Probing $H^{\pm}$ with the μ_x boosted-bottom-jet tag

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Outline

1. **2HDM — Why do we care?**
   - The extended Higgs sector
   - Experimental signatures
2. **What do we need to see $H^{\pm}$ at the TeV scale?**
   - A better b-tag ... μ_x
3. **What could we see with the μ_x tag?**
   - 14 TeV
   - 100 TeV

Two Higgs-doublet models (2HDM)

What questions precipitate two Higgs doublet models (2HDM)?

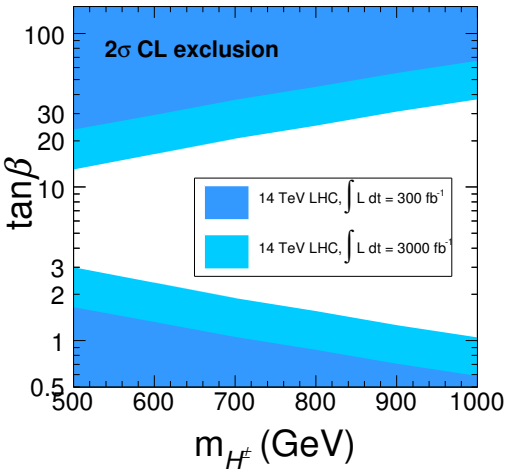
- *How can we avoid fine tuning?* **Supersymmetry**
- *Why doesn't the strong force violate CP?* **Axions**
- *Where's all the antimatter?* **CP-violating Higgs sector**

2HDM: Φ_1 and Φ_2

- 3 scalars (h, H, and $H^{\pm}$) and a pseudo-scalar (A)
- $\tan\beta \equiv v_2/v_1$

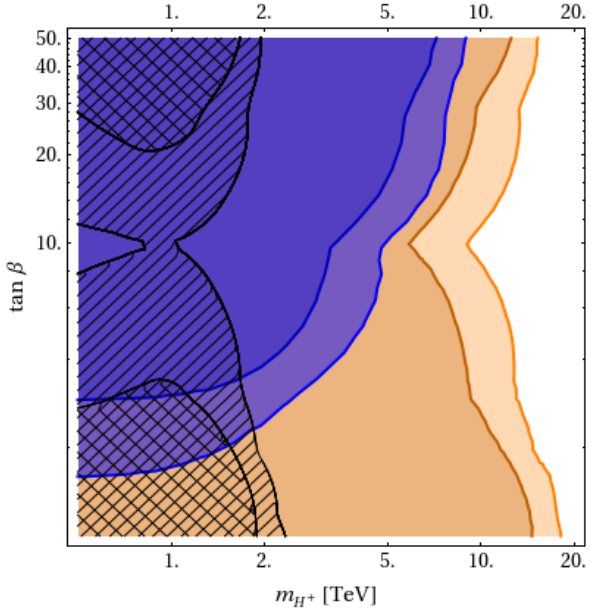
Strongly couple to top and bottom quarks; lots of b jets (b tags)!

$H^{\pm} \to tb$ 95% exclusion estimates



JHEP**1506**(15)137

300 and 3000 fb^{-1}
14 TeV



JHEP**1511**(15)124

300 and 3000 fb^{-1}
14 TeV
(checkered/hatched)

3 and 30 ab^{-1}
100 TeV
(dark/light salmon)

The dominant channels

2HDM are strongly constrained by precision eslectroweak measurements

- No flavor-changing neutral current at tree-level
  - Type-I: All quarks couple to only one of the doublets
  - **Type-II**: u_R^i and d_R^i couple to opposite doublets (SUSY, axions, ...)
- The 125 GeV scalar *really* looks like a Standard Model Higgs.
  - $H_{SM}^0 = -R(\alpha - \beta)\begin{pmatrix} H \\ h \end{pmatrix}$
  - We live near **alignment** ($H_{SM}^0 = h$) ... no HEAVY $\rightarrow$ light Higgs decays.

