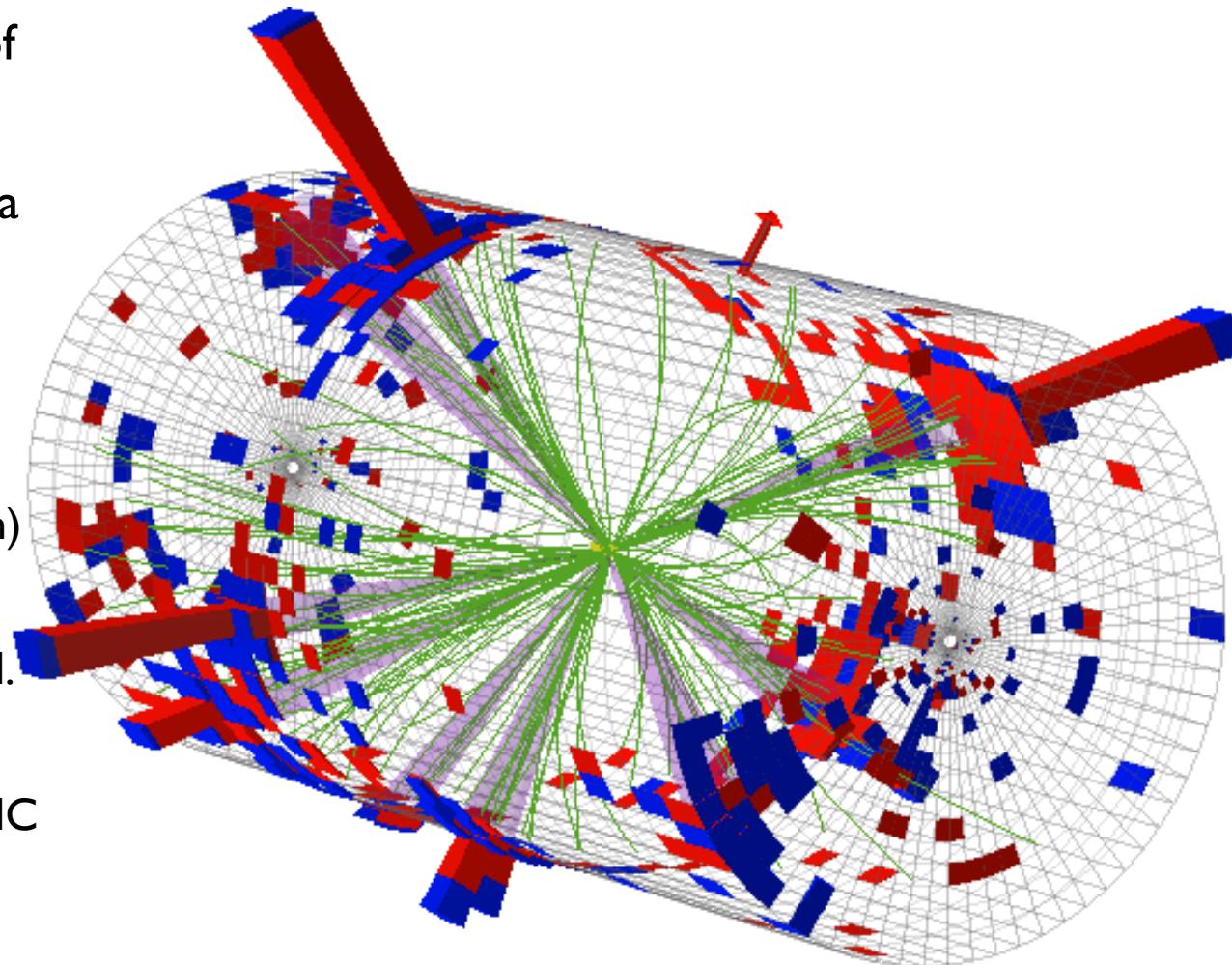




What is a jet?

- Jet is a collimated spray of particles produced by the **hadronization** of a coloured parton
- Parton can be a quark (udscb) or a gluon (or hadronic tau decay)
- Topics I will cover today:
 - ▶ Parton shower
 - ▶ Hadronization (inlc. jet composition)
 - ▶ Jet clustering
 - ▶ Particle Flow / Global sequential cal.
 - ▶ Pileup Removal
 - ▶ Jet energy scale and resolution in MC
 - ▶ JEC and JER from data
 - ▶ Heavy flavor jets
 - ▶ Quark/gluon likelihood
 - ▶ Inclusive jet cross section
 - ▶ Top mass with lepton+jet

