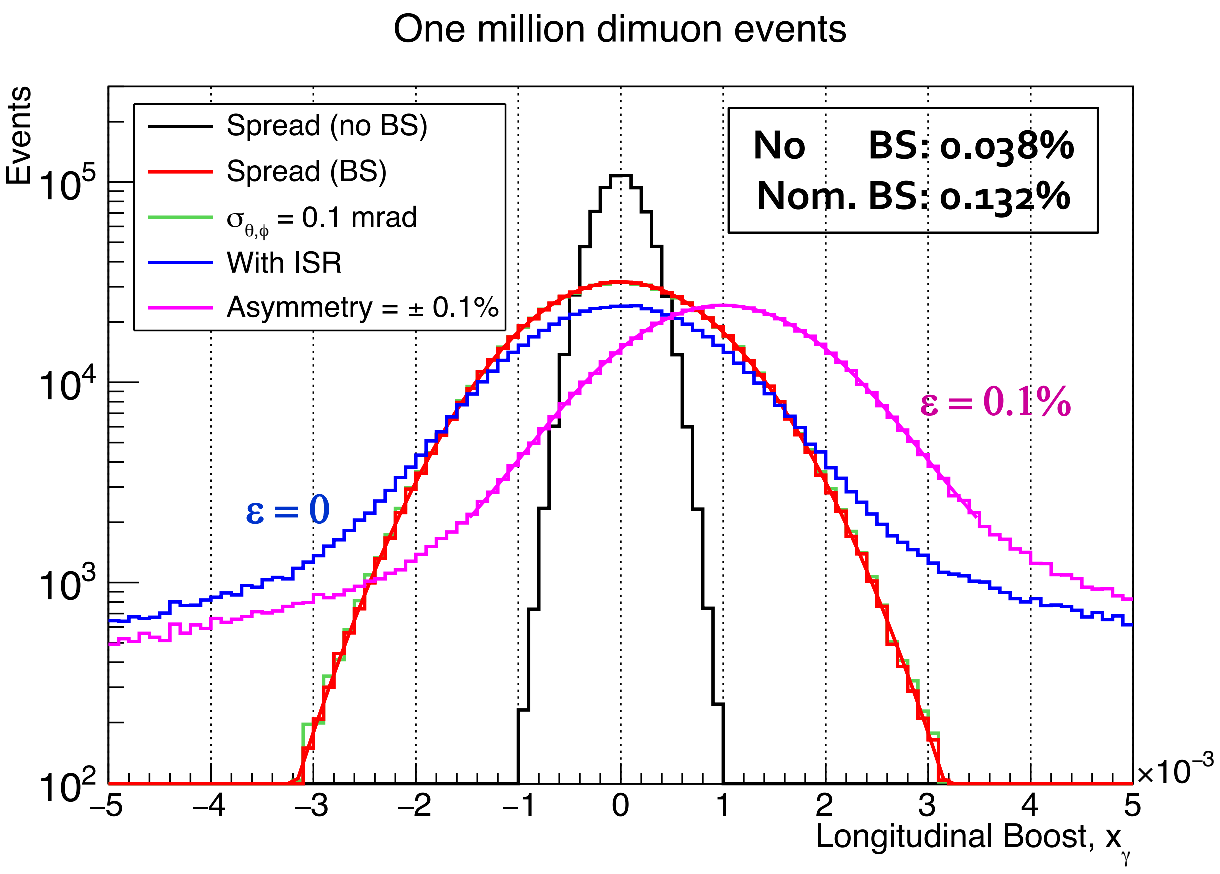
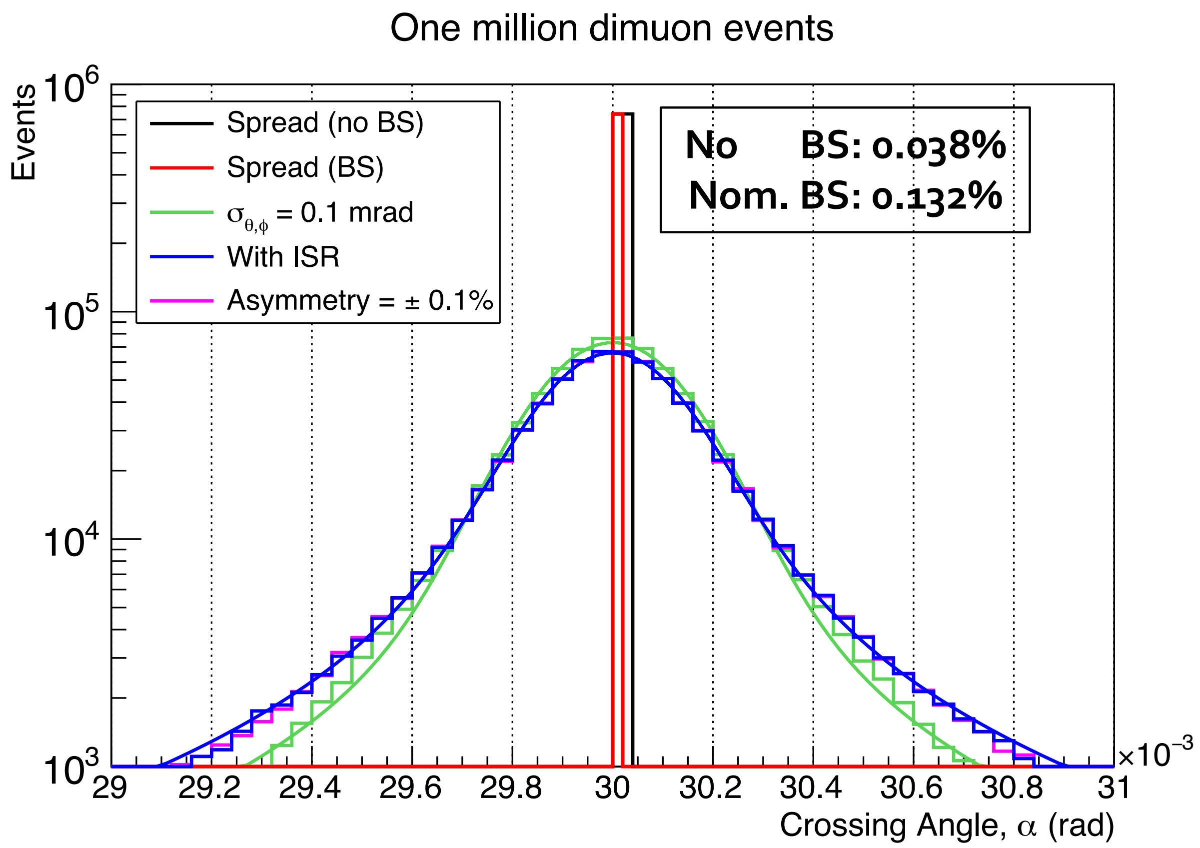
WG4 Summary – Open Questions and Task List