We assume that heavy Higgs mass spectrum is mostly degenerate

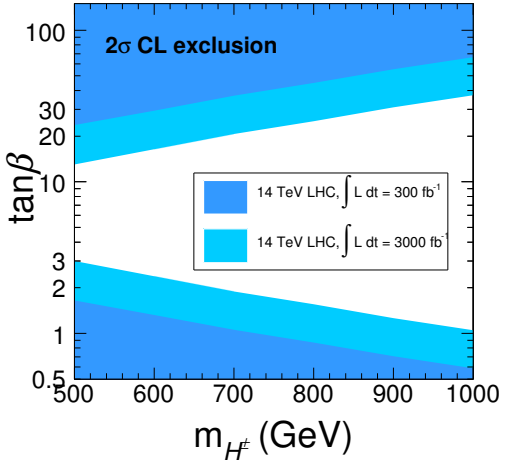
- A natural outcome of the MSSM 2HDM, in the alignment limit
- Suppresses decays *between* heavy Higgs

$$\mathcal{B}(H/A \rightarrow t\bar{t}) \approx 1 \qquad \tan(\beta) \gg 6$$

$$\mathcal{B}(H/A \rightarrow b\bar{b}) \approx 1 \qquad \tan(\beta) \ll 6$$

$$\mathcal{B}(H^\pm \rightarrow tb) \approx 1 \qquad \forall \tan(\beta)$$

$$\mathcal{B}(H^\pm \rightarrow \tau\nu) = \mathcal{O}(1\%) \qquad tan(\beta) \gg 6$$



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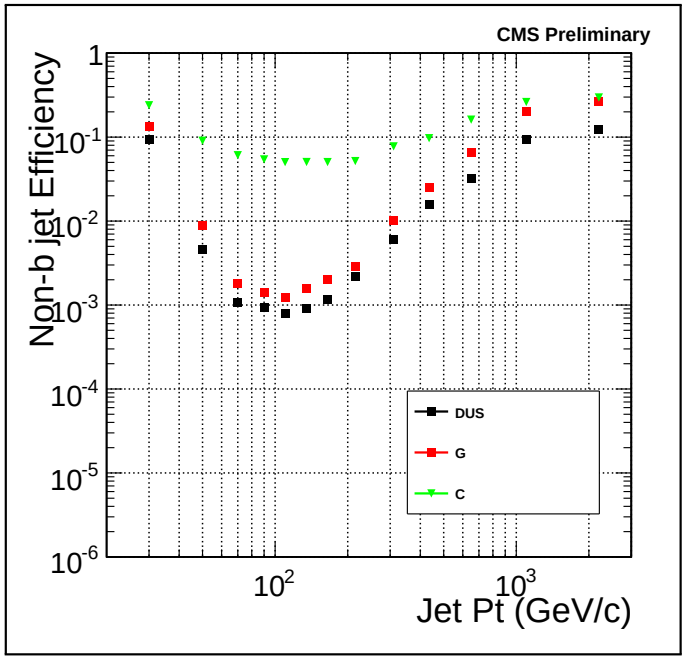
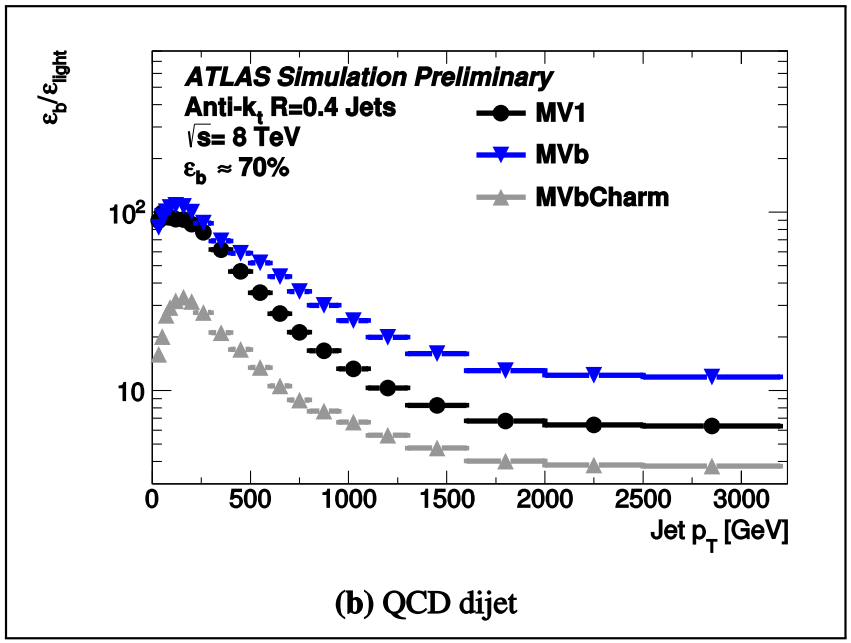
Light jets dominate channels with boosted b jets

