Diagnosing Hidden Sectors with MATHUSLA and HL-LHC

(MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles)

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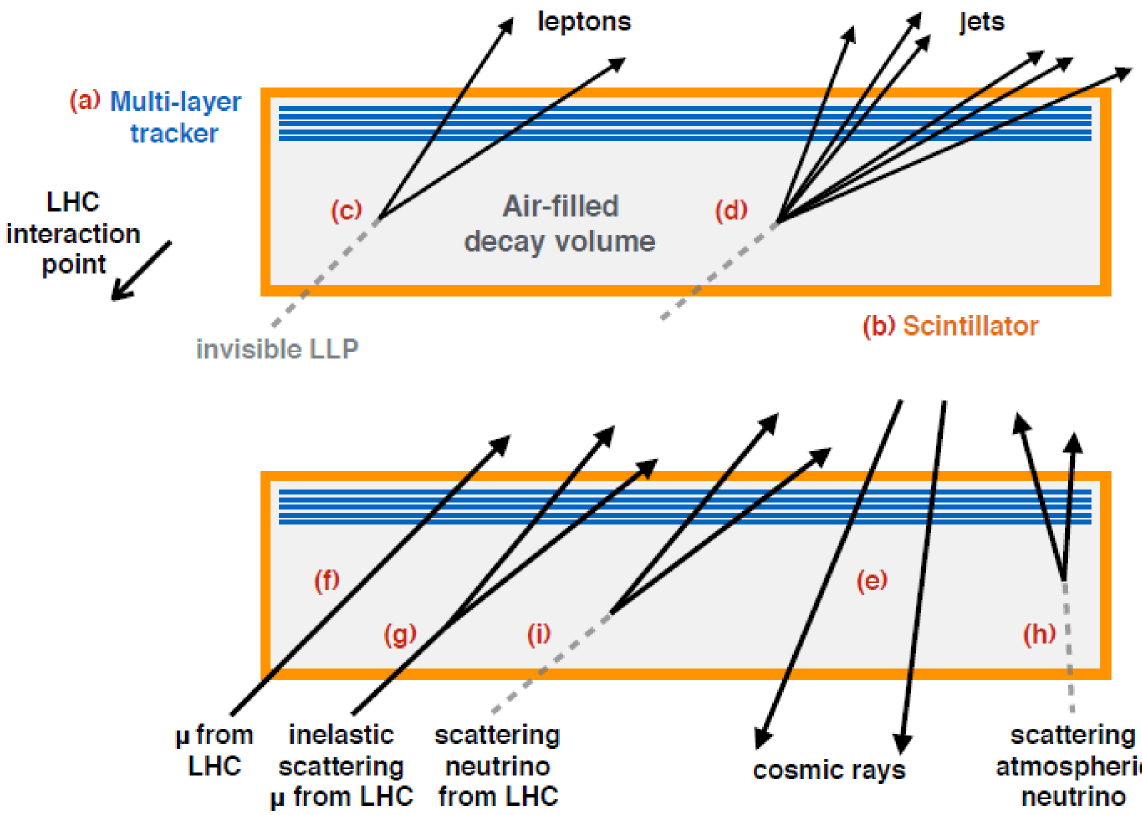
Based on work in progress with David Curtin

MATHUSLA

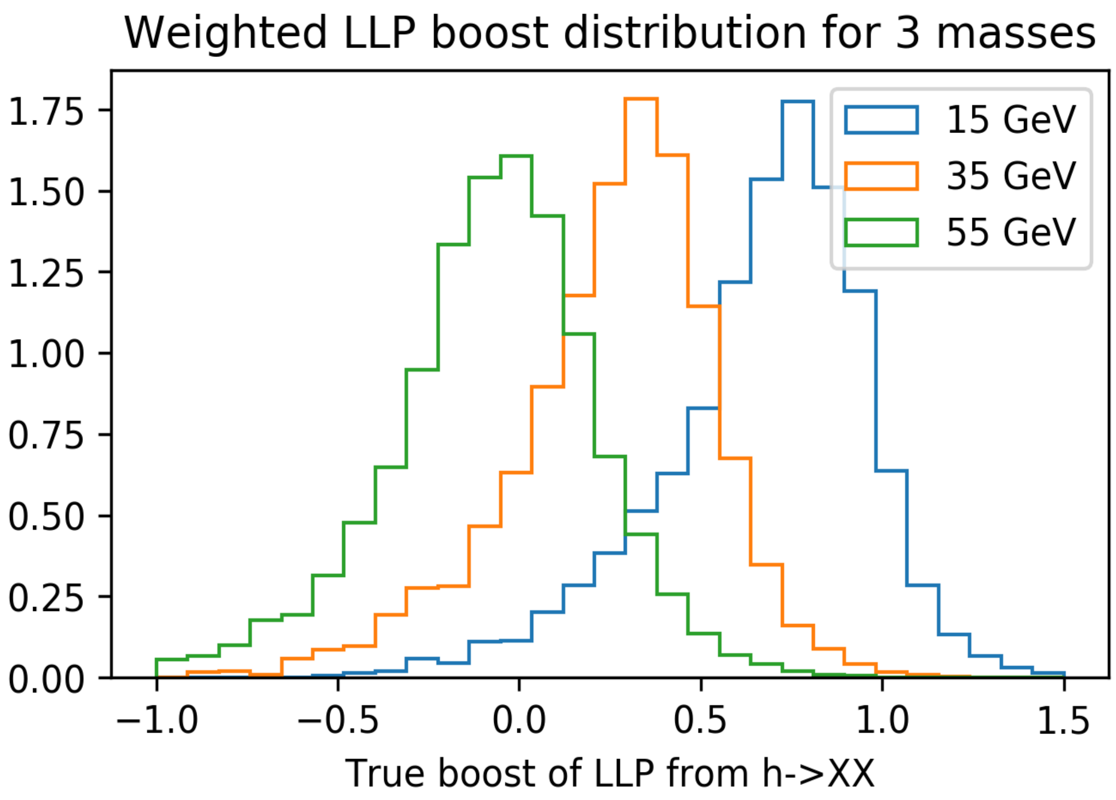
- MATHUSLA is a proposed large-volume displaced vertex detector, to be located on the surface above CMS.
  Chou, Curtin and Lubatti, 1606.06298
  Alpigiani et al., 1811.00927
- Its purpose is to detect neutral, ultra long-lived particles with decay lengths up to $O(10^7\ \mathrm{m})$.
- Search for displaced vertex events originating from LHC interaction point.
- Near zero background allows for sensitivity several orders of magnitude greater than ATLAS/CMS.



Top: LLP decay signal.
Bottom: Main backgrounds.
Alpigiani et al. 1811.00927

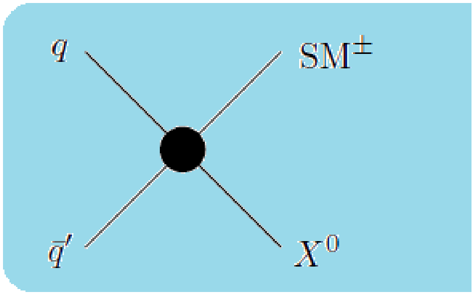
Determining LLP Mass with MATHUSLA

- One of the most well-motivated models of LLP production is by exotic Higgs decay.
- Under this production mode at the HL-LHC, the distribution of LLP boosts is highly correlated with the LLP mass, providing a method to easily evaluate LLP mass.
- Boost $b = \gamma v = |\vec{p}|/m$.
- Using the geometric information MATHUSLA collects, it is possible to determine the velocity of the long-lived particle. Curtin & Peskin, 1705.06327

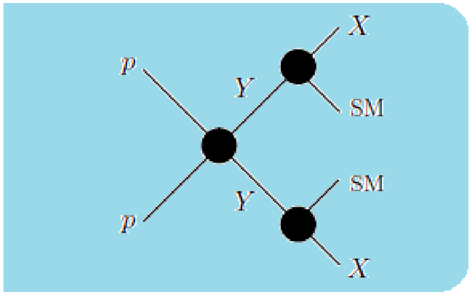


LLP Production: Simplified Models

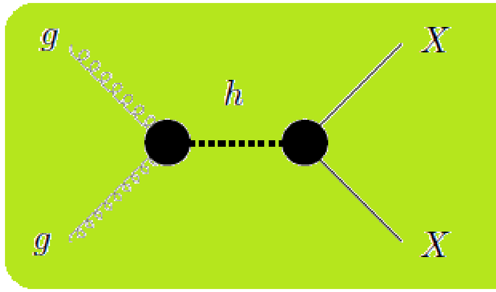
- Exotic Higgs decay is not the only scenario for LLP production.
- Simplified models/LLP production topologies from LHC-LLP whitepaper.
- LLP velocity from MATHUSLA identifies production event in HL-LHC.
- Assuming MATHUSLA triggers CMS, can we use MATHUSLA + HL-LHC main detector (CMS) information to identify LLP production mode and BSM particle masses?
- To be included: Exotic b-decay production.



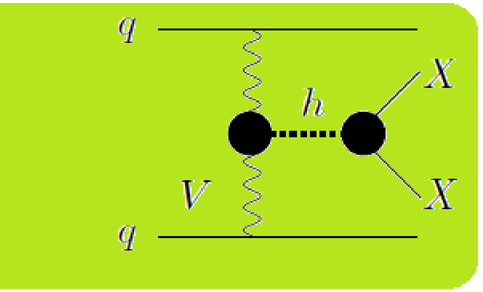
Charged Current (e.g. W')



