STATUS OF FCC-EE BEAM-BEAM STUDIES

Peter Kicsiny, X. Buffat, G. Iadarola, D. Schulte, T. Pieloni, M. Seidel

Special thanks to:
H. Burkhardt, F. Carlier, M. Hofer, K. Oide, L. van Riesen-Haupt, D. Shatilov, D. Zhou

FCC Physics Workshop 2024
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Outline

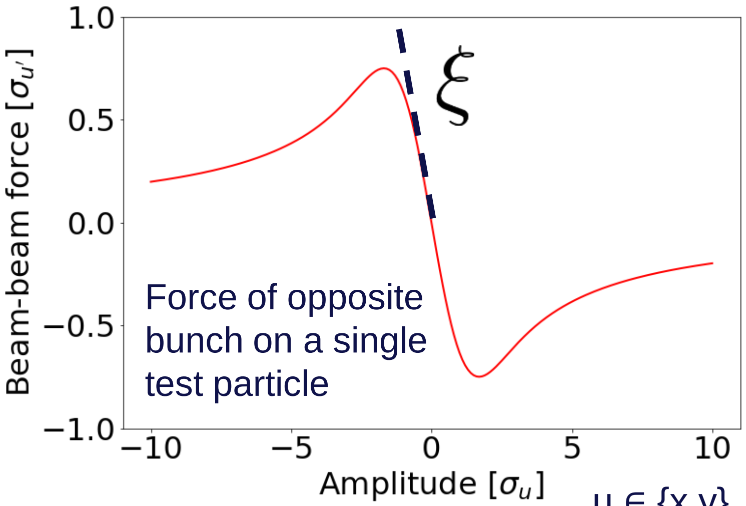
1. FCC-ee beam-beam effects
2. 3D flip-flop instability
3. Bhabha scattering
4. Summary

Beam-beam interaction

- Beam = EM potential for all other charges
- Beam acts with a force on other beam

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

  - **Nonlinear** beam-beam kick
  - Linear strength characterized by beam-beam parameter ξ
  - Harmful consequences on beam dynamics
  - No theory, simulations have to be used

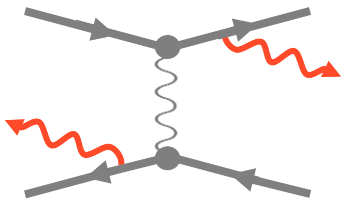


u ∈ {x,y}

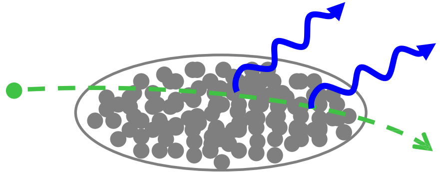
Beam-beam effects in FCC-ee

Incoherent

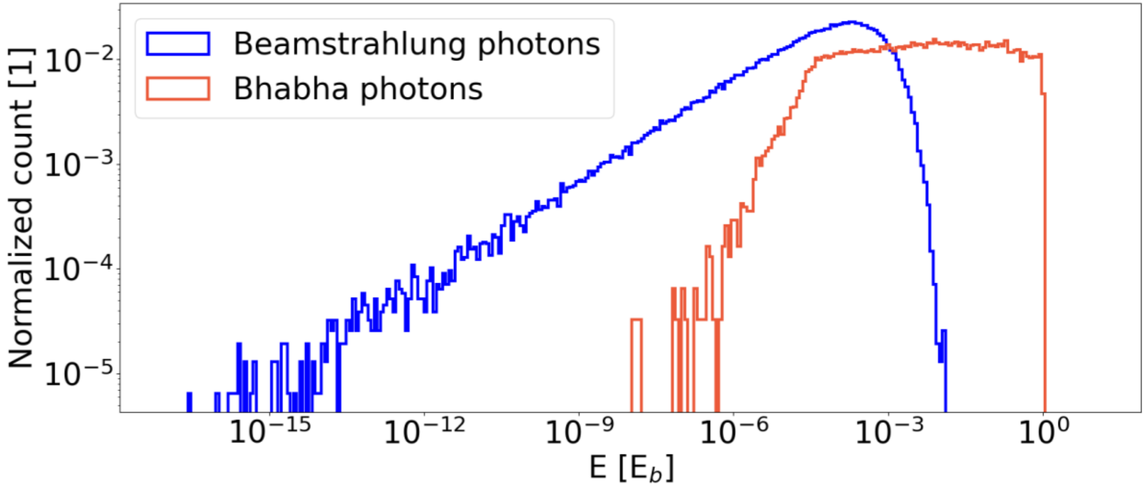
- Radiative Bhabha scattering
- Deflection in field of single particle of opposite bunch



Collective



- Beamstrahlung
- Deflection in collective field of opposite bunch

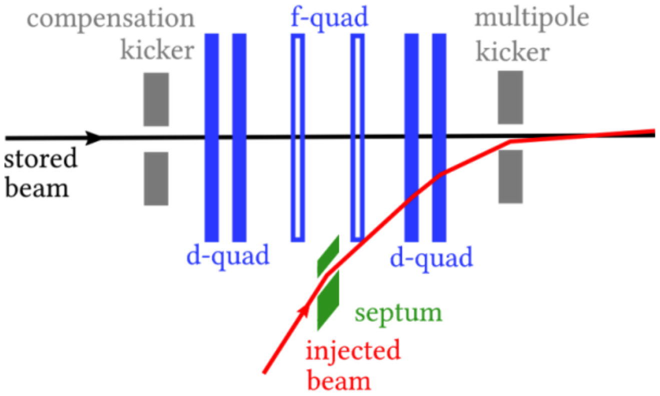


- Radiation ➡ particle losses

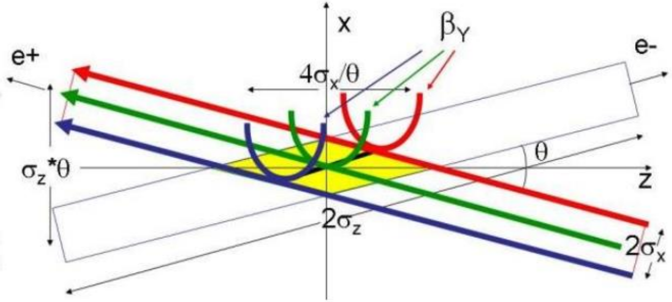
$\tau\,\mathcal{L}$ ⇓ $\sigma_z\sigma_\delta$ ⇑

Beam-beam effects in FCC-ee

1. Top-up injection scheme [1]
   - Continuous injection of new bunches
   - Maintains luminosity levels & compensates for decreased beam lifetime



