Top quark physics 2019, Sep 23-27, 2019

High energy tops including boosted top tagging at the Energy Frontier

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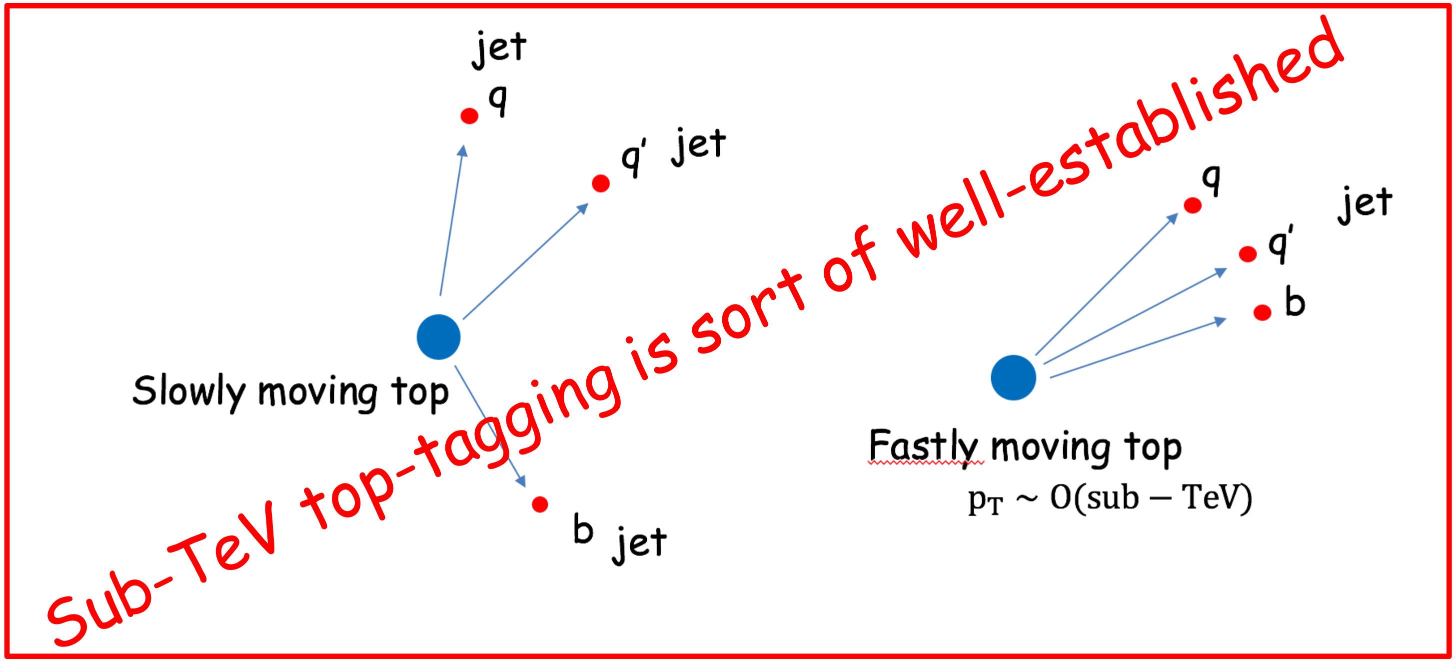
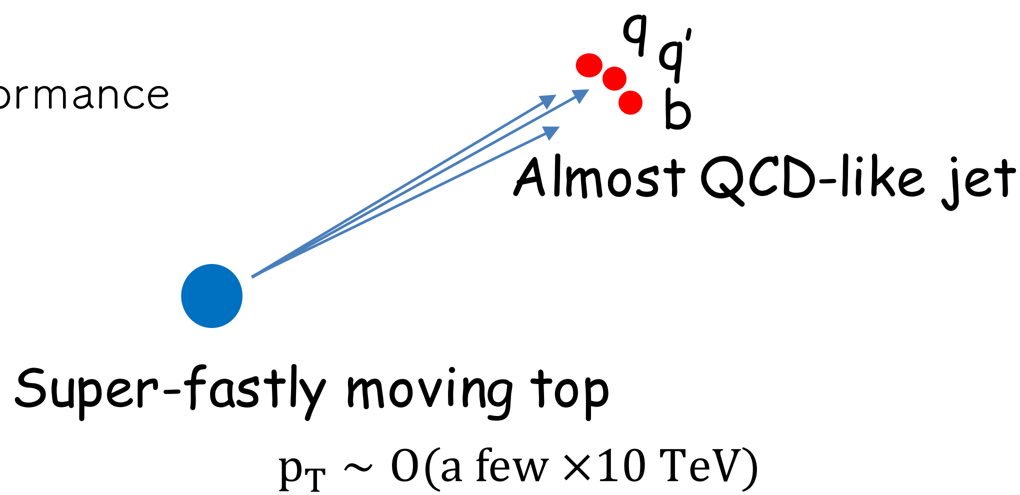
Mostly based on work with Zhenyu Han and Brock Tweedie

PRD 2018

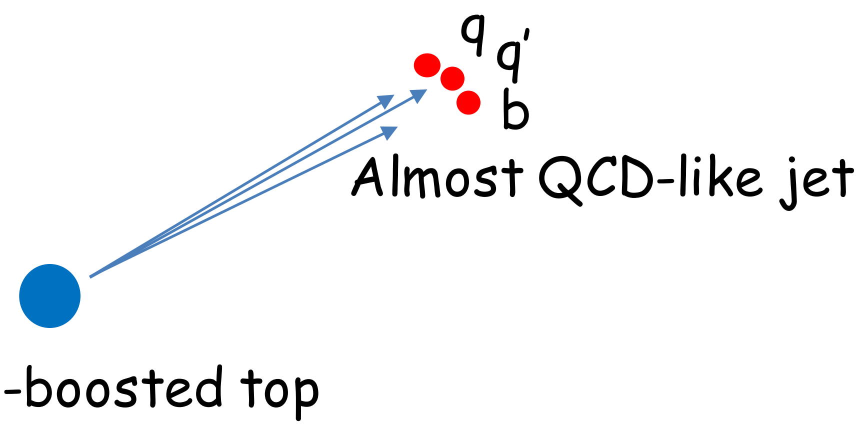


How would top tagging performance evolve with much higher p_T ?



Many challenges arise as tops enter into hyper-boosted regime

Physics,
Detector,
Tagger/optimization



$p_T \sim O(\text{a few} \times 10\ \text{TeV})$

Physics

1. Instability from soft radiation

1.1 Spurious mass scale in QCD jets

$$m^2 \sim p_T p_T^{soft} R^2 \sim m_{top}^2$$

$$p_T^{soft} \sim 5\ \text{GeV}, \quad p_T \sim 6\ \text{TeV} \quad R \sim 1$$

1.2 $\mathcal{O}(1)$ fluctuation of top-jet mass for fixed cone, $R \sim 1$

$$m^2 \sim m_{top}^2 + p_T p_T^{ISR} R^2 \sim O(1) \times m_{top}^2$$

$$p_T^{ISR} \sim \frac{m_{top}^2}{p_T R^2} \sim 5\ \text{GeV}, \quad p_T \sim \text{few} \times m_{top} \times 10,$$

Physics

1. Instability from soft radiation

1.1 Softened spurious mass scale in QCD jets

$$m^2 \sim \cancel{p_T p_T^{soft} R^2 \sim m_{top}^2}$$

$$\sim m_{top}^2 \times \beta_R^2 \frac{p_T^{soft}}{p_T}$$

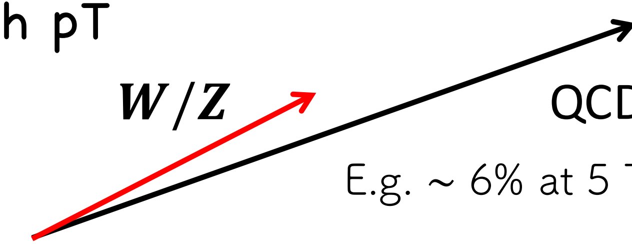
1.2 Softened fluc. of top-jet mass for shrinking cone, $R \sim \beta_R \frac{m_{top}}{p_T}$, e.g. $\beta_R \sim 4$

$$m^2 \sim \cancel{m_{top}^2 + p_T p_T^{ISR} R^2 \sim O(1) \times m_{top}^2}$$

$$\sim m_{top}^2 \left(1 + \beta_R^2 \frac{p_T^{ISR}}{p_T}\right)$$

Physics

2. EW-strahlung at high pT

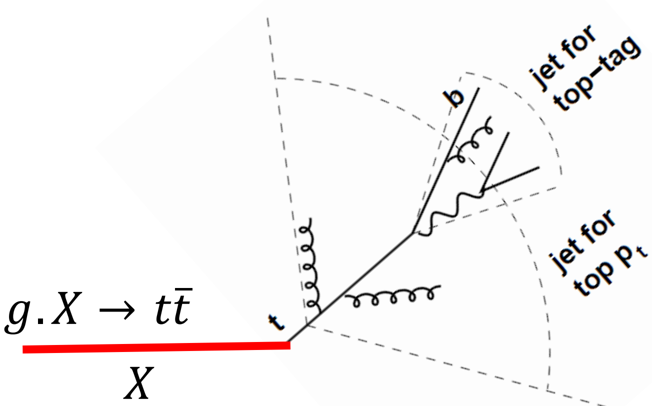


E.g. ~ 6% at 5 TeV quark-jet (unpolarized)

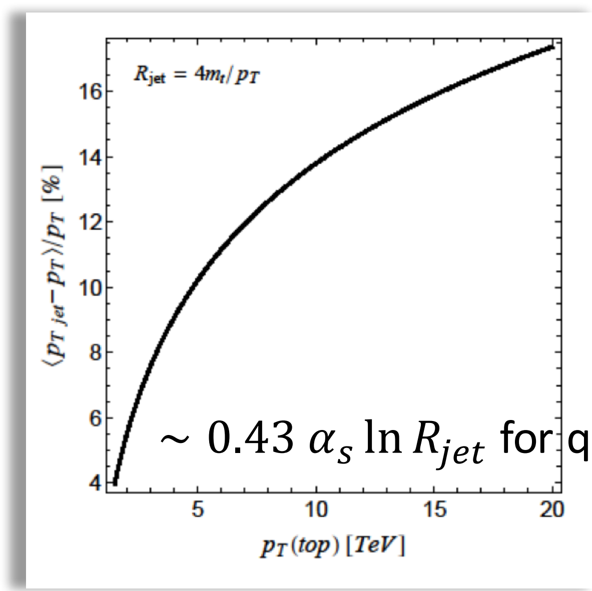
3. Dead cone, FSR, shrinking cone

FSR: junk from top-tagging point of view
FSR: important to reconstruct the correct resonance mass

$E.g. X \rightarrow t\bar{t}$



G. Salam, talk given at
LHC New Physics Forum, IWH, Heidelberg, 23-26 Feb, 2009



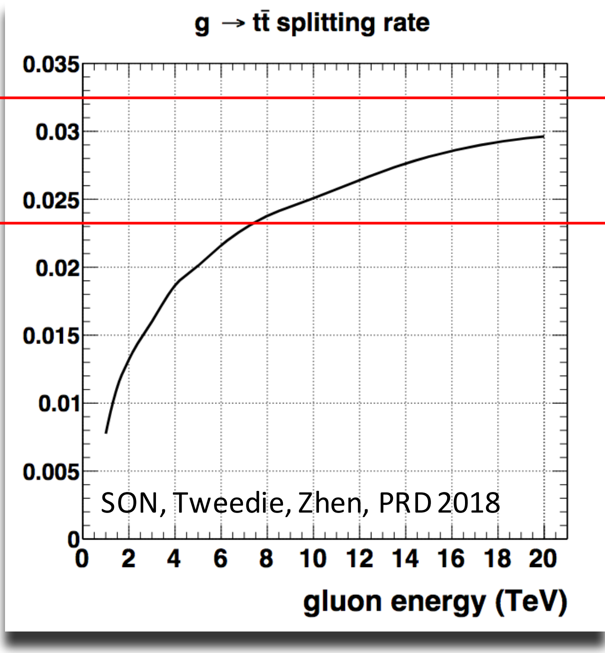
$\sim 0.43\, \alpha_s \ln R_{jet}$ for quark-jet

Salam 2010
'Towards Jetography'

Physics

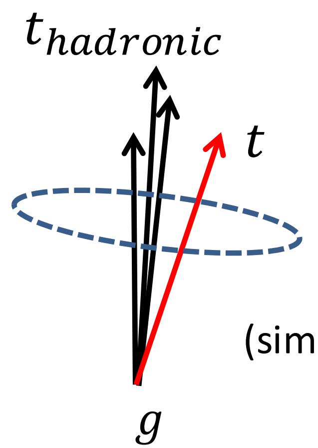
4. Merged tops from $g \to t\bar{t}$ vs prompt tops

: a gluon directly split into a $t\bar{t}$ pair, with the leading top in the pair decaying hadronically



2-3% at the scale of $\mathcal{O}(10\ \mathrm{TeV})$

: comparable to the mistag rate !!



