Electroweak Phase Transition in Exotic Higgs Decays at the CEPC

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ATLAS EXPERIMENT

a3d3 Accelerated AI Algorithms for Data-Driven Discovery

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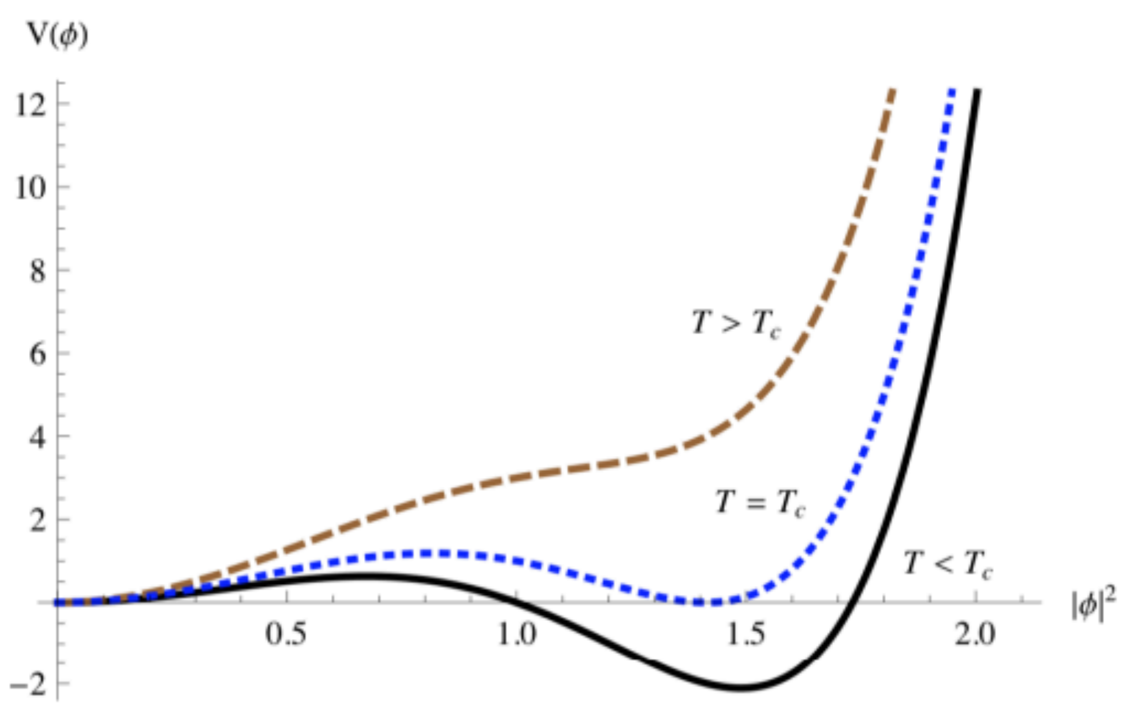
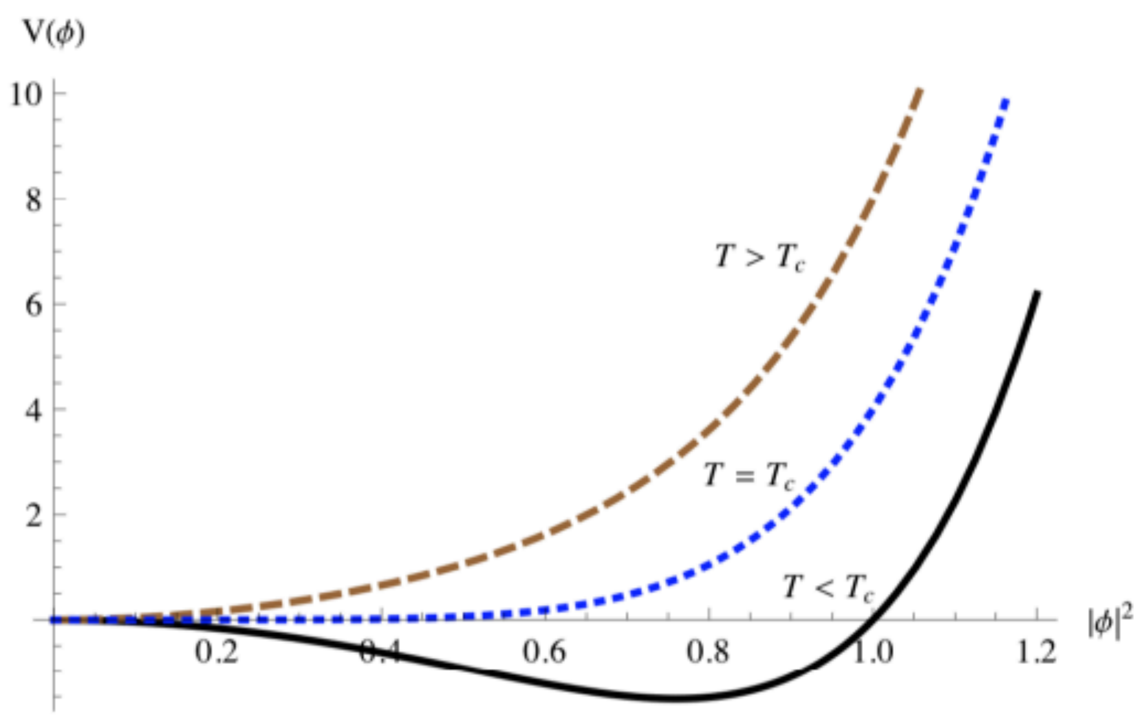
Introduction



(a) A first-order transition.



(b) A second-order transition

What is the thermal history of the **ElectroWeak Symmetry Breaking (EWSB)** in the early universe?

In SM the EWSB happens via a smooth cross-over transition

- Smooth transition between the states

This does not provide necessary condition for EW Baryogenesis

A new particle state near the EW scale can drive the electroweak phase transition (EWPT) **strongly first order**

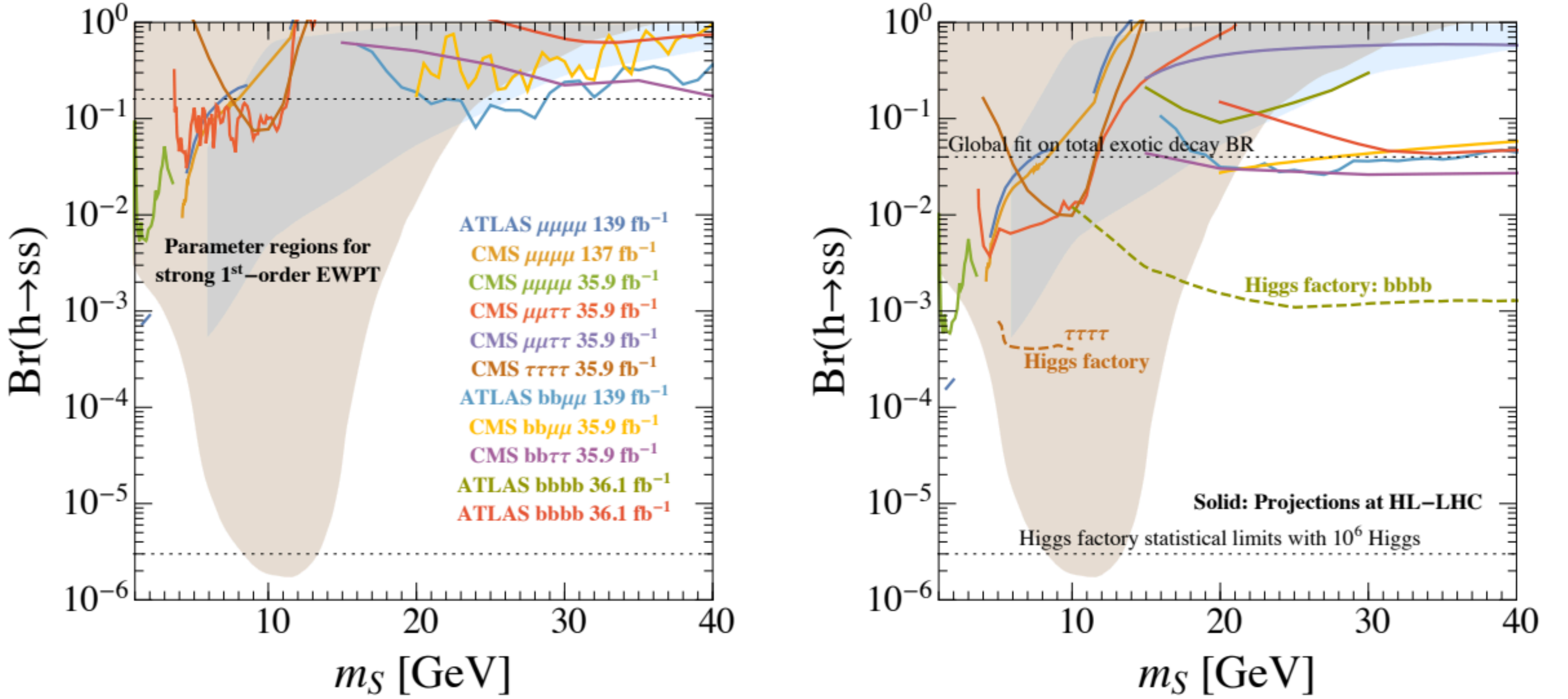
EWPT: New light scalar

1st order Phase Transition (PT) via a light particle (s) coupling with Higgs

New degree of freedom below ~ m_Z, it must be a **singlet-like scalar (s)**

Requirement: sizeable coupling with the SM-like Higgs

$$h \to ss \to XXYY$$

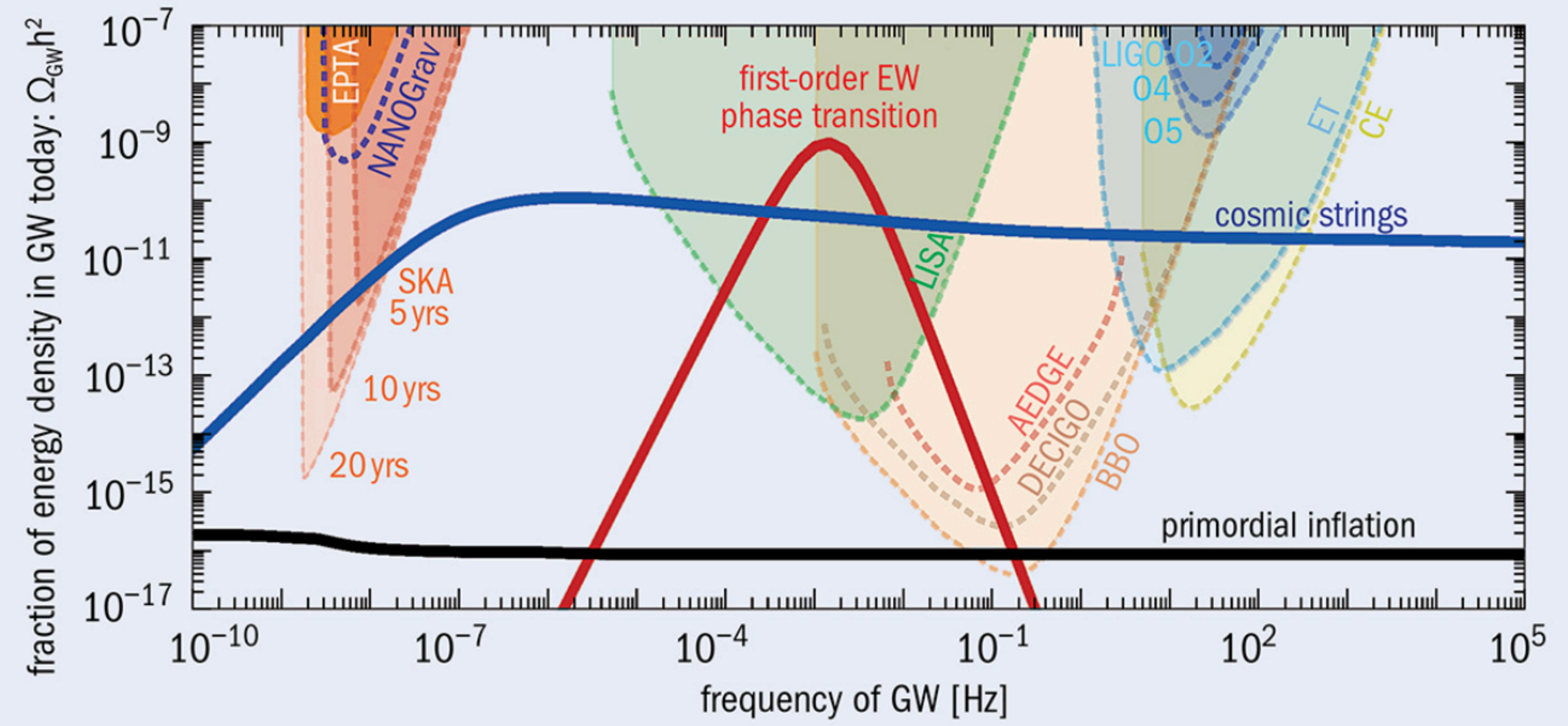


arXiv:2203.08206

Stochastic Gravitational Wave Background

During 1st order PT:

- Fluid velocities in the vicinity of colliding bubbles will generate gravitational waves (GWs)
- Appear as noise in GW detectors with a frequency (in the mHz region)
- **Detectable by the future space-based interferometer LISA.**



Primordial peak The stochastic gravitational-wave background inherited from a first-order electroweak phase transition (red) compared to the much broader backgrounds expected from inflation (black) and cosmic strings (blue), as well as sensitivity curves of future experiments. Credit: P Simakachorn

