Tracking Hyper Boosted Top Quarks @ 100 TeV

Michele Selvaggi
CP3 – UCLouvain

Larkoski, Maltoni, MS [arXiv:1503.03347]

Boost 2015

Chicago – August 14 , 2015

Why boosted tops ?

- Large number of models predict heavy particles (Z', stop , gluino ..)
- These heavy resonances couple, hence decay to highly boosted SM top quarks (colored), W/Z bosons, H (color singlets)...
- Interest for a 100 TeV p-p collider is increasing, has potential to look for heavy particles up to tens of TeV masses:

ex: $m_{Z'} = 20$ TeV decay to tops with $p_T \sim 10$ TeV

Approach

We are interested in top-tagging at multi-TeV energies

Semi-leptonic very boosted top have been studied:

$\longrightarrow$ non-isolated hyper boosted muon

Aguilar, Fuks and Mangano [1412.6654]

Study <u>fully hadronic</u> tops here (assume no b-tagging is possible)

Analysis Setup

Look at observable shapes (not total event rate)

- jet mass
- shape observables ($\tau_{3,2}$, D_3)

$1 < p_T < 20$ TeV

MadGraph5 (LO event generation) + PYTHIA 6

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

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

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

Detector simulation: DELPHES 3 (more later and back-up)

- CMS (present)
- FCC (future)

Soft Emissions

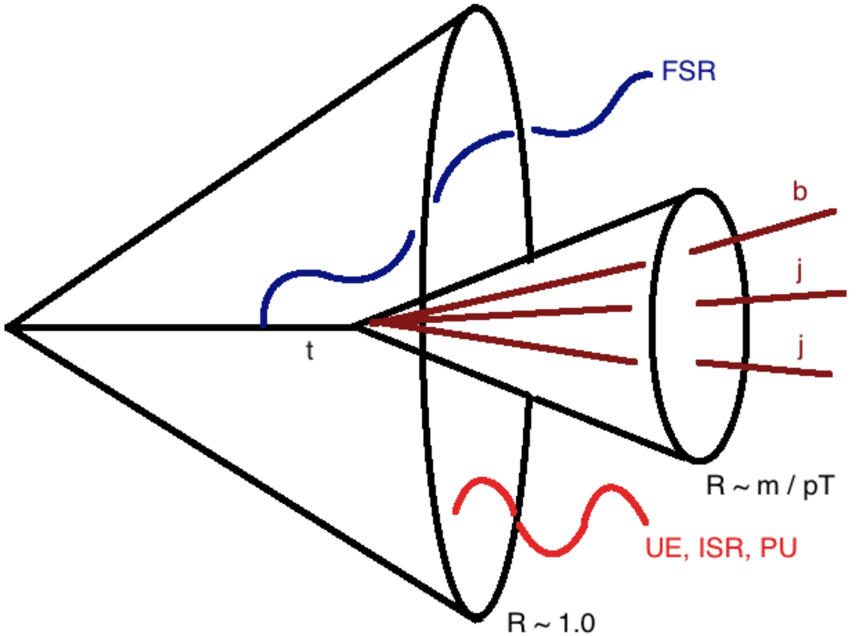
We are dealing with a wide range of energies, we want to carefully choose our jet radius...

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 and R = 1.0 adds m_{top} to the jet mass !!

Soft Emissions



Choose a jet radius such that:

- big enough to contain top decay products (and their soft emissions)
- small enough to reject isotropic soft contamination (ISR, UE, PU) + eventually top FSR

$$R \sim C\, m_t / p_T$$

(we take C = 4 to ensure 99% of decays energy is in)

Procedure

Derive the total jet p_T using all Calorimeter (or Particle-Flow) information.

1. Cluster (calo/PF) deposits with fixed size R = 1.0 into proto-jet, way derive jet p_T

$\longrightarrow$ soft radiation has small effect on the jet pT

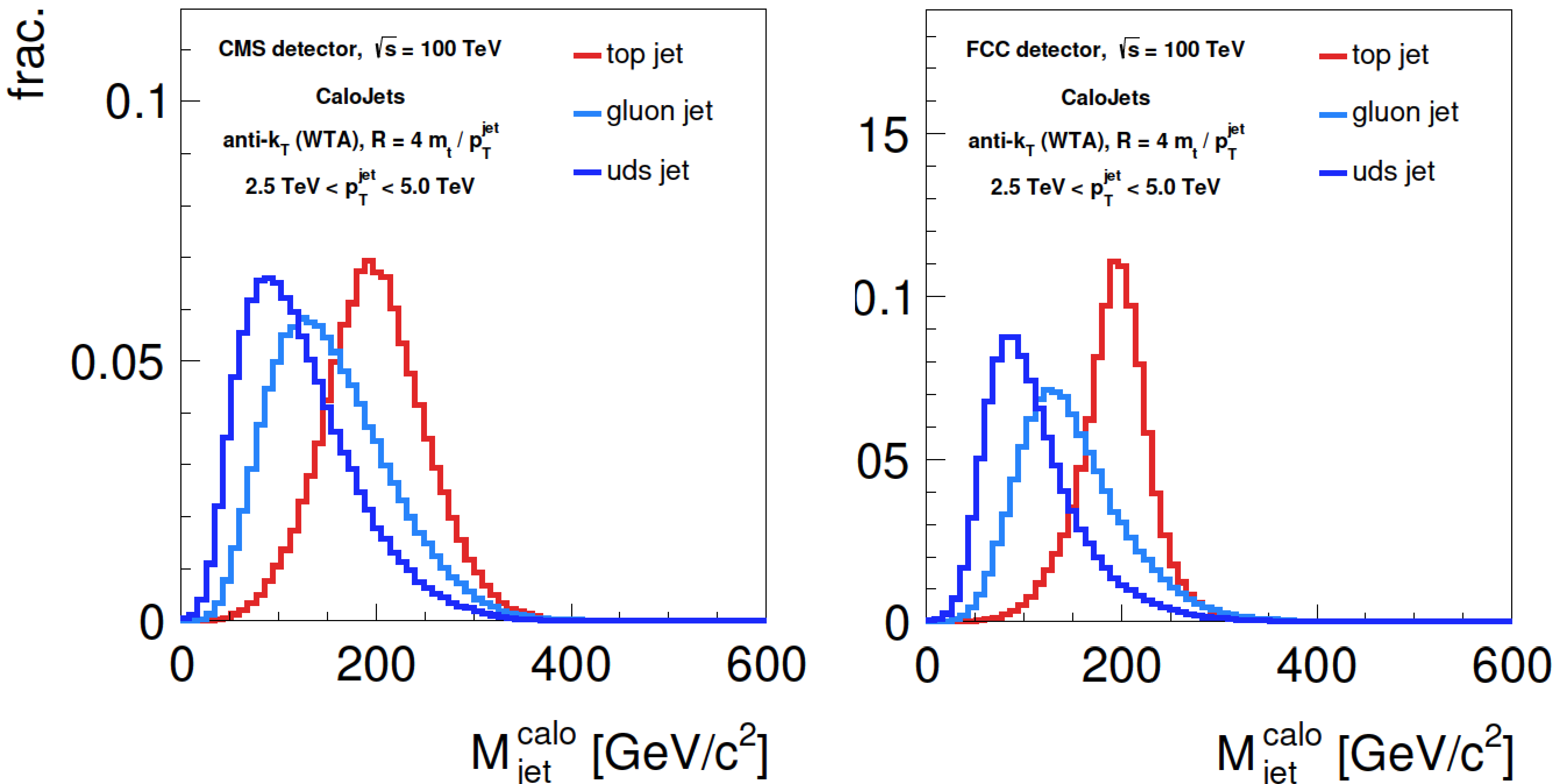
2. re-cluster "proto-jet" constituents with shrinked radius $R = 4\, m_t / p_T$, identify hardest subjet as top-candidate.

At all steps use anti-k_T $\longrightarrow$ IRC safe !!

see also [0806.0848],[0903.0392] or [1402.1494]

