$\mathsf{S} \rightarrow \mathsf{Z_d Z_d} \rightarrow 2l2\nu$

Orthogonality study (2l2j\2l2ν)

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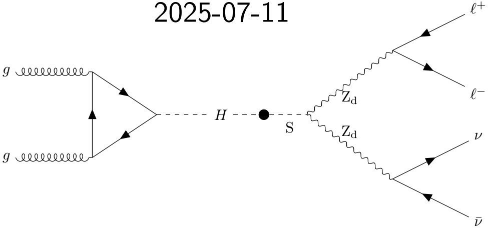


Outline

Motivation

- In our search for A/S$\rightarrow$ Z$_d$Z$_d$ $\rightarrow 2l2\nu$, we use the Hidden Abelian Higgs model [1] which could provide a viable dark matter (DM) candidate and offer a resolution to the muon g-2 anomaly.

- Considering lepton universality which include the decay of Z_d to leptons, our search is a follow up to the study of the $4l$ final states [2], where in our $2l2\nu$ channel, more events and higher sensitivity expected because the Branching Ratio in the Standard Model is: BR(ZZ $\rightarrow 2l2\nu$) = 6*BR(ZZ $\rightarrow 4l$).

- The main background is Z+jets with minor contribution from eμ ($t\bar{t}$, WW, Wt), dibosons and fakes. To suppress the background our chosen mass range is mS ≤ 183 GeV and $m_{Z_d} < 70$ GeV.

Motivation: Orthogonality Study

- There are two channels with potential overlap: $2l2\nu$ and $2l2$j.

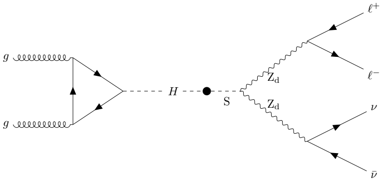


Figure a: $2l2\nu$ channel

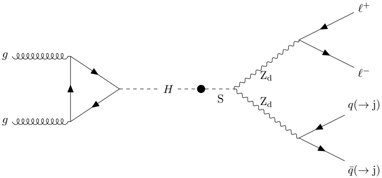


Figure b: $2l2$j channel

- Need to make sure there is no overlap between the two analyses, so that data does not get used twice[event selection indico].

- To do this, we propose to use a likelihood function that will select events for $2l2$j where the di-lepton mass matches with the di-jet mass.

Selected Diagrams for $S \to \mathrm{Z_d Z_d} \to 2l2\mathrm{j}$ Production

Note

Figure **c** and **d** are examples of diagrams for $S \to \mathrm{Z_d Z_d} \to 2l2\mathrm{j}$ production that we would like to select for the $2l2$j channel.

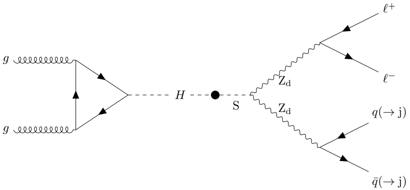


Figure c: 2l2j with 2 jets.

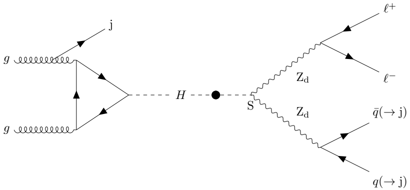


Figure d: 2l2j with 3 jets.

Invalid Diagrams for S $\rightarrow Z_d Z_d \rightarrow 2l2j$

Note

Figure **e** and **f** are examples of diagrams that we cannot use, since we cannot reconstruct the Z-dark.

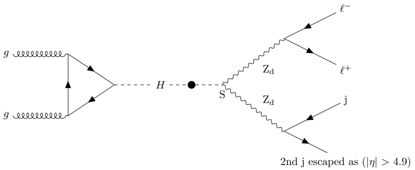


Figure e: 2l2j with 1 reconstructed jet.

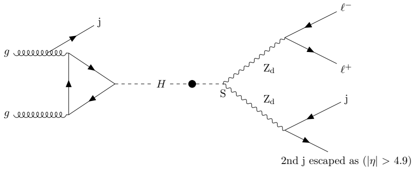


Figure f: 2l2j with 2 reconstructed jets.

Likelihood Function Overview

- Selection of events for the 2l2j production, only events with jets ≥ 2 are evaluated by the likelihood function.
- We used 5 GeV for the standard deviation of the modified dijet and dilepton invariant mass term.

The likelihood function L is defined to evaluate the compatibility between the dijet and dilepton systems:

$$L = \max_{j_1,j_2} \max_{E_1,E_2} \mathsf{G}(m_{jj}(E_1, E_2) - m_{\ell\ell} \mid 0, 5) \times \mathsf{G}(E_1 \mid E_{j_1}, \sqrt{E_{j_1}}) \times \mathsf{G}(E_2 \mid E_{j_2}, \sqrt{E_{j_2}})$$

- G: Gaussian distribution $\mathsf{G}(x \mid \mu, \sigma)$
- E_{j_1}, E_{j_2}: Measured jet energies.
- E_1, E_2: Hypothetical jet energies tested in maximization.
- $m_{\ell\ell}$: Measured dilepton invariant mass.

Likelihood Function Overview

- m_{j1j2} is the measured or initial dijet mass, computed from the four-momenta of jet 1 and jet 2 before any energy rescaling.
  - It is a fixed value, given by the invariant mass formula:

$$m_{j1j2} = \sqrt{(E_{j1} + E_{j2})^2 - (\vec{p}_{j1} + \vec{p}_{j2})^2}$$

  - Here, E_{j1}, E_{j2} are the measured jet energies, and $\vec{p}_{j1}, \vec{p}_{j2}$ are the three-momenta of the jets.
  - m_{j1j2} is the fixed, measured dijet mass, based on detector-reconstructed jet momenta and energies.

