Search for Exotic Higgs Decays to Two Light Scalars in the 6b Final State with the ATLAS Experiment

–

(my PhD project)

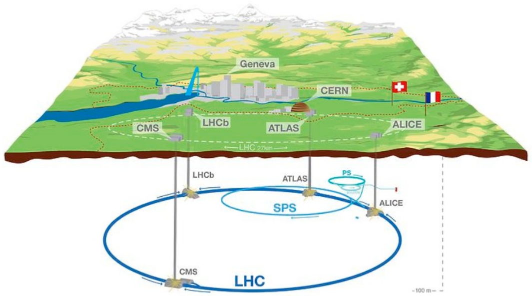
Judith Höfer (will start Postdoc position on ATLAS with Vasiliki soon)

AITANA group meeting, February 2nd 2024

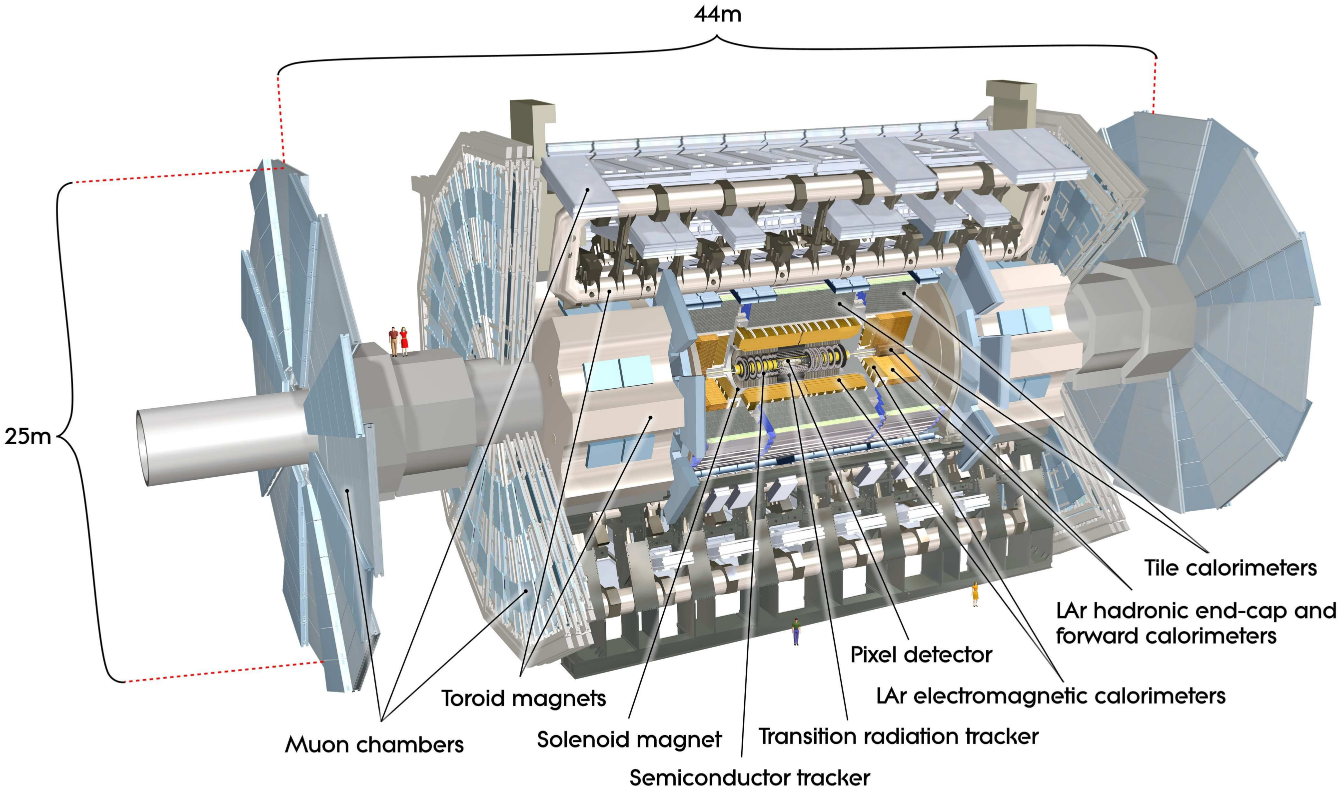
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

The ATLAS Detector



- **Multi-purpose particle detector**
- Built in the **layered structure** with tracking detectors, calorimeters and muon spectrometer



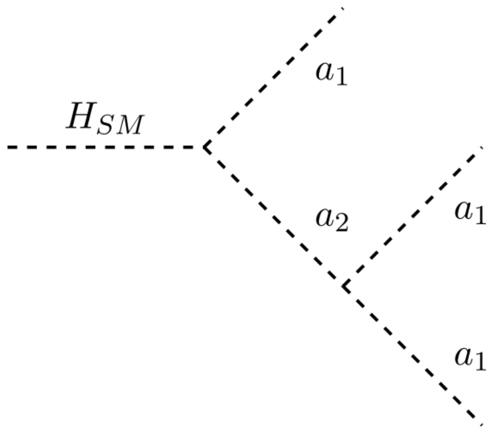
Signal Process

The TRSM and Cascade Decays

- Two Real Singlet Model (TRSM) extends Standard Model by **two additional real scalar singlets**
- They mix with Higgs boson → 3 physical scalar particles: H, a_1, a_2

- Consider mass range below m_H = 125 GeV
- Consider decay H → a_1 a_2

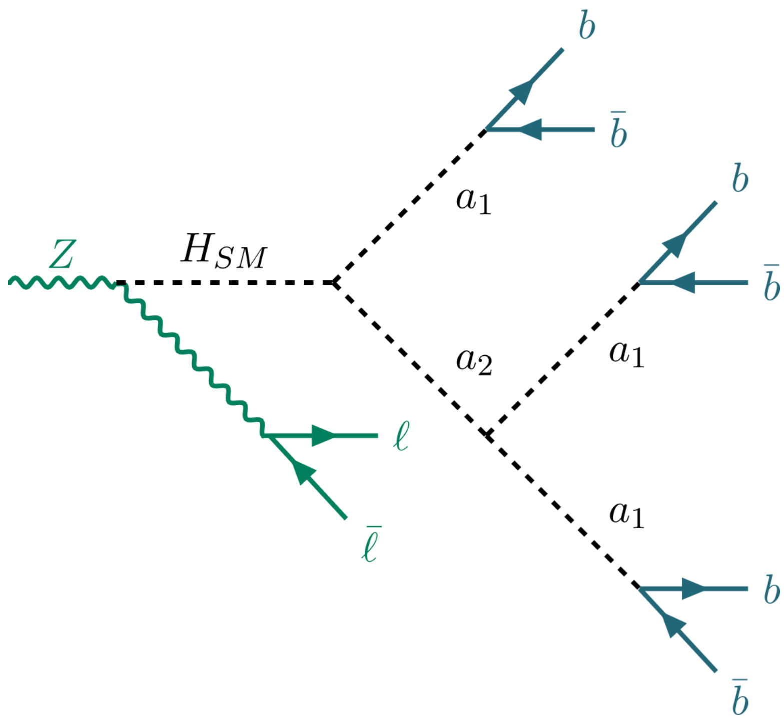
- If $m(a_2) > 2\, m(a_1)$, will decay $a_2 \rightarrow a_1\, a_1$ → **cascade decay** focus of this work



