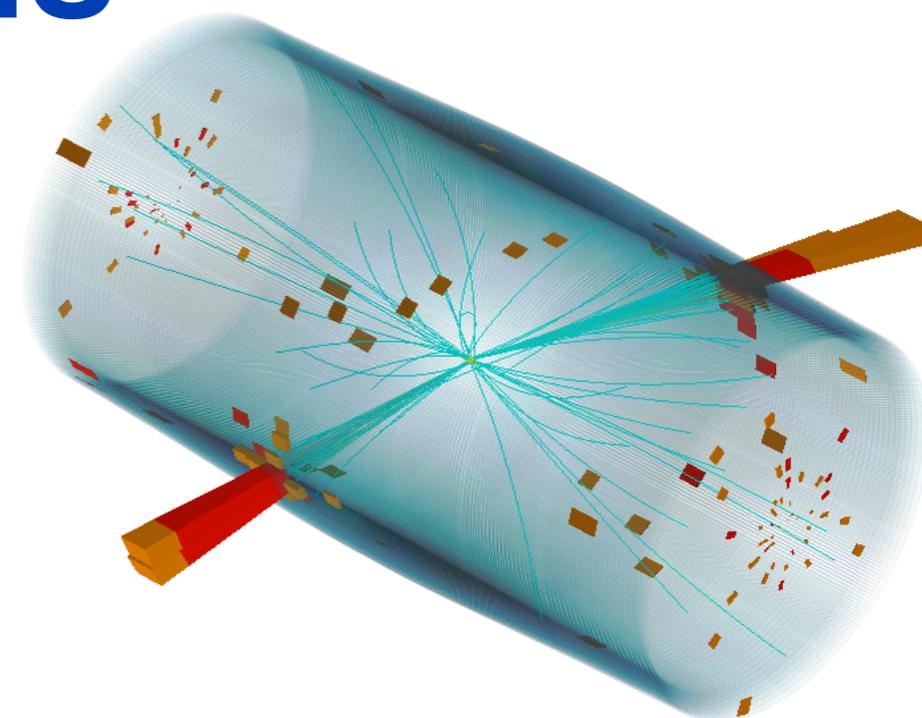


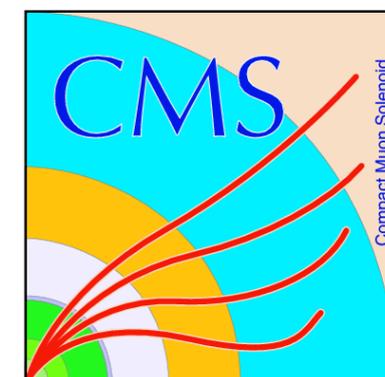
# Boosted vector boson reconstruction and polarisation studies in CMS

Candidate ZZ event  
Dijet mass: 3.2 TeV



Clemens Lange (CERN)

VBSscan Workshop: New techniques in particle reconstruction for VBS  
Krakow, Poland  
23<sup>rd</sup> October 2018



## > Workshop goals:

- review the state of the art for the physics object reconstruction in the ATLAS and CMS experiments
- identify areas where improvements could benefit VBS analyses
- what new techniques may be used
- start the work to get them done

> General jet substructure use has been discussed previously (Steven + VBSCan Kickoff Meeting)

> I will try to make this less of a review and more like an outlook

- > Reminder: jet substructure in CMS
- > Towards “state-of-the-art” jet substructure algorithms
- > Reminder: polarisation
- > Accessing polarisation in merged jets

> Jet grooming removes **soft and large angle radiation**

- ... and a lot of the difficult-to-model part

> Strategy:

- recluster jet using Cambridge-Aachen (CA) jet algorithm
- iteratively break into two subjets
- remove softer contribution (and continue with harder one) if:

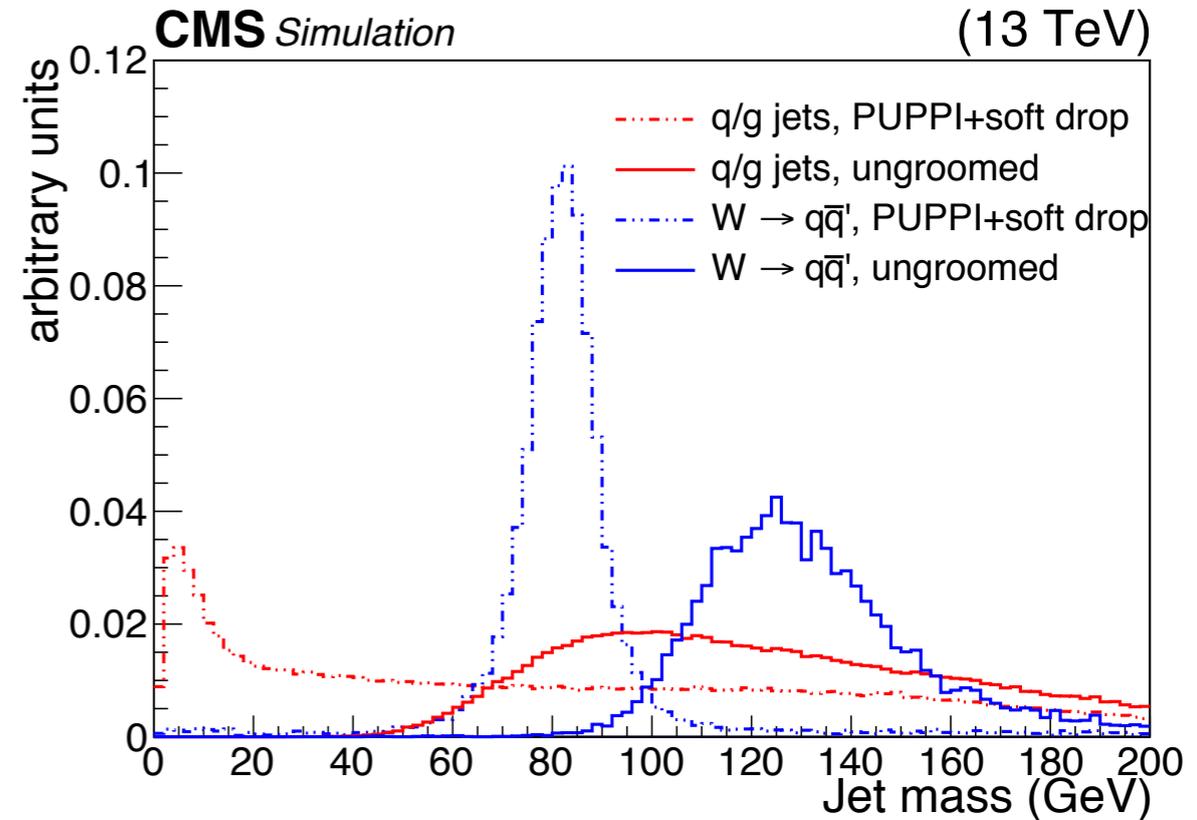
**soft-drop condition**

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} < 0.1$$

**modified mass-drop algorithm (mMDT)**

- stop otherwise

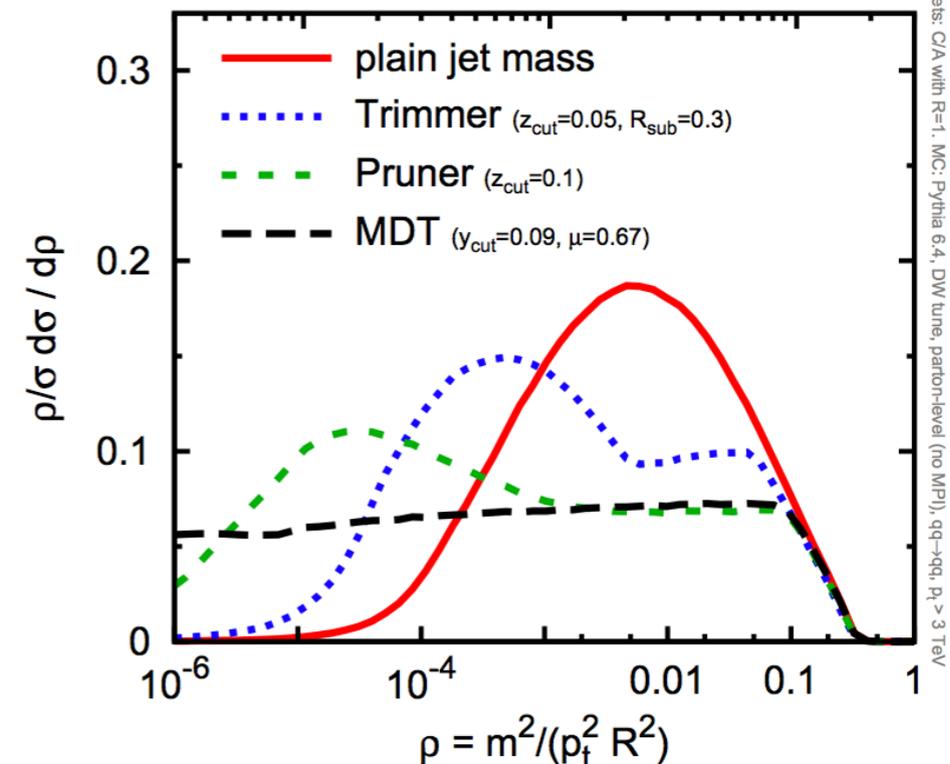
use of soft-drop algorithm new w.r.t. 2015 — previously used pruning → perturbatively robust



**quark jets (Pythia 6 MC)**

$m$  [GeV], for  $p_t = 3$  TeV,  $R=1$

10 100 1000



# N-subjettiness

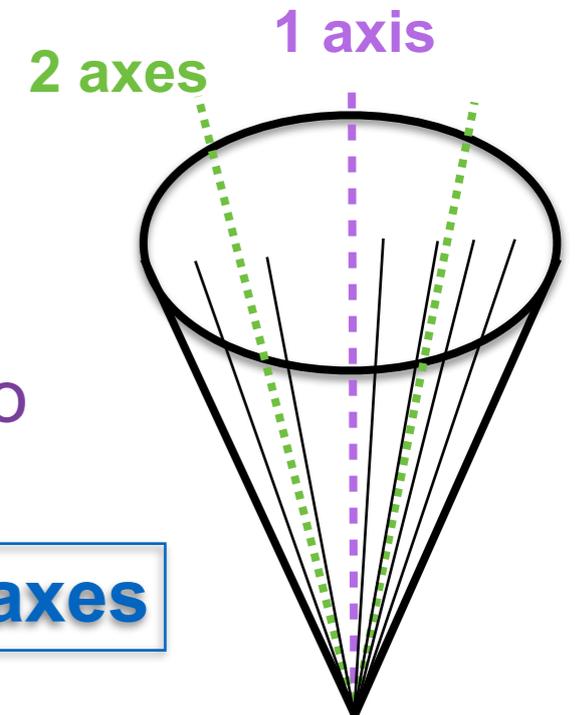
- > For **boson-tagging**: want to quantify how **2-subjetty** a jet is
- > → To what extent is energy flow aligned along 2 momentum directions (N=2)?

