Standard Model Physics at a Muon Collider

Hannsjörg Weber (Fermilab)

On behalf of

LoI #177

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Also close collaboration with Italian/ European colleagues who are working on the muon collider.

Further groups have already expressed interest in SM physics.

Executive Summary

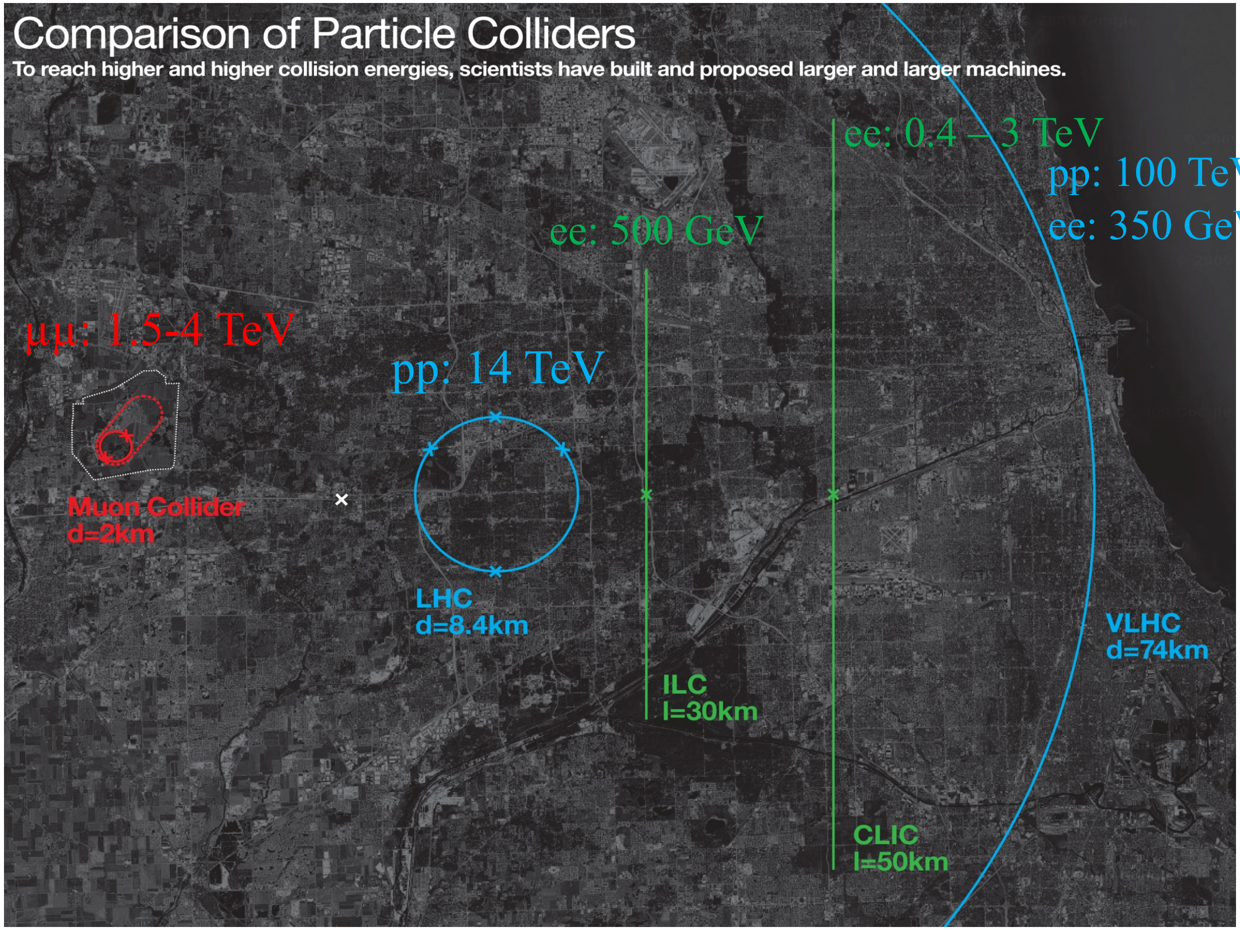
- In LoI #177 we propose to study the standard model physics sensitivity **at a muon collider**.
  - First, identify and overcome the challenges in the reconstruction (see also LoI #234).
  - Use these result to study new physics signatures. We made 4 concrete proposals:

1. Higgs physics, incl. mass/width: Two operations: @125 GeV to measure Higgs mass and width, at $\gtrsim$3-6 TeV to produce Higgs through vector boson fusion (VBF).
2. Higgs self-coupling: At high $\sqrt{s}$, VBF production of di-Higgs (HH) should be large enough to allow to extract the Higgs self-coupling with high precision.
3. Vector boson scattering (VBS): Also study electroweak (EW) bosons, measuring cubic and quartic couplings with high precision.

- Also check out LoI #228, utilizing the muon collider for new physics searches.
  - The authors of these three LoIs work together. We also work with our European colleagues.

Why muon collider?