Where: $$m_{jj}(E_1, E_2) = m_{j_1j_2}\sqrt{\frac{E_1}{E_{j_1}}}\sqrt{\frac{E_2}{E_{j_2}}}$$

- $m_{jj}(E_1, E_2)$ is the modified dijet mass used during likelihood maximization. It varies with the chosen values E_1 and E_2, and rescales m_{j1j2} accordingly.

Breakdown of Likelihood Function Terms

- **Overall Goal:** Maximize the likelihood L by adjusting hypothetical jet energies E_1, E_2 to best match the dijet system to the dilepton system.

1. Dijet-Dilepton Mass Matching Term

$\mathsf{G}(m_{jj}(E_1, E_2) - m_{\ell\ell} \mid 0, 5)$

- Penalizes mismatch between adjusted dijet mass and observed dilepton mass.
- Uses a Gaussian centered at 0 with width $\sigma = 5\,\mathrm{GeV}$.

2. Jet Energy Transfer Functions

$\mathsf{G}(E_i \mid E_{j_i}, \sqrt{E_{j_i}}) \quad \text{for } i = 1, 2$

- Probabilistic model of the "true" jet energy E_i given measured energy E_{j_i}.
- Gaussian centered at E_{j_i}, width $\sigma = \sqrt{E_{j_i}}$ (reflects calorimeter resolution).

Breakdown of Likelihood Function Terms

3. Adjusted Dijet Mass

$$m_{jj}(E_1, E_2) = m_{j_1 j_2} \sqrt{\frac{E_1}{E_{j_1}}} \sqrt{\frac{E_2}{E_{j_2}}}$$

- Rescales invariant mass based on hypothetical energies.
- $m_{j_1 j_2}$: Measured invariant mass of jets j_1 and j_2.

Key Components

Maximization:

- Loops over all jet pairs $(\mathrm{j}_1, \mathrm{j}_2)$ and energies (E_1, E_2).
- Finds combo that maximizes the likelihood L.

Gaussian Terms:

- Match modified dijet mass to dilepton mass $(m_{jj} \approx m_{\ell\ell})$.
- Compare hypothesized jet energies E_1, E_2 with measured E_{j_1}, E_{j_2}.

Interpretation:

- Higher $L \rightarrow$ more likely the event matches $2\ell2$j topology.
- Lower $-\ln\ L \rightarrow$ the event is chosen as $2\ell2$j.
- $-\ln L = nll$, which is the negative likelihood function.
- Apply a cut on nll to separate event types ($2\ell2$j vs $2\ell2\nu$).

Code

- The mathematical equation of the fit applied in the code is based on a **Gaussian likelihood** minimization.
- The full likelihood function is then:

$$L(E_1, E_2) = P_{\text{lep}}(M_{\text{combined}}) \cdot P_{\text{jet1}}(E_1) \cdot P_{\text{jet2}}(E_2)$$

.

- Each term is modeled as a Gaussian distribution.
- E_1 and E_2 are the energies of `jet1` and `jet2`,
- M_{combined} is the invariant mass of the combination of jets and leptons.

$$L(E_1, E_2) = \exp\left(-\frac{(M_{\text{combined}} - M_{\text{lep}})^2}{2 \cdot \sigma_{\text{lep}}^2}\right) \cdot \exp\left(-\frac{(E_1 - \mu_{\text{jet1}})^2}{2 \cdot \sigma_{\text{jet1}}^2}\right) \cdot \exp\left(-\frac{(E_2 - \mu_{\text{jet2}})^2}{2 \cdot \sigma_{\text{jet2}}^2}\right)$$

- μ_{jet1} and μ_{jet2} are the mean energies of `jet1` and `jet2`, i.e., the original jet energies,σ_{jet1} and σ_{jet2} are the standard deviations of the jet energies, taken as $\sqrt{E_1}$ and $\sqrt{E_2}$ in the code,
- M_{lep} is the invariant mass of the dilepton system, σ_{lep} is fixed to 5.0 GeV.

- Since likelihood is maximized in principle, the code minimizes the negative log-likelihood.

$$-\ln L(E_1, E_2) = \frac{(M_{\text{combined}} - M_{\text{lep}})^2}{2 \cdot \sigma_{\text{lep}}^2} + \frac{(E_1 - \mu_{\text{jet1}})^2}{2 \cdot \sigma_{\text{jet1}}^2} + \frac{(E_2 - \mu_{\text{jet2}})^2}{2 \cdot \sigma_{\text{jet2}}^2}$$

- Given the approximations in the code, the standard deviations for jet energies are approximated by $\sigma_{\text{jet}} \approx \sqrt{E}$, and $\sigma_{\text{lep}} = 5.0$ GeV.
- The final form minimized is:

$$-\ln L(E_1, E_2) = \frac{(M_{\text{combined}} - M_{\text{lep}})^2}{2 \cdot (5.0)^2} + \frac{(E_1 - \mu_{\text{jet1}})^2}{2 \cdot E_1} + \frac{(E_2 - \mu_{\text{jet2}})^2}{2 \cdot E_2}$$

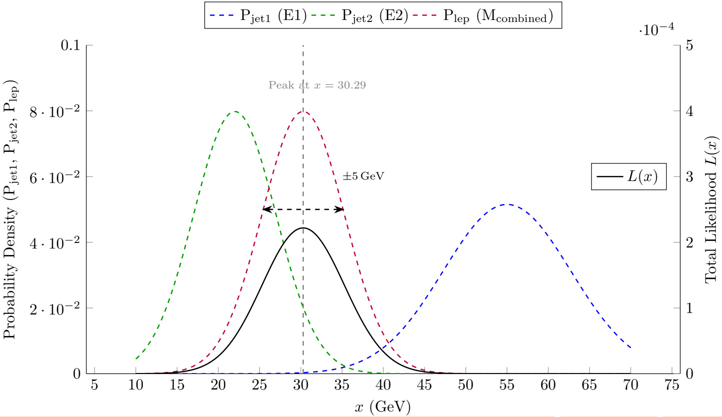
- $nll = -\ln L(E_1, E_2)$
- This is the expression to be minimized using the `Minuit2` minimizer in the ROOT-based likelihood fitting routine in the code.