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k})$$

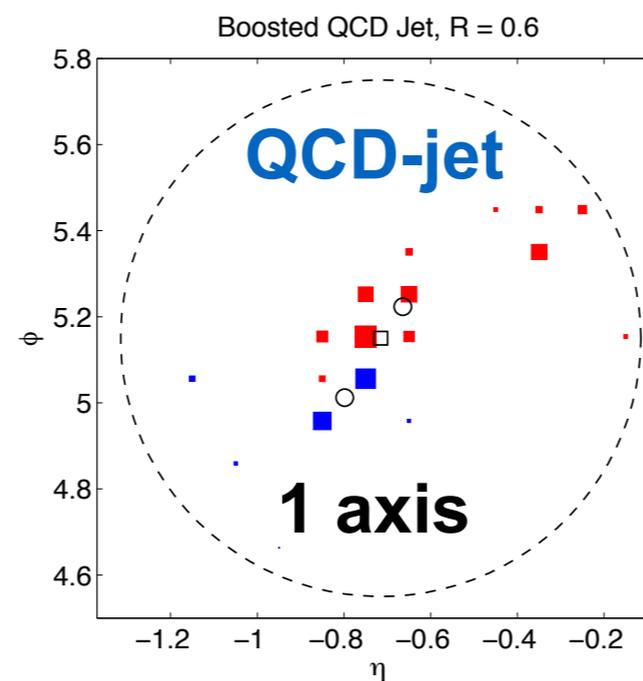
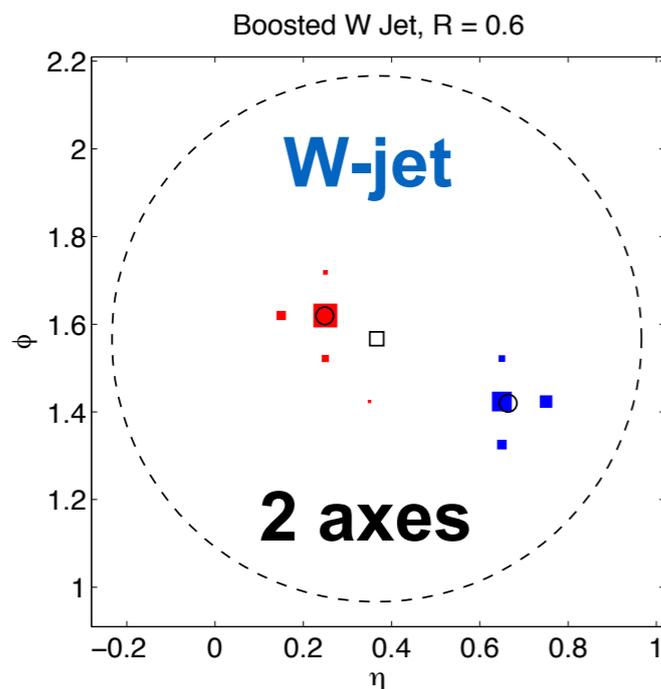
normalisation

sum over particles

minimise distance to candidate subsets

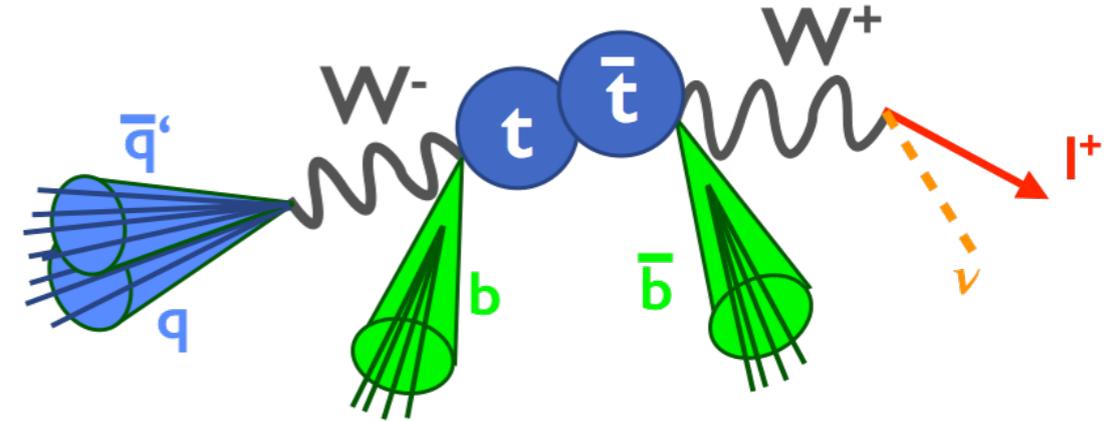


**low values of  $\tau_N$  → compatibility with the hypothesis of N axes**

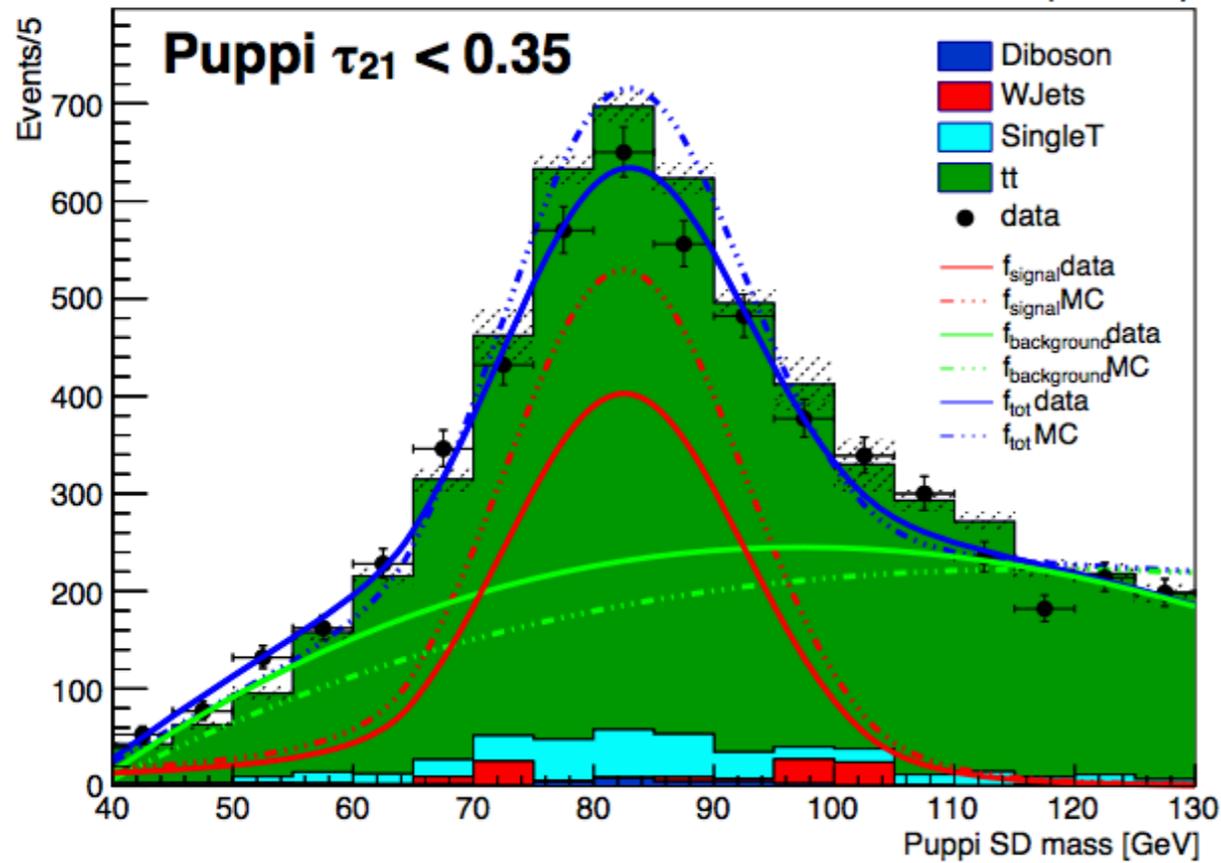


**Candidate subsets are built by de-clustering the jet using the  $k_T$  algorithm**

- > Bare  $\tau_N$  has very little discrimination power
- > Take **ratio**  $\tau_2/\tau_1$  instead
- > Note: rather **complicated variable**, difficult to model  $\rightarrow$  need to validate in data
- > Clean sample of W-jets: **top-antitop quark pairs** used for calibration (W-jet  $p_T \sim 200$  GeV)

