Discussion on full simulation and Physics studies

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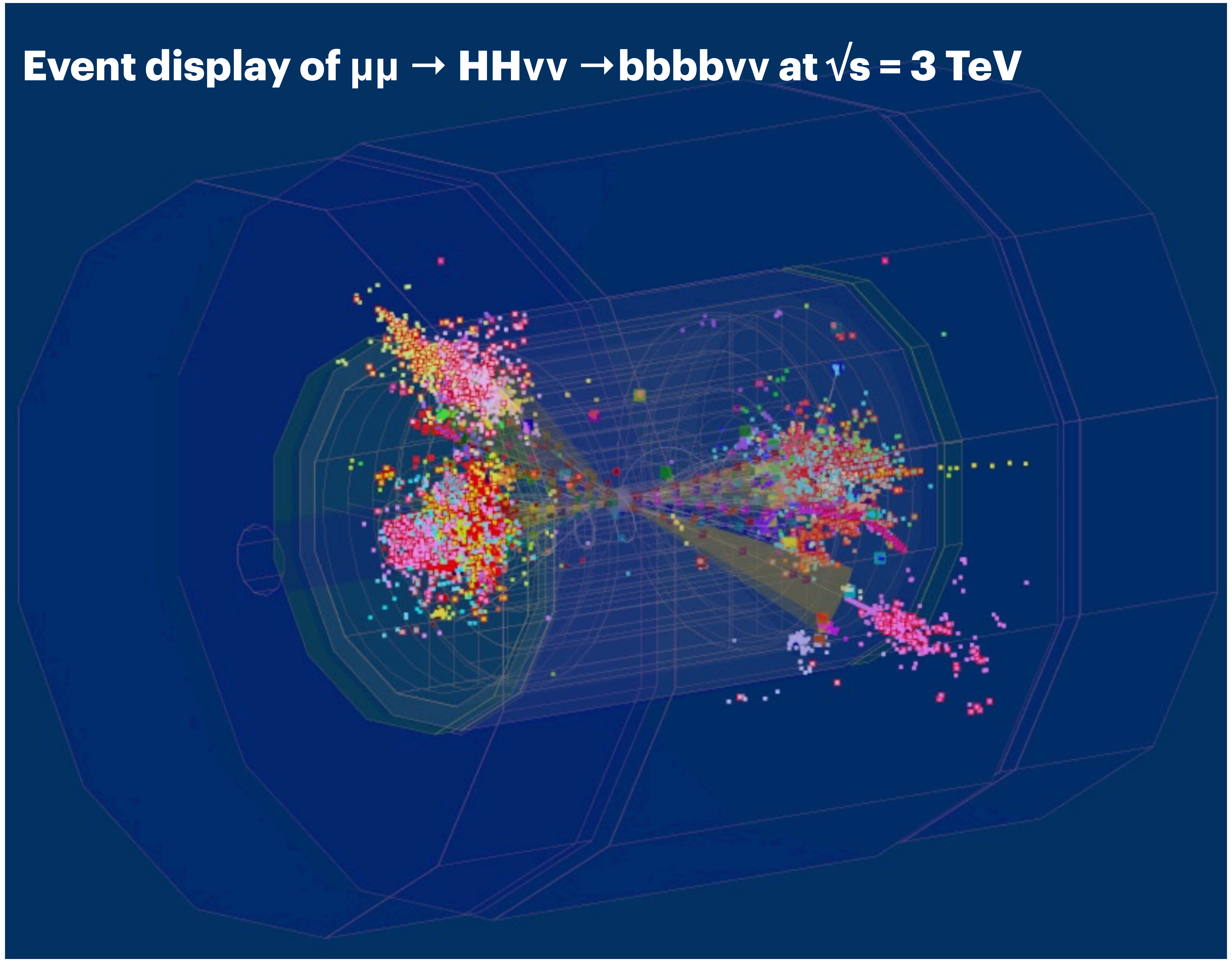
Full simulation

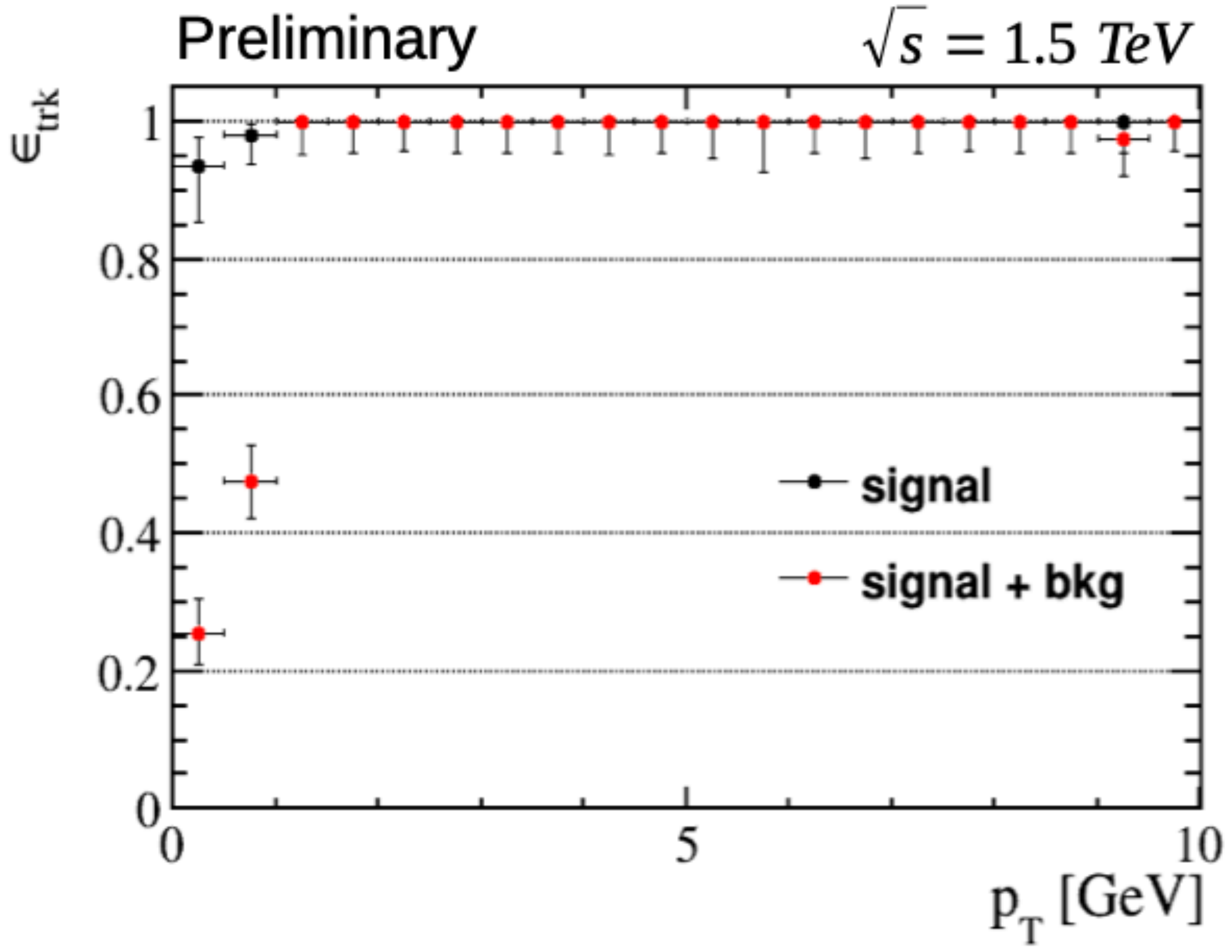
- The **muon collider experiment** features a unique environment.
- The **beam-induced background** (**BIB**) is significantly different from what is present at other colliders.
- The **full simulation** is a fundamental tool:
  - to demonstrate the physics performance and potential (**WG1**);
  - to test and validate detector technologies (**WG2**).
- Full simulation and reconstruction are performed with a branched version of **ILCSoft** (**WG3**).