Analysis: After excluding "< 2j" events, the likelihood function L is implemented to select $2l2$j vs. $2l2\nu$ events

- Their product is still a Gaussian distribution.

$$L(E_1, E_2) = P_{\text{lep}}(M_{\text{combined}}) \cdot P_{\text{jet1}}(E_1) \cdot P_{\text{jet2}}(E_2)$$

.



Analysis: $[-\ln L \equiv nll]$

- Adjust jet energies to best match leptonic decay products.
- Used in our search to select $2l2$j events from those eventually considered for the $2l2\nu$ analysis channel.
- Scan through with numerical values to establish the nll cut value.
- A cut is placed on the negative likelihood function (nll).
  - if $-\ln L <$ cut value: events classify as $2l2$j channel.
  - if $-\ln L >$ cut value: events classify as $2l2\nu$ channel.
- Scalar mass points [mS,mzd] : [70,20], [70, 35], [84, 31], [110, 30], [110, 55],[183, 50] GeV.
- The scalar mass plots have a selection of $m_{\ell\ell} < 70$ GeV as a baseline selection.
- The resulting mS is plotted for $2l2$j and Z+jets events (main background in the analysis channel).
- The percentage of events that passed the cut values (efficiency).

[mS,mzd] : scanning for the cut value to implement.

- After certain cut values, signal events are not much less than the signal events without cut on nll implemented. This is the threshold cut value.
- for $-\ln L <$ this threshold cut value, the events are for $2l2$j channel
- for $-\ln L$ otherwise, the events are made available for our $2l2\nu$ channel.

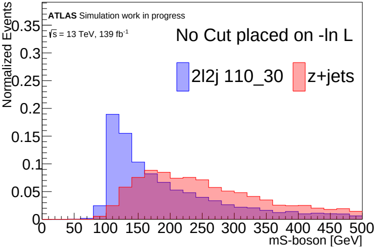


Figure g: No cut value placed on $-\ln L$ and implemented on mS.

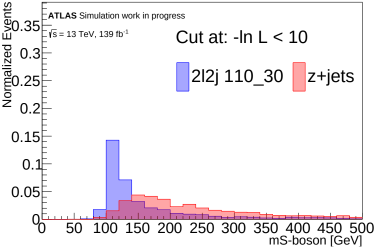
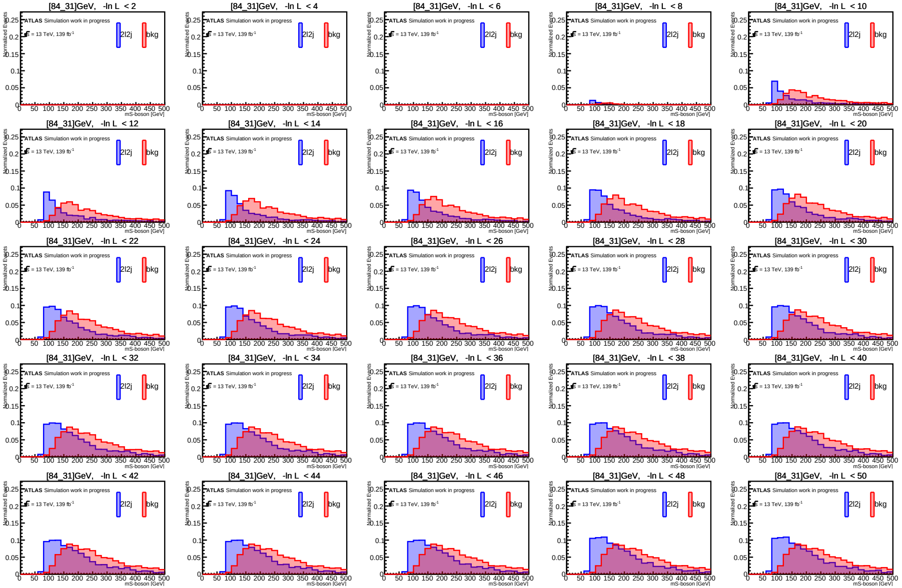


Figure h: After scanning and implementing a cut value.

[mS,mzd]=[84, 31] GeV:Scanning to establish $-\ln L$ cuts



Results: $-\ln L < 16$ on mS is the selected threshold cut.

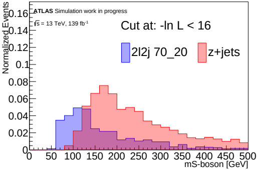


Figure 1: [70,20]GeV.

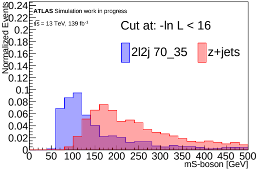


Figure 2: [70,35]GeV.

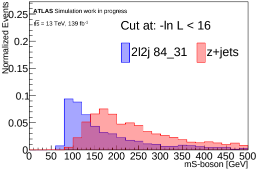


Figure 3: [84,31]GeV.

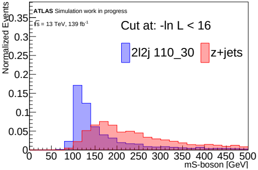


Figure 4: [110,30]GeV.