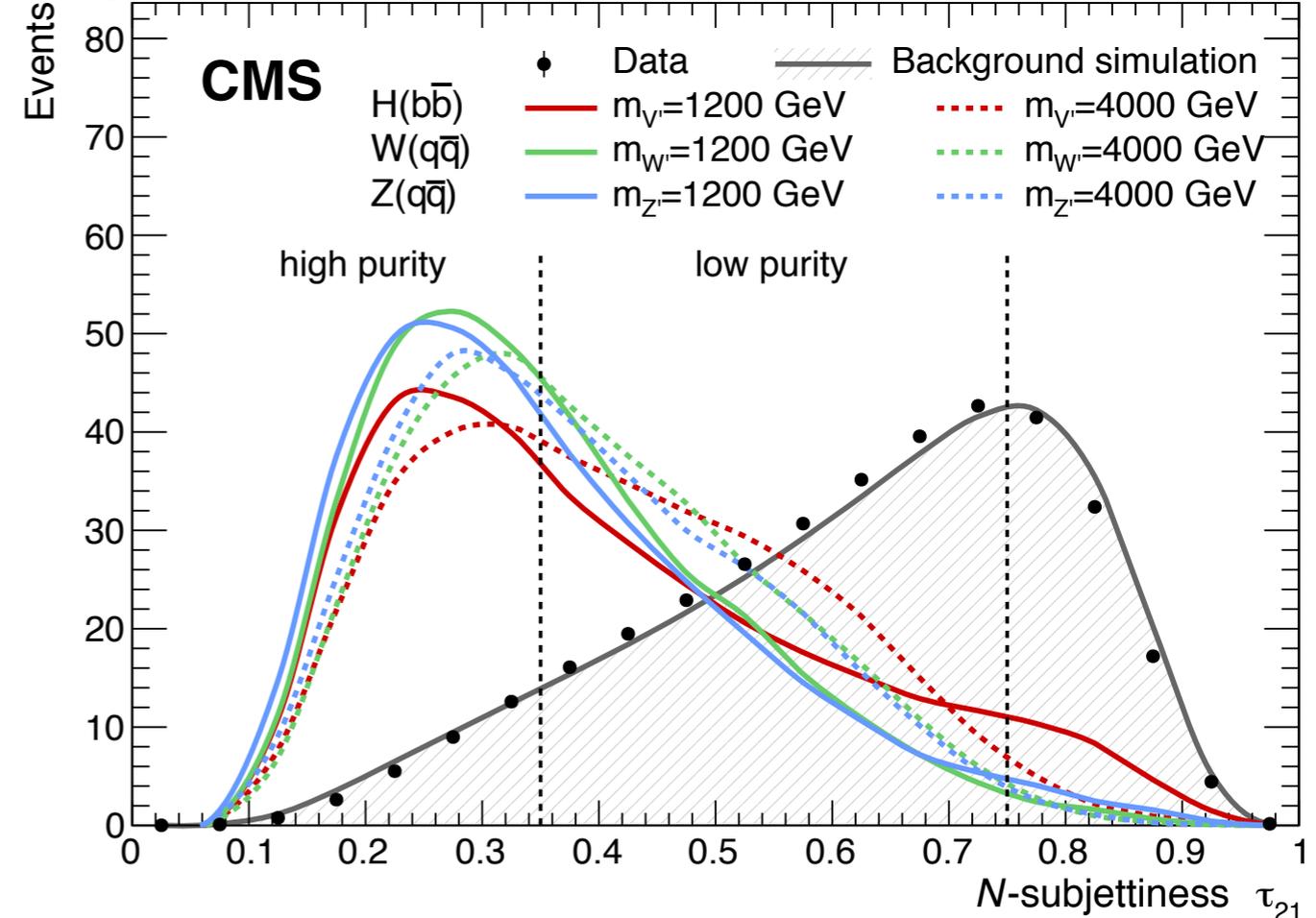


CMS Preliminary 35.8 fb<sup>-1</sup> (13 TeV)



**Attention: W polarisation can be different for signal**

35.9 fb<sup>-1</sup> (13 TeV)



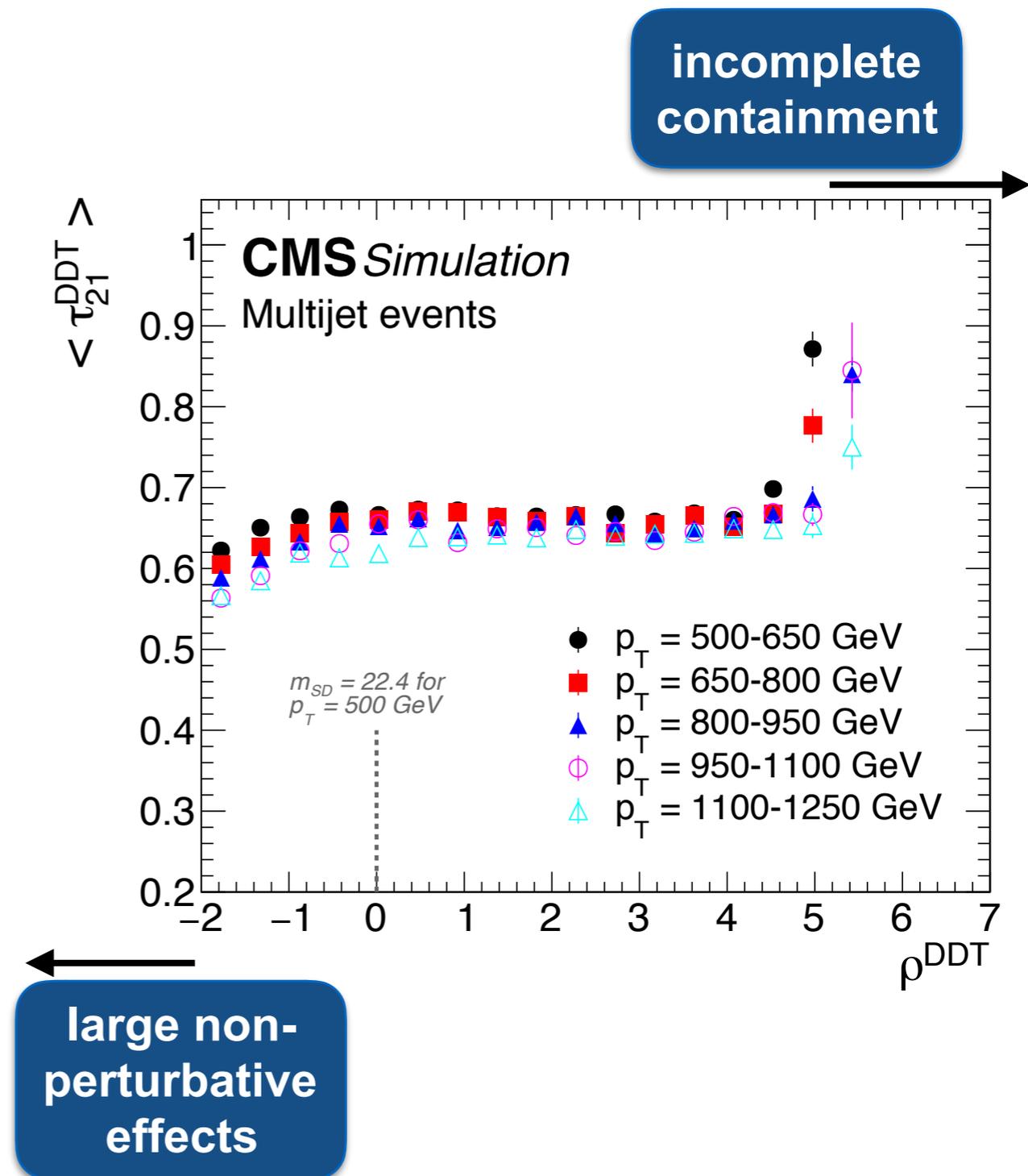
- > Jet mass and e.g.  $\tau_{21}$  as well as  $p_T$  are correlated
- > Introduces undesired **sculpting of distributions**
- > Possible solution: reduce sculpting by rescaling/decorrelating:

- Introduce dimensionless mass variable:

$$\rho^{\text{DDT}} = \ln[m_{\text{SD}}^2 / (\mu_0 p_T)], \quad \mu_0 = 1 \text{ GeV}$$

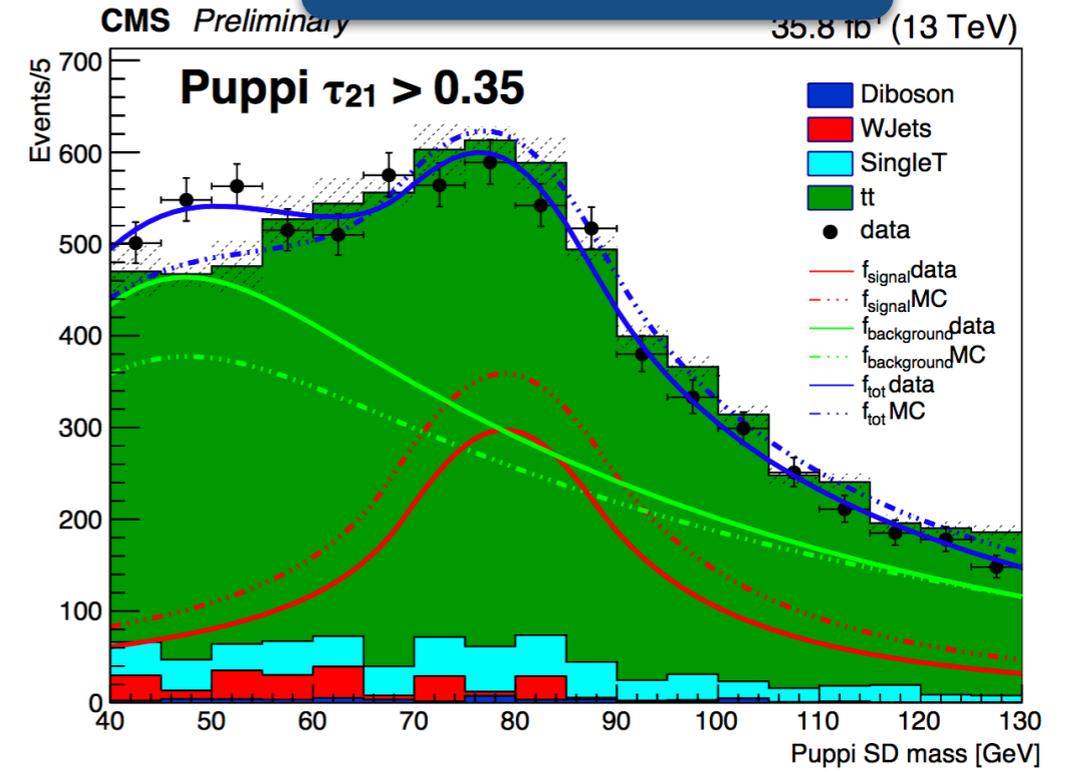
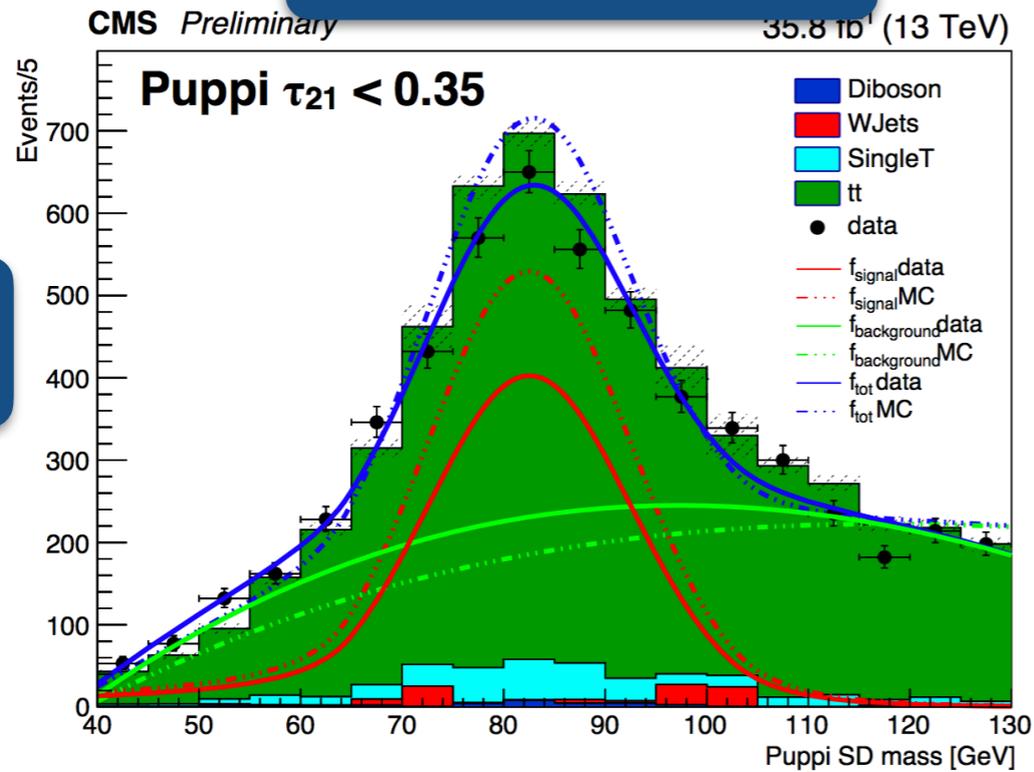
- Recalculate  $\tau_{21}$ :

