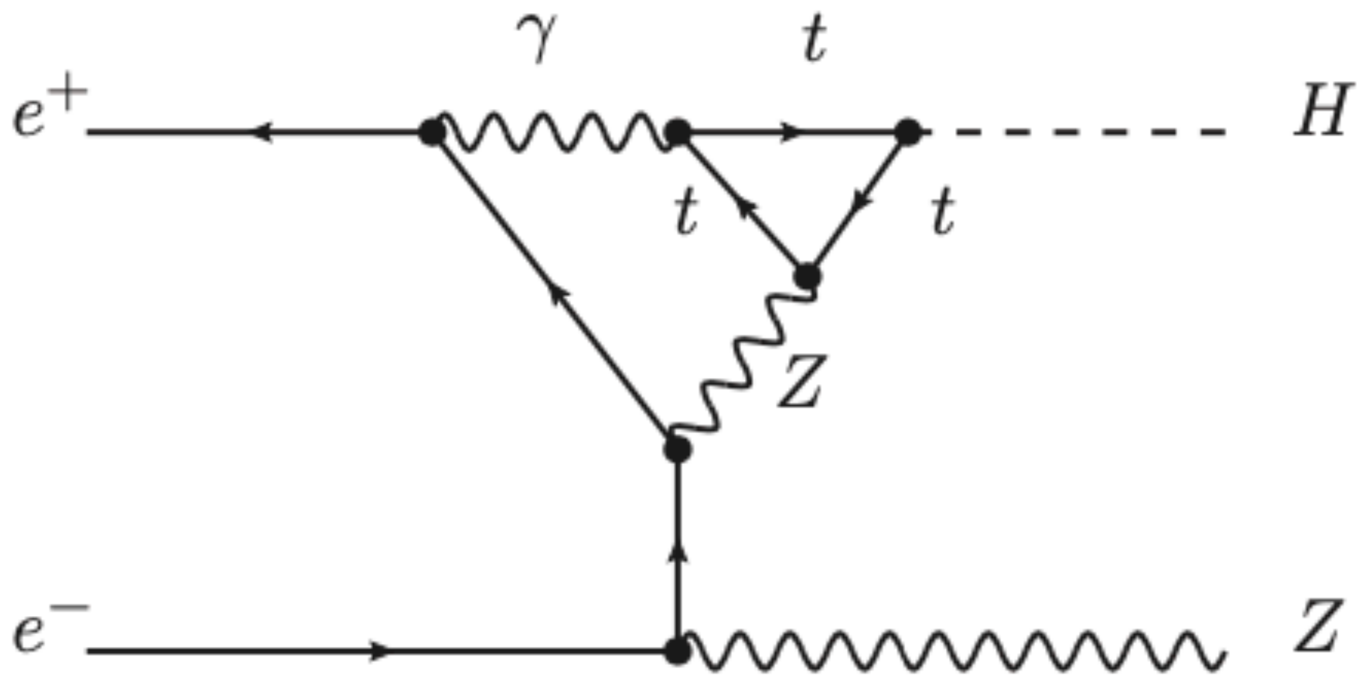
Event Generators for Future Colliders



DESY. HELMHOLTZ

Universität Hamburg
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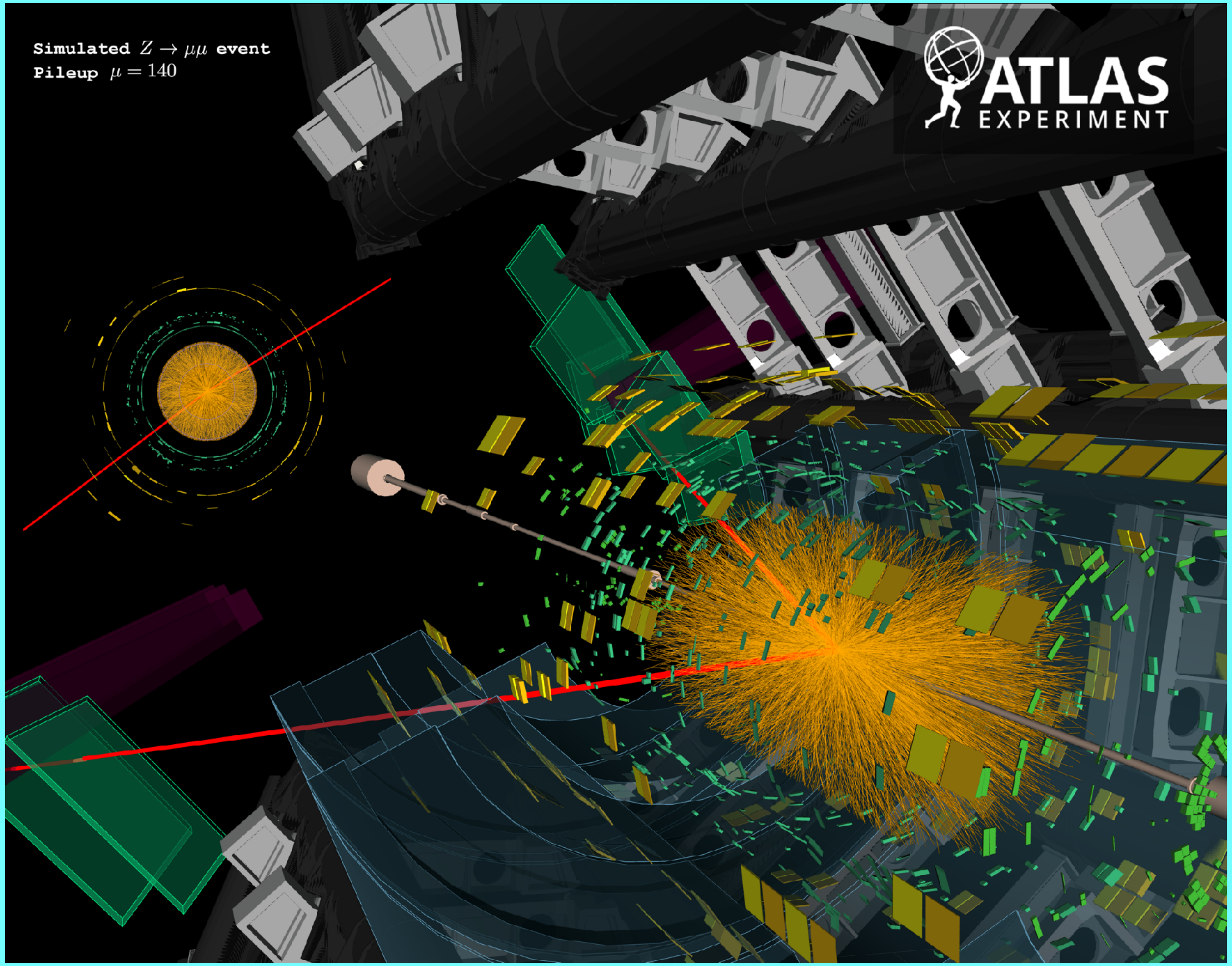
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

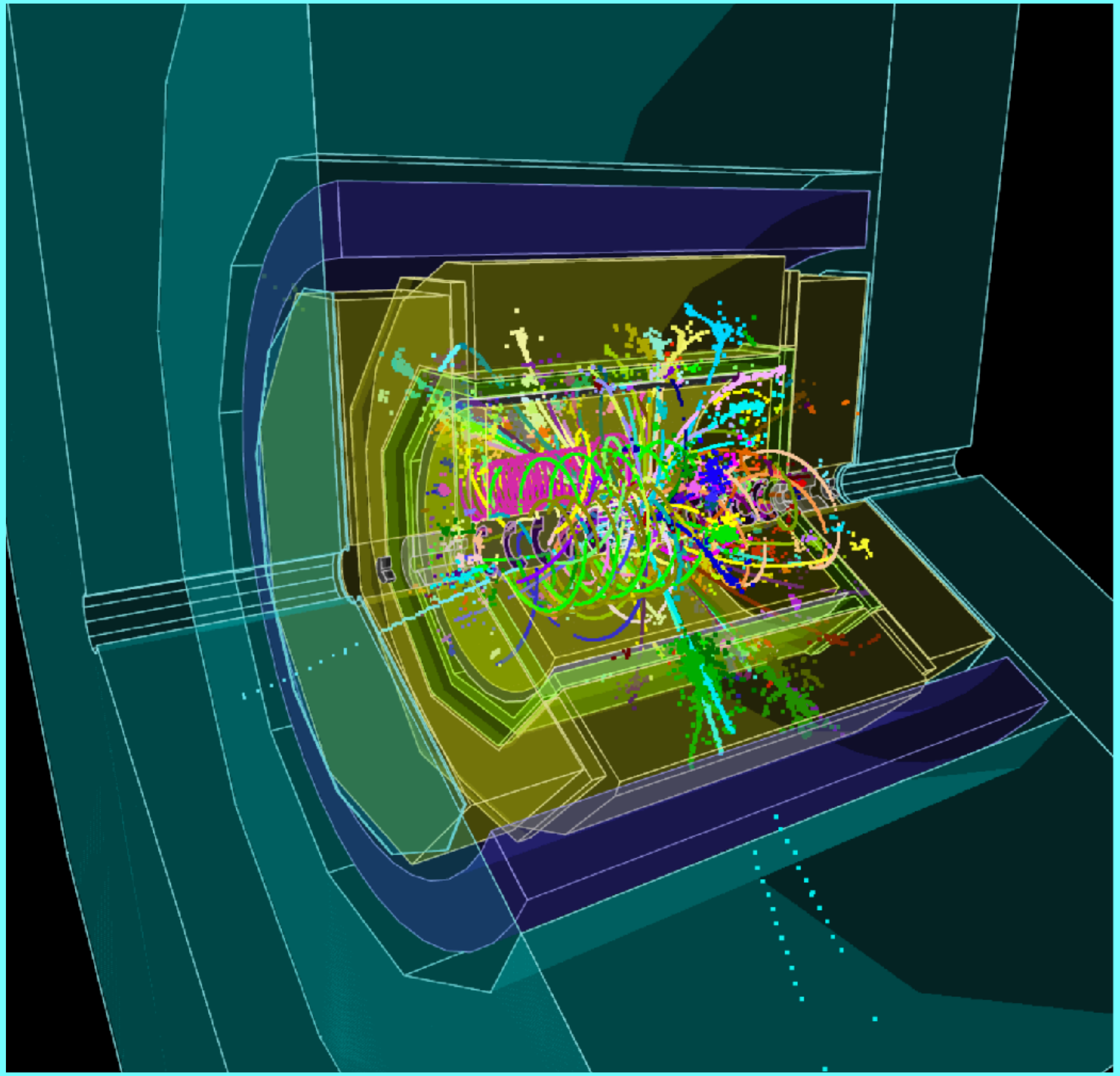
Jürgen R. Reuter

DESY.

Monte Carlo Simulation at colliders



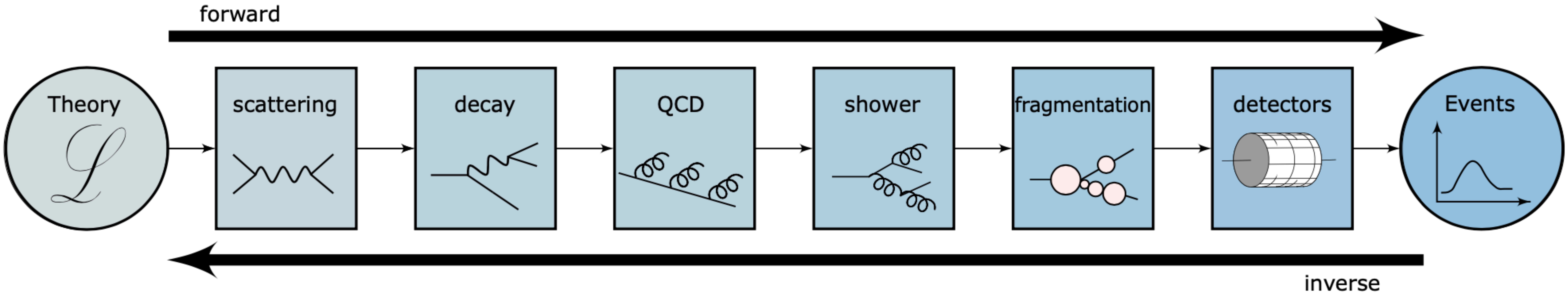
LHC, 13 TeV, $pp \to Z \to \mu^+\mu^-$, with pile-up



ILC, 1 TeV, $e^+e^- \to t\bar{t}h \to jjjjjjbb$

Simulation vs. Reconstruction

"Forward simulation": Monte Carlo generators

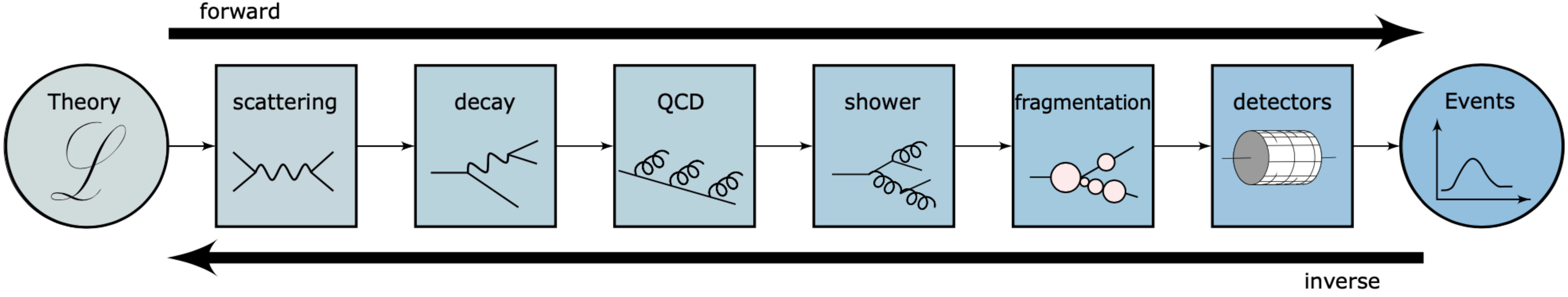


from 2211.01421

"Inverse simulation": Reconstruction

Simulation vs. Reconstruction

“Forward simulation”: Monte Carlo generators



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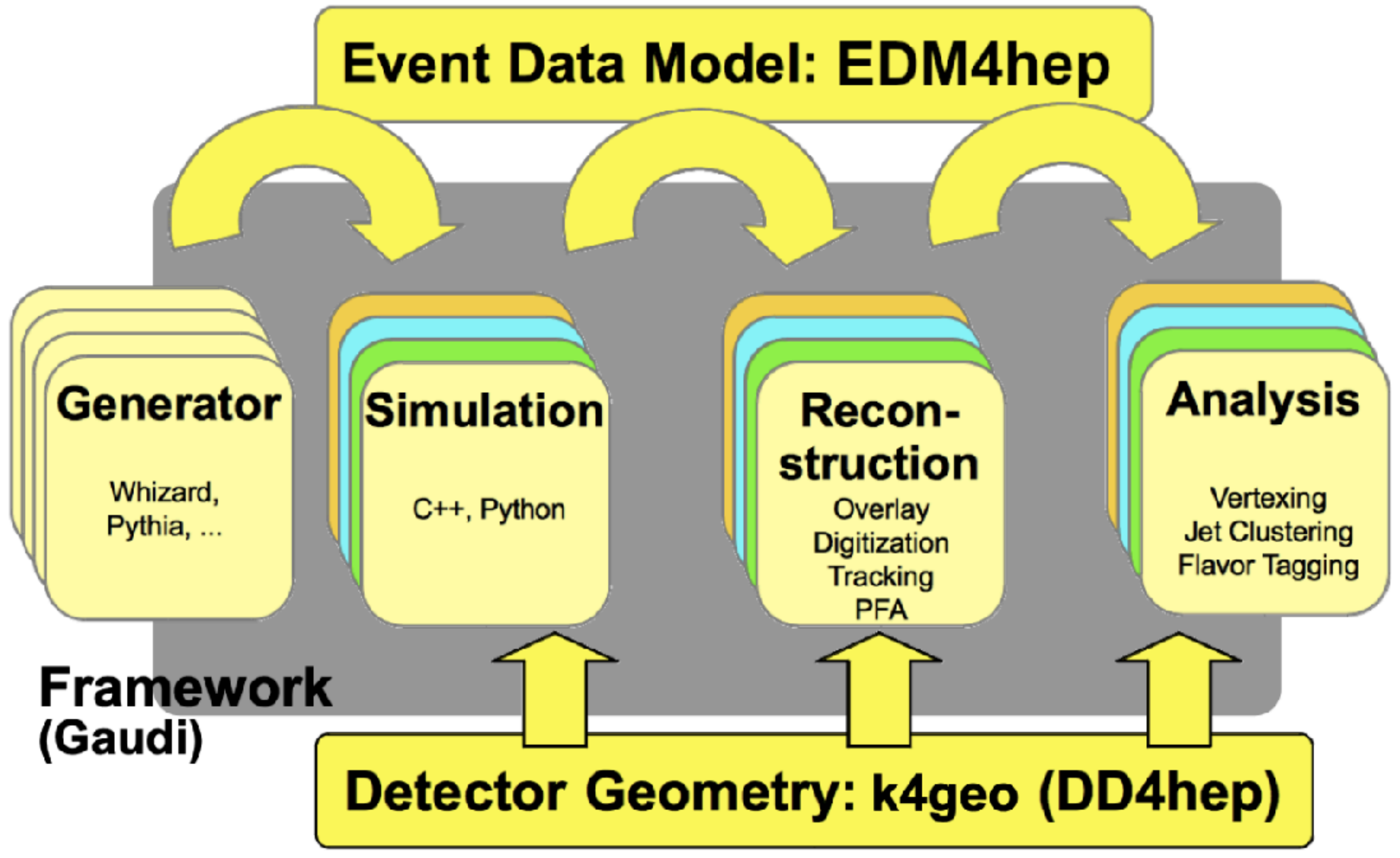
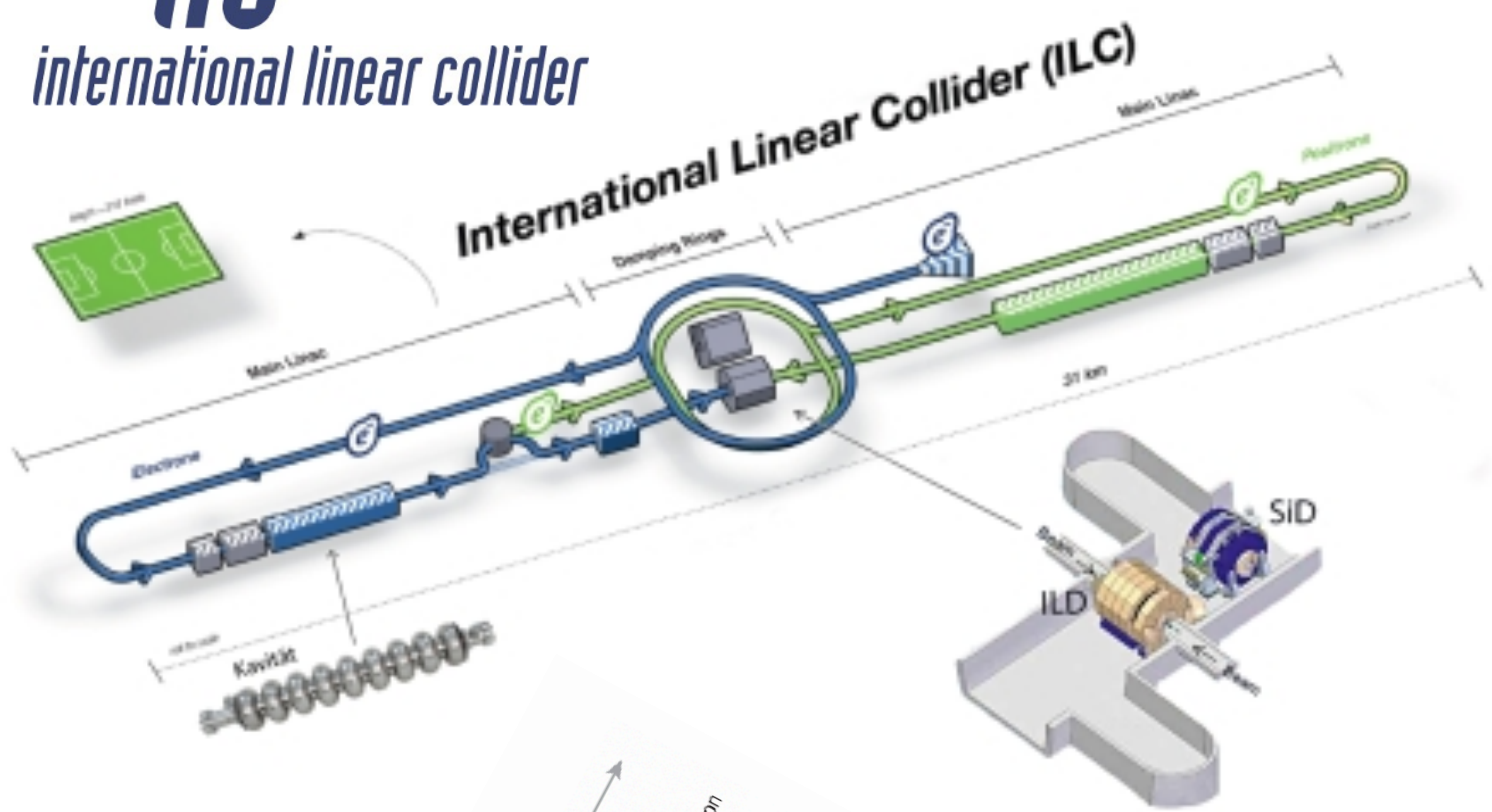


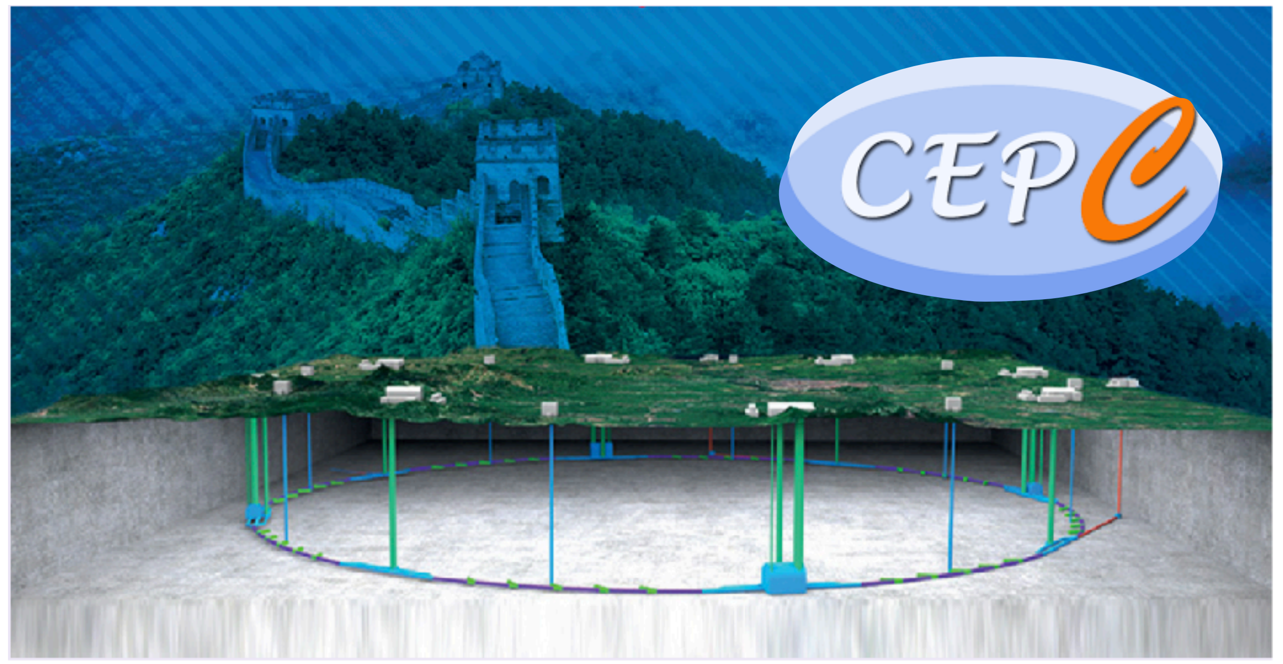
“Inverse simulation”: Reconstruction

Simulations for Future Colliders

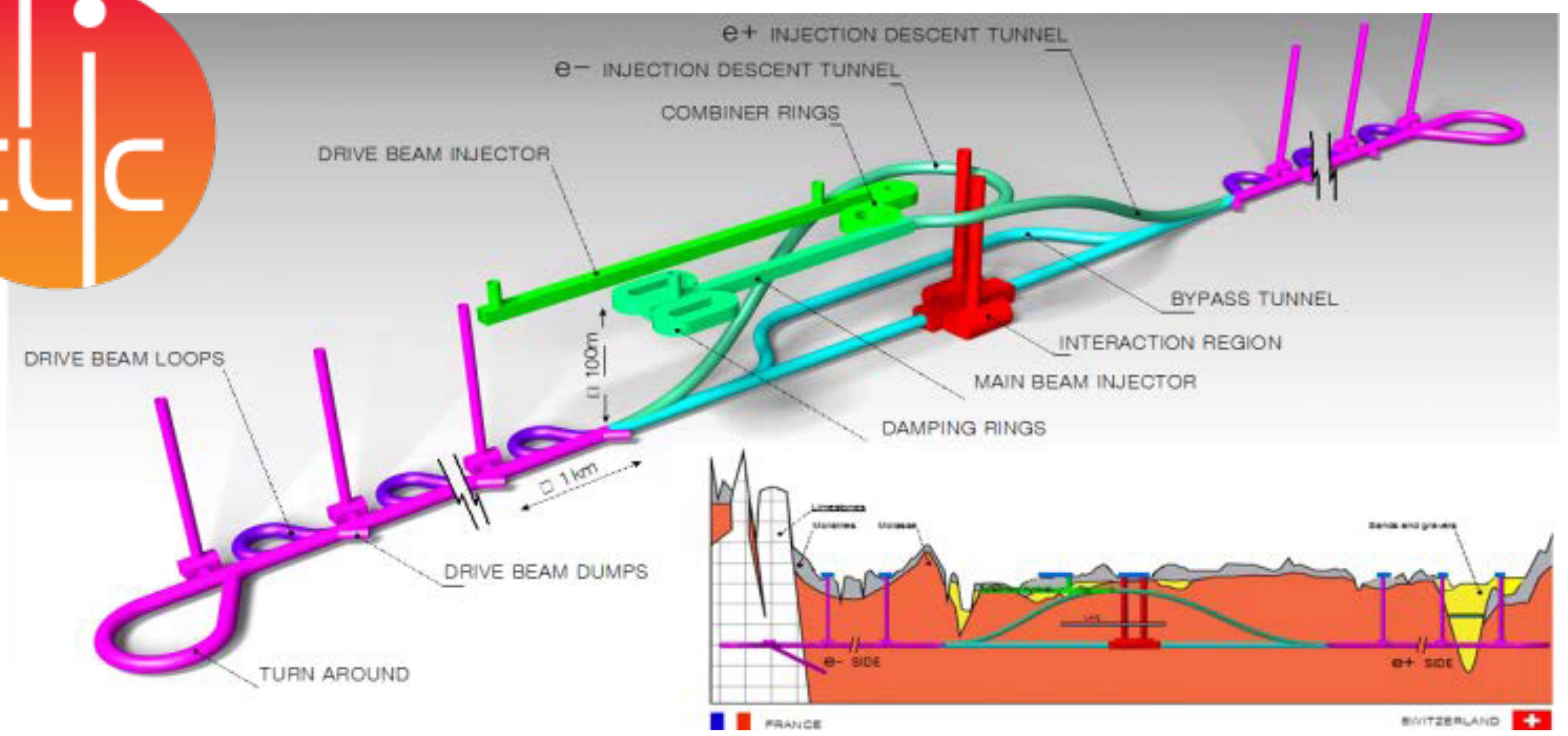
ILC



CEPC

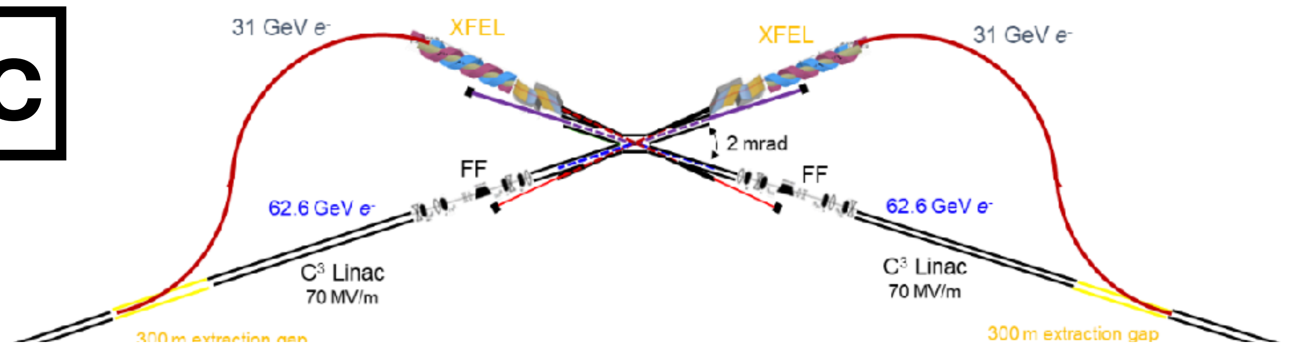


CLIC

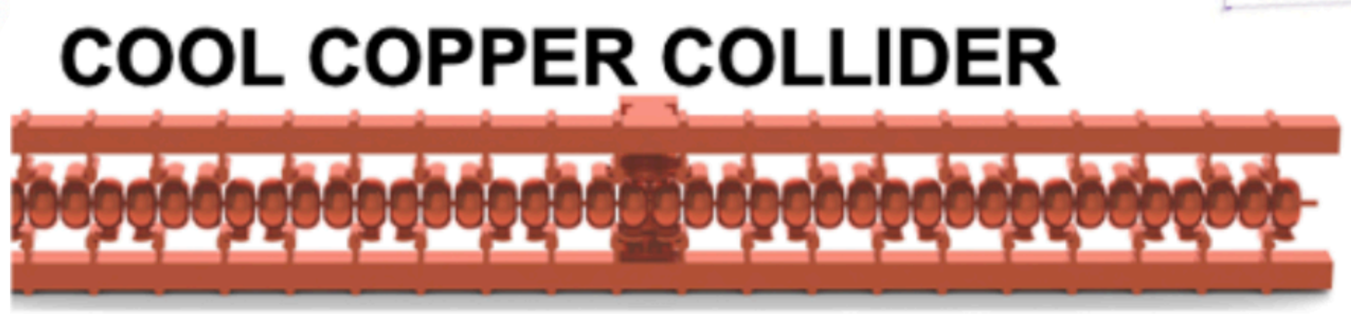


XCC

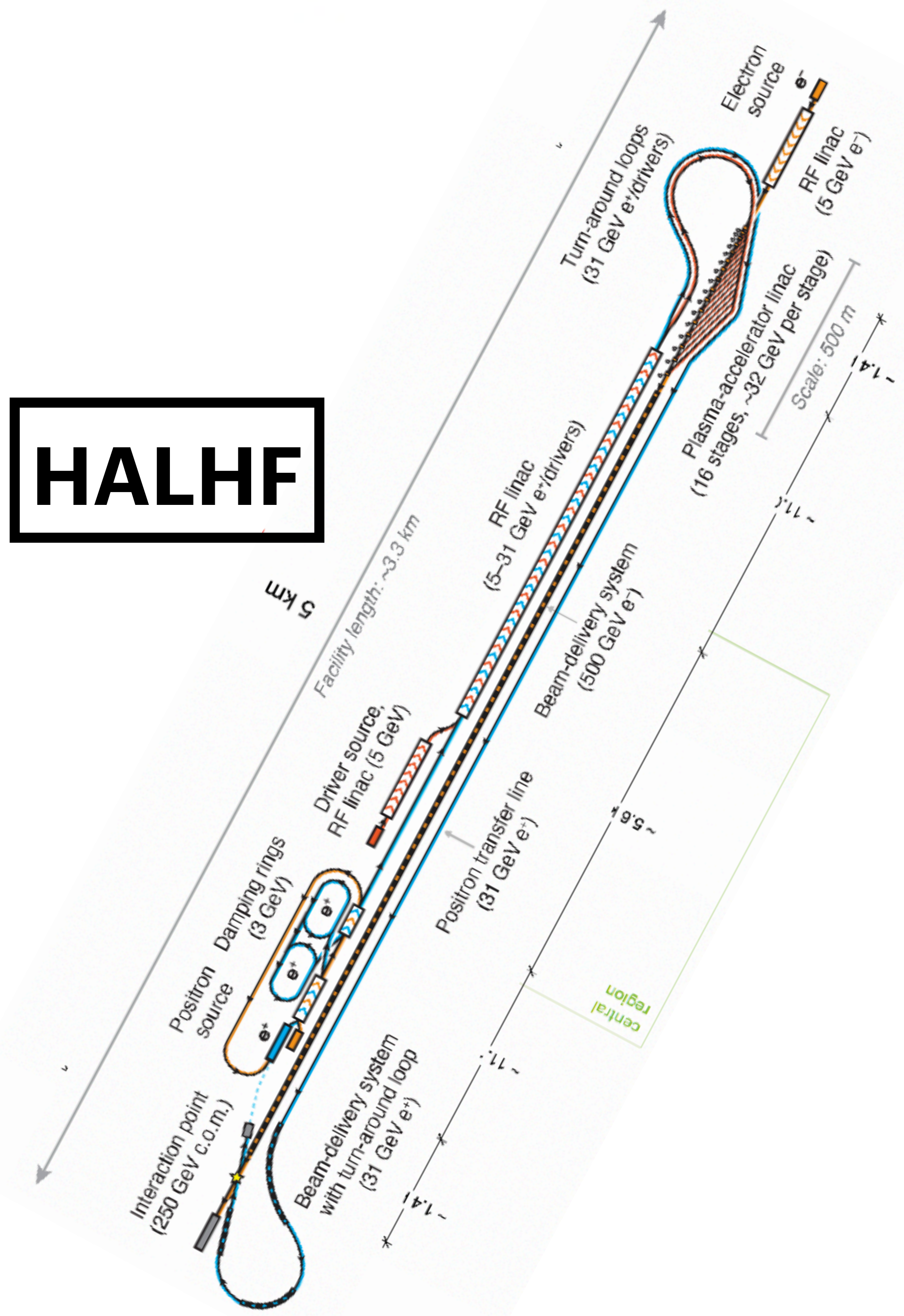
XCC s-channel $\gamma\gamma \to H$ @ $\sqrt{s} = 125$ GeV



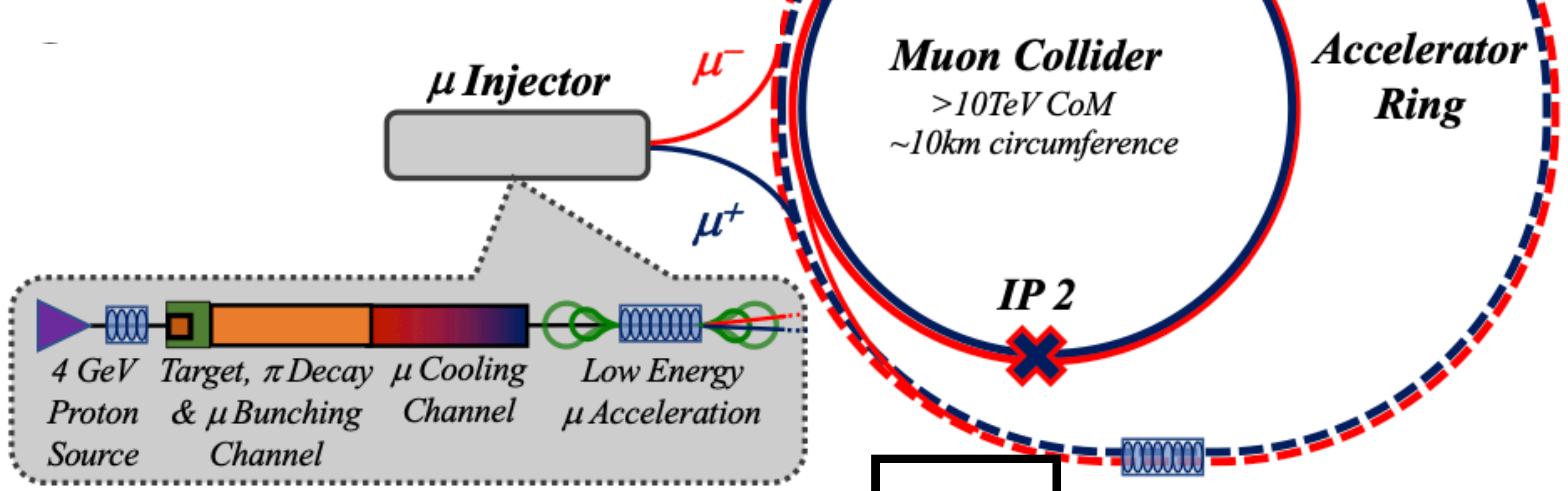
C³



HALHF

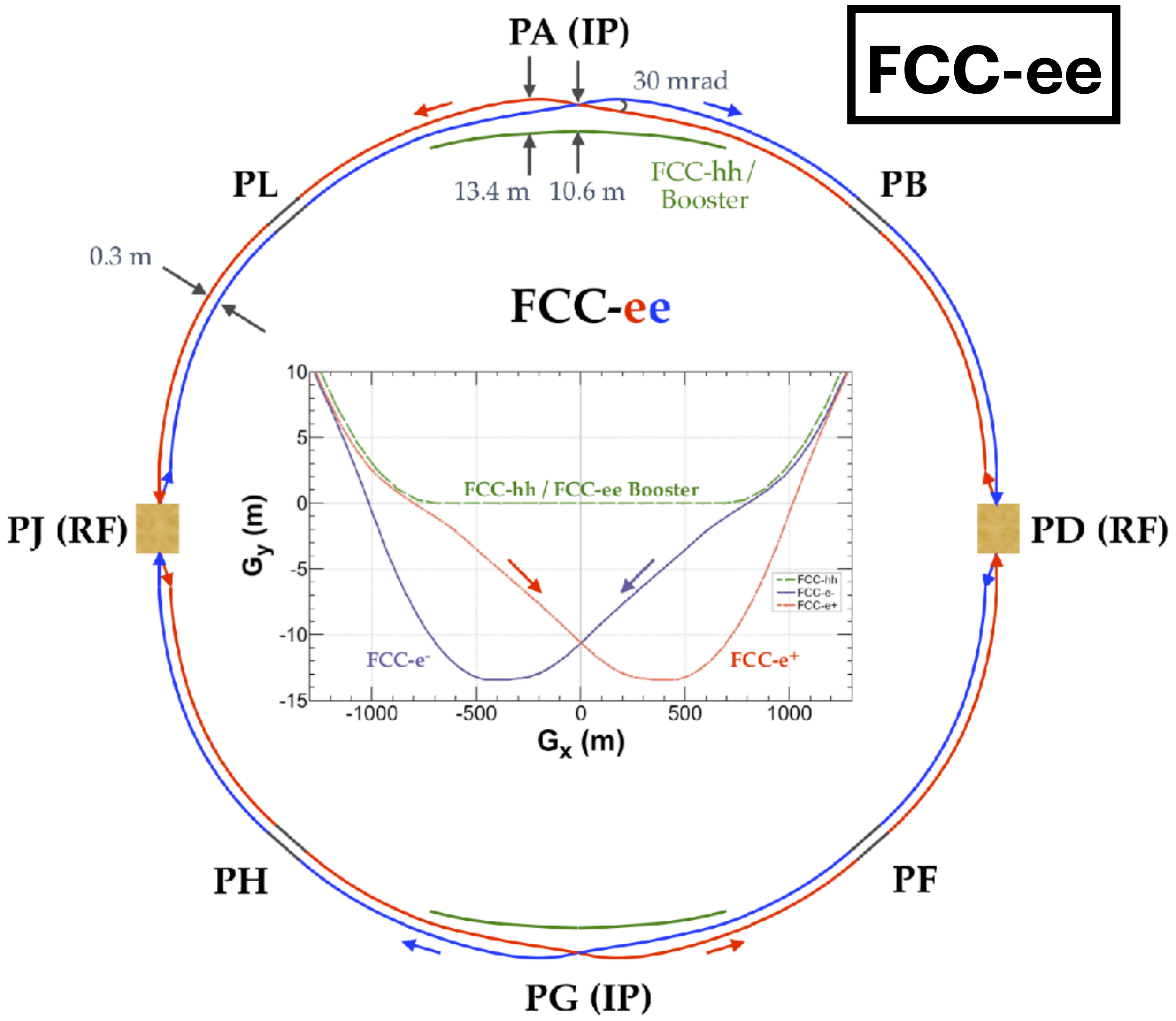


MuC



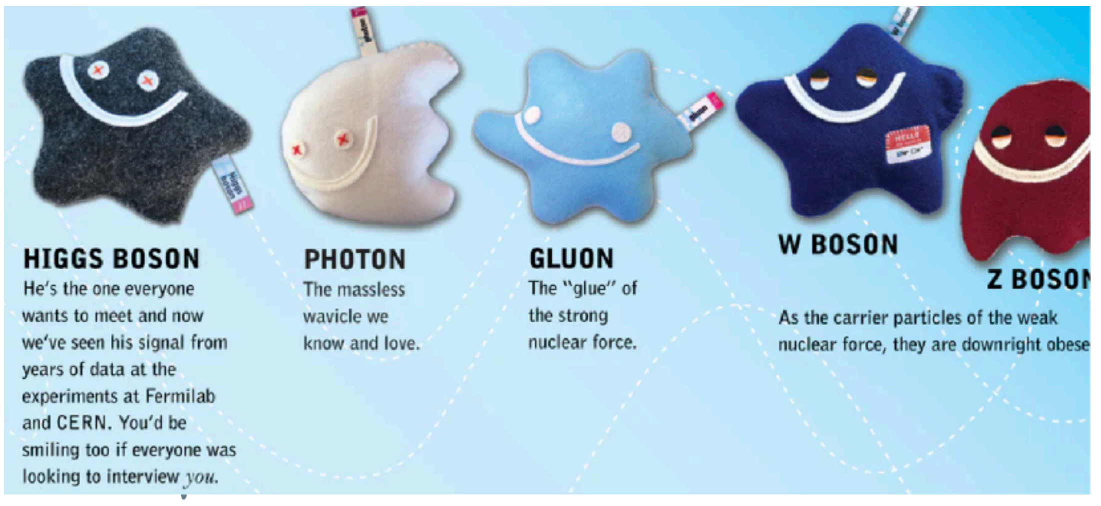
International UON Collider Collaboration

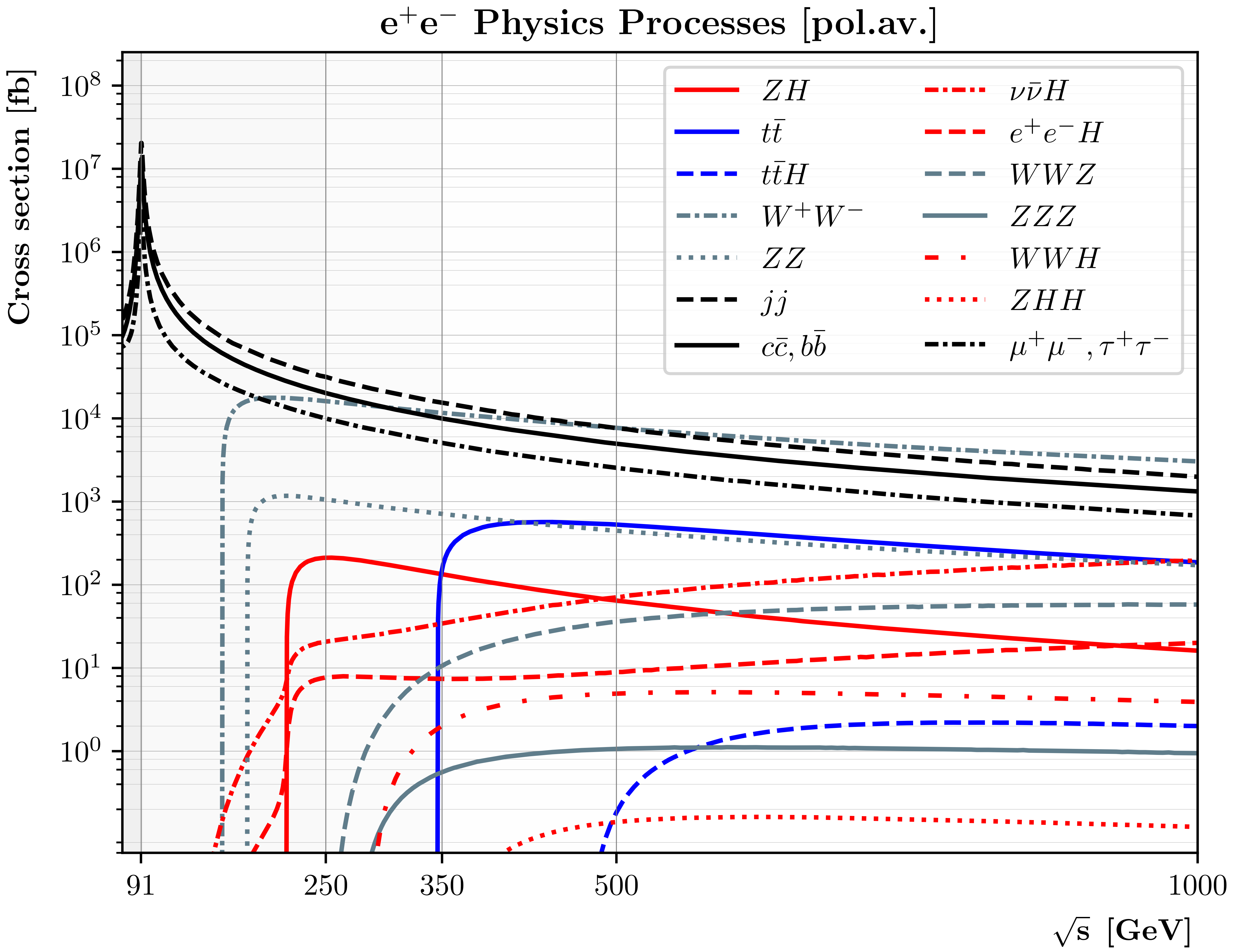
FCC-ee

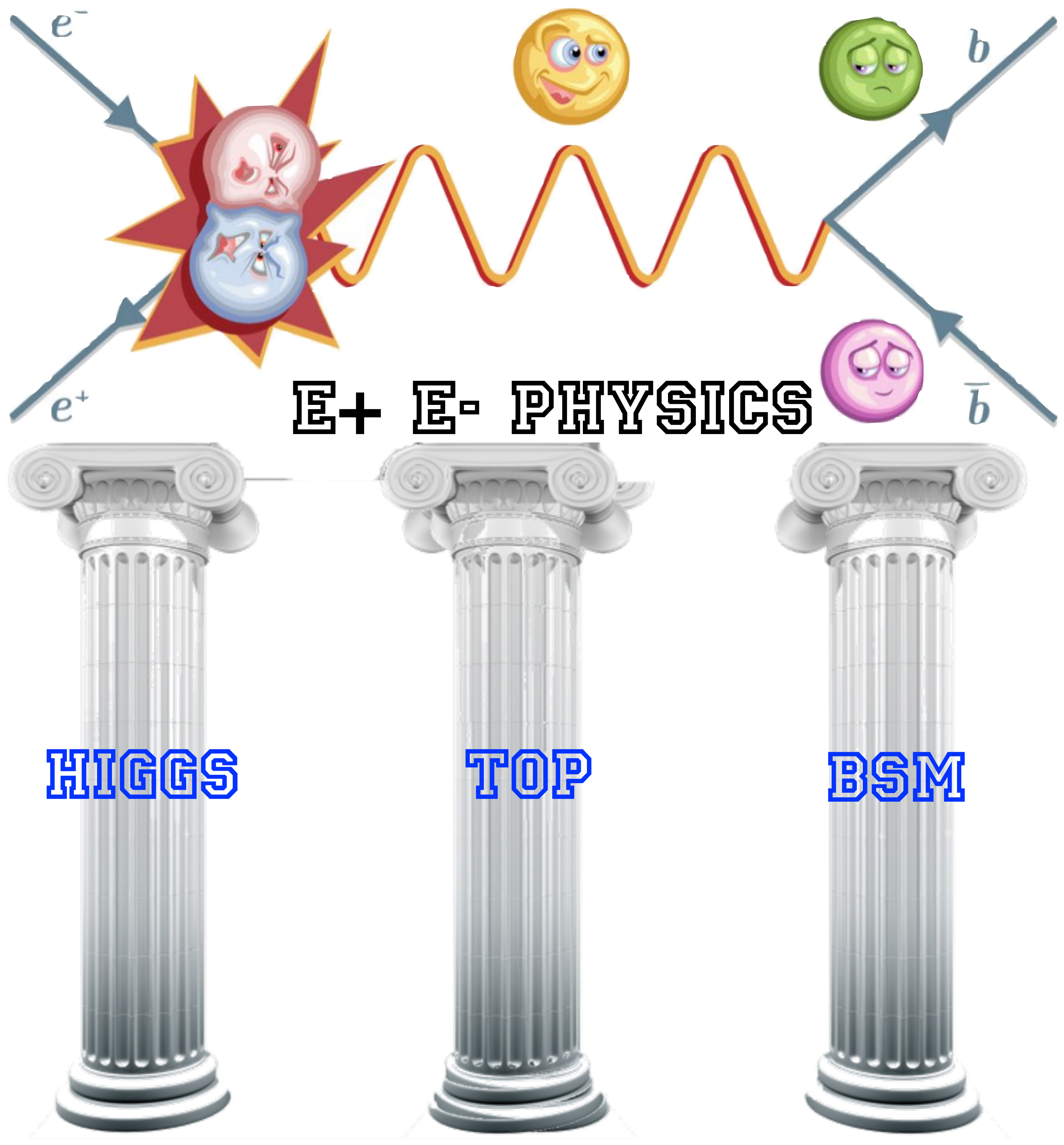


Simulating physics at a (lepton) future collider

- **Disclaimer:** focus here mostly on future lepton colliders (e^+e^- and $\mu^+\mu^-$ colliders)







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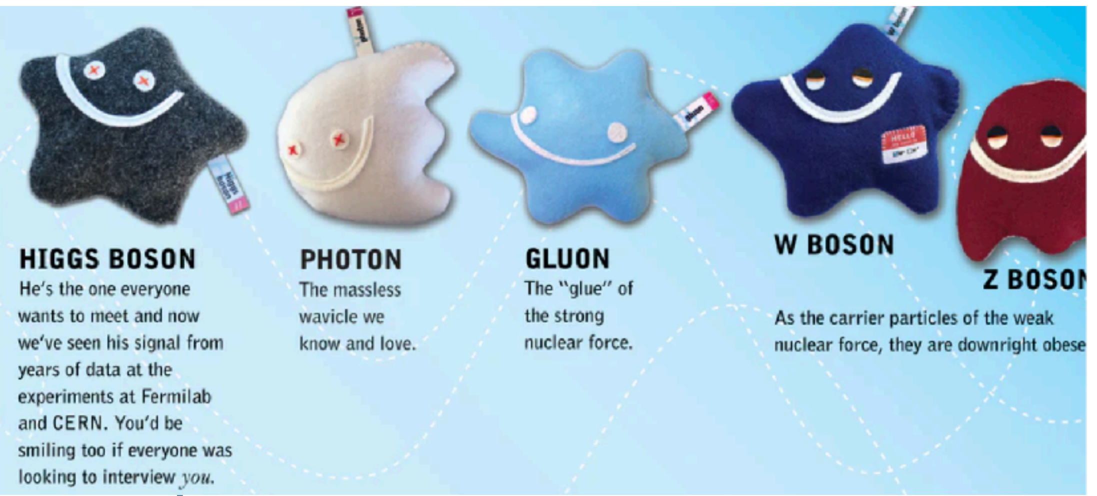

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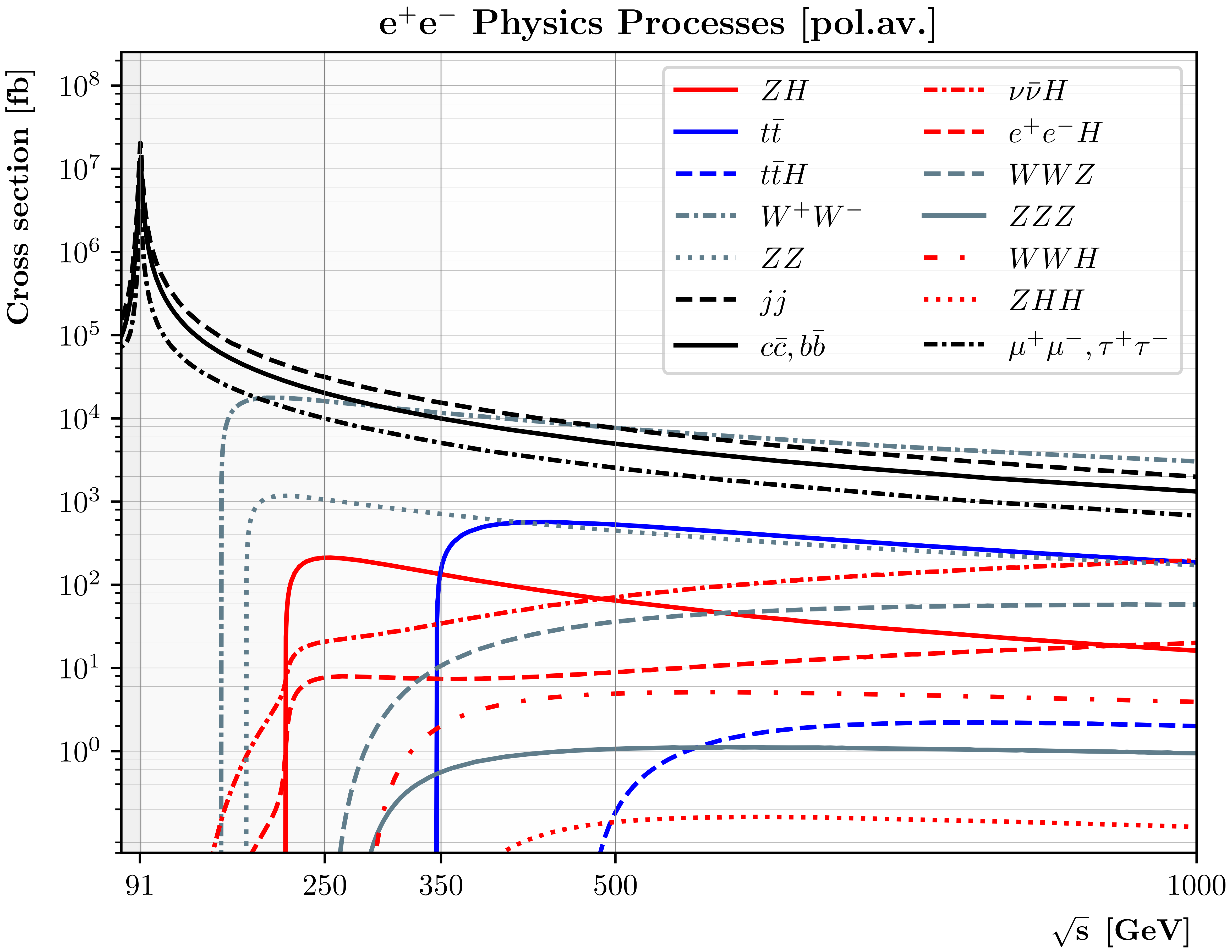
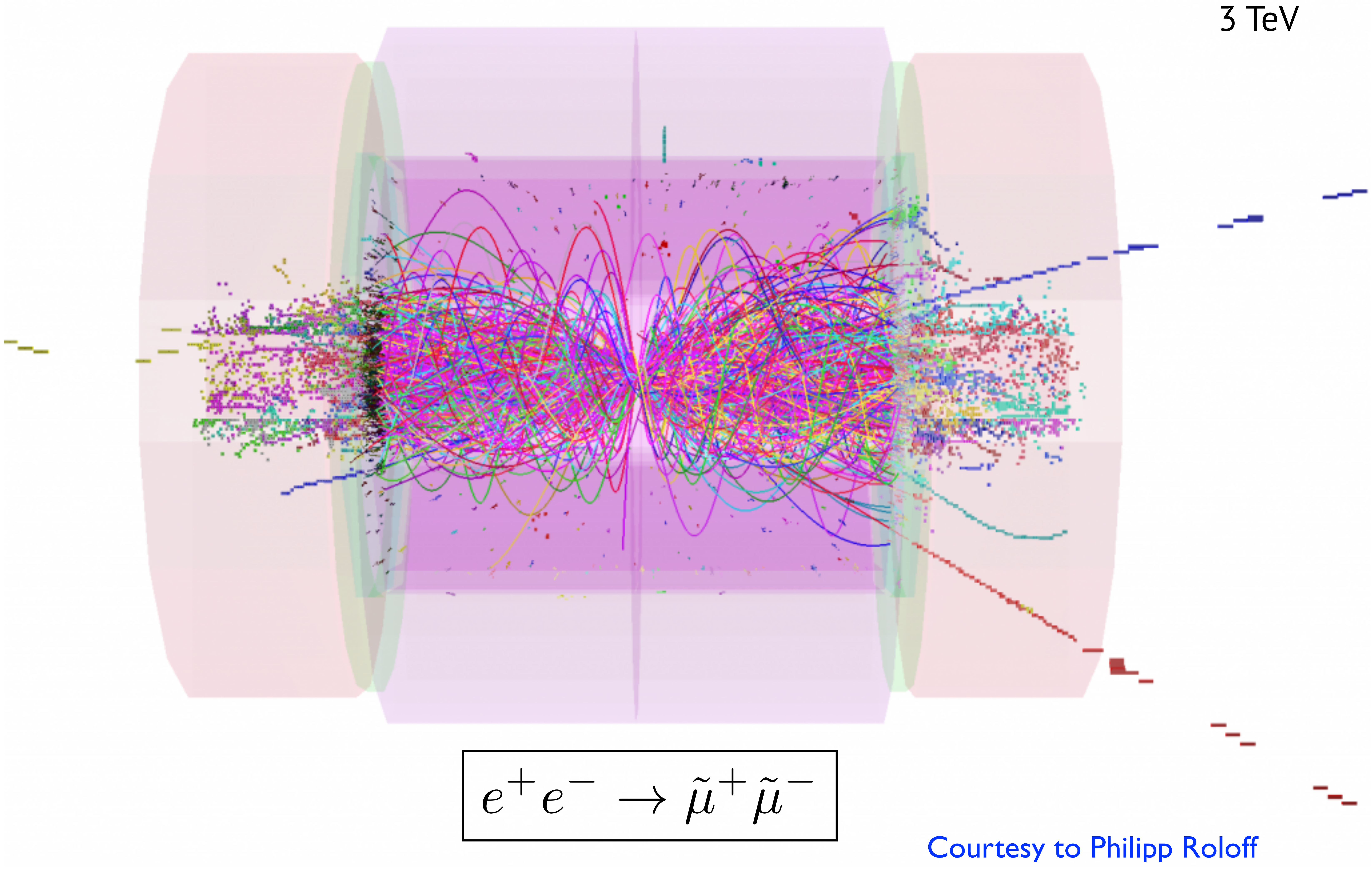