CERN Courier

Exotics Higgs at Future Lepton Colliders

Future Colliders

CEPC: unpolarized electron-positron collisions

- CM energy = **240 GeV**
- Considered luminosity = **5 ab^{-1}**

FCC-ee: unpolarized electron-positron collisions

- CM energy = **240 GeV**
- Considered luminosity = **30 ab^{-1}**

ILC: polarized electron-positron collisions

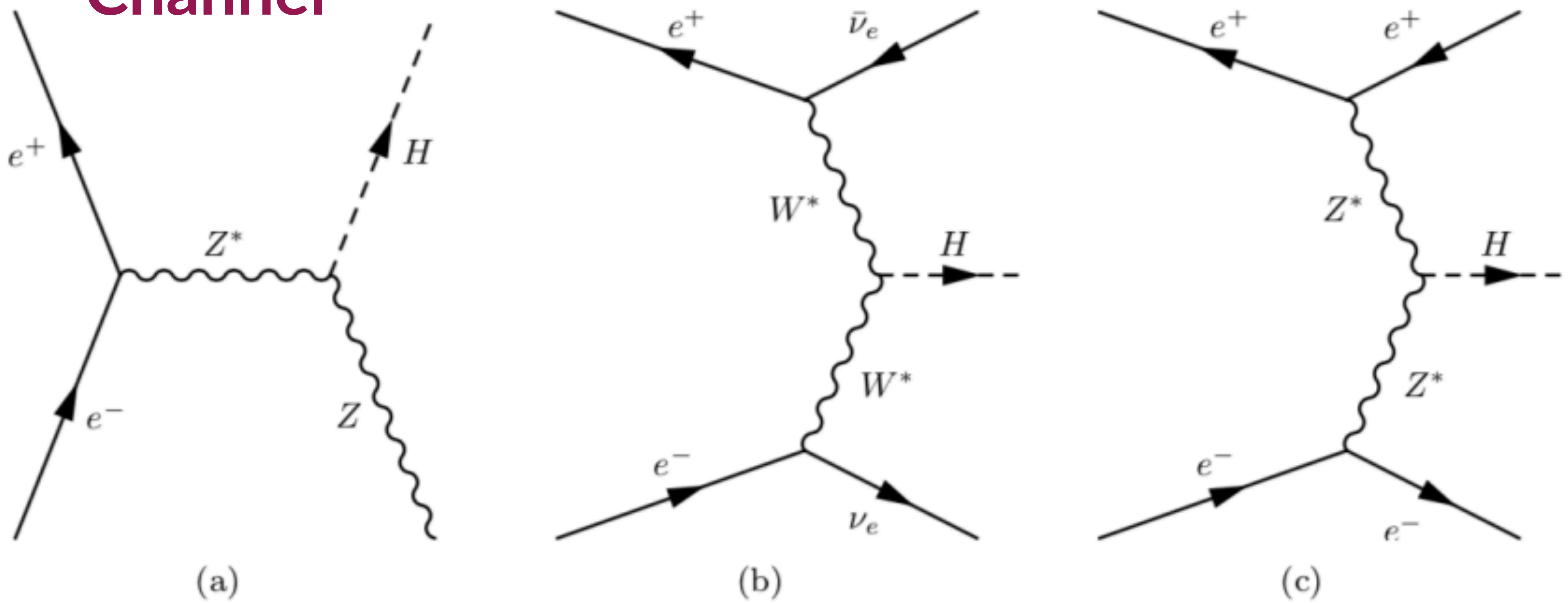
- beam polarization of $p(e^-,e^+) = (-0.8,+0.3)$
- CM energy = **250 GeV**
- Considered luminosity = **2 ab^{-1}**

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\mathrm{inst}}$ $[10^{34}]\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$\mathscr{L}$ $[\mathrm{ab}^{-1}]$	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5 (+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5 (+1)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5 (+1-2)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8 (+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

arXiv:1905.03764

Higgs production and decays

Dominant Production Channel



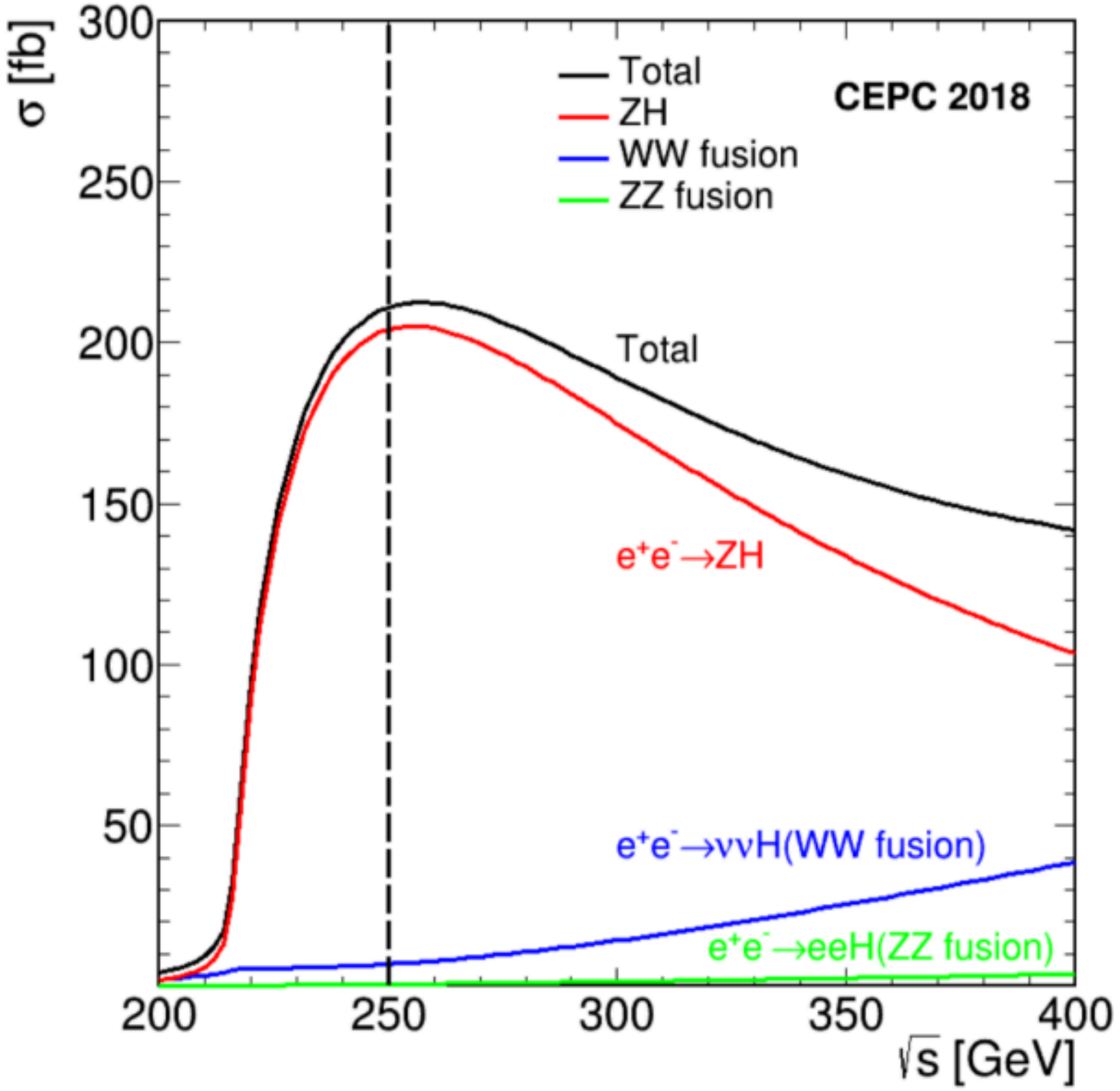
ZH associate production

W fusion

Z fusion

Vector Boson fusion (VBF)

Production cross sections



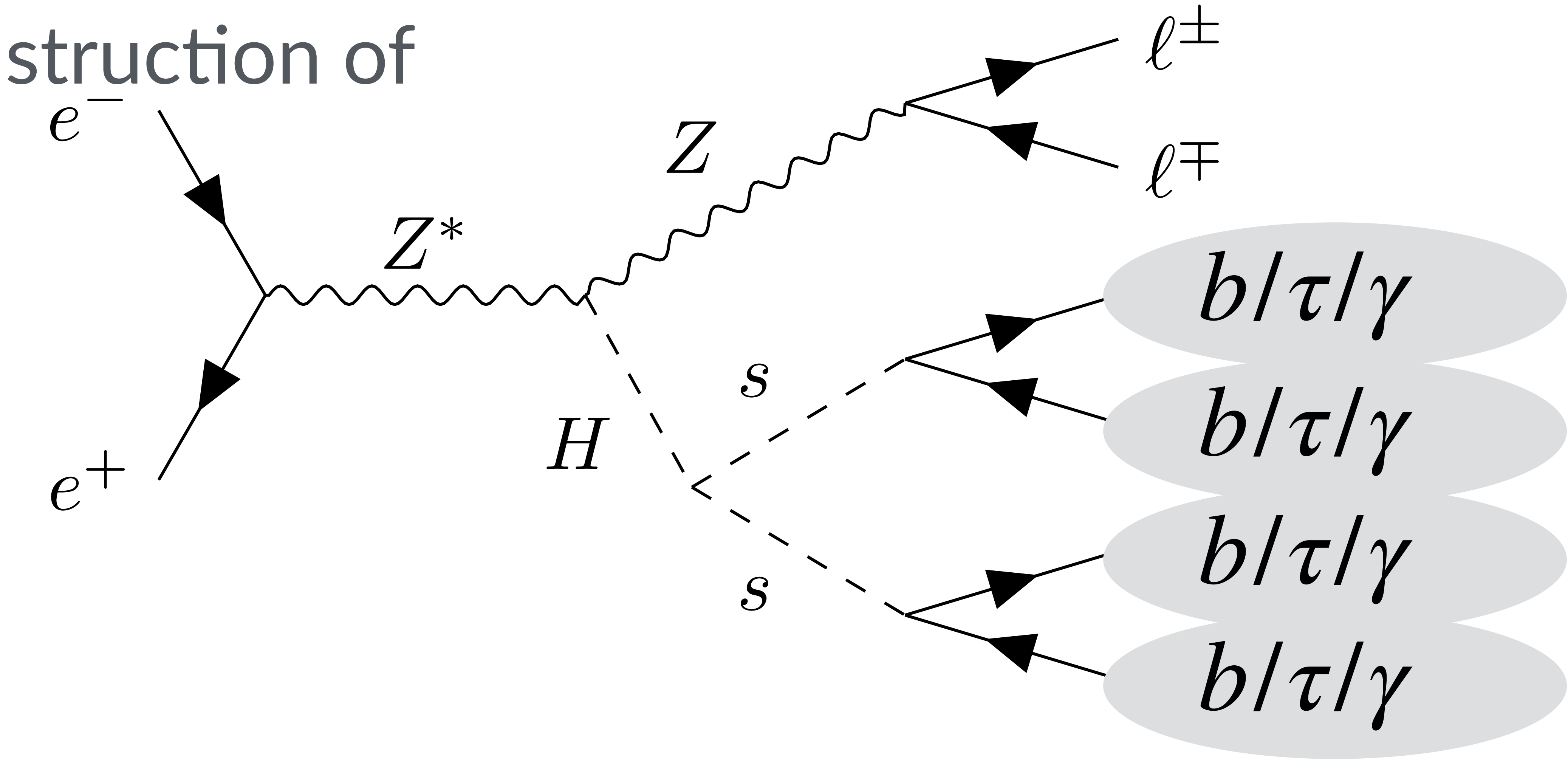
- **ZH process reaches maximum at ~250 GeV**, decreases asymptotically as 1/s
- VBF proceeds through t-channel, increases logarithmically as $\ln^2(s/M_V^2)$
- **VBF dominated by W fusion** due to small neutral-current Zee coupling

arXiv:1810.09037

ZH: H—> ss

Cleanest Channel: Z boson visible decay to two leptons
- Higgs spectator

Known initial state:
- Subtracting the Z-boson 4-momentum enables the reconstruction of the Higgs 4-momentum



Recoil Mass: $$m_{\text{recoil}} \equiv \sqrt{s - 2\sqrt{s}E_{\ell\ell} + m_{\ell\ell}^2}$$

