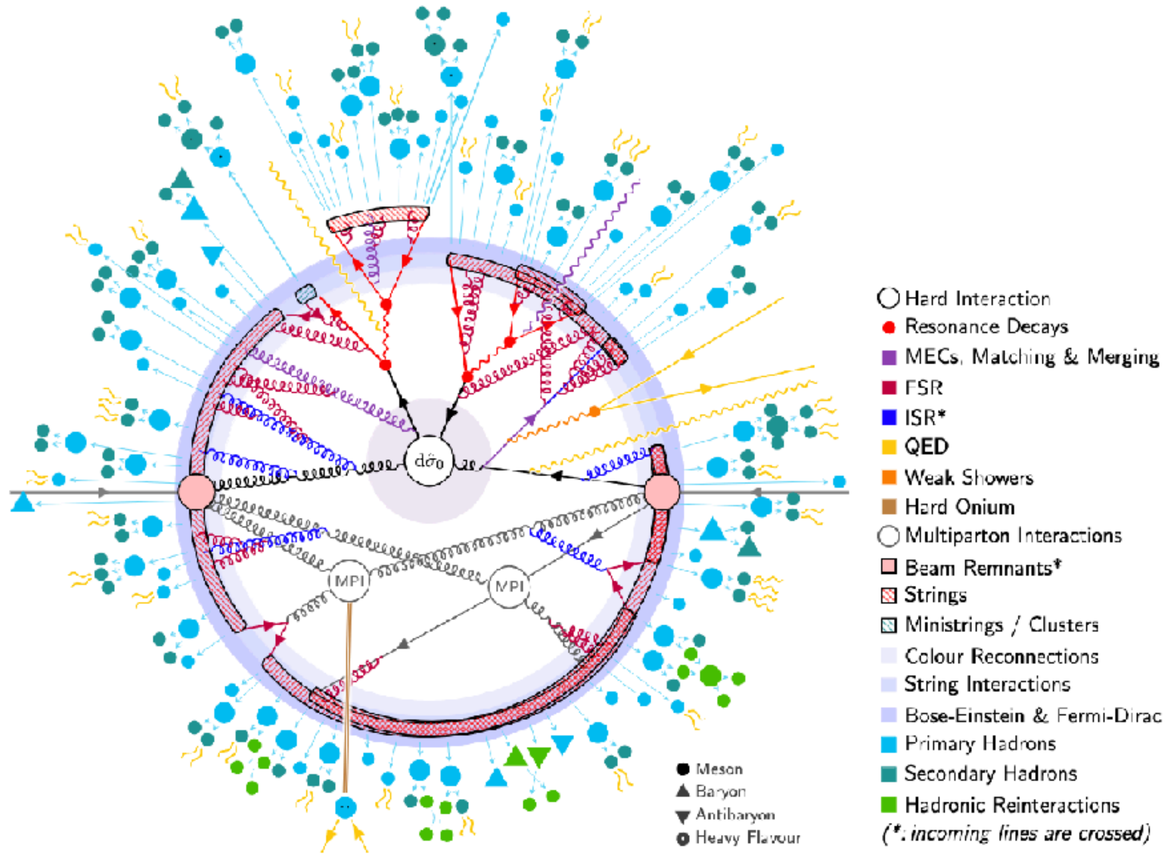
WG2/WG1 Monte Carlo generators



DESY. HELMHOLTZ

NARODOWE CENTRUM NAUKI Opus

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Jürgen R. Reuter

Great to be back at Paestum

September 1992

My first and only visit to Paestum, while ...

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September 1992

My first and only visit to Paestum, while ...

LEP was still running on the Z pole !

LEP Operation in 1992 with a 90⁰ optics

R. Bailey, T. Bohl, F. Bordry, H. Burkhardt, K. Cornelis, P. Collier, B. Desforges, A. Faugier, V. Hatton, M. Jonker, M. Lamont, J. Miles, G. de Rijk and H. Schmickler

CERN
CH-1211 Geneva 23, Switzerland

Abstract

The optics fc
60⁰ to 90⁰ a

The Energy Calibration of LEP in 1992

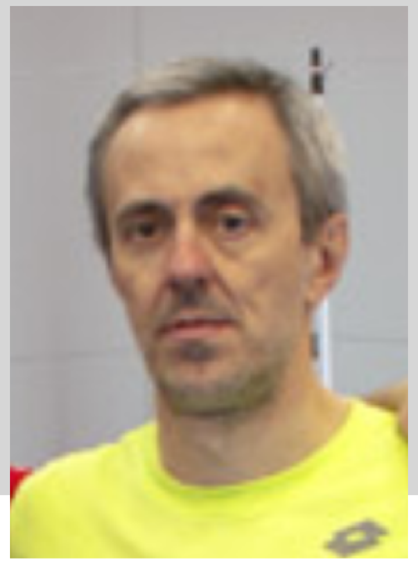
The working group on LEP energy

L. Arnaudon[1], R. Assmann[2], J. Billan[1], W. Birr[1], A. Blondel[3], G. Bobbink[4], F. Bordry[1], H. Burkhardt[1], B. Dehning[1], A. Faugier[1], J. Gascon[5], A. Grant[1], J. L. Harton[6], V. Hatton[1], C. M. Hawkes[1], K. N. Henrischen[1], A. Hofmann[1], R. Jacobsen[1], M. Koratzinos[7], J. P. Koutchouk[1], G. Musolino[1], S. Myers[1], R. Olsen[1], J. Panman[1], E. Peschardt[1], M. Placidi[1], D. Plane[1], G. Quast[8], P. Renton[1,9], L. Rolandi[1], R. Schmidt[1], H. Wachsmuth[1], J. Wenninger[1].

date	time	week	T_{16} [°C]	$E_{pol} - E_{FD}$ [MeV]	$E_{pol} - E_{FD}$ T-corr. [MeV]
13.9.92	15:42	37	24.15	-37.4 ± 1.0	-34.1 ± 1.3
14.9.92	7:20	37	24.15	-34.8 ± 2.0	-31.5 ± 2.2

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 $\Longrightarrow$ Conveners: Patrizia Azzi Fulvio Piccinini Dirk Zerwas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- Setting the stage: simulation tools, MCs, software frameworks

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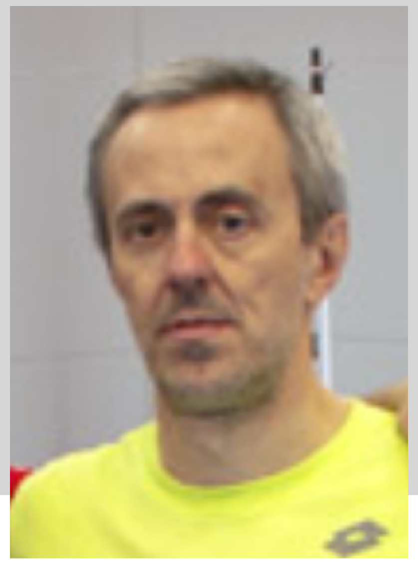


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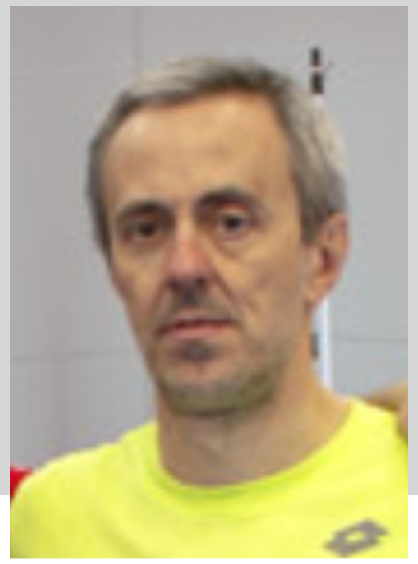


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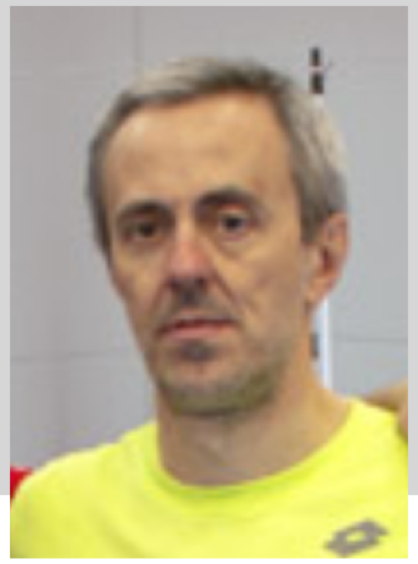


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- CERN WS "Parton Showers for Future e^+e^- colliders
  Apr 24-28, 2023 https://indico.cern.ch/event/1233329
- $\gtrsim$ 120 participants, roughly 80 at CERN
- Focus: perturbative and non-perturbative QCD

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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1. Beam simulation / luminosity spectra / polarization
2. QED: ePDFs vs. YFS, 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/QED/EW showers, fragmentation (!)
7. Special processes & tools: (Bhabha) luminometry, top/WW threshold, WW etc.
8. Specialized topics: event formats & software frameworks
9. Efficiency, speed, sustainability [left out for time reasons]
10. Launch of MC validation effort

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LEP tradition !

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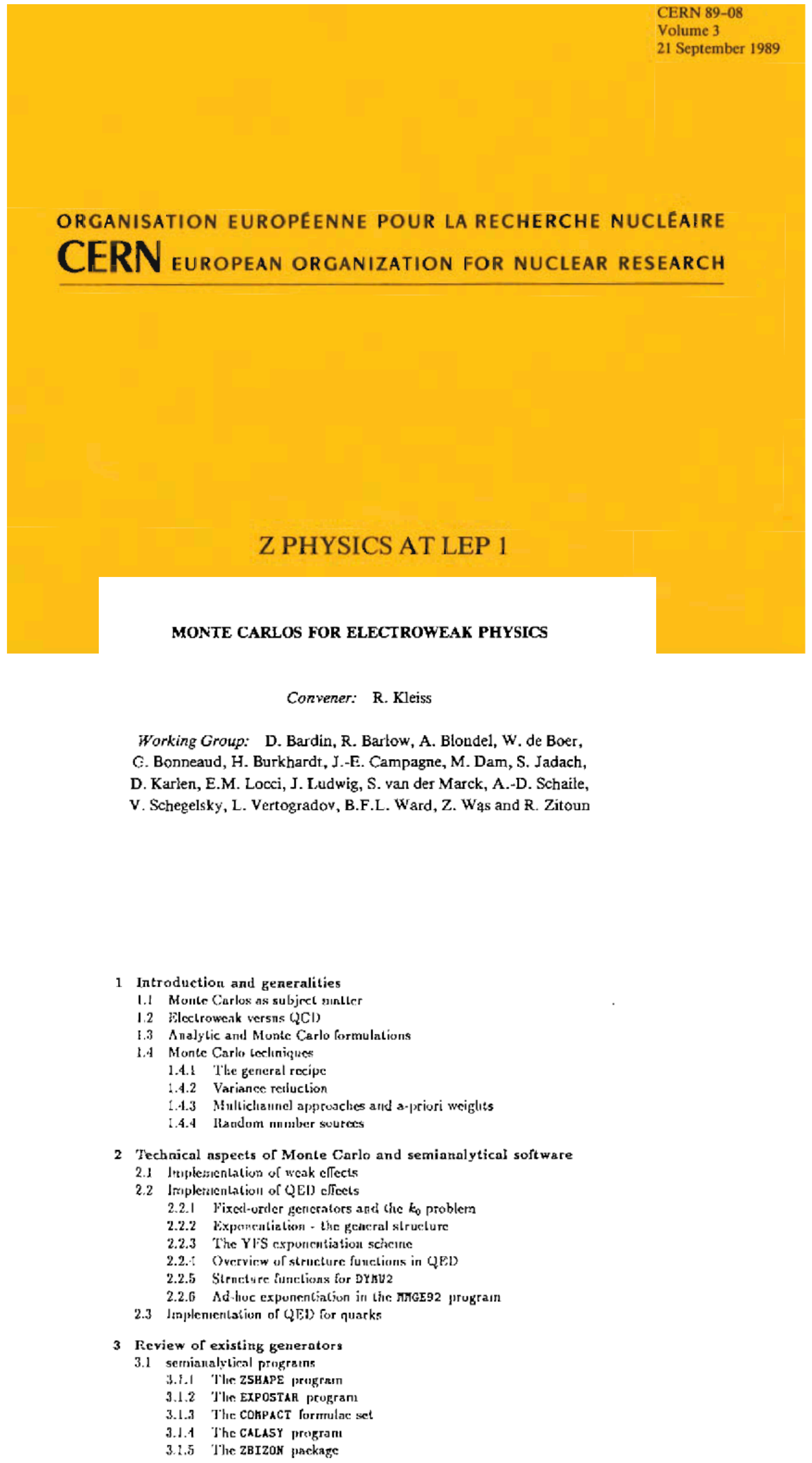

CERN 89-08
Volume 3
21 September 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

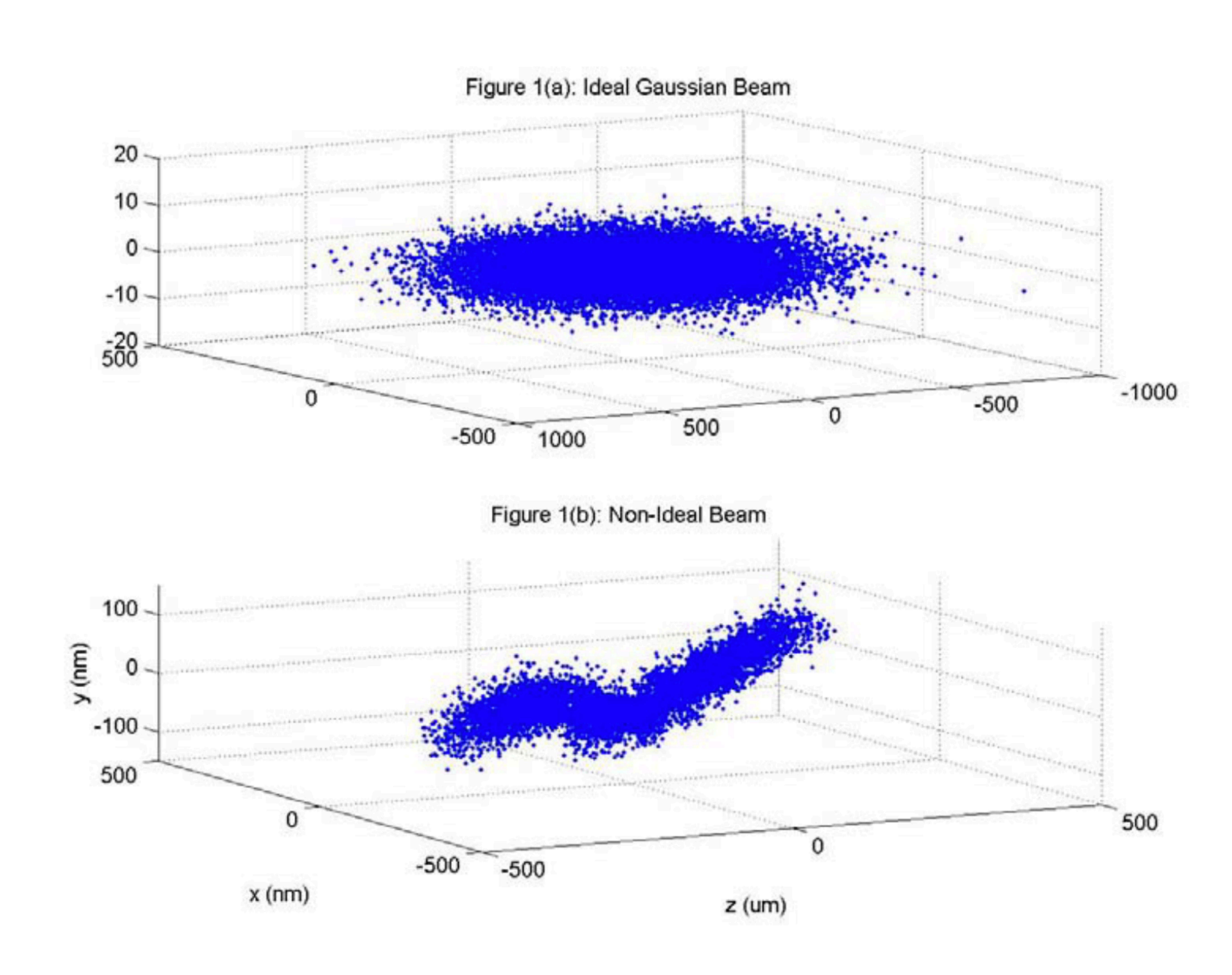
Z PHYSICS AT LEP 1

MONTE CARLOS FOR ELECTROWEAK PHYSICS

Convener: R. Kleiss

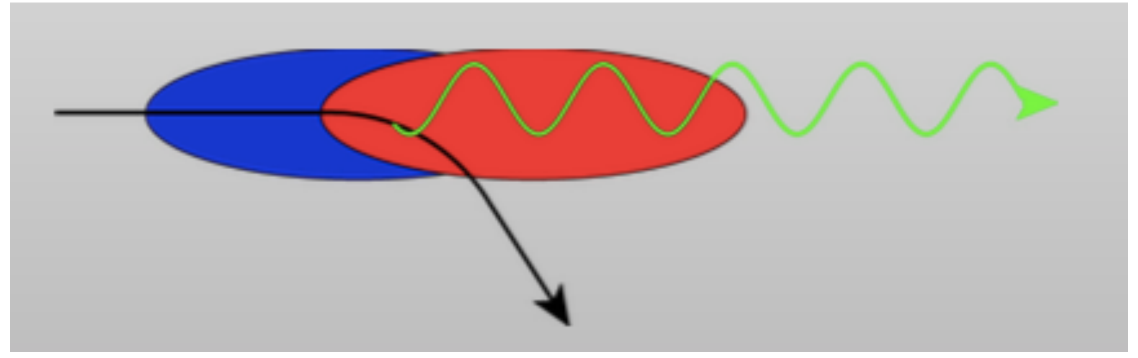
Working Group: D. Bardin, R. Barlow, A. Blondel, W. de Boer, G. Bonneaud, H. Burkhardt, J.-E. Campagne, M. Dam, S. Jadach, D. Karlen, E.M. Locci, J. Ludwig, S. van der Marck, A.-D. Schaile, V. Schegelsky, L. Vertogradov, B.F.L. Ward, Z. Was and R. Zitoun

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 $\oplus$ power law) — Avail.: (✔)
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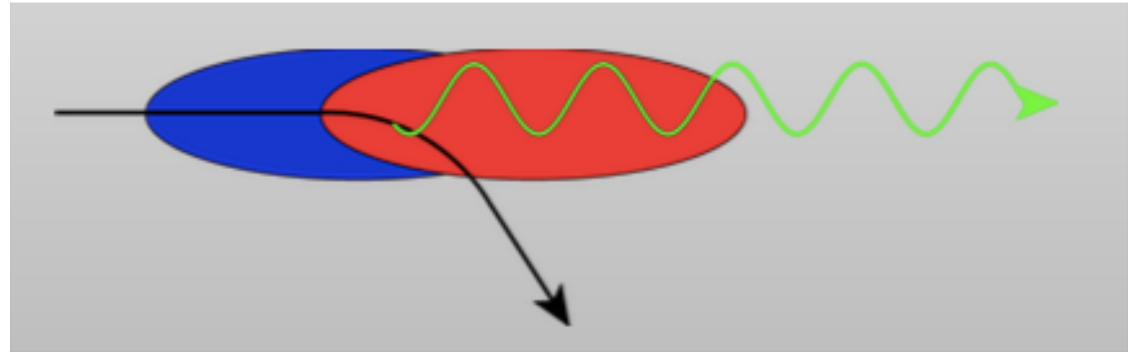

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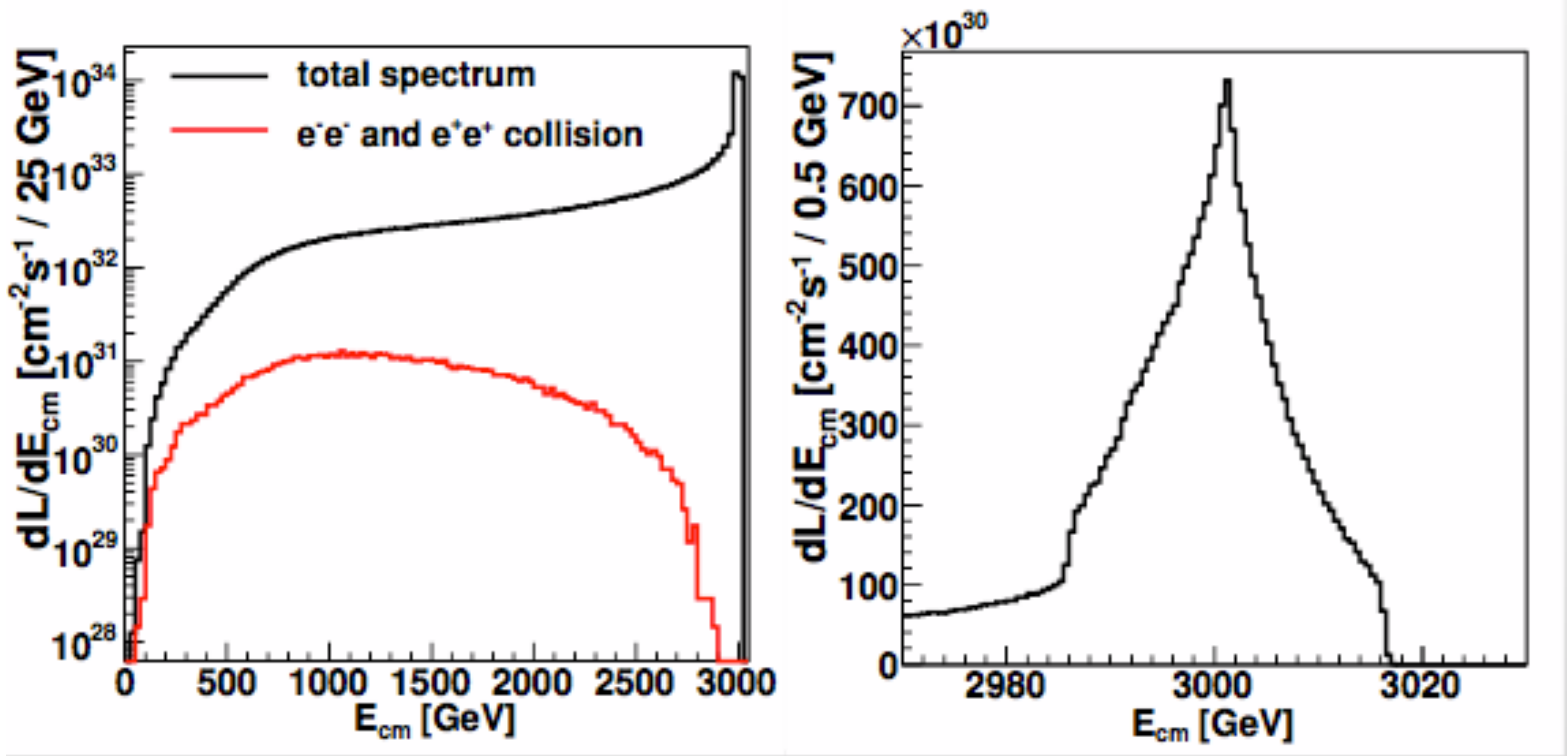

Dalena/Esbjerg/Schulte [LCWS 2011]

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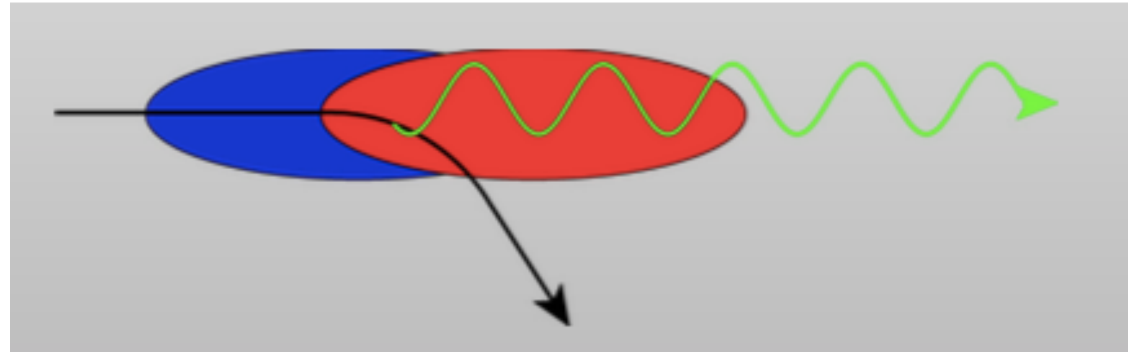

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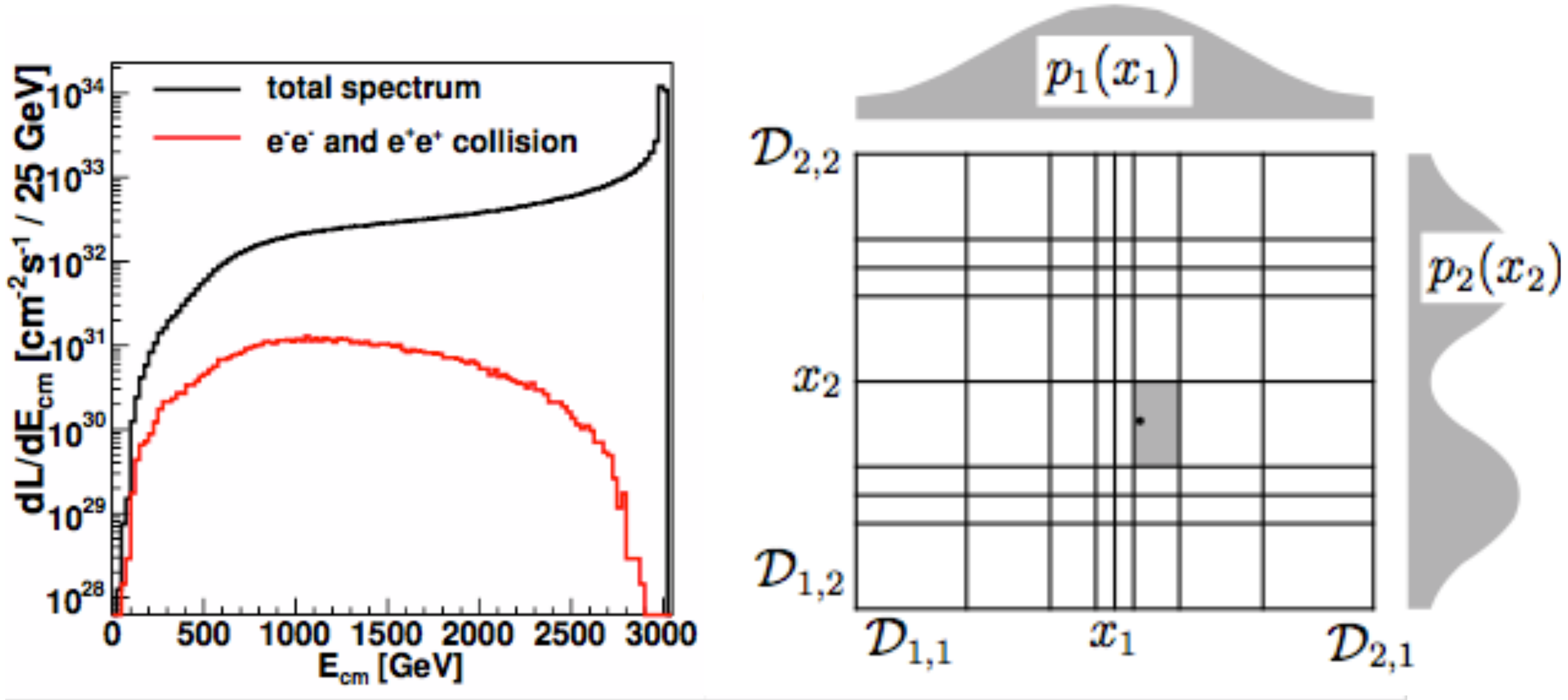

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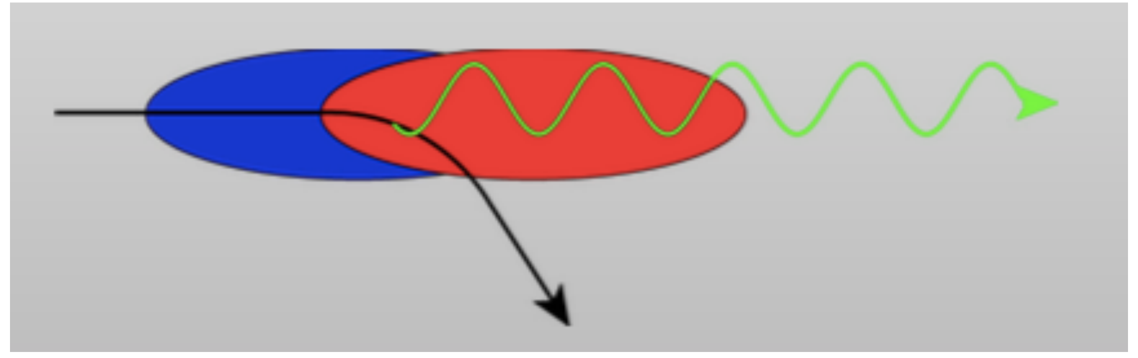

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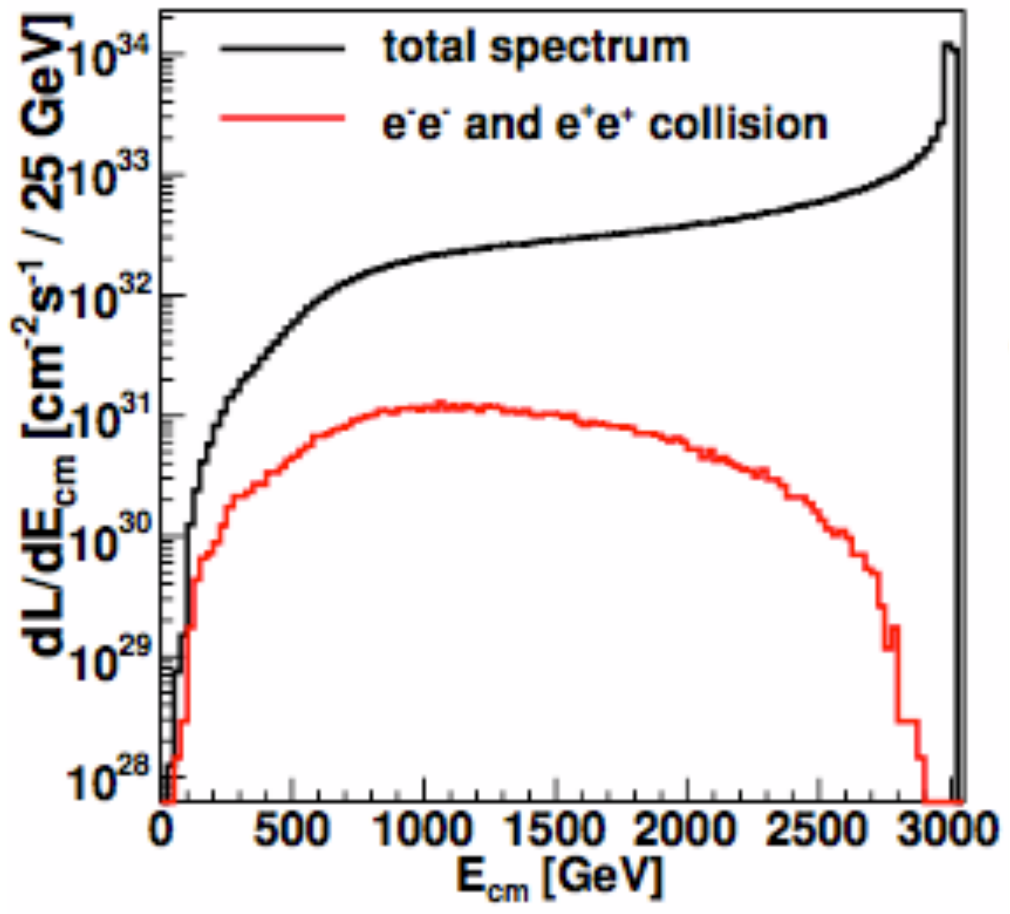