- Probability to tag light flavors *rises dramatically* for boosted jets!
  - Light jet = no b or c **hadrons**; experiments can't differentiate b-initiated jets and $g \to b\bar{b}$ jets.
- Huge (40%) systematic uncertainties in tagging efficiency can dominate experimental results/exclusions.
- Many exotic searches rely on seeing final states with b jets!

[CMS PAS BTV-09-001] Fig. 12



[ATL-PHYS-PUB-2014-014] Fig. 14b



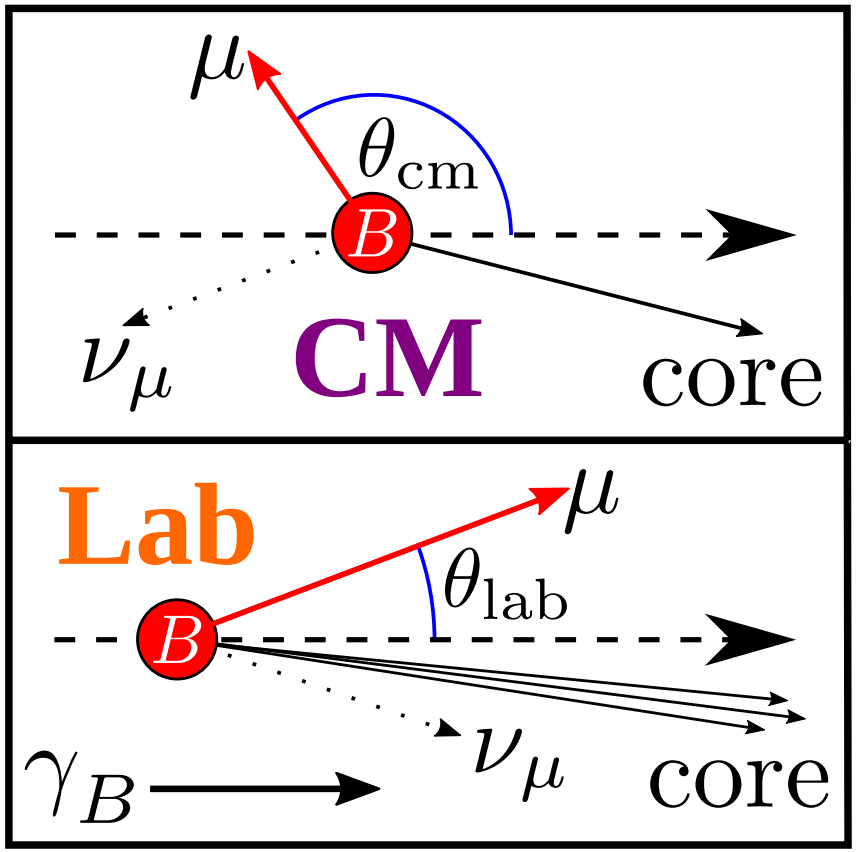
Maintaining 50% b jet efficiency

The μ_x boosted-b tag

Phys. Rev. D **93**, 014014 (2016) [arXiv:1511.05990]

- **CM**: The muon is emitted with speed $\beta_{\mu,\mathrm{cm}}$ at angle θ_{cm}.
- **Lab**: Muon is detected at angle θ_{lab} w.r.t. the centroid of the *decay subjet* (boosted by γ_{B}).