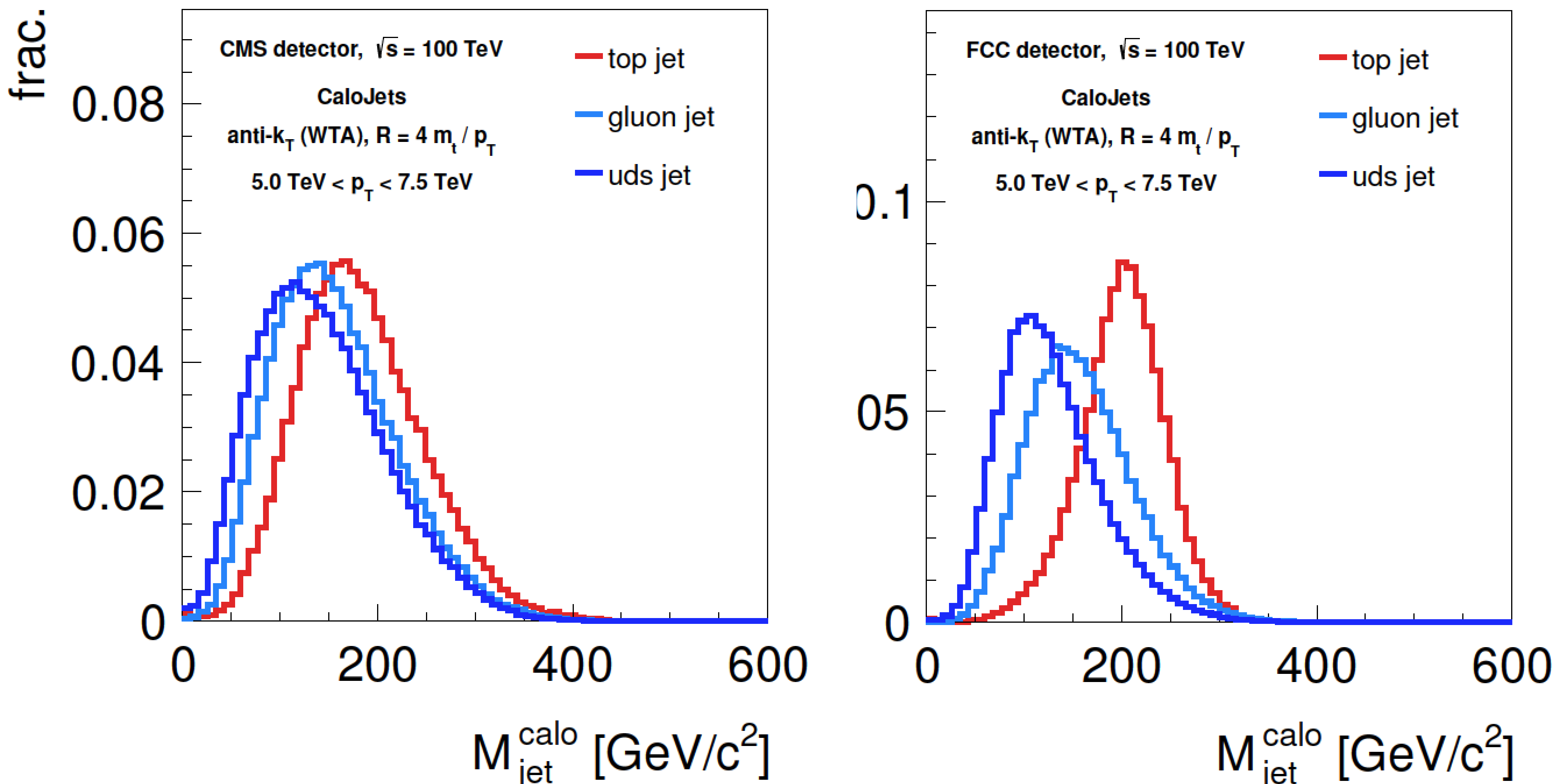
Resolution effects

$p_T \sim 2.5$ TeV



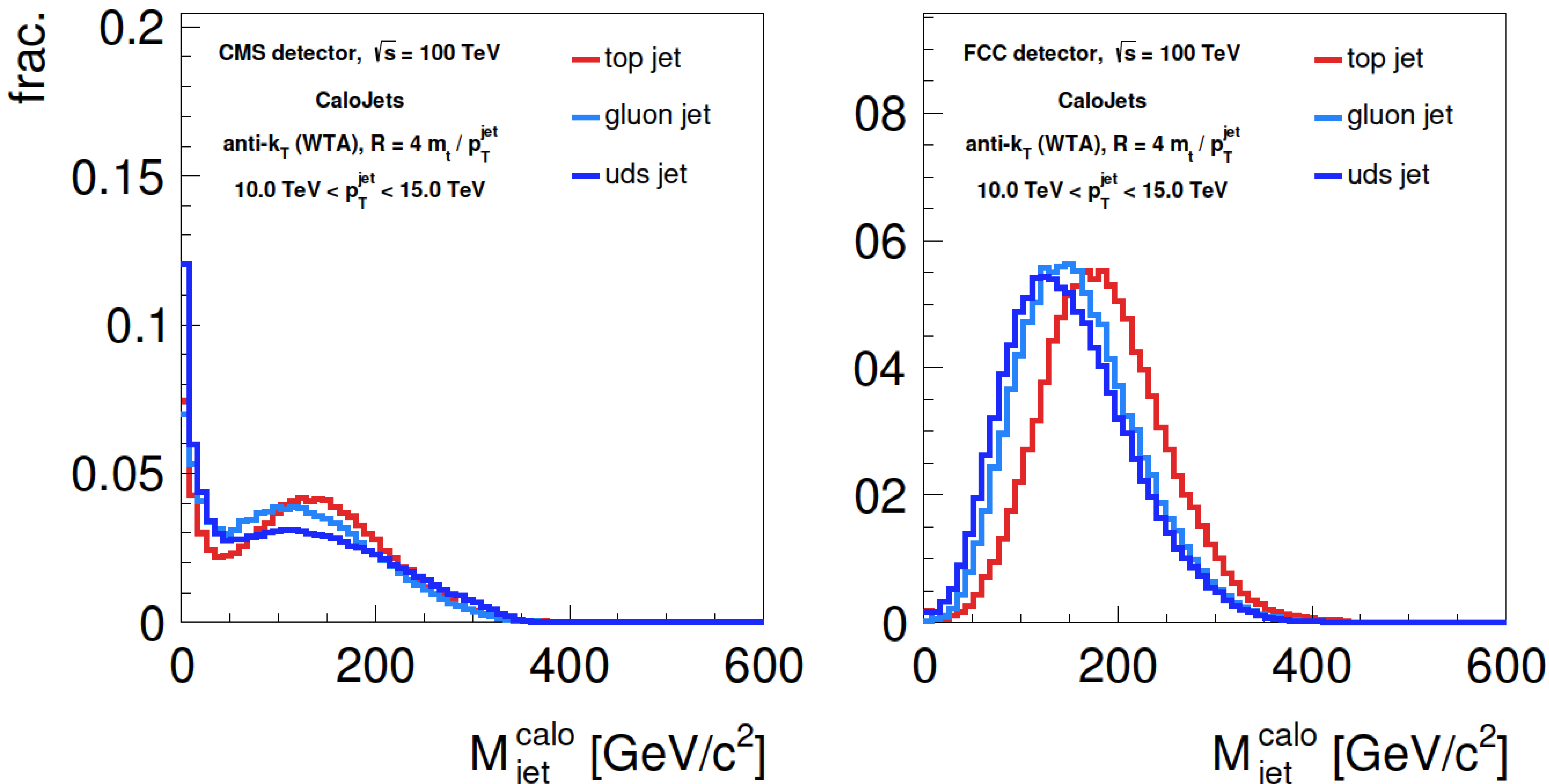
Resolution effects

$p_T \sim 5$ TeV



Resolution effects

$p_T \sim 10$ TeV



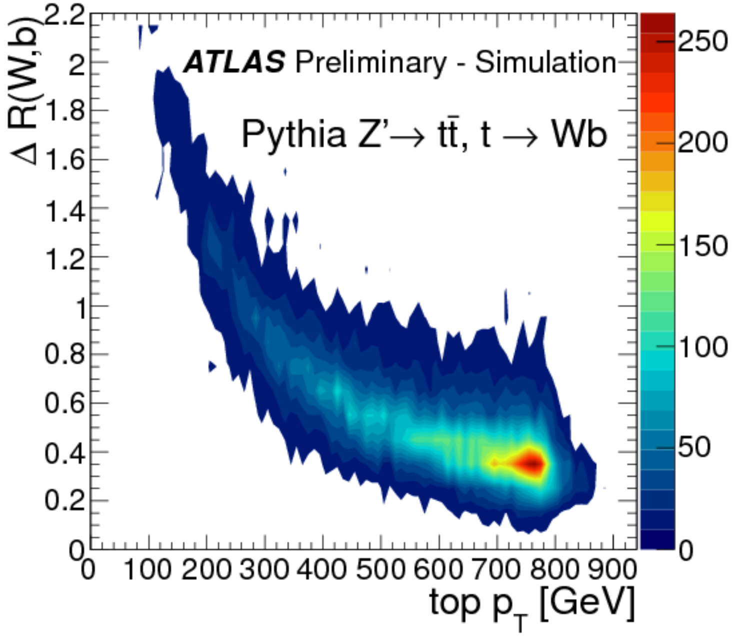
Detector considerations

ex for top:

p_T = 200 GeV → R ~ 2
p_T = 1 TeV → R ~ 0.4
p_T = 10 TeV → R ~ 0.05

min. distance to resolve two partons

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



in CMS:

Tracking → ΔR ~ 0.002
ECAL → ΔR ~ 0.02
HCAL → ΔR ~ 0.1

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

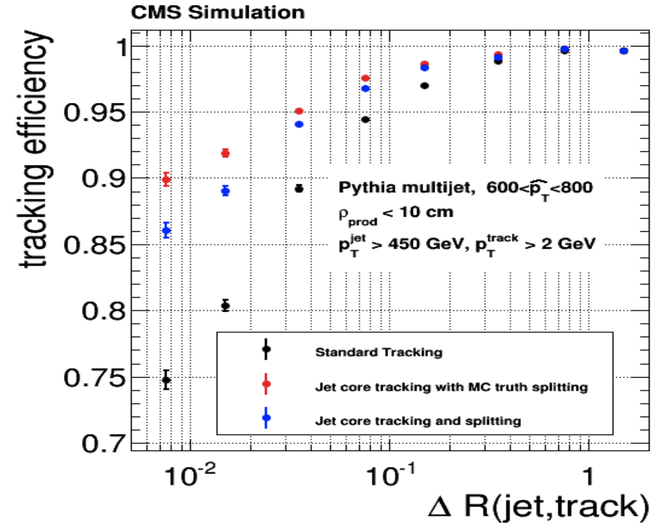
Procedure

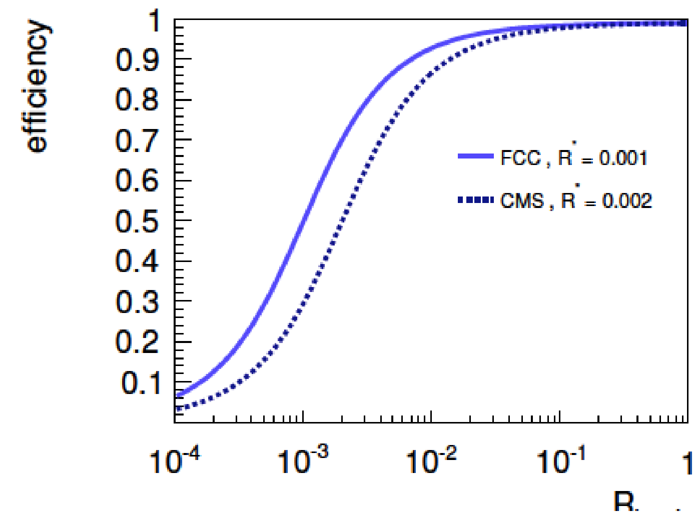
Rely on :

- tracks for angular resolution
- full (calo) detector for total p_T

Tracking in a dense environment is not easy !!