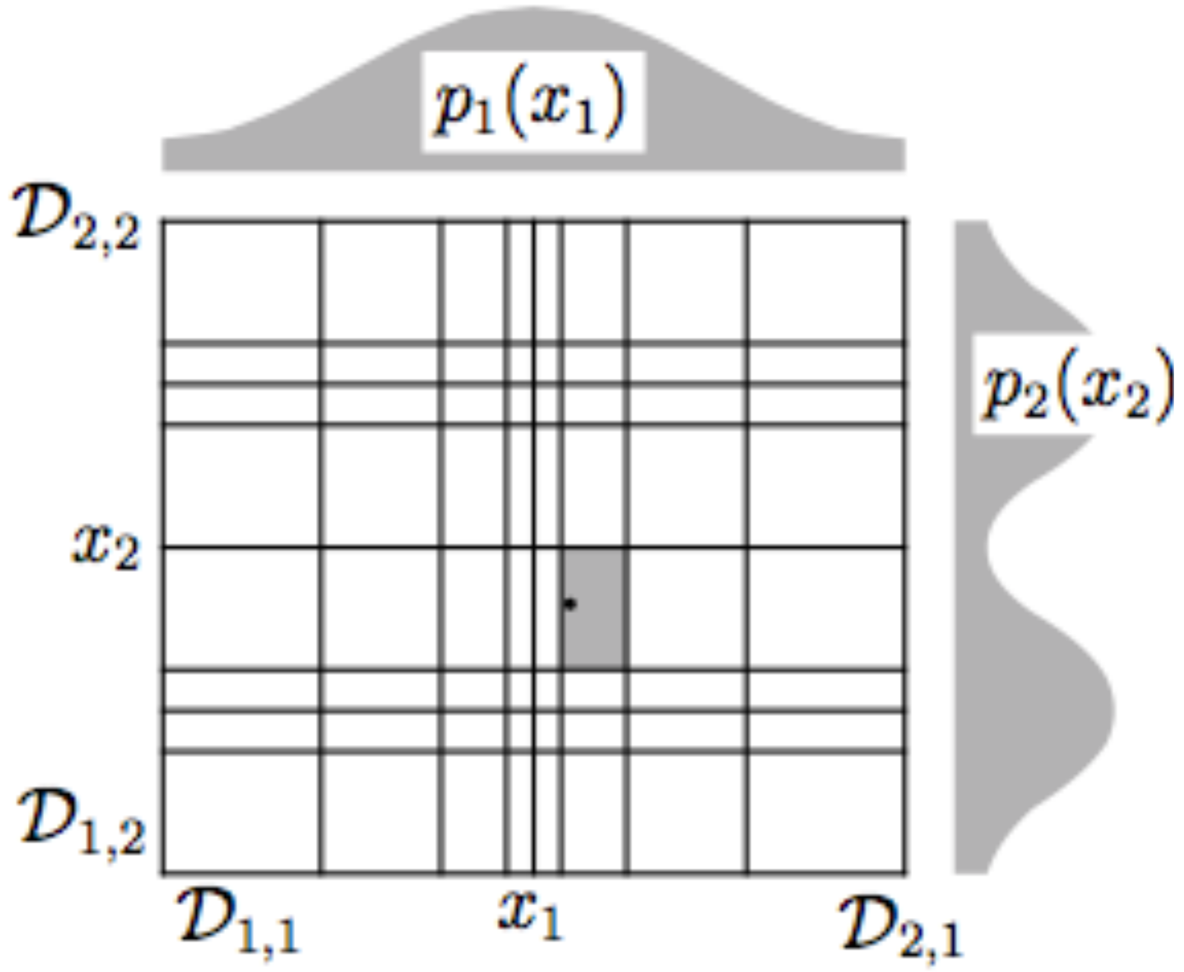

Dalena/Esbjerg/Schulte [LCWS 2011]

$$D_{B_1B_2}(x_1,x_2) \neq D_{B_1}(x_1)\cdot D_{B_2}(x_2)$$

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

- 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`

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

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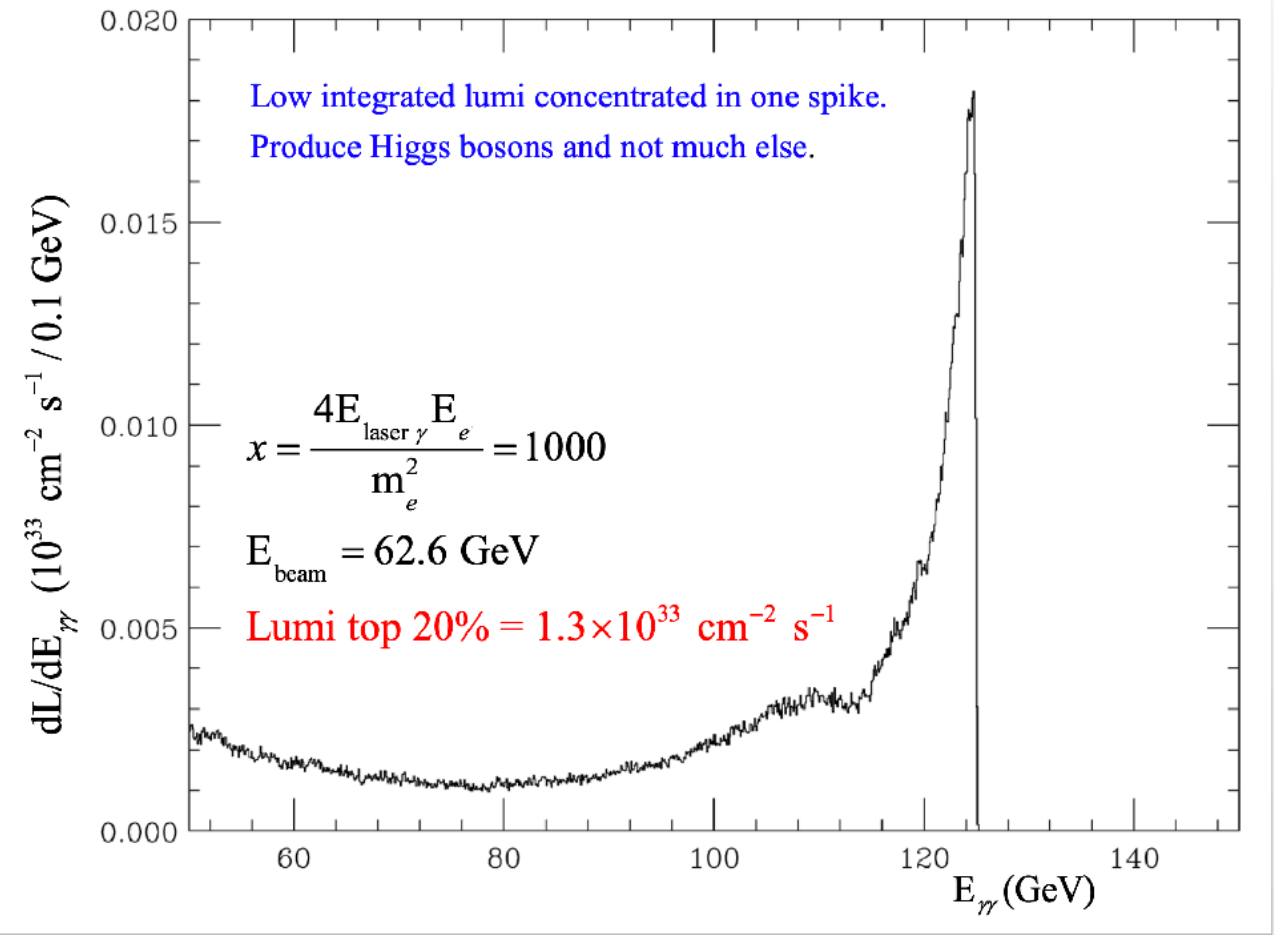
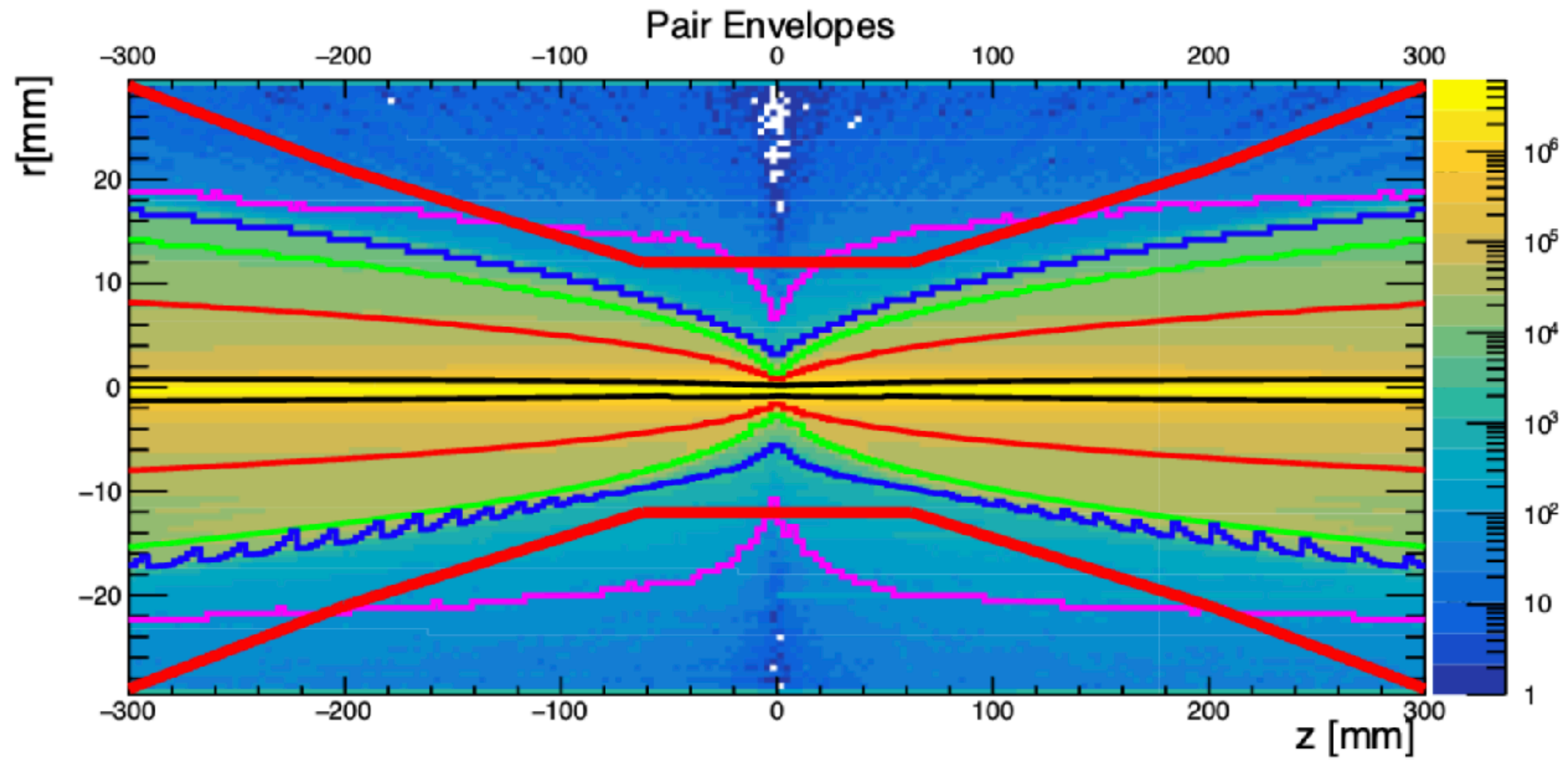
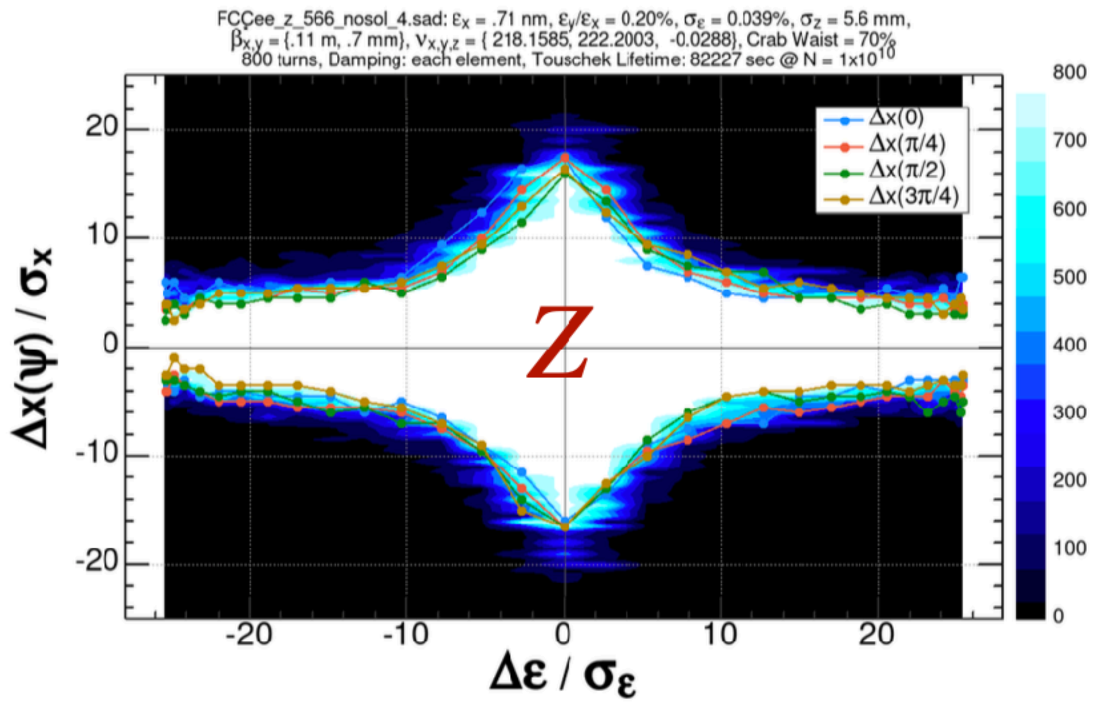
- New beam simulations for FCC-ee: 4 IPs ⇒ 1.7x lumi (91 GeV) / 1.8x lumi (161/250 GeV)
- New beam simulations for CCC and XCC (photon collider simulations)
- Photon collider simulations *not* possible with parameterized spectra
- Conclusion: `CIRCE2`-like sampling most versatile/general approach



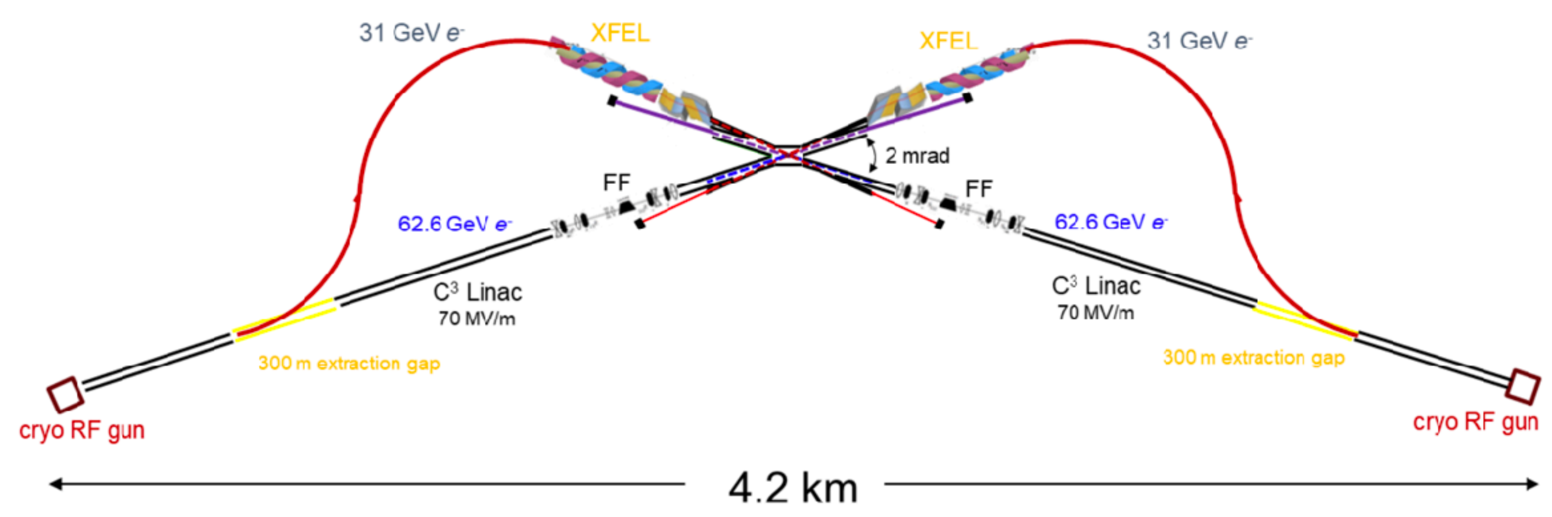


[Katsunobu Oide, FCC week]

Dynamic aperture (z-x)



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



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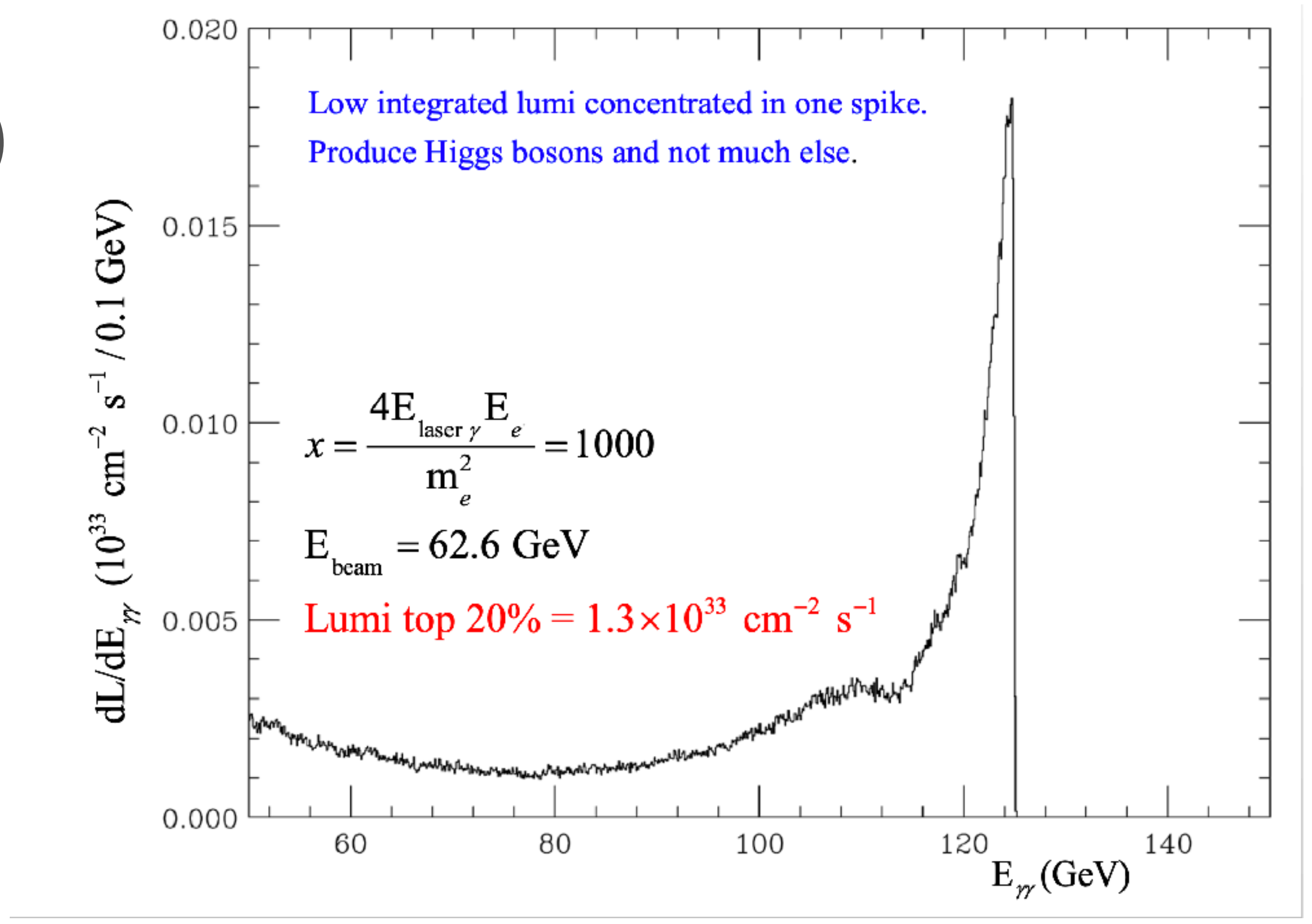

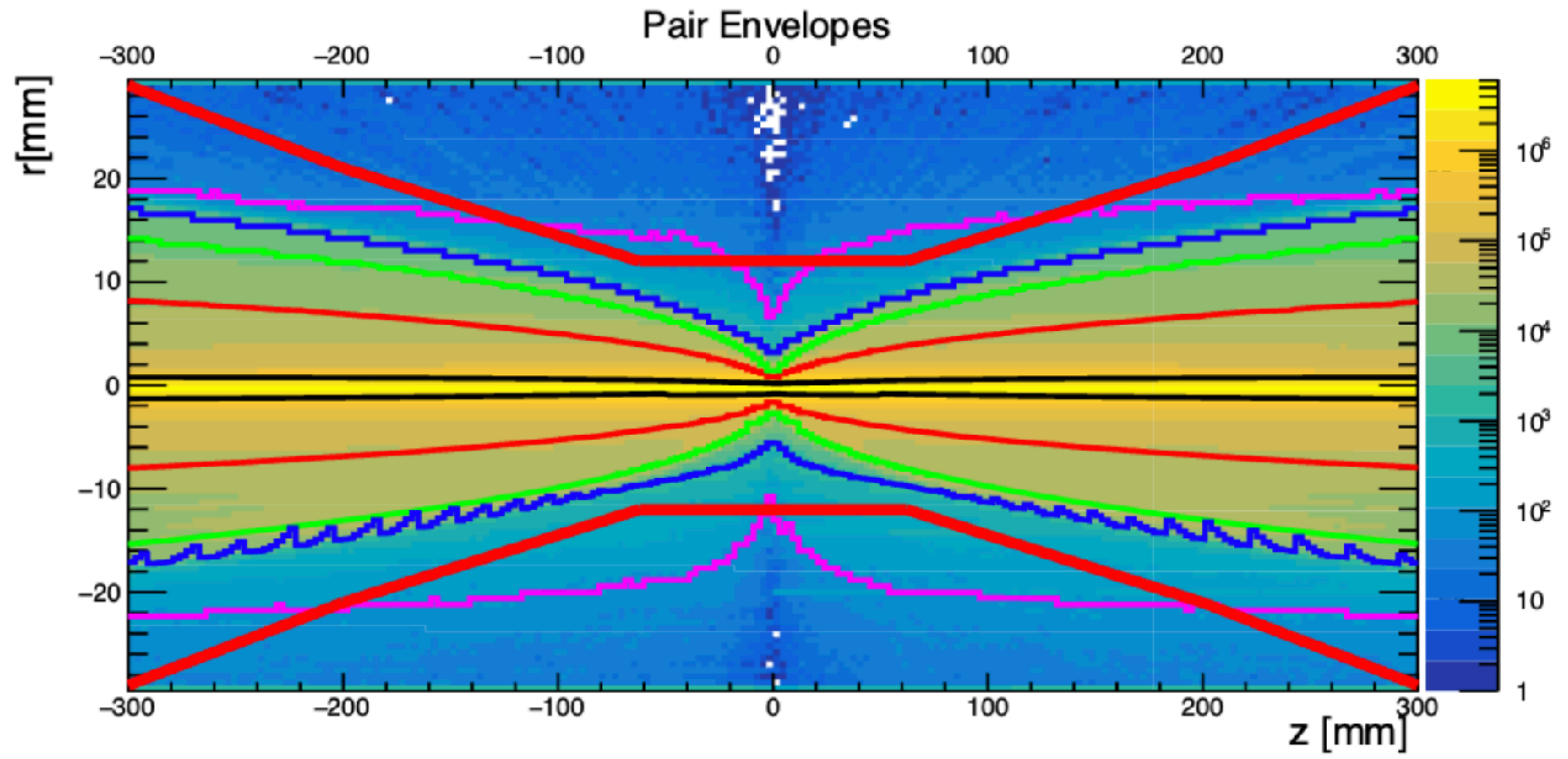

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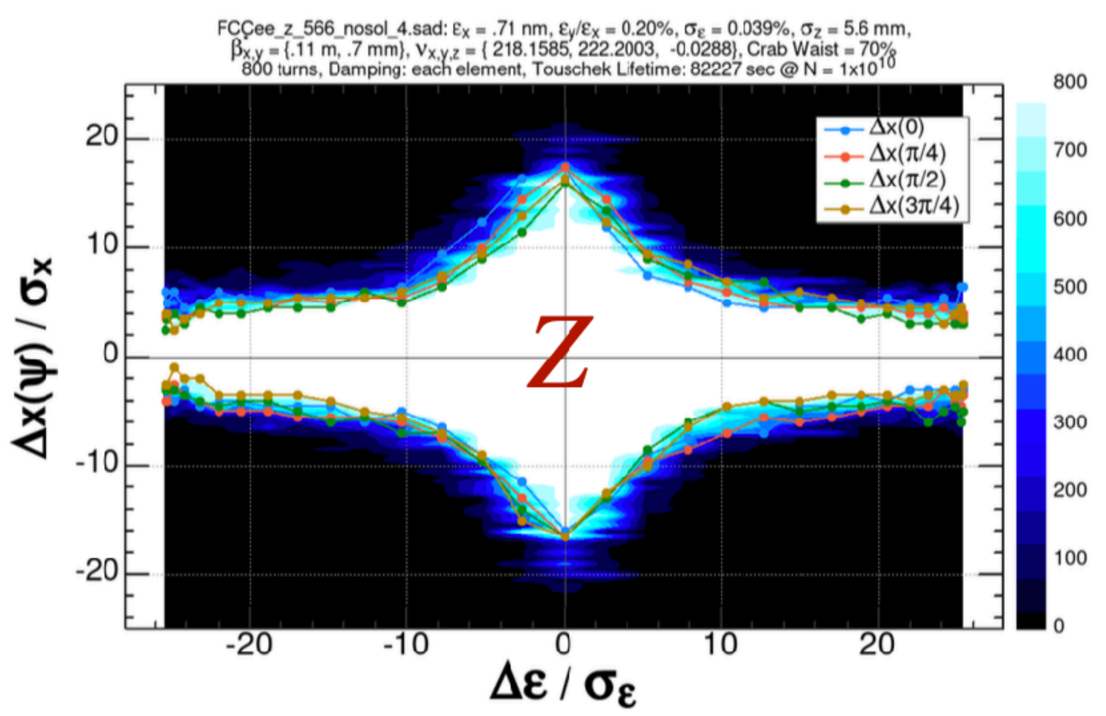
Dynamic aperture (*z*-*x*)



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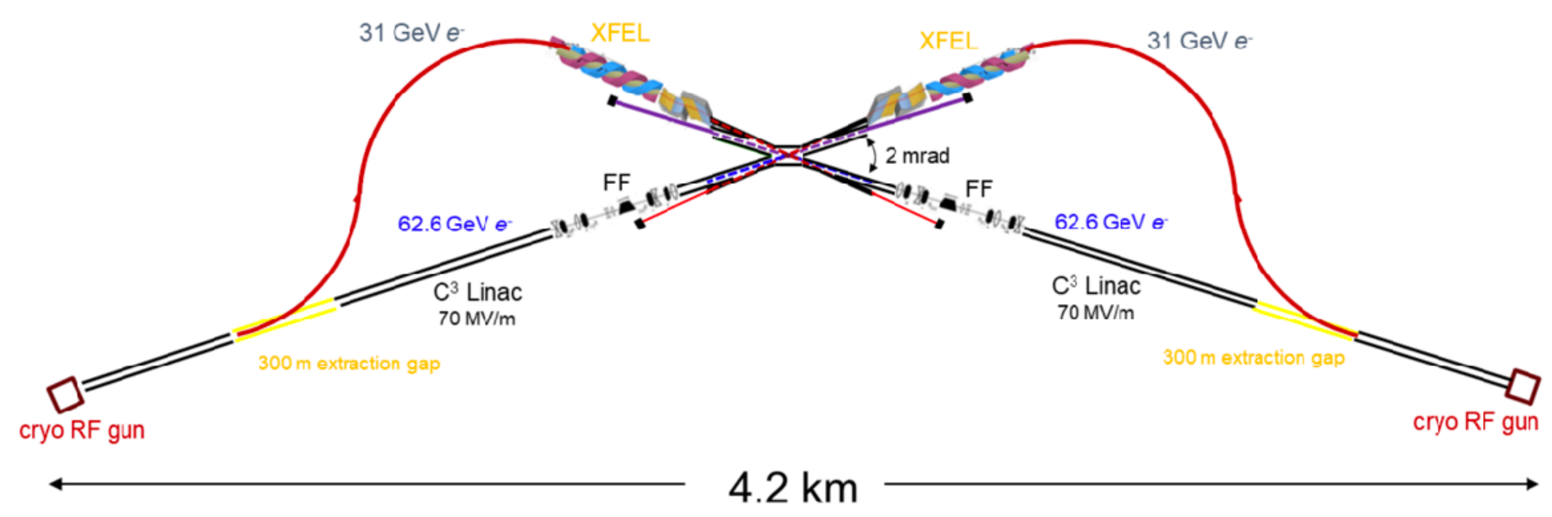
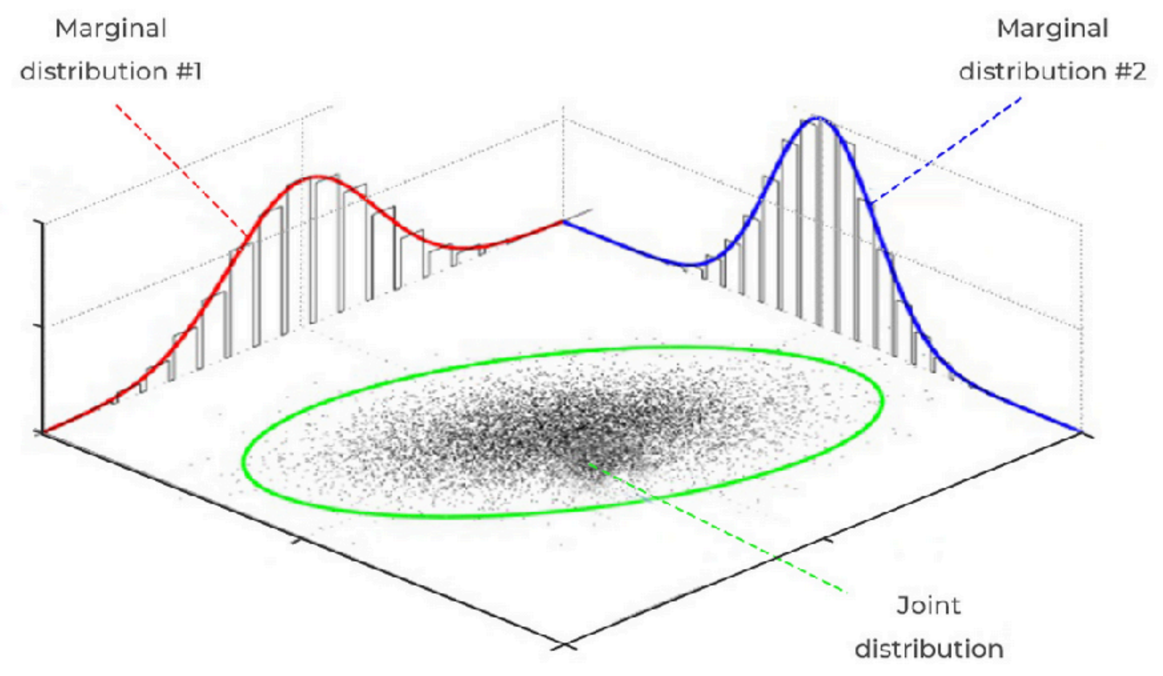
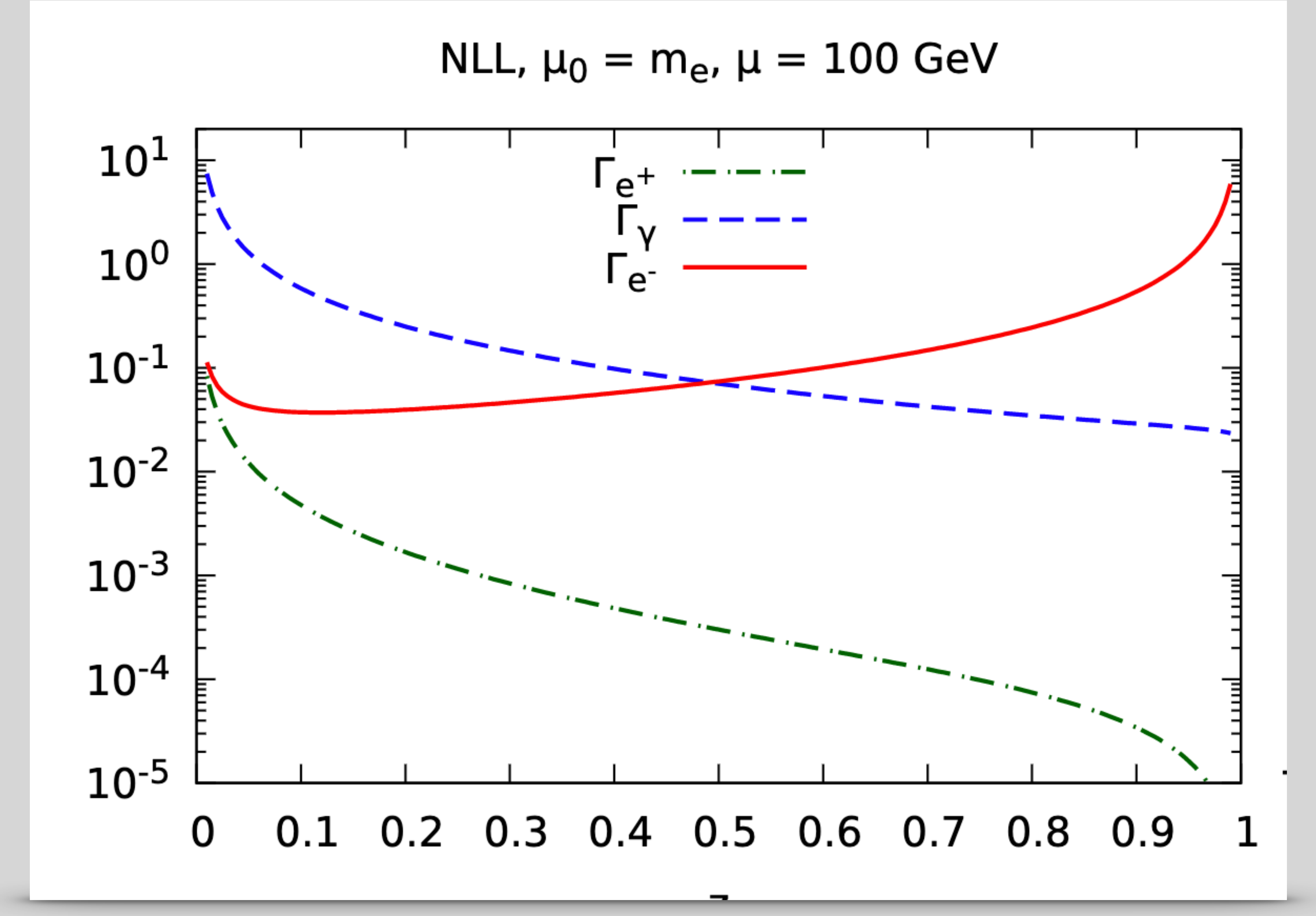


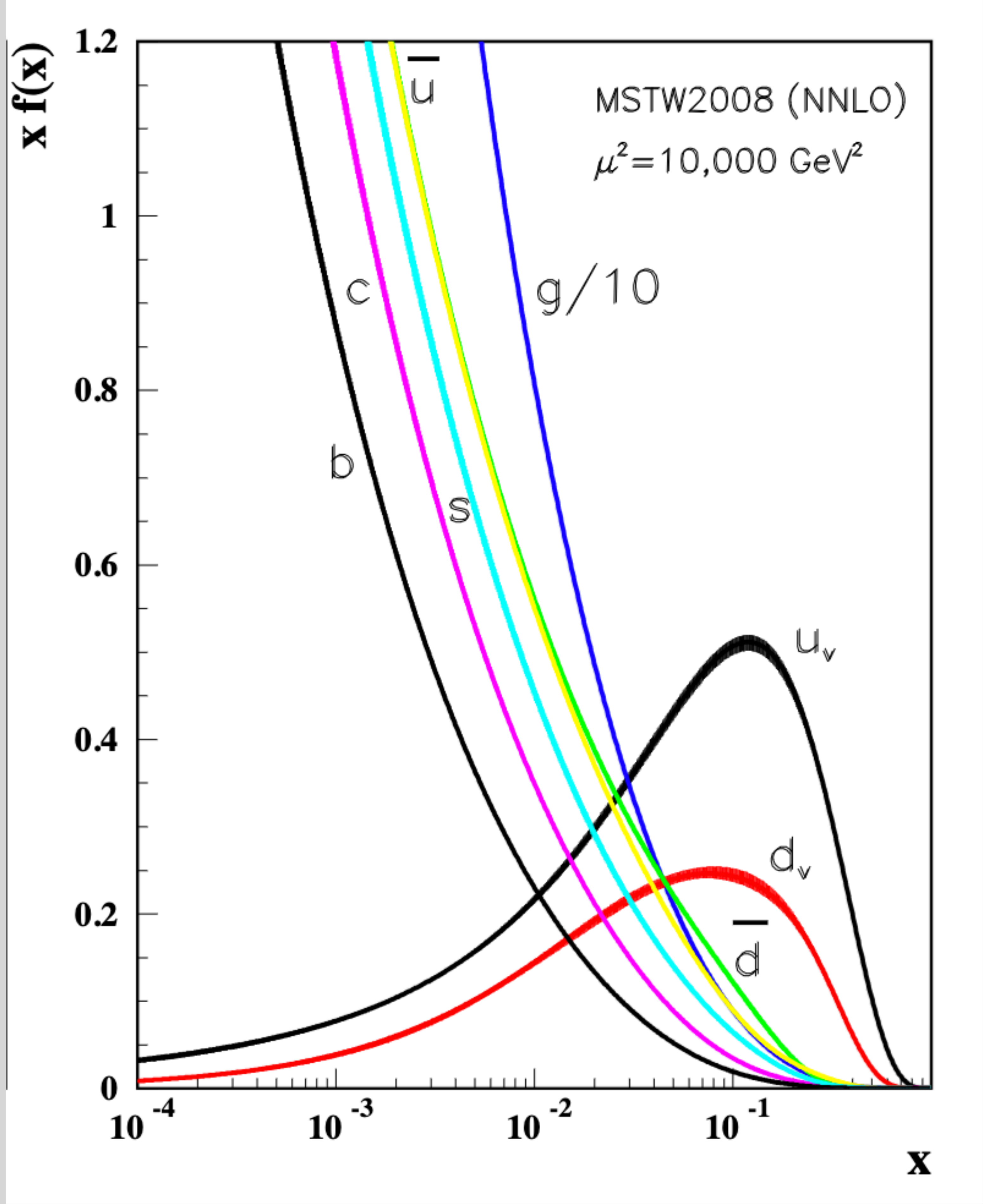
Open Issues

- 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

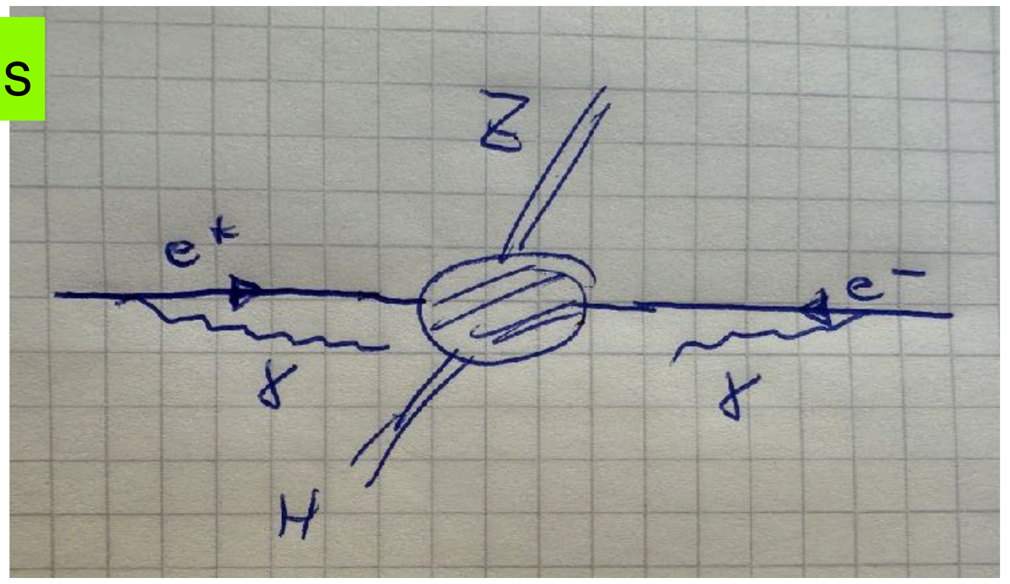




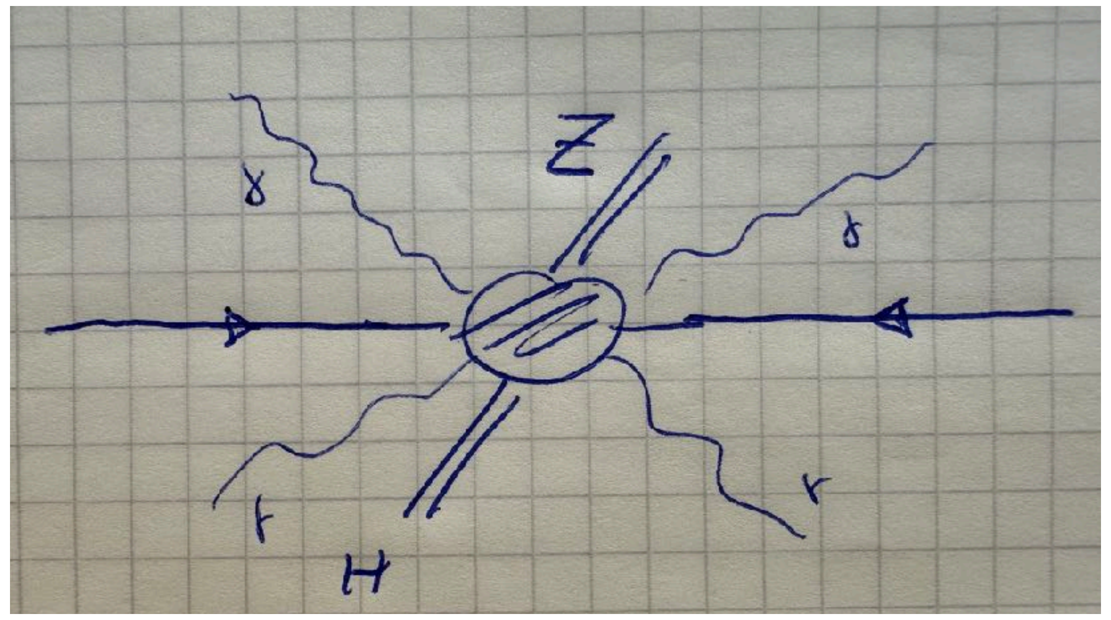
QED PDFs — QED Initial State Resummation

