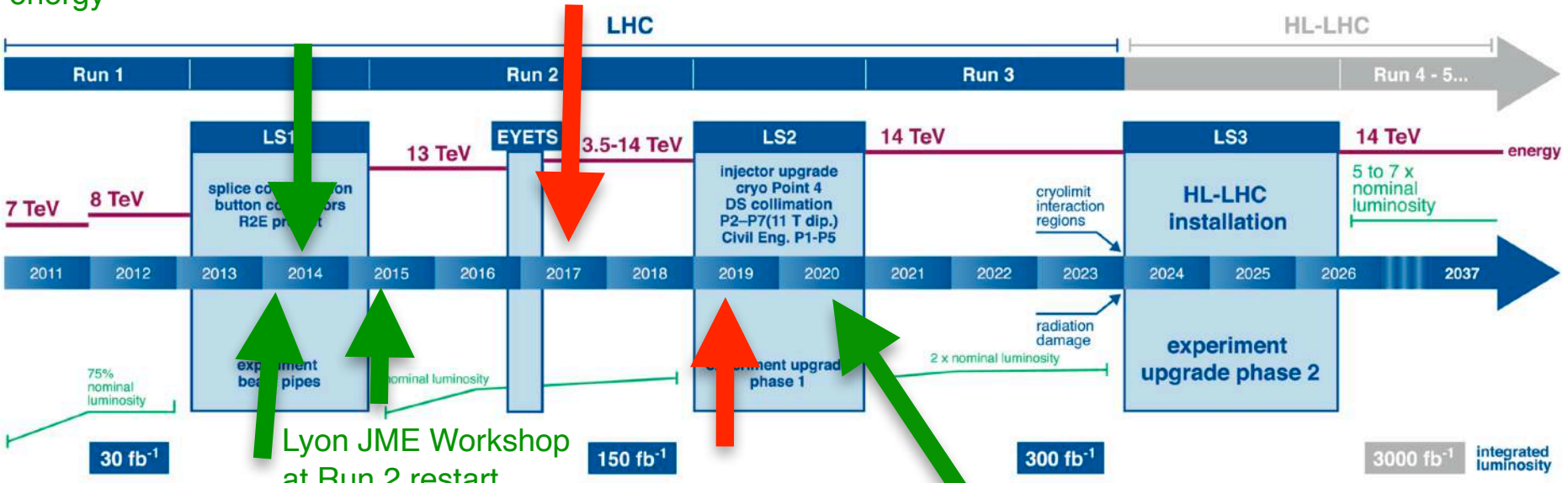

Henning Kirschenmann (Helsinki Institute of Physics)
Christine Mc Lean (SUNY Buffalo)
Laurent Thomas (Université Libre de Bruxelles)

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI
HELSINKI
INSTITUTE OF
PHYSICS

# April 2019: Plan forward

Getting ready for 13 TeV: Vienna workshop on Jets and missing energy

Helsinki JetMET workshop: physics at 100 fb-1




Lyon JME Workshop at Run 2 restart

LPC Workshop: JetMET at High Pile-up, Preparation for LHC Run II

Hamburg JetMET workshop

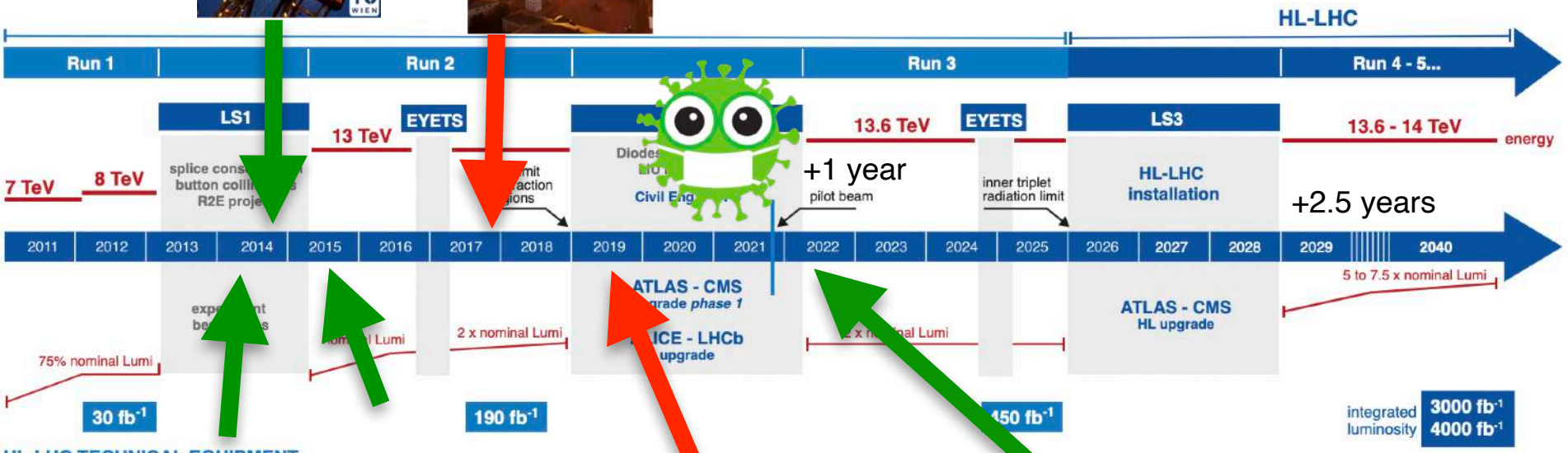
Florence: Ramping up to LHC Run 3

**JetMET workshop in Florence**

6–8 Apr 2020
Florence

# Where we are now







# 2014/2015 workshops



Jet Tagging PU *MET*s

Pileup Removal & JEC

Jets & *MET*

PF Candidates

Pulse reconstruction

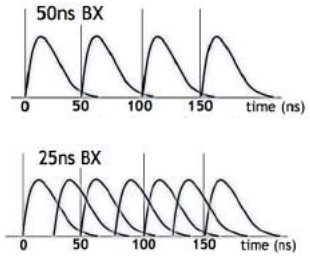
Each step tells us about the previous step

Each Level builds on previous levels

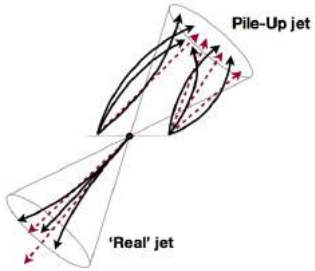
Getting ready for running

2014 we will rebuild from bottom to top

Not completely Jet*MET*



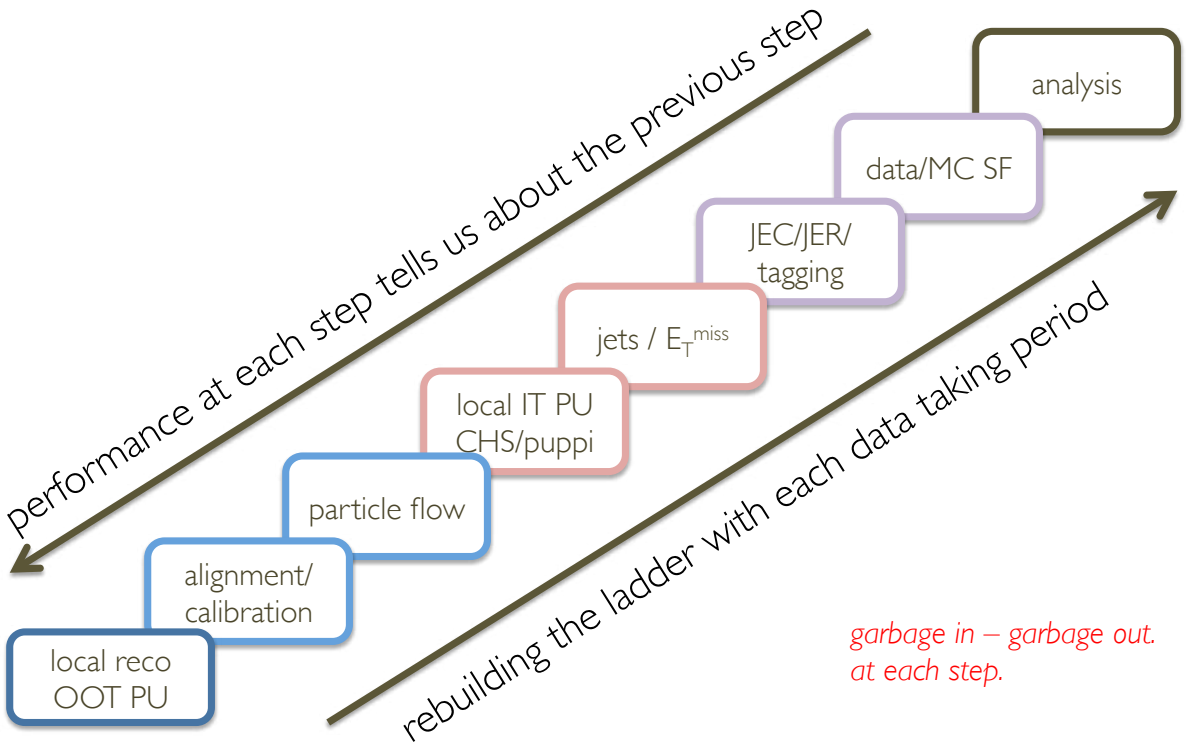

ECAL OOT simulation in Run 1; change to 25ns spacing




CHS still “new thing”

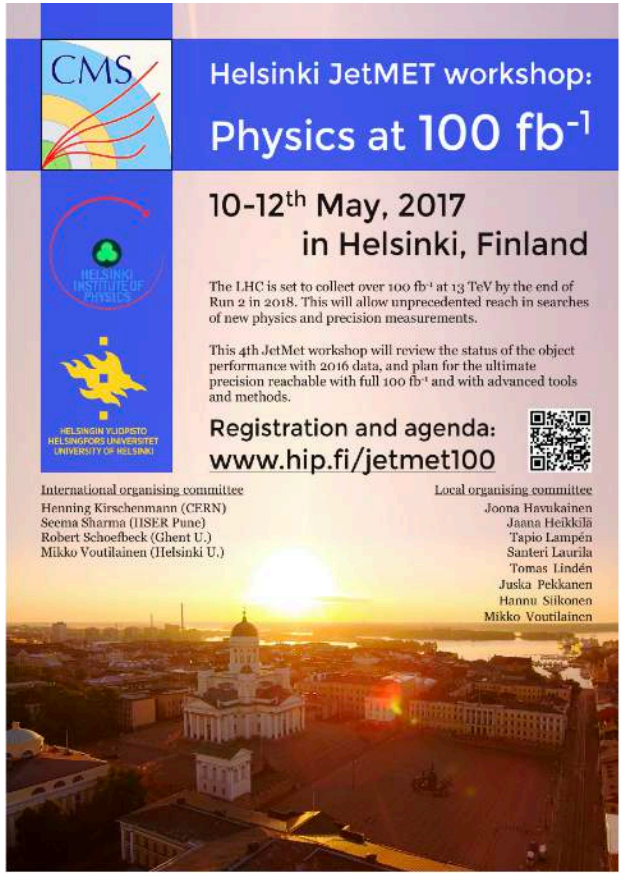
First PUPPI talk in JME in 2014

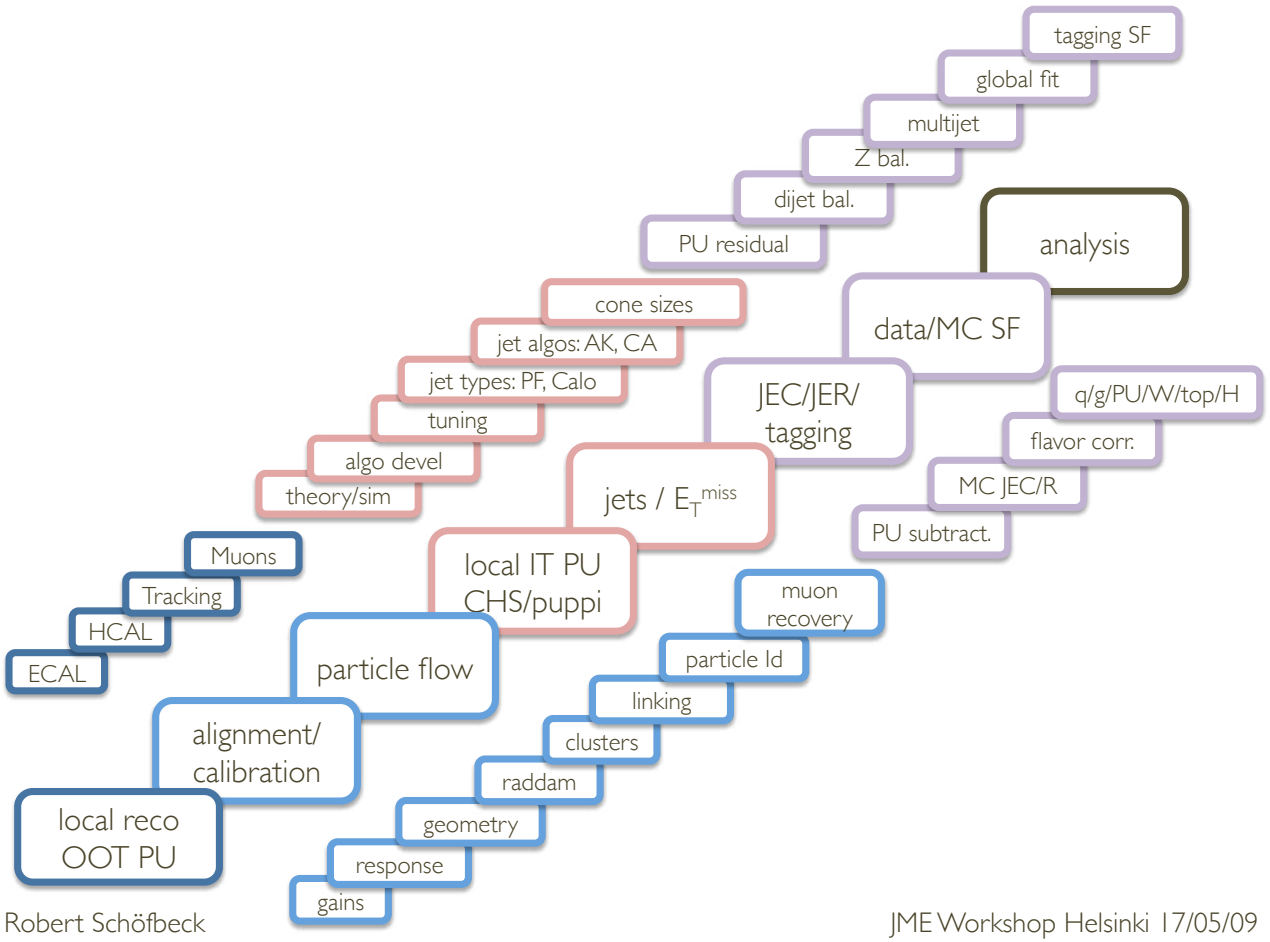
# 2017 workshop: Keep on rebuilding...


