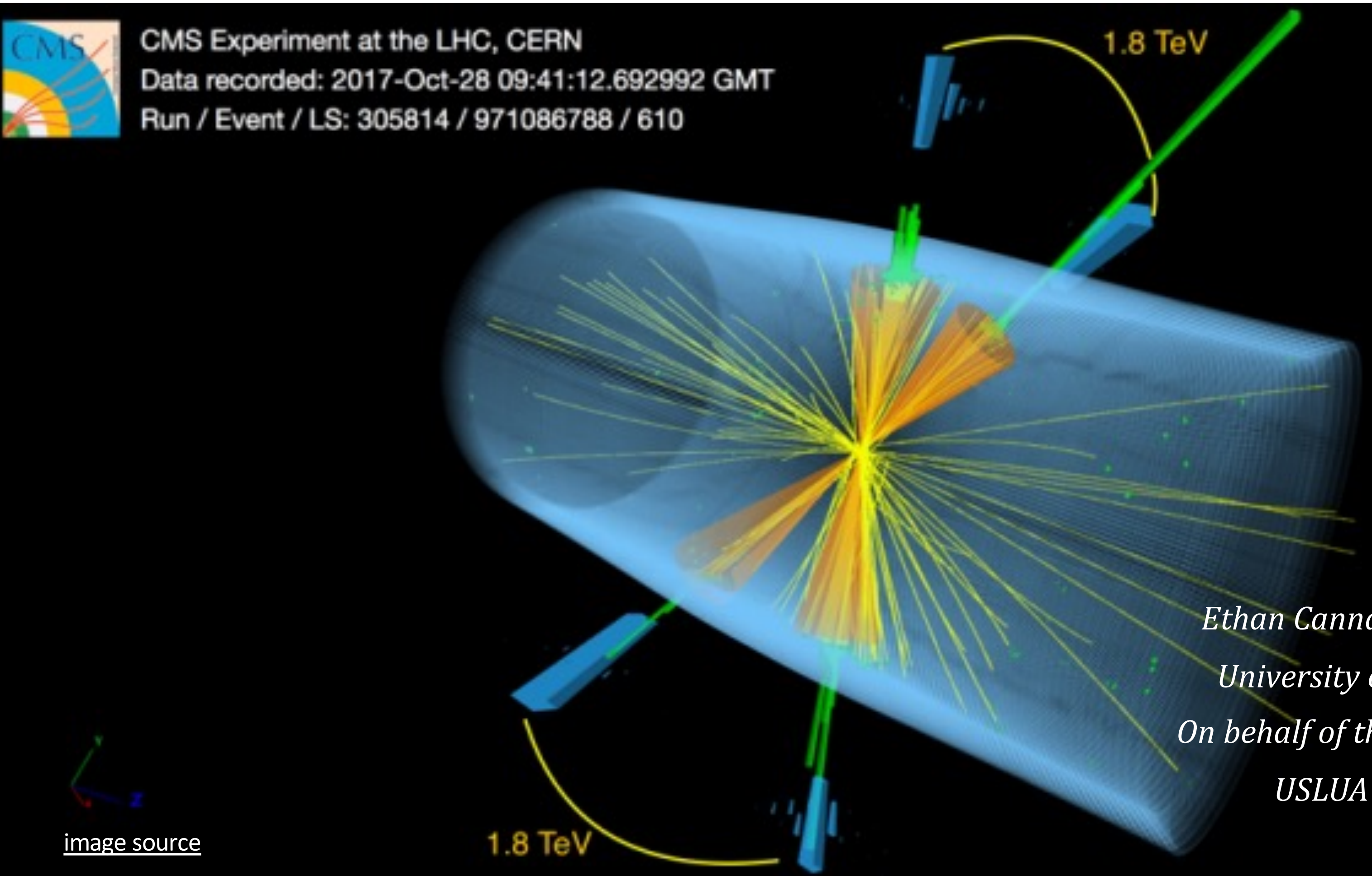
A search for ultra-heavy resonances decaying to vector-like quark pairs at the Run 2 CMS Experiment



