Higgs Physics at a Muon Collider

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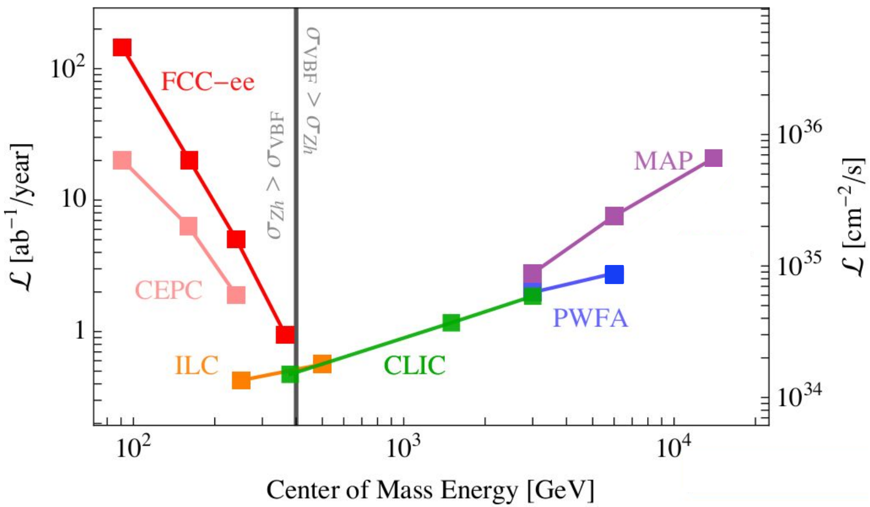
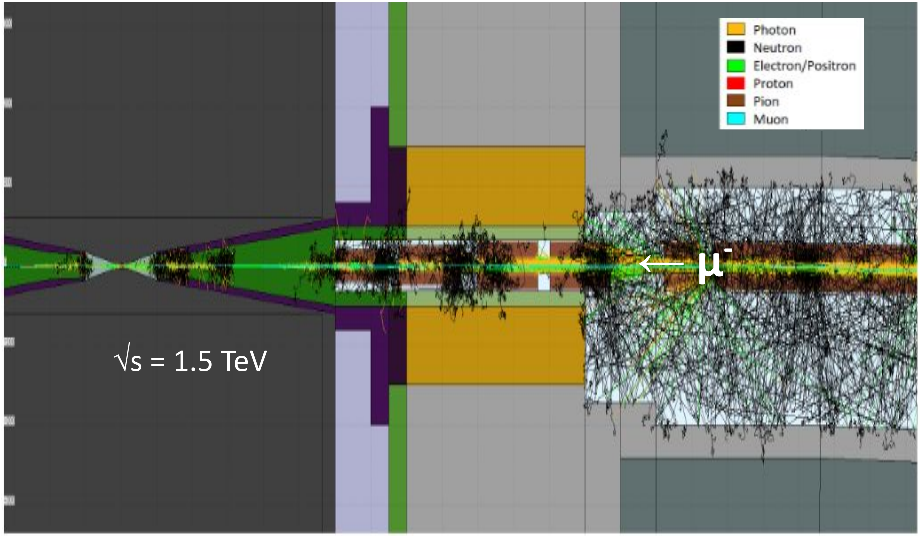
The Muon Collider

- Circular lepton collider. Collides muons, elementary particles heavier than electrons: higher energy achievable due to negligible synchrotron radiation. All beam energy is available for the scattering. Luminosity increasing with beam energy
- Muons decay in beam line: Beam Induced Background (**BIB**), large flux of particles from interaction of decay products with beam line and tunnel walls