(similarly for $t_{semileptonic}$)

$$\epsilon_{mistag} \sim r_{g\to t\bar{t}} \times \epsilon_{t\bar{t}} \sim 1\%$$

E.g. $\epsilon_{t\bar{t}} \sim 0.35$ for $\epsilon_t \sim 0.5$ (50% working pt) without extra variables

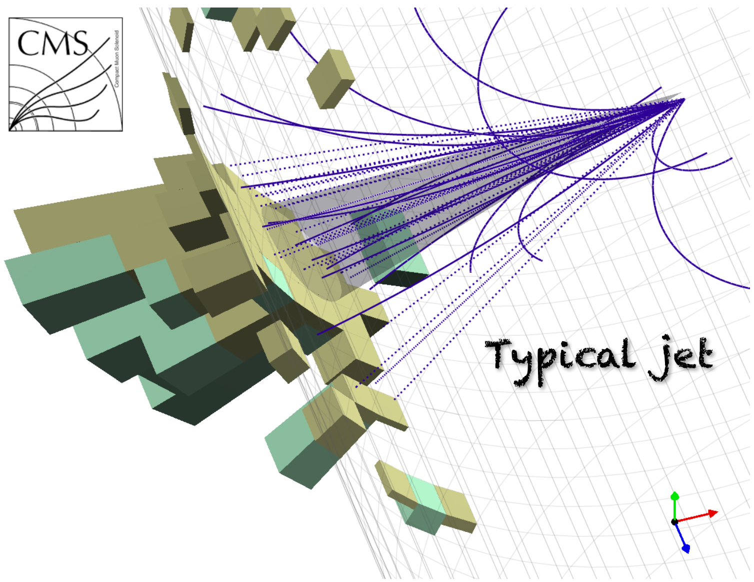
$(\sim 2/3 * 0.5)$

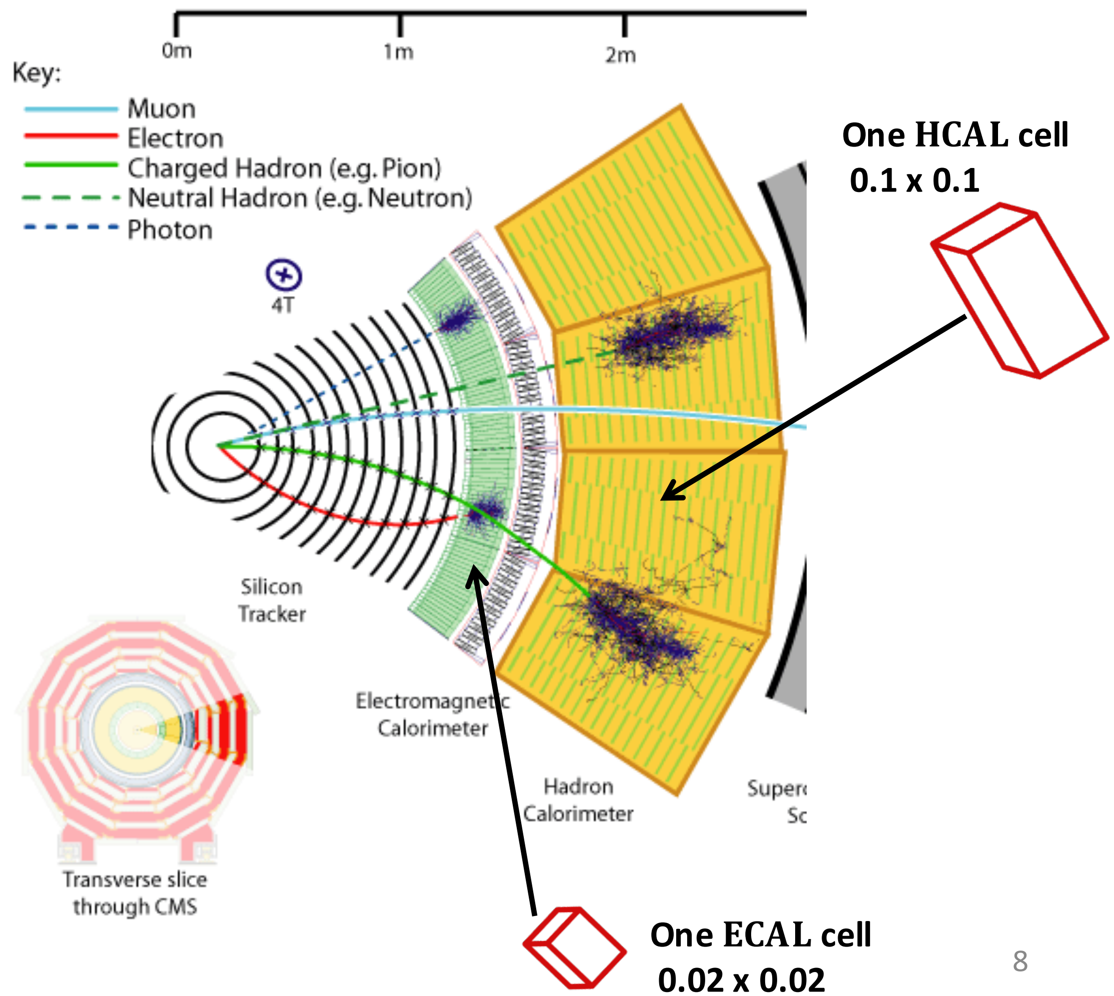
✓ counting tracks/fragmentation fraction could help

Detector : instrumental challenge

Detector granularity is becoming a big problem.

