BSM PHYSICS AT FCC-HH / EXOTICS

a review of some results found in the literature

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Workshop FCC-France
May 15th 2020

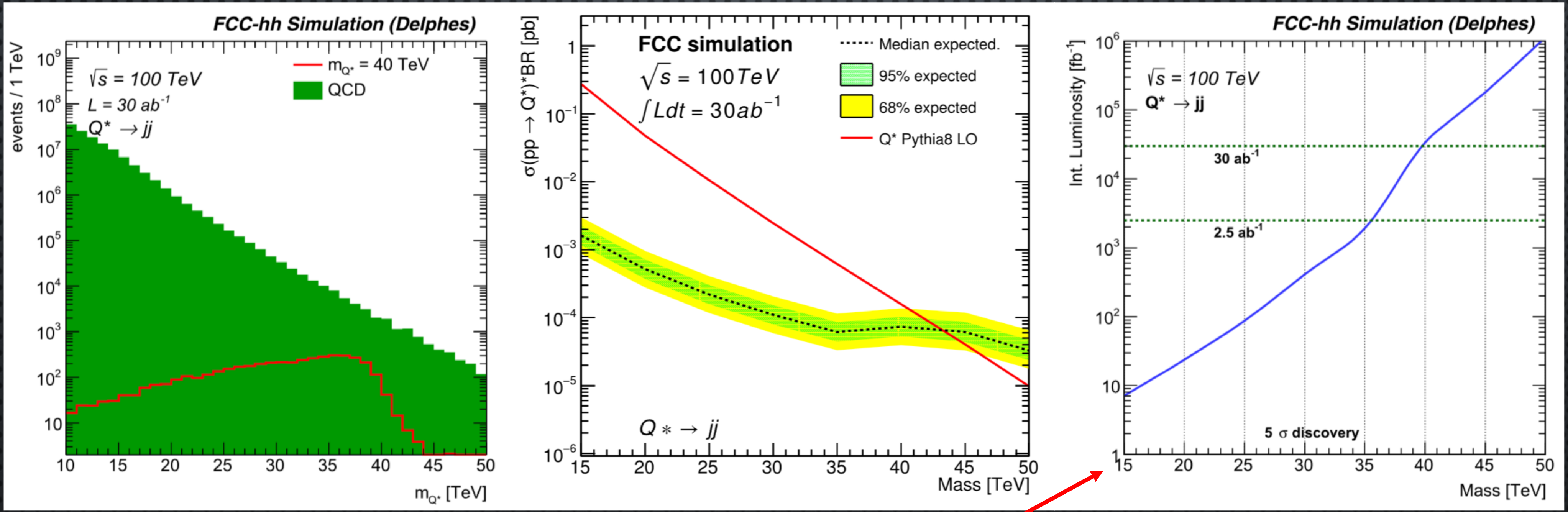
Eur. Phys. J. C (2019) 79:569

DIJET RESONANCES

<u>For all the resonant studies shown:</u>

- Signal: Pythia8
- BG: MG5_aMC in bins of HT
  - fit to smooth when necessary
  - k-factor of 2 applied
- Delphes w/ FCC-hh (see backup)

- Two jets with $p_T > 3$ TeV, $|\eta| < 3$, $\Delta(\eta_1, \eta_2) < 1.5$



HL-LHC @ ~ 8 TeV* ...
very little data needed

* ATL-PHYS-PUB-2015-004

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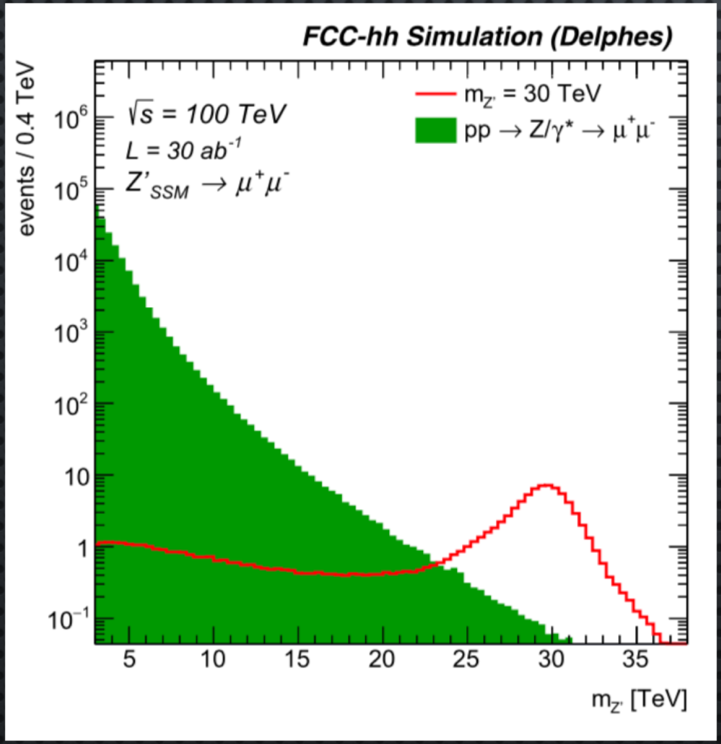
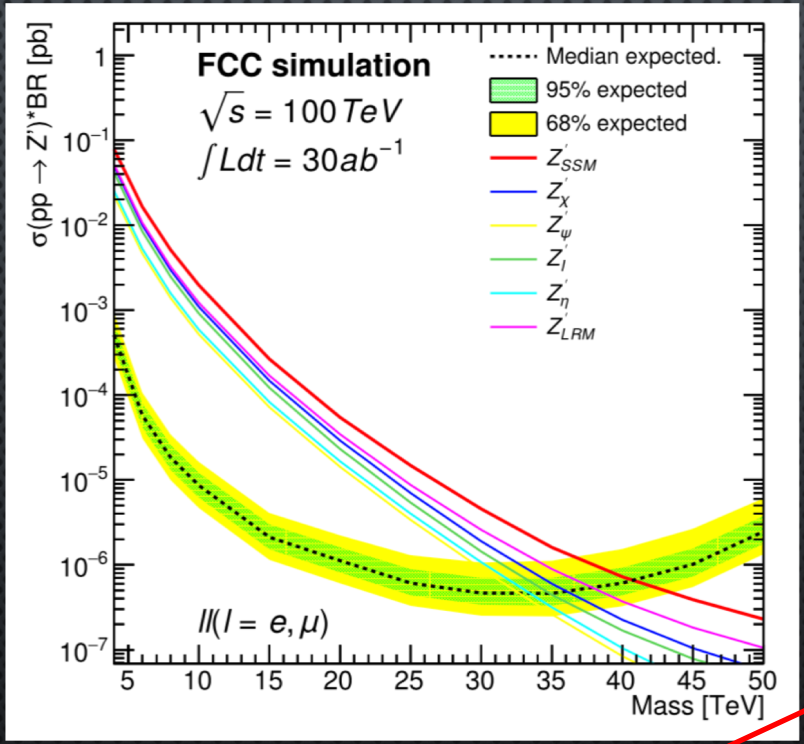
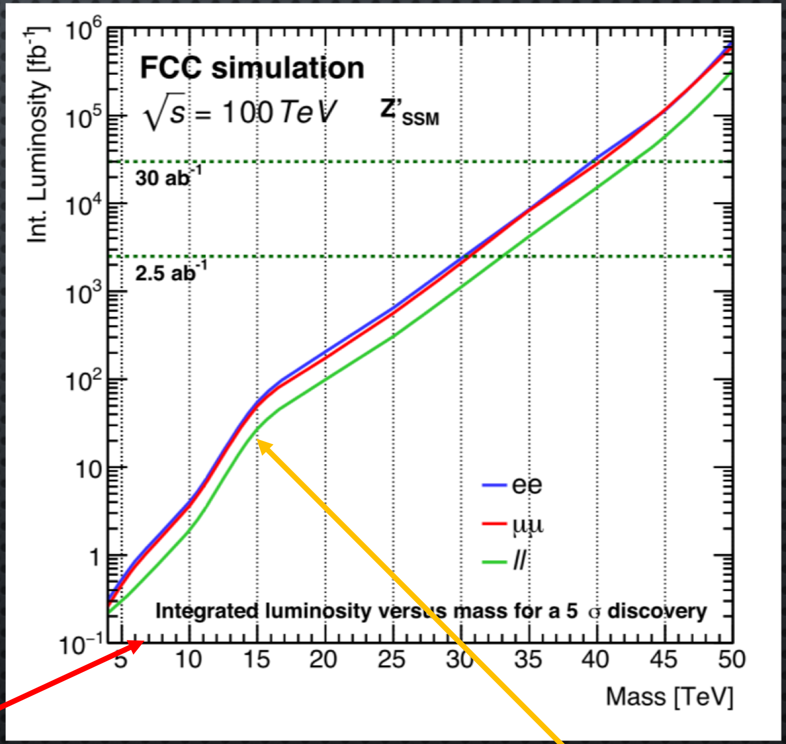
DILEPTON RESONANCE

