Unlocking the Invisible

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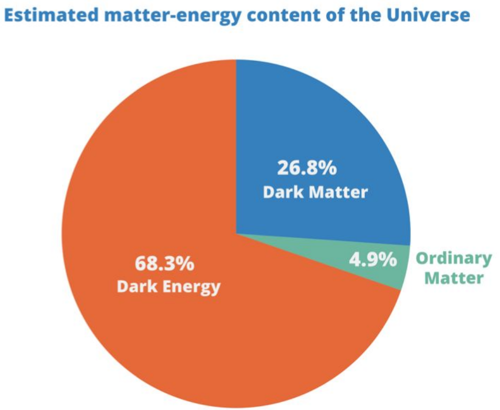
The Invisible Universe

- Existence of Dark matter has been proved by many experiments

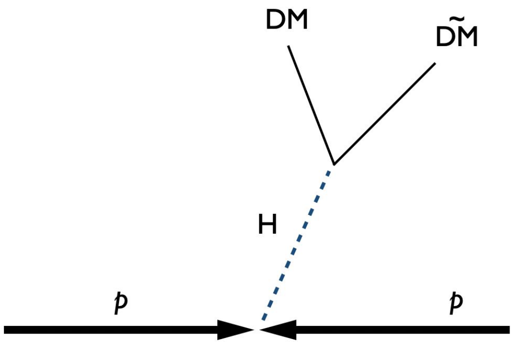
- Rich Phenomenology (BSM):
  Dark Matter Particles, axion-like particles

- Higgs-Portal models: SM Higgs acts as a mediator between the SM and the hidden DM sector

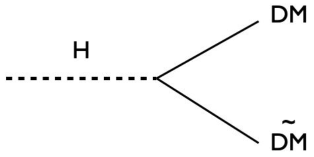
- No direct invisible Higgs decay in the SM,
  SM Higgs decay with similar signature ($H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$) very small (0.1%)



ATLAS EXPERIMENT



Invisible Higgs Decay

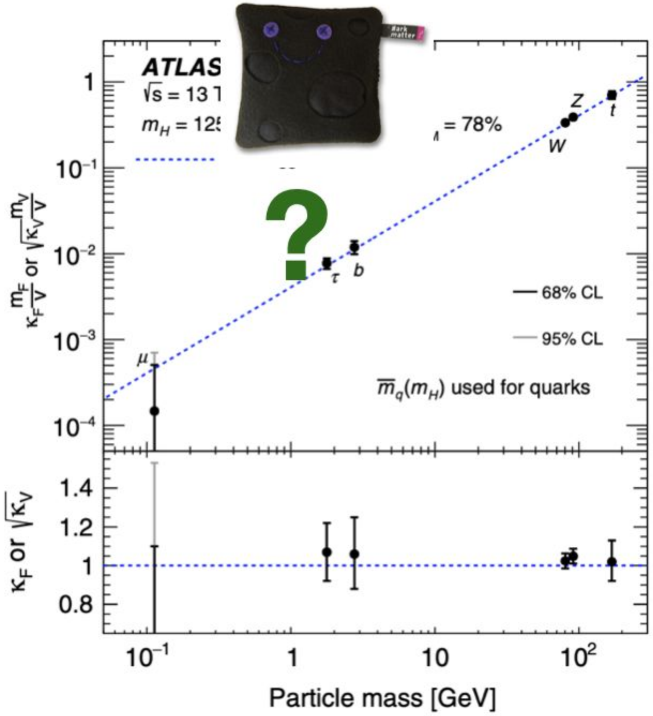


- Does the Higgs couple directly to dark matter particles ?

- For 2 x DM candidate mass < SM Higgs mass
  Direct decay of Higgs into DM particles

- Two possible ways to experimentally probe BSM decays of Higgs,
  - Measure known Higgs decays precisely
  - **Direct searches** for invisible Higgs decays

