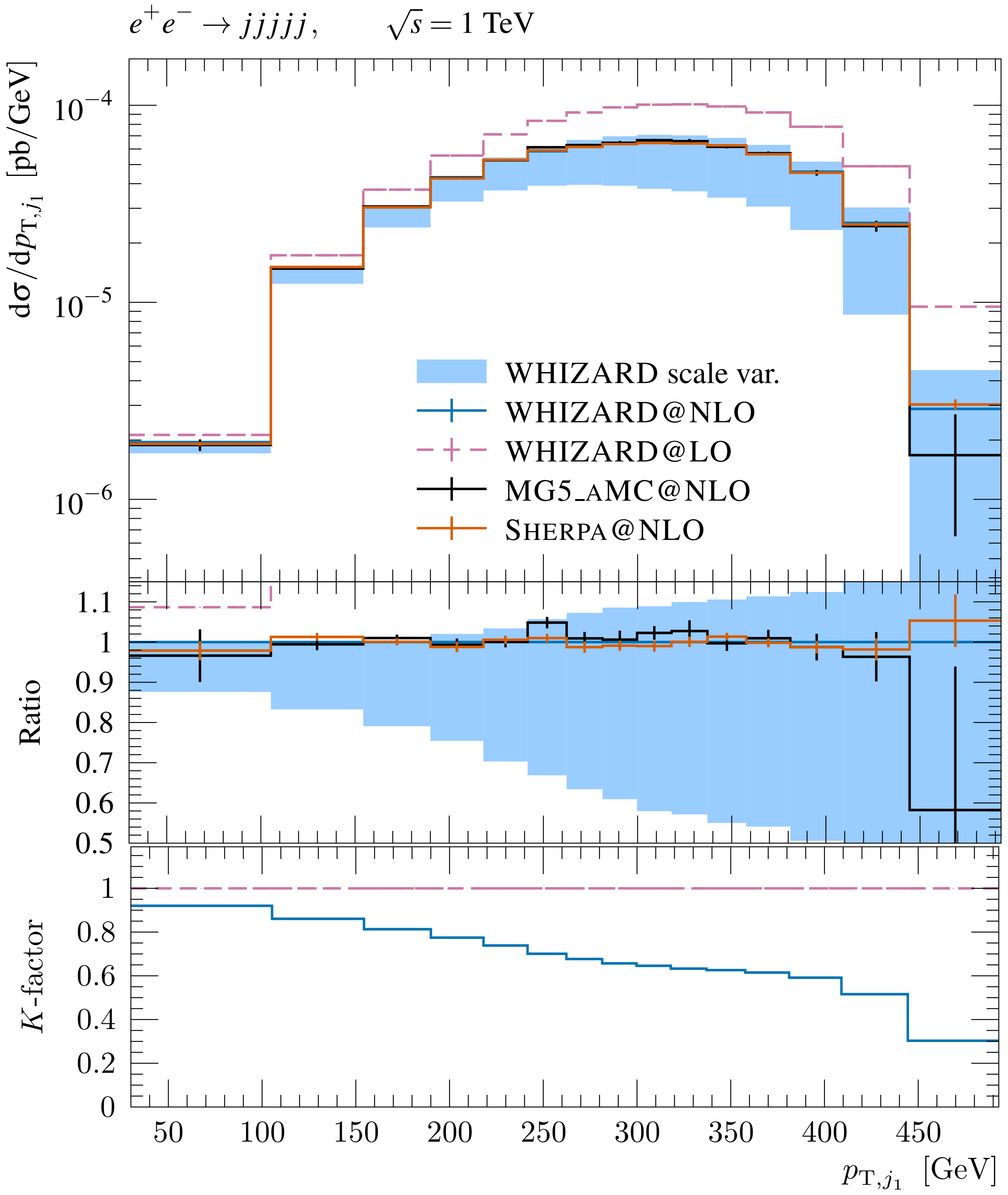
	MCSANCee[37]		WHIZARD+RECOLA			
$\sqrt{s}$ [GeV]	$\sigma^{\rm tot}_{\rm LO}$ [fb]	$\sigma^{\rm tot}_{\rm NLO}$ [fb]	$\sigma^{\rm tot}_{\rm LO}$ [fb]	$\sigma^{\rm tot}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]	$\sigma^{\rm sig}$ (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	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

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

pp @ 13 TeV, NLO QCD

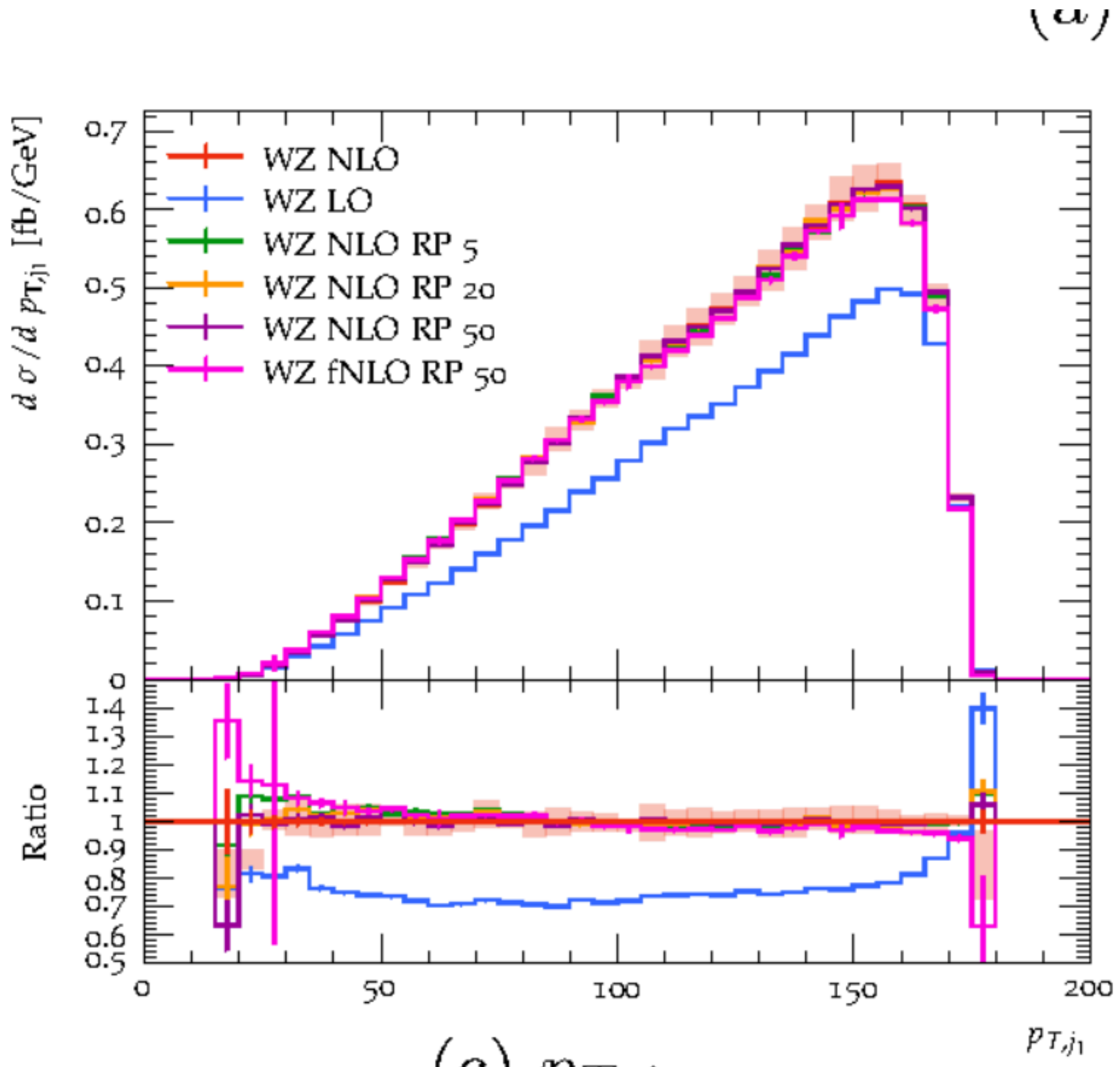


ee @ 1 TeV, NLO QCD



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

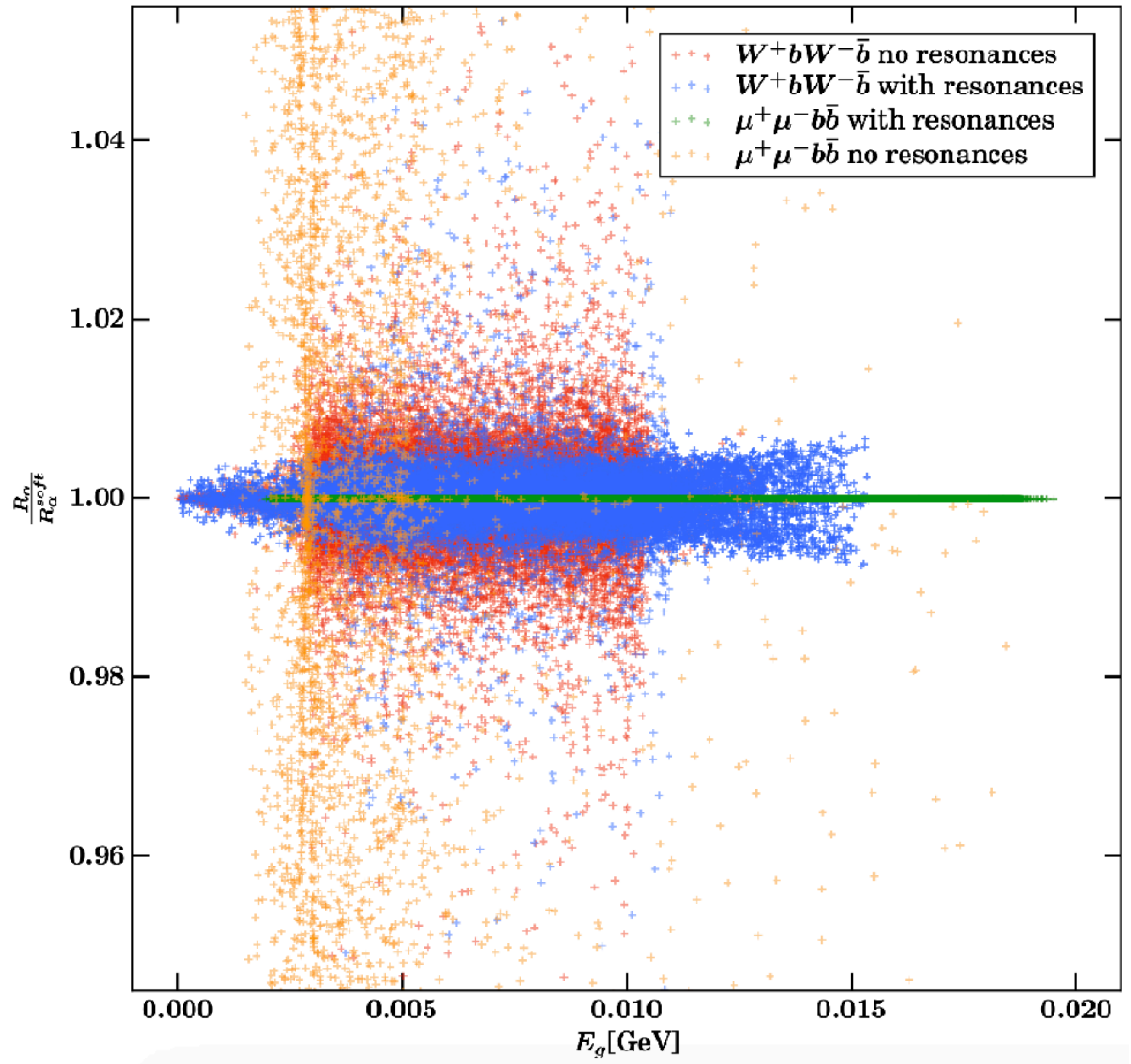
$$\mu_R = {H_T}/2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$