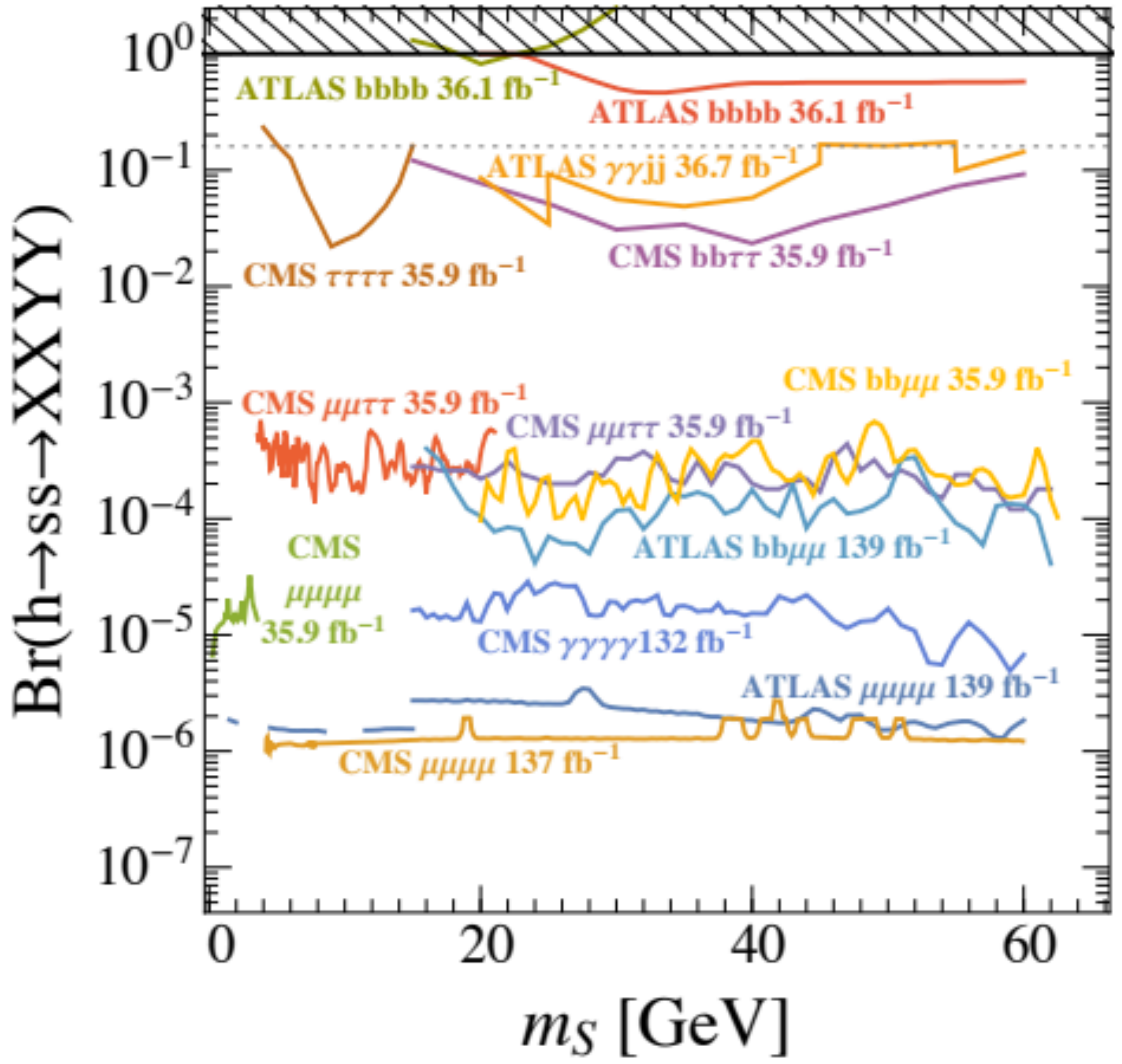
Recoil mass should peak at Higgs mass
- Selection cut around Higgs mass will remove most if of the background

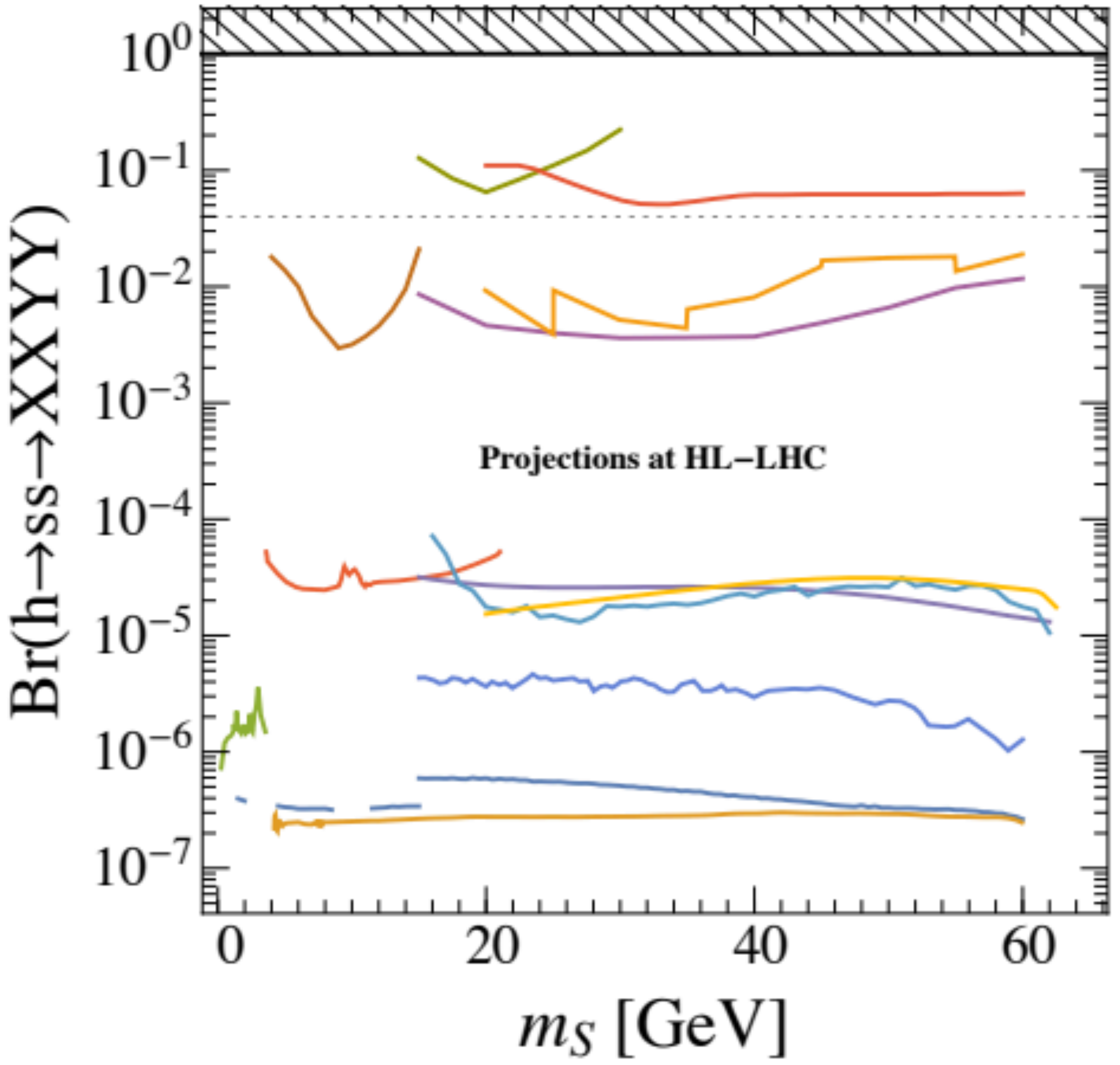
Better sensitivity in hadronic final states

LHC: Indirect limit on Exotics Higgs Branching Ration (Br) = 16%
HL-LHC (3 fb^{-1}): Forecast to constrain total exotic branching ratio to <4%

- High sensitivity reach for the leptonic final states

4b and 4tau channel will improve significantly in lepton colliders





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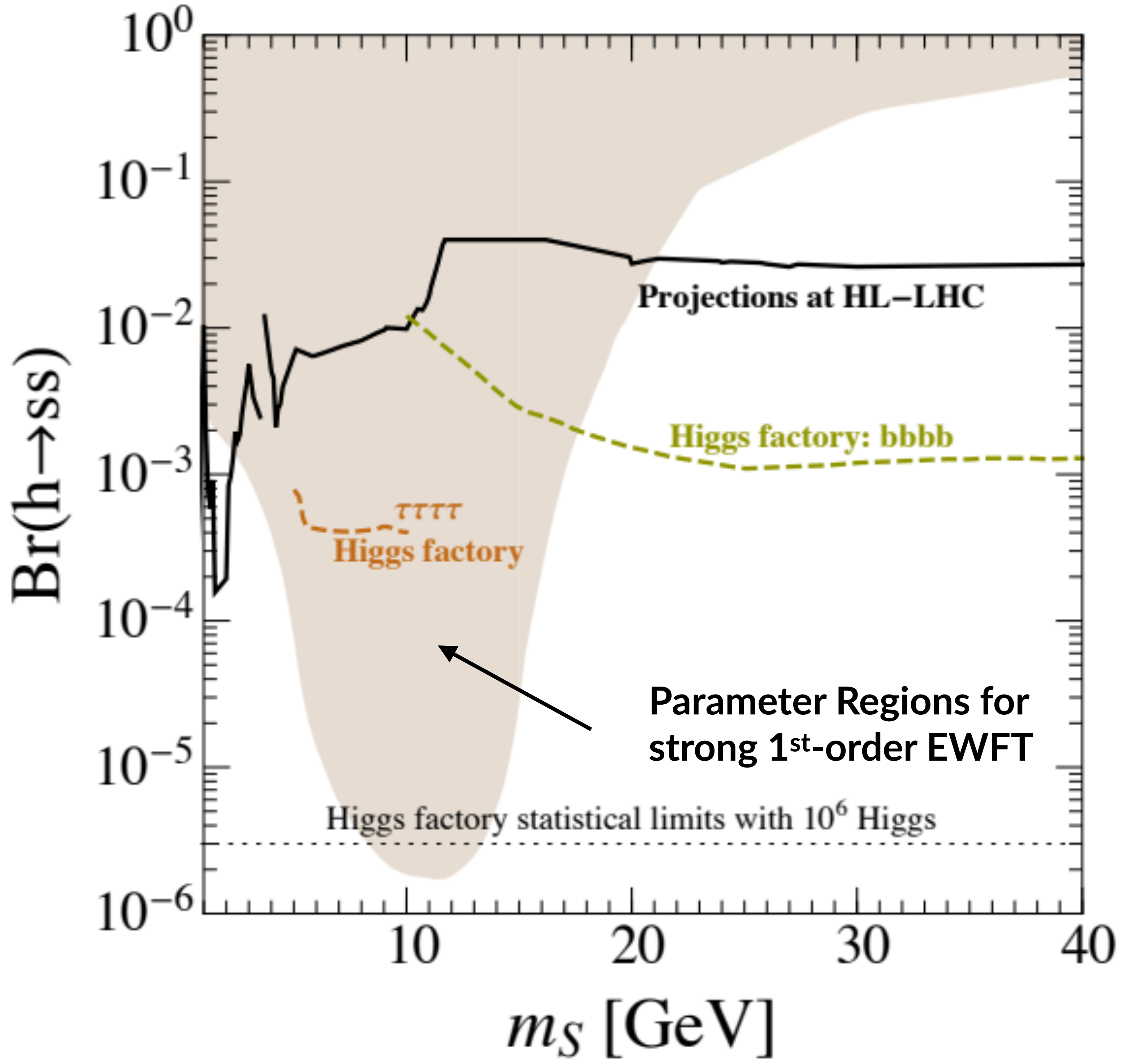


arXiv:2209.07510

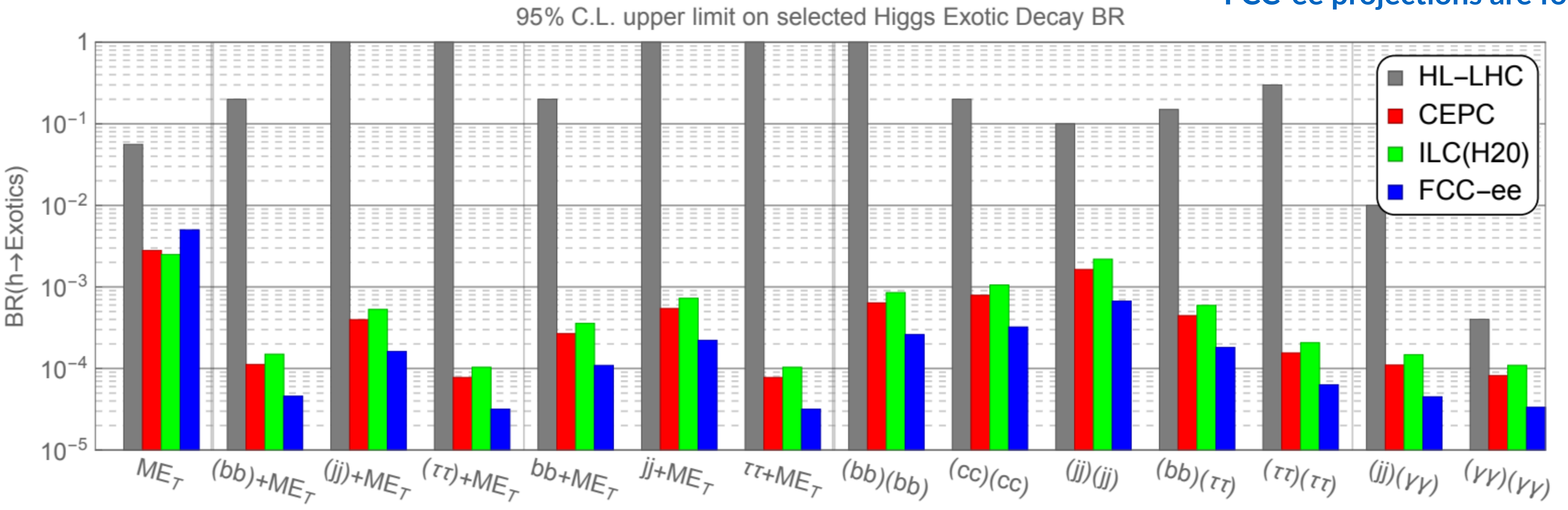
Exotic decays of the 125 GeV Higgs boson

