New search strategies for exotic H→4b

using vector boson fusion and photons

Phenomenology Symposium 2023

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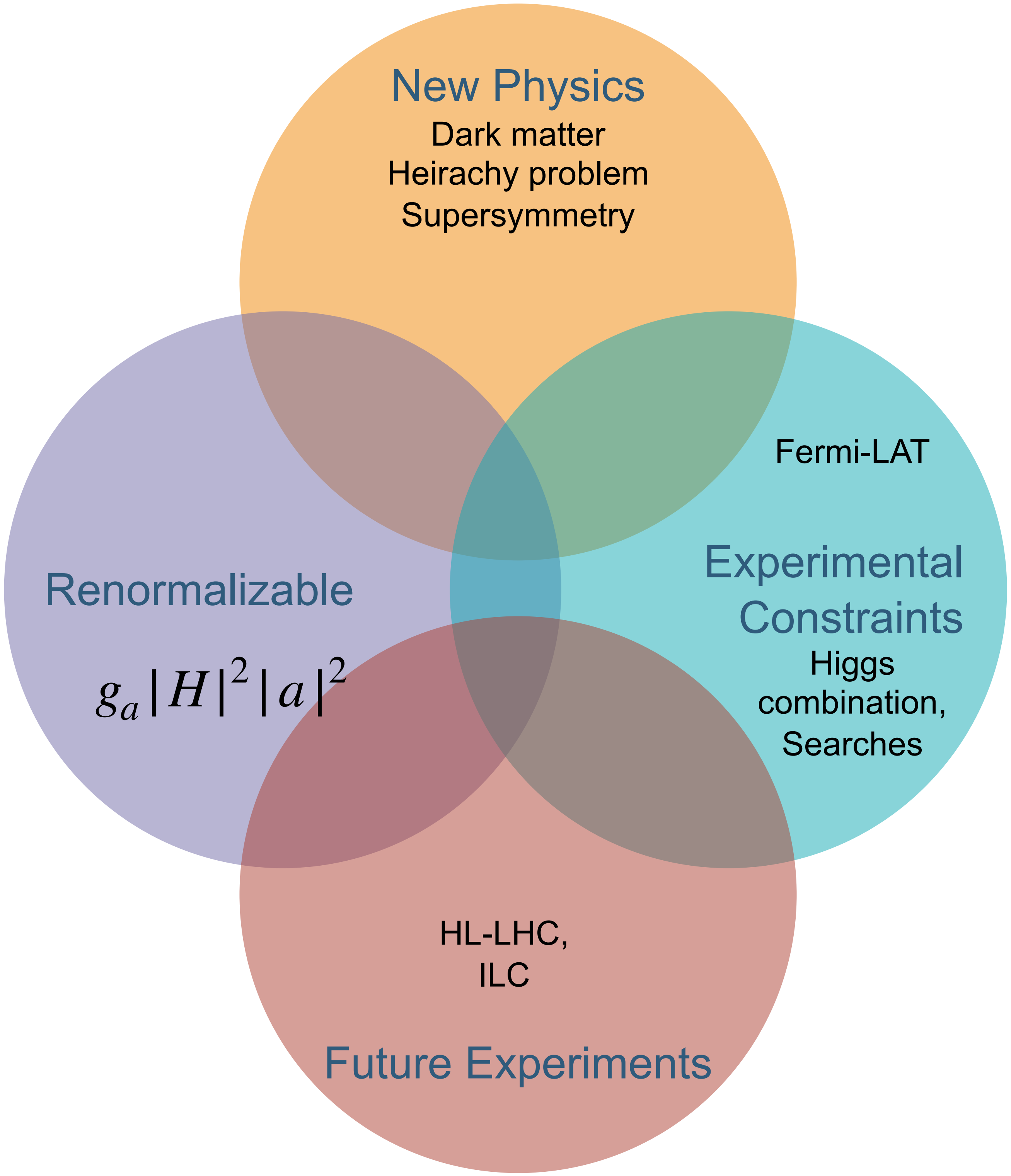
https://indico.cern.ch/event/1218225/contributions/5383838/

Ben Carlson, Steve Roche, Chris Hayes, Tae Min Hong

Based on PITT-PACC-2313
(check arXiv later this week)

Westmont College
Saint Louis University School of Medicine
University of Michigan
University of Pittsburgh

Motivation

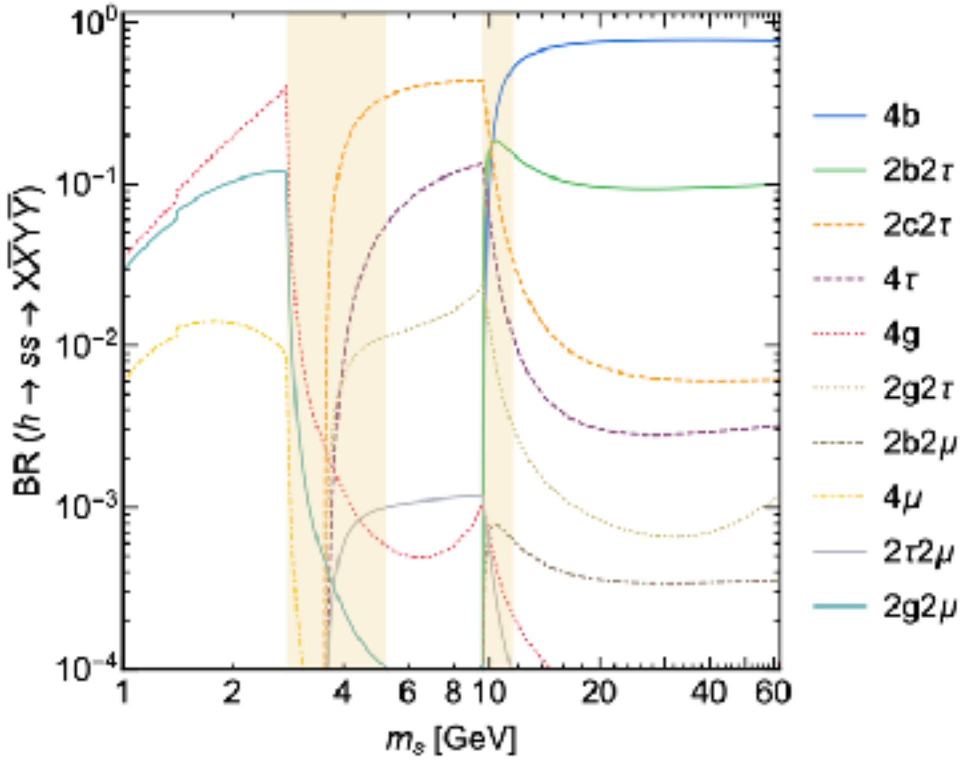


BSM Higgs decays to b-quarks are broadly motivated

- Renormalizable Higgs to pseudo-scalar (a) coupling, $g_a|H|^2|a|^2$
- Large branching ratio to b-jets in 2HDM models if $m_a > 2 \cdot m_b$

Motivation: H→4b

2HDM + s model



D. Curin et al., Phys. Rev. D 90, 075004 (2014)

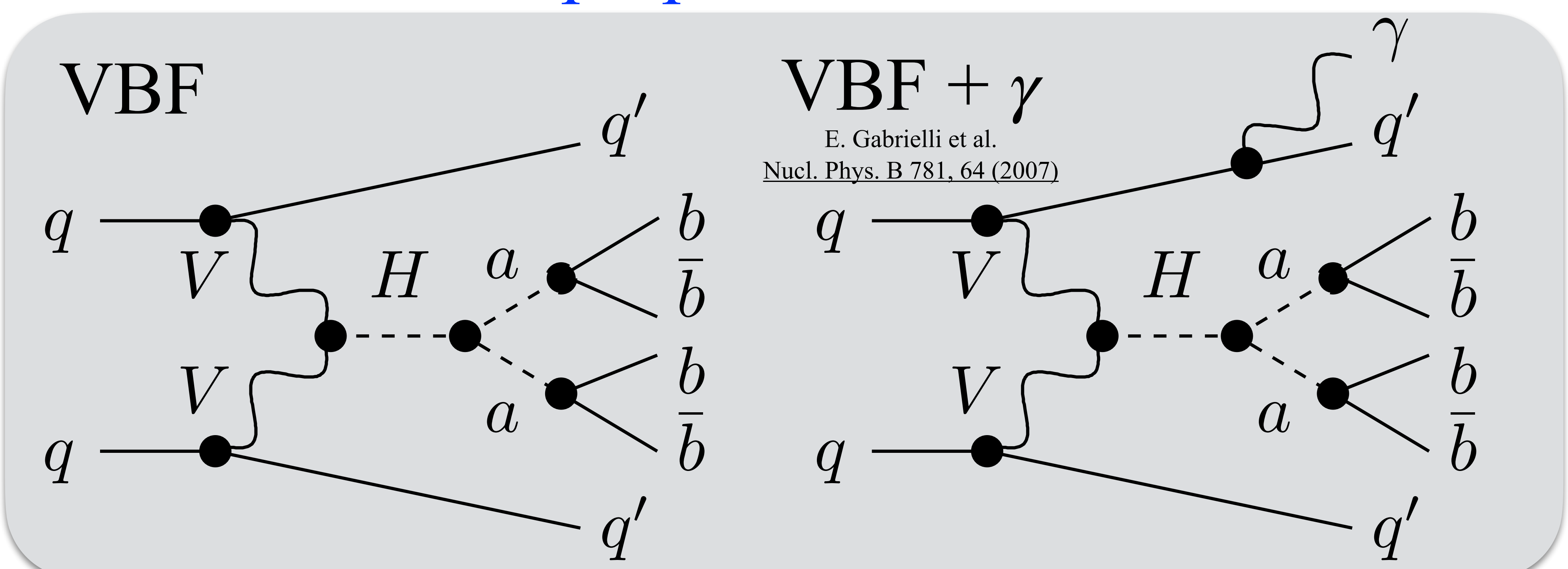
Current ATLAS search 60% observed sensitivity for m_a = 60 GeV ($Z \to \ell\ell$)