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

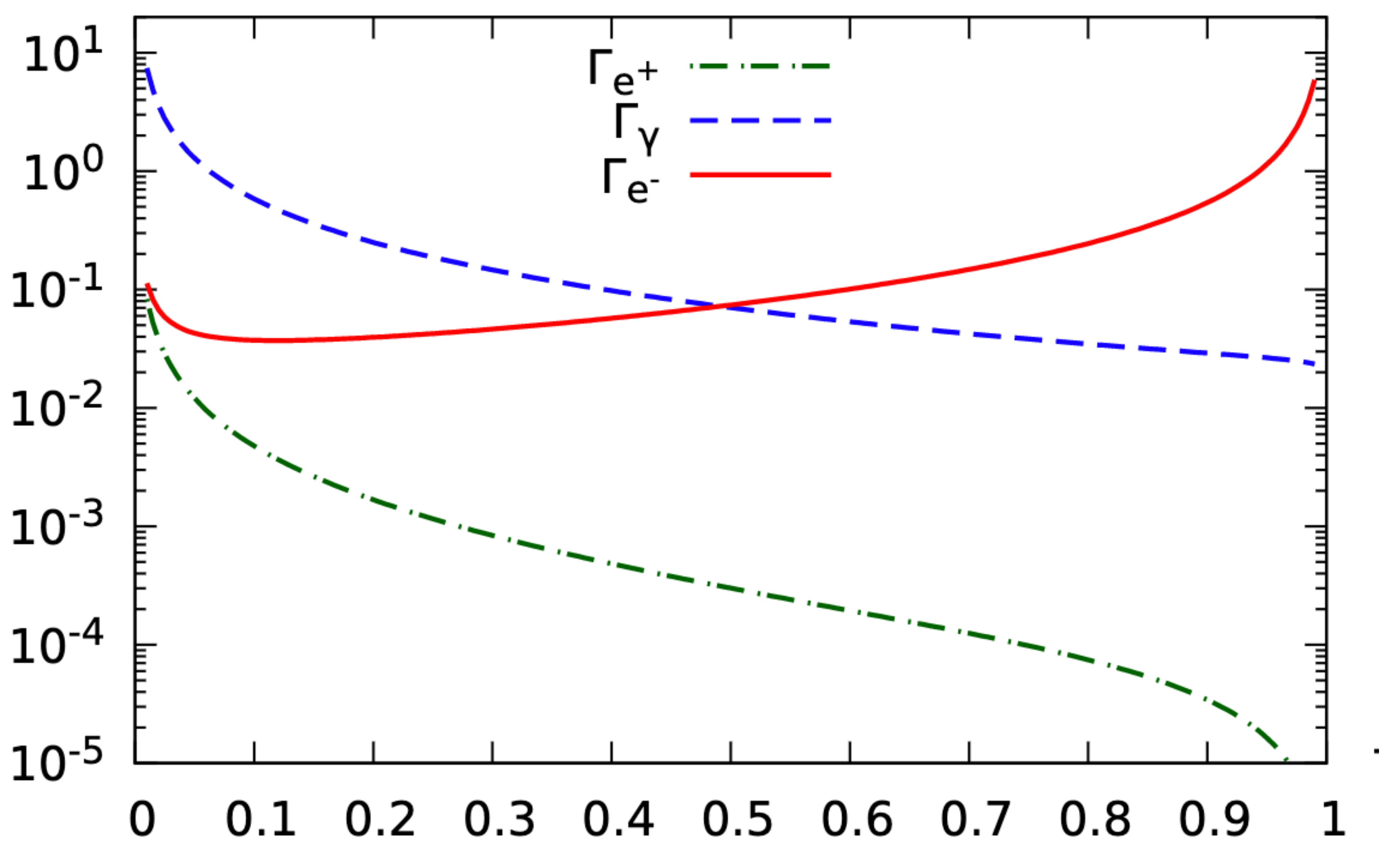
$$d\sigma = \sum_{n_\gamma}^{\infty} \frac{\exp[Y_{res.}]}{n_\gamma!} \prod_{j=1}^{n_\gamma} \left[d\text{LIPS}_j^\gamma \, S_{res.}(k_j) \right] \left[\sigma_0 + \text{corrections} \right]$$

  - 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 QED ePDFs,
  LL: $(\alpha L)^k$, NLL: $\alpha(\alpha L)^{k-1}$

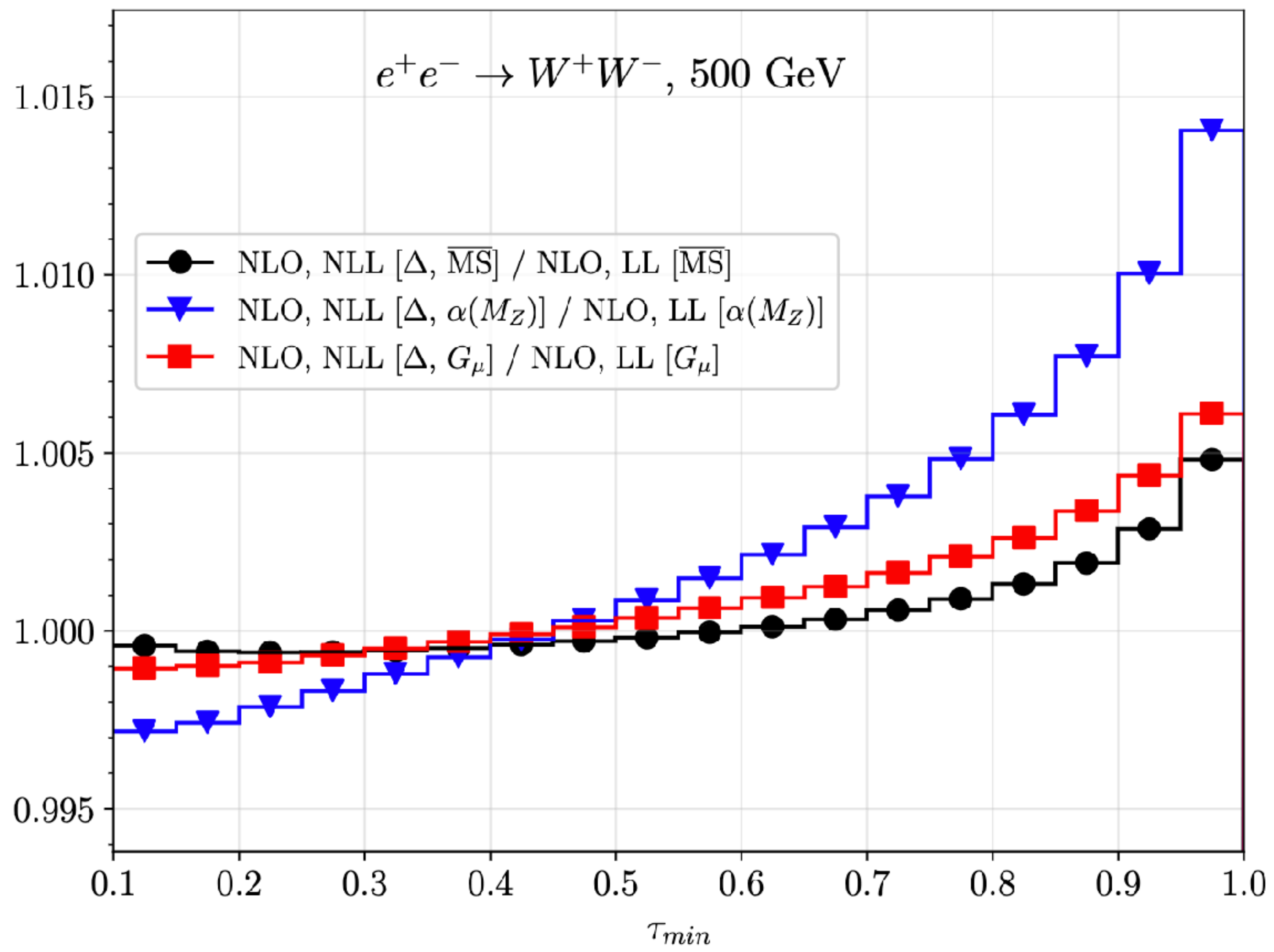
$$d\sigma_{kl}(p_k, p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \, \Gamma_{i/k}(z_+, \mu^2, m^2) \, \Gamma_{j/l}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$$

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; Talk by Marco Zaro
- 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

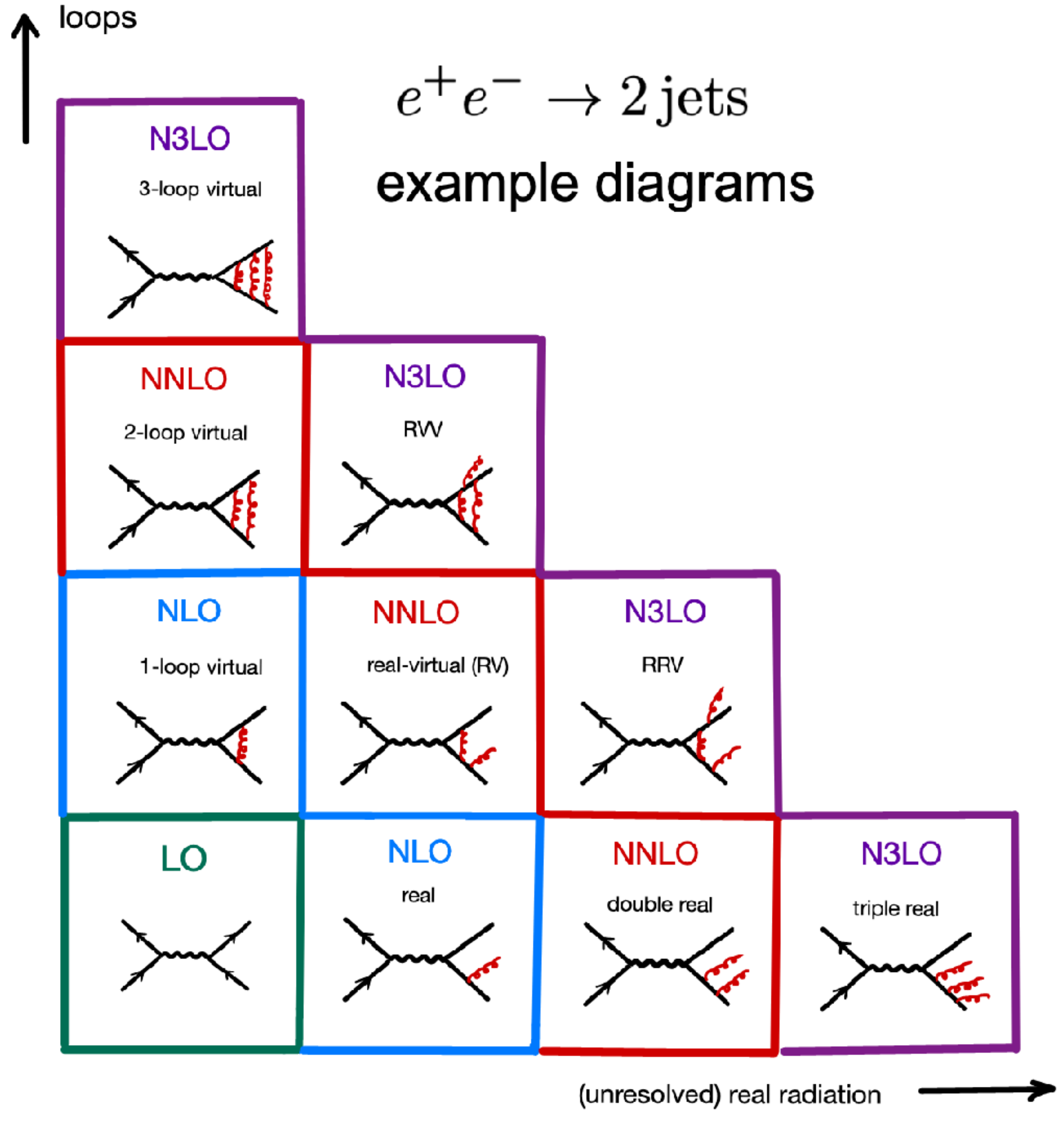


ePDFs for polarized leptons !?

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

	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

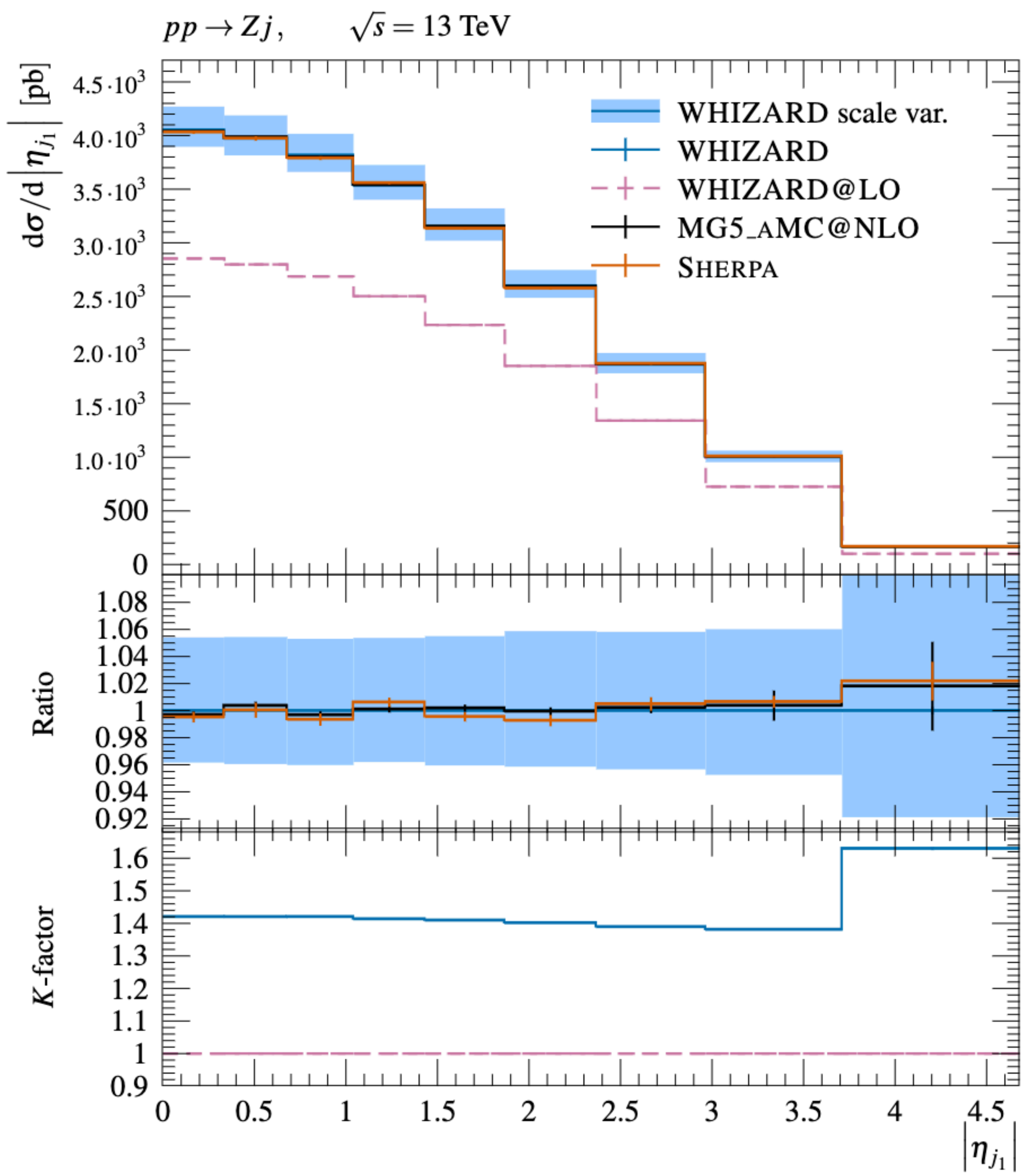
NLO EW

Pia Bredt, Phd thesis, DESY, 2022

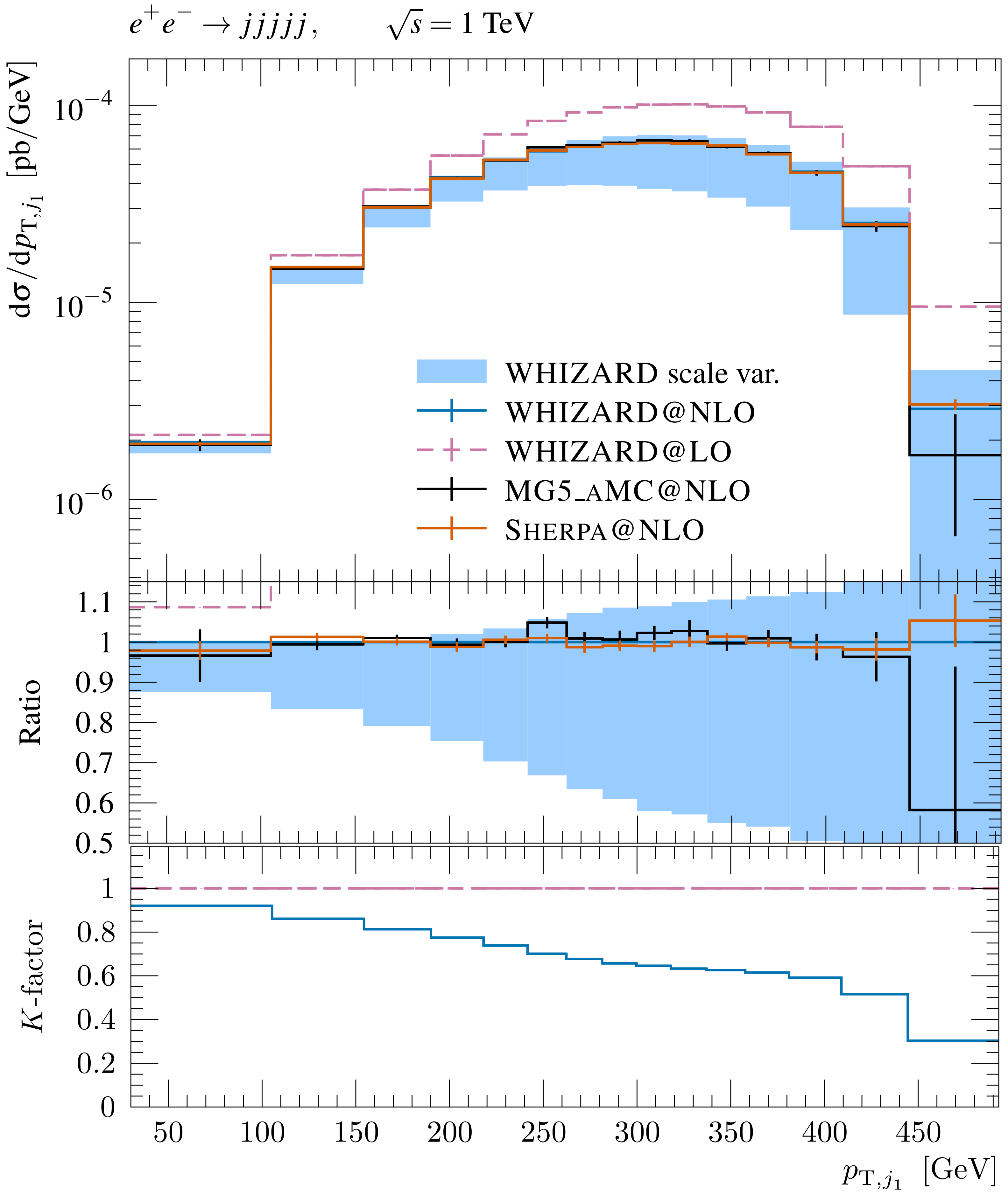
	MCSANCee[37]		WHIZARD+RECOLA			
$\sqrt{s}$ [GeV]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ_{EW} [%]	σ^{sig} (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)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

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

pp @ 13 TeV, NLO QCD

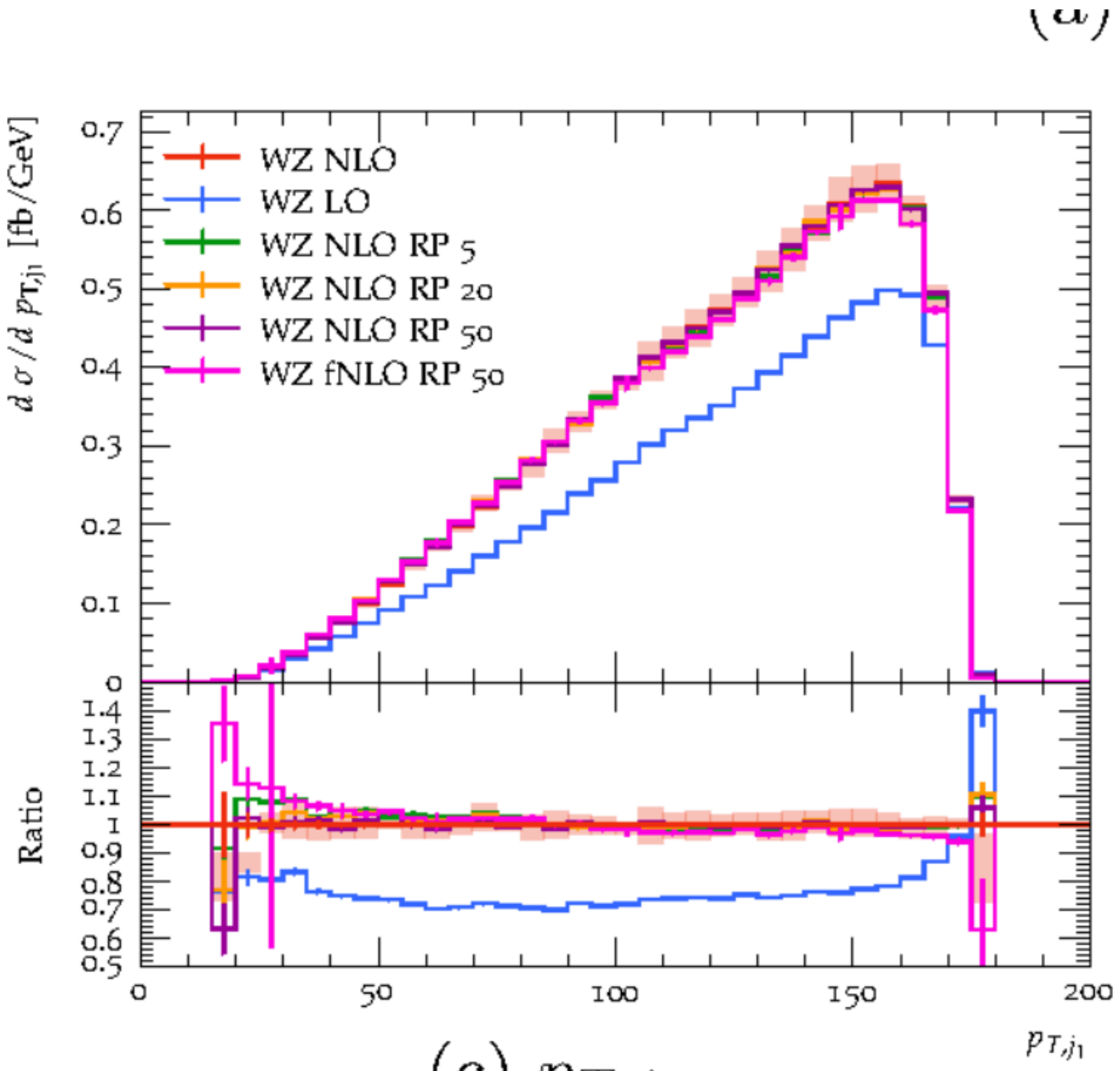


ee @ 1 TeV, NLO QCD



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

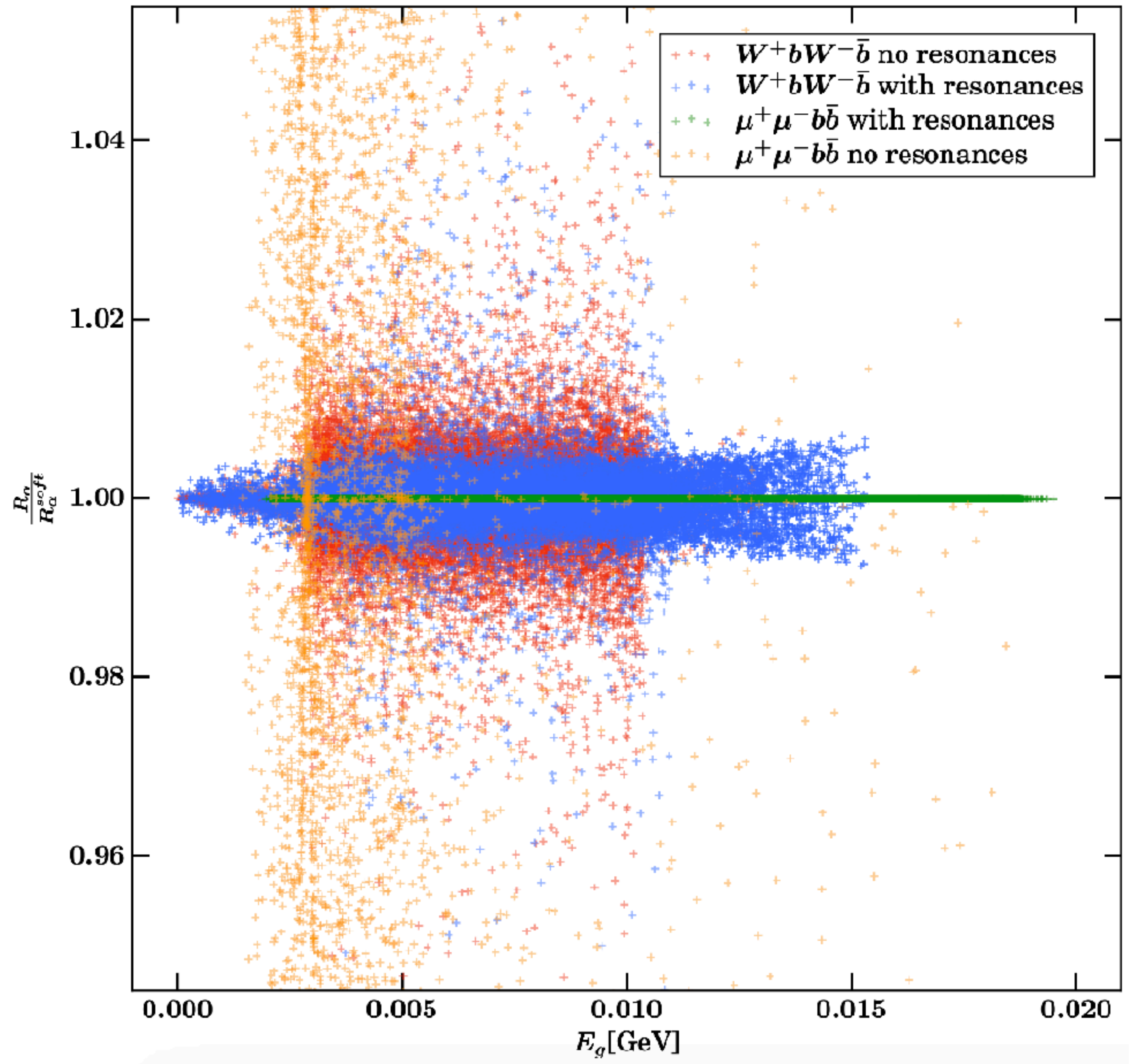
$$\mu_R = {}^{H_T}/_2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$



(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. Ježo/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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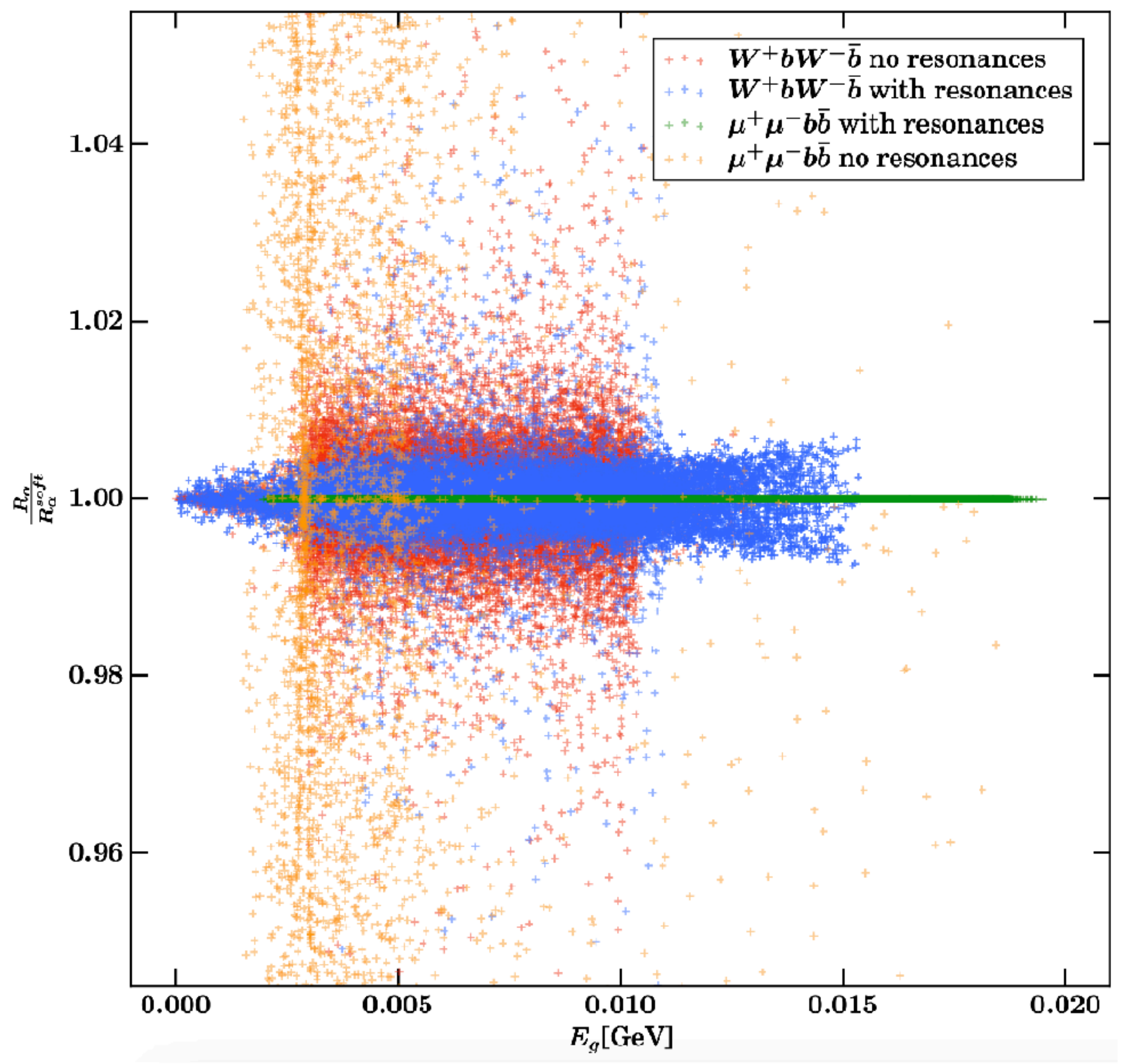