2. Large Piwinski angle + crab waist scheme [2]
   - Small beam size
   - Crossing angle
   - Crab sextupoles



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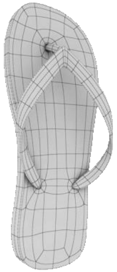
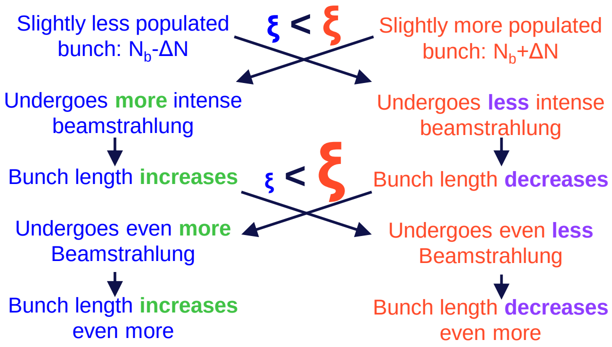
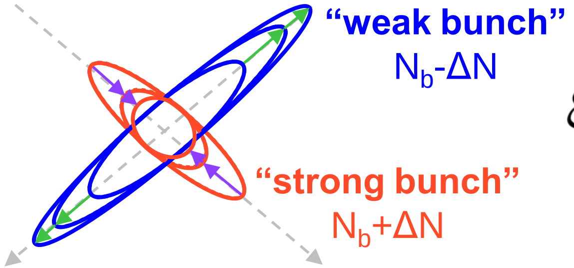
Flip-flop

- Flip-flop instability (1D) observed in other colliders (VEPP-2000) [3]
- For FCC-ee: 3D flip-flop - direct consequence of **beamstrahlung**, triggered by an initial asymmetry in **bunch intensity** [4]



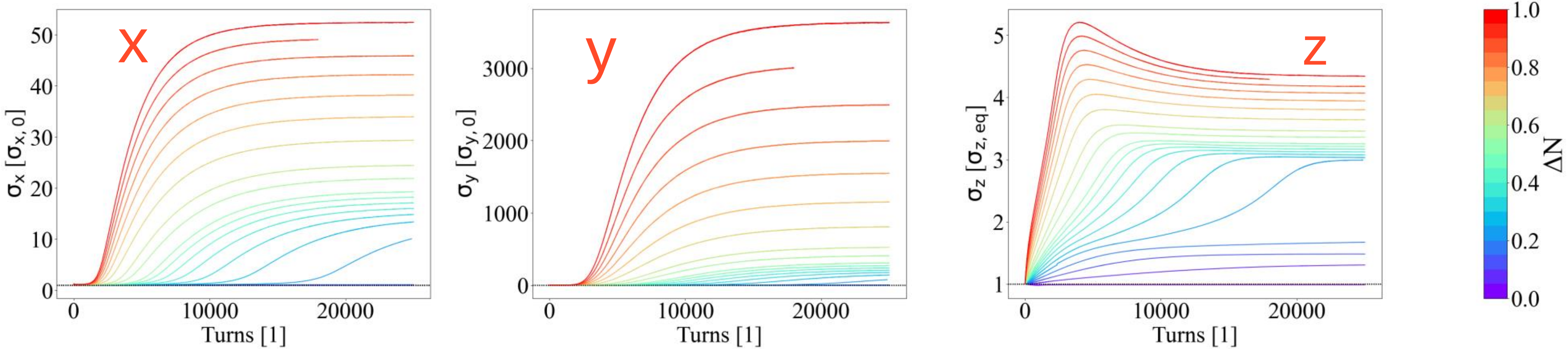




$$\xi \sim \frac{1}{\sigma_z}$$

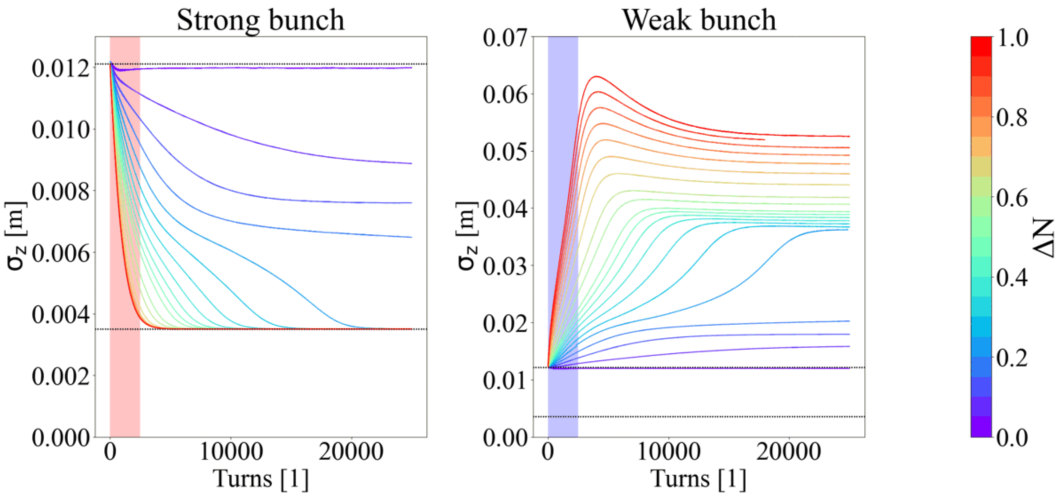
- Inflation of one bunch ➡ beam loss
- Above a threshold ξ_0 longitudinal blowup drives transverse diffusion ➡ 3D flip-flop
- Relevant for FCC-ee top-up injection

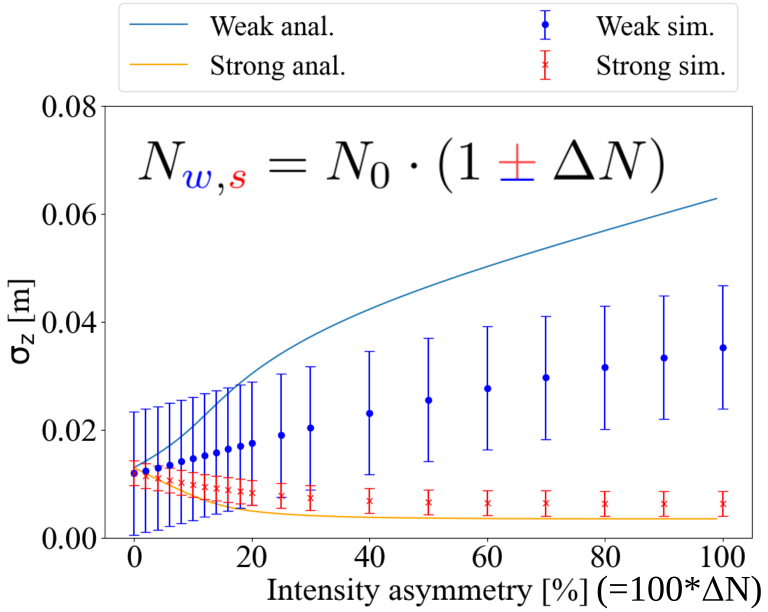
3D flip-flop



- Scanned asymmetry in bunch intensity: $N_{w,s} = N_0 \cdot (1 \pm \Delta N)$ (ΔN ∈ [0,1])
- Observed expected blowup of weak bunch