Limit comparison between HL-LHC, CEPC, ILC (H20) and FCC-ee

Exotic Higgs decay channel difficult to constrain at the LHC

- Improvement in exotic decays from the lepton collider Higgs factories

FCC-ee projections are for 30 ab^{-1}



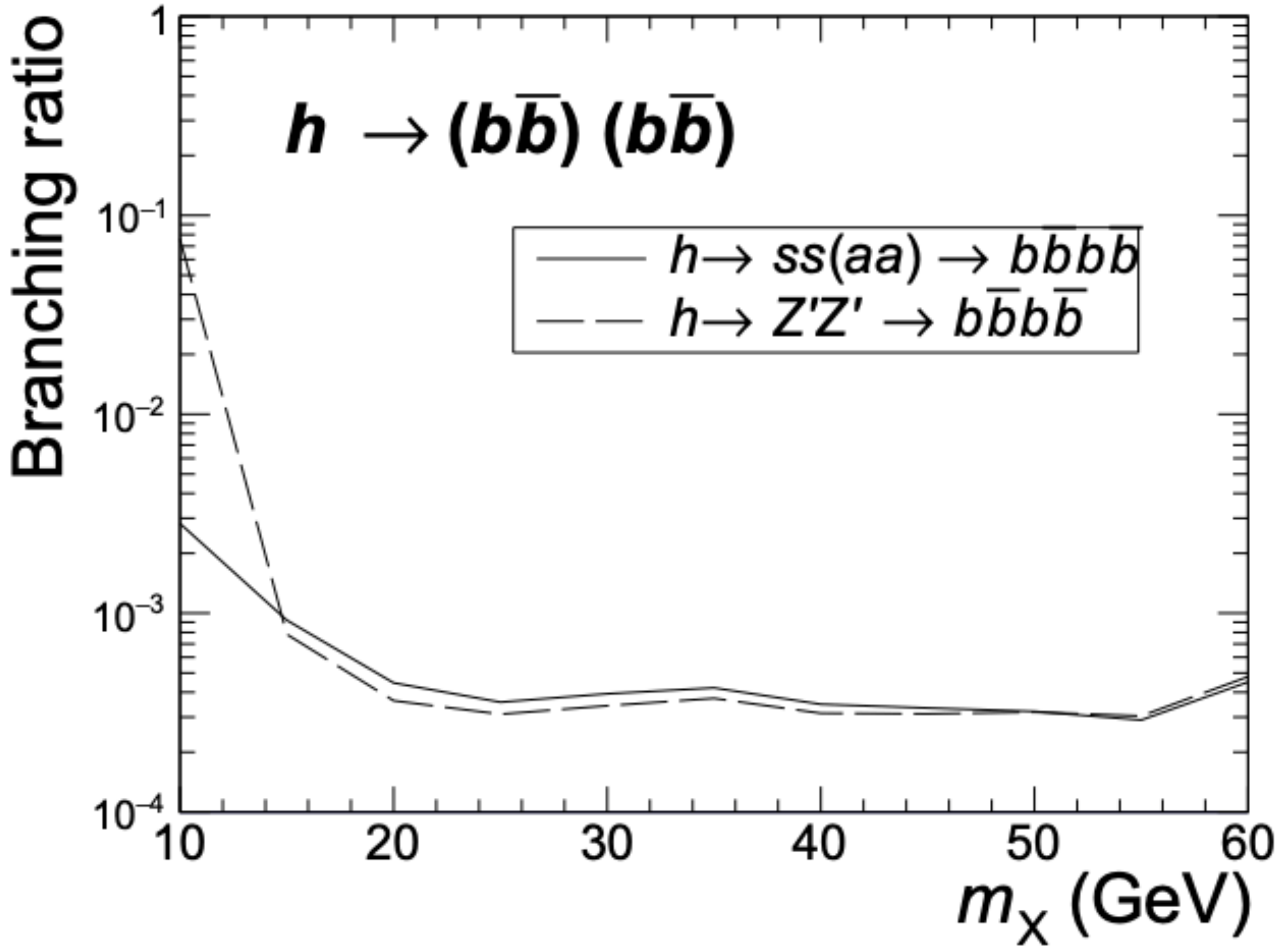
arXiv:1612.09284

4b Analysis at ILC

Target of this study: $e^+e^- \to ZH$, $Z \to ee/\mu\mu$, $H \to \varphi\varphi \to 4b$

- Mediator mass range: 15 - 60 GeV
- Mediators decay promptly

Limits from previous Pheno study:
Br(H—>4b) < 0.1%



arXiv:1612.09284

Setup:

- Full ILD detector simulation with latest model

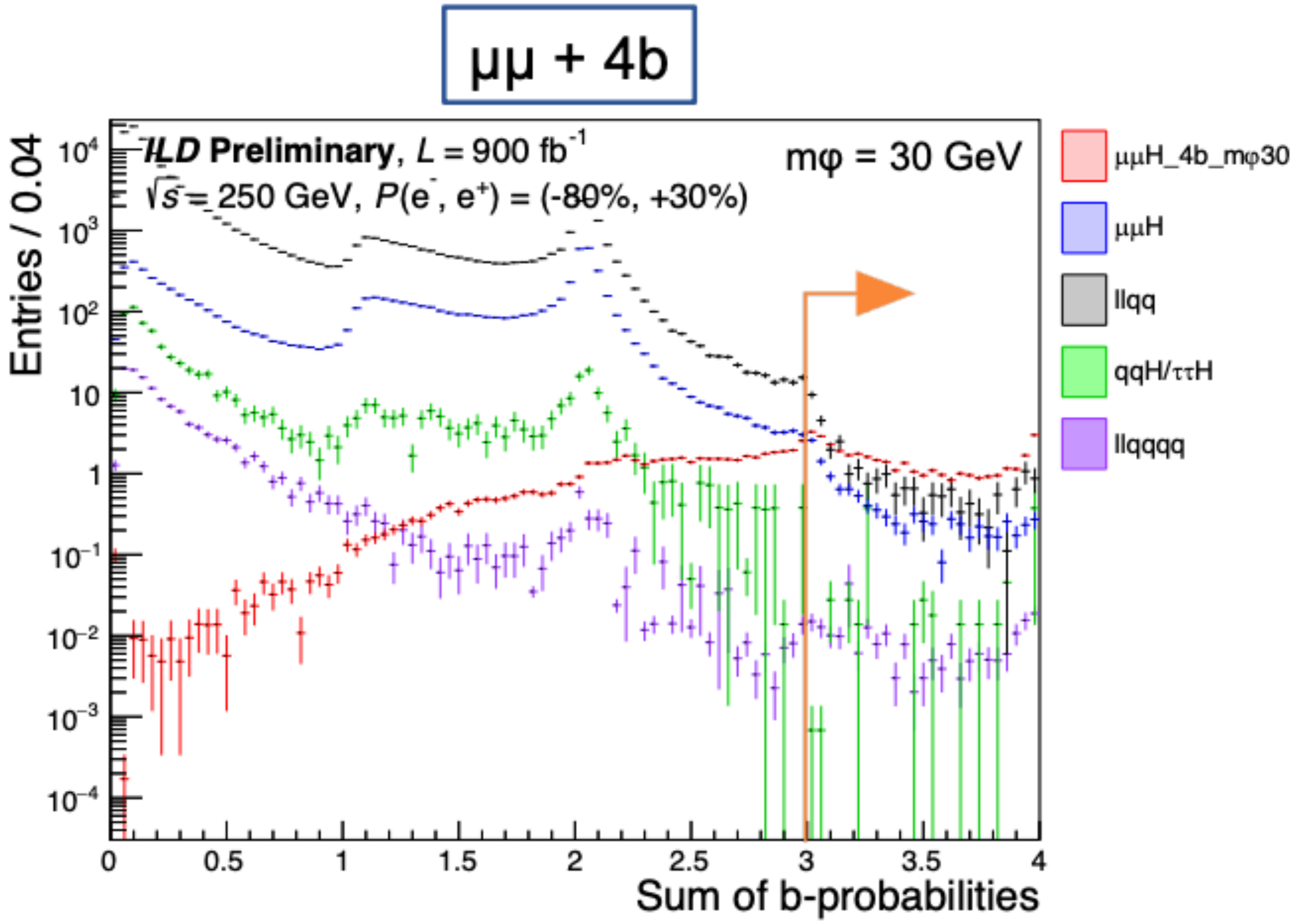
- ILC H20 scenario of $\sqrt{s}$ = 250 GeV, Luminosity = 2 ab^{-1}
- **Polarization:** P(e- ,e+) = { (-80%,+30%), (+80%,-30%) }

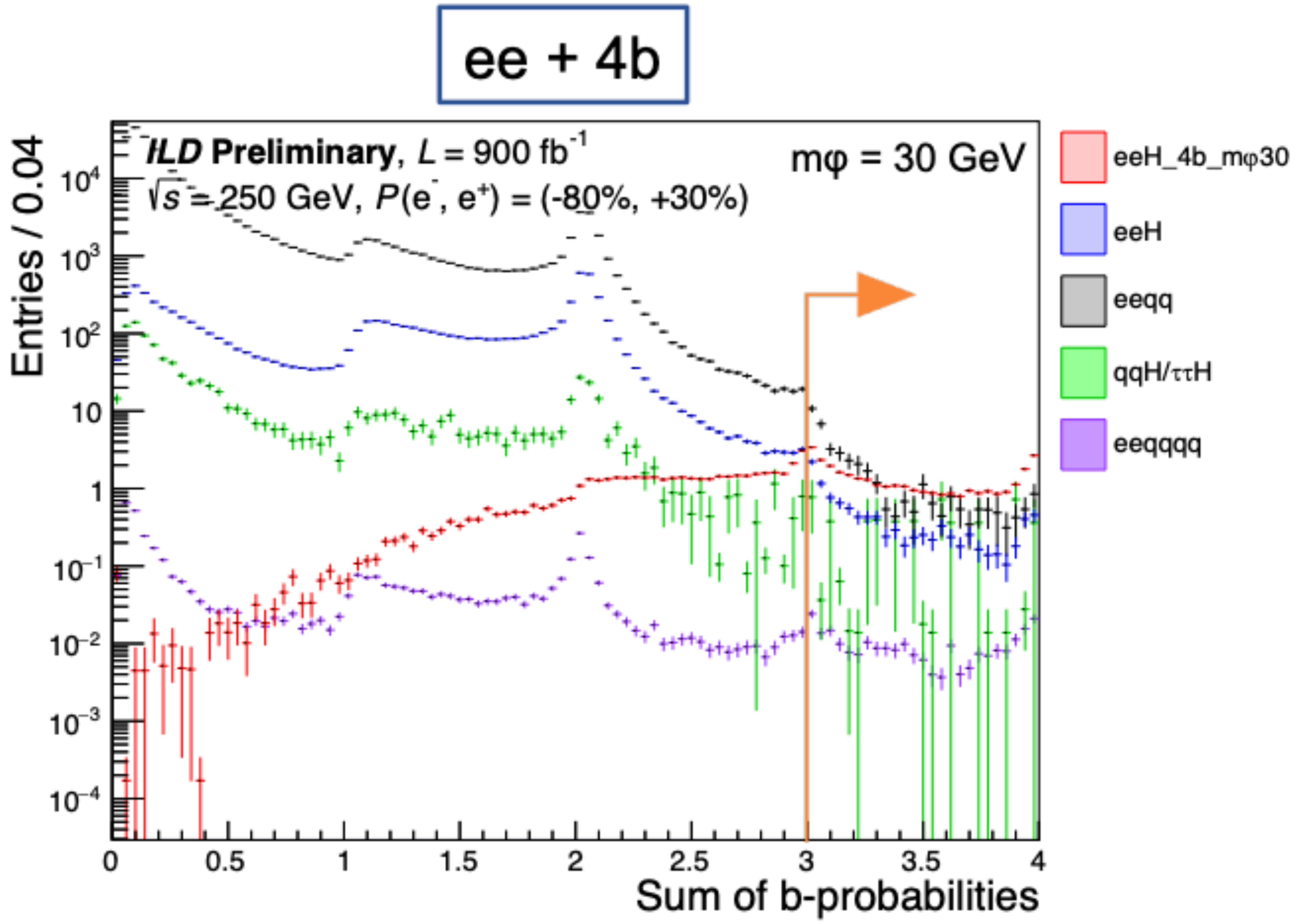
Basic Event Selection

- The number of isolated [muons / electrons] = 2
- The sum of b-probabilities of 4 jets > 3
- The recoil mass within (124, [160 / 180]) GeV

Event Selection: b-probability

- **Jet clustering & Flavor tagging:** LCFIPlus
  - Durham forced to 4 jets
- b-probability is defined for each jet
- Output from LCFIPlus flavor tagging processor





