Comparison of WarpX and GUINEA-PIG for Beam-Beam Interactions in Muon Collider

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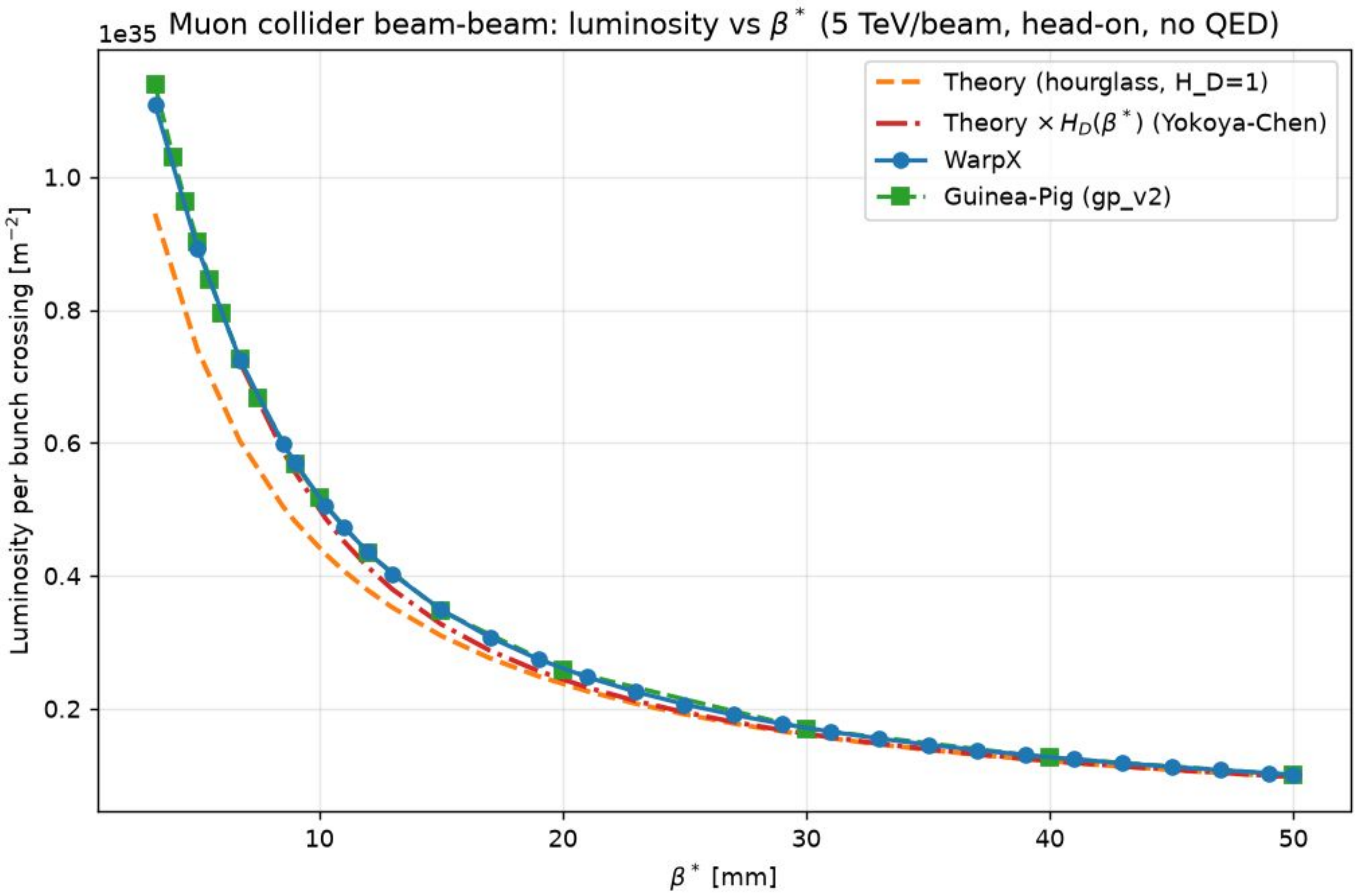
Takeaway: GUINEA-PIG and WarpX agree for muon collider beams

We were able to reach agreement between GUINEA-PIG (GP) and WarpX for beam-beam simulations in a muon collider.