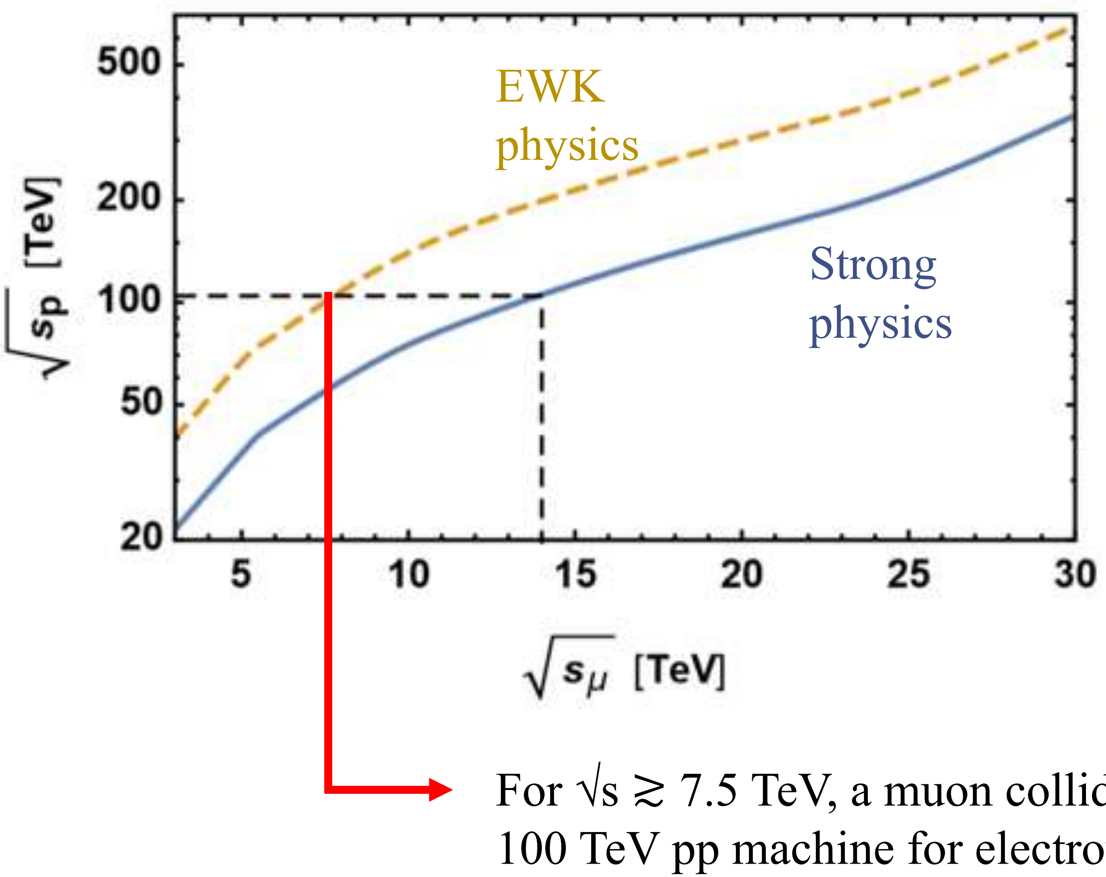
- Muons are heavy: Can build small footprint collider for multi-TeV collisions.



- With further advances could build a 6 TeV muon collider of the size of the Tevatron.

Why muon collider?

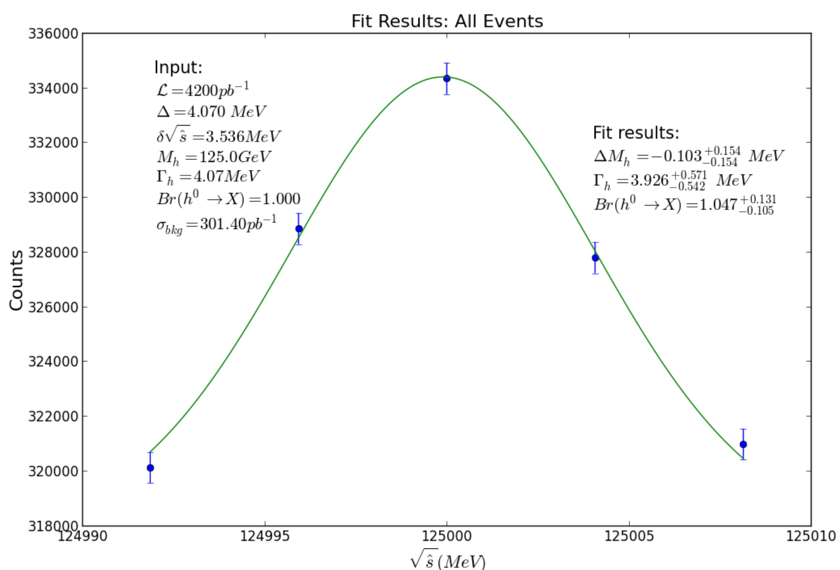
- Muons are heavy: Can build small footprint collider for multi-TeV collisions.
- Muons are fundamental particles – i.e. collisions take advantage of full c.o.m. energy of the beam.

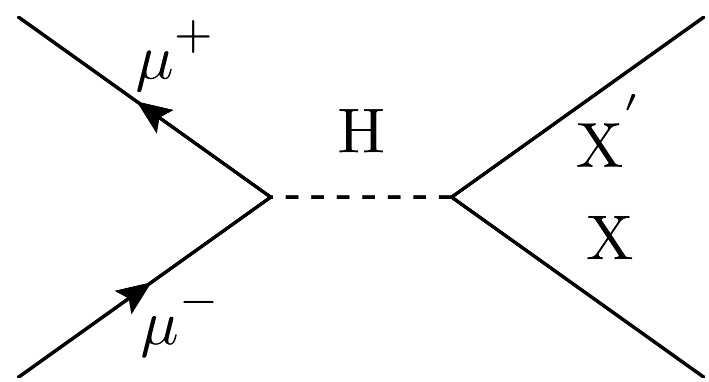


For √s ≳ 7.5 TeV, a muon collider will surpass a 100 TeV pp machine for electroweak physics.

Our proposal for studies

- Our LoI looks at 4 types of processes in general:
  - Direct Higgs production through the s-channel:
    - Precision measurement of mass and width by counting events in a √s scan.
  - Direct Higgs studies (such as couplings) at higher energies.

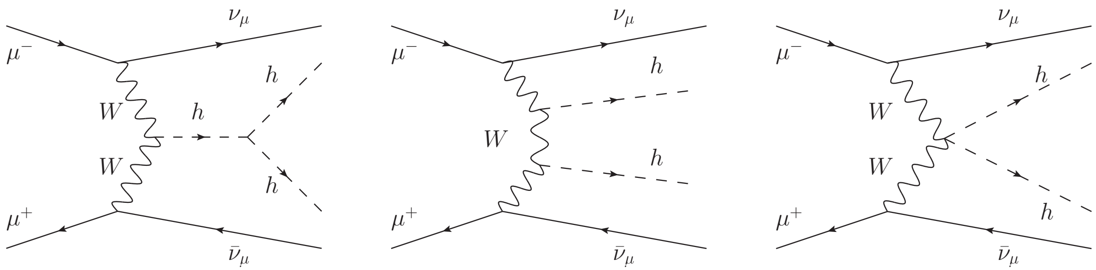




Higgs mass peak scan:
Higgs mass with a precision of **0.1 MeV**
Higgs width with **15%** precision
arXiv:1308.2143