(c) p_{T,j_1}

N(N)LO Automation in MC — Going beyond

- MC NLO implementation relies on 2 building blocks: Subtraction (Catani-Seymour or Frixione/Kunszt/Soper)
- also: resonance-aware FKS subtraction   cf. Hežo/Nason, 1509.09071; Chokoufé, 2017
- Photon isolation, photon recombination, light-, b-, c-jet selection
- Covers also loop-induced processes (“LO”, virtual-squared)



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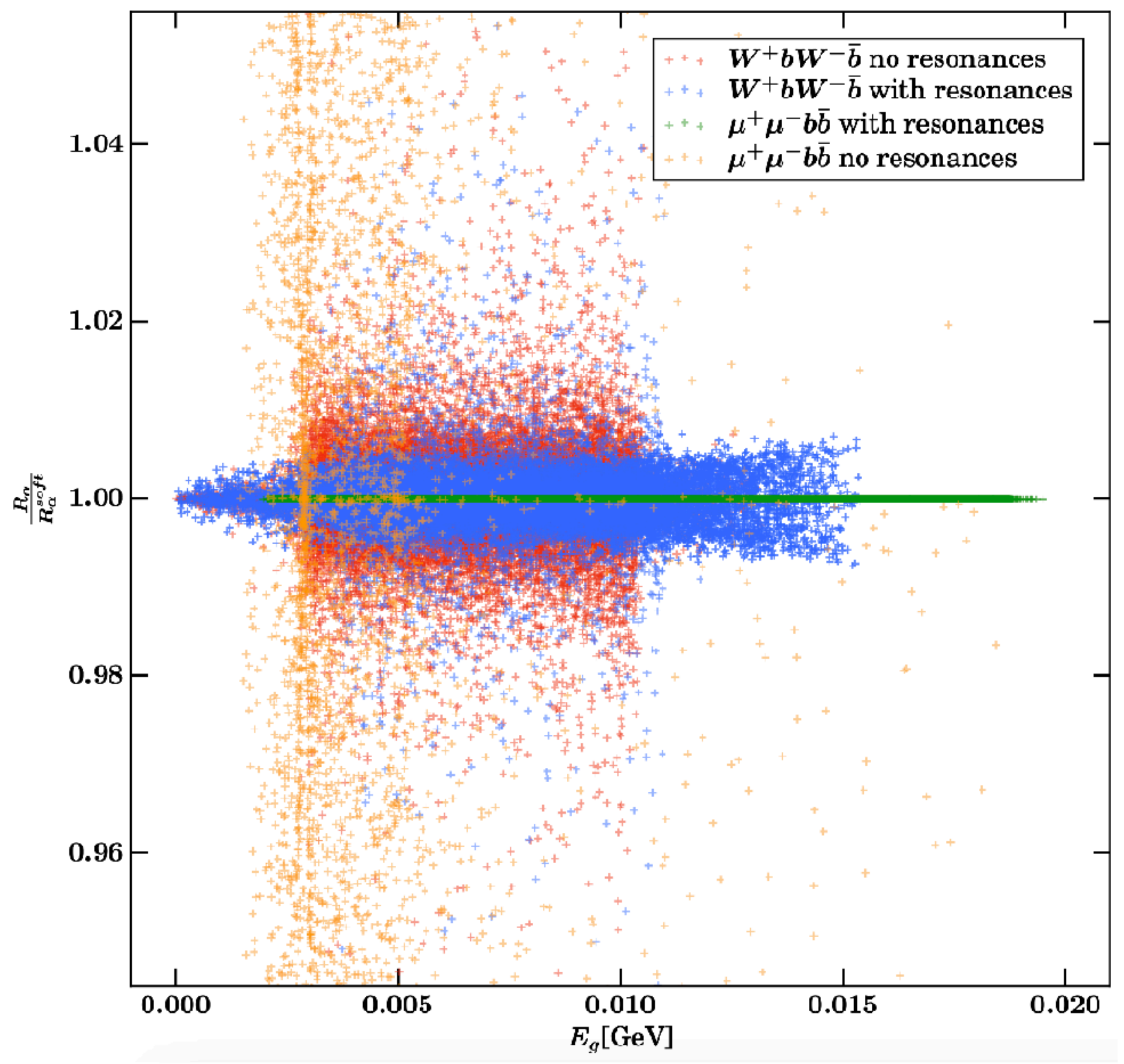

Two major bottlenecks to NNLO

- 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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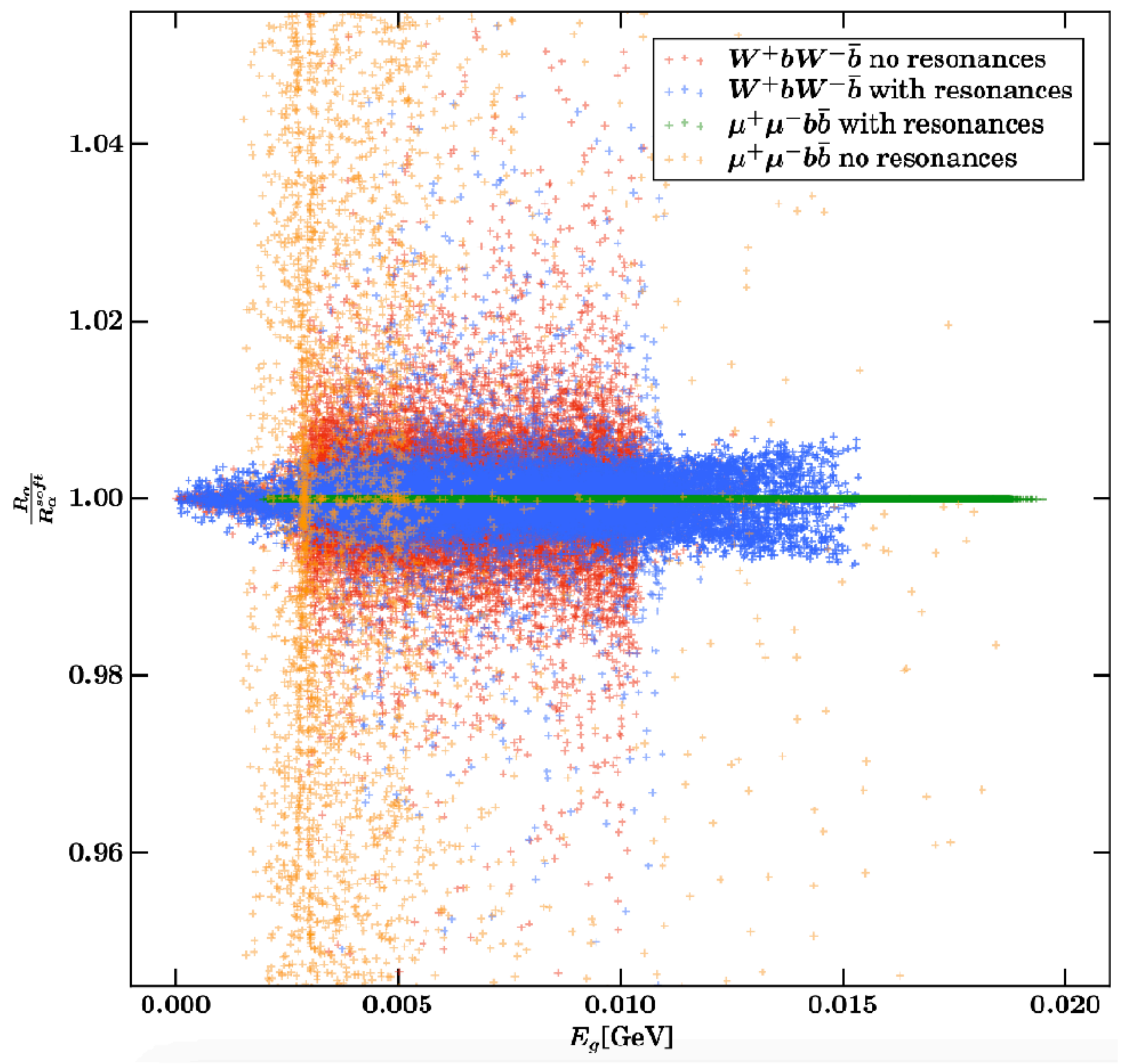

