Next steps in H → bb, beyond inclusive signal strength

ATLAS Higgs to bb / Flavor Tagging Workshop
September 5, Stony Brook

Michelangelo L. Mangano
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The abstract from the organizers:

"*which differential measurements should we produce,*
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** see Carlos's talk for direct H signals of new physics ….*
here I focus on indirect signatures

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- We often talk about "**precise**" Higgs measurements. What we actually aim at, is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- ***Sensitivity*** may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

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For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

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For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

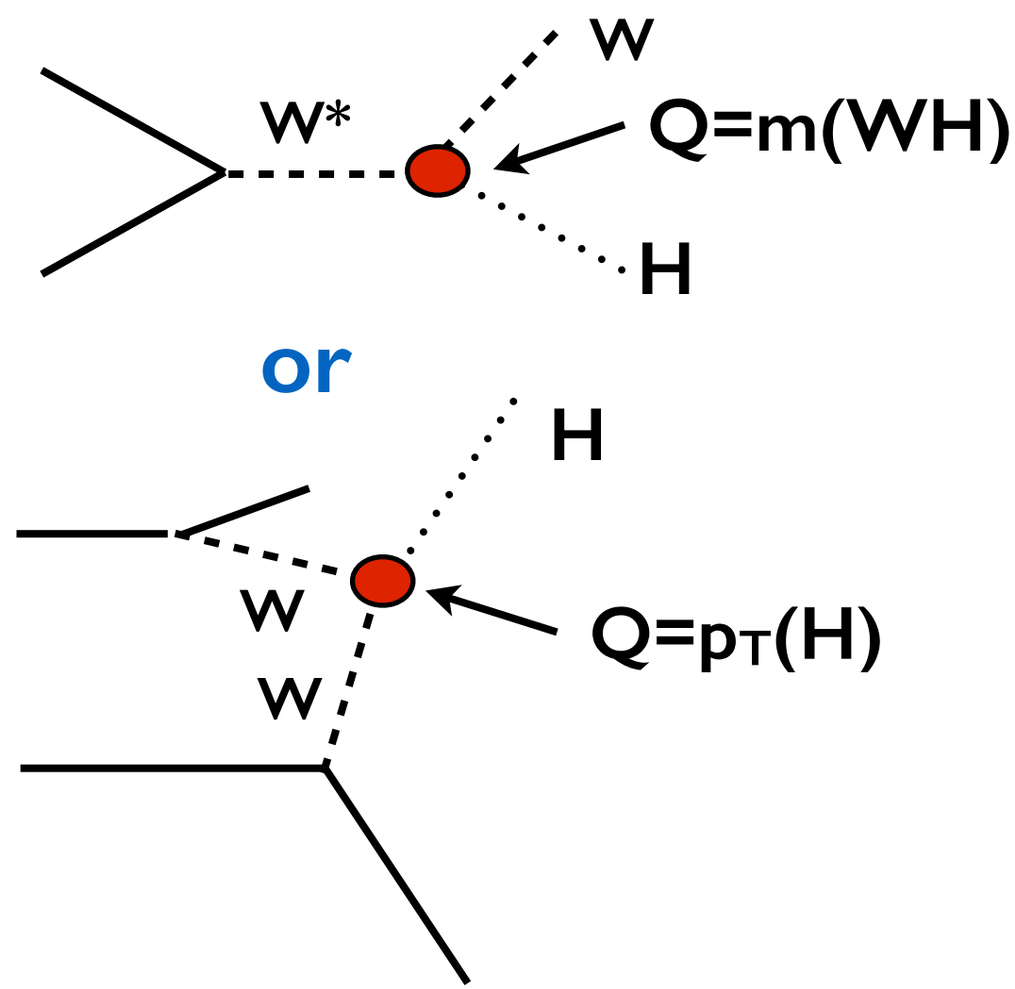
$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

e.g. $\delta O_Q = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

Examples

$\delta BR(H \rightarrow WW^*)$



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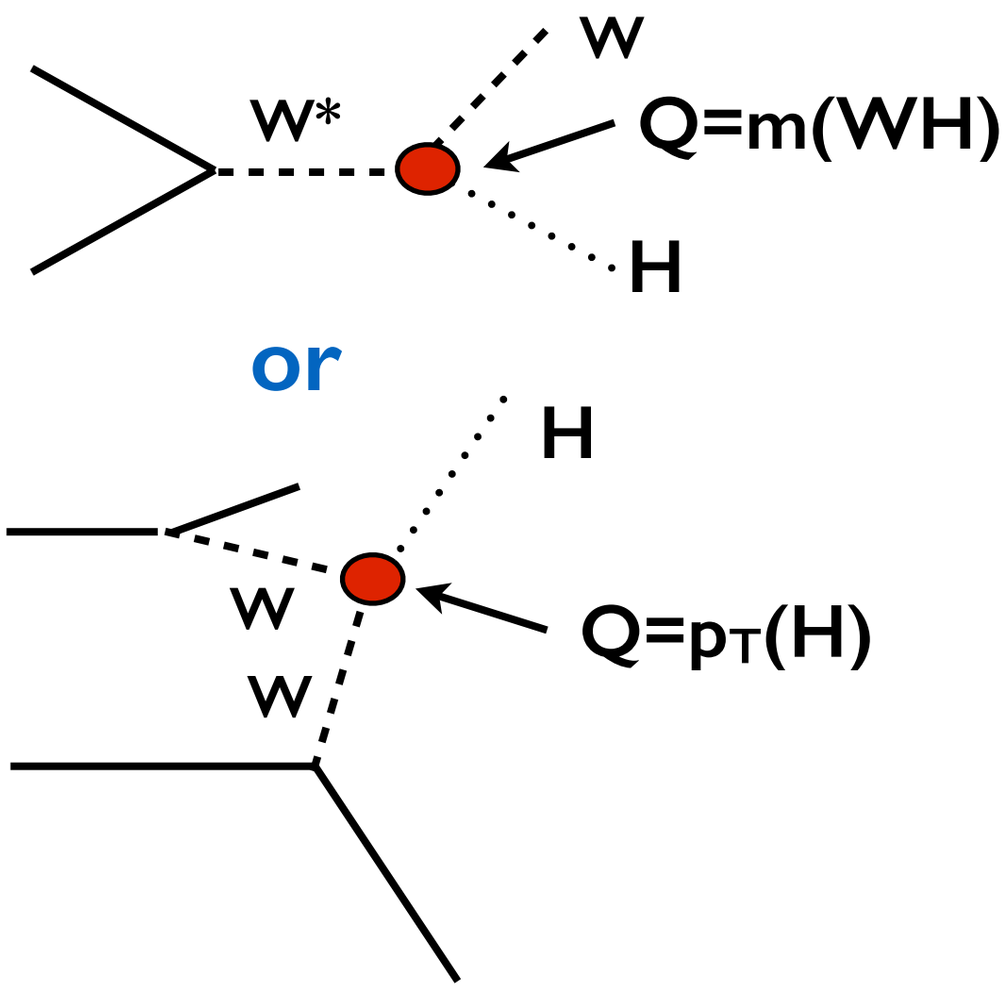
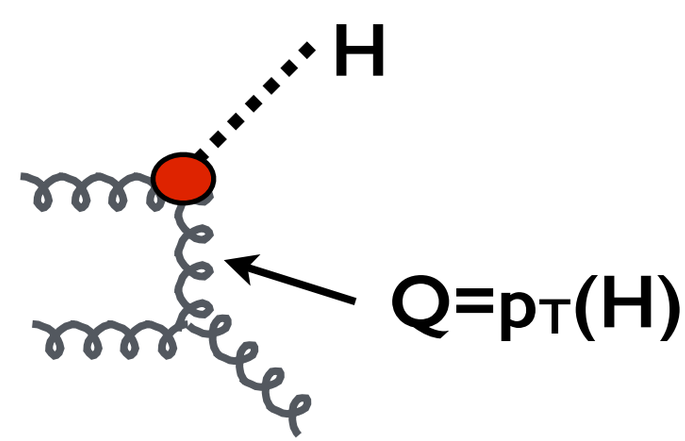
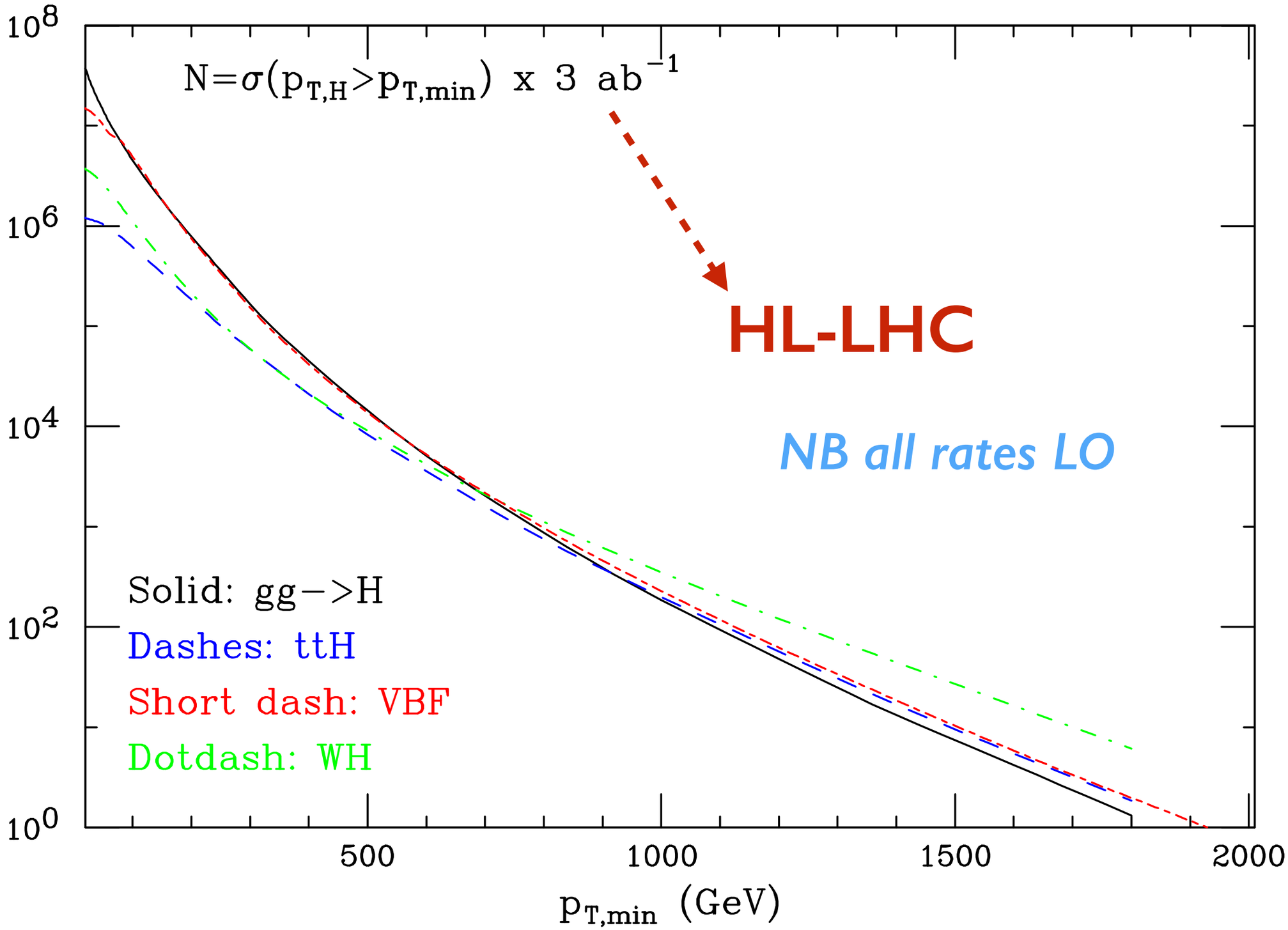