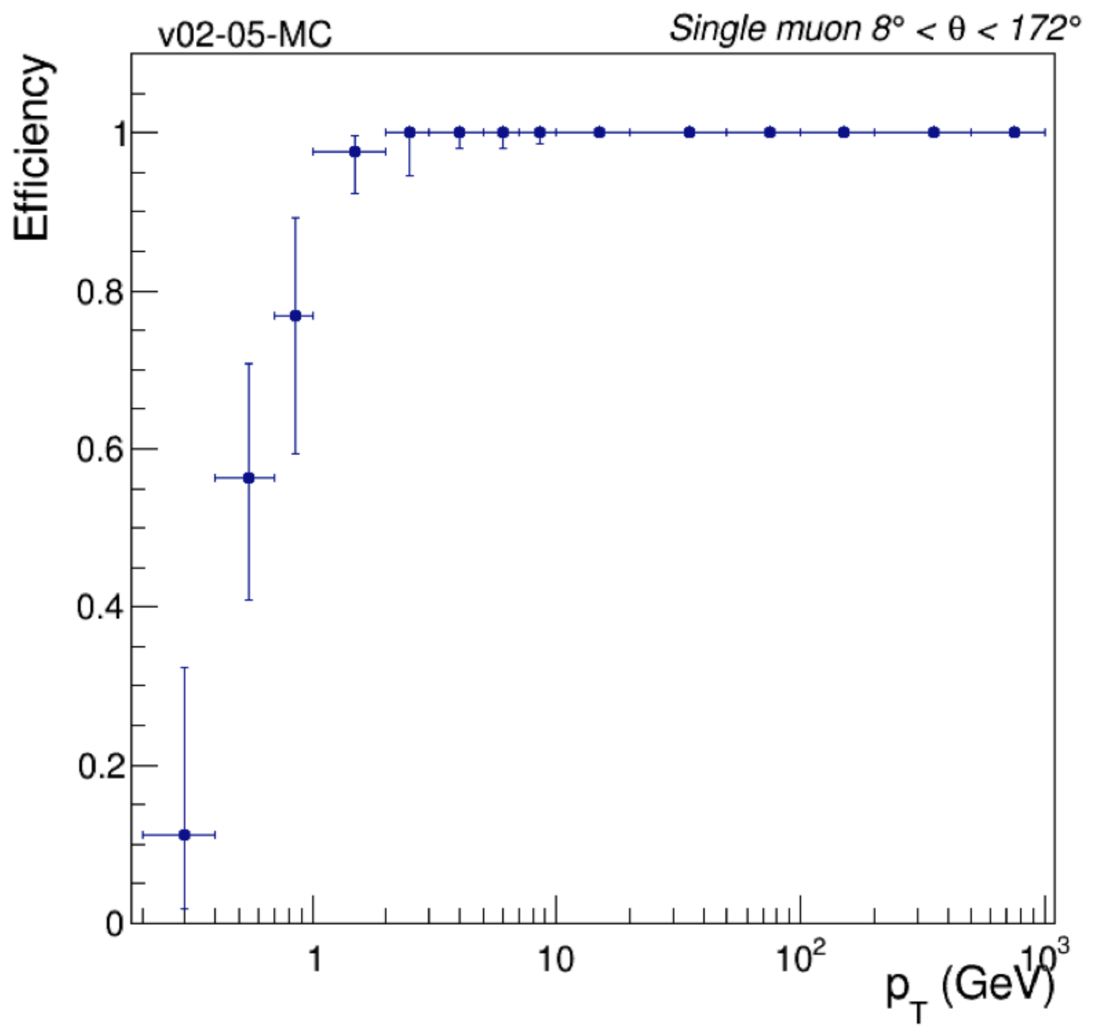
Physics objects reconstruction

Physics objects reconstruction

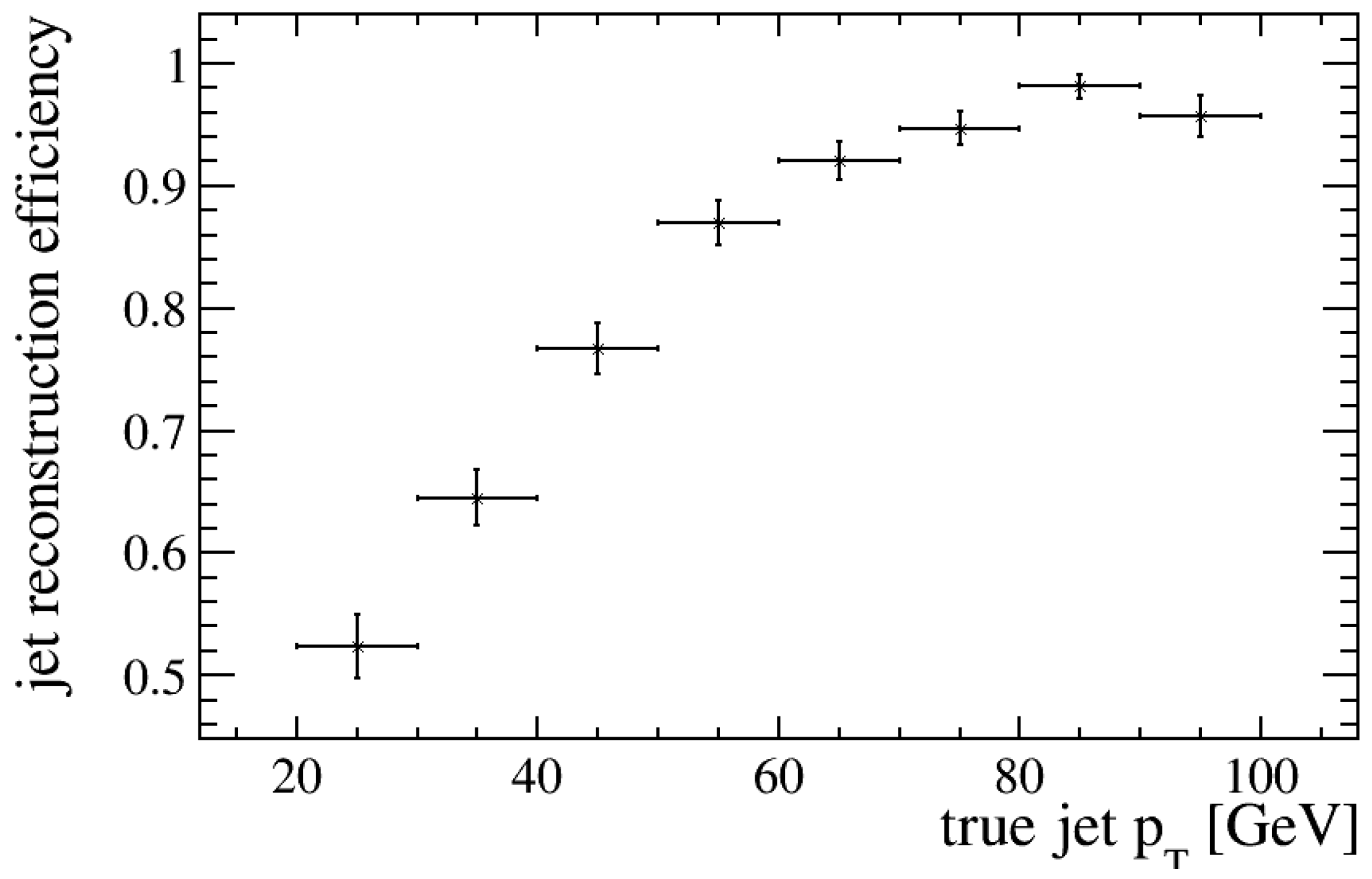
Tracking



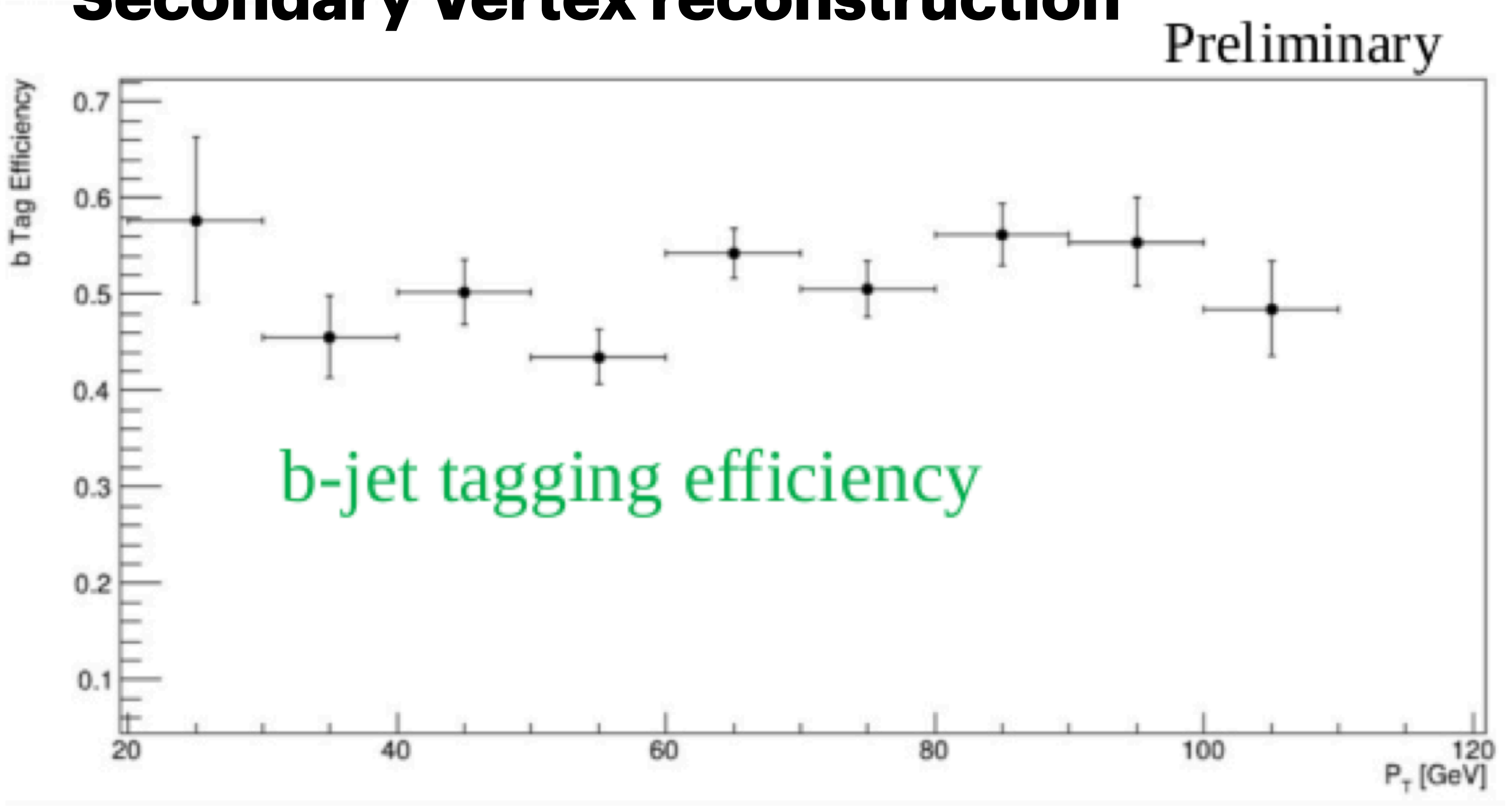
Muon reconstruction



Jet reconstruction



Secondary Vertex reconstruction



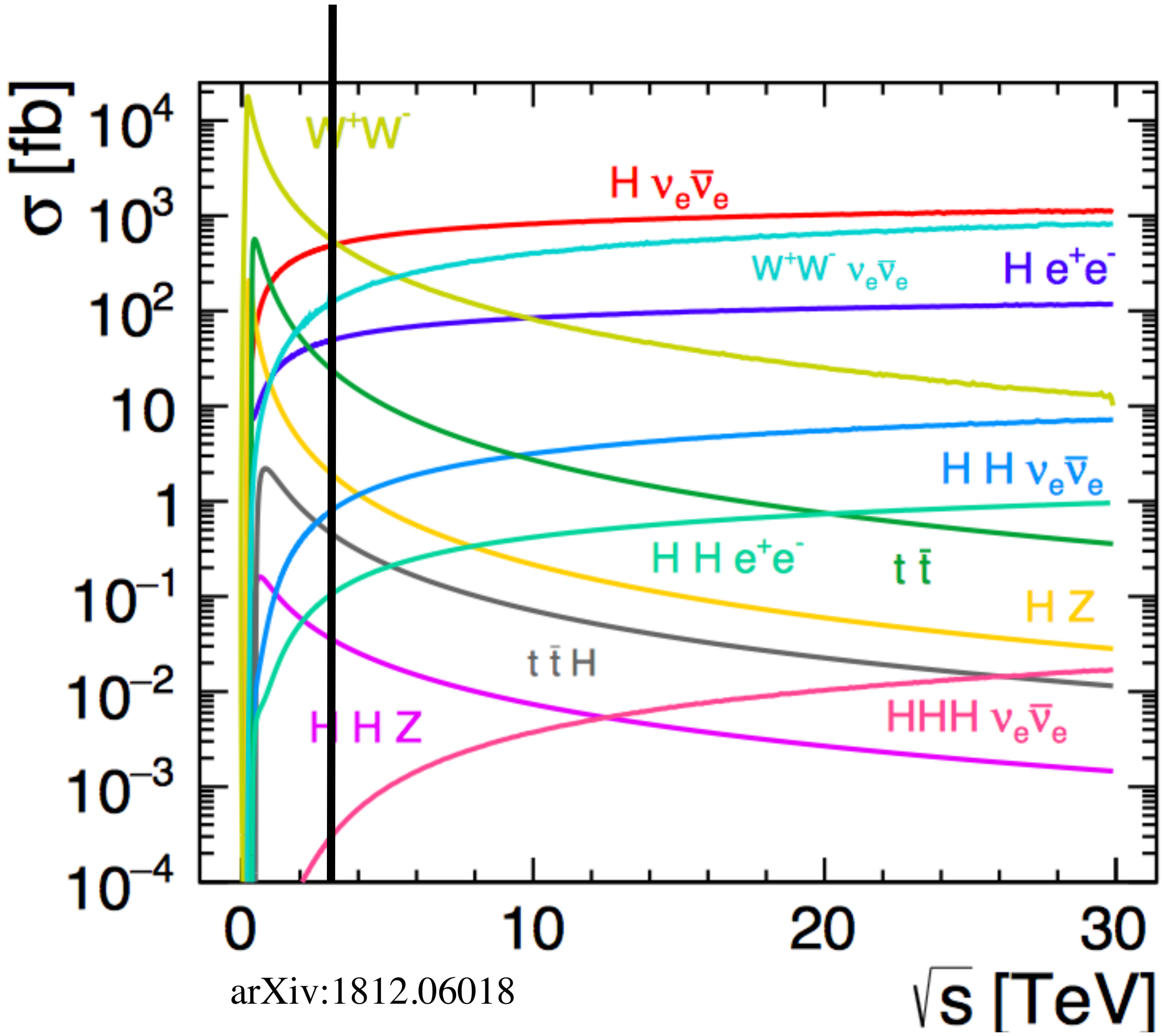
Discussion:
we are still missing photons and electrons, who is going to take care of them?

Where we want to push the performance?

Higgs Boson Physics

Higgs Physics at 3 TeV

- At 3 TeV the **Higgs boson is mainly produced via WW fusion**.
- **Reference integrated luminosity at 3 TeV: 1.0 ab^{-1}**.
- High production cross section, 500k Higgs produced: **it can be considered a Higgs factory**!
- On-going full simulation studies:
  - **H → $b\bar{b}$**
  - **H → μμ**
  - **HH → $b\bar{b}b\bar{b}$**
  - **H → WW***
  - **H → ZZ***
  - **H → $c\bar{c}$**



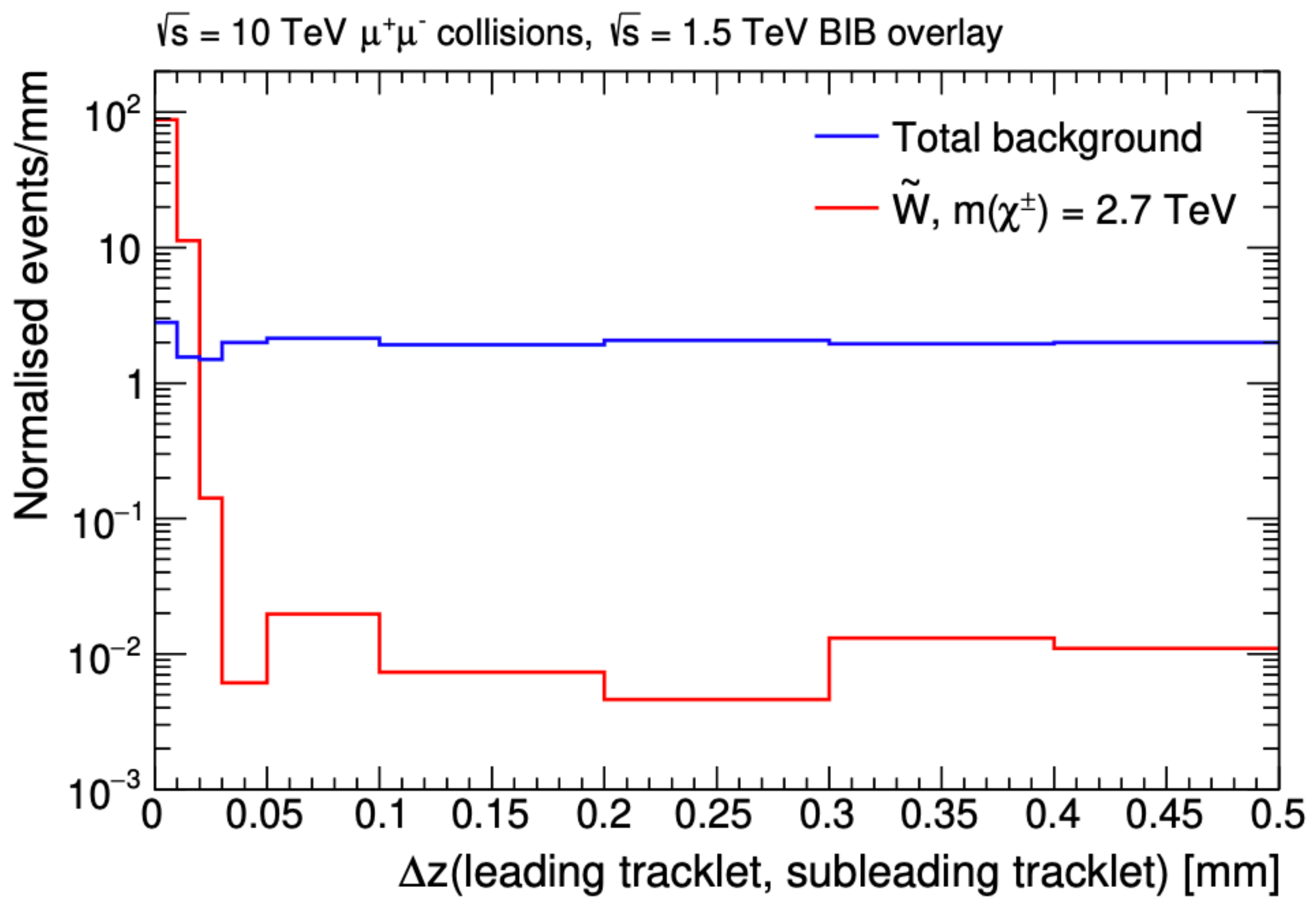
arXiv:1812.06018

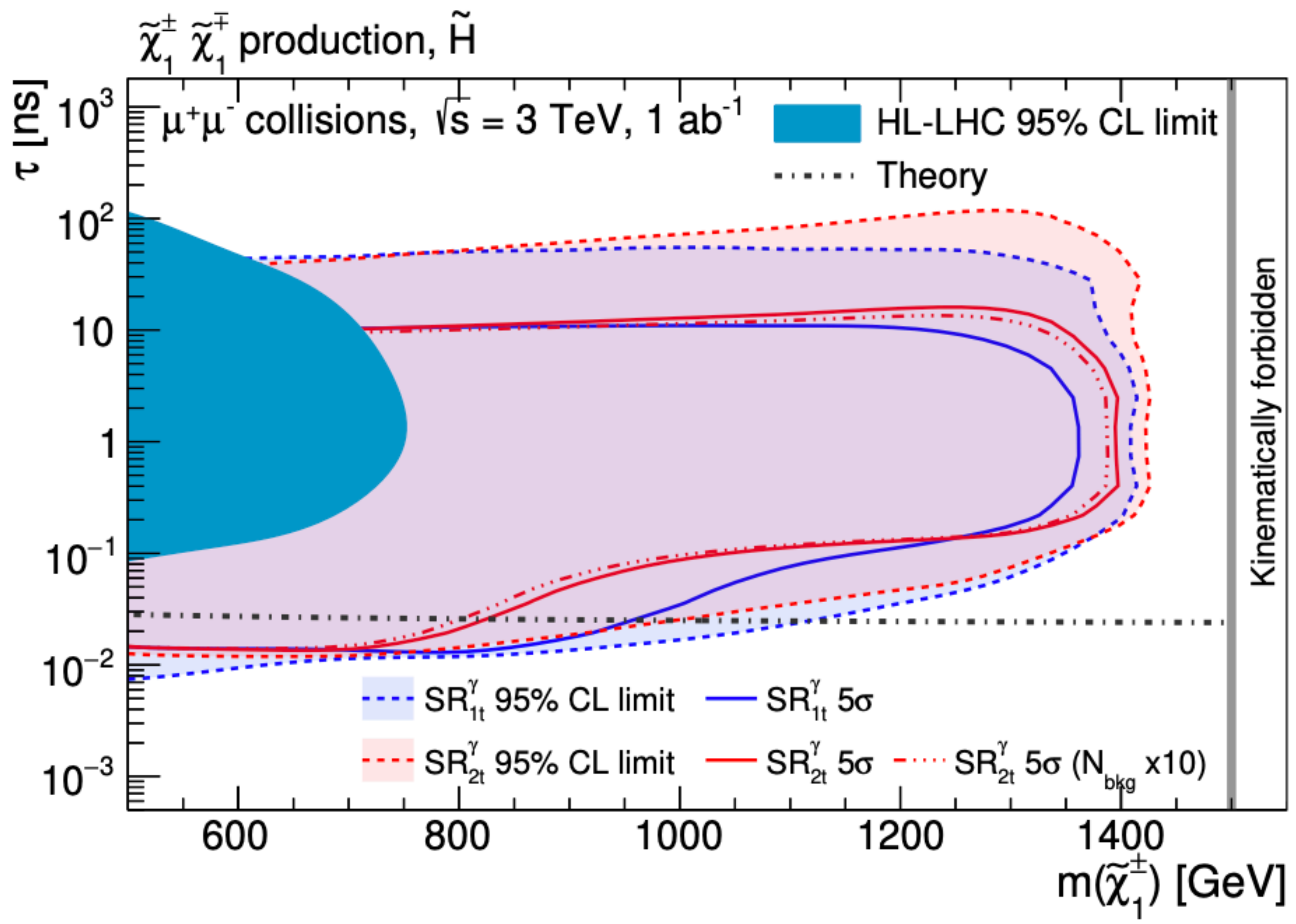
Discussion: which Higgs benchmark channels are still missing for Snowmass?

Beyond the Standard Model

Beyond the Standard Model

- **Disappearing tracks:** the full simulation is used to tune the background rejection requirements, and to determine the efficiencies.





Other full-simulation BSM studies on-going:

Dark Sector searches in muon final states

Dark photons with mono-photon signature

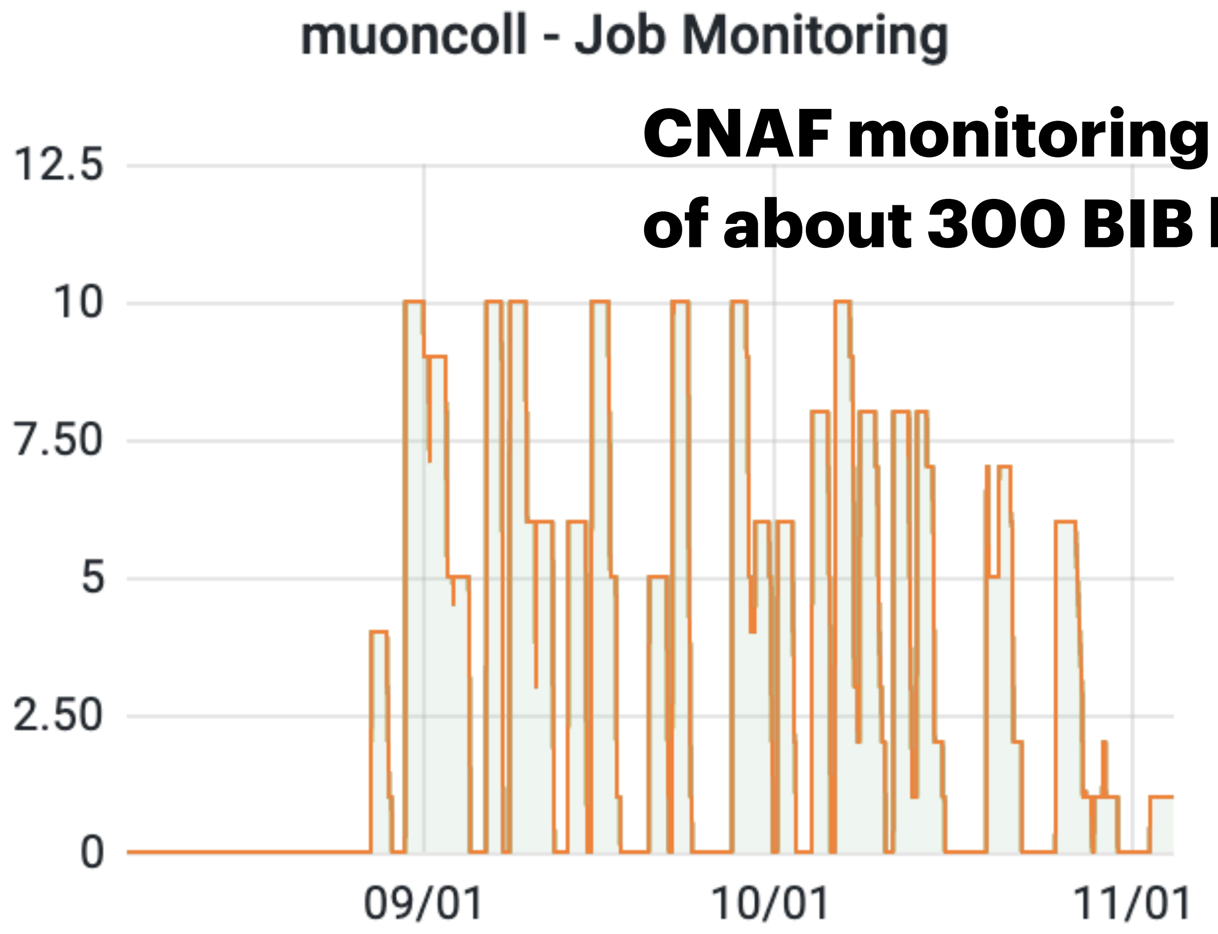
Discussion: other exotic signatures to be studied?