*garbage in – garbage out.*
*at each step.*

# 2017 workshop: Keep on rebuilding…

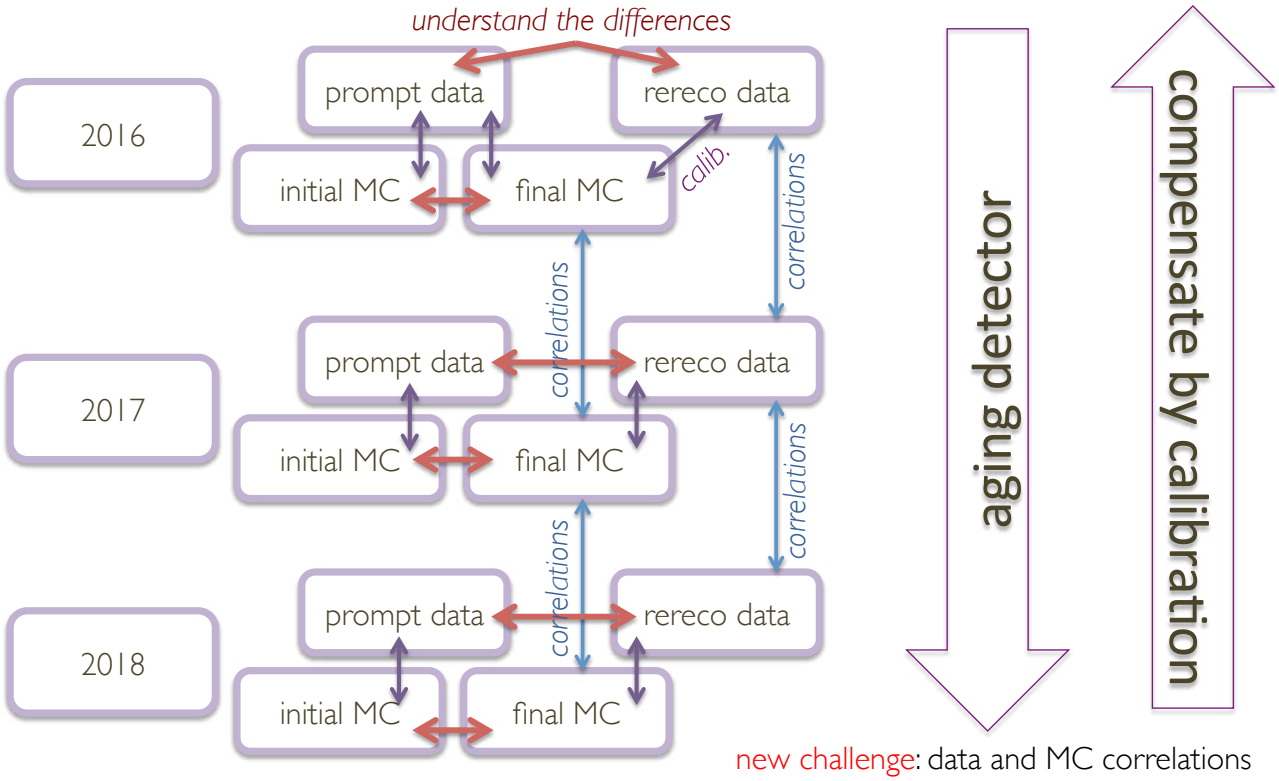



Robert Schöfbeck

JME Workshop Helsinki 17/05/09

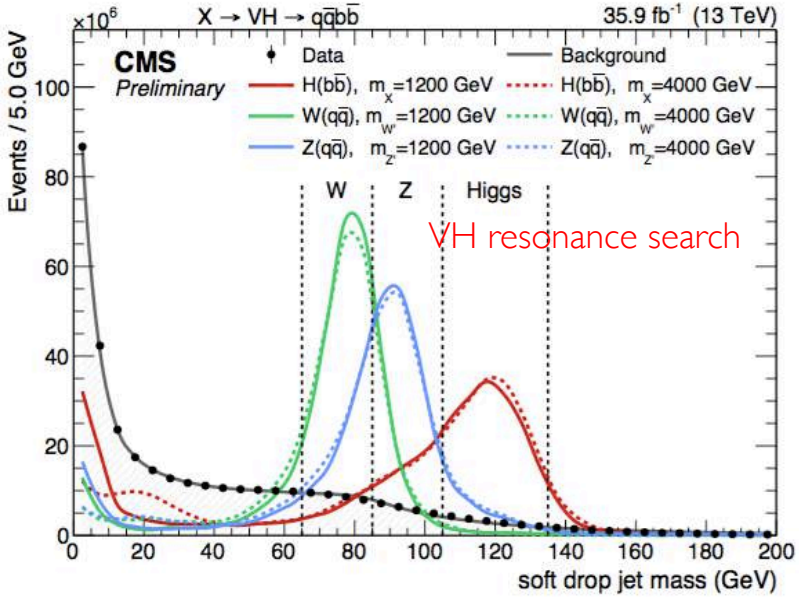
# … across the years

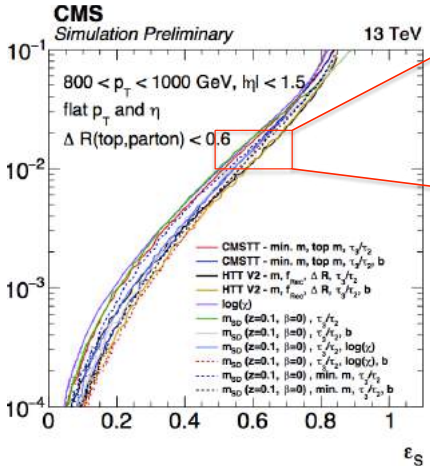
# Heavy object tagging

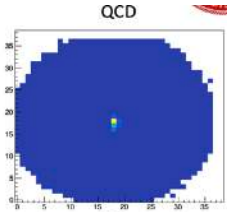

| Algorithm | $p_T$ (jet) [GeV] | t quark | W boson | Z boson |
|---|---|---|---|---|
| $m_{SD} + \tau_{32}$ | 400 | ✓ | | |
| $m_{SD} + \tau_{32} + b$ | 400 | ✓ | | |
| $m_{SD} + \tau_{21}$ | 200 | | ✓ | ✓ |

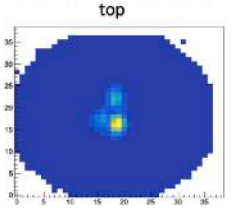
"baseline"




VH resonance search



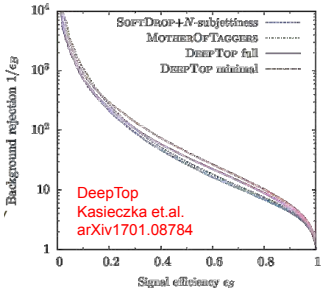




[hep-ph] 13 May 2014

**Soft Drop**

Andrew J. Larkoski,[a] Simone Marzani,[b] Gregory Soyez,[c] and Jesse Thaler[a]
[a] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Institute for Particle Physics Phenomenology, Durham University, South Road, Durham DH1 3LE, United Kingdom
[c] IPhT, CEA Saclay, CNRS URA 2306, F-91191 Gif-sur-Yvette, France
E-mail: larkoski@mit.edu, simone.marzani@durham.ac.uk, gregory.soyez@cea.fr, jthaler@mit.edu




DeepTop
Kasieczka et.al.
arXiv1701.08784

# 2019: Run2 has concluded


Algorithms, alignments and calibrations of all sub detectors

Linking of sub detector deposits and particle identification

***Aging detector***

**Local Reconstruction**

**Particle Flow**

***Huge validation efforts!***

Jet energy scale and resolution

Flavor and heavy object tagging algorithm development

**Jets / MET**

Pile up subtraction at PF (CHS & PUPPI)

Jet types (PF, Calo), algorithms (AK, CA) cones (0.4, 0.8, 1.5)

***Huge validation efforts!***

**Calibration & Tagging**

**Analysis**

Comparison of Data & Simulation

Residual corrections and scale factors

***Who forgot to take the trash out? Go back to step 1***

# 2019: Run2 has concluded


Stay tuned for early, mid, and late Run 3 challenges: They will come, stay vigilant!

**2016 Problems:**

- Dynamic pixel inefficiency - loss of performance in charged hadrons as a function of time with the
- ECAL gain switch issues - mis measurement of high energy electrons/γ

**2017 Problems:**

- Loss of transparency of the ECAL end-caps
- Pre-firing problem in L1 in the ECAL endcap detectors

Already quite significant in 2016 for endcap jets

**2018 Problems:**

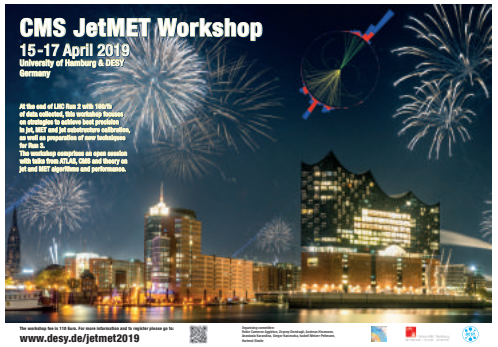
- Local reconstruction issues with HCAL (Negative energy filter)
- Loss of 2 Sectors in the HCAL Endcap

***Never ending battle: How do we move forward? For precision Run2, for Run3?***

- Time dependent MC? Can this reduce the uncertainties due to non-harmonized data?
- Streamlining the JEC analysis. Can this help coping with unprecedented amount of data is being analyzed - we need to be faster than all CMS analyzers!
- Increasing the dimensionality of the corrections? Detector started having phi-dependent problems..

# It's Good to Finally See Everyone in Person!

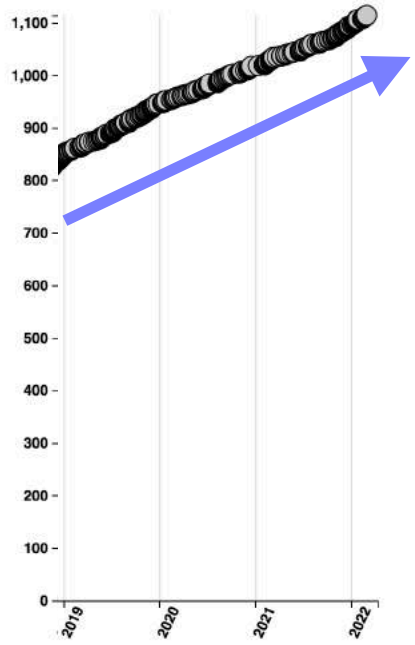
Last workshop in 2019!




~~2020 - 2021~~


2022

# We've made some progress since then…




**CMS Publications**
which rely heavily
on JetMET, of course!

## JME Publications

### Papers

Full list on CMS public results webpage

Full list on CDS

- 13 TeV 2016 Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques
- 13 TeV 2016 Pileup mitigation at CMS in 13 TeV data

### Performance notes

- 13 TeV Jet energy scale and resolution measurement with Run 2 Legacy Data Collected by CMS at 13 TeV (CMS DP-2021/033) TWiki NEW
- 13 TeV Mass regression of highly-boosted jets using graph neural networks (CMS DP-2021/017) TWiki
- 13 TeV PF Jet Performances at High Level Trigger using Patatrack pixel tracks (CMS DP-2021/005) TWiki
- 13 TeV Pileup-per-particle identification: optimisation for Run 2 Legacy and beyond (DP-2021/001) TWiki
- 13 TeV Performance of missing transverse momentum reconstruction in events containing a photon and jets collected by CMS during proton-proton collisions at sqrt(s) = 13 TeV in 2018 (DP-2020/031) TWiki
- 13 TeV W and top tagging scale factors for Run 2 data (DP-2020/025) TWiki
- 13 TeV Performance of the pile up jet identification in CMS for Run 2 (DP-2020/020) TWiki
- 13 TeV Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016-2018 (DP-2020/019) TWiki
- 13 TeV Mitigation of anomalous missing transverse momentum measurements in data collected by CMS at sqrt(s) = 13 TeV during the LHC Run 2 (DP-2020/018) TWiki
- 13 TeV Identification of highly Lorentz-boosted heavy particles using graph neural networks and new mass decorrelation techniques

***+more papers coming soon!***

# And introduced some new faces

2019 2020 2021 2022



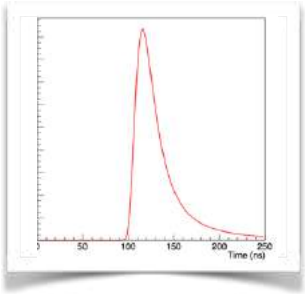



## Subgroups

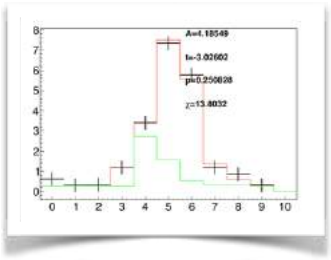
| | |
|---|---|
| JetMET Algorithms and Reconstruction (JMAR) | Leaders: Anna Benecke, Nurfikri Norjoharuddeen |
| Jet Energy Resolutions and Corrections (JERC) | Leaders: Andrea Malara, Minsuk Kim |
| Missing ET (MET) | Leaders: Matteo Cremonesi, David Vannerom |
| JetMET DQM and Validation | Leaders: Roberto Seidita, Ying An |
| JetMET Trigger | Leaders: Pallabi Das, Santiago Paredes Saenz |

# April 2019: Plan forward…

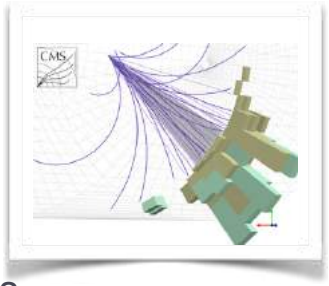
**ECAL**
pulse reconstruction

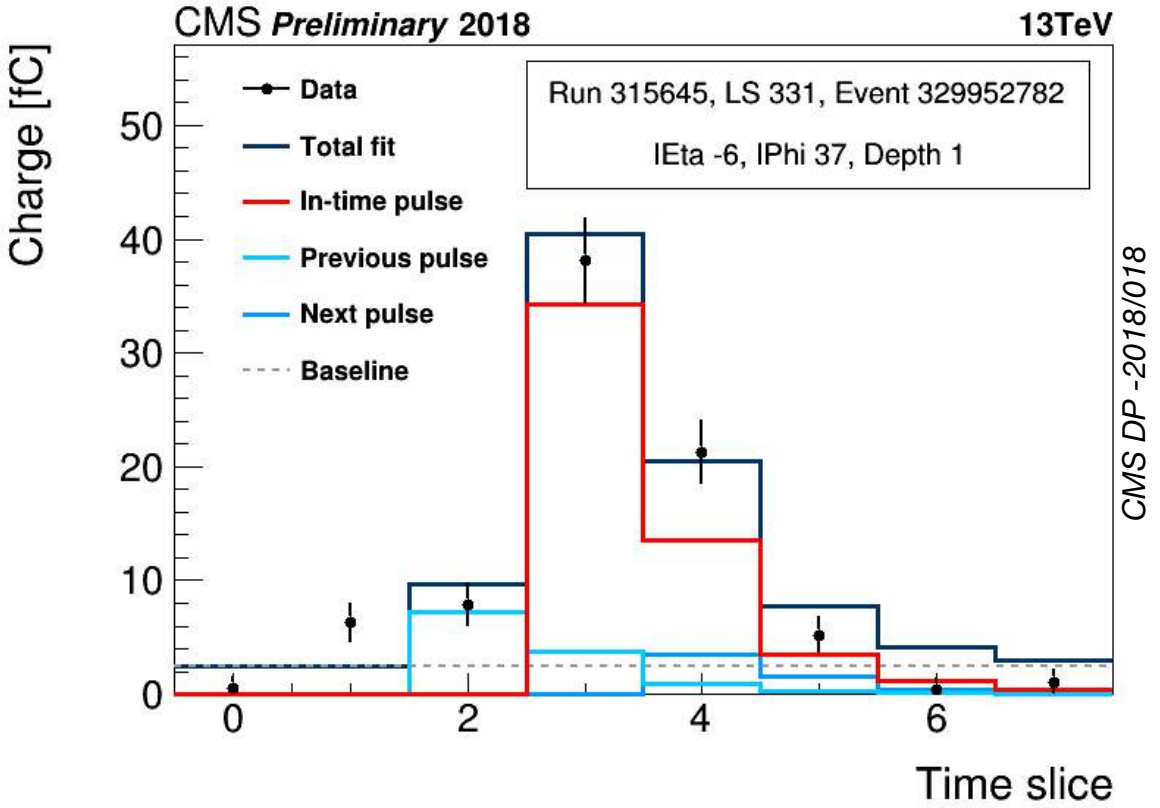


**HCAL**
pulse reconstruction



**Track**
reconstruction



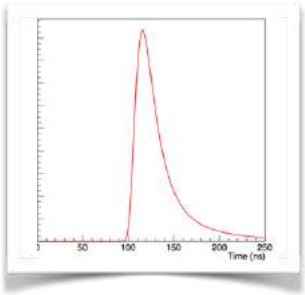



Pulse shape not contained within 25ns bins →
Overlap from previous/following bunch crossing
→ Fit of ECAL/HCAL pulses to subtract OOT-PU