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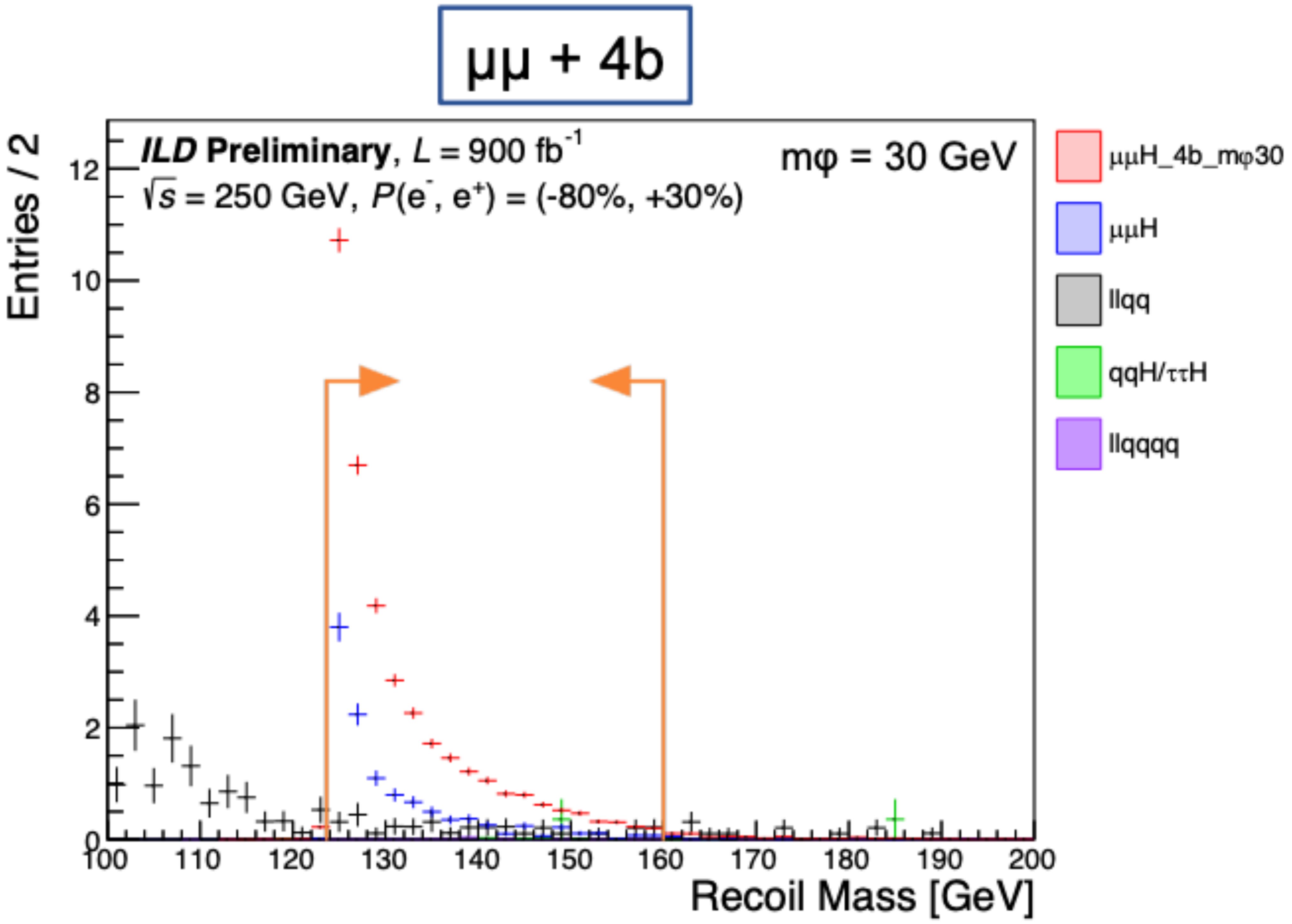
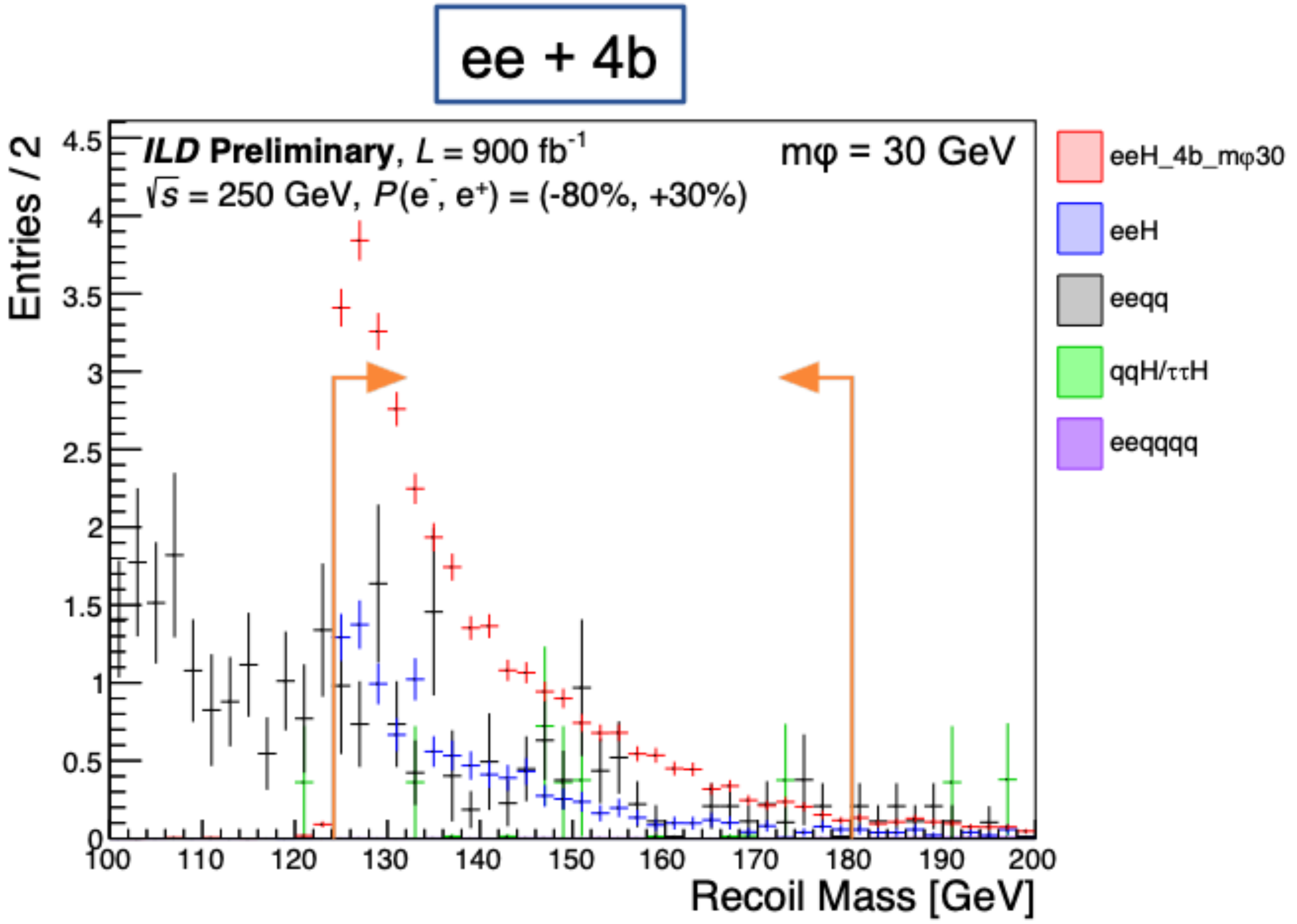
Event Selection: Recoil Mass Cut

Cut conditions:

- Muon: 124 GeV < Recoil mass < 160 GeV
- Electron: 124 GeV < Recoil mass < 180 GeV

$$m_{\text{recoil}} \equiv \sqrt{s - 2\sqrt{s}E_{\ell\ell} + m_{\ell\ell}^2}$$





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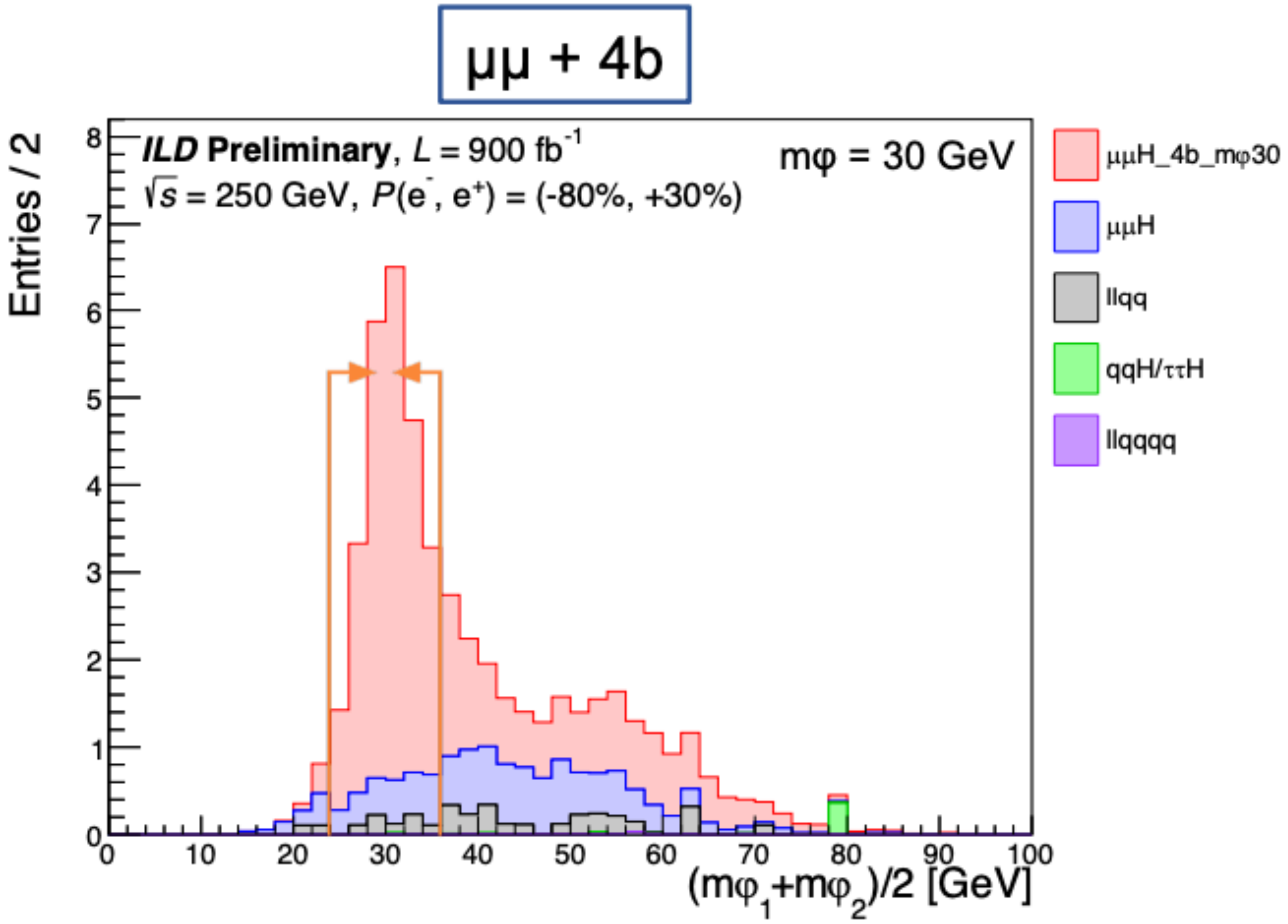
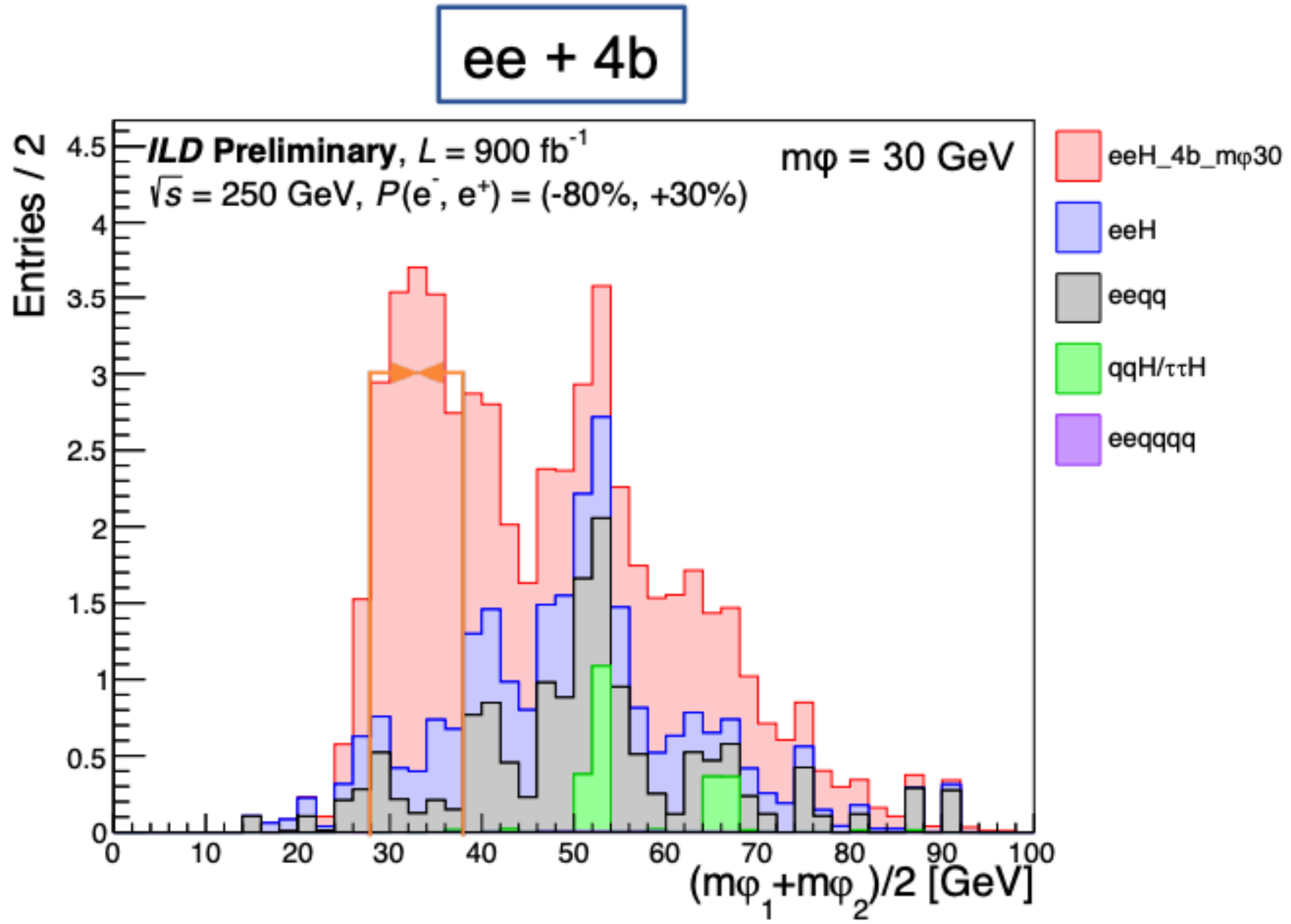
Mediator Mass

