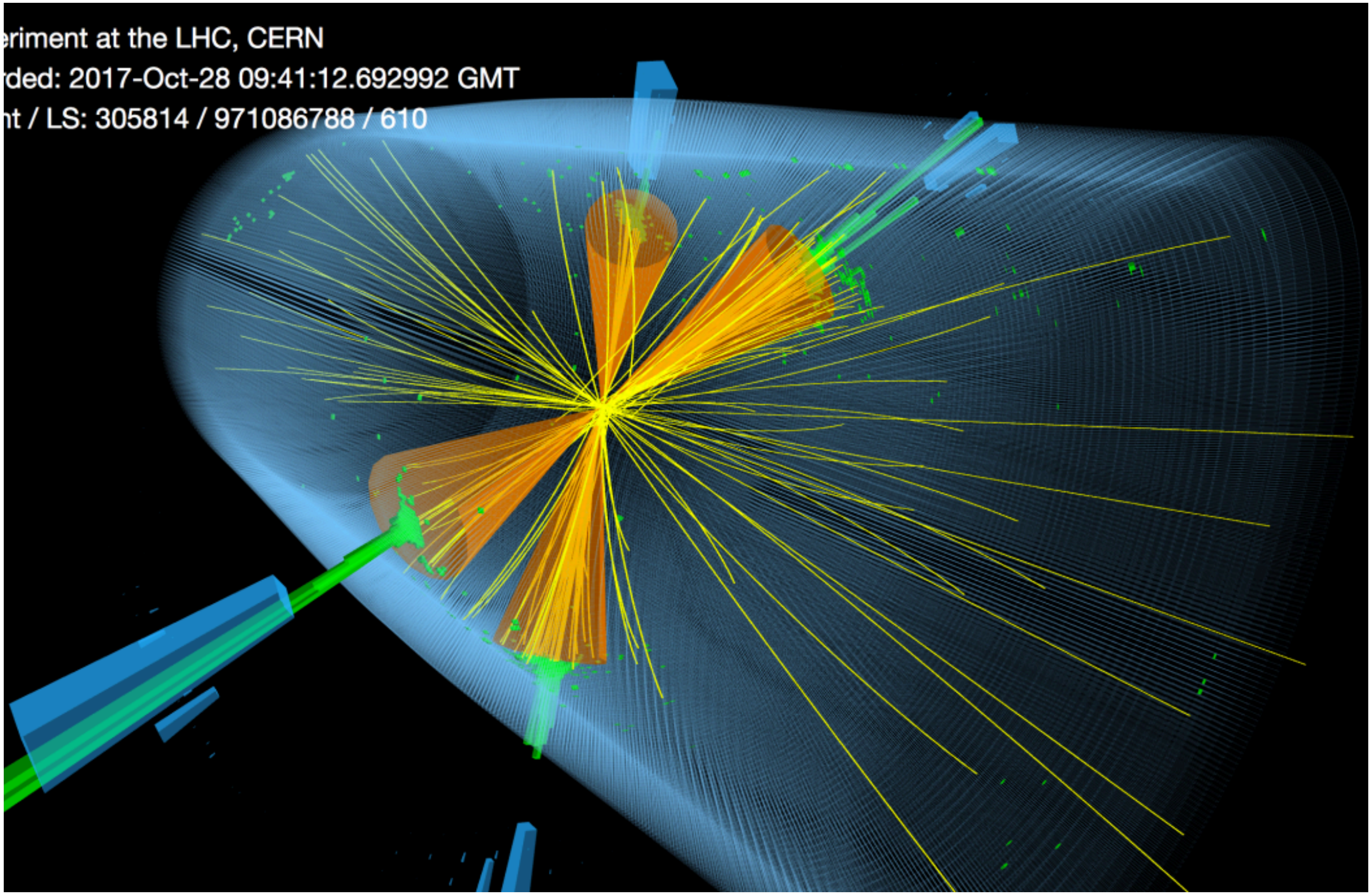
Jet Energy Scale

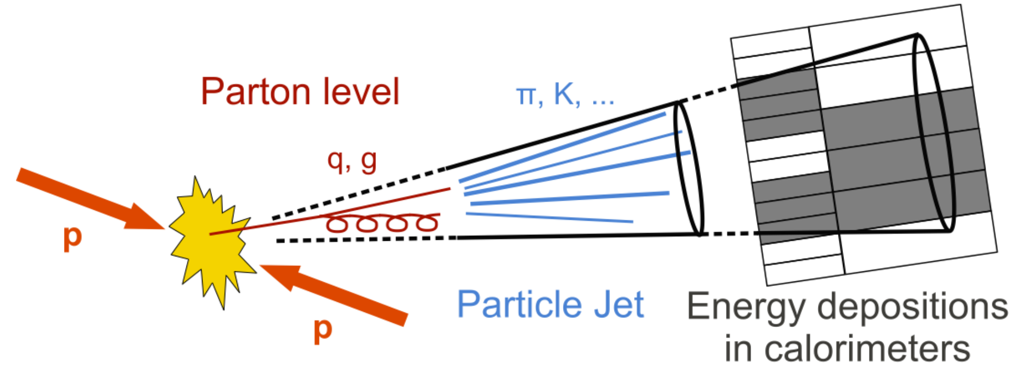
The Why and How

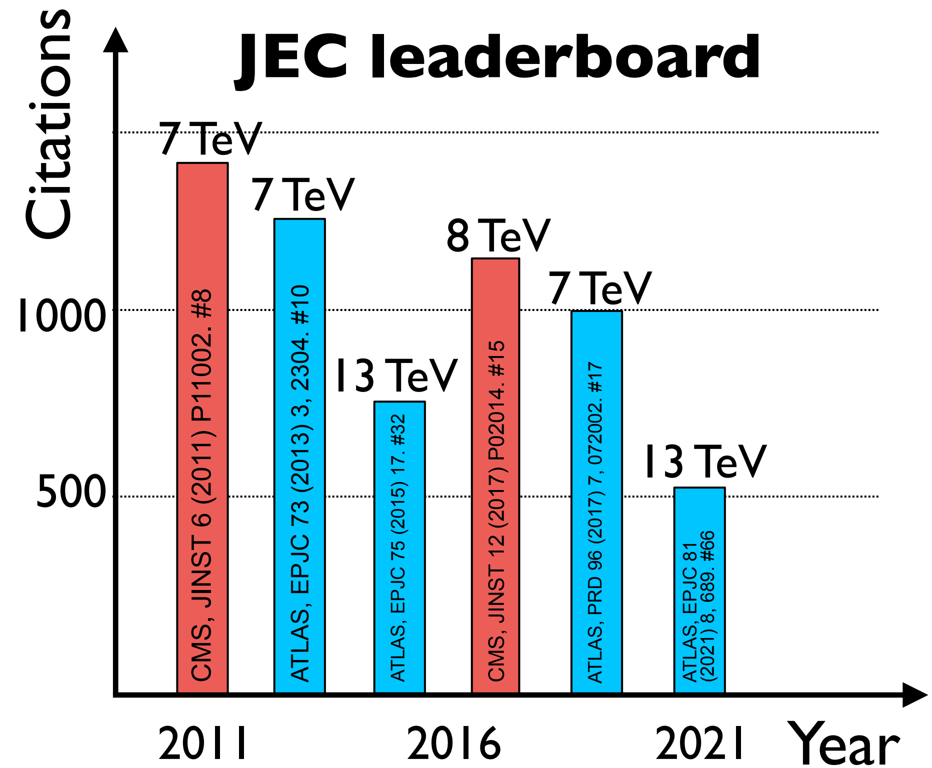


Mikko Voutilainen, Helsinki

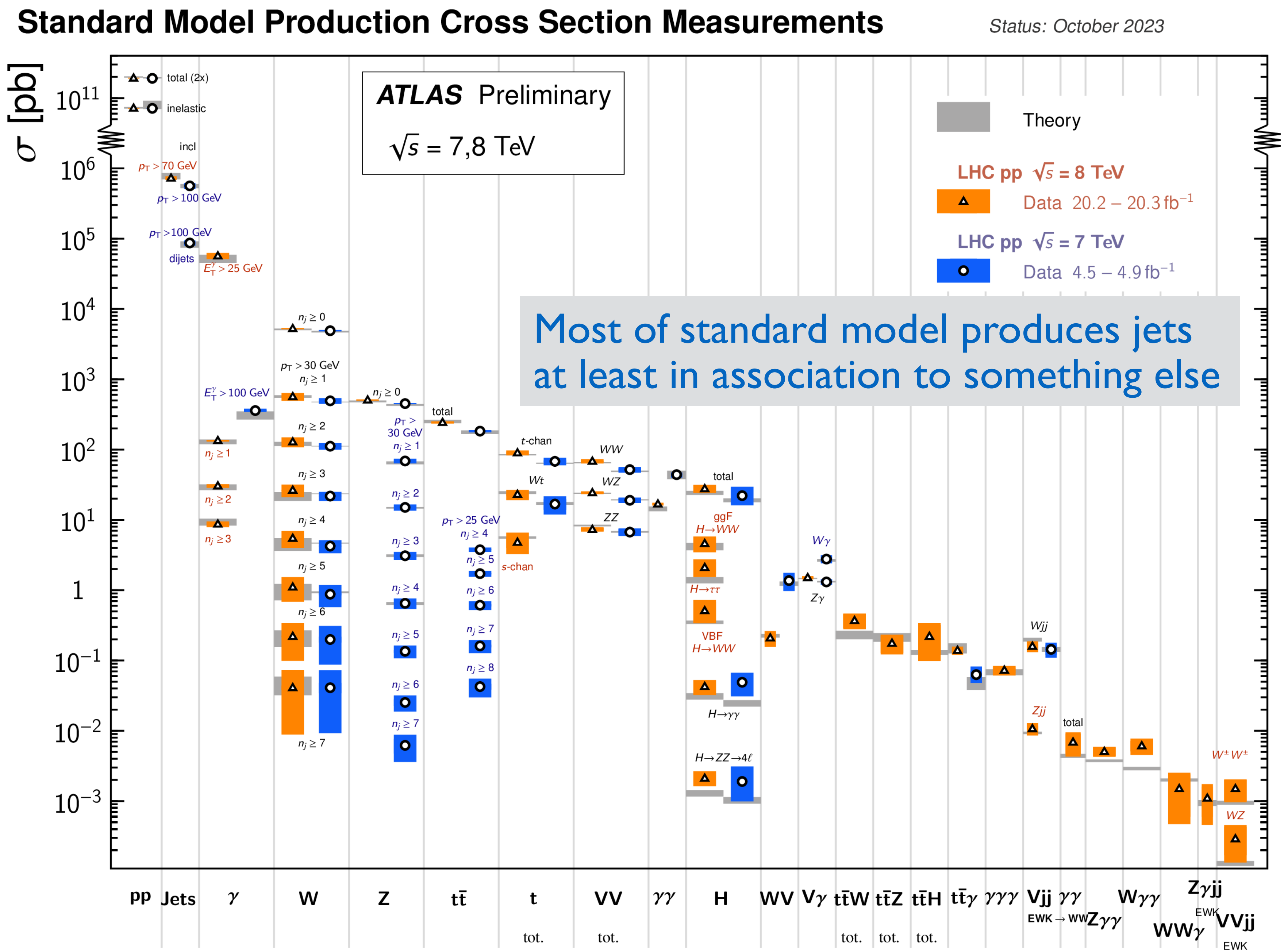
Why do we need it?

- Whenever we measure jets, we need to correct their momentum ("energy"), e.g.
  - Jet counting
  - Steep spectra
  - Resonance masses
- Calibration experimentally challenging, for reasons we cover today
  - Hardware: hadron != electron
  - Software: jet != hadron
  - Theory: parton != jet
- JES is fundamentally based on energy-momentum conservation with biases on
  - Theory: Initial and Final State Radiation (ISR+FSR) and Underlying Event (UE)
  - Phenomenology: jet flavour response with Parton Shower (PS) and hadronization
  - Experiment: approximations and uncertainties in detector simulation





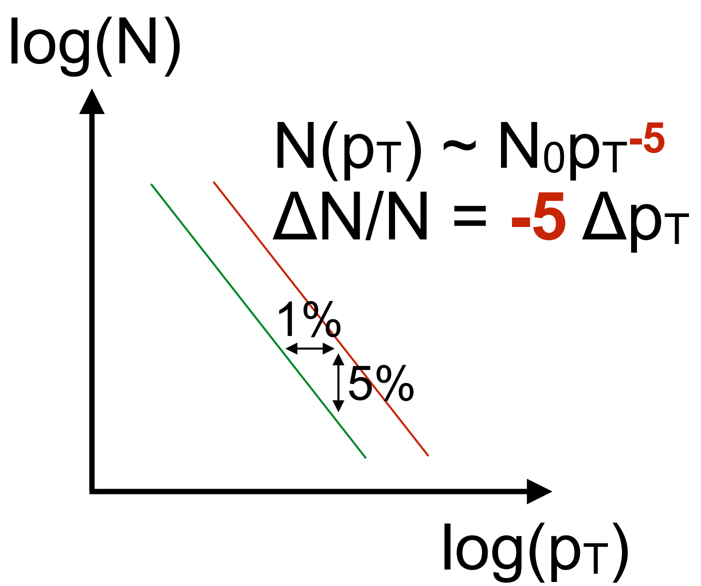
Physics examples

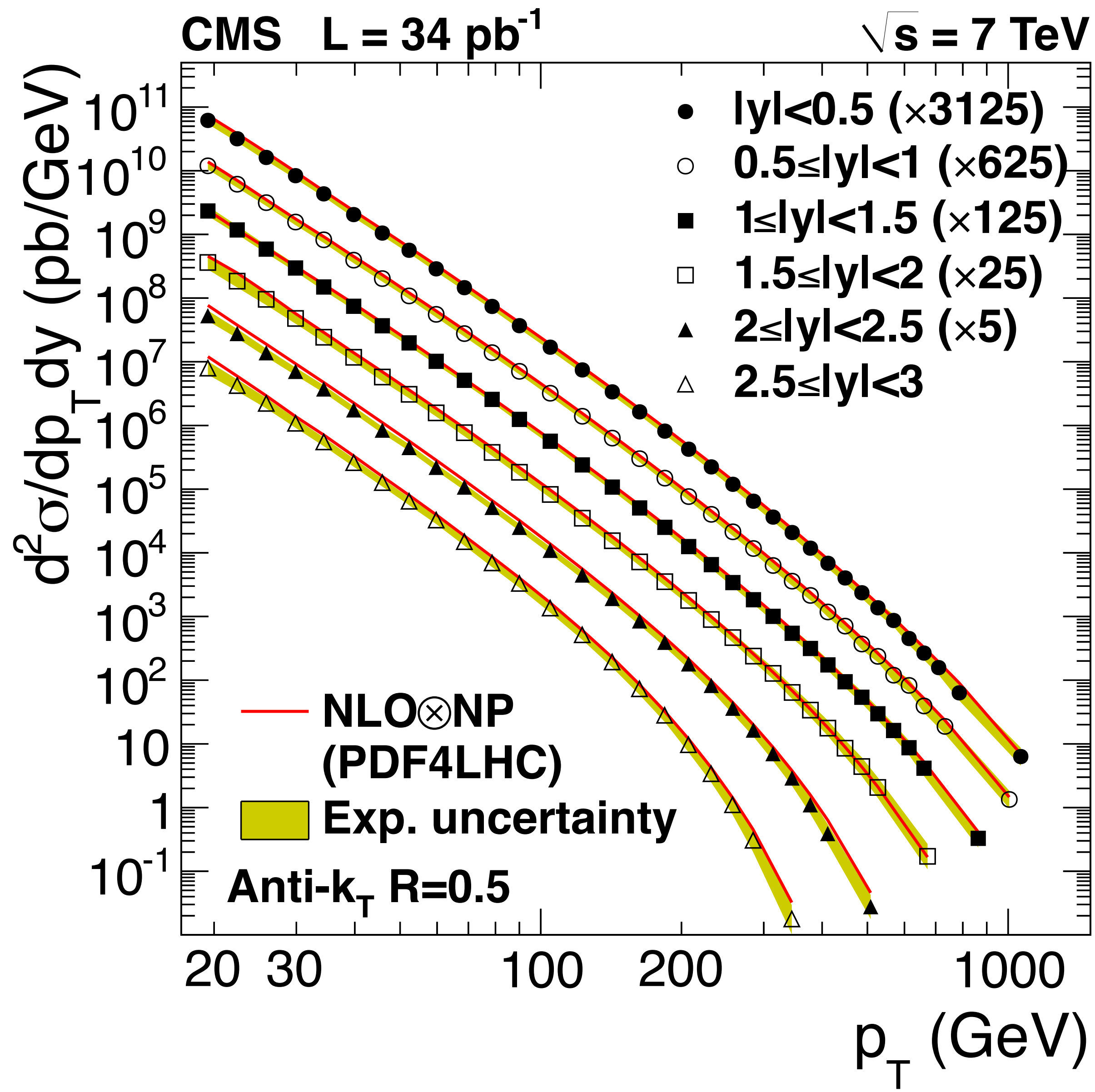


Most of standard model produces jets at least in association to something else

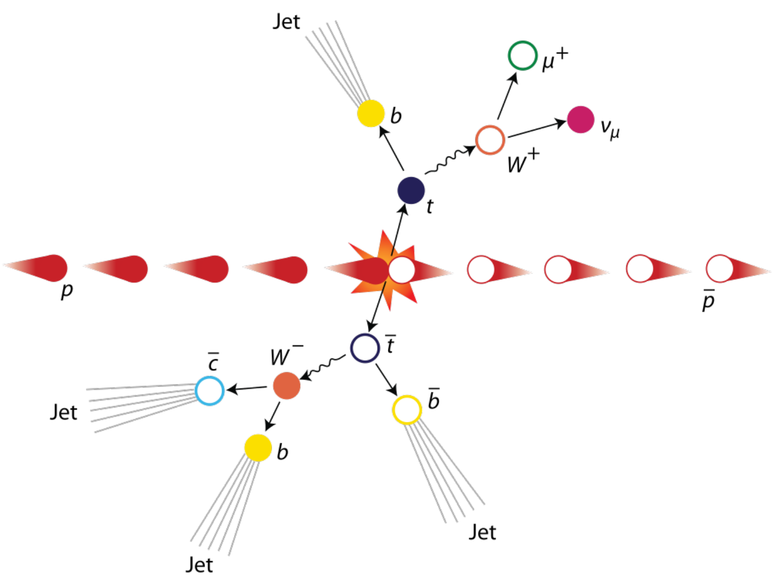
Inclusive jets

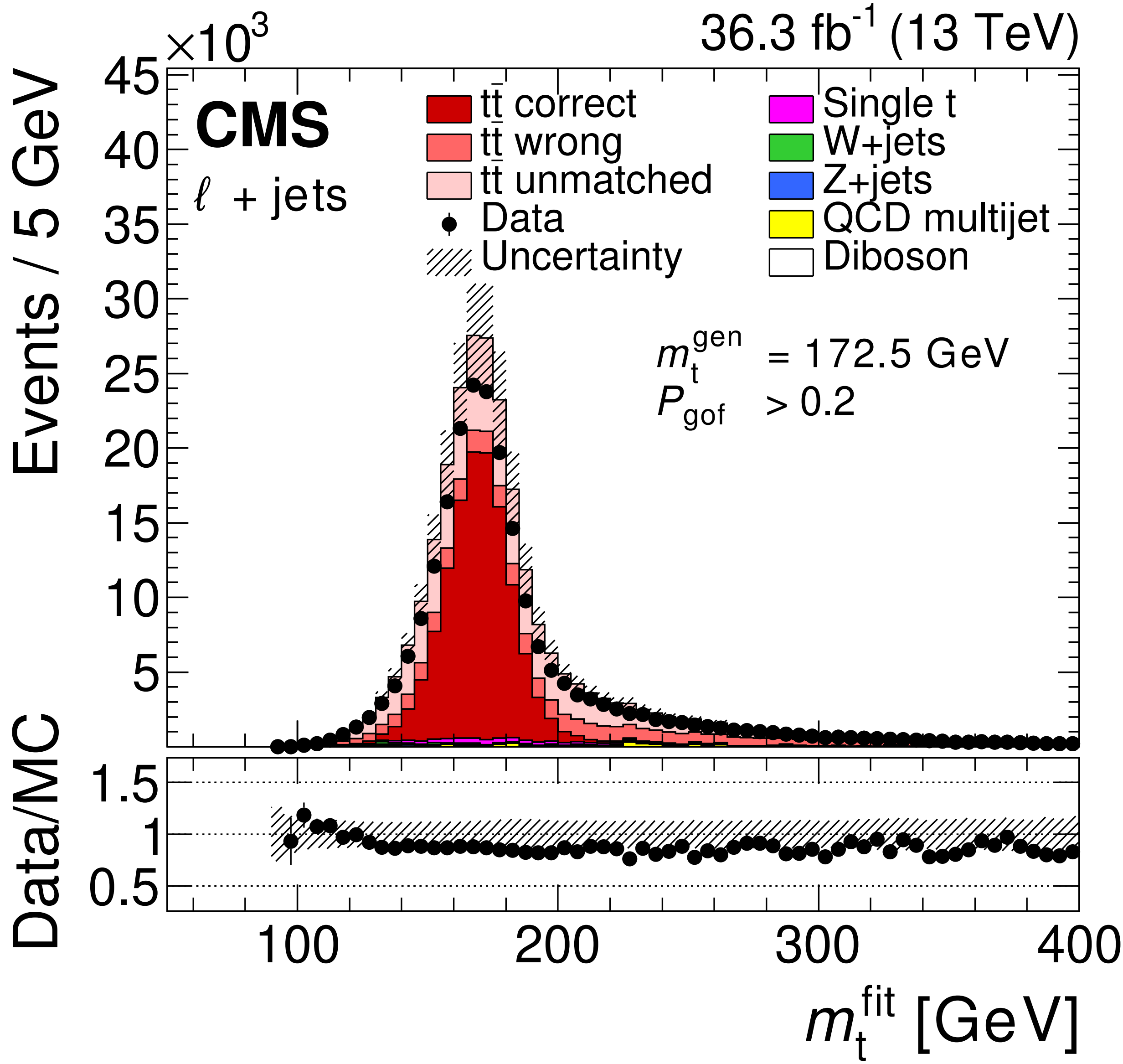
- Inclusive jets cross section is core measurement for PDFs and α_S
- Steep spectra are very sensitive to small changes on the p_T axis (=JES)
- Speciality: a significant fractions of the jets are gluon jets
- Rule of thumb: 1% in JES is 5% in cross section (and X% in α_S?)





