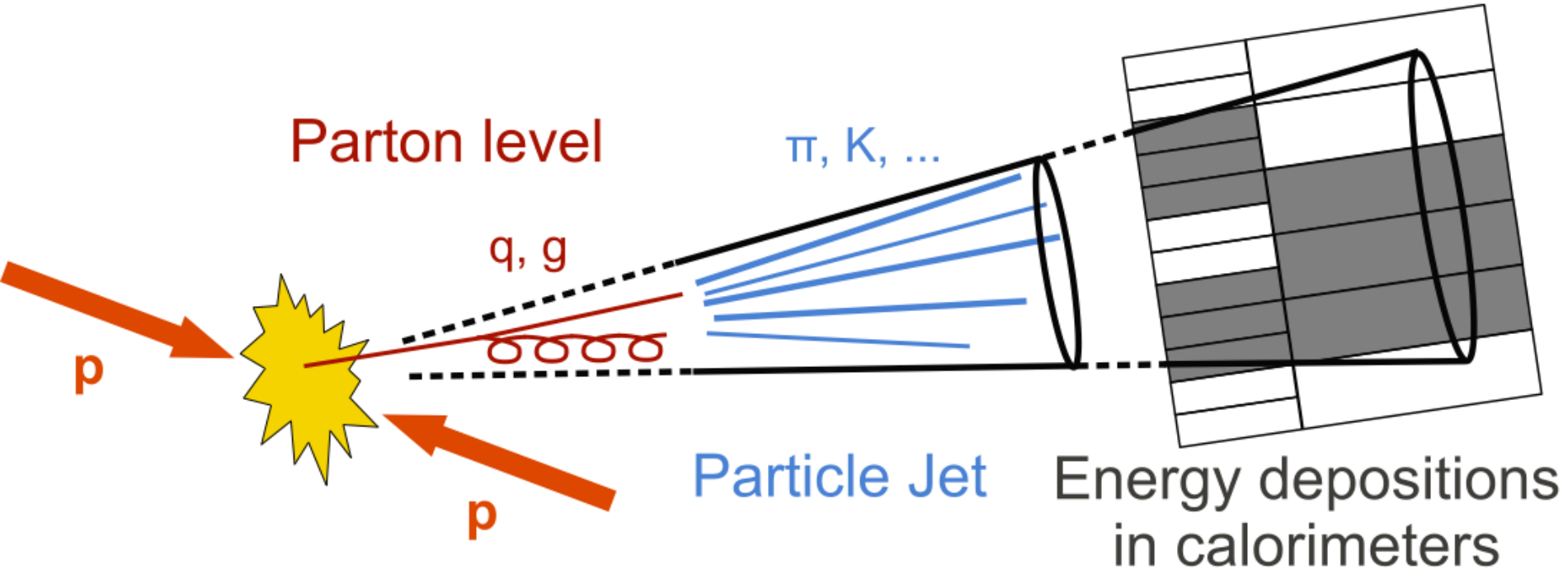
Particle flow jet algorithm for CMS and CALICE

Luiza Adelina Ciucu, Jan 2019

A jet is a stream of collimated particles originating in a quark or gluon. It deposits most of its energy in the Hadronic calorimeter.

The energy measurement is improved if each particle within the jet is reconstructed and measured independently, via a new algorithm called Particle Flow (the topic of this presentation).



Many interesting physics processes contain
jets and missing transverse energy (MET).
It is crucial to measure these with very good resolution,
at both the current or future HL-LHC, or the potential future ILC.

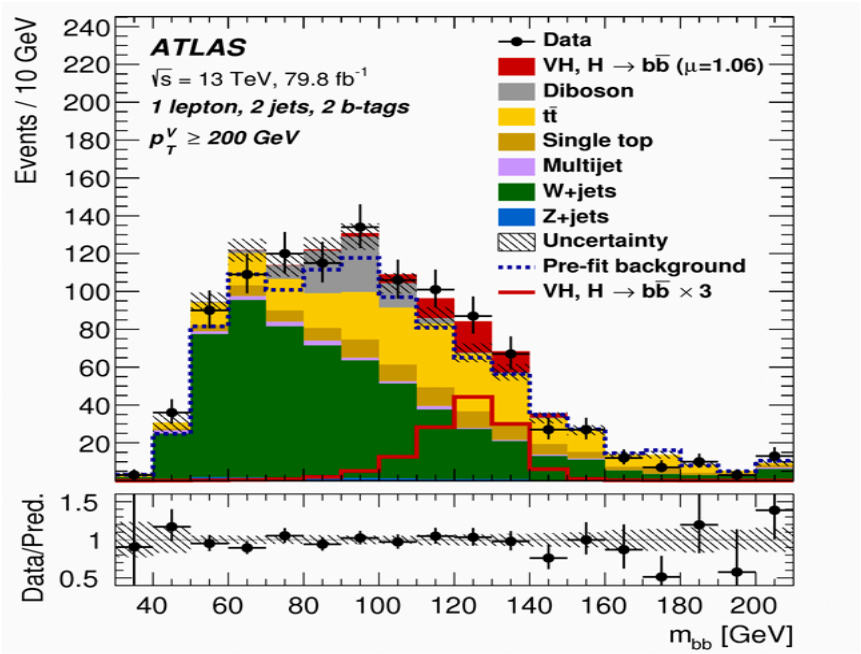


Figure 1: Distribution of mbb in the (W→ℓν)(H→bb) search channel. The signal is shown in red, the different backgrounds in various colours. The data are shown as points with error bars. (Image: ATLAS Collaboration/CERN)

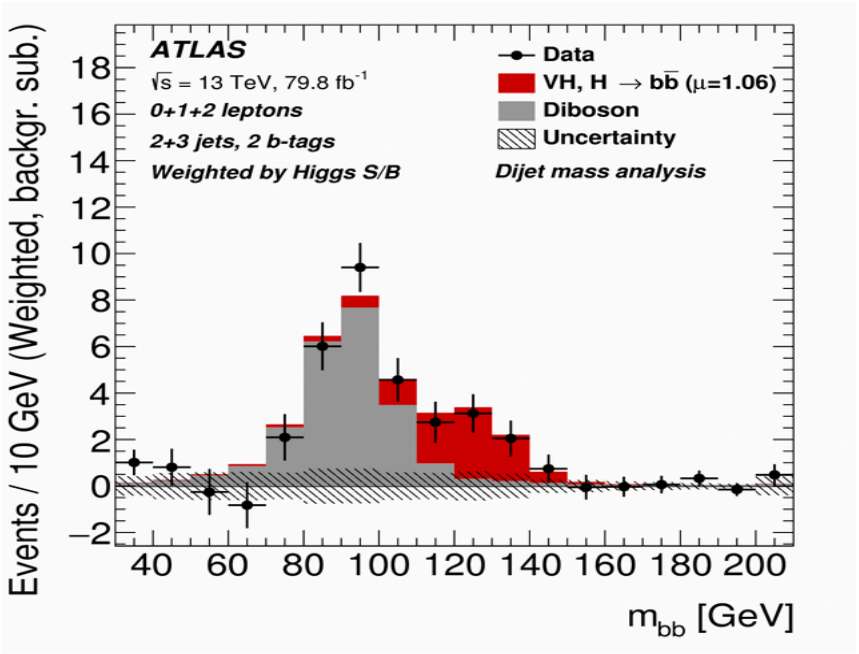
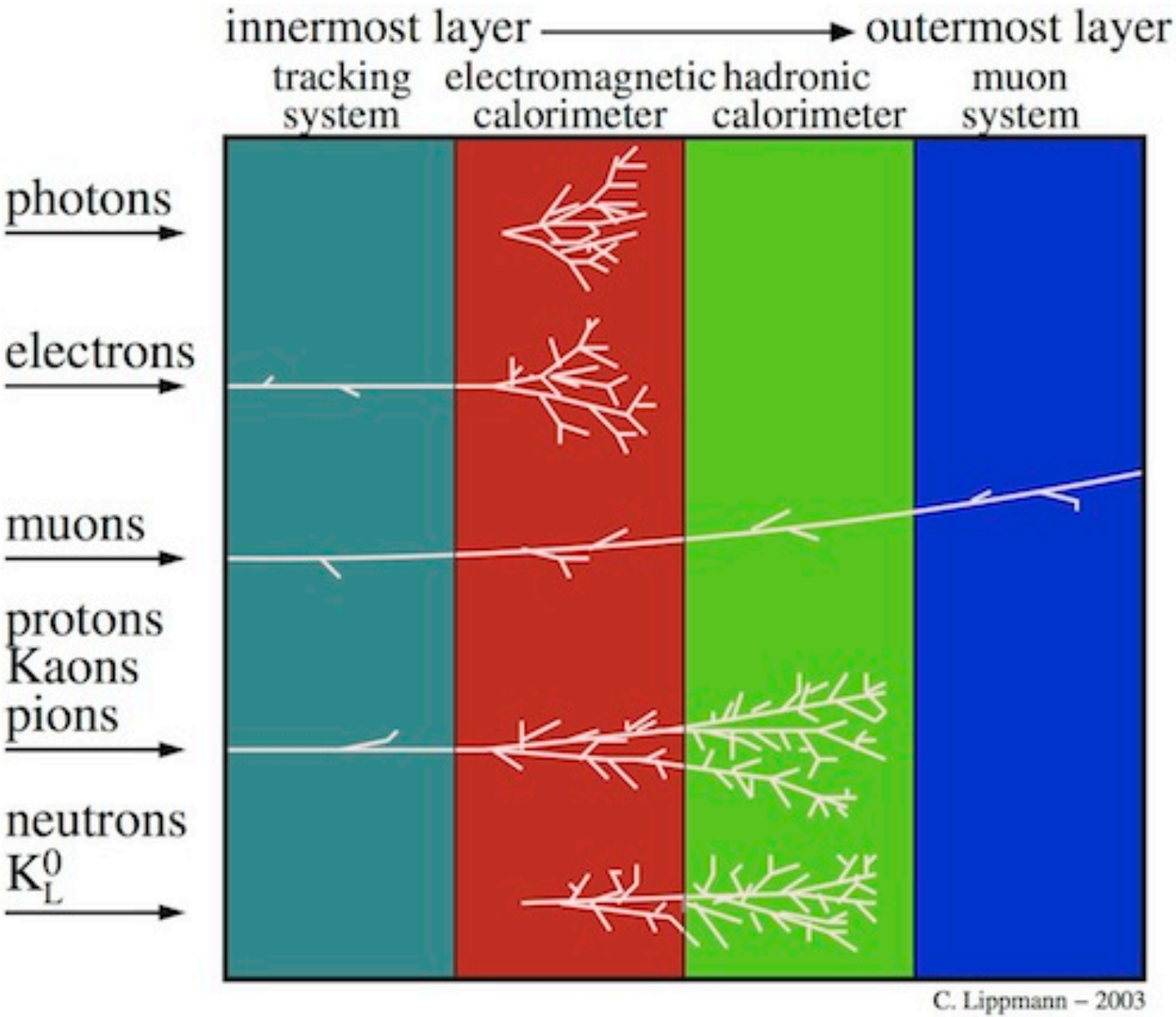


