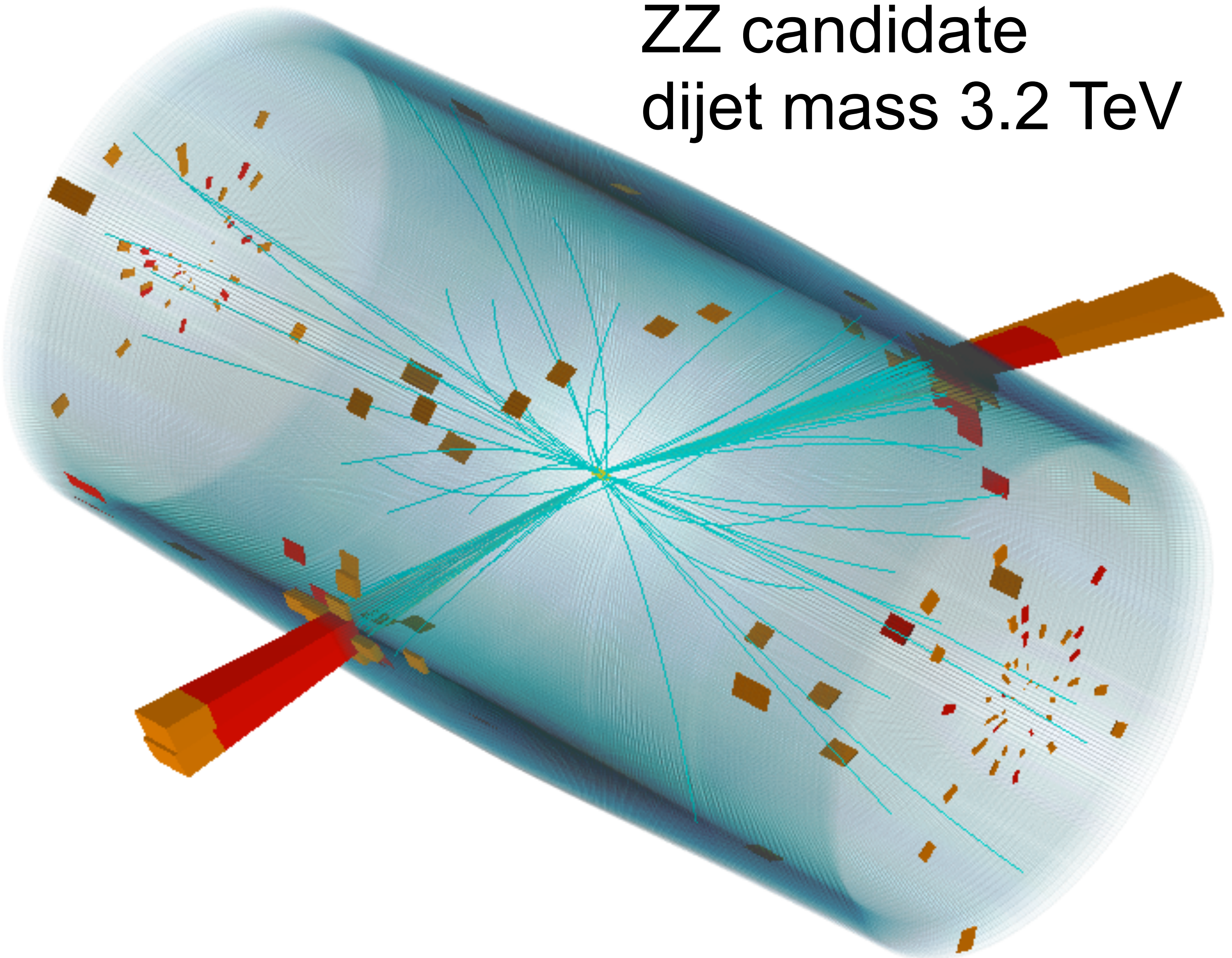
Boosted vector boson reconstruction and polarisation studies in CMS

ZZ candidate
dijet mass 3.2 TeV



Clemens Lange (CERN)

VBScan Workshop: New techniques in particle reconstruction for VBS
Krakow, Poland
23rd October 2018

Purpose of this talk

- 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 presented previously (Frédéric, Steven + VBSCan Kickoff Meeting)
- Polarisation has just been discussed (VBS Polarization workshop LLR)
- I will try to make this less of a review and more like an outlook

Outline

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

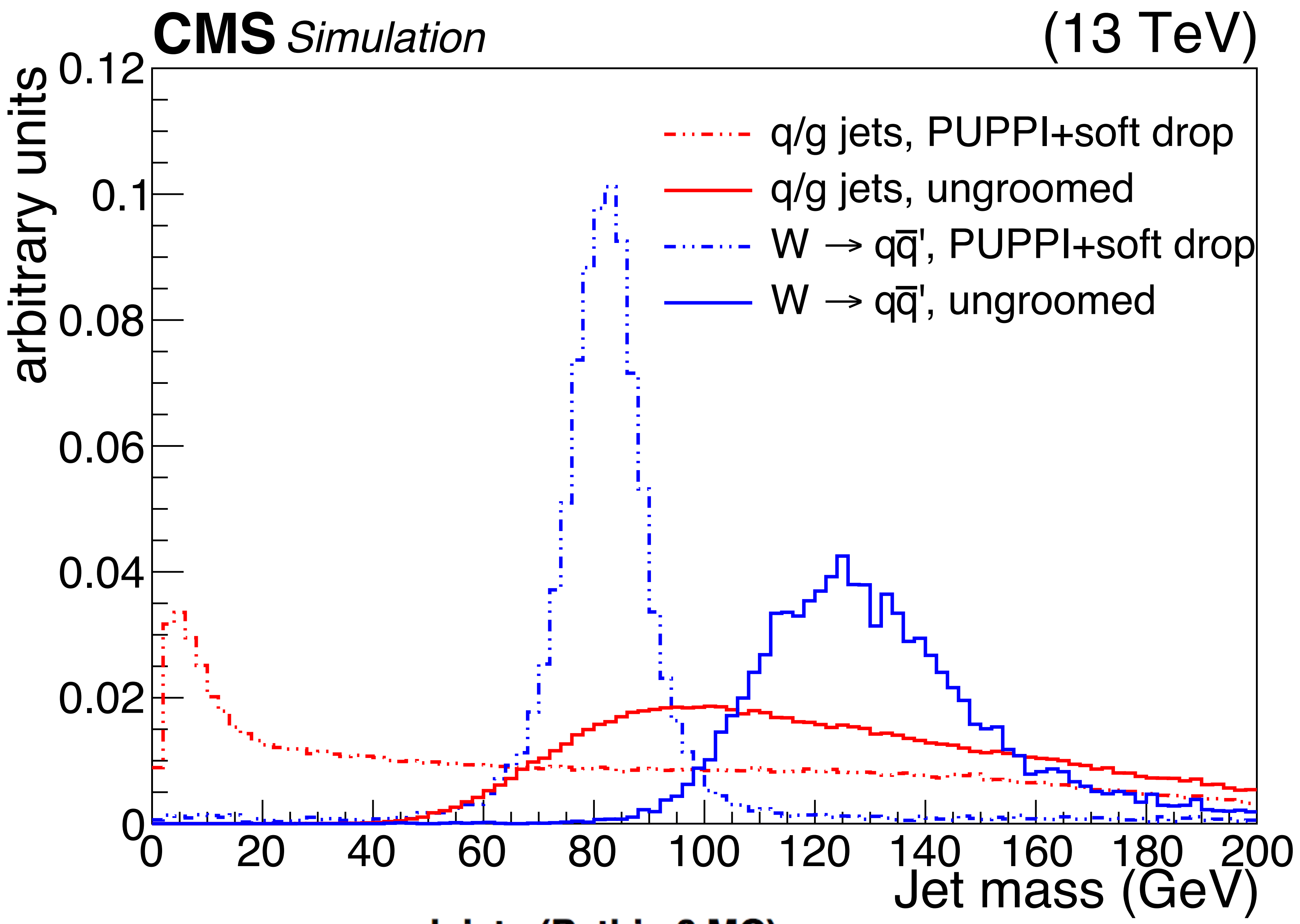
Jet grooming

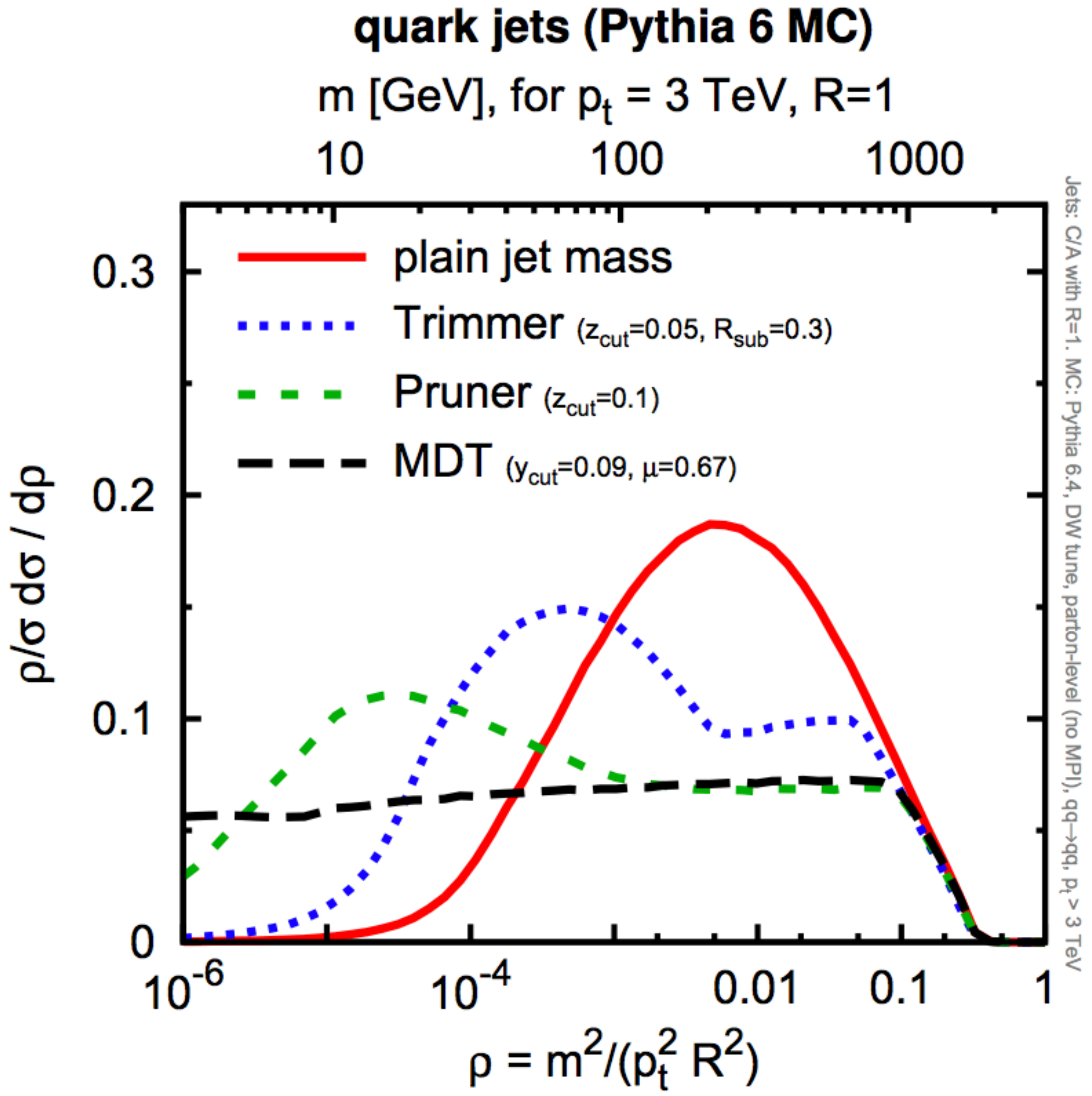
- Jet grooming removes **soft and large angle radiation**
  - … and a lot of the difficult-to-model part
- Strategy:
  - recluster jet using Cambridge-Aachen (CA) jet algorithm
  - iteratively break into two subjets
  - remove softer contribution (and continue with harder one) if:

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





N-subjettiness

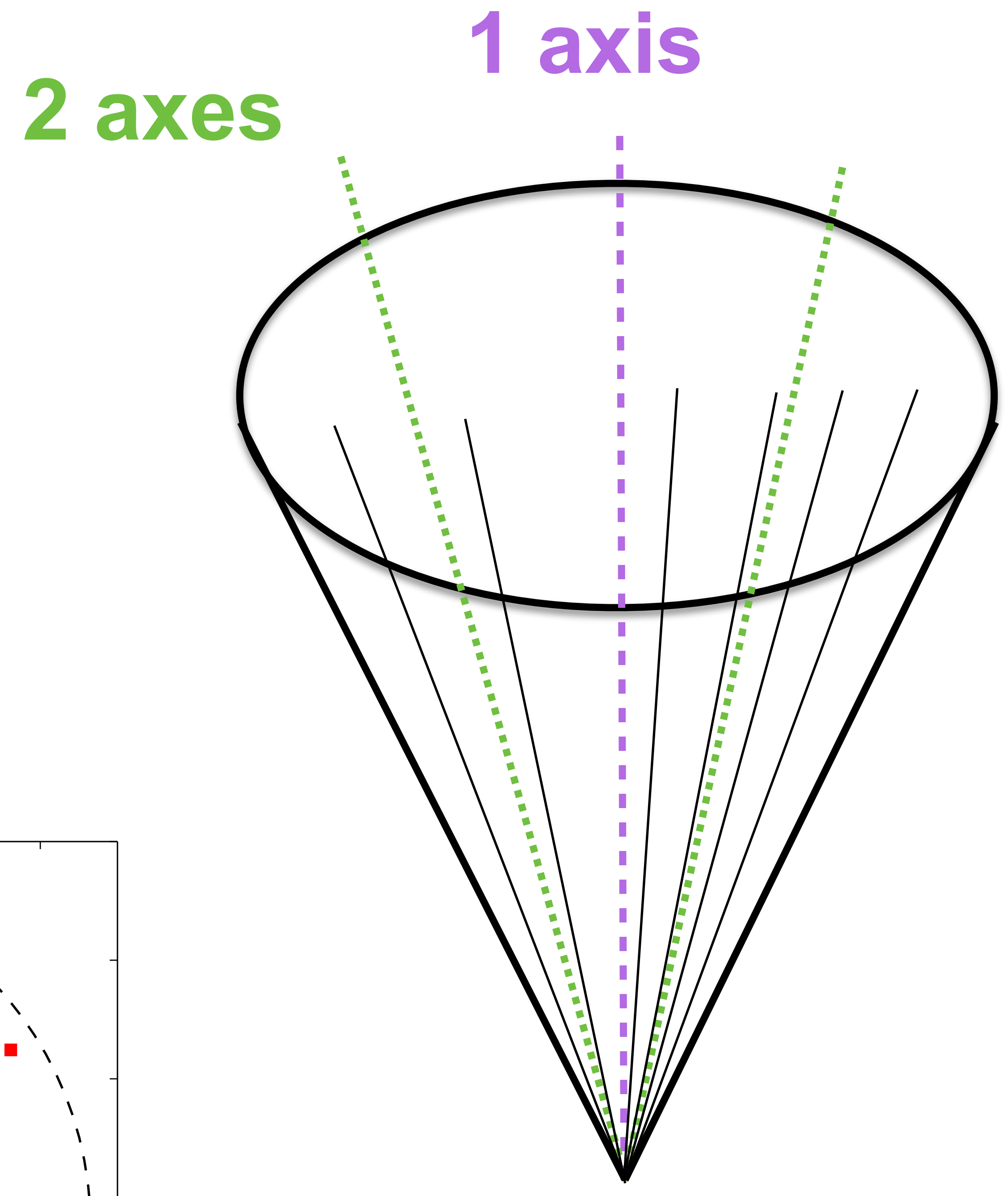
- For **boson-tagging**: want to quantify how **2-subjetty** a jet is
- ➜ To what extent is energy flow aligned along 2 momentum directions (N=2)?

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

normalisation

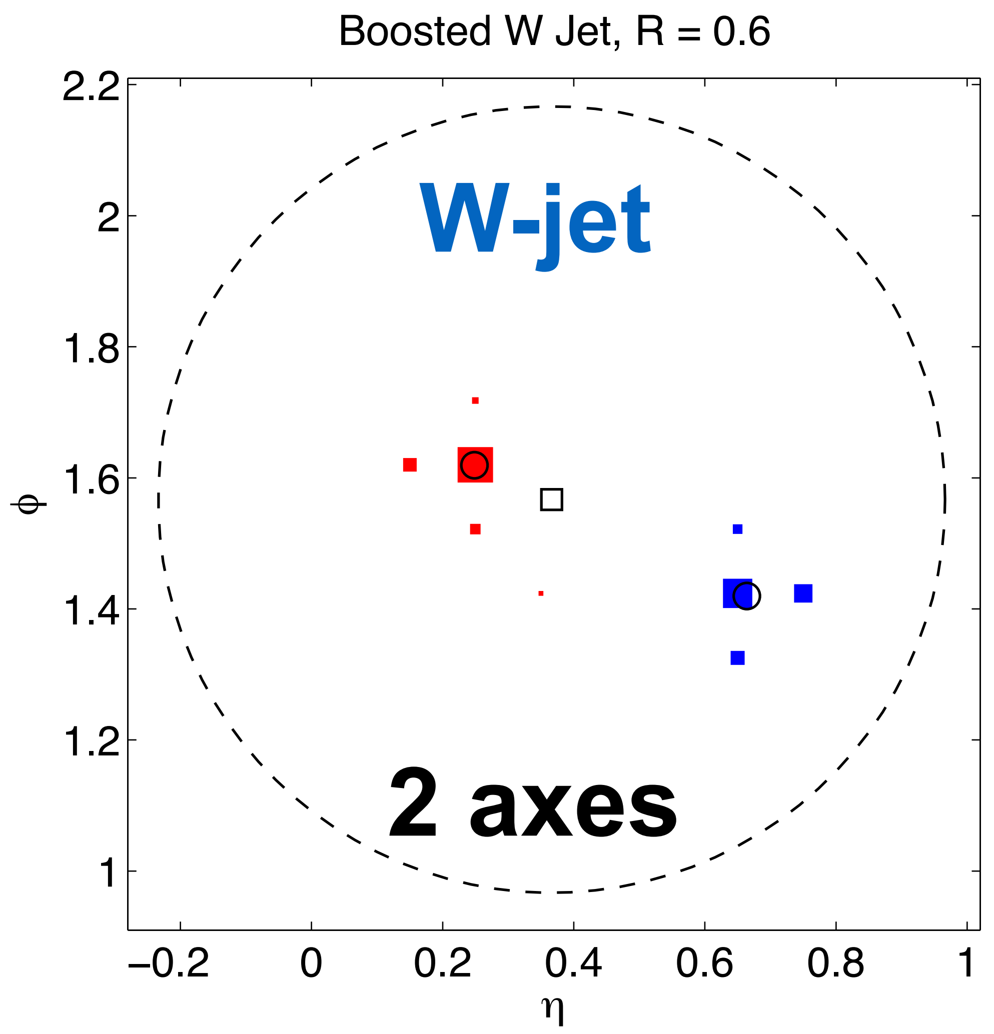
sum over particles

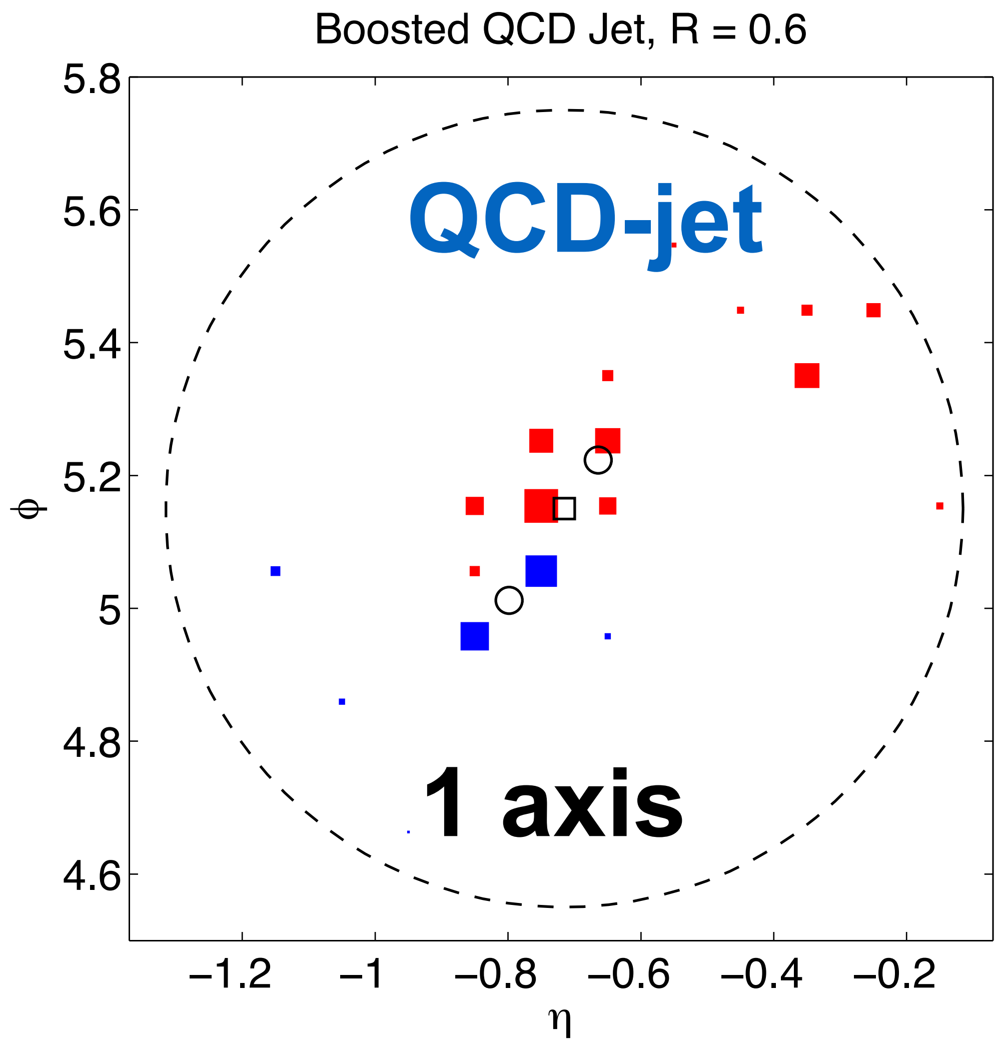
minimise distance to candidate subjets



low values of τ_N ➜ compatibility with the hypothesis of N axes

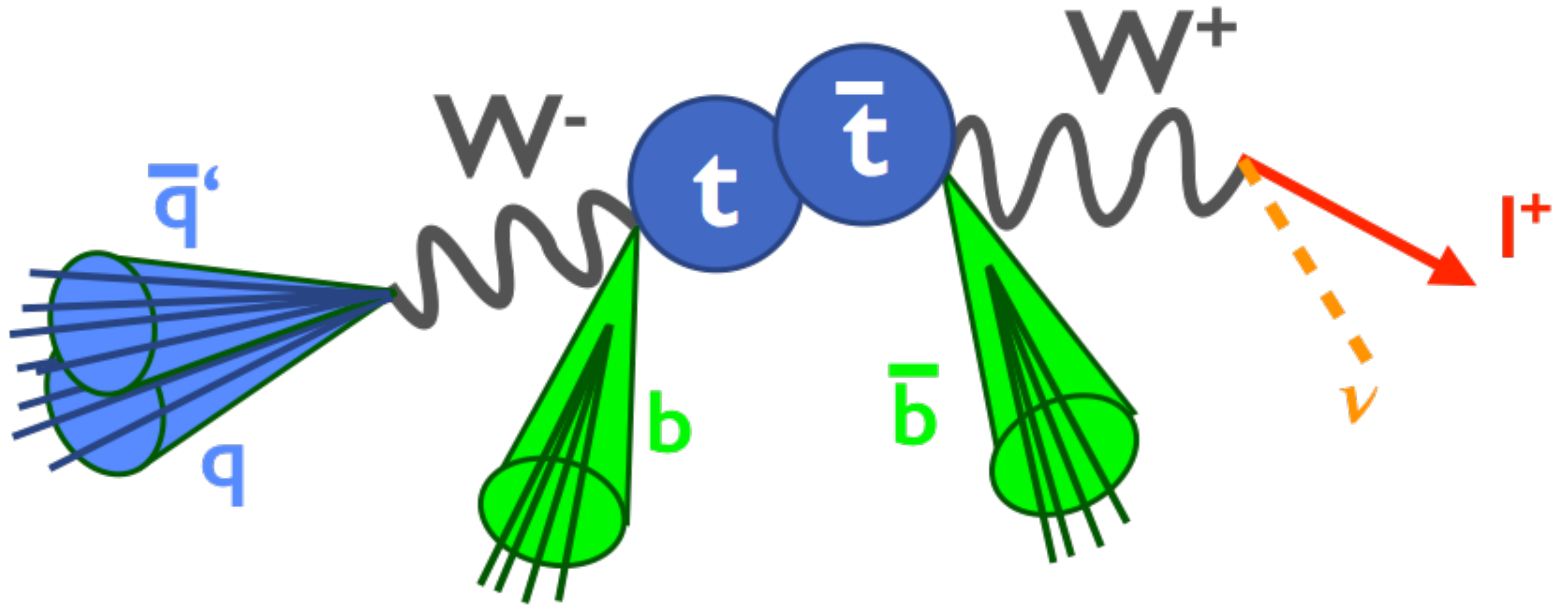
Candidate subjets are built by de-clustering the jet using the k_T algorithm