Ethan Cannaert & John Conway

University of California Davis

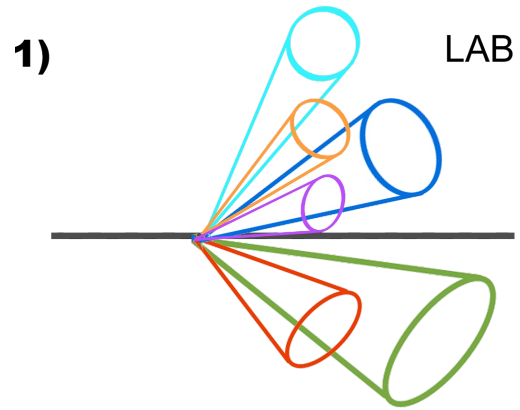
On behalf of the CMS Collaboration

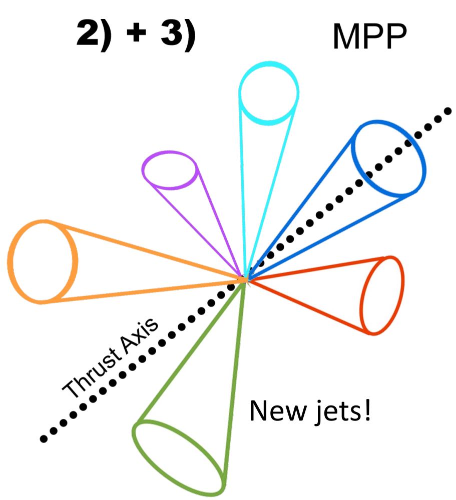
USLUA Meeting 2023

image source

A New Geometric Jet Sorting Technique!

- We have been working on a new technique to study complex, pair-produced processes in Run 2
- **Goal**
  - Use event geometry to reconstruct hadronic decays of heavy pair produced signals
  - Maintain maximum flexibility to account for many models and levels of jet merging
    - Accepts any number of jets as inputs
    - Applicable to any pair-produced signal
- **Algorithm Steps**
  1. Select high energy events with many jets
     - How loosely will jets be selected?
  2. Boost all jet particles along their axis to the frame that minimizes parallel momentum (MPP frame)
  3. Recluster particles into new jets
     - This resolves jets that were merged in the lab frame and gives the opportunity to shed soft radiation that gets clustered into the original jets



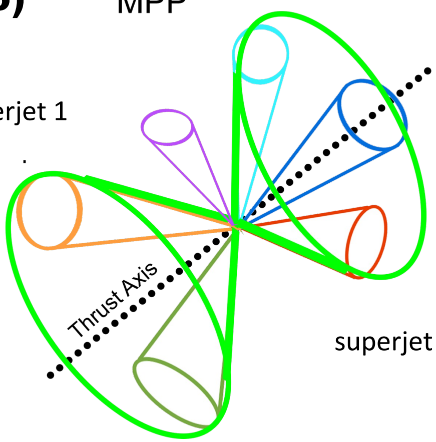


Sorting Technique Continued

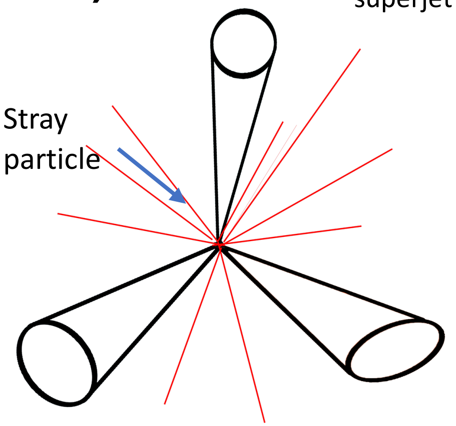
$$\text{*Thrust} = max_{|n|=1} \frac{\sum_i |n \cdot p_i|}{\sum_i |p_i|}, [9]$$

4. Calculate the MPP thrust* axis.
   - This should split the event into hemispheres
5. Sort jets into two "superjets" from their angles relative to the thrust axis.
   - Nearly perpendicular jets sorted to balance superjet mass
6. Boost superjets to their COM & recluster particles into smaller jets

4) & 5)



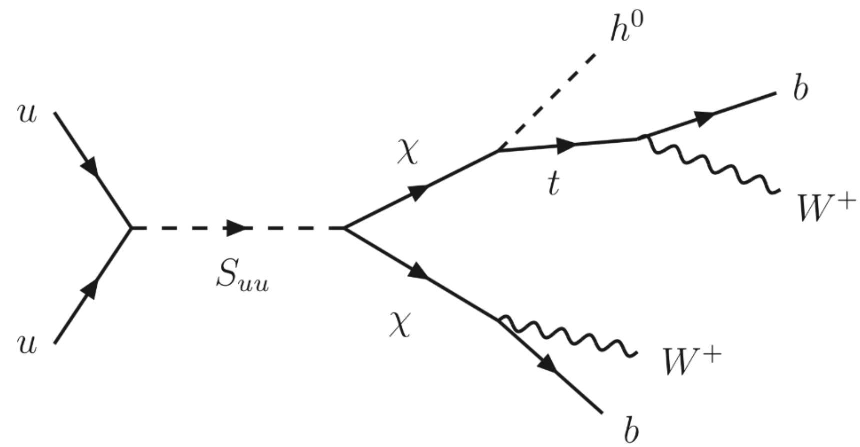
6)

