Tracking Hyper Boosted Top Quarks @ 100 TeV

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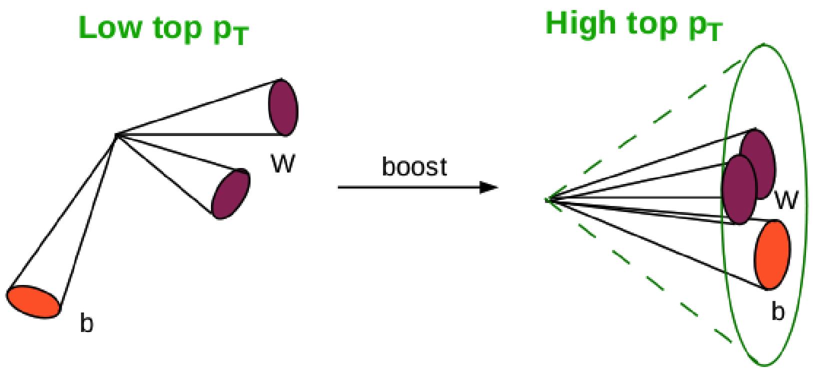
Why boosted tops ?

- Interest for a 100 TeV p-p collider is increasing
- Would potentially be able to look for undiscovered particles up to tens of TeV masses
- These heavy resonances will decay to highly boosted **top quarks**, W/Z bosons, H …
- Several techniques for identifying jet sub-structure exist, and are widely used in ATLAS and CMS

Do currently used techniques work at the Terascale?
Can we think of some observables that can help?
Can we set constraints on future detectors?

Boosted tops



min. distance to resolve two partons:

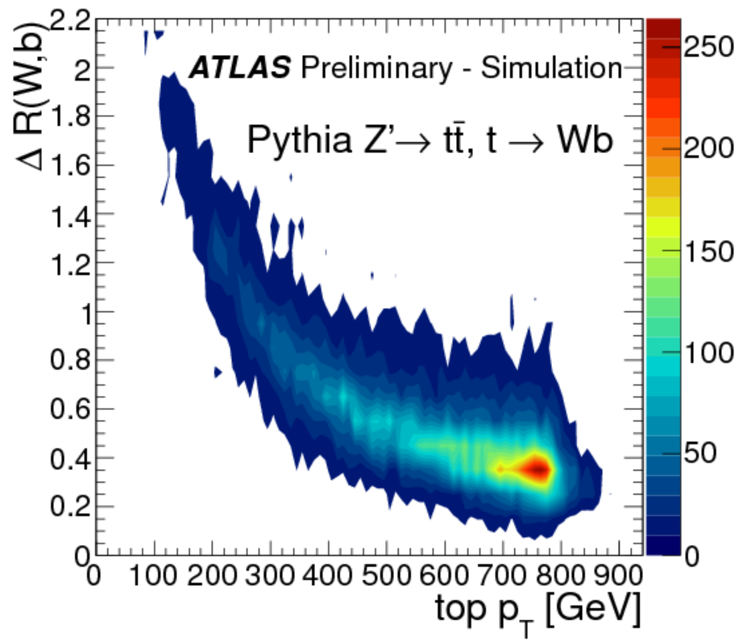
$$\Delta R \approx 2\, m \,/\, p_T$$

<u>ex for top</u>:

p_T = 200 GeV → R ~ 2

p_T = 1 TeV → R ~ 0.4

p_T = 10 TeV → R ~ 0.05



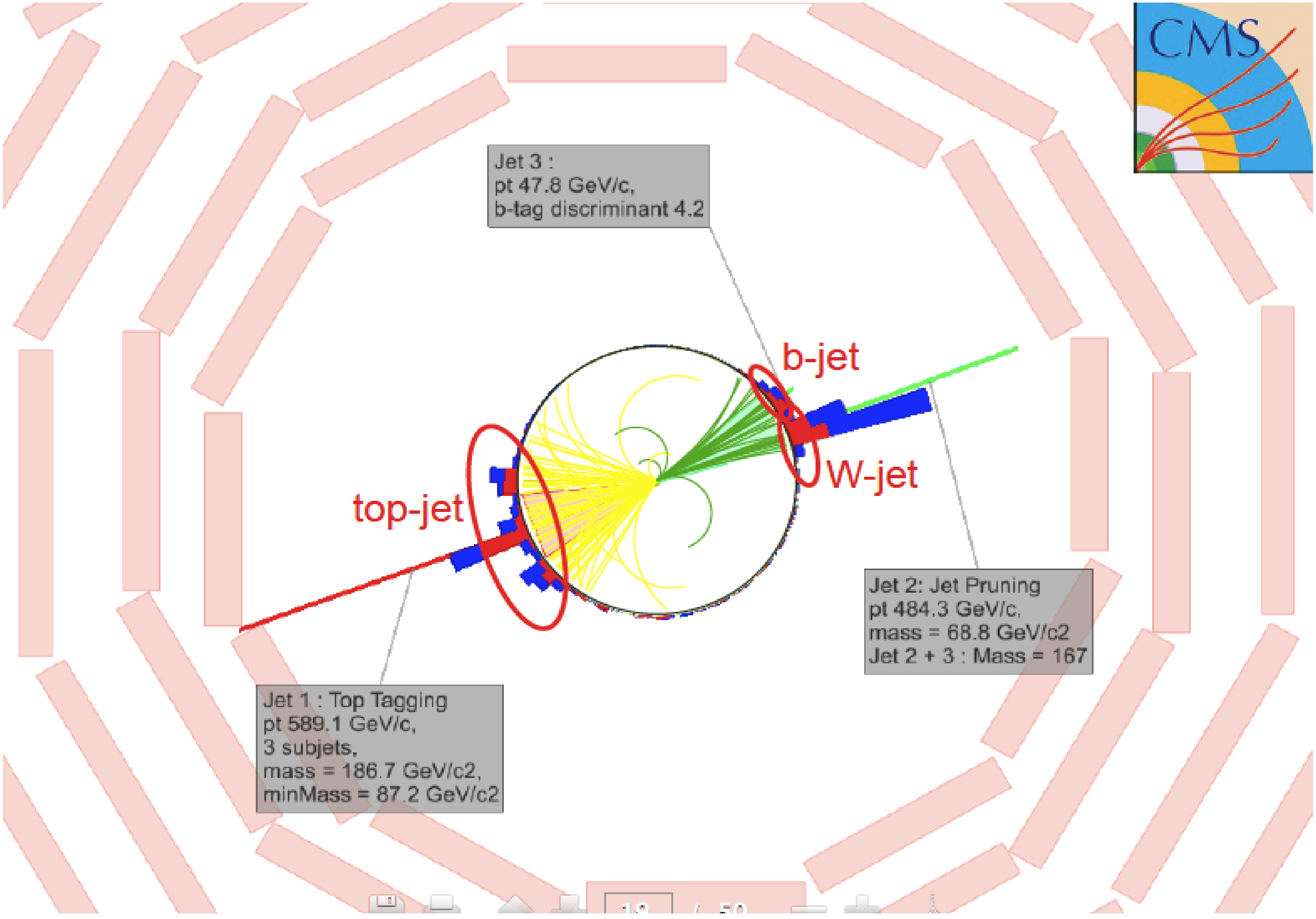
Techniques on the market

- Jet Mass
- N-subjettiness Thaler, Van Tilburg 1011.2268
- Grooming (pruning, trimming)

  Krohn et al. 0912.1342
- CMS/JHU Top Tagger CMS-PAS-JME13-007
- HepTopTagger Plehn, Spannowsky 1112.4441
- Event deconstruction Soper, Spannowsky 1402.1189
- Neural Networks Almeida et al. 1501.05968

- **Shape**
- **Kinematics**
- **Soft removal**

Event display



Analysis Setup

- MadGraph5 (LO event generation)

  $q\, q \rightarrow q\, q$ (bkg)

  $g\, g \rightarrow g\, g$ (bkg)

  $p\, p \rightarrow t_{had}\; t_{had}$ (signal)