Final Optimization

- After the event selection, a clear peak can be seen in the mediator mass distribution on the assumption of BR(H→4b) = 1%.
- The final cut conditions of mediator mass are determined to optimize the significance





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95% CL Limit on scalar mass

95% C.L. upper limit on BR(H→4b) ~ 0.1% for all mφ

ILD Preliminary

μμ + 4b

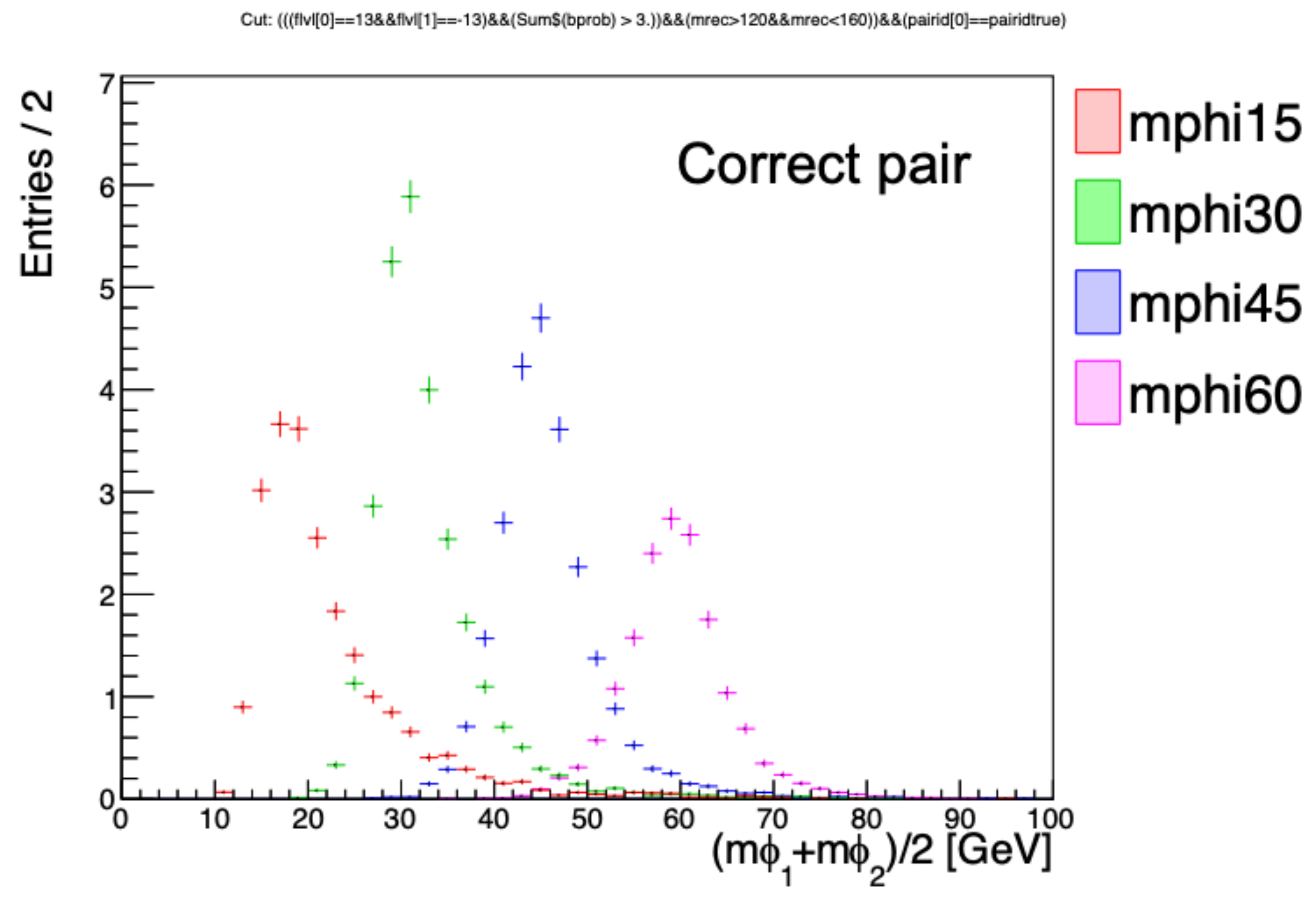
	95% C.L. upper limit on BR(H→4b)		
mφ	(-0.8,+0.3)	(+0.8,-0.3)	combined
15	0.11%	0.14%	0.09%
30	0.14%	0.17%	0.11%
45	0.15%	0.20%	0.12%
60	0.14%	0.19%	0.11%

ee + 4b

	95% C.L. upper limit on BR(H→4b)		
mφ	(-0.8,+0.3)	(+0.8,-0.3)	combined
15	0.19%	0.24%	0.15%
30	0.21%	0.25%	0.16%
45	0.24%	0.26%	0.18%
60	0.22%	0.26%	0.17%

mφ	ee + μμ
15	0.07%
30	0.09%
45	0.10%
60	0.09%

Muon channel



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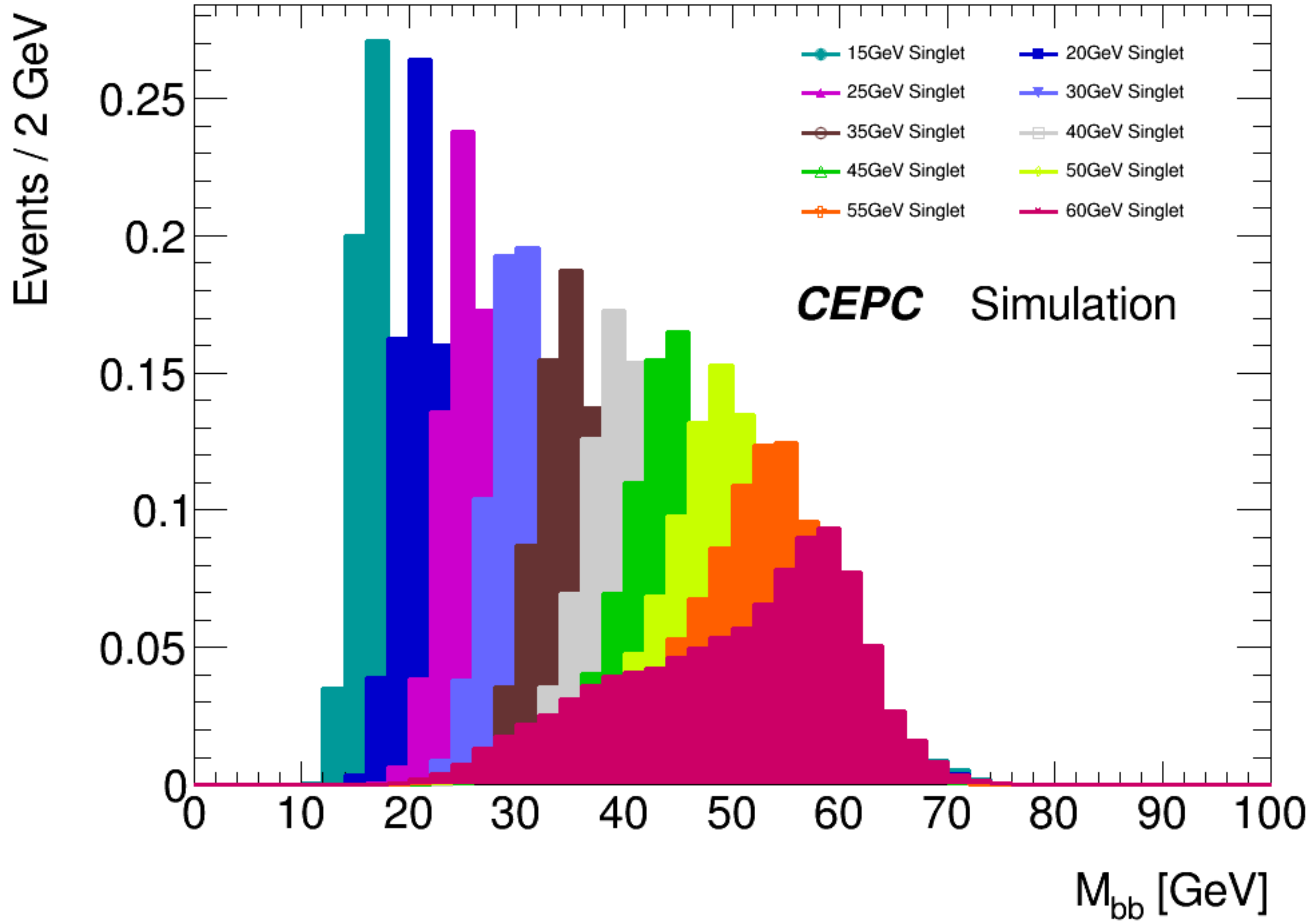
4b Analysis at CEPC

Target of this study: $e^+e^- \to ZH$, $Z \to ee/\mu\mu$, $H \to ss \to 4b$
- Mediator mass range: 15 - 60 GeV
- Mediators decay promptly

Setup:
- $\sqrt{s}$ = 250 GeV, Luminosity = 5 ab^{-1}
- Detector simulation with GEANT4 (CEPC_v4)
- Generator: Madgraph5 and Pythia8

- **Jet clustering & Flavor tagging:** LCFIPlus
  - Durham forced to 4 jets



Look at Xuliang Zhu's talk for more details

arXiv:2203.10184

BDT-based analysis

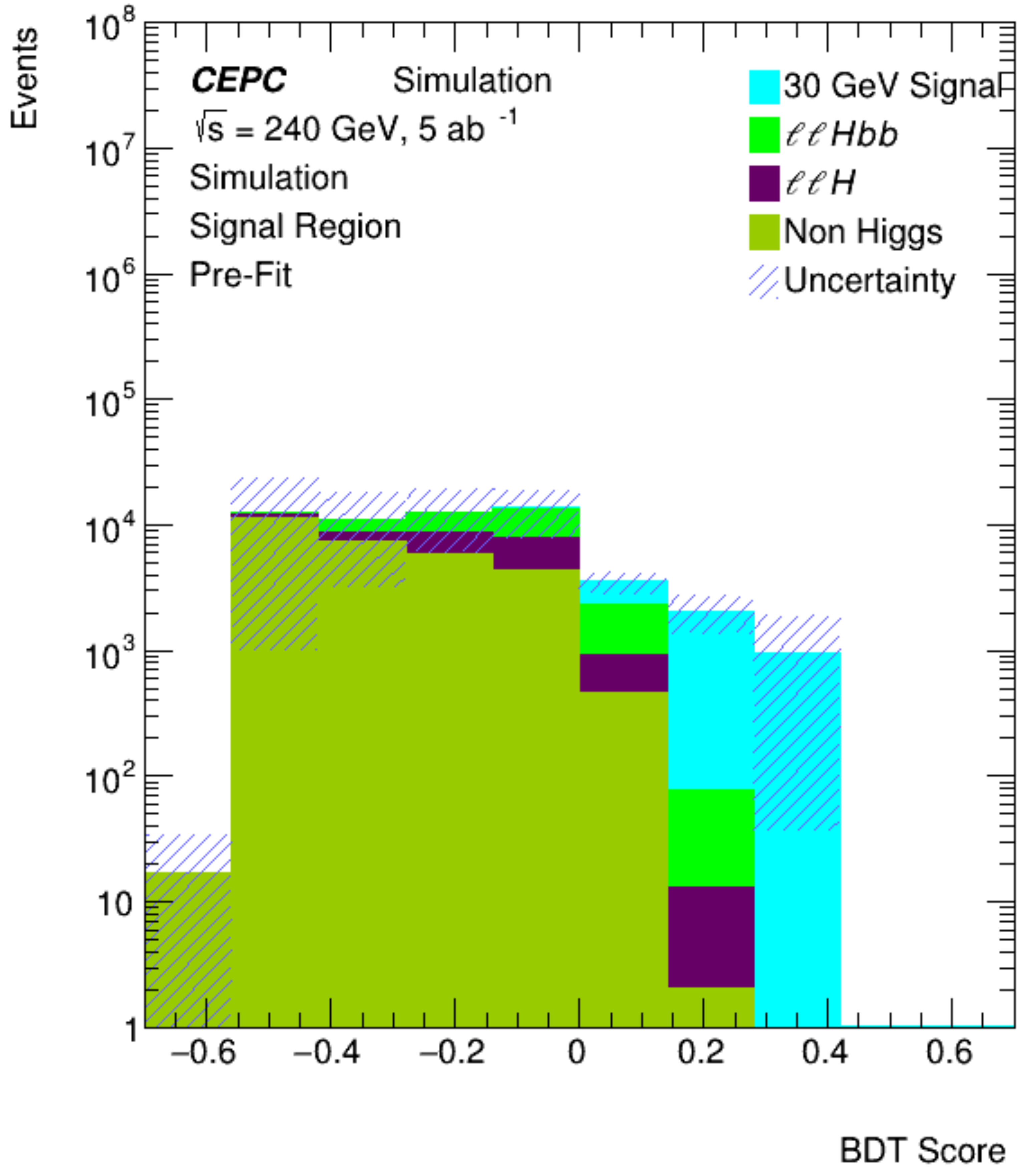
Trained the variables after some loose selections :

- Same flavor opposite sign lepton pair with $E_\ell > 20$ GeV
- $m_{\ell\ell}$ within the Z mass window [77.5, 104.5] GeV
- Recoiled mass of the lepton pair system should be within [124,140] GeV

