Experimental Introduction

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BOOST2019

What to expect from this talk

- We have come very far, but…
- … there is still so much to do.

- Goal of this talk:
  - to identify what's missing
  - to try to spur you into action…
  - …oriented in an experimentally-friendly direction.

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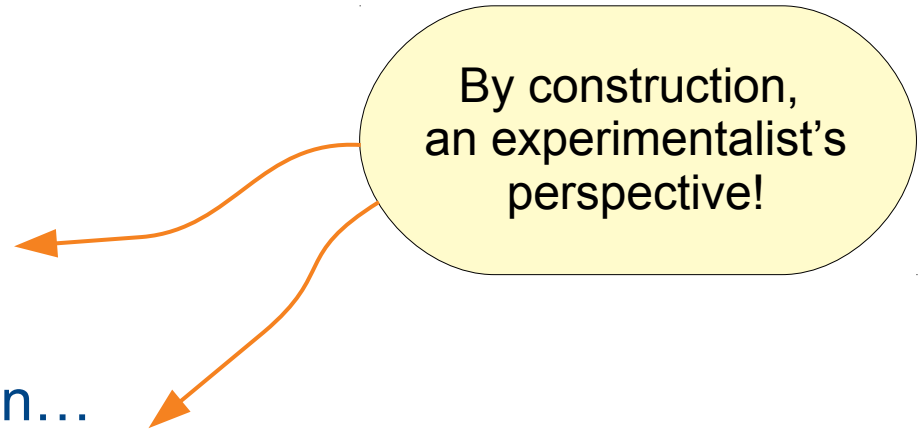

Where we succeeded: Theory

- New calculations
- New variables useful in experiment
  - e.g., N-subjetiness, ECFs, Lund Plane...
- New (now old) taggers:
  - e.g, JHU TopTagger, HEP TopTagger, etc.
- ML taggers galore
  - (too many to list here)
- ML for other things
  - e.g., JUNIPR

Where we succeded: Experiment

- "Boostin' is Legit" (Phil Harris, BOOST 2016)
  - No light BSM physics yet
    → most remaining options involve heavy new particles
    → SM (and BSM) objects are necessarily boosted
  - Now a mainstay of LHC physics
- Many jet taggers deployed over the past decade
  - We know how to estimate backgrounds
  - We know how to calibrate these taggers in data
    = measure signal efficiencies for top, W/Z, and Higgs
- The boosted life seems to be good.

A quick poll

- You are here because:

  A) You want to understand QCD

  B) You enjoy tuning MC generators and shower models

  C) You like to play with Machine Learning

  D) You feel the urge to develop yet another way to estimate the multijet background

  E) You want to find BSM physics

A quick poll

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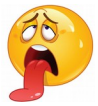
  D) You feel the urge to develop yet another way to estimate the multijet background

  E) You want to find BSM physics

While we all like and do A-D,
for many “E” is the ultimate goal.

What we need to search for BSM

- Data ✓
- Tools (taggers, new variables) to suppress background and isolate the signal ✓
  - Most ML taggers still trained on MC...
- Background estimate (minimize uncertainty)
  - If dominated by ttbar, W+jets – get away with MC… ✓
  - QCD: tricky and messy  (after lots of work… ✓)
- Signal efficiency (minimize uncertainty)
  - For top, W/Z, Higgs tagging – use standard candles ✓
  - For exotic signatures – ??? ✗

There's still work to do...

- Data ✓
- Tools (taggers, new variables) to suppress background and isolate the signal ✓
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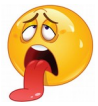
  - QCD: tricky and messy  (after lots of work… ✓)
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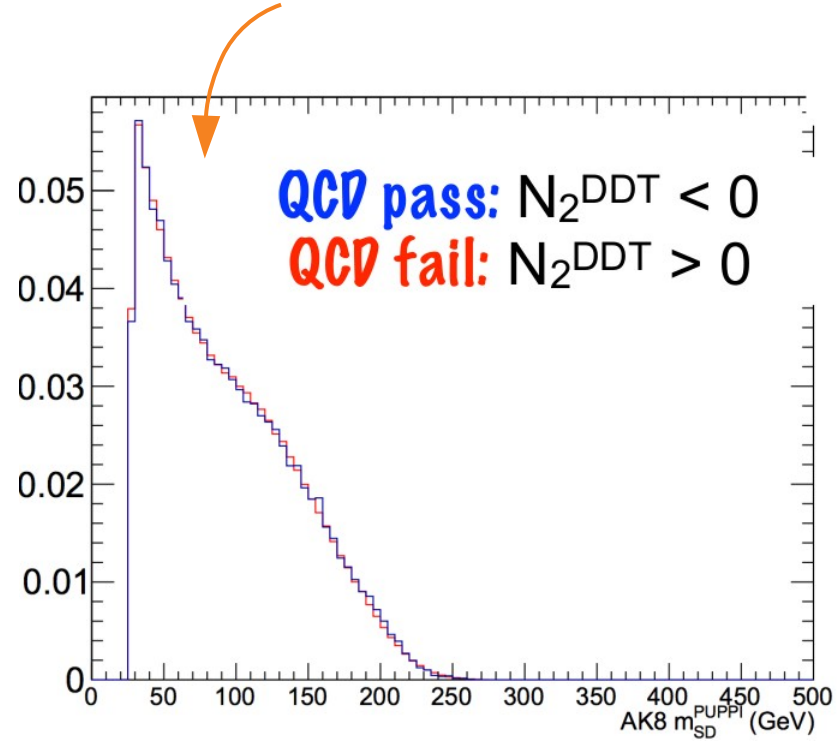
The topics of the rest of the talk.

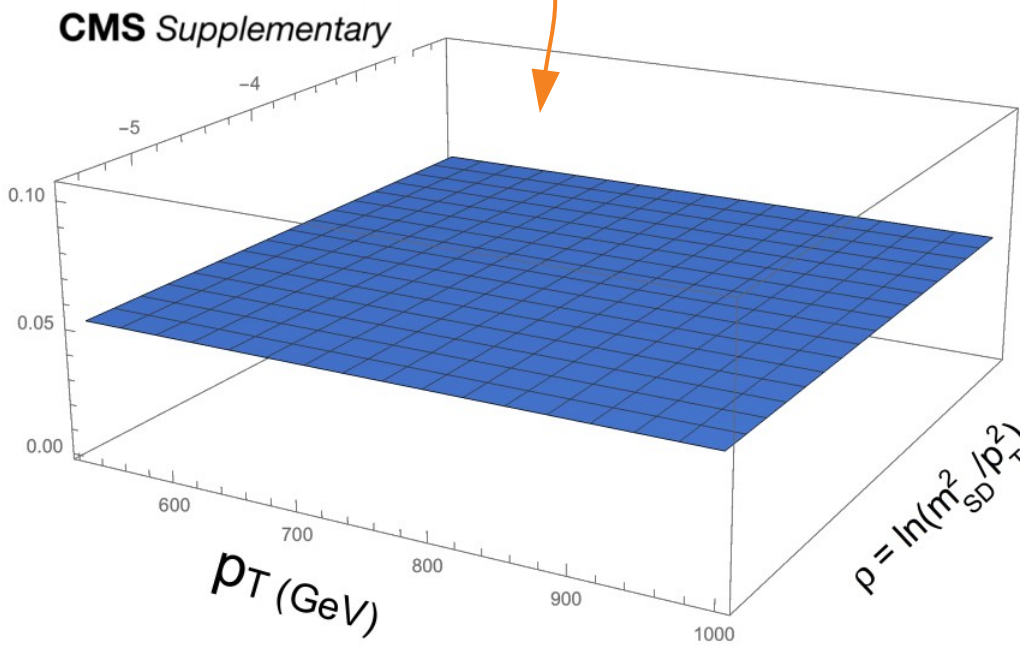
QCD bkg estimates are sometimes messy

EXO-18-012

- Fully decorrelated tagger (via “DDT map”)
  - Doesn’t mess up the jet mass shape

$\Rightarrow$ Pass (tag) and fail (anti-tag) region have same shape $\Leftrightarrow$ Pass/fail ratio $R_{\mathrm{p/f}}$ is flat … in MC



