Jet substructure at the LHC

Lais Schunk

DESY New Fellows Day

12 December 2017

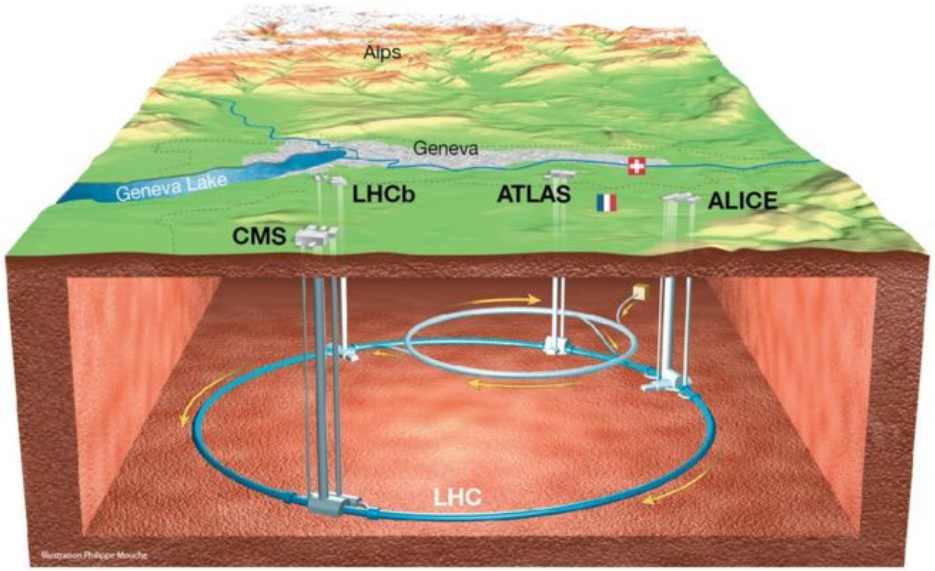
Who am I ?

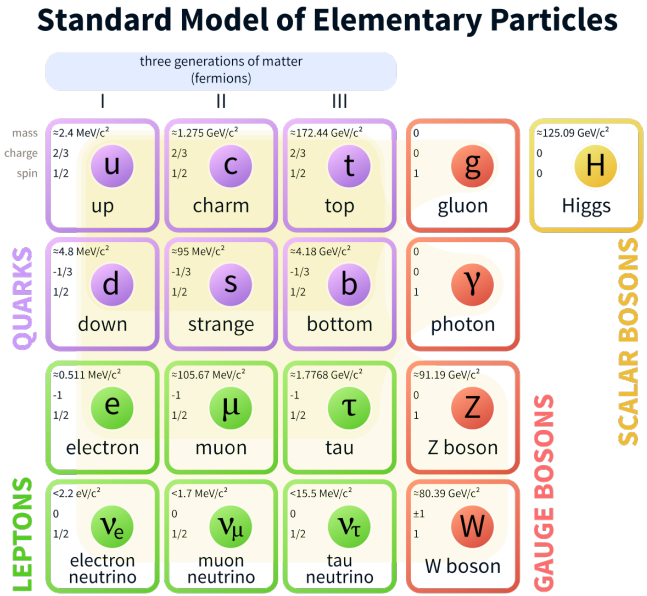
- Brazilian
- Started undergrad at Sao Paulo University (Brazil)
- Finished undergrad at Ecole Polytechnique (France)
- Masters at Ecole Normale (Paris)
- PhD at IPhT, CEA – Saclay; directed by Gregory Soyez in the subject "Understanding jet substructure at the LHC"

Now, physics...

Motivation

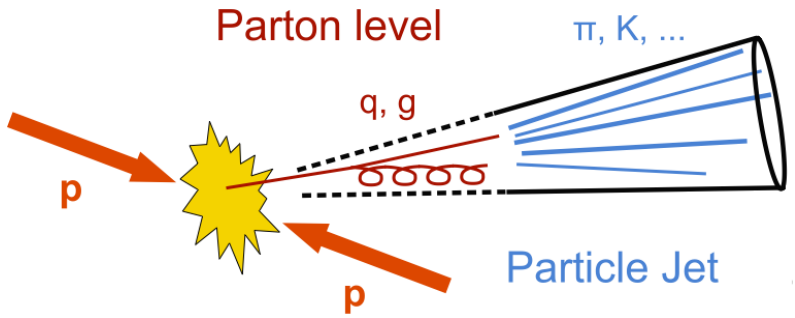
- LHC pushes the energy boundaries and probes new theories *e.g.* Supersymmetry, nature of Dark Matter ...
- Phenomenology does the connection between experiments (signals measured in detectors) and theoretical representation of particles





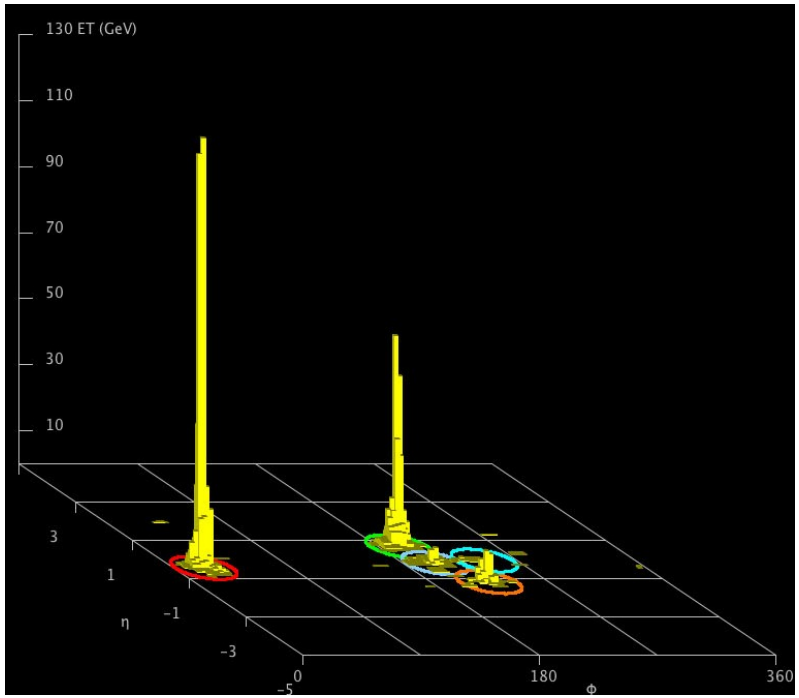
What is a jet ?

