Beam Backgrounds Simulation Challenges at Future Colliders

F9 Seminar
June 13, 2025

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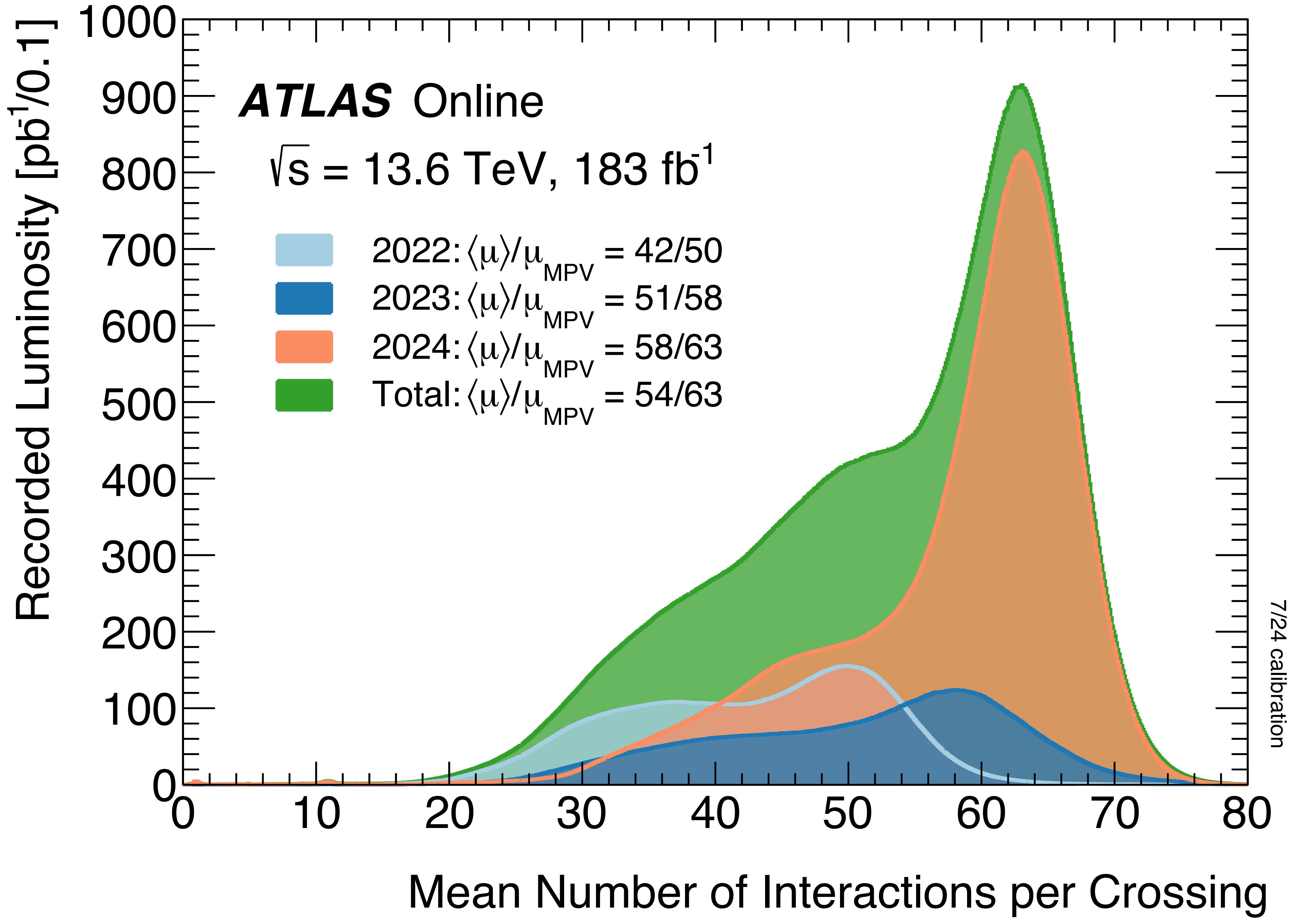
- Beam backgrounds and pile-up are important for accurate simulation of our detectors but also hard to simulate.
  - Pile-up: soft collisions in current and surrounding bunch crossings.
  - There are other types of beam backgrounds!
- What will happen when we go towards HL-LHC and future collider experiments?



Machine induced

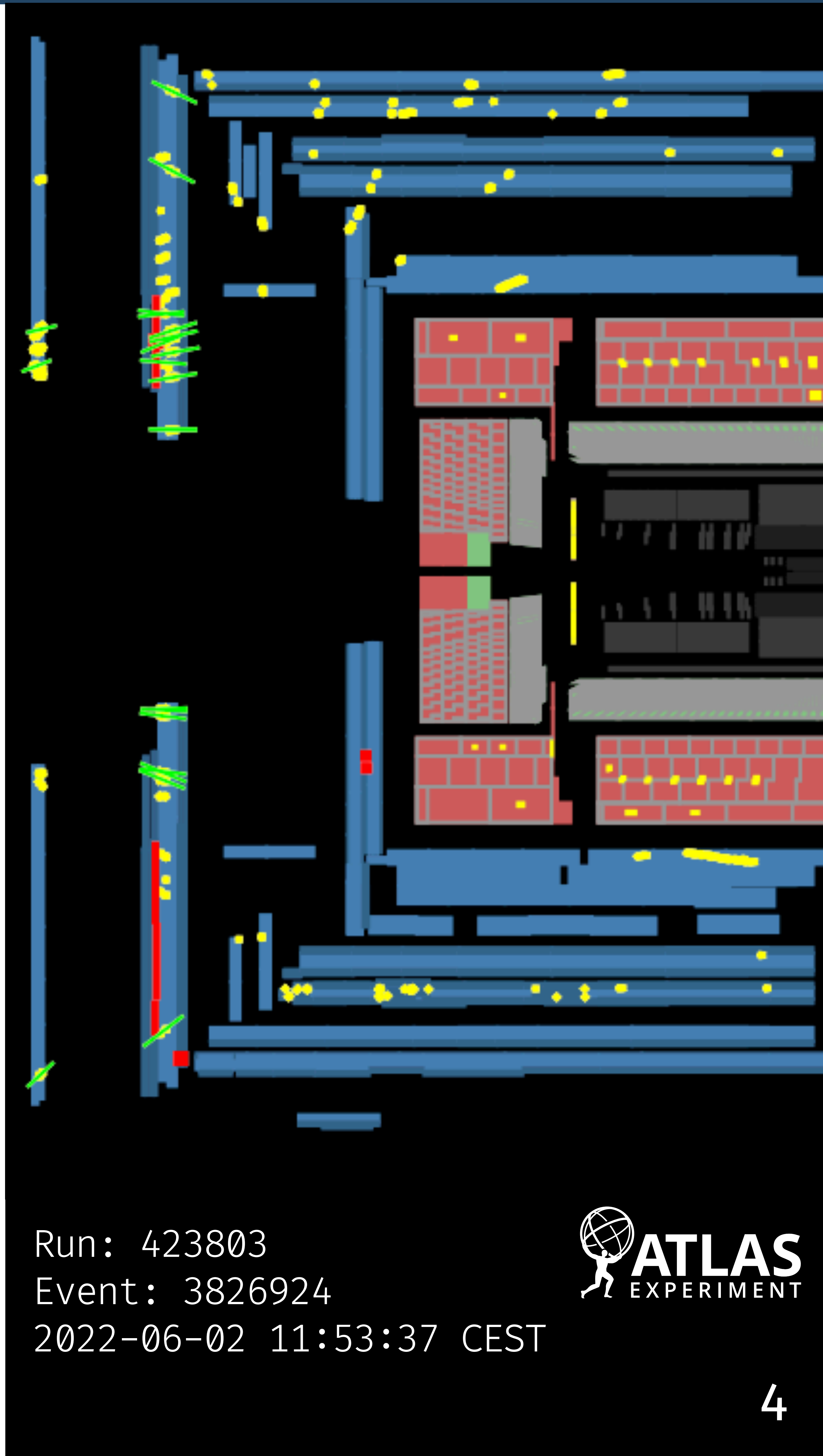
- beam gas
- beam halo

Luminosity induced

- pile-up
- cavern background

- In general all backgrounds should be simulated.
- In practice backgrounds are ranked by importance and only the dominant ones are simulated.
  - In case of ATLAS only pile-up is simulated by default.

- Beam gas: result of collisions between the beam and residual hydrogen, oxygen and carbon gasses in the beam pipe.
- Beam halo: a background resulting from interactions between the beam and upstream accelerator elements.
- Usually happen outside of the experimental cavern — simulated by the accelerator team.
    - Provide a list of particles with their 4-vectors that are relevant to the experiment.
    - Many low-momentum particles.