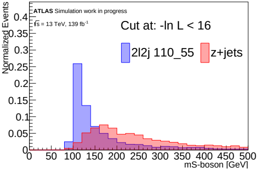


Figure 5: [110,55]GeV.

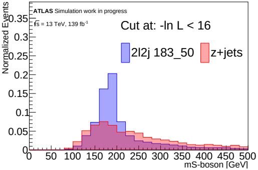


Figure 6: [183,50]GeV.

nll Classifying events as those for 212j and $2l2\nu$ channels

- As $-\ln L <$ cut value: events classify as $2l2$j channel.
- As $-\ln L >$ cut value: events classify as $2l2\nu$ channel.
- $-\ln L$ technique solves the problem of counting the same event twice.

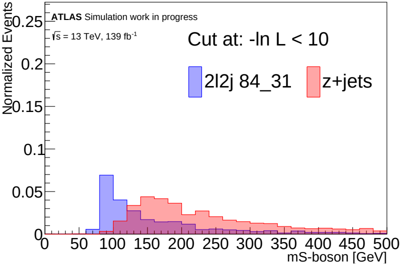


Figure x: As $nll < 16$, events are made available for the 212j channel.

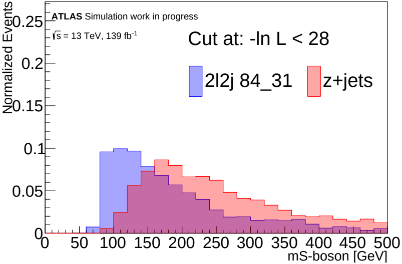


Figure y: As nll not less than 16, the events are made available for 212ν channel.

Results: % display of signal events with cut values on mS.

- As certain increment of the cut values, percentage of events tend to plateau.
- This higher yield is quite obvious in higher mass points.

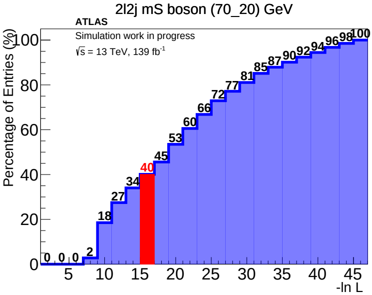


Figure 7: [70,20]GeV % of events tend to plateau

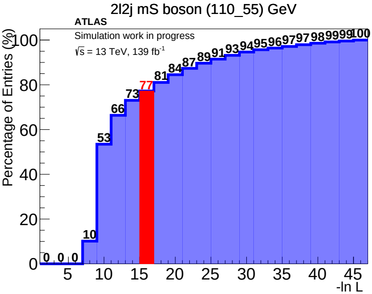


Figure 8: [110,55]GeV Higher % yield more prominent for this masspoint

Results: percentage display with nll cut on mS masspoints.

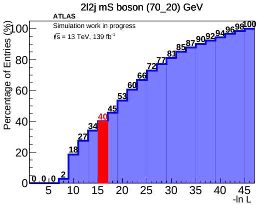


Figure 9: [70,20]GeV.

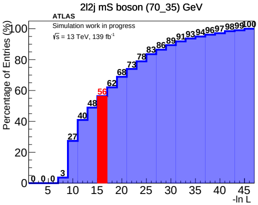


Figure 10: [70,35]GeV.

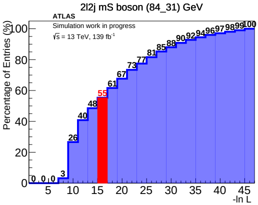


Figure 11: [84,31]GeV.

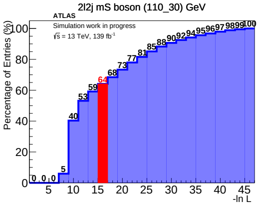


Figure 12: [110,30]GeV.

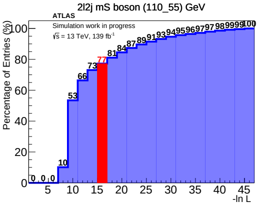


Figure 13: [110,55]GeV.

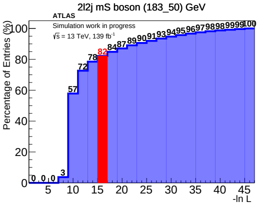


Figure 14: [183,50]GeV.

Likelihood fit function within minitrees

- The likelihood fit function is now incorporated as the minitrees are being produced.

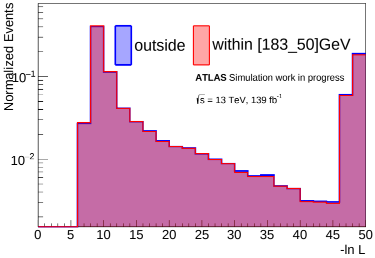


Figure 12: Validation check (I).

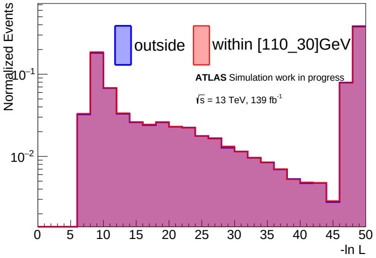


Figure 13: Validation check (II).

Conclusions and future work

- We have developed a likelihood-based method to orthogonalize the $2l2$j and $2l2\nu$ analyses.
- Aim is to select events for 2l2j that have a negative log likelihood below $(nll < 16)$.
- The $2l2$j events that are cut away in this selection are not signal-like. That is, the di-lepton and di-jet mass of these events is not (close to) equal.
- Additional opportunity to use the re-calculated jet mass for the $2l2$j analysis to improve the signal/background separation.