$$\tau_{21}^{\text{DDT}} = \tau_{21} + M\rho^{\text{DDT}}$$

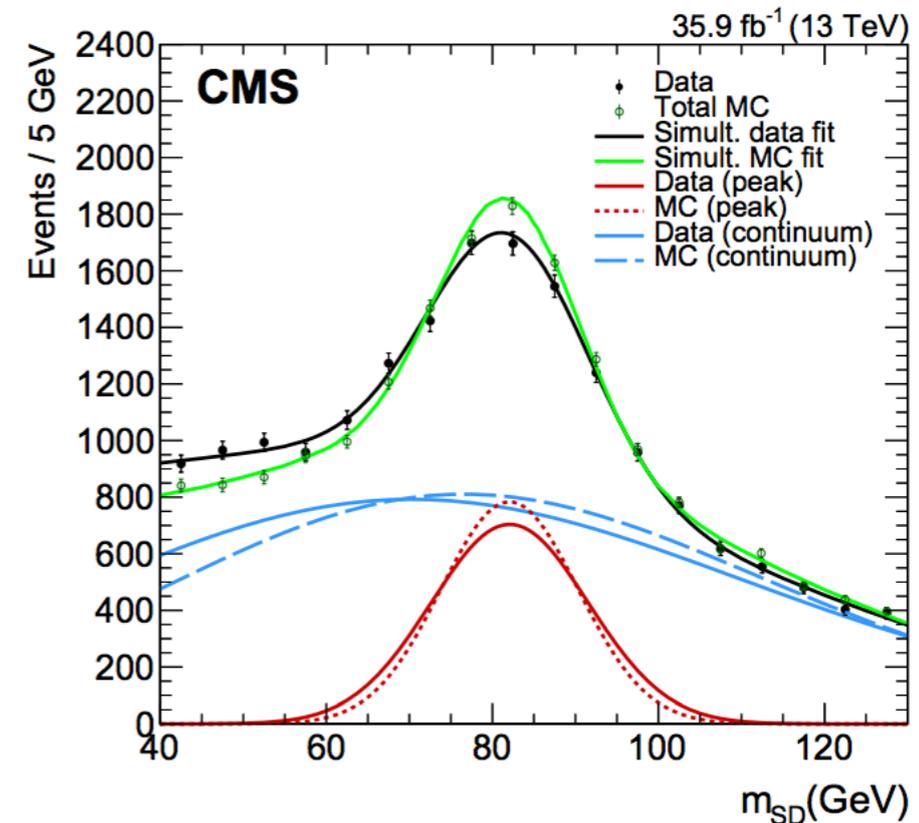
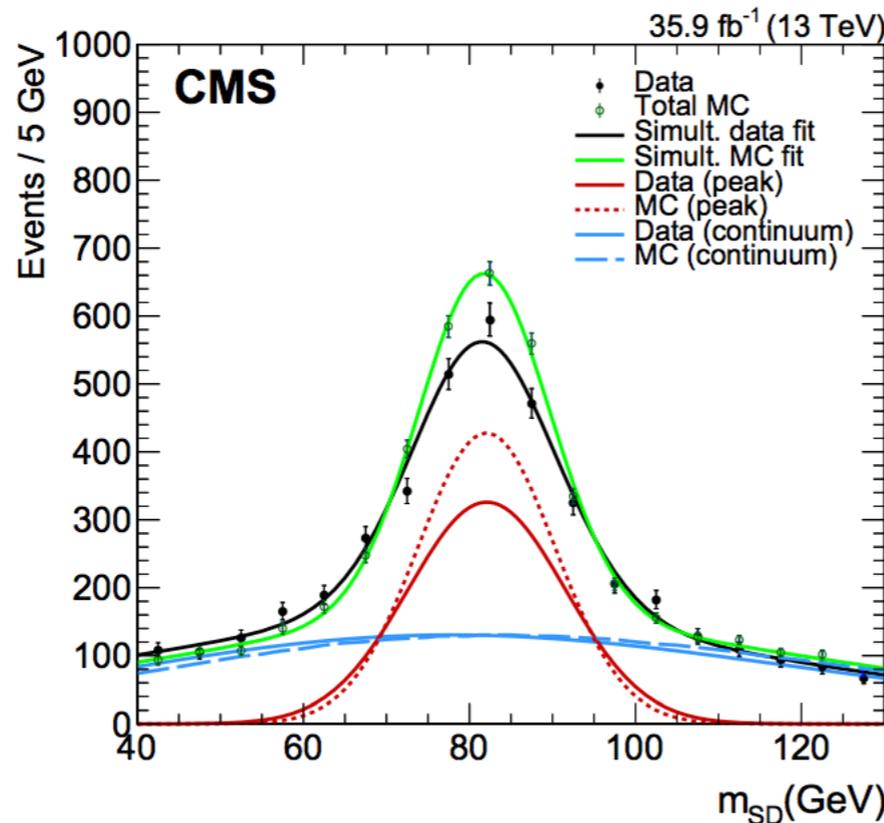


pass tagging cut

fail tagging cut



not decorrelated



decorrelated

➤ “Fail” region becomes good region for background estimation

# Energy correlation functions

- > Idea: probe n-particle correlations within a jet using IRC-safe variables
- > Here: compare  $N_2$  (axis-free) to 2/1-subjettiness

$$\tau_1 = \frac{1}{p_{T,\text{jet}}} \sum_k p_{T,k} \Delta R_{\text{jet},k}$$

$$1e_2 = \frac{1}{p_{T,\text{jet}}} \sum_{1 \leq i < j \leq n} z_i z_j \Delta R_{ij}$$

$$\tau_2 = \frac{1}{p_{T,\text{jet}}} \sum_k p_{T,k} \min \left( \Delta R_{\text{subjet1},k}, \Delta R_{\text{subjet2},k} \right)$$

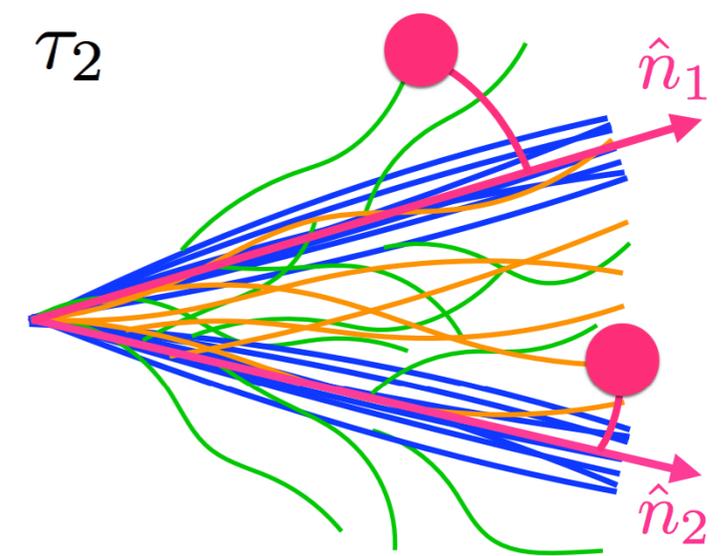
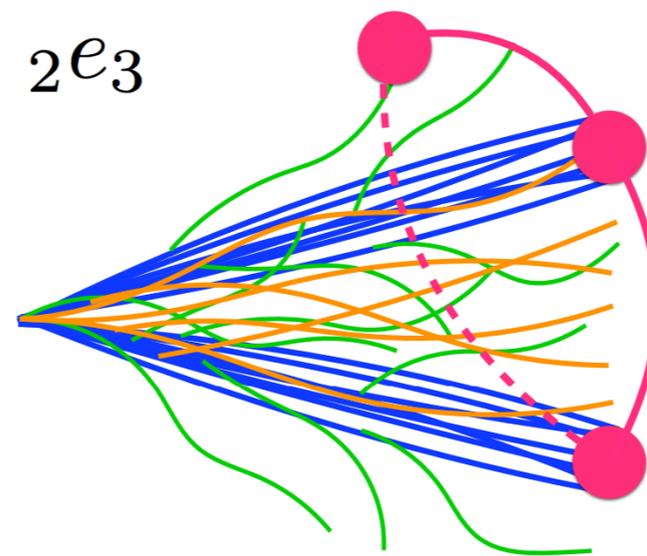
$$2e_3 = \frac{1}{p_{T,\text{jet}}} \sum_{1 \leq i < j < k \leq n} p_{T,i} p_{T,j} p_{T,k} \min \left\{ \Delta R_{ij} \Delta R_{ik}, \Delta R_{ij} \Delta R_{jk}, \Delta R_{ik} \Delta R_{jk} \right\}$$

