New Particle Searches at CEPC-SppC

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NEW PARTICLE SEARCHES AT 100 TEV

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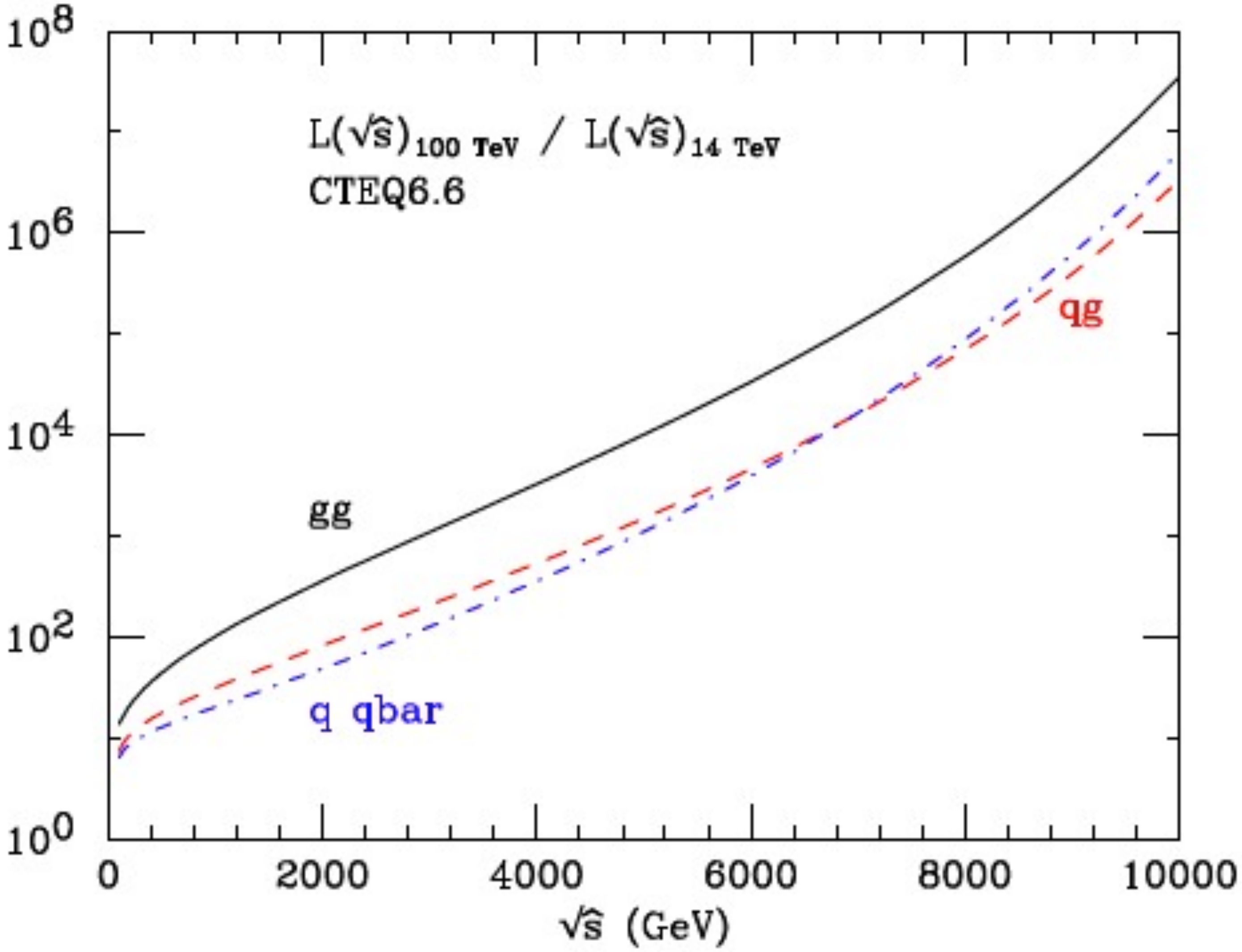
100 TeV pp Collider



[I. Hinchliffe, et.al.'05]

- Ratio of partonic luminosities at 100 and 14 TeV pp colliders
- For particles as heavy as ~ 10 TeV in either of these channels, the rate is increased by a factor larger than one million

100 TeV pp Collider

- Scaling relation [W.Barletta, et.al.'14; B. Richter'14] : assuming the reach is obtained by the same # of signal events,

$$L_{1p}\hat{\sigma}_{1p}L_1 = L_{2p}\hat{\sigma}_{2p}L_2$$

  - With an integrated luminosity

$$L_2 \sim \frac{s_2}{s_1} L_1$$ => potential mass reach $$\frac{M_2}{M_1} \sim \frac{\sqrt{s_2}}{\sqrt{s_1}}$$

- Probe new particles + new phenomena, in accessible to the LHC, at high mass scales
- Note: based on # counting of signal events. The kinematics is ignored.

Z' Benchmark Scenarios

[CEPC-SppC preCDR, '15]

	χ	ψ	η	LR	B-L	SSM	
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1	
$\hat{\epsilon}_L^q$	–1	1	–2	–0.109	1/6	$\hat{\epsilon}_L^u$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$
						$\hat{\epsilon}_L^d$	$-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^u$	1	–1	2	0.656		$\hat{\epsilon}_R^u$	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^d$	–3	–1	–1	–0.874		$\hat{\epsilon}_R^d$	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^l$	3	1	1	0.327	–1/2	$\hat{\epsilon}_L^\nu$	$\frac{1}{2}$
						$\hat{\epsilon}_L^e$	$-\frac{1}{2}+\sin^2\theta_W$
$\hat{\epsilon}_R^e$	1	–1	2	–0.438		$\hat{\epsilon}_R^e$	$\sin^2\theta_W$
$\hat{Q}_u$	2	–2	4	0.765	0	$-\frac{1}{2}$	
$\hat{Q}_d$	–2	–2	1	–0.765	0	—	

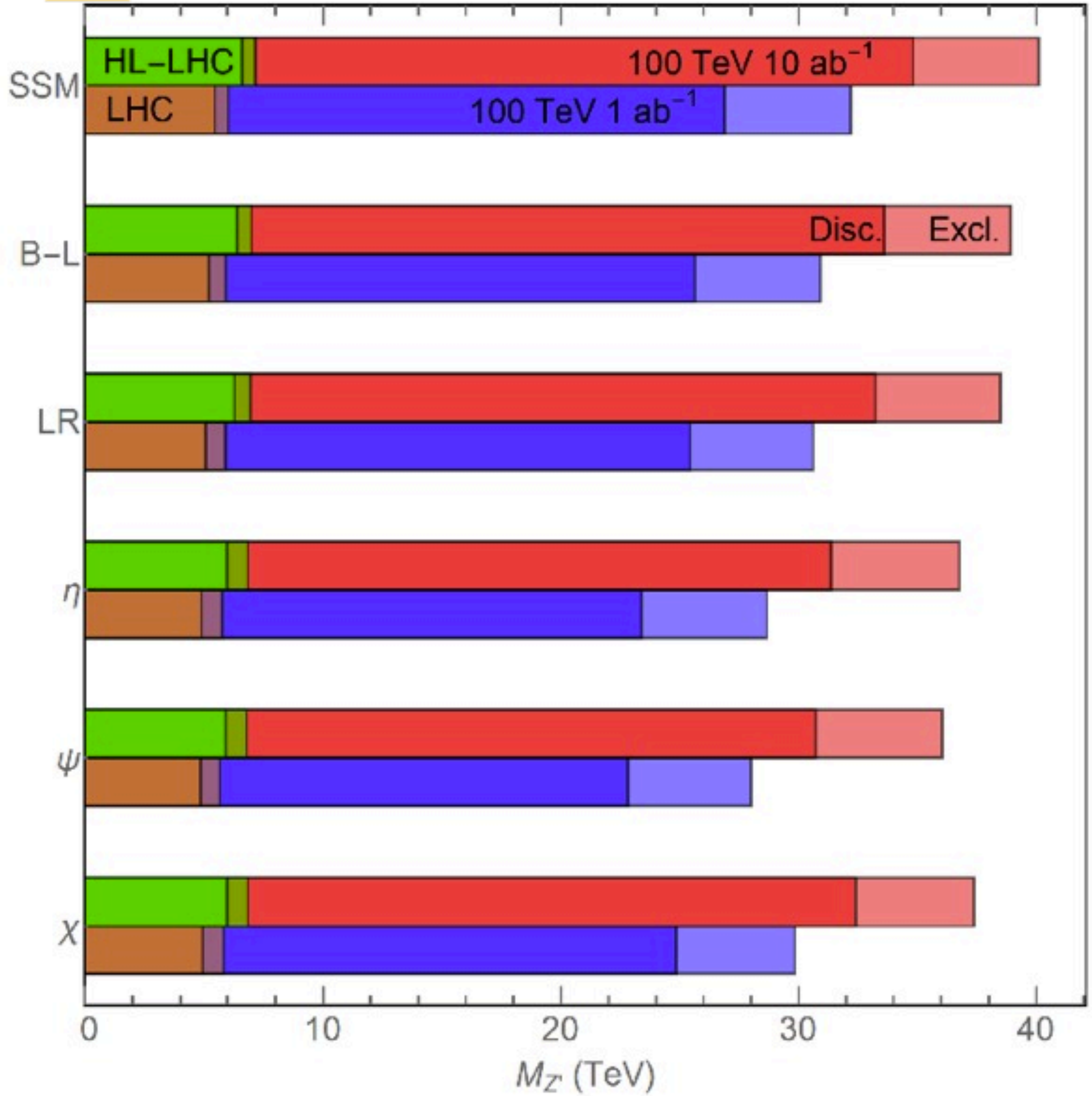
- Either E6-GUT motivated, or simply a sequential Z'

$$-L_{NC} = eJ^\mu_{em}A_\mu + g_1 J_1^\mu Z^0_{1\mu} + g_2 J_2^\mu Z^0_{2\mu},$$

$$J^\mu_\alpha = \sum_i \bar{f}_i \gamma^\mu [\epsilon_L^{\alpha i} P_L + \epsilon_R^{\alpha i} P_R] f_i.$$

- All Z' nontrivially couple with leptons, with an electroweak coupling

Z' Search via Dilepton Resonance



[CEPC-SppC preCDR, '15]

- 3/ab at LHC: mass reach to ~6 TeV and ~7 TeV for discovery and exclusion, respectively.
- 10/ab at 100 TeV: moves the discovery reach to 30-34 TeV and the exclusion reach to 36-40 TeV

Di-jet Resonance

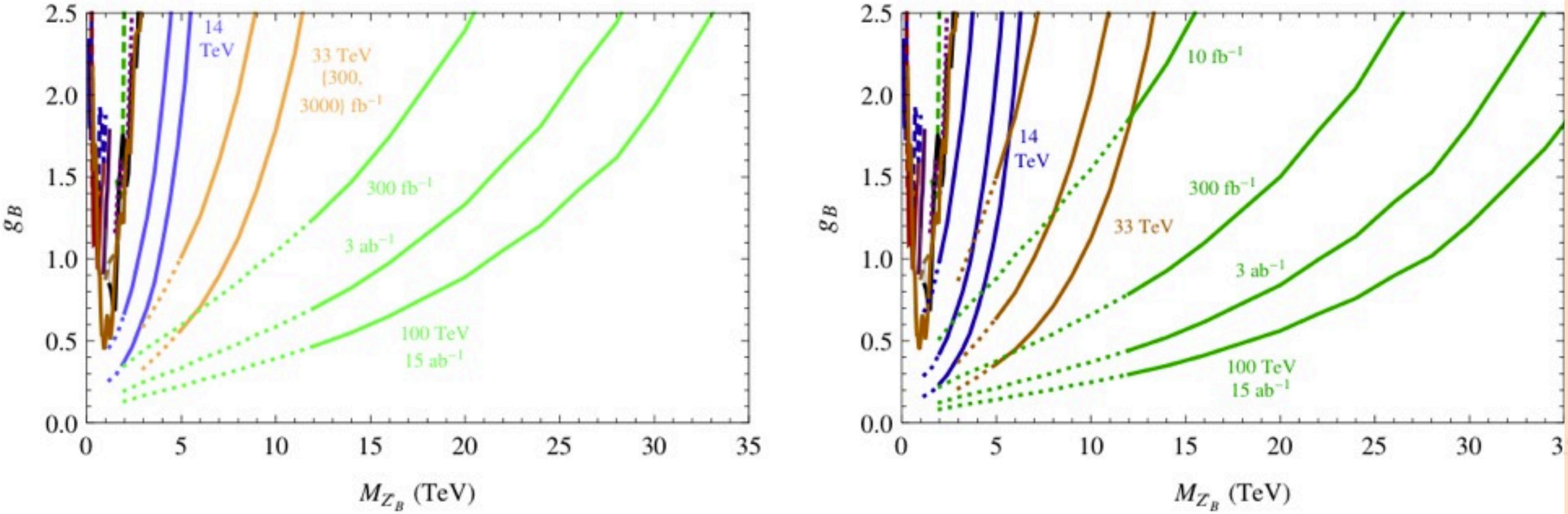
- Generic: if a new particle is produced in the s-channel at hadron colliders => decays into a pair of hadronic jets

- Simple: if its leptonic decay is suppressed, probably the simplest way for its resonance search