$\delta BR(H \to gg)$



Probing large Q:
Higgs production at large p_T



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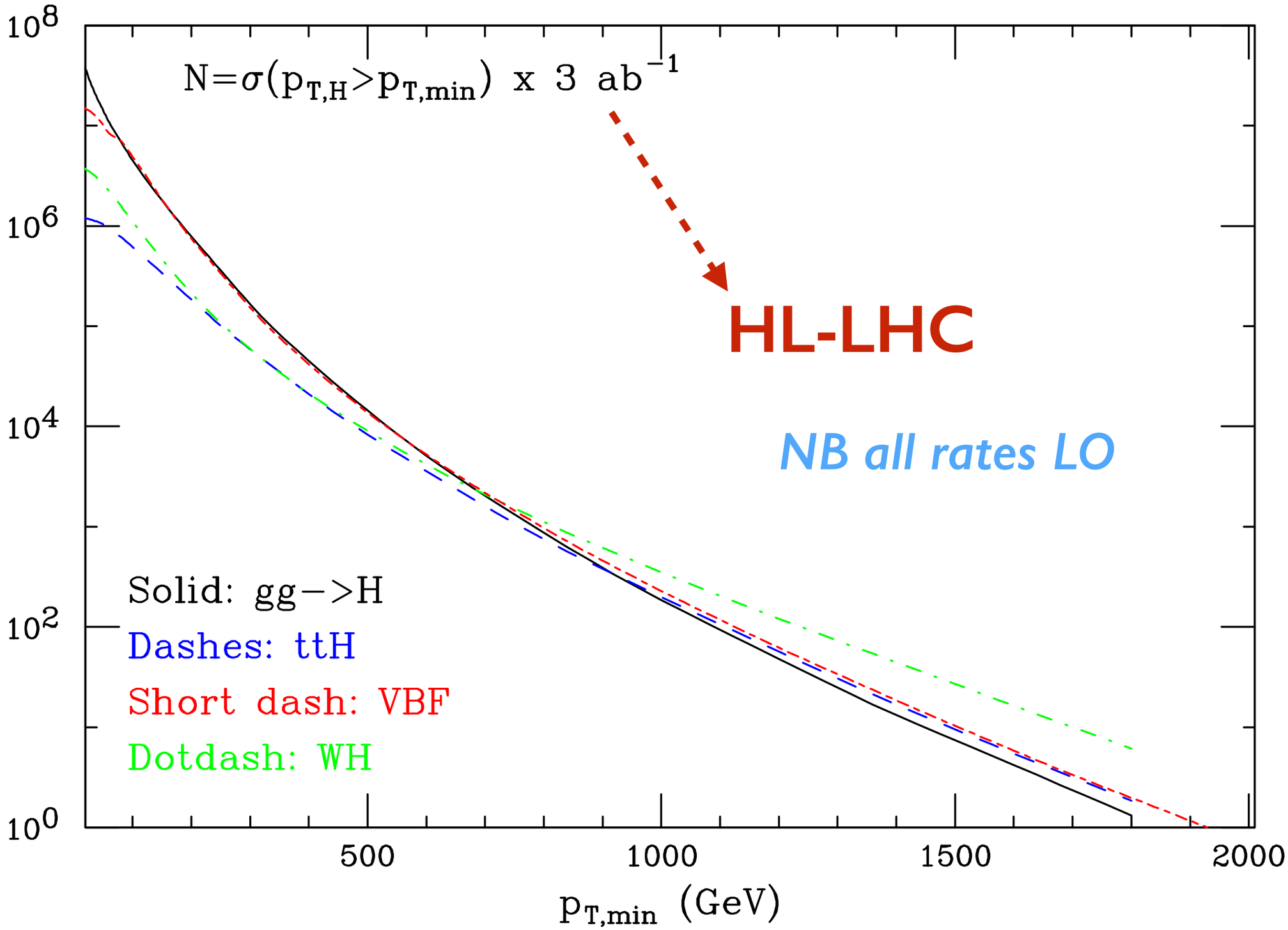


H→bb plays a special role here, since large BR can maximize the reach in Q~p_T

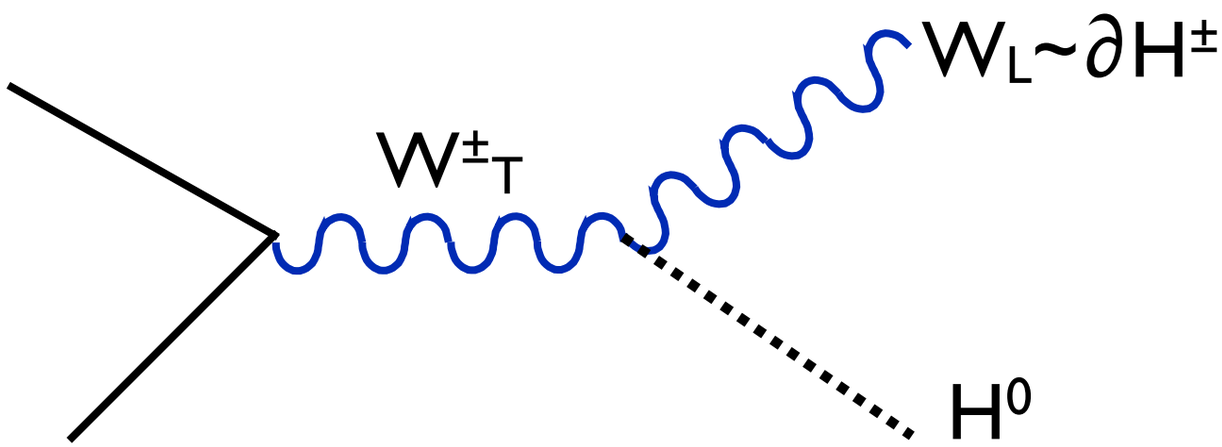
I will explore these ideas in the context of the VH(→bb) signals discussed in the current H→bb searches by ATLAS and CMS:

ATLAS, Evidence for the H→bb decay with the ATLAS detector
arXiv:1708.03299

CMS, Evidence for the decay of the Higgs Boson to Bottom Quarks
CMS-PAS-HIG-16-044

VH prodution at large m(VH) or p_T(H)

See e.g.
Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320



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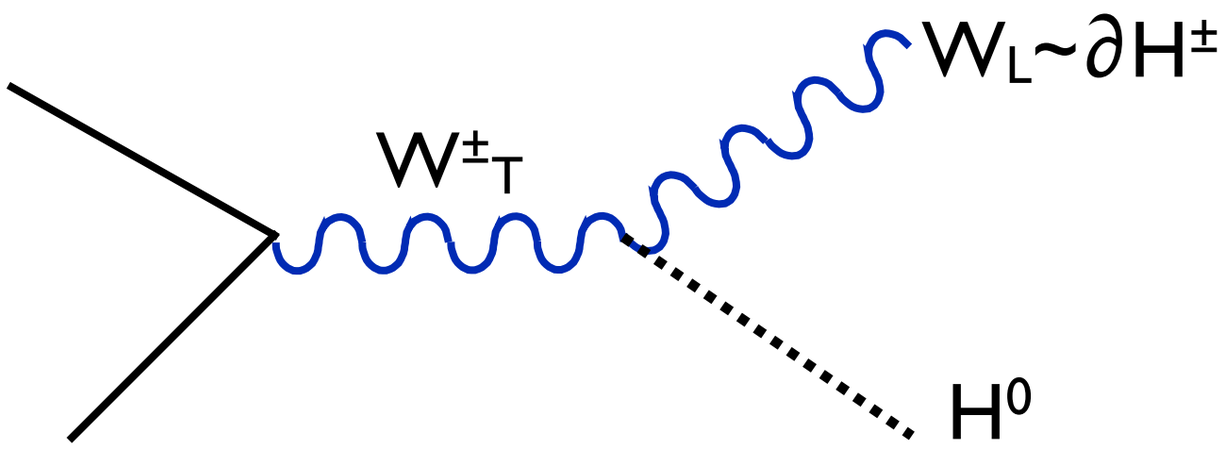

In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

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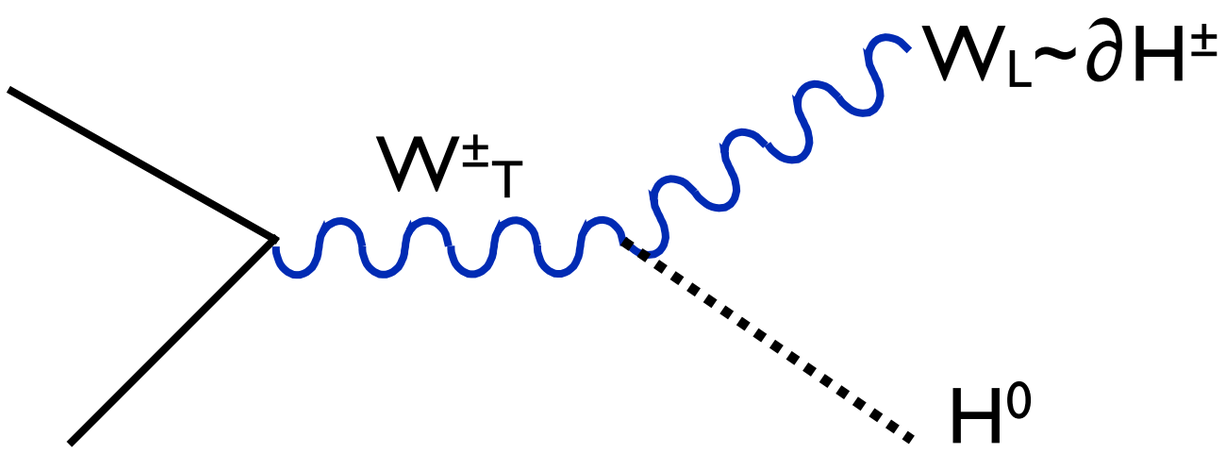