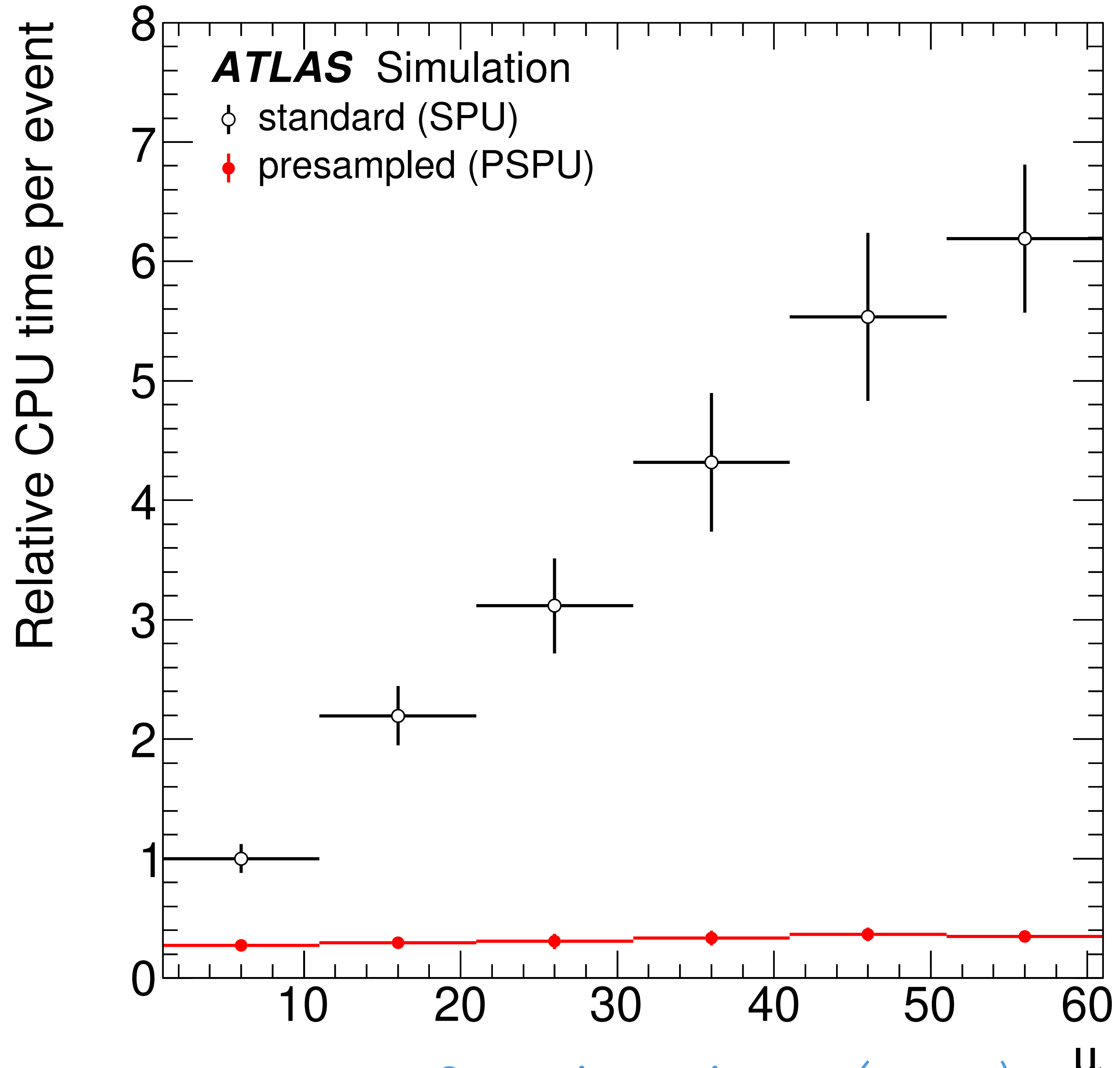


- Neutrons may propagate through the experimental cavern for a few seconds before they are thermalised.
- Produce a neutron-photon gas.
  - Low-energy electrons and protons from spallation.
- Main problem: interactions such as thermal neutron capture well below standard MC thresholds.
  - LHCb parametrised the cavern background in the muon spectrometer.

Particle	Standard MC	Low Threshold MC
Electrons/photons	500 MeV	30 keV
Hadrons (excl. neutrons)	500 MeV	100 keV
Neutrons	500 MeV	0 eV
Muons	10 MeV	10 MeV

Pile-up Simulation: the Basics

- Each individual soft collision detector response simulated separately.
  - Further split into low-p_T and high-p_T.
- Merged with hard-scatter at the digitisation stage for a specific mean number of interactions μ.
  - Require thousands of collisions due to non-instant detector response.

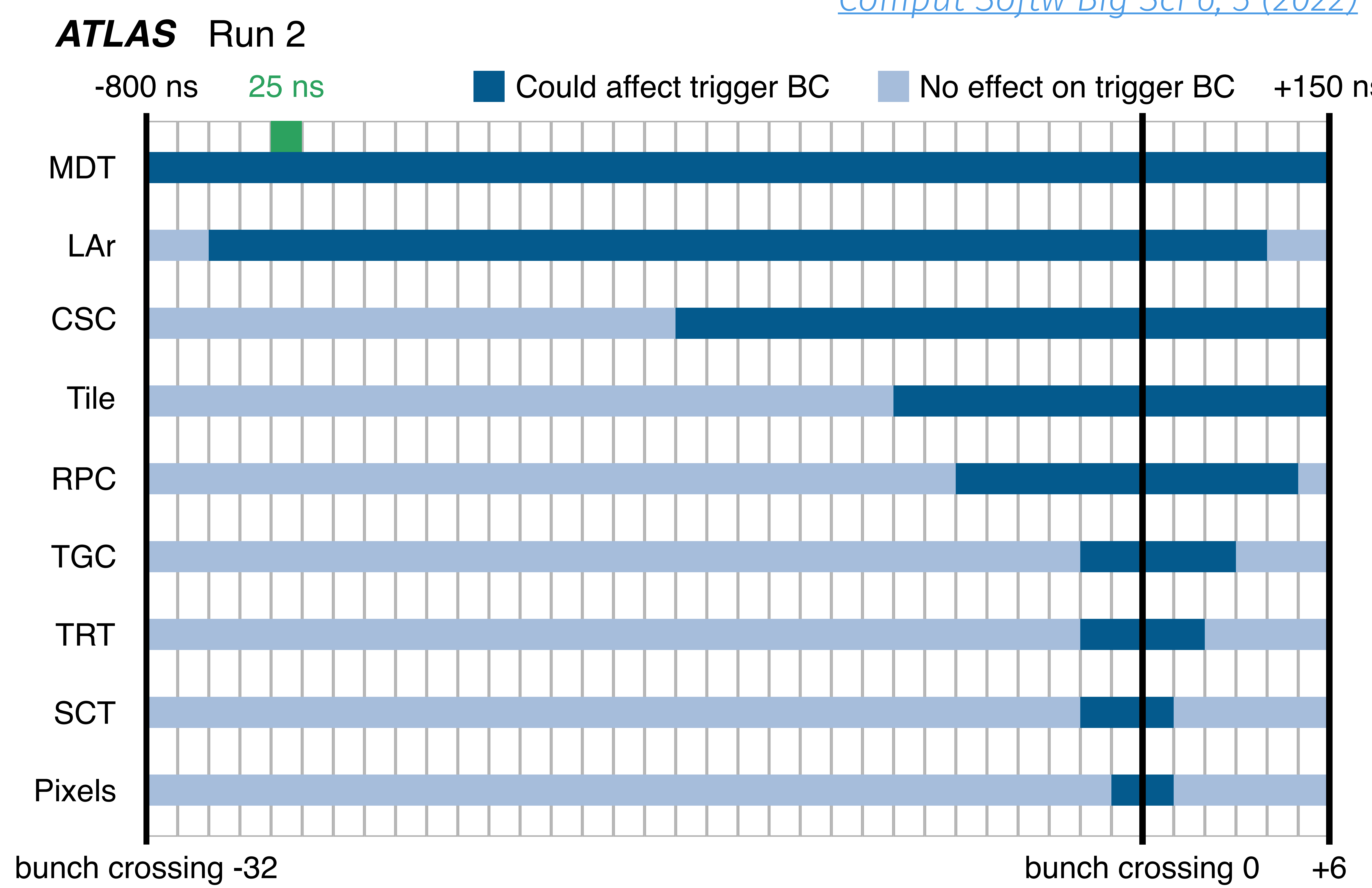


[Comput Softw Big Sci 6, 3 (2022)]

- CPU requirement fully linear with μ with coefficient ~0.1
- Optimisation: presampled pile-up
  - Combine pile-up events based on pile-up values.
  - Overlay hard-scatter on top and re-use presampled events between samples.
    - Main problem threshold effects.
  - Drawback: pile-up still needs to be presampled, much slower for μ=200 conditions expected at HL-LHC (4-5 times slower than now).

- Detectors not sensitive only to the triggering bunch crossing (BC).
- Need to simulate in-time and out-of-time pile-up effects.
- ATLAS sensitive to up to 39 BC, CMS up to 16 BC, and LHCb up to 5 BC.
  - For μ=60 this means $60 \times 39 = 2340$ interactions.
- Important to have fast detector components in future experiments.

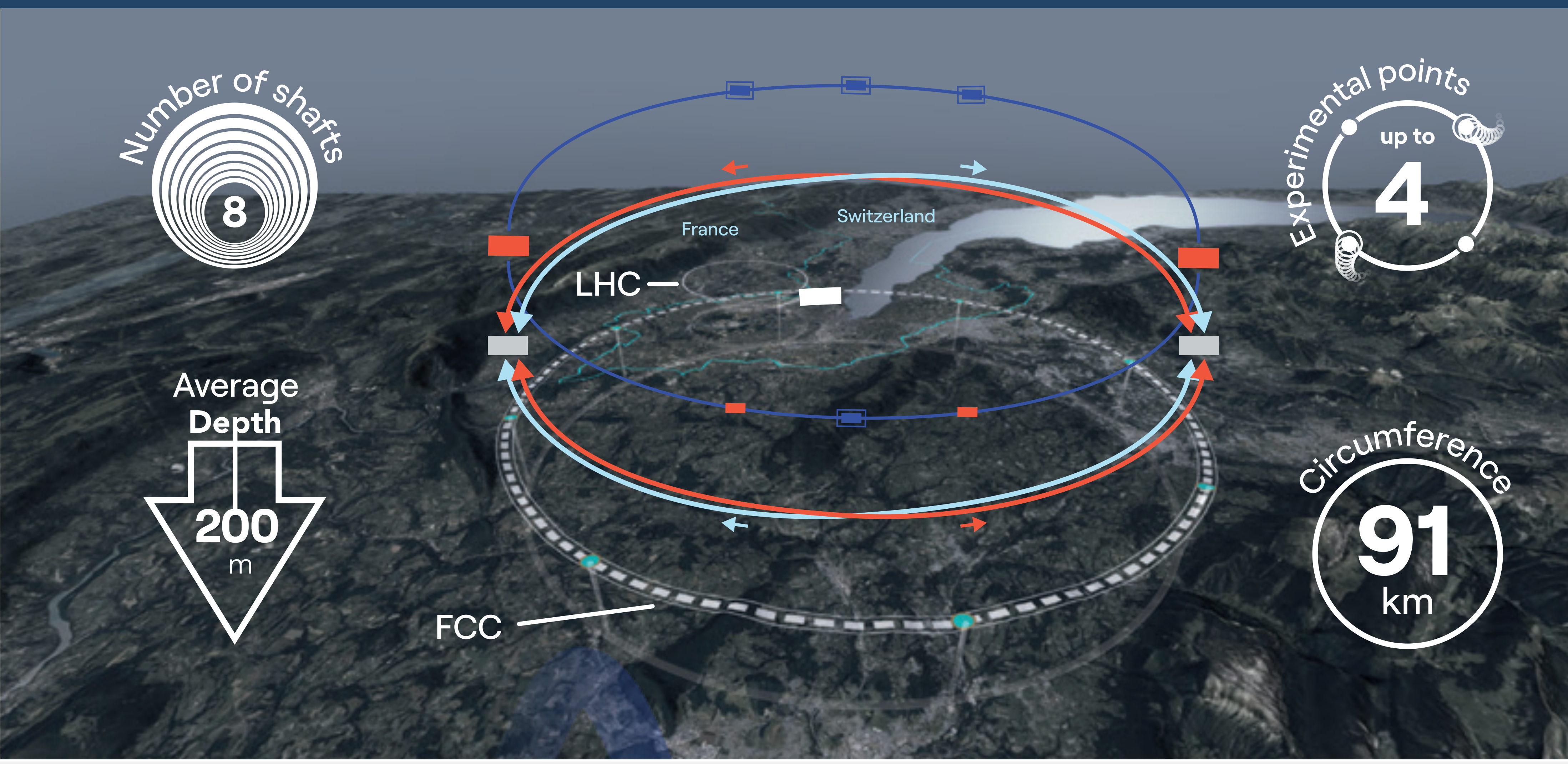
Comput Softw Big Sci 6, 3 (2022)