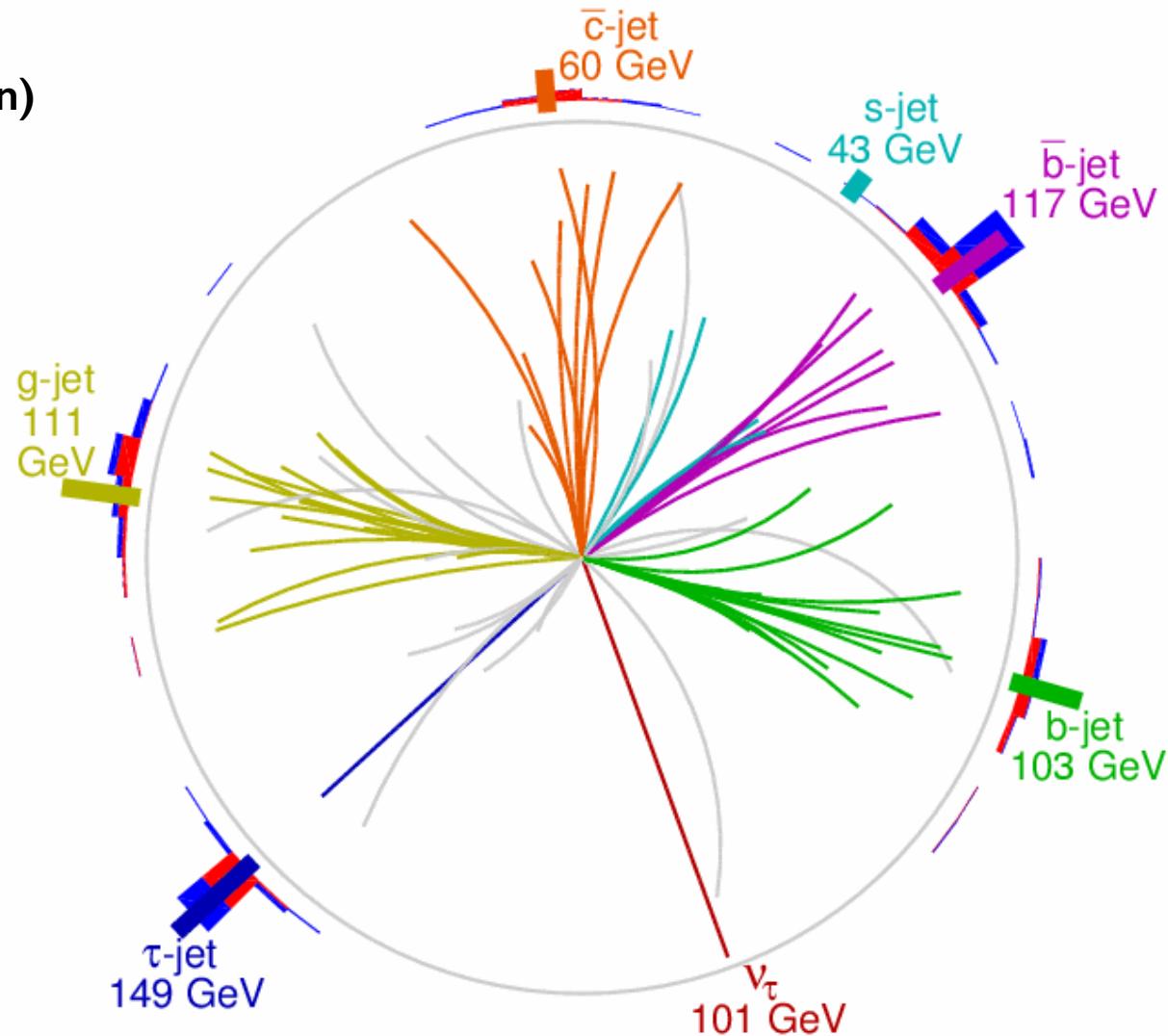


But first, anatomy of a jet

- [Click here for an in-depth anatomy tour](#)

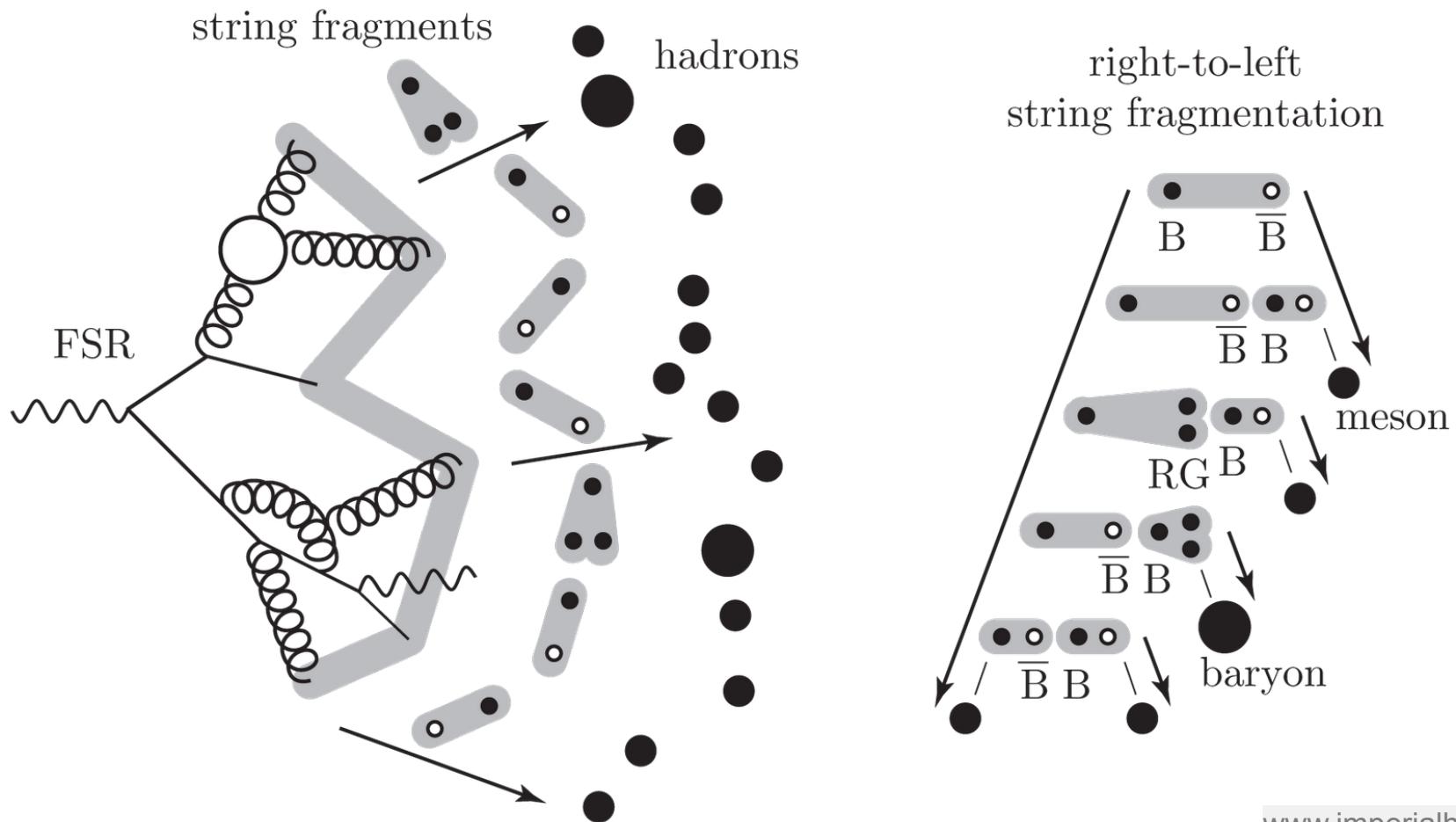
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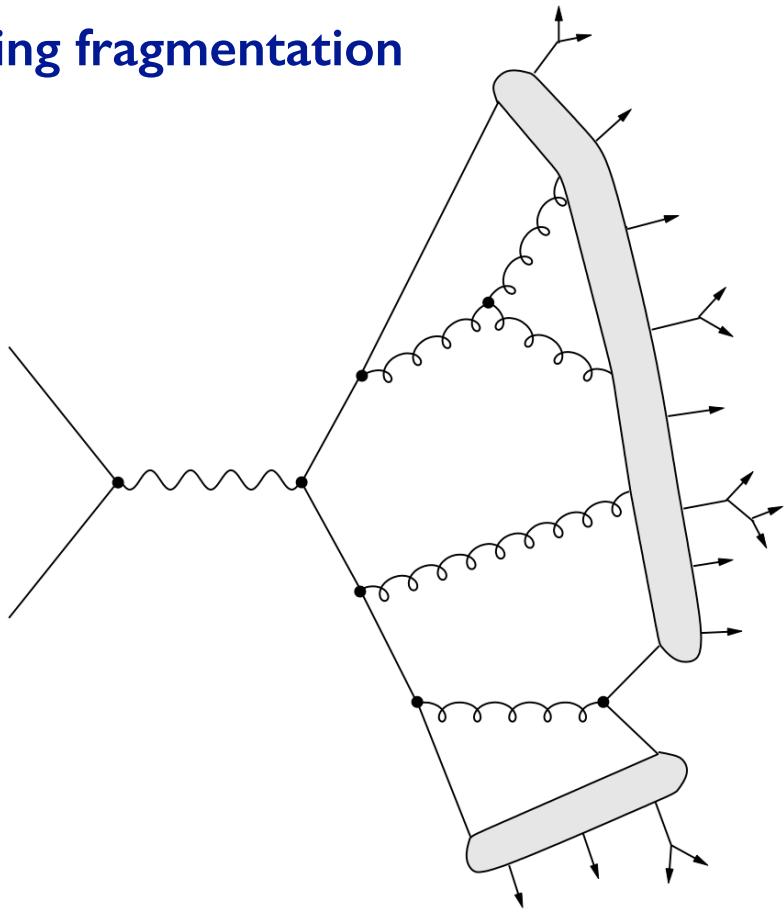
$gg \rightarrow tbH^+, t \rightarrow Wb \rightarrow scb, H^+ \rightarrow \tau\nu \rightarrow \text{hadrons}$ with a radiative gluon jet