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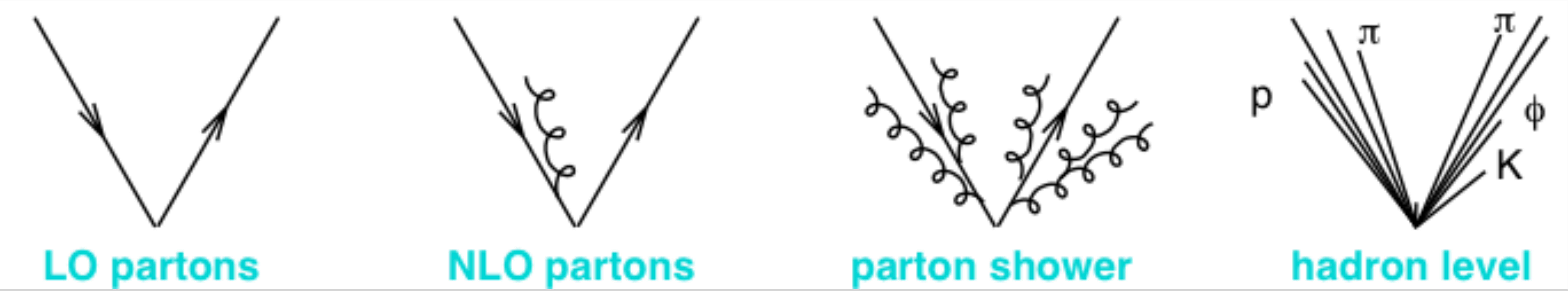
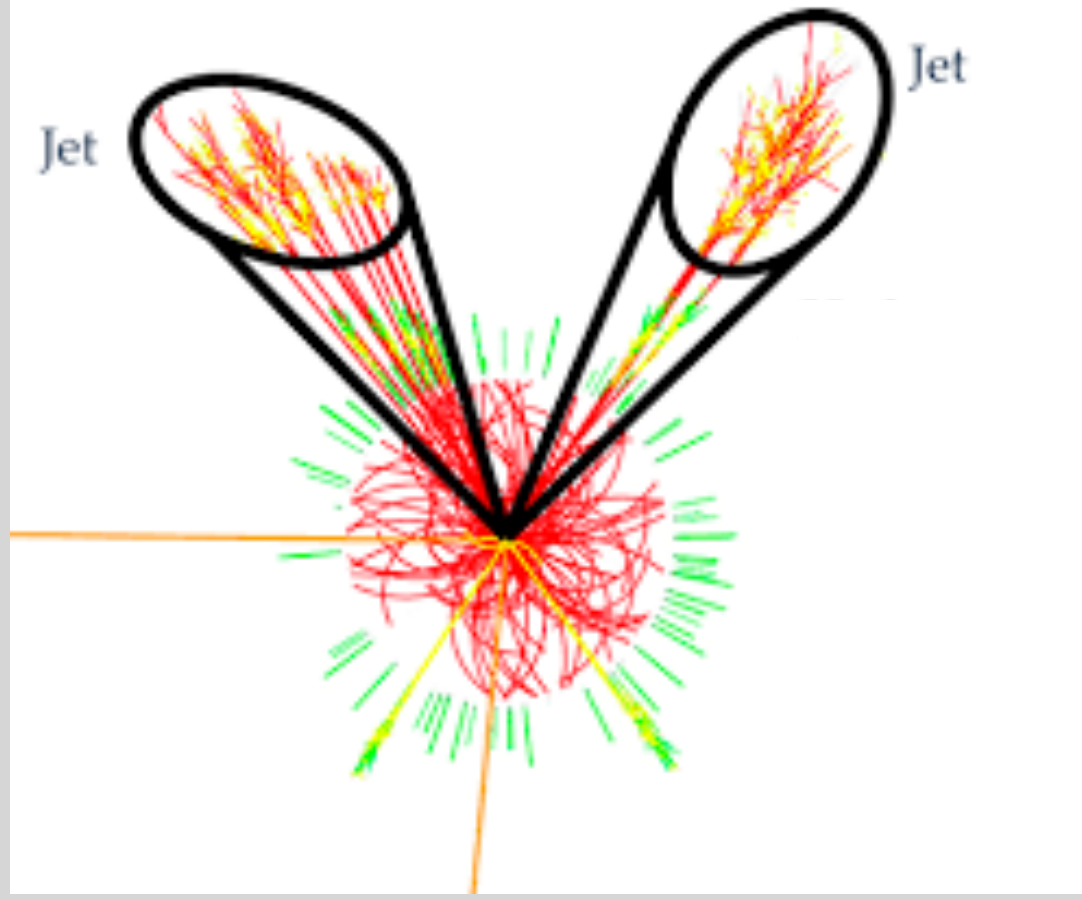
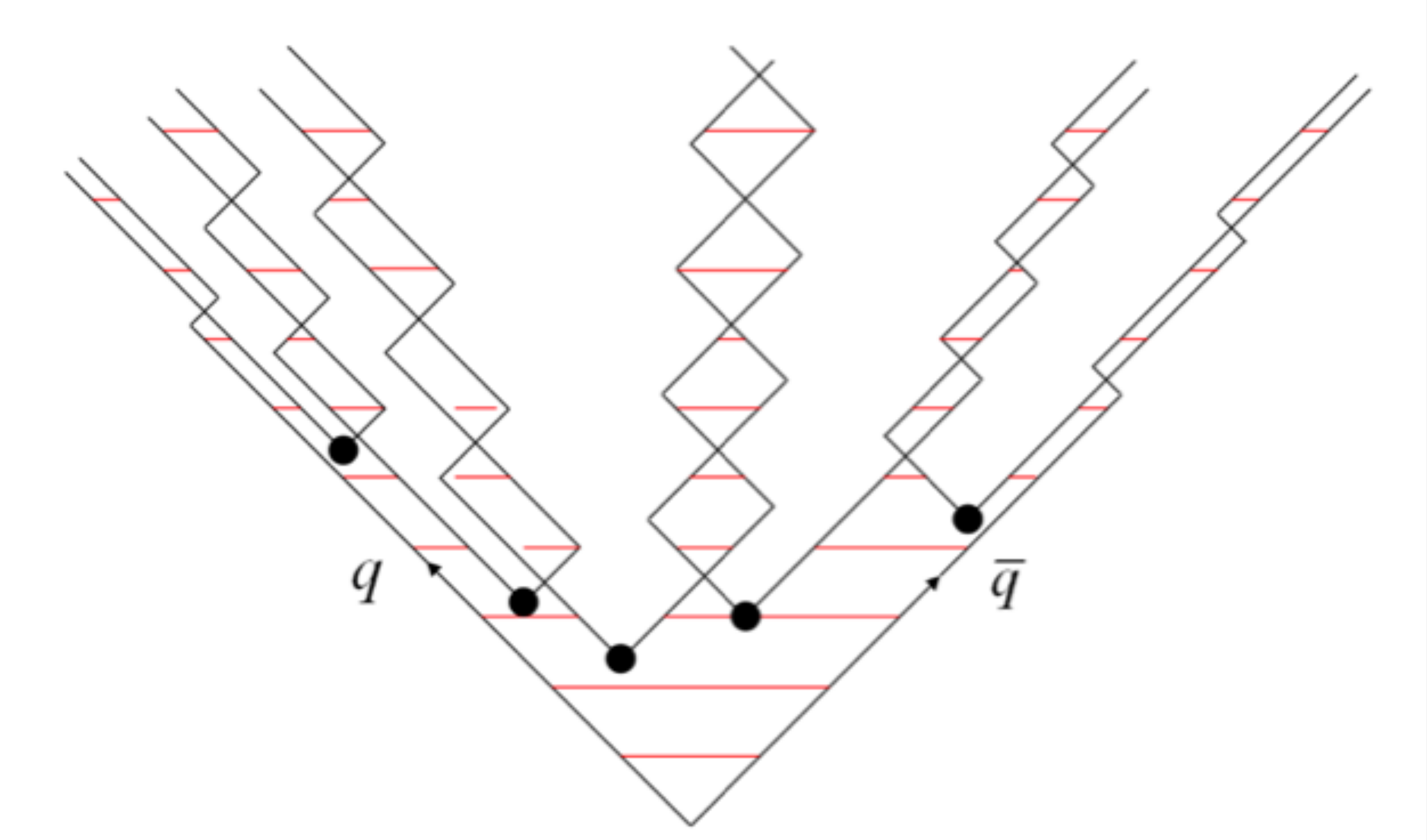
- ☐ IR pole treatment / subtraction CS, FKS, NS, Stripper, qT/sub-jettiness etc.