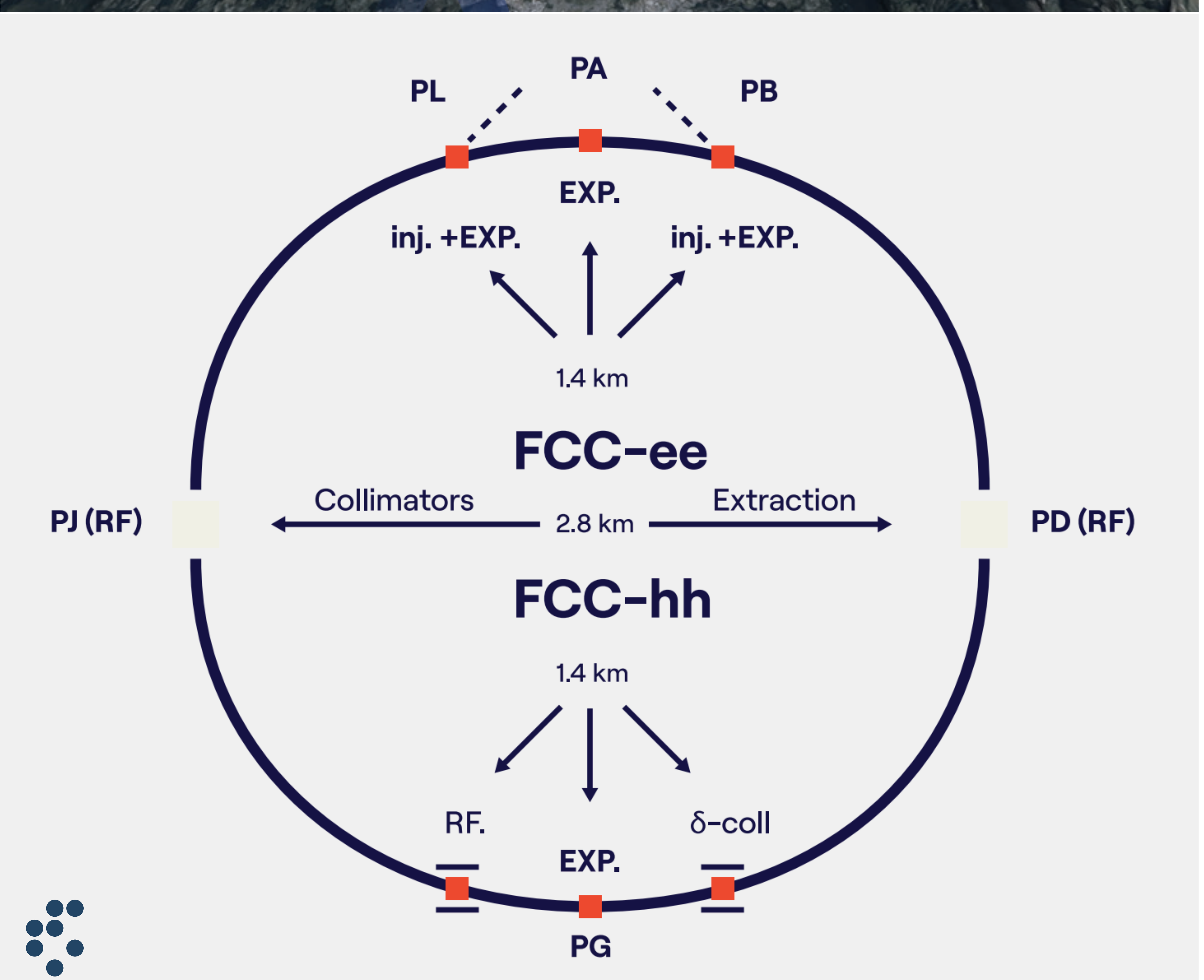


Pile-up Simulation: Can Data Be Used Instead?

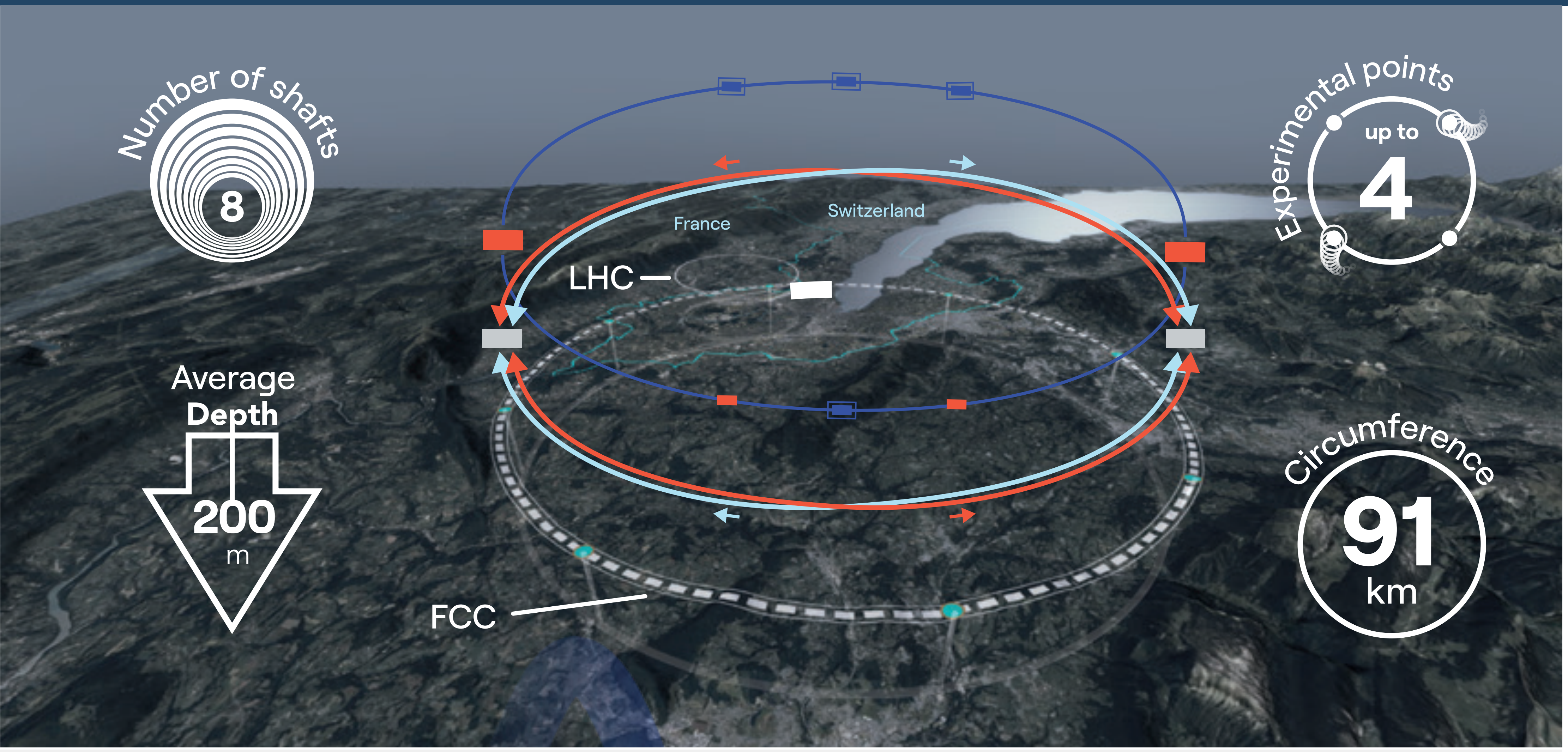
- The overlay method is input agnostic — real data can also be used.
- Already used for some specific studies, large scale use problematic as the detector conditions can change for each event.
- ATLAS (and CMS) plans to investigate zerobias data as the main source of pile-up modelling for HL-LHC
  - Automatically correct description of (most) pile-up effects, including beam backgrounds, noise, …
  - Challenging hard-scatter simulation — need to match data event conditions and detector alignment.
  - Data would need to be recorded with limited or no zero suppression.
    → Important to design future readout systems so that they are flexible enough.