Two major bottlenecks to NNLO

- 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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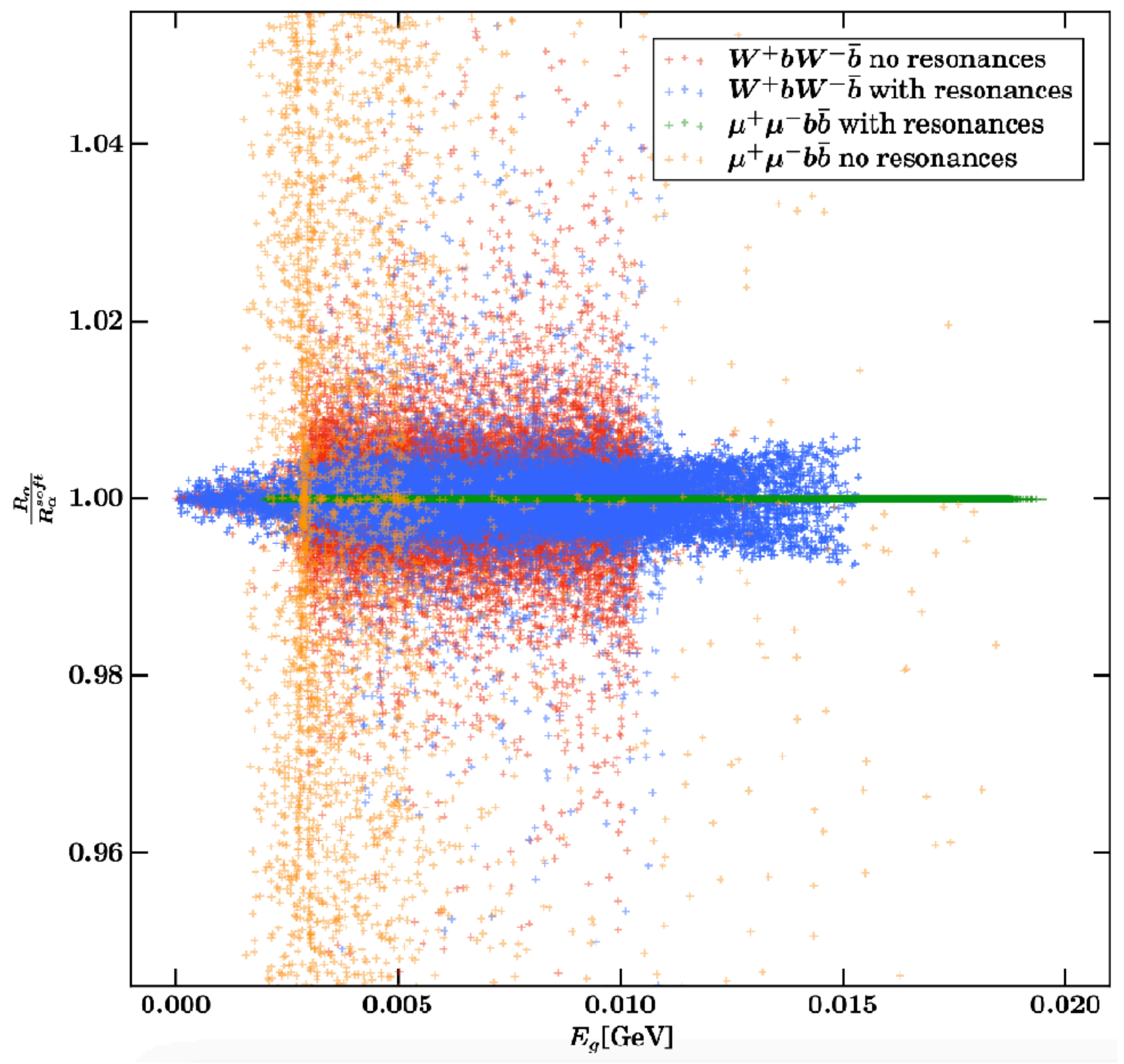

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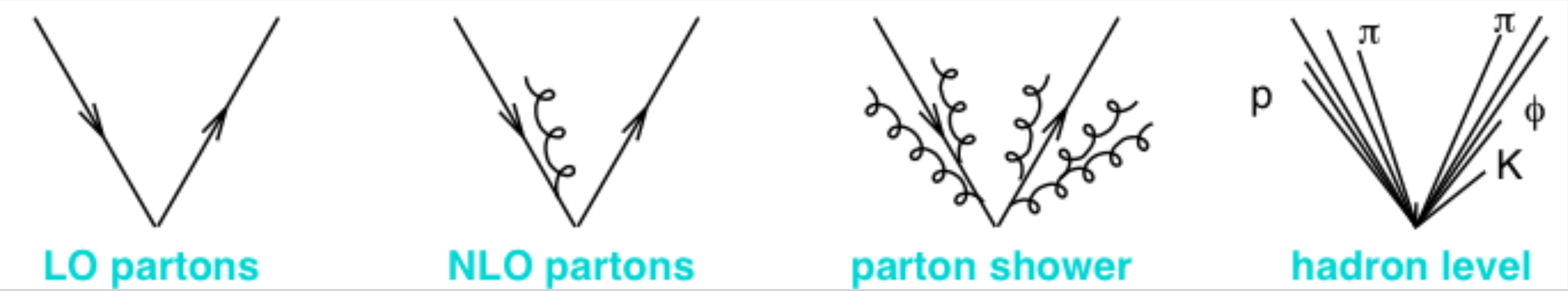
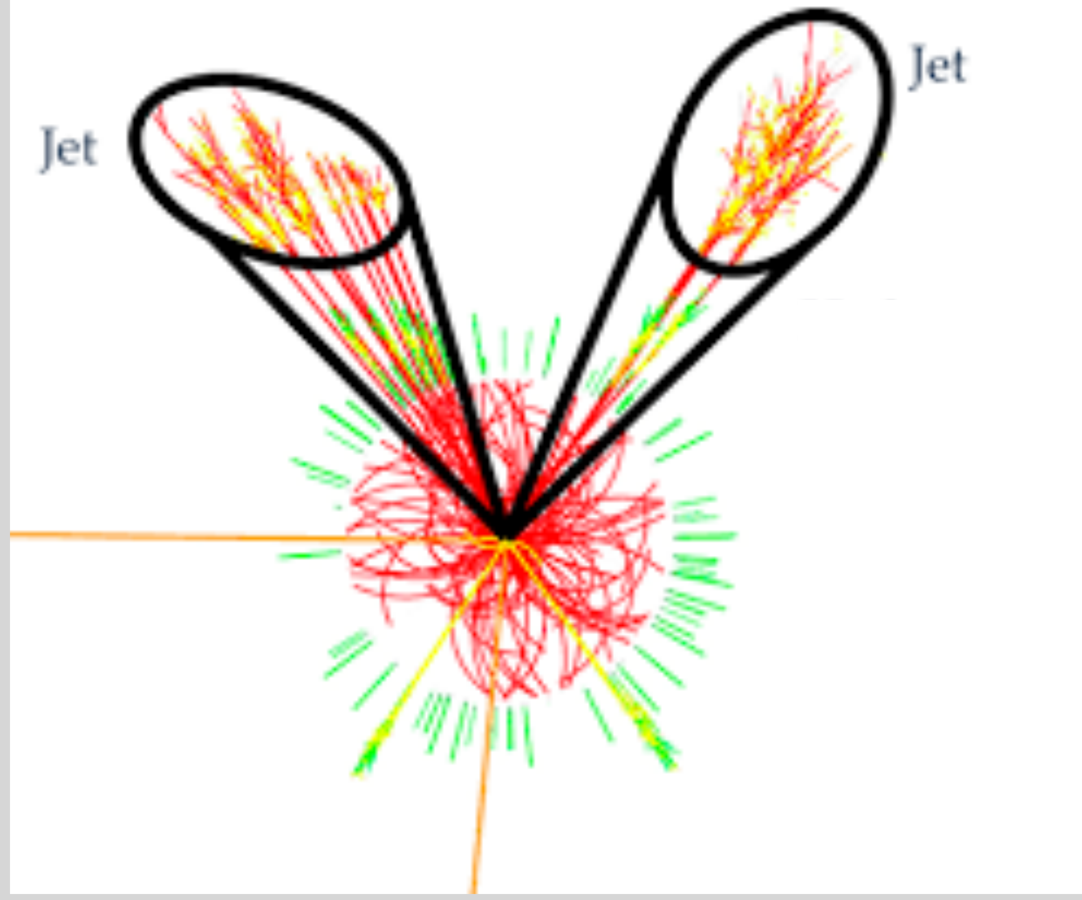
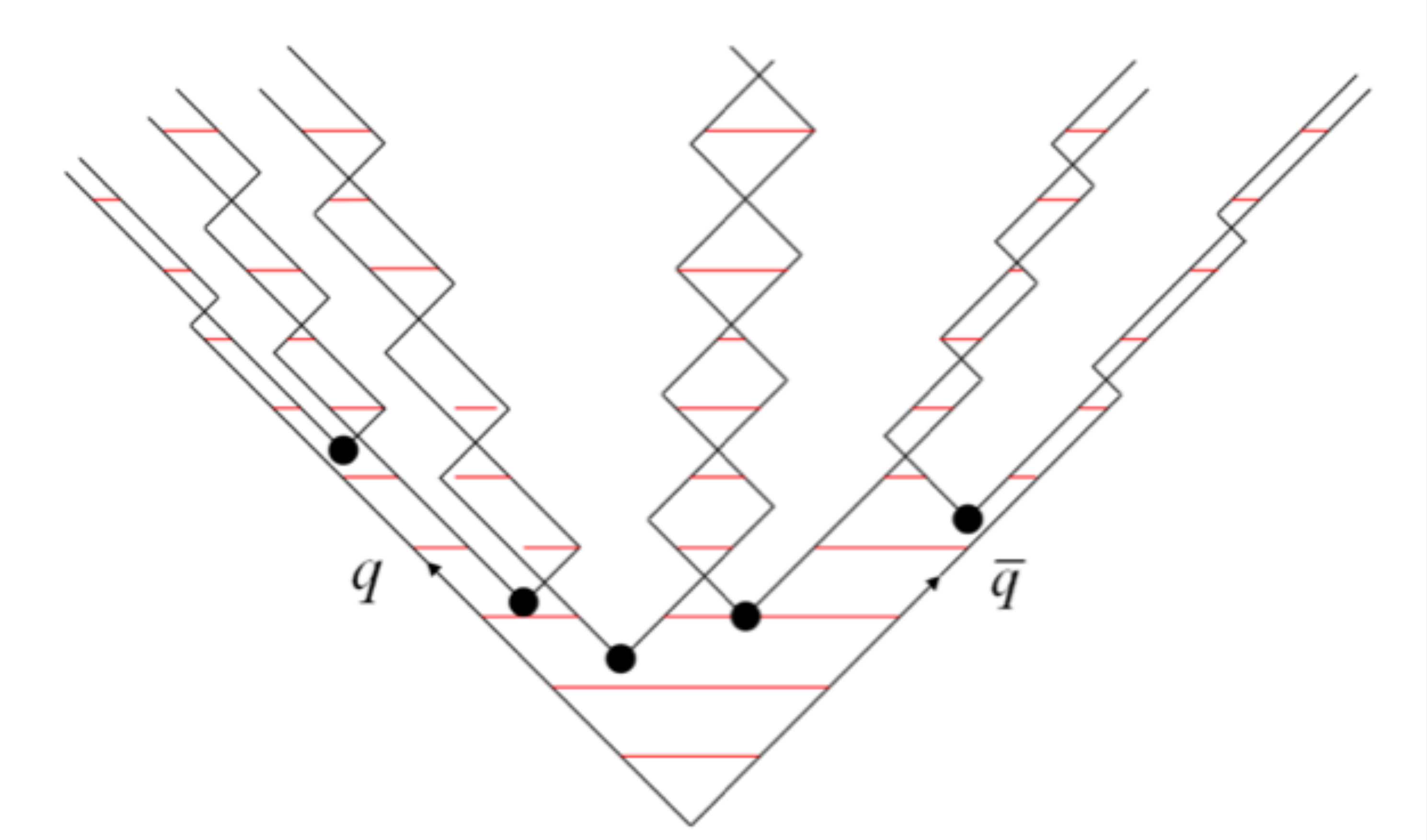
- ☑ FKS soft/eikonal subtraction sufficient for low-energy machines
- ☑ NNLO QED (massive, virtuals pending): McMule Signer ea. [Whizard]
- ☑ Baby steps to NNLO automation: Griffin Chen/Freitas, 2023
- ☑ for NNLO EW need for full-fledged soft+collinear NNLO subtraction

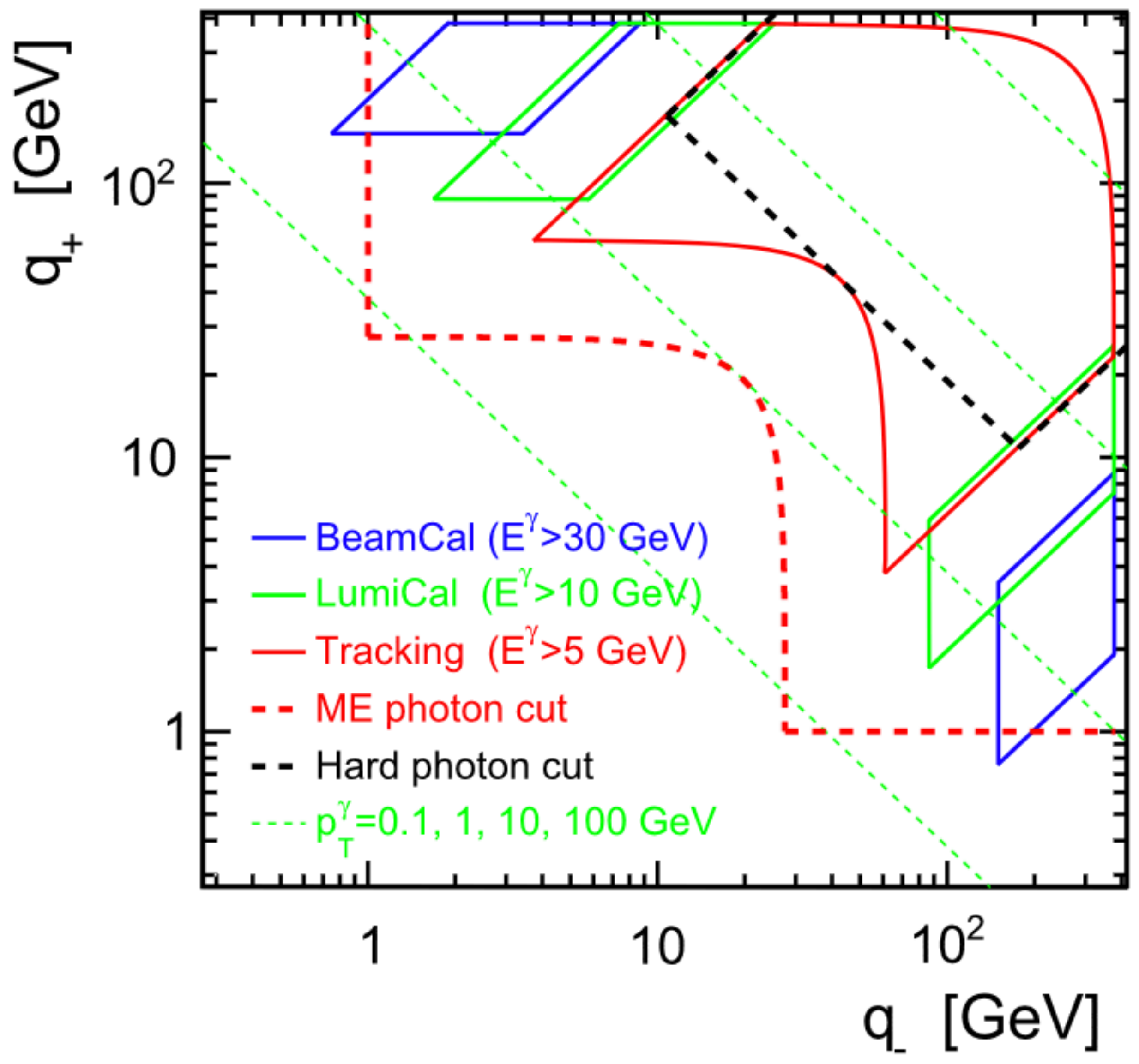
Parton Showers, Matching, Hadronization

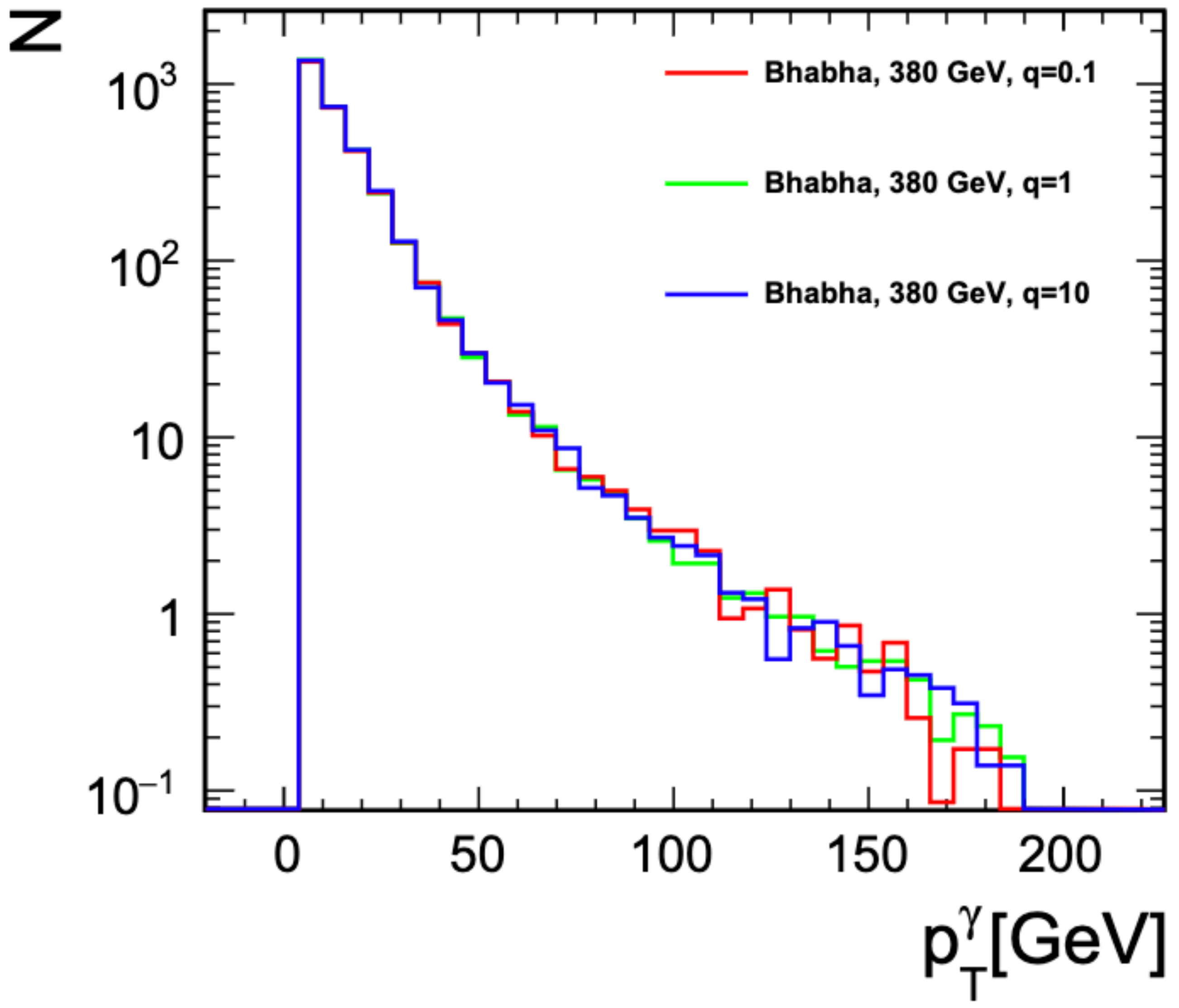






Exclusive photons



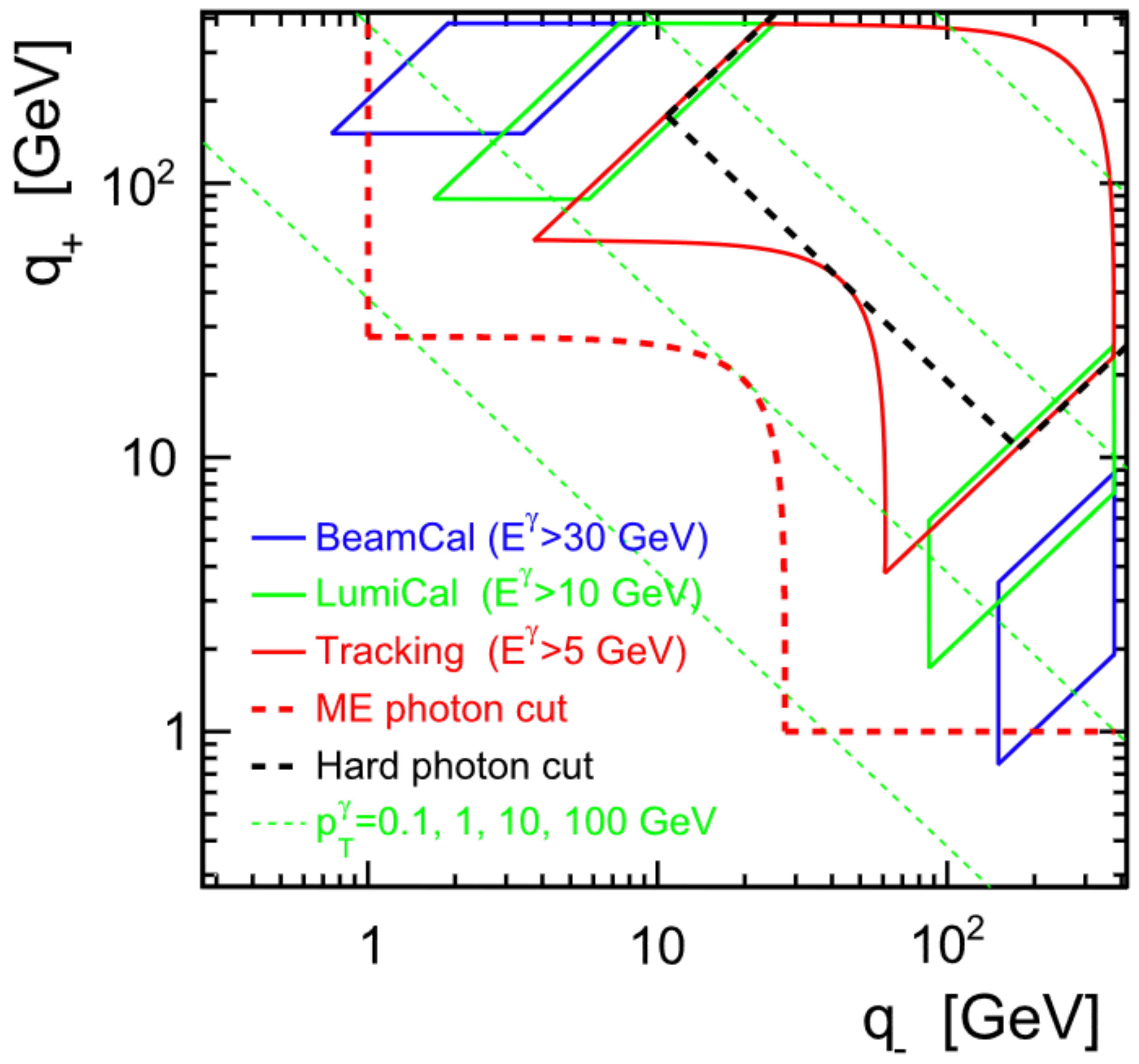


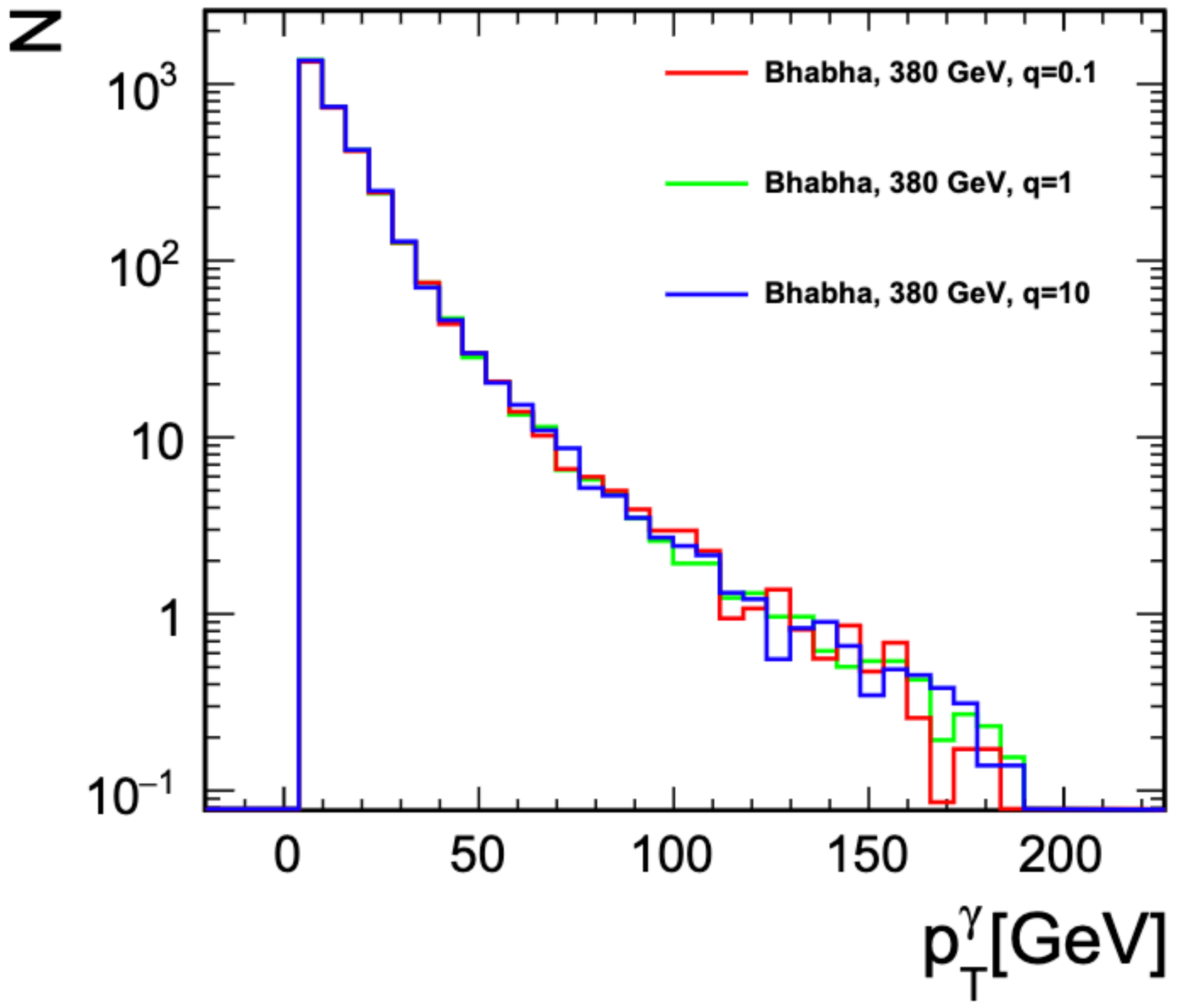
J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

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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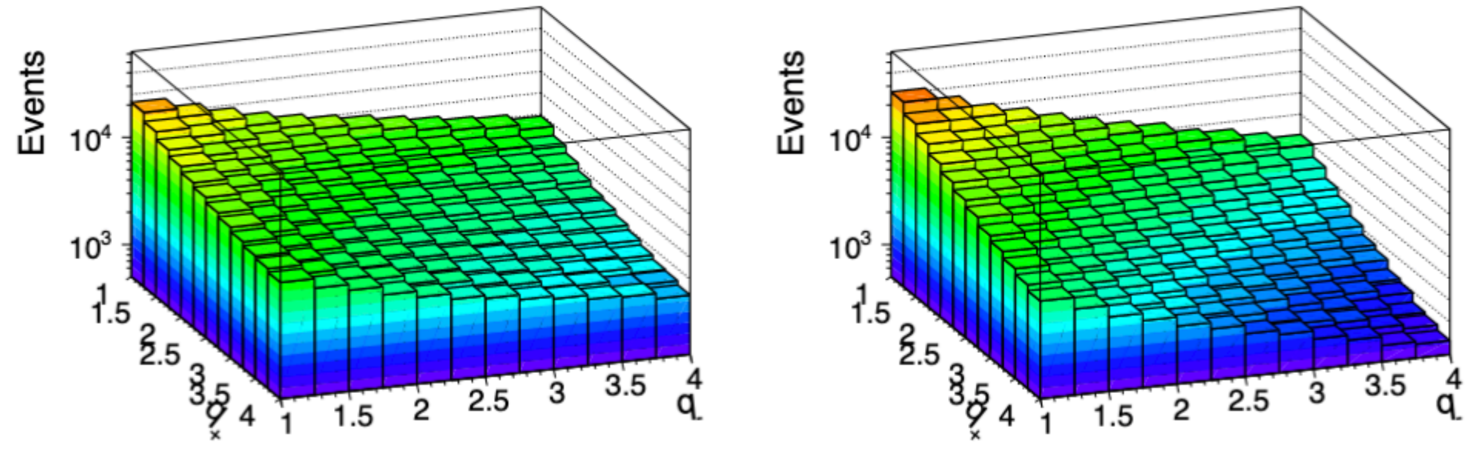
- Algorithm applied recursively (similar to massive NLO EW ISR PS construction)
- Recursive algorithm resembles a photon shower with *n* exclusive photons

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

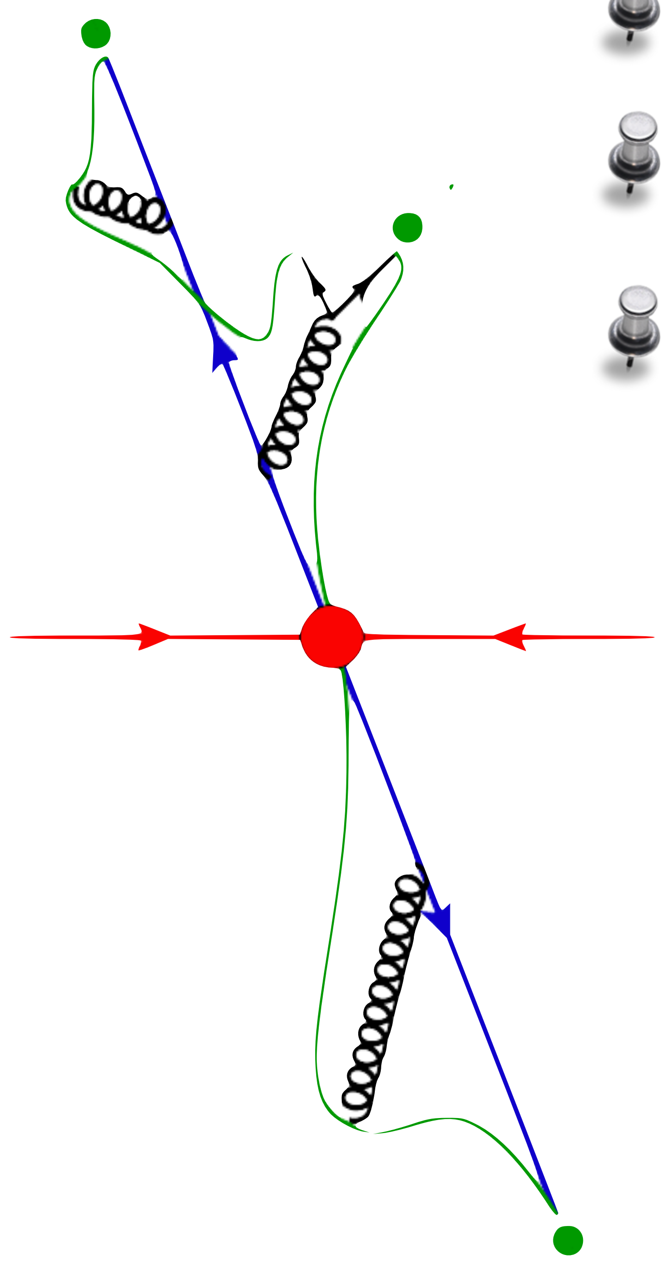
M. Berggren/W. Kilian/K. Mękała/JRR



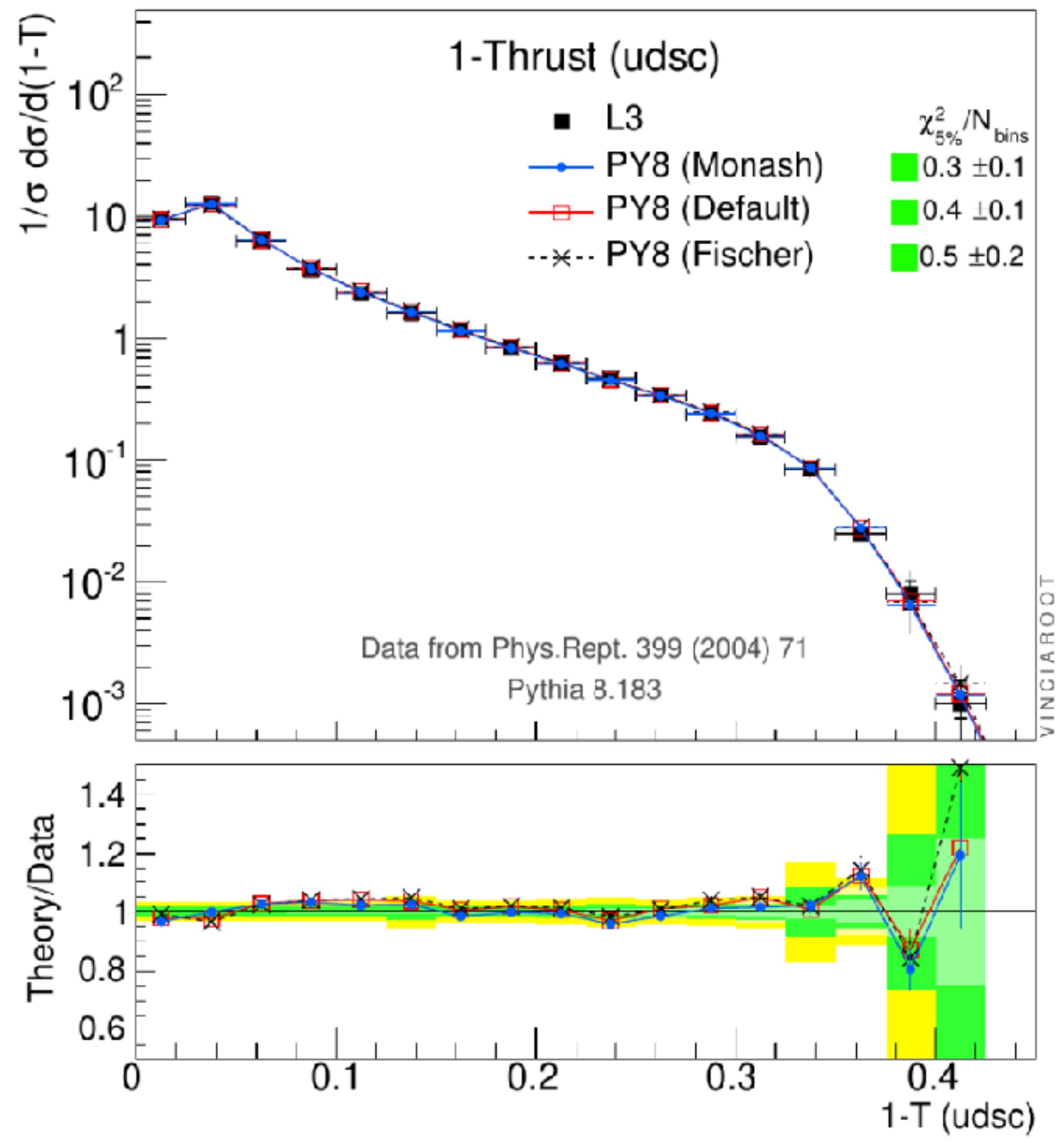
(a) Double EPA (b) Full matrix elements

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] $0 \le \beta < 1$	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