$$p_{\mathrm{subjet}} = p_\mu + p_\nu + p_{\mathrm{core}}$$



$$x \equiv \gamma_{\mathrm{B}} \tan(\theta_{\mathrm{lab}}) = \frac{\sin(\theta_{\mathrm{cm}})}{\kappa + \cos(\theta_{\mathrm{cm}})}$$

$$\kappa \equiv \beta_{\mathrm{B}}/\beta_{\mu,\mathrm{cm}}$$

$$\boxed{x = \tan(\theta_{\mathrm{cm}}/2) \qquad (\text{when } \kappa \to 1)}$$

The μ_x boosted-b tag

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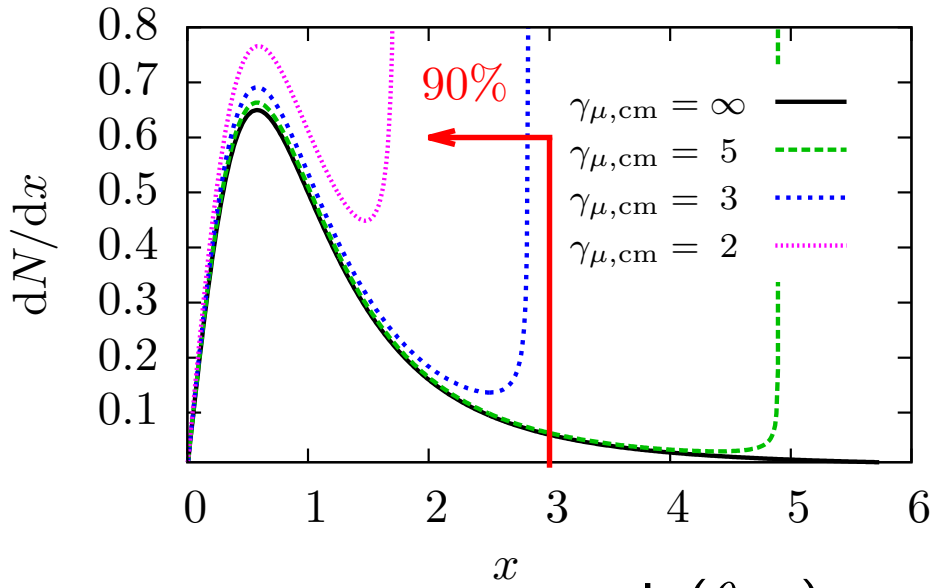
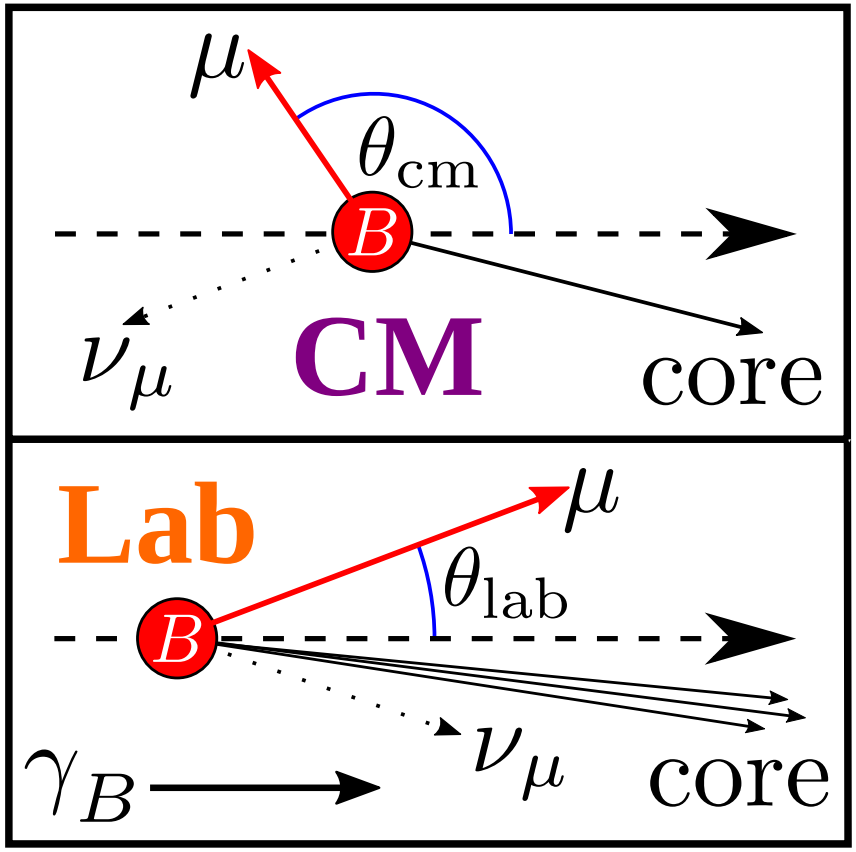
We want a **boosted** b hadron