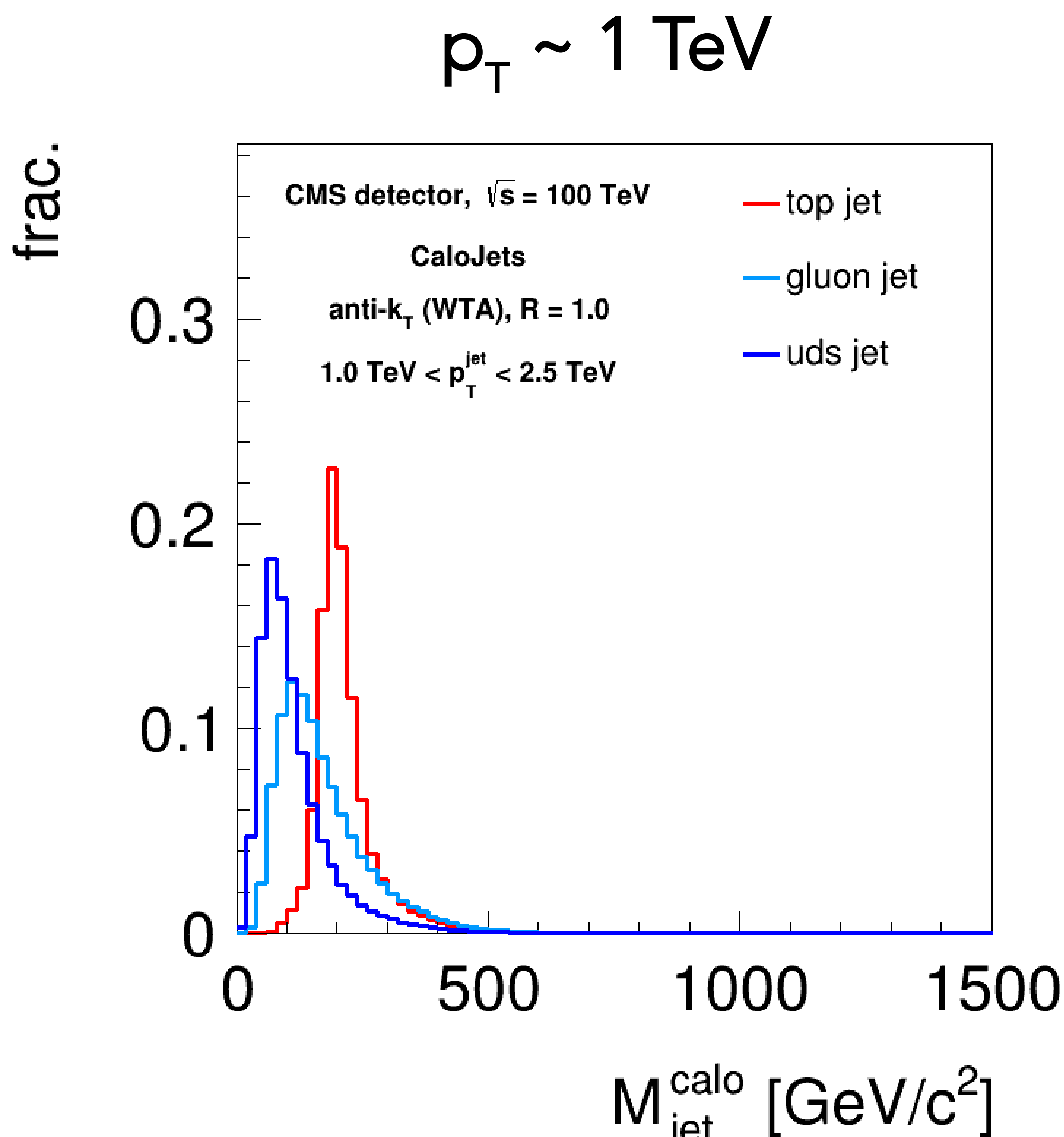
- Detector simulation: DELPHES (more later and back-up)
  - CMS (present)
  - SppC-FCC (future)

- Look at observable shapes (not total event rate)

Naive Analysis

Jet Mass

- Naive approach, do what works at the LHC
- Reconstruct "fat - jets"

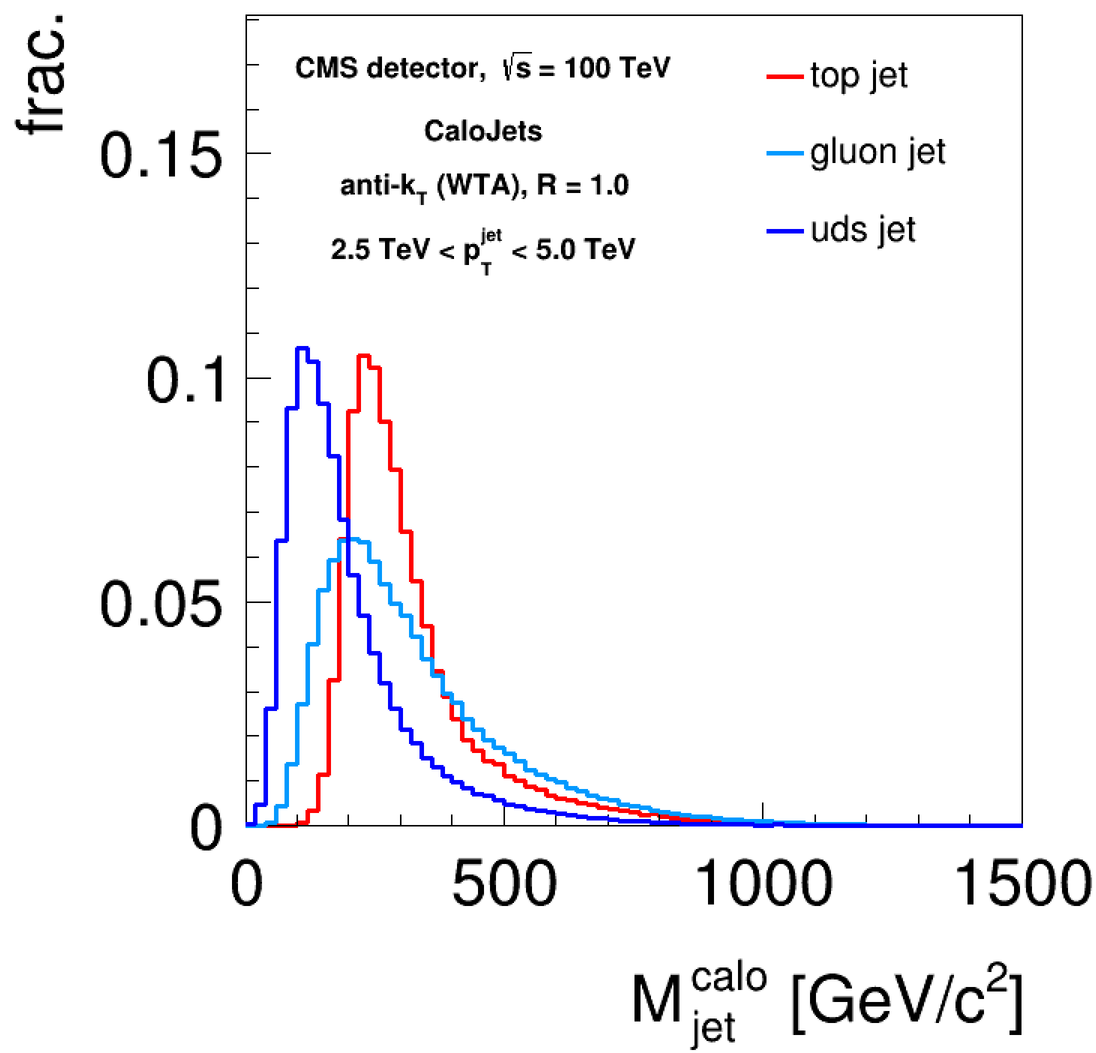


Jet Mass

- Naive approach, do what works at the LHC
- Reconstruct "fat – jets"

Mass gets shifted towards higher values

p_T ~ 3 TeV



Jet Mass

- Naive approach, do what works at the LHC
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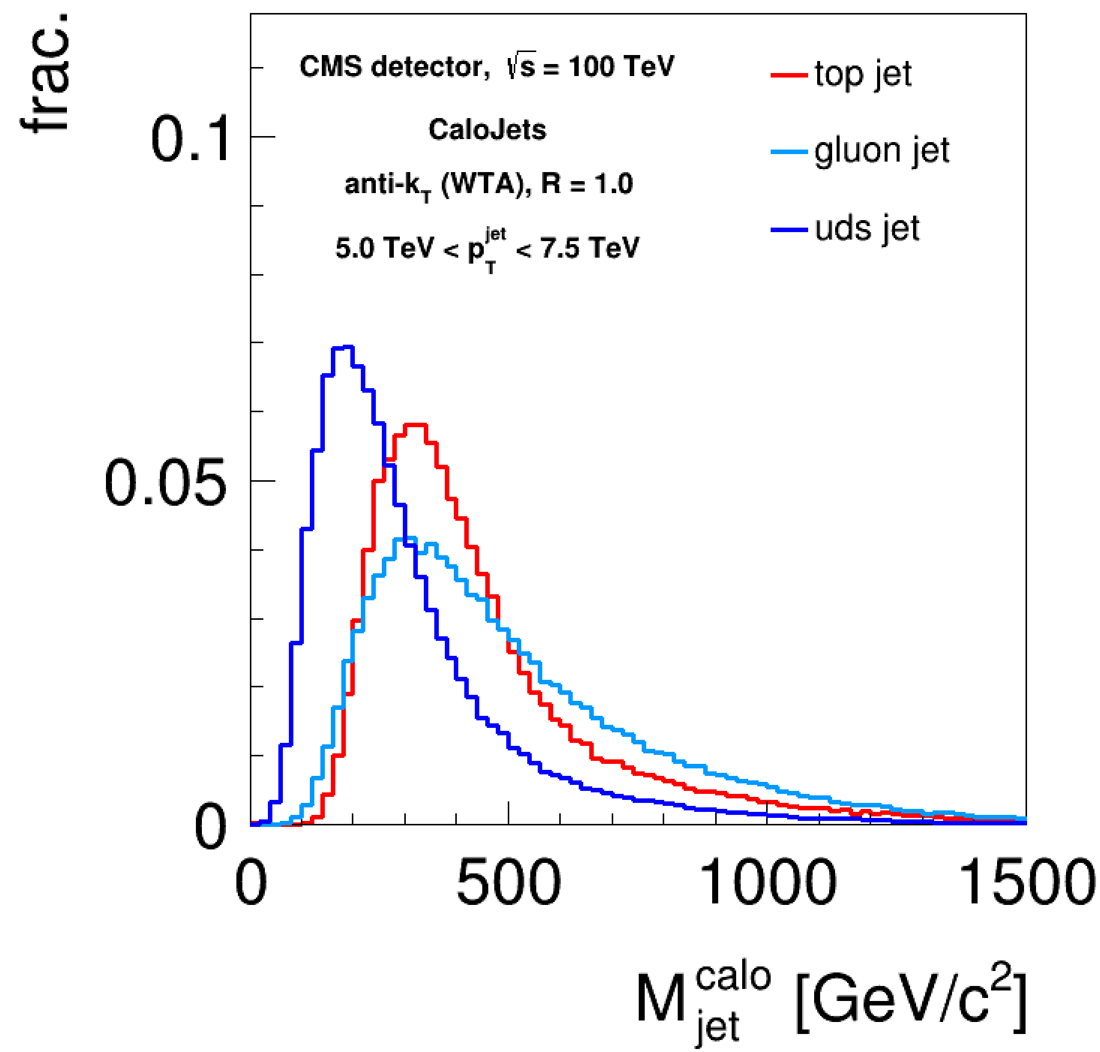
Mass gets shifted towards higher values