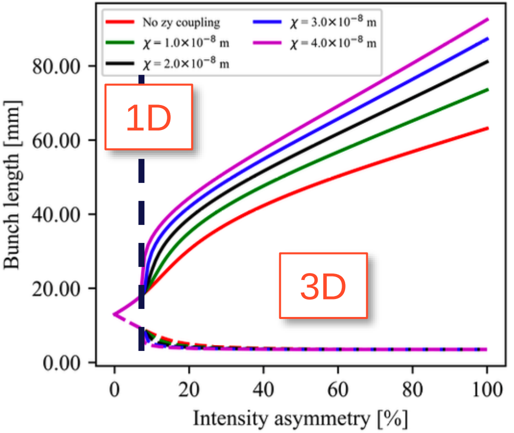
3D flip-flop – comparison to a 1D model

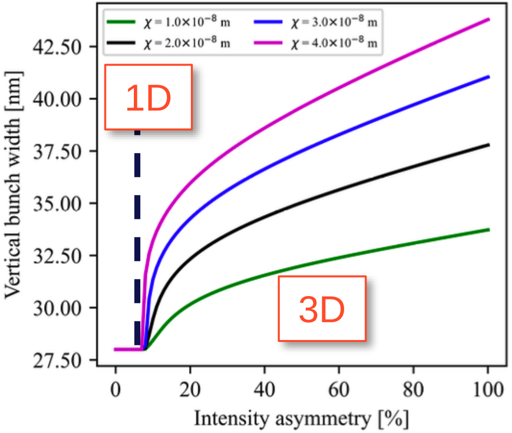




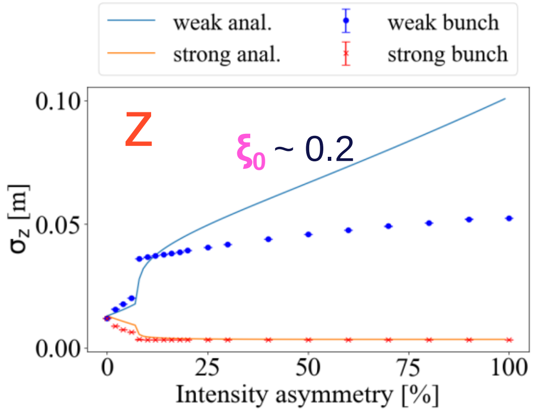
- Analytical model to estimate blowup [5]
- 1D model does not take into account nonlinear diffusion at high asymmetries
- 3D model includes diffusion in a phenomenological way

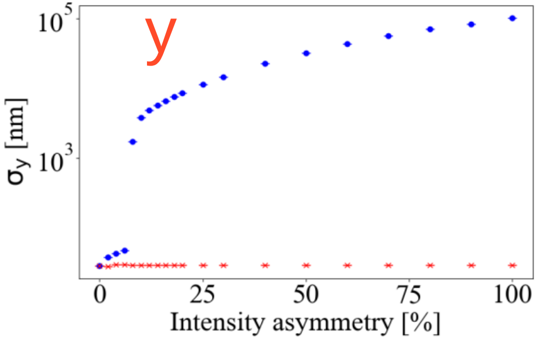
3D flip-flop – comparison to a 3D model

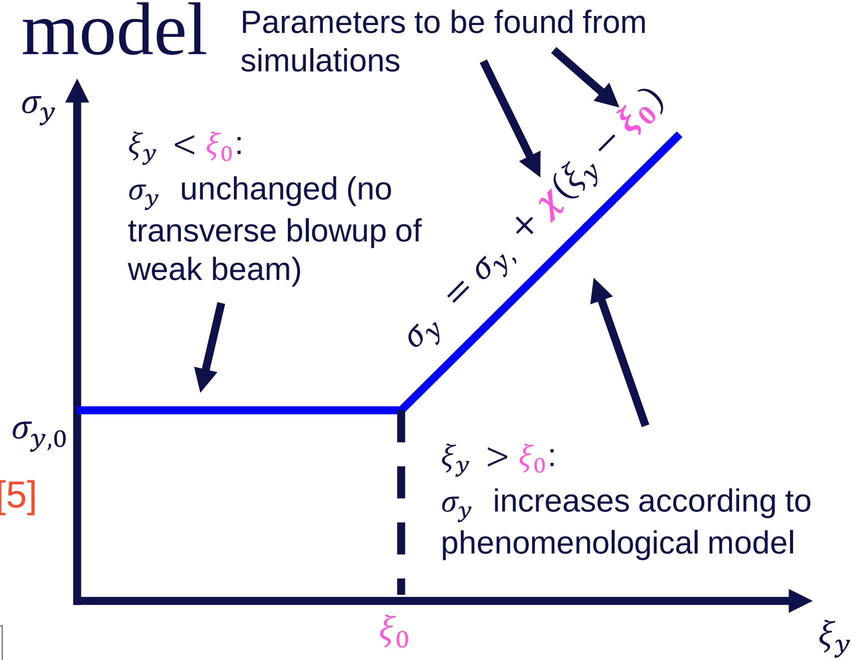




[5]

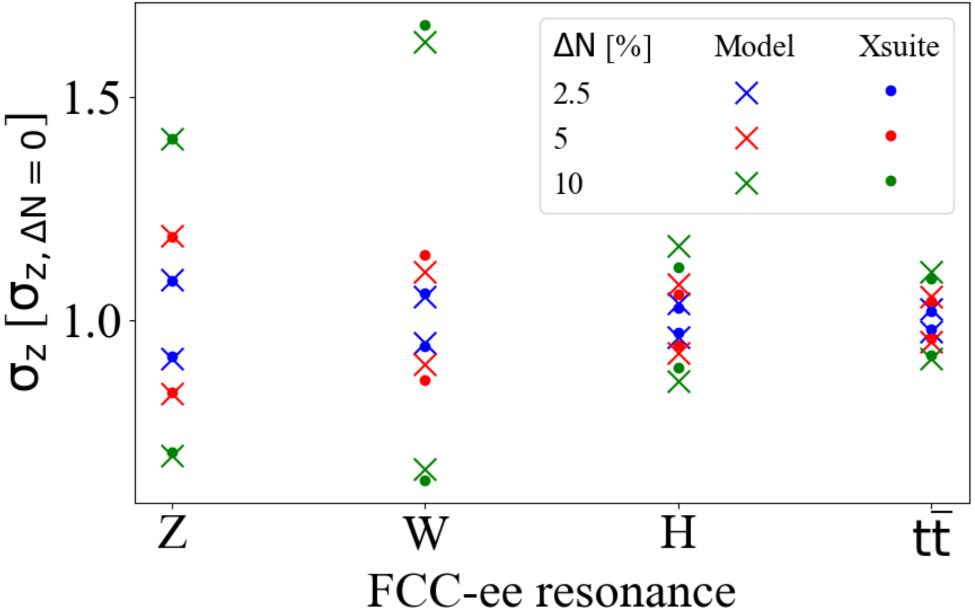






- Model validates tracking
- Good predictions at small ΔN
- Allows fast parameter scan for first estimates of blowup