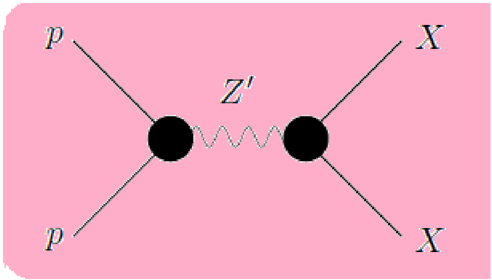
Heavy Parent



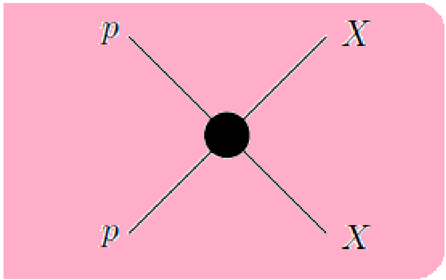
Higgs: Gluon Fusion



Higgs: Vector Boson Fusion



Heavy Resonance



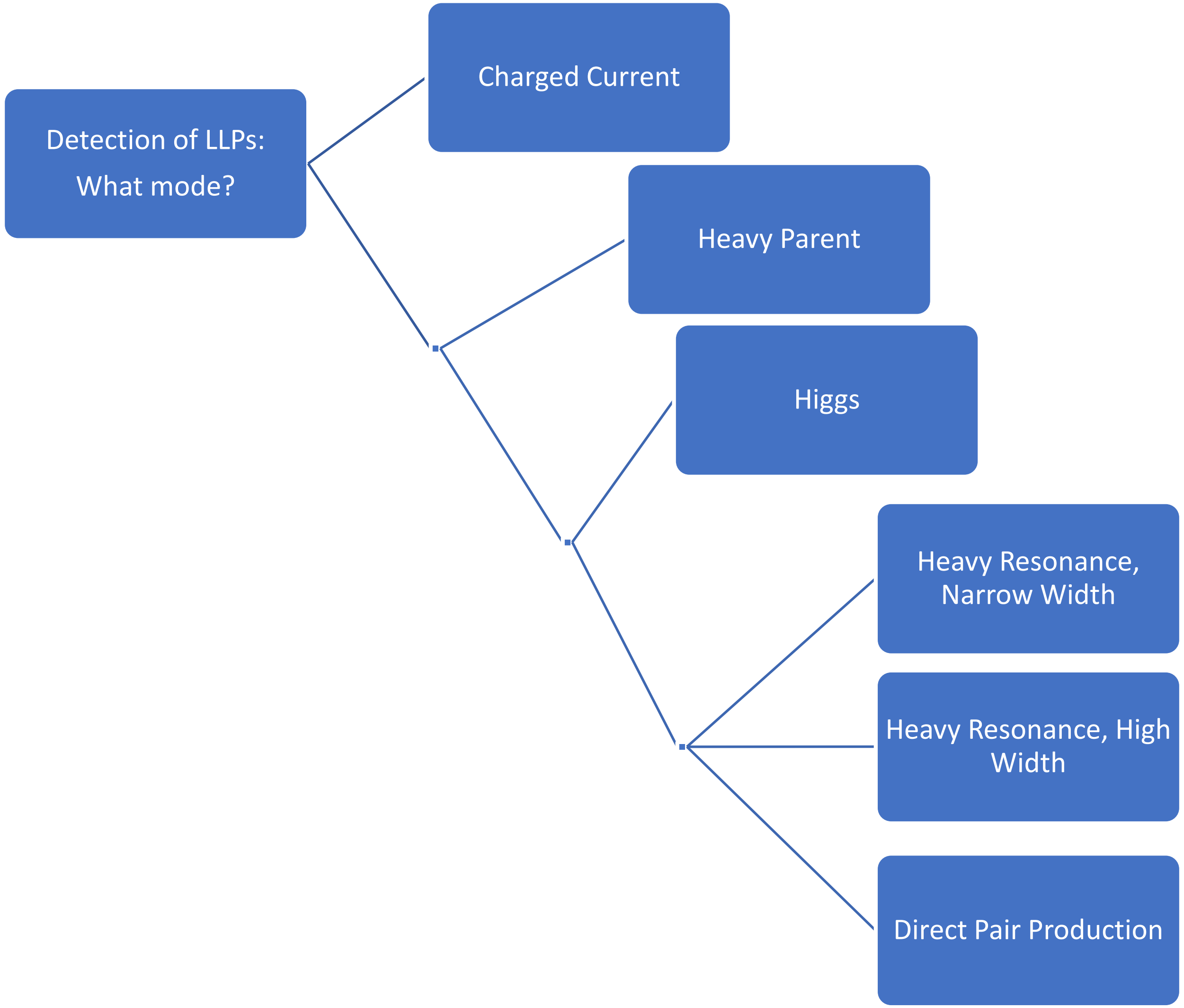
Direct Pair Production

Alimena et al. 1903.04497

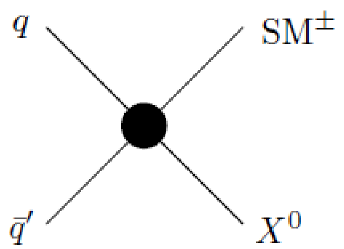
Simulation

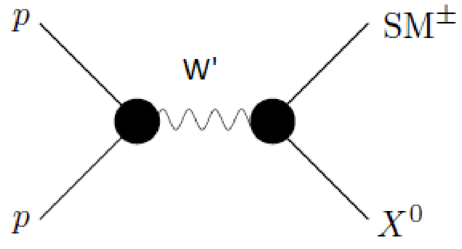
- Used the MadGraph 5 event generator to simulate events in CMS at the HL-LHC.
- Showering and hadronization with Pythia 8.
- Detector simulation with Delphes.
- Produced events for a variety of masses for each simplified model.
- Will demonstrate how a simple decision tree can identify simplified model responsible for LLP production.
- B-decays: Will use b-tagged jets to identify.

Classification

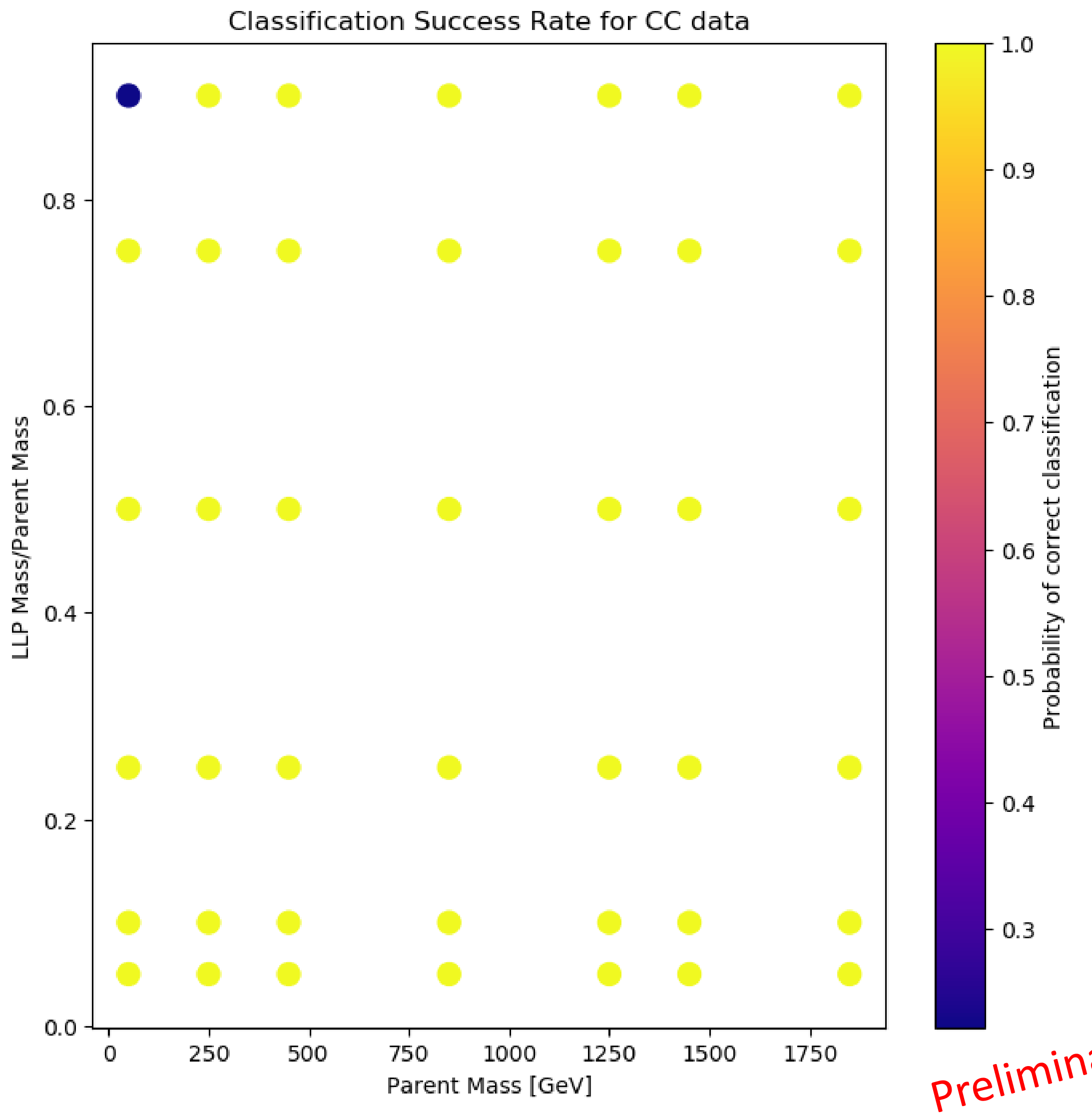


Charged Current Classification

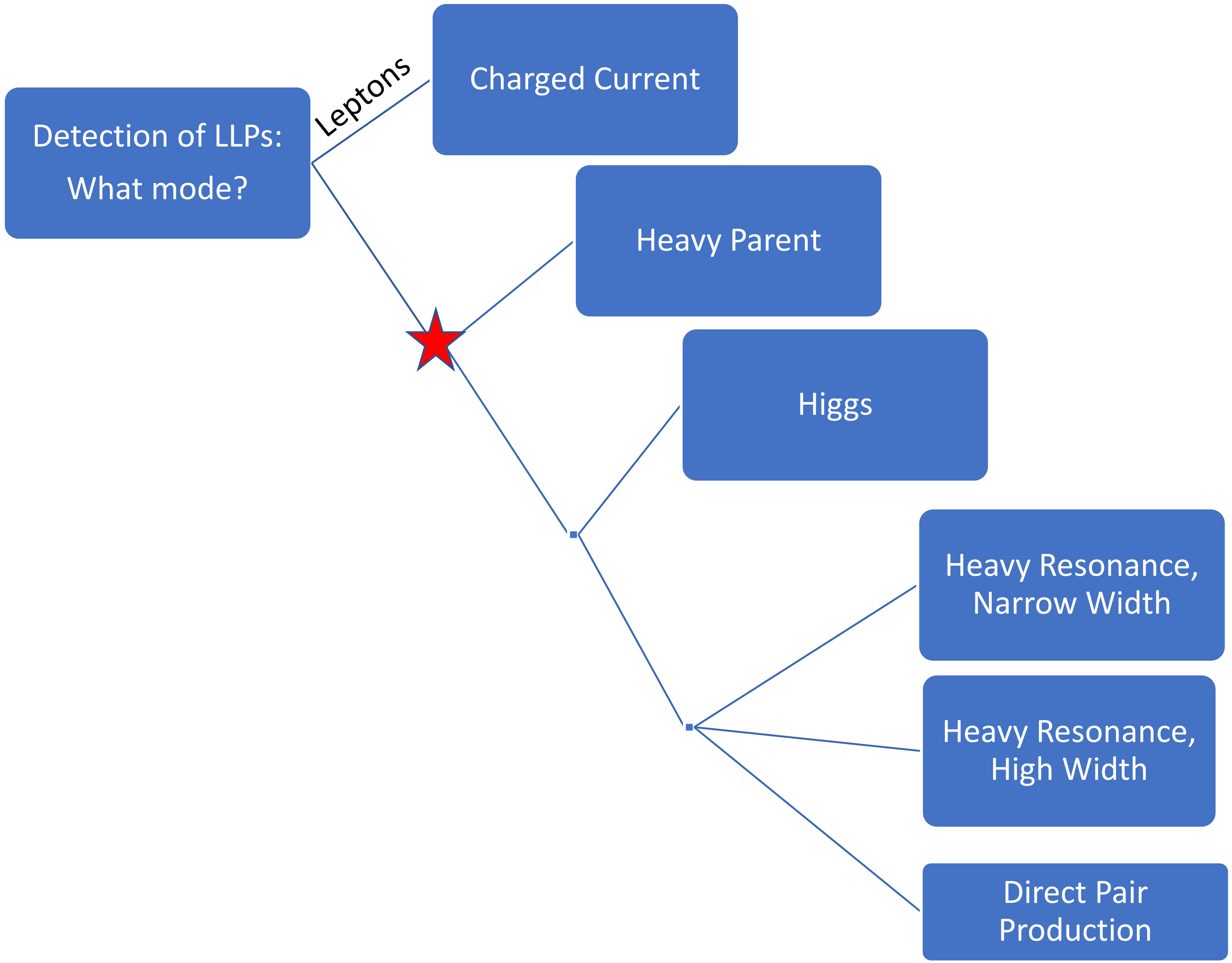




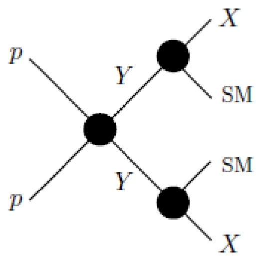
- A hard lepton (assuming muon for simplicity) is detected in >50% of these events.
- By computing the χ^2 statistic of the n_{lep} distribution under the various possible models, and finding the model with the highest average p-value, pseudo-data samples of 100 events were classified as either charged current-like or not.
- Charged current can be distinguished with probability ≈ 1 at N=100 observed events.
- M_{LLP} and $M_{W'}$ can be estimated from LLP boost and lepton kinematics.