- ☑ 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

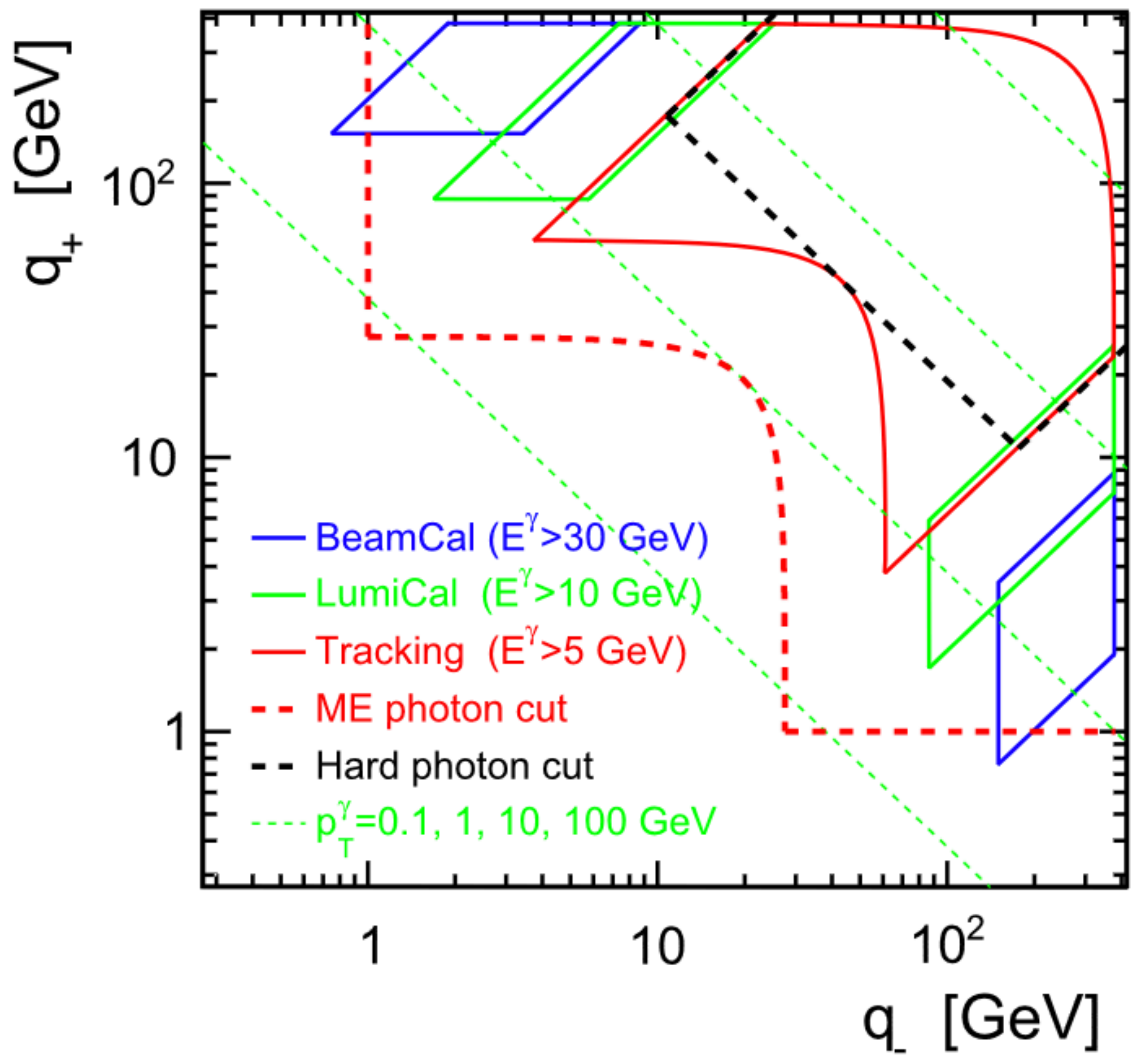
Parton Showers, Matching, Hadronization





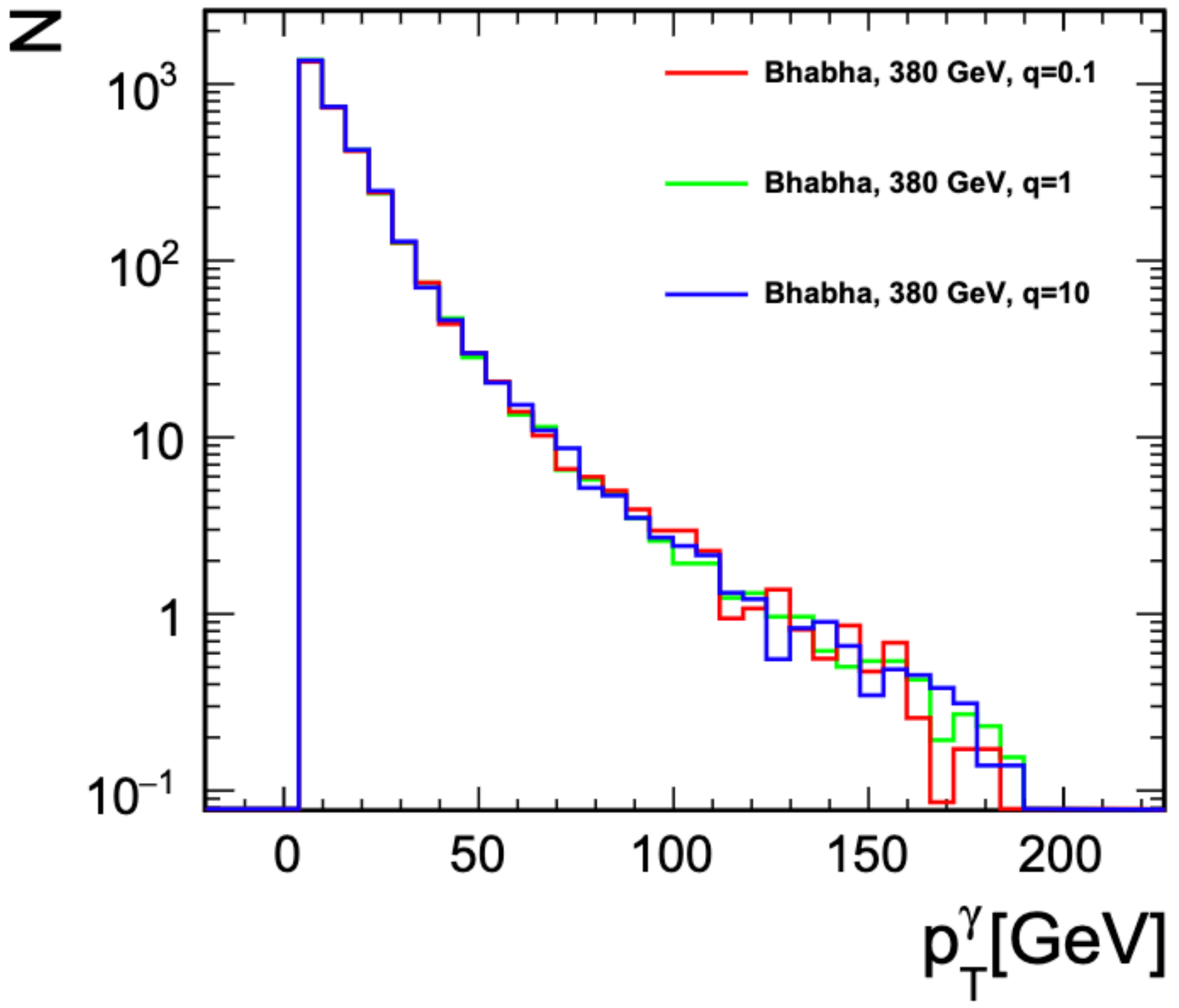


Exclusive photons



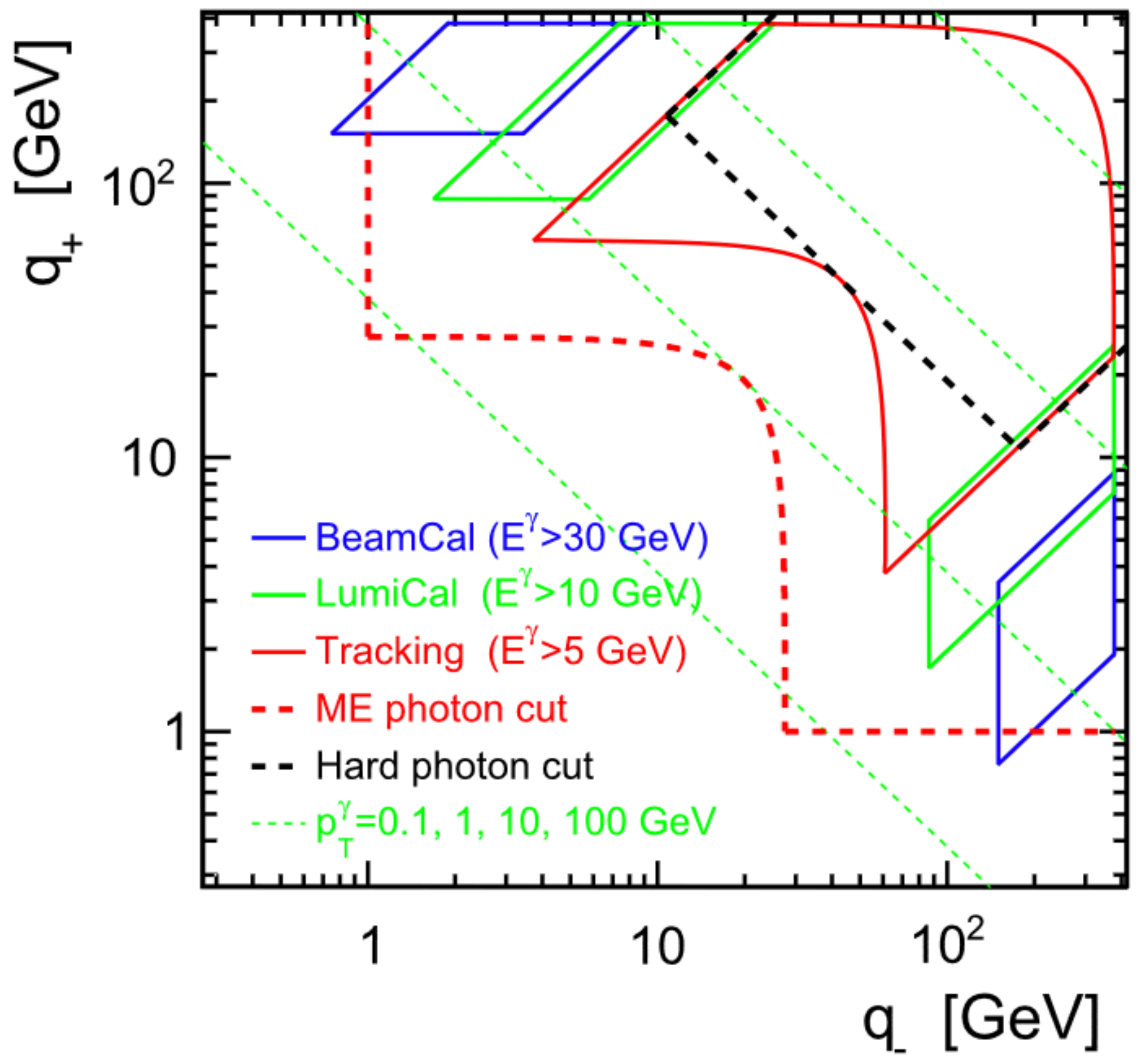
QED ISR [+FSR], matching

- 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



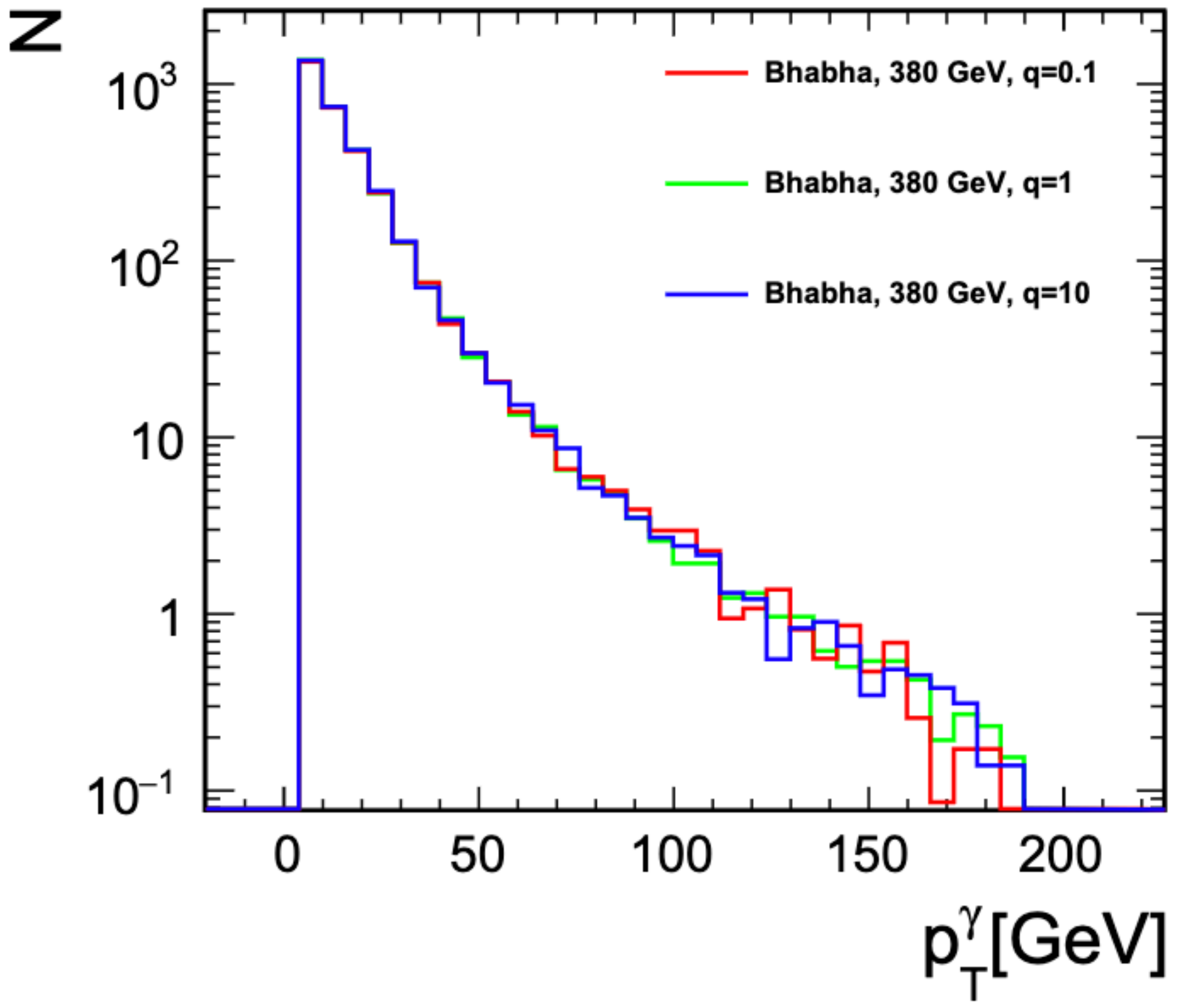
J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