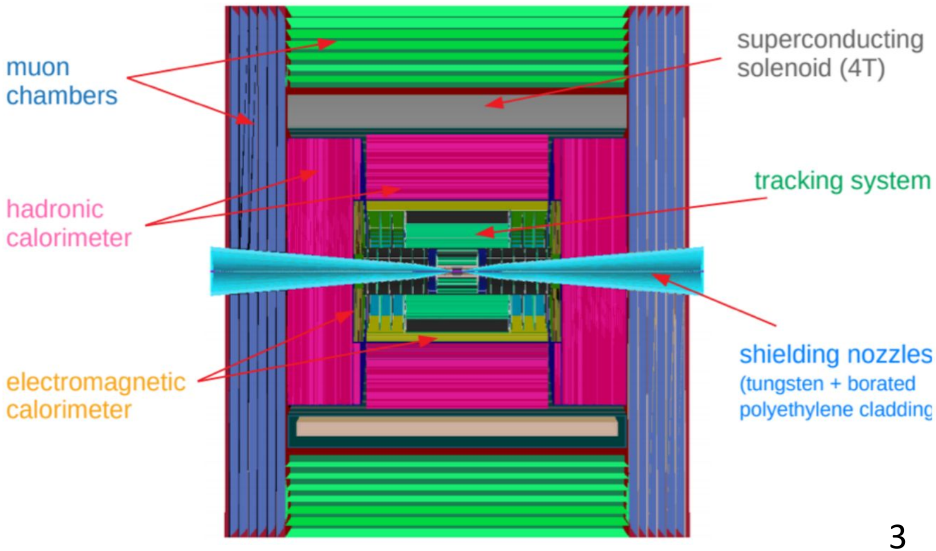


arXiv:2105.09116v2

Higgs couplings with detailed simulation

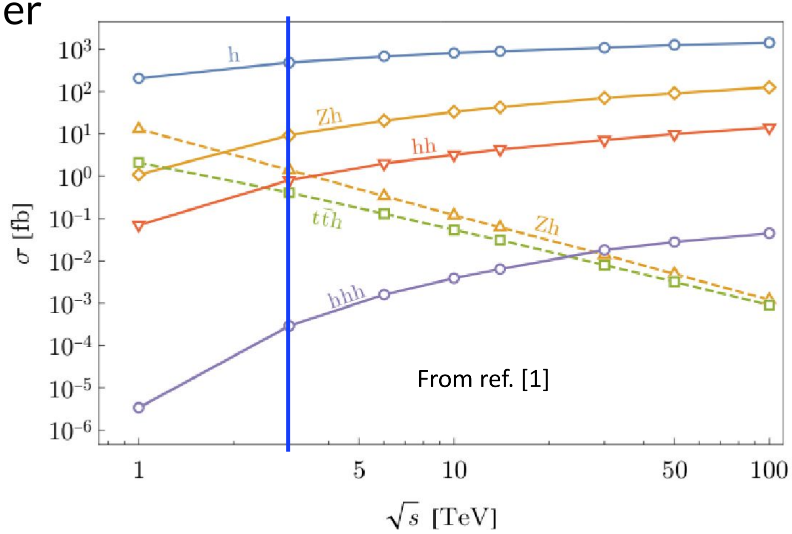
- **Detailed simulation of detector and BIB** is crucial to determine realistic physics potential and detector performance
- **Higgs physics** studies at **3 TeV considering physics background with BIB** overlaid
  - BIB events generated at 1.5 TeV, yield is expected to reduce with higher E_{CM}

- Detector:
  - Nozzles in the forward region are crucial to reduce BIB but reduce also acceptance. Optimized for 1.5 TeV
  - Tracking: very high hit multiplicity due to BIB, significant combinatorial problem
  - Calorimeters: diffuse background due to BIB



Higgs Physics at muon collider

- At leptons collider H produced via ZH (Higgsstrahlung) or VBF (Z and W)
  - W fusion is dominant at 3 TeV muon collider
- Reference: $\mathcal{L}$ = 1 ab^{-1} at 3 TeV
  ~500k Higgs bosons: → Higgs factory!
- Processes: **H->bb**, **H->μμ** and **HH->bbbb**
  - **Expected** precision with parametric simulation (10 ab^{-1} @ 10 TeV) [1]:
    - ➔ Δk_b ~ 0.16%, Δk_μ ~ 2%
  - Higgs self coupling (λ_3) also possible:
    - ➔ 5% with 10 ab^{-1} @ 10 TeV [2]
    - ➔ 25% with 1 ab^{-1} @ 3 TeV [3]



