The Higgs and new BSM physics for Run 3

Stefania Gori
UC Santa Cruz

PITT PACC Workshop: LHC physics for Run 3

April 7, 2021

Outline & Goals

Run II → Run III

What new opportunities?

Higgs (125 GeV & beyond) →

- CP violation
- Couplings to light fermions
- Di-Higgs production
- Exotic decays

New particles →

- Squeezed spectra
- Long lived particles

Flavor

Dark Matter & dark sectors

Focus: signatures and models which have not been yet covered at Run I- II

Caveat: this is a personal perspective. It is certainly incomplete.
Many additional opportunities for Run 3!

Higgs physics

Higgs (125 GeV & beyond)

The LHC Higgs precision program has started at Run I-II.

Many milestones:

1. The Higgs is responsible for electro-weak symmetry breaking
2. The Higgs mass is consistent with electro-weak precision tests
3. The Higgs couples to 3rd generation fermions
4. First evidence of the Higgs decaying into two muons
5. The Higgs is not a CP odd boson
6. …

Many open questions:

1. Is it composite?
2. Is it alone?
3. Is it self-interacting?
4. Is it connected to the baryon-antibaryon asymmetry of our universe?
5. Is it connected to Dark Matter?

Higgs and CP violation

Higgs (125 GeV & beyond)

If the Higgs has a CP odd component:

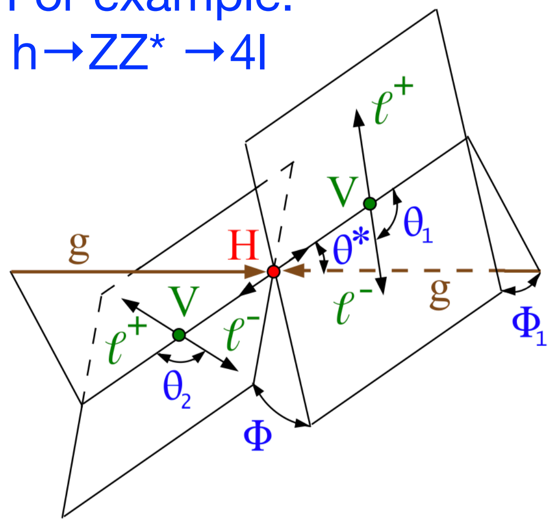
$$\mathcal{L}_{\rm eff} \supset -\frac{\tilde{g}_{hZZ}}{2}\, hZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \tilde{g}_{hWW}\, hW^{+}_{\mu\nu}\tilde{W}^{-\mu\nu}$$

$$\mathcal{L}_{\rm Yuk} \supset -\frac{m_f}{v}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

Several angular observables used to test the CP odd operators

Limits are still relatively weak, BUT
we know that the Higgs is not a 100% CP odd boson

For example:
$h \to ZZ^* \to 4l$



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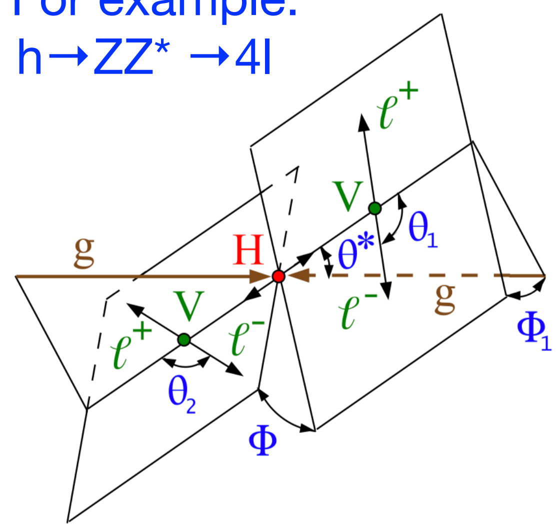
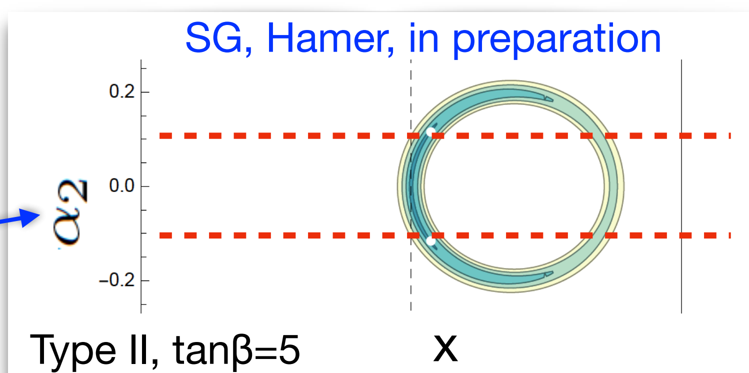


In more UV-complete models, the bounds can be competitive with bounds from Higgs rates

Example: 2HDM



Higgs CP odd component

From $h \to \tau\tau$
137 fb^{-1}
CMS-HIG-20-006-pas

How to optimize these searches with Run III data?

Higgs and CP violation (the other Higgs)

Higgs
(125 GeV &
beyond)

Frequently, models with a Higgs with a CP odd component predict the existence of additional Higgs bosons that are also a CP admixture.

New searches targeting CP violating new Higgs bosons?

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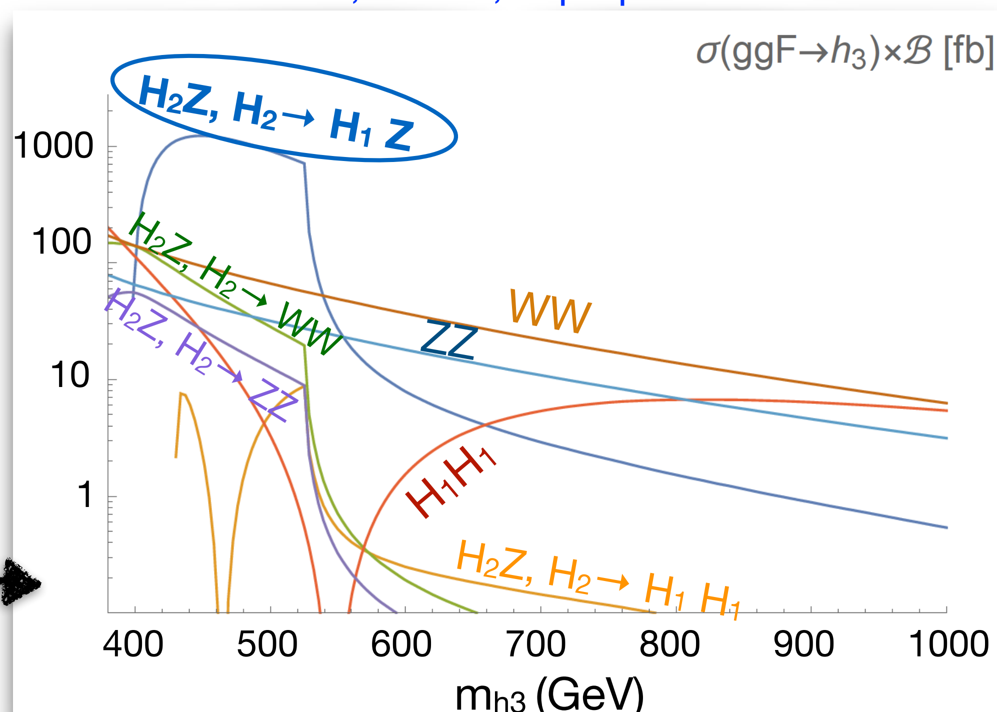
New searches targeting CP violating new Higgs bosons?

