Testing BSM Physics at the HL-LHC

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(Some of the) Questions for the future of the LHC

HL-LHC program

1. Is the SM **Higgs** the full story for electroweak symmetry breaking?

2. Are there **new particles** not too far away from the electroweak scale?

3. Does **Dark Matter/dark sector** couple to the SM?

4. Is the SM **flavor sector** the right description for flavor transitions?

5. Is there some **heavy New Physics** that modifies the pheno of SM particles?

Disclaimer: these are the questions I discuss in this talk. Many more…

Is the SM Higgs the full story for electroweak symmetry breaking? 1.

Higgs precision program

Getting to know the Higgs better

Generically, we would not have expected to see O(1) deviations in Higgs couplings

(electro-weak measurements & direct BSM searches):

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 5\%$$

scale of new physics
$\Lambda \sim 1\,\text{TeV}$

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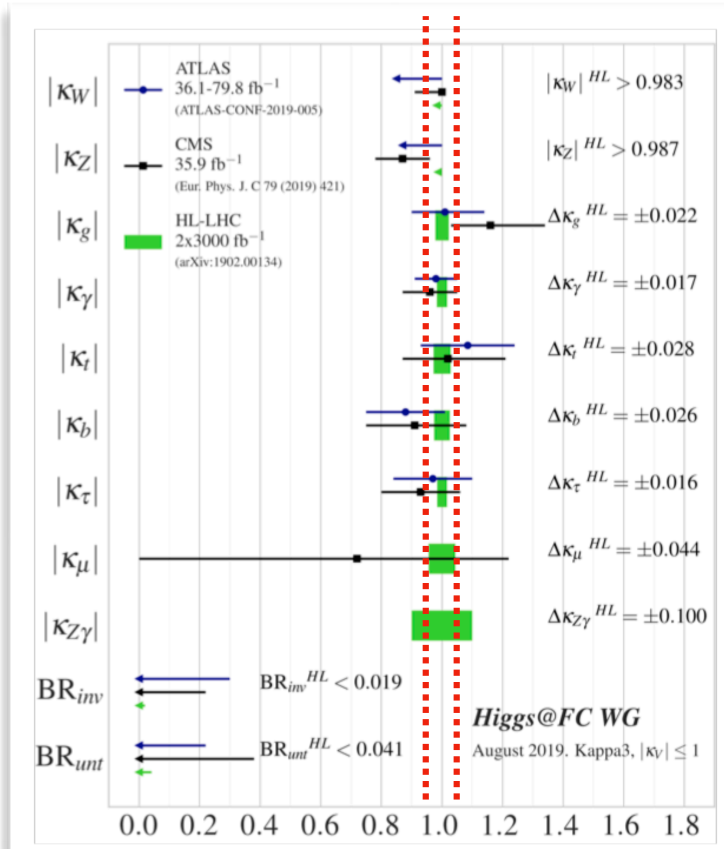
Towards a precision program:

Goal: ~few percent precision at the HL-LHC



Physics briefing book, European physics strategy, 1910.11775

This is crucial for (indirectly) testing the existence of new physics particles.

For example, new Higgs bosons mixing with the Higgs: $\kappa_V = \cos(\alpha - \beta)$

Is the SM **Higgs** the full story for electroweak symmetry breaking? 1.

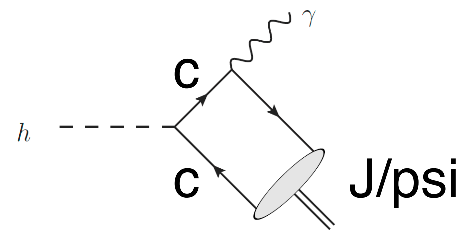
Higgs rare processes

We will get to know much more especially on

1. Rare Higgs events:

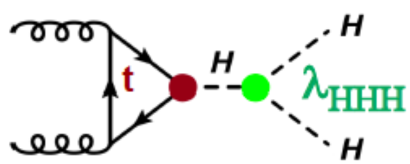
Particularly important examples:

* h→μ μ, h→J/psi γ, h→ Φ γ



Testing the flavor structure of the Higgs. Is the Higgs responsible of all masses? (including light flavors)

* pp → hh



Testing the shape of the Higgs potential and the nature of electroweak symmetry breaking

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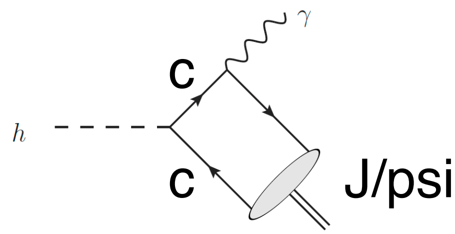
- $h \to \mu\,\mu$, $h \to J/psi\ \gamma$, $h \to \Phi\ \gamma$



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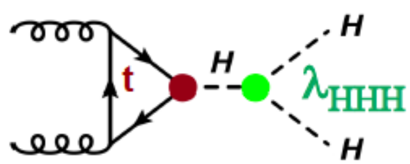


Testing the shape of the Higgs potential and the nature of electroweak symmetry breaking

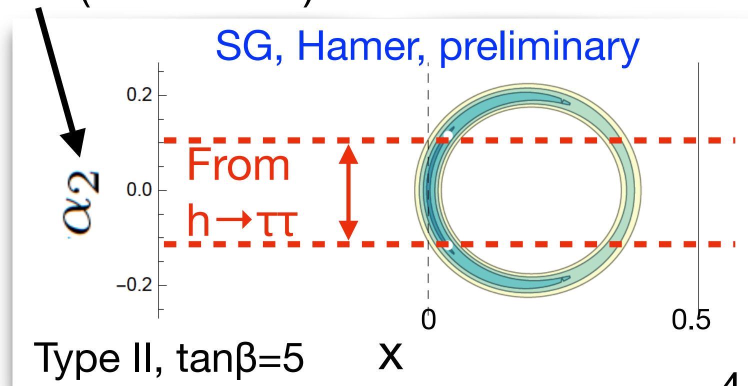
2. Higgs shape distributions

A particularly relevant example:

Study of angular distributions in $h \to ZZ^* \to 4l$, $h \to \tau\tau$.