$p_T \sim 5$ TeV

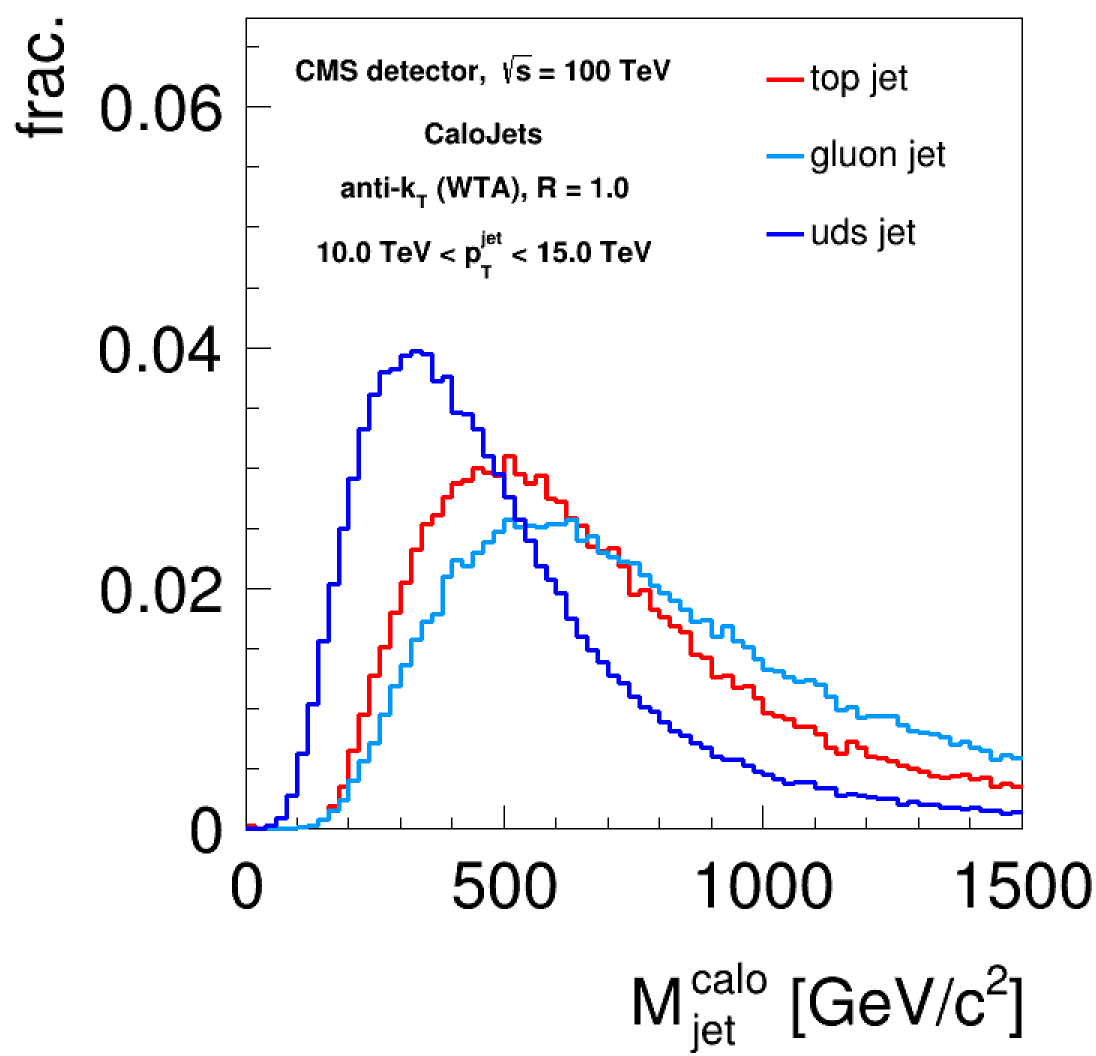


Jet Mass

- Naive approach, do what works at the LHC
- Reconstruct "fat - jets"

Mass gets shifted towards higher values

$p_T \sim 10$ TeV



Soft Emissions

We are clustering very confined decay products $\Delta R \sim 0.05$ with a large cone size $R = 1.0$

Soft QCD emissions can produce large contributions to the jet mass:

$$m_J^2 \simeq p_T^J \, p_T^e \, R^2$$

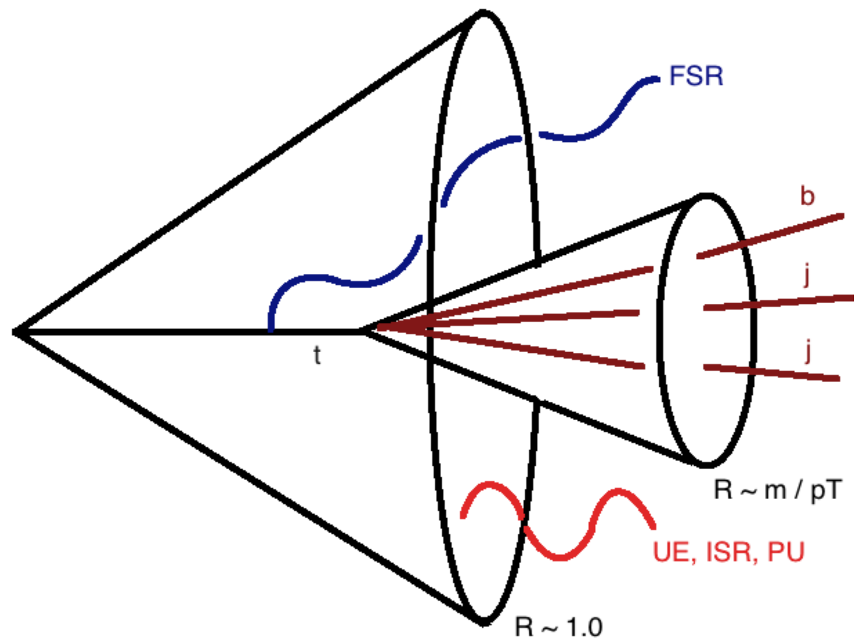
e.g. 5 GeV emission at the edge of the cone, for jet p_T = 5 TeV adds m_{top} to the jet mass !!

Soft Emissions

- Effect on jet p_T from **ISR/UE** goes like R^2 assuming uniform density/area $\rightarrow$ jet mass ~ R^2

- Top FSR also contributes outside the dead-cone region, $R_{d.c} \sim m_t / p_T$

Soft Emissions



- Best choice seems to choose a jet radius, big enough to contain top decay products, small enough to reject soft contamination:

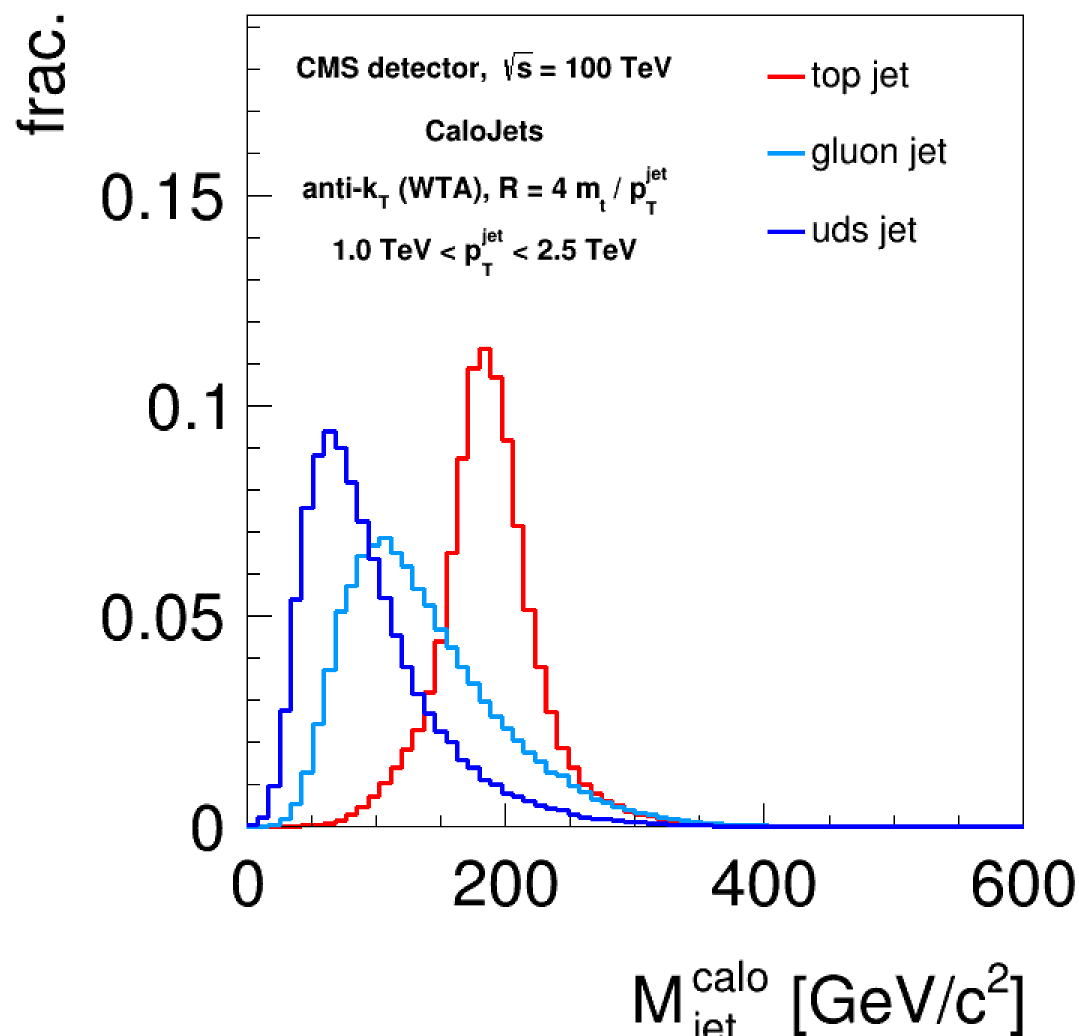
$$R \sim m_t / p_T$$ (we take $4\, m / p_T$)

Jet Mass (shrinking cone)

Prescription:

$p_T \sim 1$ TeV

- Cluster jets with fixed size R = 1.0, derive jet p_T
- Re-cluster "proto-jet" constituents with $R = 4\, m_t / p_T$, keep hardest.

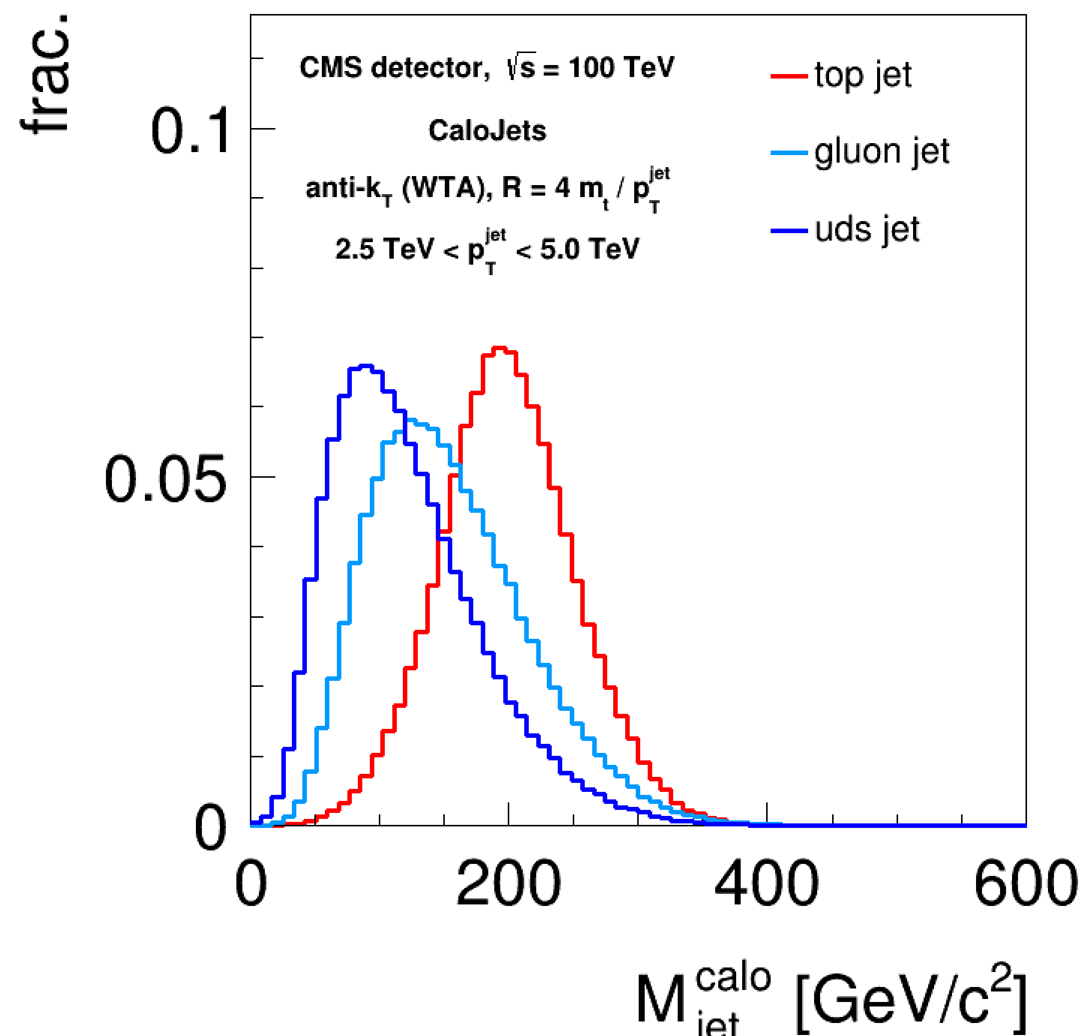


Jet Mass (shrinking cone)

$p_T \sim 3$ TeV

Distributions overlap with increasing p_T

Due to increasing boost, decay products, begin to merge into single calo-cells, hence worsening mass resolution

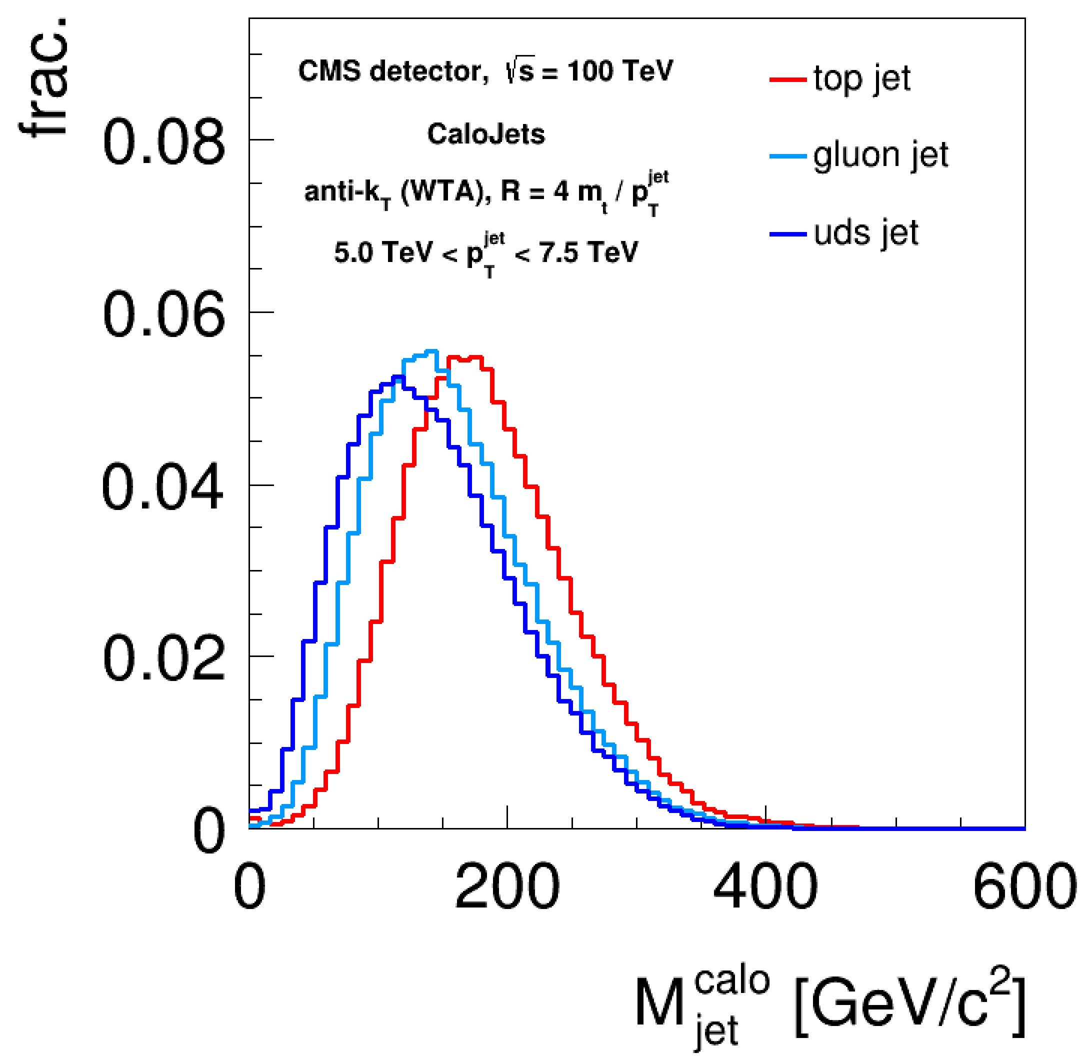


Jet Mass (shrinking cone)

