Higgs boson couplings at muon collider

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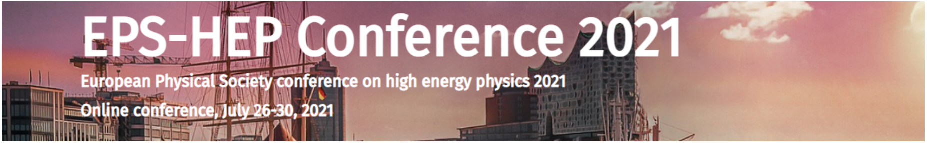
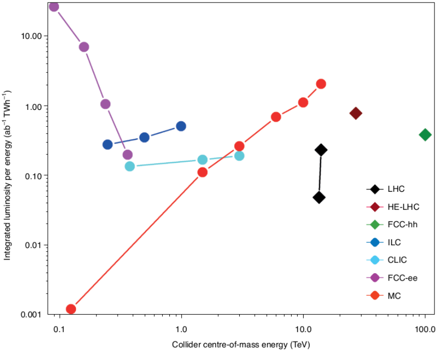
on behalf of the Muon Collider Physics and Detectors working group *

International MUON Collider Collaboration



Why a muon collider

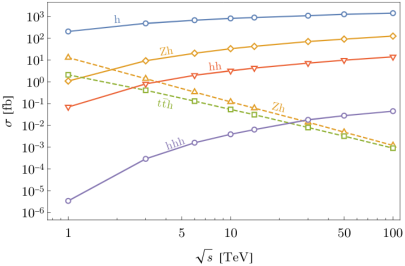
- Lepton colliders allow to exploit the full energy available in the center of mass
- Technologies to reach high energies in $e^+ e^-$ collisions require linear colliders due to synchrotron radiation loss in circular colliders
- Muon collider: above $\sqrt{s} = 2$ TeV is expected to be the most energy-efficient choice to reach high energies (very low radiation losses)



- Formed the International Muon Collider Collaboration*: focus on 3 and 10+ TeV

See Daniel Schulte's* talk tomorrow

Higgs couplings at muon collider



- At multi-TeV $\sqrt{s}$ $\mu^+\mu^- \to H\nu\bar{\nu}$, $\mu^+\mu^- \to HH\nu\bar{\nu}$ and $\mu^+\mu^- \to HHH\nu\bar{\nu}$ events mainly produced via WW fusion

- First Higgs physics comparison in The muon smasher's guide* to Higgs Boson Studies at Future Particle Colliders*. $L = 10\ ab^{-1}$. Beam-induced background (BIB) not included!

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

Higgs potential

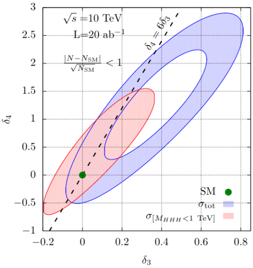
After the electroweak symmetry breaking, Higgs potential:

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_{SM}(1+\delta\kappa_3) v h^3 + \frac{\lambda_{SM}}{4}(1+\delta\kappa_4) h^4 \qquad \lambda_{SM} = \frac{m_H^2}{2v^2}$$

✦ Reach on Higgs trilinear coupling: hh → 4b

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

E [TeV]	$\mathscr{L}$ [ab^{-1}]	$N_{\rm rec}$	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%



- At 14 TeV, with 33 ab^{-1}, possible to measure $\delta\kappa_4$ with an uncertainty of 50%.