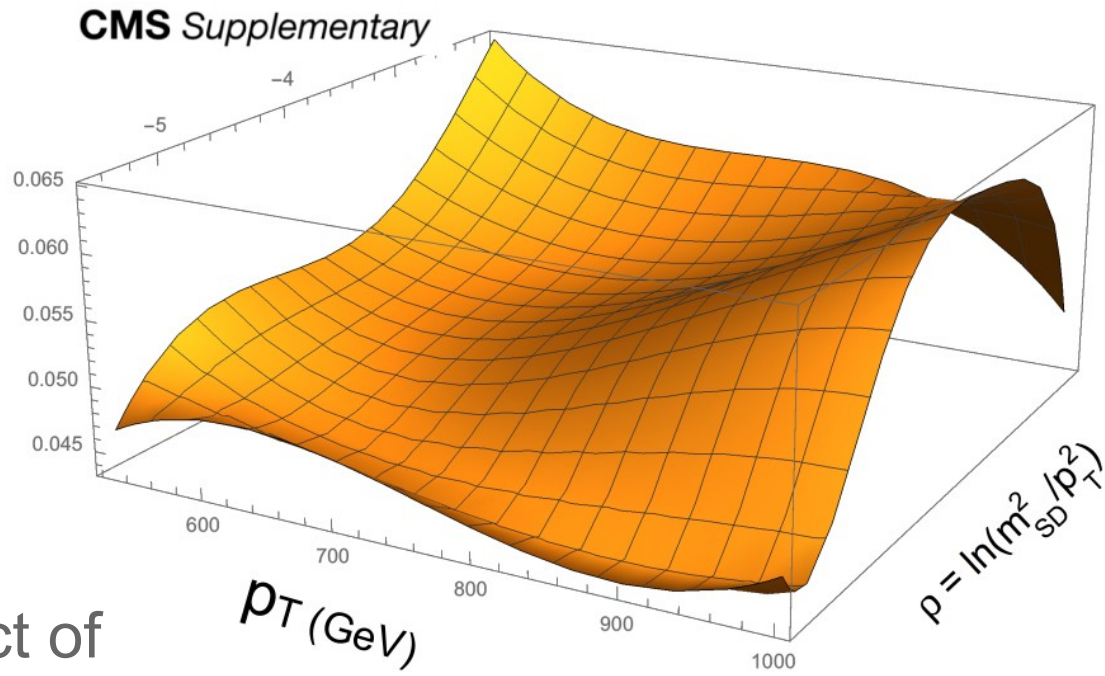


QCD bkg estimates are sometimes messy

EXO-18-012

- Account for Data/MC discrepancy by a smooth surface fit
- … can be very complicated if Data/MC differences are not trivial!

$$n^{\mathrm{QCD}}_{\mathrm{pass}} = R_{\mathrm{p/f}}\, n^{\mathrm{QCD}}_{\mathrm{fail}}$$



- For light $Z' \to q\bar{q}$:
- $R_{\mathrm{p/f}}(p_{\mathrm{T}}, \rho)$ is a product of
  - 3rd degree poly in p_{T}
  - 5th degree poly in ρ !!!

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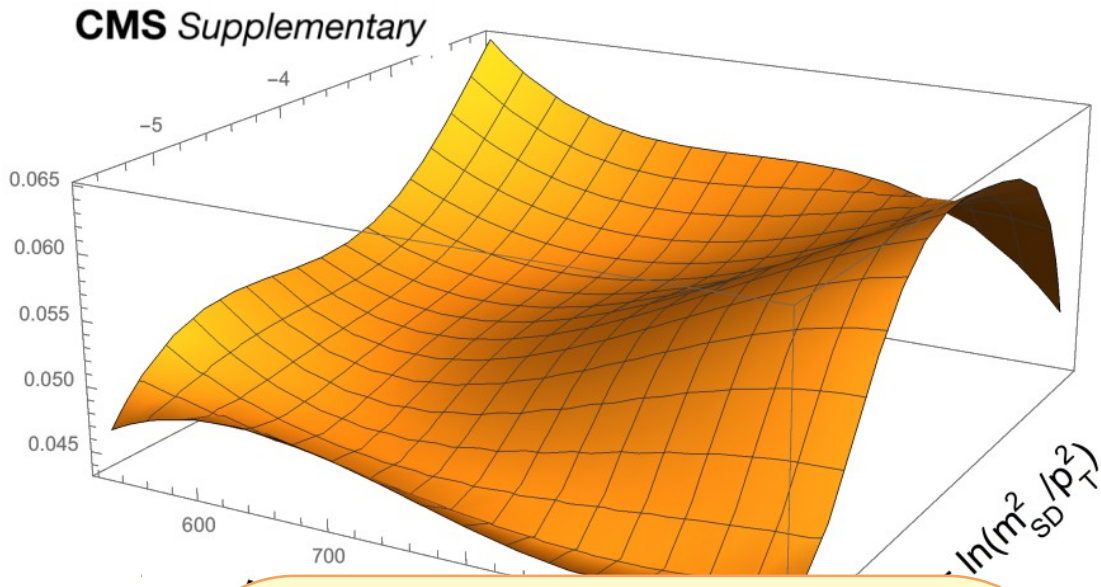

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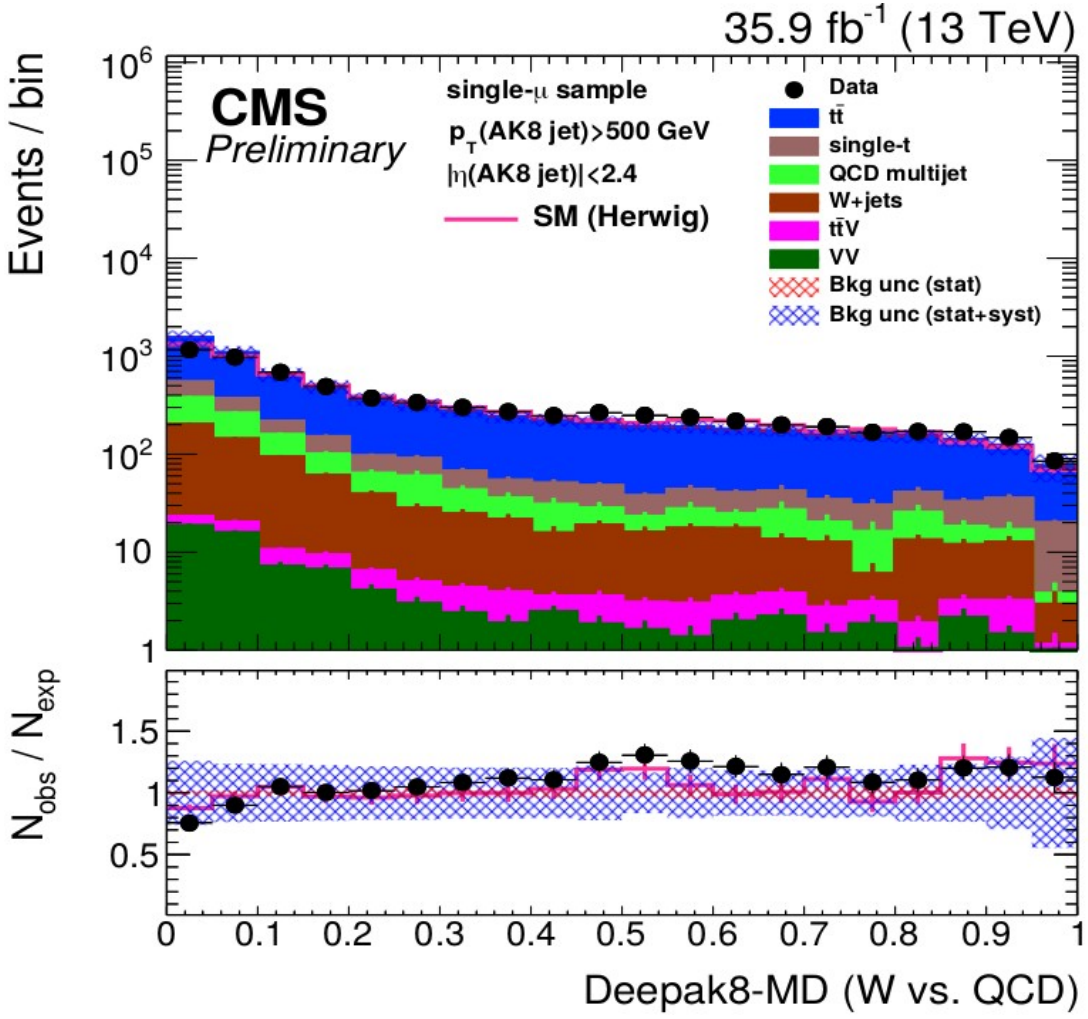
- $R_{\mathrm{p/f}}(p_{\mathrm{T}}, \rho)$ is a product of
  - 3rd degree poly in p_{T}
  - 5th degree poly in ρ !!!