- Typical: many leptophobic scenarios, e.g., coloron

- Long history - been searched more than three decades: SPS, Tevatron, LHC

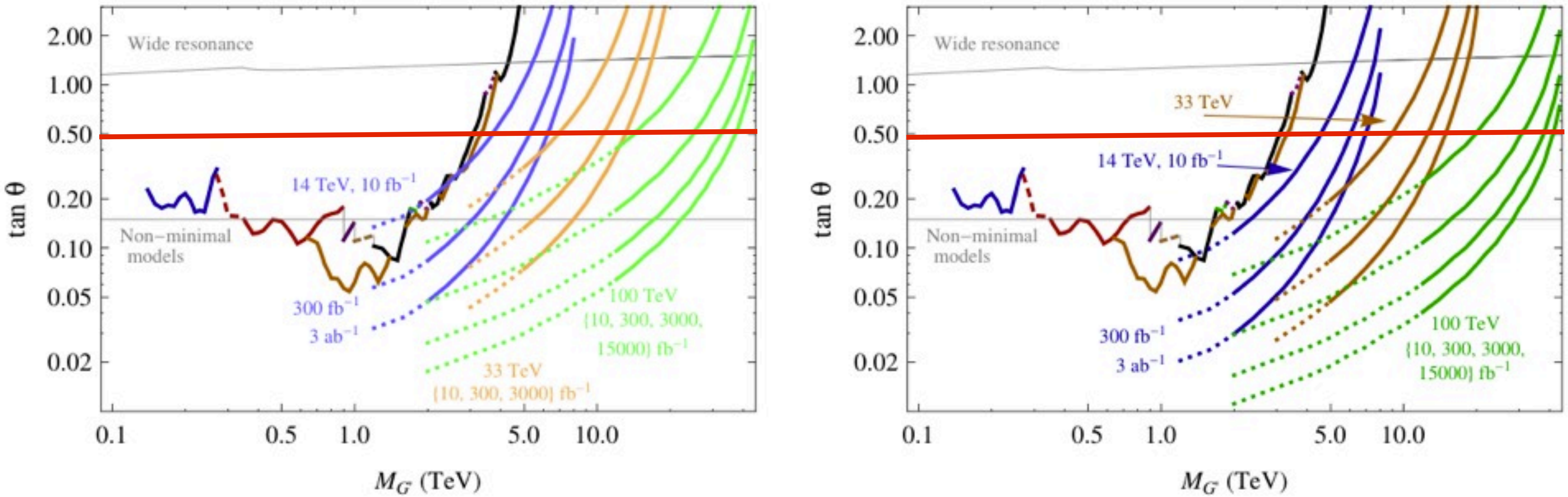
Baryonic Z_B'



[F. Yu'13]

- Z_B' is a leptophobic flavor-universal color-singlet $\mathcal{L} \supset \frac{g_B}{6} Z'_{B\mu}\bar{q}\gamma^\mu q$
- 3/ab at LHC: mass reach to ~5.5 TeV and ~6.1 TeV for discovery and exclusion for gB=2.5, respectively.
- 15/ab at 100 TeV: moves the discovery reach to ~33 TeV and the exclusion reach to ~38 TeV for gB=2.5

Coloron



[F. Yu'13]

- Coloron: massive gauge bosons from SU(3)XSU(3) breaking, leptophobic flavor universal color-octet

$$\mathcal{L} \supset g_s \tan\theta \bar{q} \gamma^\mu T^a G'^a_\mu q$$

- 3/ab at LHC: mass reach to ~6 TeV and ~6.5 TeV for discovery and exclusion for tan_theta = 0.5, respectively.
- 15/ab at 100 TeV: moves the discovery reach to ~35 TeV and the exclusion reach to ~40 TeV for tan_theta = 0.5

100 TeV - A Boosted World

- A naive gain factor expected for mass reach at an 100 TeV pp collider, with proper luminosity

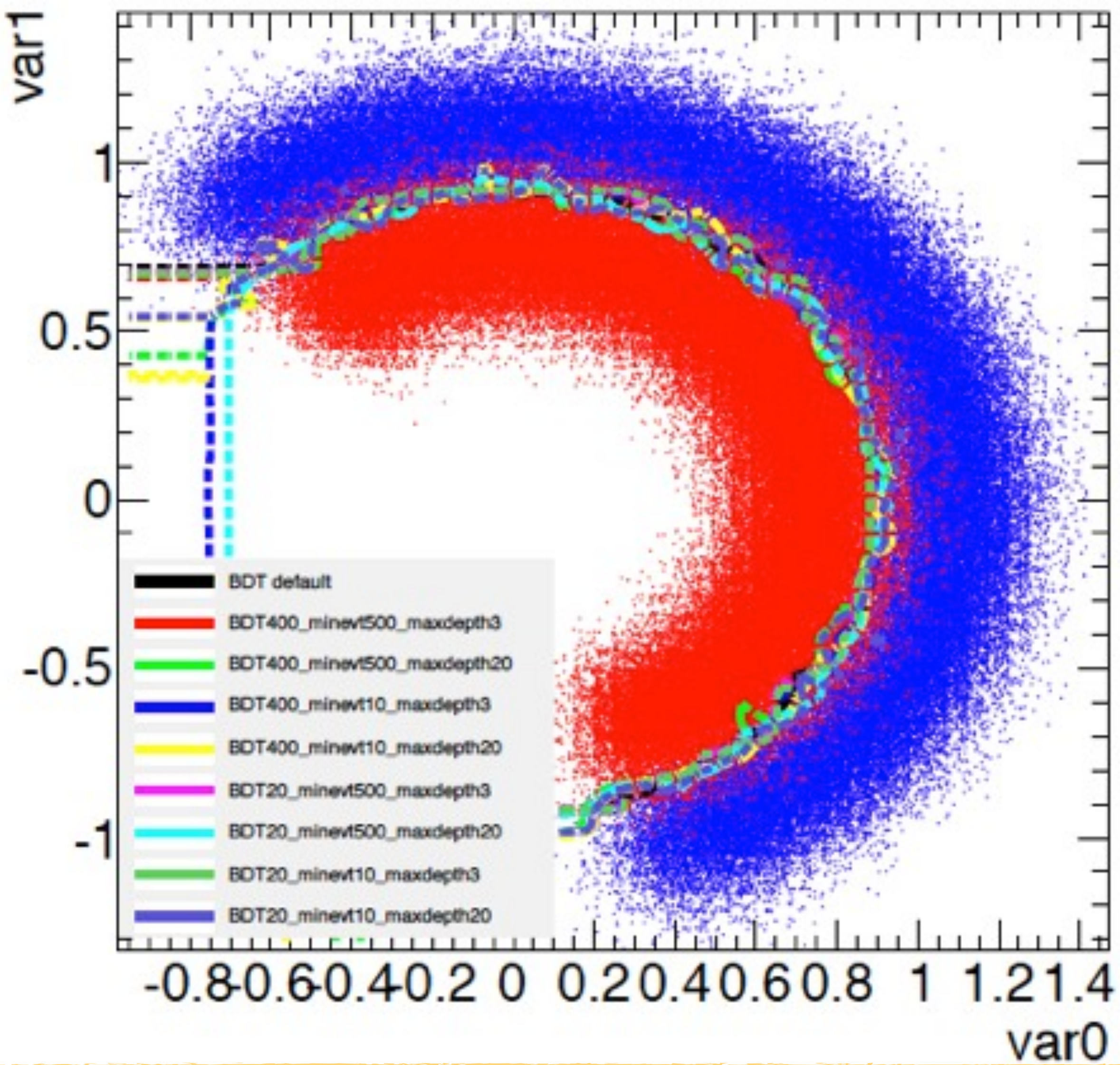
$$M_2 \sim \frac{\sqrt{s_2}}{\sqrt{s_1}} M_1 \sim 7 M_1$$

- W, Z, h, t produced via new particles of such a high mass scale are highly boosted
  - fermionic top partners -> top + Z, h; bottom + W
  - heavy Higgs bosons in 2HDM -> top + top, bottom

- Systematic study on their boosted kinematics at 100 TeV and its detector response are important for new particle search

Boosted Decision Tree

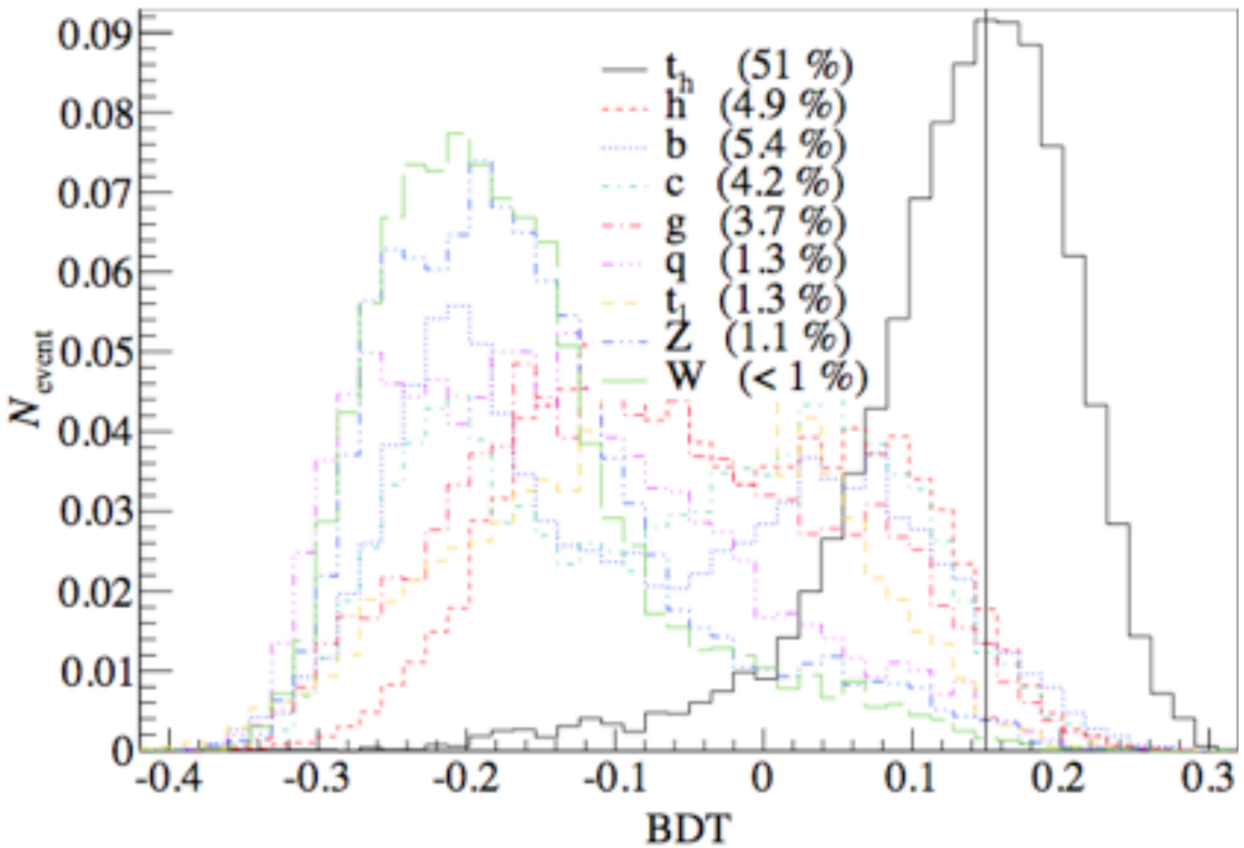
- A multi-variate method:
  - a non-linear combination of analysis cuts, with their correlation incorporated
  - optimize the efficiencies of the cuts



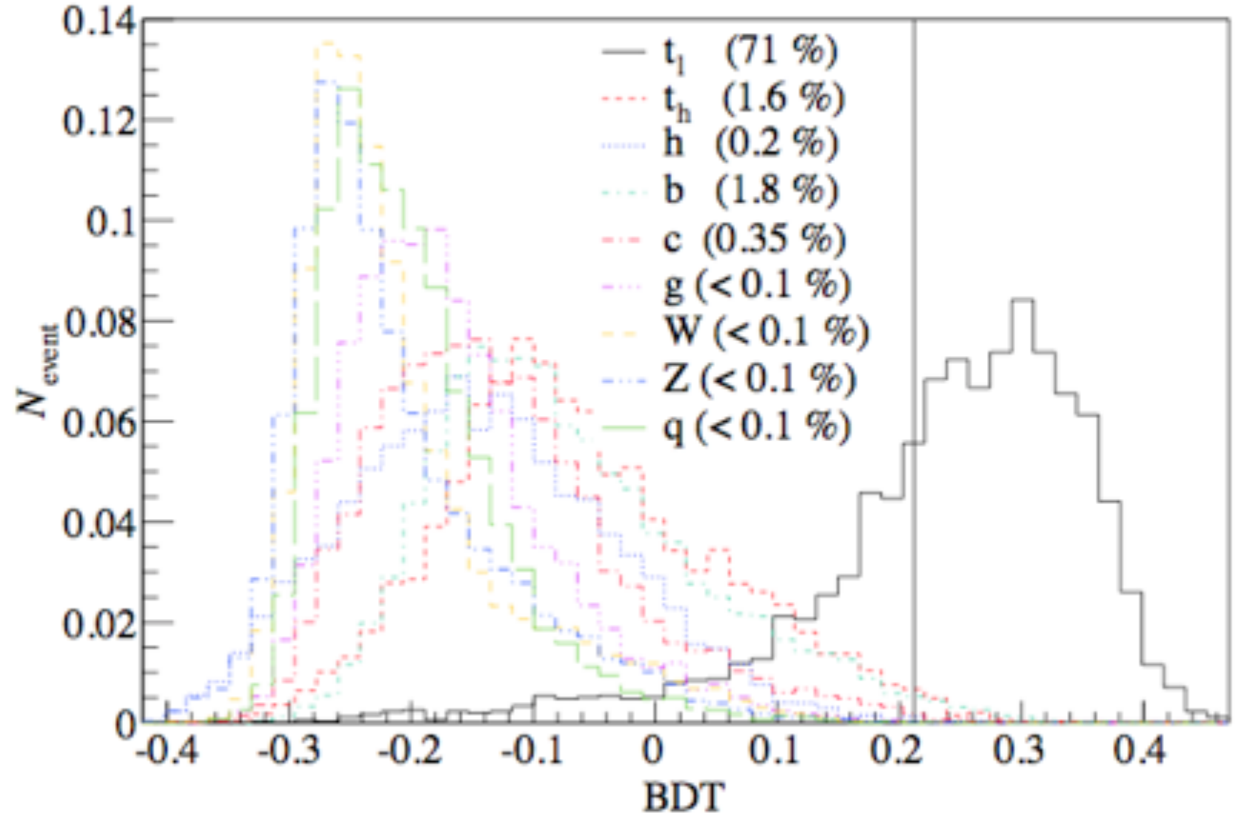
[Yann Coadou'12]