- Parton shower approximates missing perturbative orders of matrix element (often LO)
 - ▷ missing orders by generating a shower of gluon emissions and $g \rightarrow q\bar{q}$
 - ▷ early hard, wide-angle gluon emissions create **additional jets in the event**
- Hadronization handles fragmenting the shower partons to hadrons
 - ▷ e.g. Lund string model (below)

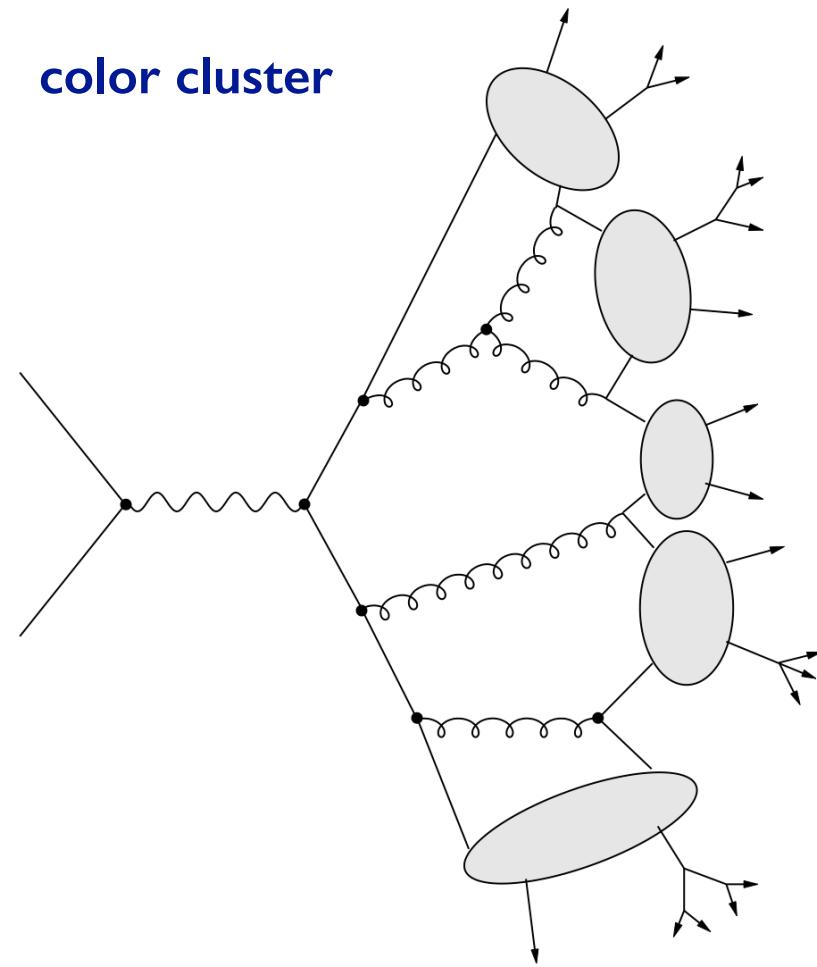


- Two leading hadronizations models: Pythia string fragmentation and Herwig color clusters
 - ▷ String model imagines $q\bar{q}$ connected by a gluonic string that breaks as quarks fly apart
 - ▷ Herwig splits each PG gluon to a $q\bar{q}$ pair that are then clustered to color singlets
- Affects the energy distribution and type of hadrons produced, i.e., **jet response**