Exclusive photons



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



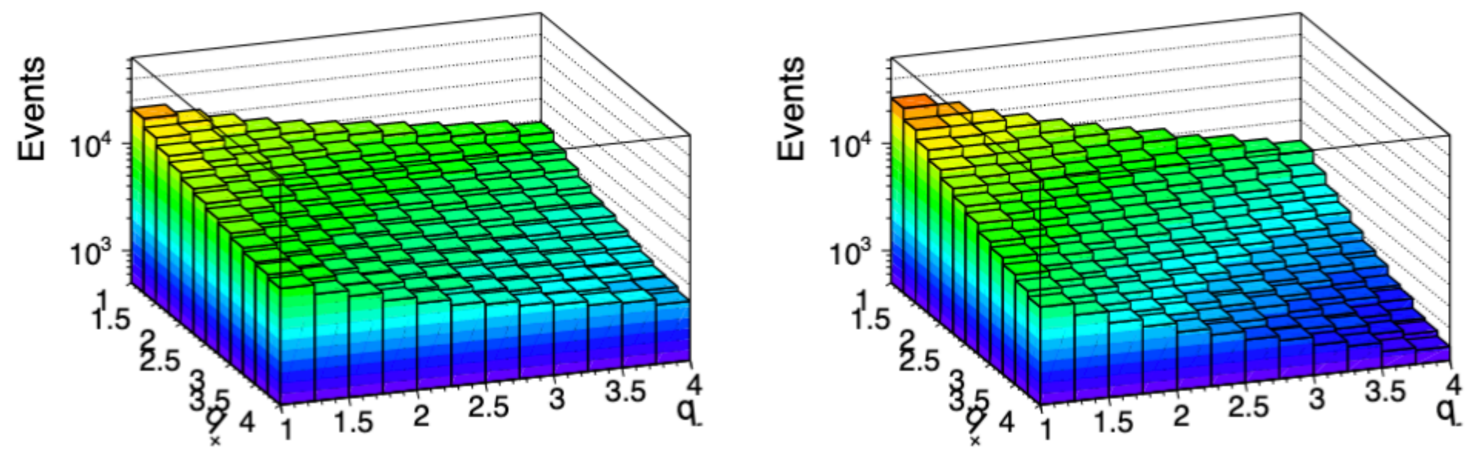
Full QED shower

- 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

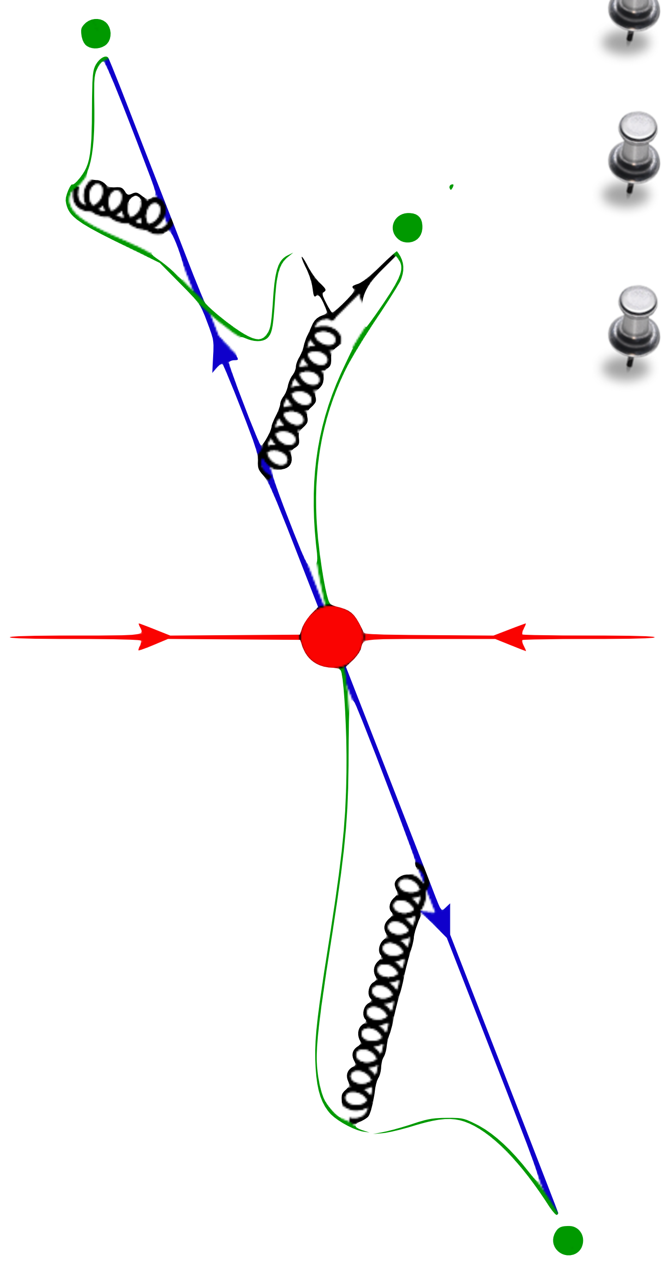
J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020



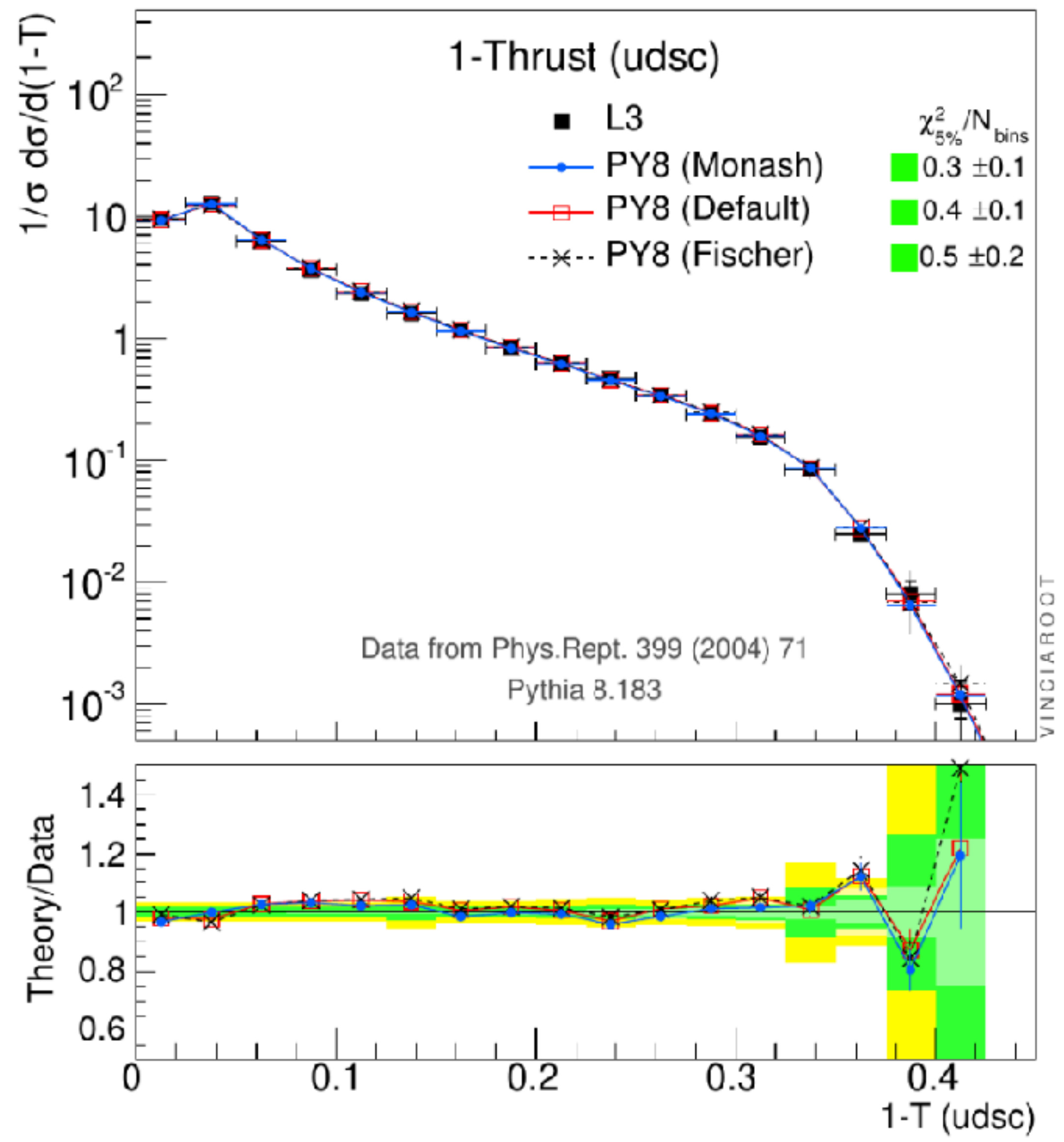
(a) Double EPA (b) Full matrix elements

Parton shower / hadronization

- Machinery of parton showers well advanced, recap of CERN workshop 04/2023
- Tuning: automated tools w/ built-in correlations (`Professor`, `AutoTunes`, `Apprentice`, ...)
- Global event shapes, α_s, charge multiplicity, hadron multiplicity
- Possible NLL parton showers (final state only!) for e^+e^- :



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



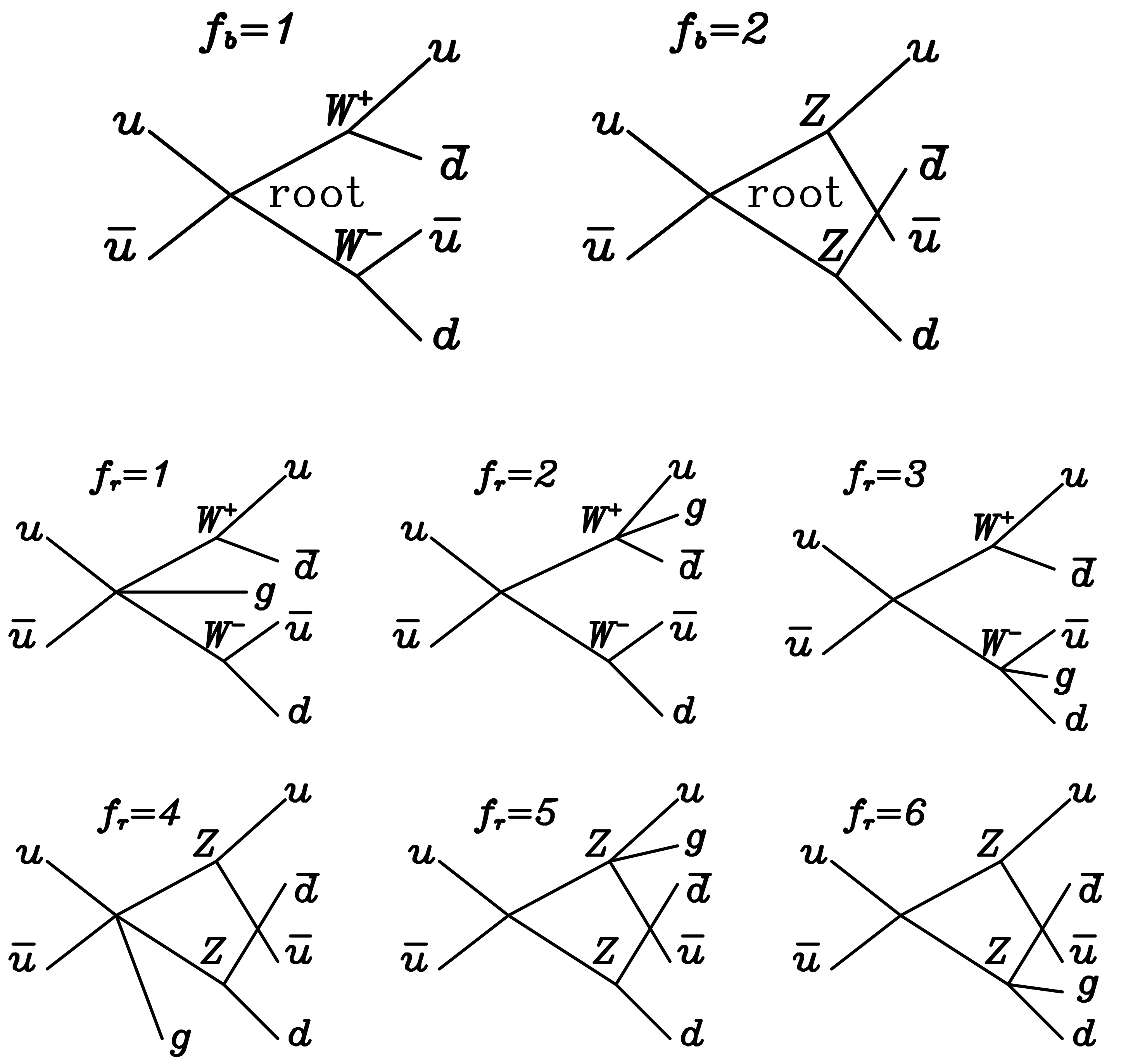
Talks by Jack Helliwell + Leif Gellersen