ATLAS JHEP 10 (2018) 031

Future benchmark:
HL-LHC: 20%
ILC: 10^{-4}

Z. Lui, L.T. Wang, H. Zhang arXiv:1612.09284

New proposed searches in VBF



More on VBF + γ, ATLAS H→bb JHEP03(2021)268, ATLAS H→inv Eur. Phys. J. C 82 (2022) 105,
H→cc B. Carlson, T. Han, S. Leung Phys. Rev. D 104, 073006

Outline

1. Hadronic signature

- Why new triggers
- How to simulate

2. Analysis selections

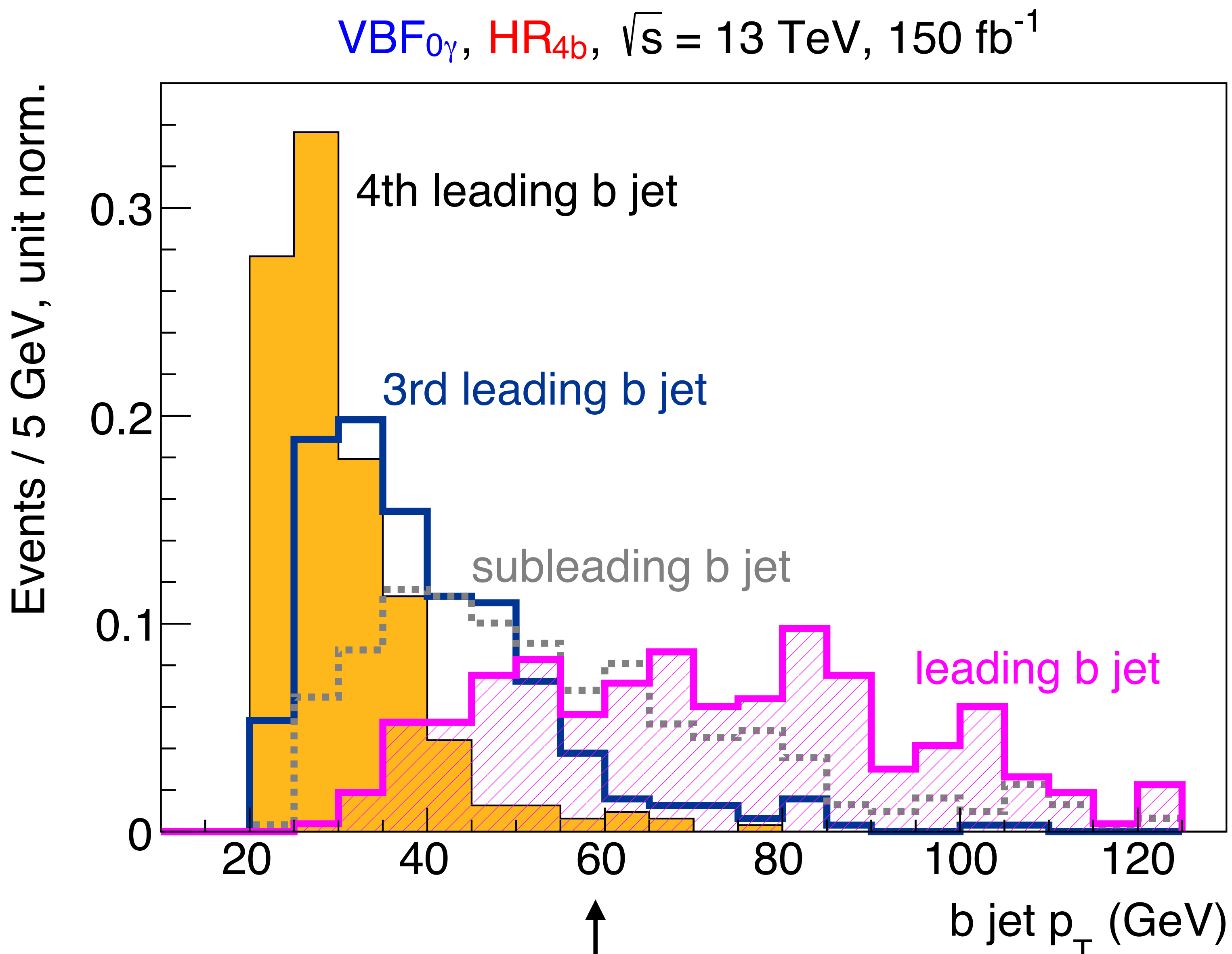
- VBF tagger
- Higgs reconstruction tagger

3. Sensitivity

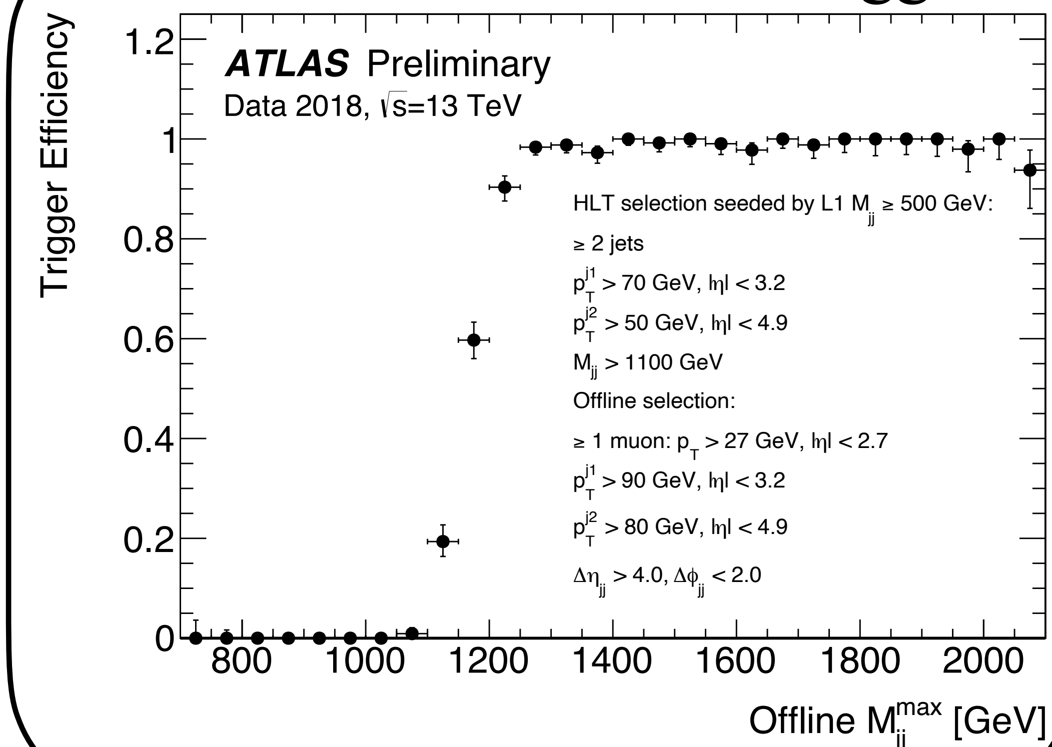
- Optimistic estimate
- Trigger variations

Why new triggers

H→4b very difficult to trigger (left)
Try VBF: large cross section motivates trigger (right)



2018 ATLAS VBF trigger



4^{th} jet L1 trigger threshold

Perform detailed analysis to motivate new triggers

Event simulation

LHC pp collisions, $\sqrt{s} = 13$ TeV

Generated a total of 1.5 B events

Event generation (MadGraph)

- Signal and background matrix element generated with leading-order
- Parton shower performed with Pythia 8

Fast detector simulation (Delphes)

- Particle-level detector resolution and efficiency functions applied using the CMS card
- Jets reconstructed using anti-k_t algorithm with R = 0.4