Testing the CP odd component of the Higgs.
Is the Higgs a 100% CP even scalar?

Higgs CP-odd component (in a 2HDM)



Is the SM **Higgs** the full story for electroweak symmetry breaking? 1.

Higgs exotic decays

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.
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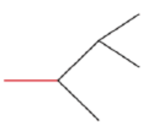
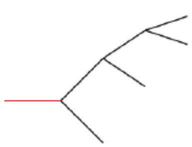
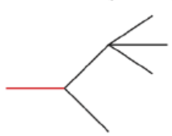

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
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$h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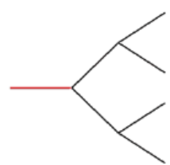
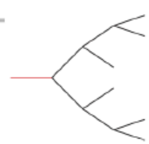
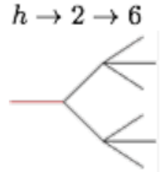

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$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
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From Z. Liu

Run II focused on "non MET" (prompt) signatures

Specific low energy triggers are needed!

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

CMS 1805.04865

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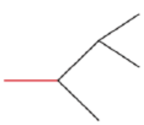
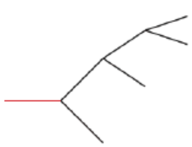
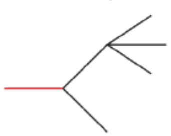

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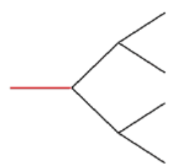
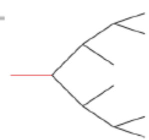
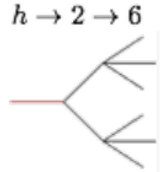

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What about
- **signatures with MET (semi-visible signatures)?**
- **displaced signatures?**

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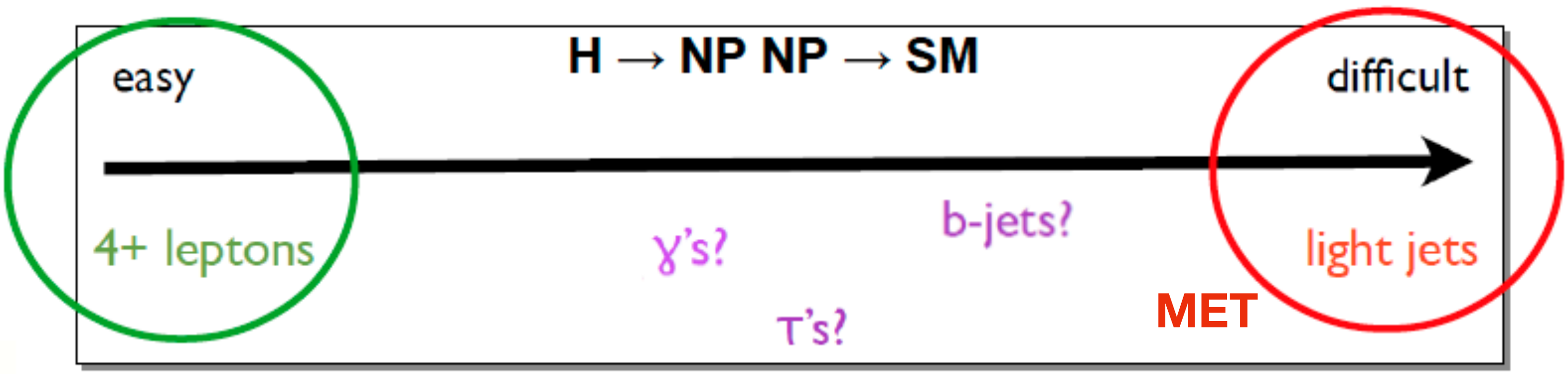
Impact of the High-Luminosity LHC:



More and more statistics

Access to sub-leading production modes (ex. tth)