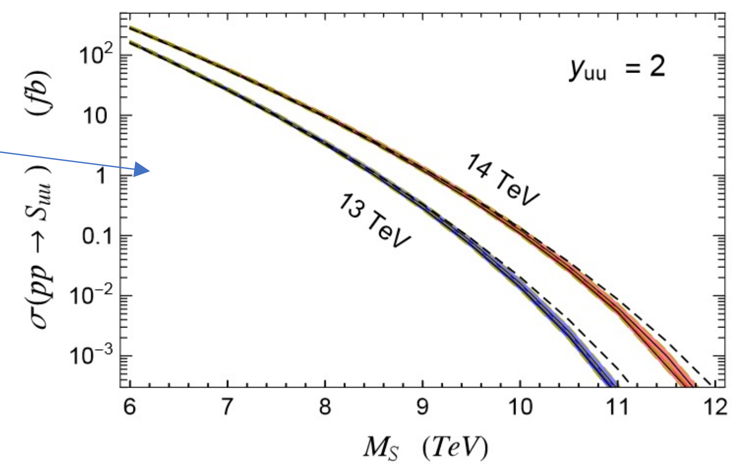


- If everything went well, you'll have two sorted superjets representing your daughter pair
- Superjet substructure is a powerful tool for discriminating against backgrounds
  - MPP frame event shape
  - superjet COM event shapes

Our Pet Process - $S_{uu} \to \chi\ \chi$

- The $\boldsymbol{S_{uu}} \to \boldsymbol{\chi\ \chi}$ process provides a fantastic opportunity to put this technique into practice
- $\boldsymbol{S_{uu}}$ - diquark, ultra-heavy resonance, couples to up quarks
- **χ** – vector-like quark
  - decays to W^+b, Z t, h t
- Relatively large σ at LHC means there is potential for Run 2 discoveries up to $M_{S_{uu}}$= 8 TeV
- Many complex hadronic final states with different levels of jet merging
- Main backgrounds – QCD multijet & top pair production





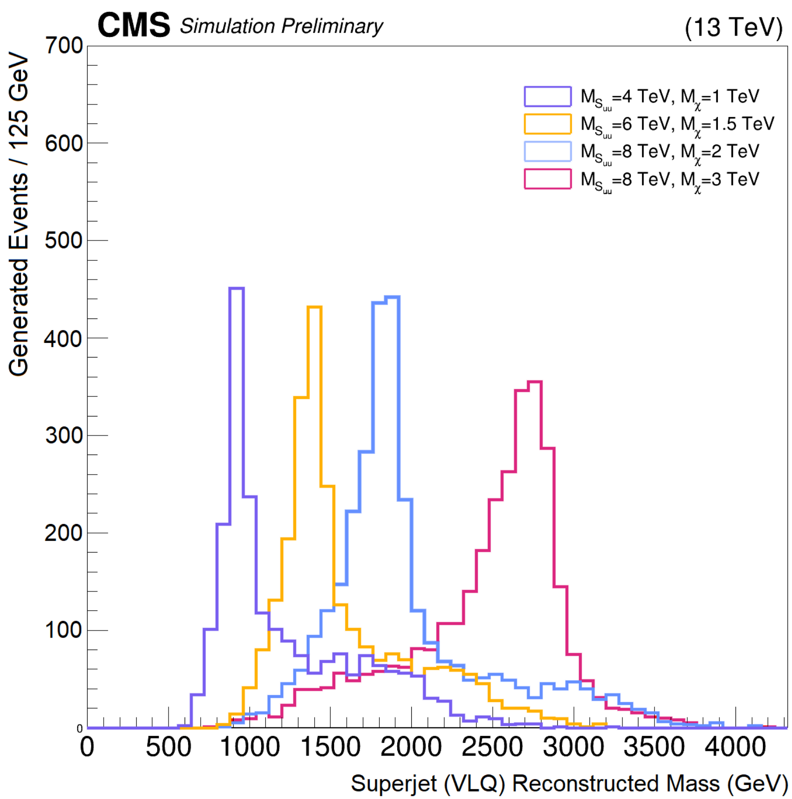
* $S_{uu} \to \chi\ \chi$ model source: Bogdan Dobrescu, Robert Harris and Joshua Isaacson, FNAL

Sorting Algorithm on MC

- How well does this work with reconstructed jets?
- Define some baseline cuts to target the hadronic channel