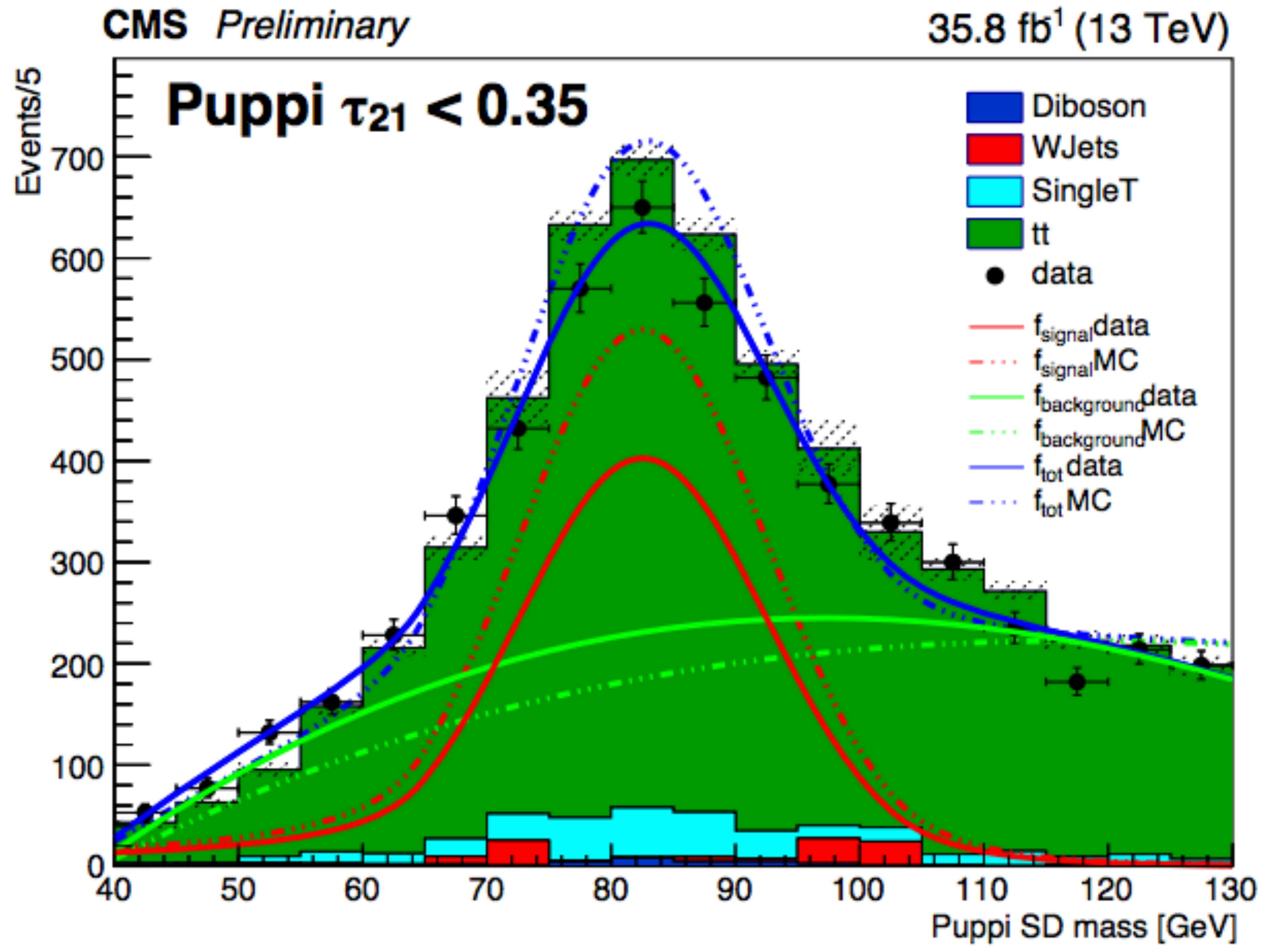




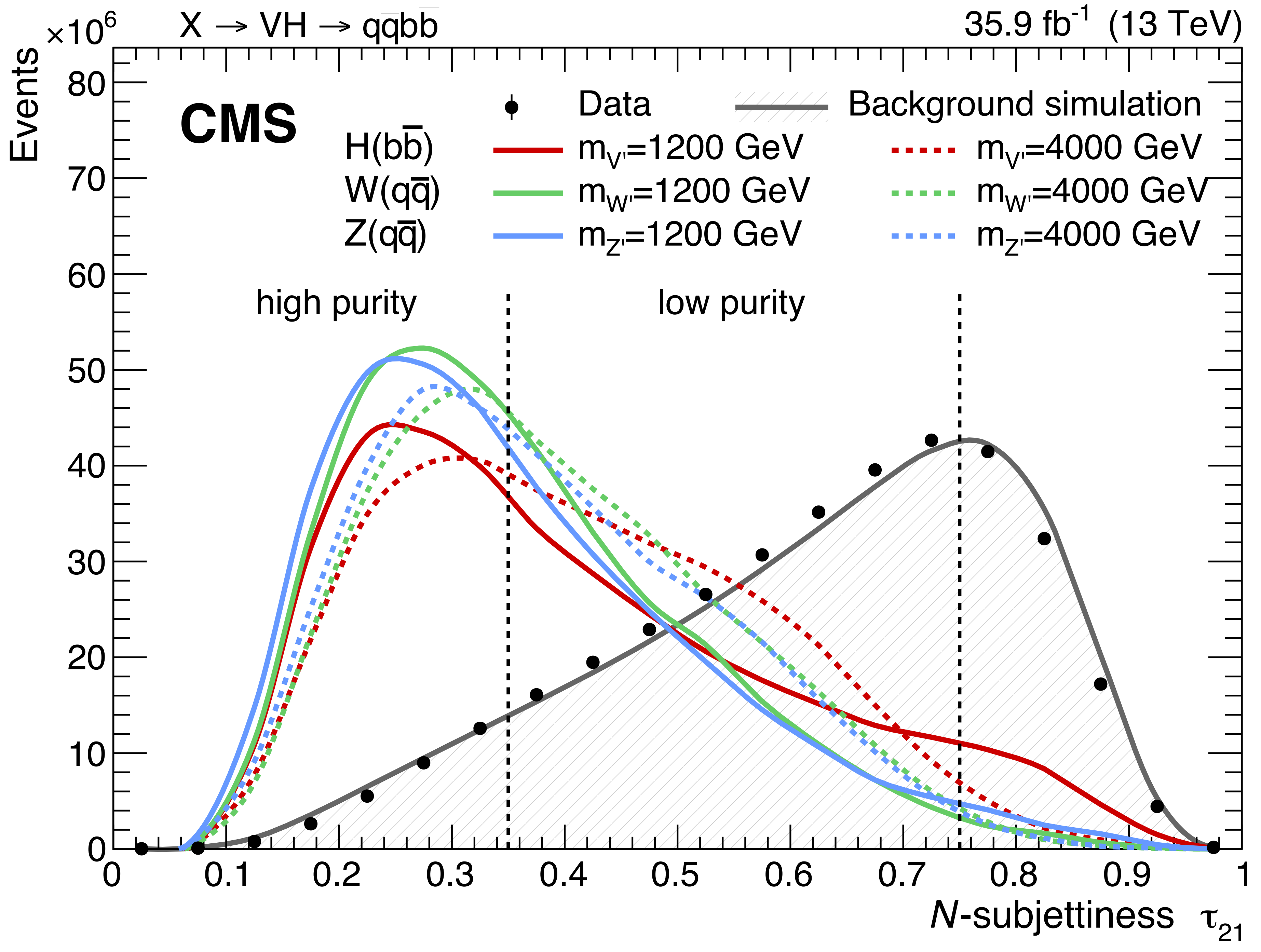
N-subjettiness ratio

- Bare τ_N has very little discrimination power
- Take **ratio τ_2/τ_1** instead
- Note: rather **complicated variable**, difficult to model ➜ need to validate in data
- Clean sample of W-jets: **top-antitop quark pairs** used for calibration (W-jet p_T ~ 200 GeV)





Attention: W polarisation can be different for signal



Decorrelating mass and two-prong taggers

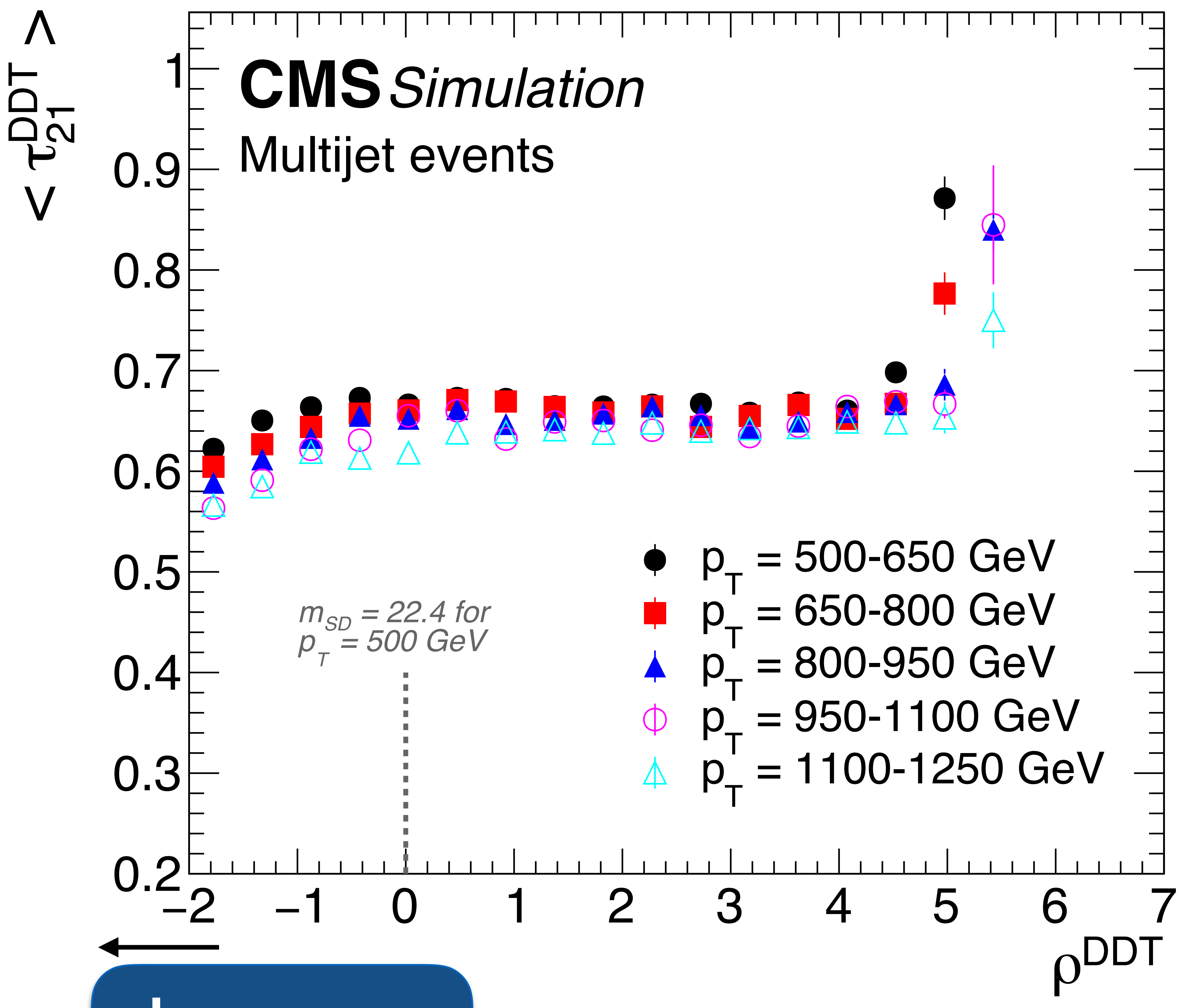
- Jet mass and e.g. τ_{21} as well as p_T are correlated
- Introduces undesired **sculpting of distributions**
- Possible solution: reduce sculpting by rescaling/decorrelating:
  - Introduce dimensionless mass variable:

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

  - Recalculate τ_{21}:

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

incomplete containment



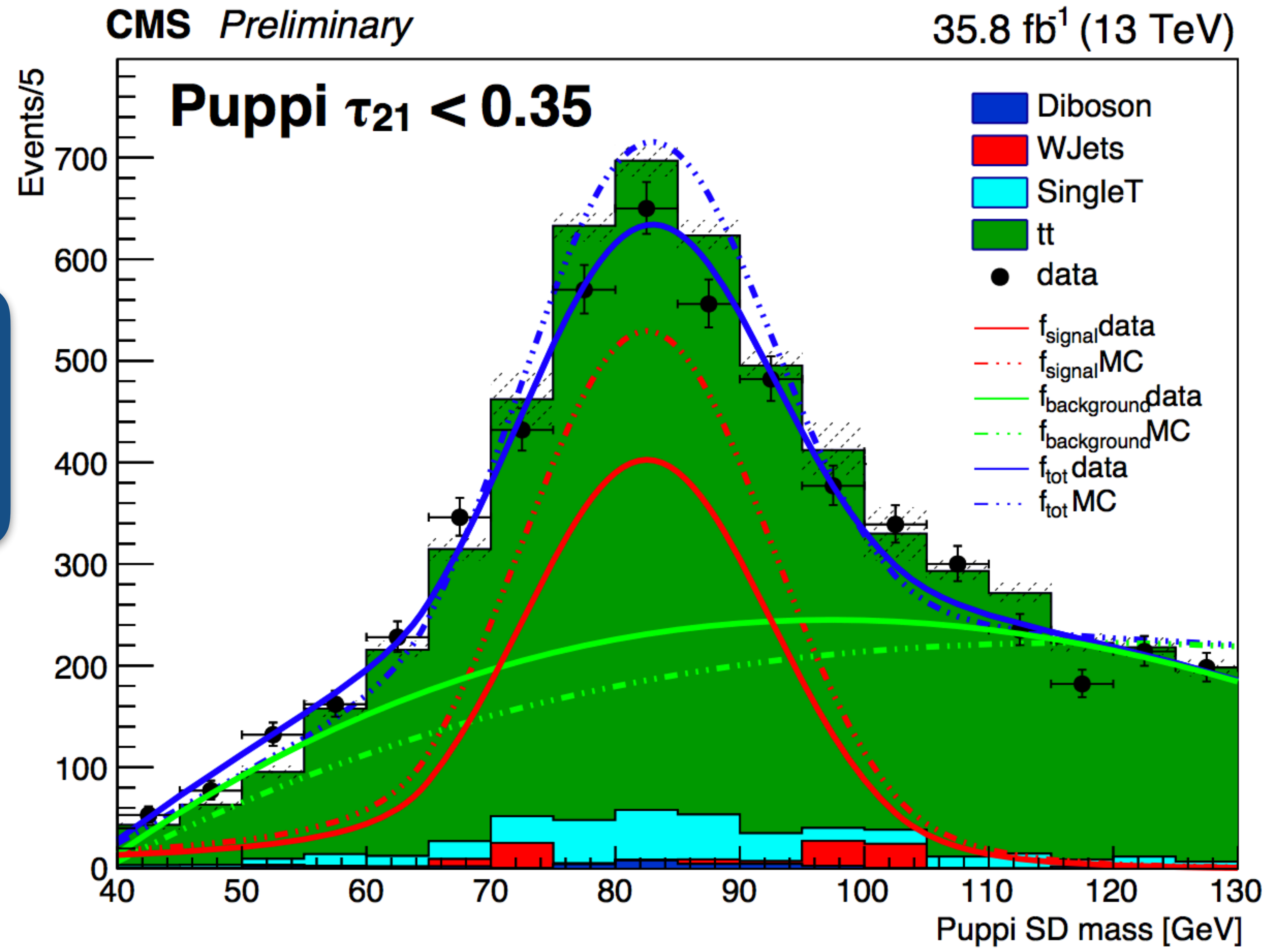
large non-perturbative effects

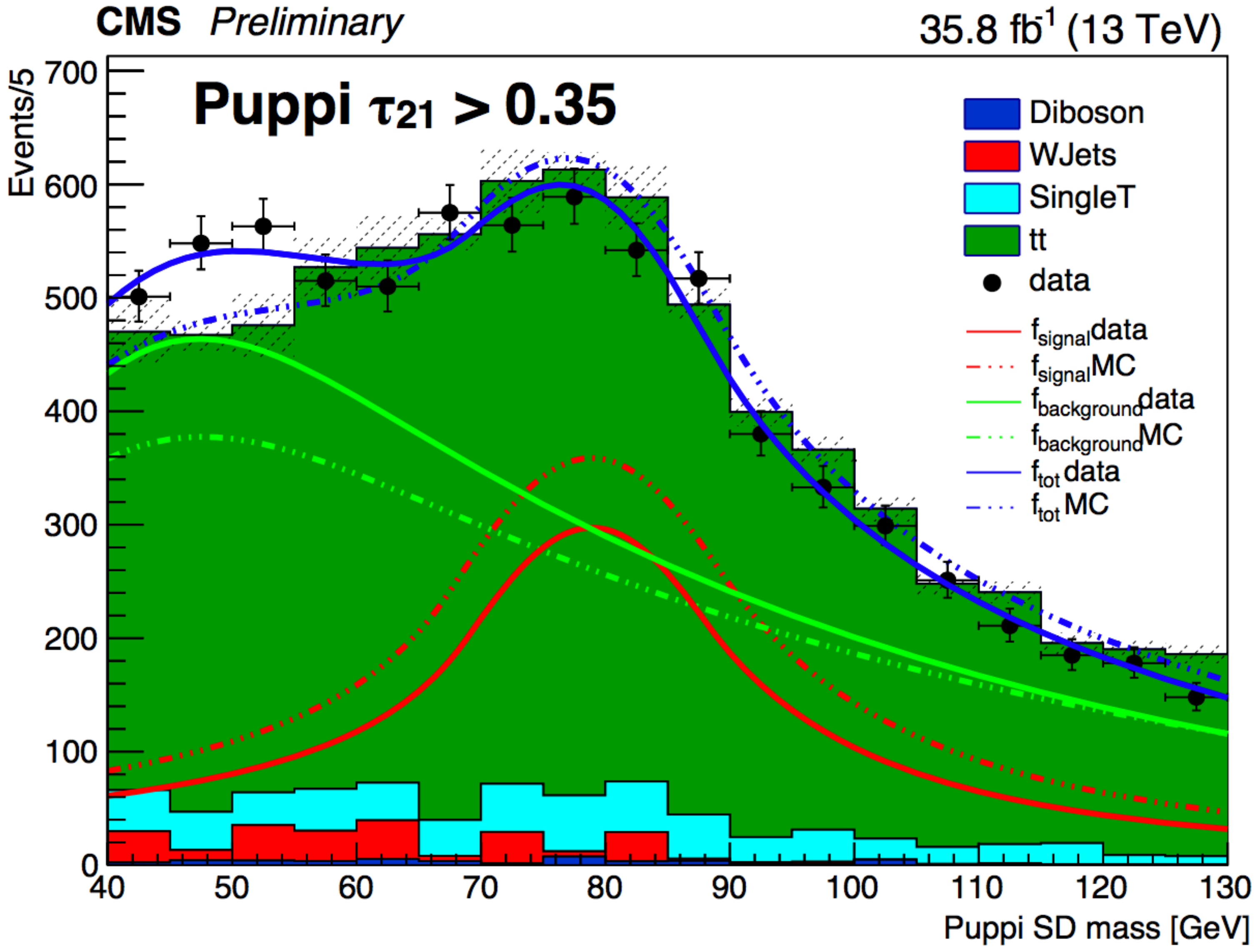
CMS DP-2017/026
EXO-17-001 (JHEP 01 (2018) 097)

Why decorrelate?

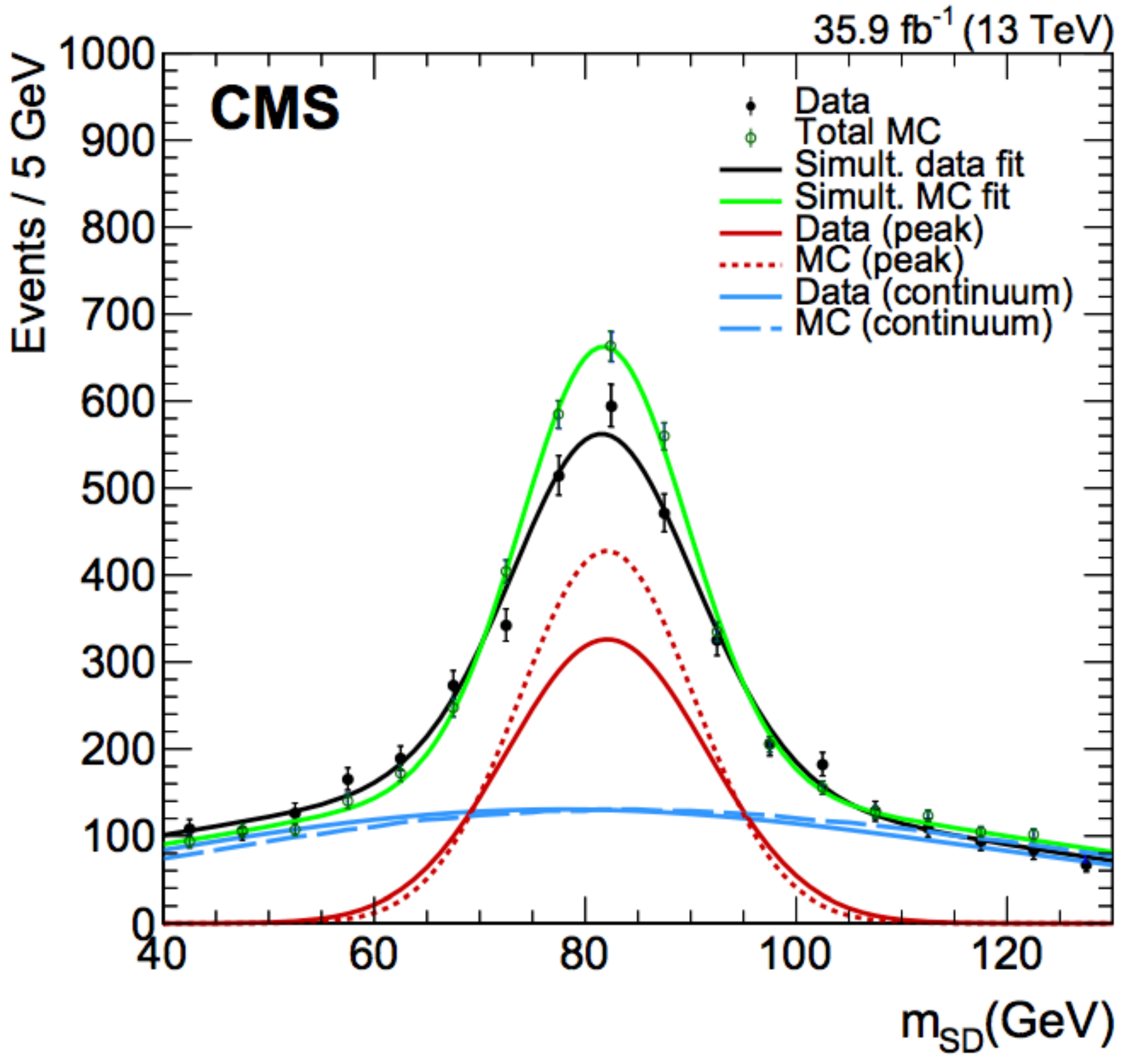
Pass tagging cut | **Fail tagging cut**

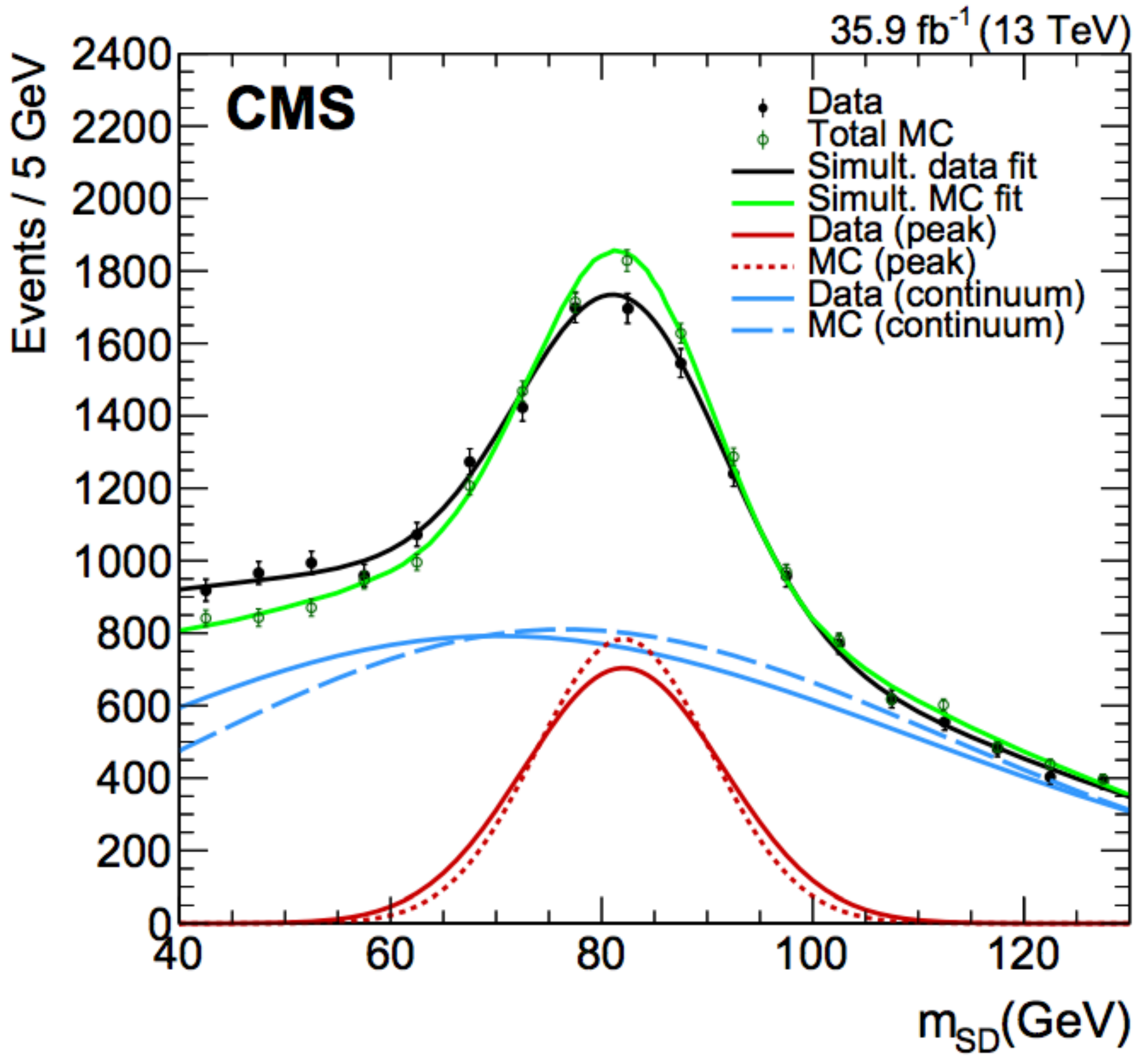
not decorrelated





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

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

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

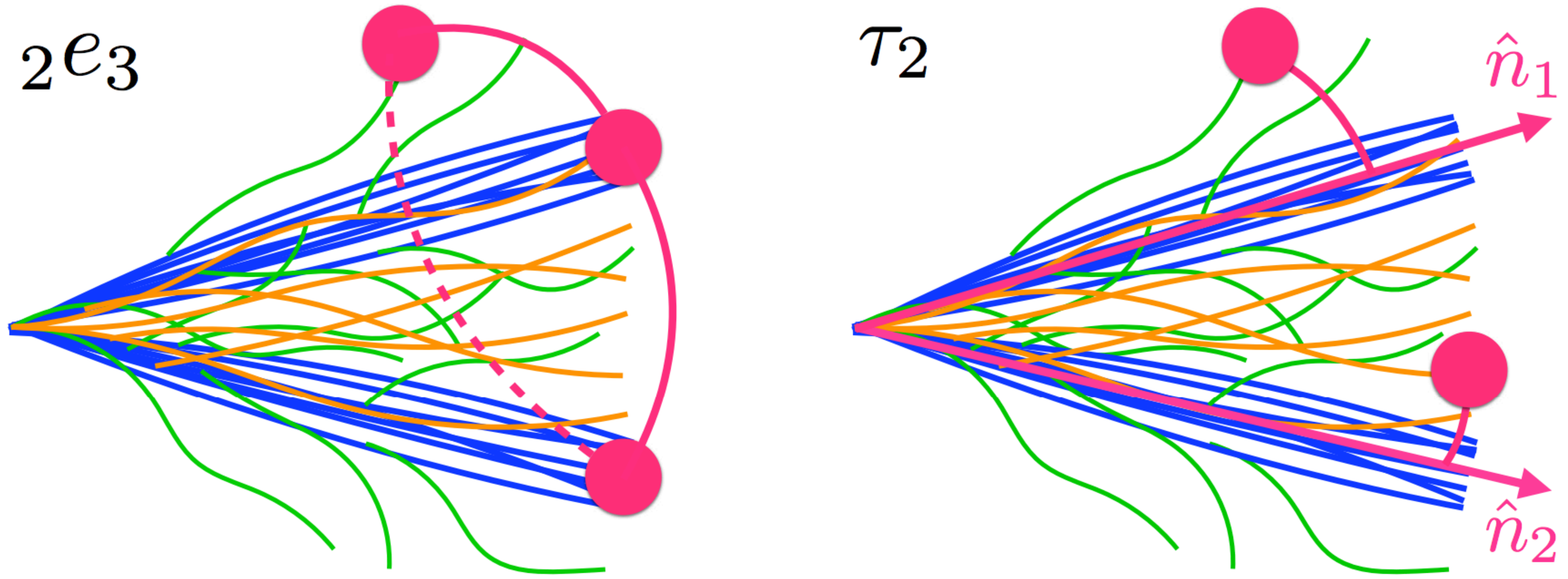
$$\tau_{21} = \frac{\tau_2}{\tau_1}$$

$${}_1e_2 = \frac{1}{p_{T,\mathrm{jet}}} \sum_{1\le i<j\le n} z_i z_j \Delta R_{ij}$$

$${}_2e_3 = \frac{1}{p_{T,\mathrm{jet}}} \sum_{1\le i<j<k\le n} p_{T,i} p_{T,j} p_{T,k} \min\left\{\Delta R_{ij}\Delta R_{ik}, \Delta R_{ij}\Delta R_{jk}, \Delta R_{ik}\Delta R_{jk}\right\}$$