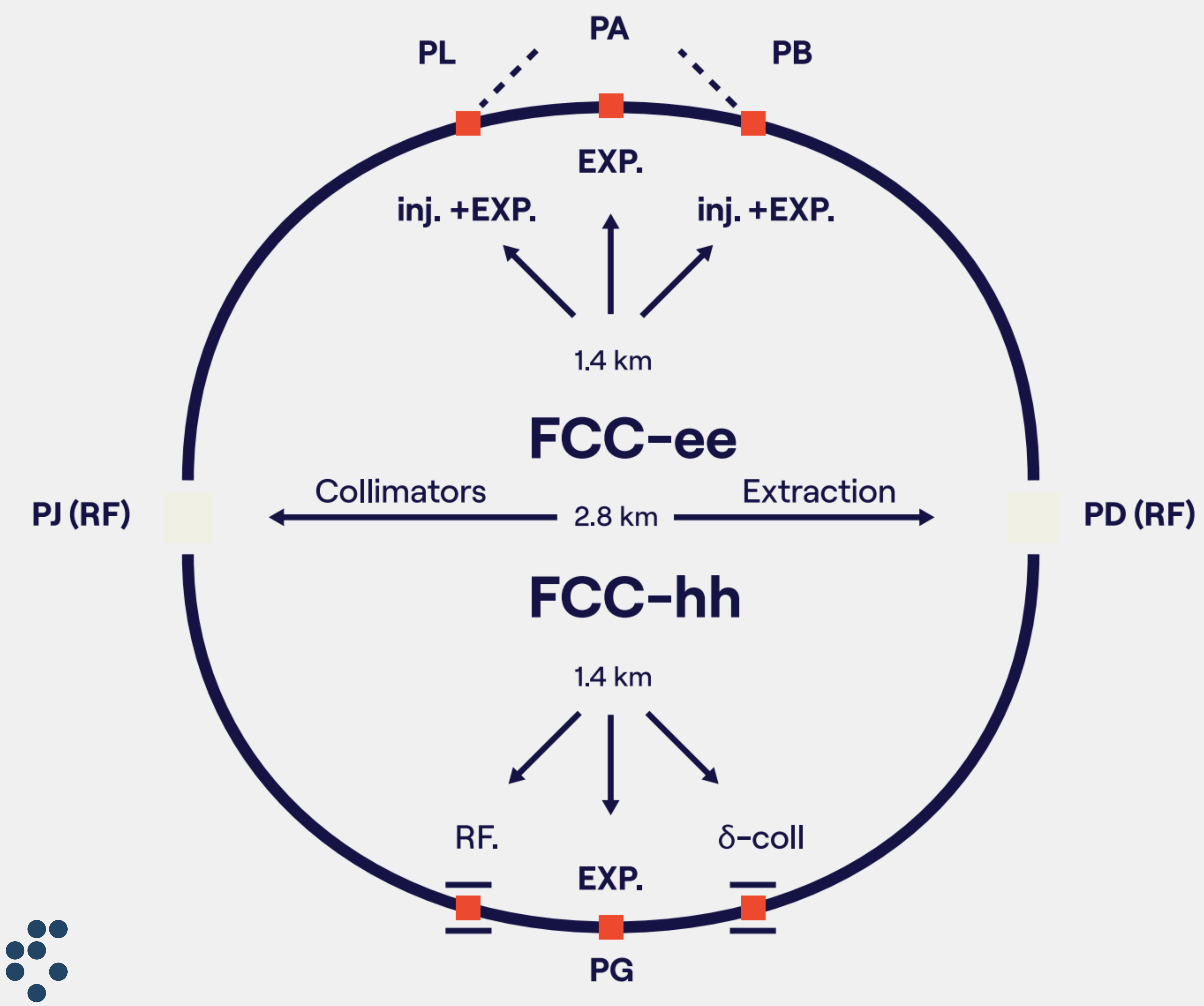
FCC-ee & FCC-hh

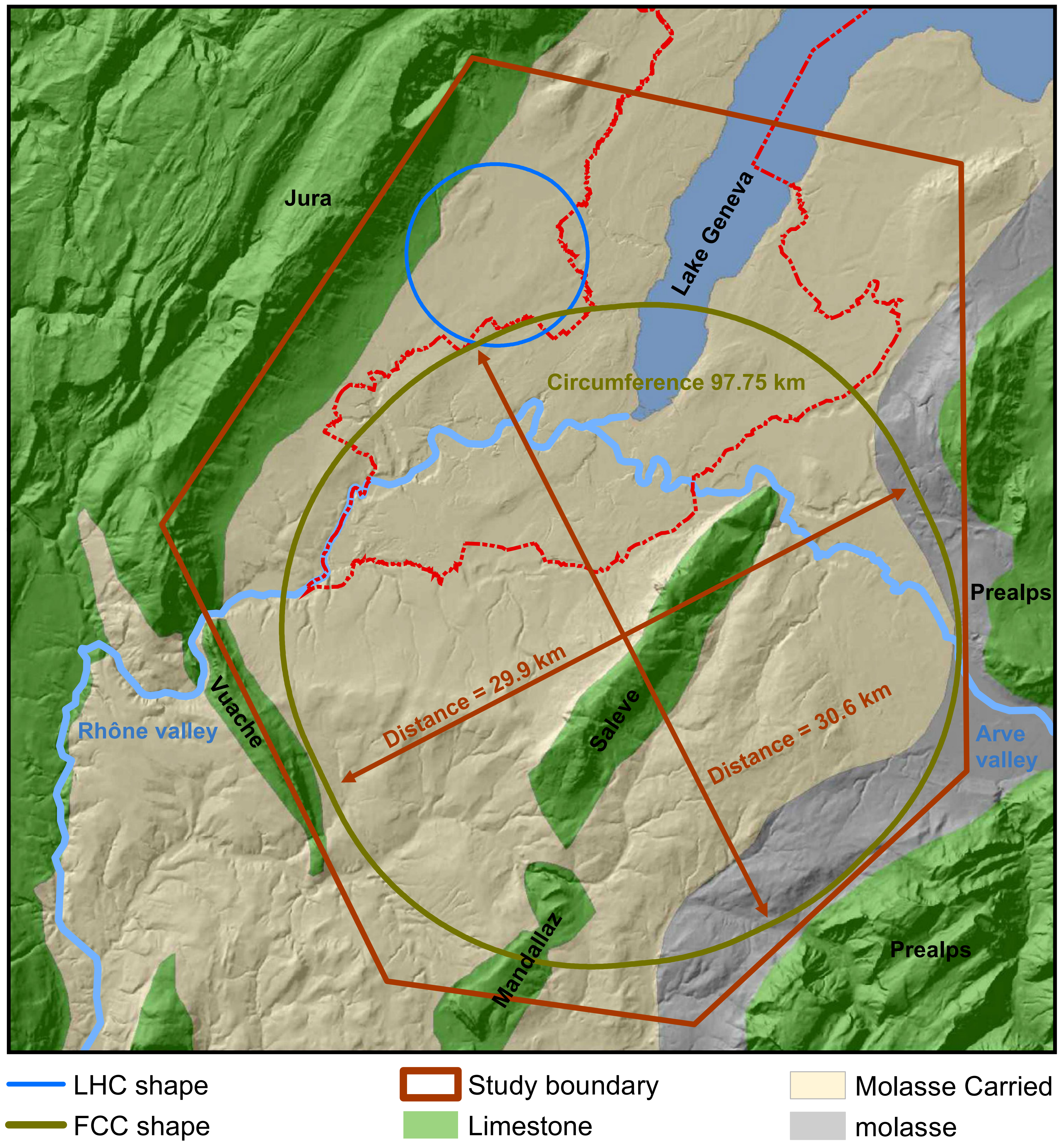




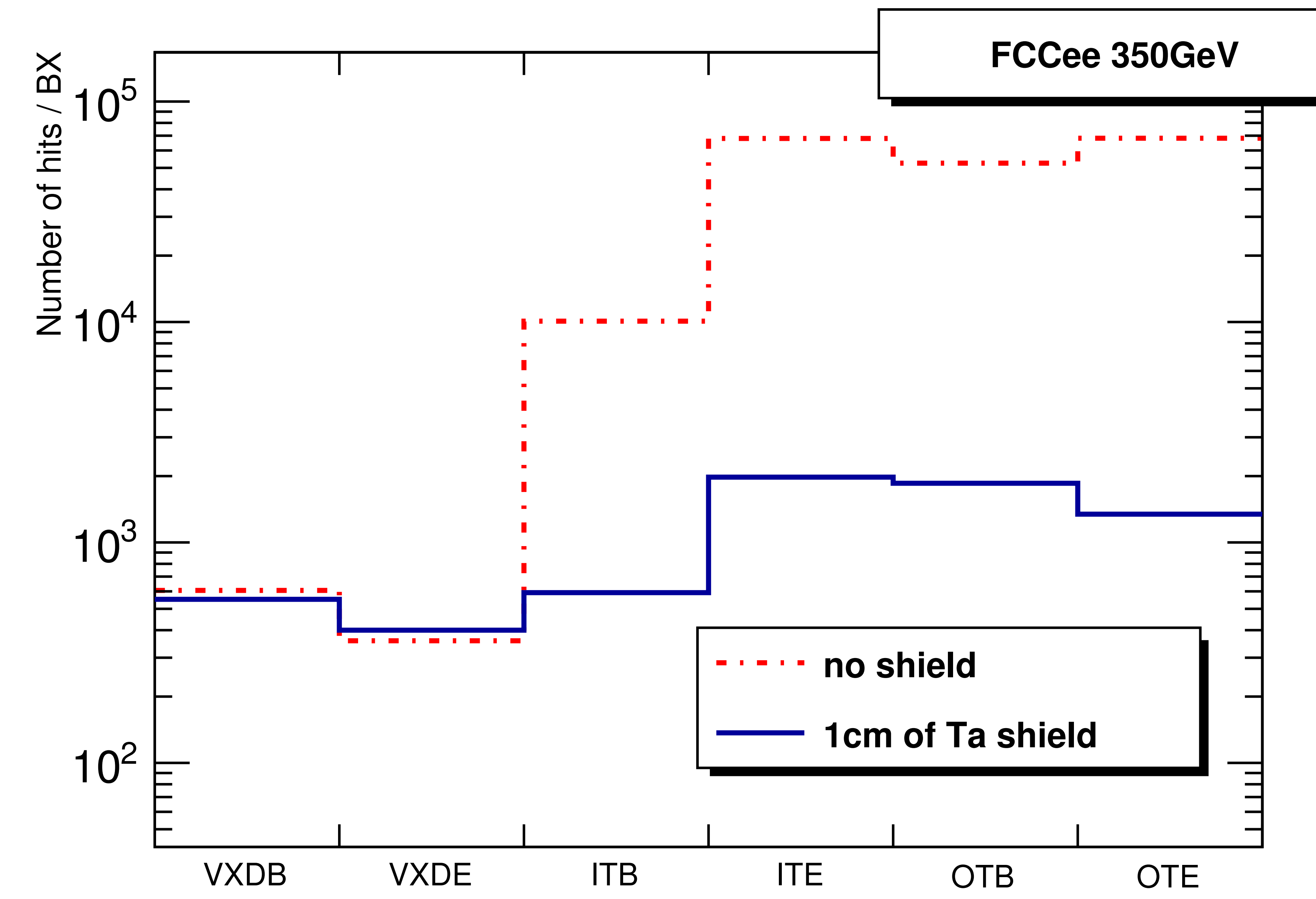
- Circular accelerator with circumference of 90.7 km.
- FCC-ee (circular lepton collider)
  - Higgs and electroweak factory
  - energies from 88 to 365 GeV
- FCC-hh (circular hadron collider)
  - direct exploration of the multi-TeV region
  - energy of 85 TeV
  - pile-up up to 1000
  - at least 5x larger luminosity compared to the LHC
  - up to 4 experiments


Number of shafts
8
Average Depth
200 m
France
Switzerland
LHC
FCC
Experimental points up to 4
Circumference
91 km