- Neither scalable with luminosity
- Nor easily transferable to other searches!

Imperfect MC is used to train ML

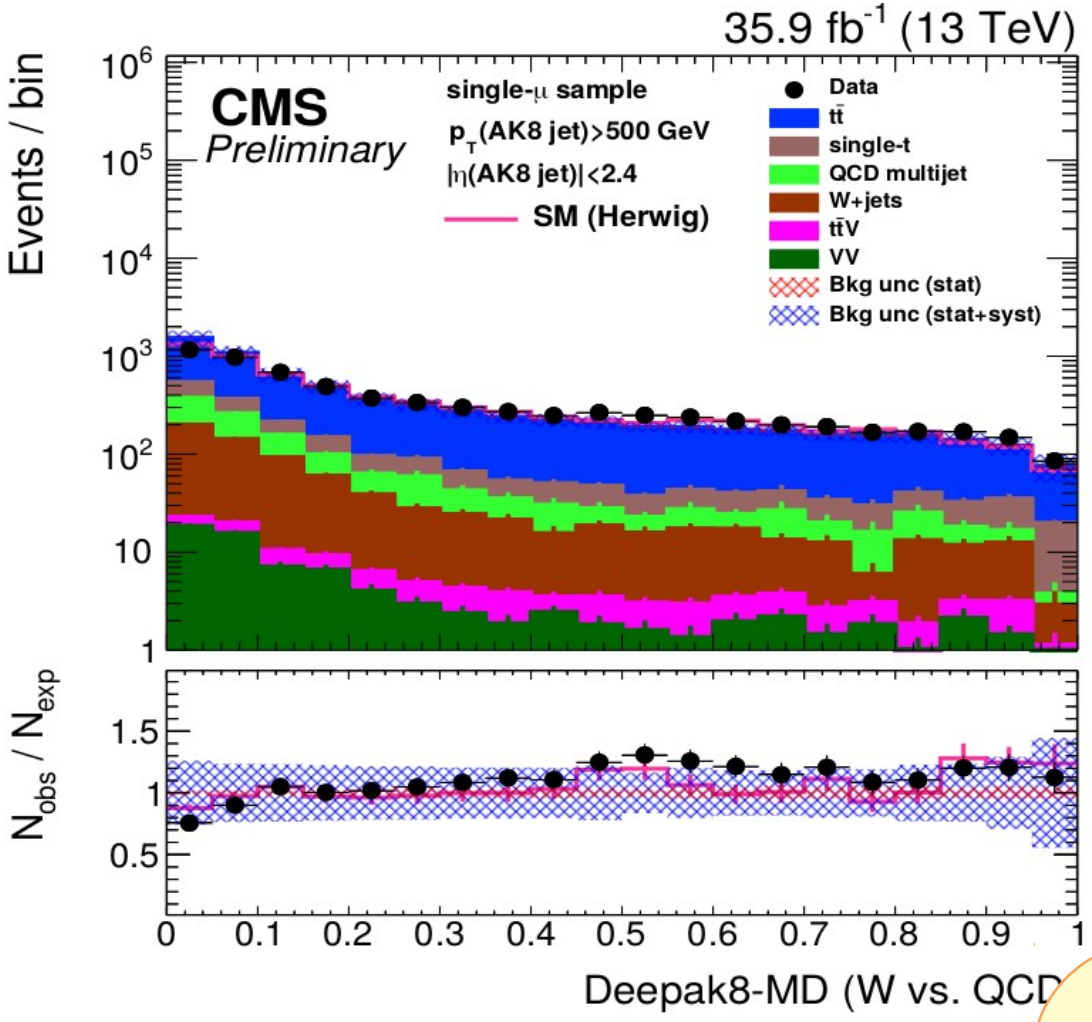
JME-18-002



- Powerful taggers, but…
- Nominally “within errors” from data
- Need to be careful:
  - Scale factors must be measured...
  - And they may be different from 1…
  - … with large error bars

Imperfect MC is used to train ML

JME-18-002



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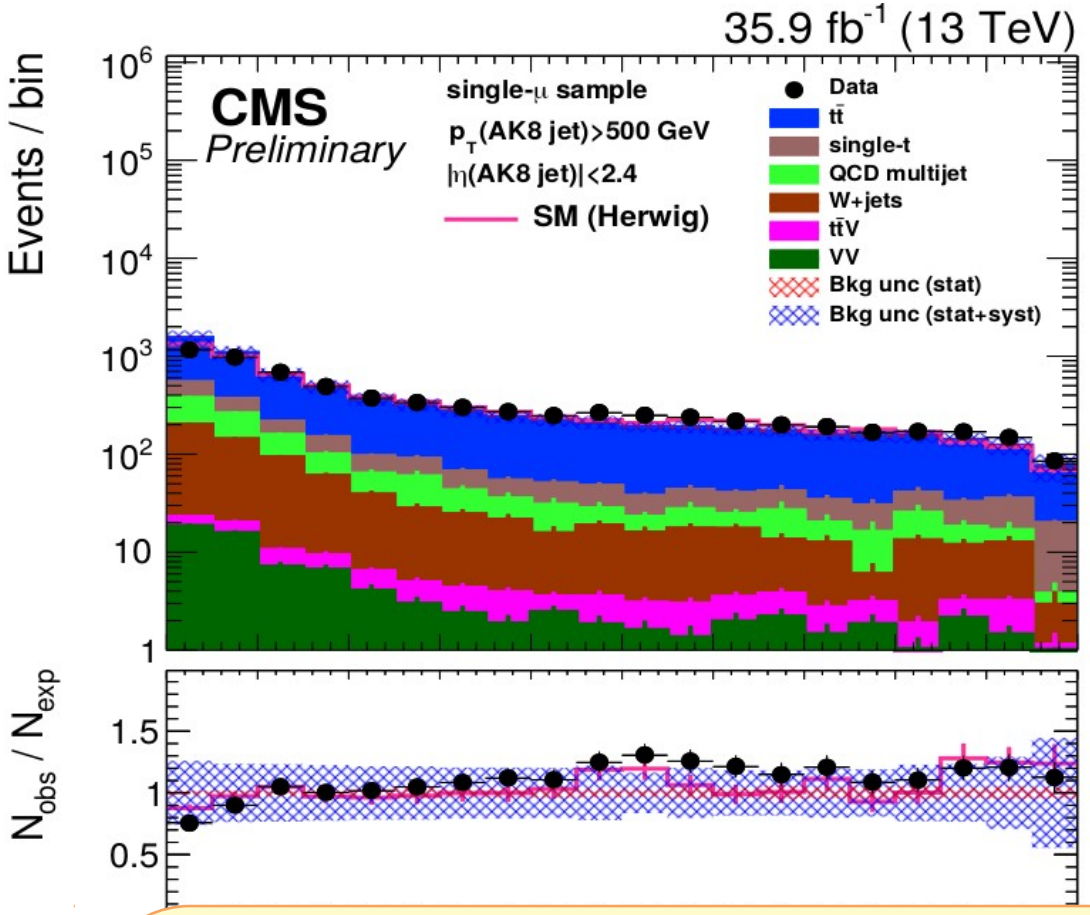
Can erase some of the gains from an improved tagger!