<u>Initial Selection</u>

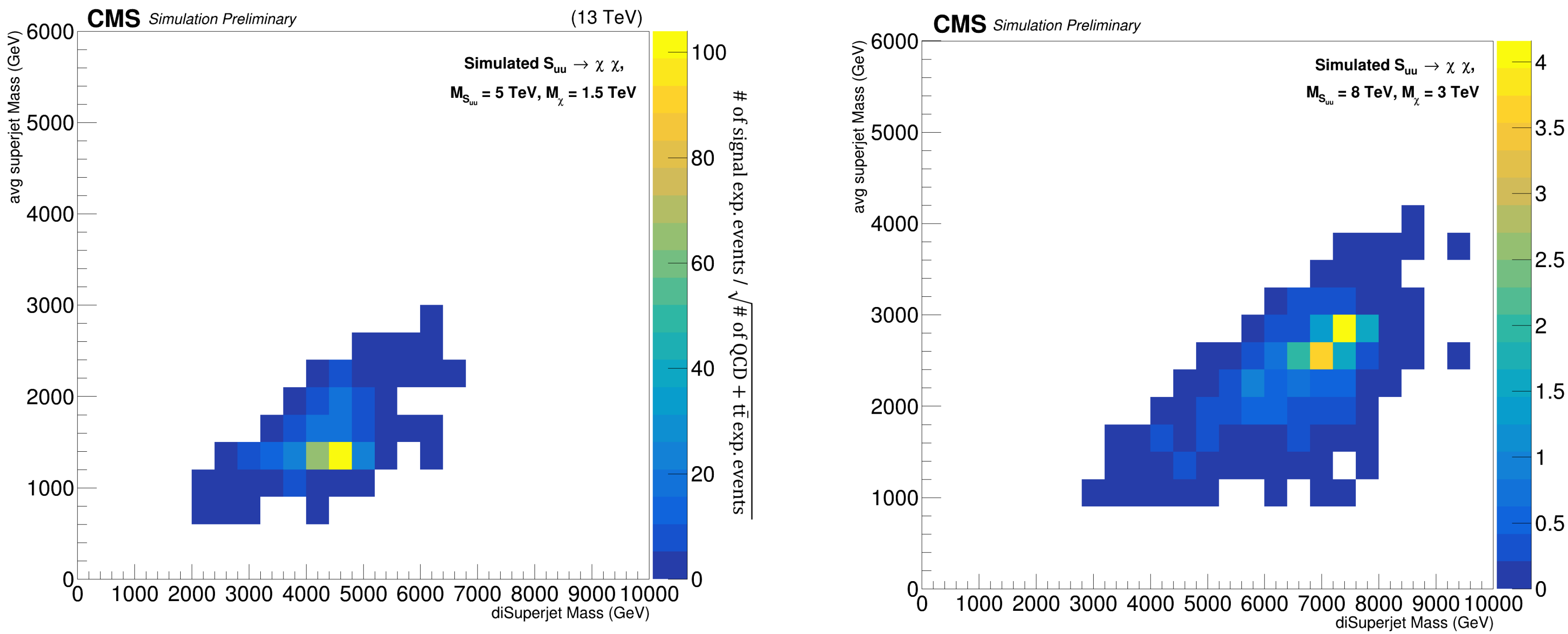
- Lepton veto
- Event H_T > 1500 GeV
- 3+ wide cone jets
- 2+ heavy wide cone jets ($M_{PUPPI,SoftDrop}$> 45 GeV) or two dijet pairs w/ M_{dijet} > 1 TeV
- 1+ tight b-tagged jets



Above: the average reconstructed superjet mass from this technique obtained from tests on various simulated $S_{uu}/\ \chi$ mass combinations.

- Tests on $S_{uu} \rightarrow \chi\ \chi$ simulation samples for various $M_{S_{uu}}$ and M_χ combinations show high resolution in M_χ reconstruction
  - $M_{S_{uu}}$: 4-8 TeV, M_χ: 1-3 TeV
- Backgrounds are not resonant, so superjet mass vs diSuperjet distribution can give extra signal sensitivity