- Required steps:
  - Modifying WarpX to input muons correctly
    - lots of smaller patches (see appendix) most which pertain to QED effects which end up being suppressed
  - Modifying a GP-for-muons code that was provided to me by Larry Lee, which needed debugging to
    - fix mu-/mu- to mu-/mu+
    - and correctly dump the initial muon beams

More details on modifications can be found in backup slides.

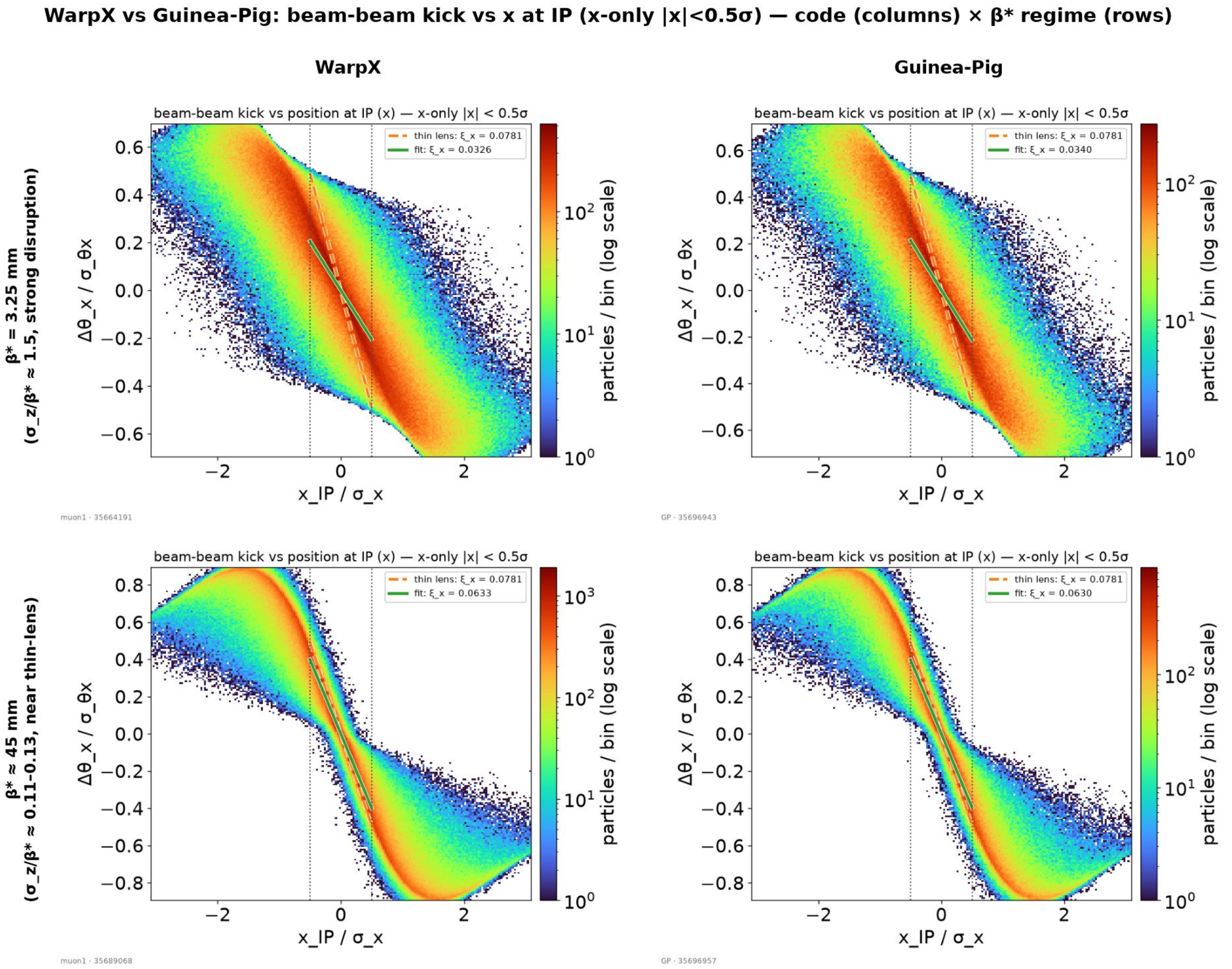
GP vs. WarpX vs. Theory: Luminosity



- GP and agree on luminosity parameter incredibly well!