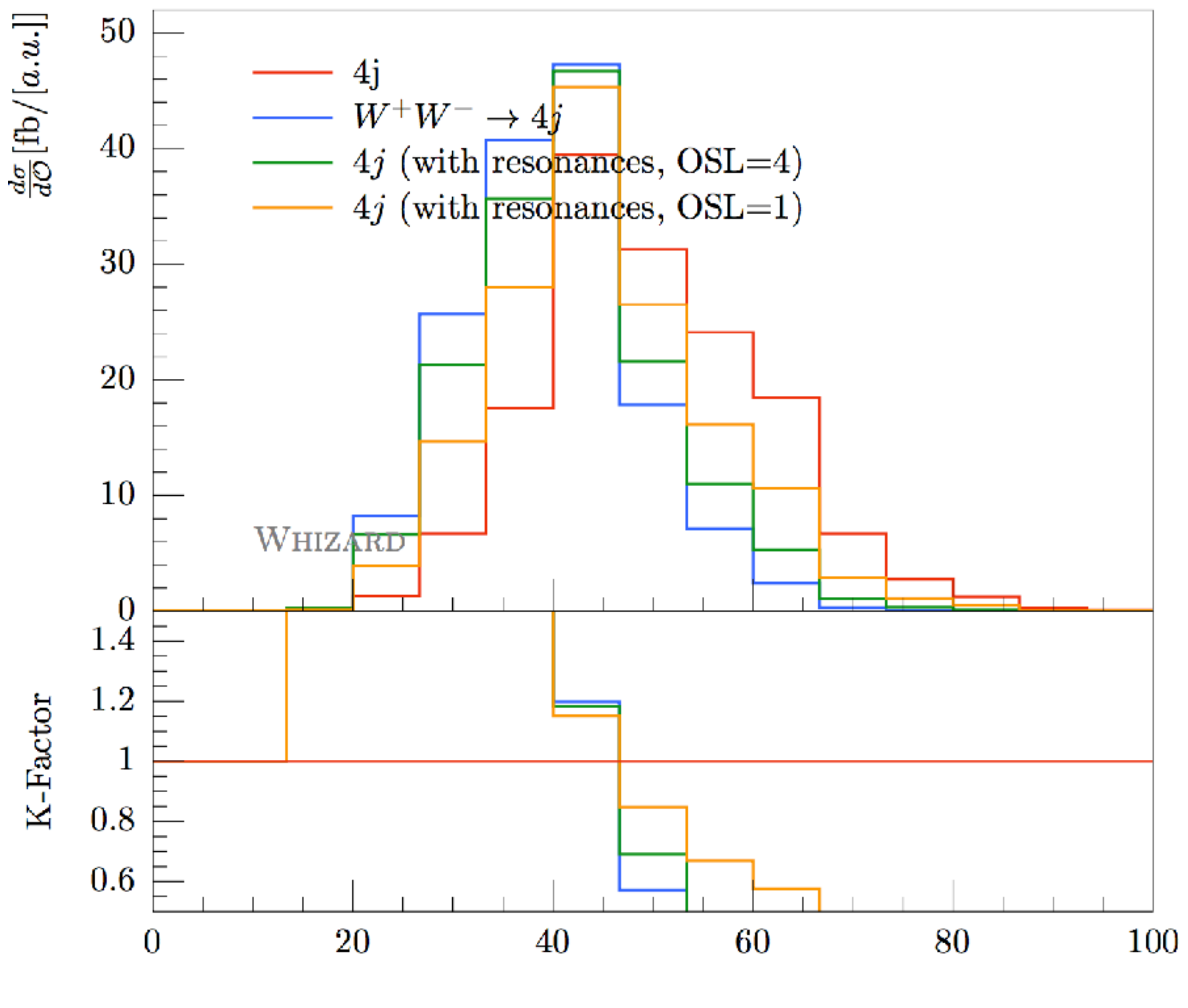
- Ongoing work towards NNLL showers, sub-leading color (FCC = full color correlations)
- NLO matching automated, different approaches, different error estimates;
- NNLO matching still process-dependent; also does not yet preserve NNLL accuracy
- Elephant in the room: fragmentation ⇒ no paradigm shift/quantum leap in last 30 years

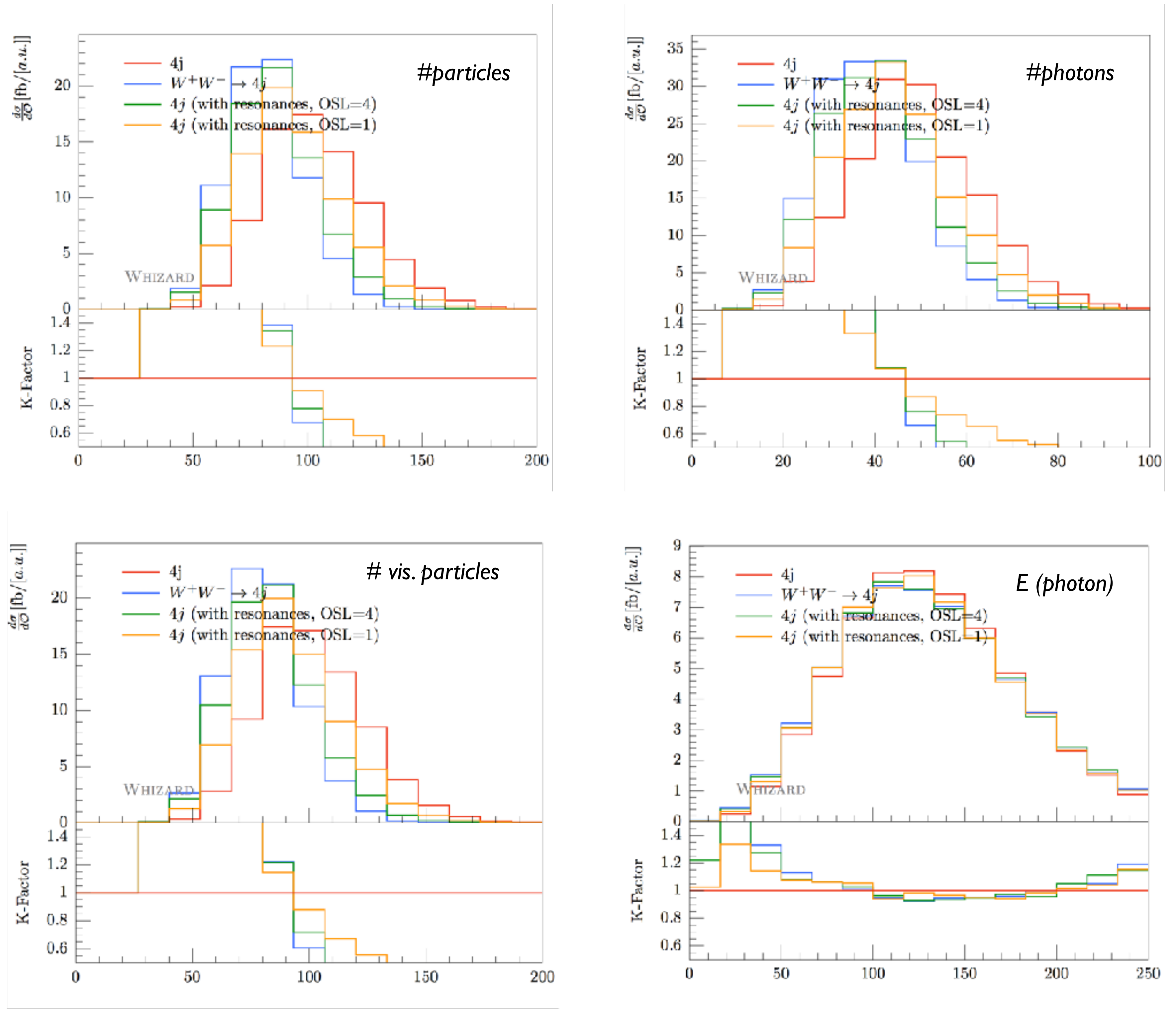
Gigantic clean data sets from Z pole and above will necessitate new models / theory

(Resonance) Matching to shower / hadronization

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



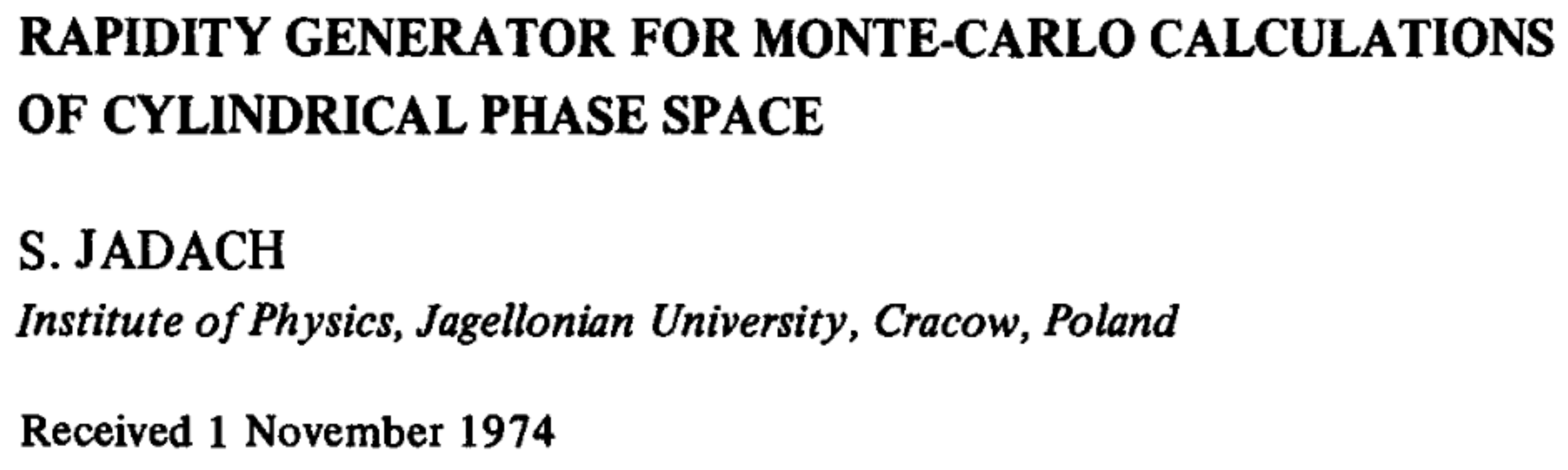




Dedicated tools for special processes

In memoriam: Staszek Jadach

Stanisław ("Staszek") Jadach, 1943 — 2023



RAPIDITY GENERATOR FOR MONTE-CARLO CALCULATIONS OF CYLINDRICAL PHASE SPACE

S. JADACH

Institute of Physics, Jagellonian University, Cracow, Poland

Received 1 November 1974

Potentially a severe impact on the development of LEP legacy Monte Carlos, YFS-style tools (the whole KKMC, YFS-WW/ZZ, Photos, Tauola, BHLumi/BHWide !