$p_T \sim 5$ TeV

Distributions overlap with increasing p_T

Due to increasing boost, decay products, begin to merge into single calo-cells, hence worsening mass resolution

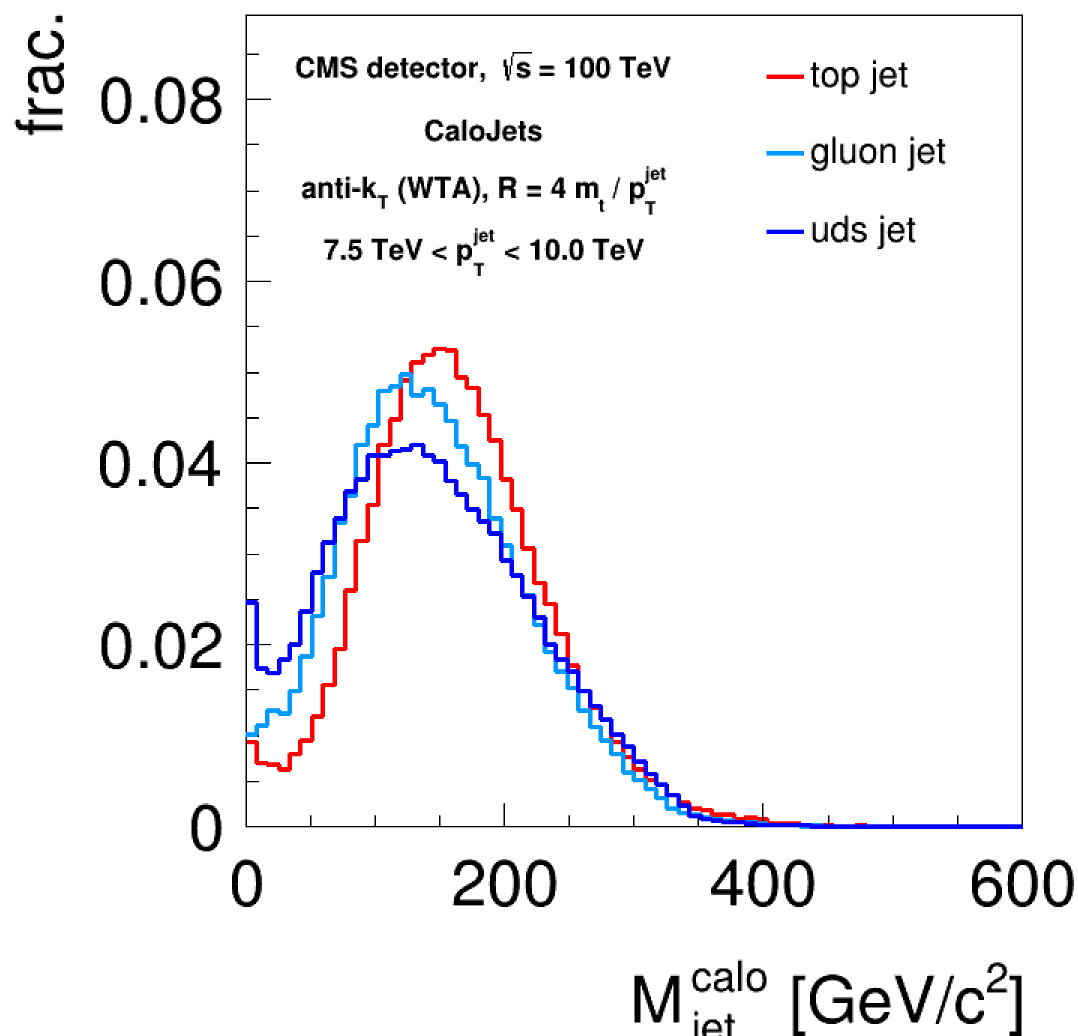


Jet Mass (shrinking cone)

p_T ~ 8 TeV

Distributions overlap with increasing p_T

Eventually jet cone size become comparable to calo cell size

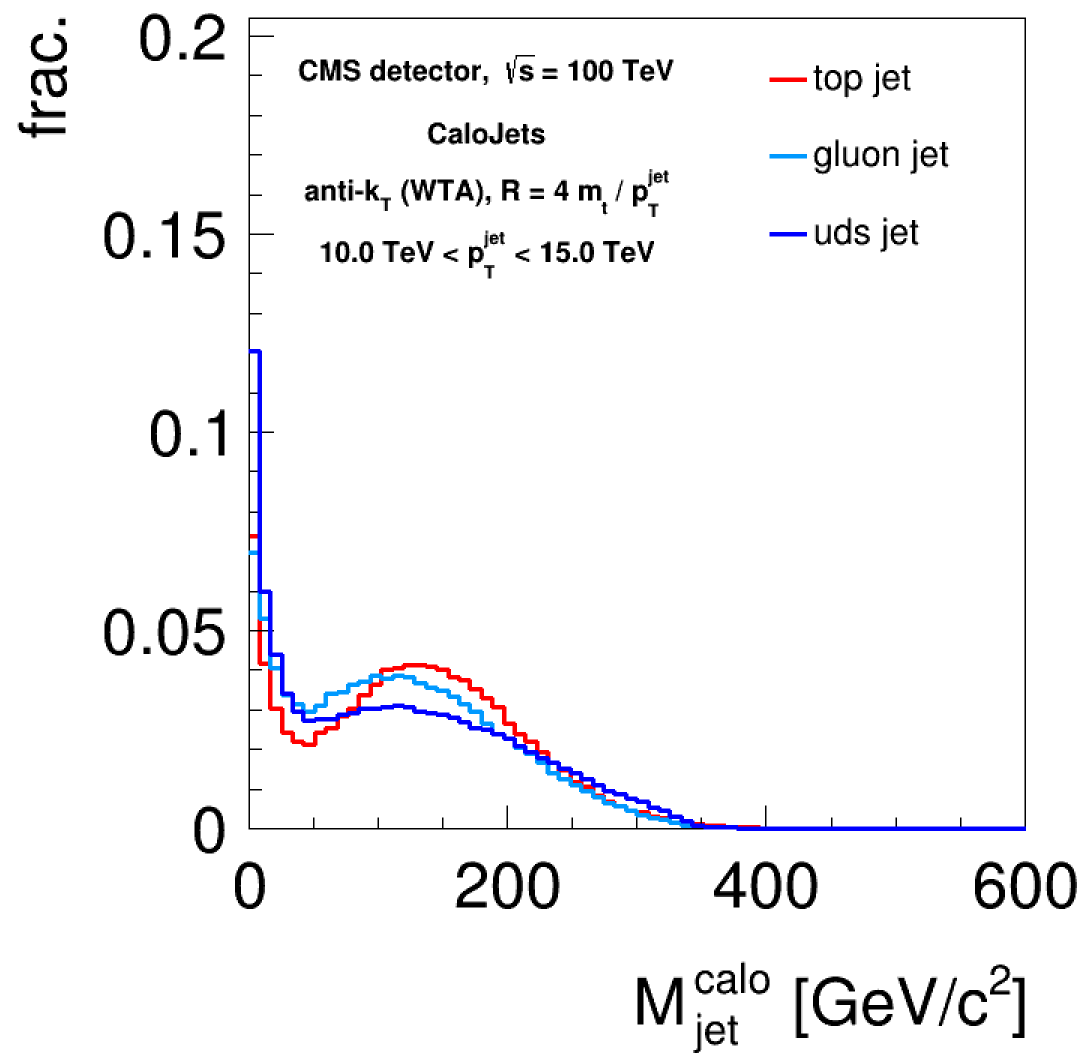


Jet Mass (shrinking cone)

p_T ~ 10 TeV

Distributions overlap with increasing p_T

Eventually jet cone size become comparable to calo cell size



Detector considerations

From the exp. persepective, boosted analysis relies on:

- **good angular resolution**
- good energy/momentum resolution

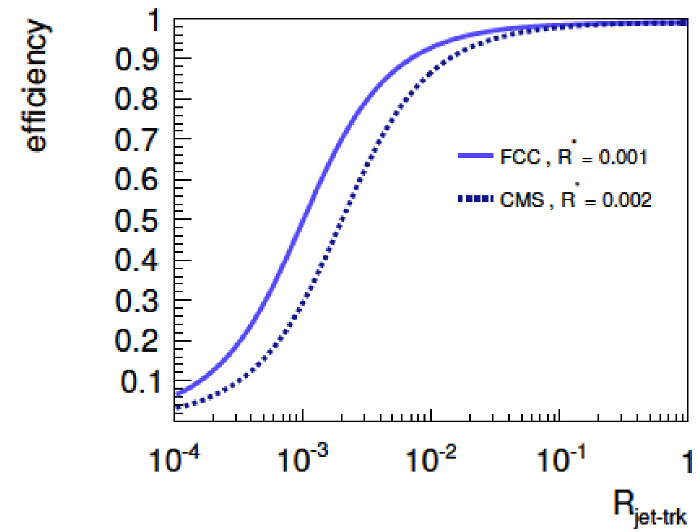
ex for CMS:

Tracking	→	$\Delta R \sim 0.002$	$\Delta p/p \sim$ 5-10%	@1TeV
ECAL	→	$\Delta R \sim 0.02$	$\Delta E/E \sim$1%	@1TeV
HCAL	→	$\Delta R \sim 0.1$	$\Delta E/E \sim$5%	@1TeV

Charged Tracks will play a major role jet structure ID in highly boosted regimes

Detector considerations

- Make maximal use of measured information on *charged particles* (for better angular resolution, more robust against pile-up)



- Look at observables built on tracking (or Particle-Flow)

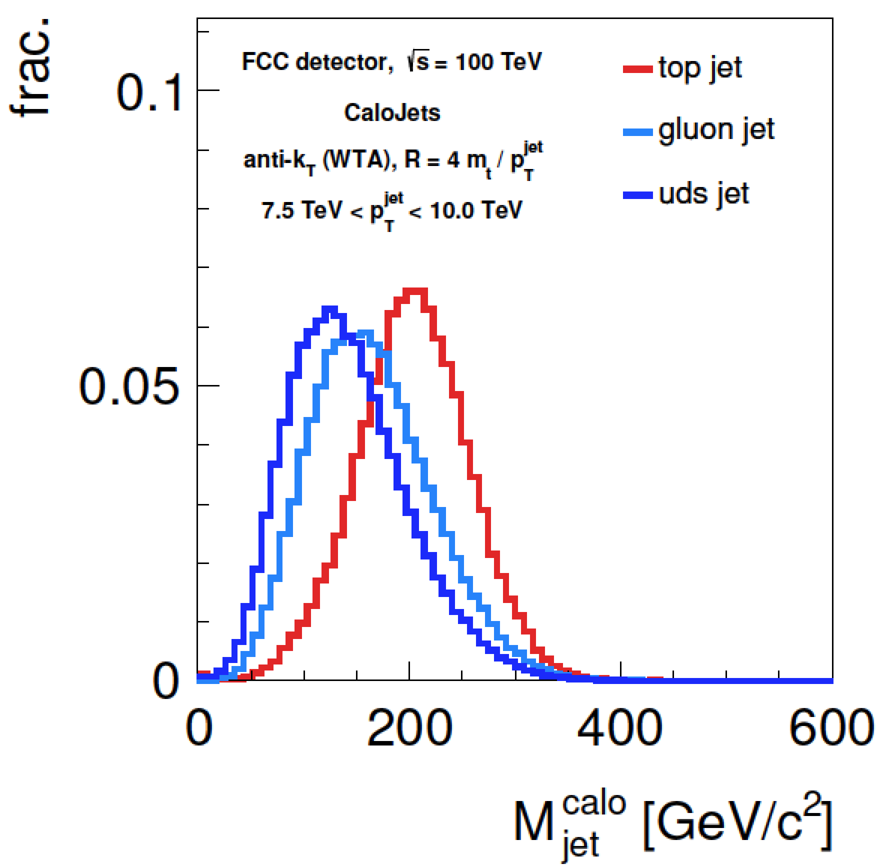
- Modify DELPHES tracking to make it more realistic in a dense environment (efficiency drop if track appears to be close to the jet core, angular smearing)

$$\epsilon(R) = \frac{2\epsilon_0}{\pi} \arctan(\frac{R}{R^*})$$

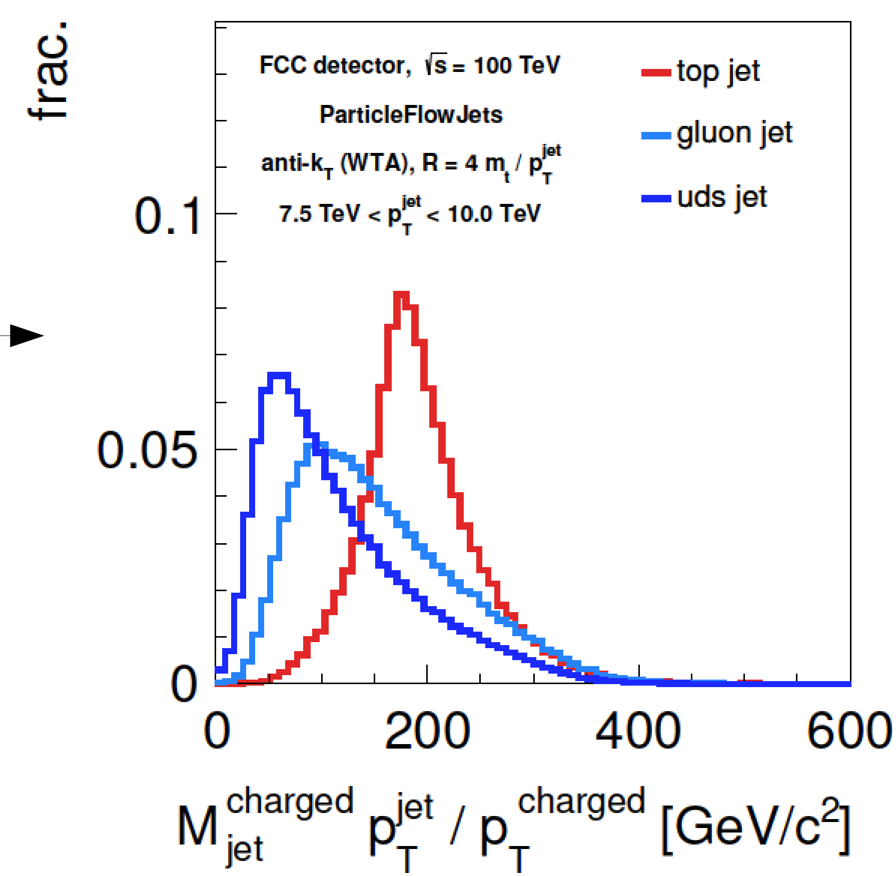
Track Based Observables

Rescaled Charged Jet Mass

Calorimeter based jet Mass



Track based jet Mass

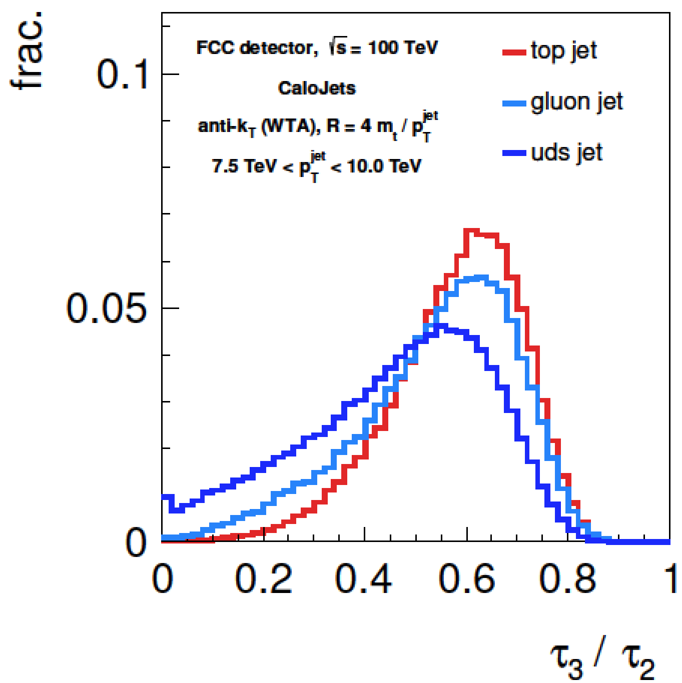


arXiv:1108.2701

Jet Structure (Nsub ratio)

$$\tau_N^{(\beta)} = \sum_{i \in J} p_{Ti} \min\{R_{i1}, \ldots, R_{iN}\}\,; \qquad \tau_{3,2}^{(\beta)} = \frac{\tau_3^{(\beta)}}{\tau_2^{(\beta)}}$$