The Signal of This Analysis

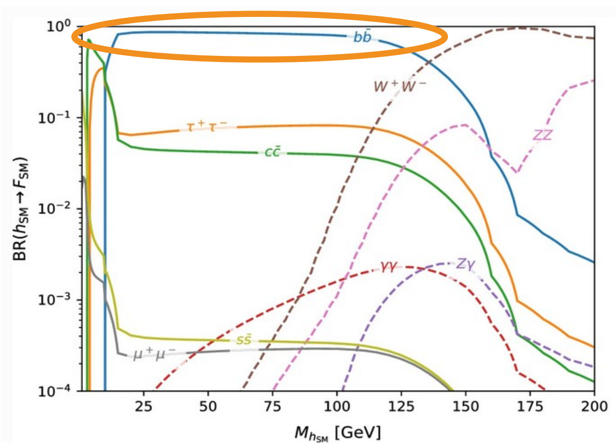
a_1 SM Higgs a_2

m_H = 125 GeV



- Cascade decay of Higgs boson
- Prompt decay of all light scalars to ***b* quarks**

  a → bb has highest branching ratio

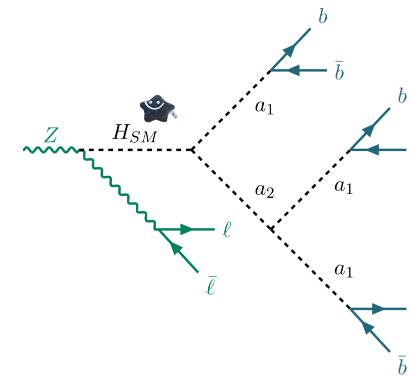


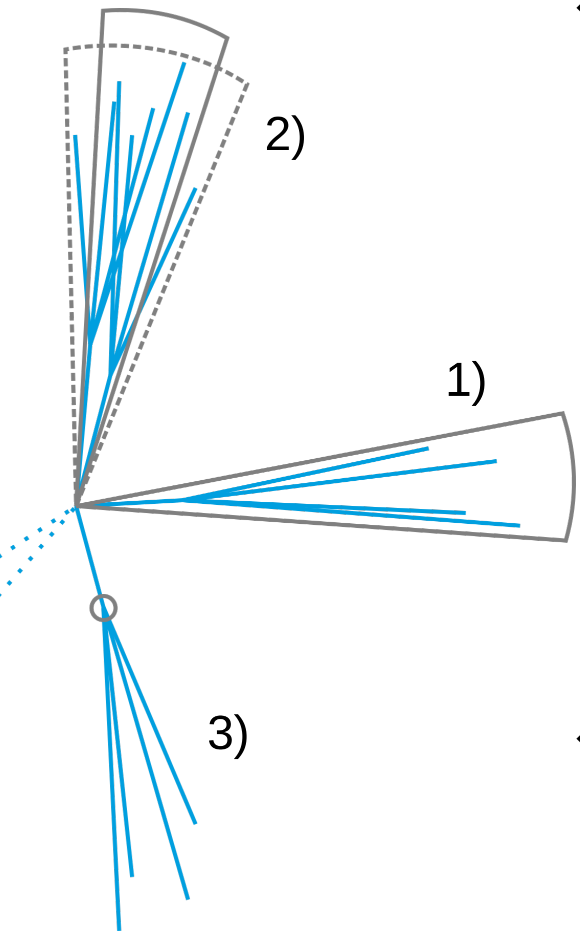
- Higgs boson produced in association with Z boson

  → Z boson decaying to charged leptons

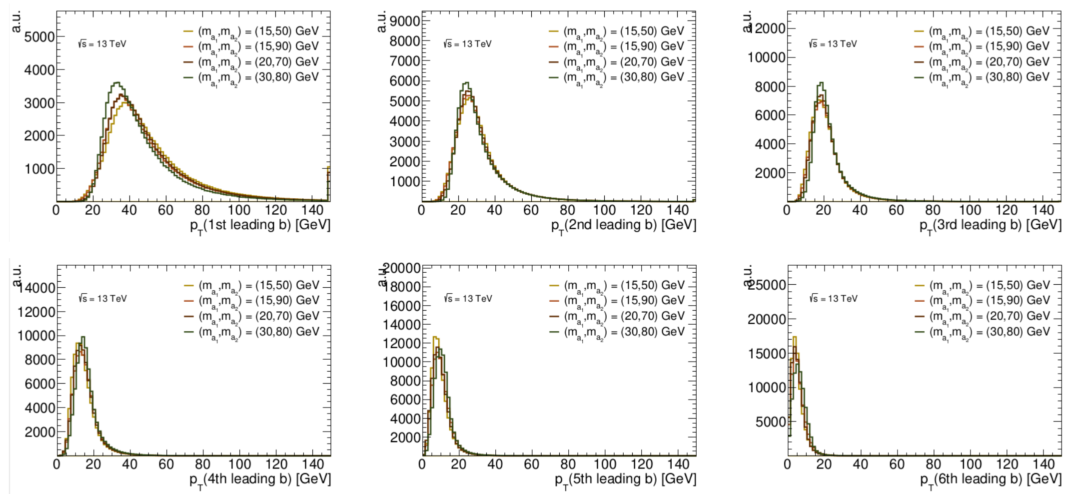
  → use charged leptons to trigger on

Low-Momentum b-Hadrons





- Signal final state consists of
  - 2 leptons
  - 6 b quarks, that have **very low transverse momentum p_T**



- Reconstruct with different **b-objects**

1) b-jets (standard ATLAS DL1r tagger)

2) double b-tagged jets (specialized DeXTer tagger)

3) soft secondary vertices (specialized TC-LVT tagger)

special objects

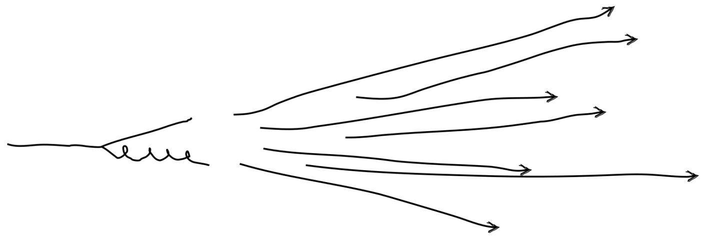
B Hadron Reconstruction

(decided to put more focus on this part)

Mechanism of Flavour Tagging

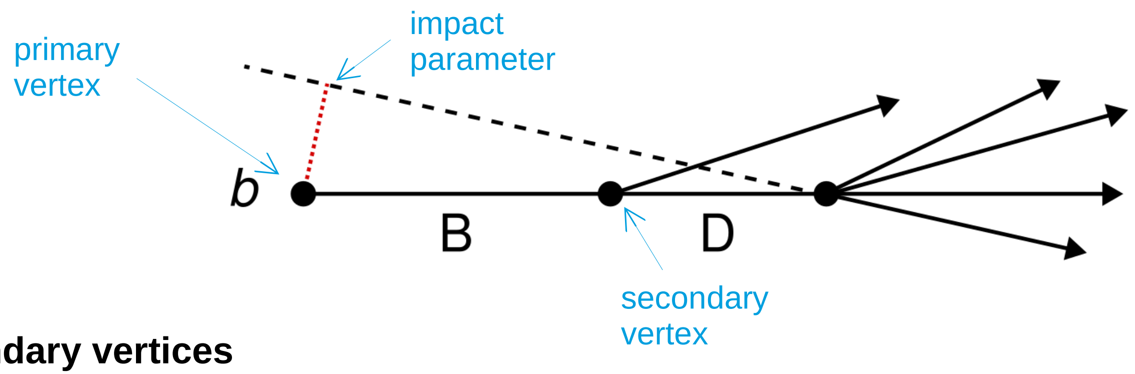
- Free quarks and gluons hadronize and form a collimated spray of particles

  → are reconstructed as **jets** from track and calorimeter information



- Hadrons containing *b* quarks tend to have a longer lifetime than many other hadrons