This Talk



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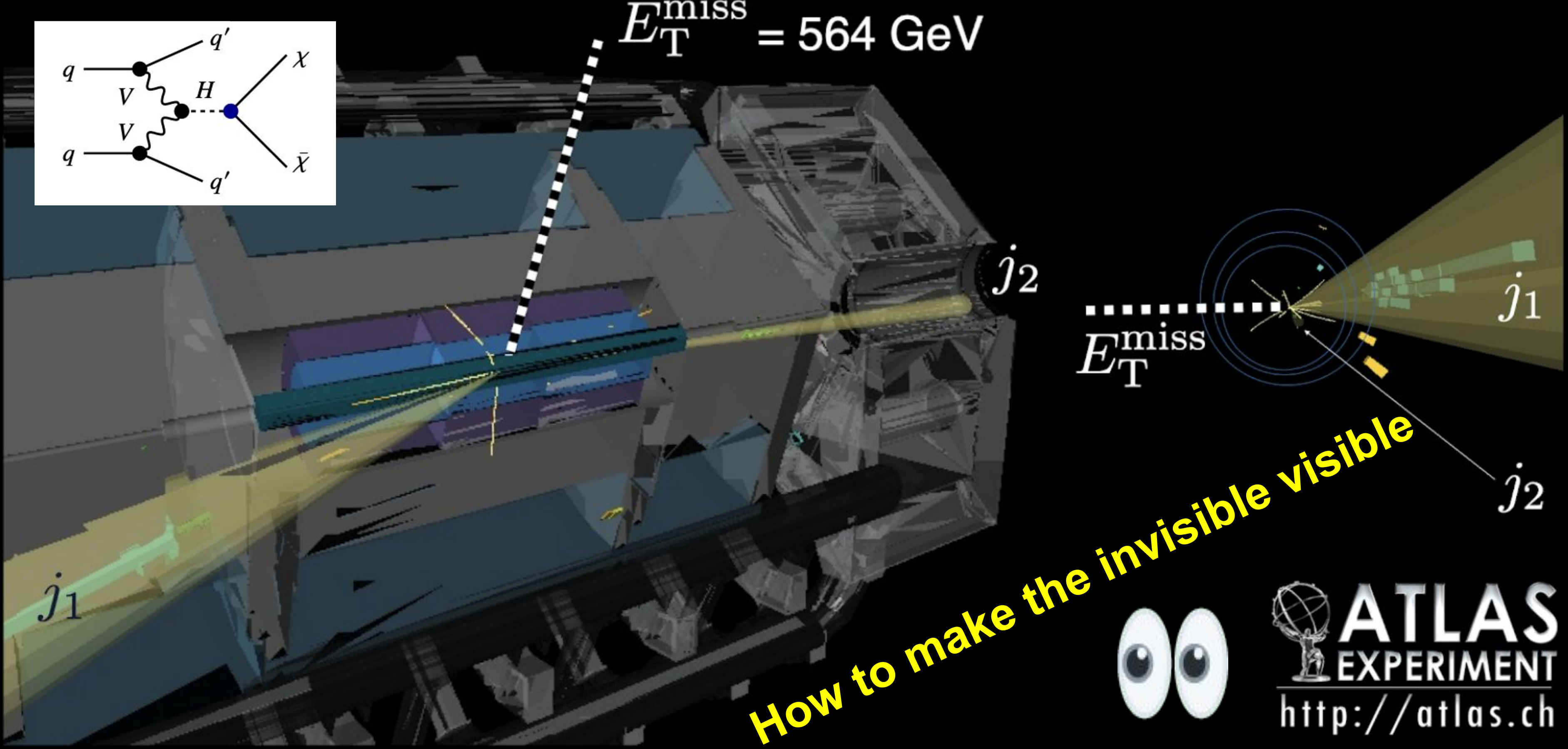
Candidate in signal region of $H \to \chi\bar{\chi}$ with two VBF jets (m_{jj} = 3.6 TeV)

Longitudinal view *Perspective x-y view*

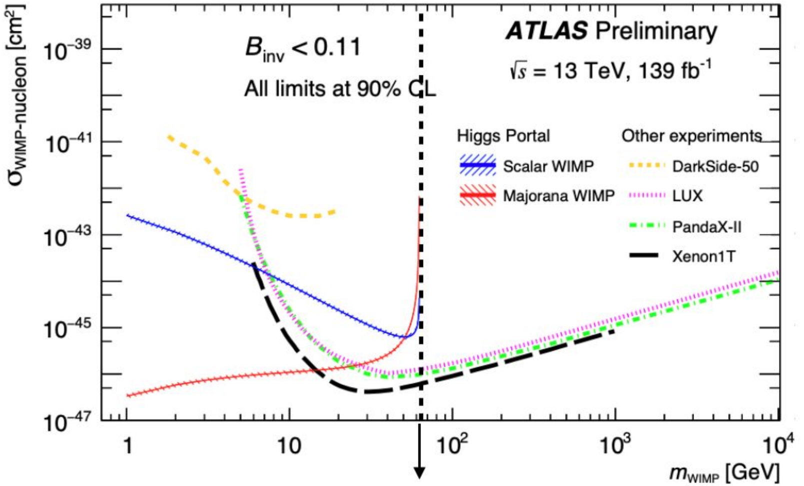


Latest ATLAS Sensitivity

- Main sensitivity to invisible decays comes from VBF Higgs production

- Experimental signature of signal:
  - Pair of quark jets with wide pseudorapidity* gap
  - missing transverse momentum signature of O(100 GeV) - decay