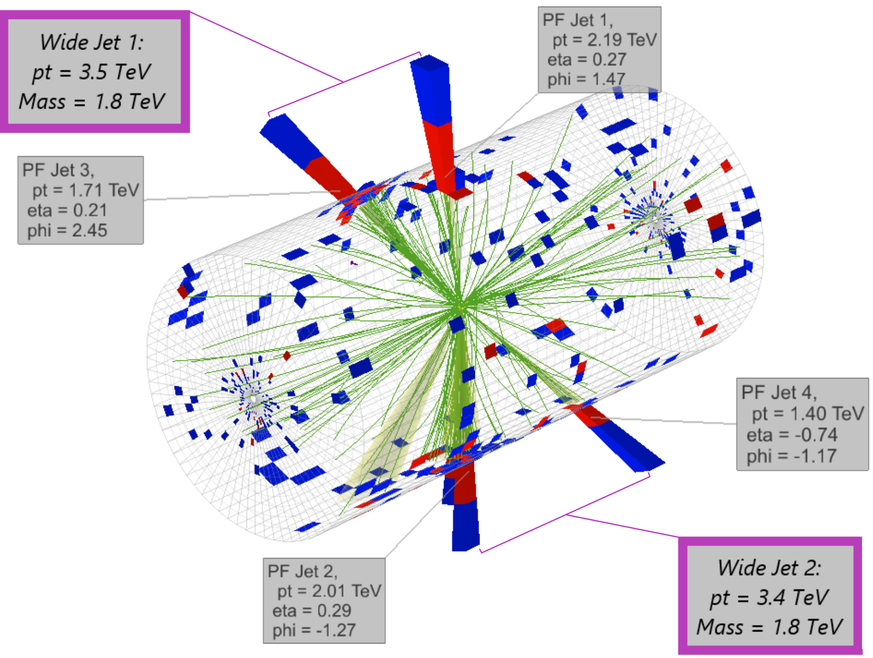
- Key parameter of the standard model relevant for vacuum stability
- Top quark mass uncertainty is dominated by JES uncertainties
- Speciality: limiting uncertainty primarily from b-flavored jets
- Rule of thumb: 1% in bJES is 1 GeV in top quark mass

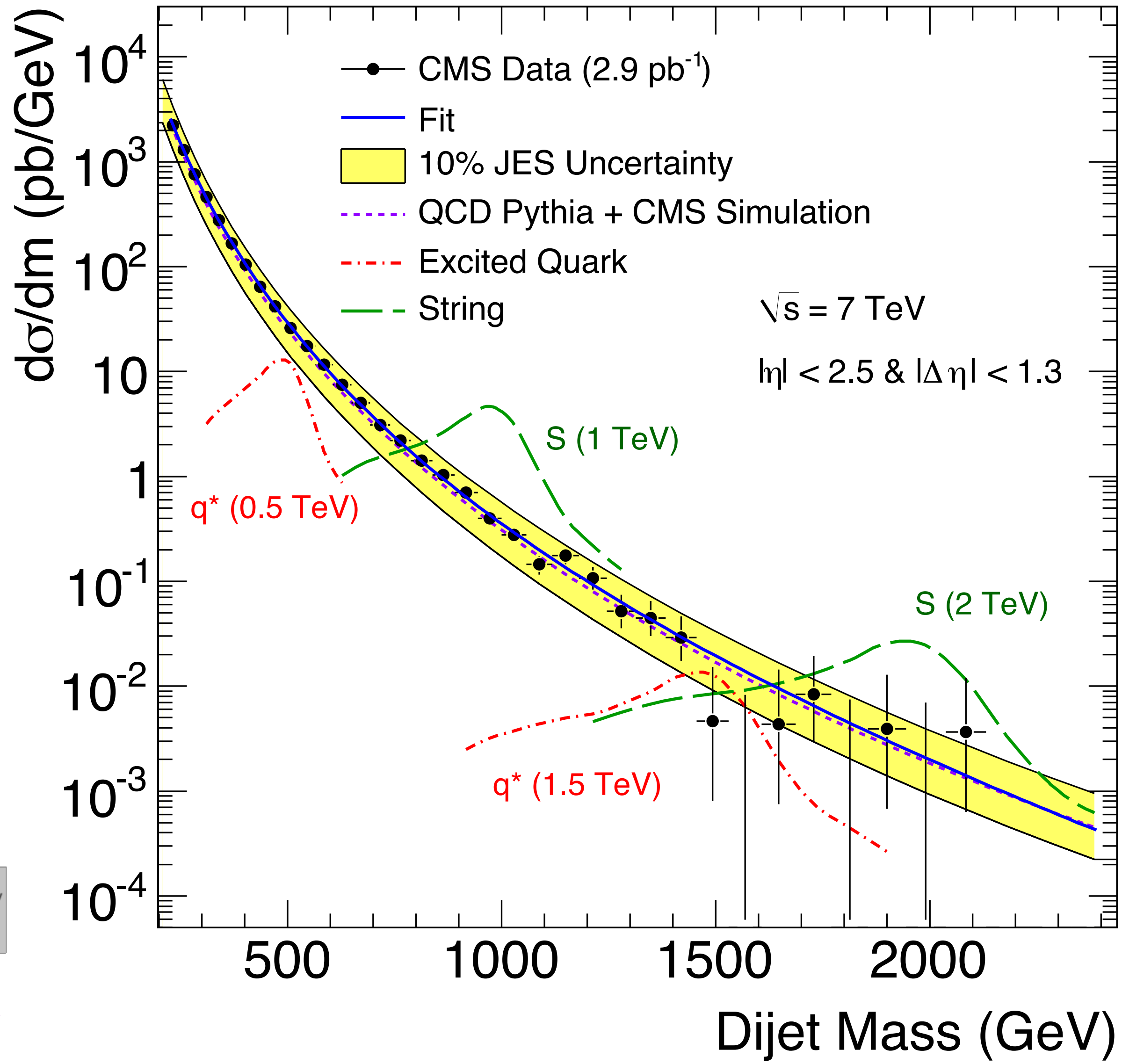




Dijet mass

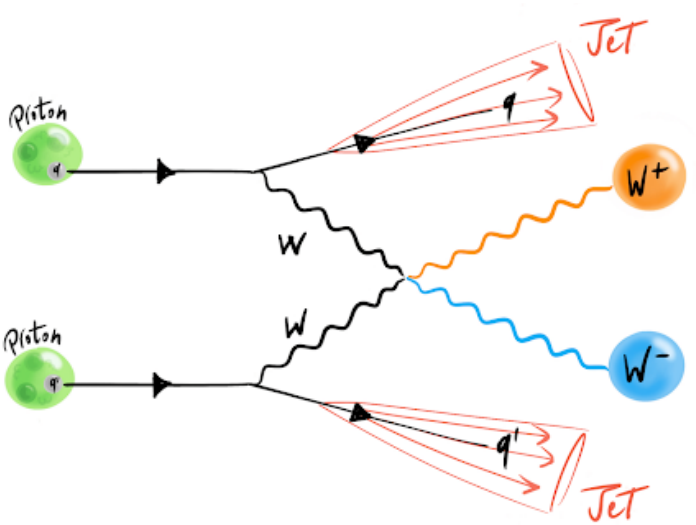
- Dijet mass is key search for new physics at the very highest scale
- JES requires extrapolation to the multi-TeV scale
- Speciality: needs early calibration
- Rule of thumb: reconstruction breaks at >2 TeV in prompt data

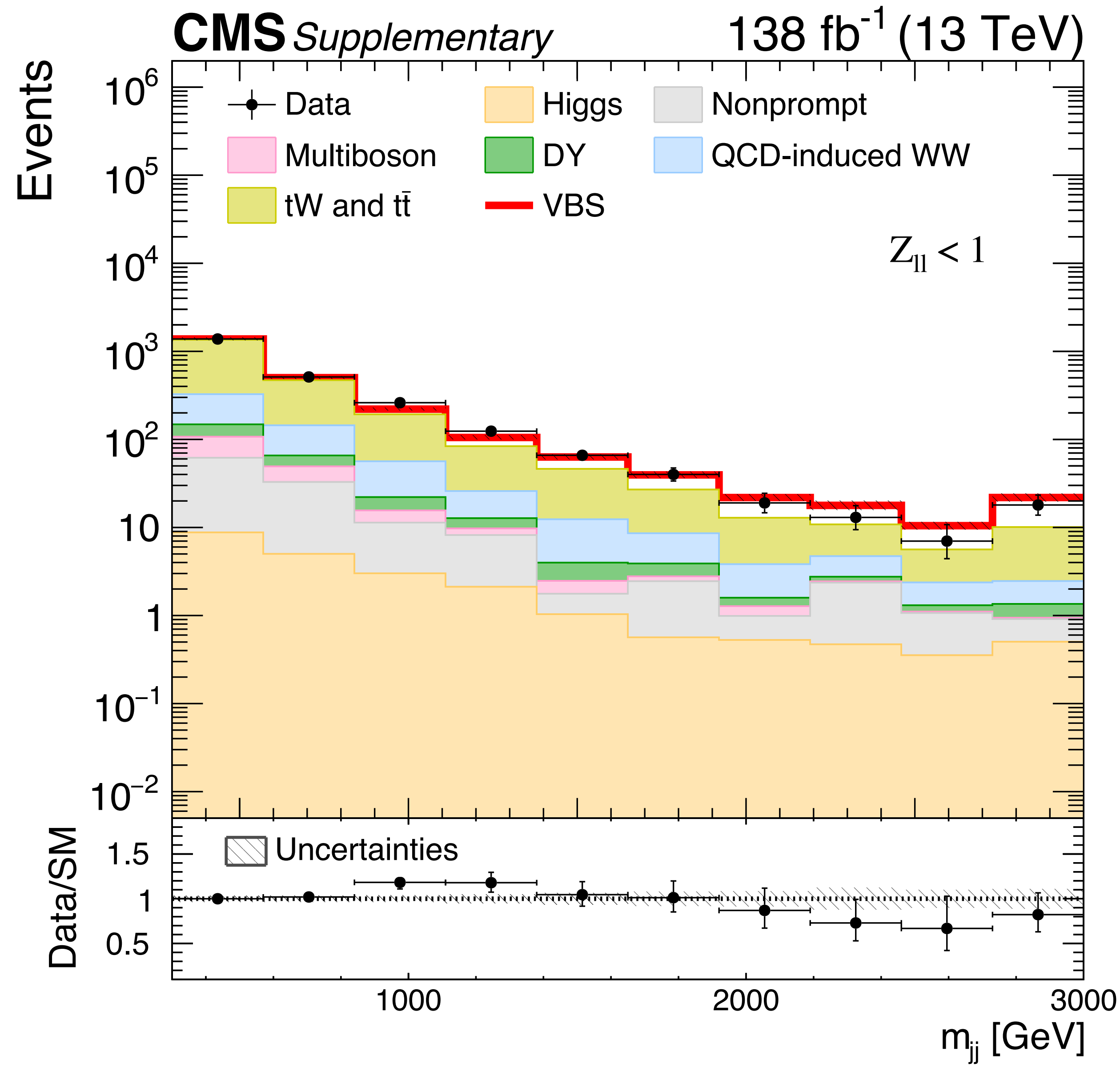




Vector boson scattering

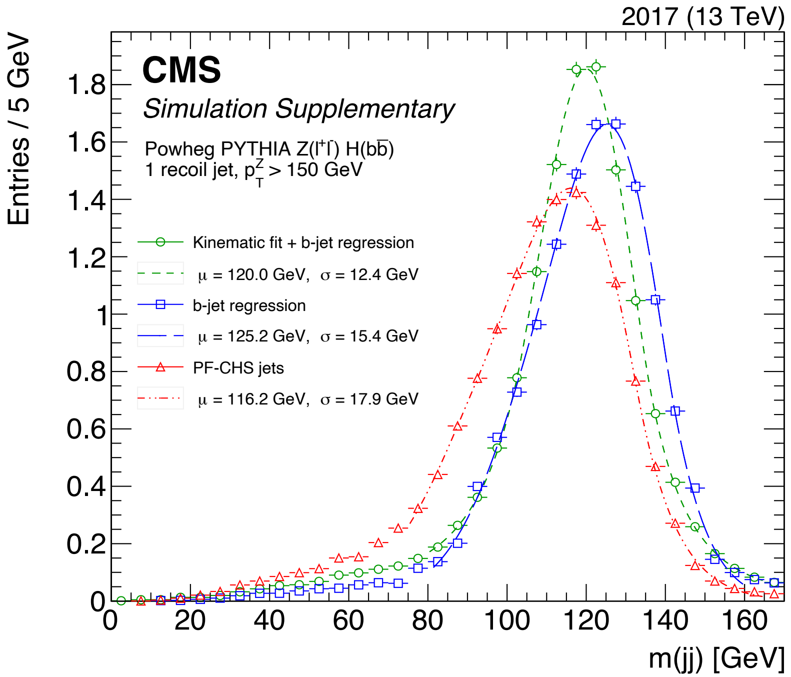
- Vector boson scattering (VBS) is a fundamental test of EW symmetry breaking
- Requires good calibration for two forward quark jets used for high m_{jj} tagging
- Speciality: jets outside tracker coverage
- Rule of thumb: tracker is better!

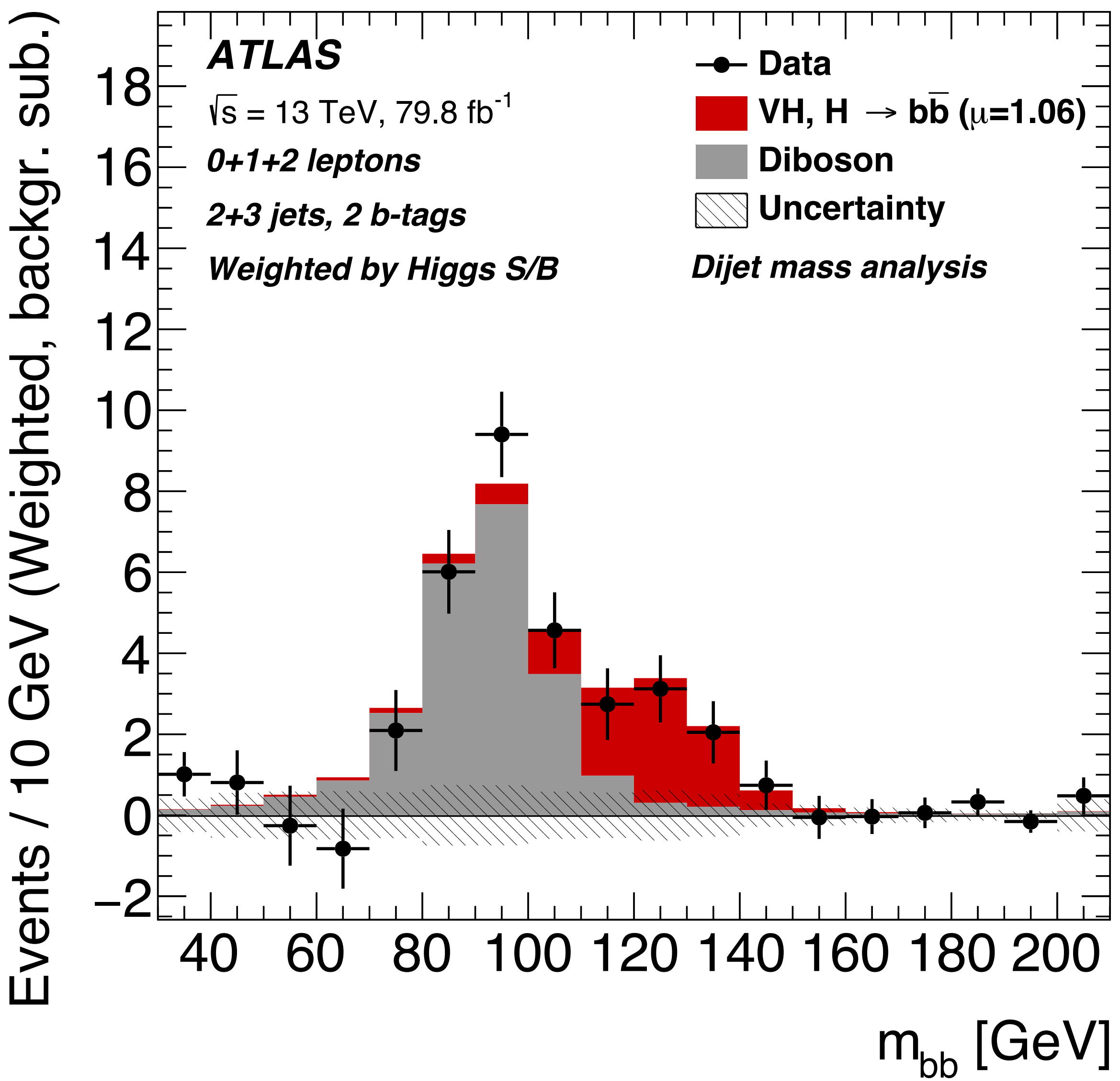




Higgs to bb

- 80% of Higgs bosons decay to bb so key decay for di-Higgs search
- B-jet scale and resolution needed to reconstruct mass peak
- Speciality: need neutrino recovery
- Rule of thumb: νs don't enter JES

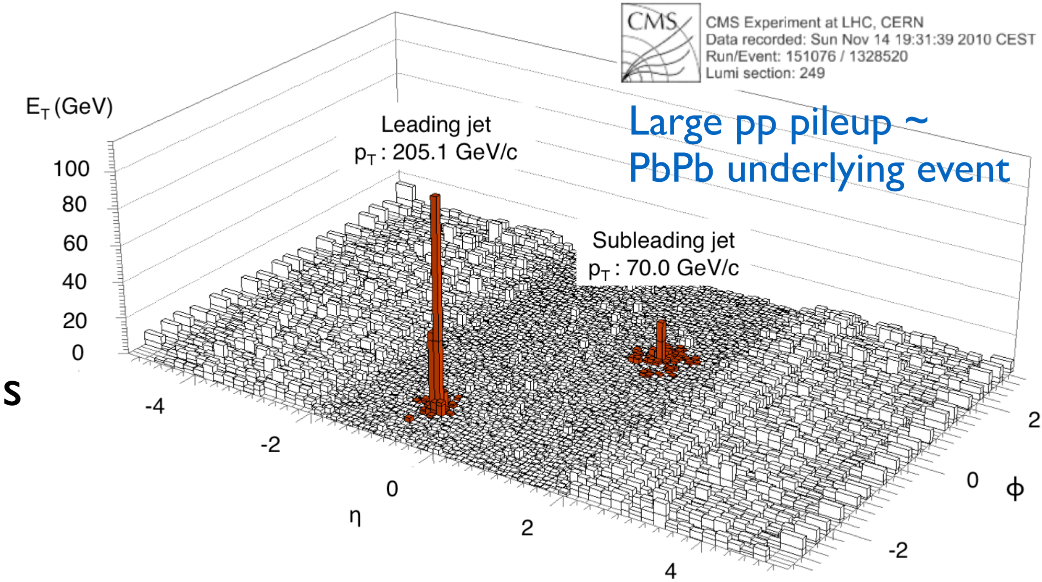


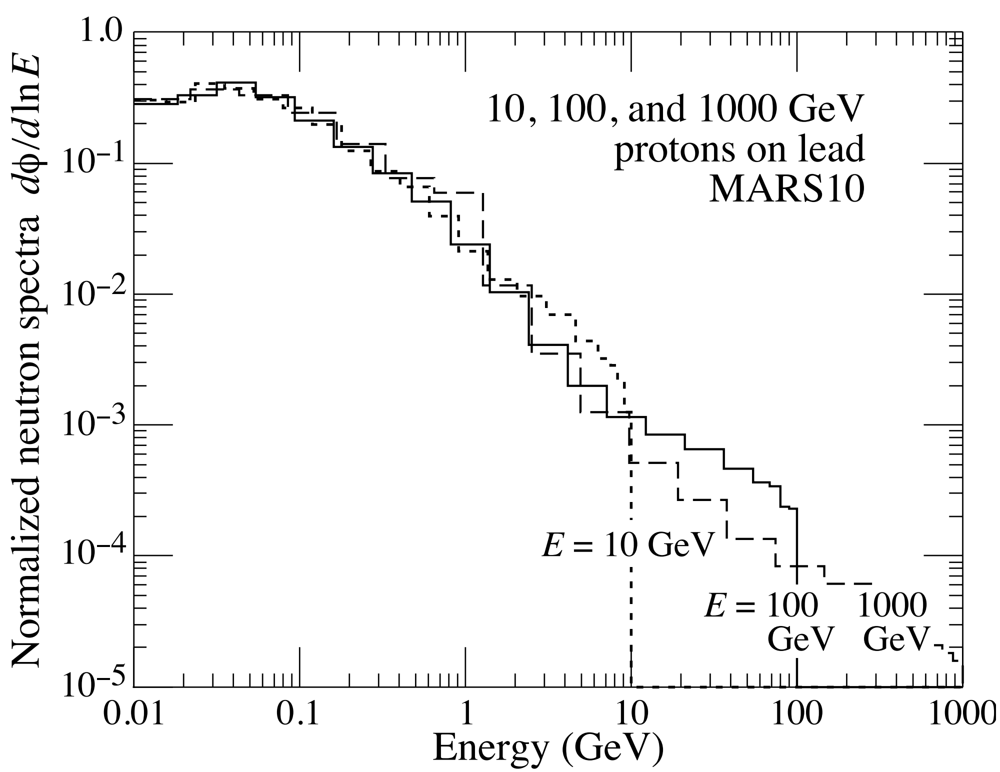


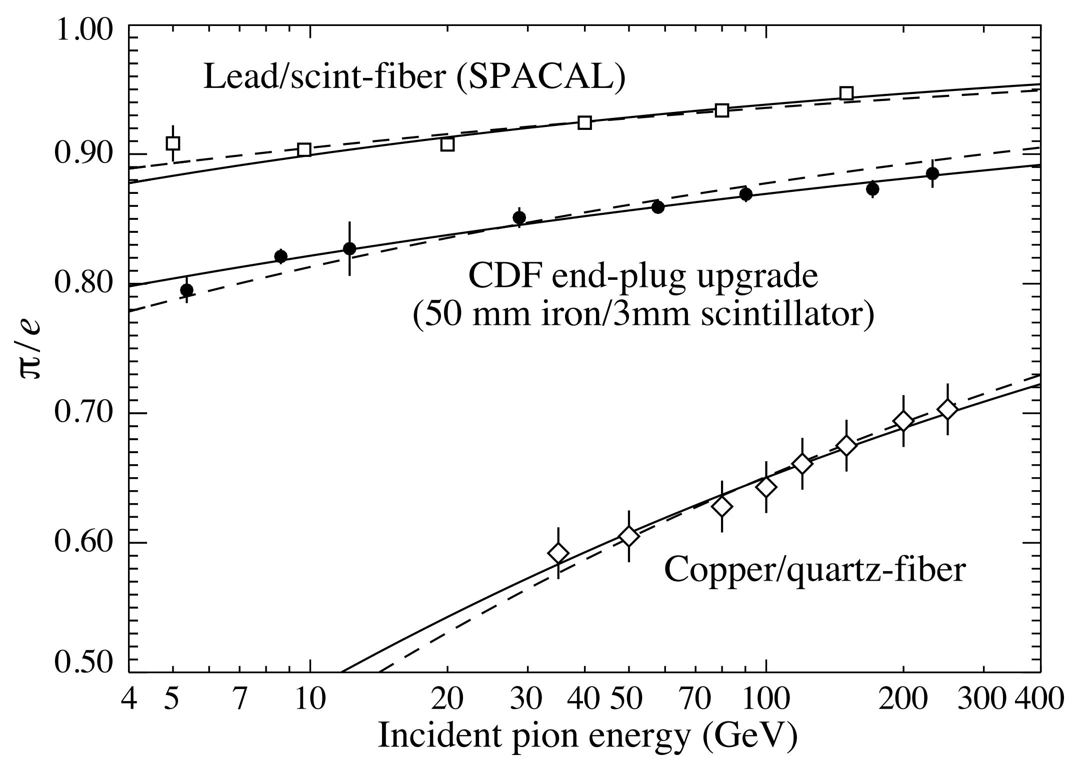
Origins of JES

Jet energy scale after calibrating detectors for individual electrons, photons and muons:

1. Particle energies (from jet or calorimeter shower) falling below detection thresholds
2. Hadrons depositing (ionisation/scintillation) energy less efficiently than electrons/photons
3. Pileup interactions adding energy offset