Top Jets

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]



(b) $1000\,\mathrm{GeV} < p_T^j < 1500\,\mathrm{GeV}$

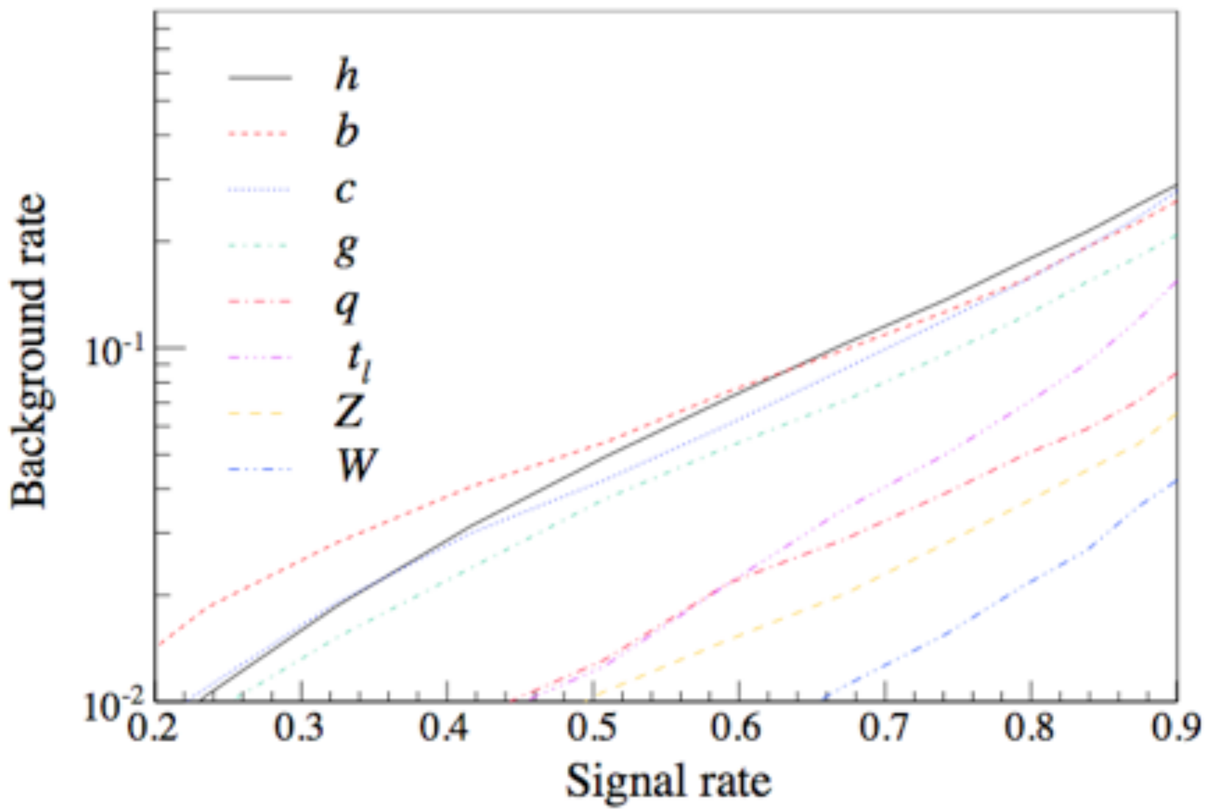


(b) $1000\,\mathrm{GeV} < p_T^j < 1500\,\mathrm{GeV}$

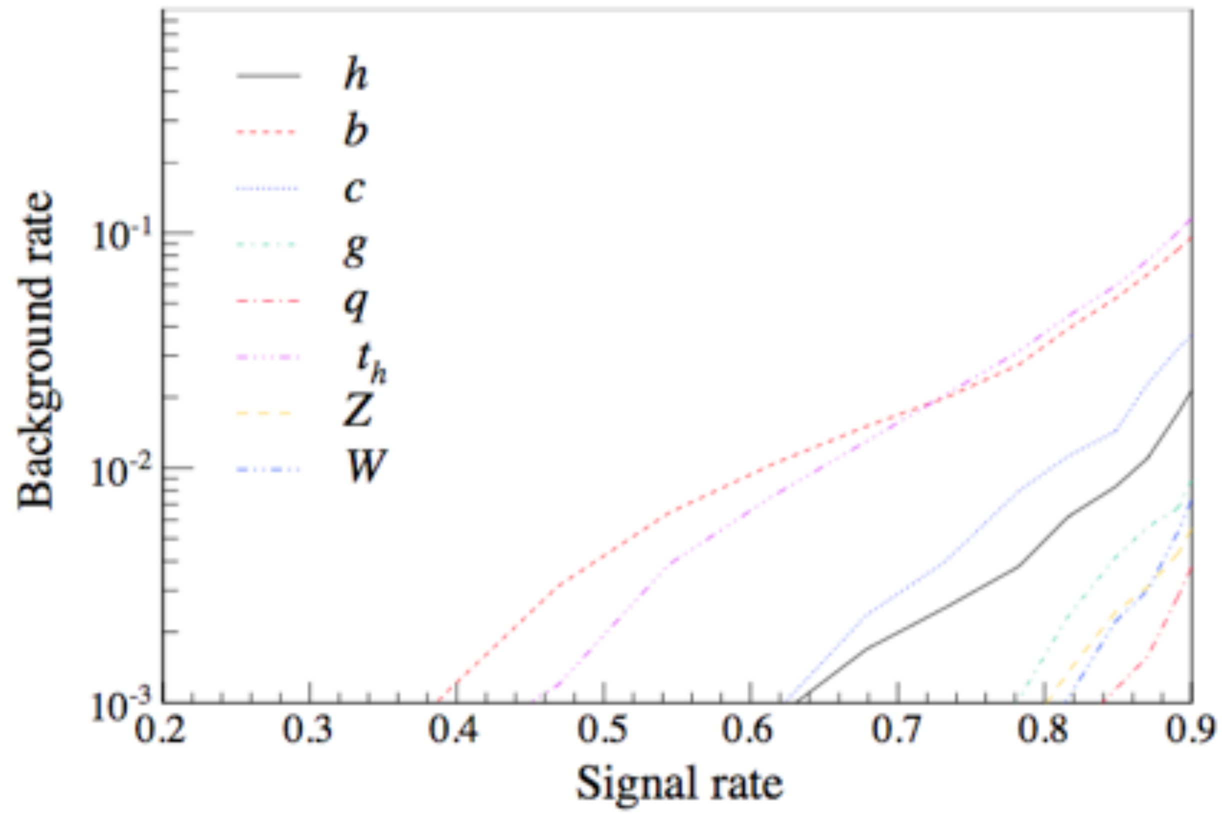
- Hadronic top-jet tagger: b secondary vertex and jet mass information, also veto hard lepton.
- Leptonic top-jet tagger: b secondary vertex and lepton information, as well as jet mass requirement

Top Jets

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]



(b) $1000\,\mathrm{GeV} < p_T^j(\mathrm{hadronic}) < 1500\,\mathrm{GeV}$

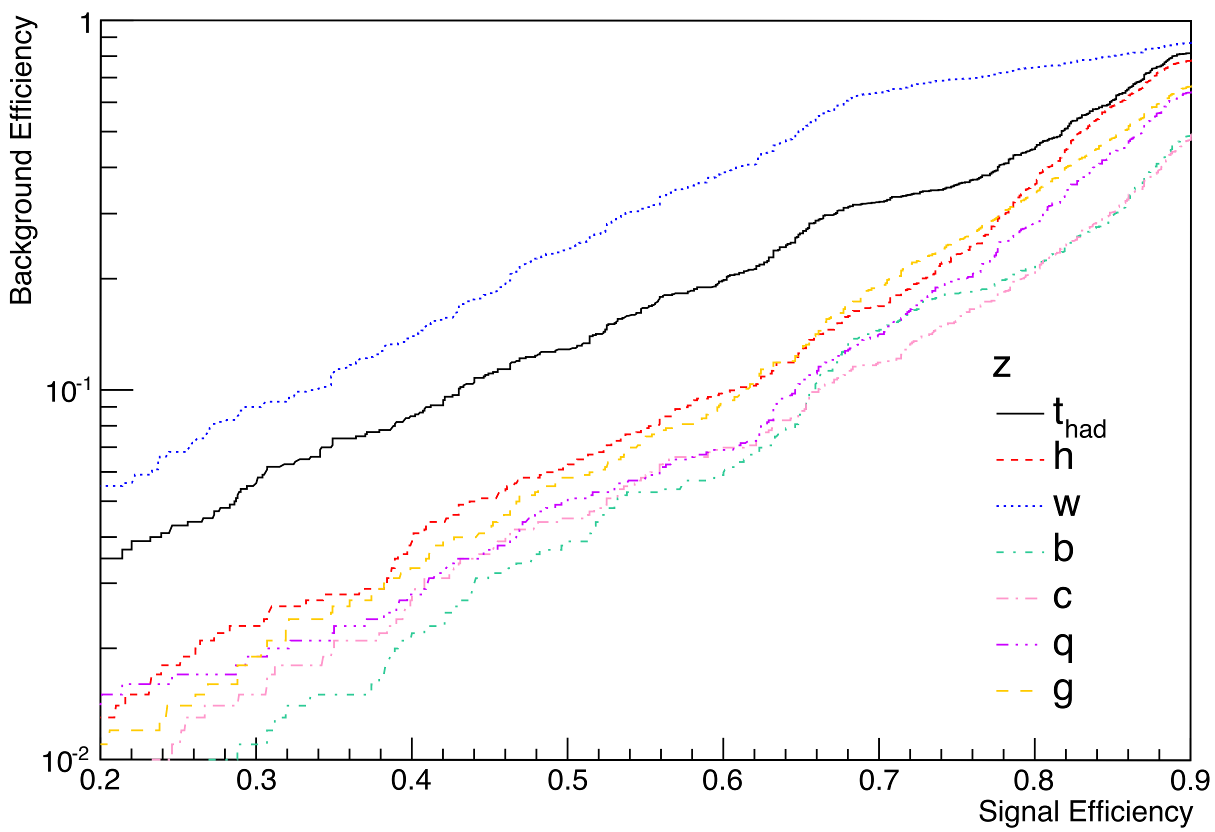


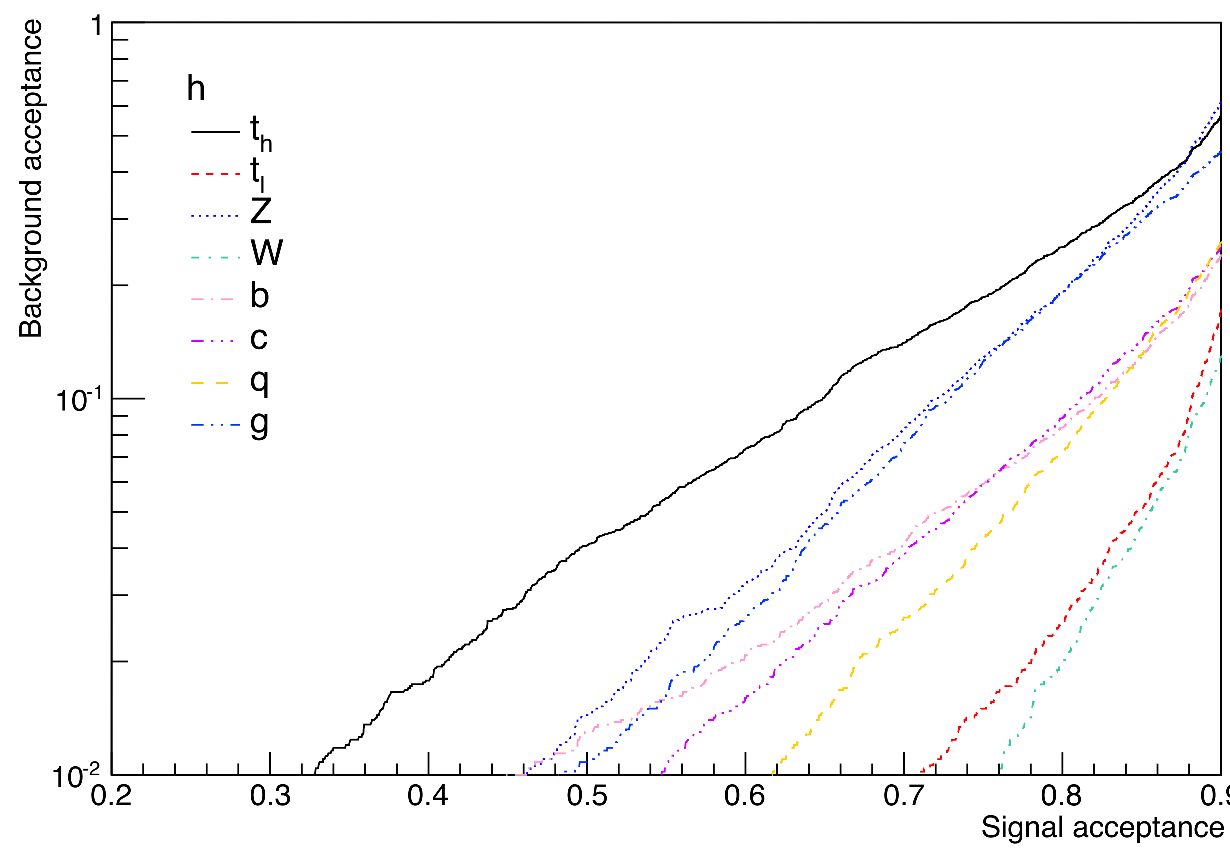
(d) $1000\,\mathrm{GeV} < p_T^j(\mathrm{leptonic}) < 1500\,\mathrm{GeV}$