[1] *The Muon Smasher's guide*, arXiv:2103.14043

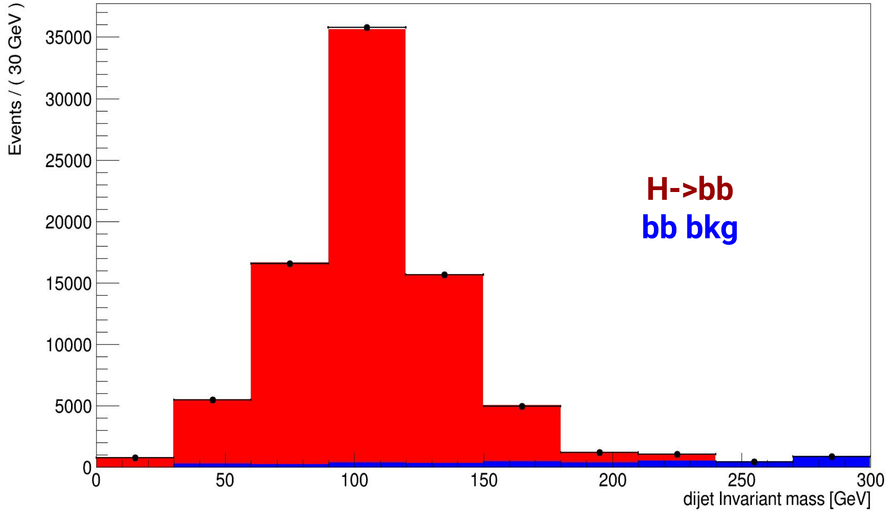
[2] *Two Paths Towards Precision at a Very High Energy Lepton Collider*, JHEP **05** (2021), 219

[3] *Electroweak couplings of the Higgs boson at a multi-TeV muon collider*, Phys. Rev. D **103** (2021) no.1, 013002

H -> bb performance with detailed simulation

- Crucial features: good jet reconstruction and b-tagging
  - **SV-tagging**: a jet including a reconstructed secondary vertex is b-tagged
  - $\varepsilon_{\text{jet reco}}$ from 50% (low p_T) to almost 100% (high p_T)
  - $\varepsilon_{\text{b-tag}}$ ~ 55%

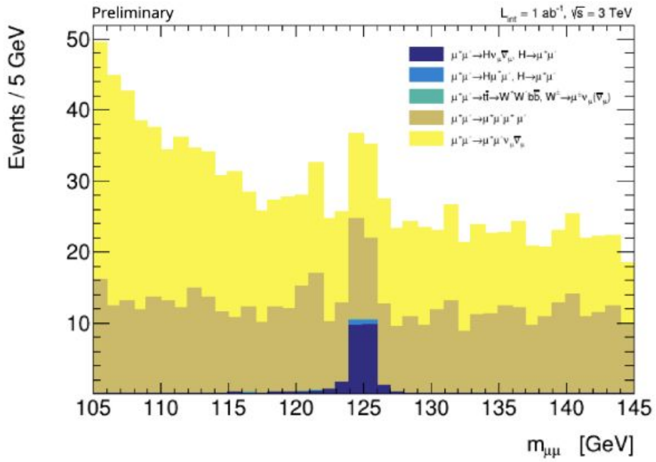
- Fiducial region: M_{jj} < 300 GeV, $|\eta^{jet}|$ < 2.5, p_T^{jet} > 20 GeV
- High signal purity: expected 79 125 signal and 3 636 bkg events with $1\ ab^{-1}$ @ 3 TeV (generated with Pythia@LO)
- Preliminary result: about **0.36%** on **σ (μμ->H)·BR(H->bb)** (stat. only)
  - **CLIC** reaches **0.3% with 2 ab^{-1}** [4]

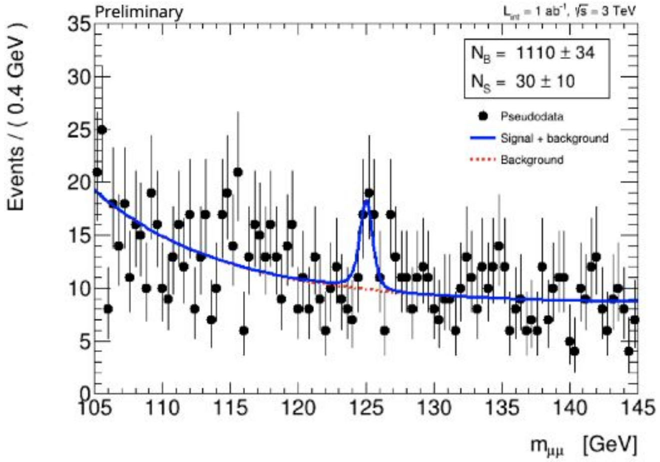


[4] *Higgs physics at the CLIC electron–positron linear collider*, Eur.Phys.J.C 77 (2017) 7, 475