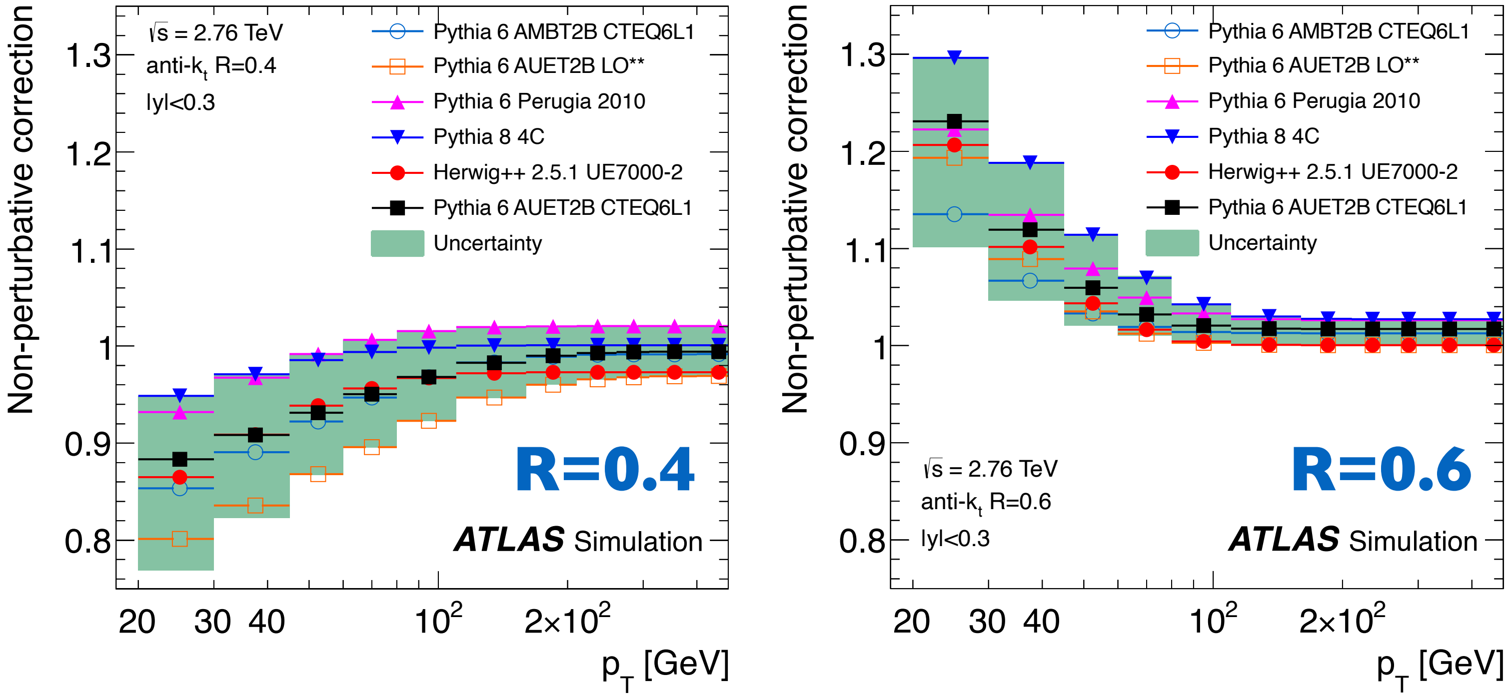






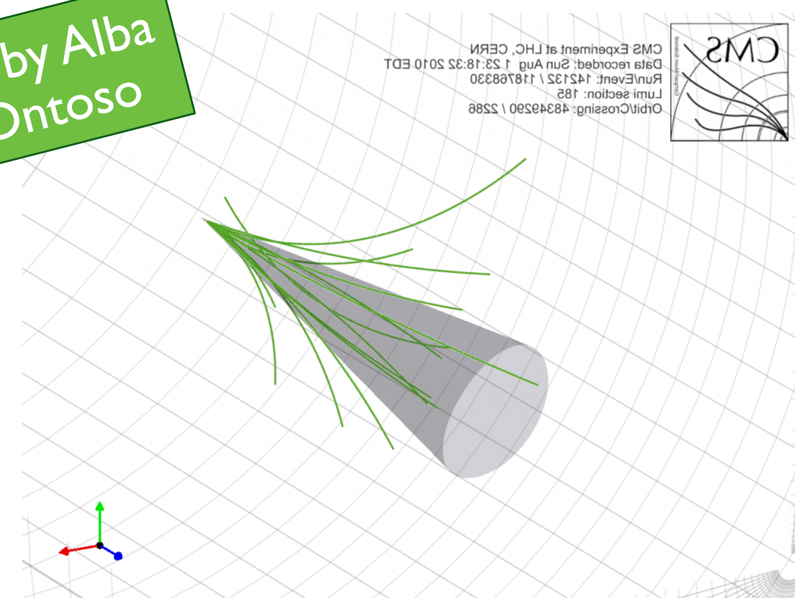
Parton => jet

Energy of particle jet /
Energy of parton



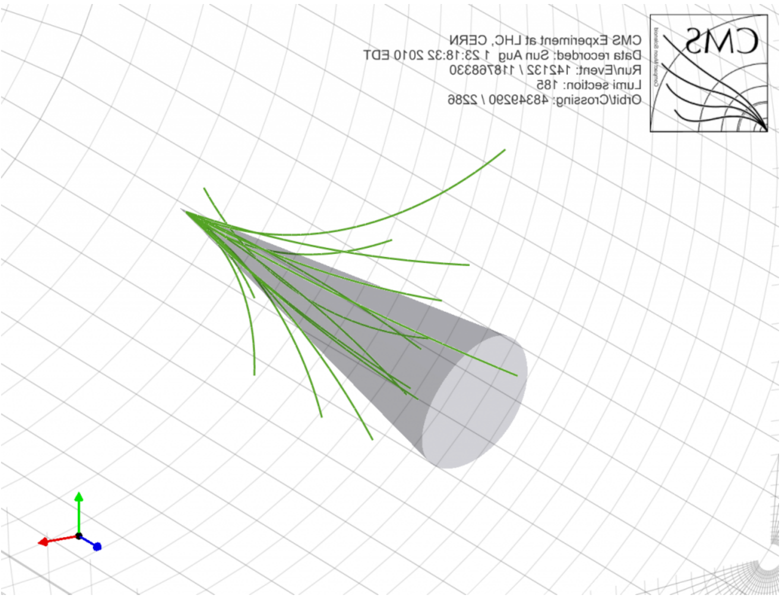
- Parton (quark, gluon) loses energy out of jet cone due to final state radiation (FSR)
- Jet cone accumulates some compensating energy from underlying event (UE)
- Jet radius typically chosen to balance the two effects out
  - NB: gluon jets need large cone than quark jets
- **This is not part of JES yet!**

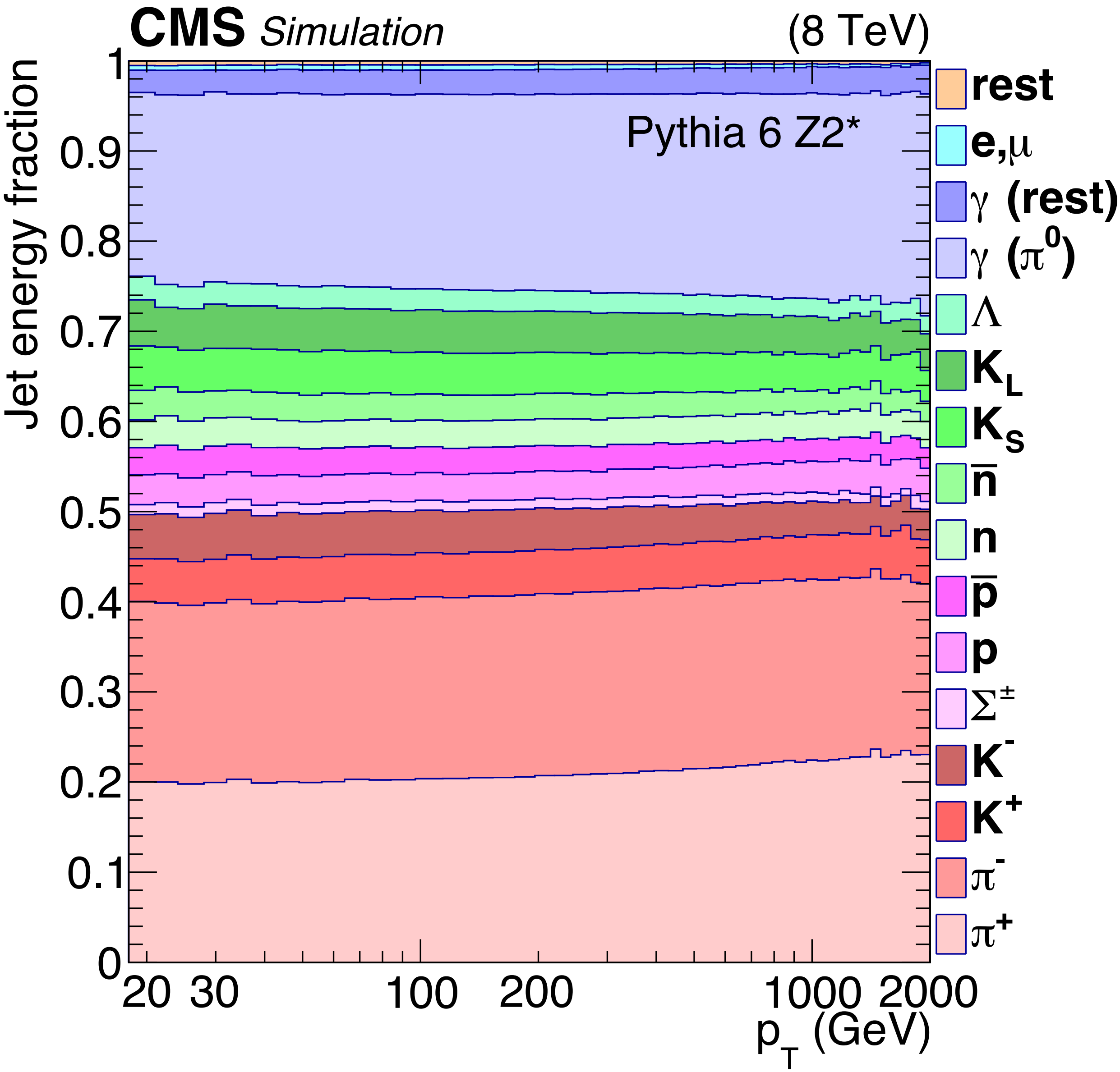
Lecture by Alba Soto Ontoso



Jet => hadrons (gen)

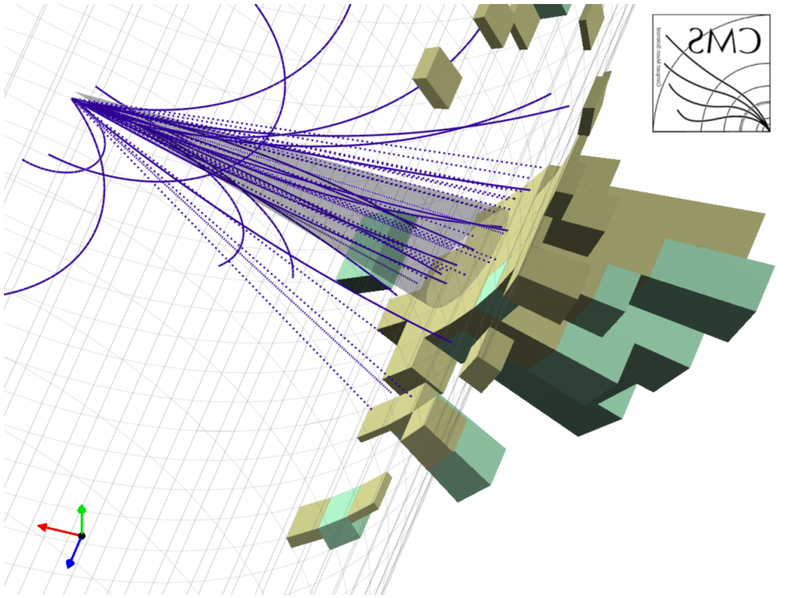
- Jet contains many kinds of hadrons
  - Ones with long lifetime (cτ>1 cm) included in the definition of JES
  - Neutrinos *usually* excluded from definition of JES (cf. b/c jets)
- Jet four-momentum is the sum of all its particle four-momenta

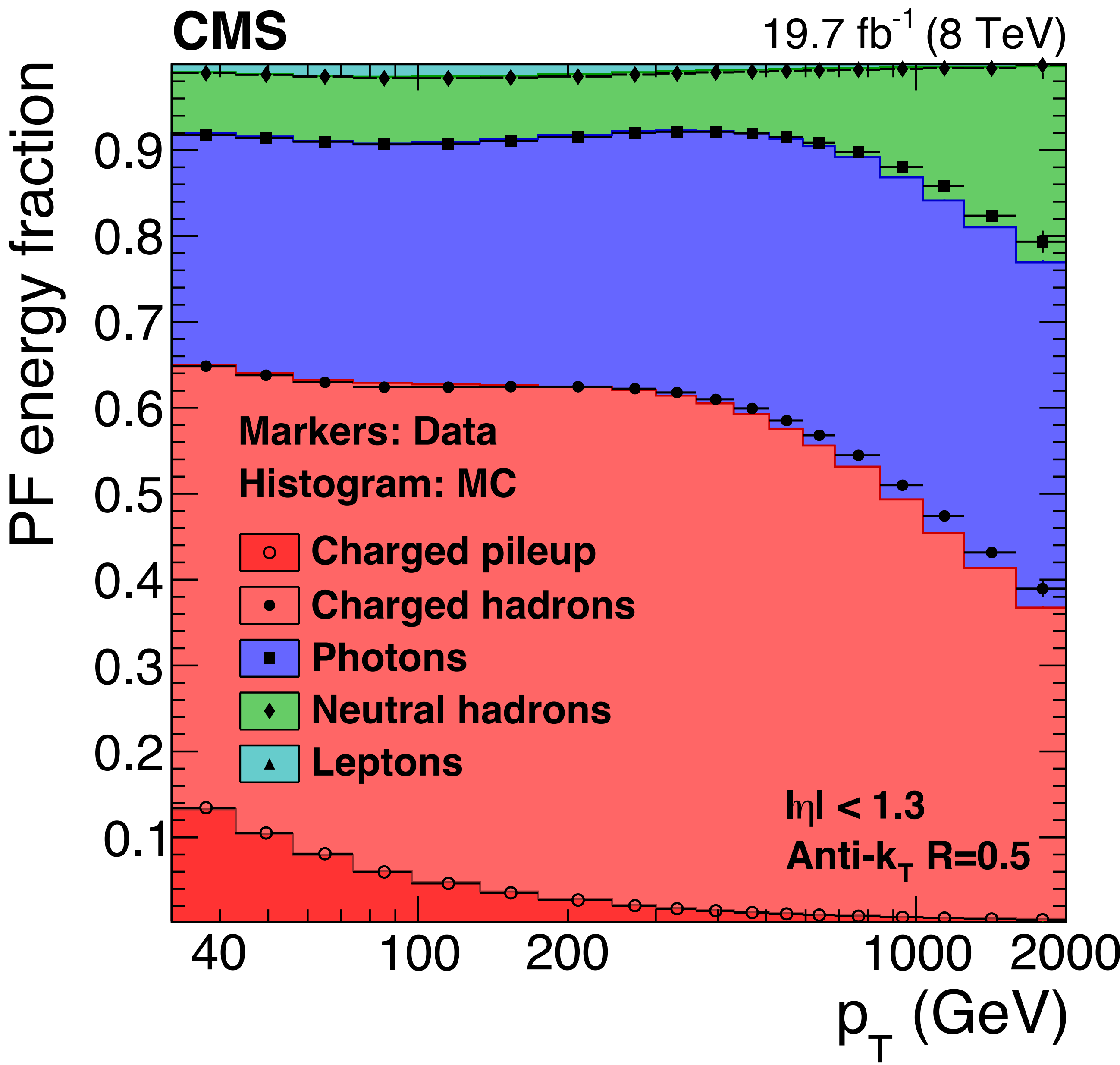




Jet => hadrons (det)

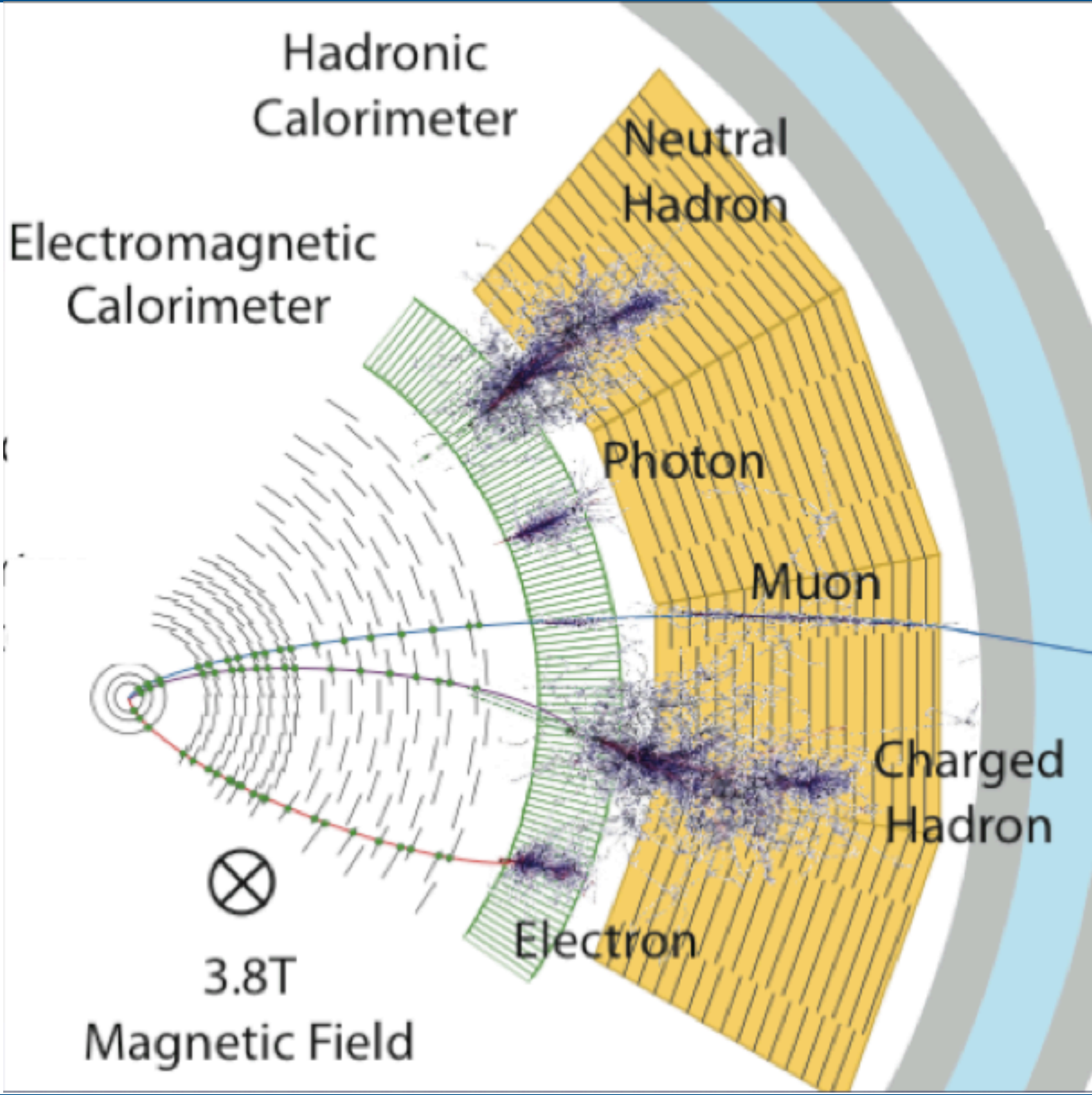
- We cannot identify hadrons so
  - Charged hadrons = track (+calorimeter cluster(s))
  - Photons = ECAL cluster
  - Neutral hadrons = HCAL cluster
  - Electron = track + ECAL cluster
  - Muon = (muon) track + no cluster





- (Neutrino p_T: missing-E_T)

- Photon and electron showers contained in ECAL (~20 X_0)
- Hadron showers can start in ECAL (~1 λ) and continue in HCAL (6–8 λ)
- Two components to hadron shower:
  - EM component: $\gamma \to e^+e^-$ pair production & bremsstrahlung $e \to e\gamma$ alternate
  - Hadronic component: $h+N \to 5\text{-}6h$, of which $\pi^0 \to \gamma\gamma$ moves energy to EM sector



Shower => electron

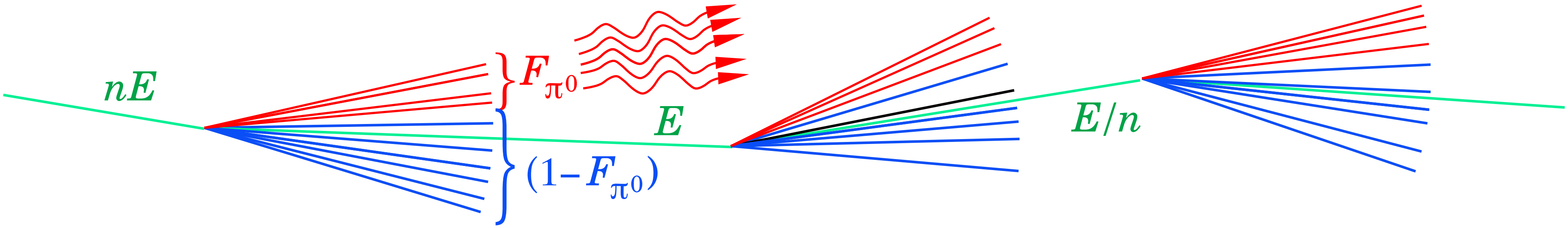


FIGURE 4. Cartoon of a hadronic cascade. It is assumed that in each generation the average energy of cascade particles decreases by a factor n and than an average fraction F_{π^0} of the energy leaves the hadronic sector via π^0 production.

- Electrons and photons in EM component of hadron shower produce ionization/ scintillation efficiently
- Hadrons in hadronic component ionize less well and lose energy to nuclear interactions
- Most of ionization by particles at the end of cascade: fraction of energy ending up in EM sector depends on log(E)