Imperfect MC is used to train ML

JME-18-002



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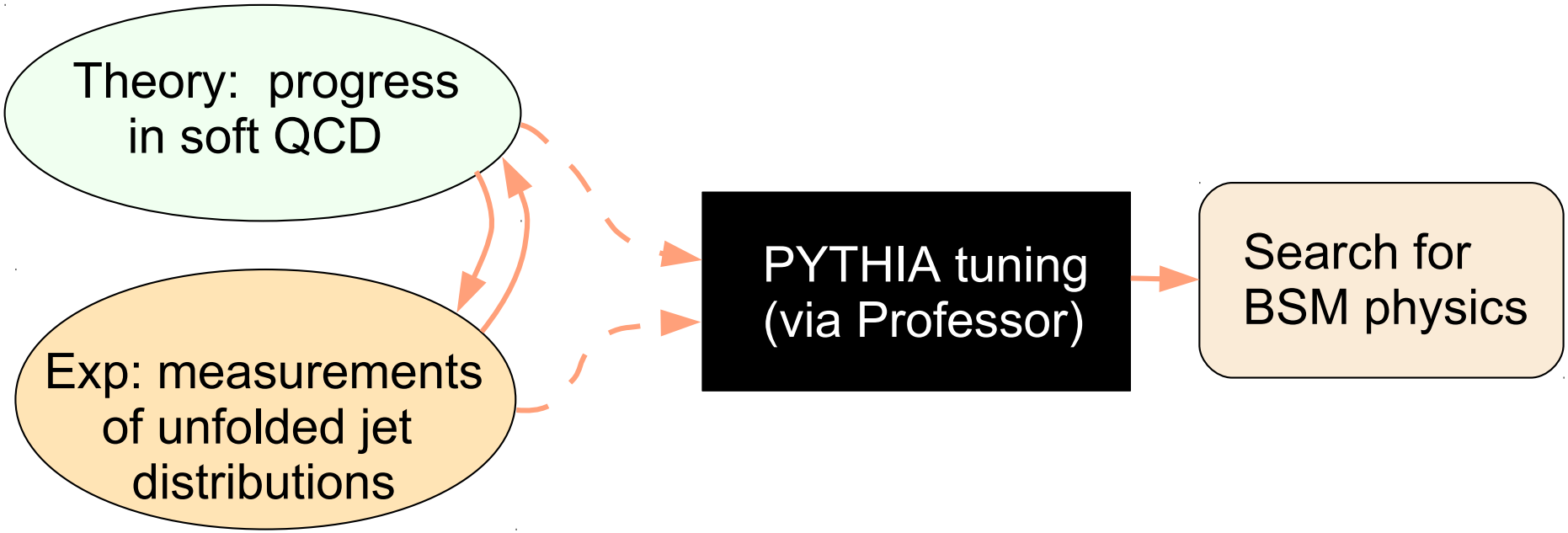
Hard to tell whether DNN is focusing on features poorly modeled in top/W/Z/H MC...

(Cf. Meenakshi Narain's talk later today.)

QCD modeling for the future

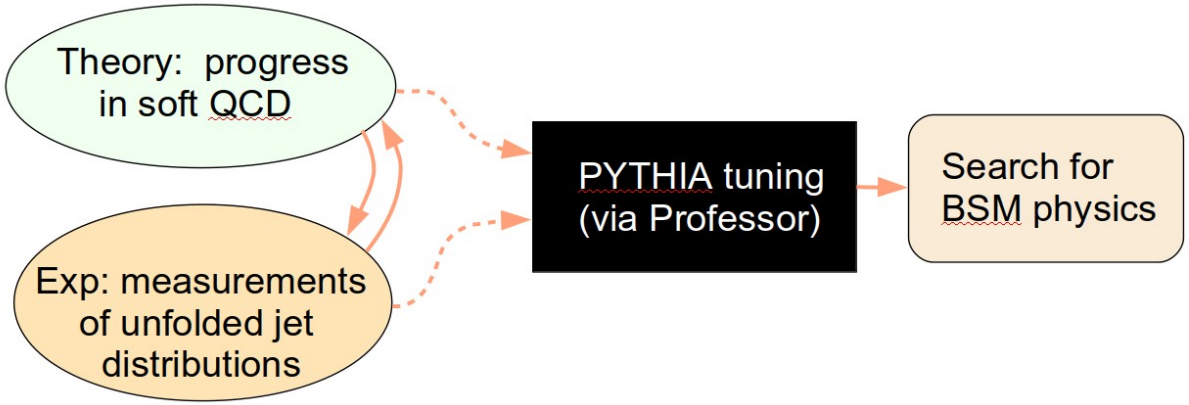
- With a better QCD modeling, we could:
  - Train ML algorithms
    - → better data/MC agreement
    - → minimize signal efficiency systematics
  - Decorrelate taggers
    - → well-behaved background shapes → better bkg estimates
    - → if there's a BSM excesses, it would be "easier" to see
  - Estimate efficiencies of tagging N-prong jets
    - (e.g. H→WW→4q or BSM)
- In general, experimentalist's life would become a lot easier

Why can't I have that?!



- Somehow, theoretical and experimental progress in soft QCD does not seem to propagate to PYTHIA we use.
  - Not enough measurements fed into "Professor"?
  - Can't tune both UE and substructure???
  - PYTHIA is insufficient for shower/hadronization?

Interlude: Sociological aspects



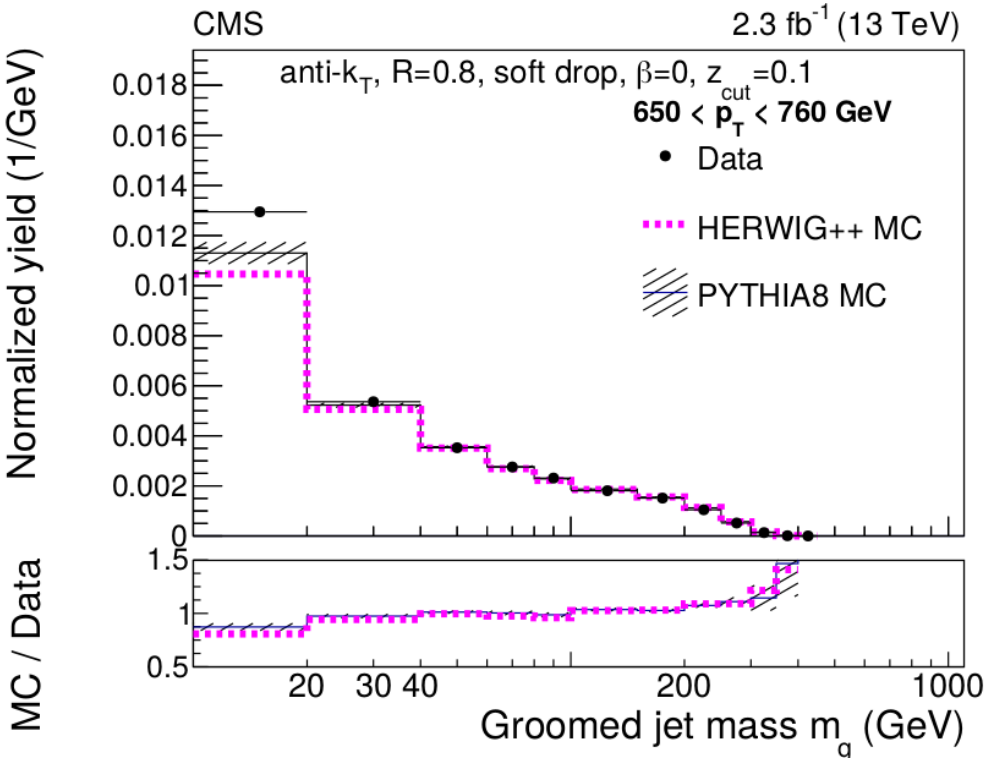
- Not enought field-wide appreciation for the importance of measuring inputs to PYTHIA tuning!
  - People doing this (also) should be hired / promoted / tenured
  - Encourage your students to do this as a part of the “service” to the field of Boosted Objects