- Hadronic top-jet tagger: most likely faked by b- and h-jets
- Leptonic top-jet tagger: low fake rates, due to hard lepton requirement

Z and Higgs jets

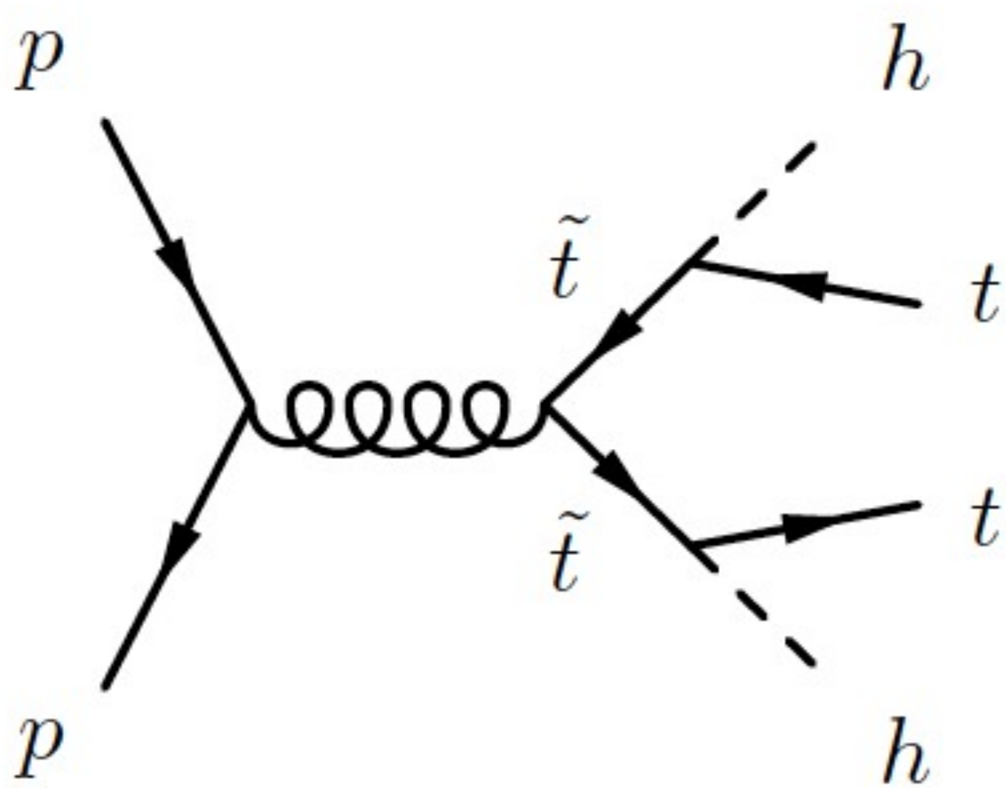
[C.-R. Cheng, J. Hajer, TL, I. Low, H. Zhang, preliminary]

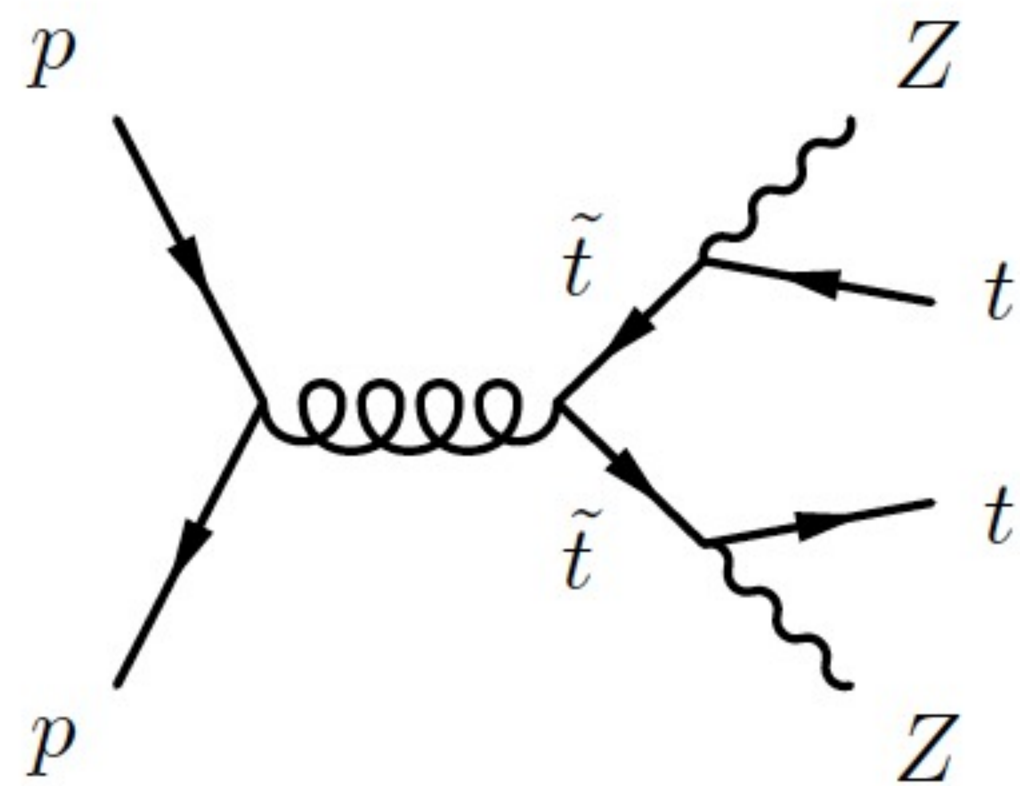




- Main variables: bottom likeliness of the constituents;
  - Z-tagger: most likely faked by W hadronic jets
  - h-tagger: most likely faked by hadronic top-jets
- Not fully optimized: jet-substructure might help, but it may suffer from detector resolution

One Application: Fermionic Top Partner





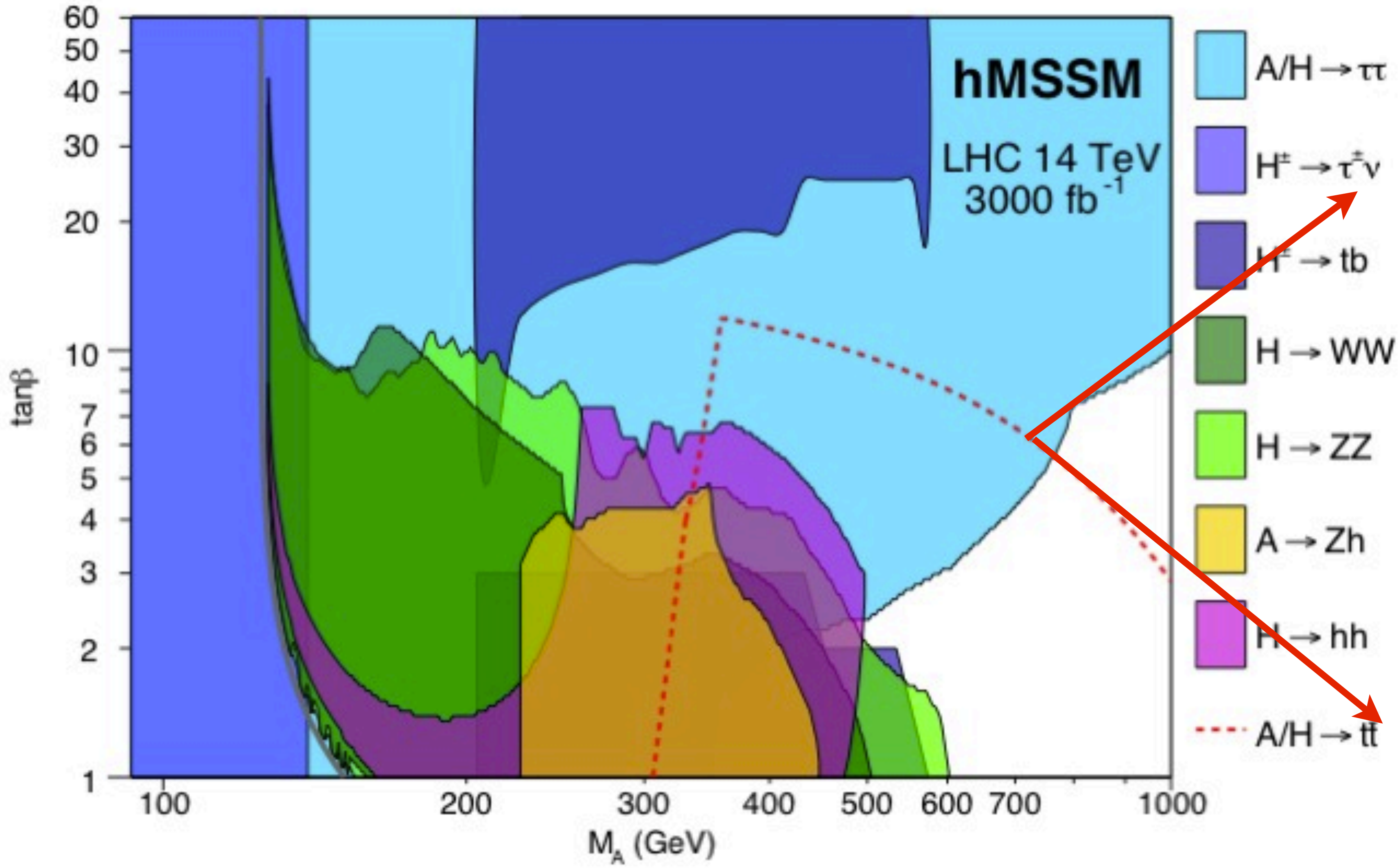
- One can use this to search for fermionic top partners and to probe the quadratic divergence cancellation in Higgs mass, via the measurement of Tth and TThh couplings.

[C.-R. Cheng, J. Hajer, TL, I. Low, H. Zhang, in progress]

Another Application: Heavy Higgs Boson Search

- Extensively exist in NP
  - Singlet: SM + S
  - Doublet: 2HDM, MSSM
  - Triplet: Type II see-saw, L-R model
  - Mixture: 2HDM + S, NMSSM
- Couple with heavy fermions strongly in many scenarios
- The MSSM Higgs sector (no CP-violation): H, A, Hc
  - Two free parameters (in additional to the SM ones) at tree-level: tan_beta, mA/mHc
  - Project sensitivity on a plane of mA/mHc - tan_beta

