Work Package 3 overview

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Work Package 3

- WP3 – Muon Beams is dedicated to R&D studies for a multi-TeV muon collider and cooling of low energy muon beams:
  - Task 3.1: *muon beams cooling*.
  - Task 3.2: *study of the beam-induced background at several centre of mass energies to optimize the beams interaction point*.
  - Task 3.3: *neutrino induced radiation hazard evaluation.*
    - ➔ This study is now coordinated by the CERN Radiation Protection Group within the IMCC, an overview of the ongoing activities was presented in:

      C. Ajdida et al., "Overview of neutrino radiation studies", IMCC and MuCol Annual Meeting 2024, CERN, March 12-15, 2024.
  - Task 3.4: *study and optimization of the detector at high energy muon beams*.

WP3 deliverables and milestons

- WP3 deliverables:
  - D3.1 - muon cooling [month 36]:
    report on the different muon cooling approaches at different energies and reacceleration schemes from low to high energy muon beams.

  - D3.2 - beam-induced background [month 22]:
    report on beam-induced background after interaction region optics optimization

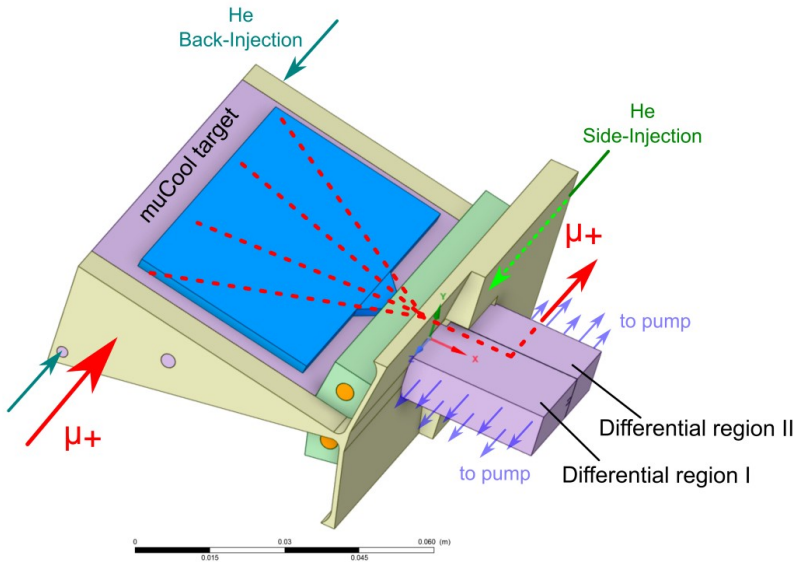
    ➔ M. Casarsa, L. Castelli, D. Lucchesi, “Interim report on The beam-induced background studies”, October 31, 2023
  - D3.3 - detector simulation for the muon collider [month 42]:
    report on detector performance and event reconstruction at different center-of-mass energies.

- WP3 milestones:
  - MS8 - muon cooling design [month 20]:
    concept design of low energy muon beams completed.

  - MS9 - muon collider detector optimization [month 29]:
    public presentation on detector optimization for high energy muon beams.