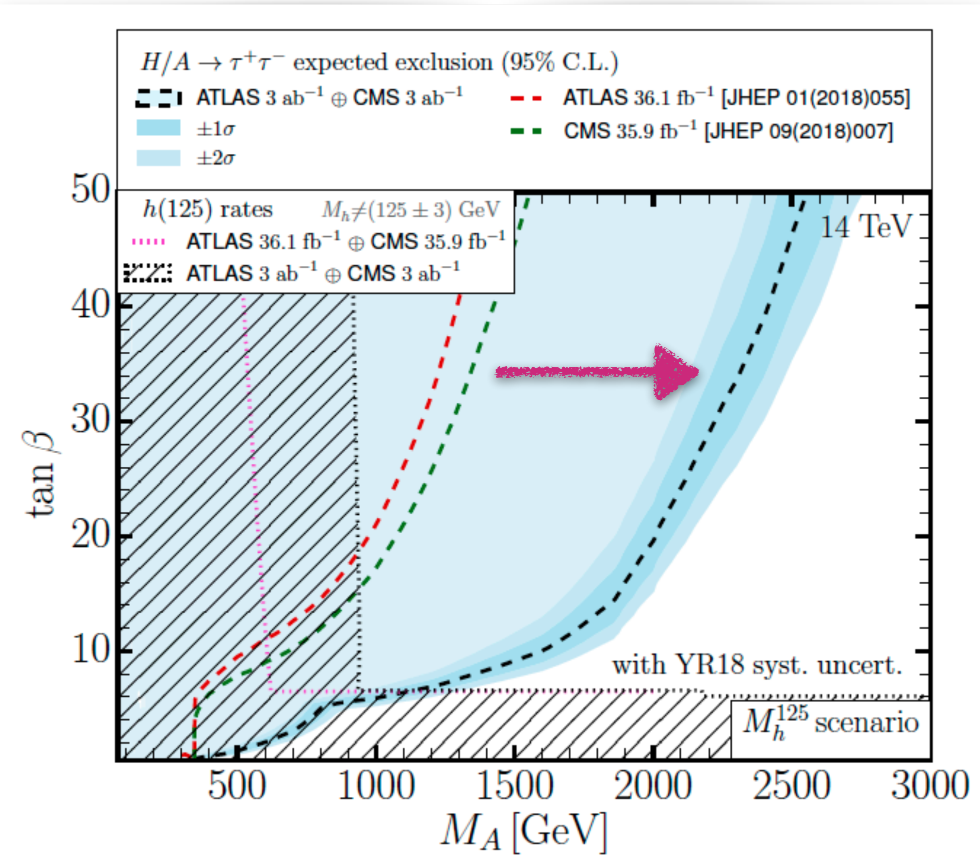
Discovery prospects!

Are there **new particles** not too far away from the electroweak scale? 2.

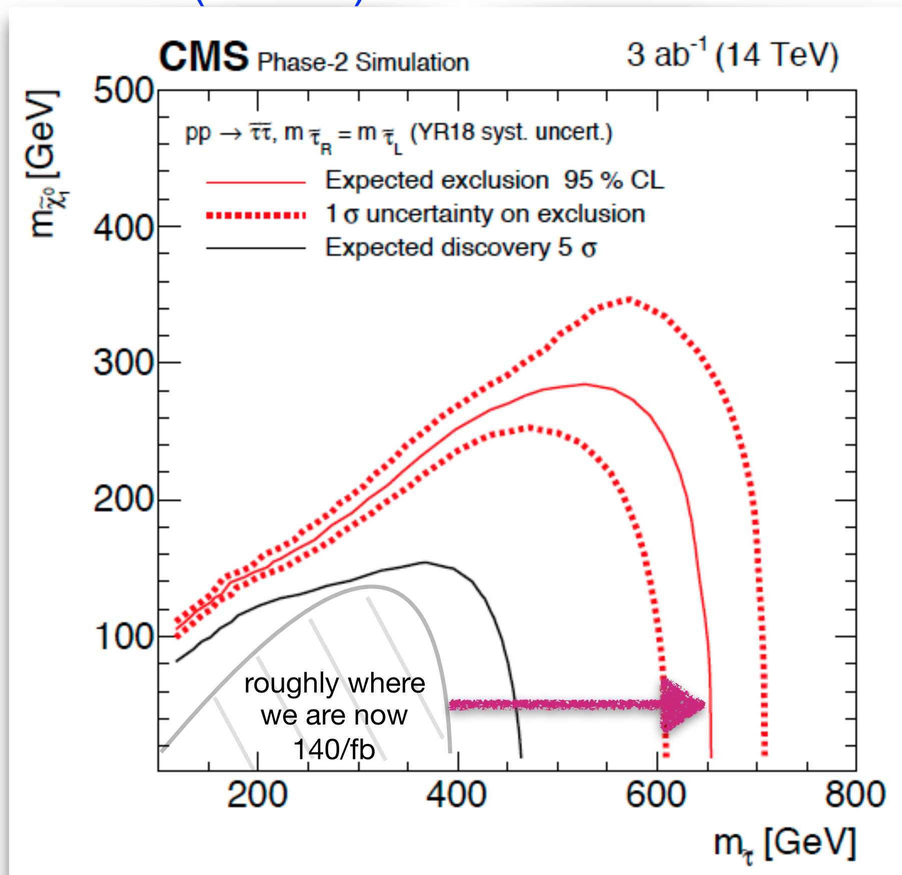
Searching for new resonances

Several open problems in particle physics could be addressed by new physics particles at around the TeV scale ⇒ **It is crucial to search for new resonances!**

New Higgs bosons at the LHC



(hidden) staus at the LHC



HL-HE LHC BSM working group report, Vidal et al., 1812.07831

Are there **new particles** not too far away from the electroweak scale? 2.