H -> μμ performance with detailed simulation

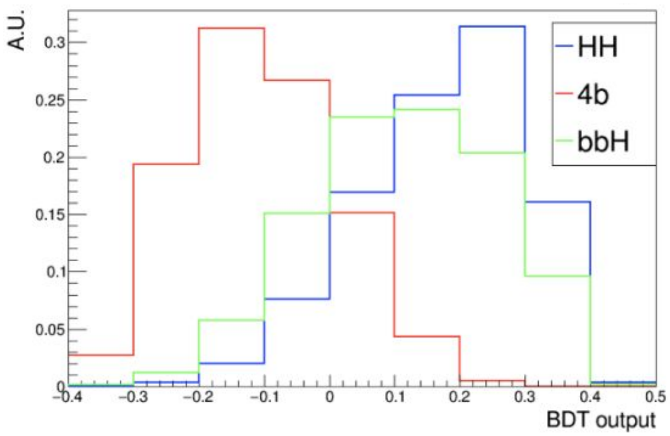
- Main backgrounds: μμ->μμνν and μμ->μμμμ (with two μ lost in nozzles)
  Expected 26 signal and 1100 background events with 1 ab^{-1} @ 3 TeV (MadGraph@NLO)
- Most of BIB hits in the muon detector are near nozzles: Cut on θ of muon track to reduce BIB to a negligible level: **10° < θ < 170°**
  - Can improve angular acceptance for BIB @ 3 TeV
- Excellent muon momentum resolution => Precise reconstructed Higgs mass
- Fit of invariant mass: about **38%** on **σ(μμ->H)·BR(H->μμ)** (stat. only)

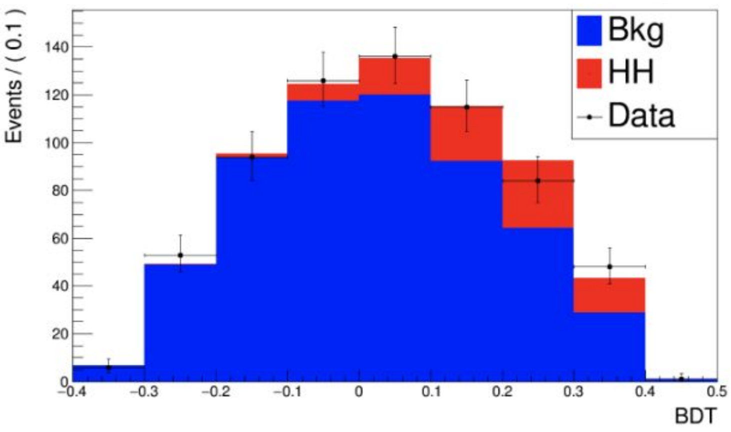




Double Higgs production

- μμ->HHvv->bbbbvv: 4 b-jets final state
  - Fiducial region: $|\eta^{jet}| < 2.5$, $p_T^{jet} > 20$ GeV, at least two SV-tagged jets
  - Irreducible backgrounds: μμ->H(->bb)bb and μμ->bbbb
  - Events generated with Whizard@NLO, reconstructed without BIB and **re-weighted** according to b-tag efficiency calculated on bb di-jet samples reconstructed **with BIB**
- A BDT is trained to separate signal from bkg exploiting kinematical information. Template fit to pseudo-data to determine cross section uncertainty
  - **Preliminary result**: **30%** on **σ(μμ->HHvv)·BR(HH->bbbb)** (stat. only, 1 ab^{-1} @ 3 TeV)