We simulate tracking inefficiencies/resolution in DELPHES (efficiency drop if track appears to be close to the (sub)-jet core, angular smearing)

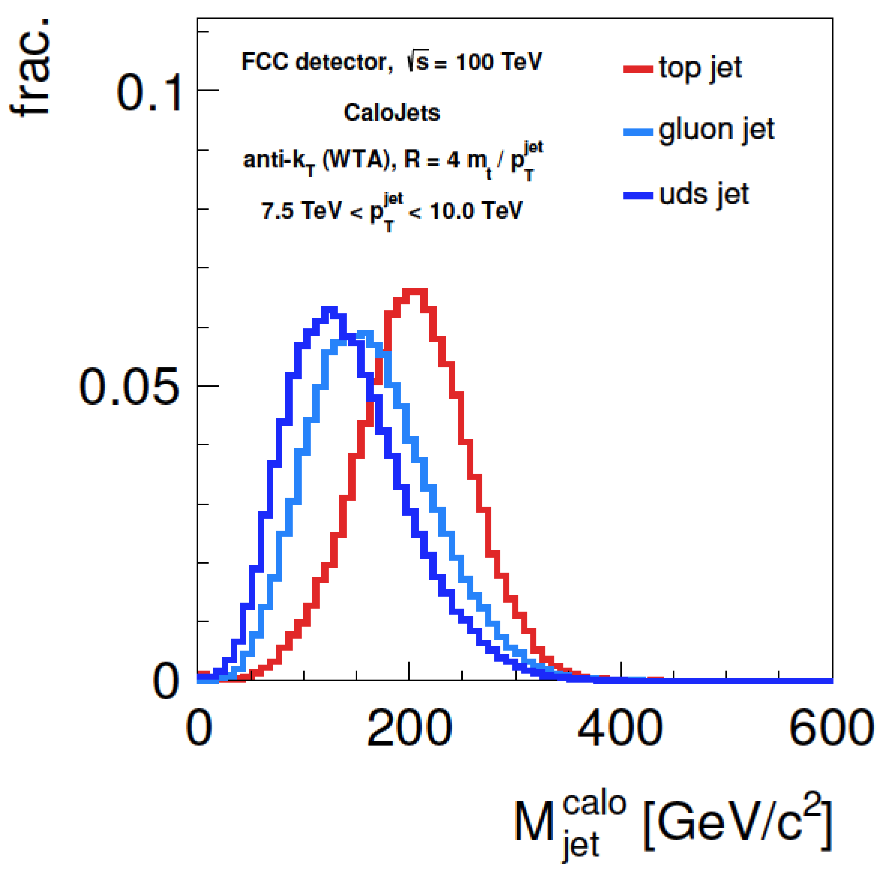




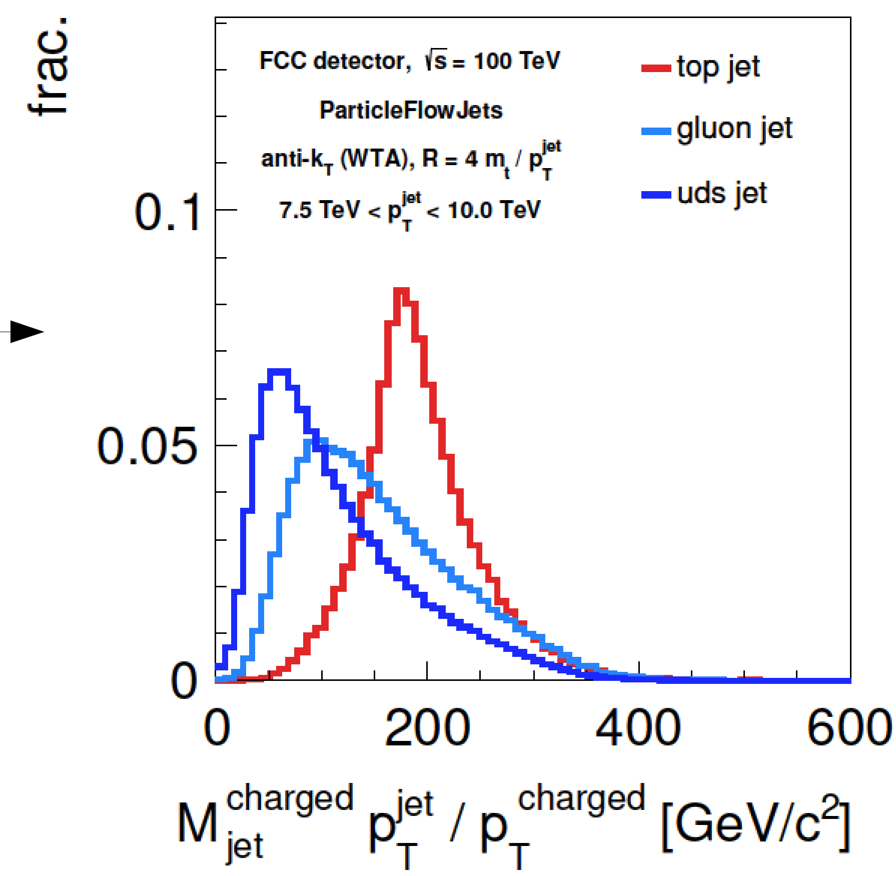
$$\epsilon(R) = \frac{2\epsilon_0}{\pi} \arctan\left(\frac{R}{R^*}\right)$$

Rescaled Charged Jet Mass

Calorimeter based jet Mass



Track- based jet Mass



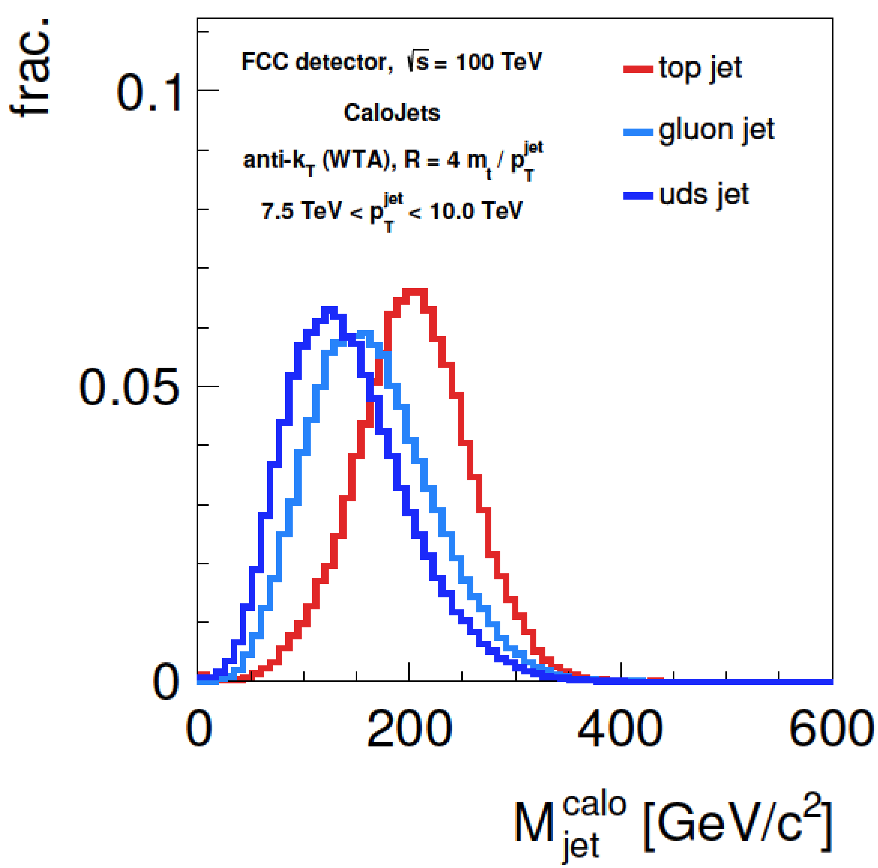
Charged Jet Mass

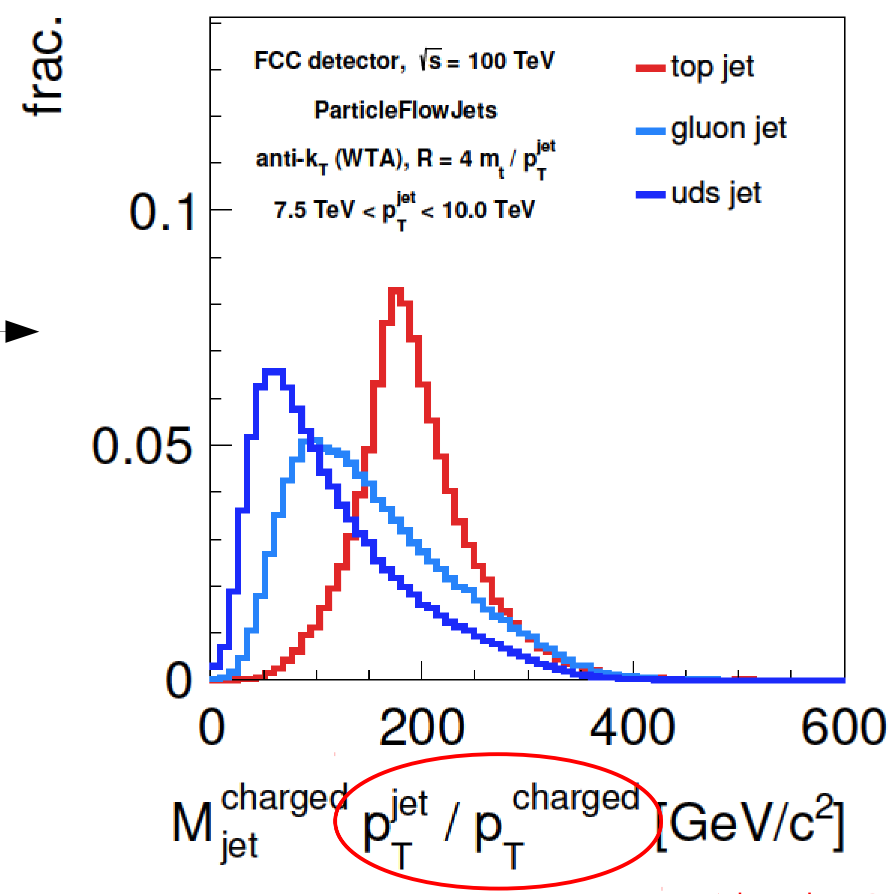
to recover correct value of top mass, rescale charged jet mass by:

$p_T / p_T^{charged}$

Calorimeter based jet Mass

Track- based jet Mass





(thanks Gavin)

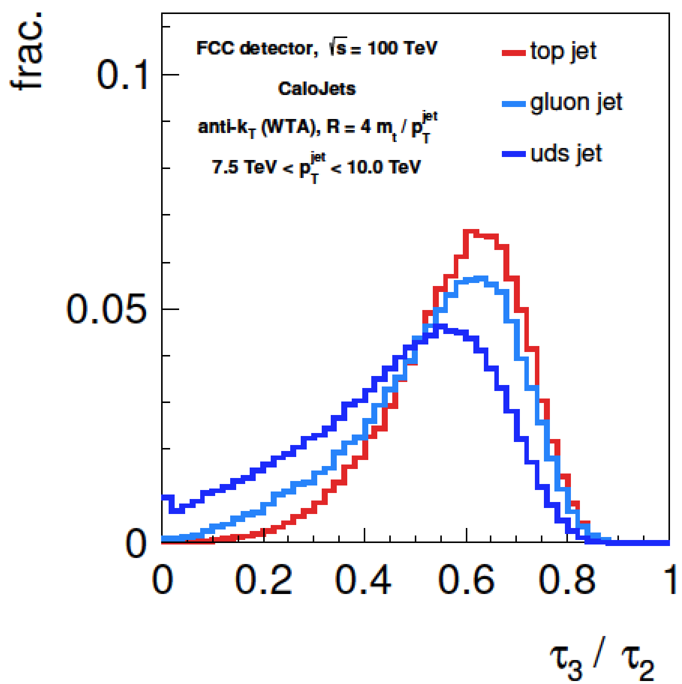
Jet Structure ($\tau_{3,2}$)