Our proposal for studies

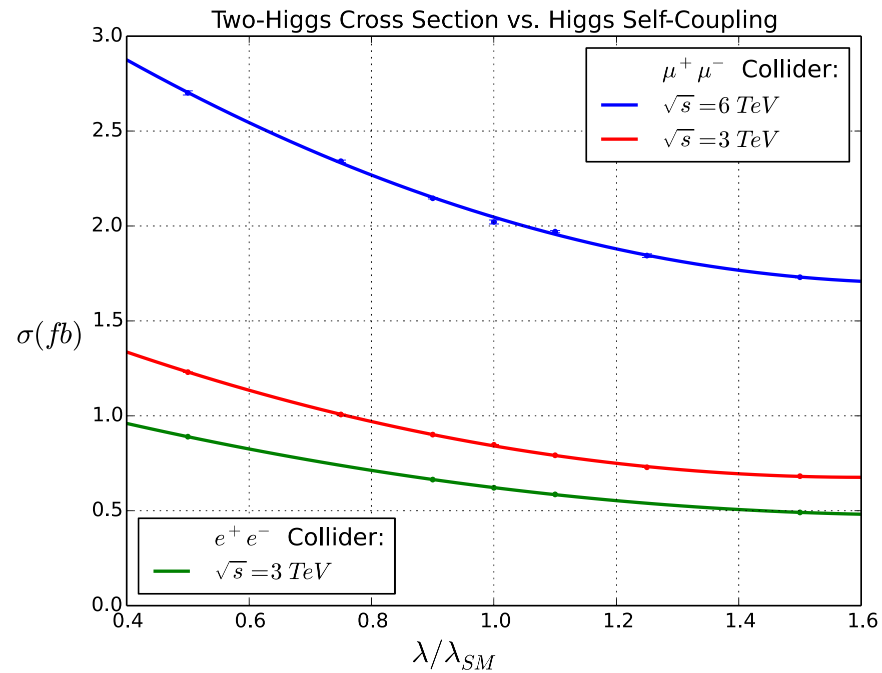
- Our LoI looks at 4 types of processes in general:
  - Di-Higgs production and Higgs self-coupling measurements.



arXiv:1405.5910

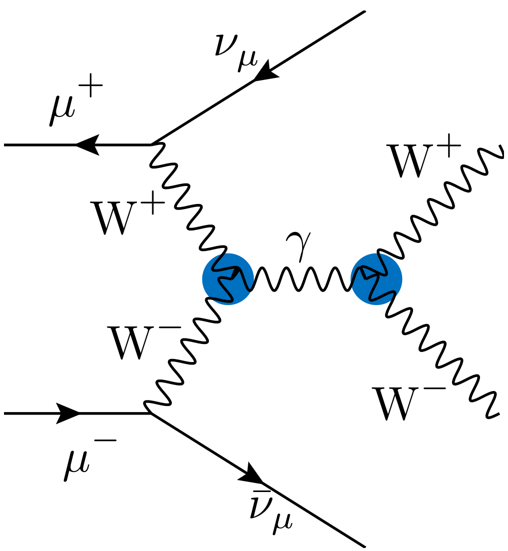
- A multi-TeV muon collider can (a) reach higher cross section for Higgs self-coupling, but also (b) probe the value more accurately (due to stronger dependence in λ).

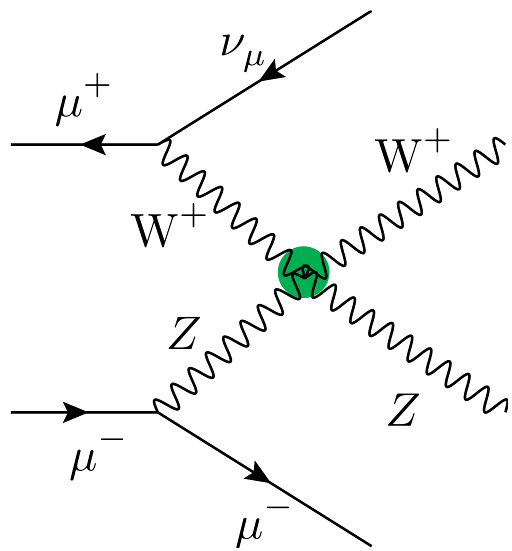
- Have potential (once going beyond ≥10 TeV) to measure quartic Higgs-coupling:
  - JHEP **09** (2020) 098

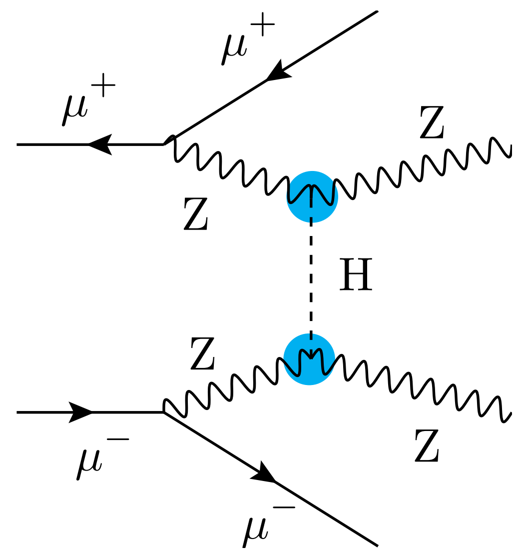


Our proposal for studies

- Our LoI looks at 4 types of processes in general:
  - Precision measurement of vector boson scattering: cubic and quartic gauge couplings are similarly important to Higgs couplings in understanding the EWSB. Especially accessing high-energetic scattering at higher rates might allow us to probe the Higgs field in an orthogonal way.