Figure 2: Distribution of mbb from all search channels combined after subtraction of all backgrounds except for WZ and ZZ production. The data (points with error bars) are compared to the expectations from the production of WZ and ZZ (in grey) and of WH and ZH (in red). (Image: ATLAS Collaboration/CERN)

ATLAS observation of Higgs boson decay to bottom-quark pairs (Press release)

The typical four layers of a particle detector
and how various particles are reconstructed with in.



A jet is a stream of collimated particles that originate in a quark or gluon. The various jets constituents, their percentage of jet energy, the energy resolution of the subdetector that measures them give rise to two jets reconstruction algorithms:

Calorimeter only (Calo) and Particle Flow (PF)

Jet constituents	% of jet energy	Calo	PF
Charge particles (hadrons)	62%	HCAL	Tracker + HCAL
Photons	27%	ECAL	ECAL
Long live neutral particles	10%	ECAL, HCAL	ECAL, HCAL
Neutrinos	1.5%	-	-

Tracker or inner detector (tracking)
$\sigma(p)/p \sim 1\%$

Electromagnetic calorimeter (ECAL)

$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E/\,\mathrm{GeV}}} \oplus \frac{12\%}{E/\,\mathrm{GeV}} \oplus 0.3\%.$$

Hadronic calorimeter (ECAL)

$$\frac{\sigma}{E} = \frac{110\%}{\sqrt{E}} \oplus 9\%,$$

CMS Particle Flow [arXiv 1706.04965]

Particle Flow reconstruction in the CMS detector structure.

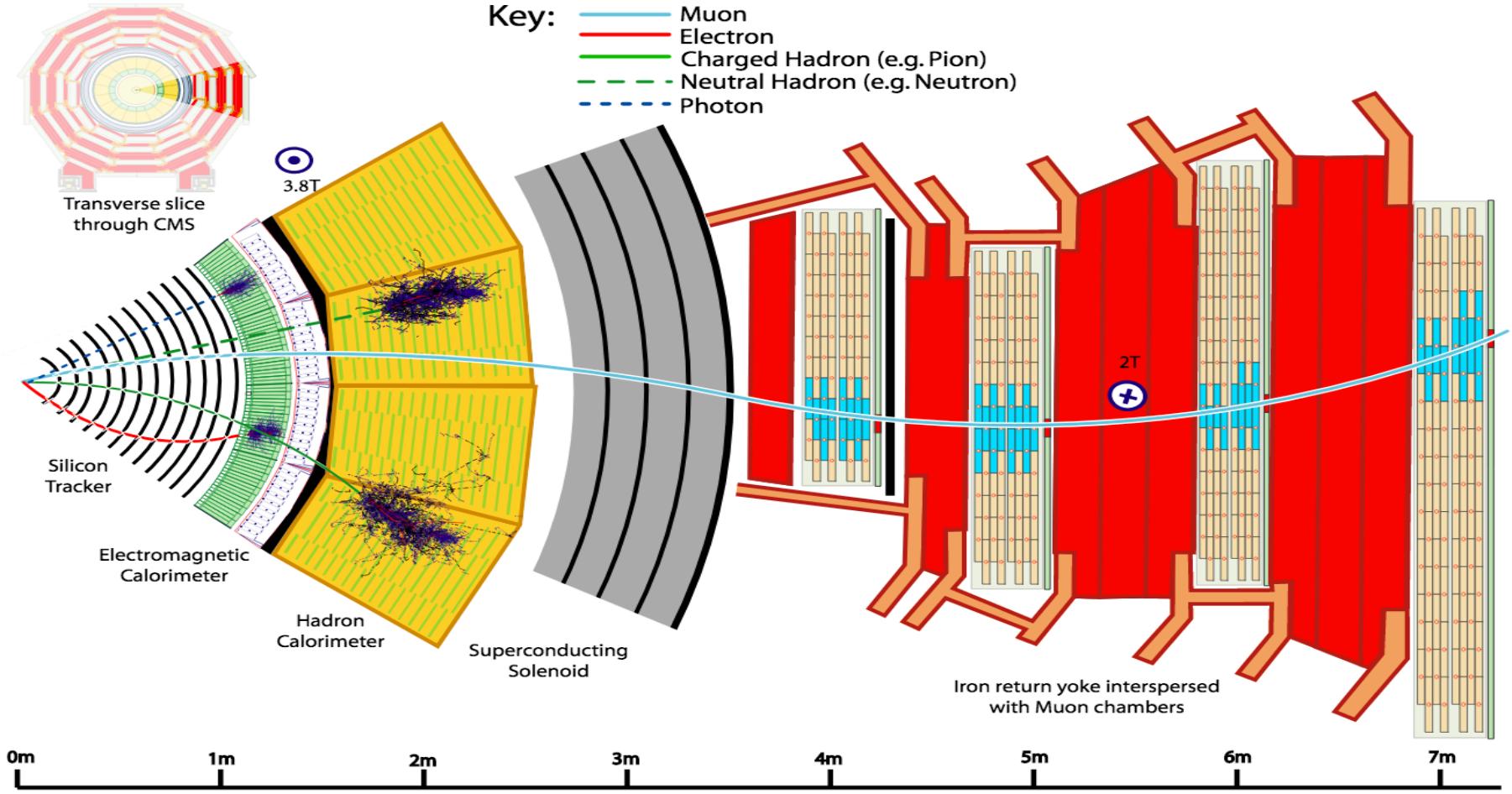
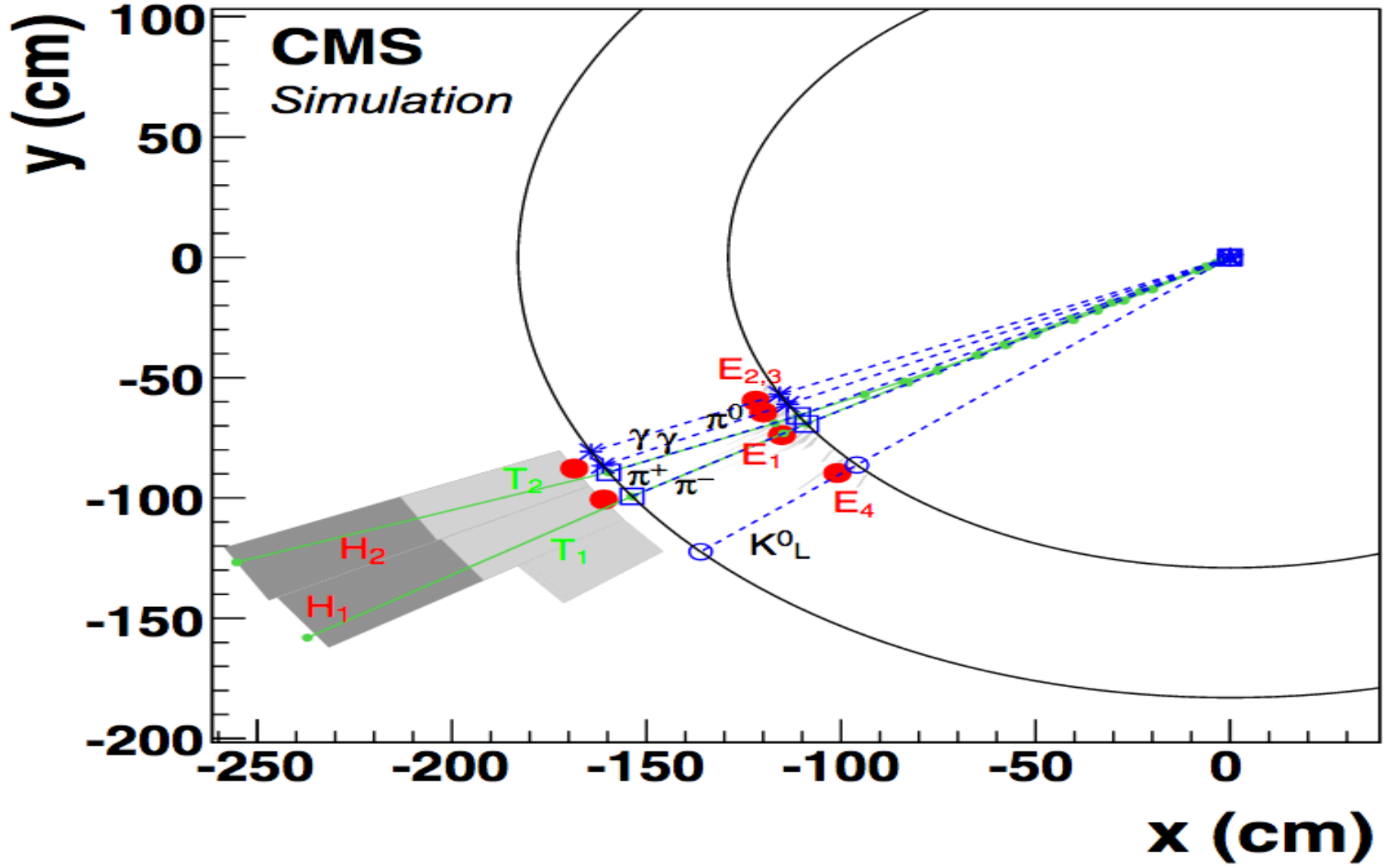