- observed (expected) upper limit of BR(H->inv) 0.13 (0.13) at 95 % CL



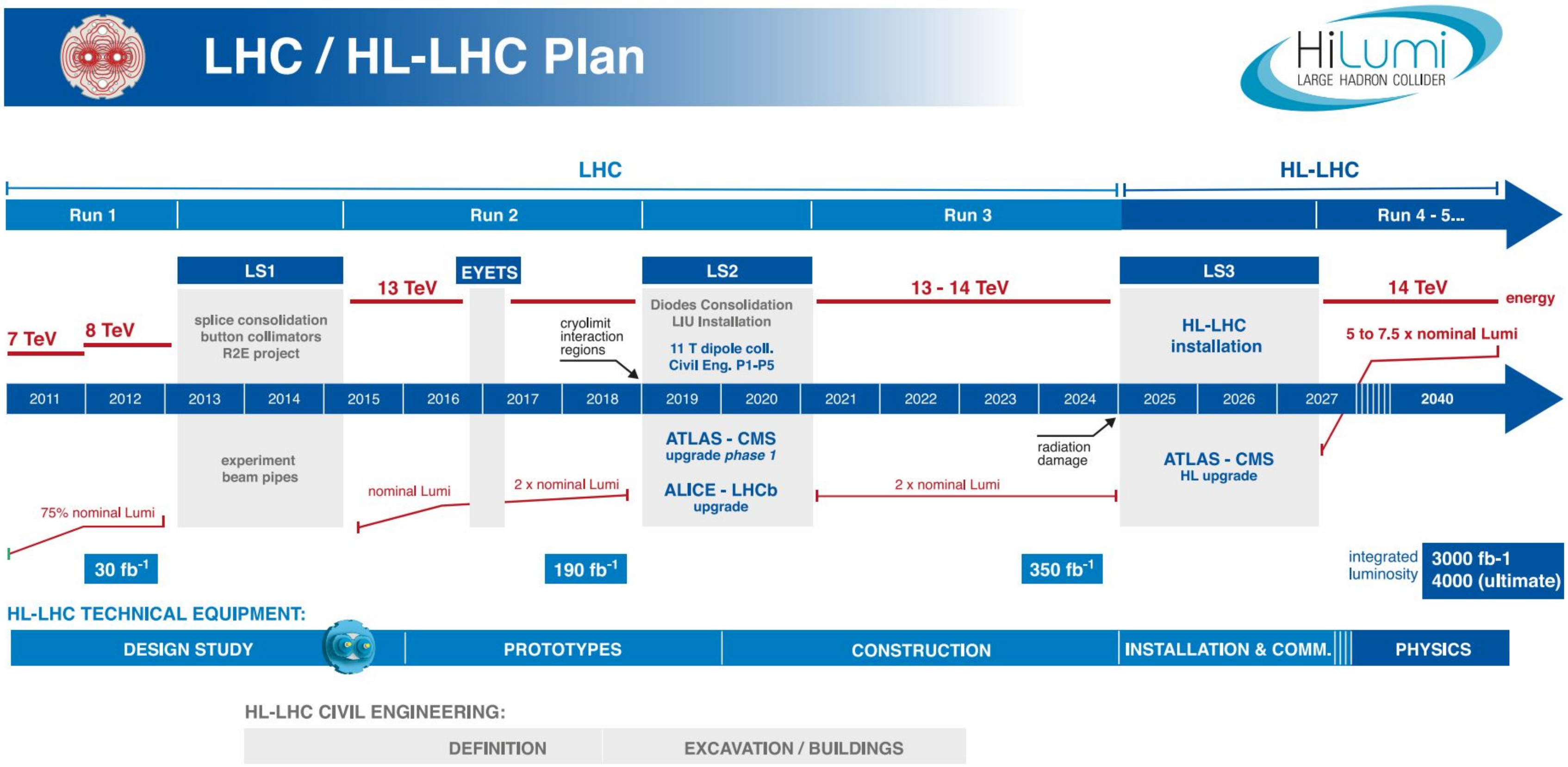
$$\frac{m_H}{2}$$

Source	Δ [%]
Jet energy scale	1.8
Jet energy resolution	5.5
Lepton	4.6
Other	1.9
Multijet	7.0
V+jets theory	1.6
Signal theory	1.0
MC stats.	7.9
Data stats.	17.3