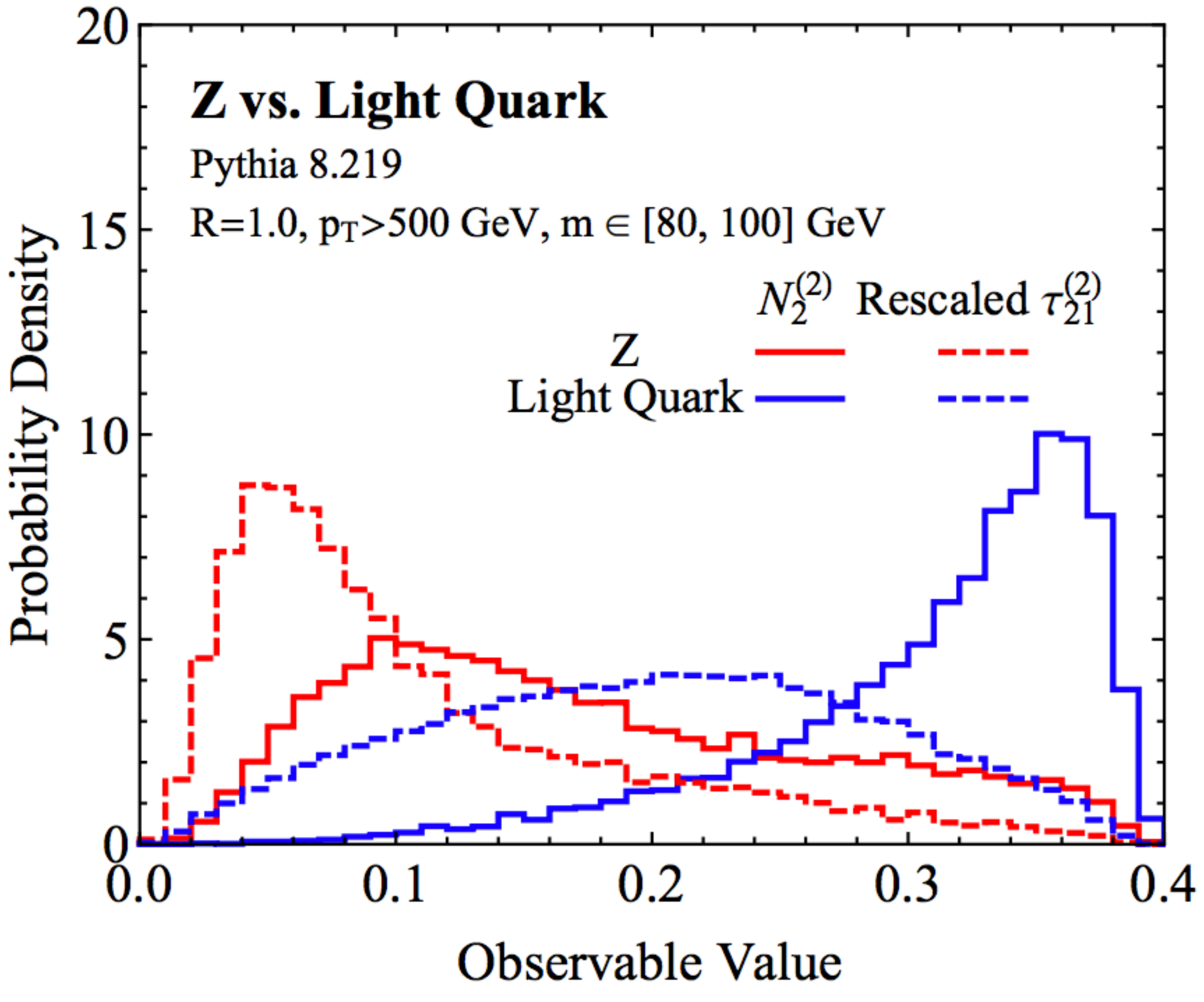
$$N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2}$$

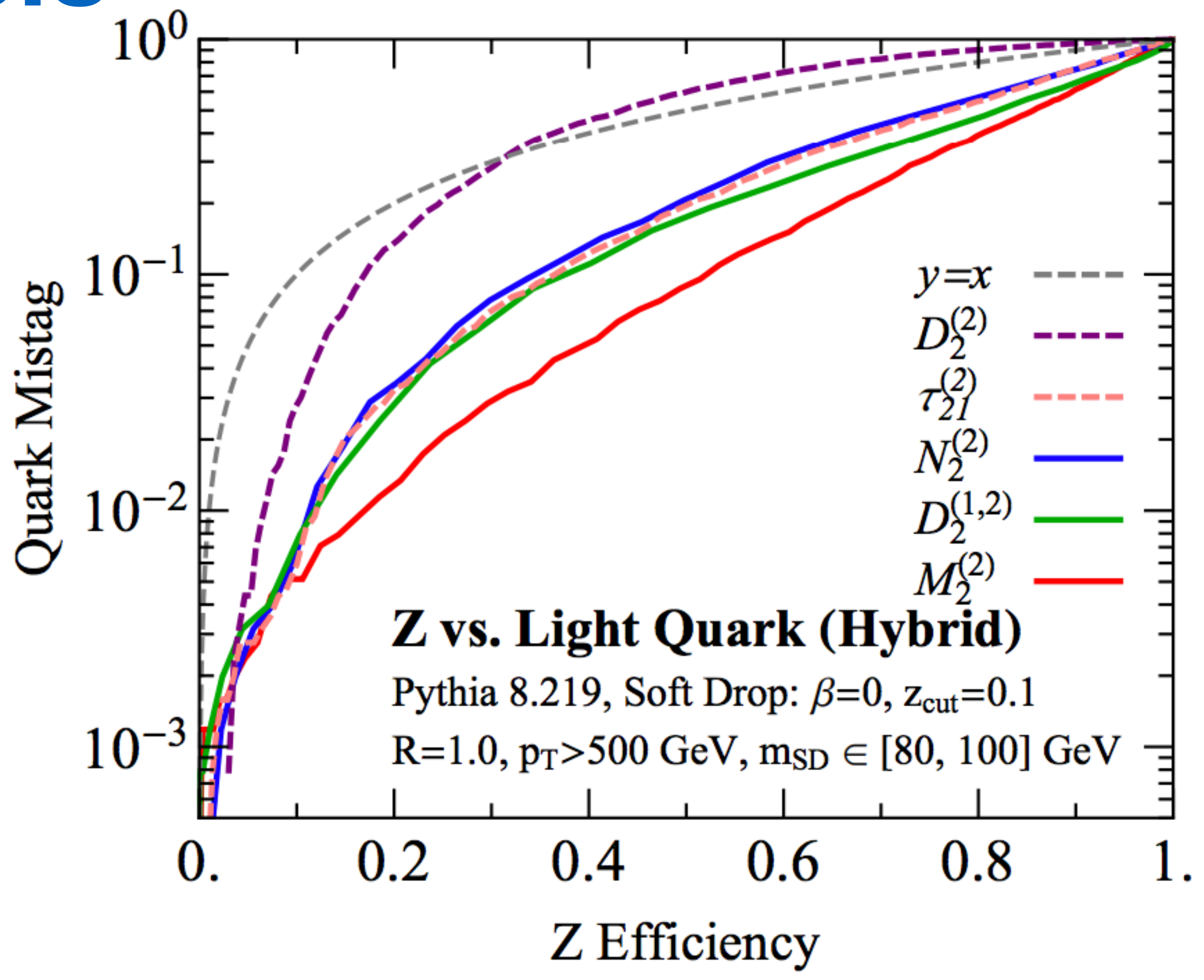
- Reduces to τ_{21} in resolved limit
  - good to combine resolved and boosted regime!