An example scenario:
in a CP violating 2HDM the three neutral Higgs bosons are a CP admixture

SG, Hamer, in preparation

H_3 and H_2 can lead to striking CPV signatures



Possible smoking guns:

NEW

- both H_3 and H_2 decaying to WW and ZZ
- $H_3 \rightarrow H_2 Z$, $H_2 \rightarrow H_1 Z$
- $H_3 \rightarrow H_1 H_2$ (Low, Shah, Wang, 2012.00773)

Higgs and flavor

Higgs (125 GeV & beyond)

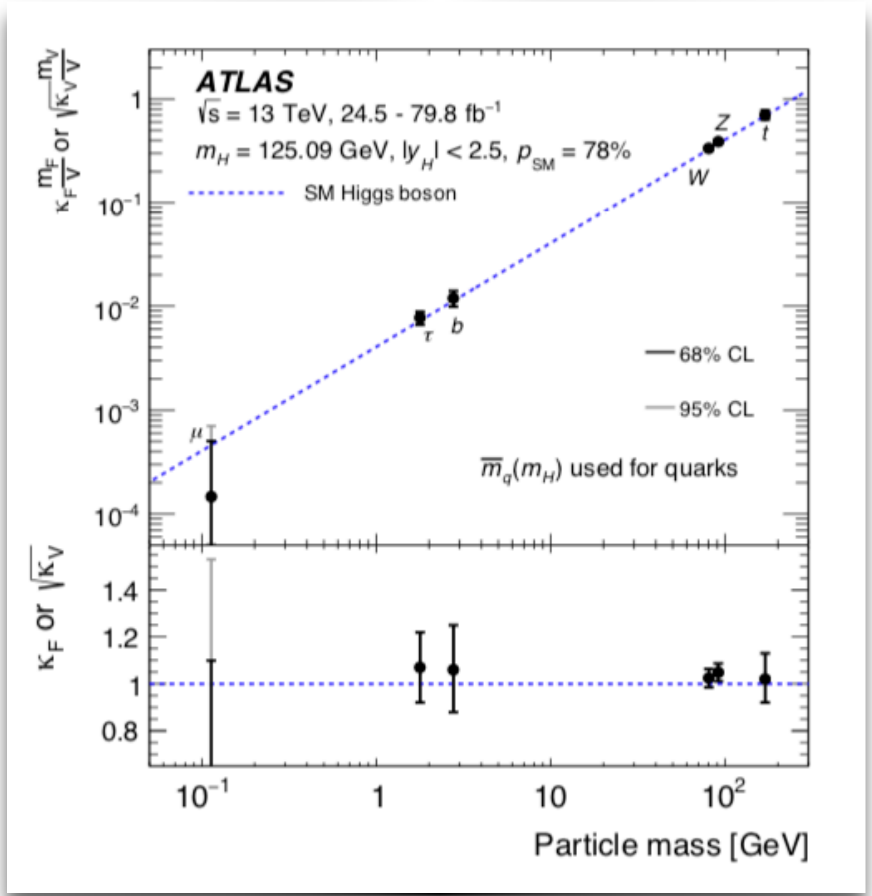
We do not know if the 125 GeV Higgs is coupled/gives mass to all flavors

Evidence for the Higgs decaying into muons!

$$\mu = 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu = 1.19^{+0.40}_{-0.39}(\mathrm{stat})^{+0.15}_{-0.14}(\mathrm{syst})$$ (CMS, 2009.04363)

Run III discovery?



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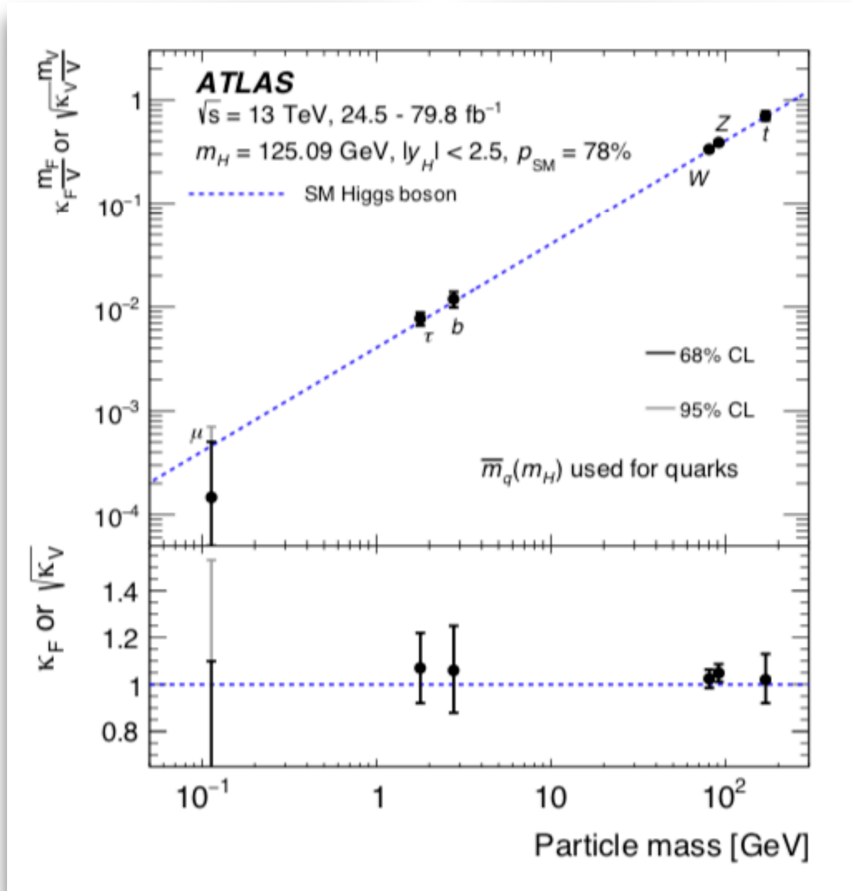

What about light quarks? (electrons?)

Strategies to probe light quark Yukawas (warning: not exhaustive)

- ✱ Higgs + charm production (Brivio, Isidori, Goertz 1507.02916)
- ✱ Higgs + jet production (Bishara, Haisch, Monni, Re, 1606.09253)
- ✱ Higgs η & p_T distributions (Soreq, Zhu, Zupan, 1606.09621)
- ✱ Rare Higgs decays (Bodwin, Petriello, Stoynev, Velasco,1306.5770)
- ✱ Charge asymmetry in $W^\pm h$ production (Yu,1609.06592) discovery with 300/fb
- ✱ Higgs + photon production (Aguilar-Saavedra, Cano, No, 2008.12538)

Higgs and flavor (the other Higgs)

Higgs (125 GeV & beyond)

If the 125 GeV Higgs does not give the (whole) mass to the light flavors, another Higgs can be involved in the mechanism of mass generation.

Multi-Higgs doublet models with a flavor structure different from Type I-IV 2HDMs

Several un-explored signatures of the new Higgs bosons

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Several un-explored signatures of the new Higgs bosons

An example: the "flavorful 2HDM"

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

125 Higgs (h) — Additional Higgses (H, A, H±)

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix},$$

$$\Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

(analogous structure in the quark sector)

Many new signatures to look for:

Top-charm resonances $pp \to H \to tc$
Boosted regime or leptonic top to trigger on the events.

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Top-charm (or top-top) resonances

fully leptonic: $pp \to t(c)H,\ H \to tc$
same-charge dilepton plus bottom and charm jets

Tau-mu resonances $pp \to t(c)H,\ H \to \tau\mu$

Light di-jet resonances $pp \to t(c)H,\ H \to cc$

Charm-bottom and charm-strange resonances (also above the top threshold). $pp \to H^\pm \to cs,\ cb$
Data scouting with bottom (charm)-tagging?

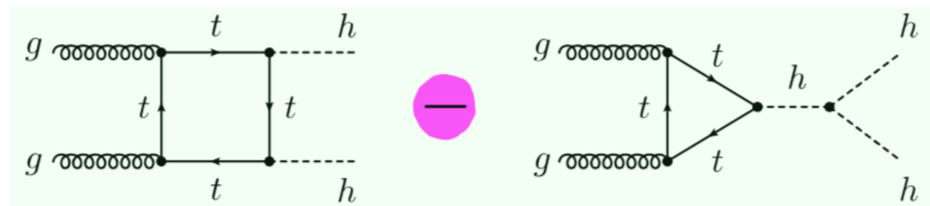
Di-Higgs production

Higgs (125 GeV & beyond)

Measurement of the h^3 term in the Higgs potential is crucial

What is the nature of the phase transition from zero to nonzero VEV?

The measurement is challenging since the **SM di-Higgs cross section is small**



Several di-Higgs searches performed at Run II:

Search channel ~36/fb	Collaboration	95% CL Upper Limit observed	expected
$b\bar{b}b\bar{b}$	ATLAS	13	21
	CMS	75	37
$b\bar{b}\gamma\gamma$	ATLAS	20	26
	CMS	24	19
$b\bar{b}\tau^+\tau^-$	ATLAS	12	15
	CMS	32	25
$b\bar{b}VV^*\,(\ell\nu\ell\nu)^*$	ATLAS	40	29
	CMS	79	89
$b\bar{b}WW^*\,(\ell\nu qq)$	ATLAS	305	305
	CMS	–	–
$WW^*\gamma\gamma$	ATLAS	230	160
	CMS	–	–
WW^*WW^*	ATLAS	160	120
	CMS	–	–
Combined	ATLAS	6.9	10
	CMS	22	13

Di Micco et al.,1910.00012

times the SM cross section

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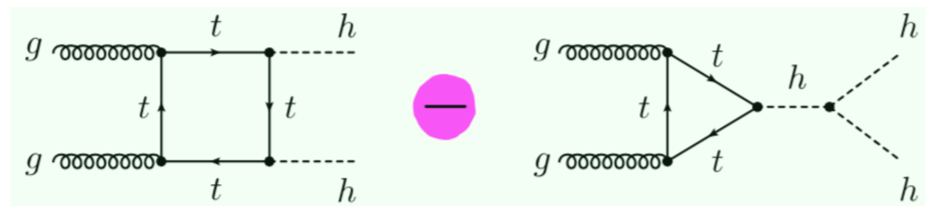

HL: bbττ, bbγγ (and bbbb) will ultimately provide the best sensitivity (combined sensitivity of ~4-4.5σ)

We should prepare in view of the HL-LHC!