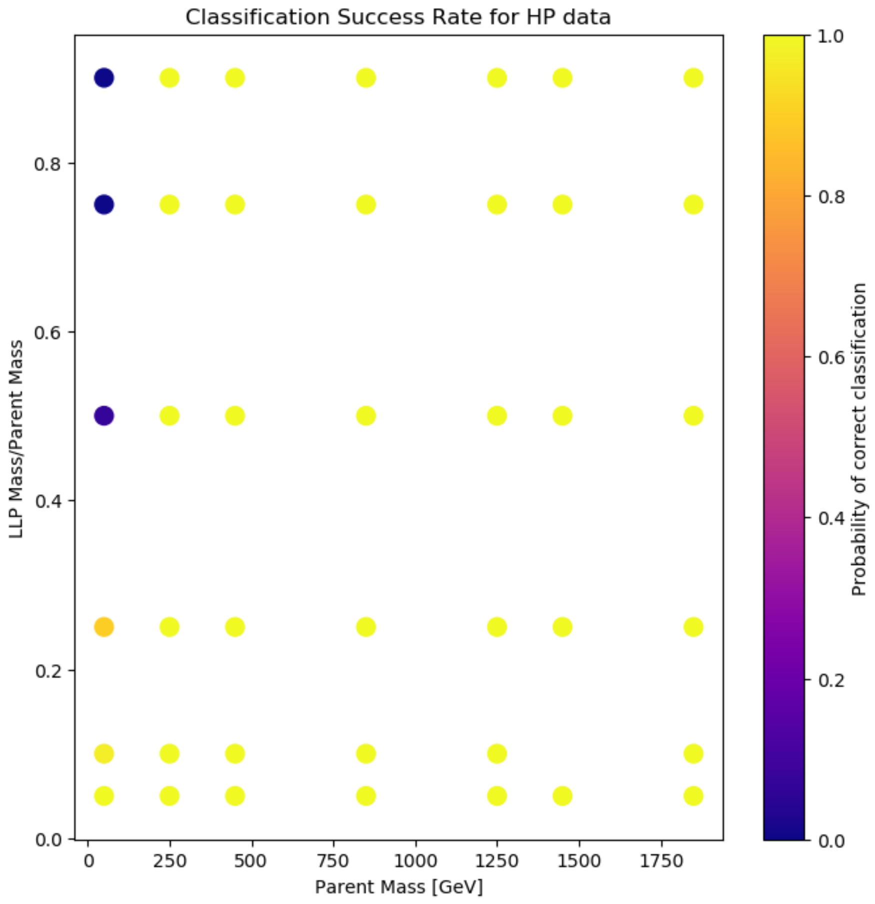
Preliminary


Detection of LLPs:
What mode?
Leptons
Charged Current
Heavy Parent
Higgs
Heavy Resonance, Narrow Width
Heavy Resonance, High Width
Direct Pair Production

Heavy Parent Classification



- High number of jets separates heavy parent from Higgs, heavy resonance, direct pair production.
- LLP boost distribution is determined by M_{LLP} and M_{Parent}.
- LLP boost + jet 4-vectors can give both masses.
- By computing the χ^2 statistic of the n_{jet} distribution for each model, 100-event pseudo-data samples were classified as either heavy parent-like or not.
- For $M_{Parent} >$ 250 GeV, heavy parent samples can be classified with probability ≈ 1.



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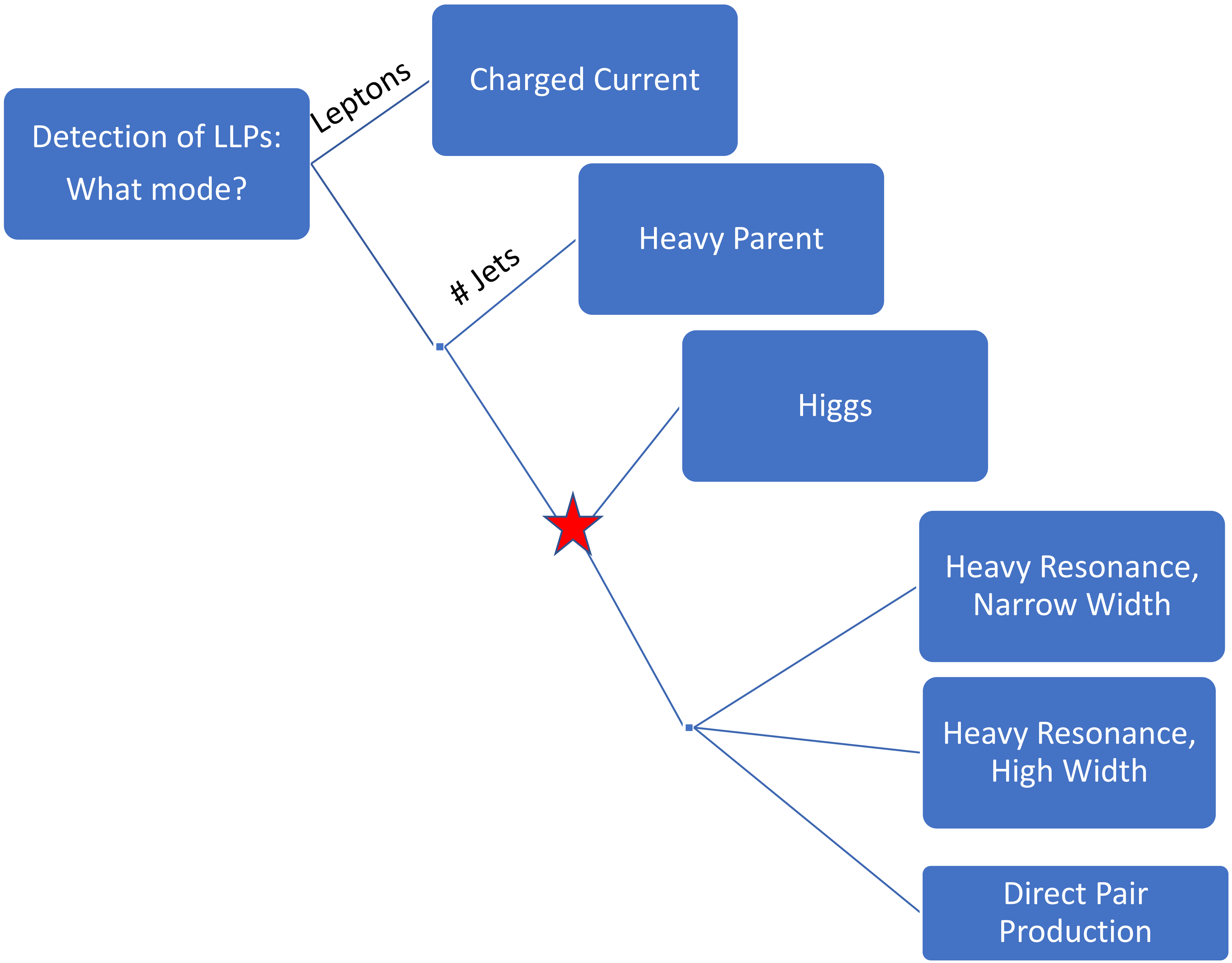
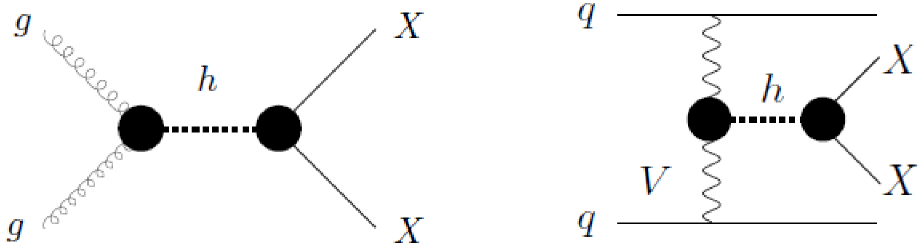
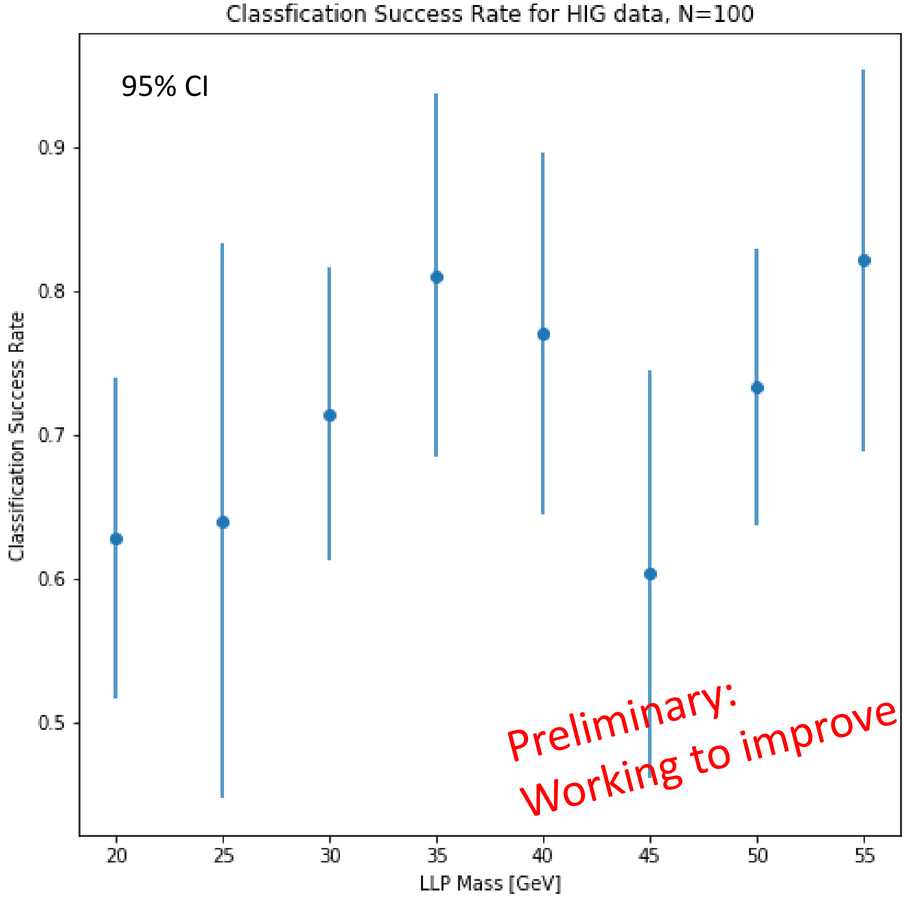
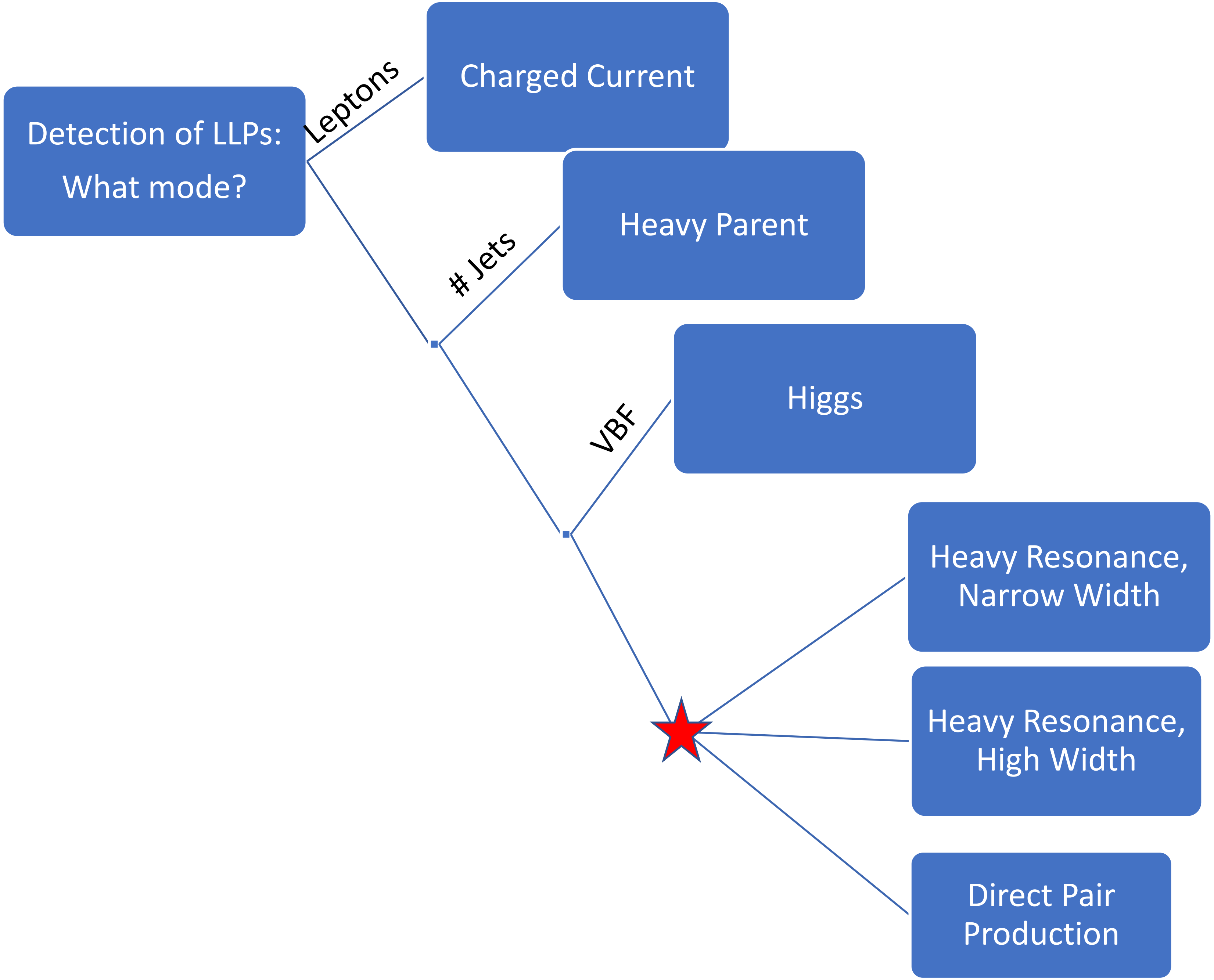