Task 3.1: towards the 2024 beam time

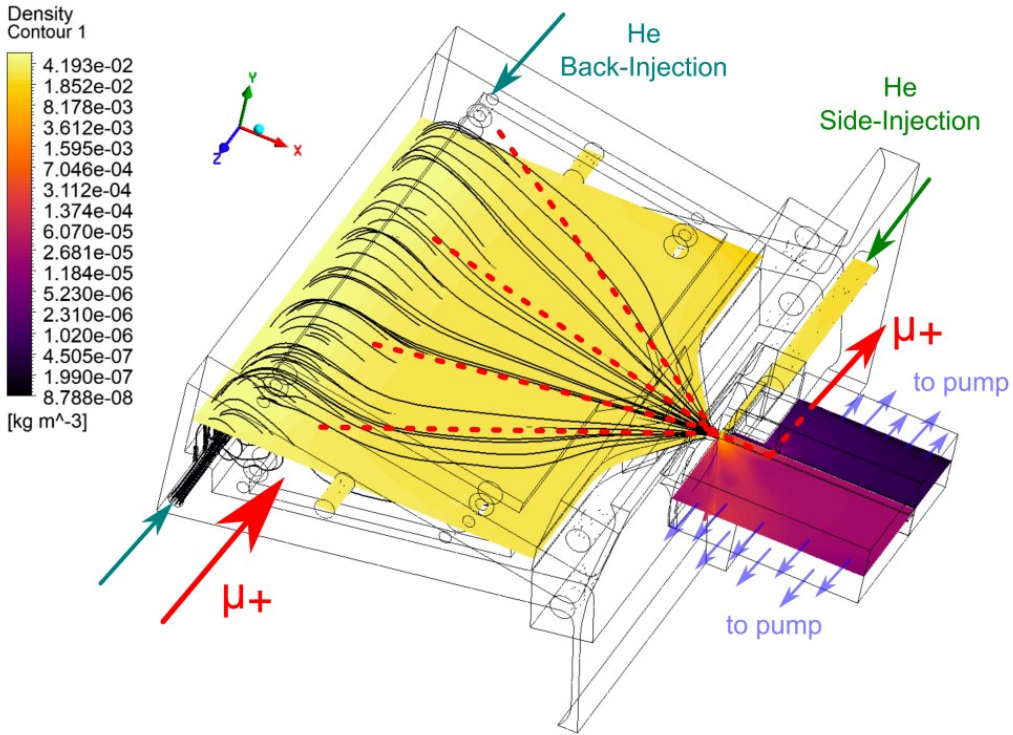
- All activities oriented towards the preparation for beam time at PSI in December 2024 to experimentally validate the muCool concept:
  - implemented a realistic GEANT4 simulation of the muCool setup: gas-flow, density, and temperature maps of the He gas in the target are precisely simulated;
  - devised an injection scheme for He gas into the muCool target, which doesn't disrupt the vertical density gradient in the target and features an abrupt change in gas density that can be matched to an E-field realizable by gluing Kapton foils;
  - plan to follow a differential pumping region approach (Roots pumps available at PSI are suitable for pumping the differential region I).



Simulation results show that it is possible to extract muons from the target efficiently and robustly.

Task 3.1: simulation of gas density and flow

- In order to extract the muons in vacuum, the control of the gas density and flow is crucial. Here is an example of the simulation results:



Task 3.1: current status

- Installation of the CAEN HV system completed.
- Implemented CAEN HV remote/slow control to be used for the target electric fields.
- Dummy production of the parts to inject the He gas without disrupting the vertical density gradient in the target.
- Preparation of the differential pumping region underway.
- Goal for the December beam time:
  - ➔ experimentally test the extraction of muons from the He-filled region in the target, where muon manipulation and cooling occur, to the vacuum.

Activities in Tasks 3.2 and 3.4

- All activities are now oriented towards the preparation for the Update of the European Strategy for Particle Physics (submission of contributions is due by March 26, 2025).

- Activities for a 3-TeV collider:
  - optimization of the nozzles and preliminary studies on the detection of very forward-scattered muons in the ZZ-fusion processes $\mu^+\mu^- \to X\mu^+\mu^-$ (L. Castelli);
  - a paper submitted to EPJC summarizes the 3-TeV detector performance and presents significant examples of the physics reach of a 3-TeV muon collider in the Higgs sector with full simulation:

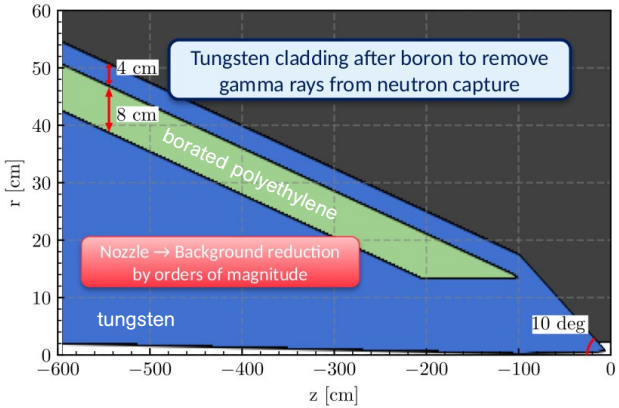
    P. Andreetto et al., "Higgs Physics at a $\sqrt{s}$ = 3 TeV Muon Collider with detailed detector simulation", arXiv:2405.19314

- The following slides will focus on muon collisions at 10 TeV.