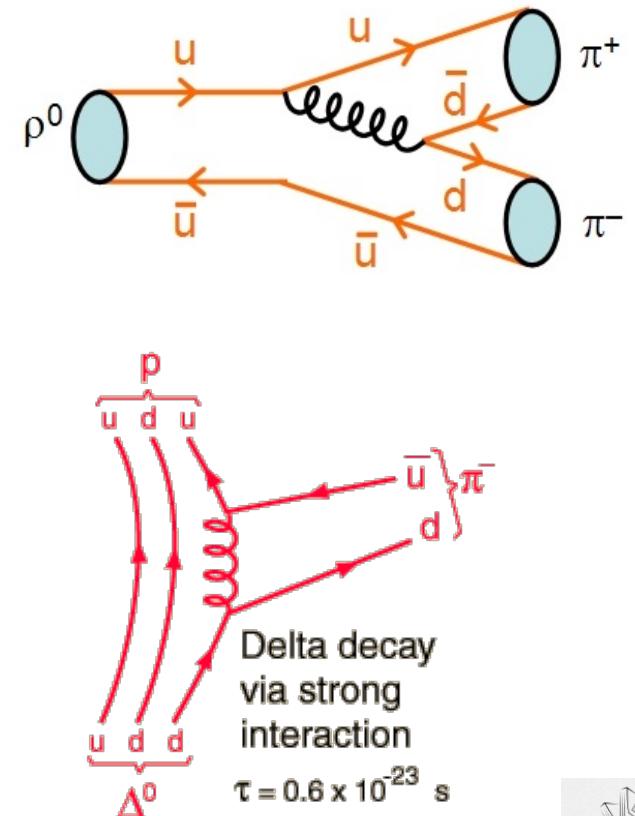
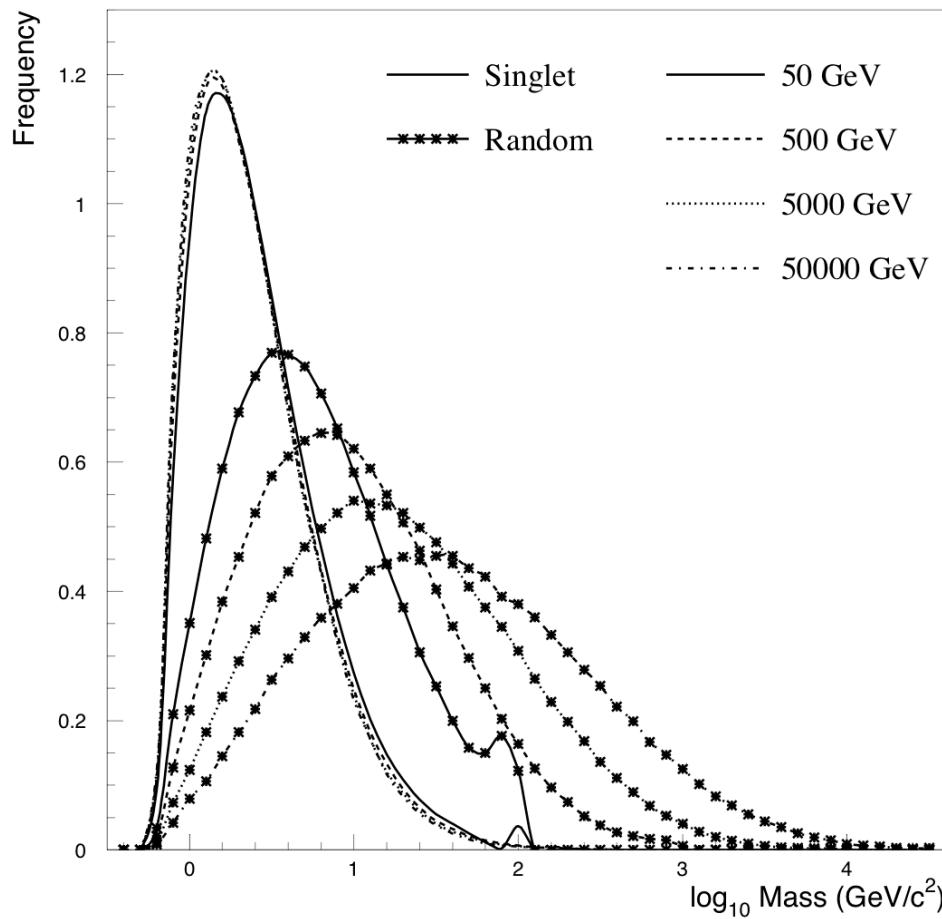
string fragmentation