Improved b-tagging performance and improved b-jet triggers?

see talk by J. Alison tomorrow

Higgs exotic decays

Higgs (125 GeV & beyond)

Many motivations to search for Higgs exotic decays ($h \to$ NP NP, NP SM):

- The 125 GeV SM Higgs width is very small ➡ it is simple to have a sizable BR into light NP particles.
- The Higgs easily couples to NP.
- Several theories predict Higgs exotic decays (SUSY, twin Higgs models, DM models, models for electroweak baryogenesis, …)

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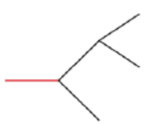
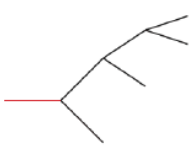
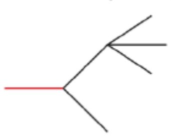
1312.4992, **prompt** decays of the NP particle

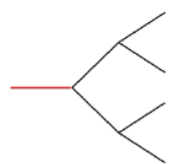
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

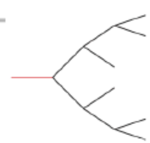


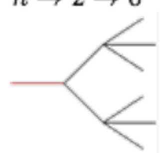




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$







From Z. Liu

Run II focused on "non-MET" signatures

What about signatures with MET (semi-visible) for Run III?

Specific low energy triggers are needed!

example:
triple-muon trigger, $p_T > 12, 10, 5$ GeV used in h→μμ ττ, CMS 1805.04865

Higgs exotic decays

Higgs (125 GeV & beyond)

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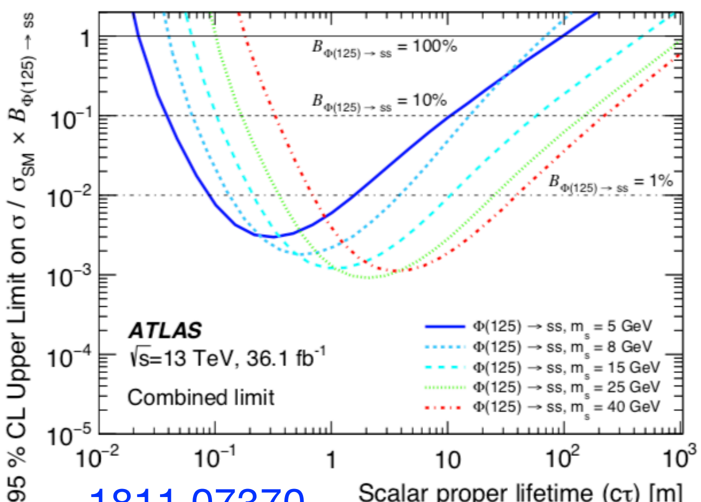
- Several theories predict Higgs exotic decays (SUSY, twin Higgs models, DM models, models for electroweak baryogenesis, …)

A particularly interesting (and challenging) case:
Higgs decaying to **long-lived particles**

- Some searches will greatly benefit from the increase in luminosity (case of low/negligible backgrounds)



1811.07370

- Significant improvements in sensitivity of many searches could be possible in future LHC runs with potential improvements in
  - timing (Liu, Liu, Wang, 1805.05957);
  - triggers (Gershtein, 1705.04321);
  - analysis strategies (e.g. Csaki et al, 1508.01522).

Higgs exotic decays (the other Higgs)

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In models with more than one Higgs boson, also **the new Higgs bosons can have exotic decays.**

Challenges are different (typically it is easier to trigger on these events, but much smaller rates)

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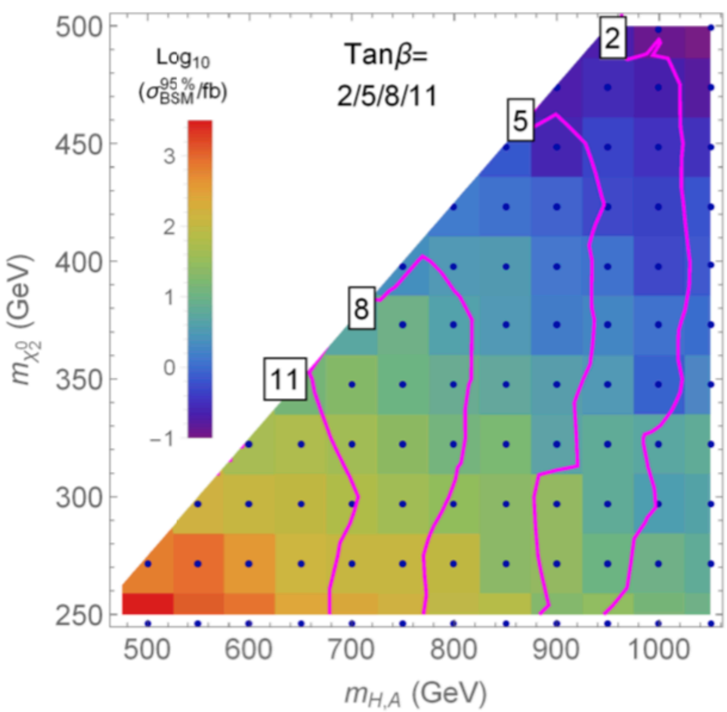
A SUSY example:

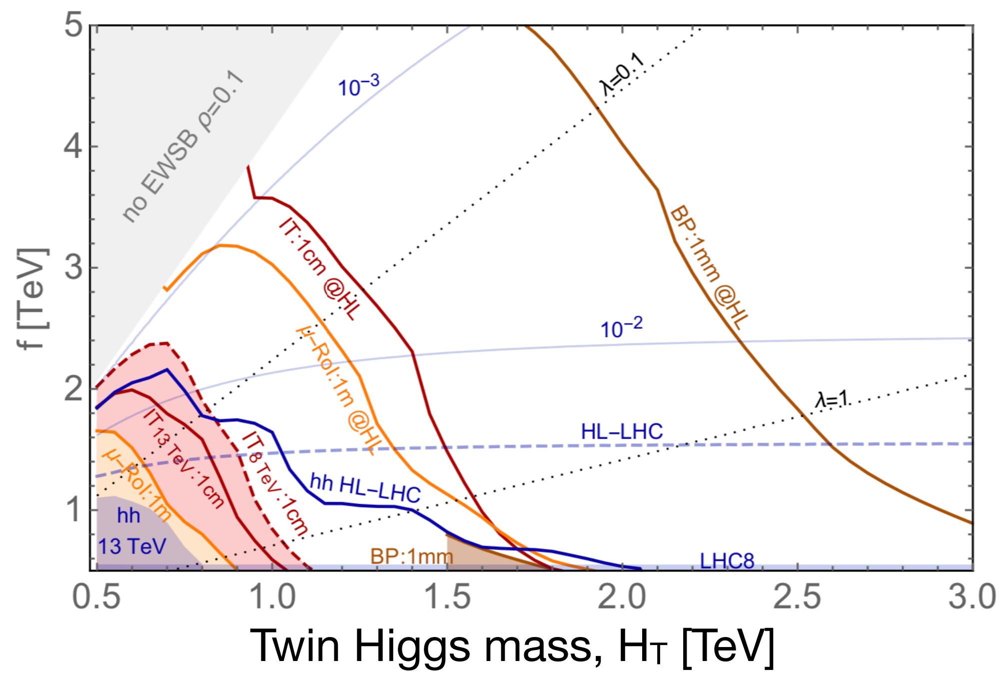
$$H, A \to \chi_1^0 \chi_2^0,\ \chi_2^0 \to \chi_1^0 Z \to \ell\ell + \text{MET}$$



SG, Liu, Shakya, 1811.11918

A Twin Higgs model example:

$$H_T \to G_0 G_0 \to 2\ \text{displaced}$$



Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

Squeezed spectra

New particles

Many models predict the existence of NP particles that are close in mass

A couple of examples:

* Inelastic DM models (DM is the lightest state of a pseudo-Dirac fermion)
* Split SUSY (Winos could be at the bottom of the SUSY spectrum and have a small mass splitting)

An example signature: $pp \to \chi_1^\pm \chi_2 \to (\chi_1 jj)(\chi_1 \ell\ell)$

soft!