Task 3.2: new nozzle design for 10 TeV

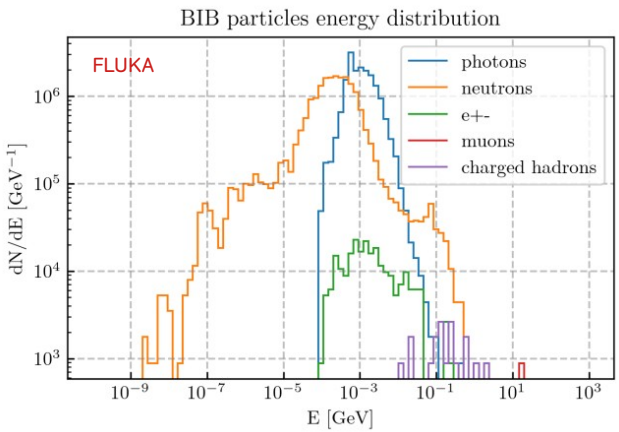
D. Calzolari

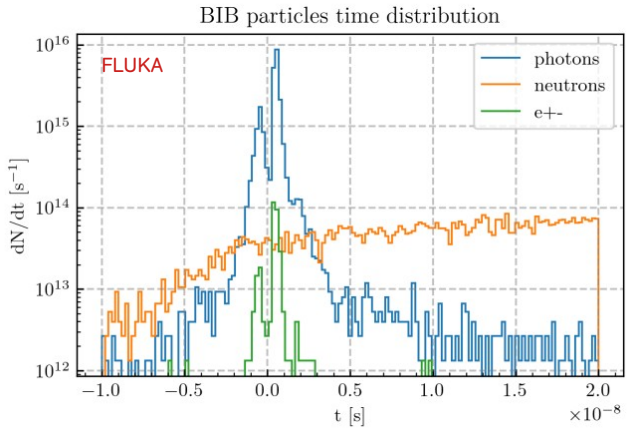
new nozzle design



realistic material composition

Component	Density [g/cm3]	Element	Atomic Fraction (mass fraction if negative)
EM Shower Absorber	18	W	-0.95
		Ni	-0.035
		Cu	-0.015
Neutron Absorber	0.918	H	0.5
		C	0.25
		B	0.25





Available high-statistics BIB sample with the new nozzles.

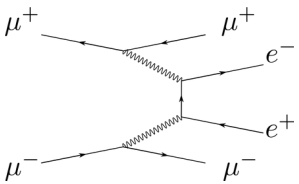
MAP's 1.5 TeV nozzle — new 10 TeV nozzle

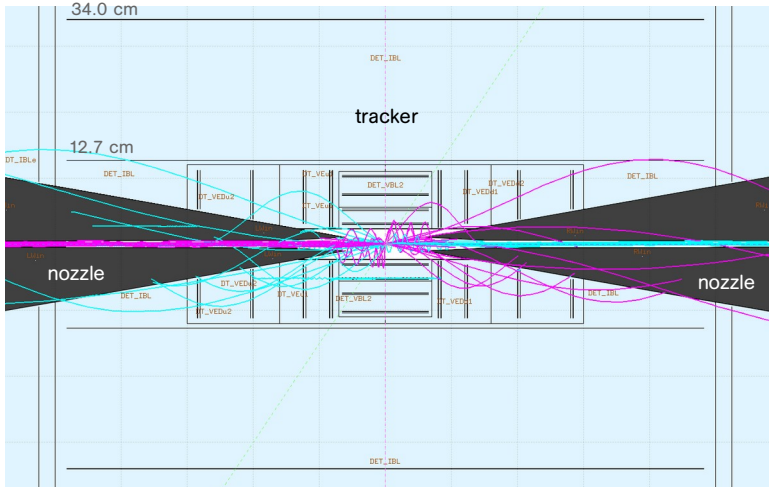
Collider energy	1.5 TeV	3 TeV	10 TeV (v 0.8)	10 TeV (EU24*)
Photons	7.1E+07	9.6E+07	1.6E+08	9.9E+07
Neutron	4.7E+07	5.8E+07	1.4E+08	1.1E+08
e+/e-	7.1E+05	9.3E+05	8.9E+05	1.2E+06
Ch. hadrons	1.7E+04	2.0E+04	5.2E+04	4.2E+04