PL
PA
PB
EXP.
inj. +EXP.
inj. +EXP.
1.4 km
FCC-ee
PJ (RF)
Collimators
2.8 km
Extraction
PD (RF)
FCC-hh
1.4 km
RF.
δ-coll
EXP.
PG


Jura
Lake Geneva
Circumference 97.75 km
Prealps
Rhône valley
Vuache
Distance = 29.9 km
Saleve
Distance = 30.6 km
Arve valley
Mandallaz
Prealps
LHC shape
FCC shape
Study boundary
Limestone
Molasse Carried
molasse

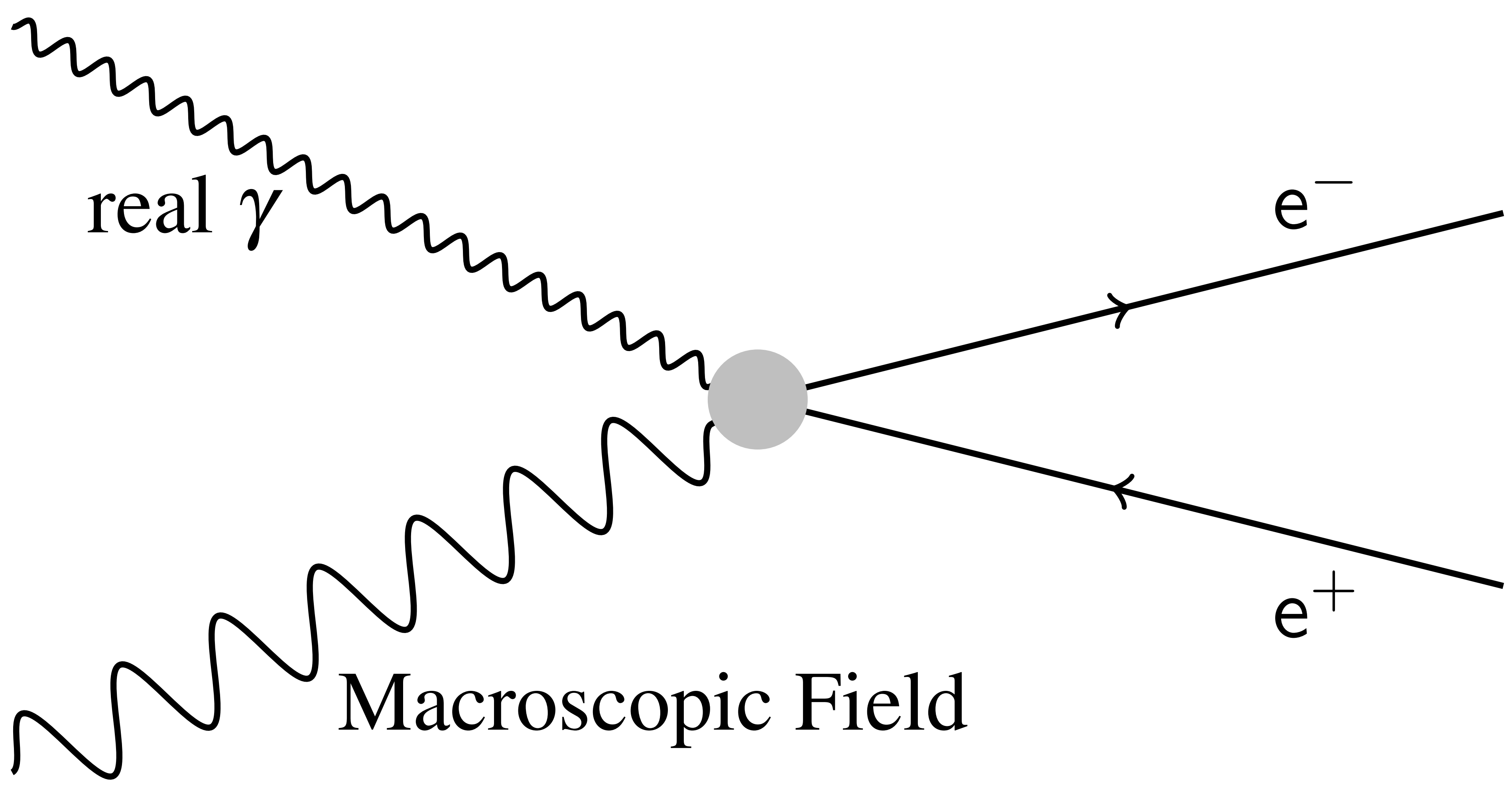
- Main background in high-energy circular electron-positron colliders is Synchrotron Radiation
  - Produced in bending and focusing magnets near interaction point.
  - $O(10^3)$ of photons still scatter in the interaction region besides shielding.
- Touschek background — caused by stray particles due to scattering between beam particles in the same bunch.
- Beam gas & beam halo



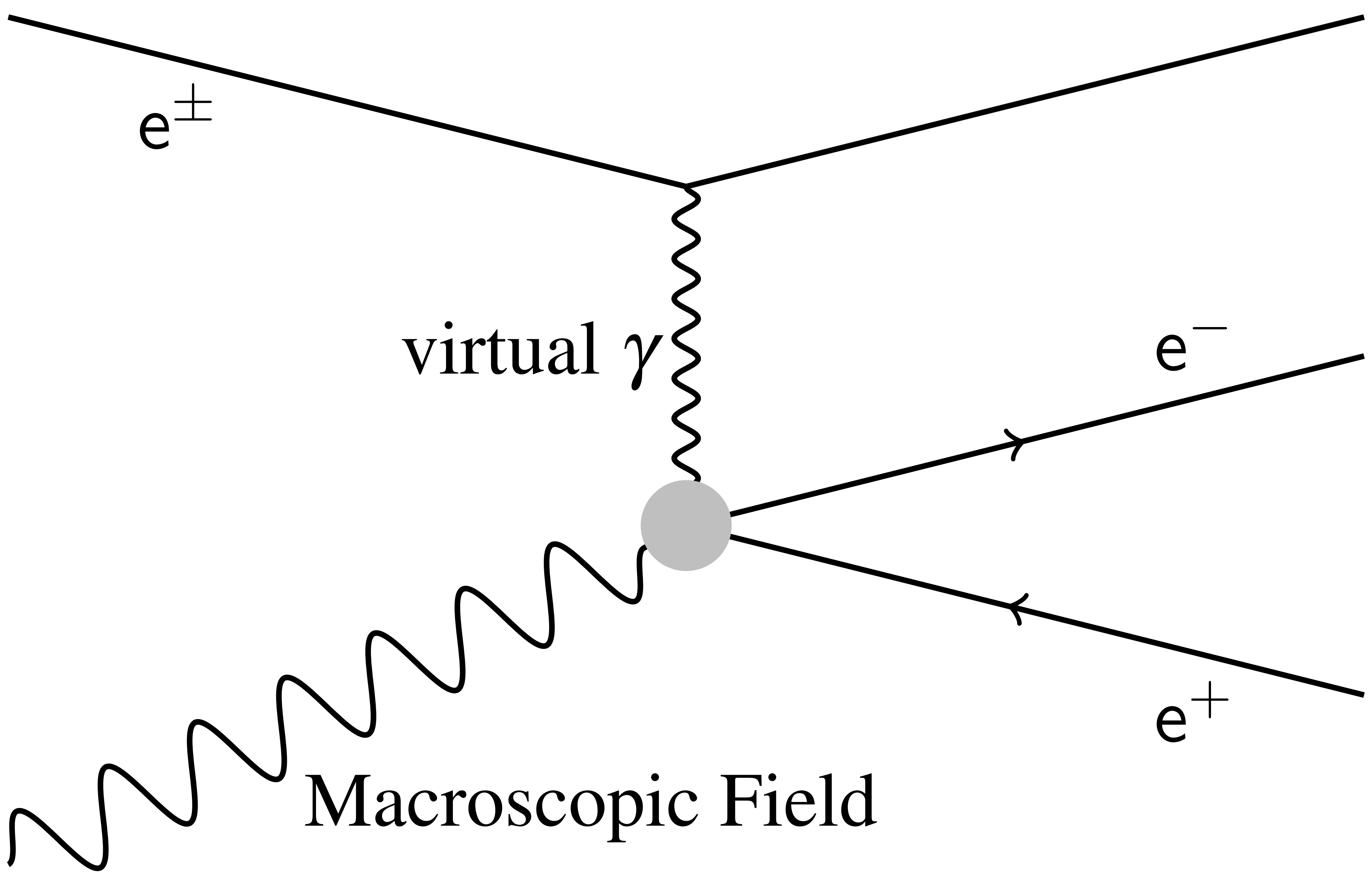
10.18429/JACoW-IPAC2017-WEPIK004

- Detector simulation performed based on the simulation provided by accelerators.

- From the electromagnetic force between the two approaching bunches — production of hard bremstrahlung photons.
- Electron-positron pair production
  - coherent (real photon + incoming bunch field)