- QCD partons → never observed isolated due to confinement principle



- What happens instead :
  → QCD particles decays into other partons
  → observed as hadrons in collimated structures called jets

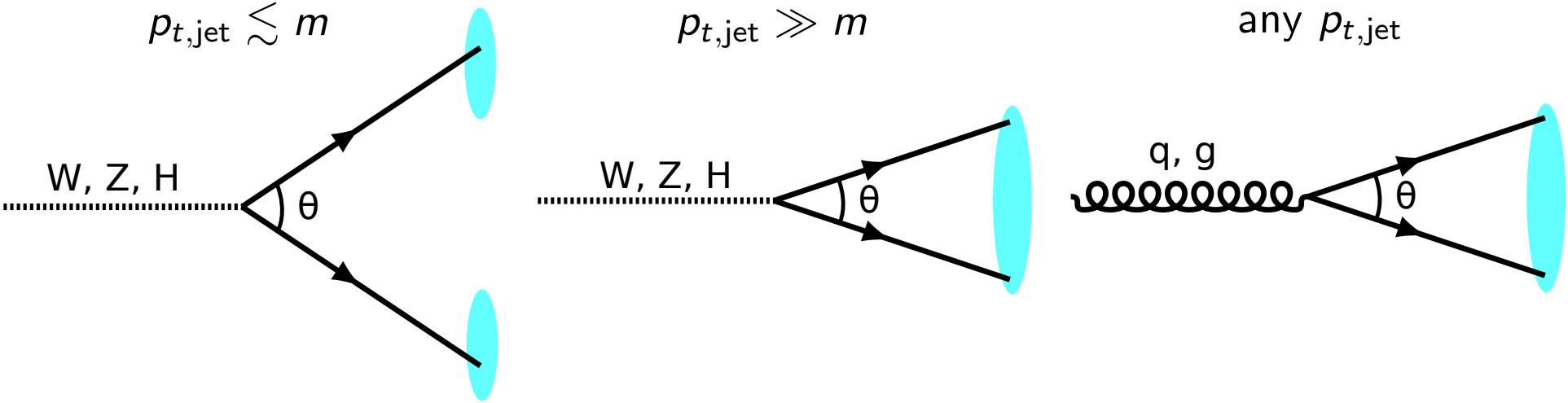
- Known for a long time in collider phenomenology
  → first jet algorithm in the 70s



Boosted jets and substructure

Boosted heavy particles

- At the LHC :
  $\rightarrow$ production of boosted heavy particles ($p_{t,\text{jet}} \gg m$)
  $\rightarrow$ opening angle is $\theta \sim m/p_{t,\text{jet}}$
  $\rightarrow$ clustered into a single jet
- Collinear divergences $\rightarrow$ QCD jets are collimated at any $p_{t,\text{jet}}$ range



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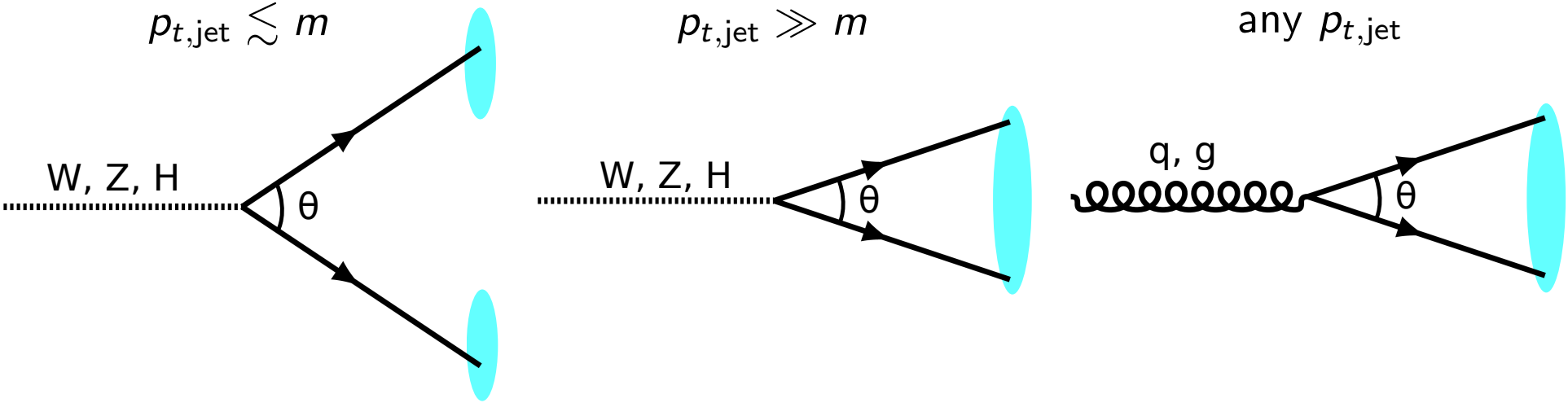
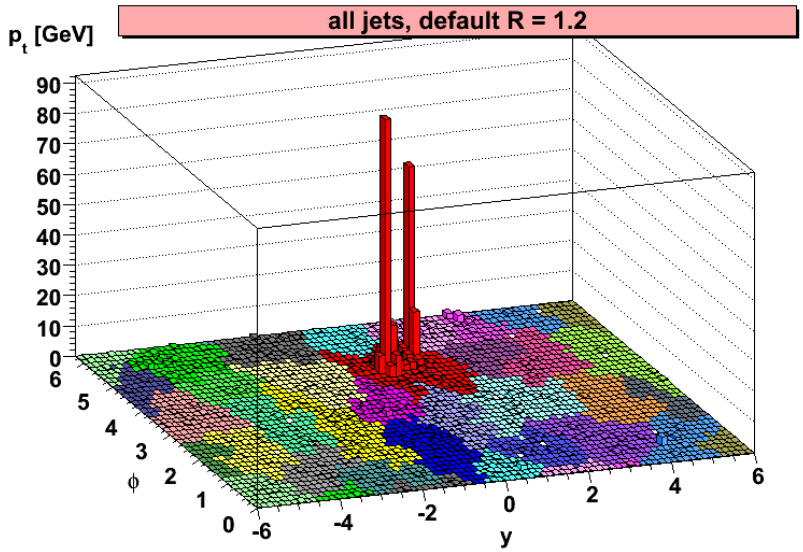


