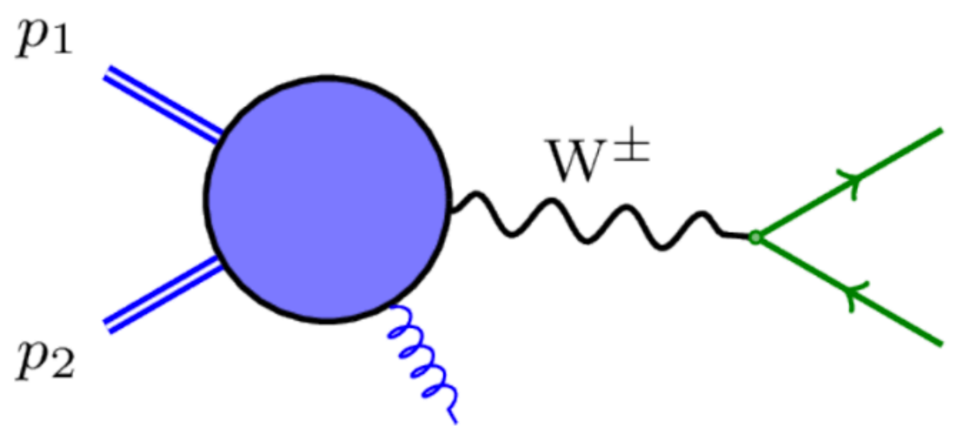
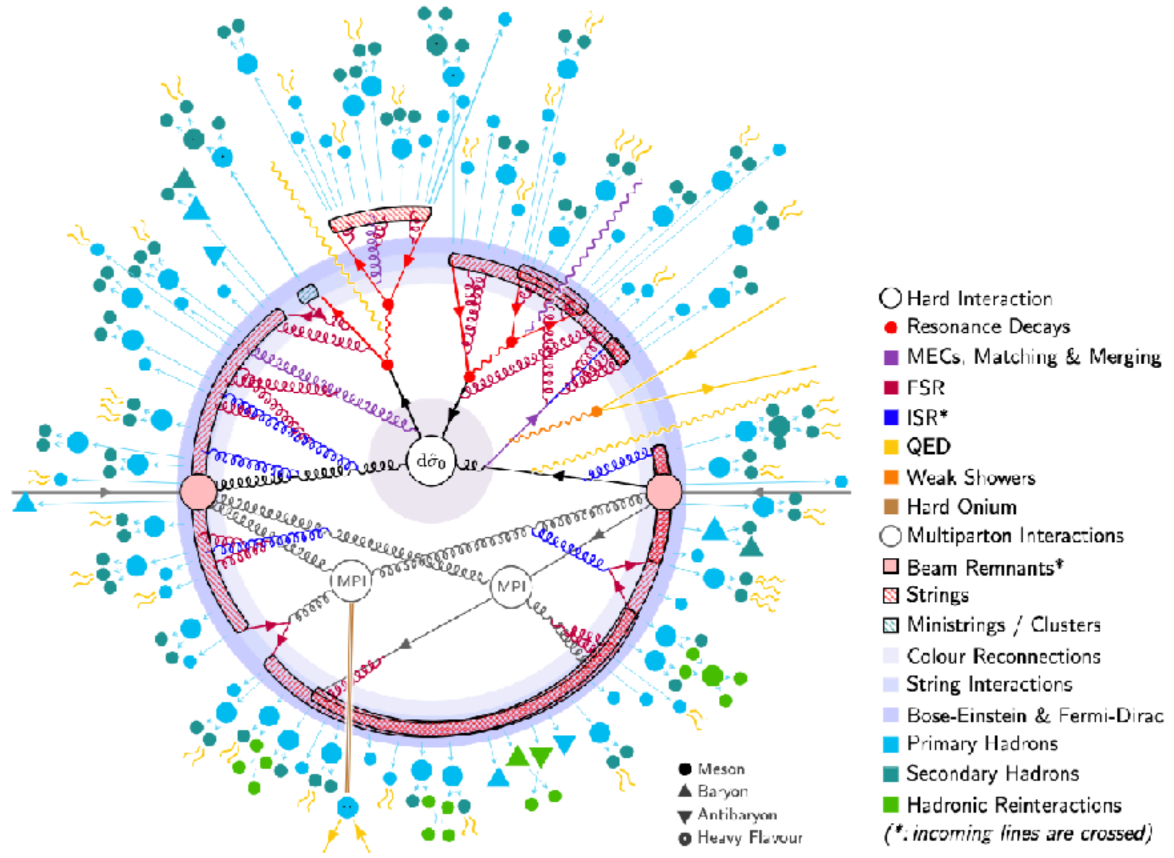
Monte Carlo generators for *FCC-ee*

HELMHOLTZ

NARODOWE CENTRUM NAUKI

Opus



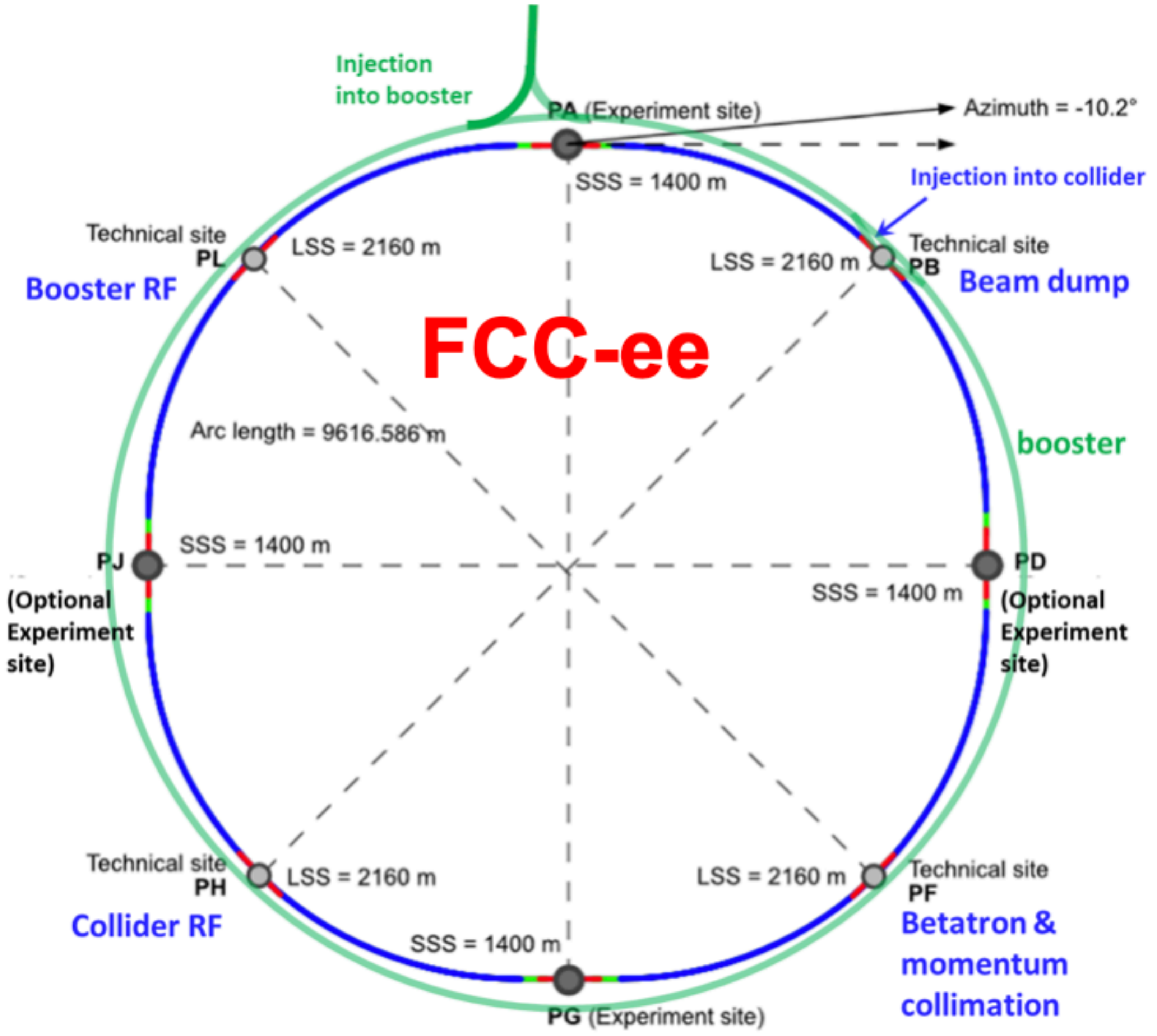


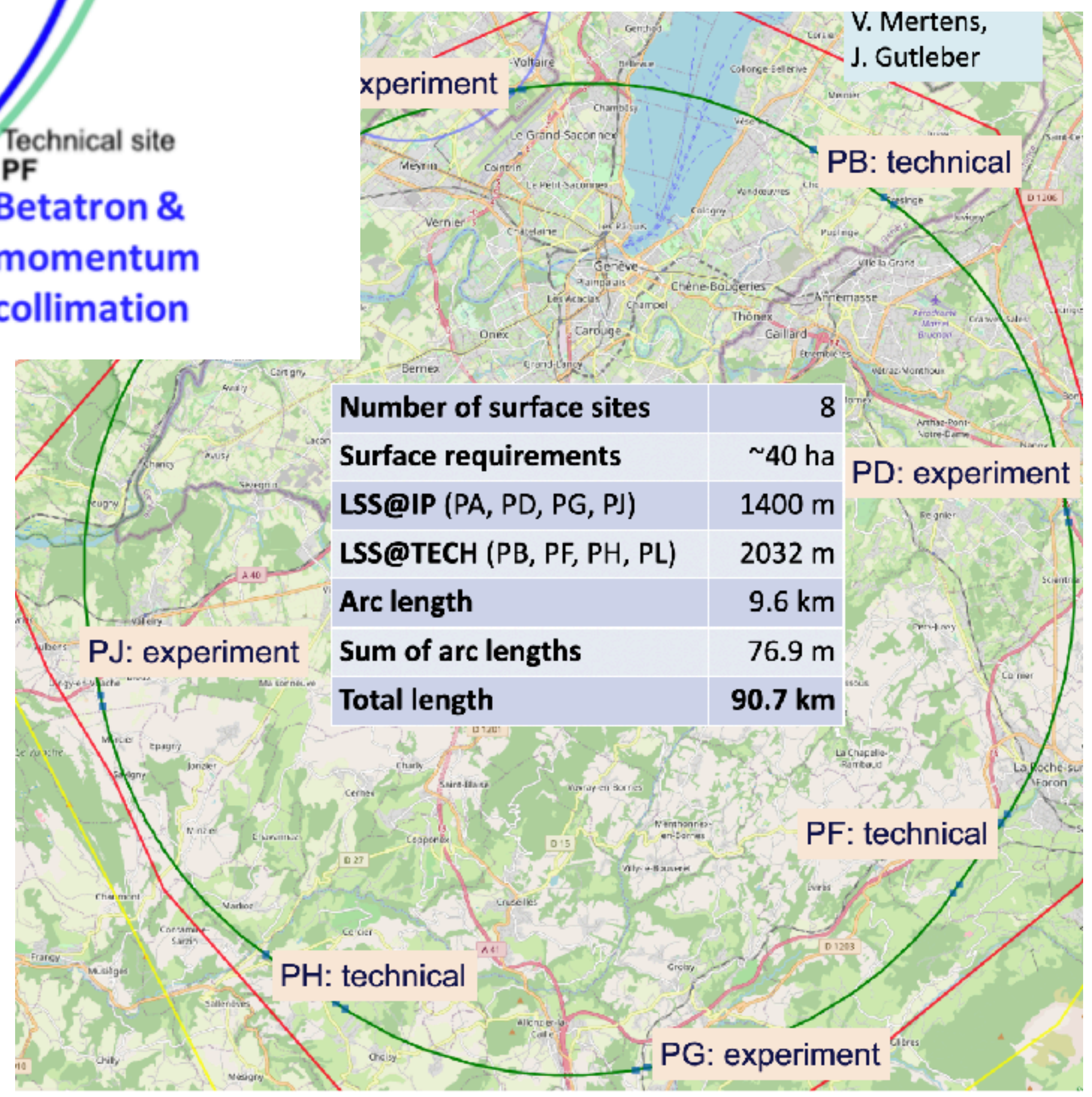
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

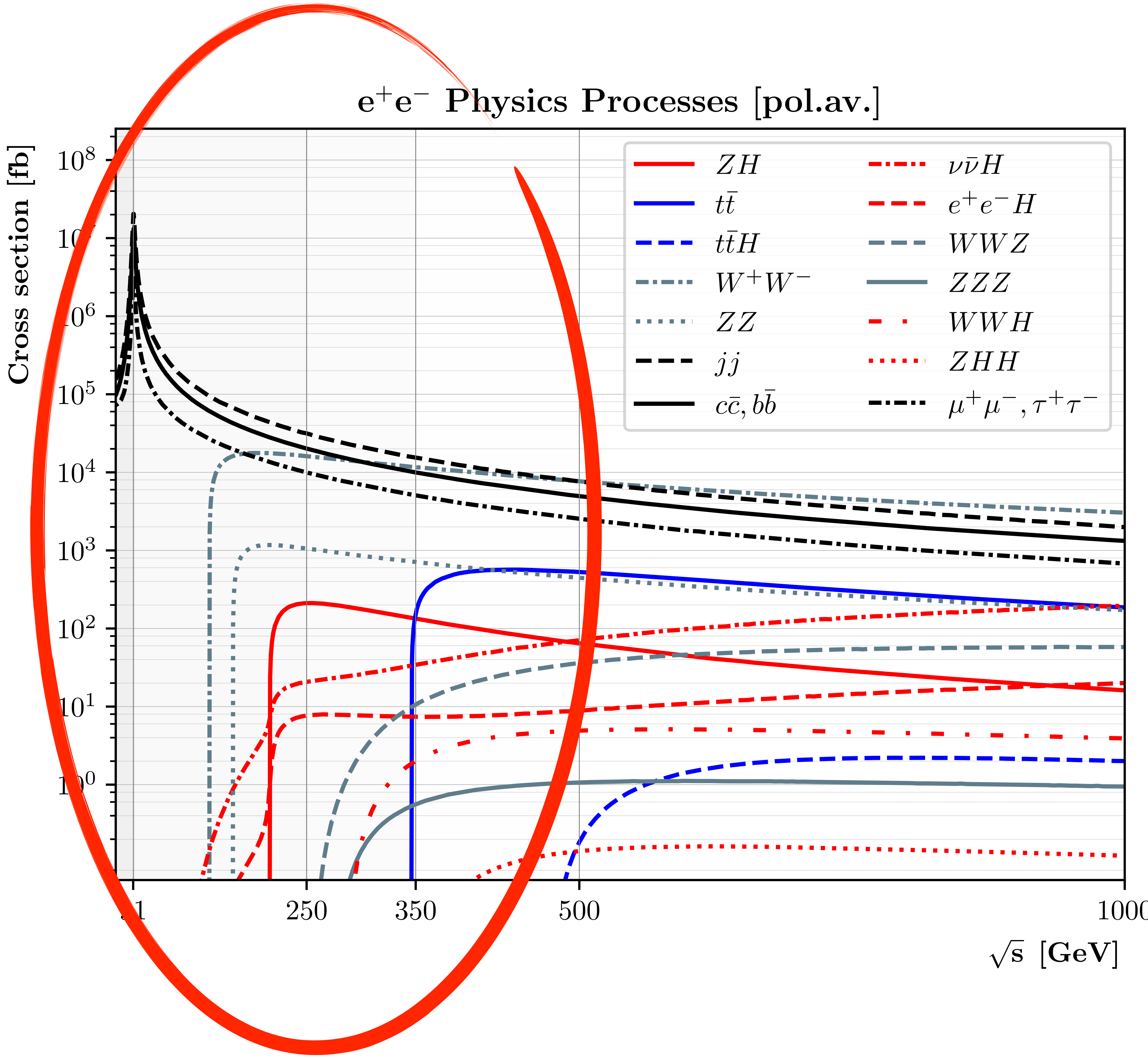
Jürgen R. Reuter

Physics program to be simulated





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

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!

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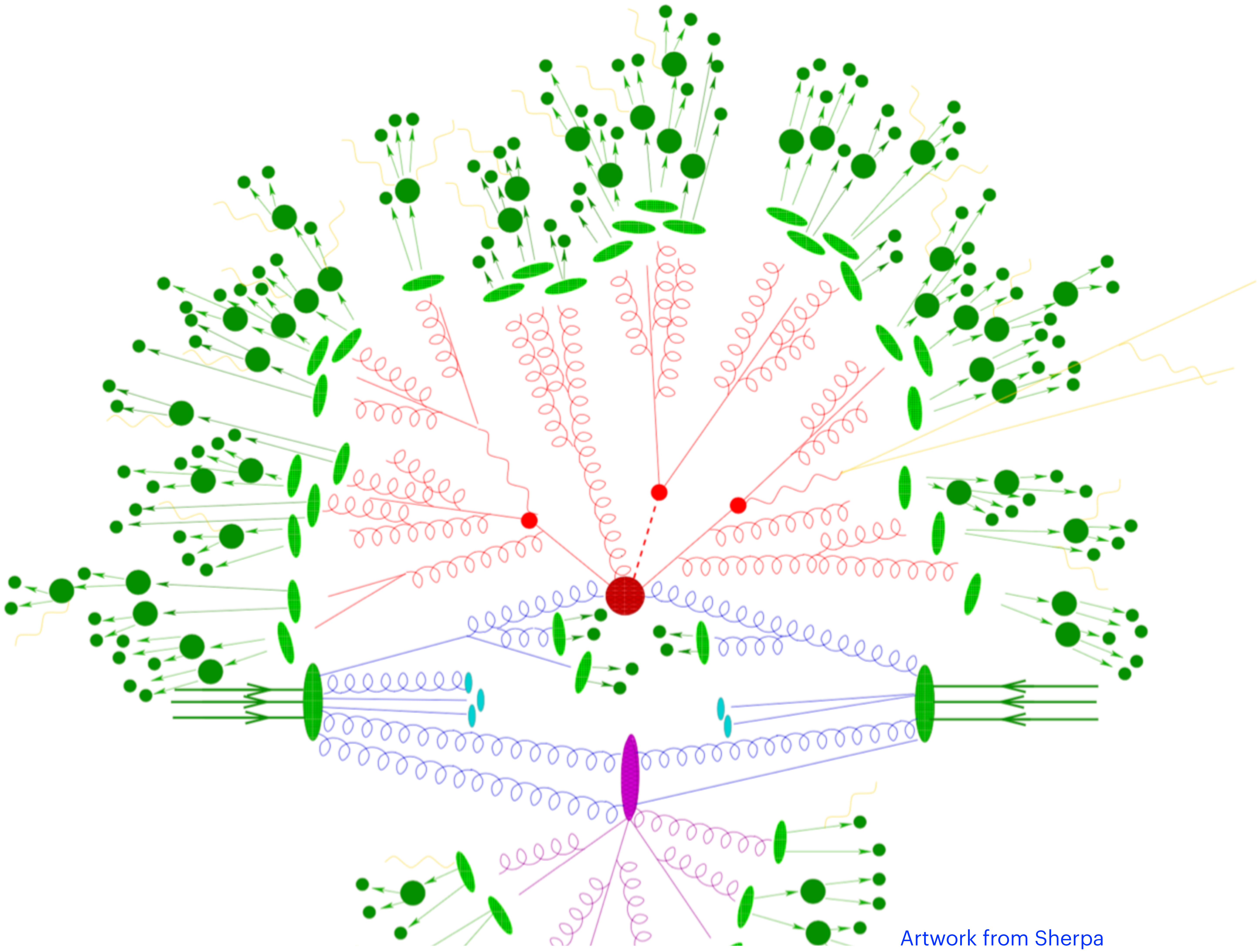

Artwork from Sherpa

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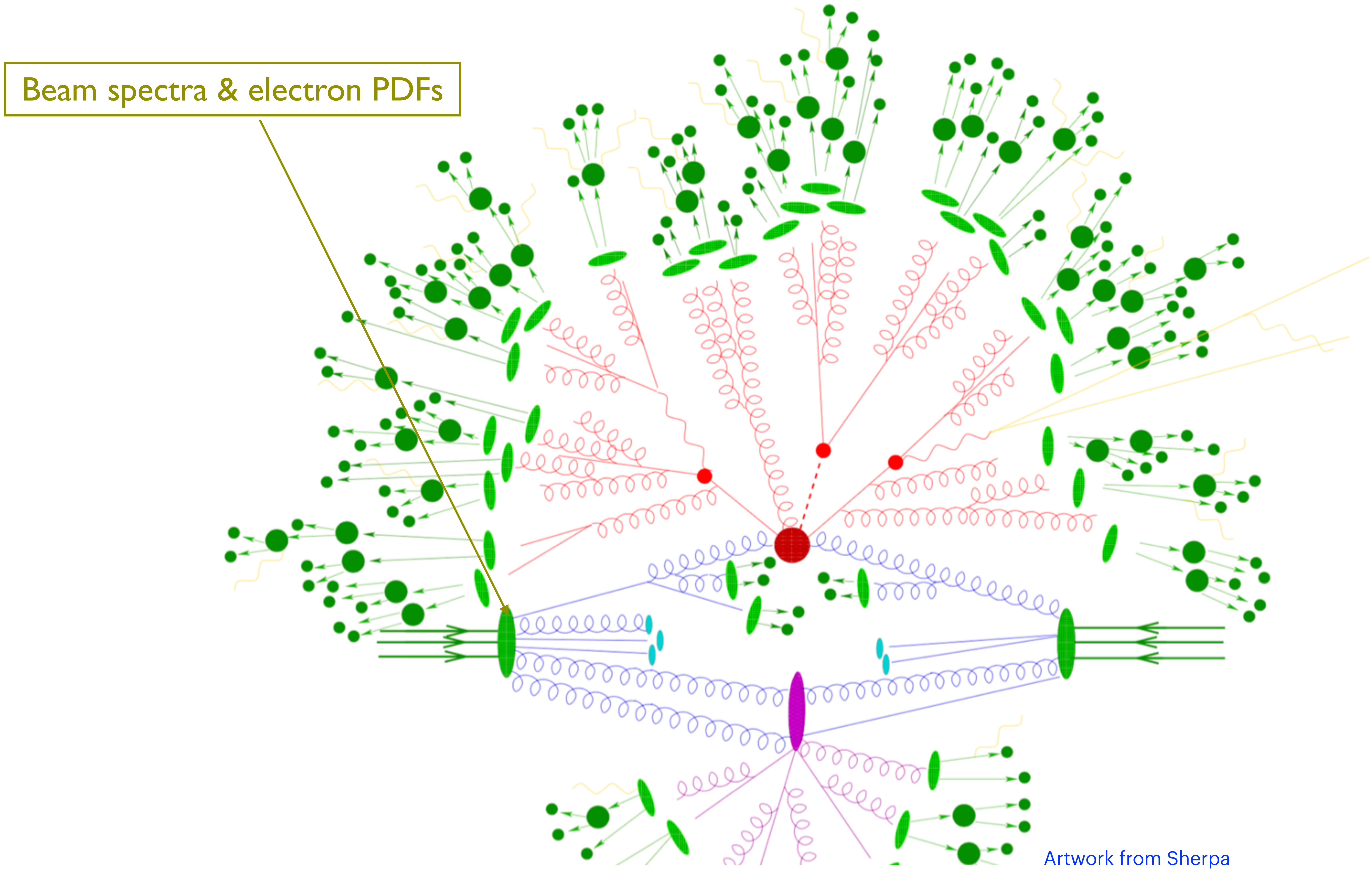

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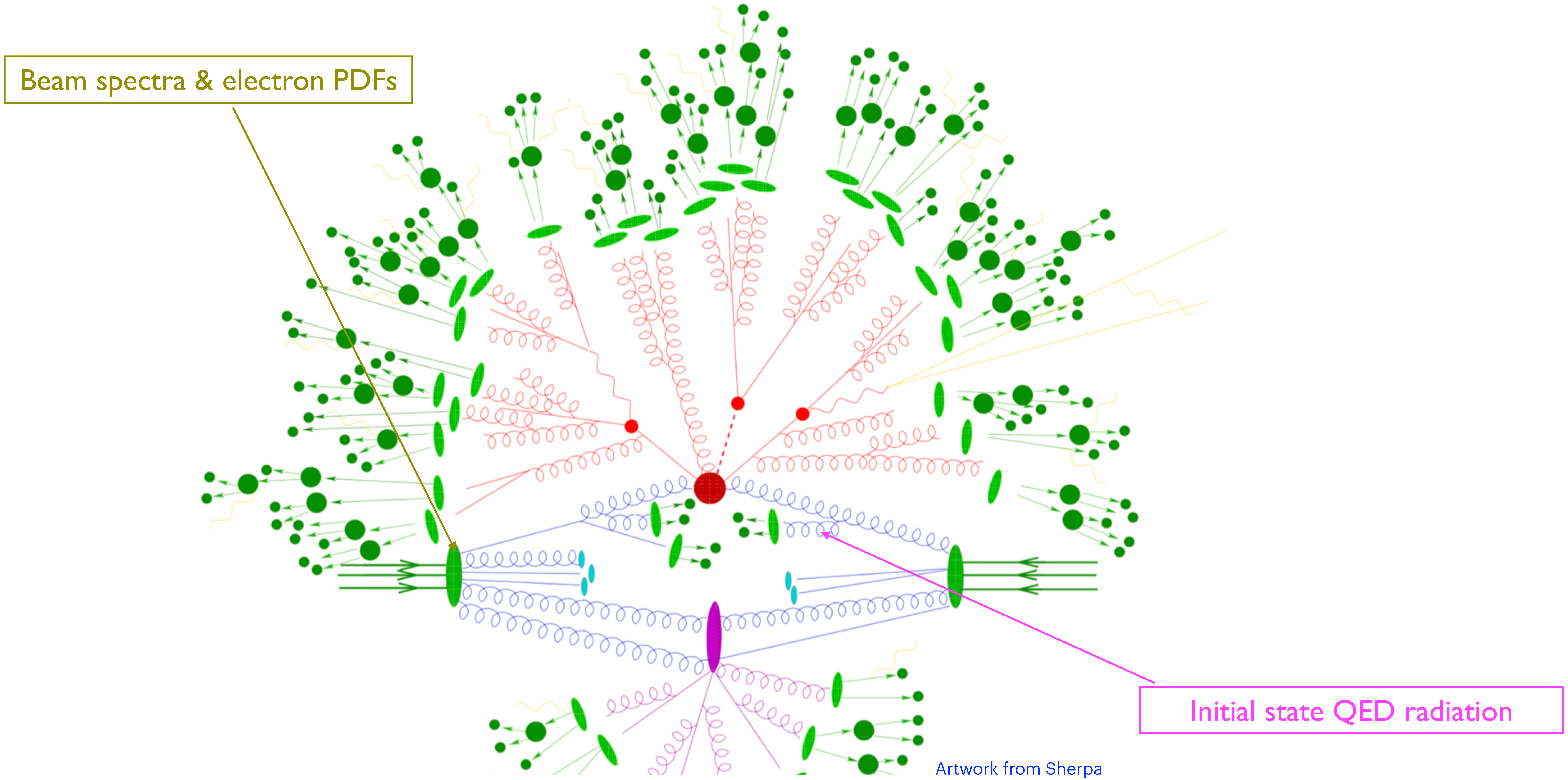

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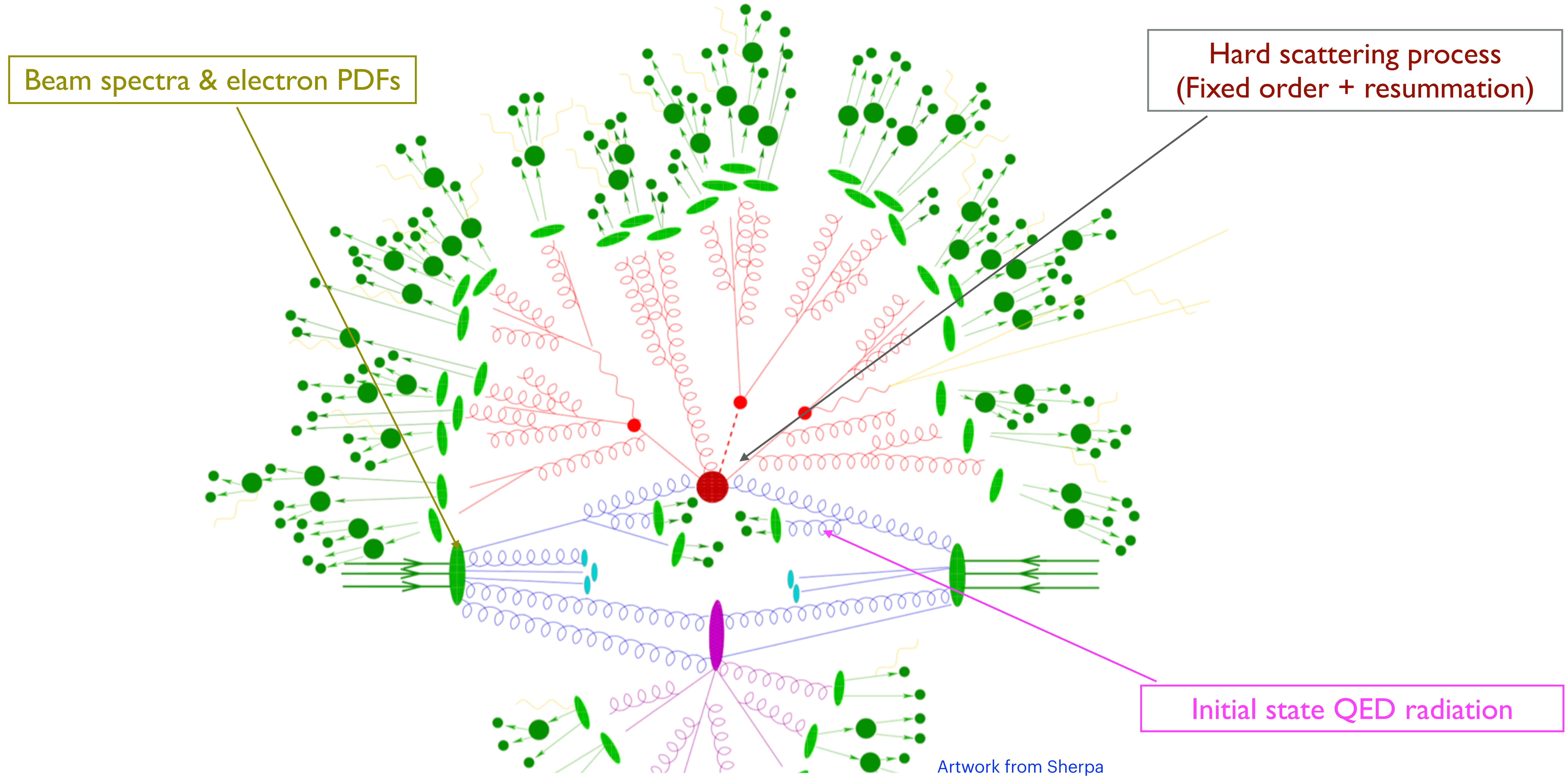

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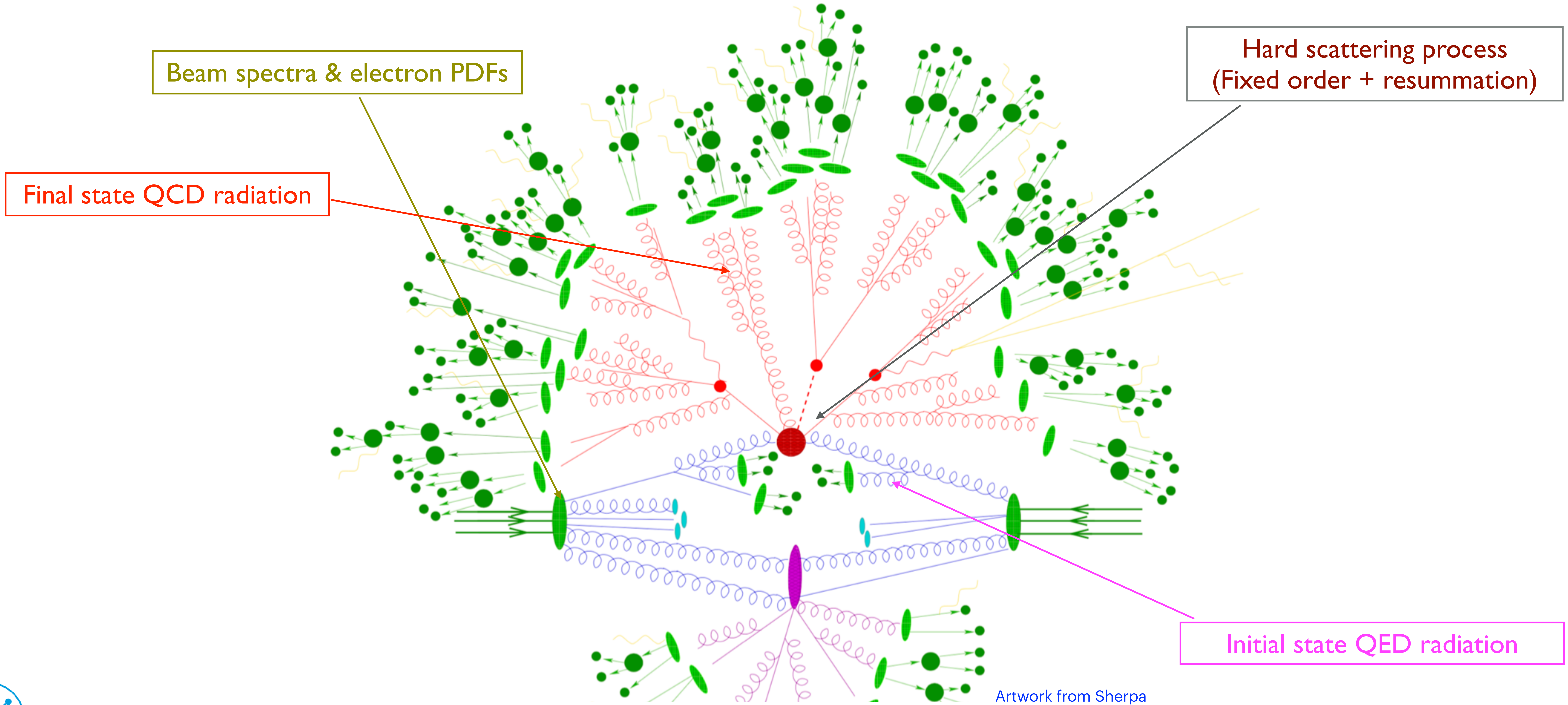

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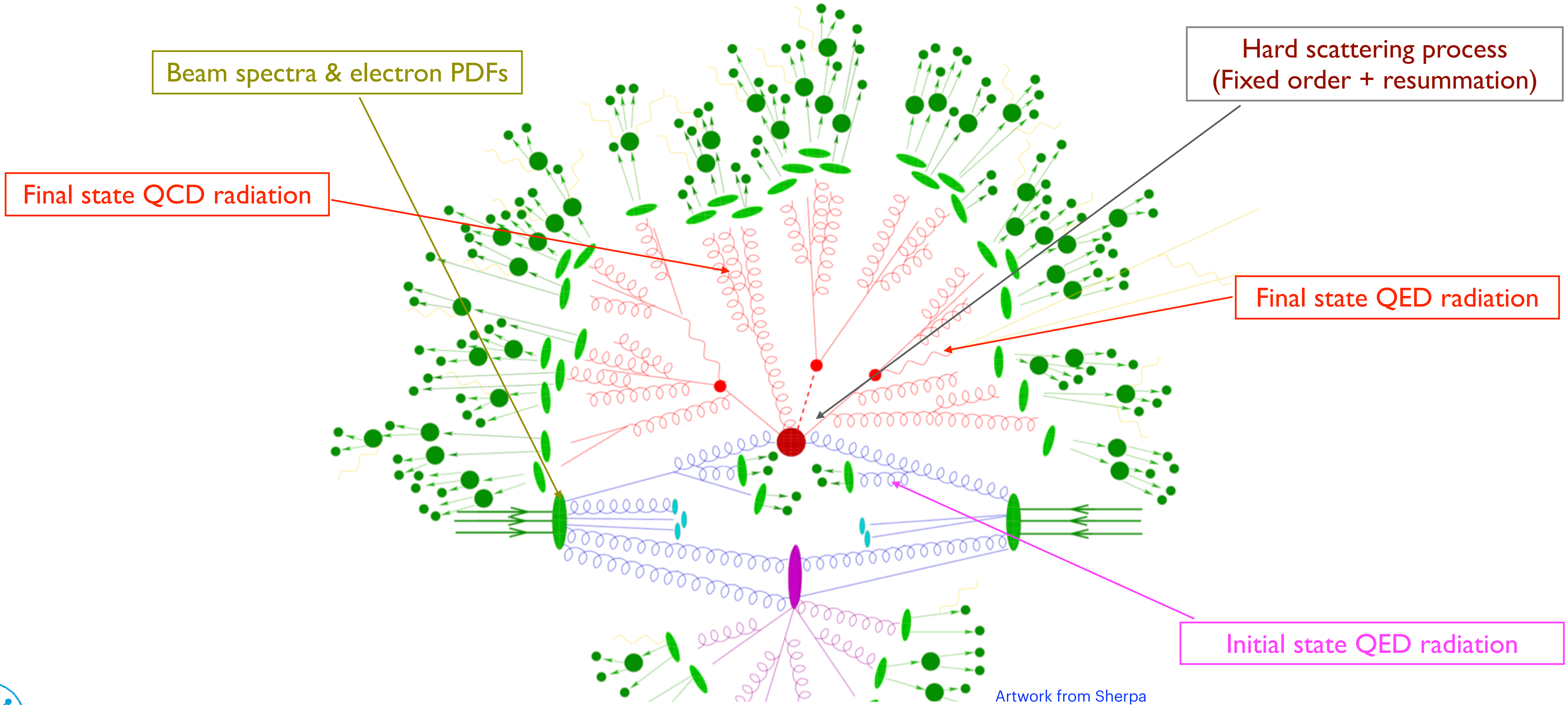