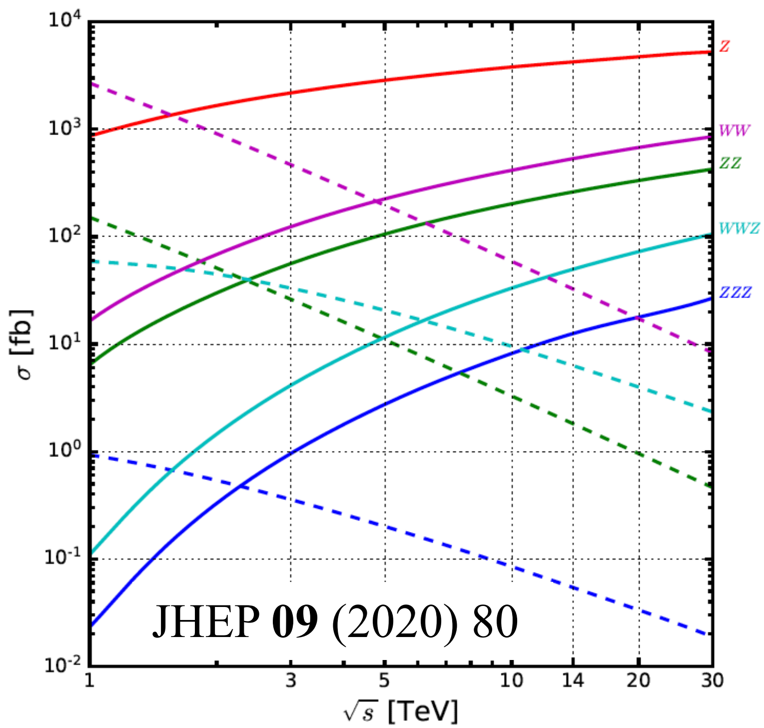
Cubic gauge coupling

Quartic gauge coupling

Cubic gauge-Higgs coupling

A deeper look into VBS

- Our LoI looks at 4 types of processes in general:
  - Precision measurement of vector boson scattering.



- Depending on the process, the VBS cross section becomes larger compared to the non-VBS di(tri)boson production around $\sqrt{s} \gtrsim$ 2-6 TeV.
- Note: following luminosities are targeted for a 5-year run time (per energy):

$\sqrt{s}$	$\mathcal{L}_{integrated}$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

A deeper look into VBS

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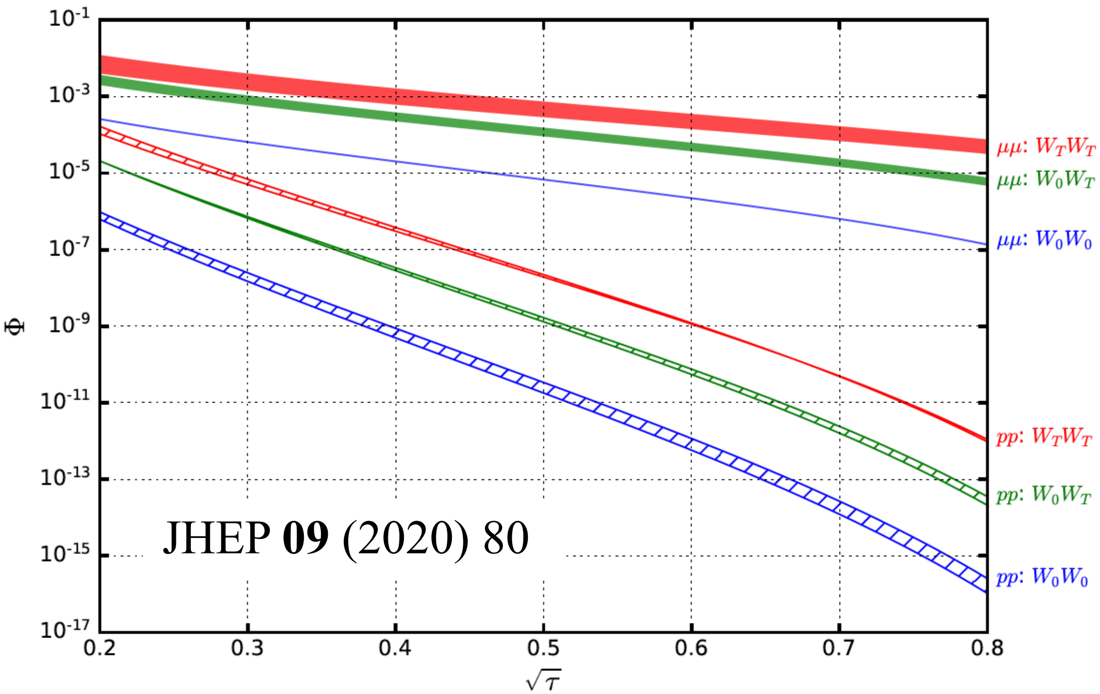

- The "VV PDFs" for muons are much greater than those for a pp machine, i.e. much higher rate of VBS at muon colliders.
- This is why the muon collider is the machine to study VBS at highest precision.

A deeper look into VBS

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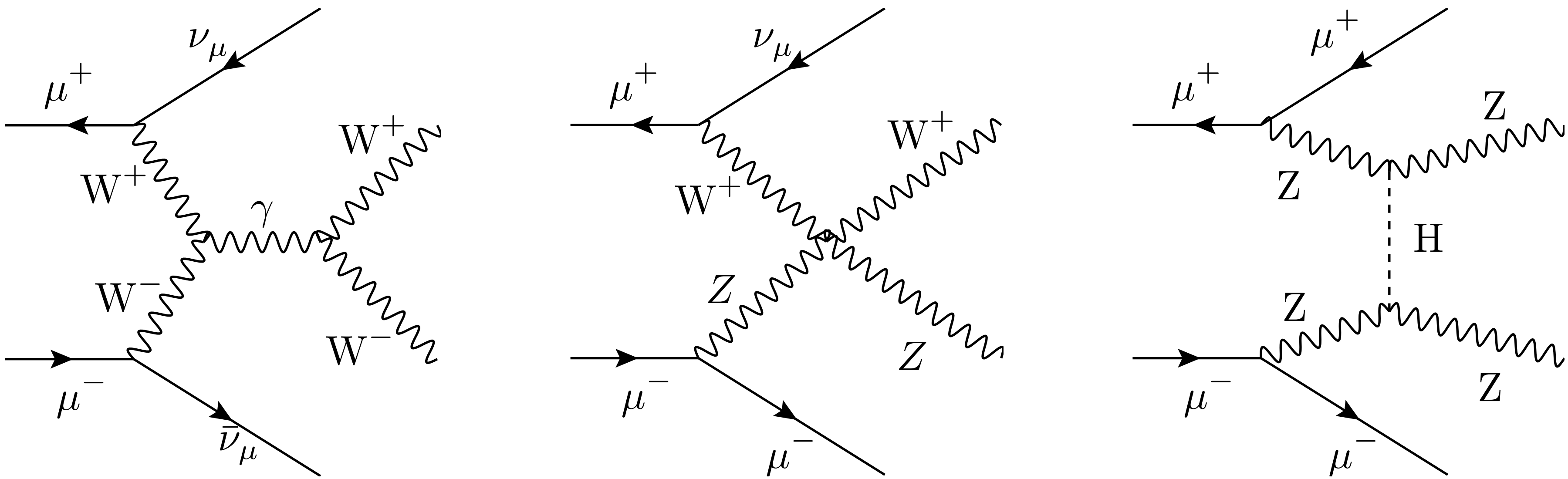

- Signatures: two forward neutrinos/muons plus two W/Z bosons:
  - For probing the SM, require 2-4 leptons + 0-2 forward leptons and p_T^{miss} *.
    - Targeting leptonic final states to be able to distinguish W/Z decays. This is not (yet) clear for hadronic W/Z decays.