- How to discriminate QCD jets and W/Z/H hadronic decay jets?
  Use **jet substructure** methods $\rightarrow$ internal dynamics of the jet

Example : (modified) Mass Drop Tagger

- Removes soft and large-angle radiation
  J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam (2008)
  M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam (2013)



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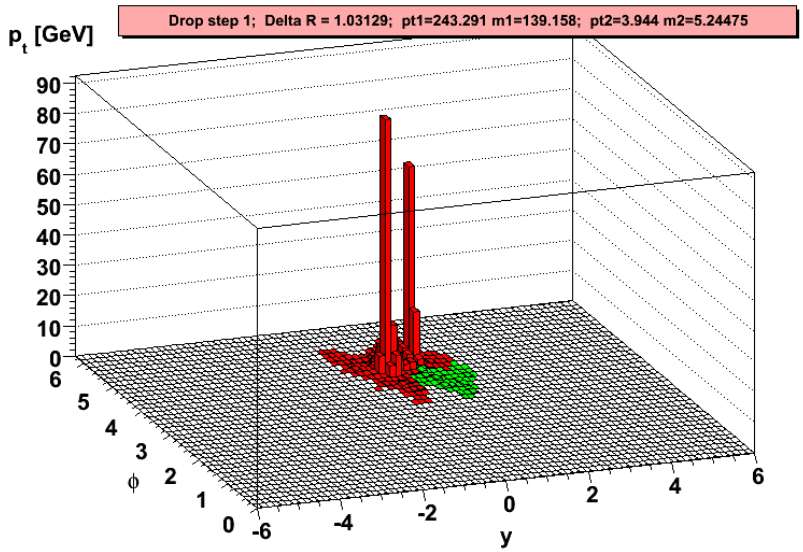
1. Break jet into two $j \to j_1 + j_2$
2. Check condition
   $\min(p_{T,1}, p_{T2})/(p_{T,1} + p_{T,2}) > z_{cut}$



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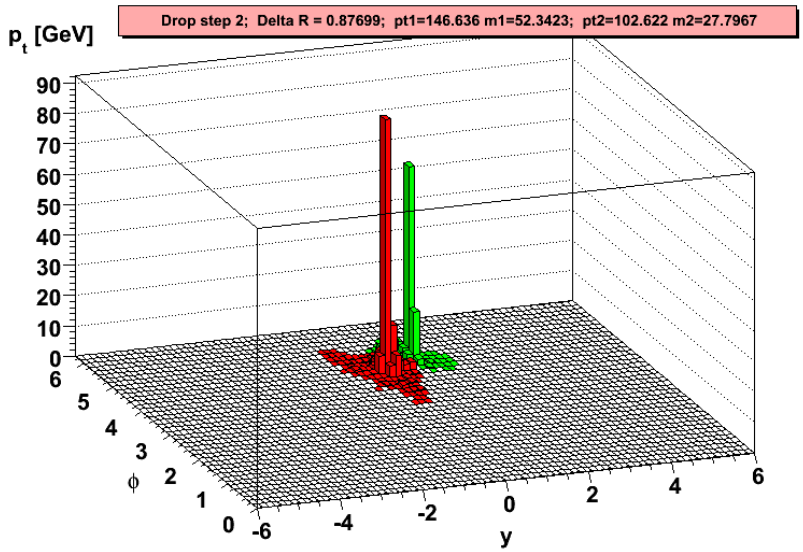