The importance of MC event generators

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

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



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

Courtesy to Philipp Roloff

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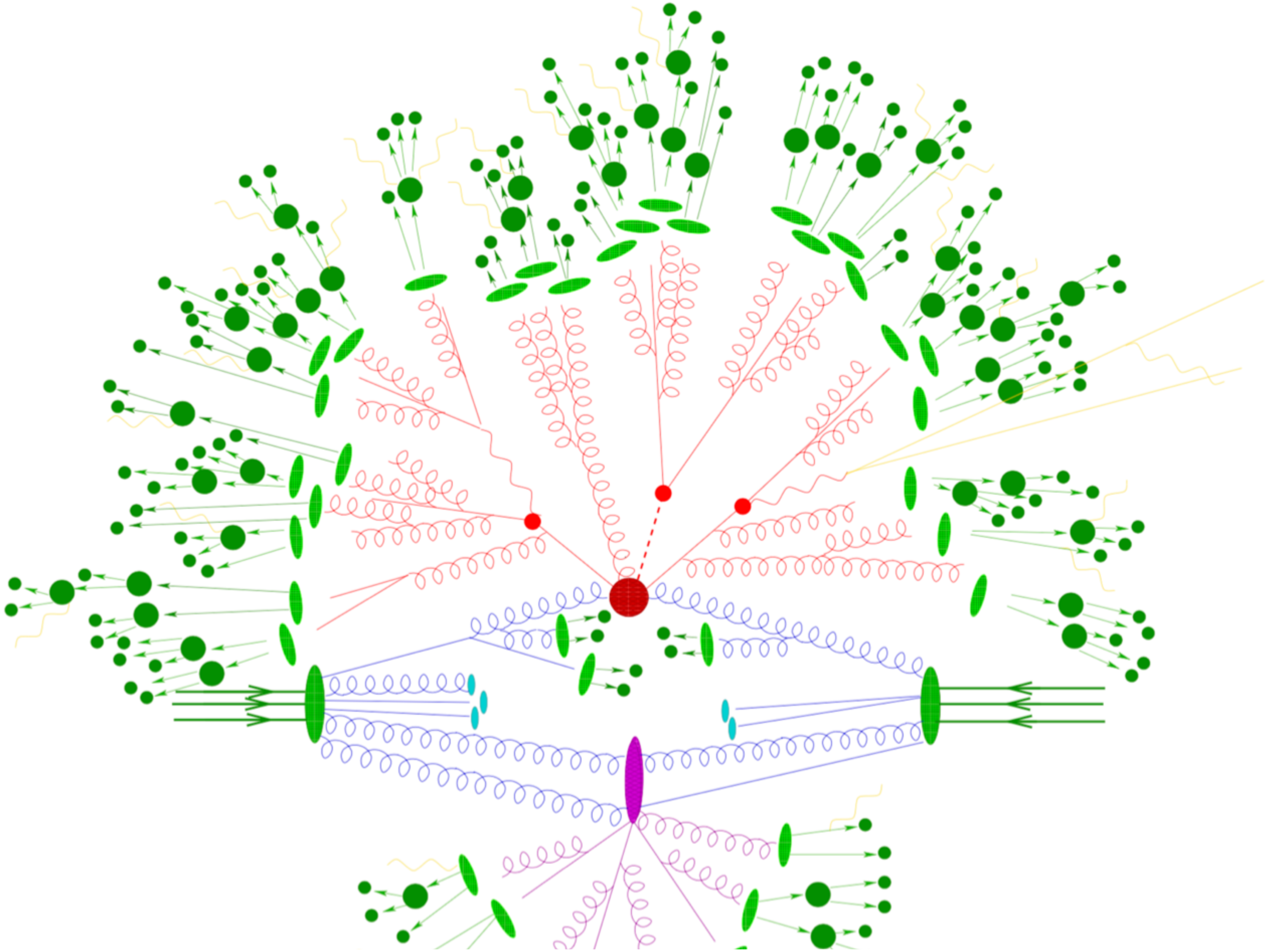

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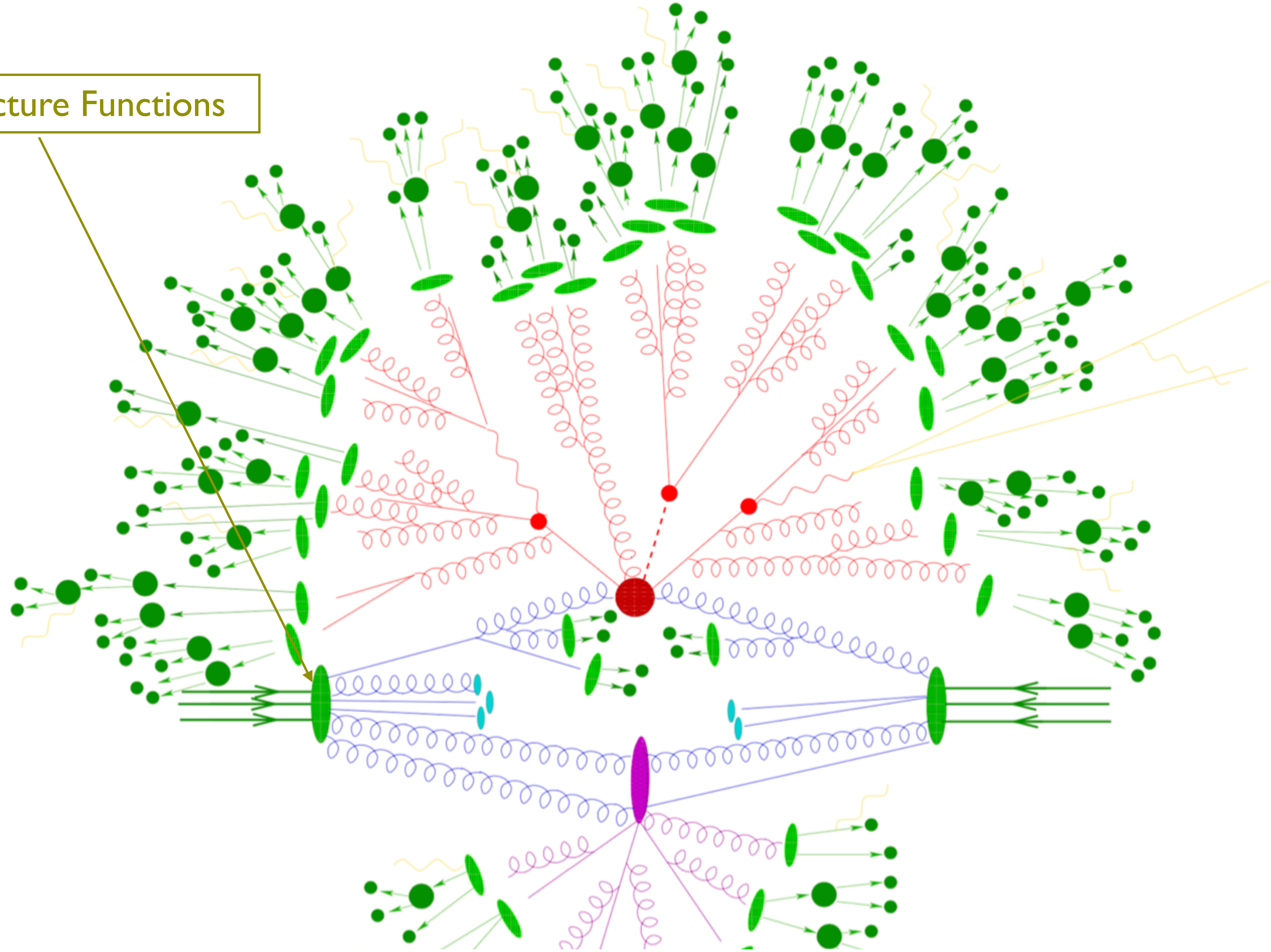
Beam spectra & ISR Structure Functions



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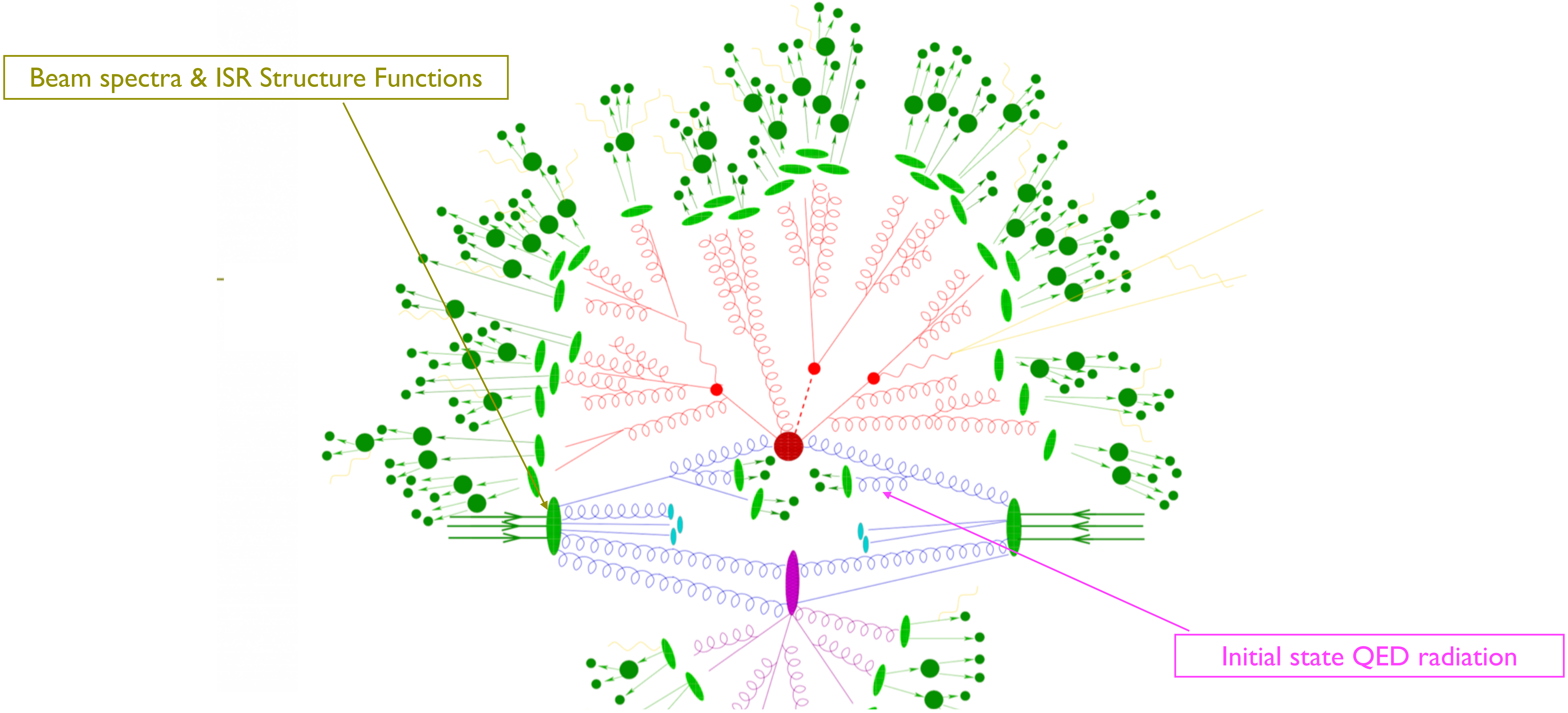

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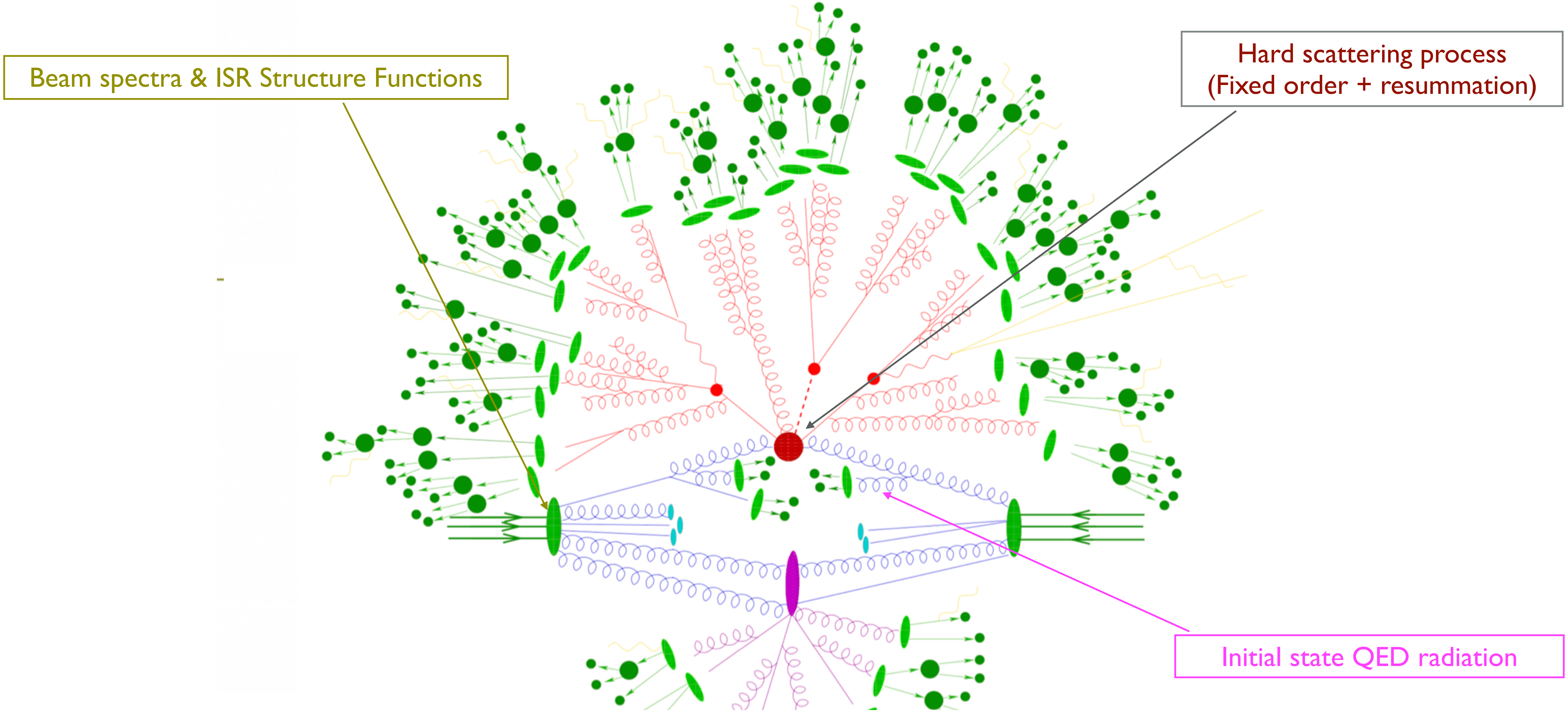

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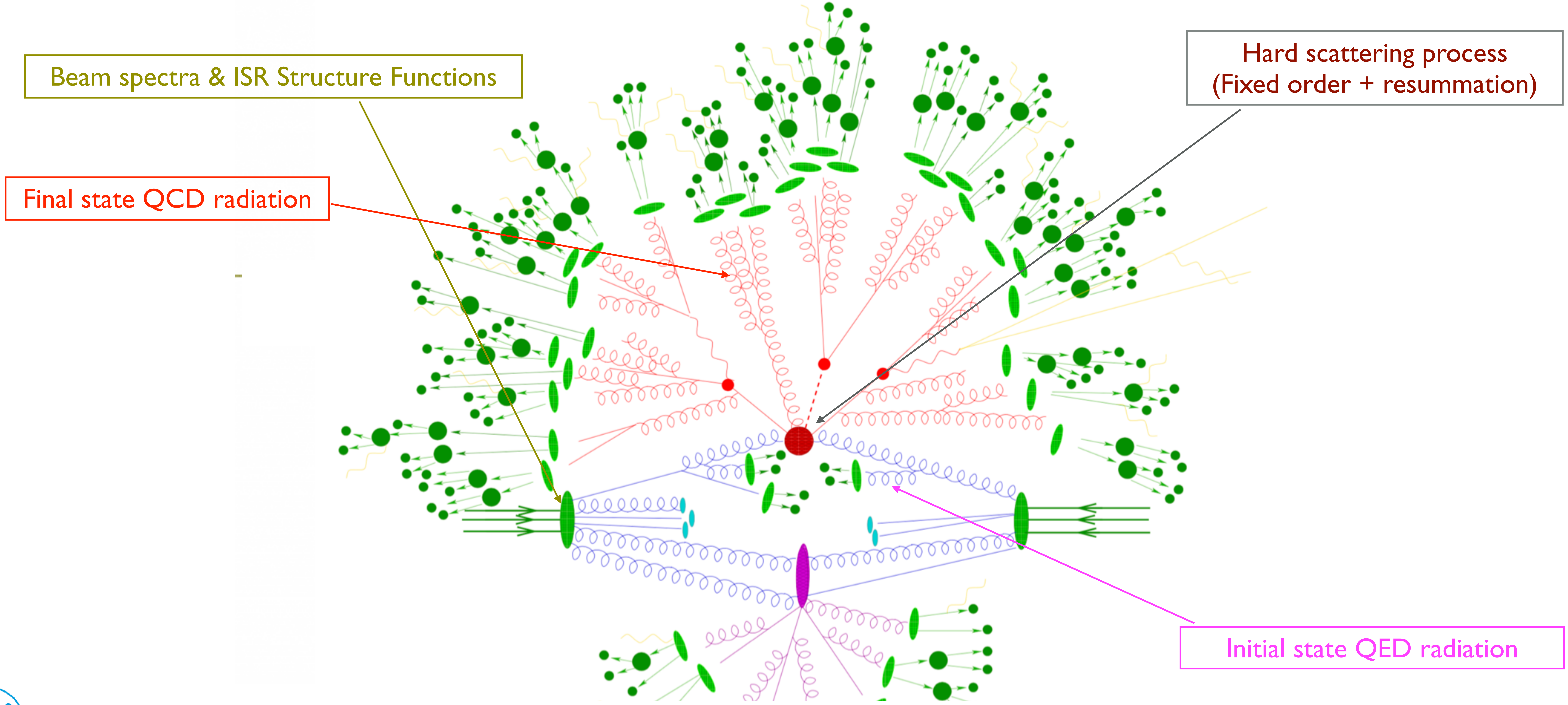

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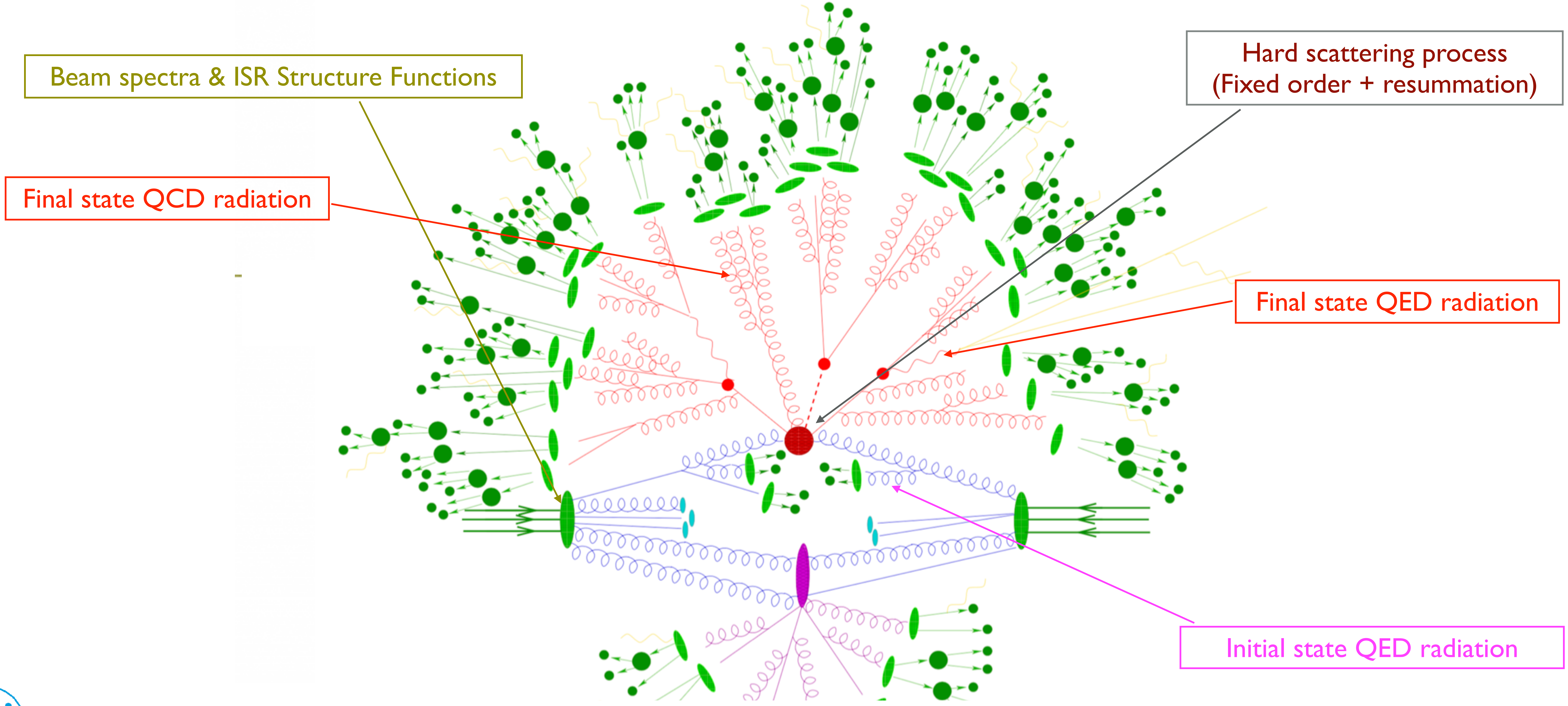

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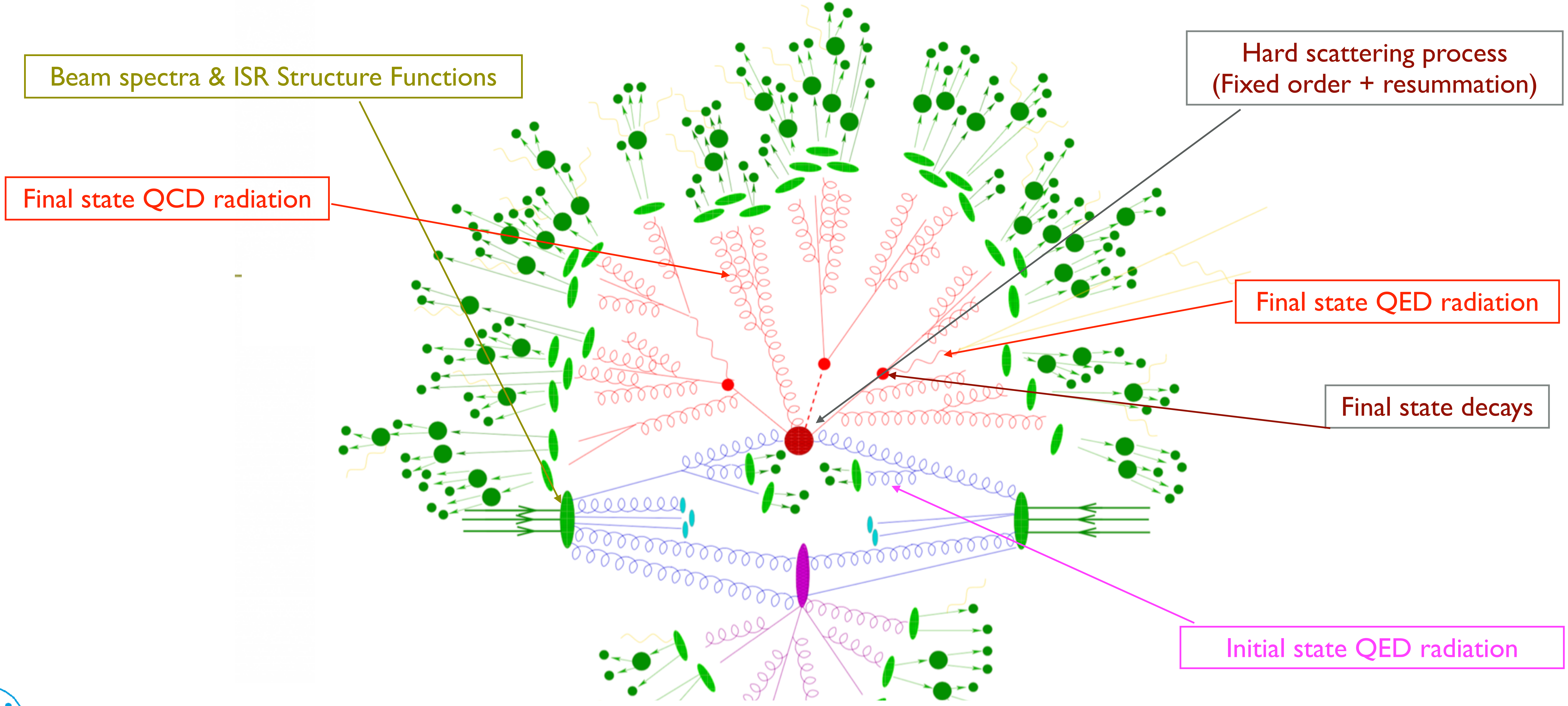

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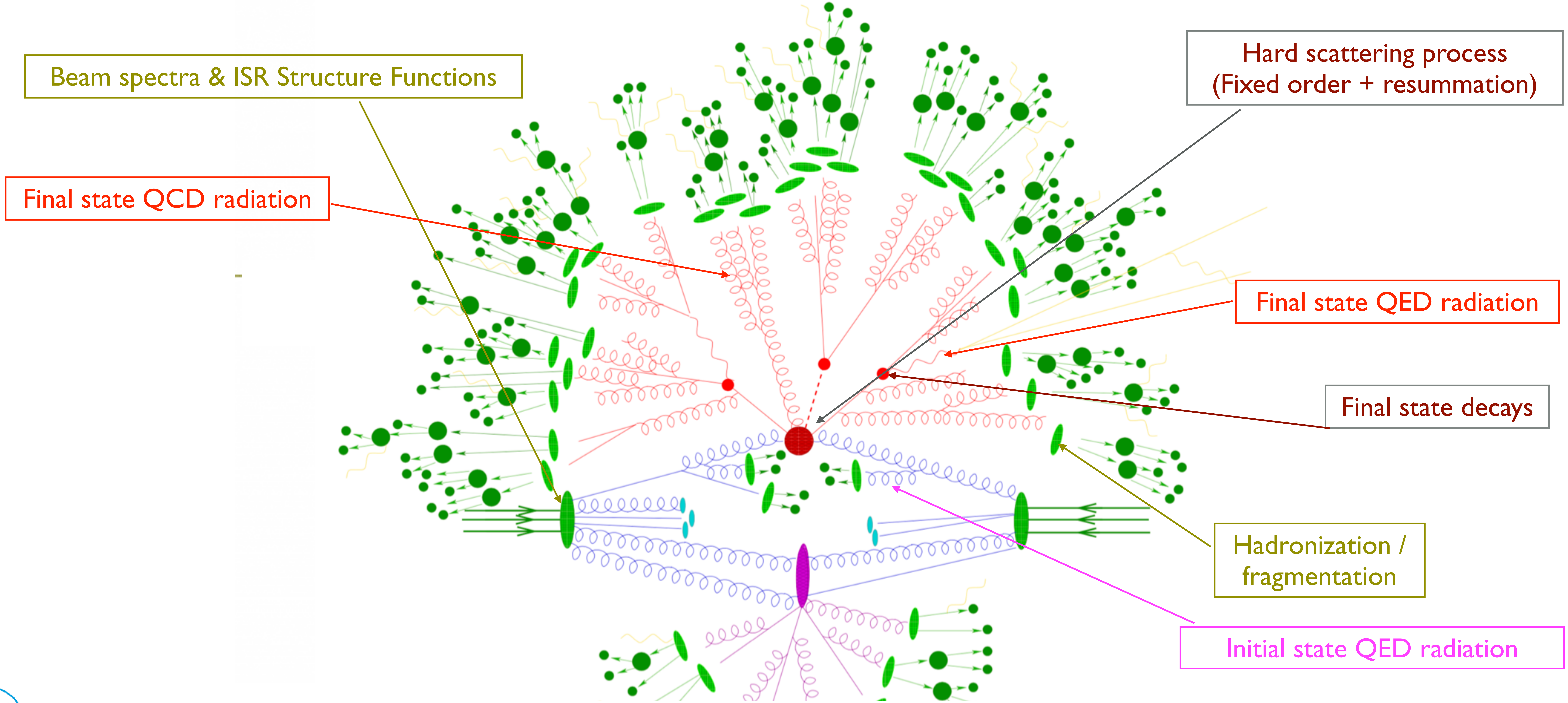

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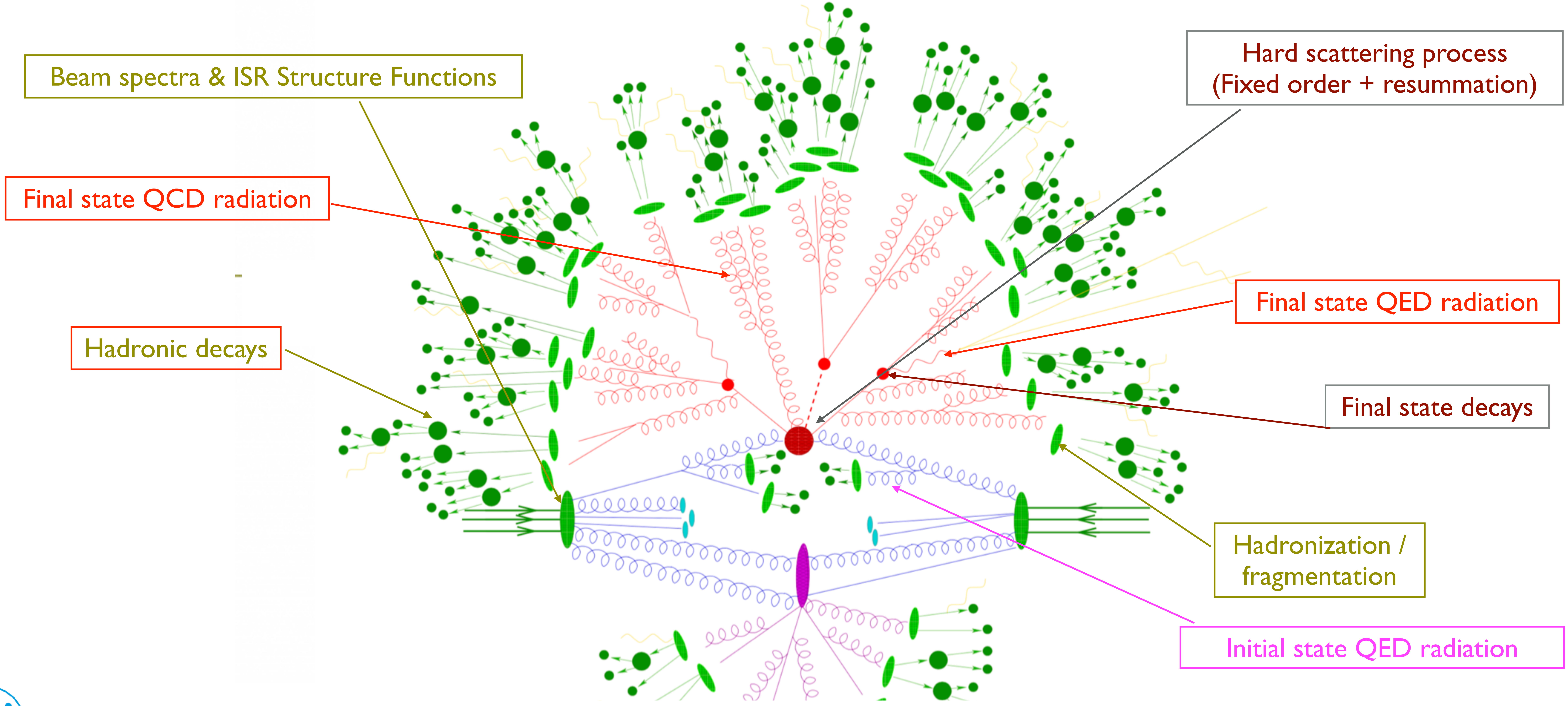

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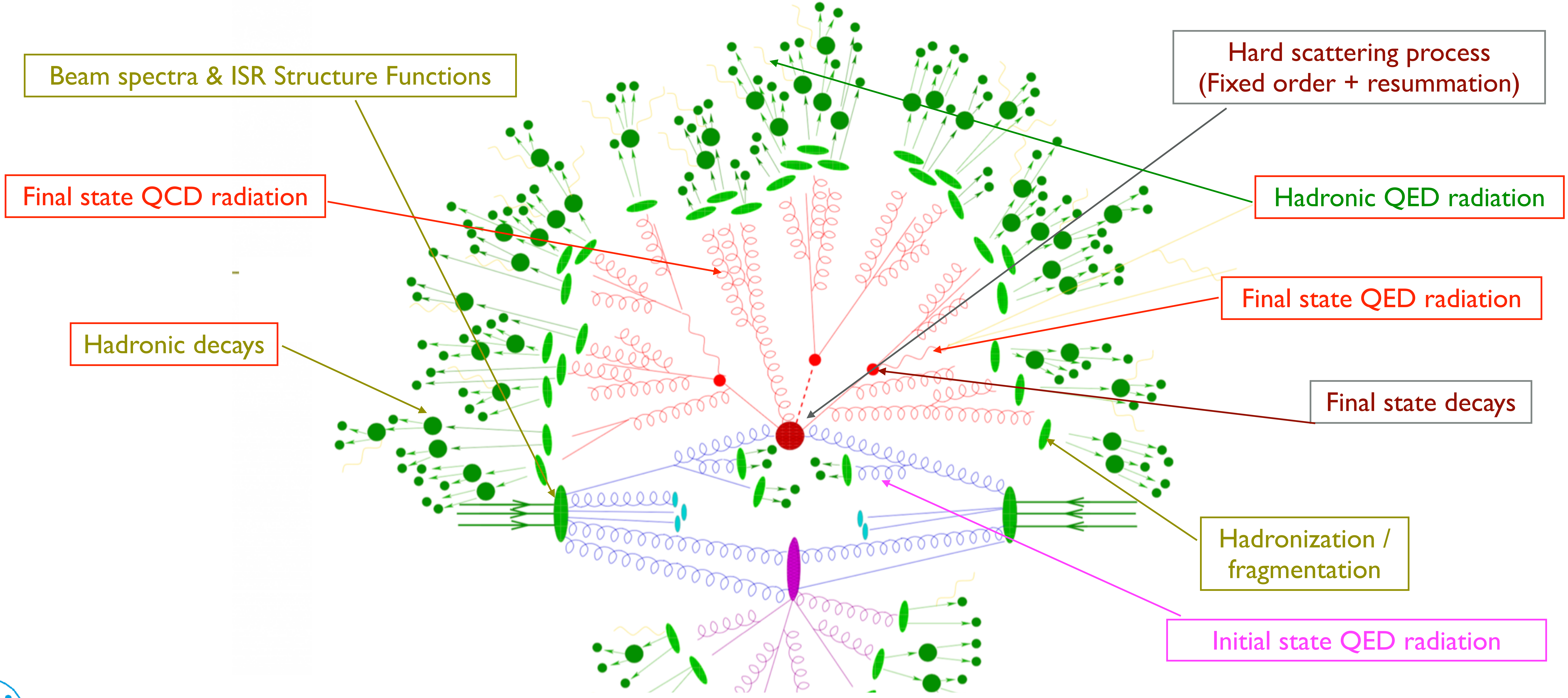

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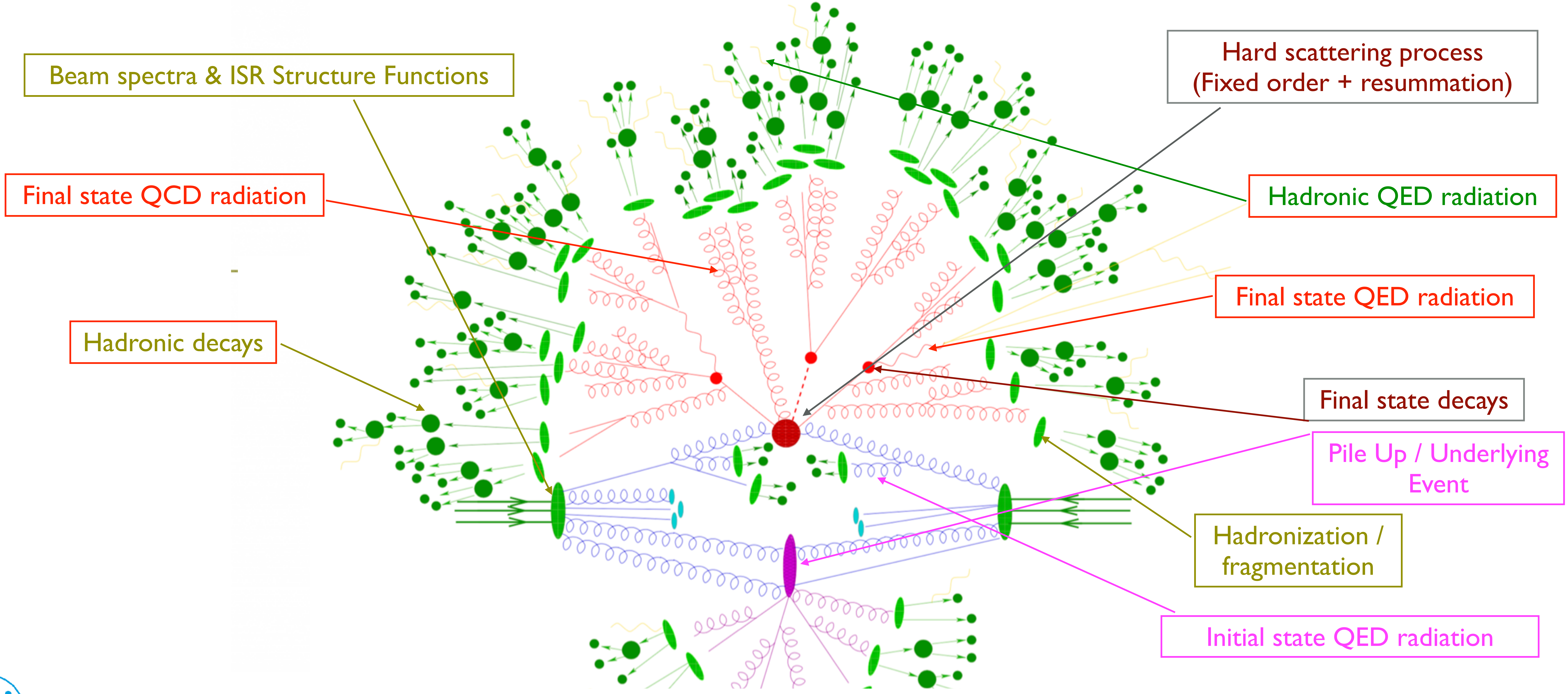

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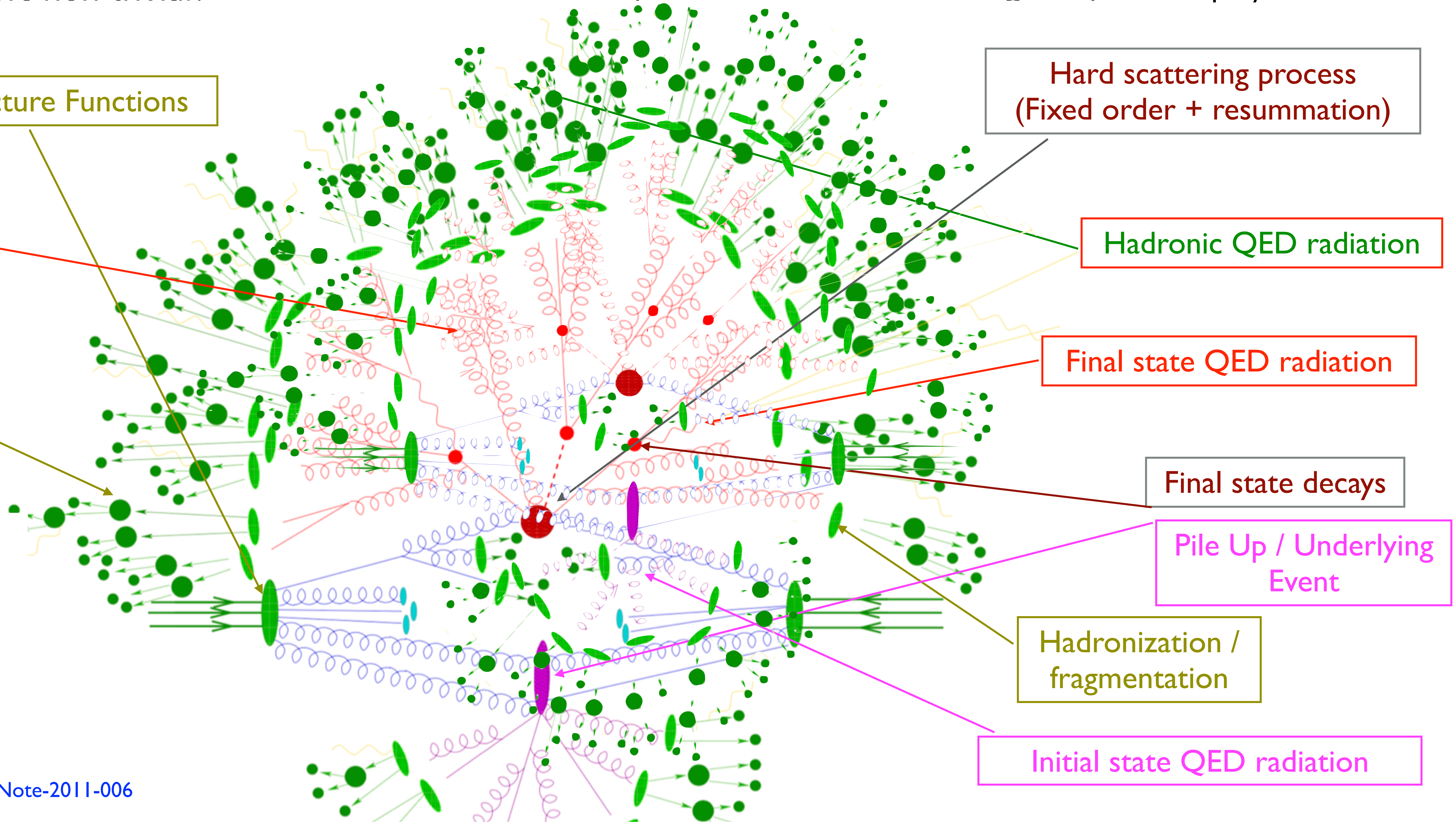
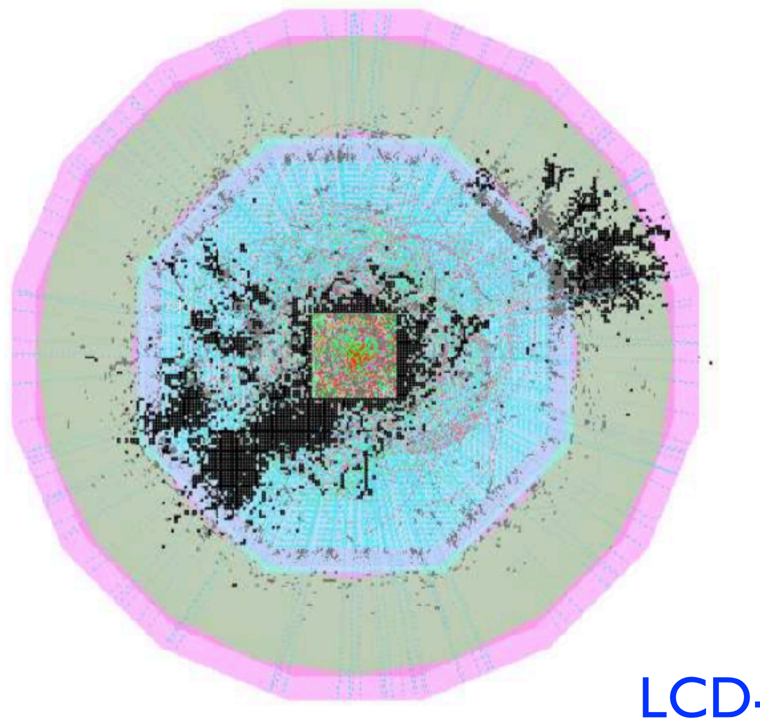




LCD-Note-2011-006

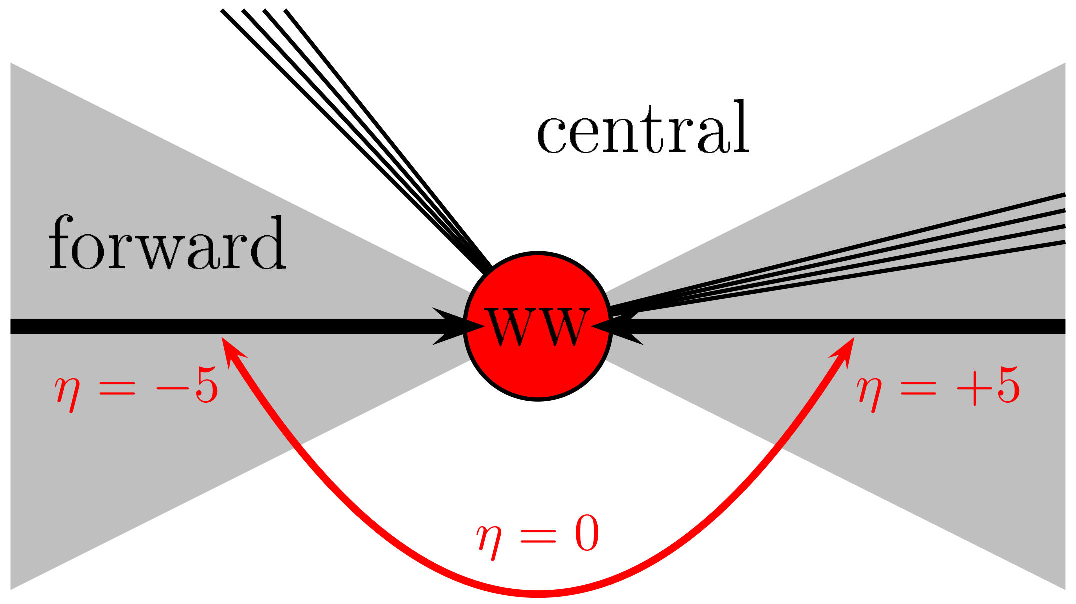
Why Monte Carlo integration/sampling?

Final State X	part.	$\dim(e^+e^- \to X)$
$\mu^+\mu^-$	2	4
jjj	3	7
$\ell^+\ell^- bb$	4	10
$\ell\ell bbj$	5	13
$\ell\nu\ell\nu bb$	6	16
$\ldots$	$\ldots$	$\ldots$
$\ell\nu\ell\nu bbjjjj$	10	28

$$\left(\prod_{i=1}^{n} \widetilde{dq_i}\right)(2\pi)^4\delta^4(p_1+p_2-\sum_{i=1}^{n} q_i) \equiv \left(\prod_{i=1}^{n}\frac{d^3 q_i}{(2\pi)^3 2q_i^0}\right)(2\pi)^4\delta^4(p_1+p_2-\sum_{i=1}^{n} q_i)$$

Dimensionality of phase space (PS) integration for *n* final state particles:
dim = 3·n – 4 (+ 2 beam parameters)

$$\sigma = \int \frac{|\mathcal{M}|^2\,\Theta(\text{cuts})}{F}\, d\Phi_n$$



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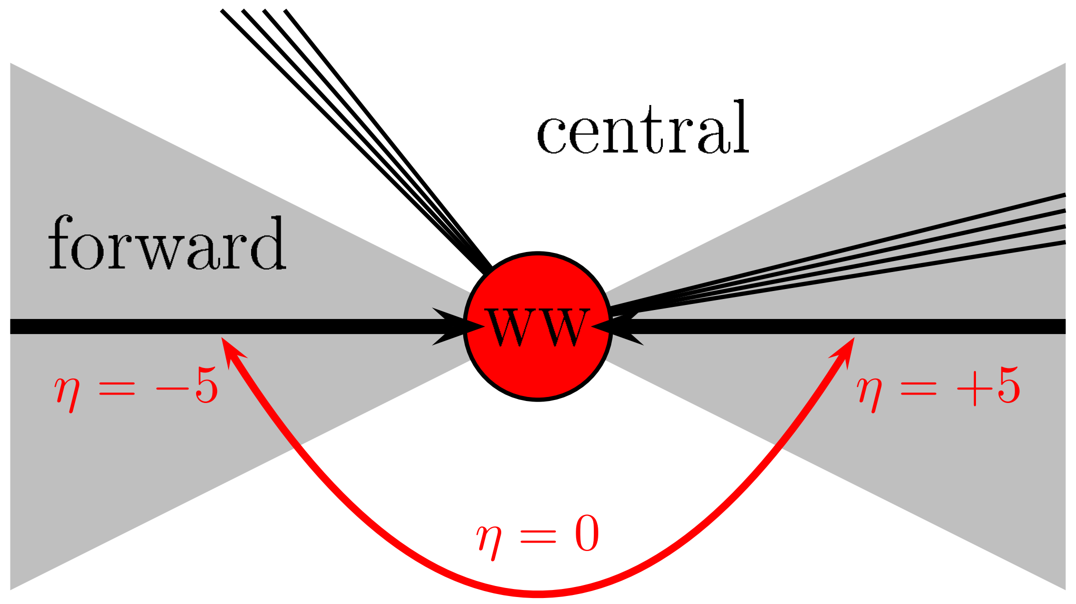

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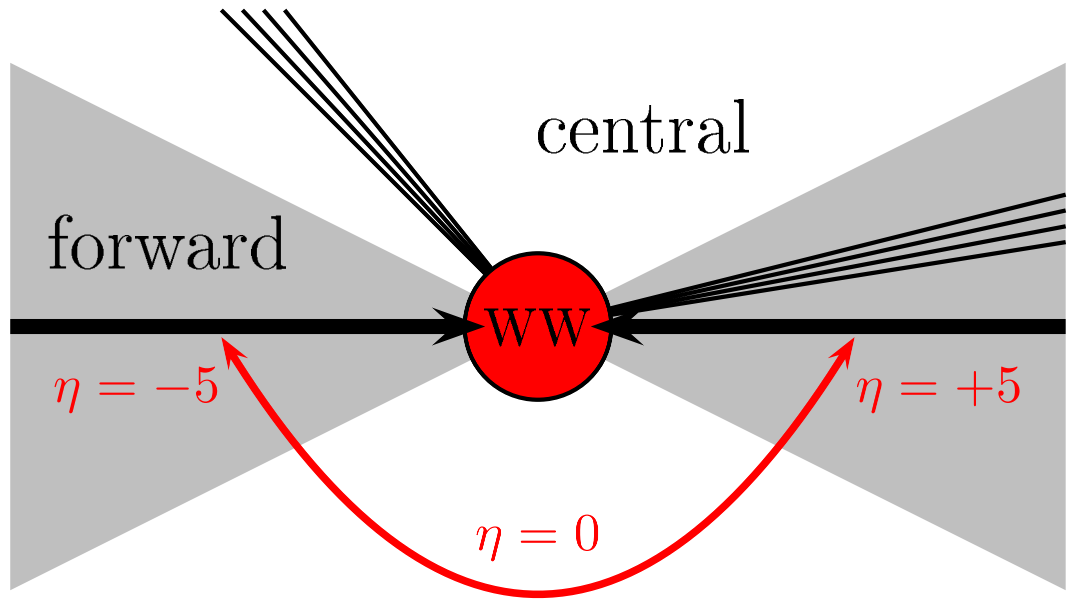

- Generate weighted events, *i.e.* pairs $(\vec{x}_i, w_i)$
- Unweighted events: event generation with same probability as
- nature [accept events with probability $P_i = w_i / w_{max}$]
- Suitably choose maximal weight w_{max}
- Avoid wildly fluctuating weights $\Longrightarrow$ clever choice of mappings

Importance Sampling — Mapping phase space channels

Reduce crude MC error by **importance sampling**: divide out singular structures of function(s)

$$I = \int f dV = \int \frac{f}{g} \, g \, dV = \left\langle \frac{f}{g} \right\rangle \pm \frac{1}{\sqrt{N}} \sqrt{\left\langle \left(\frac{f}{g} \right)^2 \right\rangle - \left\langle \frac{f}{g} \right\rangle^2}$$

Sampling flat in $\int g \, dV$

Need to know inverse and Jacobian

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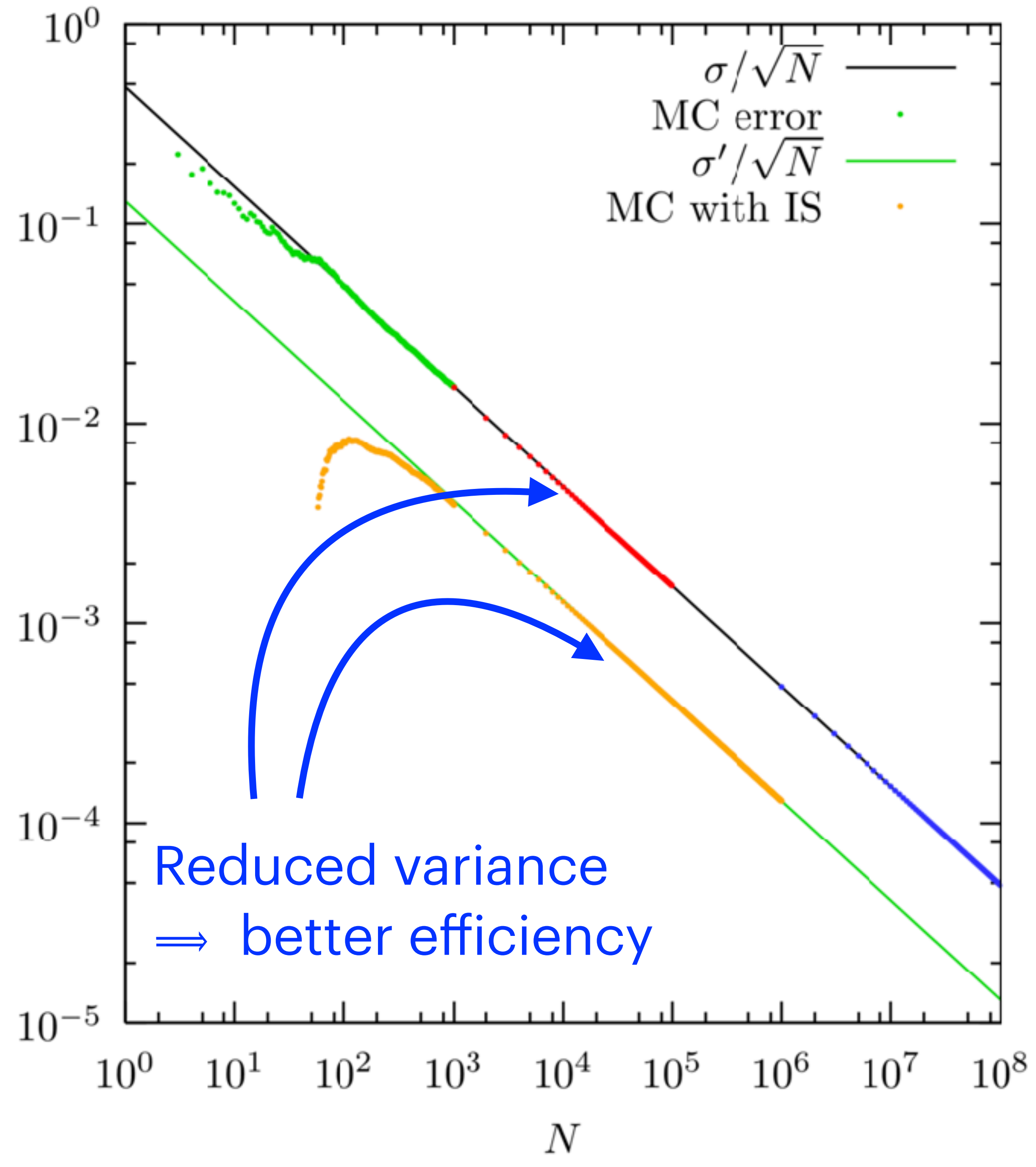

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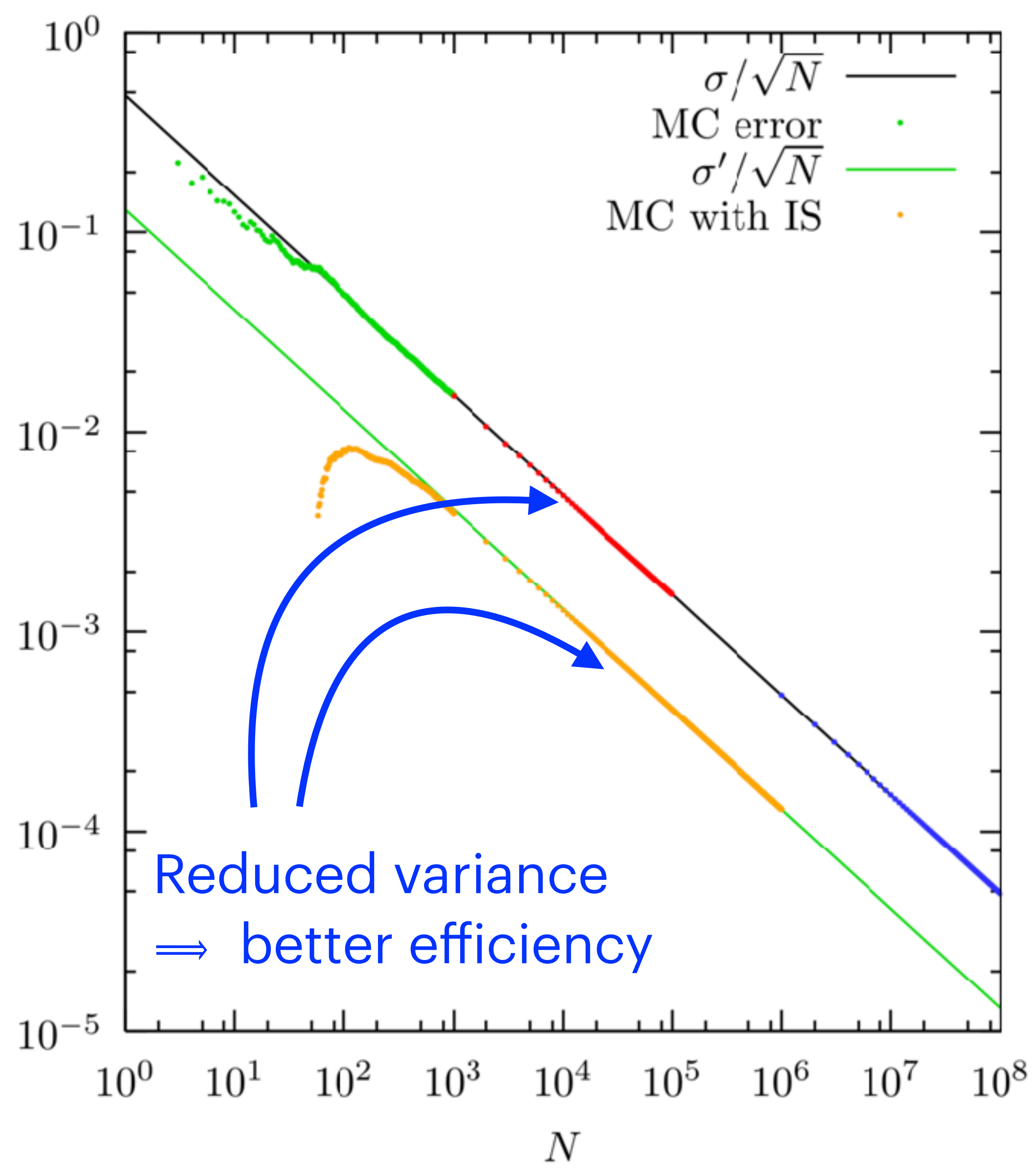

Typical application in particle physics: Breit-Wigner resonance of unstable particles:

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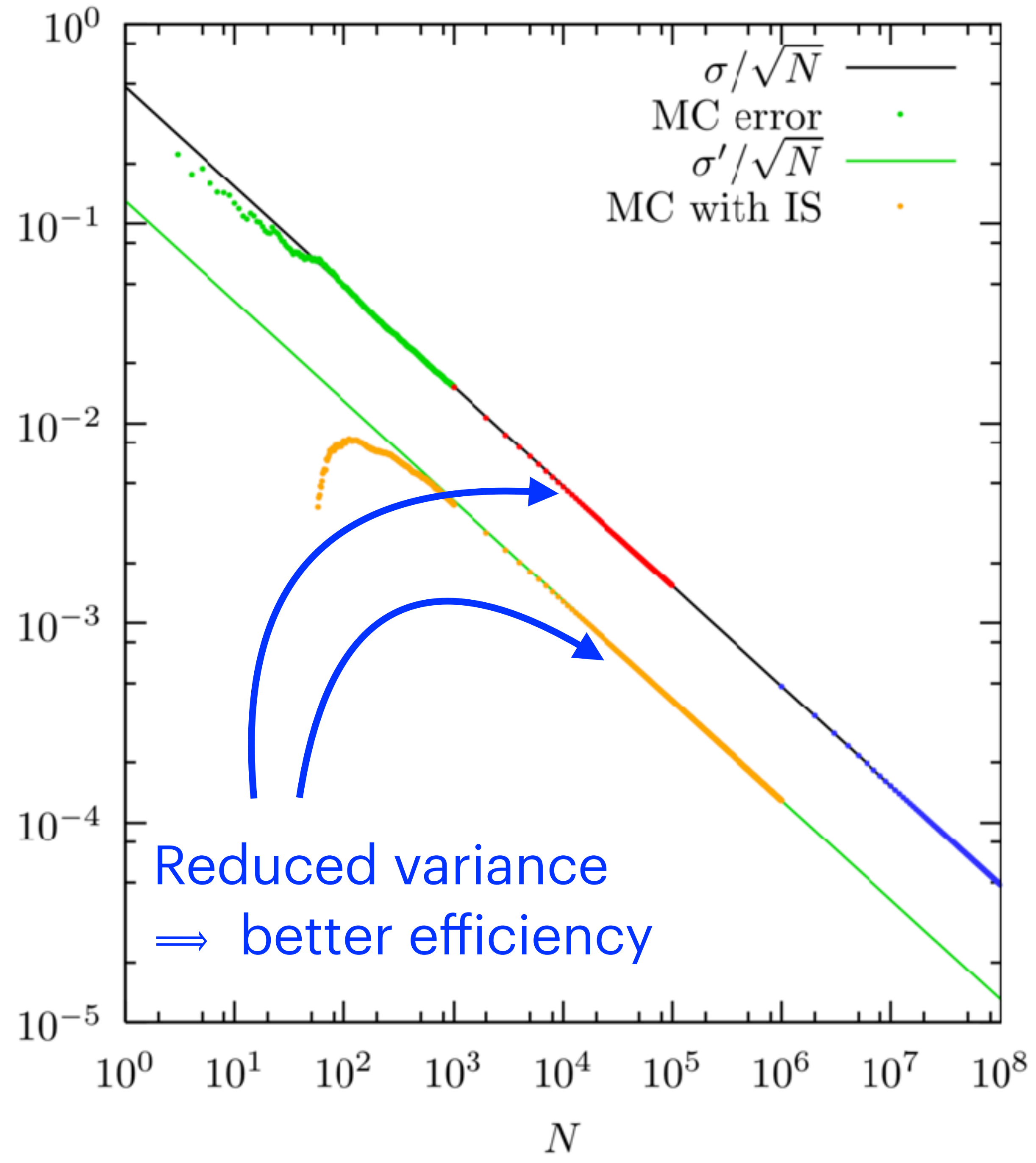