color cluster

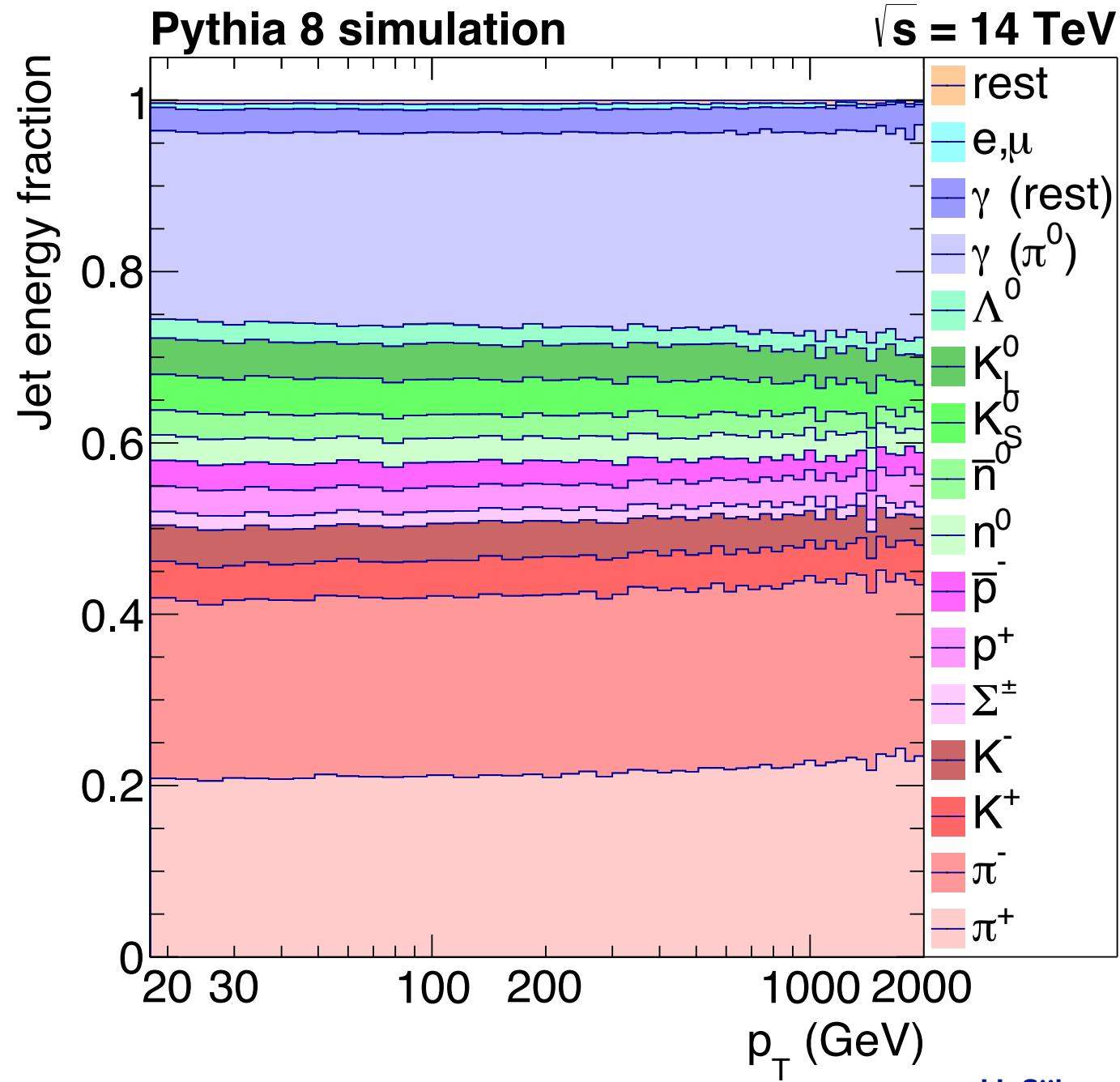


- Pythia and Herwig generate a range of masses, which result in many excited states
- Final step decays these into more stable pions, kaons etc. using PDG tables
 - ▷ a few have life times of order $c\tau \sim 1$ mm and can be left for later simulation stages (e.g. K_s , B)
 - ▷ most of states listed in '**Review of Particle Physics**' (**PDG**) actually used



Jet composition

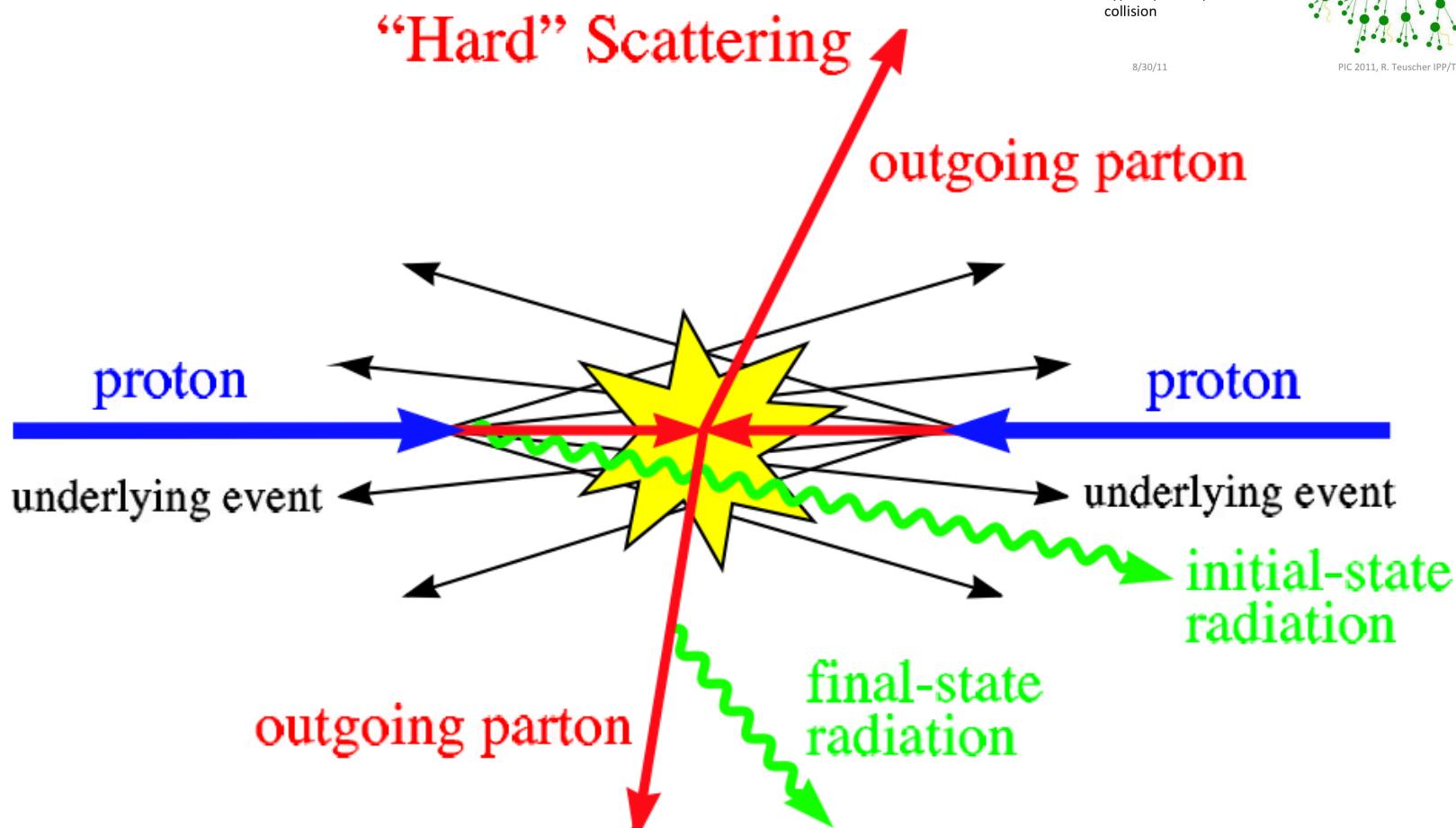
- As a result of decays of excited states, most of the jet is composed of familiar pions, kaons and nucleons
 - neutral pions immediately decay to photon pair
- Rough proportions:
 - pions: 65%
 - kaons: 15%
 - nucleons: 12%
 - rest ($\Lambda^0, \Sigma^\pm, e, \mu, \dots$): 8%
- Neutral-to-charge ratios in proportion to possible particle types:
 - pions 1:2
 - kaons 2:2
 - nucleons 2:2
 - averaged neutral-to-charge about 2:3 (60% charged)