ATLAS/CMS has three layers of main sub-detectors

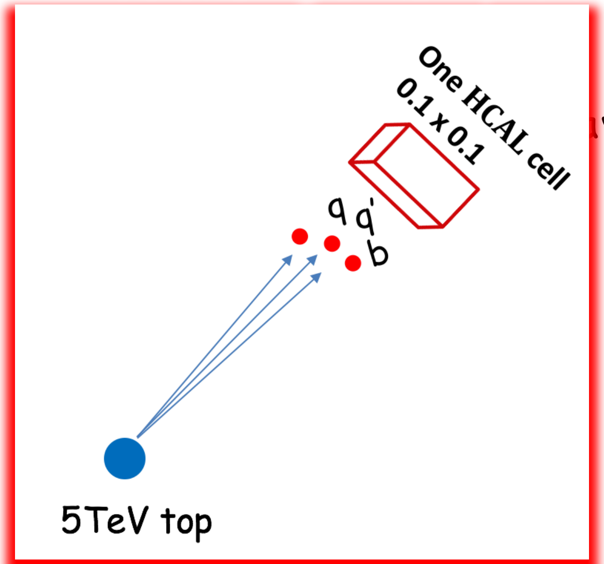


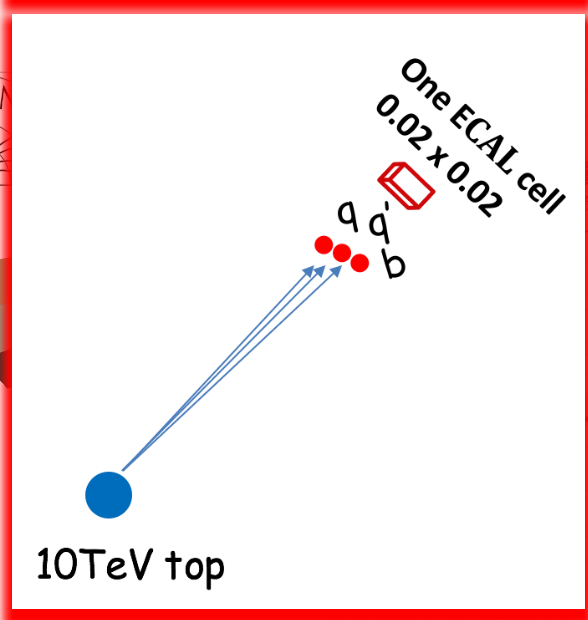


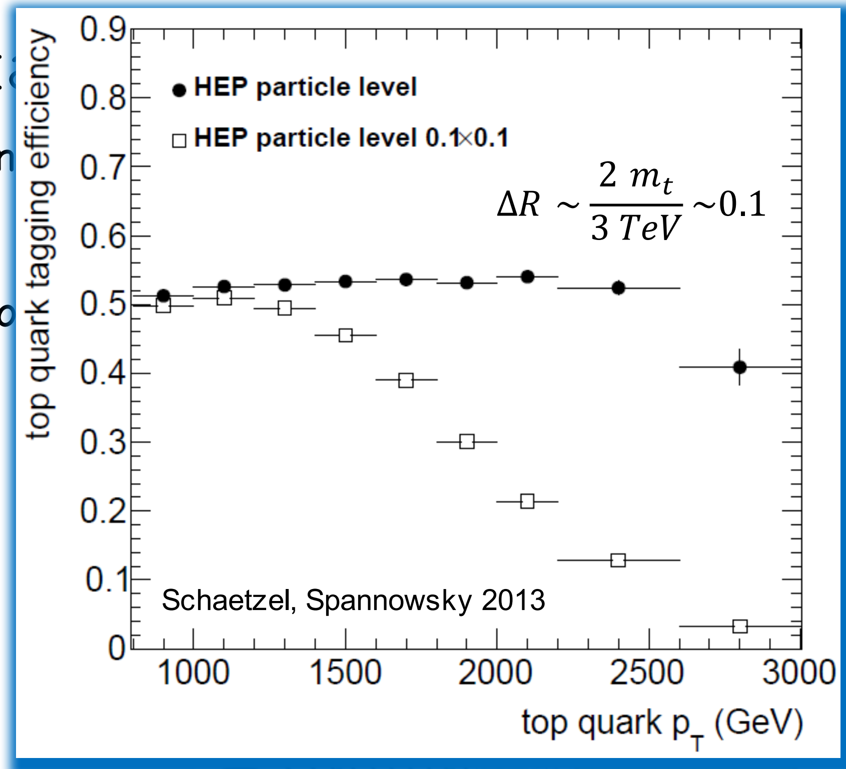
Detector : instrumenta

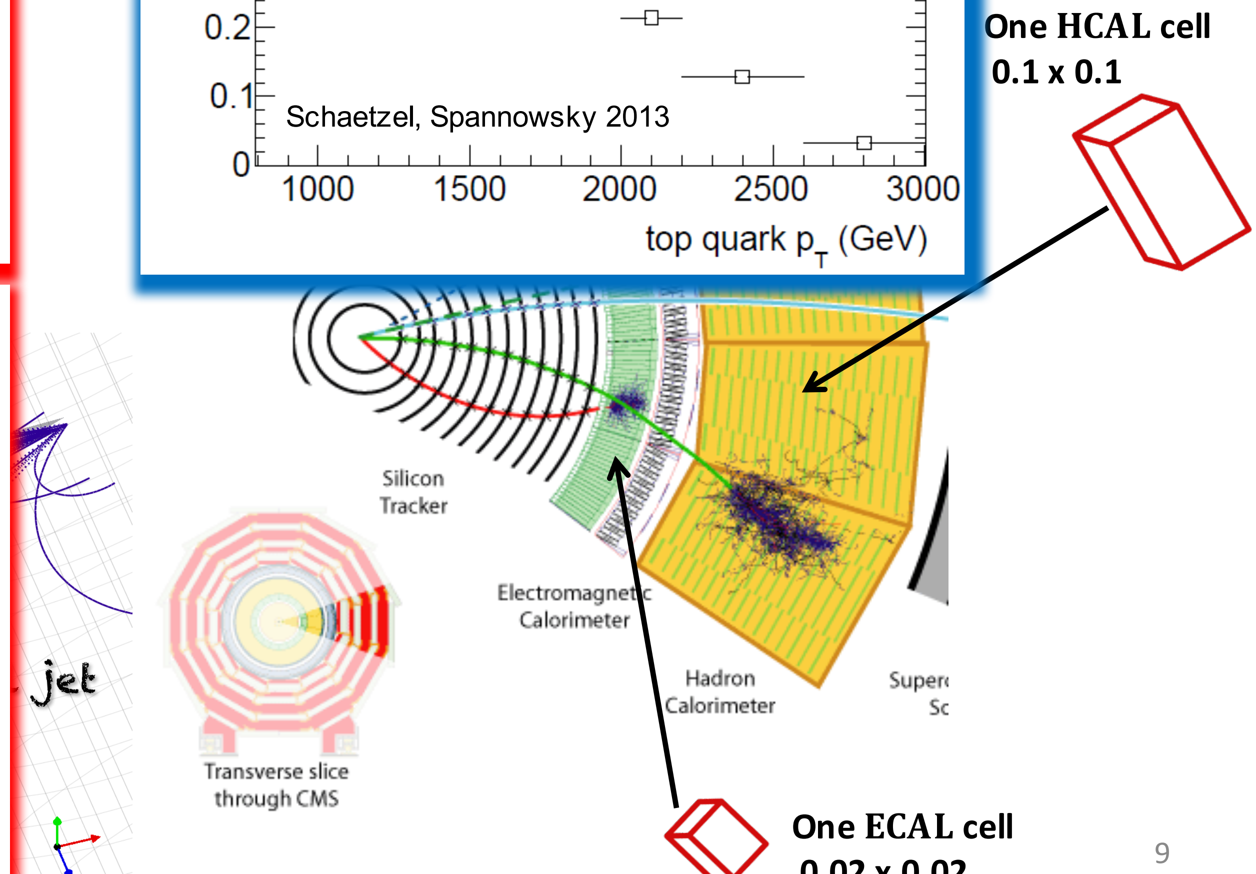
Detector granularity is becomin

yers o









Detector : instrumental challenge

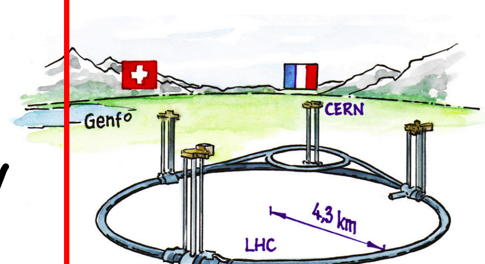
FCC (Future Circular Collider)

100 km

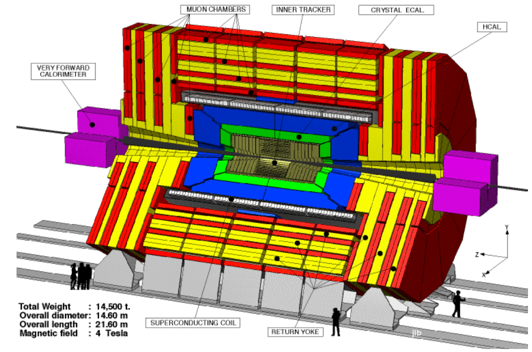
100 TeV

~ 7x upgrade of CM energy

E.g. 3 TeV top at the LHC would expect ~20 TeV tops at 100 TeV



14TeV



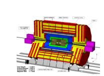
7x rescaled up from LHC

7x

Better resolution of ? Likely NEVER

HCAL, ECAL

Tracker



LHC detector

Detector technology will likely not be able to catch up with the E upgrade

✓ Understanding our current detector better is a KEY-ingredient to predict our future capability

Capability at the LHC + FCC proposal → Capability at the FCC

Three benchmark scenarios

Model	Tracking: two extremes	ECAL material	ECAL cell	HCAL cell
LHC		CMS-type ($PbWO_4$)	0.02×0.02	0.1×0.1
FCC1	Perfect/absent	$PbWO_4$ (Lead tungstate)	0.01×0.01	0.05×0.05
FCC2	Perfect/absent	Pure W (Tungsten)	0.005×0.005	0.05×0.05

Existing Literature

Katz, MS, Tweedie, Spethmann 2011, 2012
Snowmass 2013
Schaetzel, Spannowsky 2013
CMS PAS JME-14-002 2014
Spannowsky, Stoll 2015
Larkoski, Maltoni, Selvaggi 2015
Bressler, Flacke, Katz, Lee, Perez 2016
MS,Tweedie, Zhenyu 2017
Coleman, Freytsis, Hinzmann, Narain, Thaler, Tran, Vernieri 2017
Dreyer, Salam, Soyez
....

We will focus on JHU top tagger + N-subjettiness

1. Optimize JHU top tagger + N-subjettiness at particle level

   We will newly show that N-subjettiness is not just an alternative to other top-taggers, but it adds a new information to improve top/gluon discrimination

2. Introduce various detector models

   We will illustrate how one can combine information, scattered in here and there in sub-detectors, to extract a meaningful result

3. Optimize JHU top tagger + N-subjettiness in various detector models

   This step will establish the "robustness of shape variables vs declustering variables against different detector configurations"

Tagger/Optimization

Clustering/declustering/cut parameter of JHU top tagger & $\boldsymbol{\tau_{32}}$

$R_{\text{Anti-kt}} = 1.0$

$R_{jet} \equiv \beta_R \times \frac{m_t}{p_T}$: Shrinking jet-cone size

δ_p: pT asymmetry cut , $\delta_r \equiv \beta_r \times \frac{m_t}{p_T}$: min angular separation

m_{min}: min jet pair mass m_{top}: reco- top mass $\tau_{32} \equiv \tau_3/\tau_2$: N-subjettiness

Optimization over seven parameters

$$\text{Tag/mistag Rate} \equiv \frac{\#\,\text{survived to the end}}{\#\,\text{generated with } 1\%\ \text{pT window}}$$

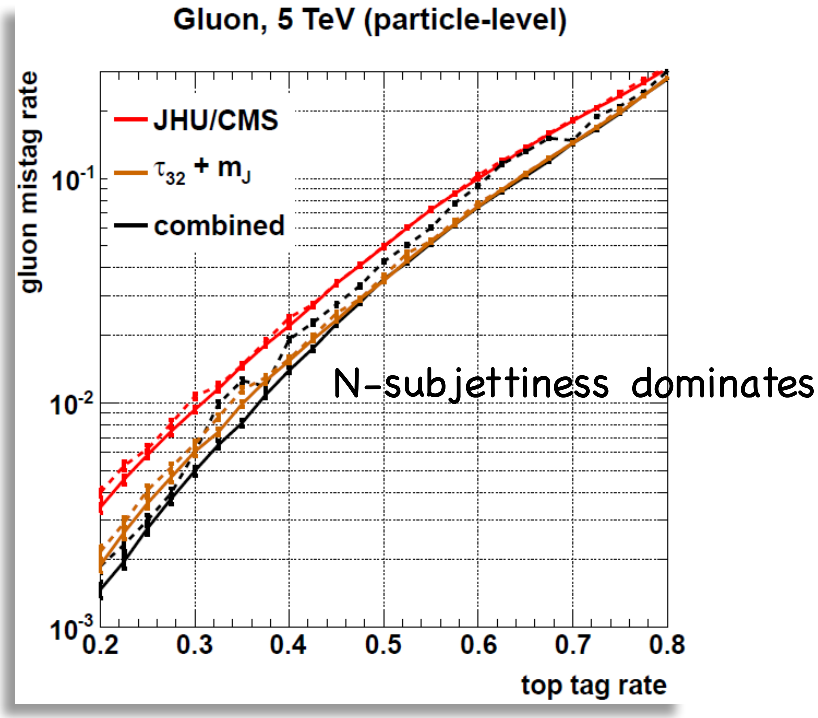
Signal: continuum $t\bar{t} \to \mu + jets$ Quark/gluon: $qZ \to q(\nu\bar{\nu})$, $gZ \to g(\nu\bar{\nu})$

: samples are restricted to $|\eta| < 1.0$, $p_T = [p_T - 1\%, p_T + 1\%]$ GeV

Top/gluon discrimination at particle level

SON, Tweedie, Zhen, PRD 2018 for top/quark discri.

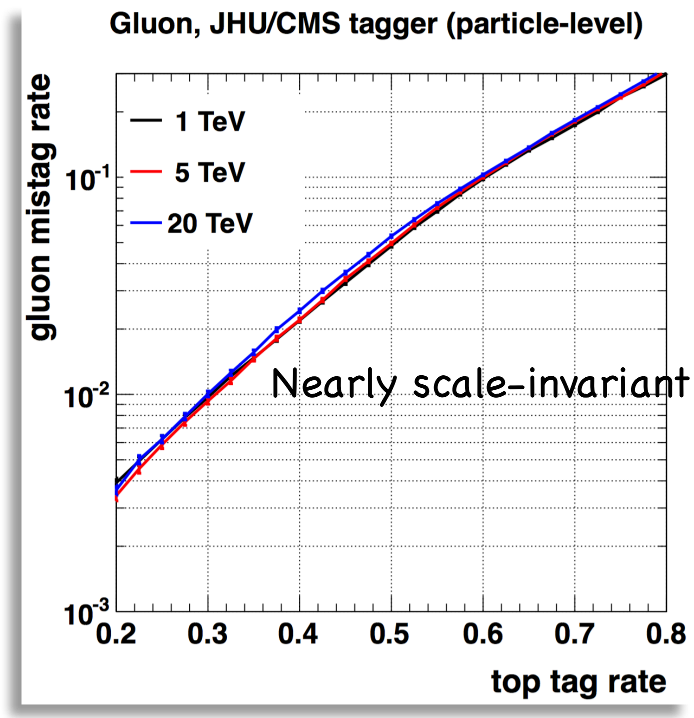
Flavor-dependent optimization



With gluon-optimized pars

With quark-optimized pars

p_T-dependent optimization



$\beta_R \sim 4,\ \beta_r \sim 0.7,\ \delta_r \sim 0.03$ for relevant tag efficiencies

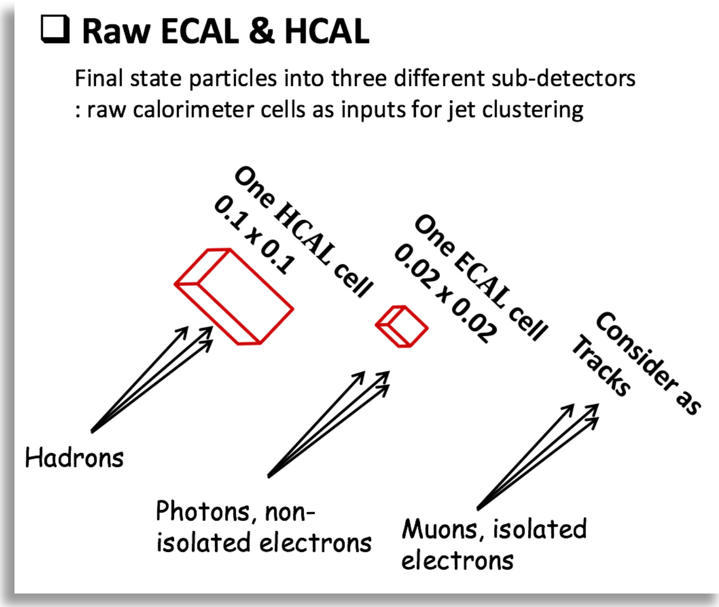
optimized β_R and β_r stay fixed, simple $\sim 1/p_T$ scaling works

- Simultaneous optimizations of the quark and gluon jets are possible
- N-subjettiness adds extra discriminating power for gluon-jets, not quark-jets

Introducing detector effect

What is a good detector model?