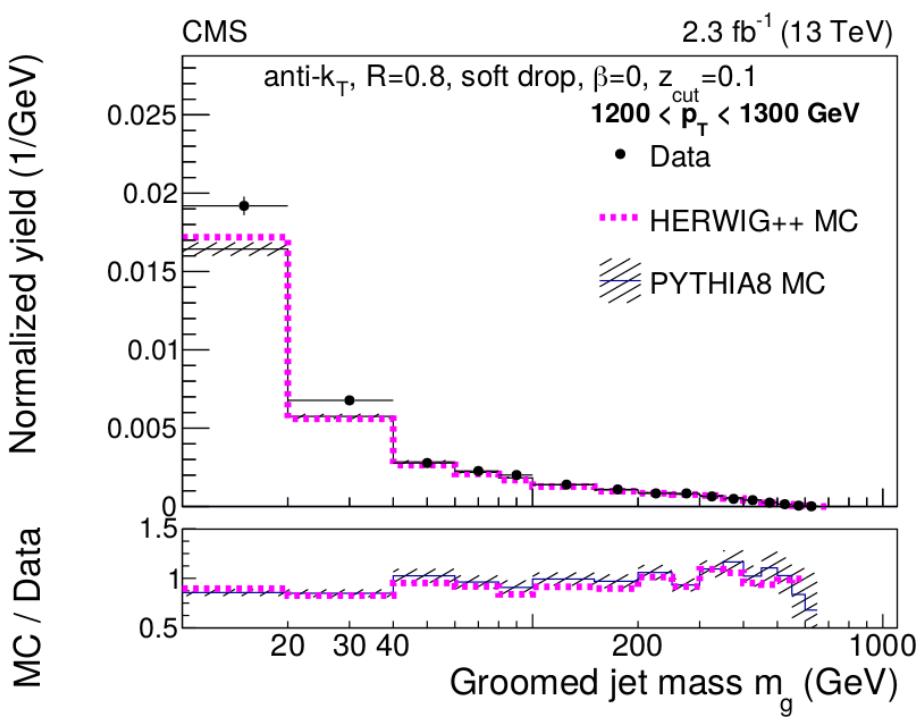
    (their background estimates will thank them).
  - We need an “outreach” into the rest of HEP!

Measurements of jet mass

JHEP 11 (2018) 113

- Both experiments have measurements of jet mass (ungroomed and groomed).





- These are then unfolded.

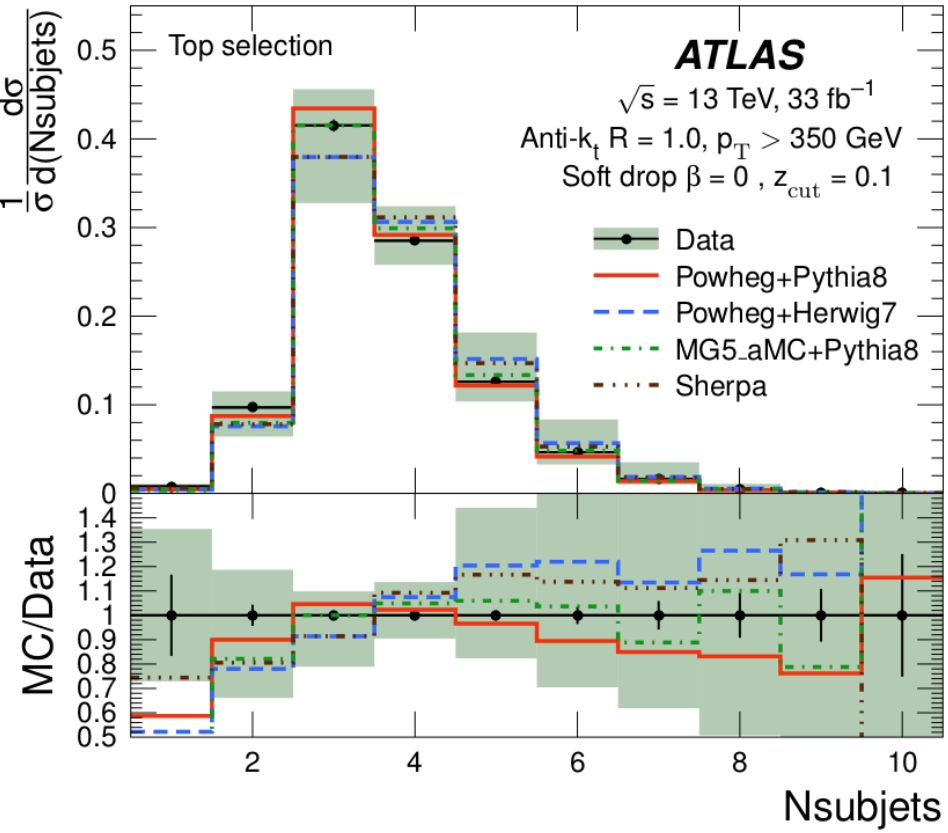
Detector level

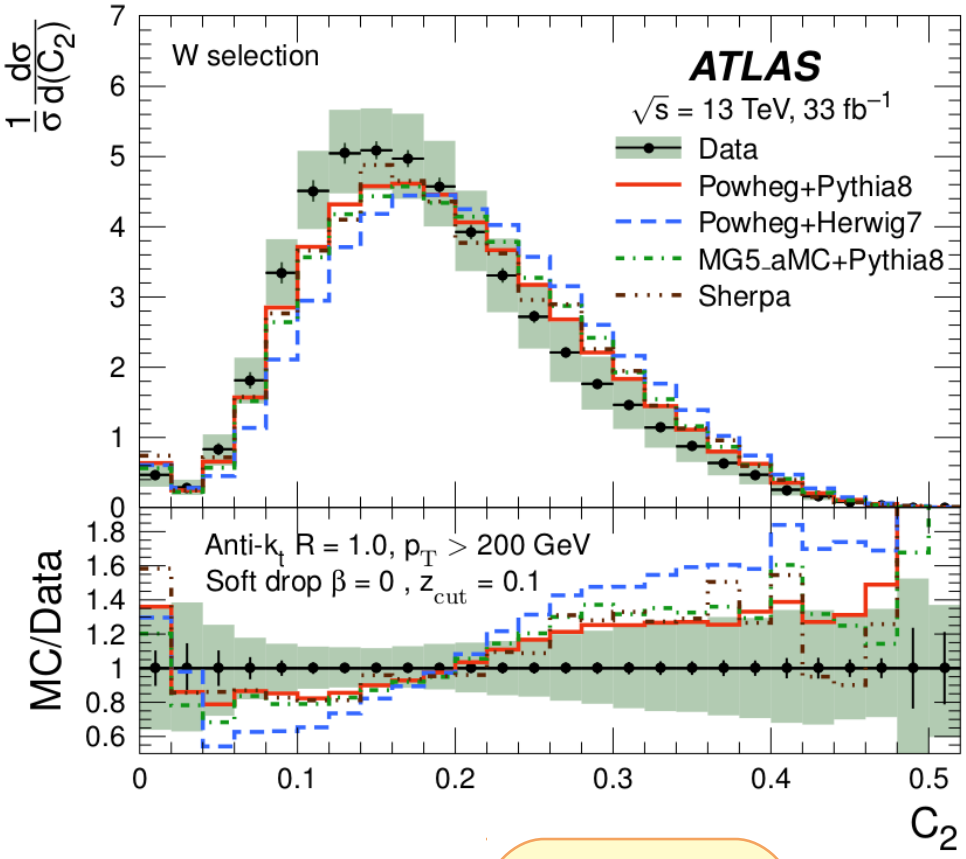
Measurements of substructure

arXiv:1903.02942
(accepted by JHEP)