Figure 1: A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. The muon and the charged pion are positively charged, and the electron is negatively charged.

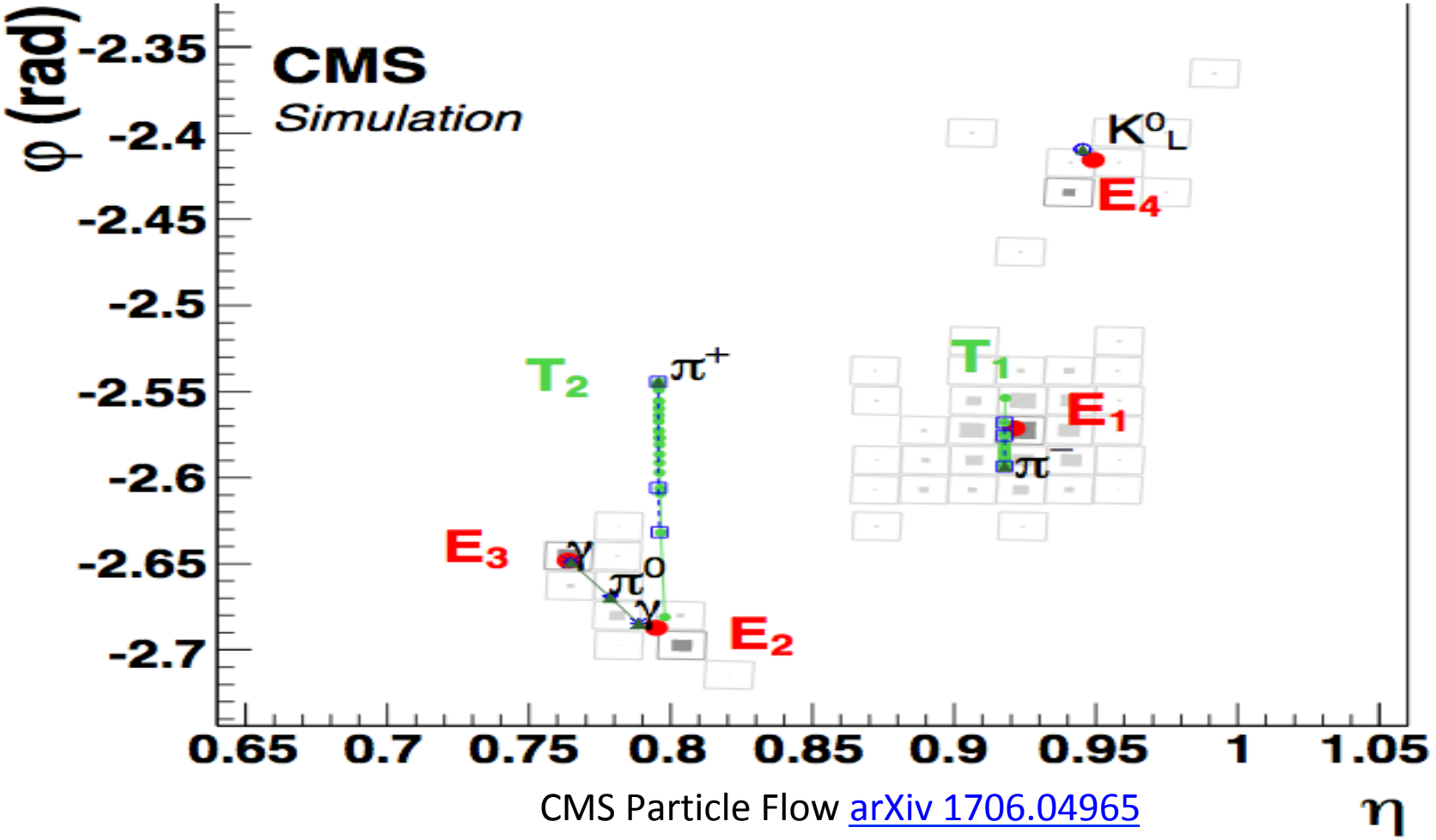
CMS Particle Flow [arXiv 1706.04965]

In PF individual particles are reconstructed in a global fit across all subdetectors that see them.



CMS Particle Flow [arXiv 1706.04965]

In Calo algorithm the jet energy is the sum of energy of calorimeter towers (E1, E2, E3, E4). **In PF** towers E1 and E2 are matched to tracks T1 and T2 because they are produced by charged hadrons π^+ and π^-. The energies E1 and E2 are replaced by momenta T1 and T2 from more precise tracking detector.



CMS Particle Flow [arXiv 1706.04965]

Performance of ***particle flow (PF)*** improves significantly energy resolution relative to regular pure ***calorimeter (calo)*** algorithm.

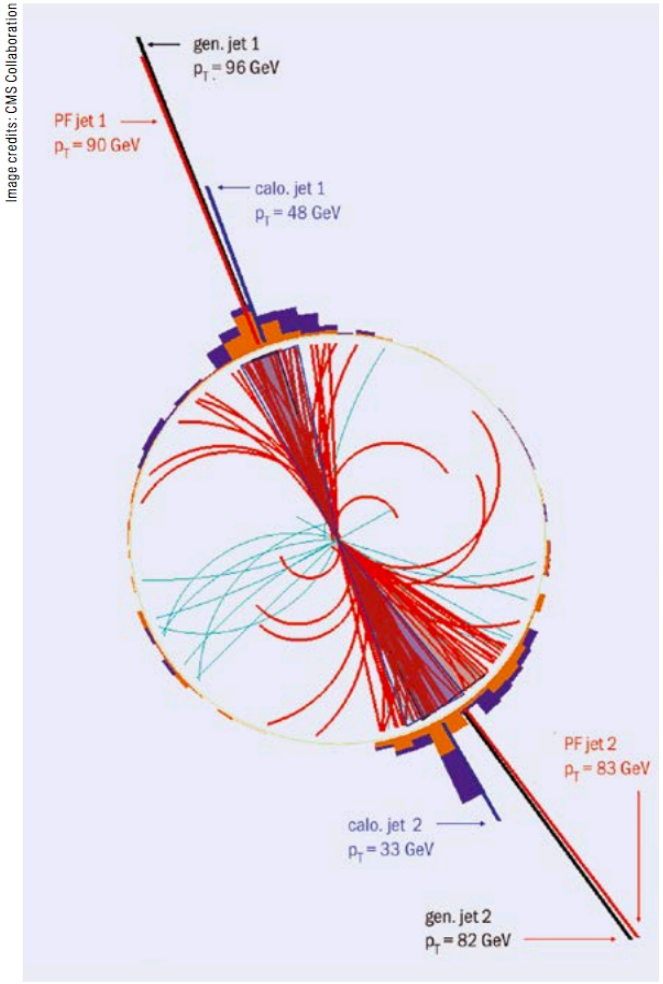


Fig. 1. Jet reconstruction in a simulated dijet event. The reconstructed particles clustered in the two jets are displayed with thicker lines. For clarity, unclustered particles with $p_T < 1$ GeV are not shown. The particle-flow jet transverse momentum, indicated as a radial line, is compared to the momenta of the corresponding generated and calorimeter jets.