In this talk, results on full simulation with BIB at $\sqrt{s} = 1.5$ TeV included:

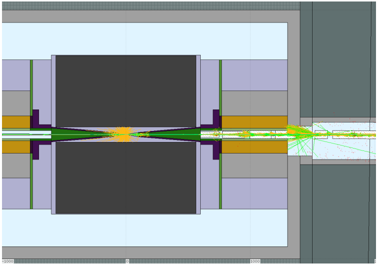
- State of the art on studies of $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ =3 TeV
- First results on the $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ =3 TeV

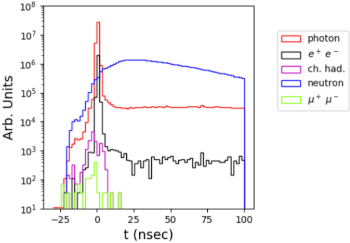
More studies:

- Studies ongoing on $H \to WW$ and $H \to cc$ and $H \to bb$ samples
- Prospects for $\sigma_H \times Br(H \to \mu^+\mu^-)$ at 3 TeV see poster * by A. Montella
- Dark-SUSY channels to study muon reconstruction performance at the Muon Collider *, poster by C. Aimè

Detector challenges

- Beam-Induced Background caused mainly by μ beam decays (at $\sqrt{s}$=3 TeV 2×10^5 muon decay/m per bunch crossing)
- BIB may affect detector performance if mitigation strategies are not applied, like:
  - Shielding inside detector
  - Proper detector design
- Machine-Detector Interface and BIB studied at $\sqrt{s} = 1.5$ TeV (see arXiv:2105.09116):

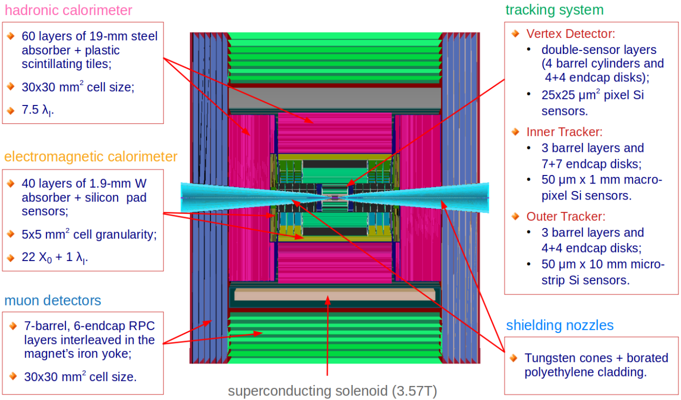




- Some studies in progress at $\sqrt{s} = 3$ TeV, lower BIB level seems achievable
- Full simulation detector studies performed including BIB.

Detector

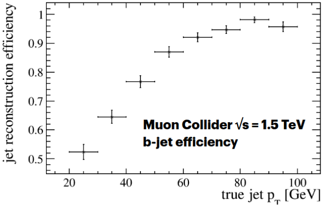
- Posters on physics objects reconstruction in BIB environment:
  - Tracking and track reconstruction at a muon collider in the presence of beam-induced background*, poster by H. Weber
  - Using cluster kinematics for beam-background suppression in a future muon collider experiment*, poster by E. Resseguie
  - Muon reconstruction performance and detector-design considerations for a Muon Collider*, talk by I. Vai
- ILCSoftware framework is used for the full simulation and reconstruction.
- Detector design is used for 3 TeV center of mass energy (nozzles still optimized for 1.5 TeV):

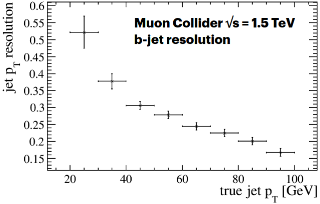


- New proposal for the ECAL: Design a calorimeter system for a Muon Collider*, poster by L. Sestini

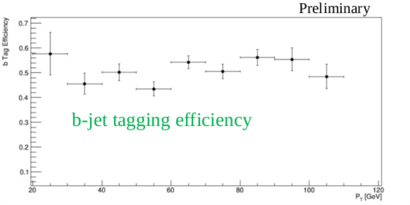
Jet reconstruction and b tagging efficiencies

- Jet reconstruction efficiency estimated on $b\bar{b}$-dijet + BIB events:
  - Average energy deposited by BIB in calorimeter cells subtracted as an underlying event.
  - Preliminary reconstruction based on cone algorithm is used





- b-jets tagging efficiency: $\sim 55\%$, light quarks mis-identification between 0.2% and $\sim 10\%$ at high p_T
- Machine Learning technique to exploit full jet information for jet identification under development