for a recent review about electroweakinos see Canepa, Han, Wang, 2003.05450

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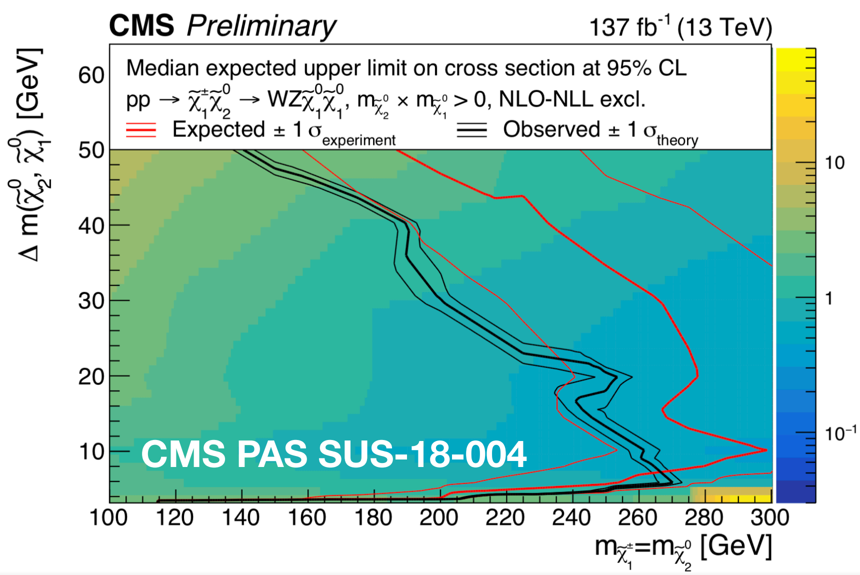
It would be beneficial to have a broad program for:

Mono-X + something **and** VBF + something **"combined" triggers?**

Reach of a large set of models!

At Run II:

- several analyses based on MET triggers.
- dedicated dimuon + MET trigger



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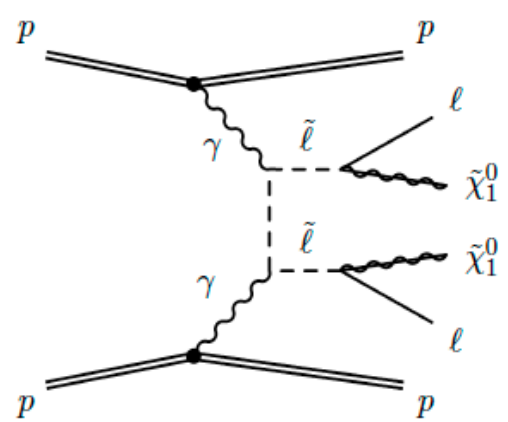
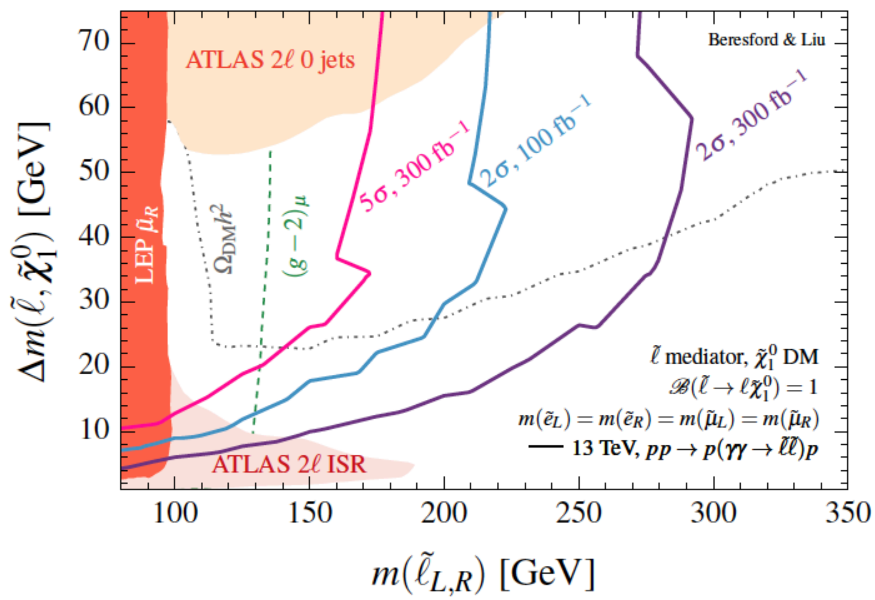
An interesting proposal to target (relatively) squeezed spectra: proton-tagged ultraperipheral collisions using forward detectors

Beresford, Liu, 1811.06465



Similarly for electroweakinos



Long lived particles (1)

New particles

Long lived particles often arise in BSM models.

The lifetime of a NP particle can be long if

- an approximate symmetry makes the particle stable;
- the decay phase space is suppressed;
- the new particle interacts only very weakly with the SM; …

Production through the decay of

- heavy NP particles charged under the SM gauge symmetry (examples: gravitinos in gauge mediated SUSY, glueballs in neutral naturalness, …)
- Higgs boson (examples: many!)
- W/Z bosons (examples: sterile neutrinos)
- B mesons (examples: axion-like-particles)

lower and lower mass

↓

in general,
more and more challenging

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A large effort of the theory/experimental community in the last few years

LHC long-lived-particles working group.

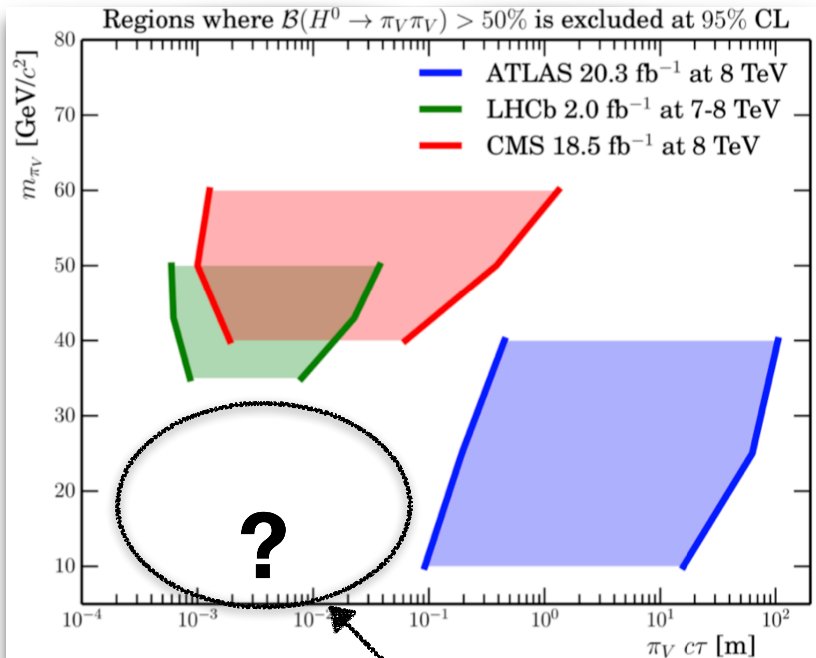
tools for simulation (dark showers), simplified models, suggestions on how to present results, reinterpretations, keep an updated survey of coverage gaps, potential new triggers, …

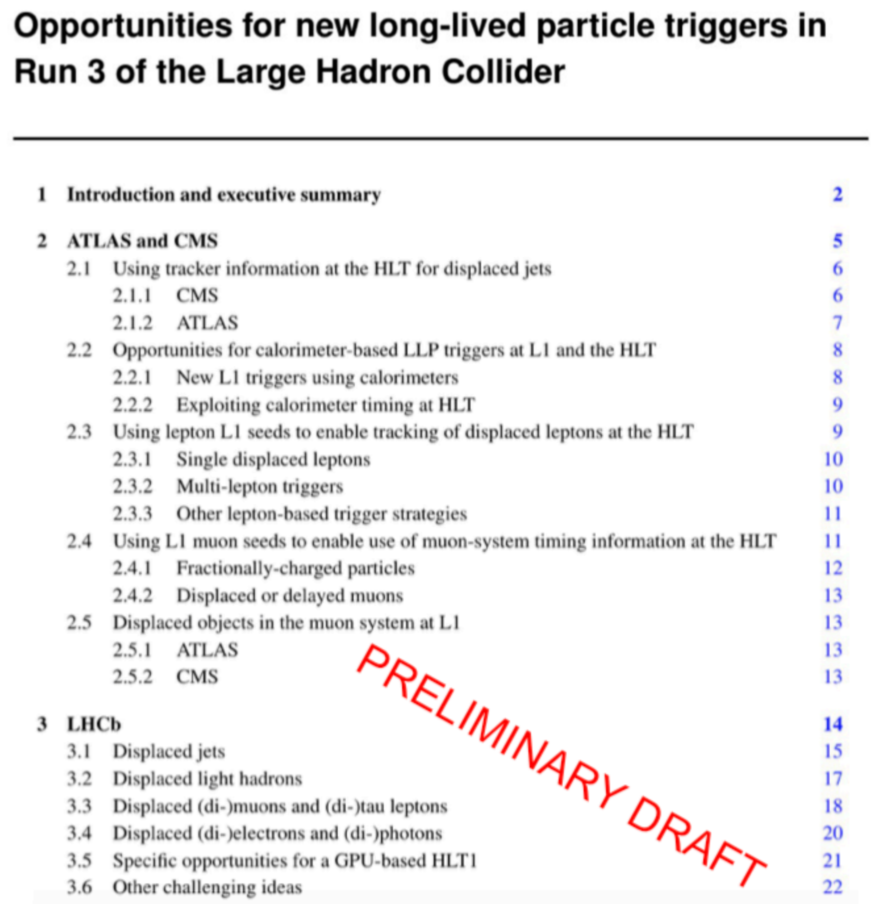
https://indico.cern.ch/event/922632/timetable/ (latest meeting, Nov. 2020)

New particles

Long lived particles (2)

A few comments/highlights:





Opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider

PRELIMINARY DRAFT

Examples:

- CMS phase II track trigger may allow for a displaced dimuon vertex trigger with qualitatively lower p_T thresholds. LLP from B meson decays (Gershtein, Knapen, 1907.00007; Evans et al, 2008.06918)
- More scouting analyses?