MSSM Higgs Bosons @ 14 TeV

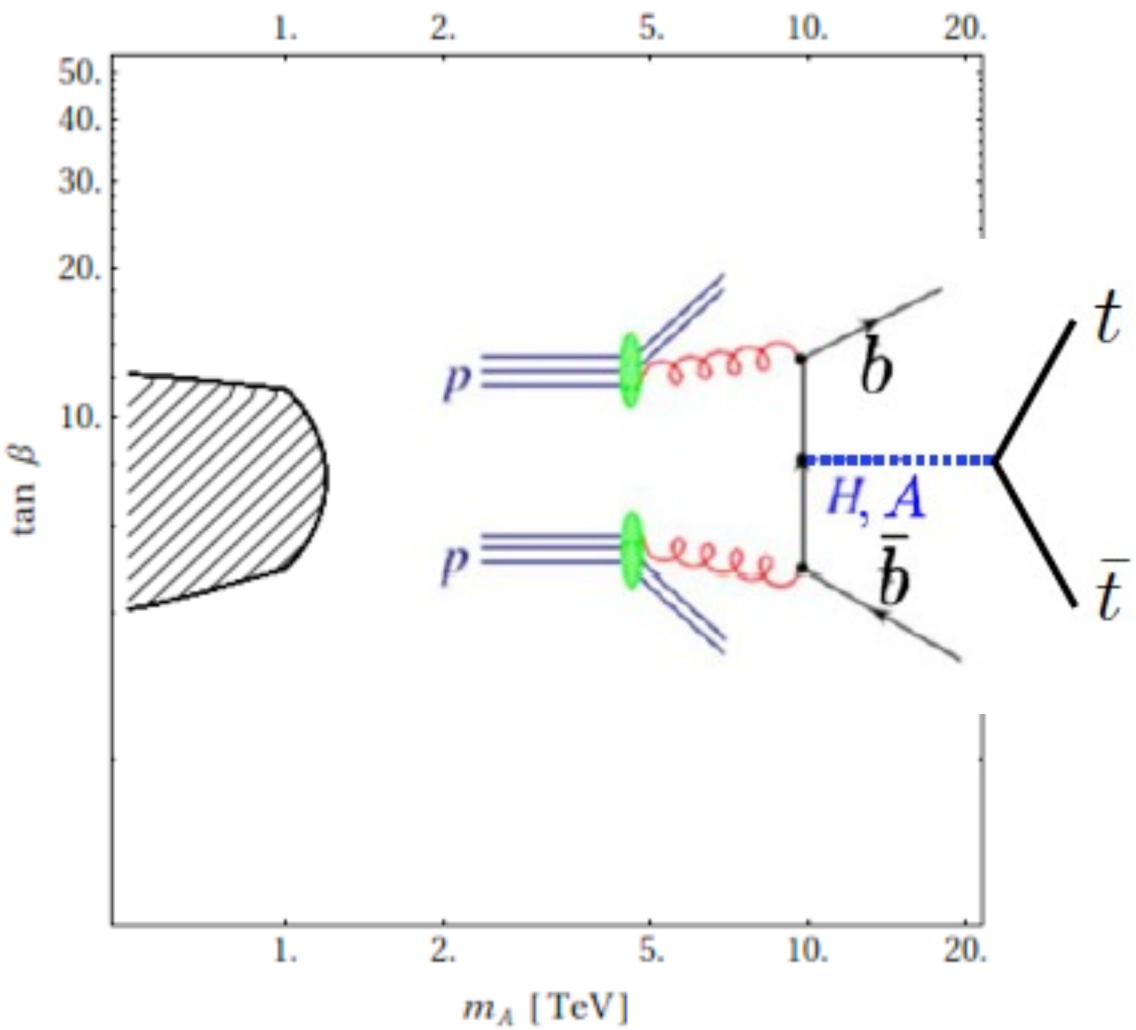


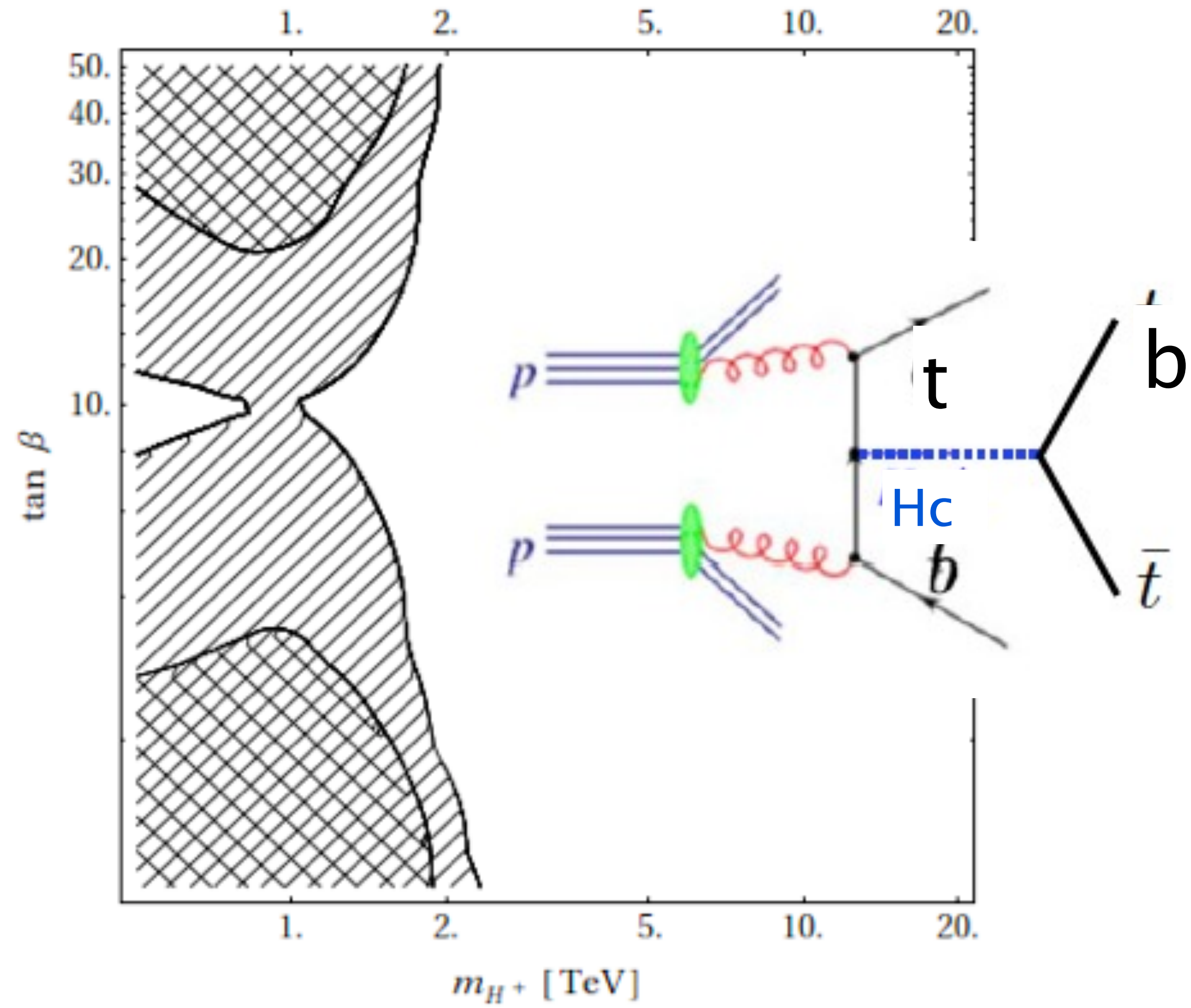
[A. Djouadi et. al.'15]

- To probe up to O(1) TeV, new strategies are needed for both moderate and low tan_beta regions

MSSM Higgs Bosons @ 14 TeV

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617,
N. Craig, et. al. arXiv:1504.04630]

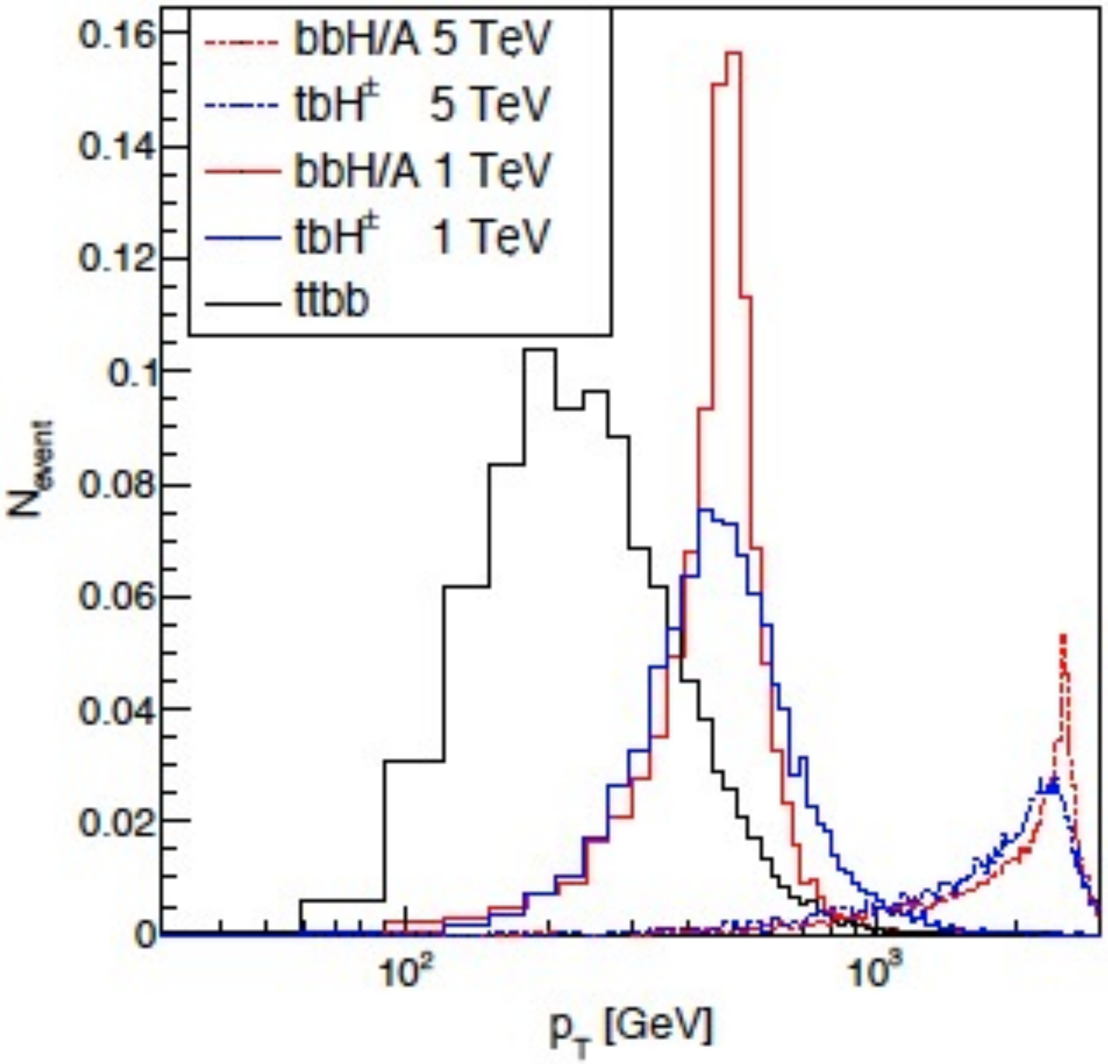




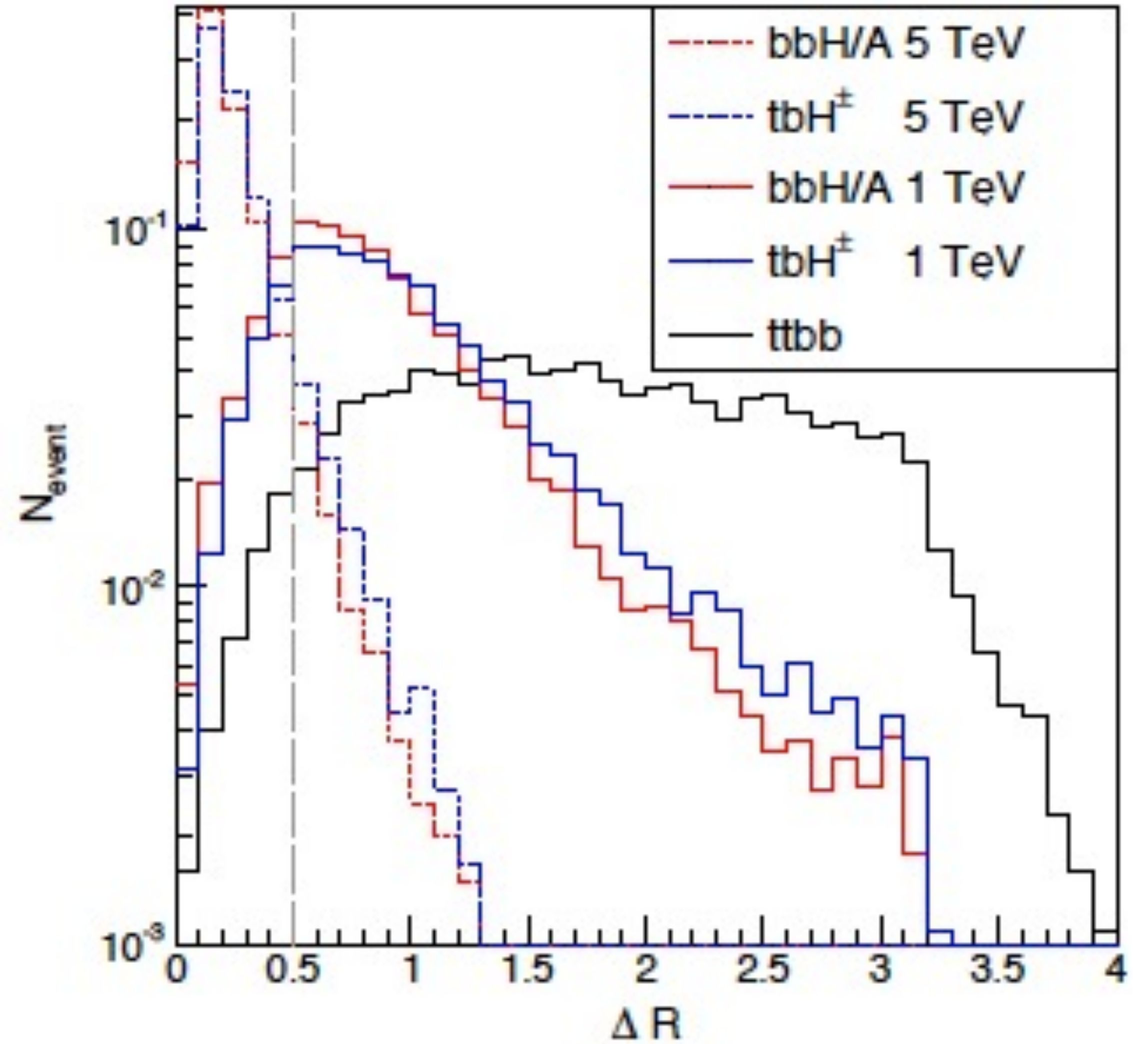
- A potential to exclude mA/mH up to 1 TeV via bbH/A -> bbtt, with tt decaying semi-leptonically, using 3/ab of data.
- Combine with bbH/A -> bbtt, tbHc->tbtb can push the exclusion limit up to ~2 TeV

Kinematics - Heavy Higgs Resonance

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]