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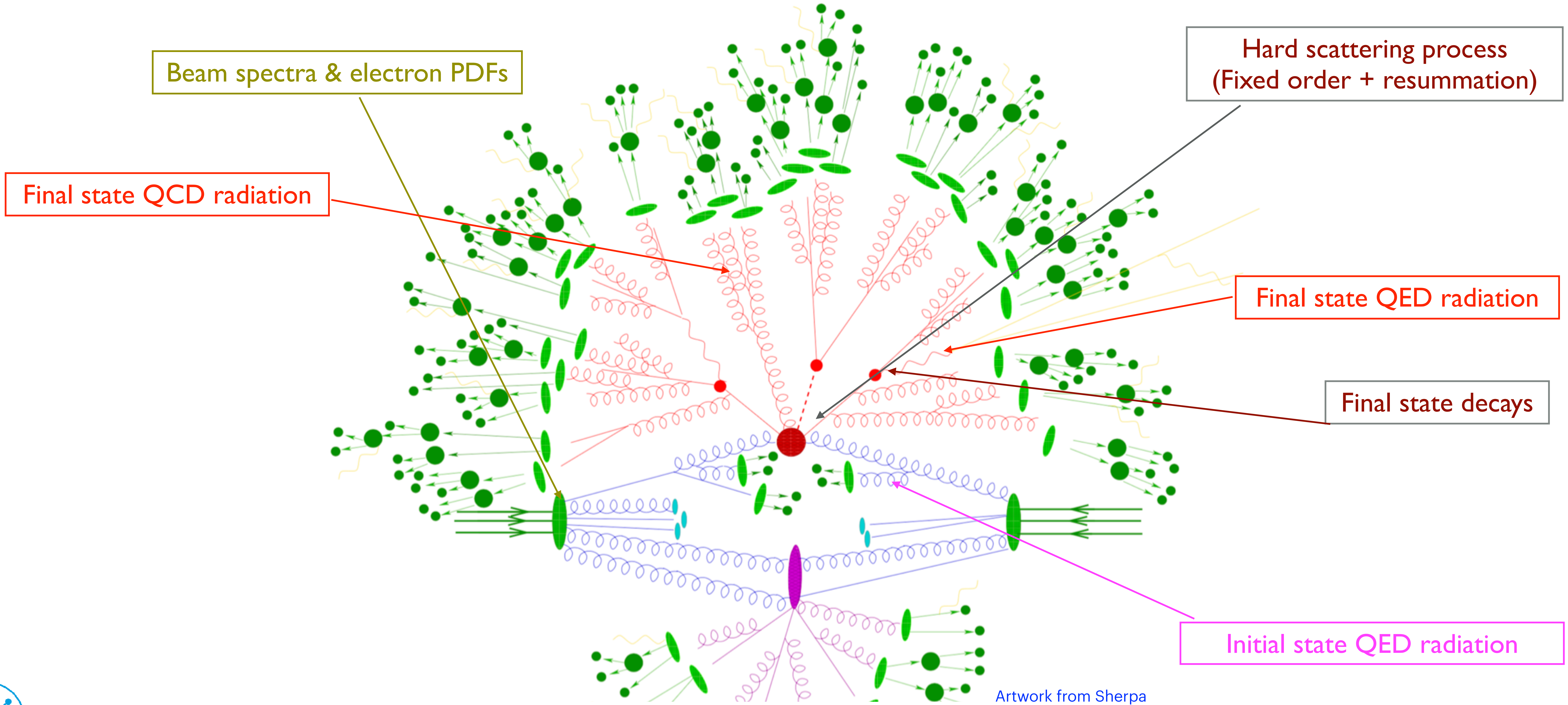

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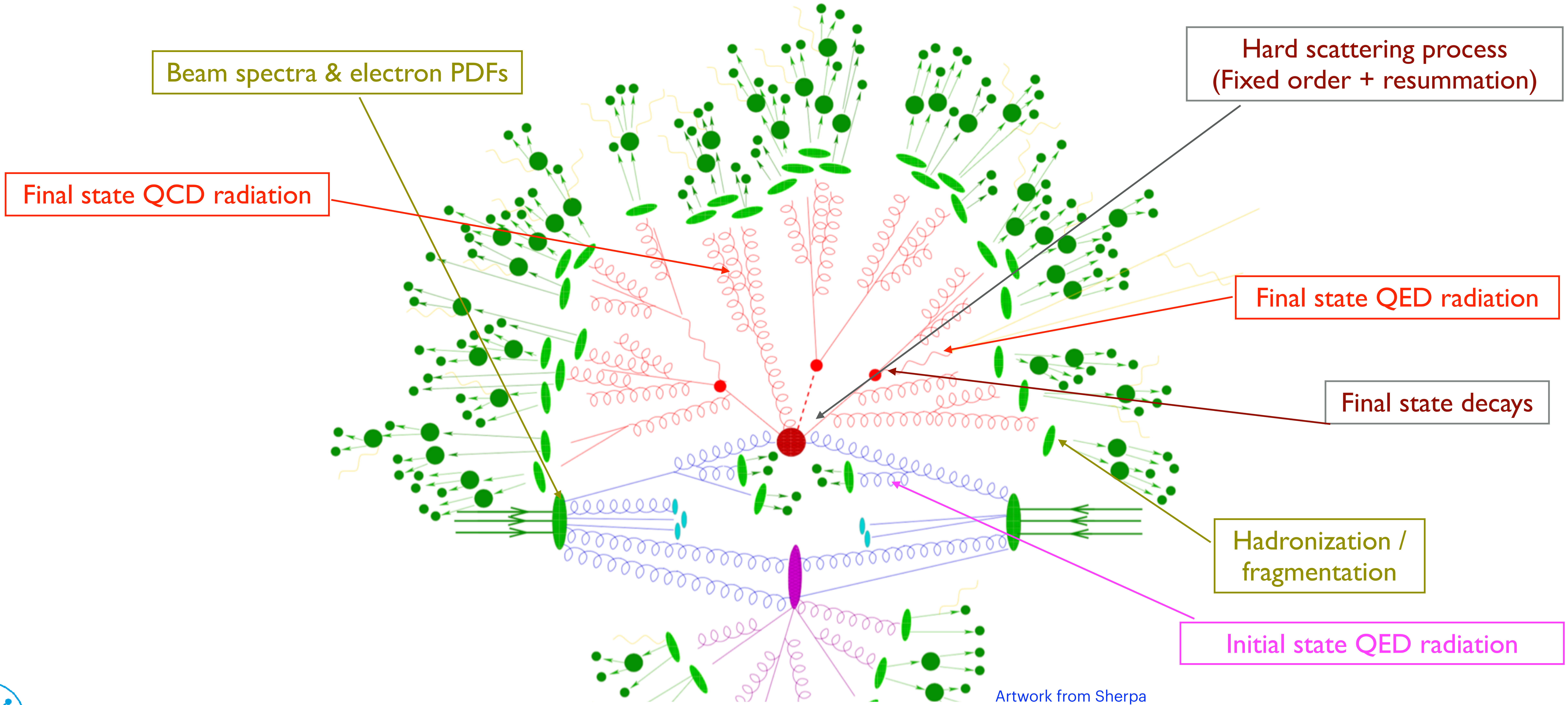

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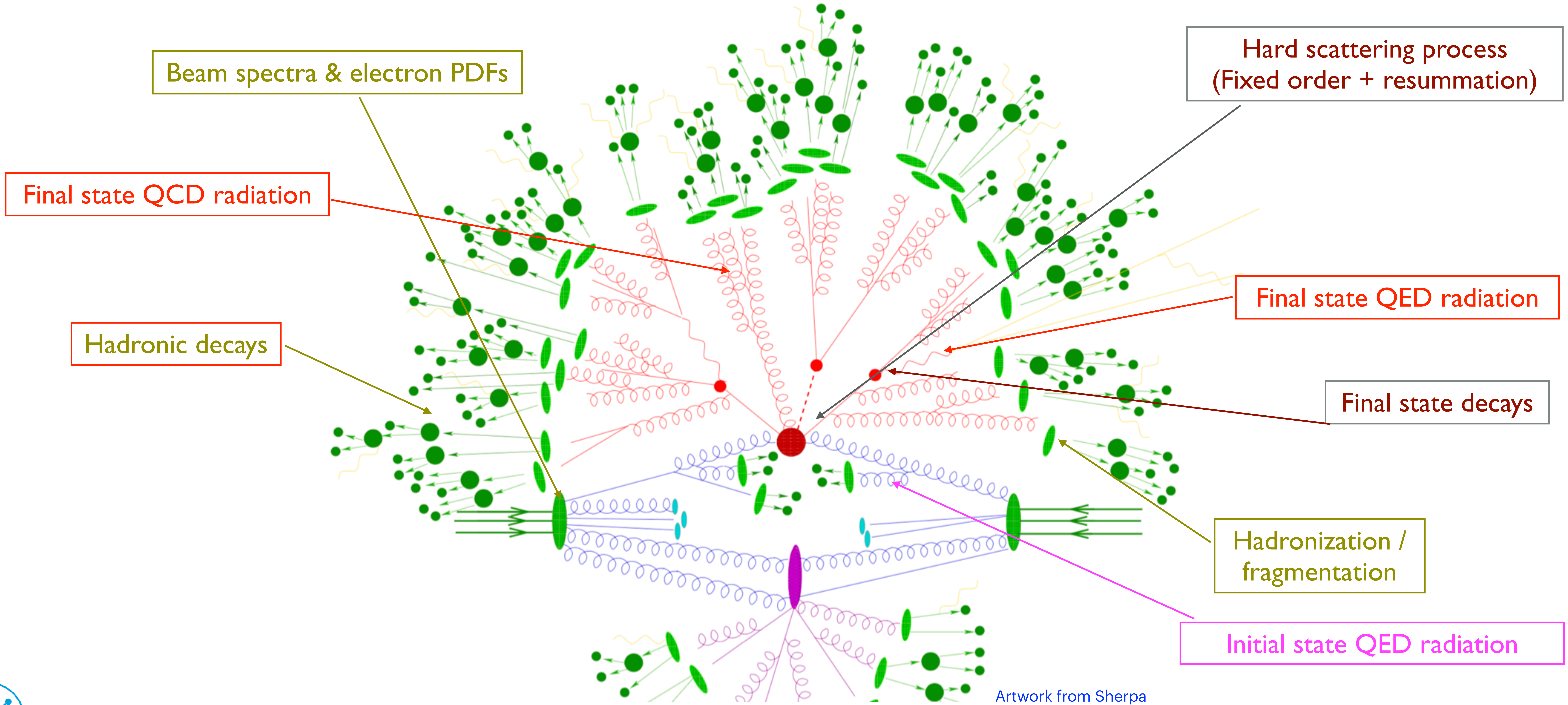

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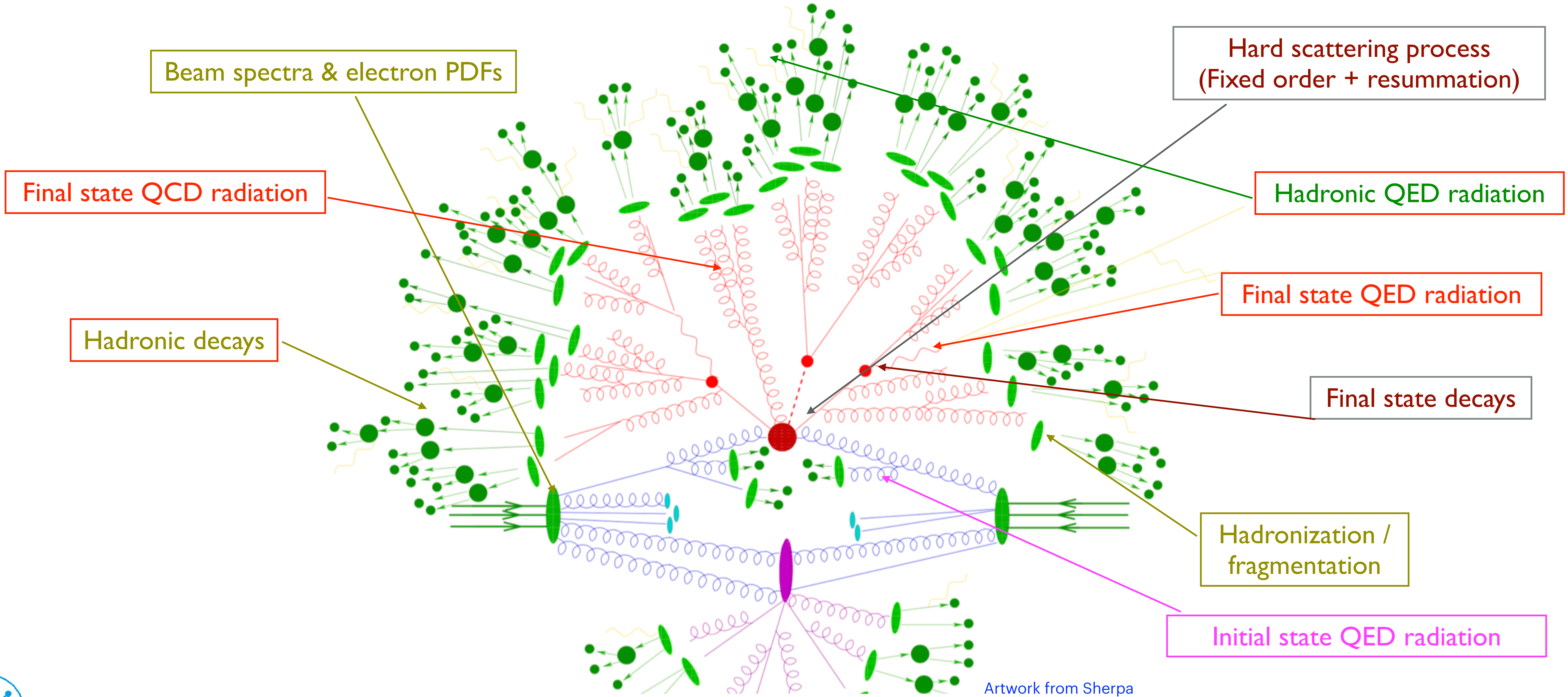

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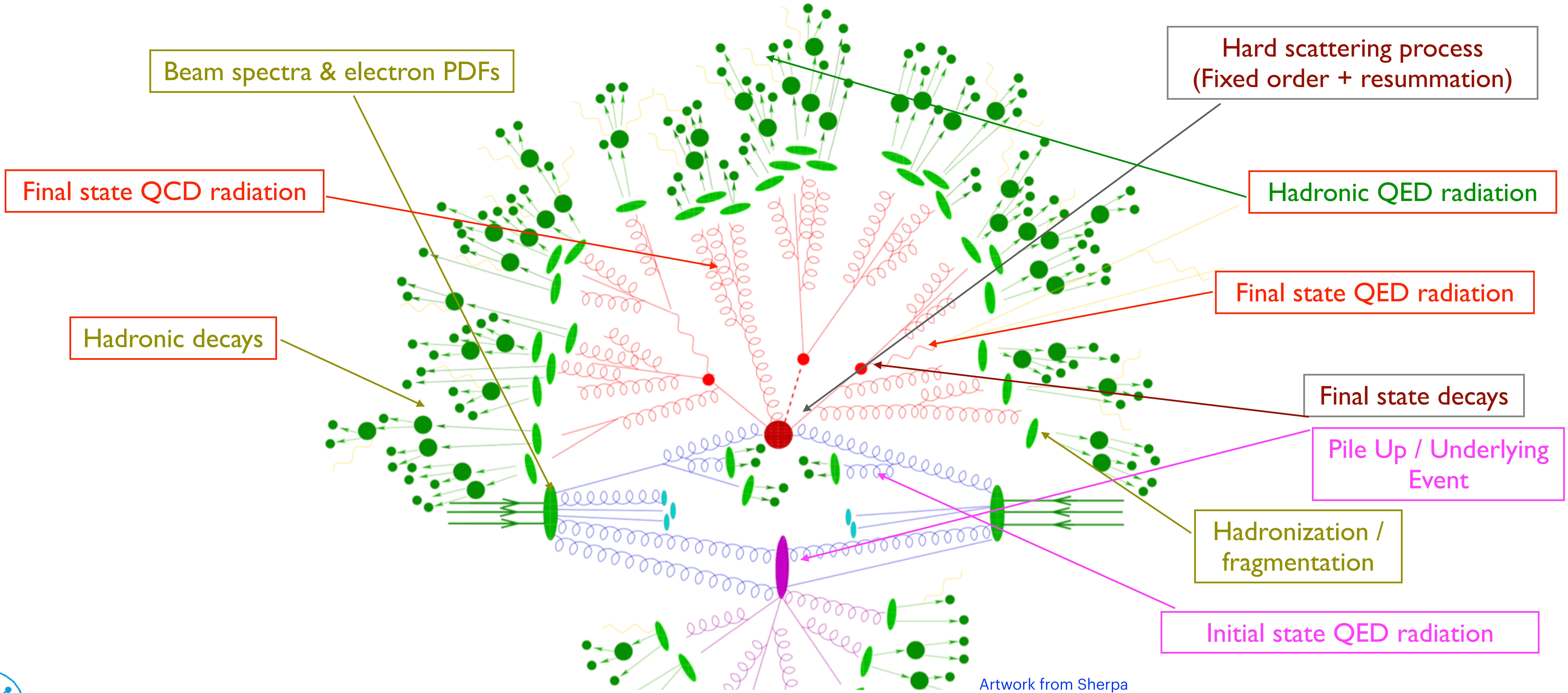

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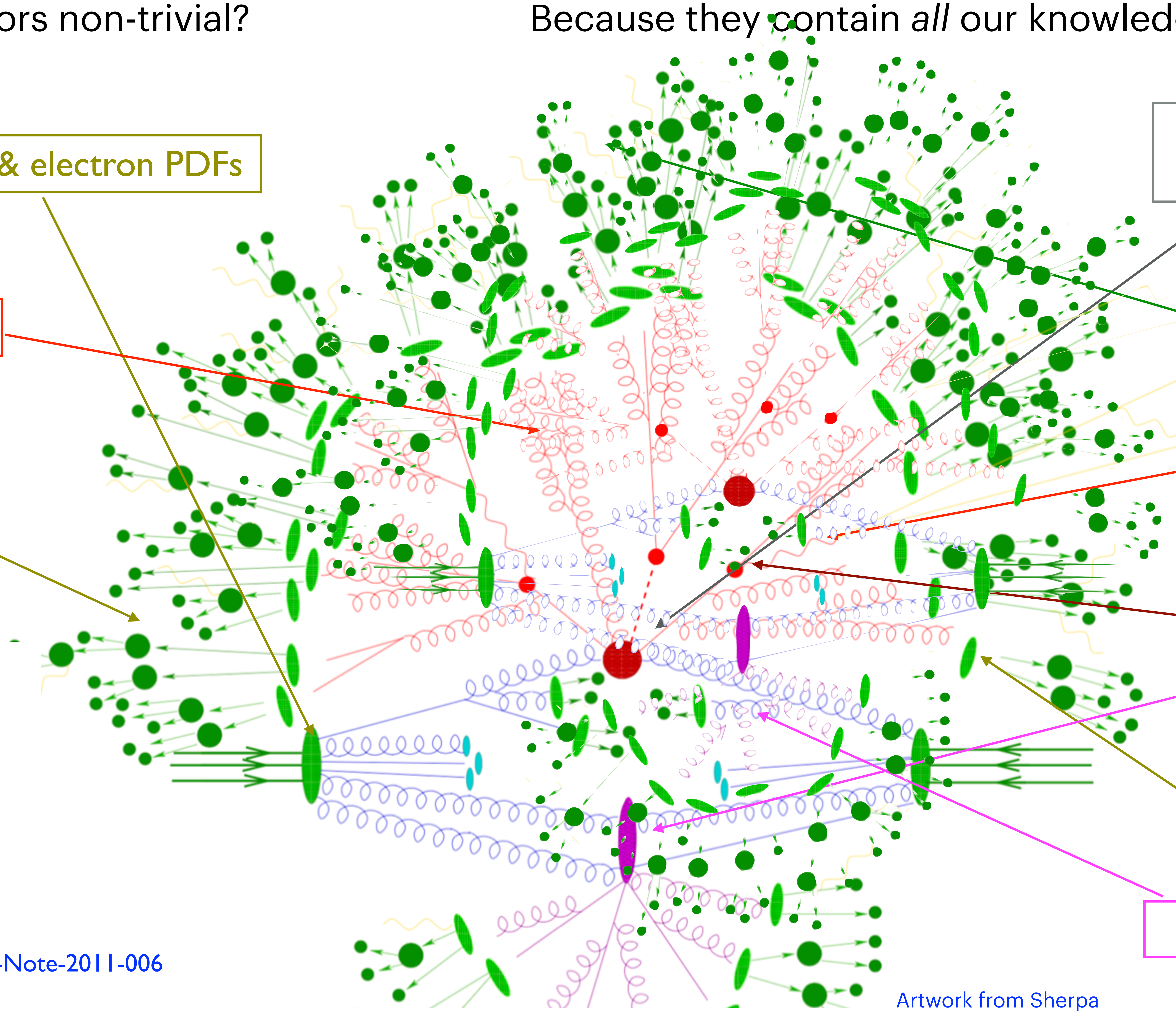

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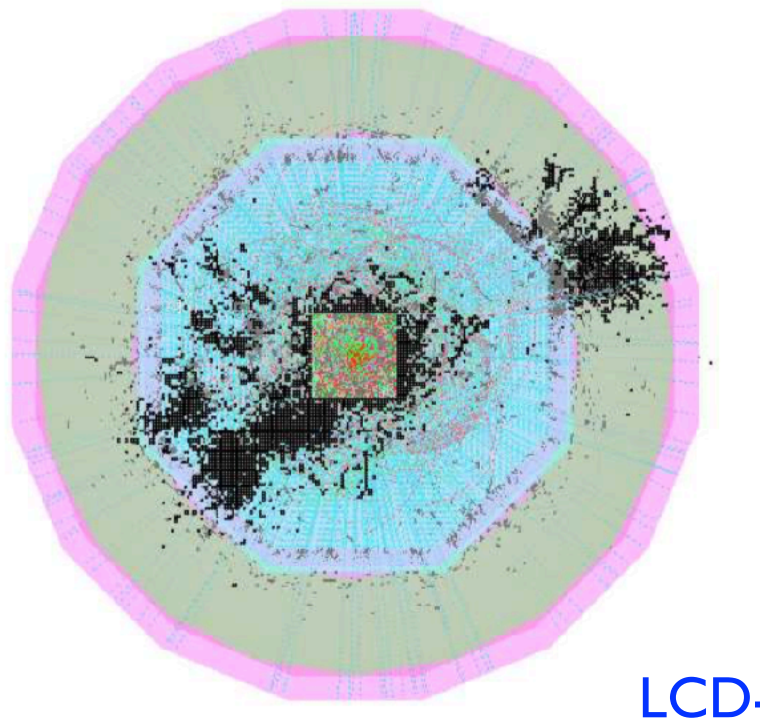
Pile up



LCD-Note-2011-006

Overview over e^+e^- generators

Process Specific

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

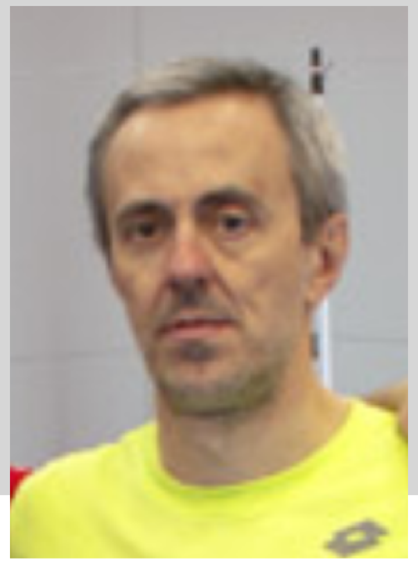
General Purpose MC

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

from Alan Price, 2nd ECFA HF WS, Paestum, 2023

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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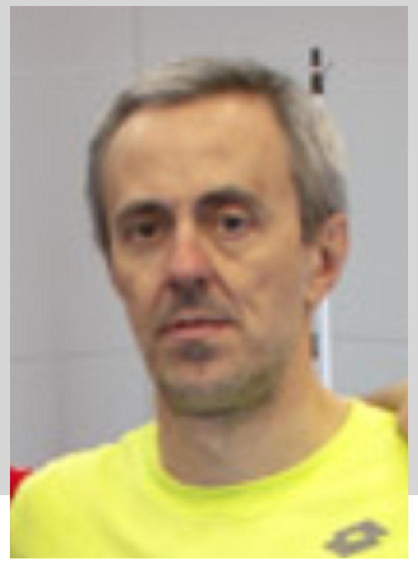


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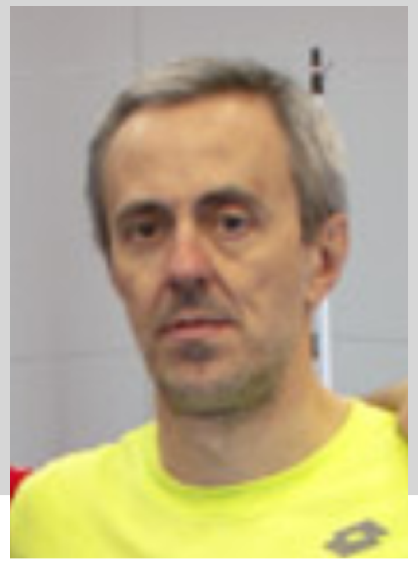


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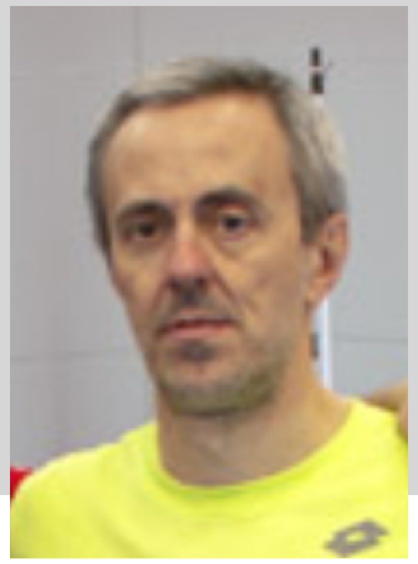


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- CERN WS "Parton Showers for Future e^+e^- colliders
  Apr 24-28, 2023 https://indico.cern.ch/event/1233329
- ≳ 120 participants, roughly 80 at CERN
- Focus: perturbative and non-perturbative QCD

The 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?
- Experience from LEP, ILC TDR+250 GeV full simulation, CEPC simulation samples

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2. QED inclusive: ePDFs vs. YFS, xsecs …
3. Hard process (SM): NLO SM automation , NNLO automation (?)
4. Hard process (BSM): any model? SMEFT? which order?
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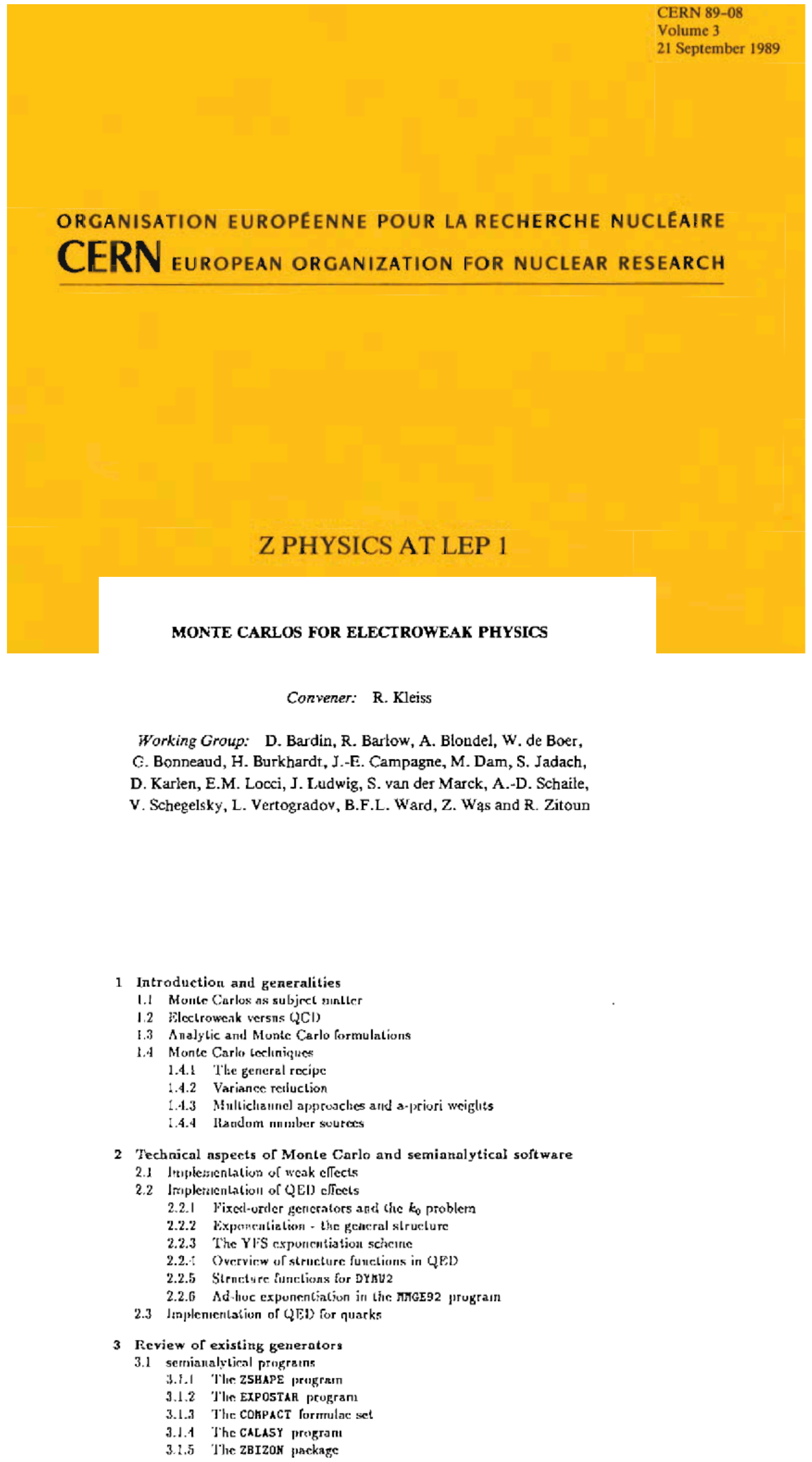

CERN 89-08
Volume 3
21 September 1989

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. Wąs and R. Zitoun

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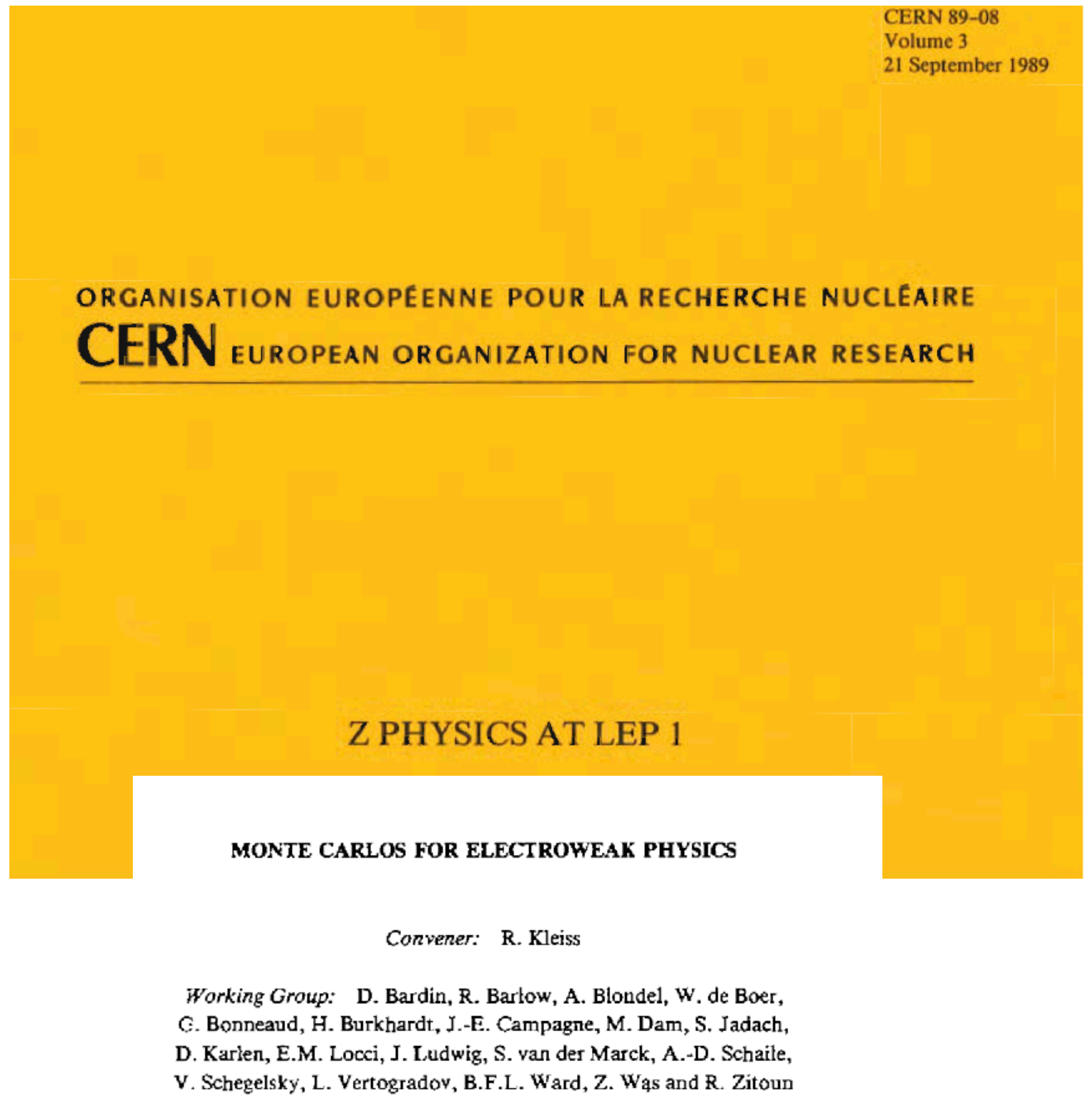
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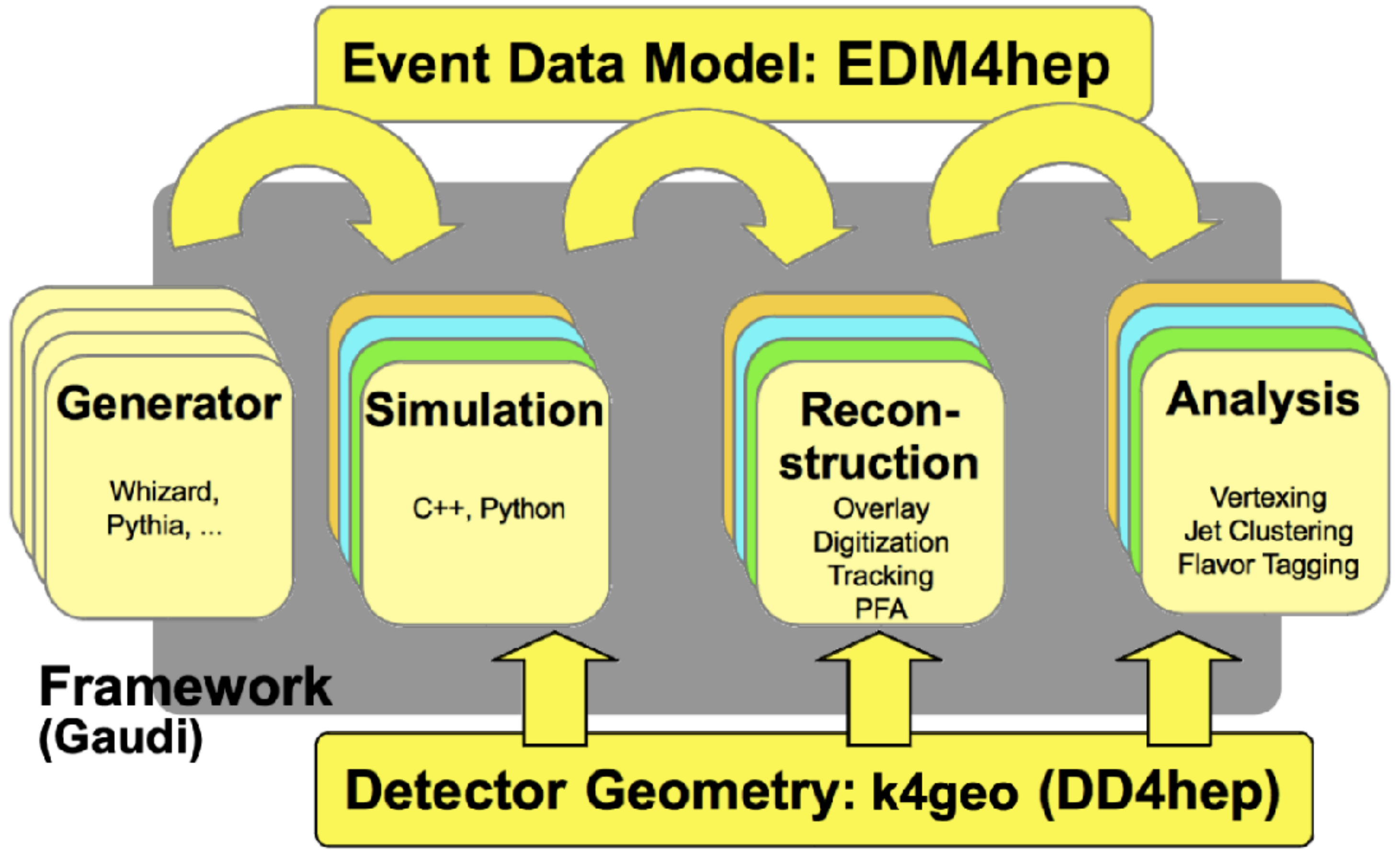
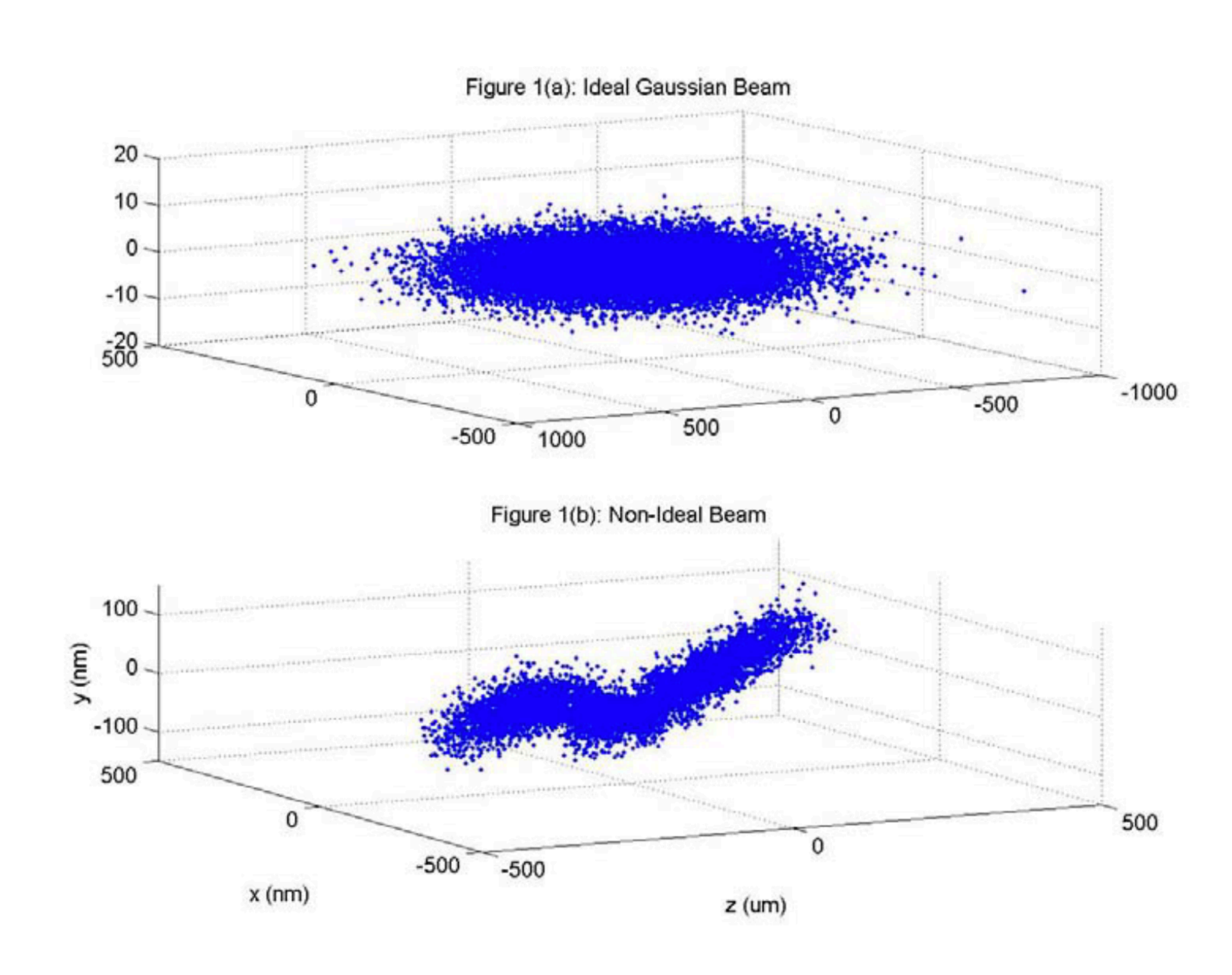
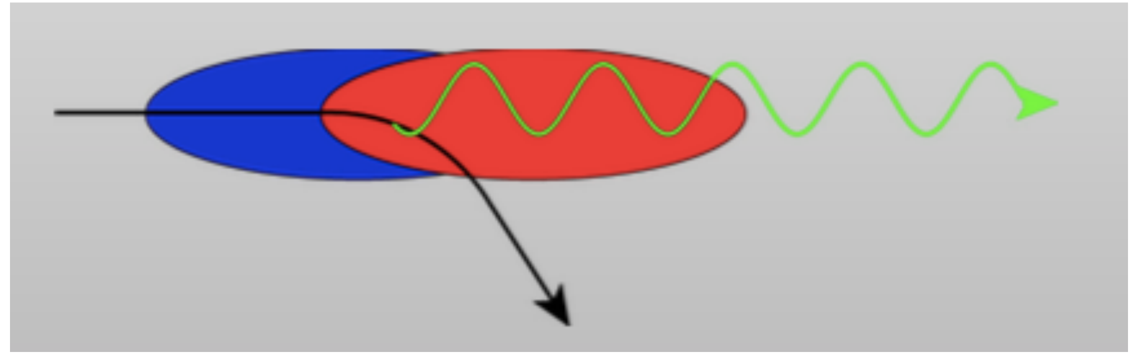