See talk by D.Curtin, https://indico.cern.ch/event/922632/timetable/

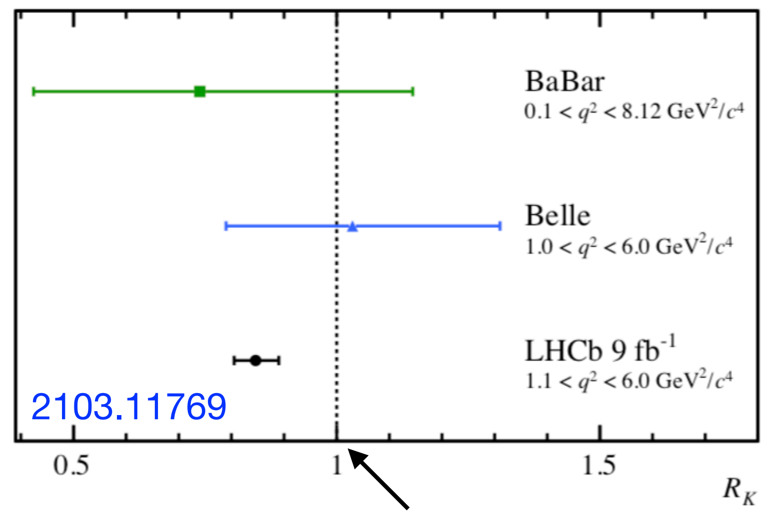
Additional complementarity with the proposed LLP experiments (Codex-b, DarkQuest, Faser, Mathusla, MilliQan, NA62, SHiP, …)

B → K(*) ll

Interesting (lepton flavor universality) anomalies observed by the LHCb collaboration in these decay modes.

Rates and angular observables (e.g. P_5') are measured.

Latest from Moriond:



SM (± 0.01)

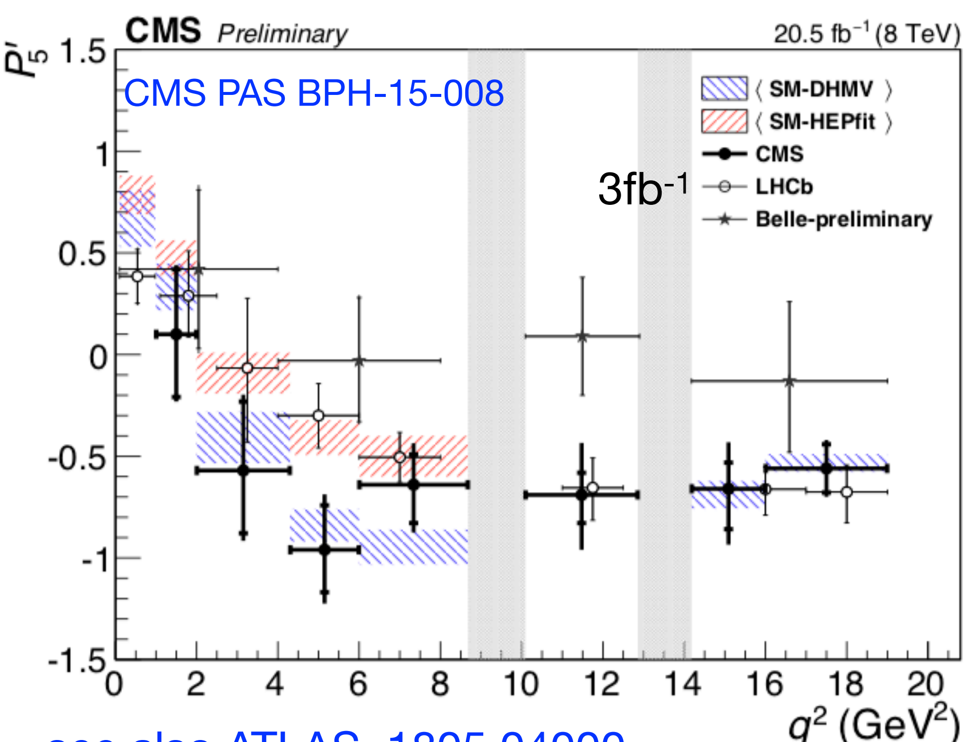
$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to K e^+ e^-)}$$

B → K$^{(*)}$ ll

Interesting (lepton flavor universality) anomalies observed by the LHCb collaboration in these decay modes.

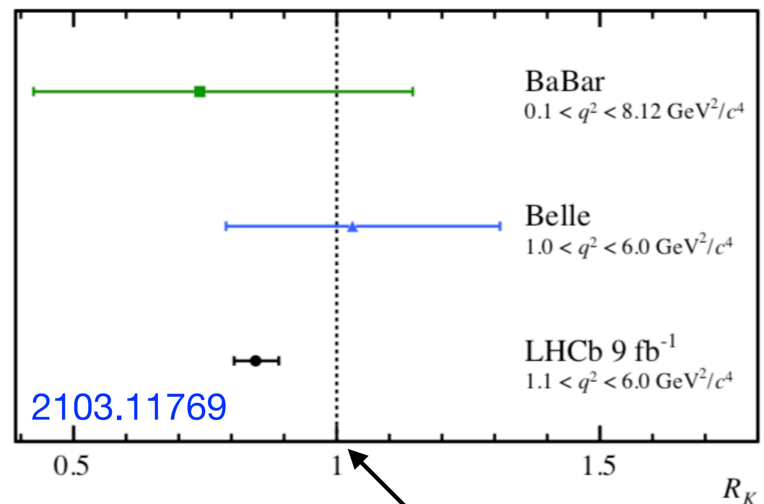
Rates and angular observables (e.g. P_5') are measured.

CMS and ATLAS have contributed to this effort using Run I data:



see also ATLAS, 1805.04000

Latest from Moriond:



SM (± 0.01)

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to K e^+ e^-)}$$

What can be done at Run III?

Other B-physics measurements?

$B_s \to \mu\mu$, …

Flavor

(High energy) flavor measurements

Several searches for top flavor changing interactions (e.g. t→ch, t→cZ, …)
What about constraining generic top EFTs?

For example, the most important constraint on $(\bar{t}\gamma_\mu c)(\bar{e}\gamma^\mu e)$ still comes from LEP.
Searches for non-resonant t→c ee?

Long standing anomaly in the Zbb coupling (A_{FB}^b) from LEP.
Can the LHC play a role probing this anomaly?

an interesting proposal: gg→Zh, Yan, Yuan, 2101.06261

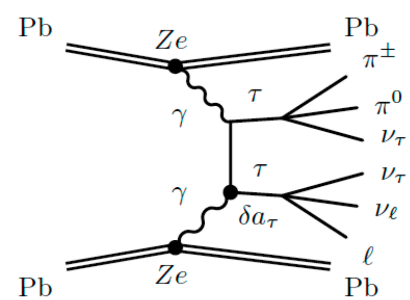
$$\frac{g_W}{2\cos\theta}\bar{b}\gamma^\mu(\kappa_v^b v_b^{\rm SM} - \kappa_a^b a_b^{\rm SM}\gamma_5)bZ_\mu + \frac{m_Z^2}{v}\kappa_z h Z_\mu Z^\mu$$

This coupling can address the anomaly.
Could be tested at the LHC

A few thoughts

$(g\text{-}2)_\tau$ is (so far) not well constrained by experiments
Ultraperipheral heavy ion collisions to probe $(g\text{-}2)_\tau$ at the LHC?
Beresford, Liu, 1908.05180

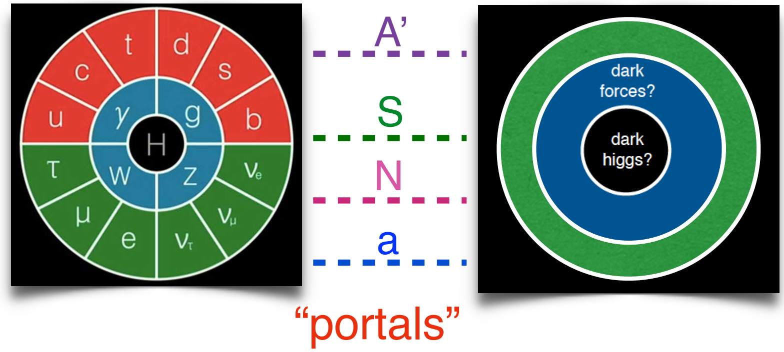
“the current 2/nb lead-lead dataset could already provide the (most stringent) constraint of $-0.0080 < a_\tau < 0.0046$”



Dark Matter & dark sectors

Dark sectors

Many extensions of the SM predict the existence of new particles not charged under the SM gauge symmetries (aka dark sectors!)