It is the one that minimally breaks the 'scale invariance' and brings the result back to our expectation at the 'particle-level'



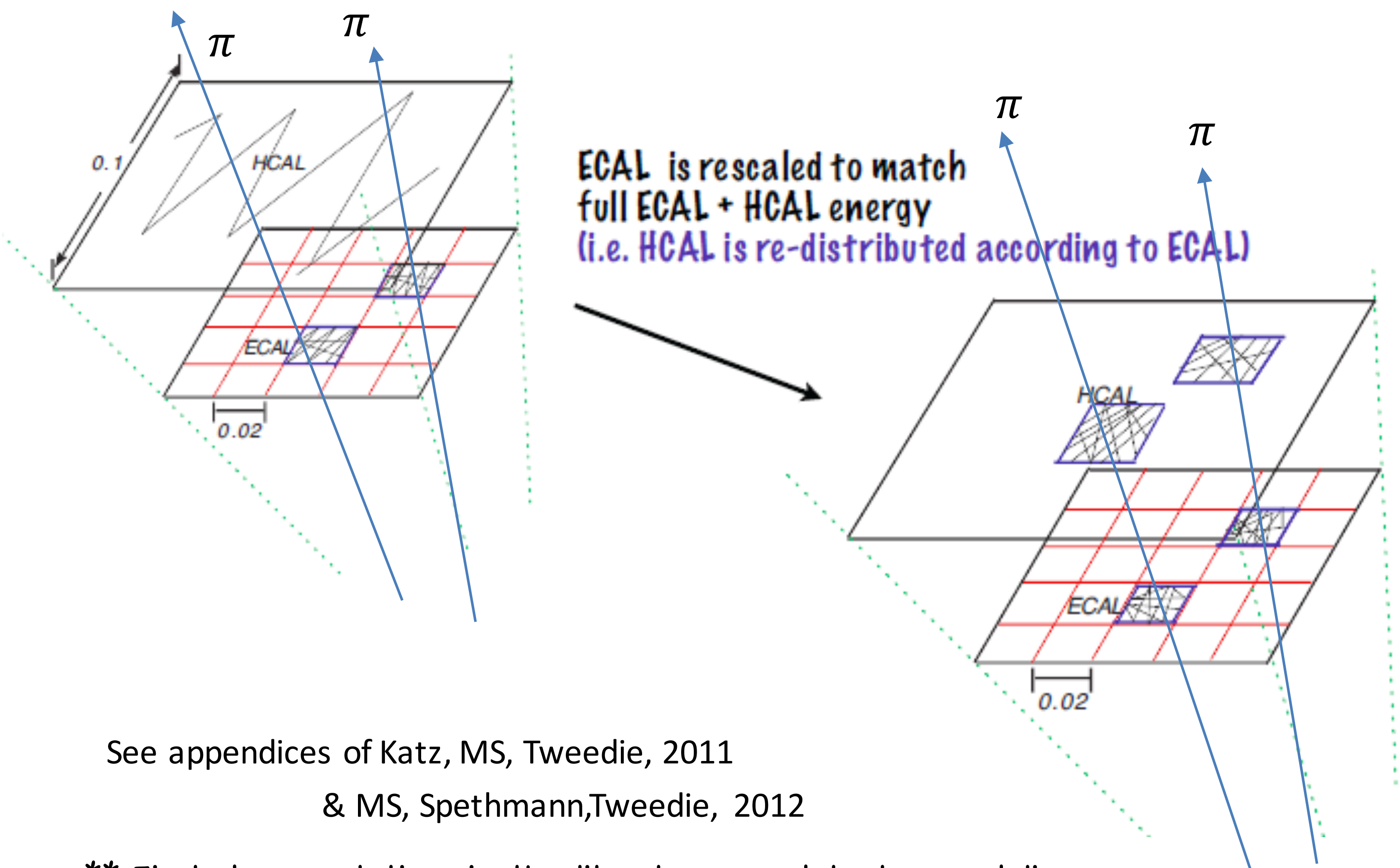
The real detectors are insanely complicated. The above simple version would not work at high pT
Our toy detector model would catch the leading effects.

Introducing detector effect

Use every bit of information from three layers of sub-detectors

(similar philosophy to CMS particle flow)

Example



See appendices of Katz, MS, Tweedie, 2011

& MS, Spethmann,Tweedie, 2012

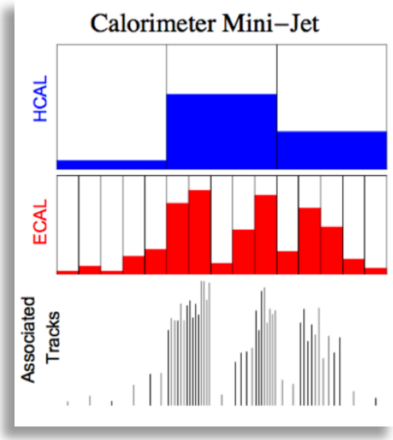
** First documentation in the literature on detector modeling

Combining information is not unique

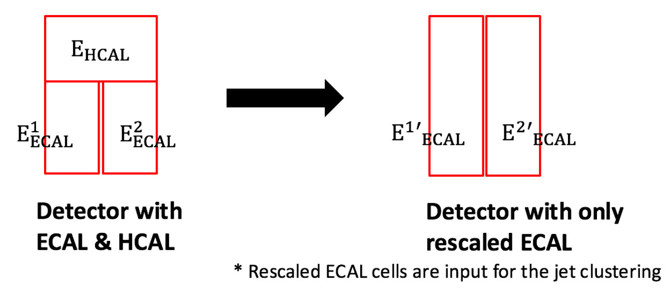
❑ EM-flow

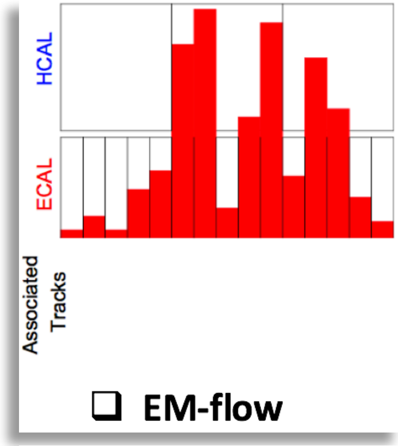
Katz, MS, Spethmann, Tweedie 2011, 2012

Pseudo-CMS type Event



Rescale ECAL cells by $\frac{E_{ECAL}+E_{HCAL}}{E_{ECAL}}$

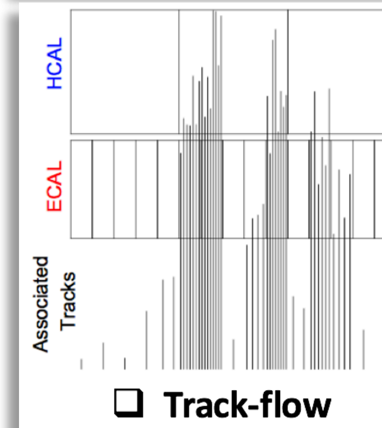




❑ Track-flow

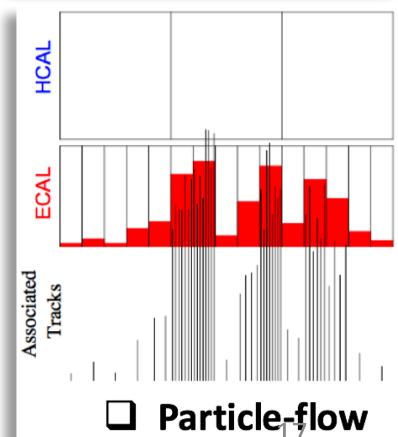
Similarly rescale tracks by $\frac{E_{ECAL}+E_{HCAL}}{E_{tracks}}$

Schatzel, Spannowsky 2014
Larkoski, Maltoni, Selvaggi 2015



❑ Particle-flow

Rescale tracks by $\frac{E_{HCAL}}{E_{tracks}}$ and leave E_{ECAL} as-is



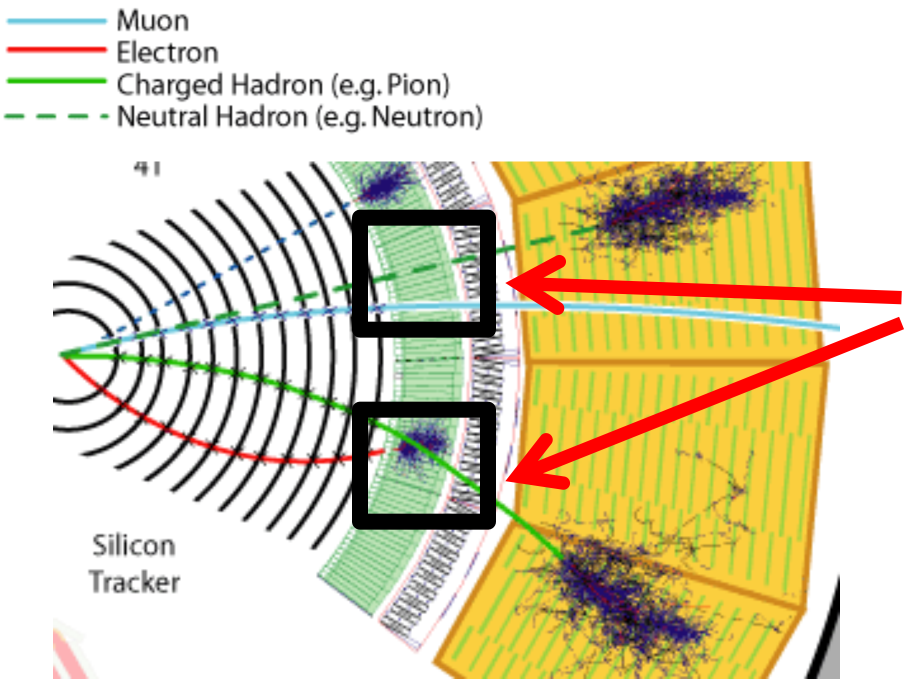
- PERFECT tracking efficiency is assumed. Reality is worse than this perfect case

Two crucial detector effects added to be more realistic

SON, Tweedie, Zhen, PRD 2018

, compared to
Katz, MS, Tweedie, JHEP 2011
MS, Spethmann,Tweedie, PRD 2012

1. **Energy-smearing into nearby calorimeter cells**
2. **Hadrons deposit their energies in ECAL cells**



Unlike the situation in this cartoon, hadrons have O(1) chance to leave their energies (e.g. via Nuclear interaction) in ECAL before reaching HCAL.