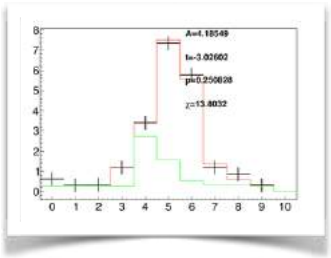

Schematic by J. Dolen

# CMS (jets and MET) reconstruction

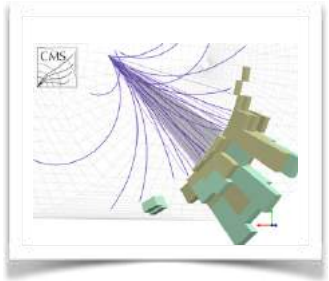
**ECAL**
pulse reconstruction

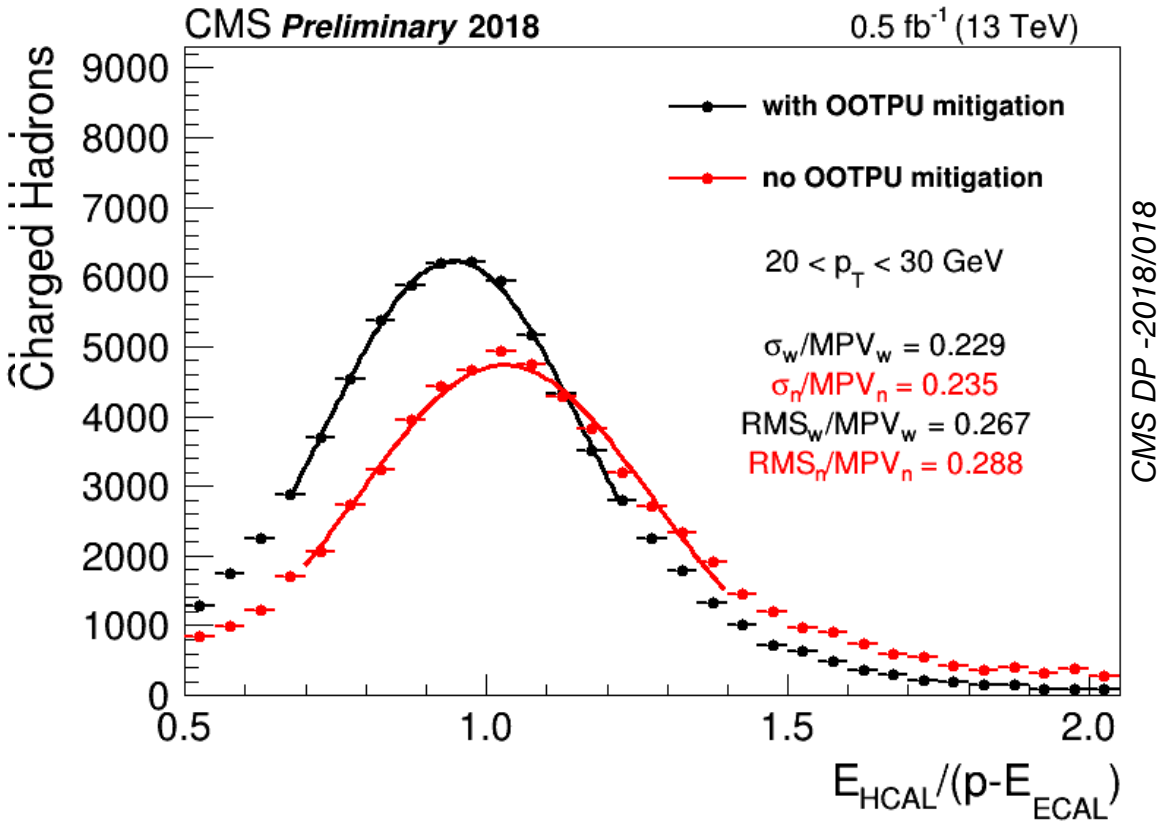


**HCAL**
pulse reconstruction



**Track**
reconstruction



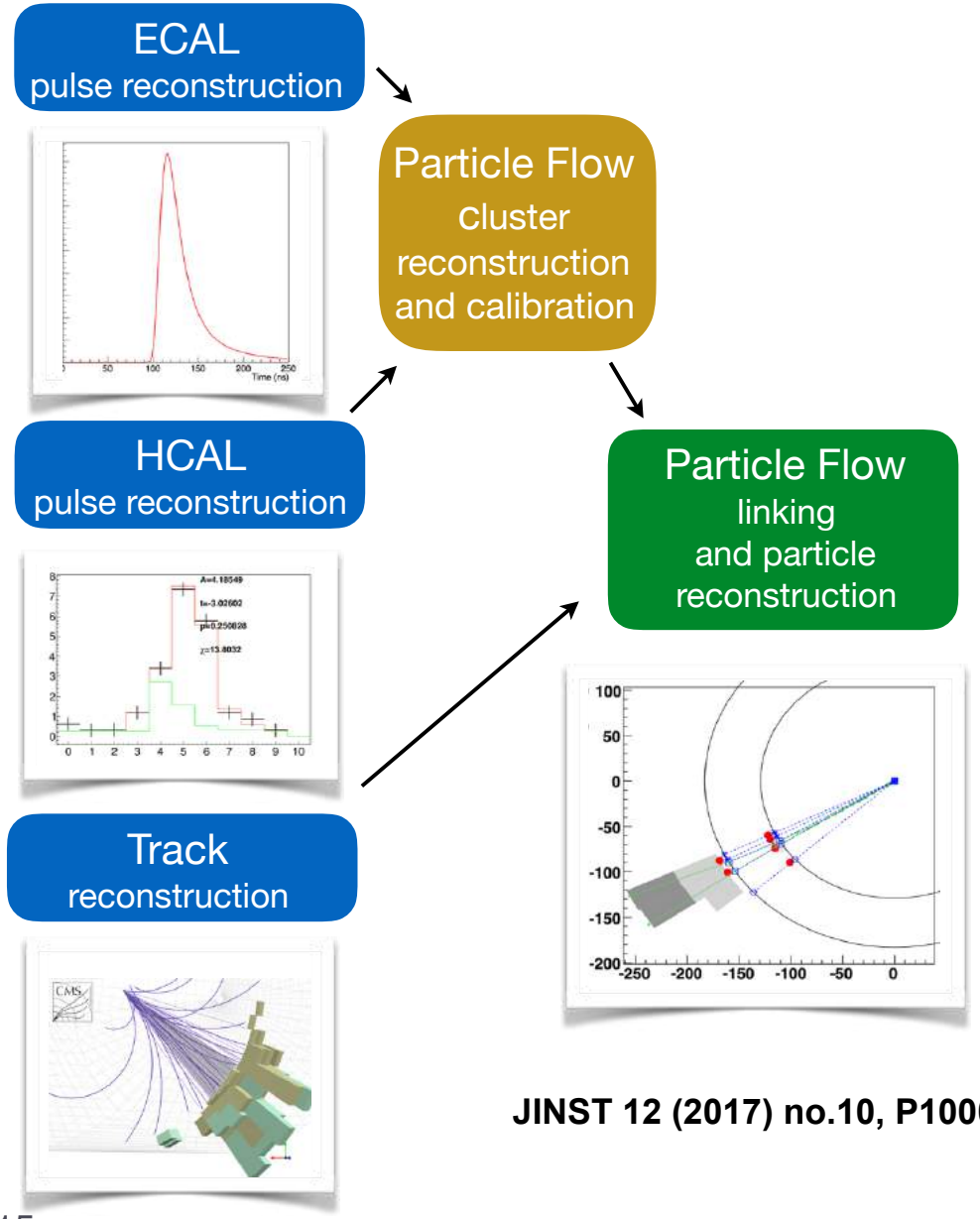



Improved resolution/scale with OOTPU mitigation



Schematic by J. Dolen

# CMS (jets and MET) reconstruction




Try to reconstruct individual particle candidates, combining information from various detectors

- Charged hadrons (tracker)
- Photons (ECAL)
- Neutral hadrons (HCAL)
- +Electrons/muons

- Form jets and MET using particle candidates
- PF greatly improves CMS jet energy resolution as compared to calorimeter-only reconstruction.

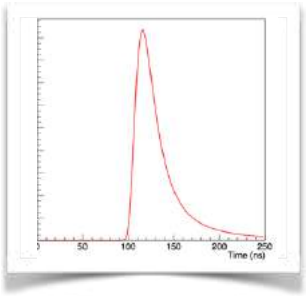
**JINST 12 (2017) no.10, P10003**



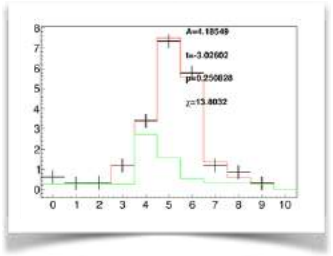
Schematic by J. Dolen

# CMS (jets and MET) reconstruction

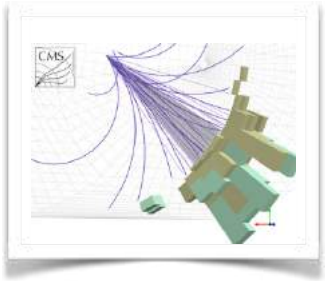
ECAL
pulse reconstruction



HCAL
pulse reconstruction

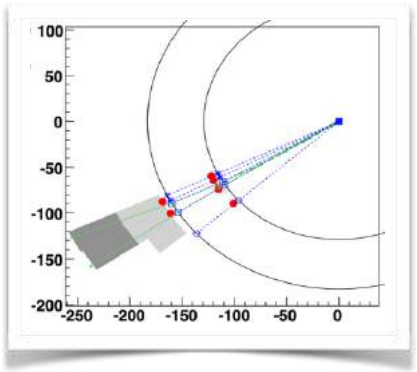


Track
reconstruction

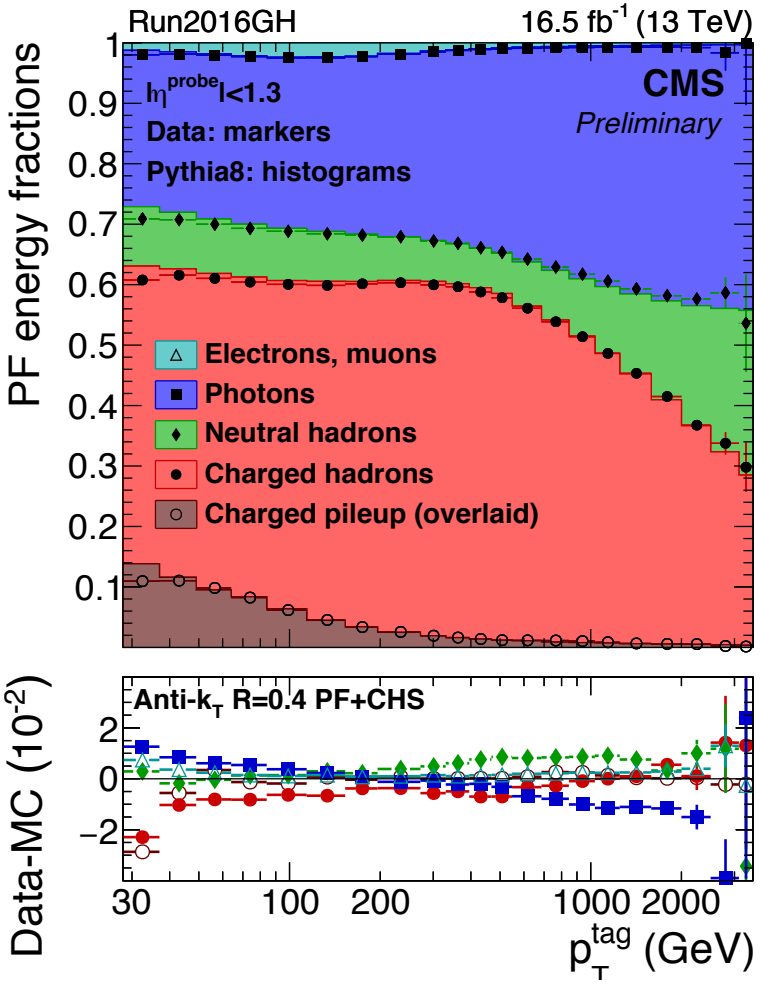


Particle Flow
Cluster
reconstruction
and calibration

Particle Flow
linking
and particle
reconstruction



JINST 12 (2017) no.10, P10003

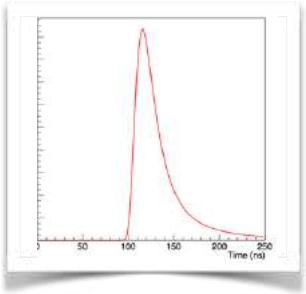




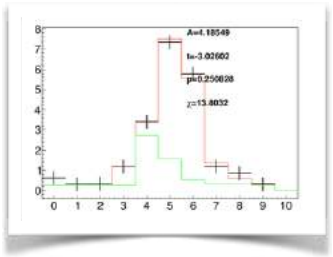

Schematic by J. Dolen

# CMS (jets and MET) reconstruction

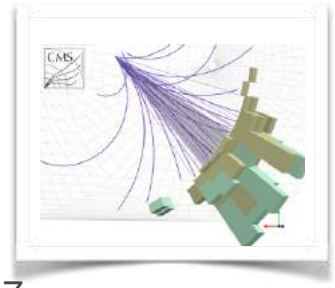
ECAL
pulse reconstruction



HCAL
pulse reconstruction



Track
reconstruction



Particle Flow
Cluster
reconstruction
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Particle Flow
linking
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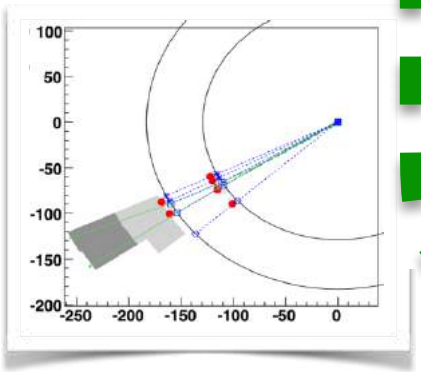
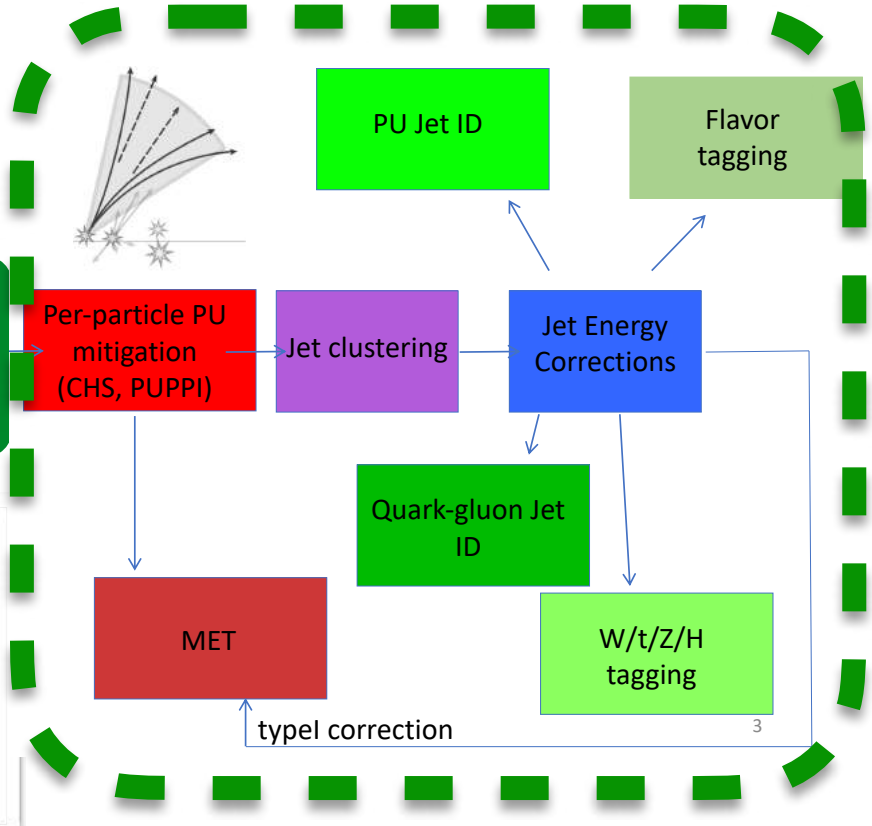