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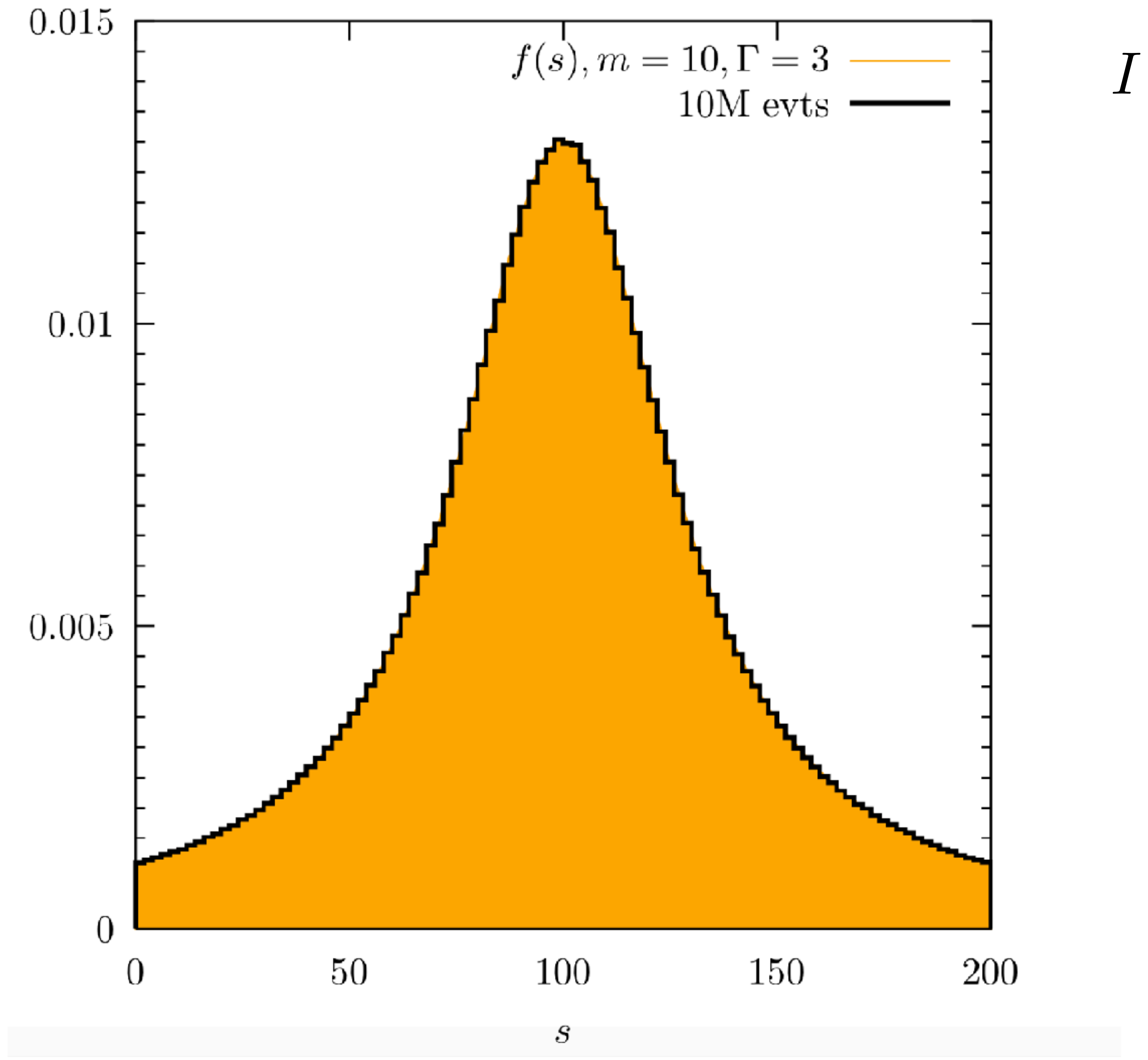

$$I = \int_{s_0}^{s_1} \frac{ds}{(s - m^2)^2 + m^2 \Gamma^2} \qquad F(s) = \arctan \frac{s - m^2}{m\Gamma} =: \xi$$

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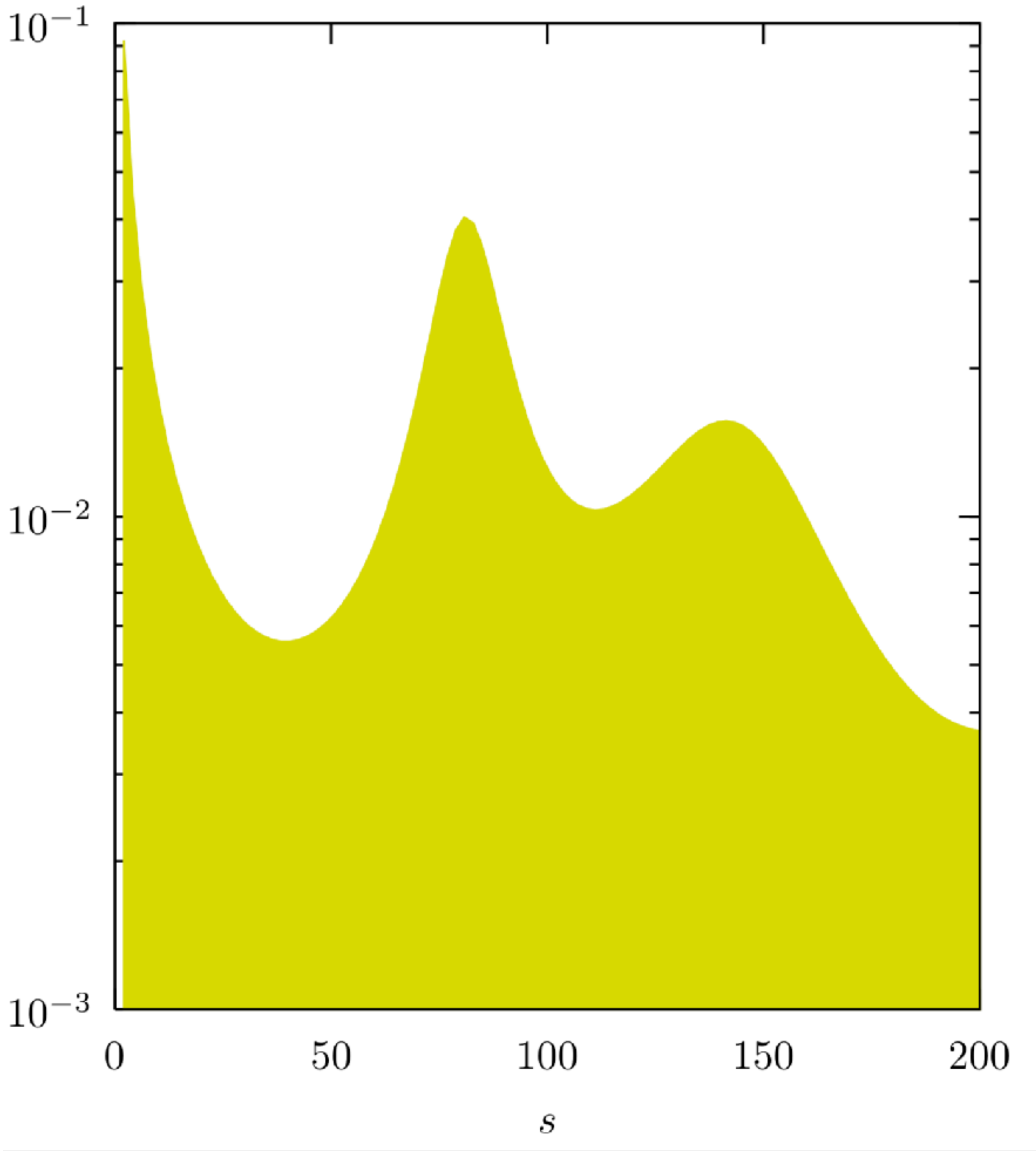

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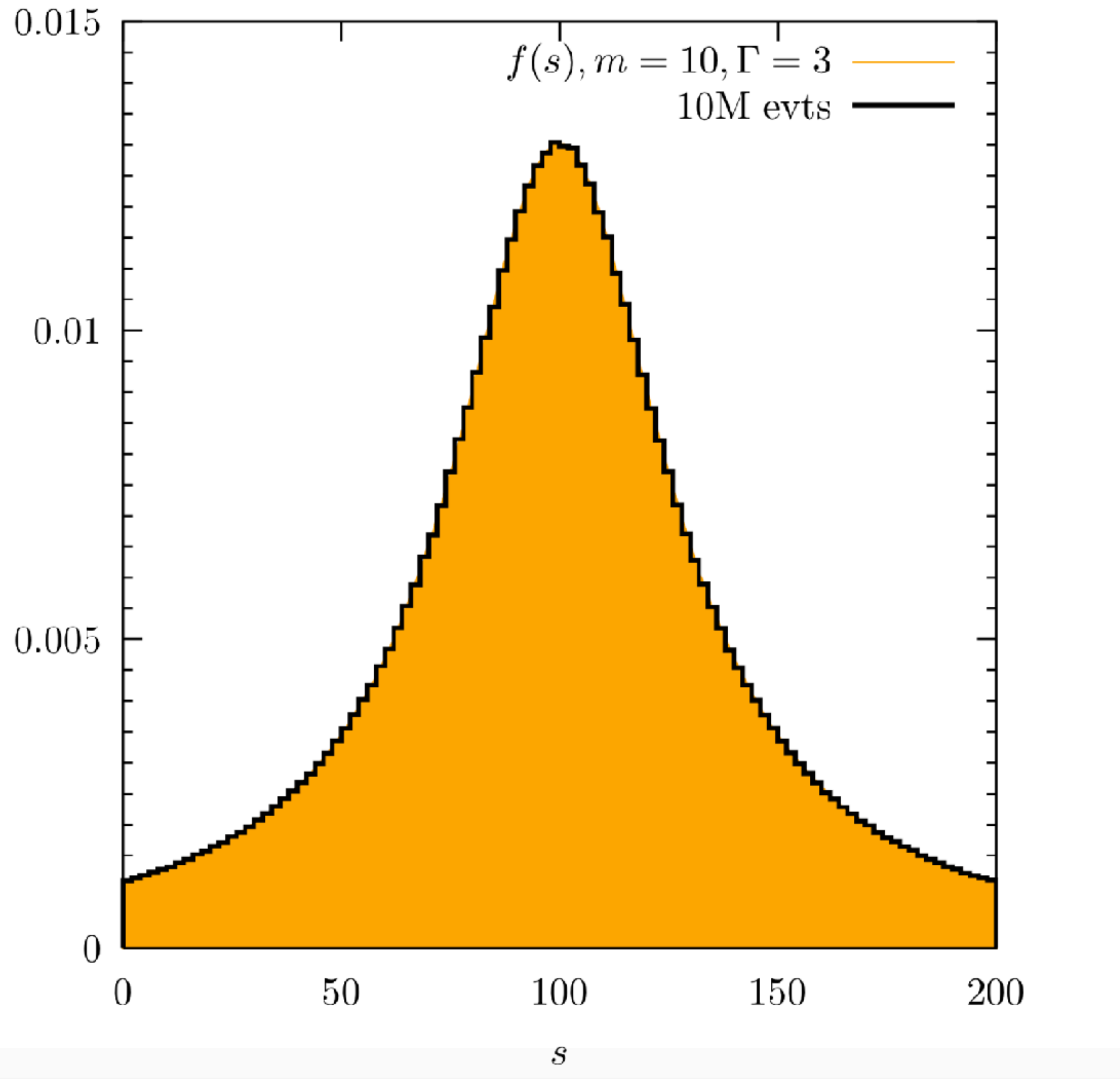

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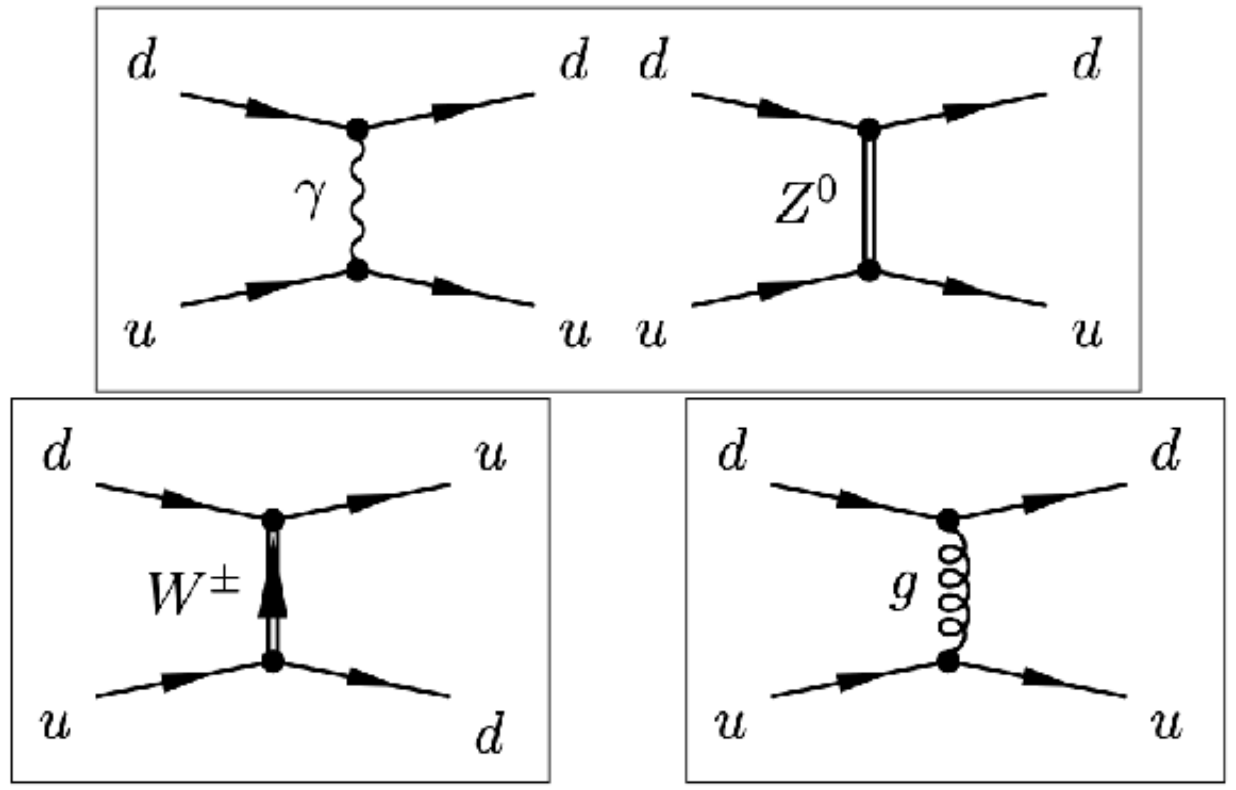
Multi-particle Matrix element:
Peak structure from multiple resonances



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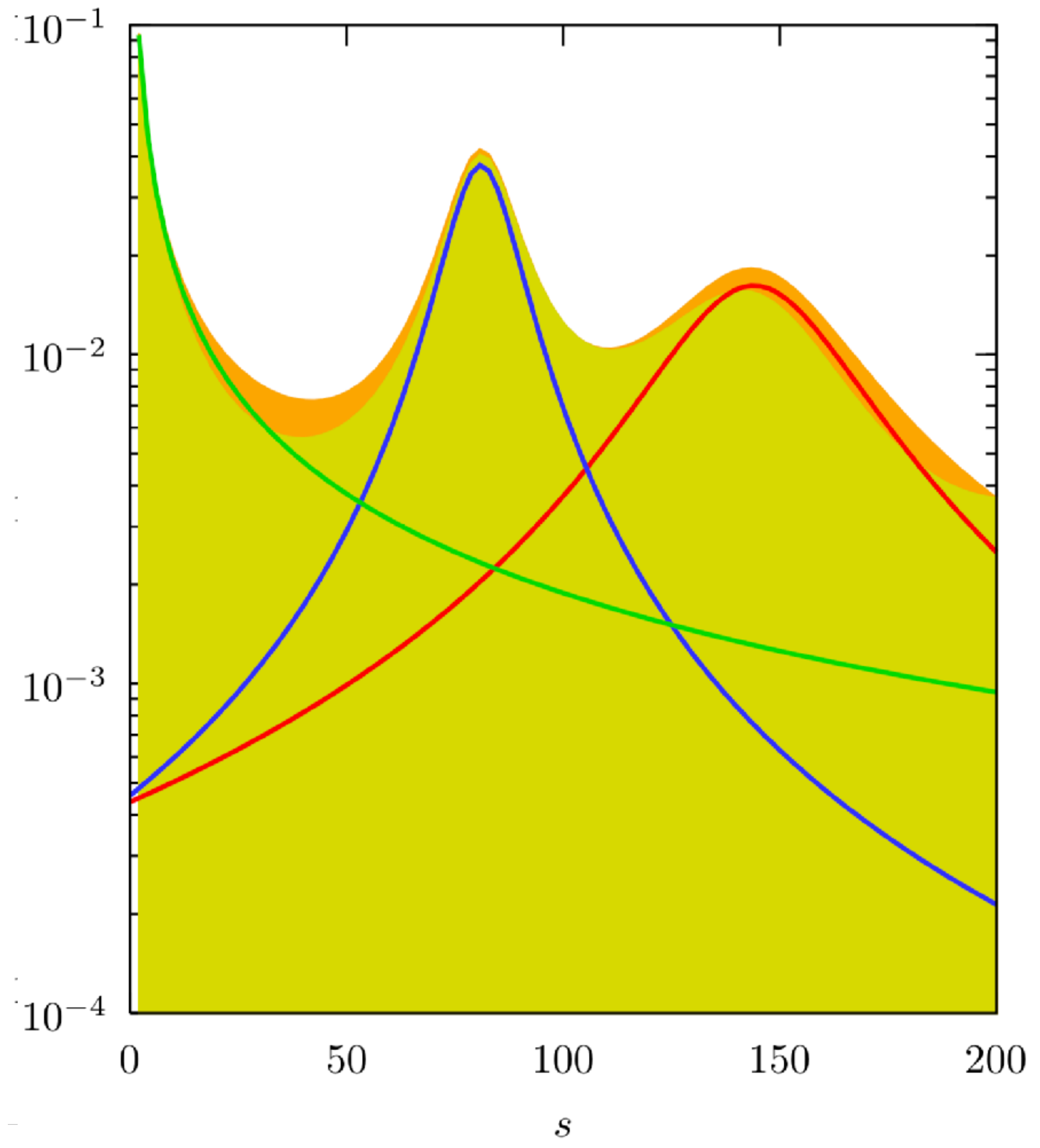

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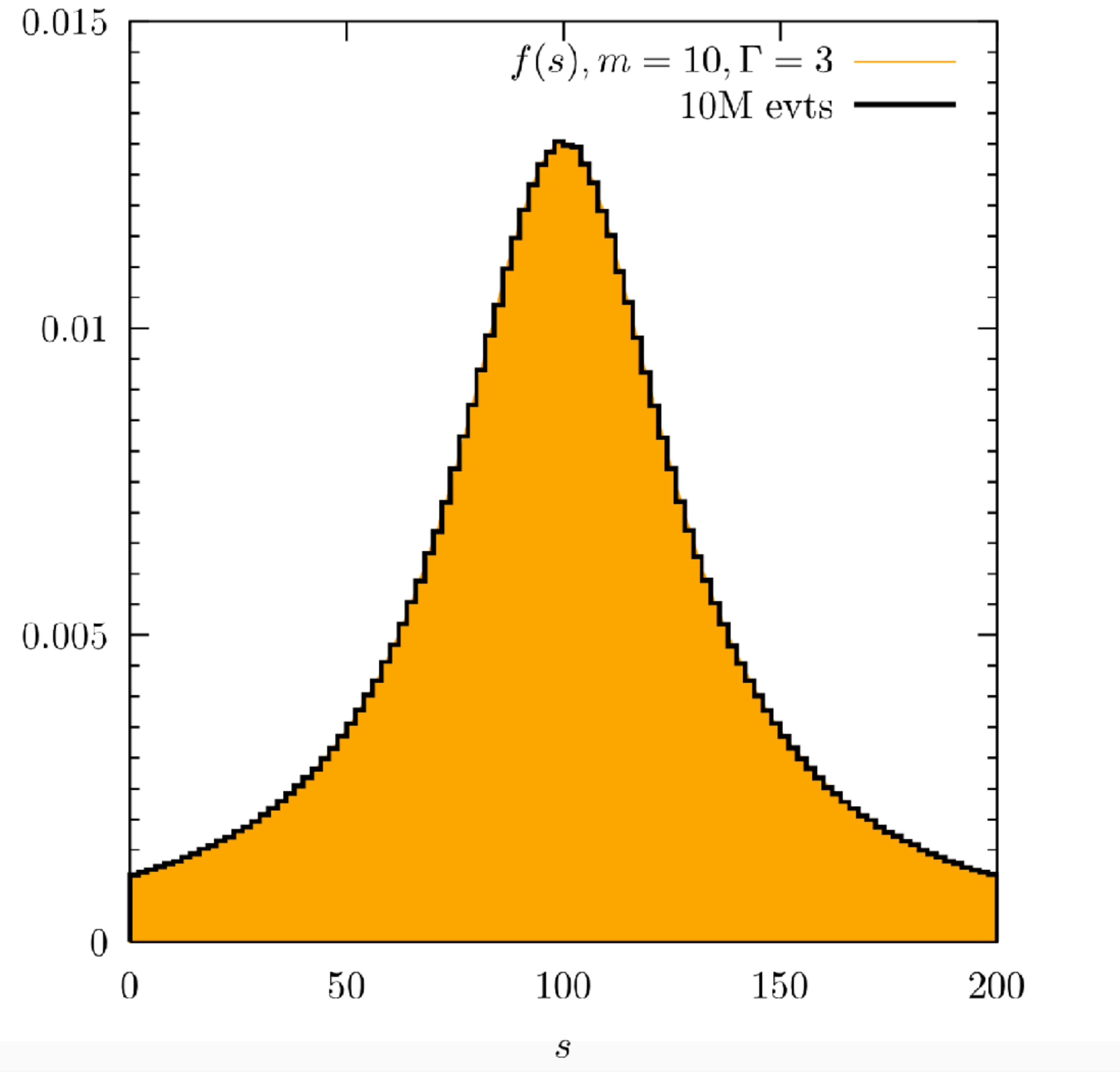

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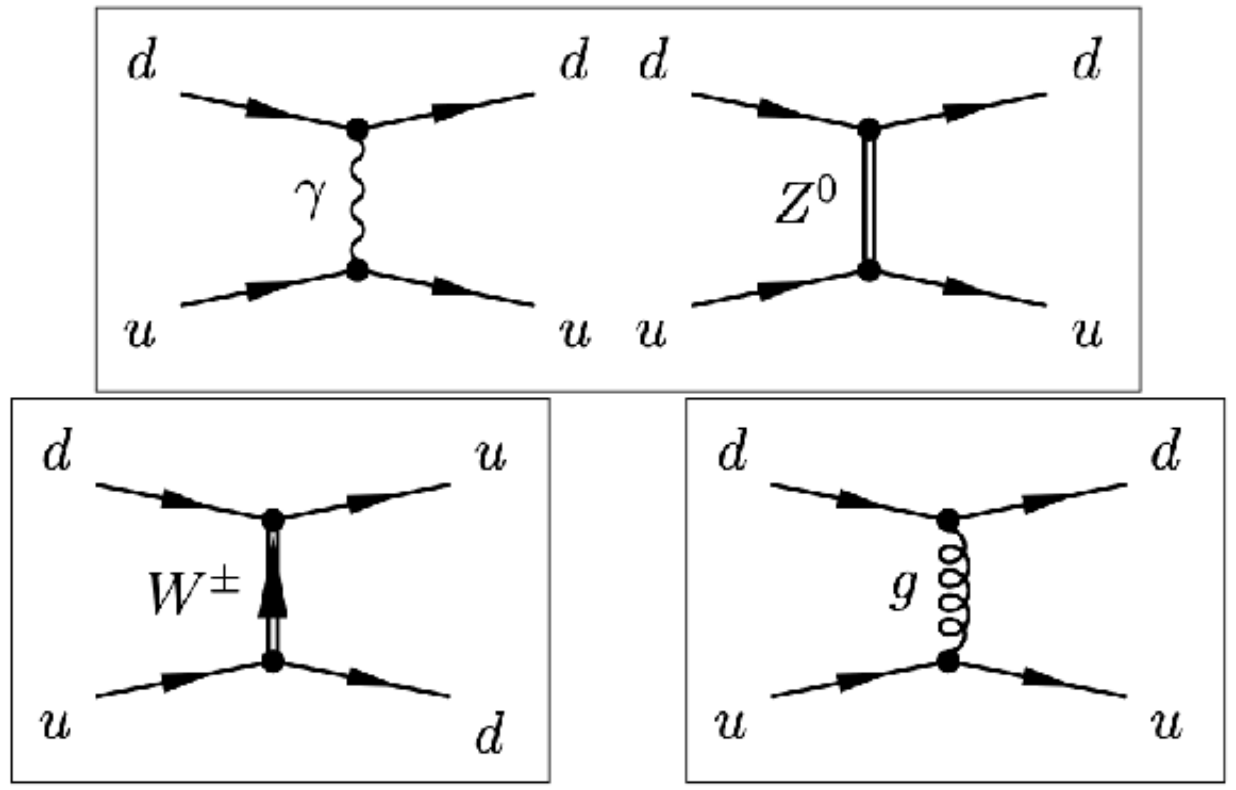


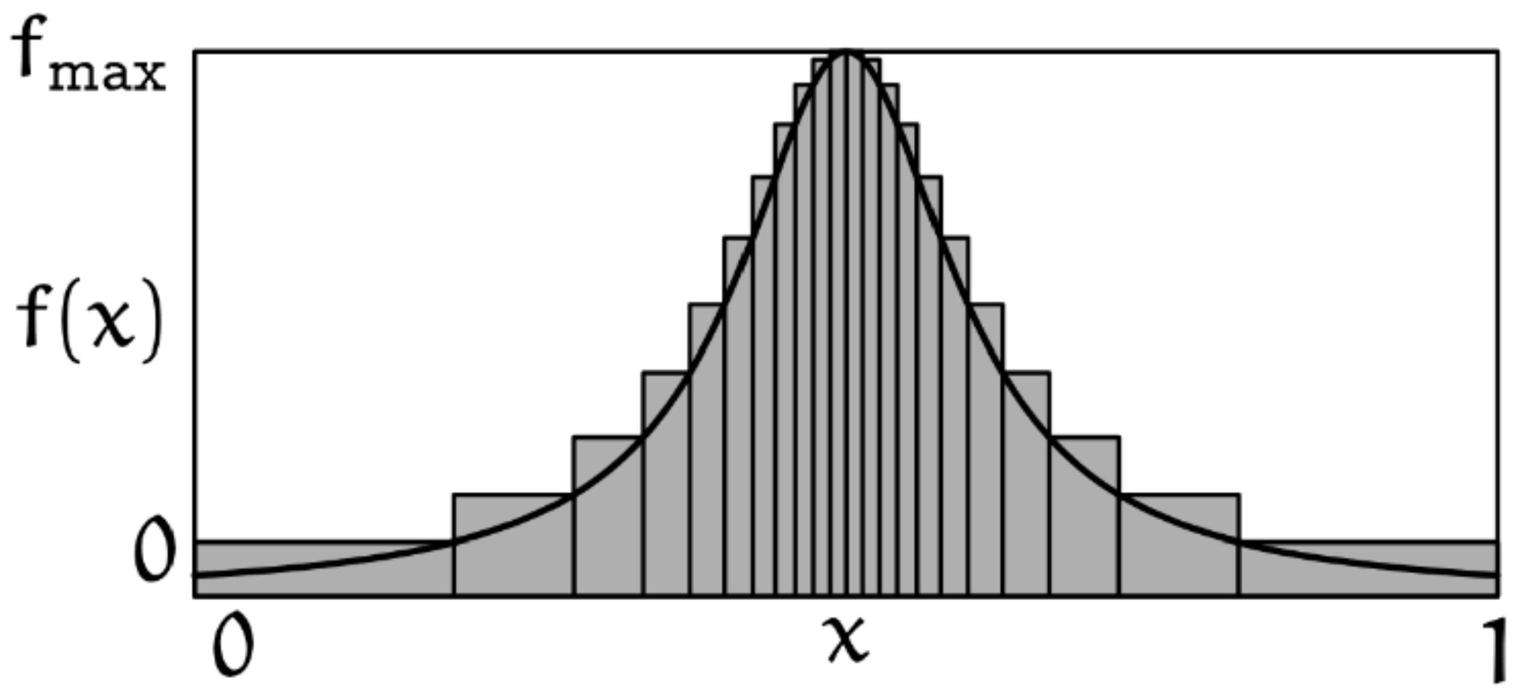
$$\int_{s_0}^{s_1} f(s) ds = \int_{s_0}^{s_1} \frac{f(s)}{g(s)} g(s) ds$$
$$= \sum_i \alpha_i \int_{s_0}^{s_1} \frac{f(s)}{g(s)} g_i(s) ds$$

Multi-Channel MC integration:
Every resonance peak corresponds to a MC integration channel

Adaptive Multi-Channel Integration

- Finding appropriate functions for importance sampling is … non-trivial
- Just use binned step function and minimize the differences to true function

- 1-dim. binned distributions work very well:
- This is adaptive MC integration



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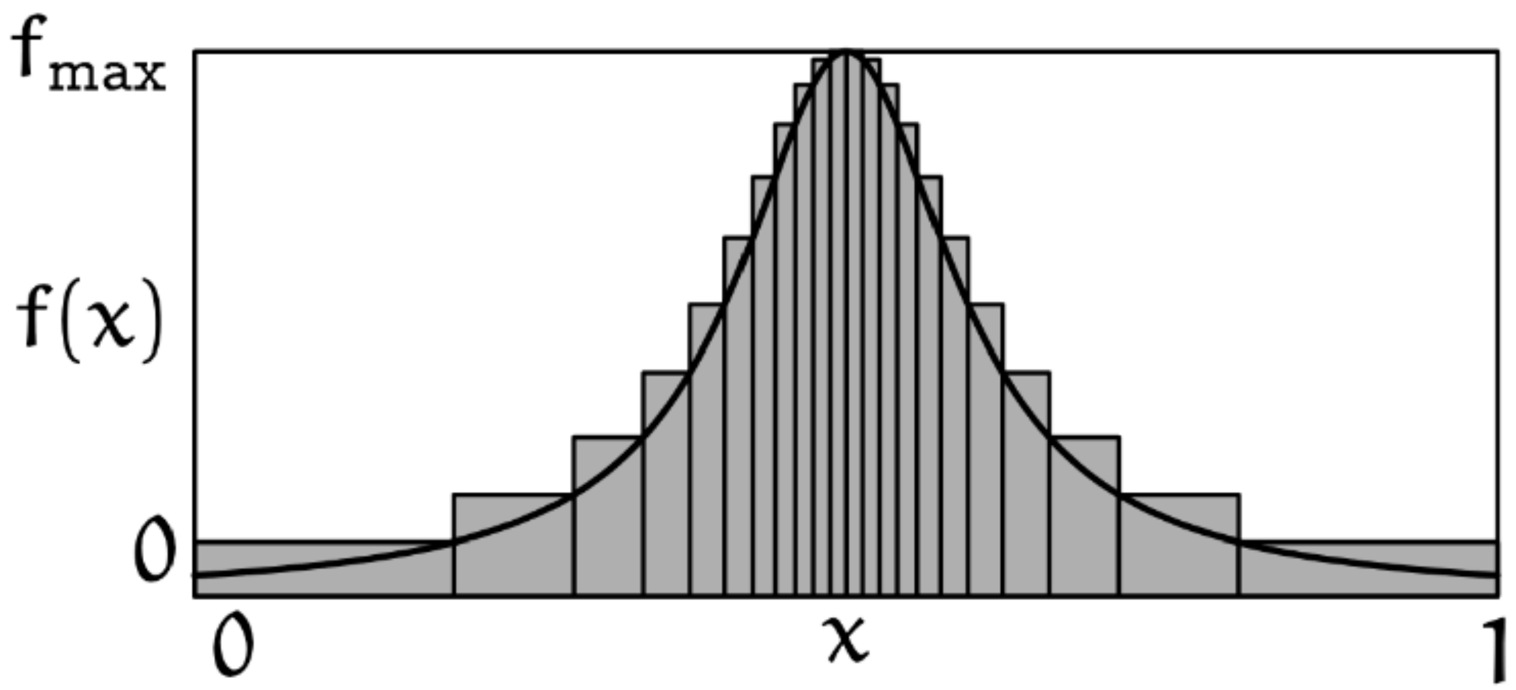

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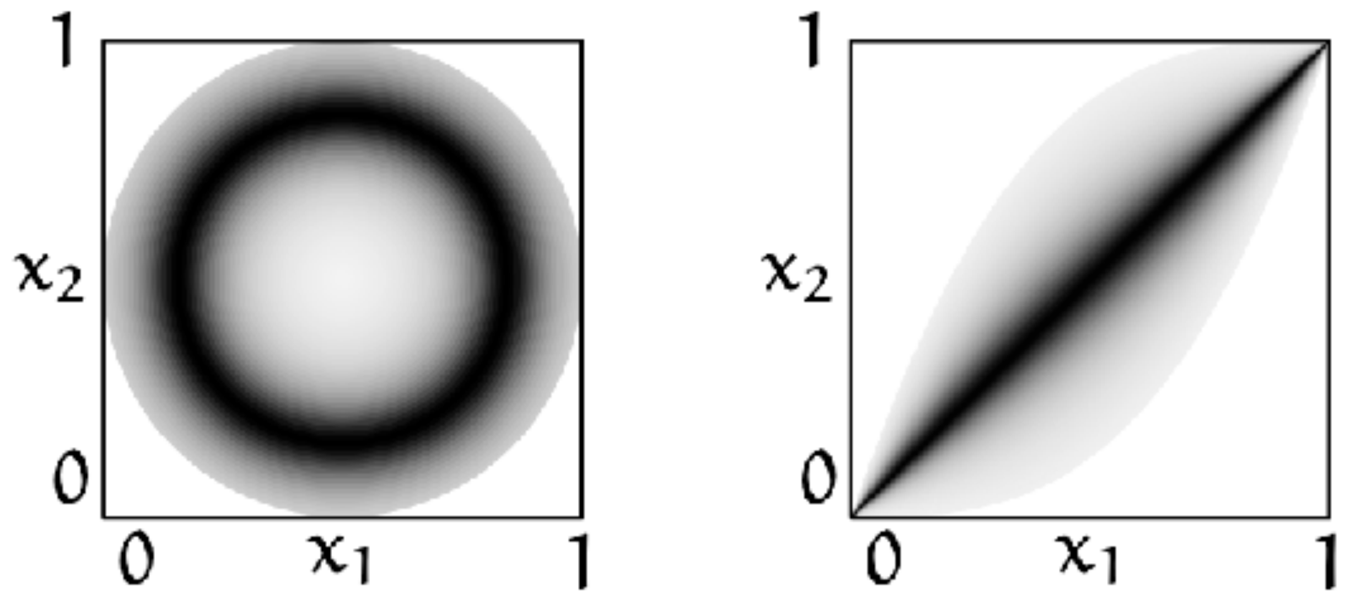
$$g(x) = g(x_1)g(x_2)\dots g(x_n)$$

- Factorize singularities from resonances
- VEGAS algorithm [Lepage, 1978]
- Works for factorizable singularities



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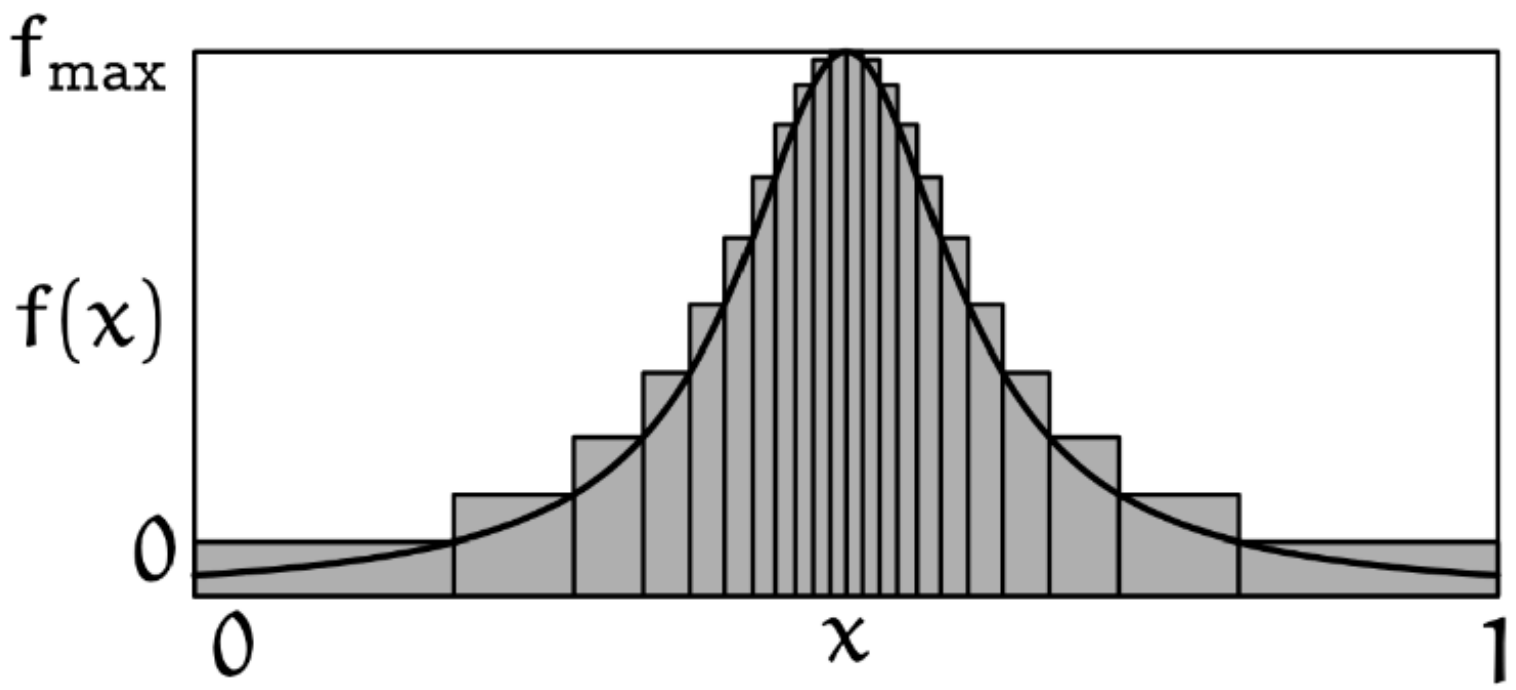

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$$\int_{s_0}^{s_1} f(s)ds = \sum_i \alpha_i \int_{s_0}^{s_1} \frac{f(s)}{g(s)} g_i(s)ds$$

adapt weights α_i of different channels i

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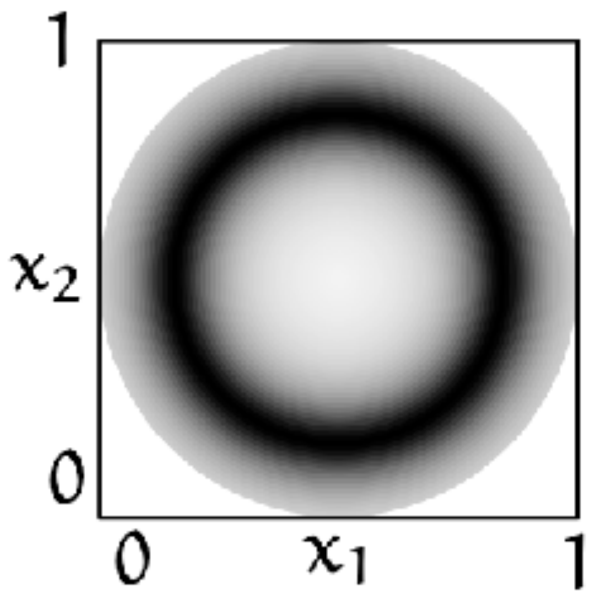
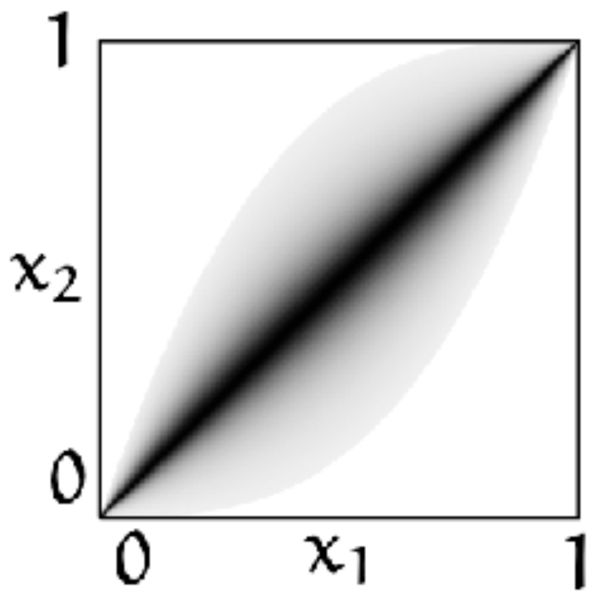
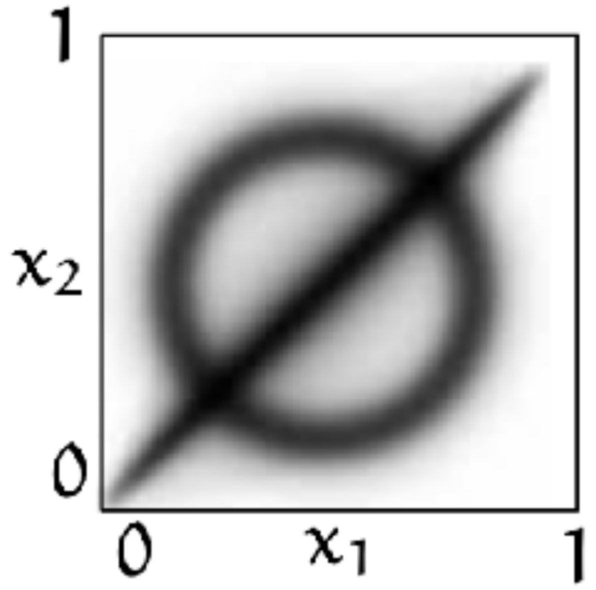
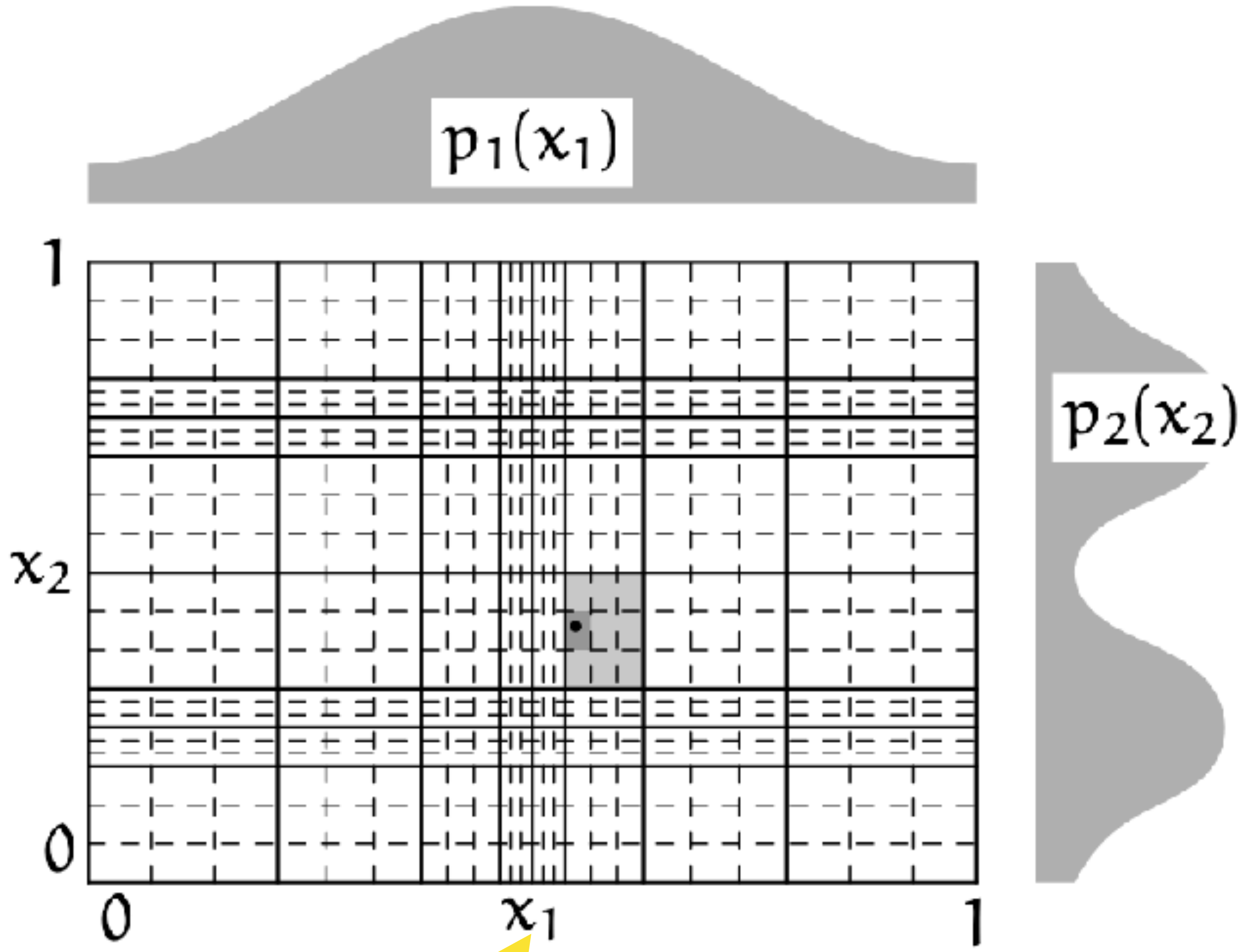




Non-factorizable singularity:



Multi-channel adaptive MC integration:



VAMP algorithm [Ohl, 1996]

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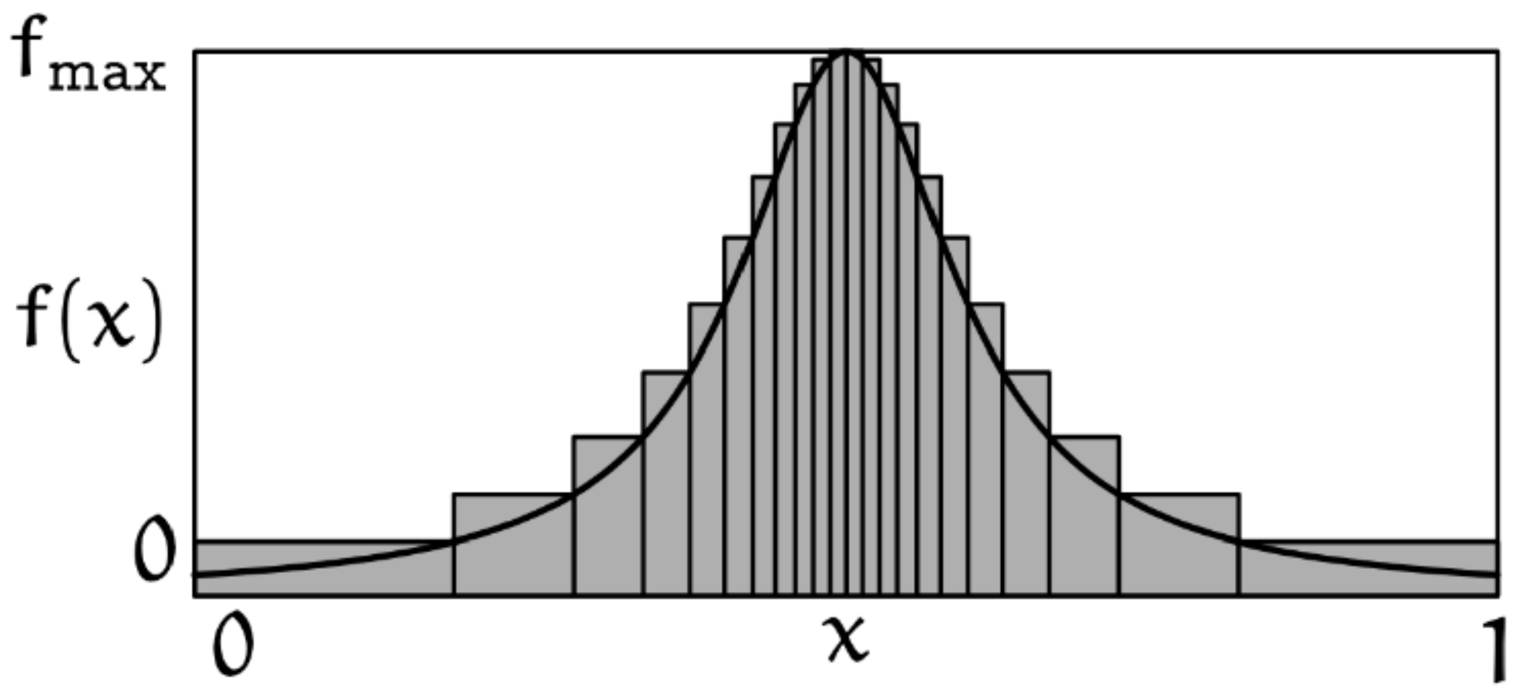

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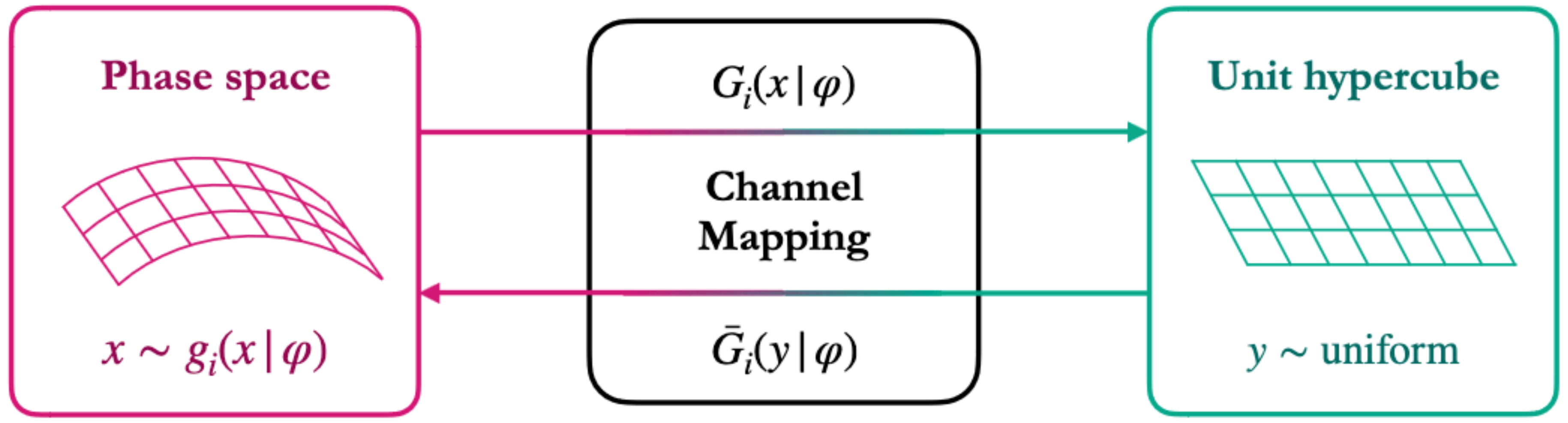
Different algorithms of phase-space construction / mappings

- flat [RAMBO]
- simplistic heuristics [ALPGEN],
- diagram-based [MadEvent],
- [QCD-]radiation driven [SAGE, Comix/Sherpa],
- resonance/singularity importance-ordered [WHIZARD]

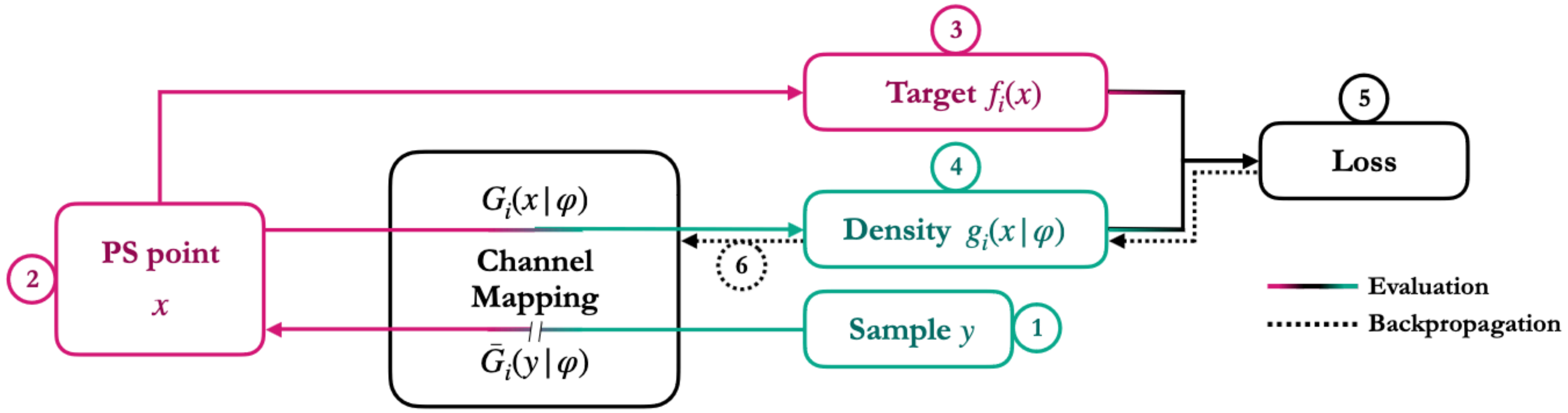
Machine Learning: MC for integration and simulation

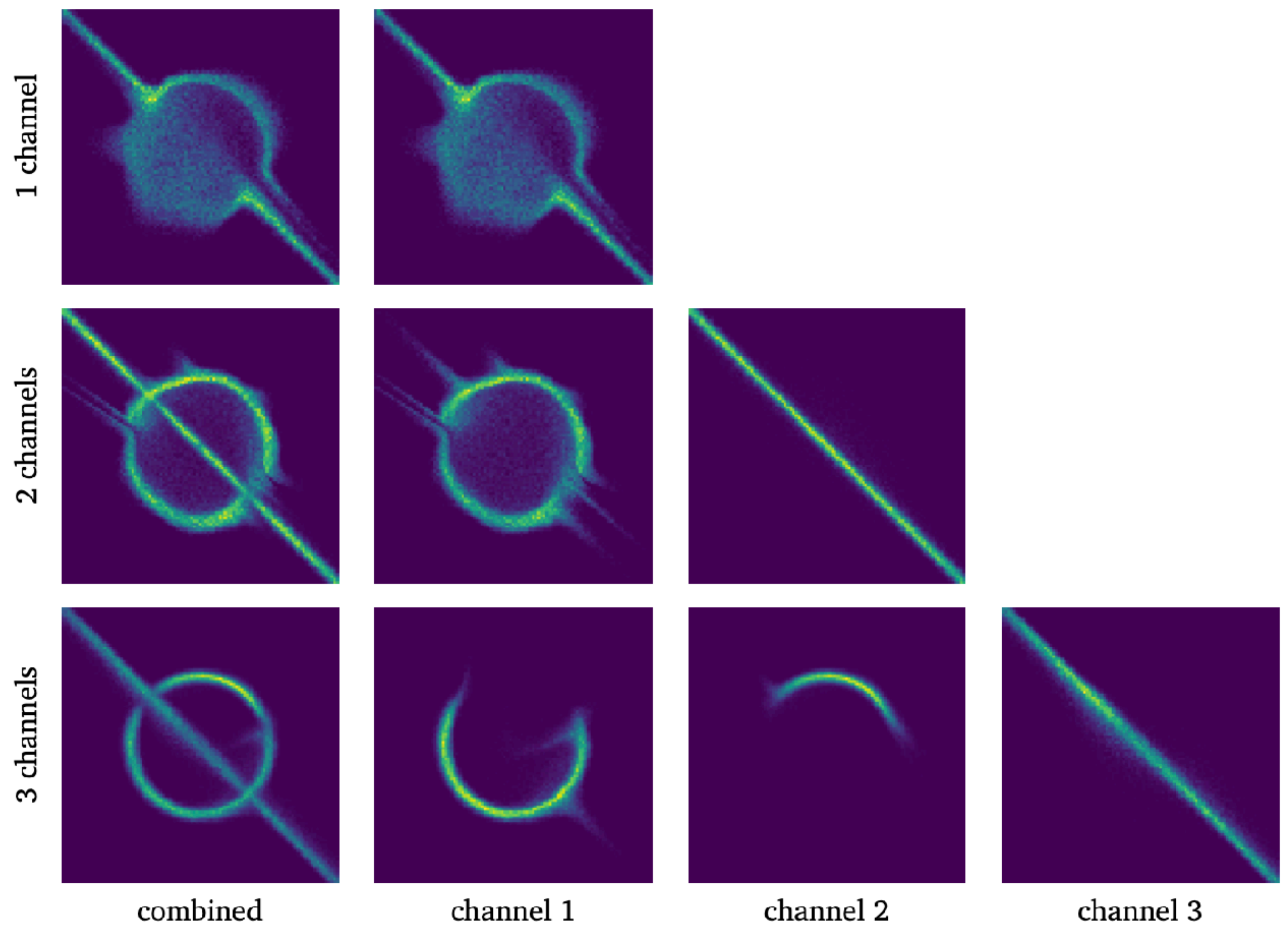
- Phase space integration / adaptation by Invertible Neural Networks (INNs) / normalizing flows
- Define divergence-based loss function
- Use of buffered losses and training
- Also still potential for improvement on "classical" VEGAS/VAMP algorithm

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

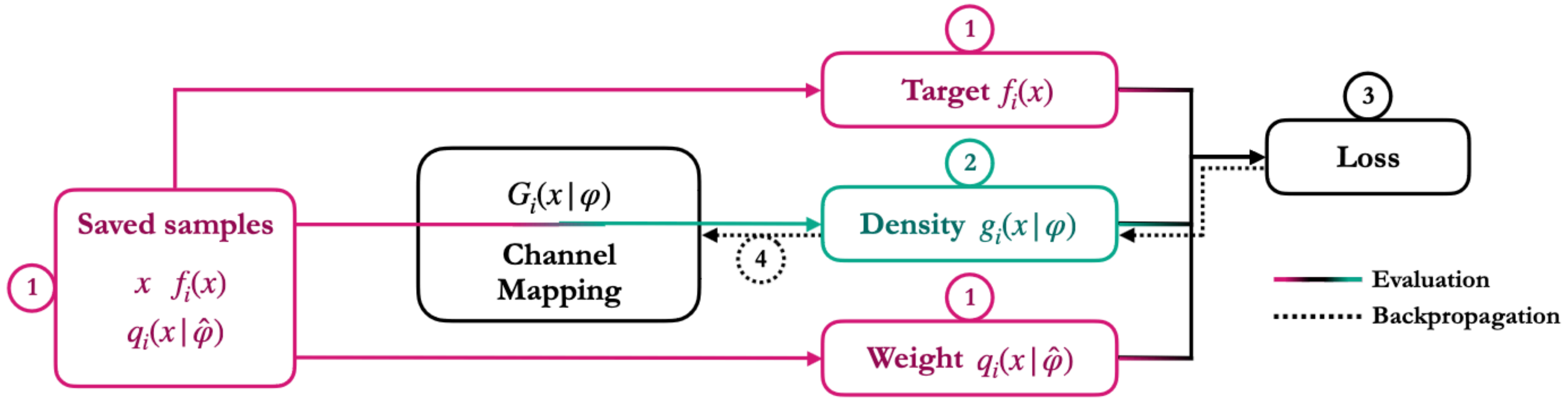


Online training:





Buffered training:



Parallel MC integration: MPI and GPUs

Preliminary: Matrix element evaluation

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

- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication (Load balancer / non-blocking communication)
- Speedups 10 to 30, saturation at O(100) [also parallel event generation]
- Integration of ($2 \to 8$) leading order (LO) processes: $\mathcal{O}$ (week) $\longrightarrow$ $\mathcal{O}$(hour)
- Becomes a must for higher-order perturbative processes (NLO, NNLO)

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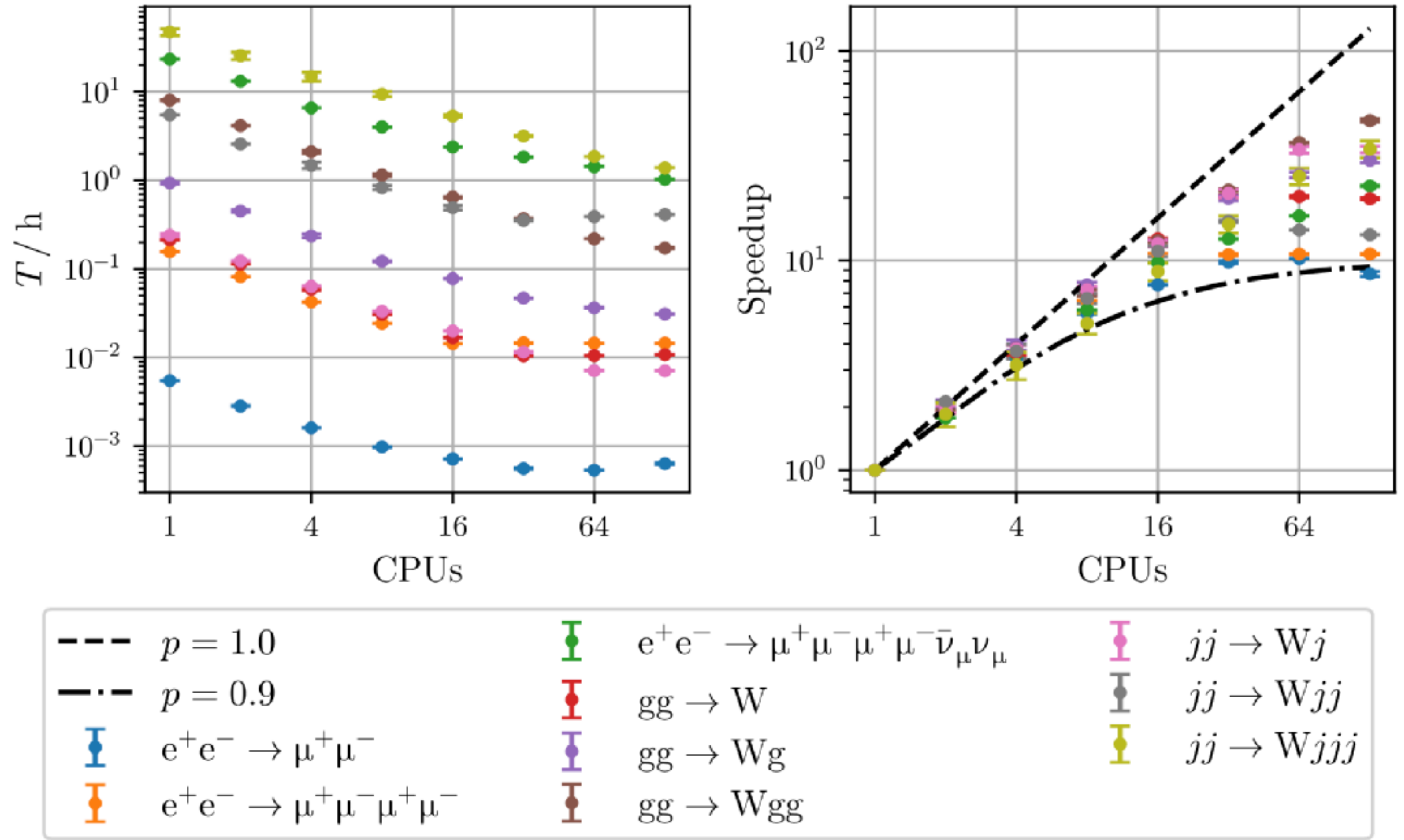

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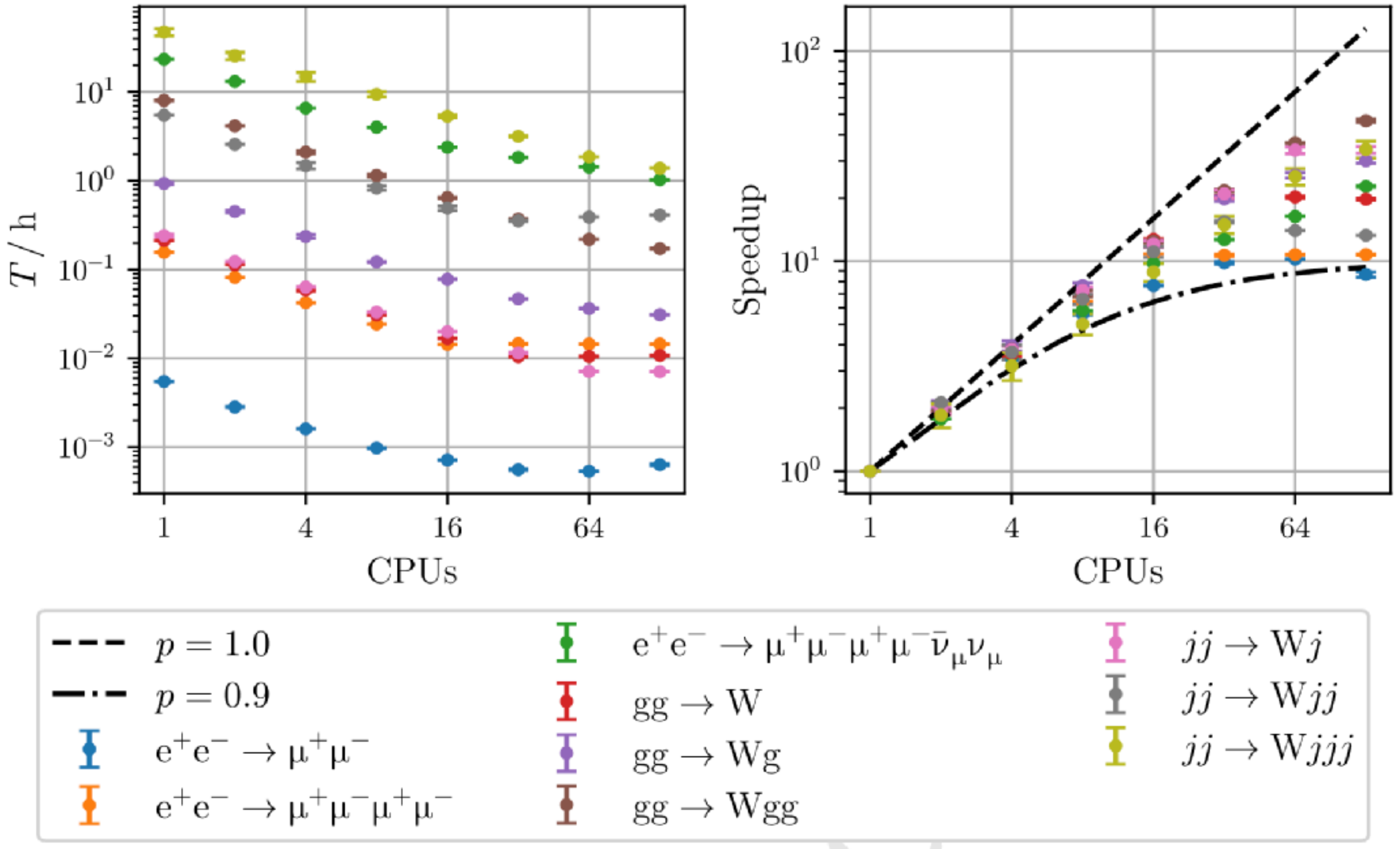
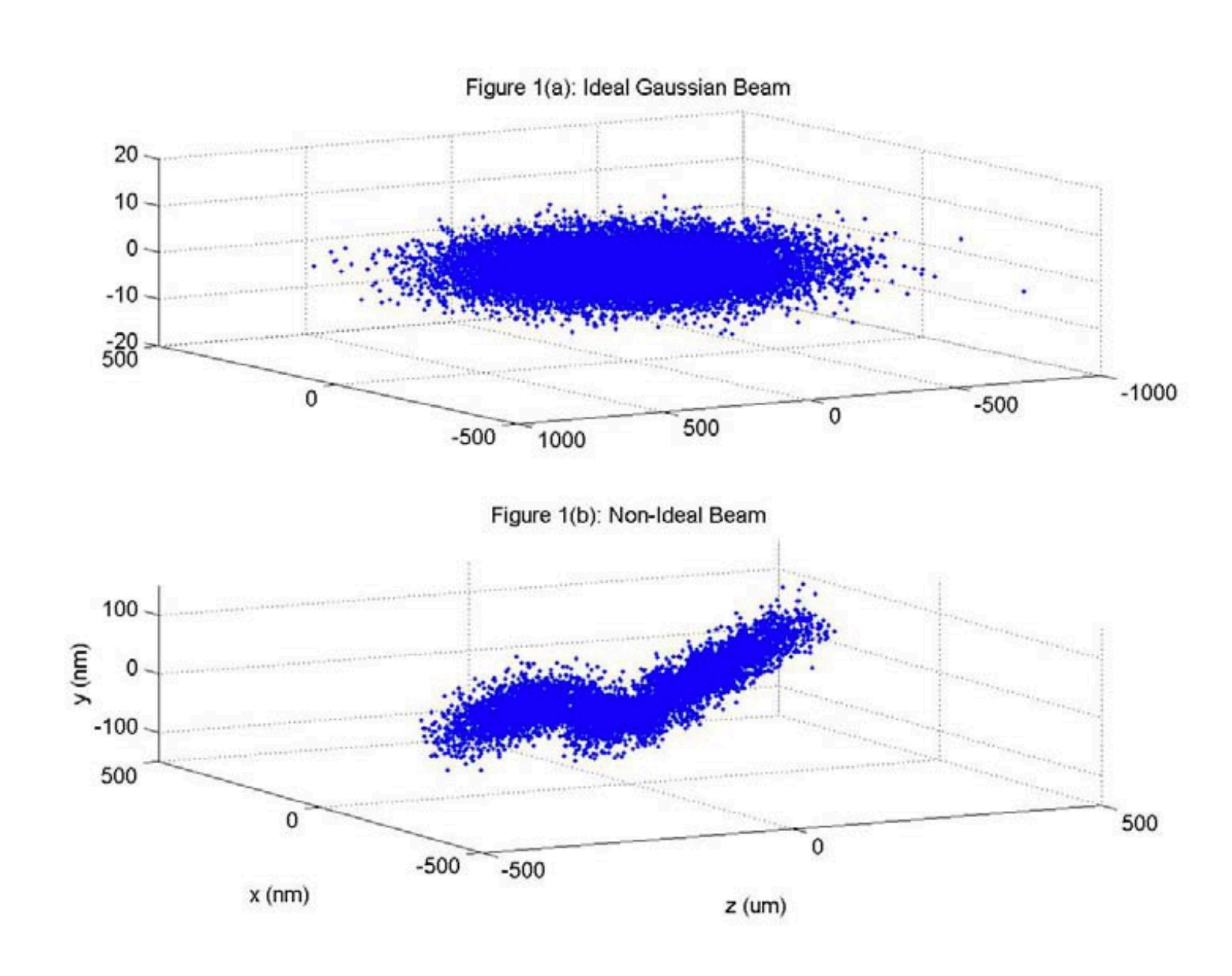
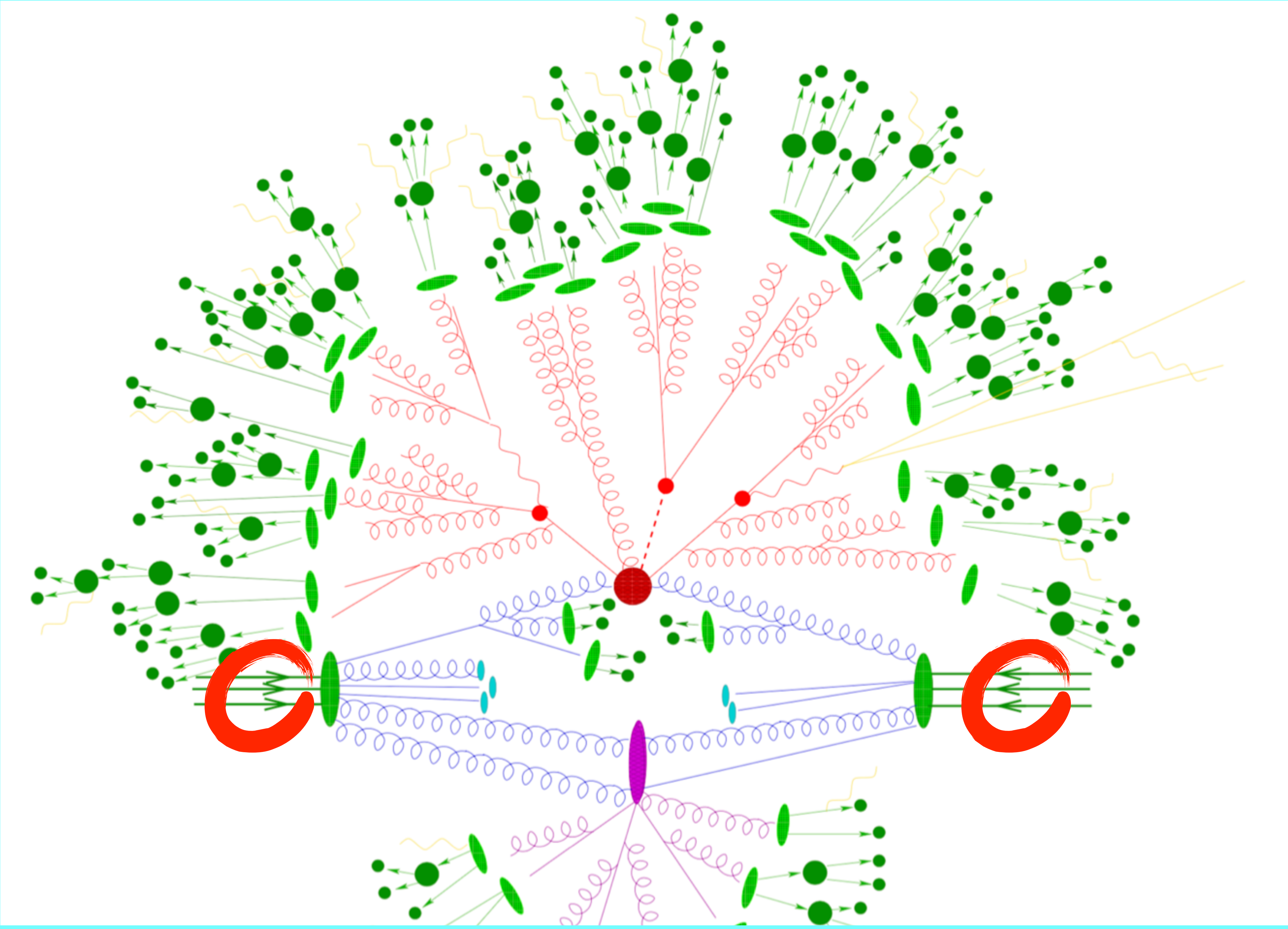


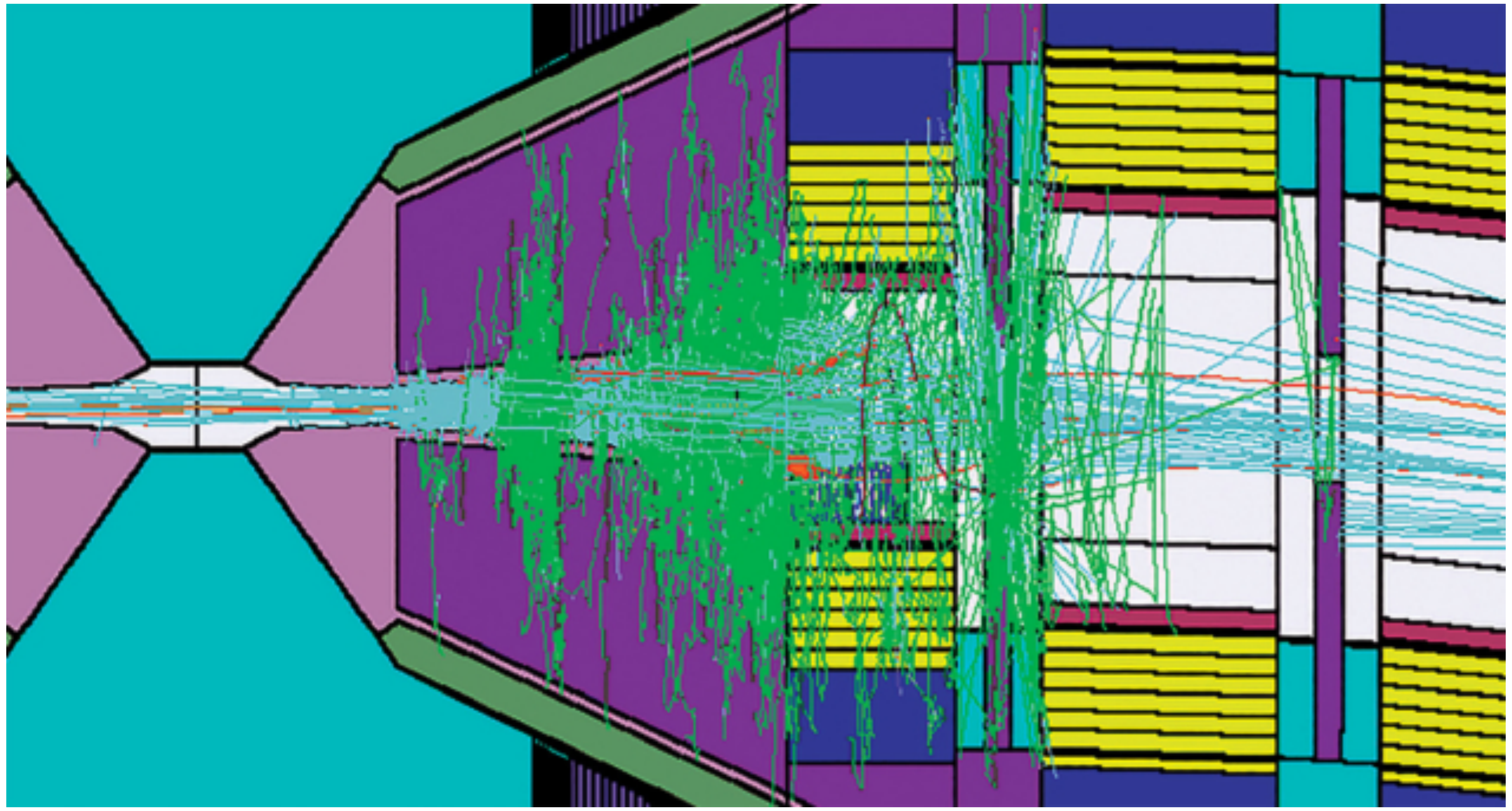
- Off-loading from CPU to GPU   Sherpa, '20; MG5 `22; Whizard, `24
- Semi-automatized ME generation for GPU in MG5 and Whizard
- Matrix-element evaluation vs. phase-space integration on GPU
  $\Longrightarrow$ Data transfer between CPU and GPU costly!
- So far no revolutionary breakthroughs
- Still a lot of work needed to make it fully competitive

Beam simulations



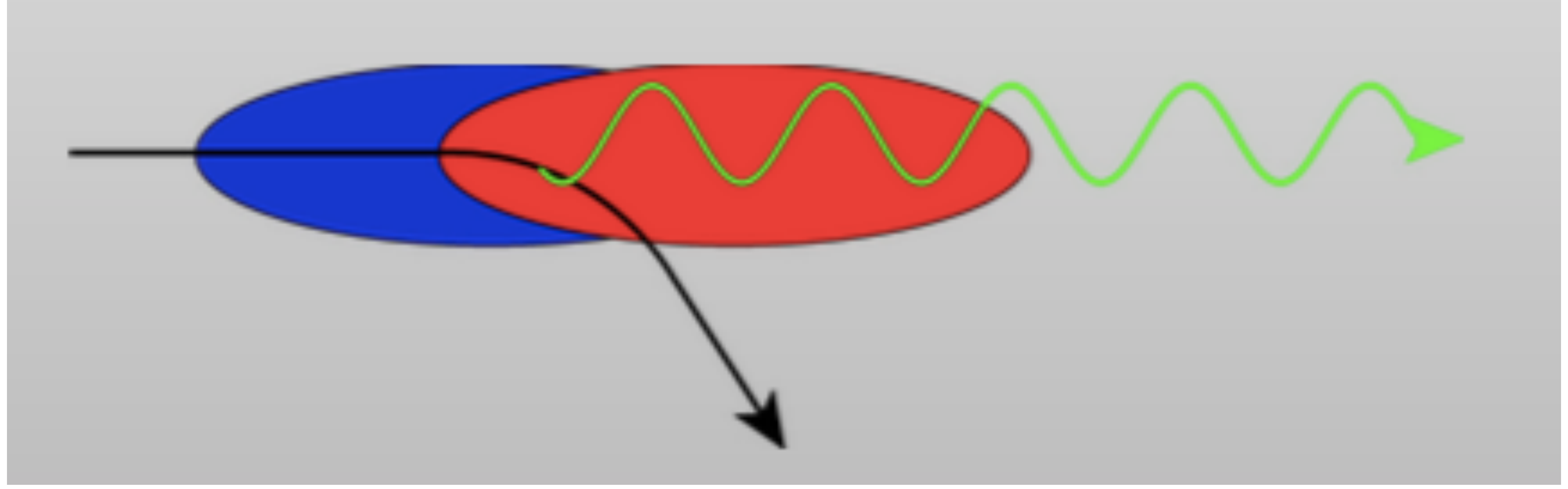


Beam structure for $\ell^+\ell^-$ colliders



Beam-induced background for the machine-detector interface (MDI)

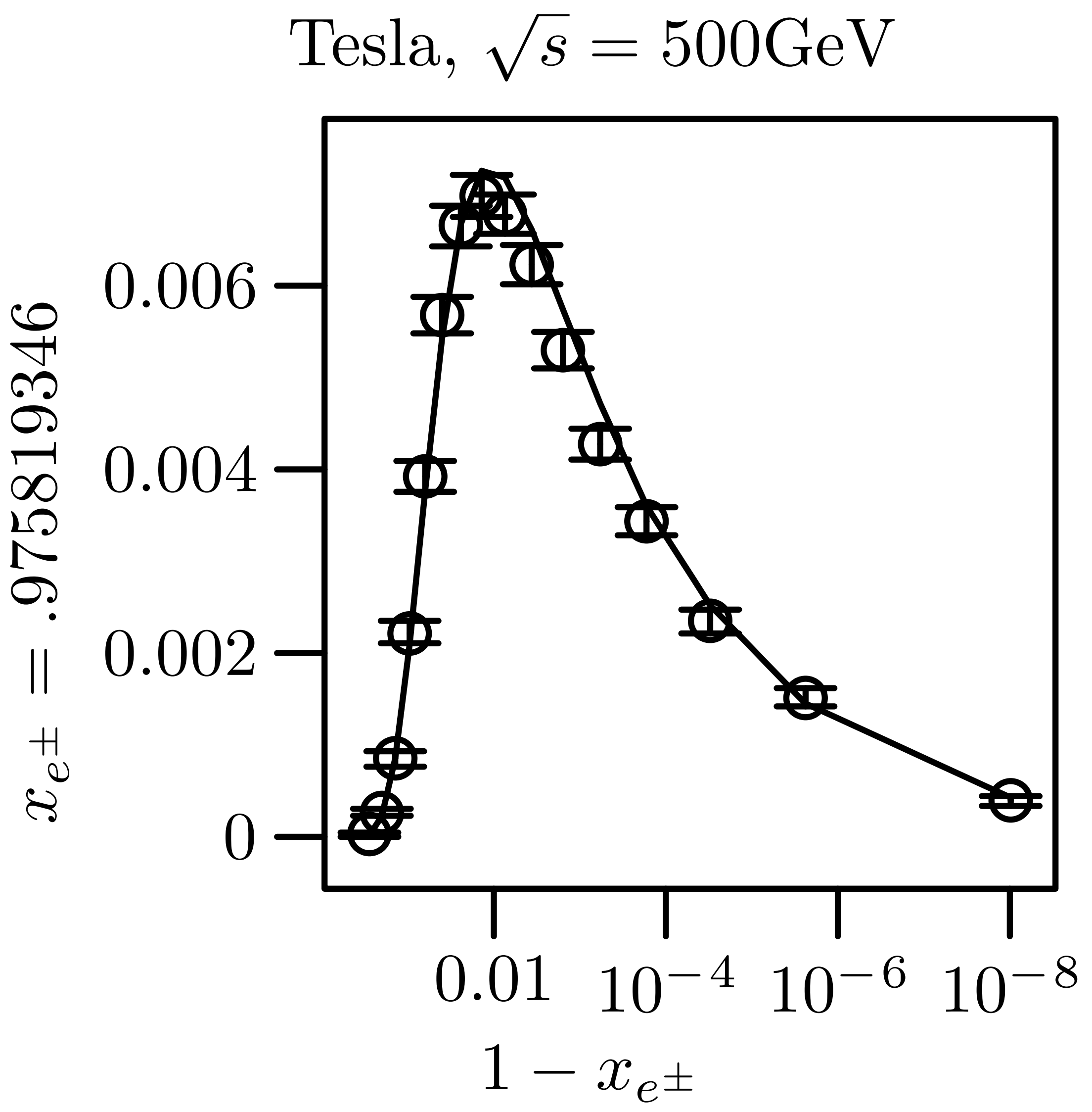
$$L \approx \frac{N}{4\pi\sigma_x\sigma_y}\frac{\eta P_{AC}}{E_{CM}}$$



- Dense beams $\Rightarrow$ strong EM fields: deflect particles in other bunch (beamstrahlung)
- Depends on damping rings, final focus magnet, crossing angle, beam optics, etc.
- Effects: beam energy spread, long power-law dominated tail

Algorithms for e^+e^- beam simulations

- Simulation tool for beam spectrum: `GuineaPig` [D. Schulte, 1998+]
- Very limited statistics: O(100k) vs. MC simulations need O(many G)



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2. Parameterized (delta peak ⊕ power law) — Avail.: (✓)
3. Generator for 2D histogrammed fit — Avail.: [✓]

$$D_{\ell_1 \ell_2}(x_1, x_2) = D_{\ell_1}(x_1) \cdot D_{\ell_2}(x_2)$$
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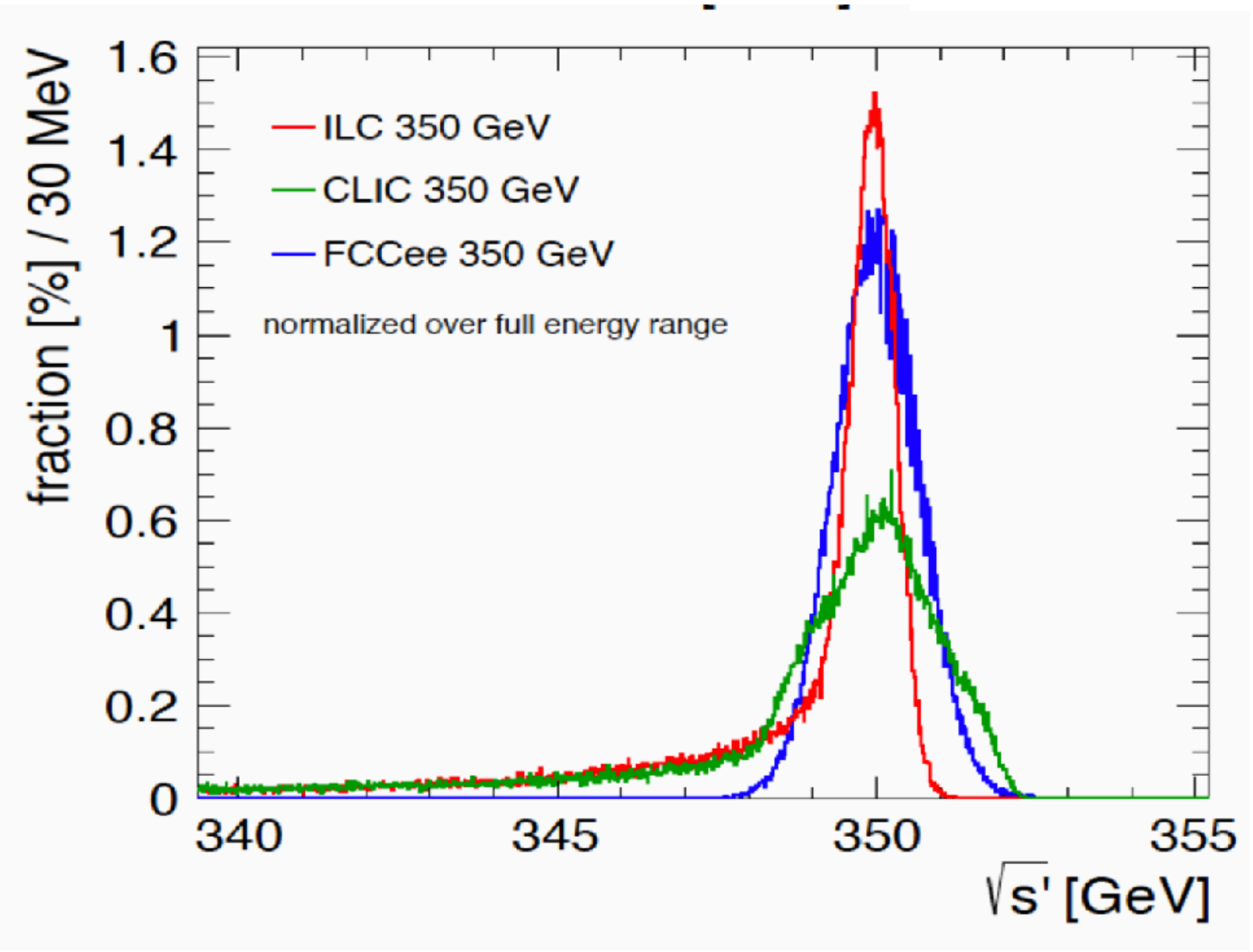

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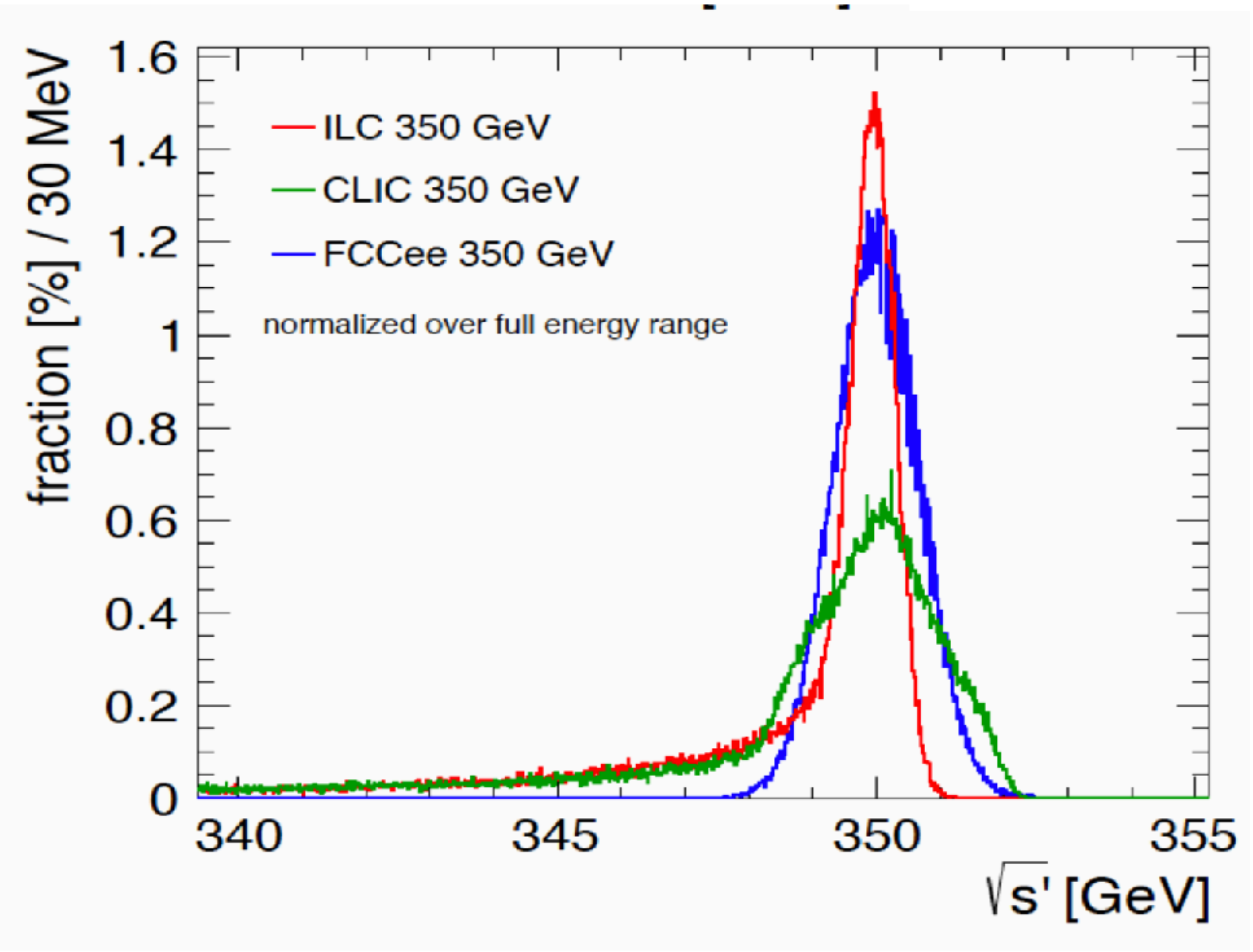

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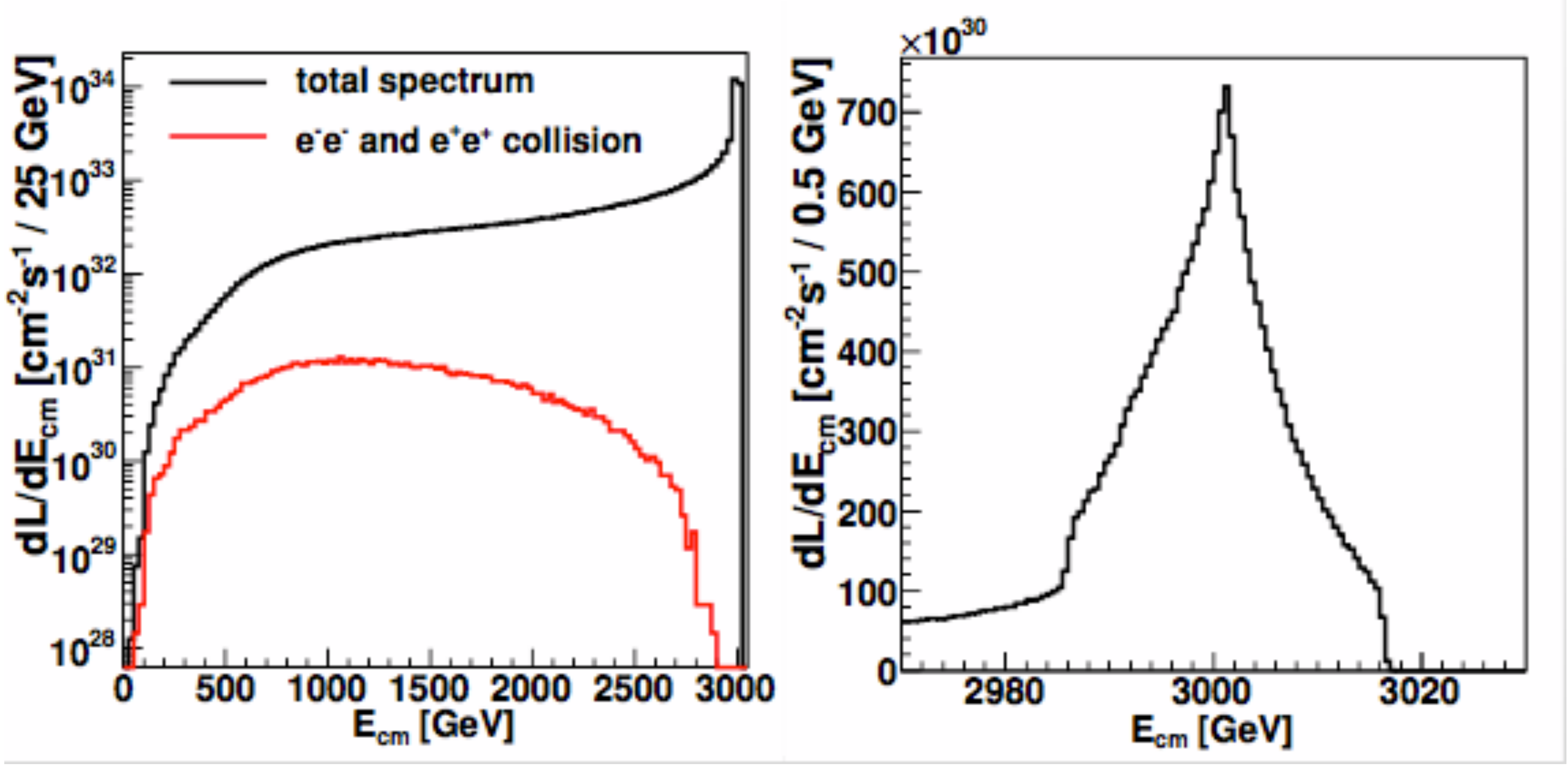

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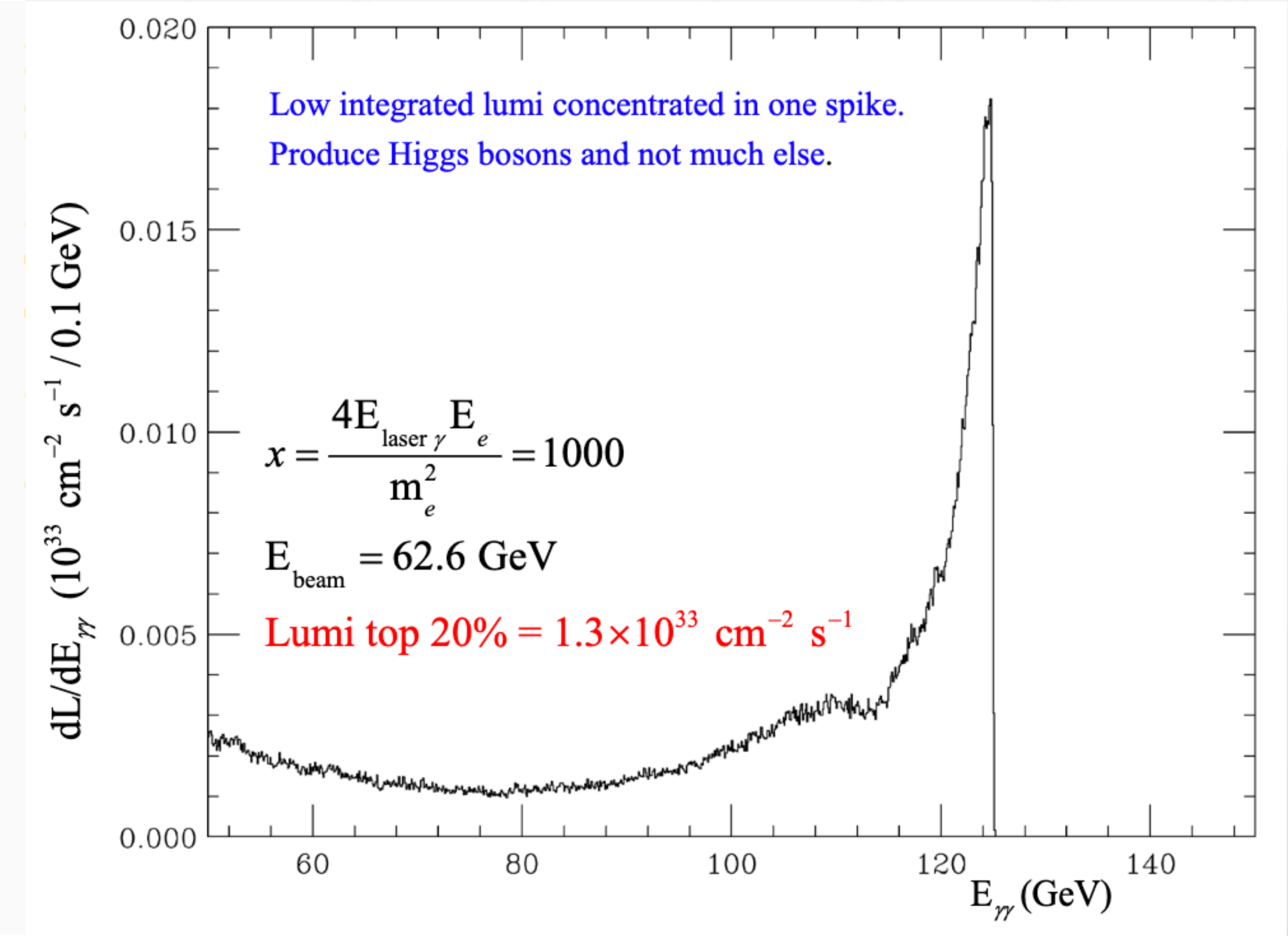
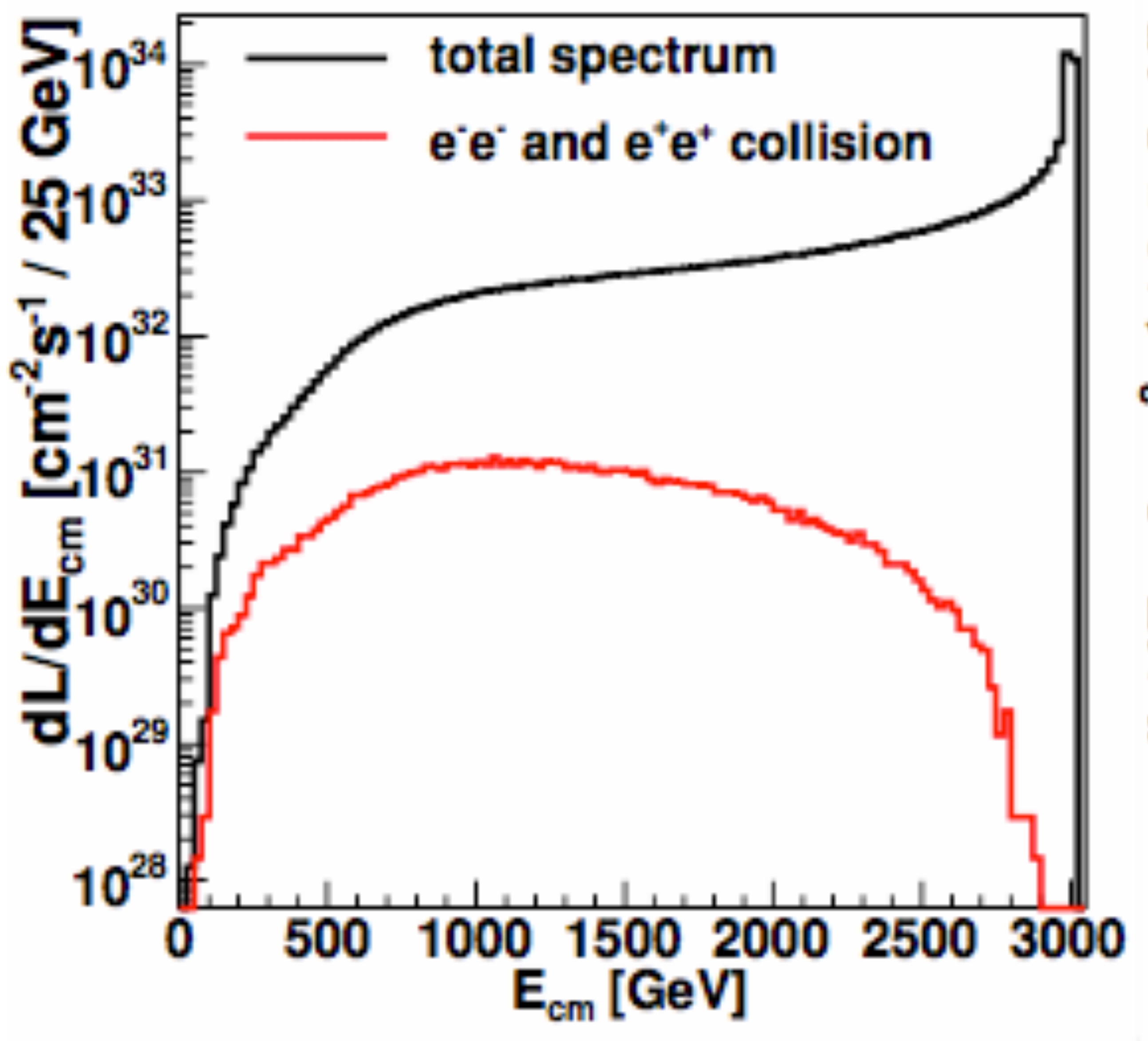
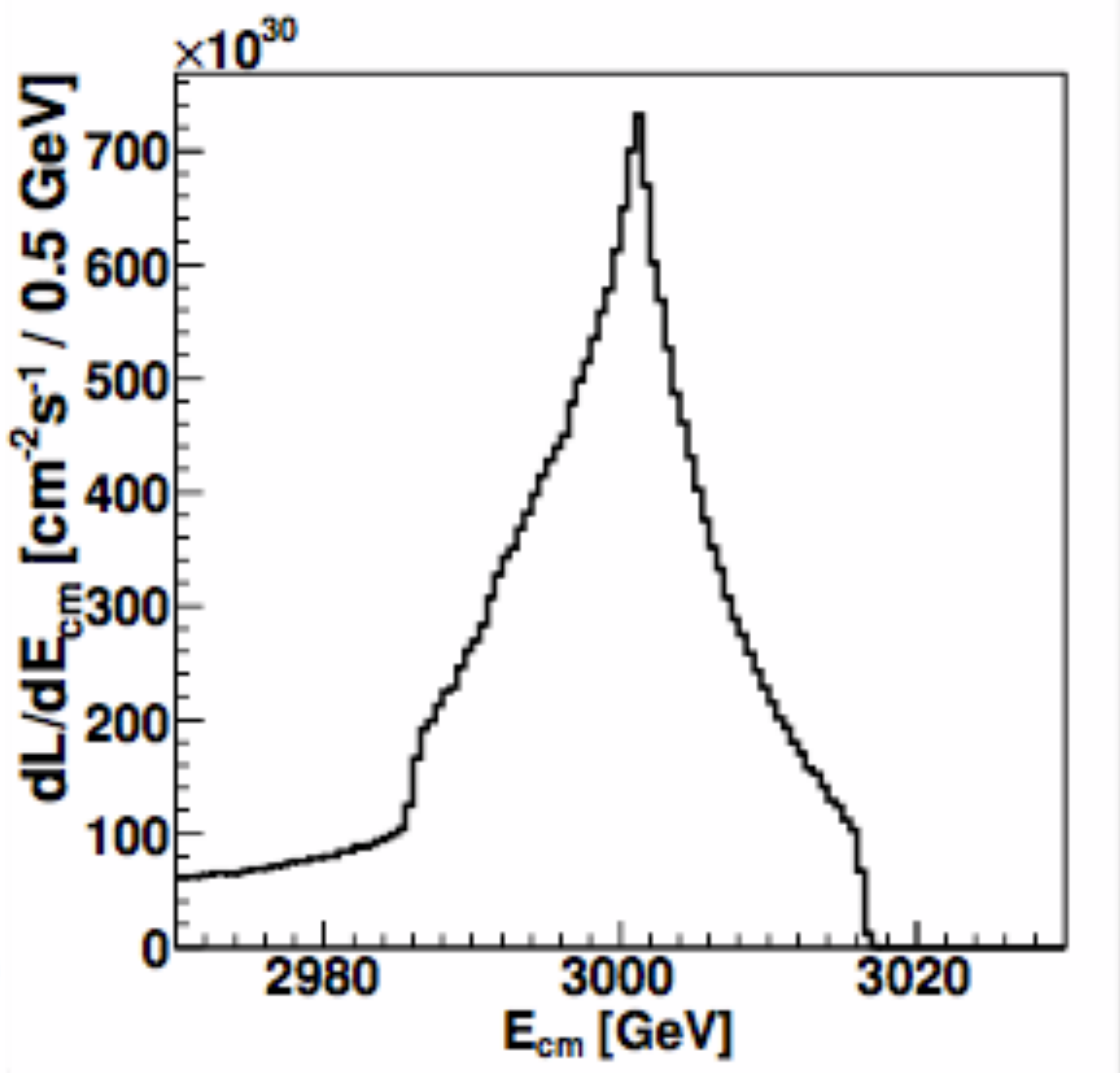


XCC $\gamma\gamma$ collider , T. Barklow, LCWS 2023





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Sampling of beam spectra

based on `Lumilinker` T. Barklow, 2001; `CIRCE2` algorithm T. Ohl, 1996, 2005

- Adapt 2D factorized variable width histogram to steep part of distribution
- Smooth correlated fluctuations with moderate Gaussian filter

  [suppresses artifacts from limited GuineaPig statistics
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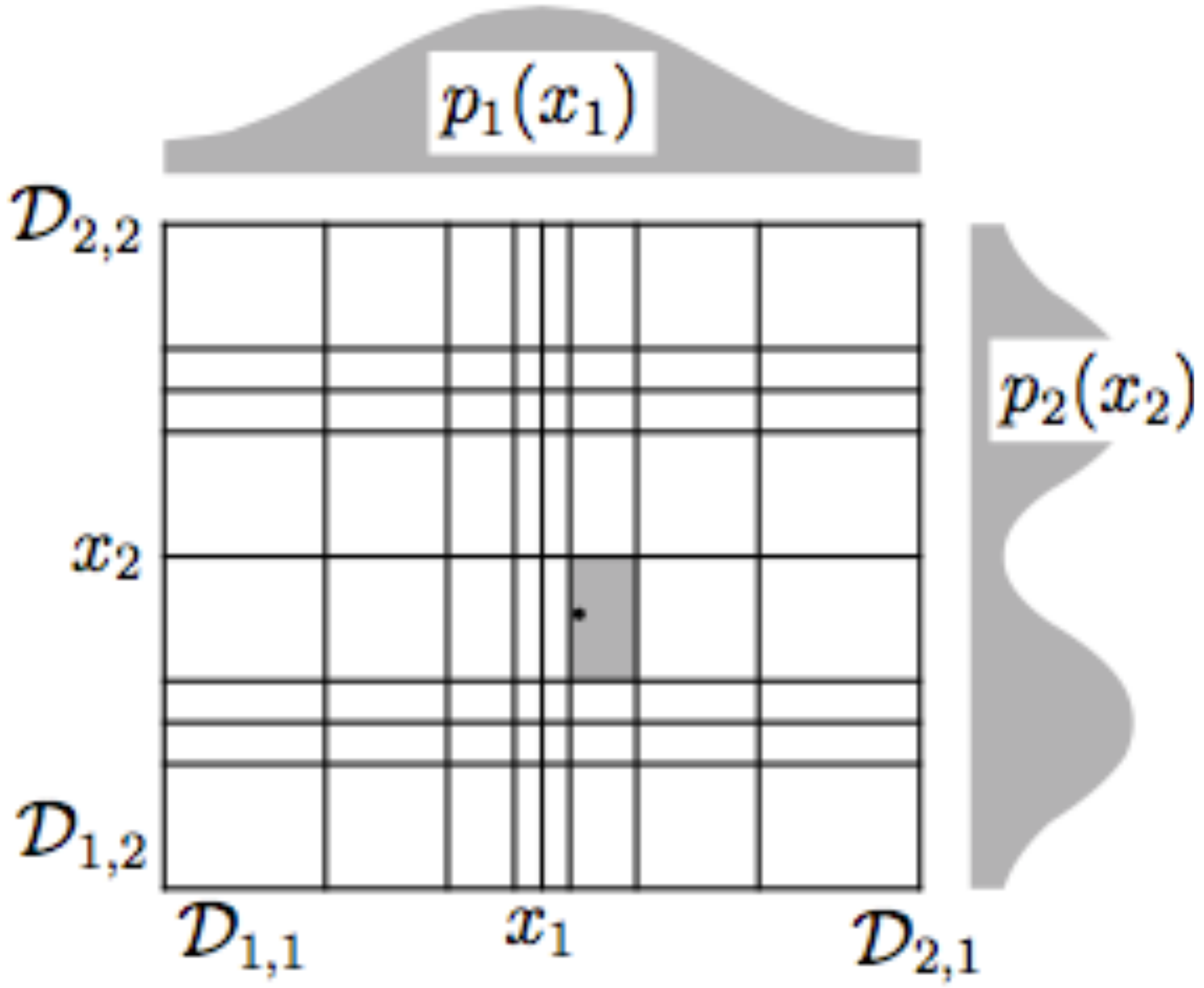
  [avoid artificial beam energy spread]
- Future work: 3D structure of spectrum, does machine learning help?