Often times, dark particles are light (below the electro-weak scale)

Direct production at the LHC through the portal operators?

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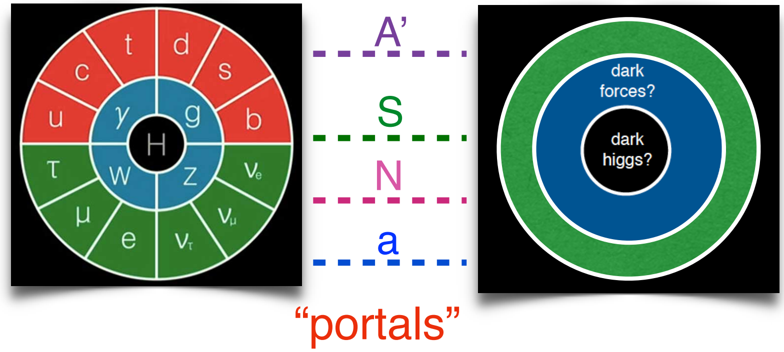


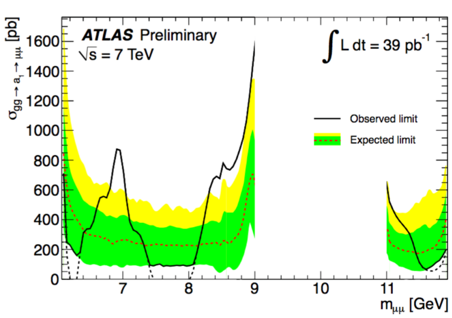
Often times, dark particles are light (below the electro-weak scale)

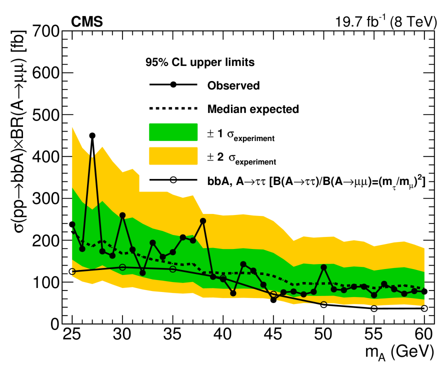
Direct production at the LHC through the portal operators?

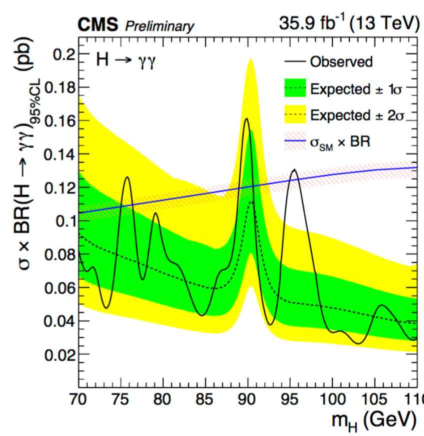
Only a few LHC searches have been performed.

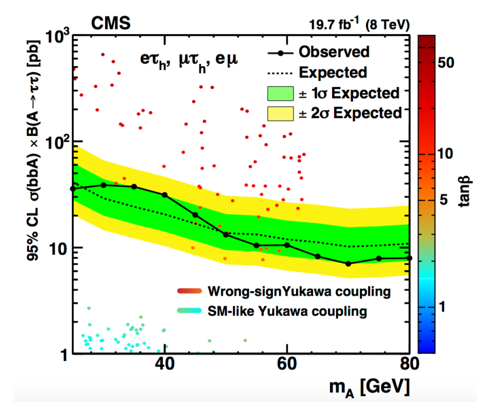
Examples are bbS, S →μμ
ggS, S →μμ, (also searched for by LHCb)
ggS, S →γγ
bbS, S →tautau

Broader range of searches on a broader mass range?







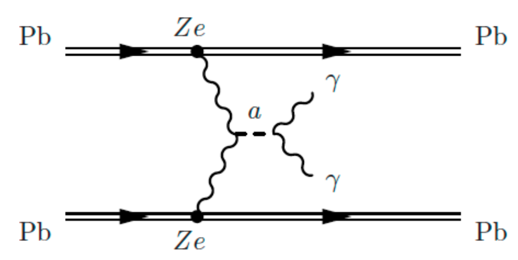


Dark sectors, heavy ion run

Dark Matter & dark sectors

Possible new searches for dark particles at heavy ion runs!

The Run-II ATLAS heavy ion run already set the most stringent bound on regions of parameter space of axion-like-particles. see also Knapen et al, 1607.06083



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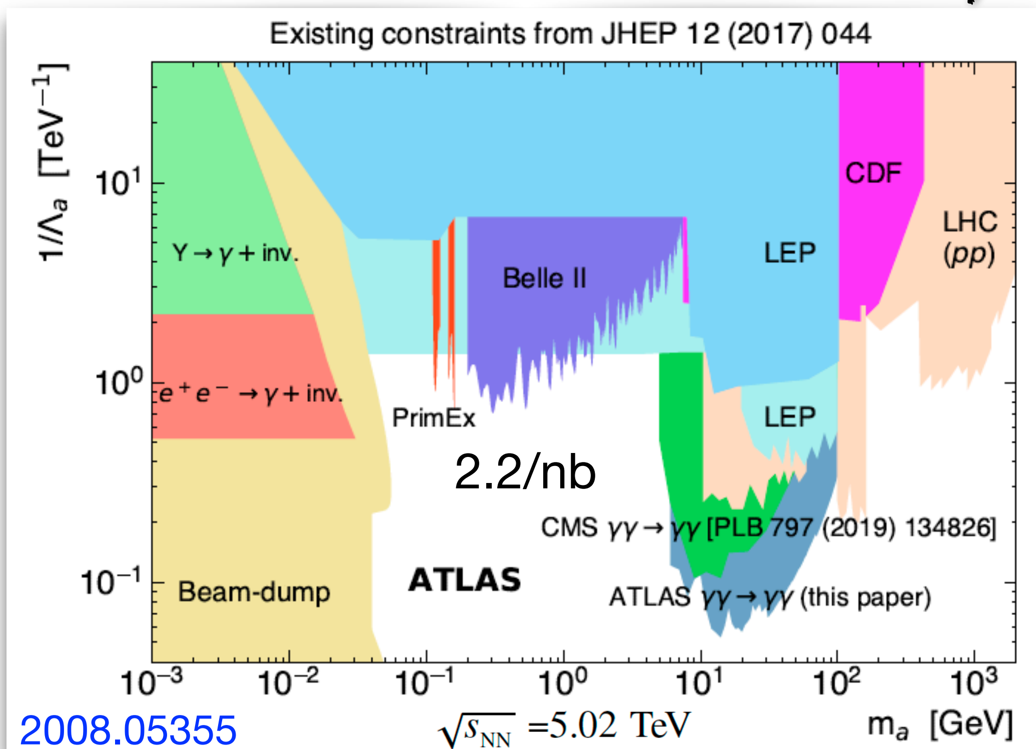