*: first reconstruction studies indicate that p_T^{miss} might perform better than p^{miss}.

A deeper look into VBS

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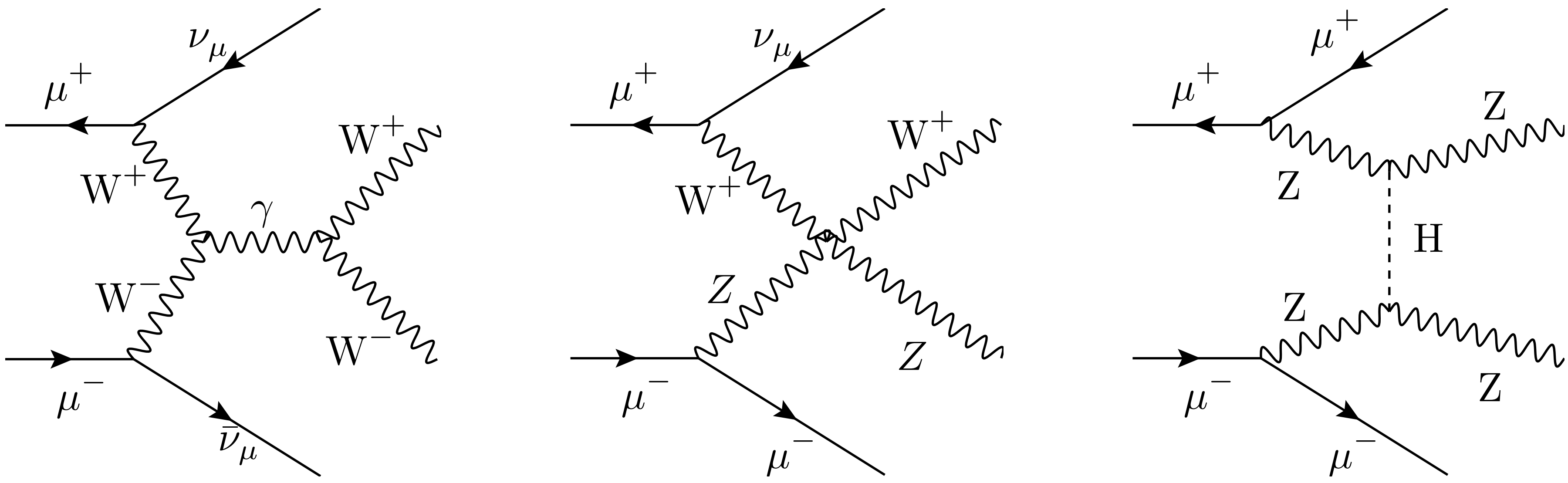


- Signatures: two forward neutrinos/muons plus two W/Z bosons:
  - For probing the EFT, we will start looking at semileptonic and possibly also fully hadronic processes.
    - Main backgrounds should be from single-boson production. Strong production such as VBF $t\bar{t}$ production should be negligible.

Where we started

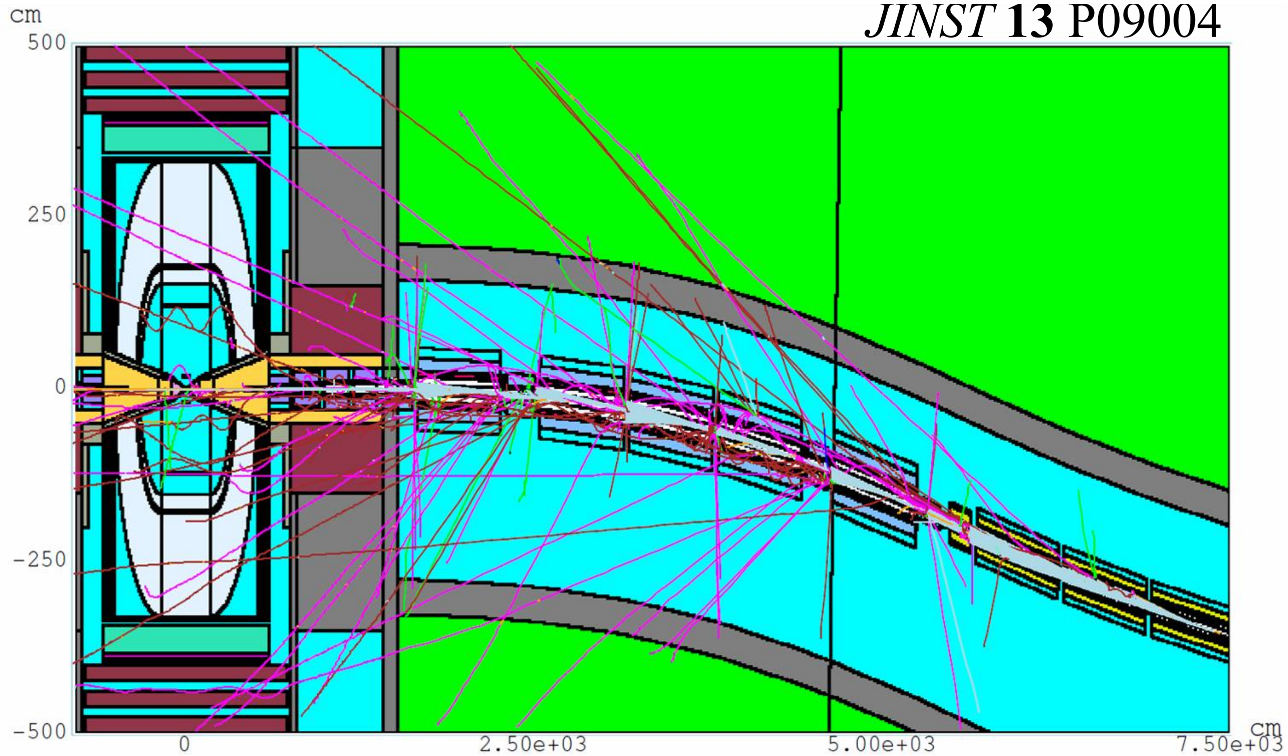
- We have not started our studies yet, although some have begun to look into generating samples to be used.
  - We will use available Delphes cards to do these studies, and if we have the time/person power also look at full simulation.