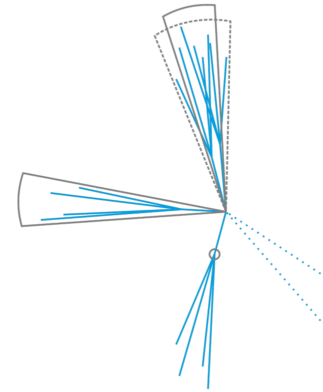
  → jets from b hadrons have recognizable features



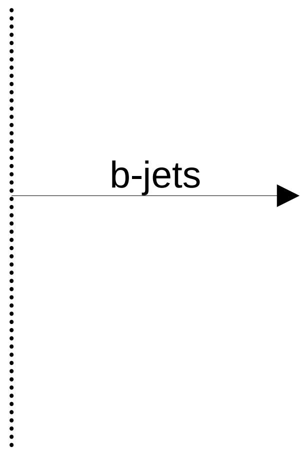
1) **secondary vertices**

2) tracks have larger distance to primary vertex, called **impact parameter**

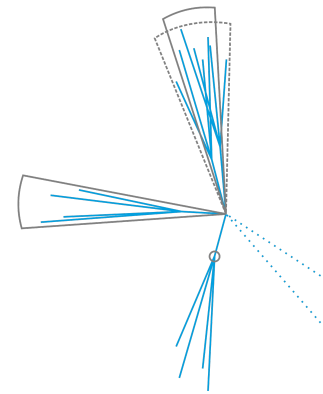
DL1r Flavour Tagging



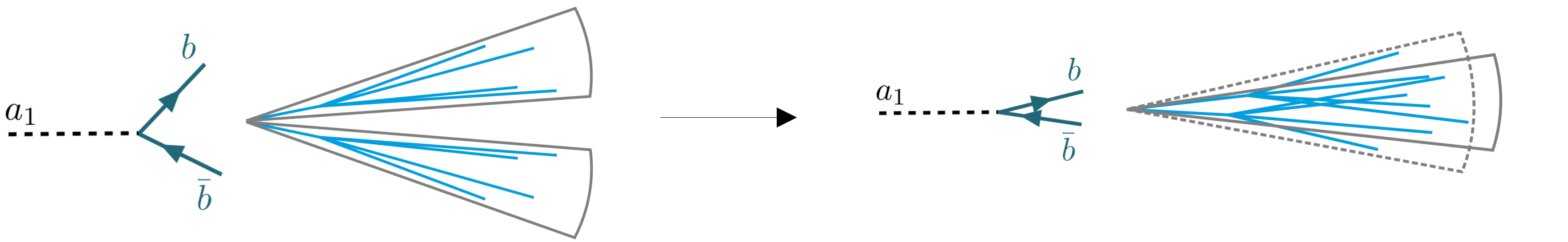
- Flavour tagging uses these recognizable features to classify jets as b-jets
- ATLAS tagger used here: **DL1r**, a deep neural network
- Inputs: secondary vertex and track variables
- Output: tagger discriminant: probability for each jet to be a b-jet



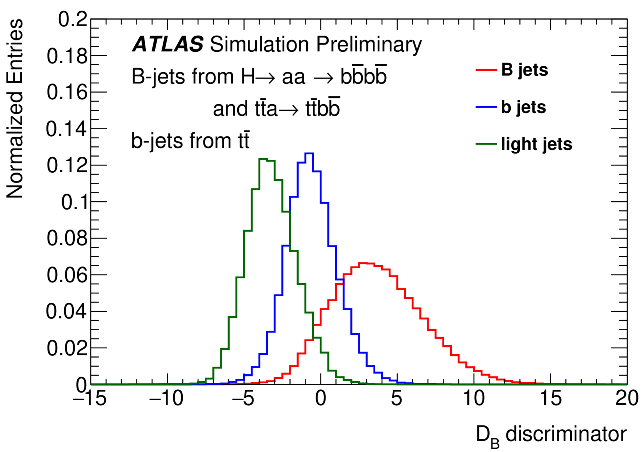
DeXTer Flavour Tagging

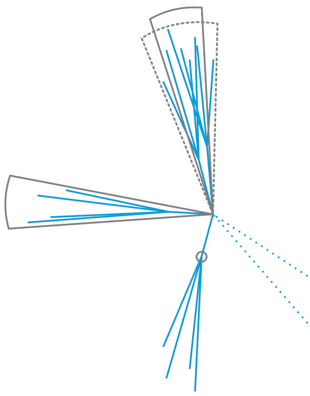


- For low a masses, the a boson has a higher momentum and is boosted
- Its decay products are collimated, and merge into one jet in the reconstruction



- Analysis team developed and calibrated specialized low-p_T $X \rightarrow bb$ tagger **DeXTer**
- Deep-Sets based neural network, aims to distinguish double-b-jets from b- and light jets





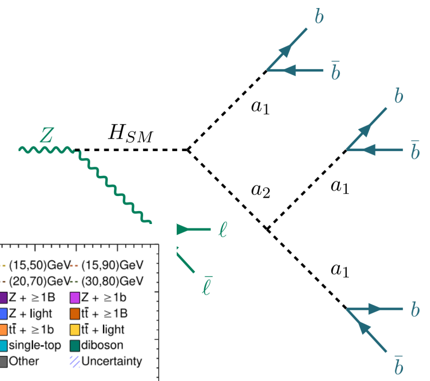
Soft Secondary Vertices

- Jet reconstruction has a lower momentum threshold of p_T > 15 GeV (here)
- But: some b hadrons are too low in momentum to be reconstructed as a jet
- Idea: reconstruct displaced vertices of b hadron decays **outside of jets**

  → **soft secondary vertices** with TC-LVT algorithm
- TC-LVT algorithm first builds track clusters:
  - Find seed tracks with high momentum, high impact parameter
  - Cluster tracks around seed track
- Apply a secondary vertexing algorithm (SSVF) to *cluster of tracks (instead of a jet)*

Analysis & Results

Analysis Strategy Overview

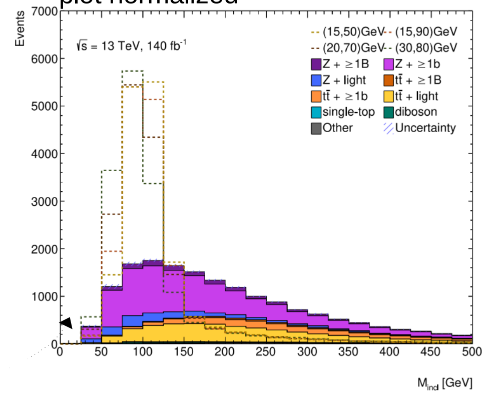


- Define **signal regions**:

  get events enriched in signal

  - Select high number of reconstructed b-jets (/ b-objects)
  - Define variables discriminating signal from backgrounds
  - Use machine learning to define signal regions