* pseudorapidity = angle of a particle relative to the beam axis


FUTURE
HI-LUMI
https://www.youtube.com/watch?v=RBLnAhzPpTQ&feature=embtitle

Future accelerator: Timeline



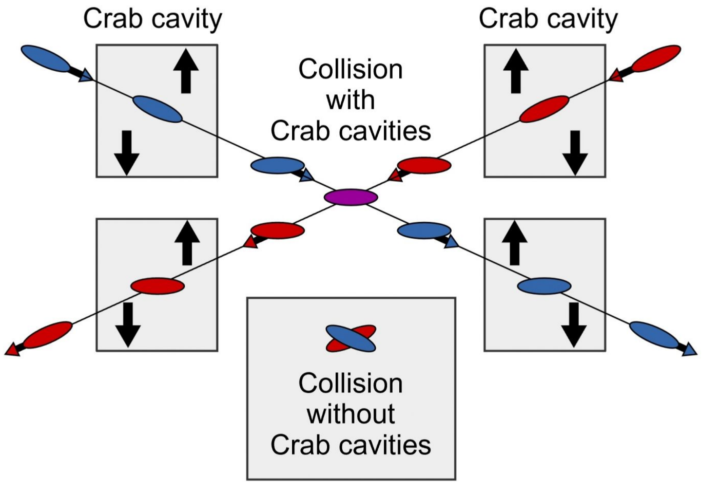
High Luminosity LHC setup

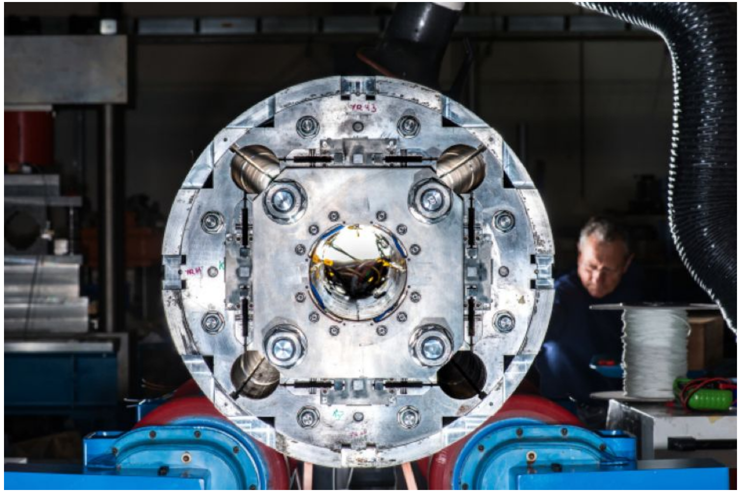
Instantaneous luminosity = # collisions per bunch crossing

⇒ HL-LHC factor ~5 more inst. luminosity

- upgrades to *make* more collisions (LHC)
- upgrades to *detect* more collisions (experiments, next slide)

1) Different superconductors for reaching >12T
   a) Needed to free up space around the experiments
   b) Better focusing
2) Increasing number of protons per bunch
3) Crab cavities





Weak points:

- Pile-up... (hadron-hadron collisions)
- vacuum degradation -> fake background

Detector Upgrades

Increased luminosity -> more collisions per bunch crossing -> more interactions with the detectors

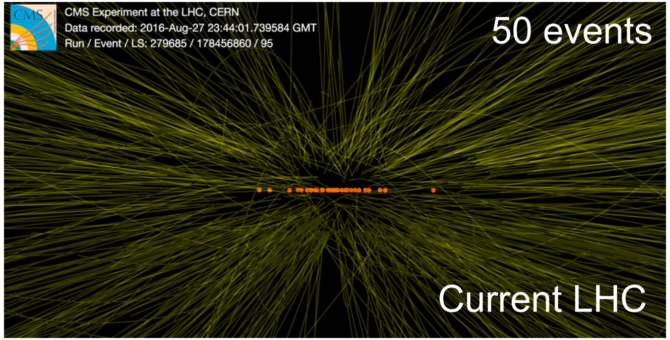
Need for upgrades in the experiments, main points:

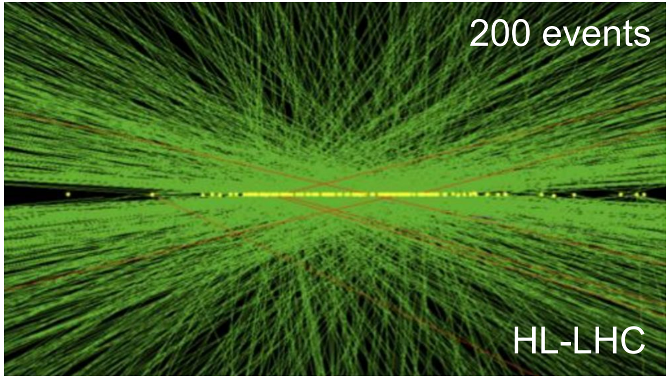
- Higher detector occupancy
  - Higher bandwidth
  - Increased radiation damage
  - Increased single event upsets
  - Faster algorithms

Solutions:

- 4D tracking (add timing detectors)
- Designing radiation hard devices
- Larger server farms - better connections

Design and test of new detectors already started for several experiments



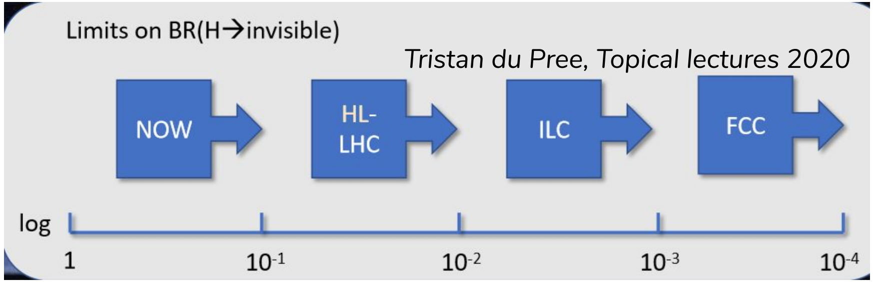


Gain in sensitivity

- Pileup mitigation technique not only will maintain but possibly improve MET performance

- Improved Lepton identification & pileup jet rejection

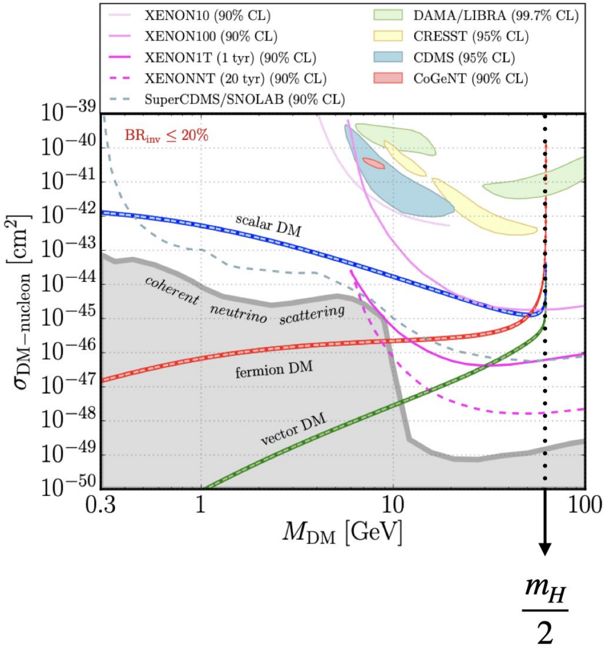
- HL-LHC - An leap in an order of magnitude for sensitivity,
  BR(inv.) < 0.025 at 95% CL for ATLAS+CMS HL-LHC
- Gain in sensitivity for BR(inv.) along with precise measurements of SM Higgs decay further improve our understanding of BSM Higgs decays BR(BSM)