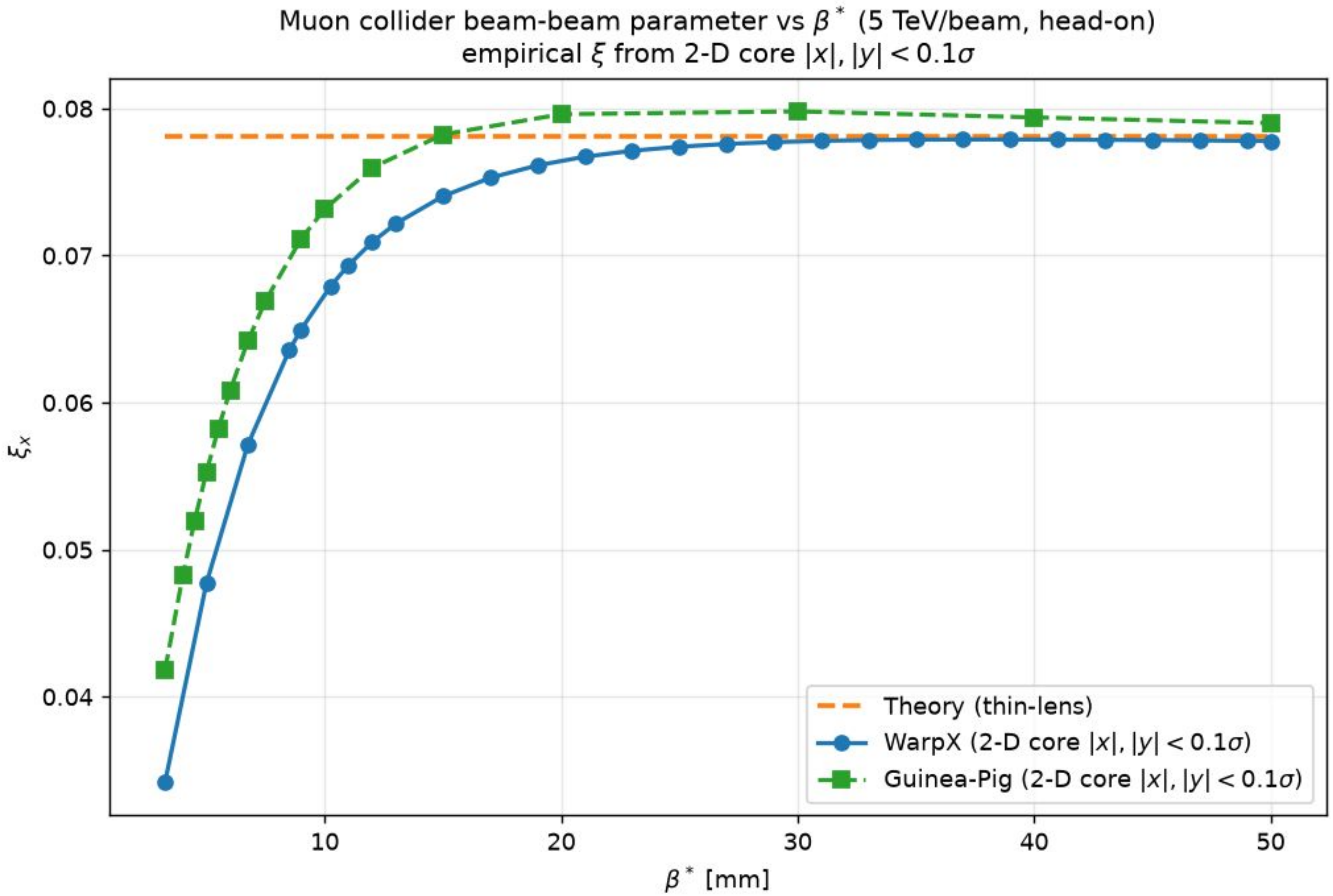
- The [Yokoya-Chen 1988](#) correction to luminosity (estimated using CAIN simulations) is a more accurate estimator than geometric luminosity.
    - only valid and plotted for disruption < 0.8