Computing

Computing resources

- **Estimated final goal:**
  - 10k simulated BIB events
  - 100k reconstructed signal+BIB events

- **That corresponds to:**
  - 35k HS06 CPU
  - 600 TB disk space



CNAF monitoring
of about 300 BIB bunch-crossing simulated

What we have received from INFN as RD_MUCOL:

- 10k euro invested in Tier 2/Cloud in Padova
- Access to 6 Computing Element (CE) at CNAF (3k HS06)
- Access to a Storage Element (SE) of 150 TB disk space (13% used) at CNAF
- We have an agreement for using resources at IBISCO Bari: 7k HS06 and 300 TB of disk space

Other resources:

- Cloud-Veneto: 200 VCPU, 740Gb ram and 89TB storage (64% used)
- Local resources

Discussion: do we need other resources?

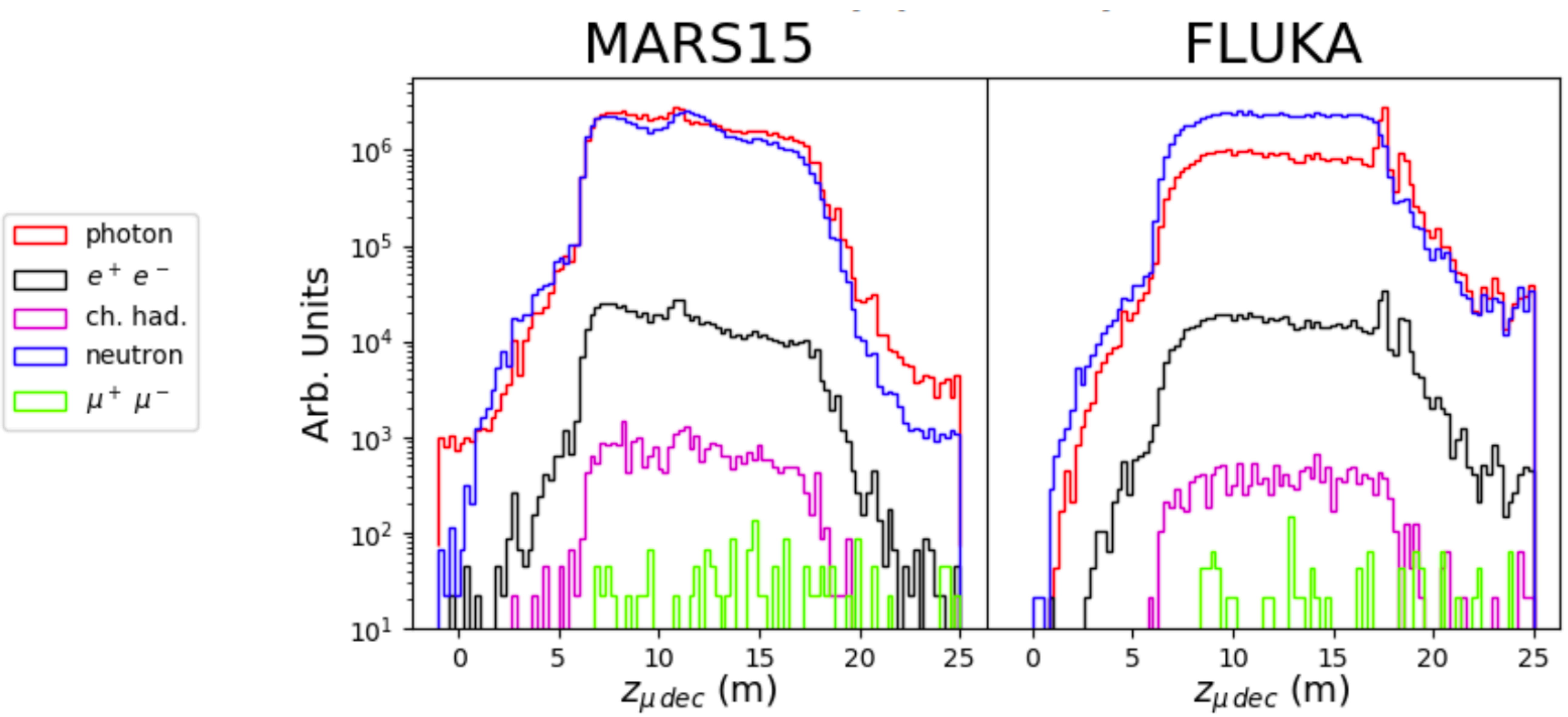
Are we able to access/use IBISCO BARI?

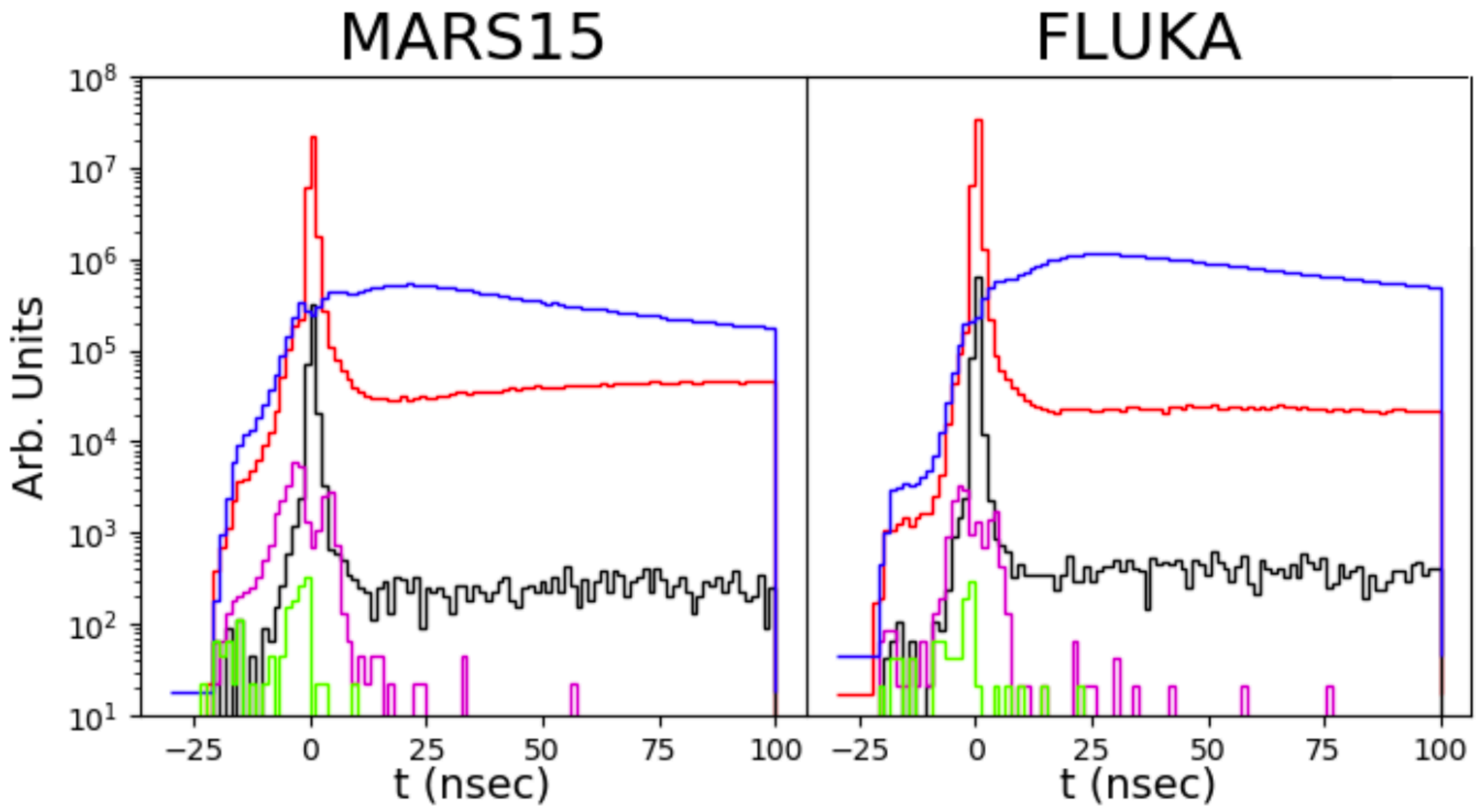
Thanks for your attention!

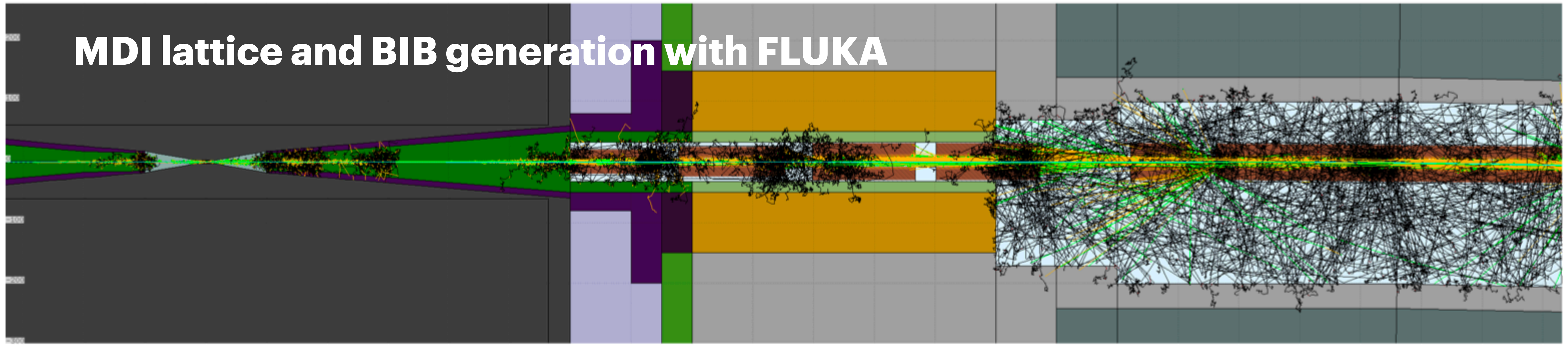
Backup

Beam-induced background (BIB)

- It is produced by the decay in flight of muons, and subsequent interactions.
- Simulated with MARS15 or FLUKA, by considering the machine and the machine-detector-interface lattice.
- BIB simulation is currently available at 1.5 TeV, work on-going for 3 TeV.
- **In this talk a conservative assumption is done**: 1.5 TeV BIB is overlaid with 3 TeV physics. → the BIB yield is expected to reduce at 3 TeV and a dedicated MDI optimization has to be studied for this case.



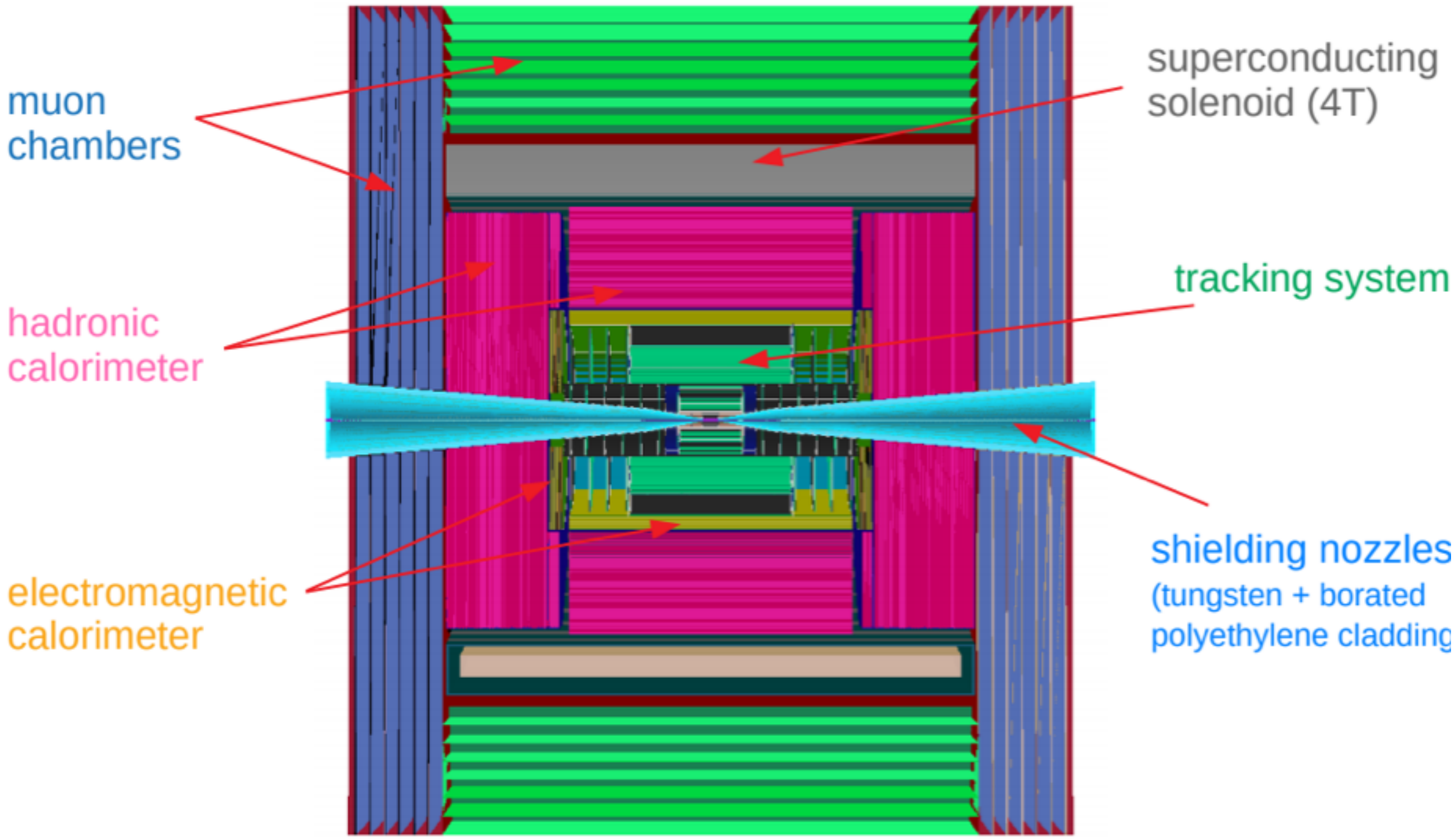




Detector and reconstruction

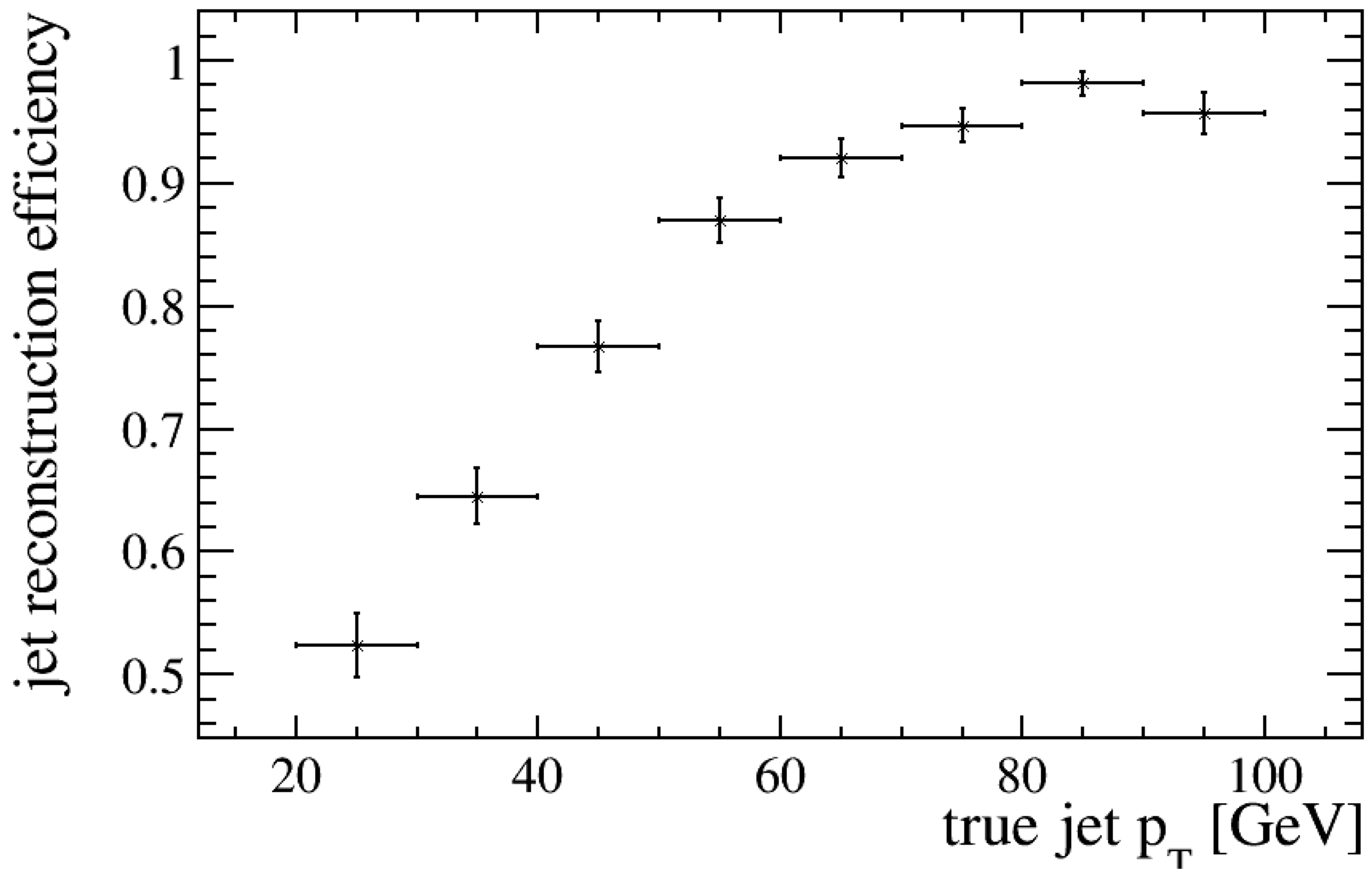
- The **muon collider detector** currently used a modified version of the CLIC detector.
- The interaction of BIB/signal with the detector is simulated with **Geant4**.
- **Reconstruction** in this environment is not trivial:
  - the **high hit multiplicity from the BIB in the vertex detector/tracking modules** produces a significant combinatorial problem;
  - A diffuse BIB background is present in the calorimeters;
  - The nozzles, that are fundamental for BIB mitigation, reduce the acceptance in the forward region.