Validation

- Reproduced jet energy resolution with ATLAS and CMS jet energy resolution to 10%
- Generated a small sample and validated analysis cut-flow with $\langle\mu\rangle = 50$, and found 20% agreement to neglecting pileup
- Compared jjbb (possible to generate) with jjjbb (too slow) and found reasonable agreement

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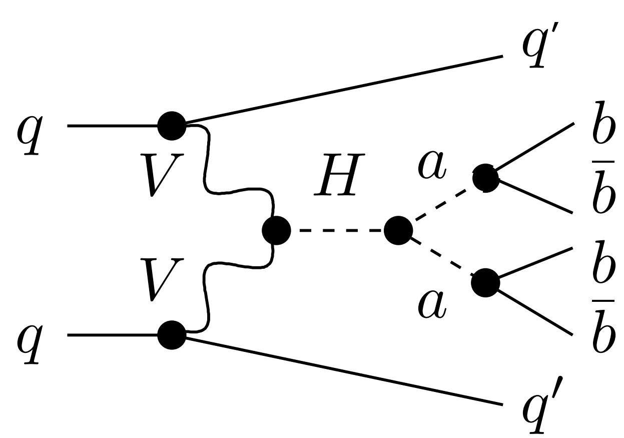
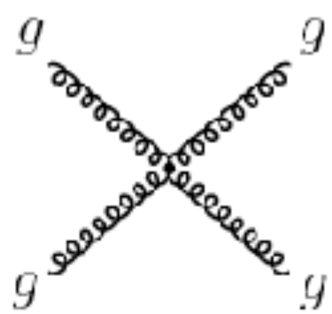
Vector boson fusion tagger

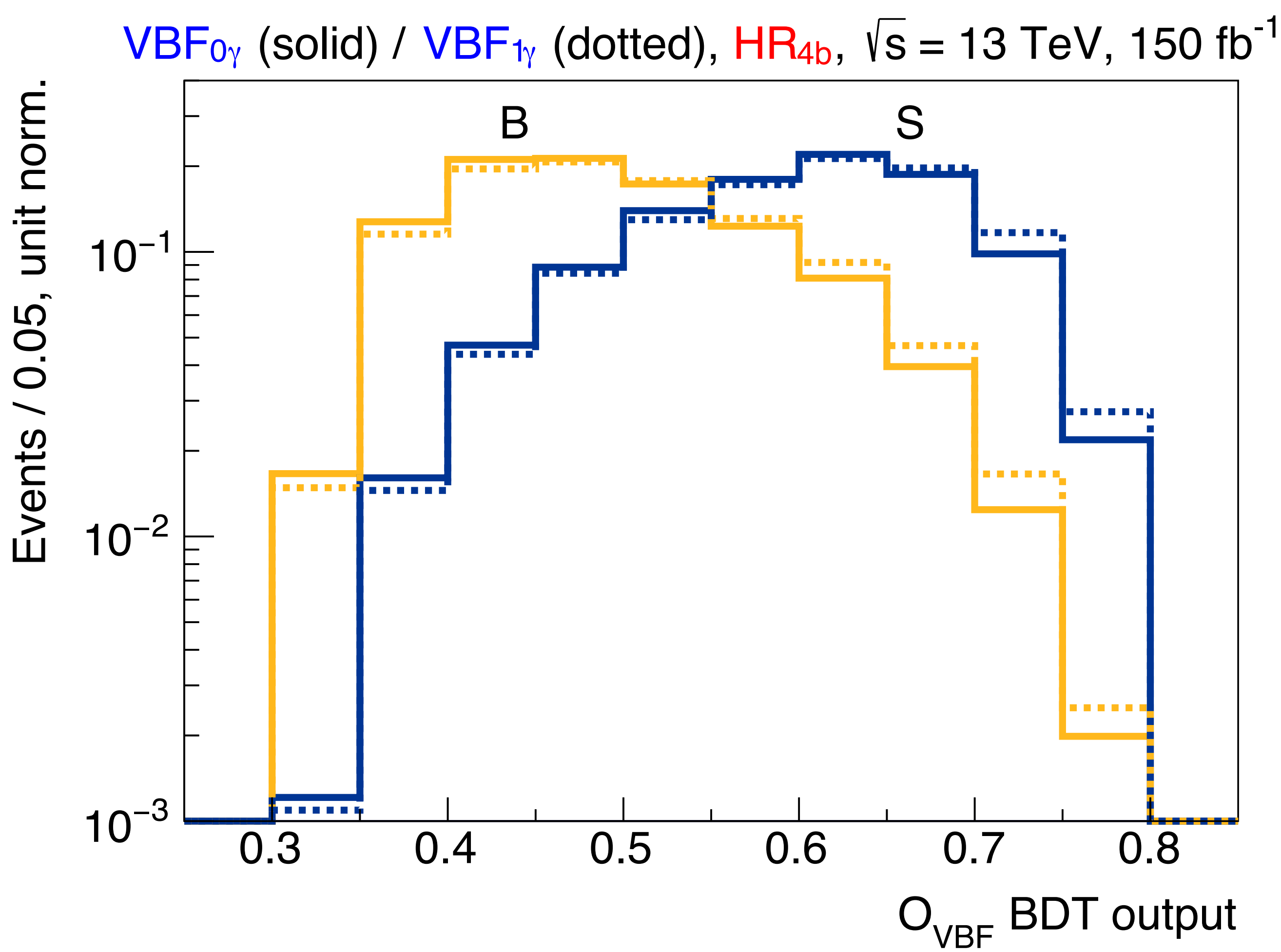


Energy deposits

Invisible decay

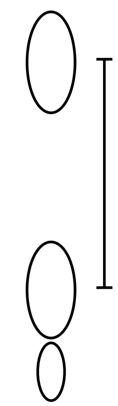


Hadronic activity (addition jets)



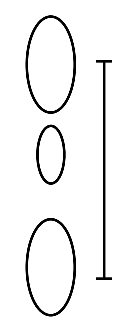
Jets

Eboli, Zeppenfeld, PLB 495 (2000)147



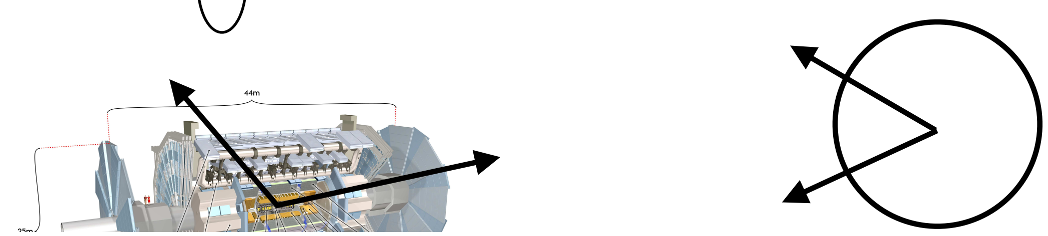
Jets widely separated (η)

Jets recoil against Higgs (small Δϕ)



Jets not as separated

Jets back to back (ϕ)