- Two isolated opposite-sign leptons with $p_T > 1$ TeV, $|\eta| < 4$, $m_{ll} > 2.5$ TeV







HL-LHC @ 6.4 TeV ...
a day of running?

Slope changes as search becomes almost BG free

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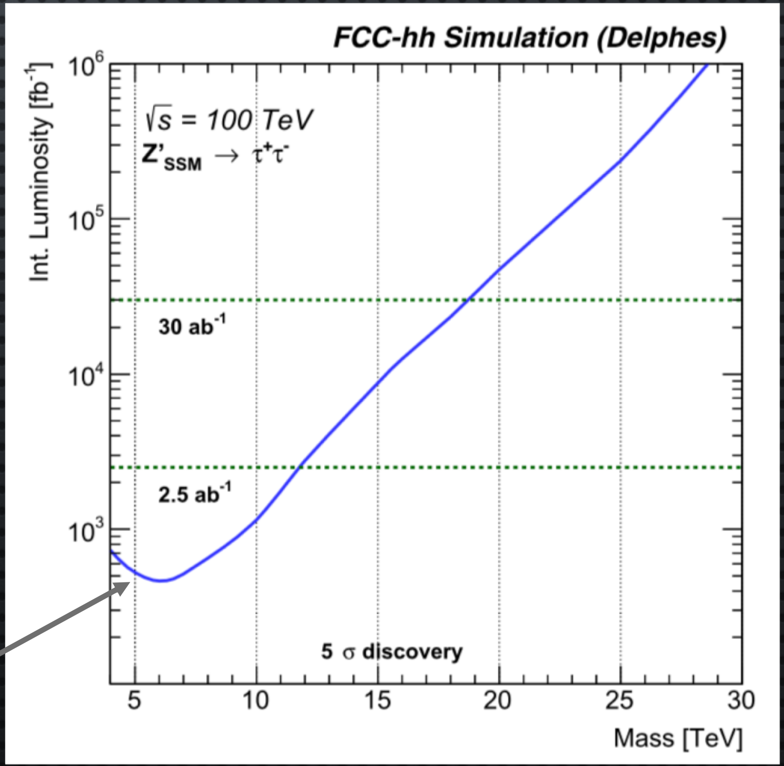
DITAU RESONANCE

- Two tau-tagged jets with p_T > 0.5 TeV and |η| < 2.5
  - ε_τ^{tag} conservatively assumed to vanish as a function of p_T (see backup) – full simulation needed to provide more realistic numbers
- Veto on e/μ with p_T > 100 GeV in jets
- Mass-dependent cuts to improve on significance

Z' mass [TeV]	$\Delta\phi(\tau_1, \tau_2)$	$\Delta R(\tau_1, \tau_2)$	E_T^{miss}
4–8	> 2.4	> 2.5 and < 3.5	> 400 GeV
10	> 2.4	> 2.7 and < 4	> 300 GeV
12–14	> 2.6	> 2.7 and < 4	> 300 GeV
16–18	> 2.7	> 2.7 and < 4	> 300 GeV
> 18	> 2.8	> 3 and < 4	> 300 GeV



Could be improved by further optimisation not done here

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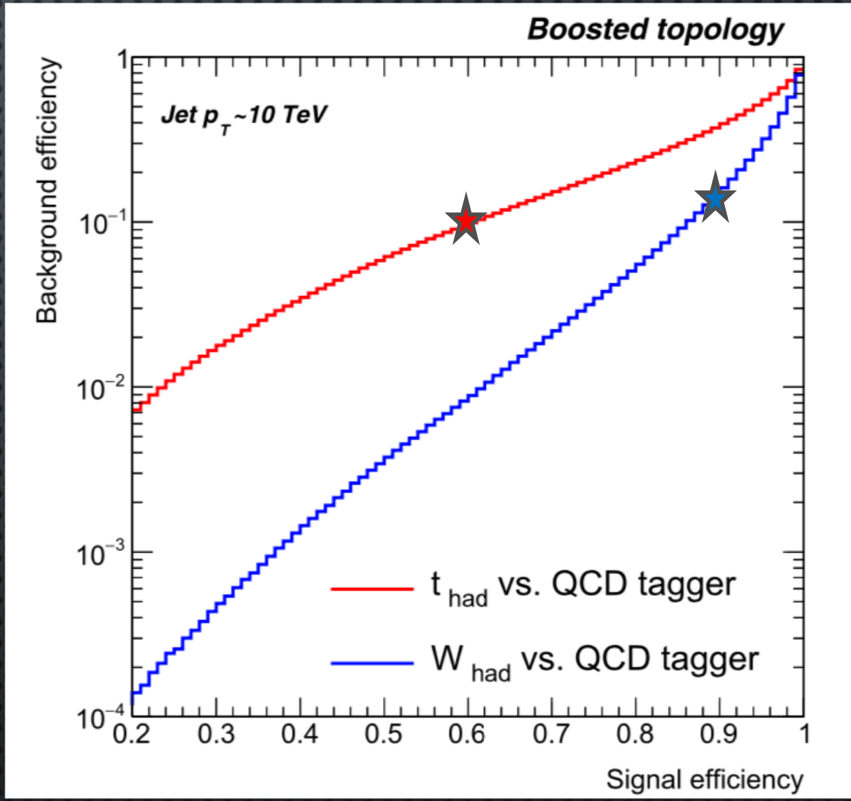
HADRONIC RESONANCES WITH SUBSTRUCTURE