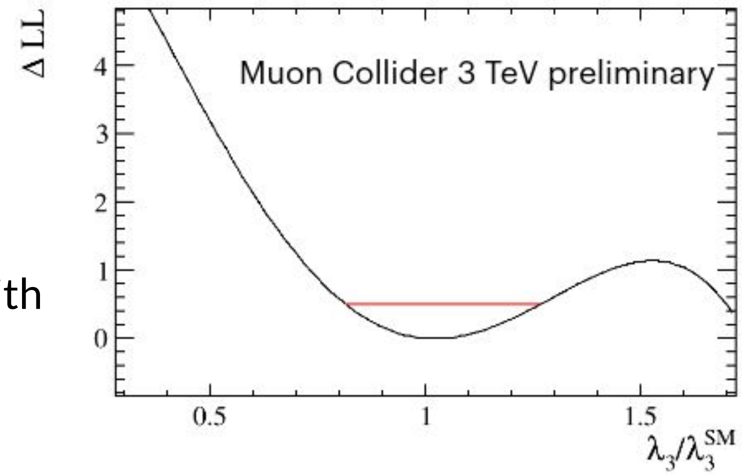




Trilinear coupling extraction

- Same final state and fiducial region. HH production occurring with **trilinear vertex is selected from total HH** production exploiting event kinematic
- Two multi-layer perceptrons (MLP) are used: **MLP(HH vs 4b)** to select signal from bkg, **MLP(HH vs trilinear)** to select HH production with trilinear vertex from total HH production

- MLP templates produced varying λ_3 are fitted to pseudo-experiments
  - Preliminary result: statistical uncertainty around **20% at 68% CL**
  - [-8%, 11%] for 5 ab^{-1} CLIC[5]: compatible with muon collider considering scaling

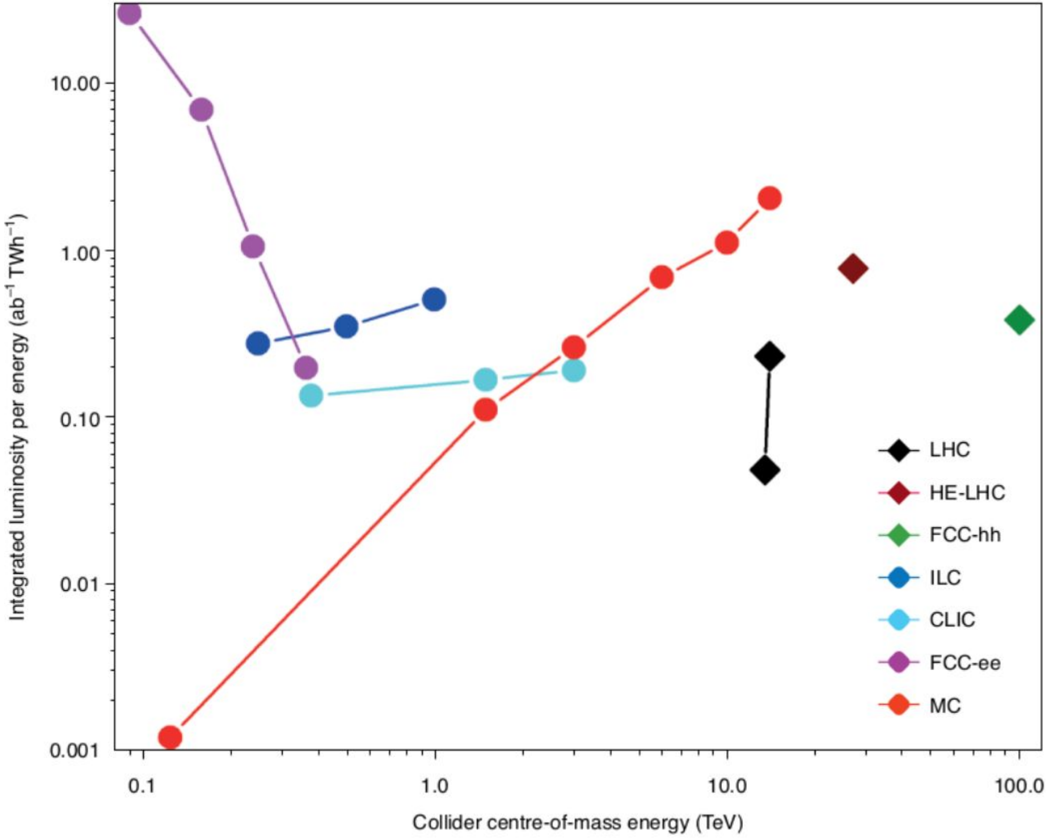


[5] *Double Higgs boson production and Higgs self-coupling extraction at CLIC*, Eur. Phys. J. C **80** (2020) no.11, 1010