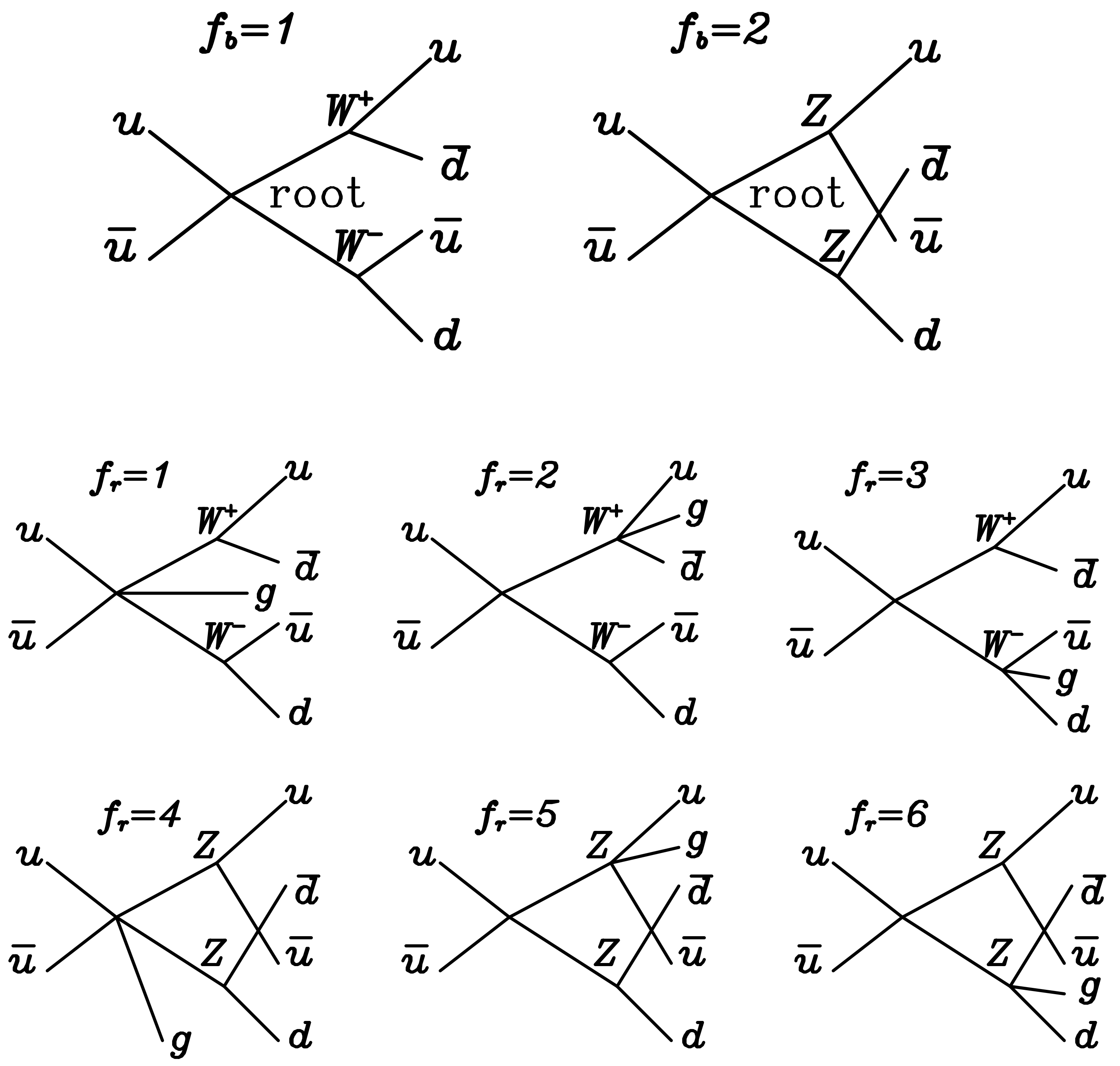
Talks by Jack Helliwell + Leif Gellersen

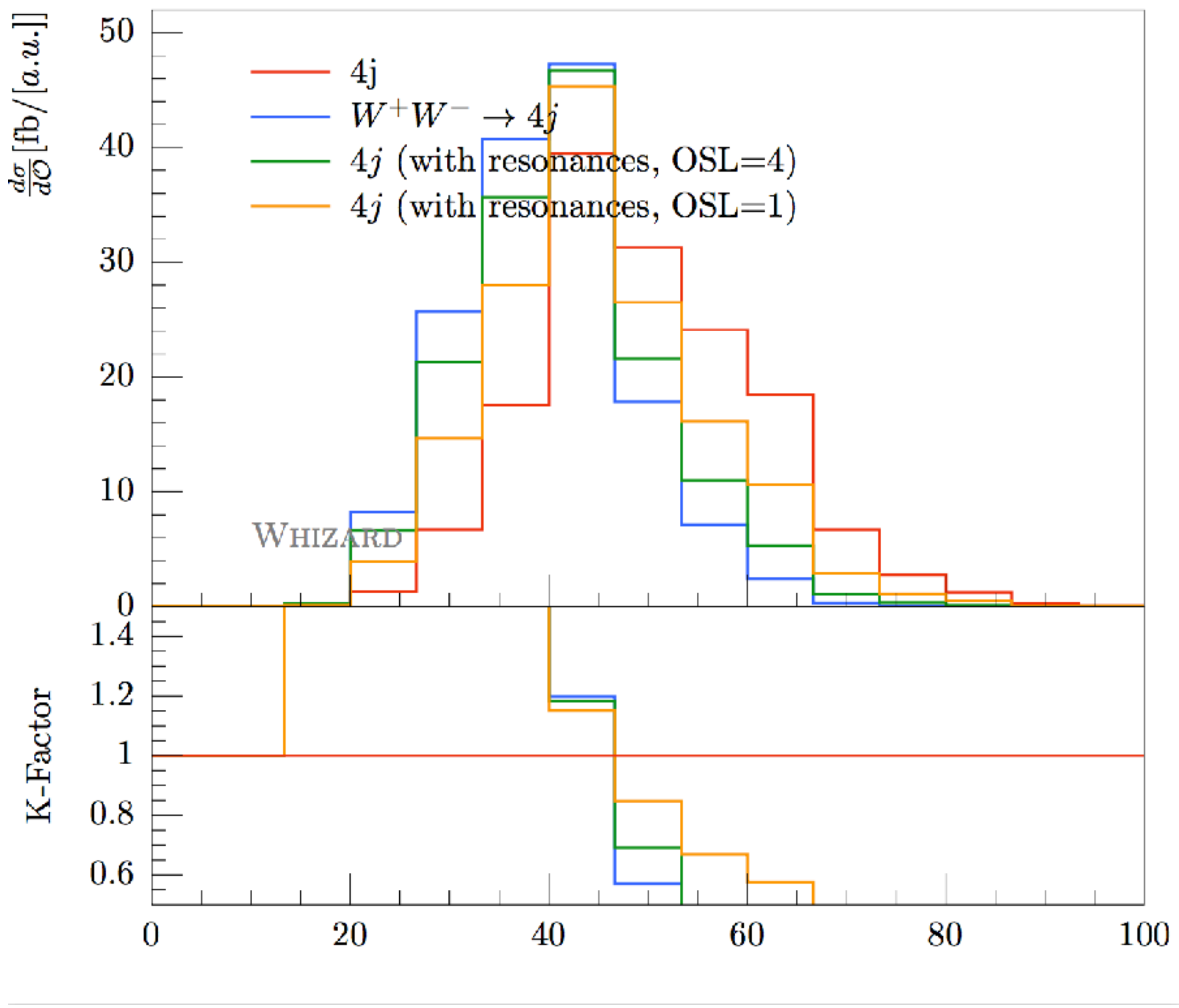
- Ongoing work towards NNLL showers, sub-leading color (FCC = full color correlations)
- NLO matching automated, different approaches, different error estimates;
- NNLO matching still process-dependent; also does not yet preserve NNLL accuracy
- Elephant in the room: fragmentation $\Rightarrow$ no paradigm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

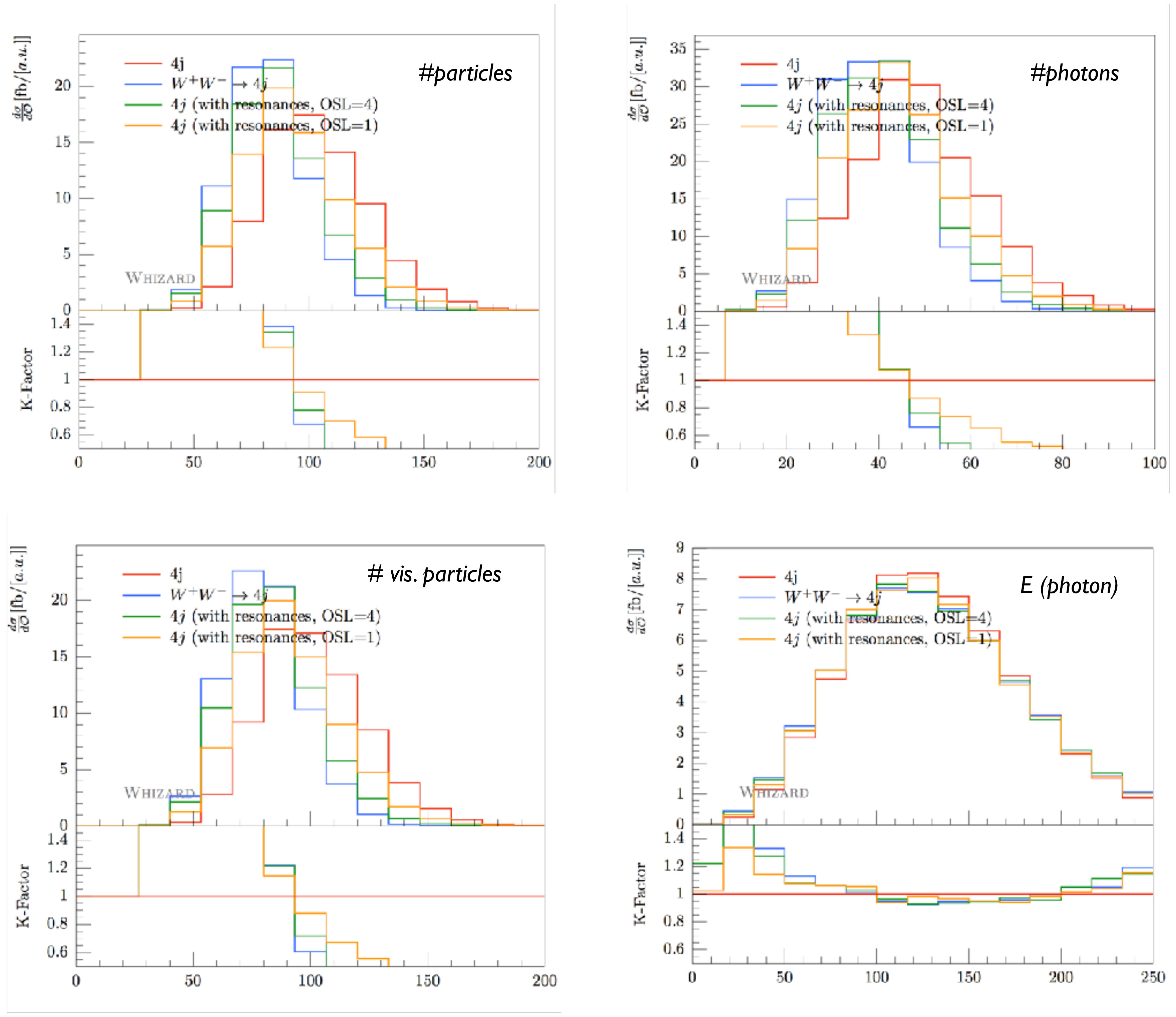
Gigantic clean data sets from Z pole and above will necessitate new models / theory

(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



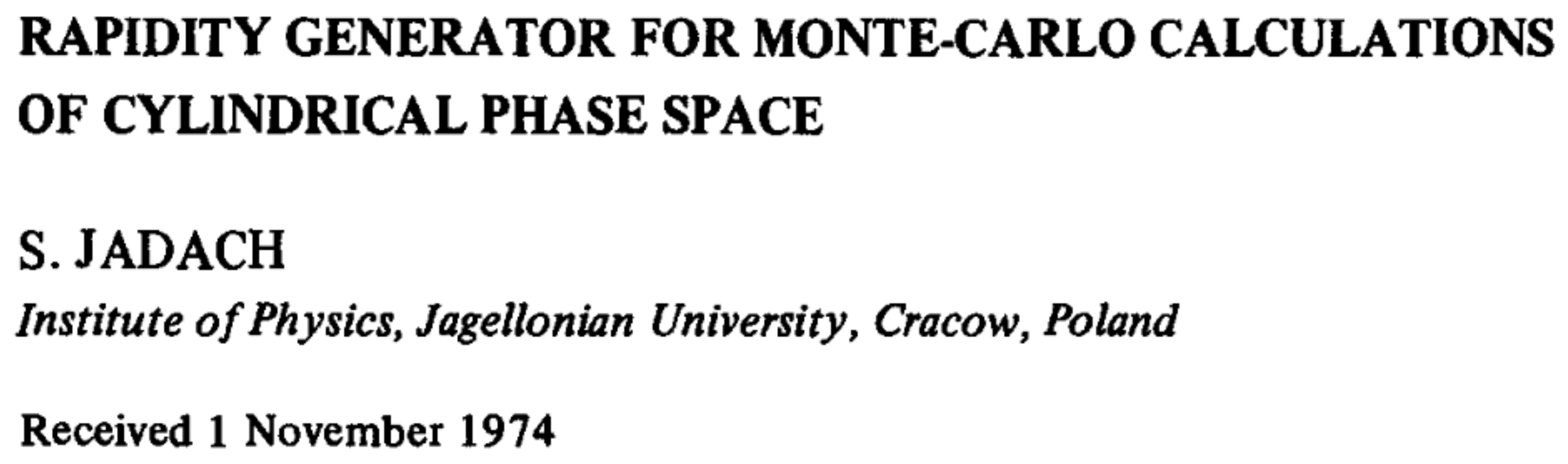




Dedicated tools for special processes

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	$28 \div 50$	M_Z	3.5×10^{-4}	1.70
FCCee	$64 \div 86$	M_Z	13.7×10^{-4}	3.37
FCCee	$64 \div 86$	240	13.7×10^{-4}	8.9
FCCee	$64 \div 86$	350	13.7×10^{-4}	13.0
ILC	$31 \div 77$	500	6.0×10^{-4}	12.2
ILC	$31 \div 77$	1000	6.0×10^{-4}	24.4
CLIC	$39 \div 134$	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%
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(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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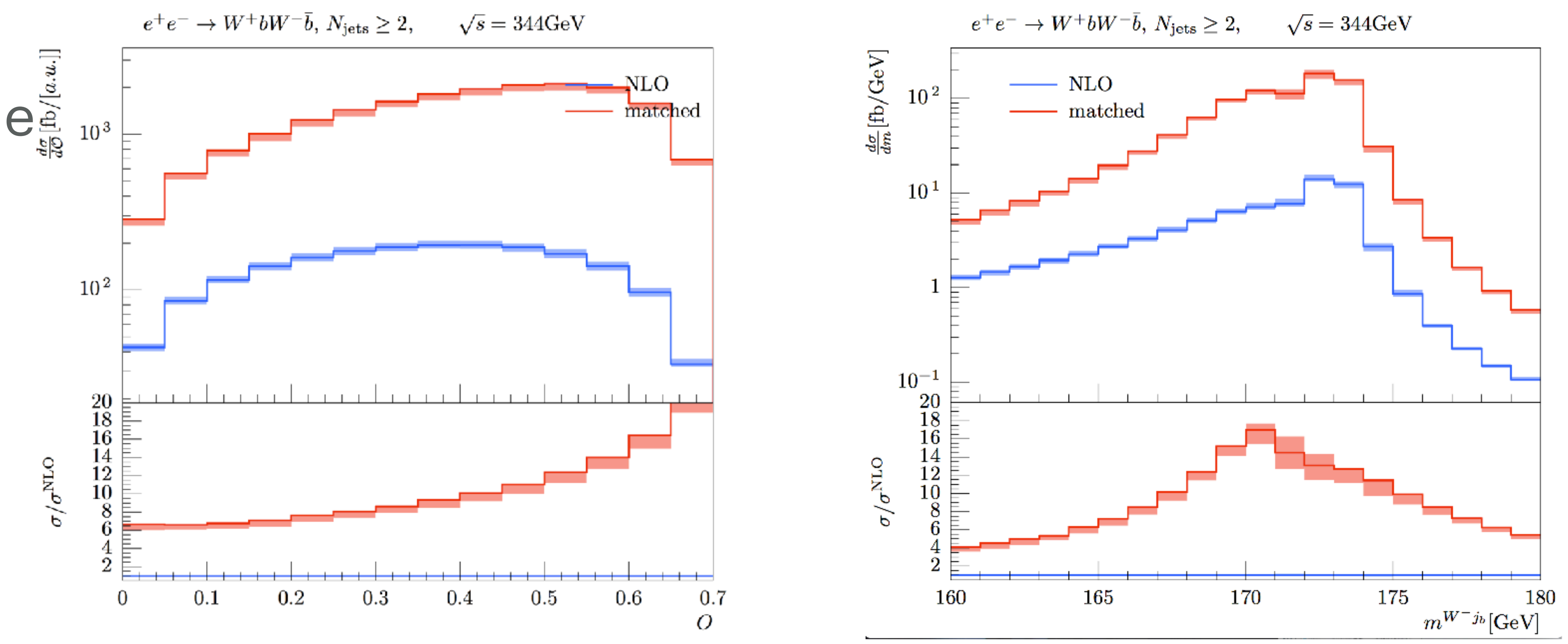
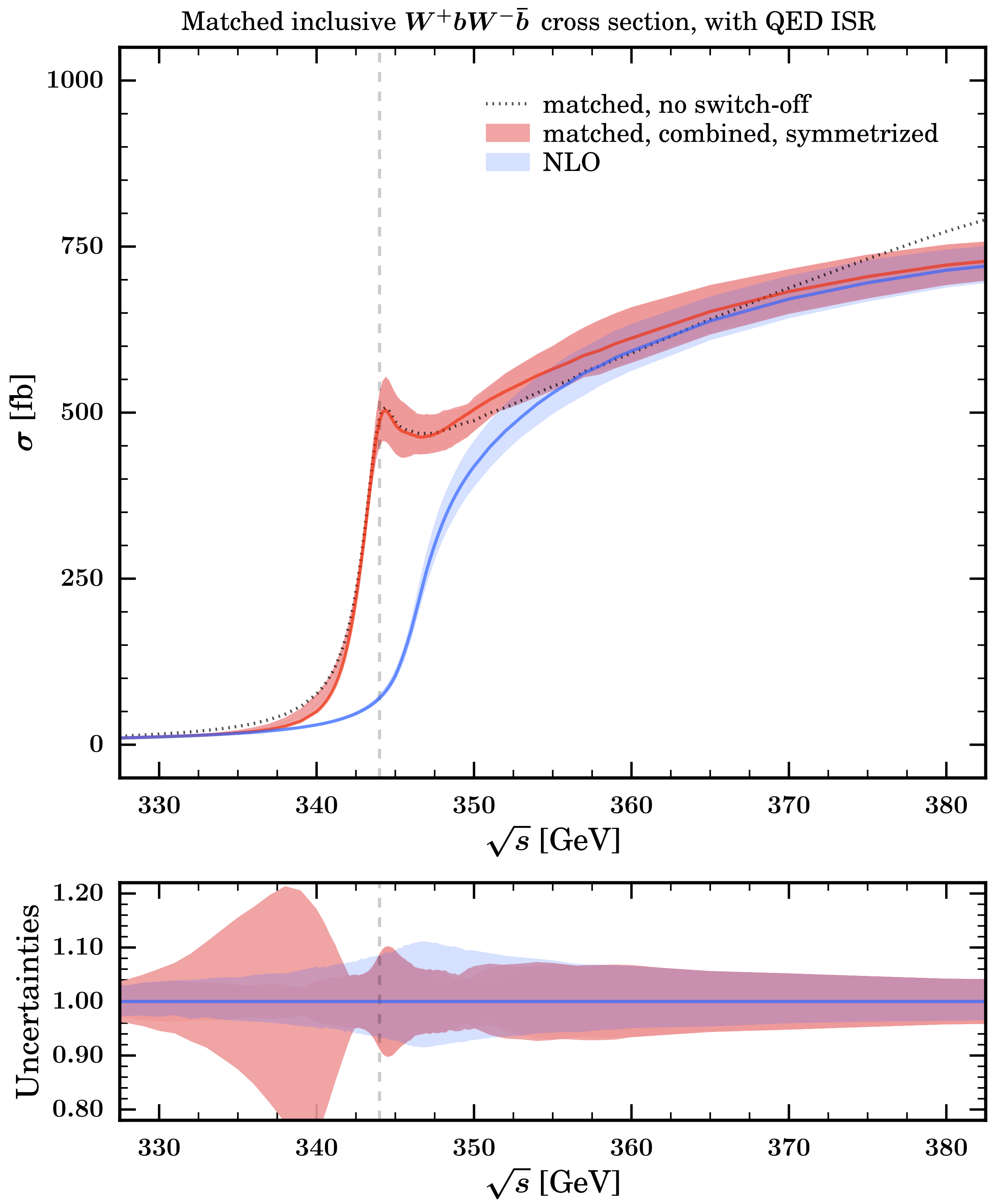
(d) Light pairs	0.5×10^{-4}	0.4×10^{-4}	0.4×10^{-4}
(e) Z and s-channel γ exch.	0.1×10^{-4}	$1.0 \times 10^{-4(*)}$	$1.0 \times 10^{-4(*)}$
(f) Up-down interference	0.1×10^{-4}	0.09×10^{-4}	0.1×10^{-4}
Total	1.0×10^{-4}	1.5×10^{-4}	1.6×10^{-4}

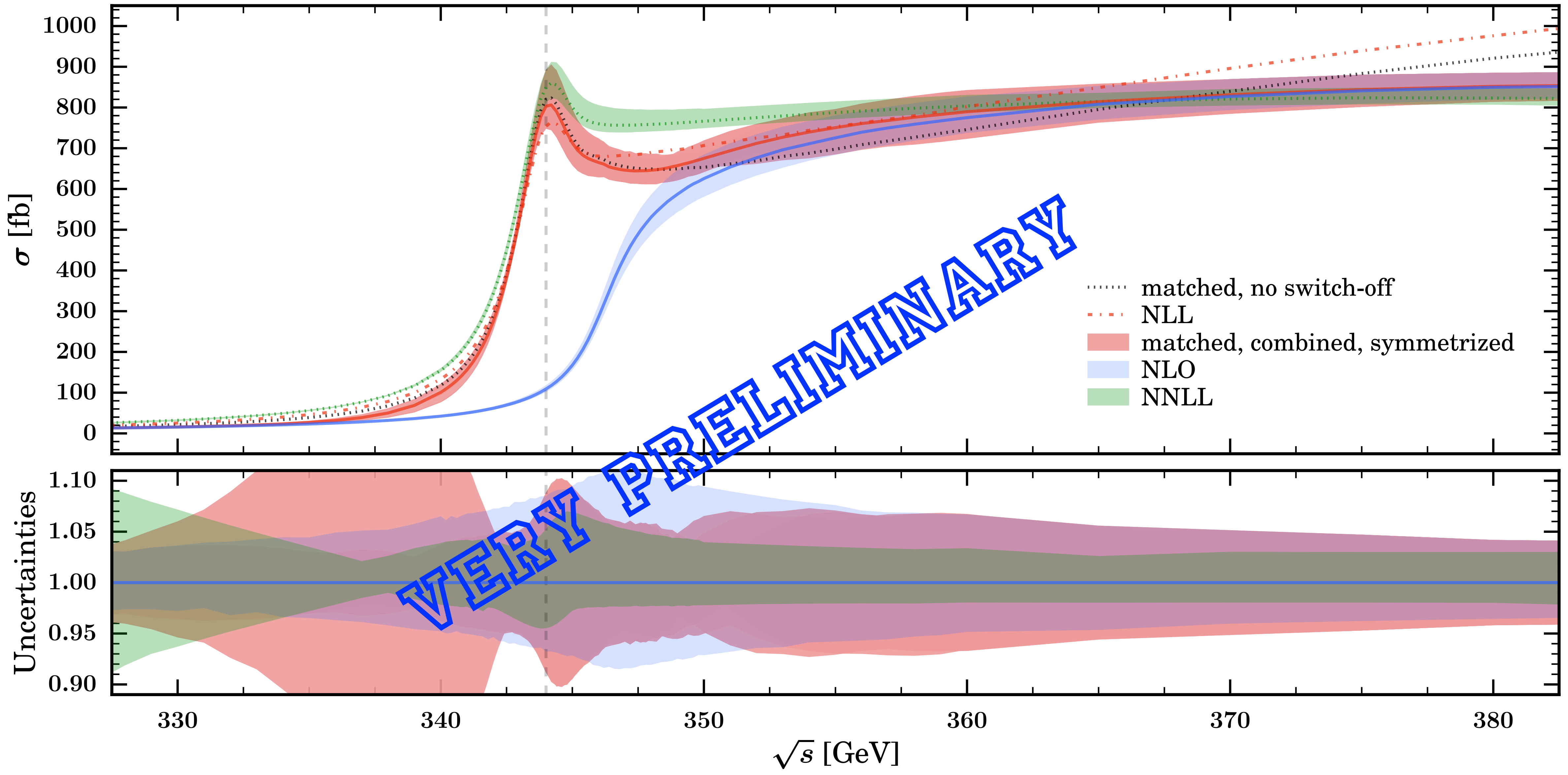
- Technical precision needs 2nd code: `BHLumi` vs. `BabaYaga` (NNLO in hard process possible)
- Major ingredients: hadronic vacuum polarization, EW corrections, light fermion pairs
- Inclusion of 4f, 4f + γ, 5f, 6f backgrounds necessary at matrix element level

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



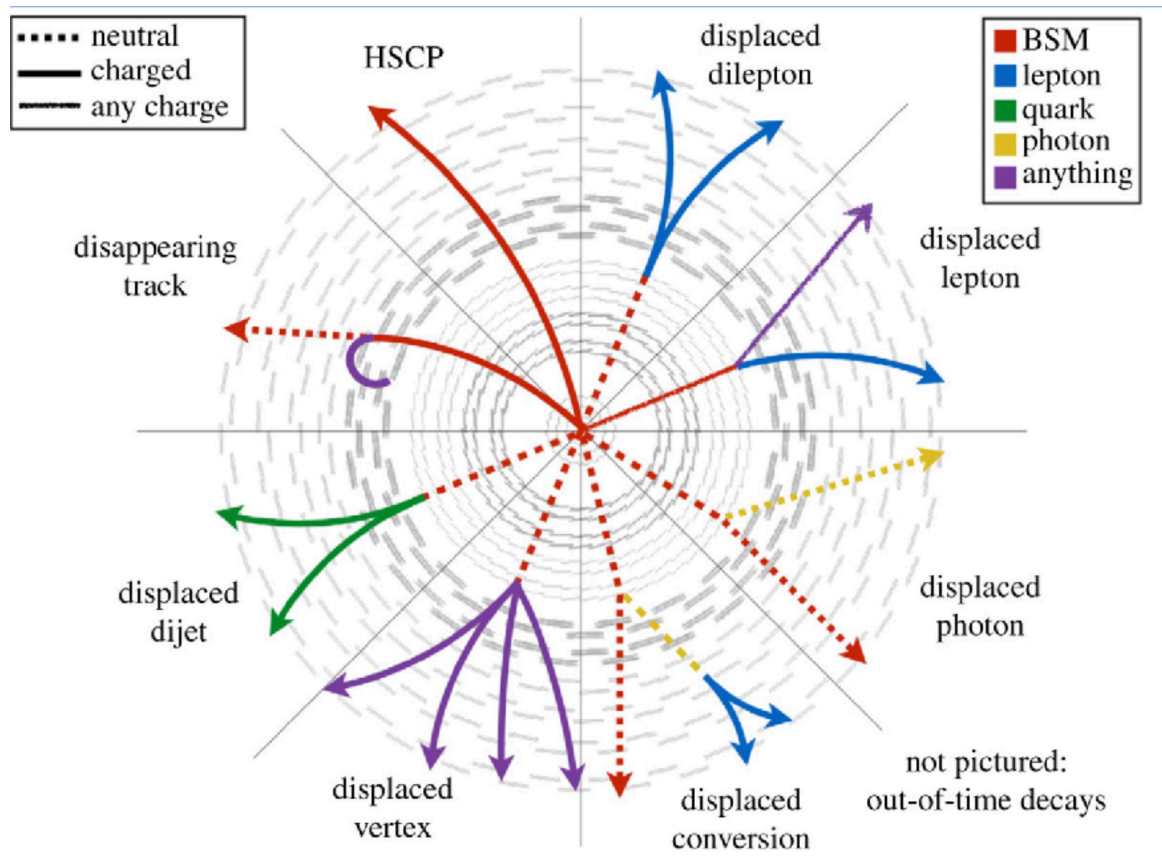




BSM Modelling in Simulation

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



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

- ☑ 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

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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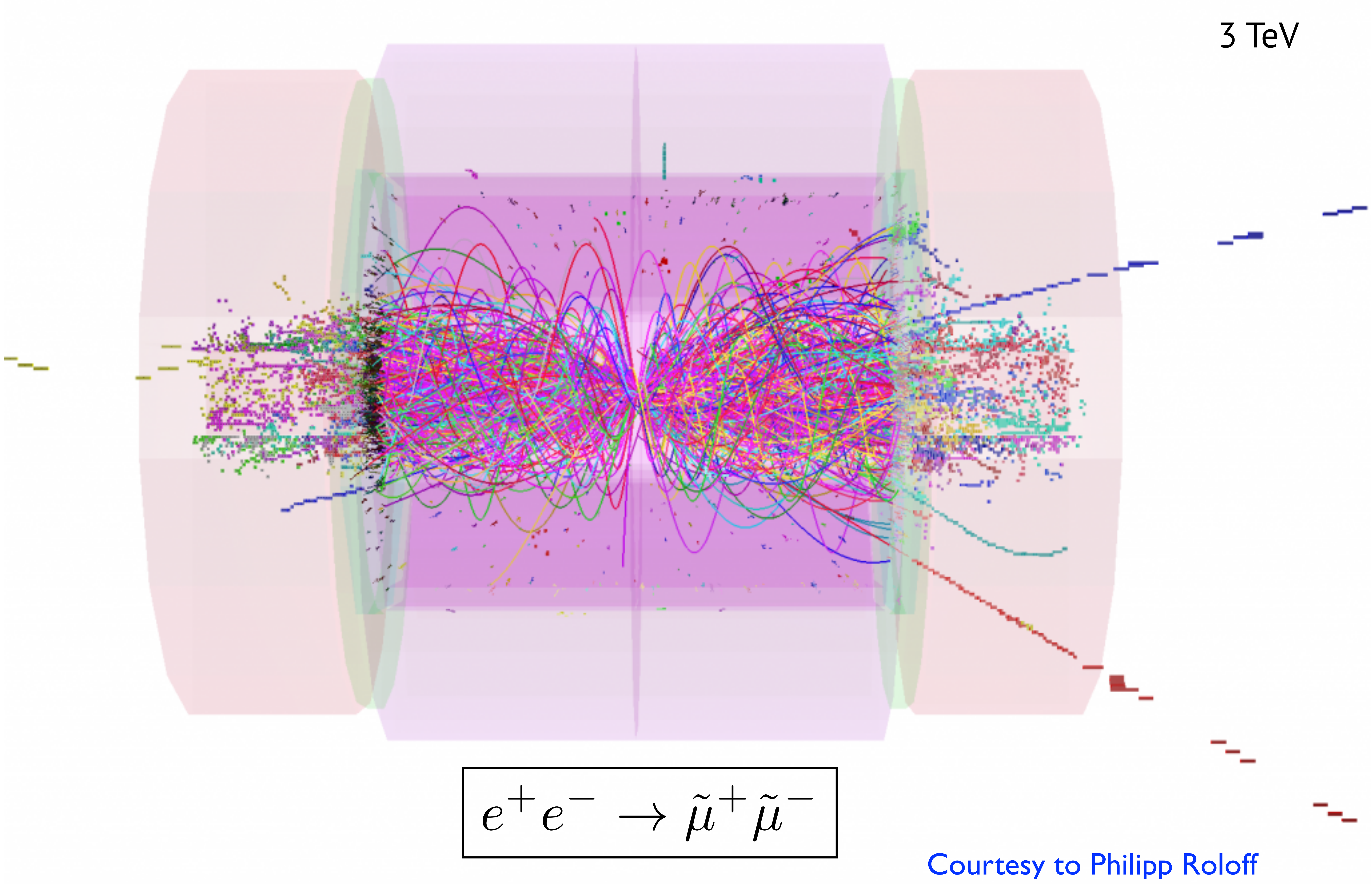
BACKUP

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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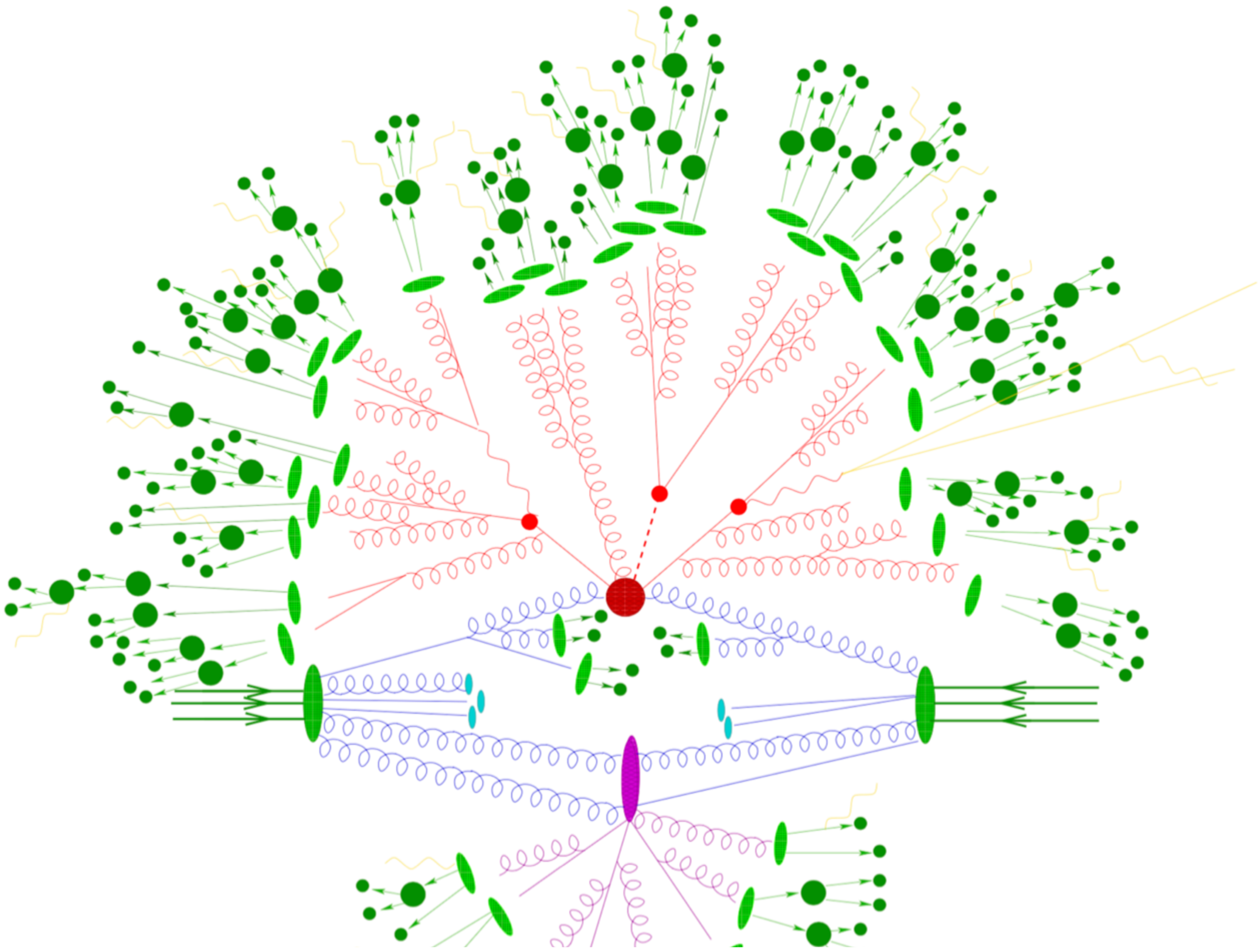