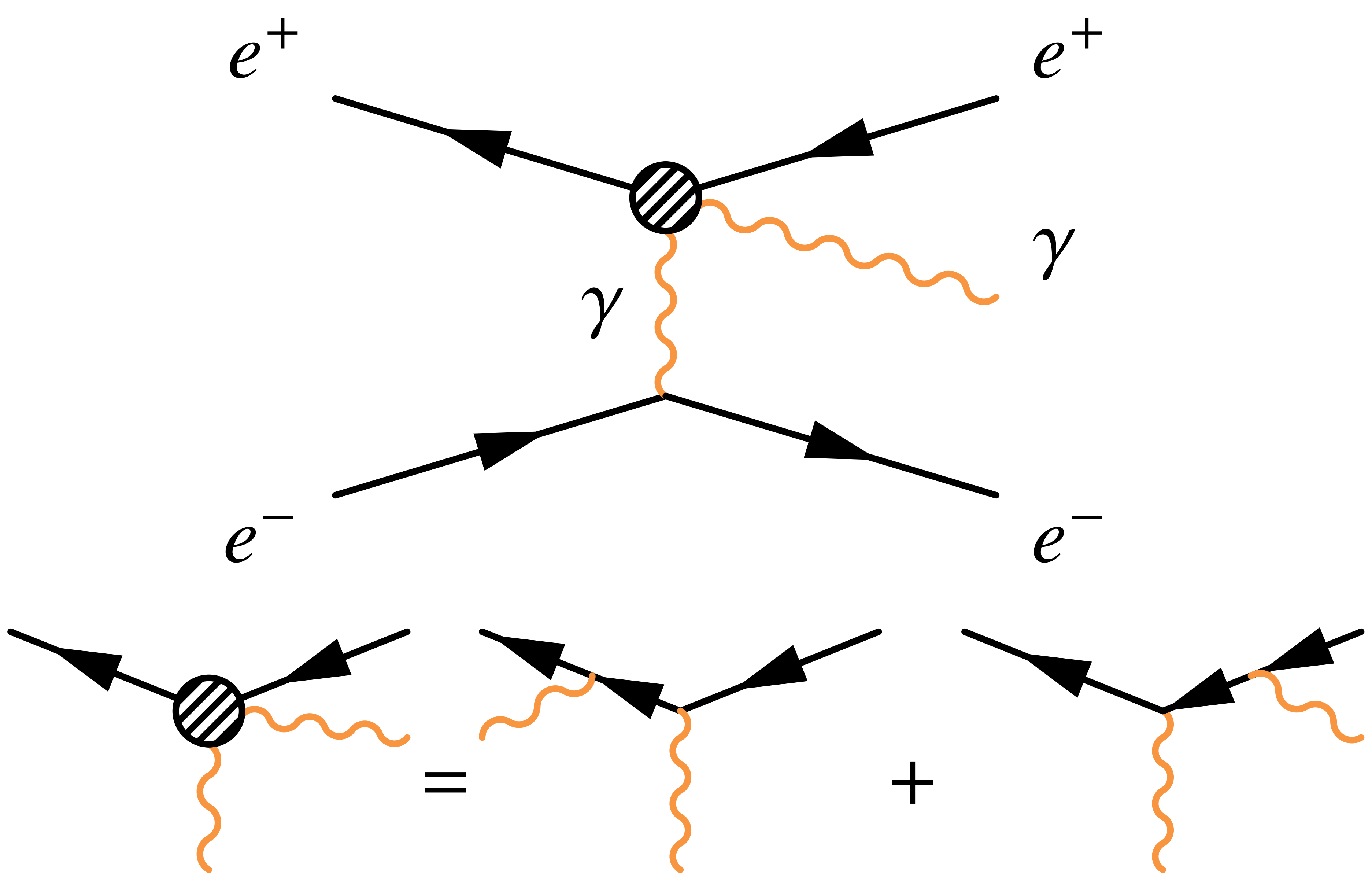


- From the electromagnetic force between the two approaching bunches — production of hard bremstrahlung photons.
- Electron-positron pair production
  - coherent (real photon + incoming bunch field)
  - trident (virtual photon + incoming bunch field)



- From the electromagnetic force between the two approaching bunches — production of hard bremstrahlung photons.
- Electron-positron pair production
  - coherent (real photon + incoming bunch field)
  - trident (virtual photon + incoming bunch field)
  - incoherent (interaction with individual particle field)
- Radiative Bhabha — scattering of electrons with the emission of a photon.
  $e^+e^- \rightarrow e^+e^-\gamma$

10.1103/PhysRevAccelBeams.27.091001



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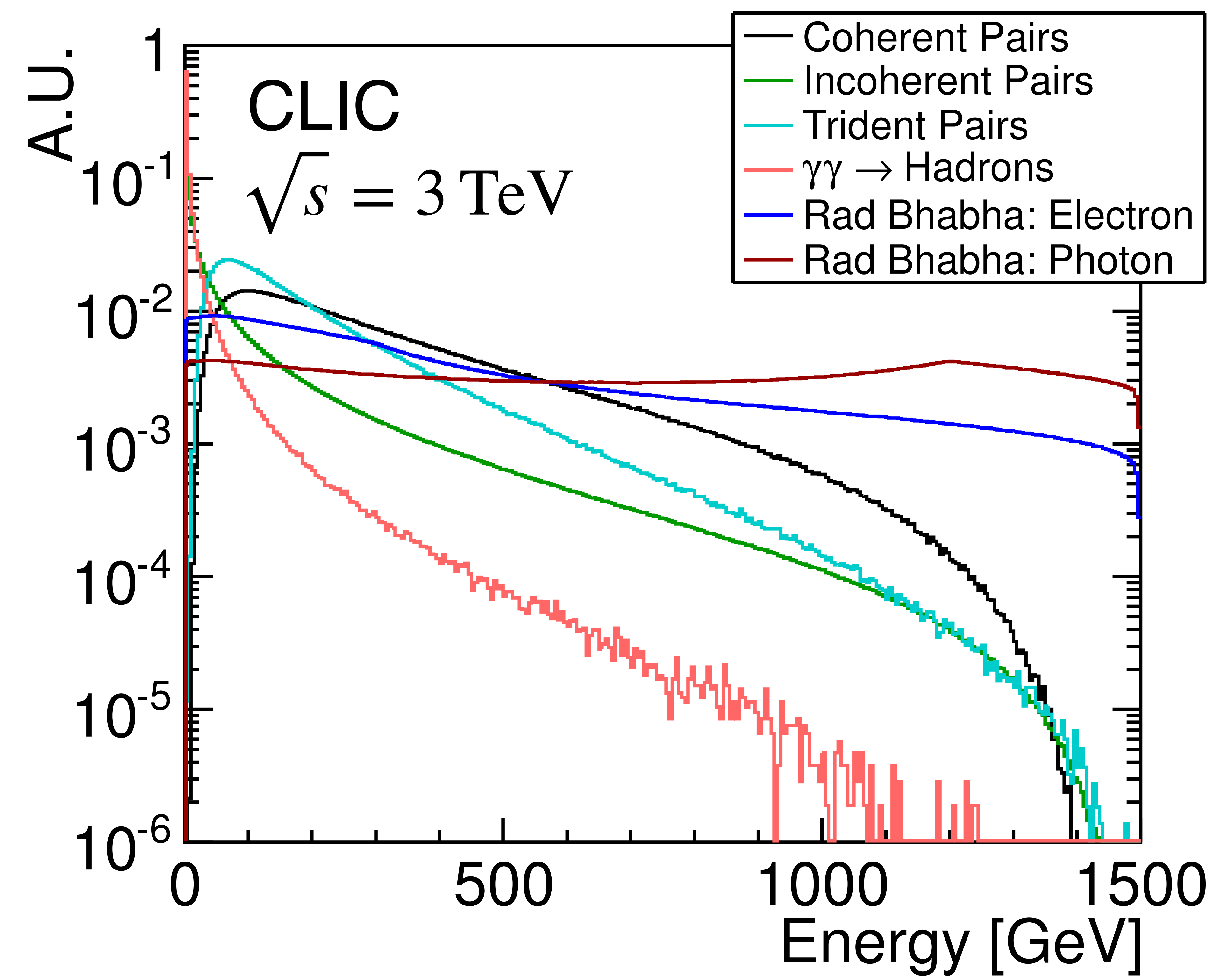
- Radiative Bhabha — scattering of electrons with the emission of a photon.
  $e^+e^- \to e^+e^-\gamma$
- Hadronic interactions — $\gamma\gamma \to$ hadrons.

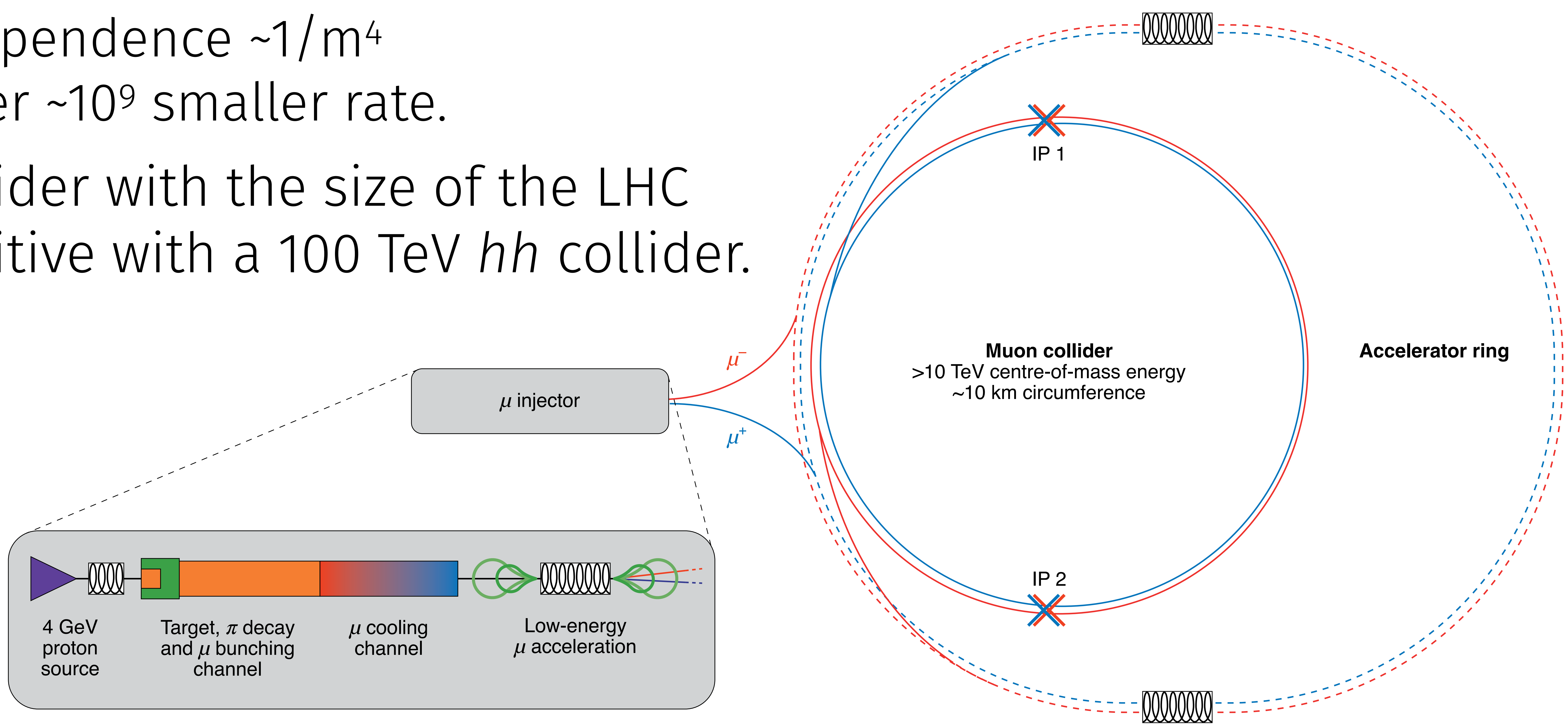
- Simulation conceptually similar to pile-up.