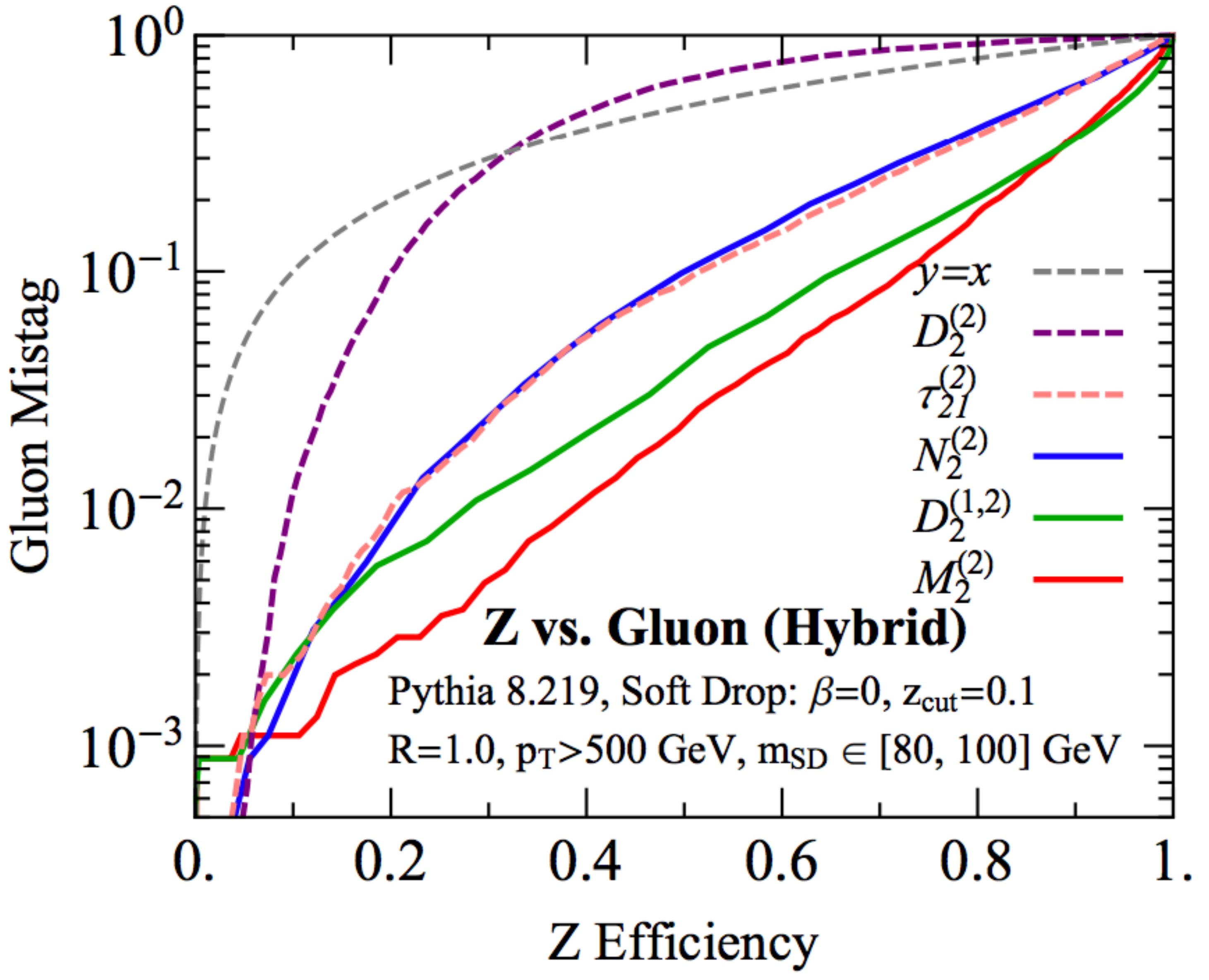


State-of-the-art substructure

- 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**



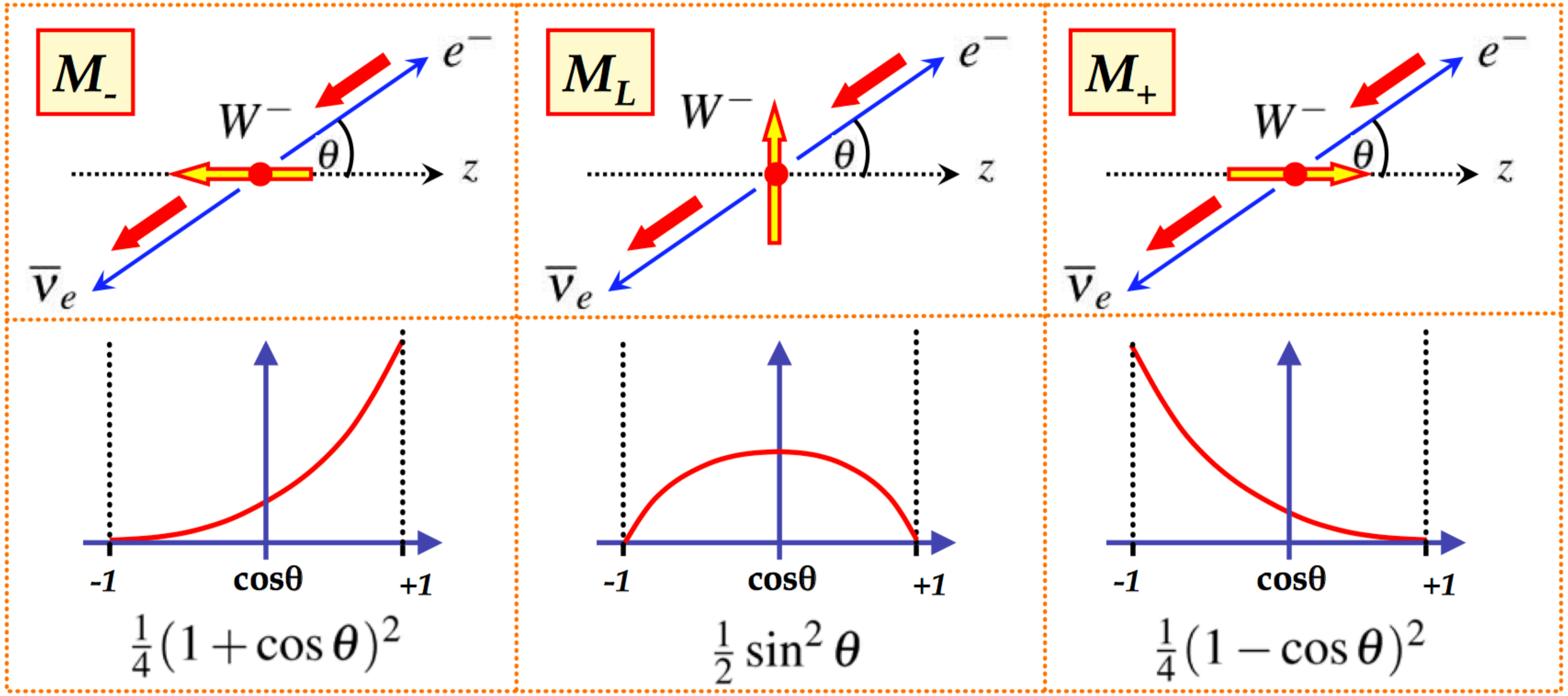




Polarisation

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

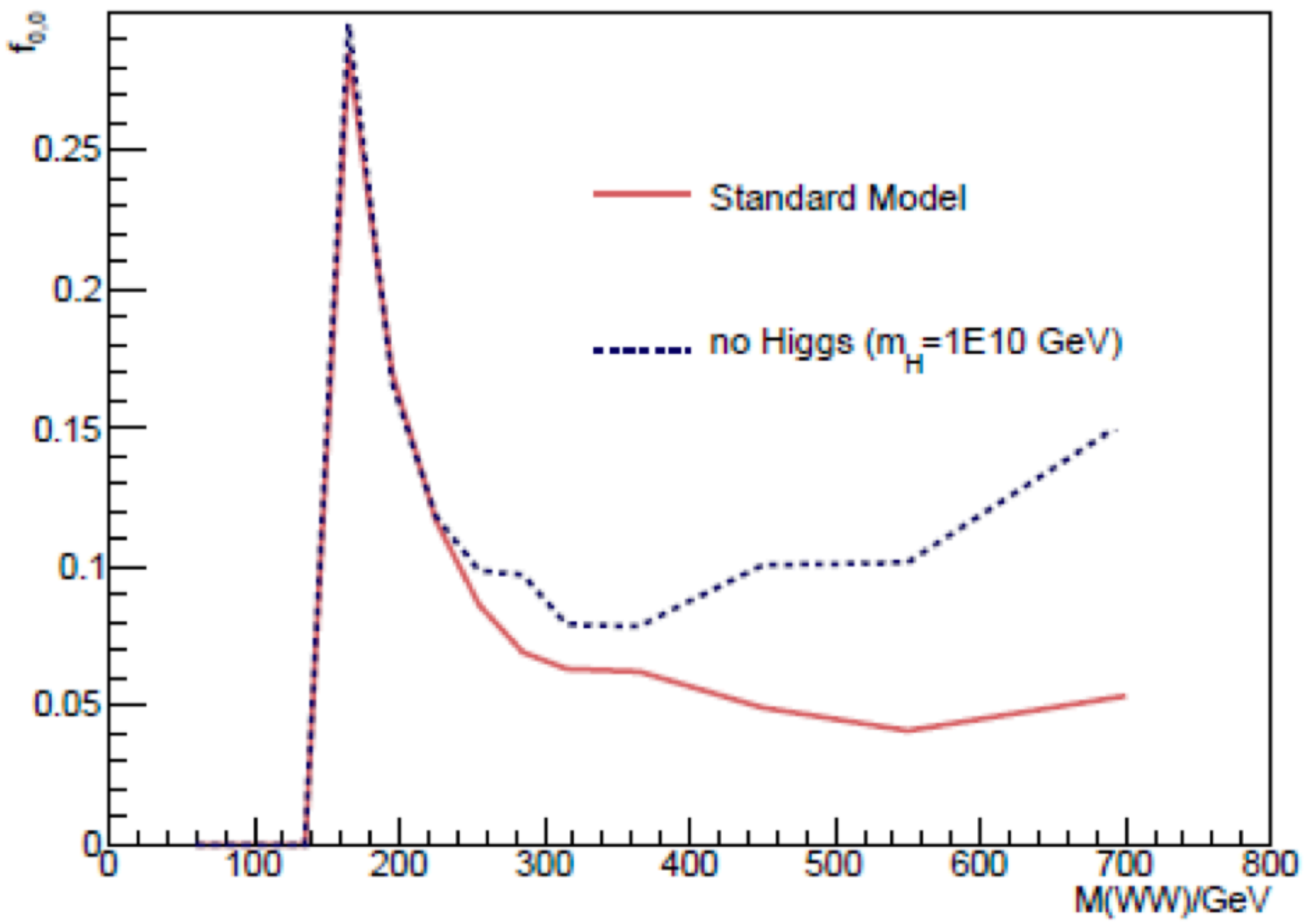


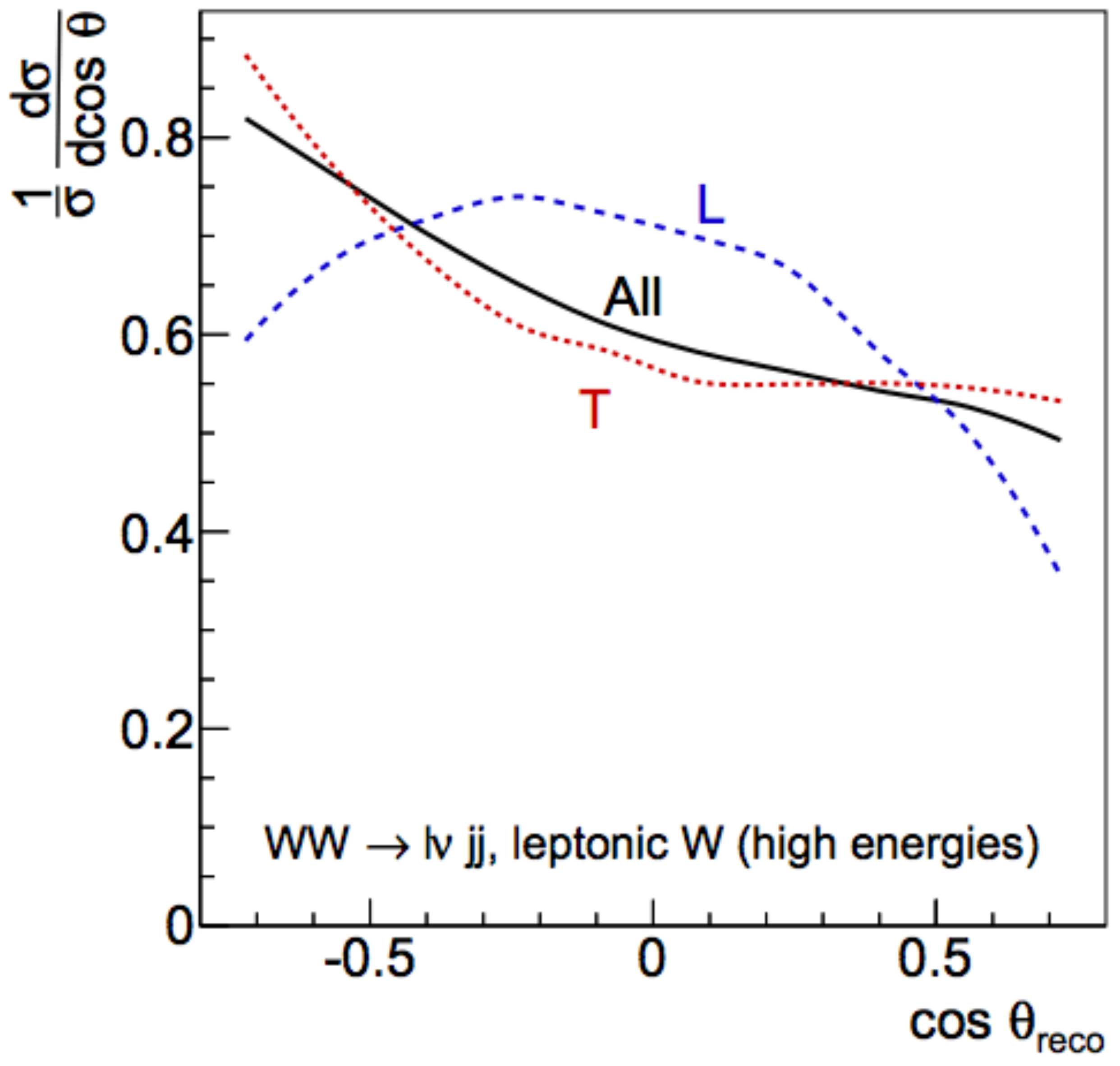
- Access the polarisation via the fermions in the decay
- Boost back into rest frame of W boson ➜ cos(θ*)