$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ =3 TeV

- In 2020 JINST 15 P05001 $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ at 1.5 TeV with BIB
- Efficiencies obtained at $\sqrt{s} = 1.5$ TeV applied to the 3 TeV case
- 4 Snowmass years of data taking

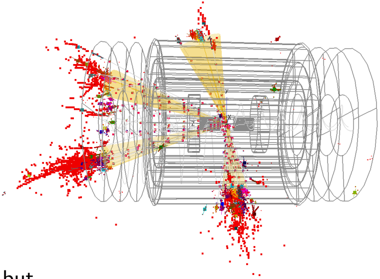
	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

- Reference for CLIC: arxiv:1608.07538
- Efficiencies: two b-tagged jets with $p_T > 40$ GeV, $|\eta| < 2.5$ were selected
- In progress: evaluation at 3 TeV $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ via full simulation, jet reconstruction down to 20 GeV $\to$ increase efficiency

$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$: some considerations

- Signal and physics backgrounds at $\sqrt{s}$=3 TeV generated with WHIZARD

Signal	Cross section [fb]
$\mu^+\mu^- \to HH\nu\bar{\nu}$	0.8
Physics background	Cross section [fb]
$\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$	3.3
$\mu^+\mu^- \to b\bar{b}H\nu\bar{\nu}$ (signal included)	1.7



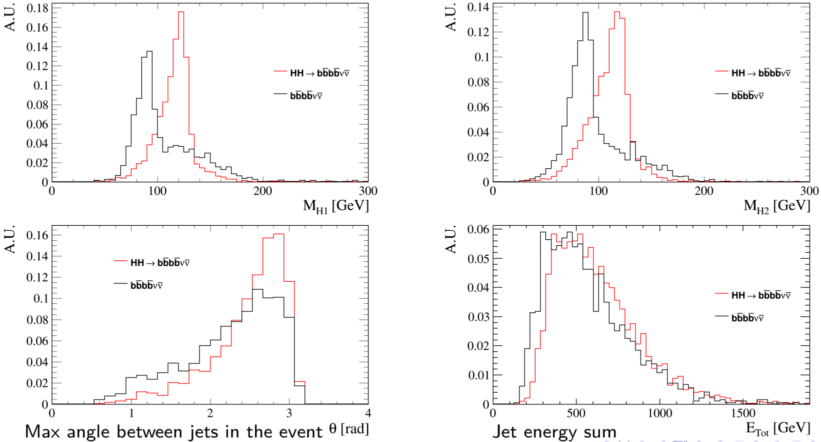
- The simulation is performed without the BIB, but
- *b*-tagging efficiency in presence of the BIB are used to weight events
- One jet for each pair is required to be tagged: processes with jets in the final states different from the *b* quark are negligible
- Reconstruction performed under conservative assumption (jet reconstruction with BIB still under optimization)

Studies of double Higgs

- Event selection: $N_{jets}>3$ and minimum transverse momentum $p_T > 20$ GeV
- Jets paired by minimizing the figure of merit: $M = \sqrt{(m_{ij} - m_H)^2 + (m_{kl} - m_H)^2}$
- Selection of the kinematic variables used to distinguish the signal ($\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$) and the physics background ($\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$): m_{H_1},m_{H_2}, $\sum E_{jets}$, max jet P_T for each pair, $\Delta\theta_{max}$.