$$\gamma_{\rm B} \gtrsim 60 \gg \gamma_{\mu,\rm cm}$$





$$x \equiv \gamma_{\rm B}\,\tan(\theta_{\rm lab}) = \frac{\sin(\theta_{\rm cm})}{\kappa + \cos(\theta_{\rm cm})}$$

$$\kappa \equiv \beta_{\rm B}/\beta_{\mu,\rm cm}$$

$$\boxed{x = \tan(\theta_{\rm cm}/2) \qquad (\text{when } \kappa \to 1)}$$

x is mostly an angular cut

The μ_x tag is two major cuts to identify b-like decays

$$\boxed{x \leq 3} \qquad p_{\text{subjet}} = p_\mu + p_\nu + p_{\text{core}} \qquad \boxed{\frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}} > 0.5}$$

For detailed explanation, see 1511.05990:

- p_ν is estimated from muon
- x is robust to measurement error in muon p_T
- $x \leq 3$ is a cut on the angle between the μ and the D remnants (**core**)

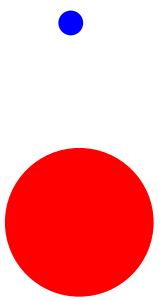
The maximum angle ξ_{max} scales linearly with E_{core} ($m_D = 1.9$ GeV)

- "Soft" muons must fall in a tight cone:

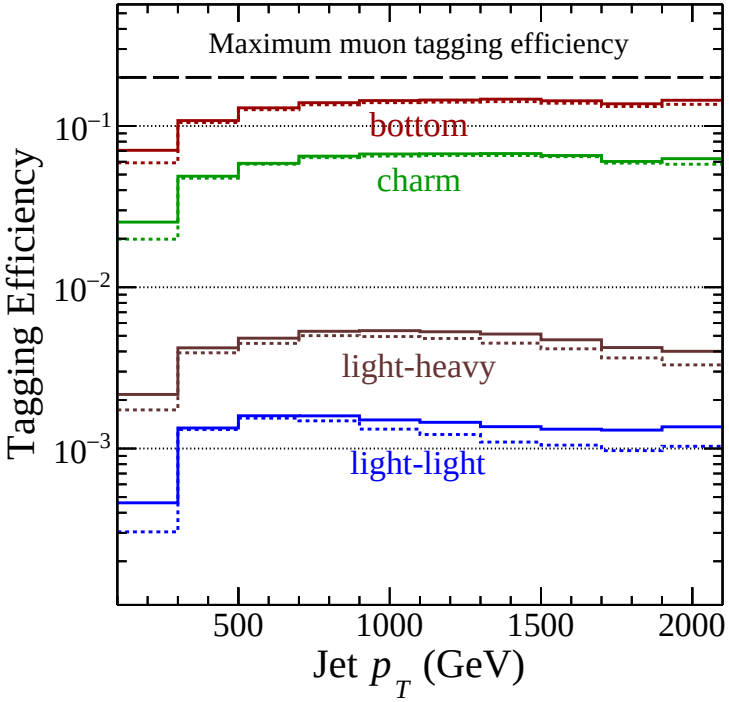
$$\xi_{\text{max}}^{\text{soft}} = 3\,\frac{m_D}{E_{\text{core}}}$$