Squeezed spectra

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:

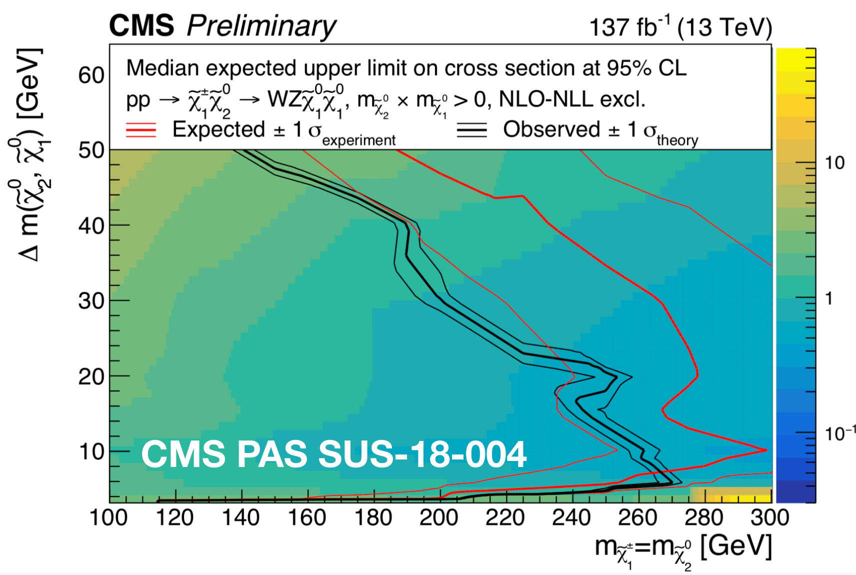
Mono-X + something **and** VBF + something **"combined" triggers?**

Reach of a large set of models!

For an early phone study of ISR + 3leptons, see SG, Jung, Wang, 1307.5952

At Run II:

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



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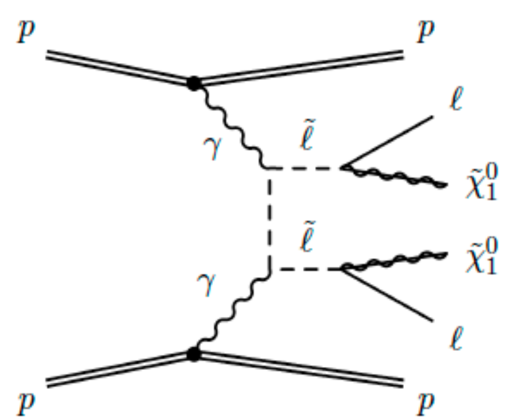
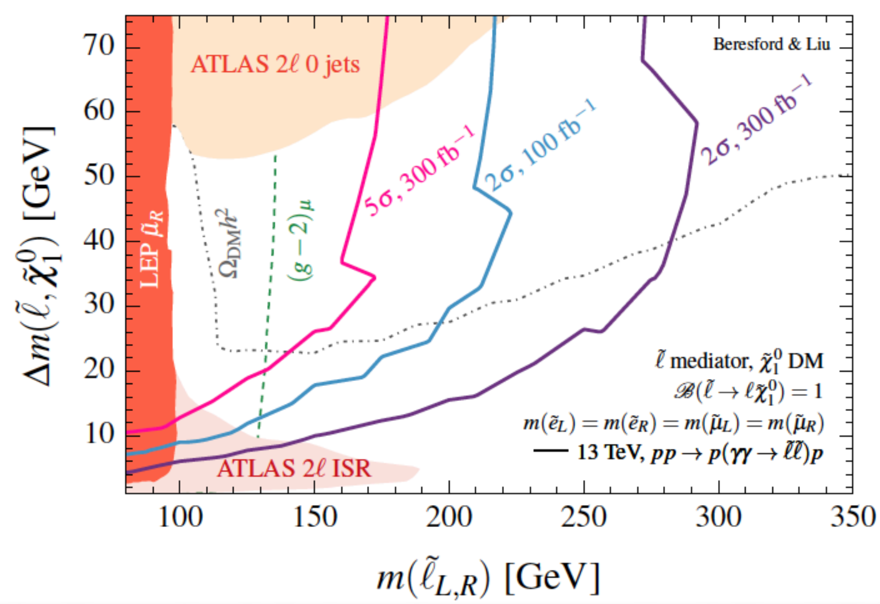
An interesting proposal to target (relatively) squeezed spectra: proton-tagged ultraperipheral collisions using forward detectors (eg. CMS-TOTEM, …)

Beresford, Liu, 1811.06465



Similarly for electroweakinos



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Long lived particles (LLPs)

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; …

Examples:

- R-parity in SUSY models
- inelastic dark matter models, split SUSY
- (many) dark sector models

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

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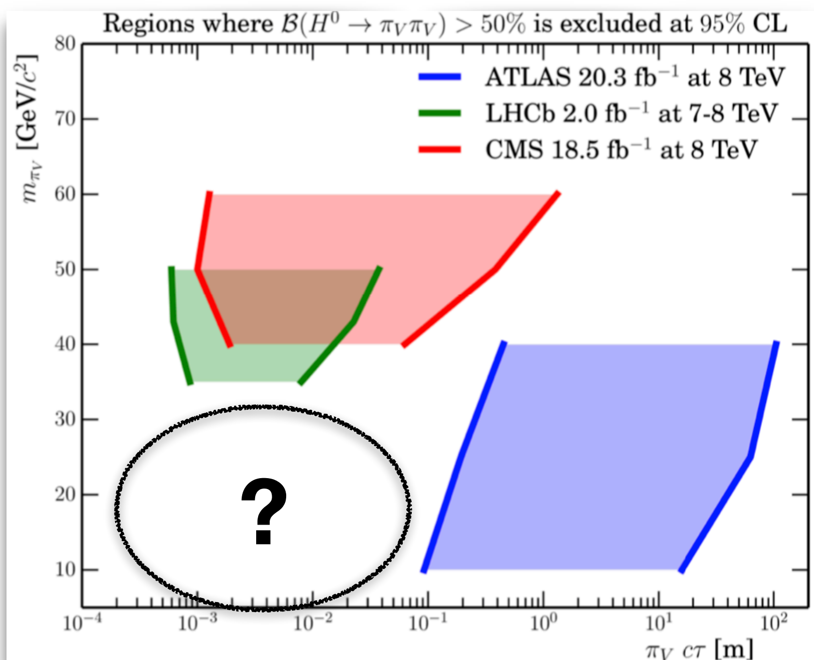