Invariant mass of the leading Higgs

Invariant mass of the sub-leading Higgs

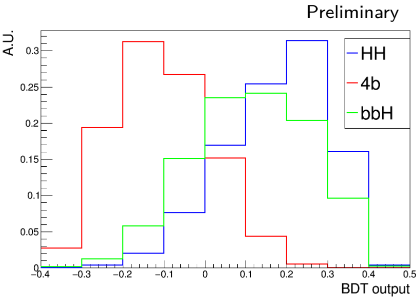


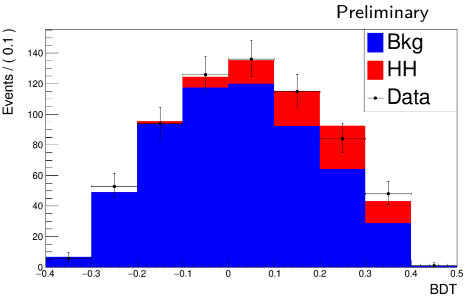
Max angle between jets in the event

Jet energy sum

HH cross section measurement

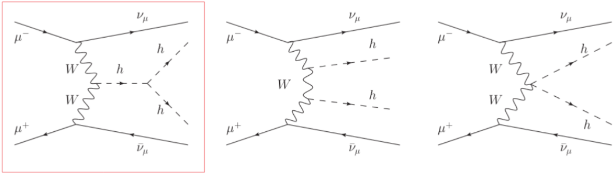
- Classification of signal and background events by using a Machine Learning technique (Boosted Decision Tree)
- With 1.3 ab^{-1} (4 years of data taking) at 3 TeV we expect to select 65 HH events and 561 background events.
- With a simple fit to the BDT an uncertainty of $\sim 30\%$ on the cross section has been obtained.



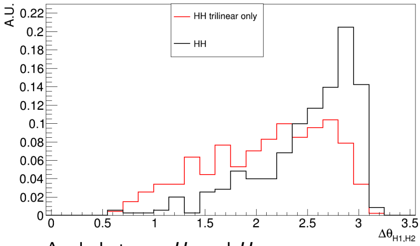


Toward trilinear coupling measurement

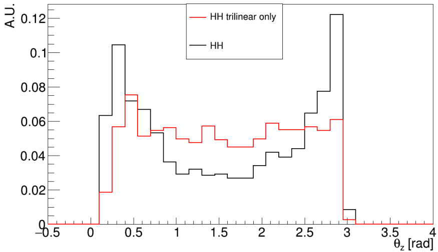
- Generation with WHIZARD and simulation of HH events just with the process mediated by the trilinear coupling



- By comparing HH from trilinear vs total HH it is possible to see differences in angular observables.



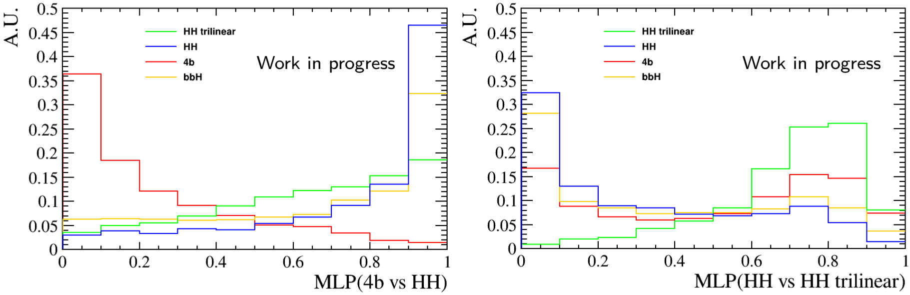
Angle between H_1 and H_2



Angle between selected jets and z axis

Toward trilinear coupling measurement

- Two Multi Layer Perceptron (MLP) discriminators are trained to separate HH-trilinear vs HH and HH vs background $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$.
- Set of $\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$ samples generated with WHIZARD Monte Carlo for different $\kappa = \frac{\lambda}{\lambda_{SM}}$=(0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6)
- Binned likelihood analysis based on pseudo-experiments gives: uncertainty on λ_3/λ_{SM} $\sim$ 20% at 68 % Confidence Level

