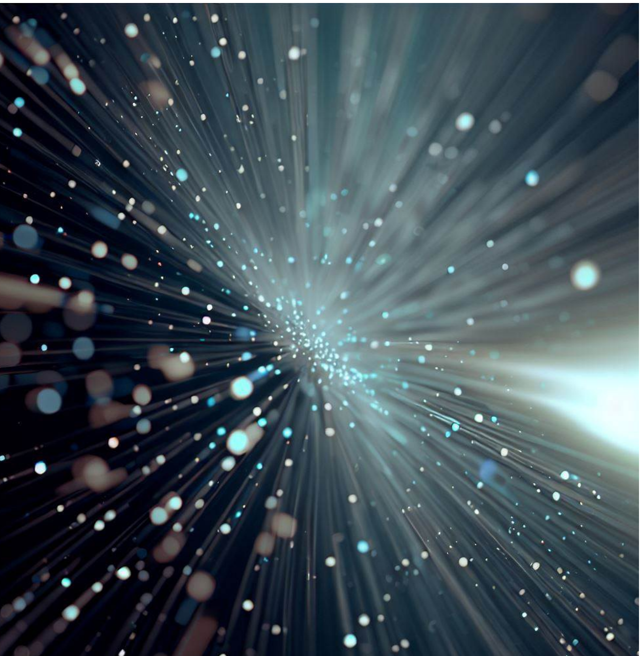
BSM at Run 3 and beyond — a theory perspective

Henning Bahl

THE UNIVERSITY OF CHICAGO



LHCP, Belgrade, 24.5.2023

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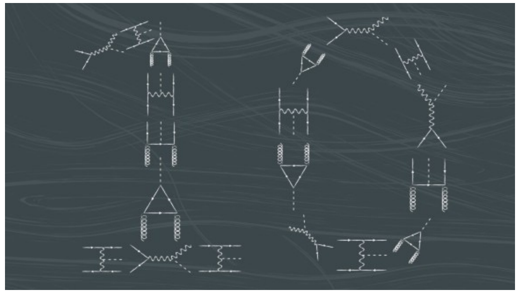
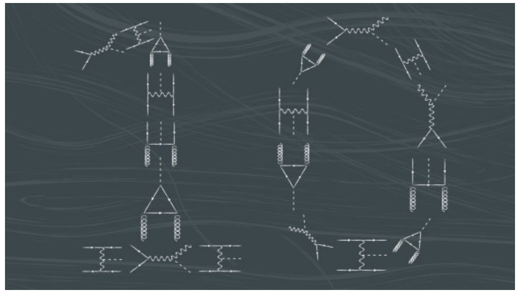


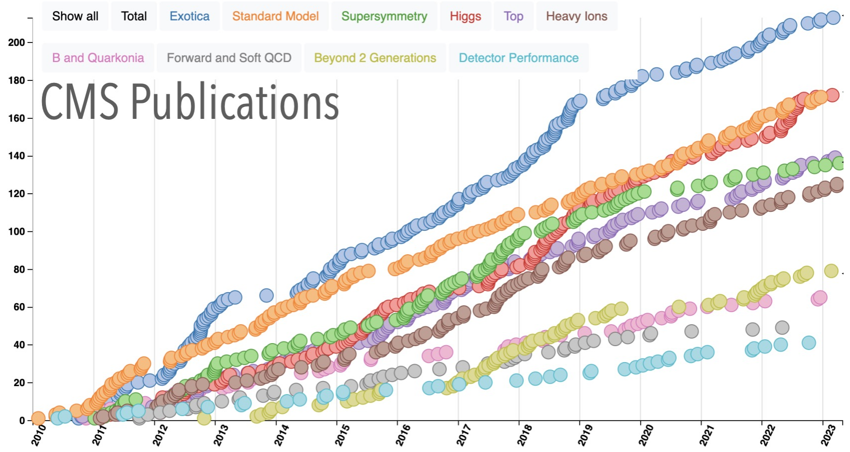
[Nature]

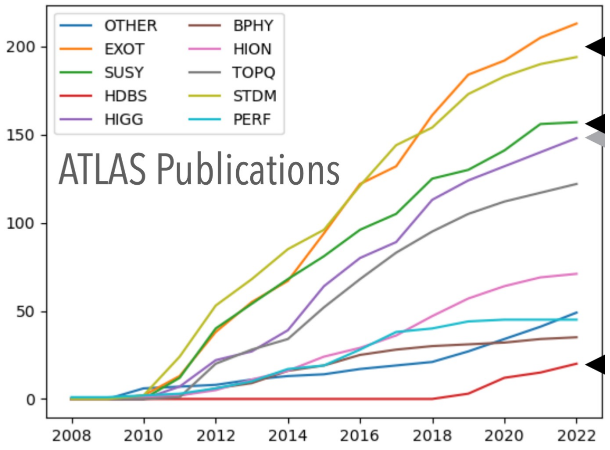
What has happened in Run-1 and Run-2?

- Higgs boson discovery in 2012.
- Many other precision measurements and searches.



[Nature]





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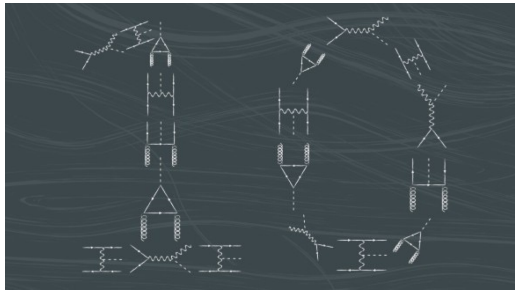

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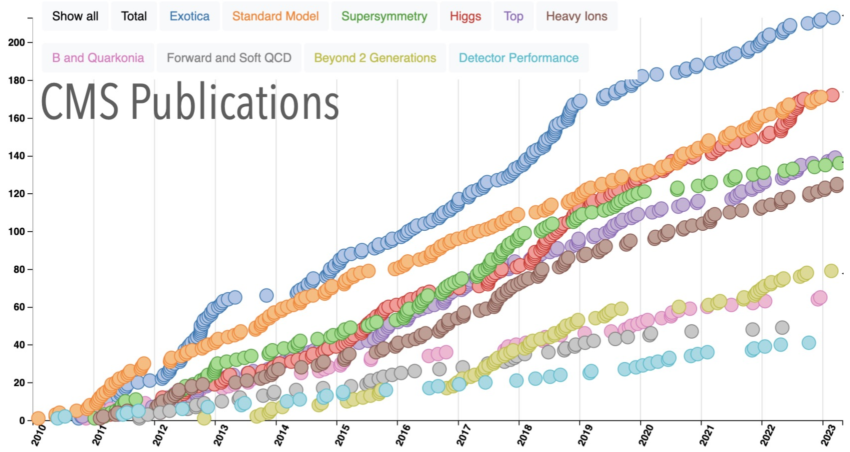
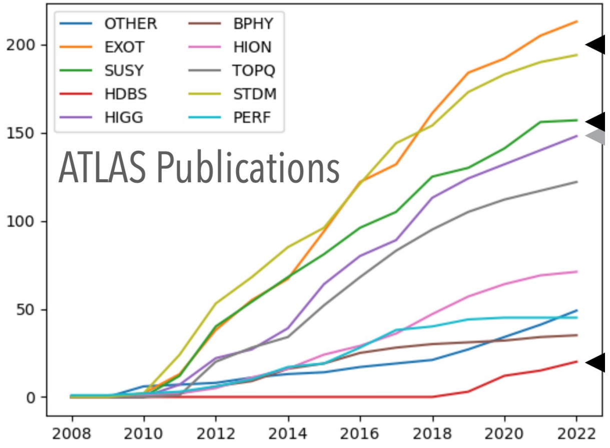
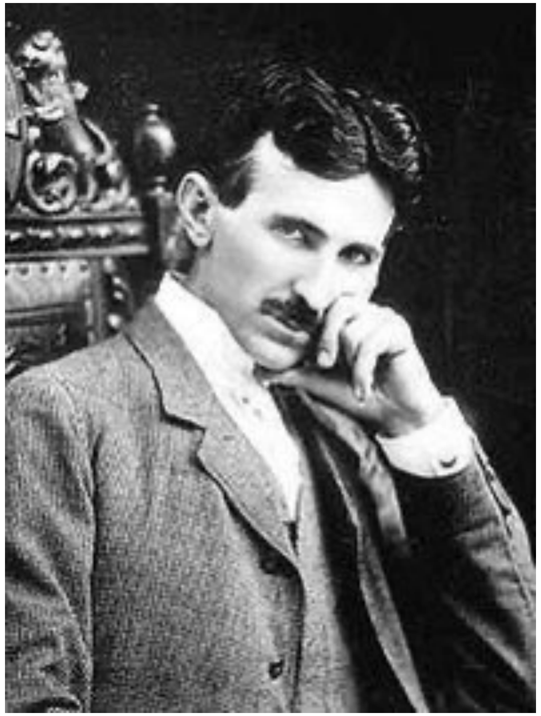




- Success!?

“We crave for new sensations but soon become indifferent to them. The wonders of yesterday are today common occurrences.”

Nikola Tesla



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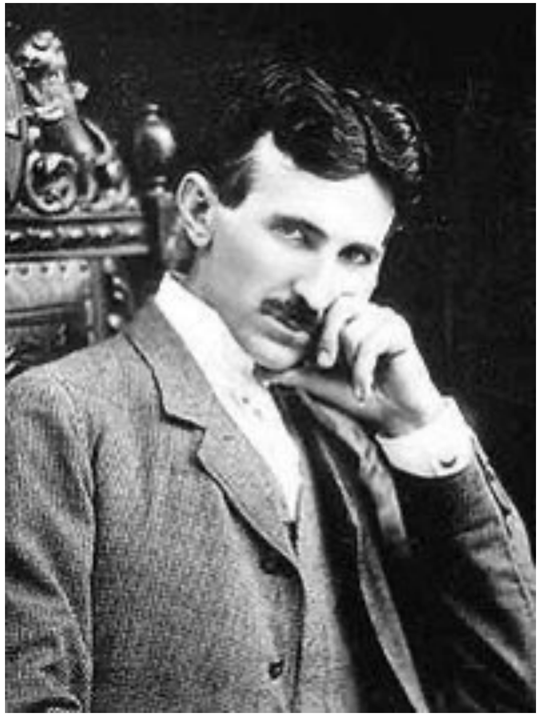

→ So far no evidence for BSM physics…

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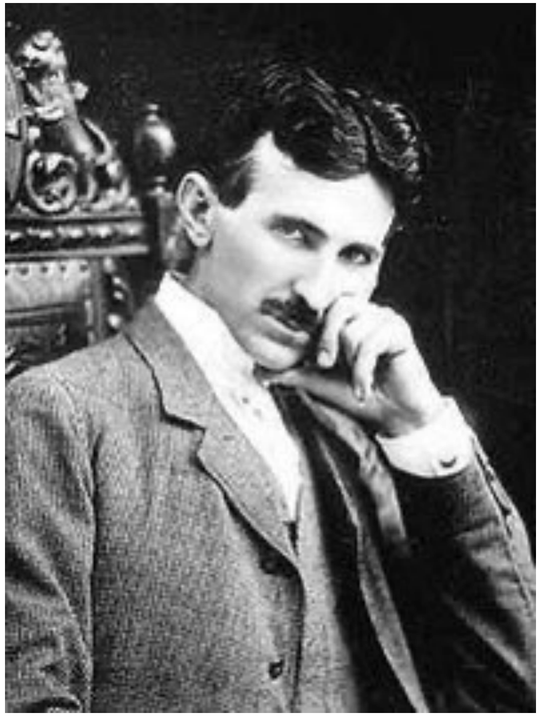

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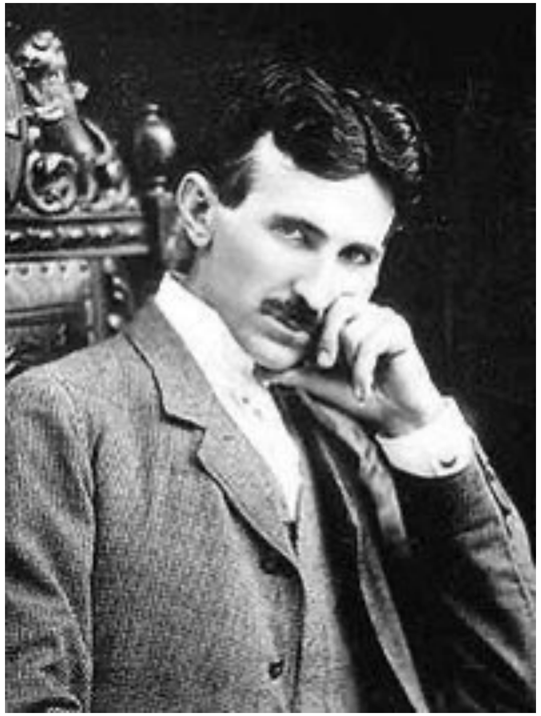

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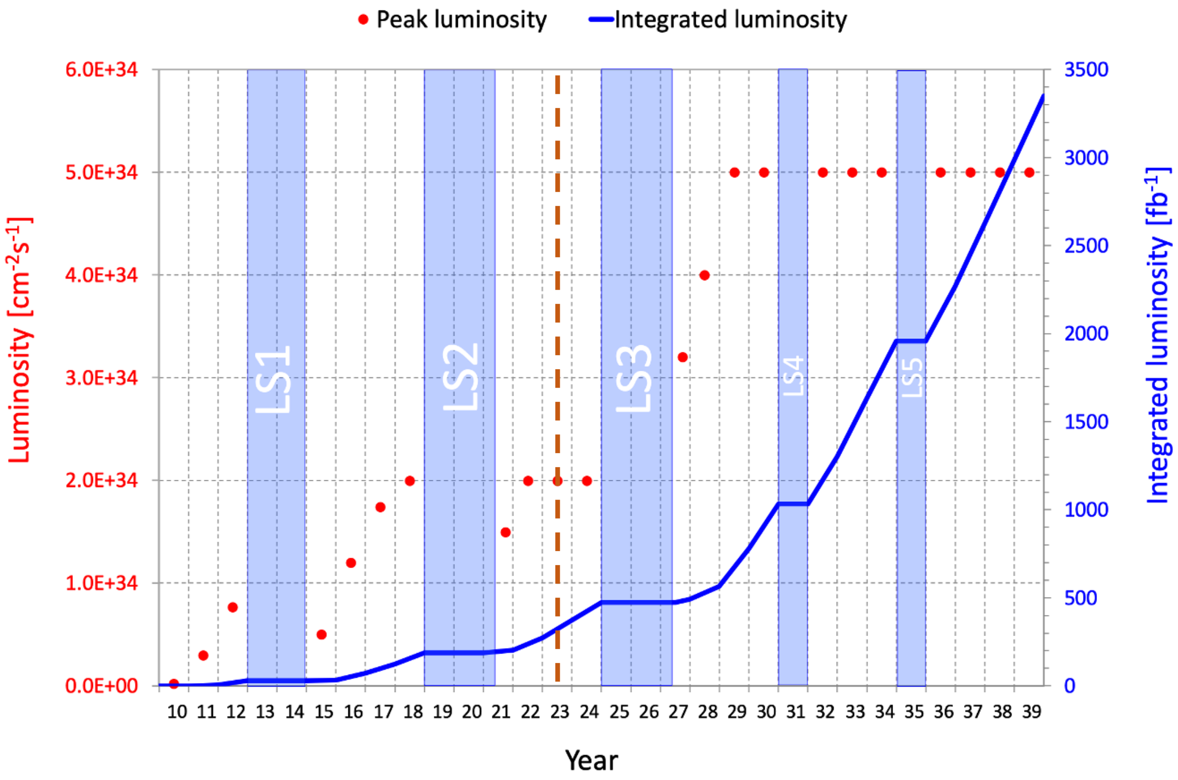
But: motivation to search for BSM physics at the LHC is still unbroken.

