Luminosity Spectra Redux

Thorsten Ohl

Institute for Theoretical Physics and Astrophysics
University of Würzburg

http://physik.uni-wuerzburg.de/ohl

3rd ECFA Workshop on e^+e^- Higgs/EW/Top Factories

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- ab-initio description of beamstrahlung and other beam transport effects outside of the scope of event generators for the hard "partonic" process
  - $\because$ depends on bunch shapes and beam optics
  - $\because$ completely independent of the hard partonic process
- physics event generators need energy distribution functions $D(x_1, x_2)$ and/or a corresponding stream of random numbers (x_1, x_2)

- beamstrahlung at FCC-ee/Z ($\sqrt{s} = 91.2\,\text{GeV}$) will be very soft:

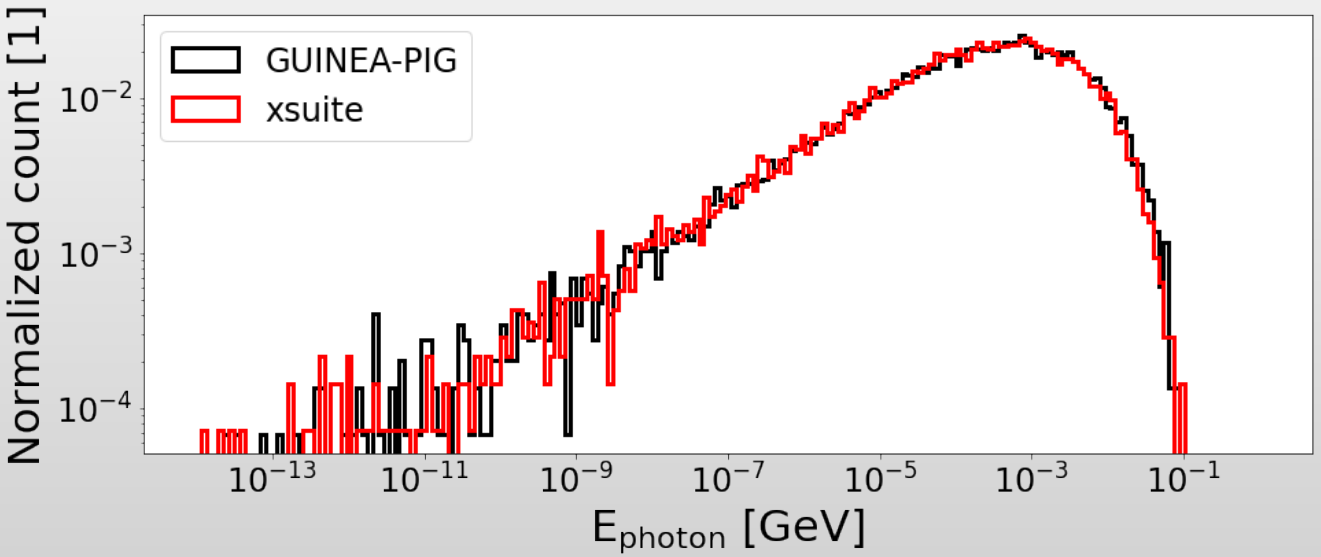

Figure 4: Energy spectrum of emitted beamstrahlung photons using `GUINEA-PIG` (black) and `xsuite` (red). Photon counts are normalised to 1.

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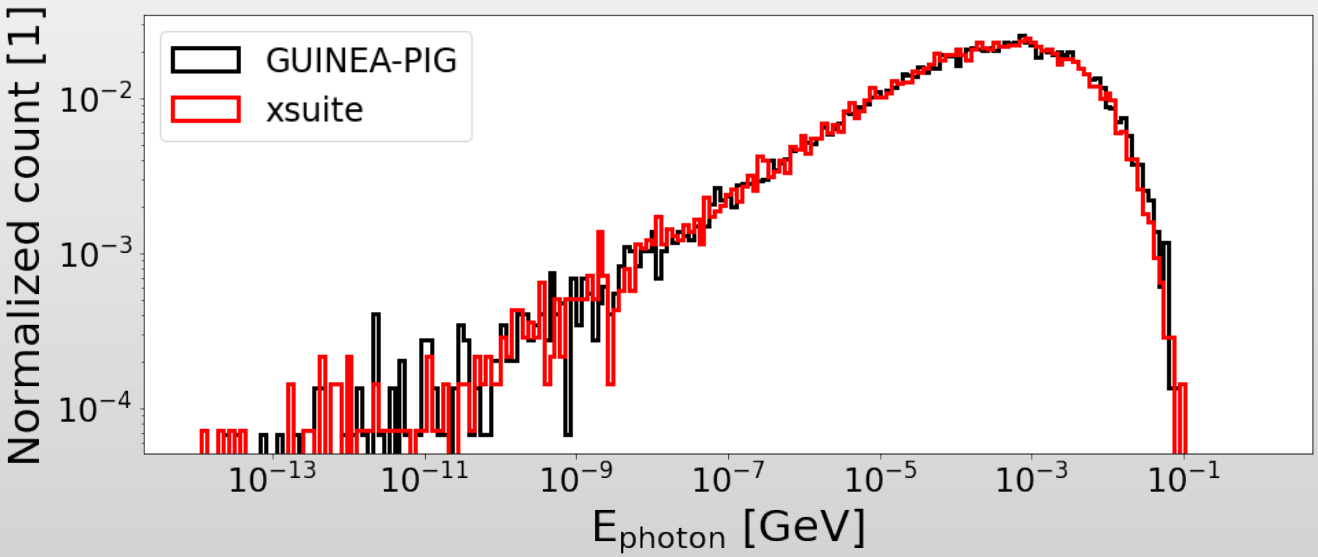

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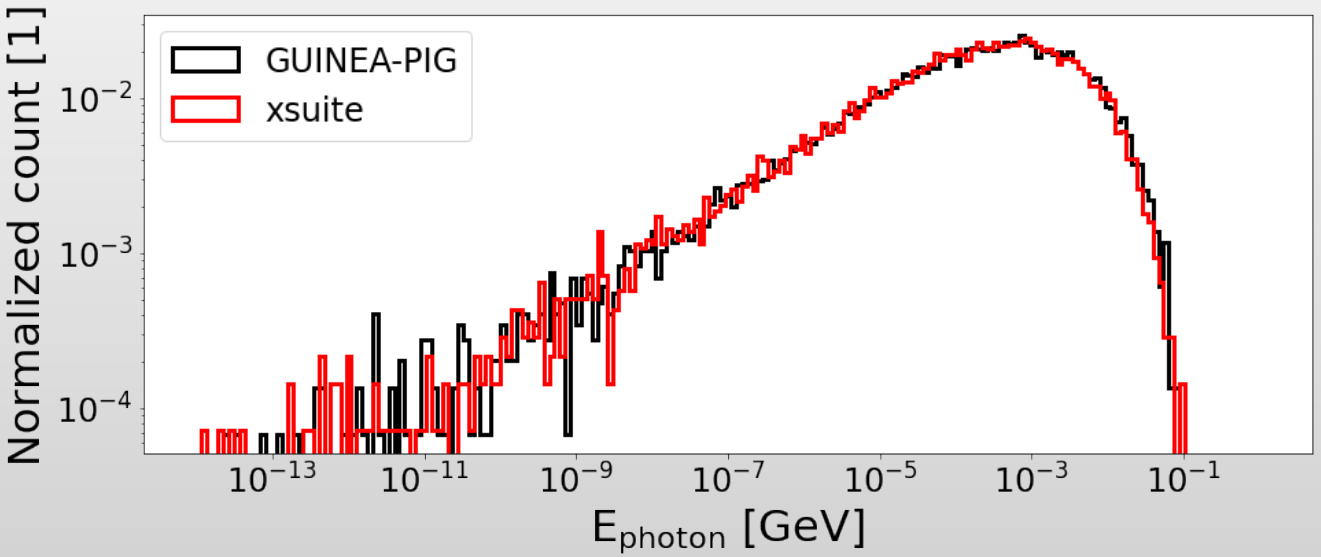

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- modeled consistently by different simulation programs
- but will not dominate the shape of e^+e^--luminosity spectrum