**JINST 12 (2017) no.10, P10003**

Will briefly go through all of these aspects

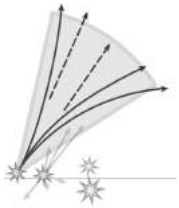


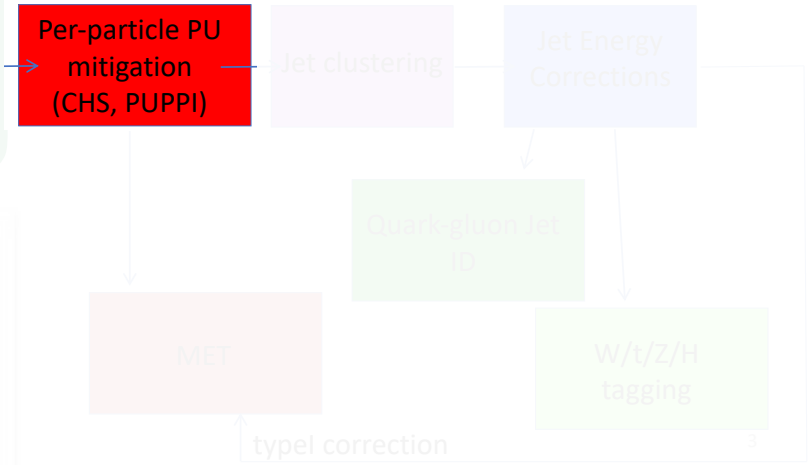
Schematic by J. Dolen

# Pileup mitigation

What can we do

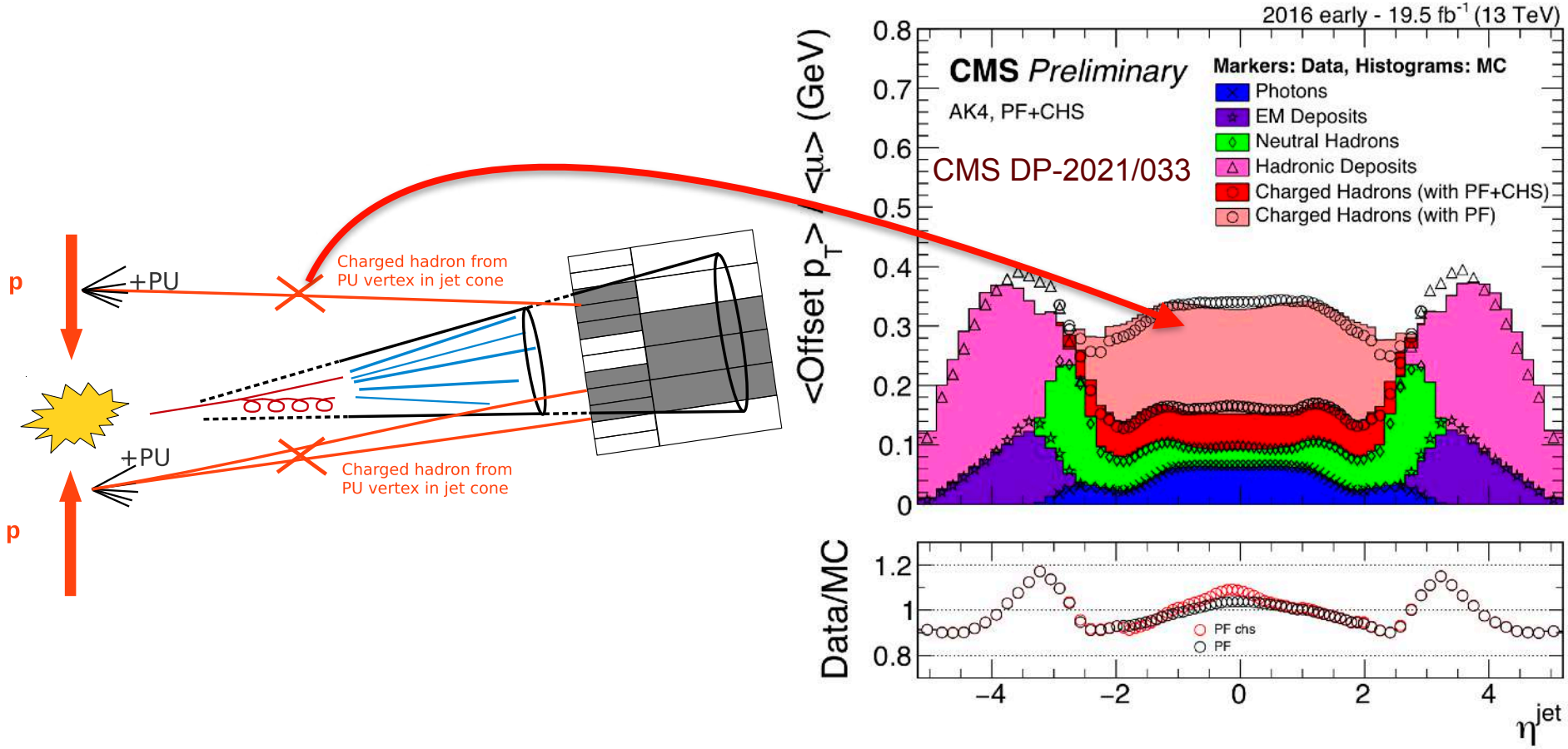
- Act on PF candidates
  - delete from list→CHS
  - assign weight based on event→PUPPI
- Act on jets
  - Correct for PU offset in JEC
  - Identify PU jets (PUJetID)






JINST 12 (2017) no.10, P10003

# Charged Hadron Subtraction for jets

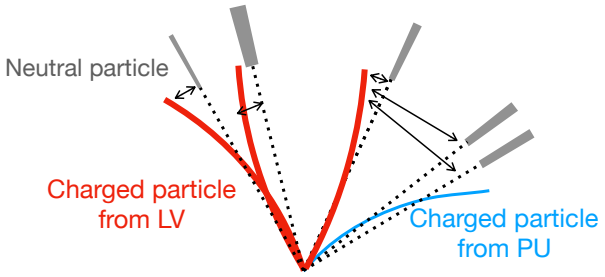



**Particle Flow Charged Hadron Subtraction (CHS)**

- Majority of pileup is from charged particles
- CHS removes individual charged hadrons from pileup vertices (ca. 2/3 of offset energy in barrel)
- Inherent limitation: Only works in tracker-covered region, only works on charged component

# Extension to neutral deposits: PUPPI in CMS

Concept : neutral particles close to charged particles from LV are likely to be from LV.



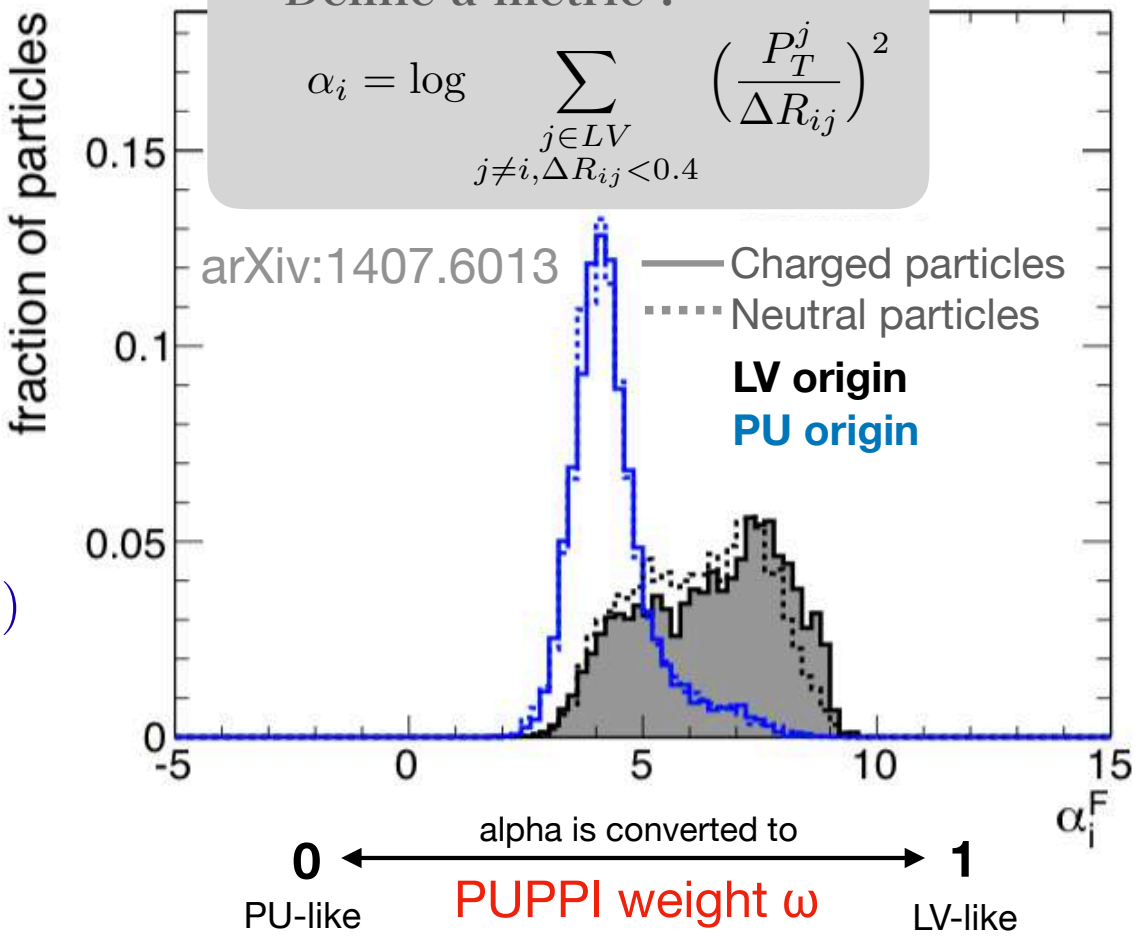

Scale momentum by its PUPPI weight :

$$P_T^{i,\ \mathrm{PUPPI}} = P_T^i \times \omega_{\mathrm{PUPPI}}(\alpha^i)$$

PUPPI is extendable to the forward region by redefining alpha with charged+neutral particles.

Define a metric :

$$\alpha_i = \log \sum_{\substack{j \in LV \\ j \neq i, \Delta R_{ij} < 0.4}} \left( \frac{P_T^j}{\Delta R_{ij}} \right)^2$$



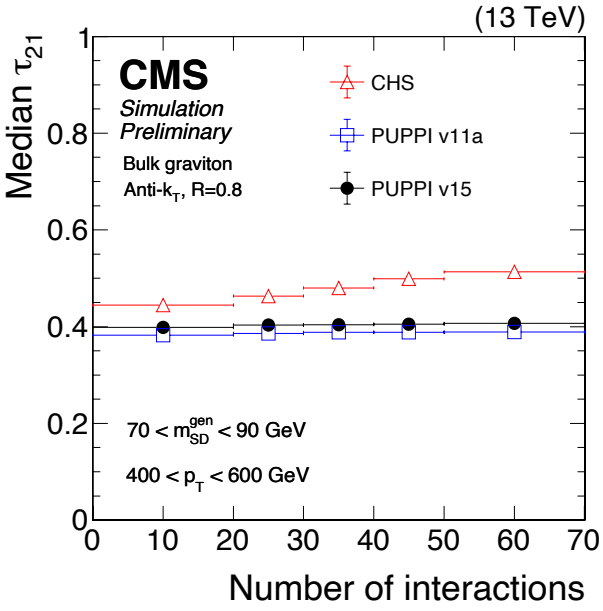


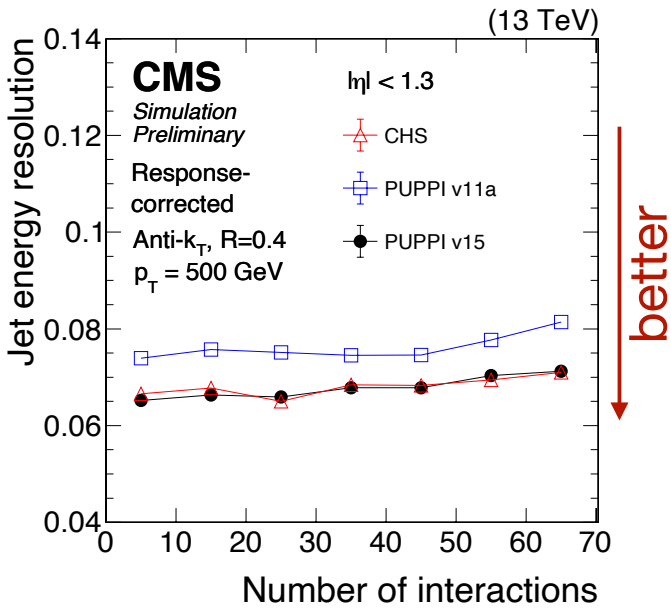
Schematic by S. Hasegawa

# PUPPI for Run 3

**More stable against PU in many variables like soft drop mass, MET resolution, jet efficiency and purity**

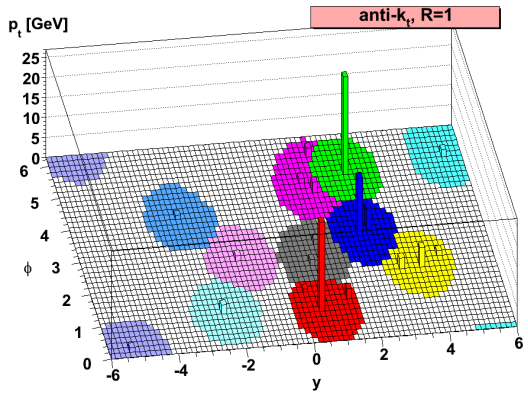
Performances of PUPPI jets/MET were extensively studied and compared to CHS jets/ PF MET in JME-18-001 and the UL tune PUPPI v15 in DP-21-001



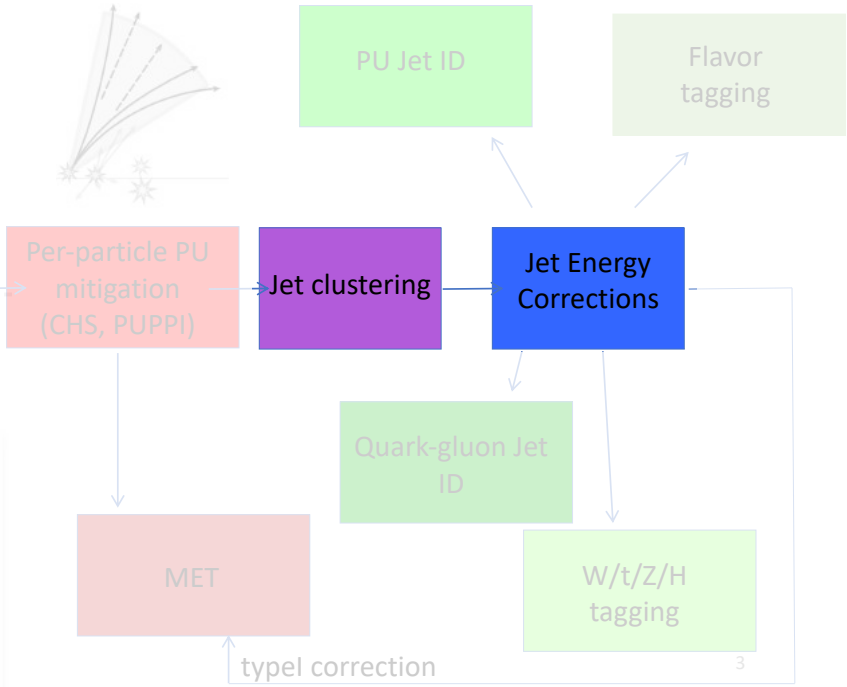




- **PUPPI** more stable against PU in jet substructure variable
- Improved JER for **PUPPI** to be better or the same than **CHS** over the whole $p_T$ range