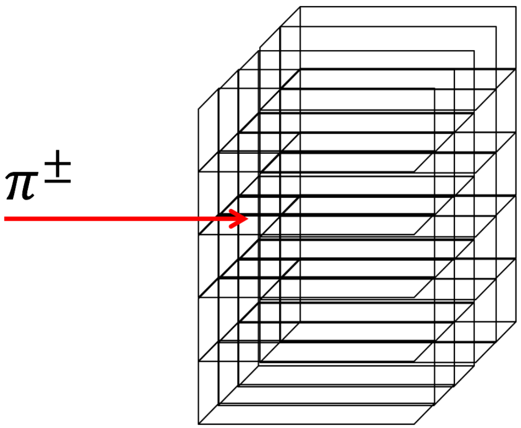
O(20%) of jet energy becomes absorbed in the ECAL in this manner

GEANT4

- ECAL smearing pattern/hadron-energy-deposit-in-ECAL will be simulated with GEANT4 whereas HCAL smearing pattern will be done by simple ansatz

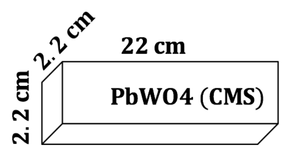
Upgraded version of MS, Spethmann, Tweedie 2012 (See Appendix of 1204.0525)

Energy smearing into nearby ECAL cells

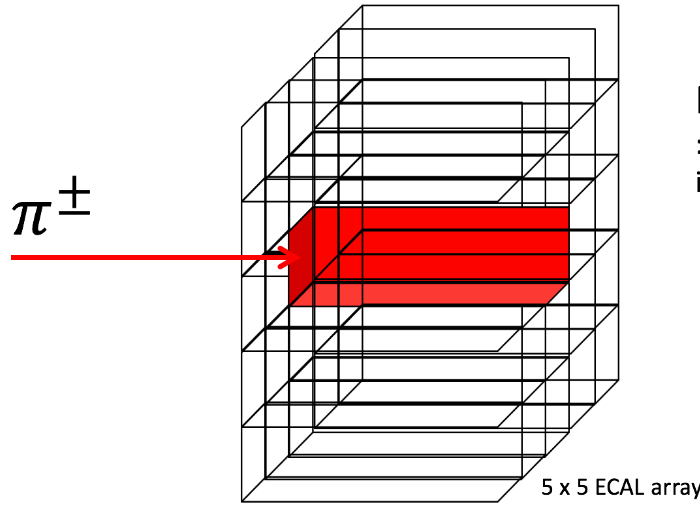


5 x 5 ECAL cells underneath one HCAL cell

A particle hitting single ECAL cell

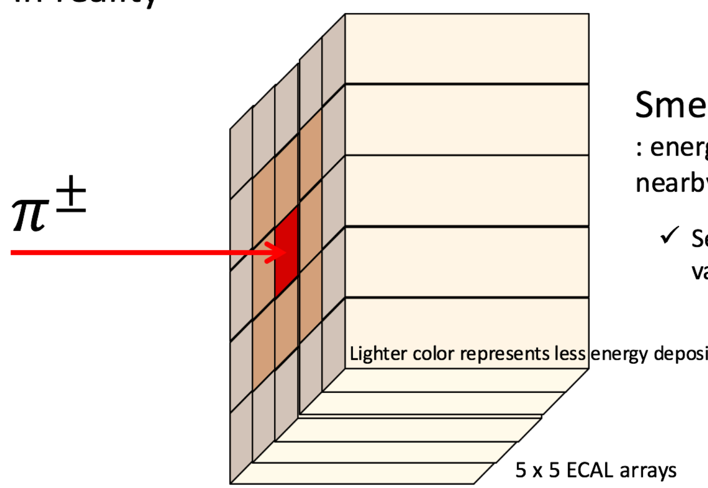


Ideal situation



NO smearing
: all energy is deposited in a single ECAL cell

In reality



Smearing
: energy is smeared into nearby ECAL cells

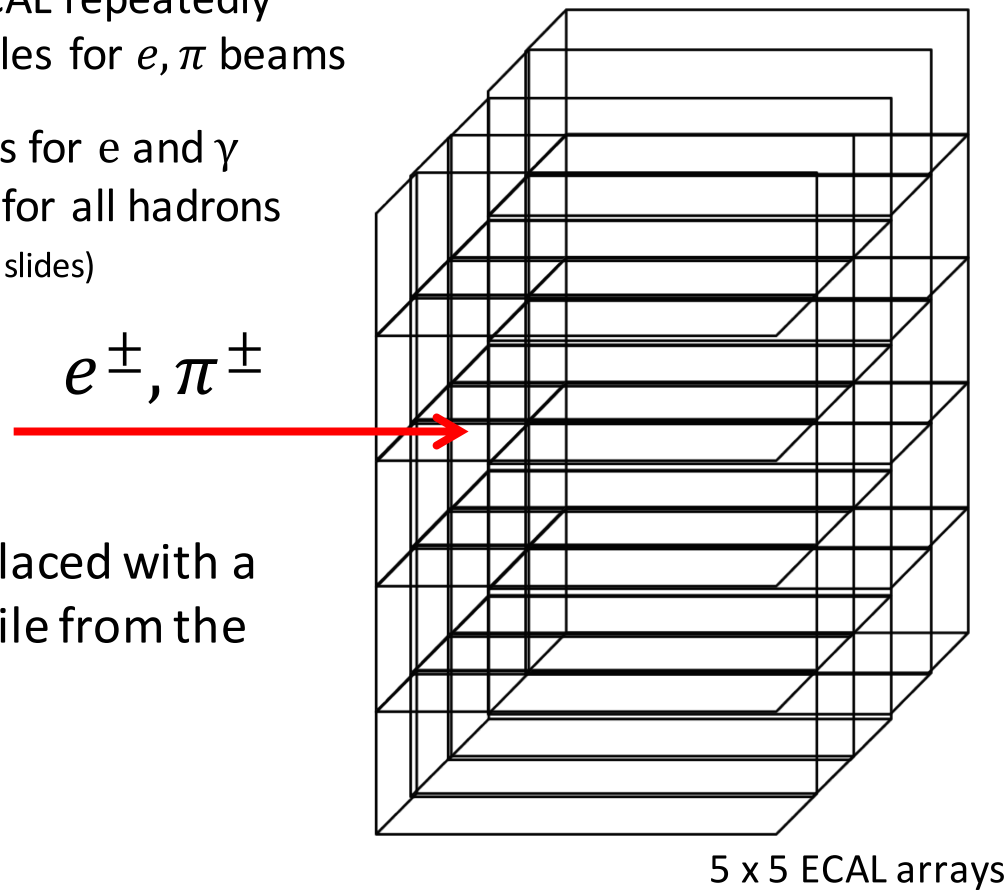
✓ Sensitive to jet substructure variables

We simulate ECAL smearing by GEANT

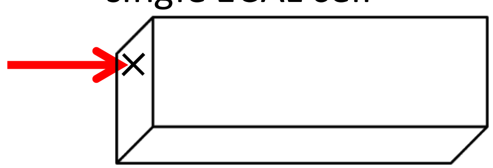
1. Prepare 9x9 ECAL cells with same dimension as CMS ECAL
2. Shoot single $e^{\pm}$, $\pi^{\pm}$ beams onto ECAL repeatedly
3. Build up a library of showering profiles for e, π beams

- ✓ e-induced showers as proxies for e and γ
- ✓ π-induced showers as proxy for all hadrons

Energy is fixed to be 100 GeV (see extra slides)



❑ Particle hitting a ECAL cell is replaced with a randomly chosen smearing profile from the library

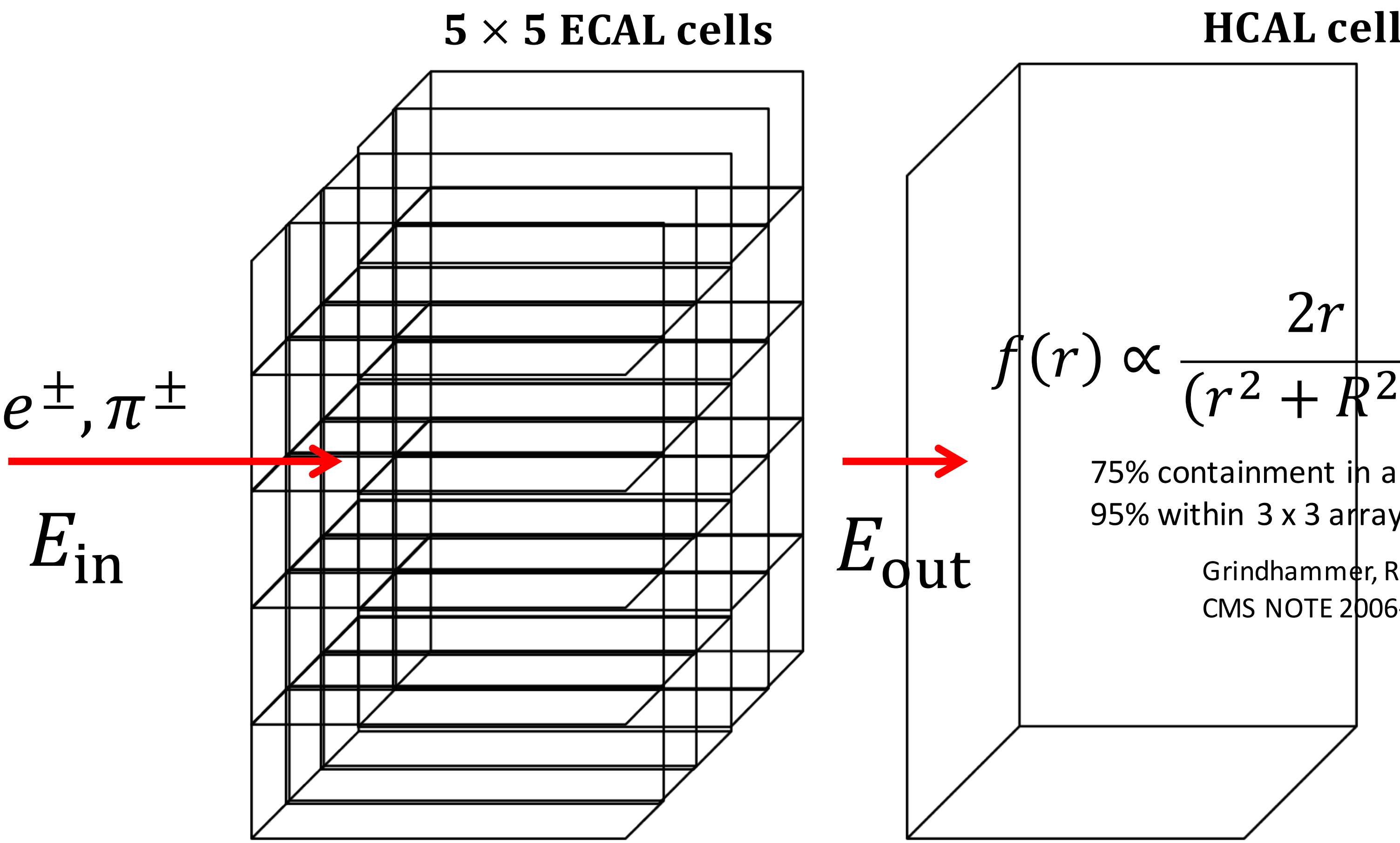


✓ Asymmetric impact point folded

: We sub-divide ECAL into 9x9=81 sub-cells to take into account asymmetric showering pattern

* Correlation between cells are automatically folded in

Profile ansatz for HCAL



$$f(r) \propto \frac{2r}{(r^2 + R^2)^2}$$

75% containment in a centrally struck cell
95% within 3 x 3 array about it

Grindhammer, Rudowicz, Peters 1990
CMS NOTE 2006-138

Replace all particles flowing out the back of an ECAL cell with a continuous angular energy distribution according to the above ansatz

Three benchmark scenarios

Model	Tracking: two extremes	ECAL material	ECAL cell	HCAL cell
LHC		CMS-type ($PbWO_4$)	0.02×0.02	0.1×0.1
FCC1	Perfect/absent	$PbWO_4$ (Lead tungstate)	0.01×0.01	0.05×0.05
FCC2	Perfect/absent	Pure W (Tungsten)	0.005×0.005	0.05×0.05