- Highly boosted hadronic decays of top/W/Z
  - extremely collimated jets: @ 10 TeV, R = 0.02 for a W (typical calorimeter cell!)
- In the following studies: jets from tracks only
- Build taggers from jet substructure observables:
  - Soft-dropped jet mass & N-subjettiness variables for top
  - Also uses “isolation-like” variables for W (absence of high-p_T FSR in the vicinity of decay products). For n 1-5, α=0.05, defined by:

$$E_F(n,\alpha) = \sum_{\frac{n-1}{5}\alpha < \Delta R(k,jet) < \frac{n}{5}\alpha} p_T^{(k)} \Big/ \sum_{\Delta R(k,jet)<\alpha} p_T^{(k)}$$



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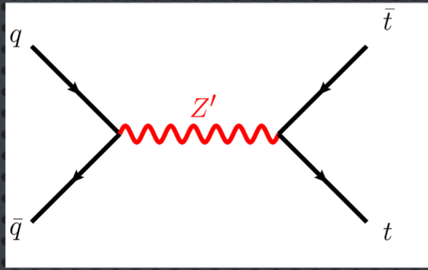
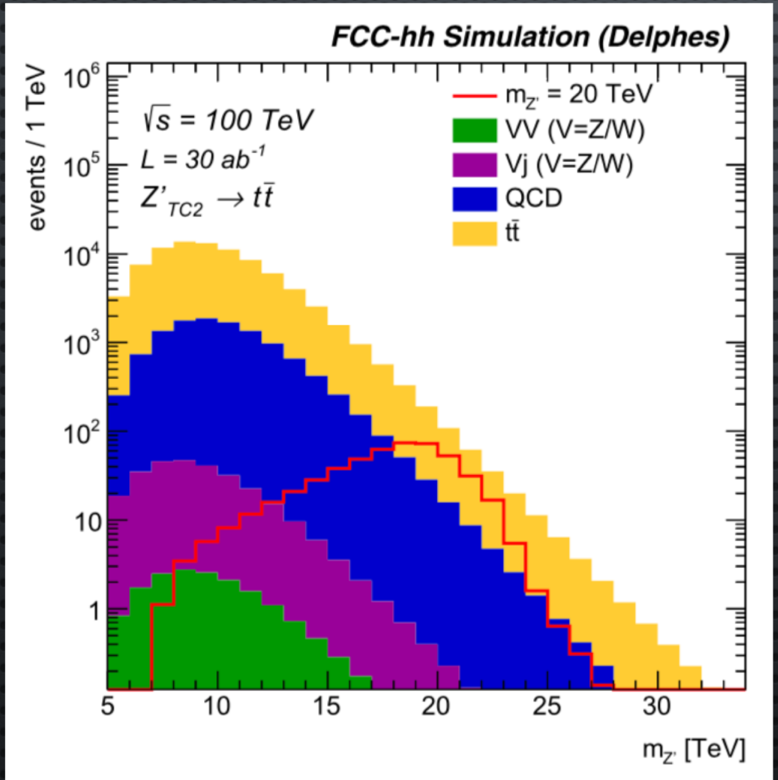
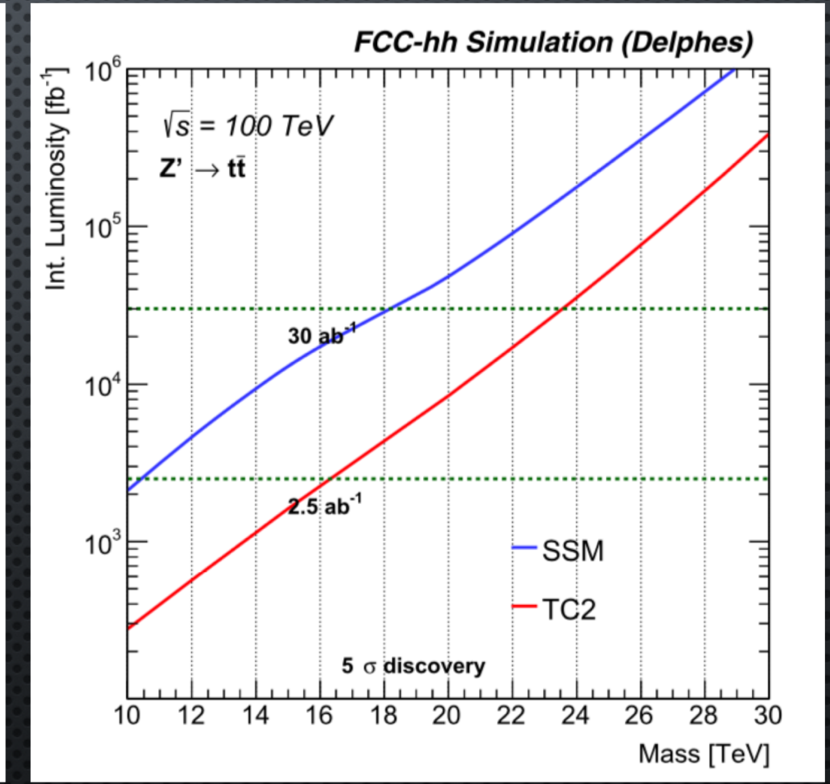
TT RESONANCES



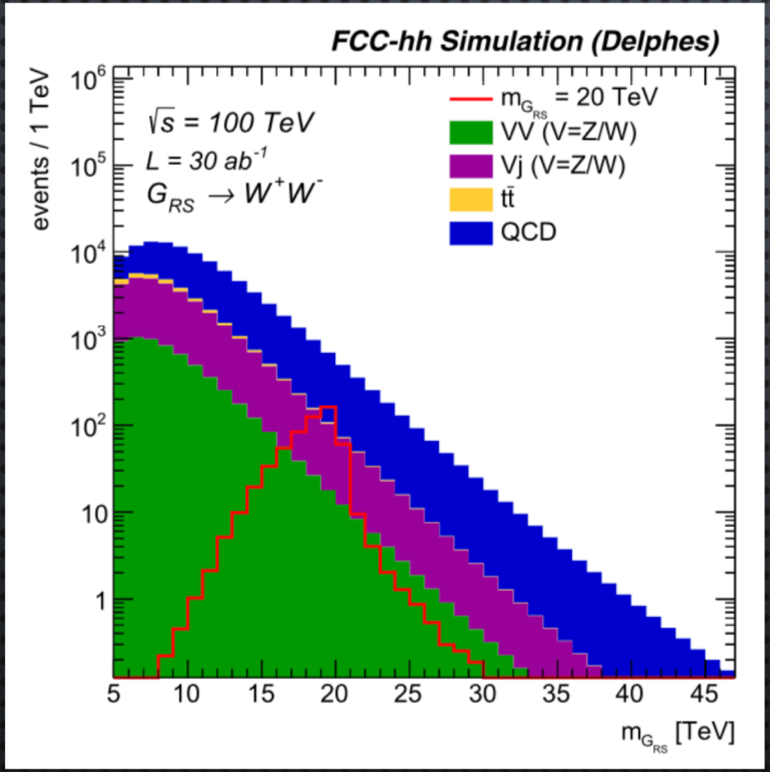
- Two top & b-tagged jets with $p_T > 3$ TeV, $|\eta| < 3$, $\Delta(\eta_1, \eta_2) < 2.4$, $m_{SD} > 40$ GeV