- Dark matter
- Nature of EWSB
- Baryon asymmetry
- Neutrino masses
- Naturalness
- …

LHC Run-3 and beyond



Much more data will be collected in the next years.

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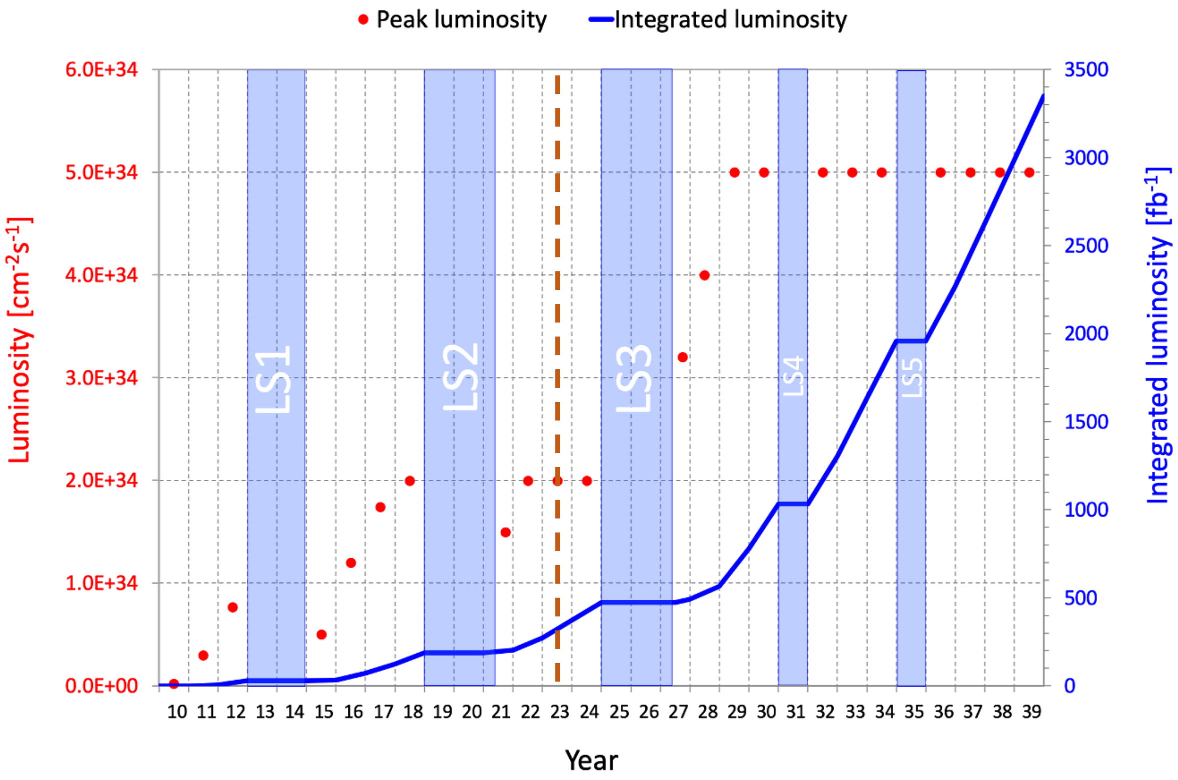

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→ The LHC program has just started.