$$\tau_{21} = \frac{\tau_2}{\tau_1}$$

$$N_2^1 = \frac{2e_3}{(1e_2)^2}$$

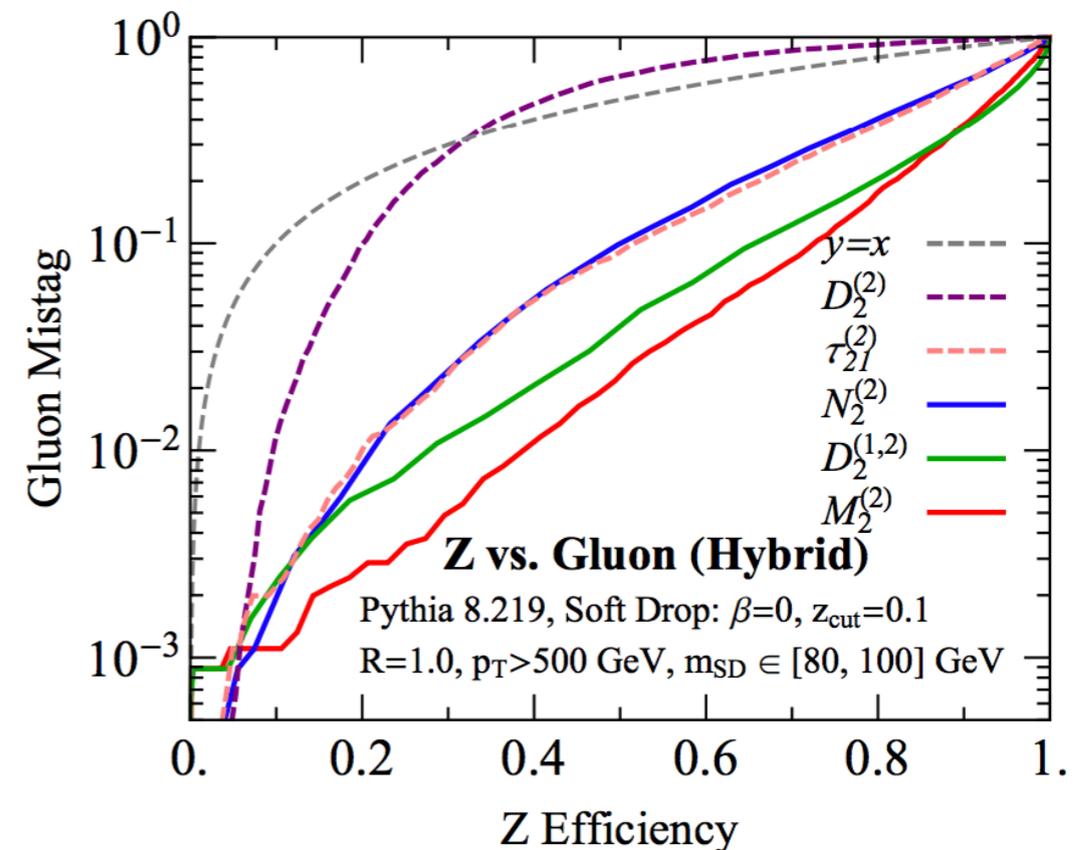
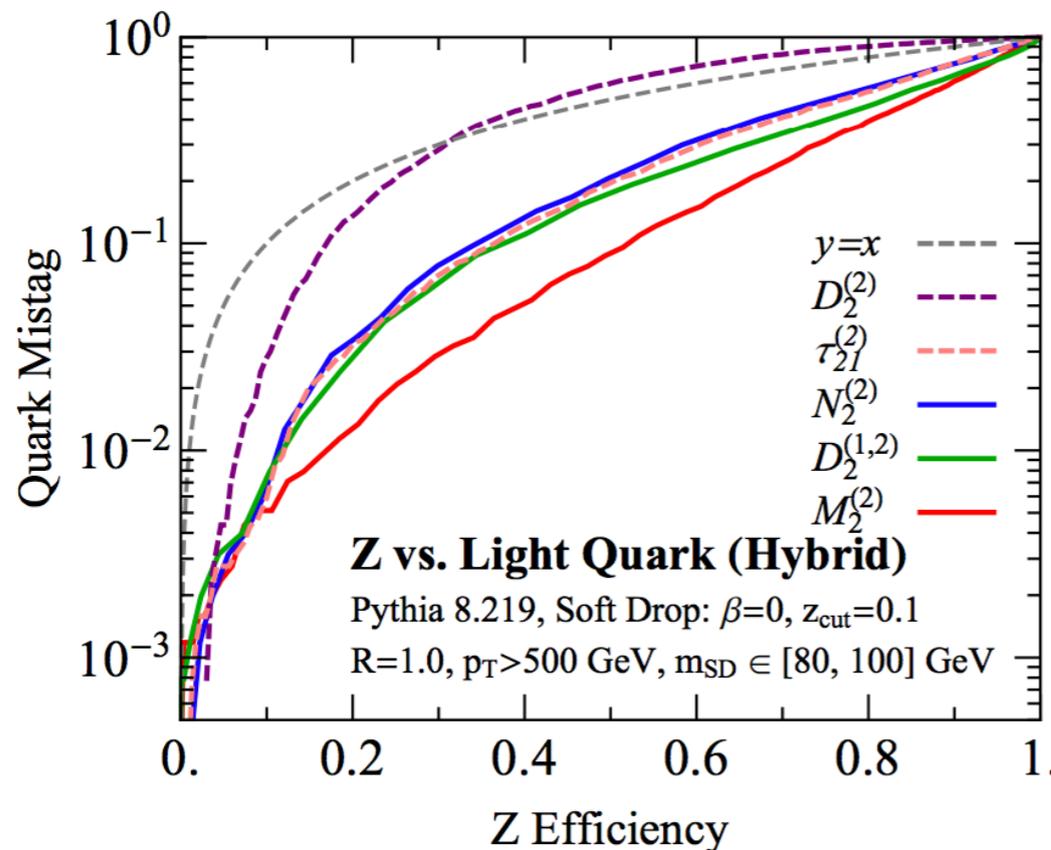
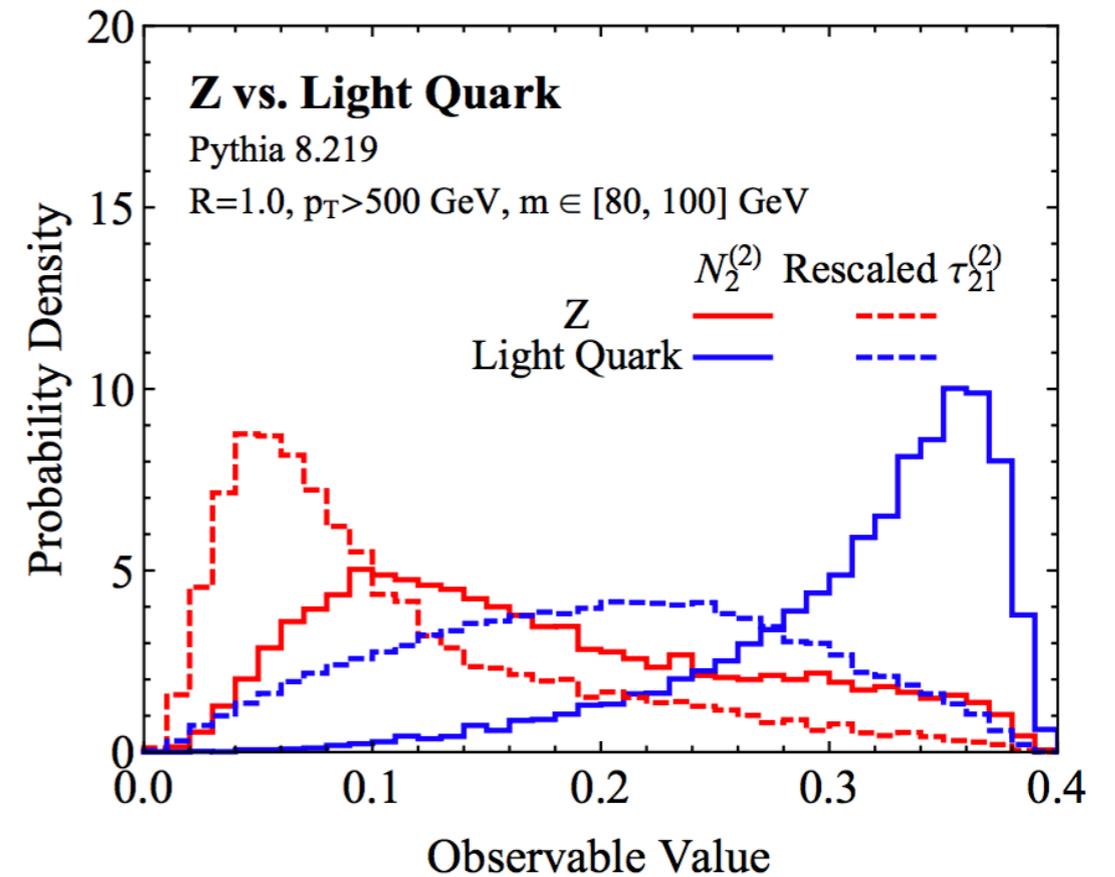
- > Reduces to  $\tau_{21}$  in resolved limit

- good to combine resolved and boosted regime!