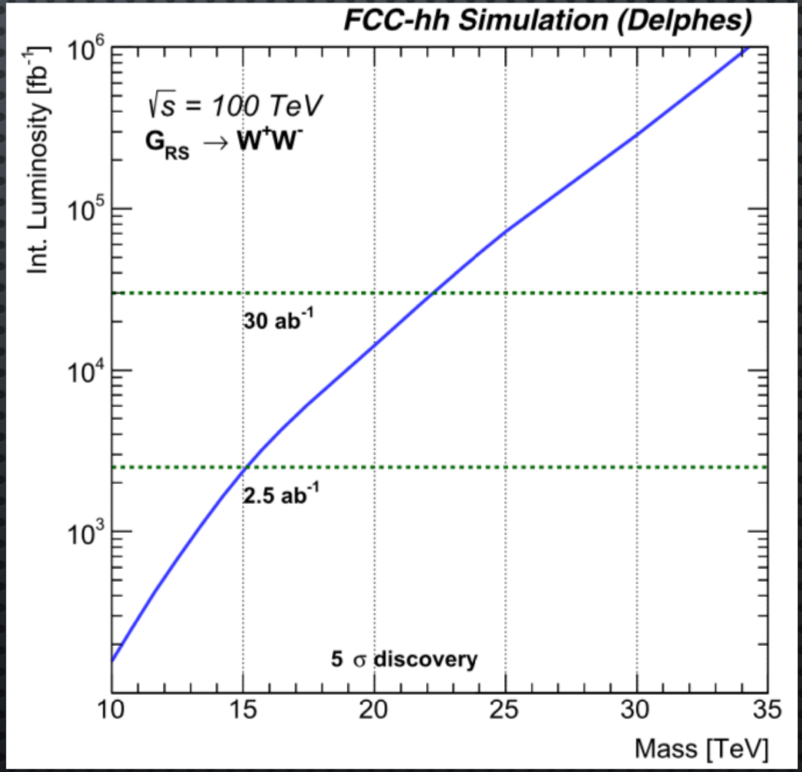




WW RESONANCES

- Two W-tagged jets with $p_T > 3$ TeV, $|\eta| < 3$, $\Delta(\eta_1,\eta_2) < 2.4$, $m_{SD} > 40$ GeV





- Combination with a leptonic channel would increase the sensitivity

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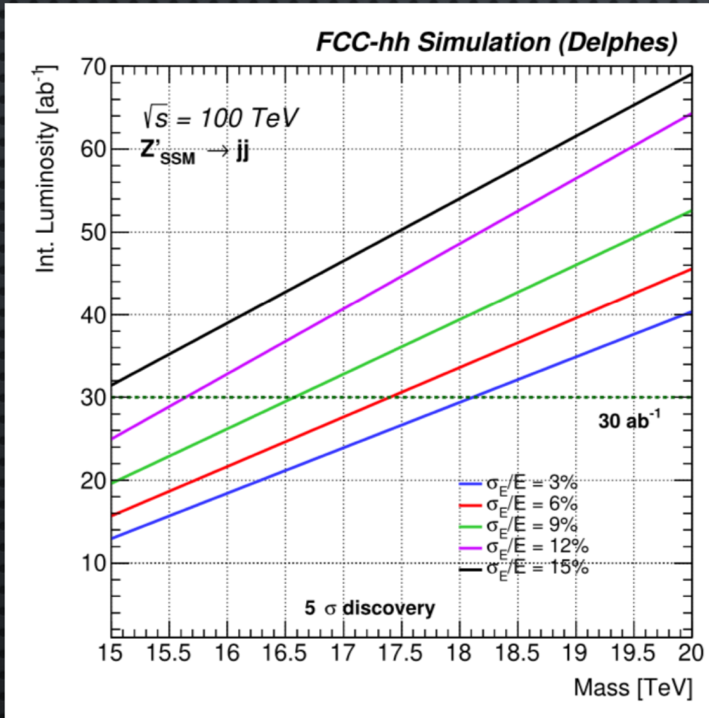
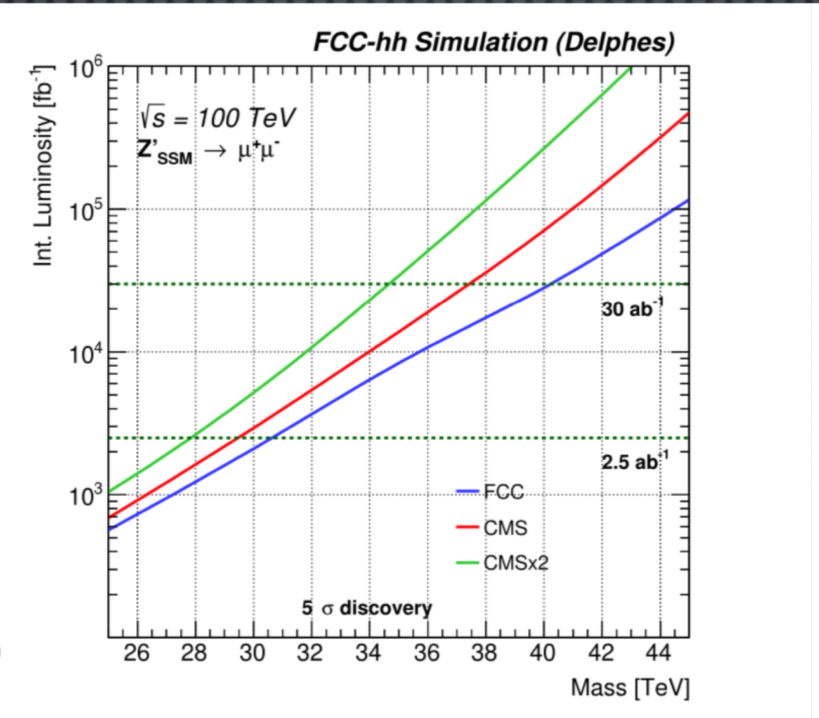
EFFECT OF DESIGN ON PROJECTIONS