Calorimeter based



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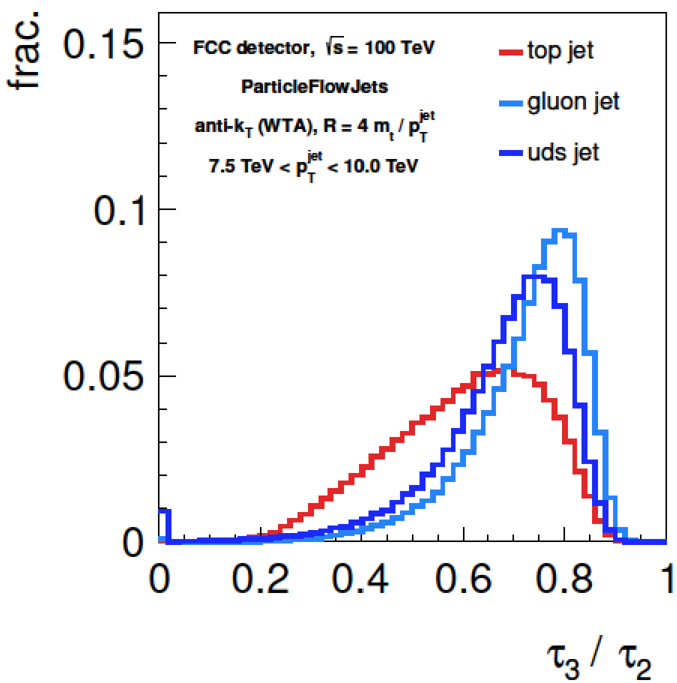
Track based

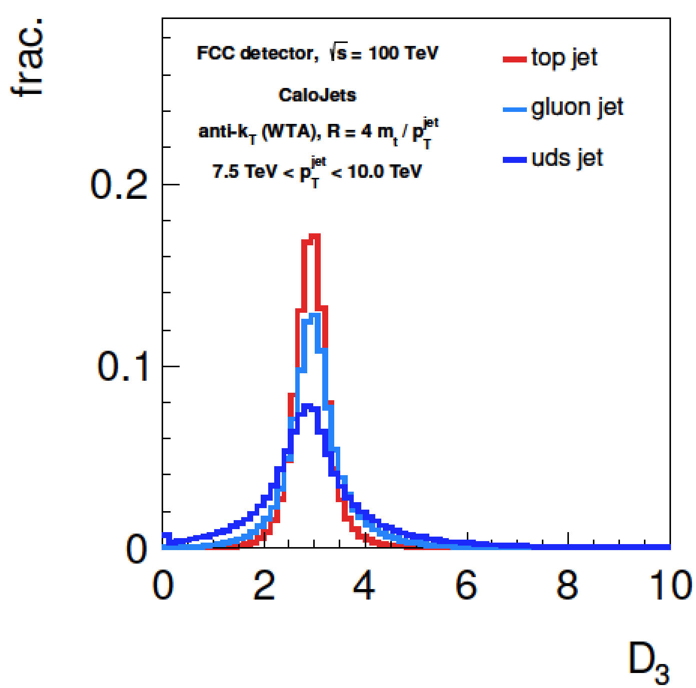


arXiv:1411.0665

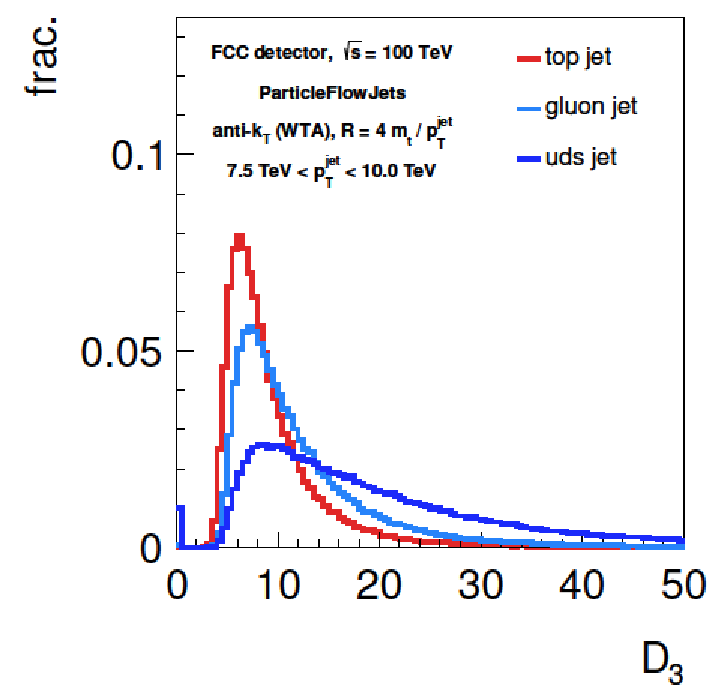
Jet Structure (D_3)

$$D_3^{(\alpha,\beta,\gamma)} \equiv \frac{e_4^{(\gamma)}\left(e_2^{(\alpha)}\right)^{\frac{3\gamma}{\alpha}}}{\left(e_3^{(\beta)}\right)^{\frac{3\gamma}{\beta}}} + x\frac{e_4^{(\gamma)}\left(e_2^{(\alpha)}\right)^{\frac{2\gamma}{\beta}-1}}{\left(e_3^{(\beta)}\right)^{\frac{2\gamma}{\beta}}} + y\frac{e_4^{(\gamma)}\left(e_2^{(\alpha)}\right)^{\frac{2\beta}{\alpha}-\frac{\gamma}{\alpha}}}{\left(e_3^{(\beta)}\right)^{2}}$$