Polarisation in VBS

- 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**

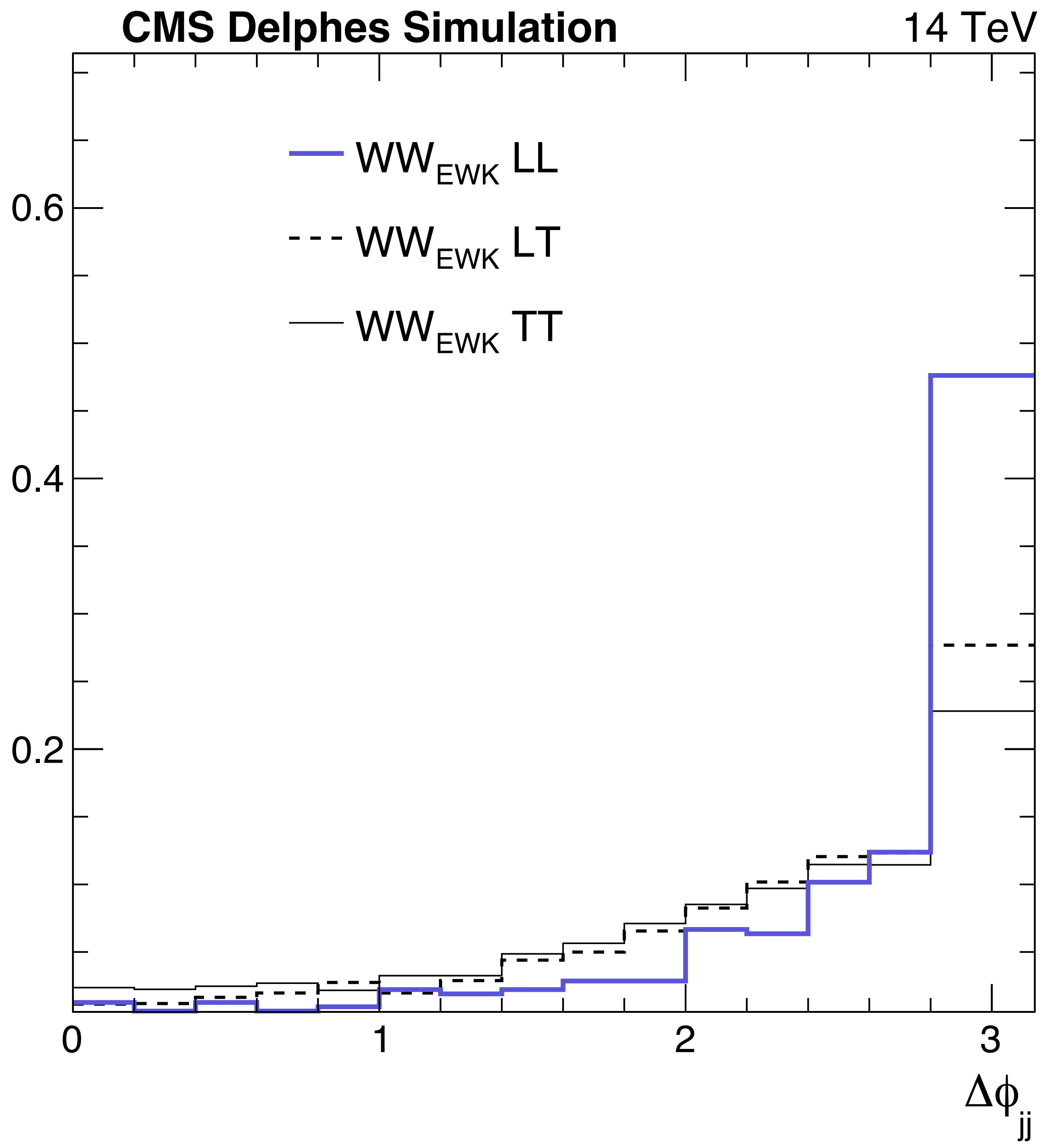
fraction of longitudinal scattering

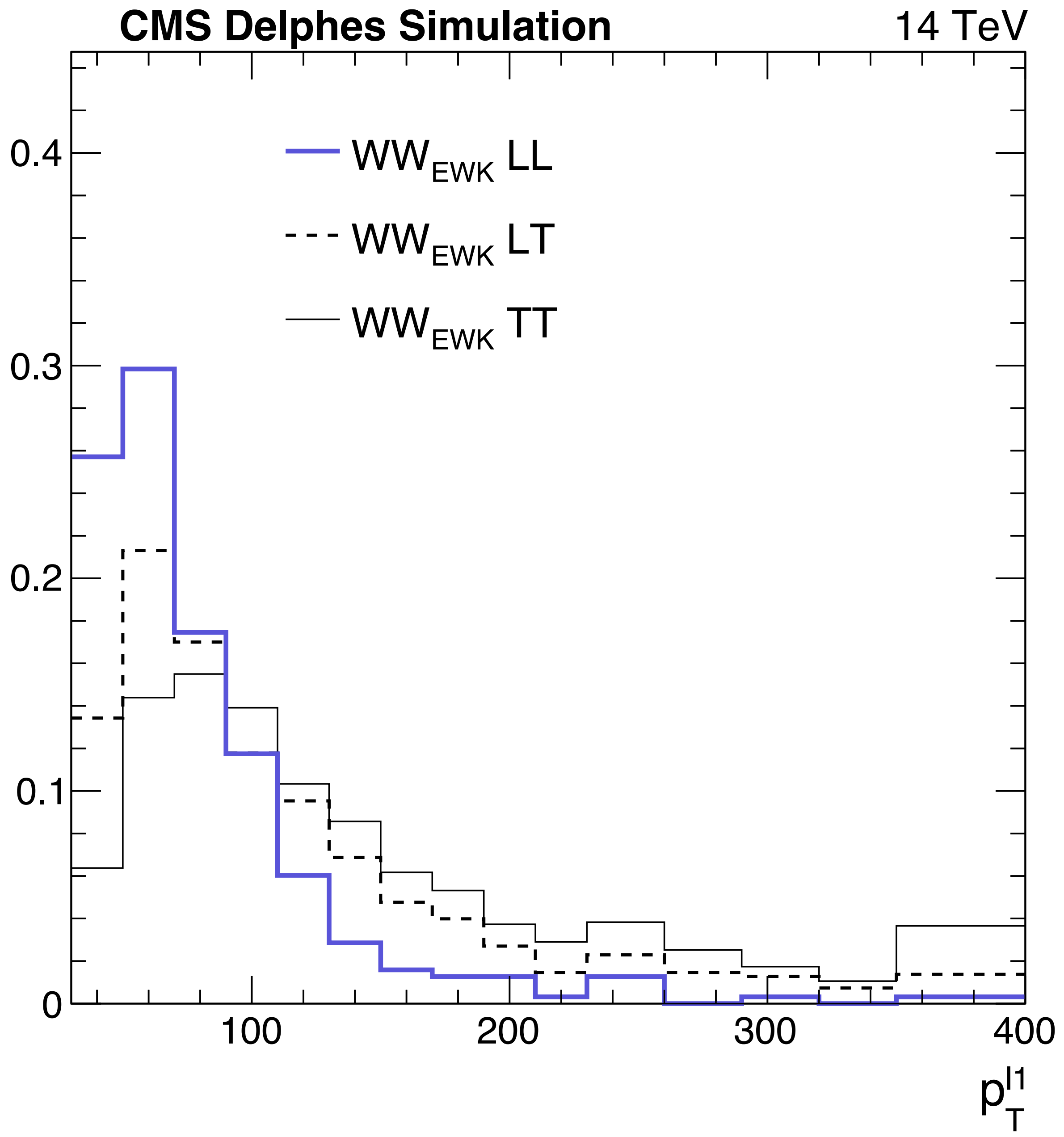




Polarisation and jet substructure

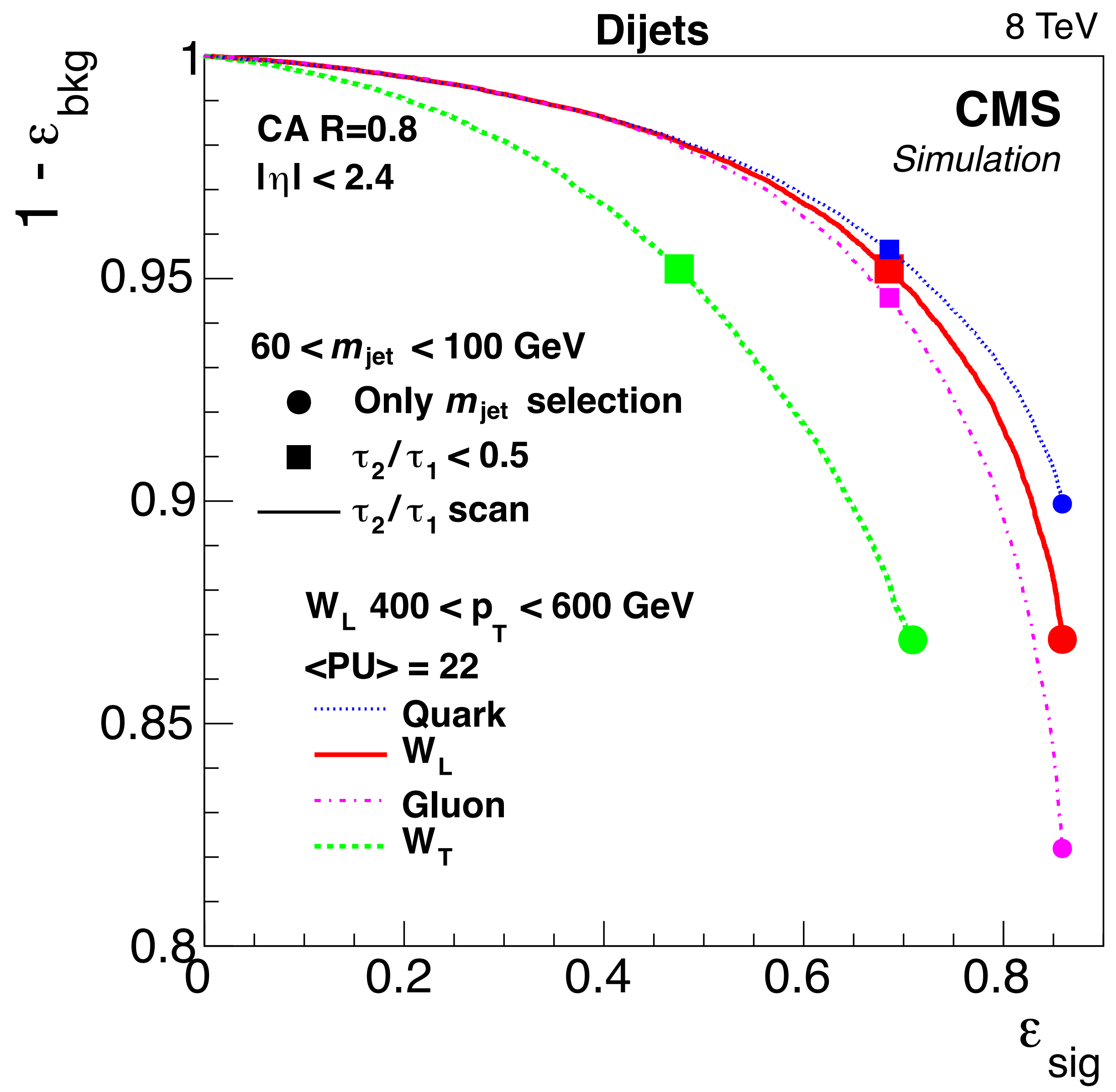
- Hadronic W boson decays yield **access to full boson kinematics**
- Increased understanding in jet substructure increases **quark-/gluon-discrimination**
- Significantly **more statistics** — but optimisation studies required
- Generally, **more than one option** to access longitudinal components: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