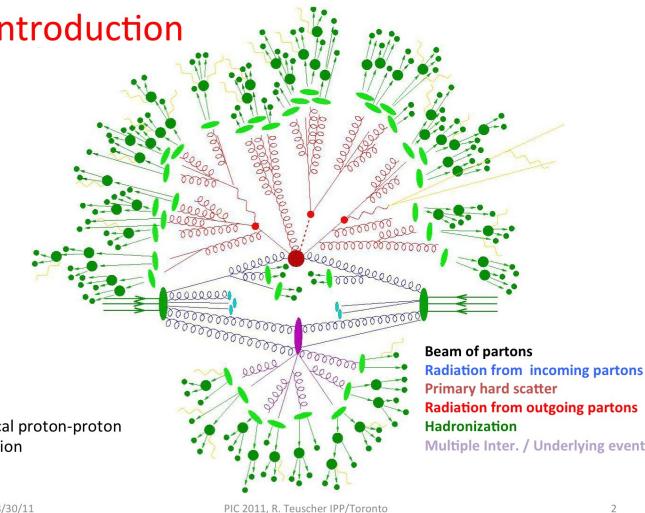
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Soft stuff

- Proton-proton collisions are messy, and jets also contain particles from additional soft parton interactions
 - ▷ aka “Underlying event” (UE)
- Adds a diffuse, fairly homogeneous offset to jets
 - ▷ “pileup” (PU) is tens of low-scale UE on top of each other

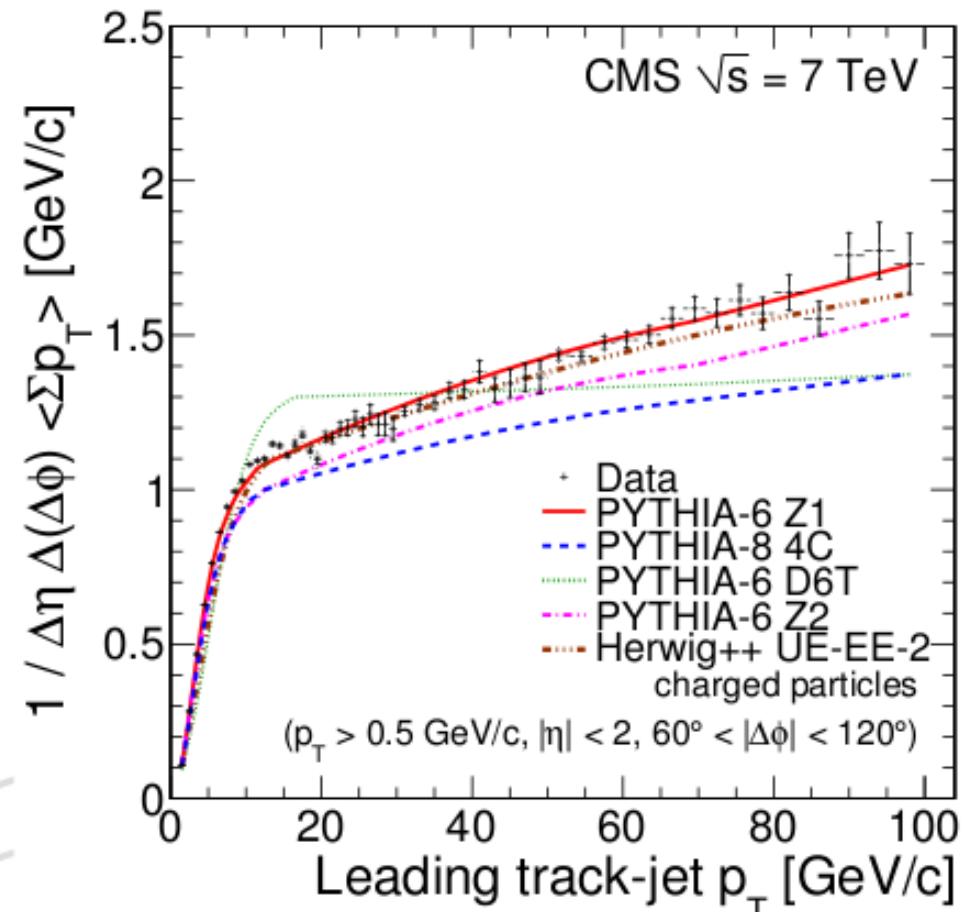
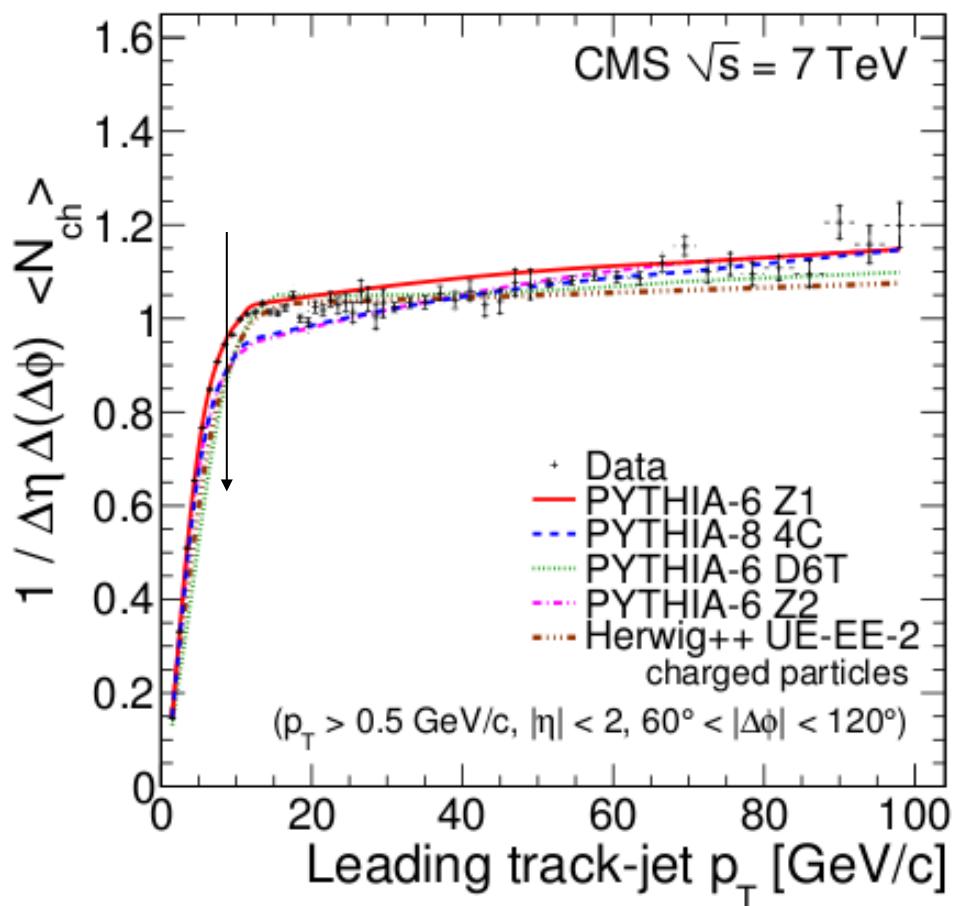