Calorimeter resolution:

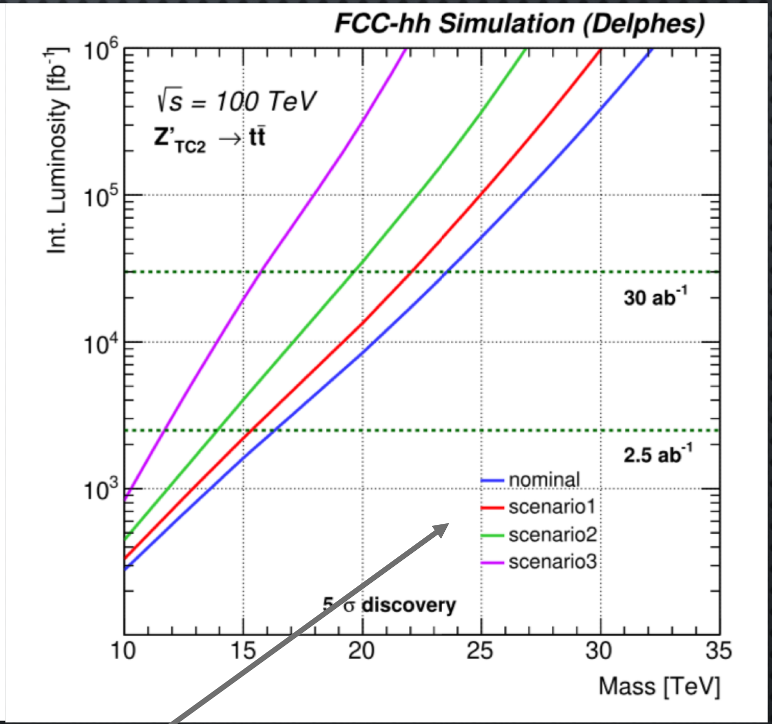


Muon resolution:



$\sigma_p/p \approx 5\%$ (CMS~40%) at $p_T = 20$ TeV

b-tagging efficiency:



b-tagging effect: scenarios 1, 2 and 3 correspond to change in the slope by a factor 25%, 33% and 50%

Nominal: $(1 - p_T\,[\mathrm{TeV}]/15) \cdot 85\%$

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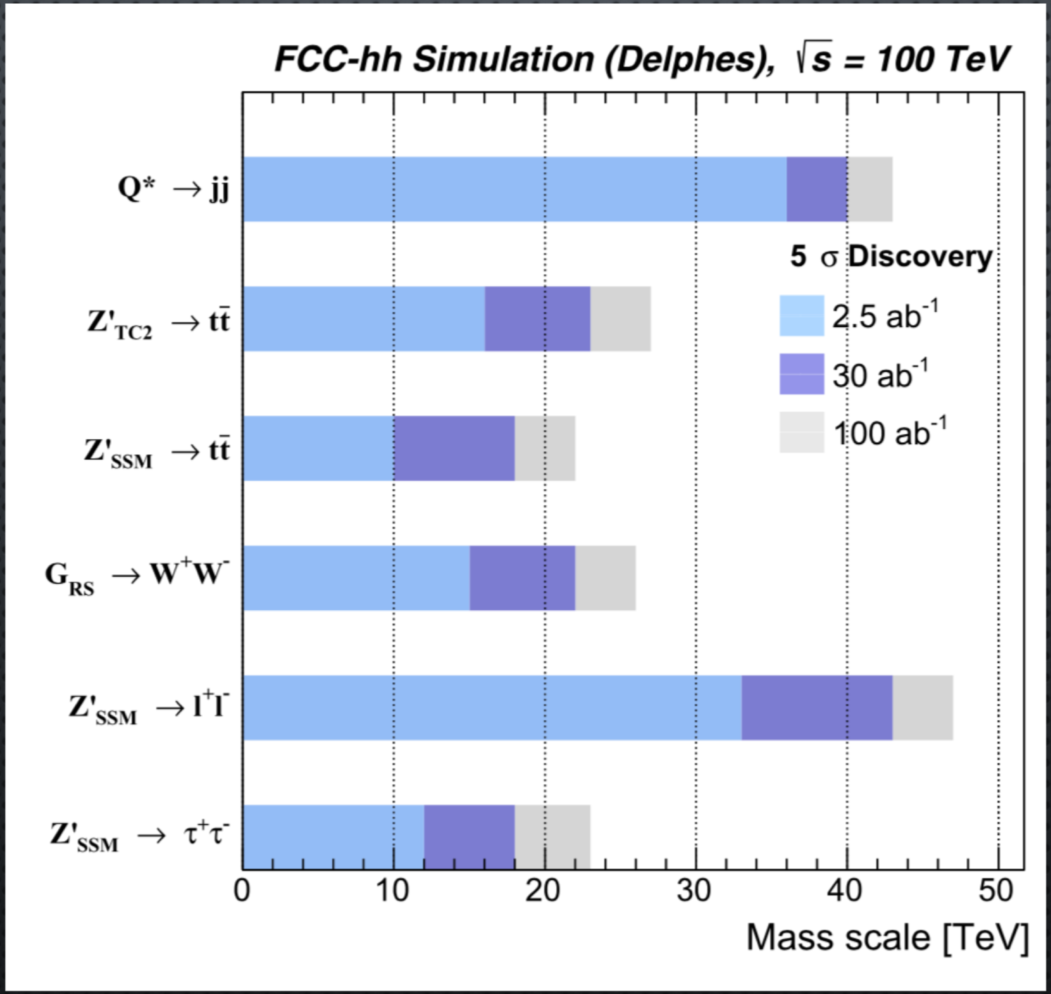
SUMMARY OF RESONANT SEARCHES



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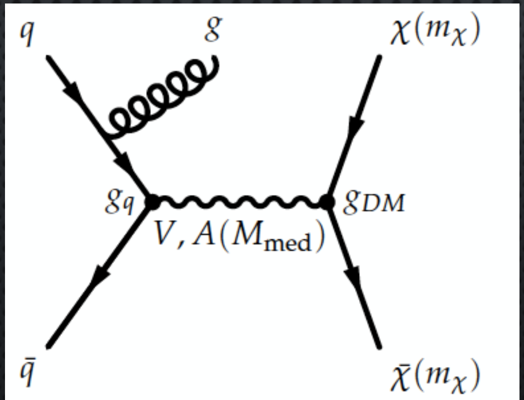
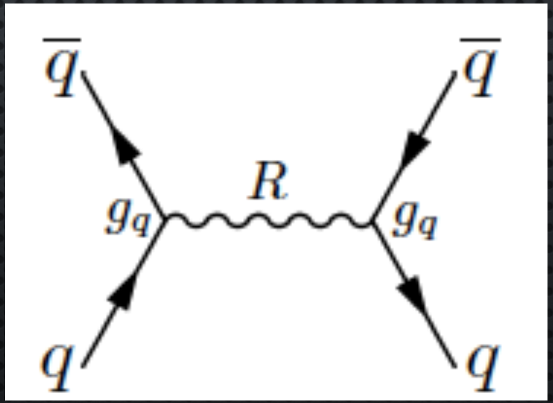
DARK MATTER SIMPLIFIED MODELS