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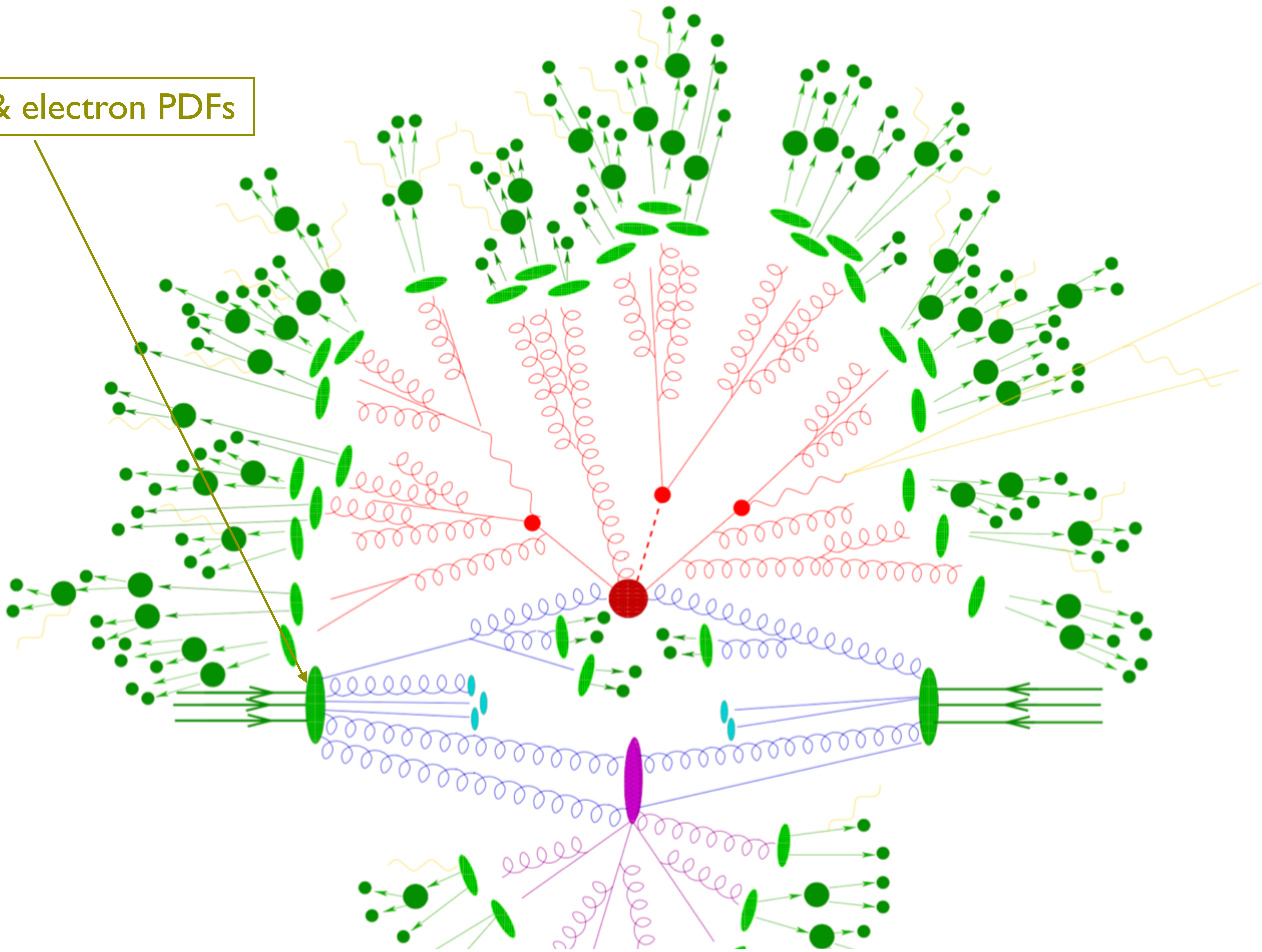
Beam spectra & electron PDFs



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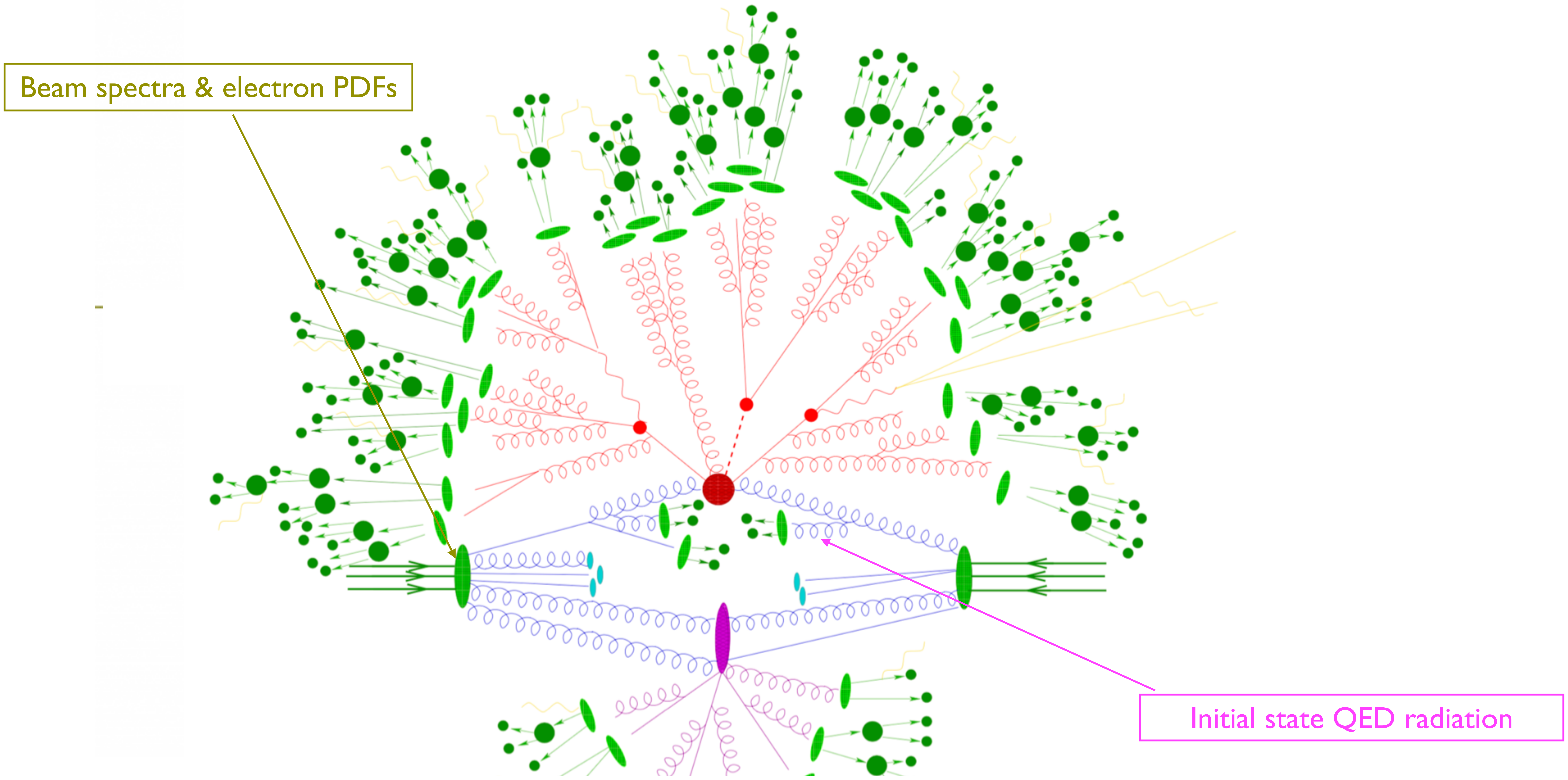

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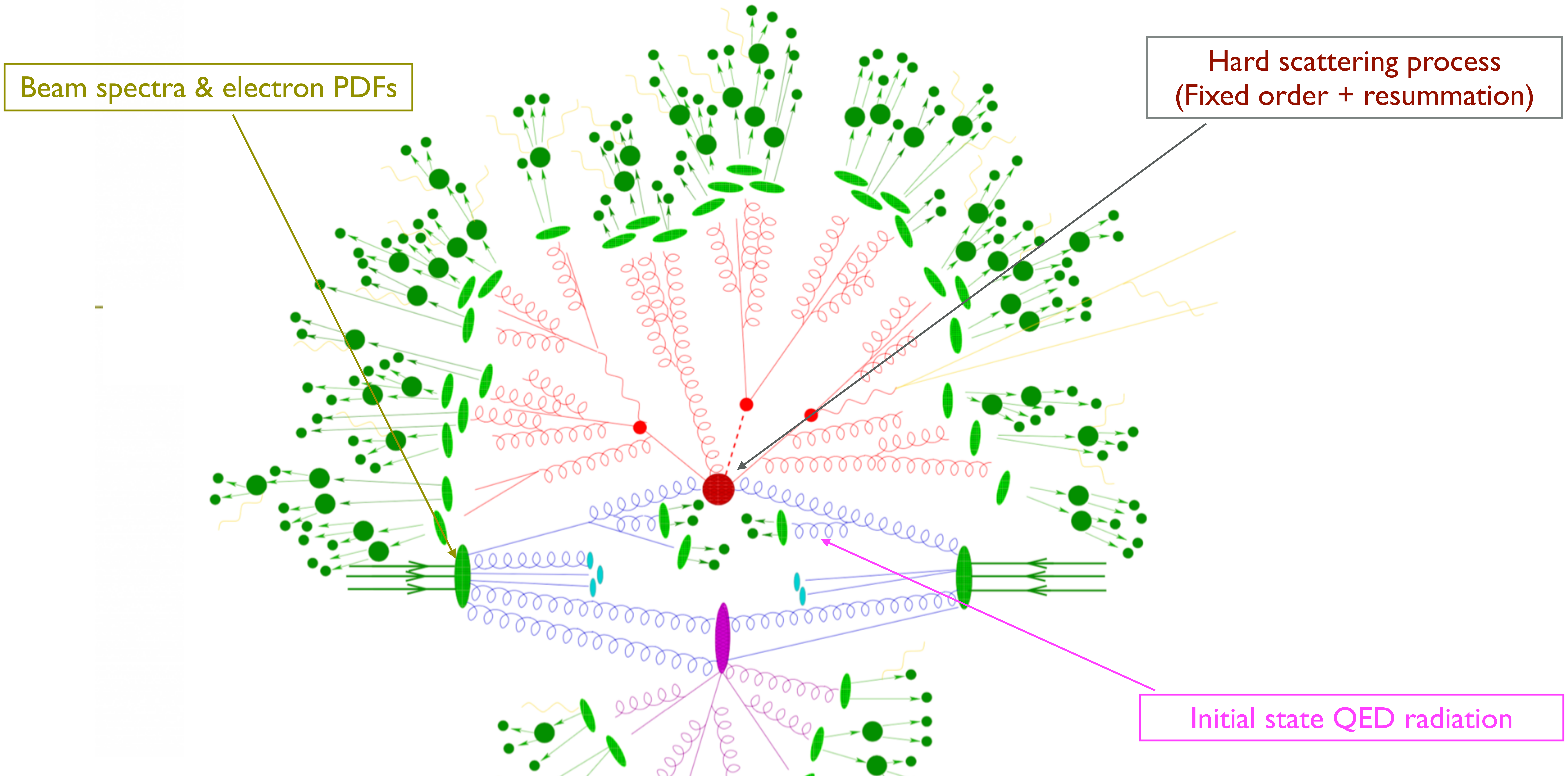

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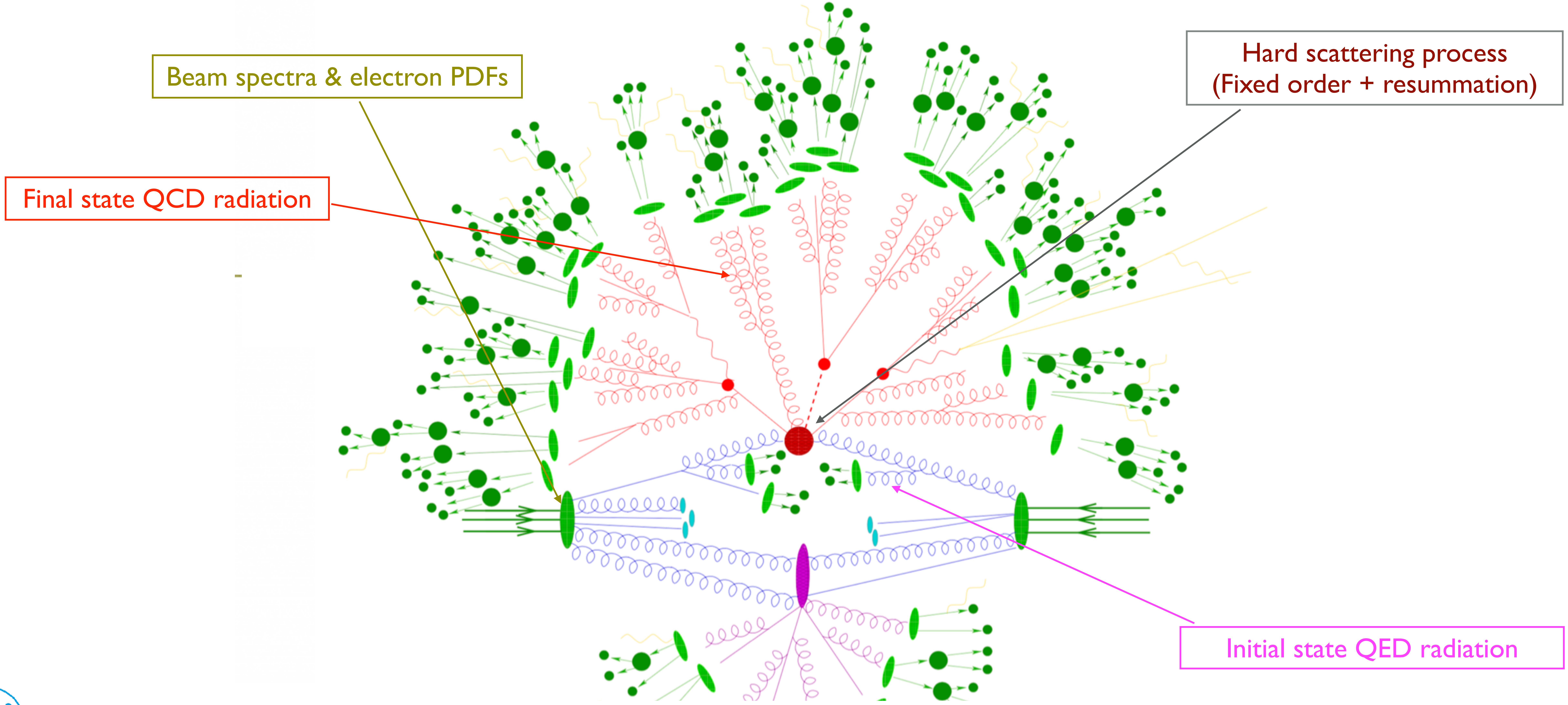

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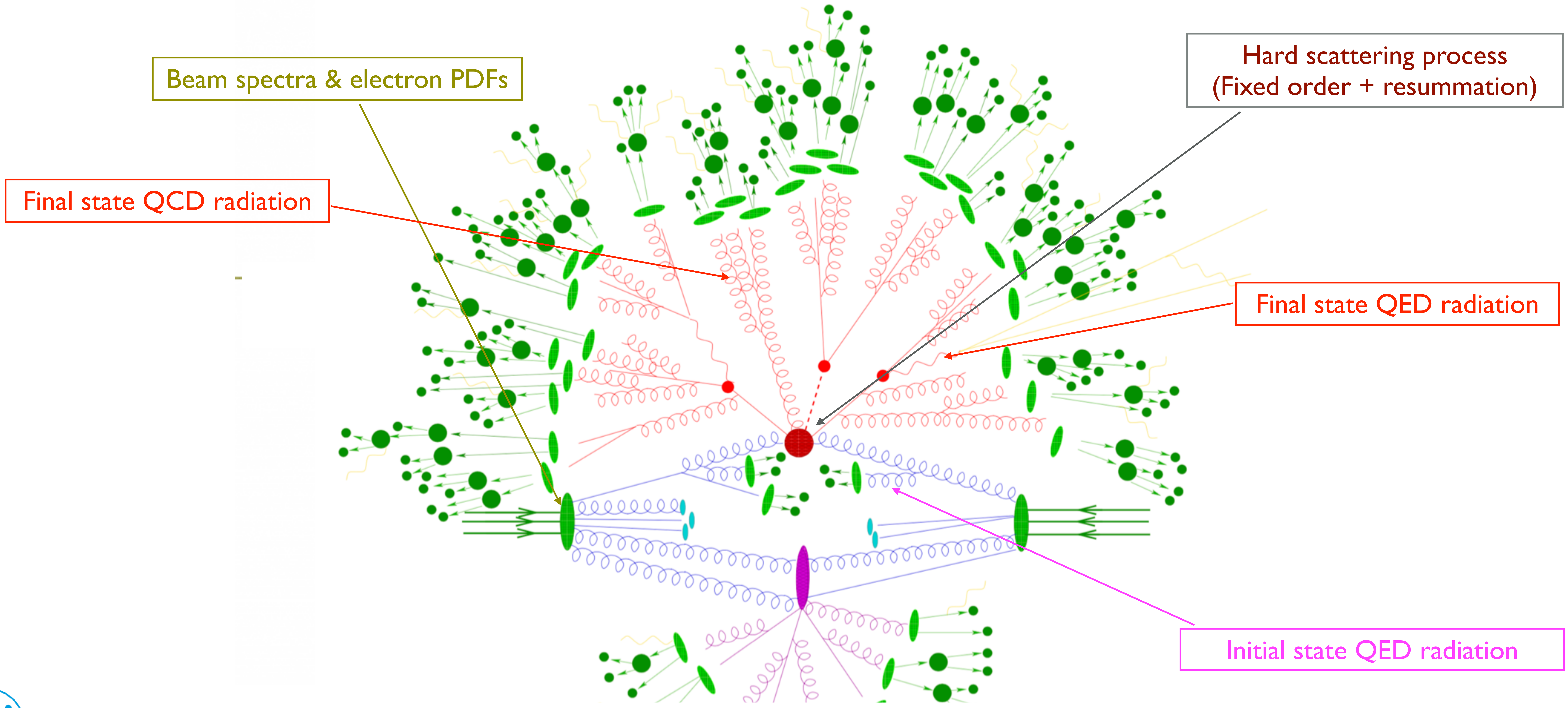

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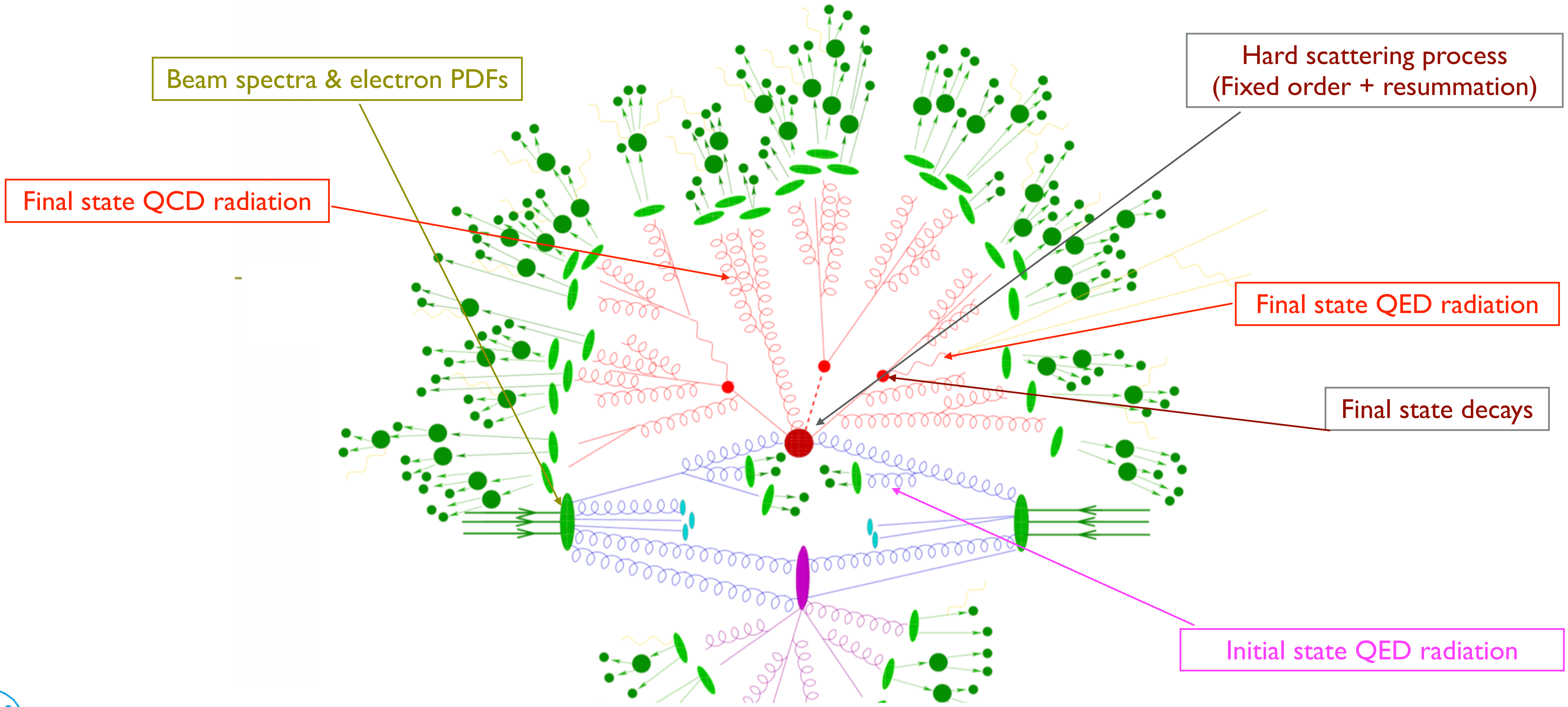

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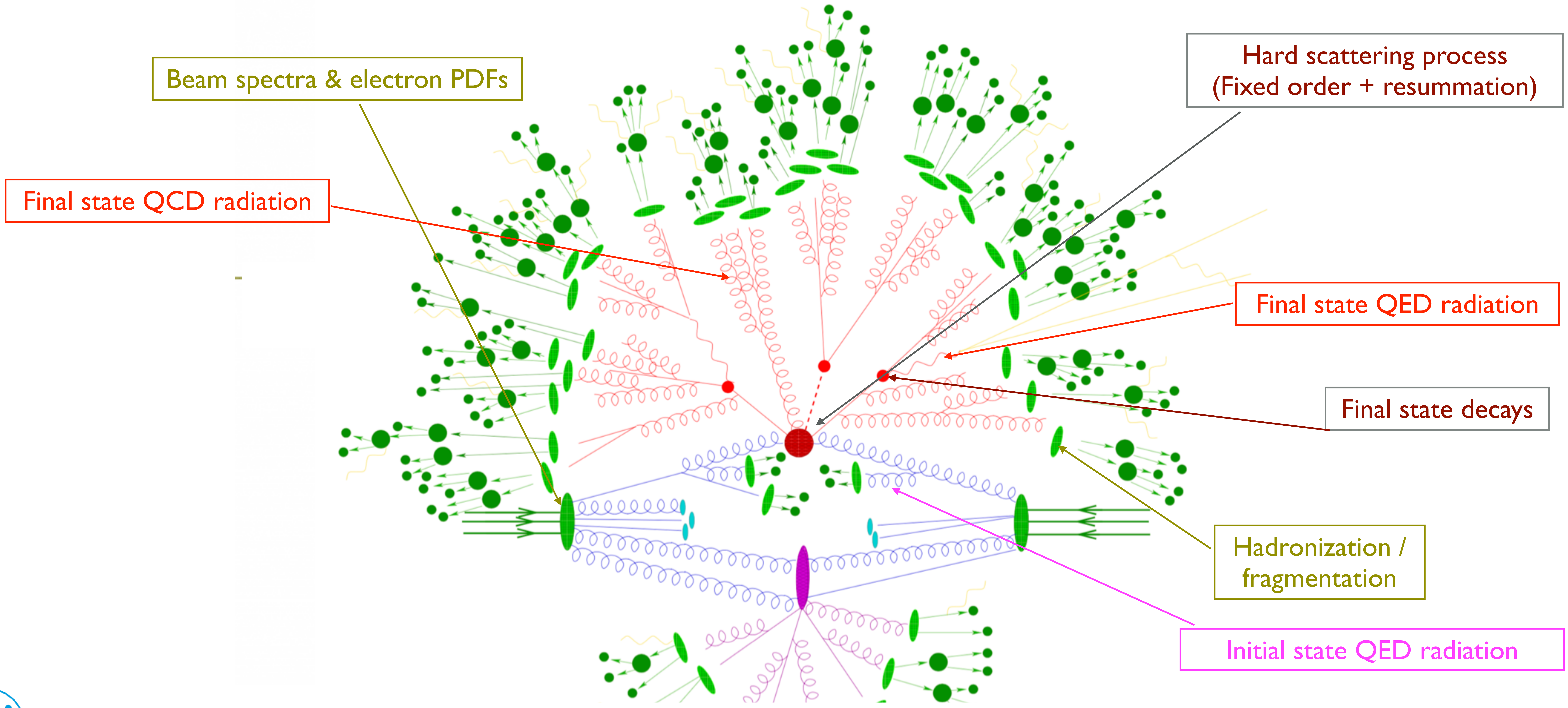

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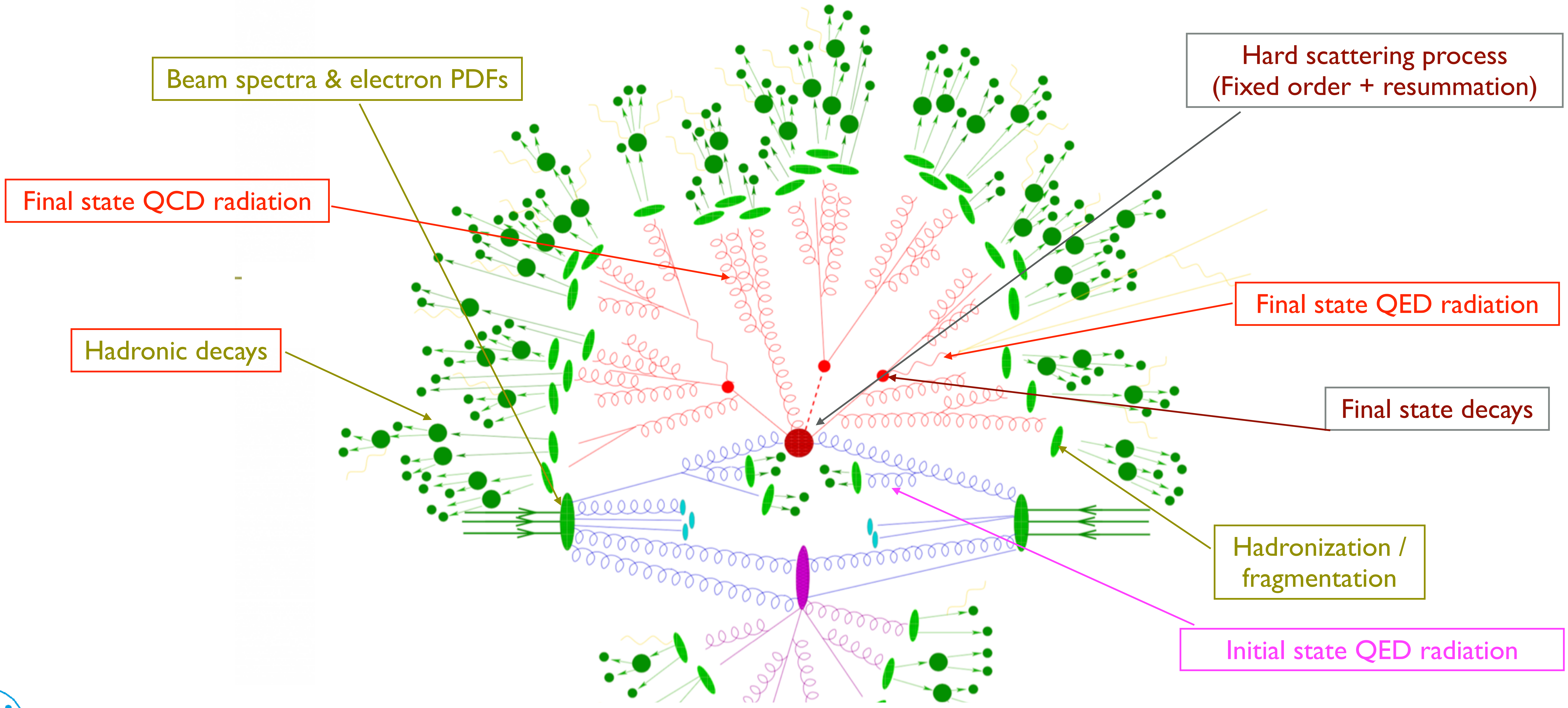

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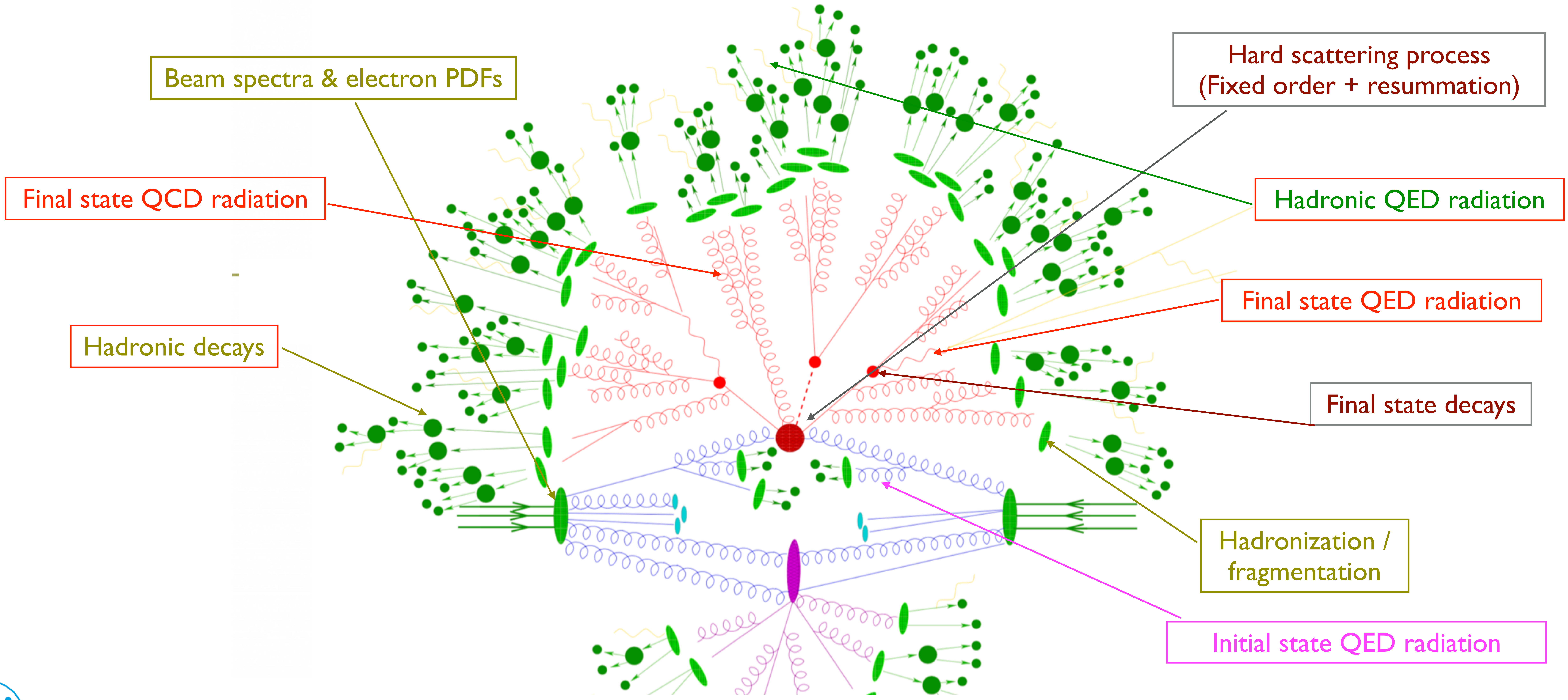

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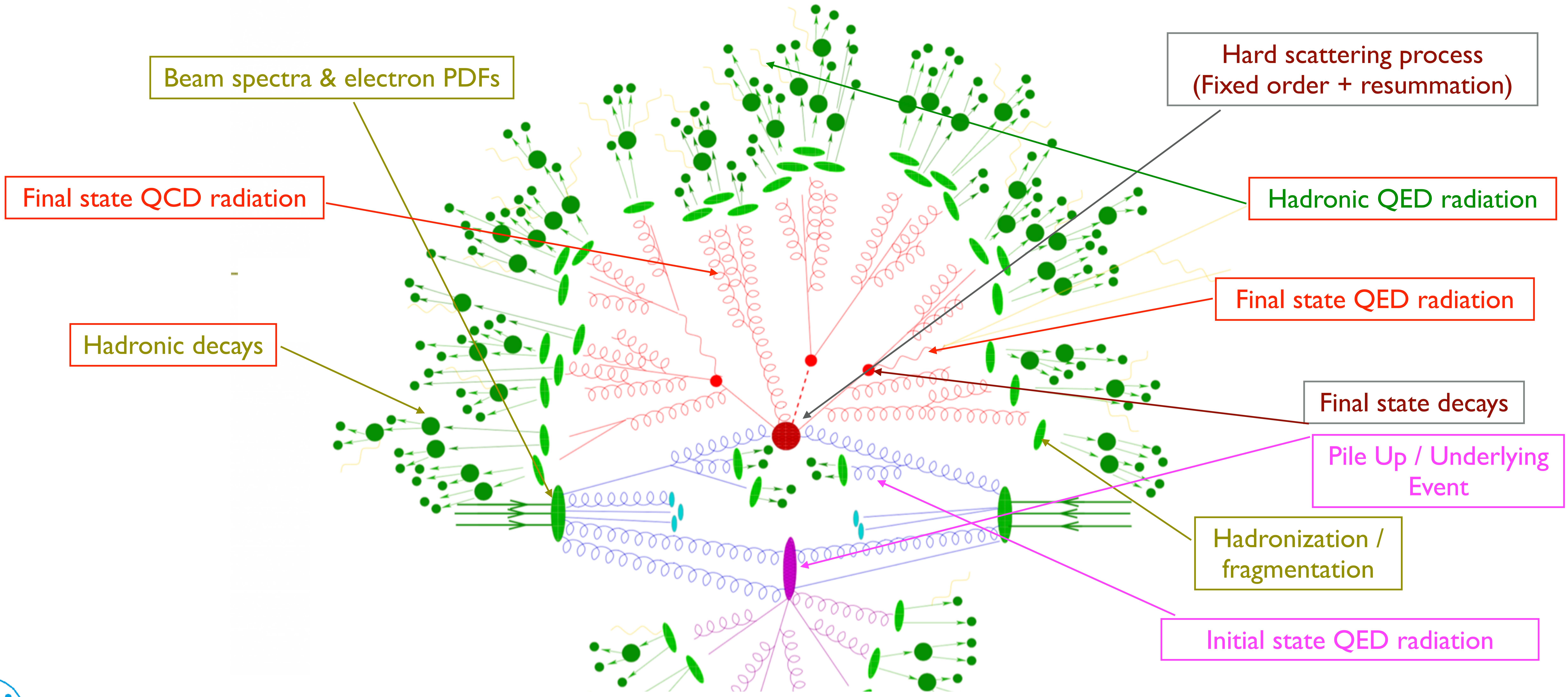