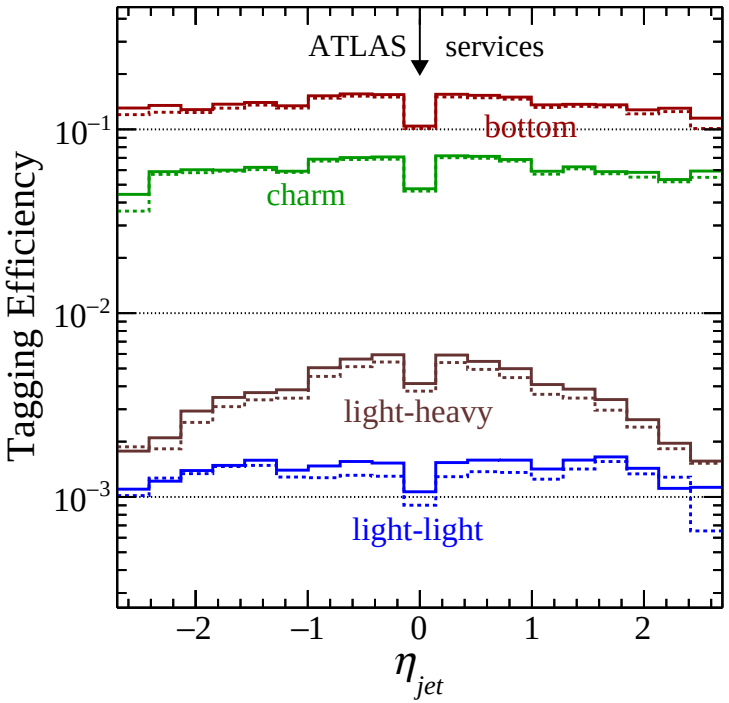
- "Hard" muons have more breathing room:

$$\xi_{\text{max}}^{\text{hard}} = 18\,\frac{m_D}{E_{\text{core}}}$$



μ_x boosted-b tagging efficiencies at the LHC





- Boosted kinematics turn on at 300 GeV.
- **Light jets** classified by hadronic origin of tagging muon (light-heavy are b jets from gluon splitting — rapidity handle?)

Signal efficiencies

- ∼14% of b-jets
- ∼6.5% of c-jets

Light jet **fake rate**

- Light-light $\mathcal{O}(0.1\%)$
- All light $\mathcal{O}(0.6\%)$

Pileup helps (a bit)

- *Solid*: no pileup
- *Dotted*: $\mu = 40$

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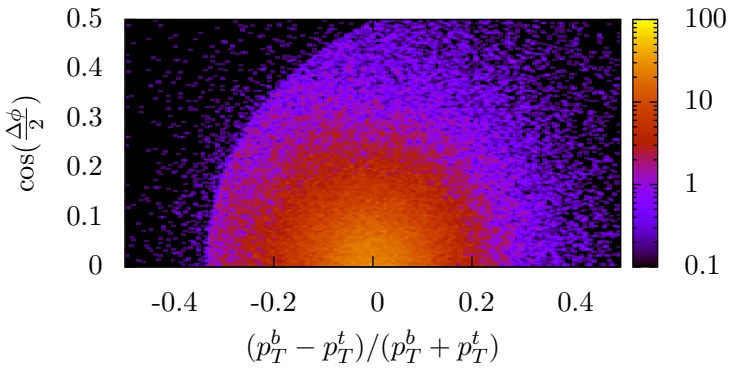
$H^{\pm} \to tb$ with the μ_x tag

μ_x is well-suited for detecting TeV-scale $H^{\pm}$ in a semi-leptonic channel:

$$pp \to t_{l^{\mp}}(b)H^{\pm} \to t_{l^{\mp}}(b)t_{\mathrm{had}}b_{\mu_x}$$

- Boosted-b via μ_x tag ($R_{kt^{-1}} = 0.4$) — high purity across TeV range
- Boosted hadronic top using existing substructure tags ($R_{\mathrm{CA}} = 0.8$) (CMS PAS JME-09-001 / CERN-EP-2016-010)
- Leptonic top via isolated lepton and normal track-based b-tag (much lower p_T than boosted b, tag is more stable).
- caveat: $\not{E}_T$ is heavily smeared by neutrino intrinsic to the μ_x tag, minimally useful for top reconstruction.
- $H^{\pm}$ is very heavy, minimal transverse boost; require $\Delta Z < 0.4$:

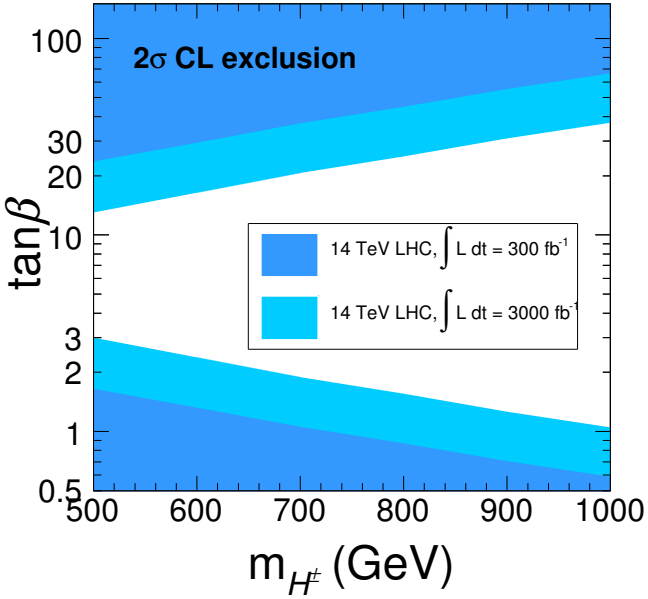
$$\Delta Z = \sqrt{\left(\frac{p_T^b - p_T^t}{p_T^b + p_T^t}\right)^2 + \cos(\frac{\Delta\phi}{2})^2}$$



Extending the mass reach at 14 TeV

FeynRules → MadGraph5 → PYTHIA 8 → Delphes 3 (w/ `FastJet 3`)

- $bg \to H^{\pm} t$ is a significant contribution to σ
- $ttj(j)$ is dominant BG, followed by $ttbb/ttcc$ and $ttb(j)/ttc(j)$
- Our results look like **an extension** of Craig et al. above a TeV



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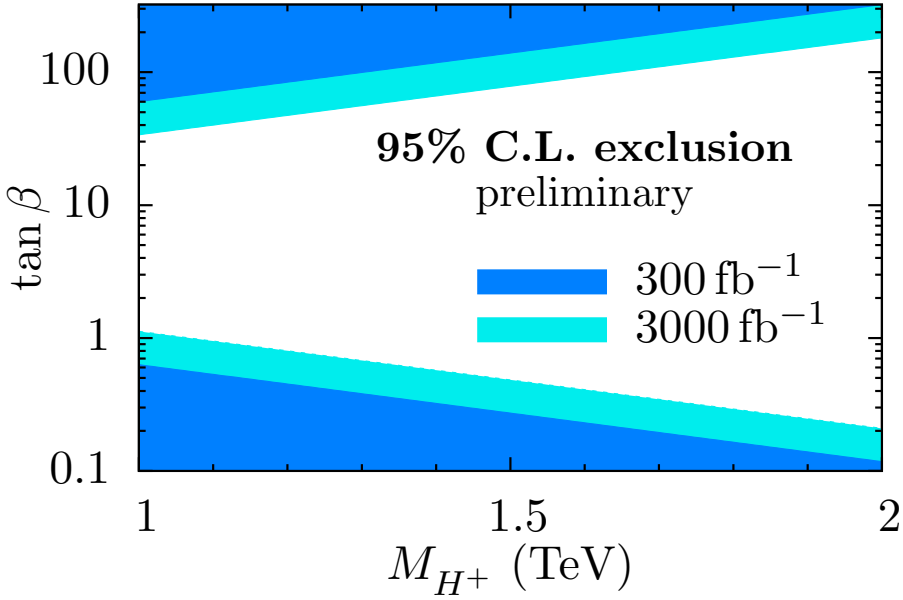
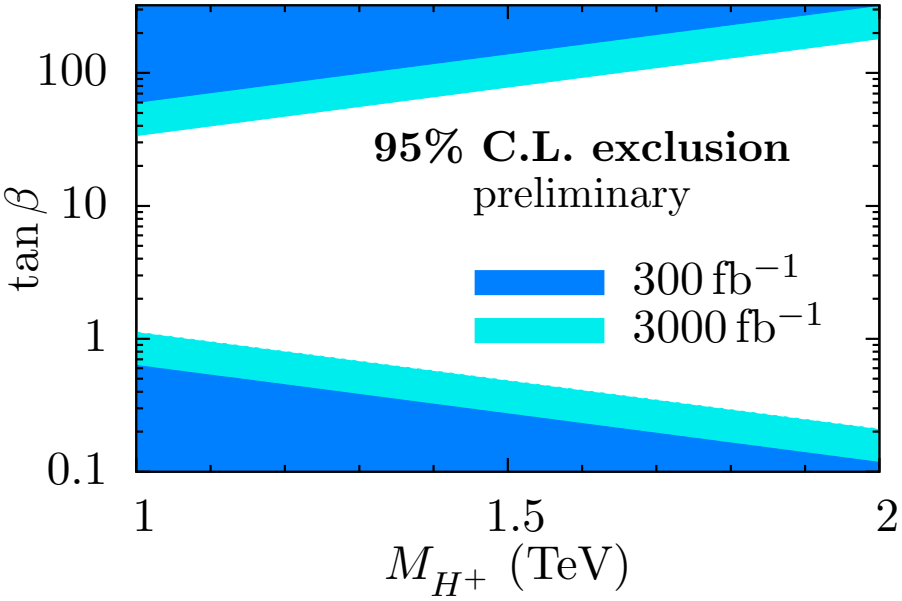