- ATLAS compared a bunch of substructure-related variables to data. Examples:

$$C_2 = \frac{e_3}{(e_2)^2}$$





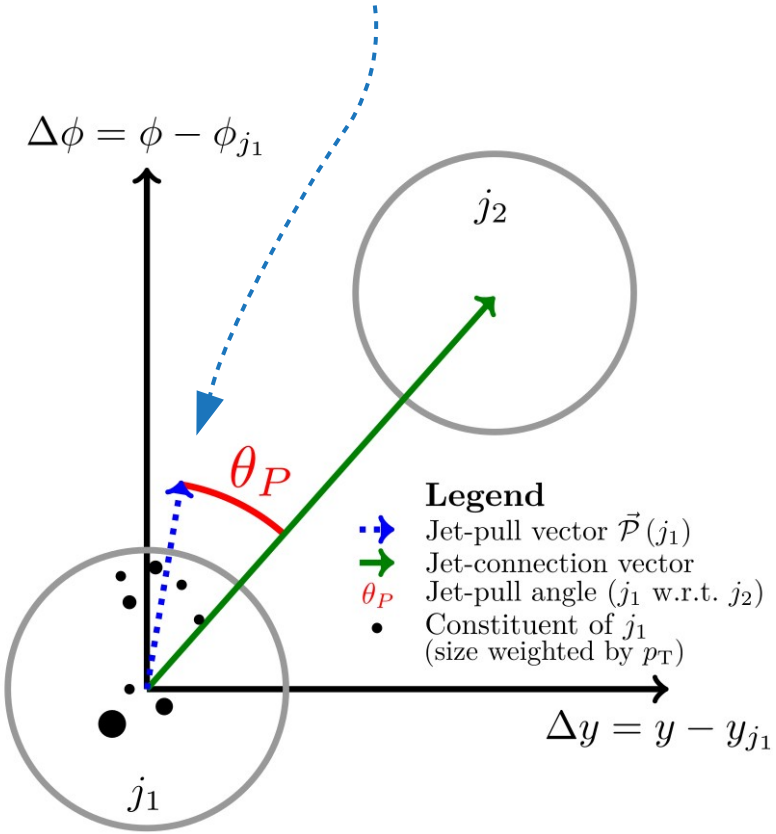
- These (and others) are then unfolded.

Unfolded

Substructure: jet pull (color flow)

EPJC78 (2018) 10, 847

- Encodes color connections between partons
  - Jet pull vector: angle and magnitude



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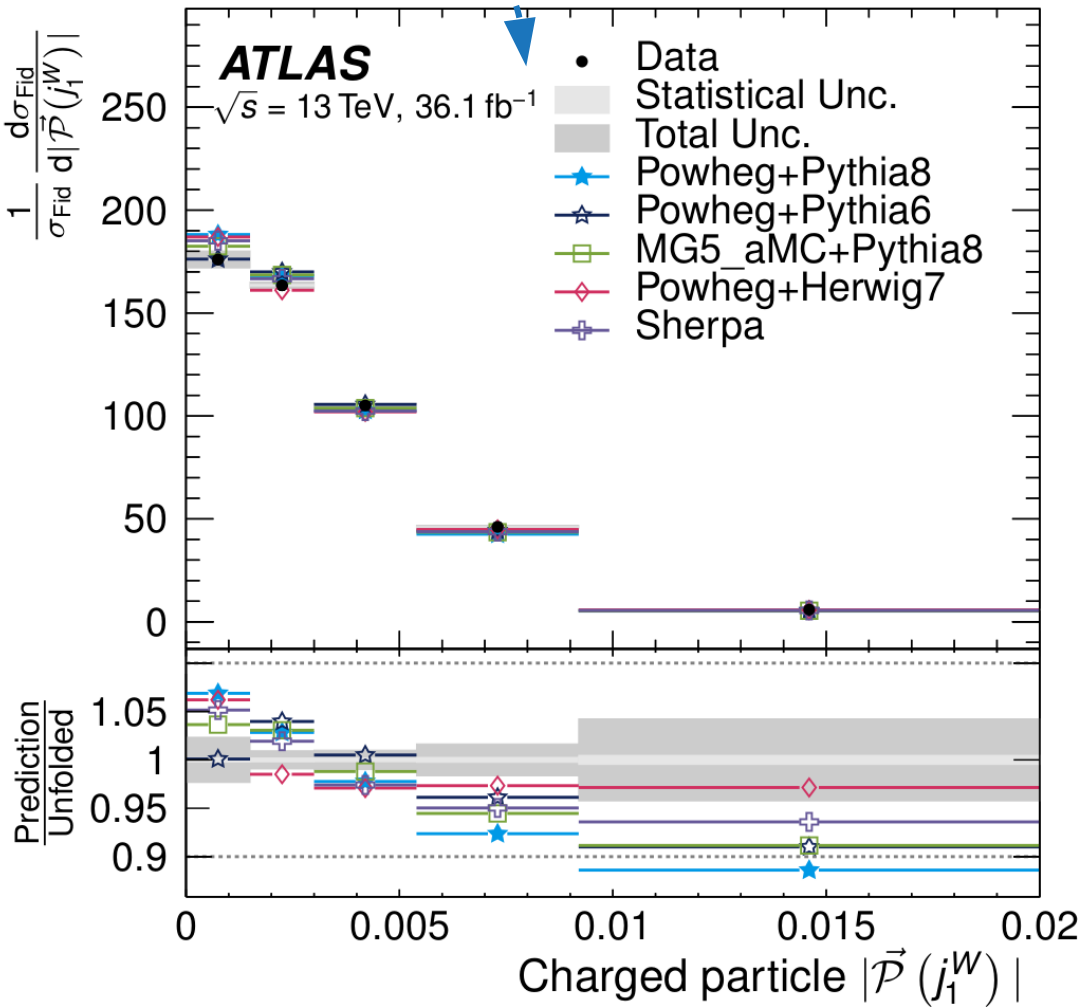
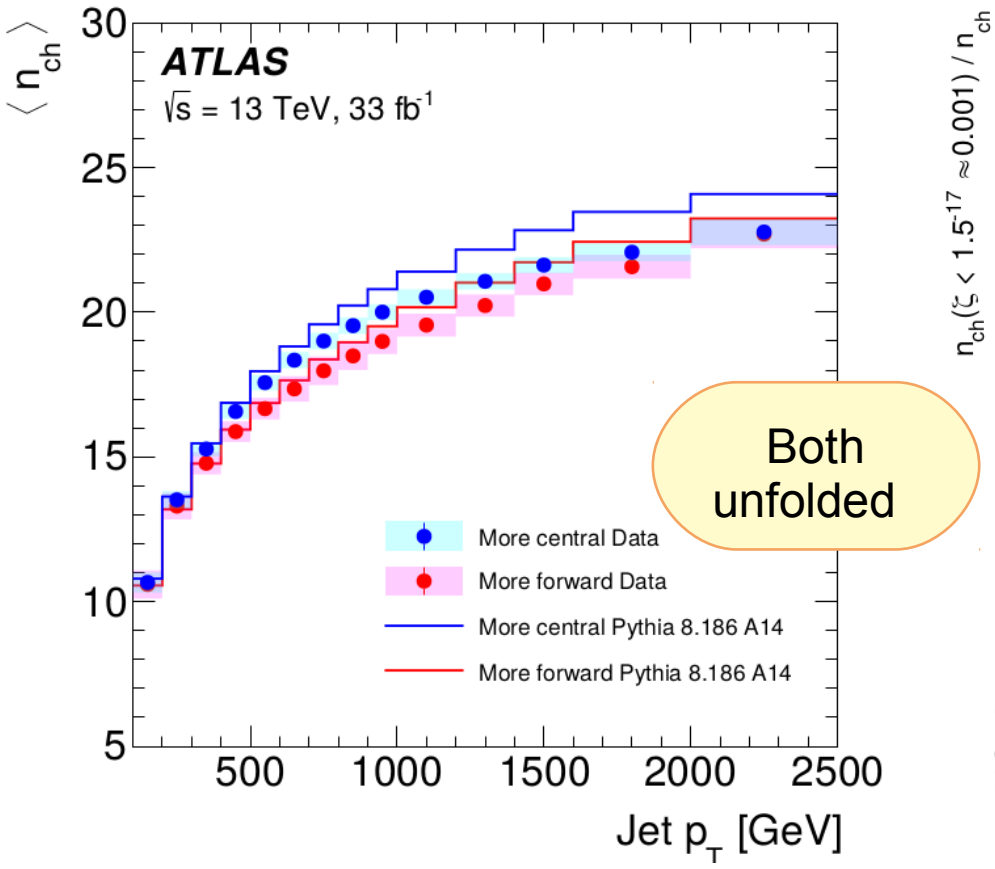