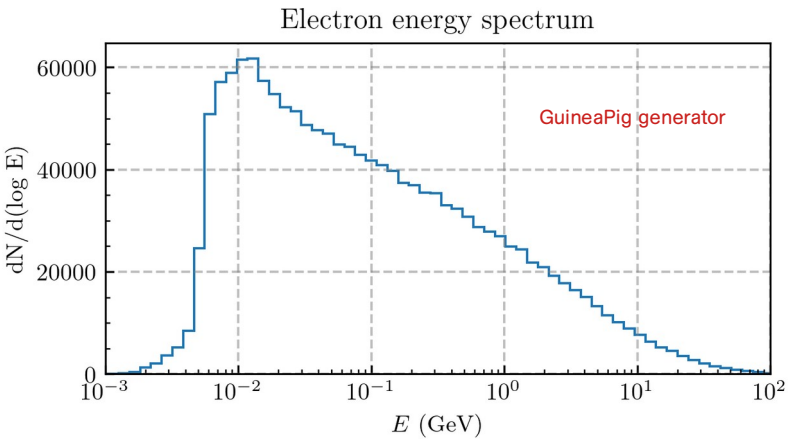
Task 3.2: incoherent e^+e^- pair production

D. Calzolari

- An additional significant background from incoherent e^+e^- pairs produced at bunch crossing is now taken into account:
  - relatively high-energy $e^\pm$ enter the detector at the interaction point in time with the bunch crossing;
  - the solenoidal B field confines most of the $e^\pm$ in the innermost region close to the beampipe;
  - mainly the vertex detector and the inner tracker layers are affected.







10 TeV	BIB	e^+e^- pairs
Photons	9.9E+07	4.0E+06
Neutron	1.1E+08	1.3E+05
e+/e-	1.2E+06	2.1E+05

Task 3.4: new detector concept for 10 TeV

- The requirements for the detector specifications from physics are similar to those of other multi-TeV machines to reconstruct:
  - boosted low-p_T physics objects from Standard Model processes;
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
- Constraints from the machine design: final focusing quadrupoles at ± 6 m from the interaction point.
- Machine background conditions.

Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background.

Task 3.4: the MuSIC detector concept

The MuSIC detector (Muon Smasher for Interesting Collisions)

D. Zuliani

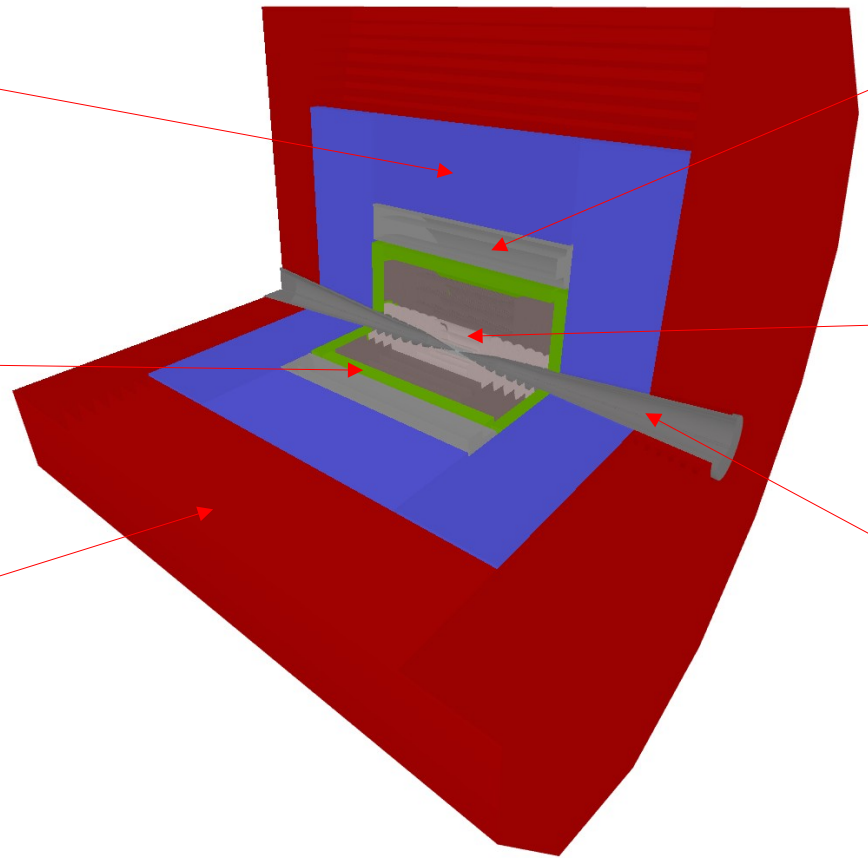
hadronic calorimeter:

- Fe-scintillator;
- Fe absorber serves as B-field flux return.

electromagnetic calorimeter:

- CRILIN (6 layers).

muon detectors



superconducting solenoid:

- B = 5 T.

vertex detector and tracking system:

- full-silicon (pixels and macro pixels).

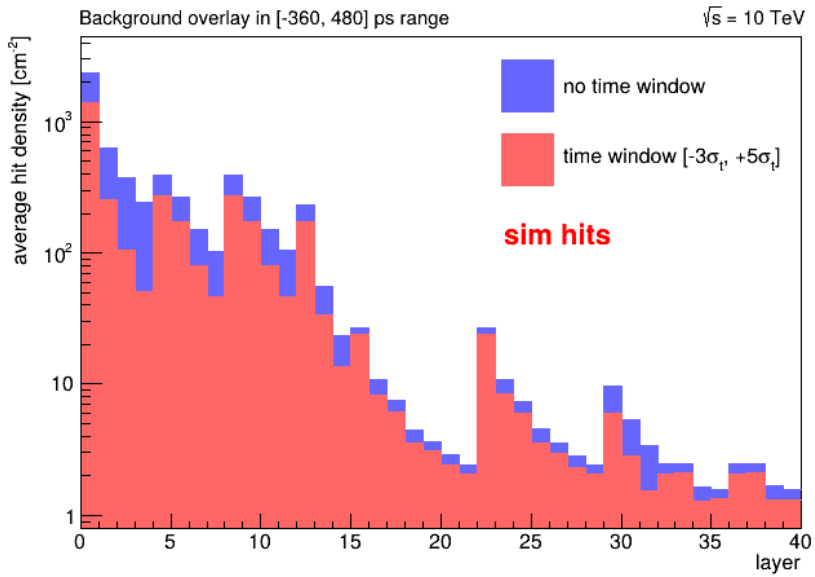
new 10-TeV nozzles

fully integrated in MuonColliderSoft

Task 3.4: first detector studies at 10 TeV

- Using the new 10-TeV BIB samples:
  - first studies on the machine background impact on the tracking system and the electromagnetic calorimeter;
  - performance assessment and revision/tuning of the reconstruction algorithms for tracks, photons, electrons (D. Zuliani, C. Giraldin, L. Palombini).