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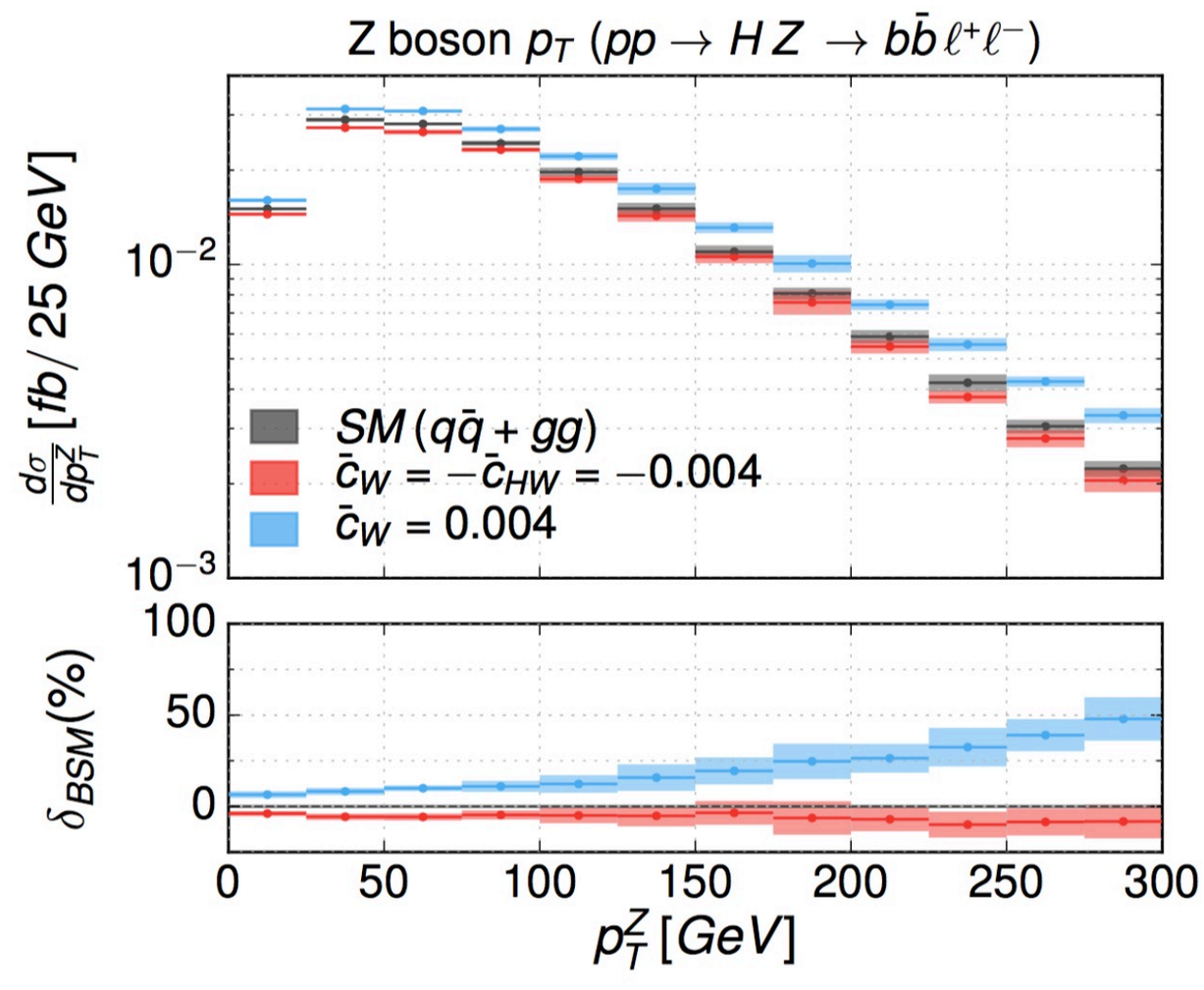

Mimasu, Sanz, Williams, arXiv:1512.02572v

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$$\sqrt{s} \sim \Lambda / \sqrt{c_w}$$

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When Q is limited (e.g. at 7-8 TeV, or as the 13 TeV lum is still small), and given that Λ cannot be too small since we would have directly seen the new physics, one can only constrain a special class of strongly-interacting theories, which generate large Wilson coefficients c_w.

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This will change at 14 TeV and high lumi ….

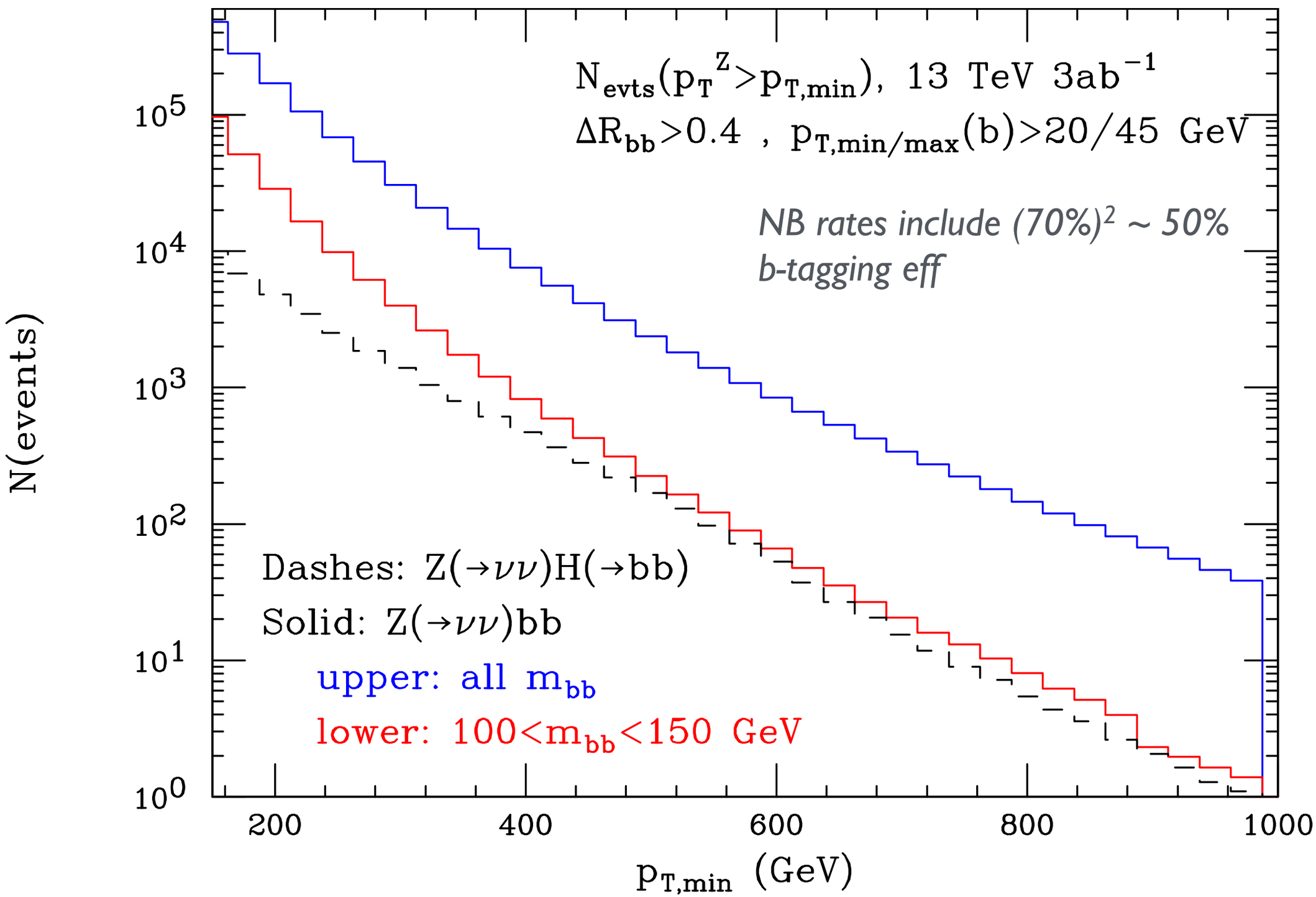
from the ATLAS note:

Table 13: The fitted Higgs boson signal and background yields for each signal region category in each channel after the full selection of the multivariate analysis. The yields are normalised by the results of the global likelihood fit. All systematic uncertainties are included in the indicated uncertainties. An entry of "–" indicates that a specific background component is negligible in a certain region, or that no simulated events are left after the analysis selection.

Signal regions	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag		75 GeV $< p_T^V <$ 150 GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	–	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z + cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
Z + HF	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W + ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W + cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
W + HF	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	–	–	102 ± 66	27 ± 68	–	–	–	–
Multi-jet μ sub-ch.	–	–	133 ± 99	90 ± 130	–	–	–	–
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708

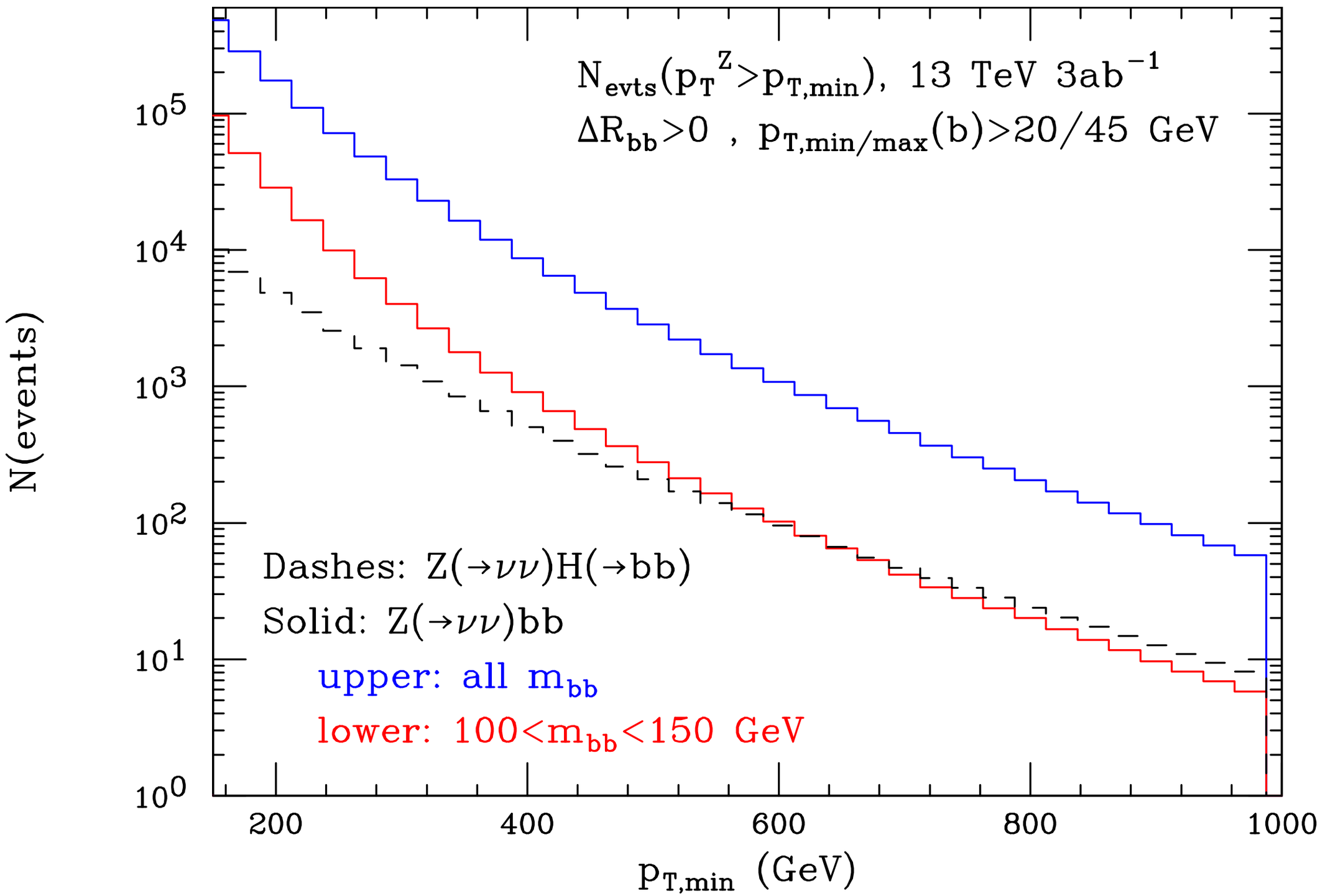
best S/B and S/$\sqrt{B}$ => focus here on ***HZ(→)νν***