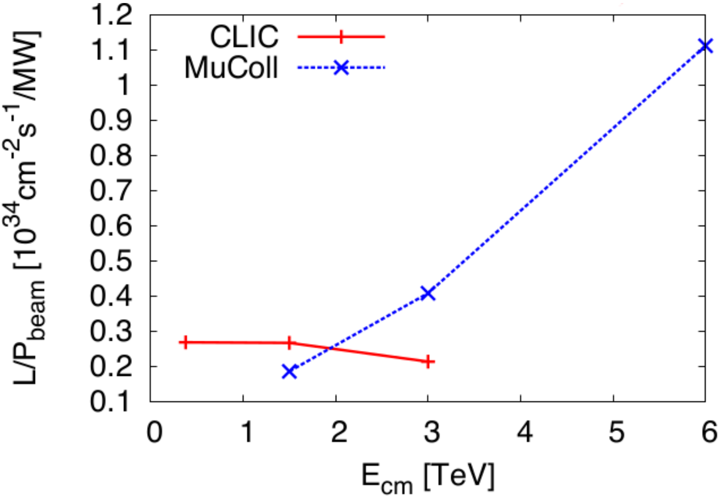


Conclusions and future plans

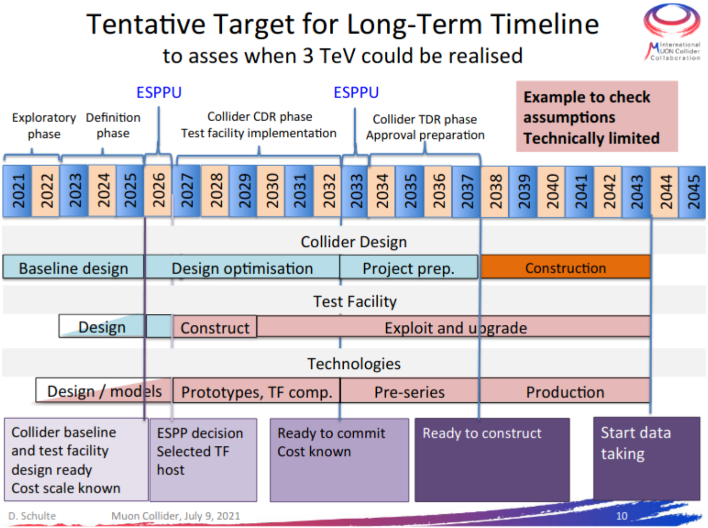
- Muon Collider performs very well on Higgs physics $\rightarrow$ see The muon smasher's guide*
- Theoretical expectations are under confirmation with full simulation
- At 3 TeV, conservative studies show that muon collider performs as well as e^+e^- on $H \rightarrow bb$, $H \rightarrow \mu^+\mu^-$ and $HH \rightarrow 4b$
- Studies with full simulation on $H \rightarrow WW$, $H \rightarrow bb$, $H \rightarrow ZZ$ are in progress.
- Physics objects reconstruction algorithms exploiting AI methods are under development

The International Muon Collider Collaboration aims to fully study the Higgs at 3 TeV and then at 10 TeV for the full Higgs potential determination

Luminosity muon collider



Luminosity muon collider



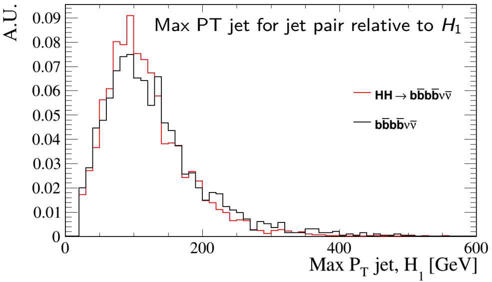
Luminosity Goals

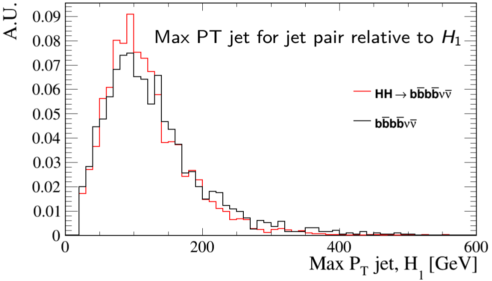
Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

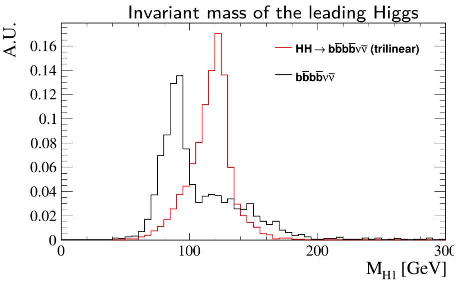
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