WarpX vs. GP: beam-beam parameter fits



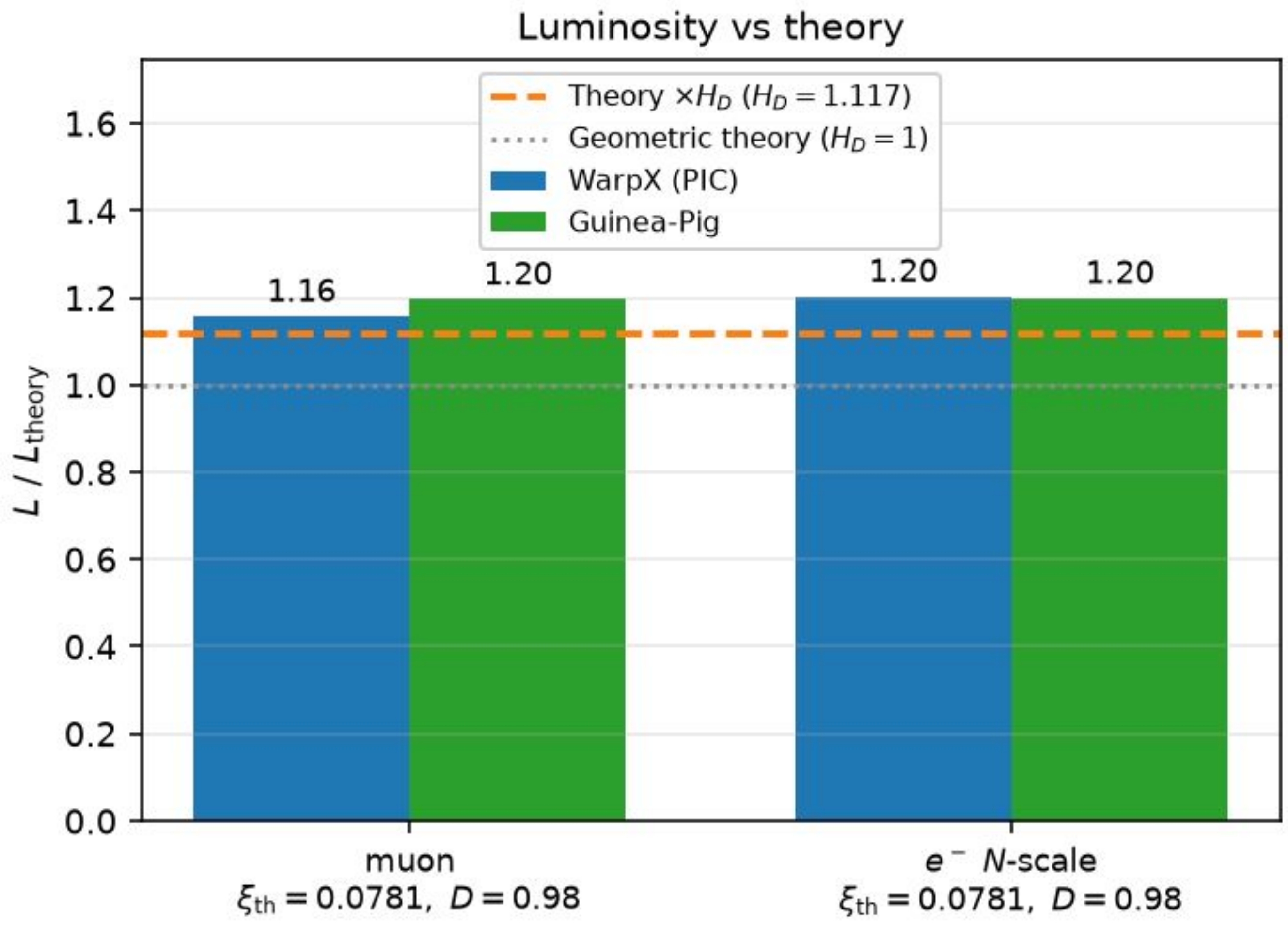
- We want to extract beam-beam parameter from these simulations
  - by fitting the slope of particle position vs. kick
- GP and WarpX dump similar particle data, and achieve very similar beam-beam fits
  - for highly disrupted muon beams (top)
  - and low disruption (bottom)

GP vs. WarpX vs. Thin-lens approximation: Beam-Beam



- GP and WarpX mostly agree on beam-beam parameter
  - both converge to thin-lens prediction at large Beta* / low disruption
- Low Beta*, as the muon collider specs require, leads to highly disrupted beams

WarpX vs. GP: beam-beam parameter fits



- As a cross-check, I compared WarpX and GP for an 'equivalent' e+ e- collision parameters.
  - Analogous disruption and beam-beam parameters accomplished by scaling down the bunch size
  - see appendix for scaling math on mass

Conclusions

1. GP and WarpX, modified to appropriately handle muons, **agree on muon collider luminosity and beam-beam parameter!**

2. Muon collider luminosities and beam-beam parameter **agree with those obtained by simulating from a comparable e-e collider** with analogous classical parameters (accomplished in this case by scaling the bunch size).