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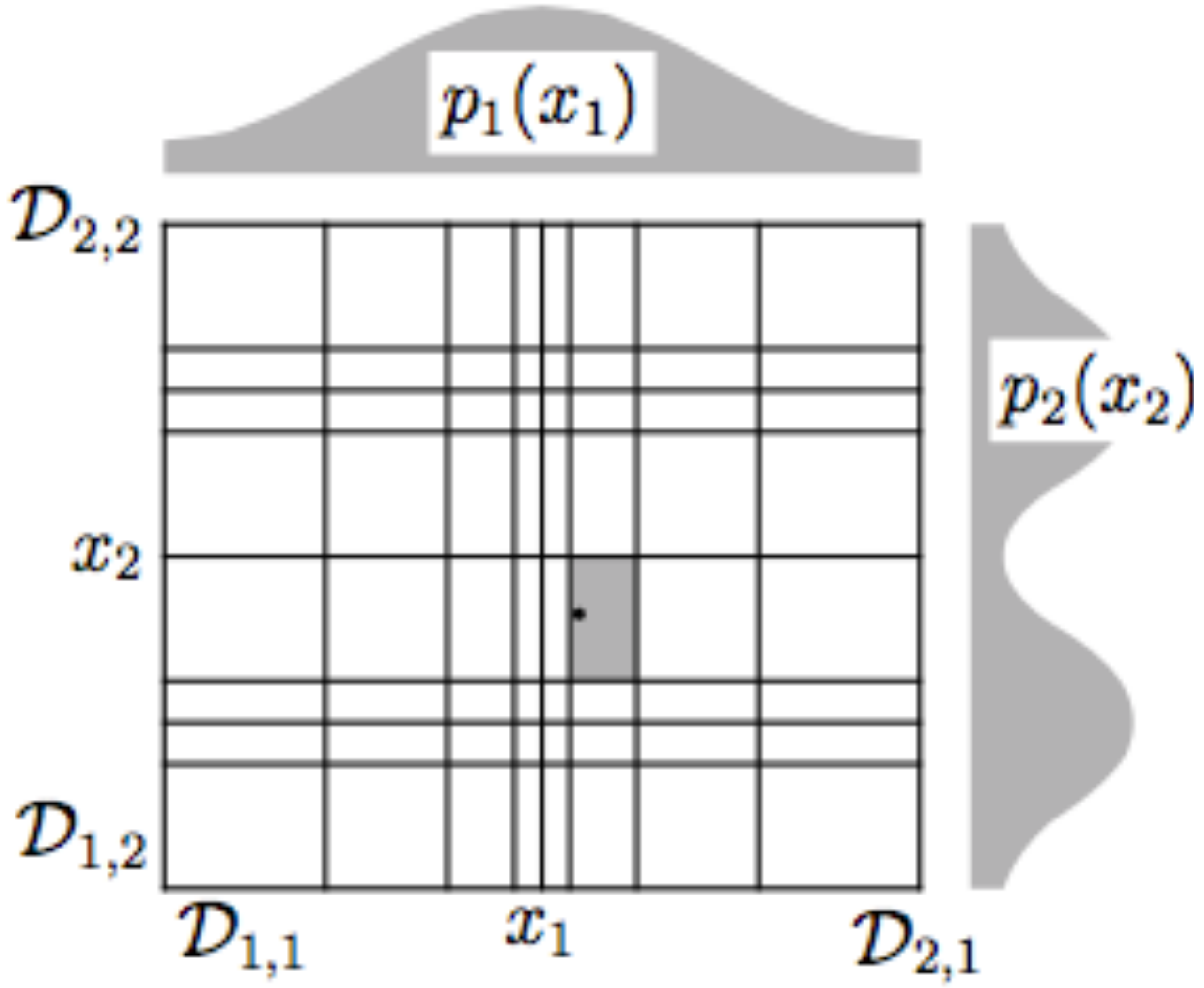

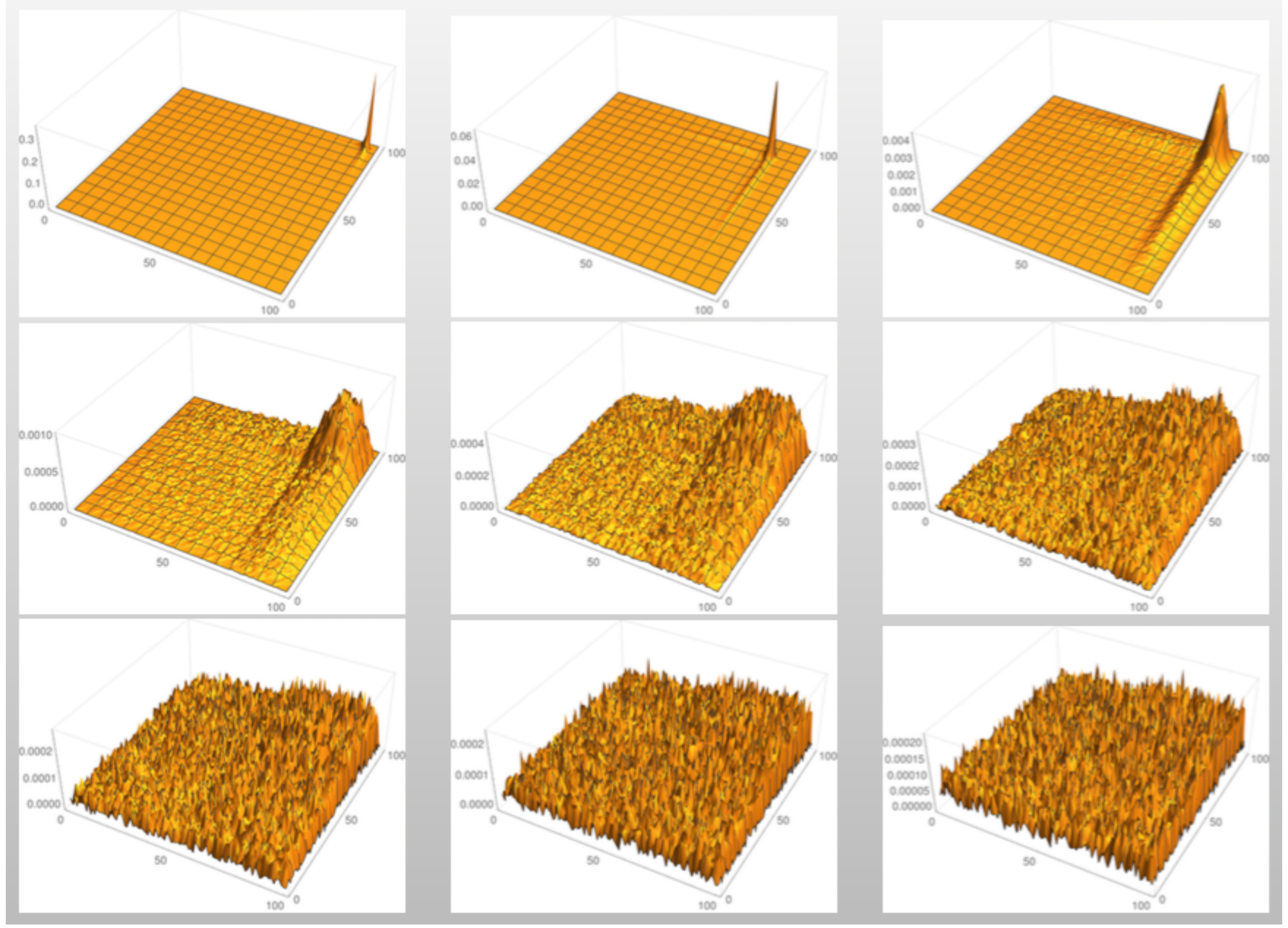

(171,306 GuineaPig events in 10,000 bins)

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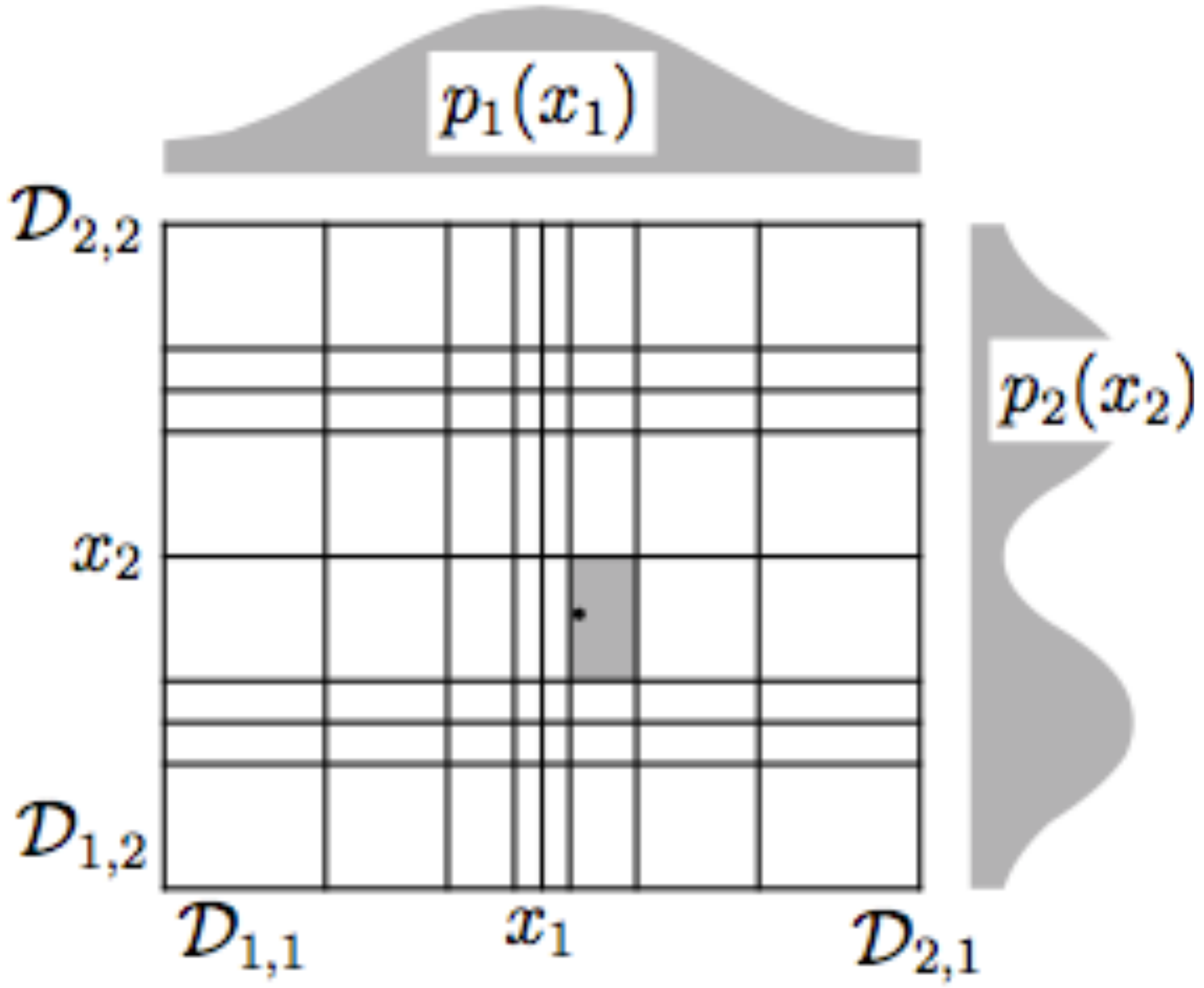

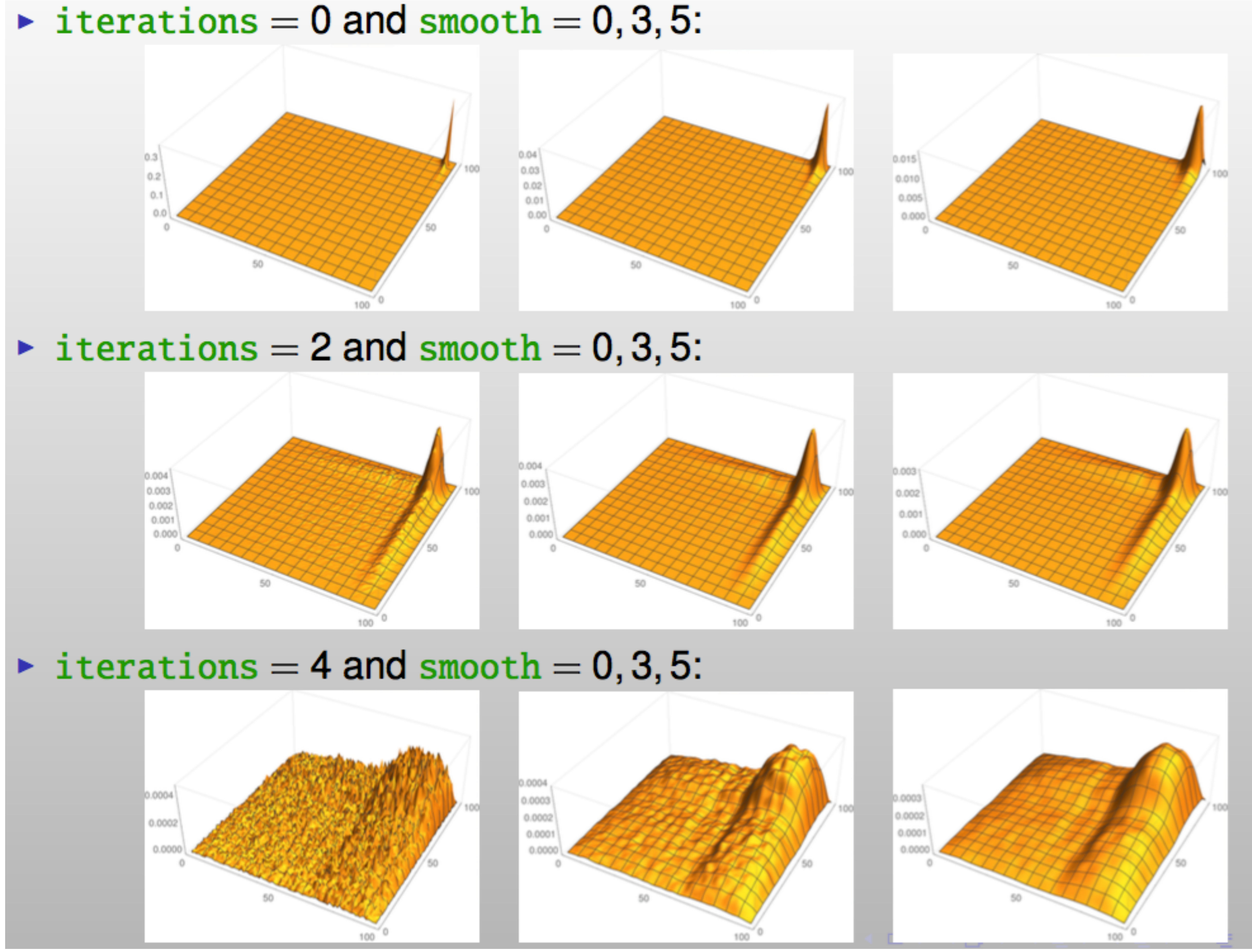

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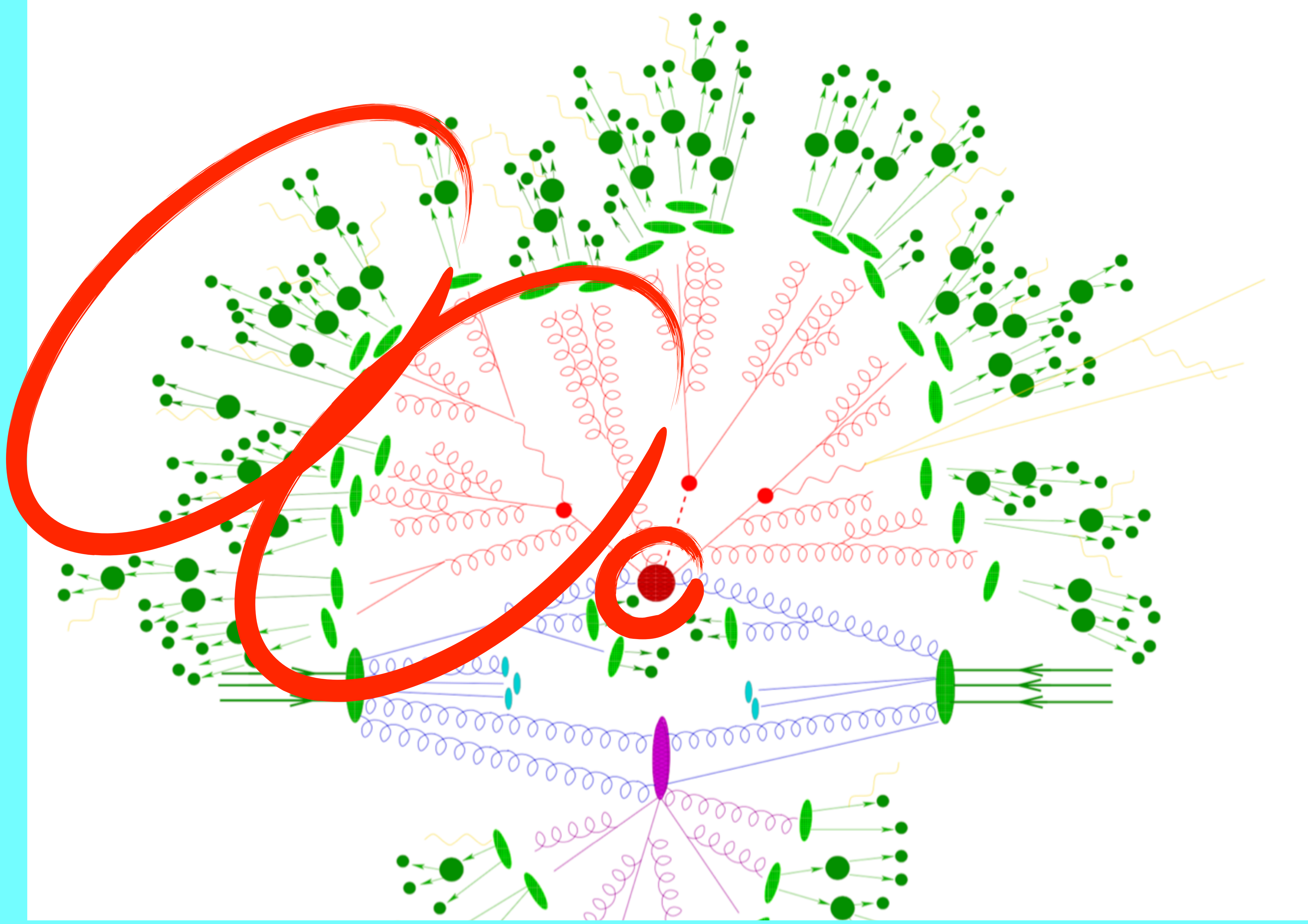
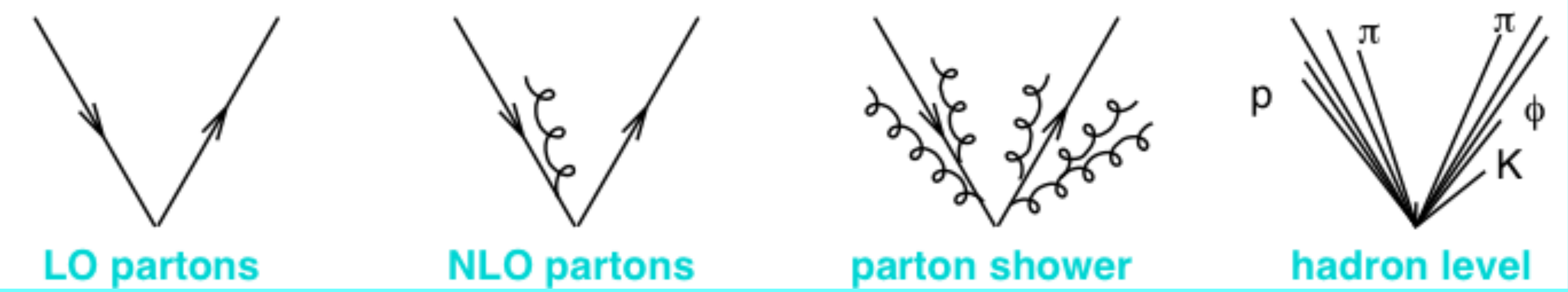
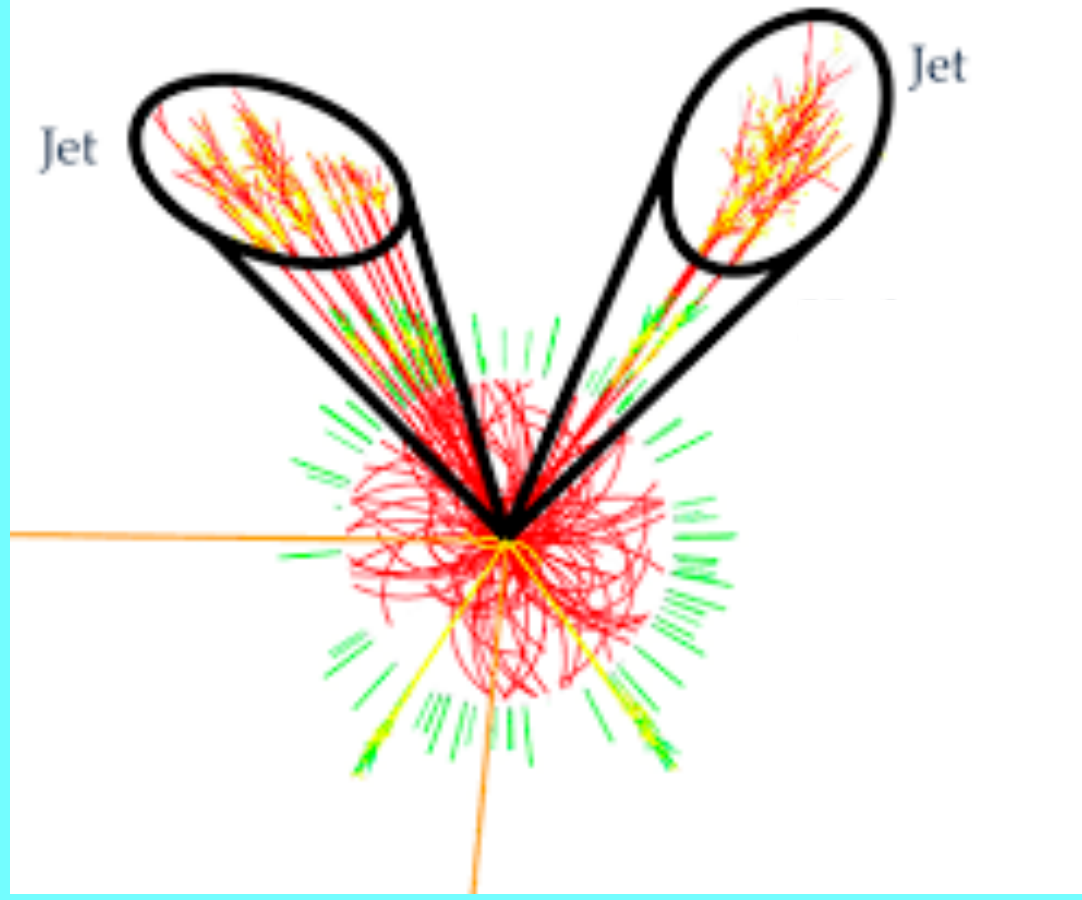
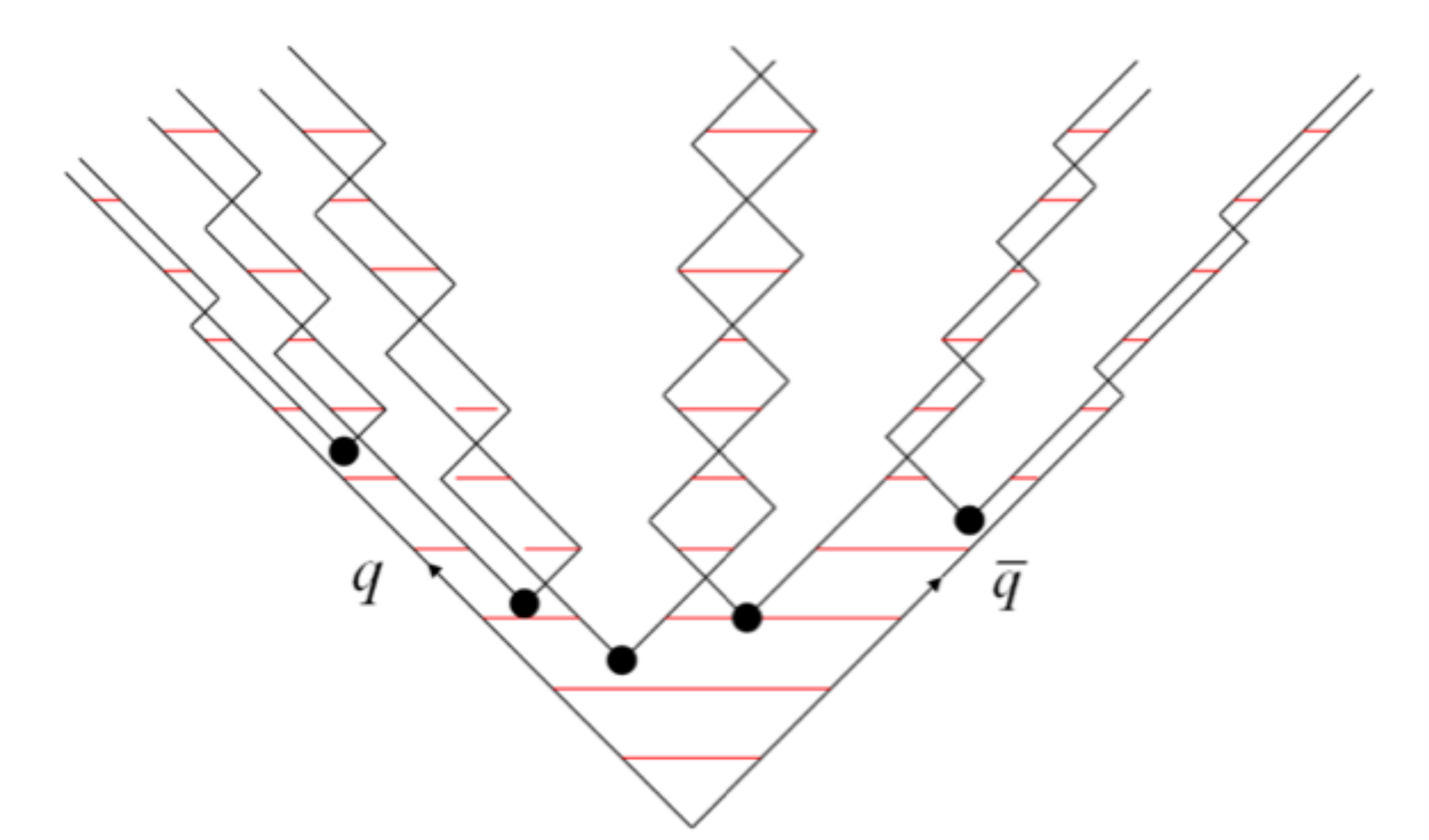
Hard processes, shower, hadronization and all that

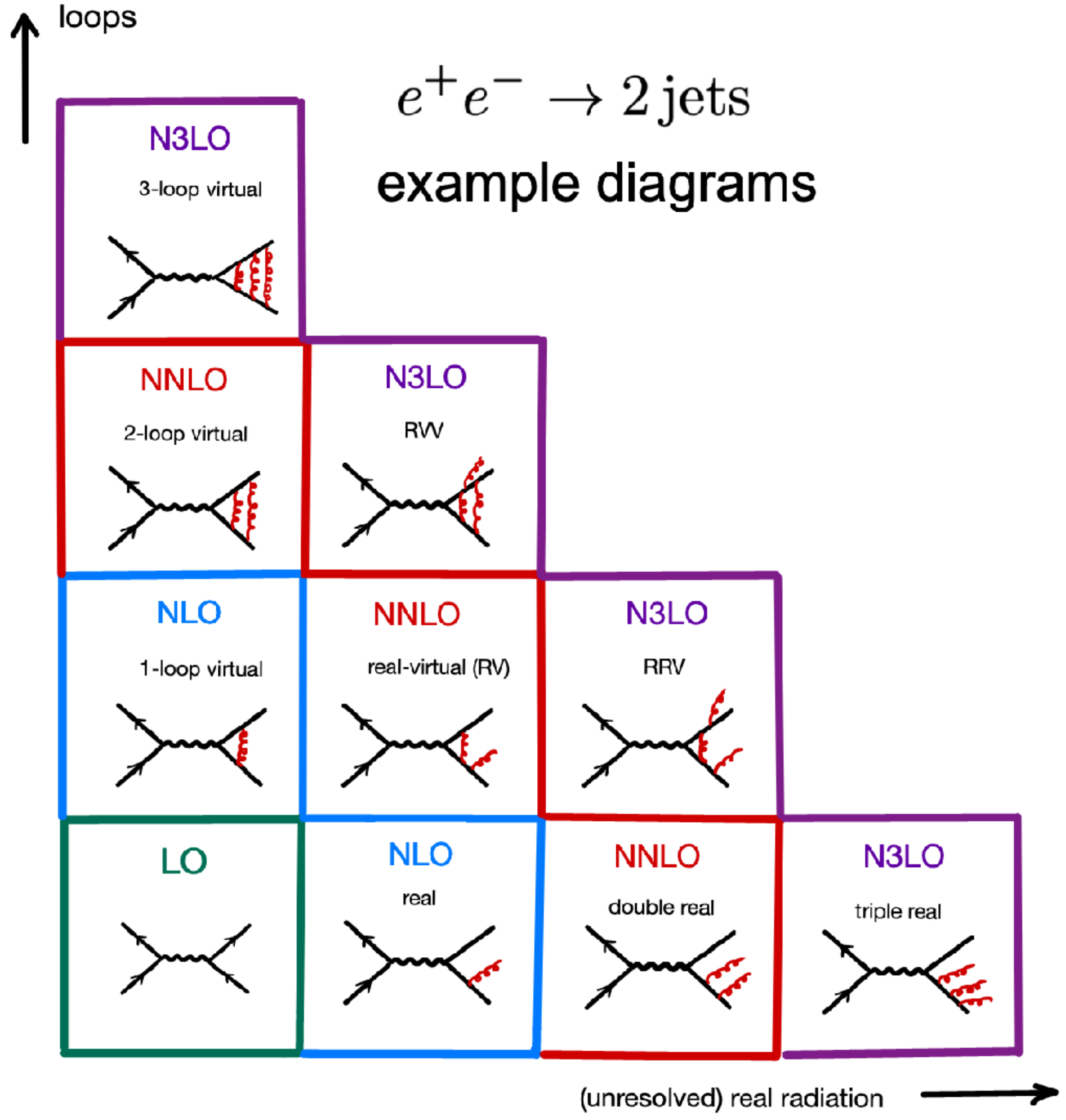








Fixed-Order Perturbation Theory — Recursion Rules



- Perturbative amplitudes for $2 \to n$ scattering grows factorially with n
- Recursive algorithms [Parke/Taylor, '86; Berends/Giele, '88; Caravaglios et al., 1998; Ohl/JRR, 2000/2023; Papadopoulos, 2001]
- Full recursiveness: Directed Acyclical Graphs (DAGs) [O'Mega]

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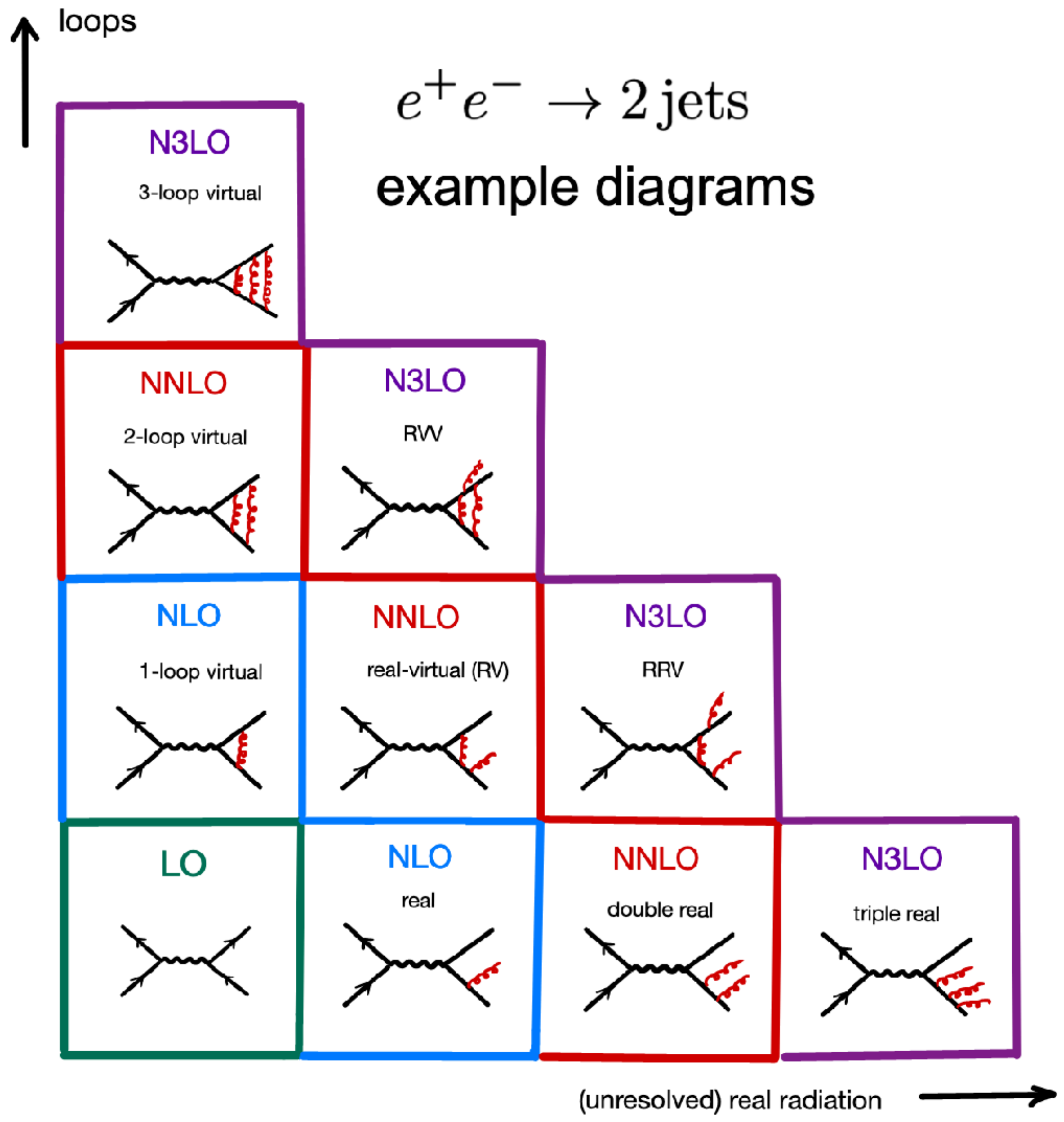

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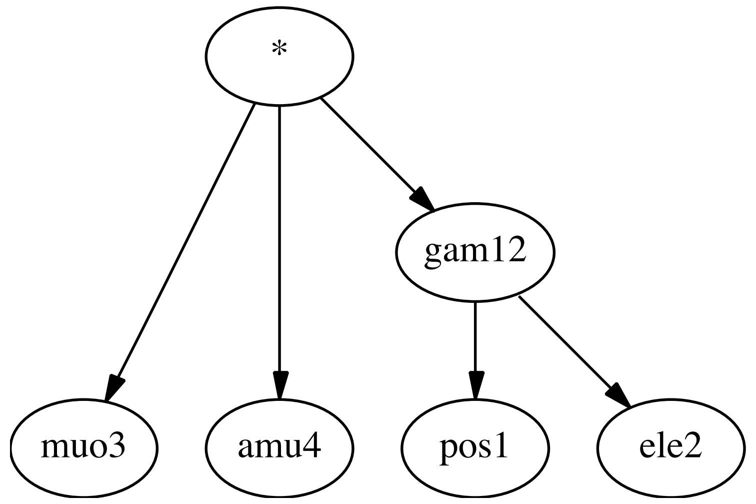

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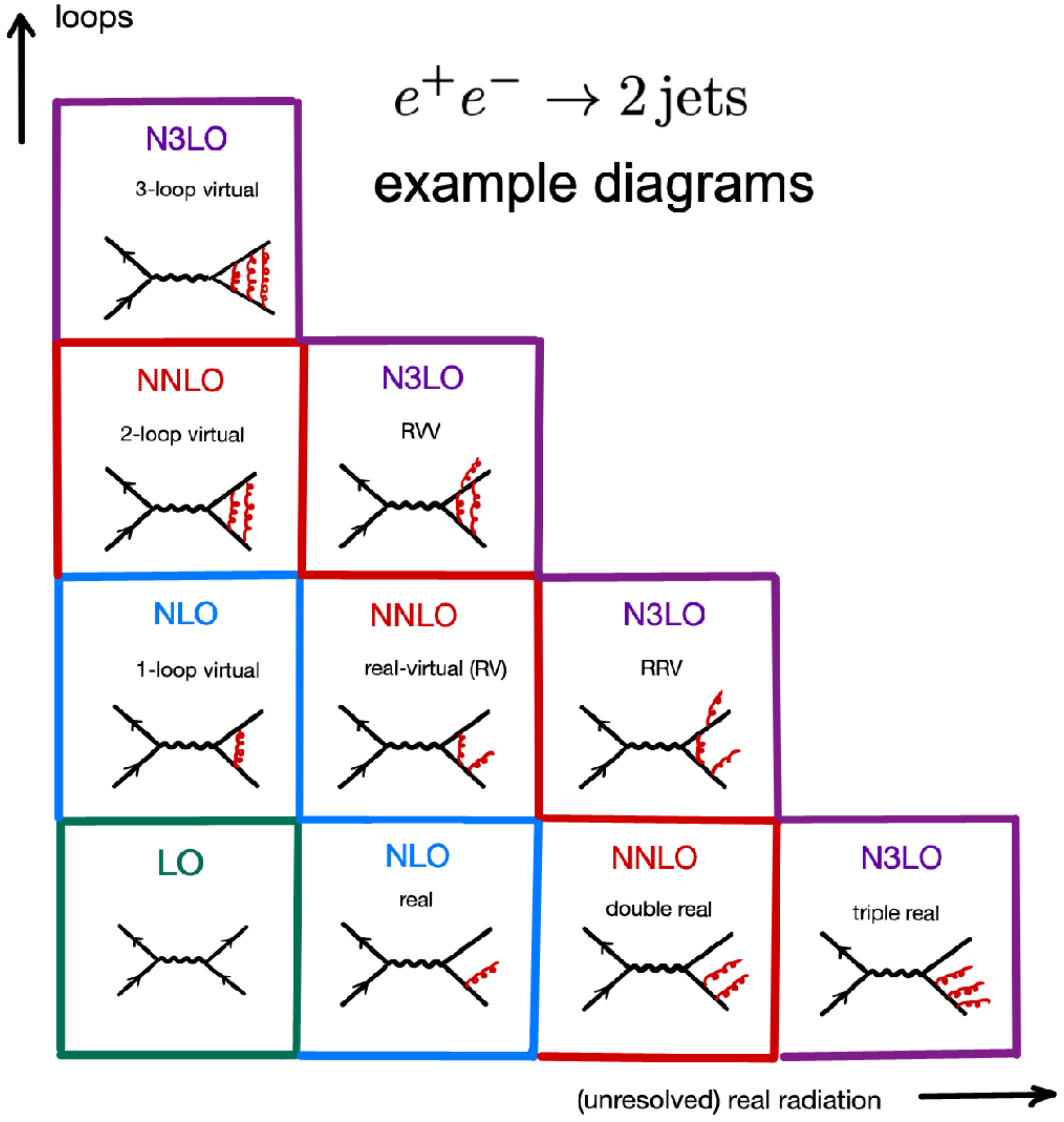

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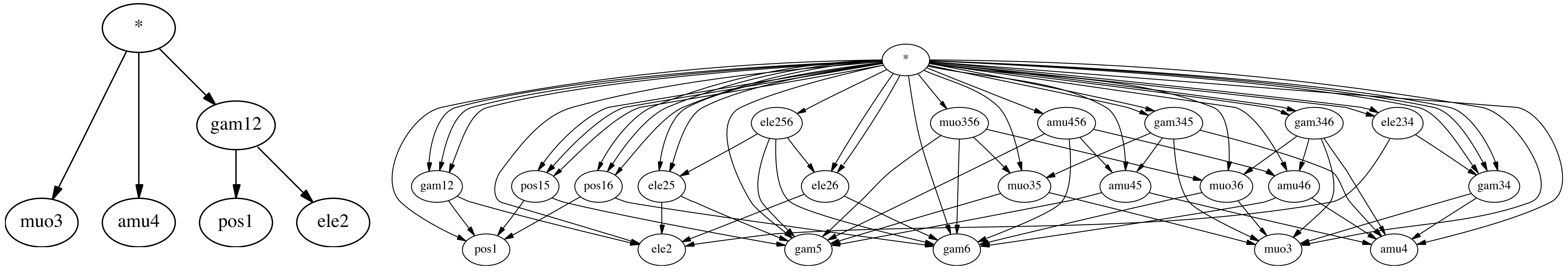

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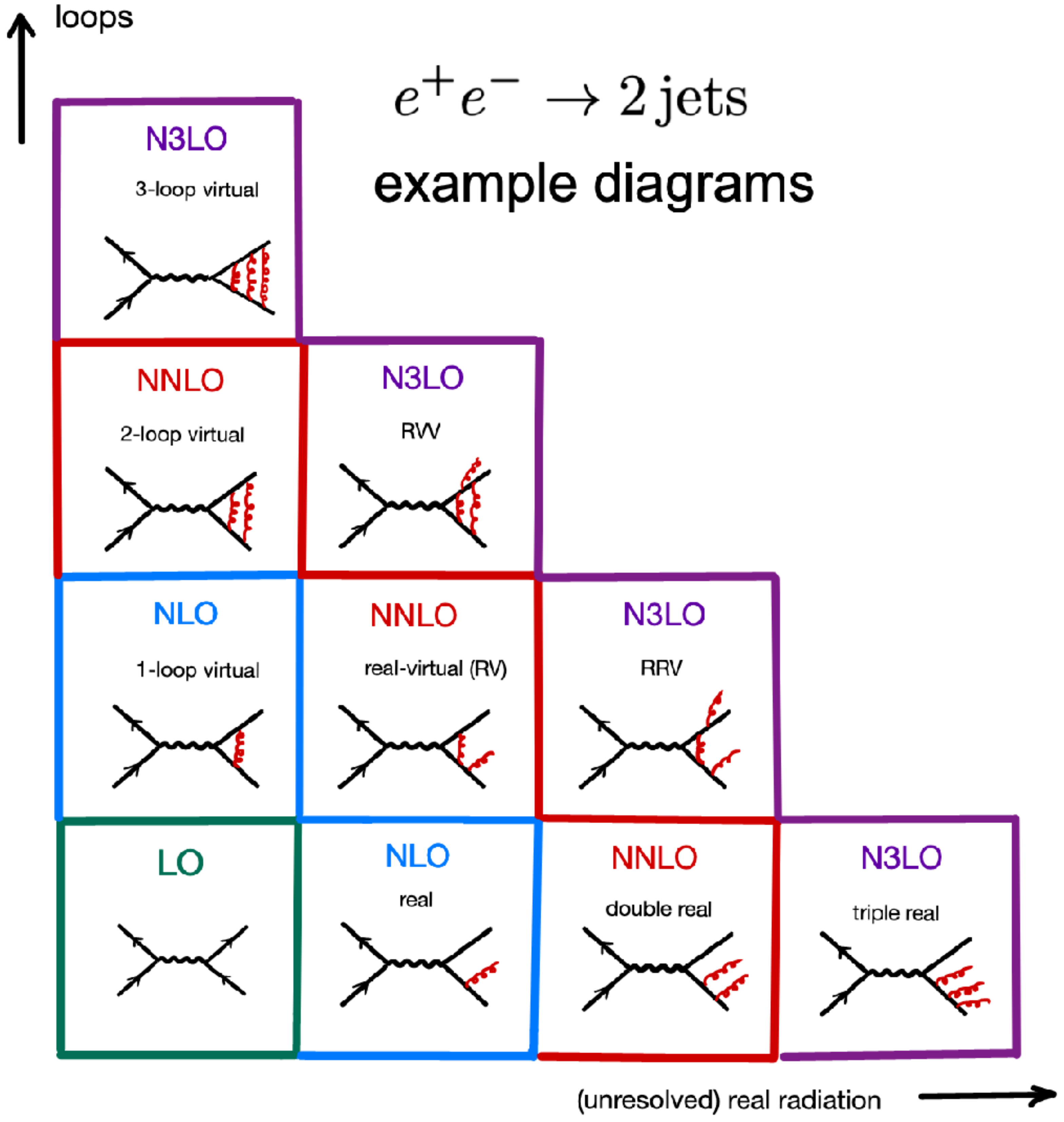

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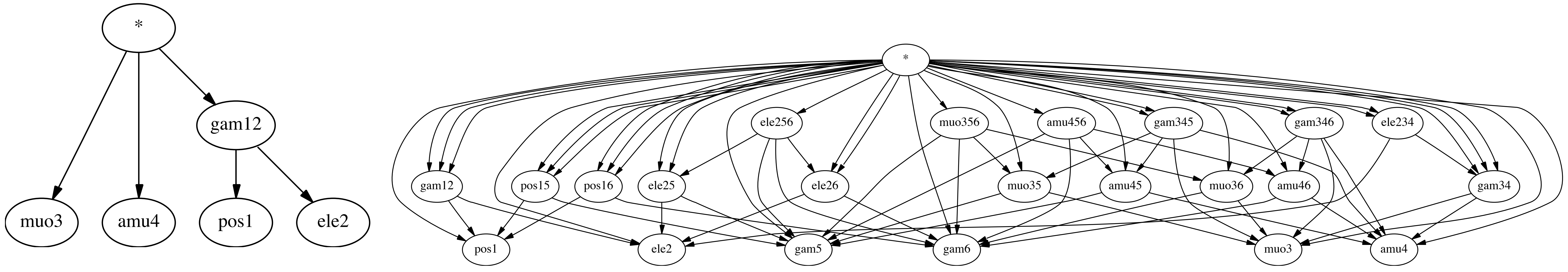
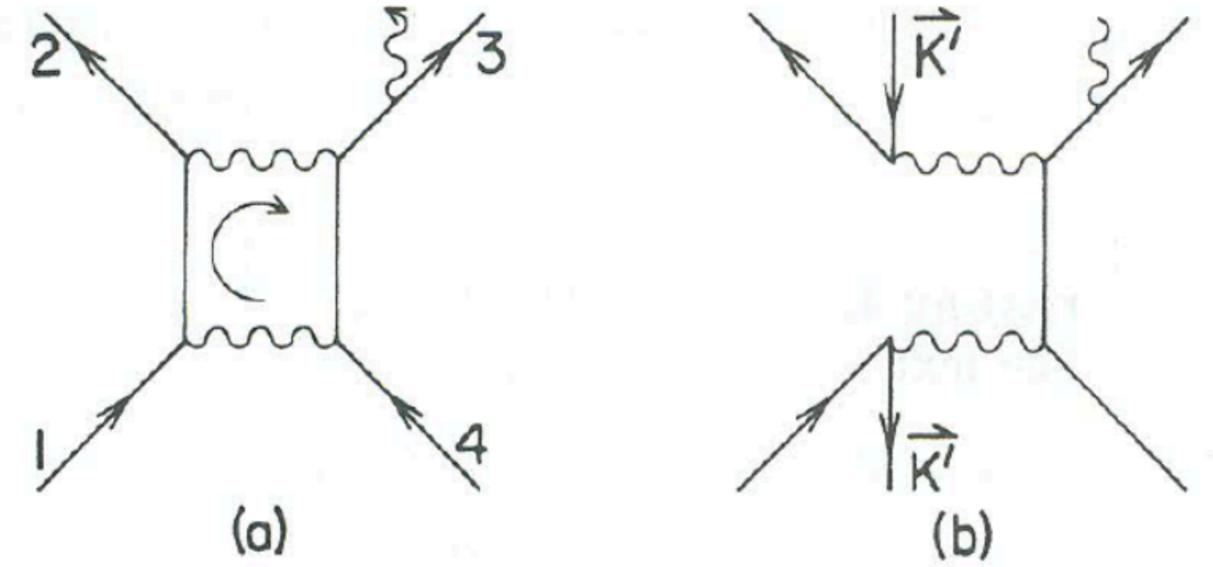
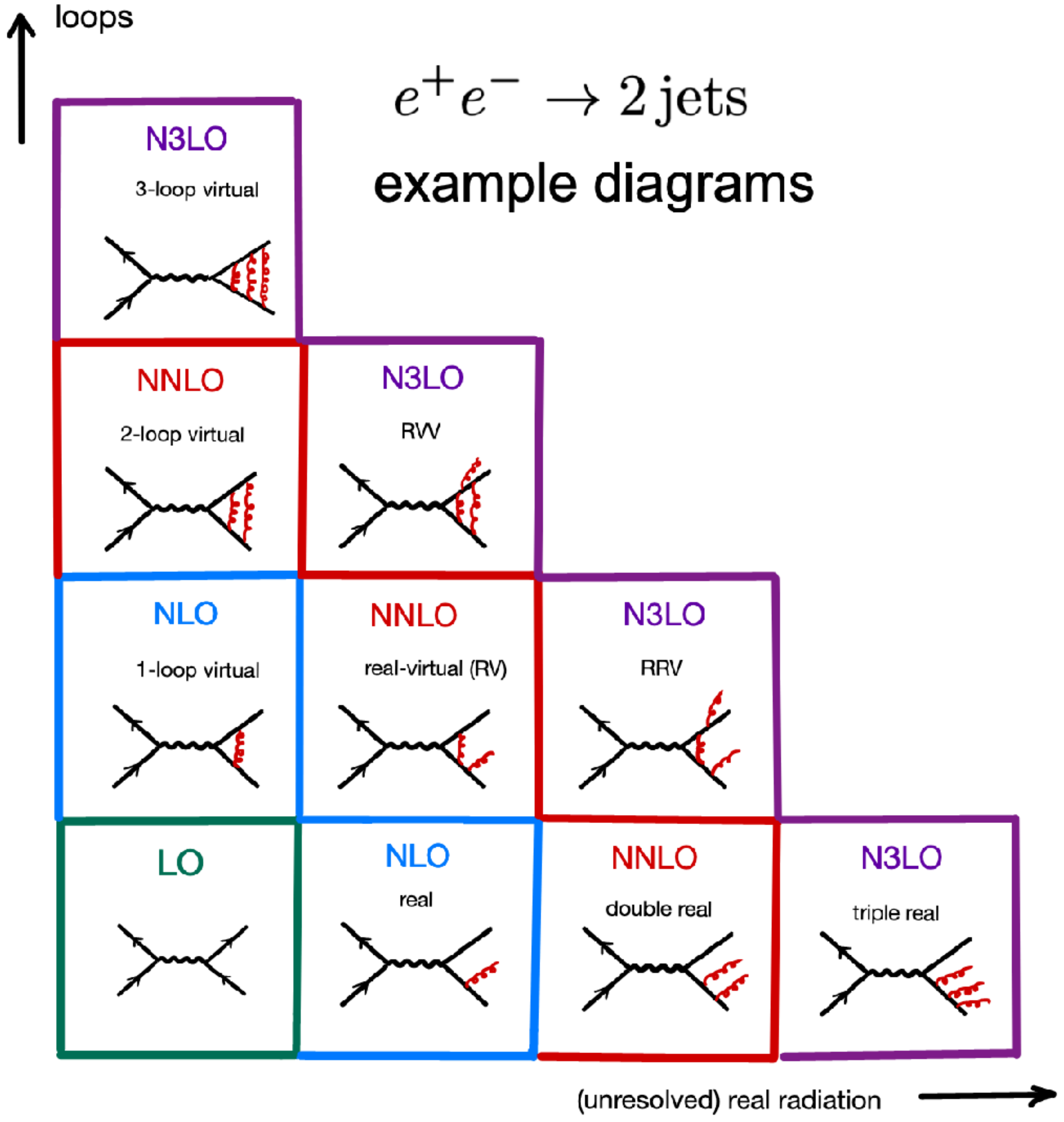
- Full recursiveness: Directed Acyclical Graphs (DAGs) [O'Mega]



- Tree-level problem solved for matrix elements, part. transferrable to 1-loop/[2-loop]



Fixed-Order Perturbation Theory — Recursion Rules



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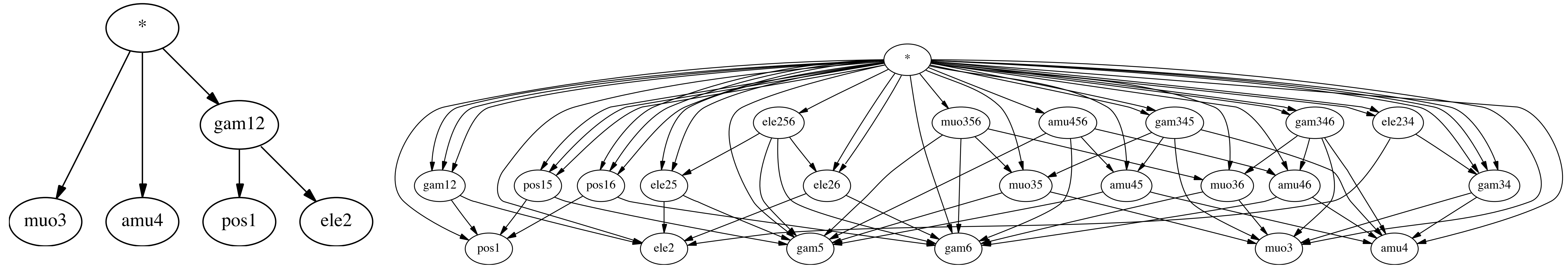

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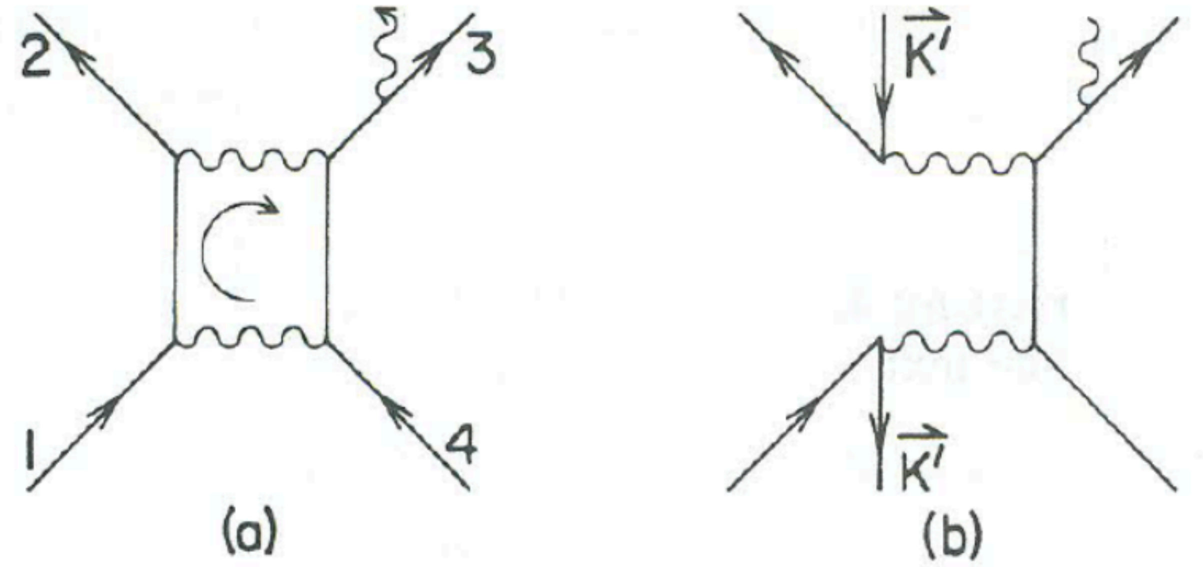
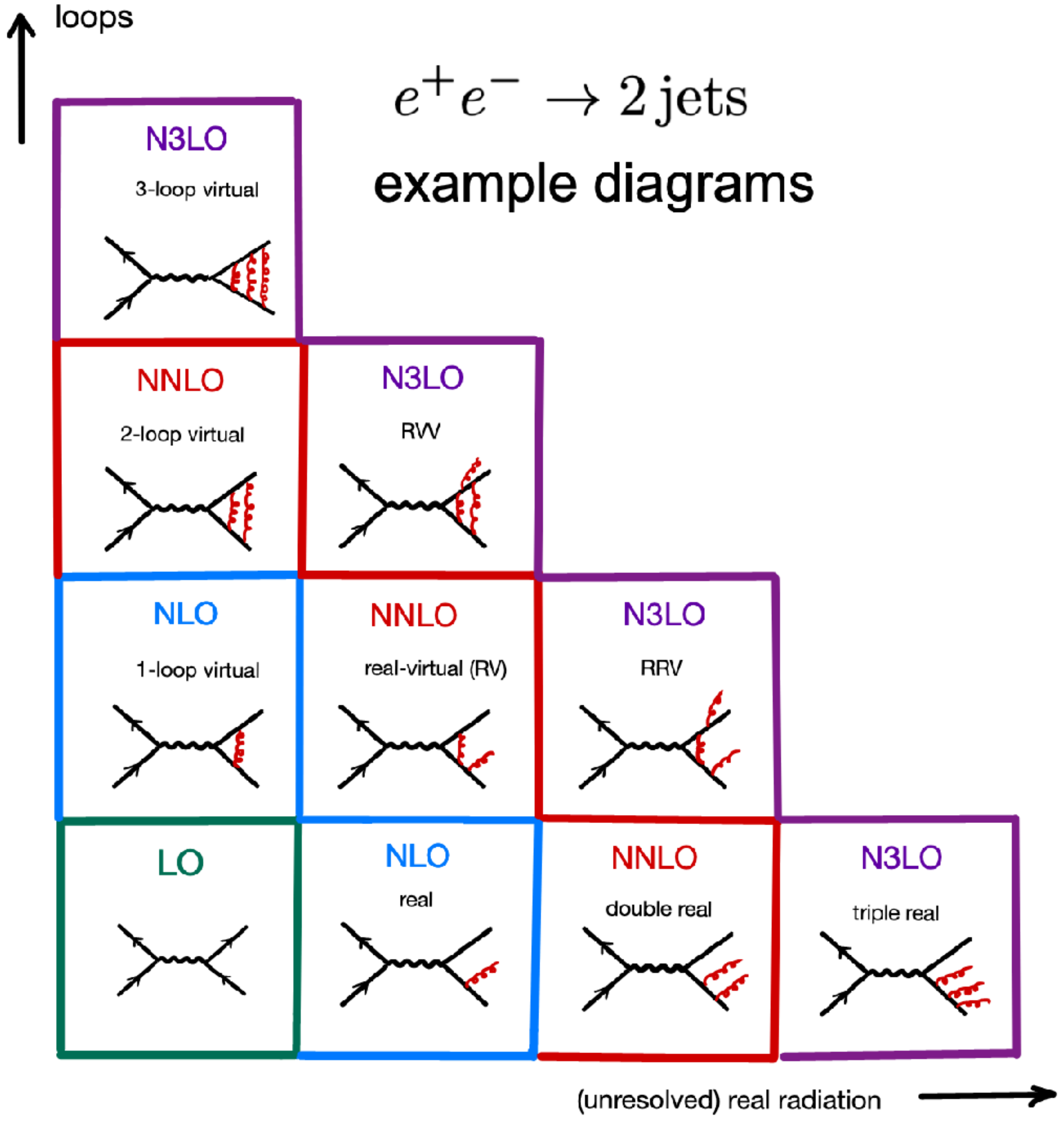


- NLO QCD ⊕ EW automated: Sherpa, MadGraph5_aMC@NLO, Whizard
- Lepton collider: Signal & bkgd. samples at full SM QFT interference level
- Need $e^+e^- \to$ *2f, 3f, 4f, 5f, 6f, [7-10f]* @ NLO QCD ⊕ EW (w/ cuts, fully differential)

Fixed-Order Perturbation Theory — Recursion Rules



$e^+e^- \to 2\,\text{jets}$

example diagrams

- Perturbative amplitudes for $2 \to n$ scattering grows factorially with n
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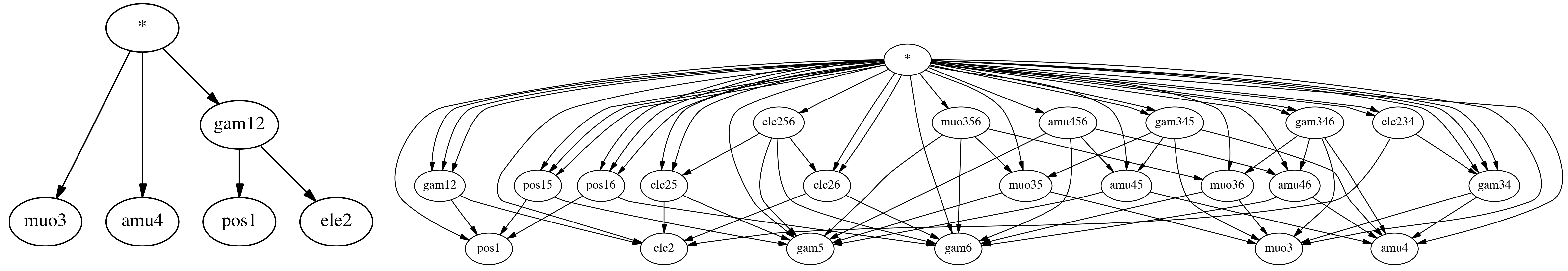

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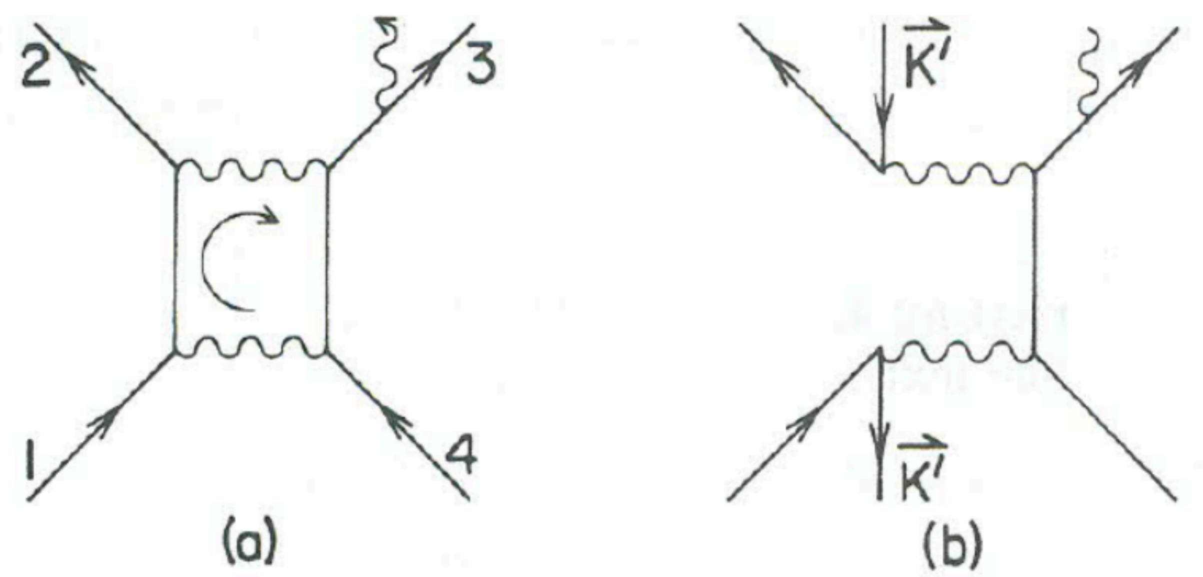

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AUTOMATION WORKS AS LONG AS THE FIRST PROCESS CRASHES

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

ee @ 250 GeV, NLO EW polarized

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

Process	WHIZARD+OpenLoops σ_{LO} [fb]	σ_{NLO} [fb]
$e^+e^- \to jj$	622.737(8)	639.39(5)
$e^+e^- \to jjj$	340.6(5)	317.8(5)
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$\mu\mu$ @ 3 TeV, NLO EW

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

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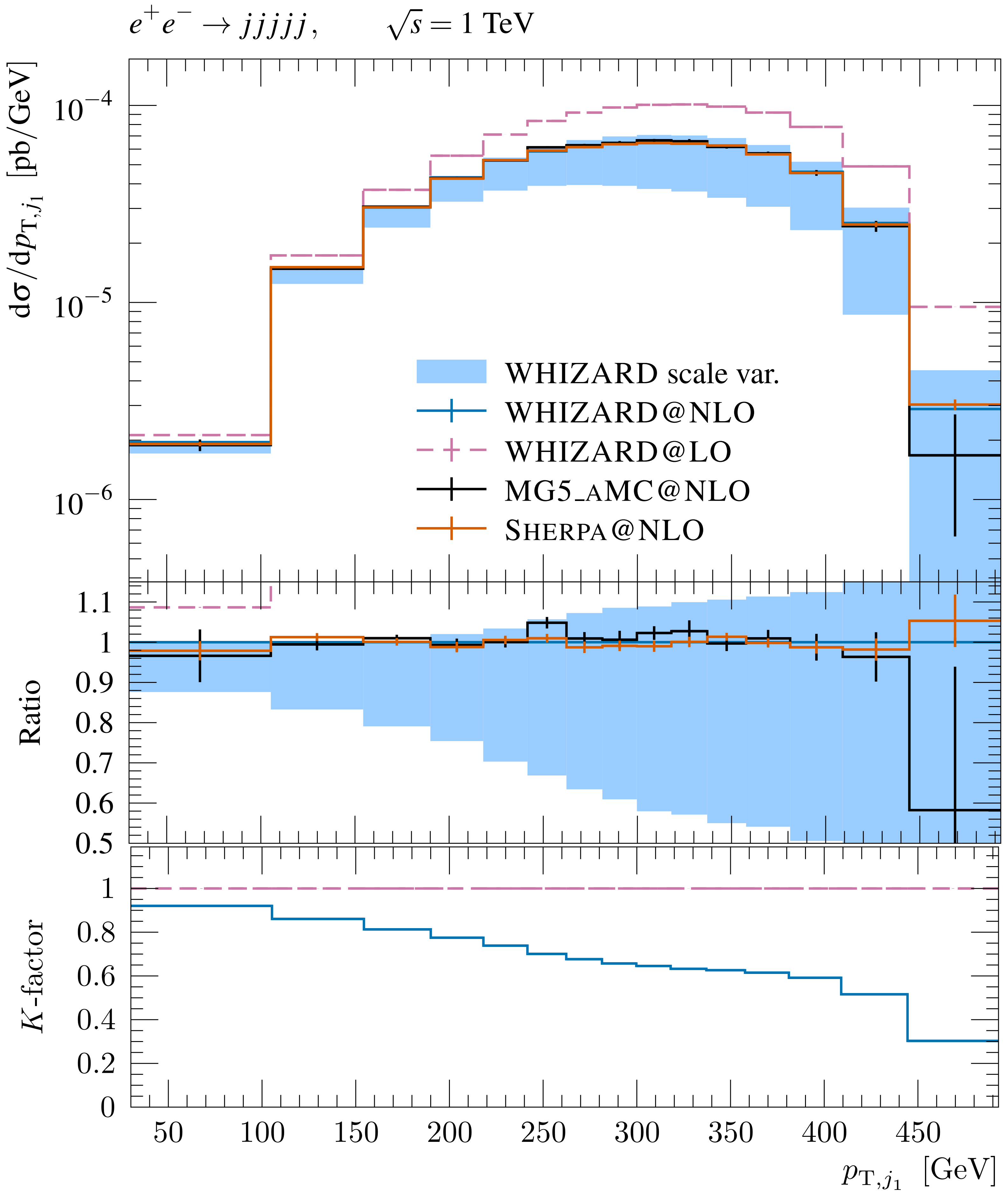