BDT inputs

VBF jet variables: $\Delta\phi_{jj}$, $\Delta\eta_{jj}$, Δm_{jj}

Jet variables: $p_{T1}, p_{T2}, E_1, E_2,$

Leading/sub-leading

Analysis selection

$N_{\text{jet}} = 5{,}6$

Highest m_{jj} jet pair: VBF jets

VBF BDT

No photon

$N_\gamma = 0$

3 b-jet

4 b-jet

VBF + ISR photon

$N_\gamma = 1$

3 b-jet

4 b-jet

HR3b

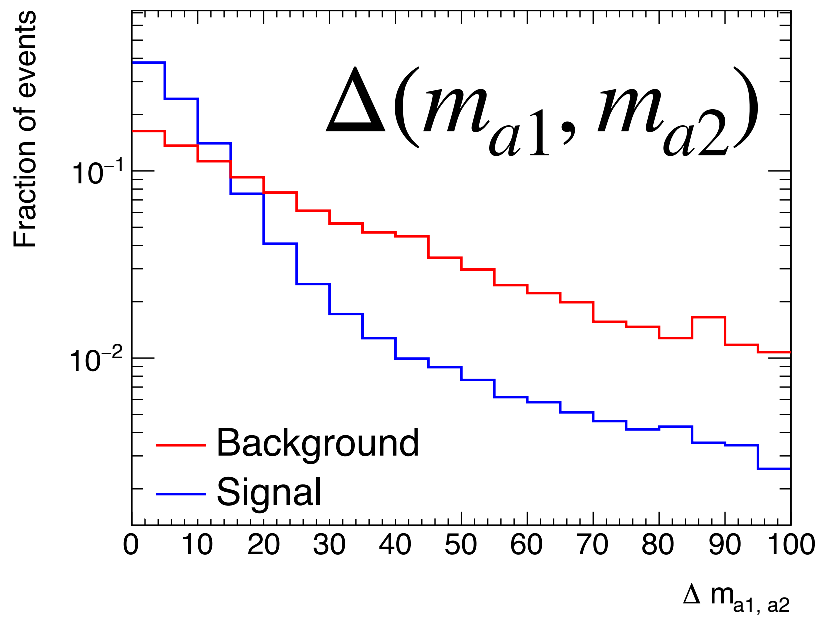
HR4b

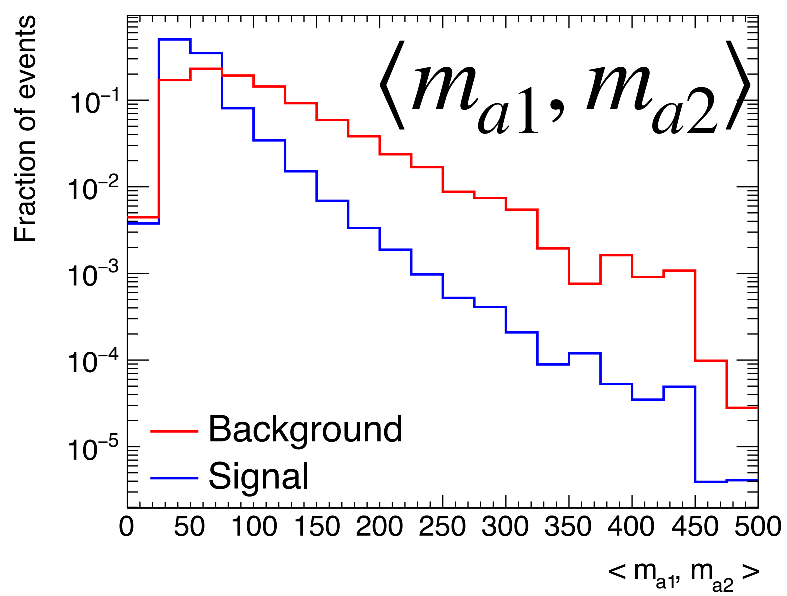
Two Higgs reconstruction (HR) channels

Higgs reconstruction

Classifier BDT trained for two separate categories

Inputs for the 4b BDT for m_a = 50 GeV





3 b-jet

- m_{3b}
- $m_{b1,b2}, m_{b2,b3}, m_{b1,b3}$
- ΔR_{bb}^{avg}
- ΔR_{bb}^{min}

BDT output

O_{3b}

4 b-jet

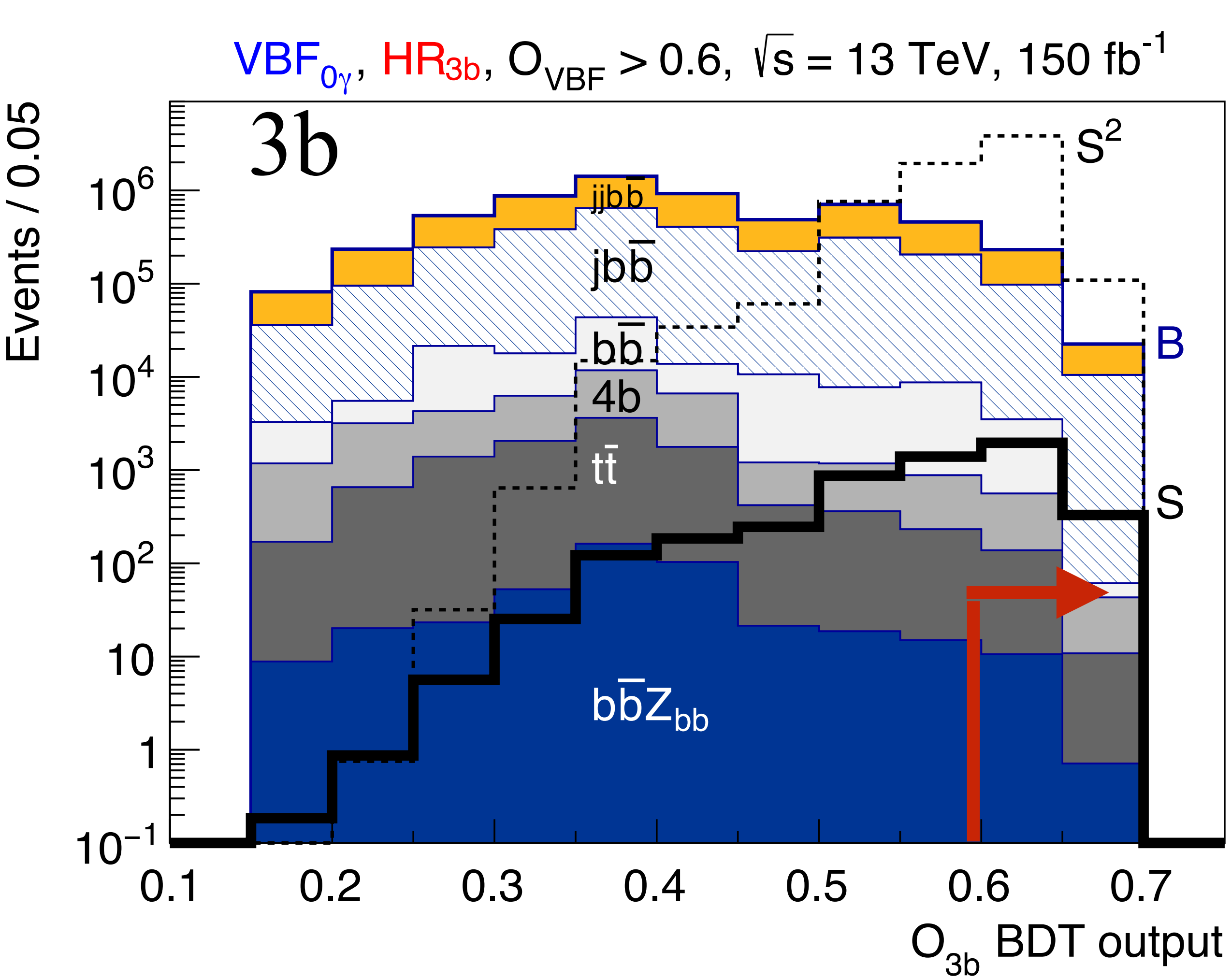
- m_{4b}
- $\langle m_{a1}, m_{a2} \rangle$
- $\Delta(m_{a1}, m_{a2})$

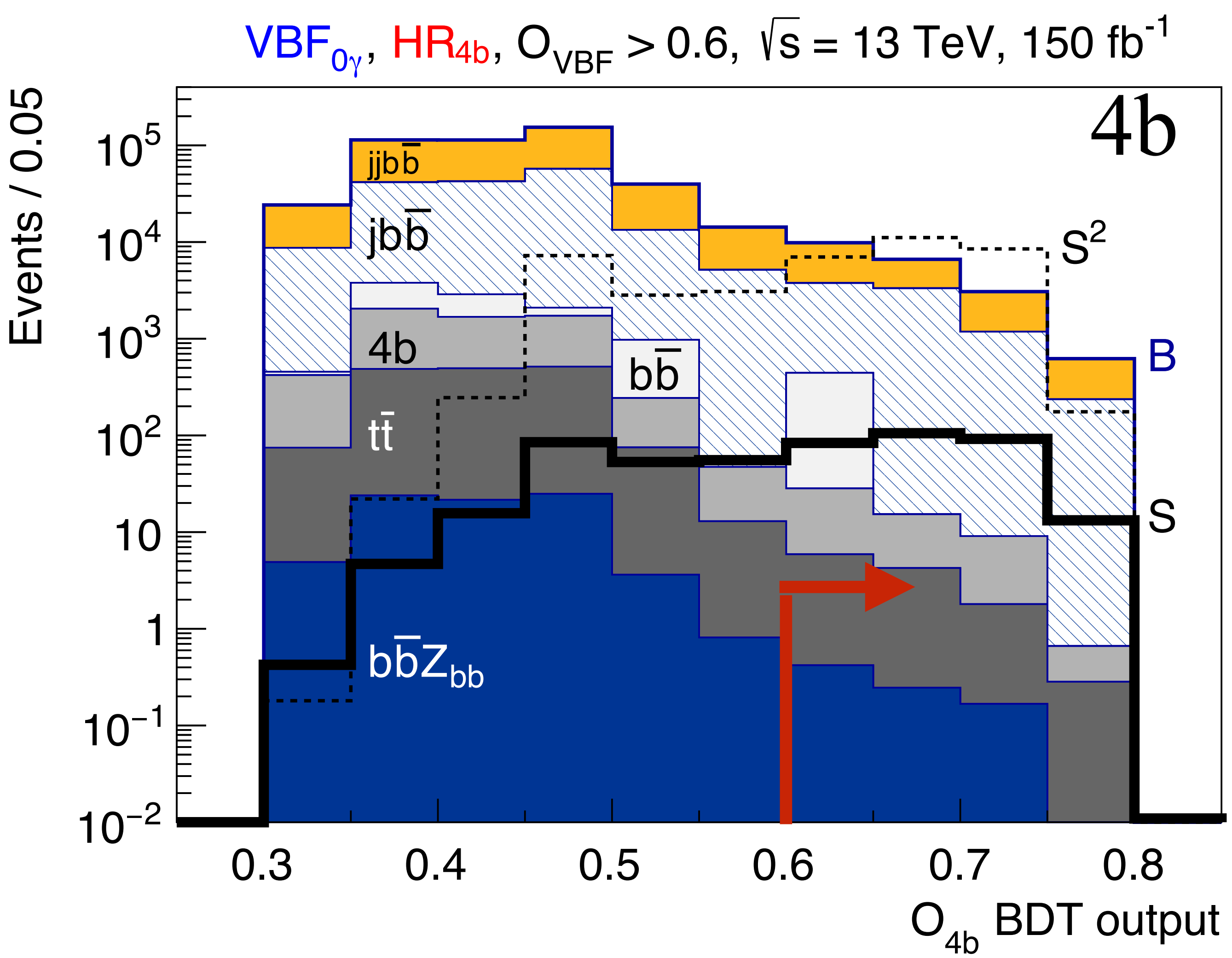
BDT output

O_{4b}

VBF (no photon)