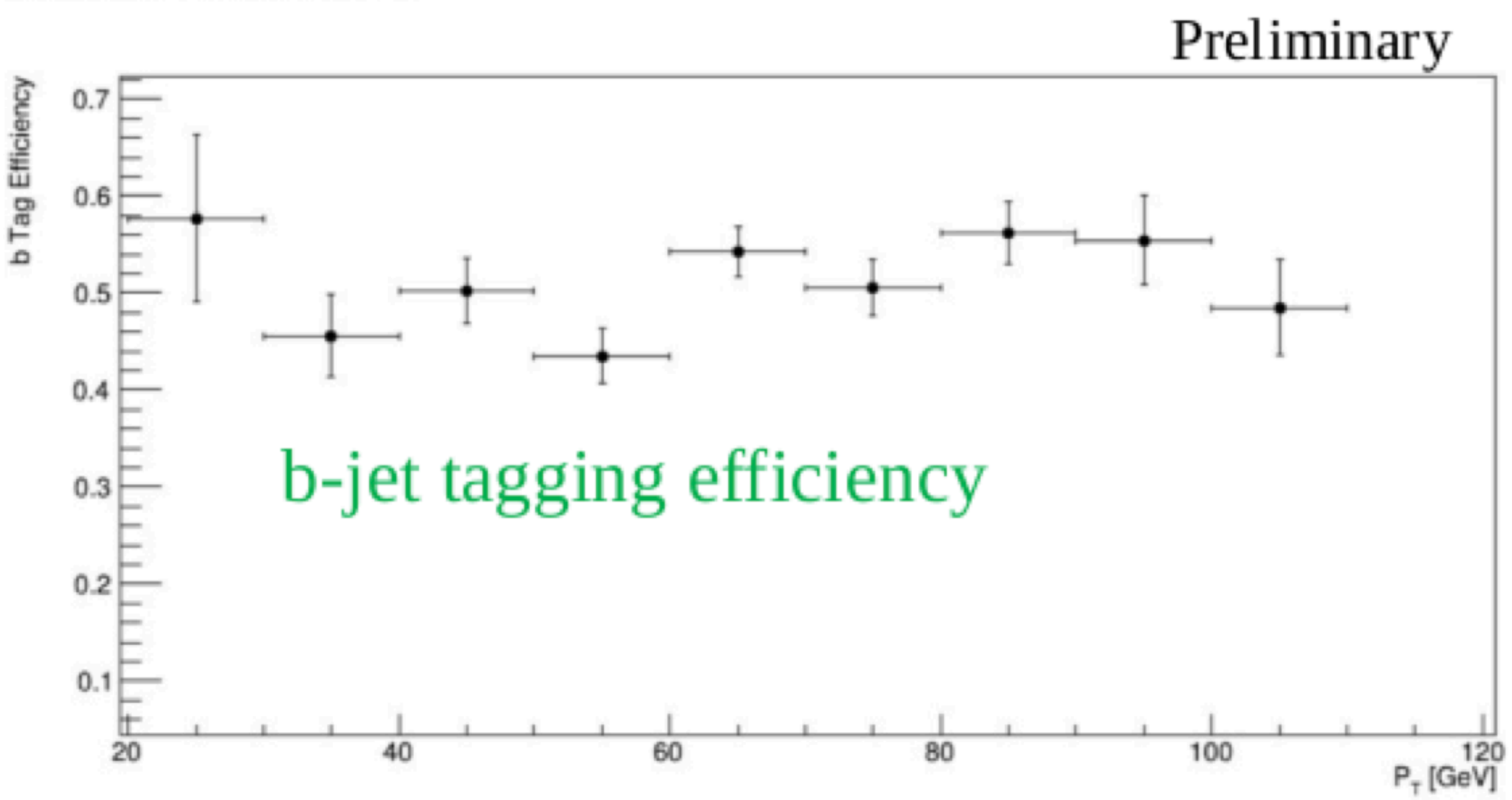
- **We have to re-think our reconstruction strategies, but today you are going to see that physics measurements are definitely possible!**



$H \to b\bar{b}$

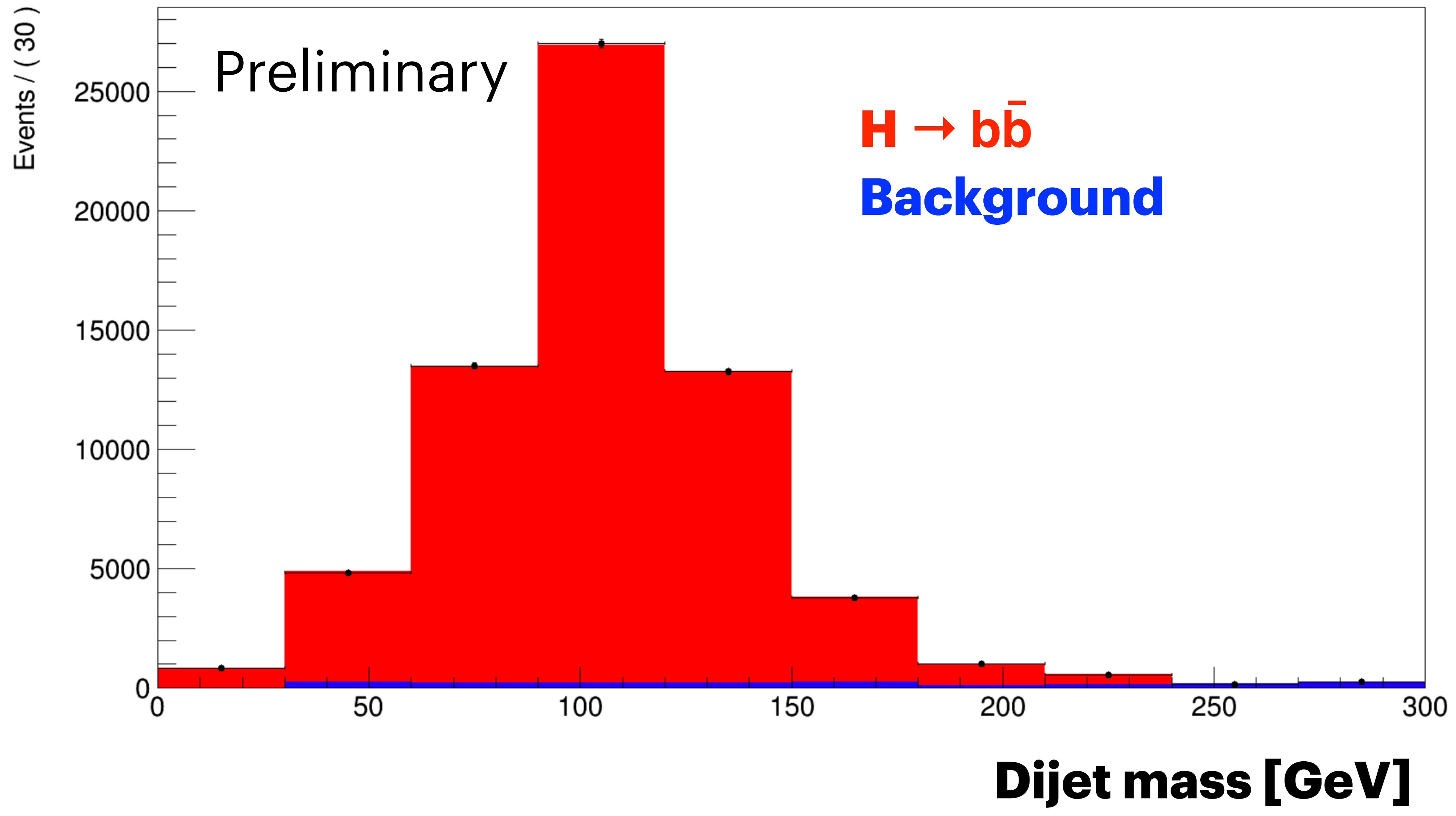
- Key ingredients for the measurement of the $H \to b\bar{b}$ process are the **jet reconstruction** and the **b-tagging**.
- A **particle flow algorithm with a BIB subtraction technique** is used for jet reconstruction, but there is a lot of room for optimization.
- **A secondary-vertex reconstruction algorithm is used to tag jets**. In order to have a negligible mis-identification (from BIB combinatorial) the efficiencies are kept low, but we are confident that **we can significantly improve by using advanced algorithms** (e.g. machine learning).





$H \to b\bar{b}$

- Electroweak/multi-jet background is obtained at leading-order.
- **High signal purity is found**: 49000 $H \to b\bar{b}$ signal and 1300 background events are expected in the [0,300] GeV invariant mass window and in the $|\eta(\text{jet})|<2.5$, $p_T(\text{jet})>20$ GeV fiducial region.
- In comparison with the CLIC case, **we do not have the multi-jet background produced by e-γ and γ-γ interactions, that is negligible at the muon collider**.



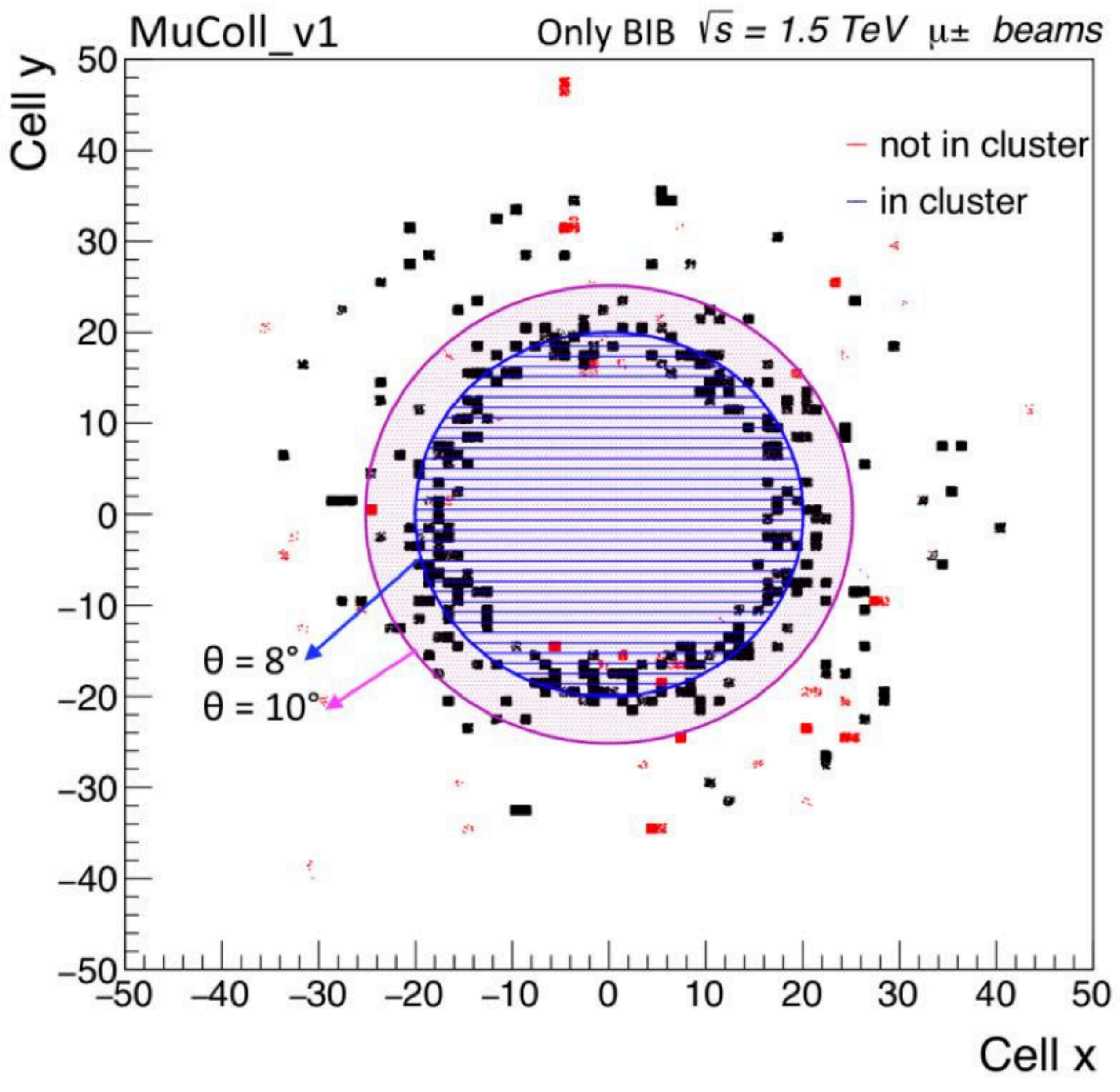
Backgrounds

Process
$\mu^+\mu^- \to \gamma^*/Z \to q\bar{q}$
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to q\bar{q}$ +X
$\mu^+\mu^- \to \gamma^*/Z\gamma \to q\bar{q}\gamma$

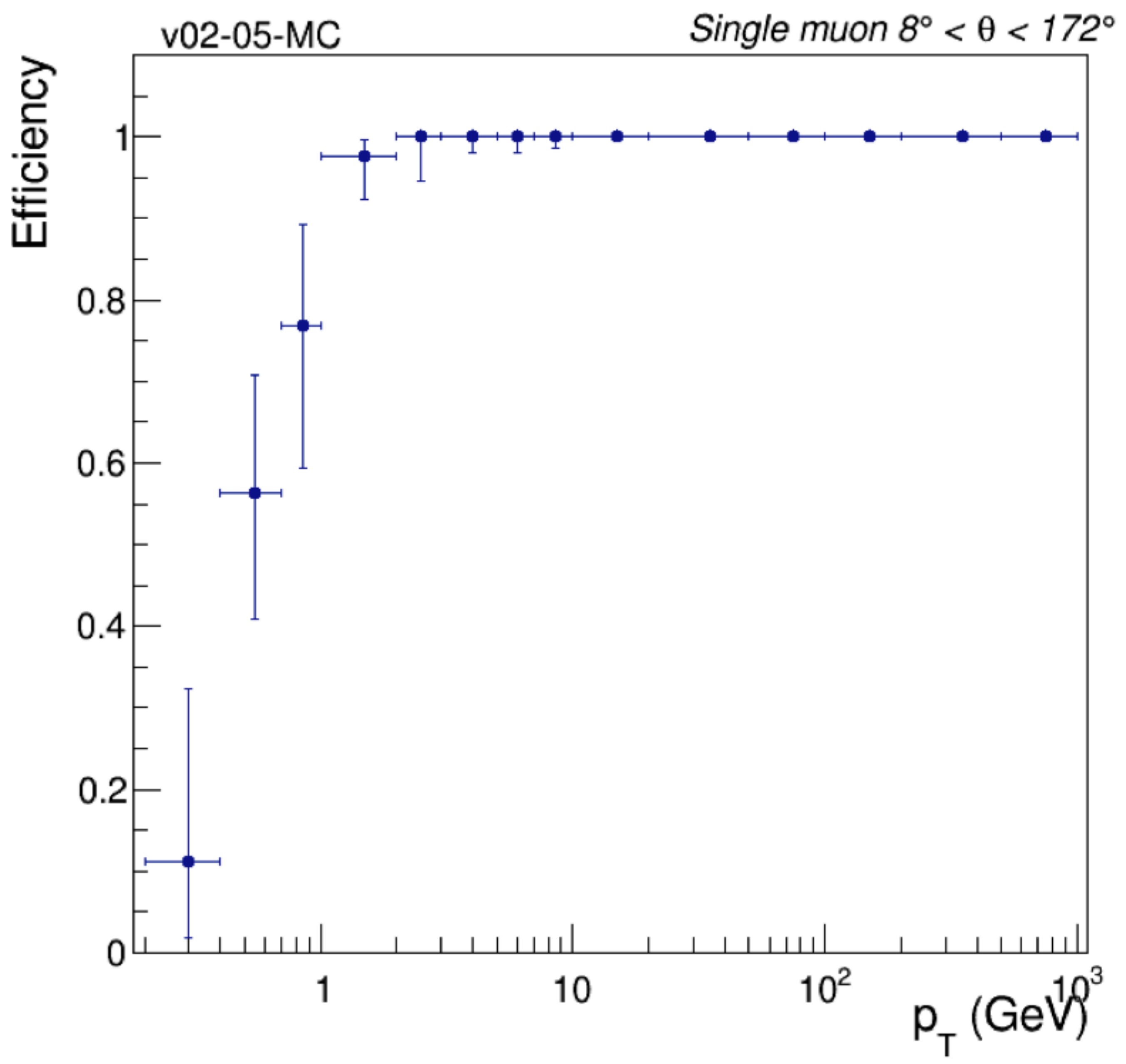
- The expected (preliminary) **statistical uncertainty on $\sigma(\mu\mu\to H)\cdot BR(H\to b\bar{b})$ is 0.4% at 1.0 ab^{-1}.** CLIC has 0.3% [*Eur. Phys. J. C 77, 475 (2017)*].
- In order to determine the sensitivity on the g_{Hbb} coupling, the measurement of the H→WW* decay is necessary (on-going).