- harder spectra at higher energy designs

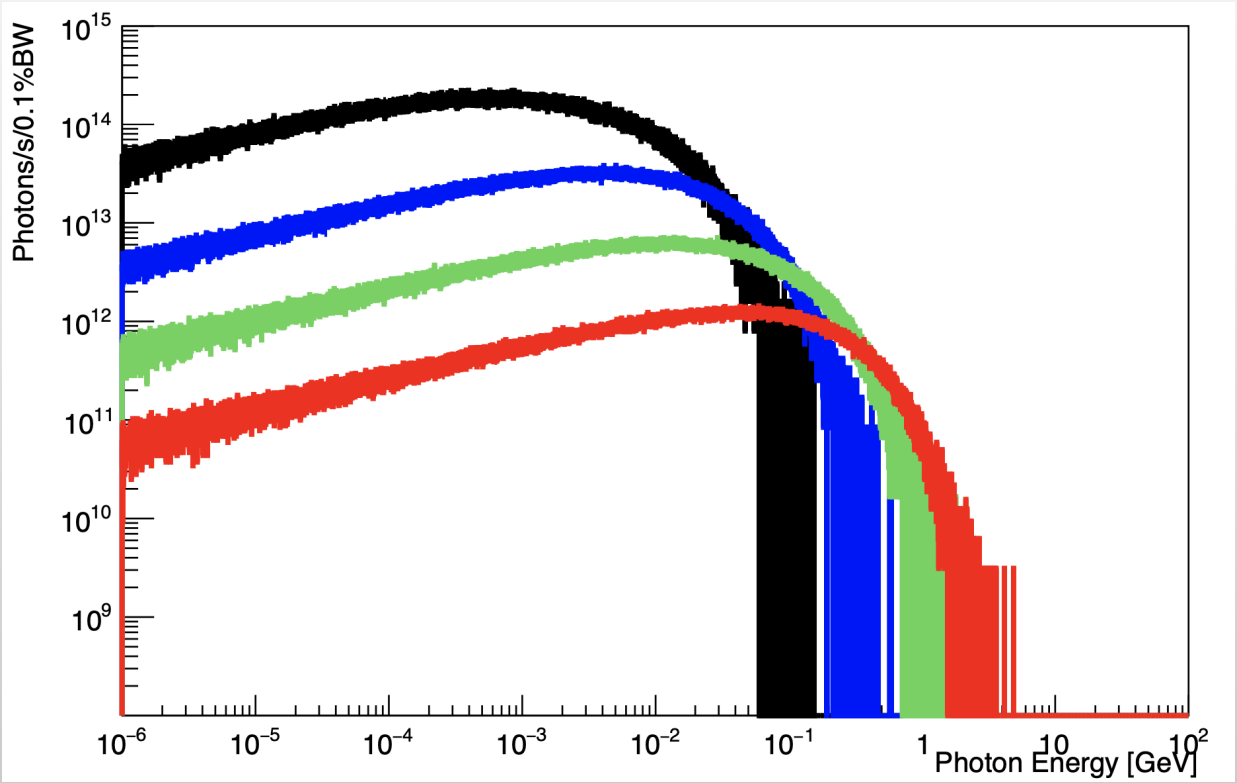
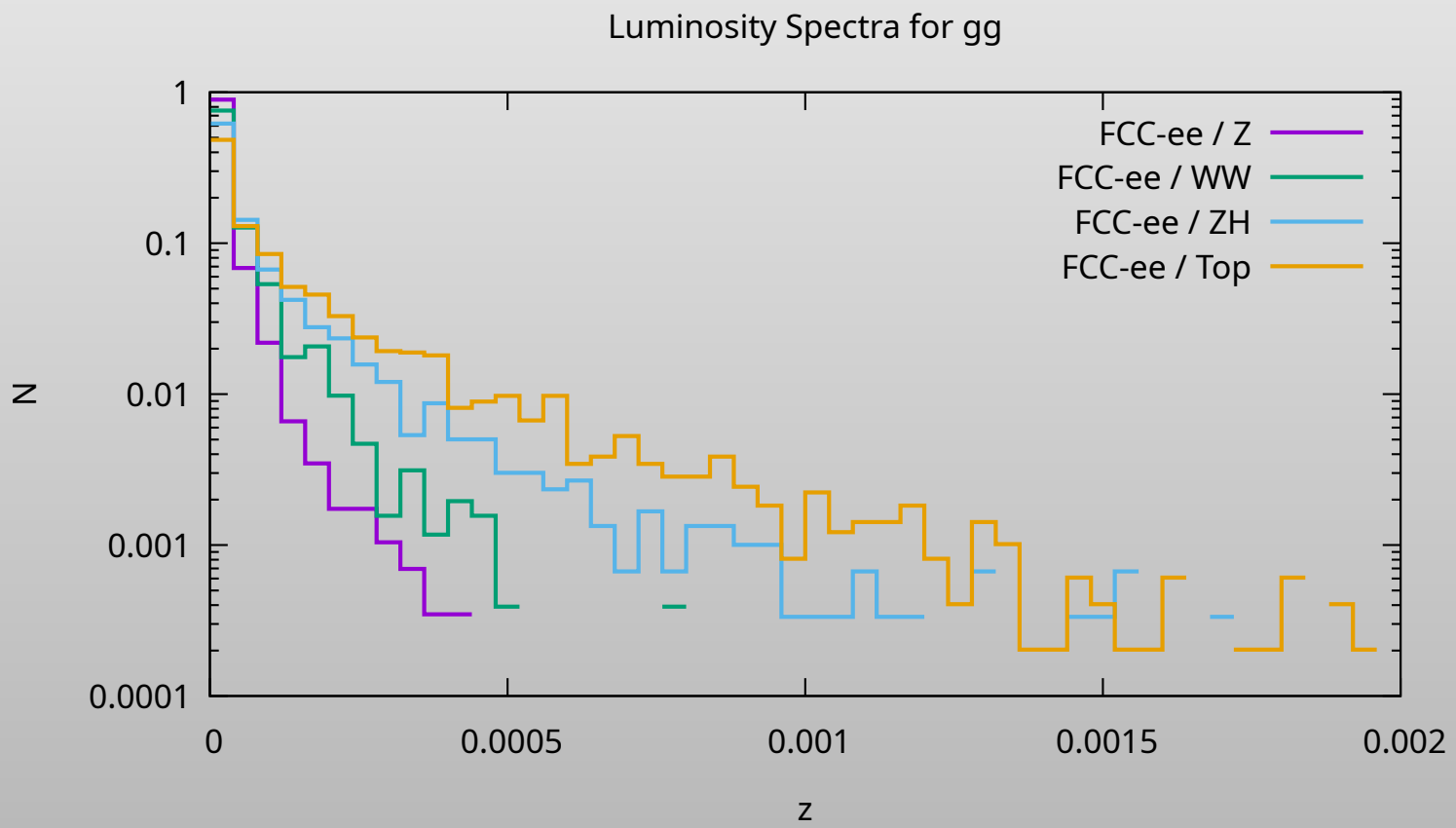


FIG. 1: Flux of the BS radiation as a function of their energy, emitted for the four FCC-ee working points, 45.6 GeV (black), 80.0 GeV (blue), 120.0 GeV (green), and 182.5 GeV (red).

[Boscolo & Ciarma, 2023]

- the spectra become harder even as fractions of the nominal beam energies

$$z = \sqrt{\frac{E_{e^-}}{E_{\text{beam}}} \frac{E_{e^+}}{E_{\text{beam}}}}$$



- FCC parameters, June 2024:

FUTURE CIRCULAR COLLIDER

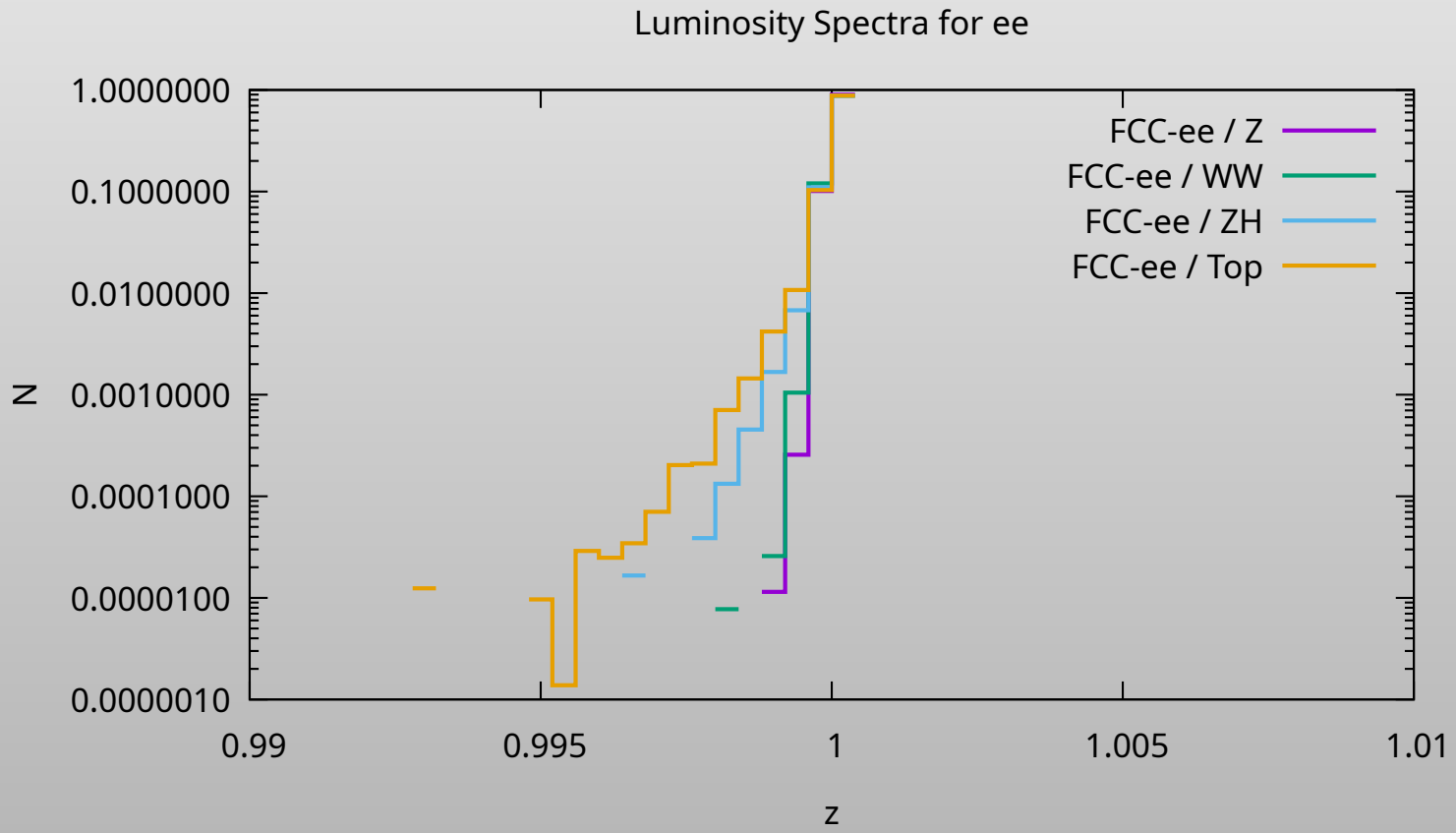
FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

[Frank Zimmermann, FCC Week, June 2024]