- The reason why studies have not studied yet is that is that our first focus is on the reconstruction that comes with special challenges at a muon collider.
  - Physics studies can be done at generator or Delphes level (including studies performed by theorists), however an important question is whether these studies can be trusted in the presence of the beam induced background (BIB), and this is what we are trying to answer.
  - I will present quickly those challenges here.

Challenges of physics at a muon collider

- Muons are unstable, and decay in-flight.
  - This plot is done with MARS simulation at $\sqrt{s} = 1.5$ TeV.

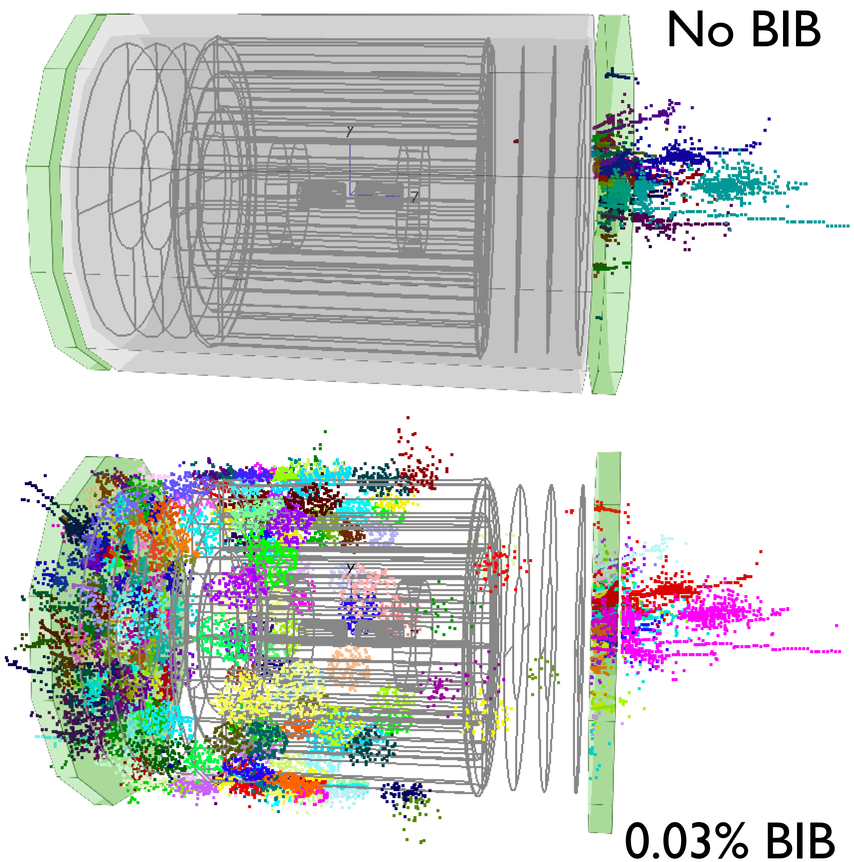
JINST **13** P09004



Challenges of physics at a muon collider

- Muons are unstable, and decay in-flight.
  - The detector is bombarded by particles.

M. Swiatlowski



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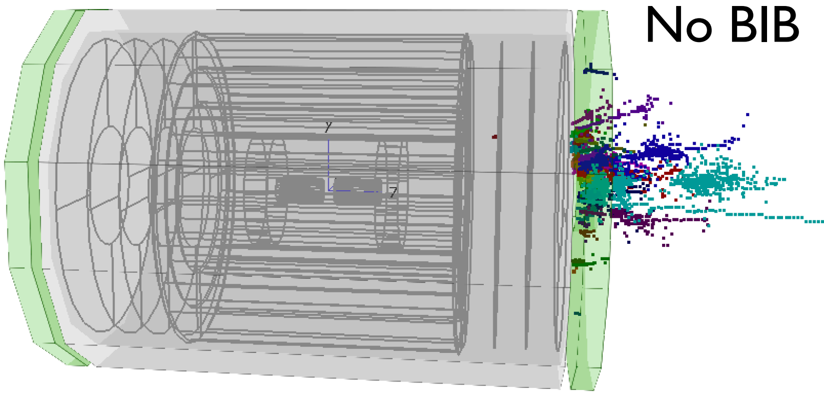
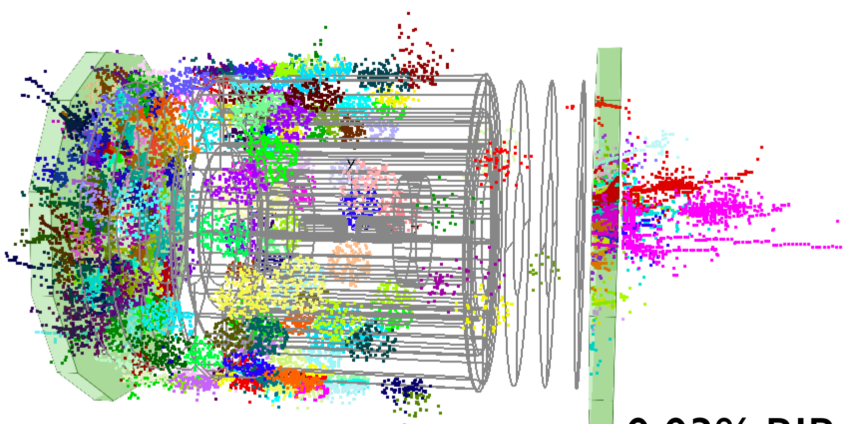
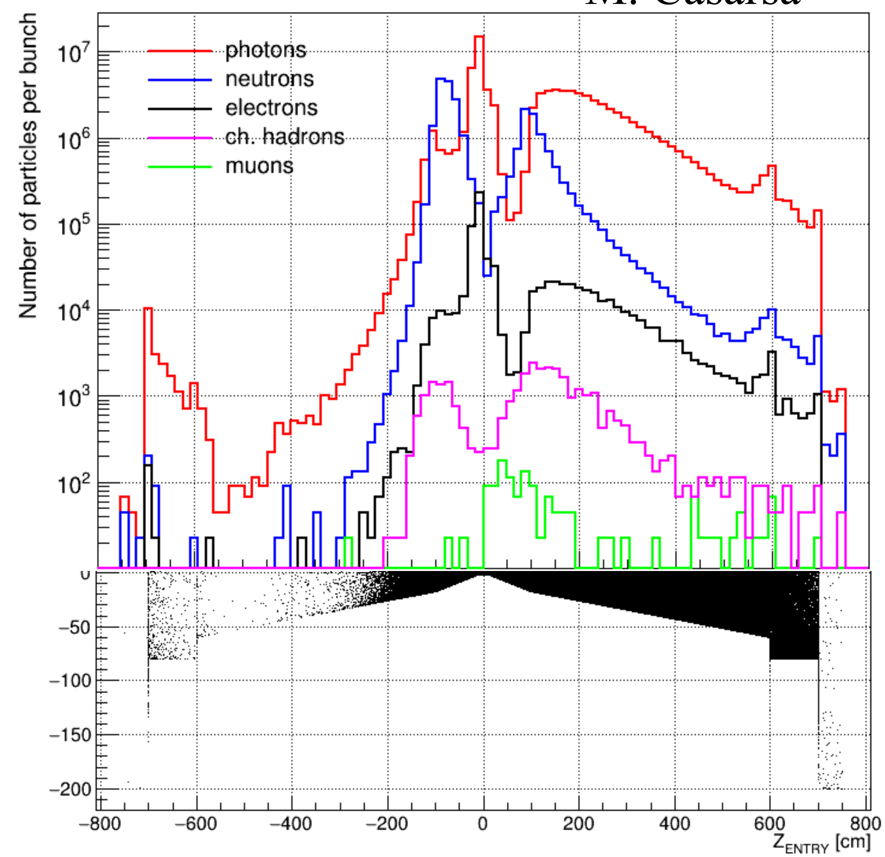