Several new techniques can be better exploited at the HL-LHC:

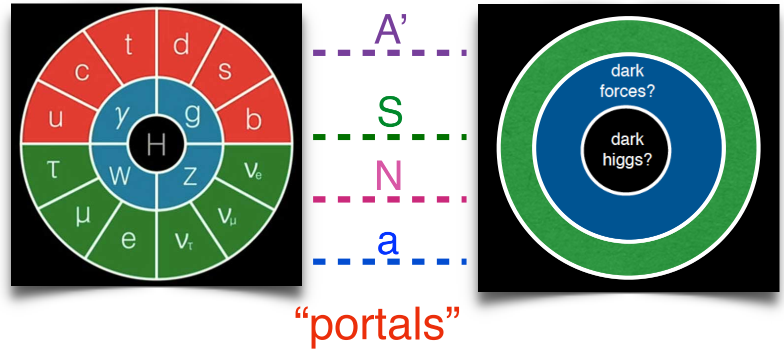
- CMS displaced dimuon vertex trigger with low p_T thresholds. LLP from B meson decays (Gershtein, Knapen, 1907.00007; Evans et al, 2008.06918)
- Precision timing can suppress SM backgrounds and enhance sensitivity to LLPs (Liu, Liu, Wang 1805.05957)

In general, LLP signatures can be spectacular (but with small rates) ⇨ **Ideal for the HL-LHC**

Dark sector particles

Does **Dark Matter/dark sector** couple to the SM?
3.

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 electroweak scale)
Direct production at the LHC through the portal operators?

Does **Dark Matter/dark sector** couple to the SM? **3.**

Dark sector particles

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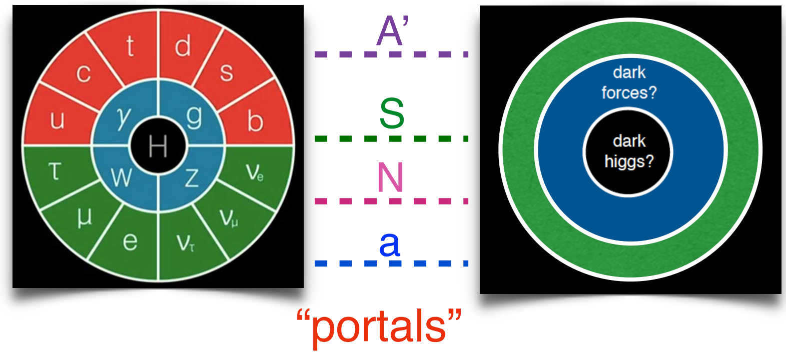

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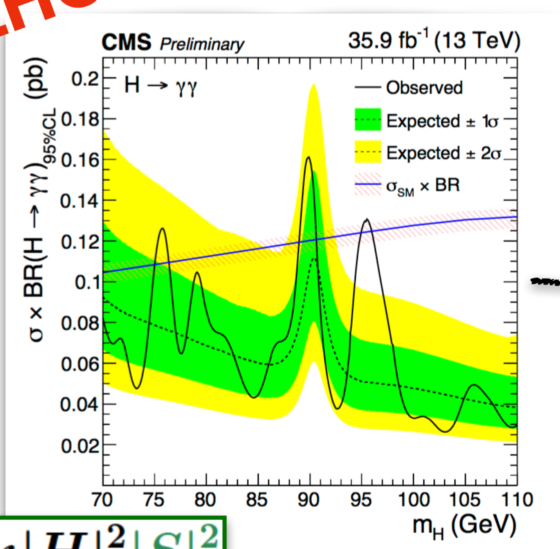
Direct production at the LHC through the portal operators?