# Jet clustering and corrections

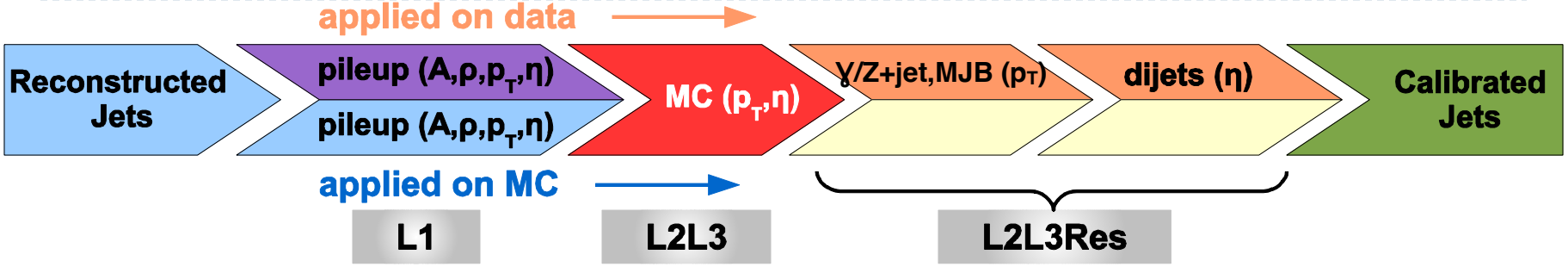



arXiv:0802.1189v2




CMS: Typical choice for small-R jets: R=0.4; R=0.8 for large-R jets

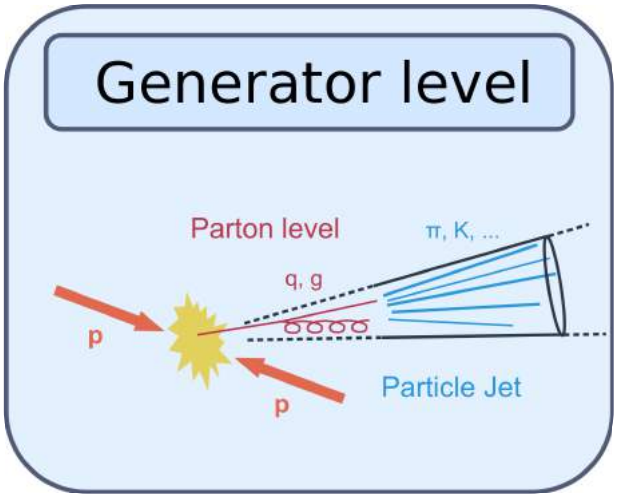
# Jet energy corrections

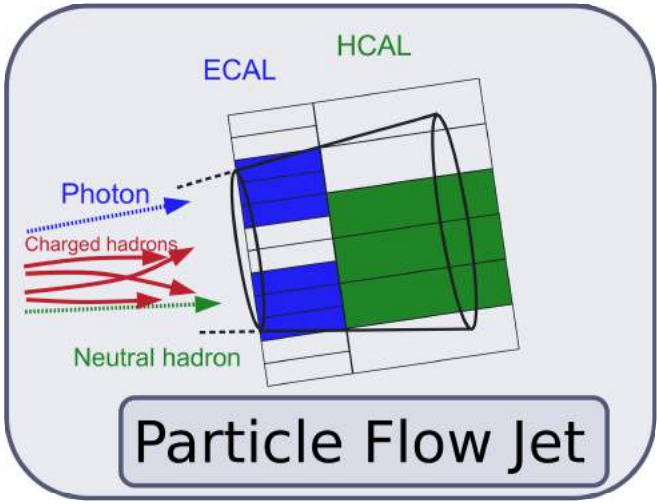



JEC corrects reconstructed jets - on average - back to particle level

$< p_T^{reco} > / < p_T^{gen} > = 1$

(vs. $p_T^{gen}$ , η, A, pileup μ)

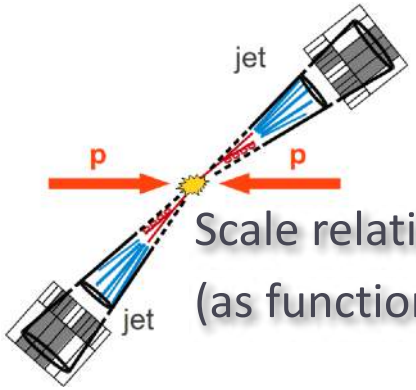


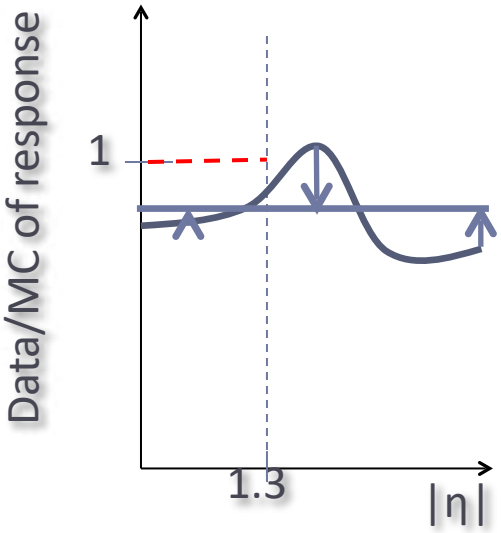

**Factorized approach to JEC:**

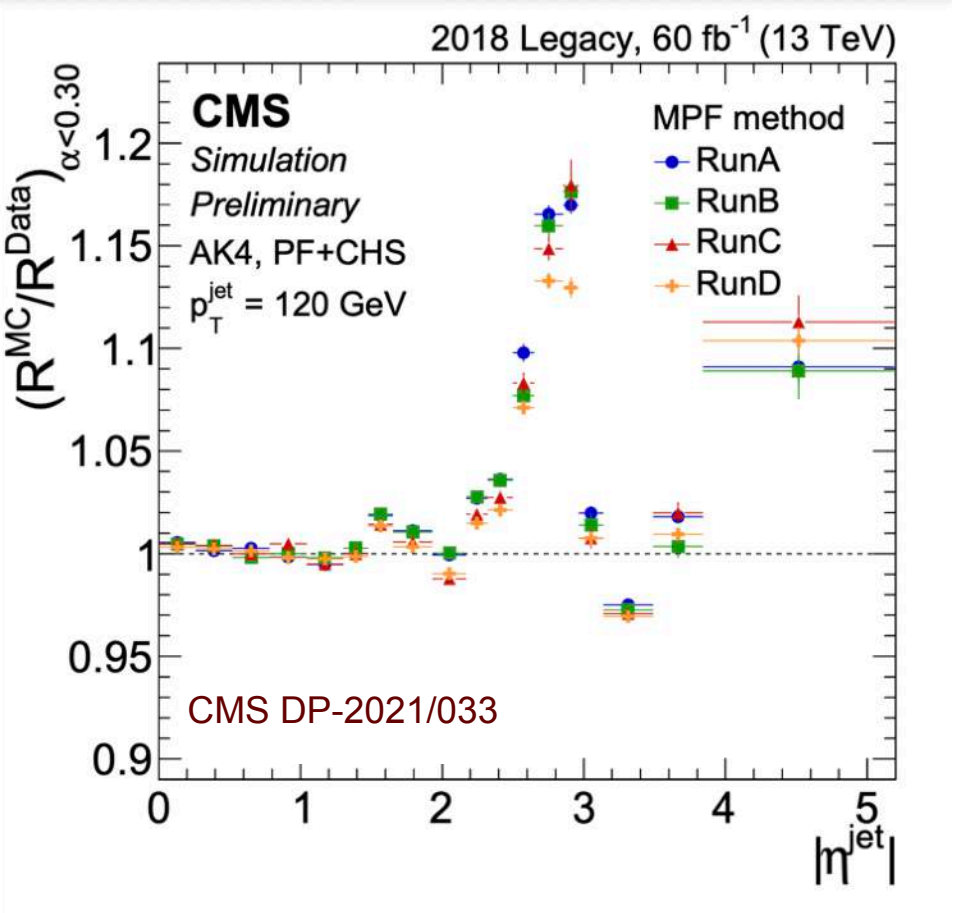
- Pileup corrections to correct for offset energy (noPU vs. PU jet matching)
- Correction to particle level jet vs. $p_T$ and η from simulation
- Only for data: Small residual corrections (Pileup/relative and absolute) to correct for differences between data and simulation

# Jet energy scale determination in data




Scale relative to $|\eta|<1.3$ (as function of $\eta$)



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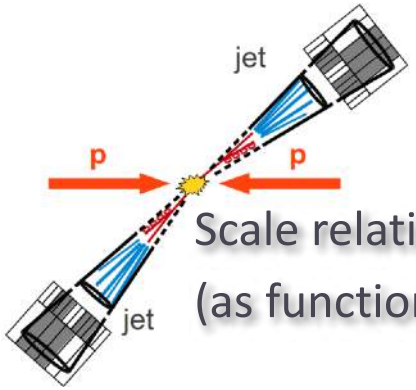


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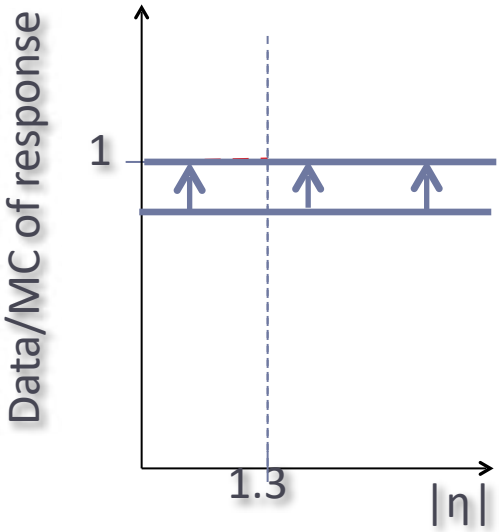
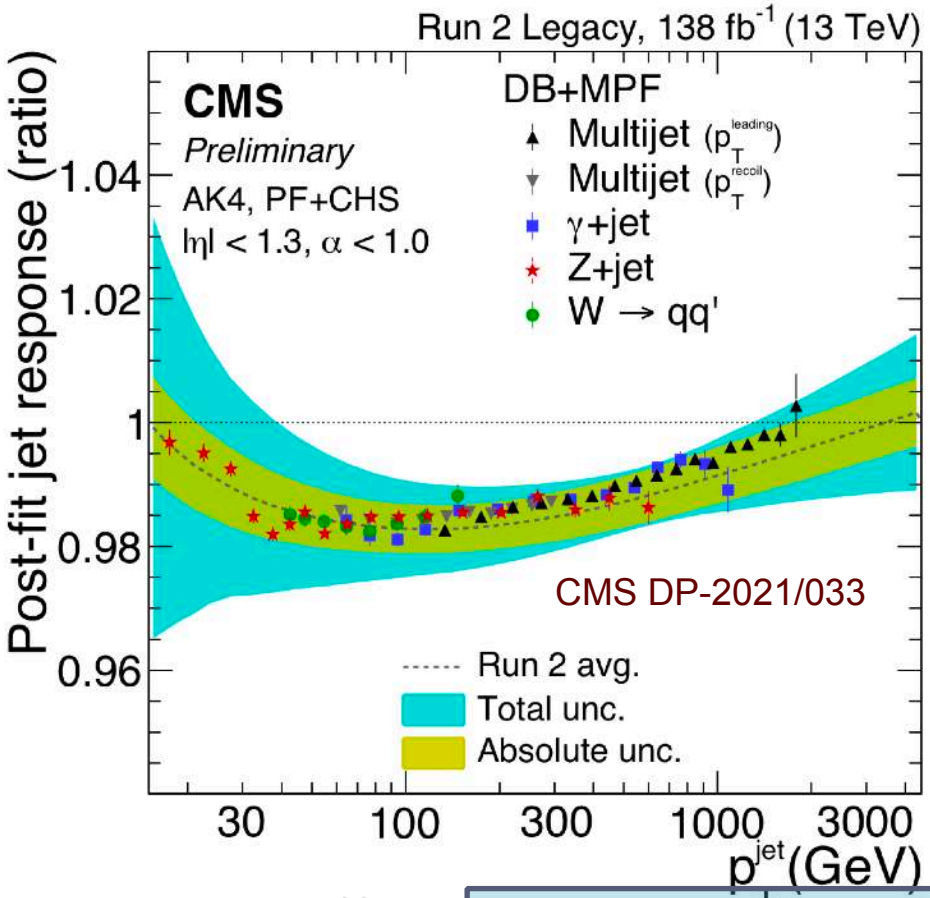
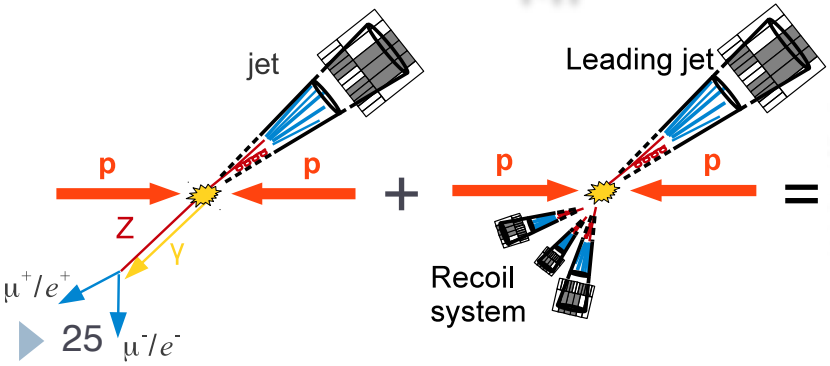
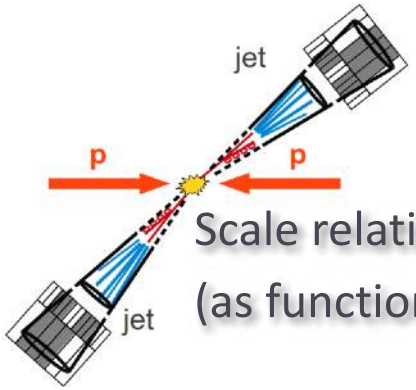


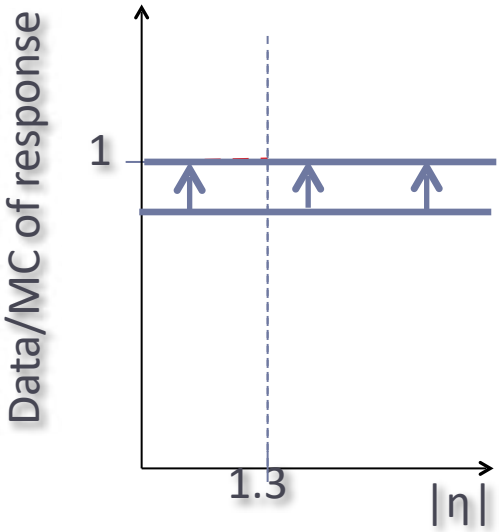



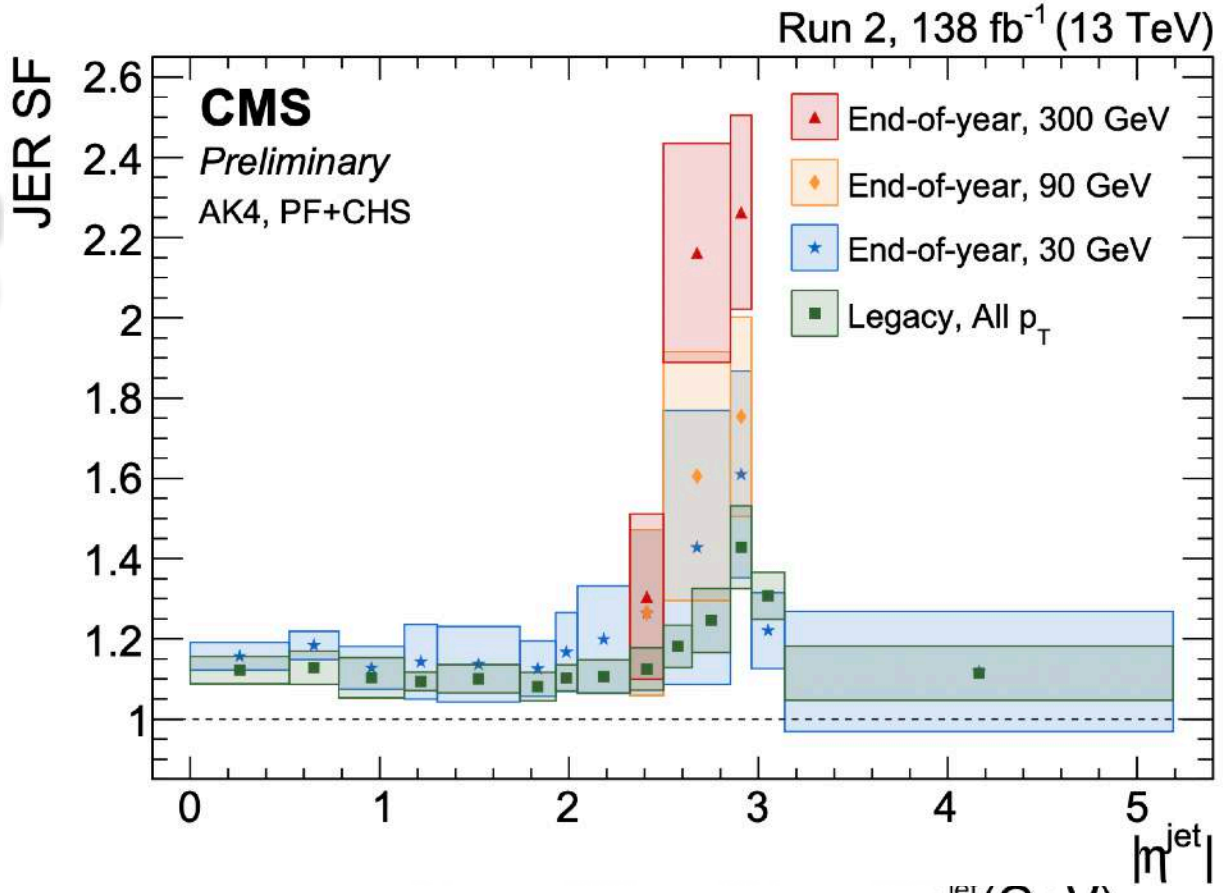

Average absolute scale in $|\eta|<1.3$

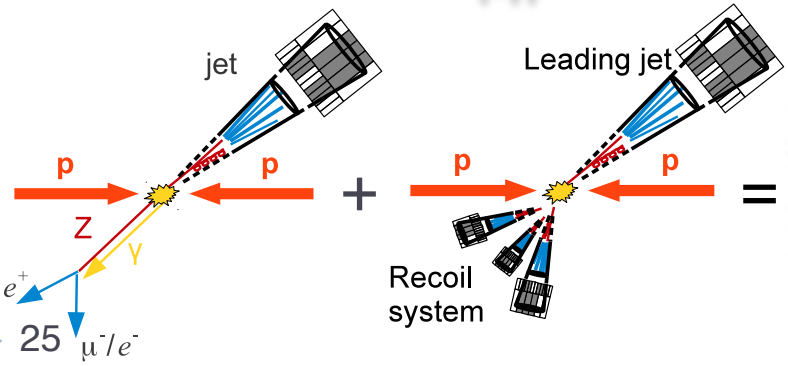
# Jet energy scale determination in data