- **WG4 = EPOL-related measurements in particle-physics experiments**
  - **See also PJ, GW, AB talks on Mon 19, Thu 22, Mon 26 September**
    - **Nothing new has happened with WG4 since**
      - → **Only a short repetition today.**





Summary

- **Measurements relevant for EPOL performed with collision events**
  - Centre-of-mass energy and absolute uncertainty, above the Z pole
    - With $e^+e^- \rightarrow Z(\gamma)$, W^+W^- and ZZ events
  - Centre-of-mass energy point-to-point uncertainty at the Z pole
    - With $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events
  - Centre-of mass energy spread, crossing angle, collision boost, absolute alignment
    - With $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events
  - Correlations of the above with the position, time, angle of the collision
    - All measurable, event-by-event, by the experiments
- **Principle well established since the Energy Calibration paper arXiv:1909.12245**
- **New possibilities presented during this workshop**
  - Extensive use (and pertaining calibration) of muon momenta (example of ILC)
  - Potential use of Bhabha events (example of CLIC)
  - Use of correlation between time and crossing angle (for $\sqrt{s}$ RDP determination)

Open questions

- Many measurements based on processes with Initial State Radiation
  - Simplifying assumptions are used throughout: only one ISR photon in the beam direction
    - Is Initial State Radiation predicted with enough precision?
- The distribution of the radiated photon energy contains information on
  - $\sqrt{s}$, $\sqrt{s}$ spread, boost, ISR, muon angular resolutions
- The distribution of the crossing angle contains information on
  - ISR, muon angular resolution, detector alignment, crossing angle spread
    - Can these information be extracted individually?
    - Are muon angular resolution measurable with enough precision?
- These information are correlated with the time, position, plane of the collision
    - Can these correlations be simulated and measured with enough precision?
    - Can these correlations be exploited to improve the measurements?

Open questions

- Most of the measurements in arXiv:1909.12245 use the muon angles only
  - Except the $\sqrt{s}$ point-to-point uncertainty, which uses muon momenta as well
    - Should the muon momenta be used throughout in addition (and how)?
    - Can the muon momenta be calibrated with enough accuracy and how?
    - What is the statistical bonus on $\sqrt{s}$ and boost determination?

- Most of (all) the measurements in arXiv:1909.12245 done with $e^+e^- \to \mu^+\mu^- (\gamma)$ events
  - Statistics is of essence, especially if all correlations are to be mastered
    - Can we use Bhabha events? [especially useful for the forward region]
    - Can we use di-tau events? [angular resolution?!]
    - Can we use di-jet events? [order-of-magnitude larger stats]

- All the measurements will be affected by systematic biases (especially when absolute)
    - Can these biases be calibrated away and how?