- vice-versa, the luminosity spectra for e^+e^- from beamstrahlung alone are very steep, in particular on the Z-pole

$$z = \sqrt{\frac{E_{e^-}}{E_{\text{beam}}} \frac{E_{e^+}}{E_{\text{beam}}}}$$



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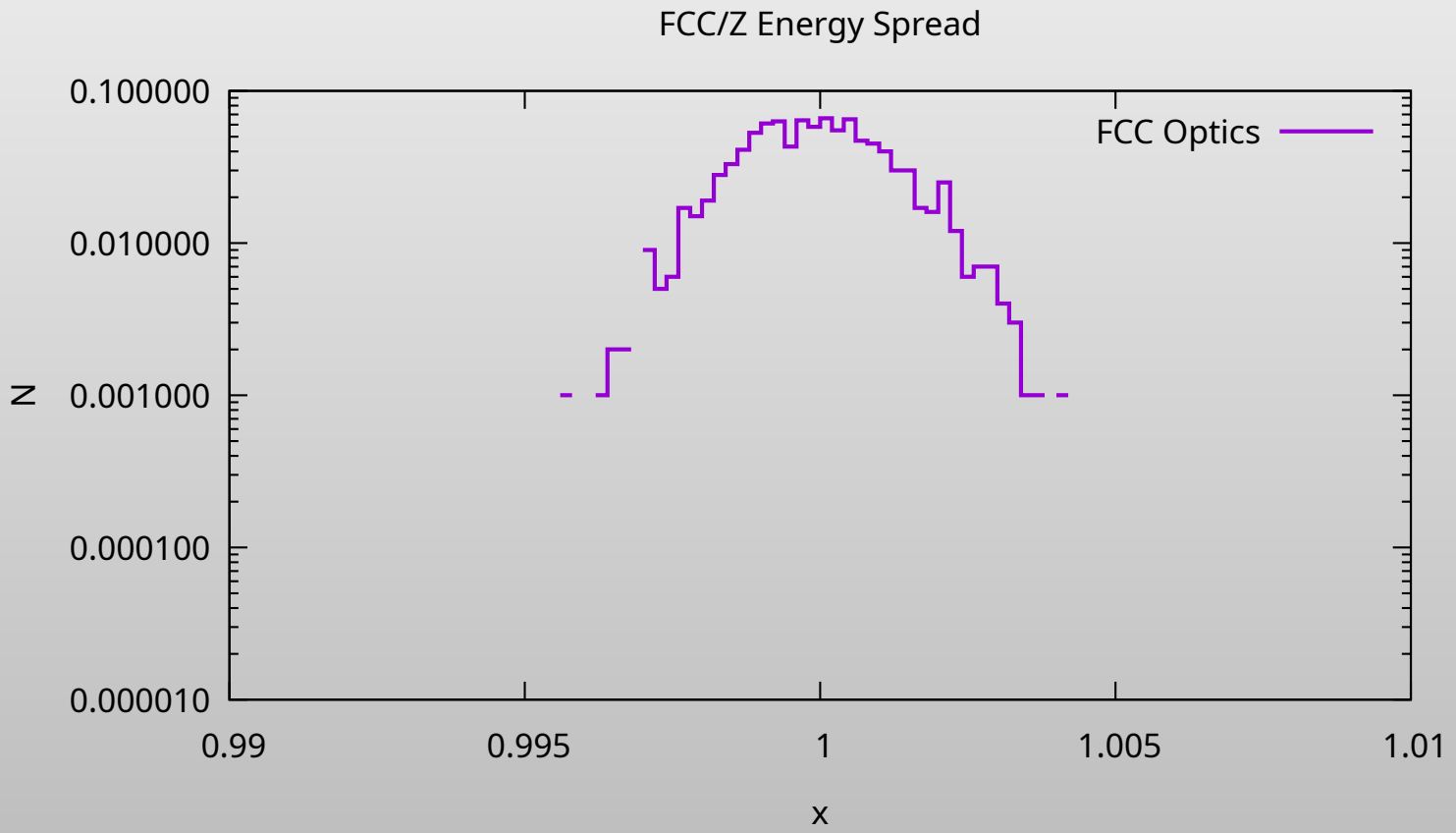

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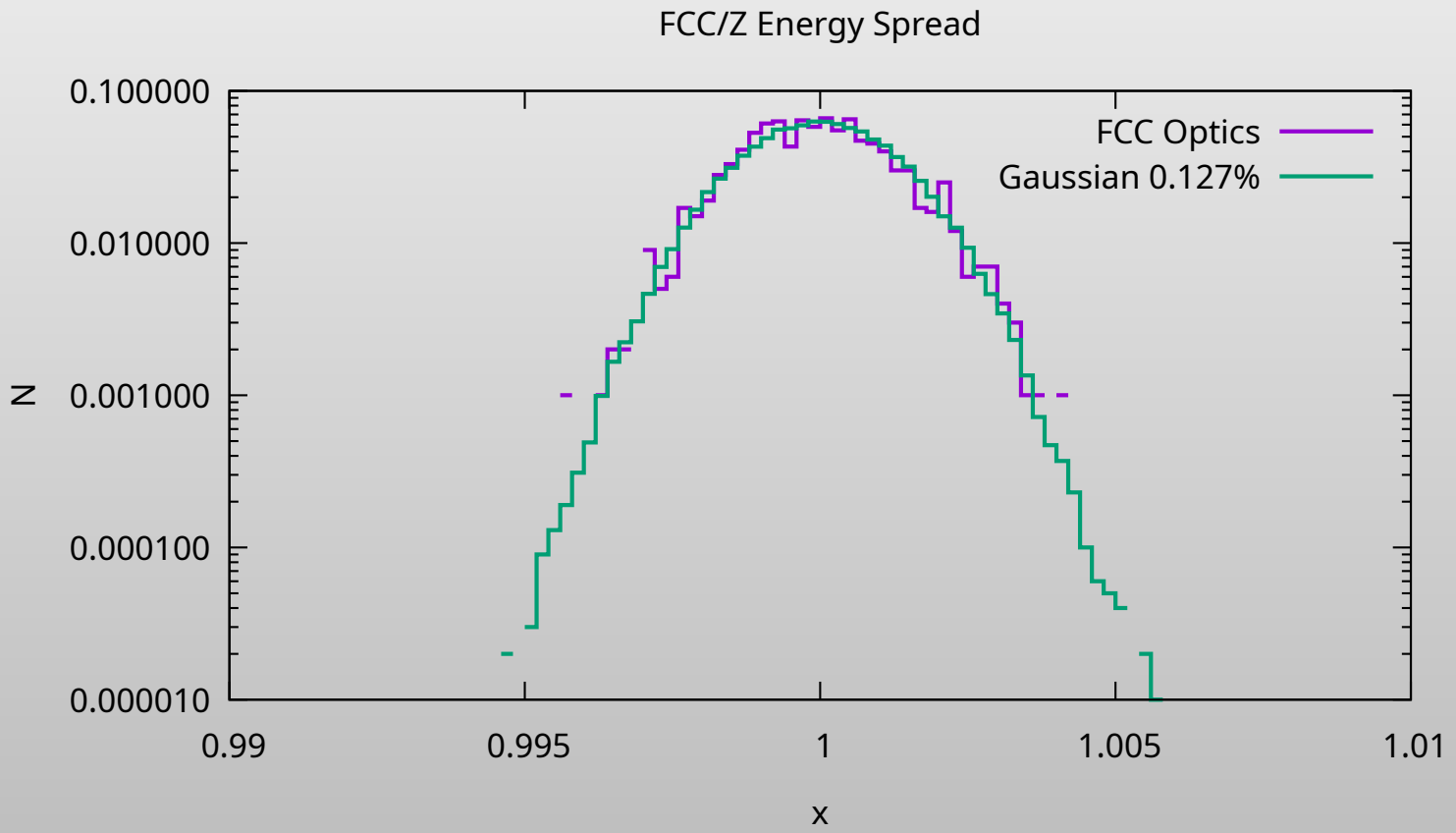

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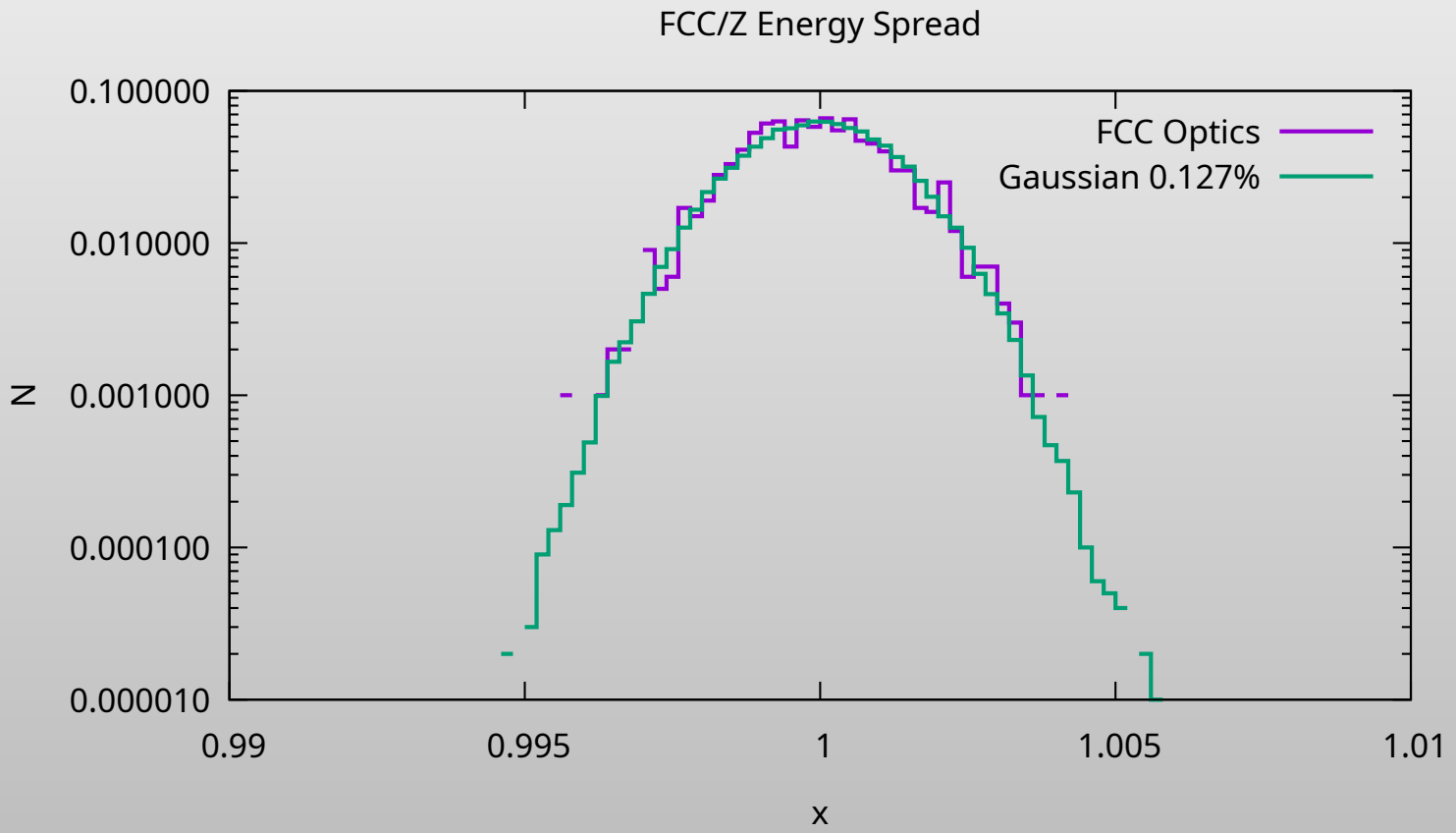

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- note that the x-scale is the same!