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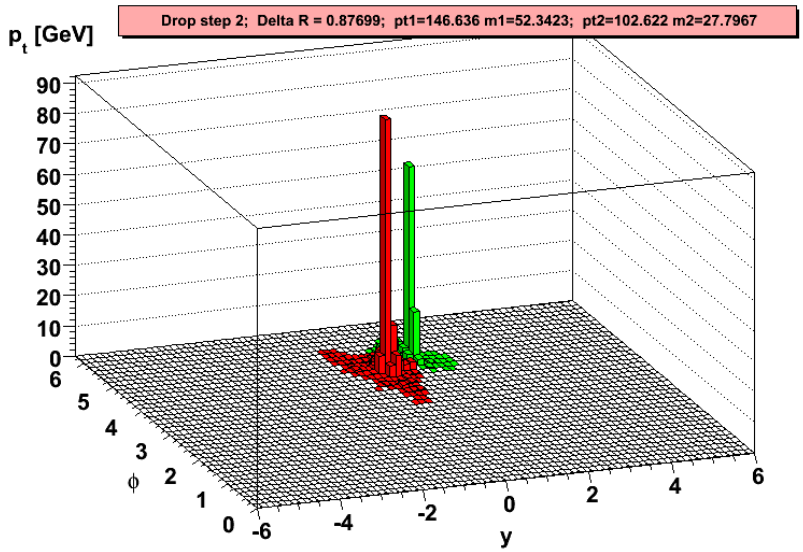
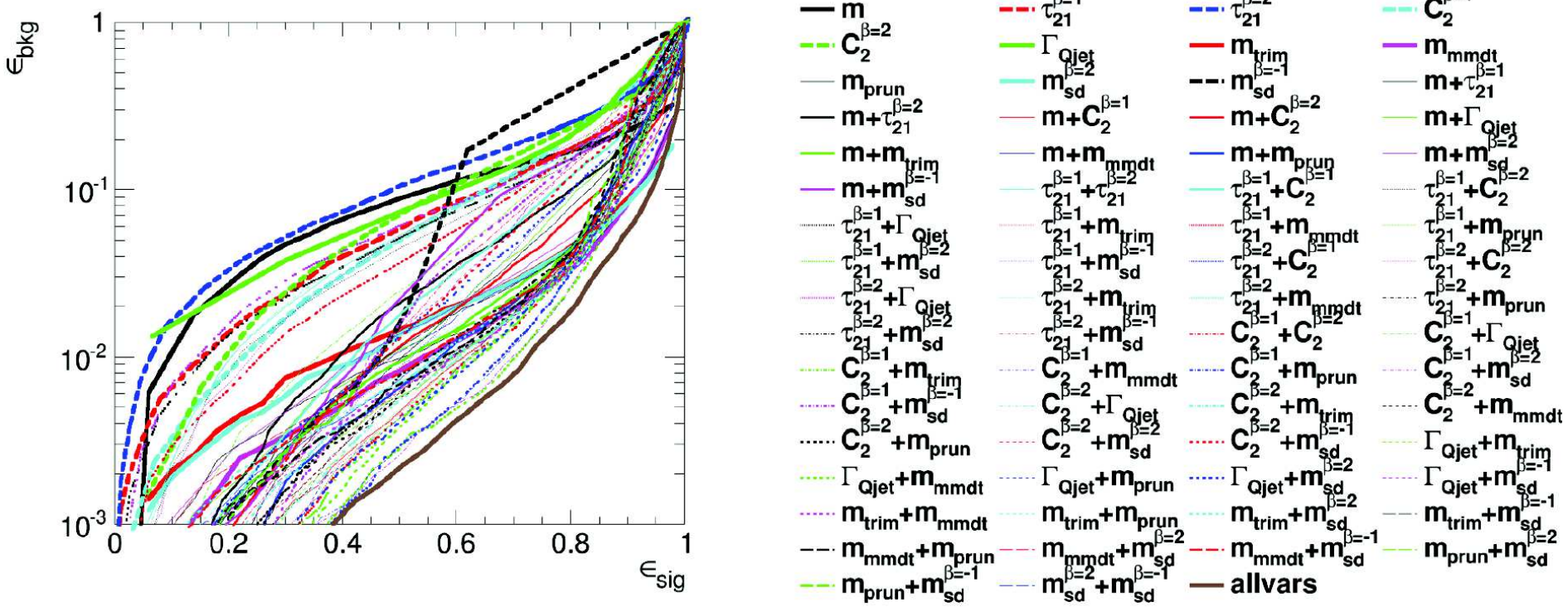
3. If fails, removes the subjet with lower p_T
4. If passes, stop recursion



Study of jet substructure

- Initially, jet substructure research based on Monte Carlo simulations
- Very useful tools, but numerically costly and physical message not always clear



Analytical approach to jet substructure

- Pioneering work in analytical approach to jet substructure in 2013
  Dasgupta, Fregoso, Marzani, Salam (2013)
- Understand dependency on each parameter
- Use insight from calculations to develop jet substructure
  $\rightarrow$ combining existing tools optimally
  $\rightarrow$ creating new tools
- Reliable evaluation of theoretical uncertainty bands

Phenomenological study of groomed jet mass

JHEP 1707 (2017) 132

Groomed jet mass

- Connection between measurements and calculations

  See also: Frye, Larkoski, Schwartz, and Yan, 2016

  CMS-PAS-SMP-16-010 and CERN-EP-2017-231

- Jet mass is one of the simplest observables

- Grooming eliminates part of UE contamination

- We studied modified MassDrop Tagger and SoftDrop

Our calculation

- For boosted jets $p_T \gg m \to \rho \equiv m/(p_T R) \ll 1$
  $\to$ log enhancements $\alpha_s^n \log^{2n}(1/\rho)$

  Needs to be resummed at all orders

- For mMDT it becomes $[\alpha_s f(z_{\text{cut}}) \log(1/\rho)]^n$ at leading-log

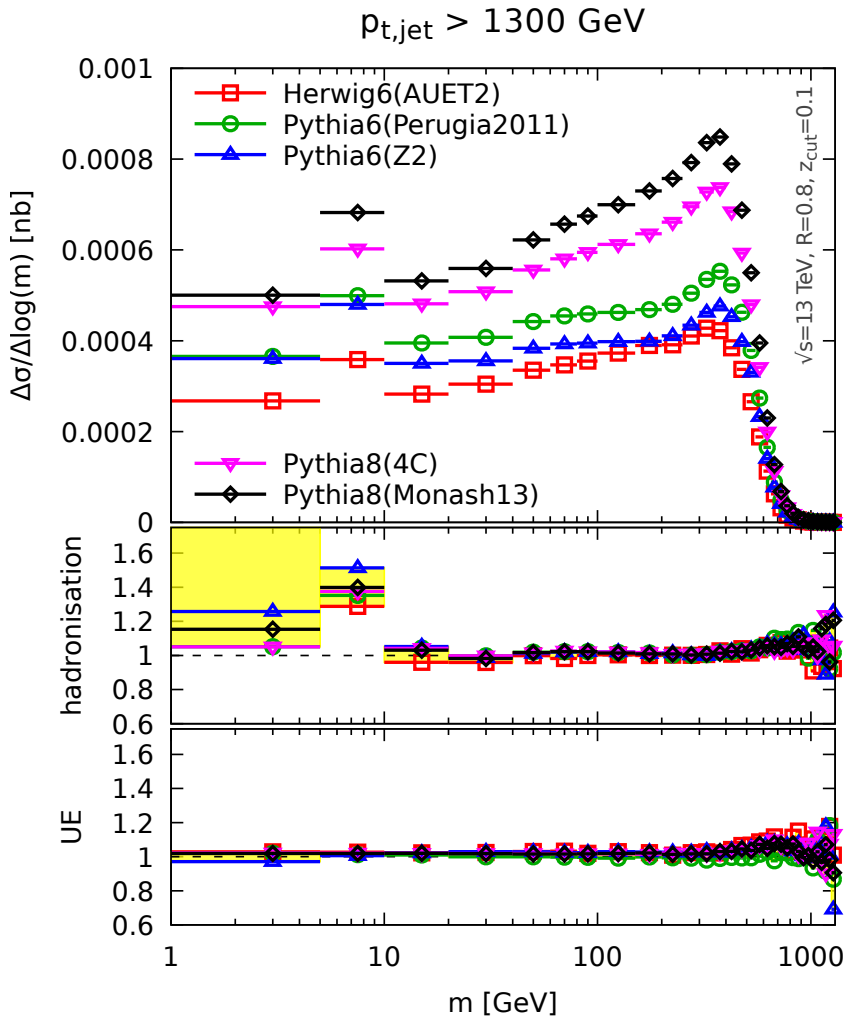
- Compare with experiment $\to$ needs a matching procedure:

$$\underbrace{N^k LL}_{\text{small } \rho} + \underbrace{N^m LO}_{\text{large } \rho}$$

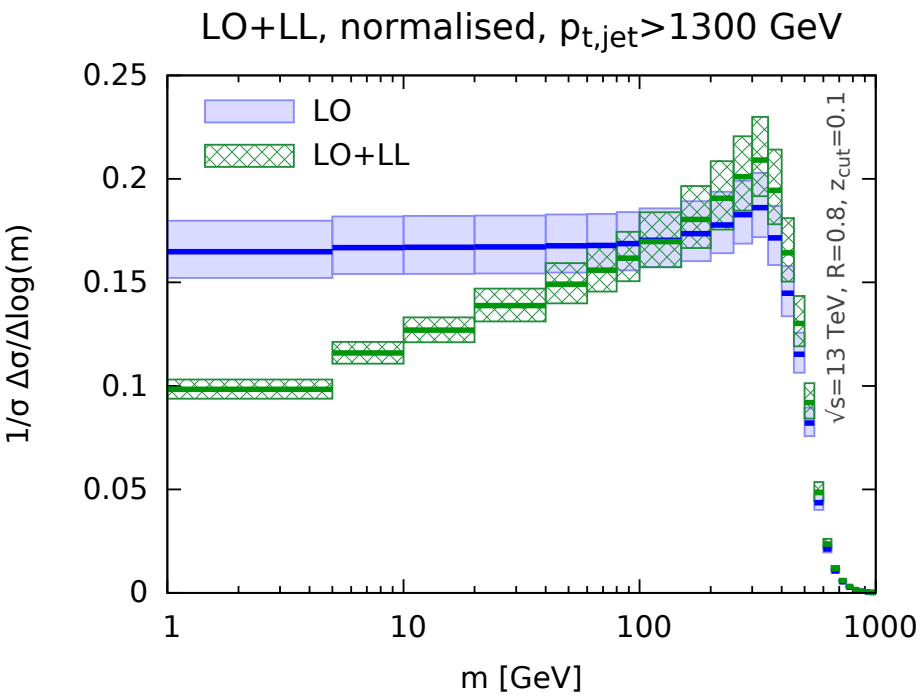
Small ρ $\to$ resummation of large logarithms
Large ρ $\to$ fixed-order (exact at $\mathcal{O}(\alpha_s^m)$)

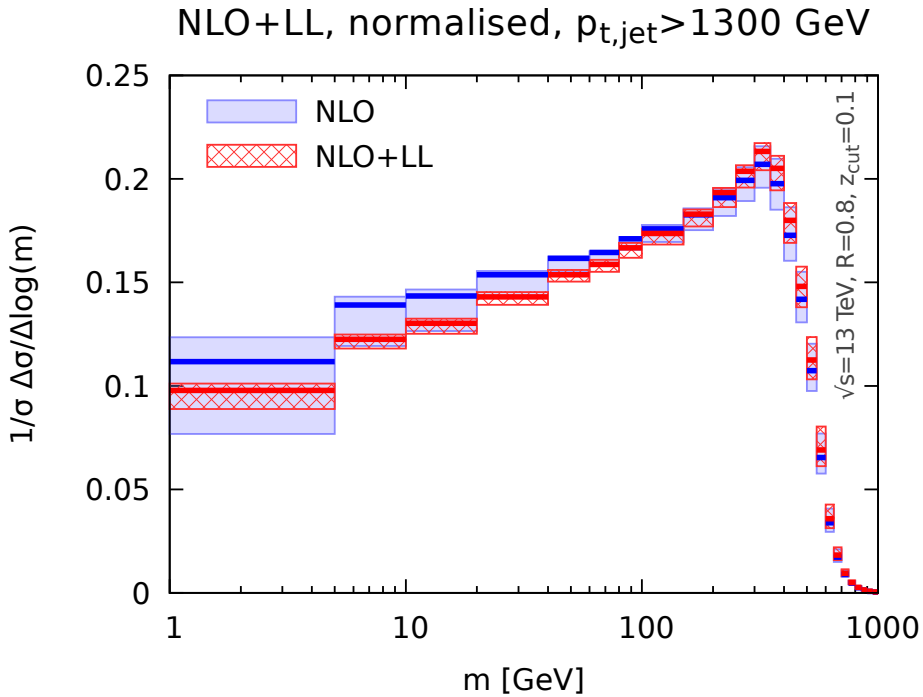
Uncertainties and corrections

- **Perturbative uncertainties**
  - Vary μ_R and μ_F around $p_{t,\text{jet}}R$
  - Vary μ_Q around $p_{t,\text{jet}}R$
  - Vary matching scheme (optional)
  - Vary α_s freezing scale
- **Non-perturbative corrections**
  - Extract NP corrections from different generators and tunes
  - Average of corrections as a multiplicative factor
  - Envelope as uncertainty