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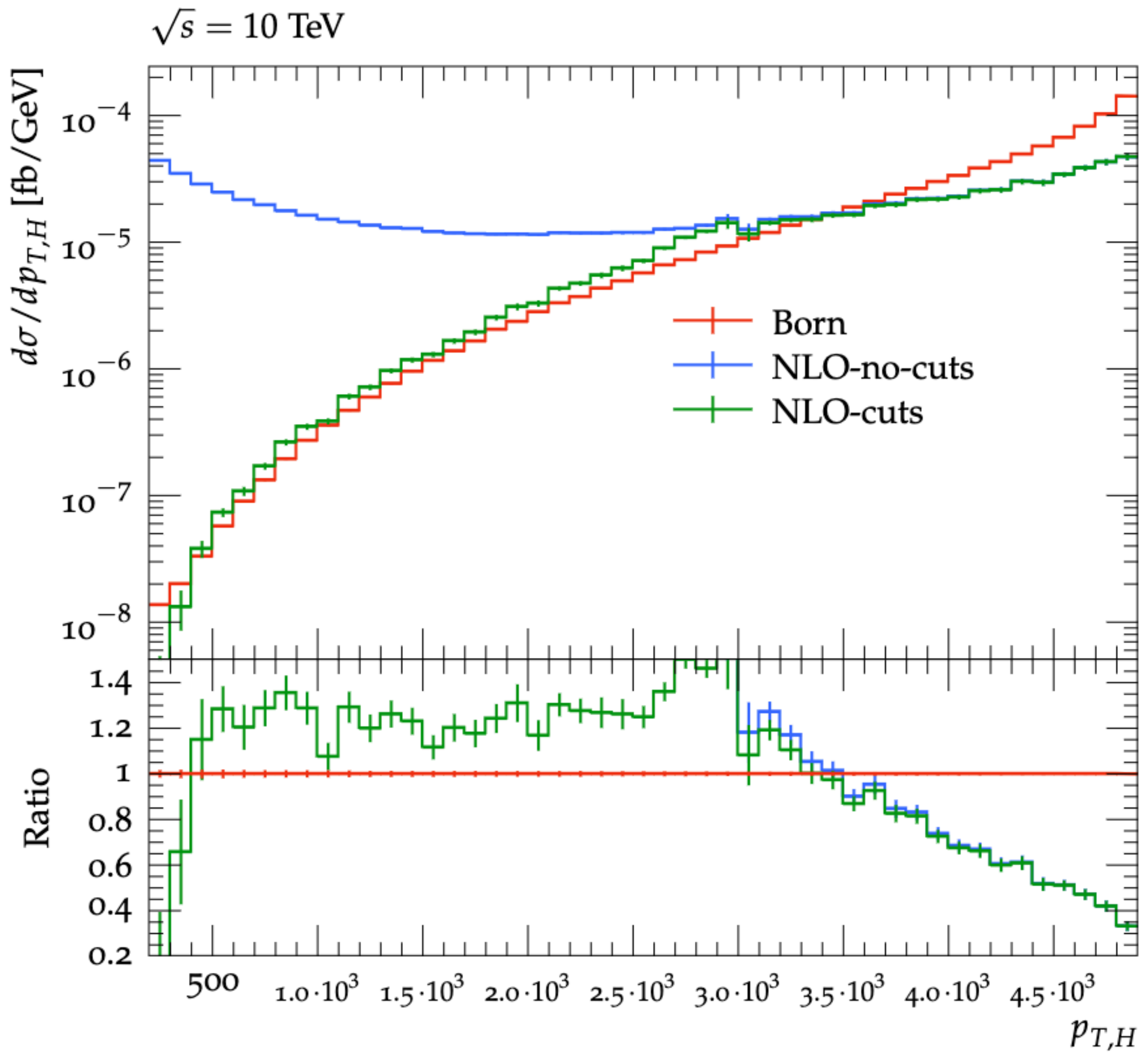

arXiv: 2208.09438

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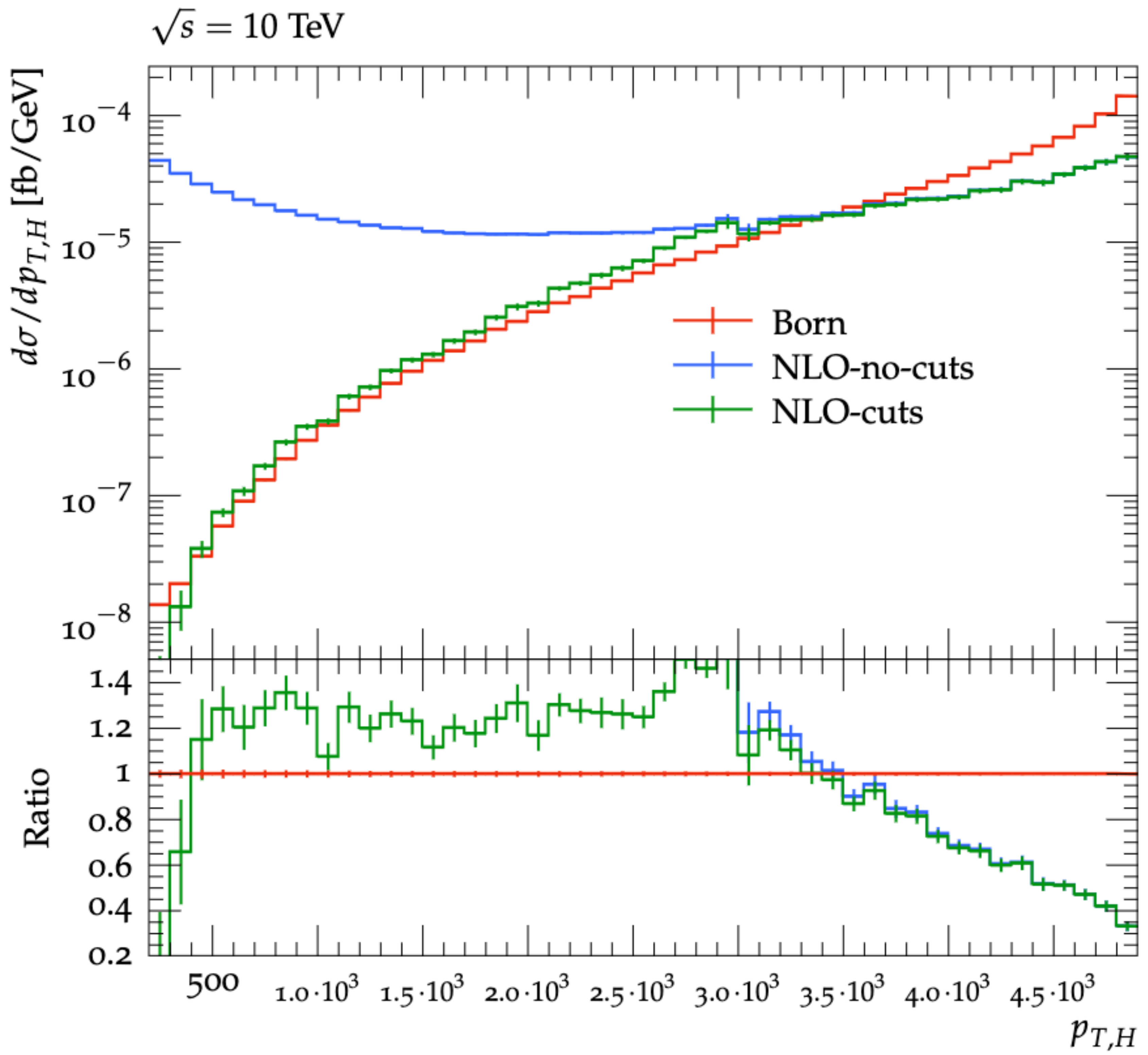
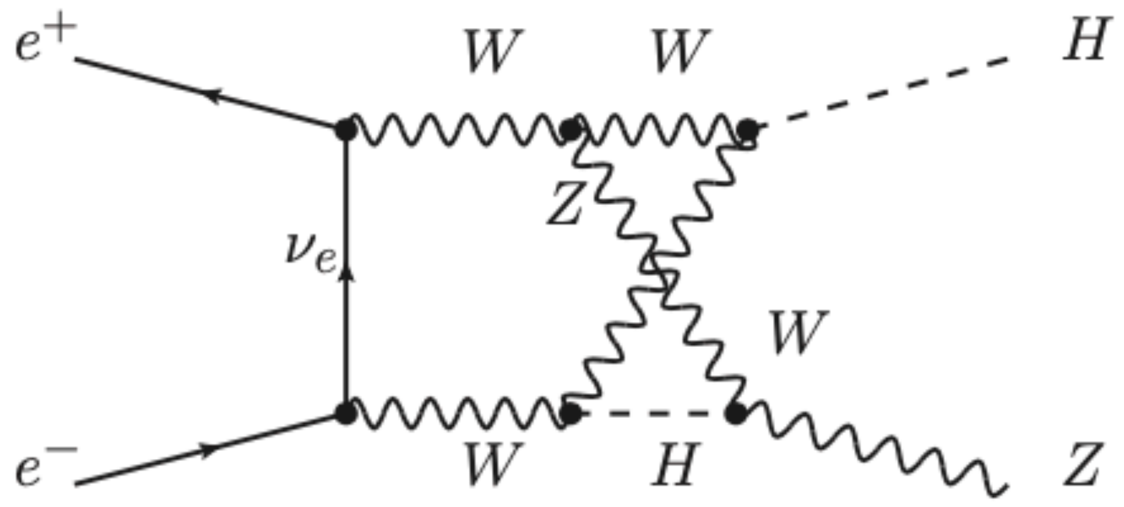
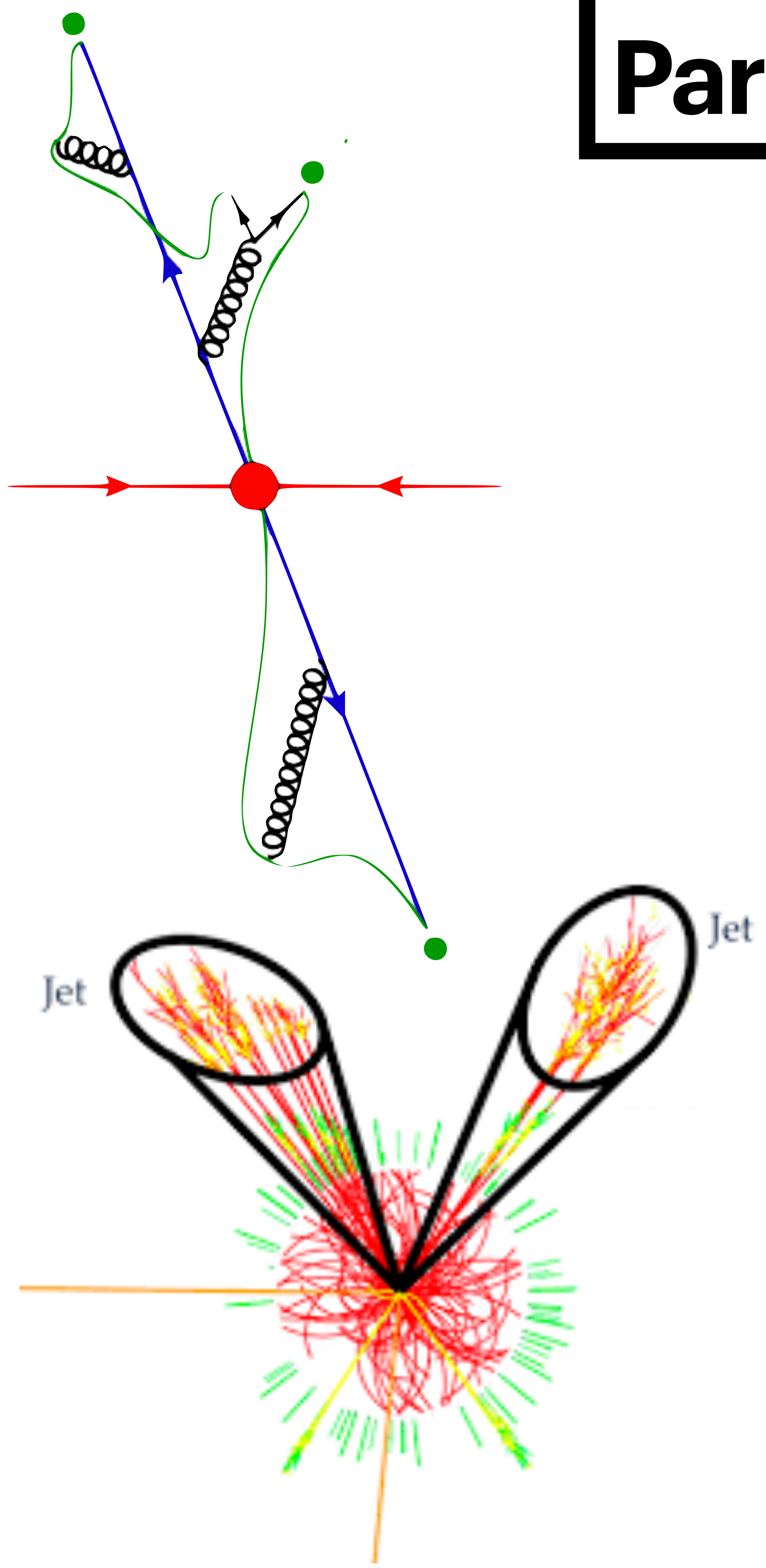




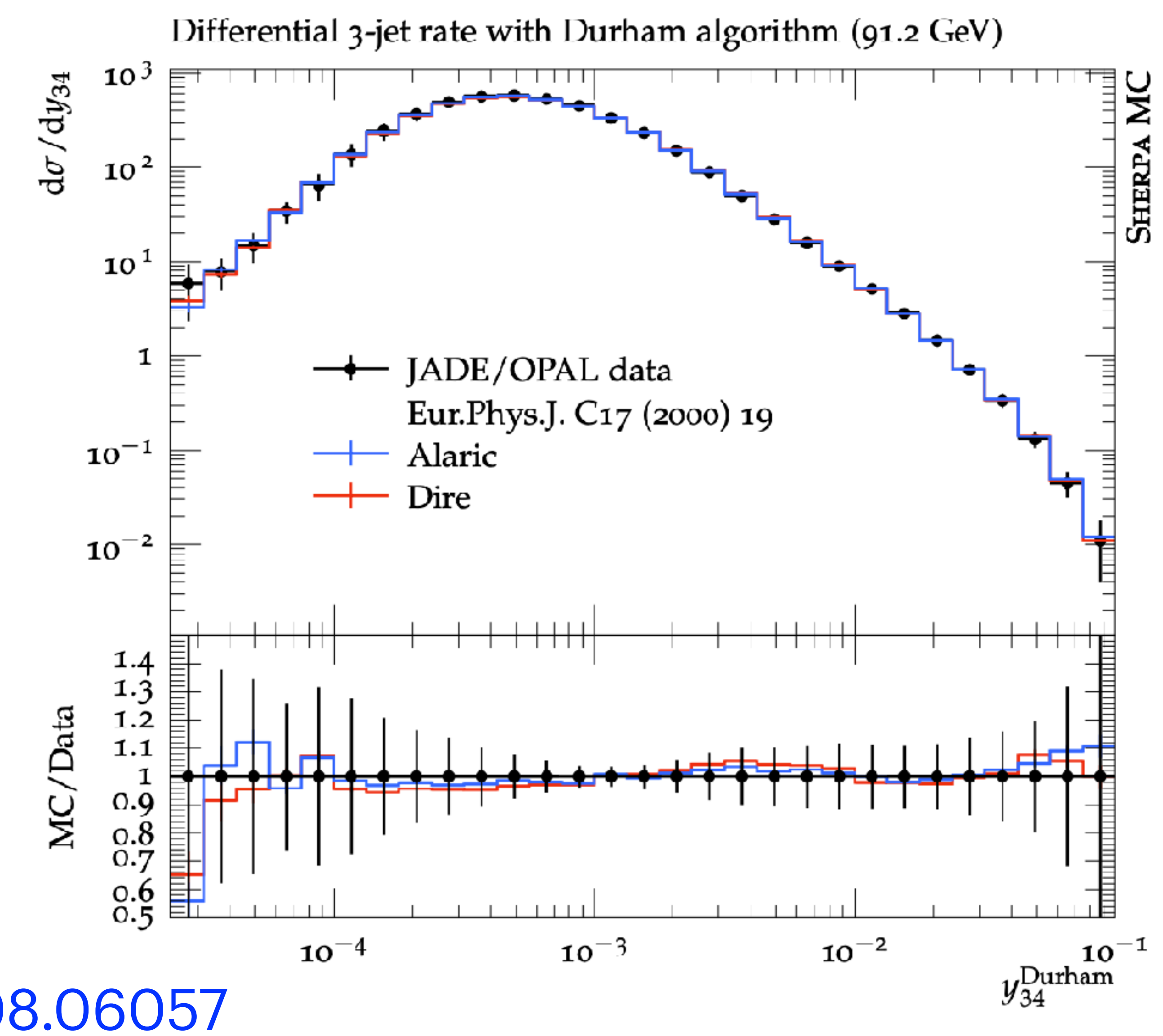
Three major bottlenecks to go to NNLO

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

Parton Showers, Matching, Merging, Hadronization



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



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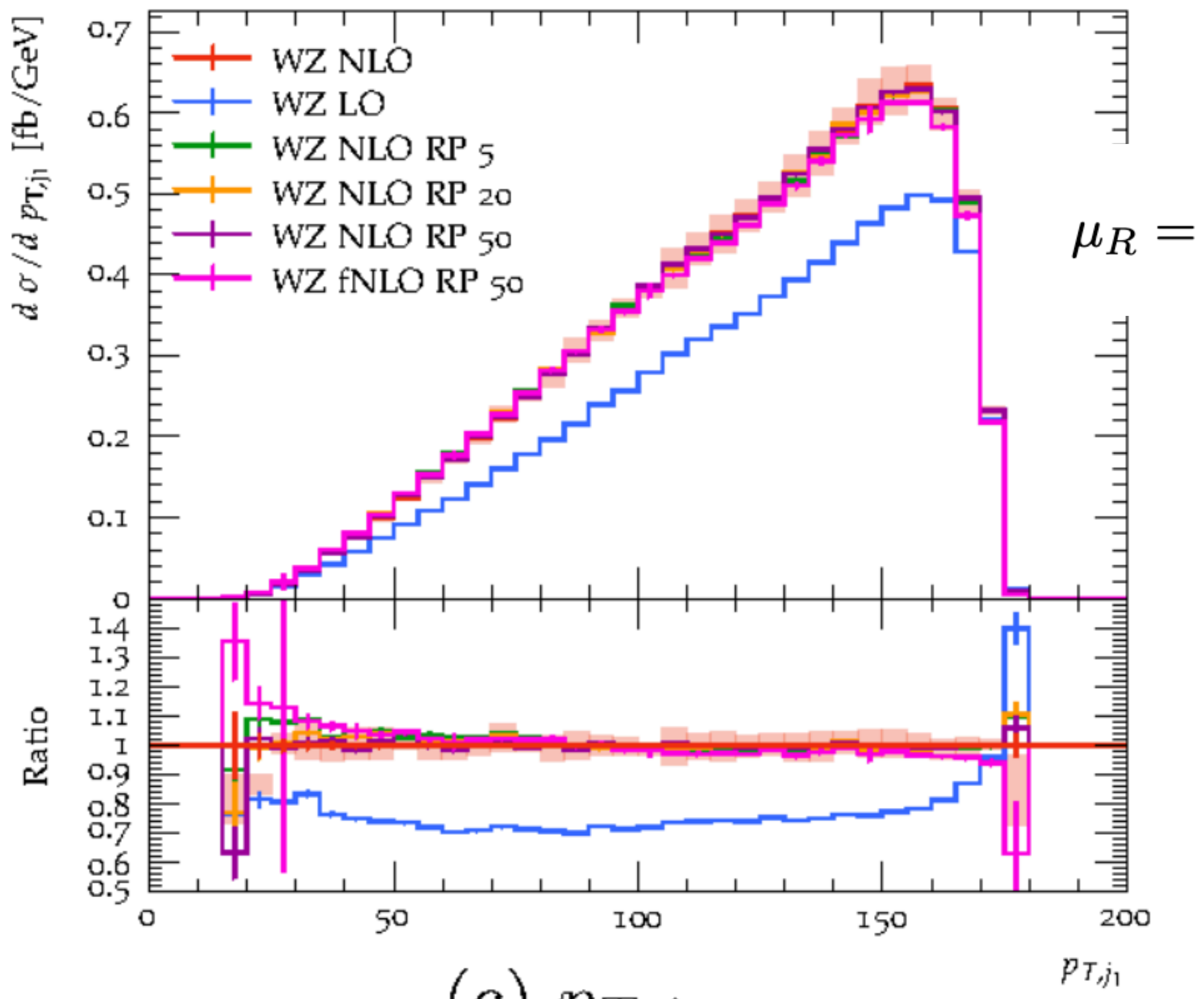

(c) p_{T,j_1}

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

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

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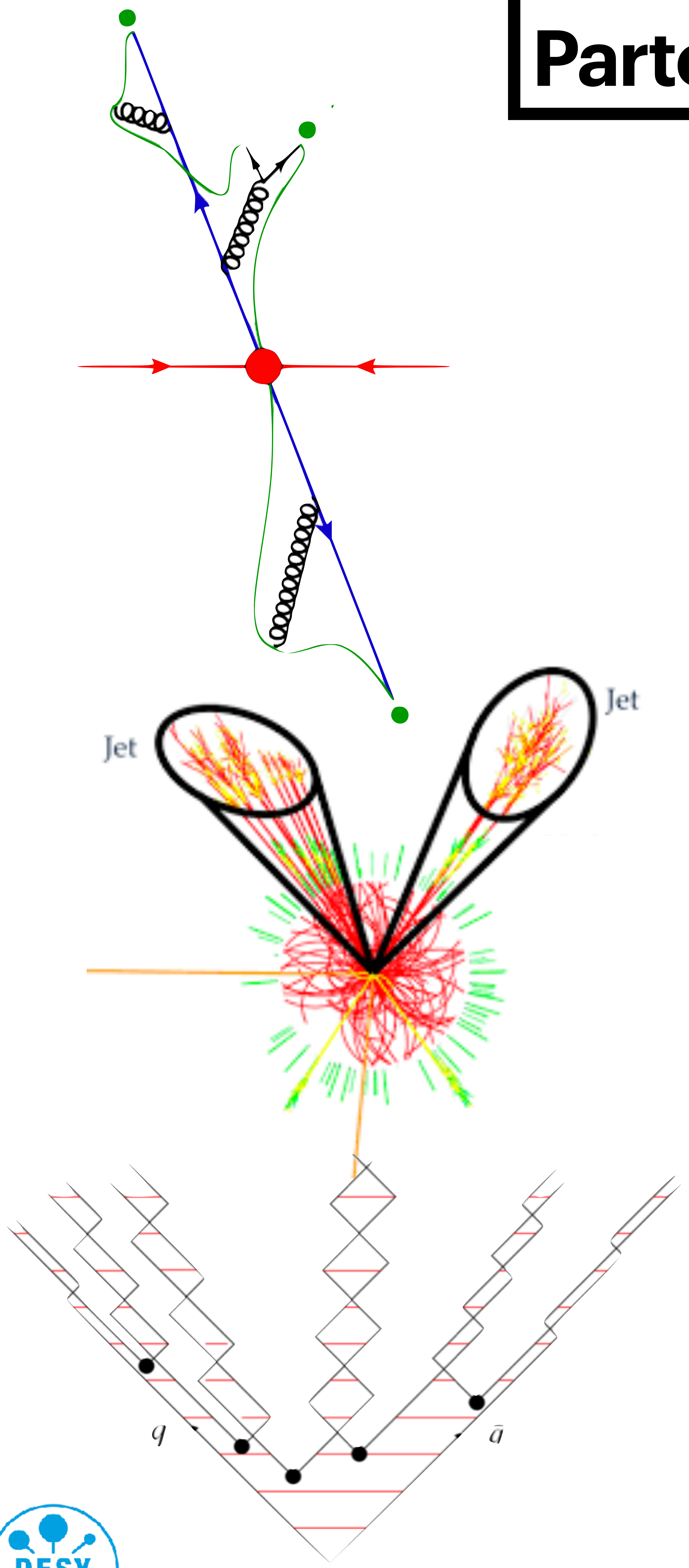

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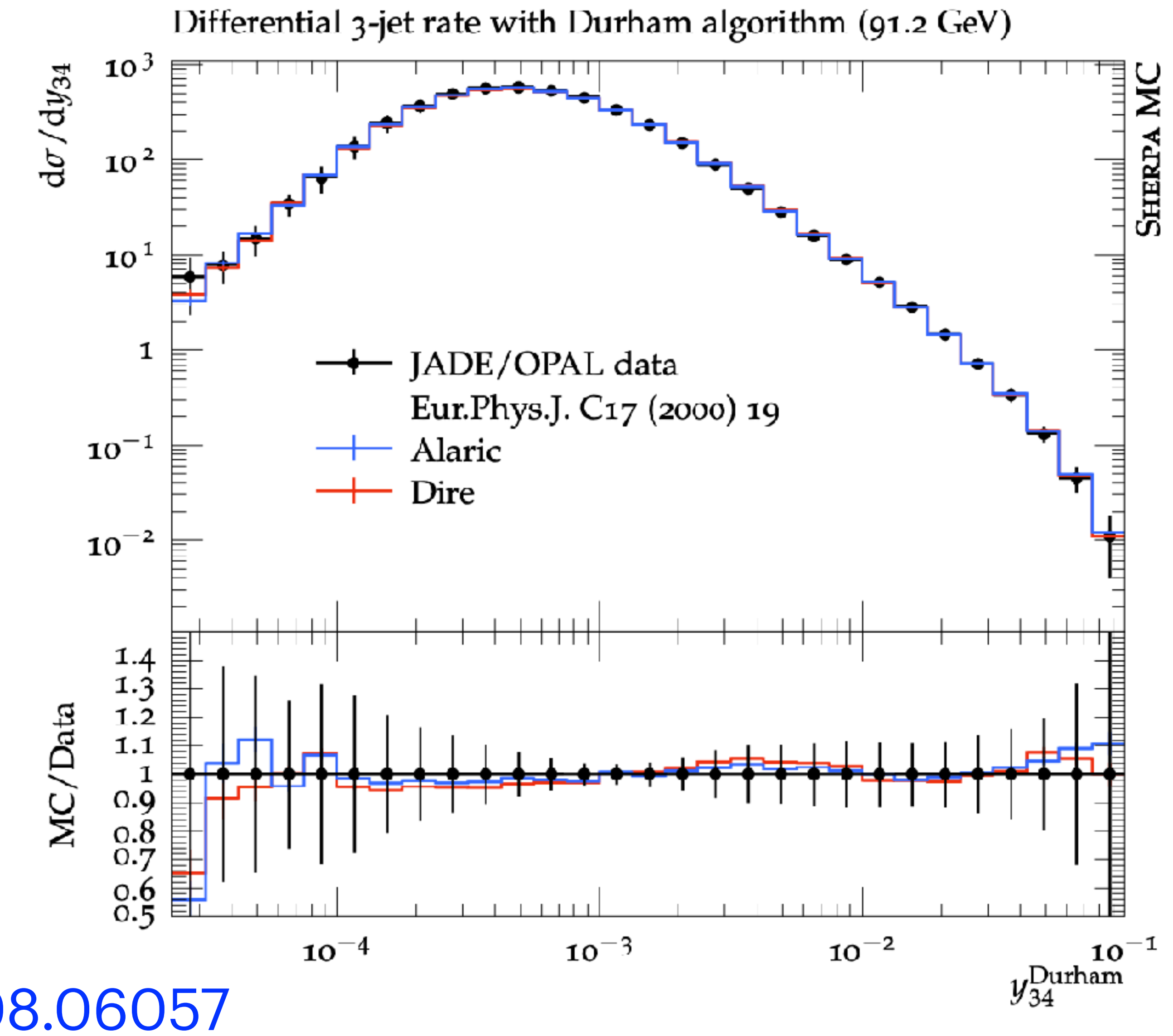

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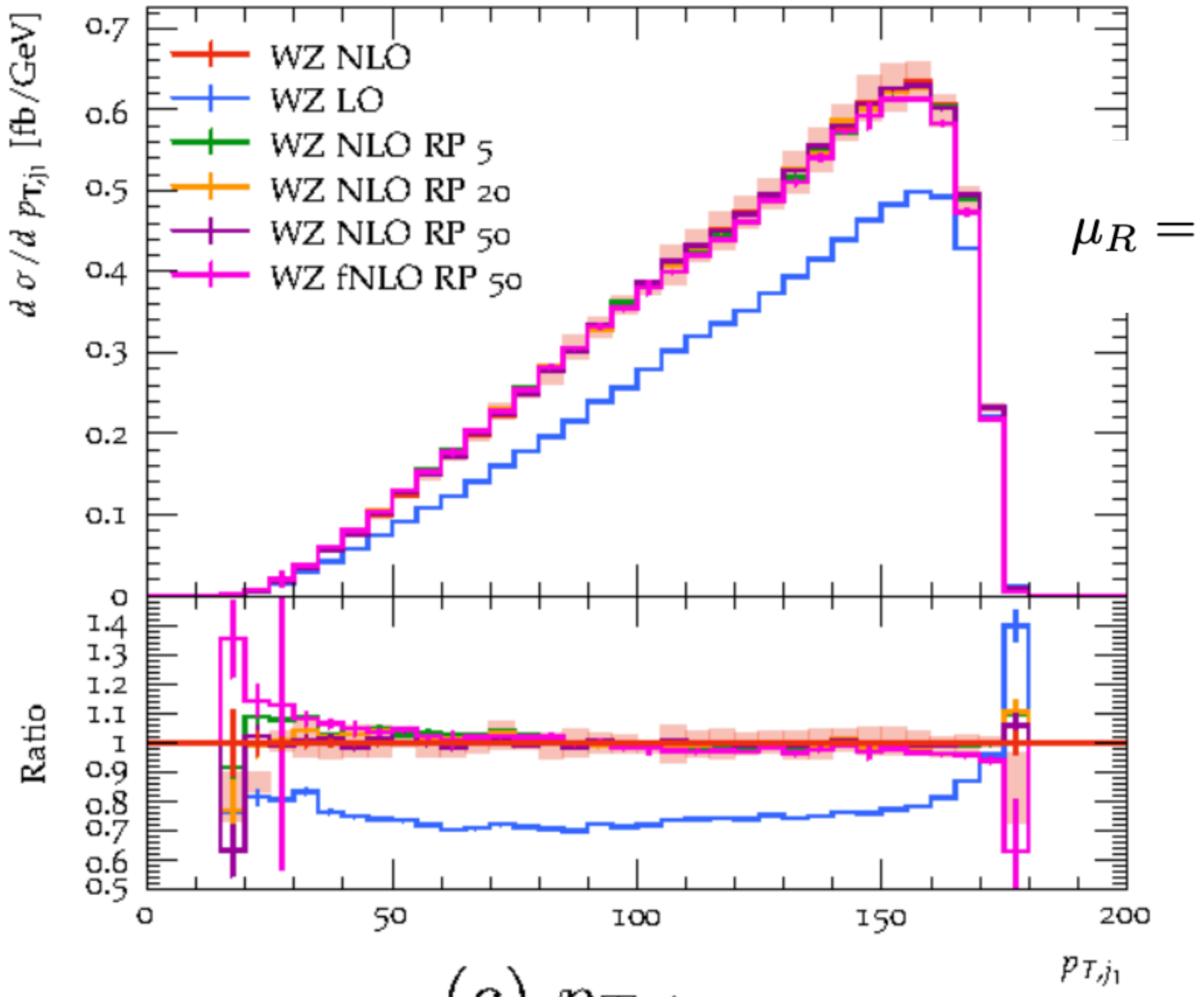

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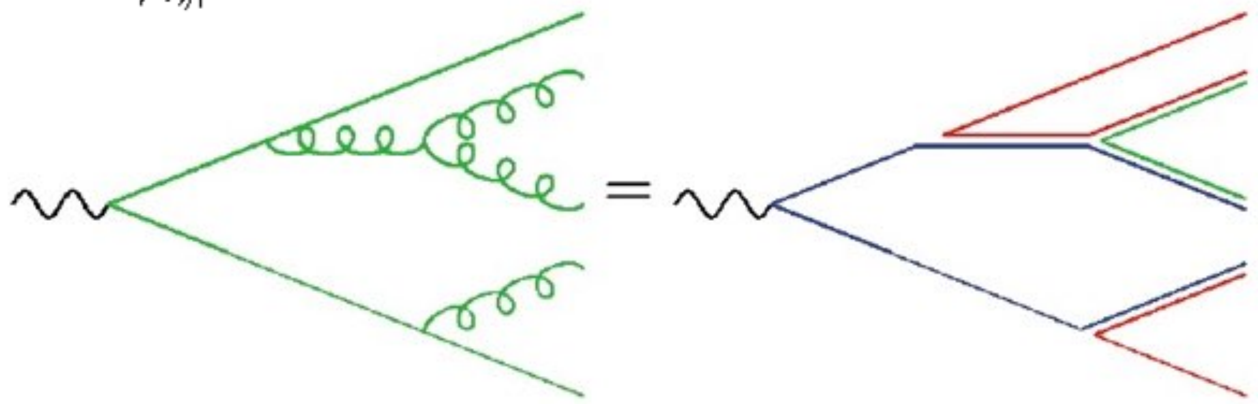
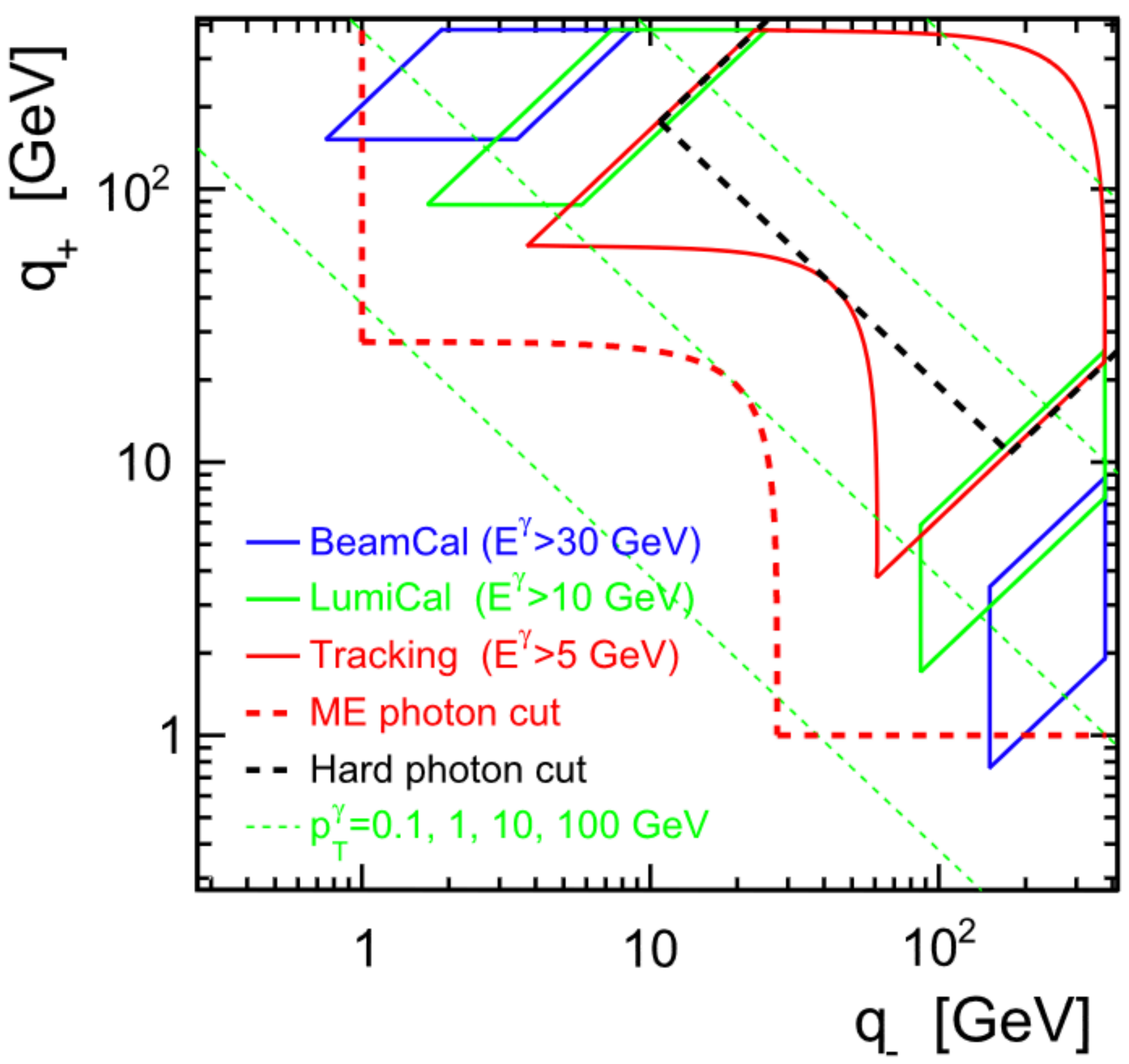
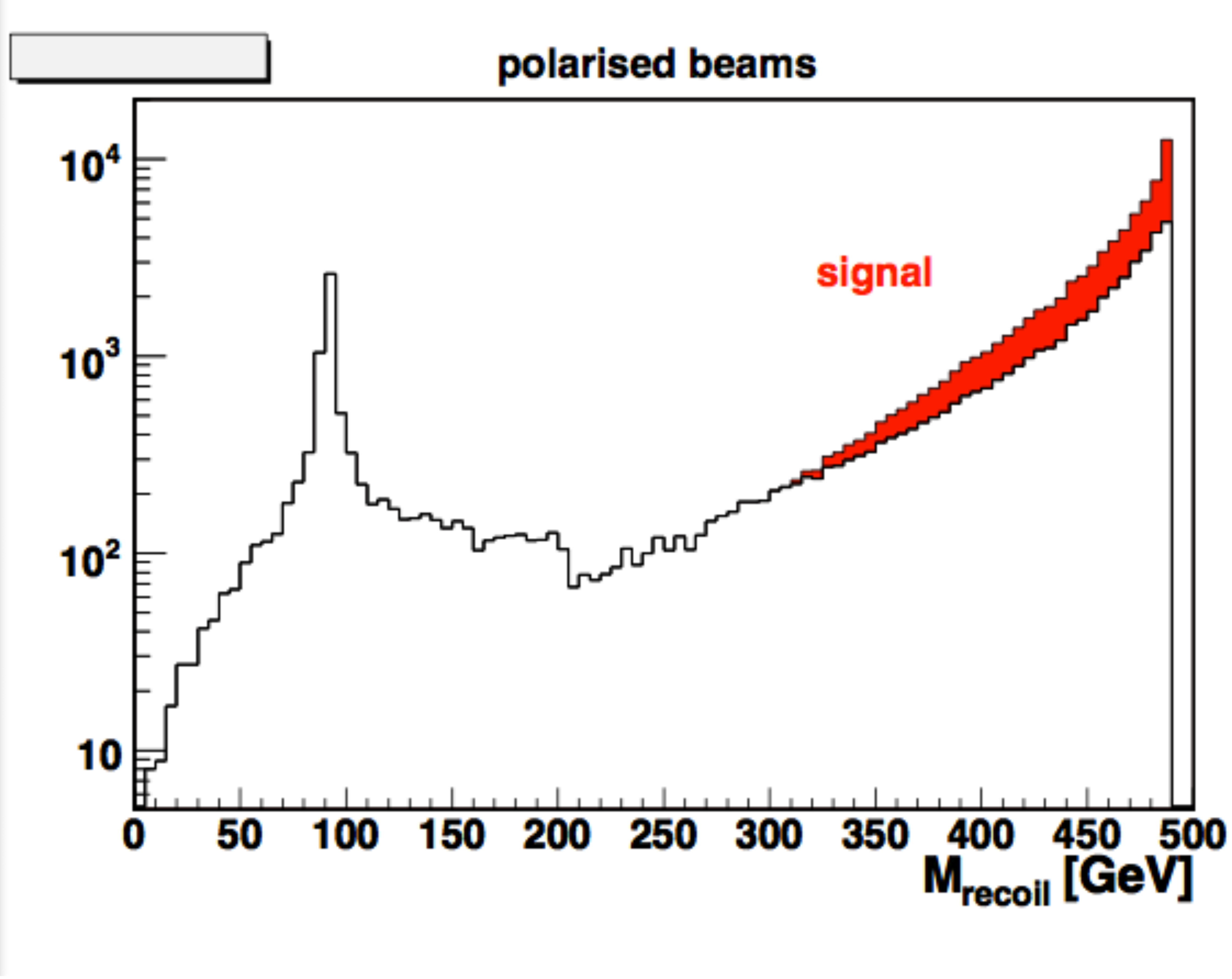
$\mu_R = H_T/2$ with $H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$

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



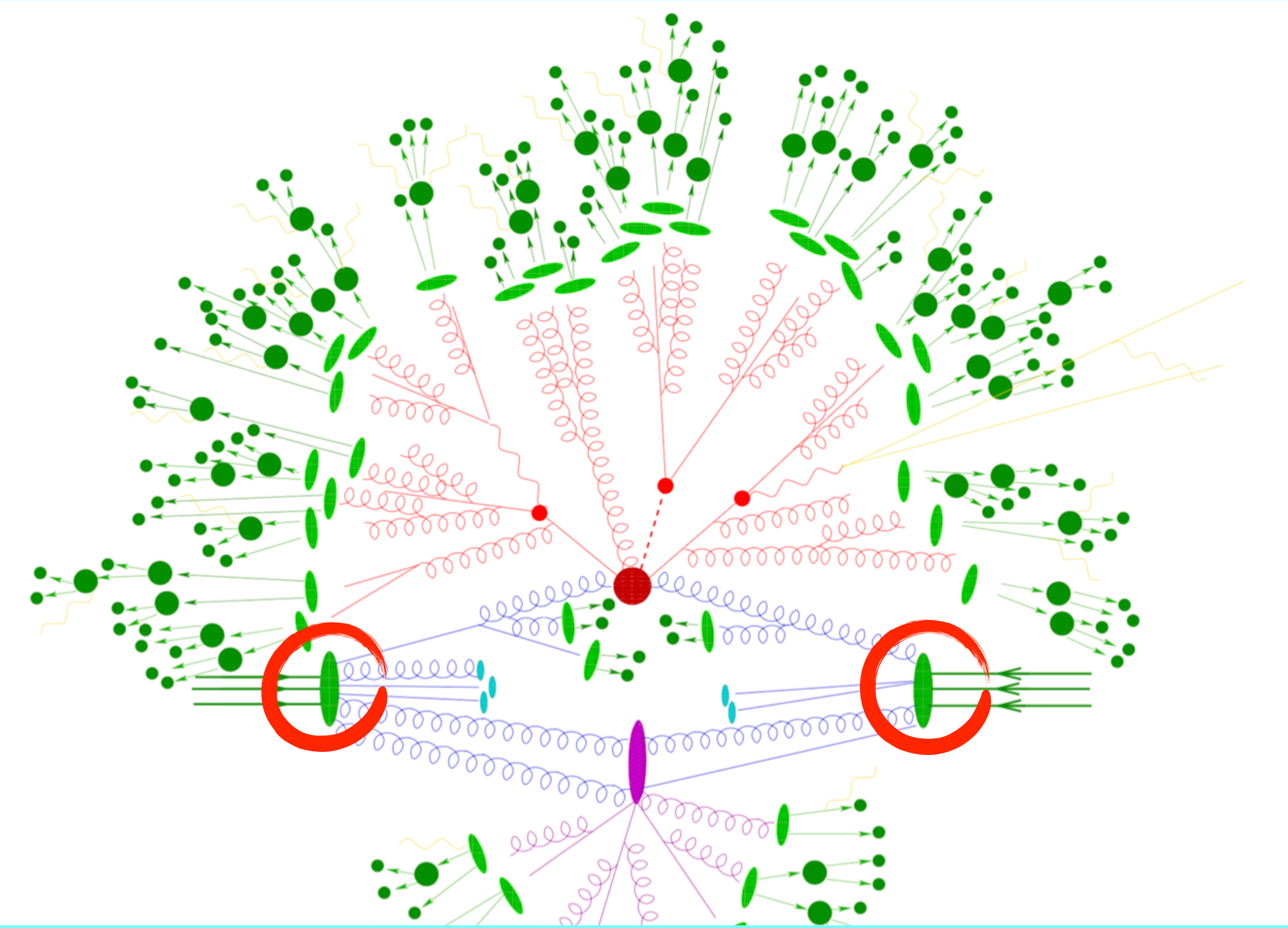
Exclusive Photon Simulation





- Exclusive photon distribution important for detector optimization / mono-photon searches etc.
- Different algorithms: QED shower, soft/eikonal resummation (YFS), recursive algorithms

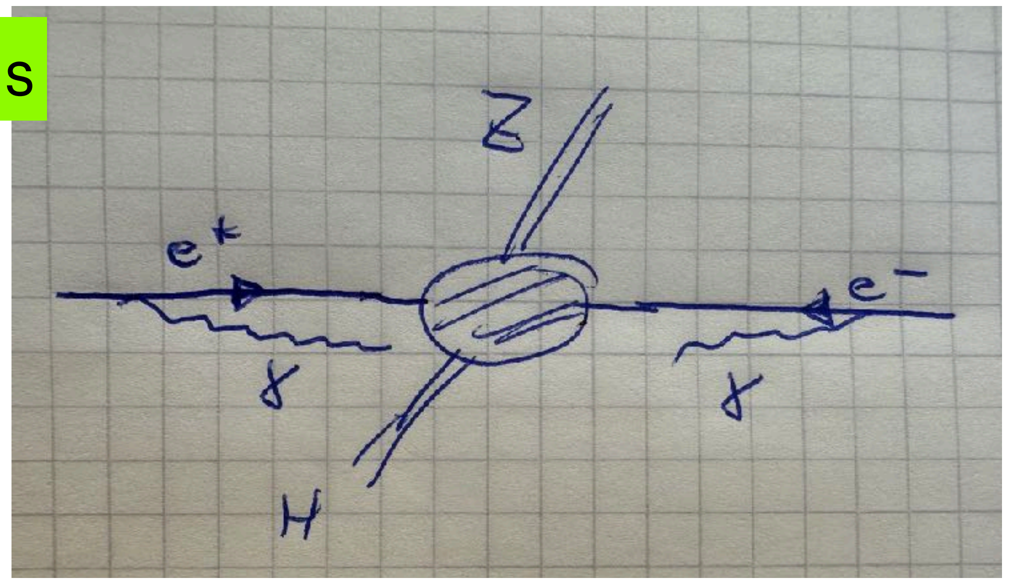
Initial State Radiation — Lepton PDFs



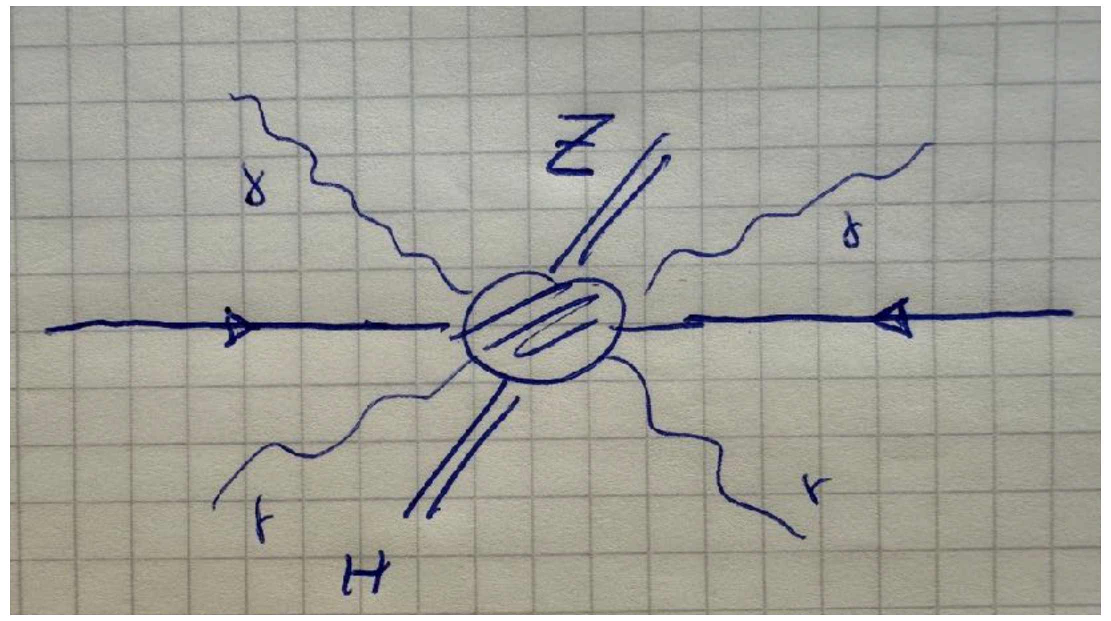
QED PDFs — QED Initial State Resummation

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

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

- For QCD: non-perturbative bound-state PDFs need to be fitted from data
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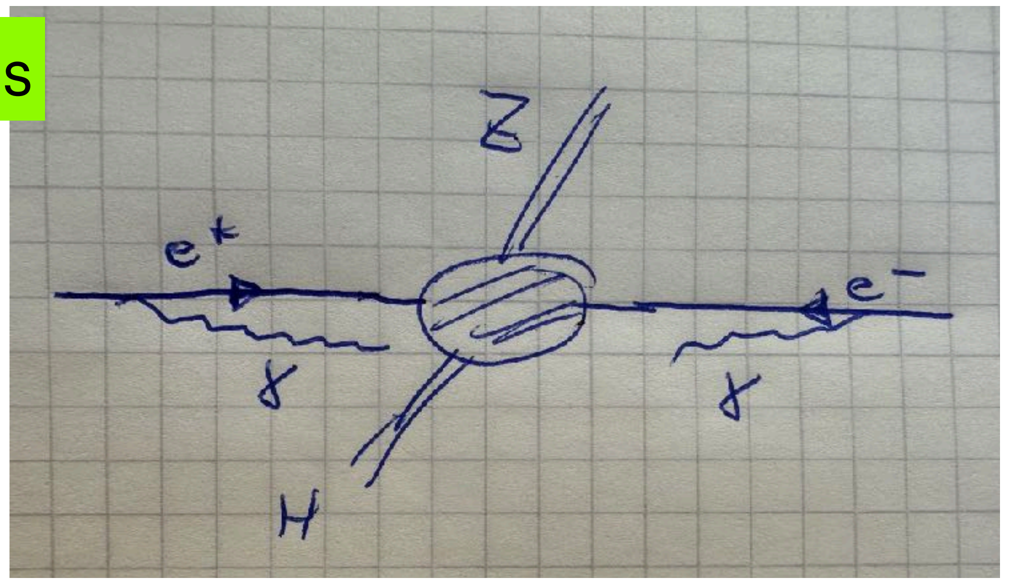

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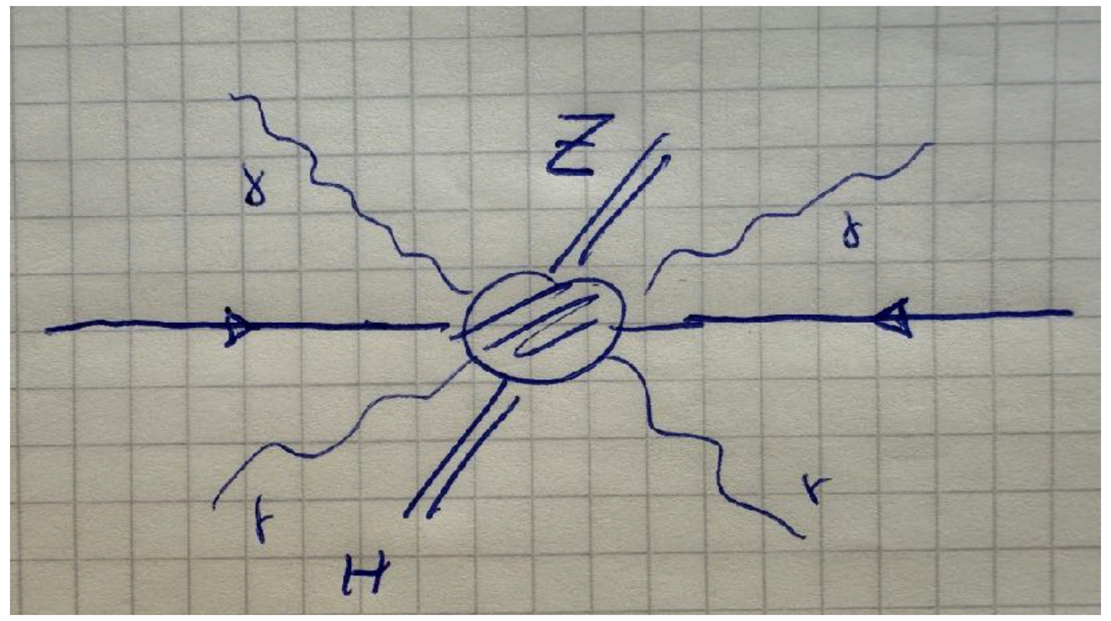

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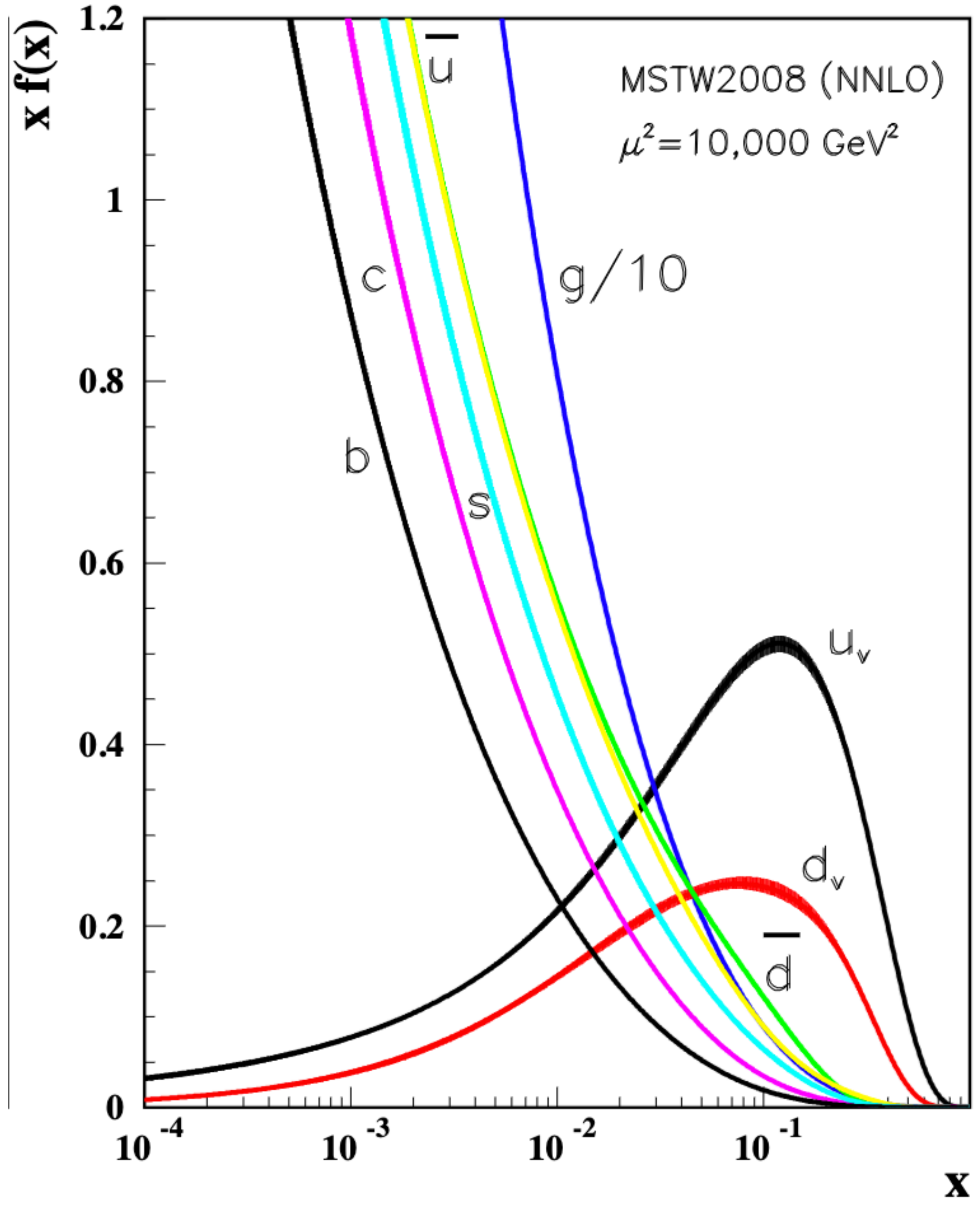

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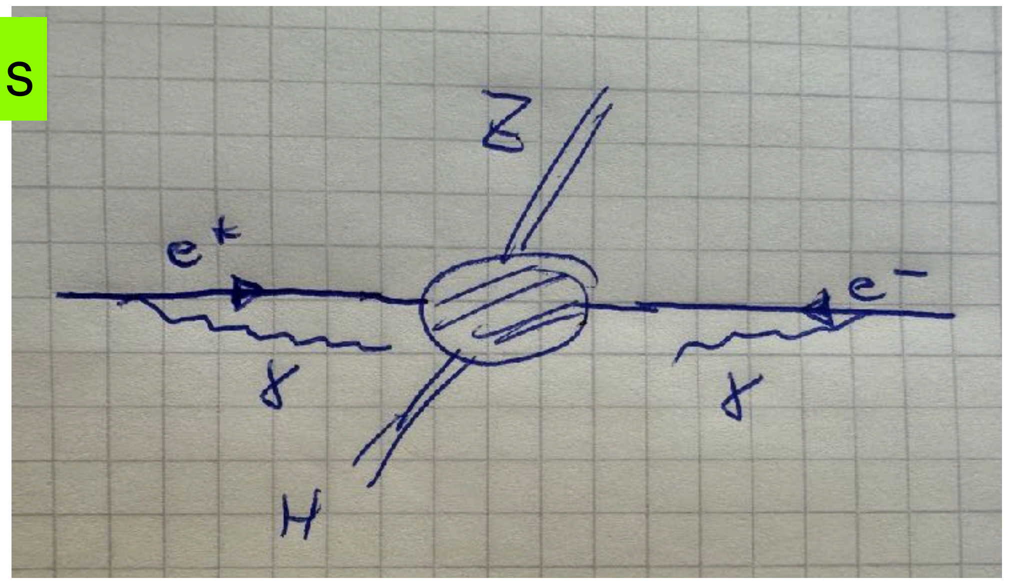

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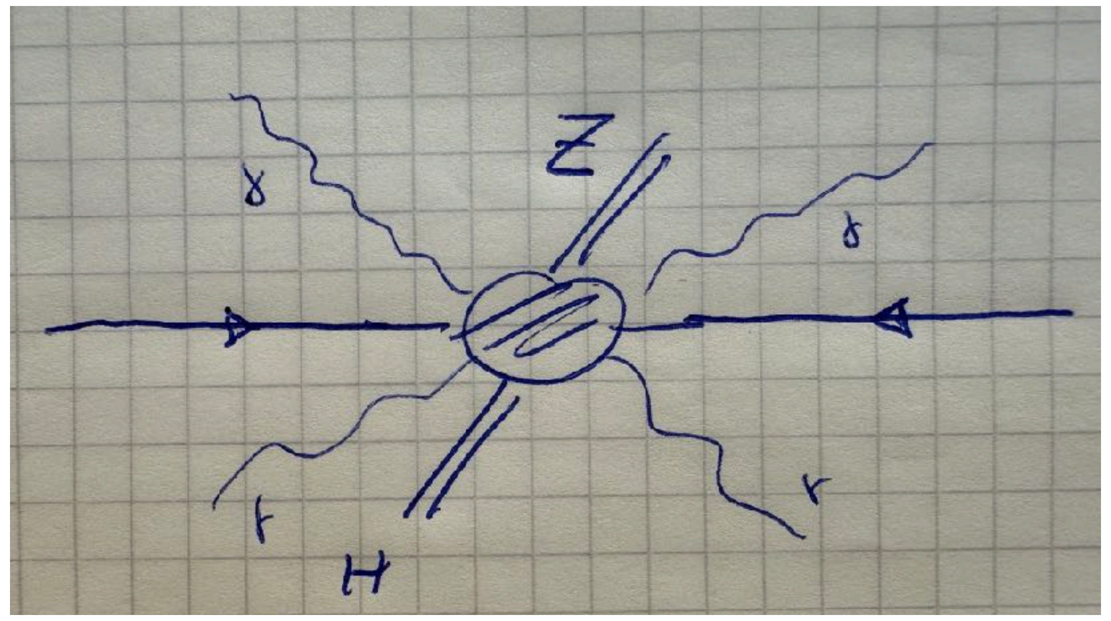