(a) Hardest t-quark

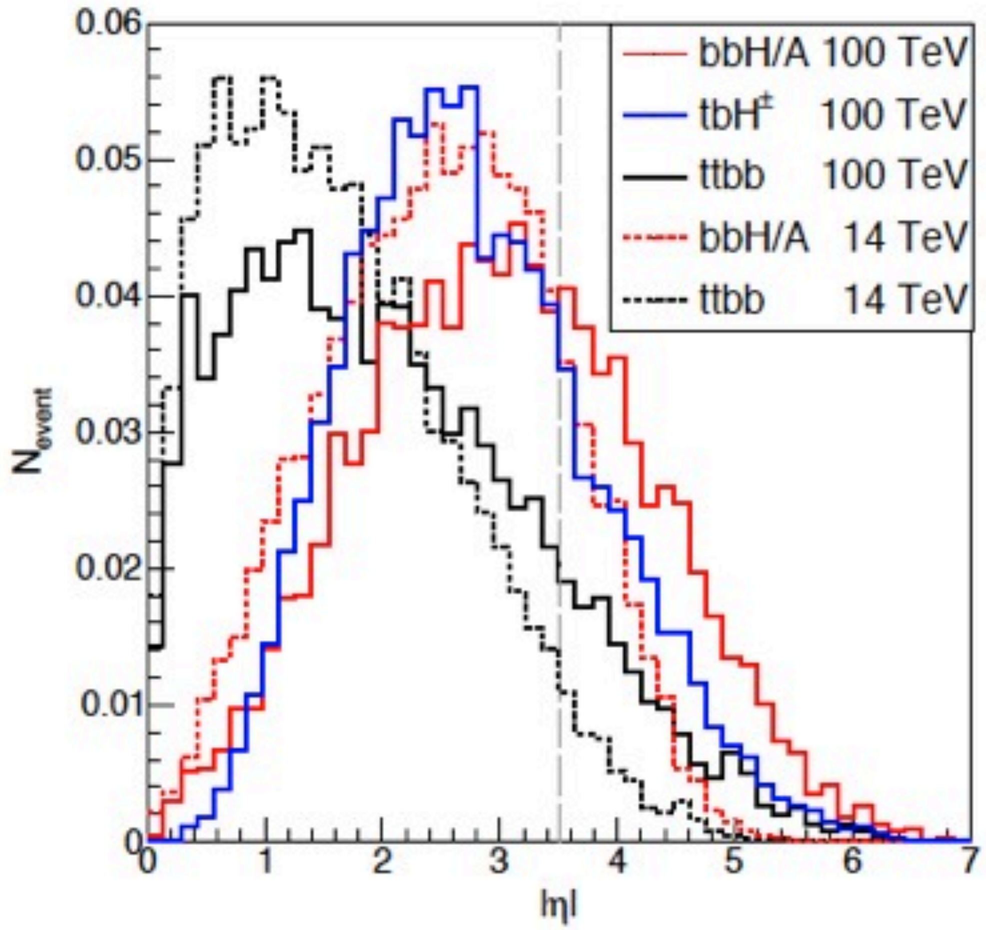


(c) Top opening angle

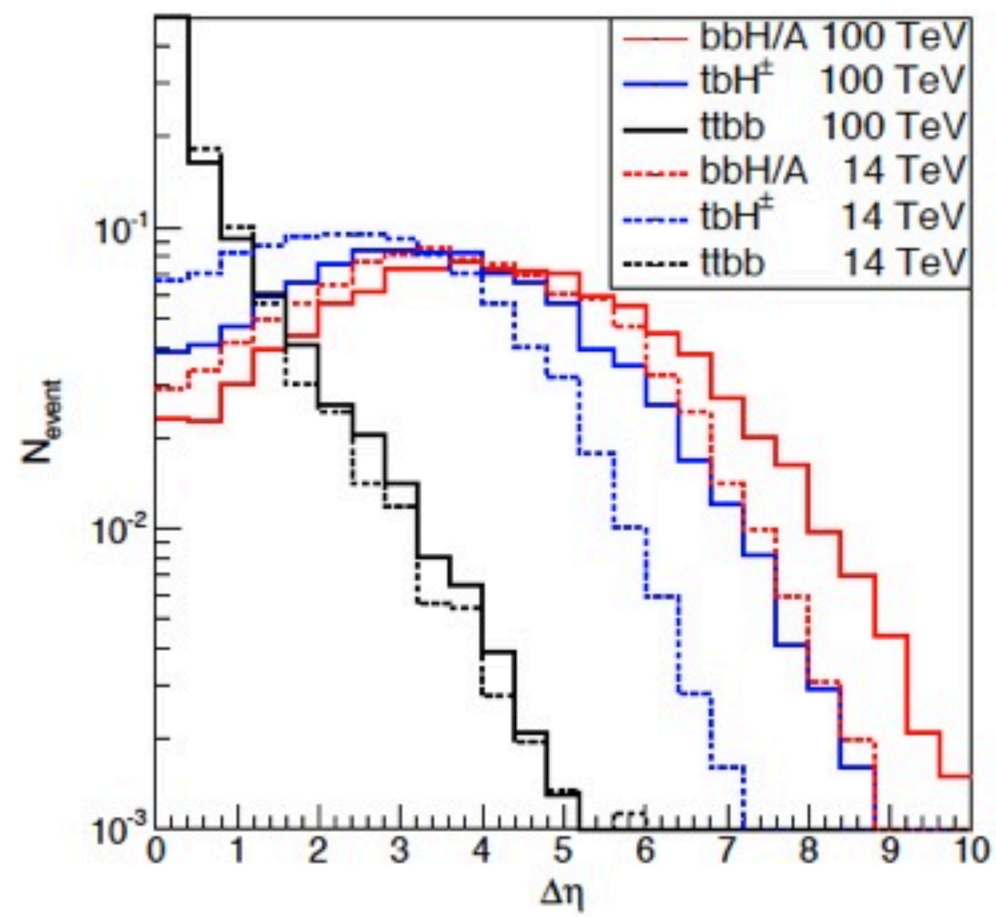
- Benefit from top-jet tagging

Kinematics - Particles Accompanying Higgs Production

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]



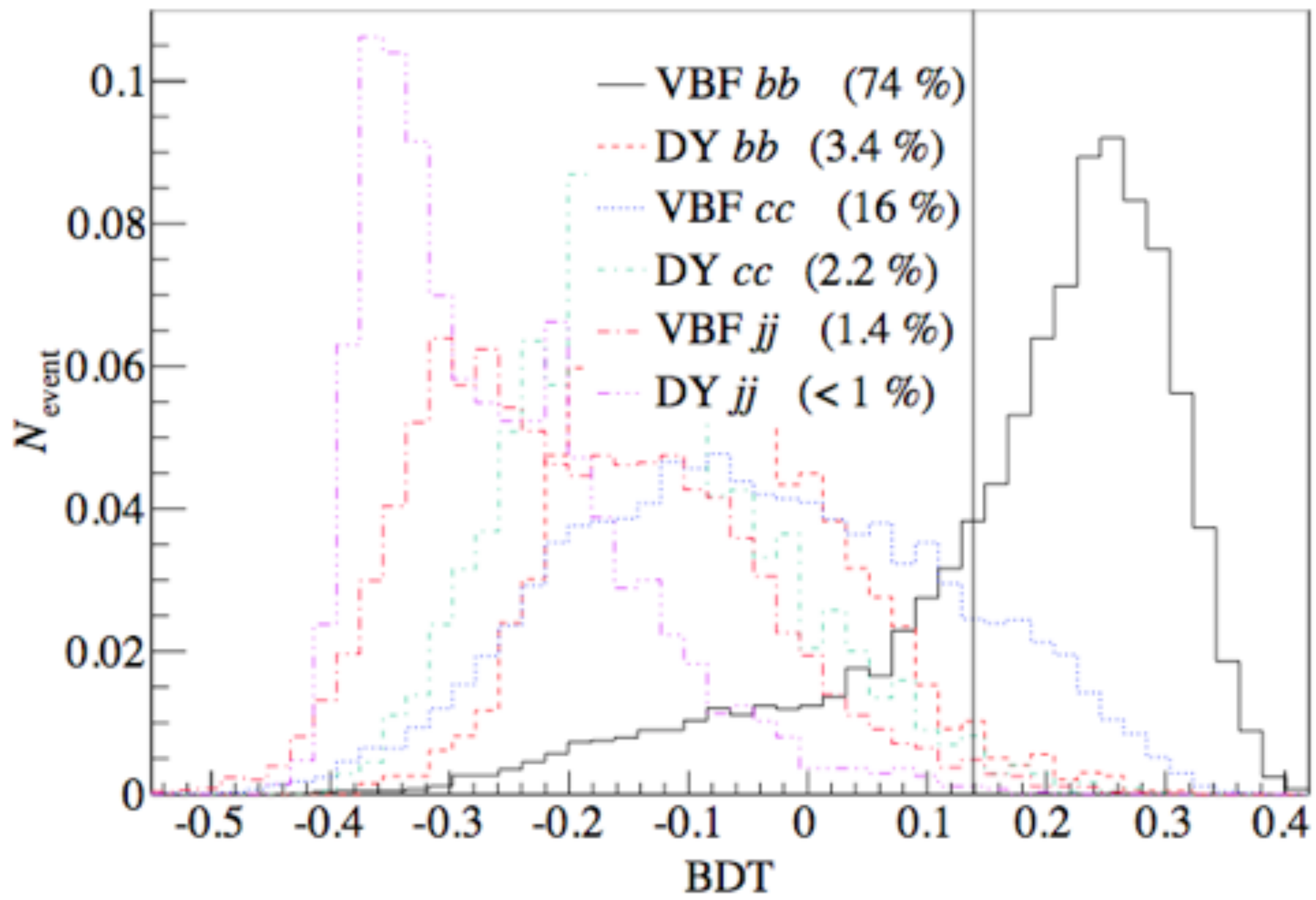
(a) b-quarks accompanying Higgs production



(b) $\Delta\eta$ between the two accompanying b-quarks

- The b-quarks accompanying Higgs production tend to be forward and backward => large delta eta

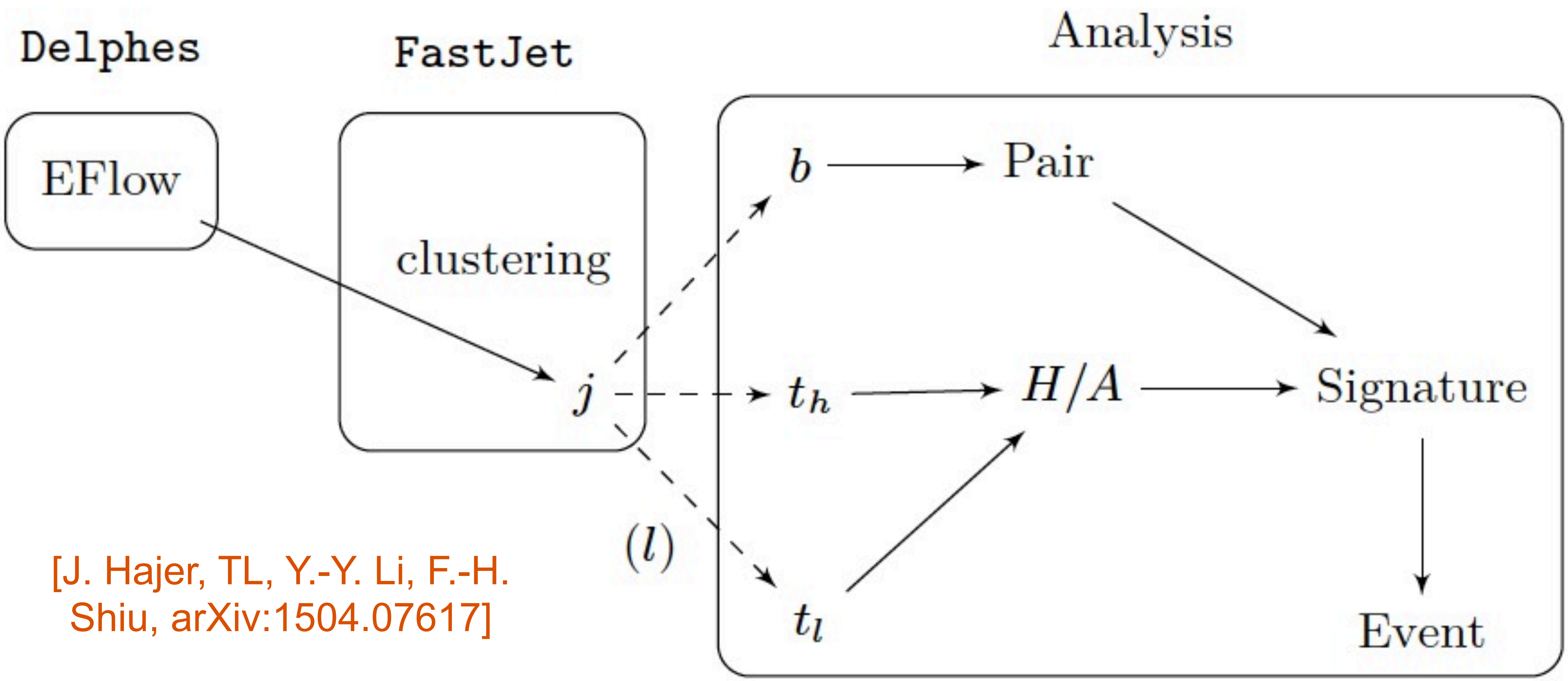
Bottom Fusion Pair BDT



- Large eta requirement: suppress DY process background.
- b secondary vertex: suppress non-b jets.

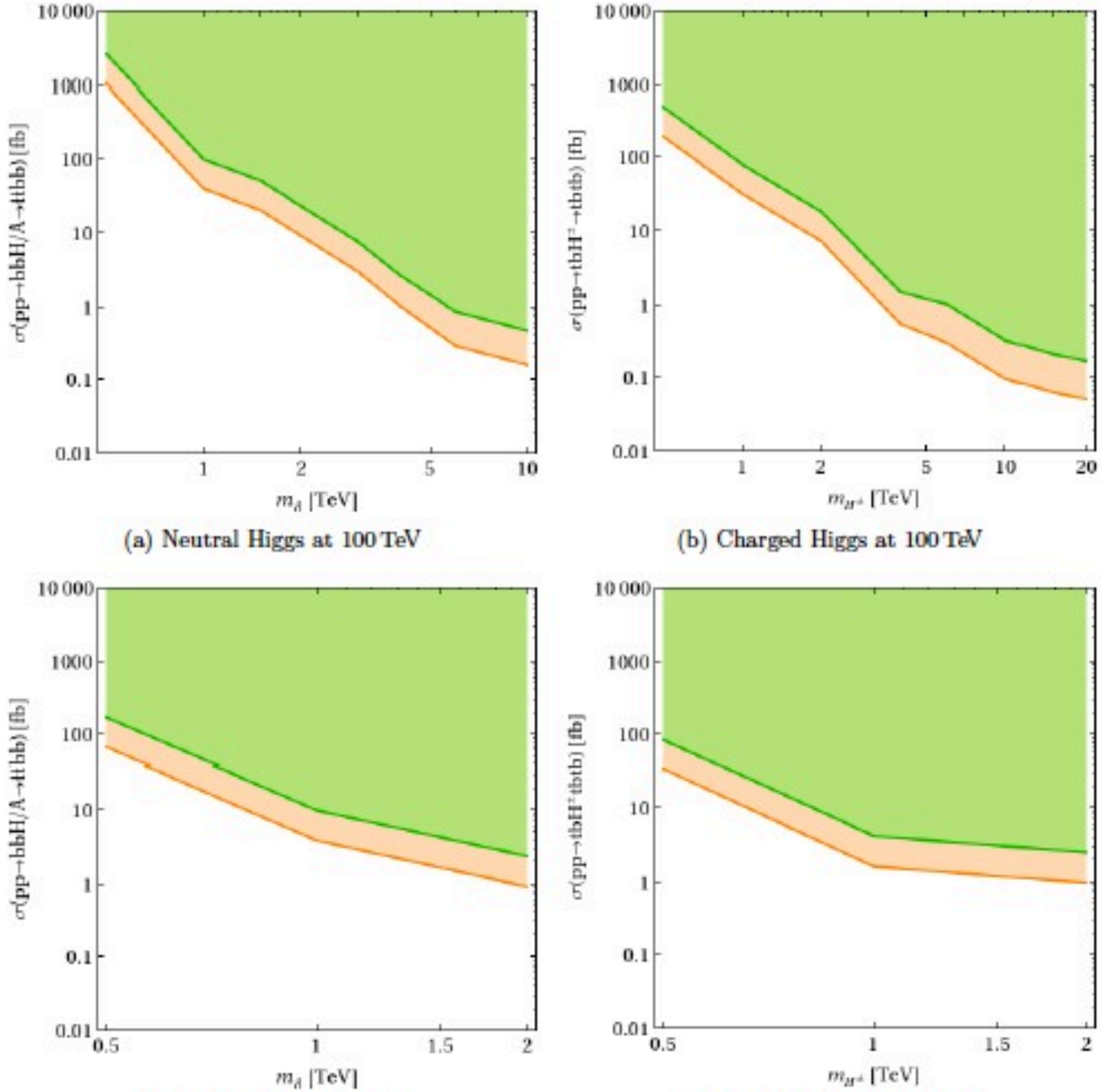
Overall Strategies

- Kinematic features of (the resonance + the accompanying products)
  - Example 1: bbH/A -> bbtt: two hard top jets (one hadronic, one leptonic) with Higgs reconstruction + two b jets with large delta eta
  - Example 2: bt Hc -> btbt: one hard leptonic top jet and one hard b jet with Higgs reconstruction + two additional b jets with large delta eta