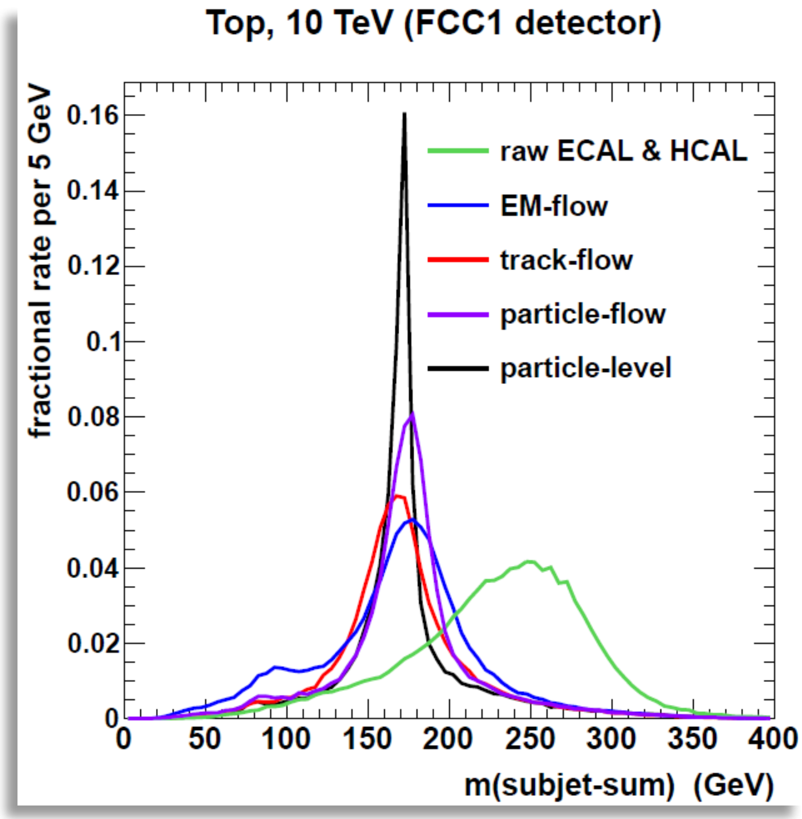
We will see how our detector models perform in three benchmark scenarios

- ❑ **Raw ECAL & HCAL**
- ❑ **EM-flow**
- ❑ **Track-flow**
- ❑ **Particle-flow**
- ❑ **Particle-level**

- Effective Moliere radius of pure W is bigger than what is assumed. Consider Pure W as a place-holder for any new material with a half-sized effective Moliere radius

Filtered top-jet mass of 10TeV top at FCC1

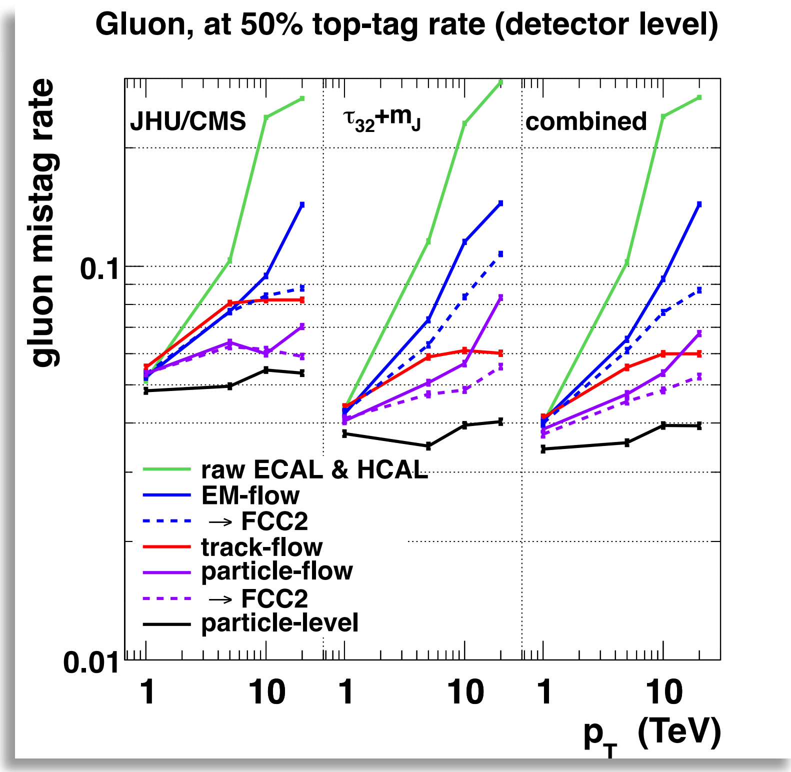
: equivalent to 5TeV top at the LHC

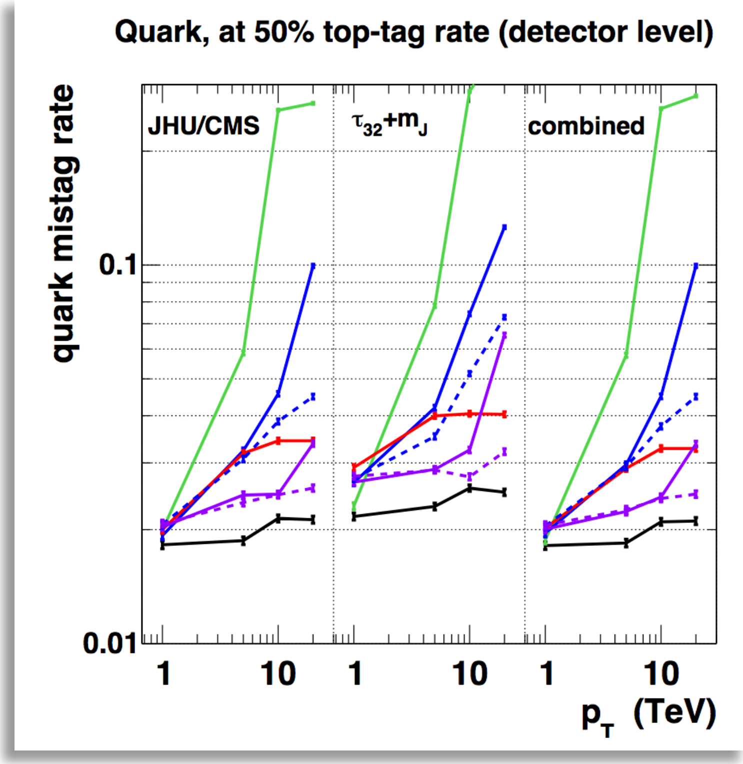


- pile-up and magnetic field are not included in this study w.r.t. CMS-type ECAL, HCAL

FCC1 : ECAL 2x, HCAL 2x (default)

FCC2 : ECAL 4x, HCAL 2x





Naïve exp when doing nothing

Improvement using our idea

✓ EM-flow looks very promising. It can solely cover up to 20TeV tops assuming FCC2 configuration (ECAL 4x, HCAL 2x)

* See extra slides for more detailed plots

Extra Slides

Summary

- The performance of our optimization of JHU TopTagger combined with N-subjettiness

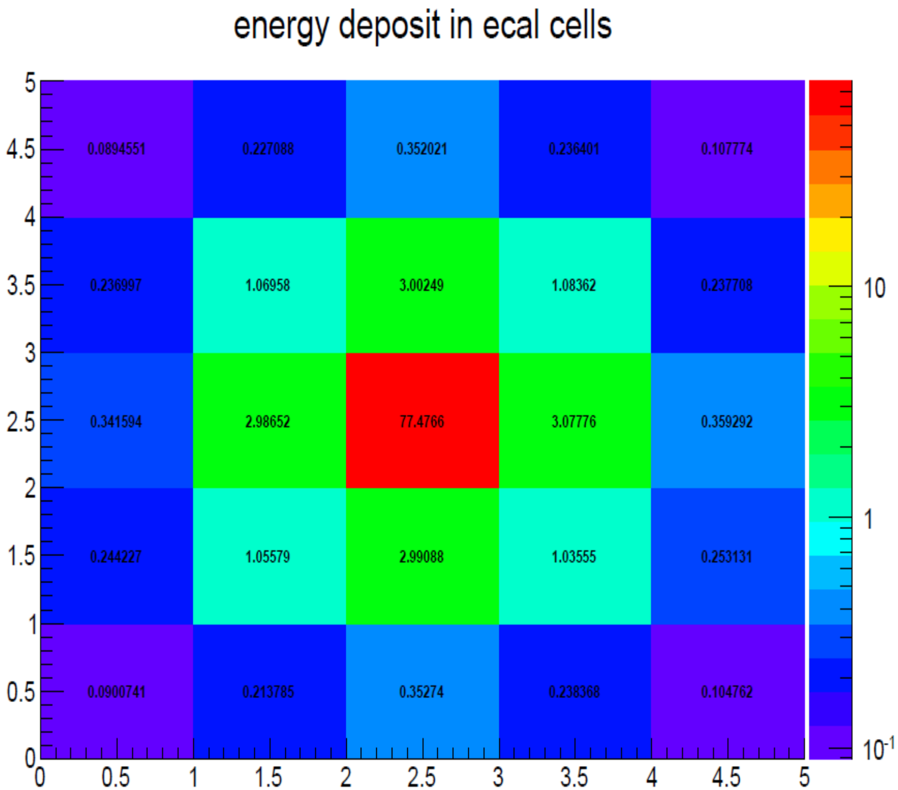
  1. Quark- and gluon-jets can be simultaneously optimized within JHU TopTagger
  2. Adding N-subjettiness to e.g. JHU top tagger, can make $O(1)$ improvement of top/gluon discrimination
  3. N-subjettiness is effective when tracks are available
  4. JHU is more robust than N-subjettiness under more pessimistic detector assumptions

- EM-flow looks very promising. It can solely cover up to 20TeV tops assuming FCC2 configuration (ECAL 4x, HCAL 2x)

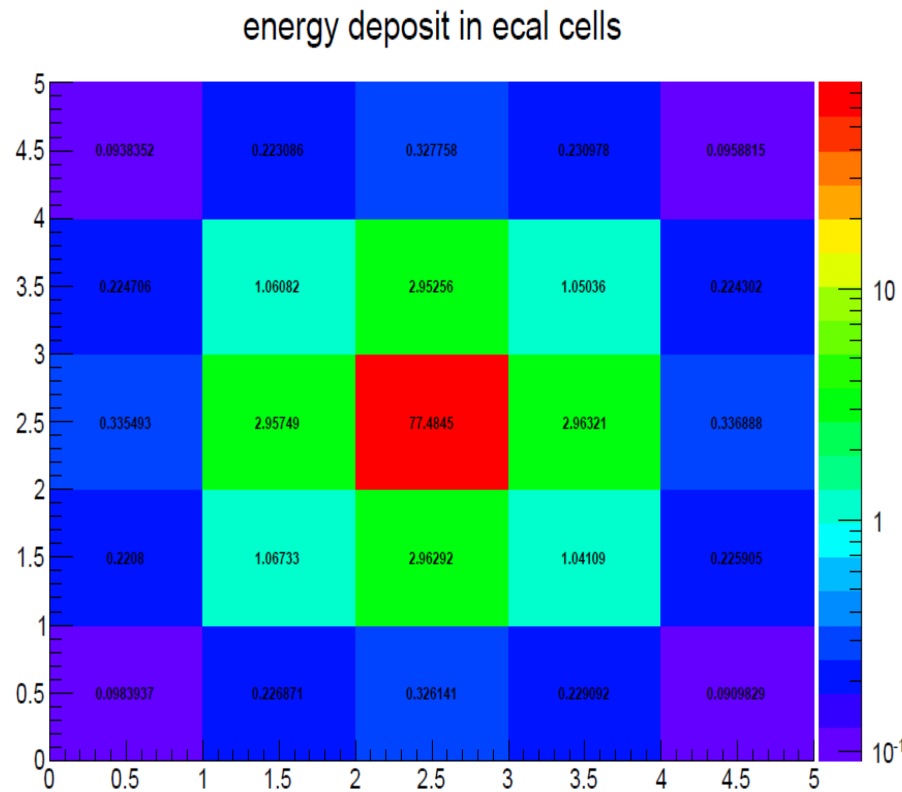
  1. Trackers become crucial to tag tops beyond it
  2. Unless the FCC detectors are constructed with near-perfect trackers, some additional investment in ECAL granularity would be beneficial