Energy Spread

- FCC parameters including energy spread:

Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x\sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)[b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

7

[Katsunobu Oide, FCC Week, June 2023]

- $e^{\pm}$ energy spread from BS and average photon energy much smaller than beam energy spread $\Delta E_{e^{\pm}}/E_{\text{beam}} \approx 0.15\%$ after many bunch crossings:

FCC 2024	$\Delta_{\text{BS}} E_{e^{\pm}}$/Gev	$\langle E_{\gamma} \rangle_{\text{BS}}$/Gev	$0.15\% \cdot E_{e^{\pm}}$/Gev
Z	0.0012	0.0016	0.07
WW	0.0039	0.0059	0.12
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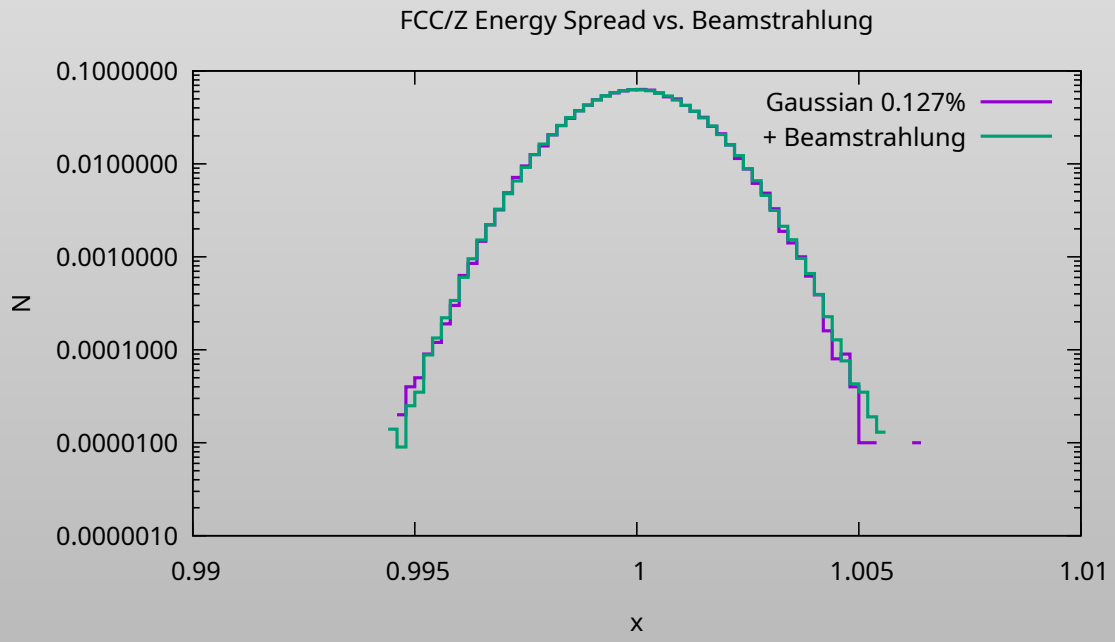

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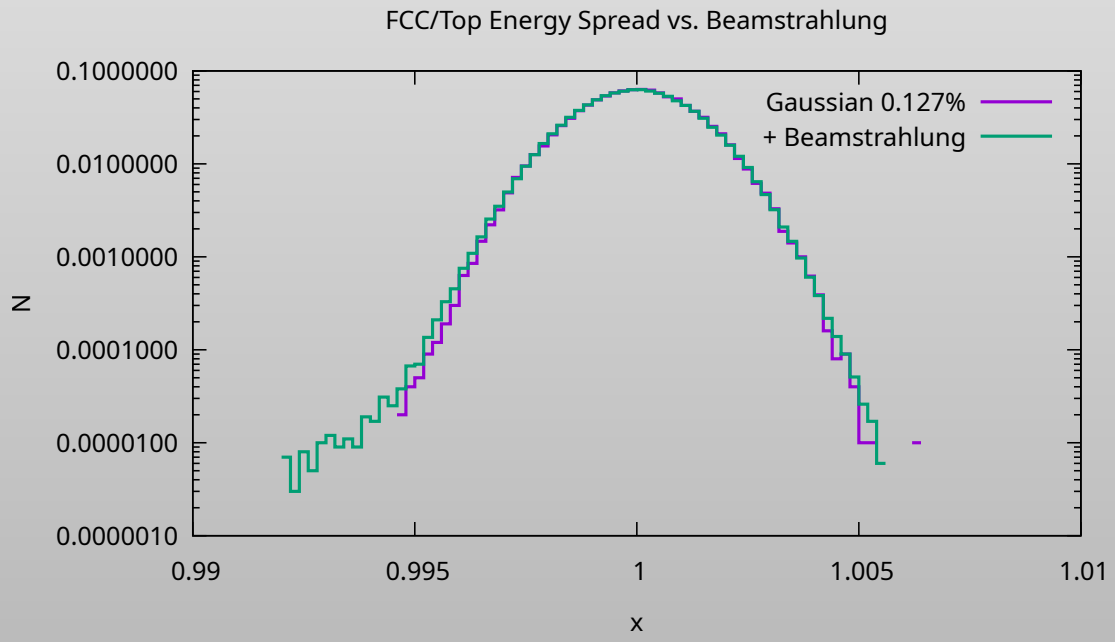

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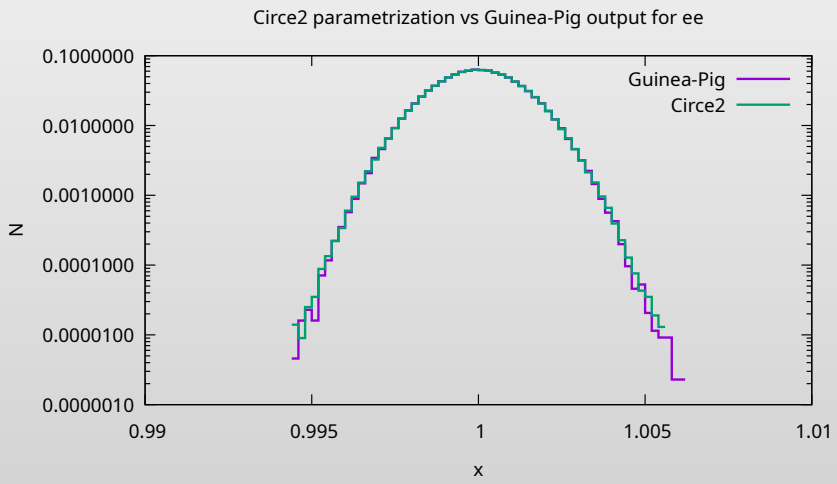
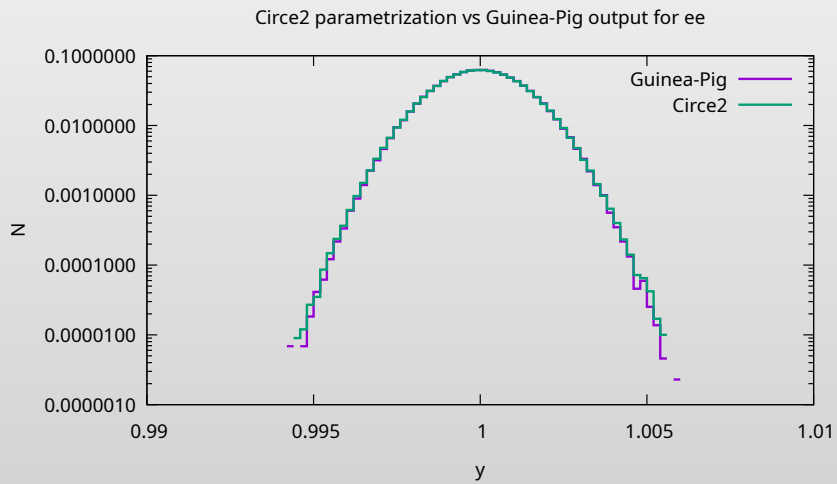
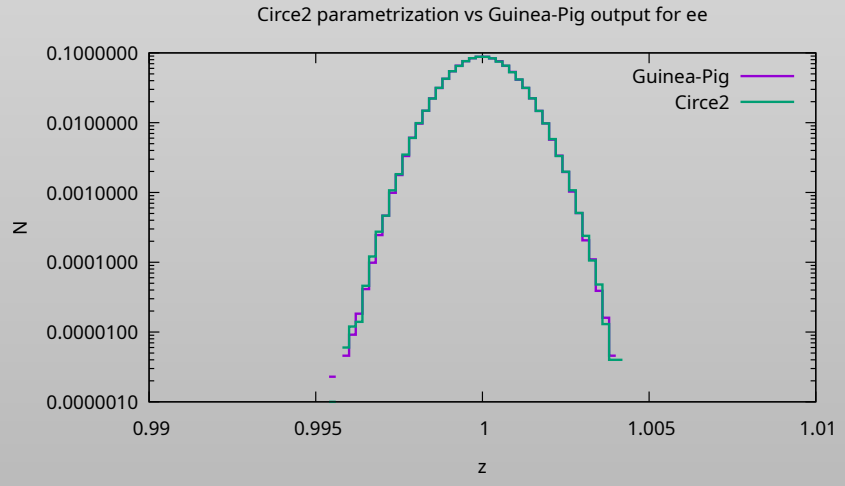
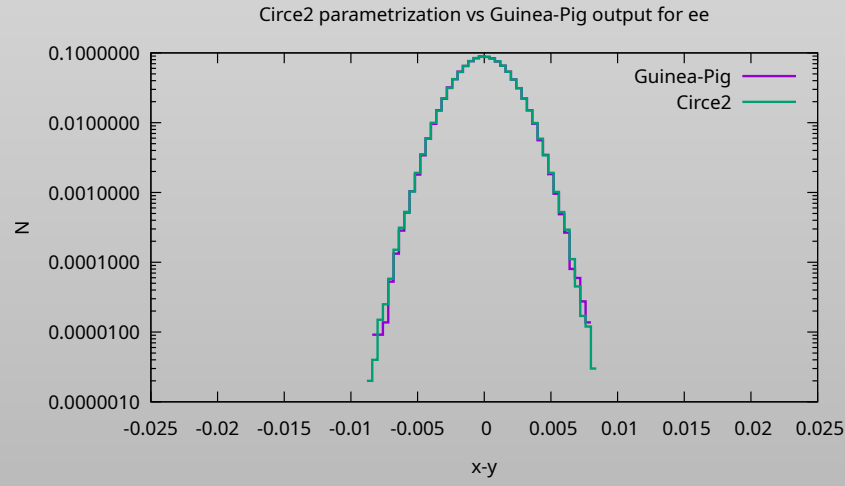
- $e^- e^+$ at FCC/Z