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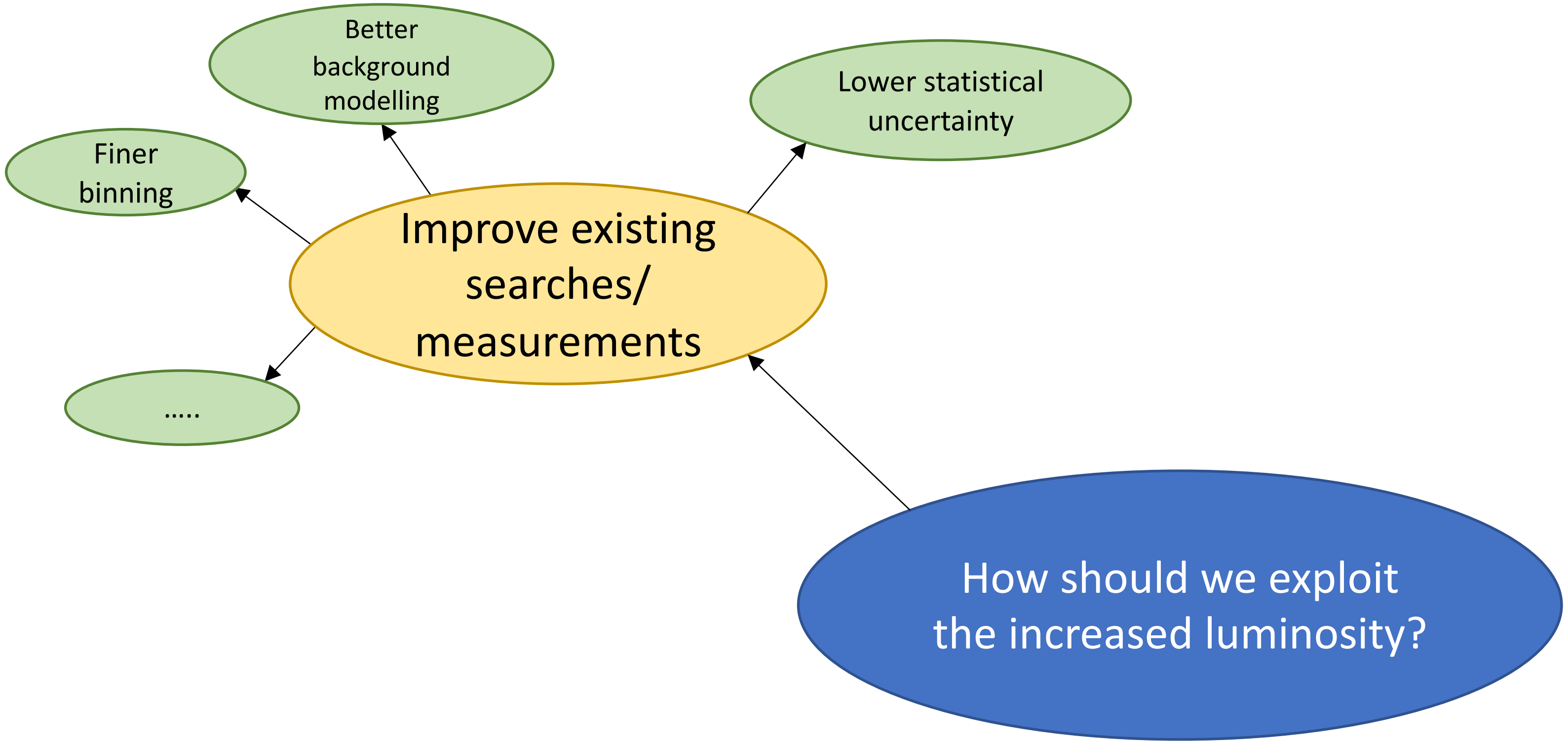
the increased luminosity?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Finer binning
Improve existing searches/ measurements
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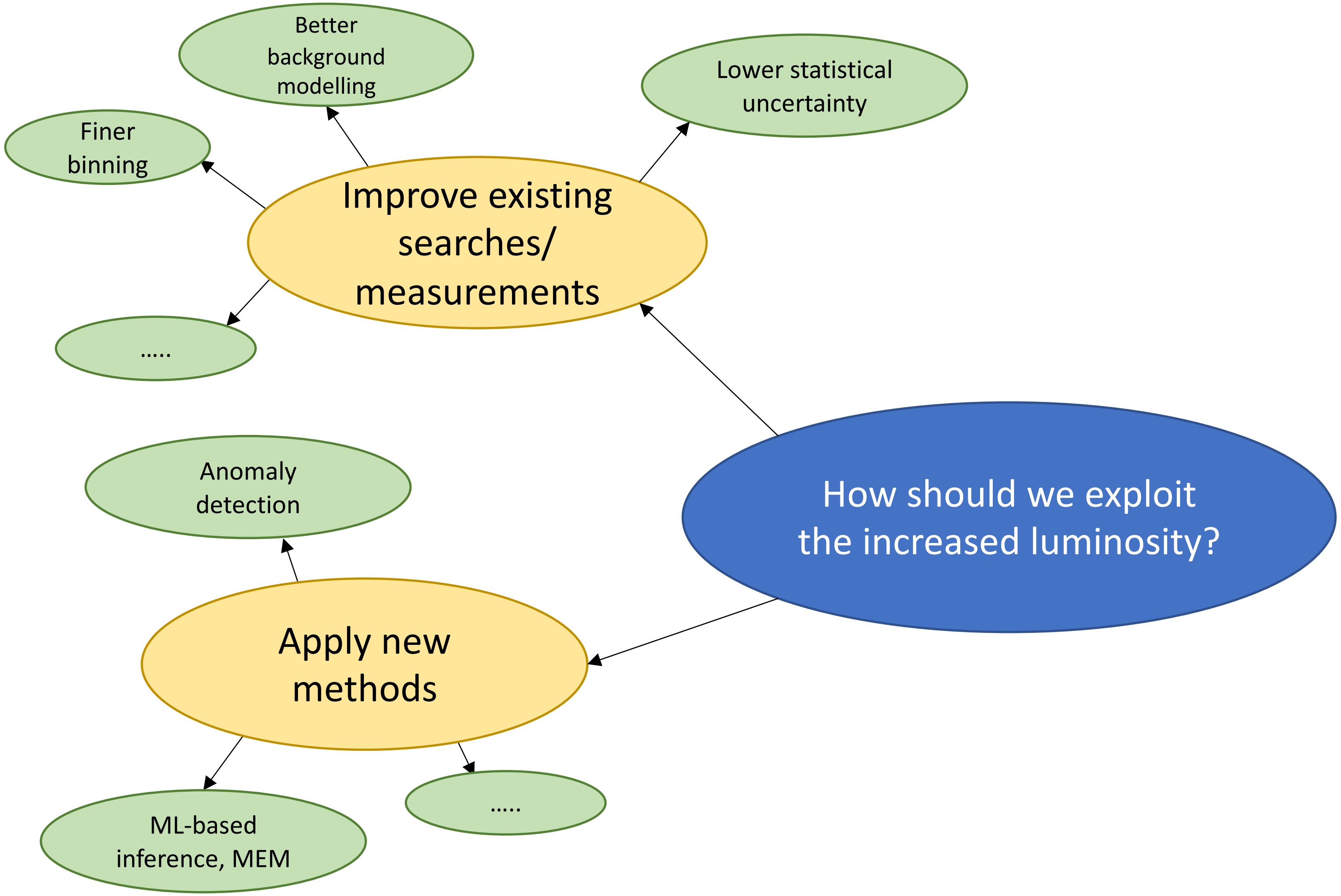
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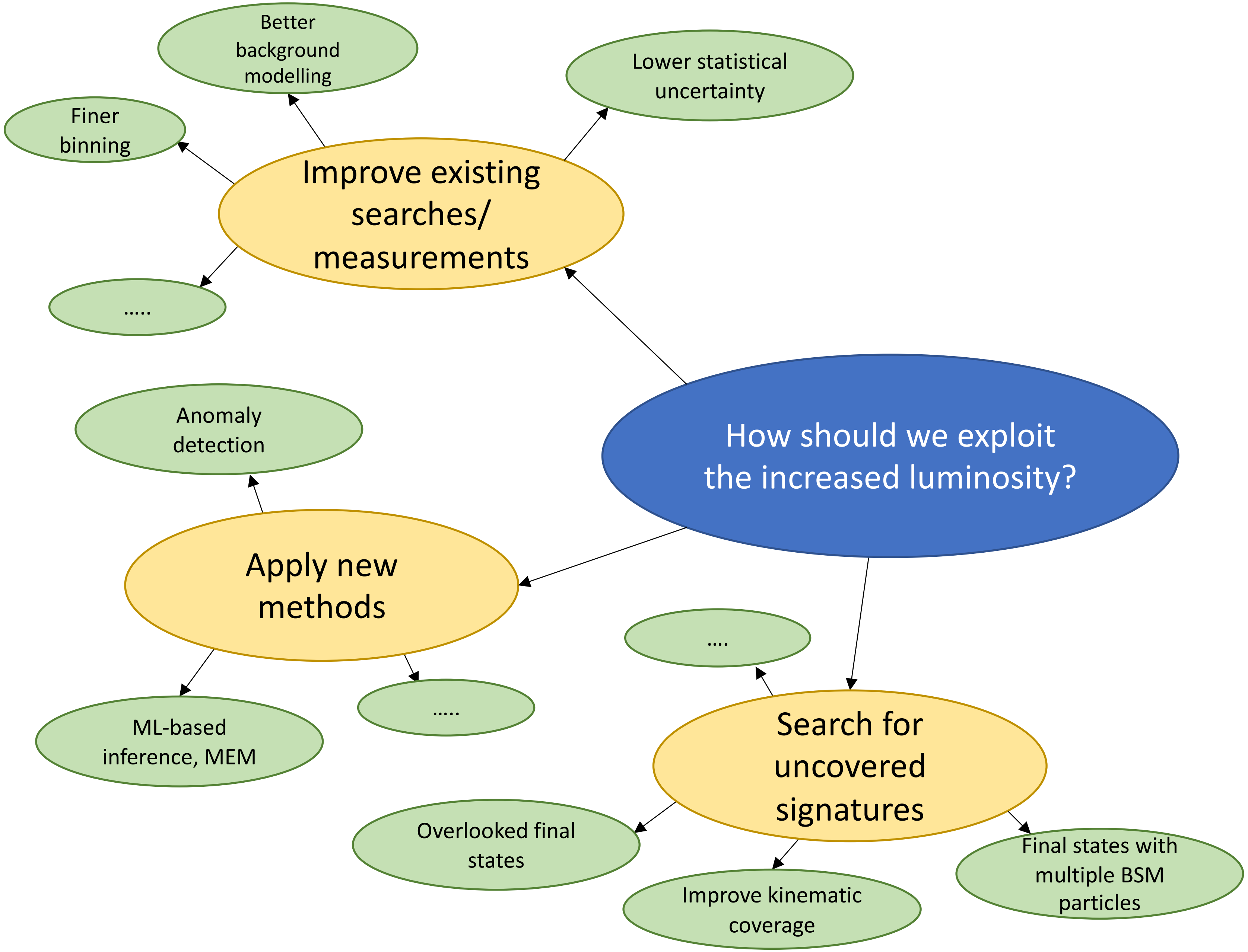
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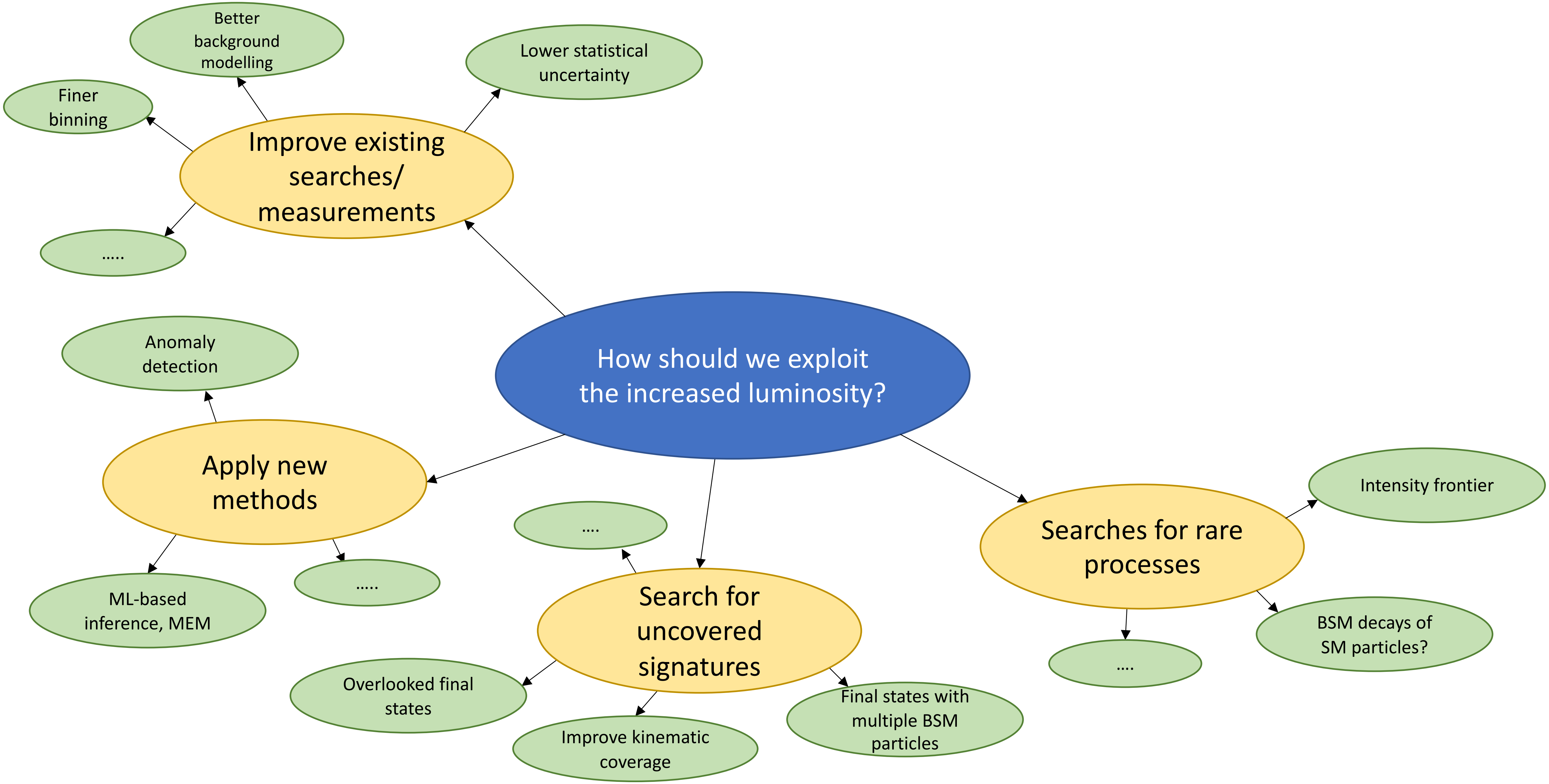
Final states with multiple BSM particles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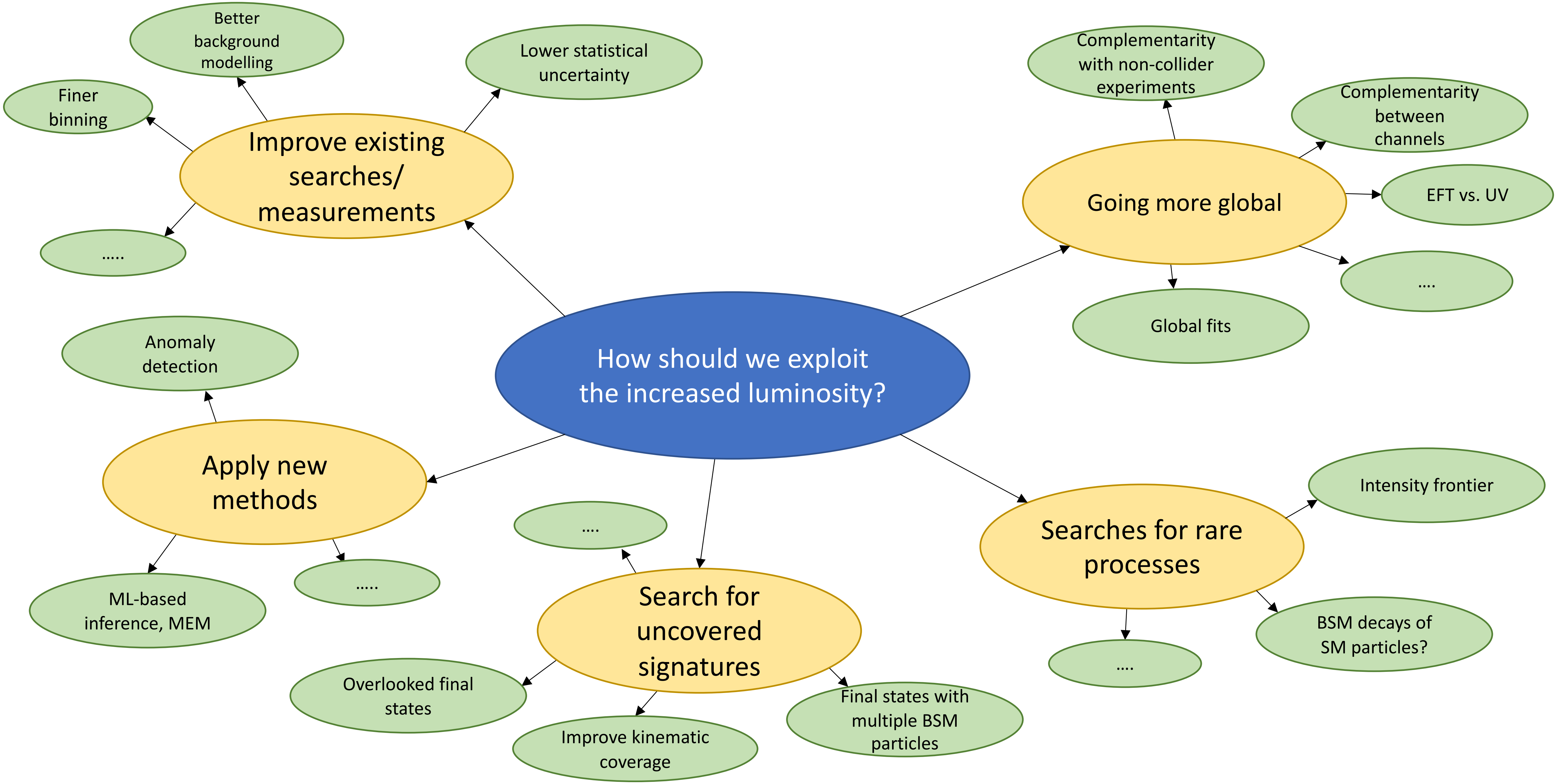
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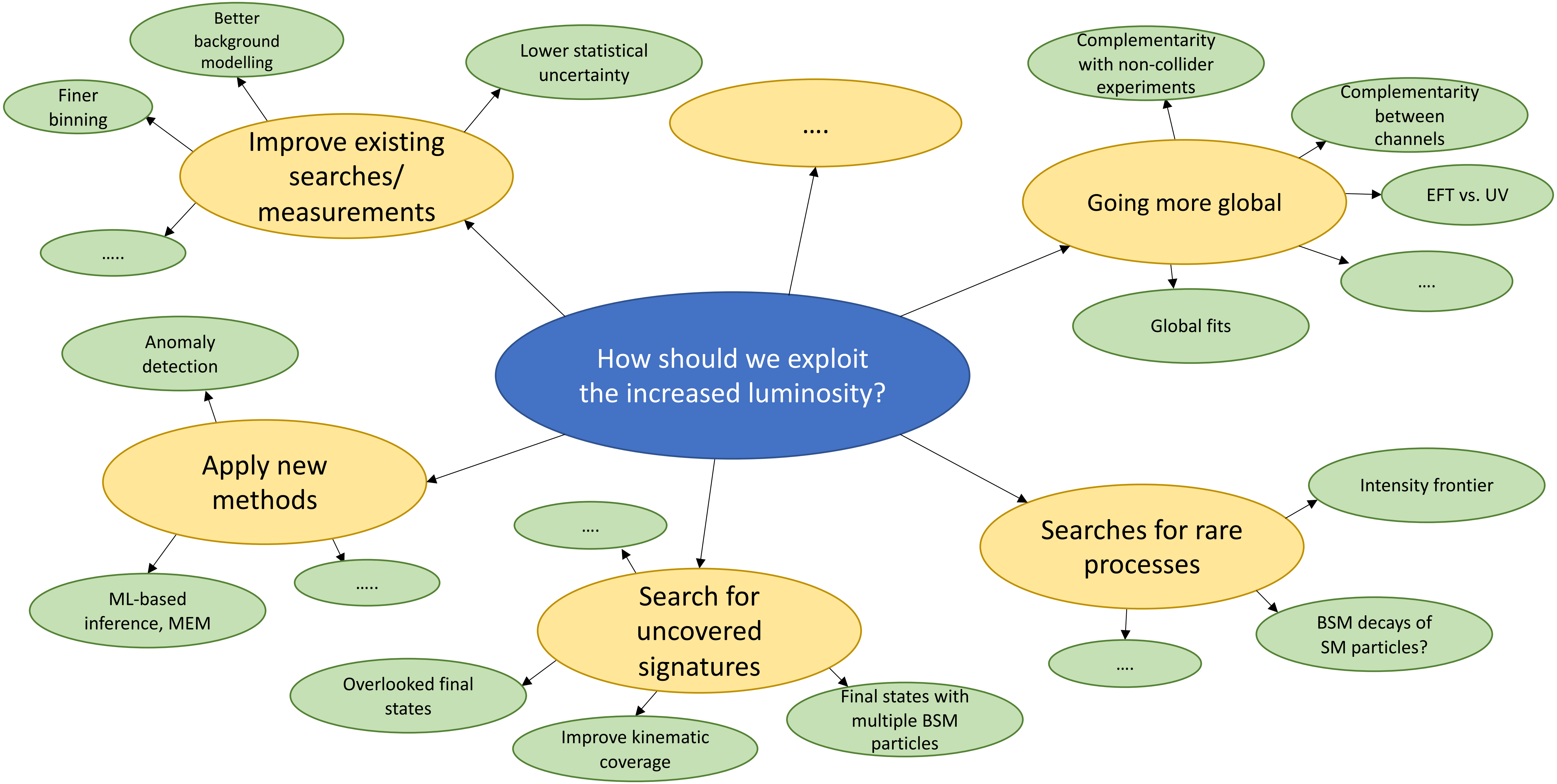
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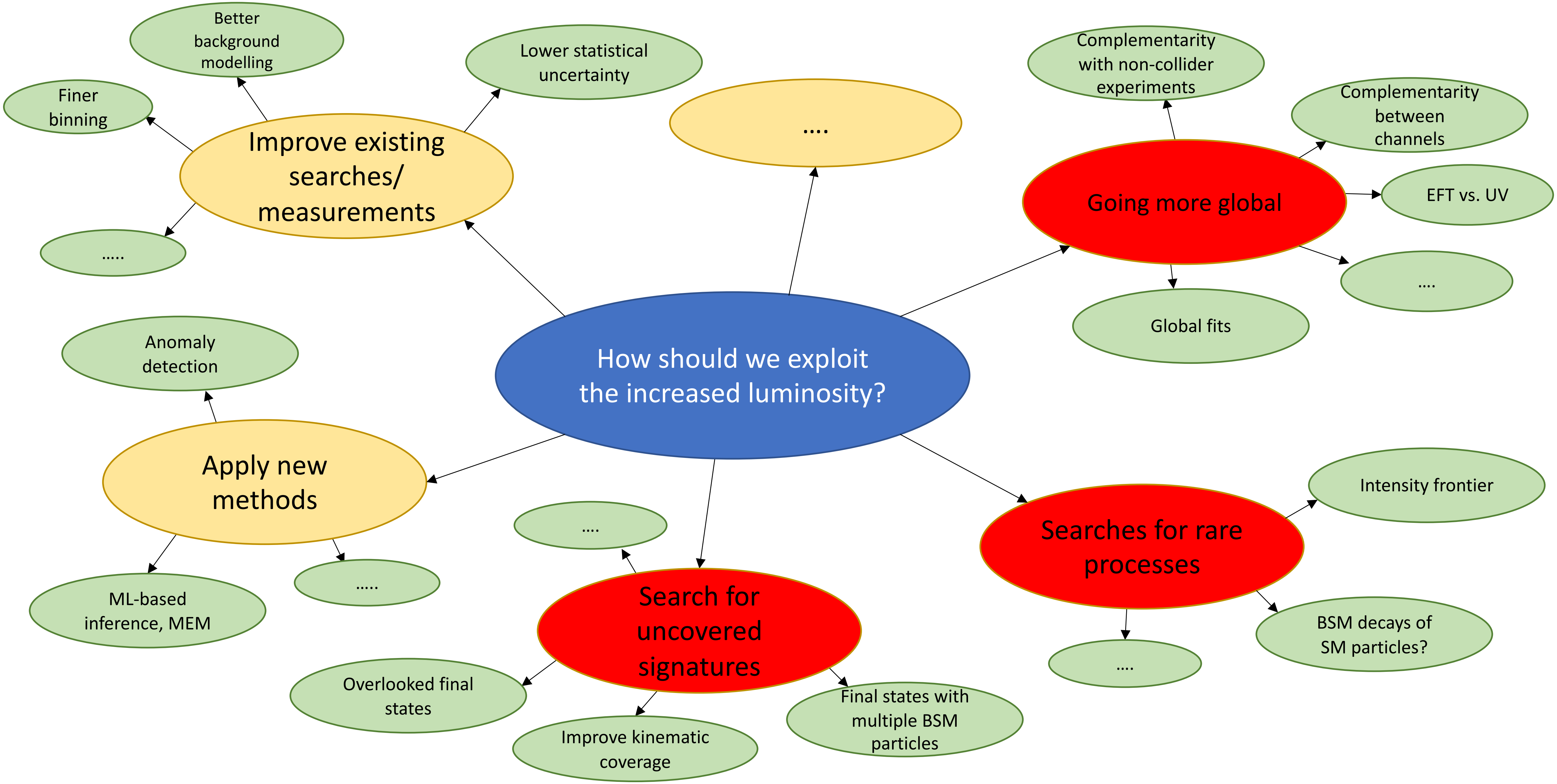
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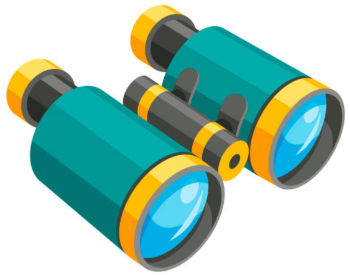