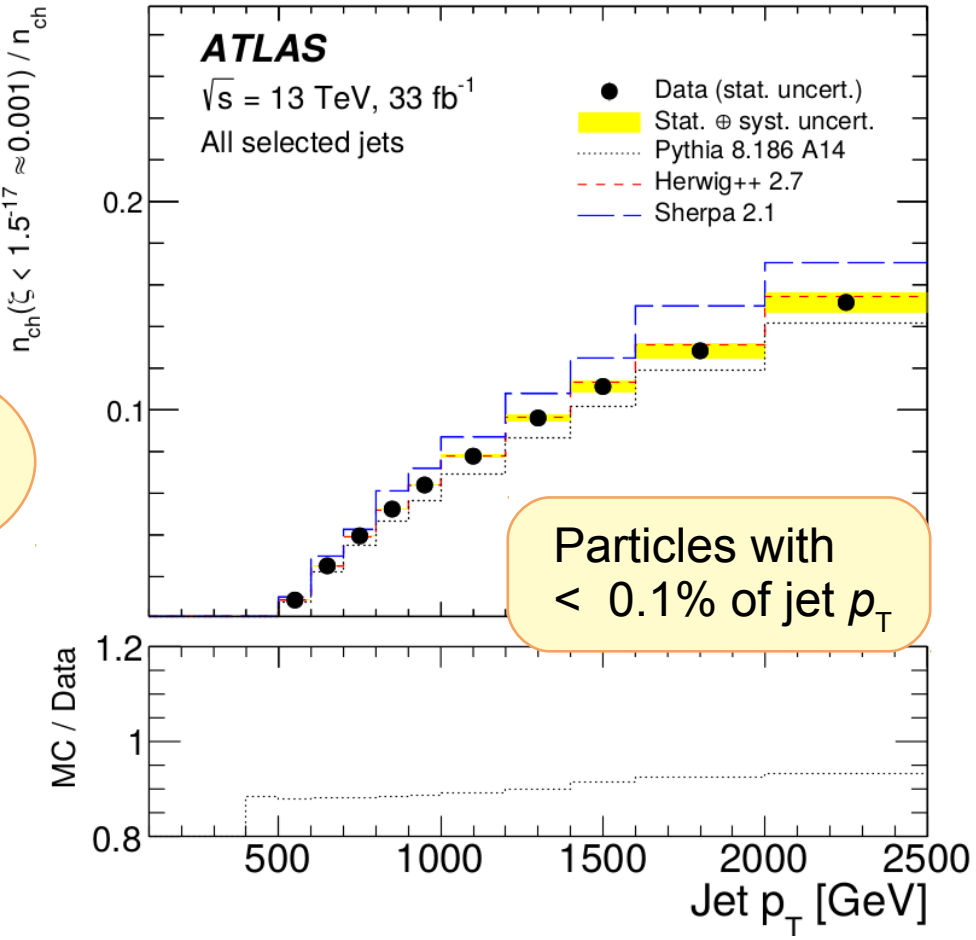
Hadronization

arXiv:1906.09254

- Using charged particles in jets to calc. several variables
  - reasonable description overall
  - also noticeable differences, especially for gluon-like jets



Both unfolded



Particles with < 0.1% of jet p_T

What if PYTHIA doesn't have enough knobs?

- Make a better PYTHIA, or another shower program. Then tune to data. (Repurpose the Professor?)

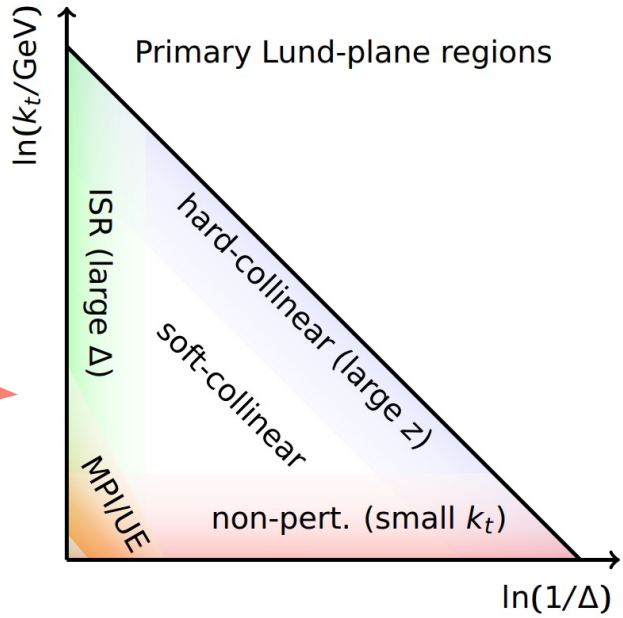
- Or, correct simulation *a posteriori*.
  - Reweight using the Lund Plane?
  - JUNIPR?
  - …. or something else?

  - Maybe the best:
    measure → tune PYTHIA → reweight residual differences.

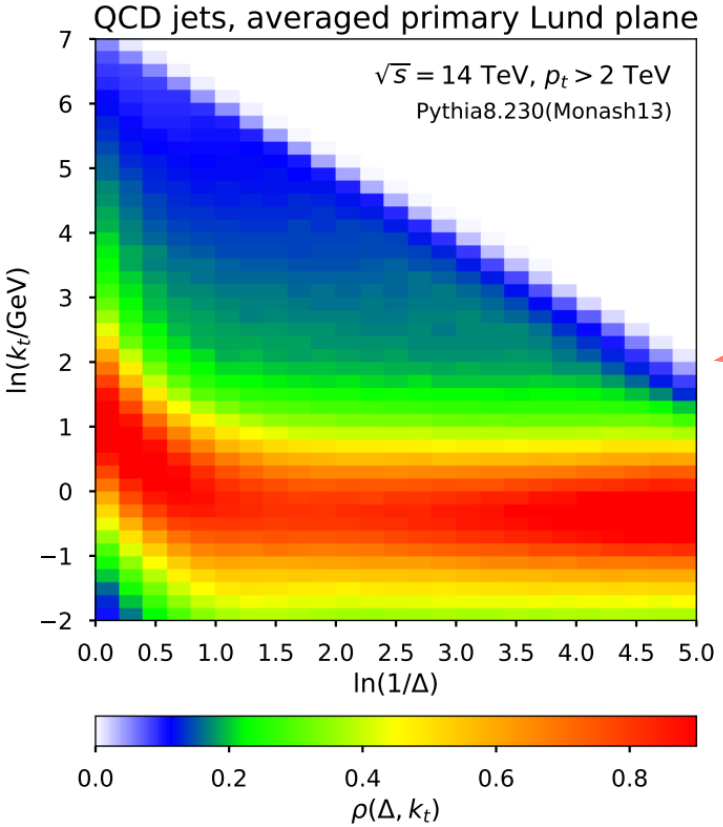
  - Experimentally, **the key question**: what are the *uncertainties* on the result of this procedure?

Primary Lund Plane

- "Jet is an unordered set", I know… but...
- Access to low-level physics directly
- Intuitive and thus appealing



(Frederic Dreyer, BOOST'18)