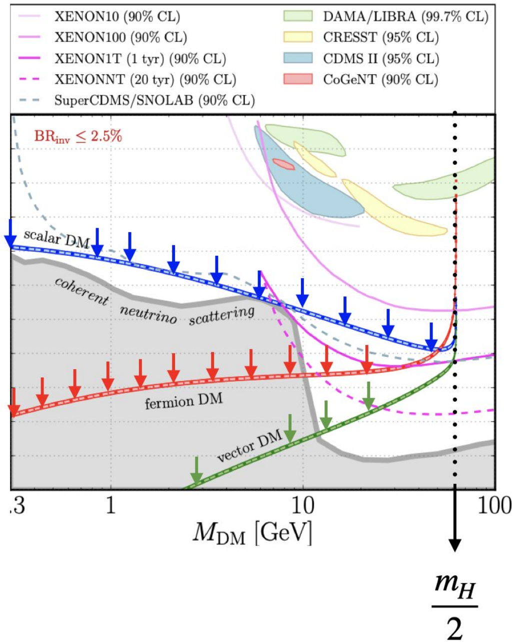
HL-LHC sensitivity to Dark Matter

- Higgs-portal model is an attractive option to test signatures of New Physics in collider and direct detection environments

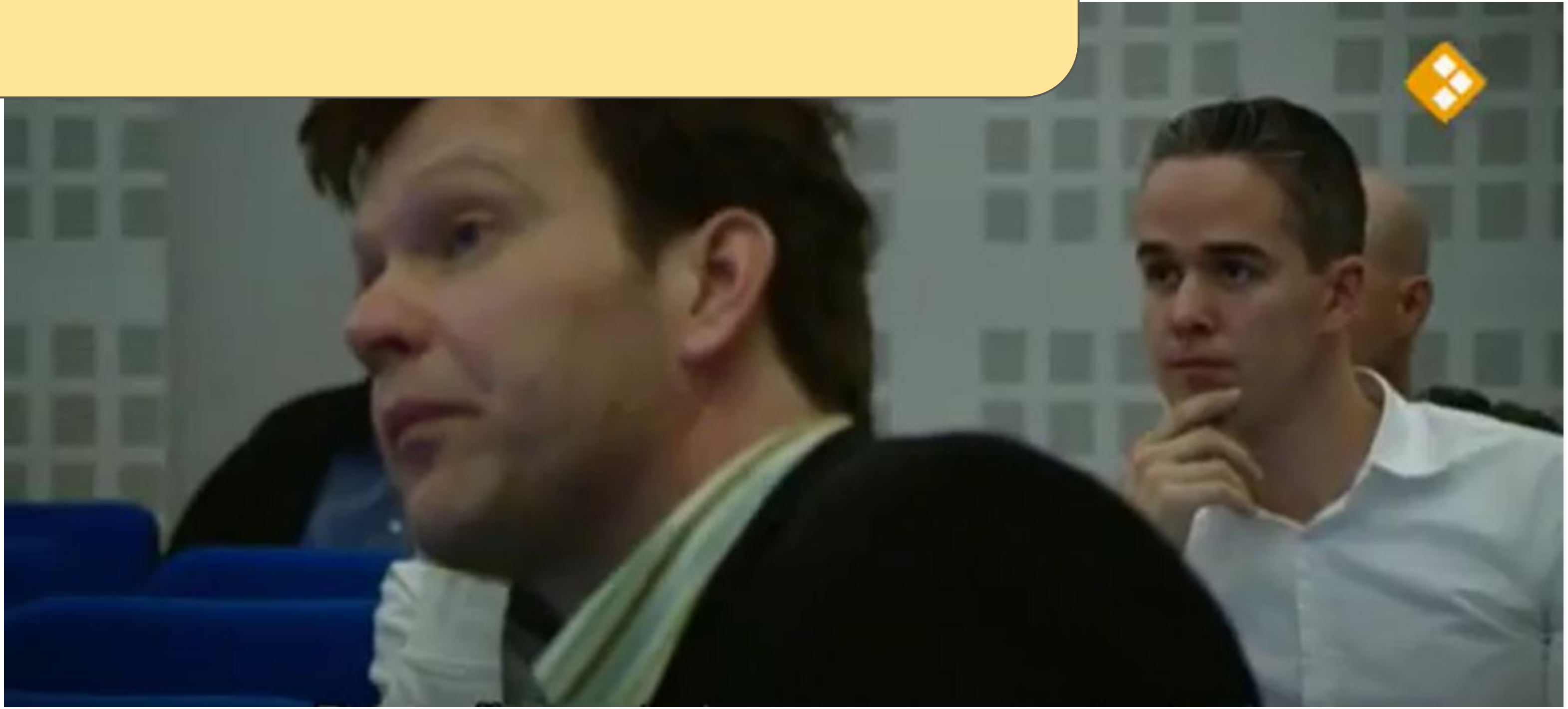
~ Present



@ HL-LHC



Thank you for your attention



https://higgsfilm.com/ https://www.youtube.com/watch?v=o8o_GA9v0P4

References

Papers

- Latest iteration of Higgs coupling measurements (ATLAS) https://cds.cern.ch/record/2688596/files/scoap3-fulltext.pdf Aad, G., Abbott, B., Abbott, D. C., Abdinov, O., Abud, A. A., Abeling, K., ... & Abramowicz, H. (2020). Combined measurements of Higgs boson production and decay using up to 80 fb− 1 of proton-proton collision data at s= 13 TeV collected with the ATLAS experiment. *Physical Review D*, *101*(1), 012002.
- Combined search for H to inv (ATLAS) https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.122.231801 Aaboud, M., Aad, G., Abbott, B., Abbott, D. C., Abdinov, O., Abud, A. A., ... & Abramowicz, H. (2019). Combination of searches for invisible Higgs boson decays with the ATLAS experiment. *Physical review letters*, *122*(23), 231801.
- Higgs Physics at HL-LHC https://arxiv.org/pdf/1902.00134.pdf Cepeda, M., Gori, S., Ilten, P., Kado, M., Riva, F., Khalek, R. A., ... & Asawatangtrakuldee, C. (2019). Higgs physics at the HL-LHC and HE-LHC. *arXiv preprint arXiv:1902.00134*.
- https://arxiv.org/pdf/2003.01662.pdf Wang, K., & Zhu, J. (2020). Funnel annihilations of light dark matter and the invisible decay of the Higgs boson. *Physical Review D*, *101*(9), 095028.

Presentations:

- Input to the update of the European Strategy for Particle Physics 2018-2020: The physics potential of HL-LHC https://indico.cern.ch/event/765096/contributions/3295995/attachments/1785339/2906404/HLLHC.pdf
- Higgs@HL-LHC brief summary of the Higgs chapter of the HL-LHC Yellow report https://indico.cern.ch/event/787473/contributions/3280723/attachments/1780373/2896465/SummaryHiggsHLLHC.pdf
- Invisible decays of the Higgs boson at the HL-LHC: experimental overview https://indico.cern.ch/event/756370/contributions/3185631/attachments/1739204/2814044/magnan_hinvftr_181023.pdf