plot normalized



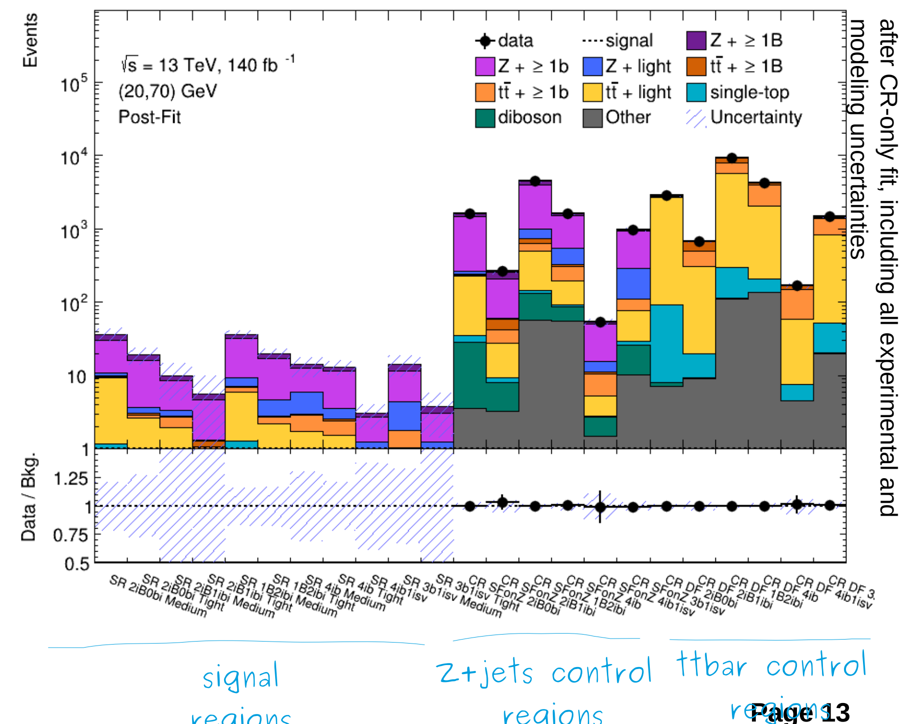
- Define **control regions**:

  control modeling of backgrounds

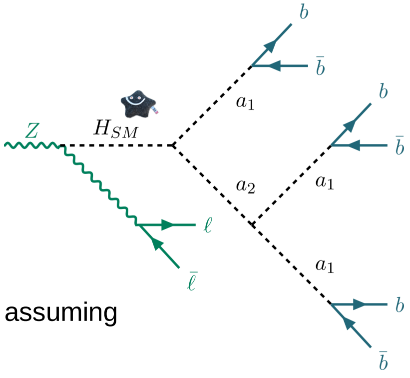
  - Close to signal regions, but low signal contamination

- Extract **signal strength** in stat. analysis:

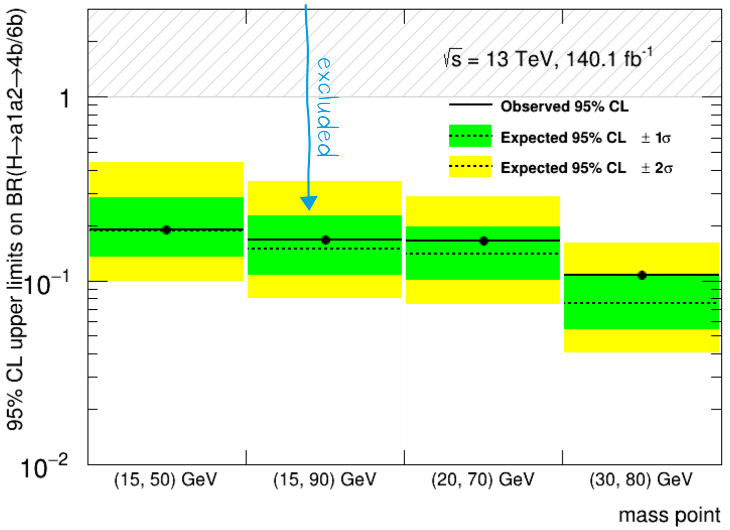
  - profile llh fit to
    compare simulated data to measured data



Limit on the Signal



- **No signal is observed** → calculate **limit** on signal strength (limit on BR(H → a_1a_2 → 6b), assuming SM cross section for ZH production)
- Determined for different signal scenarios, ranges from 11 – 19 %



Conclusion

- Novel b hadron reconstruction techniques are the backbone of the analysis
- Set first ever limit on this H → a_1a_2 → 6b signal

Thanks for listening.

Any questions? :)

Contact

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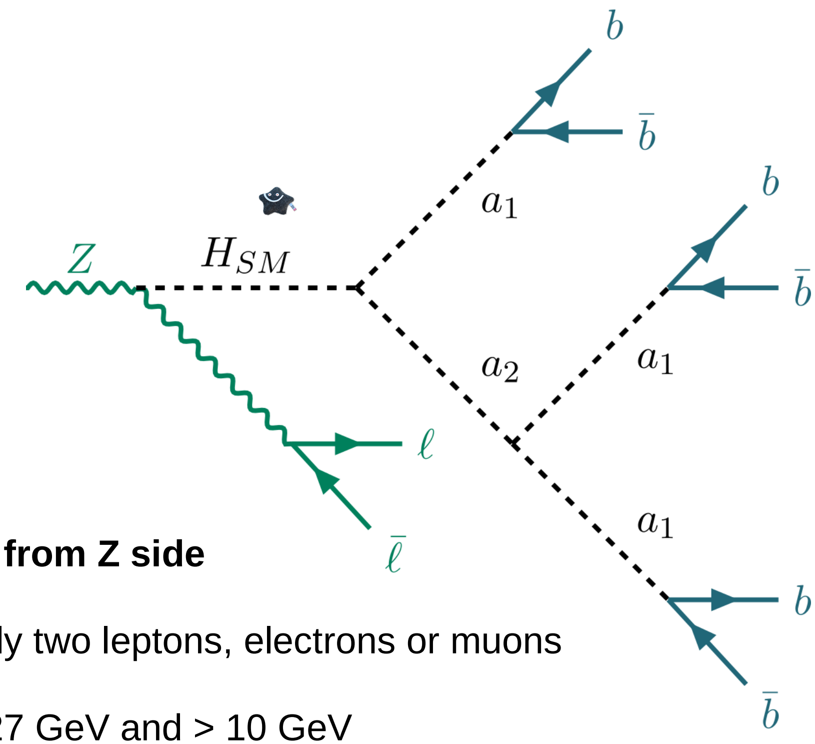
Object and Event Selection

Analysis is based on full Run2 data, 140/fb



leptons from Z side

- exactly two leptons, electrons or muons
- p_T > 27 GeV and > 10 GeV
- Same flavour, opposite charge
- 71 GeV < mll < 111 GeV

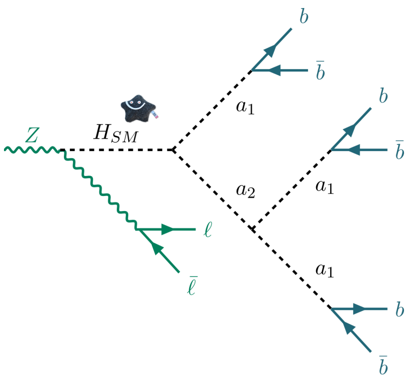
b-objects from Higgs side

1) standard **b-jets** (DL1r)
2) double-b-tagged **B-jets** (DeXTer)
3) **soft secondary vertices** (TC-LVT)

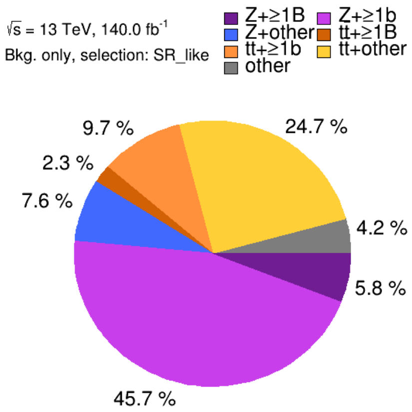
- at least 4 b-objects (B-jets count double)

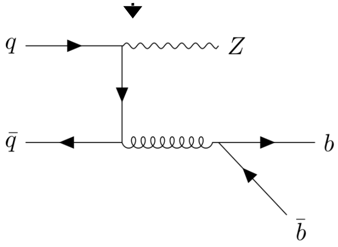
$$(2 \cdot N_{\text{B-jets}} + N_{\text{b-jets}} + N_{\text{soft SV}}) \geq 4$$