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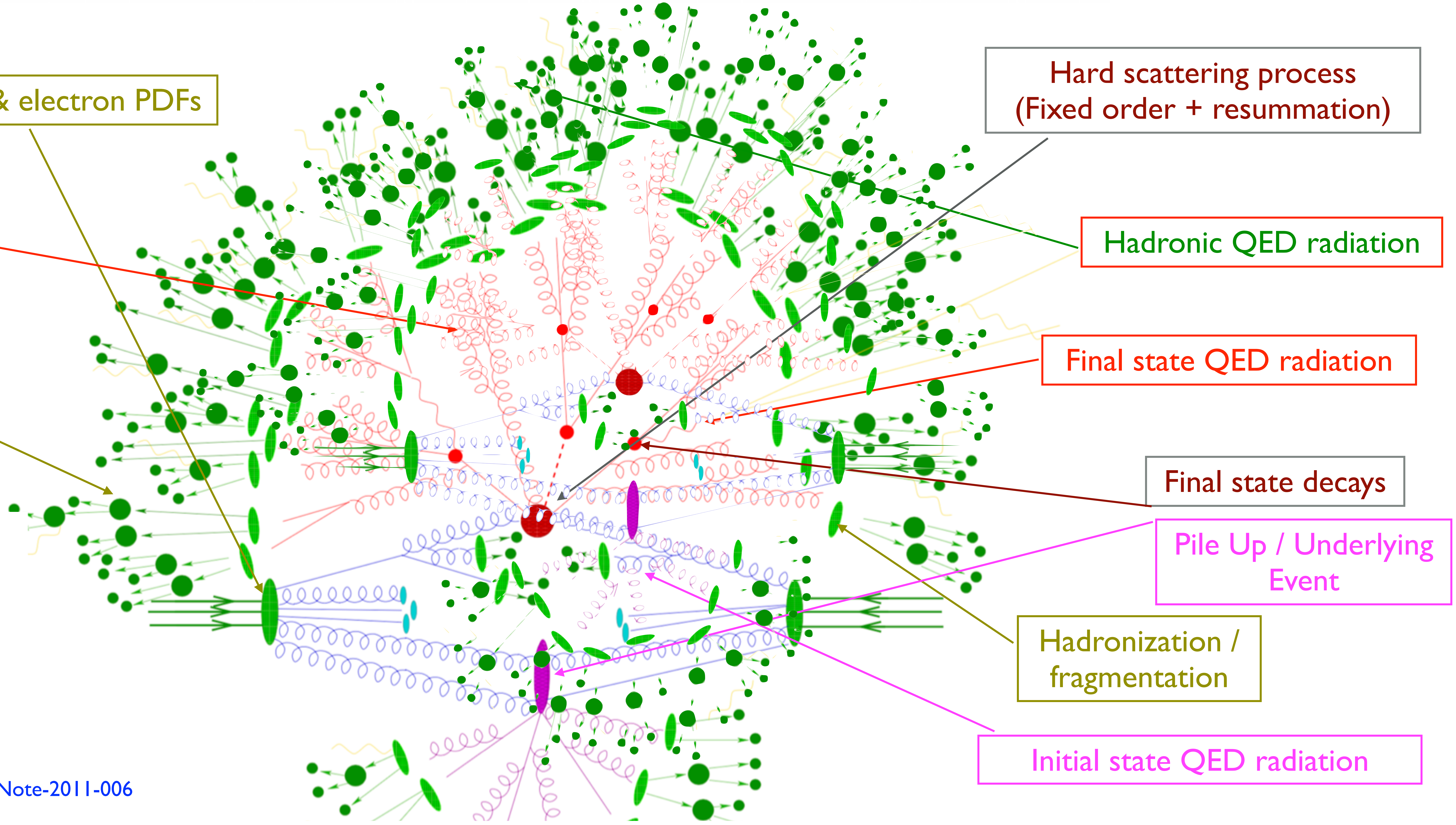
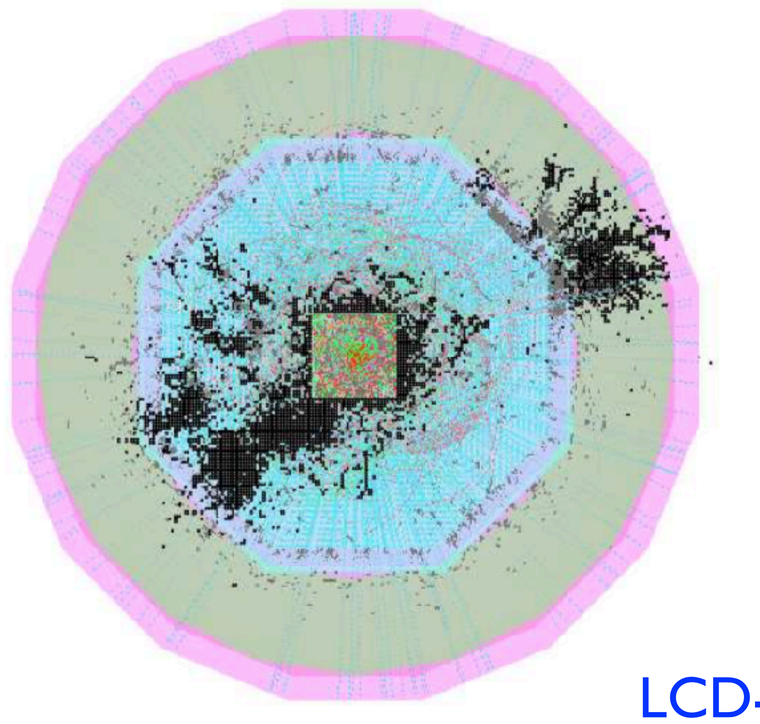




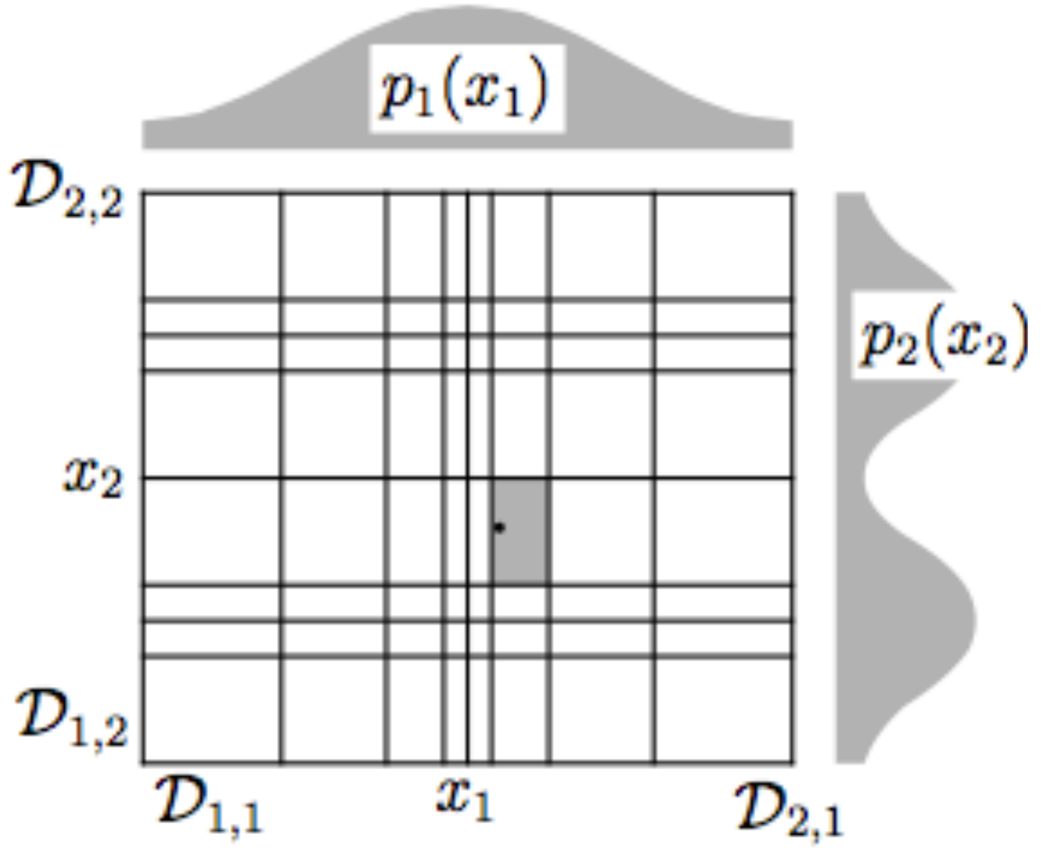
LCD-Note-2011-006

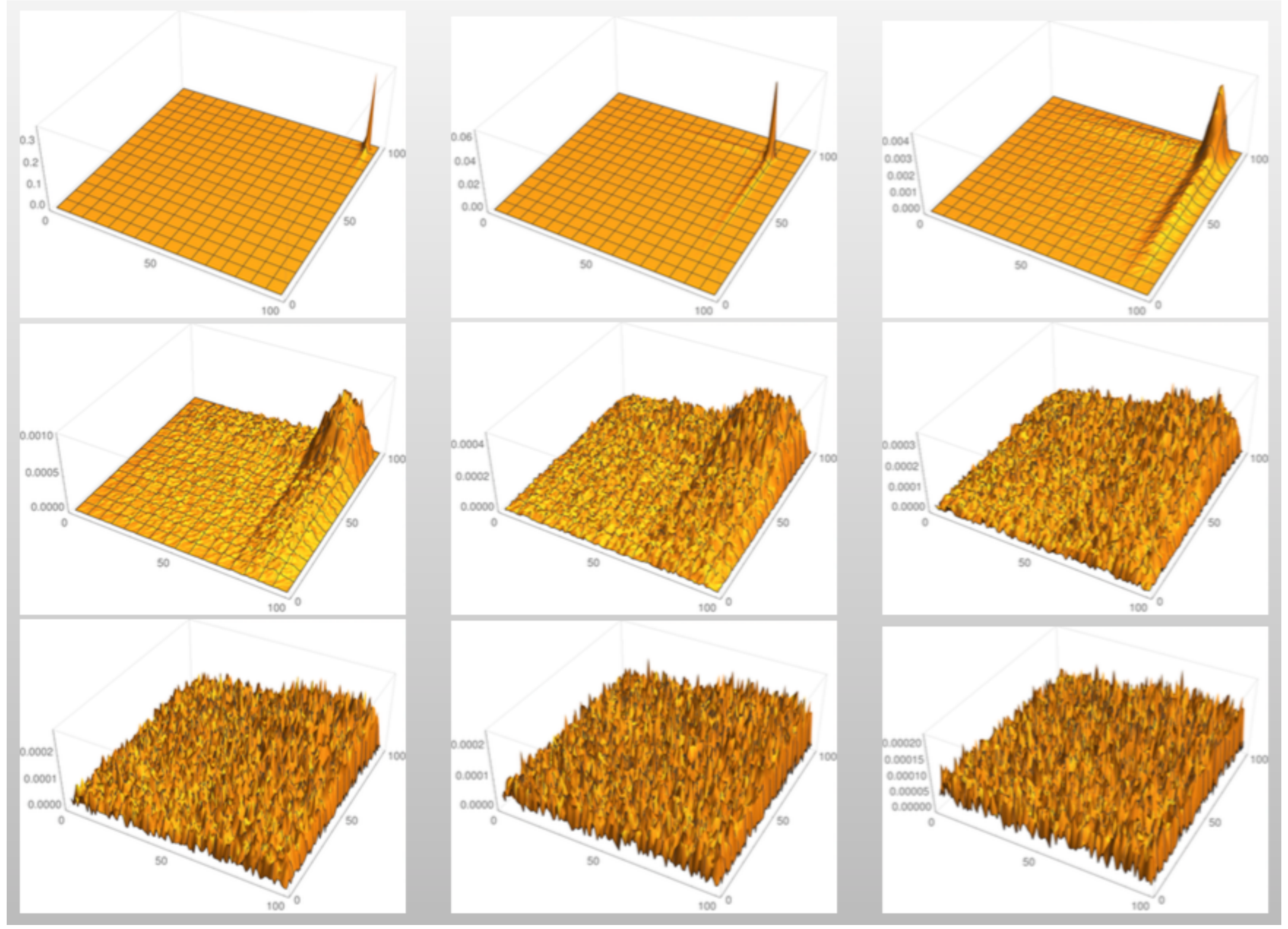
Beam simulations (technial details)

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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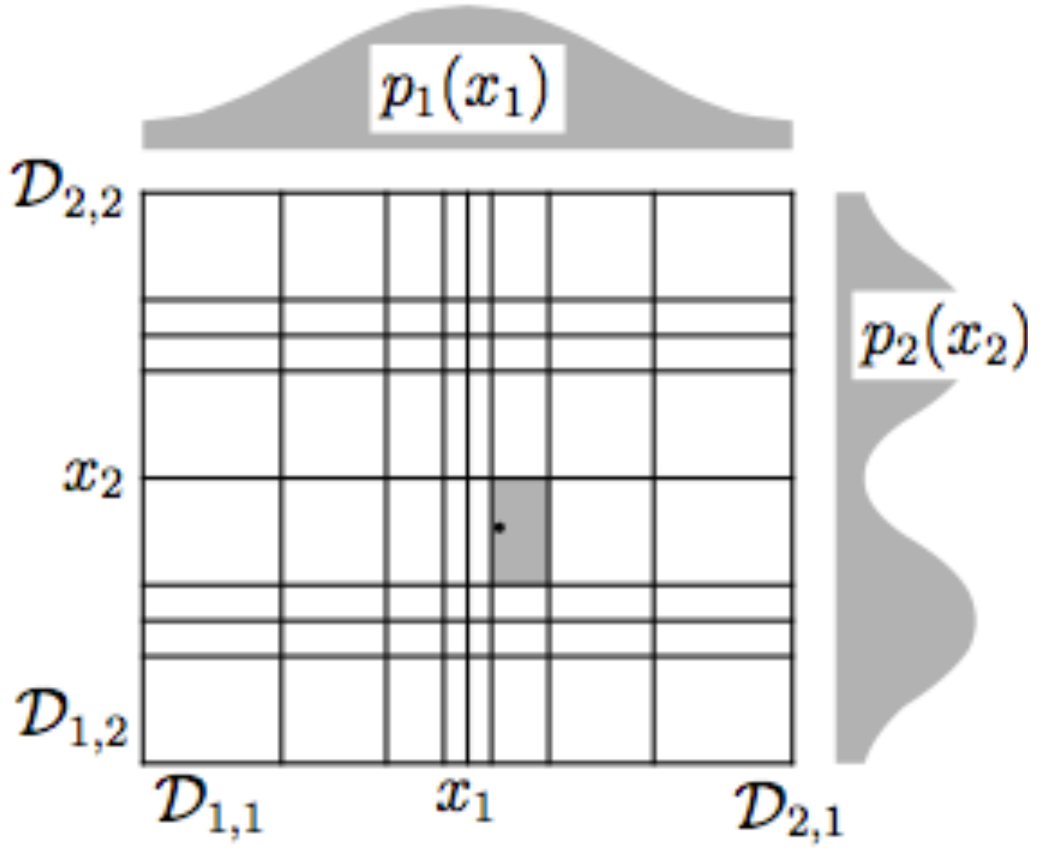

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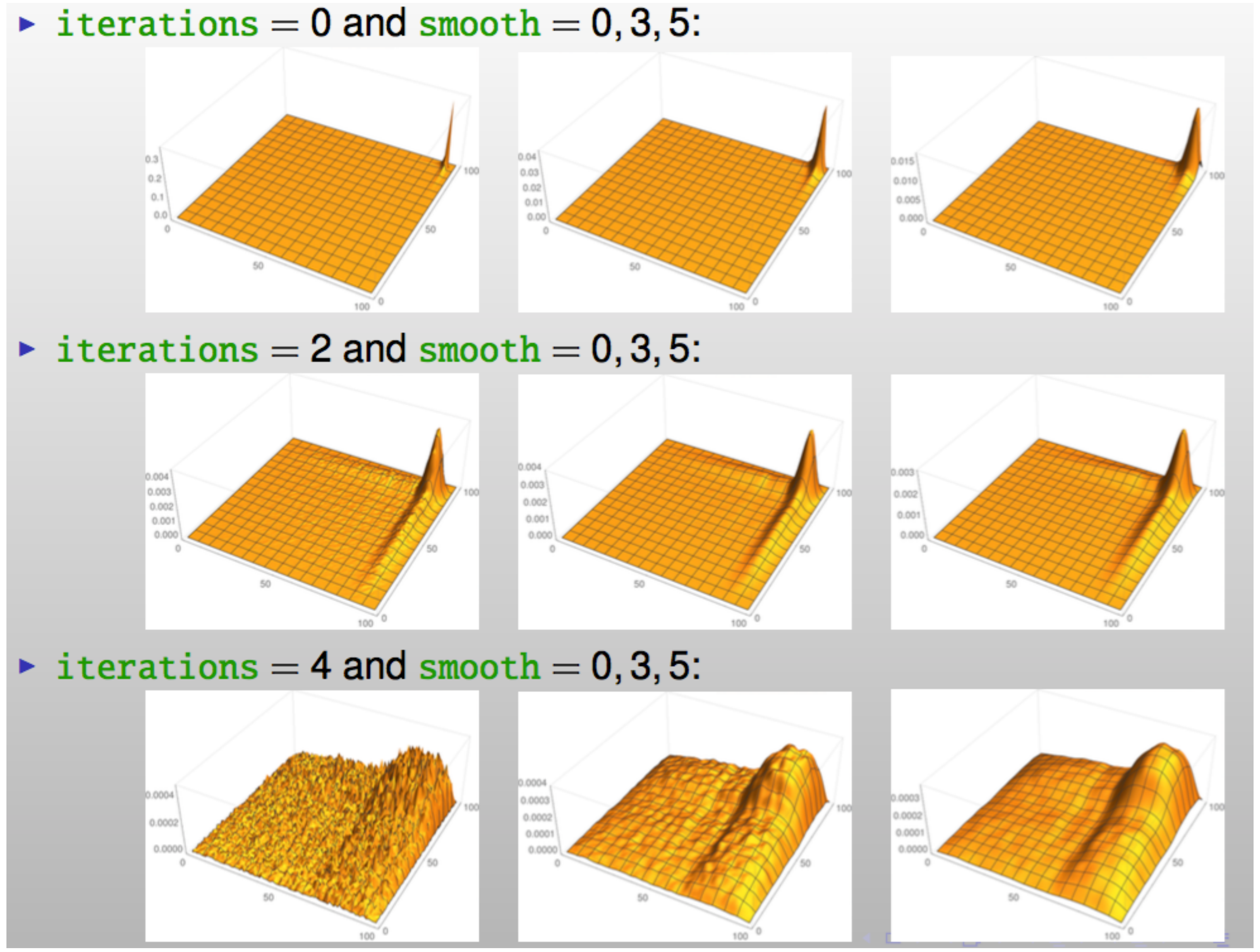

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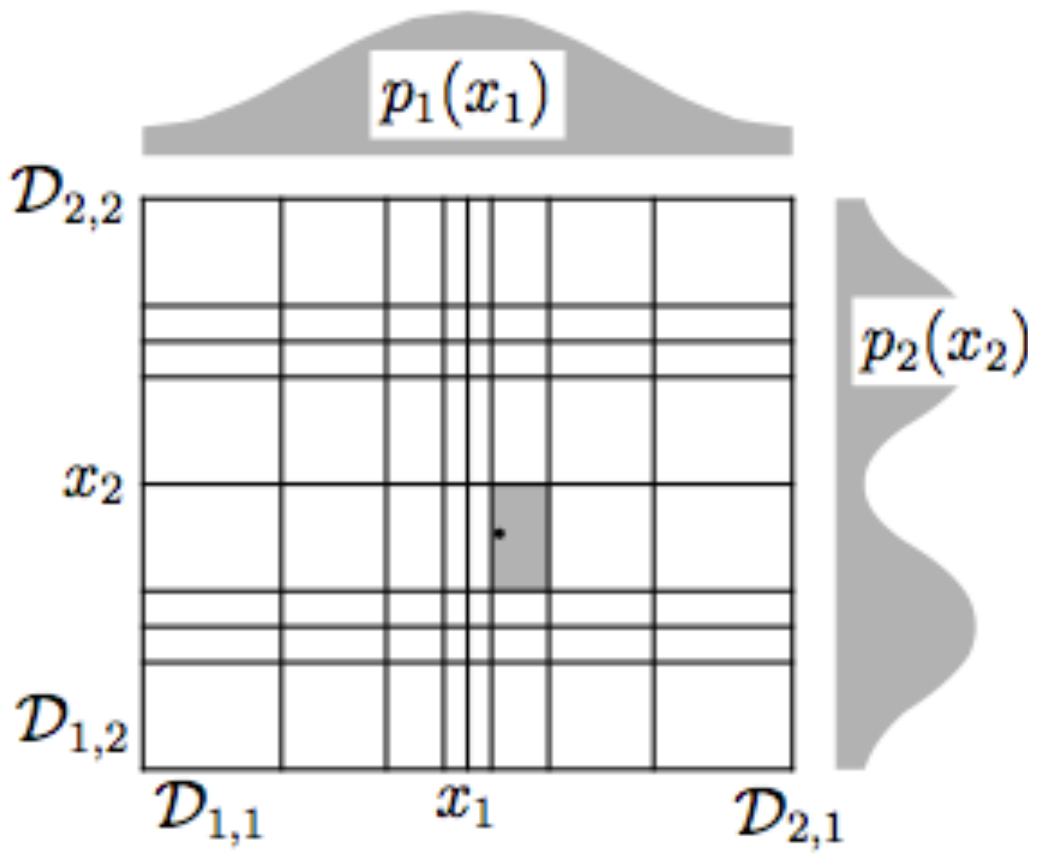

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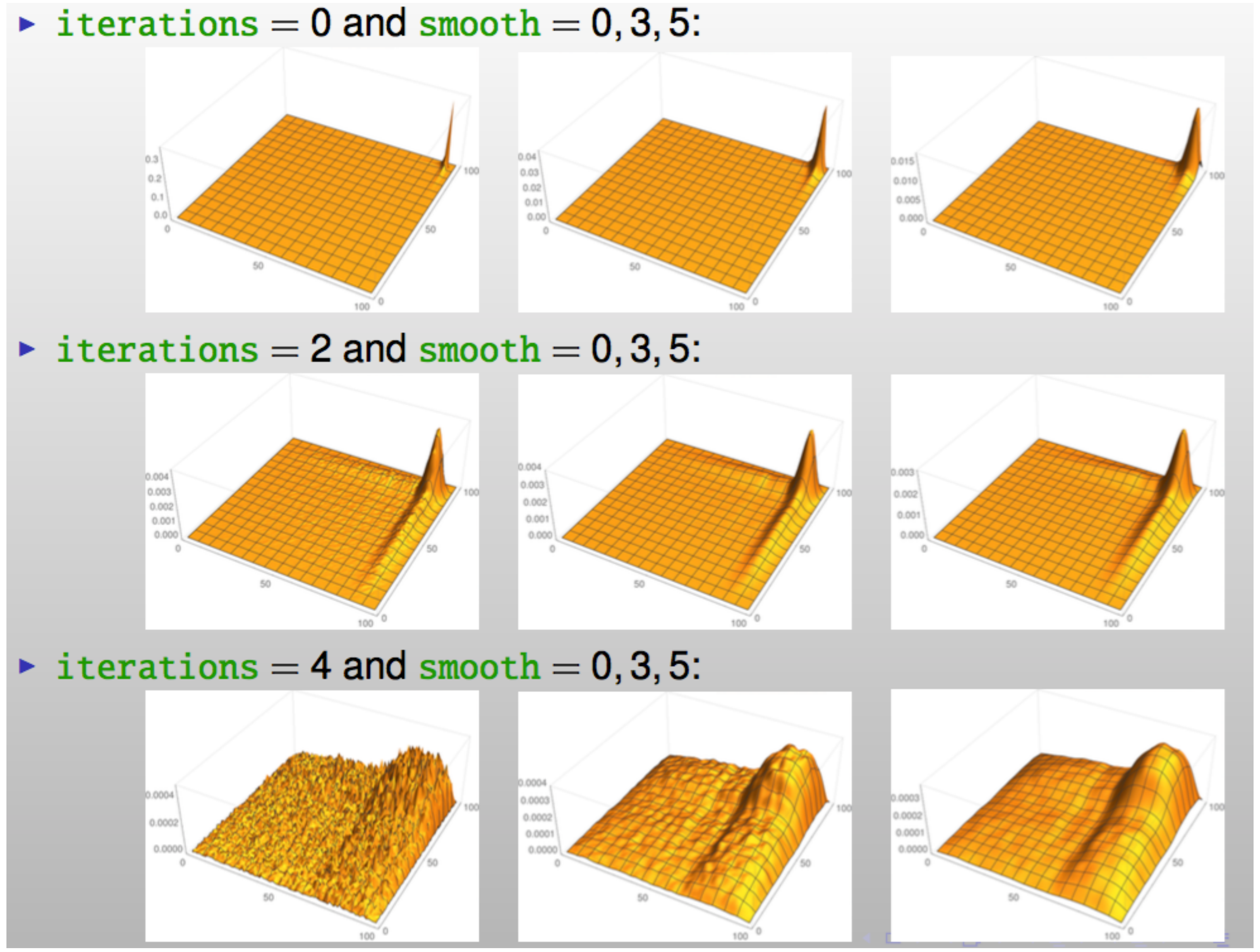