# State-of-the-art substructure

- There are lots of new algorithms on the market
- Some are theoretically more stable
- Others make use of machine learning
- Overall, often, but not always better performance guaranteed — needs **to be studied for each analysis**



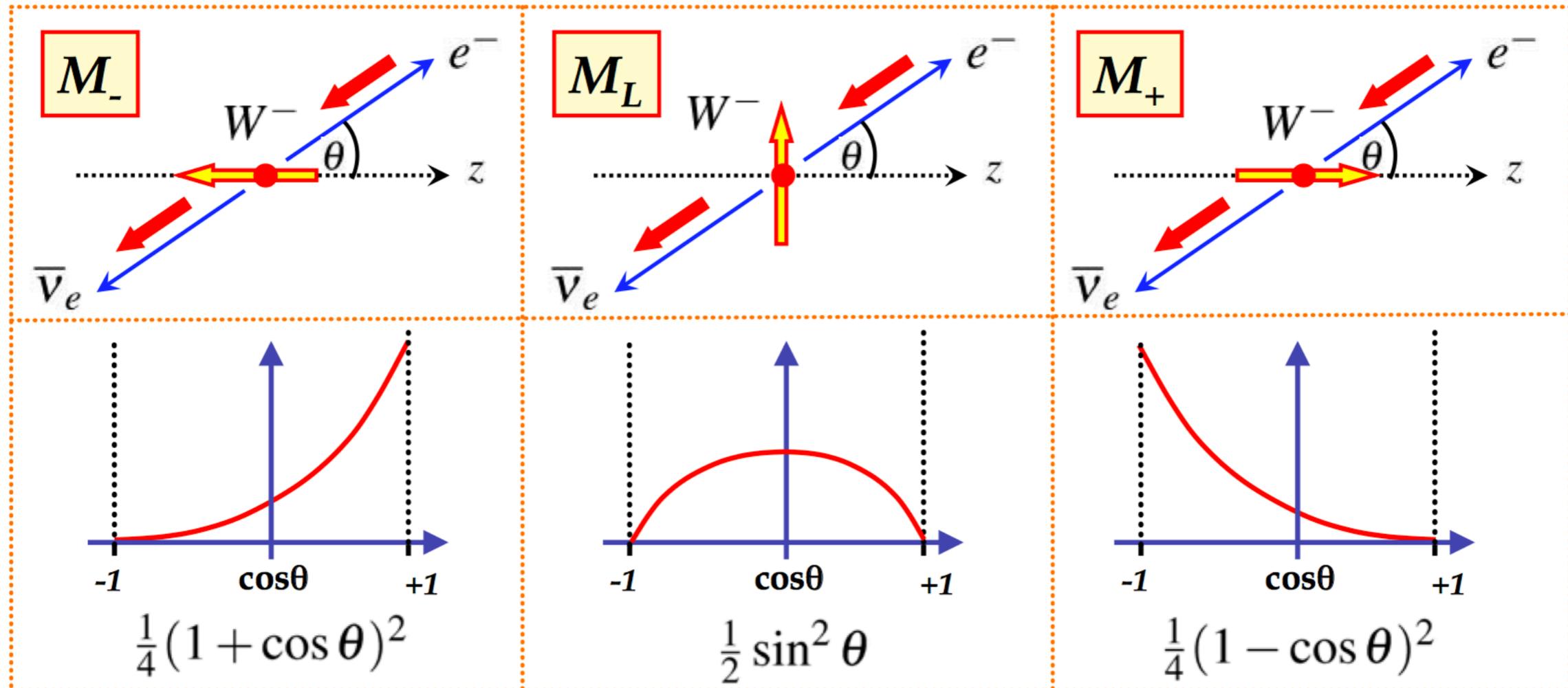


# Polarisation



# Reminder: polarisation

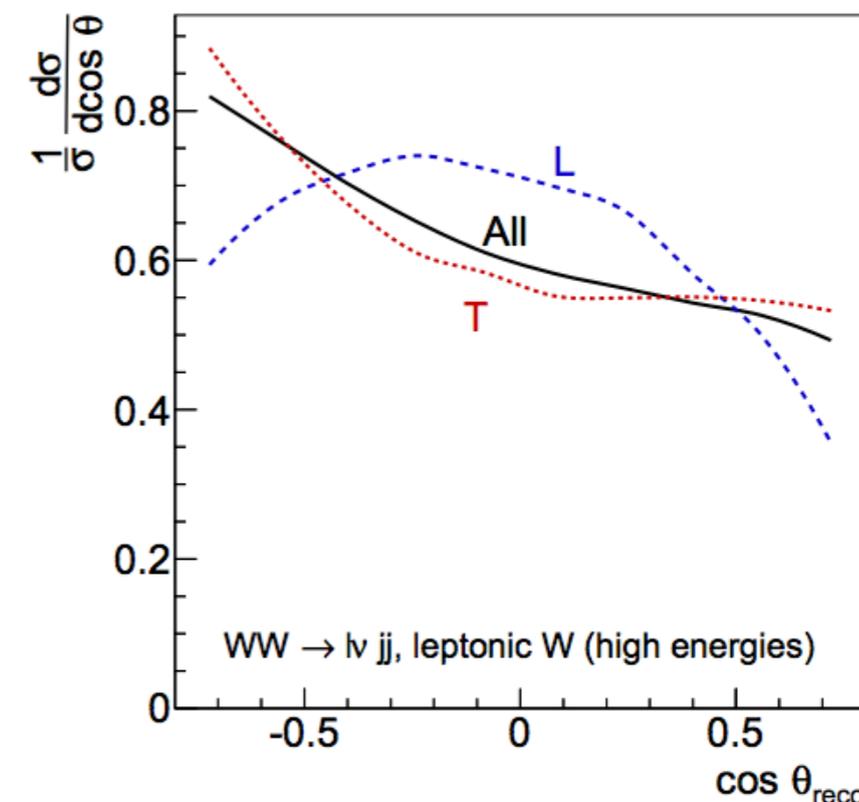
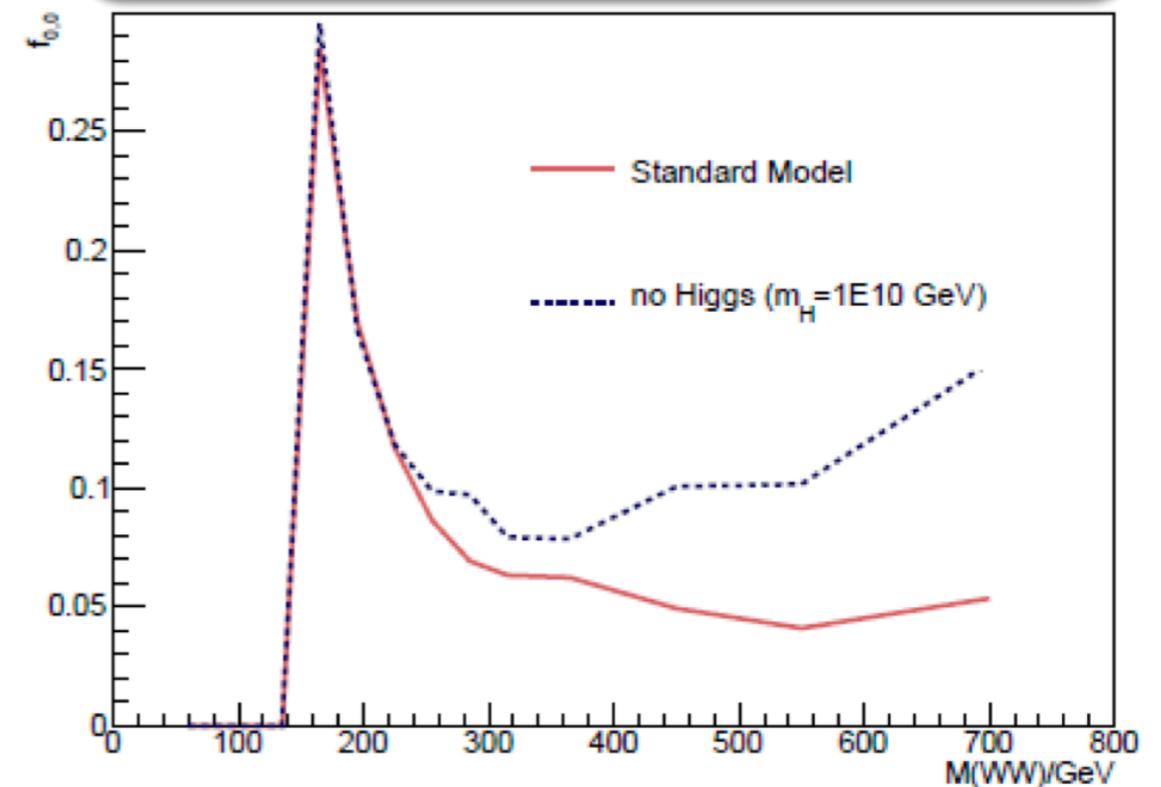
- A real (i.e. not virtual) massless spin-1 boson can exist in two transverse polarisation states, a massive spin-1 boson also can be longitudinally polarised



- Access the polarisation via the fermions in the decay
- Boost back into rest frame of  $W$  boson  $\rightarrow \cos(\theta^*)$