References I

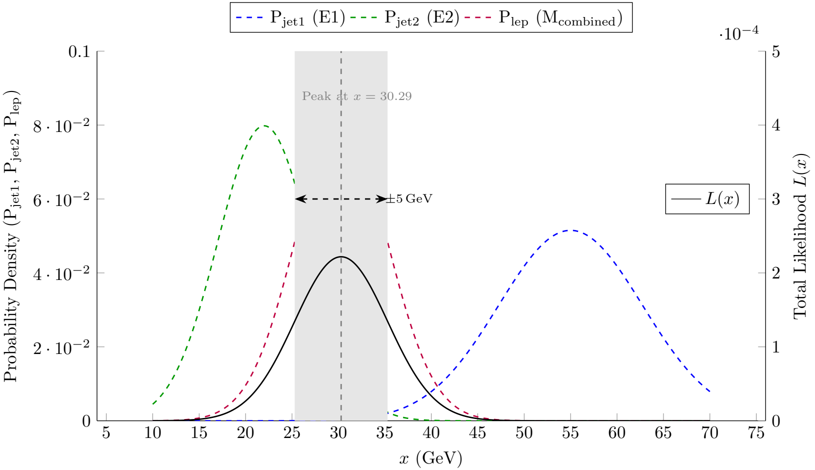
[1] A. Collaboration, *Search for Higgs boson decays to hidden-sector particles in the prompt lepton-jet channel with the ATLAS detector*, ATL-PHYS-PROC-2025-029, 2025. [Online]. Available: https://cds.cern.ch/record/2898771.

[2] ATLAS Collaboration, *Search for a new scalar decaying into new spin-1 bosons in four-lepton final states with the atlas detector*, arXiv:2410.16781 [hep-ex], CERN-EP-2024-248, 2024.

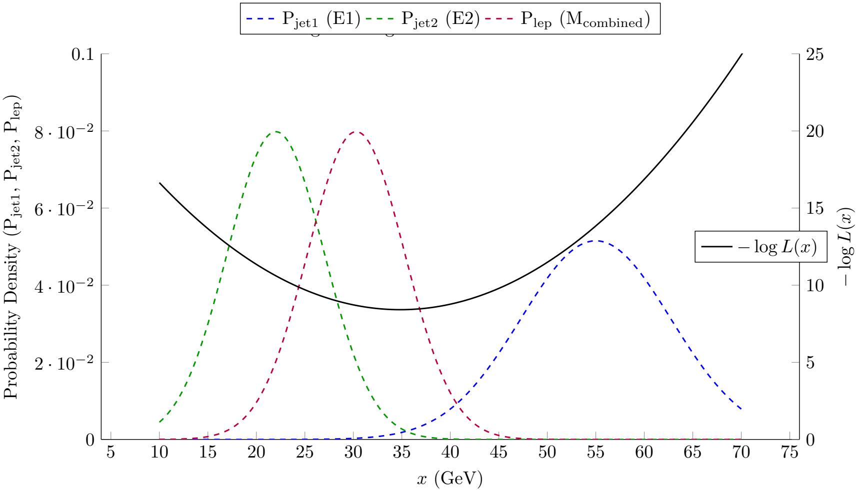
THANK YOU

BACK UP

L used to select $2l2$j events within the gray shaded area.

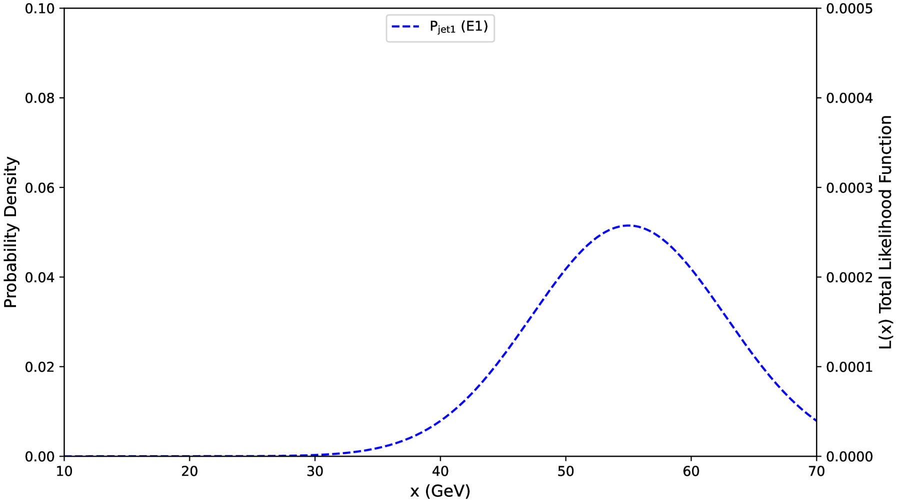


Analysis: $-\ln L(E_1, E_2)$

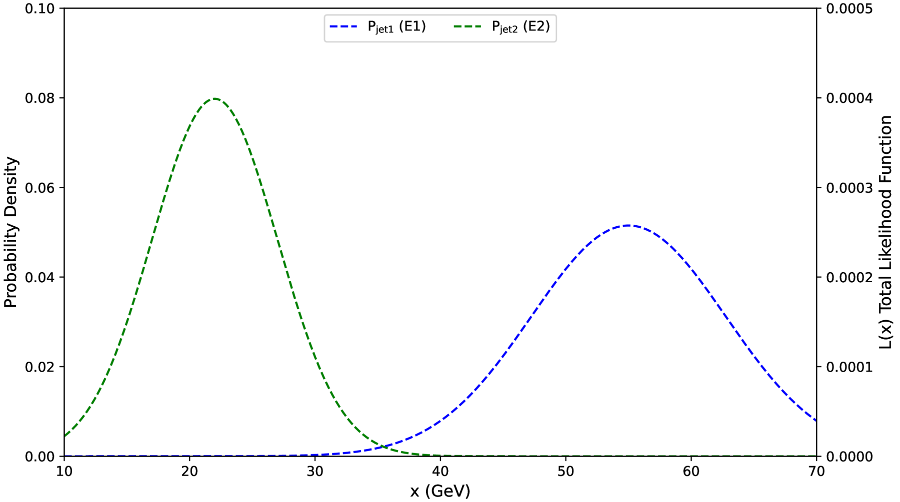


Data-driven plots for $2l2$j events.