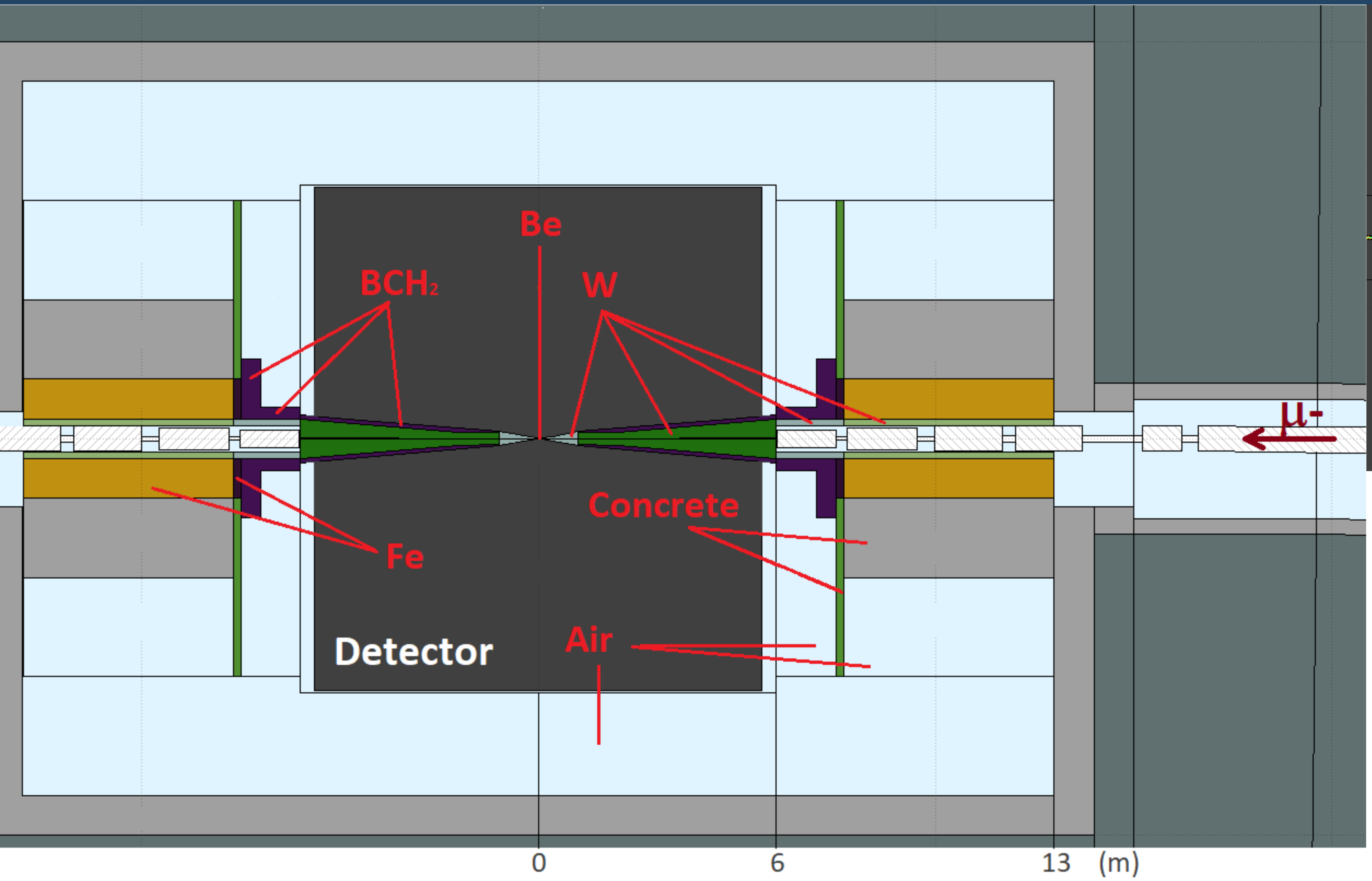
LCD-Note-2011-021

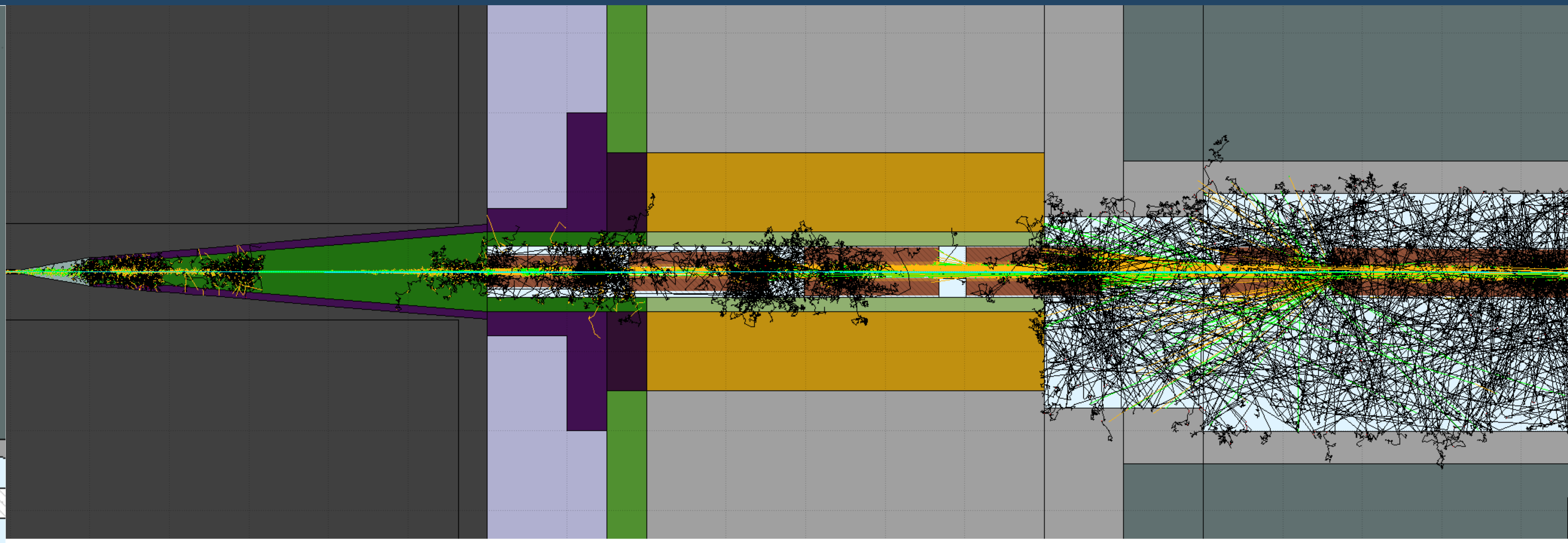
Background	Particles per BX: Total	$\theta > 10$ mrad	$\theta > 7.3°$ and $p_T > 20$ MeV
Coherent pairs	$6 \cdot 10^8$	≈ 0	0
Trident pairs	$7 \cdot 10^6$	≈ 0	0
Incoherent pairs	$3 \cdot 10^5$	$8 \cdot 10^4$	60
Radiative Bhabha $e^\pm/\gamma$	$1 \cdot 10^5$	3/0	0/0
$\gamma\gamma \to$ hadrons	102	96 (47 charged)	54 (25 charged)