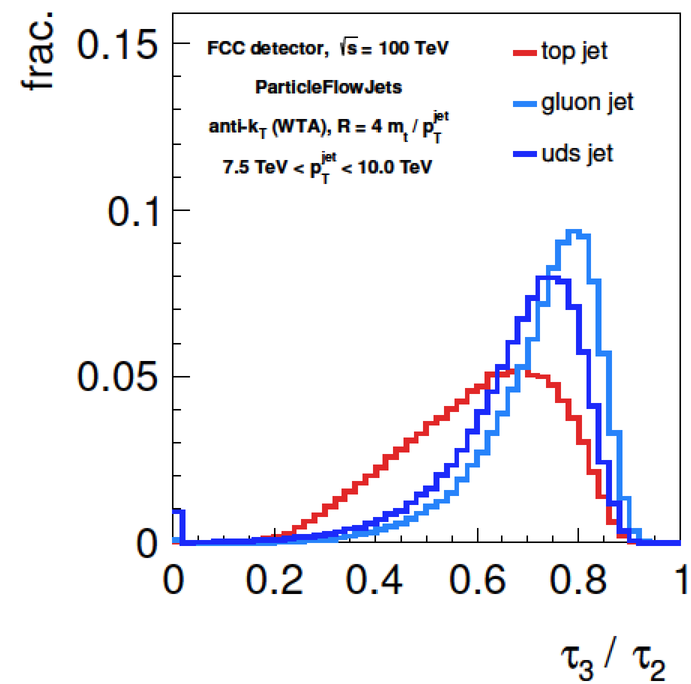
$$\tau_N^{(\beta)} = \sum_{i \in J} p_{Ti} \min\{R_{i1}, \ldots, R_{iN}\} \, , \qquad \tau_{3,2}^{(\beta)} = \frac{\tau_3^{(\beta)}}{\tau_2^{(\beta)}}$$

Calorimeter based

Gluon discrimination

Track based



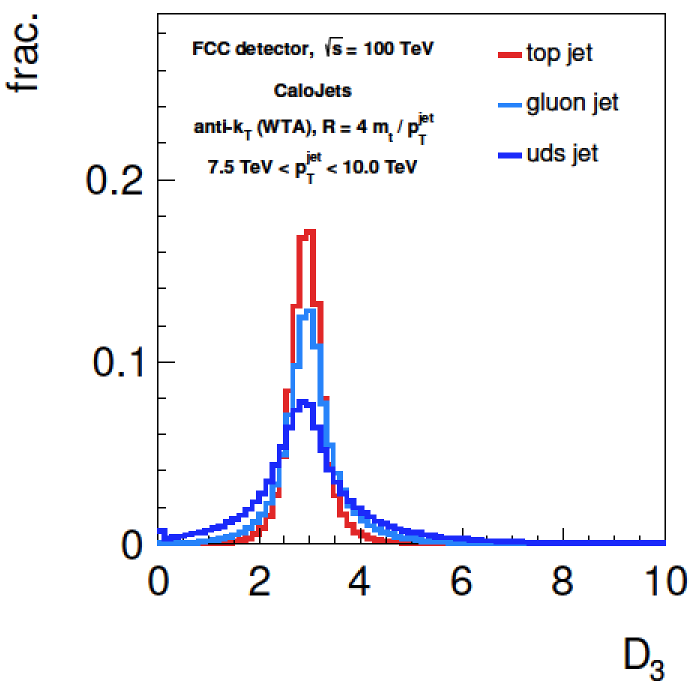


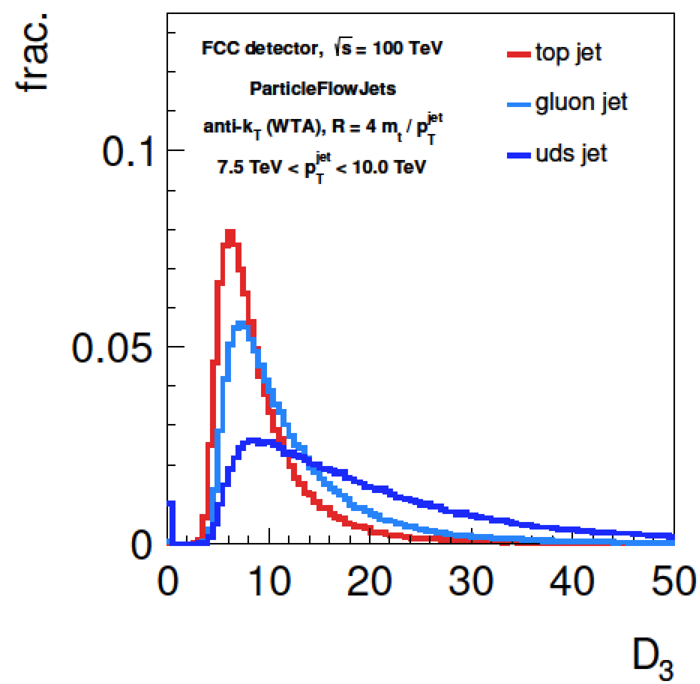
Thaler and Van Tilburg [1108.2701]

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 | quark discrimination | Track based



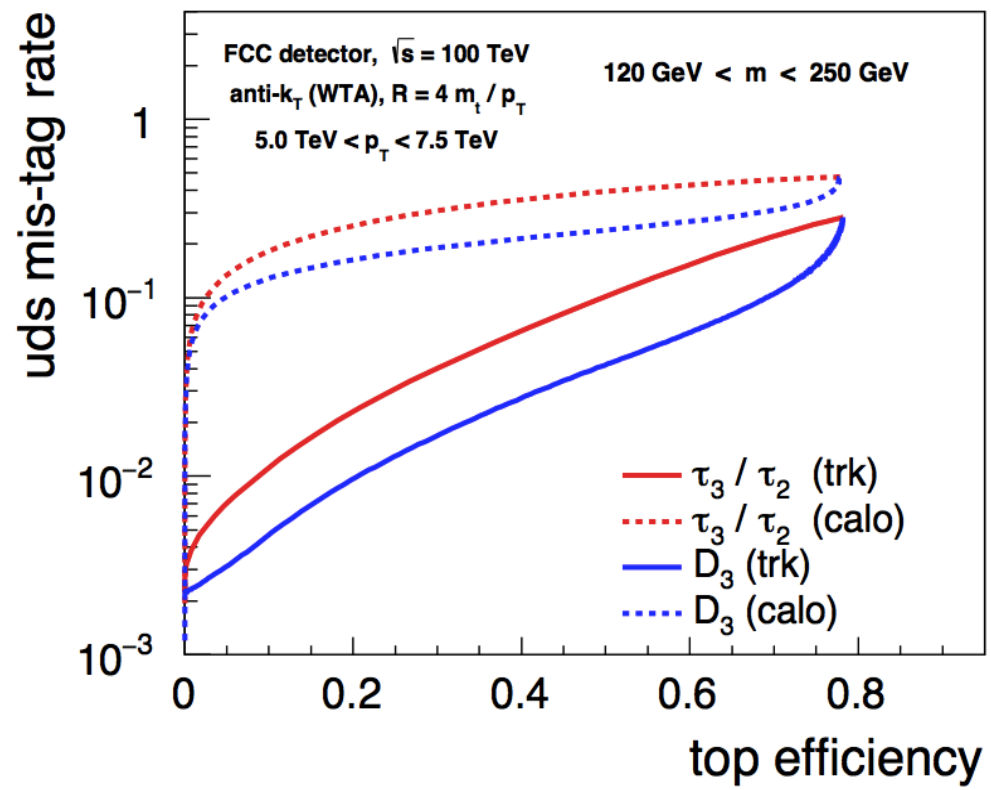


Larkoski, Moult and Neill [1411.0665]

Performance (light)