Apply requirement on $O_{VBF} > 0.6$





Require $O_{3b/4b} > 0.6$

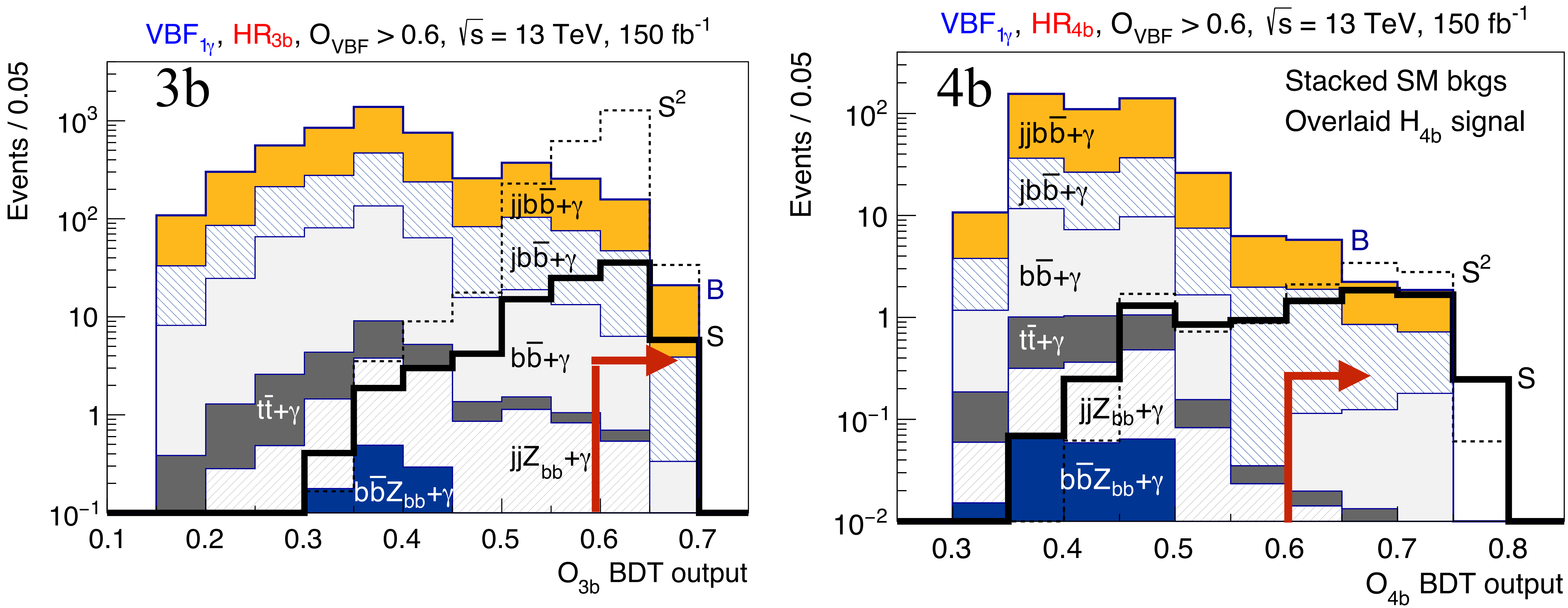
m_a = 50 GeV
S = 2293, B = 2.5 x 10^5

m_a = 50 GeV
S = 295, B = 2.0 x 10^4

Large background, large signal

VBF + photon

Apply requirement on $O_{VBF} > 0.6$



Require $O_{3b/4b} > 0.6$

$m_a = 50$ GeV

$S = 41, B = 178$

$m_a = 50$ GeV

$S = 5.2, B = 9.9$

Small background, small signal

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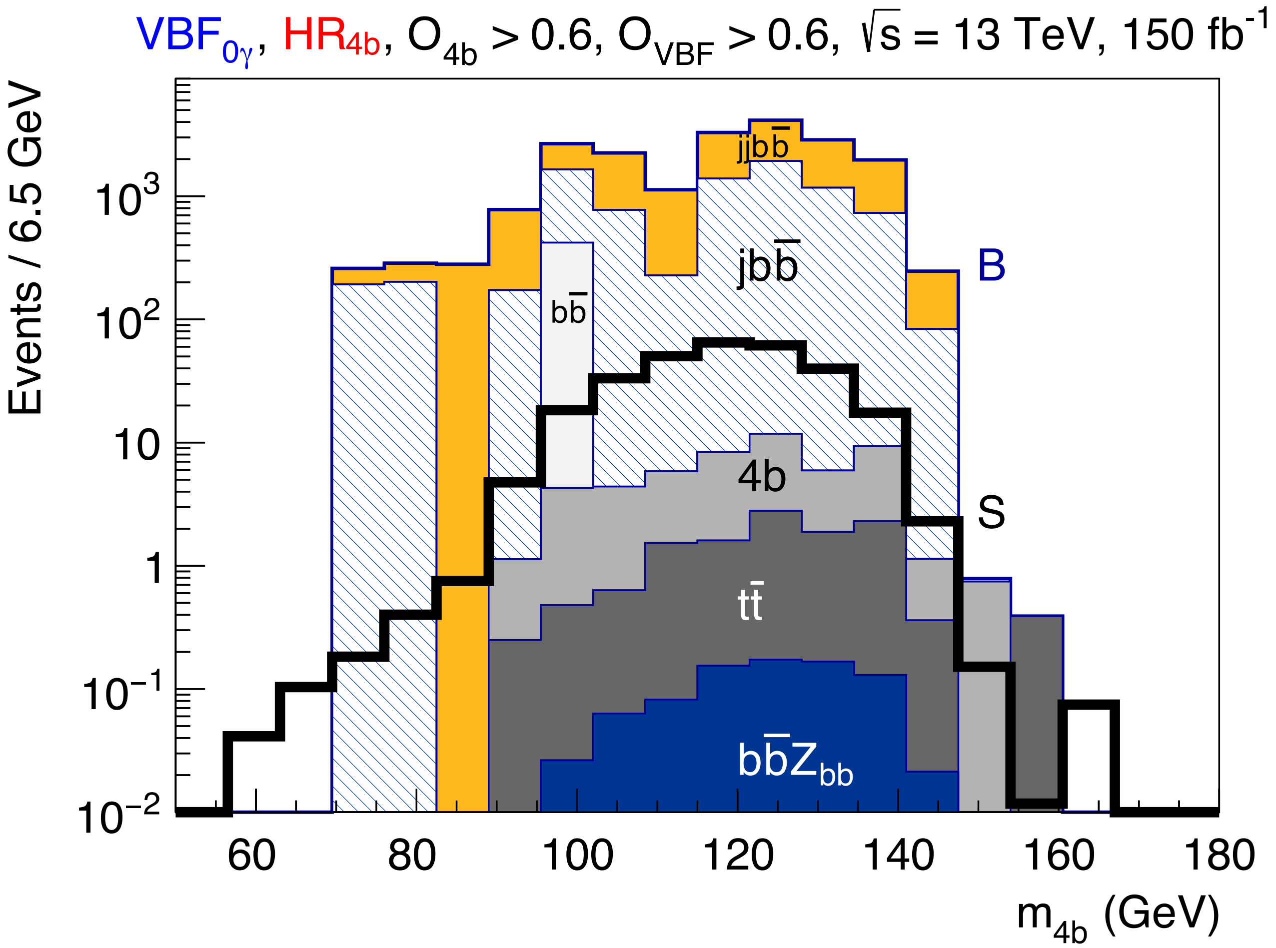
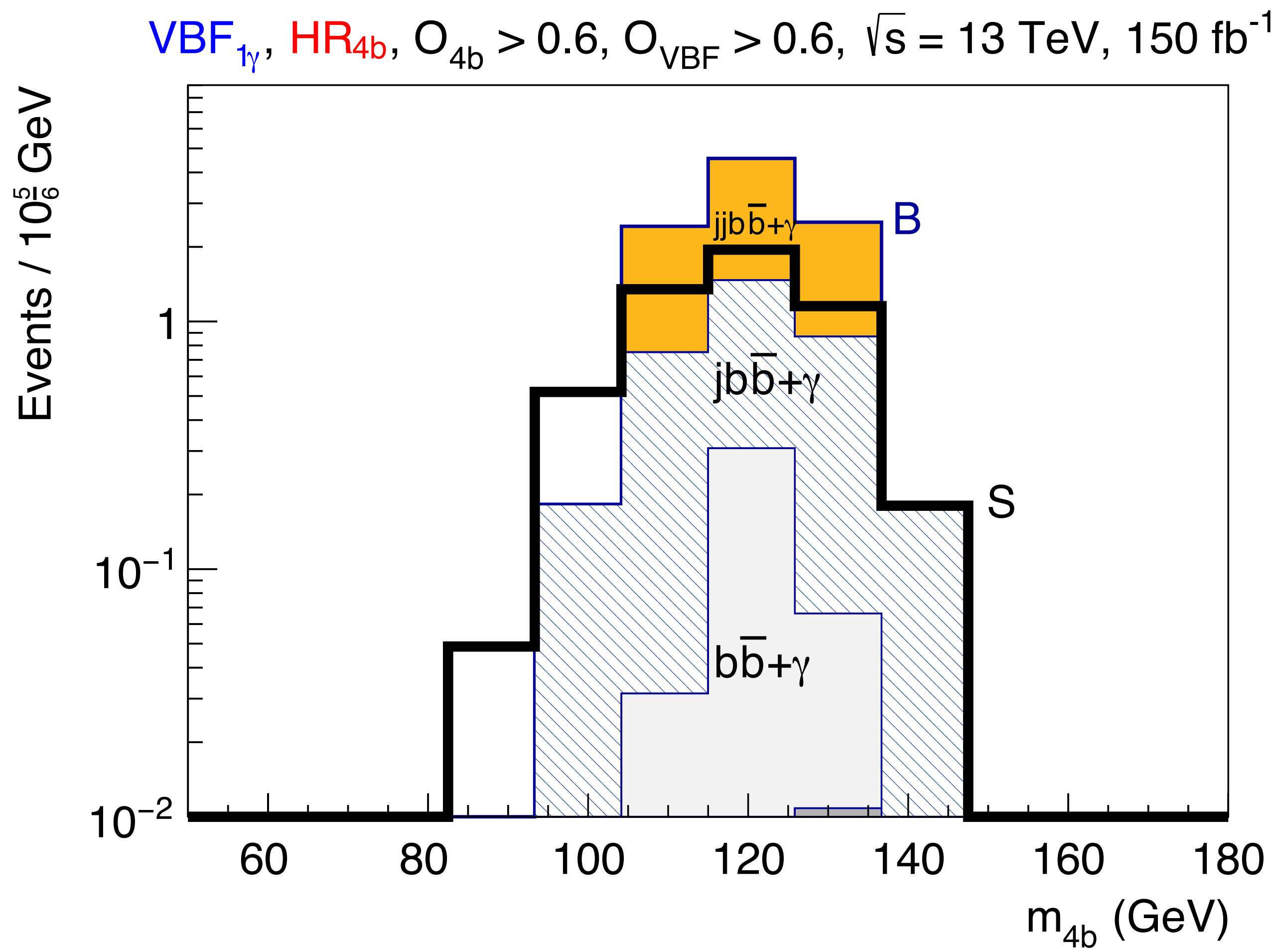
Mass discriminant