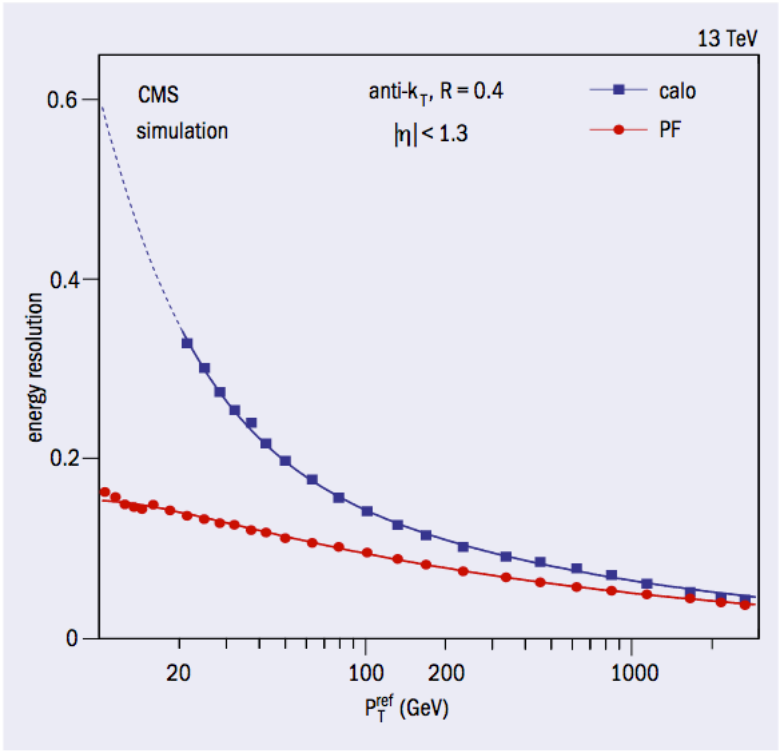


Fig. 2. Jet-energy resolution for calorimeter and particle-flow jets as a function of the jet transverse momentum. The improvement in resolution, of almost a factor of two at low transverse momentum, remains sizable even for jets with very high transverse momentum.

CMS PF algorithm (CERN Courier)

Response of jet transverse momentum (p_T) is improved (is closer to 1) by PF over Calo. The improvement is larger as jet p_T is smaller.

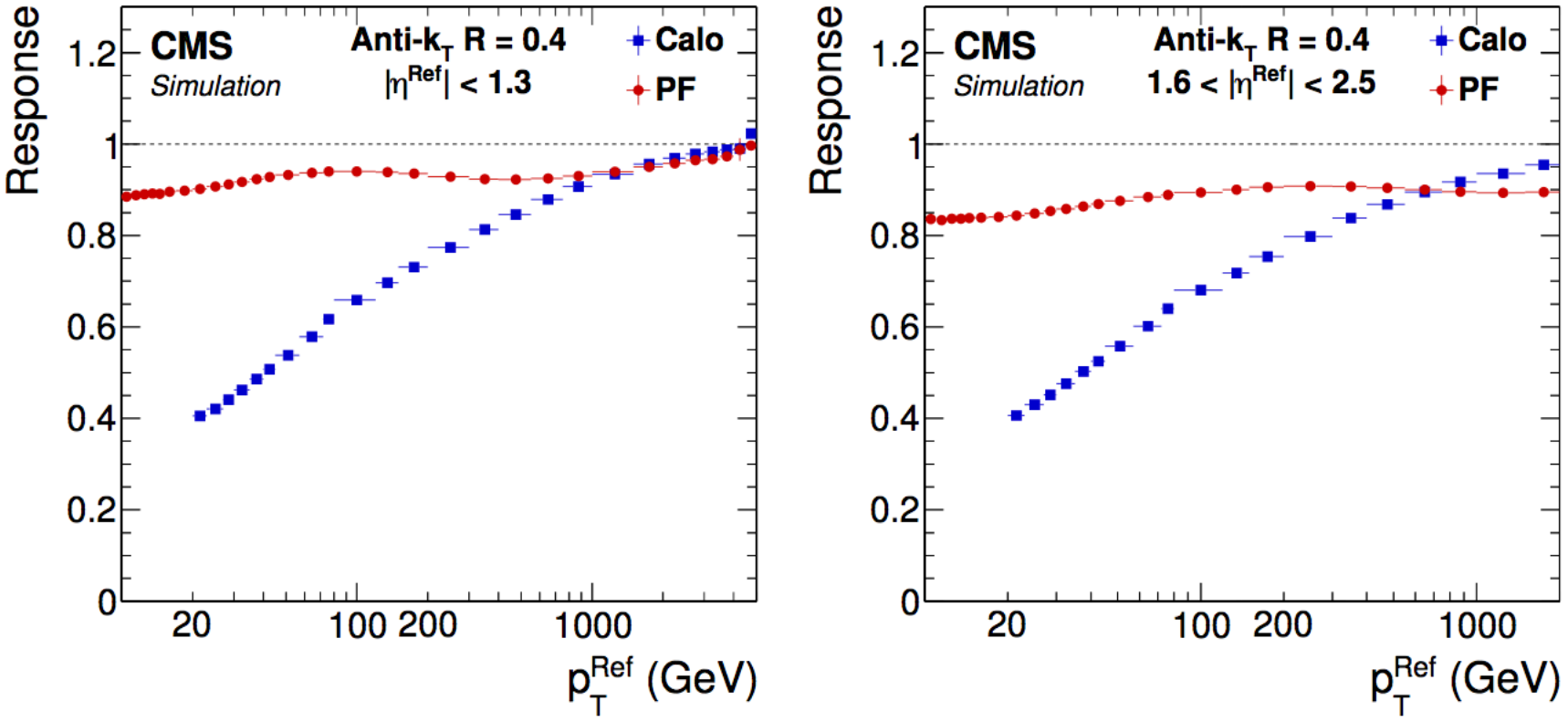
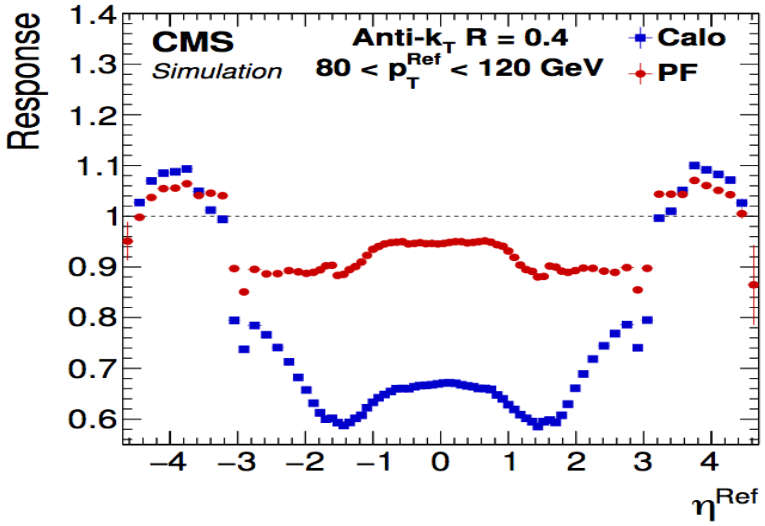


Figure 12: Jet response as a function of η^{Ref} for the range $80 < p_{\mathrm{T}}^{\mathrm{Ref}} < 120\,\mathrm{GeV}$ (top) and as a function of $p_{\mathrm{T}}^{\mathrm{Ref}}$ in the barrel (left) and in the endcap (right) regions.

CMS Particle Flow [arXiv 1706.04965]

Angular response (eta)
and resolution (eta, phi)
are improved by PF over Calo.