BDT trained on 12 variables

Main discriminant: BDT Score —> used for setting limits

Process	Yields
$\ell\ell Hbb$	130.7 ± 104.4
$\ell\ell H$	15.1 ± 19.5
Non Higgs	14.3 ± 18.6
Total Bkg	160.1 ± 107.8
Signal ($m_s = 30$ GeV)	2210.1 ± 1731.1



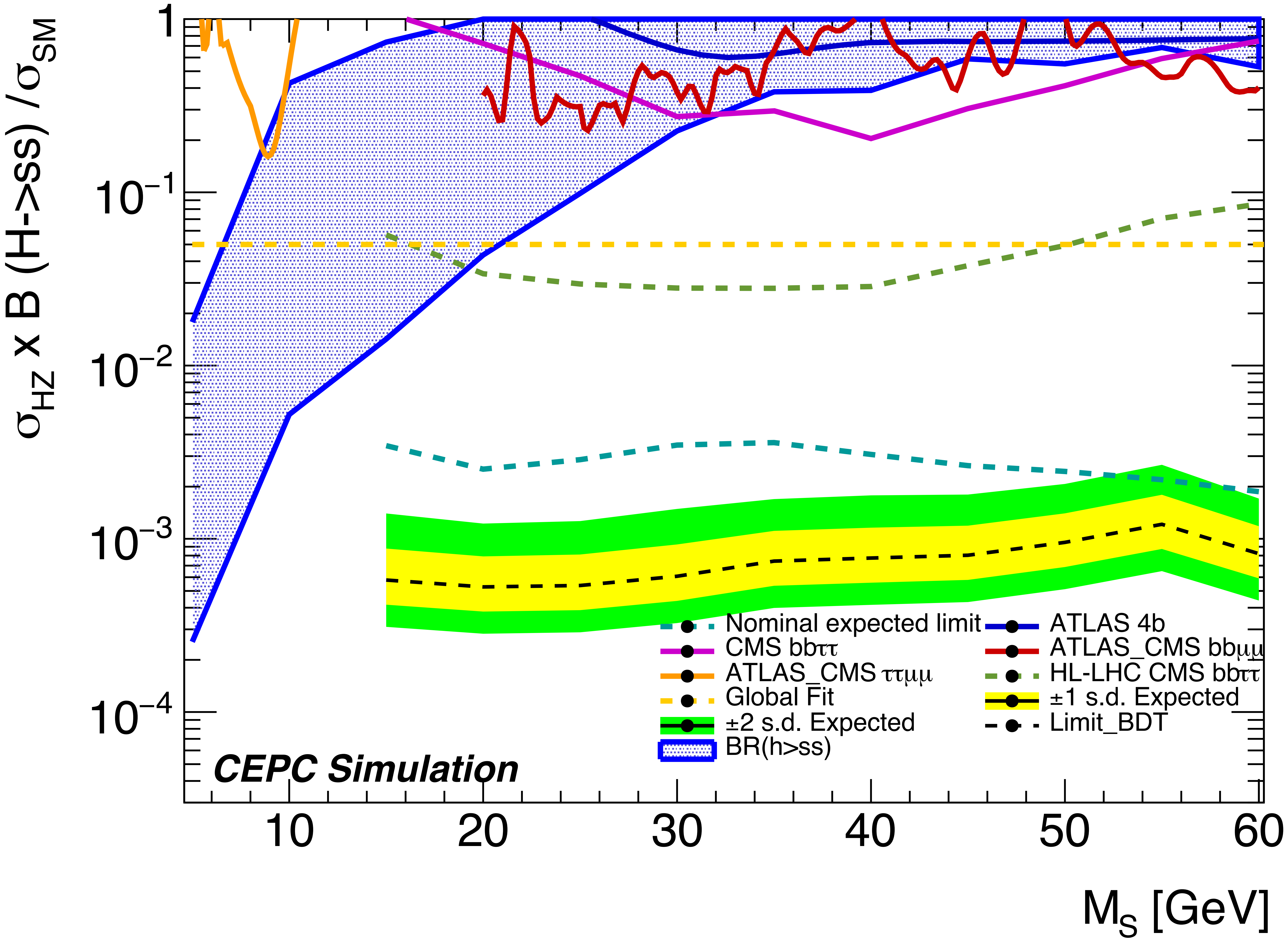
arXiv:2203.10184

95% CL Limit on scalar mass

The analysis considers some systematics uncertainties coming from:

- Background estimation
- b-tagging
- Jet Energy Resolution

Final Limits are < 0.1% for s between 15 GeV and 60 GeV



arXiv:2203.10184

4 Tau Final state

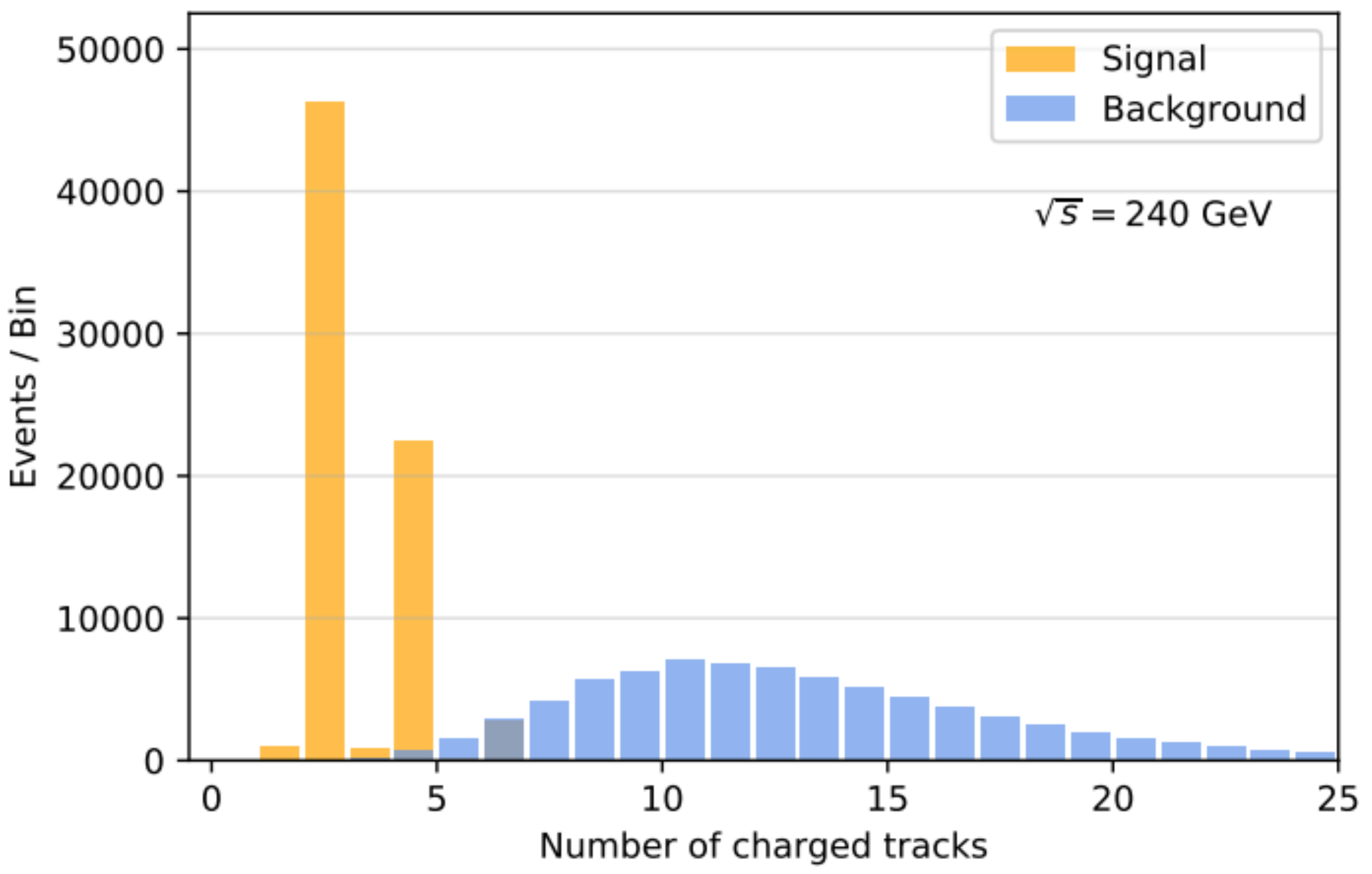
Target of this study: $e^+e^- \to ZH$, $Z \to ee/\mu\mu$, $H \to ss \to 4\tau$

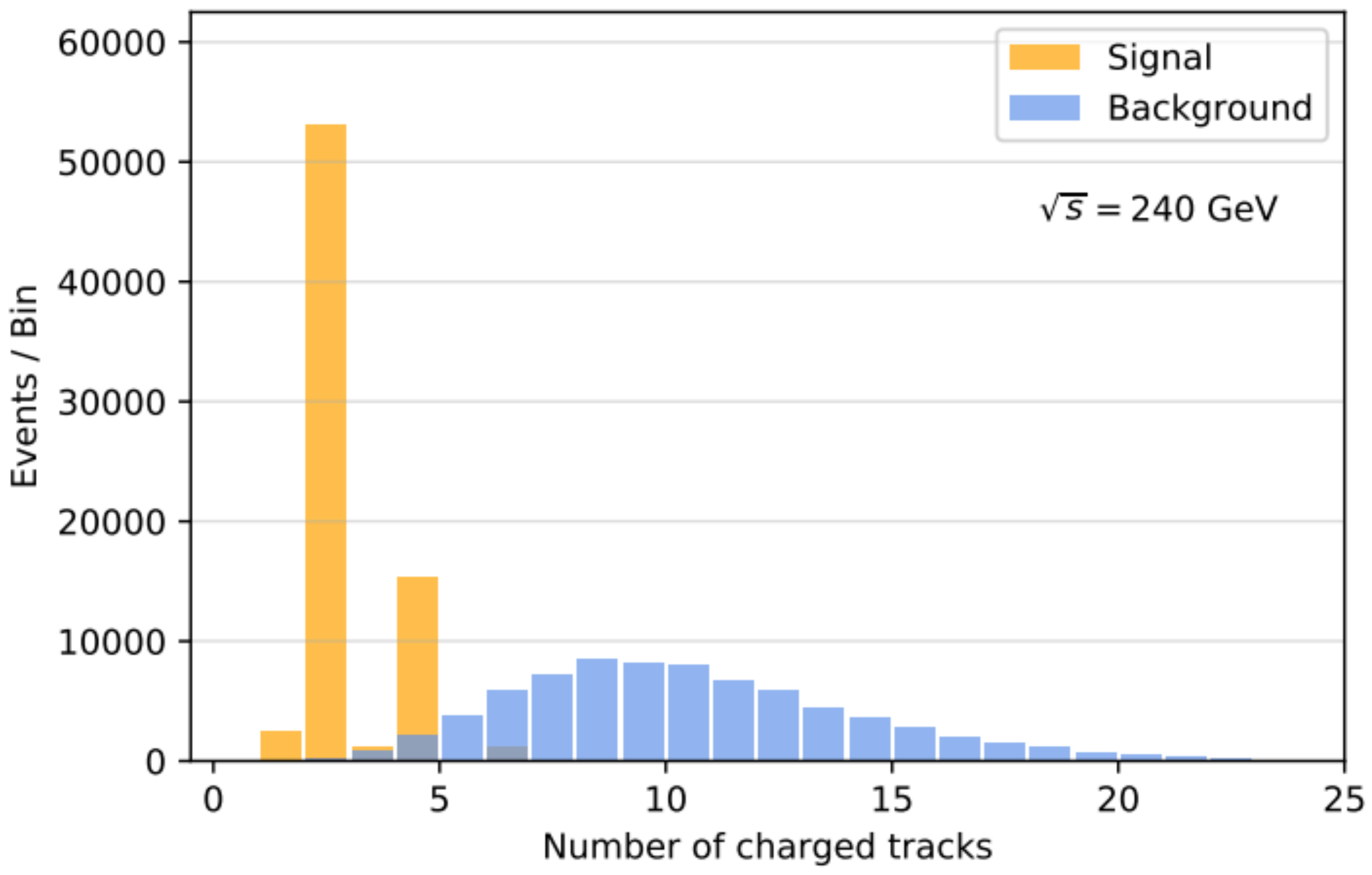
Studied exotics Higgs with m< 10 GeV

- $\sqrt{s}$ = 250 GeV, Luminosity = 5 ab^{-1}

Selection:

- $|m_{\ell\ell} - m_Z| < 10$ GeV
- Charged track multiplicity within two hardest fat jets (R=1.3)