Beam simulations



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.: ✓
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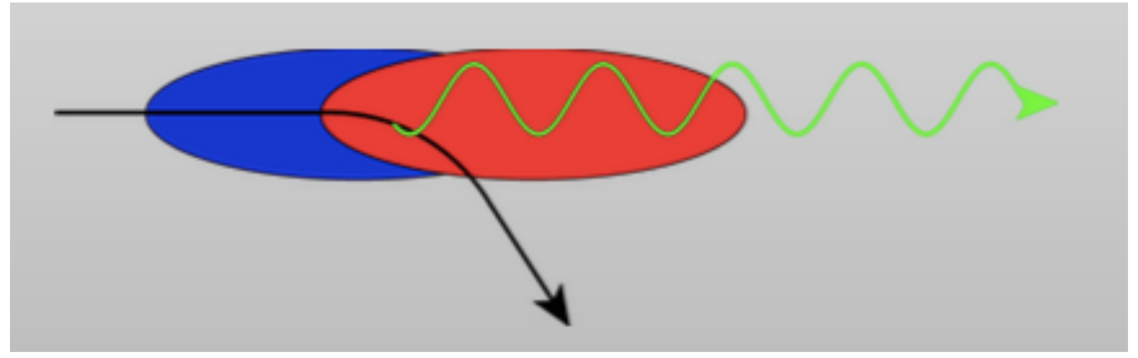

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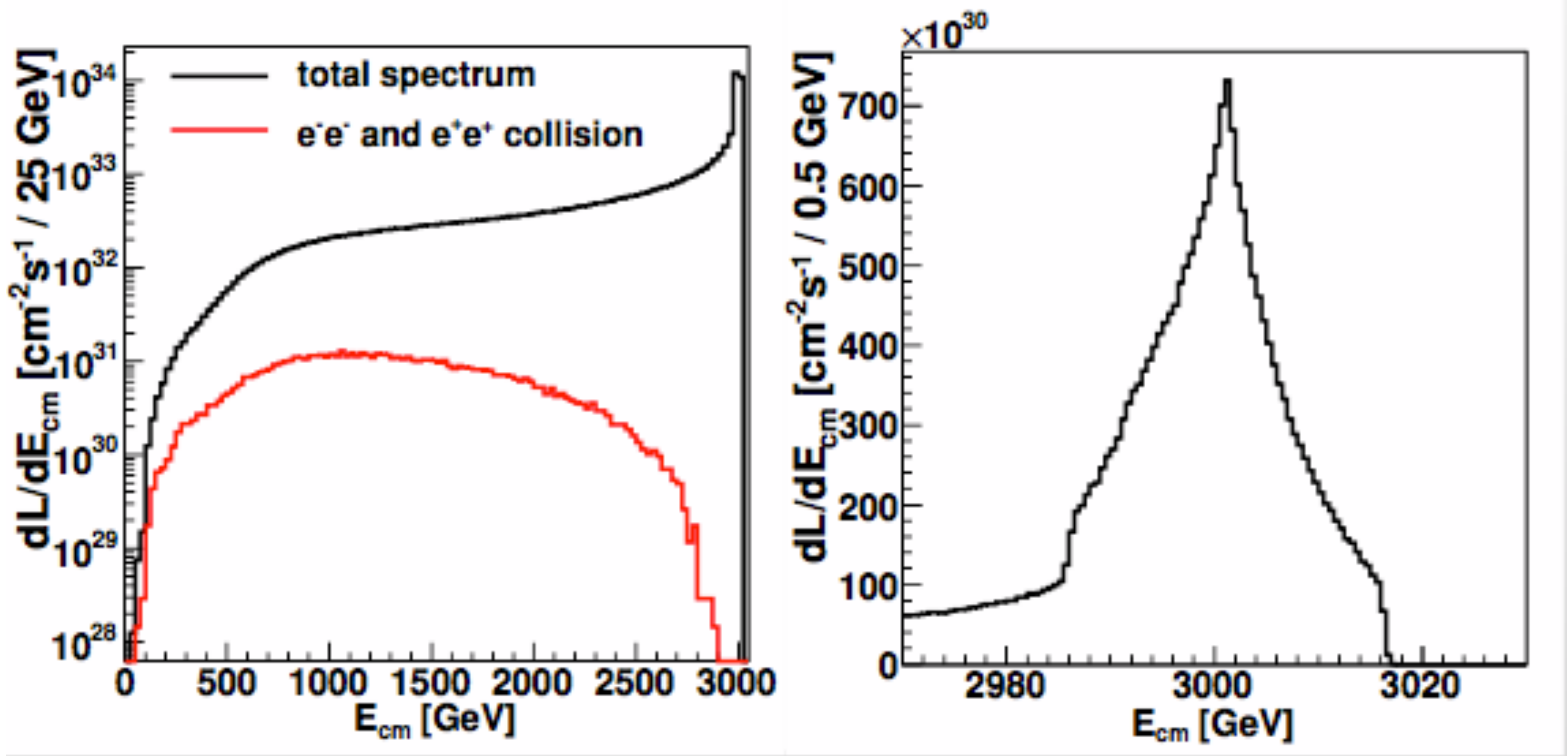

Dalena/Esbjerg/Schulte [LCWS 2011]

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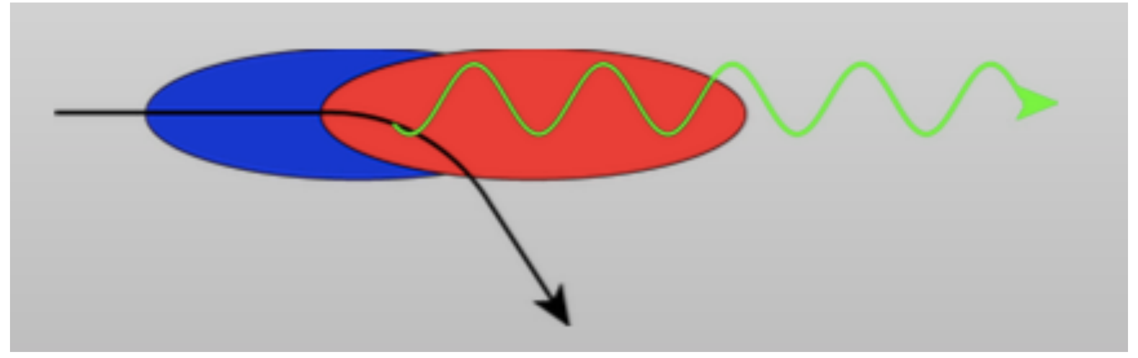

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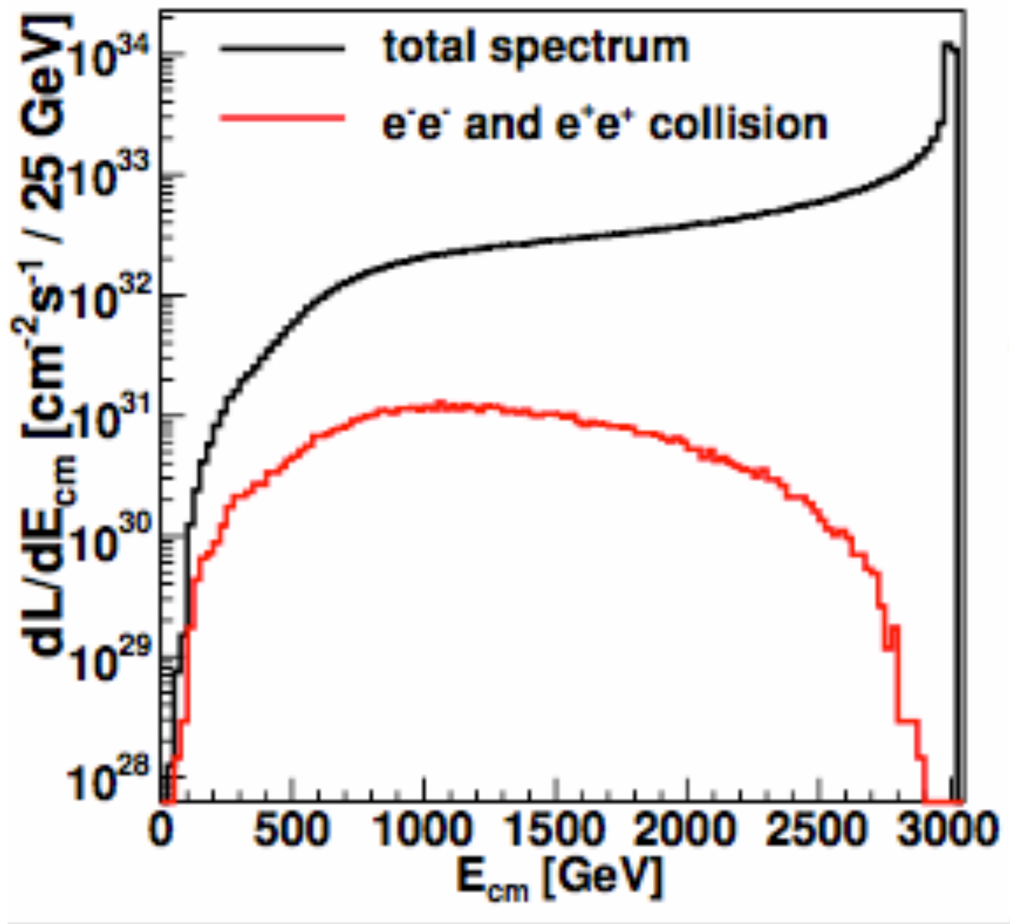

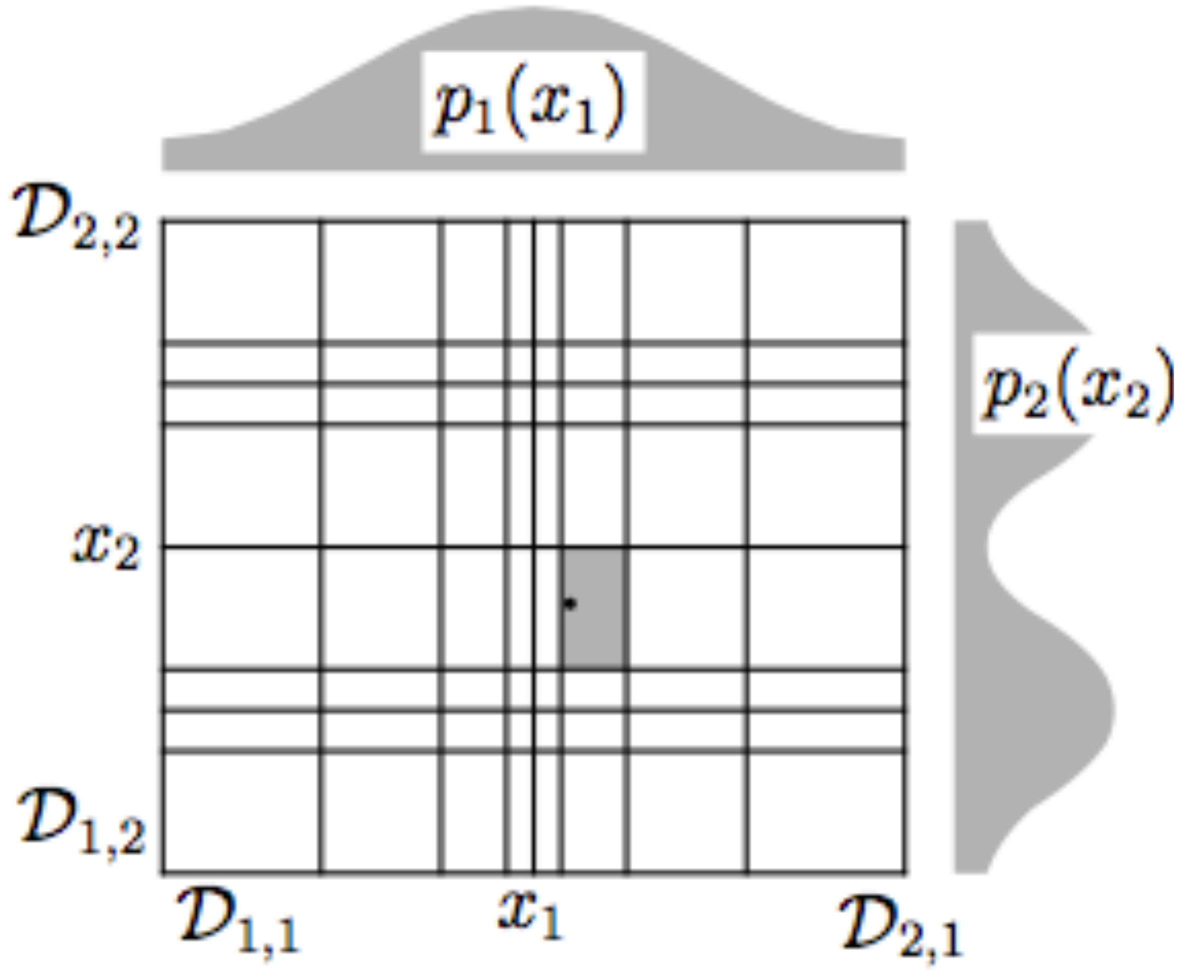

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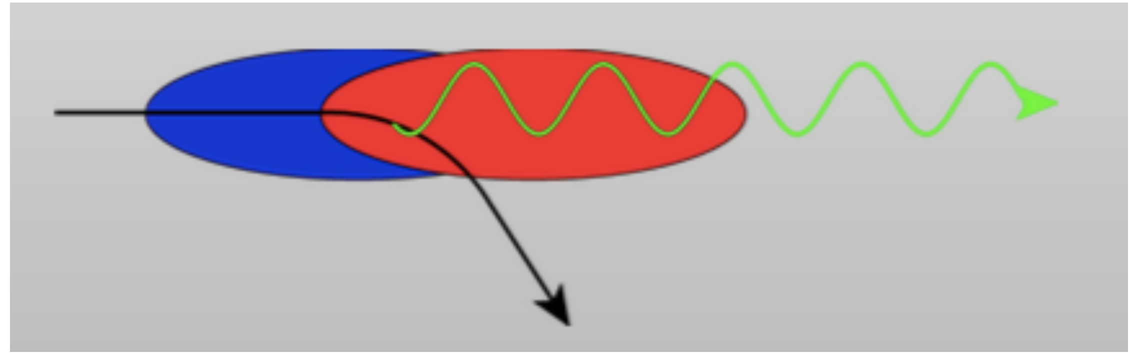

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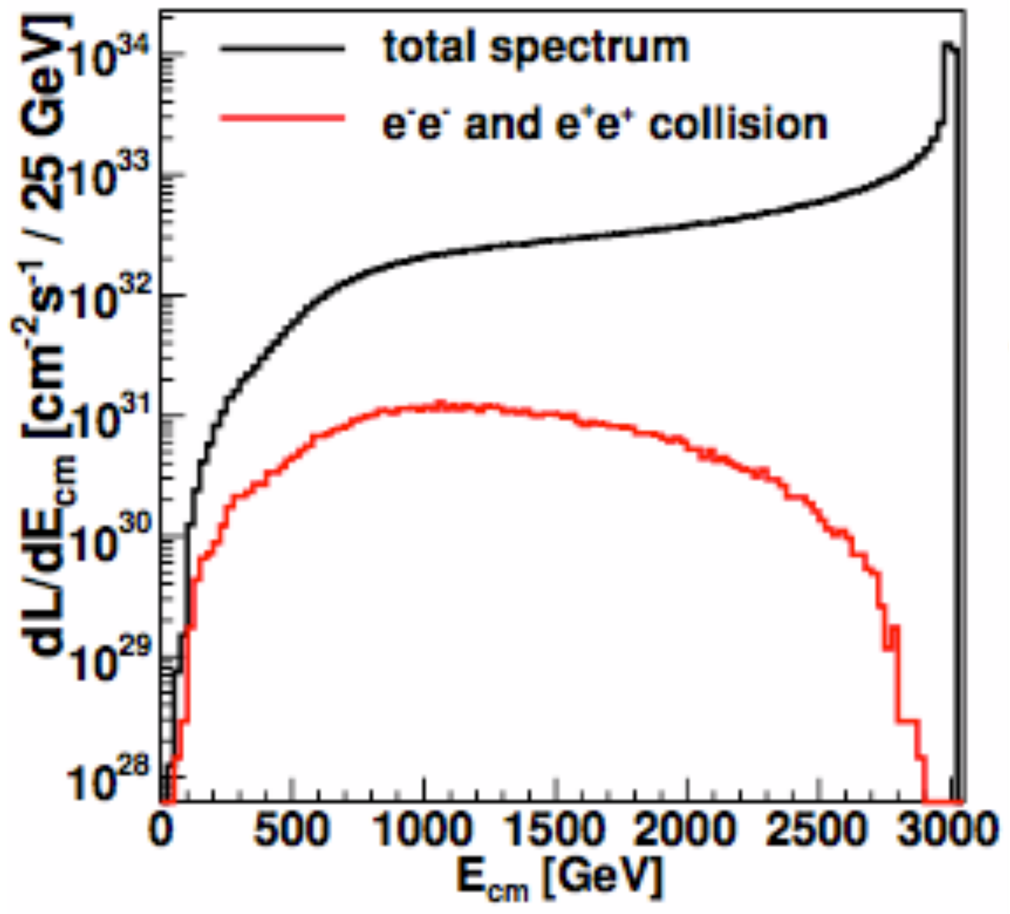
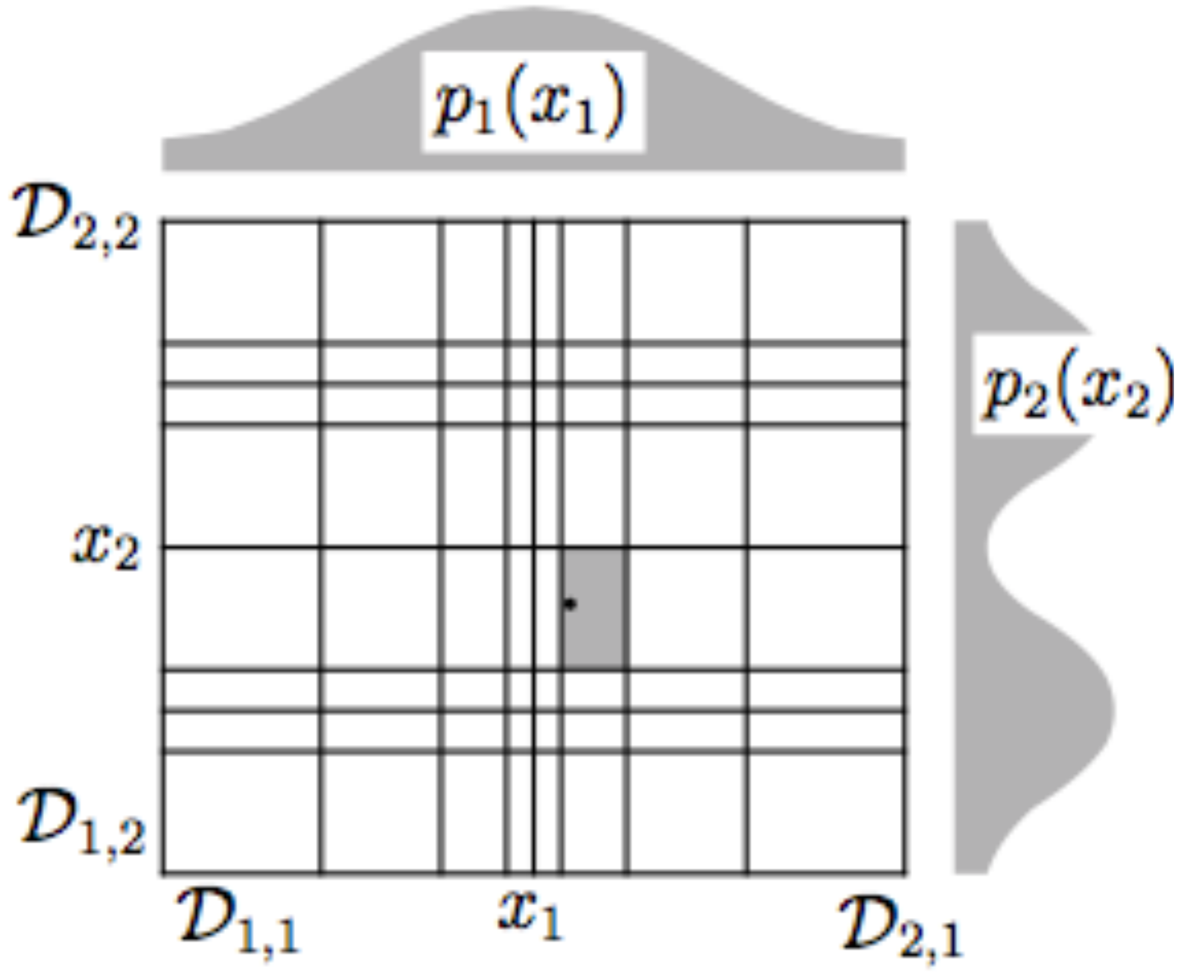




Dalena/Esbjerg/Schulte [LCWS 2011]

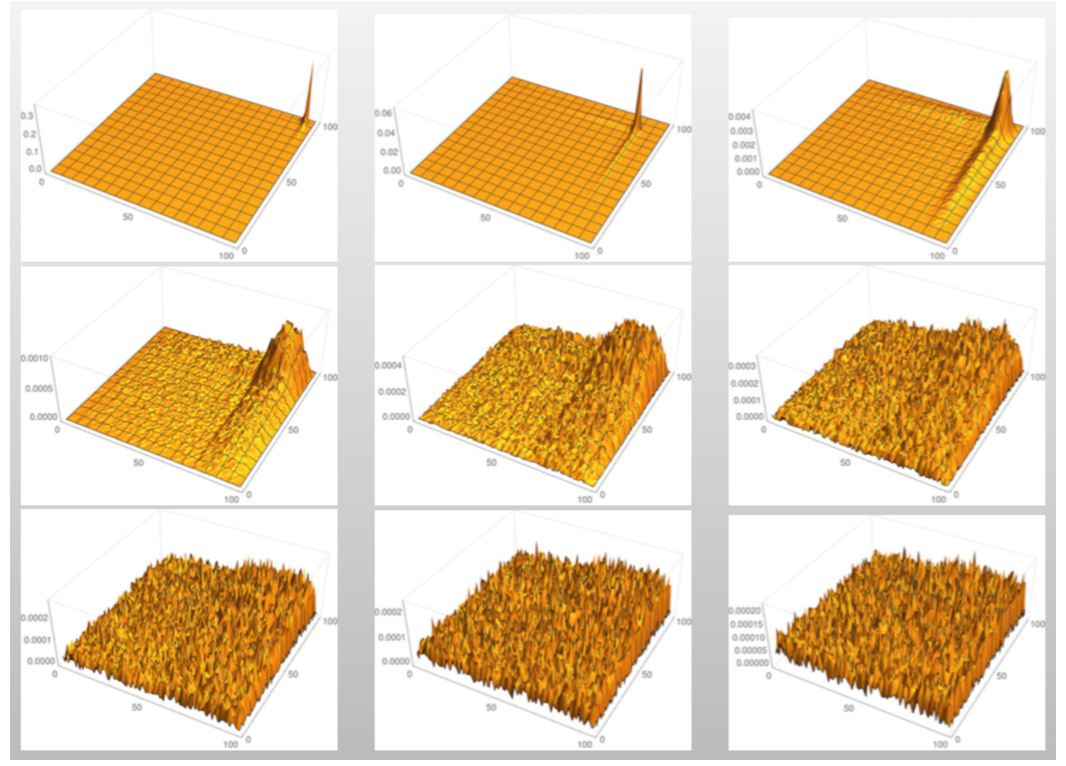
$$D_{B_1B_2}(x_1,x_2) \neq D_{B_1}(x_1)\cdot D_{B_2}(x_2)$$
$$D_{B_1B_2}(x_1,x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1}x_2^{\alpha_2}(1-x_2)^{\beta_2}$$

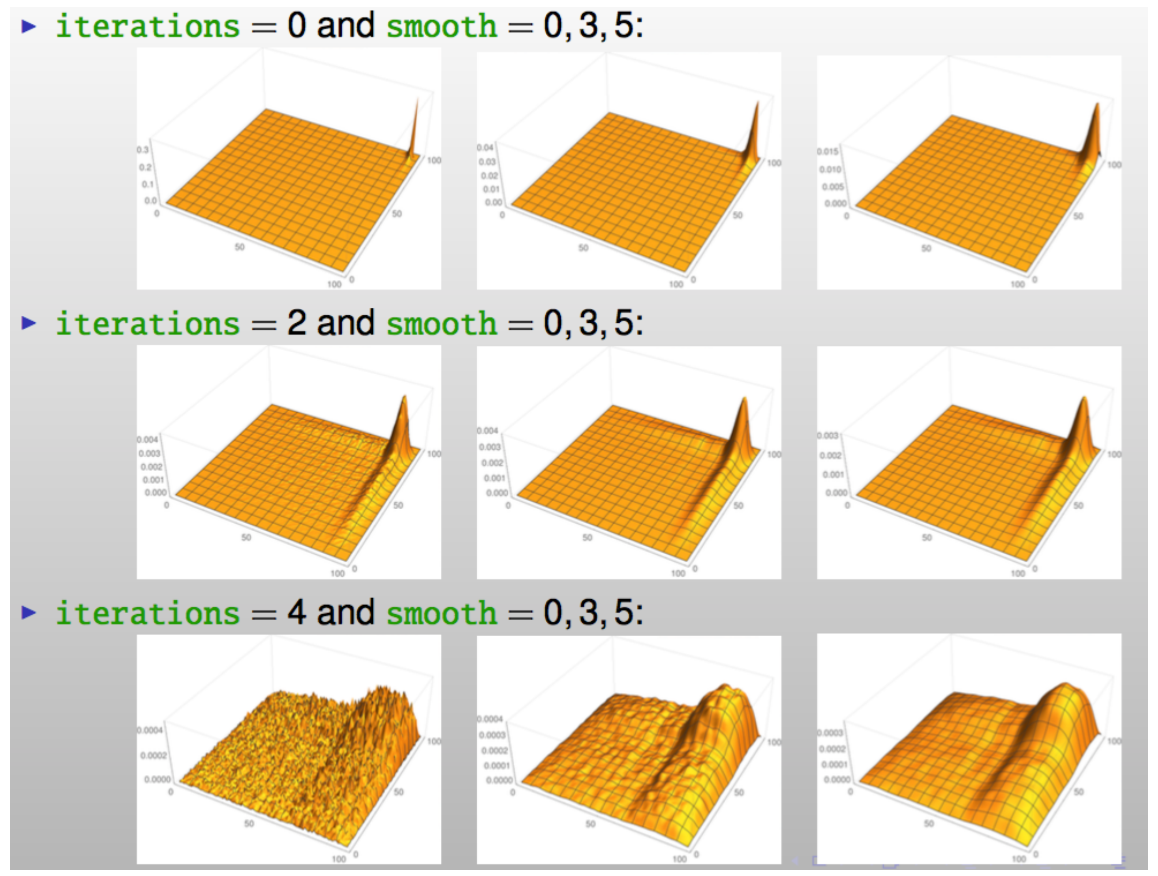
- Pro (1.): Easy implementation, covers main features
- Con (1.): Gaussian approximative, exceeds nominal collider energy
- Pro (2.): Relatively easy implementation
- Con (2.): Delta peak behaves badly in MC, beams maybe not factorizable/simple power law
- Pro (3.): most exact simulation, generator mode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

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

Beam simulations

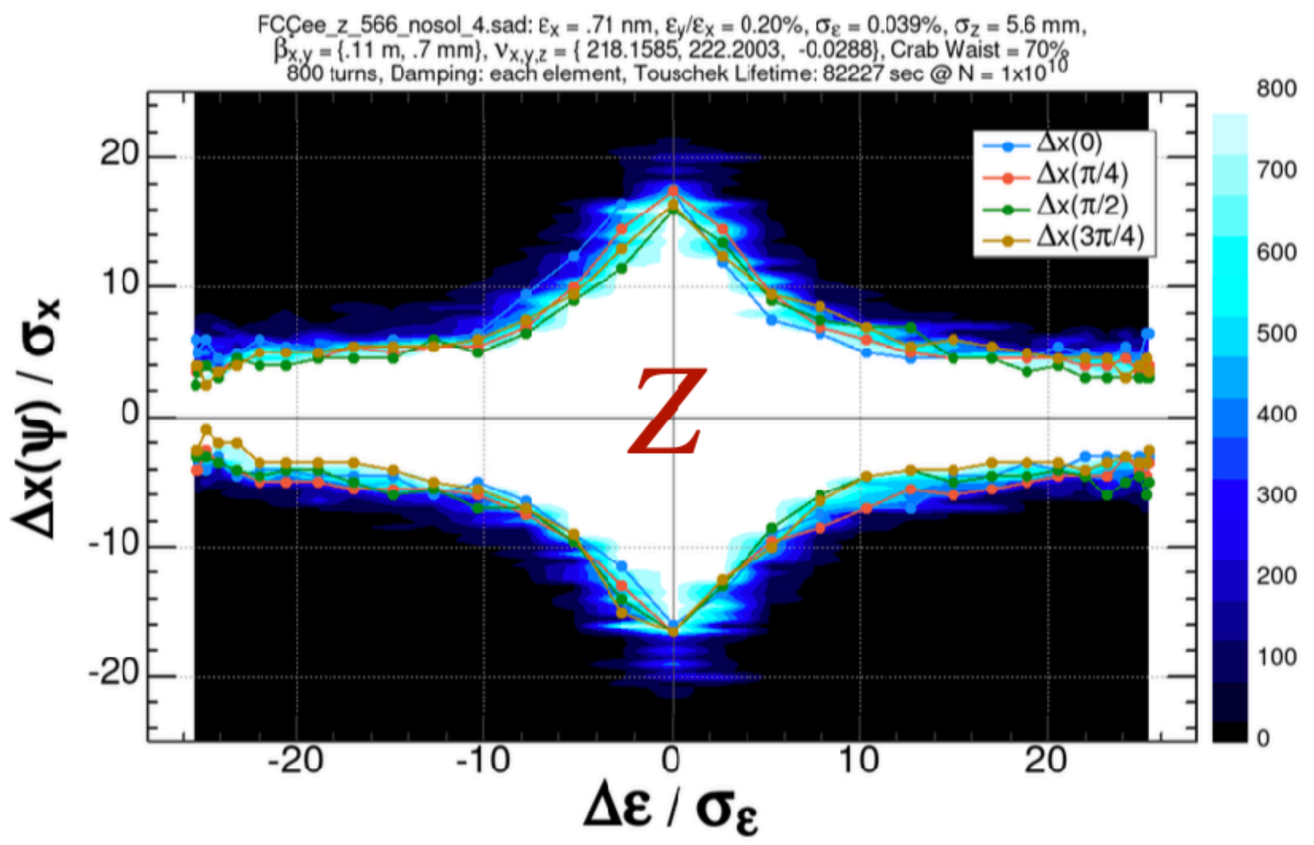
- New beam simulations for FCC-ee: 4 IPs ⇒ 1.7x lumi (91 GeV) / 1.8x lumi (161/250 GeV)
- Parameterized spectra + Gaussian spread mostly sufficient for FCC-ee scenarios
- FCC+ERLs most likelt *not* adequate with parameterized spectra
- Conclusion: `CIRCE2`-like sampling most versatile/general approach
- Parameterized spectra easier to handle in sampling (esp. NLO simulations)





(171,306 GuineaPig events in 10,000 bins)

Dynamic aperture (*z*-*x*)



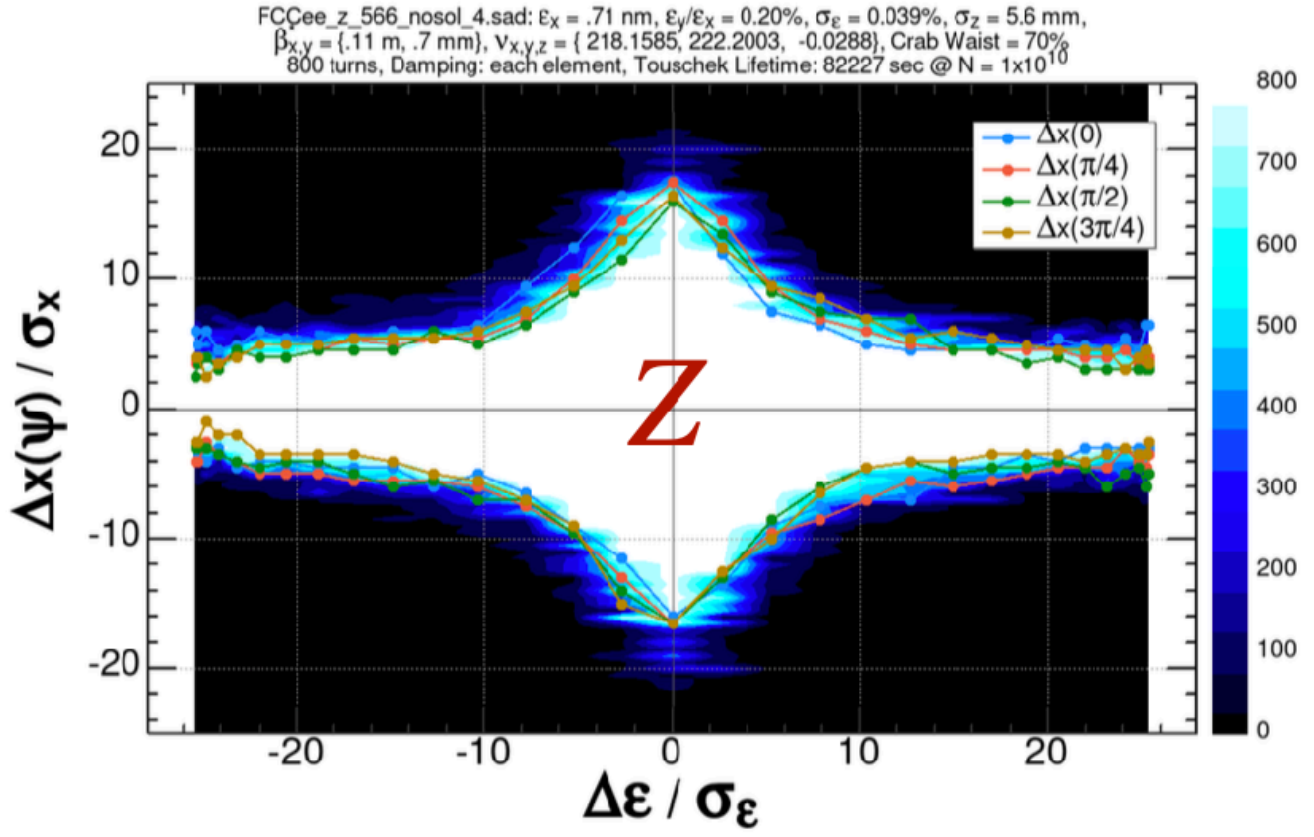
[Katsunobu Oide, FCC week 2023]