- Consider a simplified dark matter model with an axial-vector mediator linking the quarks to the DM particles
- Free parameters: m_{DM}, m_{med}, g_q, g_{DM}
- Direct production through a mediator of DM particles (mono-jet signature with ISR), or mediator resonant seach in a dijet final state:





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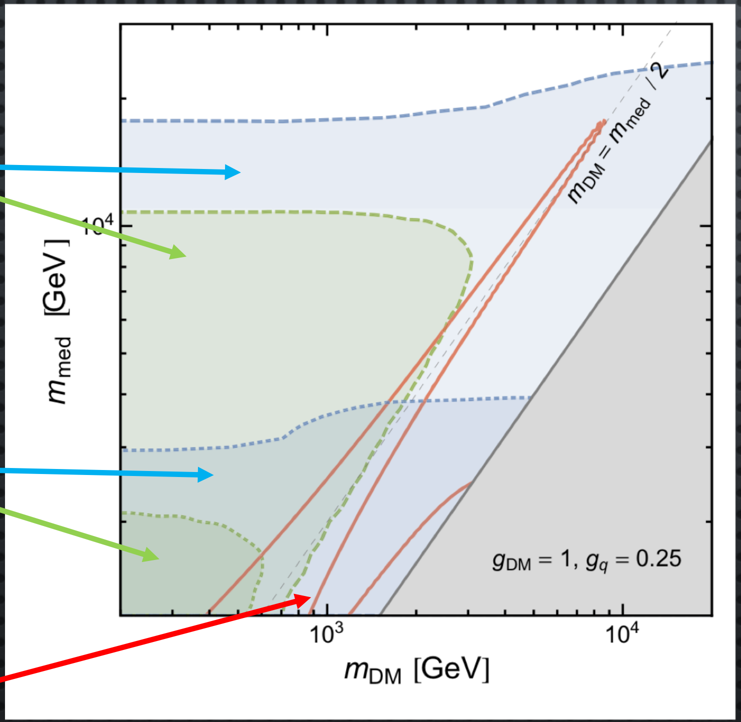
DM SIMPLIFIED MODELS

Monojet and dijet search reach:

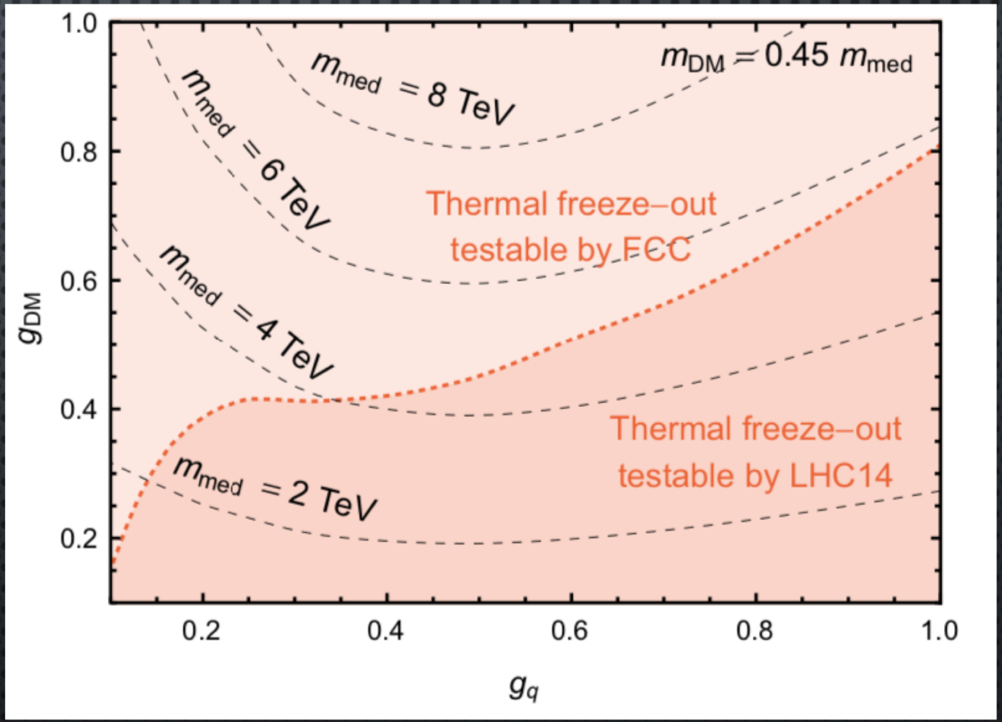
FCC-hh

HL-LHC

Relic density*



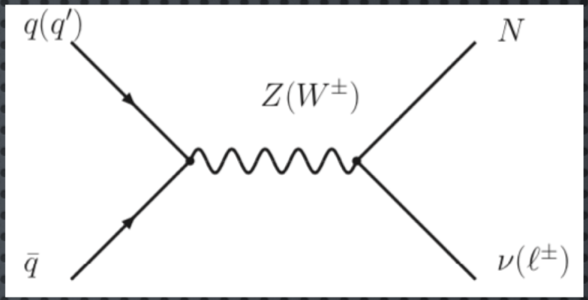
Fixed couplings, varying masses

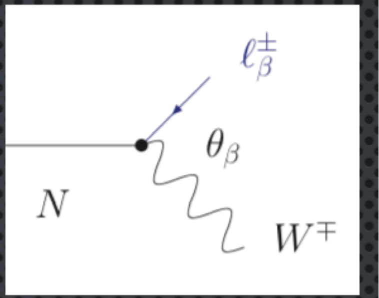


Varying couplings, masses fixed to get proper relic density*

* *guideline, but it remains a simplified model...*

Int J. Mod. Phys. A 32 (2017) 14, 1750078

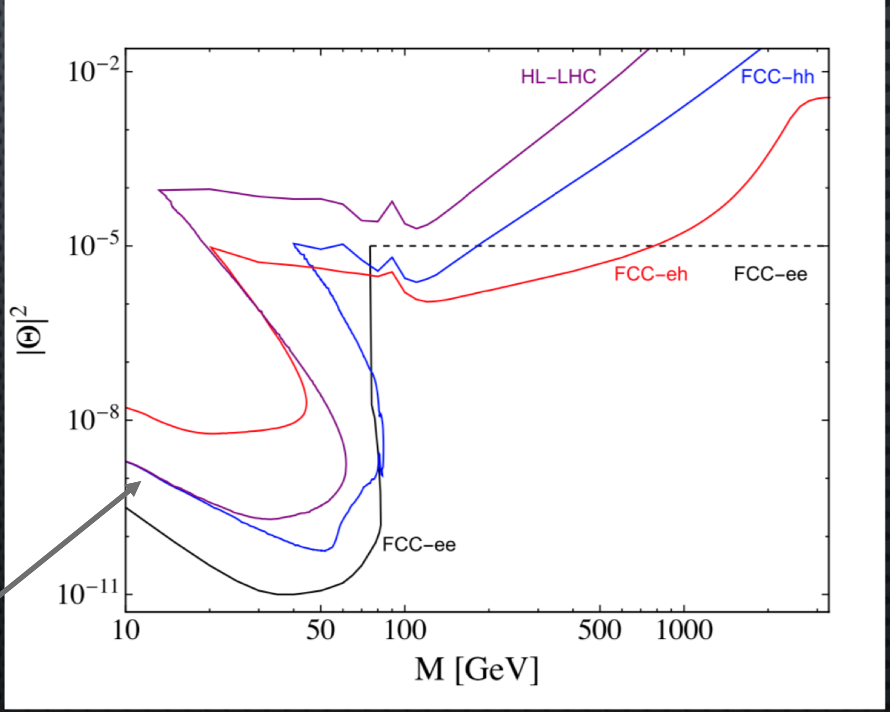




HEAVY NEUTRAL LEPTONS

- Introduce sterile neutrinos to generate the observed light neutrino masses; in some theories, can have masses around the electroweak scale
- Multiple final states to cover various production and decay modes:

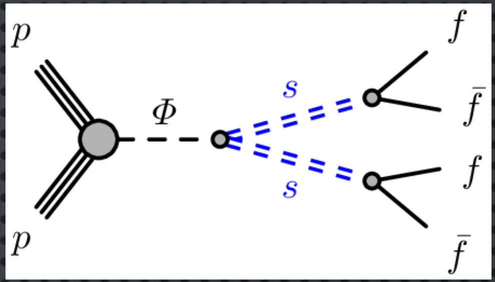
Name	Final State	Channel [production,decay]
dilepton-dijet	$\ell_\alpha \ell_\beta jj$	$[\mathbf{W_s}, W]$
trilepton	$\ell_\alpha \ell_\beta \ell_\gamma \nu$	$[\mathbf{W_s}, \{W, Z(h)\}]$
lepton-dijet	$\ell_\alpha \nu jj$	$[\mathbf{W_s}, Z(h)]$, $[\mathbf{Z_s}, W]$
dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$[\mathbf{Z_s}, \{W, Z(h)\}]$
mono-lepton	$\ell_\alpha \nu\nu\nu$	$[\mathbf{W_s}, Z]$
dijet	$\nu\nu jj$	$[\mathbf{Z_s}, Z(h)]$



- Can also lead to a displaced vertex for $M<M_W$ and a small active-sterile mixing

parton-level analysis
FCC-hh @ 20 ab^{-1}

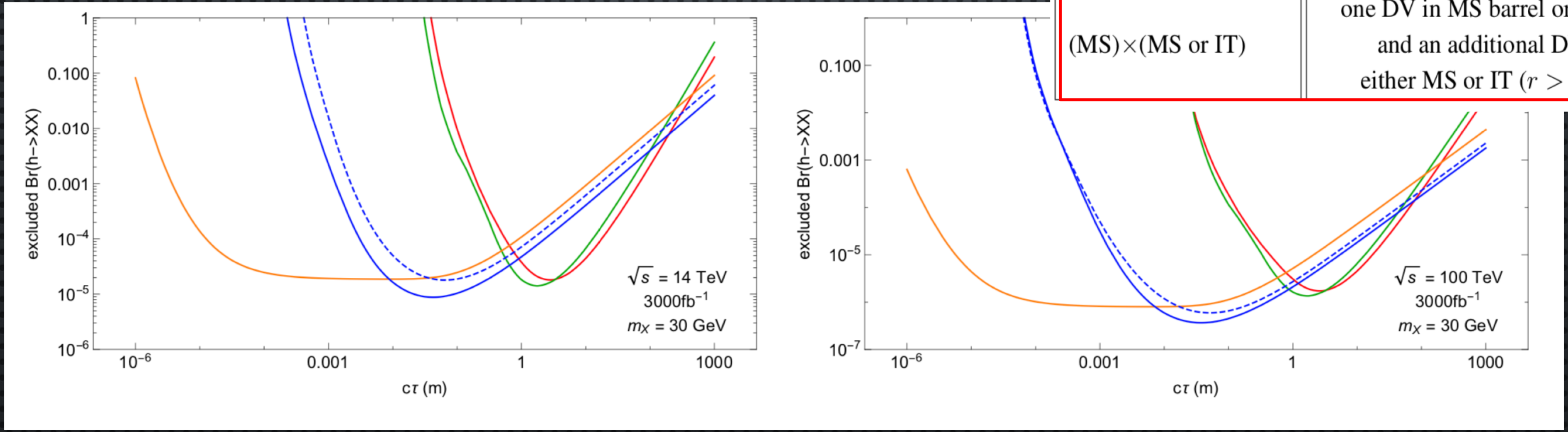
JHEP12(2015)072



HIGGS TO LONG-LIVED SCALARS

- Models of neutral naturalness can lead to exotics higgs decay through long-lived scalars, with multiple signatures depending on the lifetime

Search	Displaced Vertex requirements
(IT, $r > 50\mu$m)×(1L)	one DV in IT with $r > 50\mu$m
(IT, $r > 4$cm)×(VBF)	one DV in IT with $r > 4$cm
(HCAL)×(HCAL)	two DVs in HCAL barrel or endcap
(MS)×(MS or IT)	one DV in MS barrel or endcap and an additional DV in either MS or IT ($r > 4$ cm)



- Caveats: present-day experiment limitations assumed, and 0-BG hypothesis (quite unlikely for HCAL search), optimistic IT cut for the first category

HIGGS TO ALPS

- Axion-like particles (ALPs) are light, gauge-singlet pseudoscalar particles
- Effective couplings to SM
- Can be non-thermal candidates for Dark Matter
- Interesting at hadron colliders: look for Higgs production $pp \to h \to aa \to 4\gamma$

$$\Gamma(h \to aa) = \frac{m_h^3\, v^2}{32\pi\, \Lambda^4} |C_{ah}^{\text{eff}}|^2 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\Gamma(a \to \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left|C_{\gamma\gamma}^{\text{eff}}\right|^2$$