1) simple (rescaled) jet charged jet mass cut

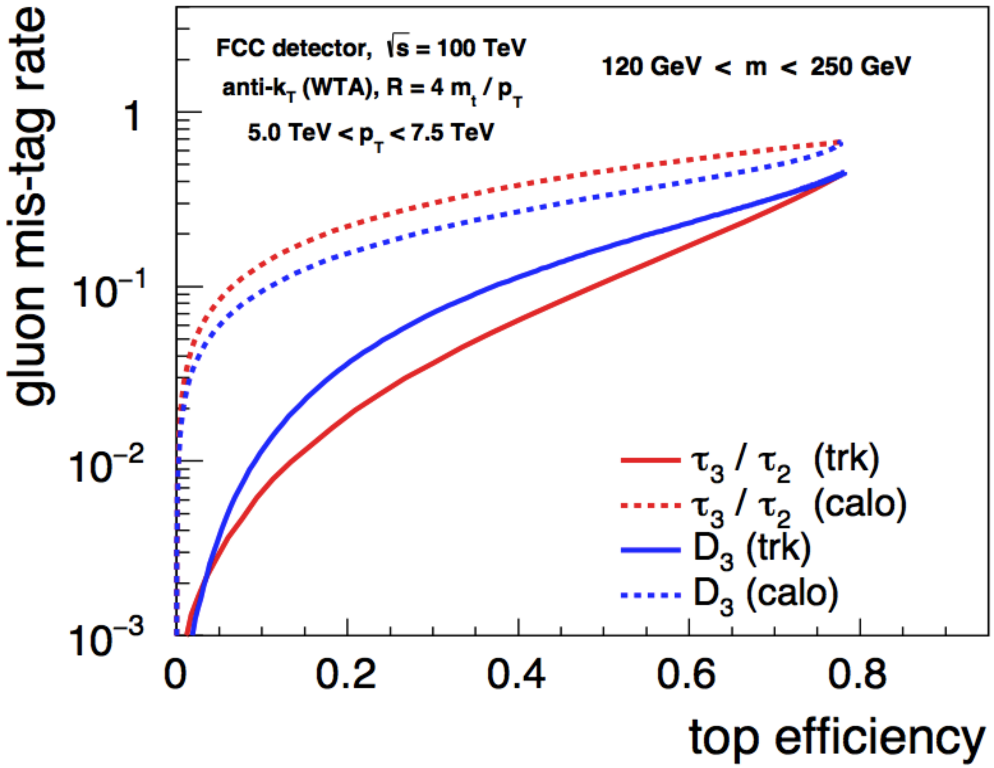
2) scan over D_3



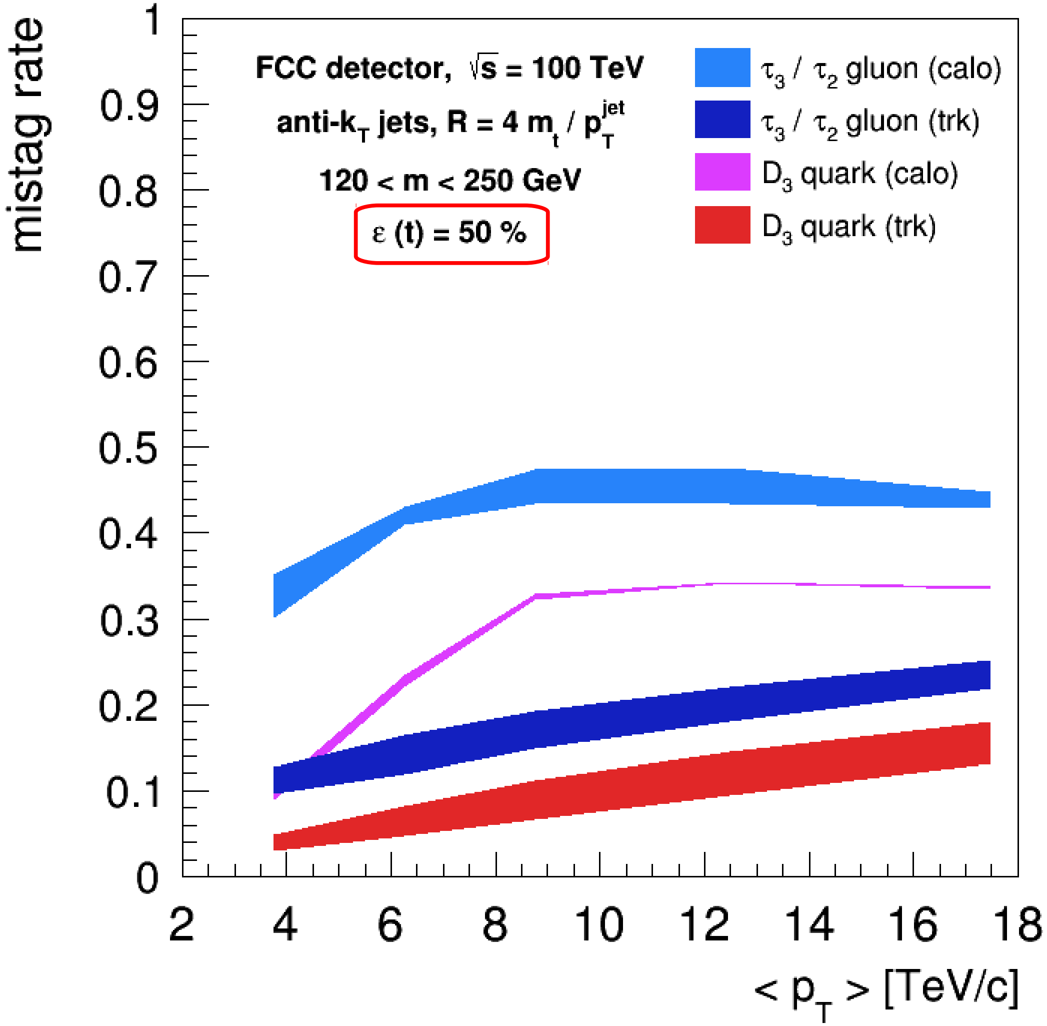
Performance (gluon)

1) simple (rescaled) jet charged jet mass cut

2) scan over $\tau_{3,2}$



Performance



Summary and outlook

- We build "top jet candidate":
  - use all detector information to get overall jet p_T
  - recluster with shrinking R ~ 1 / p_T see also [0806.0848],[0903.0392] or [1402.1494]
  - use tracks constituents for constructing high res. observables

    see also [1308.0540]
- This simple analysis can provide some useful benchmark for present and future performance for highly boosted tops (can be extended also to color singlets)

Summary and outlook

Open questions, possible improvements:

- neglected pile-up (but should impact mostly overall jet energy, less charged-based observables)

- is b-tagging possible at 100 TeV?

- neglected EW boson emissions from quark line (could become relevant in high purity sample)

- angular size of jets becomes extremely small at high momenta (is it safe?)

- for accurate predictions on obervables that were used, might need model for fragmentation into charged hadrons

Backup

"Boosted" cross-sections

		Process	Cross section at pp, $\sqrt{s} = 100$ TeV $p_T > 1$ TeV (pb)	$p_T > 5$ TeV (fb)	$p_T > 10$ TeV (ab)
Standard Model	Signals	$pp \to t\bar{t}$	12	2.8	24
		$pp \to t\bar{t}j$	77	670	280
		$pp \to tj$	0.67	0.46	0.76
		$pp \to t\bar{t}V$	0.4	0.3	4
		$pp \to t\bar{t}H$	0.19	7.4e-02	0.65
		$pp \to t\bar{t}t\bar{t}$	0.17	8.5e-02	0.51
	Bkgds	$pp \to jj$	3500	1000	11000
		$pp \to jjV$	110	130	2200
BSM		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 3$ TeV)	4.6	-	-
		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 15$ TeV)	7.1e-03	4.7	-
		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 30$ TeV)	7.1 e-05	6.5e-02	48
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 1$ TeV)	0.49	7.8e-03	-
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 5$ TeV)	7.5e-04	0.063	-
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 10$ TeV)	4.4e-06	0.27e-03	0.024
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 2$ TeV)	2.5	0.94	-
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 5$ TeV)	2.7e-02	1.5	11
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 10$ TeV)	1.9e-04	0.12	4.5

S / B ~ 0.05 ($p_T > 5$ TeV)

Simulation parameters (I)

	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.

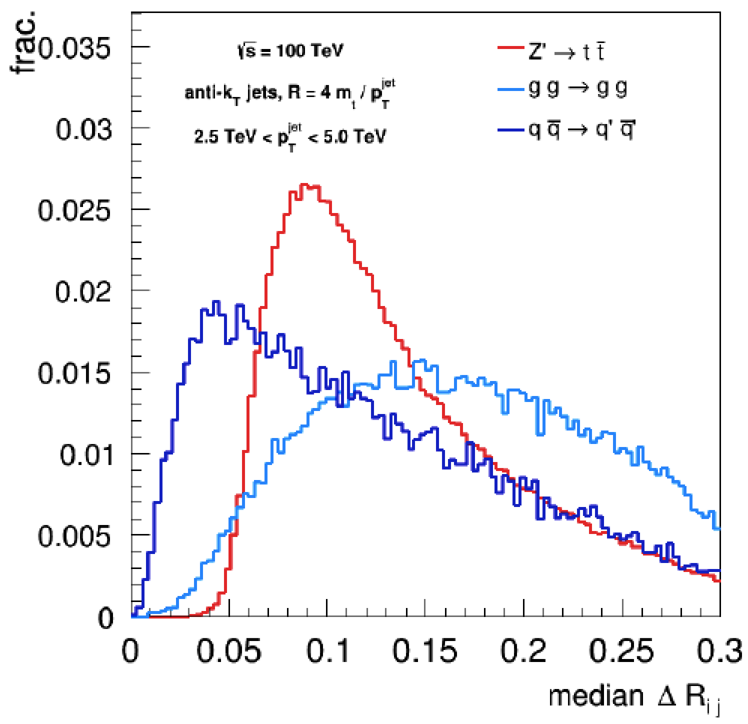
$$\frac{\sigma(p_T)}{p_T} \approx \frac{\sigma_{r\phi}}{B \cdot L^2}$$

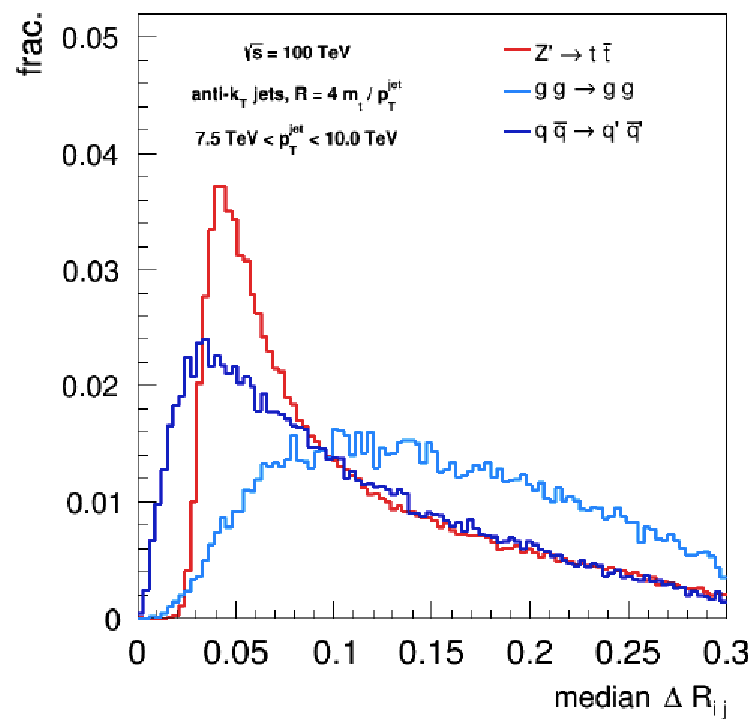
Simulation parameters (II)

	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.