Open questions

- All these measurements will vary
  - With time
  - With machine settings
  - From one bunch to the other
    - Can we monitor these variations?

- All these measurements simulated with home-made generator and smearing
  - With ISR, $\sqrt{s}$ spread, and boost
  - With uniform Gaussian smearing of muon momenta and angles
  - Without any variation of / correlations with position, time, plane, angle of collision
  - Some of the predictions result from back-of-the-envelope estimates
    - Are the predictions in arXiv:1909.12245 robust and reliable?

- Can these measurements help monitor monochromatisation @ $\sqrt{s}$ = 125 GeV? How?

Task list

- Main task(s): Answer the open questions!
- Many specific projects presented already in the opening talk
- A lot is still to be done with $e^+e^- \to \mu^+\mu^- (\gamma)$ events
  - At the theoretical level
    - Required precision of ISR prediction
  - At the generator level
    - Generate collision energy, boost, position, time, plane, angle, $\sqrt{s}$ spread
      - ➔ AND THEIR CORRELATIONS
  - At the simulation level
    - Increase the level of detail of the simulation (from fast to full)
  - At the analysis level
    - Implement complete analyses and develop calibration methods (e.g., $e^+e^- \to Z(\gamma)$) at all $\sqrt{s}$
  - At the detector level
    - Extract the detector requirements to reach the desired performance

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"Repeat" with other dileptons and with di-jets
Also exploits diboson (ZZ & WW) events

Task list

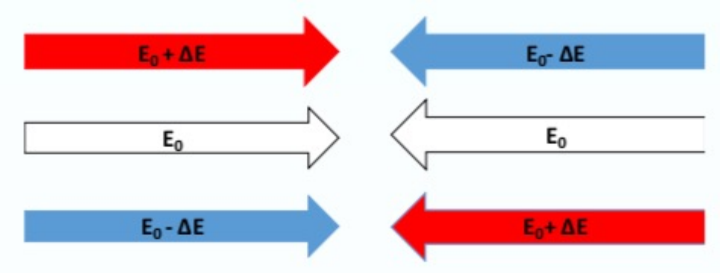
- **Speaking of desired performance**
  - Determine quantitatively the statistics needed to measure the collision parameters
    - So that they do not affect the statistical precision of the FCC-ee measurements
      - ➔ At all centre-of-mass energies
      - ➔ For each of the many measurements, e.g.,

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
m_H (MeV)	125250 ± 170	**2.5**	0.8	From ZH direct reconstruction $\sqrt{s}$ calibration
m_{top} (MeV)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate

- **Think out of the box**
  - Get new ideas
  - Implement them
  - Publish the result

Task List: Example

- A first look at monochromatization at $\sqrt{s}$ = 125 GeV, from a specific example
  - Beam energy spread: 0.052% (~32 MeV)
  - $\sqrt{s}$ spread: 13 MeV
  - Anti-correlation: -90%