Electron-induced ECAL showering pattern by GEANT

10 GeV e^{-} beam



100 GeV e^{-} beam

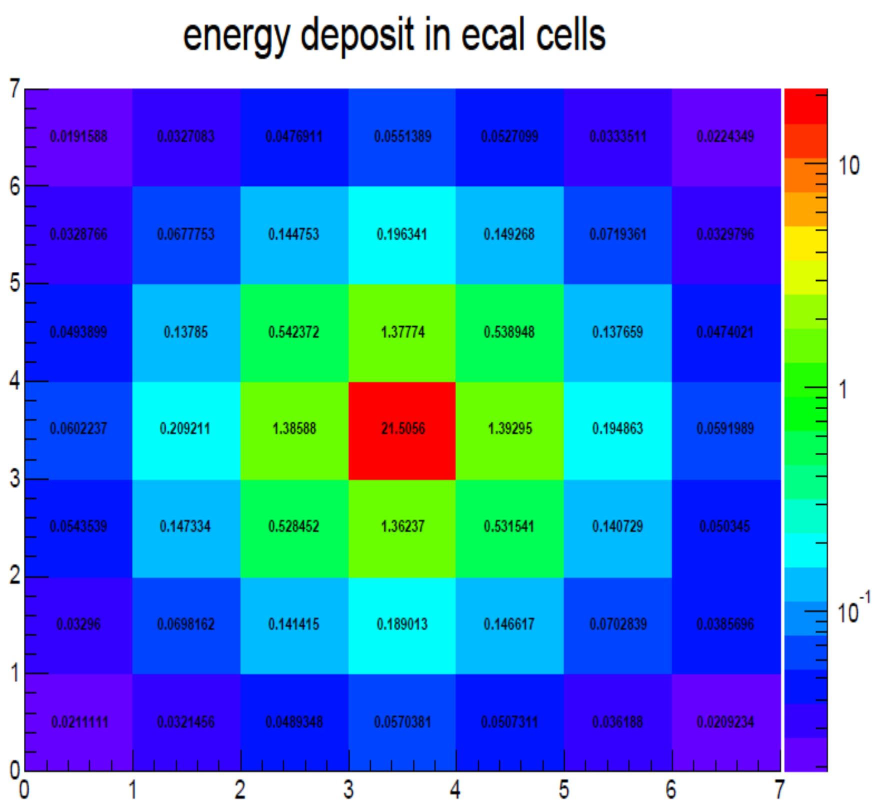


$E_{\text{cell}}/E_{\text{incident electron}}$, not w.r.t $E_{\text{total deposit}}$

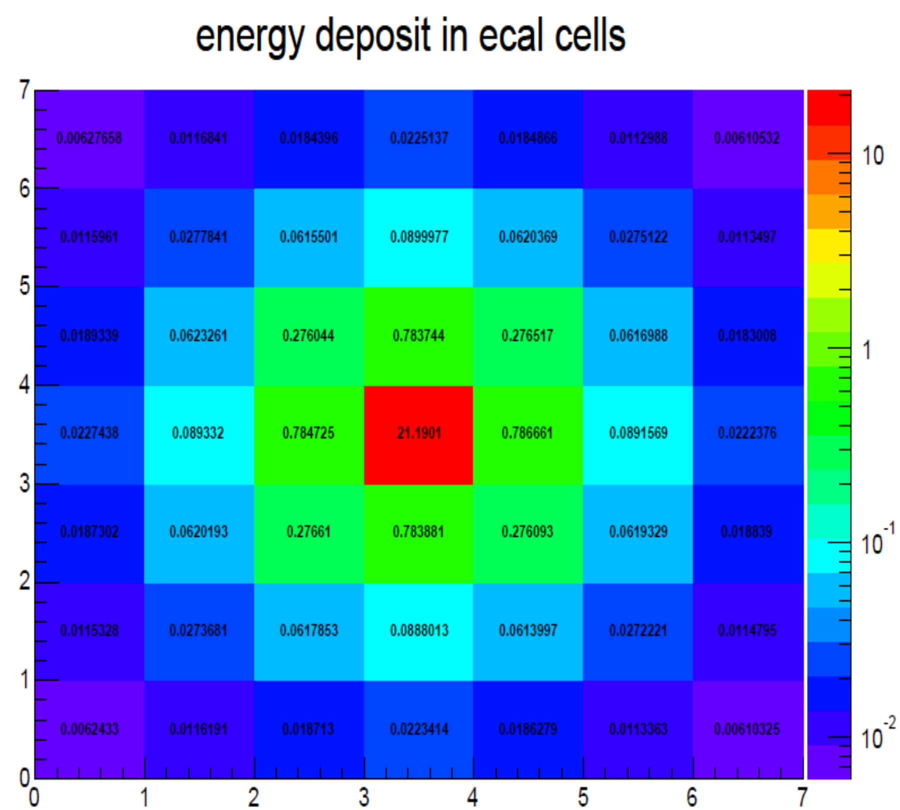
- Nearly pT-independent. It justifies our proxies simulated at 100GeV

Pion-induced ECAL showering pattern by GEANT

100 GeV $\pi^{\pm}$ beam



3 TeV $\pi^{\pm}$ beam



$E_{cell}/E_{incident\,pion}$, not w.r.t $E_{total\,deposit}$

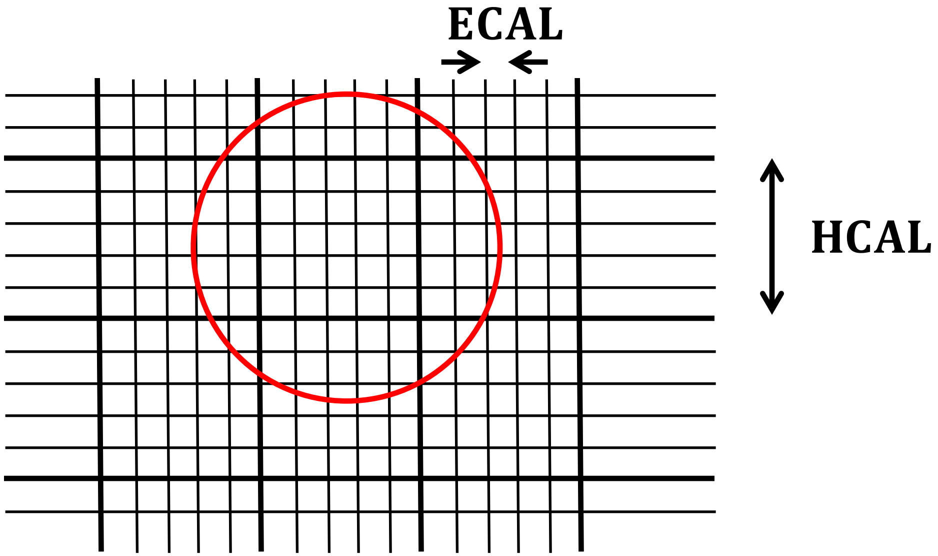
- Nearly pT-independent. It justifies our proxies simulated at 100GeV

Spurious structure due to smearing

Smearing into nearby cells can introduce spurious structure when a rescaling is done within each HCAL cell

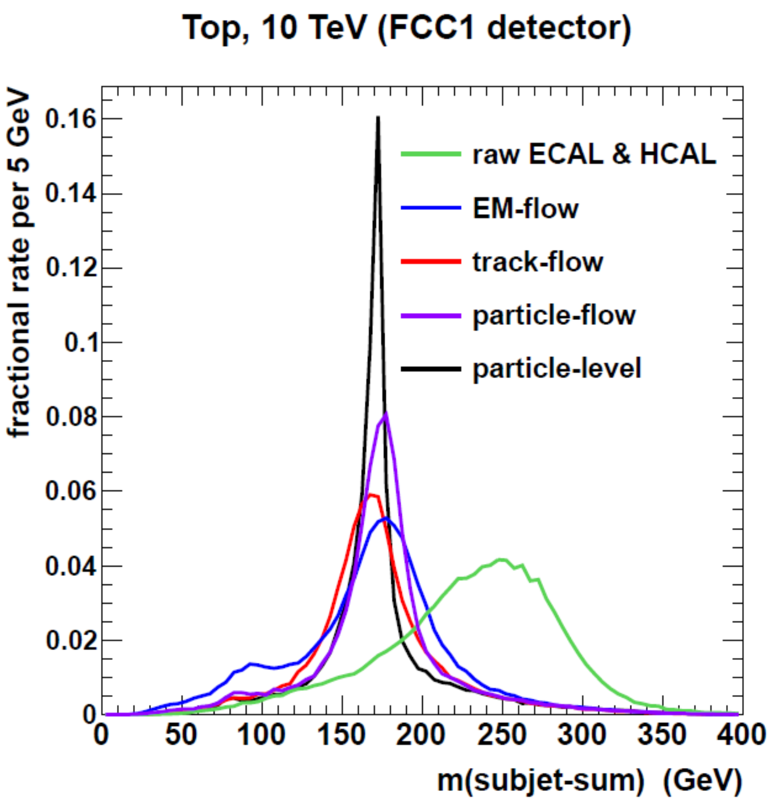
Mini-jet clustering

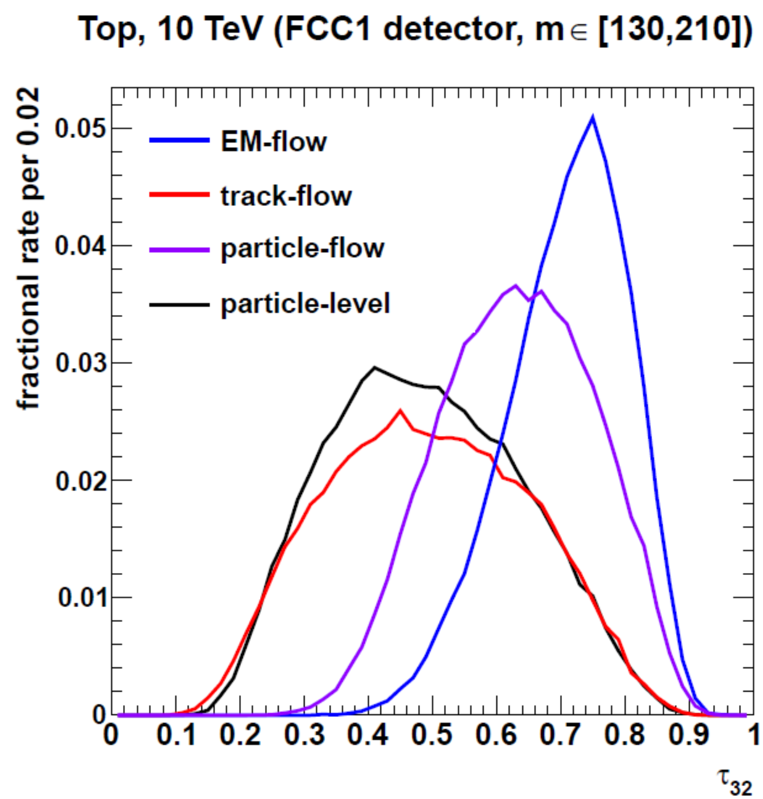
✓ deals with HCAL energy spreading:
e.g. in EM-flow, the entire collection of ECAL and HCAL cells are clustered into mini-jets with the anti-k_T algorithm with the size comparable to the HCAL size. Rescaling is carried out within each mini-jet