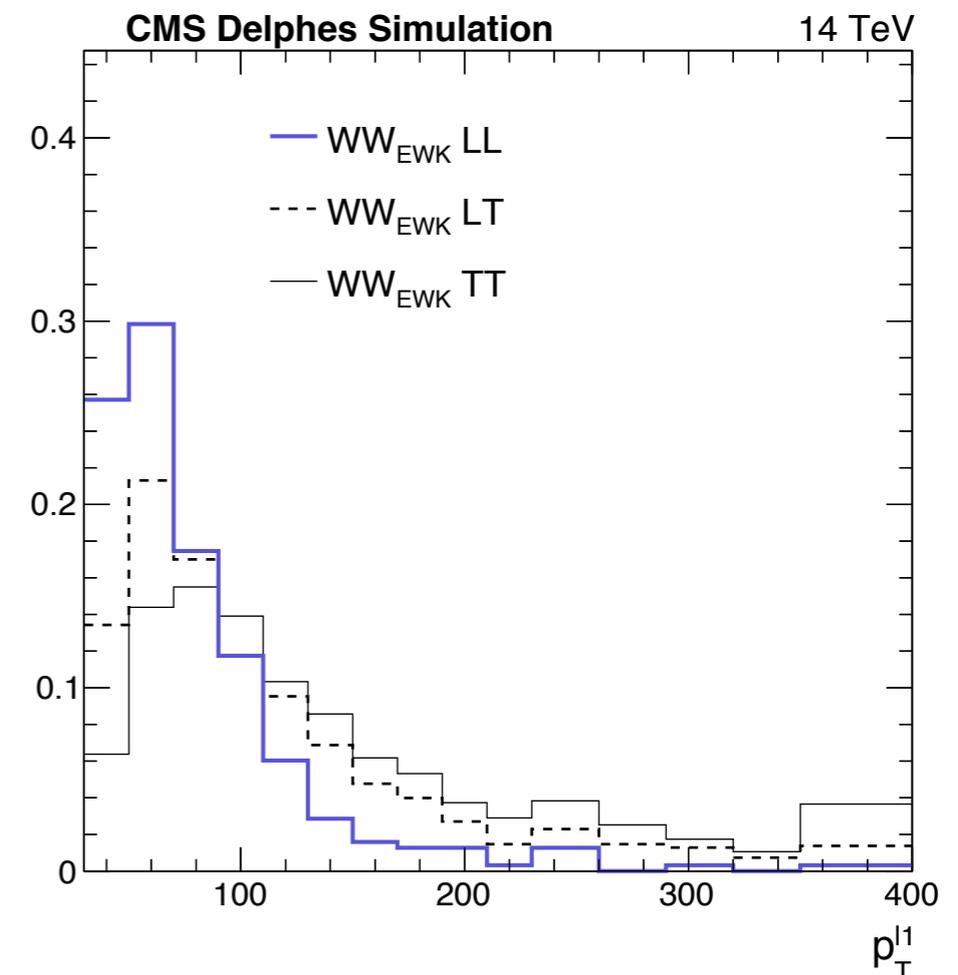
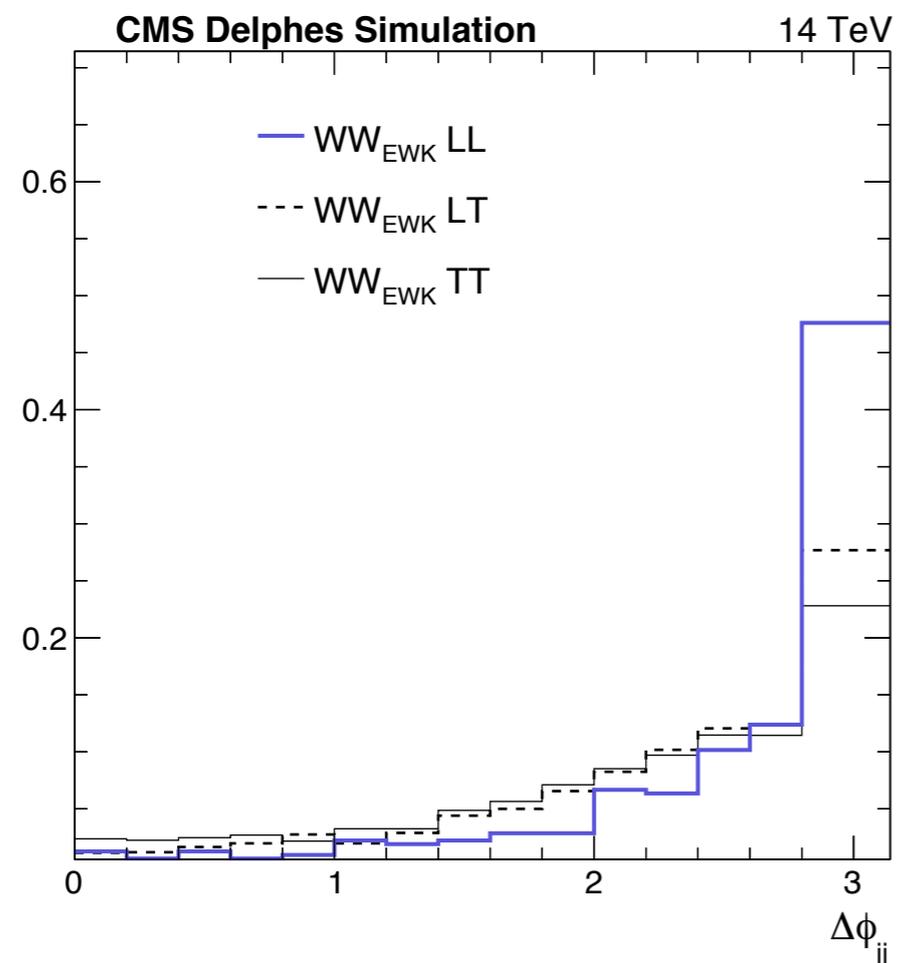
- > Without the Higgs boson, the  $V_L V_L$   $\rightarrow V_L V_L$  amplitude would **diverge at the TeV scale**
- > Longitudinal component amounts to **5-10%** from  $m_{VV} > 250$  GeV
- > In the no-Higgs case, the longitudinal component increases to the same level as the transverse one
- > **Reconstruction effects** reduce separation power further
- > Overall challenge: discriminate **VBS from QCD VV** production, then **separate polarisations**

## fraction of longitudinal scattering



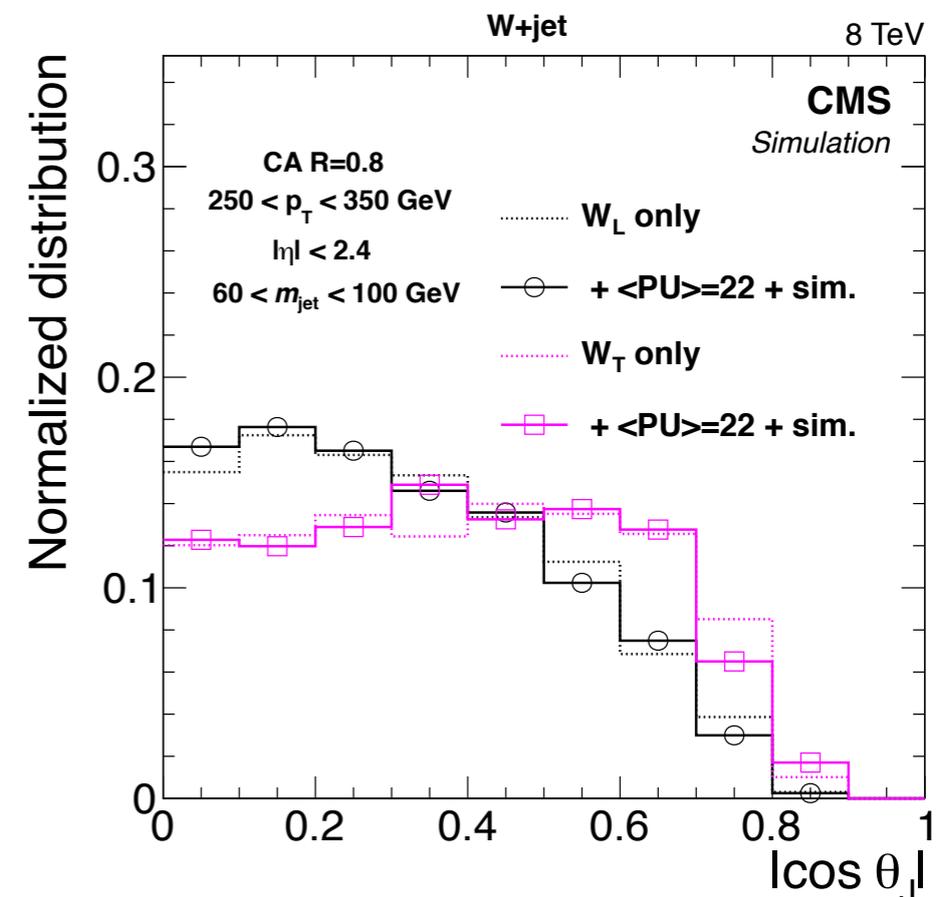
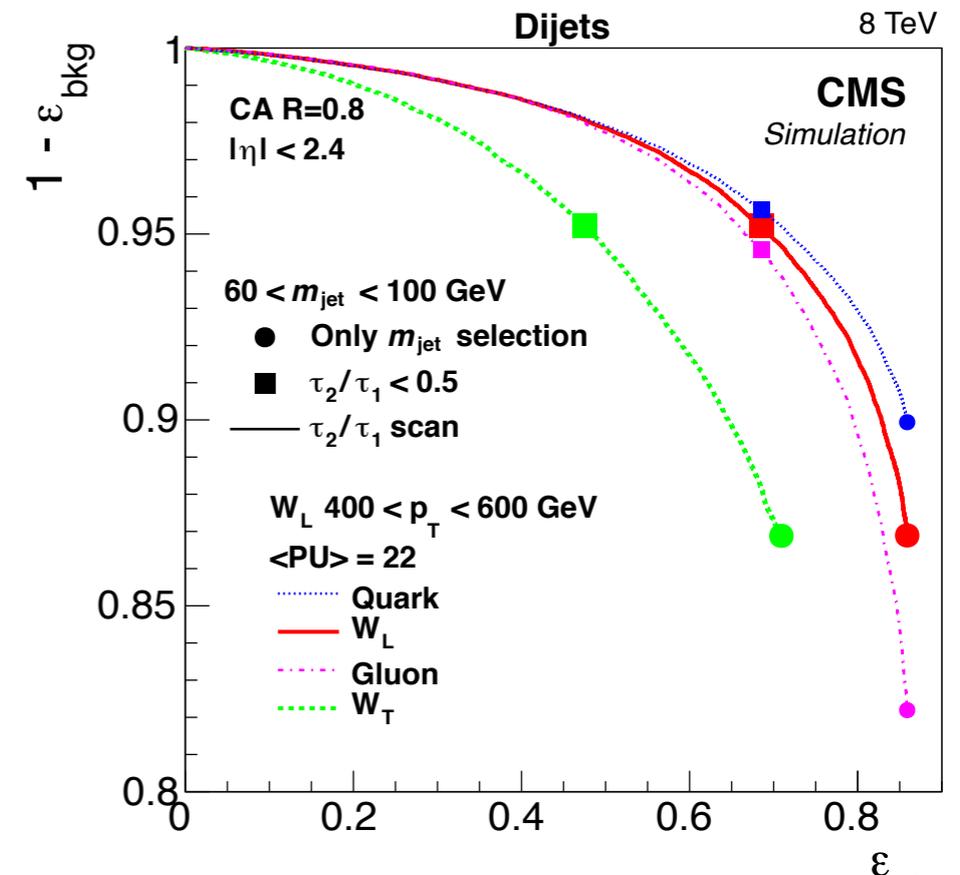
# Polarisation and jet substructure

- > Hadronic W boson decays yield **access to full boson kinematics**
- > Increased understanding in jet substructure increases **quark-/gluon-discrimination**
- > Significantly **more statistics** — but optimisation studies required
- > Generally, **more than one option** to access longitudinal components:
  - via spectator jets (below) or via the vector bosons themselves (next slides)