Apply $O_{VBF} > 0.6$ and $O_{3b/4b} > 0.6$



m_{4b}



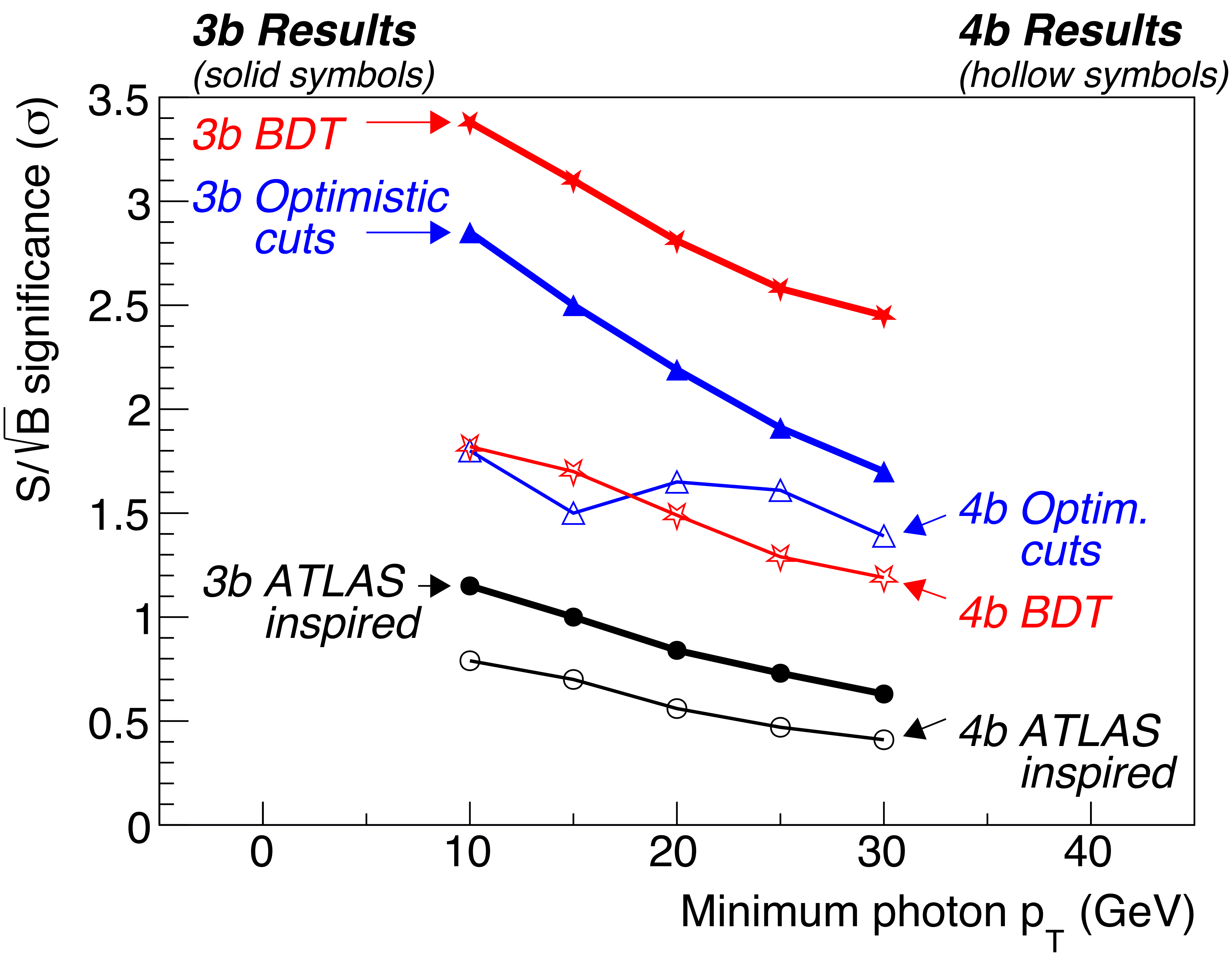
m_{4b}

$m_a = 50$ GeV

	Nγ = 0		Nγ = 1	
	4b	3b	4b	3b
Sensitivity	2.1σ	4.6σ	1.7σ	3.1σ
3 & 4b	5.1σ		3.5σ	
All channels	6.1σ [BR(H→4b) < 33%]			

Trigger variations

Significant gain in potential new triggers with BDT and cut-based



Up to 50% variation in photon p_T

Conclusions

BSM Higgs decays to b-quarks are broadly motivated

- Renormalizable, $g_a |H|^2 |a|^2$, connected to new physics
- Large branching ratio to b-jets