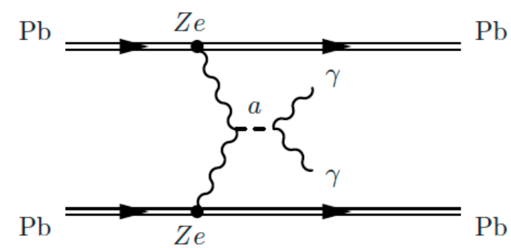

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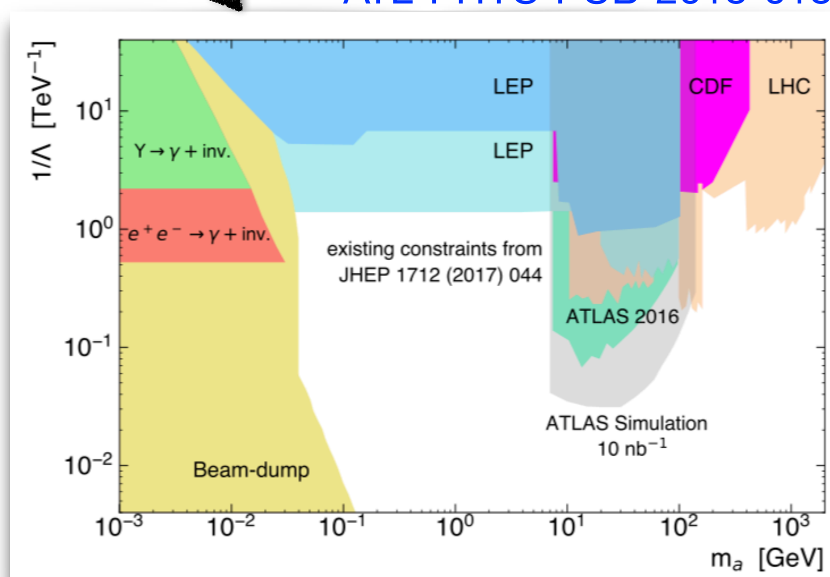


$$\frac{a}{4\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

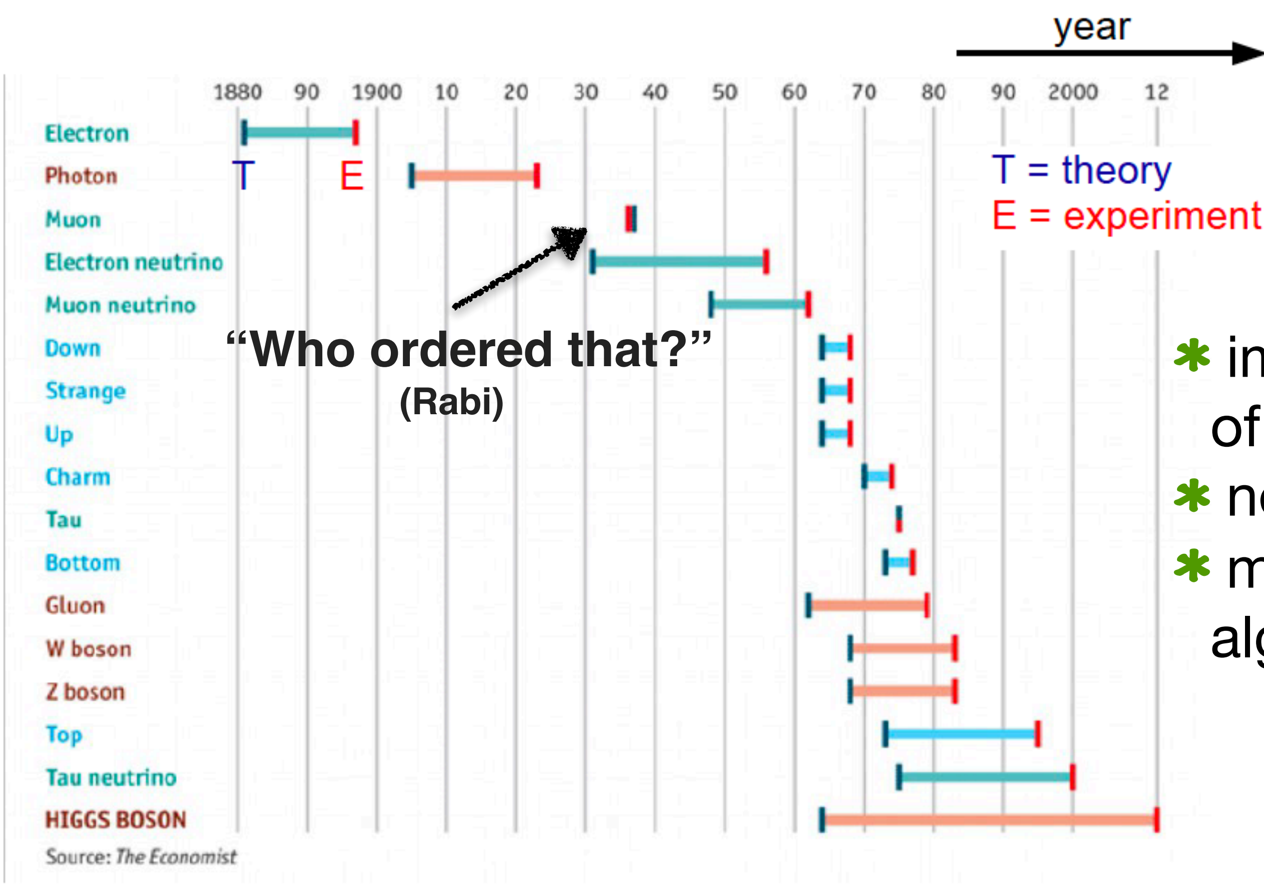
Additional opportunities?

prospects for Run 3+4

The unknown (i.e. “theory-free” searches)

All physics we have discussed so far has “conceptual questions” (hierarchy problem, nature of dark matter, flavor puzzle, baryogenesis, …) as guideline.

What if we are missing something?



- ✱ importance of broad searches of BSM particles
- ✱ need for exploration
- ✱ modern machine learning algorithms for anomaly detection

Outlook

Plenty of opportunities for Run III LHC!

Higgs (125 GeV & beyond)