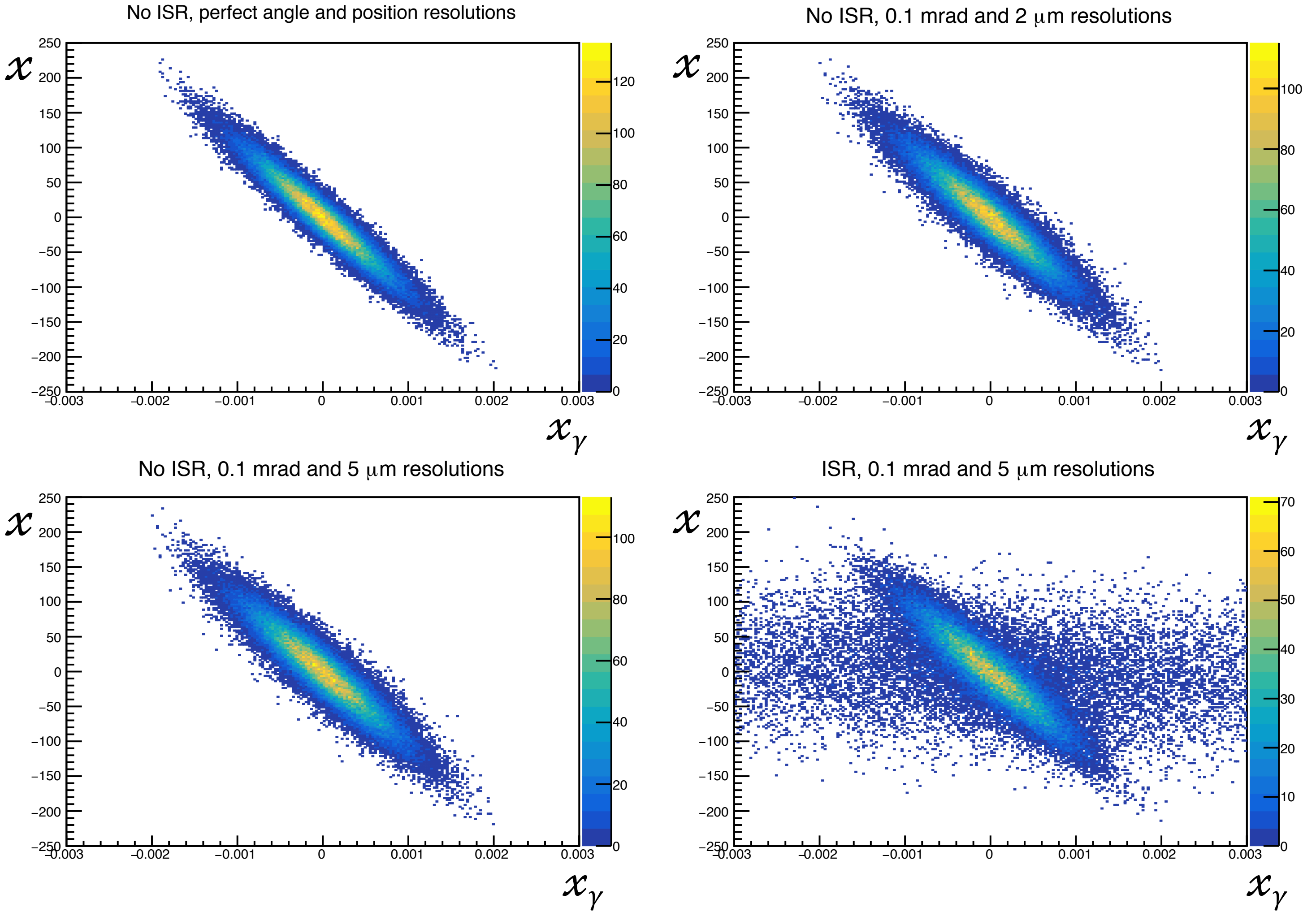
  - $x = D_x^* \times \Delta E/E$
  - For a given ΔE, $\sigma_x^* = \sqrt{\beta_x^* \varepsilon_x}$ = 15 μm
  - $L = 2.6 \times 10^{35}$ cm^{-2}s^{-1} , $\sigma_{\mu\mu}$ = 8.3 pb
    - 2.16 $e^+e^- \to \mu^+\mu^-$ events / second
    - 250 events every 2 minutes

Parameter	Symbol	Unit	Value
Center-of-mass energy	W	GeV	125
Horizontal, vertical rms emittance with (without) beamstrahlung	$\varepsilon_{x,y}$	nm	2.5 (0.51), 0.002
Relative rms momentum deviation	σ_δ	%	0.052
Rms bunch length	σ_z	mm	3.3
Horizontal dispersion at interaction point	D_x^*	m	0.105
Interaction-point beta function	$\beta_{x,y}^*$	mm	90, 1
Rms beam size at the interaction point	$\sigma_{x,y}^*$	μm	55, 0.045
Full crossing angle	θ_c	mrad	30
Vertical beam-beam tune shift	ξ_y		0.106
Total beam current	I_e	mA	395
Bunch population	N_b	10^{10}	6.0
Bunches per beam	n_b		13420
Luminosity (luminosity without crab cavities) per IP	L	cm^{-2}s^{-1}	2.6×10^{35} (2.3×10^{35})
Rms center-of-mass energy spread (total spread w/o crab cavities)	σ_W	MeV	13 (25)

Example chosen: with crab cavities

Task List: Example

- **Measured horizontal position (in microns) vs relative longitudinal boost (10^5 events)**
  - Easy fit for the first three plots
    - Bivariate normal distribution
  - Expected √s spread precision
    - 0.5% for 100,000 events
    - 5% for 1000 events
    - 10% for 250 events
  - 10% precision every 2 minutes
    - To be checked with ISR
  - Repeat with other schemes !



A lot of work ahead !

- But also a lot of fun (speaking from experience)
  - And a possibility for many single-author publications

- REMINDER ! A tutorial took place on Thursday afternoon (Marcin)
  - We learned how to generate, simulate, analyse dimuon events and more in FCCSW
  - Repeat the exercises
    - And apply what you have learnt to determine √s, spread, boost, angles, axes, etc.

- To the young physicists: Your participation is essential
  - After all, you are going to operate this machine, right ?
    - These EPOL-related measurements make an ideal entry point to the FCC study
      - ➔ With physics, software, detector, machine aspects all at once
      - ➔ While being an ideal and orthogonal complement to your LHC day-to-day work