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

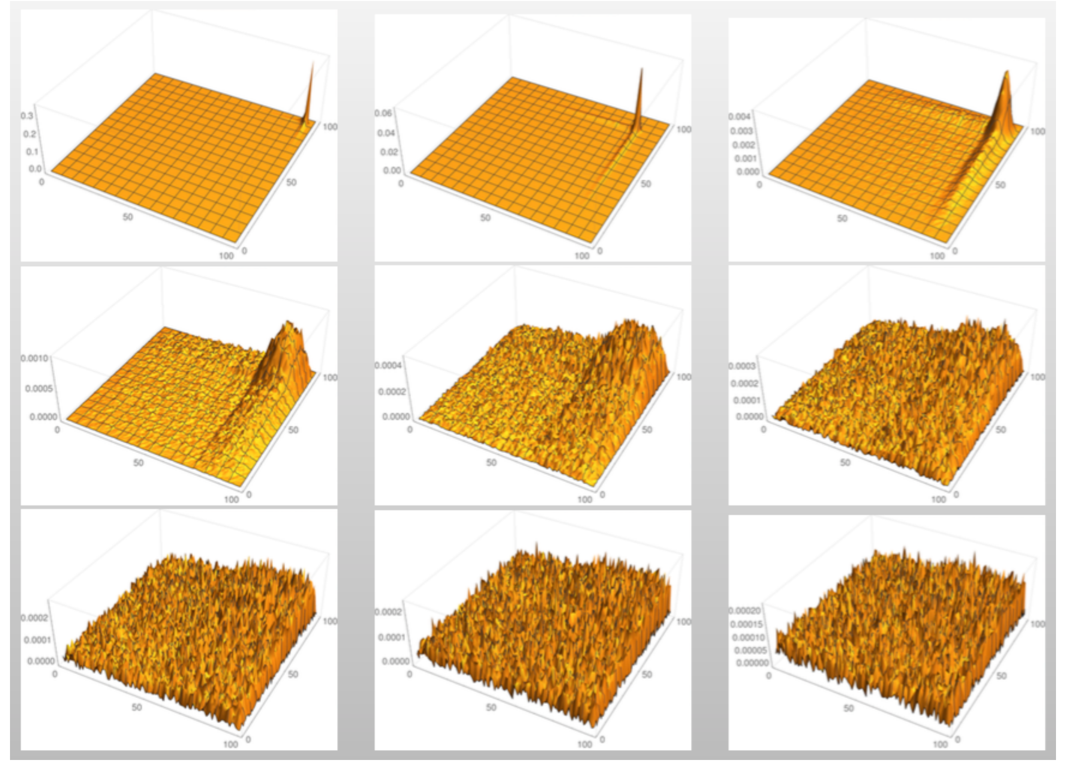
Beam simulations

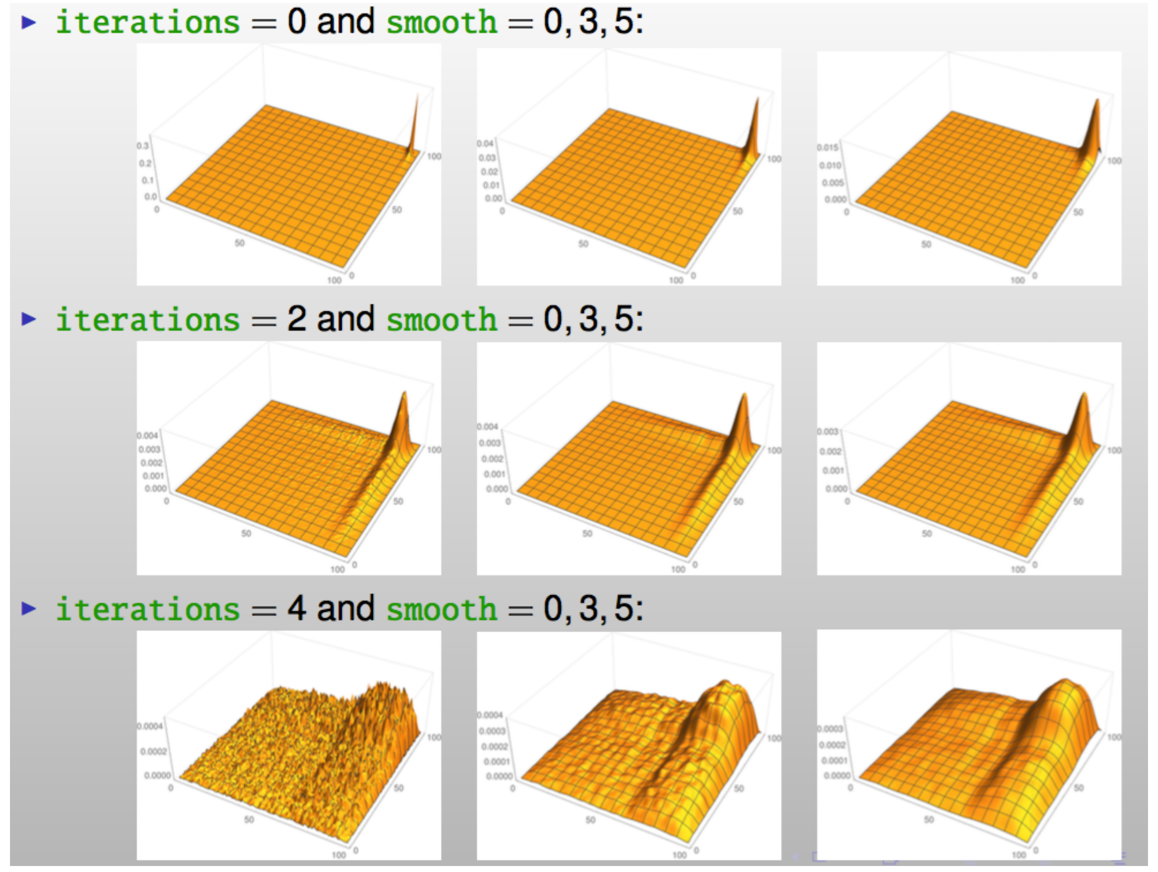
- New beam simulations for FCC-ee: 4 IPs ⇒ 1.7x lumi (91 GeV) / 1.8x lumi (161/250 GeV)
- Parameterized spectra + Gaussian spread mostly sufficient for FCC-ee scenarios
- FCC+ERLs most likelt *not* adequate with parameterized spectra
- Conclusion: `CIRCE2`-like sampling most versatile/general approach
- Parameterized spectra easier to handle in sampling (esp. NLO simulations)

Dynamic aperture (z-x)



[Katsunobu Oide, FCC week 2023]

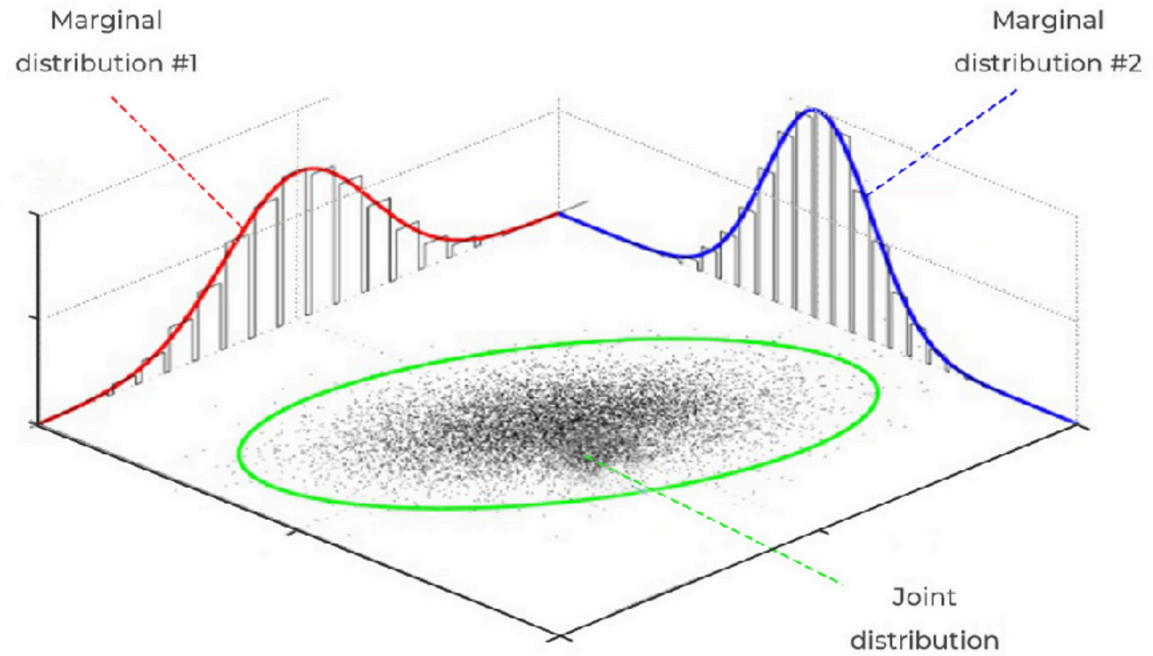




(171,306 GuineaPig events in 10,000 bins)

Open Issues

- Machine learning for sampling beam spectra not yet started (expected performance?)
- 2D-/3D-structure of beam spectra (z-dependence, copulas)



Initial state / beam setup: energy spread + crossing angle

- FCC-ee plans for 30 mrad crossing angle $\Longrightarrow$ crossing angle simulations needed
- Several MCs offer such simulations:

Beams with crossing angle

```
beams_momentum = 120 GeV, 120 GeV
beams_theta = 15 mrad, -15 mrad
```

Beams with rotated crossing angle

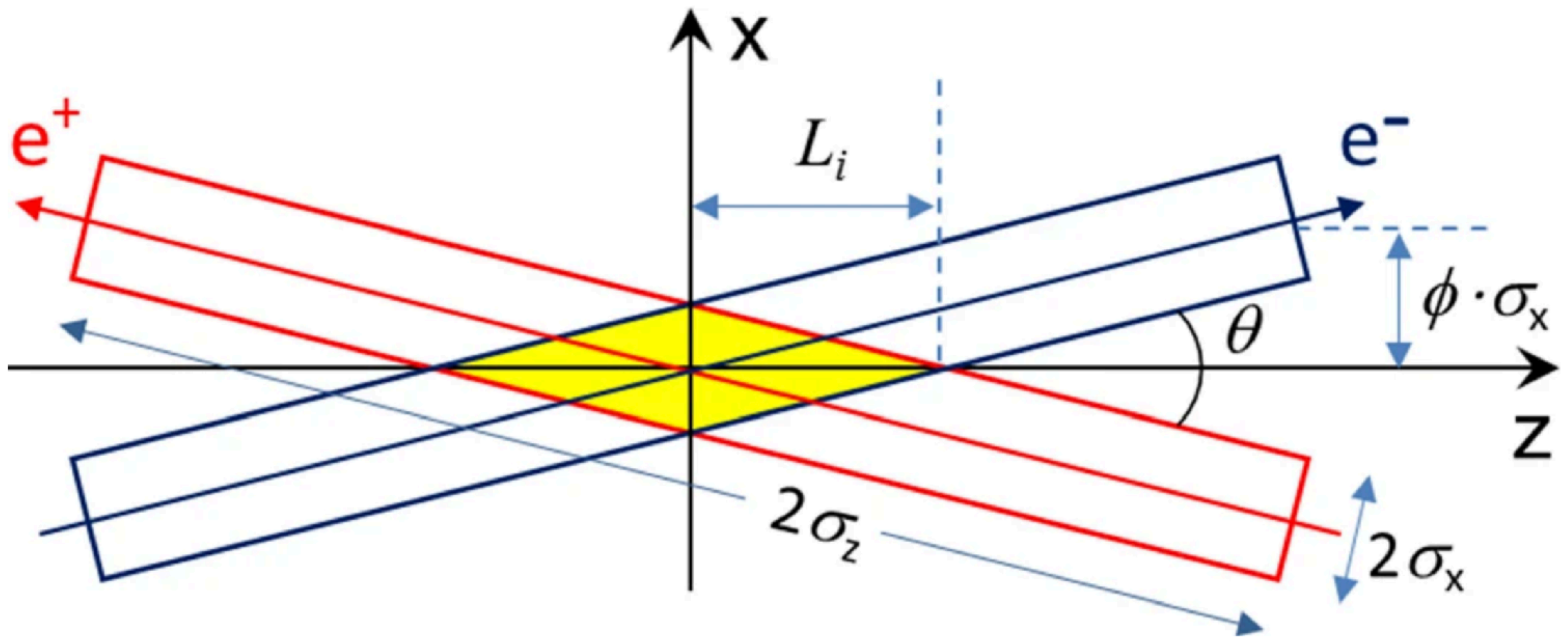
```
beams_momentum = 120 GeV, 120 GeV
beams_theta = 15 mrad, -15 mrad
beams_phi   = 0, 45 degree
```

Asymmetric collisions

```
beams_momentum = 500 GeV, 31 GeV
```

```
Beams:pzA =  119.987    Beams:pzB = -119.987
Beams:pxA =    1.800    Beams:pxB =   -1.800

Beams:pyA =      xxx    Beams:pyB =   -x.xxx
```



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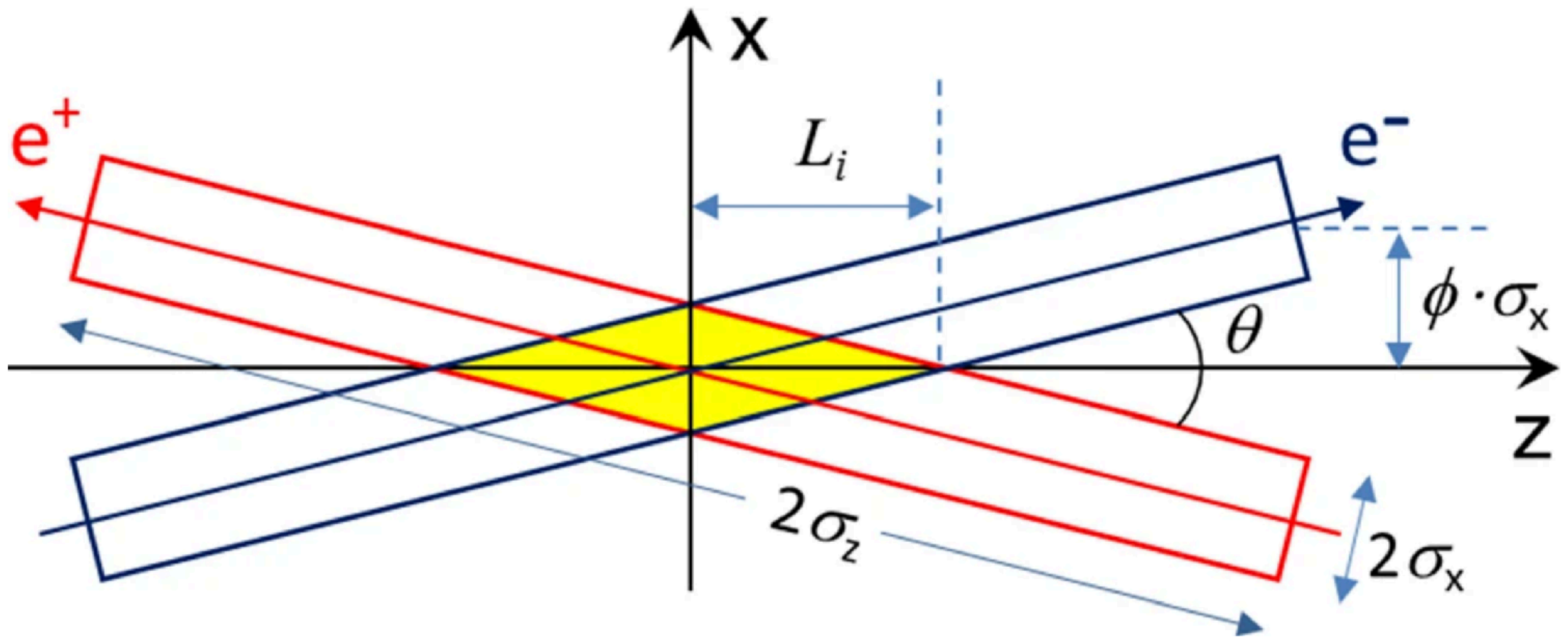
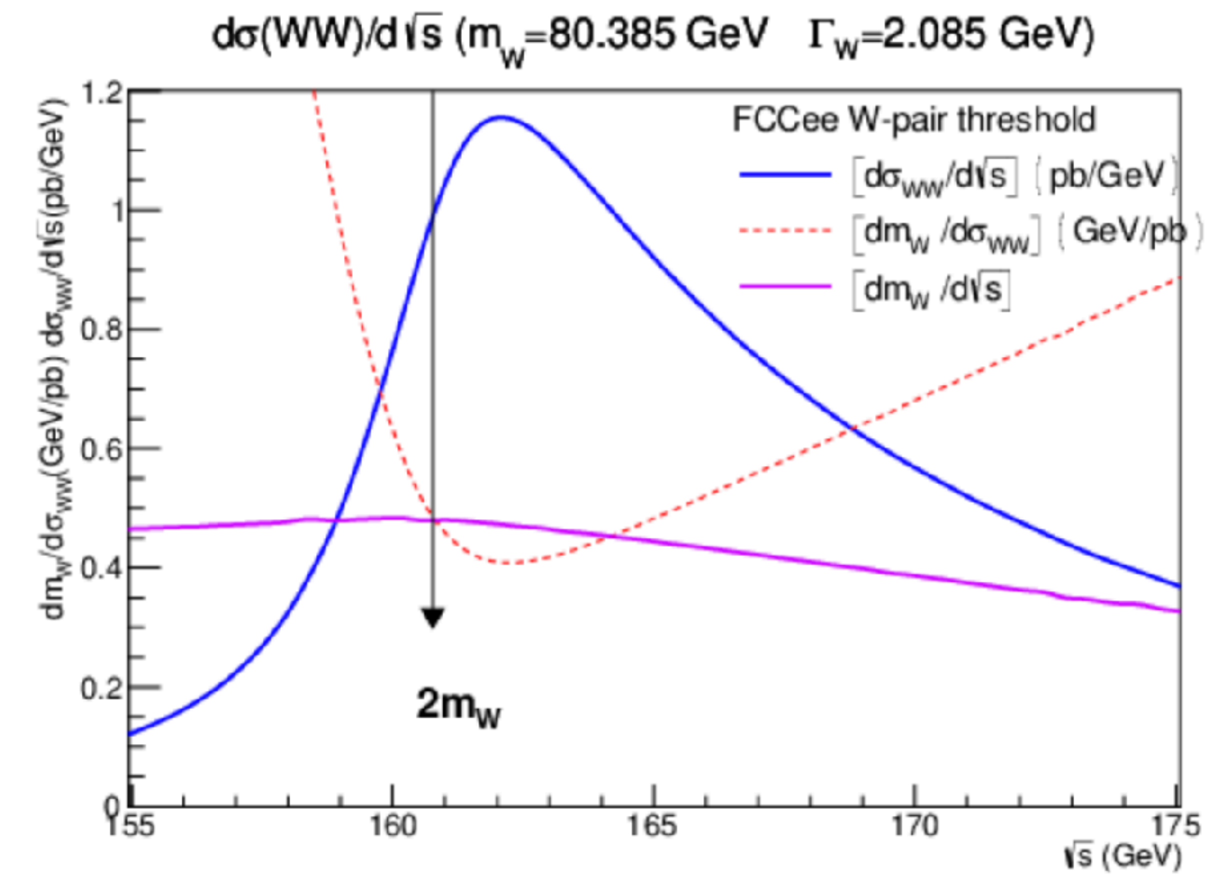


- Simulation of beam energy spread: available in many MCs (`KKMC, Pythia, Sherpa, Whizard, ...?`)
- Note: total cross sections do depend on the crossing angle as well as the beam profile
- Is there also need for spread in transverse directions?

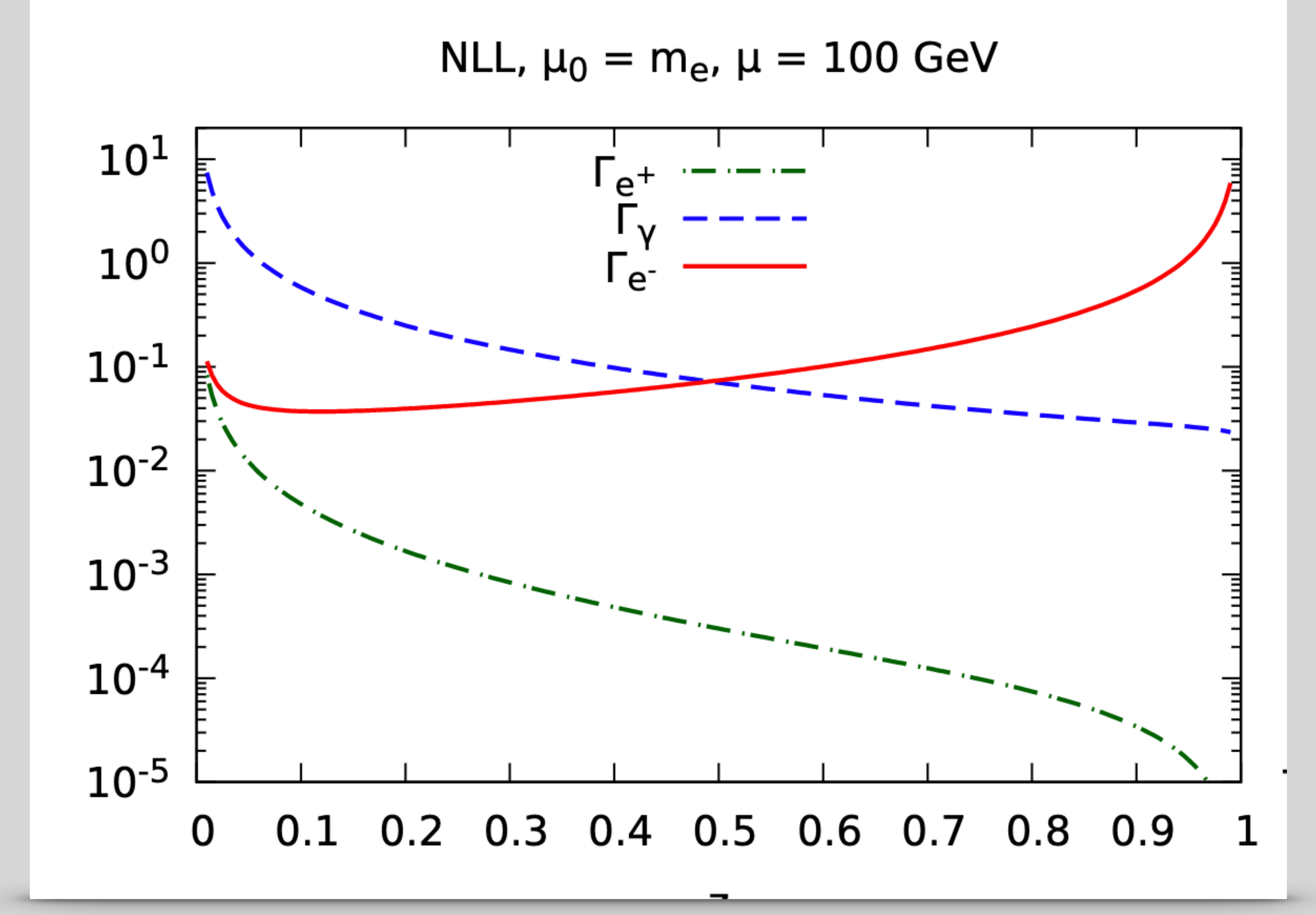
```
beams = e1, E1 => gaussian
gaussian_spread1 = 0.13%
gaussian_spread2 = 0.13%
```

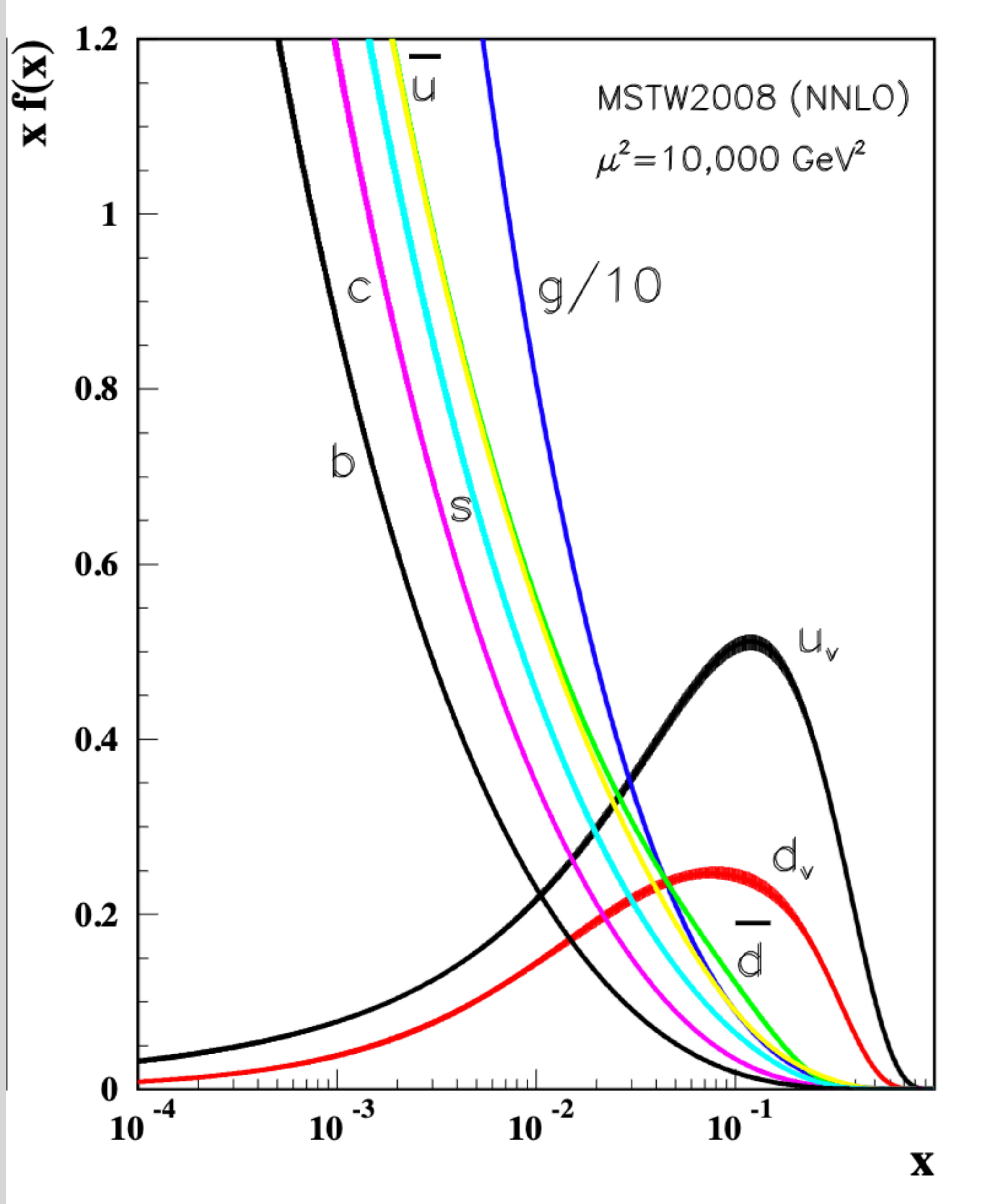
```
Beams:allowMomentumSpread = on
Beams:sigmaPzA = 0.156

Beams:sigmaPxA = xxxx

Beams:Shape class
```



arXiv:1909.12245

Initial State Radiation — Lepton PDFs

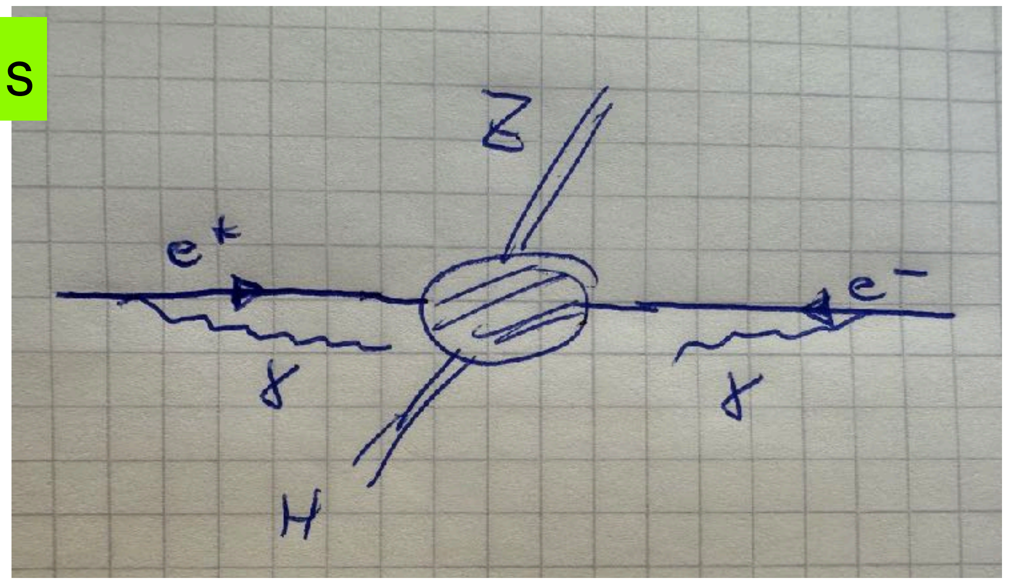




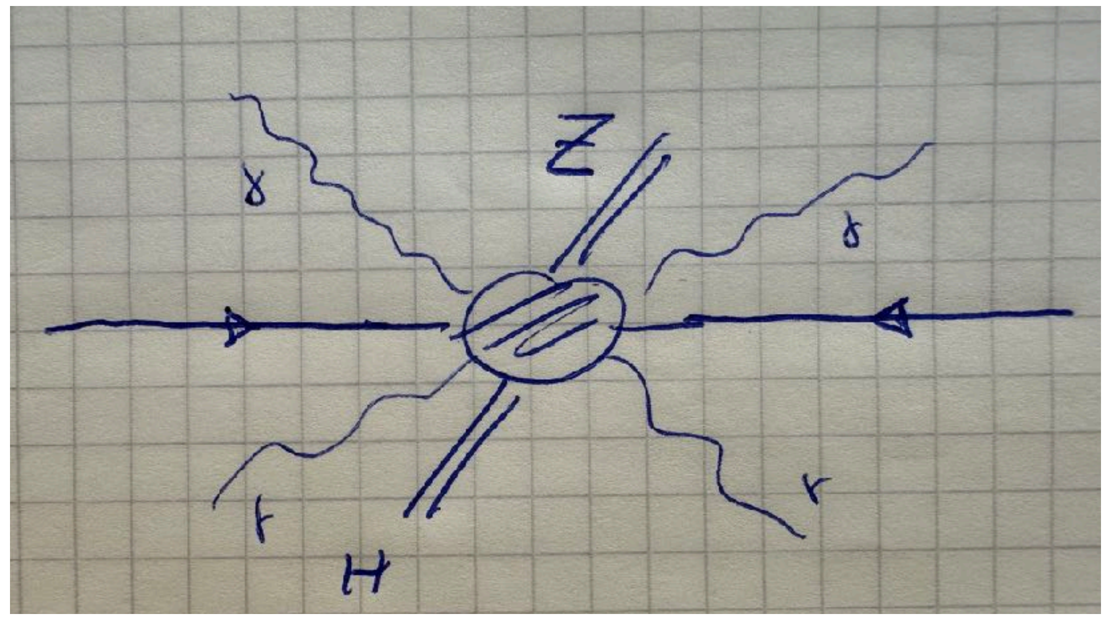
QED PDFs — QED Initial State Resummation

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

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

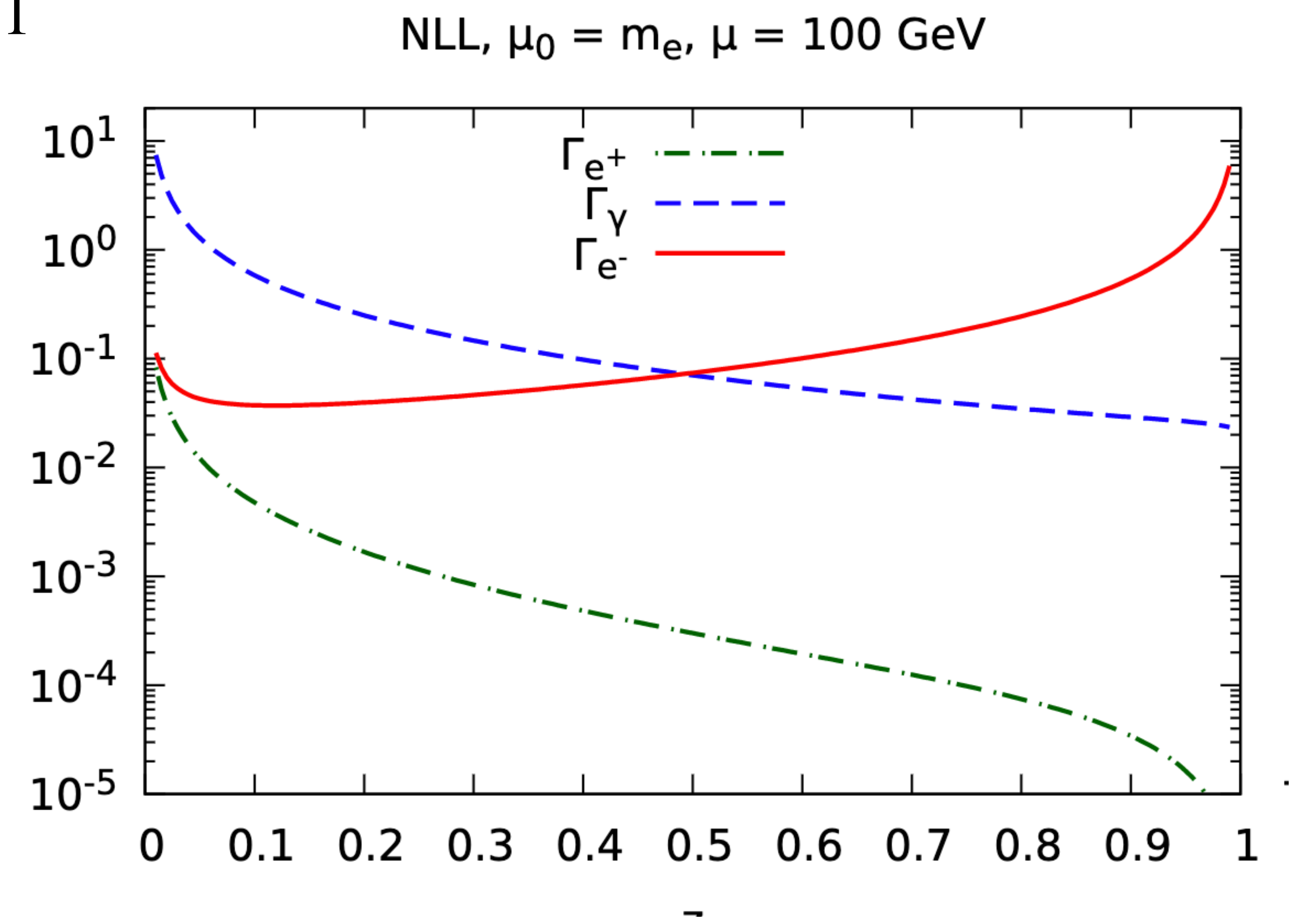
- Different factorization schemes: focus on collinear logs, $\log \frac{Q^2}{m_\mu^2}$, vs. soft logs, $\log \frac{Q^2}{E_\gamma^2}$, cf. 2203.12557
- YFS (Yennie-Frautschi-Suura), cf. e.g. 2203.10948 $d\sigma = \sum_{n_\gamma}^{\infty} \frac{\exp[Y_{res.}]}{n_\gamma !} \prod_{j=1}^{n_\gamma} \left[d\text{LIPS}_j^\gamma S_{res.}(k_j) \right] [\sigma_0 + \text{corrections}]$
    - 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: $\alpha(\alpha L)^{k-1}$

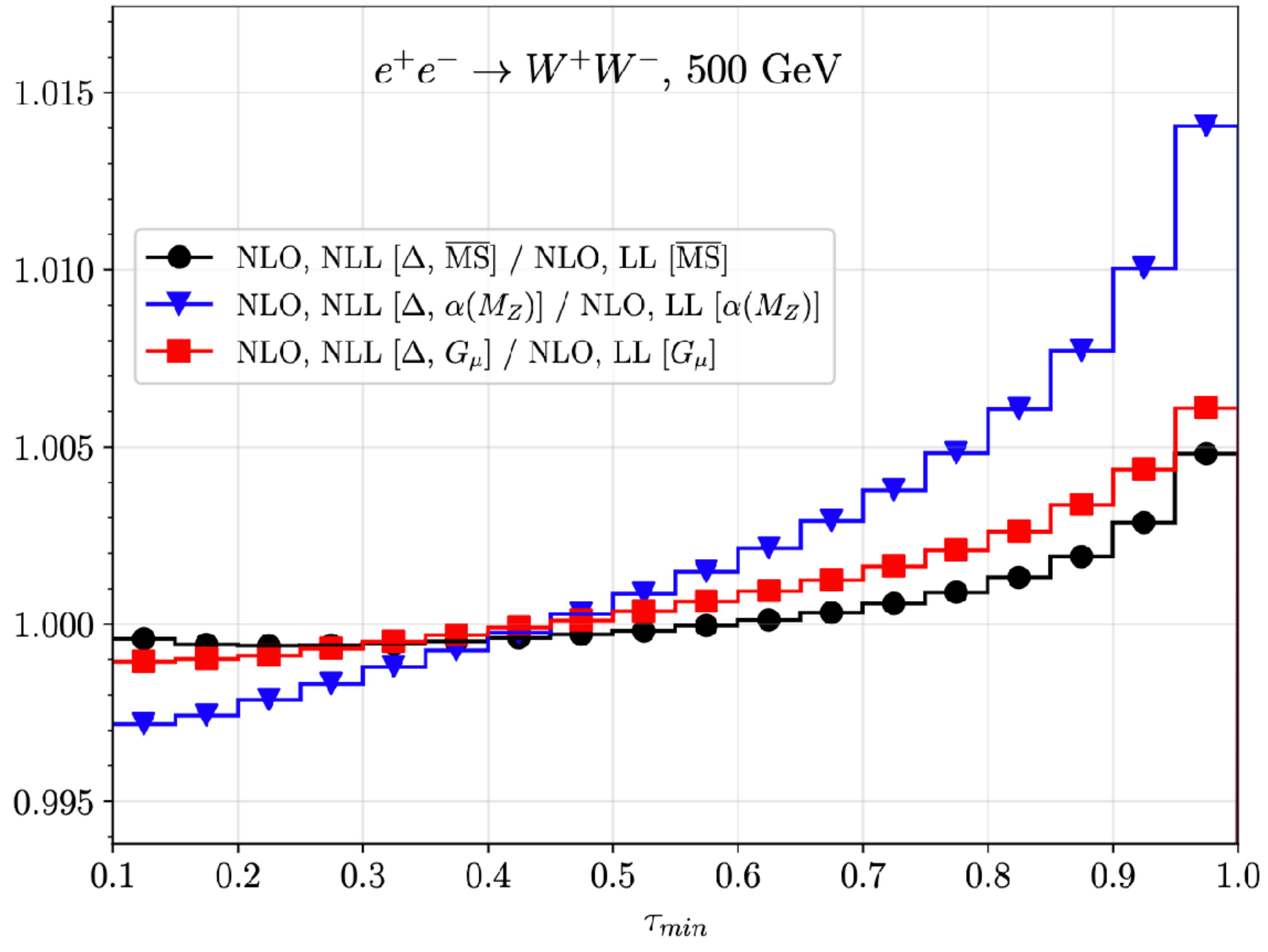
$$d\sigma_{kl}(p_k, p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \, \Gamma_{i/k}(z_+, \mu^2, m^2) \, \Gamma_{j/l}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_k, z_- p_l, \mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$$

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 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





↪ Talks by Stefano Frixione & Giovanni Stagnitto

ePDFs for polarized leptons !?