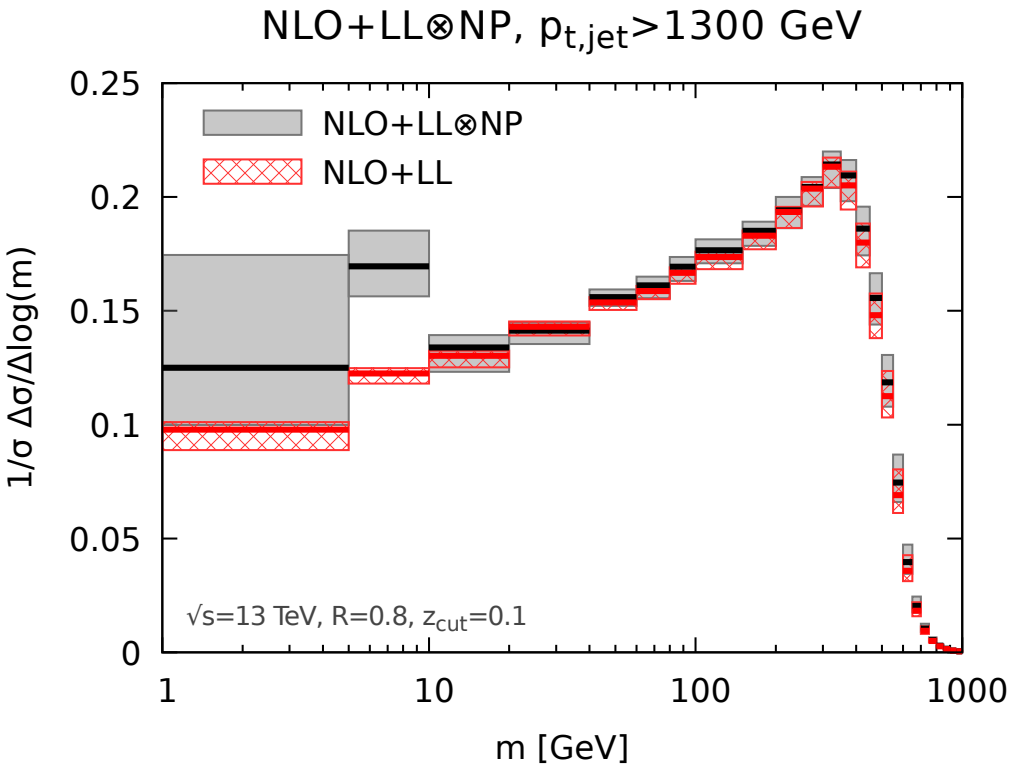
Perturbative results at (N)LO + LL





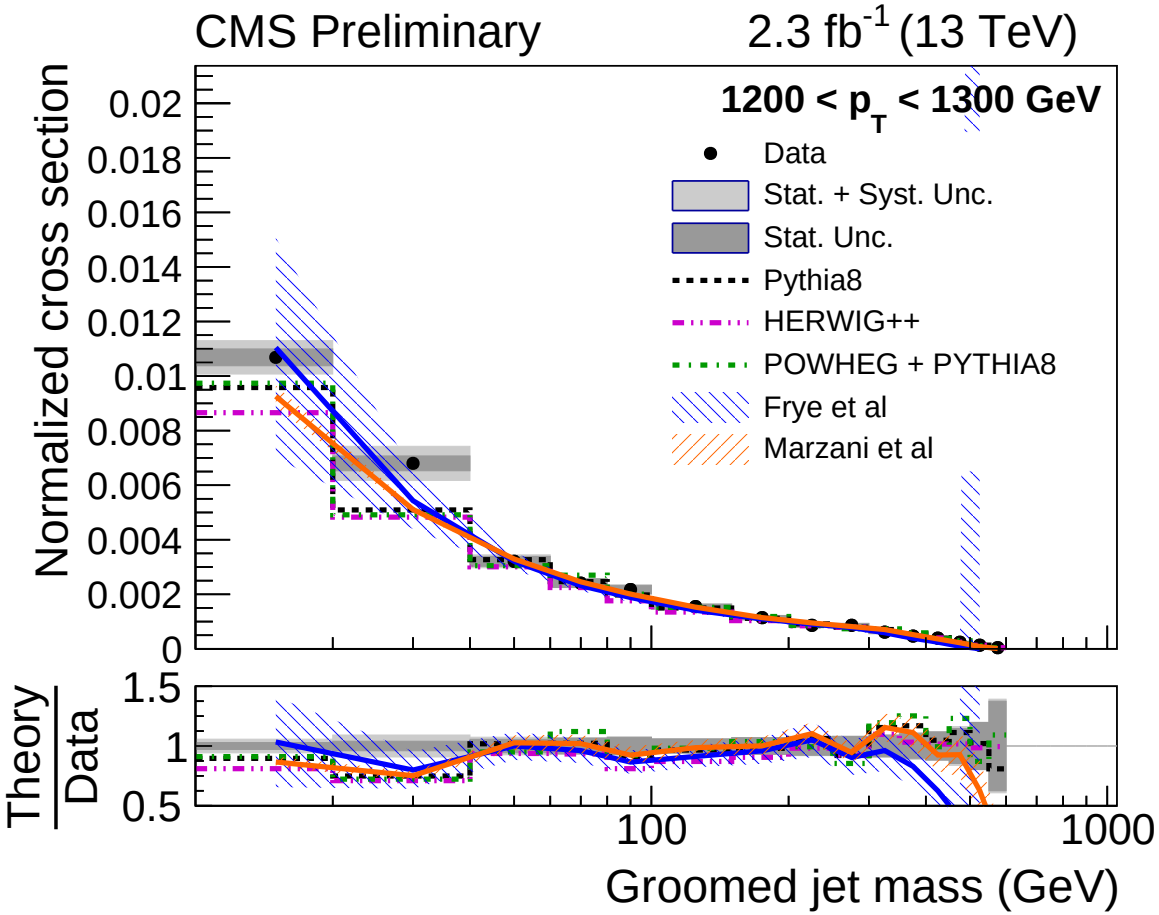
- Going from LO $\rightarrow$ NLO has large impact in uncertainties
- Smaller effects from resummation at NLO