3. The muon collider as designed involves a *highly disrupted beam with non-linear behavior* that is in need of further study.

Next Steps

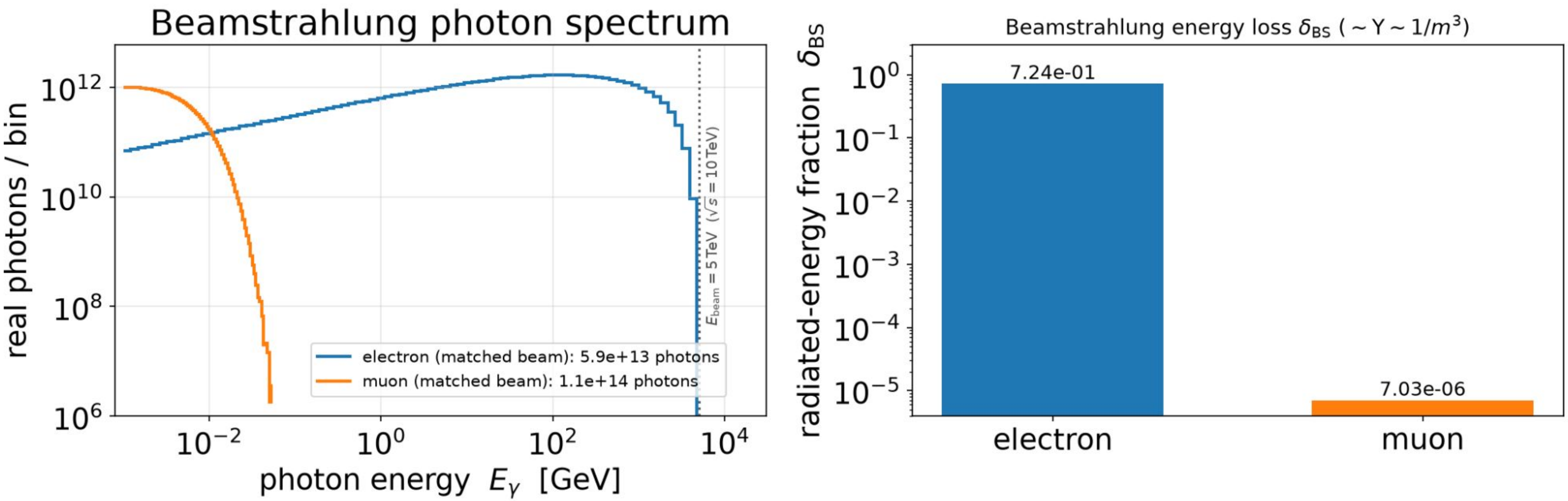
- In order to do multi-turn analysis (combining WarpX and GP with X-suite), we need more detailed information about the design of the collider ring.

- As of now , we only know about the interaction point.

- We hope you can provide us with a single turn matrix or a full lattice, depending on what is available.

Appendix: Mass suppression of radiation and quantum effects (WarpX)

Quantum-synchrotron suppression: WarpX, identical beams, e vs μ (10 TeV CoM)



measured δ_{BS} suppression ≈ 1.0e+05 (lower bound: the electron is quantum-saturated at $\delta_{BS} \lesssim 1$; the intrinsic Y ratio is $(m_\mu/m_e)^3 = 8.8 \times 10^6$)

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Appendix: Scaling of classical beam parameters with Beta*

$$\sigma_0 = \sqrt{\frac{\varepsilon_N \beta^*}{\gamma}} \propto \sqrt{\beta^*}, \qquad \sigma_0^2 \propto \beta^*$$

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_0^2} F_{\text{hg}}\left(\frac{\beta^*}{\sigma_z}\right) H_D\big(D(\beta^*)\big) \propto \frac{1}{\beta^*} F_{\text{hg}}\left(\frac{\beta^*}{\sigma_z}\right) H_D\big(D(\beta^*)\big)$$

$$D = \frac{rN\sigma_z}{\gamma\sigma_0^2} = \frac{rN\sigma_z}{\varepsilon_N \beta^*} \propto \frac{1}{\beta^*},$$

$$\xi = \frac{rN\beta^*}{4\pi\gamma\sigma_0^2} = \frac{rN}{4\pi\varepsilon_N} \propto (\beta^*)^0.$$