Initial state / beam setup: polarization

Beam polarization (transversal, longitudinal, arbitrary)

```
beams_pol_density = @([<spin entries>]), @([<spin entries>])
beams_pol_fraction = <degree beam 1>, <degree beam 2>
```

$|m| = 2$ massless

$|m| = 2j+1$ massive

Initial-state spin-density matrix: ρ

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Unpolarized beams $\rho = \frac{1}{|m|}\mathbb{I}$

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beams_pol_density = @()
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```
beams_pol_density = @()
```

Circular polarization $\rho = \mathrm{diag}\left(\frac{1 \pm f}{2}, 0, \ldots, 0, \frac{1 \mp f}{2}\right)$

```
beams_pol_density = @(±j)
beams_pol_fraction = f
```

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```

Transversal polarization (along axis)

$$\rho = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \frac{f}{2}\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ \frac{f}{2}\,e^{i\phi} & \cdots & \cdots & 0 & 1 \end{pmatrix}$$

```
beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
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Polarization along arbitrary axis (θ,Φ)

$$\rho = \frac{1}{2} \cdot \begin{pmatrix} 1 - f\cos\theta & 0 & \cdots & \cdots & f\sin\theta\, e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ f\sin\theta\, e^{i\phi} & \cdots & \cdots & 0 & 1 + f\cos\theta \end{pmatrix}$$

```
beams_pol_density = @(j:j:1-cos(theta),
      j:-j:sin(theta)*exp(-I*phi), -j:j:1+cos(theta))
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beams_pol_fraction = f
```

Diagonal / arbitrary density matrices

$$\rho = \left(x_{m,m'}\right)$$

```
beams_pol_density = @({m:m′:xm,m′})
```

SM precision in hard processes — Loops and Legs

Getty Villa, Pacific Palisades, Etruscan, 525 BC

Final state polarization, factorized processes, cut selections etc.


```
unstable "W+" { decay_helicity = 0 }
```

- Trivial things: cut selections (angular cuts etc.), clustering, particle containers
- Factorization into production and decay (w/ full spin correlation, intermediate polarization)
- Final state polarizations (w/ spin density matrices) — not directly usable in event formats

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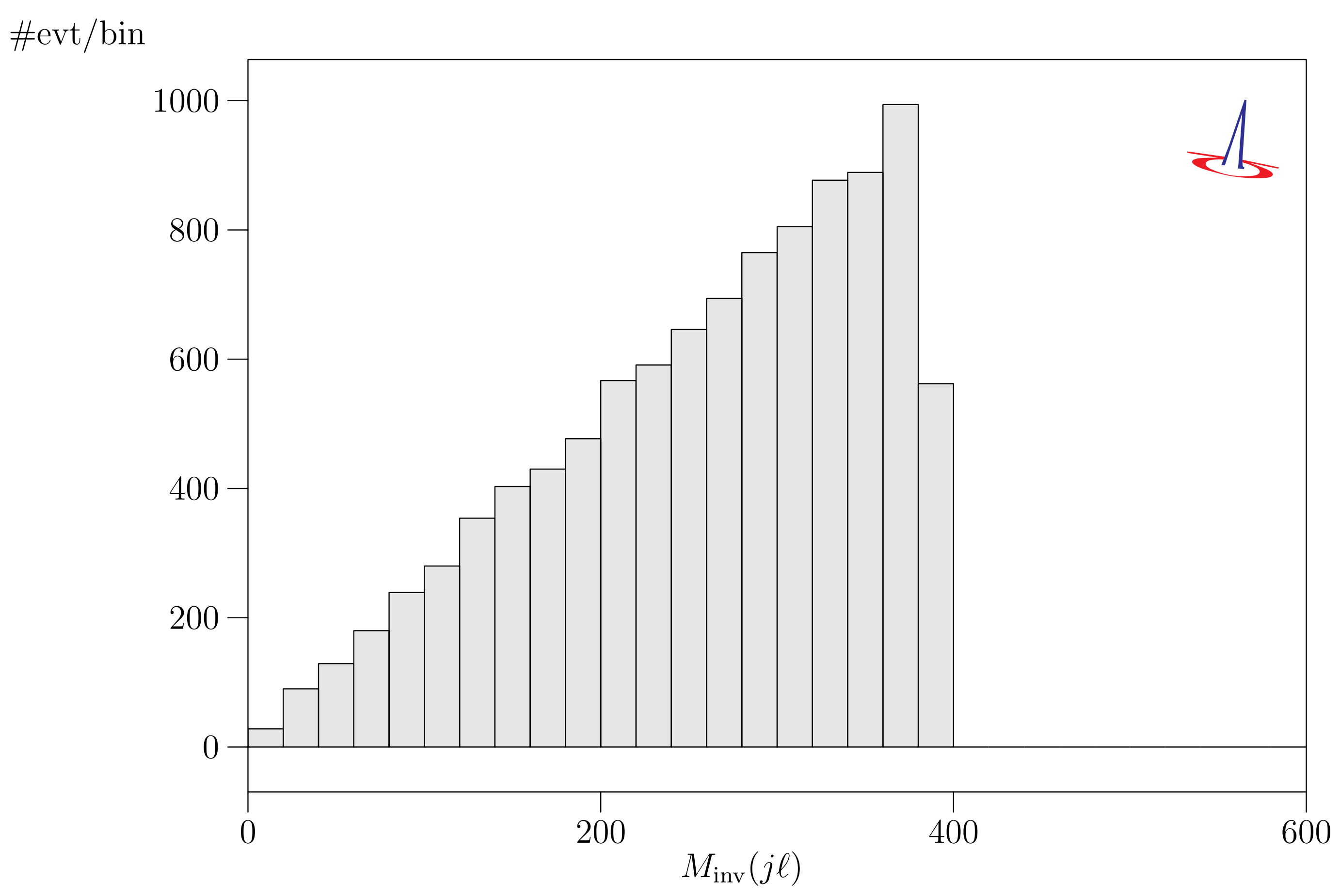
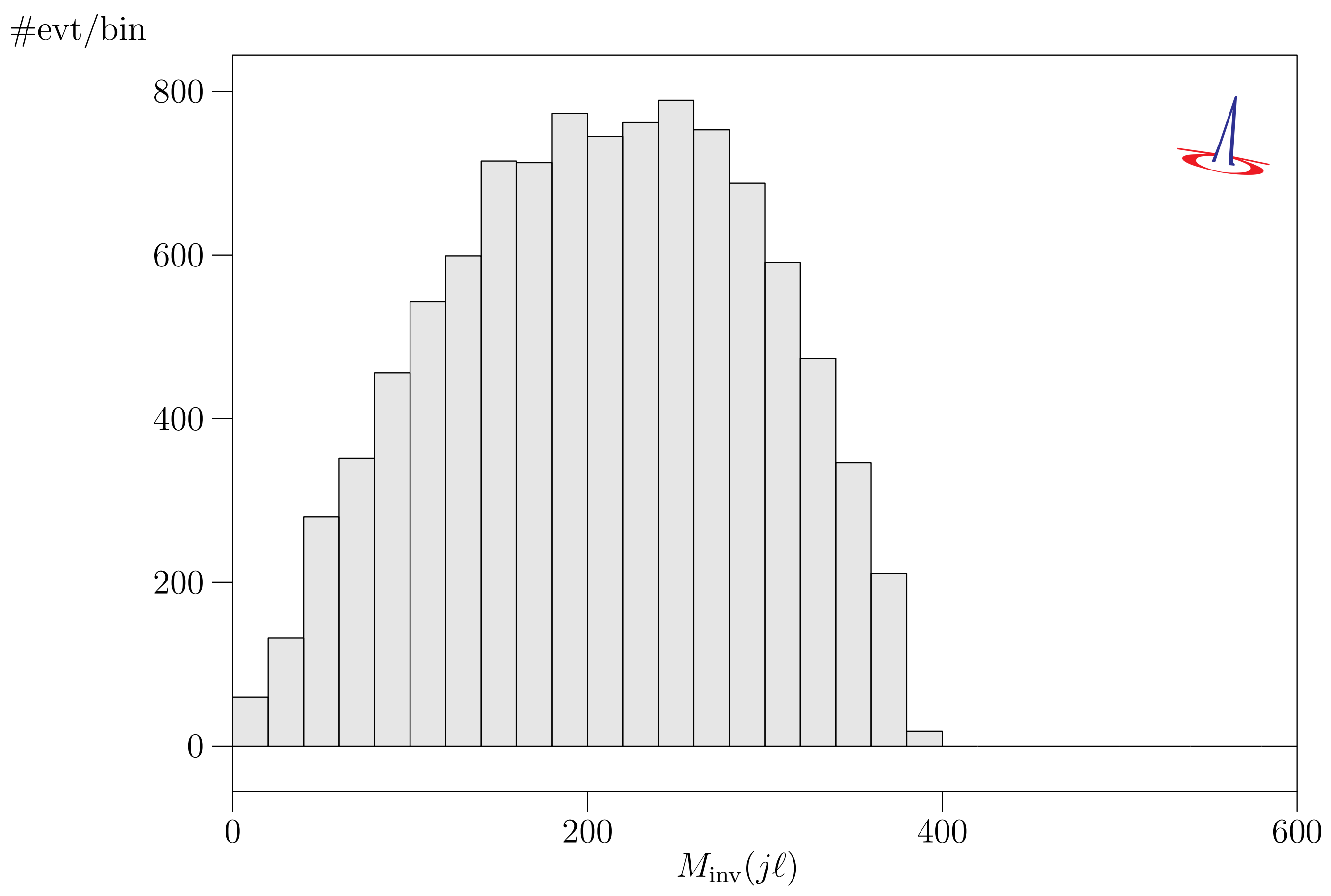
`?isotropic_decay = true`



`simulate (casc)`



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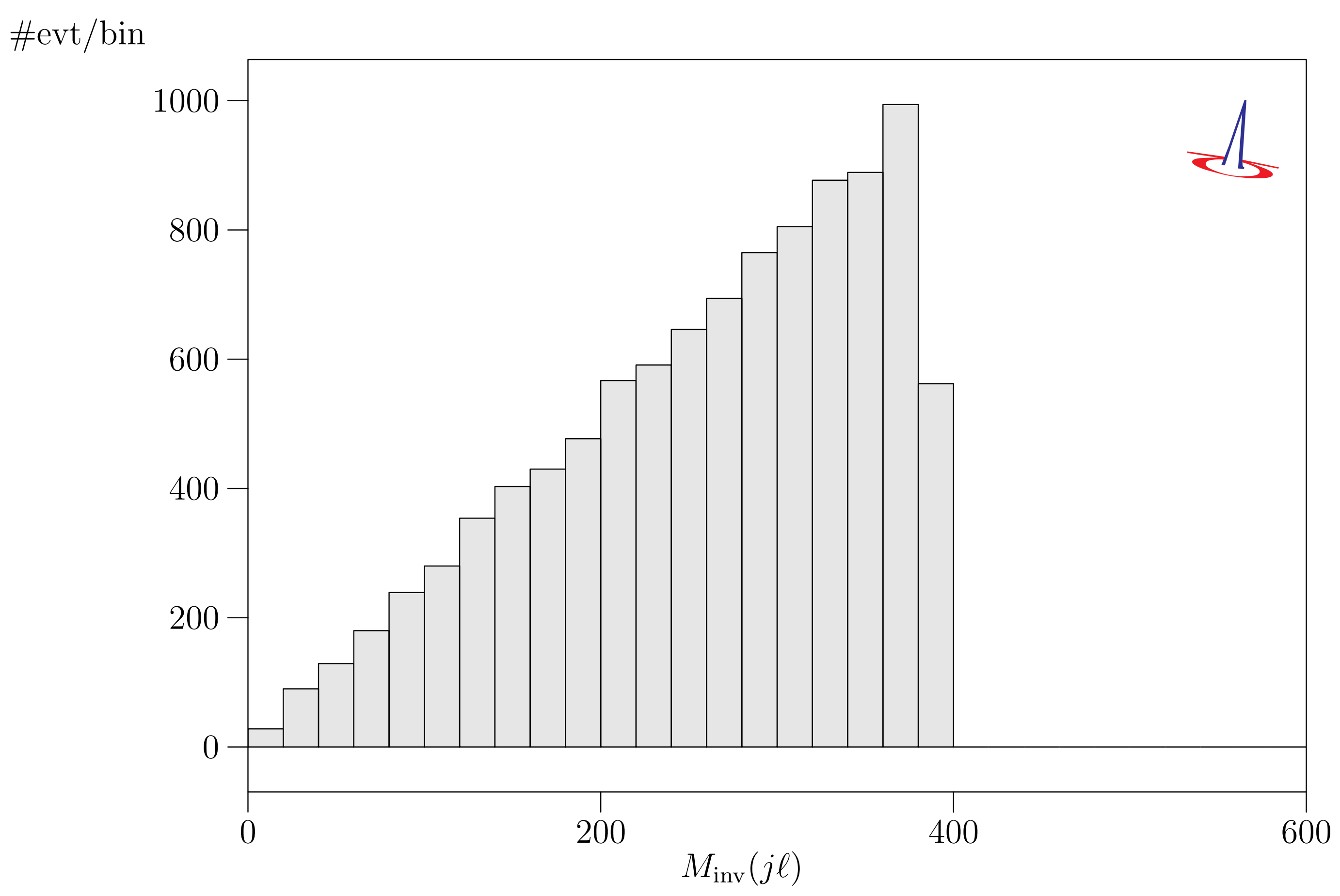

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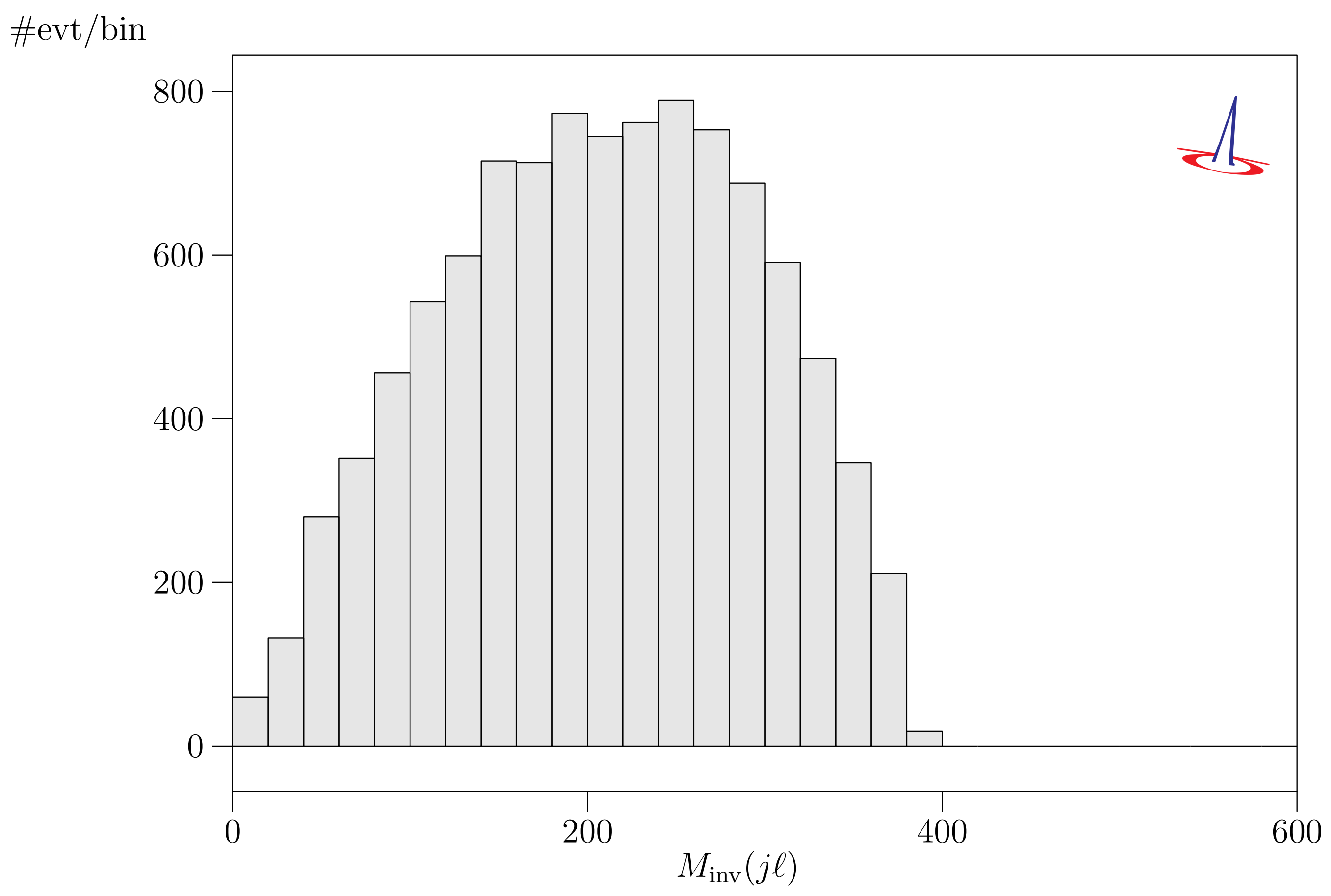

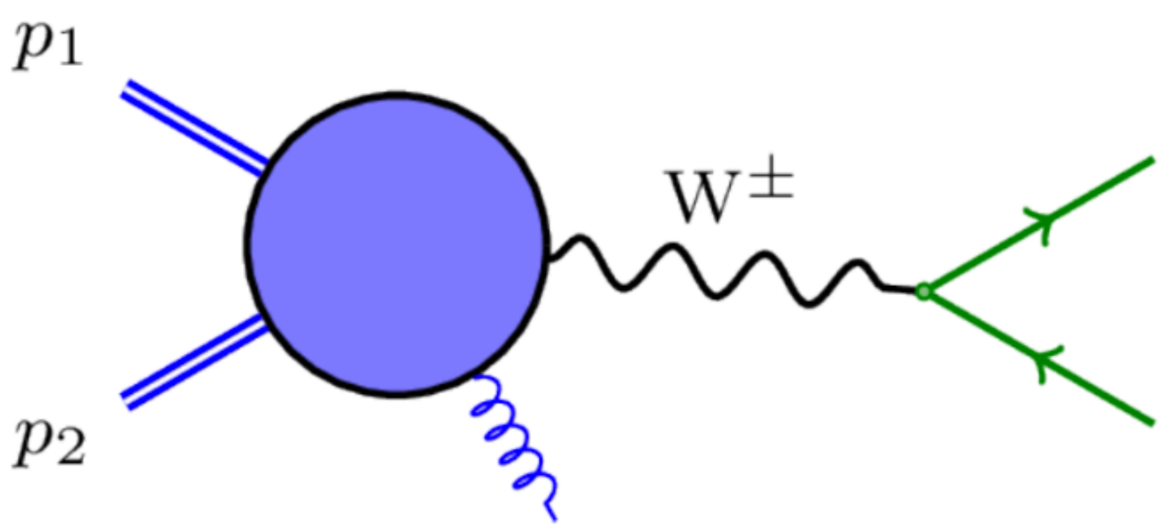

$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + i M_V \Gamma_V} \cdot \mathbf{D}_\nu$$

$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} \longrightarrow \sum_\lambda \epsilon_\lambda^{\mu\,*} \epsilon_\lambda^\nu$$

On-shell vector bosons (NWA or DPA)

Final state polarization, factorized processes, cut selections etc.

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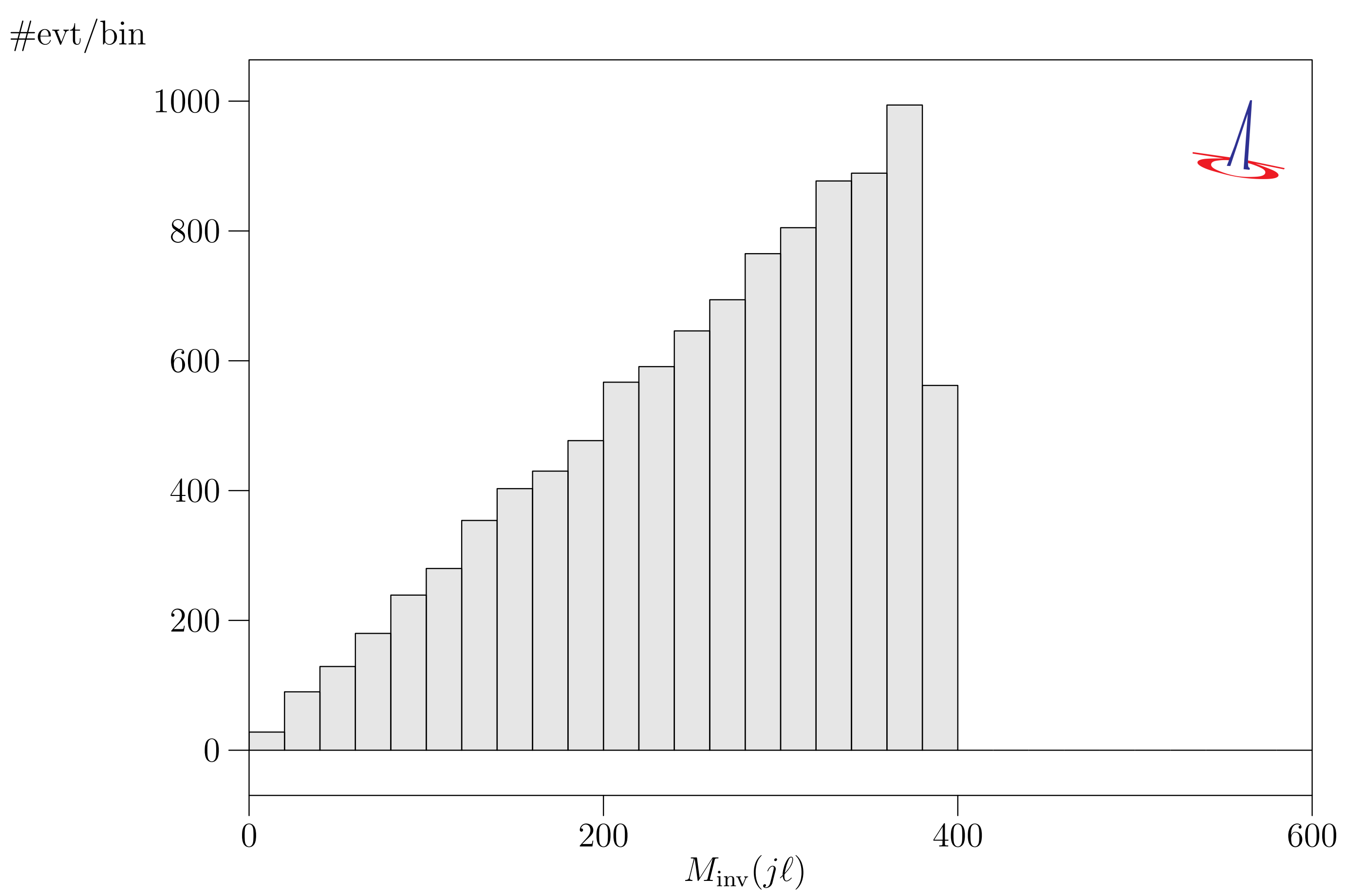


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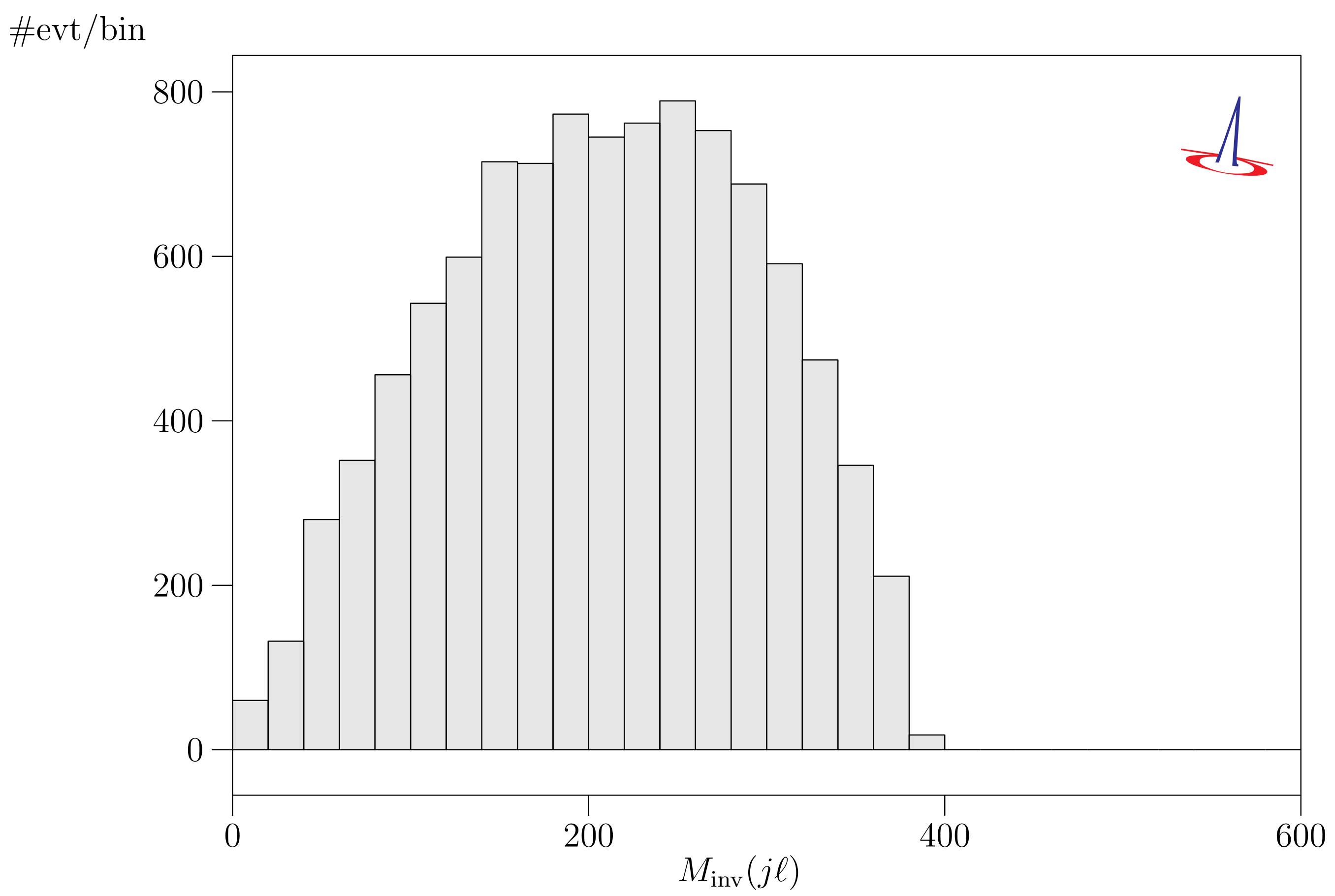

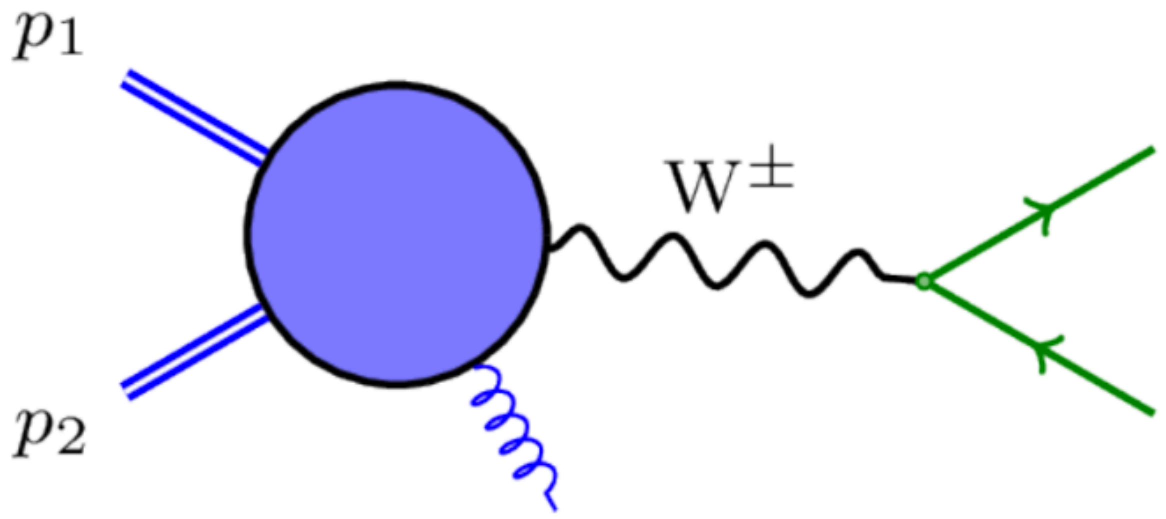

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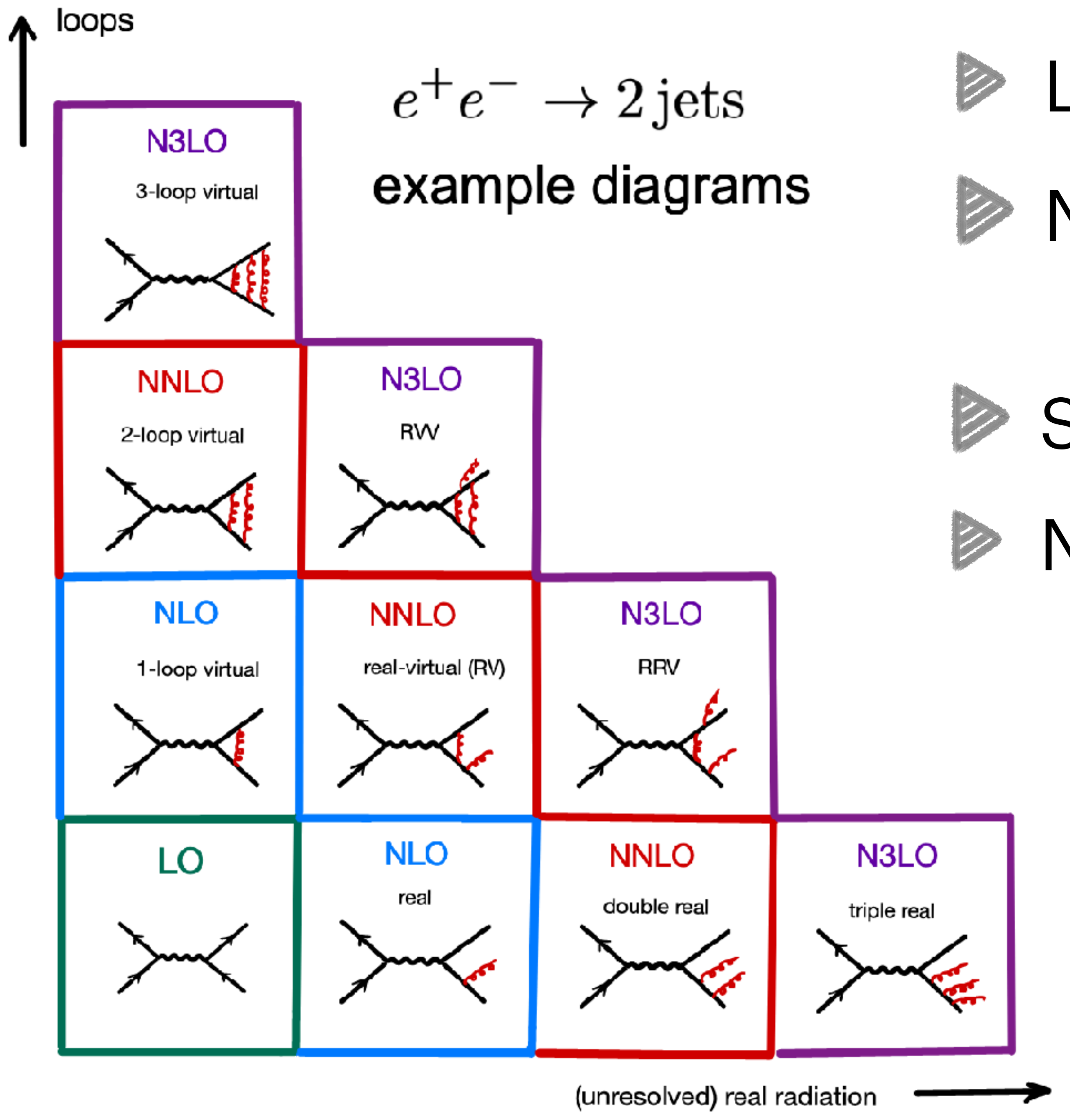
On-shell vector bosons (NWA or DPA)

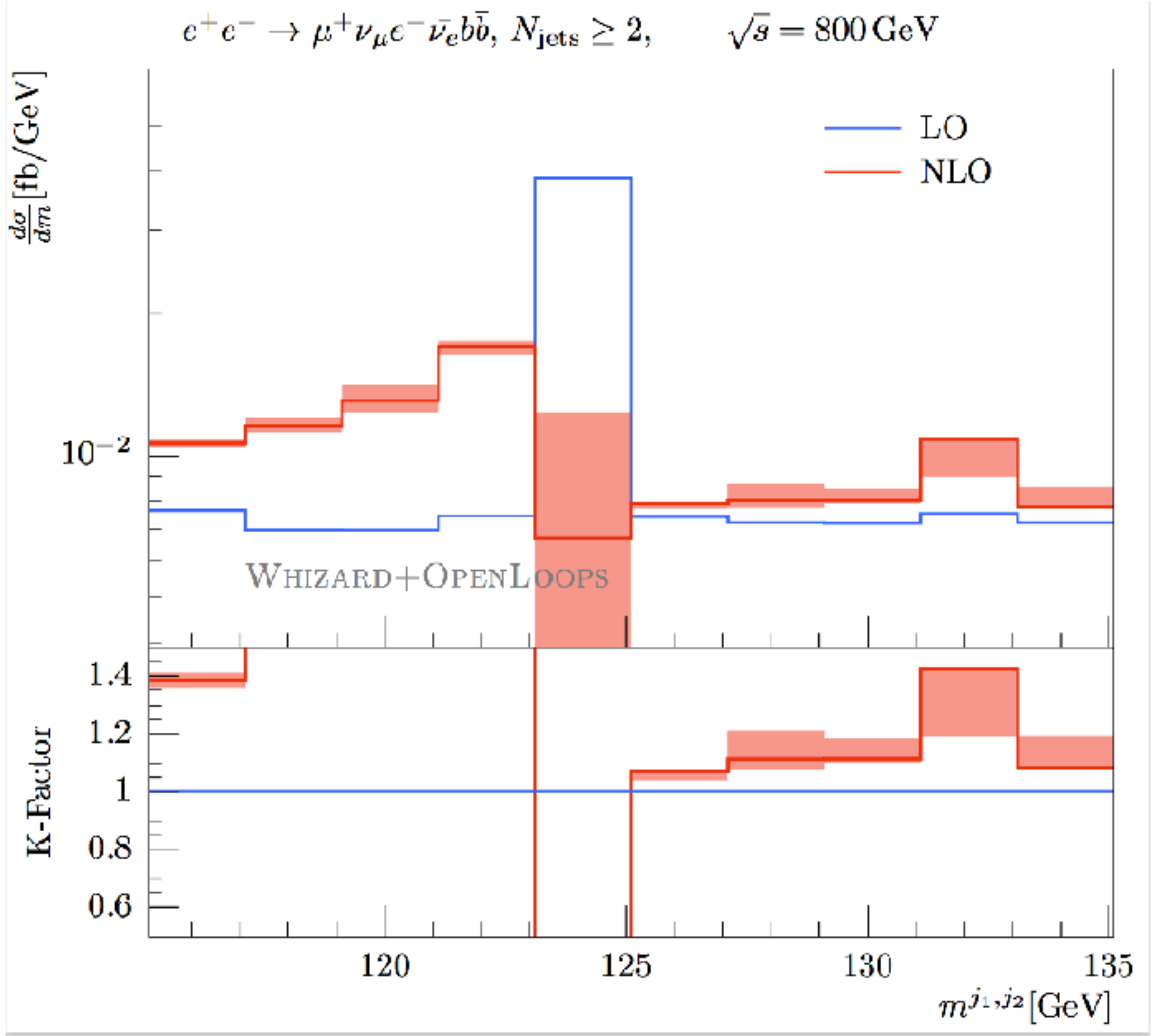
- Intermediate polarization of resonances (e.g. *W / Z / [t]*): projection to on-shell state
- Necessary to have this in machinery of established MC generator to calibrate simulation
- Automated for LO — work in progress for NLO