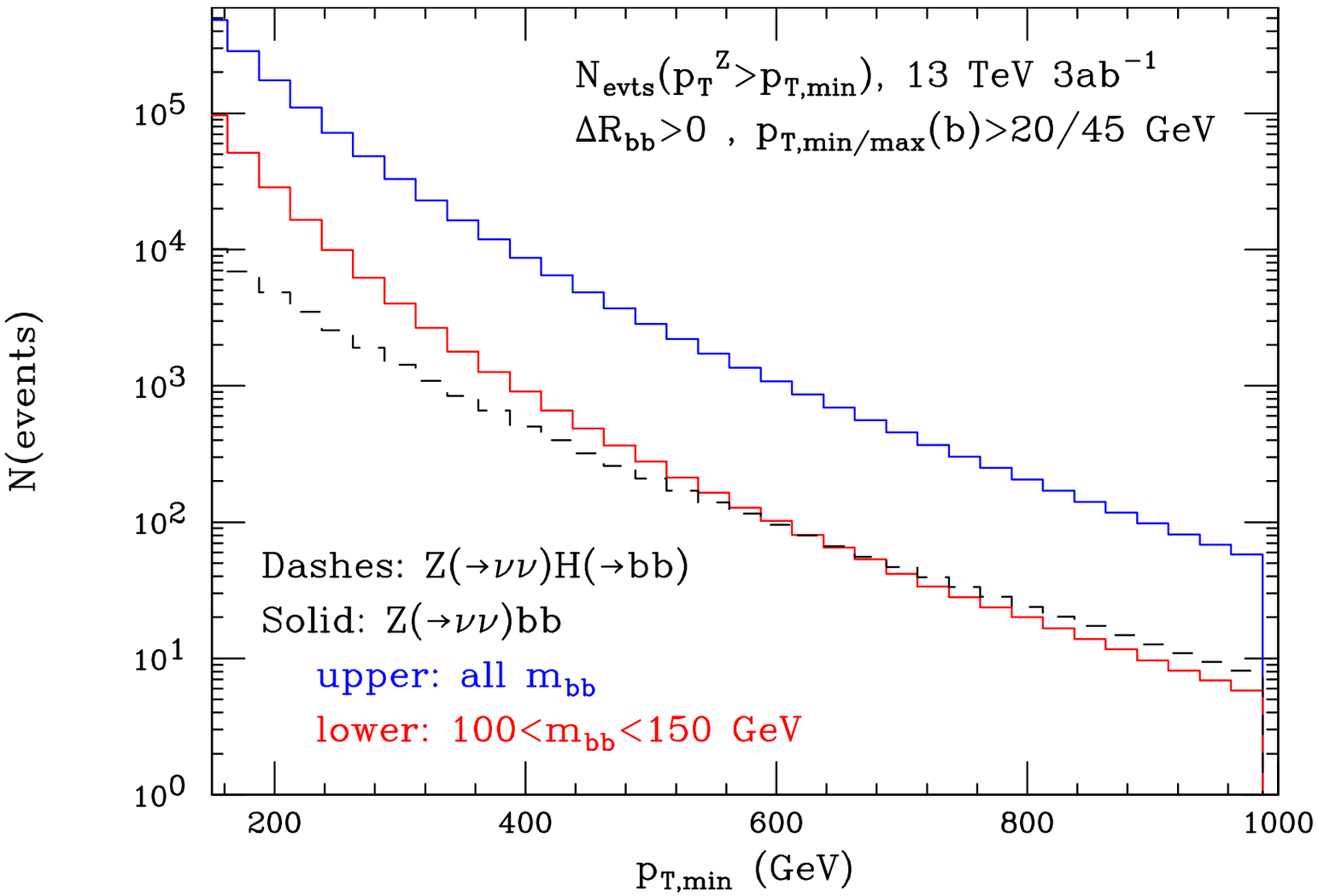
For simplicity consider only Z+HF bg, others will be suppressed at high p_T

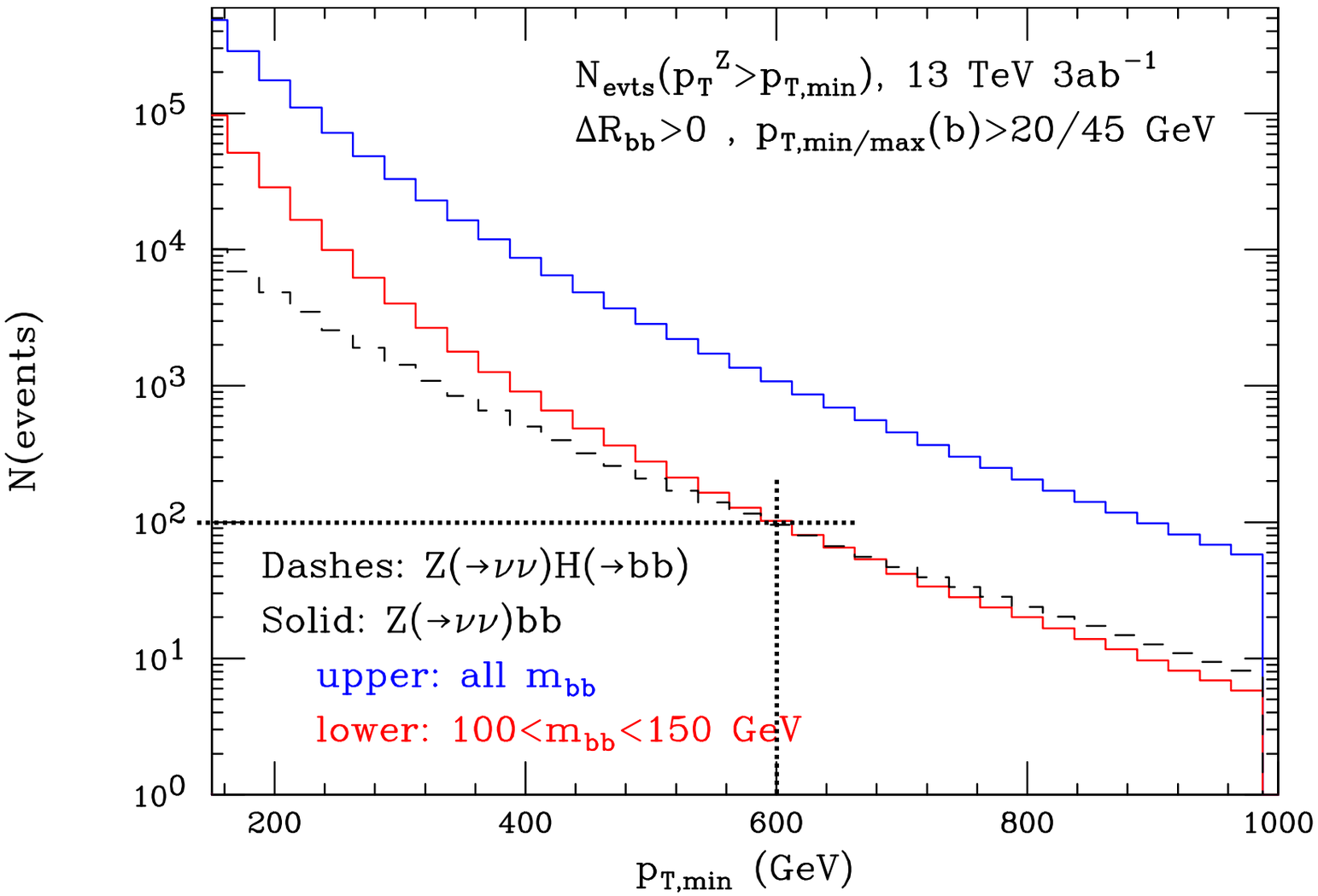


- m_{bb} cut very important!
- loss of efficiency with ΔR cut at large p_T

Remove ΔR cut => look at fat jets with double b-tag

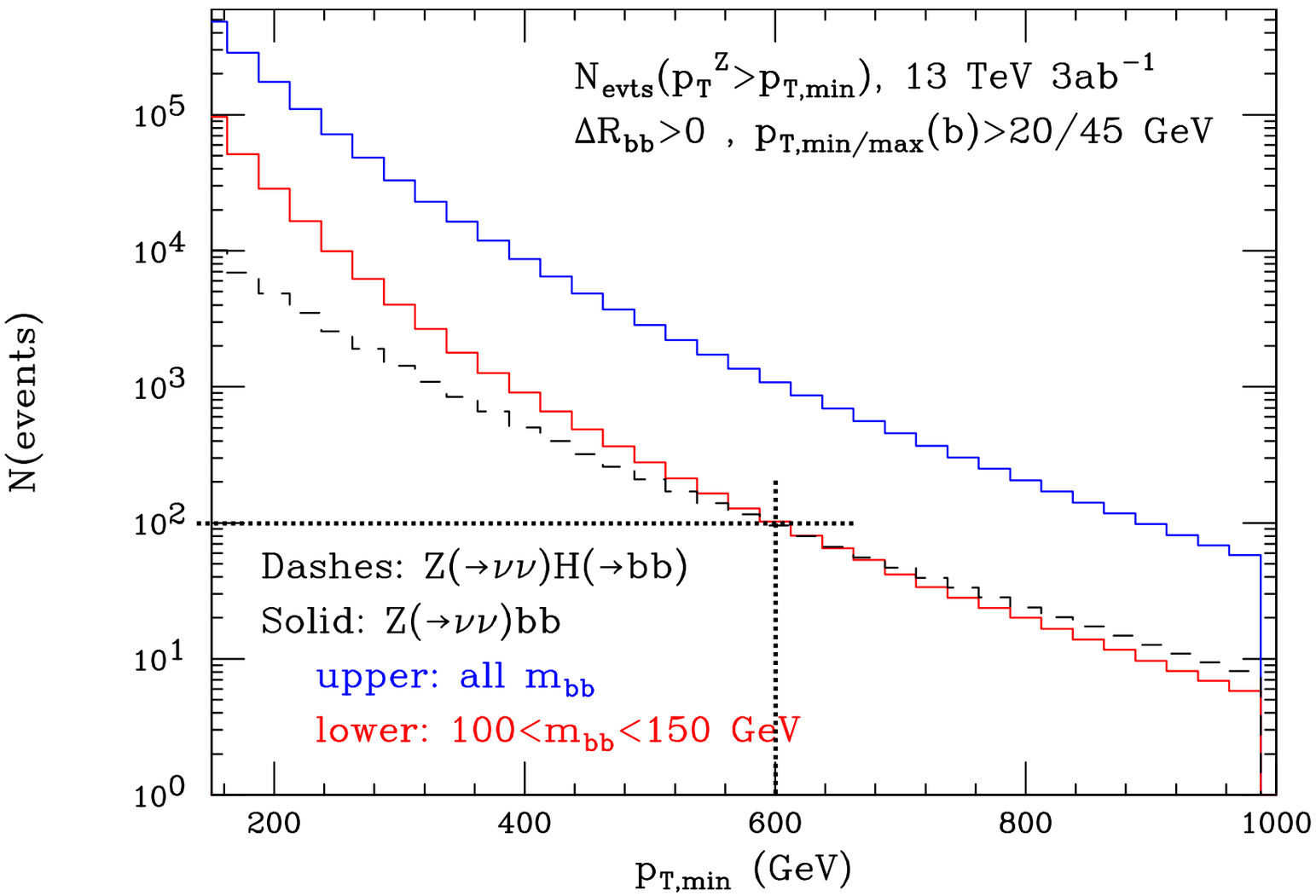



$N_{evts}(p_T{}^Z > p_{T,min})$, 13 TeV 3ab^{-1}
$\Delta R_{bb} > 0$, $p_{T,min/max}(b) > 20/45$ GeV
Dashes: $Z(\to\nu\nu)H(\to bb)$
Solid: $Z(\to\nu\nu)bb$
upper: all m_{bb}
lower: $100 < m_{bb} < 150$ GeV
N(events)
10^0
10^1
10^2
10^3
10^4
10^5
200
400
600
800
1000
$p_{T,min}$ (GeV)