Estimated the sensitivity

- Accessible in Run 3 with new triggers
- Provided variety of trigger scans

With new triggers: sensitive within Run 3

For m_a = 50 GeV: 6σ sensitivity Br < 33%

Further sensitivity possible for the HL-LHC

Backup

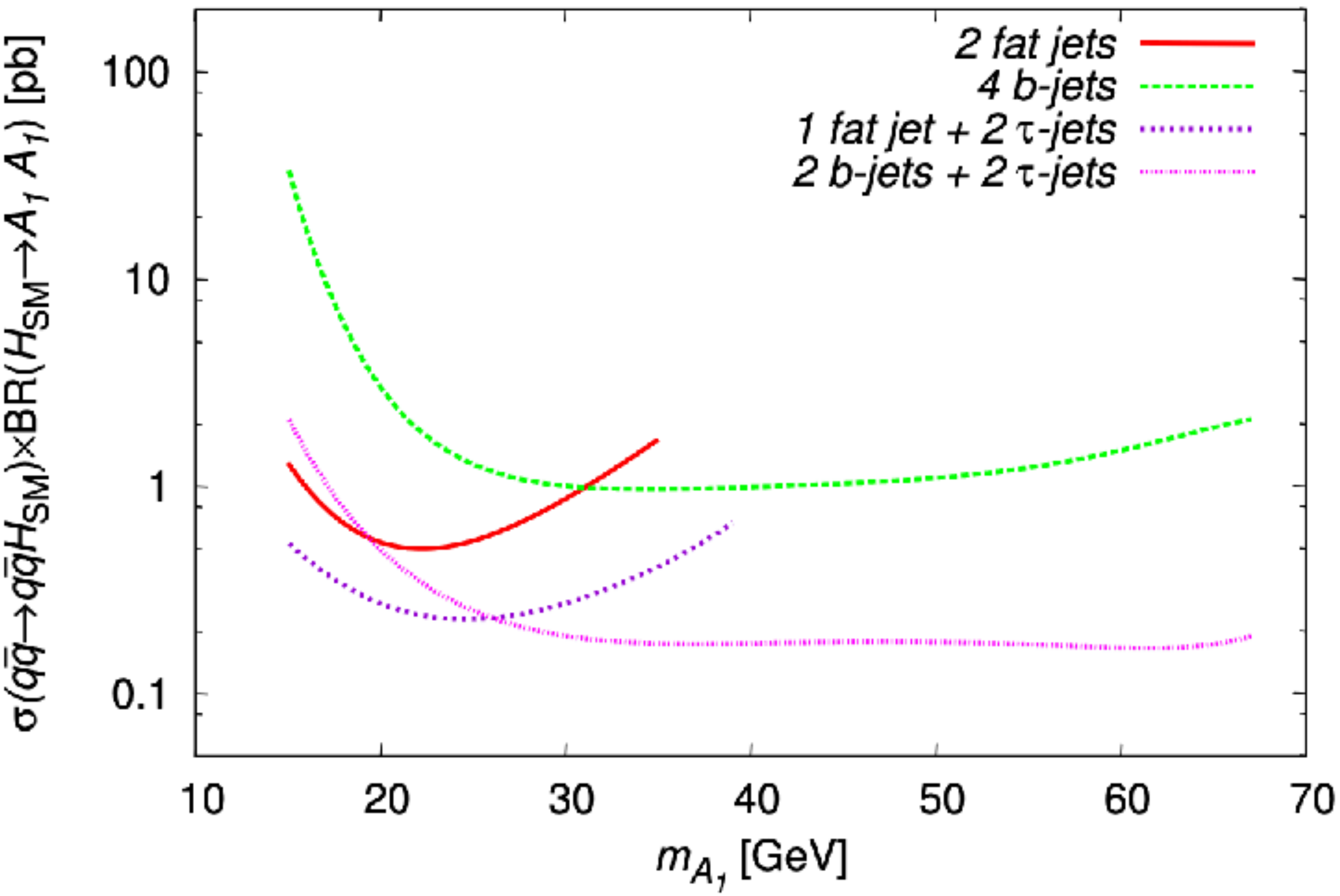
4b projections

Z. Lui, L.T. Wang, H. Zhang arXiv:1612.09284

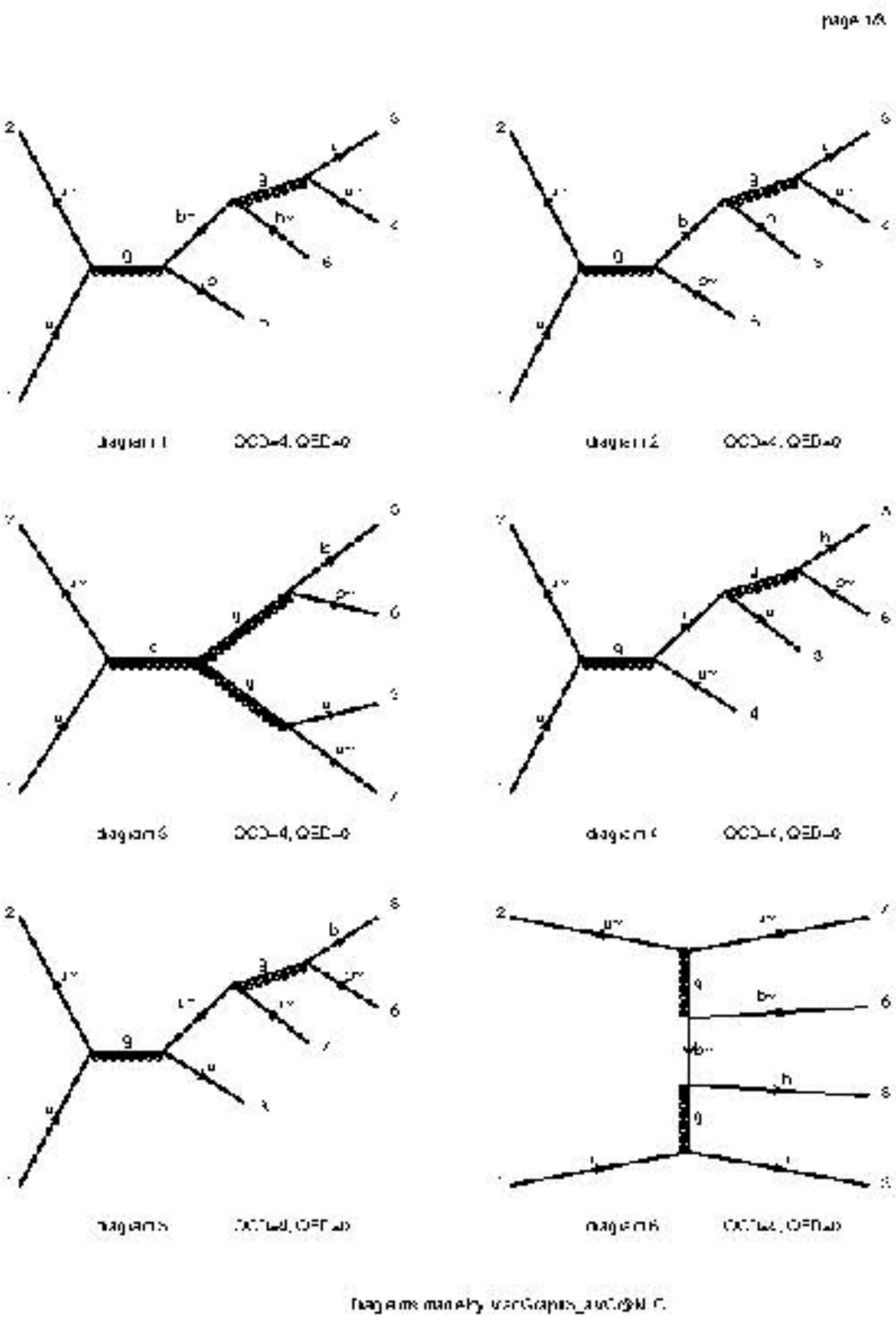
Decay Mode	95% C.L. limit on Br				
	LHC	HL-LHC	CEPC	ILC	FCC-ee
$\not{E}_T$	0.23 [49, 50]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b})+\not{E}_T$	–	[0.2]	1×10^{-4}	2×10^{-4}	5×10^{-5}
$(jj)+\not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)+\not{E}_T$	–	[1]	$8\times10^{-4}*$	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 ∼ 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}