1. Run Guinea-Pig++ with

```
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

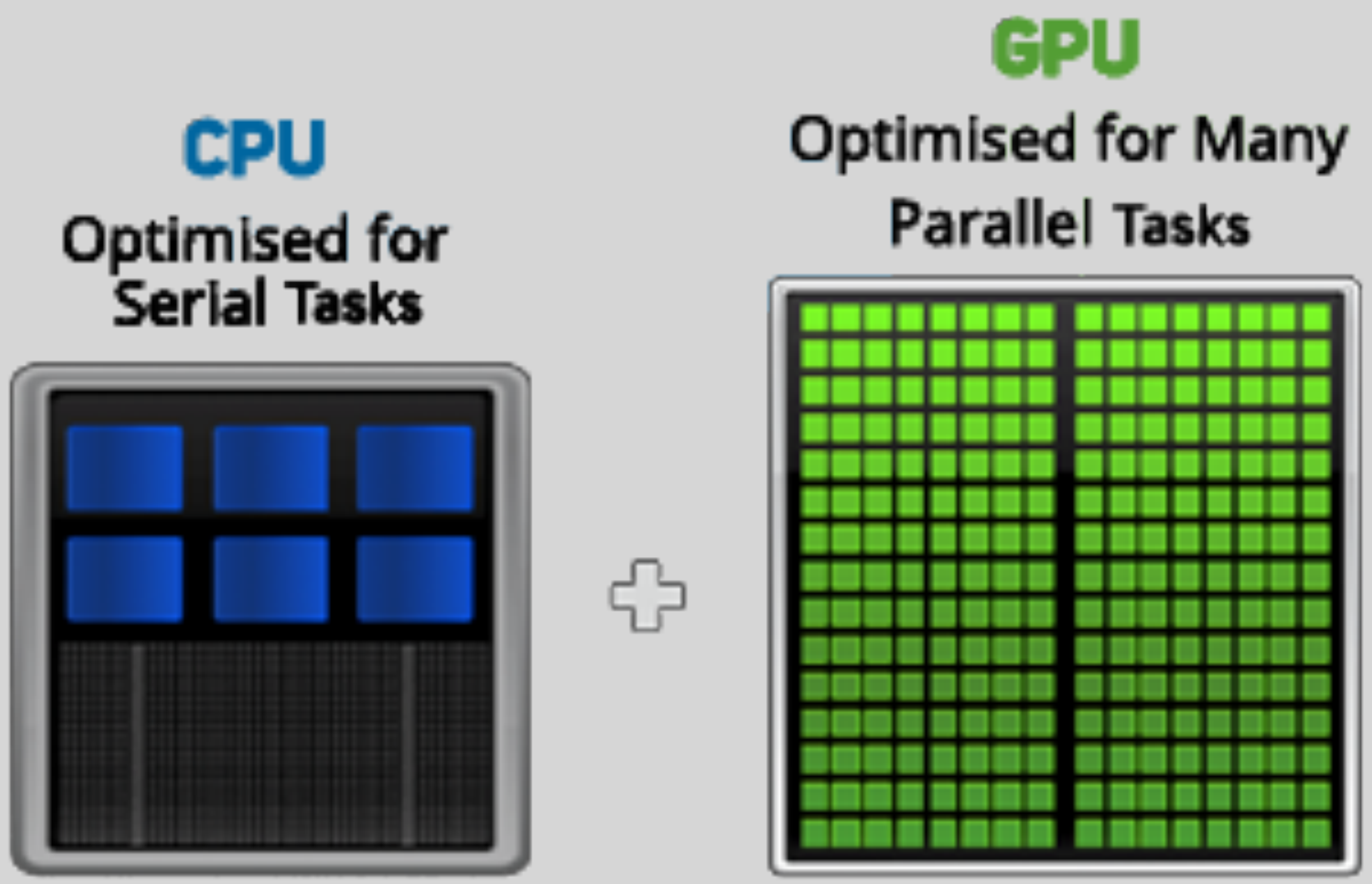
3. Run WHIZARD with SINDARIN input:

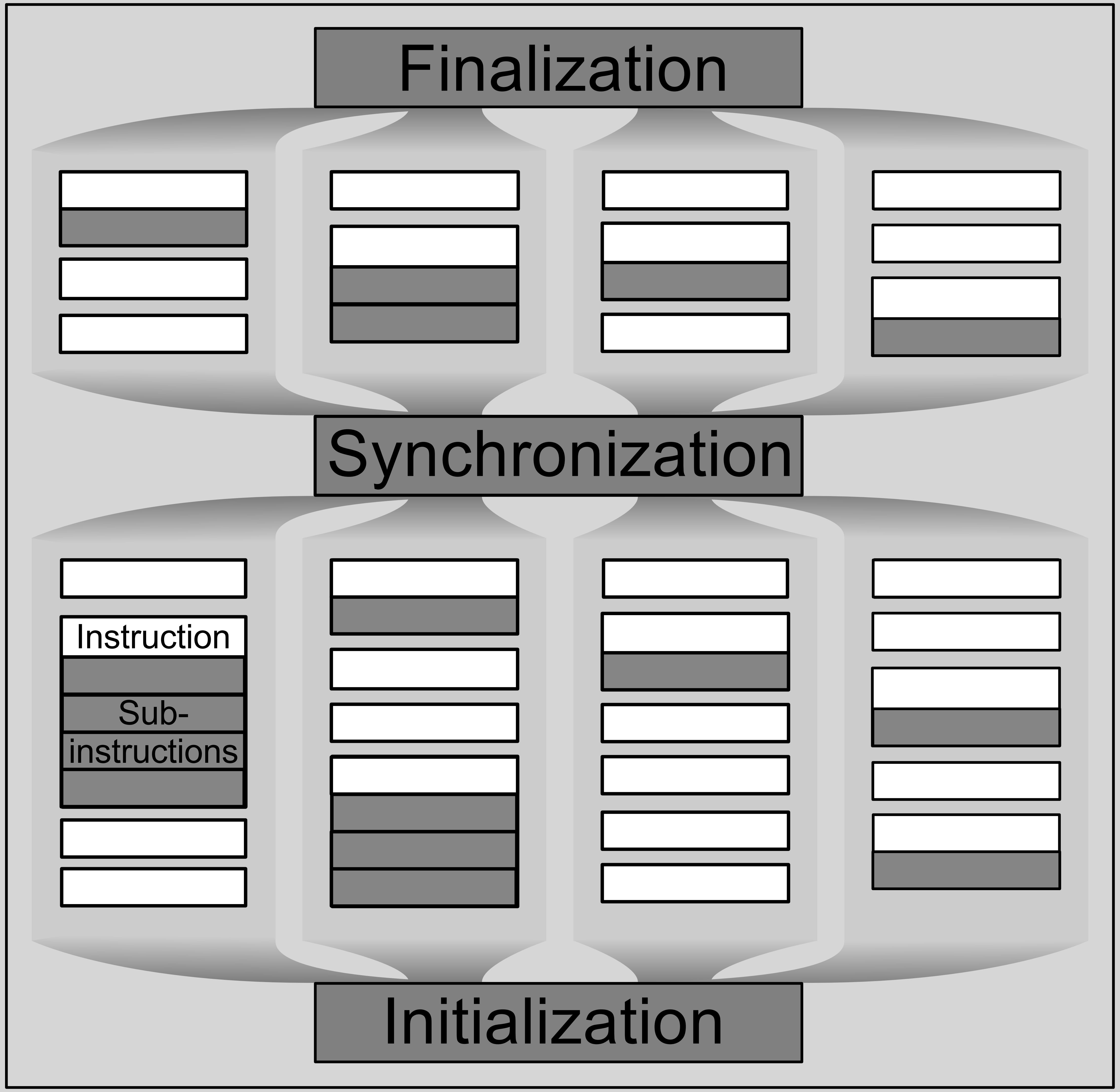
```
beams = e1, E1 => circe2
$circe2_file = "ilc500.circe"
$circe2_design = "ILC"
?circe_polarized = false
```

3 simulation options

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

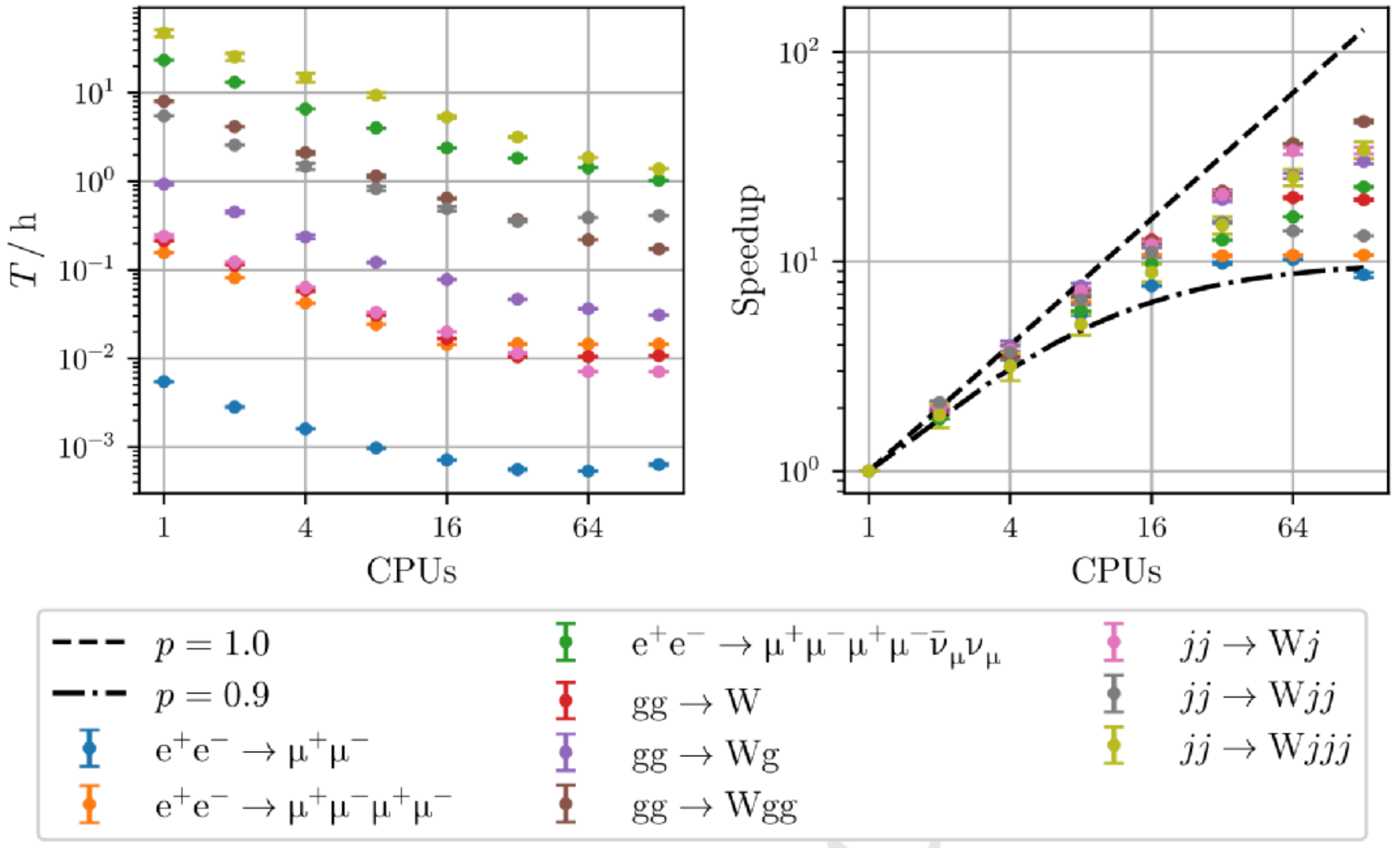
Monte Carlo Efficiency / Speed Up





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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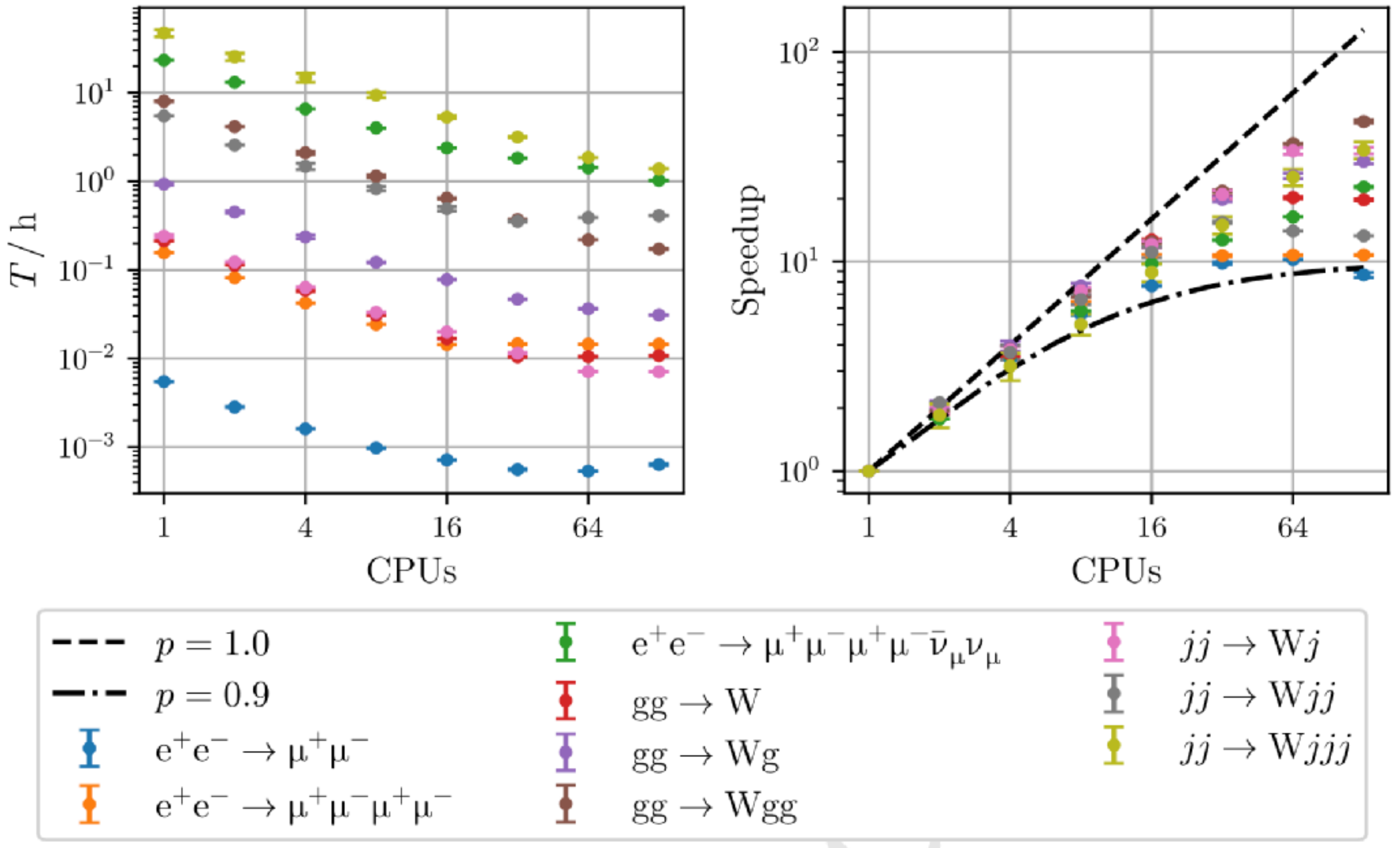

- Offloading of MEs / parts of infrastructure code to GPU
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- Still a lot of work needed to make it fully competitive

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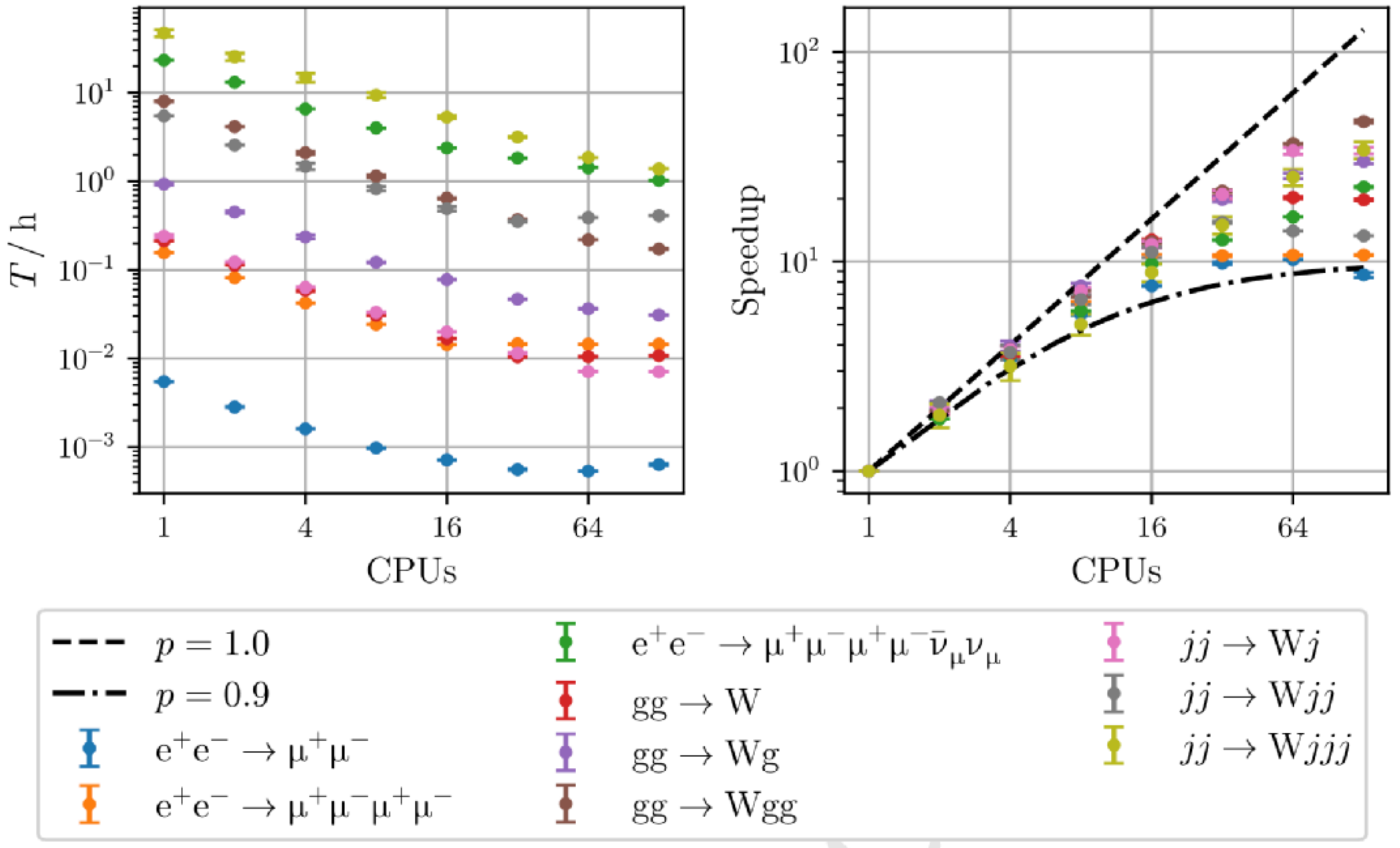

Very preliminary:

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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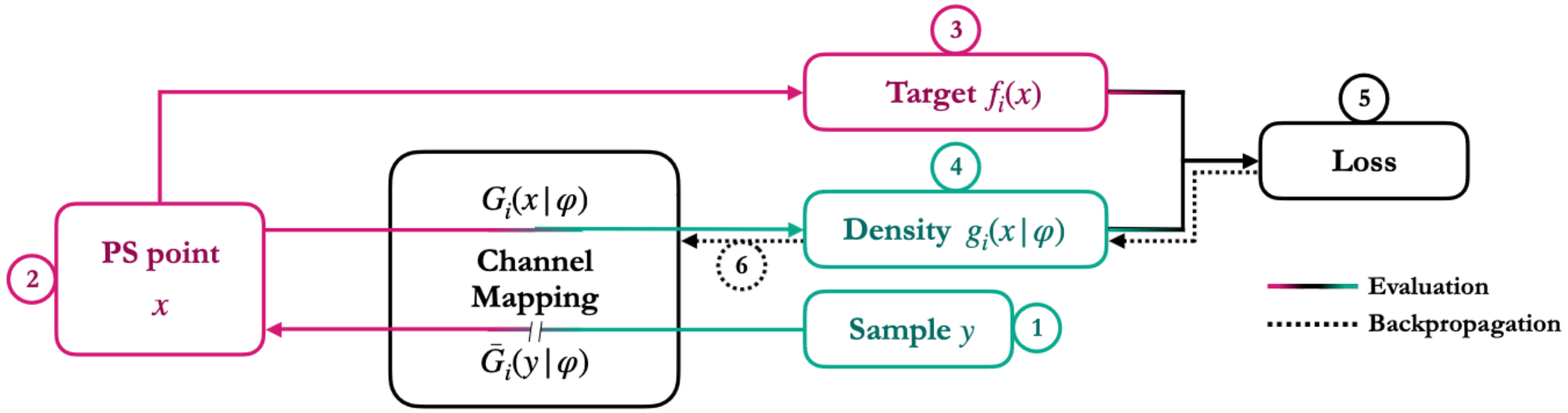
Machine Learning: MC for integration and simulation

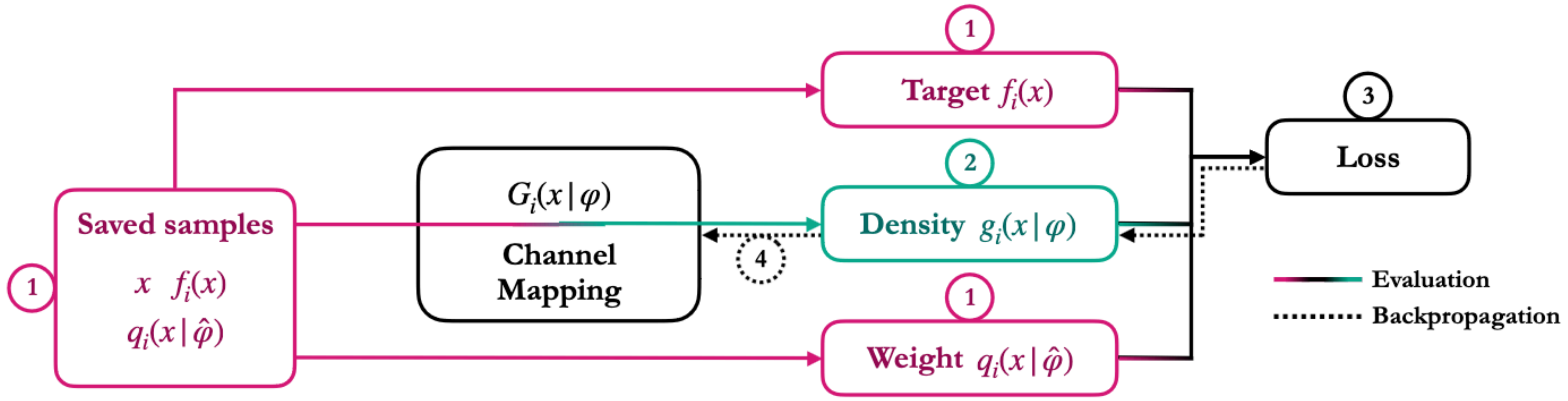
- Phase space integration / adaptation by Invertible Neural Networks (INNs) / normalizing flows
- Define divergence-based loss function
- Use of buffered losses and training

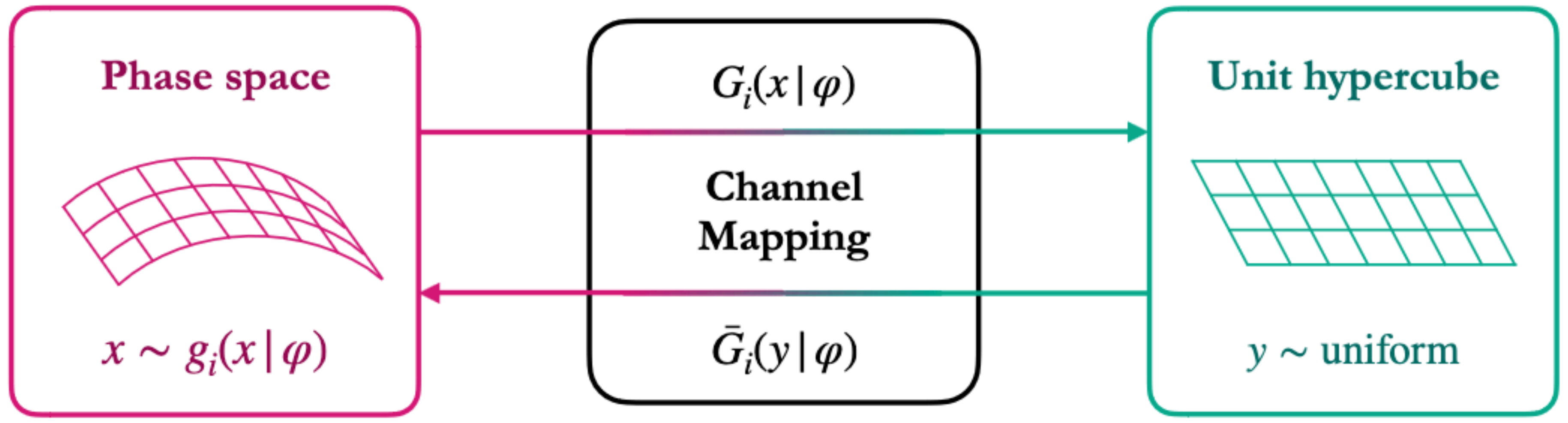
Hoeche ea., 2001.10028, Heimel/ Winterhalder ea., 2212.06172

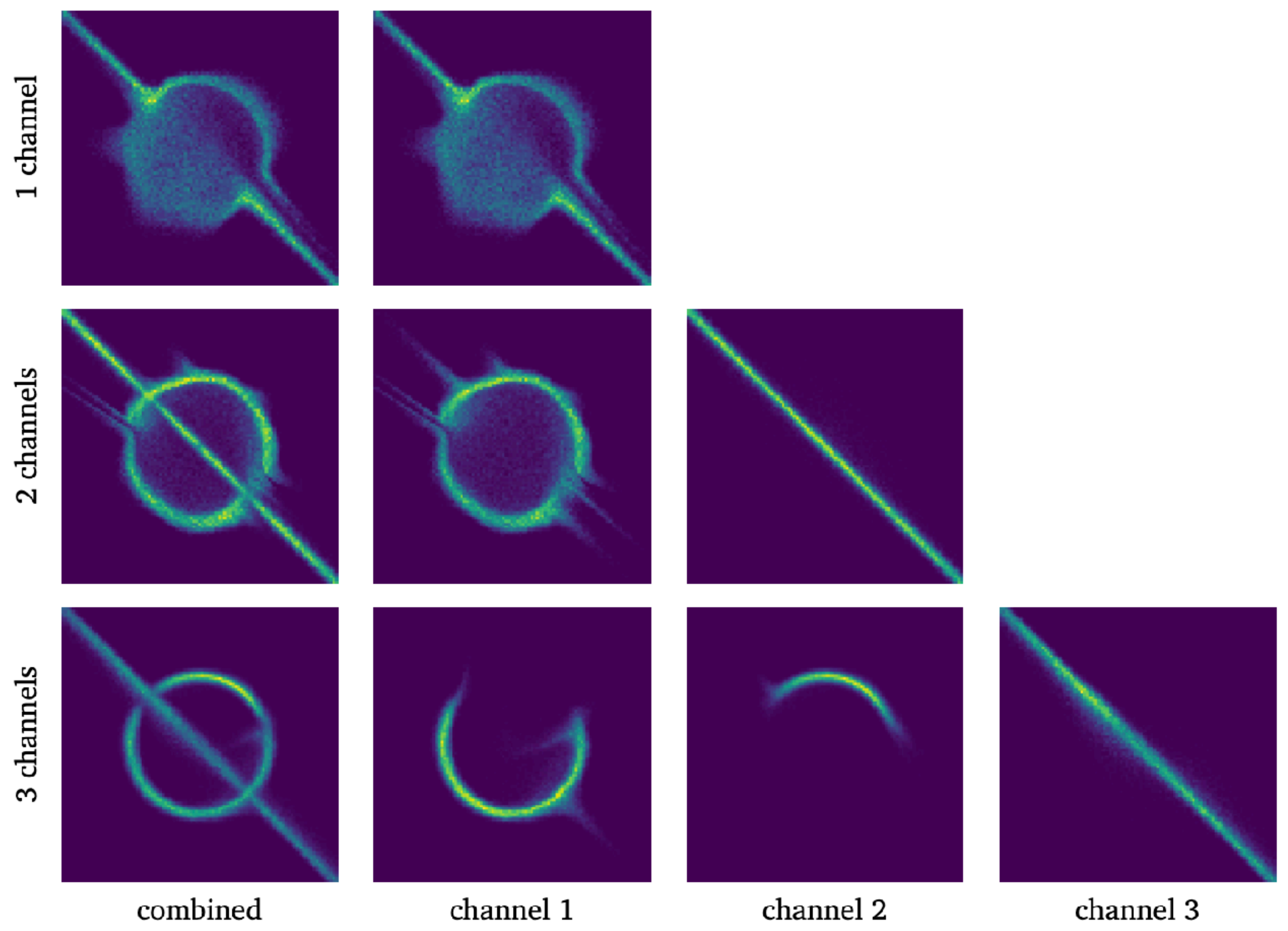
Online training:



Buffered training:







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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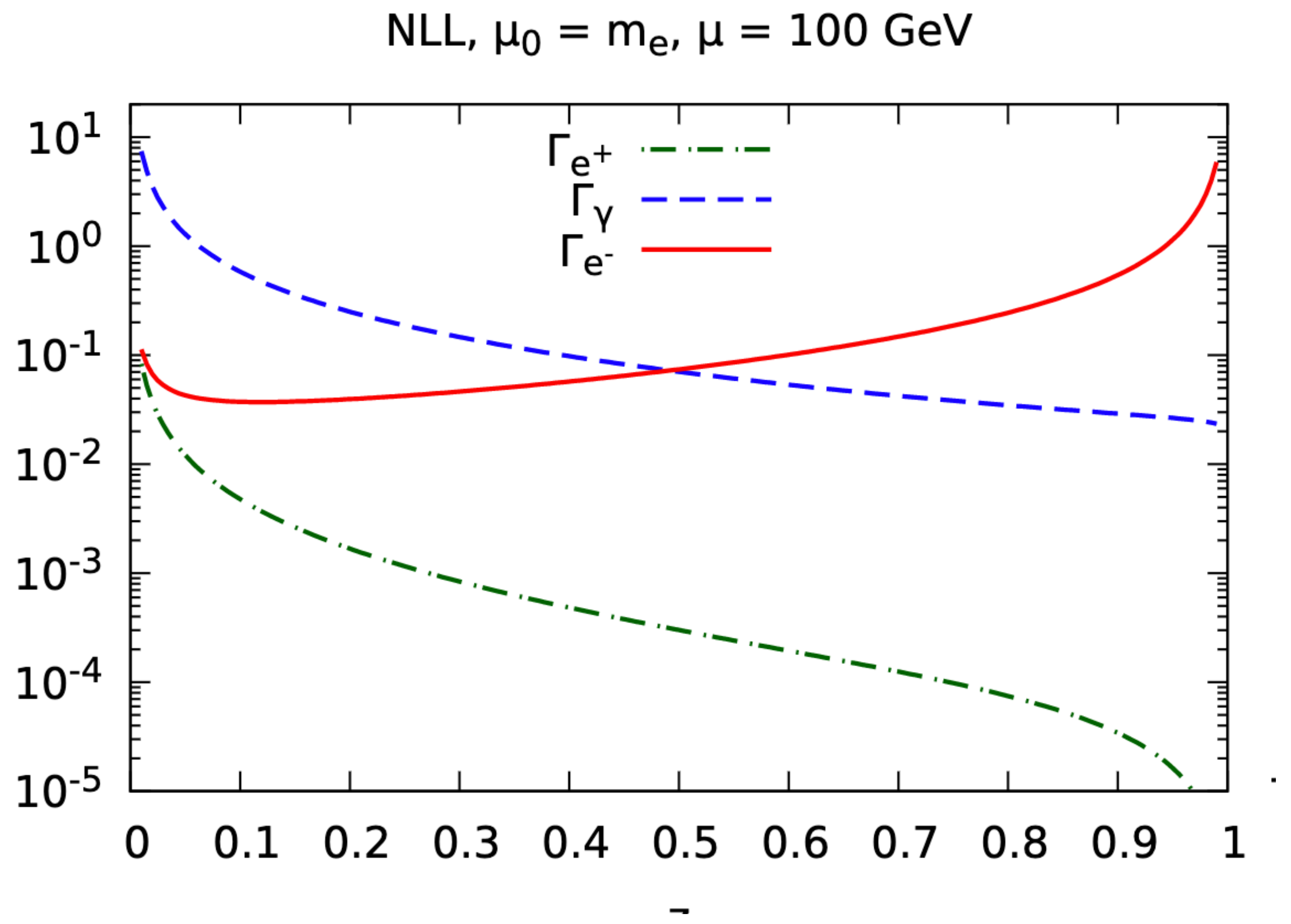

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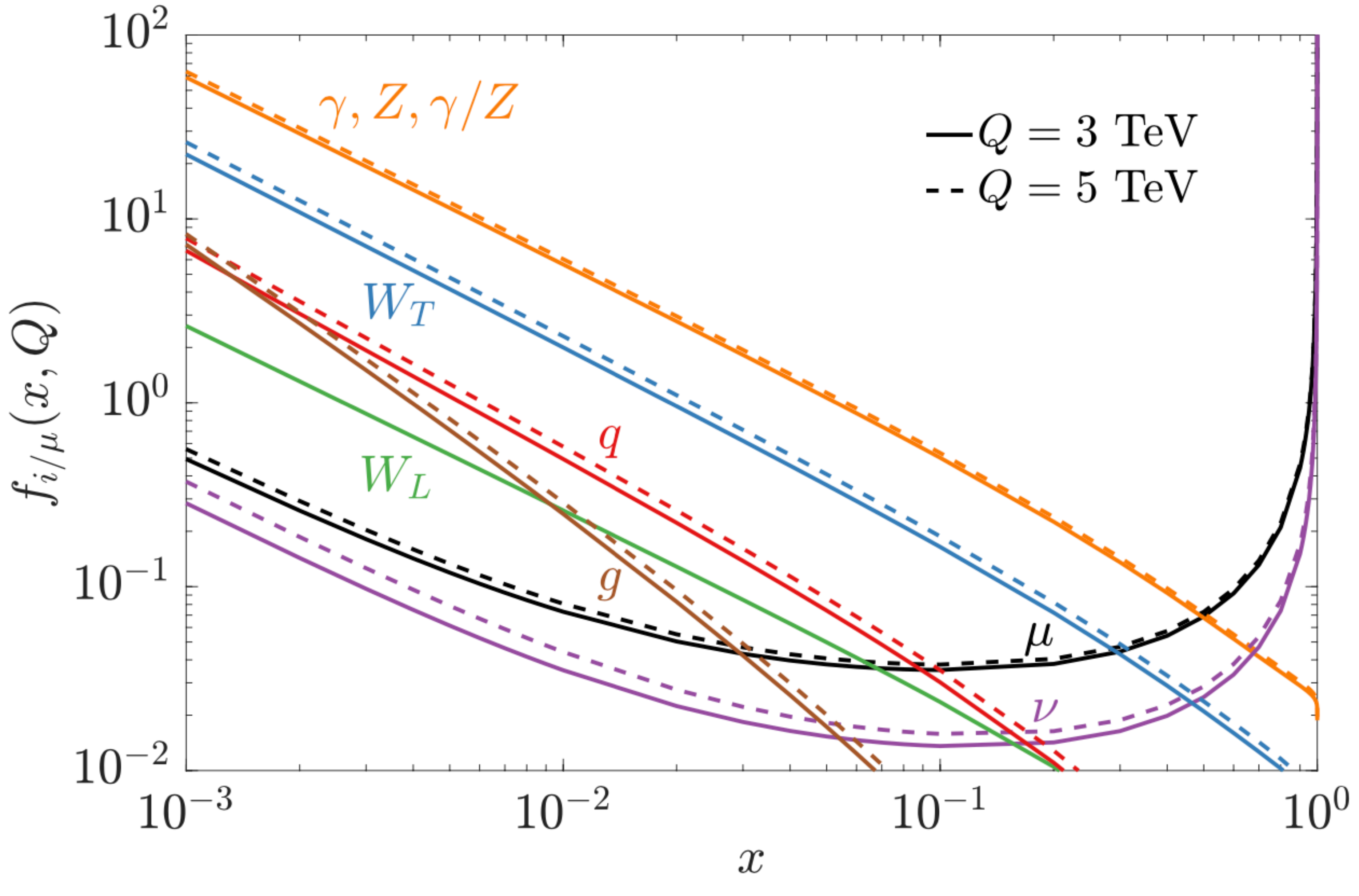

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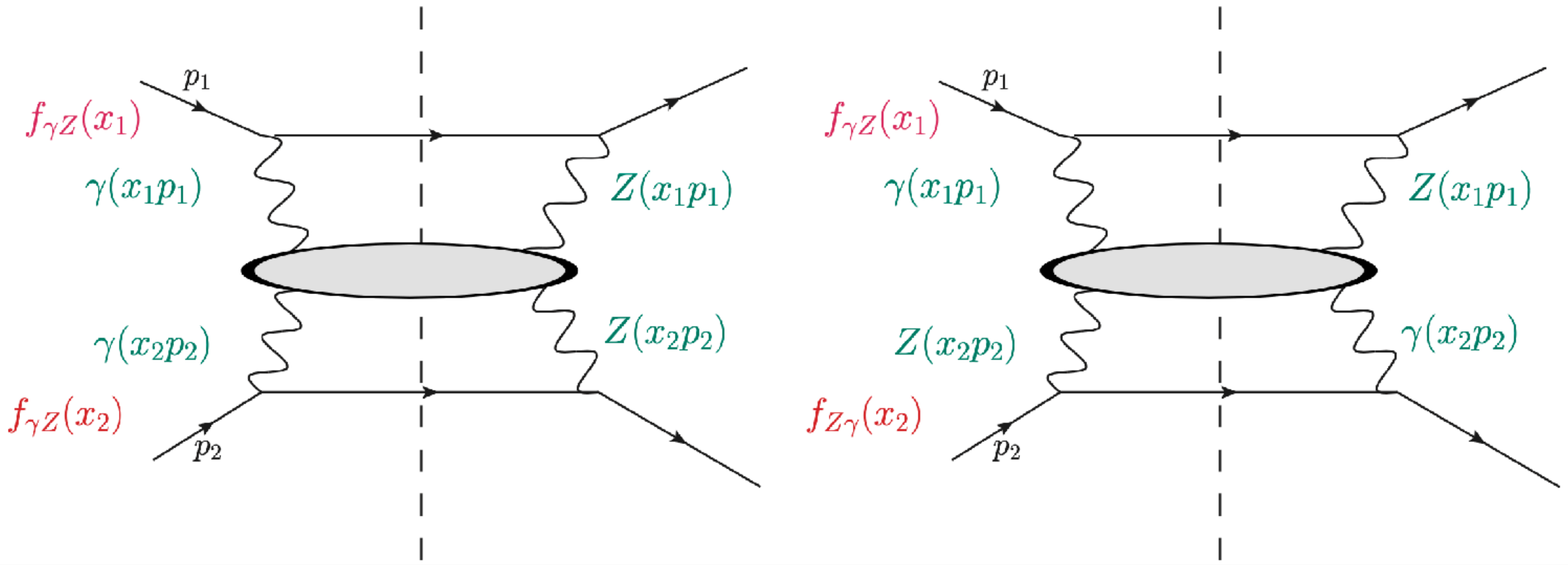
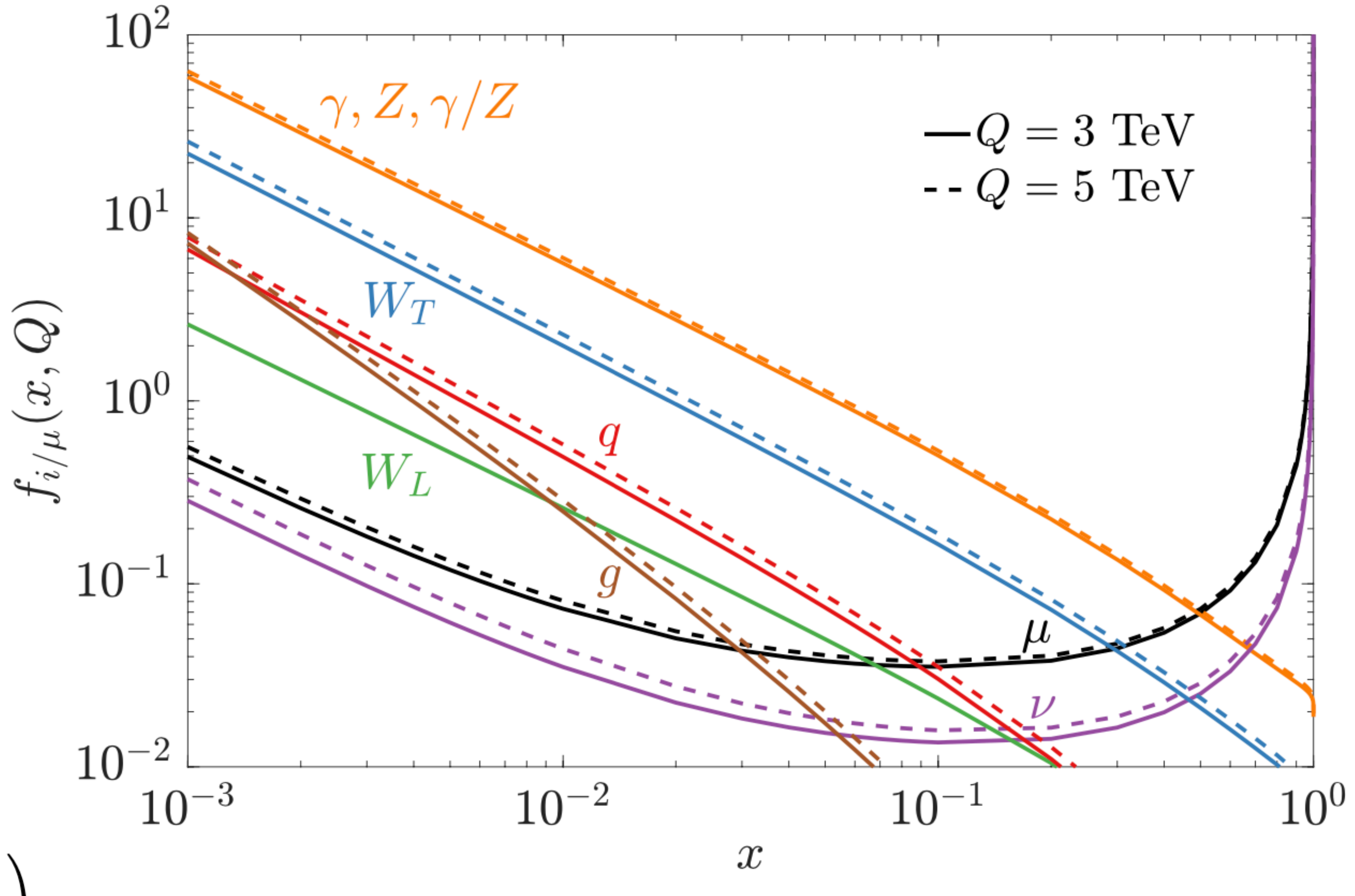


$$\begin{array}{cc} & \begin{array}{ccc} \gamma & Z & \gamma/Z \end{array} \\ \begin{array}{c} \gamma \\ Z \\ \gamma/Z \end{array} & \begin{pmatrix} \hat\sigma(\gamma,\gamma) & \hat\sigma(\gamma,Z) & \hat\sigma(\gamma,\gamma/Z) \\ \hat\sigma(Z,\gamma) & \hat\sigma(Z,Z) & \hat\sigma(Z,\gamma/Z) \\ \hat\sigma(\gamma/Z,\gamma)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



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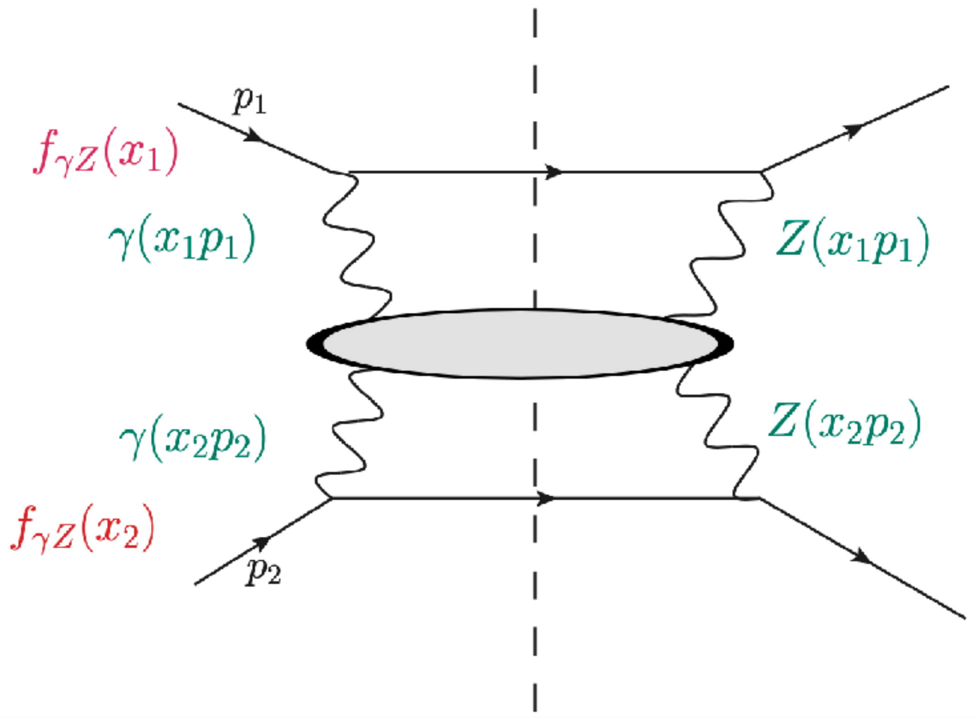

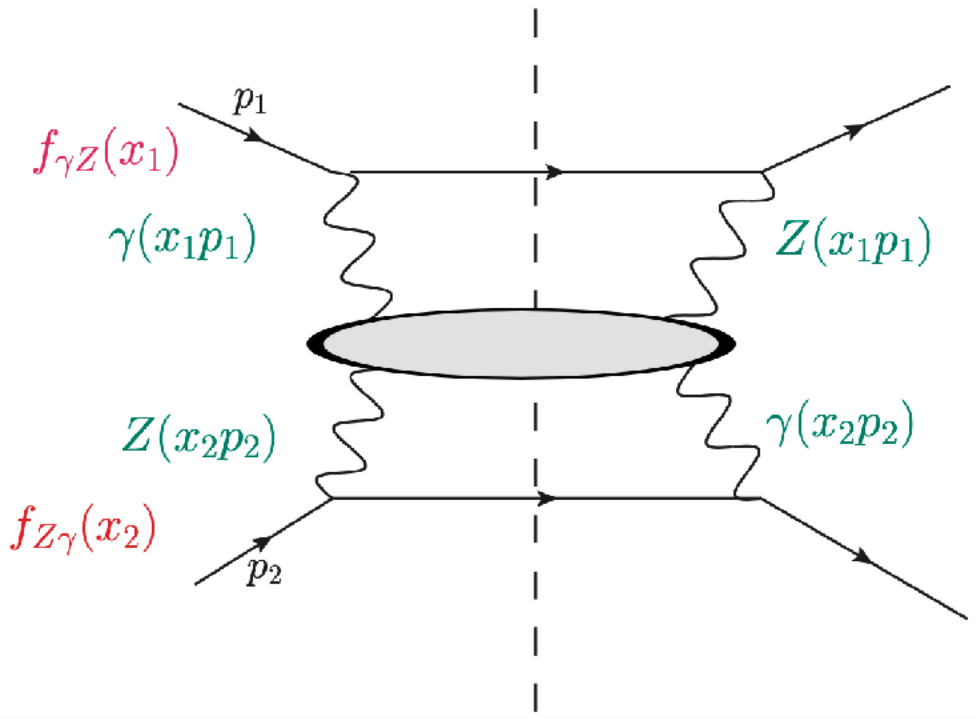

$$\begin{array}{c|ccc} & \gamma & Z & \gamma/Z \\ \hline \gamma & \hat\sigma(\gamma,\gamma) & \hat\sigma(\gamma,Z) & \hat\sigma(\gamma,\gamma/Z) \\ Z & \hat\sigma(Z,\gamma) & \hat\sigma(Z,Z) & \hat\sigma(Z,\gamma/Z) \\ \gamma/Z & \hat\sigma(\gamma/Z,\gamma) & \hat\sigma(\gamma/Z,Z) & \hat\sigma(\gamma/Z,\gamma/Z)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

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