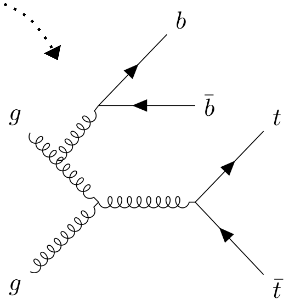
Main Backgrounds



- Given the event selection, the main backgrounds are **Z+jets and tt**

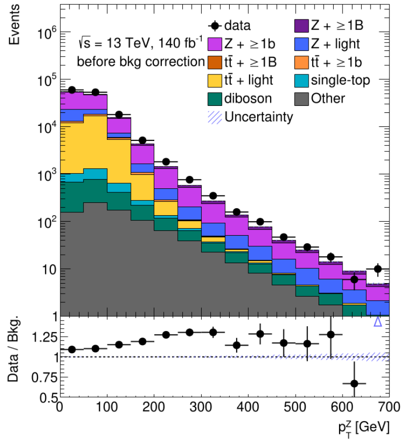


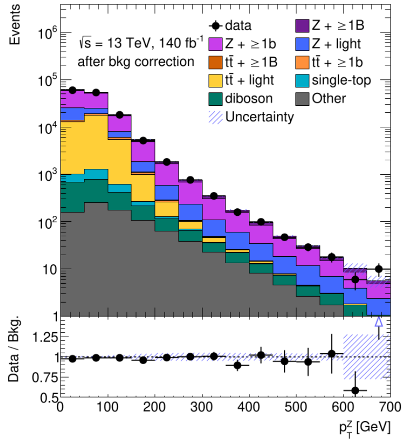




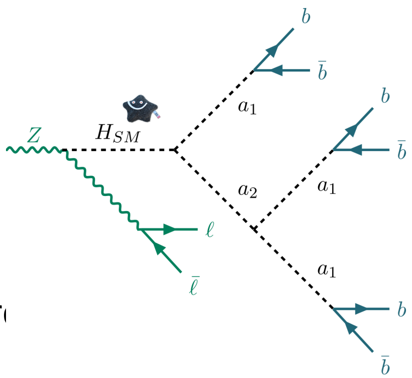
- Modeling of backgrounds, especially with larger numbers of additional jets, is imperfect

- Analysis team carried out a background correction, correcting background modeling based on flavour and kinematic variables





Multiplicity Regions

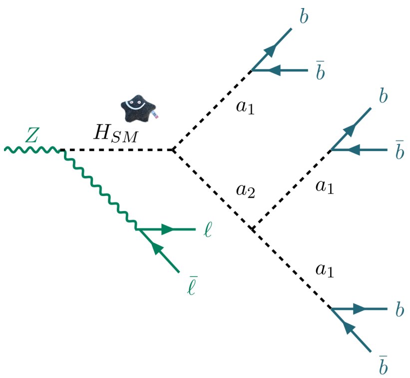


- To design **signal-enriched regions**, target partially reconstructed final states here
- Usually not all 6 b hadrons in the final state are reconstructed:
  - limited detector acceptance
  - limited object reconstruction and tagging efficiencies

  → select events with 4 or more b-objects (B-jets count double)
- Categorize events in 6 orthogonal **multiplicity regions**

region	B-jets	b-jets	soft SVs	number of b-objects
2iB0bi	≥ 2	$= 0$	any	≥ 4
2iB1ibi	≥ 2	≥ 1	any	≥ 5
1B2ibi	$= 1$	≥ 2	any	≥ 4
4ib	$= 0$	≥ 4	$= 0$	≥ 4
4ib1isv	$= 0$	≥ 4	≥ 1	≥ 5
3b1isv	$= 0$	$= 3$	≥ 1	≥ 4

Discriminating Variables



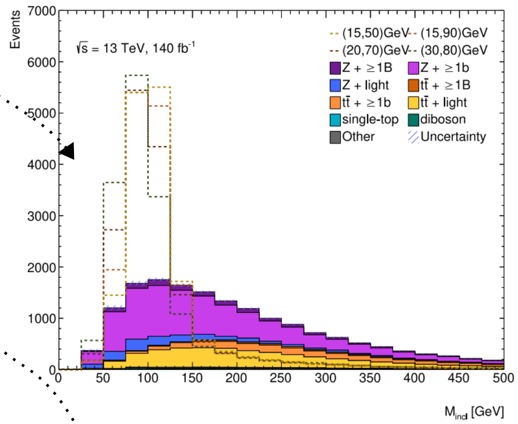
- Select variables that discriminate signal from backgrounds
- **Invariant mass of all b-objects**

  → in signal it reconstructs to about the SM Higgs mass
- (average) **angular distance between b-jets**

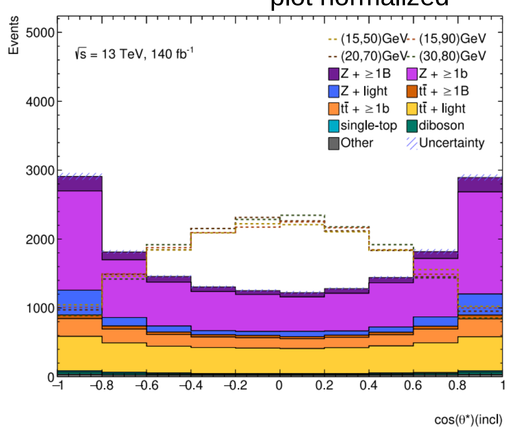
  → smaller in signal, as b pairs come from one parent particle
- **Polar angle of Higgs** in ZH rest frame
  (with Higgs from b-objects, Z from leptons)

  → sensitive to spin-0 nature of Higgs

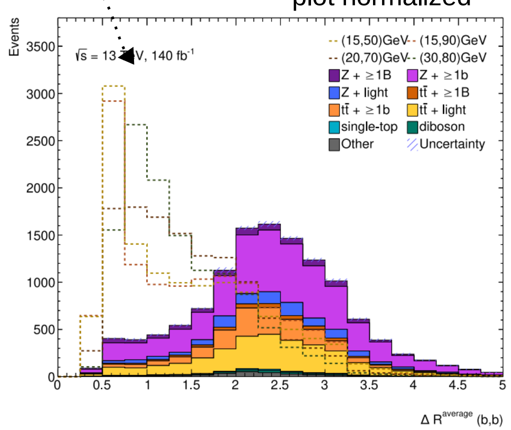
plot normalized



plot normalized

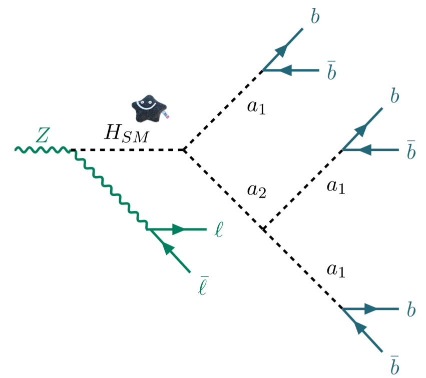


plot normalized



Part 6: Analysis

Multi-Variate Analysis



- Utilize multi-variate analysis (BDT) for signal - background discrimination
- Train BDT **for each mass point in each multiplicity region**
- Input: discriminating variables, output: discriminant score

plots normalized

1B2ibi region

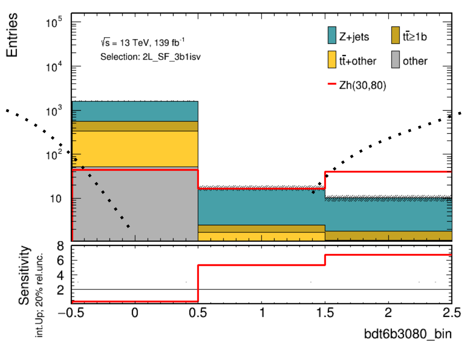
4b region

3b1isv region

- Select binning on output discriminant to get 3 bins (optimized with significance)