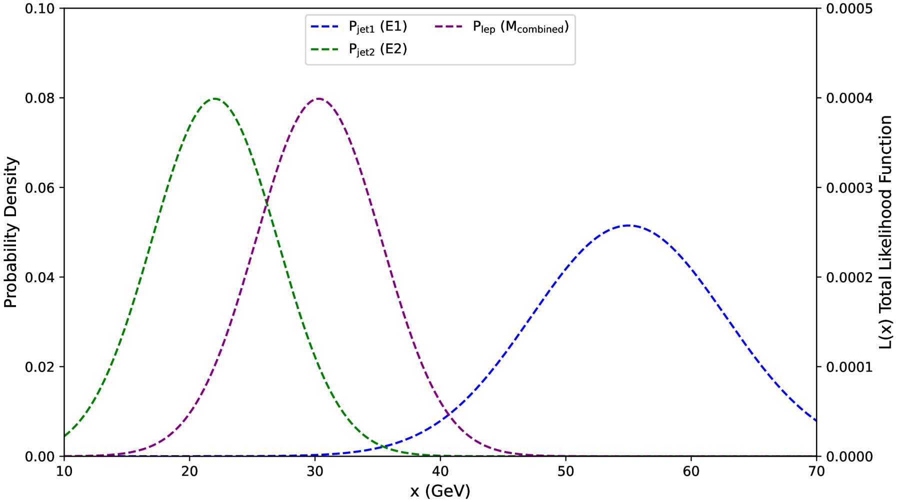
Distribution: $P_{\text{jet1}}(E_1) = \exp\left(-\frac{(E_1-\mu_{\text{jet1}})^2}{2\cdot\sigma_{\text{jet1}}^2}\right)$



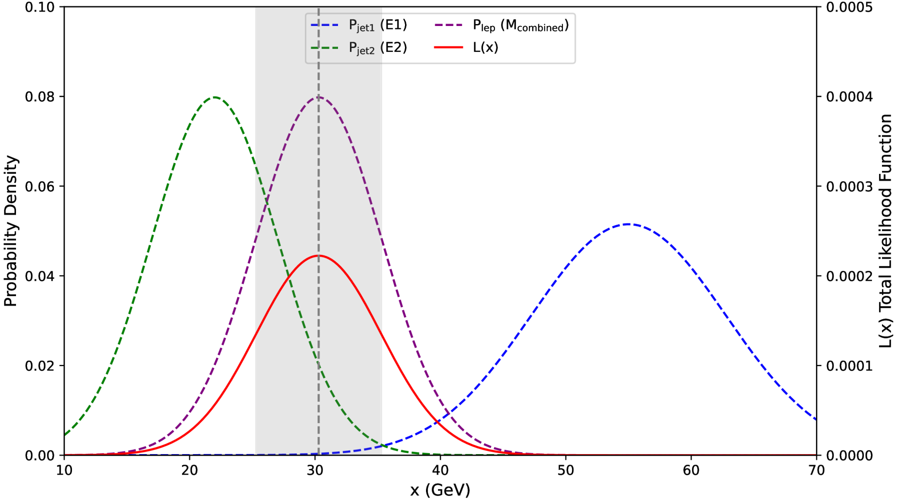
Distribution: $P_{\text{jet2}}(E_2) = \exp\left(-\frac{(E_2-\mu_{\text{jet2}})^2}{2\cdot\sigma^2_{\text{jet2}}}\right)$



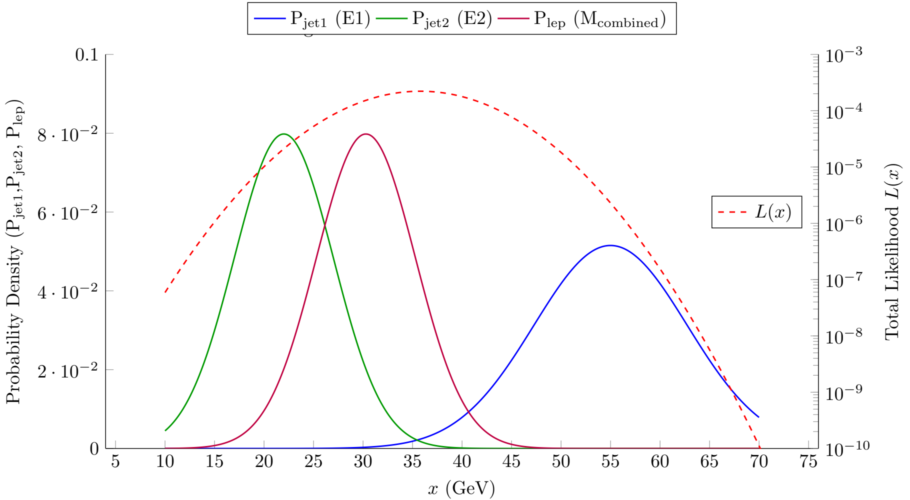
Distribution: $P_{\text{lep}}(M_{\text{combined}}) = \exp\left(-\frac{(M_{\text{combined}} - M_{\text{lep}})^2}{2 \cdot \sigma_{\text{lep}}^2}\right)$



$$L(E_1, E_2) = P_{\text{lep}}(M_{\text{combined}}) \cdot P_{\text{jet1}}(E_1) \cdot P_{\text{jet2}}(E_2)$$