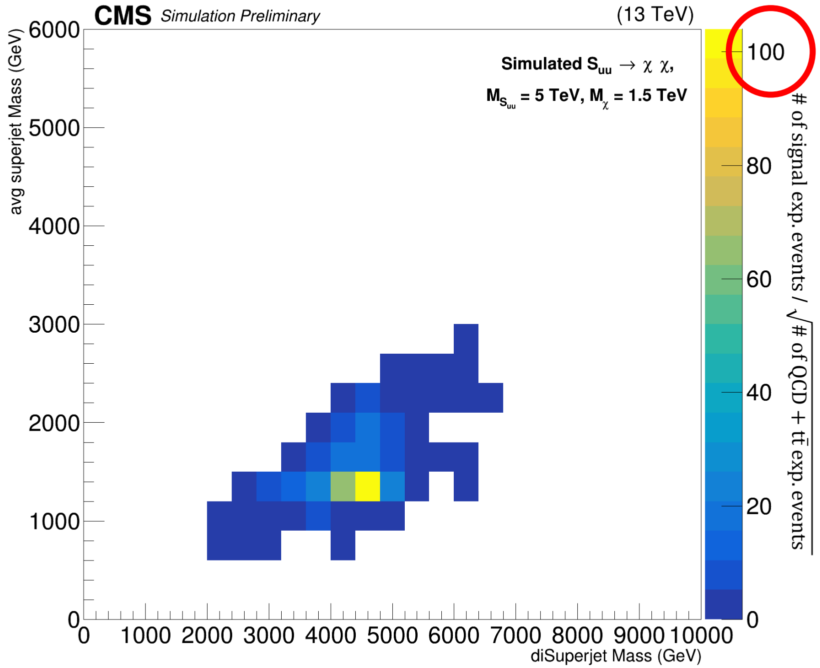
Sorting Algorithm on MC

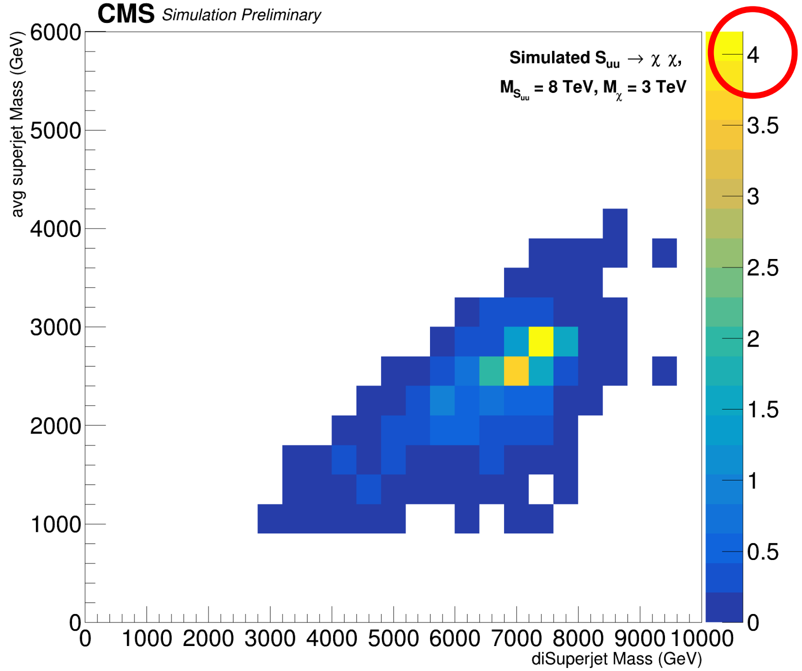


Above: Expected signal sensitivity, given by $\frac{N_{signal\ events}}{\sqrt{N_{QCD+tt\ events}}}$, from simulation for this technique as a function of the average superjet mass and diSuperjet mass. The distributions are shown for two different $S_{uu}/\ \chi$ mass combinations

- Comparison of scaled signal to backgrounds (QCD & $t\bar{t}$) shows sensitivity greater than 4 in the signal region up to 8 TeV in average SJ vs diSJ masses
- $\sigma_{S_{uu}\to\chi\ \chi}$ is only an estimate, but this gives a lot of breathing room for this to float

Sorting Algorithm on MC





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Future Additions & Summary

- **This technique has been designed with maximum adaptability in mind to accommodate any pair-produced model**
  1. Any number of jets are accepted as inputs
  2. Steps are in place to counteract the effects of highly-boosted topologies
  3. A new class of superjet substructure variables become available for study
- Results on $S_{uu} \rightarrow \chi\,\chi$ simulation show the ability to consistently reconstruct VLQ masses with reasonable resolution
  - The resulting signal sensitivities in the superjet vs diSuperjet plane and expected S_{uu} cross-section facilitate Run 2 studies up to $M_{S_{uu}}$ = 8 TeV
- Room remains to add sophistication
  - Iterative rounds of jet reclustering to remove unwanted particles
  - Machine learning for sorting jets and recognizing superjet substructure
  - Optimization of initial boost value of all jets
- We hope the ideas we have worked on will be expanded and carried over to Run 3
- In the meantime, keep an eye out for our $S_{uu} \rightarrow \chi\,\chi$ Run 2 analysis!

Good hunting in Run 3!