Introduction

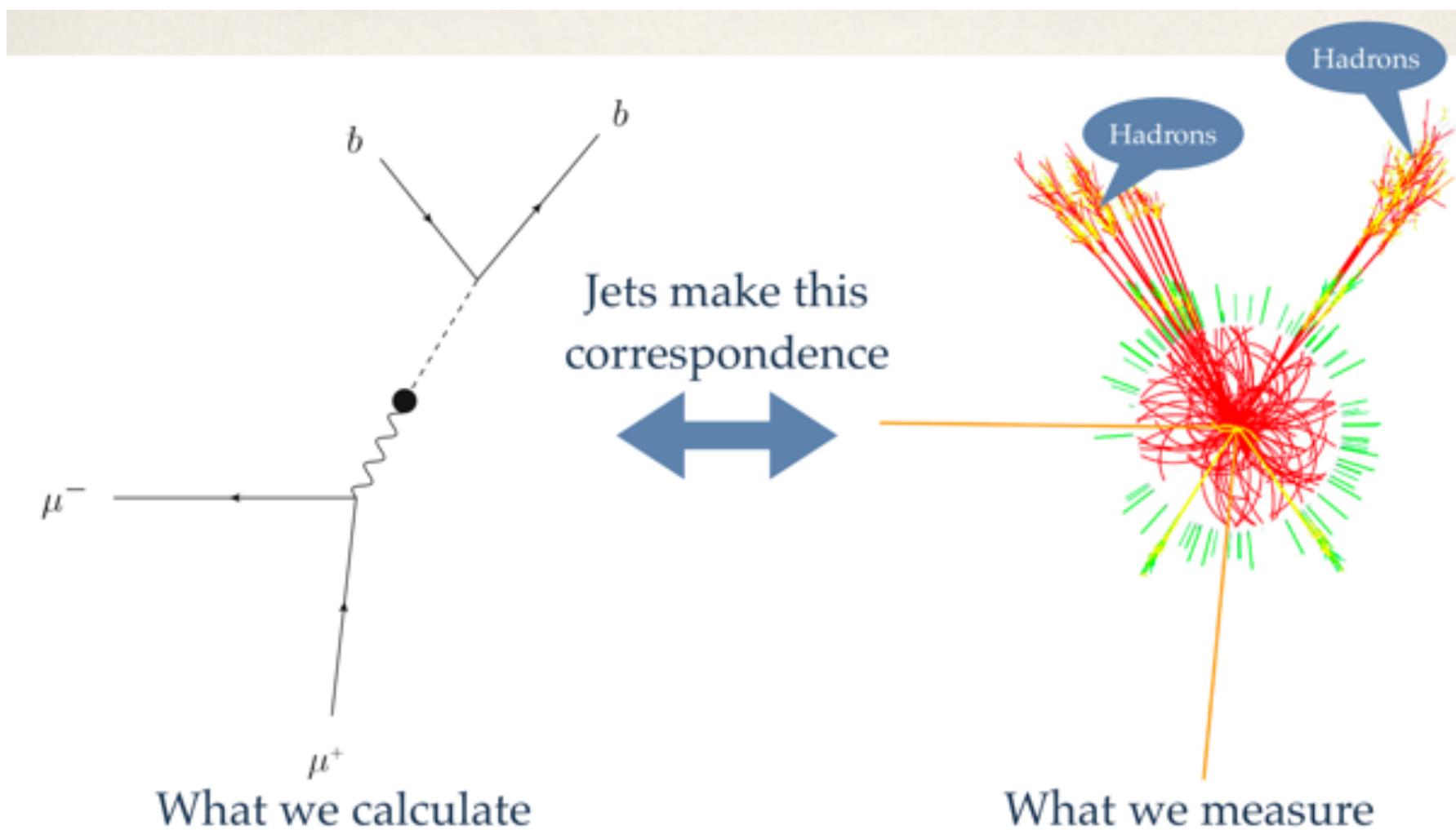


Underlying event

- Underlying event (UE) for Minimum Bias events is the basis of simulating pileup
 - ▷ Careful tuning of Pythia6 to LHC UE at CMS (Z1,Z2,Z2*) and ATLAS (AMBT)
 - ▷ Herwig tunes not quite as elaborate for MinBias (rising edge)
- UE quickly saturates for hard collisions ($p_{T,\text{ch-jet}} > 10 \text{ GeV}$, or $p_{T,\text{jet}} > 15 \text{ GeV}$)
 - ▷ slow rise on the plateau is due to additional jets in transverse region