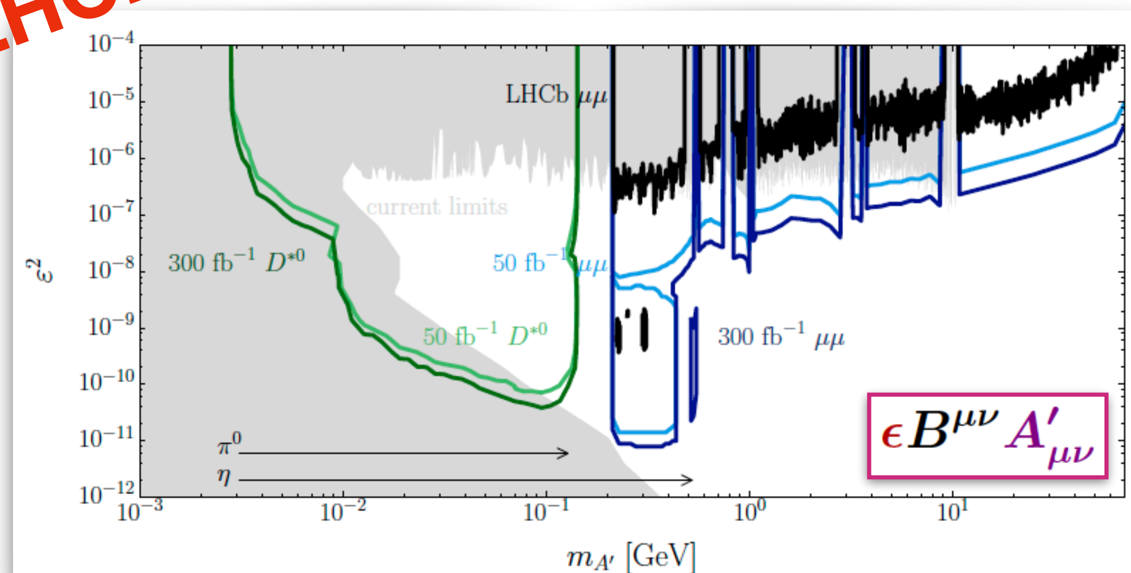
LHC **pp→S→ γ γ**



$\kappa|H|^2|S|^2$

HL-LHC?

LHCb **A'→μ μ, ee**



Broader range of searches on a broader mass range?

Testing BSM with flavor

Is the SM **flavor sector** the right description for flavor transitions?
4.

The LHCb will collect ~50 more B mesons in the HL (300/fb) stage.

⇒ **Many new key measurements to test BSM physics**

Is the SM flavor sector the right description for flavor transitions? 4.

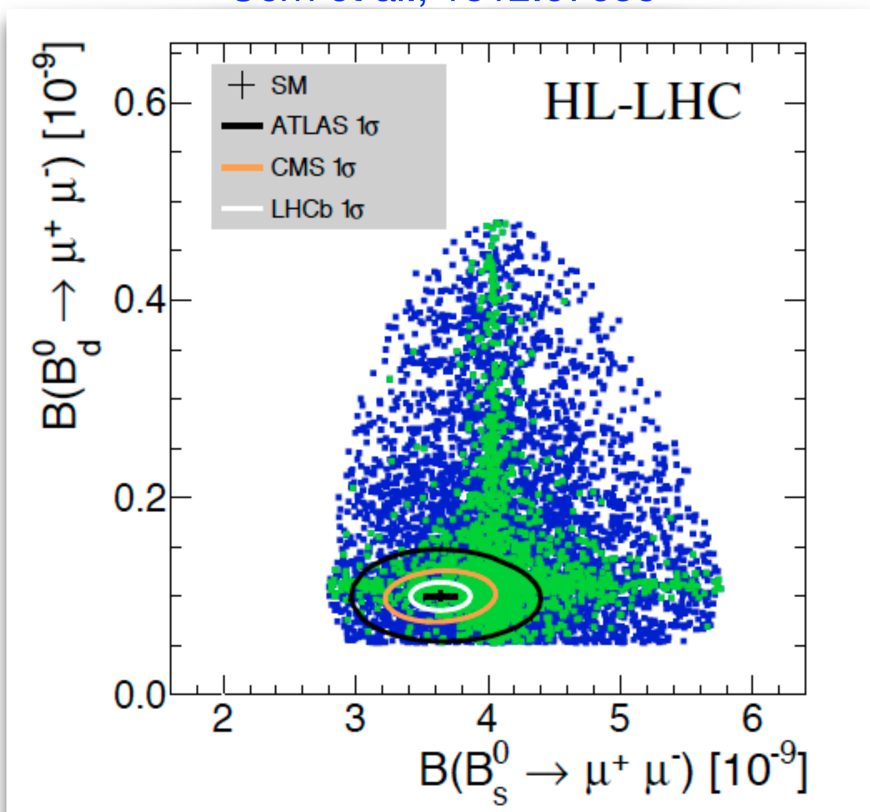
Testing BSM with flavor

The LHCb will collect ~50 more B mesons in the HL (300/fb) stage.

⇨ **Many new key measurements to test BSM physics**

An example:

Cerri et al., 1812.07638



Why is this important for BSM?

It tests the minimal flavor violation (MFV) structure of the theory:

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{MFV}}}{\mathrm{BR}(B_d \to \mu^+\mu^-)_{\mathrm{MFV}}} \sim \frac{\widehat{B}_{B_d}}{\widehat{B}_{B_s}} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{\Delta M_s}{\Delta M_d}$$

very clean, both theoretically and experimentally

goal: 10% measurement for the ratio

Is there some heavy New Physics that modifies the pheno of SM particles? 5.

Testing very heavy New Physics

New Physics can be at energies larger than what is directly tested by the LHC.

Heavy New Physics can nevertheless induce measurable deviations from SM predictions.

We parametrize our ignorance on the UV physics with effective field theories. Some operators are best tested at high energy hadron colliders (as opposed to low energy lepton colliders like LEP).