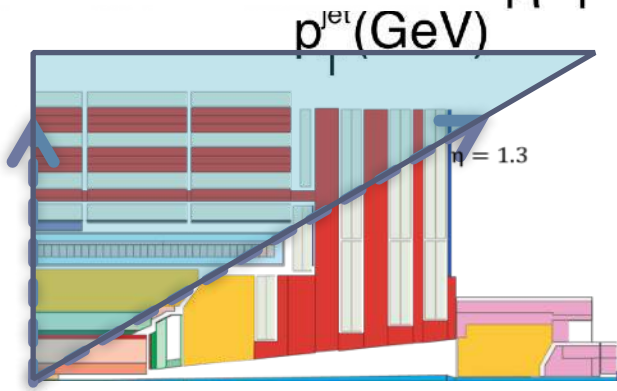

Scale relative to |η| (as function of η)



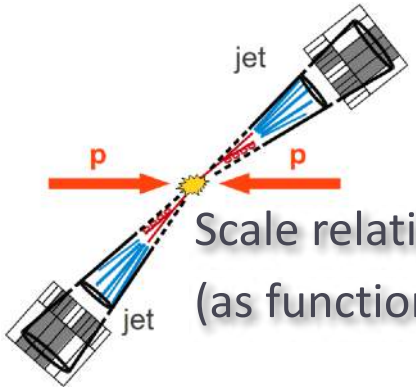




Average absolute scale in |η|<1.3



# Jet energy scale determination in data

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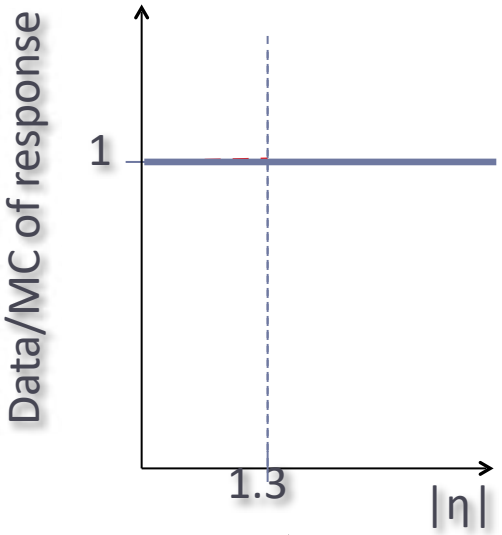
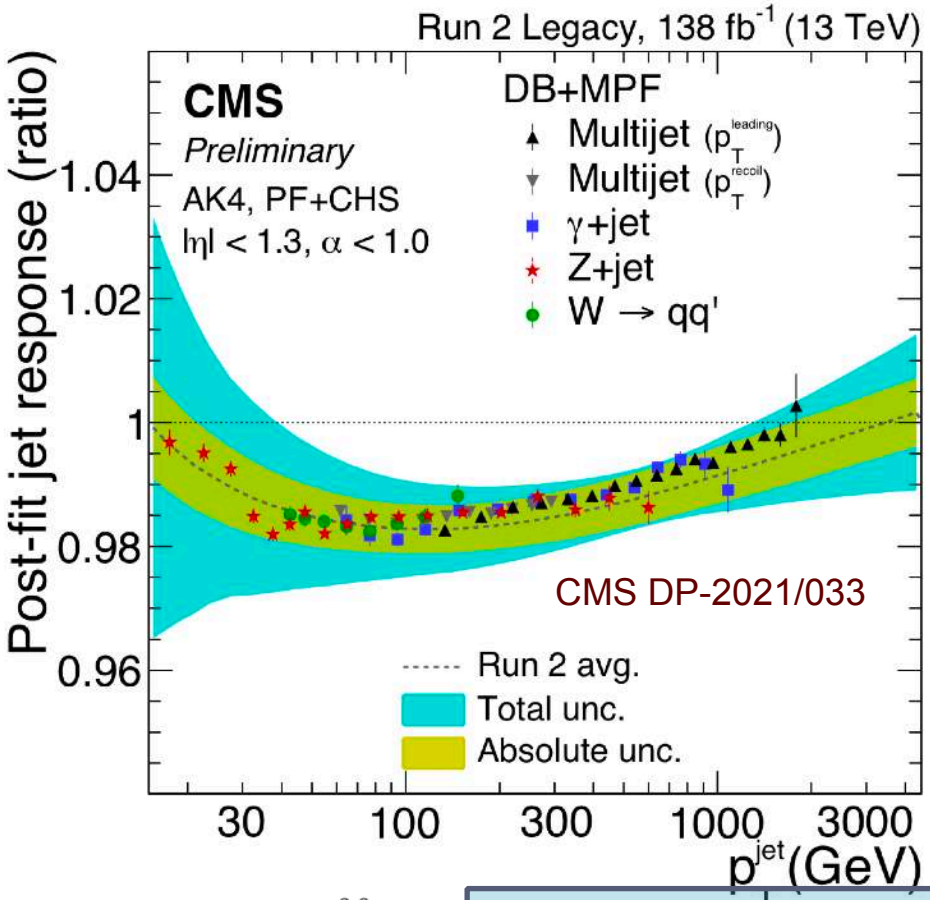
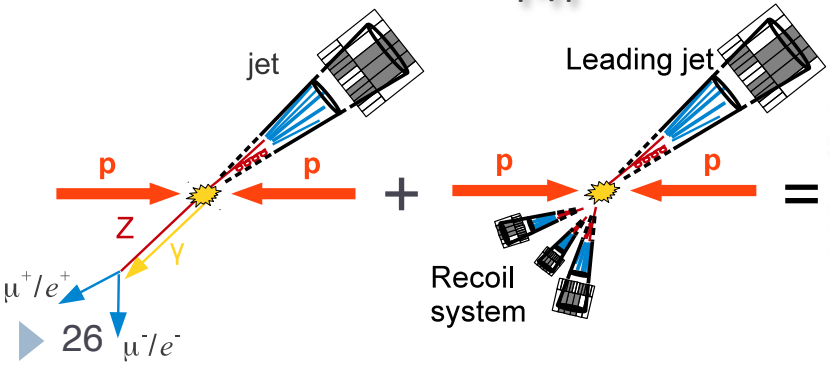
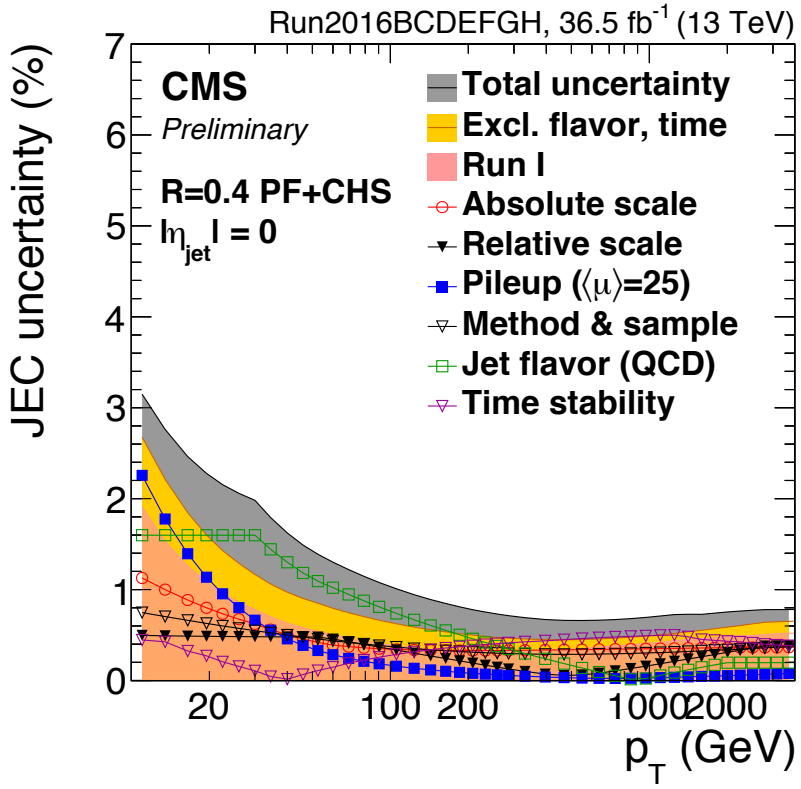


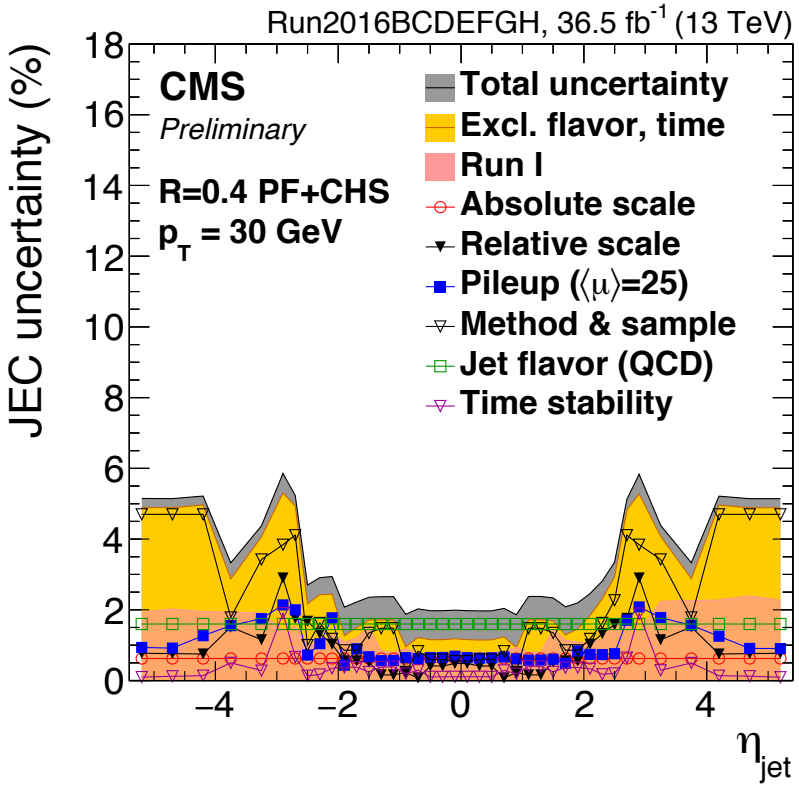




Average absolute scale in $|\eta|<1.3$

# Jet energy scale uncertainties (old)




- Below 1% uncertainty in the barrel region (but slightly higher than in Run 1 as of now (stay tuned)), ultimate goal: 0.1%
- Challenging Run 2 conditions: High PU, ageing detector, different run periods have significantly distinct features
- Evolving methods to cope: combine all available channels “everywhere”, introduce new channels, increase selection efficiency, introduce more ML.

# Jet energy scale uncertainties (old)

**Henning Kirschenmann** kirschen 25d

Dear all,

We would like to congratulate first and foremost Mikko for the great achievement of securing an ERC Consolidator Grant 1 4 for one of the most central JetMET topics: taking the precision of jets to a new level and innovating and future-proofing the procedures in view of HL-LHC!

Congratulations extend to the Helsinki 2 1, JERC, and overall JetMET teams as the environment in which this project evolved and will be carried out.

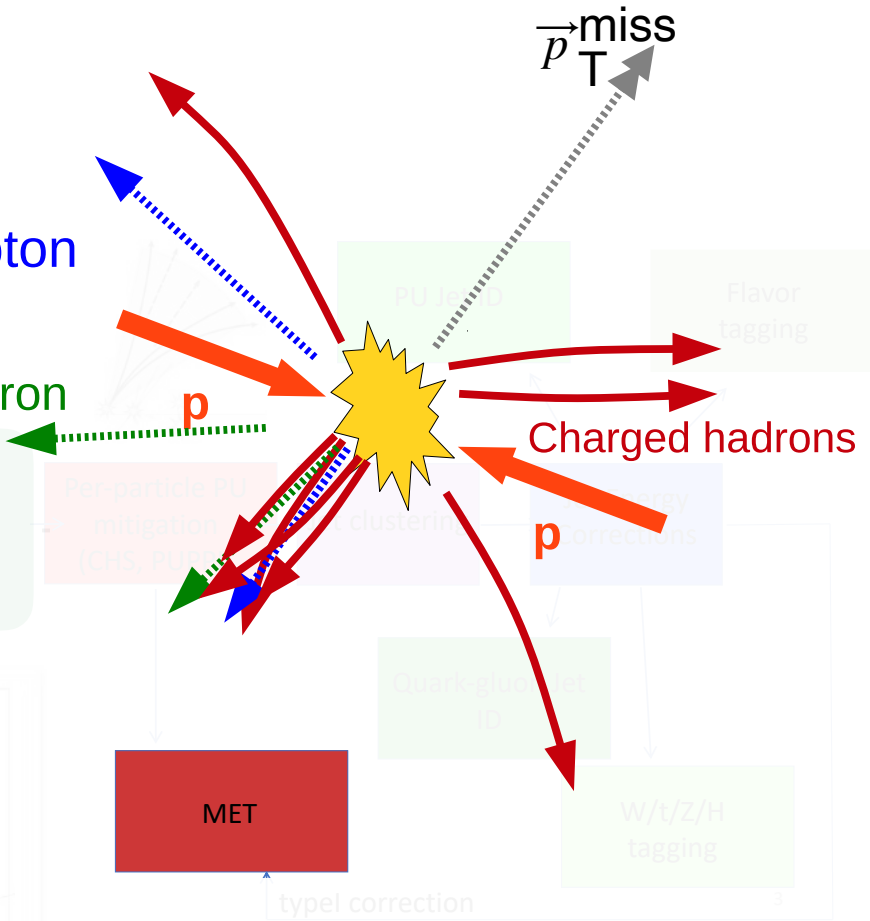
For those curious on the big picture, we are happy to have Mikko report on the project in our JME General meeting on Monday at 2 pm CERN time:
https://indico.cern.ch/event/1141125/ 7

Best regards,
Christine and Henning
(on behalf of all of JME)

- Below 1% uncertainty in the barrel region (but slightly higher than in Run 1 as of now (stay tuned)), ultimate goal: 0.1%
- Challenging Run 2 conditions: High PU, ageing detector, different run periods have significantly distinct features
- Evolving methods to cope: combine all available channels “everywhere”, introduce new channels, increase selection efficiency, introduce more ML.