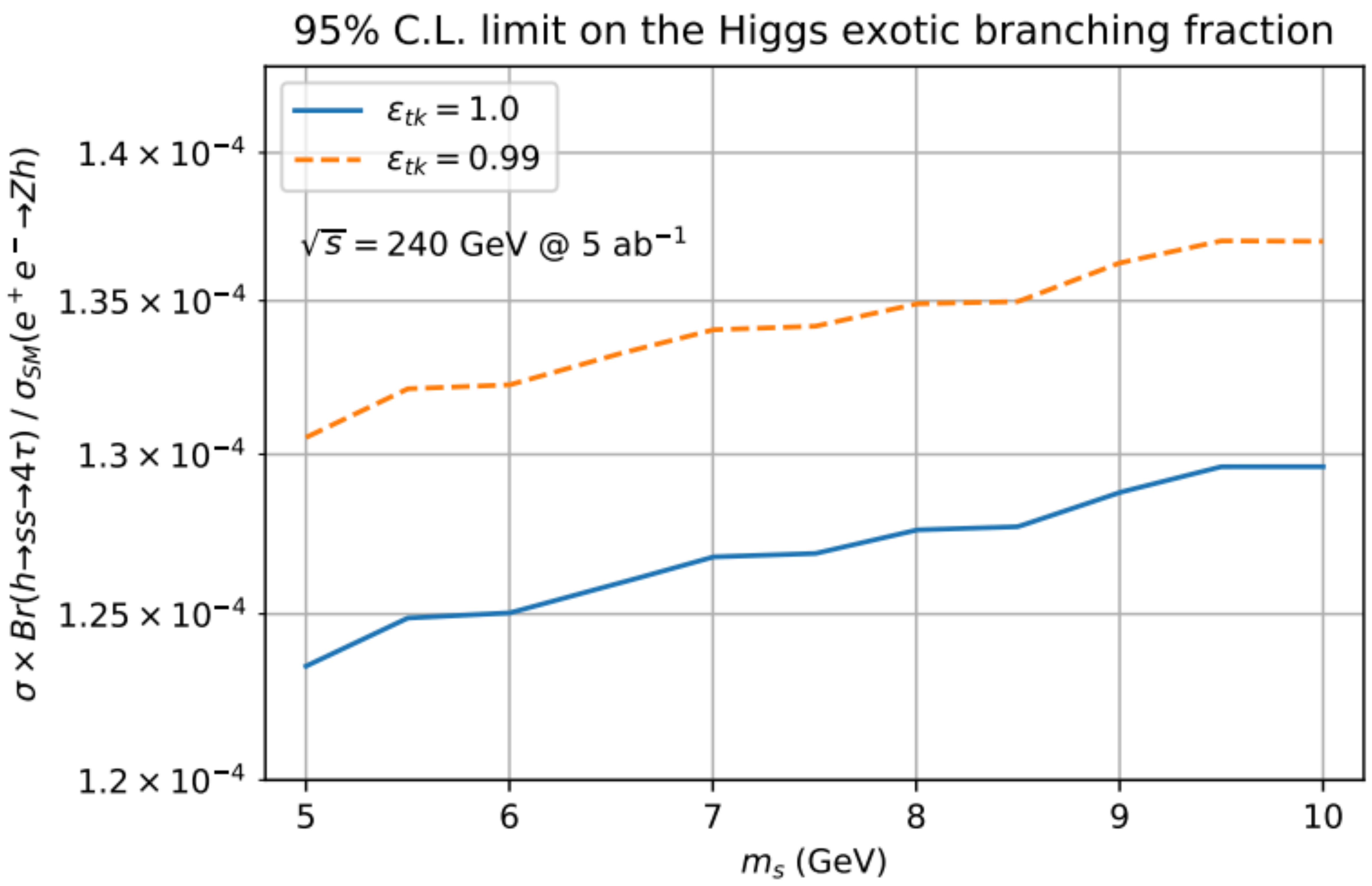
arXiv:2110.13225

95% CL Limit on scalar mass

Two Scenarios are consider:

- Perfect tracking
- Flat track reconstruction efficiency of 0.99

	Simulated events	Selected events	Efficiency	Events in 5 ab^{-1}
Signal ($m_s = 7.5$ GeV)	5×10^5	168995	0.338	27039.2 $\times Br$
SM background	100×10^5	54	5.4×10^{-6}	0.2997
Signal, $\epsilon_{tk} = 0.99$	5×10^5	162558	0.3251	26009.3 $\times Br$
SM background, $\epsilon_{tk} = 0.99$	100×10^5	63	6.3×10^{-6}	0.3497



Final Limits are < 0.013% for s between 5 - 10 GeV

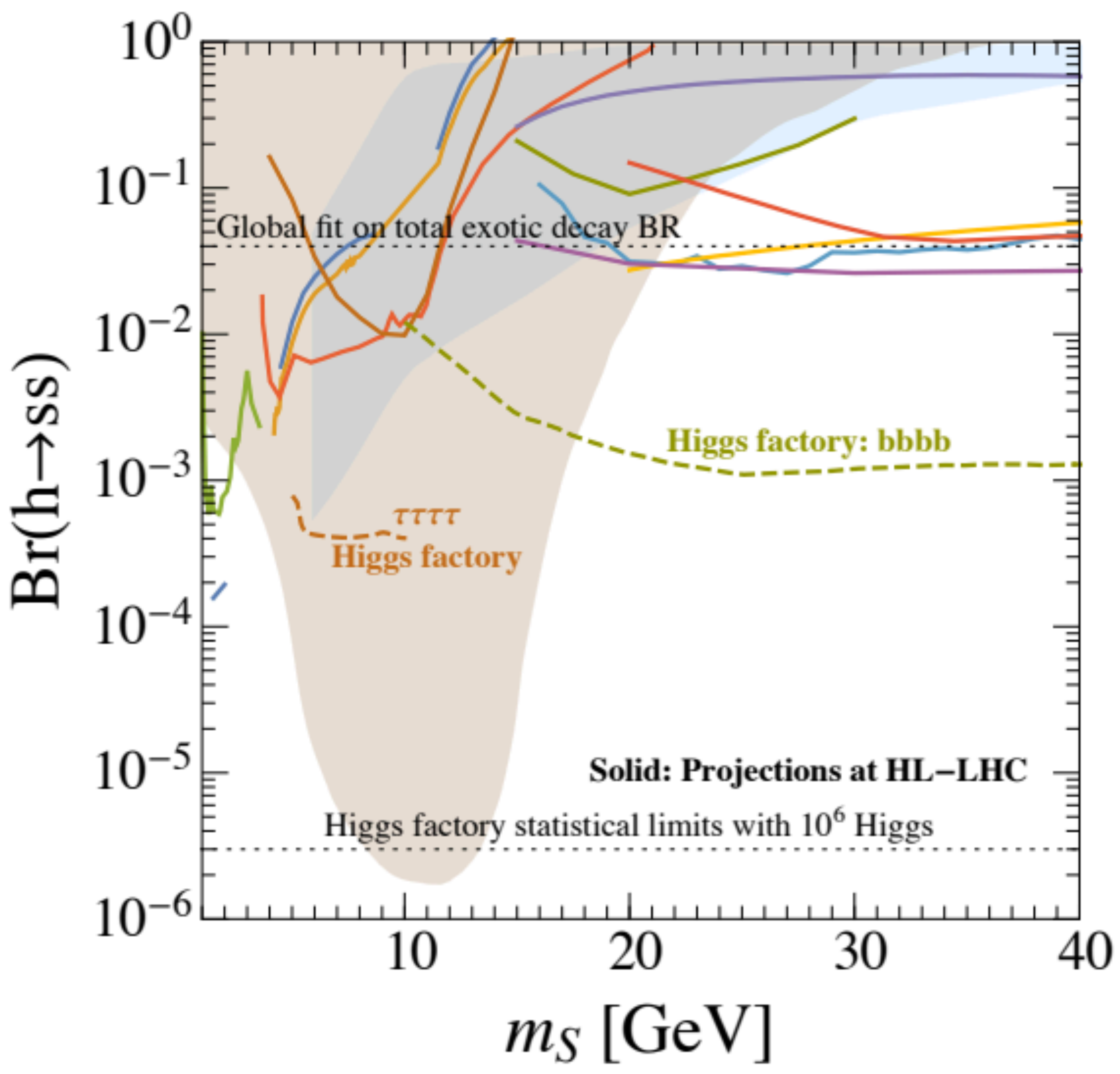
arXiv:2110.13225

Summary

- Strong 1st order EWPT can be obtained by adding a light scalar particle (< m_Z)
  - Generates stochastic gravitational-wave background

- We can search for these exotics scalar particles at the collider experiments

- Future e+e- collider like CEPC, FCC-ee, ILC will improve the sensitive of the hadronic final states (b, tau) significantly



arXiv:2203.08206

Thank You!

BACKUP

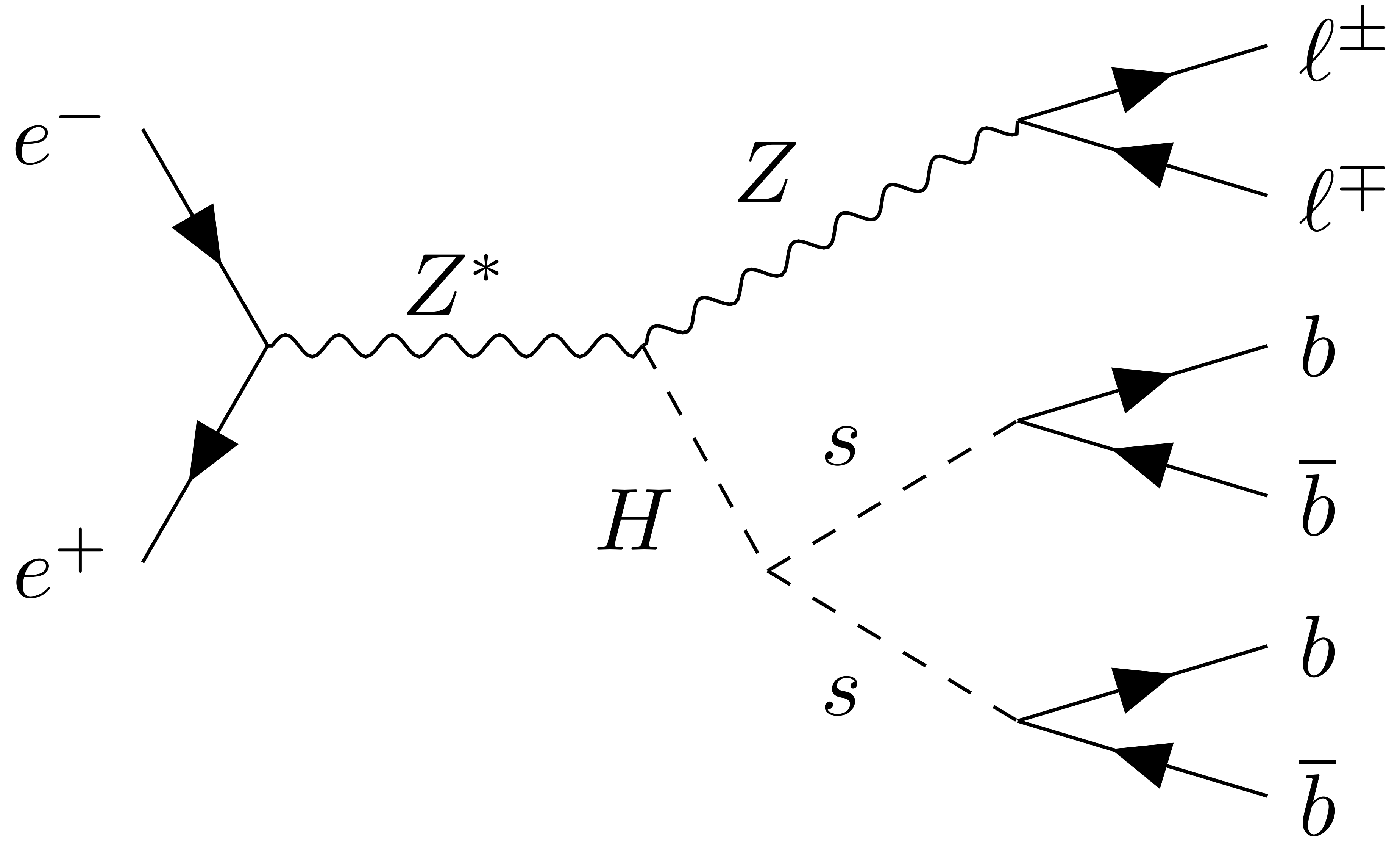
Limits on Exotics Higgs Decay

Decay Mode	95% C.L. limit on Br				
	LHC	HL-LHC	CEPC	ILC	FCC-ee
$\not{E}_T$	0.23 [49, 50]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b})+\not{E}_T$	–	[0.2]	1×10^{-4}	2×10^{-4}	5×10^{-5}
$(jj)+\not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)+\not{E}_T$	–	[1]	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$b\bar{b}+\not{E}_T$	–	[0.2] [39]	3×10^{-4}	4×10^{-4}	1×10^{-4}
$jj+\not{E}_T$	–	–	5×10^{-4}	7×10^{-4}	2×10^{-4}
$\tau^+\tau^-+\not{E}_T$	–	–	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$(b\bar{b})(b\bar{b})$	1.7 [51]	(0.2)	4×10^{-4}	9×10^{-4}	3×10^{-4}
$(c\bar{c})(c\bar{c})$	–	(0.2)	8×10^{-4}	1×10^{-3}	3×10^{-4}
$(jj)(jj)$	–	[0.1]	1×10^{-3}	2×10^{-3}	7×10^{-4}
$(b\bar{b})(\tau^+\tau^-)$	[0.1]* [52]	[0.15]	$4\times10^{-4}*$	6×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]* [53]	[0.2$\sim$0.4]	$1\times10^{-4}*$	2×10^{-4}	5×10^{-5}
$(jj)(\gamma\gamma)$	–	[0.01]	1×10^{-4}	2×10^{-4}	3×10^{-5}
$(\gamma\gamma)(\gamma\gamma)$	[7×10^{-3}] [54]	$4\times10^{-4}*$	1×10^{-4}	1×10^{-4}	3×10^{-5}

95% CL limits on Higgs branching ratios

Channel	HL-LHC	ILC	FCC-ee
E_T^{miss}	0.056	.0025	.005
$b\bar{b}b\bar{b}$	0.2	9×10^{-4}	3×10^{-4}
$b\bar{b}E_T^{miss}$	0.2	2×10^{-4}	5×10^{-5}
$jj\gamma\gamma$	0.01	2×10^{-4}	3×10^{-5}

TABLE XII: Representative 95% CL limits on Higgs branching ratios to a pair of light scalars which then decay to the indicated channels.[50, 125]


e^-
e^+
Z^*
Z
H
s
s
$\ell^\pm$
$\ell^\mp$
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b
$\bar{b}$