Important rôle of Belle 2 program: active usage of many of these programs!

Luminometry

Bhabha cross sect. depends on detector acceptance angles

$$\sigma_{Bh} \simeq 4\pi\alpha^2 \left(\frac{1}{t_{\rm min}} - \frac{1}{t_{\rm max}} \right) = 4\pi\alpha^2 \left(\frac{t_{\rm max} - t_{\rm min}}{\bar{t}^2} \right), \quad \bar{t} = \sqrt{t_{\rm min} t_{\rm max}}$$

Machine	$\theta_{\rm min} \div \theta_{\rm max}$ [mrad]	$\sqrt{s}$ [GeV]	$\bar{t}/s \simeq \bar{\theta}^2/4$	$\sqrt{\bar{t}}$ [GeV]
LEP	28÷50	M_Z	3.5×10^{-4}	1.70
FCCee	64÷86	M_Z	13.7×10^{-4}	3.37
FCCee	64÷86	240	13.7×10^{-4}	8.9
FCCee	64÷86	350	13.7×10^{-4}	13.0
ILC	31÷77	500	6.0×10^{-4}	12.2
ILC	31÷77	1000	6.0×10^{-4}	24.4
CLIC	39÷134	3000	13.0×10^{-4}	108

[Maciej Skrzypek; Brussels Topical Workshop]

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Current BHLUMI precision forecast for FCCee			
Type of correction / Error	M_Z (2019) [1]	240 GeV	350 GeV [2]
(a) Photonic $\mathcal{O}(L_e\alpha^2)$	0.027%	0.032%	0.033%
(b) Photonic $\mathcal{O}(L_e^3\alpha^3)$	0.015%	0.026%	0.028%
(c) Vacuum polariz.	0.009%	0.020%	0.022%
(d) Light pairs	0.010%	0.015%	0.015%
(e) Z and s-channel γ exchange	0.09%	0.25% (0.034%)	0.5% (0.07%)
(f) Up-down interference	0.009%	0.010%	0.010%
(g) Technical Precision	[0.027%]		
Total	10×10^{-4}	25×10^{-4} (6×10^{-4})	50×10^{-4} (8.7×10^{-4})

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(c) Vacuum polariz.	0.6×10^{-4}	1.0×10^{-4}	1.1×10^{-4}
(d) Light pairs	0.5×10^{-4}	0.4×10^{-4}	0.4×10^{-4}
(e) Z and s-channel γ exch.	0.1×10^{-4}	$1.0 \times 10^{-4(*)}$	$1.0 \times 10^{-4(*)}$
(f) Up-down interference	0.1×10^{-4}	0.09×10^{-4}	0.1×10^{-4}
Total	1.0×10^{-4}	1.5×10^{-4}	1.6×10^{-4}

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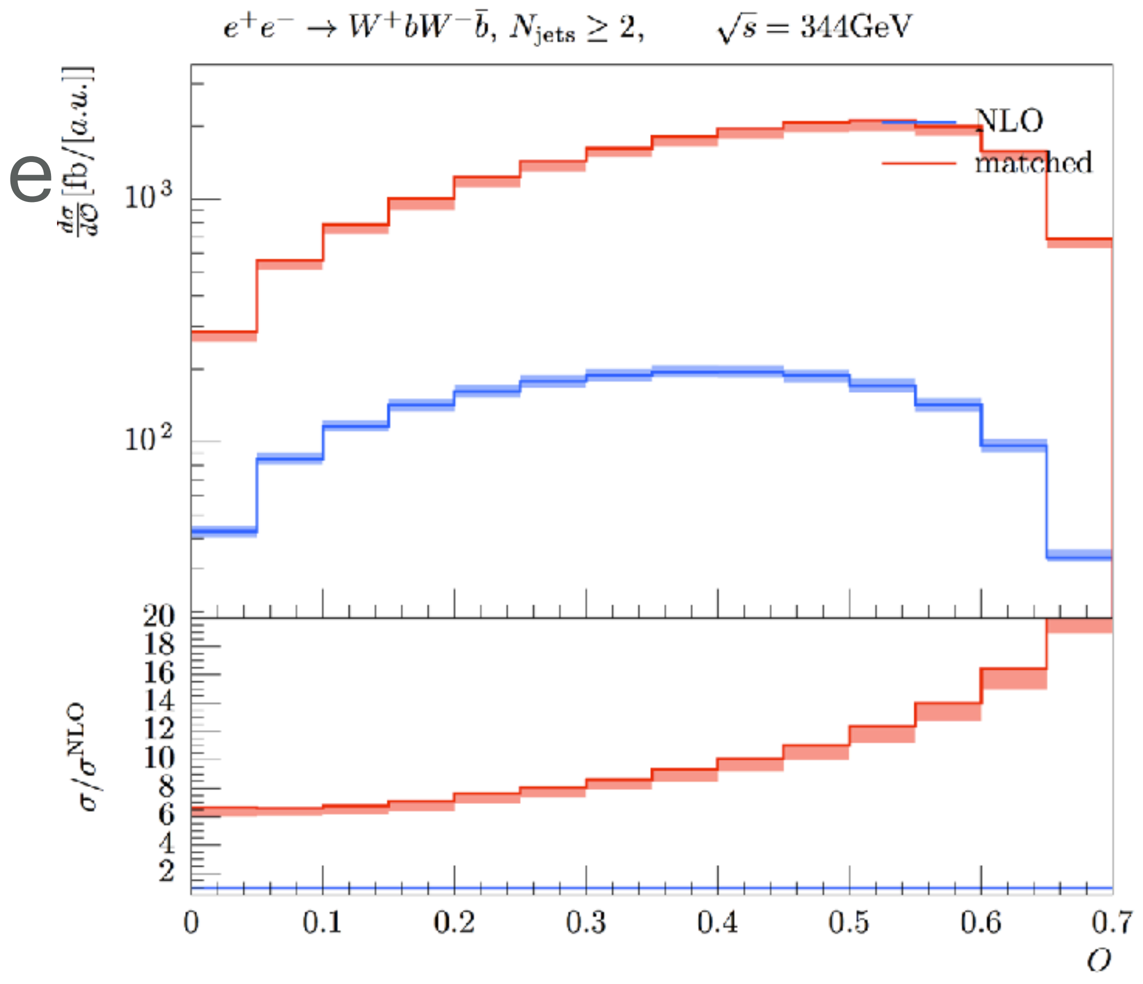
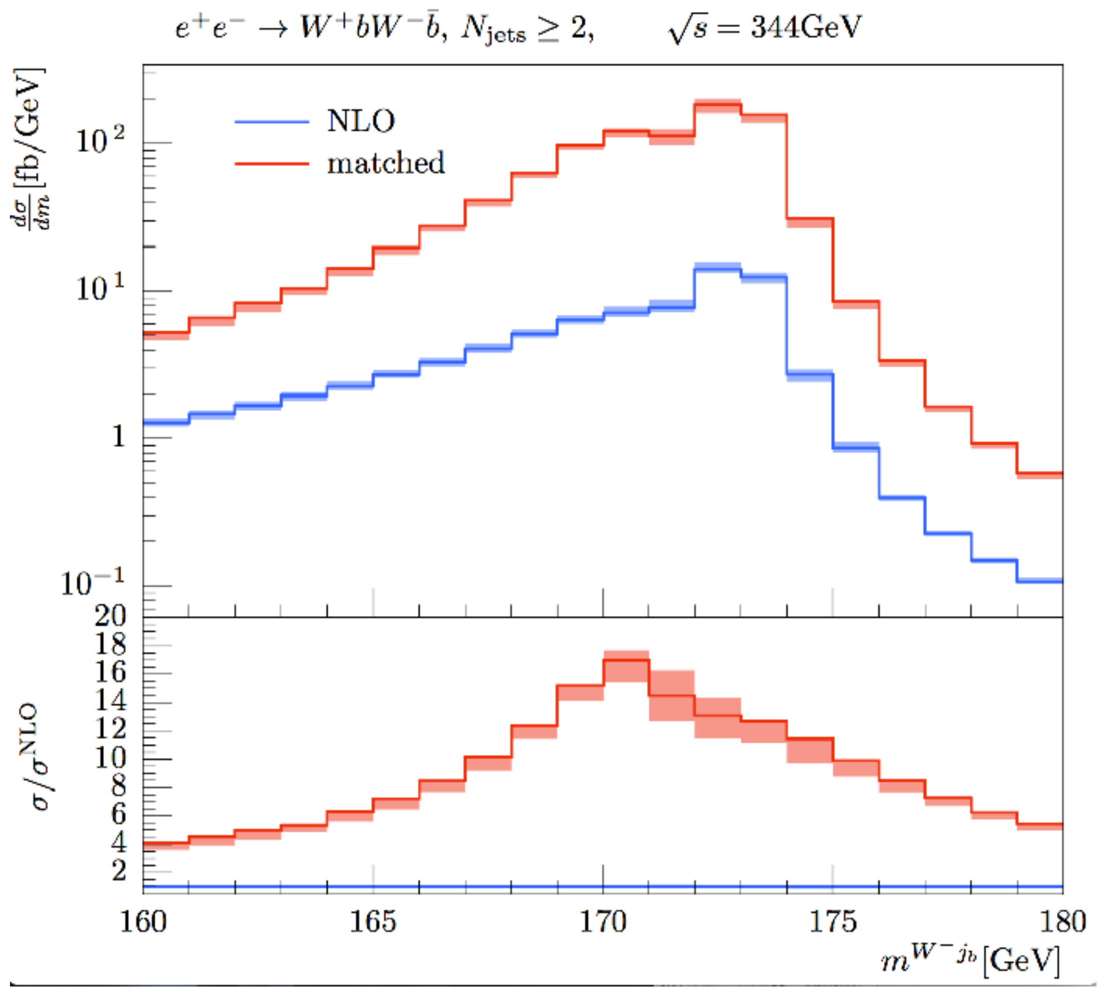
Total	1.0×10^{-4}	1.5×10^{-4}	1.6×10^{-4}