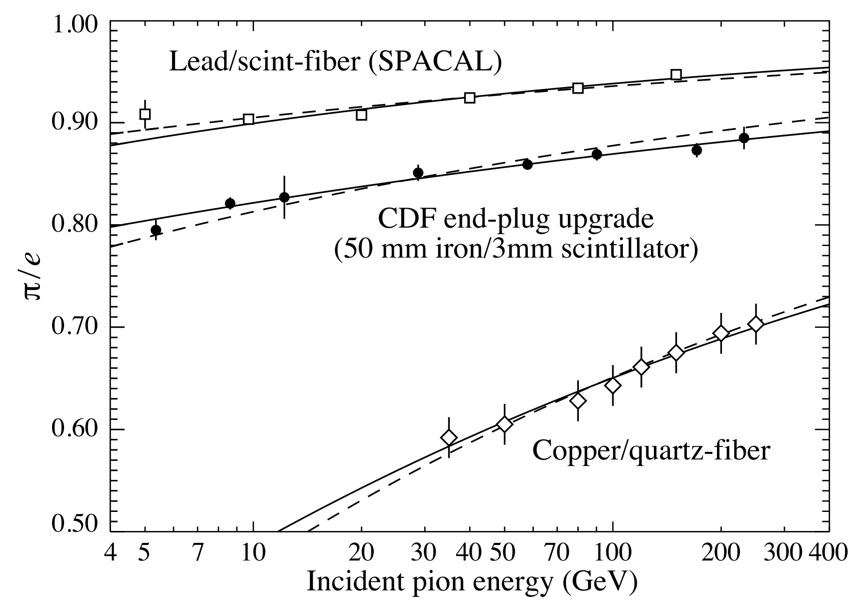
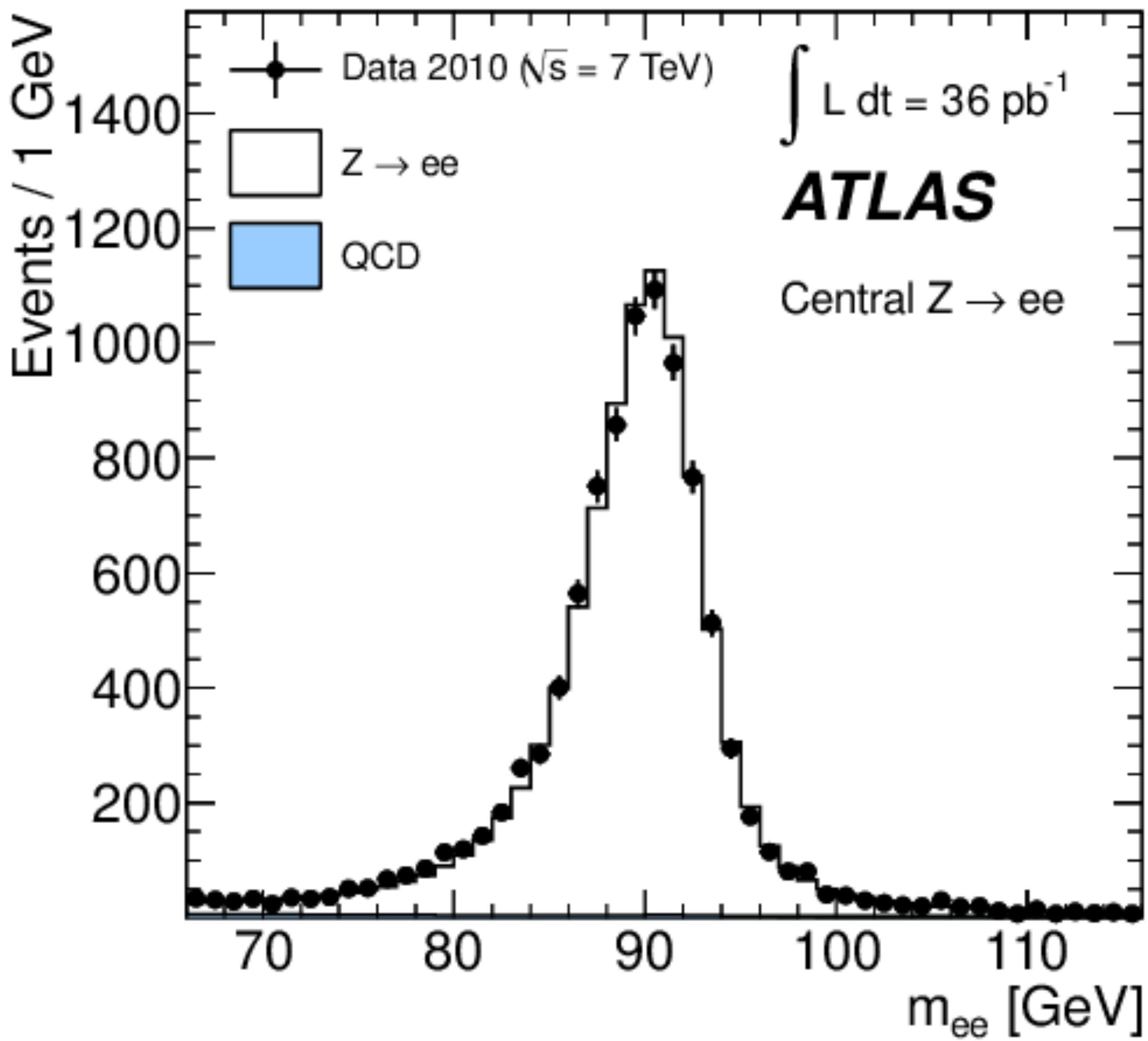
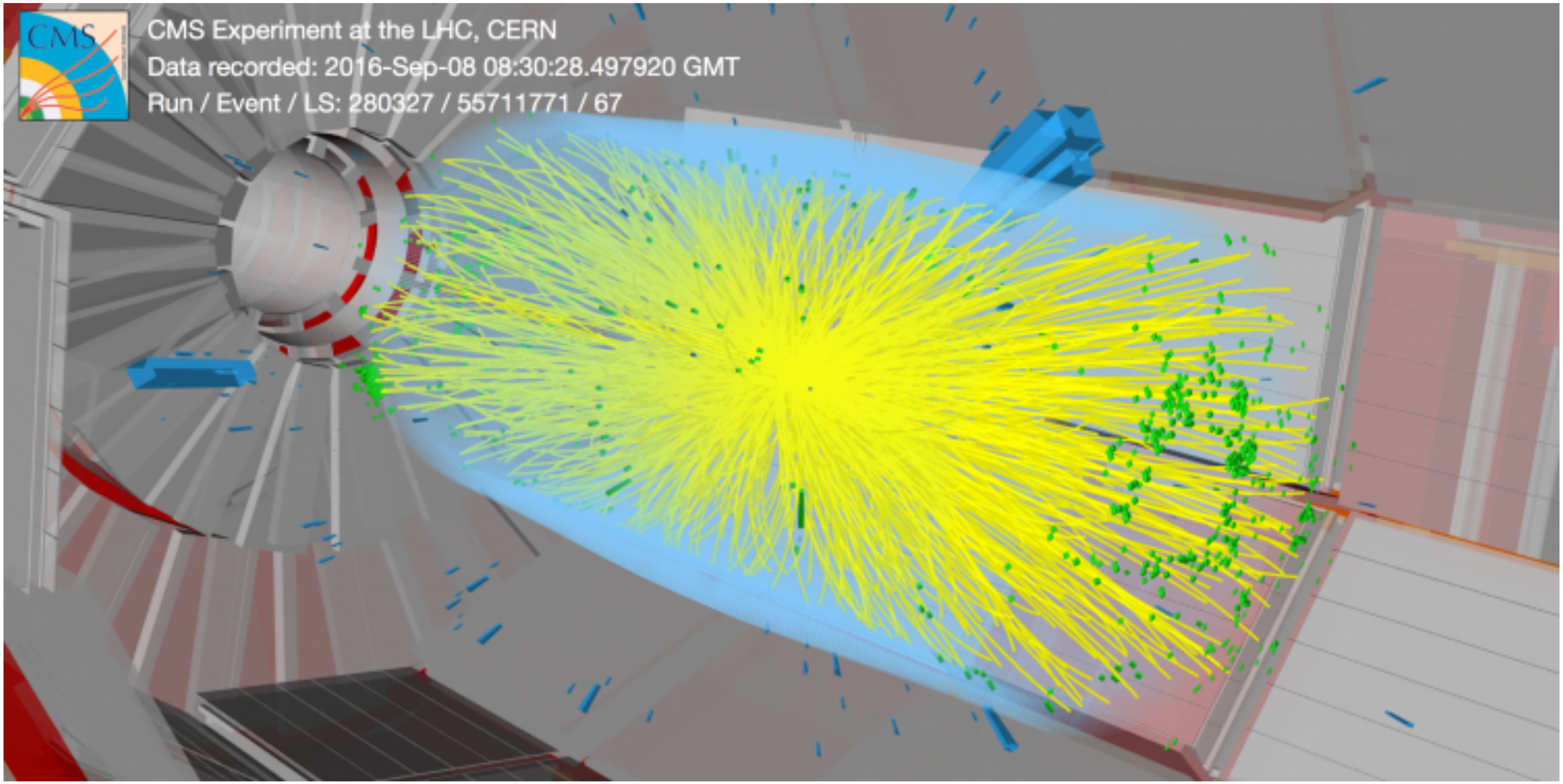


FIGURE 5. Fits to test-beam results for a lead/scintillator-fiber)[4], for the CDF upgrade end-cap hadron calorimeter (50 mm iron/3 mm scintillator sheets)[5] and for a copper/quartz-fiber test calorimeter[6].

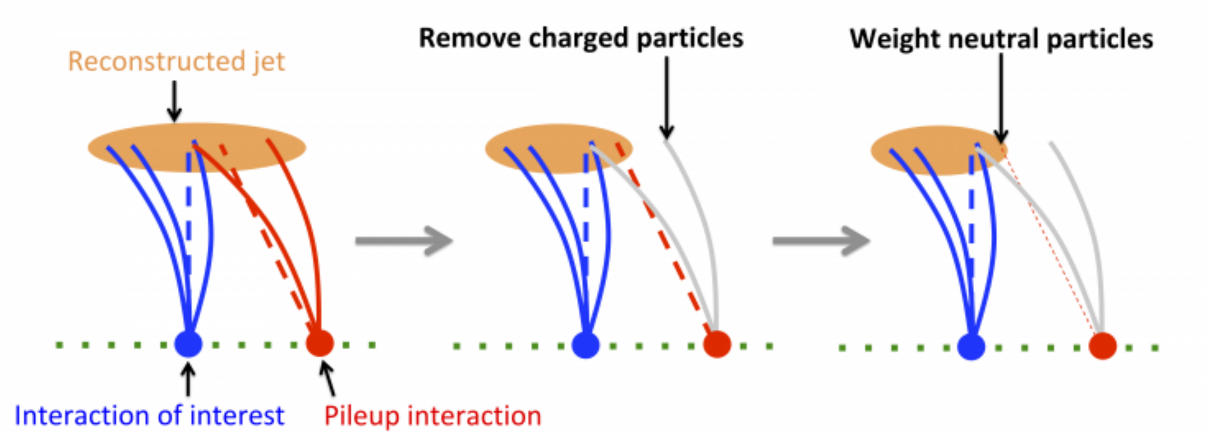
- In the end, hadron energy is transferred to electrons counted by electronics
- High-energy electrons from Z>ee standard candle are the foundation of calorimeter calibration



Add (and remove) pileup

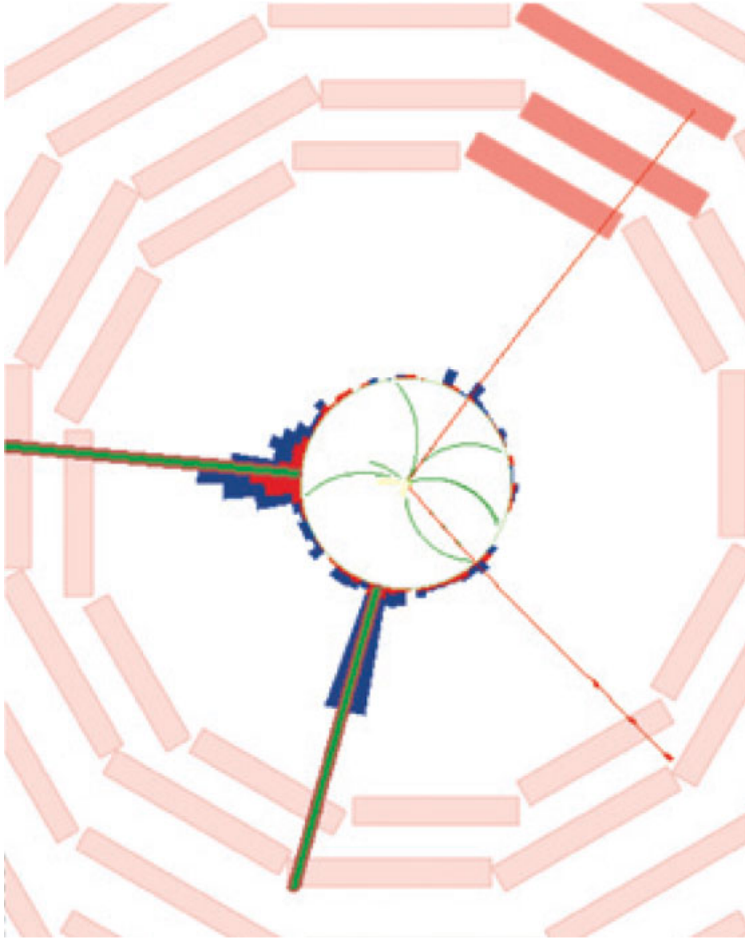


- LHC adds a lot of pileup (2023: <μ> > 50)
- Charged pileup removed using vertex association
- Neutral pileup removed either on average or using weights



- Three fundamental principles:

1. Improve MC wherever you can: best JES is no JES (residual)
2. Start with Z>μμ standard candle
3. Enforce energy and momentum conservation

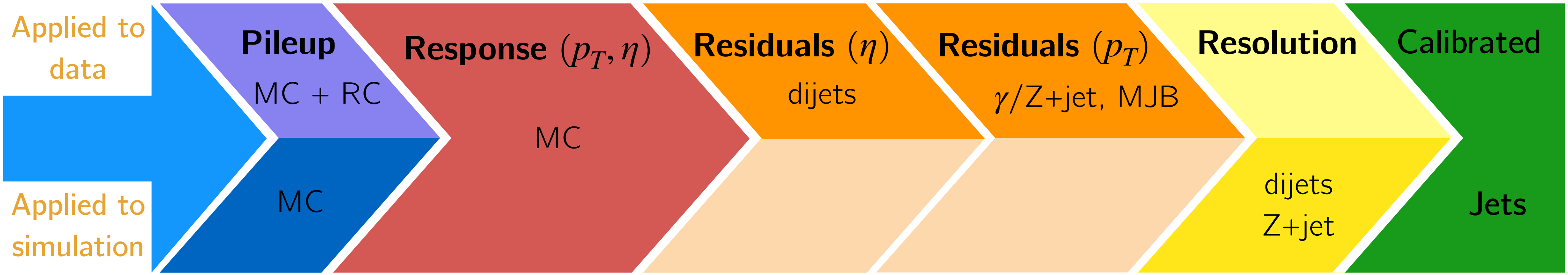


ATLAS

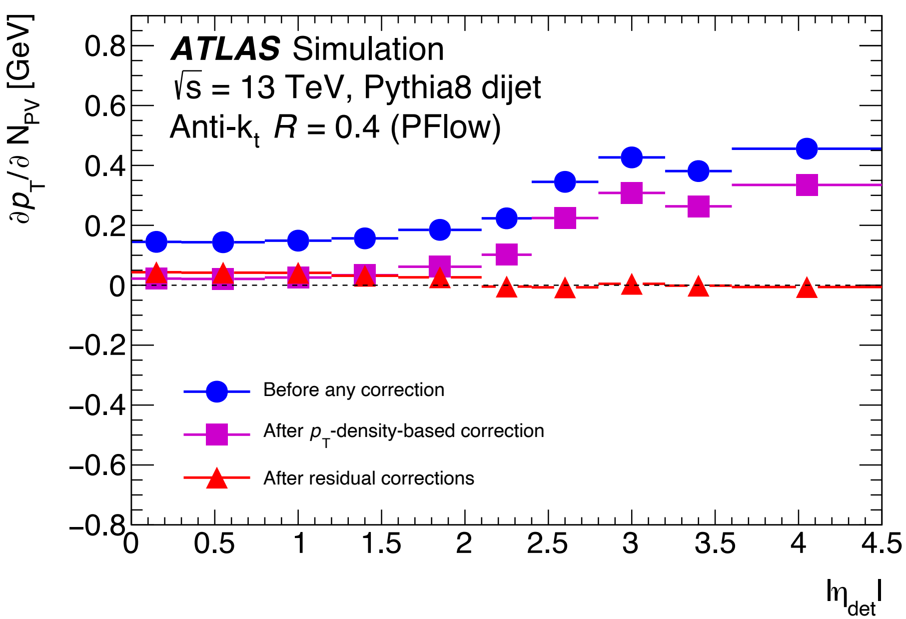
Reconstructed jets → **p_T-density-based pile-up correction** → **Residual pile-up correction** → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

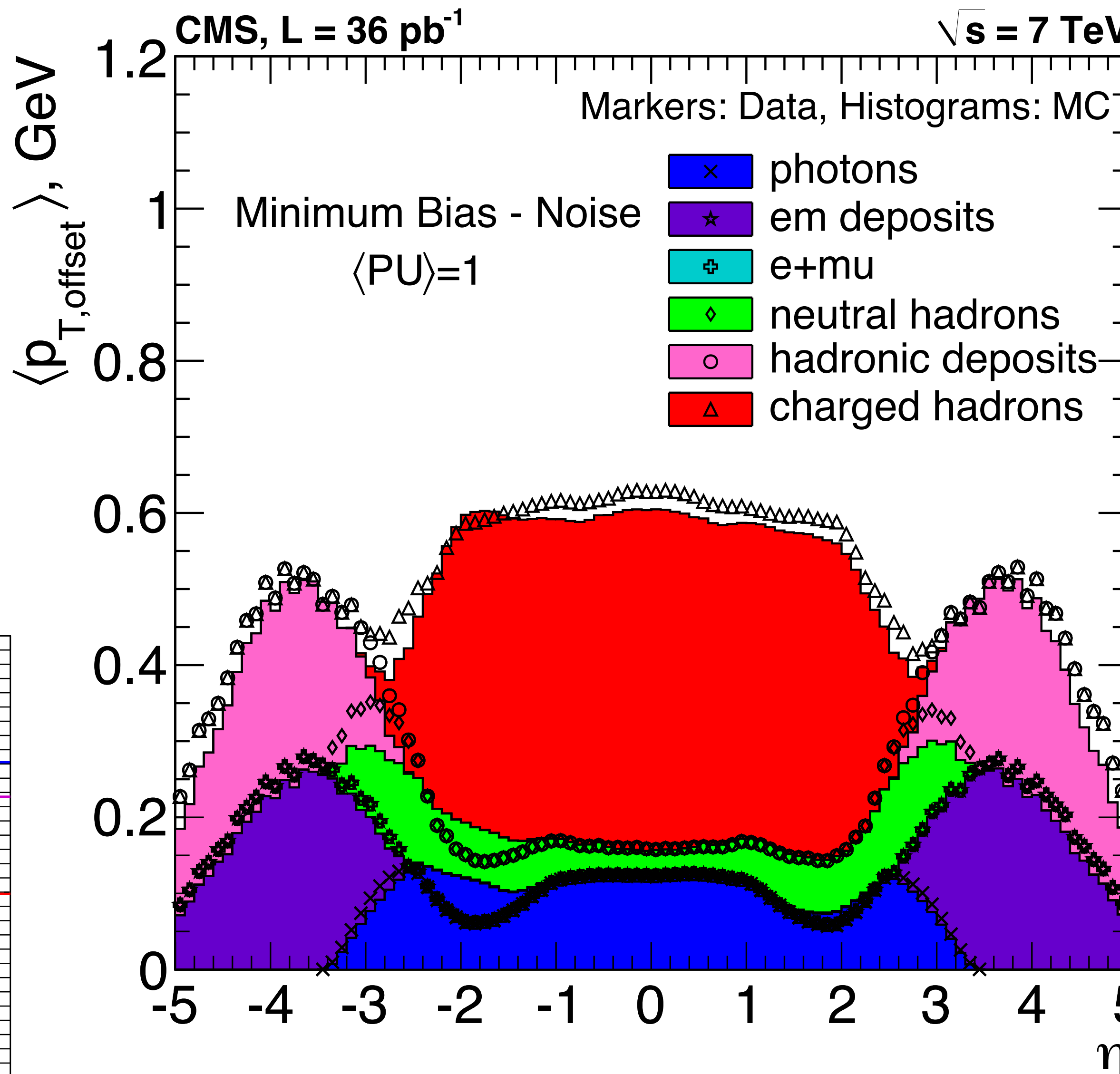
- **Reconstructed jets**: *Jet finding applied to tracking- and/or calorimeter-based inputs.*
- **p_T-density-based pile-up correction**: *Applied as a function of event pile-up p_T density and jet area.*
- **Residual pile-up correction**: *Removes residual pile-up dependence, as a function of μ and N_{PV}.*
- **Absolute MC-based calibration**: *Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.*
- **Global sequential calibration**: *Reduces flavour dependence and energy leakage effects using calorimeter, track, and muon-segment variables.*
- **Residual *in situ* calibration**: *A residual calibration is applied **only to data** to correct for data/MC differences.*

CMS



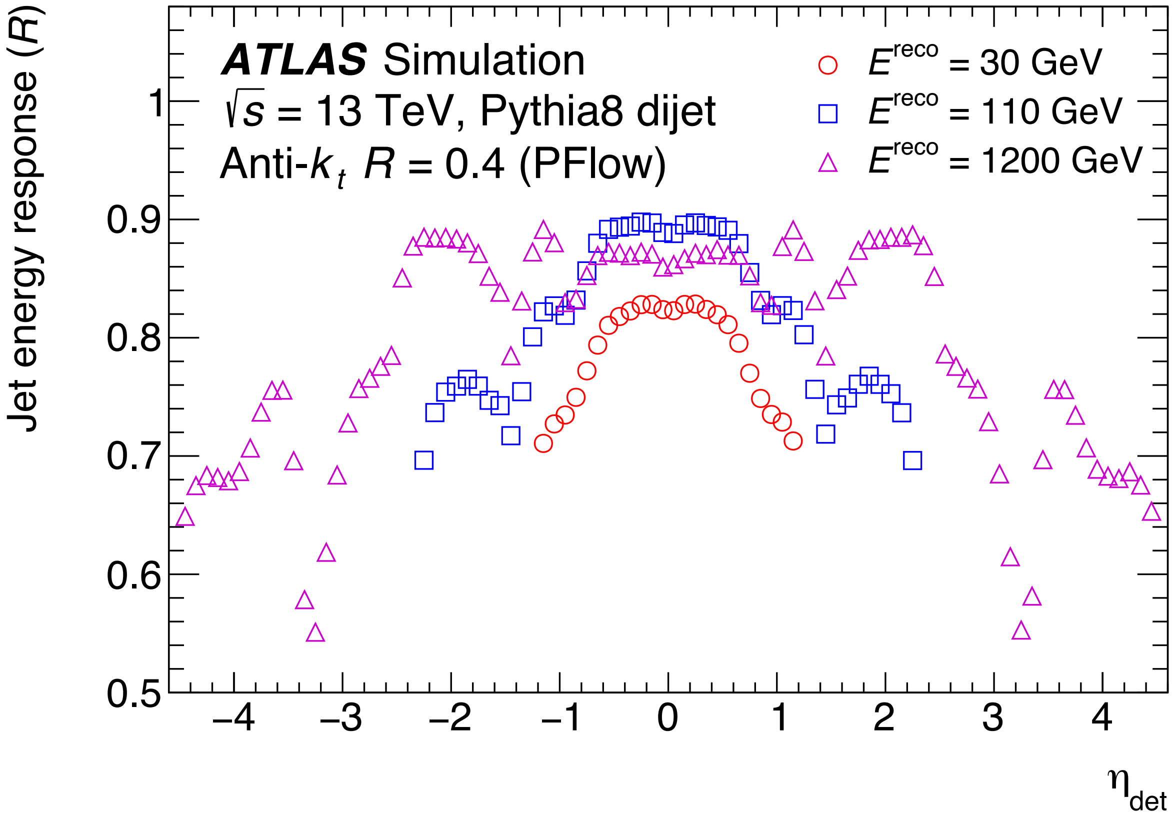
- Pileup is easiest to measure with random cones
- Closely related method is FastJet energy density ρ from either
  - Median p_{Tjet}/A_{jet} of k_T-clustered jets
  - Median $p_{T,grid}/A_{grid}$ from fixed grid
- Interference between signal and pileup best left for MC, e.g.
  - un-zero-suppression of signal+PU
  - μ-dependent tracking efficiency

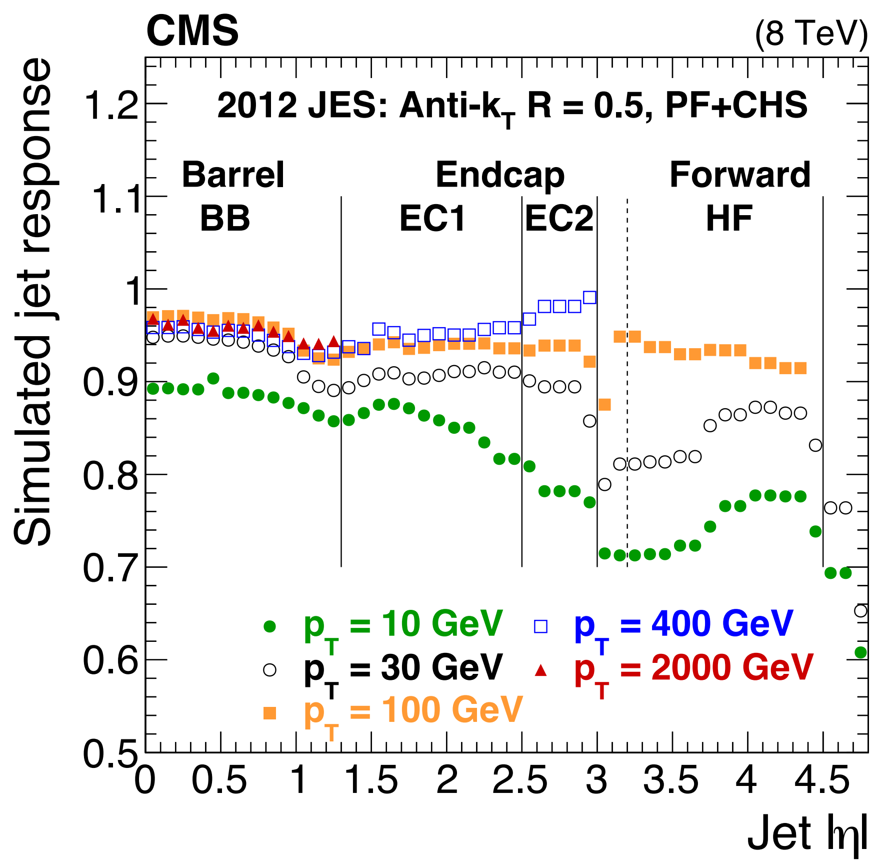




Detector simulation

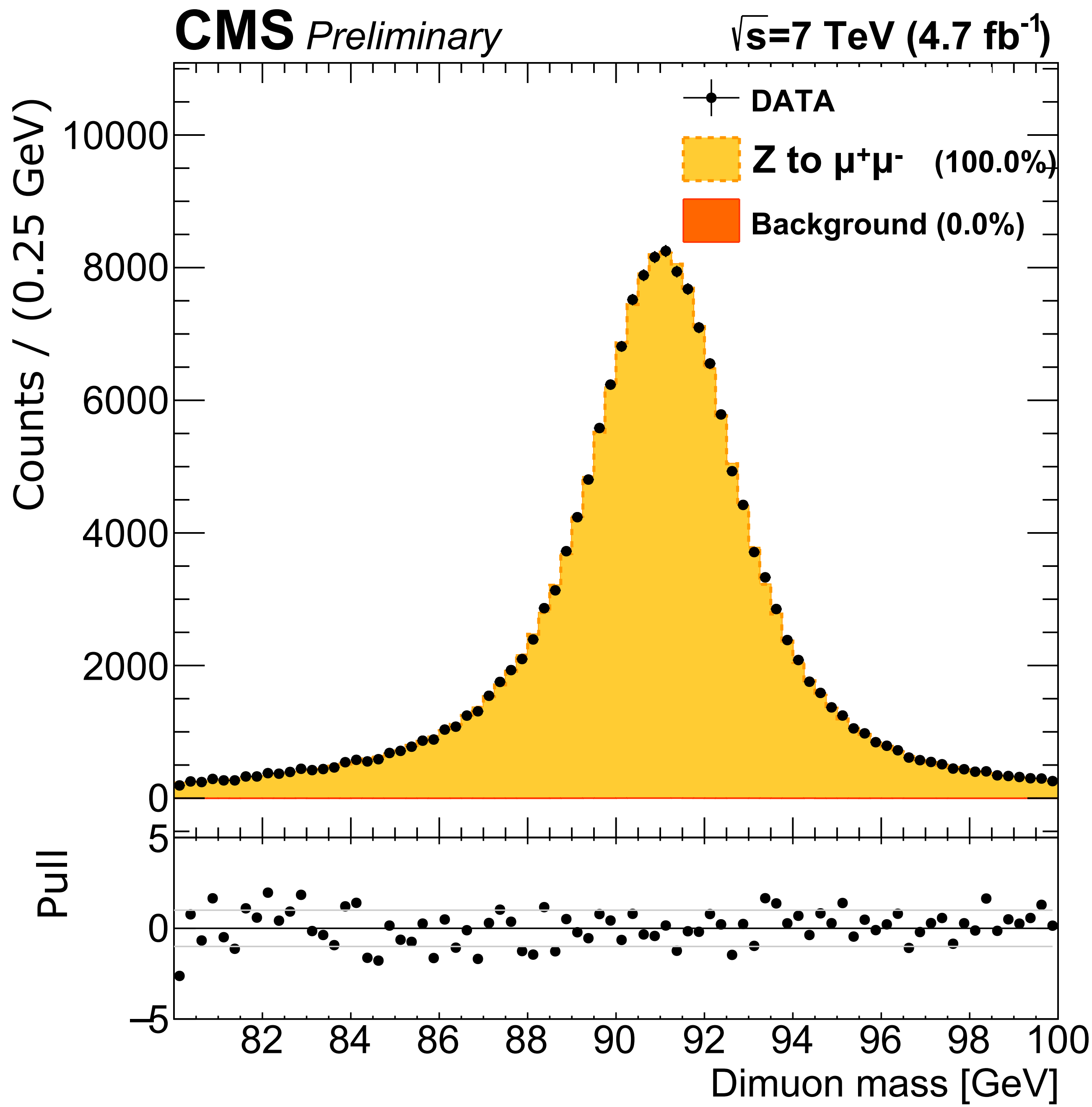
- Detector simulation is (supposed to be) bulk of corrections: best JES is no JES (residual)
- Accounts for (at least partly)
  - Tracking inefficiencies (dynamically increasing at higher pileup)
  - Calorimeter thresholds (raised at higher integrated luminosity)
  - Calorimeter non-linearity for π/e response (evolving over time)
  - Calorimeter radiation damage (crystal/plastic scintillator transparency)
  - Dead detector regions (persistent and transient)
  - … etc. ***Lots and lots of subtle effects!***