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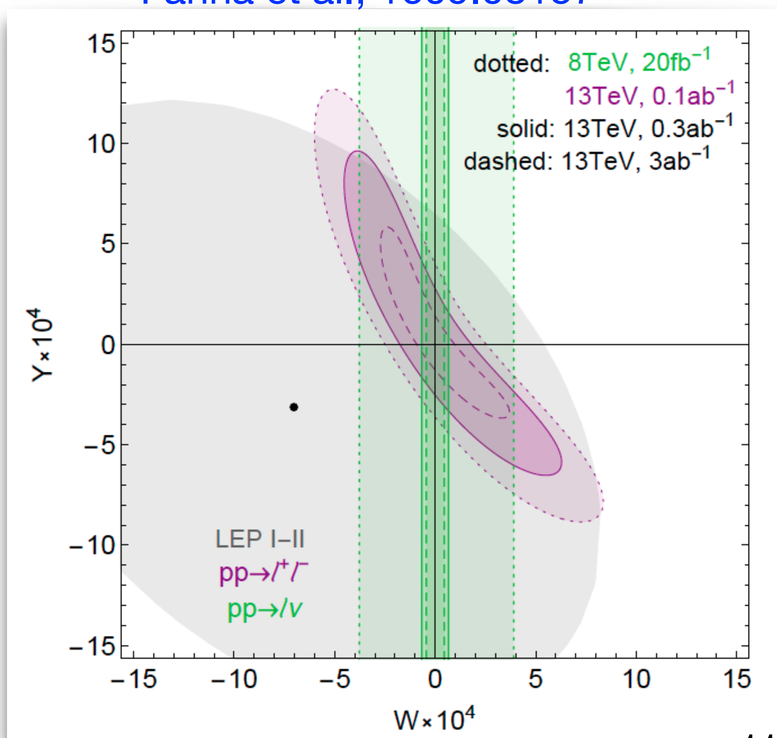
For example:

$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2, \quad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

grows with energy

tested by Drell-Yan pp→ll, l nu precision measurements

Farina et al., 1609.08157



Summary

The HL-LHC offers a unique opportunity to test BSM physics

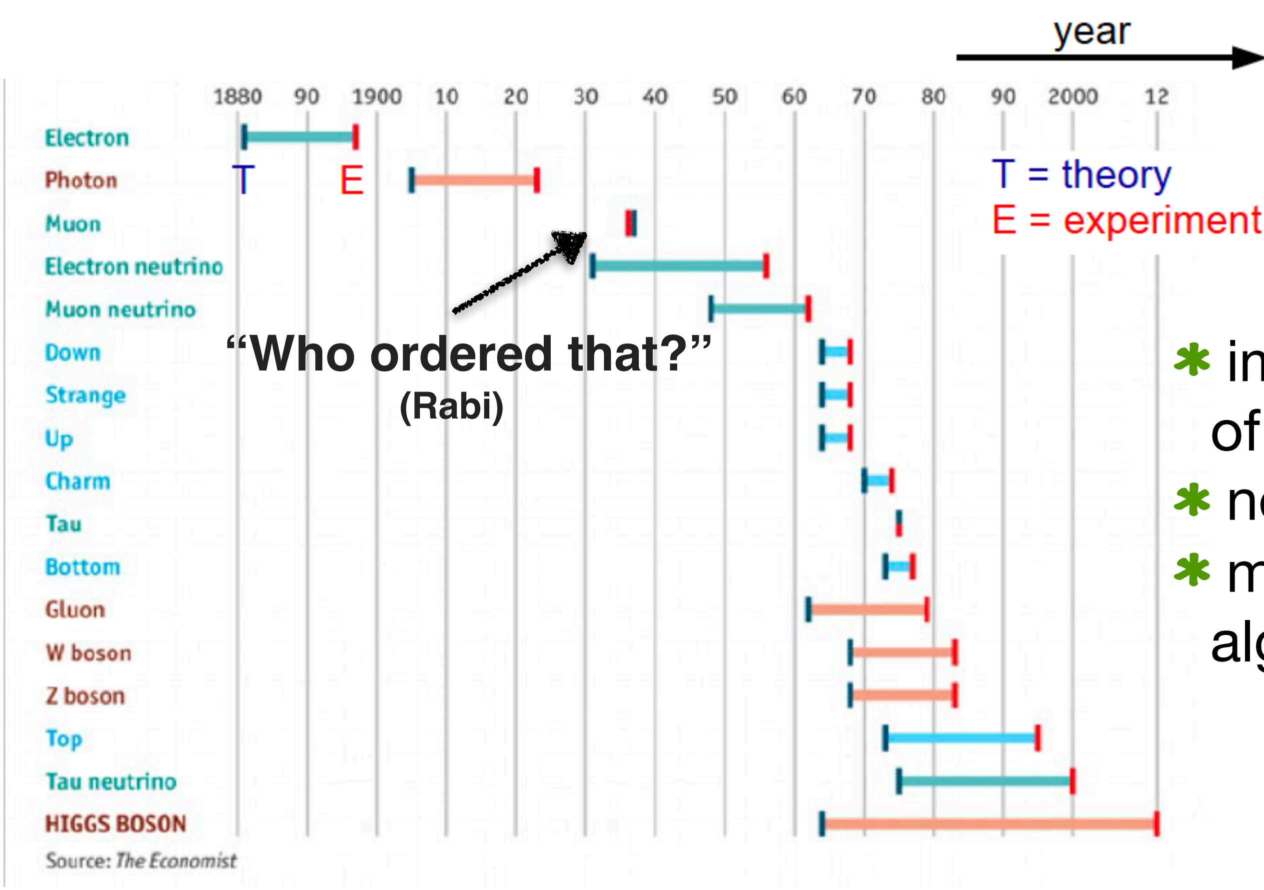
	Opportunities	Open problem in particle physics
Higgs & electroweak symmetry breaking	Precision program, rare events, CPV	EWSB
New particles	New resonances, squeezed spectra, long lived particles	hierarchy problem
Heavy New Physics	Effective field theories & effects in distributions at high energy	
Dark Matter/dark sector	Light dark resonances at the LHC/LHCb!	Dark matter, baryon anti-baryon asymmetry, strong CP problem,
Flavor sector	Indirect tests of flavorful New Physics	flavor puzzle