- Doug Schafer's talk - contains the latest ATLAS measurements for VBF H-> inv. https://indico.cern.ch/event/868253/attachments/2023520/3384212/vbf_cern_phys_seminar.pdf (for instance on slide 31 and 32 has info on comparison of the measurement to other experiments

Bonus - Signal Region Definition

Events entering the signal region (SR) must satisfy the following requirements:

- The event contains no lepton candidate, nor a photon.
- The leading and sub-leading jets have $p_{\mathrm{T}} > 80\,\mathrm{GeV}$ and $50\,\mathrm{GeV}$, respectively. Both jets need to fulfil JVT or fJVT requirements indicating that they are stemming from the hard scattering process.
- The event contains two, three or four jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$.
- To ensure orthogonality to other searches, it is required that not more than one of the jets are b-tagged. The fraction of events removed by this requirement is less than 0.02% because most of the jets are outside the acceptance of the tracking detector.
- In the case of a third (i = j3) or fourth (i = j4) jet, the centrality of the additional jets must fulfil $C_i < 0.6$; for each of those jets m_i^{rel} has to be small: $m_i^{\mathrm{rel}} < 0.05$.
- The event has $E_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$, which strongly suppresses the multijet background.
- The soft track term of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is less than 20 GeV. This requirement removes $W \to \mu\nu$ in which the muon is not identified but reconstructed as a track. It further removes events from strong V+jets processes in a similar way like a veto on a third jet, which has such a low p_{T} that it is included in the soft track term.
- Further suppression of the multijet background is achieved by requiring $H_{\mathrm{T}}^{\mathrm{miss}} > 180\,\mathrm{GeV}$.
- The leading two jets are not back-to-back: $\Delta\phi_{\mathrm{jj}} < 2.0$.
- The leading two jets lie in opposite longitudinal hemispheres: $\eta^{\mathrm{j1}} \cdot \eta^{\mathrm{j2}} < 0$ and are well separated in η: $\Delta\eta_{\mathrm{jj}} > 3.8$.
- The invariant mass of the leading two jets is large: $m_{\mathrm{jj}} > 0.8\,\mathrm{TeV}$.