at p_T>150 GeV: $B=10^5$ $S=10^4$ => $\delta=\sqrt{B}/S\sim3\%$

at p_T>600 GeV: $B=10^2$ $S=10^2$ => $\delta=\sqrt{B}/S\sim10\%$



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at p_T>600 GeV: $B=10^2$ $S=10^2$ => $\delta=\sqrt{B/S}\sim 10\%$

$$\delta \sim (p_{T,min}/\Lambda)^2 \Rightarrow \Lambda \sim p_{T,min}/\sqrt{\delta} \Rightarrow$$

$$\Lambda_{600}/\Lambda_{150} = 600/150 * \sqrt{(3\% / 10\%)} \sim 2.3$$

While the measurement at p_T>150 is 3x more precise, the measurement at p_T>600 has 2x the reach in sensitivity for Λ

Further remarks

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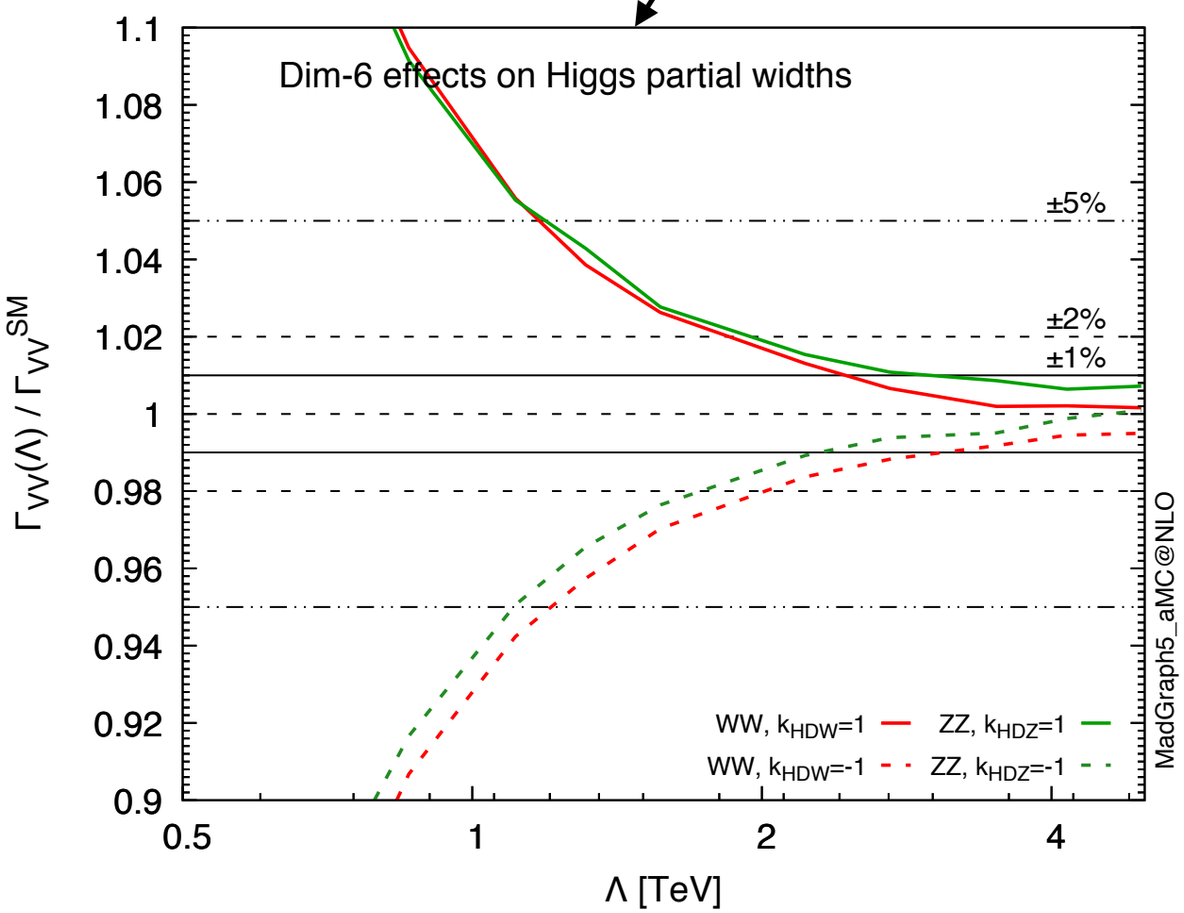
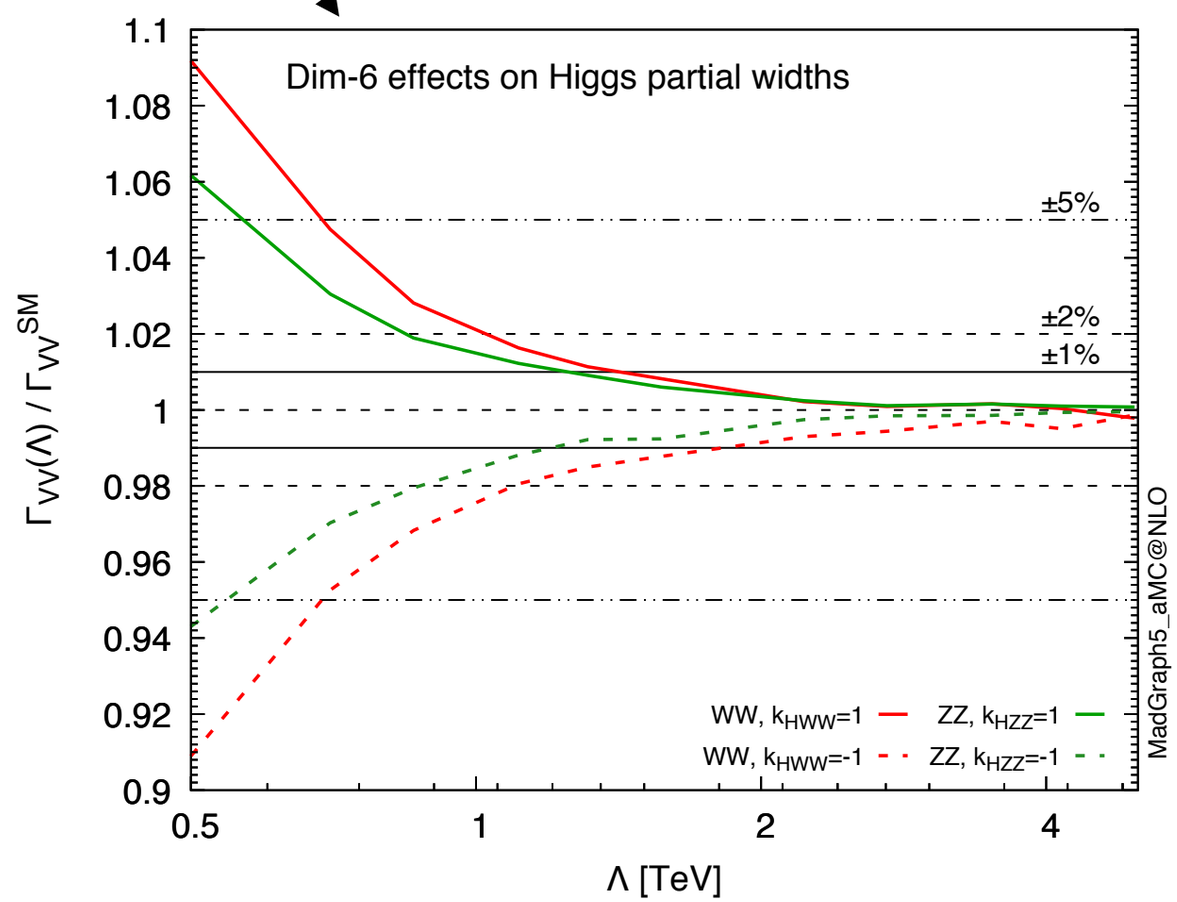
- On the experimental side, systematics of Higgs-tagging algorithm efficiency (jet substructure, ML, …) vs $p_{T,H}$ (for S and B) is probably the most relevant issue. But measurement of Zbb in the mbb sidebands is probably a robust handle ….