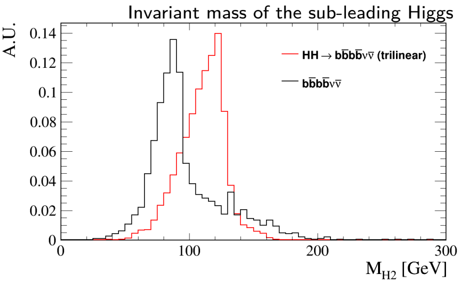
Additional variables for the uncertainty on the HH cross section analysis

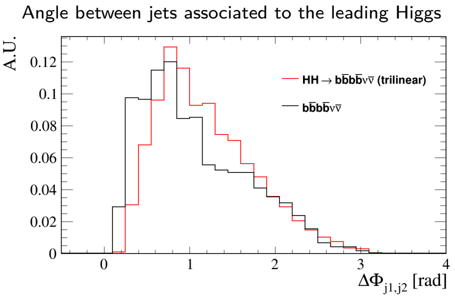


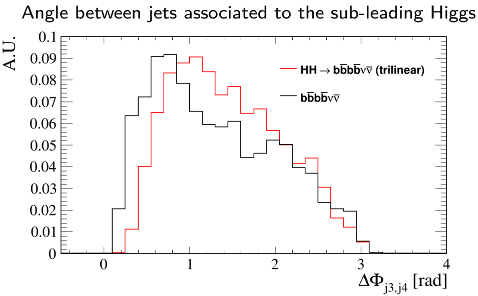


Variables for the uncertainty on the trilinear coupling analysis



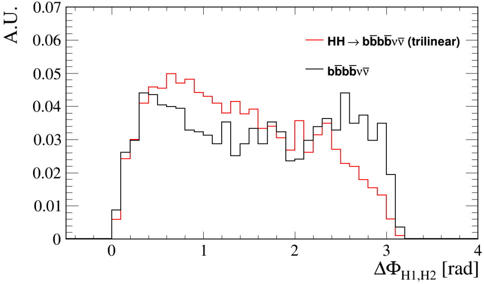




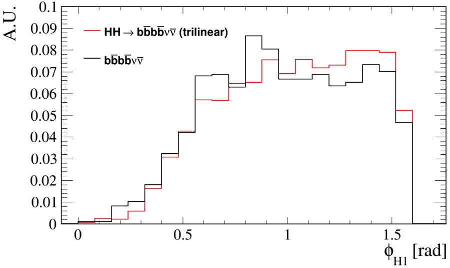


Variables for the uncertainty on the trilinear coupling analysis (II)

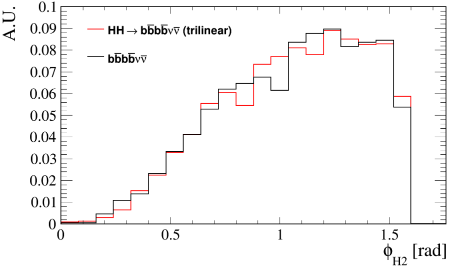
Angle between the two Higgs



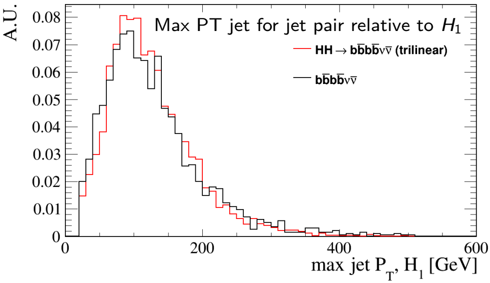
Helicity angle between the outcoming jets wrt H1