# Missing transverse momentum

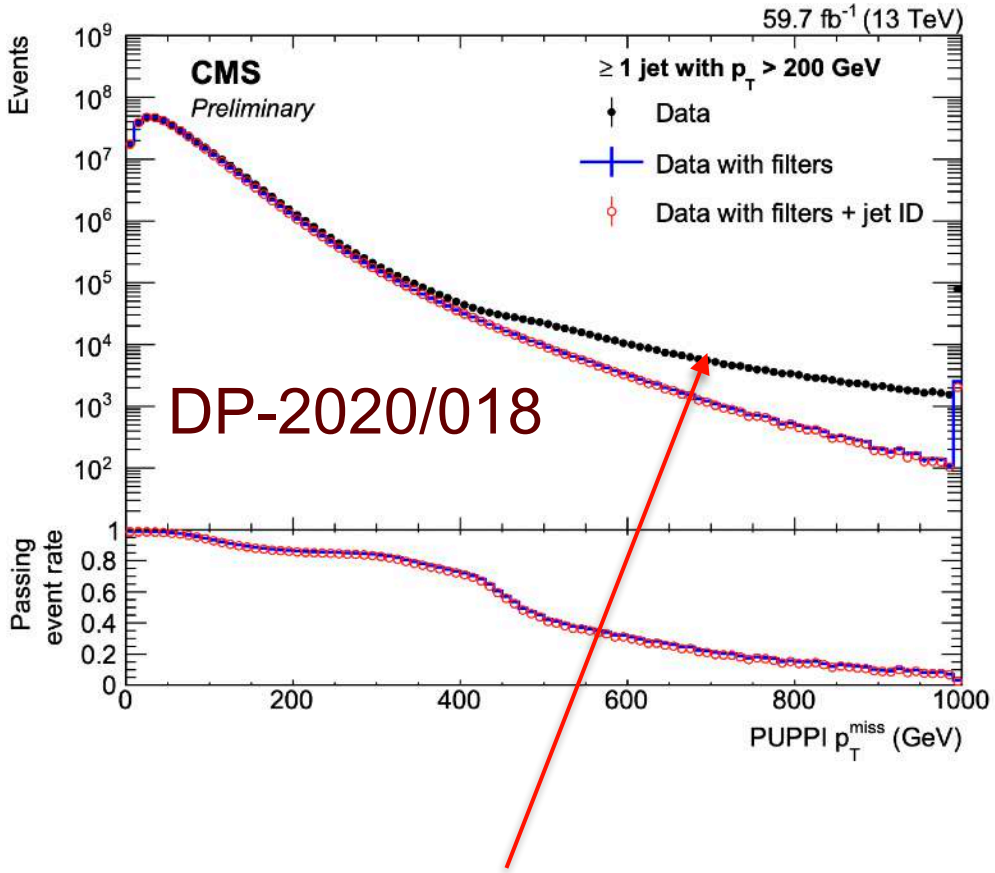
- Negative vector sum of $p_T$ of all PF candidates (weighted in the case of PUPPI MET)
- JEC propagated to clustered energy contribution of $p_T^{miss}$ (Type I MET )



# Missing transverse momentum: Cleaning

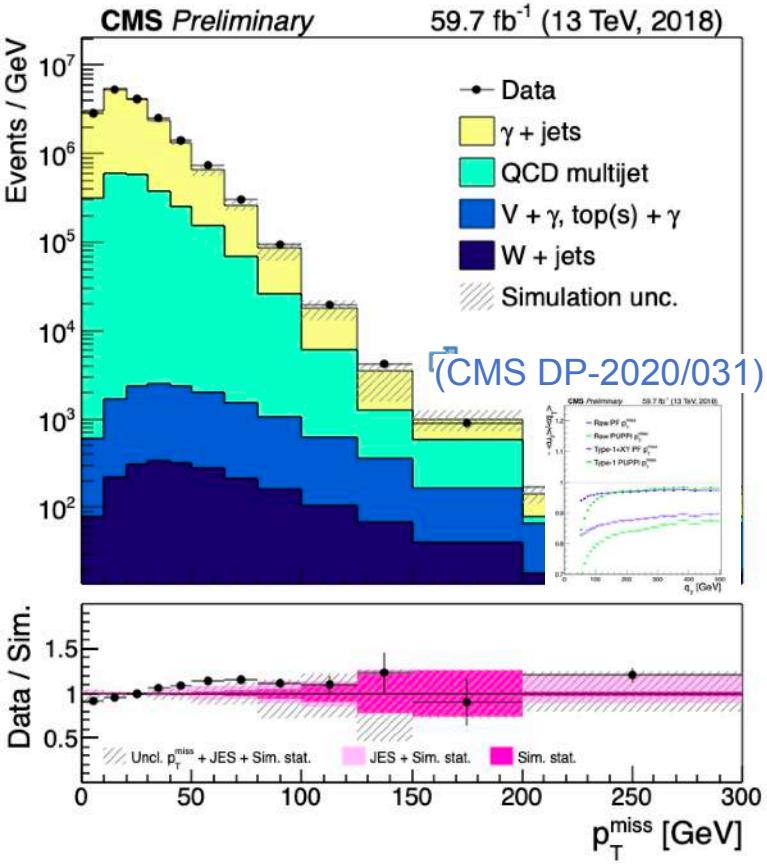
Several datasets used for MET studies

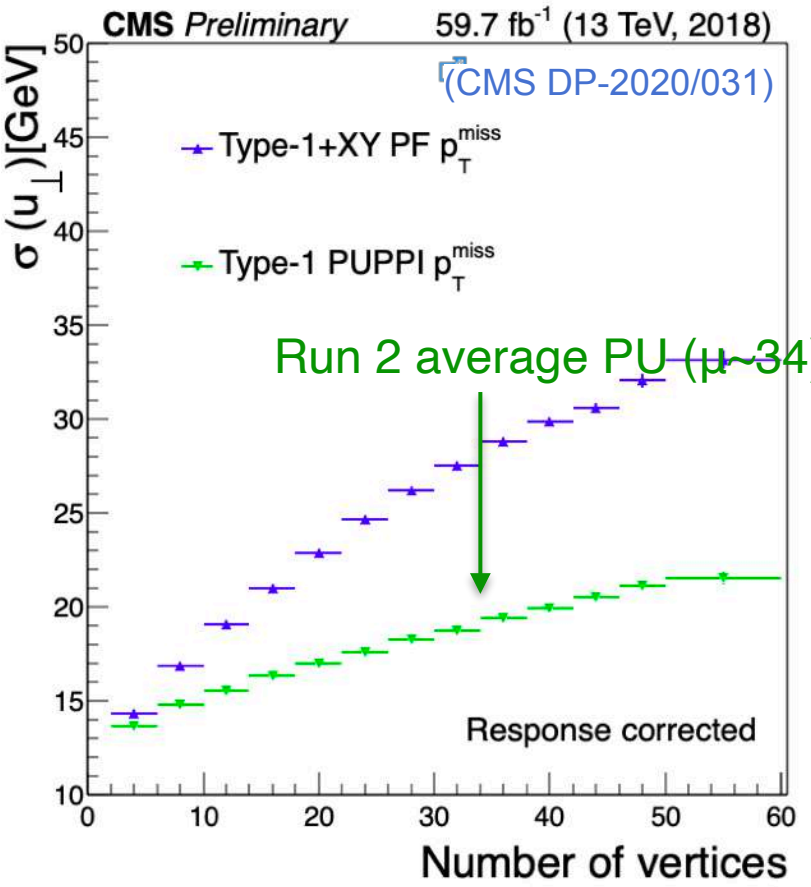
- Monojet, dijet
  (MET cleaning studies)
- Dilepton (Z→μμ, ee)
  and single-photon
  (MET scale and resolution)
- Single-lepton
  (MET performances in
  events with genuine MET)

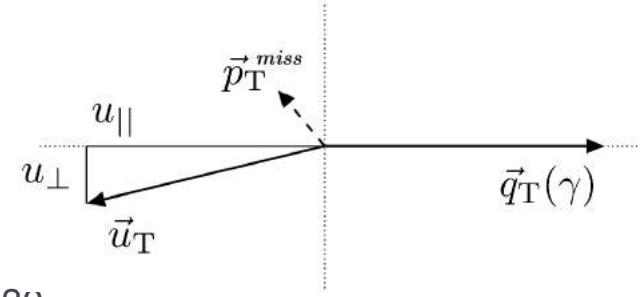



Anomalous MET arising from detector noise, machine-induced background or reconstruction failure; needs to be adapted each year

# Missing transverse momentum: PUPPI



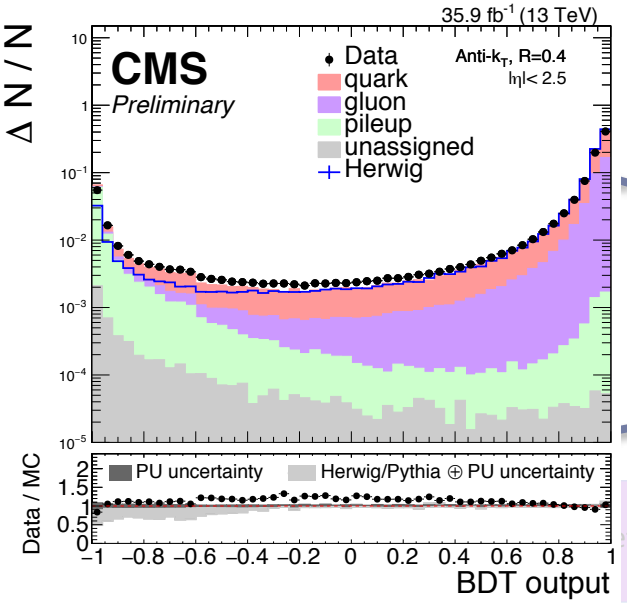



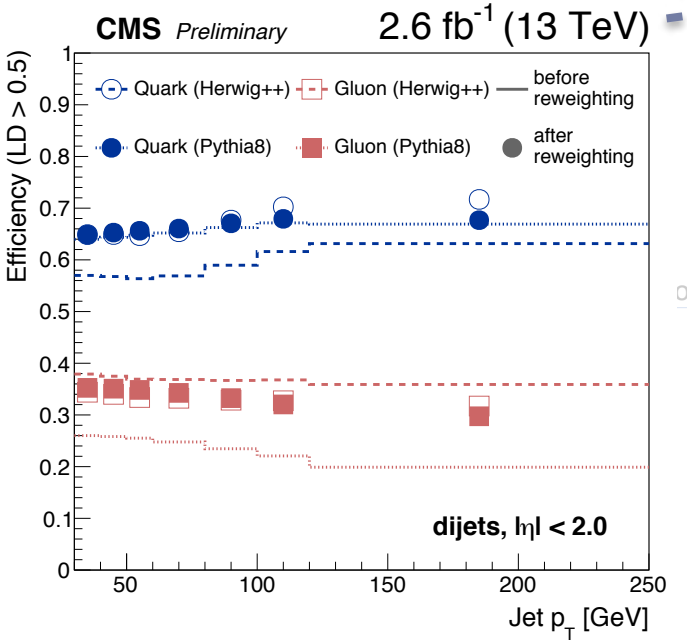



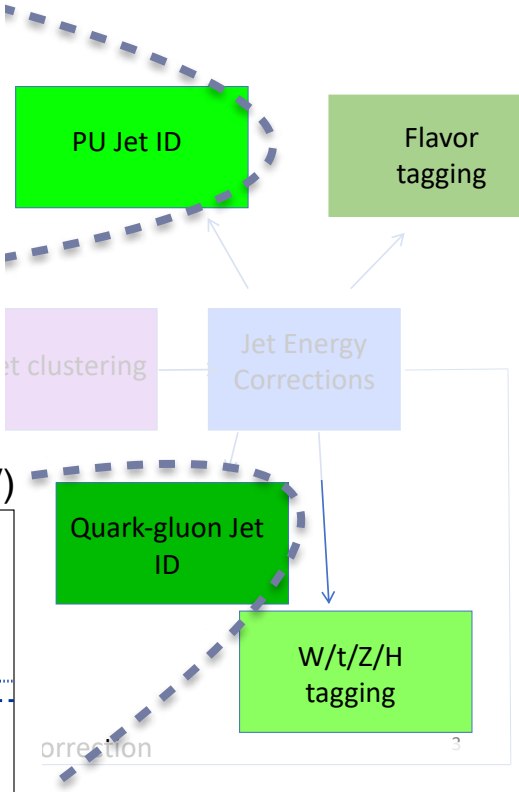

- MET using PUPPI weights **significantly better resolution** for average Run 2 PU
- Stable vs. PU
- Scale turn-on to be improved; tails can behave differently

# Jet classification

- Multi-variant technique to reject PU jets. Relevant for PFCHS jets
- 12 variables used for BDT training: differences in jet shapes, and tracking related quantities, q/g variables
- PU jets much reduced by PUPPI




- Likelihood discriminant using 3 variables: $p_T D$, $\sigma_2$, multiplicity
- Data somewhere between PYTHIA and Herwig
- BDT/DNN approaches under study as well

# Jet classification

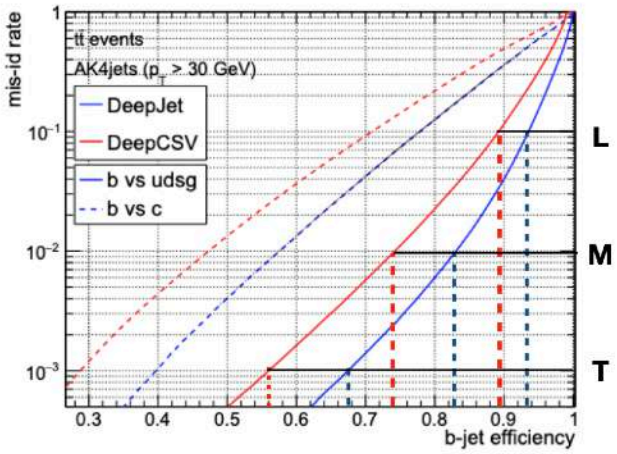
## A history of HF tagging in Run 2

| NN based | → | DNN based |
|---|---|---|
| High level variables | → | High + low level variables |
| CSV | DeepCSV | DeepFlavour |

- DNN-multiclassification standard CMS tagger for heavy flavour ID in Run2
- Also classes for light quarks/gluons

b
bb
lepb
c
l
g

JINST 15 (2020) P12012




Flavor tagging

- Heavy object tagging benchmark paper
- And new developments since then (e.g. ParticleNet mass regression, DP-2021-017)


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-037
2020/06/09

CMS-JME-18-002

Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques

The CMS Collaboration*

Abstract

Machine-learning (ML) techniques are explored to identify and classify hadronic decays of highly Lorentz-boosted W/Z/Higgs bosons and top quarks. Techniques without ML have also been evaluated and are included for comparison. The identification performances of a variety of algorithms are characterized in simulated events and directly compared with data. The algorithms are validated using proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. Systematic uncertainties are assessed by comparing the results obtained using simulation and collision data. The new techniques studied in this paper provide significant performance improvements over non-ML techniques, reducing the background rate by up to an order of magnitude at the same signal efficiency.

"Published in the Journal of Instrumentation as doi:10.1088/1748-0221/15/06/P06005."