3D flip-flop – blowup at small asymmetries

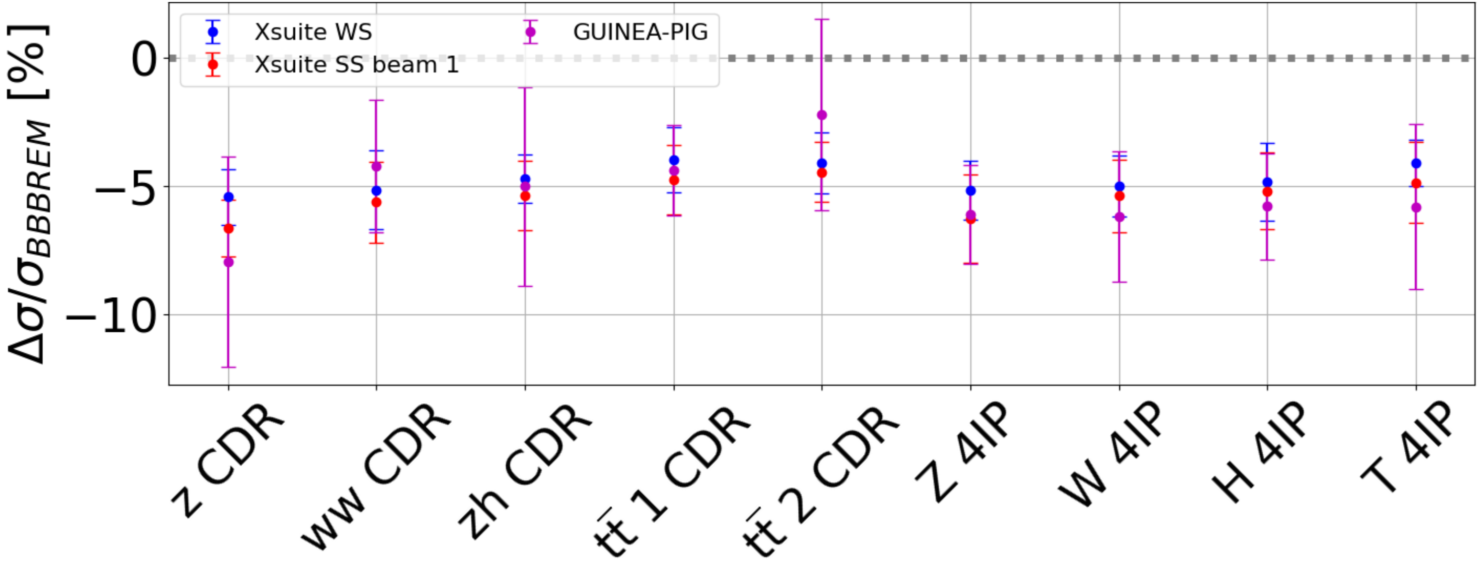


- 3D model for W
- 1D model for Z, H, ttbar
- Good overall agreement
- Top-up injection simulation ongoing

Outline

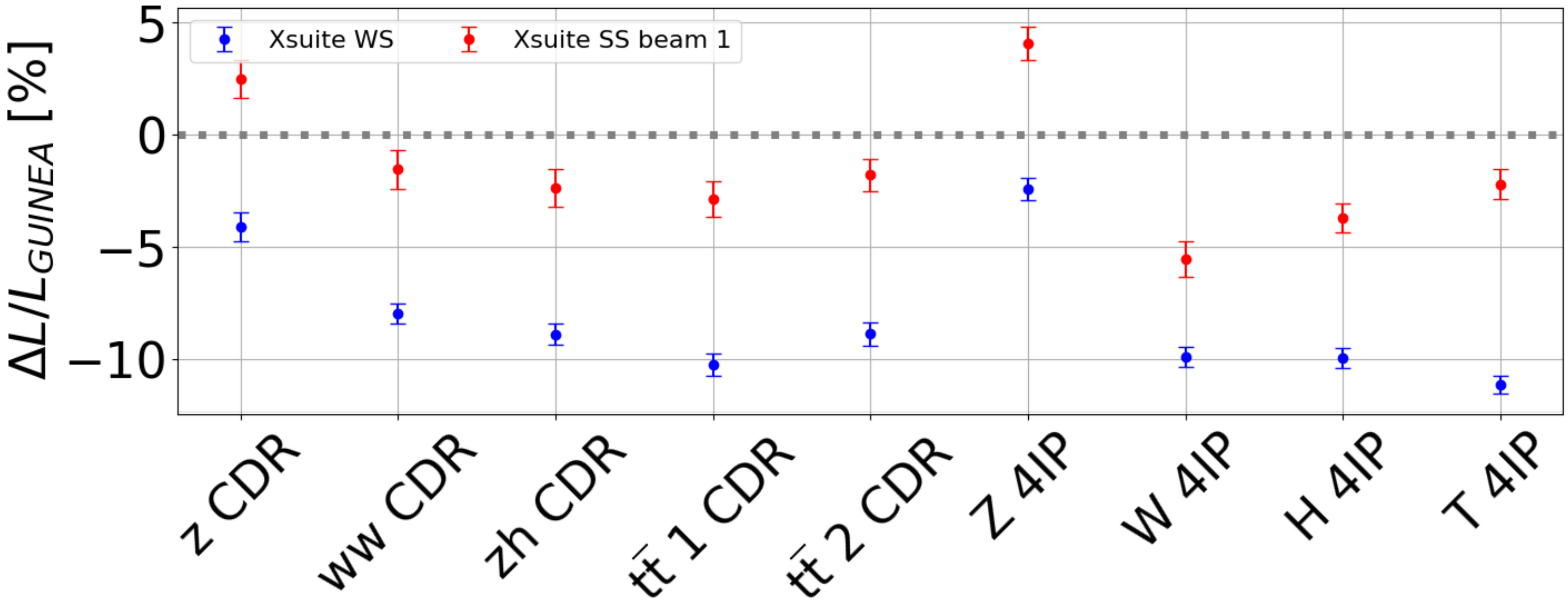
Bhabha scattering – Cross section

- Event generator adapted from GUINEA-PIG [6]
- Method of equivalent photons:
  1. Generate virtual photons of beam 1 slice
  2. Compton scatter virtual photons on beam 2 macroparticle
- Bhabha cross section from single collision: count emitted photons above mom. acceptance (1-2%, from [7] & [8])



Bhabha scattering - Luminosity

- Comparison of luminosity in GUINEA-PIG and Xsuite
- **PIC vs soft-Gaussian**
- Xsuite WS to GUINEA-PIG: ~10% less lumi
- Xsuite SS to GUINEA-PIG: ~5% less lumi, except Z where soft Gaussian is the least accurate