Loose

control regions
for Z+jets



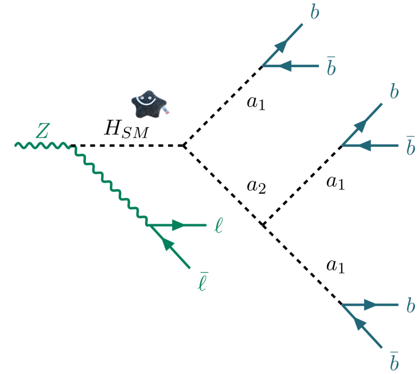
Medium and Tight

signal regions

Region Definitions

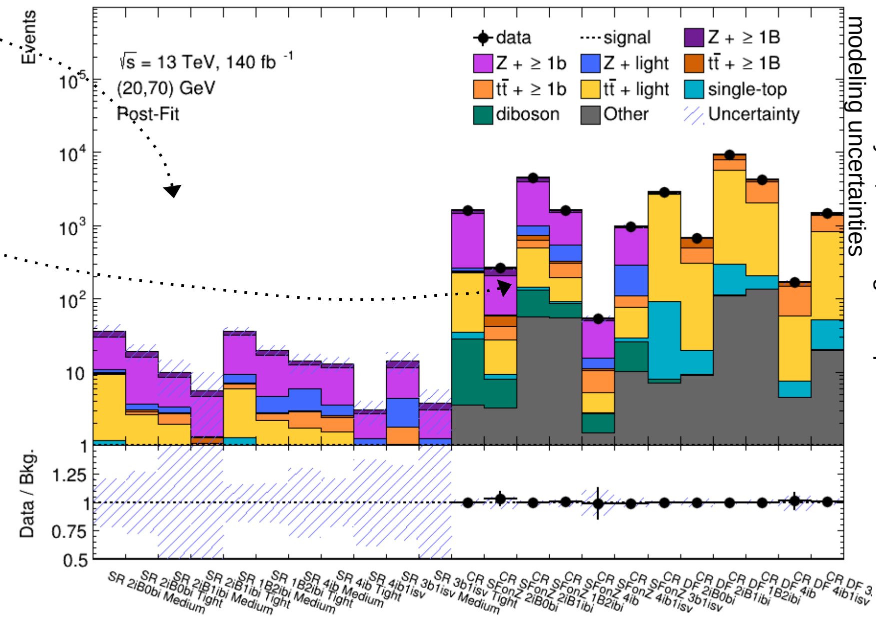
multiplicity regions

	B-jets	b-jets	soft SVs
2iB0bi	≥ 2	= 0	any
2iB1ibi	≥ 2	≥ 1	any
1B2ibi	= 1	≥ 2	any
4ib	= 0	≥ 4	= 0
4ib1isv	= 0	≥ 4	≥ 1
3b1isv	= 0	= 3	≥ 1



- **Signal regions**
  - based on multiplicity regions
  - in each multiplicity region, select *Medium* and *Tight* BDT bins

- Define two sets of **control regions**
  - Z+jets CRs:
    - same multiplicity regions
    - *Loose* BDT bin
    - tighter mll requirement and E_t^{miss} selection
  - ttbar CRs:
    - same multiplicity regions
    - two leptons: different flavour (eμ), opposite sign



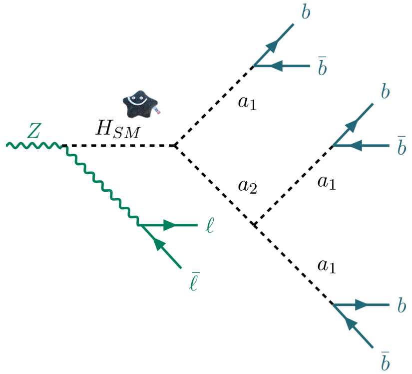
after CR-only fit, including all experimental and modeling uncertainties

signal regions

Z+jets control regions

ttbar control regions

Uncertainties

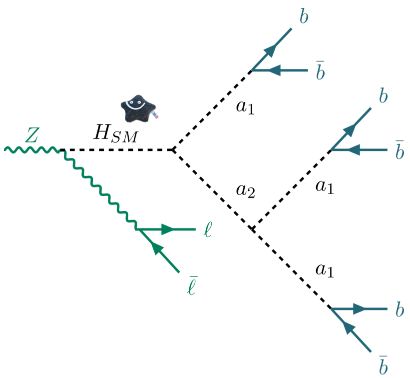


- **Experimental uncertainties** are considered for all objects and all processes
  - Luminosity, Pile-up
  - Leptons, Lepton trigger efficiencies
  - Jets, Tracking
  - DL1r and DeXTer flavour tagging, Soft secondary vertices (from calibration carried out here)
  - Uncertainties from kinematic background reweighting

- **Modeling uncertainties** are considered for **signal** and the **Z+jets and tt backgrounds**
  - Renormalization and Factorization Scale
  - ISR and FSR Modeling
  - PDF Uncertainties
  - Parton Shower and Hadronization

Part 7: Results

Summary and Conclusion



- The Standard Model is a very successful theory, but we know it is incomplete
- Additional light scalars are a prominent extension

- Performed a search for exotic Higgs decays to two new scalars in the **full b final state**, considering **cascade** decay process
- **Novel b hadron reconstruction techniques** are the backbone of the analysis
- Use multiplicity regions and multi-variate analysis to define signal and control regions

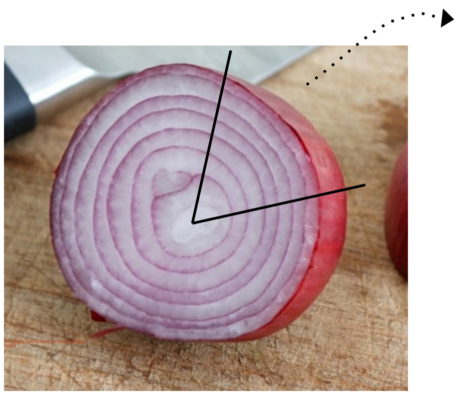
- No signal was observed
- Set **first ever limit** of an LHC analysis on the decay of the SM Higgs boson to two light scalars of different mass undergoing a cascade decay