Image source

References

- [1] M. Cacciari, G. P. Salam and G. Soyez, “The anti-kt jet clustering algorithm”, 2008, arXiv:0802.1189
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- [3] Bogdan A. Dobrescu, Robert M. Harris, Joshua Isaacson, “Ultraheavy resonances at the LHC: beyond the QCD background”, arXiv:1810.09429
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- [5] CMS Collaboration, “Pileup-per-particle identification: optimisation for Run 2 Legacy and beyond”, 2020, CMS-DP-2021-001
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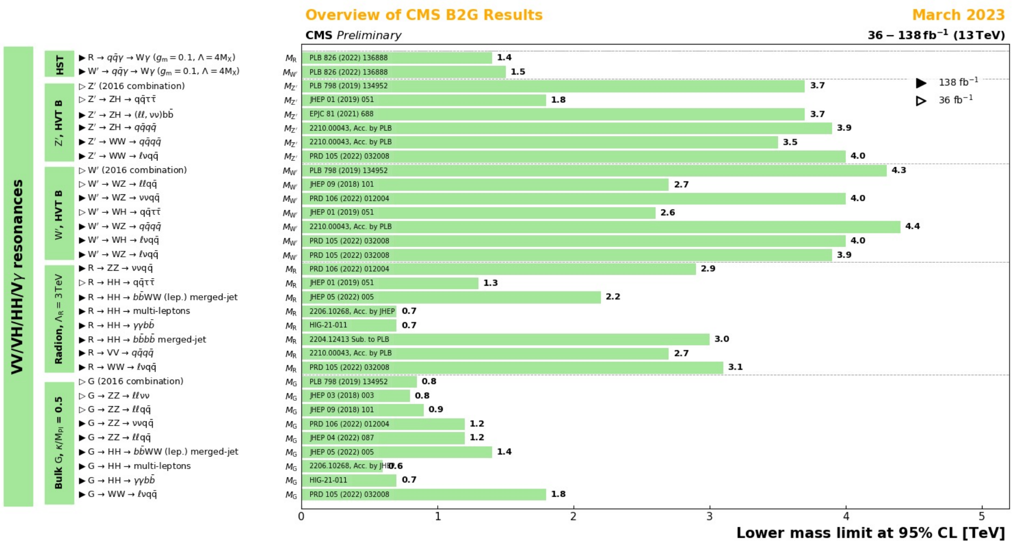
- [8] CMS Collaboration, “Identification of hadronic tau lepton decays using a deep neural network”, 2022, arXiv:2201.08458
- [9] V. D. Barger, R. J. N. Phillips, “Collider Physics” Frontier in Physics, p. 284, 1997, Addison-Wesley Publishing Company, Inc.

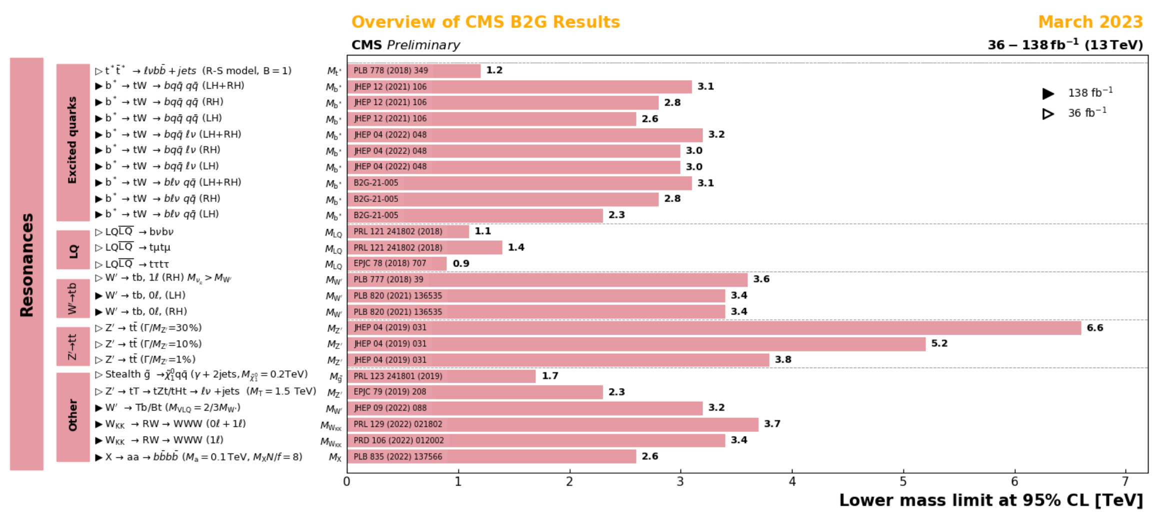
Backups

Resonance Searches in Run 2



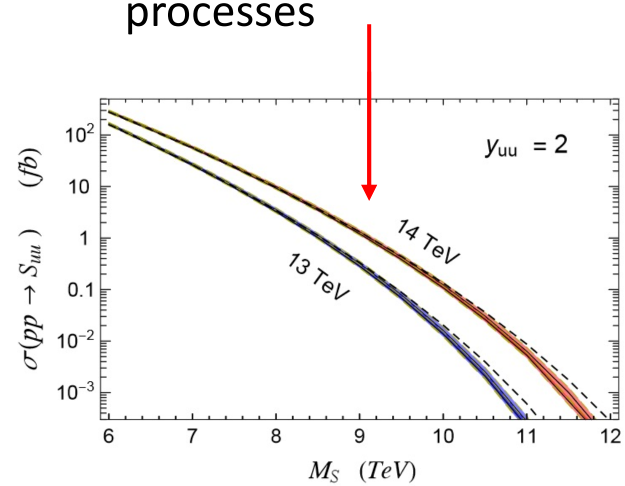
- Run 2 CMS analyses extended our limits on many resonance searches up to several TeV and beyond
- Much of the possible phase space has been covered
- [Check out more CMS B2G analyses](#)!