Conclusions

- Muon collider would collide **elementary particles at high energy,** but muons decay producing BIB. **Detailed simulation** is fundamental to assess realistic sensitivity. **BIB at 1.5 TeV** with 3 TeV physics is a **conservative assumption**.
- In this presentation, **sensitivities on σ·BR** for **H->bb**, **H->μμ** and **HH->4b** have been shown. These measurements are the starting point to obtain Higgs couplings (g_{Hbb}, $g_{H\mu\mu}$, λ_3)
- **Preliminary results are promising**, improvement expected with ML analysis techniques
  - σ(μμ->H)·BR(**H->bb**) -> 0.36%
  - σ(μμ->H)·BR(**H->μμ**) -> 38%
  - σ(μμ->HHvv)·BR(**HH->bbbb**) -> 30%
  - Precision on $\boldsymbol{\lambda_3}$ ~ 20%
- In order to extract all Higgs couplings, a measurement of H -> WW is necessary to measure g_{HWW} for VBF production. Work is ongoing

Backup: energy efficiency



Muon colliders to expand frontiers of particle physics, Nature Phys. **17** (2021) no.3, 289-292, arXiv:2007.15684

Backup: effect of nozzles on BIB

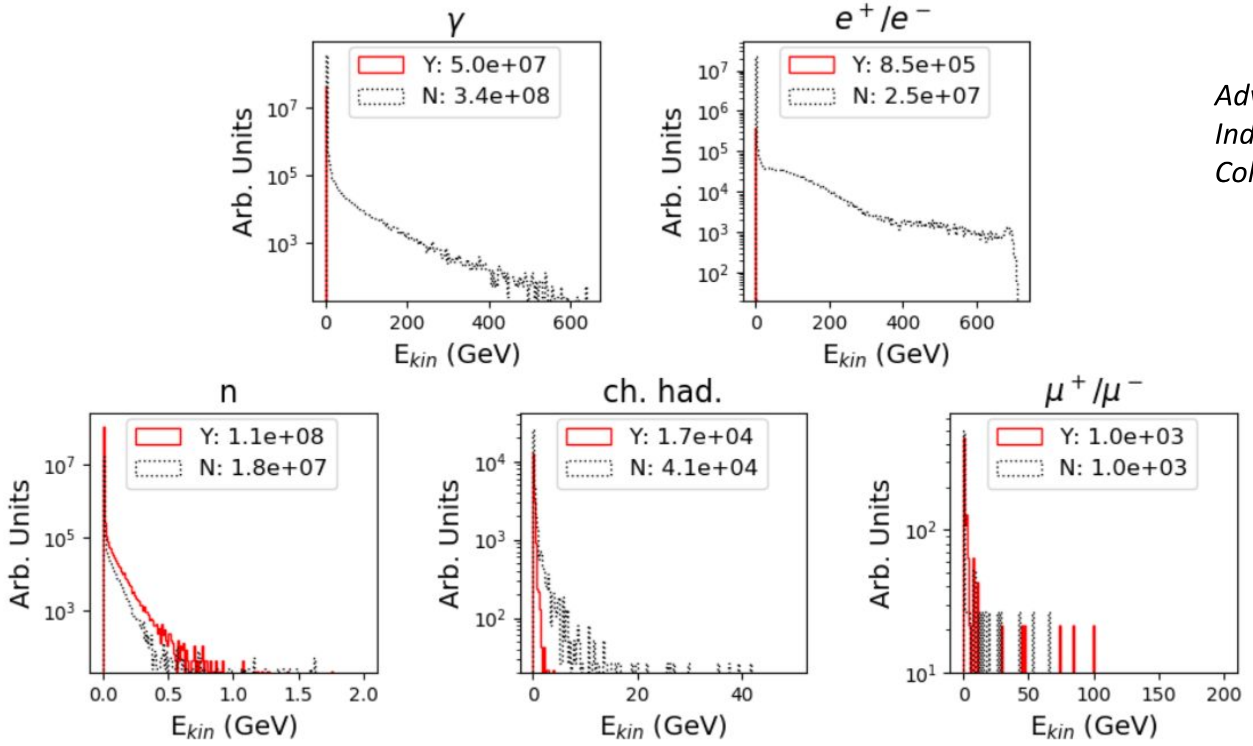


Figure 11. Comparison of number and energy spectra of the BIB: with nozzles (Y) in solid red line and without nozzles (N) in dotted black line.

Advanced assessment of Beam Induced Background at a Muon Collider, arXiv:2105.09116v2