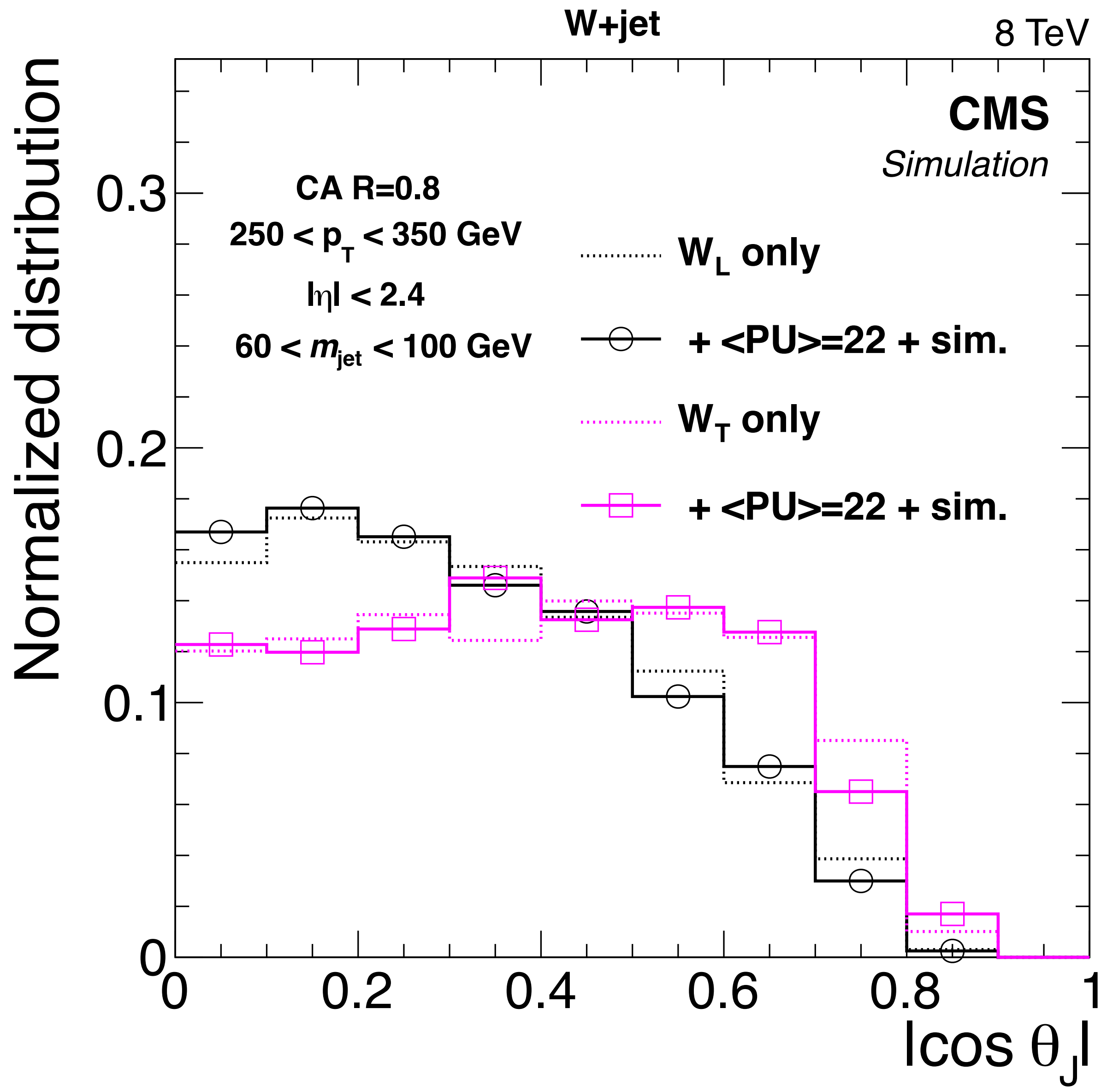




Polarisation in W tagging

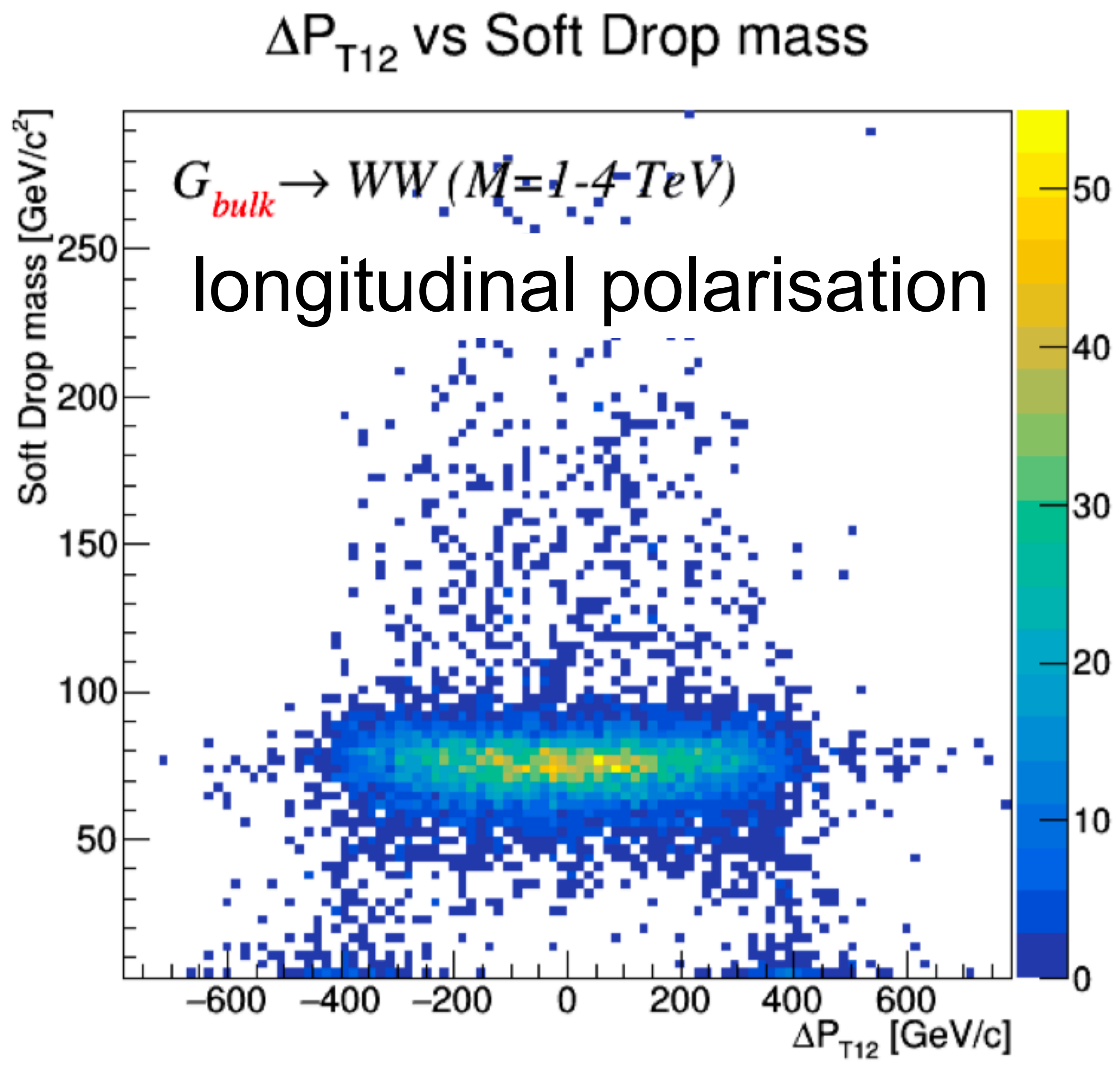
- Mostly studied in the context of heavy **diboson resonance searches**
- Standard taggers show **different performance** for longitudinal and transverse polarisation
  - mind that these are relatively old studies
- Caveat of hadronic boson decays: cannot (easily) **distinguish fermion and antifermion**
  - 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

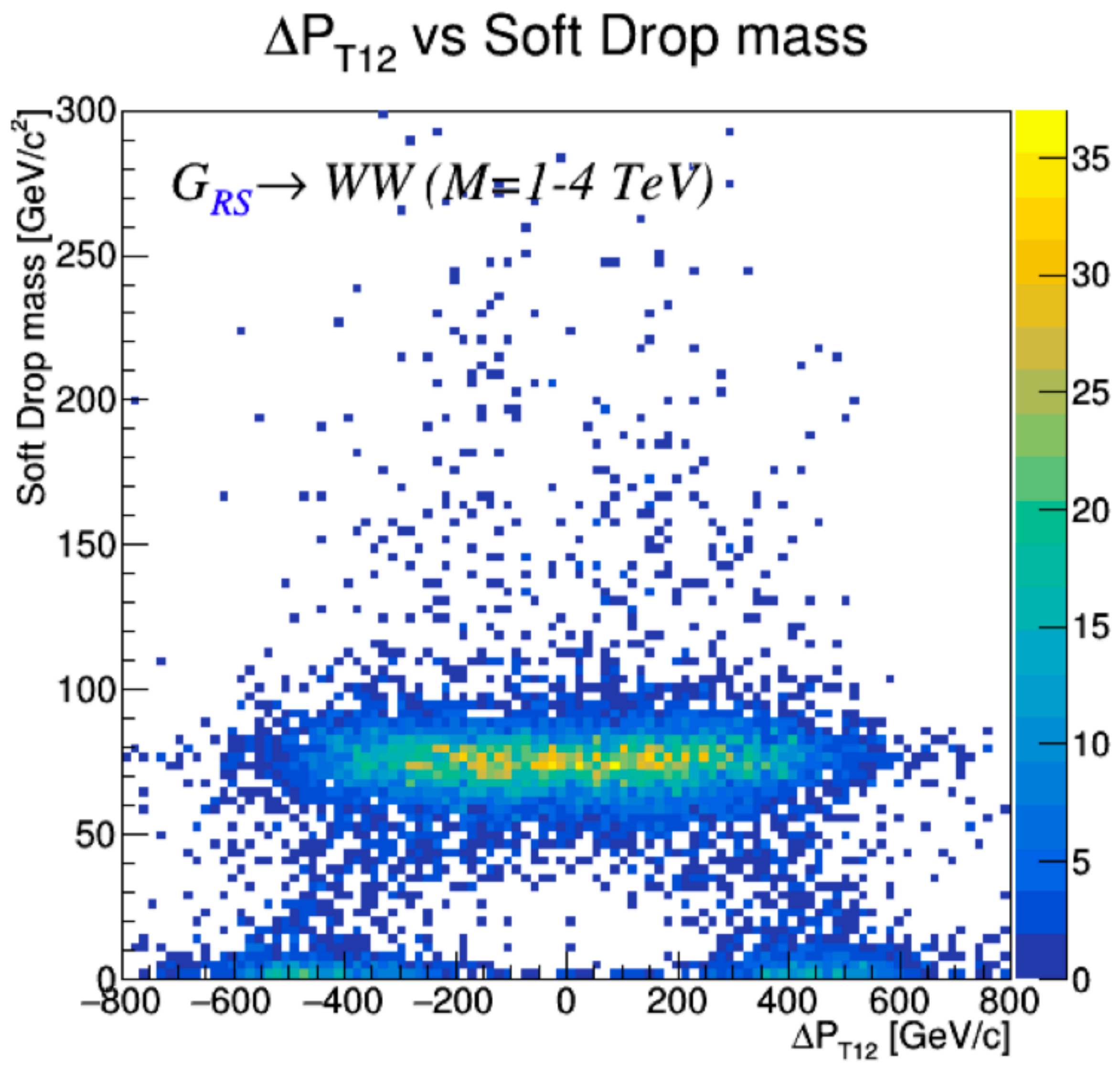


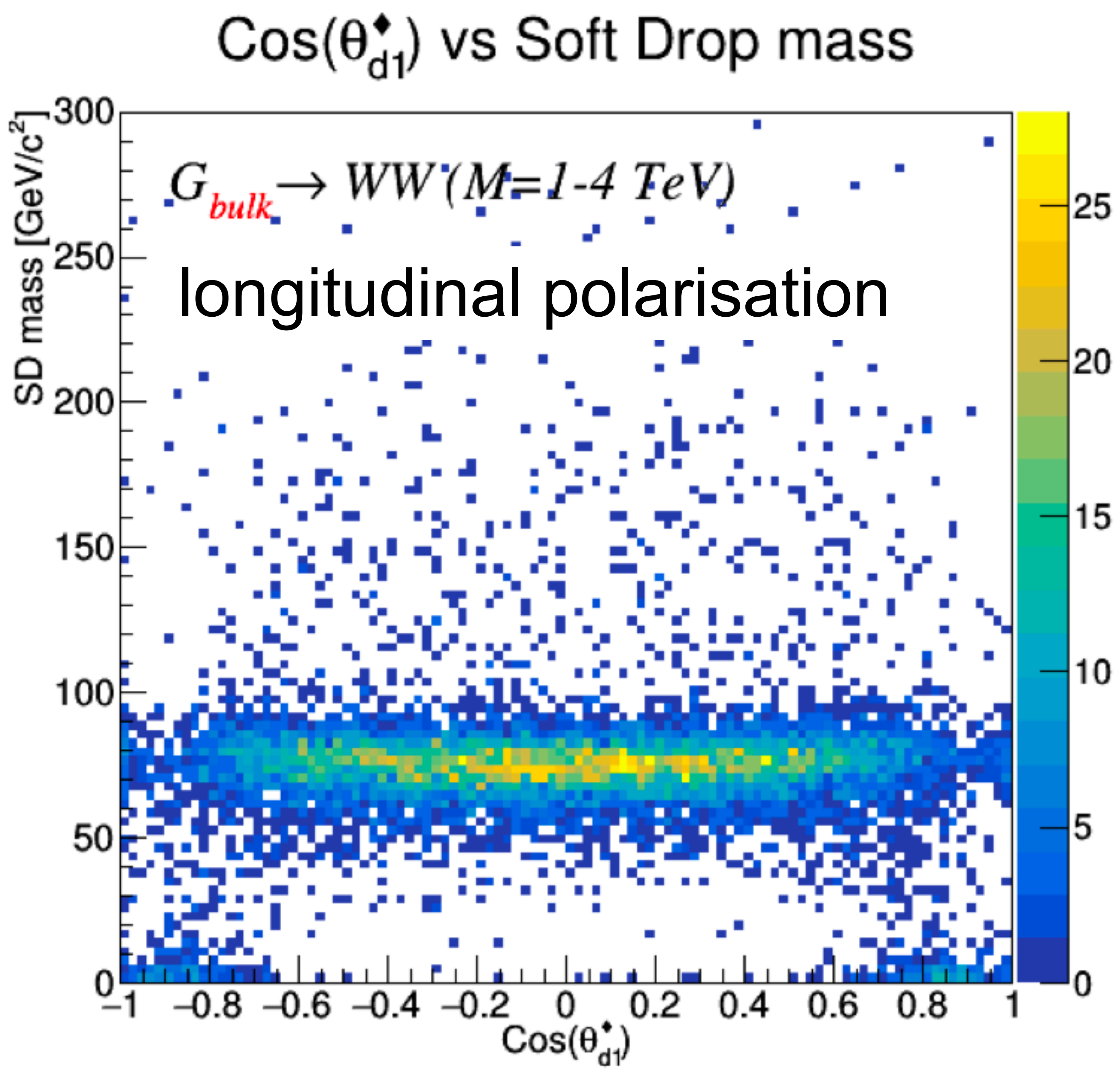


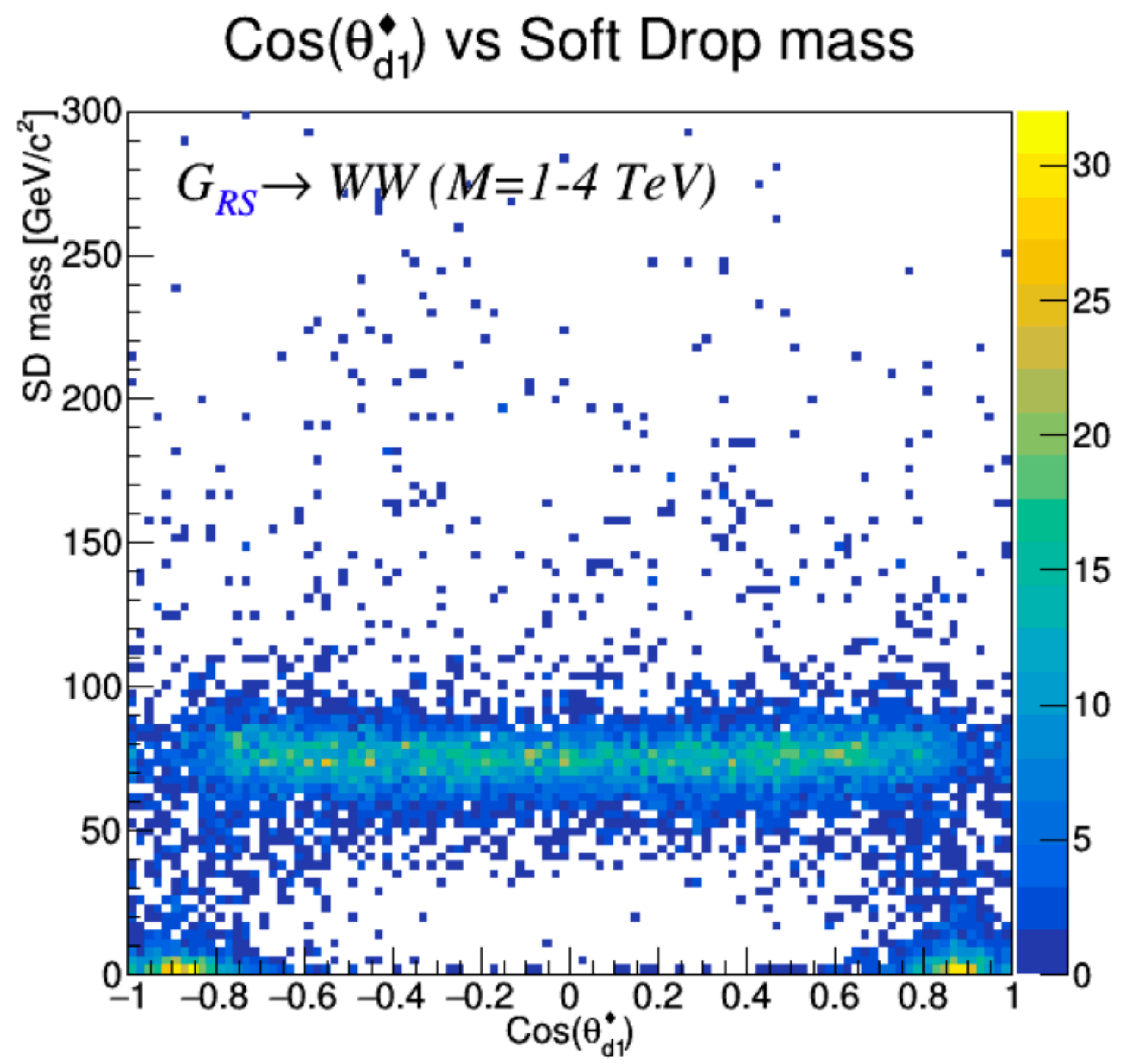
Acceptance/reconstruction effects

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









Conclusions and to-do list

- 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