H → $\mu^+\mu^-$

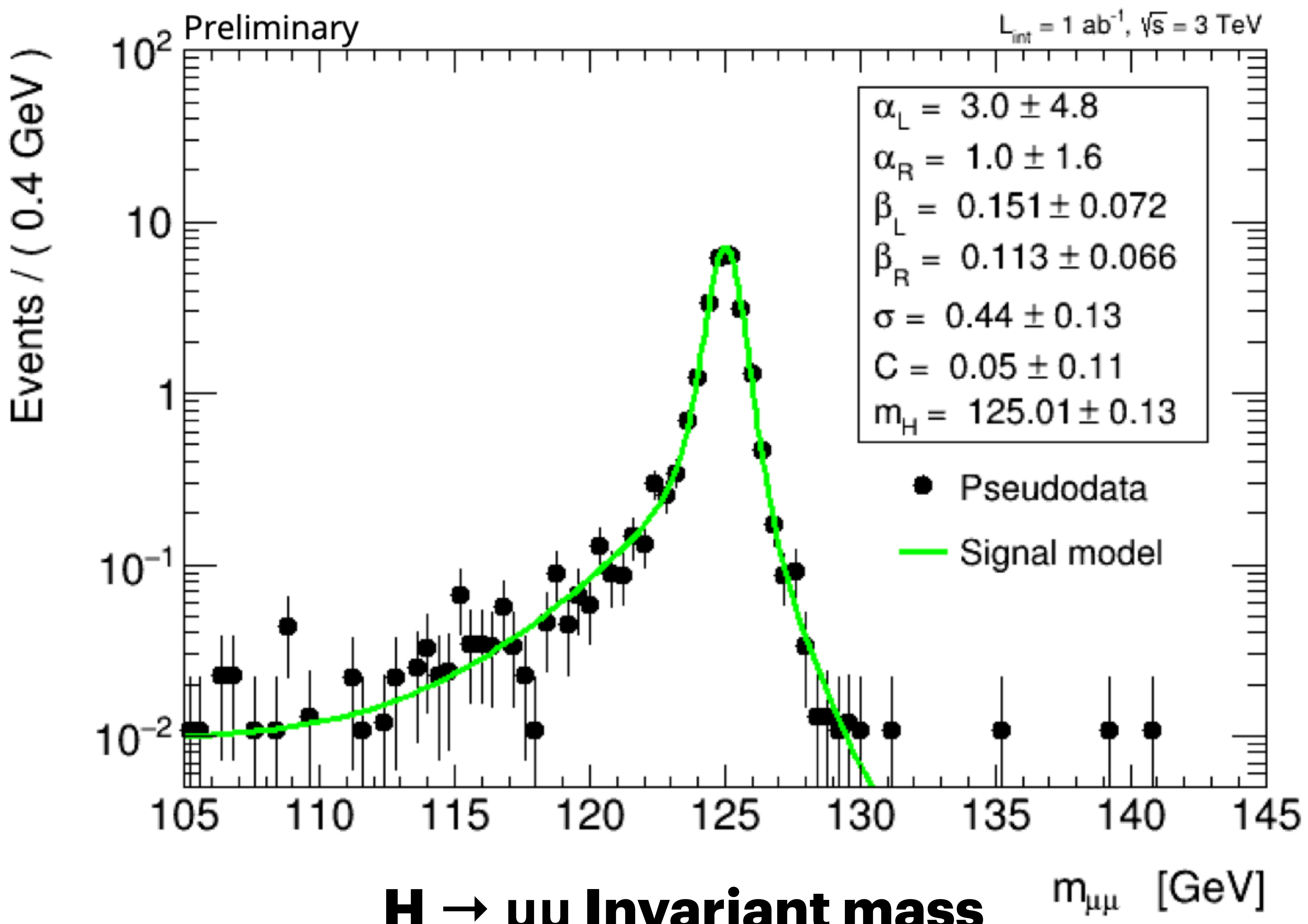
- Most of the BIB hits in the Muon System are **located near the nozzles**.
- A cut on the track θ (angle wrt beam axis) can reduce the BIB combinatorial to a negligible level: **10° < θ < 170°**
- **Excellent muon momentum resolution leads to a precise H → μμ mass reconstruction**.



BIB hits distribution in Muon System



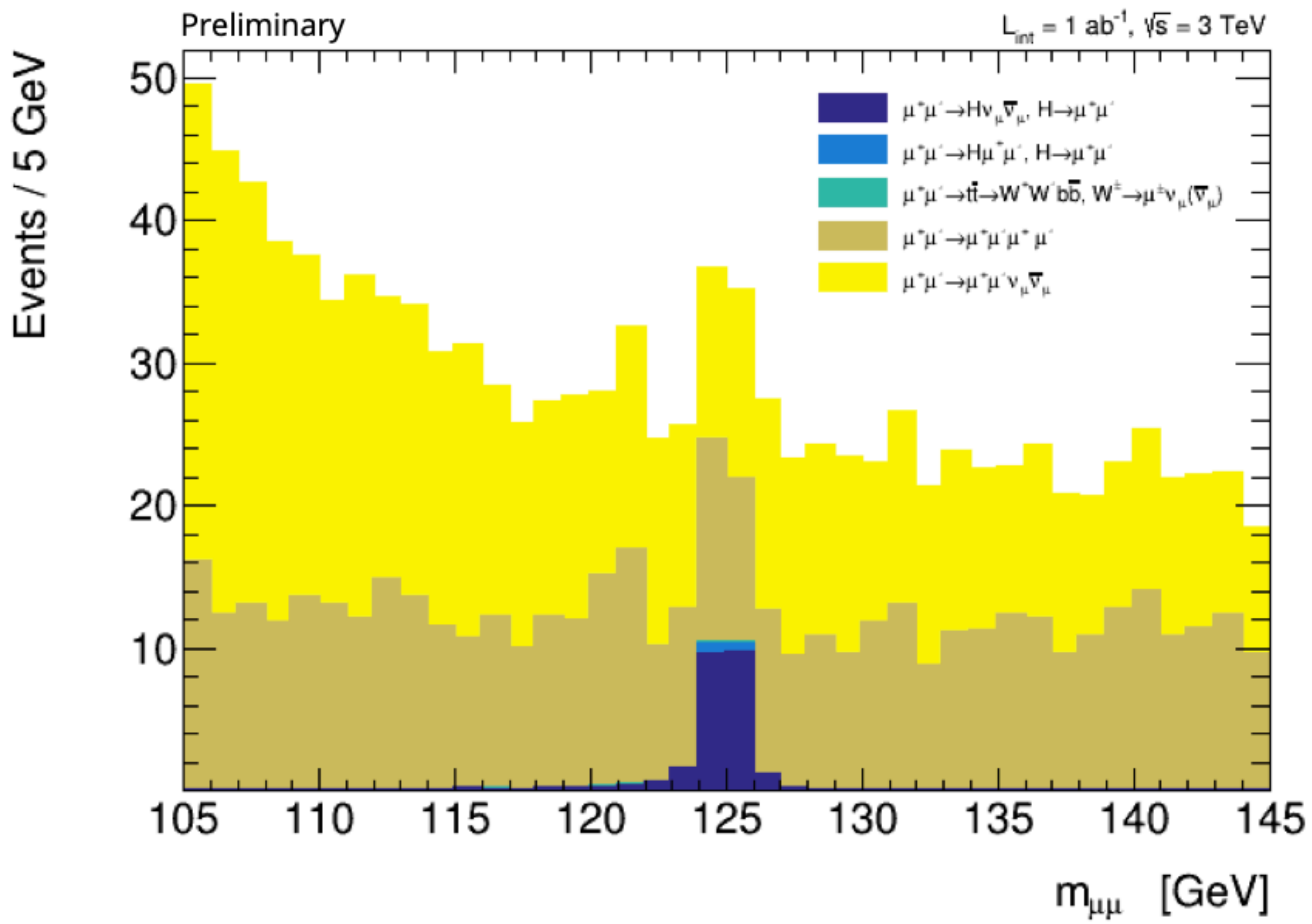
Efficiency for muon reconstruction

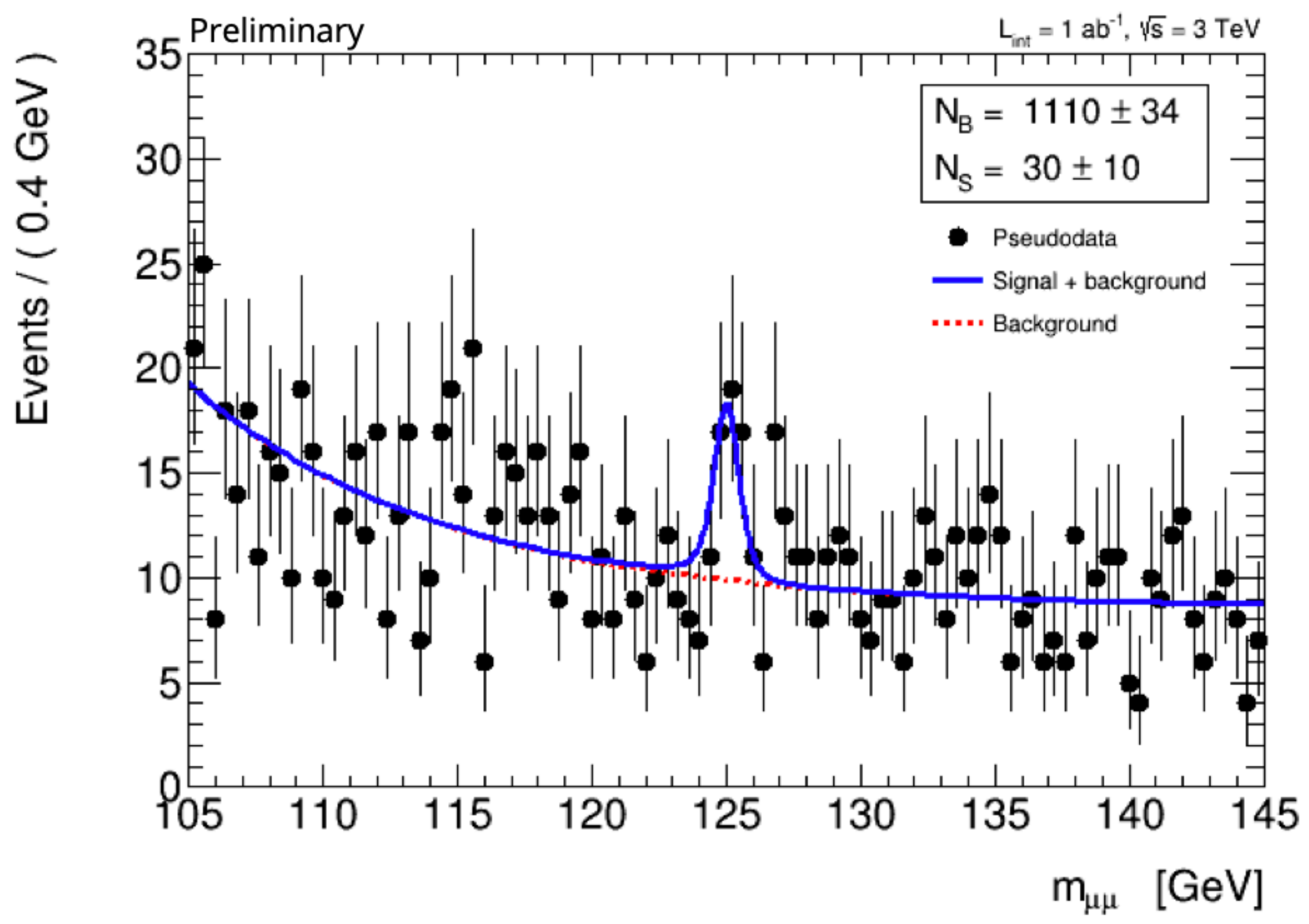


H → μμ Invariant mass

H → $\mu^+\mu^-$

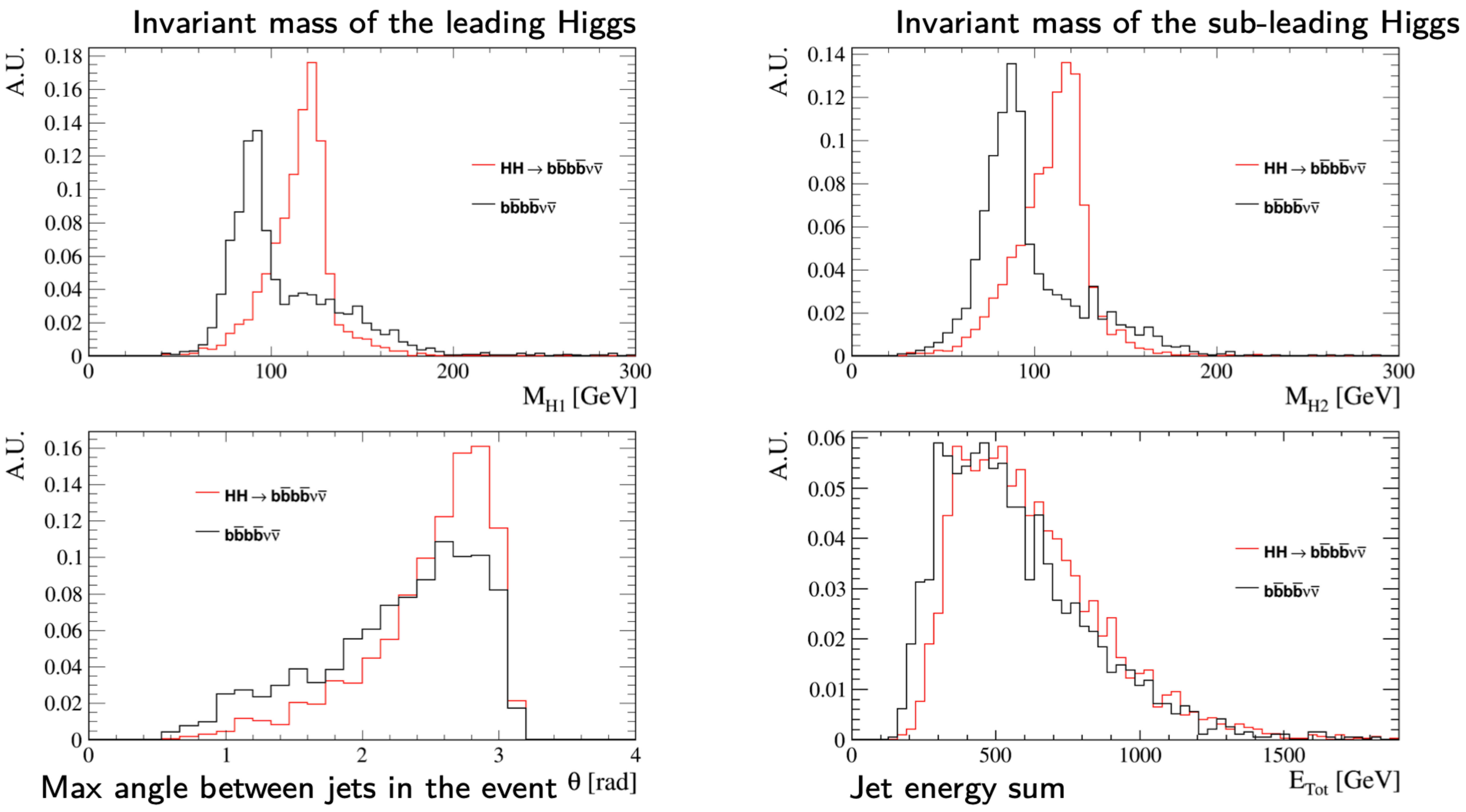
- Backgrounds are evaluated at NLO with Madgraph: 26 signal and 1100 background events are expected.
- Main background sources are **μμ → μμνν and partially reconstructed μμ → μμμμ (one or more muons may be lost in the nozzles region)**.
- The uncertainty on the **H→μμ** cross section is obtained with a fit to the invariant mass.
- Preliminary estimated statistical uncertainty on **σ(μμ→H)•BR(H→μμ)** is **38% at 1.0 ab^{-1}**. **In particular we can improve the acceptance by tuning the nozzle angle specifically for the 3 TeV case**.