Unexplored BSM signatures

What have we missed so far?

Uncovered BSM signatures

Uncovered BSM signatures

- Many examples of well-motivated BSM signatures which evade current searches.

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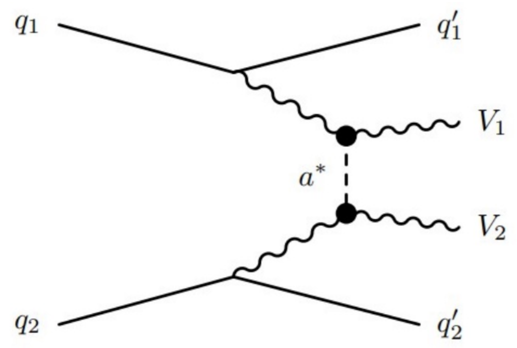
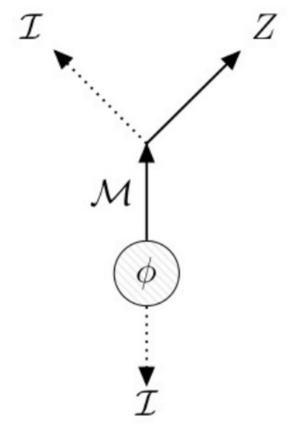
- Examples:
  - Axion-like particle (ALP) with large couplings to vector bosons. [Bonilla et al. 2202.03450]
  - Dark matter searches with a balanced $E_{T,\text{miss}}$ distribution. [Adan, HB et al. 2112.12656,2302.04892]
  - Electroweakino searches with soft photon + hard jet + $E_{T,\text{miss}}$. [Baum et al. 2303.01523]
  - …

See Victor M. Lozano's talk on Monday





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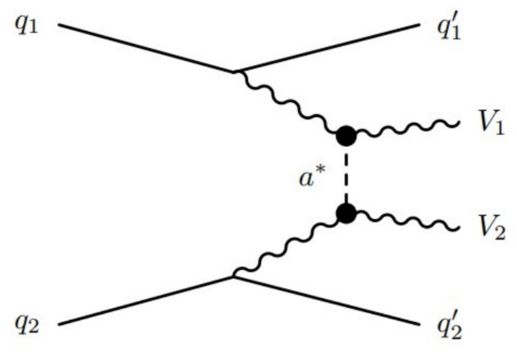
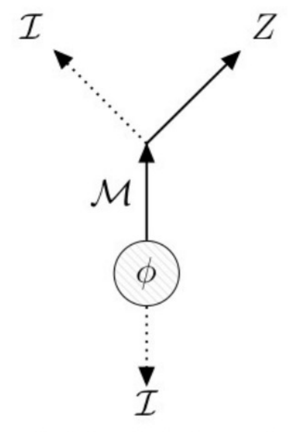




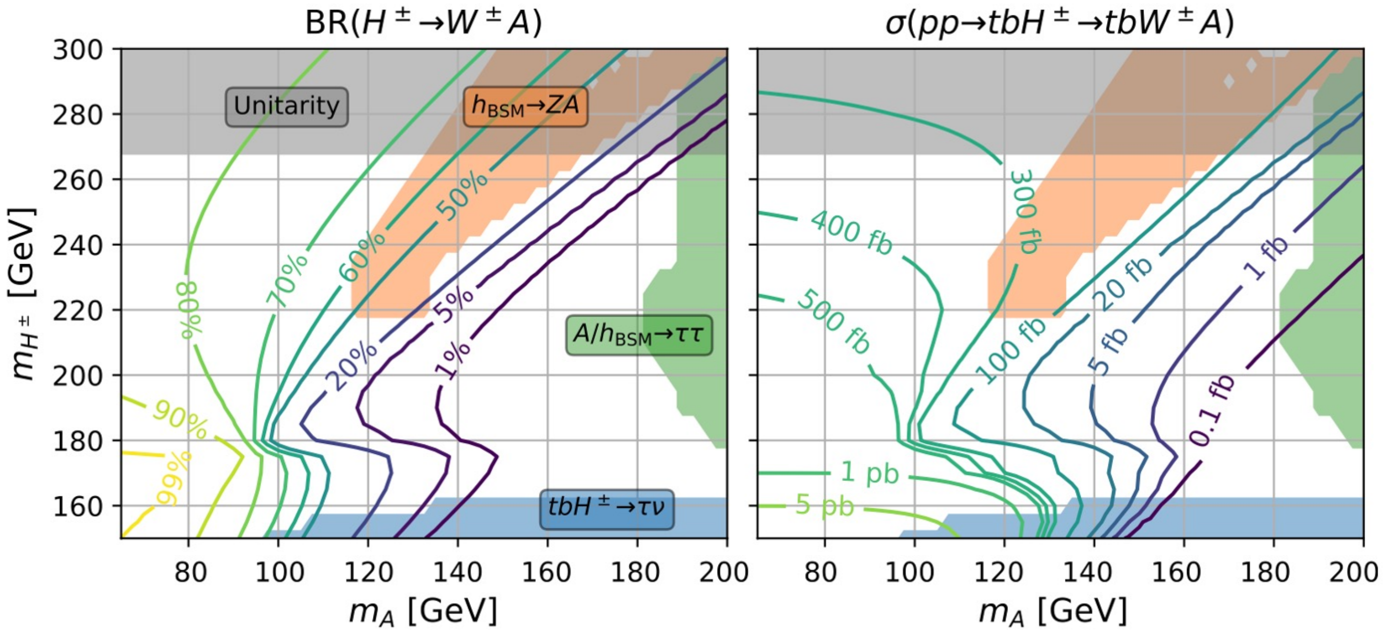
→ Discuss one further example here: bosonic charged Higgs boson decays.

Unexplored signatures — bosonic $H^{\pm}$ boson decays

[HB, Wittbrodt, Stefaniak, 2103.07484]

2HDM: CP-even h, H, CP-odd A, and charged $H^{\pm}$ boson
Exemplary benchmark plane for $H^{\pm} \to W^{\pm}A$ decays:

$\sin(\beta - \alpha) = 1,$
$\tan\beta = 3,$
$m_{h_{BSM}} = m_{H^{\pm}}$



- Large BR($H^{\pm} \to W^{\pm}A, W^{\pm}H$) expected if decay kinematically allowed.
- Also large production XS $\Rightarrow \mathcal{O}(1)$ pb signal rates possible.

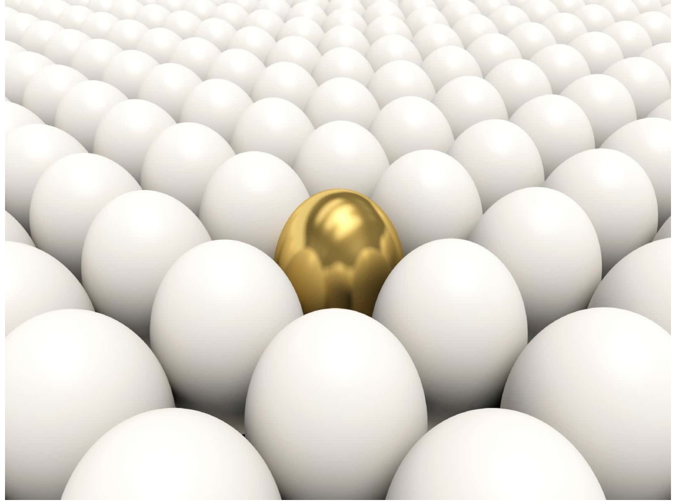
But so far no comprehensive searches. (existing searches limited to specific mass configurations)

Other scenarios and signatures

- Various scenarios with distinct phenomenology can be constructed:
  - $H^\pm \to W^\pm h_{\text{BSM}}$ or $H^\pm \to W^\pm A$ dominant,
  - light h_{BSM} ($m_{h_{\text{BSM}}} < m_{h_{125}}$),
  - leptophilic h_{BSM},
  - fermiophobic h_{BSM},
  - …
- Different production mechanisms can be investigated.
- Lot of activities on the pheno side.
  […, Krab et al. 2210.09416, Bhatia et al. 2212.14363, Kim et al. 2302.05457, Mondal et al. 2304.07719, Fu & Gao, 2304.07782, Moretti & Song 2304.12627, Sanyal & Wang 2305.00659, Li et al. 2305.05788]

Production process	Higgs decay processes	Final state particles
$pp \to H^\pm tb$	$H^\pm \to W^\pm\phi$ and $\phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$tbW^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm\phi$	$H^\pm \to W^\pm\phi$ and $\phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix} \otimes \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$
$pp \to H^\pm W^\mp$	$H^\pm \to W^\pm\phi$ and $\phi \to \begin{cases} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{cases}$	$W^\pm W^\mp + \begin{bmatrix} bb \\ \tau\tau \\ WW \\ ZZ \\ \gamma\gamma \end{bmatrix}$

→ Rich phenomenology waiting to be explored experimentally!



Search for rare processes

BSM decays of SM particles

Search for rare processes — top-quark decays

Top quarks are produced in large numbers at the LHC:

- $\sigma_{t\bar{t}}^{13.6\ \mathrm{TeV}} \simeq$ 900 pb
- $\rightarrow \sim 5 \cdot 10^8$ top quarks at the end of Run-3
- $\rightarrow \sim 5 \cdot 10^9$ top quarks at the end of HL-LHC

⇒ Unique opportunity to search FCNC via rare top-quark decays induced by BSM physics!

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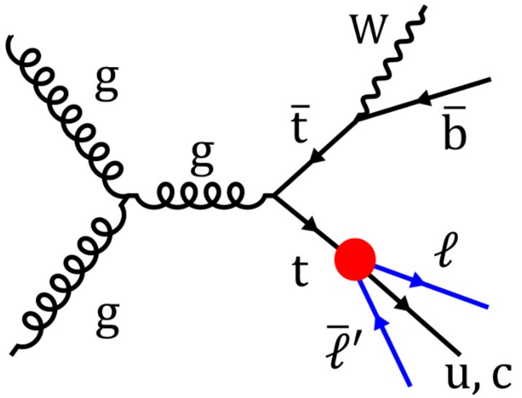

[CMS 2201.07859]

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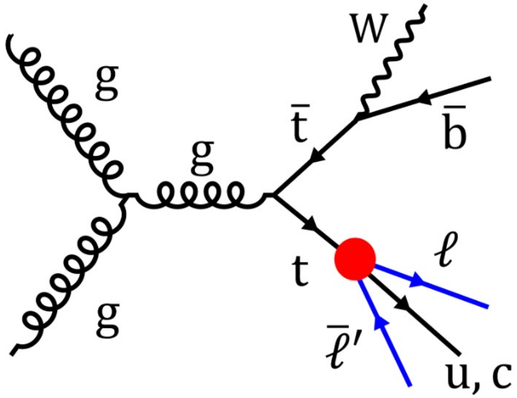
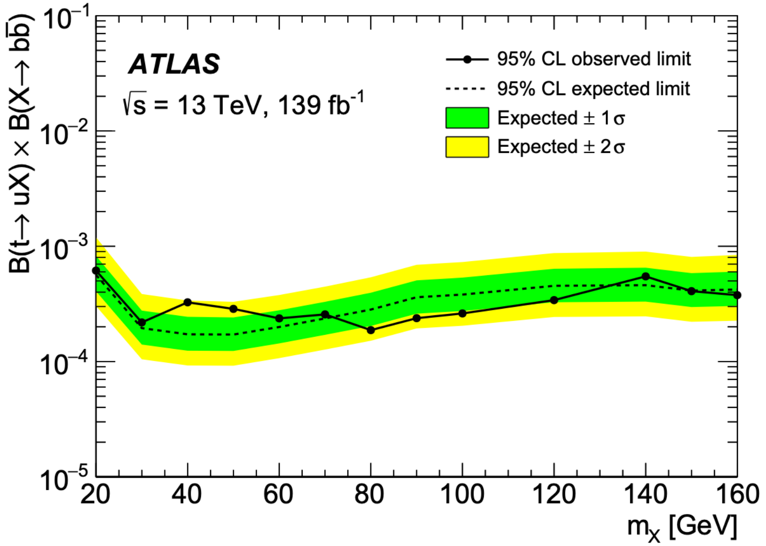


[CMS 2201.07859]

Existing experimental searches:

- SM final states: $t \to Hq, Zq, \gamma q, \ell^+\ell^- q$
- BSM final states: $t \to X(\to b\bar{b})q$ with X being a scalar



[ATLAS 2301.03902]

Rare top decays — EFT classification

- Rare top-quark decays with SM final state can be parameterized using SMEFT (see e.g. [Bradshaw & Chang 2304.06063]).