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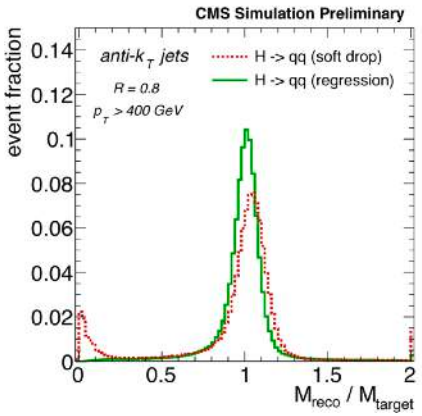
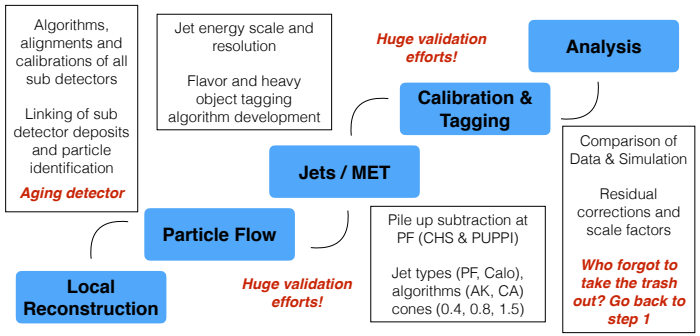
*See Appendix A for the list of collaboration members

arXiv:2004.08262v2 [hep-ex] 6 Jun 2020

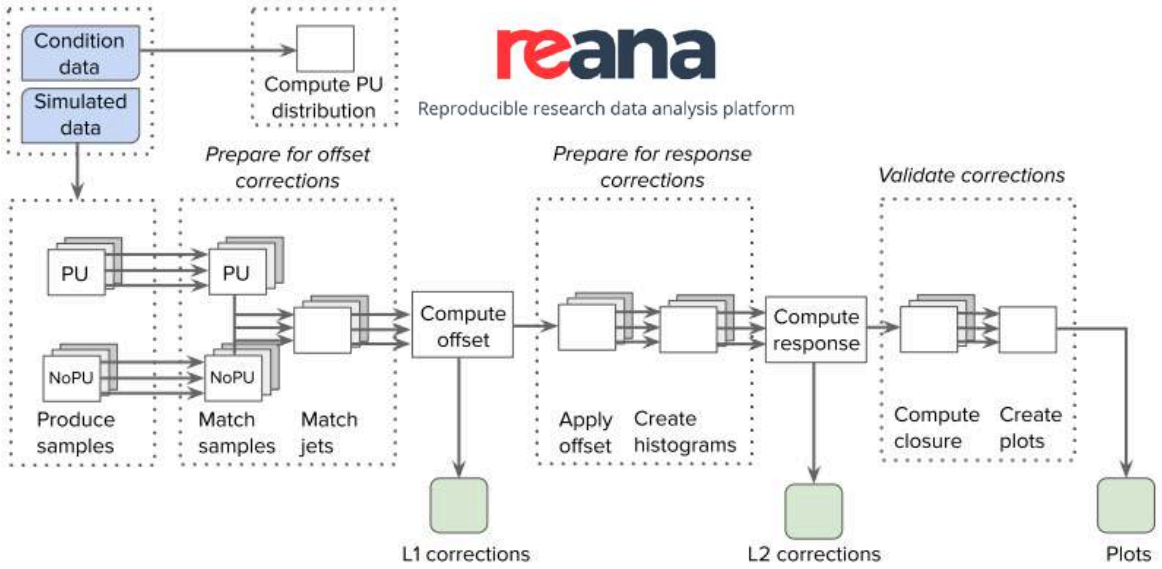


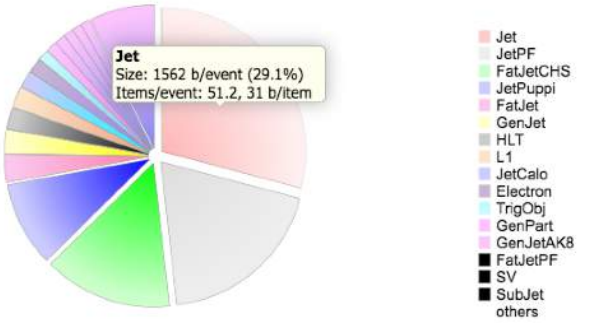

W/t/Z/H tagging

# Way forward




- This cycle is here to stay, so need to:
  - Maximise time on physics understanding
  - Minimise time on technical overhead: Streamlining of JME workflows

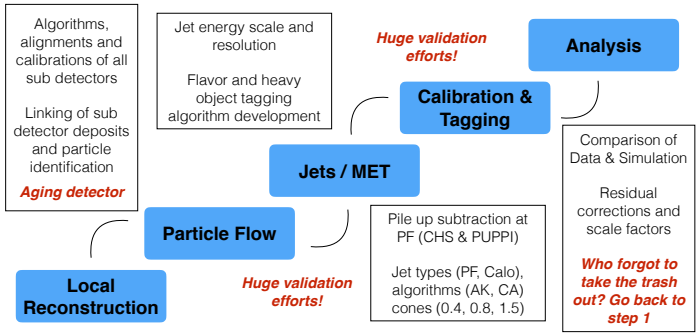



```
In [11]: print("Events/s:", output['cut
Events/s: 101204.09323190614
```

Need to put the pieces together

# Way forward




- This cycle is here to stay, so need to:
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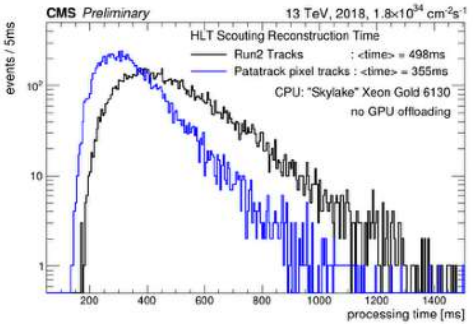
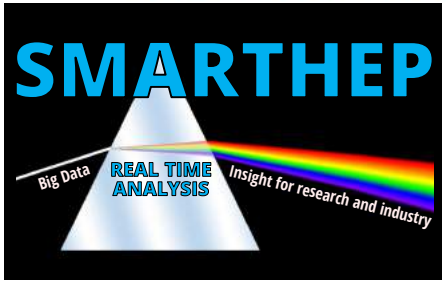
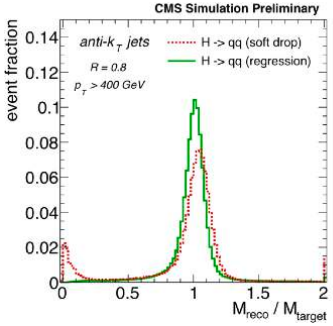
- Keep innovating:
  - New detector upgrades
  - But also still so much to gain with current detector - L1, HLT, precision, ML


**Jet Energy Corrections for High-Luminosity LHC**

**ERC-Consolidator Grant 2022—2027 "= Run 3"**



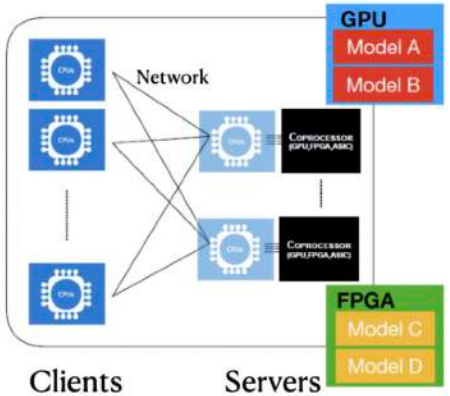
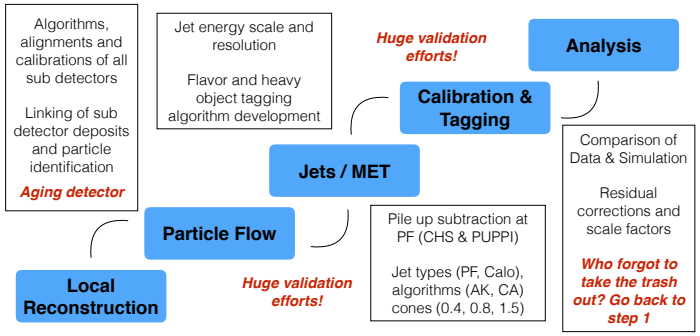




Illustration of "as a Service" (aaS) paradigm

# Way forward

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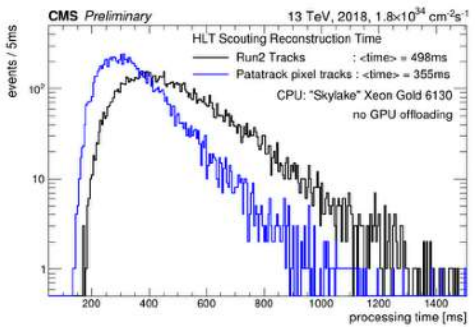
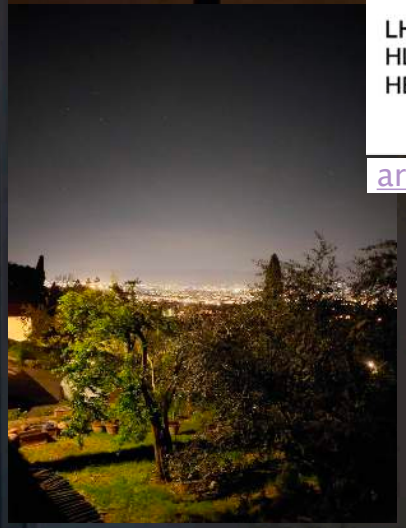
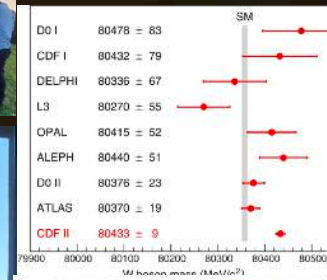
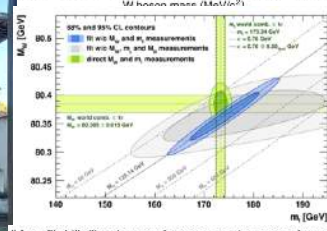



- Hadronic final states are a major part of the LHC physics program: Backgrounds/signals/pileup
- Wrapping up Run2 results and finishing up Run3 preparations. Close interplay with low-level reconstruction and PF group for best Jet/MET performance.

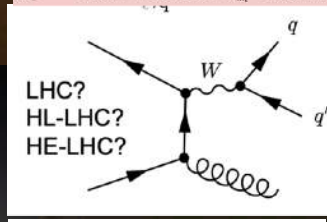




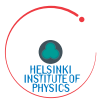

"A profiled likelihood approach to measure the top quark mass in the lepton+jets channel at $\sqrt{s} = 13$ TeV"
CMS-PAS-TOP-20-008

$m_t^{MC} = 171.77 \pm 0.38$ GeV ($\frac{\sigma_{m_t}}{m_t} = \pm 0.22\%$)

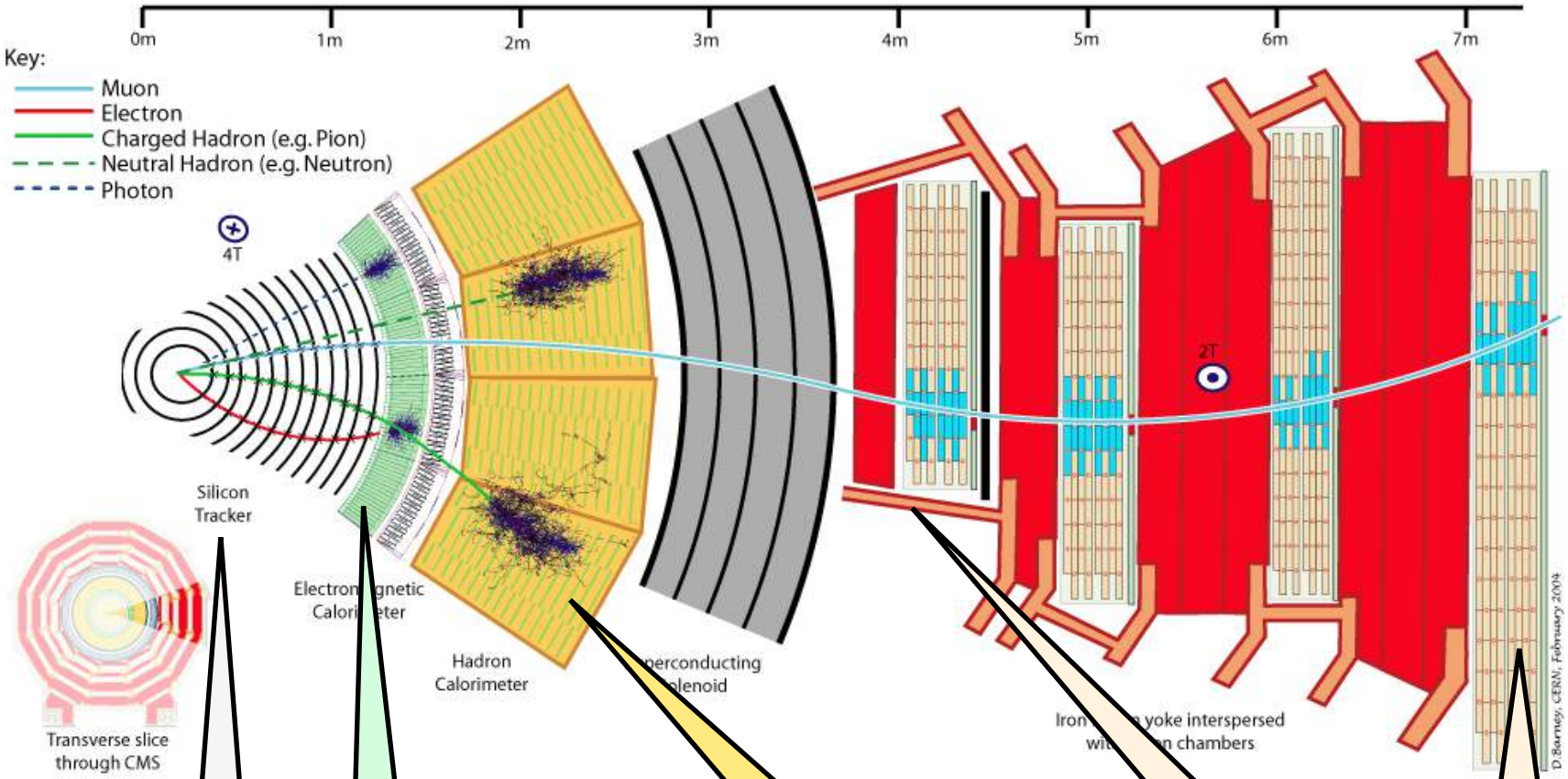



arXiv:1807.07454v3

# Backup


# Particle Flow (PF) approach




Silicon Tracker

Position, momentum of charged particles : **$e^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$**

Electromagnetic Calorimeter

Position & ID, energy of **$e^{\pm}$,$\gamma$, $\pi^0$**

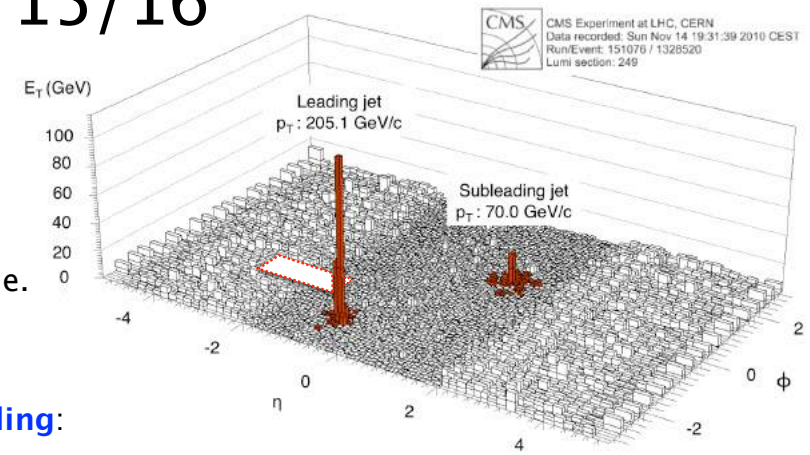
Hadron Calorimeter

Energy of hadrons : **p, n, $\pi^{\pm}$, K ..**

Muon Chambers

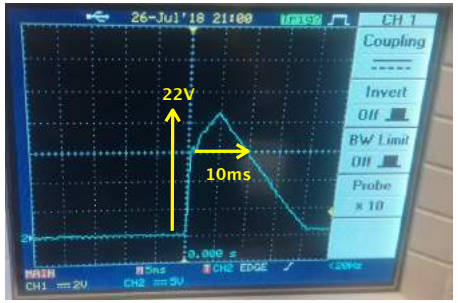
Position & momentum of **$\mu^{\pm}$**

# HCAL endcap sectors 15/16




- Following power interlock on June 30, **two endcap sectors are not functional**.
  - **40° in one endcap, 2% of HCAL** coverage.

- Five-week campaign led to **full understanding**:
  - On power up after interlock, 10V **power supply** (PS) **unable to read internal calibration**.
  - PS sent 22V/10ms pulse to detector
    - exceeded its own 14V max rating
    - **damaged on-detector components** with 12V rating.

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- HCAL **installed secondary safety system** to mitigate risk of damage from potential future transients.

- **PS manufacturer** working to understand and address
  - why the PS fails to read its calibration
  - why the PS sends high voltage when the calibration fails

- **Physics impact:**
  - trigger rates are OK
  - effect on MET resolution is small but measureable
  - PF reconstruction reduces impact of loss.
  - Additional modifications of reconstruction in progress to minimize impact.