Large p_T Higgs in VBF

$$L_{D=6} \sim c_{H\partial V}\frac{v}{\Lambda^2}V^\nu\partial^\mu V_{\mu\nu}H + c_{HVV}\frac{v}{\Lambda^2}V^{\mu\nu}V_{\mu\nu}H$$





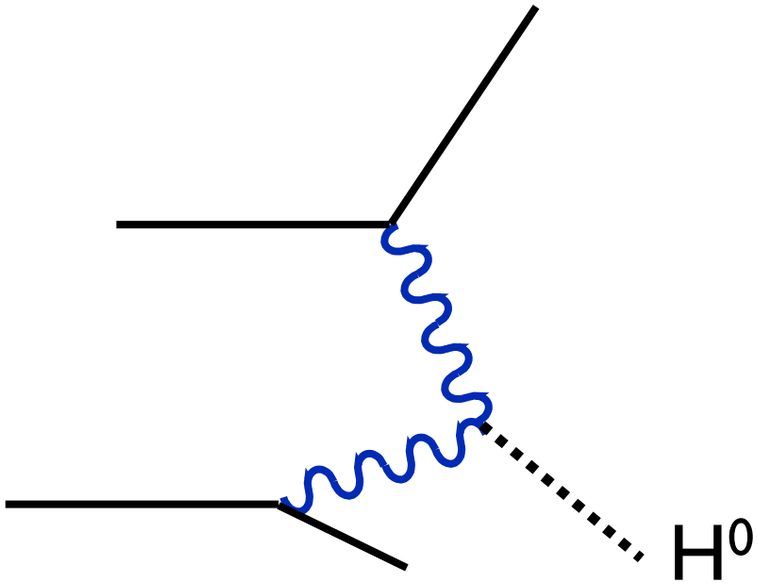
~2% deviations in B(H→VV*)

⇒ Λ~ 1.8 TeV ⇒ Λ~ 0.8 TeV

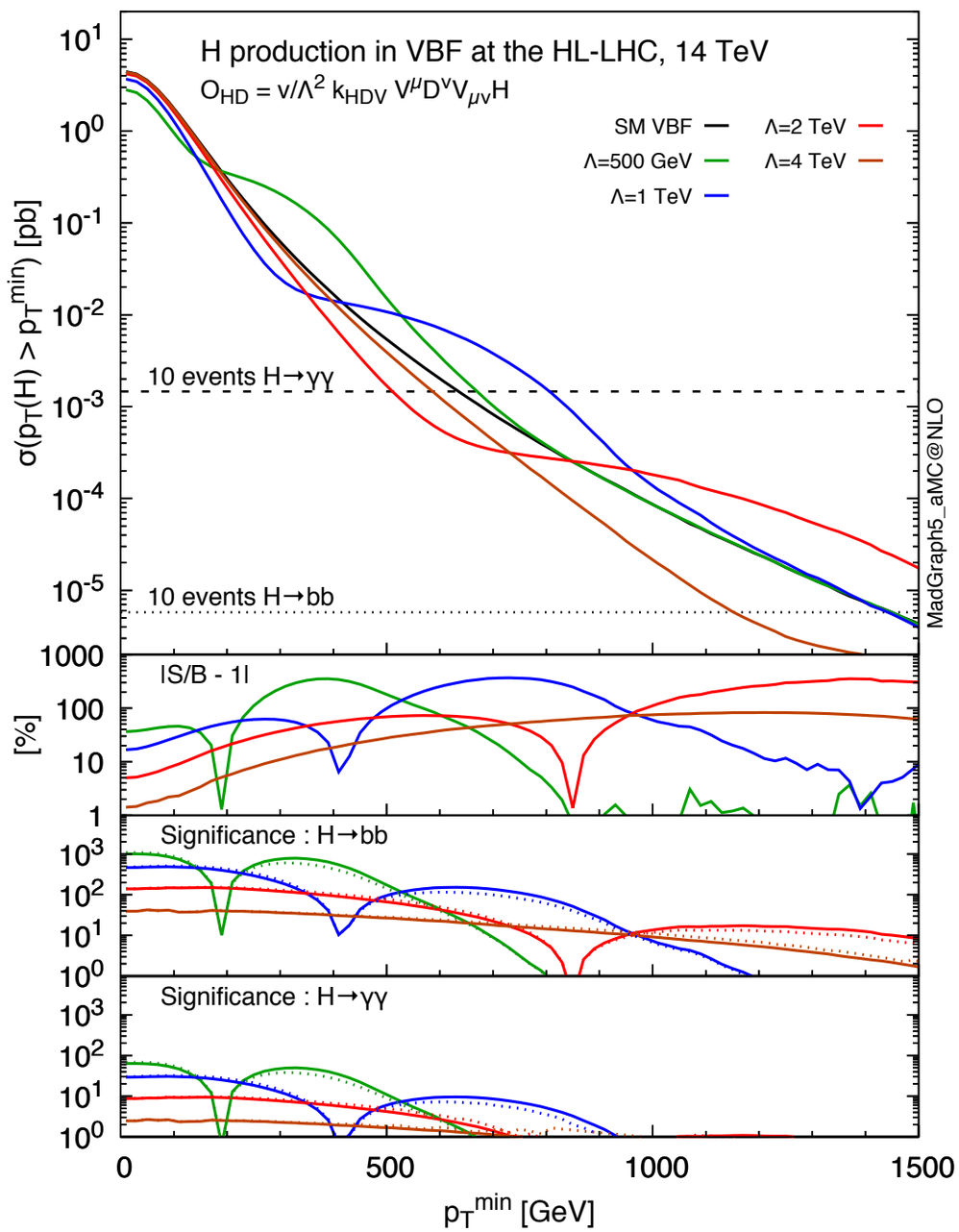
(for c~1)

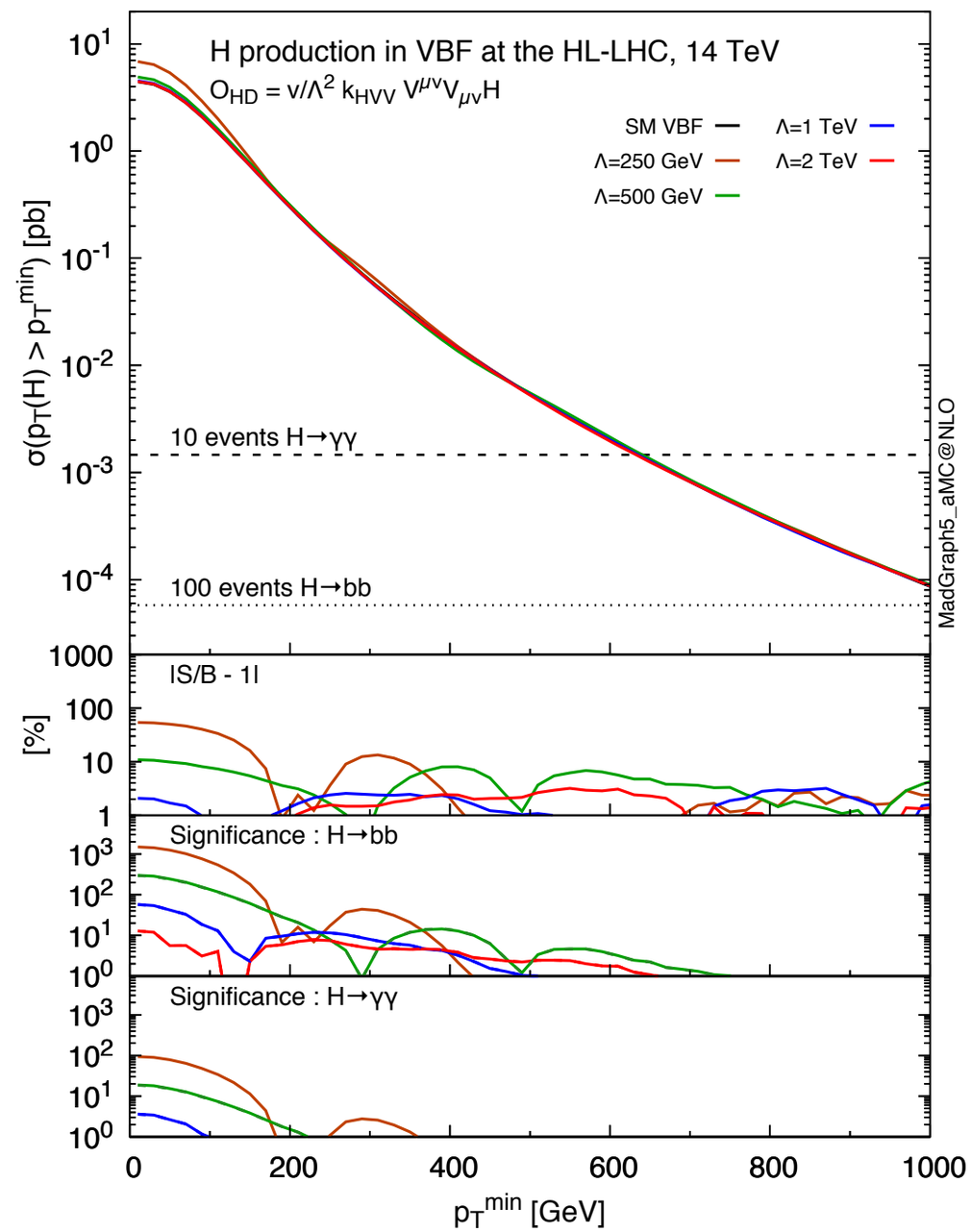
Large p_T Higgs in VBF

MG5_aMC@NLO
study by M.Zaro



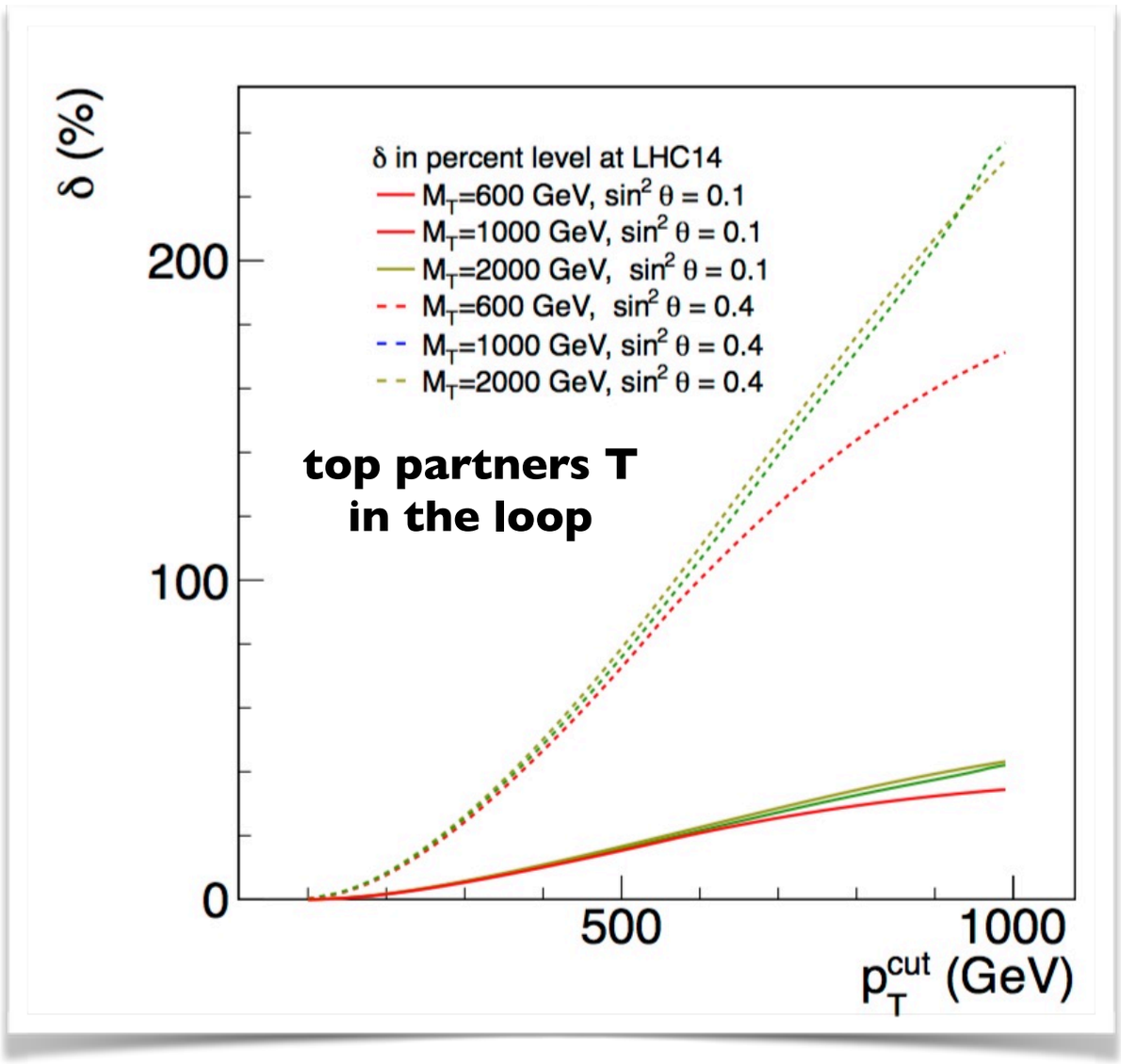
$$\frac{\sigma}{\sigma_{SM}} \sim 1 + \frac{v^2}{m_V^2}\left(c_{H\partial V}\frac{p_{T,H}^2}{\Lambda^2} + c_{HVV}\frac{s}{\Lambda^2}\right) + O(1/\Lambda^4)$$