Detection of LLPs:
What mode?
Leptons
Charged Current
Jets
Heavy Parent
Higgs
Heavy Resonance,
Narrow Width
Heavy Resonance,
High Width
Direct Pair
Production

Higgs Decay Classification



- Higgs production by vector boson fusion adds a pair of hard, well-separated jets to $\approx 10\%$ of events in the exotic Higgs decay mode.
- Used $(m_{jj}, \Delta\eta_{jj})$ distribution to classify 100-event pseudo-data samples as either Higgs-like or not.
- Exotic Higgs decay samples can be correctly classified with **at least** $60 - 80\%$ probability, even with coarse binning in $m_{jj}, \Delta\eta_{jj}$.
- Could also use leptons from VH production, given enough observed events.




Detection of LLPs:
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VBF
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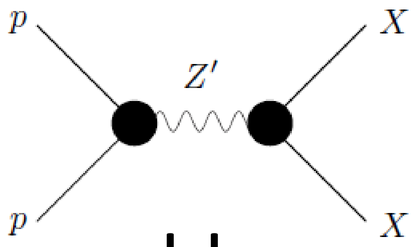
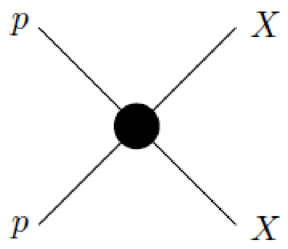
Heavy Resonance, Narrow Width
Heavy Resonance, High Width
Direct Pair Production





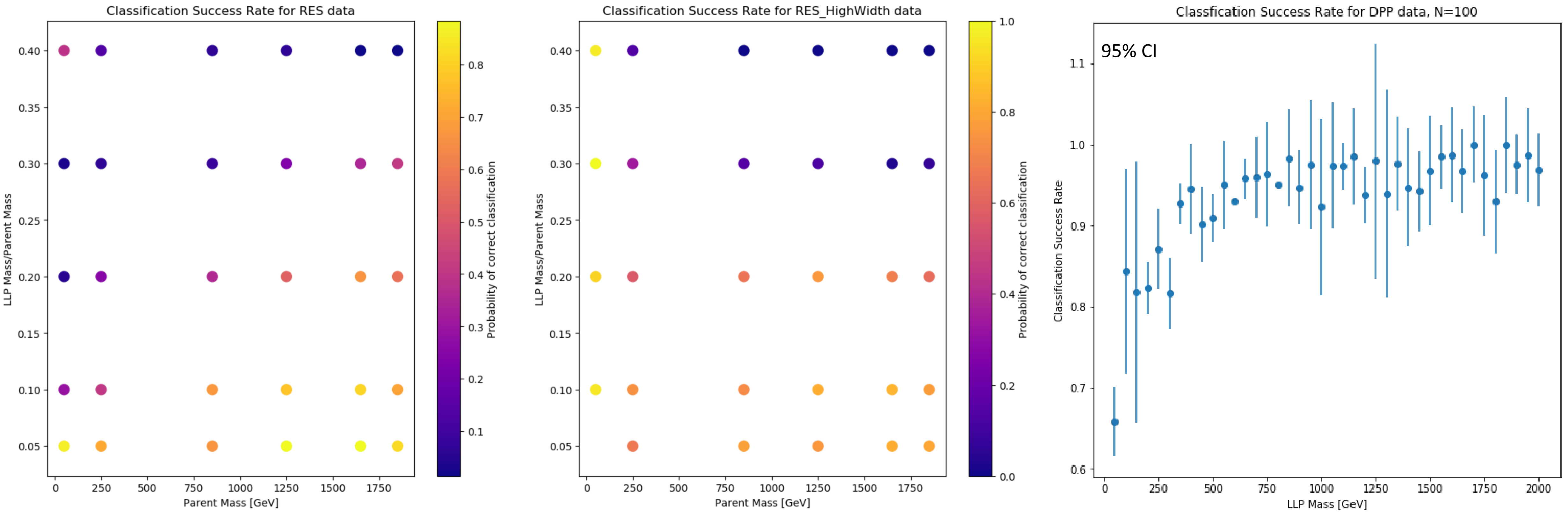
Heavy Resonance vs Direct Pair Production

- Direct pair production and heavy resonance with a large width have larger spread in boost distribution than narrow width heavy resonance.
- There are also differences in jet statistics (i.e. n_{jet}), depending on particle masses.
- Discrimination between these modes is possible in large regions of parameter space.

Boost distribution gives you LLP mass for DPP.
Boost + jet statistics gives LLP mass and Z' mass for HR.

Heavy Resonance and Direct Pair Production Classification

- Pseudo-data sets of 100 events were classified as either heavy resonance with 1% width, 30% width, or direct pair production by computing the χ^2 statistic of the (b_{LLP}, n_{jet}) distribution under the various production models. At N=1000, classification accuracies approach 100%.



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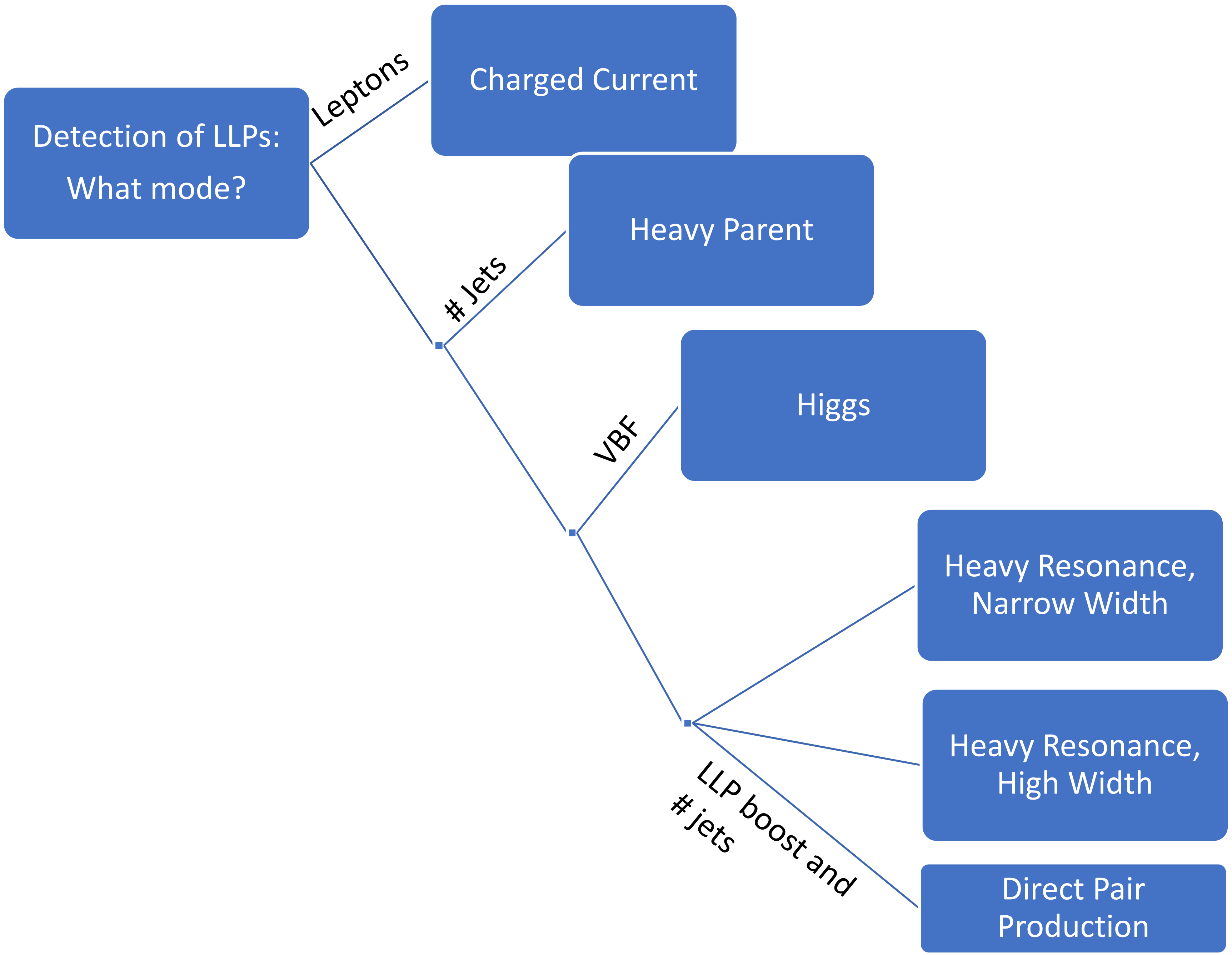

Detection of LLPs:
What mode?
Leptons
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Heavy Parent
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Higgs
Heavy Resonance,
Narrow Width
Heavy Resonance,
High Width
LLP boost and
jets
Direct Pair
Production

Conclusion

- Offline correlation of MATHUSLA and LHC events allows the production topology to be specified for a wide range of LLP masses.
- More sophisticated analyses can certainly improve classification accuracy.
- Once the production mode has been identified, LLP mass and other production mode parameters can usually be identified. (e.g. M_{Parent})
- Detailed analysis of parameter estimation abilities still to be performed.
- There is useful information to be gained by using MATHUSLA as a Level 1 trigger for CMS.

References

[1] Juliette Alimena et al. Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider. 2019.

[2] Cristiano Alpigiani et al. A Letter of Intent for MATHUSLA: A Dedicated Displaced Vertex Detector above ATLAS or CMS. 2018.

[3] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 07:079, 2014.

[4] John Paul Chou, David Curtin, and H. J. Lubatti. New Detectors to Explore the Lifetime Frontier. *Phys. Lett.*, B767:29–36, 2017.