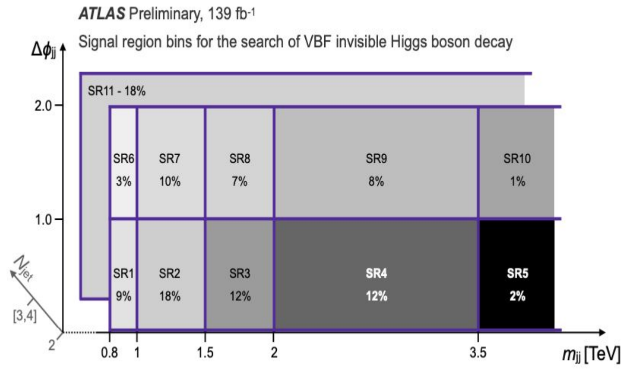
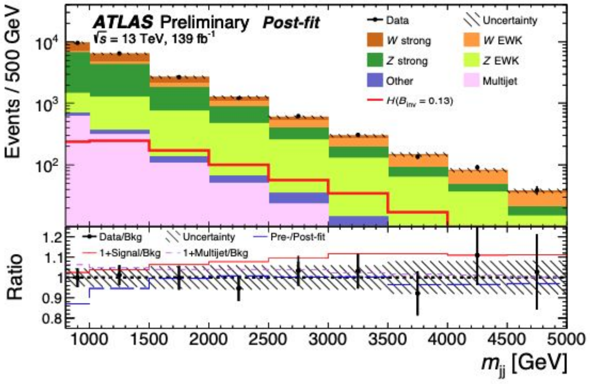
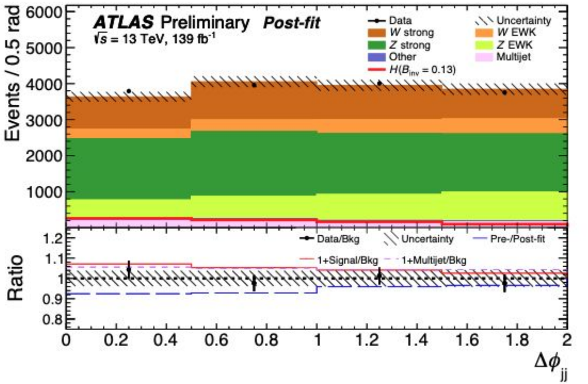
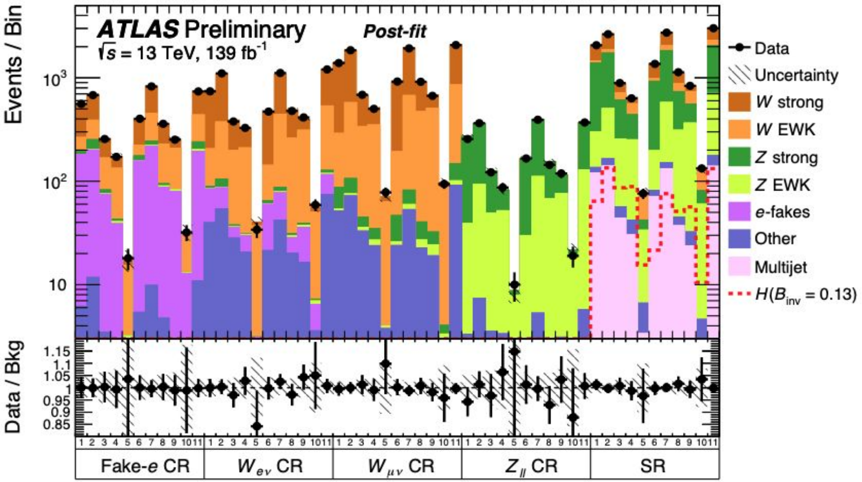


Figure 2: Schematic view of the eleven bins in the signal region. The shading indicates the signal to background ratio and a darker grey corresponds to a higher value. The percentage gives the distribution of signal from invisibly decaying Higgs bosons to each of the bins.

Bonus - Post-fit plots







Higgs Invisible

Connection between Higgs & Dark Matter

Run2 Limit ~20% @ 95%CL (in both experiments sensitivity dominated by the VBF channel)

From the global coupling fit, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\%$ @ 95% CL

Prospects of direct searches @ 14TeV:

VH: ATLAS, 2013: <8% @ 95%CL
VBF: CMS, 2018: <3.8% @ 95%CL

In the VBF case: full reoptimization of the analysis at 200PU to handle the impact of PU in MET