HH and trilinear coupling

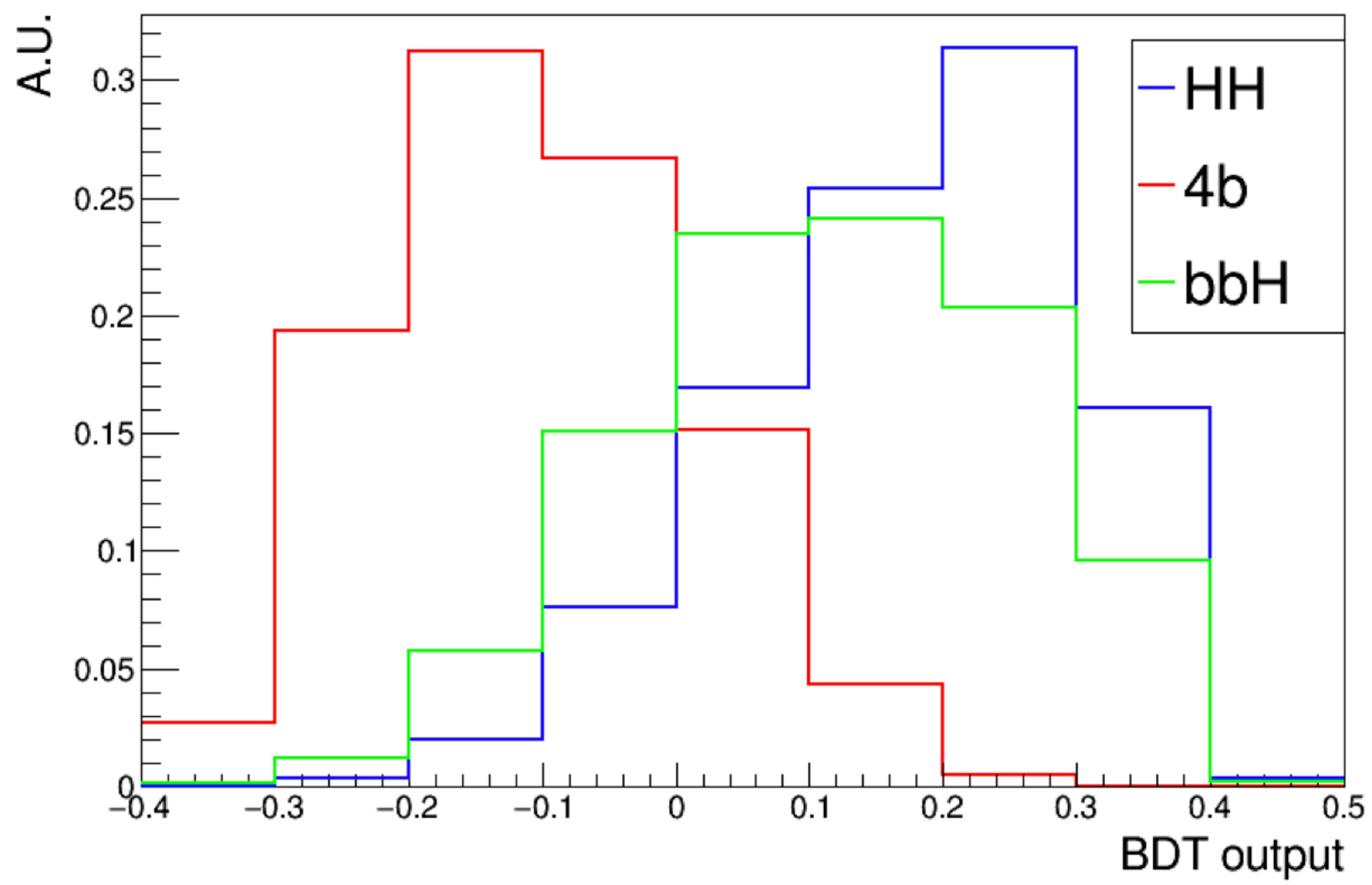
- **μμ → HHνν** is reconstructed in the four b-jets final state.
- |η(jet)|<2.5, p_T(jet)>20 GeV fiducial region, two SV-tag out of four jets are required.
- Signal and backgrounds are generated at NLO with WHIZARD.
- Irreducible backgrounds are $b\bar{b}b\bar{b}$ and H(→ $b\bar{b}$)$b\bar{b}$
- Kinematical variables can be used to separate the signal from the background.



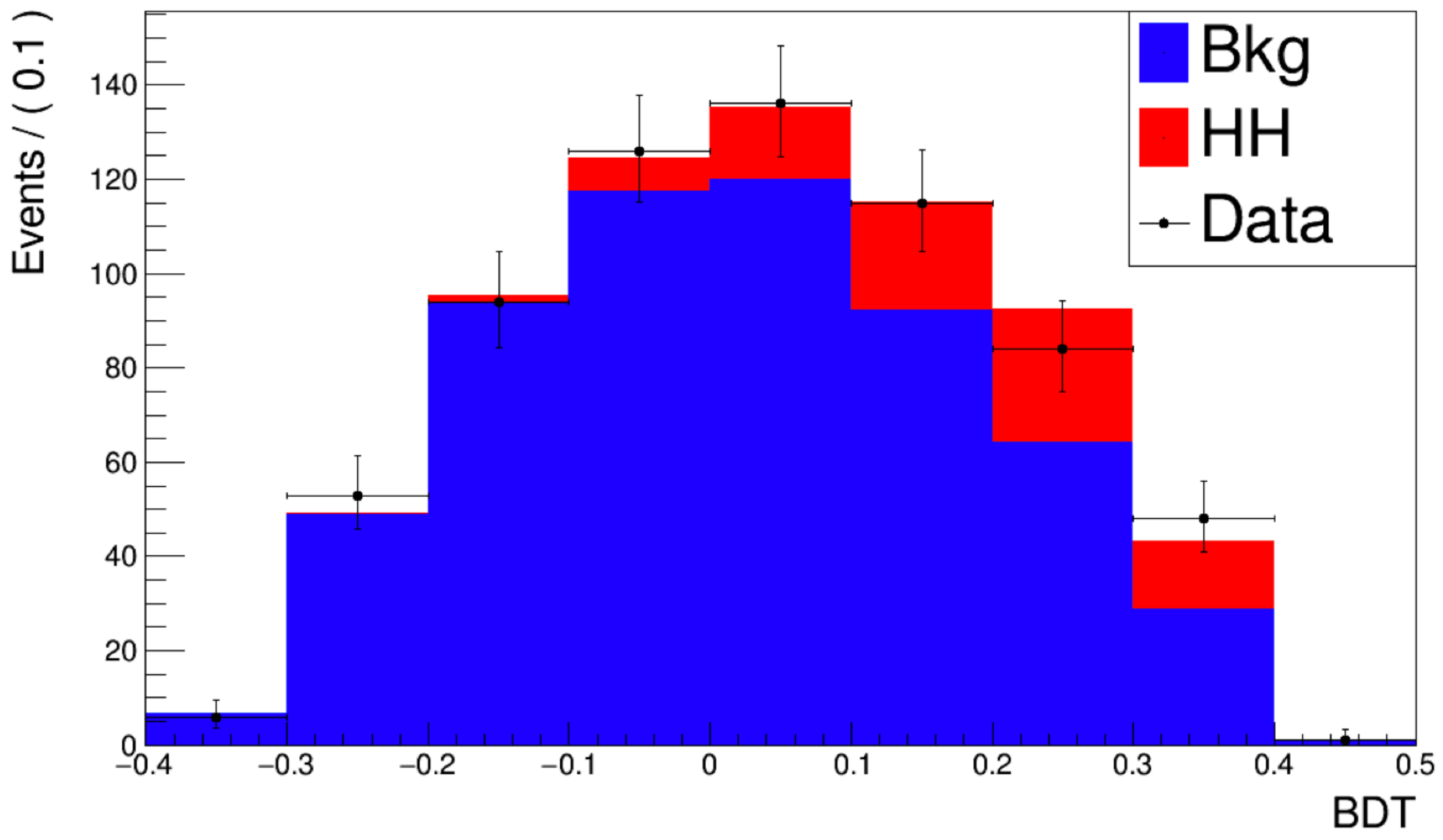
HH and trilinear coupling

- 50 HH and 432 background events are expected with 1 ab^{-1}.
- A boosted decision tree (BDT) is trained to separate the signal from the background.
- A fit to the BDT output is performed to determine the cross section uncertainty.
- A preliminary statistical uncertainty on **$\sigma(\mu\mu \rightarrow HH\nu\nu) \cdot BR(HH \rightarrow b\bar{b}b\bar{b})$** of about **30%** is found.