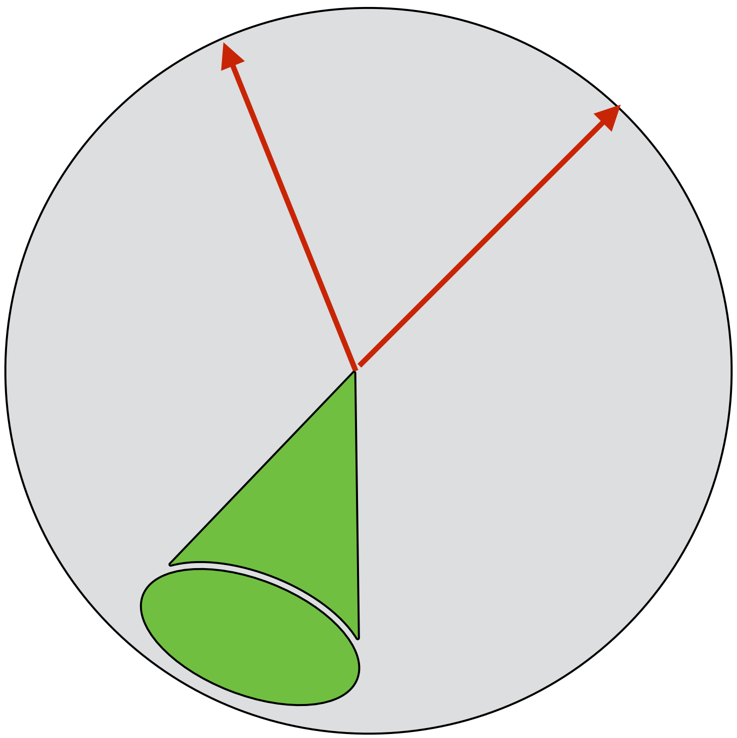


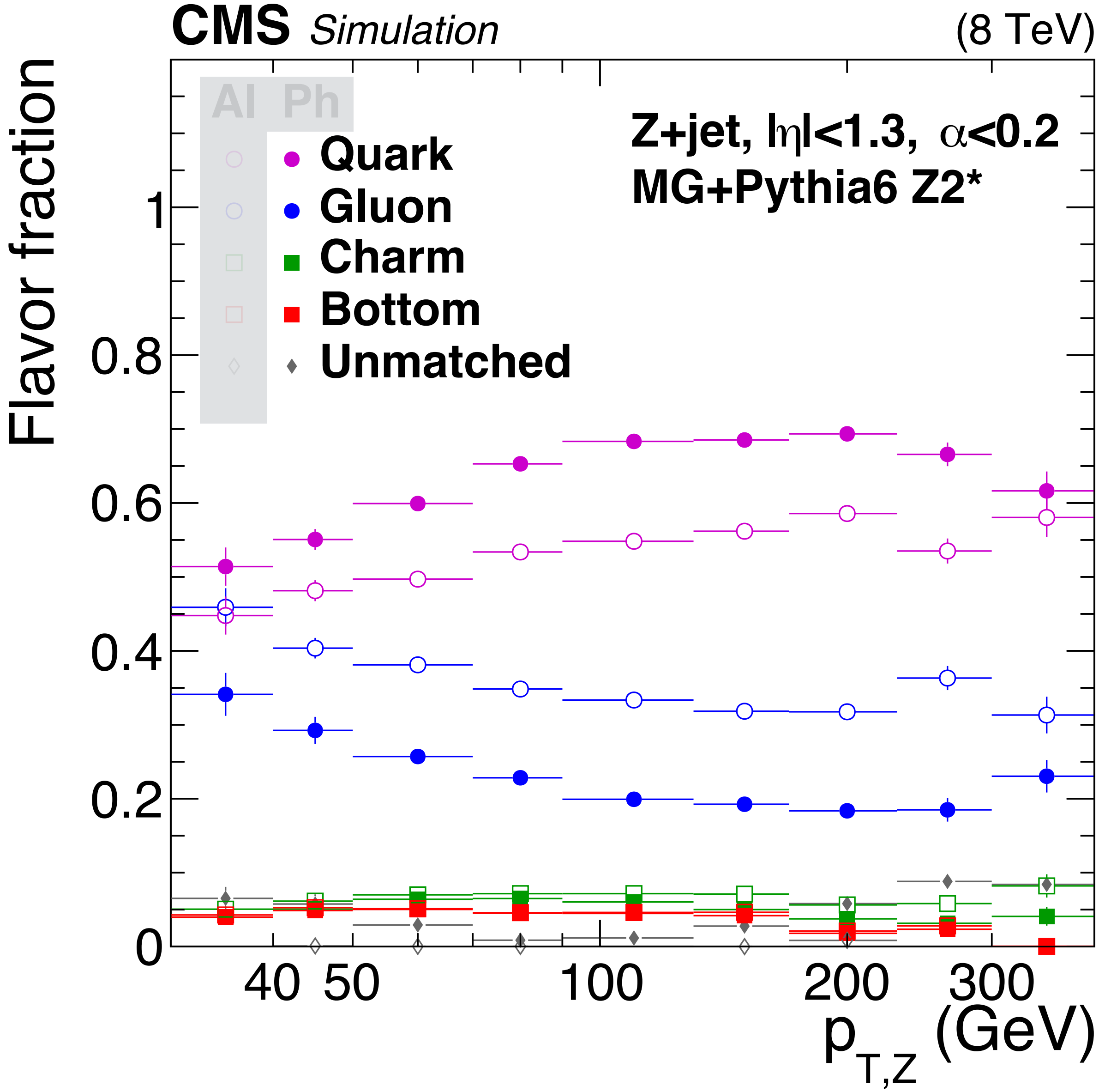
Z mass

- Z boson mass reconstructed from muons is possibly the most precise quantity at LHC
- Z boson p_T provides reference momentum for jet calibration
- Z boson decay to electrons also used as a reference for jets and photons

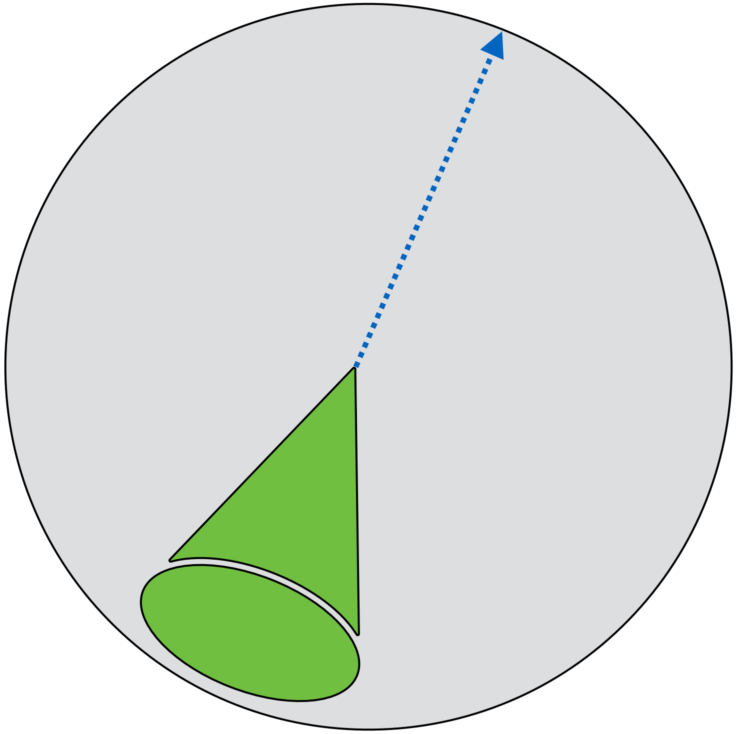


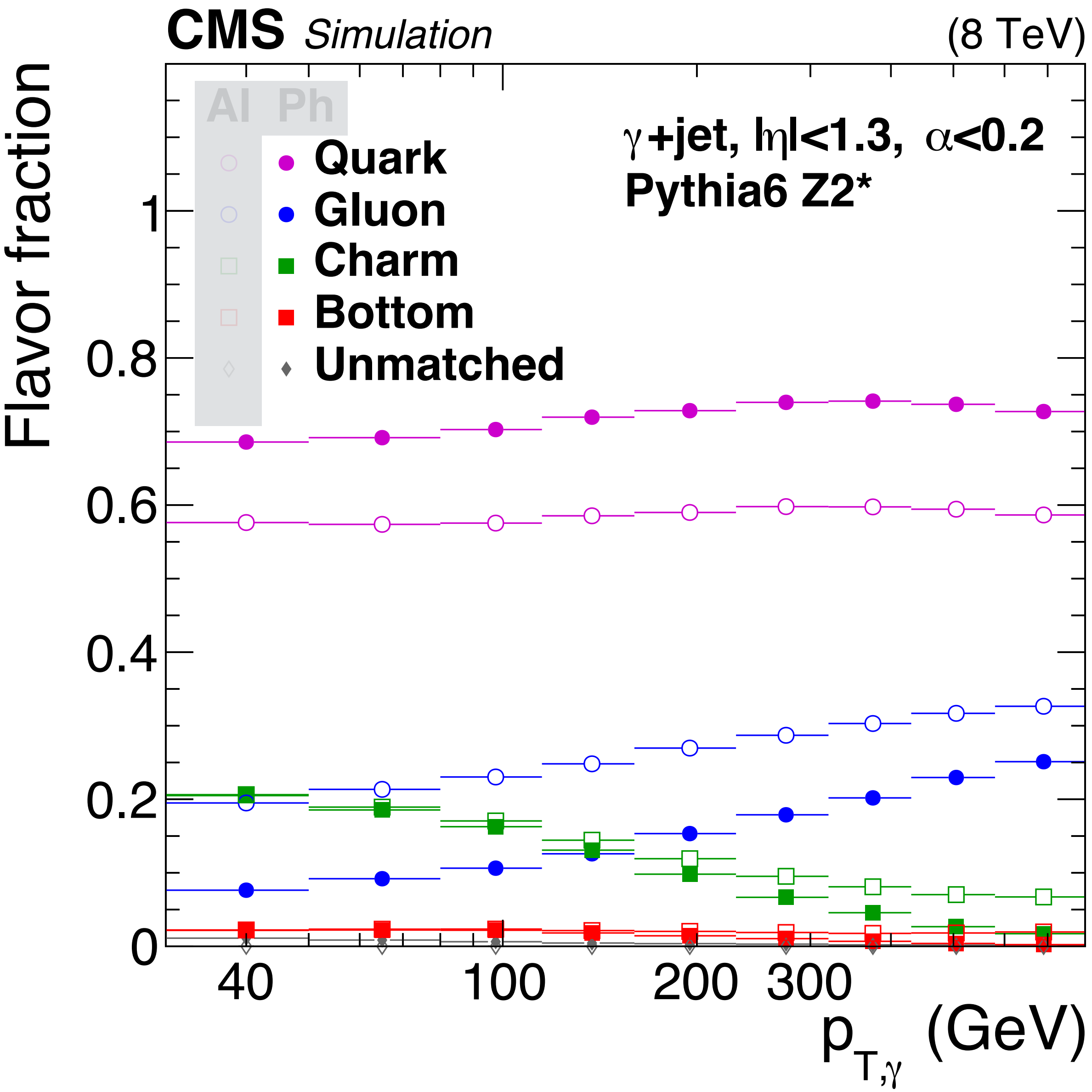
- Step 1: transfer Z(>μμ) scale to mostly quark jets in barrel





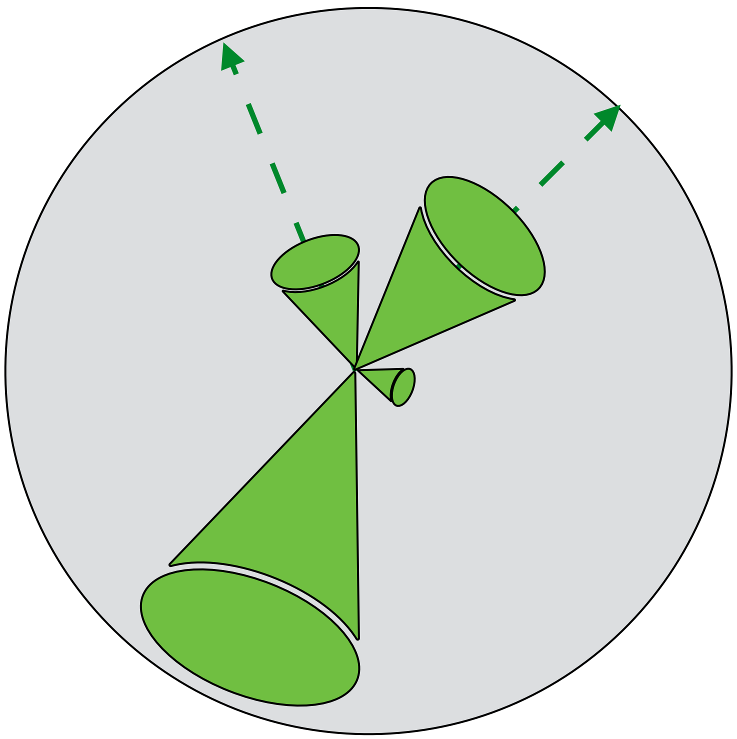
- Step 2: extend to higher p_T using more numerous γ+jet events
- Photon calibrated with Z(>ee)
- High p_T photon scale confirmed with Z(>μμ)+jet overlap region

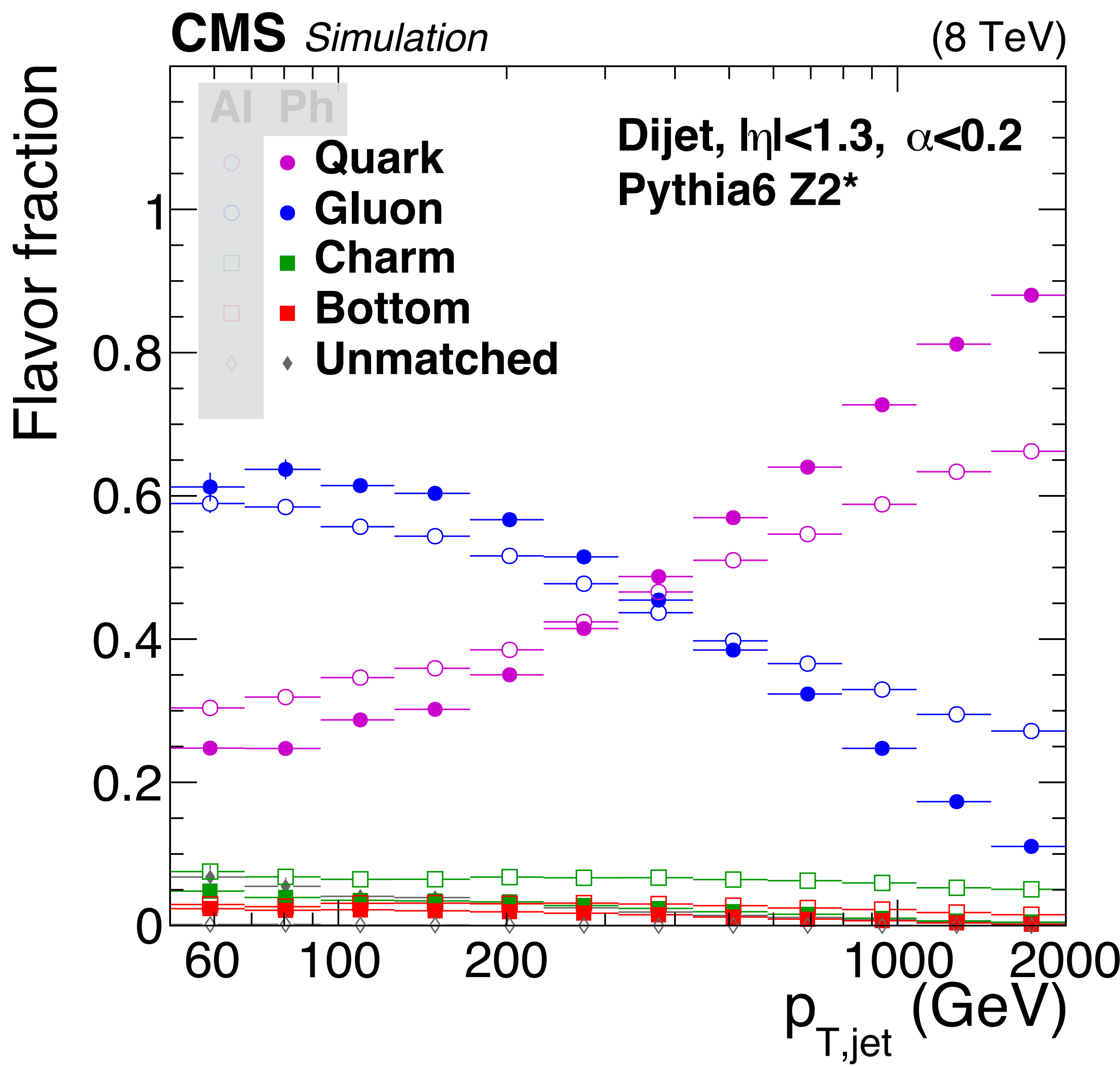




Multijet balance

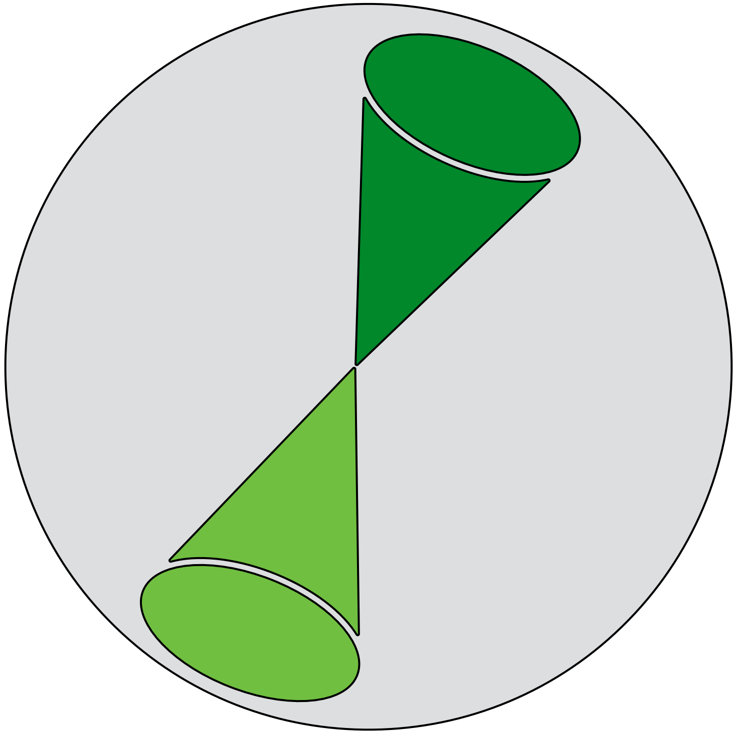
- Step 3: Extrapolate to highest p_T using leading jet in multijet events
- Lower p_T recoil jets calibrated with γ+jet overlap region