No BIB



0.03% BIB

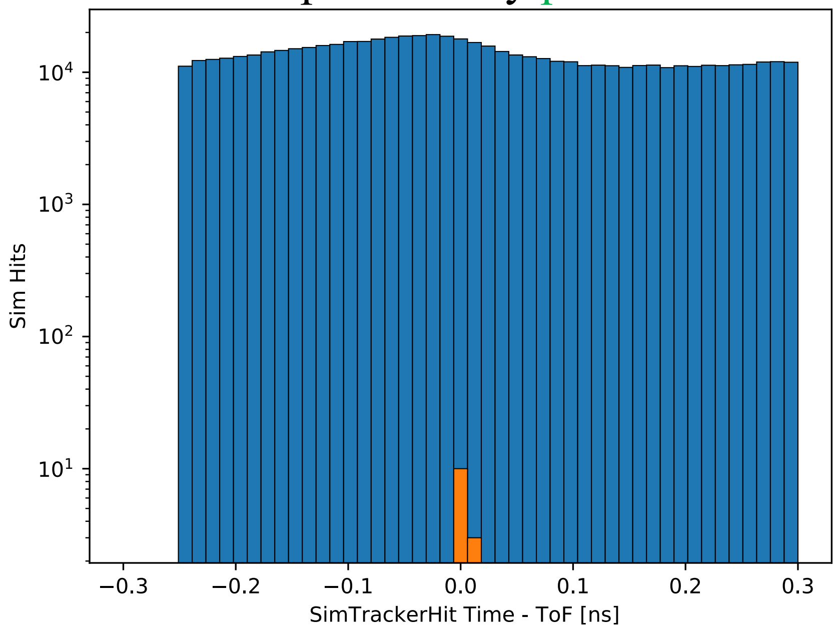
M. Casarsa

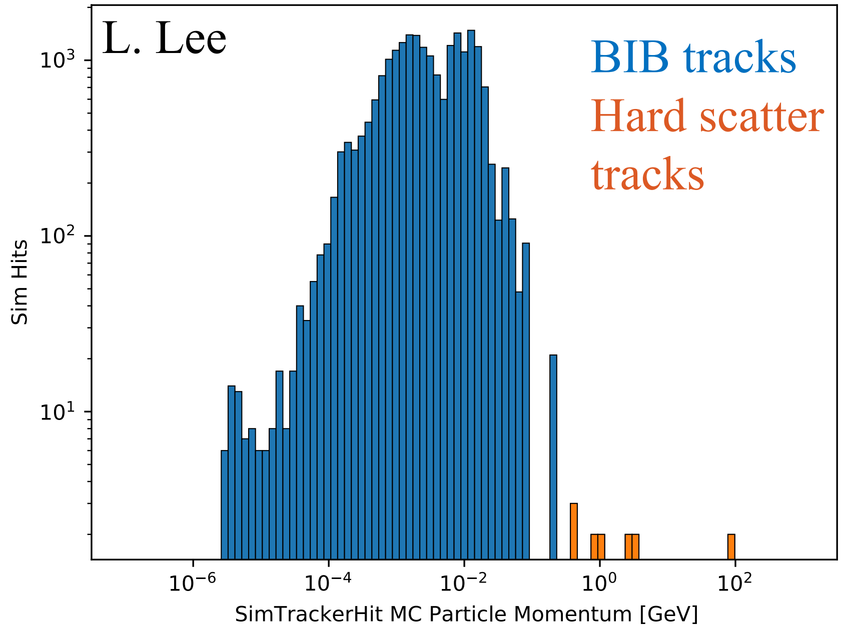


750-GeV μ^- beam

Challenges of physics at a muon collider

- Muons are unstable, and decay in-flight.
  - The detector is bombarded by particles.
  - Need all experimental handles available to us:
    - Detector with in-built absorber against the beam-induced background (BIB).
    - BIB are not in-time.
    - BIB is extremely soft.
    - BIB particles fly parallel to the beam.