Final results LL + NLO



- Relatively small NP corrections (UE and hadronization) above $m = 10\text{GeV}$

Comparison to experiment

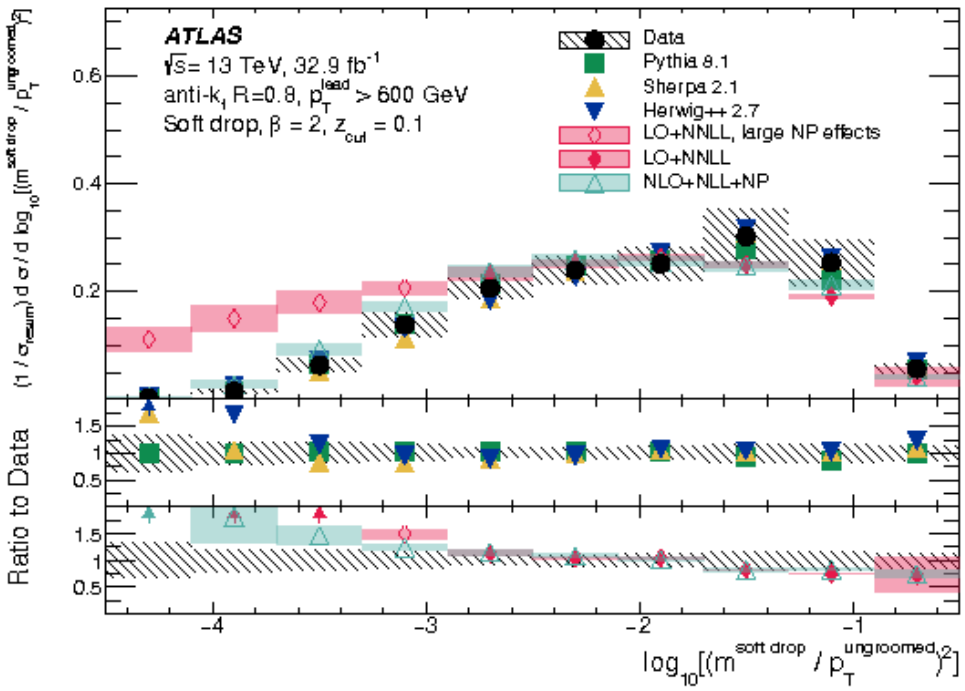


- Good agreement with experimental measurements

  Plot from CMS-PAS-SMP-16-010

Extension to Soft Drop (extra parameter $\beta > 0$)

- Leading contribution now is double-logarithm
- Our accuracy is NLL + NLO
- Non-perturbative effects increase for larger β values
- Good agreement with experimental measurements



Plot from CERN-EP-2017-231

Conclusion

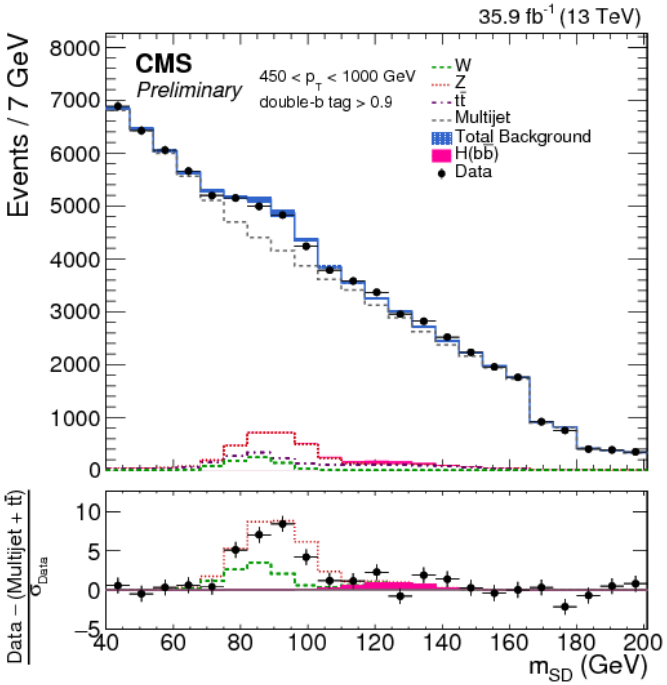
Conclusion

- **Analytical approach to jet substructure** allows better understanding of techniques largely used in experiments
- **Resummation** have many other applications in particle physics *e.g.* Drell-Yan process
- During my postdoc here at DESY
  - **Phenomenological aspects** $\rightarrow$ better and more reliable results
  - Learn more resummation techniques
    $\rightarrow$ in particular effective theories : **SCET, SCET+**
  - Study **matching** techniques