[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]

Model-independent Exclusion Limits



(a) Neutral Higgs at 100 TeV

(b) Charged Higgs at 100 TeV

(c) Neutral Higgs at 14 TeV

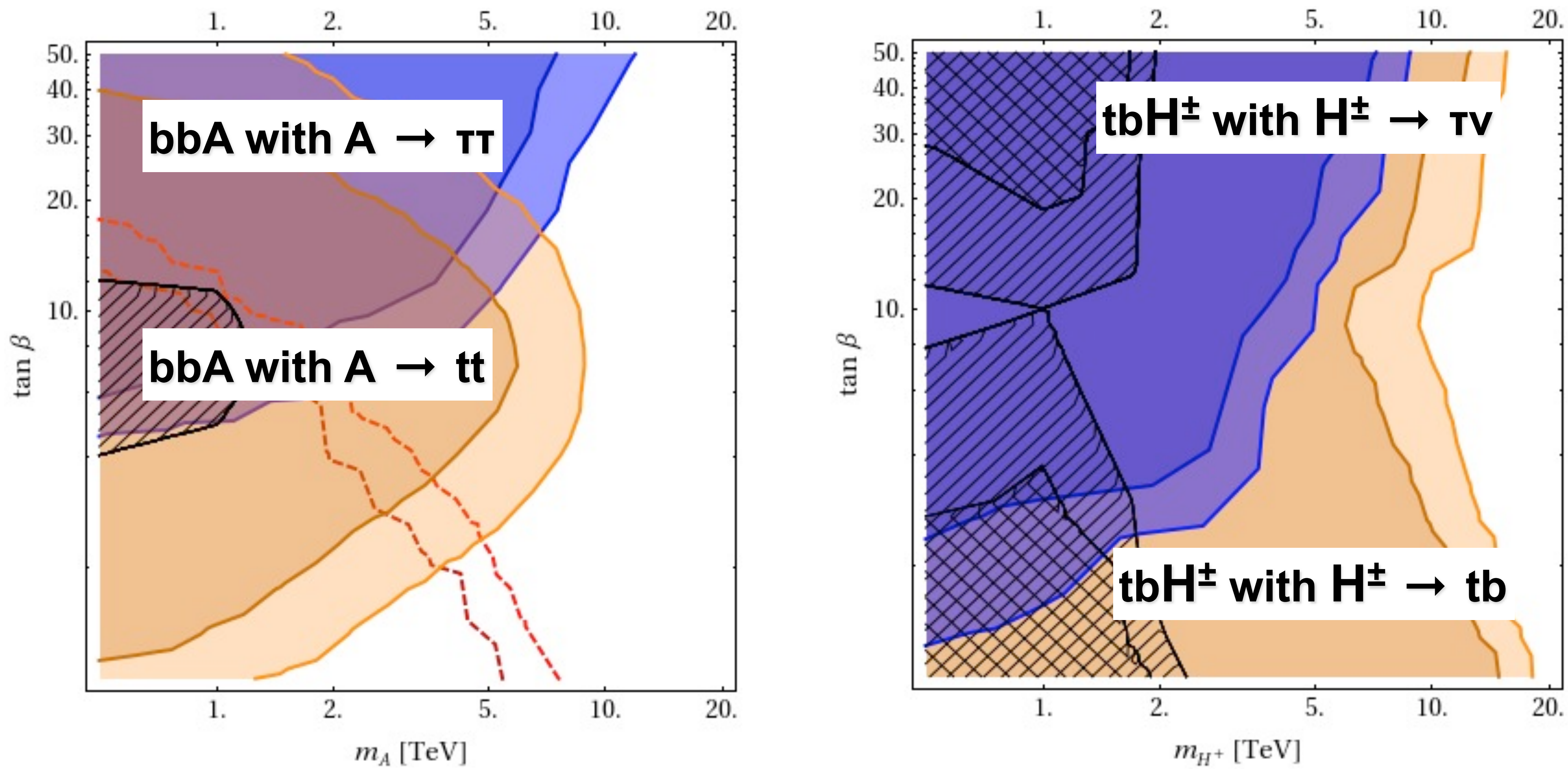
(d) Charged Higgs at 14 TeV

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]

- The constraints are weaker at 100TeV.
- As mass increases, the constraints become stronger.

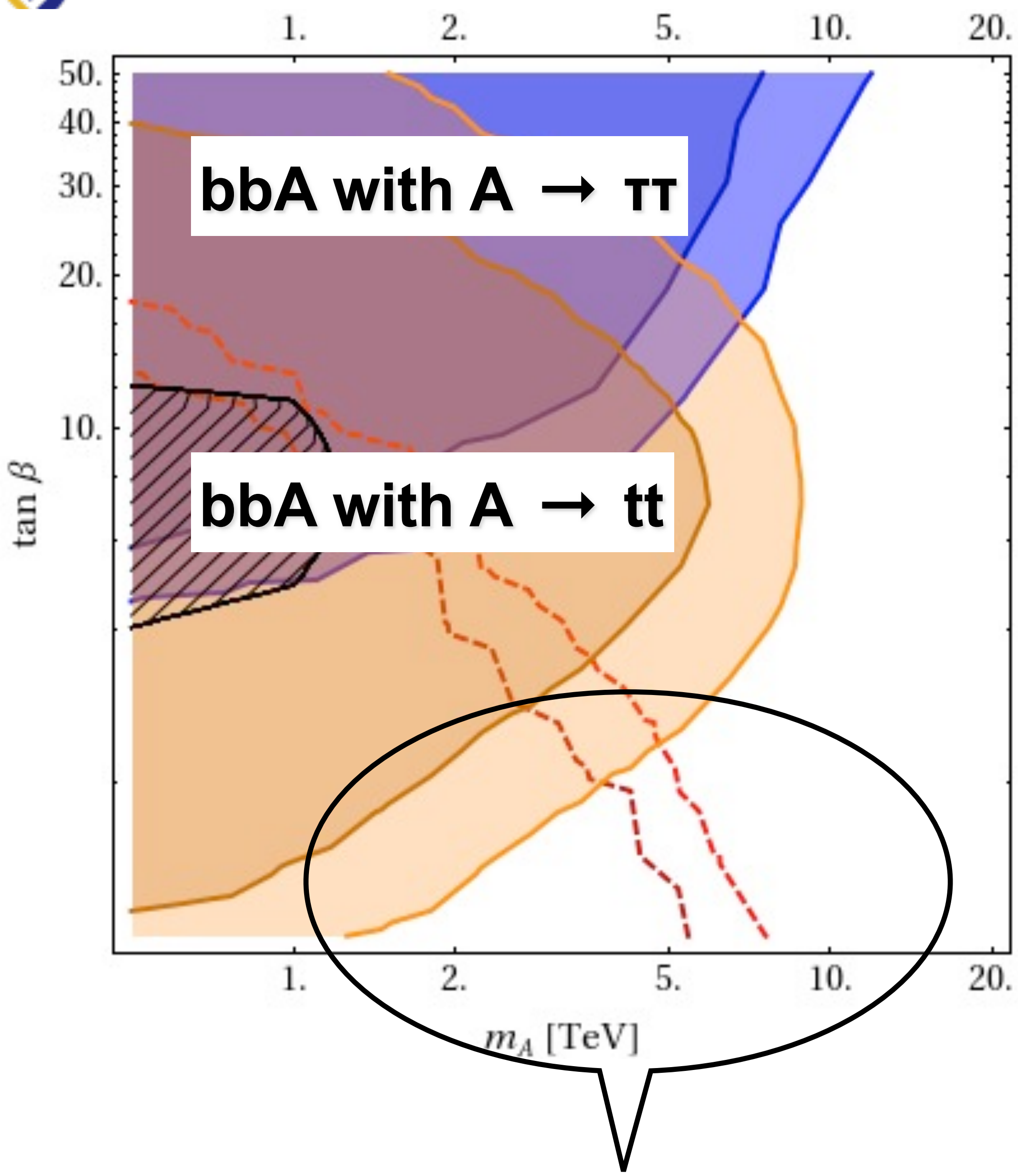
MSSM Higgs Bosons @ 100 TeV pp

[J. Hajer, TL, Y.-Y. Li, F.-H. Shiu, arXiv:1504.07617]

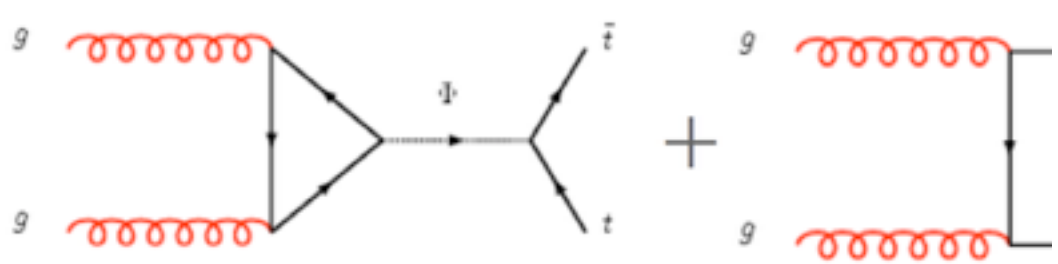


- LHC: up to O(1) TeV
- 100 TeV pp: push the exclusion limits up to O(10) TeV

MSSM Higgs Bosons @ 100 TeV pp

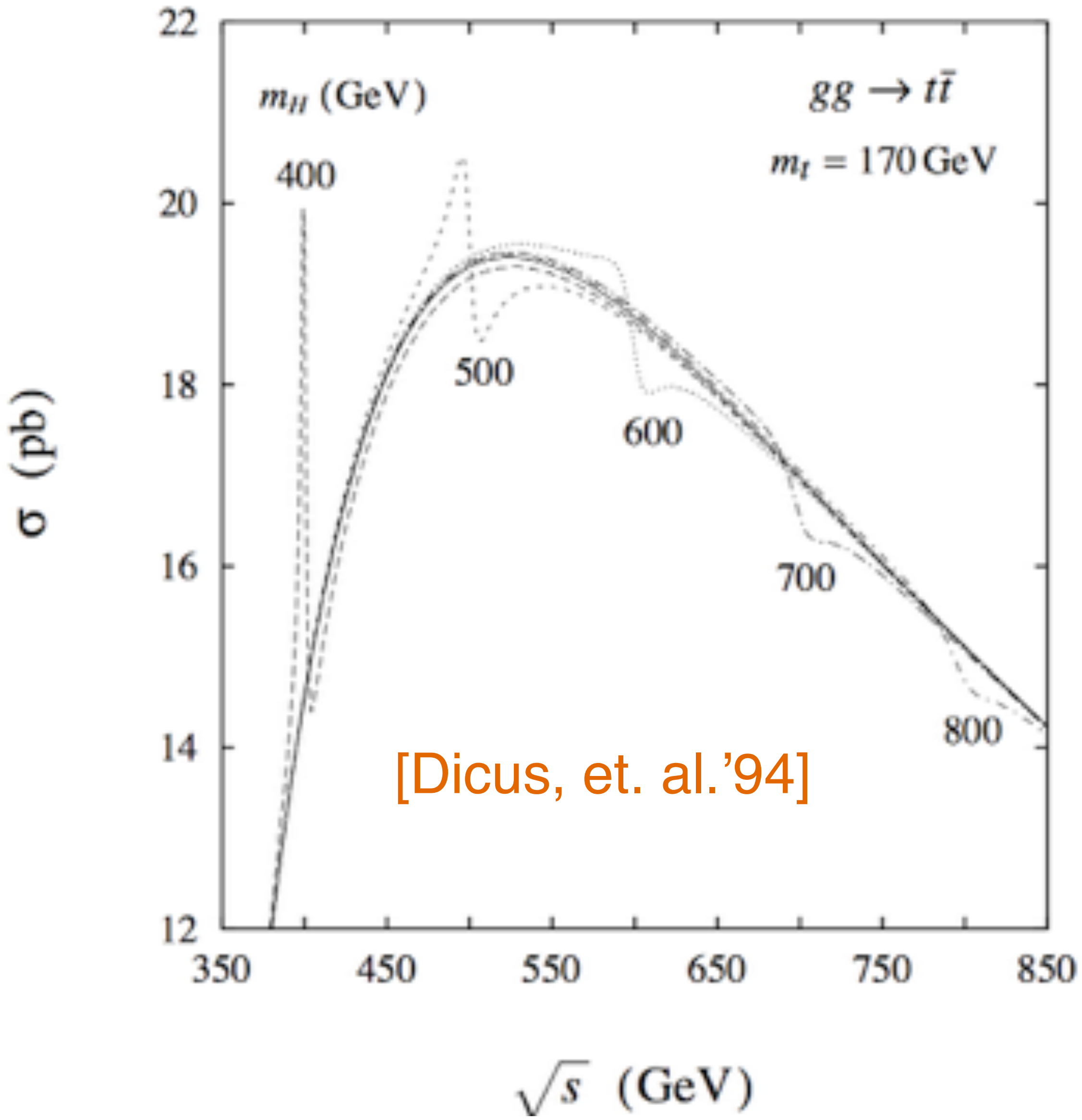


gg -> H/A -> tt doesn't help much!!