[5] David Curtin et al. Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case. 2018.

[6] David Curtin and Michael E. Peskin. Analysis of Long Lived Particle Decays with the MATHUSLA Detector. *Phys. Rev.*, D97(1):015006, 2018.

[7] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi. DELPHES 3, A modular framework for fast simulation of a generic collider experiment. *JHEP*, 02:057, 2014.

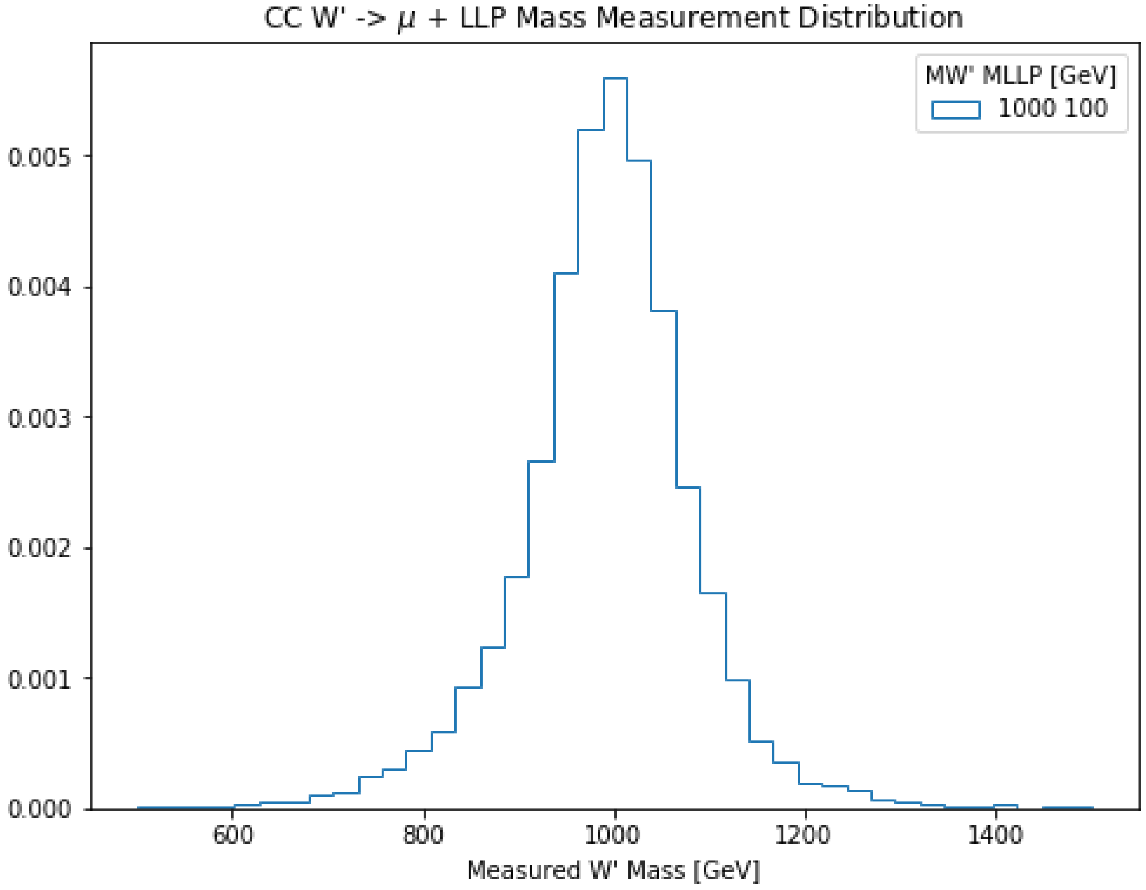
Background: Long-lived Particles (LLPs)

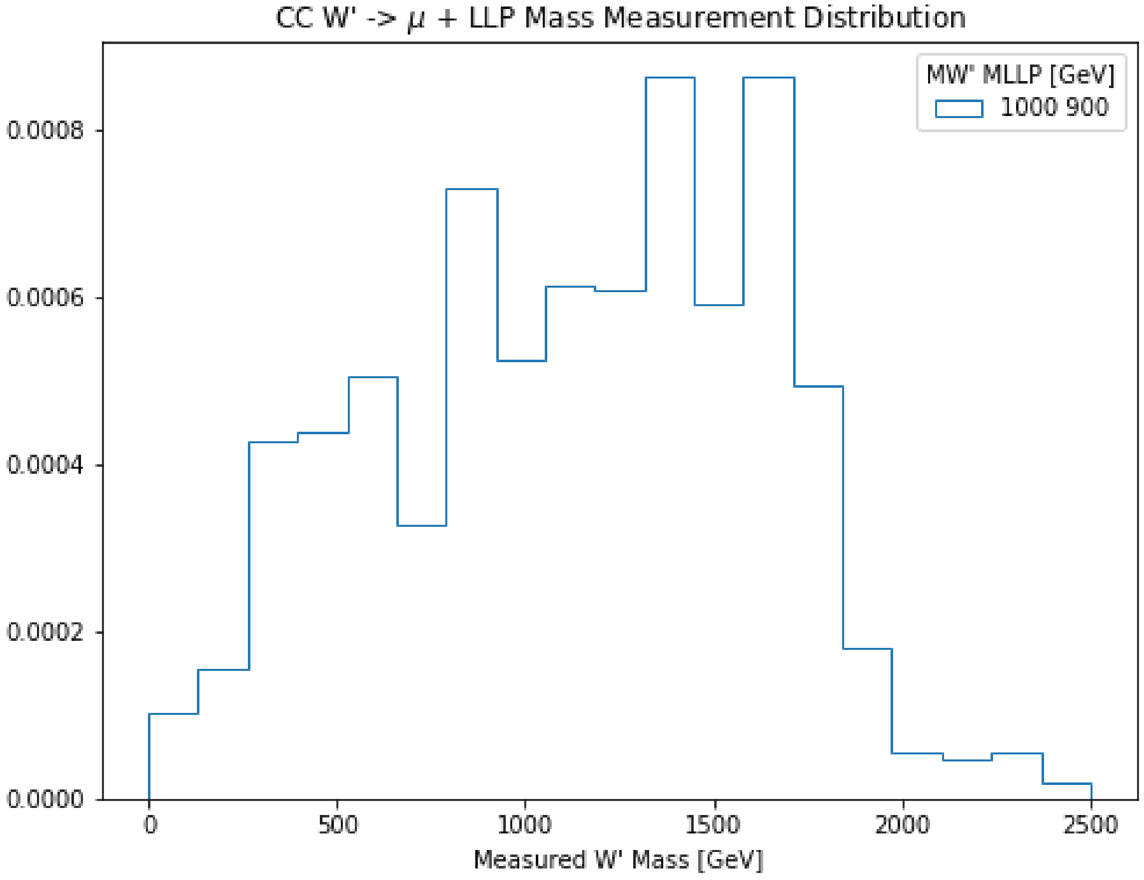
- Dark matter, baryon asymmetry, the hierarchy problem, and neutrino masses all point to BSM physics.
- The LHC has not yet yielded any observations of BSM particles.
- The LHC was designed to search for heavy particles that promptly decay to visible SM final states.
- There are many BSM models that motivate the search for long-lived BSM particles.

Curtin et al., Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case 1806.07396

- LLP searches in ATLAS/CMS are difficult in the long lifetime regime because of backgrounds and low signal rate.