gg→H at large p_T

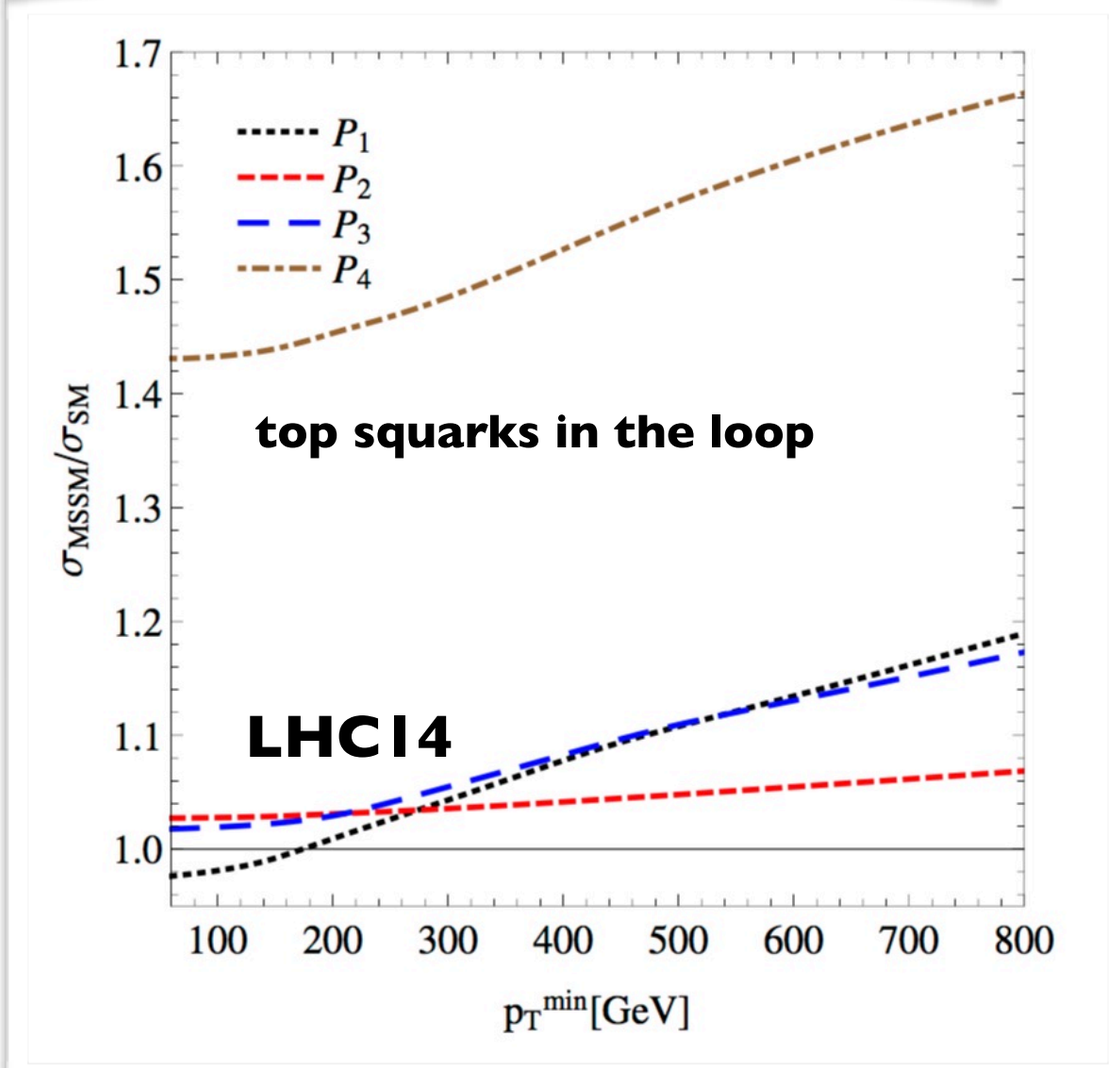
(See also
Azatov and Paul arXiv:1309.5273v3)



Banfi Martin Sanz, arXiv:1308.4771

Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\text{GeV}$, $M_2 = 1000\,\text{GeV}$, $\mu = 200\,\text{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was set to 125 GeV.

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18



Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

CMS, Inclusive search for the standard model Higgs boson produced in pp collisions at $\sqrt{s}$=13 TeV using H→bb decays

CMS-PAS-HIG-17-010

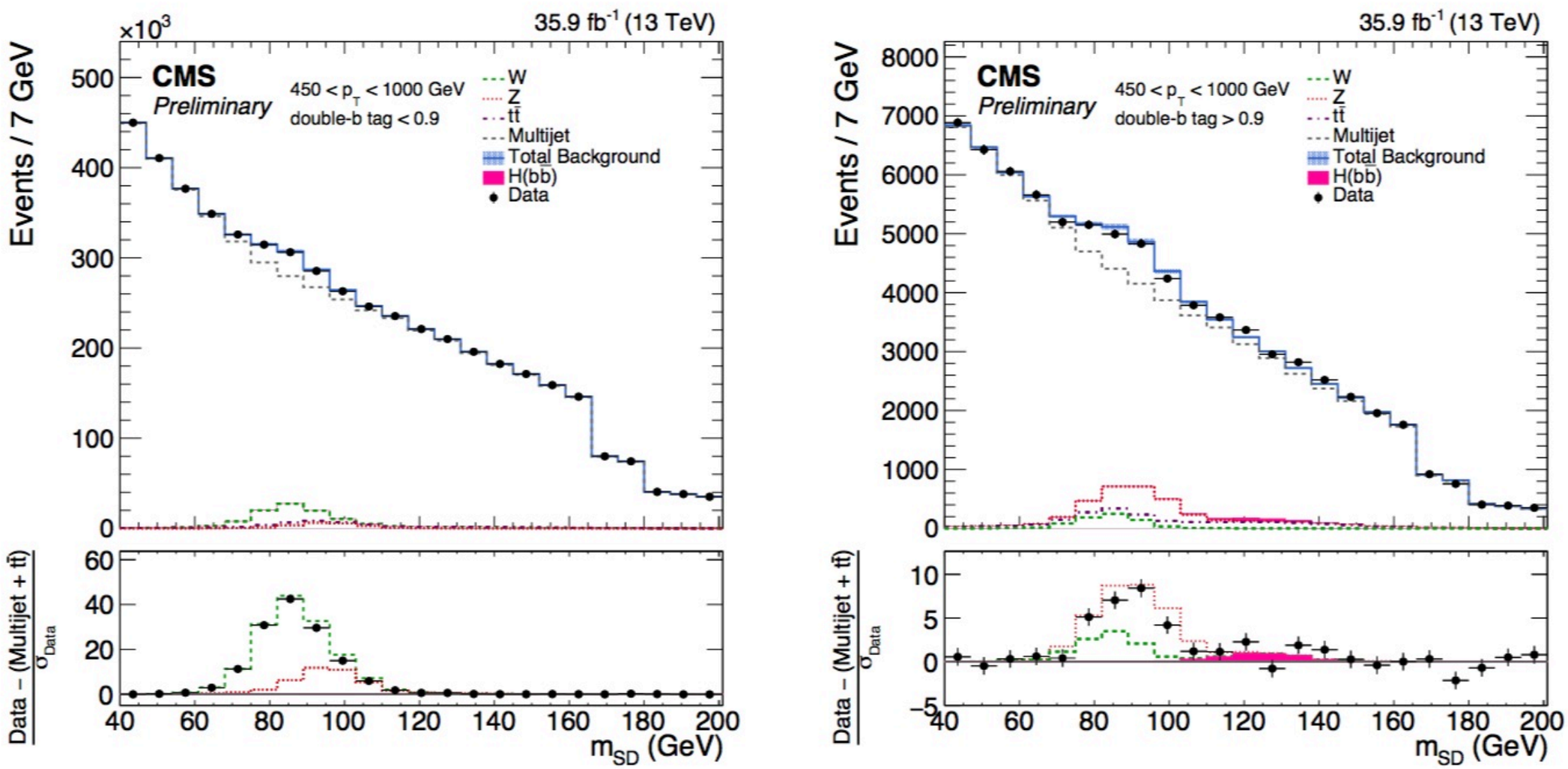
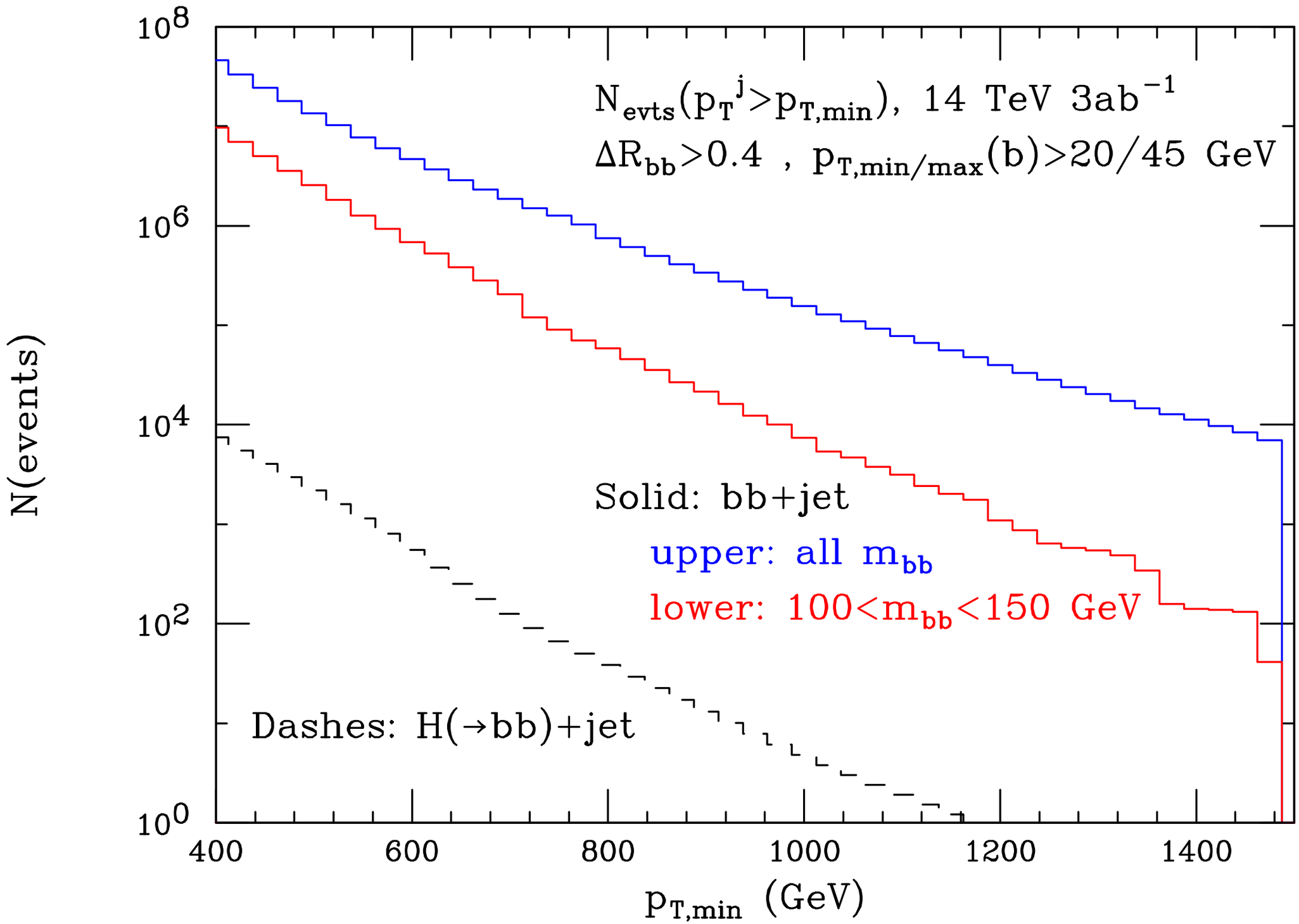