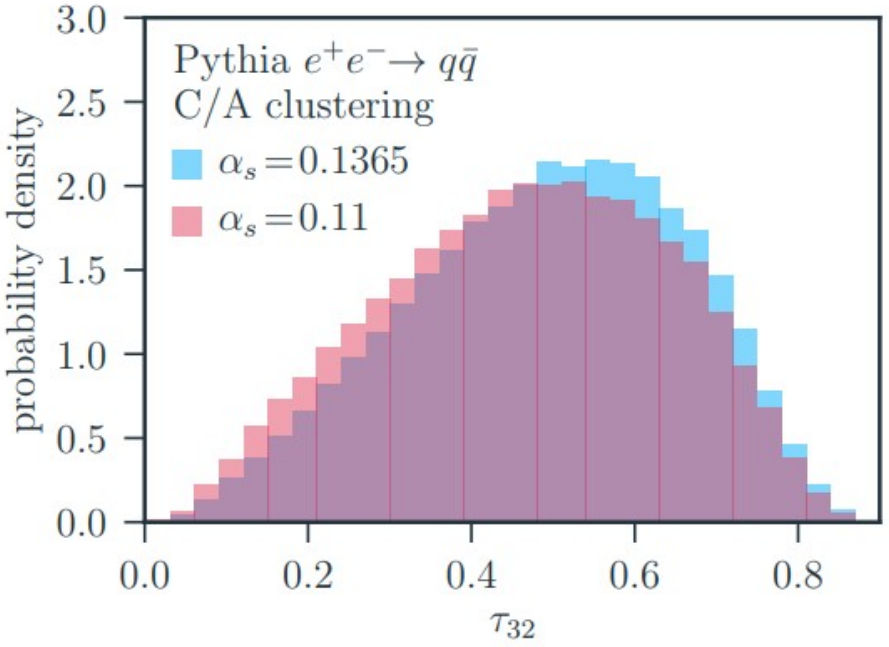


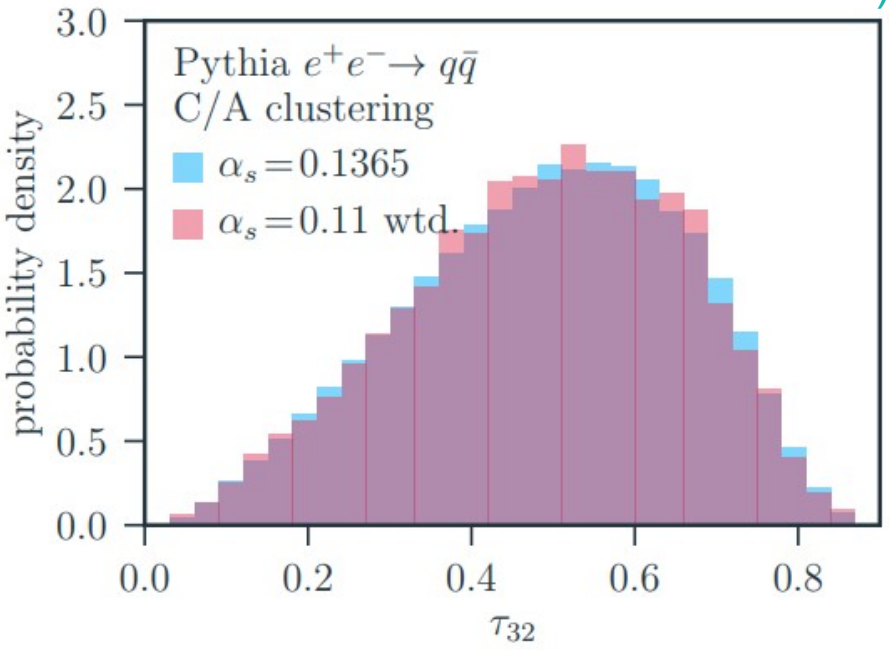
- Average Lund Plane (many jets)
  - one jet = set of point in this plane
- Can we reweight jets using the ratio of Lund Planes in data and MC?
- Unfolded 2D distribution of the Lund Plane????

JUNIPR

- Recursive NN, unsupervised learning on data
  - (A talk on more advance JUNIPR reweighting later this week!!!)
- Data/MC reweighting was one of its main goals!

(Cris Frye, BOOST'18)





- Works in MC: turns one PYTHIA into another.
- Will it work in data?

Do we need QCD MC at all?

- For multijet background estimates, we don't need MC
  - Have been data-driven anyway
  - Although there could be subtle correlations…
- Unsupervised learning from data…
  - Learns QCD: e.g., autoencoder with LoLa
  - Learns QCD in the presence of other backgrounds: e.g., CWoLa
- Can we interpolate between two sidebands
  - e.g., CWoLa hunting
- Can we *extrapolate* from one CR to another???

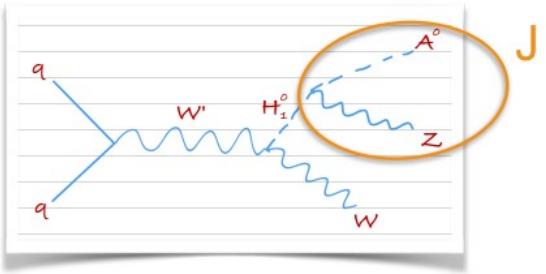
N-pronged jets?

- The future of searches with substructure?

(Juan-Antonio Aguilar Saavedra, BOOST 2018)

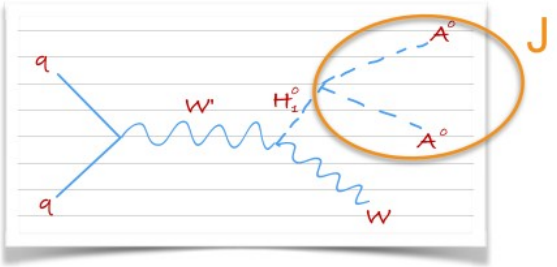
Case 11: Merged multibosons

If intermediate particles are `light´, their decay products are merged



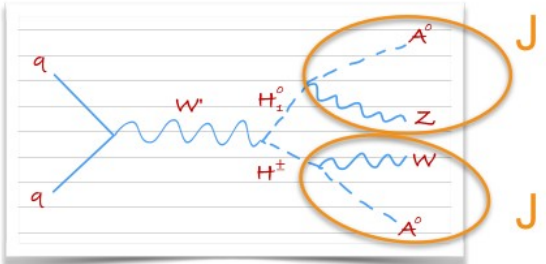
$M_{W'} \gg M_{H_1^0} \gtrsim M_Z + M_{A^0}$

$Z \to qq$ / …
$A^0 \to bb$ → W + fat jet J



$M_{W'} \gg M_{H_1^0} \gtrsim 2M_{A^0}$

$A^0 \to bb$ → W + fat jet J



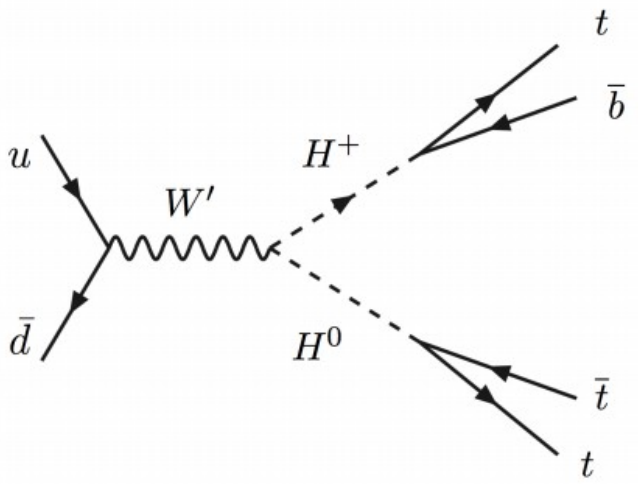
$M_{W'} \gg M_{H_1^0}, M_{H^\pm} \gtrsim M_Z + M_{A^0}$

$W, Z \to qq$ / …
$A^0 \to bb$ → two fat jets J

More N-pronged jets?

- More cool signatures with 4- and 6-pronged jets

Heavy Higgs bosons decay directly into a pair of the heaviest fermions:



For $M_{W'} \gg M_{H^+}$:

$(t\bar{b})$-tagged jet + $(t\bar{t})$-tagged jet

For $M_{W'} > M_{H^+} \gg m_t$:

three t-tagged jets + b

(Bogdan Dobrescu, BOOST 2017)

- Easy to do a cut-based analysis (let alone a DNN)
- But how to get the efficiency?

What to do about N-pronged jets?

- Give up, can't be done:
  - Can't measure efficiency in data
  - These analyses are always going to be out of reach
- Report limit on $\sigma_X \cdot \mathcal{B}(X) \cdot \underline{\epsilon_X}$ (David Miller's suggestion)
  - Let the consumers of the paper worry about the signal efficiency
  - Would not affect the discovery, only limits
  - May actually spur progress in this area :-/
- Or try to make it work?
  - Learn how to reweight single quark jets from MC
  - Verify that the procedure works for W and top (2,3-prong)
  - Assign further systematics for 4,5,6-prong...

Conclusions

- Since BOOST #1 (~ past 11 years)
  - Boosted objects are useful and necessary
    - integral part of the LHC program
  - Lots of progress in understanding substructure and (sub)jet physics
  - Powerful new taggers and variables
  - top, W, Higgs taggers calibrated in data
- But, in some aspects, I feel we're running in place:
  - Many of these improvements do not percolate to better/easier measurements
  - More complicated jets are under question until we figure out how to estimate signal efficiencies
- We still have (so much) work to do!