- Is new physics hiding in plain sight or on the horizon?
- What is the limit of what can be discovered at the LHC?
  - Run 2? Run 3?



Resonances in Run 3

- With Run 3 underway, it's an exciting time to be studying ultra-heavy resonances!
- Increased luminosity and ~4.5% increase in energy that significantly enhances many of these processes



Exploring the laws of nature with CMS, Dobrescu 2020

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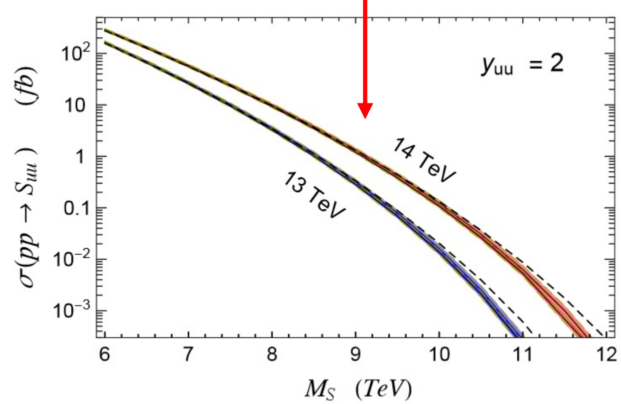
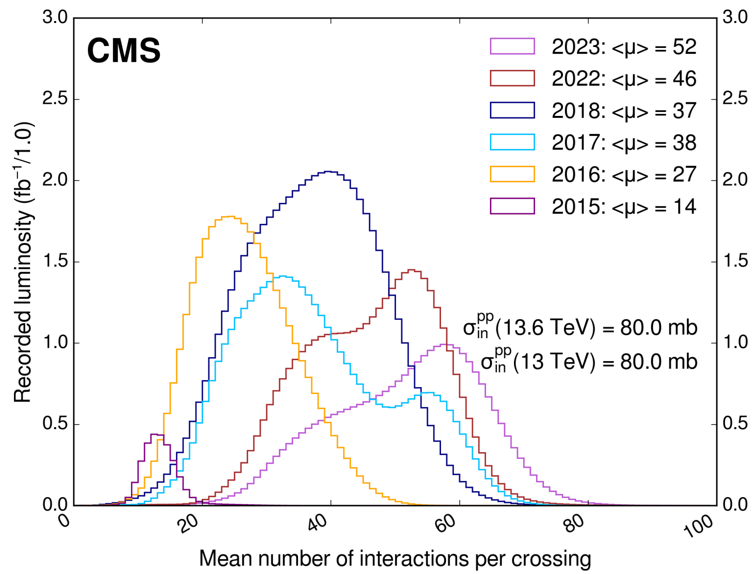


Exploring the laws of nature with CMS, Dobrescu 2020

Challenges in Run 3

- Increased pileup → increased jet multiplicity that complicates jet sorting
- Increased energy → more highly boosted events with many overlapping jets
- Conventional techniques often break down at high energies
- If you are looking at fully hadronic channels, these are all challenges that need to be considered
- On top of this, there is often a large phase space to cover
- New techniques must be flexible to various kinematics yet robust enough to function at high energy