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



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

- Signal + background samples (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

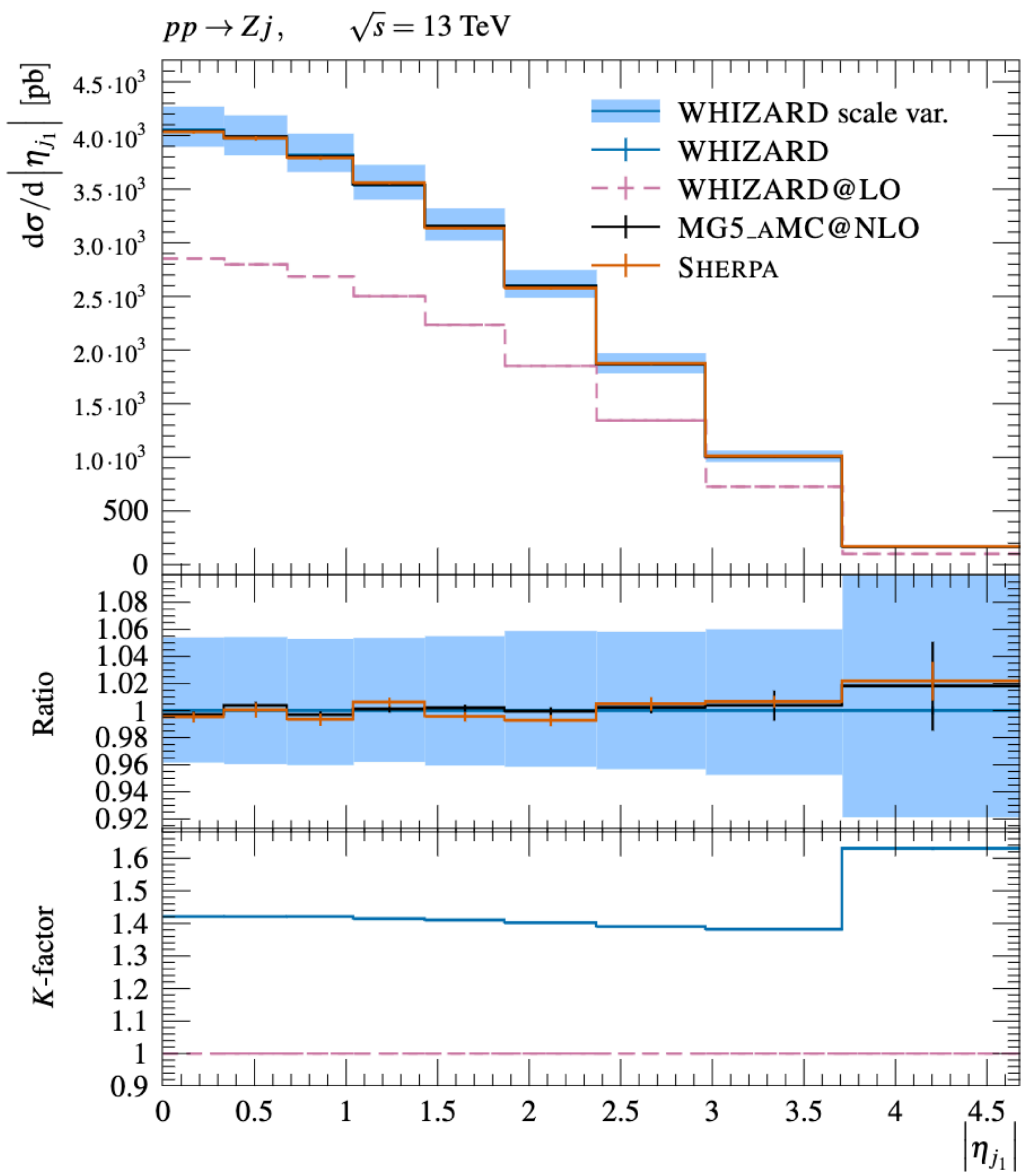
NLO EW

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

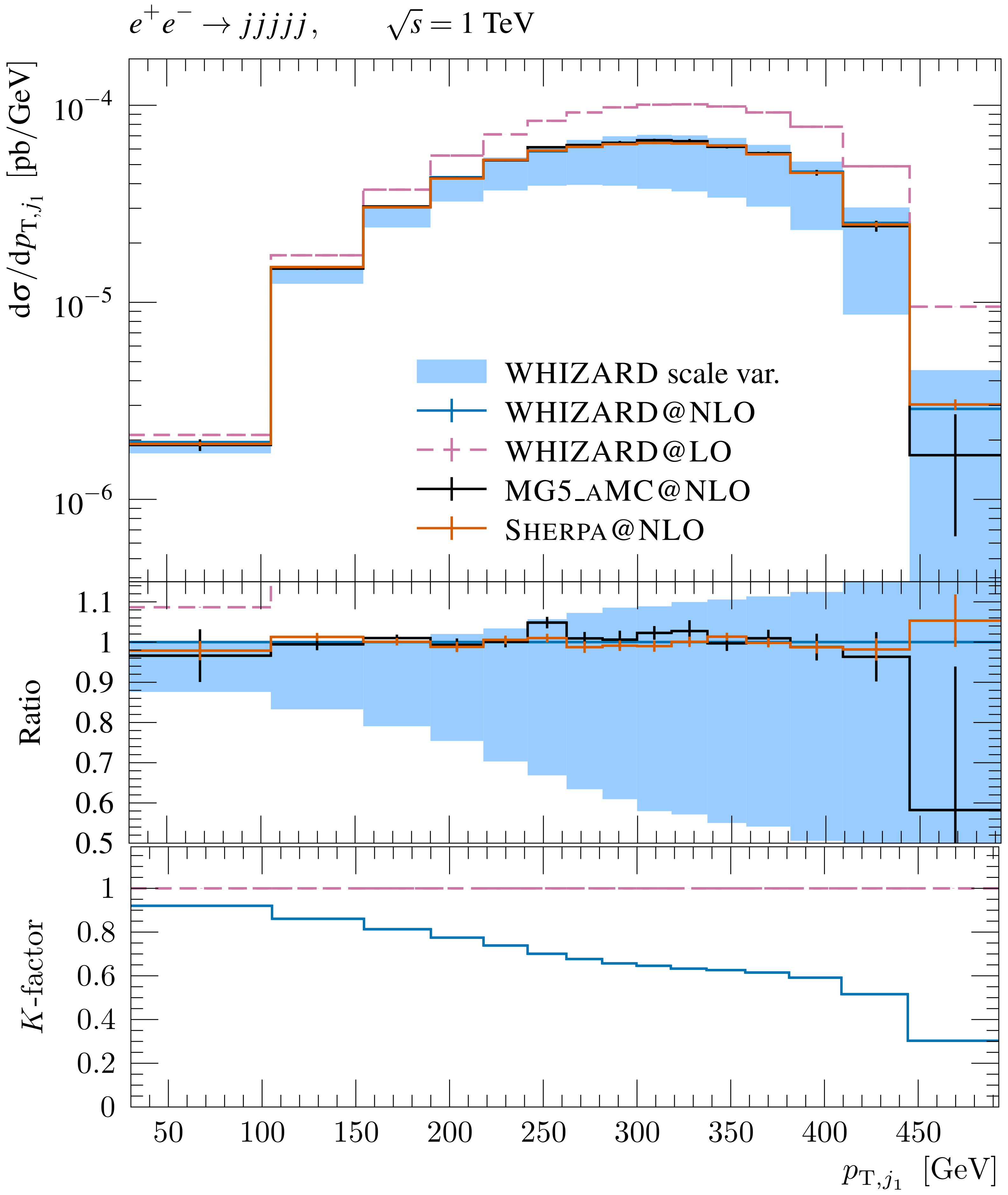
	MCSANCee[37]		WHIZARD+RECOLA			
$\sqrt{s}$ [GeV]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ_{EW} [%]	σ^{sig} (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)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

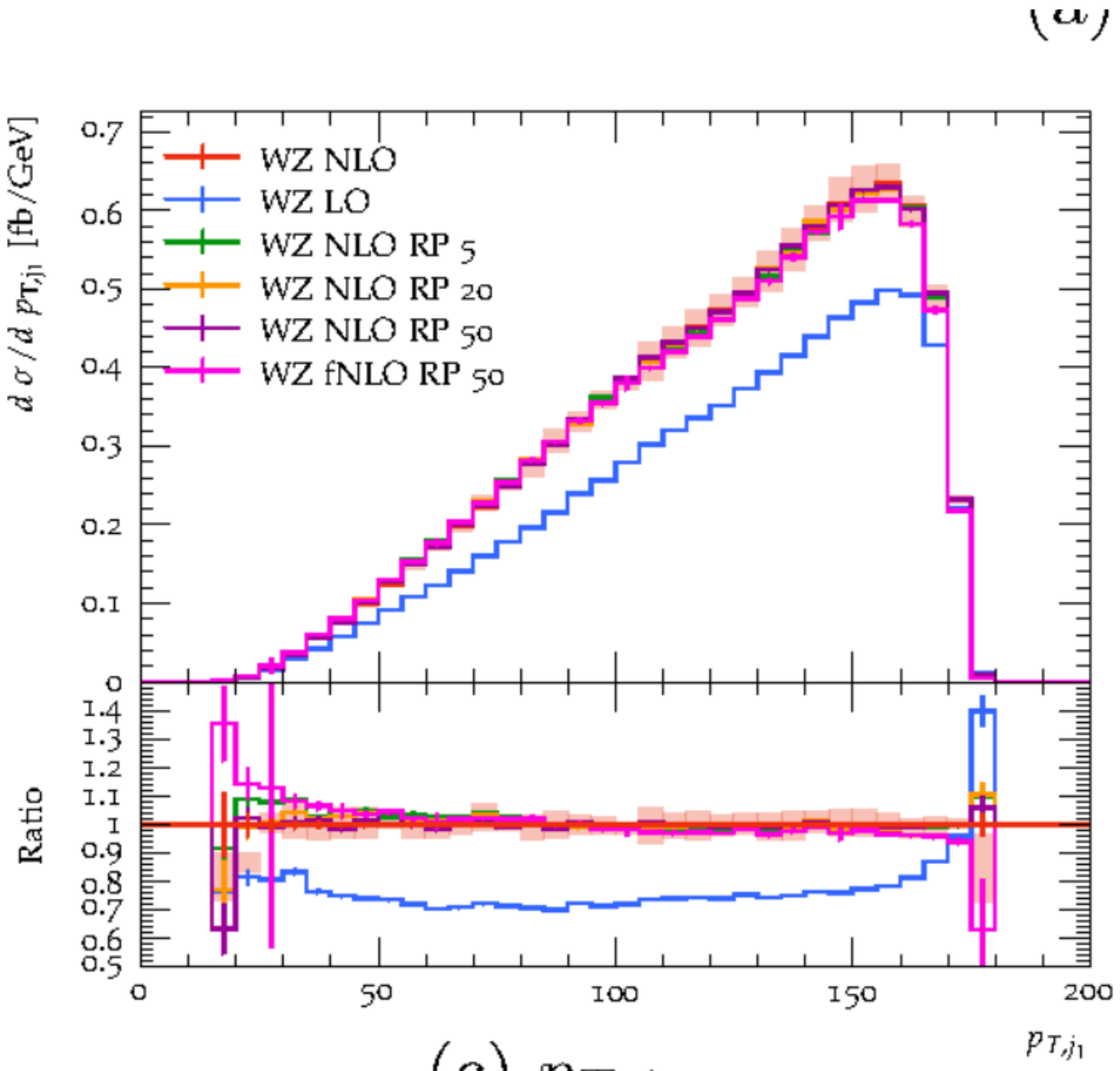


ee @ 1 TeV, NLO QCD



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

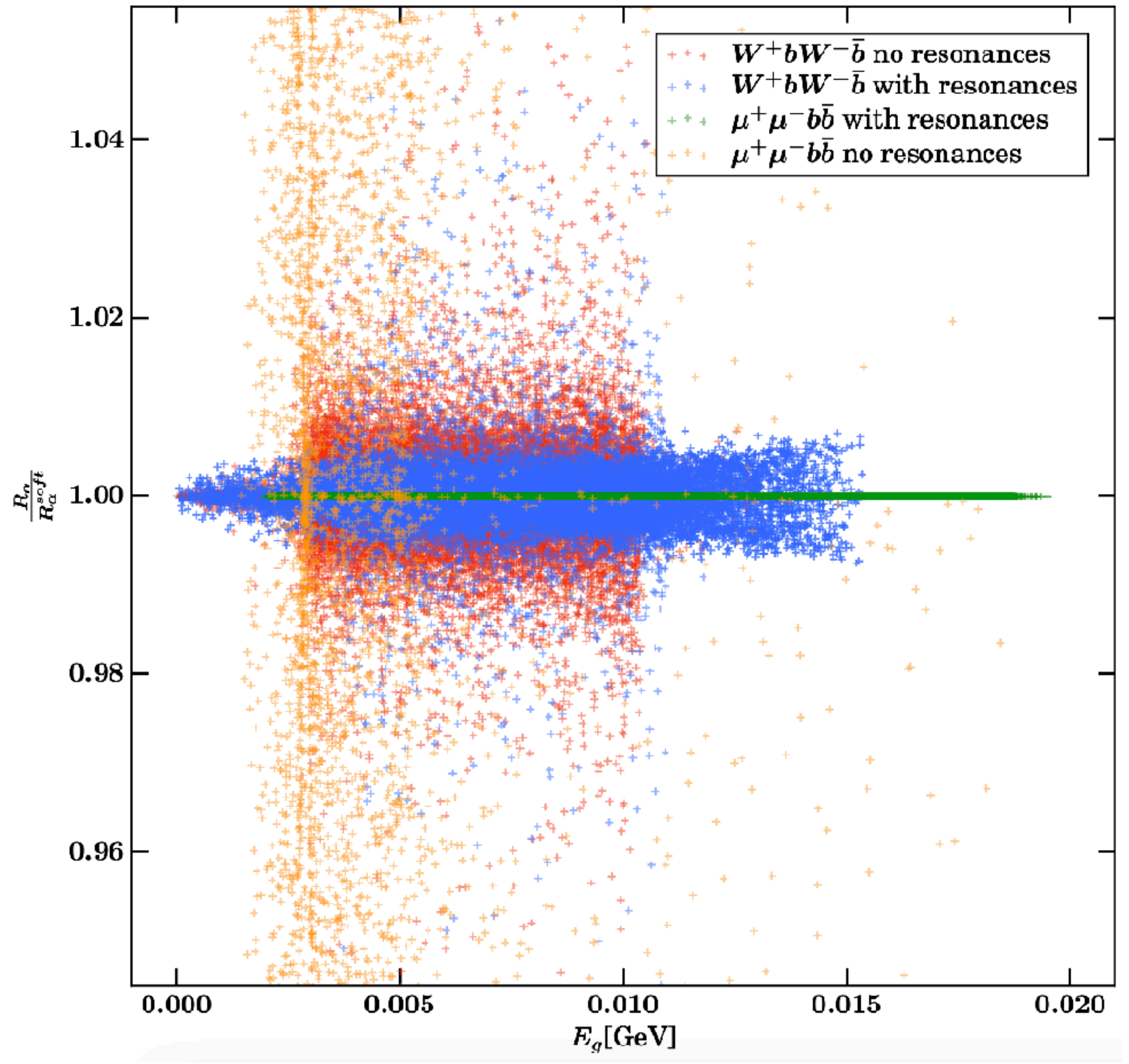
$$\mu_R = H_T/2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$



(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/Signer)
- 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)



↪ Talk by Qian Song (Thu)

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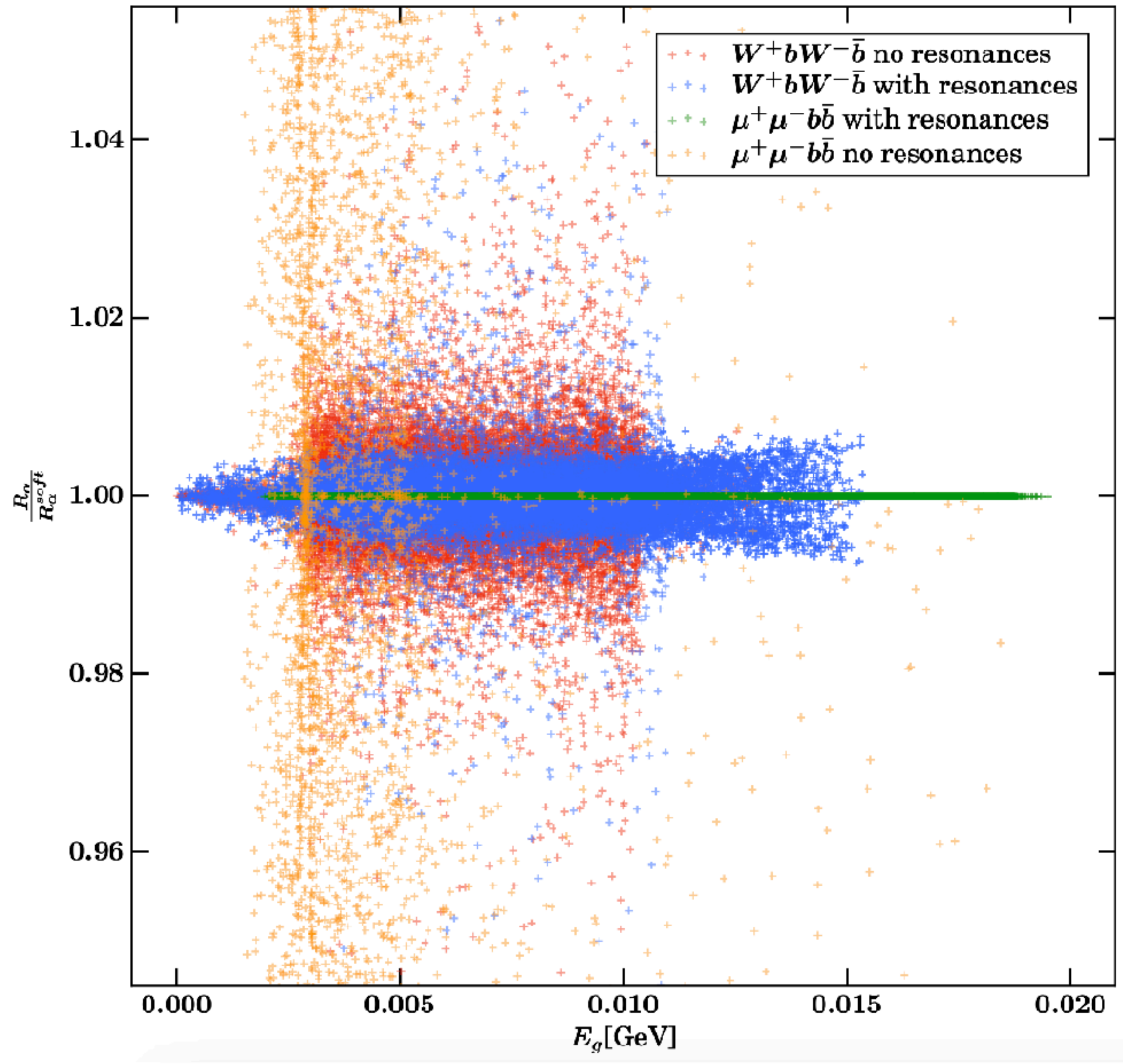

Two major bottlenecks to NNLO

- ☐ 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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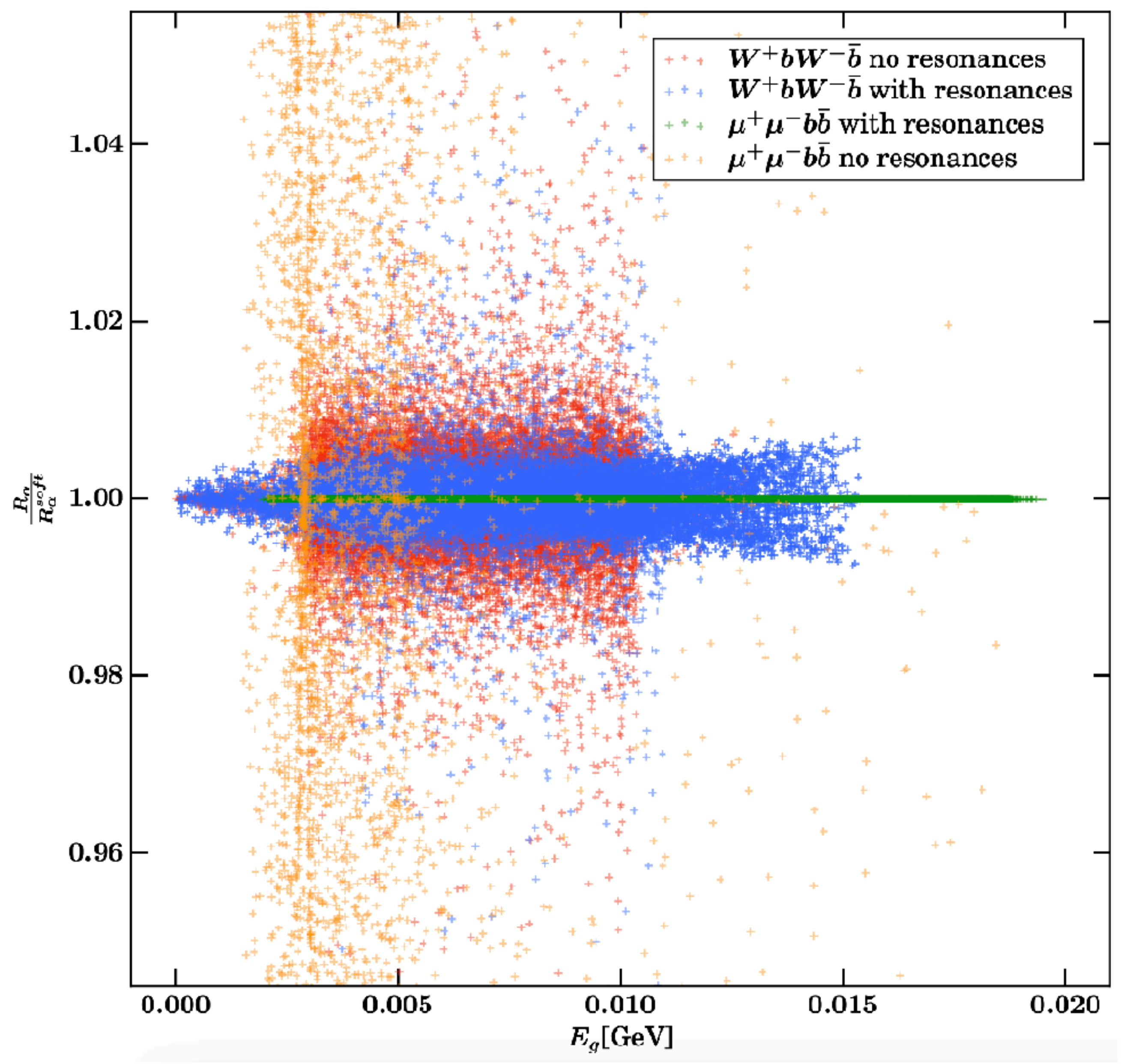

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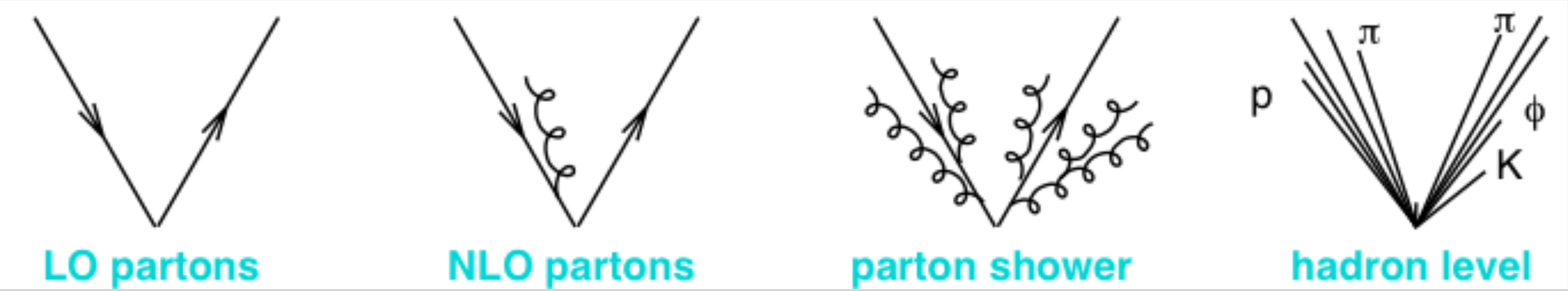
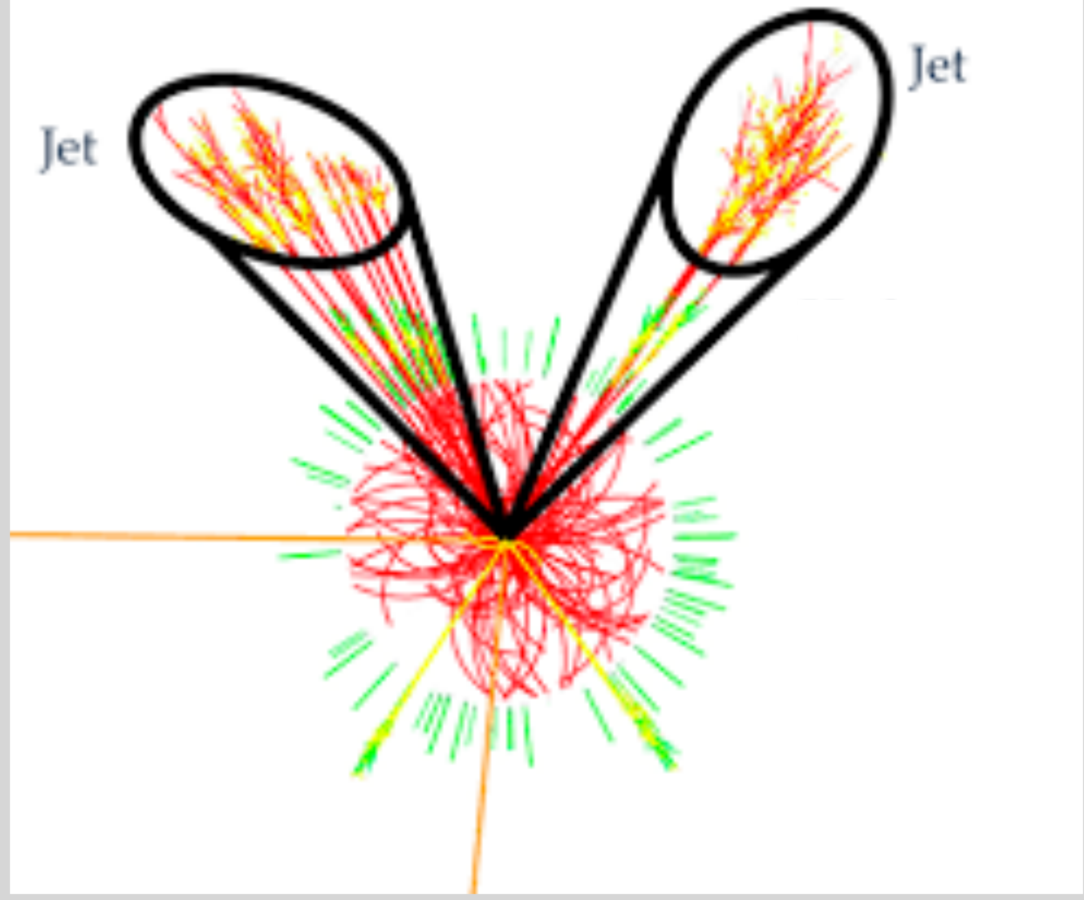
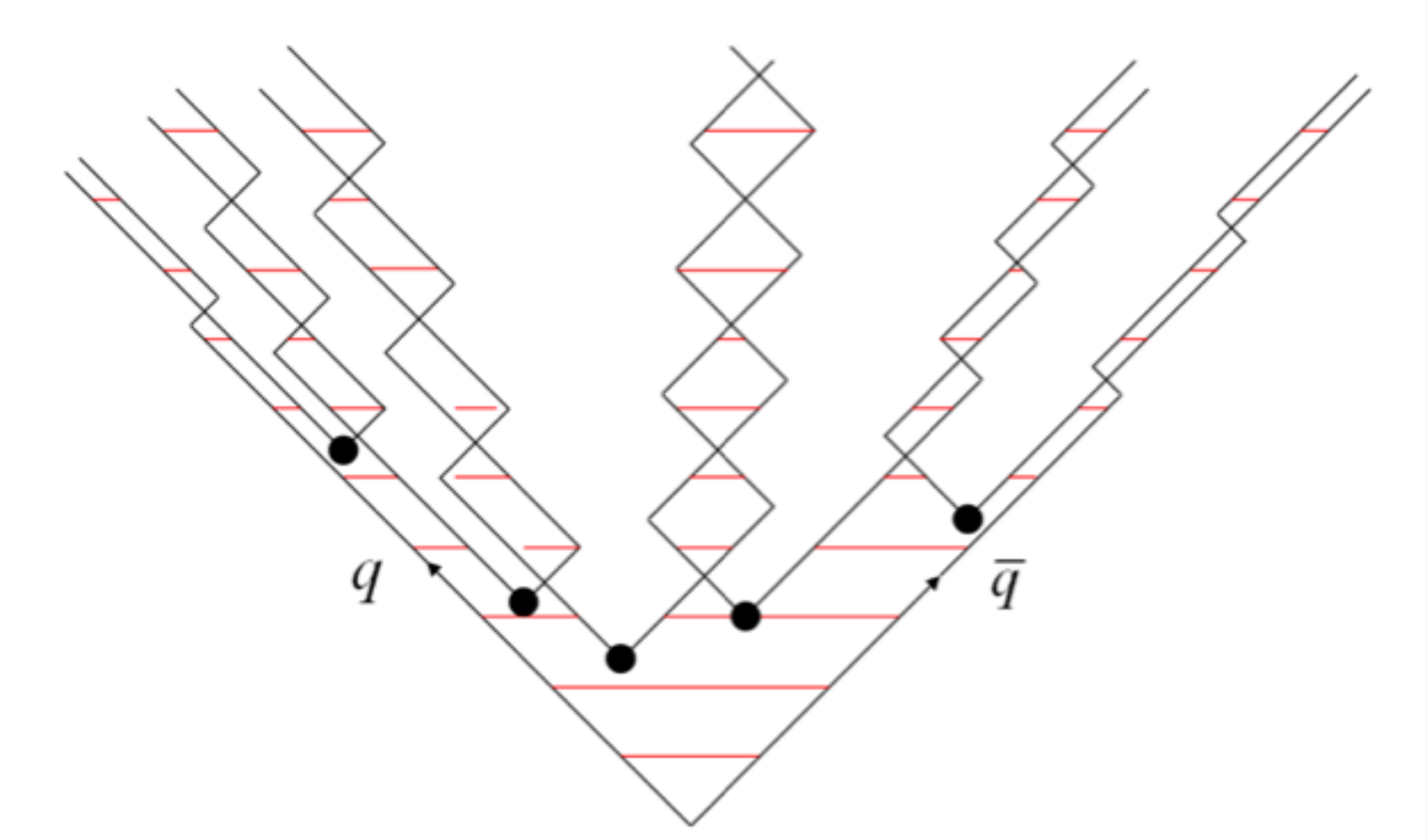
- ☑ FKS soft/eikonal subtraction sufficient for low-energy machines
- ☑ NNLO QED (massive, virtuals pending): `McMule` Signer ea. `[Whizard]`
- ☑ Baby steps to NNLO automation: `Griffin` Chen/Freitas, 2023
- ☑ for NNLO EW need for full-fledged soft+collinear NNLO subtraction `[Stripper]`

↪ Talk by Qian Song (Thu)