average BIB hit density in the tracking system layers



origin point of particles in the first layer of ECAL

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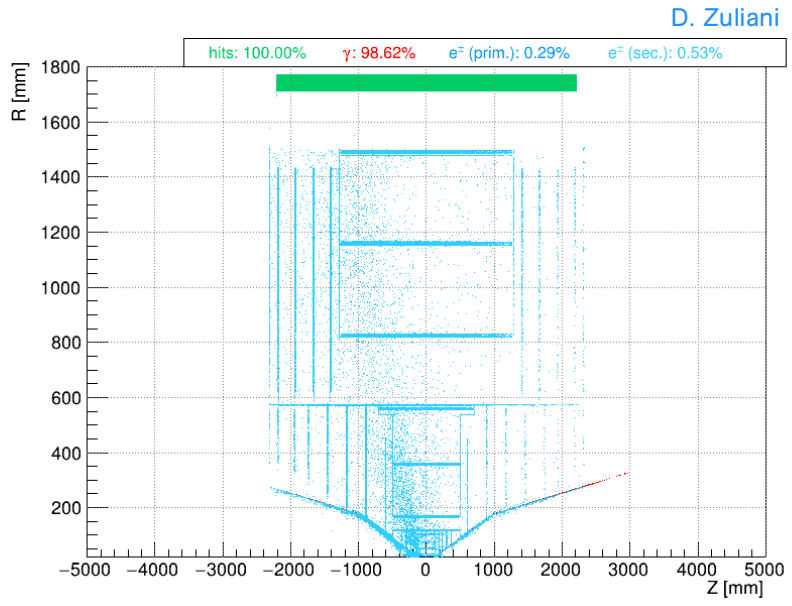
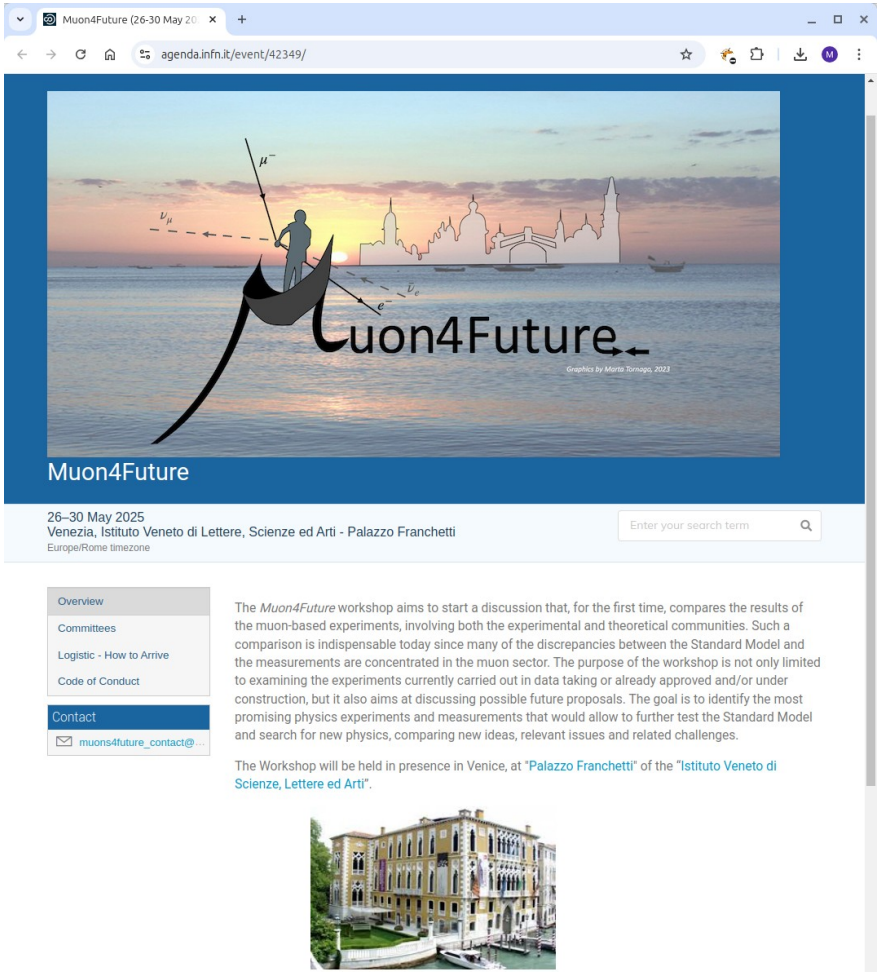


Task 3.4: plans for the ESPP update

- The detector performance at 10 TeV will be assessed on a set of benchmark physics processes, representative of the muon collider physics program:
  - featuring low- and high-p_T physics objects in the final state;
  - studied with a detailed detector simulation that includes the machine backgrounds from muon decay and incoherent e^+e^- pair production.
- Physics benchmarks to be studied (assuming $\sqrt{s}$ = 10 TeV and 10 ab^{-1}):
  - double Higgs boson production to estimate the sensitivity to the trilinear self-coupling: $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}W^+W^-$.
  - production of a new heavy state $Z' \to e^+e^-$ to estimate the mass reach in direct and indirect searches.

Muon4Future 2025



New edition of the Muon4Future workshop in 2025 from May 26 to May 30 in Venice.

https://agenda.infn.it/event/42349

Muon4Future 2023