CMS Particle Flow [arXiv 1706.04965]



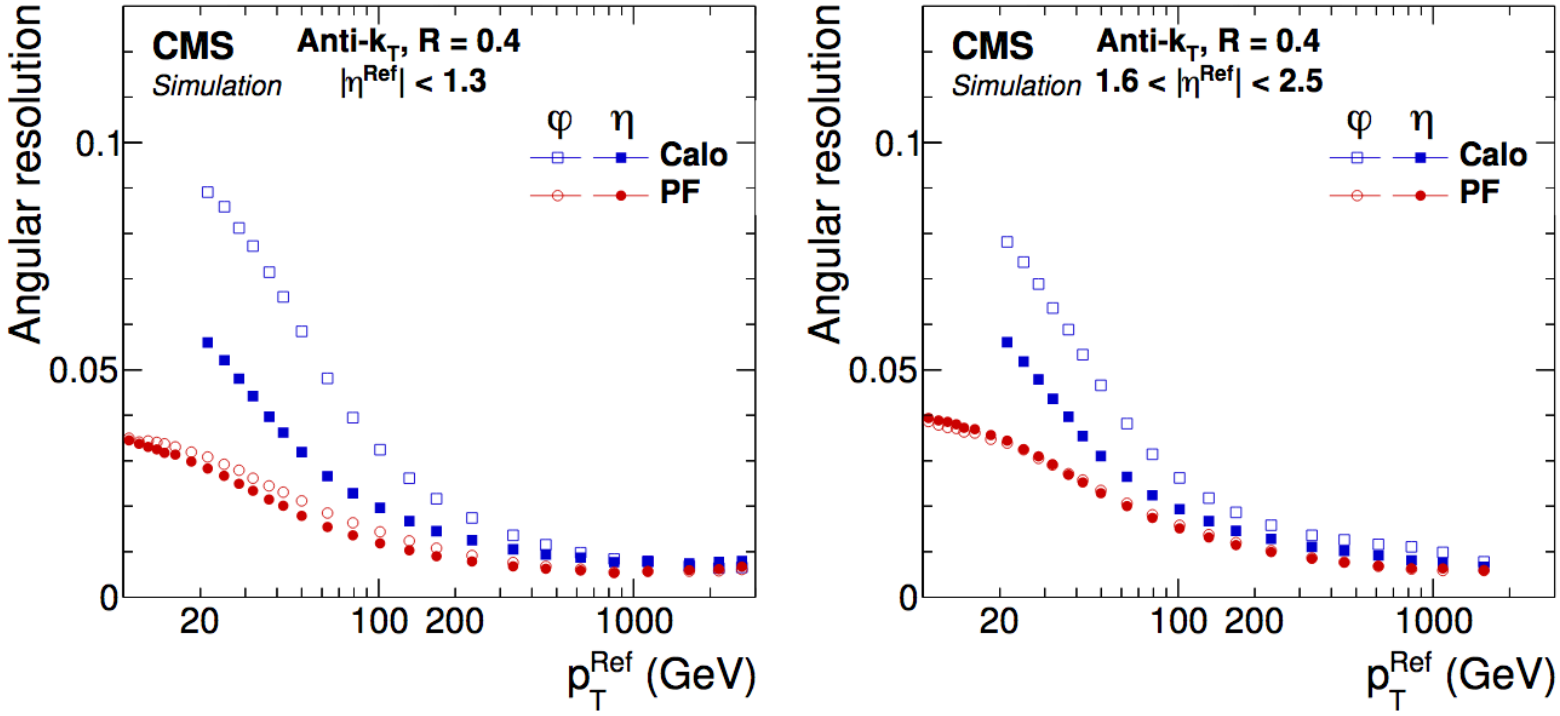
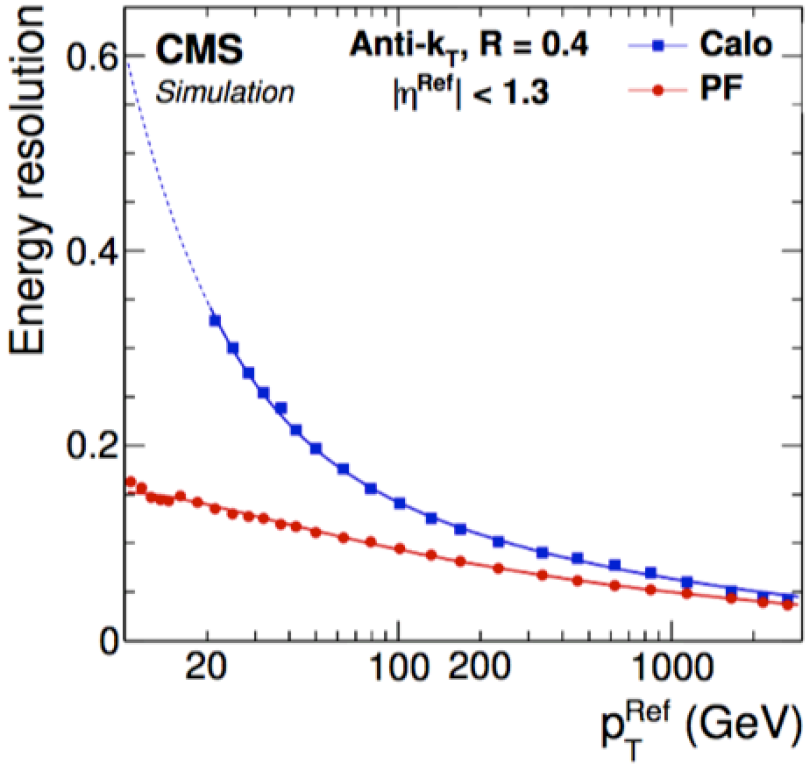
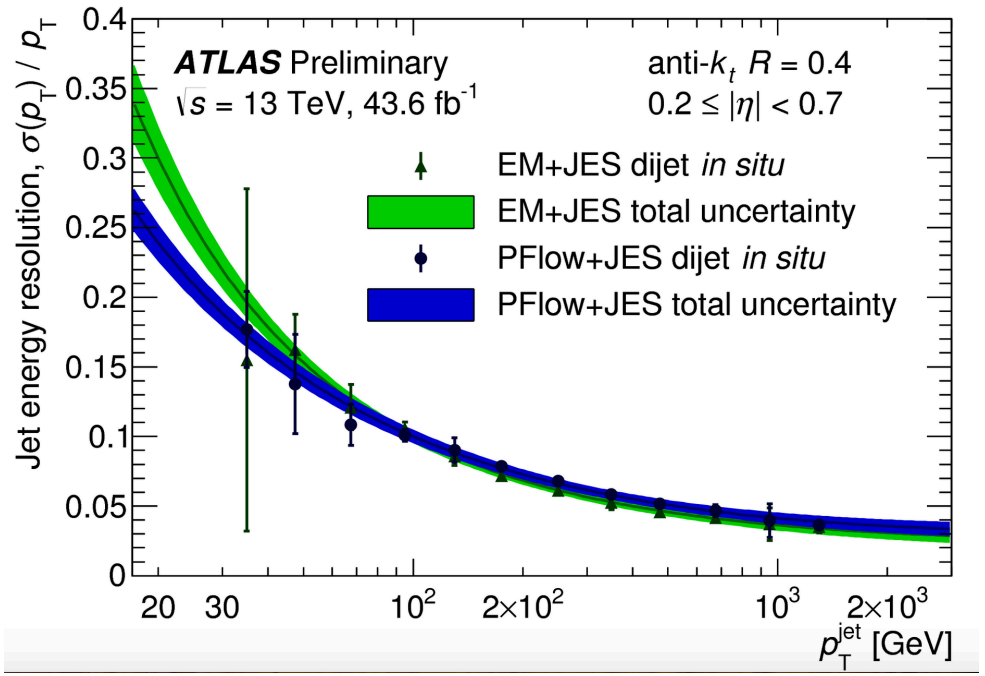


Figure 10: Jet angular resolution in the barrel (left) and endcap (right) regions, as a function of the p_T of the reference jet. The φ resolution is expressed in radians.