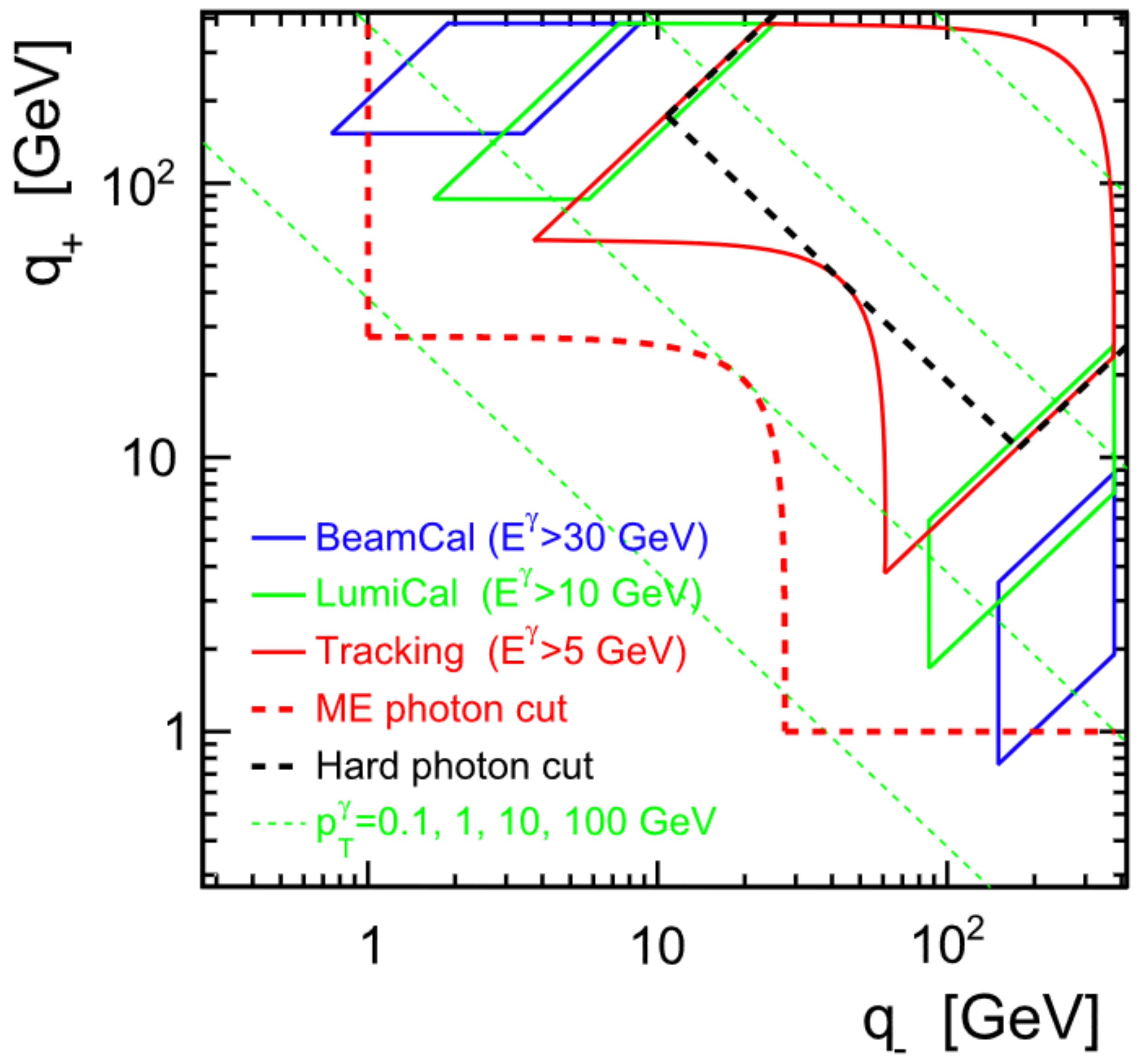
Parton Showers, Matching, Hadronization





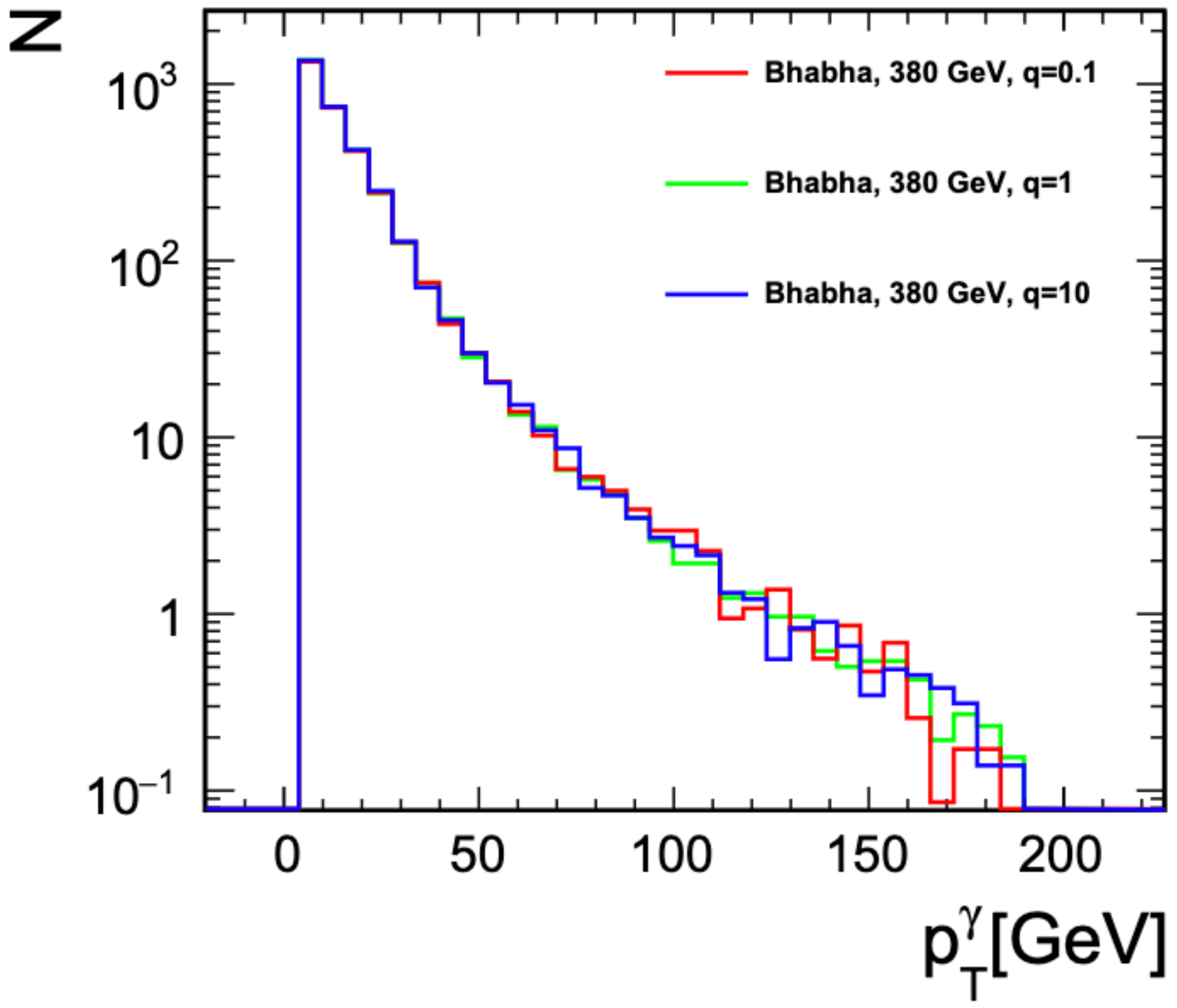


Exclusive photons



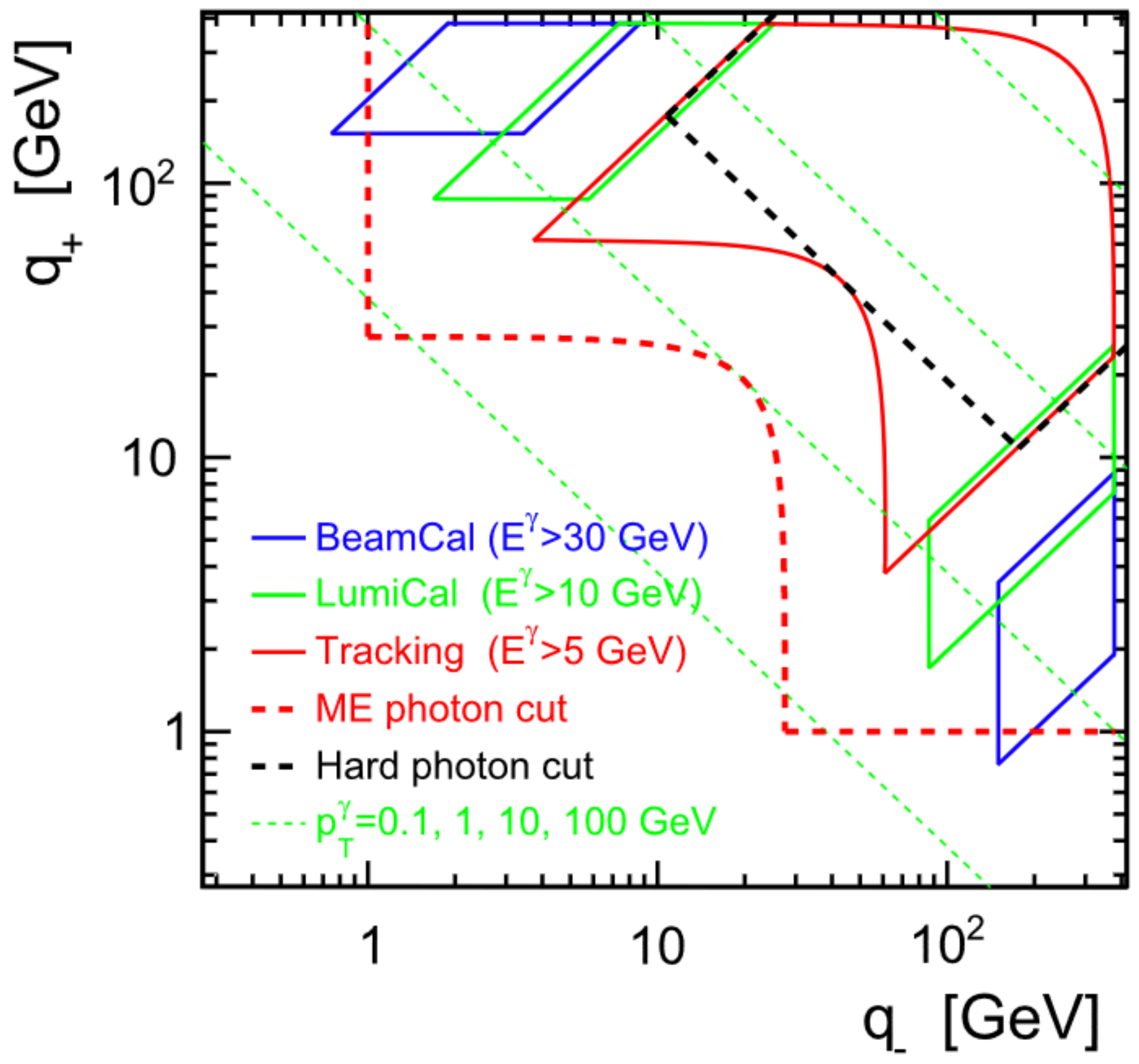
QED ISR [+FSR], matching

- 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



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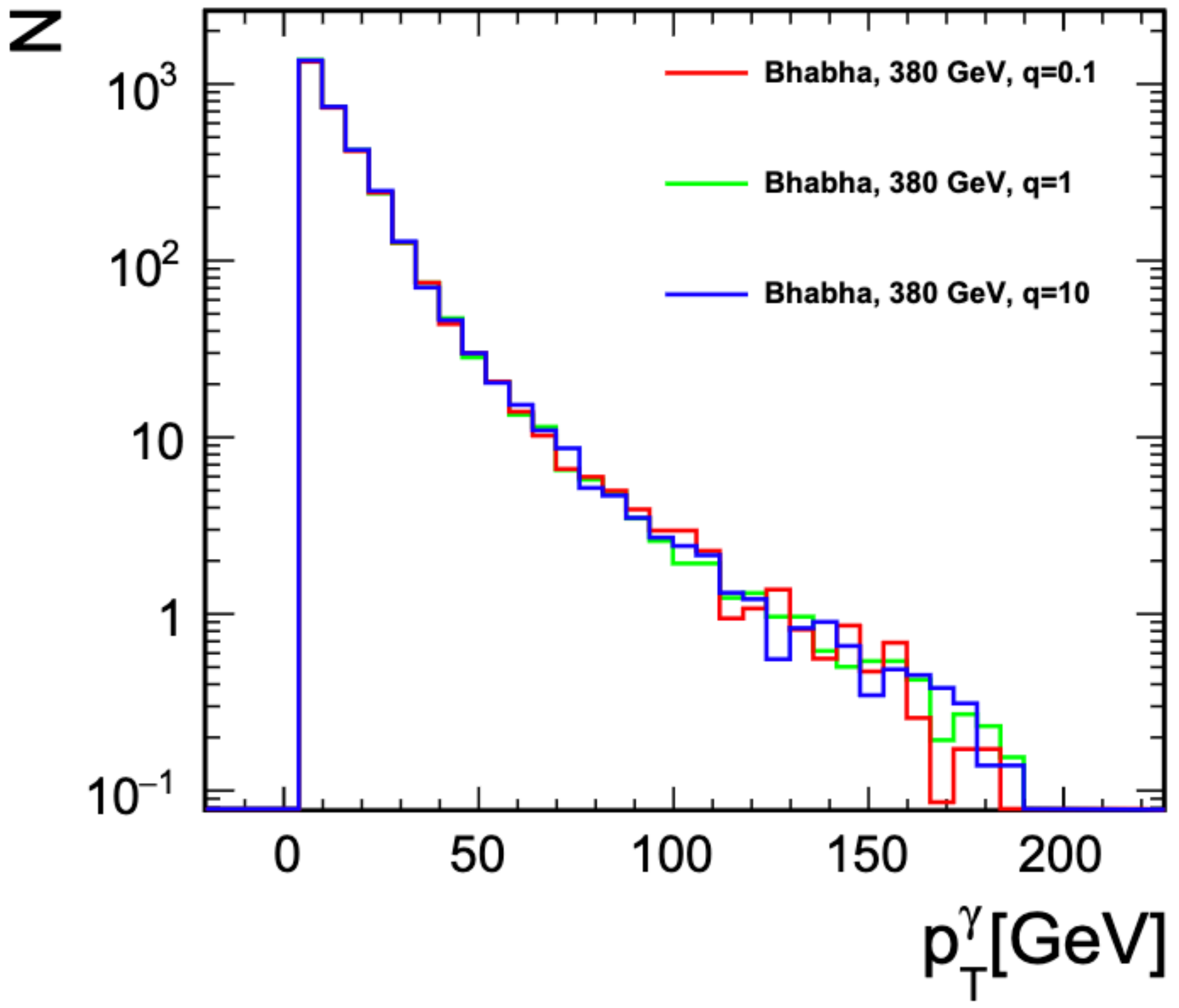


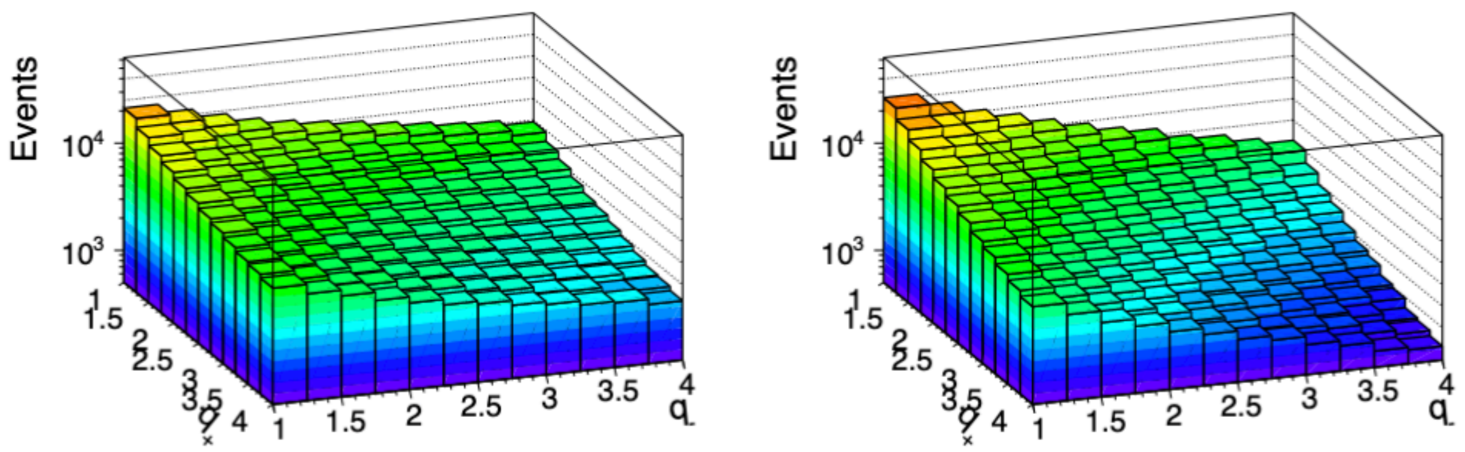
J. Kalinowski/W. Kotlarski/P. Sopicki/A.F. Zarnecki, 2020

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

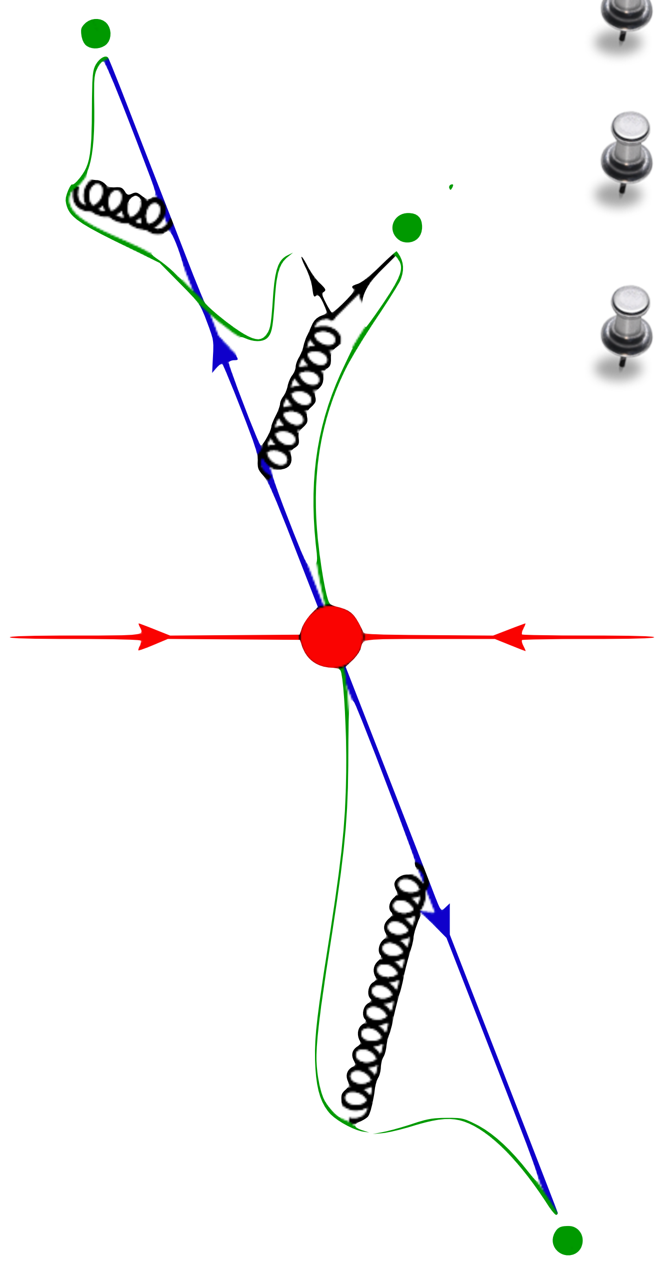


(a) Double EPA

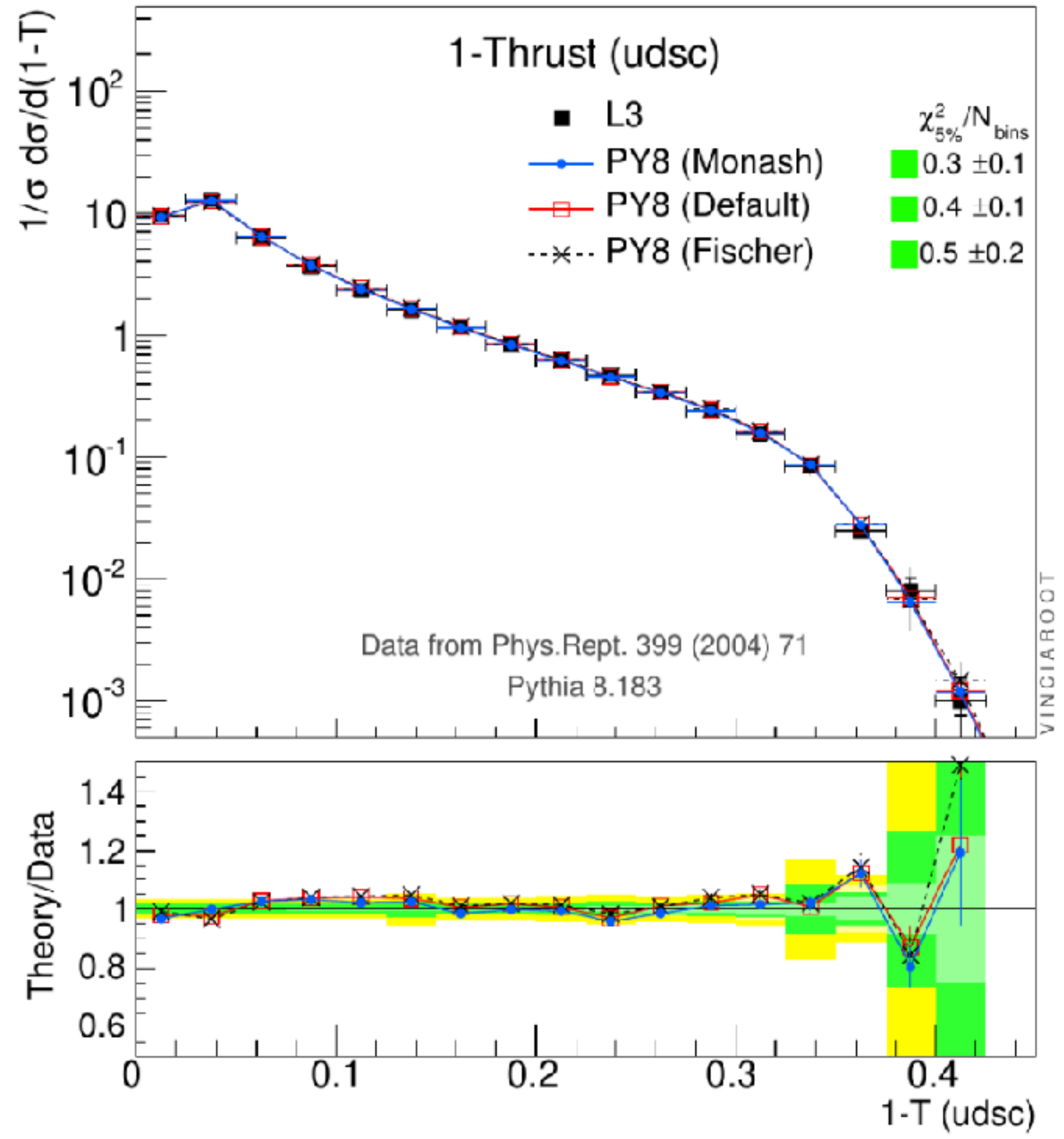
(b) Full matrix elements

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]	$k_t, \Lambda\ \ (\beta = 0, 1)$	Analytical and numerical tests for thrust
Manchester-Vienna [2003.06400]	$k_t\ (\beta = 0)$	Analytical for thrust and multiplicity



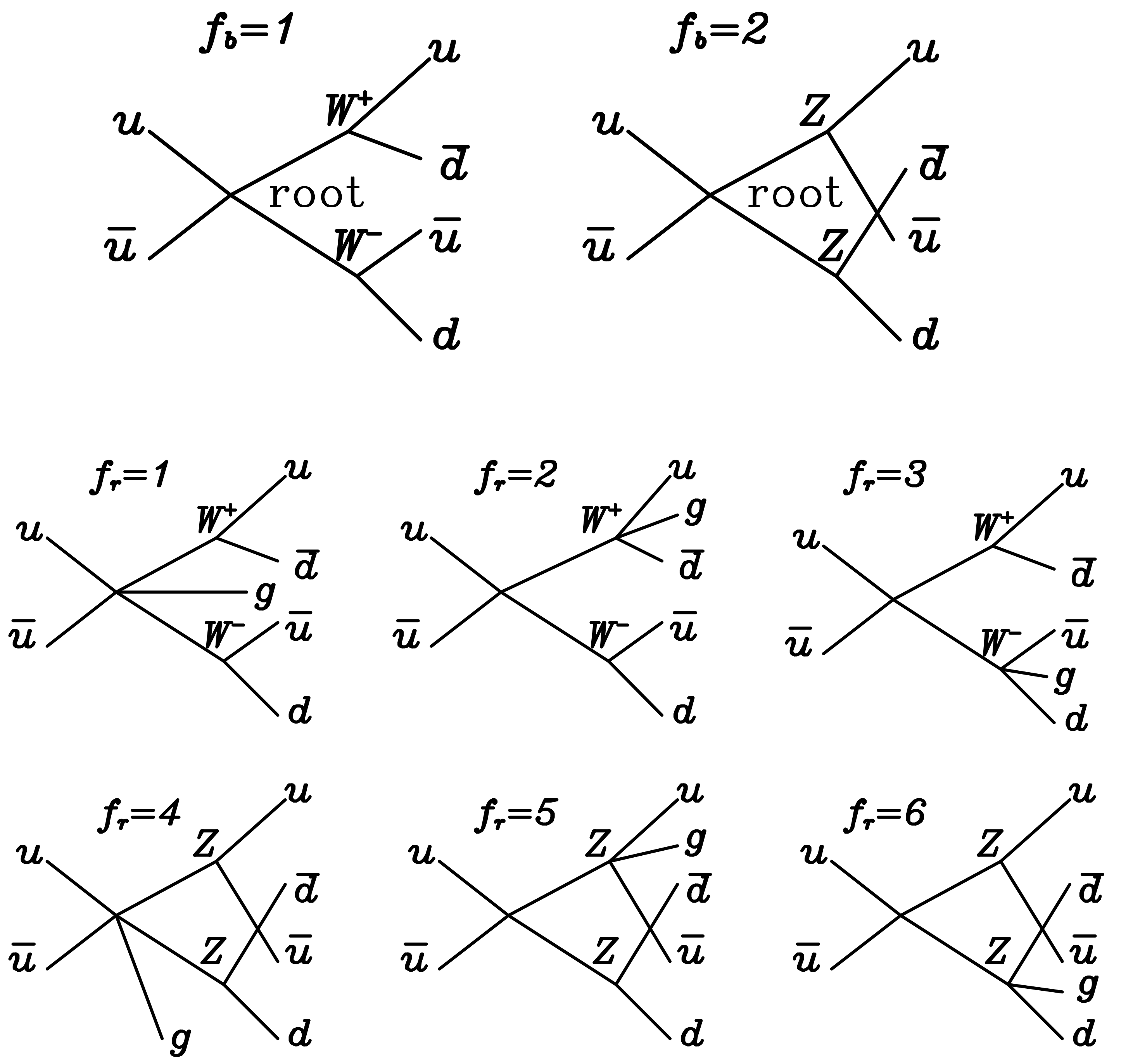
↪ Talk by Melissa van Beekveld / Pier Monni

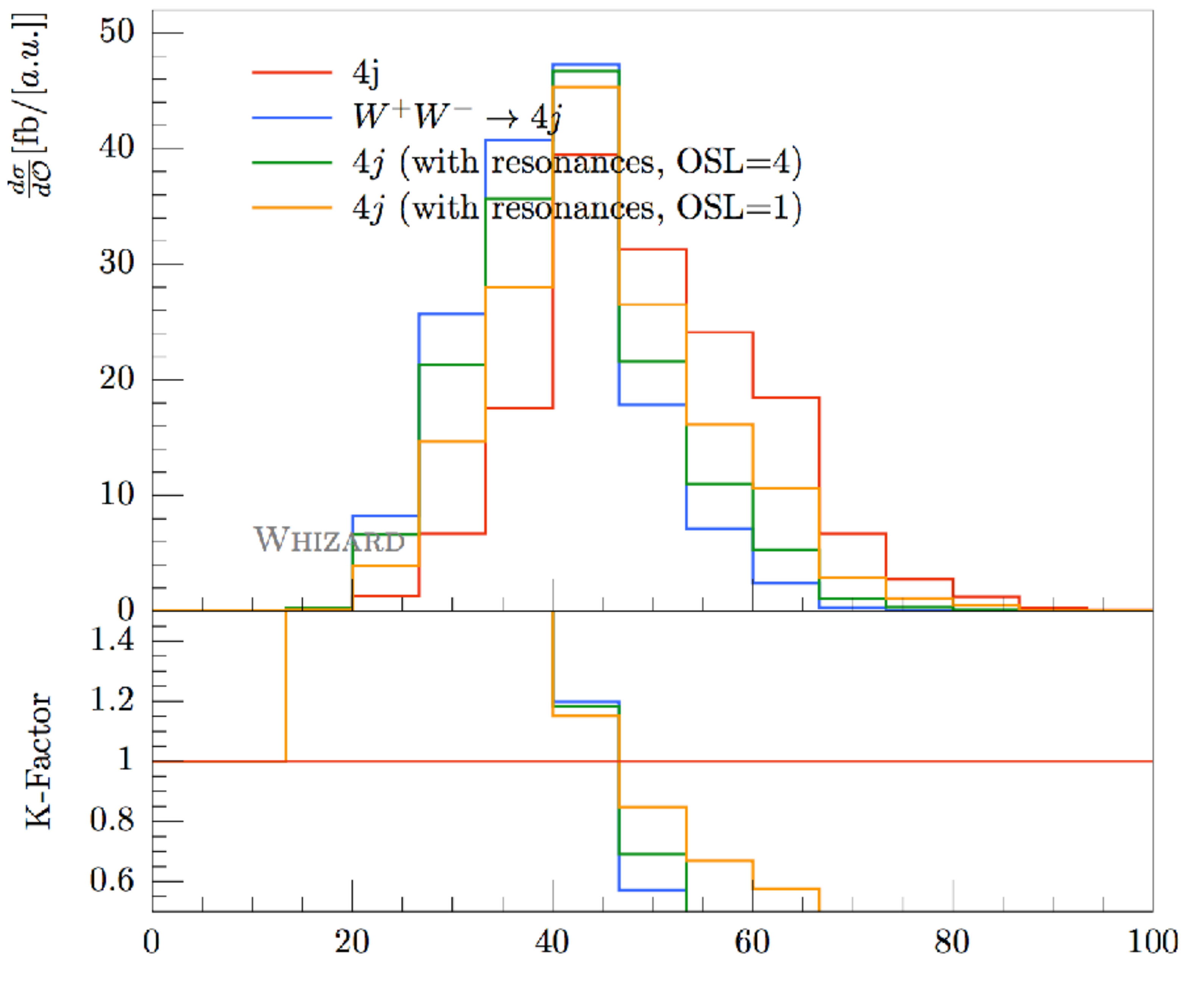
- Ongoing work towards NNLL showers, sub-leading color (FCC = full color correlations)
- NLO matching automated, different approaches, different error estimates;
- NNLO matching still process-dependent; also does not yet preserve NNLL accuracy
- Elephant in the room: fragmentation ⇒ no paradigm shift/quantum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

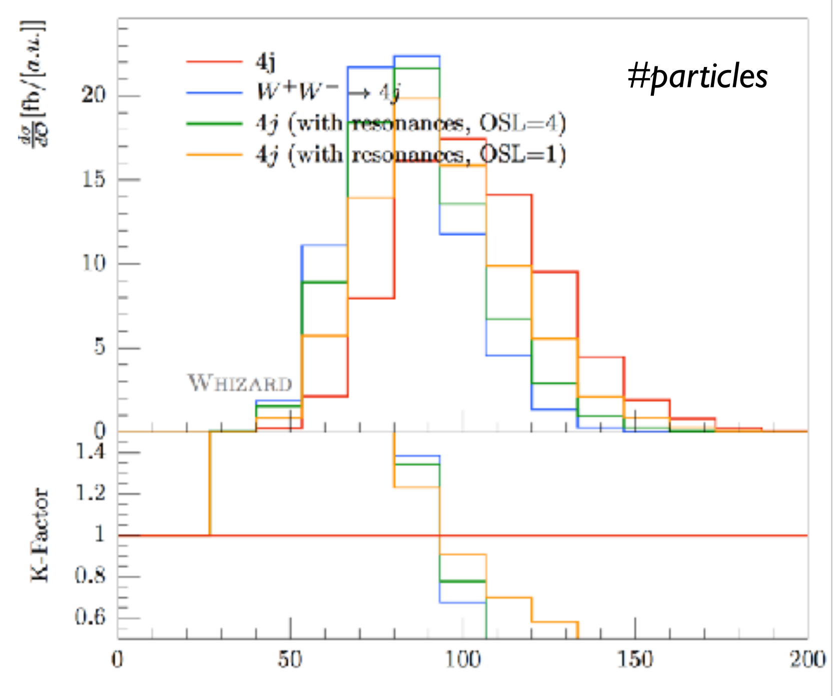
  Gigantic clean data sets from Z pole and above will necessitate new models / theory

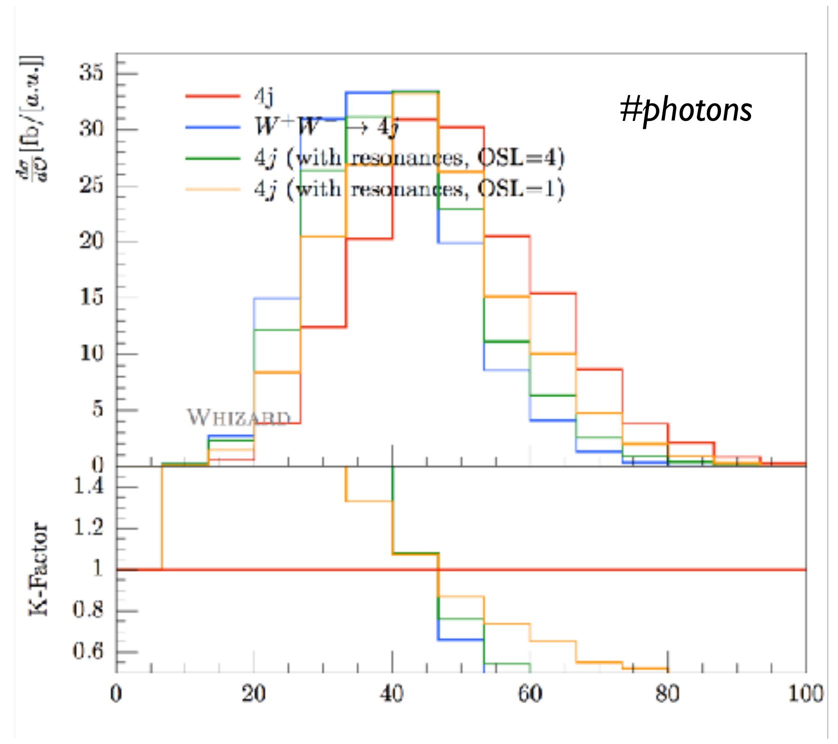
(Resonance) Matching to shower / hadronization

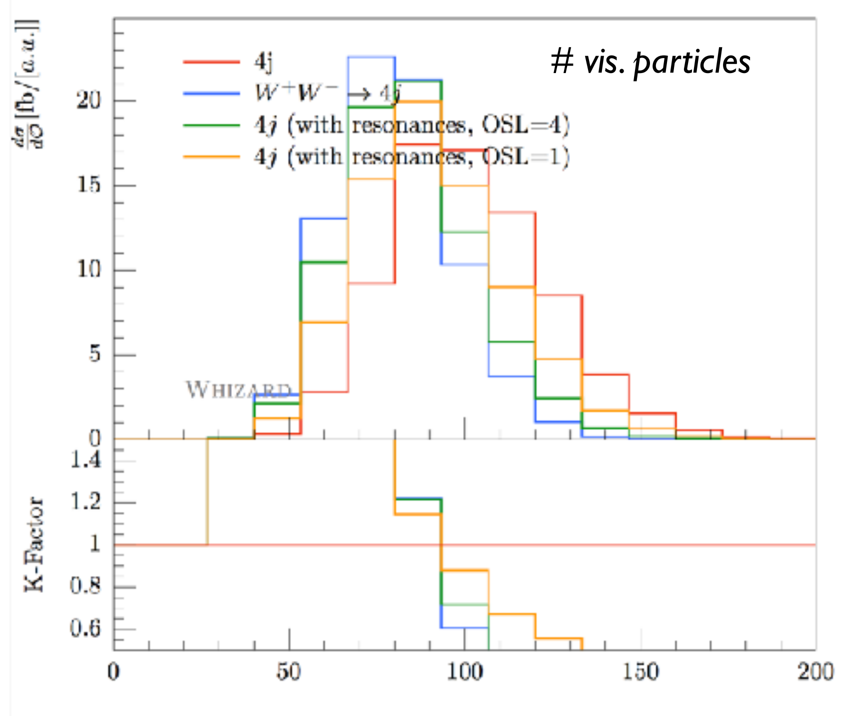
- **Problem:** $e^+e^- \to jjjj$ not dominated by highest α_s power, but by resonances
- **Solution:** proper merging w/ resonant subprocesses by resonance histories
- MC generators allow to pass resonance history to Shower MC

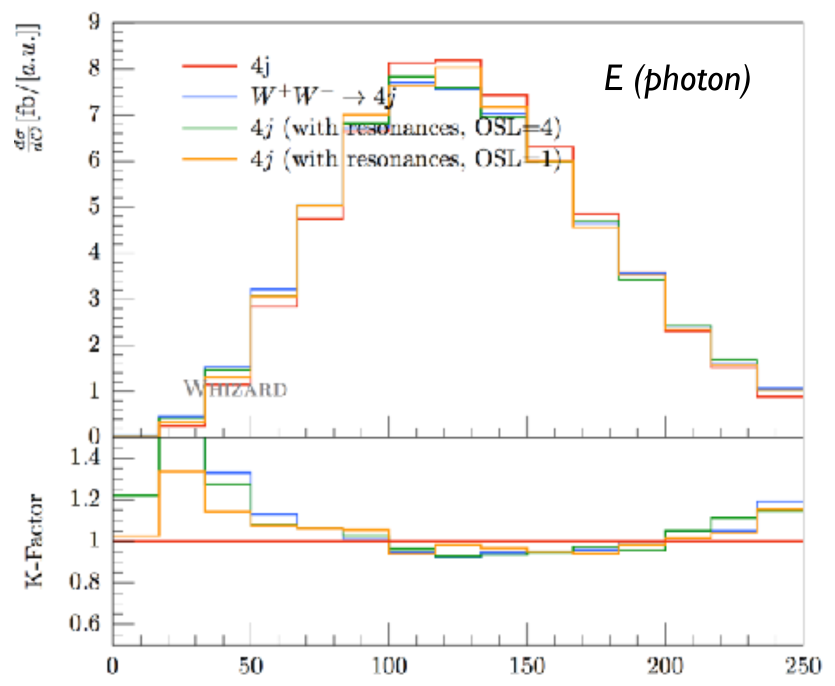












Dedicated tools for special processes

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!