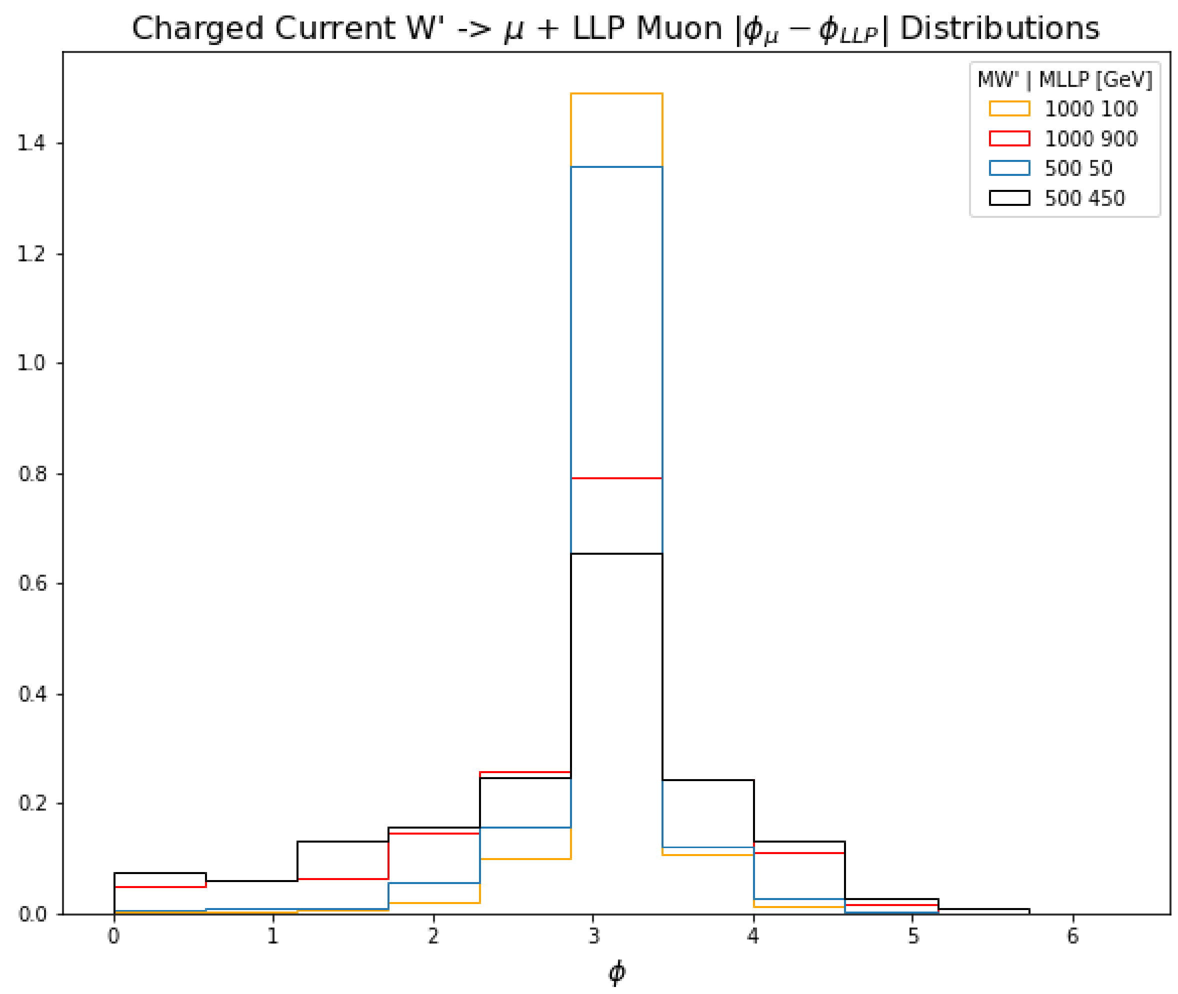
Charged Current: Mass Measurement

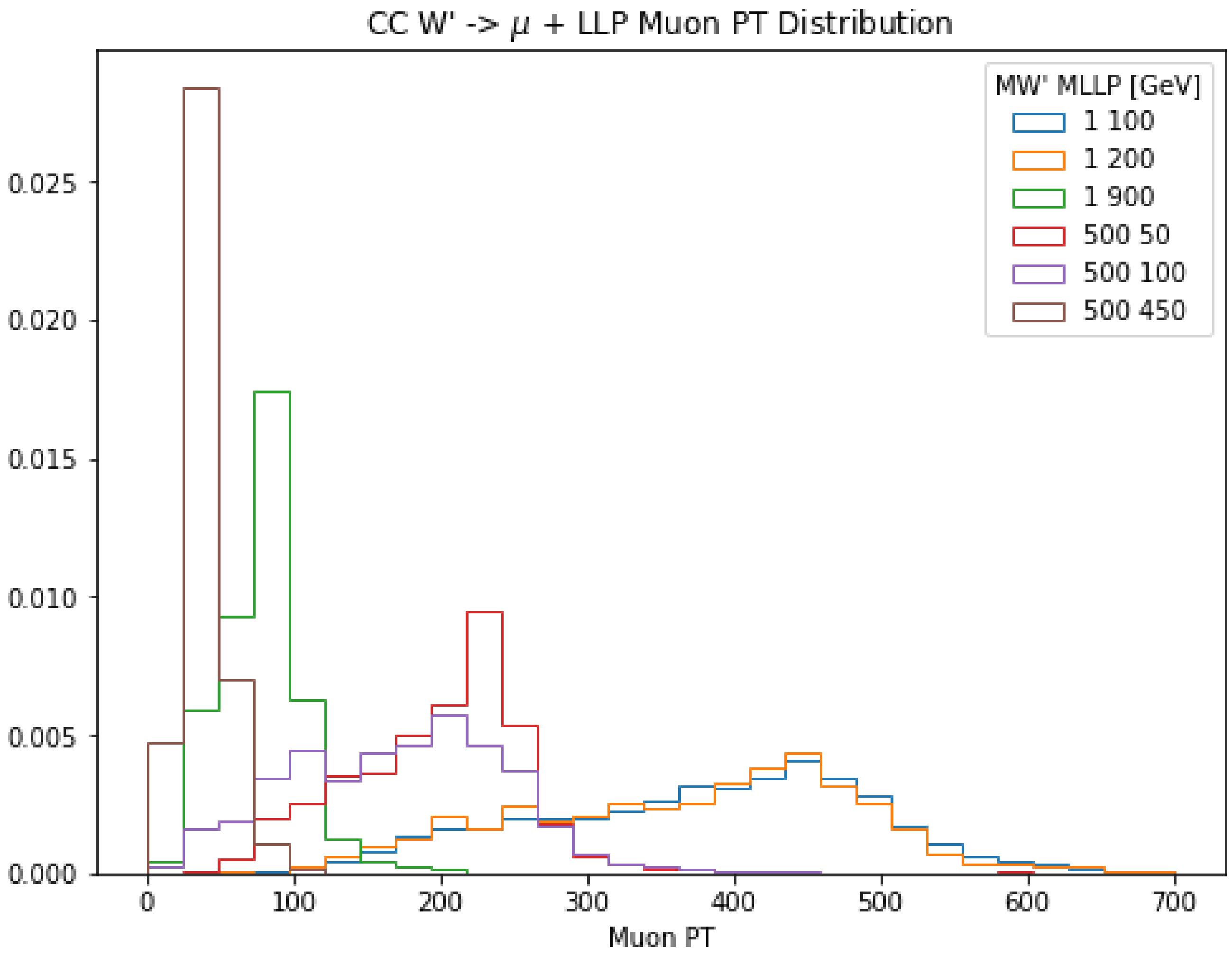




Preliminary

Charged Current: Muons

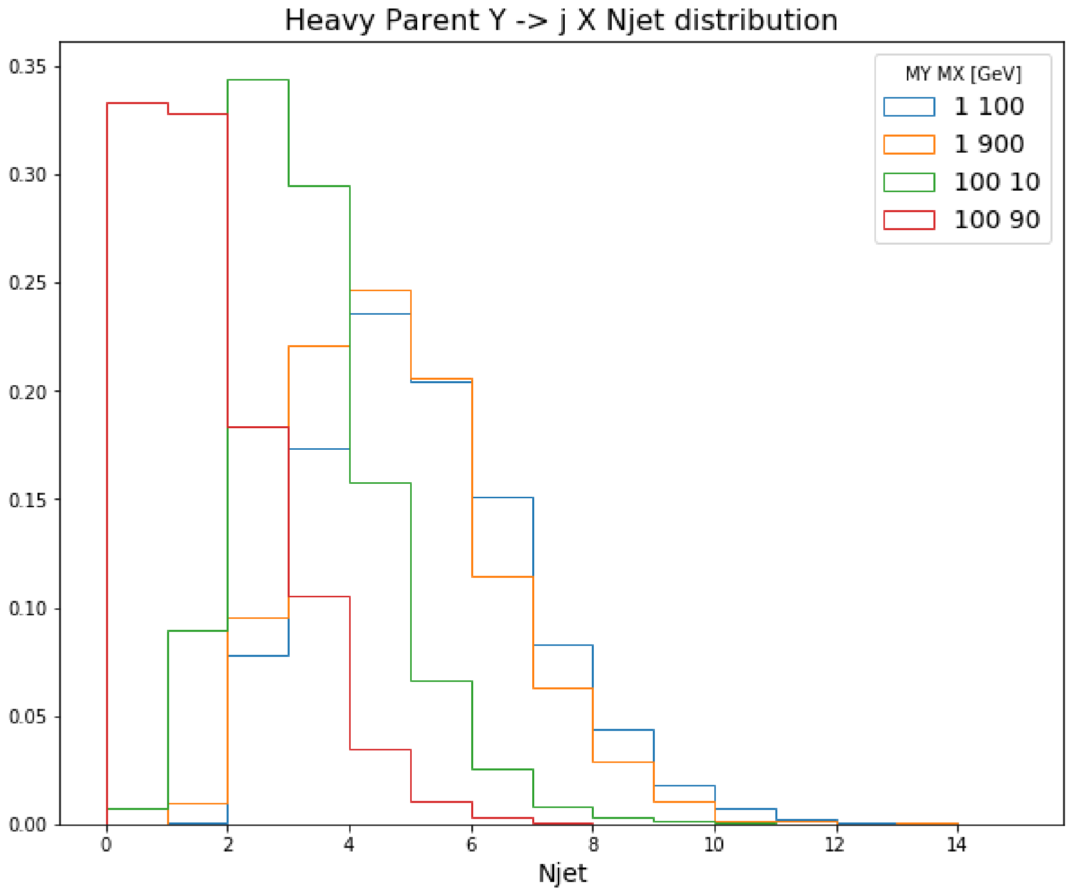




Preliminary

Heavy Parent, QCD 2 body decay

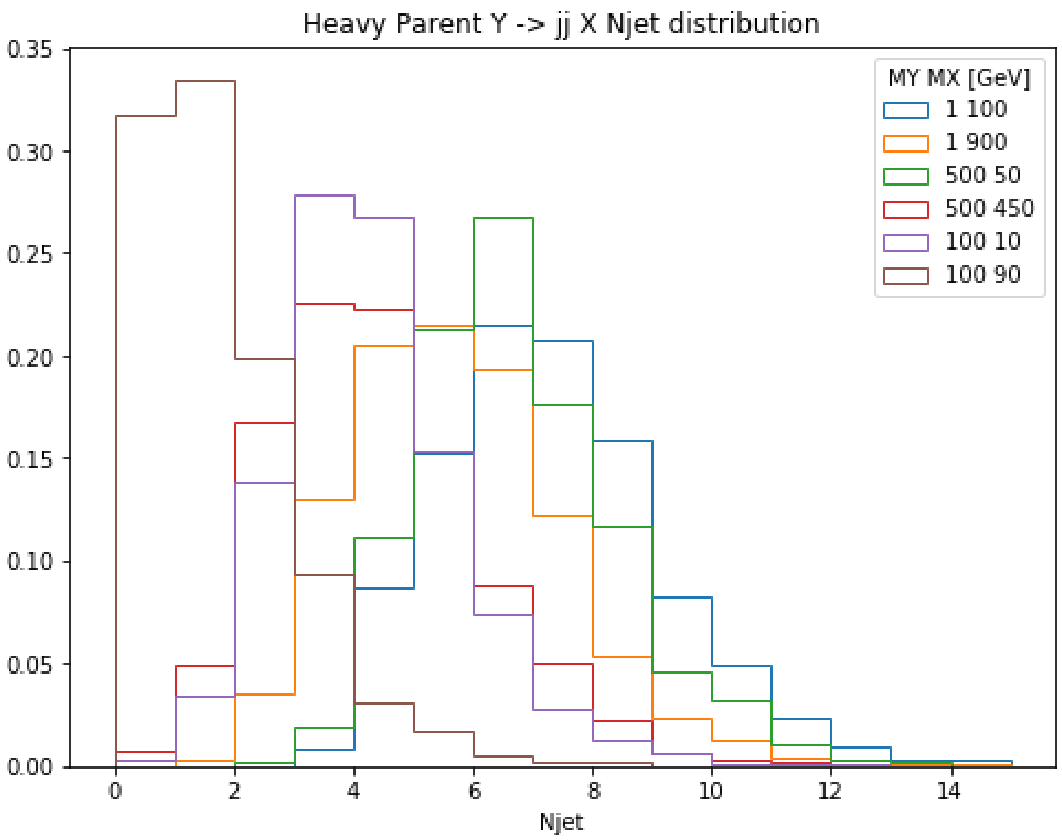
- For $M_{Parent} = 1$ TeV, $M_{LLP} =$ 100 GeV, $\approx$ 50% of events have >4 jets with $p_T > 20$ GeV.
- For $M_{Parent} = 100$ GeV, $M_{LLP} =$ 90 GeV, $\approx$ 1% of events have >4 jets with $p_T > 20$ GeV.
- For Higgs, Heavy Resonance, and Direct Pair Production, this fraction is $\approx 1 - 2$ %.



Preliminary

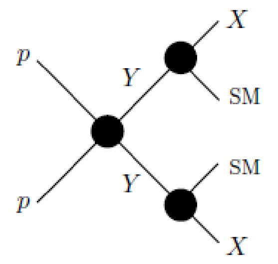
Heavy Parent QCD 3 body decay

- 3 body decay has even more jets than 2 body.
- Exception: Small M_{Parent}, $\frac{M_{LLP}}{M_{Parent}} \sim 1.$