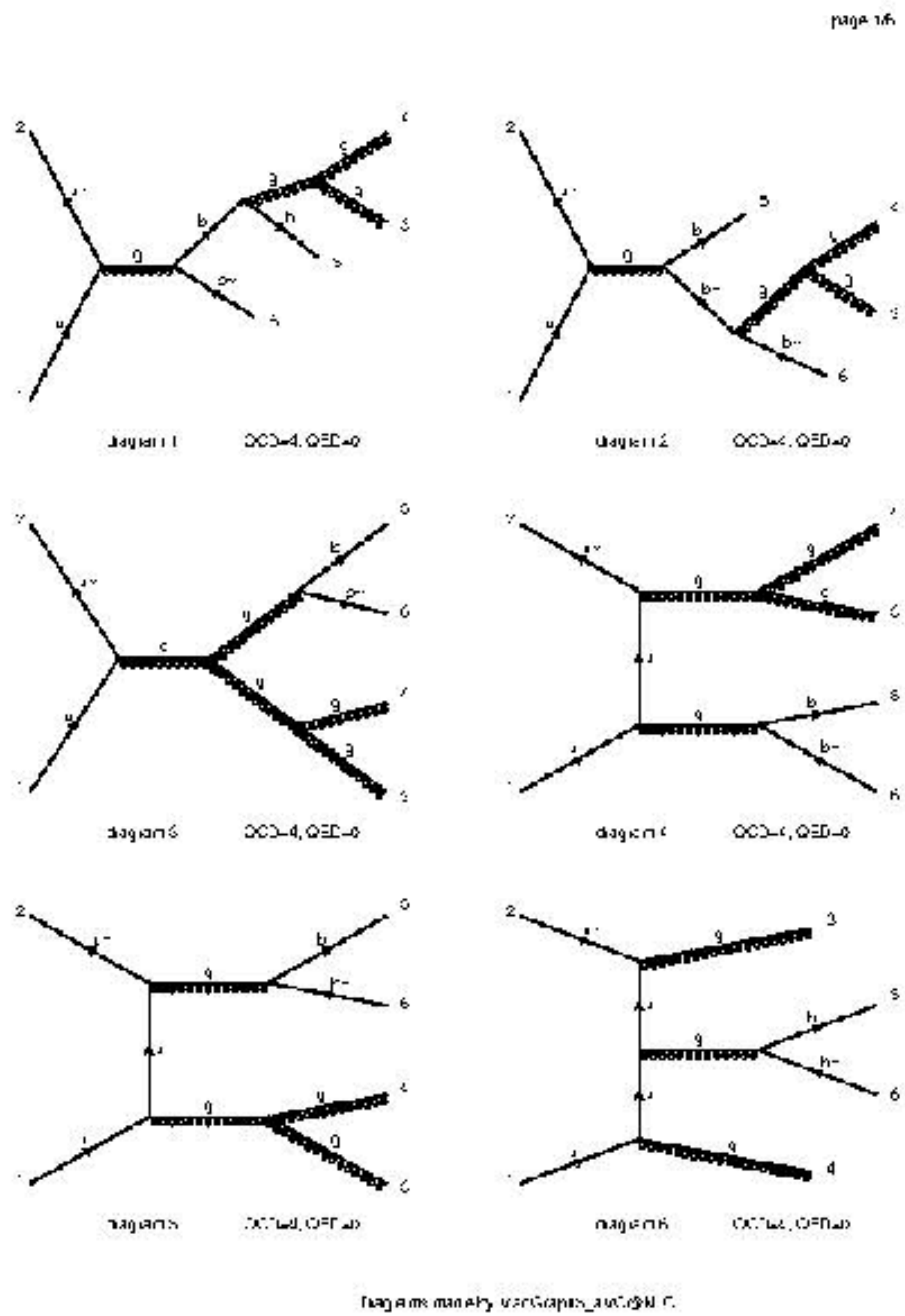
Previous studies in VBF

N. Bomark, S. Moretti, L. Roszkowski 1503.04228

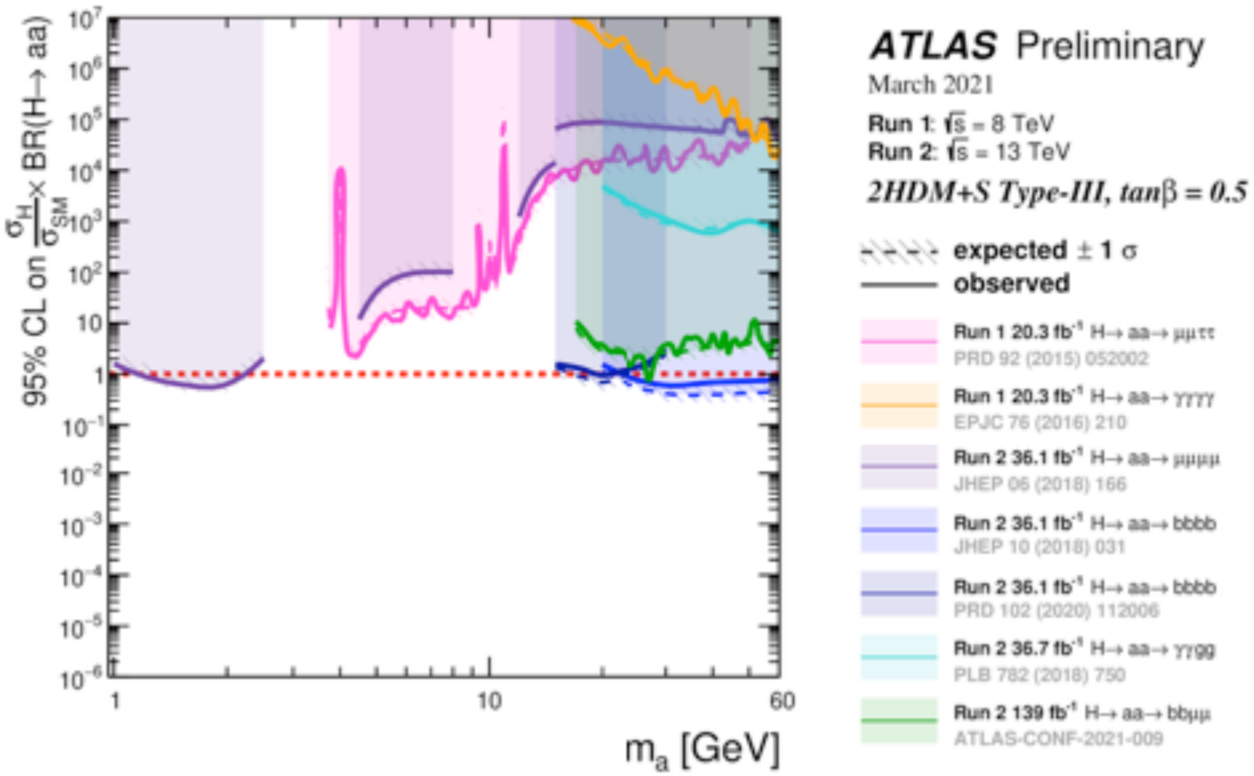


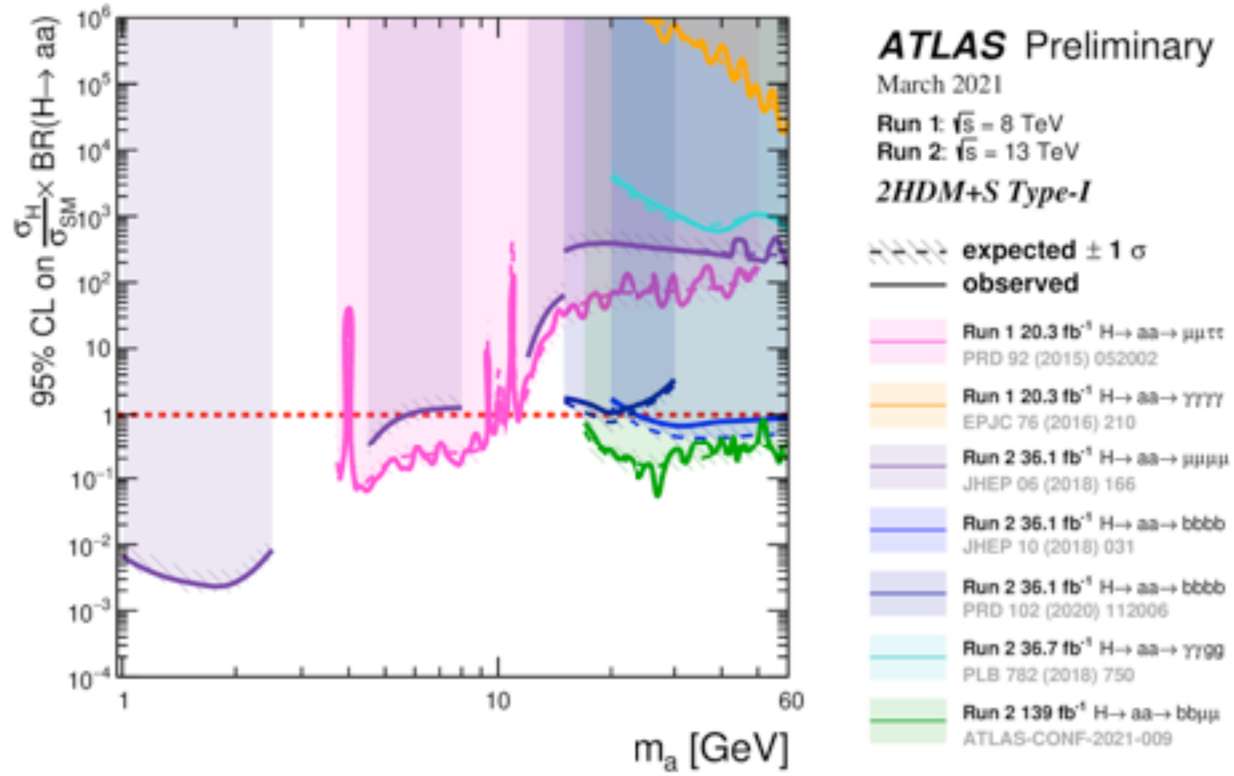
Matrix element for jjbb





Sensitivity comparison





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