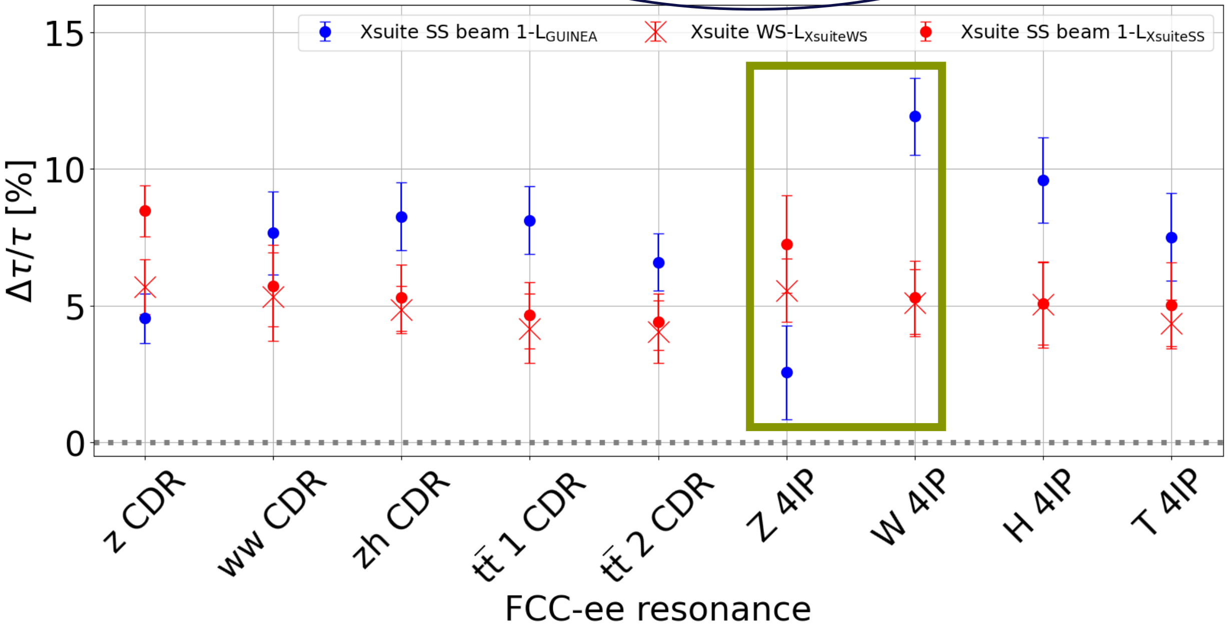


Bhabha lifetimes

from BBBREM | from Xsuite/GUINEA-PIG | Bhabha count > mom. acc.

$$\frac{1}{\tau} = \frac{1}{N_b}\frac{dN_b}{dt} = \frac{1}{N_b}\sigma_{Bhabha} L_{inst} \cdot N_{IP} = \frac{1}{N_b} R_b \cdot f_{rev} \cdot N_{IP}$$

reference | simulation



	FCC-ee pole	D_x $[10^{-3}]$	D_y [1]
CDR [8]	Z	0.138	0.886
	WW	0.558	1.231
	ZH	0.599	1.340
	$t\bar{t}1$	2.238	1.829
	$t\bar{t}2$	2.239	1.774
4 IP [7]	Z	0.154	0.940
	W	1.039	1.861
	H	0.459	0.880
	T	1.551	1.577

1. Red: σ_{BBBREM} + L_{Xsuite}: ~5% syst. unc. of event generator compared to BBBREM
2. Blue: σ_{BBBREM} + $L_{GUINEA-PIG}$: unc. up to ~10% due to 1. + lumi error from PIC-soft-Gaussian difference

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Summary

3D flip-flop

- Good agreement with analytical model for small asymmetries
- Longitudinal top-up injection studies ongoing

Bhabha lifetimes

- Successful benchmarks:
  - Xsuite with BBBREM & GUINEA-PIG
  - Lifetimes using linear tracking + hard edge acceptance
- Can be used in other types of studies (MDI & collimation)
- In progress: lifetimes from tracking in nonlinear lattice

Thank you!

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References

[1] Y. Dutheil, Top-up injection baseline scenario
https://indico.cern.ch/event/1202105/contributions/5383638/attachments/2659520/4609063/2023_06_FCCweek_topup_injection_scheme.pdf

[2] M. Zobov, Crab Waist collision scheme: a novel approach for particle colliders
https://iopscience.iop.org/article/10.1088/1742-6596/747/1/012090/pdf

[3] D. Shwartz et al., Recent Beam-Beam Effects at VEPP-2000 and VEPP-4M
arXiv:1409.5590

[4] D. Shatilov, Beam-beam Effects at High Energy e^+e^- Colliders
https://doi.org/10.18429/JACoW-eeFACT2018-TUYBA02

[5] K. Le Nguyen Nguyen, Analytical Description of the Impact of Intensity Asymmetry in Colliders with Strong Beamstrahlung
https://indico.cern.ch/event/1193165/contributions/5015797

[6] GUINEA-PIG
https://gitlab.cern.ch/clic-software/guinea-pig-legacy

[7] K. Oide, FCC-ee Collider Optics
https://indico.cern.ch/event/1202105/contributions/5408583/attachments/2659051/4608141/FCCWeek_Optics_Oide_230606.pdf