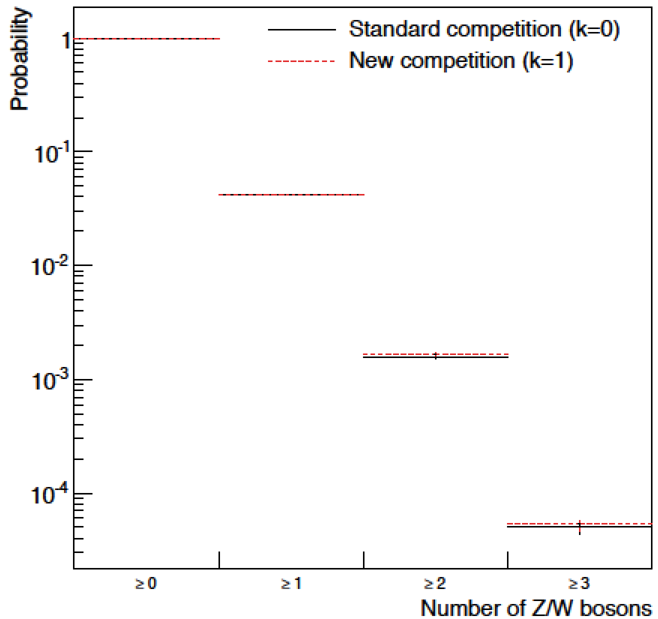
Constituents R_{ij}



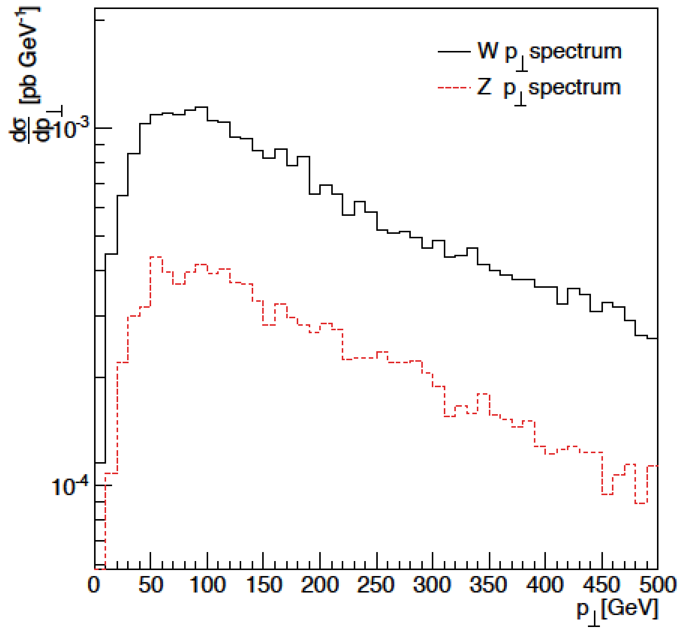


EW parton shower effects

Christiansen, Sjostrand 1401.5238



$p_T > 1$ TeV



EW emission from light quarks has similar pheno as soft gluon emission (especially when $m_W \ll pT$ (jet))

Soft Emissions

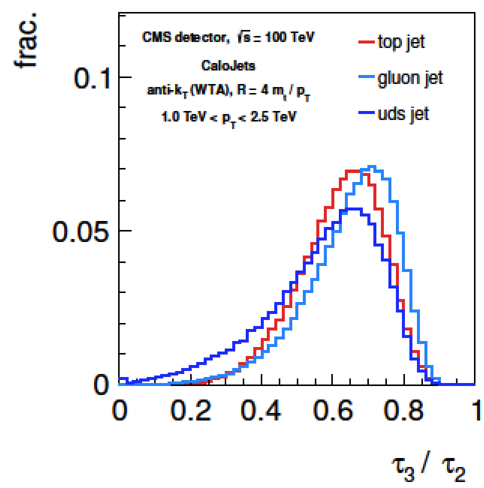
- Effect on jet p_T from **ISR/UE** goes like R^2 assuming uniform density/area → jet mass ~ R^2

- Top direct FSR also contributes outside the dead-cone region, $R_{d.c} \sim m_t / p_T$, while FSR from top decay products is more confined

- May want to remove top direct FSR or not depending on purpose

  - if aim is simply to identify top, ok to remove top FSR
  - if aim is to reconstruct Z' mass, careful, FSR has to be included

Substructure variables (calo)



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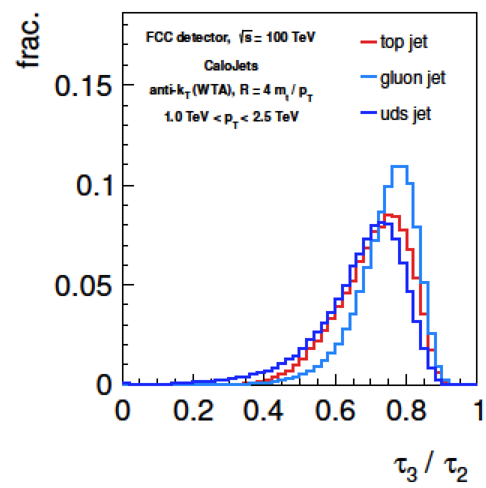

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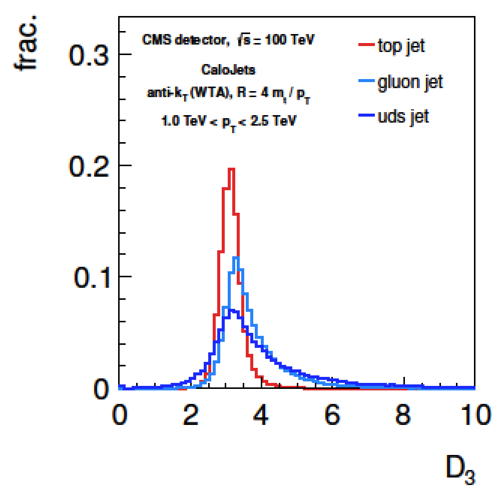

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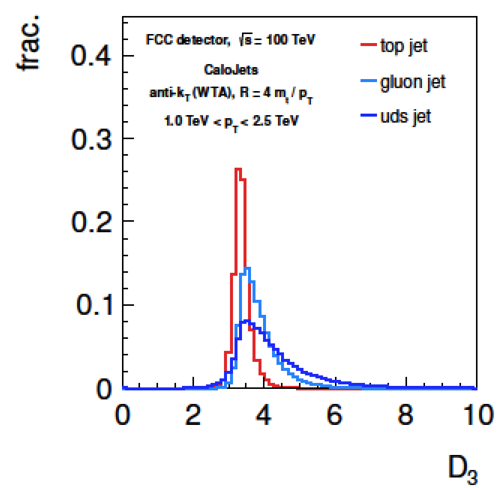

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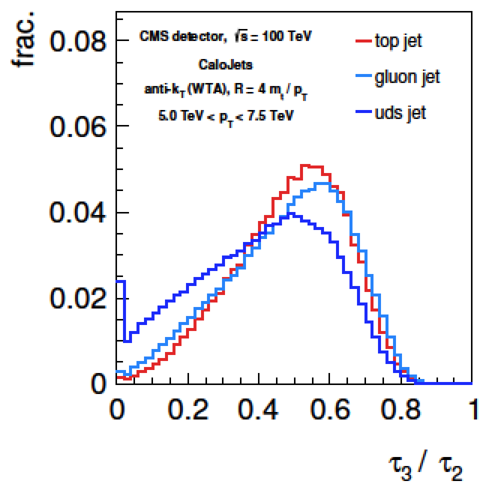

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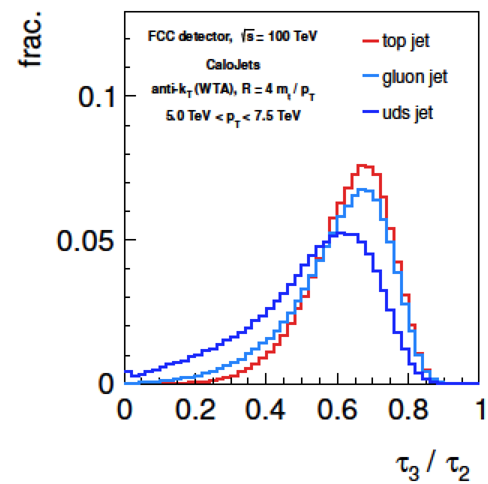

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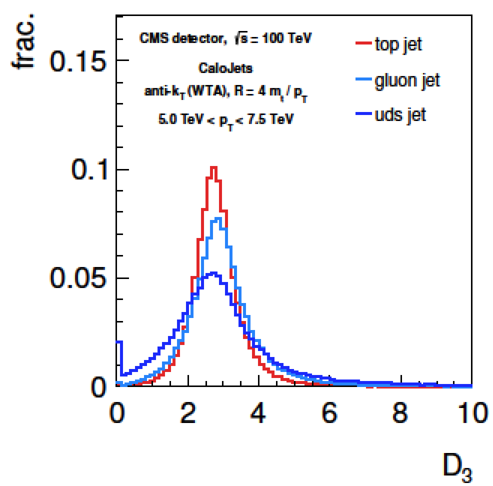

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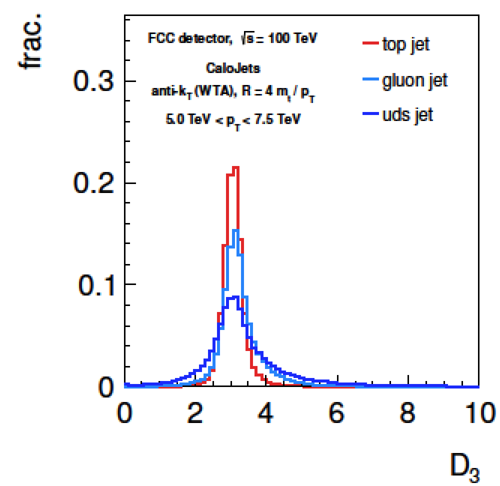

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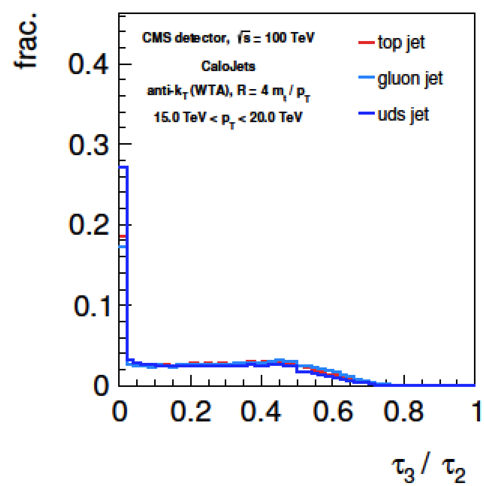

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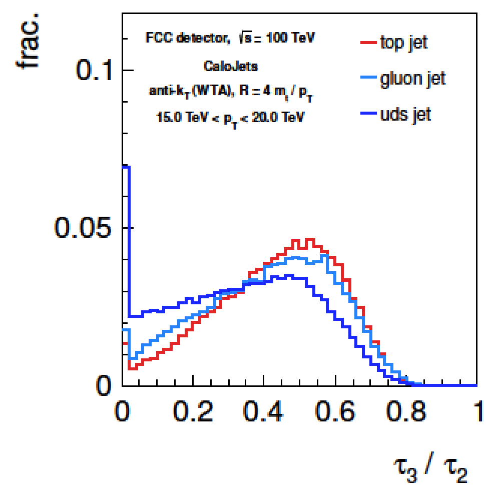

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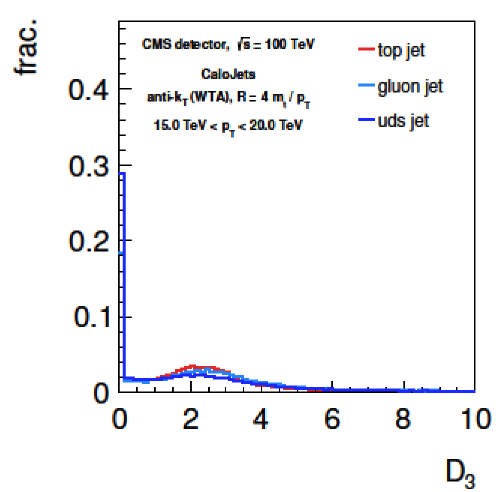