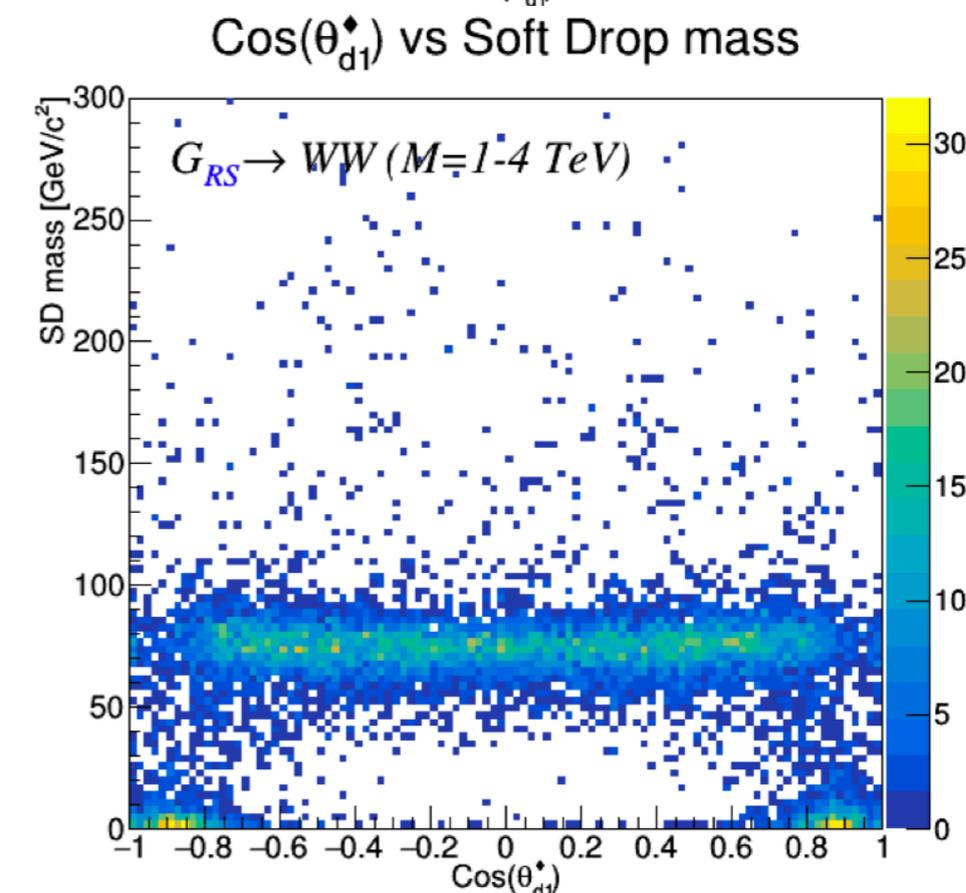
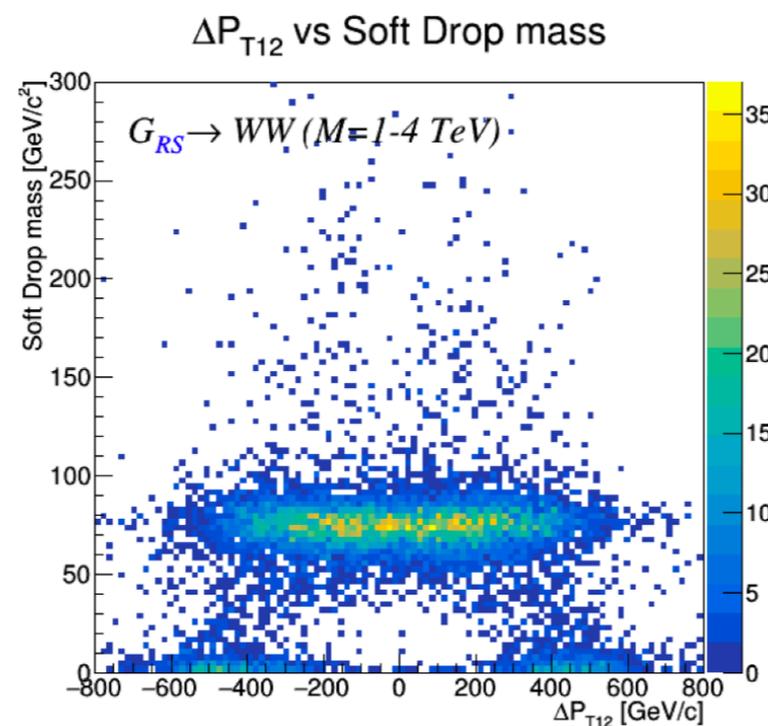
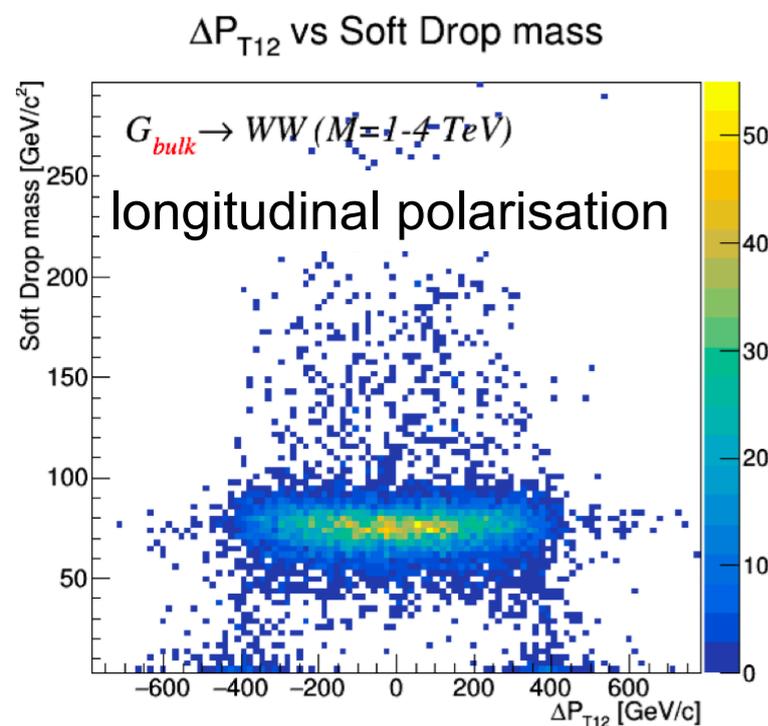
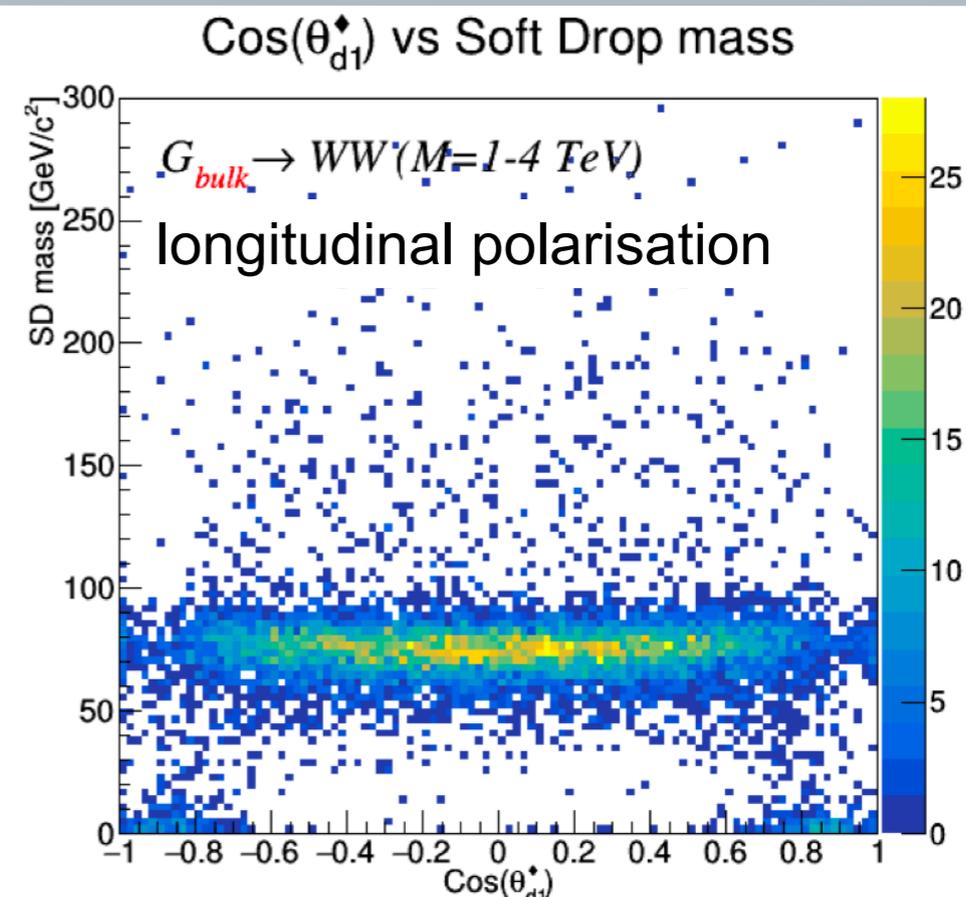


# Polarisation in W tagging

- > Mostly studied in the context of heavy **diboson resonance searches**
- > Standard taggers show **different performance** for longitudinal and transverse polarisation
  - mind that these are relatively old studies
- > Caveat of hadronic boson decays: cannot (easily) **distinguish fermion and antifermion**
  - restrict to  $|\cos(\theta_J)|$
  - attempt to measure subjet electric charge (see e.g. [SMP-15-003](#))?
- > Depletion of events at  $|\cos(\theta_J)| \approx 1$  is due to two acceptance effects



- >  $\theta_J \approx 0$ : overlapping partons  $\rightarrow$  difficult to find two subjets
- >  $\theta_J \approx \pi$ : one subjet much softer than the other  $\rightarrow$  loss or misidentification of the subjets
- > Angular resolution in the laboratory frame is  $\sim 10$  mrad
  - translates to  $\sim 65$  mrad on  $\theta_J$  in the  $W$  rest frame



- > Jet substructure provides **powerful tool** for the reconstruction of boosted vector bosons (and quark-/gluon-discrimination)
- > Possibility to access polarisation

## Tasks:

- > Need to evaluate and commission **state-of-the-art** boson tagging algorithms
- > Make use of variable **decorrelation**
- > Performance of tagging algorithms for polarisation needs to be studied in more detail
  - recover acceptance effects?
  - weigh loss of  $W$  vs.  $q/g$  discrimination power against polarisation sensitivity
  - mind potential in spectator forward jets