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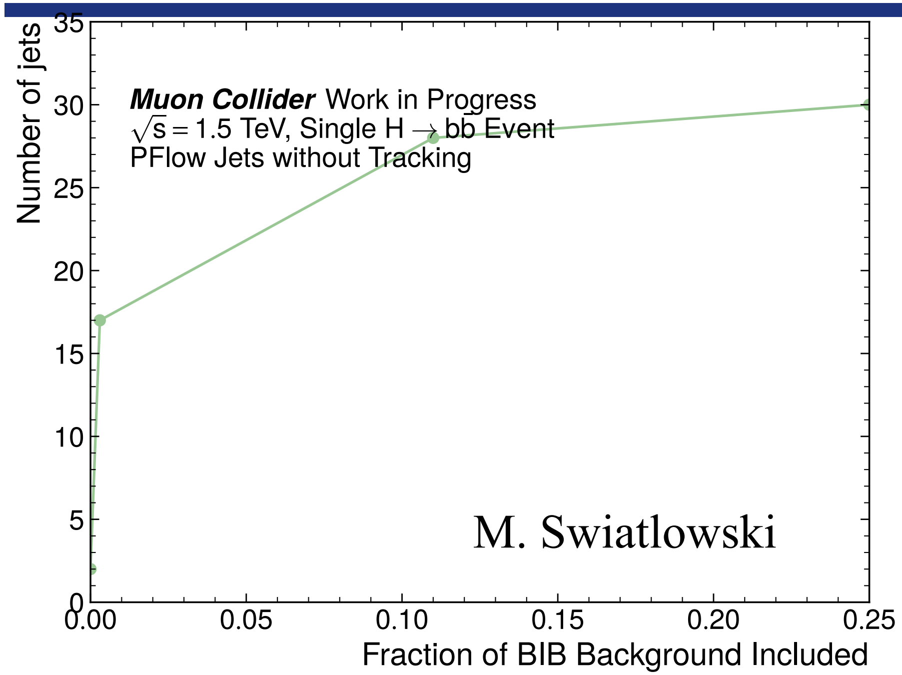
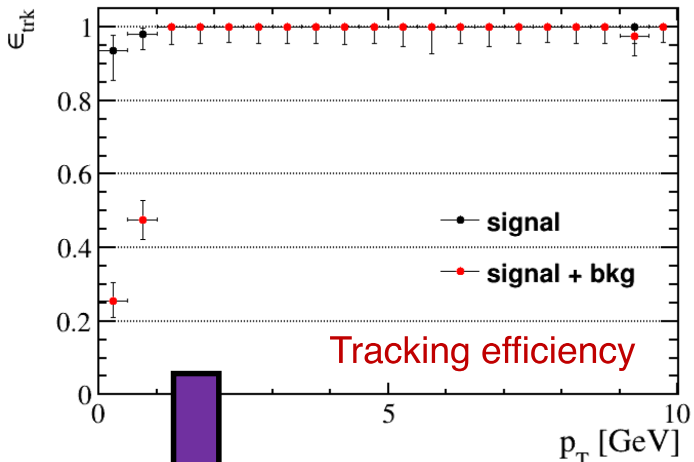
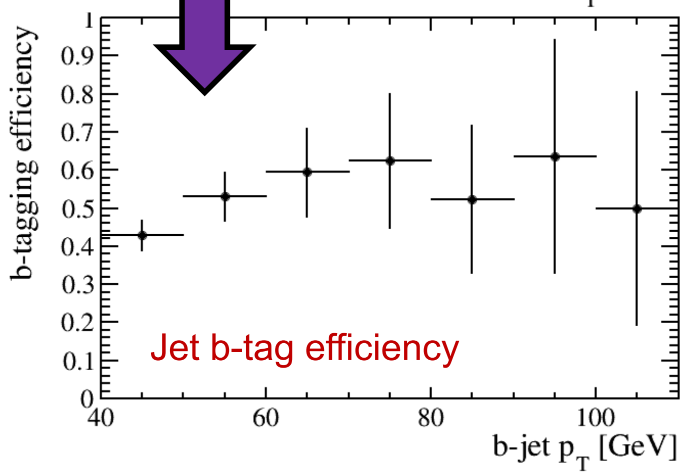
    - BIB are not in-time.
    - BIB is extremely soft.
    - BIB particles fly parallel to the beam.
  - But still, some work ahead of us!



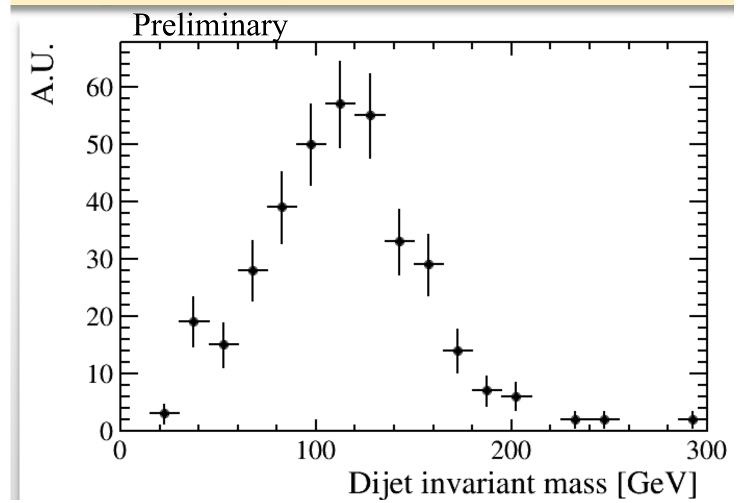
Challenges can be overcome

- Our European colleagues used the full simulation to do a H(bb) measurement at √s = 1.5 TeV.





$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
	1.5	0.5	1.9
Muon Collider	3.0	1.3	1.0
	10	8.0	0.91

Looking ahead

- We have done already progress on the reconstruction studies (with a lot of work done by our European colleagues), but still more work needed to fully understand the impact of the BIB on the physics performance at a muon collider experiment.

- Parallel, the first delphes card has been created:
  - https://github.com/delphes/delphes/blob/master/cards/delphes_card_MuonColliderDet.tcl
- As the first Delphes card was finalized last month, we have no physics studies to show (yet), but we are starting organizing these studies now.
  - Our group has already grown with respect to the LoI author list.
  - As we are starting physics studies "only" now, if you are interested: it is a great time to join! – Just contact me or any other author.

- One question to be discussed is what are the best plots/numbers to produce that allow to compare a muon collider experiment to those at e^+e^- or pp colliders?
  - For numbers likely limits on EFT operators?

Backup

Muon collider experiment