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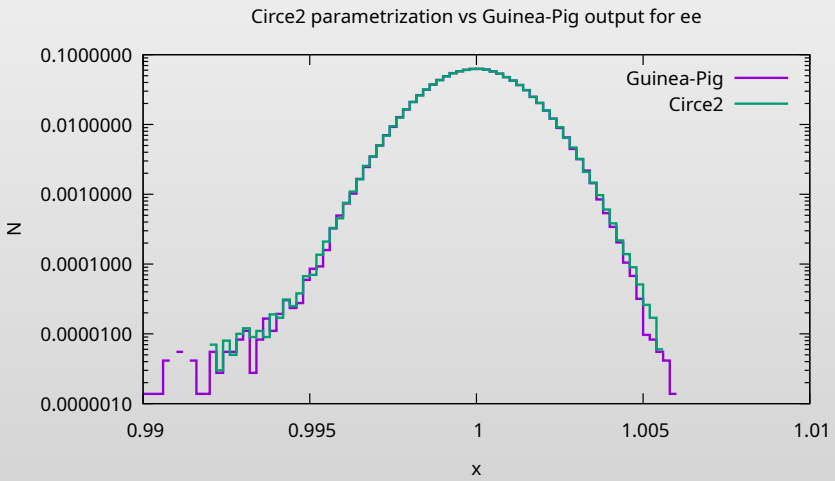
- only apply minimal additional smoothing

```
smooth = 1 [0,1.1] [0,1.1]
```

- e^-e^+ at FCC/Top


Circe2 parametrization vs Guinea-Pig output for ee
Guinea-Pig
Circe2
N
x
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0.99
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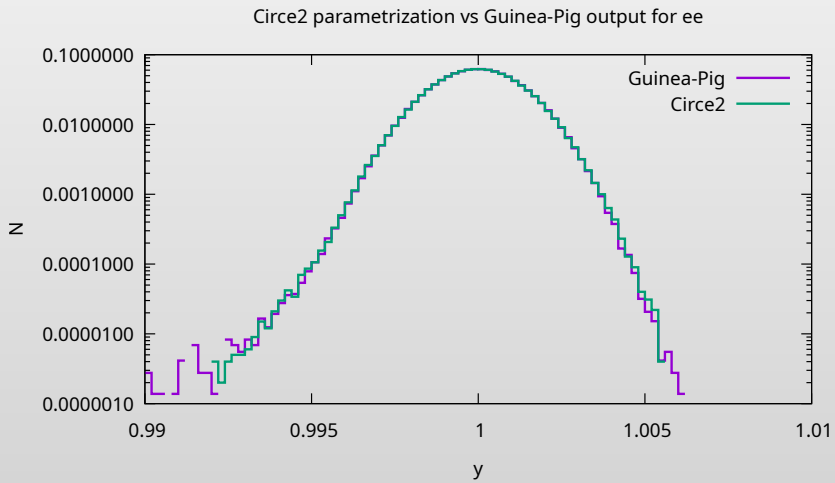
1
1.005
1.01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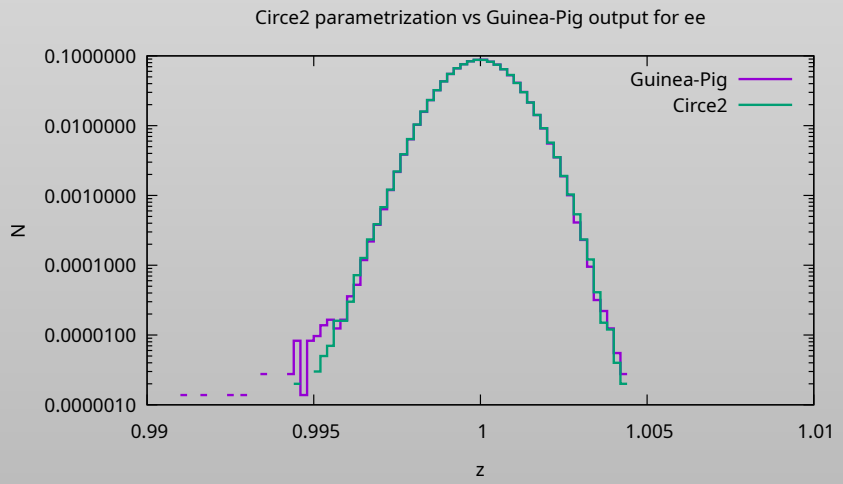
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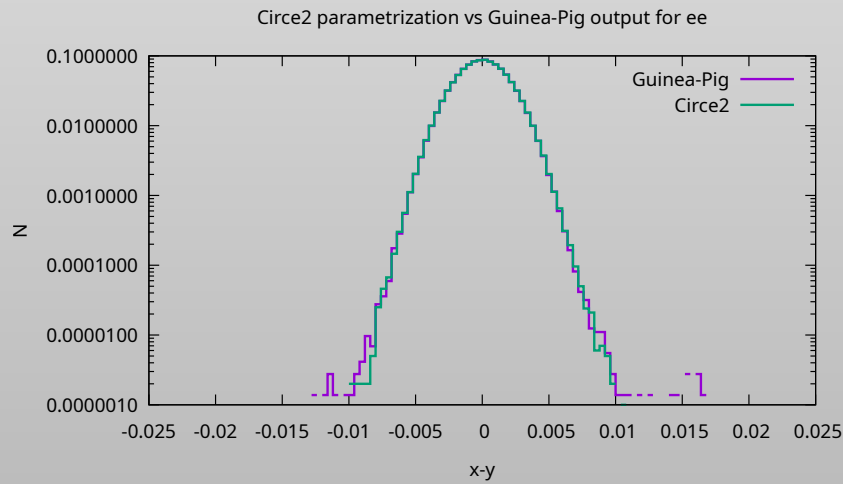
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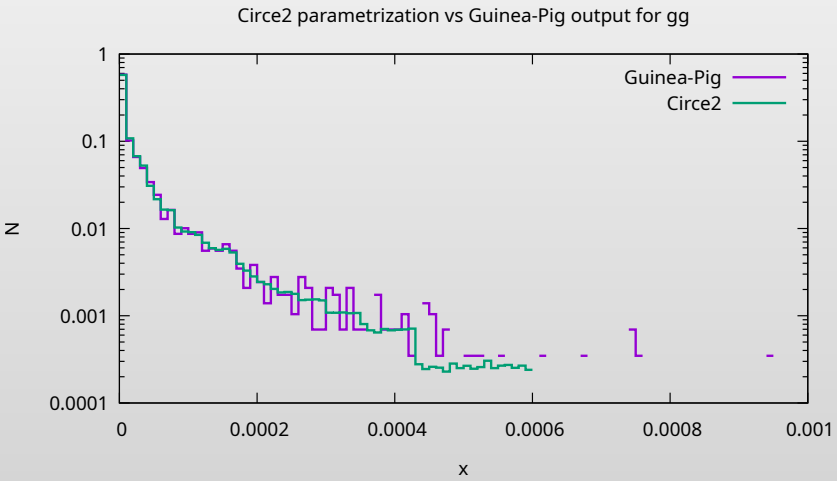
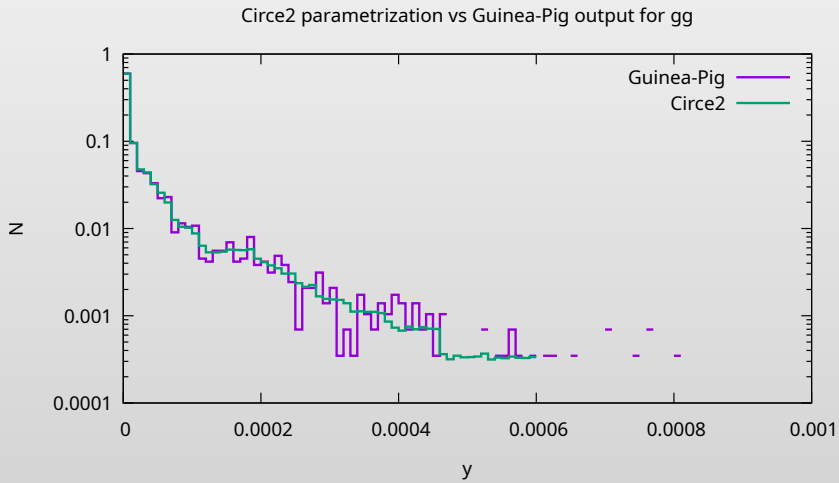
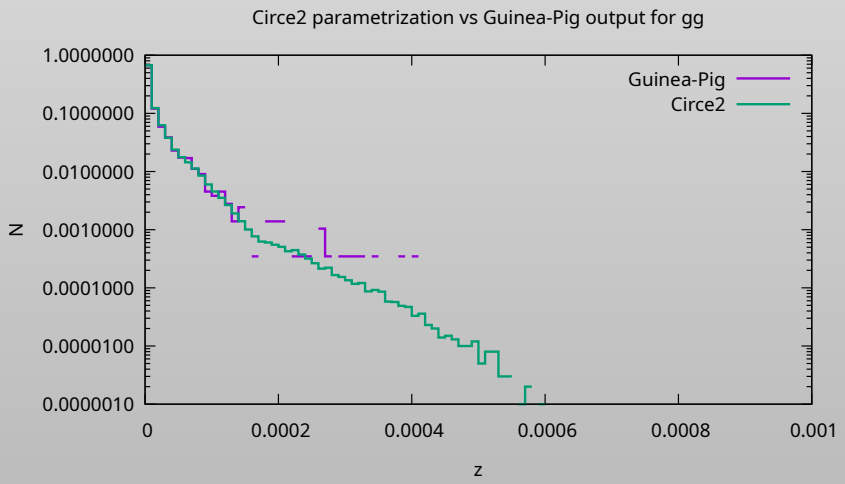
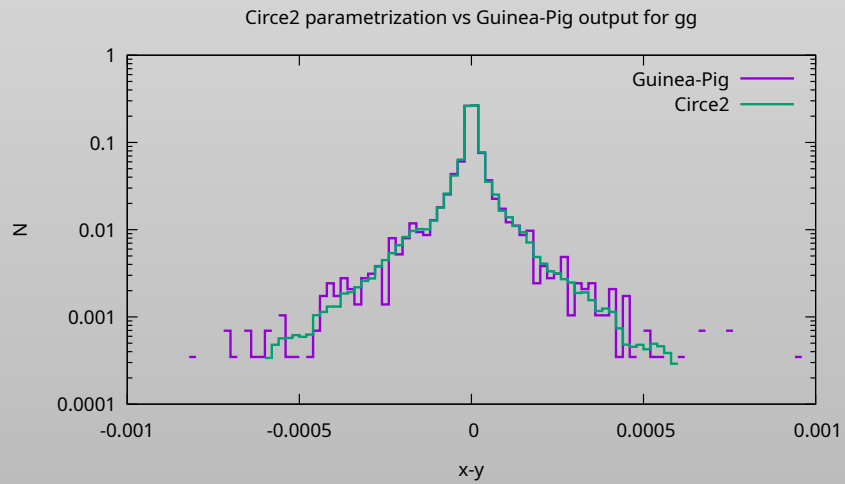
- $\gamma\gamma$ at FCC/Z