Many more opportunities…

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

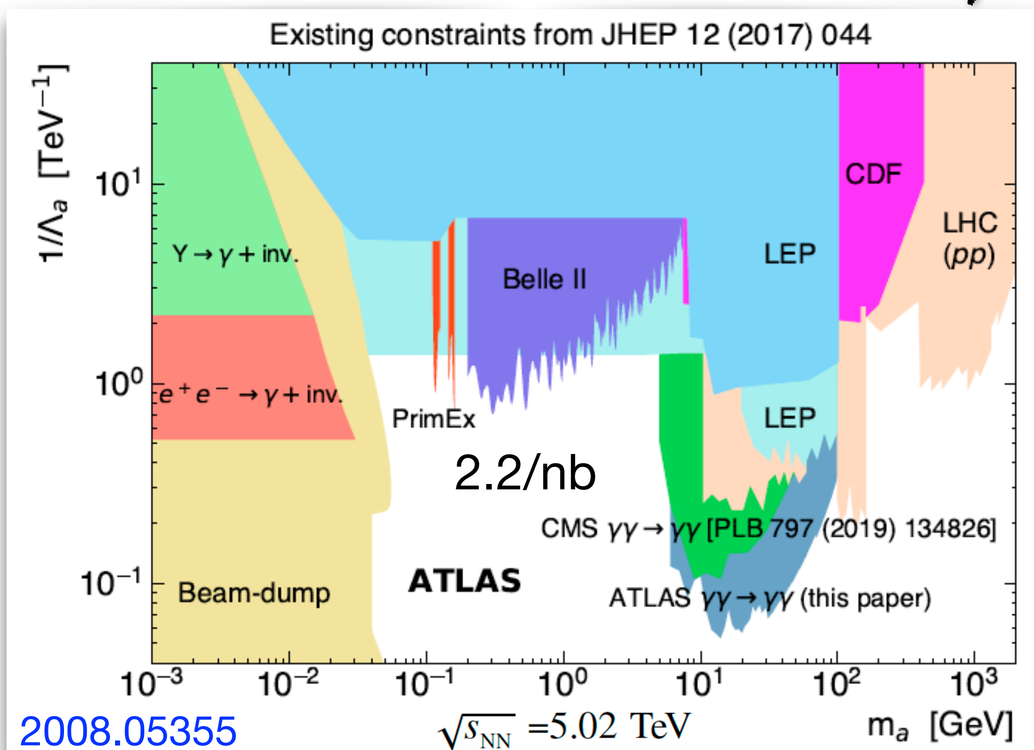
Dark sectors, heavy ion run

Does **Dark Matter/dark sector** couple to the SM?

3.

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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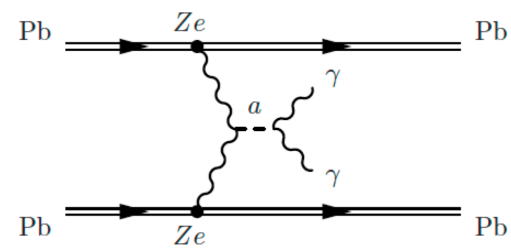

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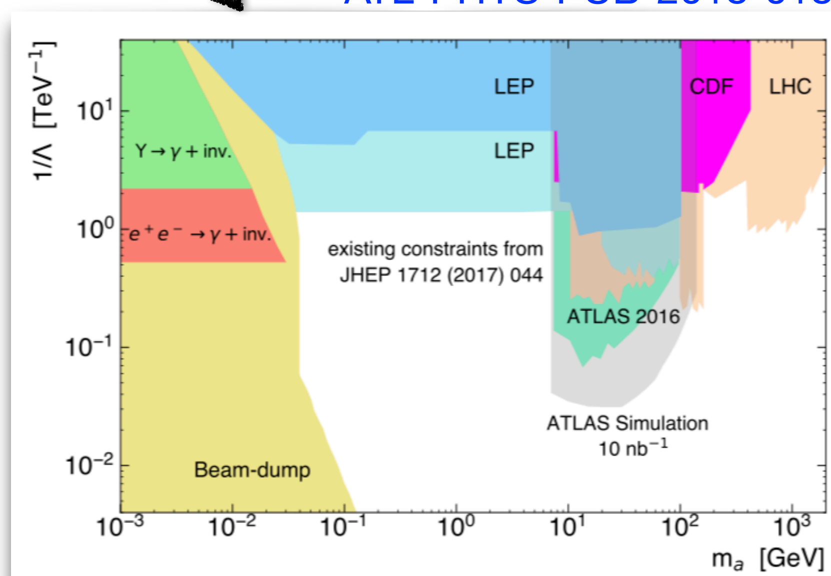

$$\frac{a}{4\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Additional opportunities?

prospects for Run 3+4

S.Gori

Backup