Backup

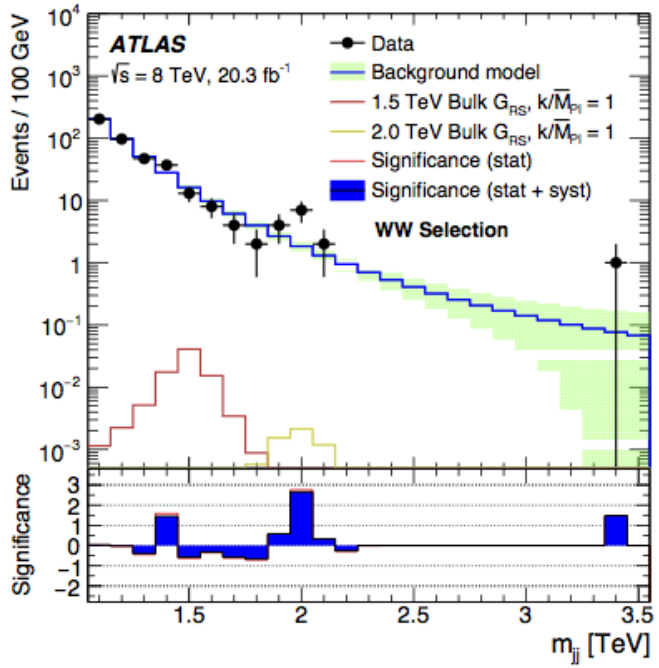
Examples of jet substructure in experiments

- Search for Higgs boson in $H \to b\bar{b}$ decays.



CMS-PAS-HIG-17-010

- Temporary Diboson excess at the end of Run-I.

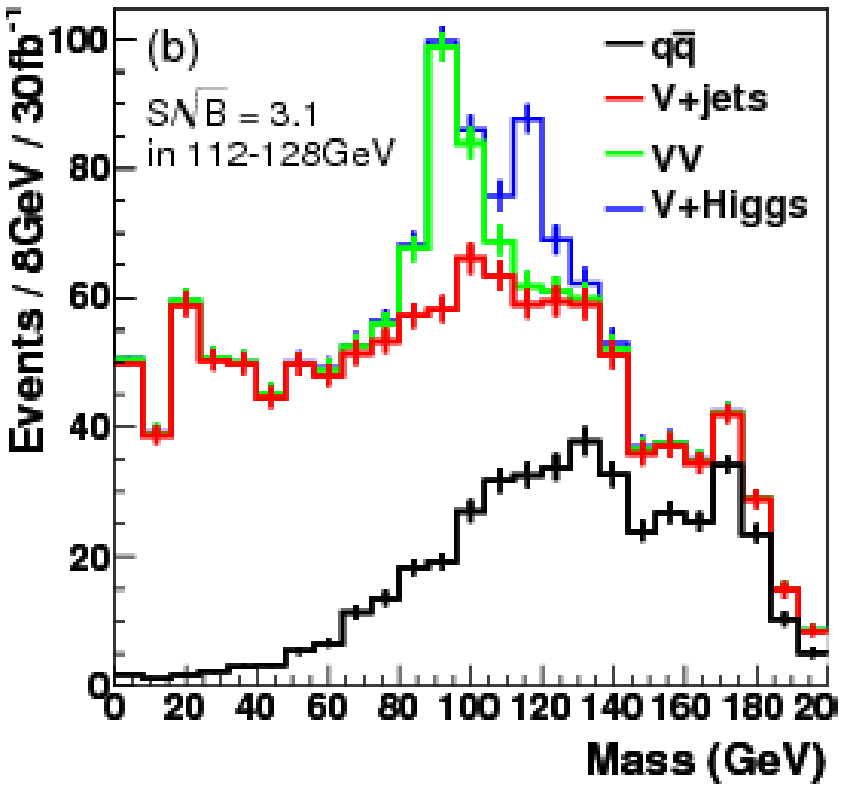


CERN-PH-EP-2015-115,

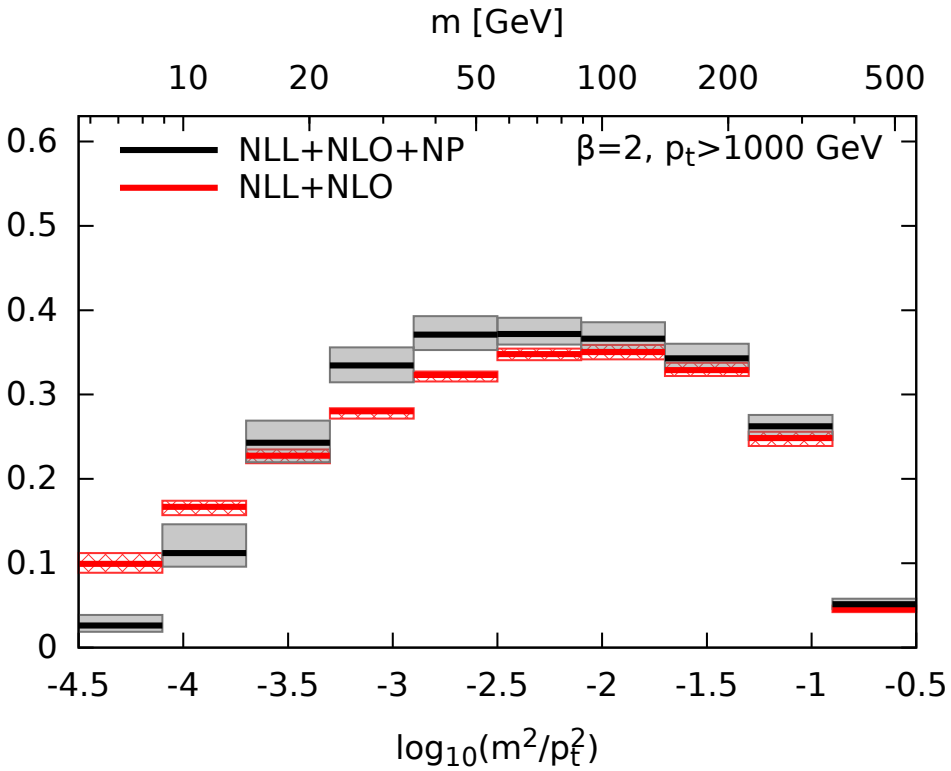
see also CMS-PAS-EXO-15-002

Example : (modified) Mass Drop Tagger

- Signal and background for a 115 GeV SM Higgs.



Final results NLL + NLO, $\beta > 0$



- Non-perturbative effects increase for larger β values.