Preliminary



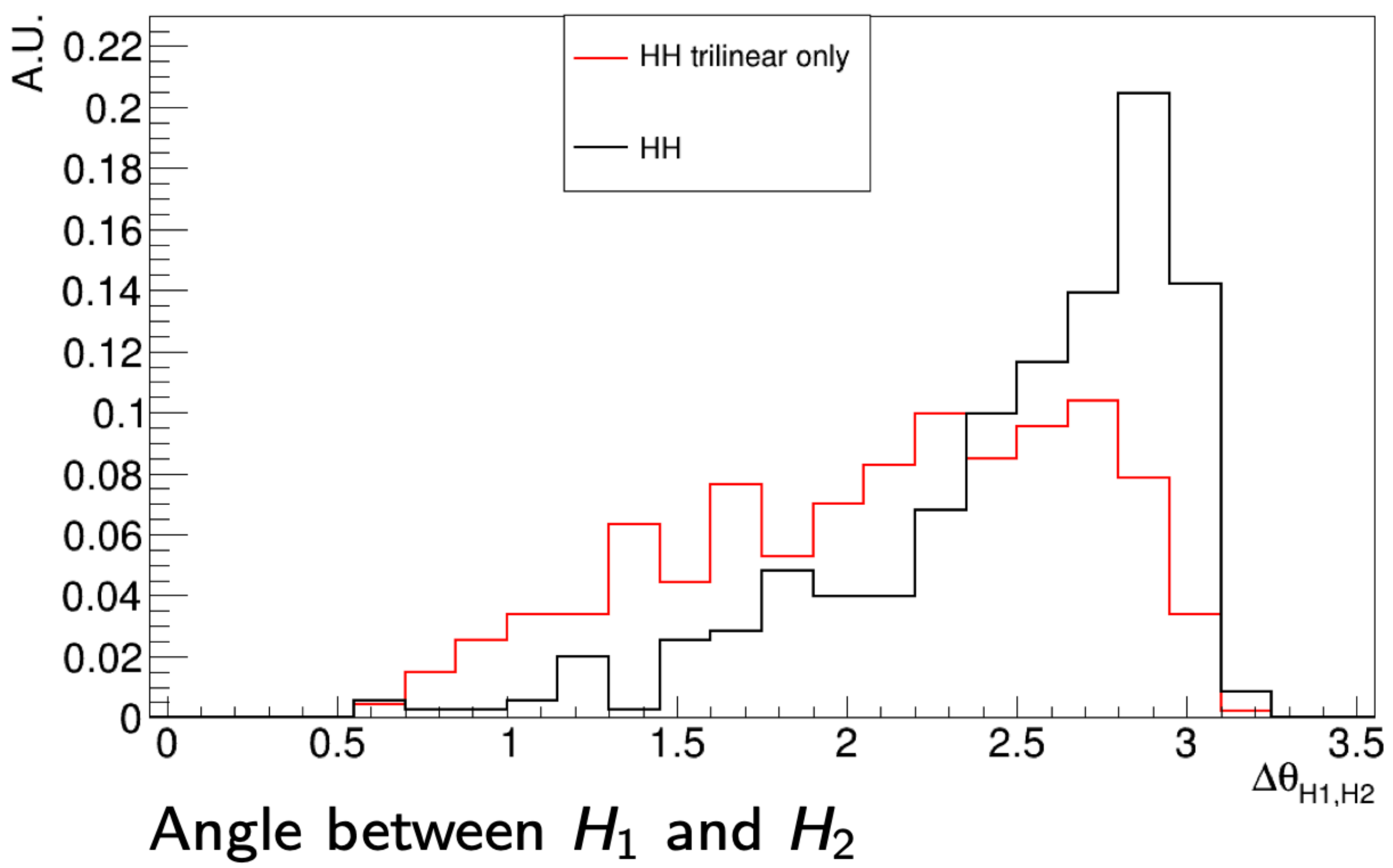
Preliminary

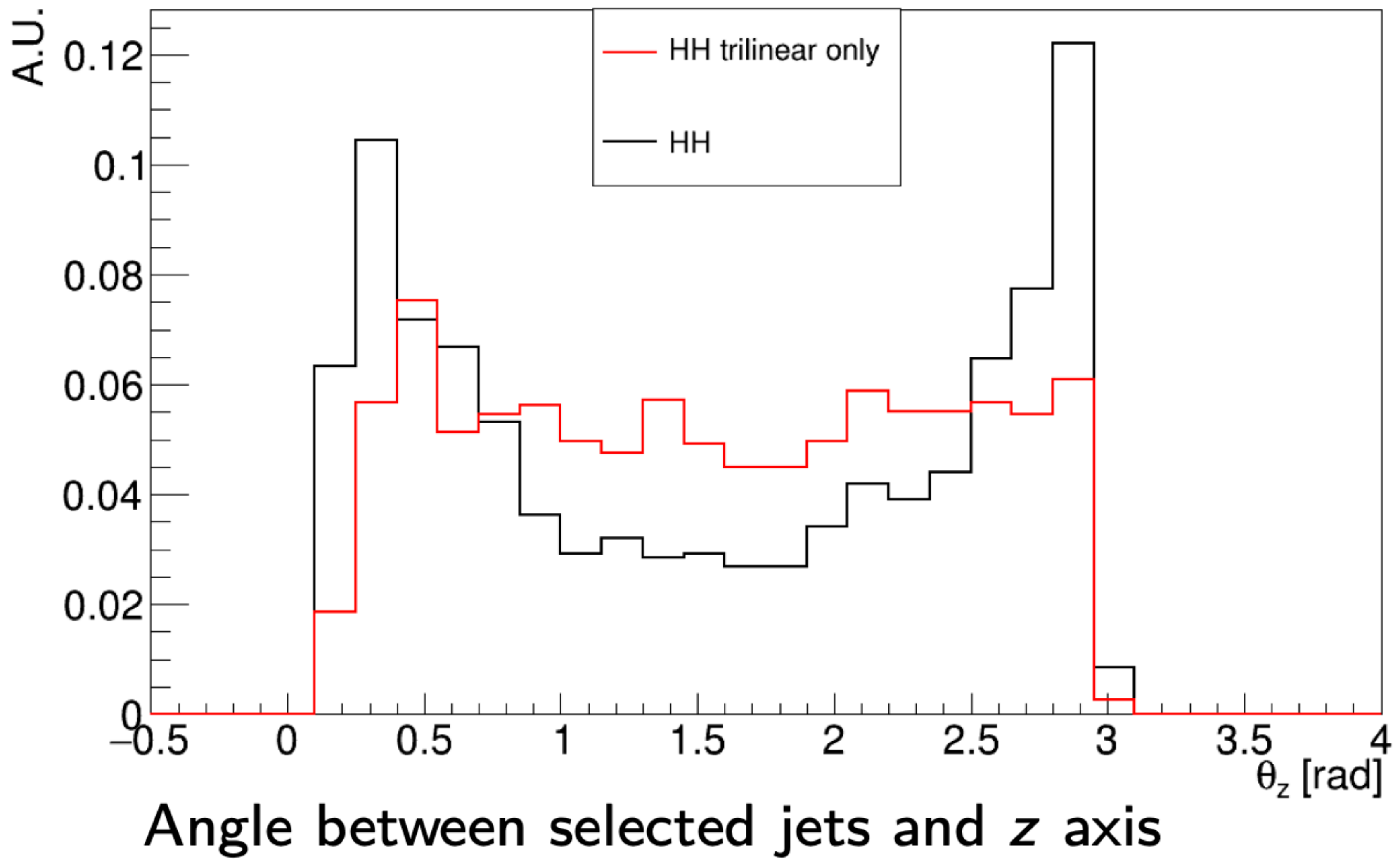


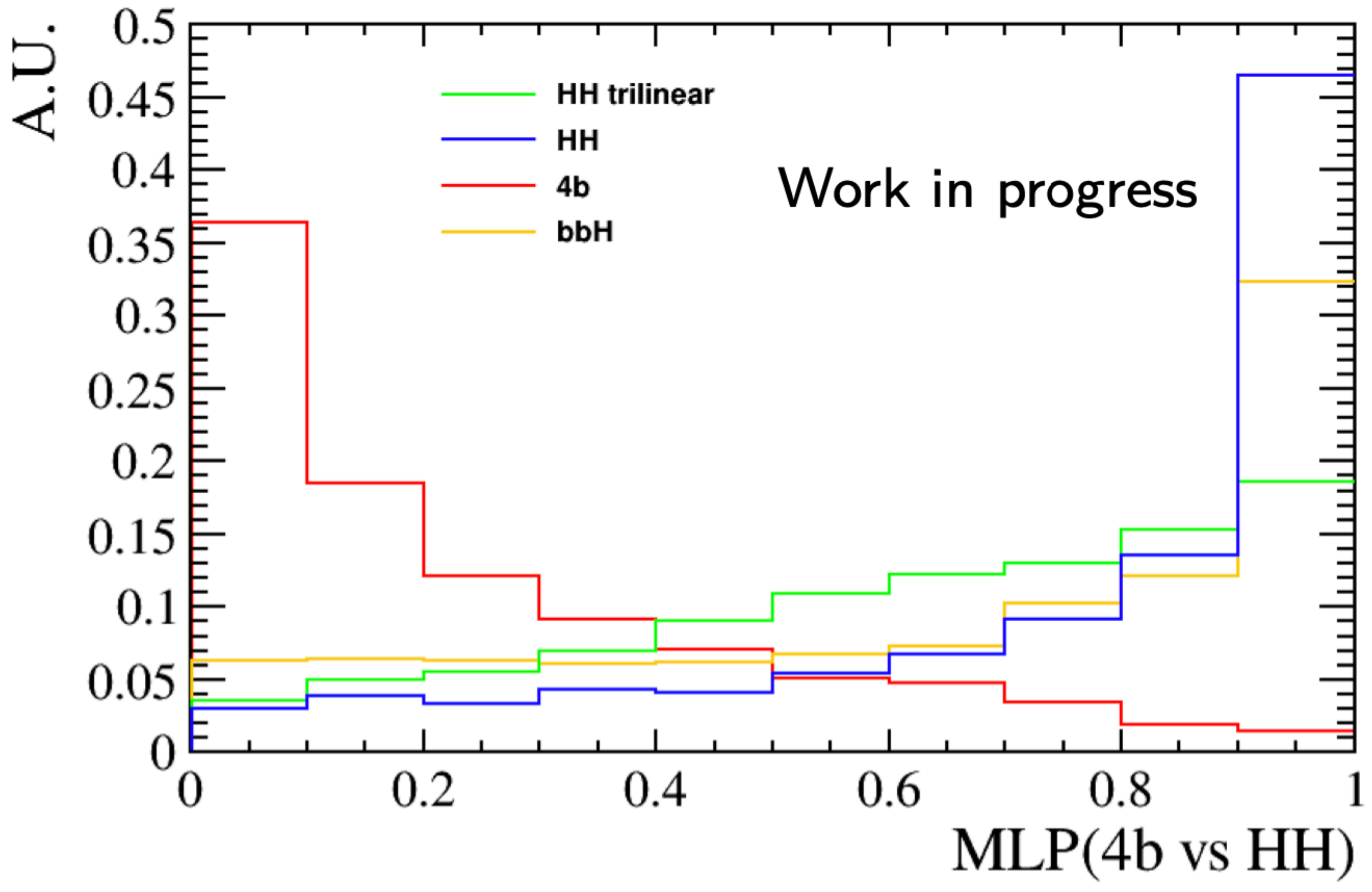
HH and trilinear coupling

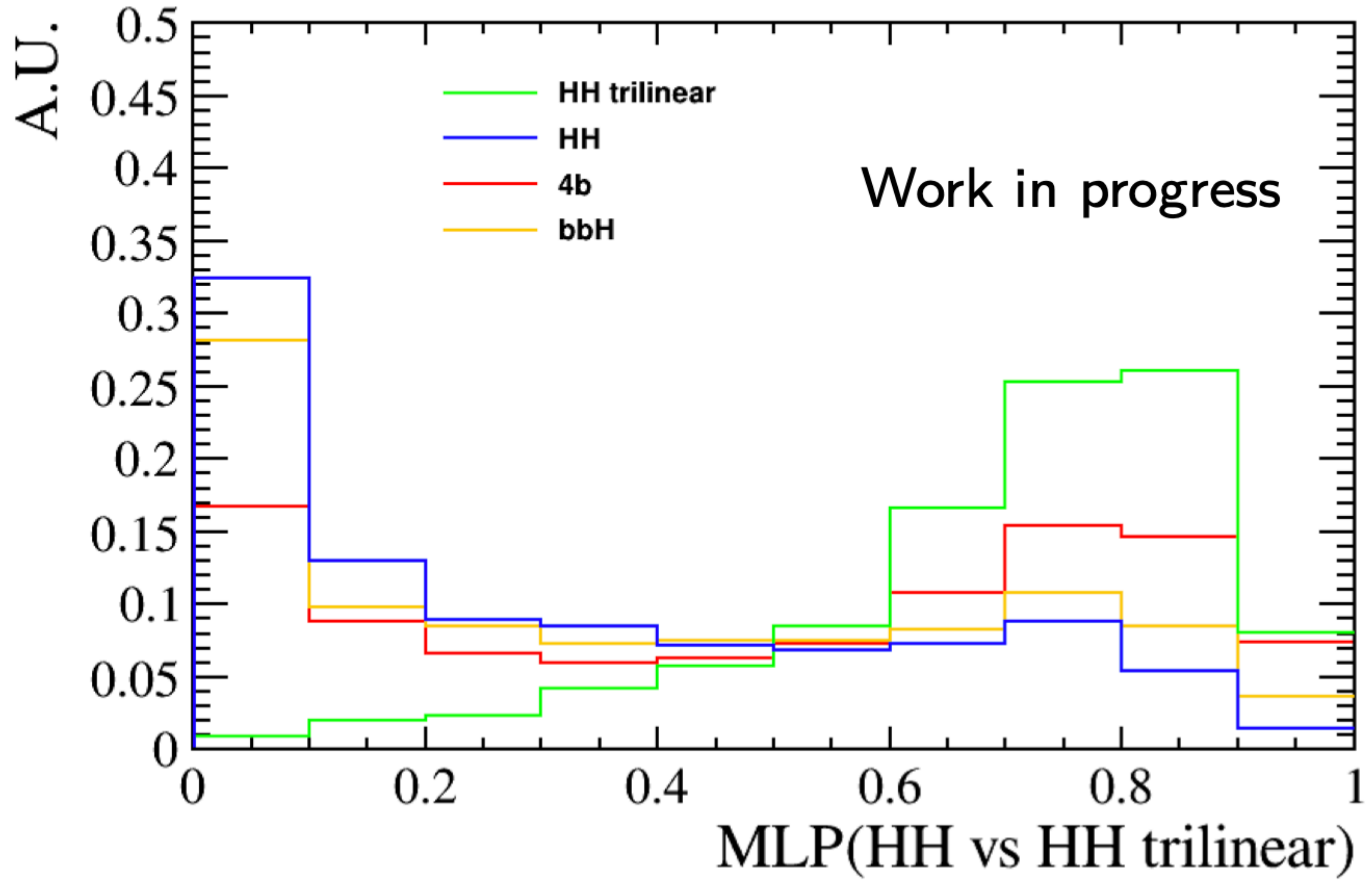
- The kinematic of the HH process is also used to **separate the HH from the HH trilinear-only contribution**.

- Two multi-layer perceptrons are trained: **MLP (4b vs HH)** and **MLP(HH vs HH trilinear)**.



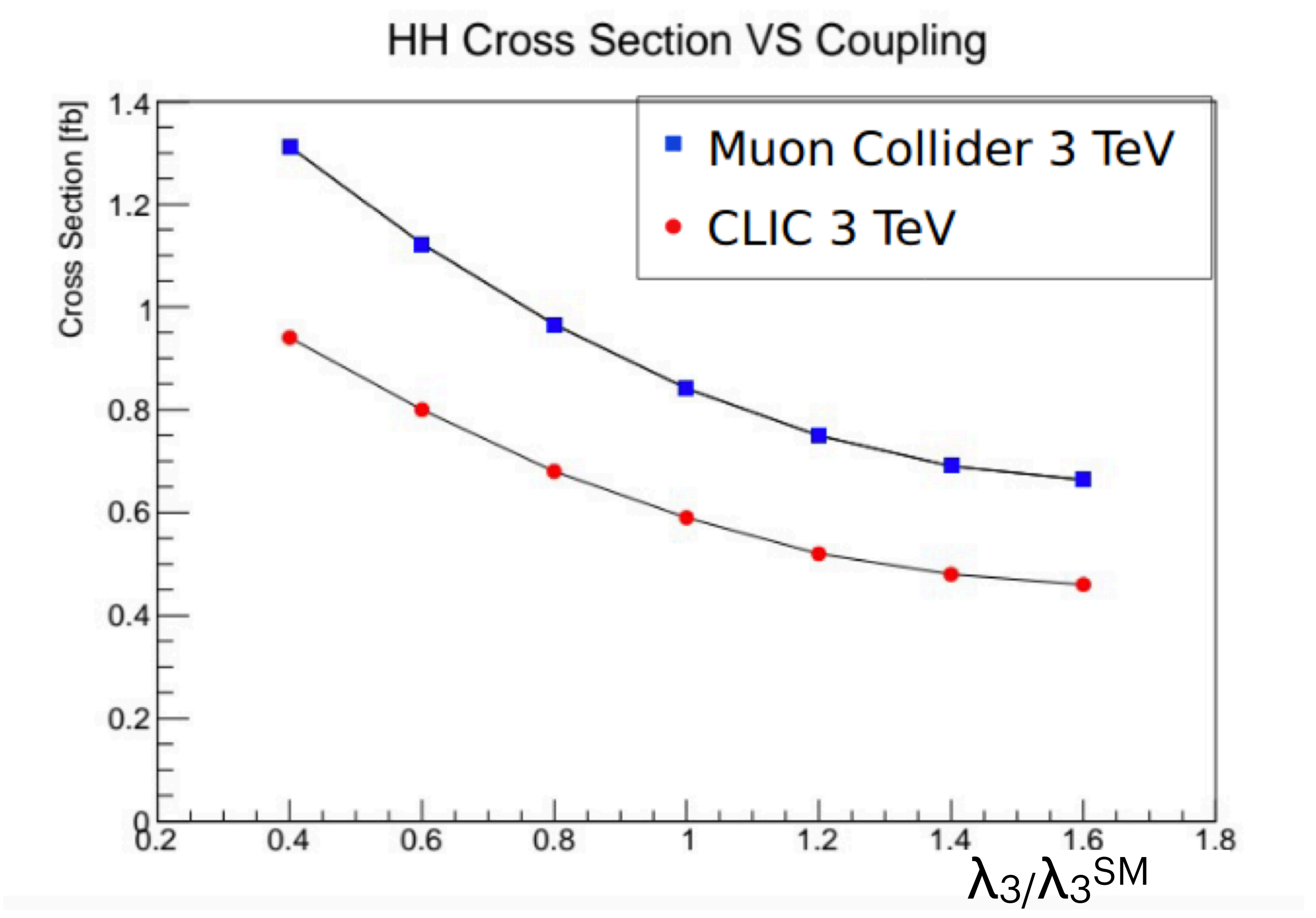


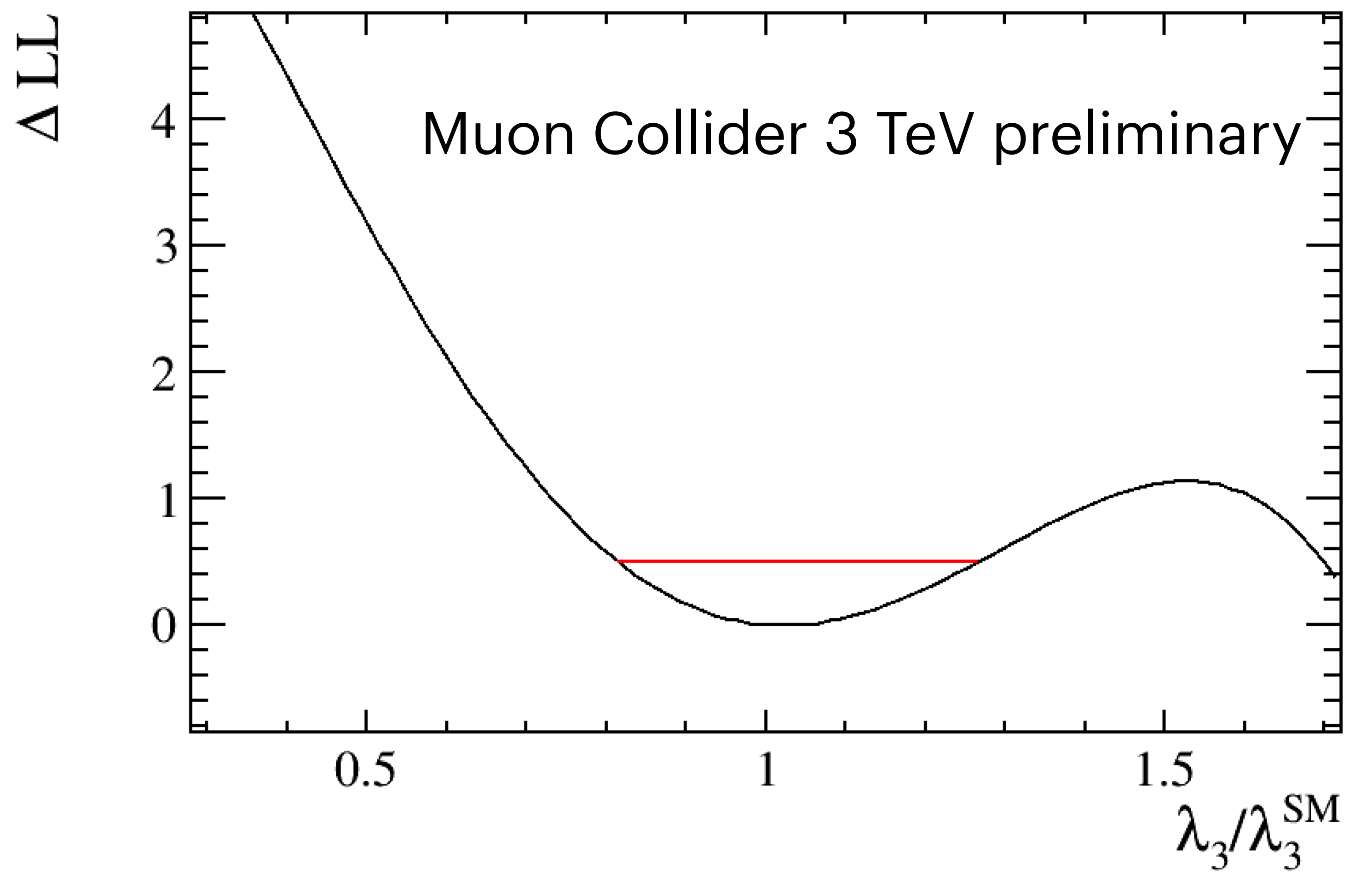




HH and trilinear coupling

- A likelihood technique is used to determine the sensitivity on λ_3.
- The MLPs templates obtained with different coupling hypotheses are compared with pseudo-experiments.
- The preliminary result **on the λ_3 statistical uncertainty is** of about **20% at 1.0 ab^{-1}** (at 68% CL).
- CLIC has [-8%,+11%] at 68% CL with 5 ab^{-1} [*Eur. Phys. J. C 80, 1010 (2020)*].
- The two results are compatible considering the statistical scaling.





The result is expected to improve with an optimized jet reconstruction and b-tagging, overlay with 3 TeV BIB (instead of 1.5 TeV), dedicated BIB mitigation strategy for 3 TeV

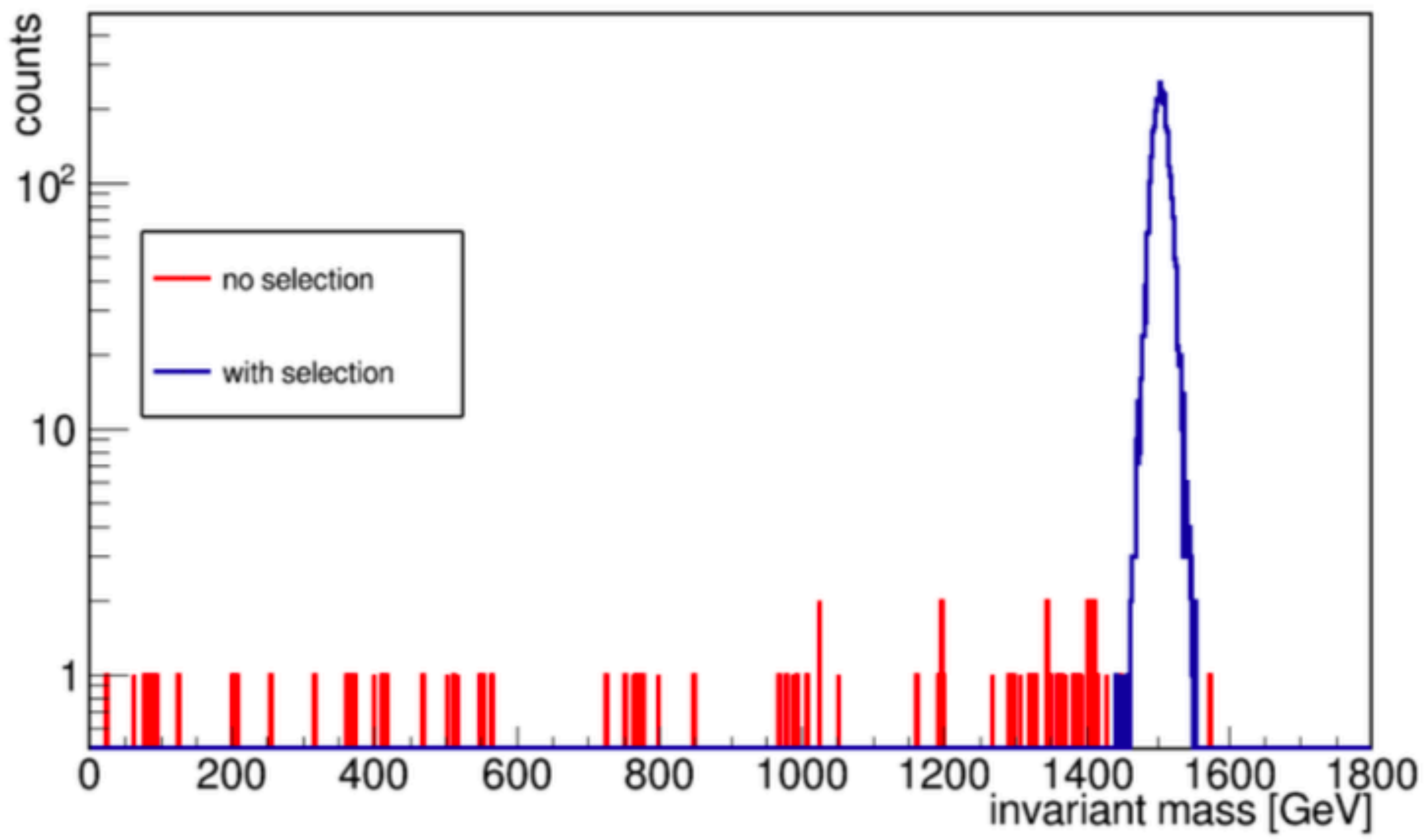
Luminosity measurement

μμ → μμ Bhabha events counting

$$\frac{\Delta L_{int}}{L_{int}} = \sqrt{\frac{\Delta N_{ev}{}^2}{N_{ev}{}^2} + \frac{\Delta \sigma_B{}^2}{\sigma_B{}^2}} = \left(\frac{\Delta N_{ev}}{N_{ev}}\right) \oplus \left(\frac{\Delta \sigma_B}{\sigma_B}\right)$$