[N. Craig, et. al.'15; S. Jung et. al.' 15]

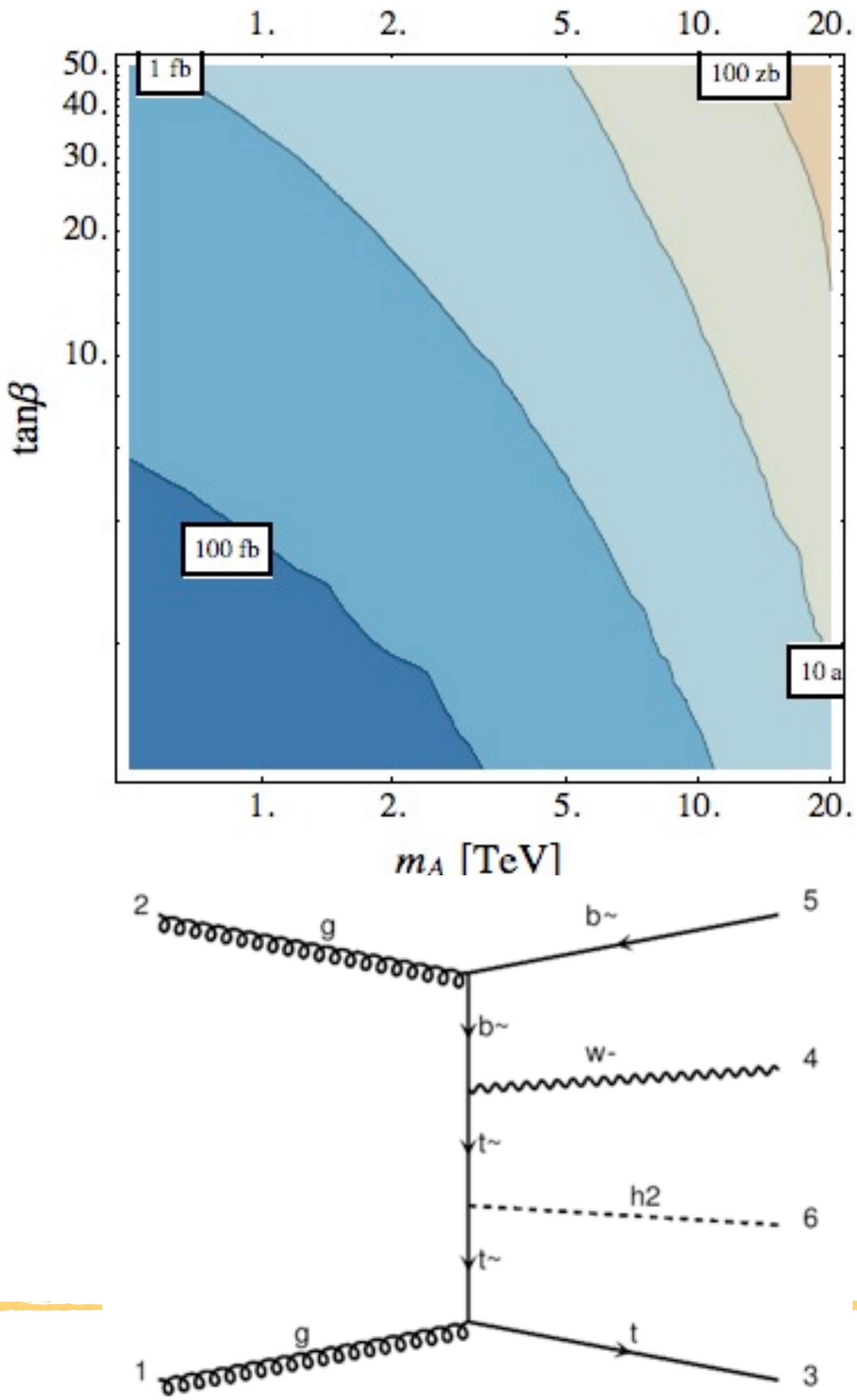
$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \frac{M^4}{(\hat{s} - M^2)^2 + M^4 w^2} \times \left[\frac{2(\hat{s} - M^2)}{M^2} \hat{\sigma}_{\rm int} c_\phi + \hat{\sigma}_{\rm res} \left(1 + \frac{2w}{R} s_\phi \right) \right]$$

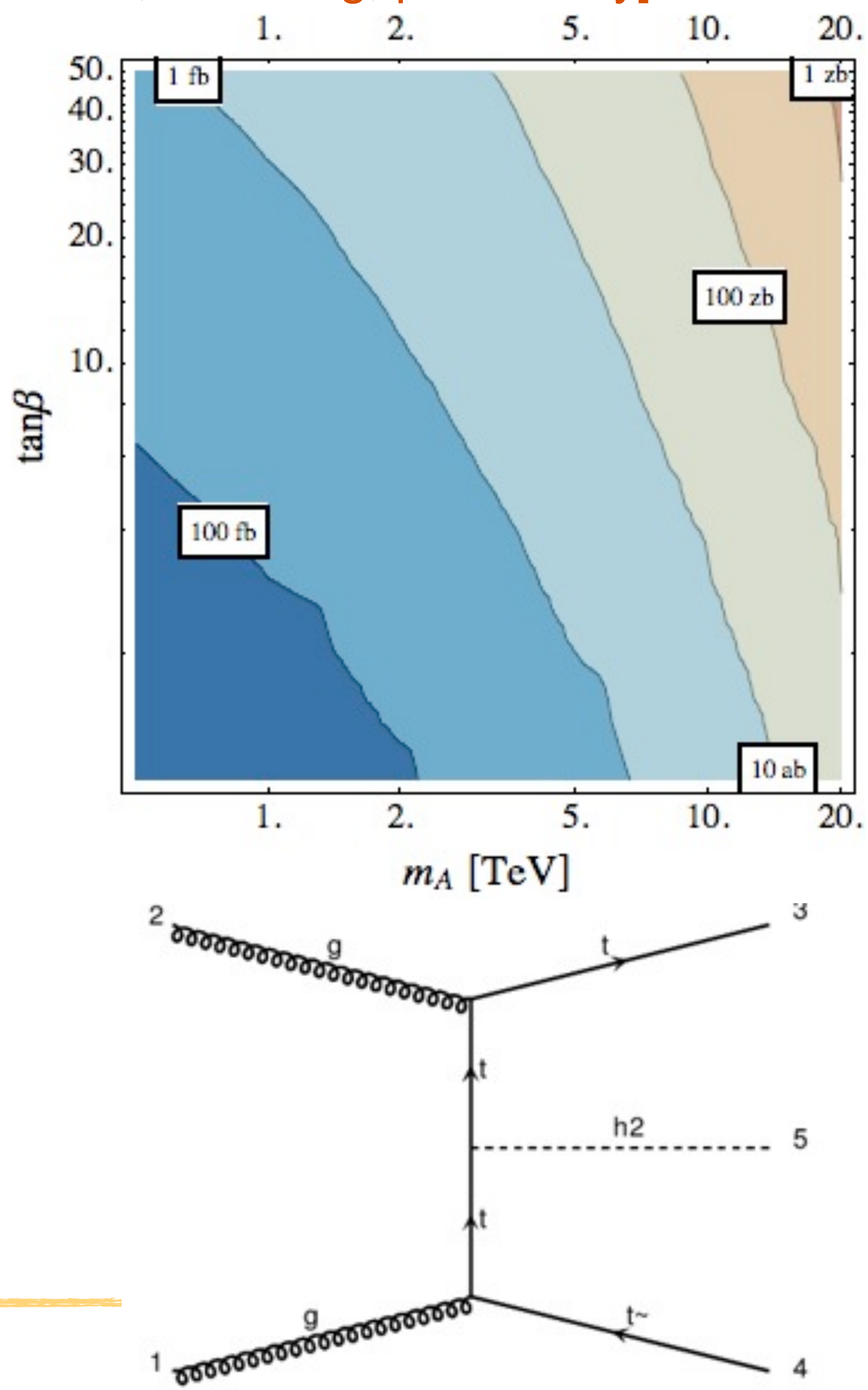


[Dicus, et. al.'94]

Strategy: Three- and Four-Top Channels

[N. Craig, J. Hajer, TL, Y.-Y. Li, H. Zhang, preliminary]





Strategy: Three- and Four-Top Channels

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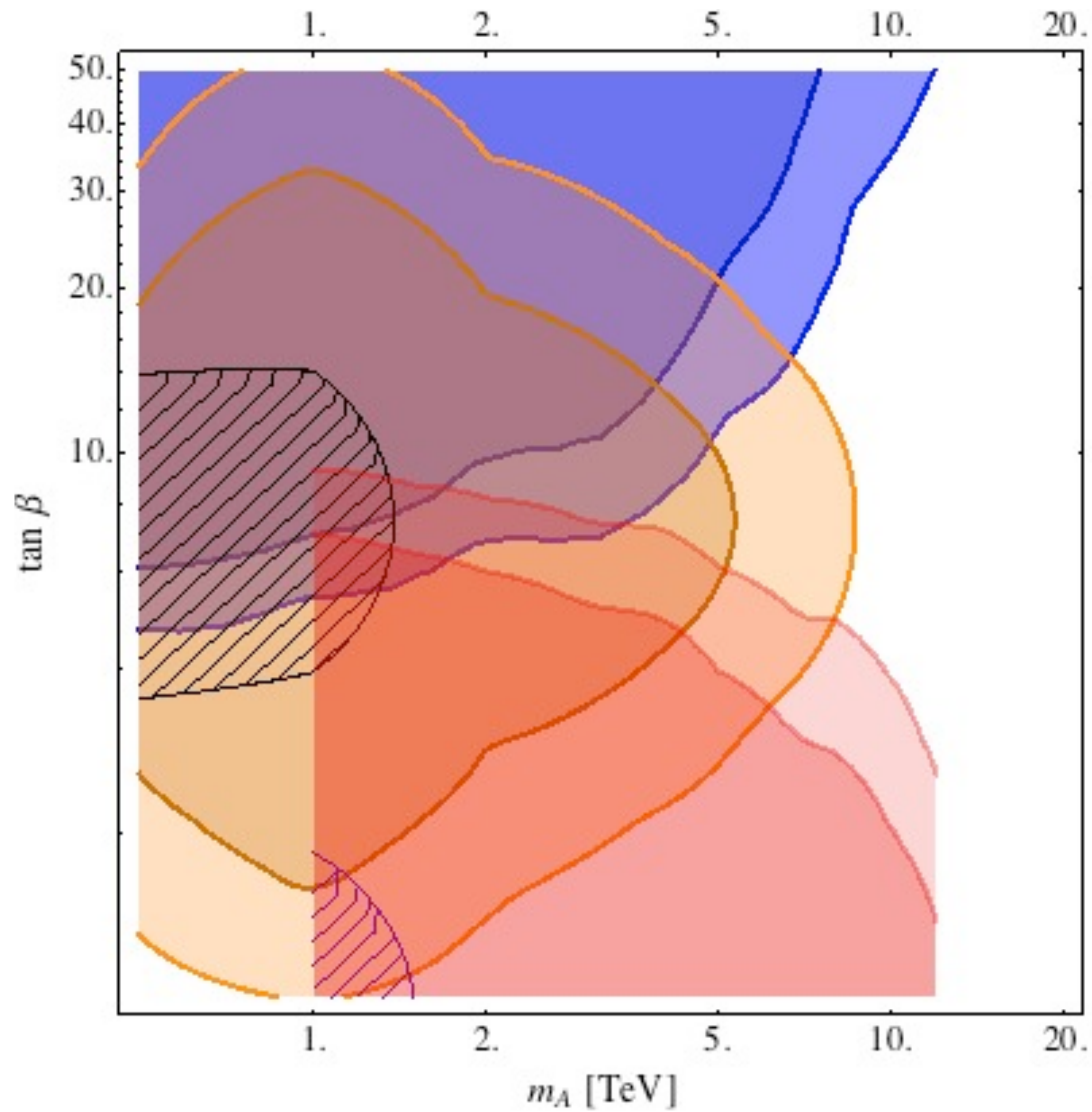

SSDL + Higgs BDT reconstruction + two b with large delta_eta + X

Summary

- A 100 TeV pp collider such as SppC will provide us great opportunities for searching for new particles, in accessible to the LHC, at high mass scales

- The involved kinematics could be highly non-trivial. More realistic simulation of, e.g., detector response, needs to be done in the future.

- New particles can provide a handle to explore new physics and new fundamental rules involved. The 100 TeV machine will continue to play a crucial role in this regard, if it does discover any.


Thank you!

Strategy: Three- and Four-Top Channels

[N. Craig, J. Hajer, TL, Y.-Y. Li, H. Zhang, preliminary]