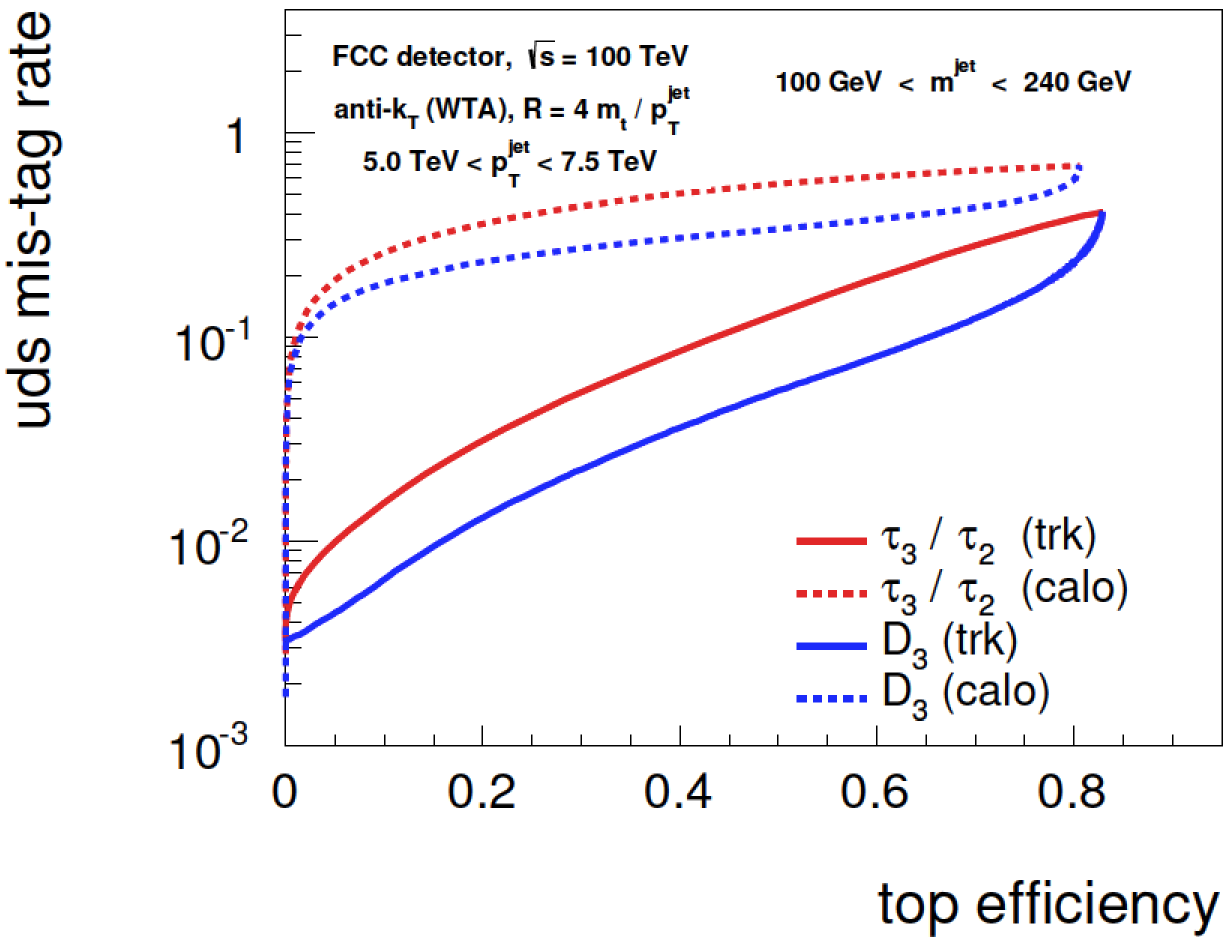
Calorimeter based



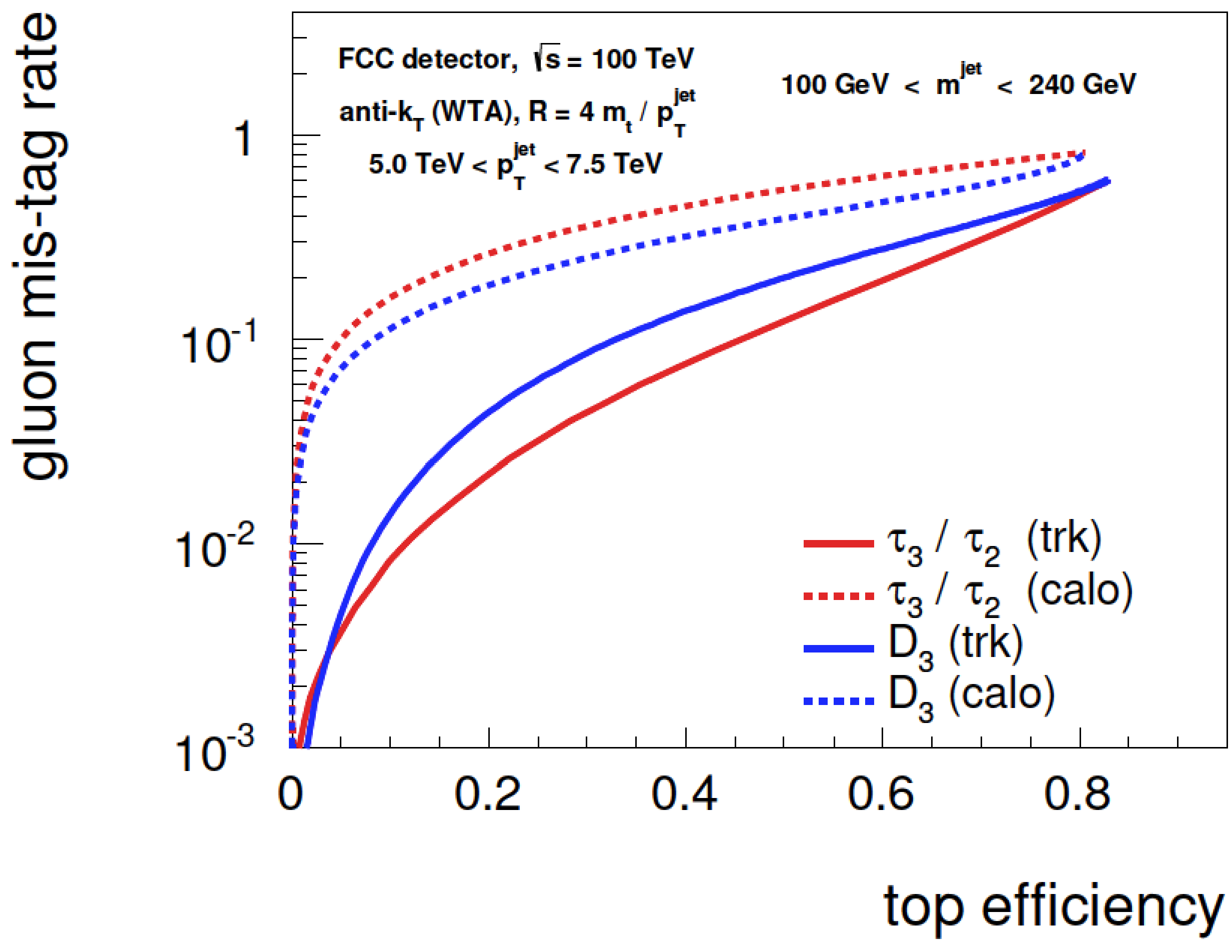
Track based



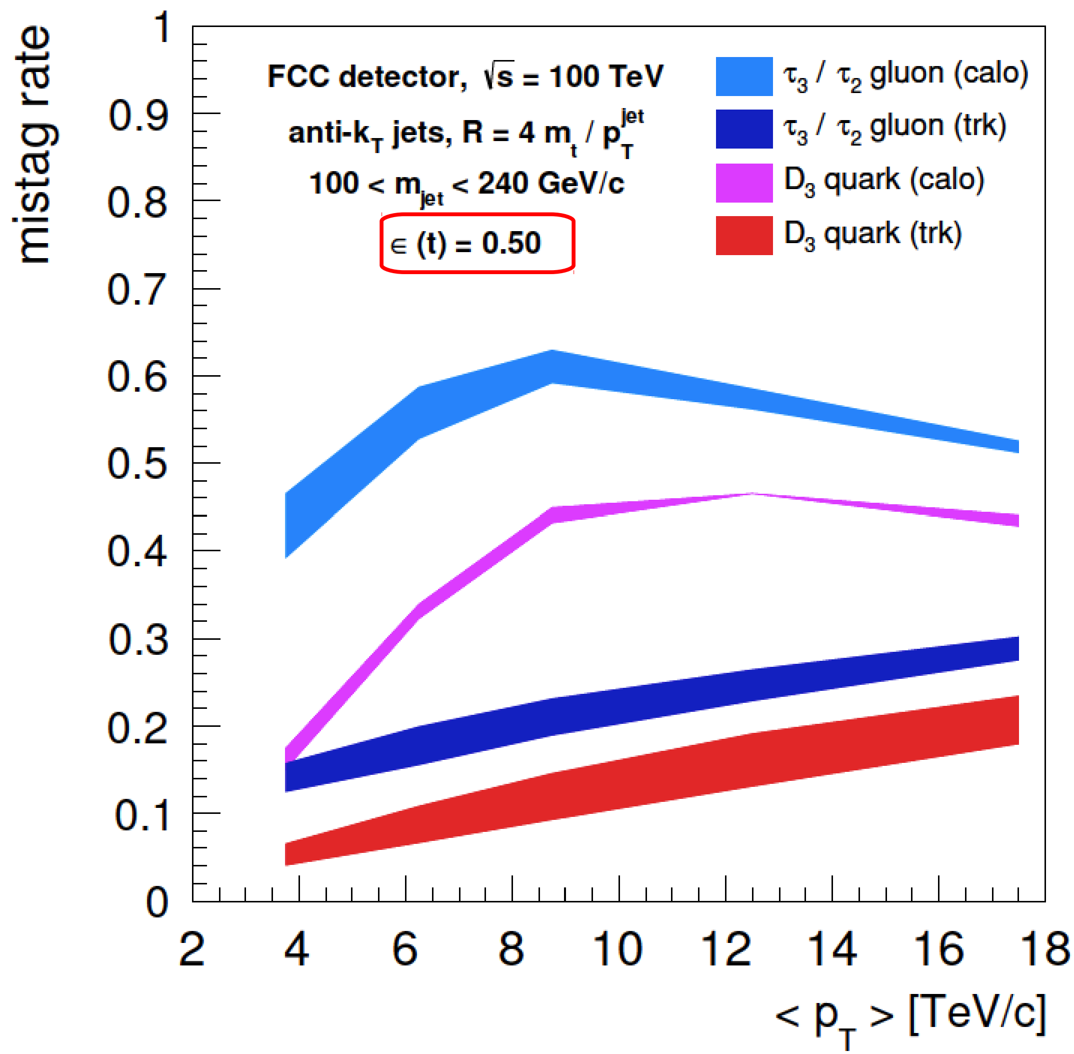
Performance (light)



Performance (gluon)



Performance



Summary and outlook

- In highly boosted regime, constituents merge inside calorimeter cells. Tracks have better angular resolution and can be used.

- We cluster tracks into “top jet” with a shrinking cone size, in order to reduce soft unwanted contamination, and build shape and mass observable out of charged constituents.

- We used DELPHES for detector simulation (and improved tracking for this study)

- We have shown that tracking based observables can discriminate between QCD and top at extreme energies (where calorimeter will fail)

Backup

	CMS	FCC
B_z (T)	3.8	6.0
Length (m)	6	12
Radius (m)	1.3	2.6
ϵ_0	0.90	0.95
R^*	0.002	0.001
$\sigma(p_T)/p_T$	$0.2 \cdot p_T$ (TeV/c)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(\eta, \phi)$	0.002	0.001

Table 3: Tracking-related parameters for the CMS and FCC setup in Delphes.

$$\frac{\sigma(p_T)}{p_T} \approx \frac{\sigma_{r\phi}}{B \cdot L^2}$$

Backup

	CMS	FCC
$\sigma(E)/E$ (ECAL)	$7\%/\sqrt{E} \oplus 0.7\%$	$3\%/\sqrt{E} \oplus 0.3\%$
$\sigma(E)/E$ (HCAL)	$150\%/\sqrt{E} \oplus 5\%$	$50\%/\sqrt{E} \oplus 1\%$
$\eta \times \phi$ cell size (ECAL)	(0.02×0.02)	(0.01×0.01)
$\eta \times \phi$ cell size (HCAL)	(0.1×0.1)	(0.05×0.05)

Table 4: Calorimeter parameters for the CMS and FCC setup in Delphes.