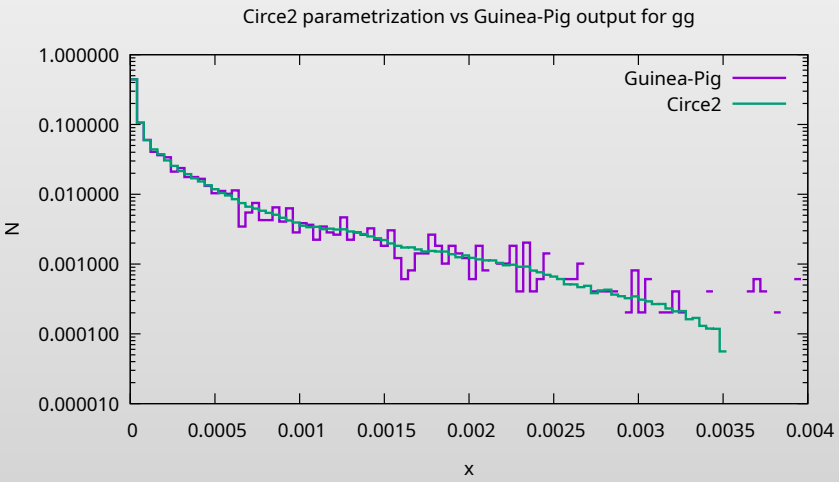


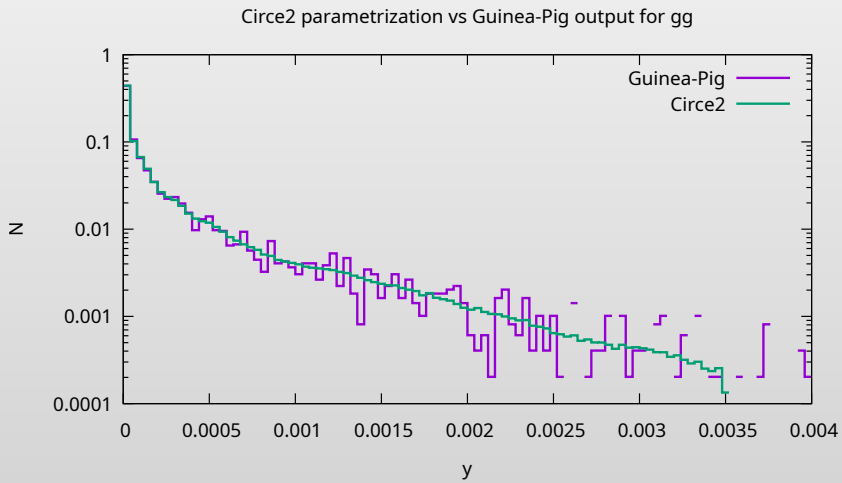


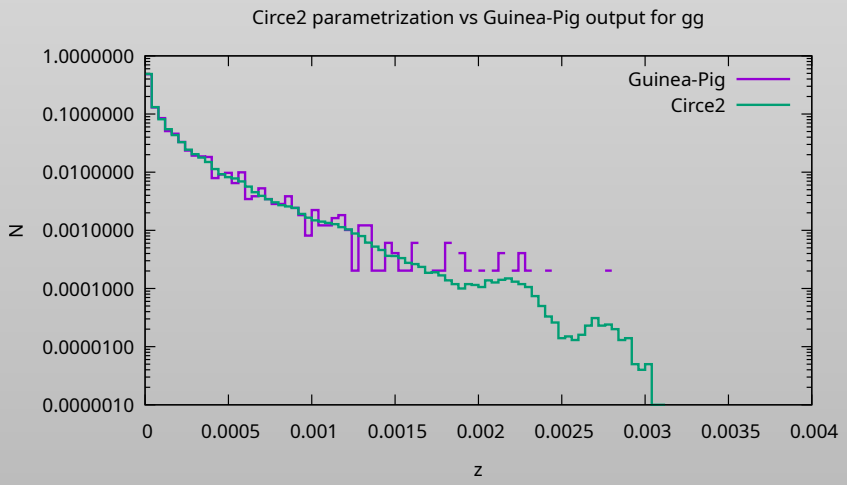




- $\gamma\gamma$ at FCC/Top







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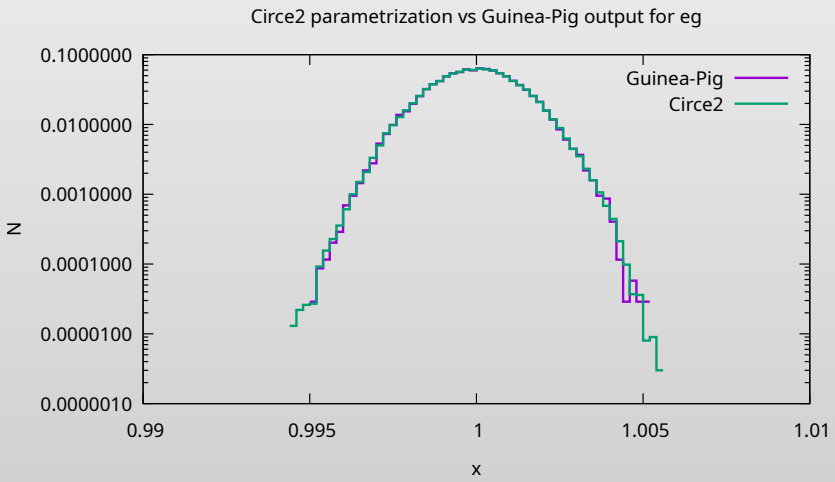
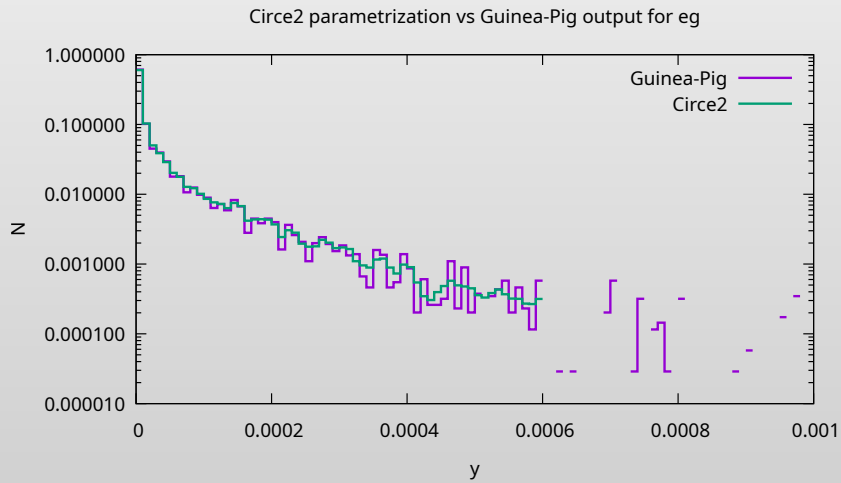
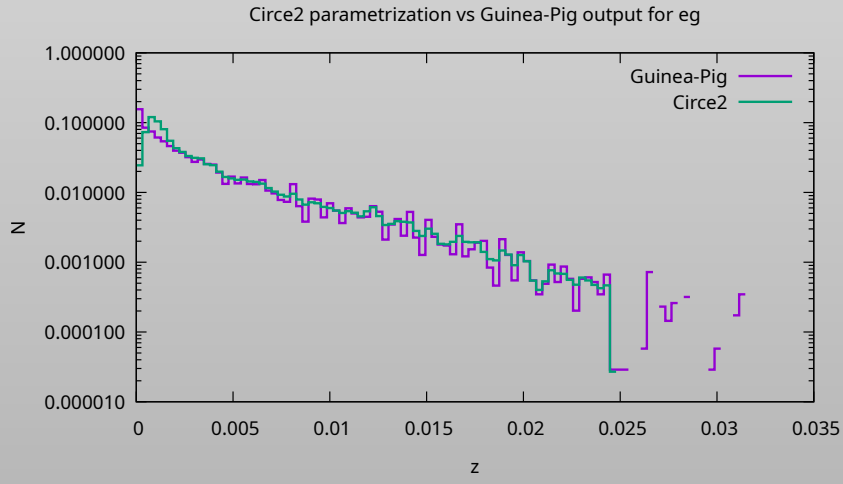
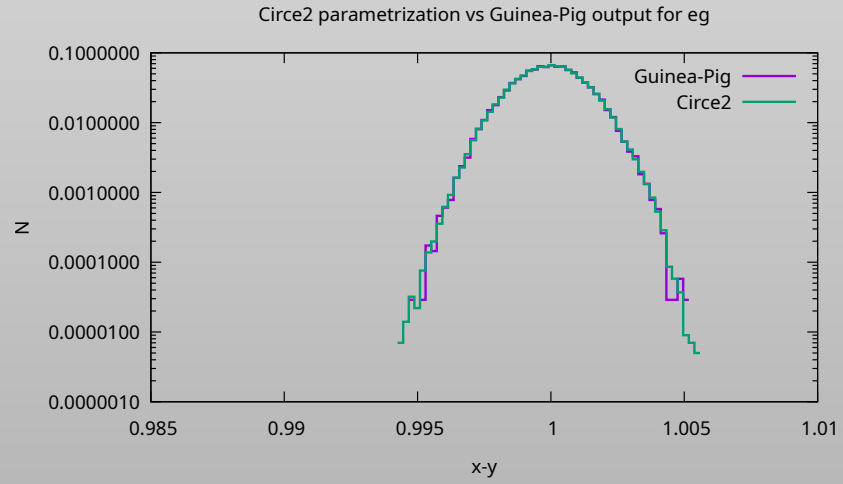
- $z = \sqrt{xy}$ is contains an artifact that is not visible from the individual distributions:

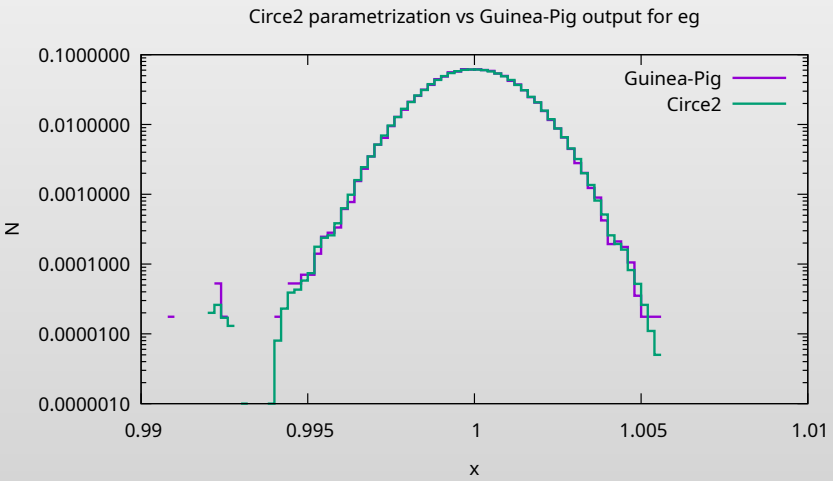


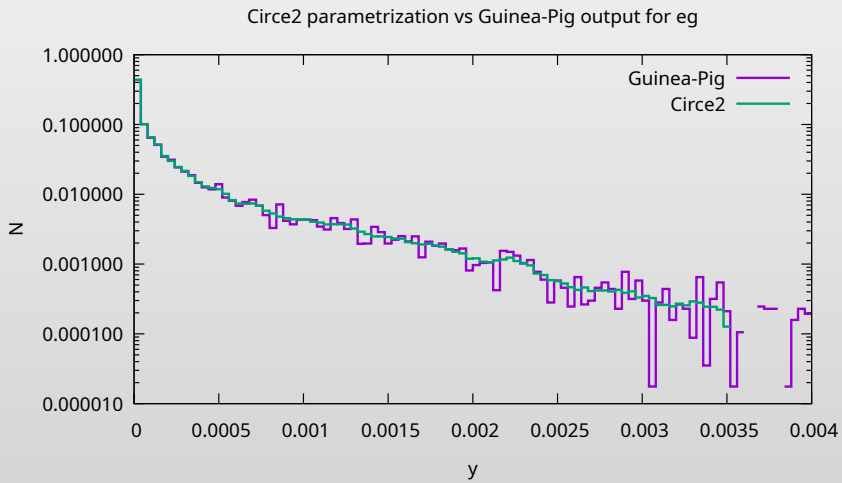


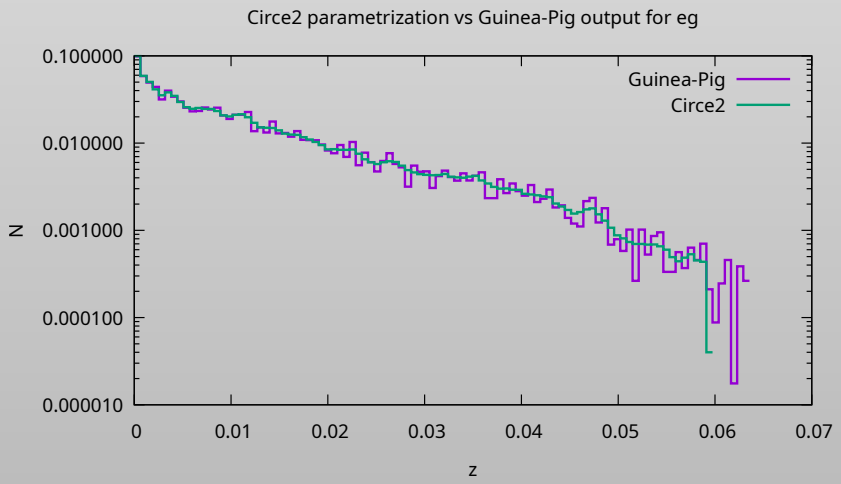


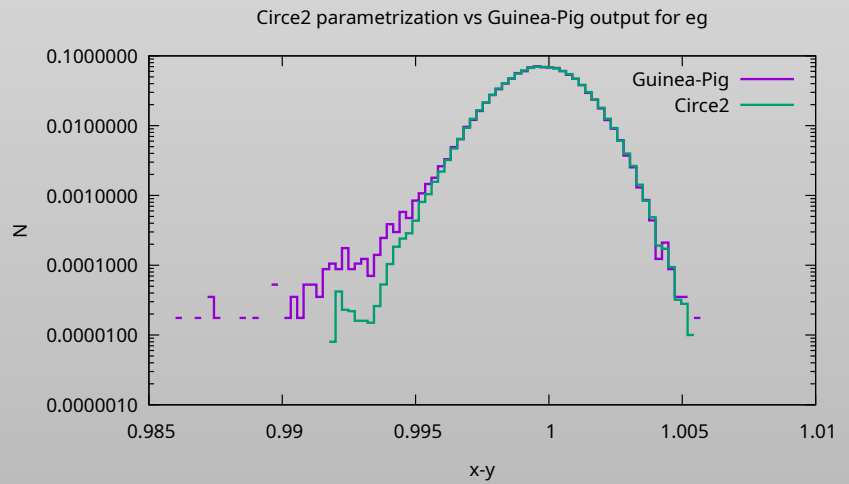


- $e^-\gamma$ at FCC/Top

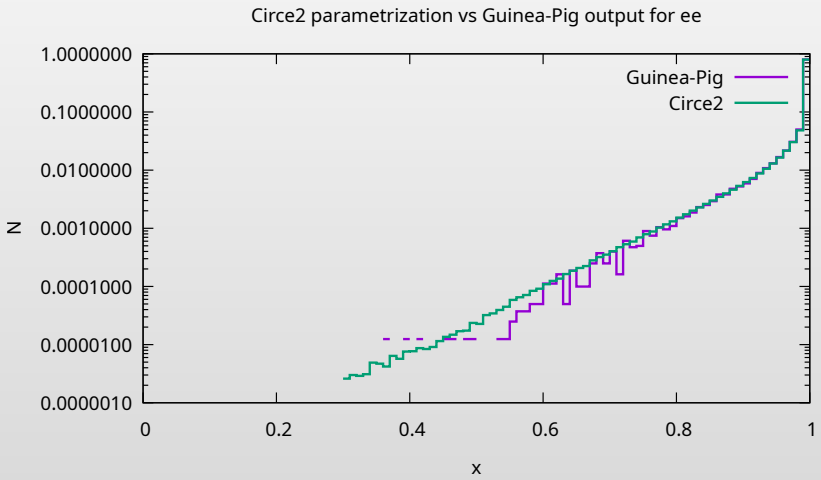


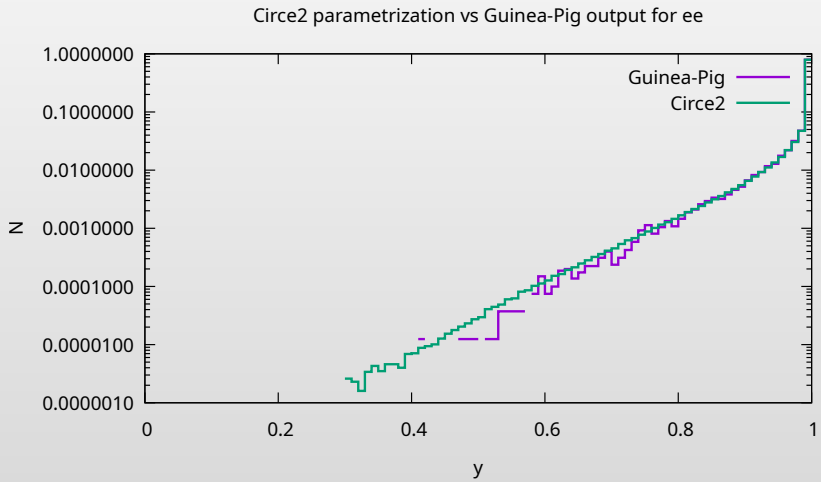


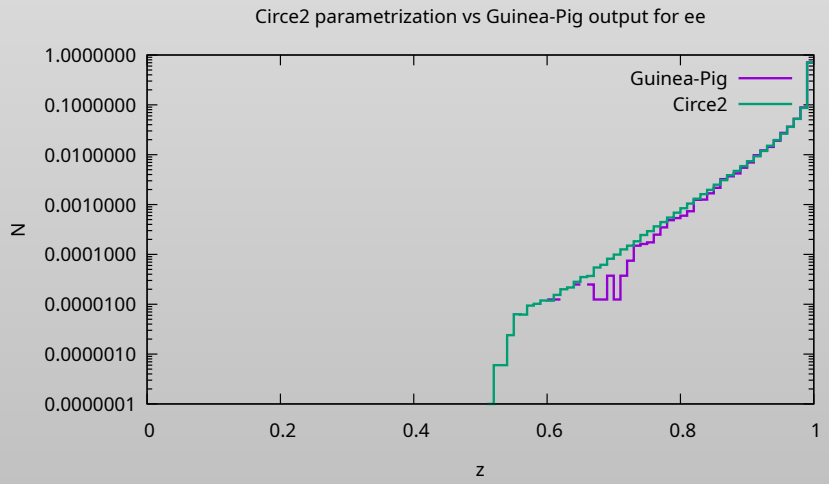


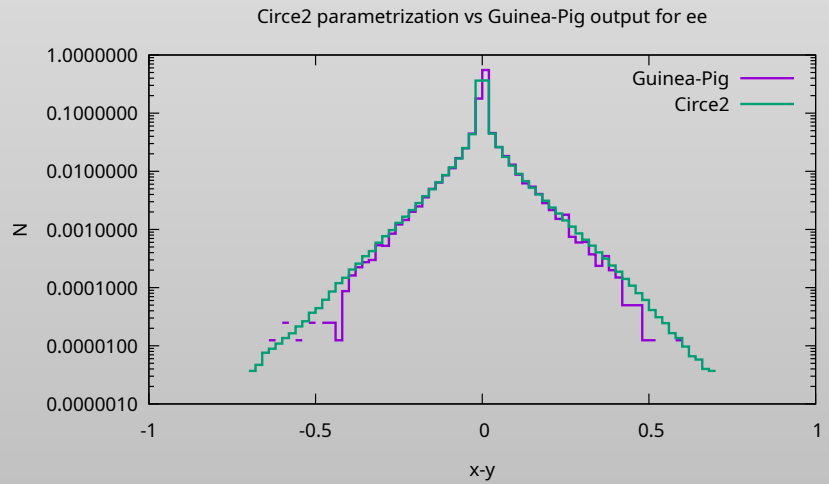


- for comparison: $e^- e^+$ at C3 [Lindsey Grey]