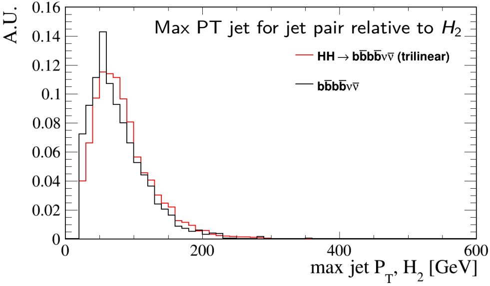


Helicity angle between the outcoming jets wrt H2



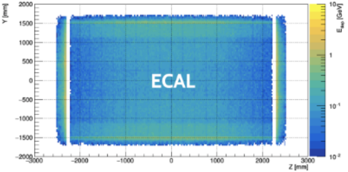
Variables for the uncertainty on the trilinear coupling analysis (III)

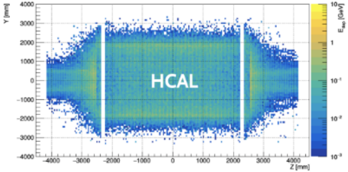




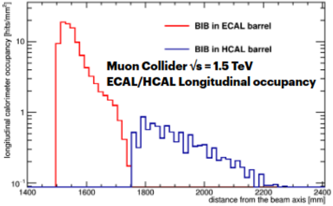
BIB on ECAL from Lorenzo Sestini's talk at APS April 17-20 Meeting 2021

Beam induced background in calorimeters





Energy deposition in calorimeters per bunch crossing



- **BIB is diffused in the calorimeters**: at the ECAL barrel surface the flux is 300 particles/cm², most of them are photons with <E>=1.7 MeV.
- BIB occupancy is lower in HCAL with respect to ECAL.

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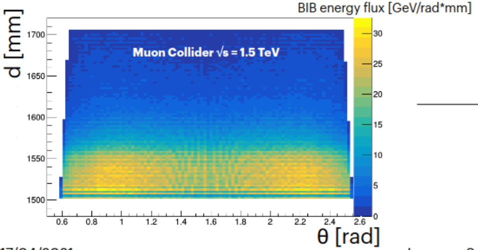
BIB on ECAL from Lorenzo Sestini's talk at APS April 17-20 Meeting 2021

BIB subtraction in ECAL for jet reconstruction

- ECAL is divided in **(θ,d) regions**: **θ** angle wrt z-axis, **d** distance wrt beam axis.
- In each region the average BIB hit energy E_{BIB} and standard deviation σ_{BIB} is determined.
- In signal+BIB reconstruction an ECAL hit is accepted if $E_{HIT} > E_{BIB} + 2\sigma_{BIB}$.
- The energy of the accepted hit is corrected: $E_{HIT} \rightarrow E_{HIT} - E_{BIB}$.



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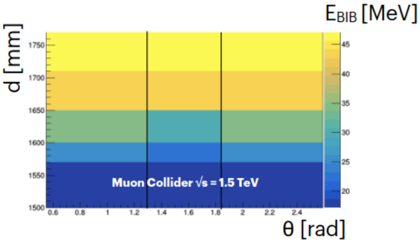

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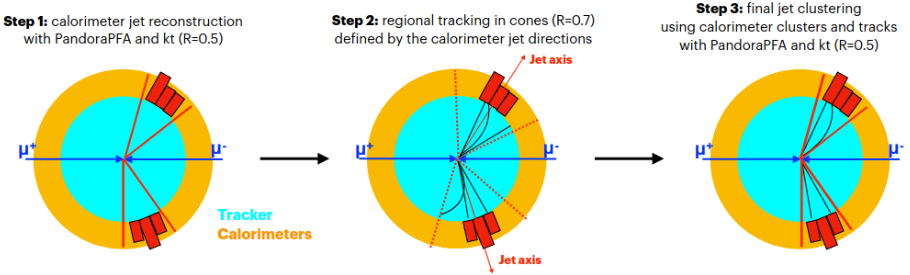
BIB on ECAL from Lorenzo Sestini's talk at APS April 17-20 Meeting 2021

Full jet reconstruction algorithm

- To recover the jet energy, **we should perform the full reconstruction with tracking+calorimeters.**
- In order to reduce the tracking combinatorial problem, **a regional tracking strategy is employed.**



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Cross section HH different couplings