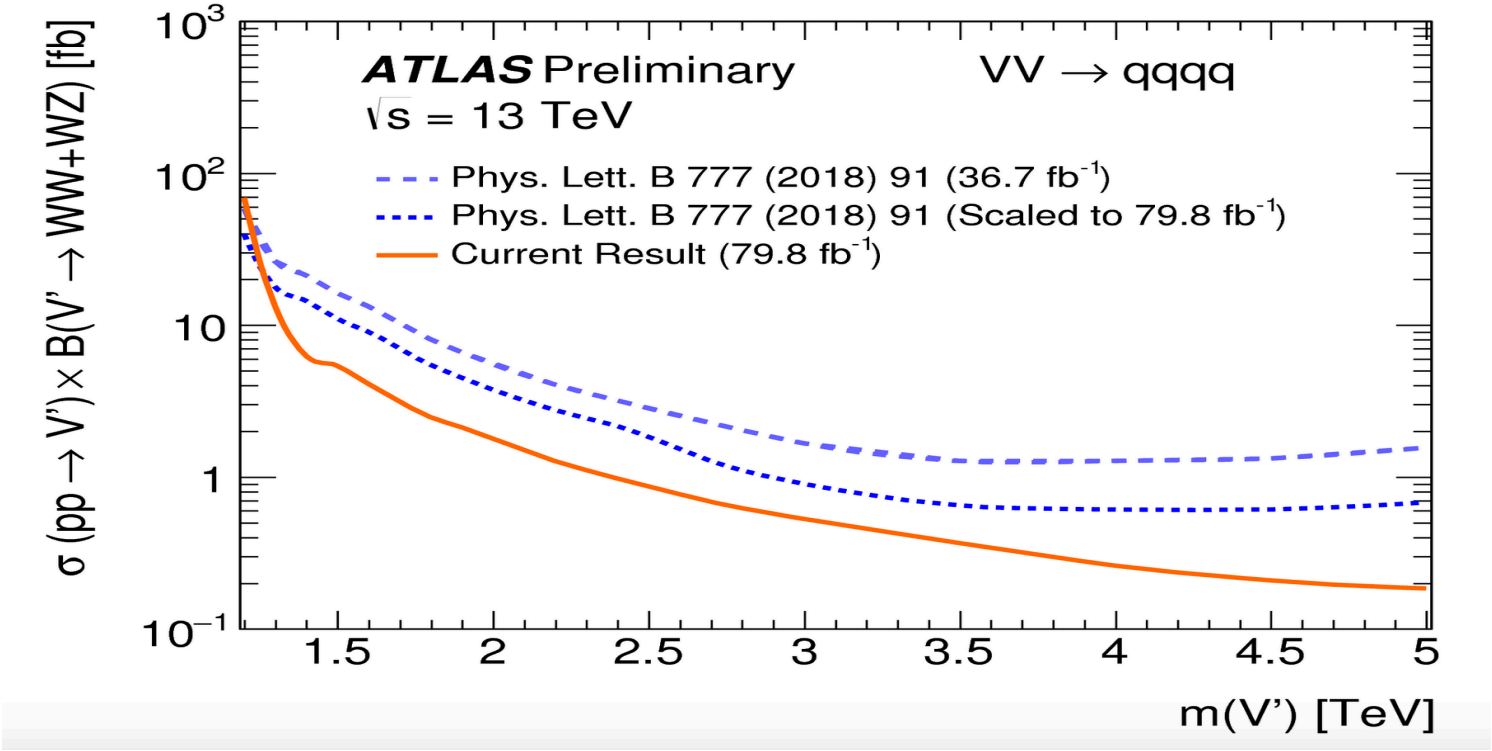
ATLAS gains less than **CMS** in Jet energy resolution when moving from Calo to PF reconstruction algorithms, due to the better performance of the ATLAS hadronic calorimeter, but worse tracking and muon reconstruction.
CMS was forced to use PF from the beginning of Run-1, while ATLAS is now planning to switch to PF to improve a bit the low p_T jets.





ATLAS notes on Jets (1, 2, 3).

ATLAS analysis searching for a new massive particle decaying to quarks, improves significantly the expected limit by going from the **Calo algorithm (blue)** to **a new type of PF (orange)**.
These high p_T jets get their energy measurement from the calorimeter, but the direction from the tracking detector.



ATLAS analysis paper

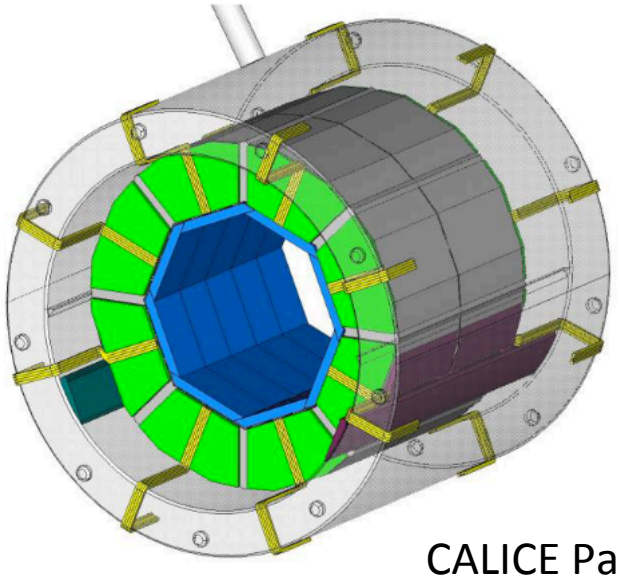
The **International Linear Collider (ILC)** will need to be even more precise than the LHC, hoping to separate the two W and Z peaks when they decay to quarks.

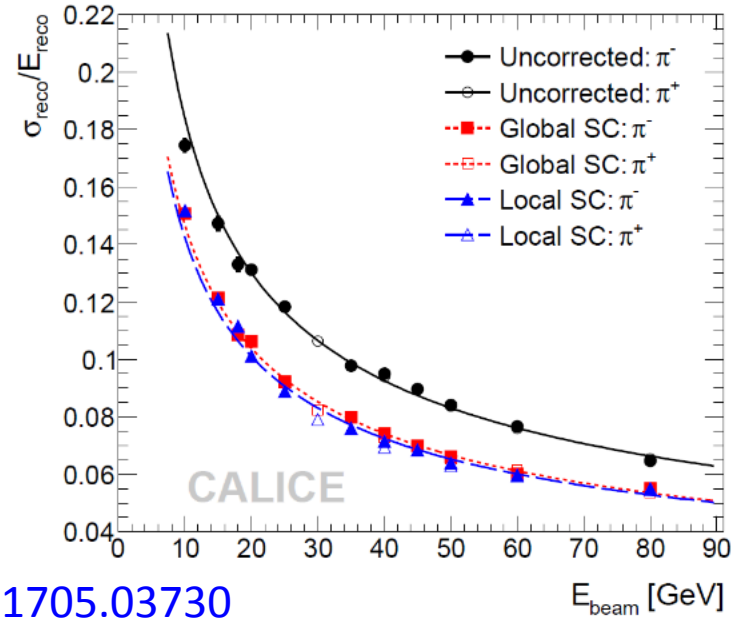
1) The PF algorithm is a must.
2) The best granularity and design for calorimeter is the task of the **CALICE collaboration**, much improved over CMS.

Possible design from their paper:

ECAL: absorber (tungsten) + sensor (silicon)

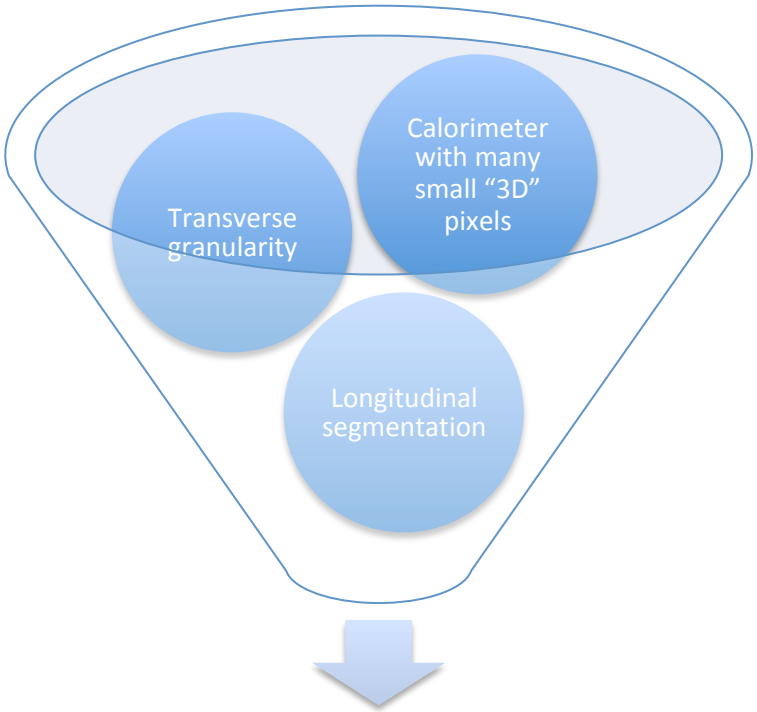
HCAL: absorber (steel) + sensor (scintillator)



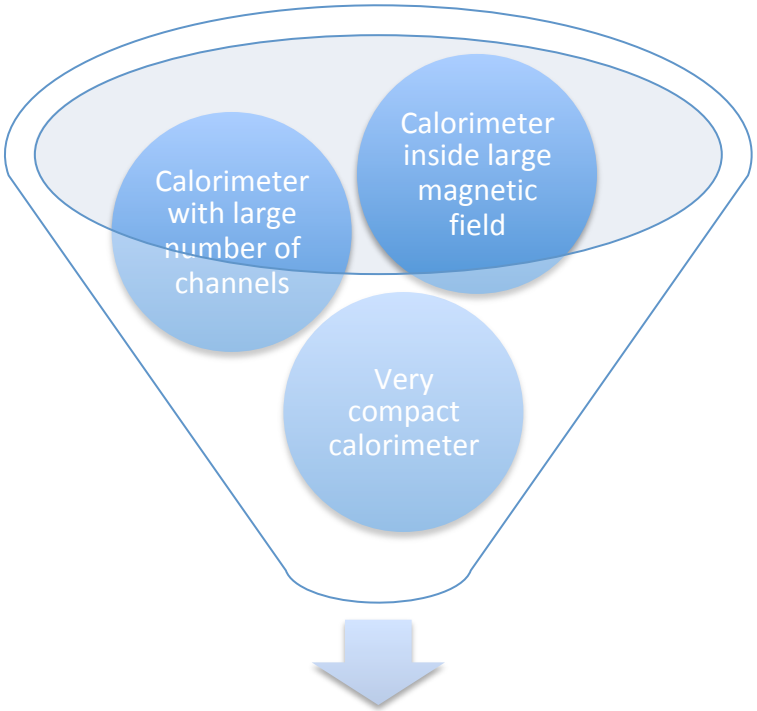


CALICE Particle Flow [arXiv 1705.03730]

PF requires to reconstruct separately individual particles in jet. In particular, to separate the showers of charged and neutral hadrons. And match the showers of charged hadrons to their tracks.