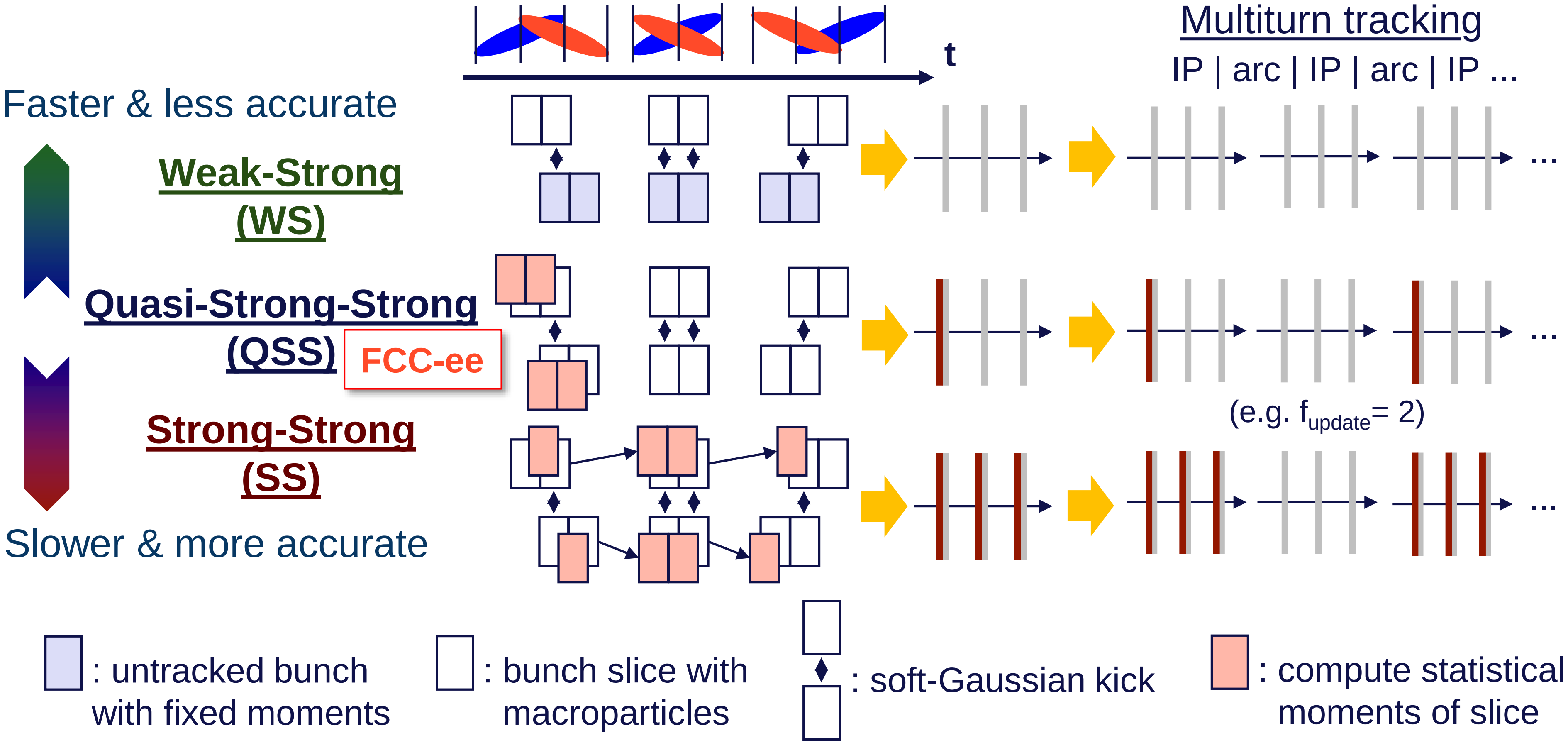
[8] Future Circular Collider Conceptual Design Report Volume 2
https://cds.cern.ch/record/2651299/files/CERN-ACC-2018-0057.pdf

BACKUP

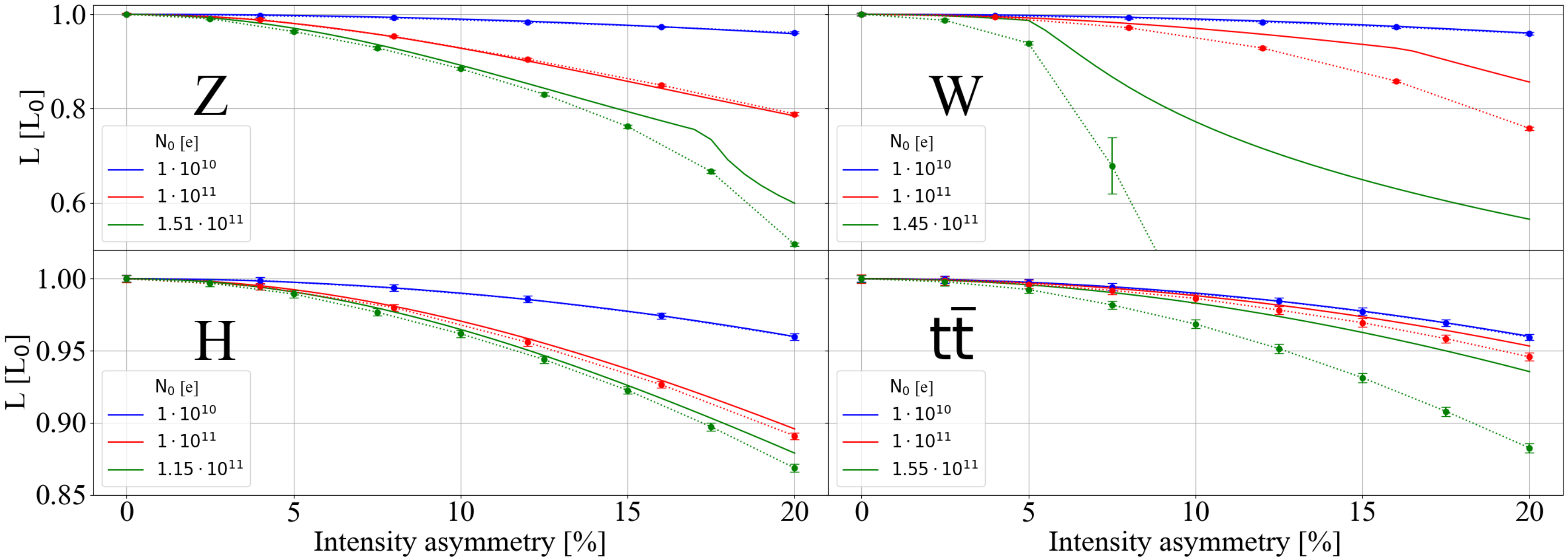
Simulation parameters

Slide #	7, 8 & 9	10
FCC-ee setup	Z (CDR, 2 IP)	Z / W / H / T (4 IP)
Beam-beam model	quasi-strong-strong (f_{update}=100)	quasi-strong-strong (f_{update}=100)
# slices in beam-beam	300	100 (300 for Z)
# macroparticles	1e7	1e5
# turns	2.5e4	2e4 / 1e4 / 5e3 / 5e3

Beam-beam in Xsuite



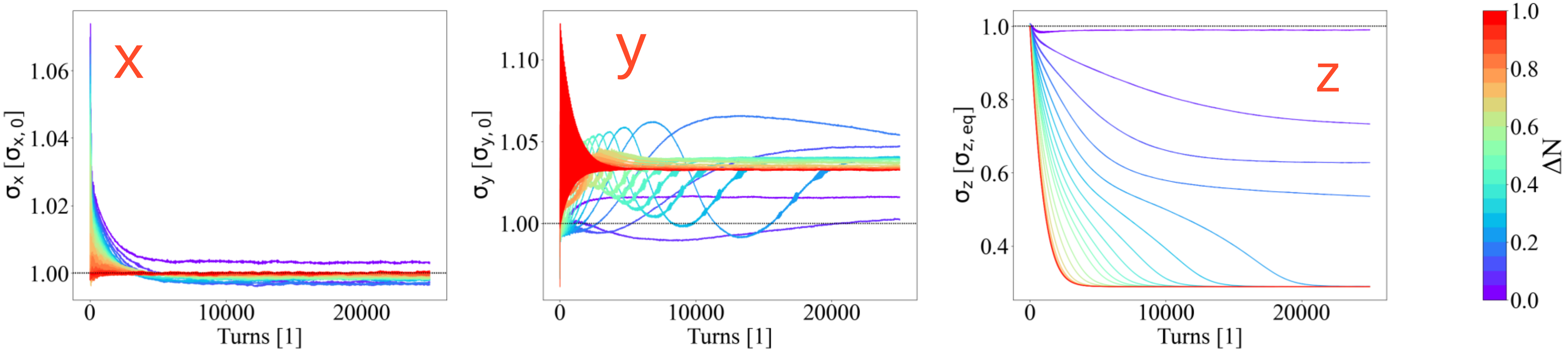
3D flip-flop – luminosity



$$\mathcal{L} = \frac{N_l N_h}{T_{\mathrm{rev}}} \frac{\cos(\theta_c/2)}{2\pi} \frac{1}{\sqrt{\sigma_{y,l}^{*2} + \sigma_{y,h}^{*2}}} \times \frac{1}{\sqrt{(\sigma_{x,l}^{*2} + \sigma_{x,h}^{*2}) \cos^2(\theta_c/2) + (\sigma_{z,l}^2 + \sigma_{z,h}^2) \sin^2(\theta_c/2)}}$$ [1]