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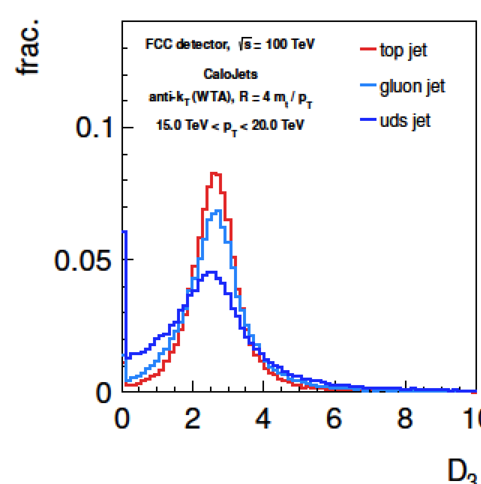

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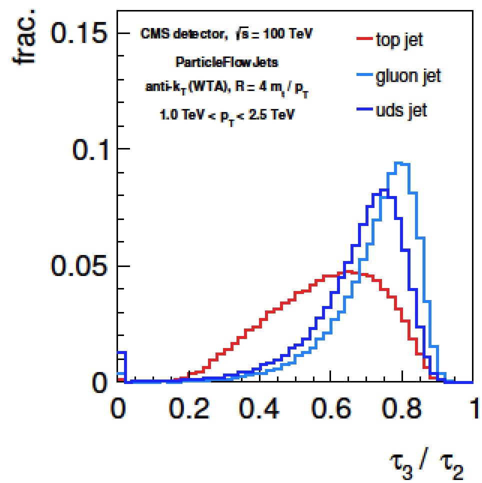
Substructure variables (trk)



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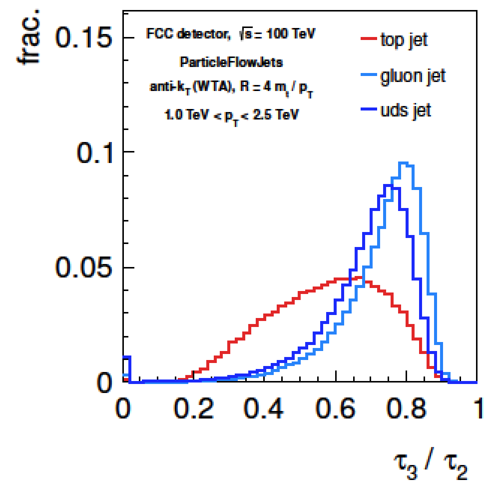

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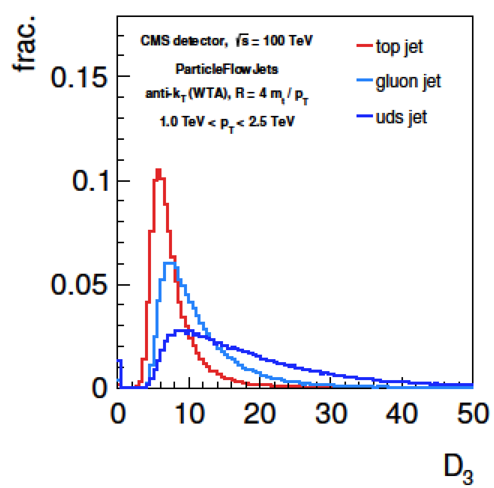

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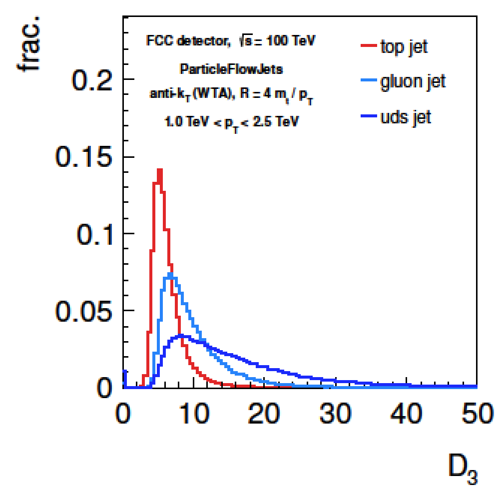

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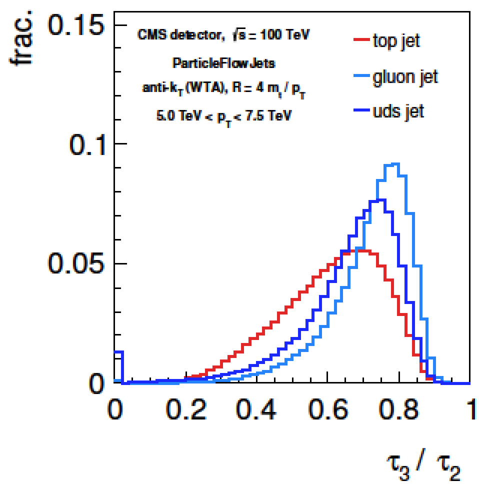

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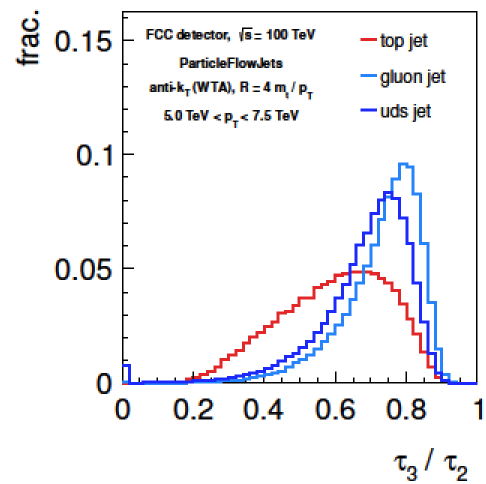

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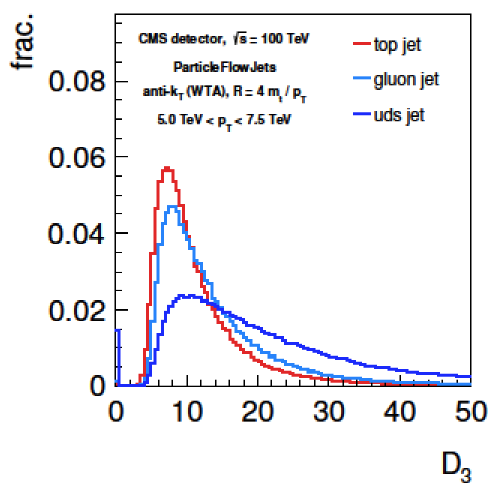

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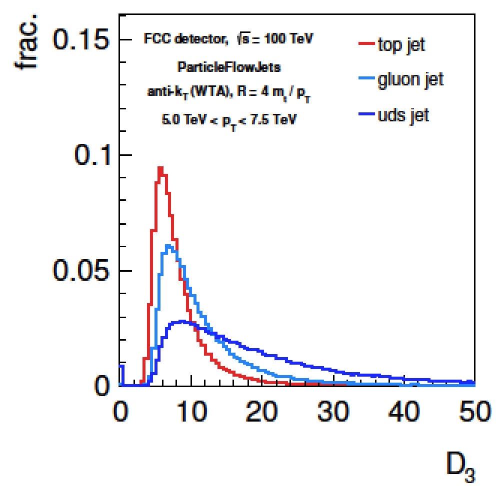

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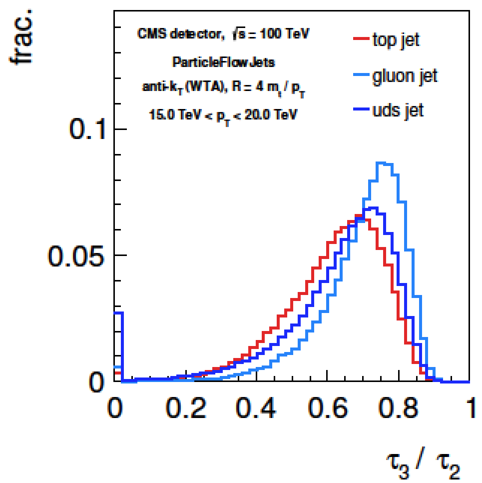

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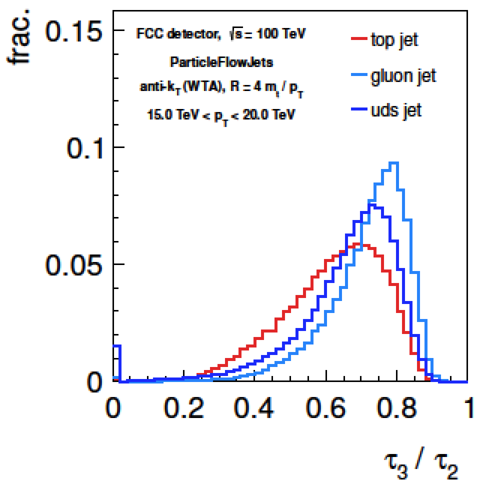

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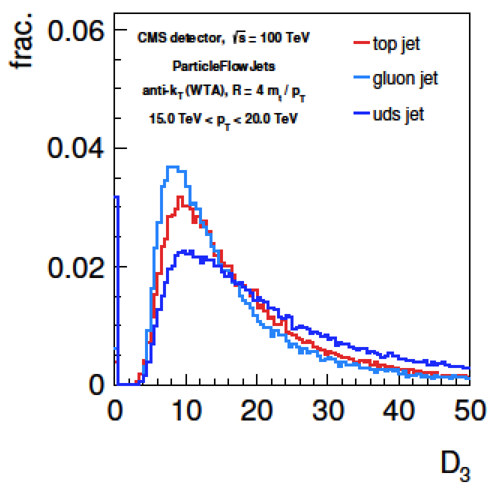

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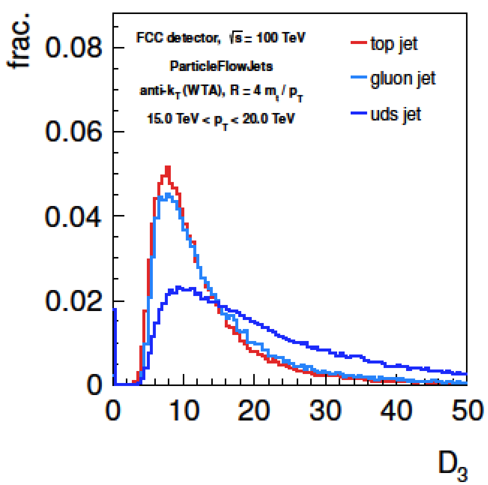