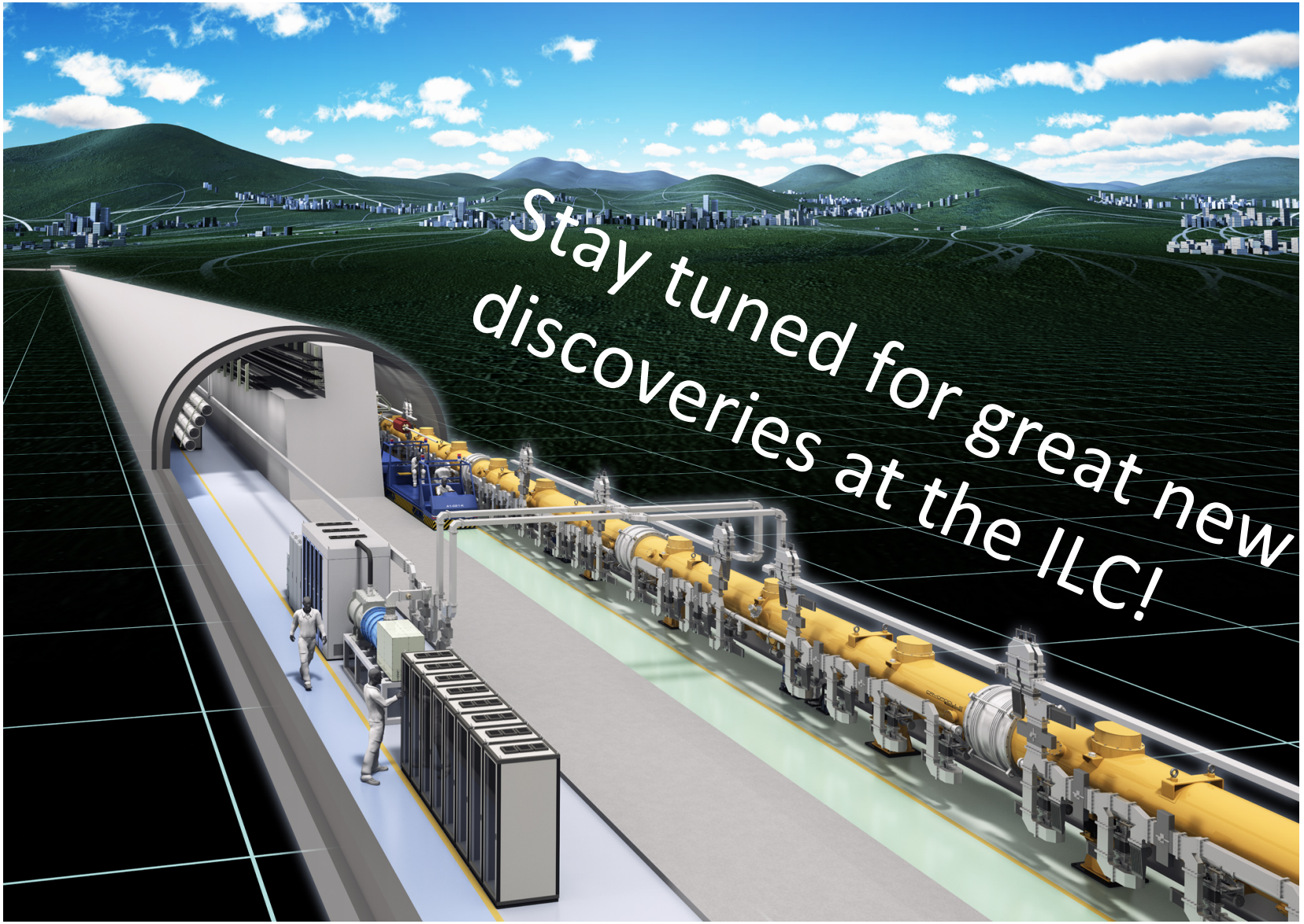
Constraints on PF-motivated calorimeter design



Constraints on particle detector design

Overall, ILC detectors are expected to be very similar in structure with the current CMS detector at the LHC, where PF jet reconstruction algo. has been very successful. CALICE Particle Flow article

Particle Flow jet reconstruction algorithm is key for the potential ILC experiments. Its calorimeters are designed specifically for Particle Flow.



Back-up slides

Jet energy resolution is improved (becomes smaller) by PF over Calo. The improvement is larger as jet p_T is smaller.

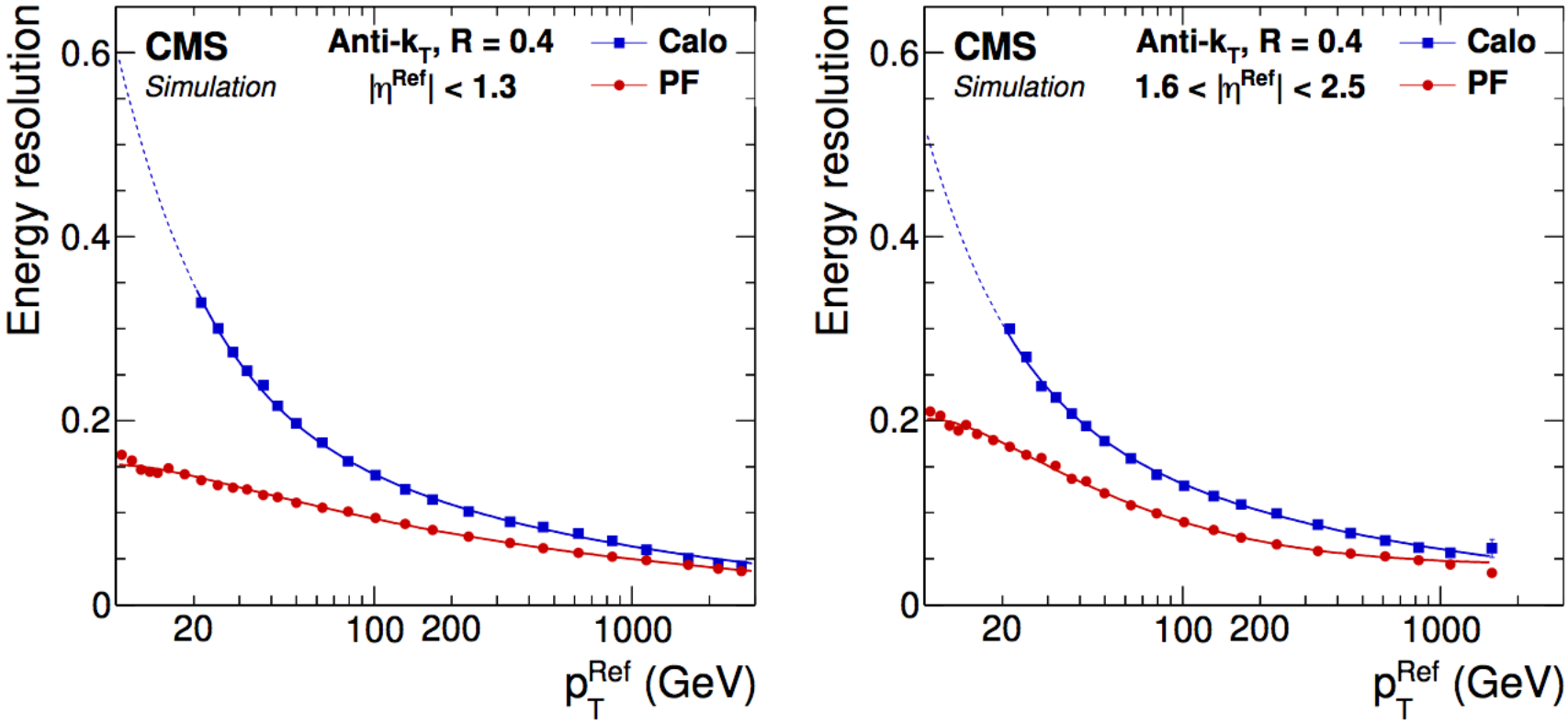


Figure 13: Jet energy resolution as a function of p_T^{Ref} in the barrel (left) and in the endcap (right) regions. The lines, added to guide the eye, correspond to fitted functions with ad hoc parametrizations.