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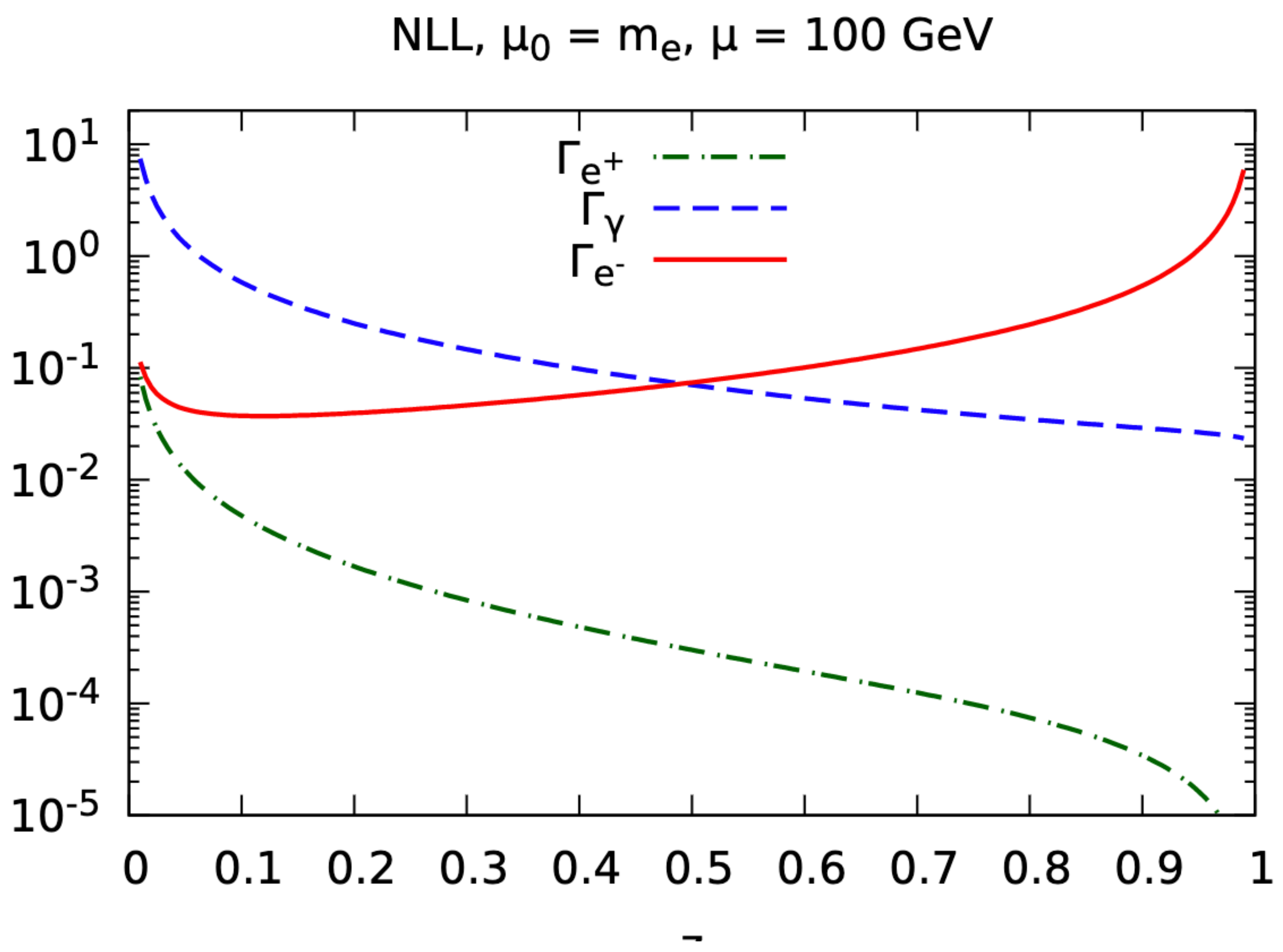
Integrable power-like singularity 1/(1-z) for $z \to 1$



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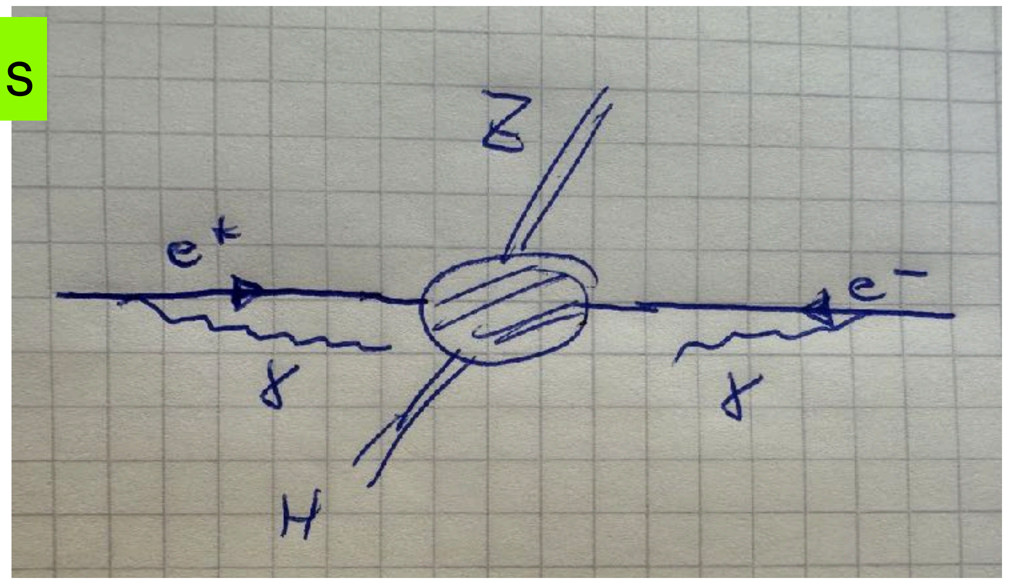
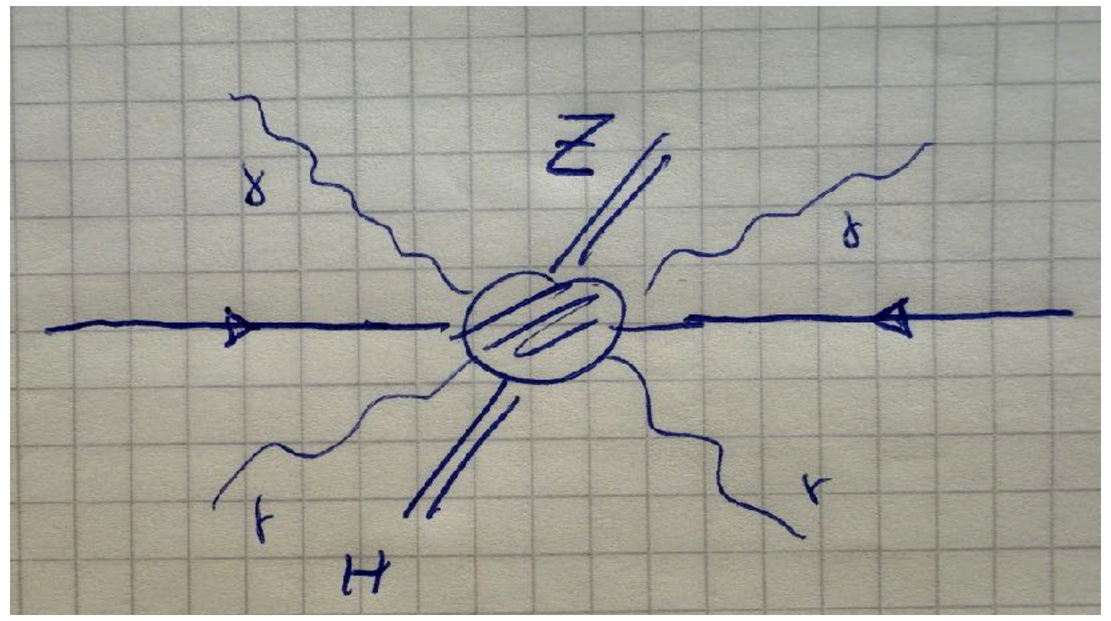


$$\sigma = \alpha^b \sum_{n=0}^{\infty} \alpha^n \sum_{i=0}^{n} \sum_{j=0}^{n} \varsigma_{n,i,j} L^i \ell^j$$



Soft logarithms

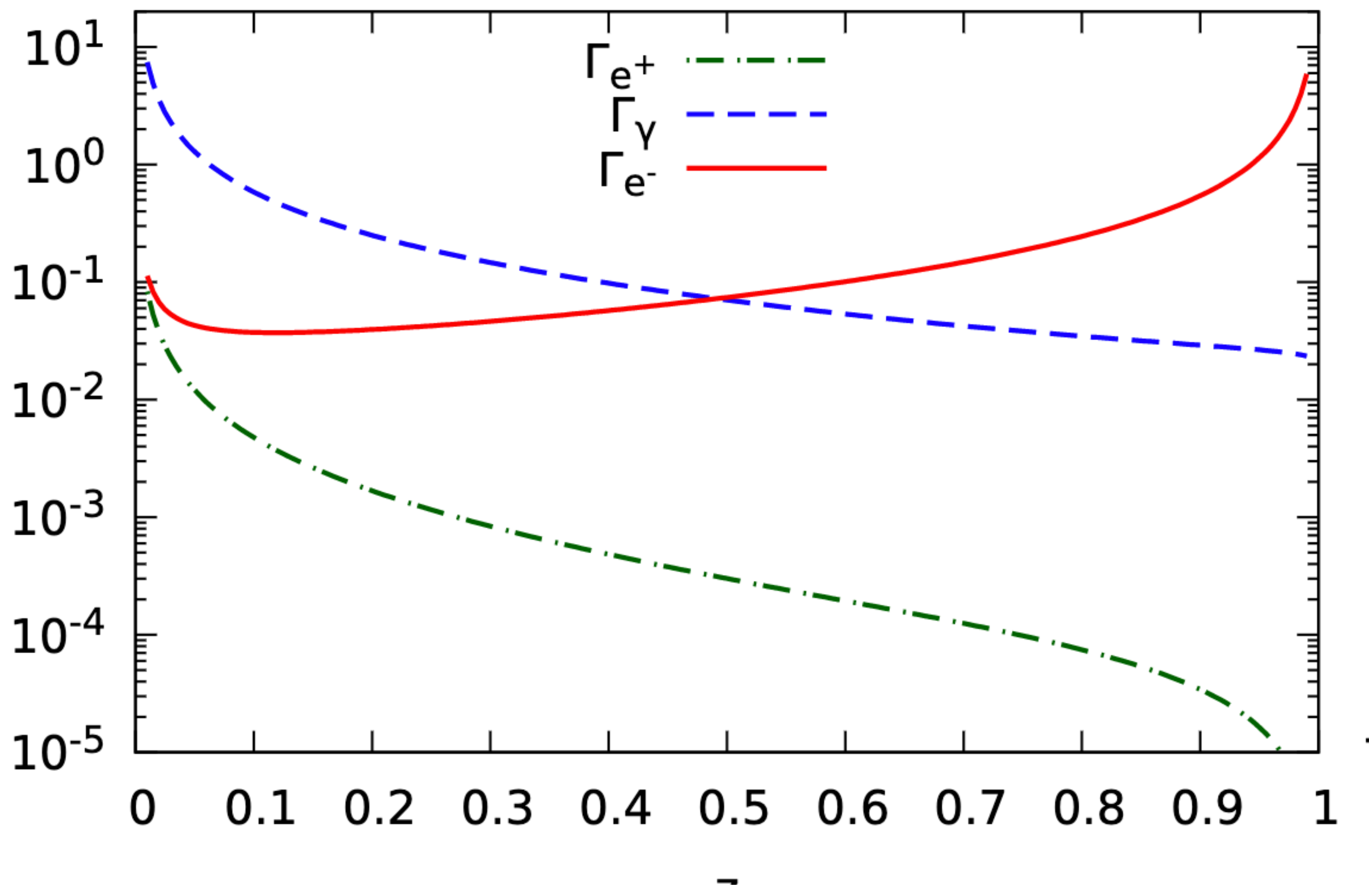
$$\ell = \log \frac{Q^2}{\langle E_\gamma \rangle^2}$$

- For QCD: non-perturbative bound-state PDFs need to be fitted from data
- For QED / EW: calculable from first principle (collinear factorization)

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

- QED PDFs = electron/ISR structure functions, ISR structure functions
- Gives most precise normalization of total cross section
- Very intricate numerical behavior at peak, especially at NLO
- "Photon PDF" (a.k.a. EPA, Weizsäcker-Williams) Γ_γ, peaked at small z

NLL, $\mu_0 = m_e$, $\mu = 100$ GeV



FCC-hh / MuC / PWFA: SM PDFs — SM Collinear Factorization

- Collinear factorization not in QED, but in full SM   Han/Ma/Xie, 2007.14300, 2103.09844; Garosi/Marzocca/Trifinopoulos, 2303.16941
- Fully inclusive in collinear/forward/beam direction
- At very (, very) high energies lepton colliders become $\gamma\gamma/VV$ colliders   (like LHC is gg)
- Work in progress in Krakow, DESY, Pittsburgh
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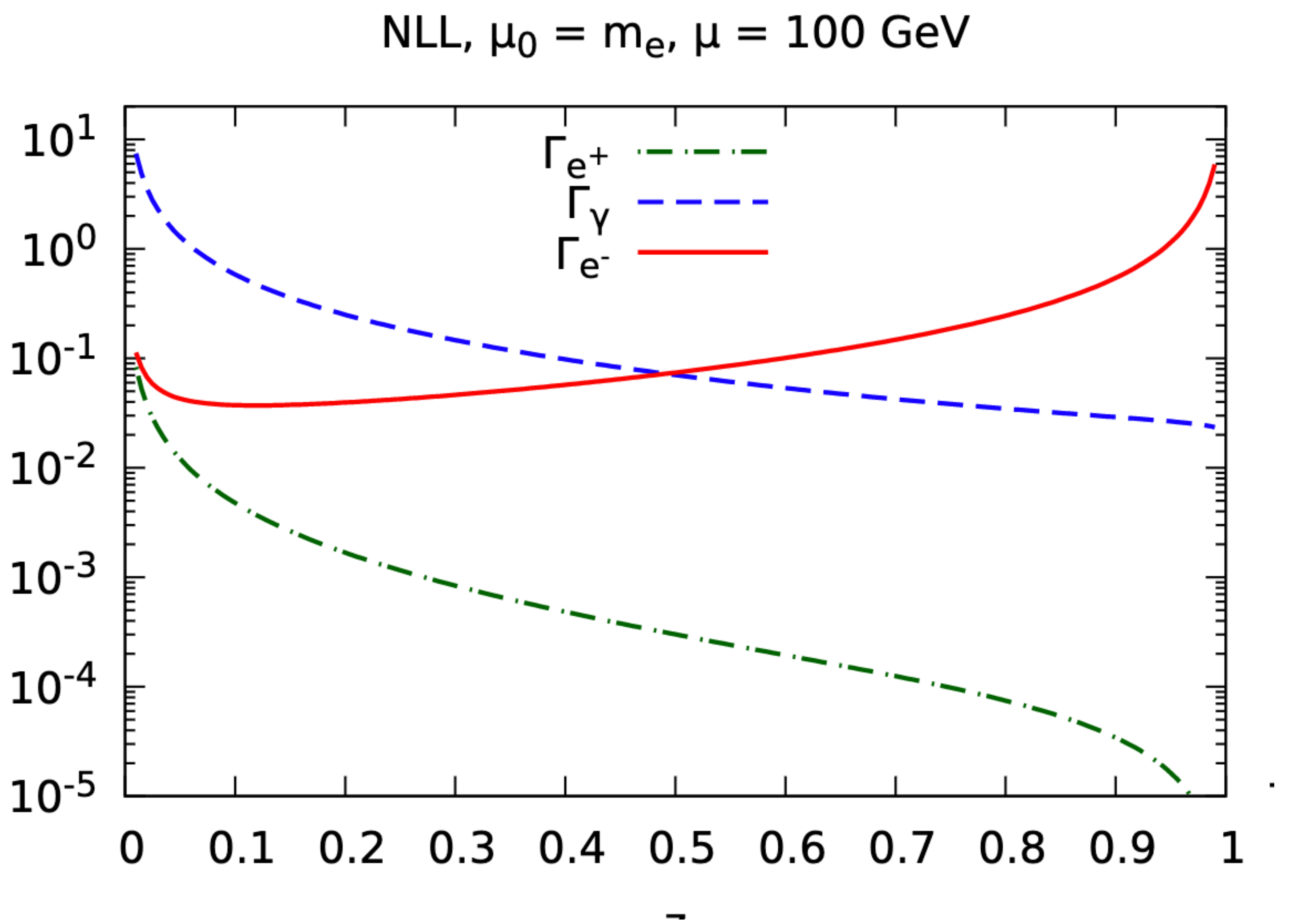

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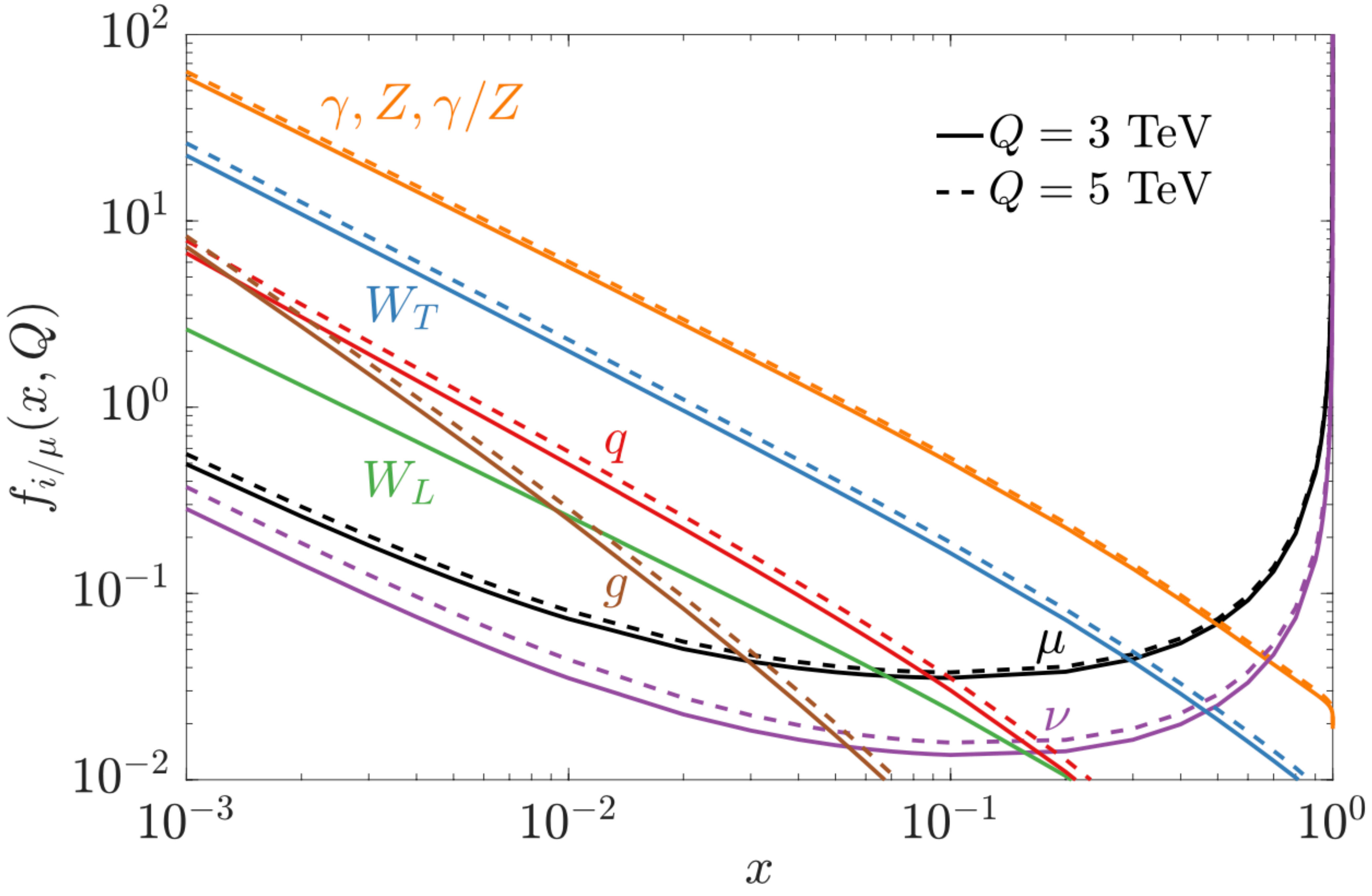

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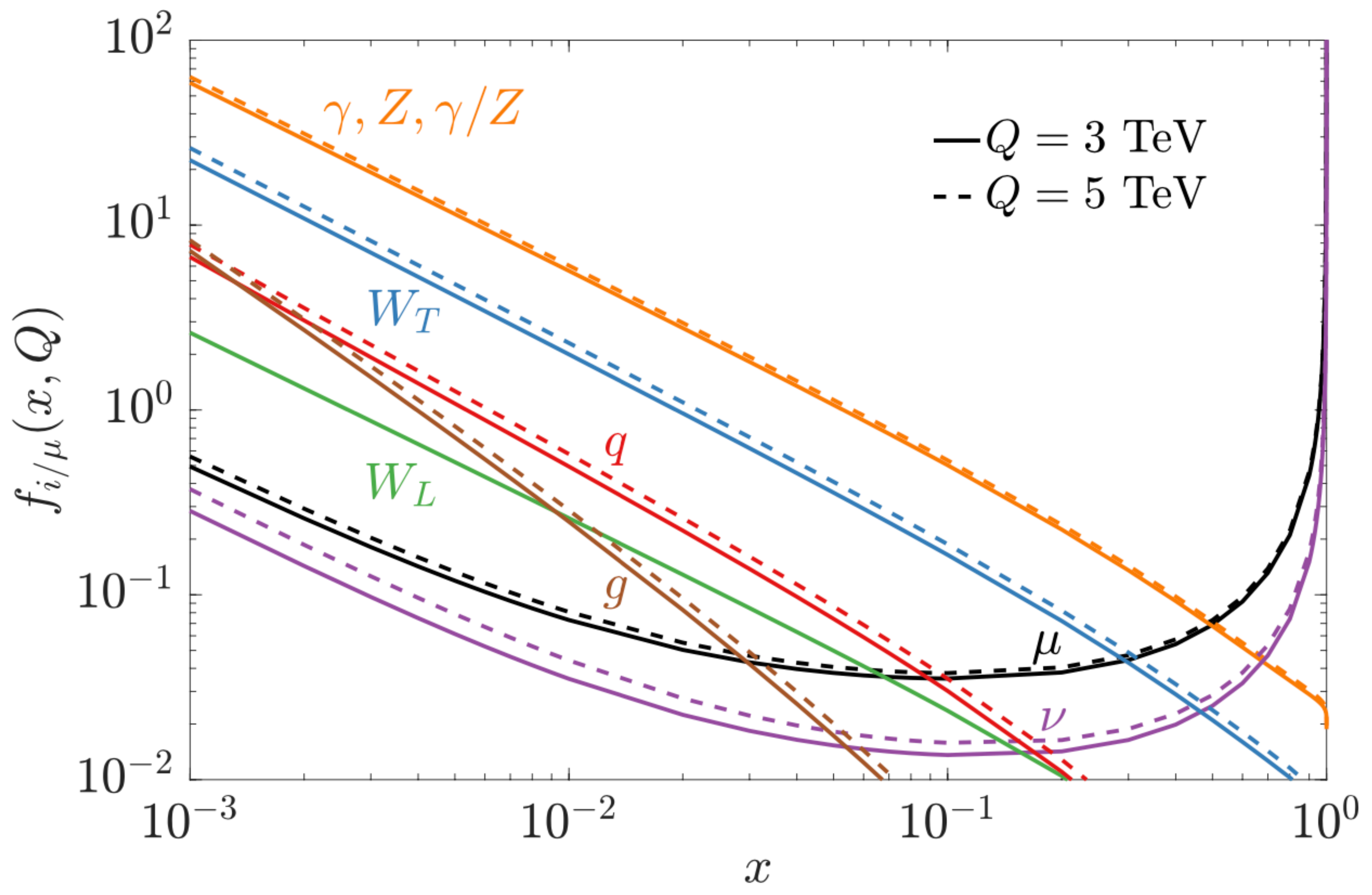

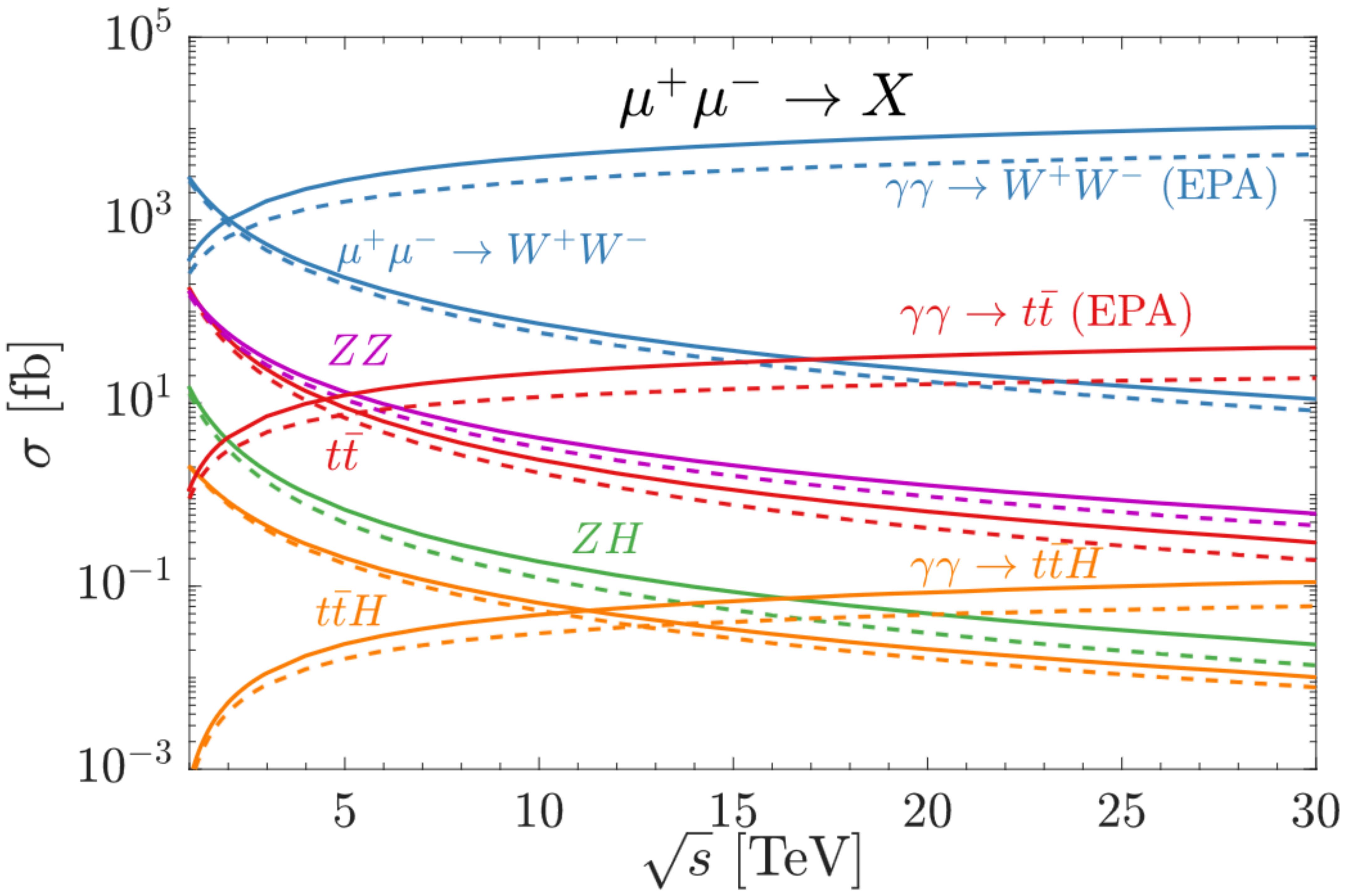

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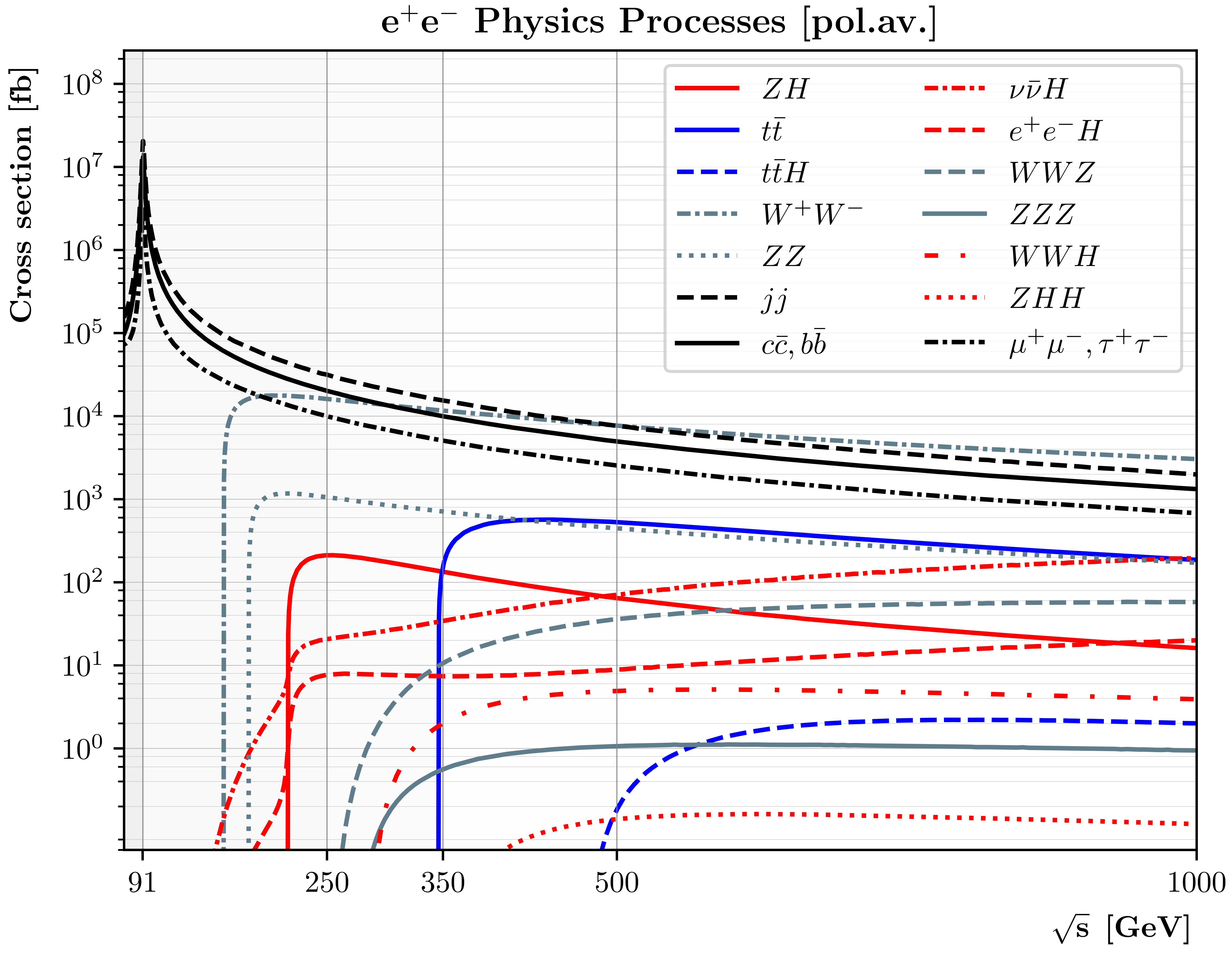

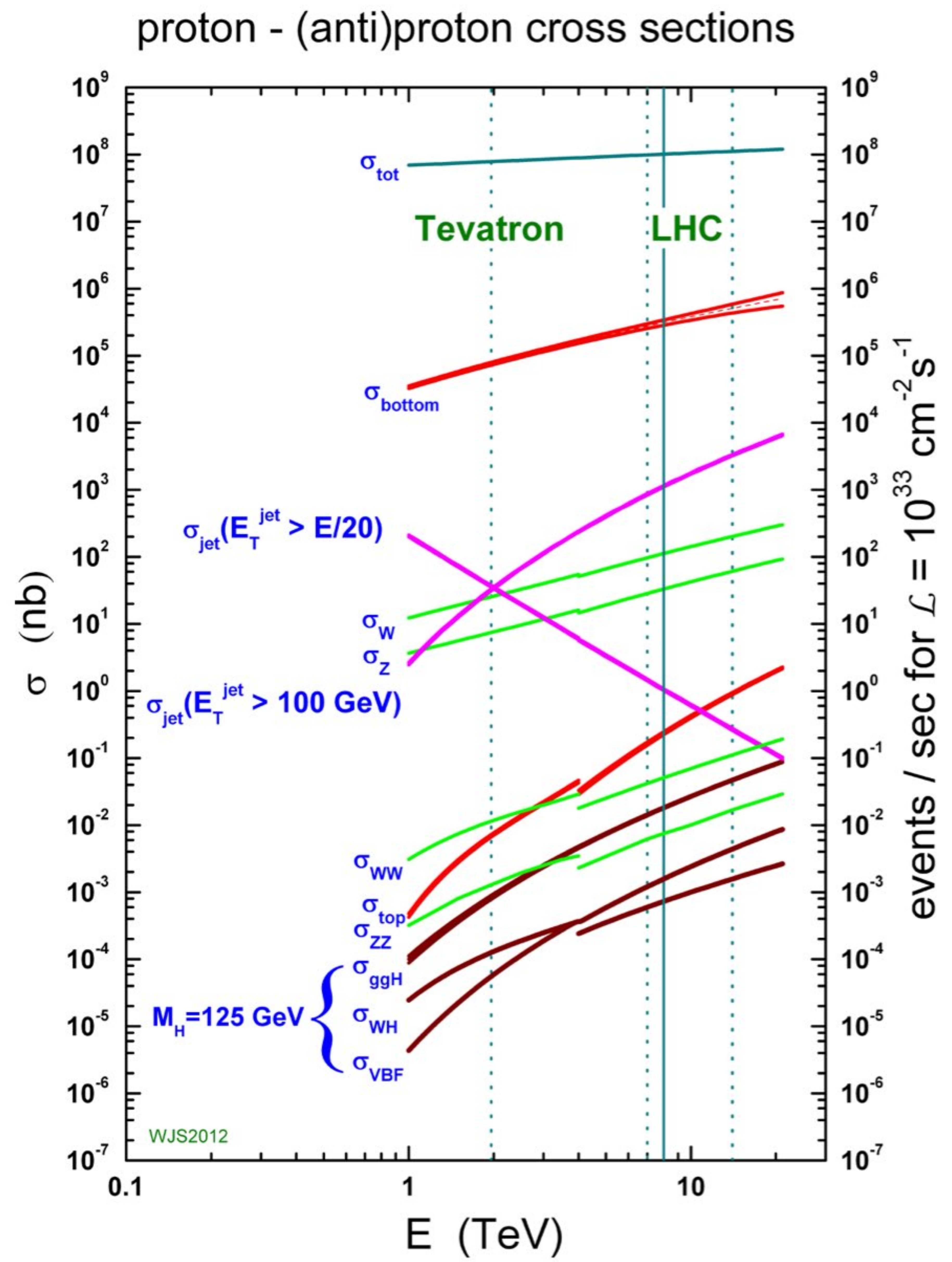

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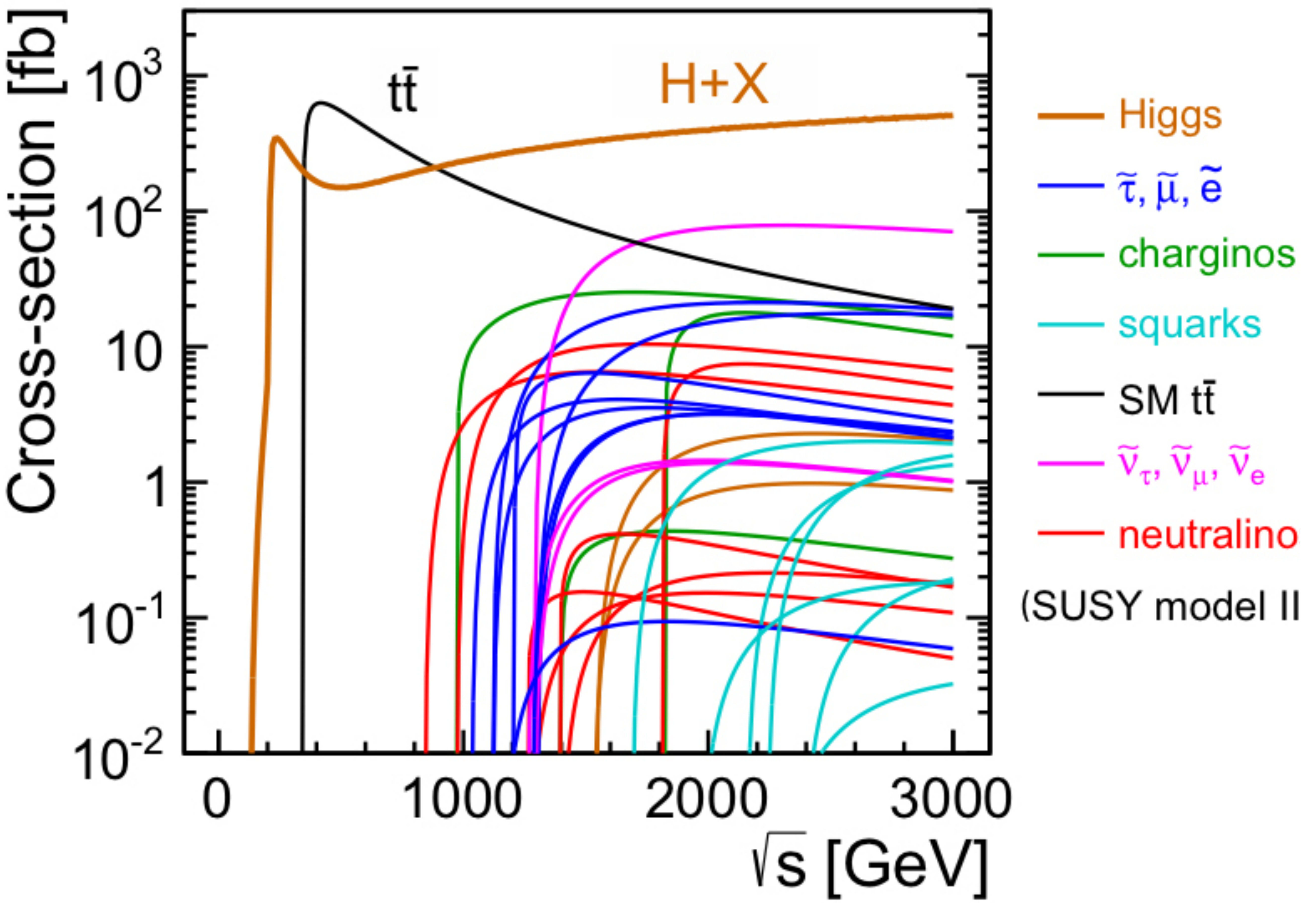
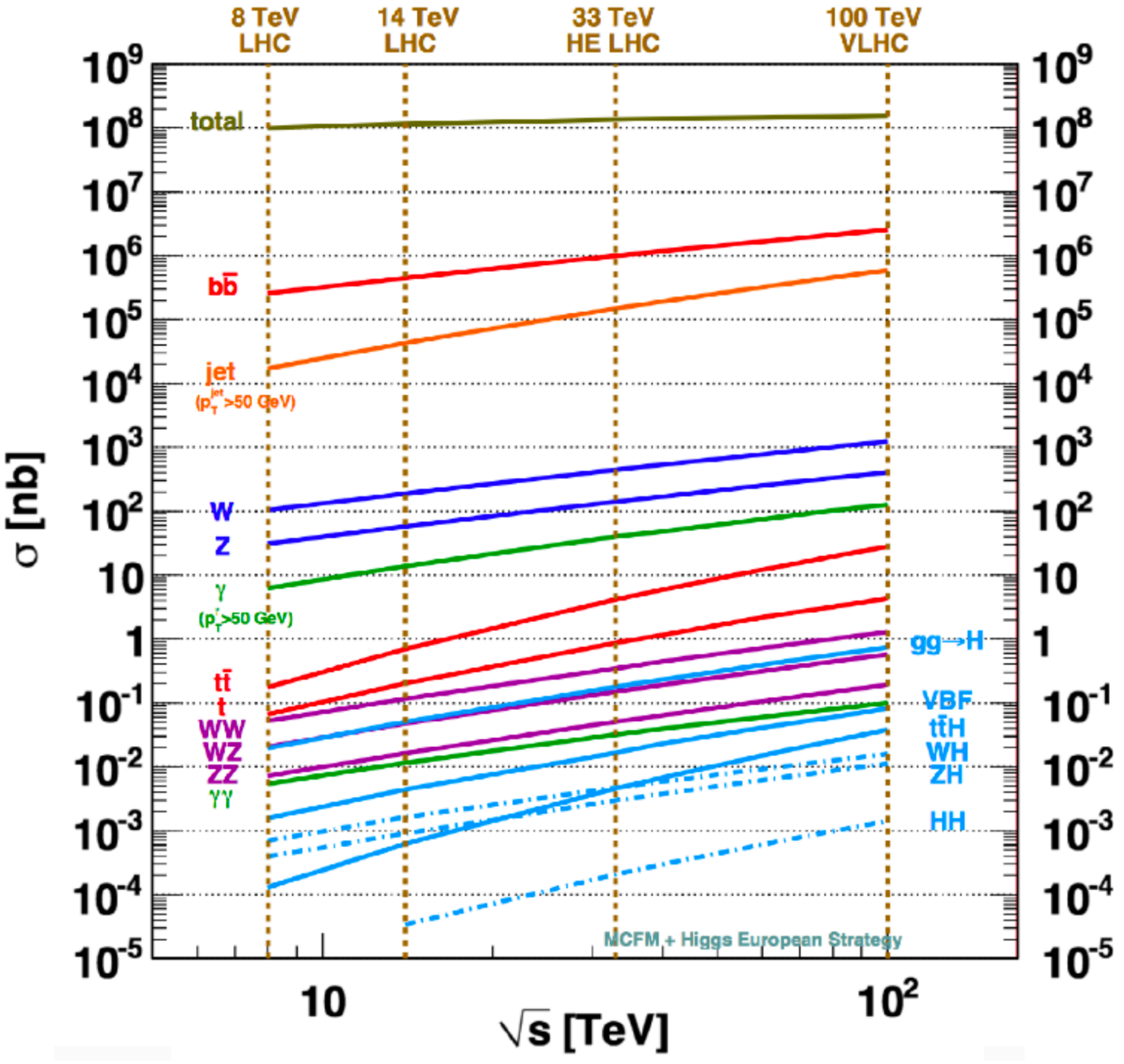
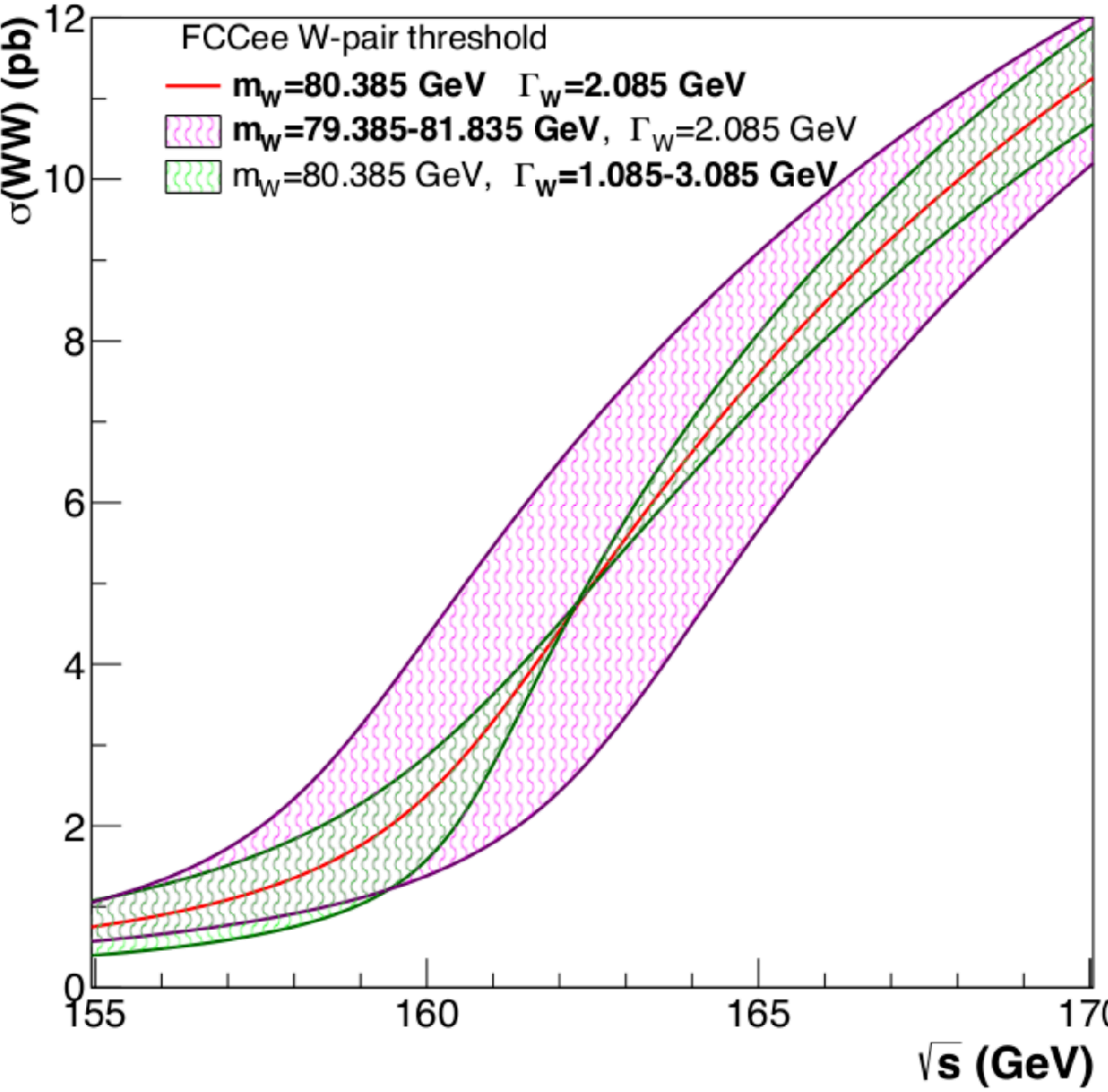


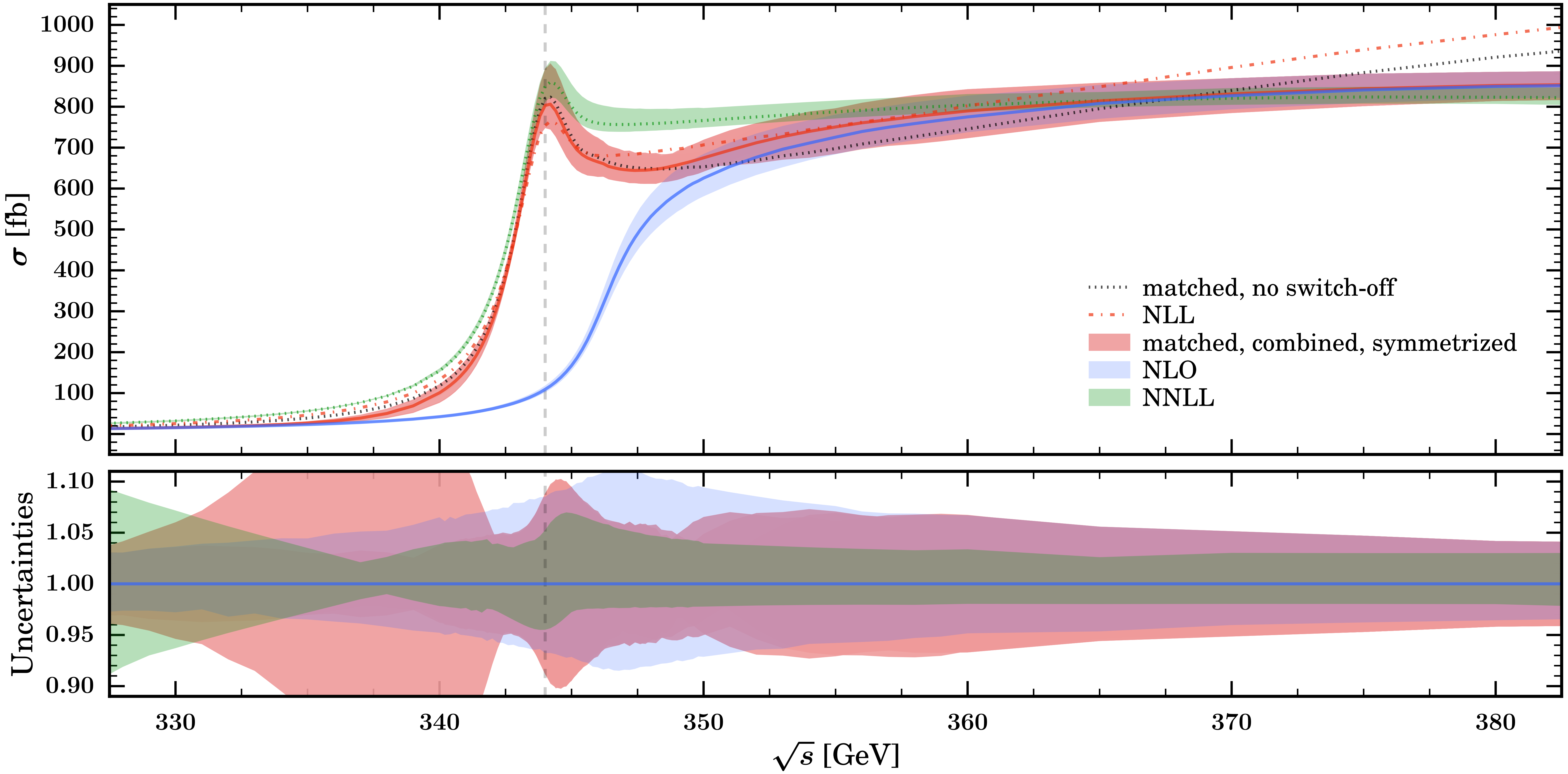


E (TeV)

Thresholds and "special processes"

- Luminometry: Special treatment for Bhabha scattering ($\ell^+\ell^- \to \ell^+\ell^-$) and diphotons ($\ell^+\ell^- \to \gamma\gamma$) $[10^{-4} - 10^{-5}$ precision]
- *t* and *W* mass measurements with precisions at $10^{-4} - 10^{-5}$ precision
- Exclusive Monte Carlo need to take into account QED and QCD threshold effects

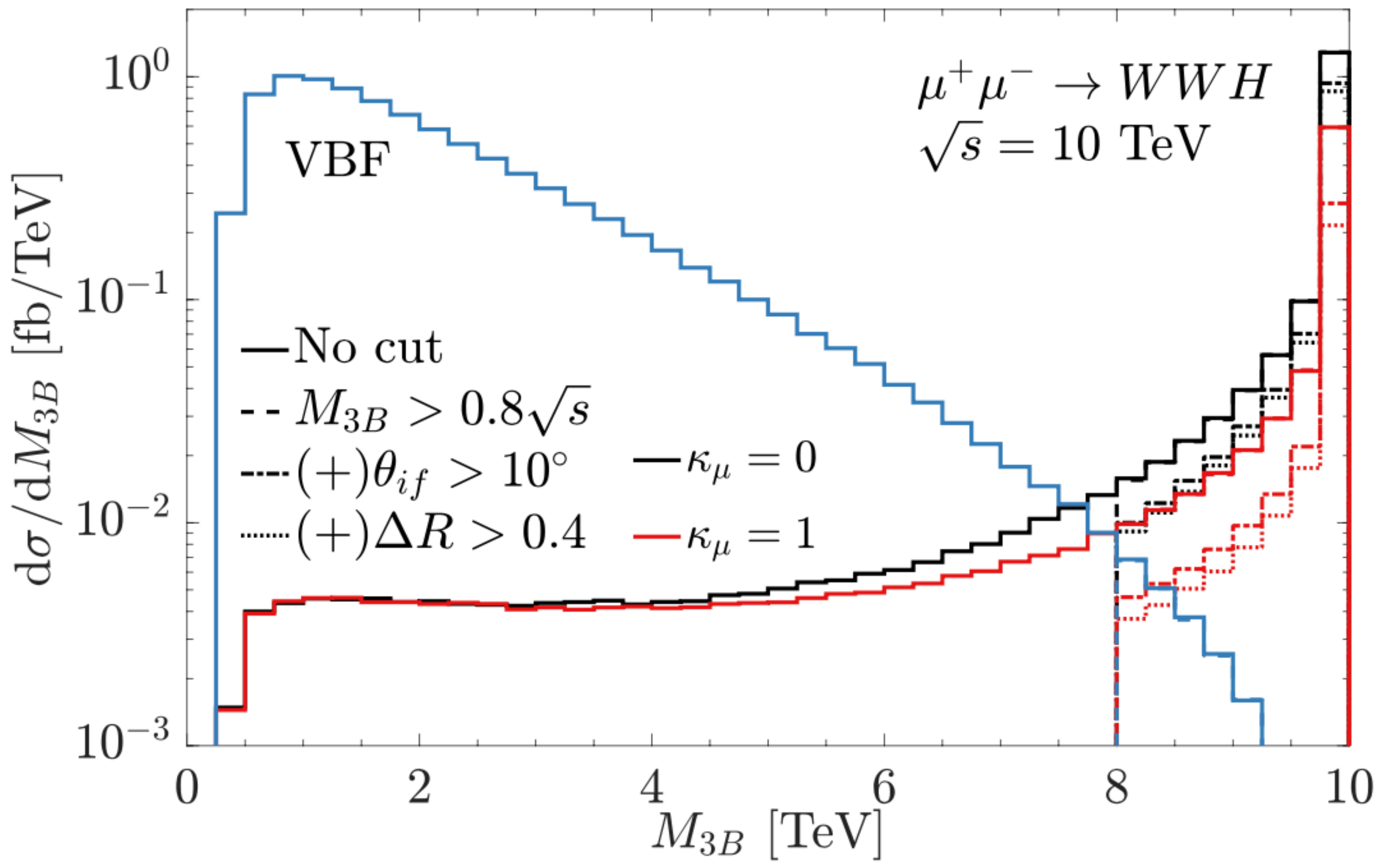




Beyond SM (BSM) Modelling in Simulation

BSM Models: UFO magic avoids hard-coding

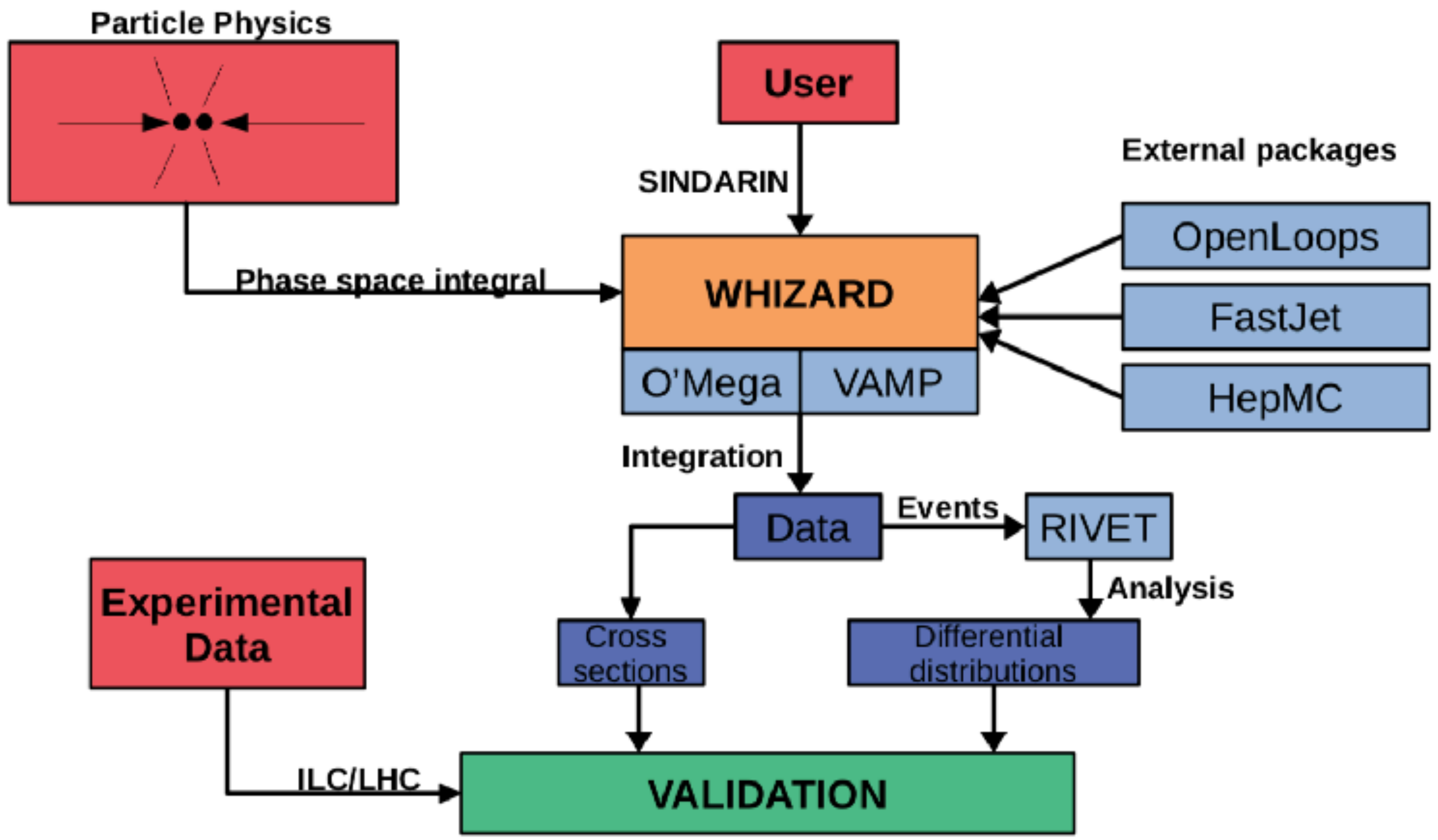
- Old school: hard-coding by hand
- BSM models from Lagrangian level tools L ∈ {LanHEP, SARAH, FeynRules}
- Allows for all Lagrangian-based BSM models
- Each tool L needs specific interfaces to each MC generator X (tedious!)