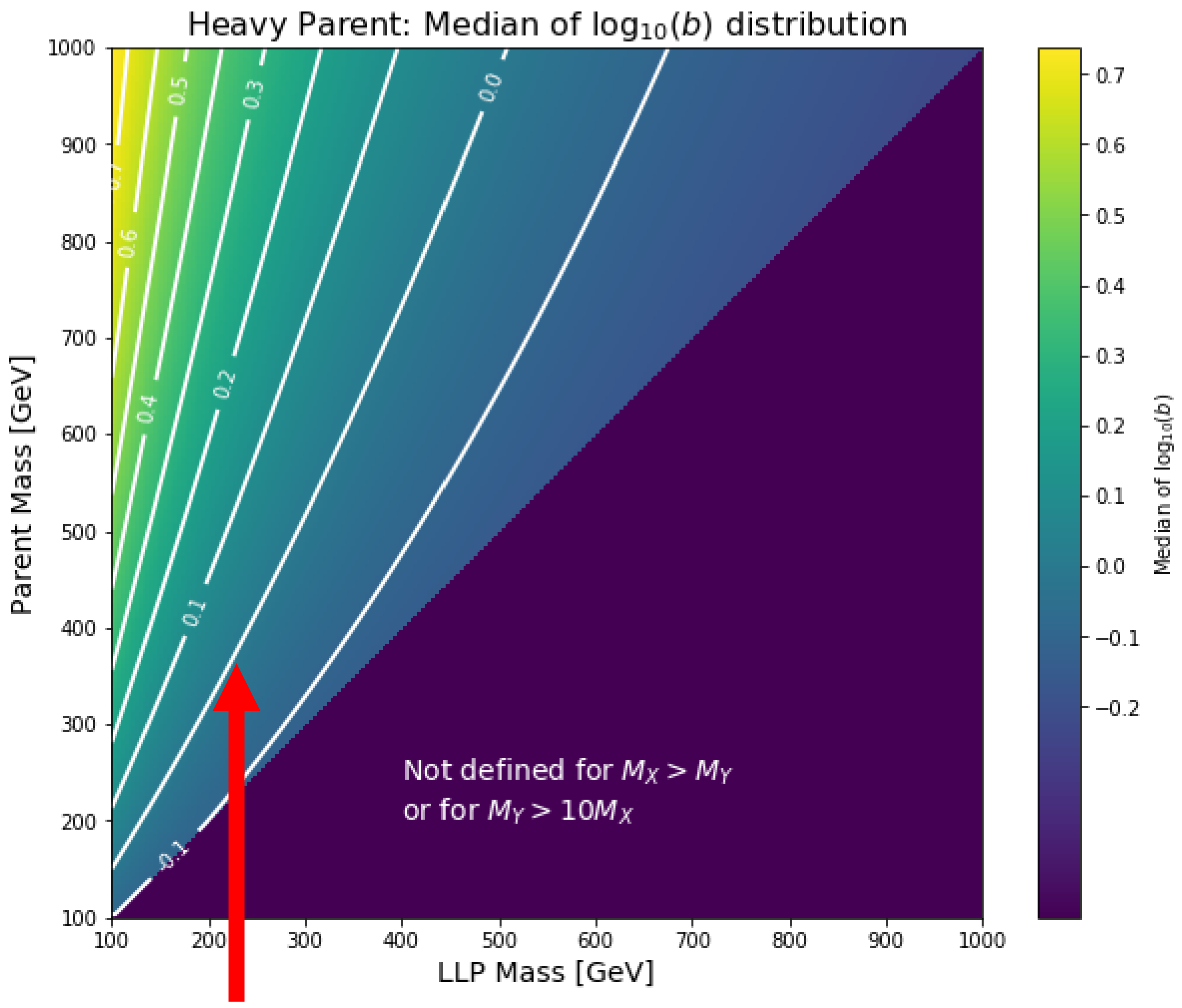
Preliminary

Heavy Parent vs the rest



- High number of jets separates heavy parent from Higgs, heavy resonance, direct pair production.
- A curve in the (M_{LLP}, M_{Parent}) plane maps to one value for the median of the LLP boost distribution.
- To determine M_{LLP}, we perform a procedure similar to that for CC.
- Pair the LLP with each of the jets in the event, and reconstruct M_{Parent}.

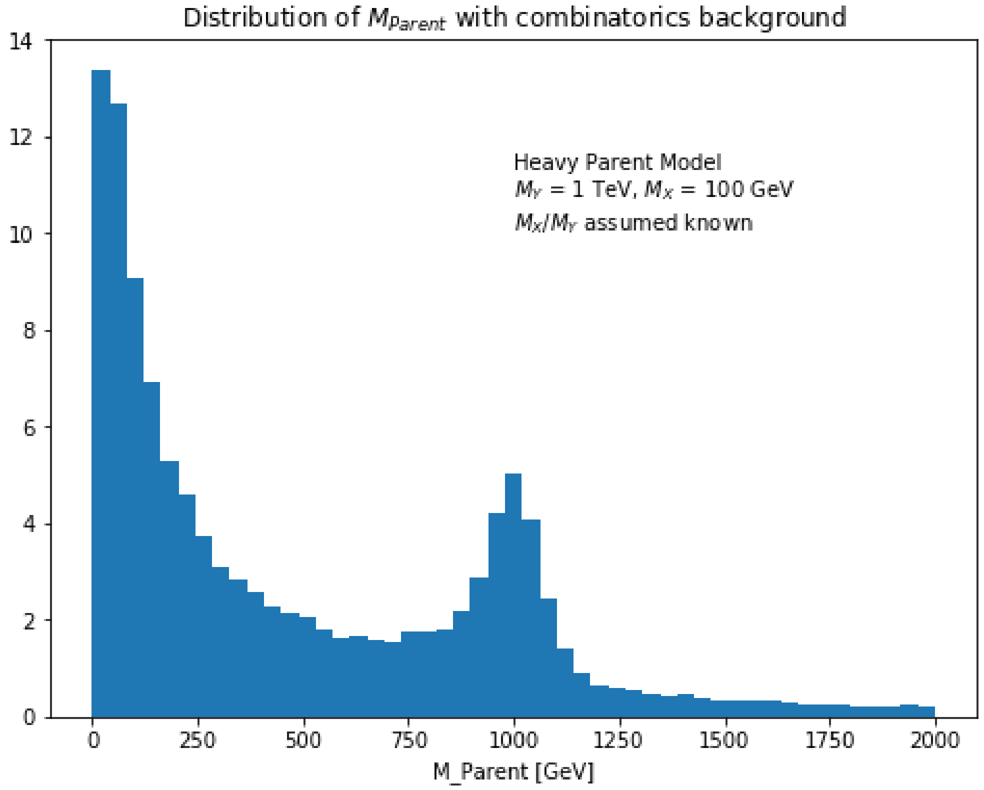
You can (still) solve for both masses.

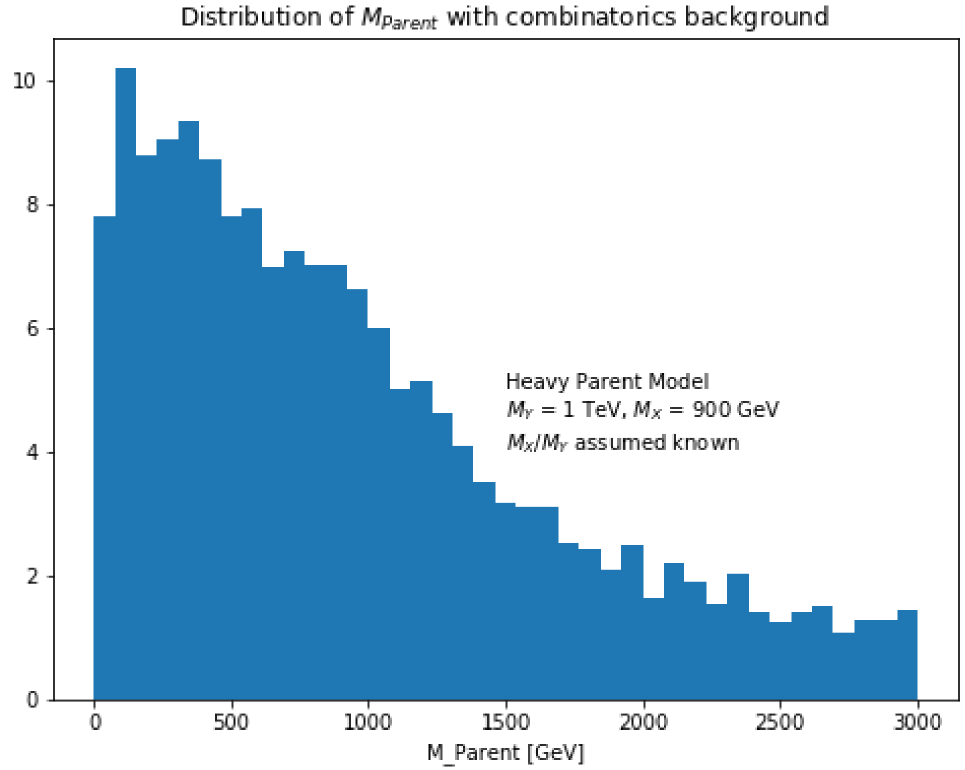


MATHUSLA tells you which curve you're on.