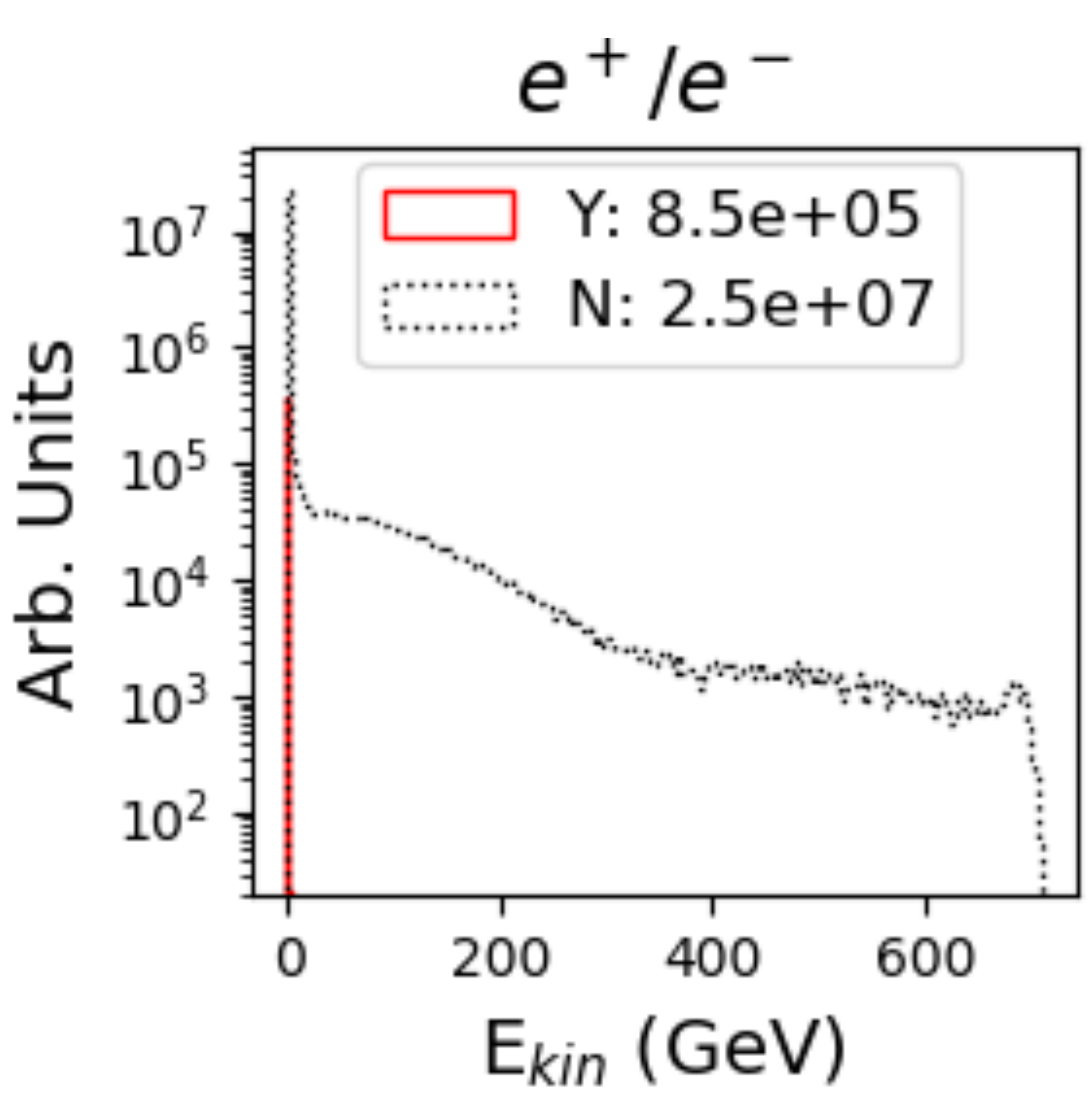


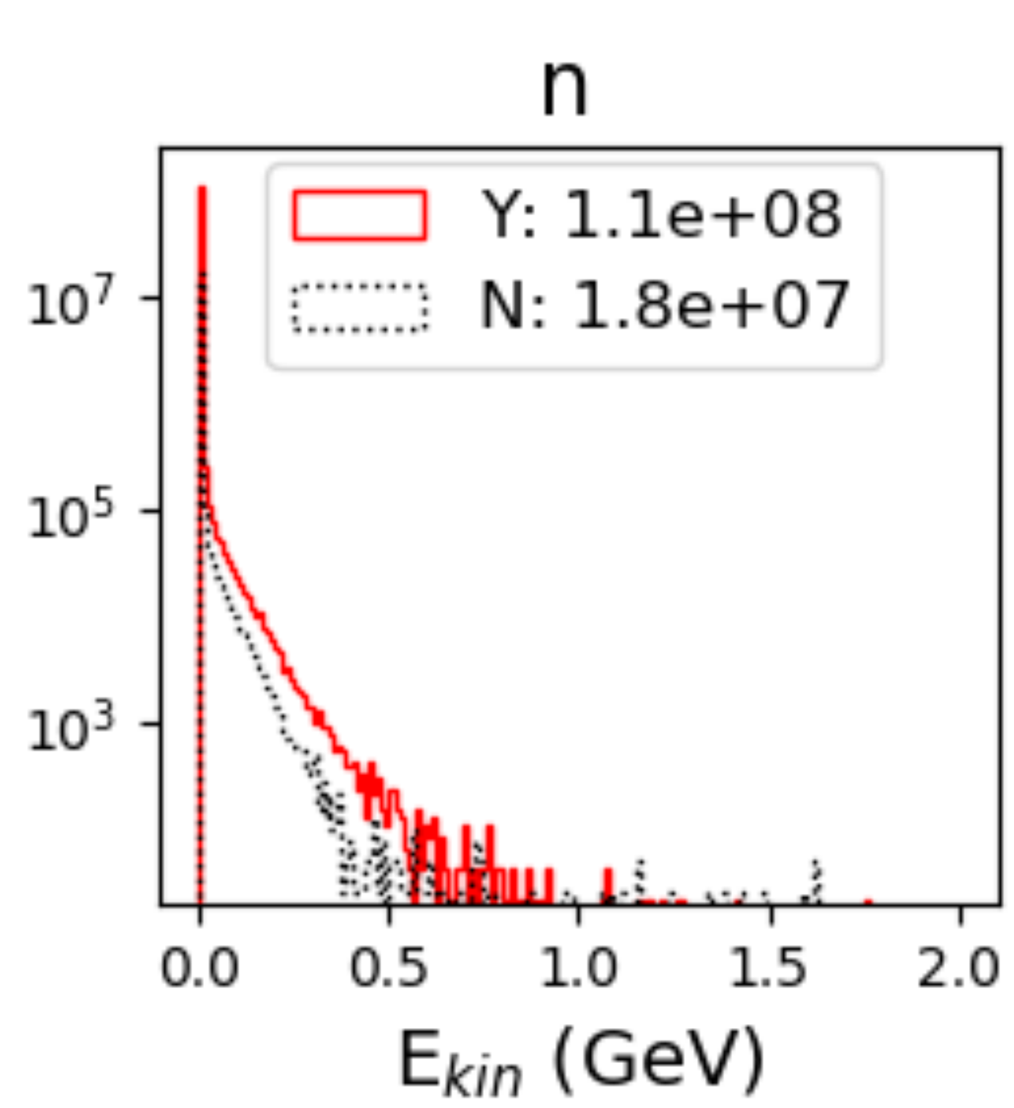
- Muons are short-lived particles:
  - 2.2 μs in rest frame → 21 ms at 1 TeV
- Muon collider application similar to electron-positron one but can go to much higher energies — no issues with synchrotron radiation.
  - SR emission dependence ~$1/m^4$
    → muon collider ~10^9 smaller rate.
- 10 TeV muon collider with the size of the LHC could be competitive with a 100 TeV *hh* collider.











- The main background at muon detectors are muon decays and the products of their interaction.
- Demanding to simulate
  - Decays can happen everywhere (inside or outside experimental cavern).
- Special shielding nozzles can be used to reduce the backgrounds significantly.

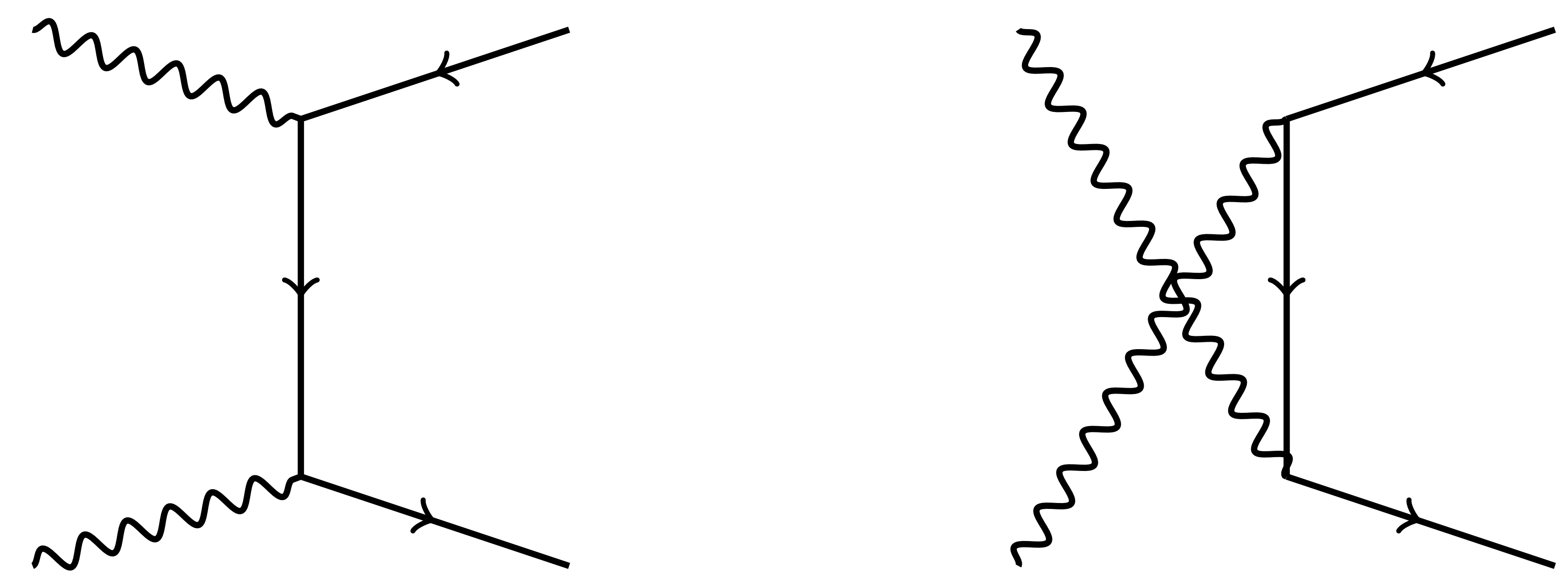
10.1088/1748-0221/16/11/P11009

Summary & Conclusions

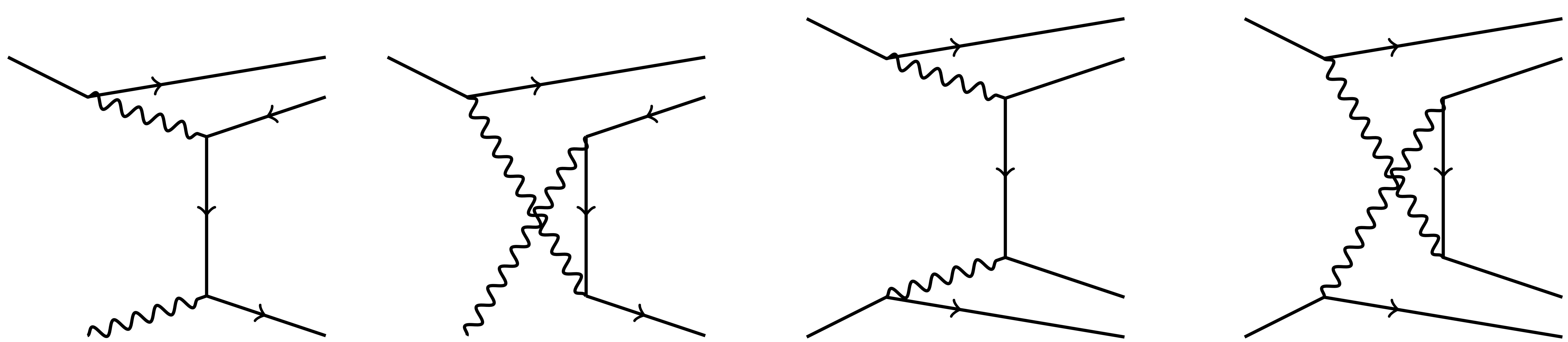
- Beam backgrounds are very demanding to simulate.
  - A lot of particles/interactions.
  - May happen outside of experimental cavern.
- Future colliders will bring even more hostile environment.
- Need to be taken into consideration when designing a future experiment.
  - Shield the detectors as much as possible.
  - Allow low readout thresholds to allow data-driven background estimates.
- Summarised in a review paper "Detector Simulation Challenges for Future Accelerator Experiments", 10.3389/fphy.2022.913510


ATLAS
EXPERIMENT
HL-LHC Simulated Event
200 pile-up interactions
88 reconstructed primary vertices

Incoherent Pair Production Diagrams



(a) Breit–Wheeler



(b) Bethe–Heitler

(c) Landau–Lifschitz

Figure 5: Incoherent pair production processes [20]. These diagrams are also applicable to the $\gamma\gamma \to$ hadron events.