Flavor

New particles

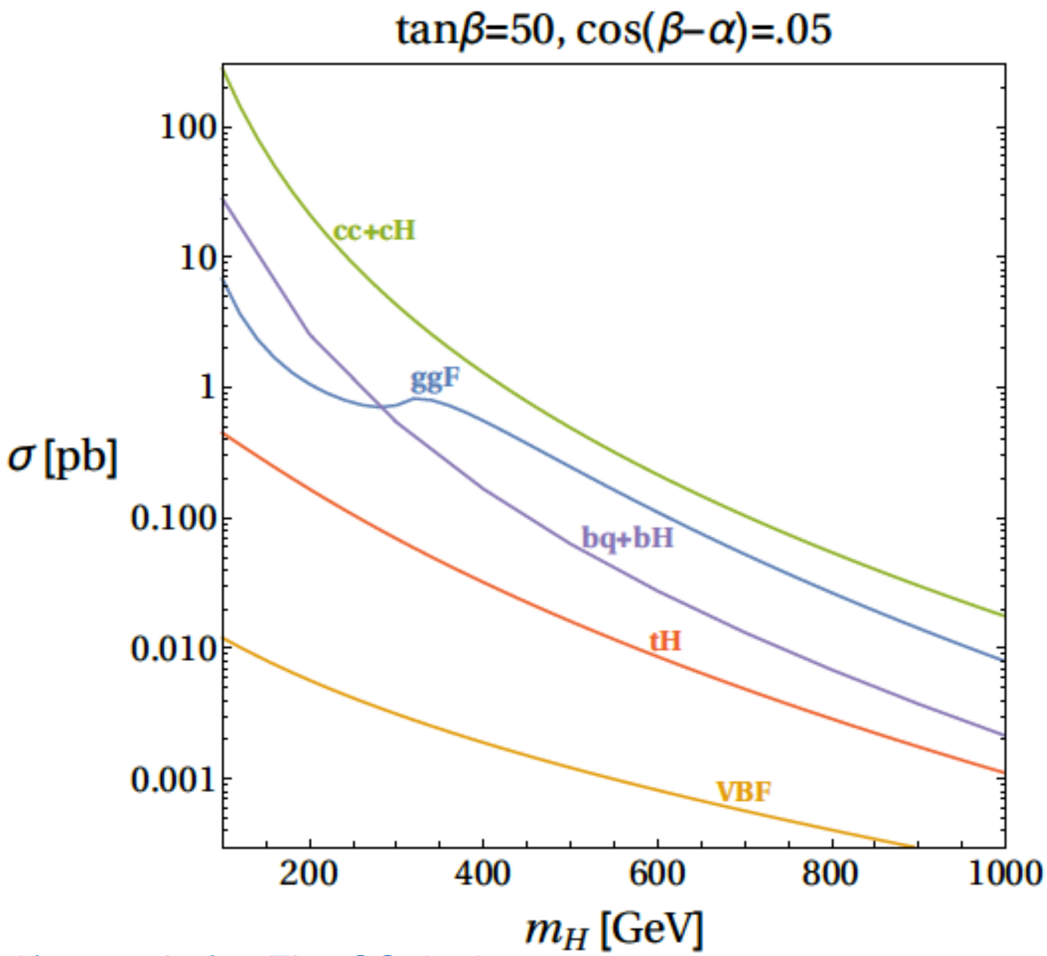
Dark Matter & dark sectors

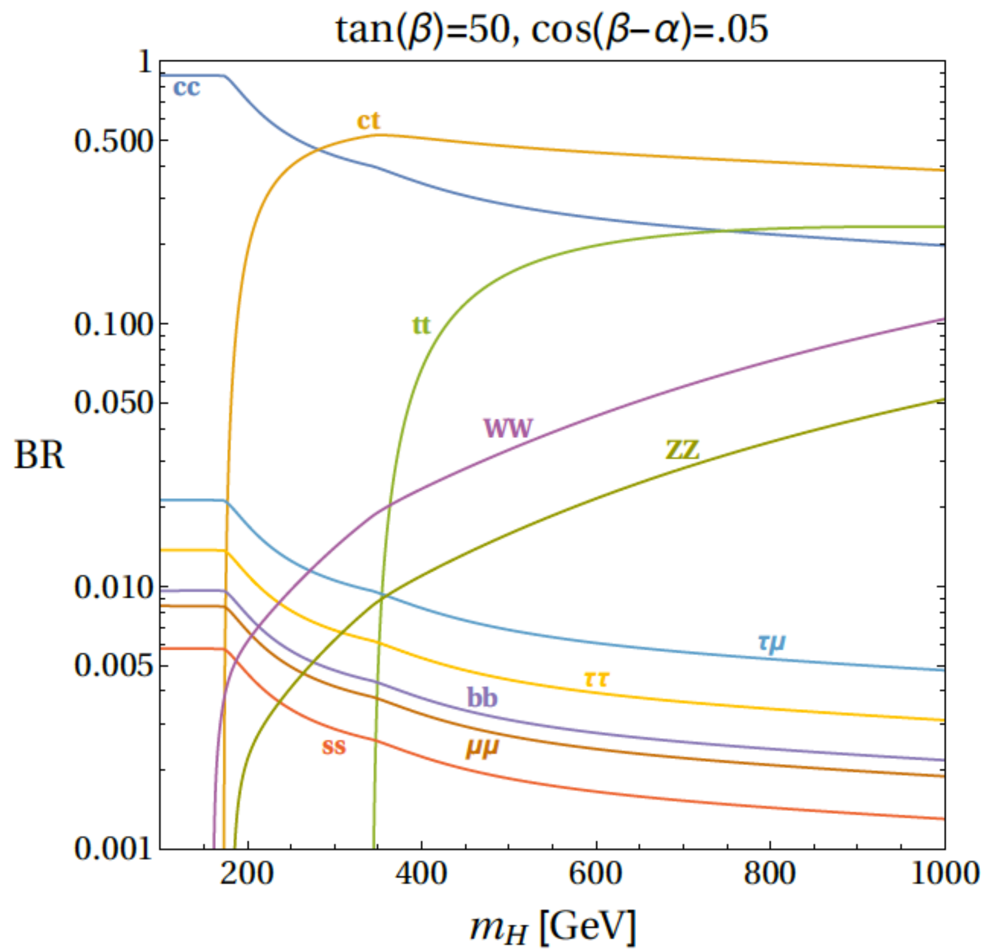
Many unexplored models/regions of parameter space
(Higgs distributions, light particles, long lived particles, …)

Beyond models: anomaly detection!

Need for exploration!

Production & decays of the scalar H



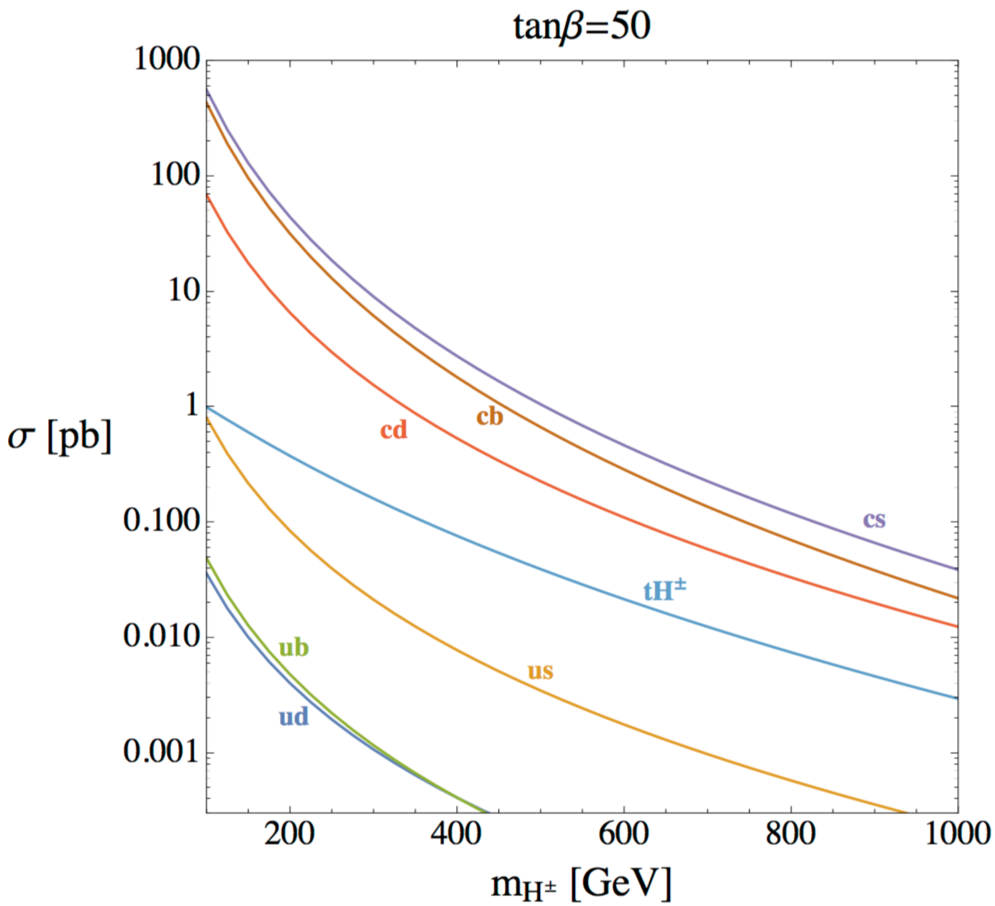


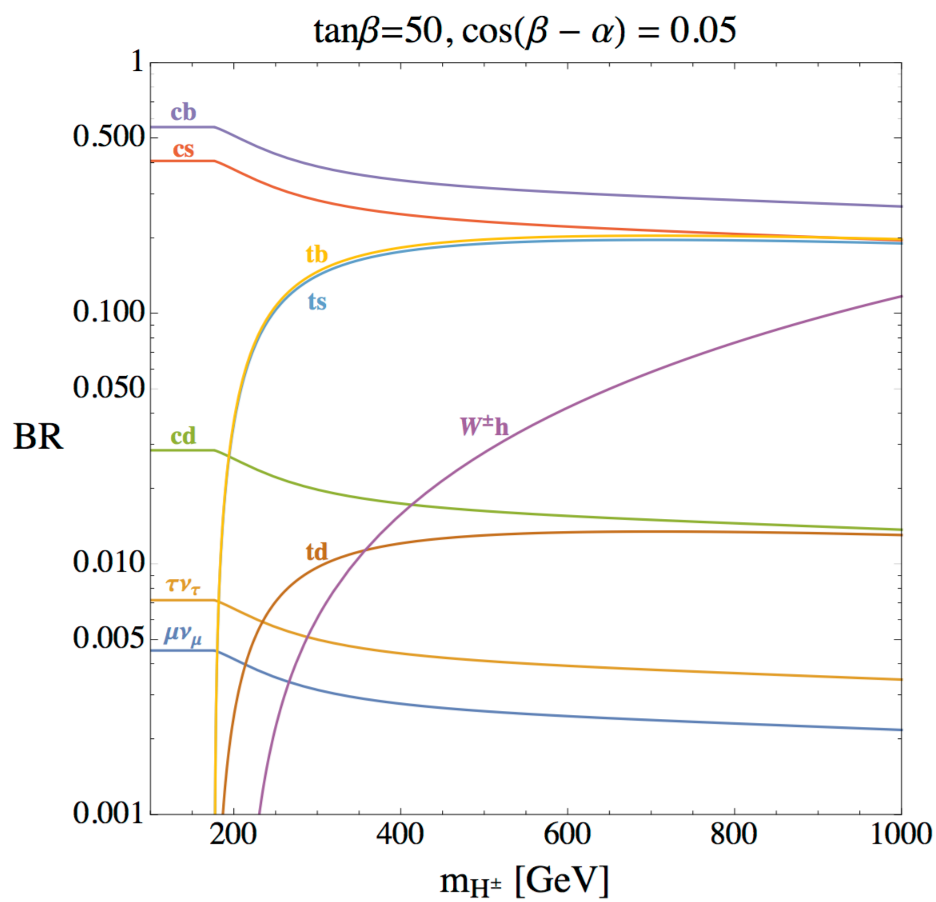
Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

The branching ratio to the "golden" channel, τ τ, is suppressed

bH typically suppressed, if compared to Type II 2HDMs

Production & decays of the scalar H±





s-channel production (quark-quark fusion) is the dominant one

The branching ratio to the "golden" channels, tb, τν, are suppressed