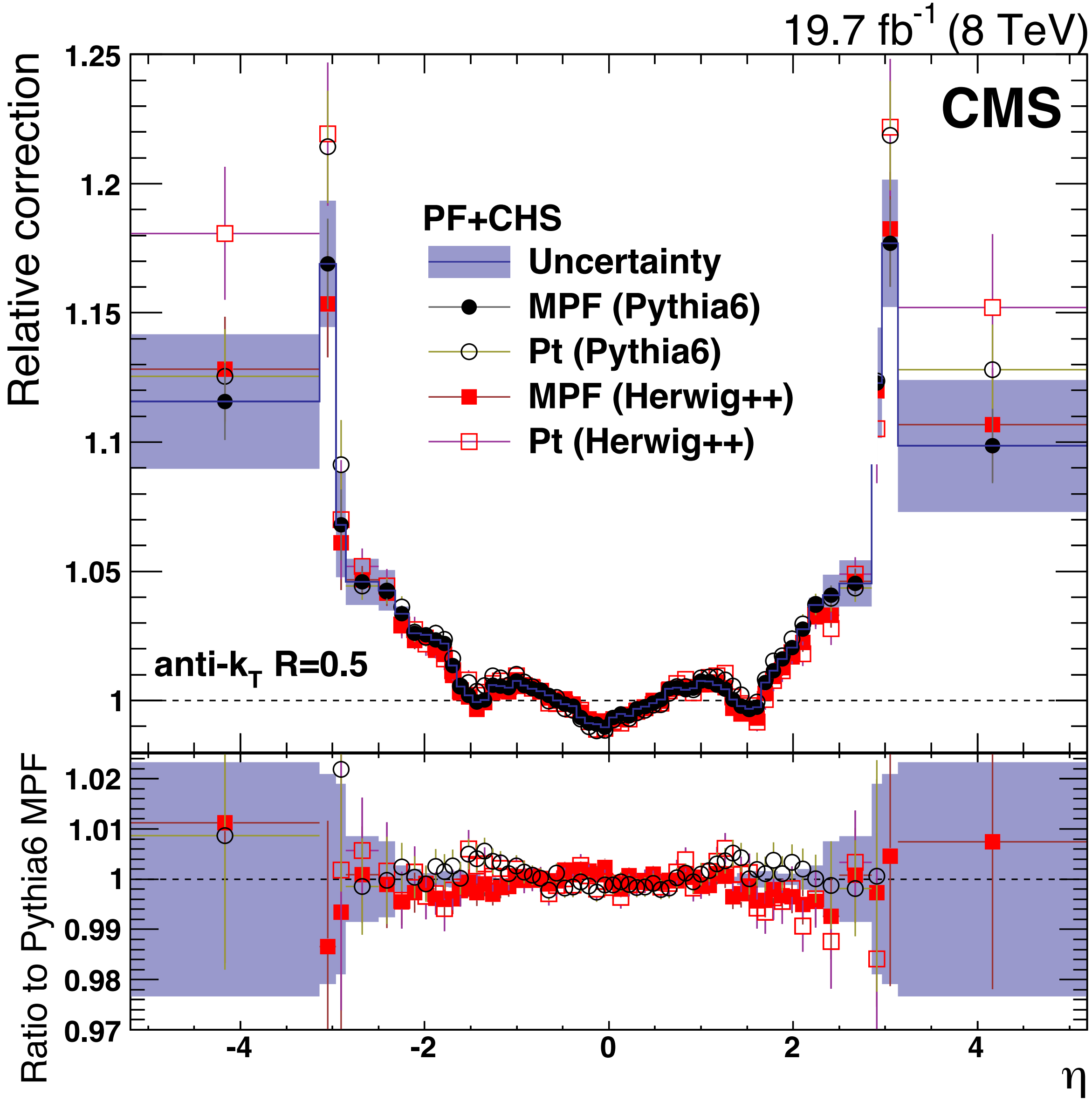




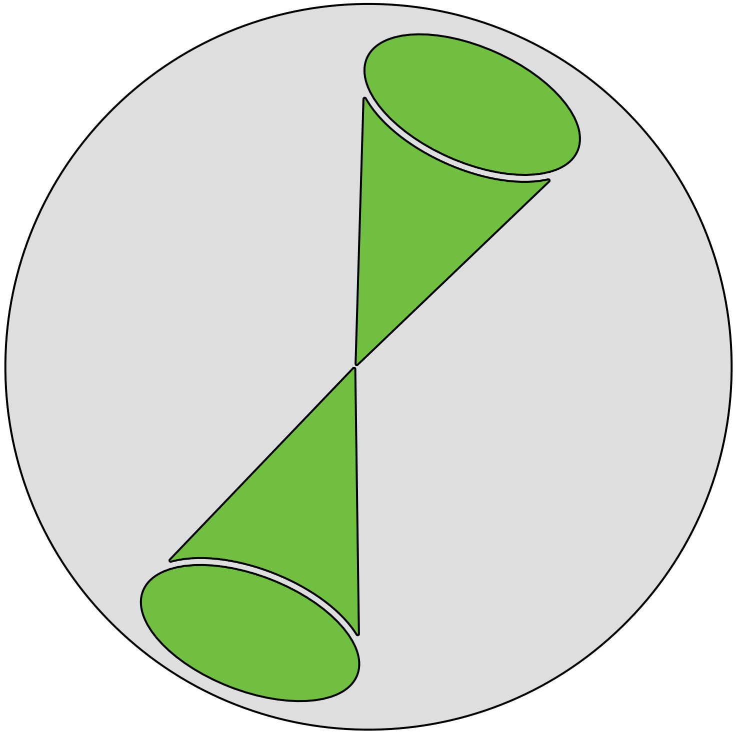
Dijet balance

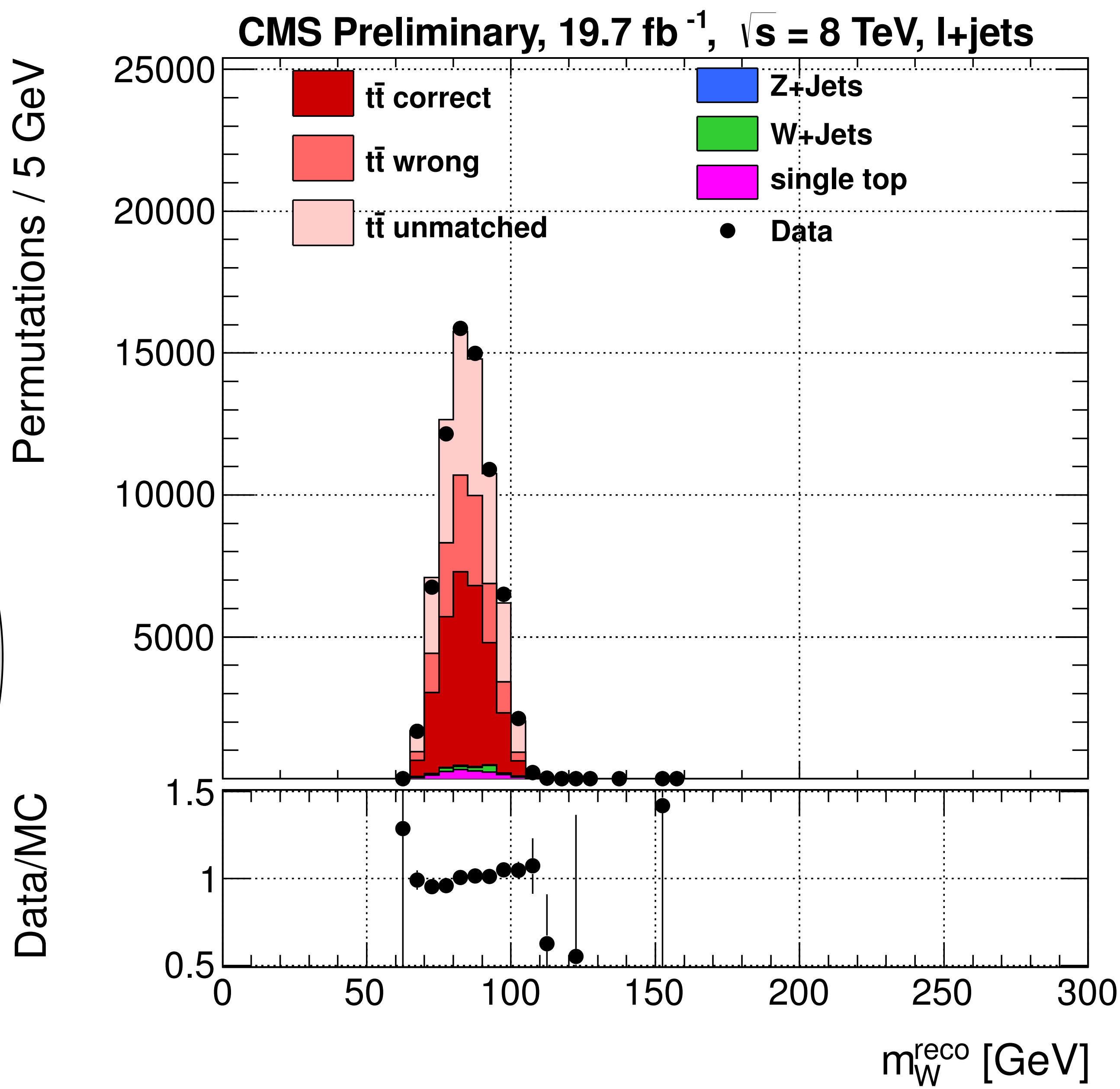
- Step 4: Extend barrel calibration to other parts using dijet events
- One jet in barrel calibrated by Z/γ/multijet, another more forward
- Main caveat: barrel jet more often gluon jet than in Z/γ+jet events





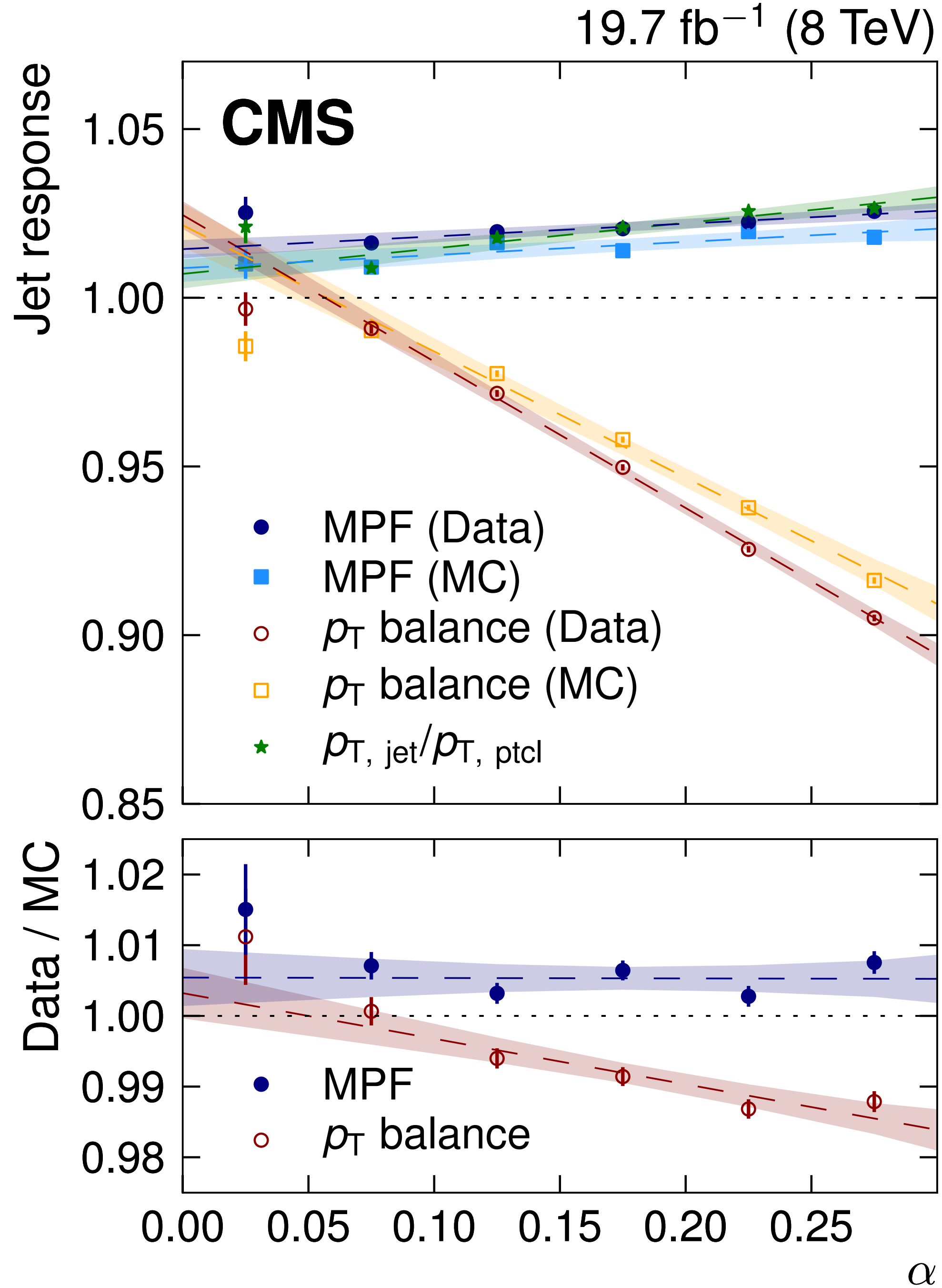
- Step 5: confirm qJES + ISR+FSR + UE + vs with known W(qq') resonance mass in tt
- In-situ calibration often used in m_t measurements
- Mostly ud, cs jet pairs



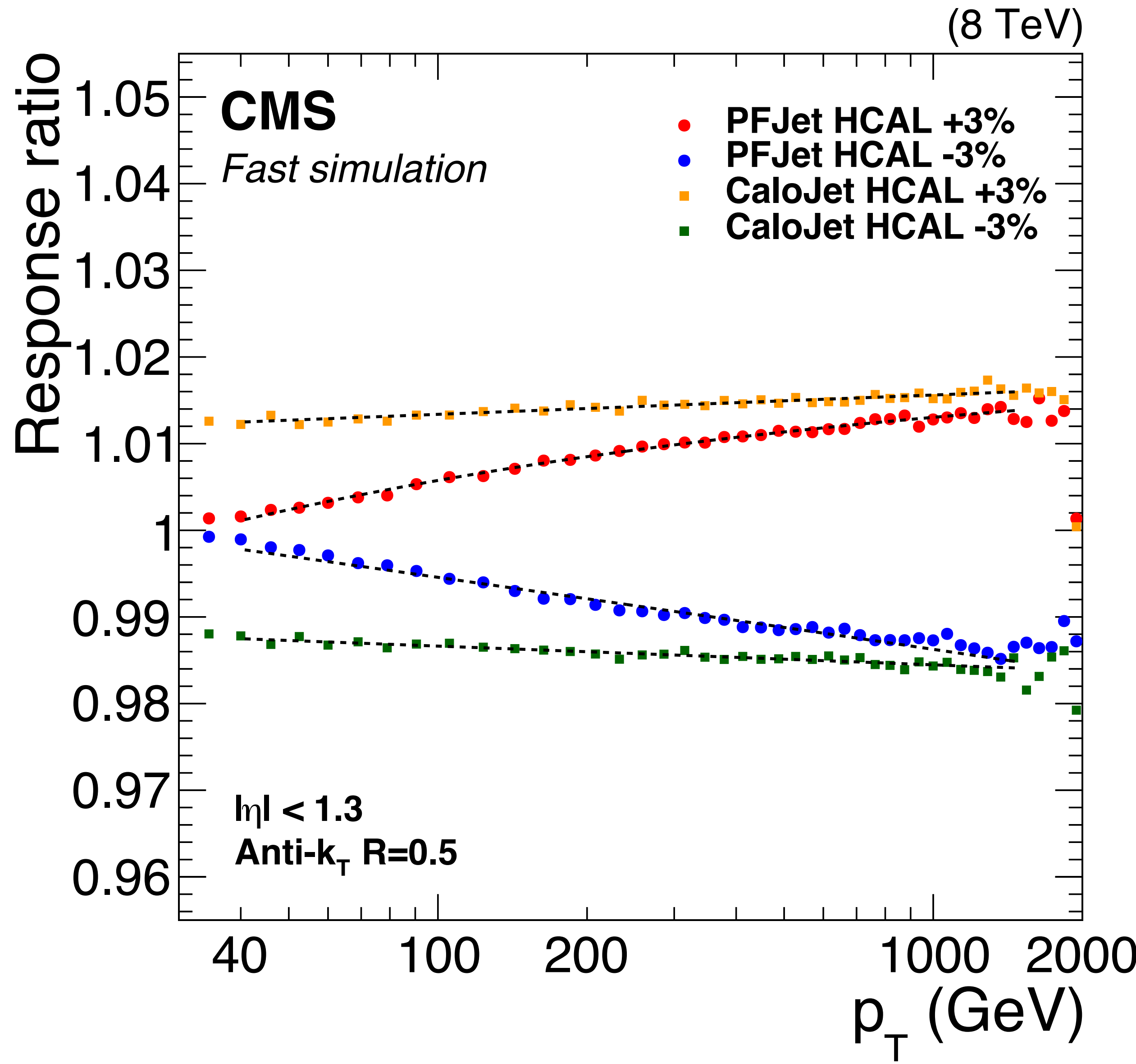


Missing-E_T Projection Fraction

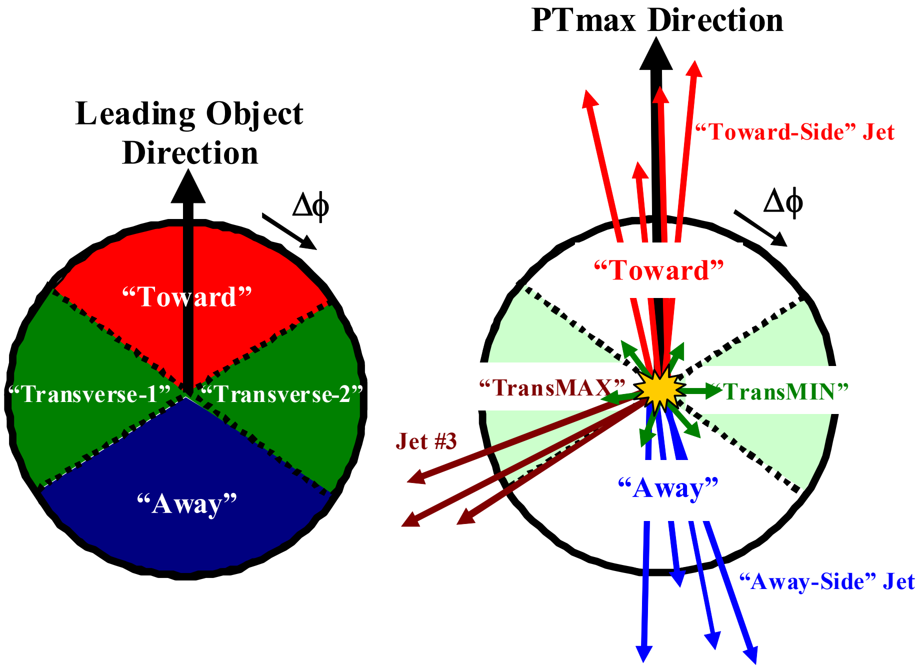
- Methods based on direct p_T balance are biased depending on how much extra radiation is allowed
  - α is defined as hardest extra jet p_T over reference p_T, e.g. $p_{T,2}/p_{T,Z}$
- Measurement of full hadronic recoil (jet+FSR) through missing E_T (MPF) is less biased and agrees better with data
- MPF is modern baseline, but many early JES measurements used p_T balance
  - Data/MC difference is reduced by using higher order MC (NLO or multileg-LO)

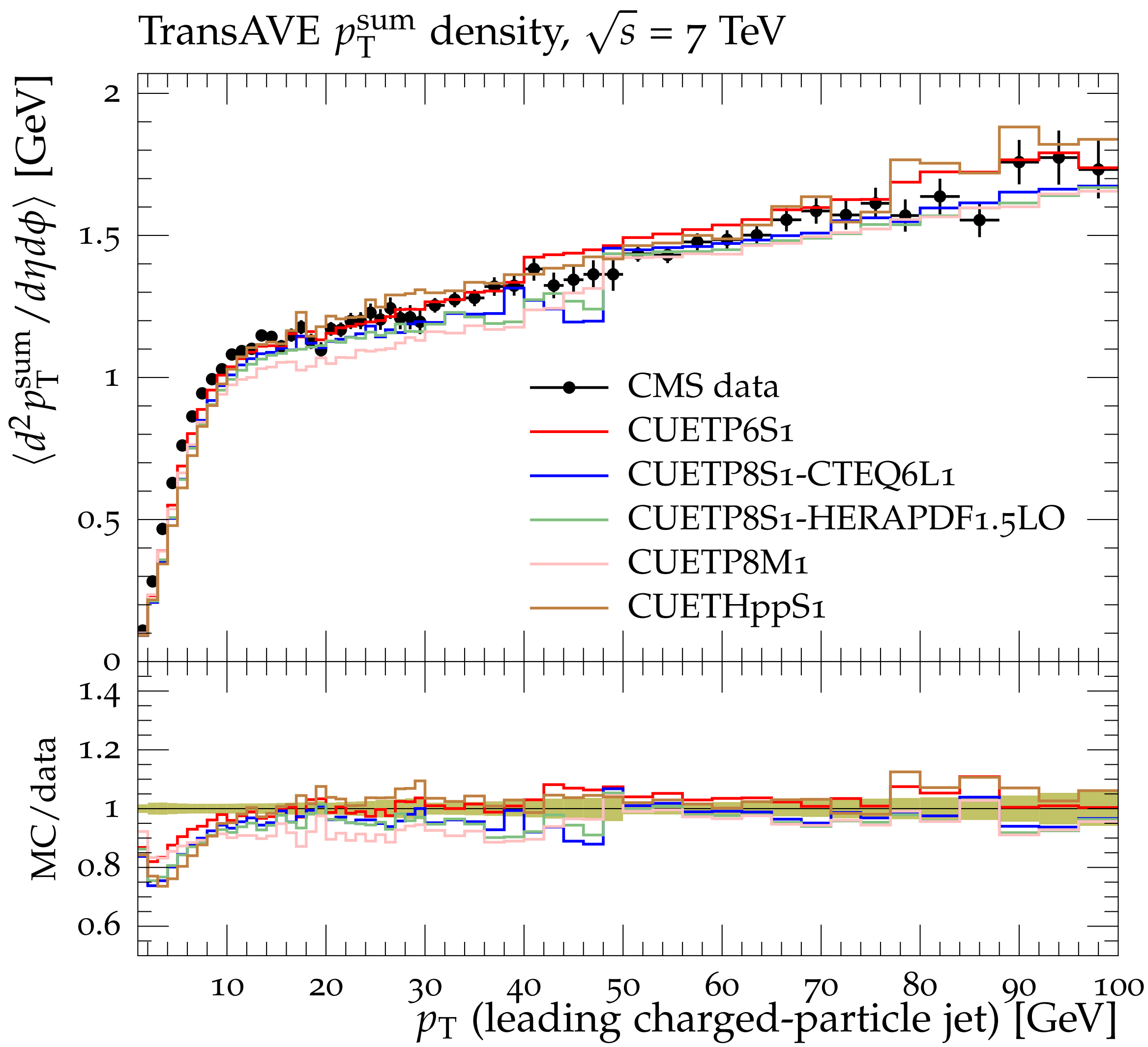


- Parameterizing JES at or outside edges of phase space is challenging
- Currently best approach is to model leading effects in MC
  - e.g. here variation of HCAL scale by +/-3% for PF and Calo jets
  - tracking in PF reduces dependence on HCAL scale at low p_T, while Calo jet JES change is more uniform
- Past calibrations have often used simple log-linear approximations
  - JES = $p_0 + p_1 * \log(p_T)$
  - can over- or undershoot outside the range of data used for JES fit