$$\frac{\Delta N_{Bhabha}}{N_{Bhabha}} = \frac{1}{\sqrt{N_{Bhabha}}} = 0.002$$

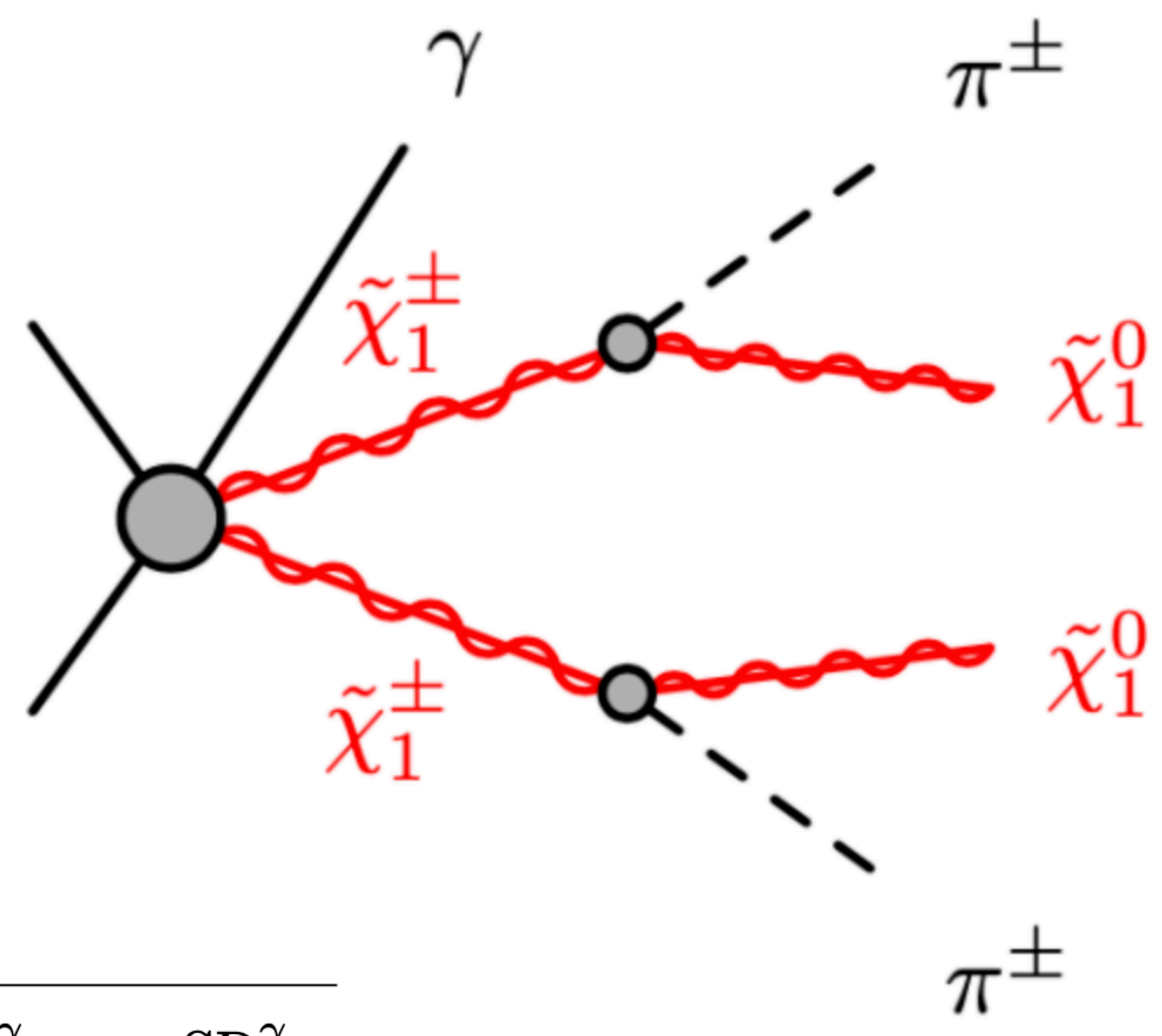
Study at 1.5 TeV

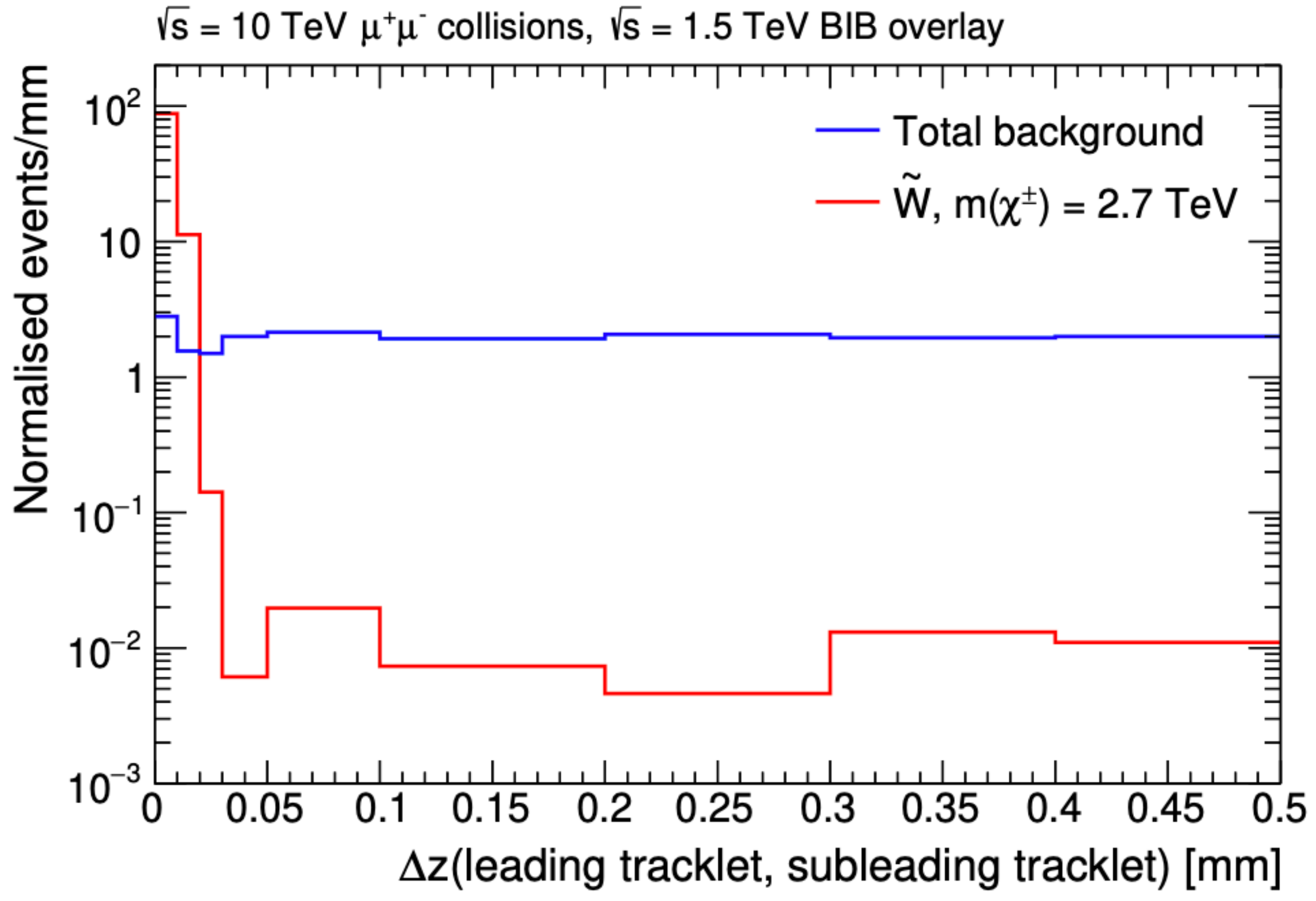


Disappearing tracks

10.1007/JHEP06(2021)133

- Search for Electroweak multiplets, by looking at the **disappearing tracks** signature.
- Unusual track length requires dedicated reconstruction algorithms, developed and optimized using full-simulation
- Tracks are vetoed if they have hits in the first layer of the inner tracker or beyond (**disappearing condition**).
- The full simulation is used to tune the background rejection requirements, and to determine the efficiencies.
- The main background source is the **tracklets combinatorial from the BIB**.





Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

Disappearing tracks

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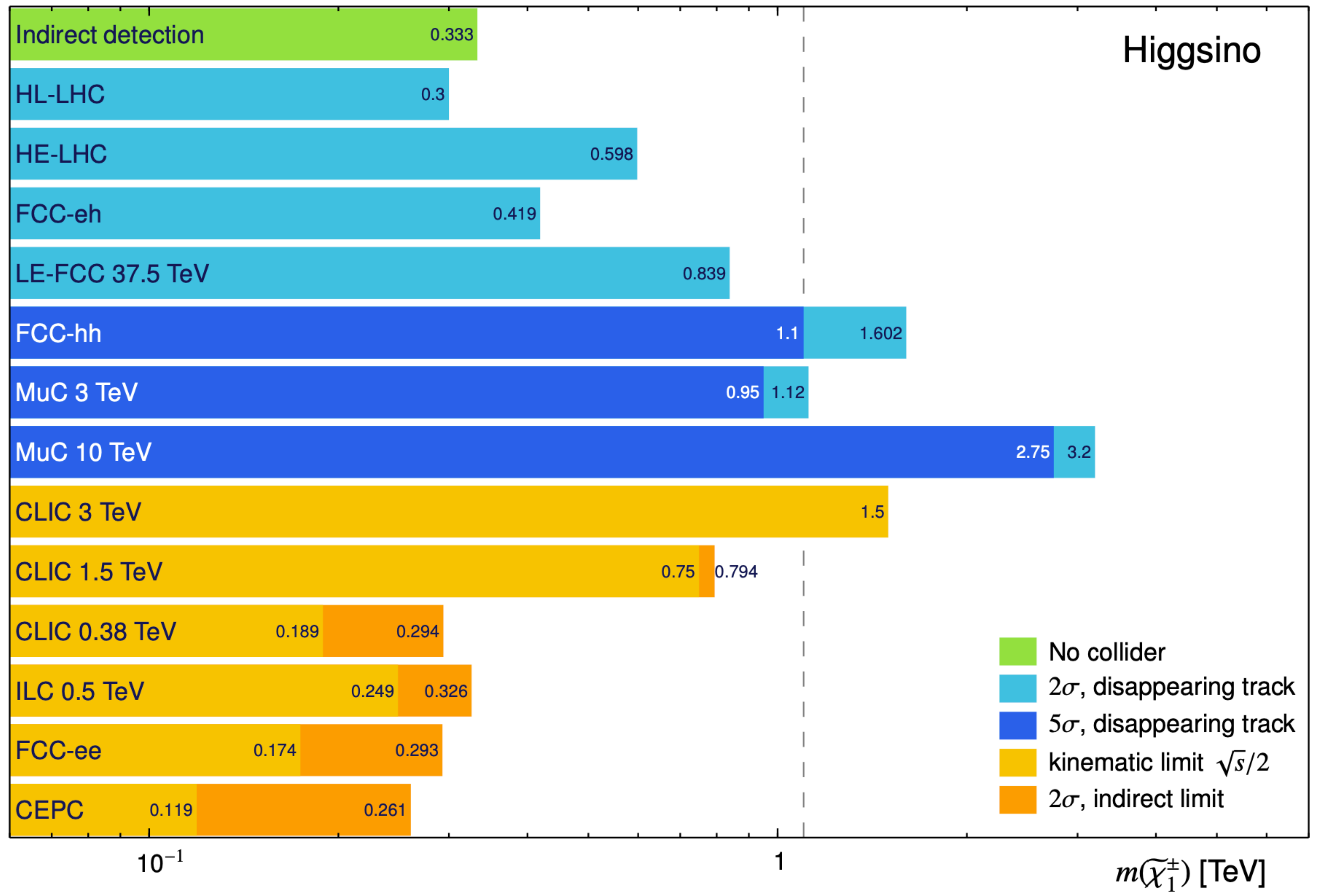
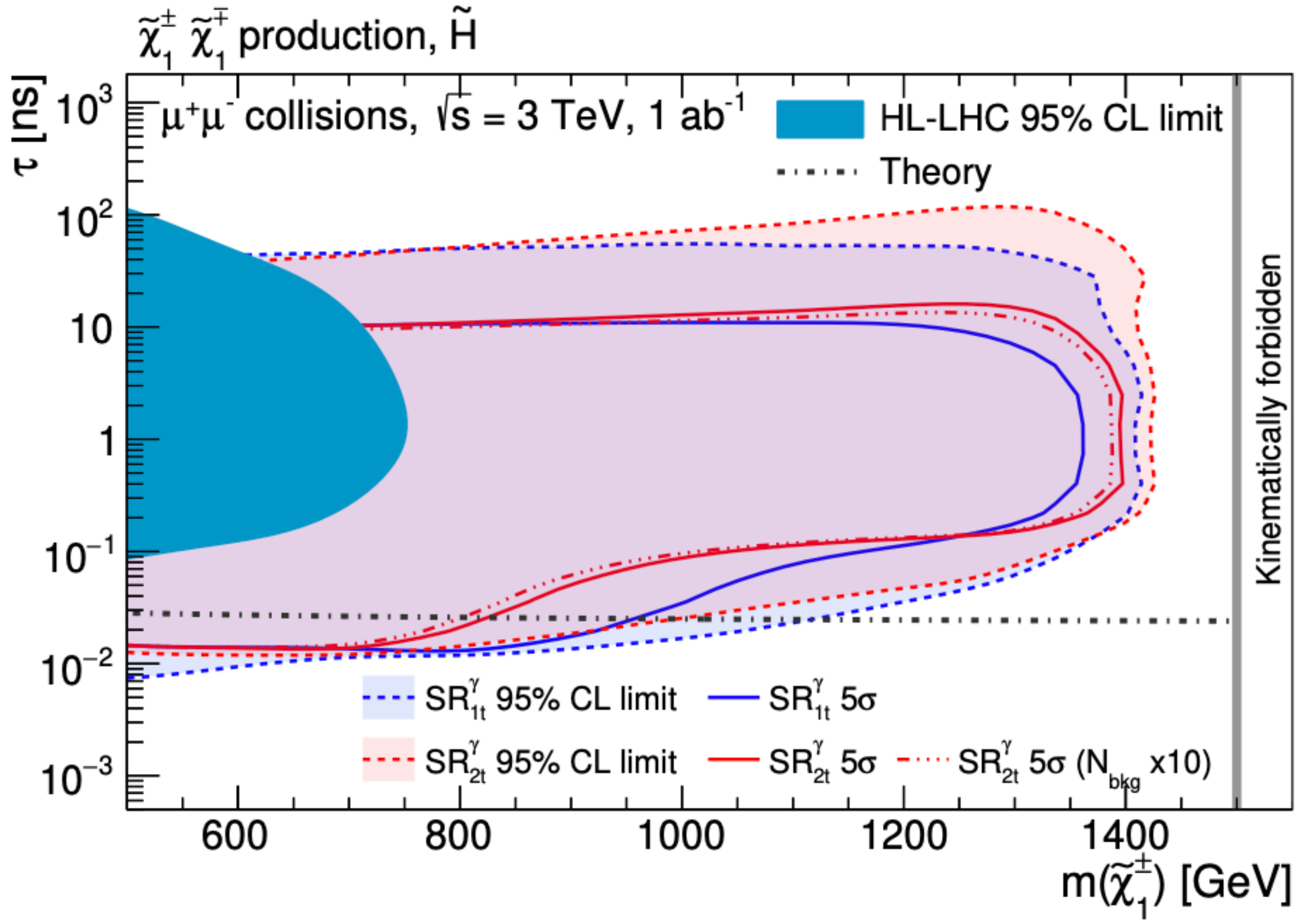
- At 3 TeV, a larger parameter space with respect to HL-LHC can be excluded.
- The excluded chargino mass region at 95% CL is close to the √s/2 kinematic limit.
- **The thermal Higgsino hypothesis can be excluded at 95% CL**.





BSM studies on-going:
Dark Sector searches

Disappearing tracks and Wino

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