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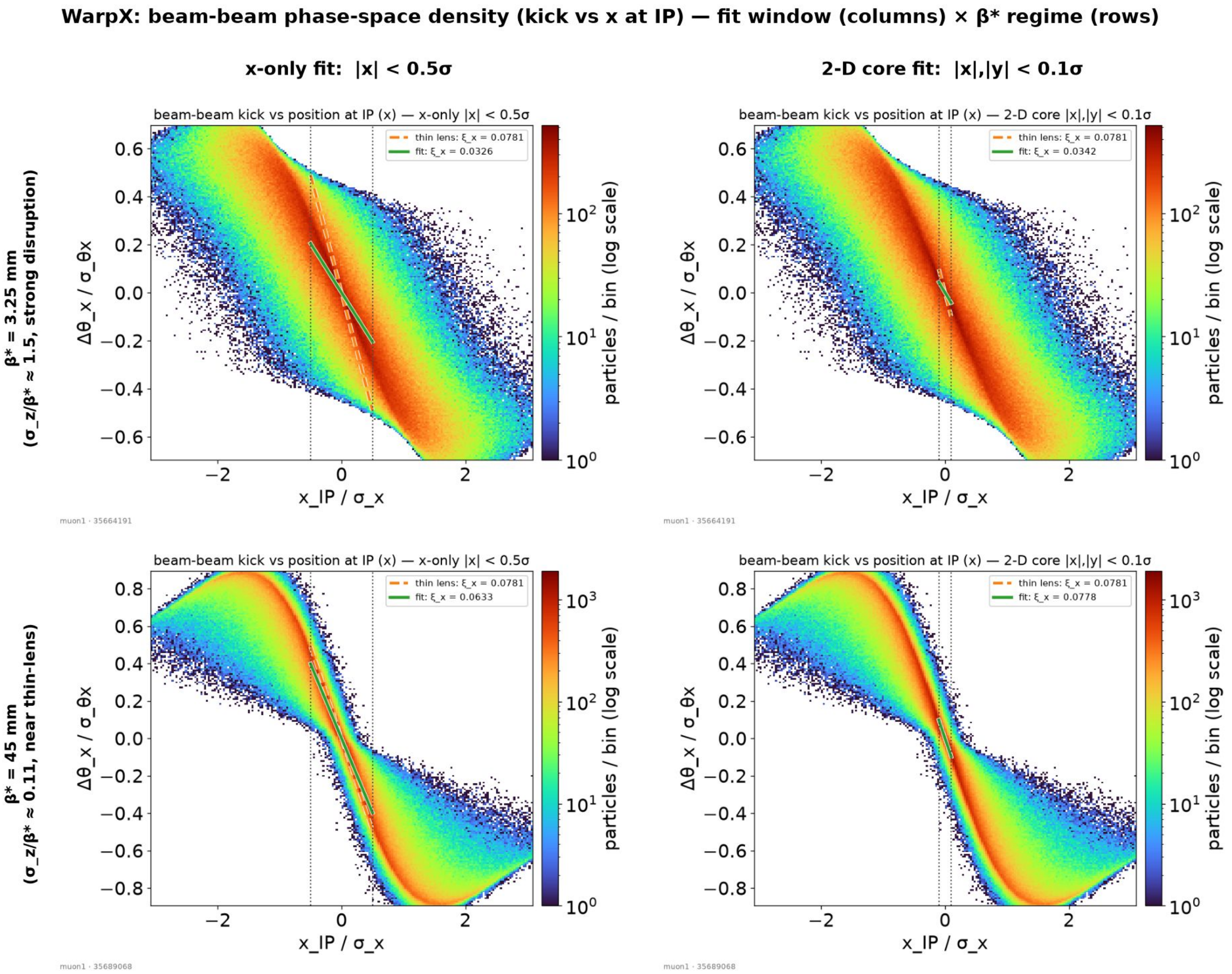
Appendix: beam-beam parameter fits with diff fitting procedures



- For a round beam, fitting the core
    - ‘Analogous disruption and beam-beam parameters accomplished by scaling down the bunch size.
    - see appendix for scaling math

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Appendix: Mass scaling of classical beam parameters

$$r \propto \frac{1}{m}, \qquad \gamma \propto \frac{1}{m}, \qquad \sigma_0 \propto \sqrt{m}$$