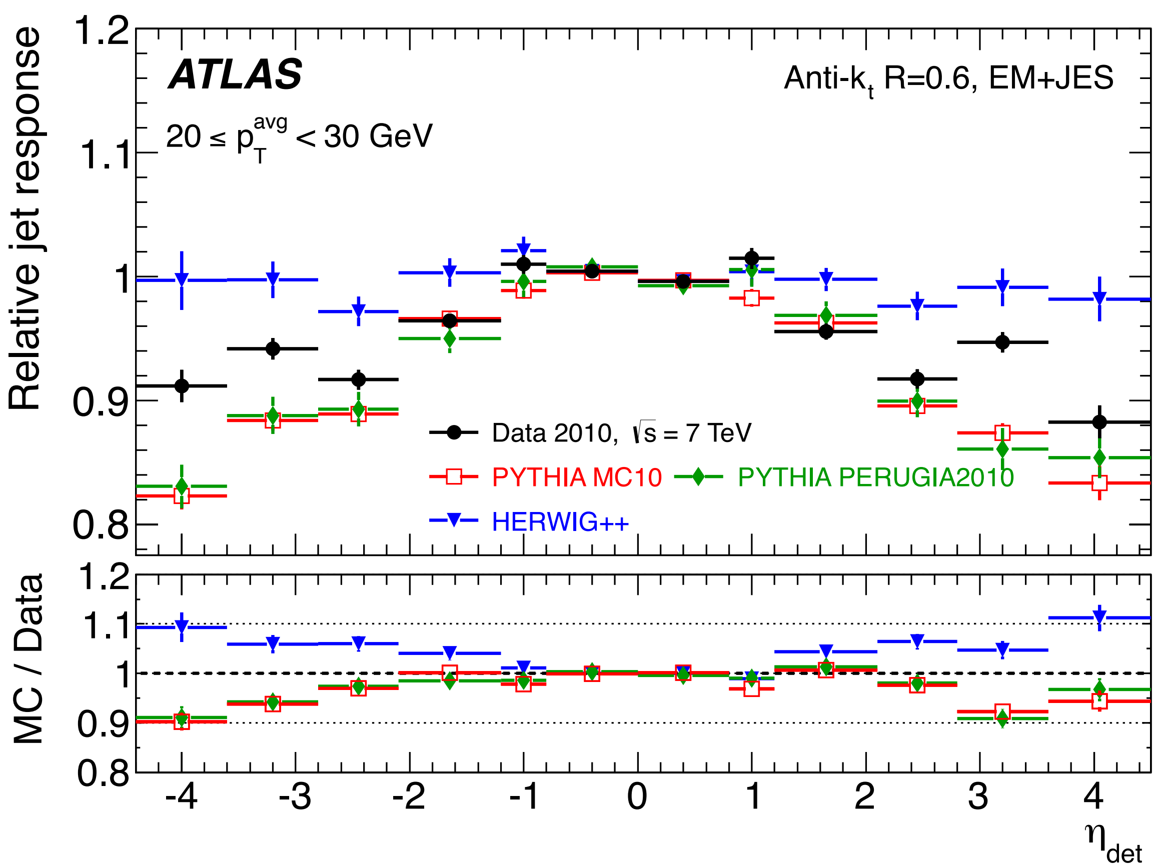


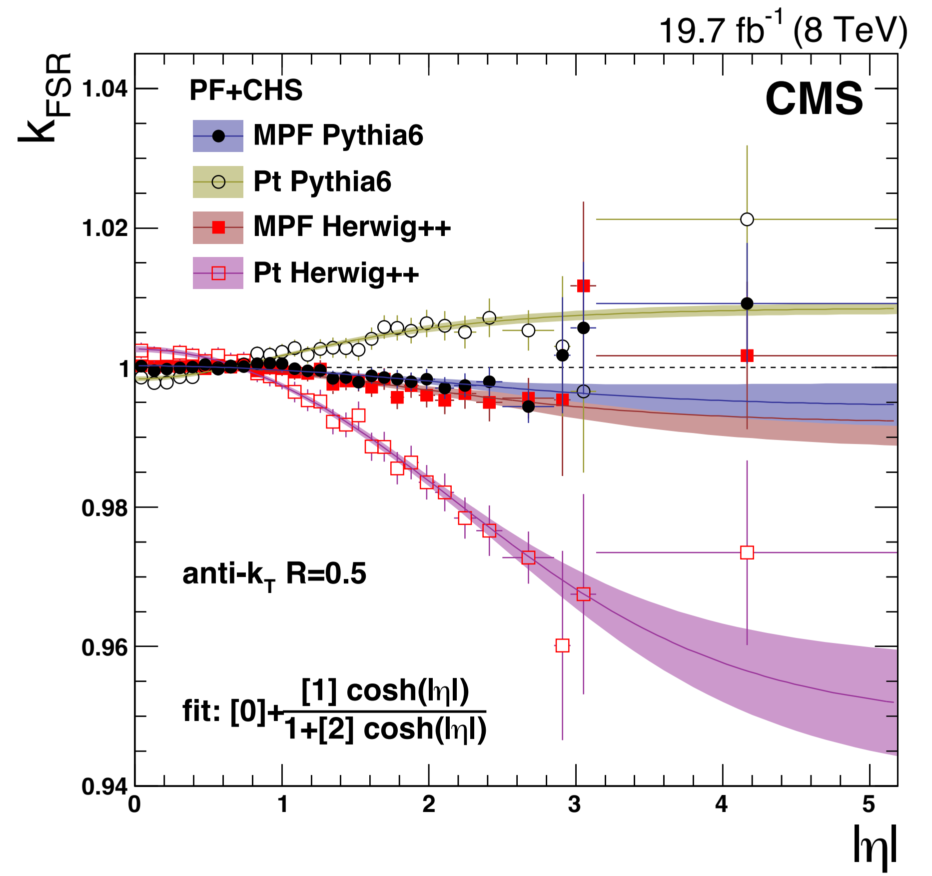
- MPF-method is insensitive to UE: isotropic so cancels out in missing E_T
- Direct p_T balance sensitive to UE relative to parton level
- Offset subtraction with ρ removes UE with PU, unless explicitly fixed
- Mostly rely on good modelling of UE (and PU) through MC tuning





- Simulation of ISR+FSR is better in NLO and multileg MC
  - Biases observed especially for multijet balance and central-forward dijet pairs with LO MCs
  - Opposite effects for angular-ordered (Herwig++) and p_T-ordered (Pythia6) showers in the past
  - Modern alternatives Powheg, Sherpa and MadGraph aMC@NLO generally better, but not perfect
- Caveat for early Run 1 results using direct p_T balance and LO MC for JES

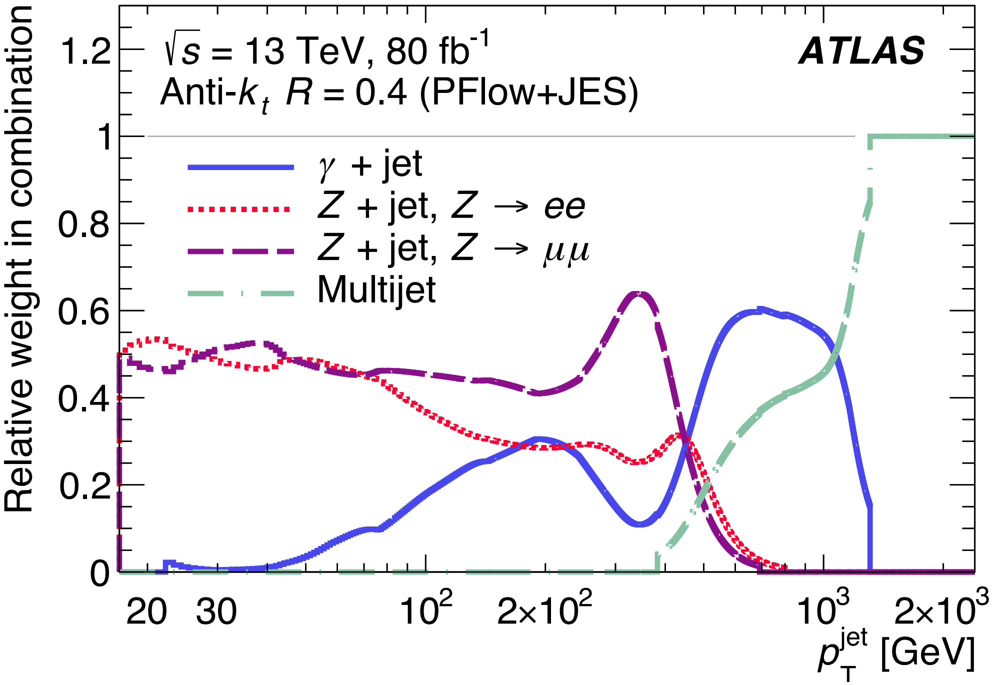




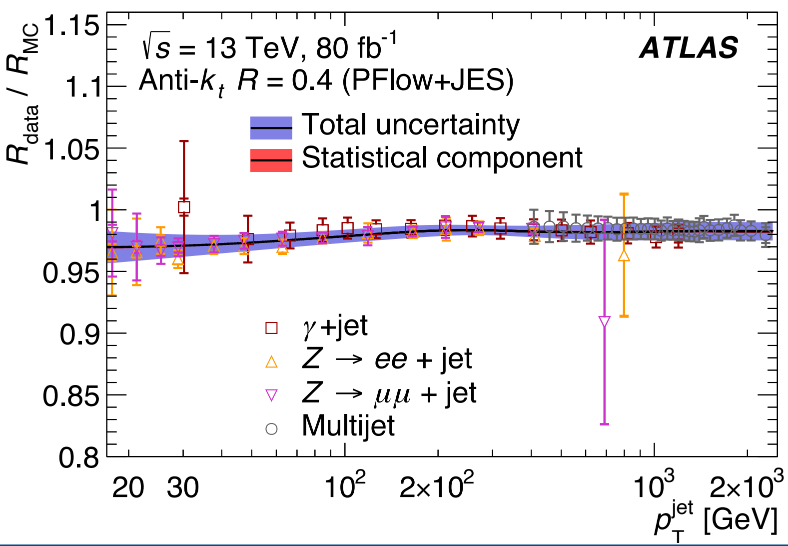
We [CMS] find p_k and ε_j given D_i that minimise

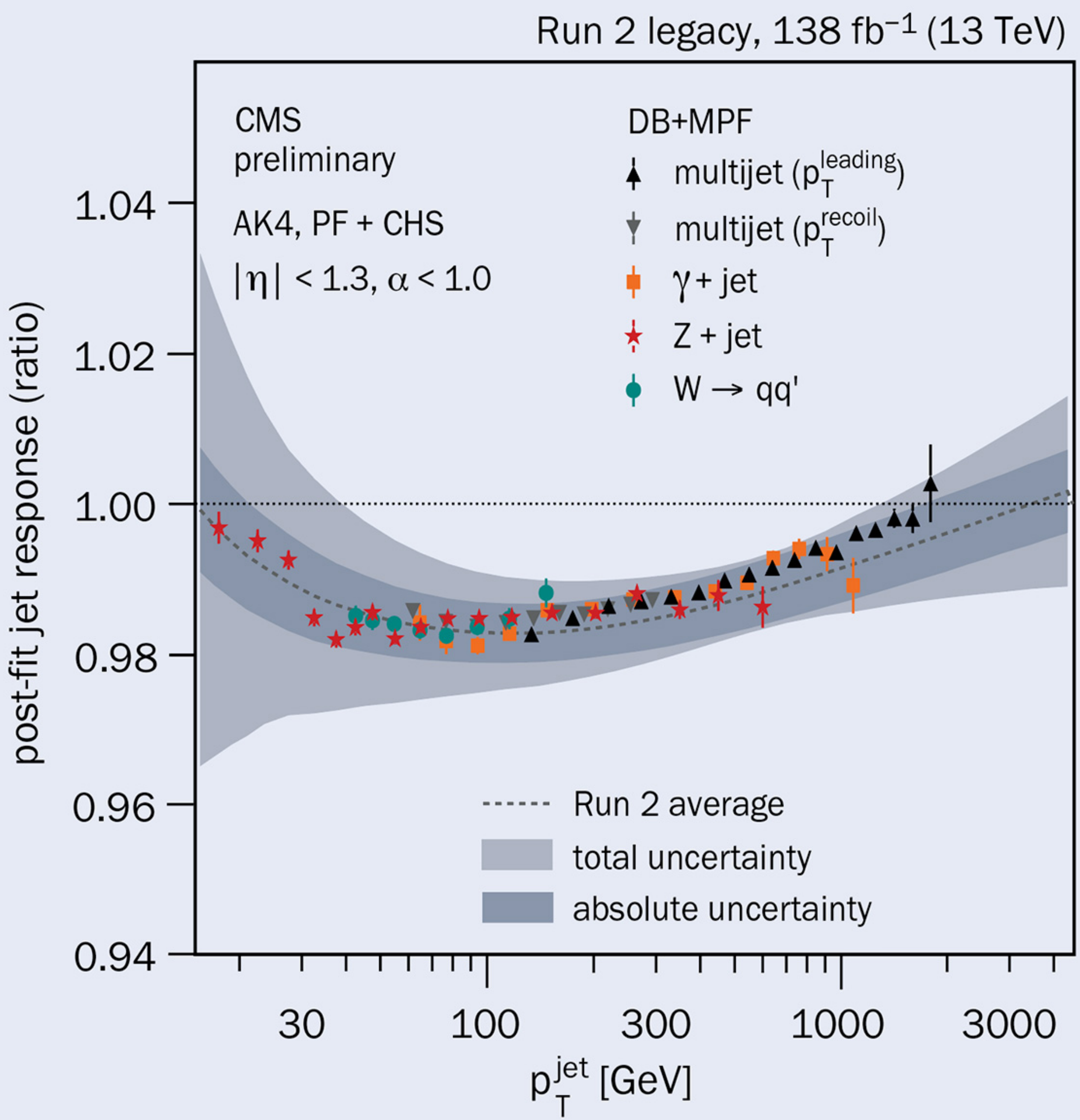
$$\chi^2 = \Sigma_i((D_i+\Sigma_j\varepsilon_j\delta_{ij}) - \mathrm{JES}(p_{T,i};\ p_k))^2/\sigma_i^2 + \Sigma_j\varepsilon_j^2 + \Sigma_k p_k^2\ ,$$

where D_i are data points
at jet transverse momentum $p_{T,i}$
given statistical uncertainty σ_i
and systematic uncertainties δ_{ij}
scaled by nuisance parameters ε_j
and fitted with JES with parameters p_k
with prior distribution Gaus(0,1)
that also contribute to chi-squared $\chi 2$



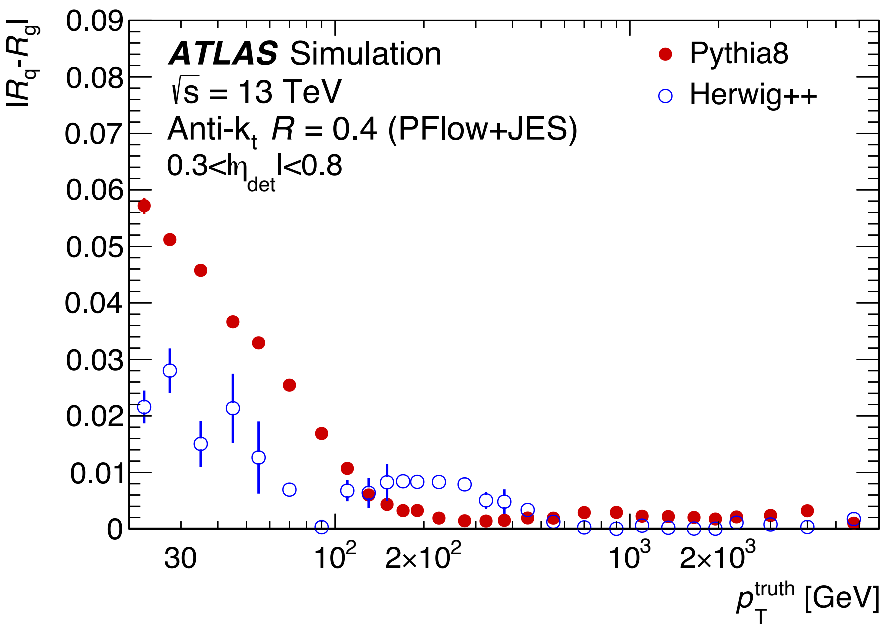
- Run 2 results from CMS and ATLAS using PF converge to ~2% residual
- Potentially shared biases in MC modelling of non-perturbative effects, e.g.
  - Flavor JES
  - Baryon number
  - Strangeness
  - Particle multiplicity
  - Leading particle

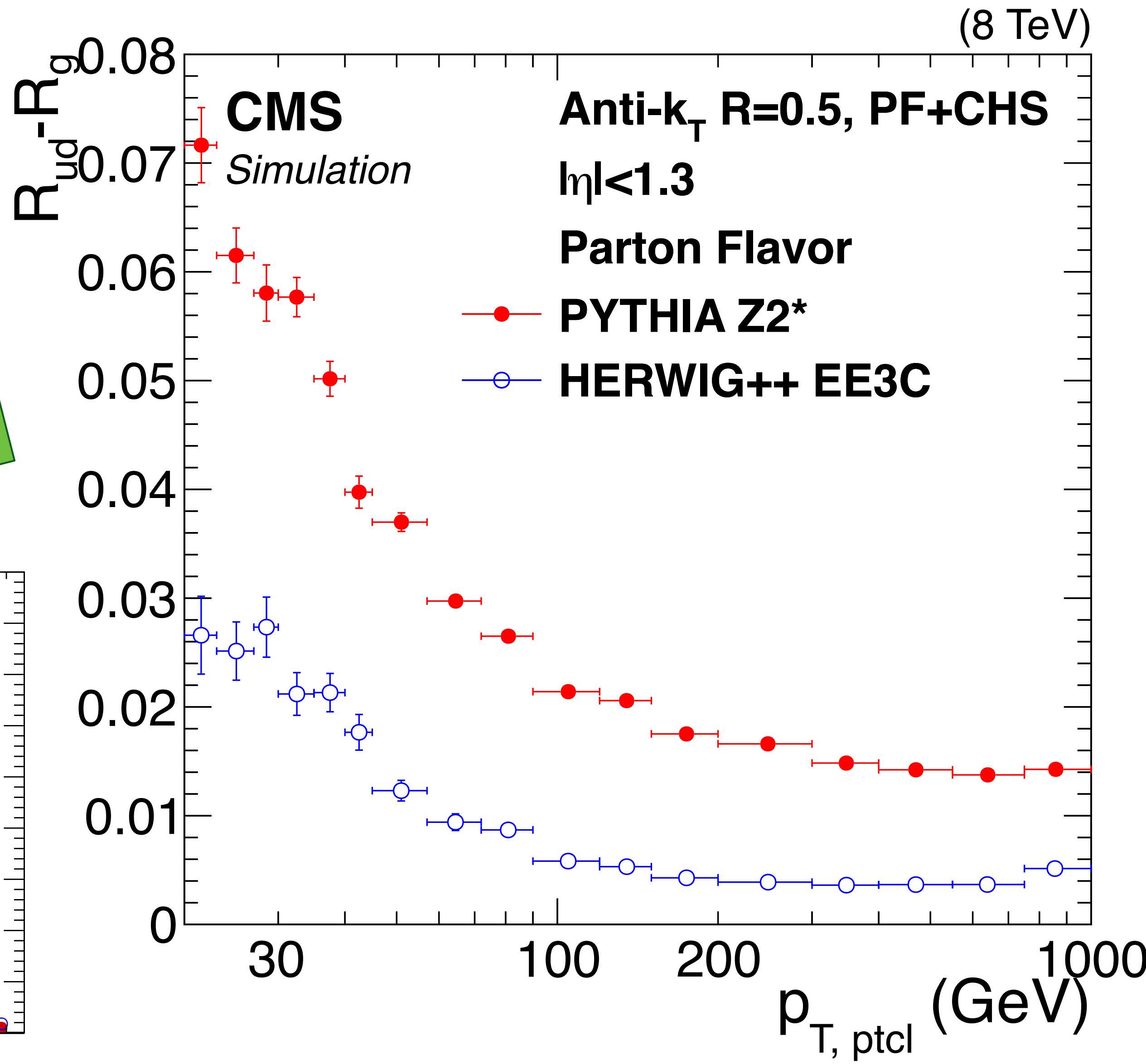




- One obviously badly modelled effect is gluon JES
- Both ATLAS and CMS have so far relied on Pythia for MC JES
  - Herwig used as alternative to assess systematic uncertainties
  - Data almost certainly miscalibrated

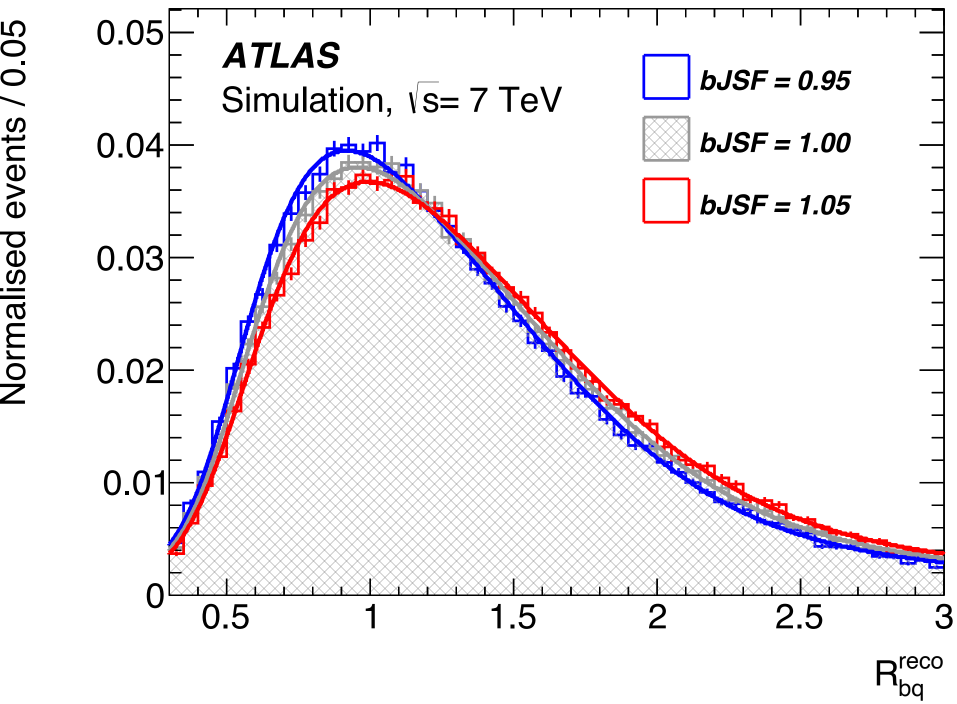
Talk by Nico Toikka

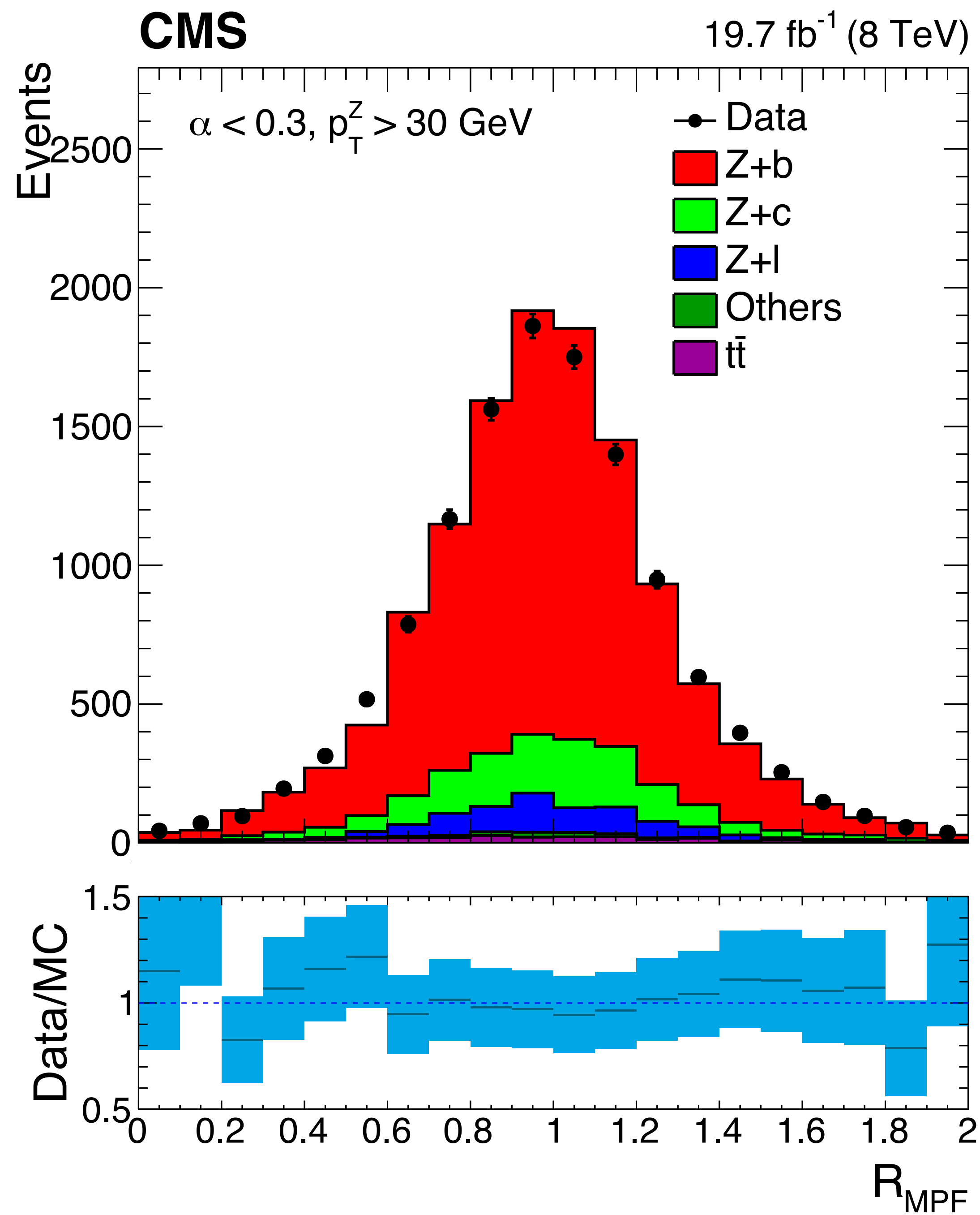




Bottom JES

- Bottom JES not well constrained due to lack of statistics
  - Only 3–4% of dijet events with b jets
  - Similar for Z+jet
- Leading candidate methods will improve on full Run 2 data set at 13 TeV
  - Z+b (CMS Z+jet)
  - $R_{bq} = (p_{T,b1}+p_{T,b2})/(p_{T,q1}+p_{T,q2})$ (ATLAS tt)