μ_x boosted-bottom-jet tagging

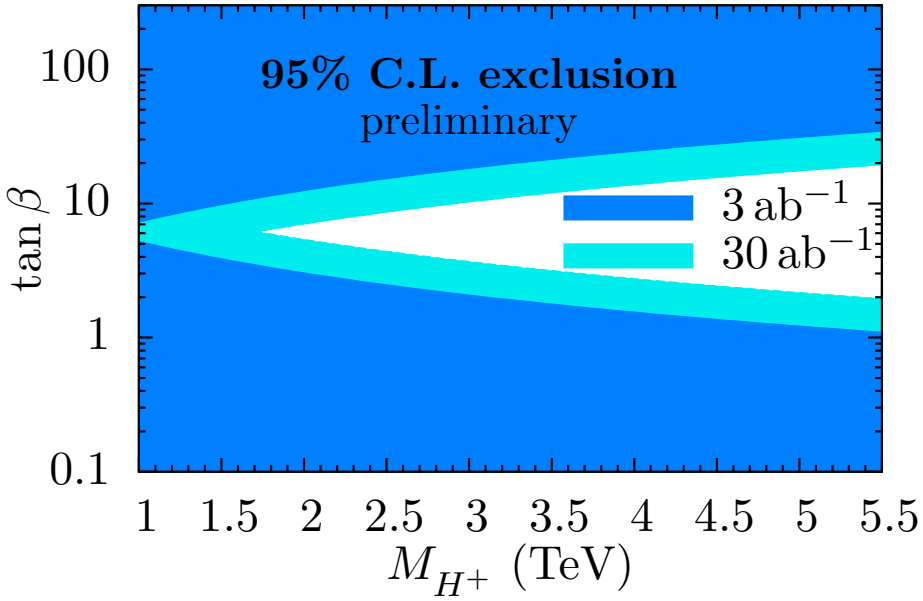
14 TeV cross section is too small to plug "the wedge" ... 100 TeV?

A case for 100 TeV

- In 100 TeV pp collisions, $H^{\pm}$ gets a strong kick from the beam. Discard "back-to-back" ΔZ cut.
- Background is still dominated by same QCD processes as 14 TeV, use $\Delta\eta$ cuts to suppress t-channel.



14 TeV



100 TeV

- $\sqrt{s} = 100$ TeV provides access to useful 2HDM parameter space.
- It's important to use realistic b-tagging fake rates (even at 14 TeV)!

Thank you

Thank you for your attention!

μ_x tags applied to b, c, and light initiated jets