Figure 4: Post-fit m_{SD} distributions in data for the pass and fail regions and combined p_T categories by using a polynomial 2nd order in ρ and 1st order in p_T. The features at 166 GeV and 180 GeV in the m_{SD} distribution are due to the kinematic selection on ρ, which affects each p_T category differently.

local 1.5σ, $\sigma_{H\to bb} = 74^{+51}_{-49}$ fb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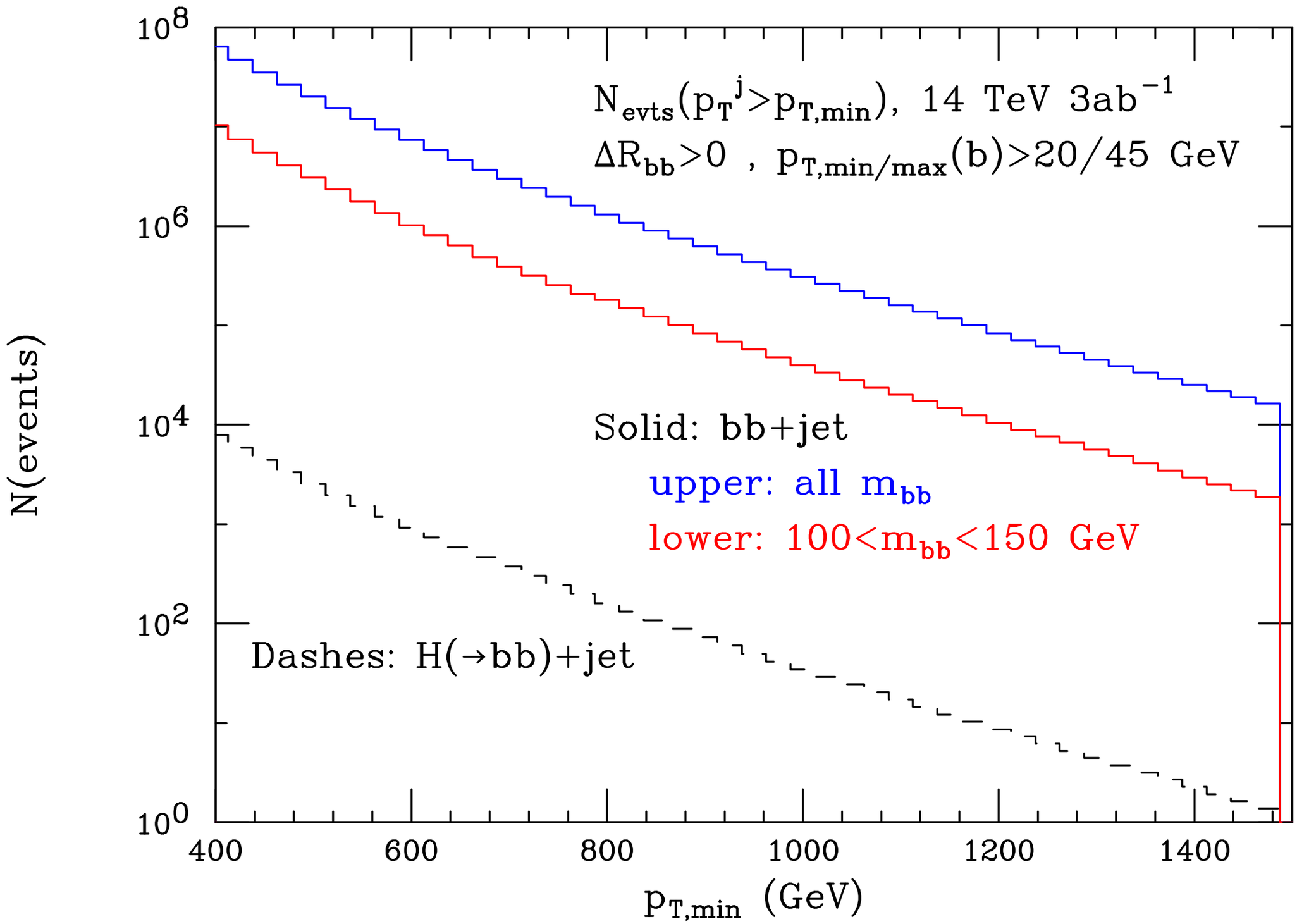
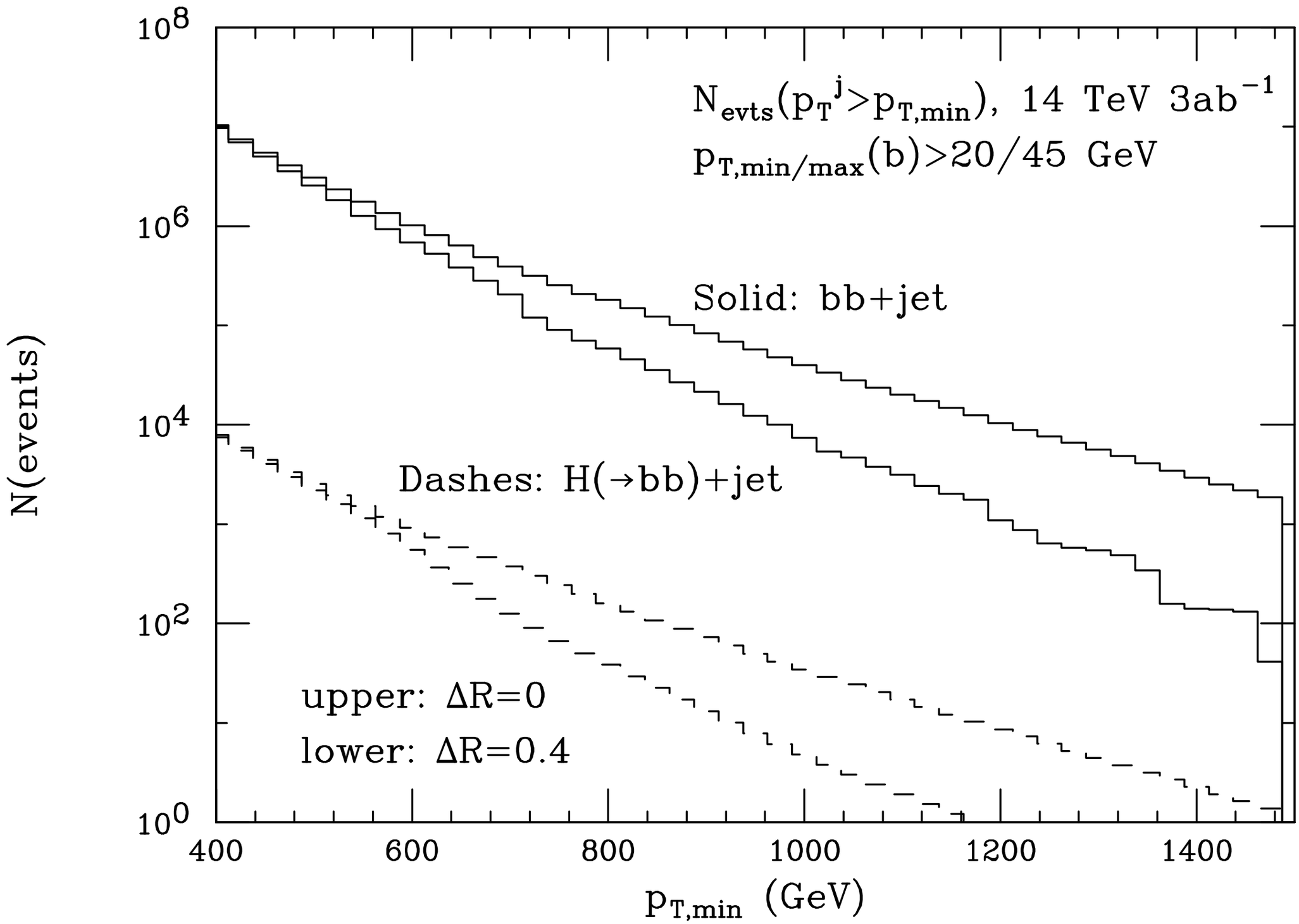
$\Delta R_{bb} > 0.4$, $p_{T,min/max}(b) > 20/45$ GeV
Solid: bb+jet
upper: all m_{bb}
lower: $100 < m_{bb} < 150$ GeV
Dashes: H(→bb)+jet
N(events)
10^8
10^6
10^4
10^2
10^0
400
600
800
1000
1200
1400
$p_{T,min}$ (GeV)


$N_{evts}(p_T{}^j > p_{T,min})$, 14 TeV 3ab^{-1}
$\Delta R_{bb} > 0$, $p_{T,min/max}(b) > 20/45$ GeV
Solid: bb+jet
upper: all m_{bb}
lower: $100 < m_{bb} < 150$ GeV
Dashes: H(→bb)+jet
N(events)
10^8
10^6
10^4
10^2
10^0
400
600
800
1000
1200
1400
$p_{T,min}$ (GeV)


$N_{evts}(p_T{}^j > p_{T,min})$, 14 TeV $3ab^{-1}$
$p_{T,min/max}(b) > 20/45$ GeV
Solid: bb+jet
Dashes: H(→bb)+jet
upper: ΔR=0
lower: ΔR=0.4
N(events)
10^8
10^6
10^4
10^2
10^0
400
600
800
1000
1200
1400
$p_{T,min}$ (GeV)

Final remarks

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- more work to be done, in TH and EXP, to assess more conclusively the potential of these measurements. Plenty of room for improvements
- Contrary to the direct BSM search programme, which will approach its asymptotic limits well before the $3ab^{-1}$ are collected, the study of Higgs properties will dominate the endgame (cfr $m_{W,top}$ at Tevatron)