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_0^2} H_D \quad \propto \quad \frac{1}{m}$$

$$D = \frac{rN\sigma_z}{\gamma\sigma_0^2} = \frac{e^2 N\sigma_z}{4\pi\varepsilon_0\, E\, \sigma_0^2} \quad \propto \quad \frac{1}{m}$$

$$\xi = \frac{rN\beta^*}{4\pi\gamma\sigma_0^2} = \frac{e^2 N\beta^*}{16\pi^2\varepsilon_0\, E\, \sigma_0^2} \quad \propto \quad \frac{1}{m}$$

- Holding fixed emittance and beam size, classical beam parameters scale linearly with the mass of particle.
- Therefore, in order to do a 1-1 comparison of the muon collider vs. e collider, it's necessary to 'scale' at least one of the parameters.
  - For now, we try just scaling N to compensate.

Appendix: Muon Collider Input Parameters (GP and WarpX)

#	Parameter	Unit	Table 6.1 relaxed | target	WarpX (muon1_input.txt)	GUINEA-PIG (gp_template.acc)
1	Center of mass energy	TeV	**10**	`energy = 5*TeV (CoM = 2x)`	`energy=5000 (GeV, CoM = 2x)`
2	Geometric luminosity	10^{34} $cm^{-2}s^{-1}$	**5.77 | 19.2**	`OUTPUT (ColliderRelevant, DiffLumi_beam1_beam2)`	`OUTPUT (do_lumi / num_lumi; here do_lumi=0)`
3	Beam energy	TeV	**5**	`energy = 5*TeV`	`energy=5000 (GeV)`
4	Relativistic Lorentz factor	-	**47322**	`gamma = energy/mc2, mc2 = m_mu*c^2 [correct]`	`gamma_beam = ebeam/EMASS [electron mass -> WRONG]`
5	Circumference	km	**≈ 10**	–	–
6	Dist. of last magnet to IP	m	**6**	–	–
7	Repetition rate	Hz	**5**	`– (no rep-rate concept)`	`f_rep=1.0 (Hz) [≠ 5]`
8	Bunch intensity (1 bunch/beam)	10^{12}	**1.80**	`npart = 1.80e12 (charge = q_e*npart)`	`particles=180.0 (x1e10), n_b=1`
9	Injected beam power per beam	MW	**7.2**	–	–
10	Normalized transverse rms emittance	µm	**25**	`emit_n = 25*micro (emitx_n = emity_n)`	`emitt_x=emitt_y=25.0 [muon-patched build]`
11	Longitudinal norm. rms emittance	eVs	**0.025**	`implied by sigmaz x espread`	`implied by sigma_z x espread`
12	Relative rms momentum spread	10^{-3}	**0.3 | 1**	`espread = 0.3e-3 * gamma (rel. = 0.3e-3)`	`espread=0.0003 (relative)`
13	RMS bunch length in space	mm	**5 | 1.5**	`sigmaz = 5*milli`	`sigma_z=5000.0 (µm)`
14	RMS bunch length in time domain	ns	**.017 | 0.005**	`derived = sigmaz/c`	`derived = sigma_z/c`
15	Twiss betatron function at the IP	mm	**5 | 1.5**	`beta = 5*milli (betax = betay)`	`beta_x=beta_y=5.0 (mm)`
16	Energy loss per turn	MeV	**≈ 27.2**	–	–
17	Integrated RF gradient	MV	**30**	–	–

Direct 1:1 input · Derived, not an input · Output, not an input · No correspondence · Patched build required · Mismatch / divergence

Appendix: WarpX muon-patches

File (everything in subdirectory Source/Particles/ElementaryProcess/)	**Description of change**
QEDInternals/QedChiFunctions.H	Add mass scaling in computation of Schwinger field χ: χ ∝ (m / m_e)^3
QEDInternals/QuantumSyncEngineWrapper.H	Propagate input mass through everything that calls χ
Input file change	Numerical integrals of T(χ) [a modified Bessel function] normally has a pre-computed table; Since χ can now range over orders of magnitude, we have to modify the range over which T(χ) is computed.
QEDPhotonEmission.H	WarpX 'cleans' low energy photons by dropping photons under a certain energy, computed using the mass of the electron. This threshold needs to be lowered for heavier lepton.
PICSAR [Particle In Cell Scalable Application Resources] dependency: quantum_sync_engine_core.hpp, gamma_functions.hpp	PICSAR library is used to compute dN/dt [# photons/time] and hard codes the electron mass, so this has to be updated to pass through as well.