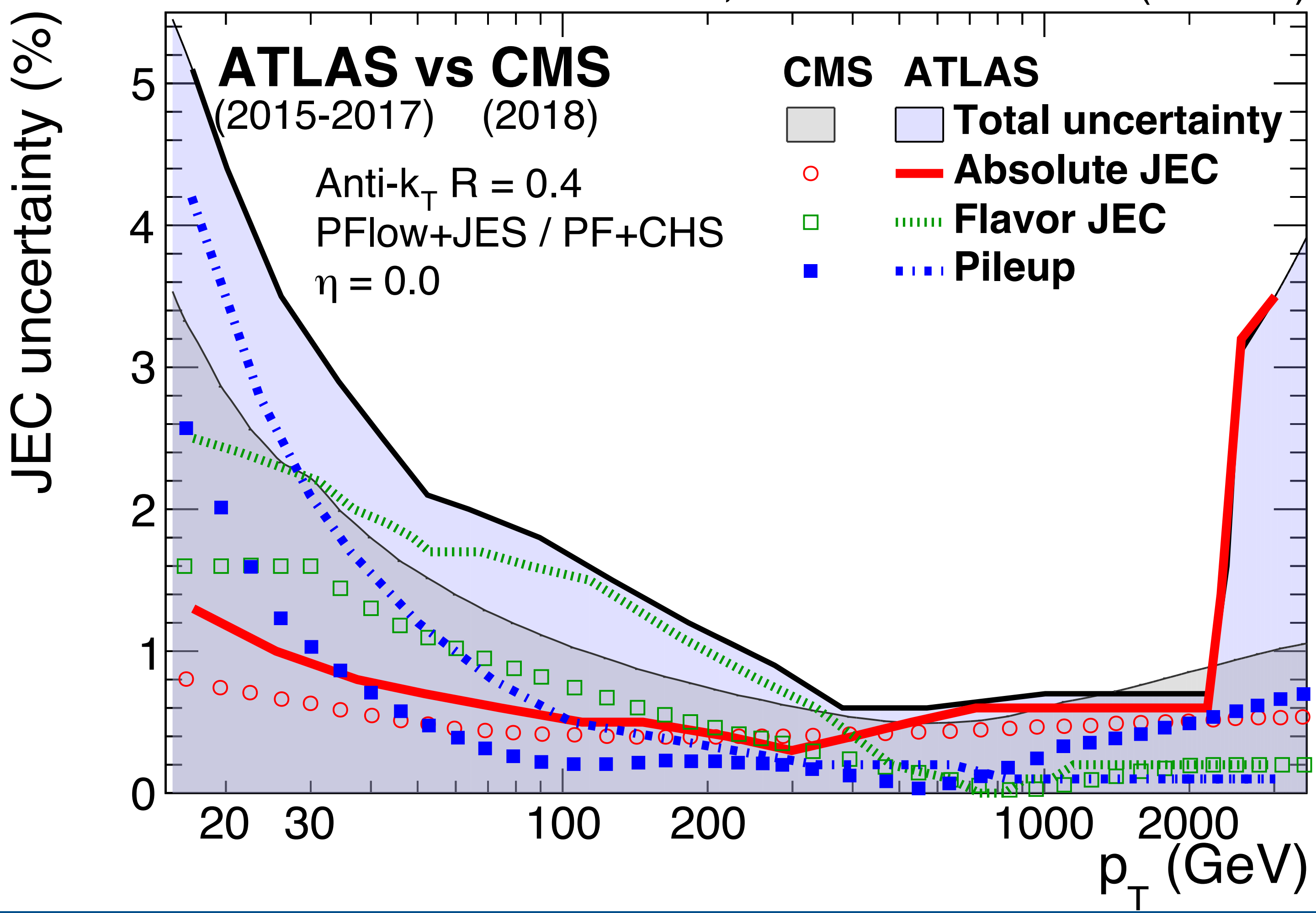




Systematics

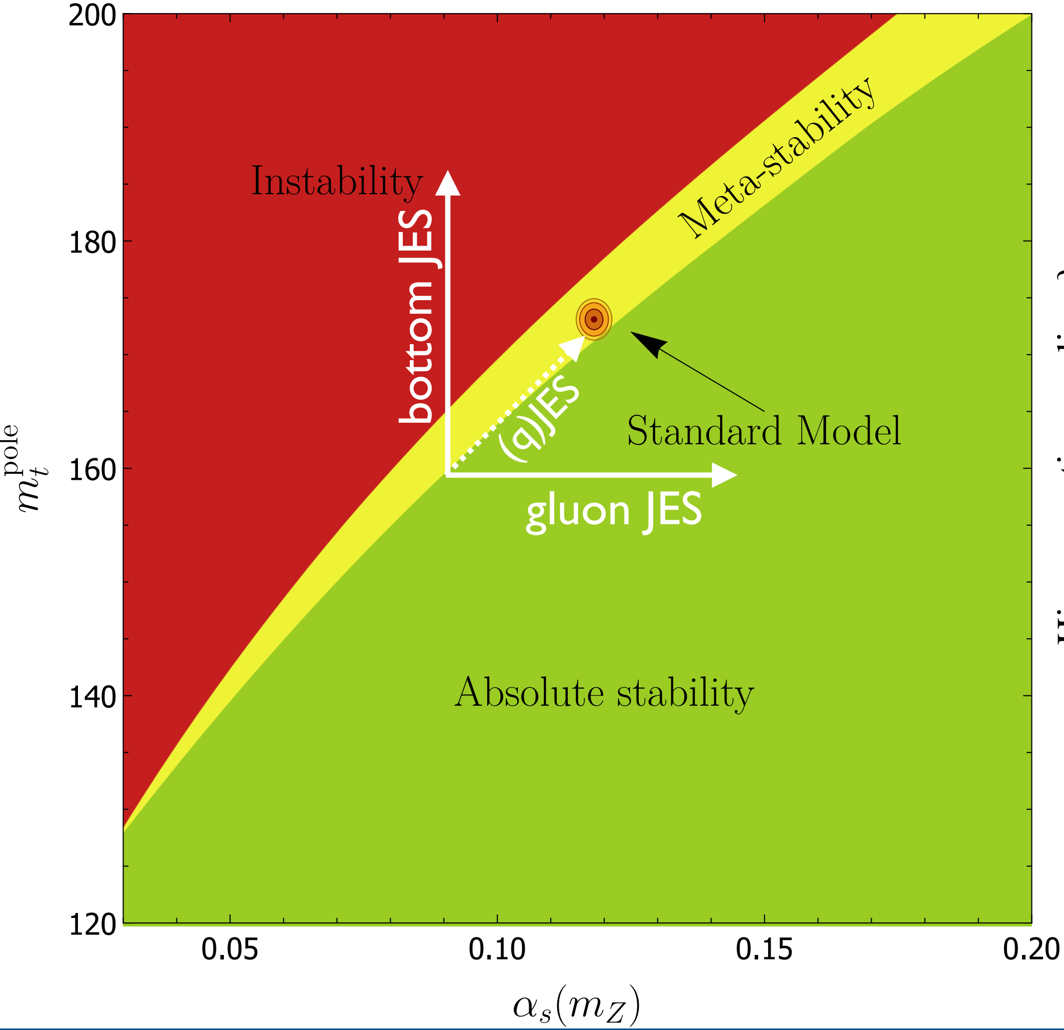
- Leading systematic uncertainty across much of phase space is flavour JEC (gluon JES)
- Absolute scale uncertainties from e, μ, γ scales are ultimately small
  - systematics more FSR, limited statistics and channel inconsistencies (again flavour JES)
- Pileup significant at low p_T, but absorbed into JES in range of Z/γ+jet data (explicit in CMS)

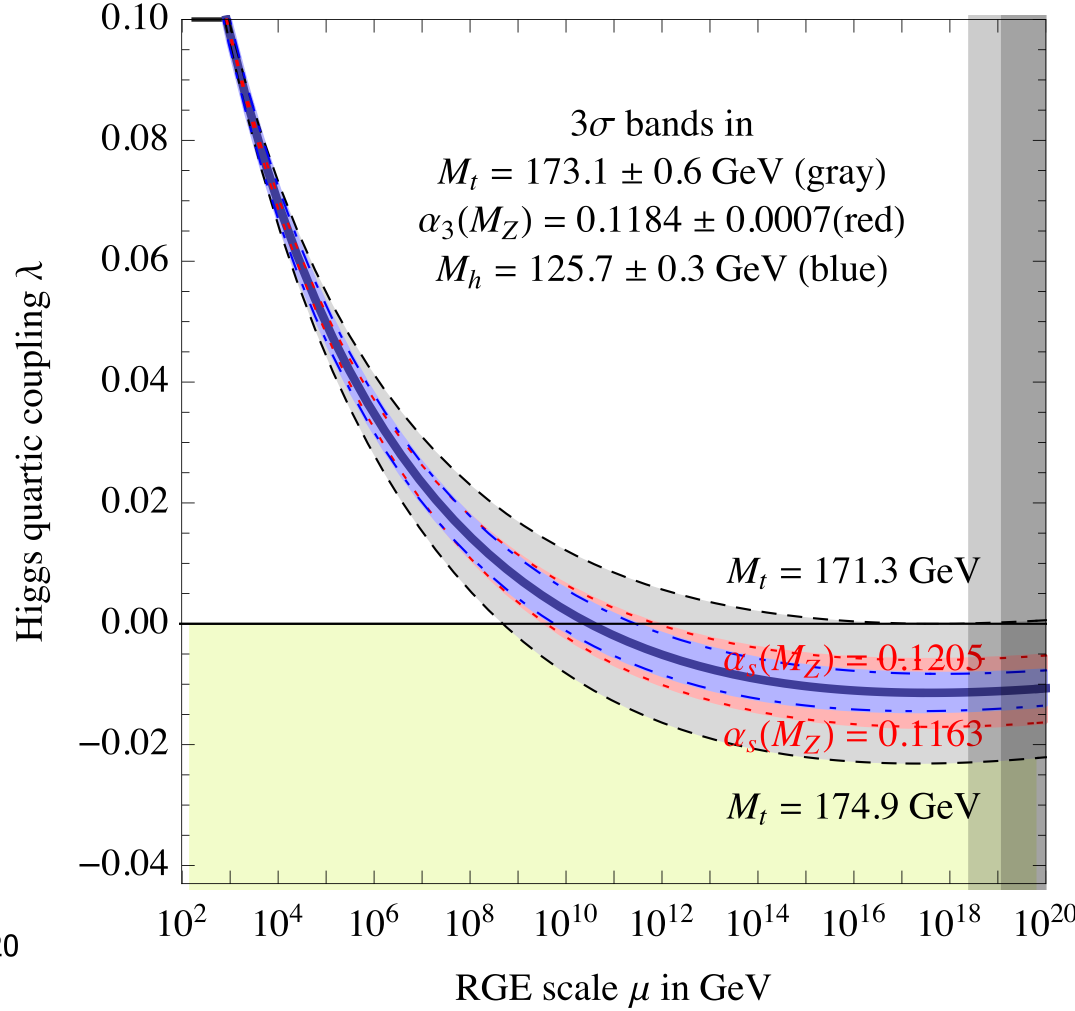
arXiv:2007.02645, CMS-DP-2020-019 (13 TeV)



Impact statement

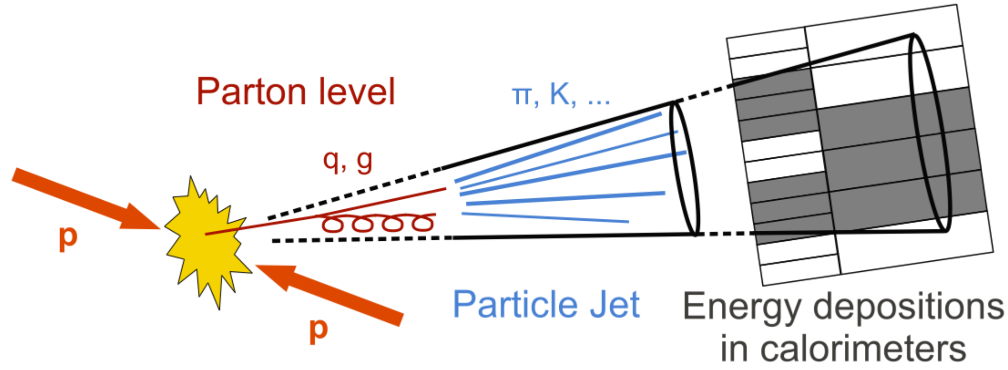
- For vacuum metastability, regular JES would move m_t and α_S along diagonal or cancel out
- Flavor JES can produce non-trivial effects towards or away from stability boundary
  - No (precise enough) LHC measurement from data yet for either b JES or gluon JES
- In absence of new fields and particles, implications on upper scale of vacuum stability

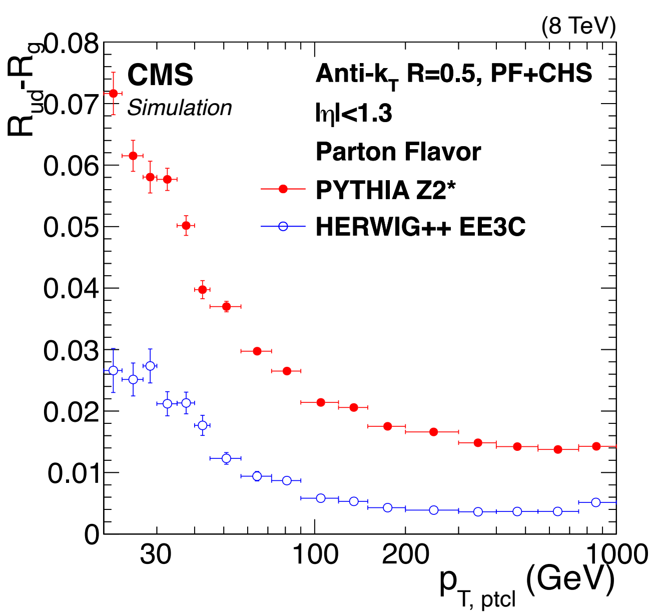


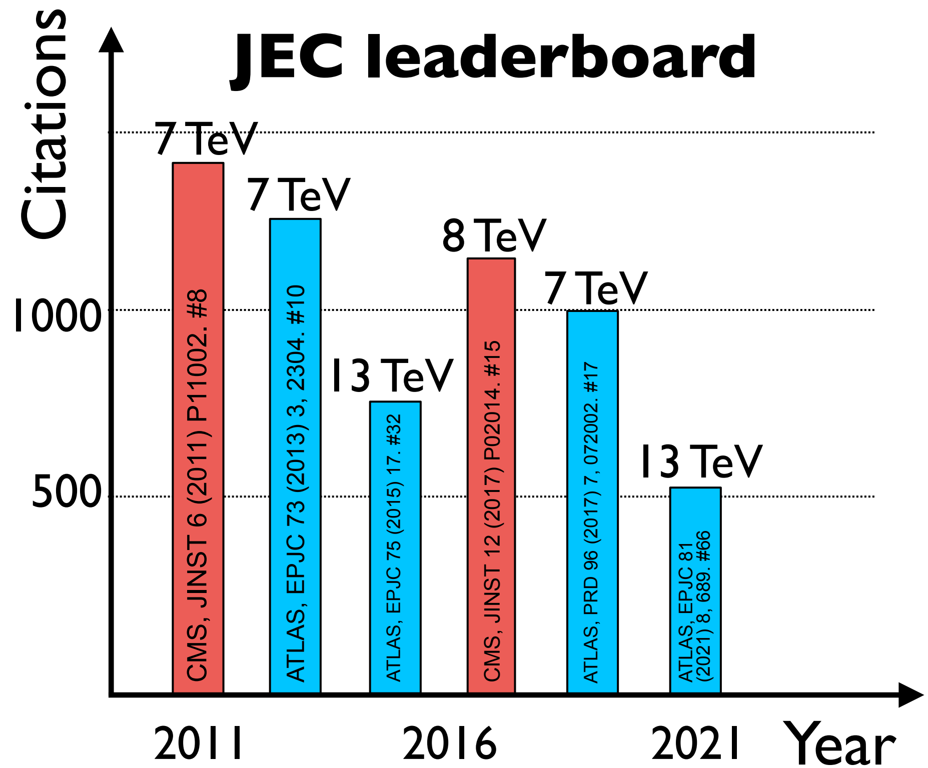


Summary

- Jet energy scale corrects to *particle* level ($c\tau$>1 cm, no ν, ignore ISR+FSR and UE)
- Used across CMS and ATLAS in thousands of analyses with special needs
- Data-based calibration: Zμμ and momentum conservation through MET
  - Dijet, γ+jet, multijet extend phase space
- Open issue: flavour JES
  - Currently based on MC only
  - Particularly gluon JES and b JES important







- Find a way to measure α_S at LHC x2 more precisely than PDG world average in 2024
  - Rules: must compare to NNLO pQCD prediction or higher. Must reduce theory scale uncertainty
  - Can assume (flavour)JES at ultimate 0.1–0.2% level

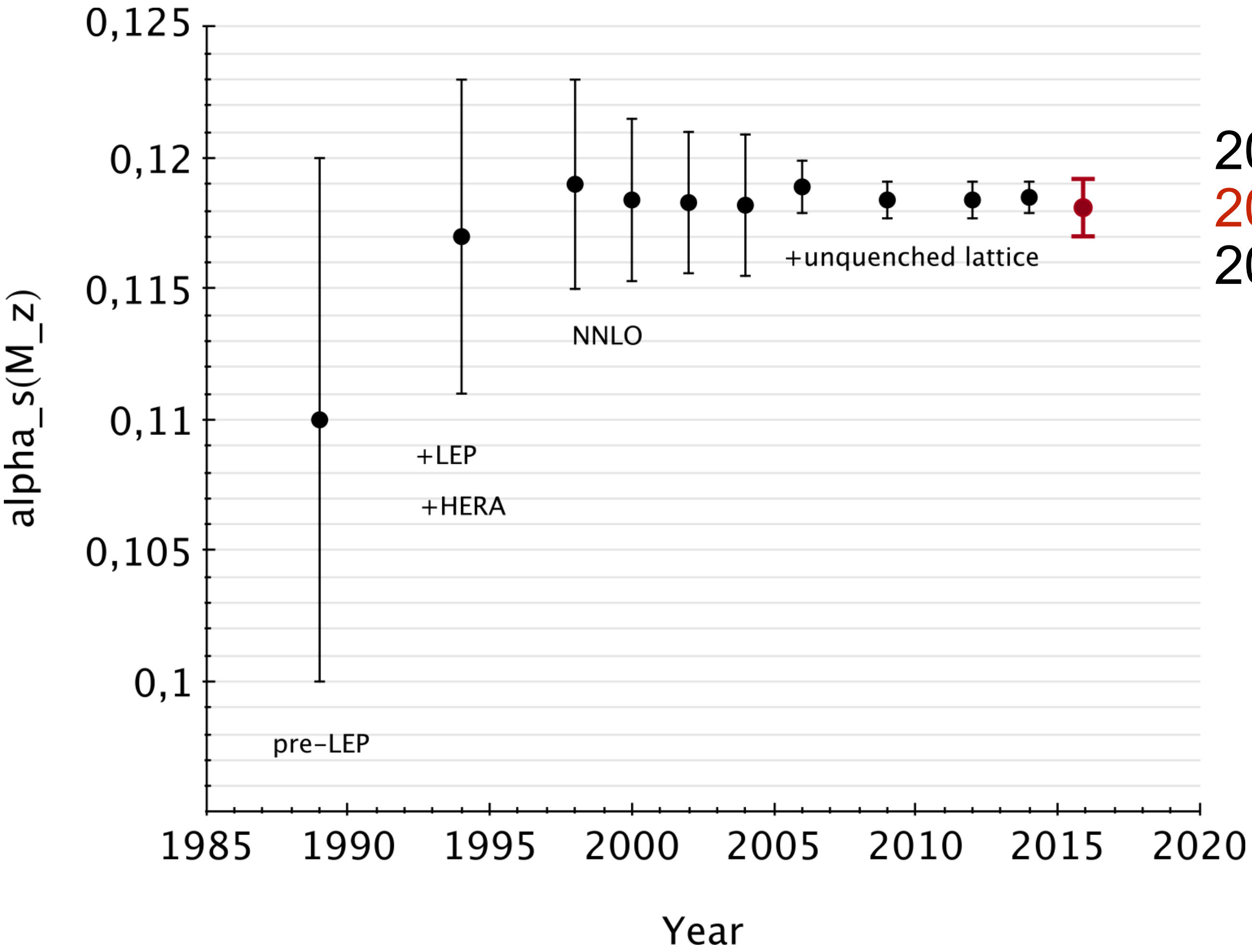
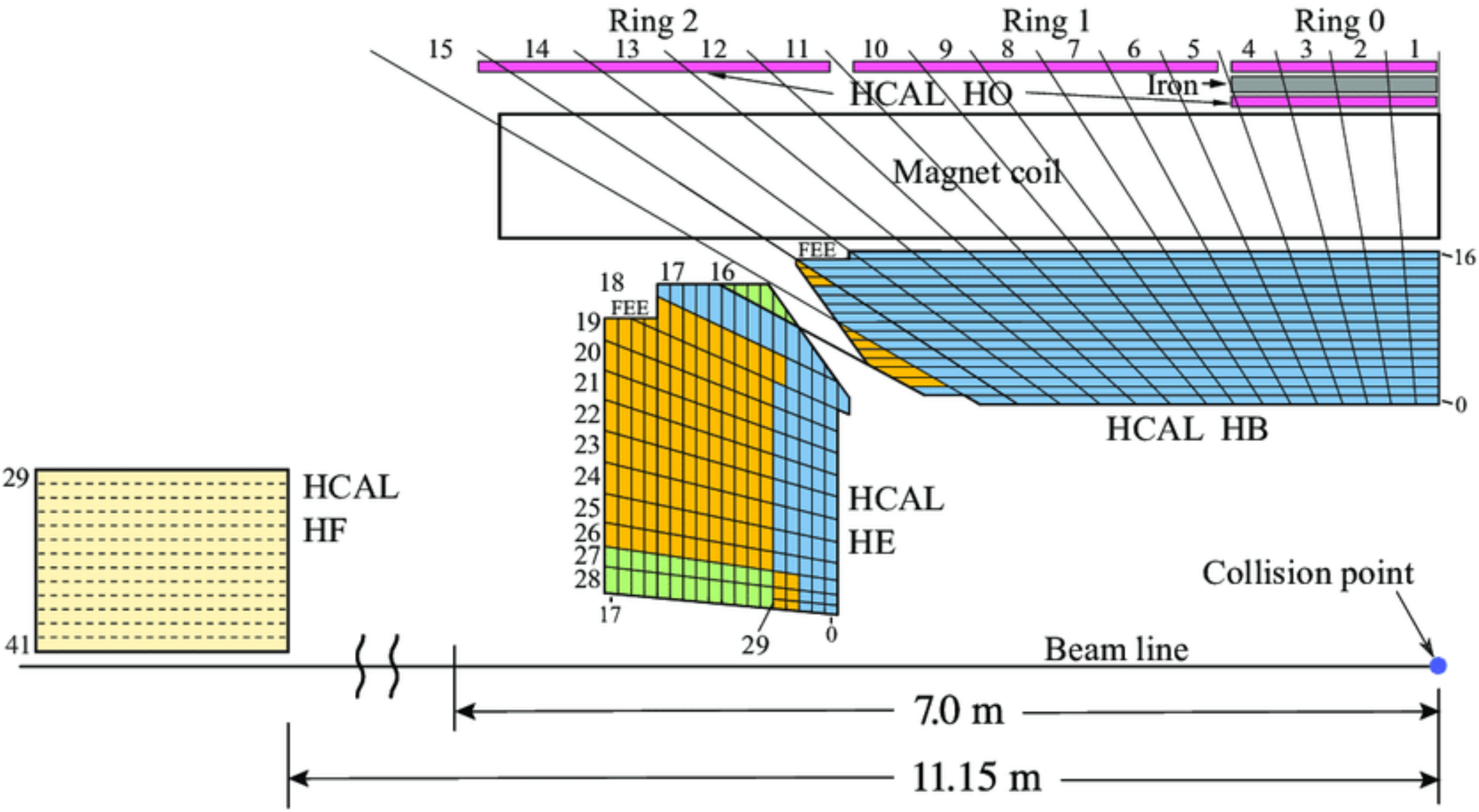


Figure 1: World average values of $\alpha_s(m_z)$ over time.

2015: 0.1185 +/- 0.0006 (0.5%)
2016: 0.1181 +/- 0.0011 (0.9%)
2024: 0.1180 +/- 0.0009 (0.8%)

Backup


Ring 2
Ring 1
Ring 0
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
HCAL HO
Iron
Magnet coil
FEE
16
0
HCAL HB
18 17 16
FEE
19 20 21 22 23 24 25 26 27 28
17
29
0
HCAL HE
29
41
HCAL HF
Collision point
Beam line
7.0 m
11.15 m