[1] H. Damerau
https://cds.cern.ch/record/905072/

3D flip-flop – strong bunch



- Scanned asymmetry in bunch intensity: $N_{w,s} = N_0 \cdot (1 \pm \Delta N)$ (ΔN ∈ [0,1])
- Strong bunch shrinks

Analytical approximation of bending radius [1]

- Local curvature of a particle in the weak bunch, flat beam approximation, due to transverse electric field from strong bunch:

$$\frac{1}{\rho(x,y,z,s;t)} = \sqrt{\frac{2}{\pi}}\frac{2r_e N_b}{\gamma\sigma_z}\exp\left[-\frac{(2s-z)^2}{2\sigma_z^2}\right]\frac{\exp\left[-\frac{x^2}{2\sigma_x^{*2}}\right]}{\sigma_x^*}$$

$$\times\left[\left(\frac{y}{\sigma_y^* G\left(x-\left(s-\frac{z}{2}\right)\theta_c, s\right)}\right)^2+\left(\frac{x-\left(s-\frac{z}{2}\right)\theta_c}{\sigma_x^*}\right)^2\right]^{\frac{1}{2}}$$

Approximations:

$$\sigma_x^* \gg \sigma_y^*$$

$$|x| < \sigma_x^*$$

$$|y/G| < \sigma_y^*$$

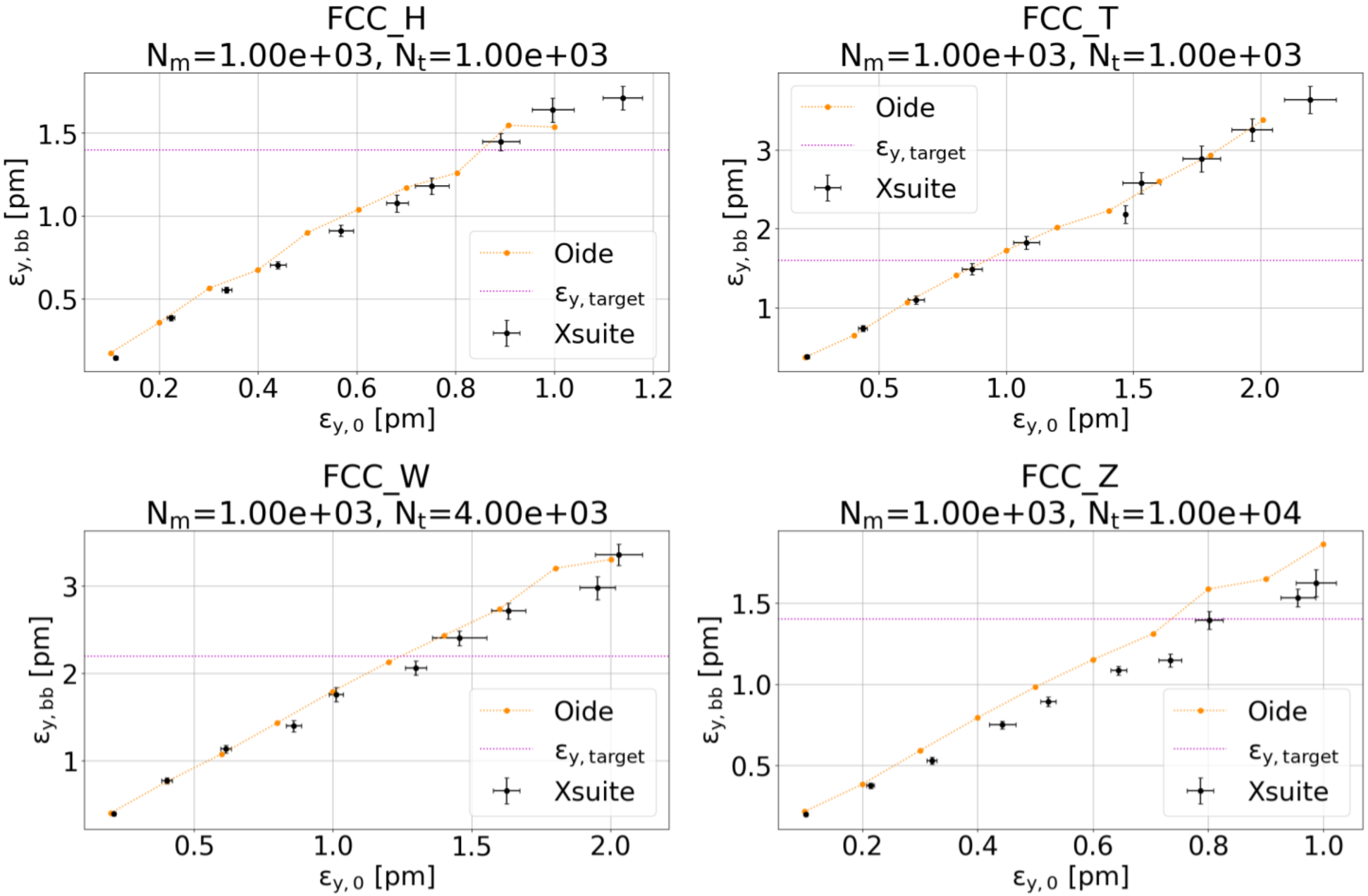
$$G(x,s) = \sqrt{1+\left(\frac{s+\frac{x}{\theta_c}}{\beta_y^*}\right)^2}$$

[1] M.A.Valdivia Garcia, F. Zimmermann
https://cds.cern.ch/record/2702811

Emittance scan results

- $\varepsilon_{y,0}$: only lattice
- $\varepsilon_{y,bb}$: with beam-beam+beamstrahlung

- Black: tracked results with Xsuite
- Pink: ε_y "target" from parameter table (~desired max. ε_y with beam-beam) [1]
- Orange: data provided by K. Oide



Workflow – everything in Xsuite

Prepare Xtrack line once [6]:

- load MAD-X sequence [7]
- add wigglers
- convert to Xtrack line
- build + twiss 4D
- slice sequence
- build + twiss 4D
- save Xtrack line

Loop over a range of ε_y values:

- load Xtrack line
- add observation point @ RF
- build + twiss 4D
- twiss 6D mean synrad + tapering
- match ε_y
- twiss 6D mean synrad + tapering