Detection Principles

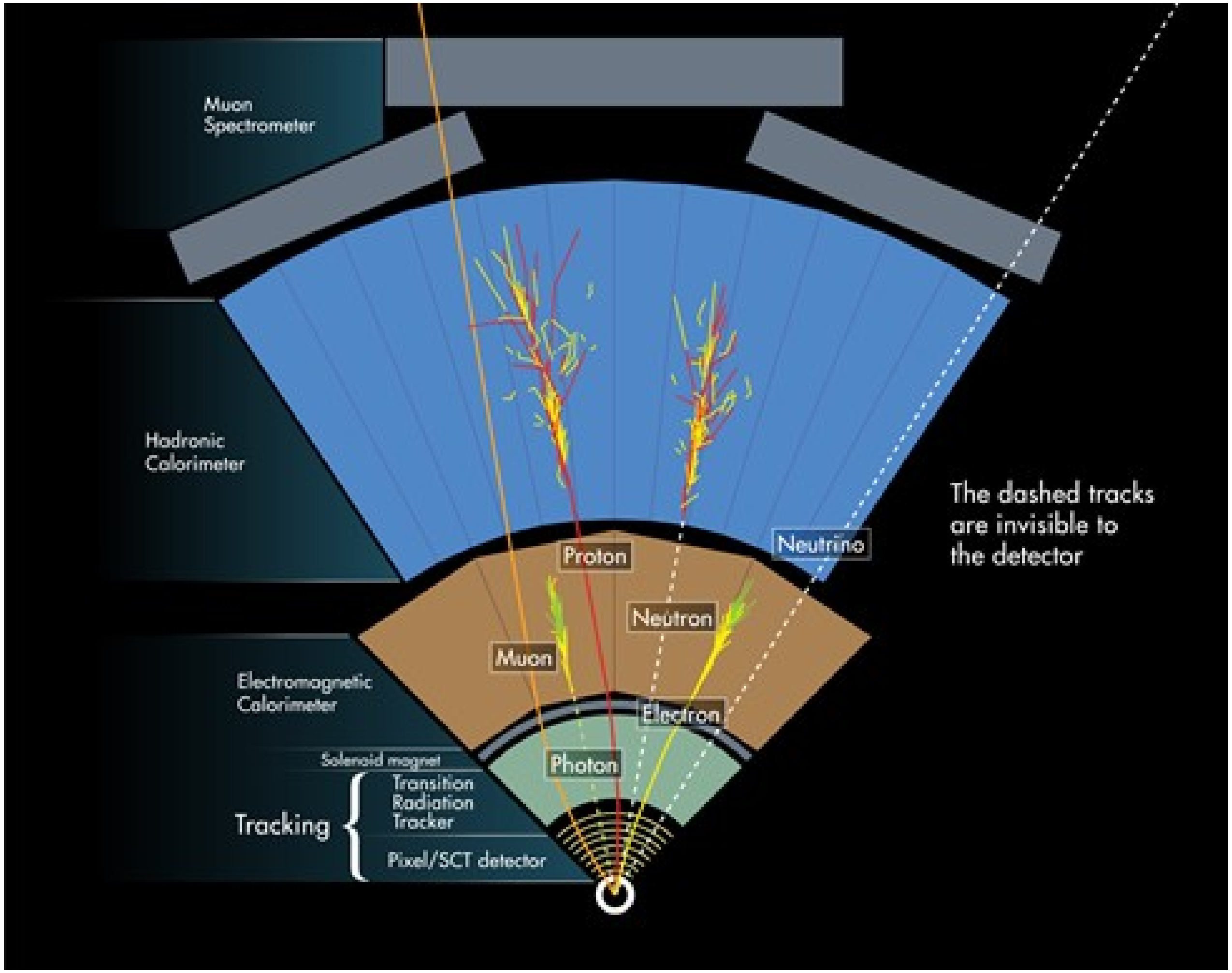
- Newly produced particles and decay products have different interactions with detectors

  → utilize different detection principles

  → build detectors having **many layers**



https://atlanticeyeinstitute.com/4-ways-to-reduce-tearing-while-cutting-onions/



Backup

Additional Material: Theory and Other Measurements

Backup

Current constraints on H → undetected

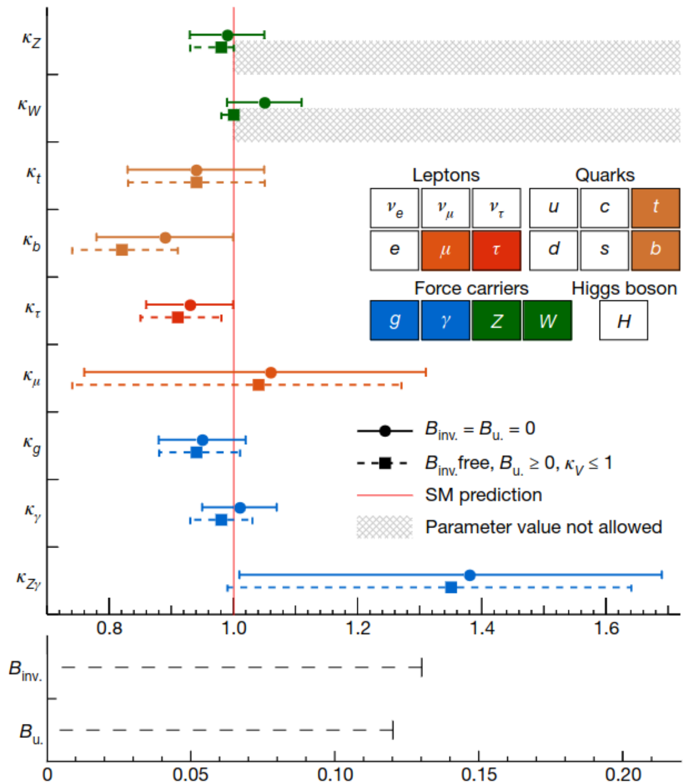
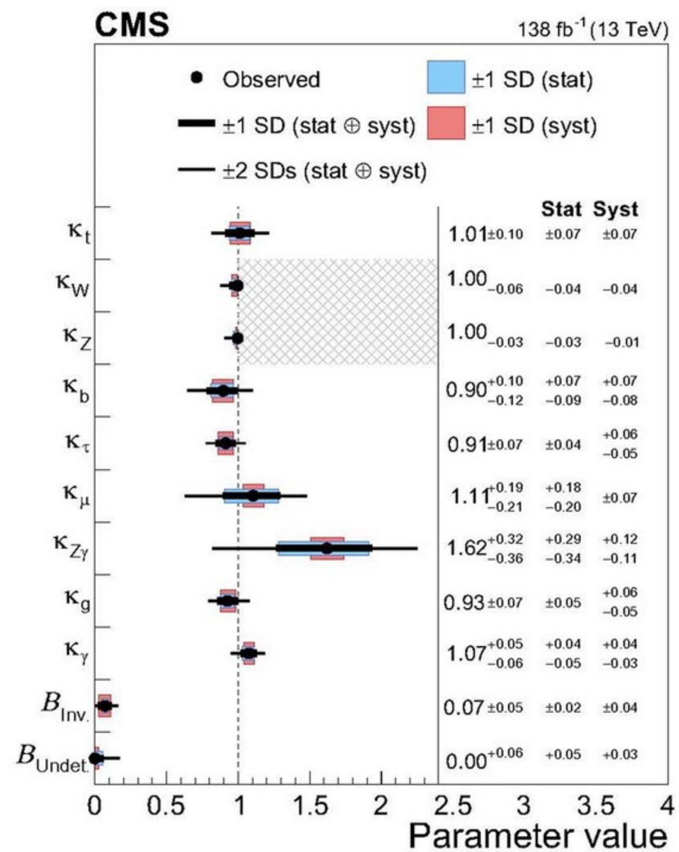


Fig. 6 | Reduced coupling strength modifiers and their uncertainties per particle type with effective photon, $Z\gamma$ and gluon couplings. The horizontal bars on each point denote the 68% confidence interval. The scenario in which $B_{inv.} = B_{u.} = 0$ is assumed is shown as solid lines with circle markers. The *p* value for compatibility with the standard model (SM) prediction is 61% in this case. The scenario in which $B_{inv.}$ and $B_{u.}$ are allowed to contribute to the total Higgs boson decay width while assuming that $\kappa_V \leq 1$ and $B_{u.} \geq 0$ is shown as dashed lines with square markers. The lower panel shows the 95% CL upper limits on $B_{inv.}$ and $B_{u.}$. Data are from ATLAS Run 2.



“The 95% CL upper limit on B_Undet. is found to be <0.16, with only small changes to the other κi fitted values”.