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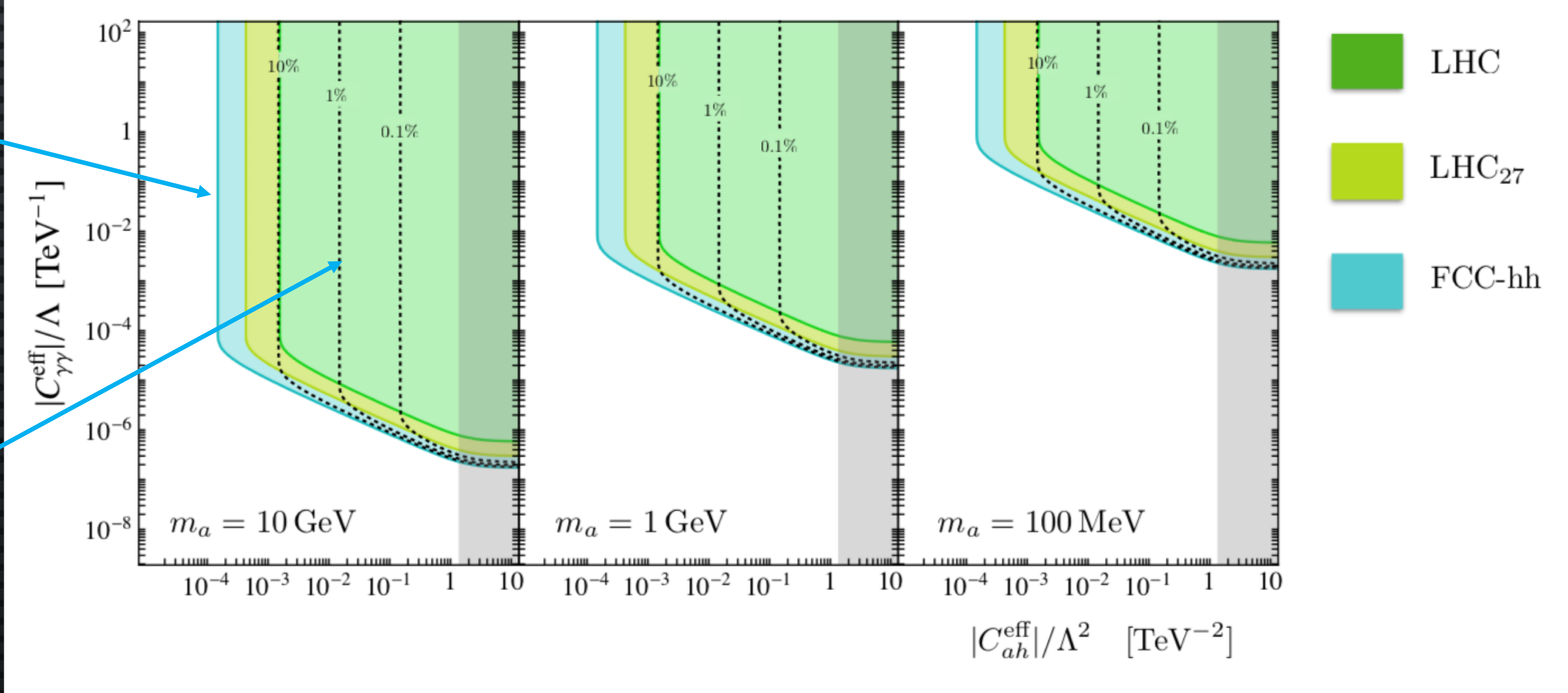
HIGGS TO ALPS

- Reach: observing 100 events
- Gray regions: excluded by BR(h → BSM) < 0.34 (at 95% CL)

BR(a→γγ)=1

Other BRs



SUMMARY

- These were only some examples of the discovery capacity of FCC-hh
  - extends the reach significantly beyond HL-LHC at high mass, but also for very weakly coupled BSM particles at lower mass
- Did not address FCC-ee today, but there is also great complementarity in some cases (eg HNL in Z decays...)
- Many analyses have been considered covering a wide scope of models / final states
  - Interesting to check the effect of design on the prediction as done for the resonance paper I discussed, as some were done in an exploratory fashion as a first step (eg at particle level, w/o dedicated optimisation,...)
  - See ***A framework and goals for FCC-hh physics studies at Snowmass 2021*** for a 'how-to-start' with links to software repositories including some benchmark analyses (see a snapshot of the list in backup)
    - Ongoing work on an updated FCC-hh DELPHES card (PU, ToF, 4D vertexing, dE/dx...) for a more realistic response + opening the possibility to study more exotics final states like LLPs

BACKUP

RESONANT SEARCHES: DELPHES PARAMETERS USED

Tracking:

	FCC-hh
B_z (T)	4
Length (m)	10
Radius (m)	1.5
ϵ	0.95
$\sigma(\eta, \phi)(mrad)$	1
$\sigma(p_T)/p_T$ (tracks)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(p_T)/p_T = 5\%$ (muons)	$p_T = 15$ TeV

Calorimeters:

	FCC-hh
$\sigma(E)/E$ (ECAL)	$10\%/\sqrt{E} \oplus 1\%$
$\sigma(E)/E$ (HCAL)	$50\%/\sqrt{E} \oplus 3\%$
$\eta \times \phi$ cell size (ECAL)	(0.01×0.01)
$\eta \times \phi$ cell size (HCAL)	(0.025×0.025)

ID efficiency and mis-tags:

	Electrons (%)	Muons (%)	Photons (%)	b-jets	τ-jets
FCC-hh	99	95	95	$(1 - p_T\ [\text{TeV}]/15)\cdot 85\%$	$(1 - p_T\ [\text{TeV}]/30)\cdot 60\%$

	Light (b-tag)	Charm (b-tag)	QCD (τ-tag)
FCC-hh	$(1 - p_T\ [\text{TeV}]/15)\cdot 1\%$	$(1 - p_T\ [\text{TeV}]/15)\cdot 5\%$	$(8/9 - p_T\ [\text{TeV}]/30)\cdot 1\%$

No event is cut based on its *b*-tagging count, but instead all the events are weighted to avoid stat issues.

Branch: master ▾ FCCAnalyses / FCChhAnalyses / FCChh /

Create new file | Find file | History

This branch is 3 commits ahead of clementhelsens:master.

Pull request | Compare

vvolkl add interpreter example and update doc — Latest commit ff161d2 on Feb 26

..		
Dijet_reso	Fix installation of the module	13 months ago
RSGraviton_ww	Fix installation of the module	13 months ago
W_top_vs_QCD_tagger	Fix installation of the module	13 months ago
Zprime_ll	Fix installation of the module	13 months ago
Zprime_mumu_flav_ano	Fix installation of the module	13 months ago
Zprime_tautau	Fix installation of the module	13 months ago
Zprime_tt	Fix installation of the module	13 months ago
h2l2v	Fix installation of the module	13 months ago
h4l	Fix installation of the module	13 months ago
haa	Fix installation of the module	13 months ago
hh_boosted	Fix installation of the module	13 months ago
hhbbaa	Fix installation of the module	13 months ago
hhbbaa_cms	Fix installation of the module	13 months ago
hmumu	Fix installation of the module	13 months ago
hza	Fix installation of the module	13 months ago
ttV_test	Fix installation of the module	13 months ago
tth_4l	add interpreter example and update doc	3 months ago
tth_boosted	Fix installation of the module	13 months ago
tth_mumu	Fix installation of the module	13 months ago
tttt	Fix installation of the module	13 months ago
vbs	Fix installation of the module	13 months ago
vbs_ww	Fix installation of the module	13 months ago
__init__.py	Fix installation of the module	13 months ago

Link to repository