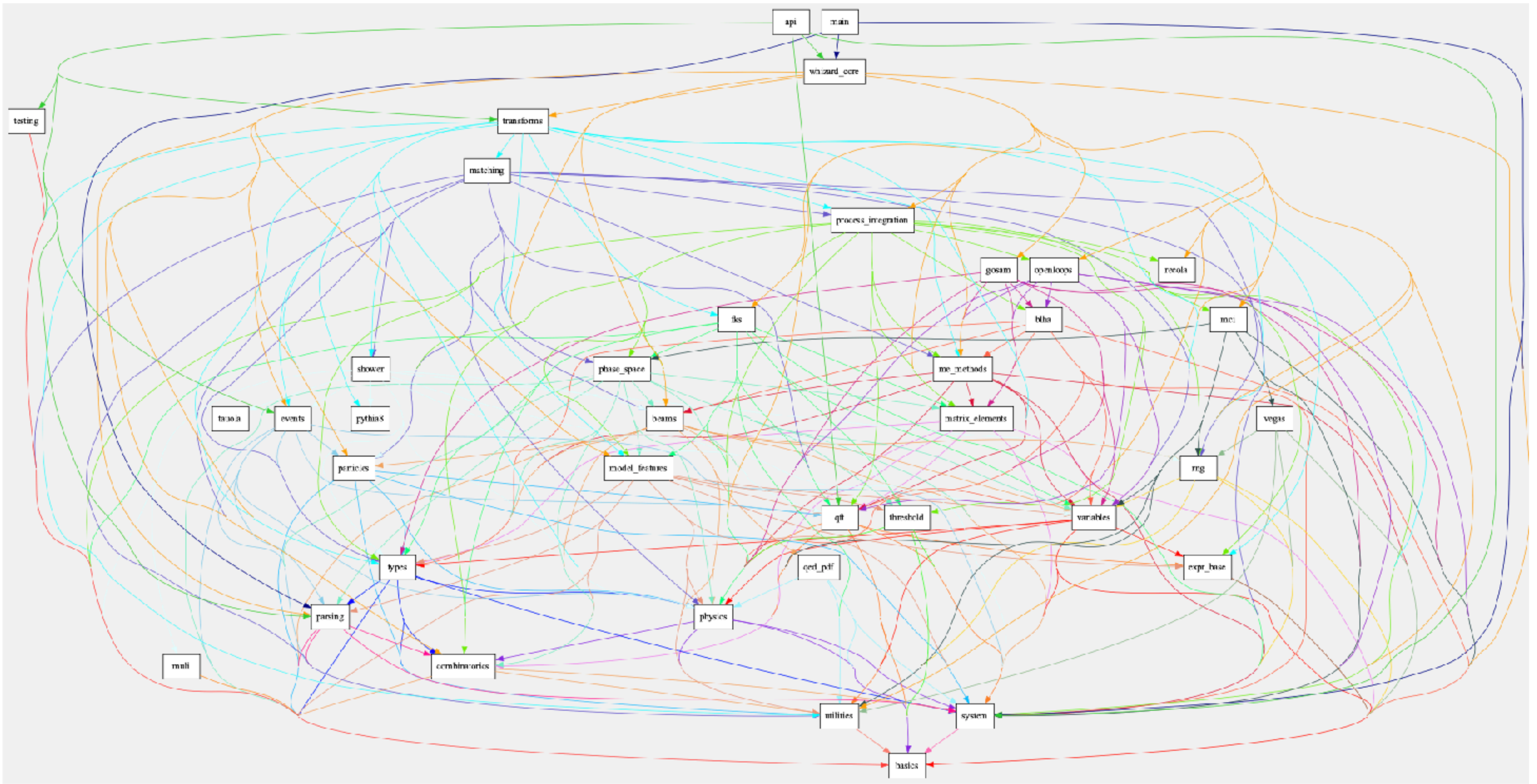


- Meta-Layer between Lagrangian-level tools and MC generators: **UFO format**
- Python-based Universal Feynman Format v1 1108.2040 v2: 2304.09883

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

Challenges of Monte Carlo Event Generators





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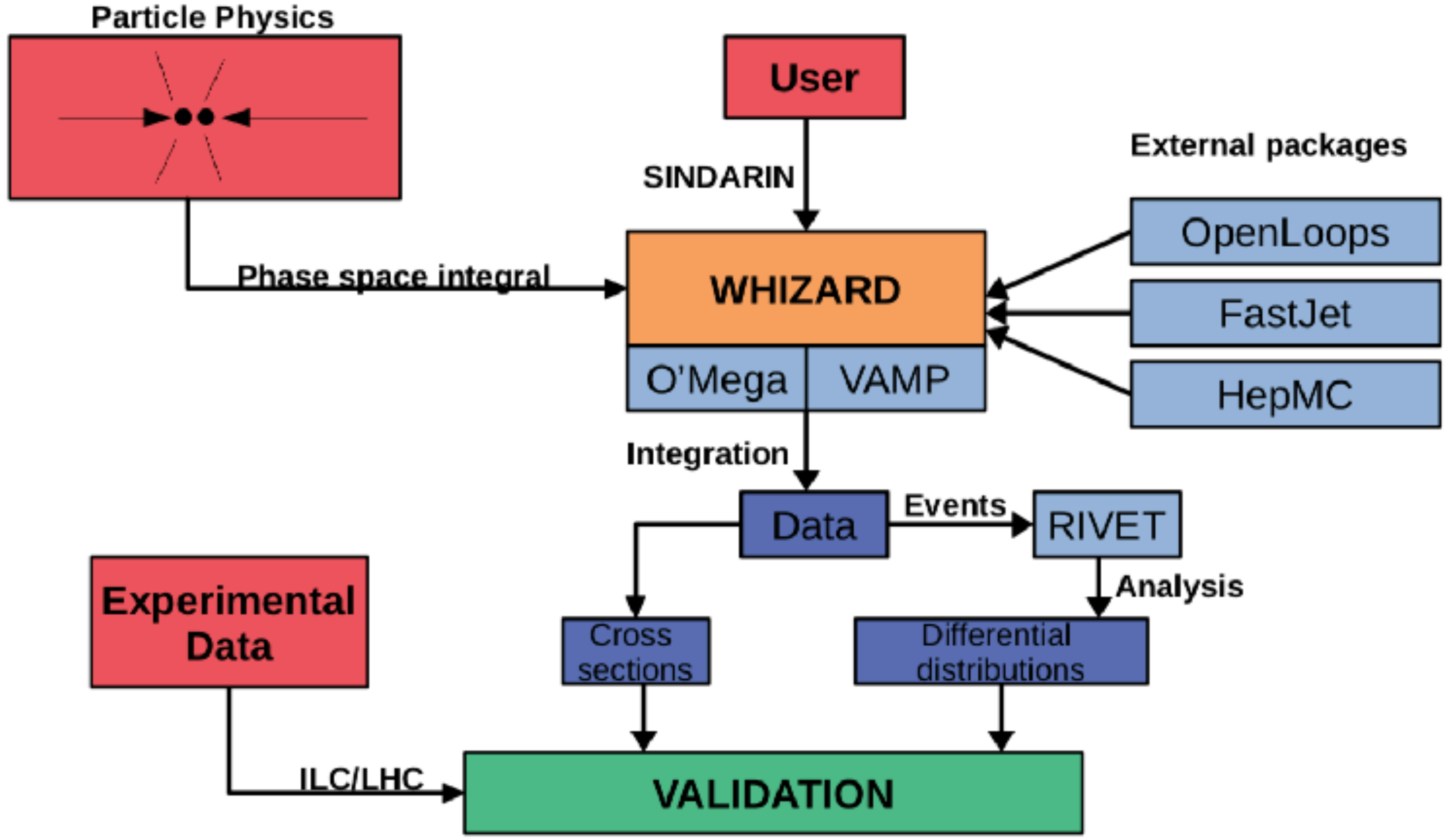

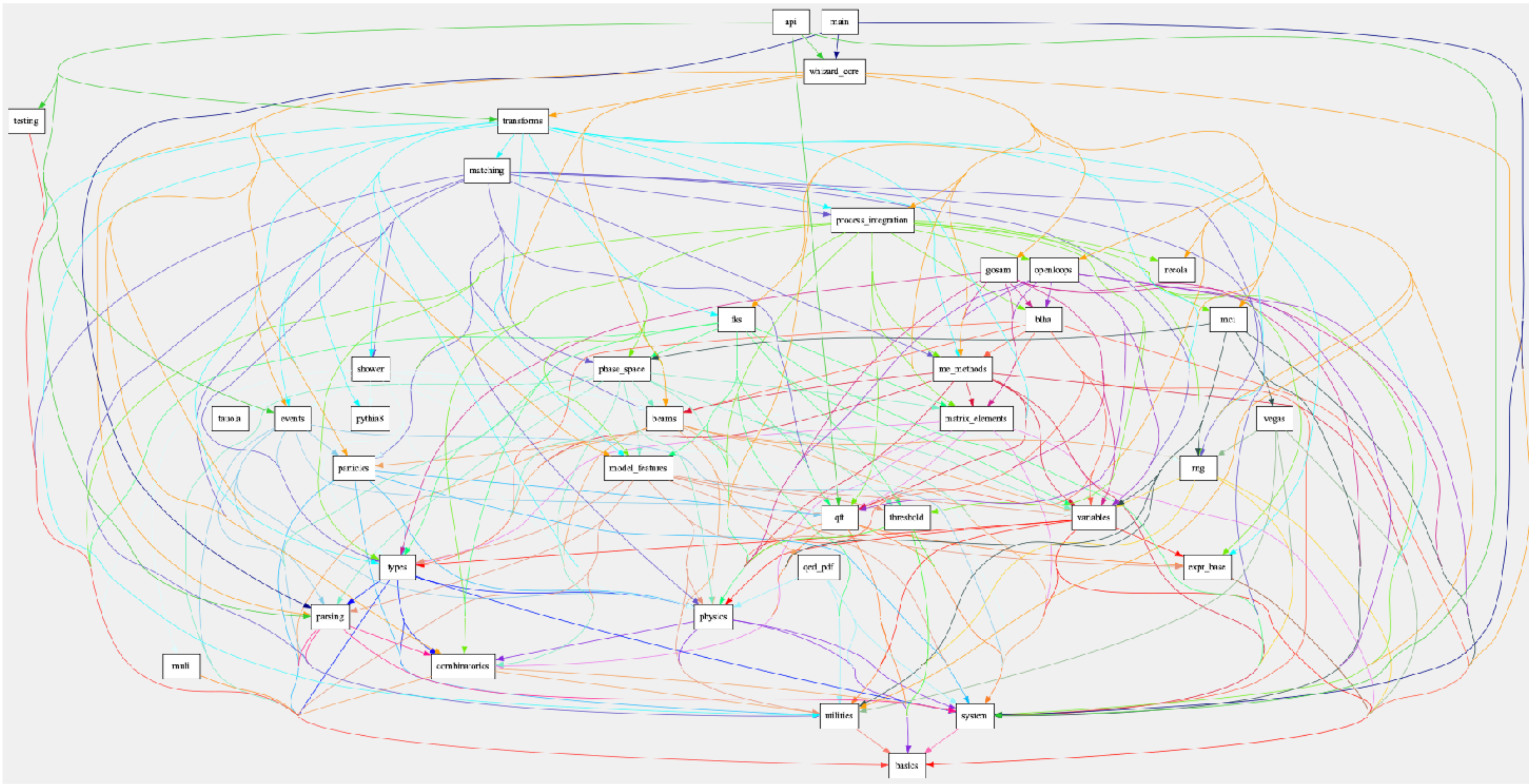

- Typical MC generator $\gtrsim$ 0.5M lines of code
- Many physics parts: necessity of a team/collaboration
- No tool implements all physics (and probably never will)
- Modularity and interchangeability is a must
- e.g. typically interfaces to ca. 15 external libraries
- Unit testing & Continuous integration

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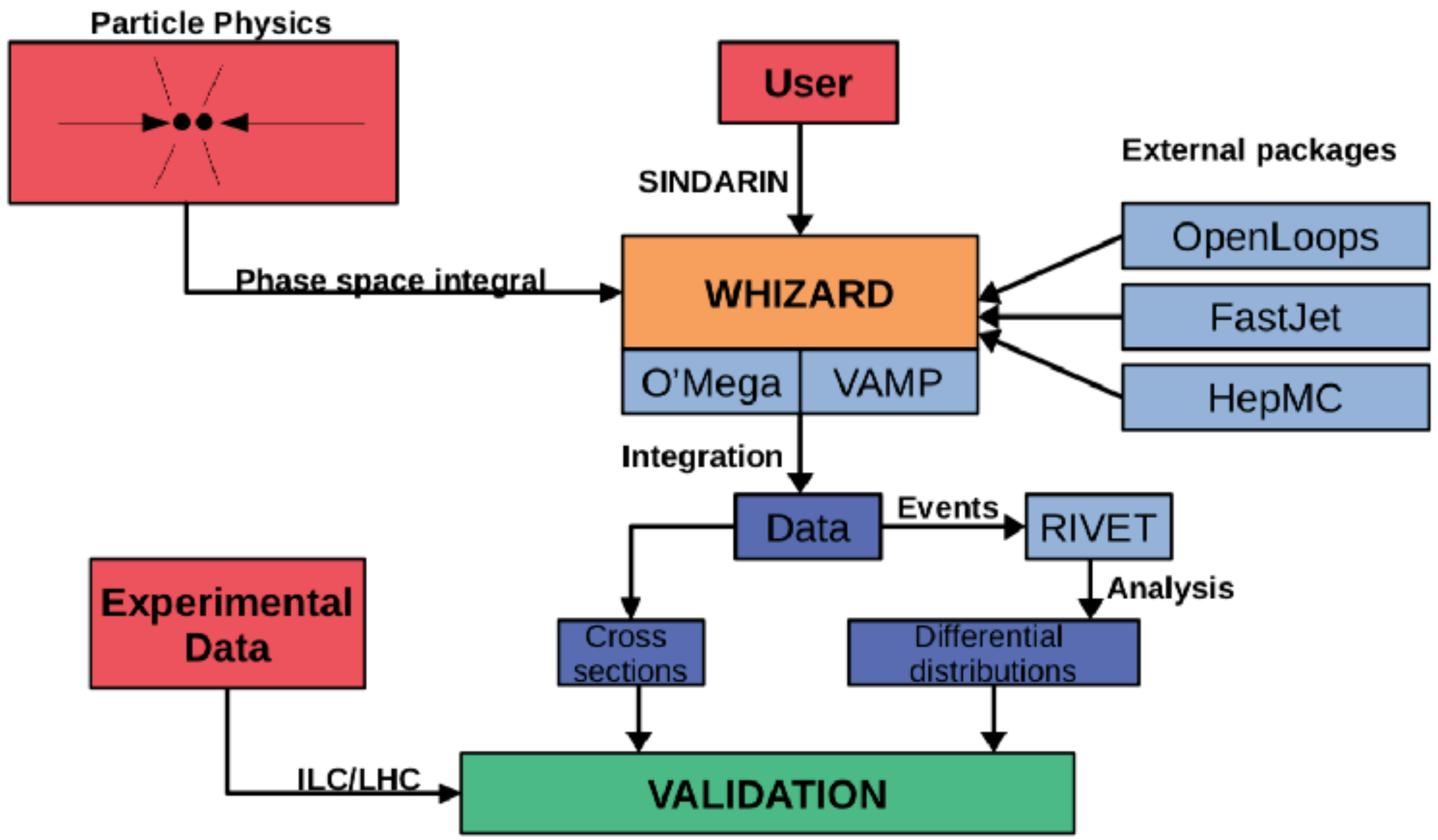

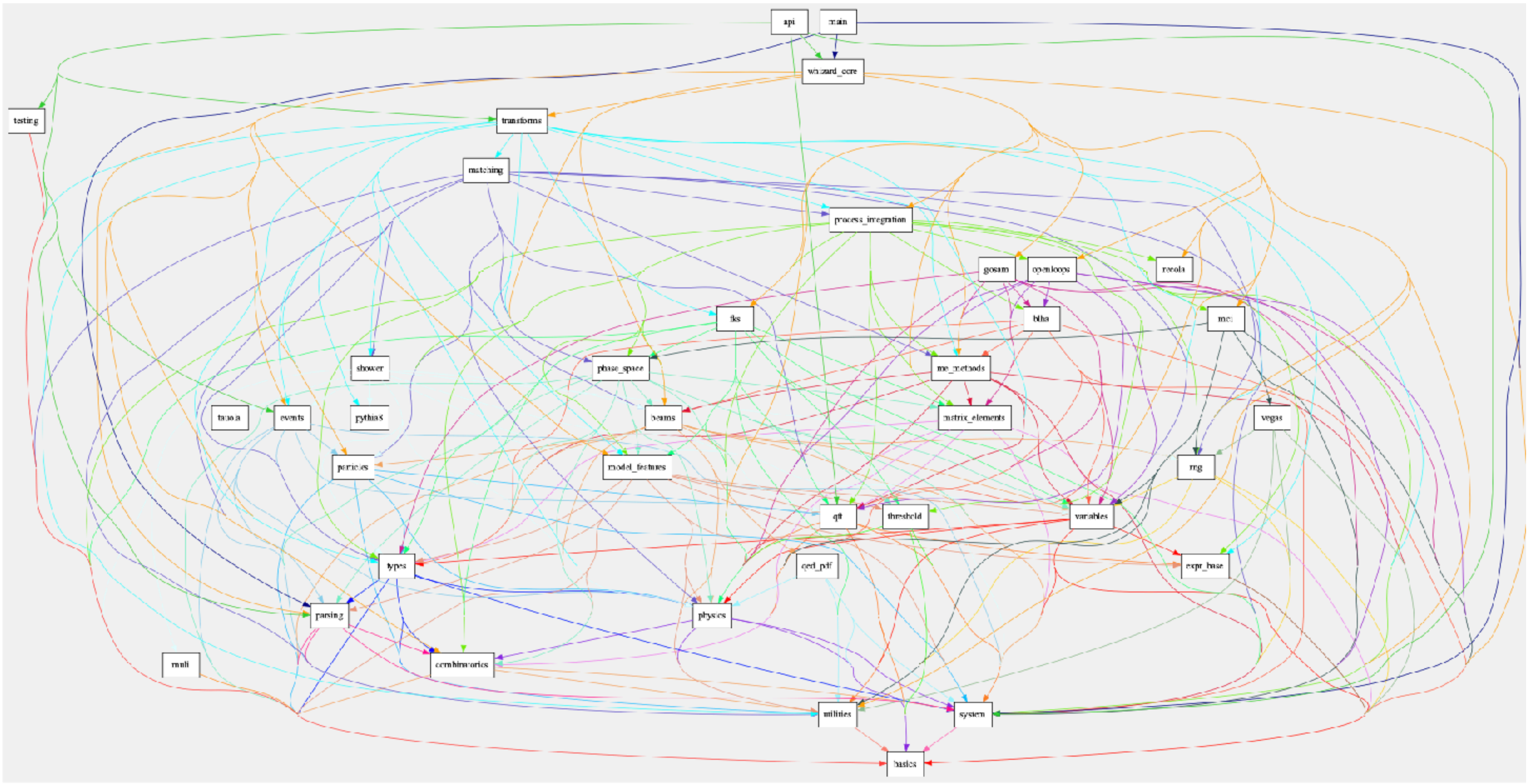

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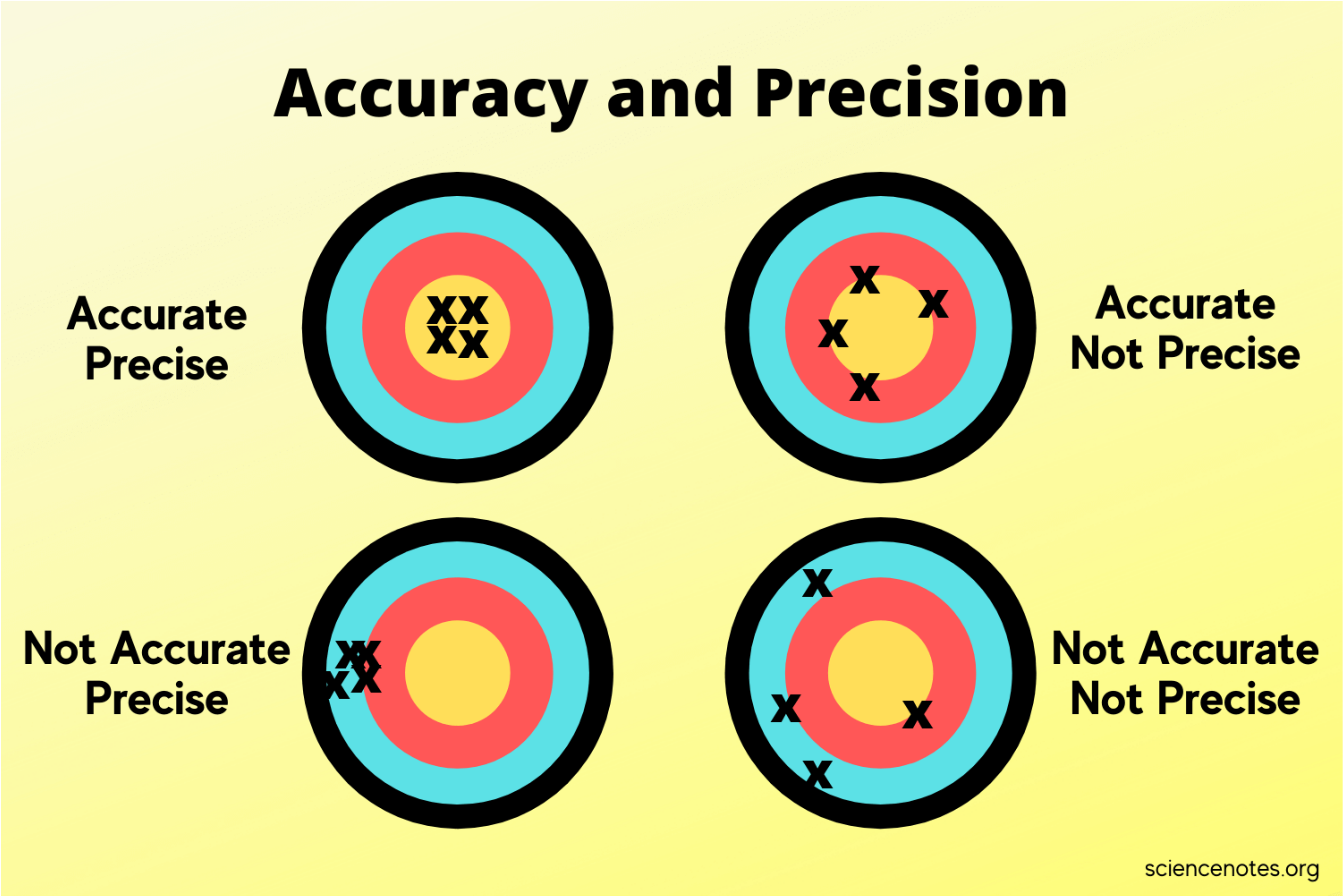
- 3—5 major MC event generators
- Most of these MC members will retire around 2040-45
- Need for ca. MC 8—10 staff positions world-wide
  in the next ca. 20 years
- Already many example of “zombie codes” in experiments

Conclusions & Outlook

- Monte-Carlo generators almighty workhorses of particle physics!!
- MCs implement *all* necessary SM and BSM physics
- Tedious work for MC collaboration members
- Tremendous progress on QCD corrections driven by 15 years of LHC running
- NLO QCD+EW for SM and NLO QCD BSM (mostly) under control, attempts for NNLO automation
- Precision in initial-state QED radiation resummation and exclusive photons crucial
- Parton Showers for QCD and QED radiation much matured (now up to NLL for FSR)
- Hadronization will be probed with much enhanced precision at future e^+e^- collider
- Computing bottlenecks: parallelization & optimization of phase space integration, negative weights
- Quite extensive activities at DESY: many opportunities to participate

Event generators: Accuracy vs. Precision



BACKUP

Hadronization / Fragmentation

- Quark and gluon jets hadronize at low energy scales (fragmentation)
- Non-perturbative physics: has to be extracted from experiment [mainly $e^+e^- \to$ hadrons, DIS, LHC]
- Old models [1970s]: flux tubes, independent fragmentation [Feynman/Field, 1970; **Isajet**: Paige et al.]

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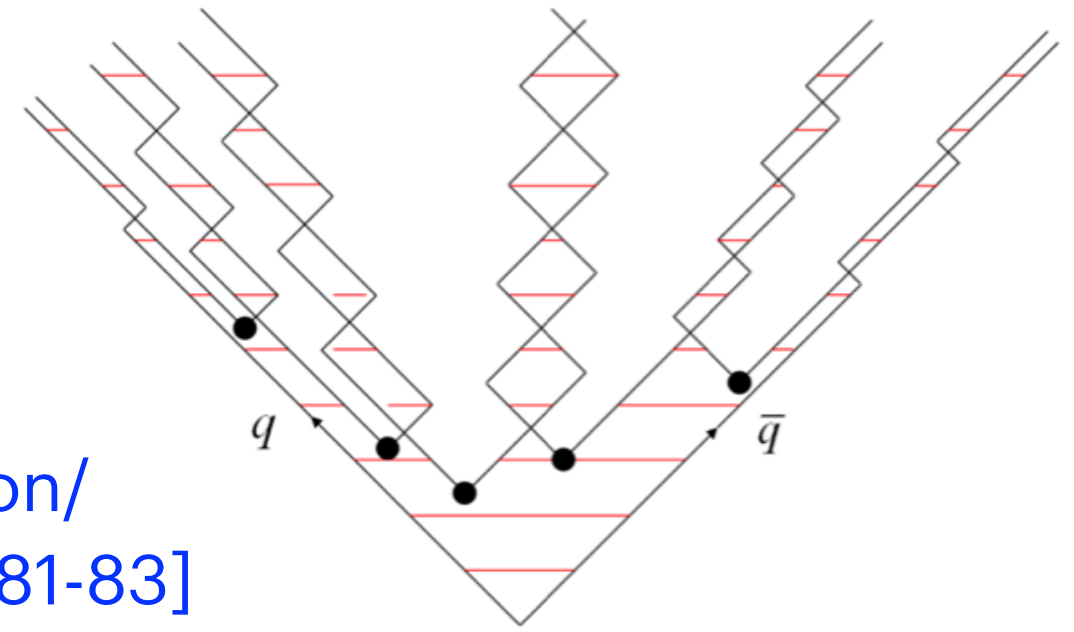
Lund string fragmentation model **[Pythia]**

- based on old string model of strong interactions
- Strong physical motivation, but: invented without parton shower in mind
- Universal description of data (ee fit → hadrons)
- Plethora of parameters: ~ *O(1)* per hadron
- Baryon production difficult [string junctions, popcorn]

[Nielsen/Olesen, 1973; Anderson/Gustafson/Ingelman/Sjöstrand, 1981-83]



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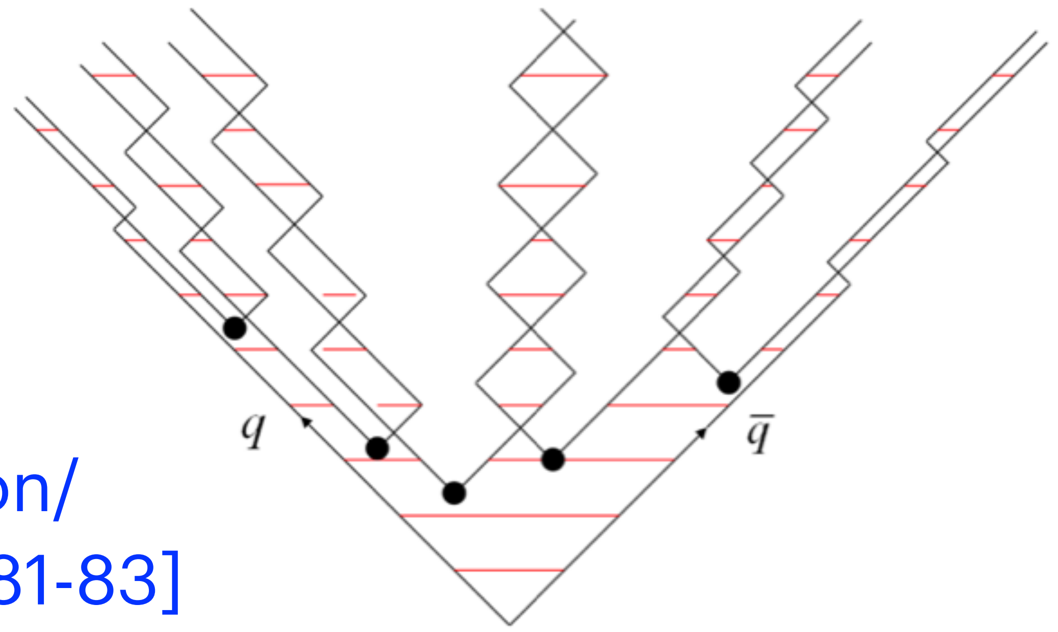
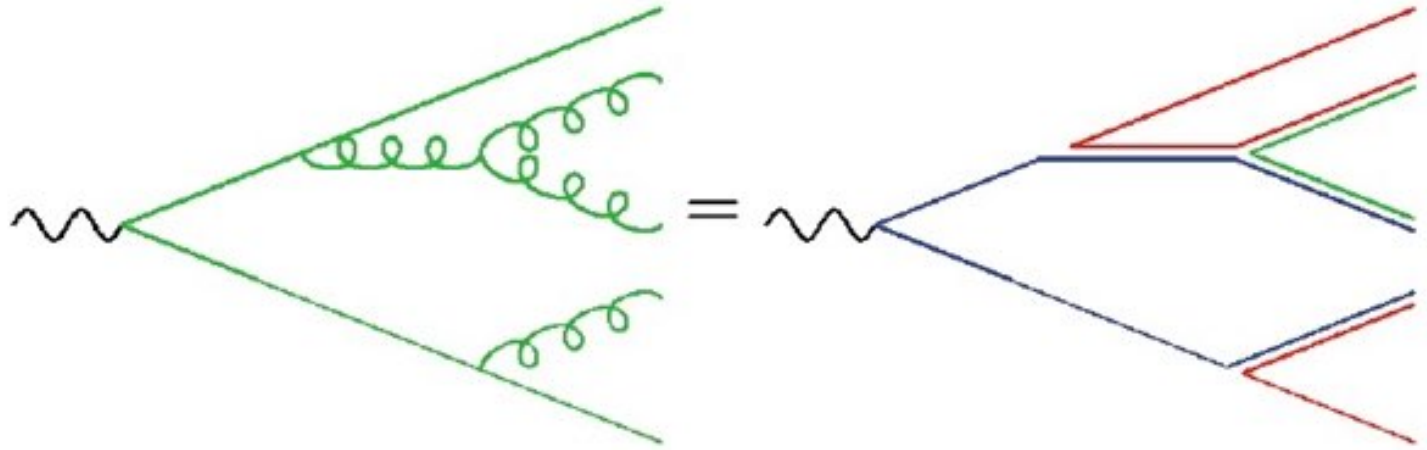


Cluster fragmentation model **[Herwig]**

- Parton shower orders partons in color space
- Large N_C limit: planar graphs dominate
- Cluster: continuum of high-mass resonances, decay to hadrons
- No spin info, just plain phase space
- Cluster spectrum determined by PS (perturbation theory)



[Marchesini/Seymour/Webber, 1992]

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All MC programs use either Lund or Cluster or a Hybrid version of both!

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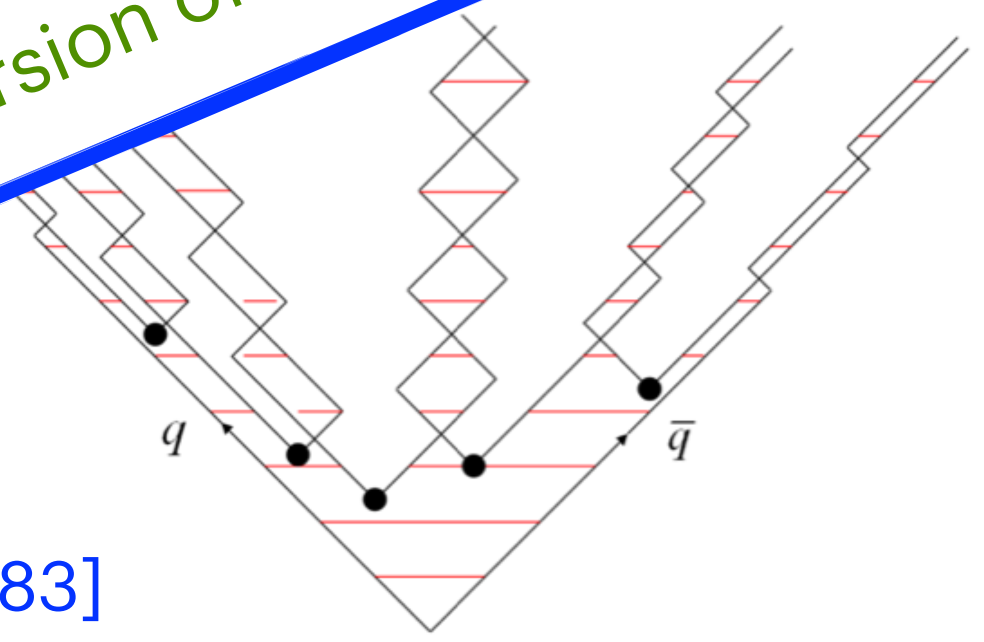

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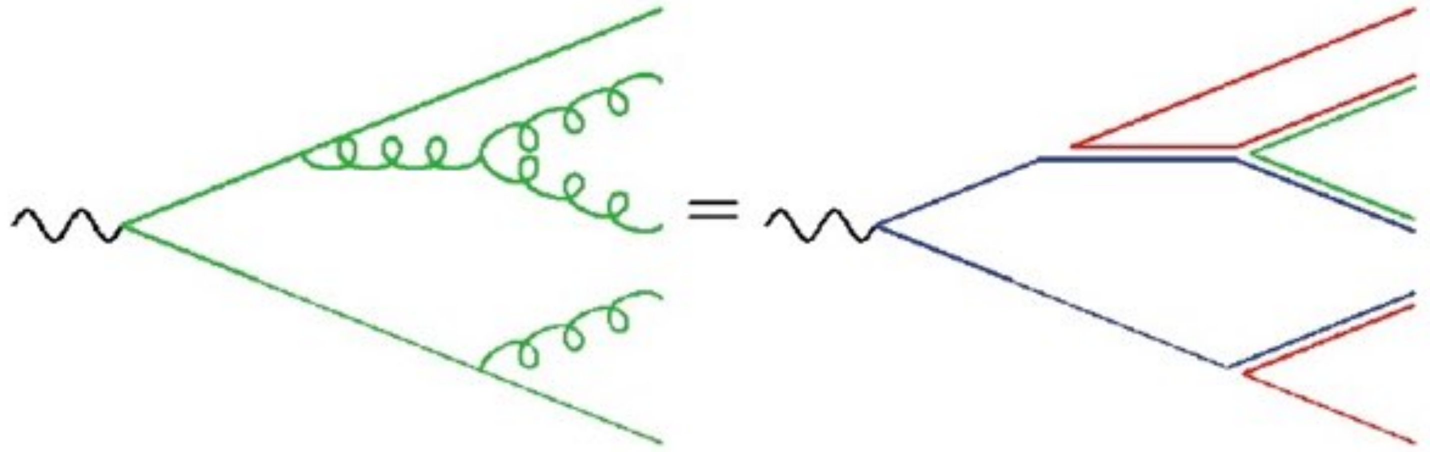

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Challenge: any e^+e^- Higgs factory will generate hugh amounts of hadron data ⟹ Big challenge for th…

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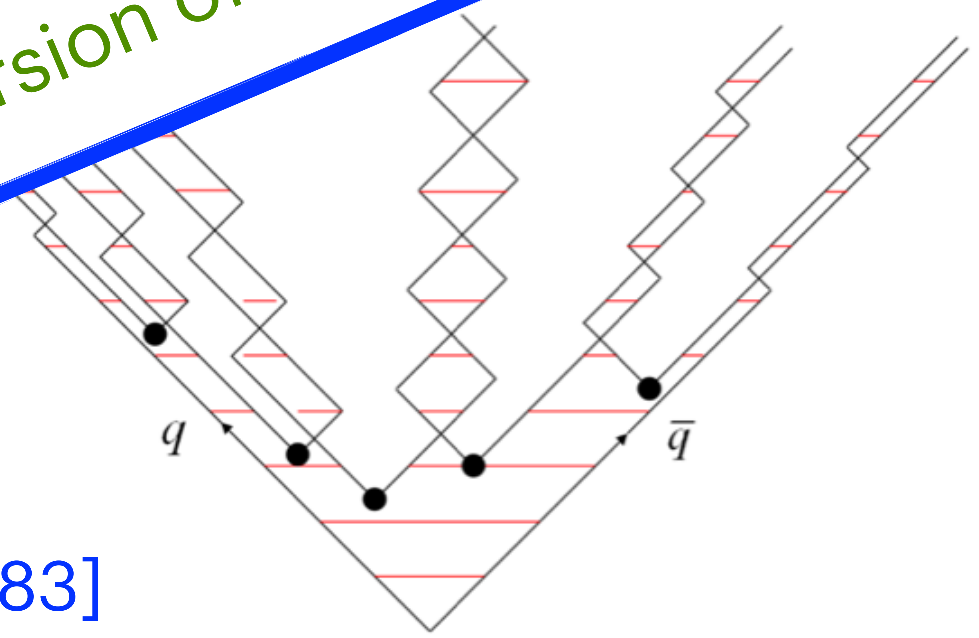

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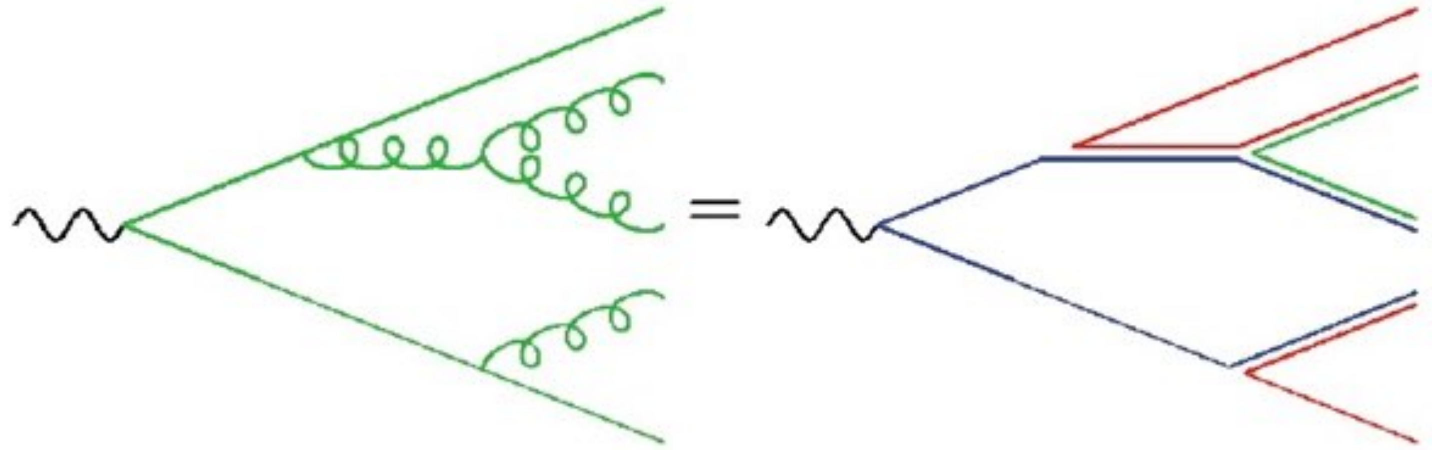

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A hadronic decay chain of typical complexity:

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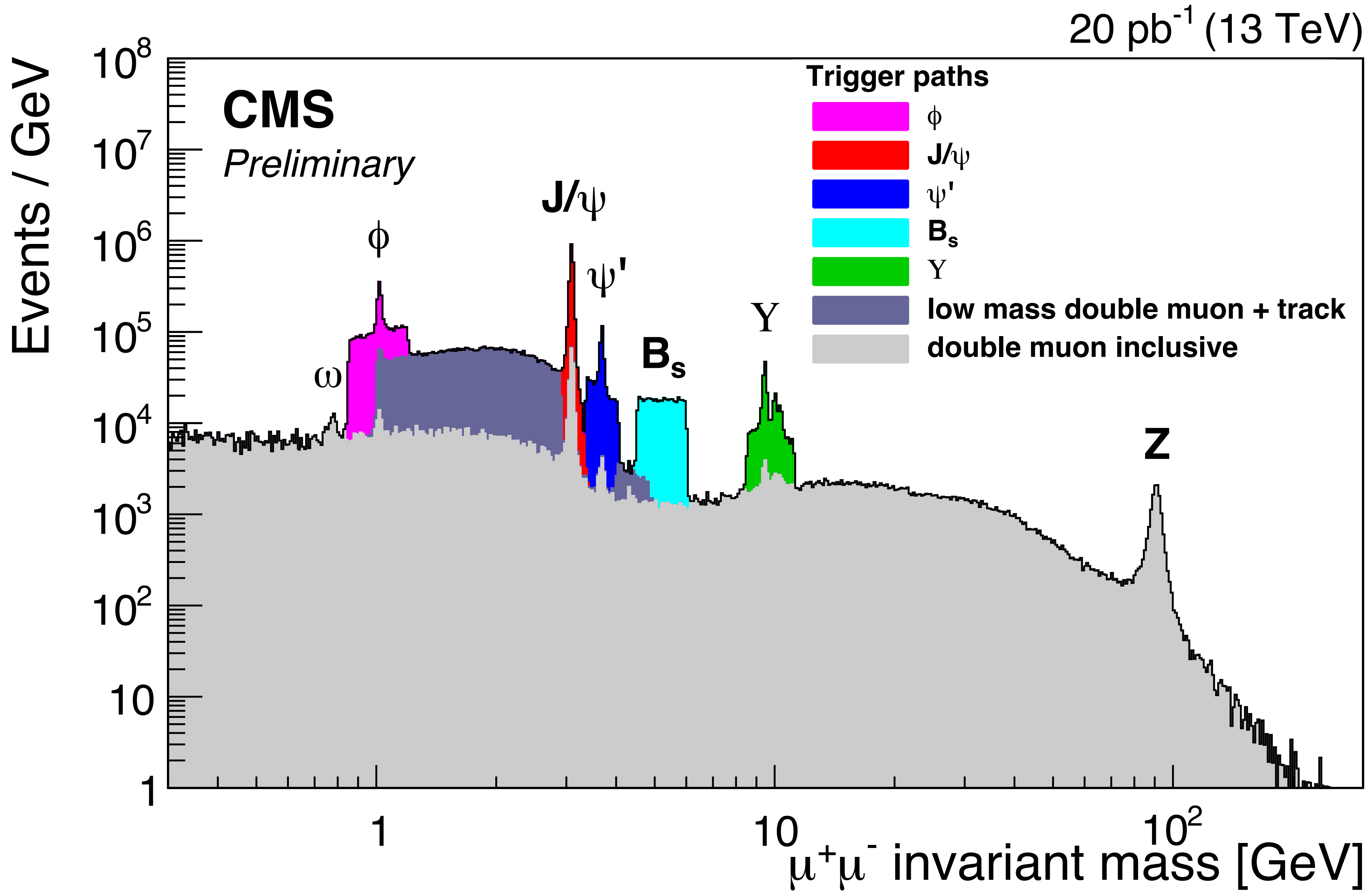
Final-state hadronic QED radiation for shower shapes and correct distributions



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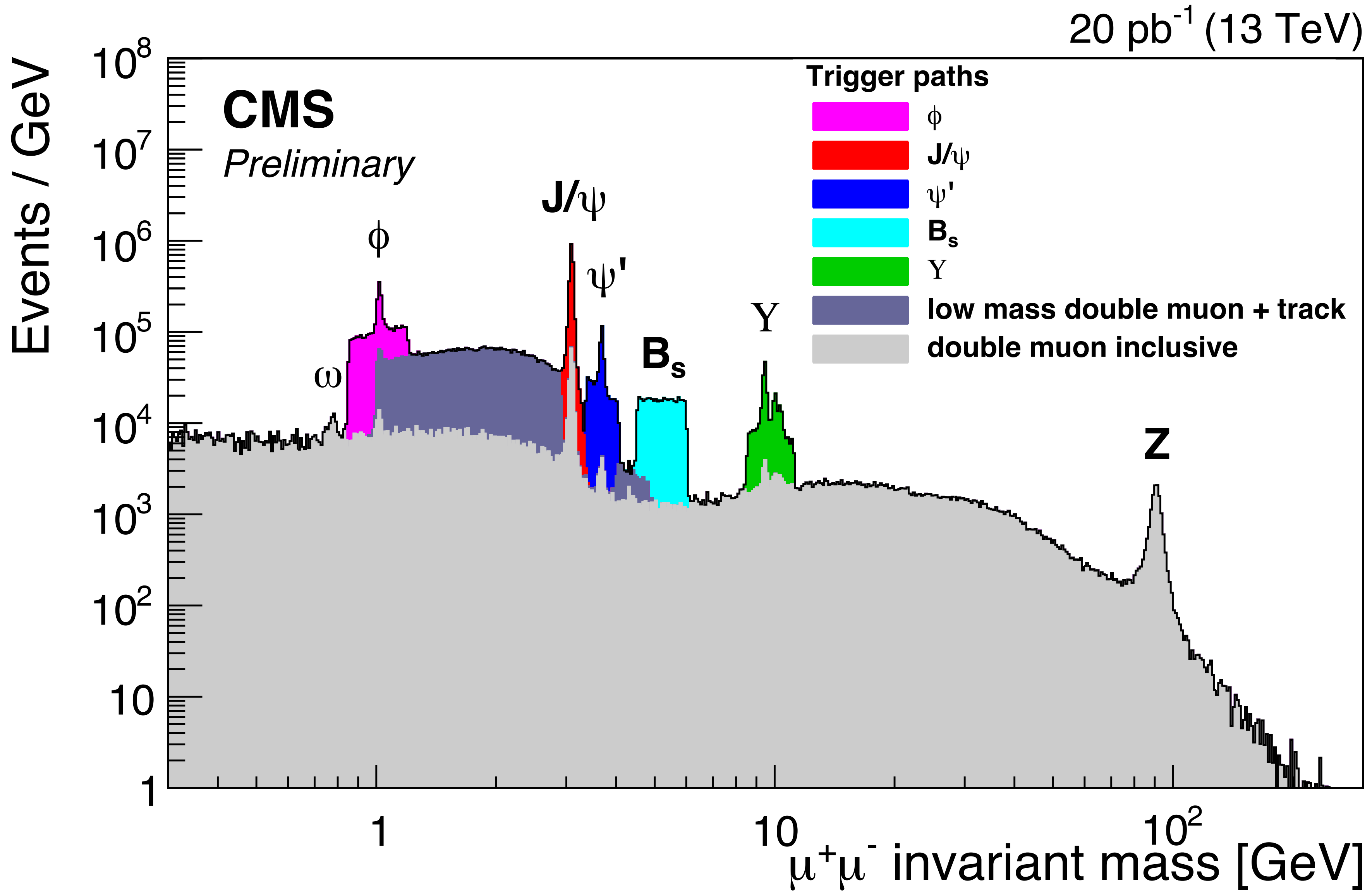
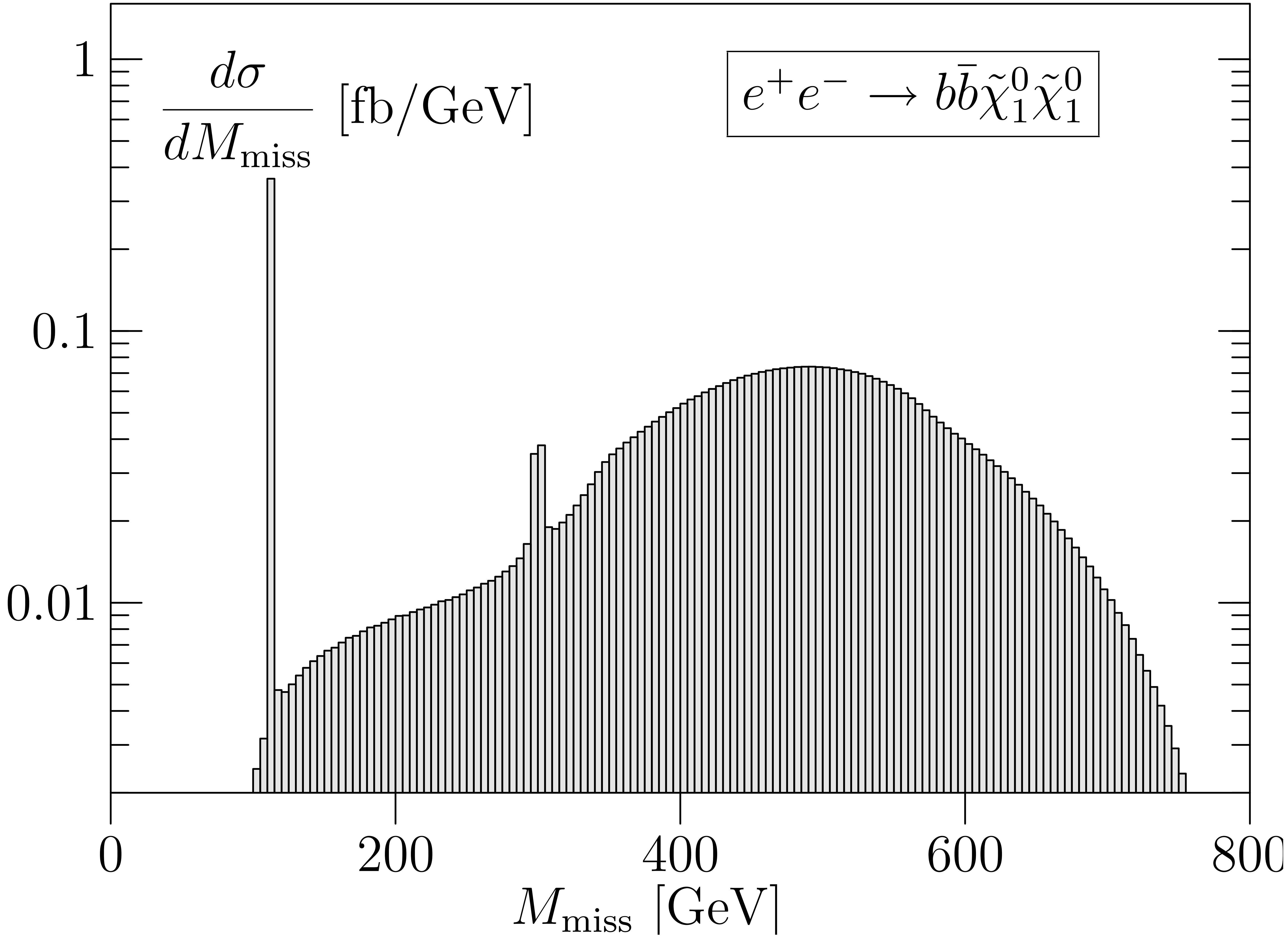


PDG: 100s of particles, 1000s of decay modes, form factors, peak shapes, special cases, “PDG unitarity violation” ….

Inclusive and exclusive ISR effects

Example: Search for low-mass sbottoms at a 800 GeV e^+e^- collider



C.A.T.P.I.S.S. collaboration, 12/2005

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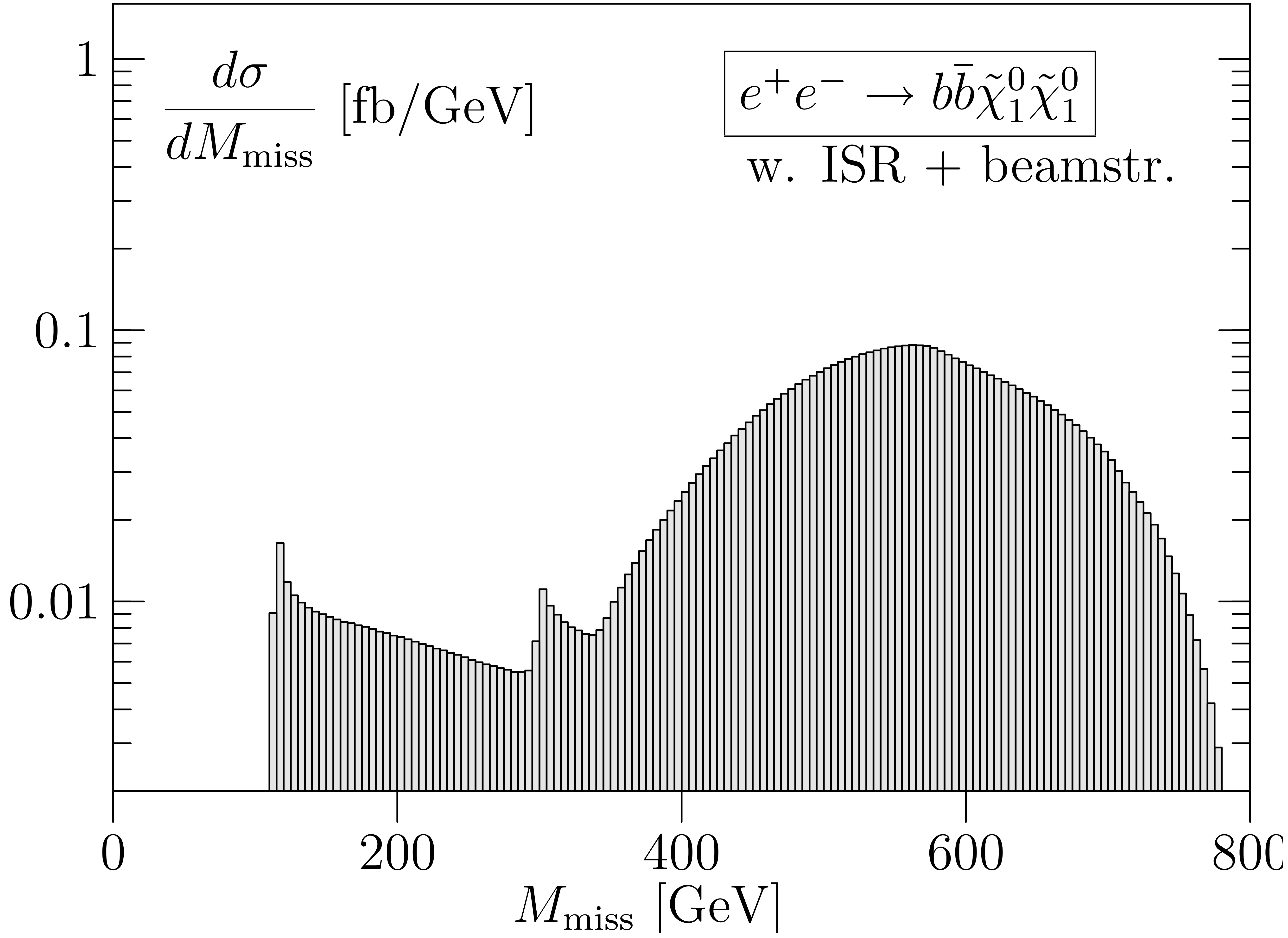

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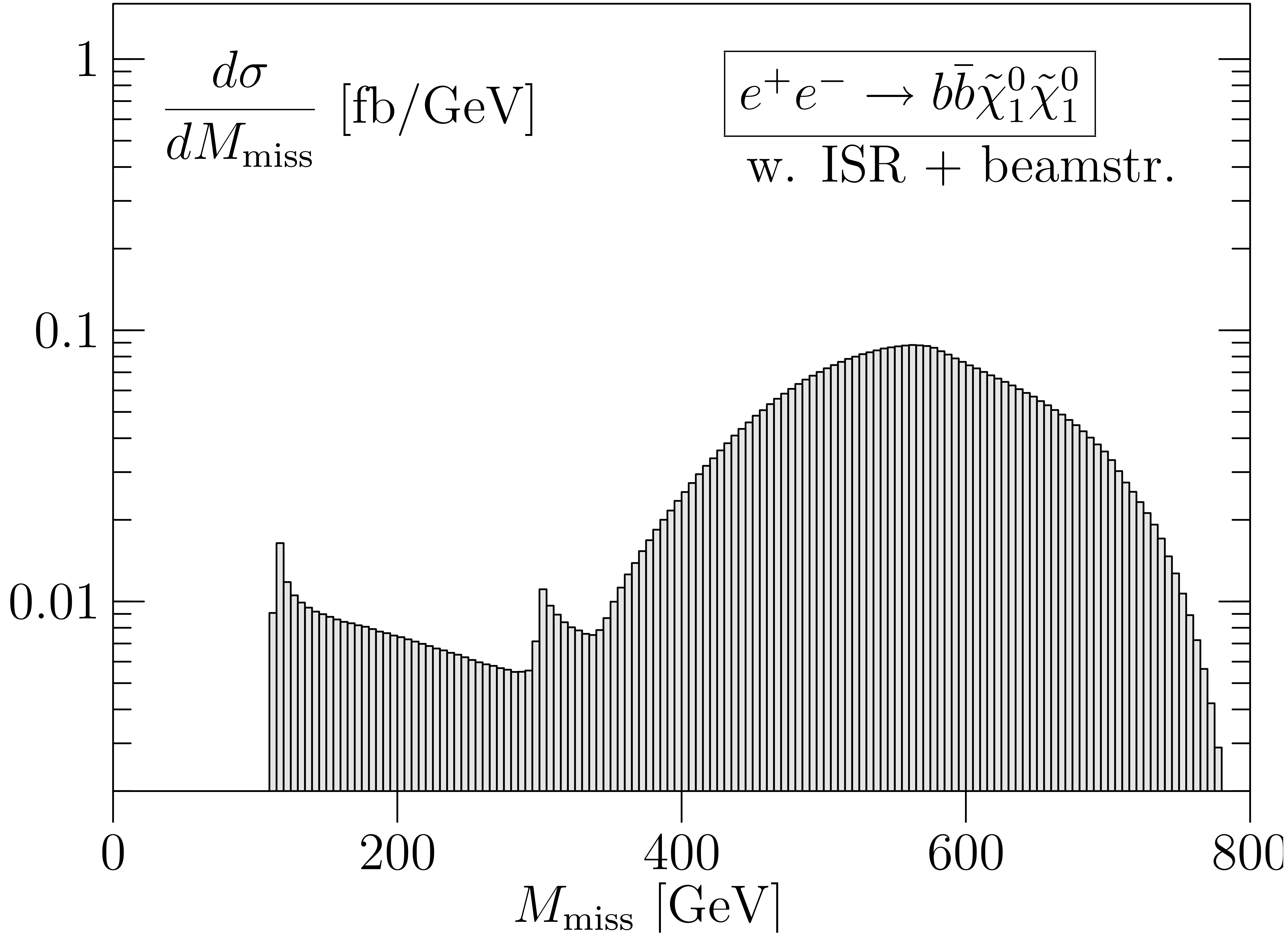

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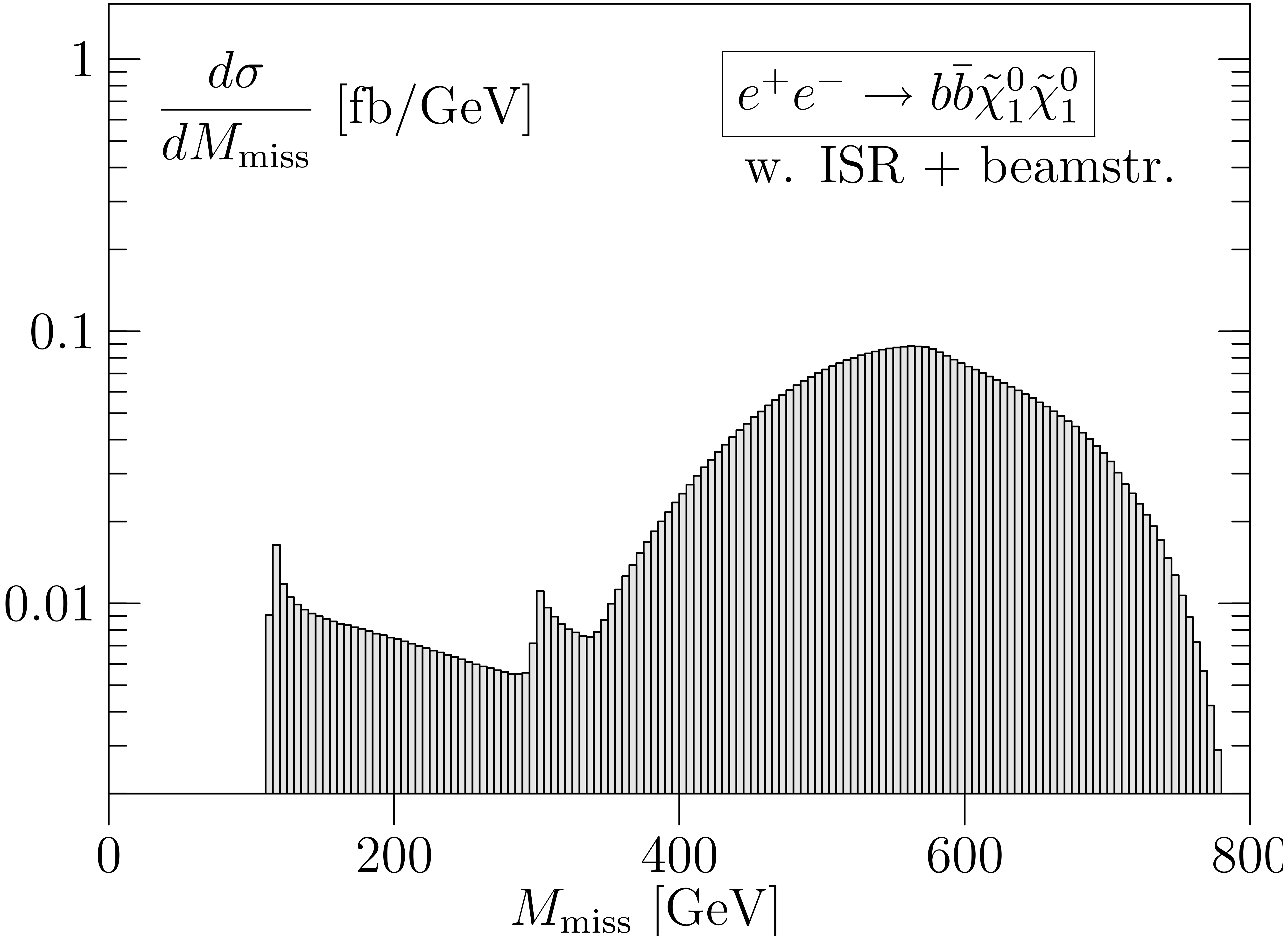

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- Also soft factorization / exponentiation
- YFS: Yennie/Frautschi/Suura, 1961;
- Presumably best description for thresholds: soft effects
- Collinear corrections can be added in principle

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

$[\sigma_0 + \text{corrections}]$