Parameter space for 1st order EWPT, light scalars

2203.08206

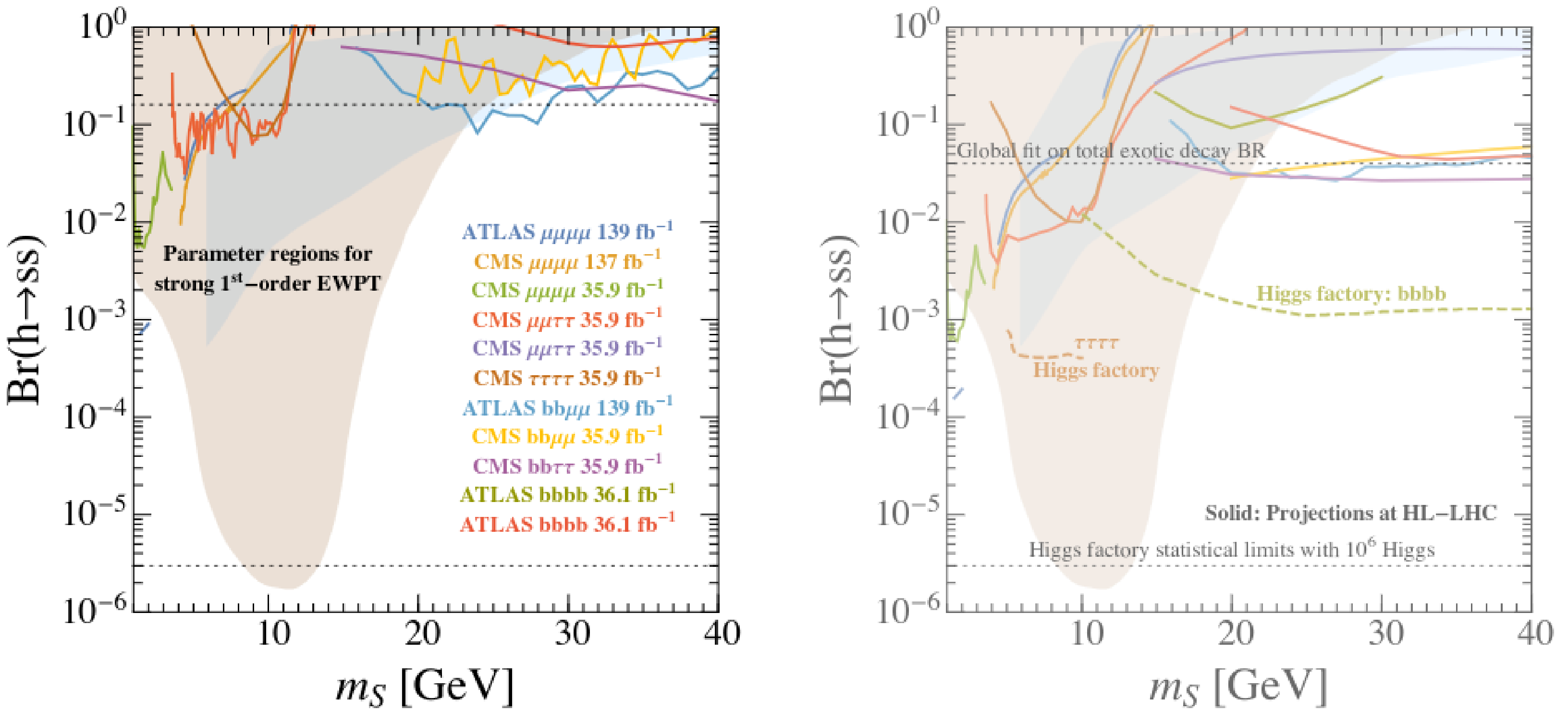


FIG. 4: The current bounds on Higgs exotic decay $h \to ss$ and the projections at the HL-LHC, assuming the s decays to SM particles are mediated by the mixing, and the corresponding branching ratios are taken from Ref. [17]. The upper and lower horizontal dotted lines are the expected upper limit for Higgs exotic decay branching ratio at the HL-LHC (4% [39]) and statistical limit of 10^6 Higgs at future lepton colliders, respectively. The brown and light blue shadowed regions are the strong first-order EWPT regions from Refs. [6, 7], see text for details. Projections of the reach of future lepton colliders are shown in dashed lines.

Other light scalar searches

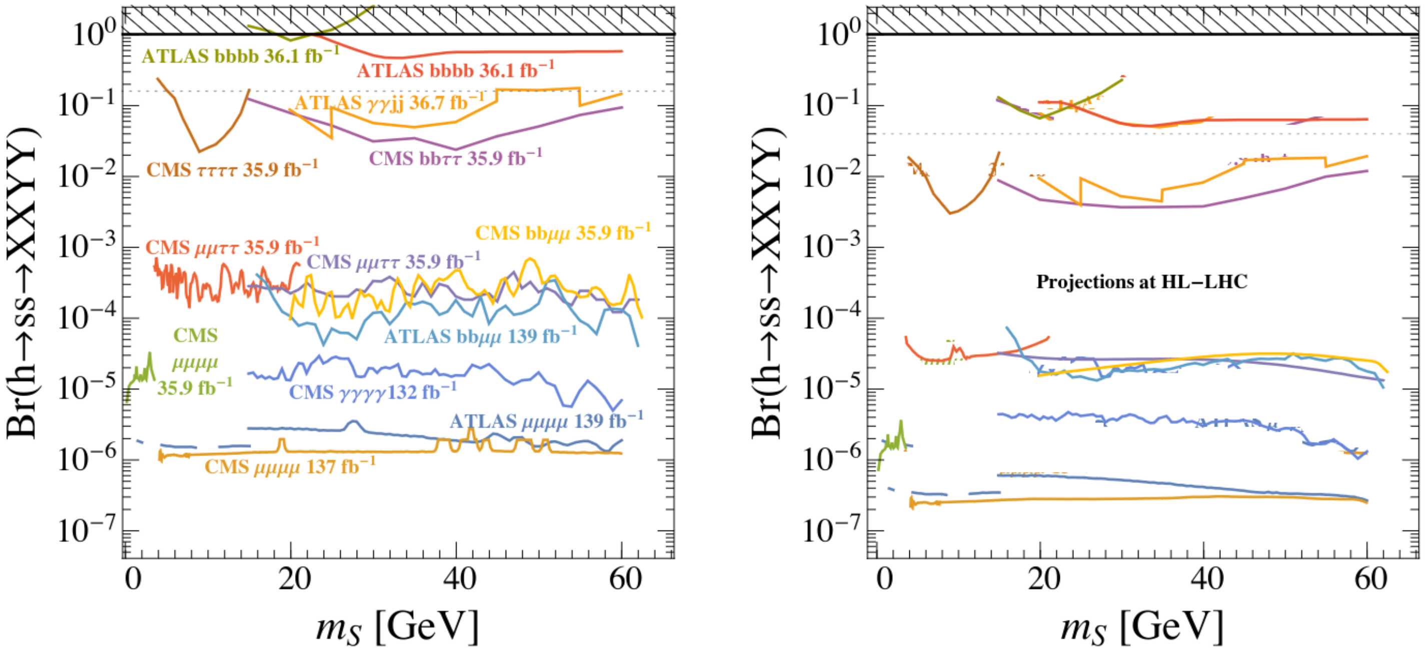


FIG. 3: Current bounds (left panel) on exotic Higgs decays $h \to ss \to XXYY$ and corresponding projections (right panel) at the HL-LHC. The horizontal dotted line is the current and future projection of upper limit for the exotic Higgs branching ratio from global fits to Higgs properties (16% and 4% respectively).

CKM matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97373 \pm 0.00031 & 0.2243 \pm 0.0008 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0408 \pm 0.0014 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.014 \pm 0.029 \end{bmatrix}.$$