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,n} \frac{c_n}{\Lambda^i} \mathcal{O}_i^n$$

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SMEFT

Dim 6
$(\bar{Q}_i u_j)\,(\bar{Q}_k d_\ell)$
$(\bar{Q}_i u_j)\,(\bar{L}_k e_\ell)$
$(\Phi^\dagger \Phi)(\bar{Q}_i u_j \tilde{\Phi})$
$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}_i^\dagger \gamma^\mu Q_j)$
$(\bar{Q}_i \sigma^{\mu\nu} \tau^A u_j)\widetilde{\Phi} G^A_{\mu\nu}$
$(\bar{Q}_i \sigma^{\mu\nu} \tau^I u_j)\widetilde{\Phi} W^I_{\mu\nu}$
$(\bar{Q}_i \sigma^{\mu\nu} u_j)\widetilde{\Phi} B_{\mu\nu}$

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- Additionally, consider the possibility of light BSM particles:
  - scalar singlet S (e.g. ALP),
  - fermionic singlet N (e.g. sterile neutrino),
  - light gauge boson Z' (e.g. from gauging $B_3 - L_3$),
  - not discussed here: light charged Higgs boson.

⇒ New operators and final states.

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$(\bar{Q}_i \sigma^{\mu\nu} u_j)\widetilde{\Phi} B_{\mu\nu}$

BSM EFT

Dim 5
$S(\bar{Q}_i \not{D} Q_j)$
$S(\Phi^\dagger \bar{Q}_i u_j)$
Dim 6
$(\bar{Q}_i d_j)\,(\bar{L}_k N_\ell)$
$(\bar{Q}_i Q_j)\,(\bar{N}_k N_\ell)$
$S^2(\bar{Q}_i \not{D} Q_j)$
$S^2(\Phi^\dagger \bar{Q}_i u_j)$
$(\bar{Q}_i \sigma^{\mu\nu} u_j)\widetilde{\Phi} F'_{\mu\nu}$

Rare top-quark decays — expect BRs

[HB, Koren, Wang, work in progress]

- Investigate operators individually.
- Set $\Lambda = 1$ TeV, $c_i^n = 1$, and $m_S = m_N = m_{Z'} = 10$ GeV as a benchmark.
- Calculate branching ratio for different final states.

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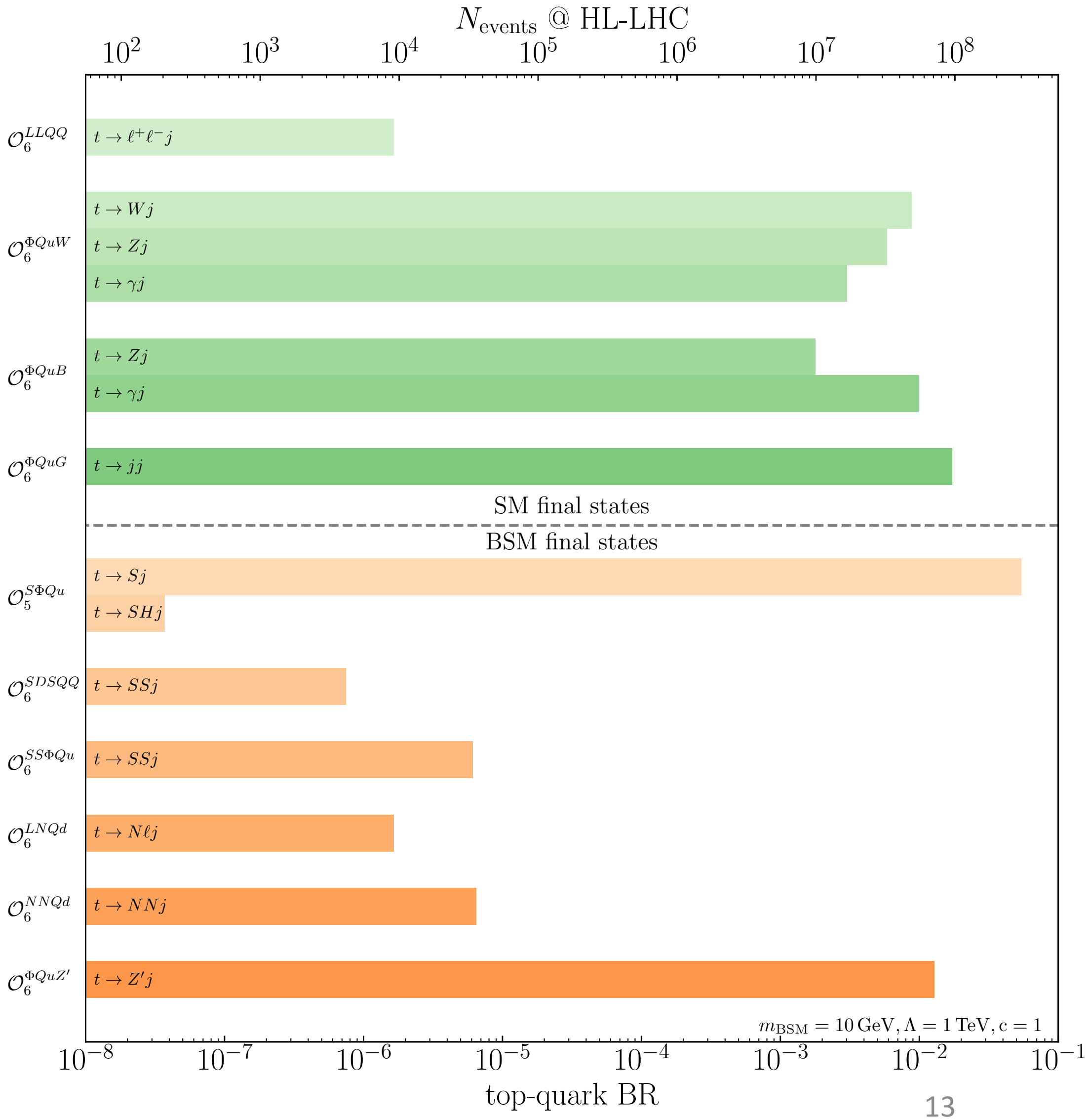

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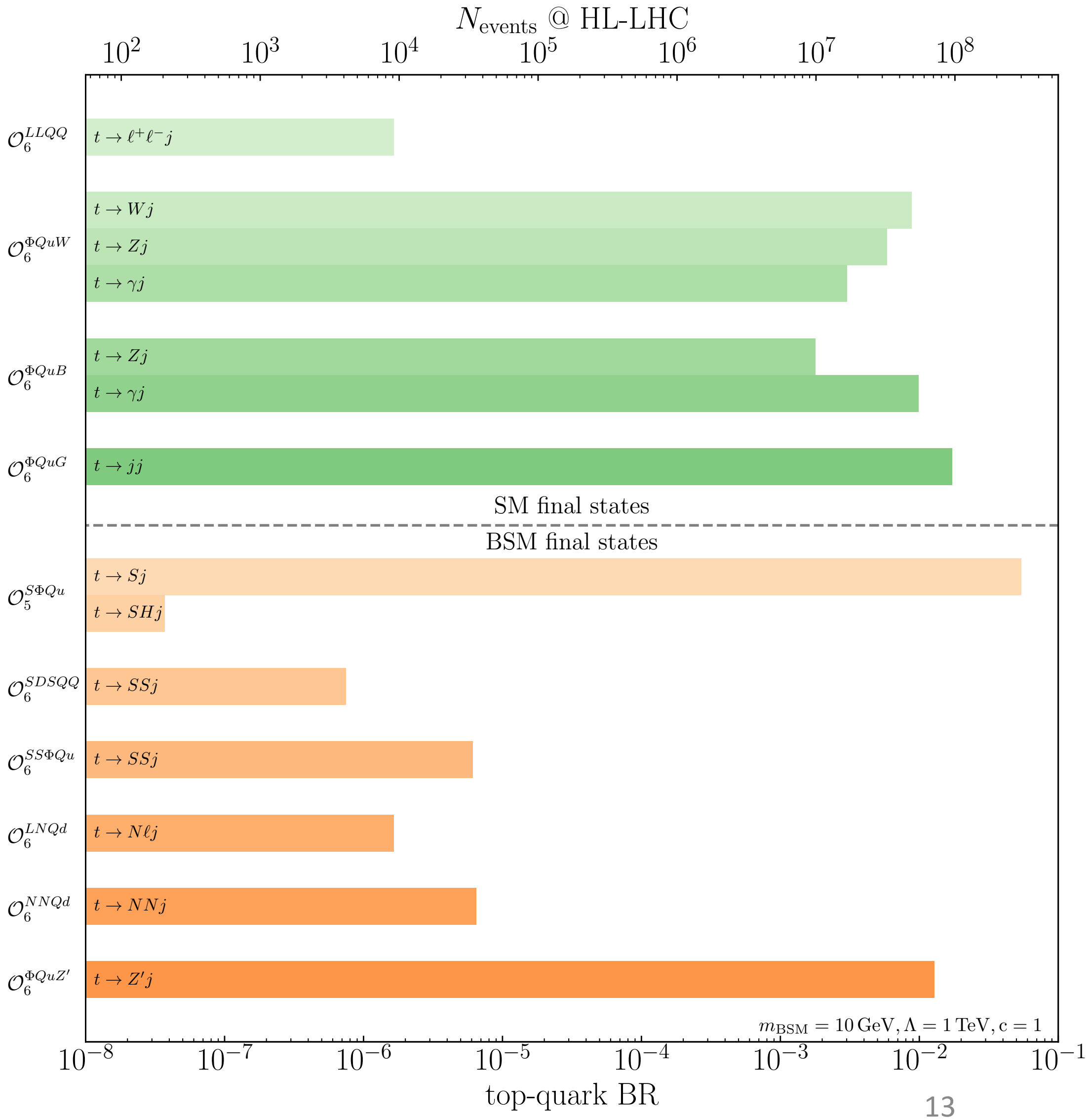

- Sizeable branching ratios/number of events for various operators.
- Various final states which can be probed with current and future data.

⇒ Huge potential for future searches!

Rare top-quark decays II

- Decays of BSM particles can be parameterized by adding additional operators (not involving the top-quark):
  - e.g. $S \to b\bar{b}, \tau^+\tau^-, \gamma\gamma$ etc.
    (see e.g. [Banerjee et al. 1806.02836, Bhattacharyya et al. 2212.09061]),
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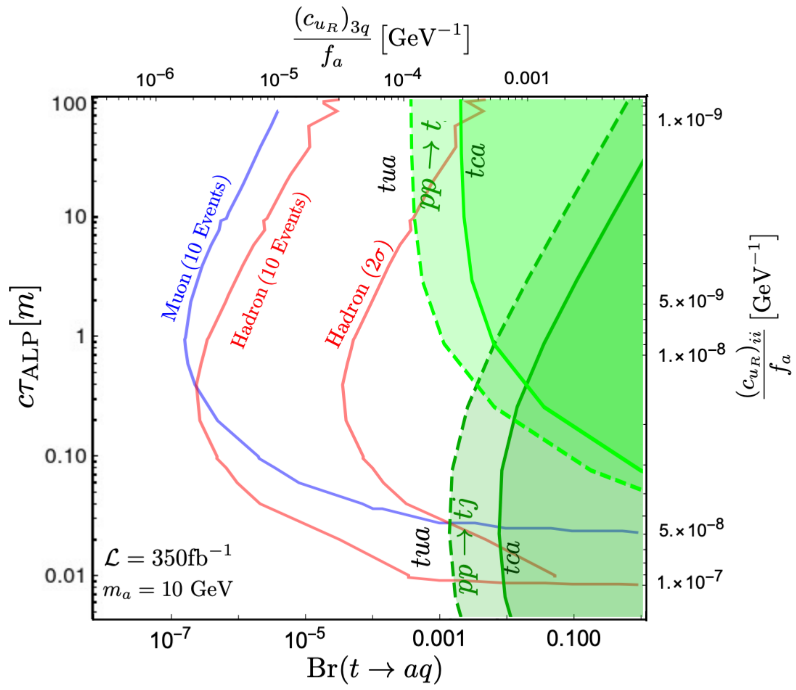

[Carmona et al. 2202.09371]