↪ Talk by Fulvio Piccinini

Luminometry

Bhabha cross sect. depends on detector acceptance angles

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

Machine	$\theta_{min} \div \theta_{max}$ [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
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[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%
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(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}	$1.0 \times 10^{-4(*)}$	$1.0 \times 10^{-4(*)}$
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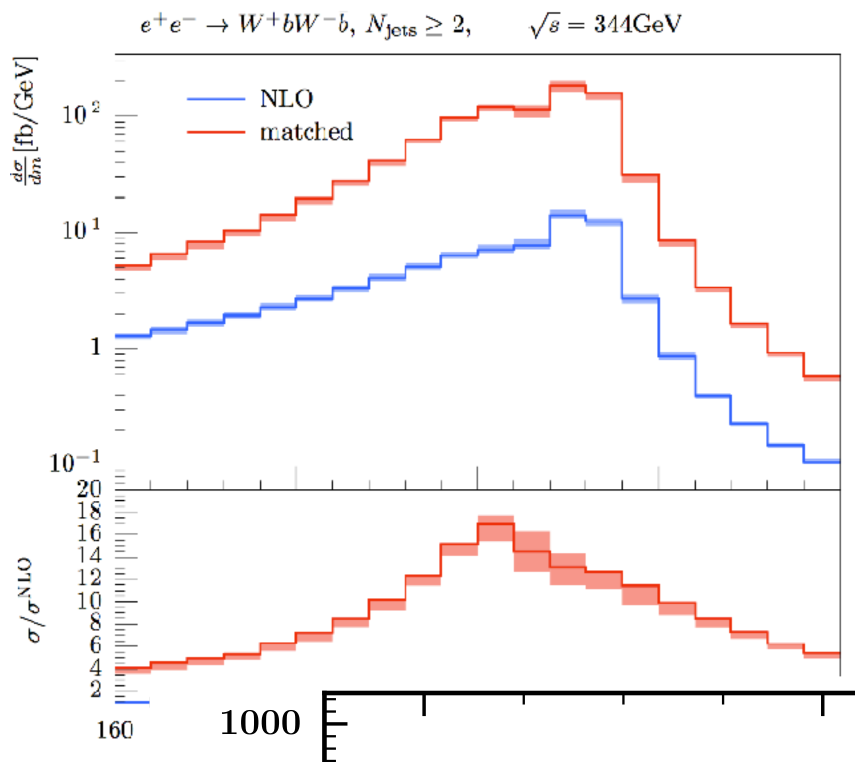
(f) Up-down interference	0.1×10^{-4}	0.09×10^{-4}	0.1×10^{-4}
Total	1.0×10^{-4}	1.5×10^{-4}	1.6×10^{-4}

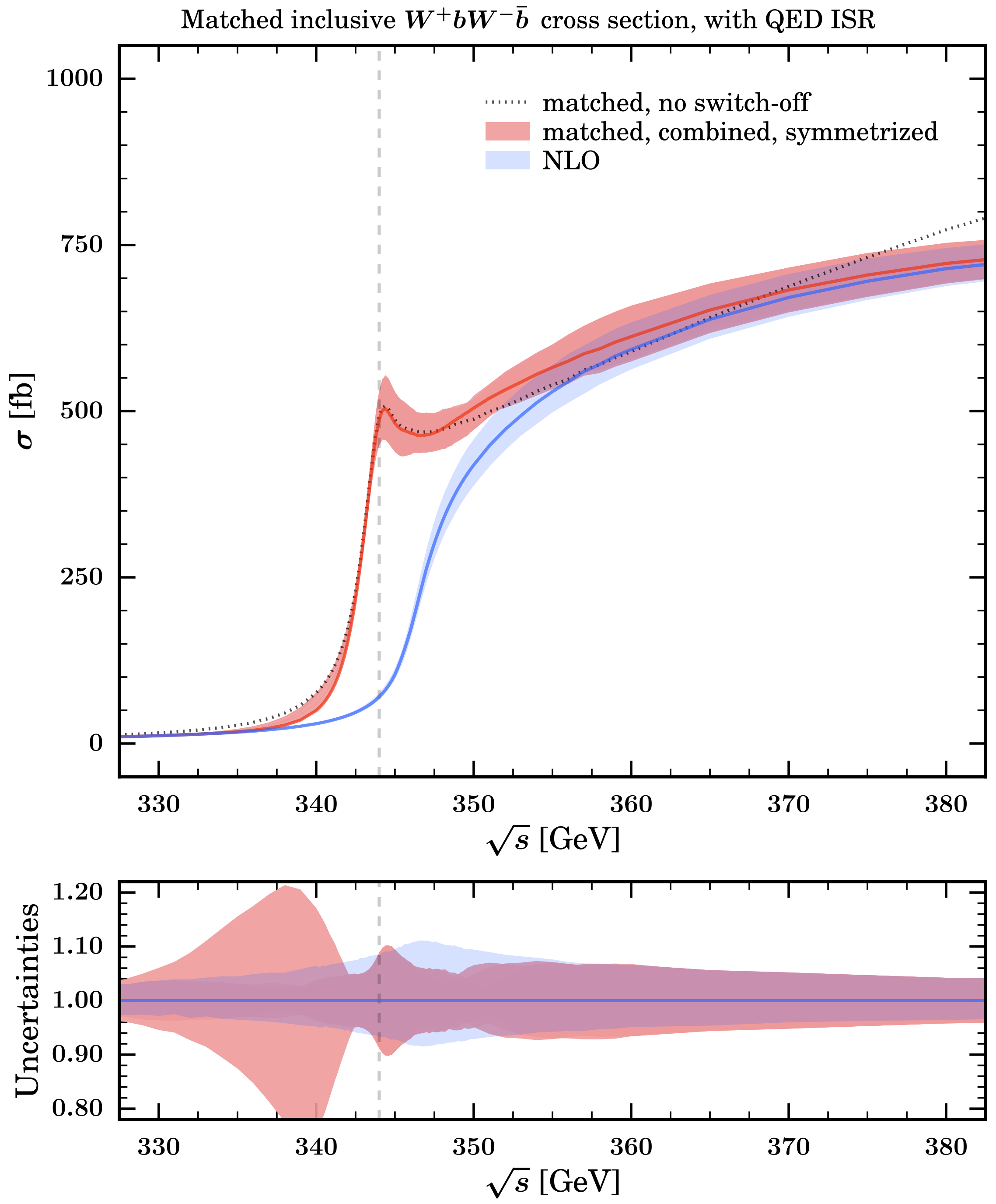
- Technical precision needs 2nd code: `BHLumi` vs. `BabaYaga` (NNLO in hard process possible)
- Major ingredients: hadronic vacuum polarization, EW corrections, light fermion pairs
- Inclusion of 4f, 4f + γ, 5f, 6f backgrounds necessary at matrix element level

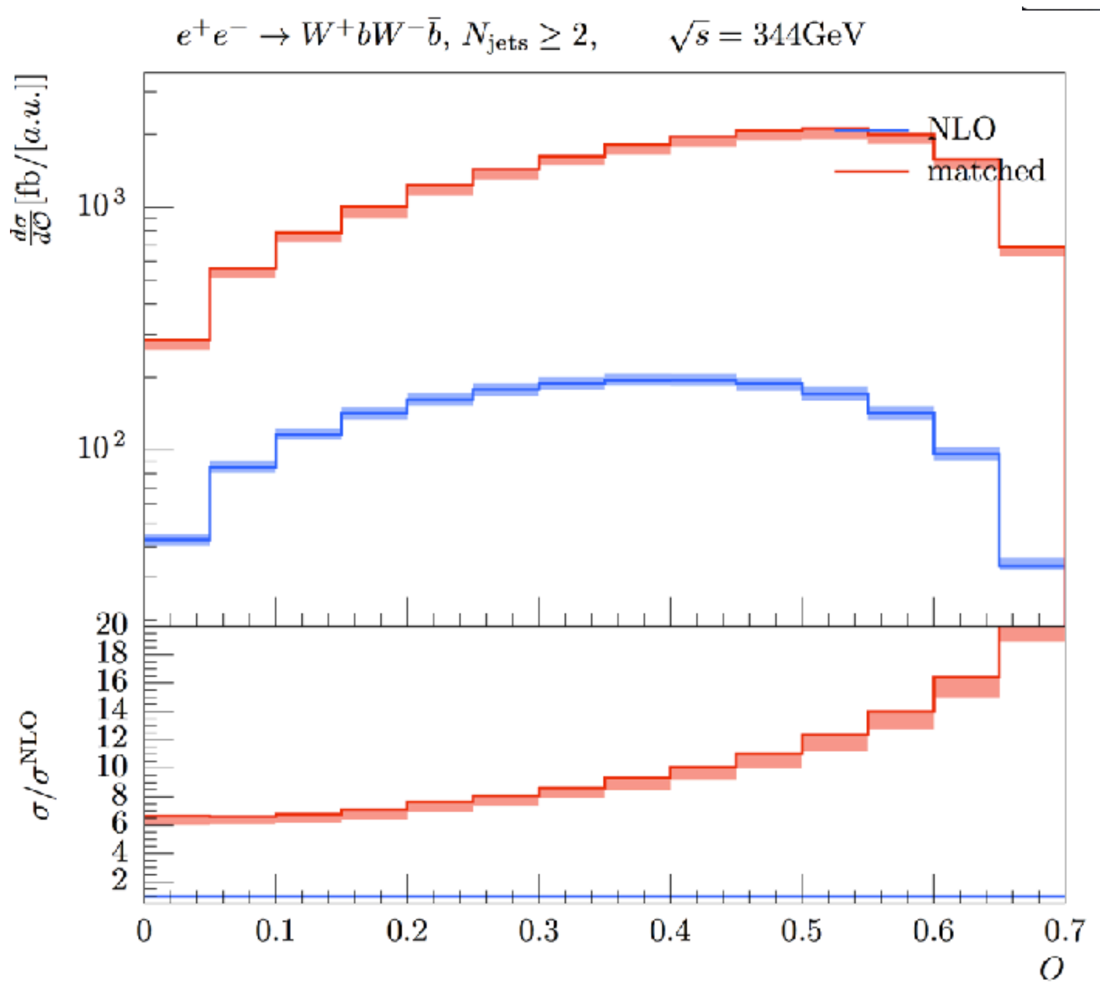
WW / Top Threshold Simulation

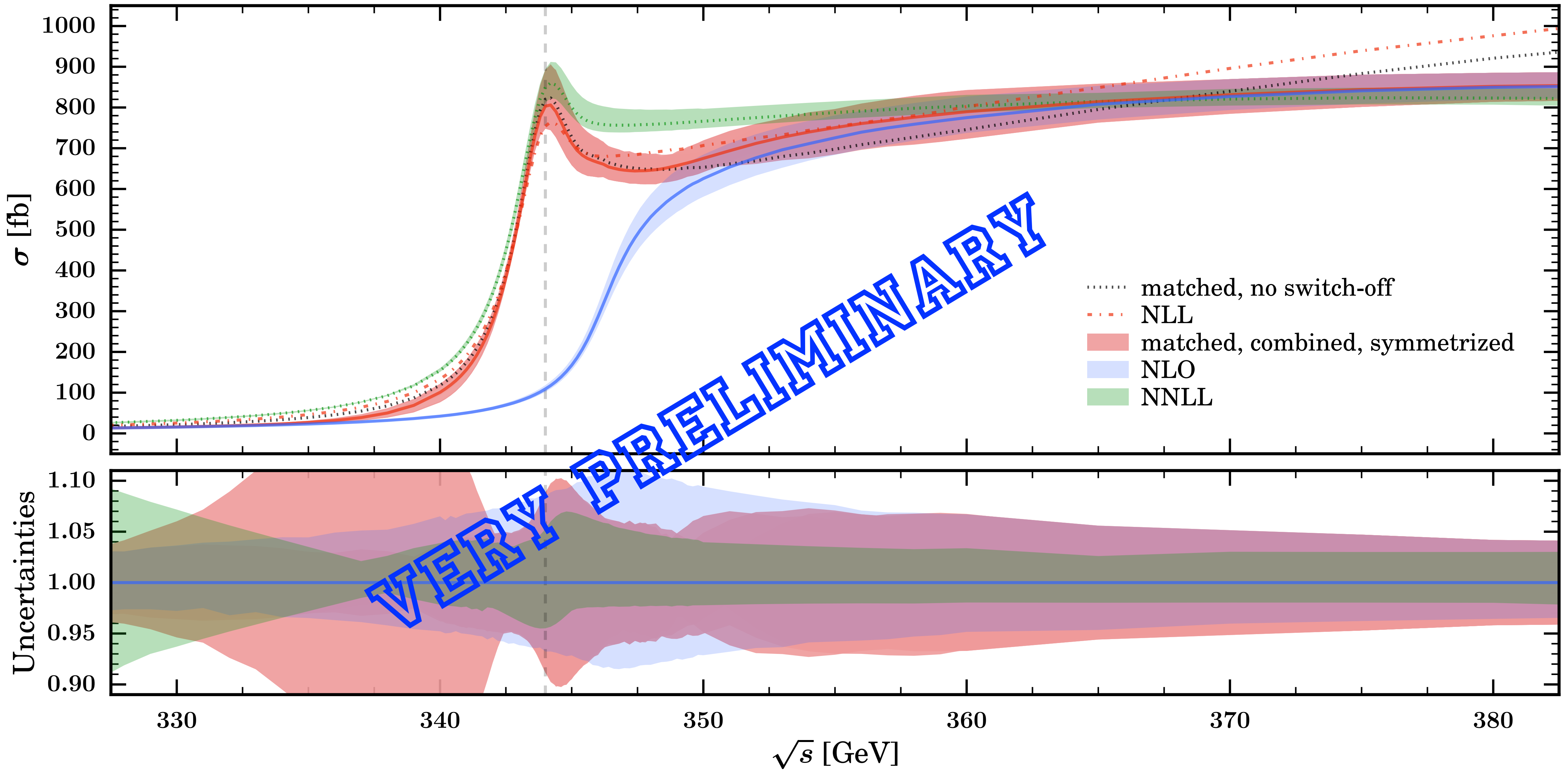
- Special implementations for *WW* / *tt* threshold (resummation)
- Differential distributions at top threshold, systematics
- Exclusive Top threshold NLL-NLO QCD matched available
- Recent improvement in axial form factor matching
- Technical issues (person power)
- Improvement needed (e.g. shower matching)

no cuts σ_{tot} [fb]	$\sqrt{s} = 200$ GeV Born	$\sqrt{s} = 200$ GeV best	$\sqrt{s} = 500$ GeV Born	$\sqrt{s} = 500$ GeV best
YFSWW3	659.64(07)	622.71(19)	261.377(34)	279.086(97)
RacoonWW	659.51(12)	621.06(14)	261.400(70)	280.149(86)
(Y–R)/Y	0.02(2)%	0.27(4)%	−0.01(3)%	−0.38(5)%
***bare* cuts** σ_{tot} [fb]	$\sqrt{s} = 200$ GeV Born	$\sqrt{s} = 200$ GeV best	$\sqrt{s} = 500$ GeV Born	$\sqrt{s} = 500$ GeV best
YFSWW3	627.18(07)	592.68(19)	181.507(33)	197.933(84)
RacoonWW	627.22(12)	590.94(14)	181.507(63)	198.696(76)
(Y–R)/Y	−0.01(2)%	0.29(4)%	0.00(4)%	−0.39(6)%





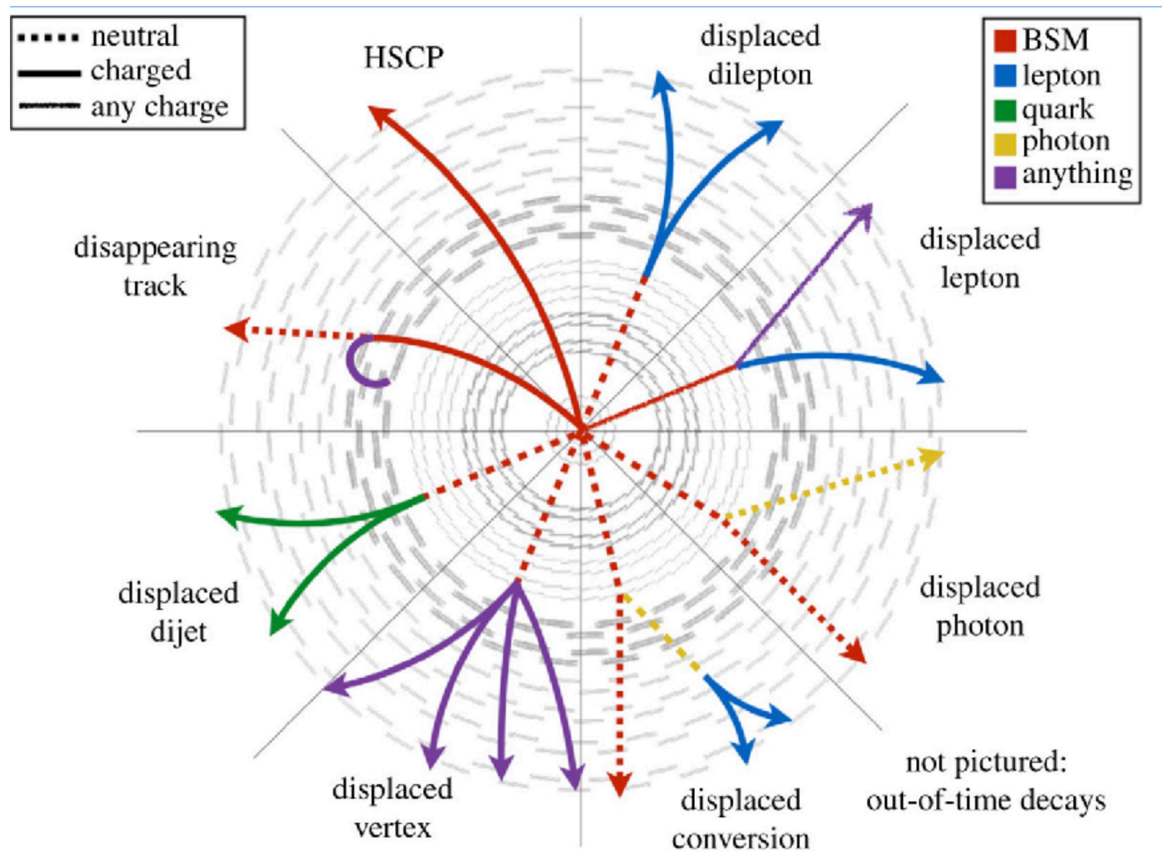




BSM Modelling in Simulation

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 (especially "full" SMEFT / HEFT)
- ☑ 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

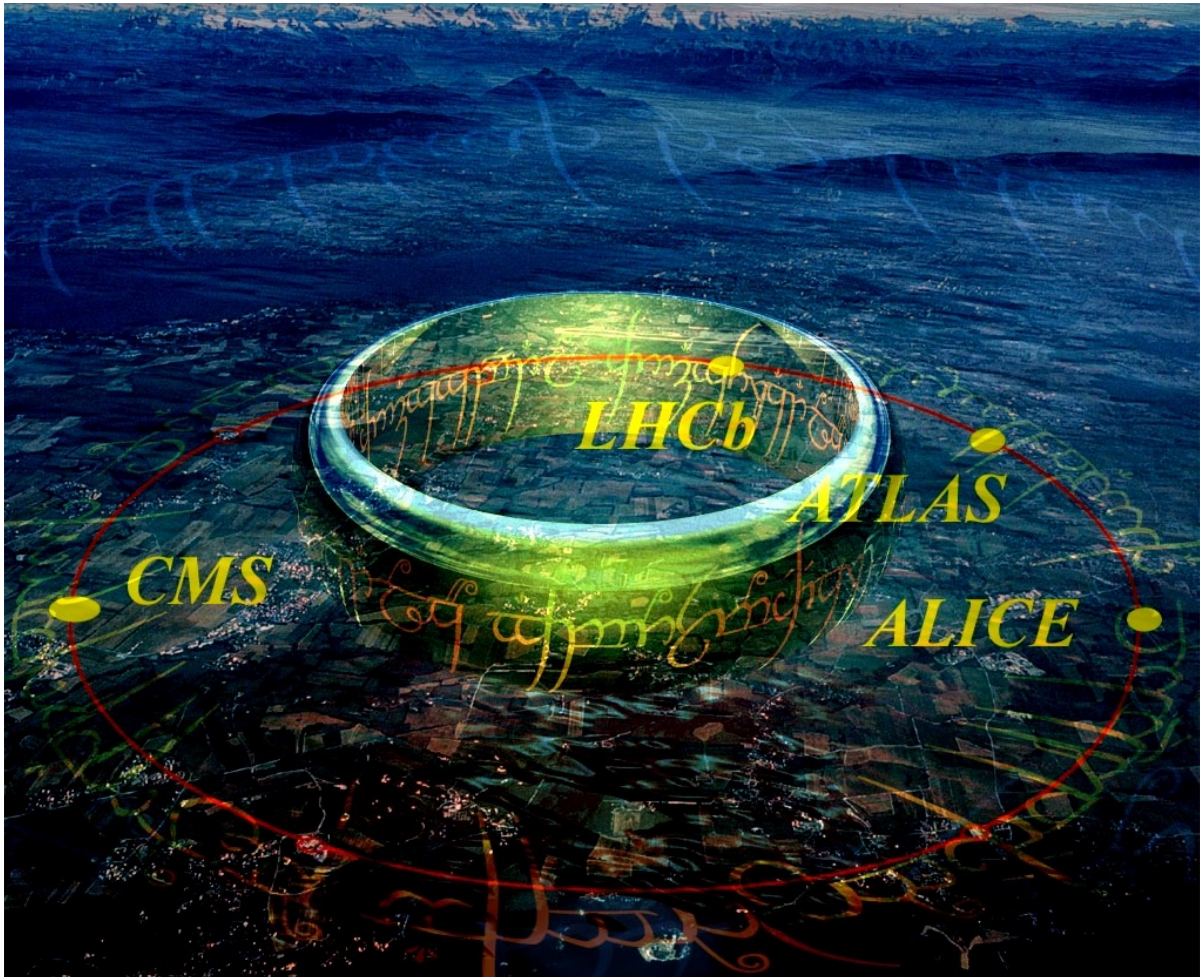
Axion Like Particles (ALPs)

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!
- Technical aspects: crossing angle, polarization (density matrices), beam spectra, event formats ....
- Will depend a lot on support on young researchers/theorists working
- Also need for dedicated MCs, e.g. for luminosity measurement ($e^+e^- \to e^+e^-, \gamma\gamma, W^+W^-, t\bar{t}$)
- Not to forget: QCD showers + fragmentation [FCC-ee Z-pole will boost to a new precision!]

One Ring To Find Them,



One Ring To Rule Them Out

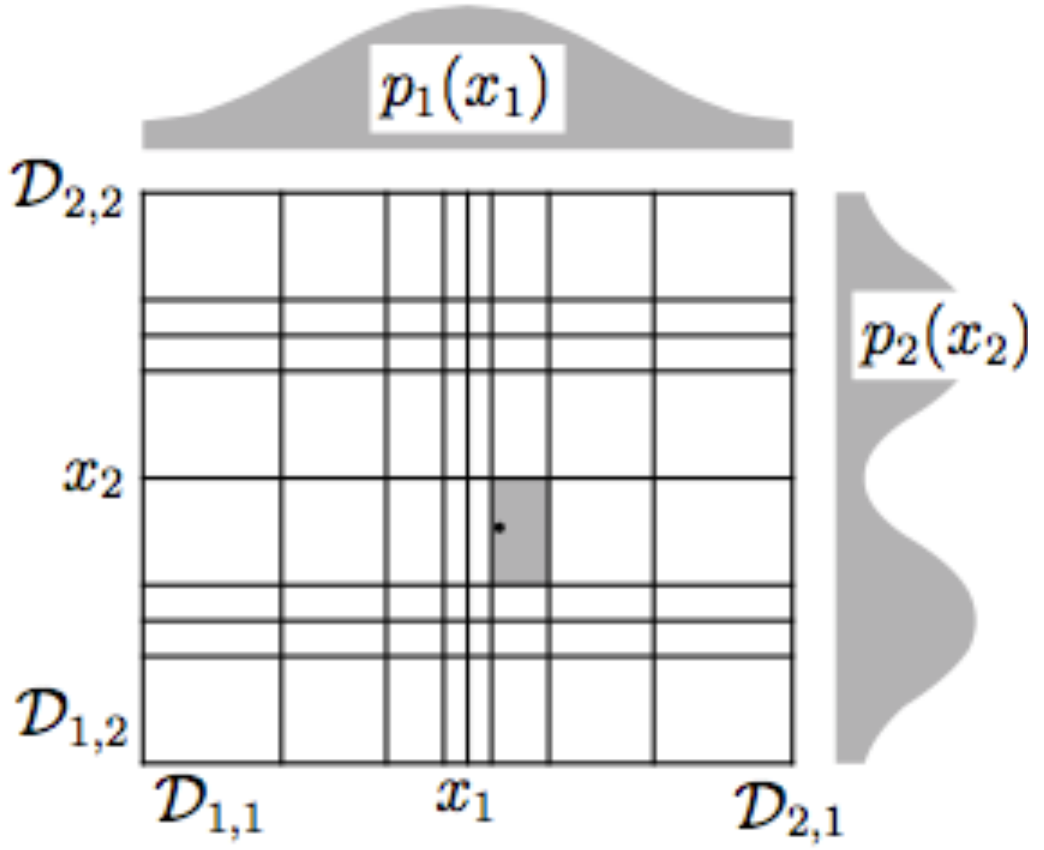
BACKUP

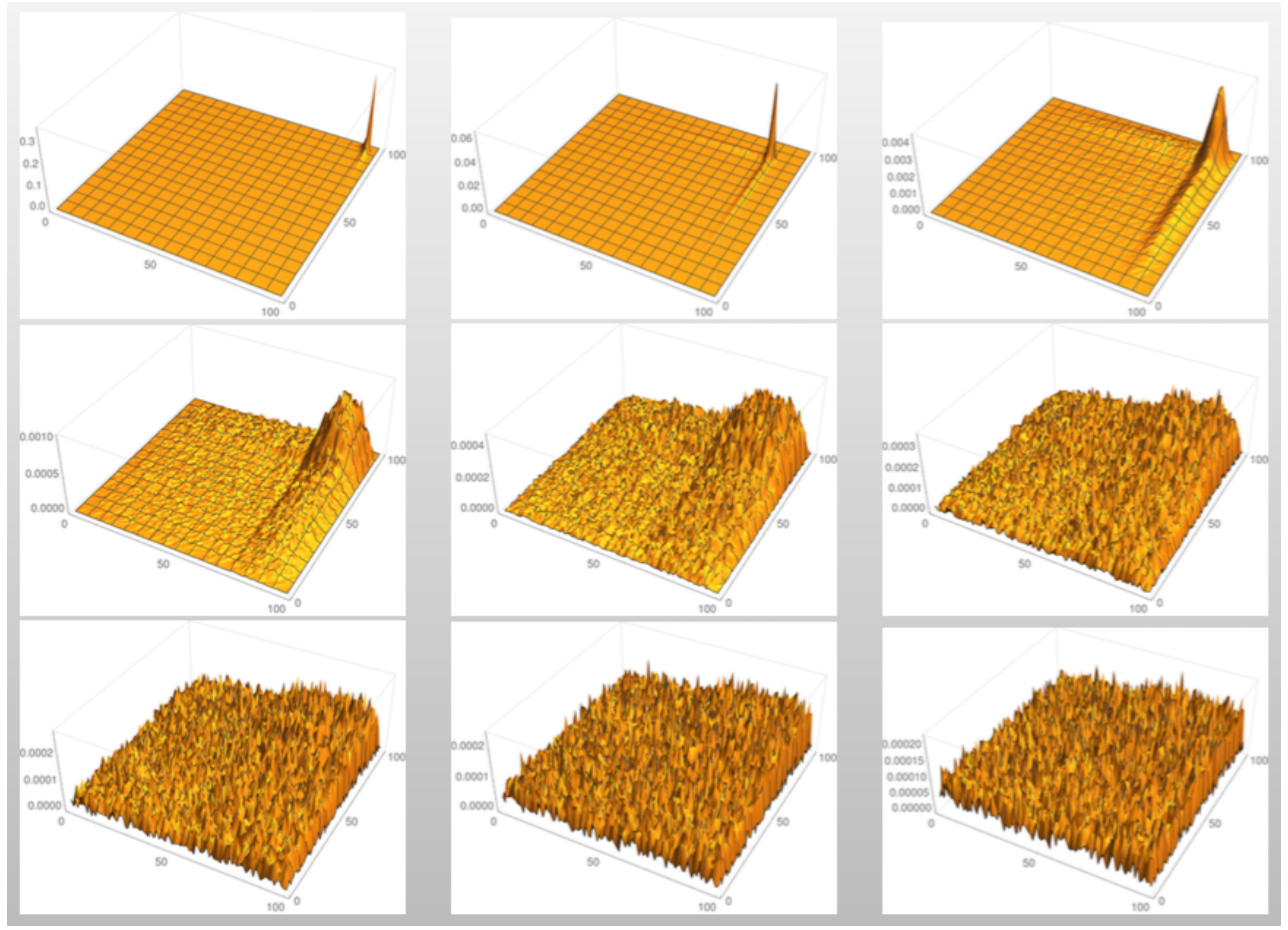
Beam simulations (technial details)

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)

Beam simulations (technial details)

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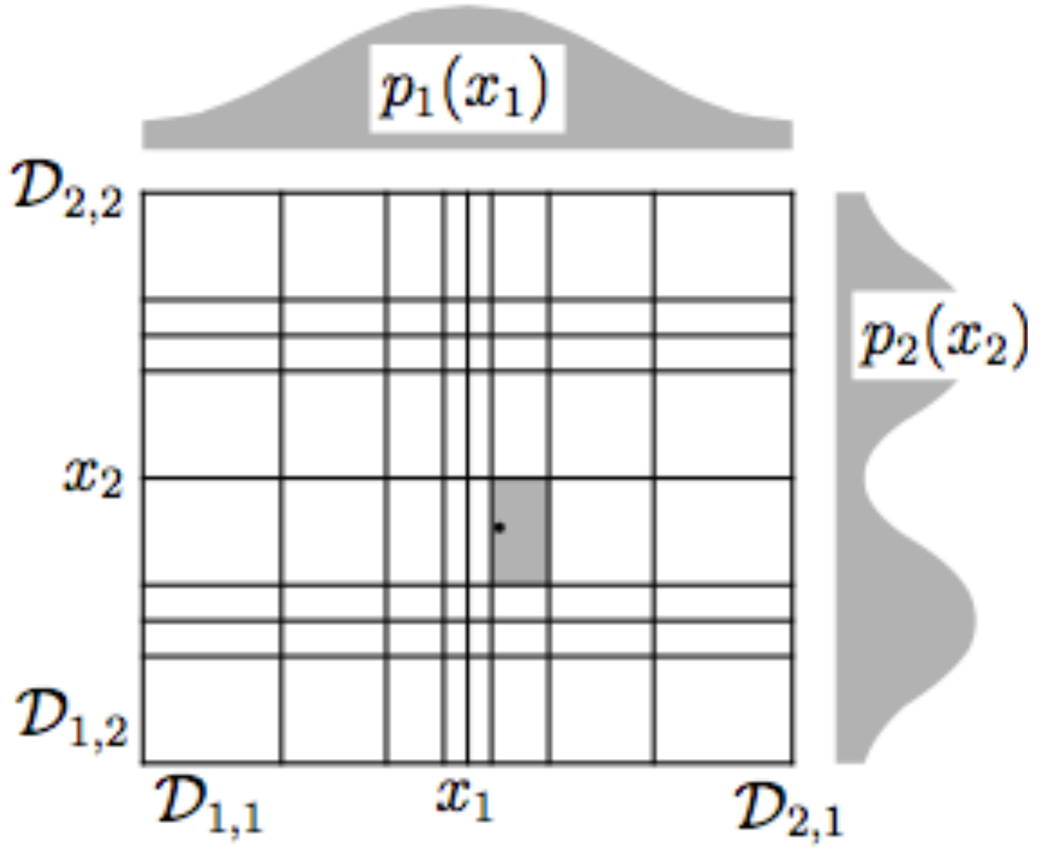

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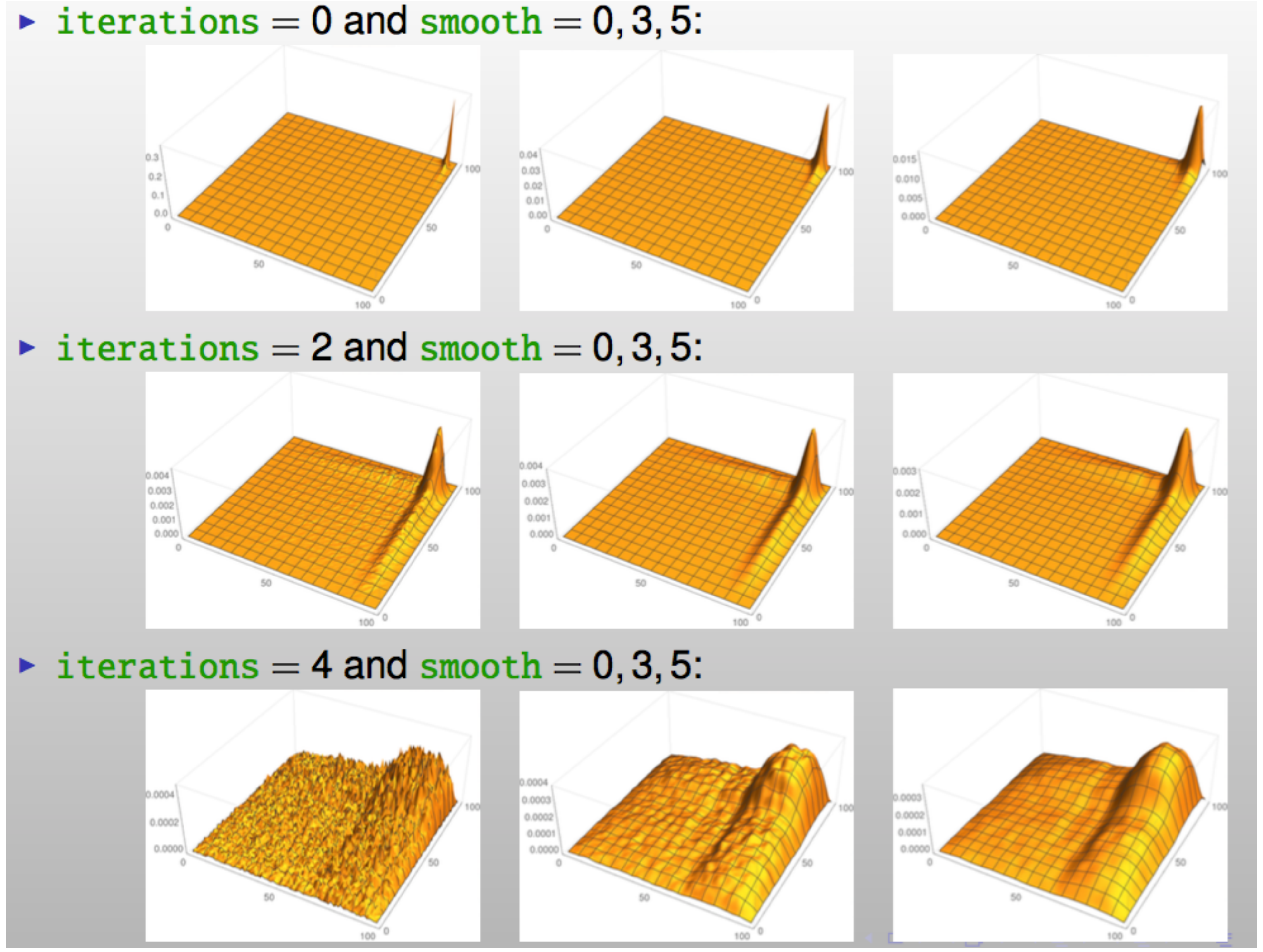

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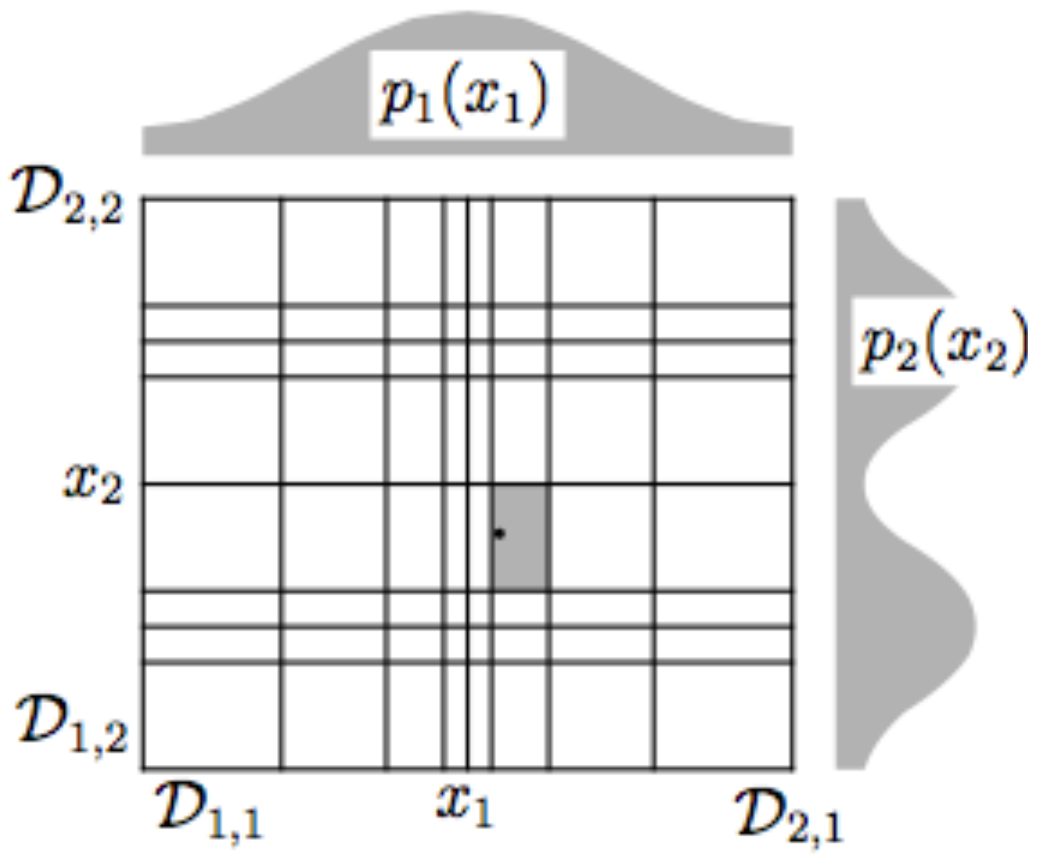

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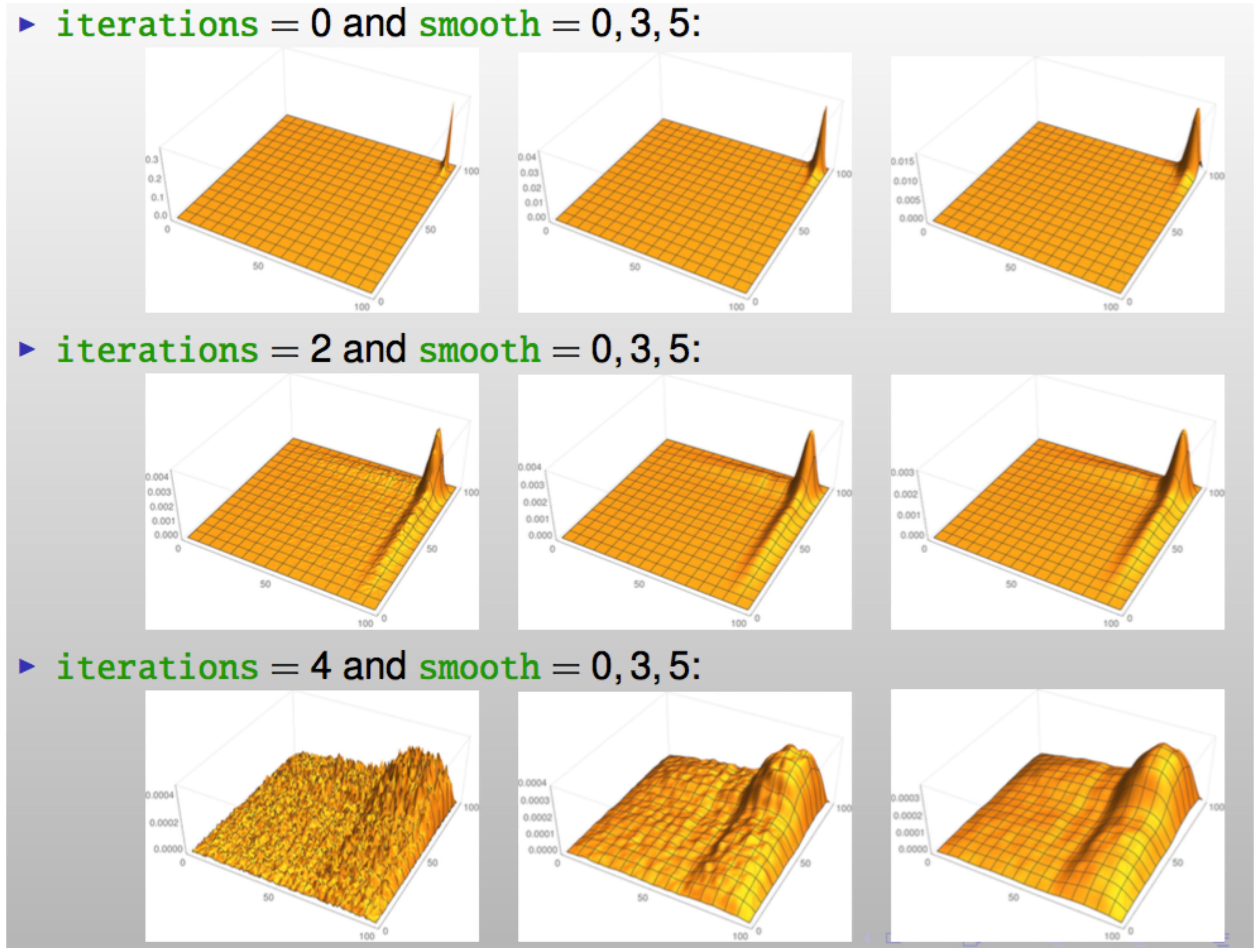

1. Run Guinea-Pig++ with

```
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