Preliminary

Heavy Parent Combinatorics Background

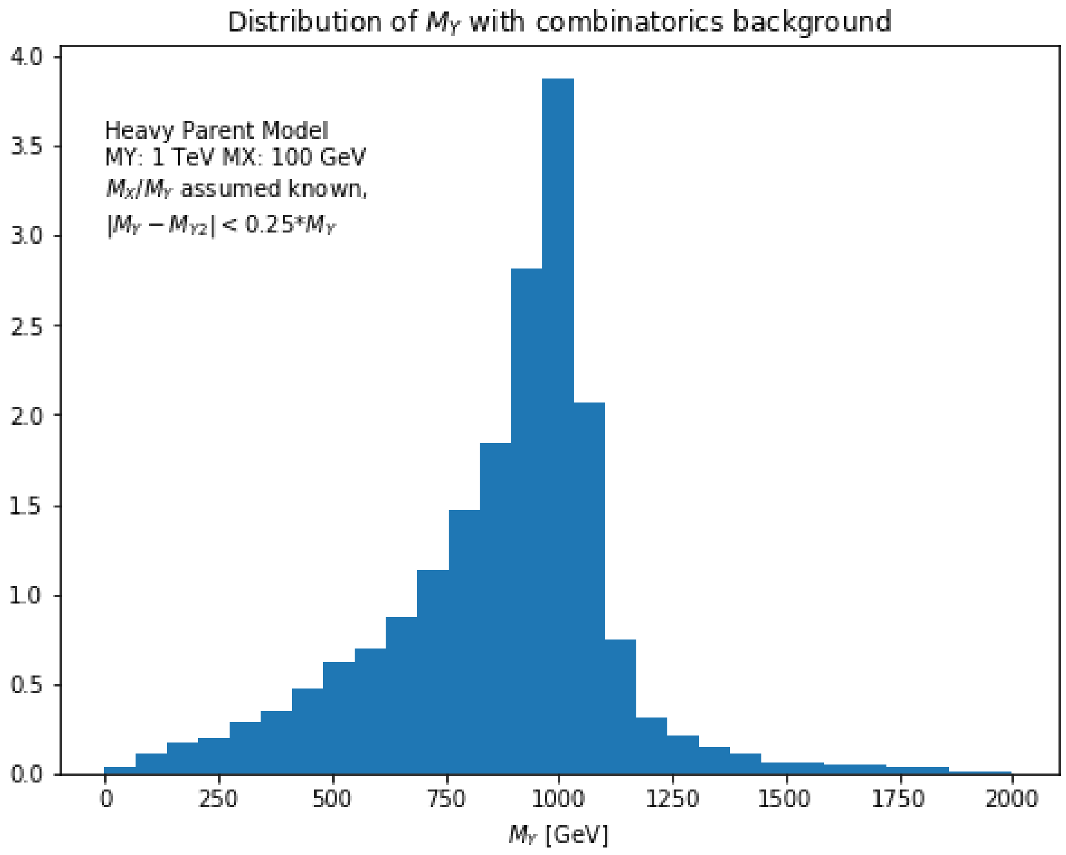


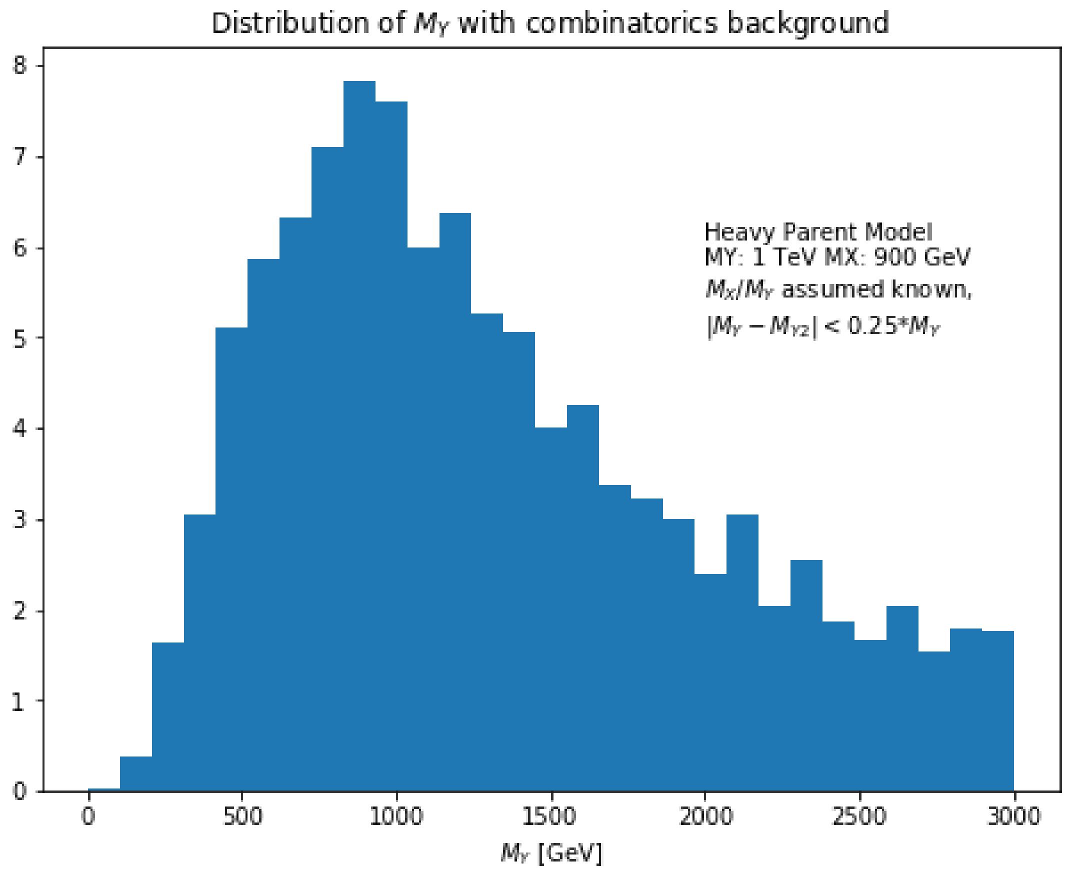


The combinatorics background can be reduced by imposing a minimum p_T cut on the jets. Alternatively, by using missing E_T information, one can reconstruct a mass for the second parent particle, and require that the two reconstructed masses be close together.

Preliminary

Heavy Parent Combinatorics Background

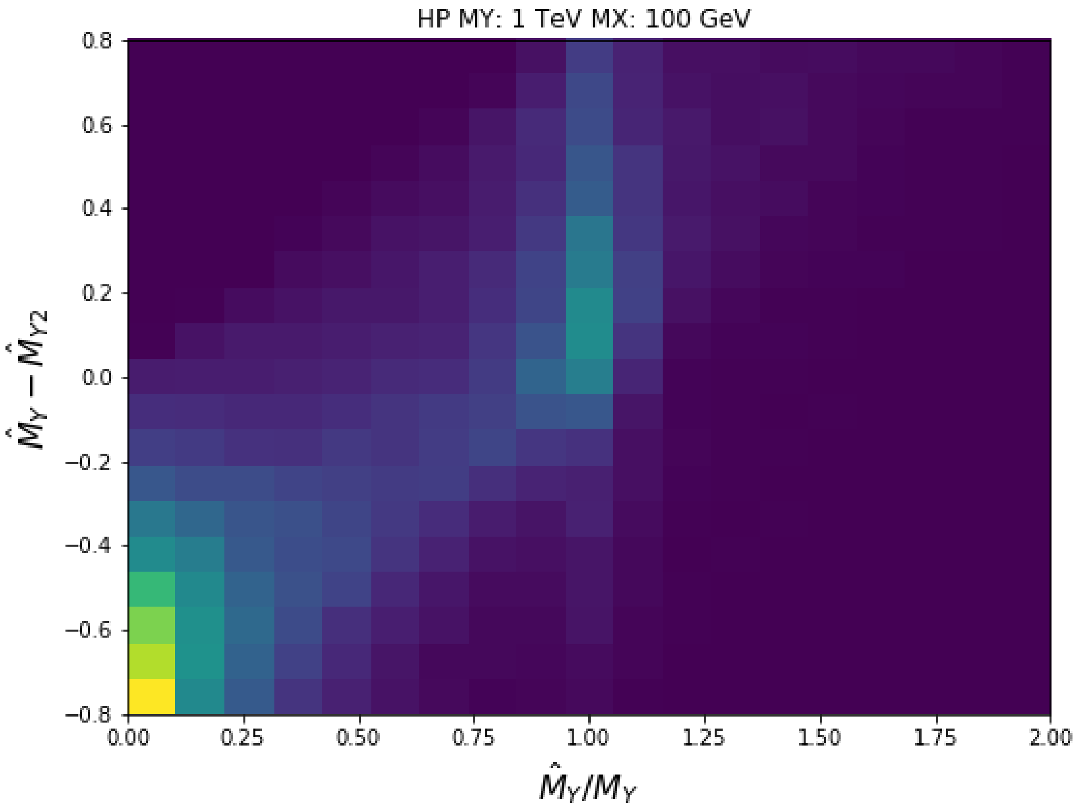


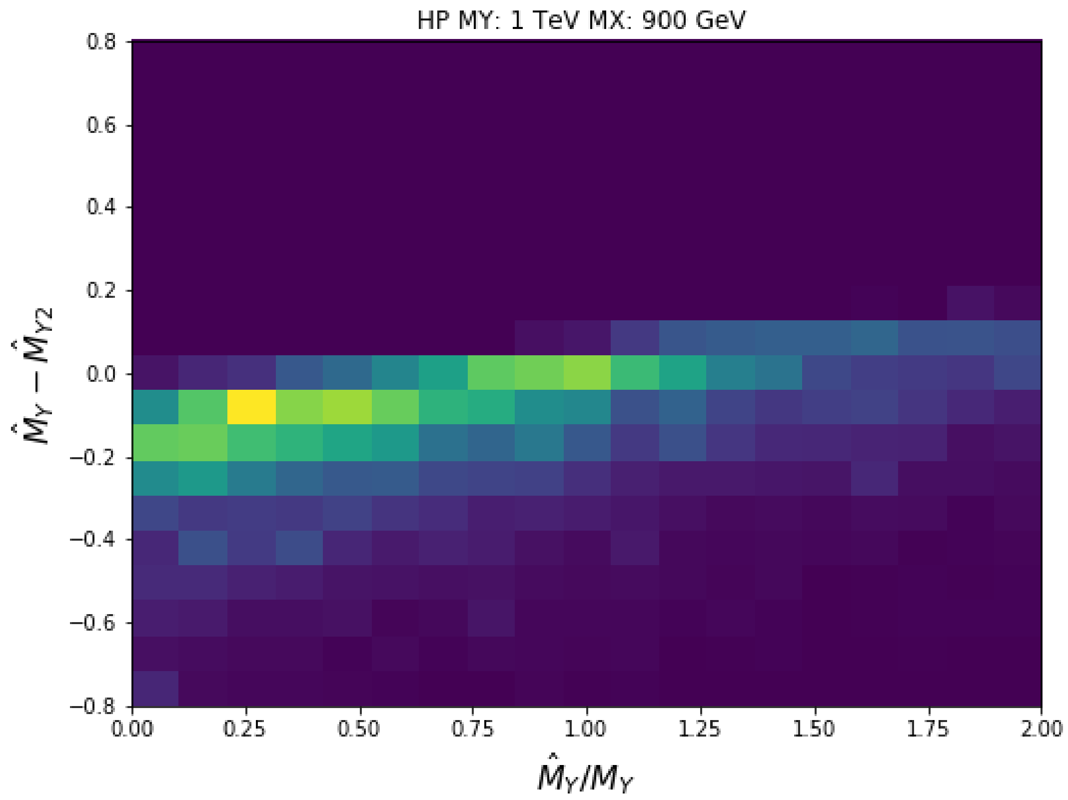


After removing combinatorics background.

Preliminary

Heavy Parent: Combinatorics Background



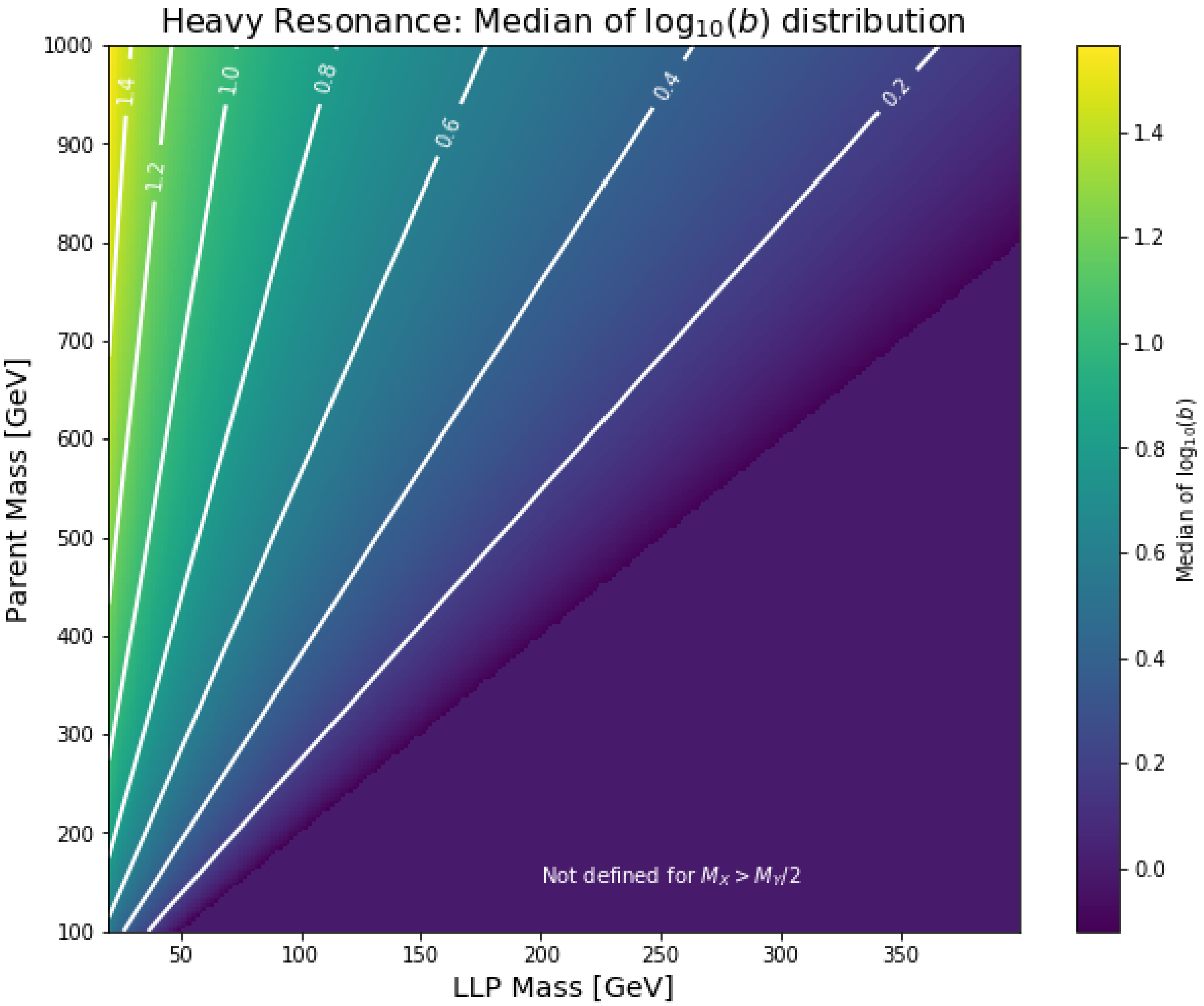


Preliminary

Identifying Exotic Higgs Decay

- Higgs production by vector boson fusion add a pair of hard, well-separated jets to $\approx 10\%$ of events in the exotic Higgs decay mode.
- Heavy resonance and direct pair production only produce jets due to initial-state radiation.
- An example of a possible variable: The proportion of events whose two highest-p_T jets have an invariant di-jet mass > 100 GeV, and a separation in pseudorapidity > 3.
- 12% of Higgs events.
- 2-6% of heavy resonance events.
- 5-8% of direct pair production events.

Heavy Resonance



Preliminary