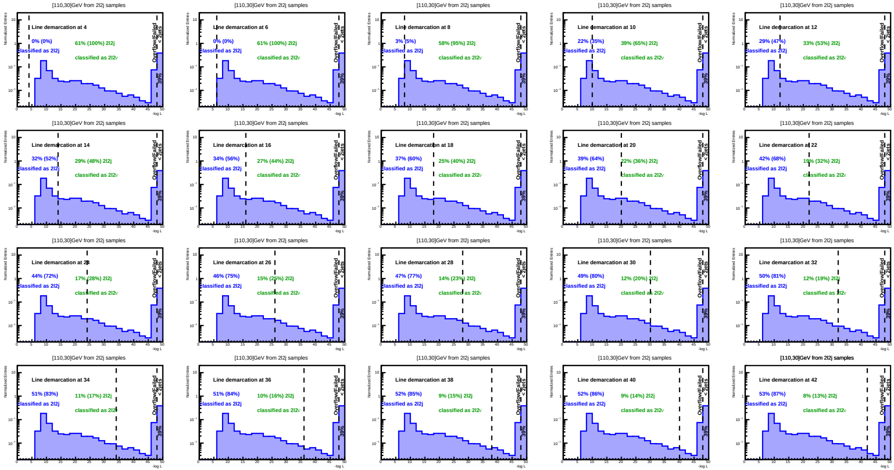


L fit function: zoomed-in (log scale)

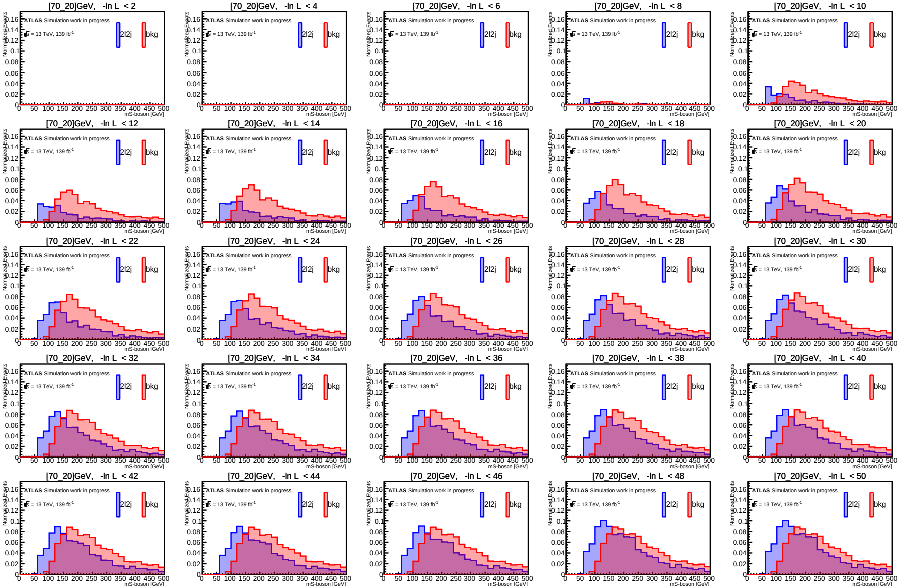


[mS,mzd]=[110,30]GeV :After excluding "< 2j" events, classified $2l2$j vs. $2l2\nu$ with varying line demarcation.

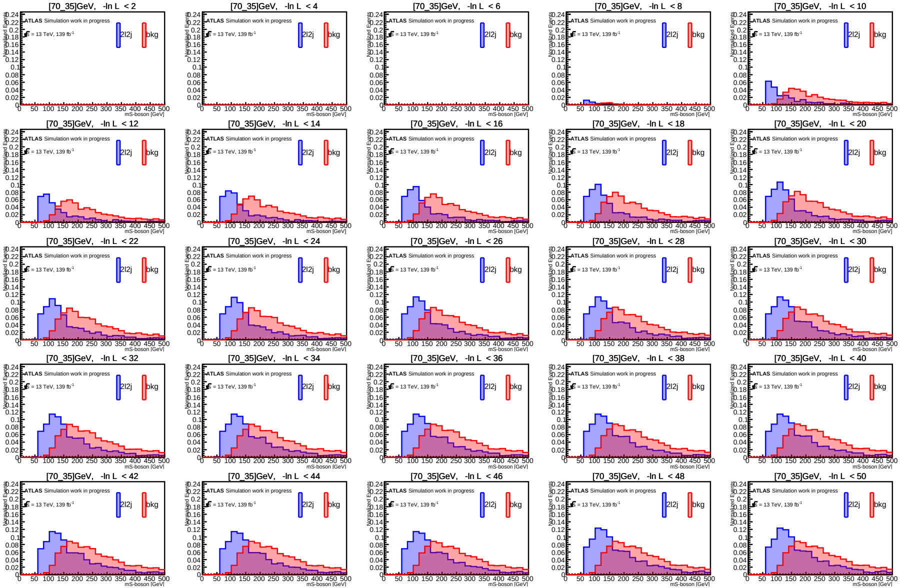
- $(100\ \%)_{2l2\mathrm{j}}$ samples $= [(\%)_{<2\mathrm{j}} + (\%)_{2l2\mathrm{j}} + (\%)_{2l2\nu}]$ events.