Filtered top-jet mass & τ_{32} of 10TeV top at FCC1

: equivalent situation to 5TeV top/gluon at the LHC





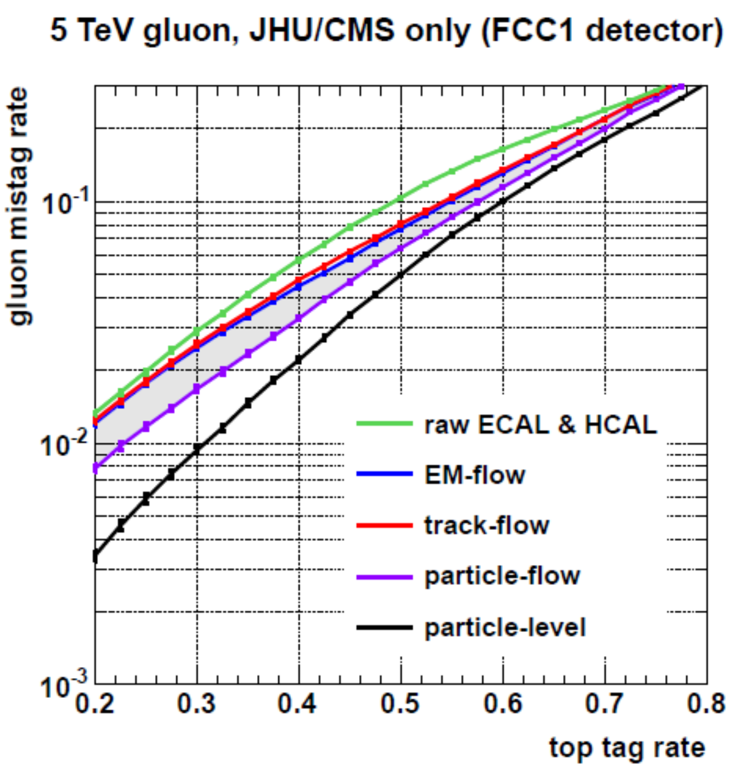
- pile-up and magnetic field are not included in this study

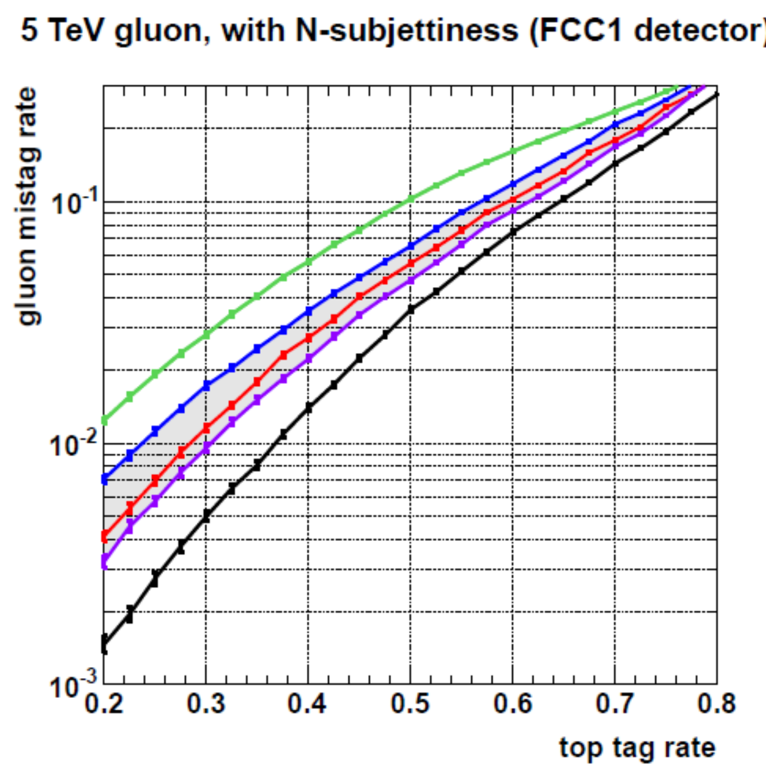
N-subjettiness is doing great whenever tracks are available

τ_{32} seems to probe a property within JHU/CMS subjets, rather than in-between them

5TeV top/gluon discrimination at FCC1

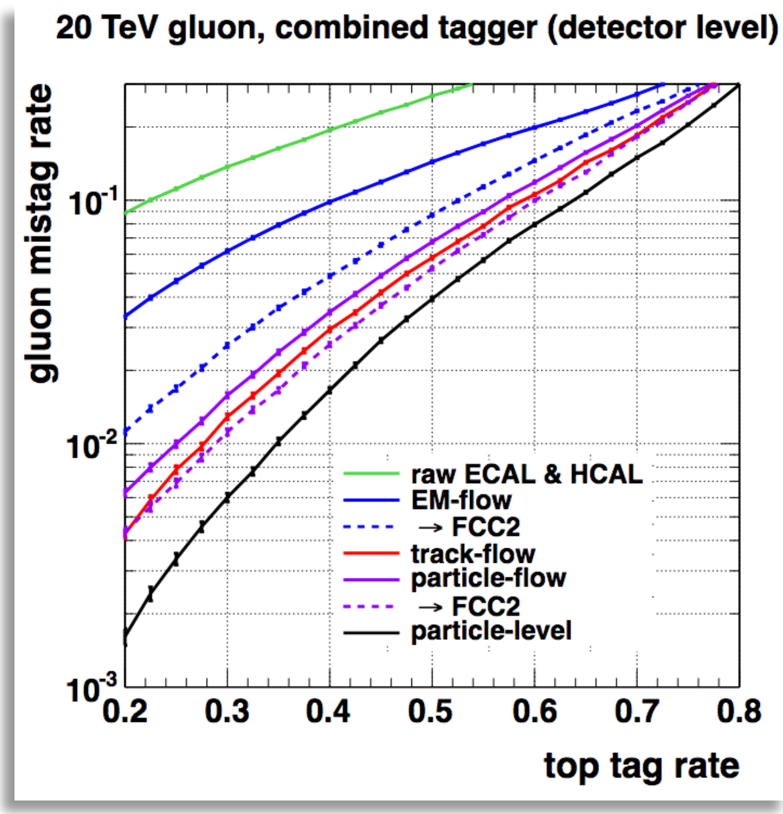
: equivalent to 2.5 TeV top/gluon-jets at the LHC

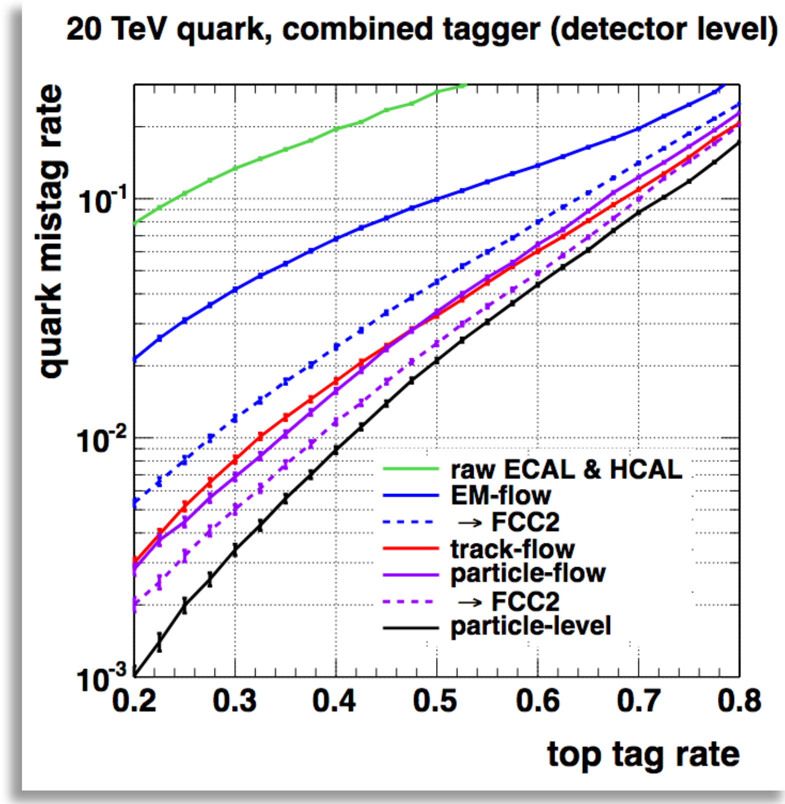




- Particle-flow is universally the best option (as it should be)
- Track-flow works better with N-subjettiness, and EM-flow is less effective at capitalizing on N-subjettiness

20TeV top/gluon/quark discrimination at FCC

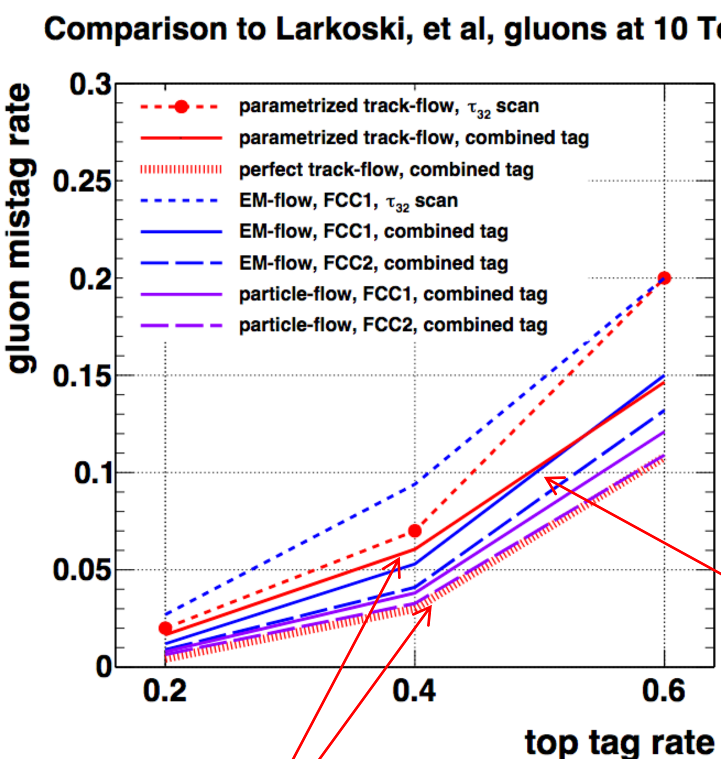


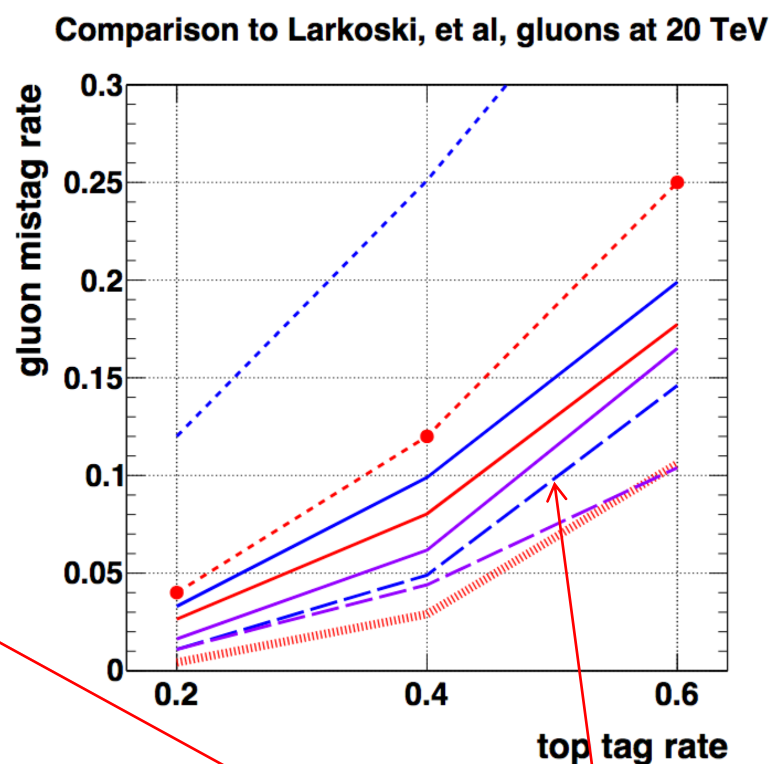


Comparison to an existing study using track-based variables

Larkoski, Maltoni,Selvaggi 2015

* We first validated our procedure by reproducing Larkoski et al.





Perfect vs. imperfect tracking

ECAL 2x

Note that Larkoski et al. (dotted red)
scaned over τ_{32} with the fixed jet mass window

EM-flow can cover up to 20
TeV at FCC2 ~ 10TeV at FCC1