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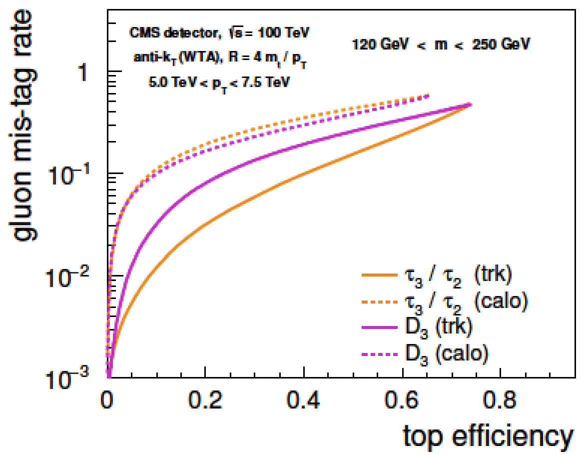
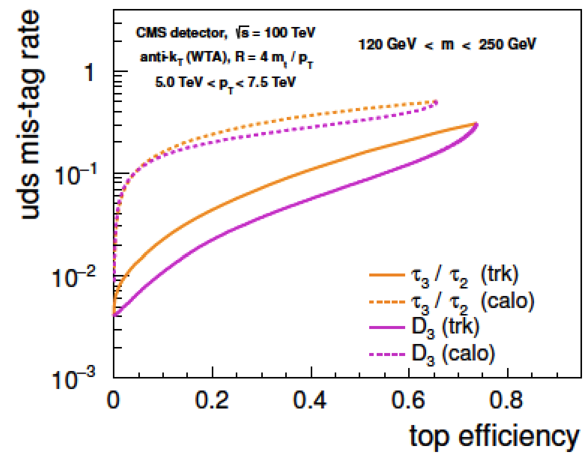
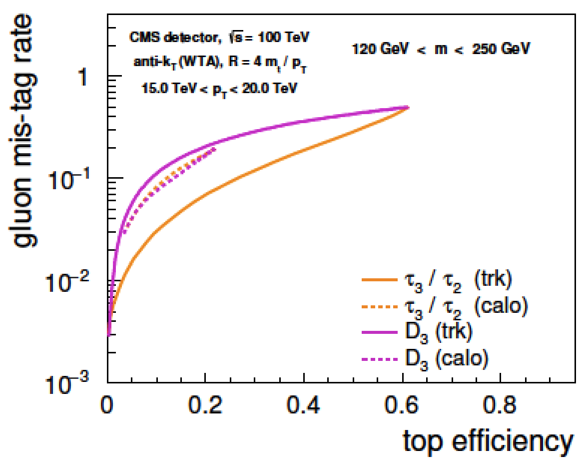
ROC (CMS)


CMS detector, $\sqrt{s}$ = 100 TeV
anti-k_T (WTA), R = 4 m_t / p_T
5.0 TeV < p_T < 7.5 TeV
120 GeV < m < 250 GeV
τ_3 / τ_2 (trk)
τ_3 / τ_2 (calo)
D_3 (trk)
D_3 (calo)
gluon mis-tag rate
top efficiency
10^{-3}
10^{-2}
10^{-1}
1
0
0.2
0.4
0.6
0.8

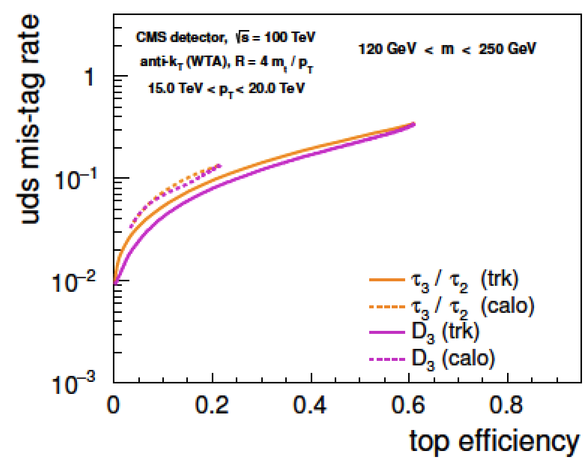
(c)


CMS detector, $\sqrt{s}$ = 100 TeV
anti-k_T (WTA), R = 4 m_t / p_T
5.0 TeV < p_T < 7.5 TeV
120 GeV < m < 250 GeV
τ_3 / τ_2 (trk)
τ_3 / τ_2 (calo)
D_3 (trk)
D_3 (calo)
uds mis-tag rate
top efficiency
10^{-3}
10^{-2}
10^{-1}
1
0
0.2
0.4
0.6
0.8

(d)

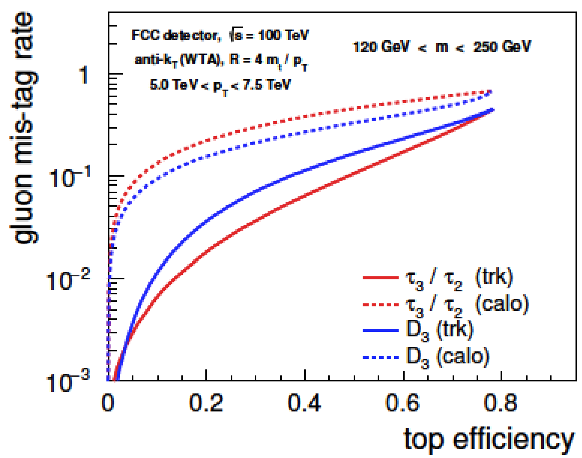

CMS detector, $\sqrt{s}$ = 100 TeV
anti-k_T (WTA), R = 4 m_t / p_T
15.0 TeV < p_T < 20.0 TeV
120 GeV < m < 250 GeV
τ_3 / τ_2 (trk)
τ_3 / τ_2 (calo)
D_3 (trk)
D_3 (calo)
gluon mis-tag rate
top efficiency
10^{-3}
10^{-2}
10^{-1}
1
0
0.2
0.4
0.6
0.8

(e)


CMS detector, $\sqrt{s}$ = 100 TeV
anti-k_T (WTA), R = 4 m_t / p_T
15.0 TeV < p_T < 20.0 TeV
120 GeV < m < 250 GeV
τ_3 / τ_2 (trk)
τ_3 / τ_2 (calo)
D_3 (trk)
D_3 (calo)
uds mis-tag rate
top efficiency
10^{-3}
10^{-2}
10^{-1}
1
0
0.2
0.4
0.6
0.8

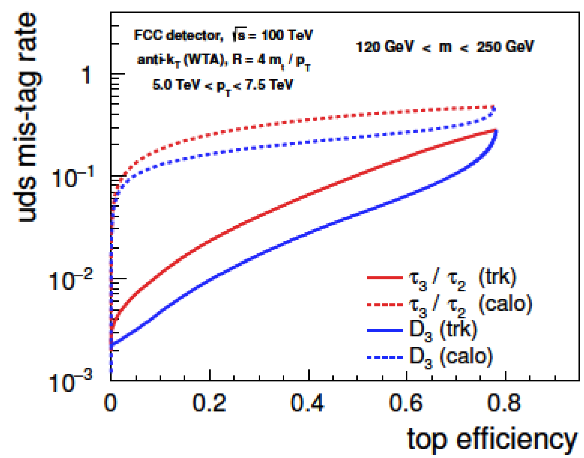
(f)

ROC (FCC)



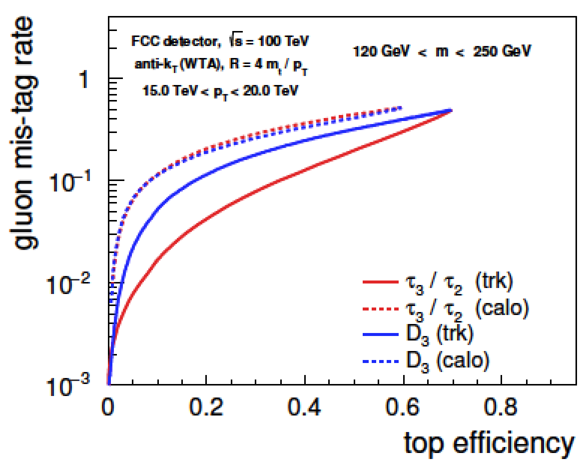
FCC detector, √s = 100 TeV
anti-k$_T$ (WTA), R = 4 m$_t$ / p$_T$
5.0 TeV < p$_T$ < 7.5 TeV
120 GeV < m < 250 GeV
gluon mis-tag rate
top efficiency
τ$_3$ / τ$_2$ (trk)
τ$_3$ / τ$_2$ (calo)
D$_3$ (trk)
D$_3$ (calo)

(c)



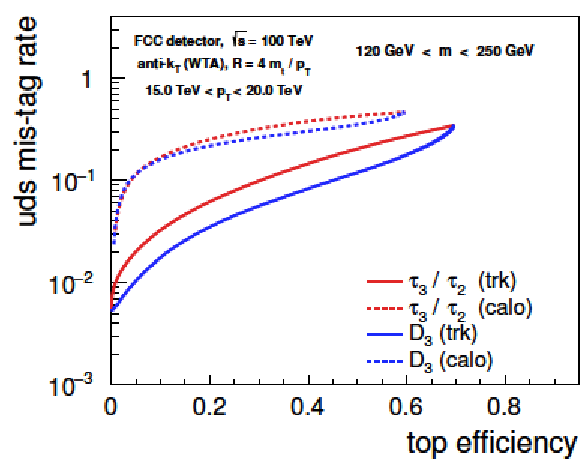
FCC detector, √s = 100 TeV
anti-k$_T$ (WTA), R = 4 m$_t$ / p$_T$
5.0 TeV < p$_T$ < 7.5 TeV
120 GeV < m < 250 GeV
uds mis-tag rate
top efficiency
τ$_3$ / τ$_2$ (trk)
τ$_3$ / τ$_2$ (calo)
D$_3$ (trk)
D$_3$ (calo)

(d)



FCC detector, √s = 100 TeV
anti-k$_T$ (WTA), R = 4 m$_t$ / p$_T$
15.0 TeV < p$_T$ < 20.0 TeV
120 GeV < m < 250 GeV
gluon mis-tag rate
top efficiency
τ$_3$ / τ$_2$ (trk)
τ$_3$ / τ$_2$ (calo)
D$_3$ (trk)
D$_3$ (calo)

(e)



FCC detector, √s = 100 TeV
anti-k$_T$ (WTA), R = 4 m$_t$ / p$_T$
15.0 TeV < p$_T$ < 20.0 TeV
120 GeV < m < 250 GeV
uds mis-tag rate
top efficiency
τ$_3$ / τ$_2$ (trk)
τ$_3$ / τ$_2$ (calo)
D$_3$ (trk)
D$_3$ (calo)

(f)