CMS Particle Flow arXiv 1706.04965

Jets originating from different types of quarks (b, c, s, u, d, gluon) have jet energy responses that are quite different using the standard Calo algorithm (left), but responses are quite similar using PF (right).

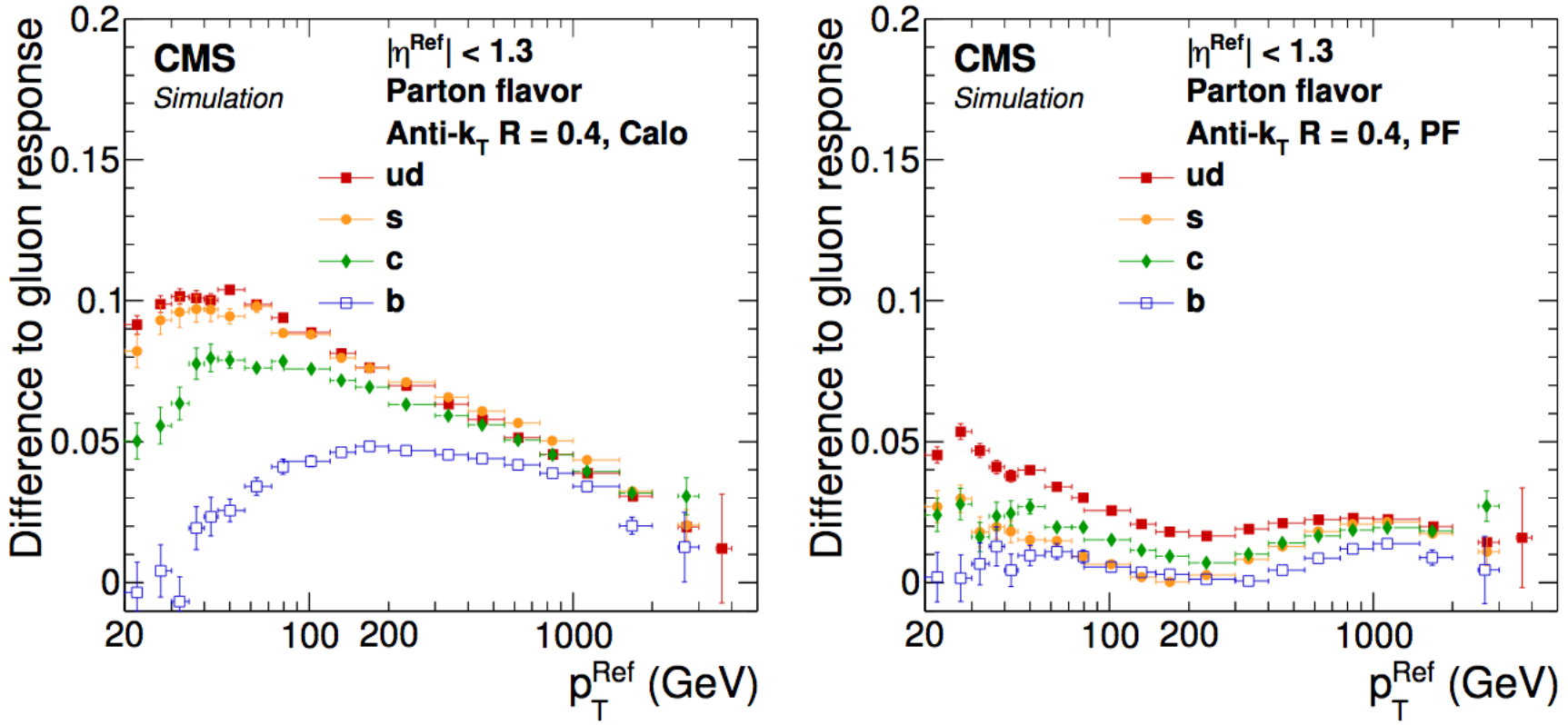


Figure 14: Absolute difference in jet energy response between quark and gluon jets as a function of p_T^{Ref} for Calo jets (left) and PF jets (right).

CMS Particle Flow arXiv 1706.04965

Missing transverse energy (MET) improves both energy resolution (left) and the resolution of the angle phi in the transverse plane (right), across the entire energy range.

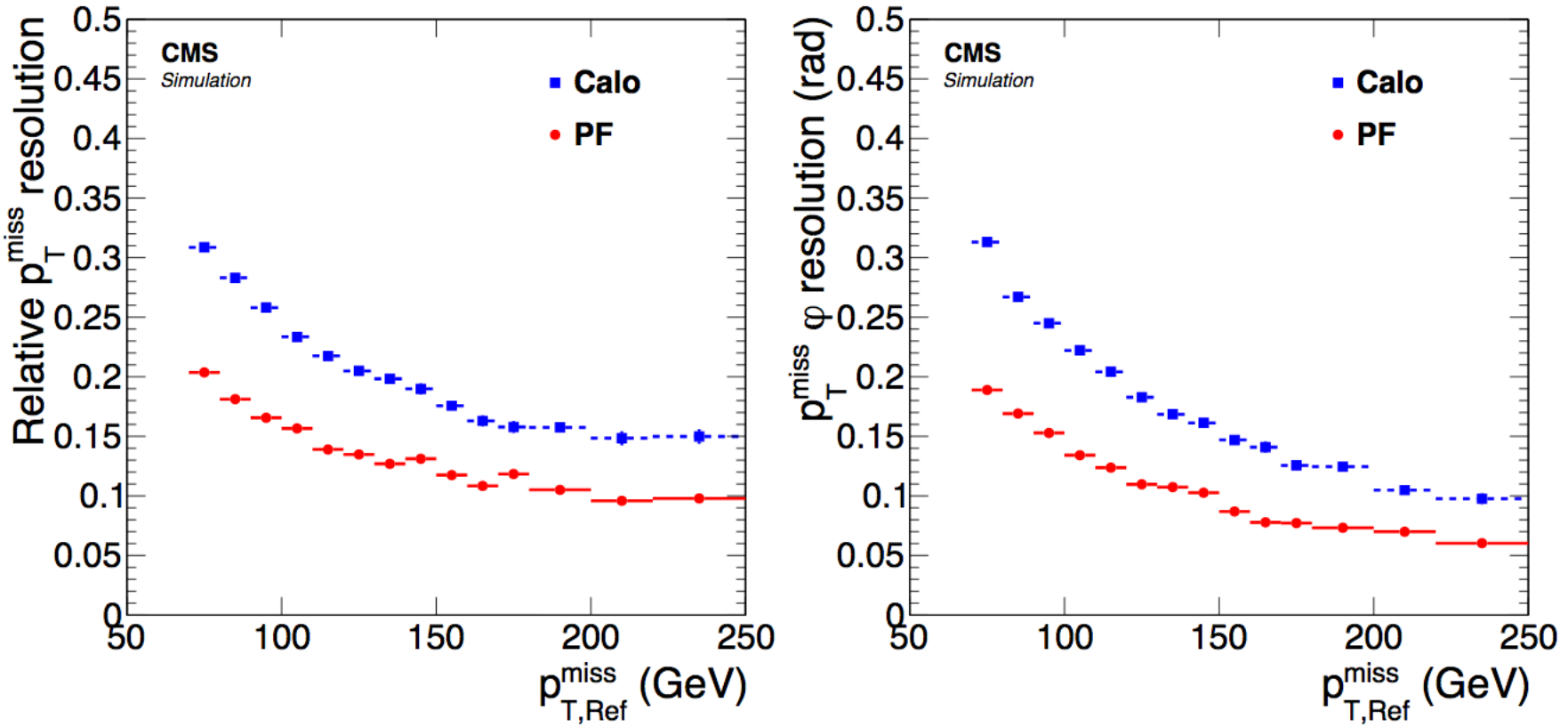


Figure 15: Relative p_T^{miss} resolution and resolution on the $\vec{p}_T^{miss}$ direction as a function of $p_{T,Ref}^{miss}$ for a simulated $t\bar{t}$ sample.

CMS Particle Flow [arXiv 1706.04965]

Standard calorimeter algorithm (Calo): jet is reconstructed as clusters from calorimeter towers. The energy and direction is the weighted average of those towers.

Particle flow algorithm (PF):

1. Reconstruct all the particles in the event using all the sub-detectors (not only the calorimeters, but also ID and muon detector).
2. For each particle, measure its energy and direction (4-vector) by combining info from several sub-detectors.
3. The jet 4-vector is the sum of 4-vector of the particles in jet.

27% photons and 10% neutral charged particles the same in both algo.

The difference is made by 62% charged hadrons. Measured in calo for standard, but in ID for PF**. Also muons used in PF**.

The best resolution: 1) the best detector granularity; 2) best algo.
PF challenges: 1) double counting; 2) not counting at all.

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CMS Particle Flow arXiv 1706.04965