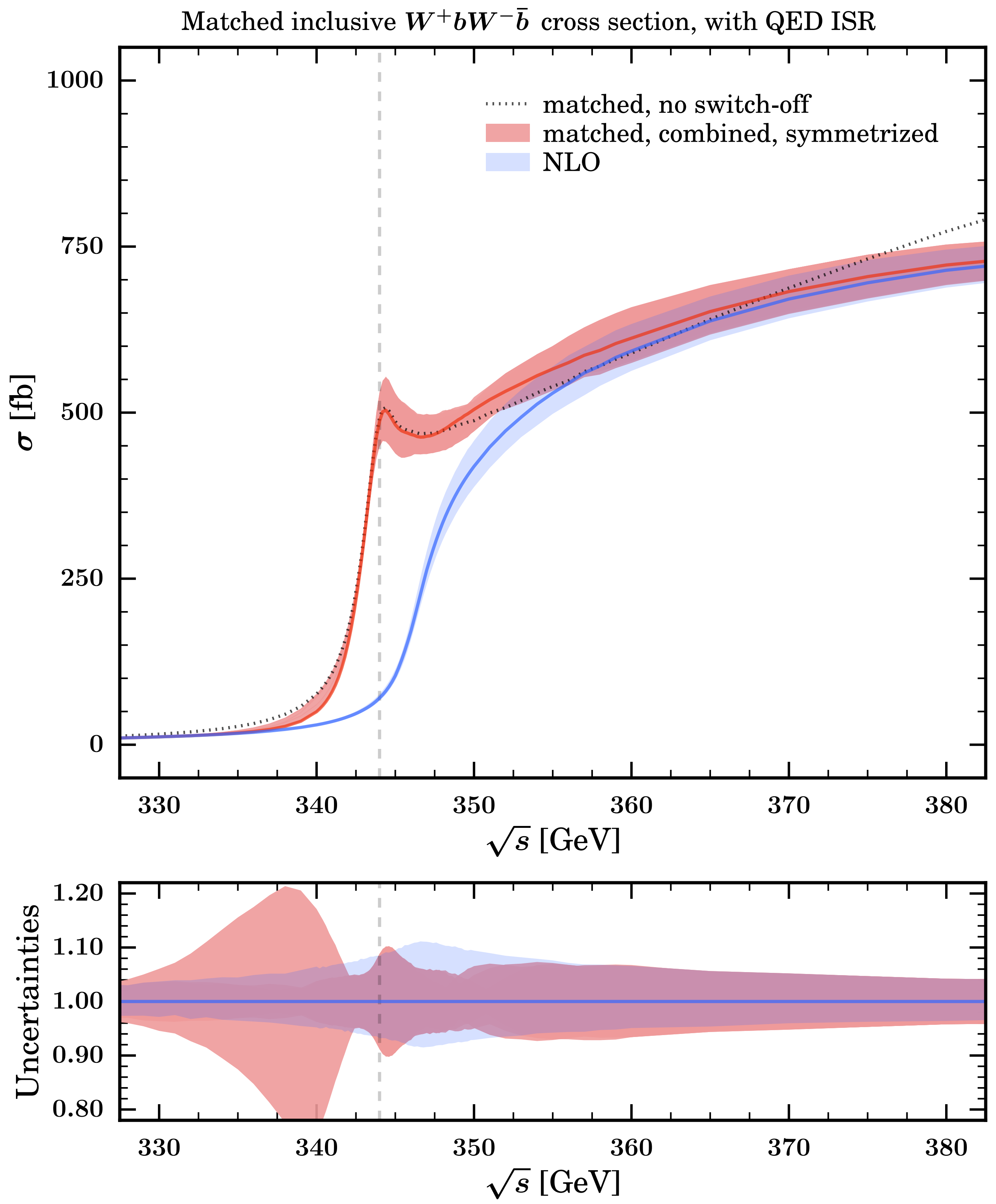
- Technical precision needs 2nd code: `BHLumi` vs. `BabaYaga` (NNLO in hard process possible)
- Major ingredients: hadronic vacuum polarization, EW corrections, light fermion pairs
- Inclusion of 4f, 4f + γ, 5f, 6f backgrounds necessary at matrix element level

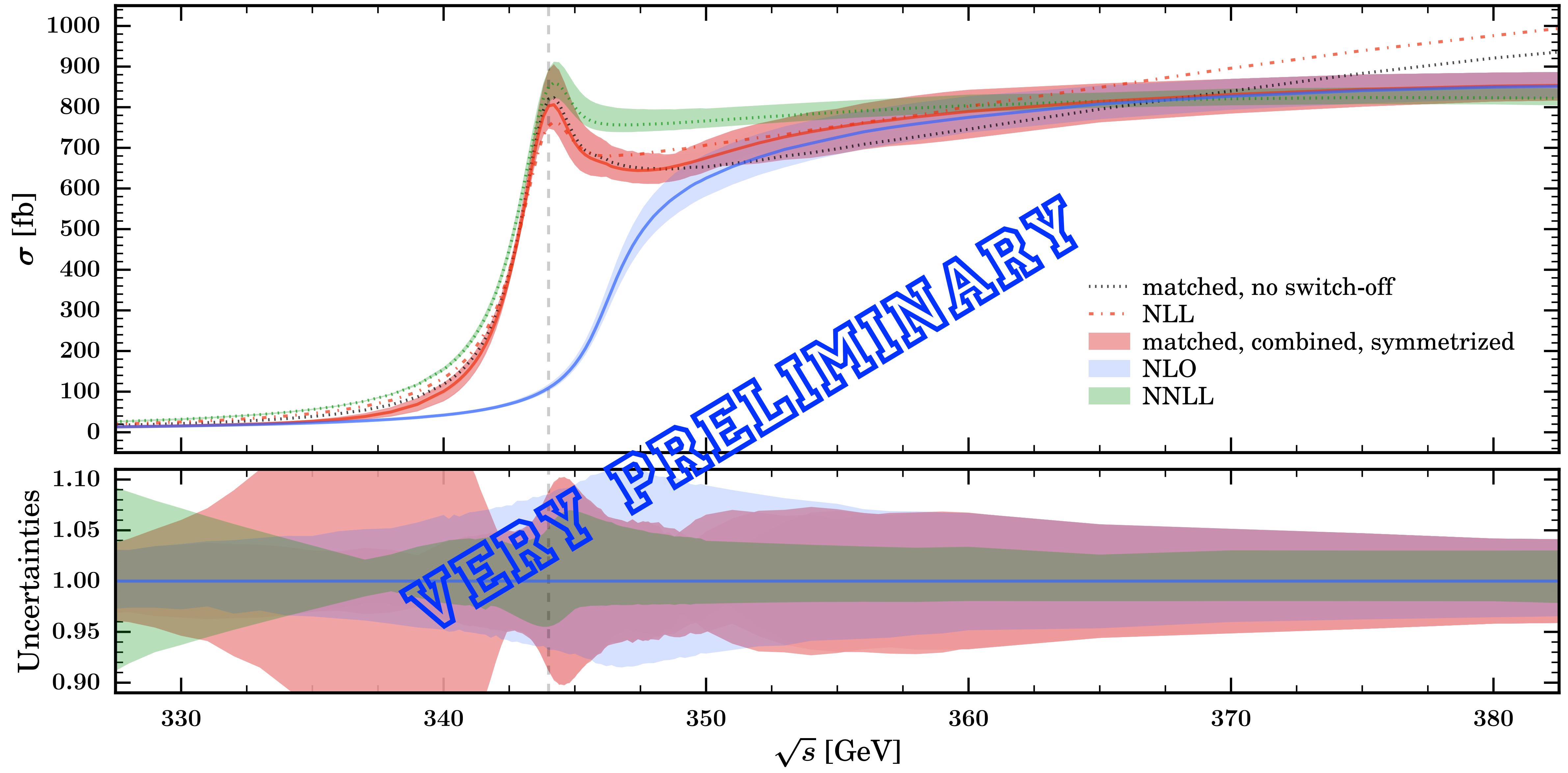
Top Threshold Simulation

- Differential distributions at top threshold, systematics
- Exclusive Top threshold NLL-NLO QCD matched available
- Recent improvement in axial form factor matching
- Technical issues (person power)
- Improvement needed (e.g. shower matching)







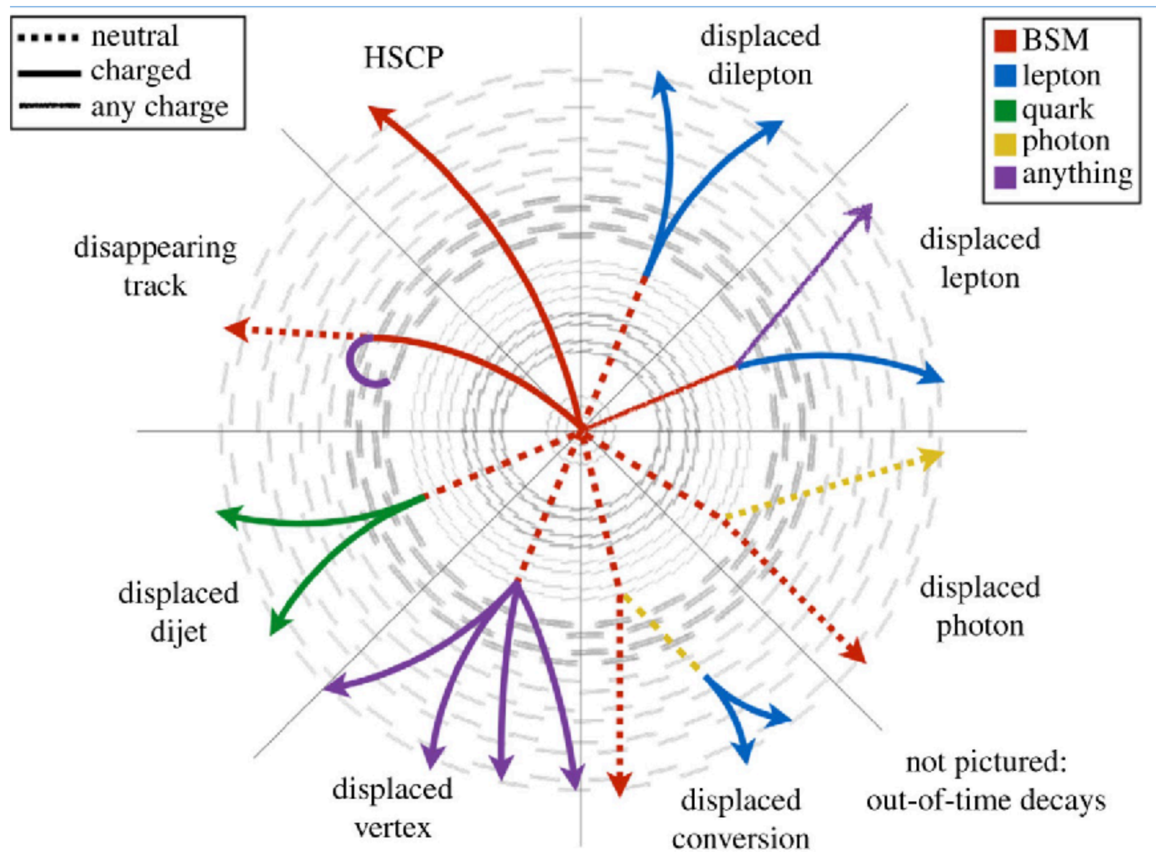


BSM Modelling in Simulation

BSM Models: UFO magic

- BSM models 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

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



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)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Conclusions & Outlook

- Monte-Carlo event generators implement *all* necessary SM and BSM physics
- Modularity and redundancy of codes very important
- Fixed-order NLO QCD+EW for SM and NLO QCD BSM under control (mostly)
- First attempts to go to NNLO for QED (with certain caveats)
- LL/NLL ePDF in collinear factorization vs. YFS soft/eikonal factorization
- Matching prescriptions for exclusive photon radiation
- 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!
- Will depend a lot on support on young researchers/theorists working
- Also need for dedicated MCs, e.g. for luminosity measurement ($e^+e^- \to e^+e^-, \gamma\gamma$)
- Not to forget: QCD showers + fragmentation [Higgs/EW/top factories will boost to new precision!]

Conclusions & Outlook

Stefano Frixione, 2nd ECFA Generator WS

Optimistic conclusions

A lot remains to be done (e.g. exclusive simulations), but we are a generation away: there is plenty of time

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Optimistic conclusions

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Pessimistic conclusions

A lot remains to be done (e.g. exclusive simulations), but we are a generation away: there is ~~plenty of~~ too much time