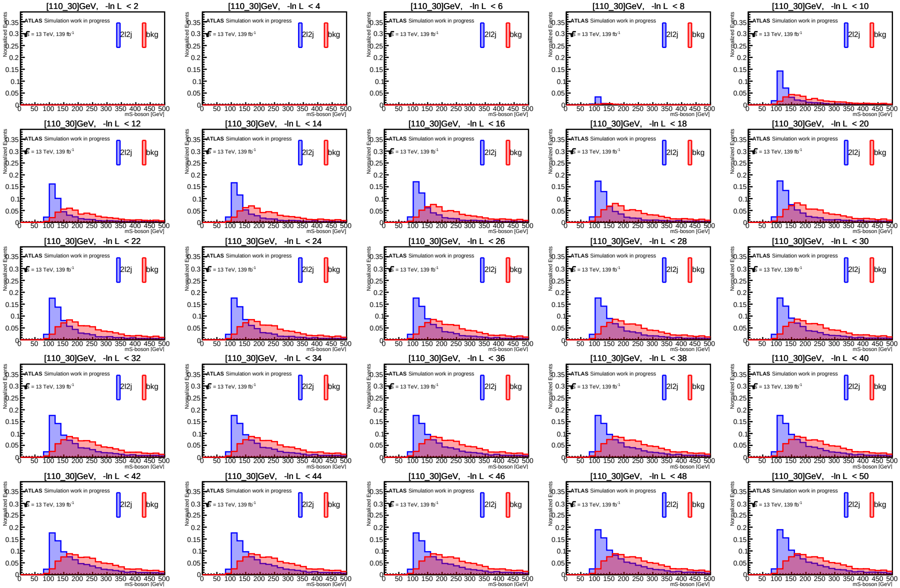
[mS,mzd]=[70, 20] GeV:Scanning to establish nll cuts



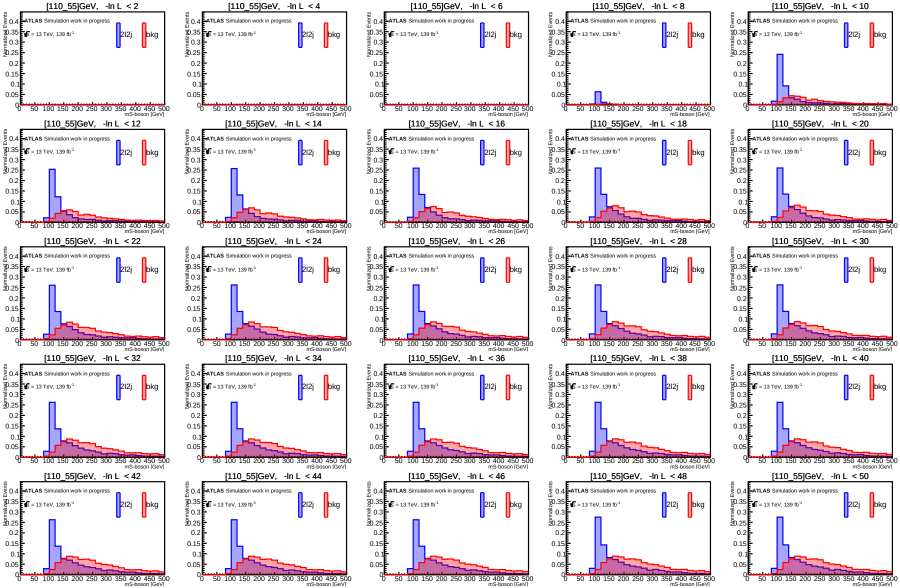
[mS,mzd]=[70, 35] GeV:Scanning to establish nll cuts



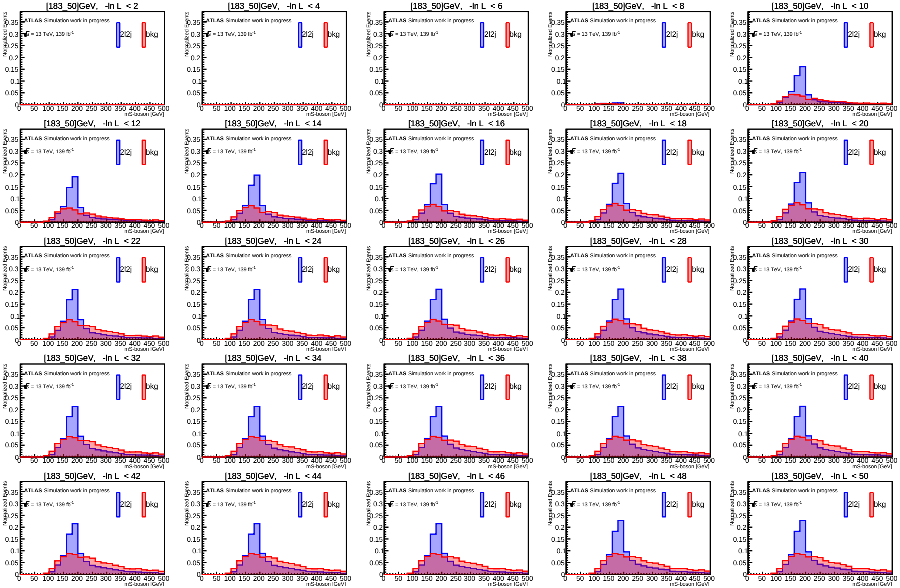
[mS,mzd]=[110, 30] GeV:Scanning to establish nll cuts



[mS,mzd]=[110, 55] GeV:Scanning to establish nll cuts



[mS,mzd]=[183, 50] GeV:Scanning to establish nll cuts



[mS,mzd]=[183,50]GeV : Classified $2l2$j vs. $2l2\nu$ with varying line demarcation.