Rare top-quark decays II

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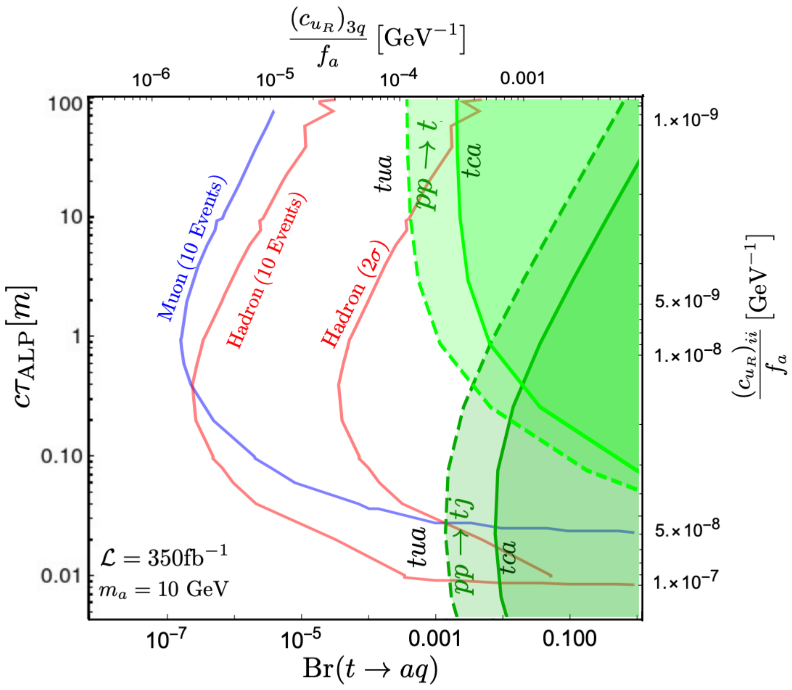

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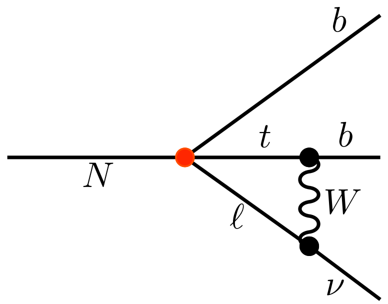

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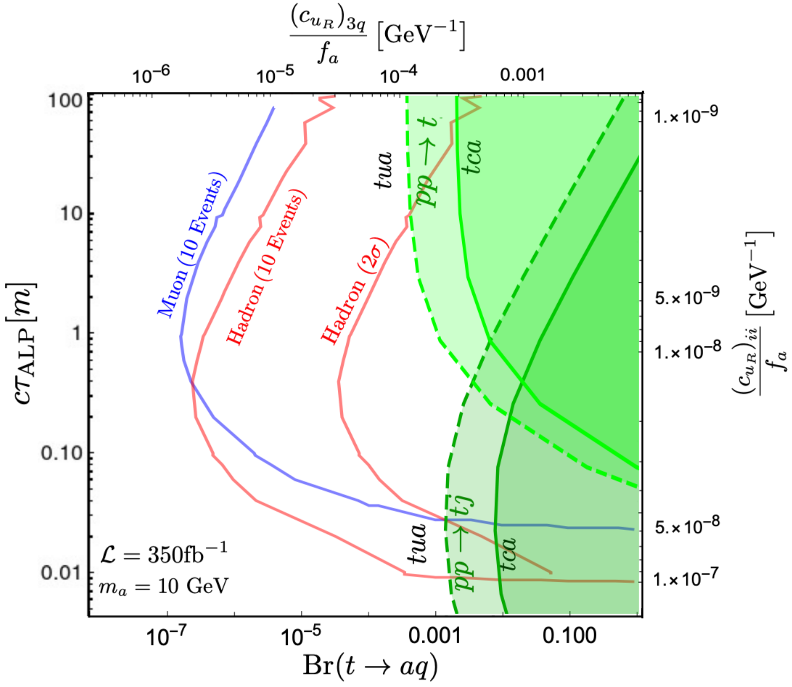

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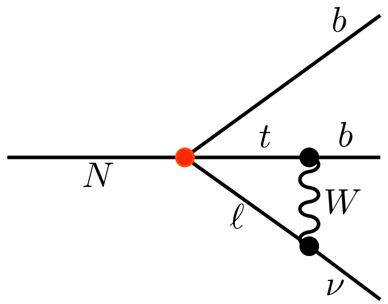
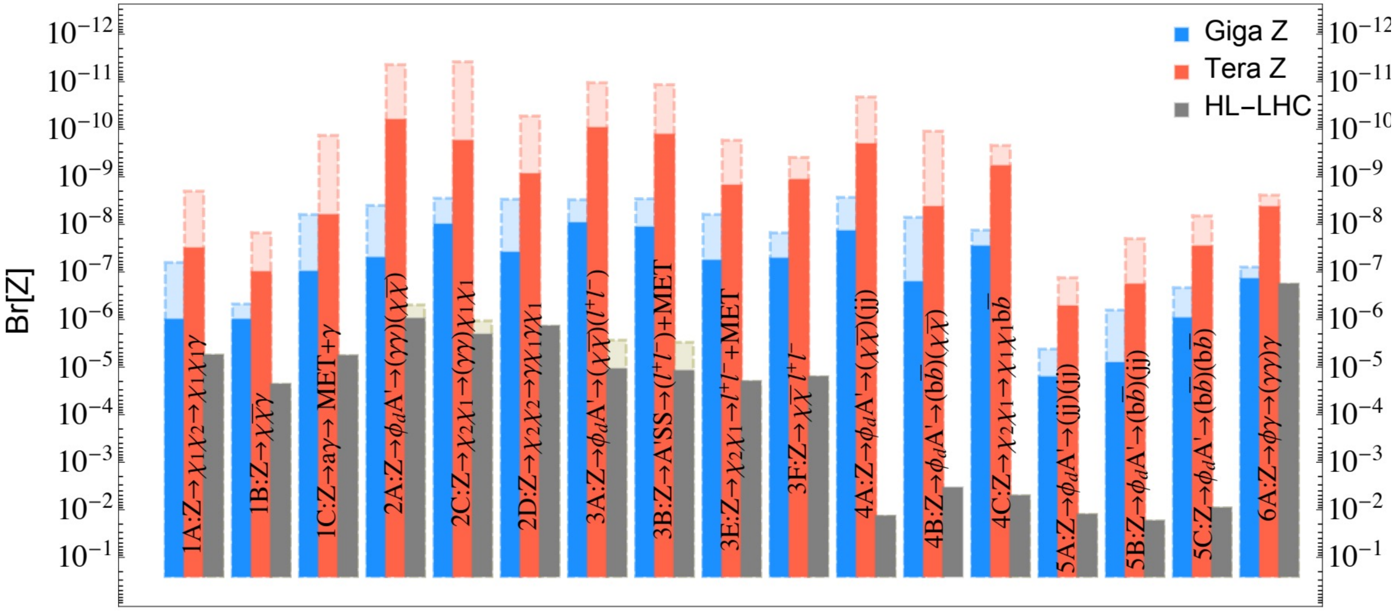


➡ Many interesting signatures for prompt and long-lived searches.

Other searches for rare BSM decays

Also other SM particles could have rare BSM decays:

- rare Higgs boson decays (→ see Maxwell Chertok's on Friday),
- rare Z boson decays,
- …



[Liu et al., 1712.07237]

Going global

Exploiting different LHC channels and non-collider measurements

Complementarity with non-collider experiments — electroweak phase transitions

- Shape of the Higgs potential largely unconstrained.
- Zero-temperature potential can be probed e.g. via di-Higgs boson production.
- How can be probe the thermal development of the Higgs potential?

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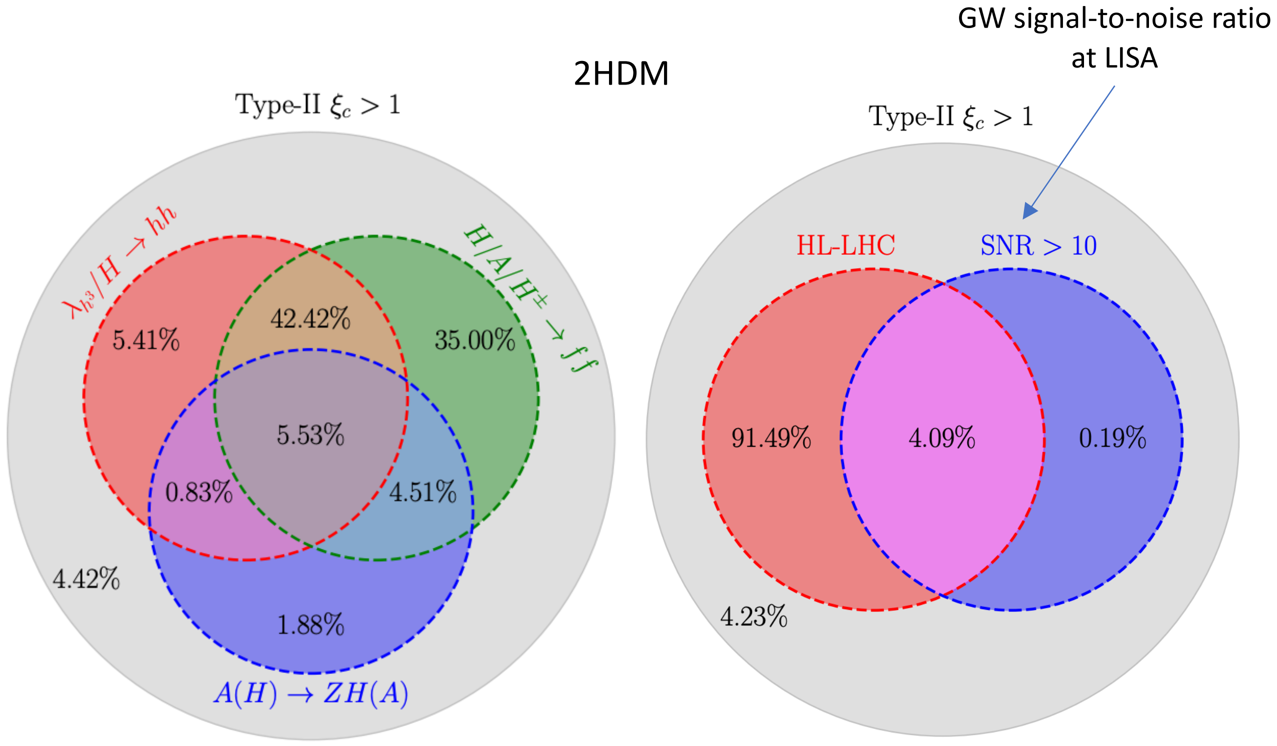

[Goncalves et al. 2108.05356; see also Biekötter et al. 2208.14466, …]

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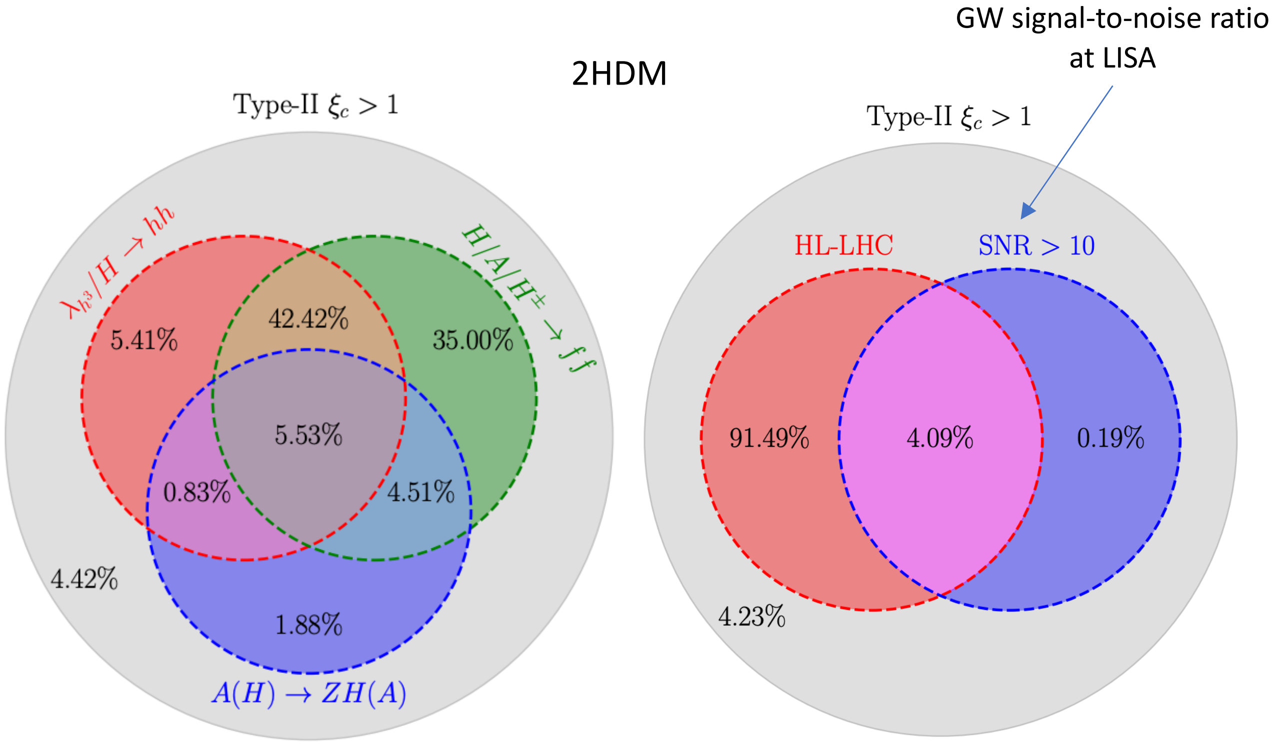

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➡ Exploit complementarity between different LHC channels + GW observatories.