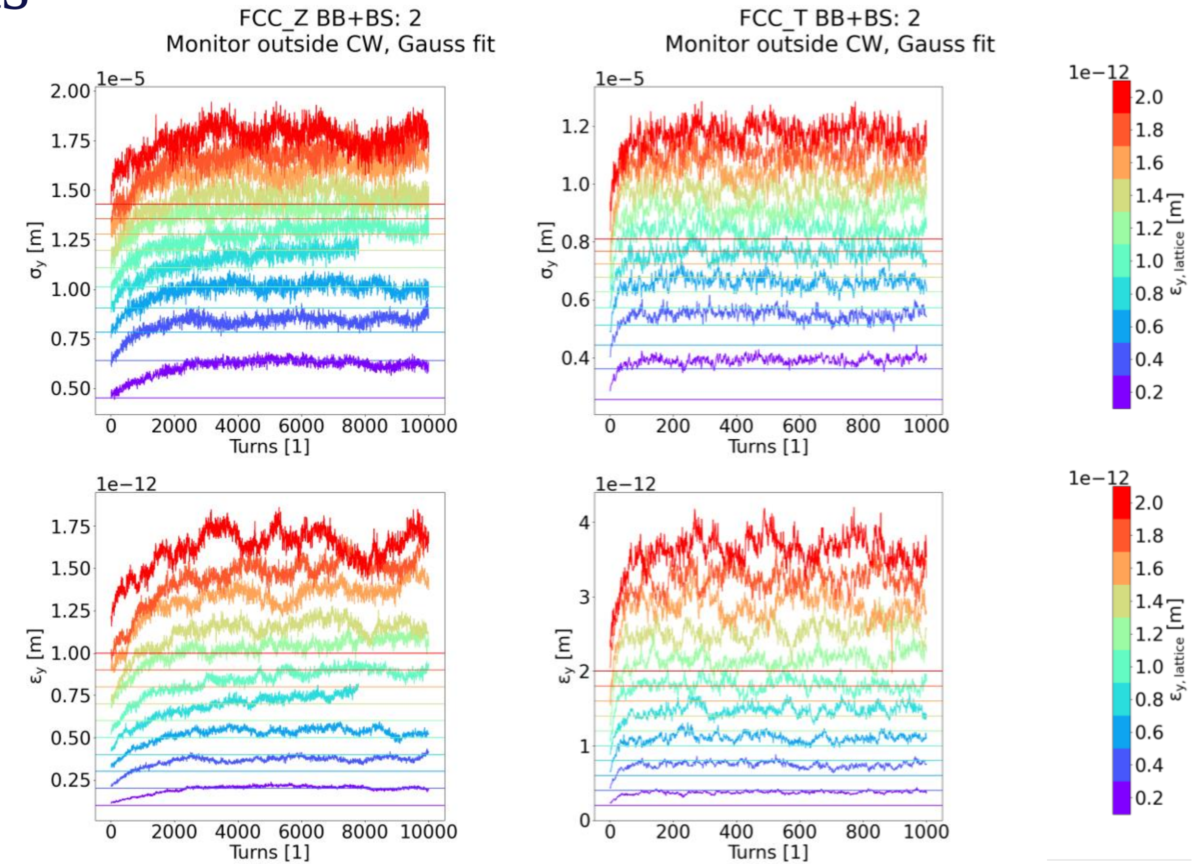
⋮

⋮

- add beam-beam element (optional)
- build
- set quantum synrad
- track
- repeat with next ε_y

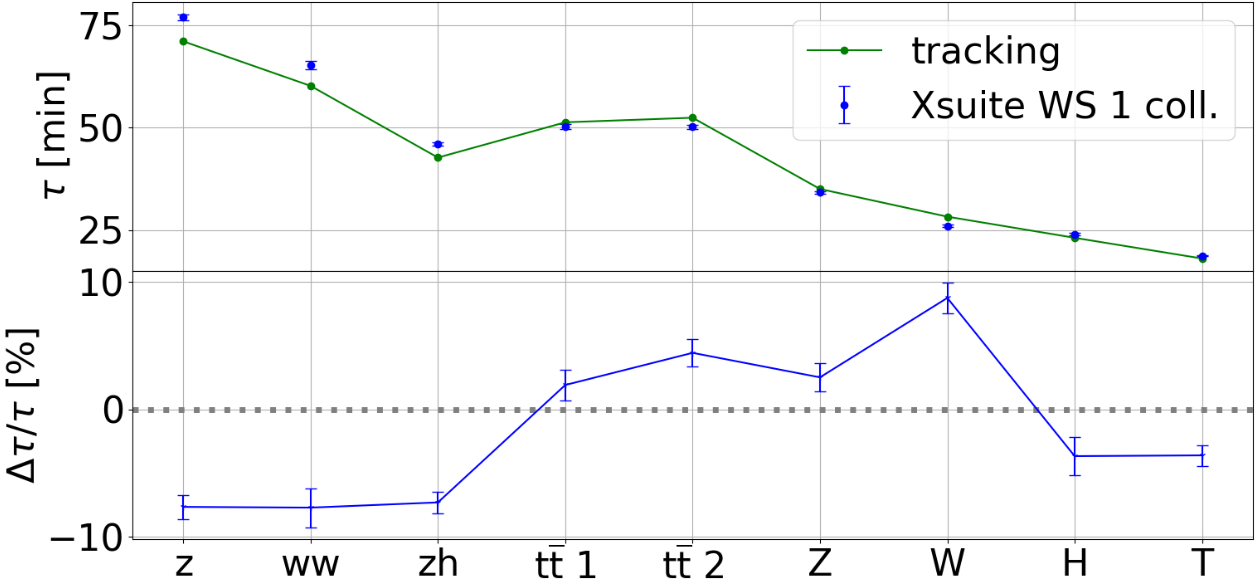
Emittance scan results

- Small discrepancy compared to SAD results
- Xsuite likely not yet converged
- Need more turns to see converged emittances



Bhabha lifetimes

- Linear lattice
- Hard edge momentum acceptance



Bhabha lifetimes

$$\frac{1}{\tau} = \frac{1}{N_b}\frac{dN_b}{dt} = \frac{1}{N_b}\sigma_{Bhabha}L_{inst} \cdot N_{IP} = \frac{1}{N_b}R_b \cdot f_{rev} \cdot N_{IP}$$

- τ: Bhabha lifetime [s]
- N_b: bunch intensity [1]
- σ_{Bhabha}: Bhabha cross section [m^2]
- N_{IP}: number of Ips [1]
- $L_{inst}=L*f_{rev}$: instantaneous lumi of 1 bunch crossing [m^-2 s^-1]
- L: integrated lumi of a single collision (collision luminosity) [m^-2]
- f_{rev}: revolution frequency [s^-1]
- $R_b= \sigma_{Bhabha}*L$: number of emitted Bhabha photons with E above mom. acceptance [1]