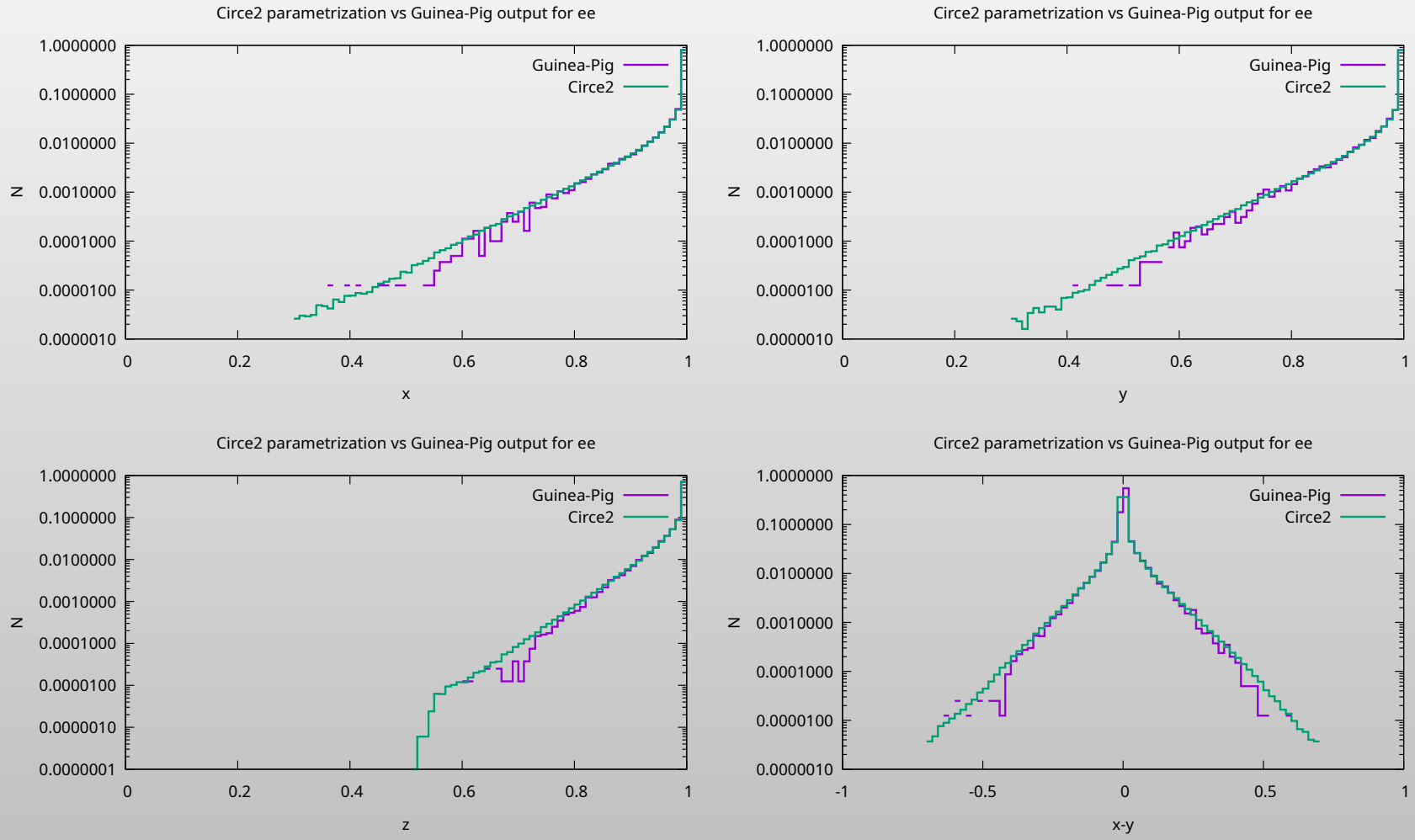








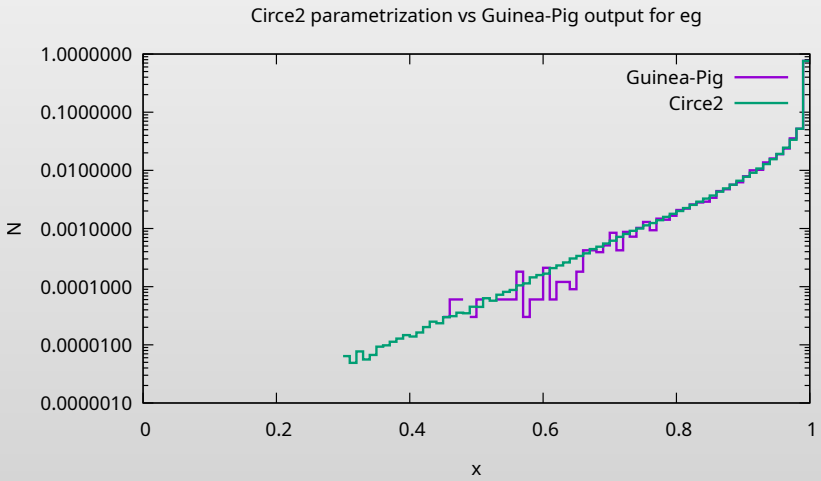
- for comparison: $e^- e^+$ at C3 [Lindsey Grey]

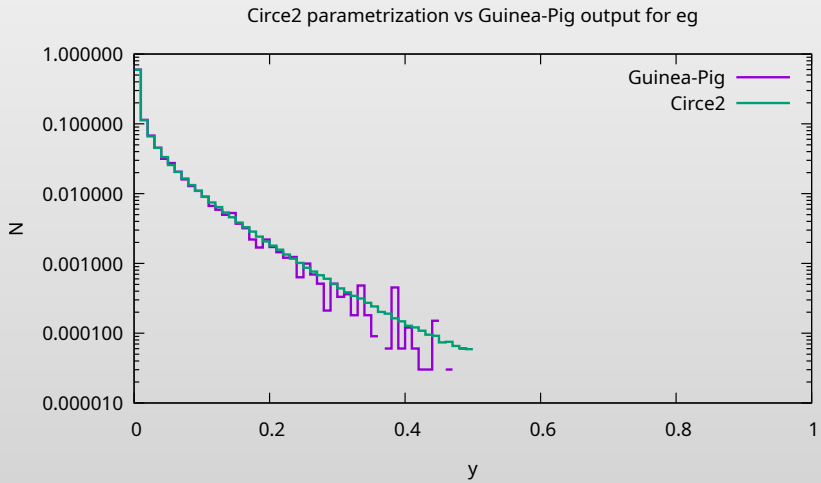


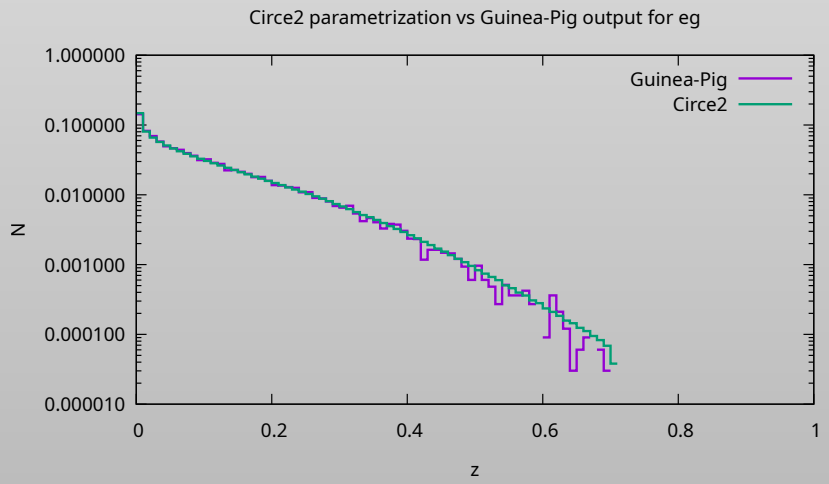
- filtering empty regions and applying power maps

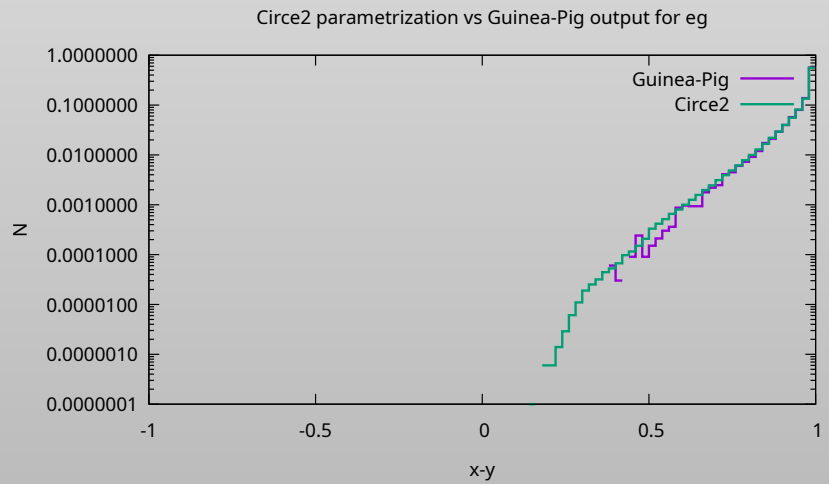
```
map = null { 1 [0, 0.3] }
map = power { 99 [0.3, 1] beta = -0.7 eta = 1 }
```

- $e^-\gamma$ at C^3


Circe2 parametrization vs Guinea-Pig output for eg
Guinea-Pig
Circe2
N
x
1.0000000
0.1000000
0.0100000
0.0010000
0.0001000
0.0000100
0.0000010
0
0.2
0.4
0.6
0.8
1


Circe2 parametrization vs Guinea-Pig output for eg
Guinea-Pig
Circe2
N
y
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0
0.2
0.4
0.6
0.8
1


Circe2 parametrization vs Guinea-Pig output for eg
Guinea-Pig
Circe2
N
z
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0
0.2
0.4
0.6
0.8
1


Circe2 parametrization vs Guinea-Pig output for eg
Guinea-Pig
Circe2
N
x-y
1.0000000
0.1000000
0.0100000
0.0010000
0.0001000
0.0000100
0.0000010
0.0000001
-1
-0.5
0
0.5
1

- $\gamma\gamma$ at C3