Complementarity with non-collider experiments — Higgs CP

[HB et al. 2202.11753; see also Brod et al. 2203.03736, Fuchs et al. 2003.00099, …]

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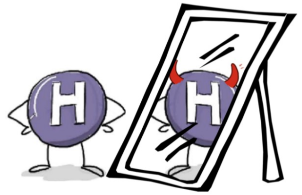

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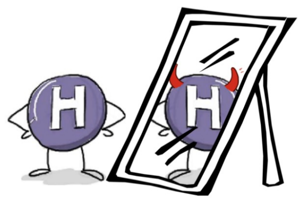

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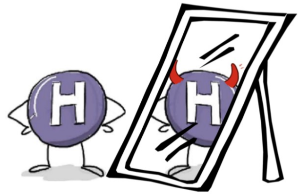

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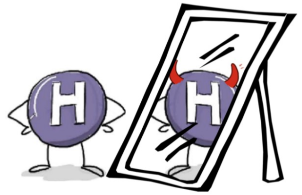

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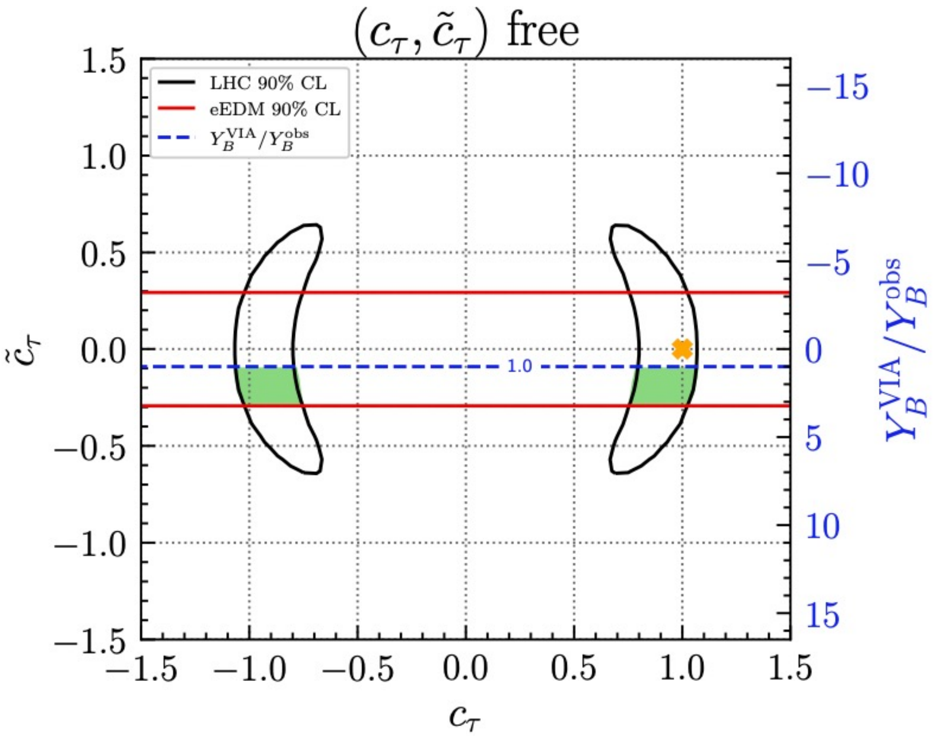

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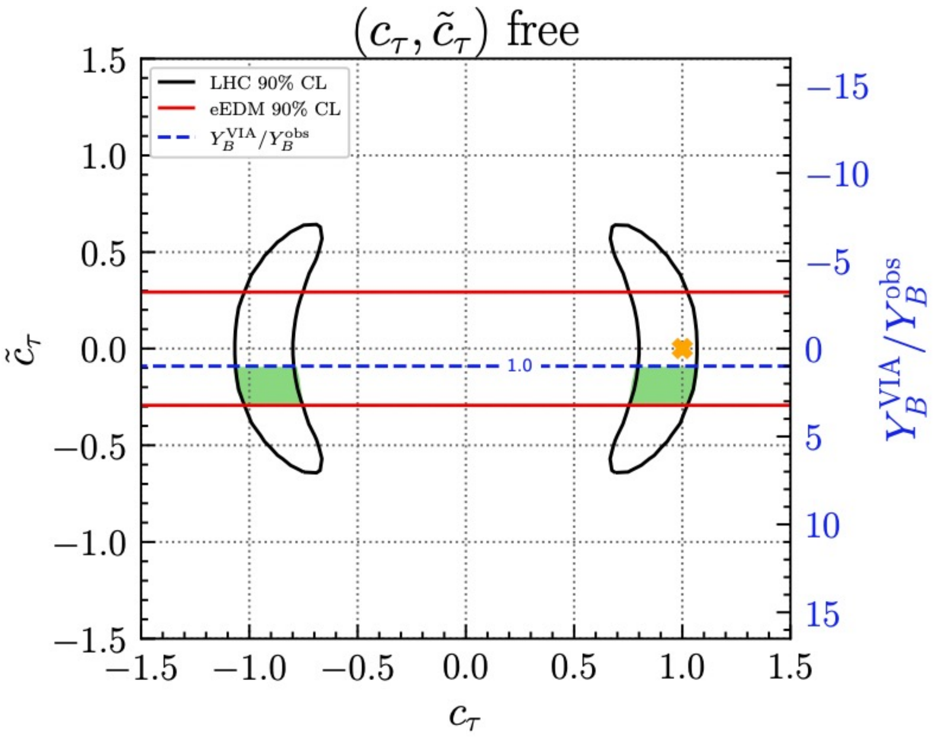

⇒ CP violation in tau-Yukawa coupling could give sizeable contribution to baryon asymmetry!

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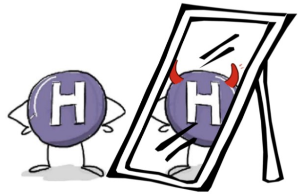

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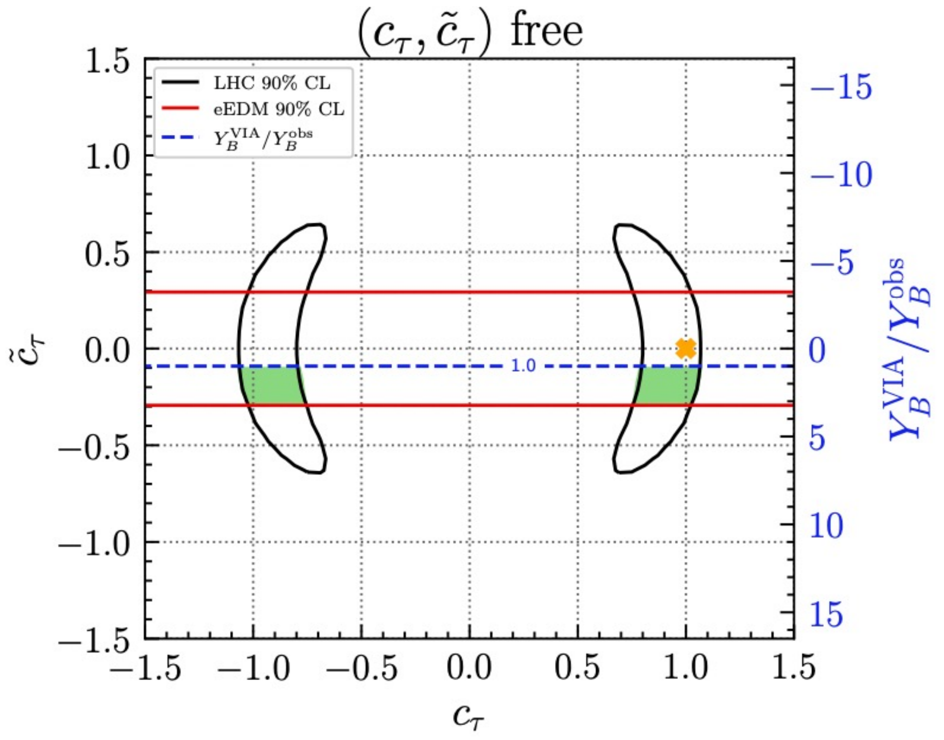

→ See talk by Marco Menen this afternoon for more details.
→ Dedicated LHC Higgs WG 2 effort.

Conclusions

BSM at Run-3 and beyond

Conclusions: objectives for Run-3 and beyond

Motivation to search for BSM physics is unbroken.

<u>How to go forward?</u>

- Improve upon existing searches/measurements using increased luminosities.
- Use new analysis methods to fully exploit data.
- Look out for uncovered signatures.
- Ensure reinterpretability of results.
- Going global: exploit complementarity between different channels and with non-collider measurements.

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Thanks for your attention!

Unexplored signatures — bosonic $H^{\pm}$ decays

- Charged Higgs bosons appear in many BSM extensions of the SM Higgs sector.
- Existing experimental searches:

Production process	Higgs decay	Final state	# of exp. searches
$pp \to H^{\pm}tb$	$H^{\pm} \to \tau\nu_\tau$	$tb(\tau\nu_\tau)$	7
$pp \to H^{\pm}tb$	$H^{\pm} \to tb$	$tbtb$	4
$pp \to tt, t \to H^{\pm}b$	$H^{\pm} \to cb$	$tbcb$	2
$pp \to tt, t \to H^{\pm}b$	$H^{\pm} \to cs$	$tbcs$	3
$pp \to H^{\pm}qq'$ (VBF)	$H^{\pm} \to W^{\pm}Z$	$W^{\pm}Zqq'$	4
$pp \to tt, t \to H^{\pm}b$	$H^{\pm} \to W^{\pm}A$	$tbW^{\pm}\mu^+\mu^-$	3
$pp \to tt, t \to H^{\pm}b$	$H^{\pm} \to W^{\pm}H$	$tbW^{\pm}\tau^+\tau^-$	1
$pp \to H \to H^{\pm}W^{\mp}$	$H^{\pm} \to W^{\pm}h$	$W^{\pm}W^{\mp}bb$	1

} Limits only for specific mass configurations

→ 16 searches in fermionic channels, 9 searches in boson channels (of which 4 only appear in triplet extension)

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$pp \to H \to H^{\pm}W^{\mp}$	$H^{\pm} \to W^{\pm}h$	$W^{\pm}W^{\mp}bb$	1

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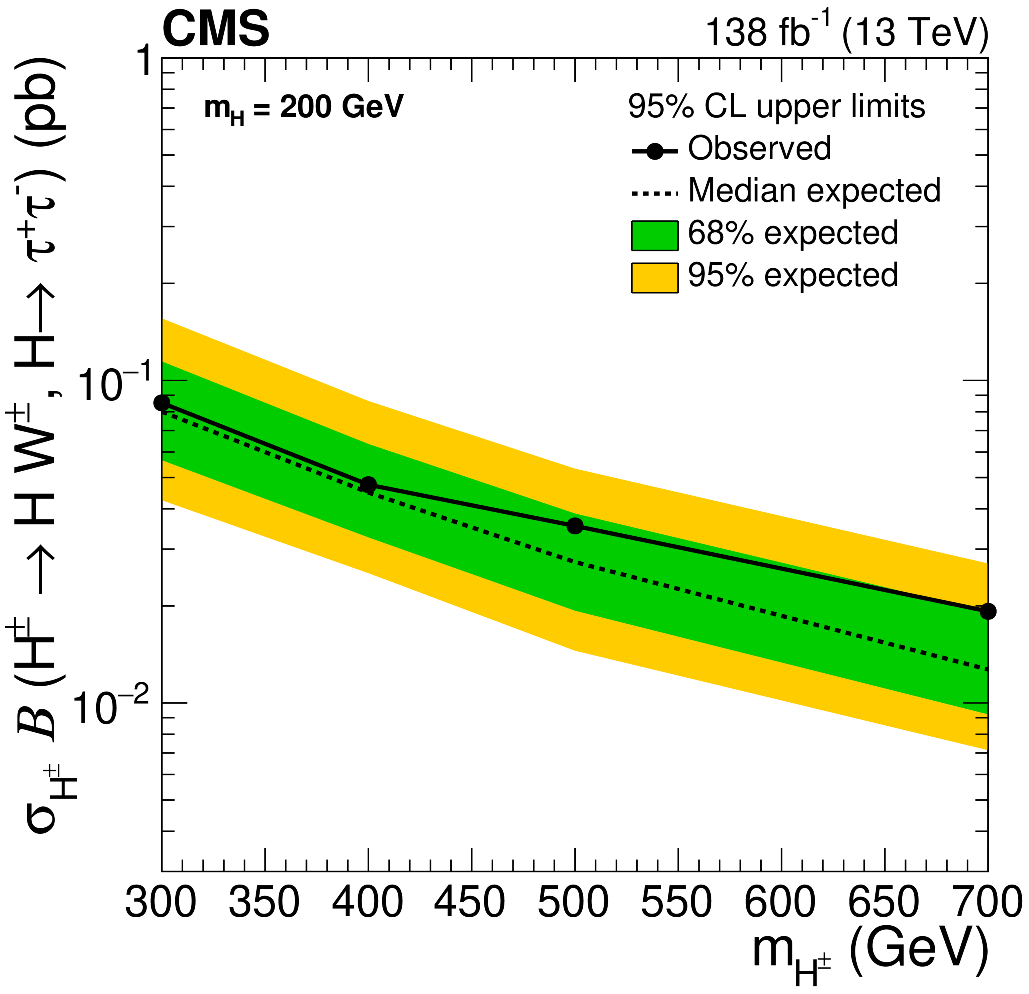
Are the bosonic channels theoretically less motivated?