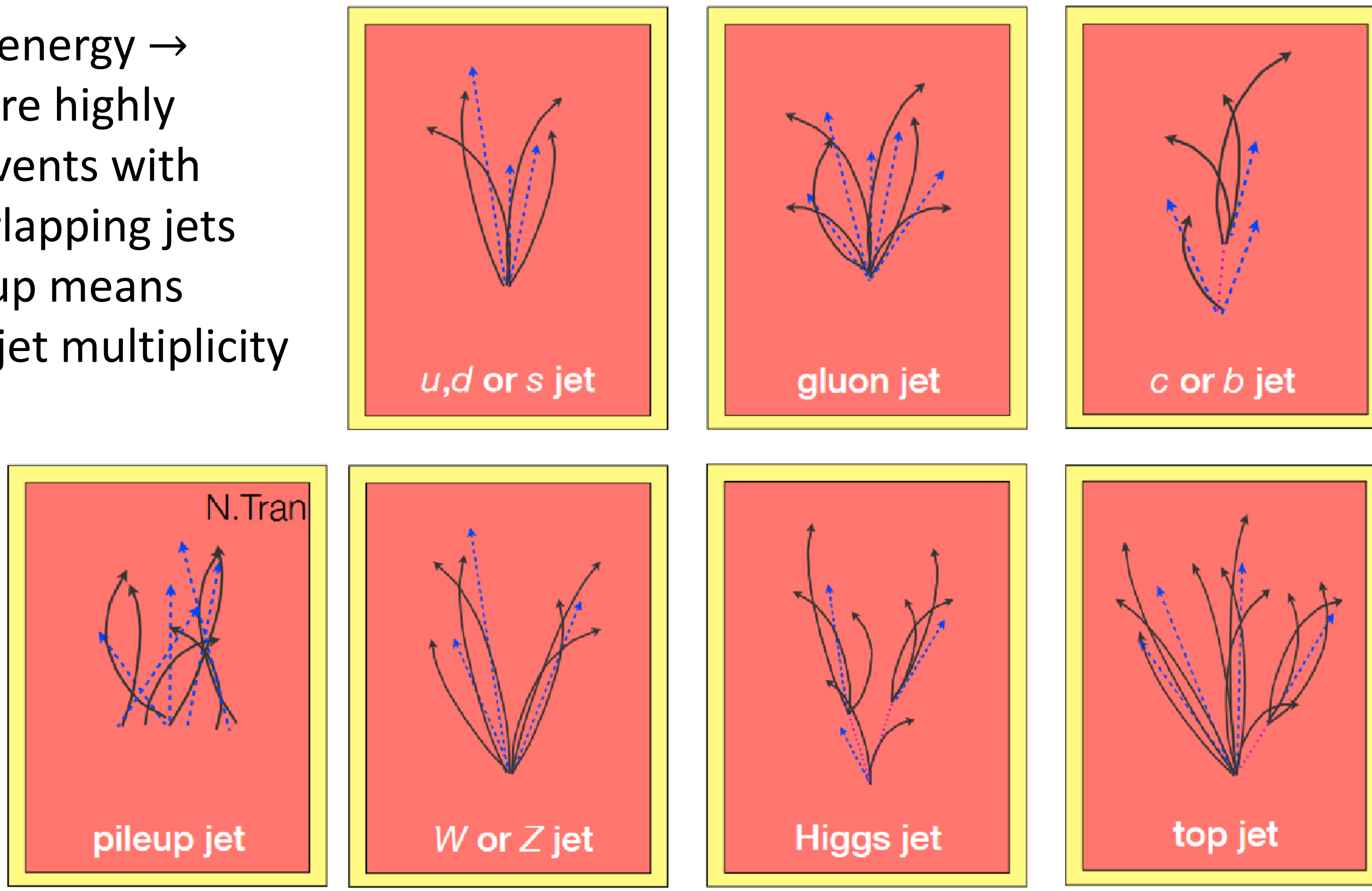


Above: Distribution of the average number of interactions per crossing (pileup) for pp collisions at the LHC for years 2011-2012, 2015-2018 and 2022-2023. Source: Public CMS Luminosity Results, The CMS Collaboration, 2023, link to luminosity results

Challenges in Run 3

- Increased energy → busier, more highly boosted events with many overlapping jets
- More pileup means increased jet multiplicity

Imagine these jets all superimposed, overlapping, etc.



Jet substructure, The CMS Collaboration, 2022

Analysis Regions

Signal Region
- Lepton veto (medium IDs + isolations)
- PFHT_1050 trigger pass + further 1500 HT cut
- 3+ AK8 jets (pT > 300 GeV, medium ID)
- 2+ heavy AK8 jets (M > 45 GeV) or two dijet pairs w/ $M_{dijet} > 1$ TeV
- 1+ tight b-tagged AK4 jet
- Require each SJ have 2+ recluster AK4 jets with E>300 GeV or be tagged by NN

QCD Control Region
- Lepton veto (medium IDs + isolations)
- PFHT_1050 trigger pass + further 1500 HT cut
- 3+ AK8 jets (pT > 300 GeV, medium ID)
- 2+ heavy AK8 jets (M > 45 GeV) or two dijet pairs w/ $M_{dijet} > 1$ TeV
- 0+ tight b-tagged AK4 jet
- Require each SJ have 2+ recluster AK4 jets with E>300 GeV or be tagged by NN

Anti-tag Region
- Lepton veto (medium IDs + isolations)
- PFHT_1050 trigger pass + further 1500 HT cut
- 3+ AK8 jets (pT > 300 GeV, medium ID)
- 2+ heavy AK8 jets (M > 45 GeV) or two dijet pairs w/ $M_{dijet} > 1$ TeV
- 0+ tight b-tagged AK4 jet
- One (randomly selected) SJ does not pass substructure cuts or is not tagged by NN

TTbar Control region - pending