CMS $H^{\pm} \to HW^{\pm}$ search ($m_H = 200$ GeV fixed) [CMS, 2207.01046]



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In the 2HDM, we have (with h_i being the CP-even Higgs bosons ordered by mass)

$$g(H^\pm W^\mp h_1) \propto \cos(\beta-\alpha)\,, \qquad g(H^\pm W^\mp h_2) \propto \sin(\beta-\alpha)\,, \qquad g(H^\pm W^\mp A) = -\frac{g}{2}$$

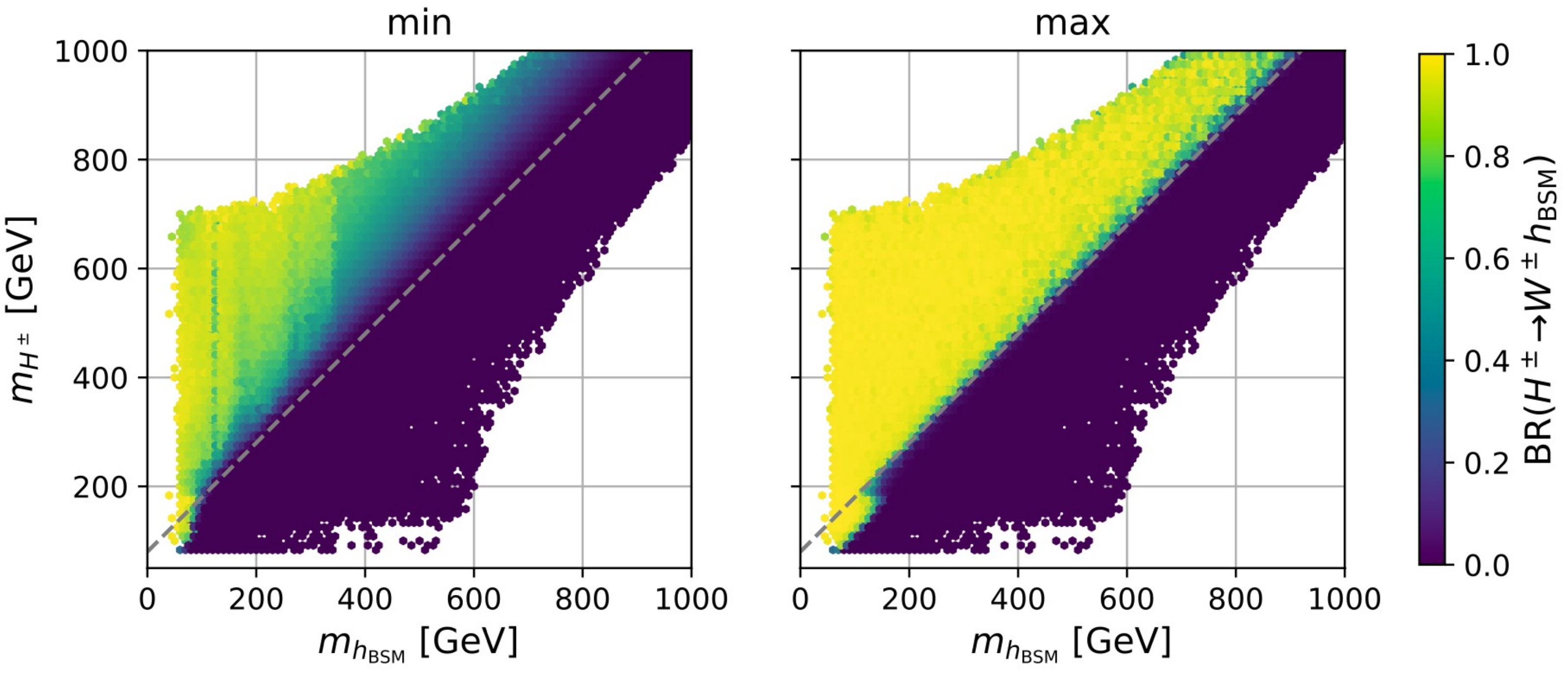
Alignment limit: h_1 SM-like $\Rightarrow \cos(\beta-\alpha) \to 0$; h_2 SM-like $\Rightarrow \sin(\beta-\alpha) \to 0$

Alignment limit strongly motivated by h_{125} measurements
$\Rightarrow$ Charged Higgs boson couplings to W boson and $h_{\rm BSM}$ or A boson close to maximum!

Unexplored signatures — bosonic $H^{\pm}$ boson decays

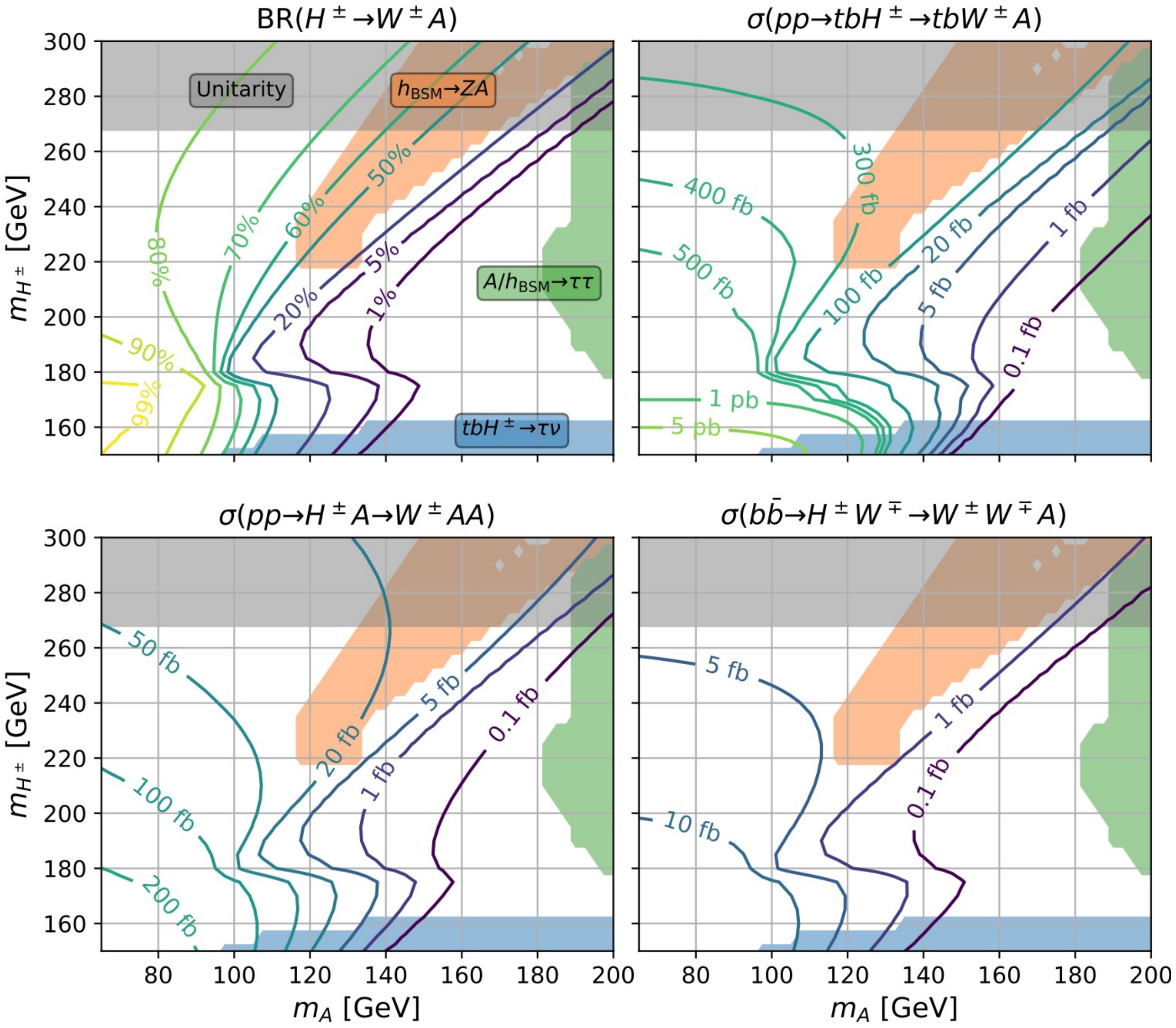
[HB, Wittbrodt, Stefaniak, 2103.07484]

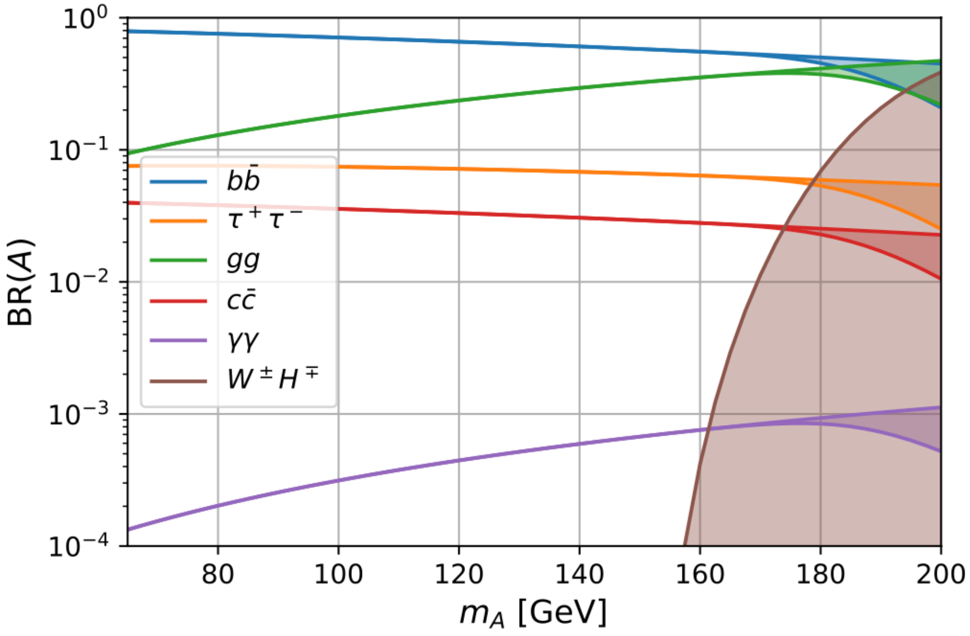
2HDM parameter scan applying theoretical and experimental constraints:



$\sin(\beta - \alpha) = 1,$
$\tan\beta = 3,$
$m_{h_{BSM}} = m_{H^\pm}$

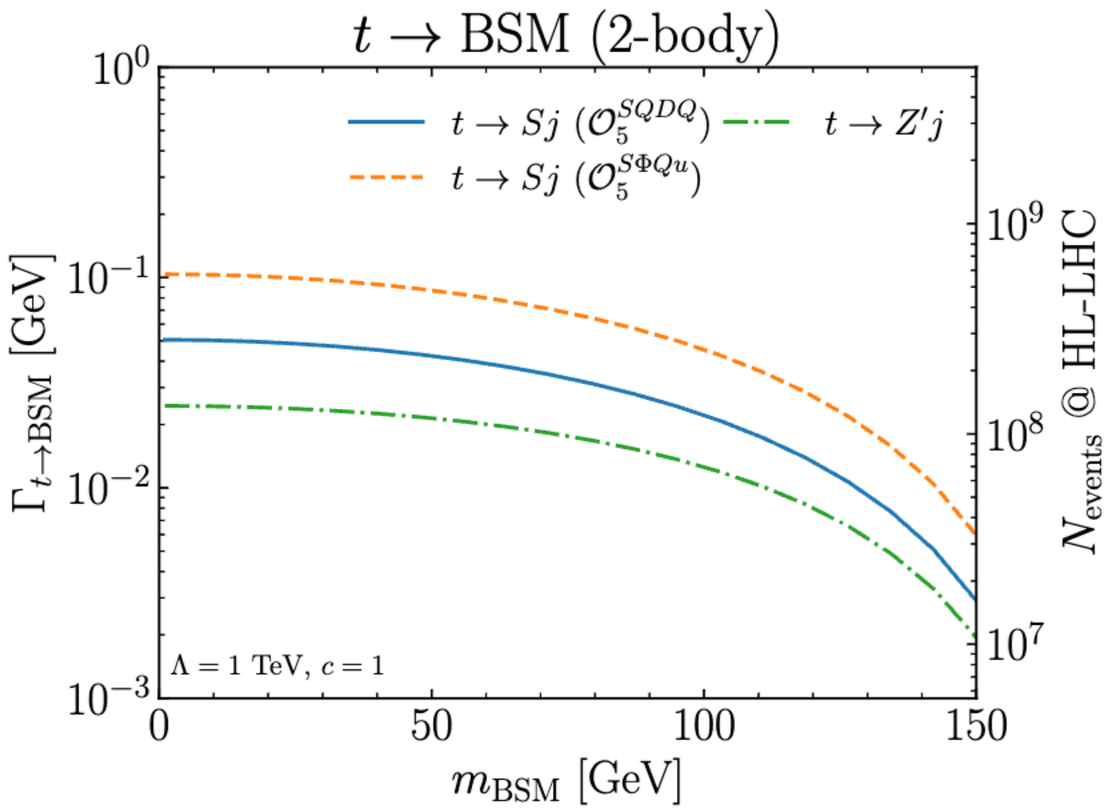
Example scenario with $H^\pm \to W^\pm A$

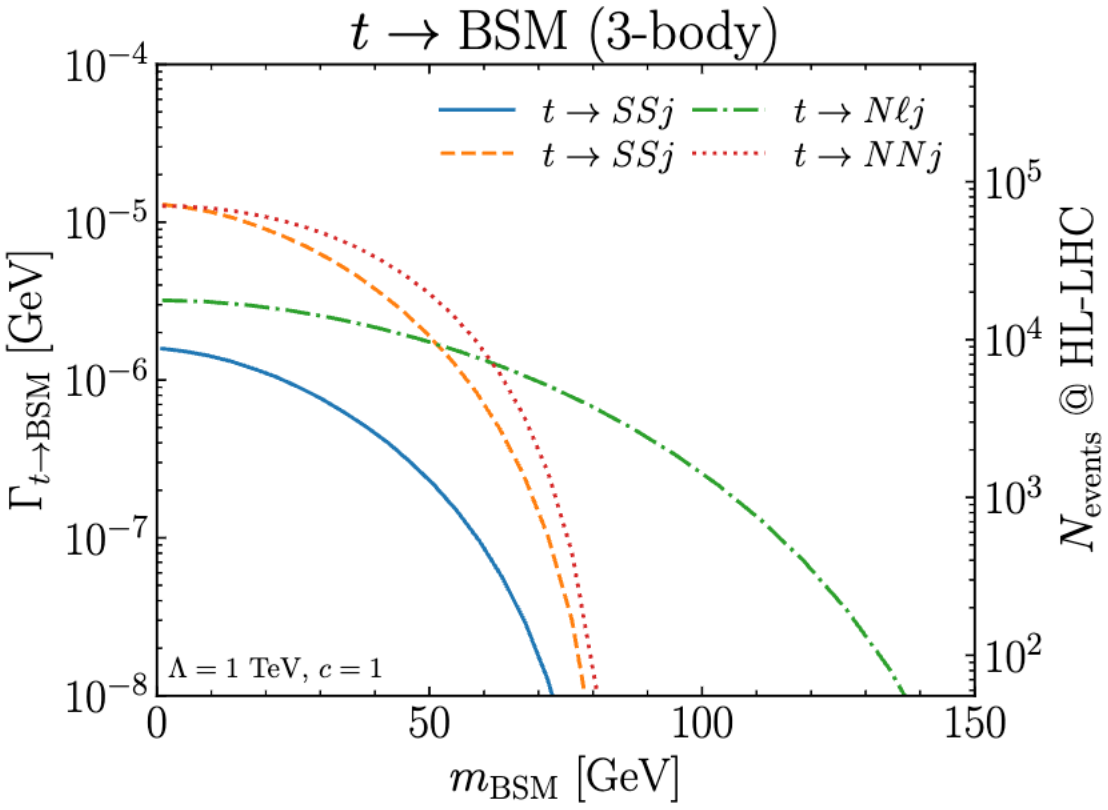




Large rates possible which are not constrained by existing searches!

Rare top decays — mass dependencies





S and Z' loop-induced decays