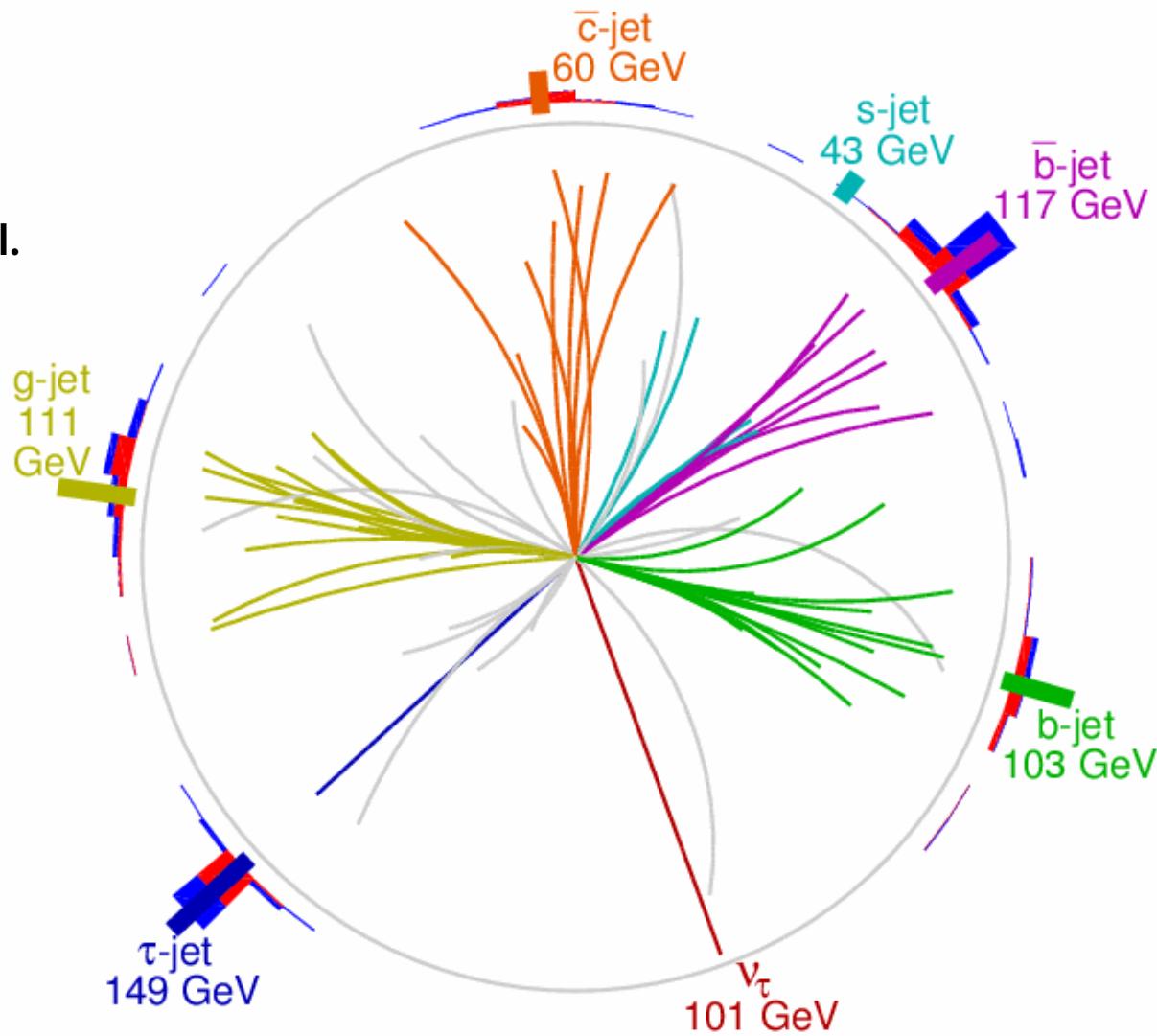


- What we have is a bunch of measured hadrons
- What we want is a couple of partons
- Now, try to invert this relation, taking into account all the nasty detector effects



Jet reconstruction

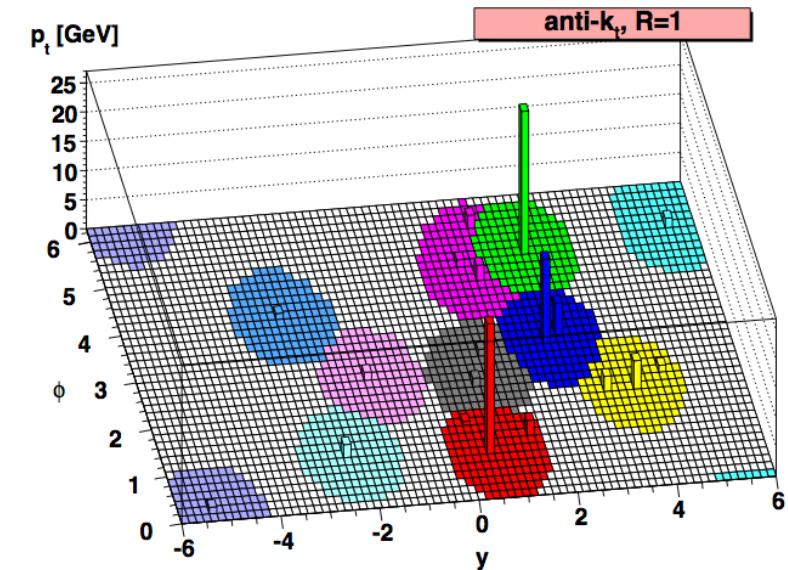
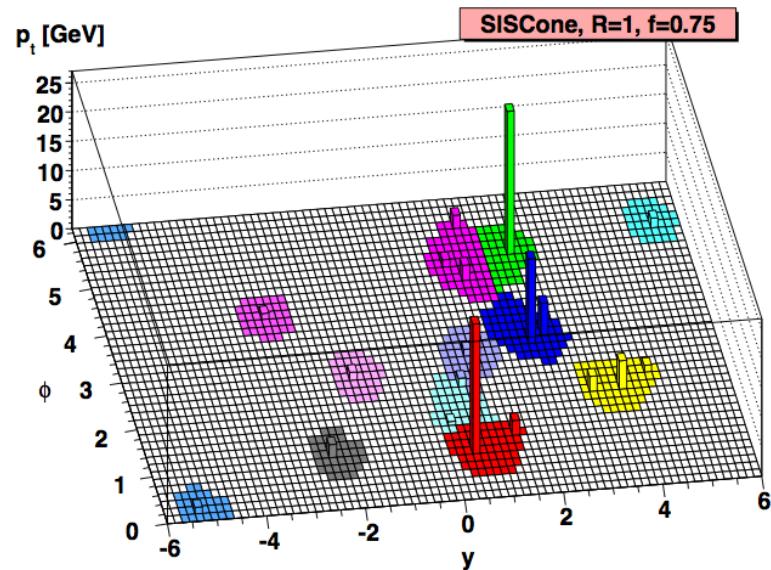
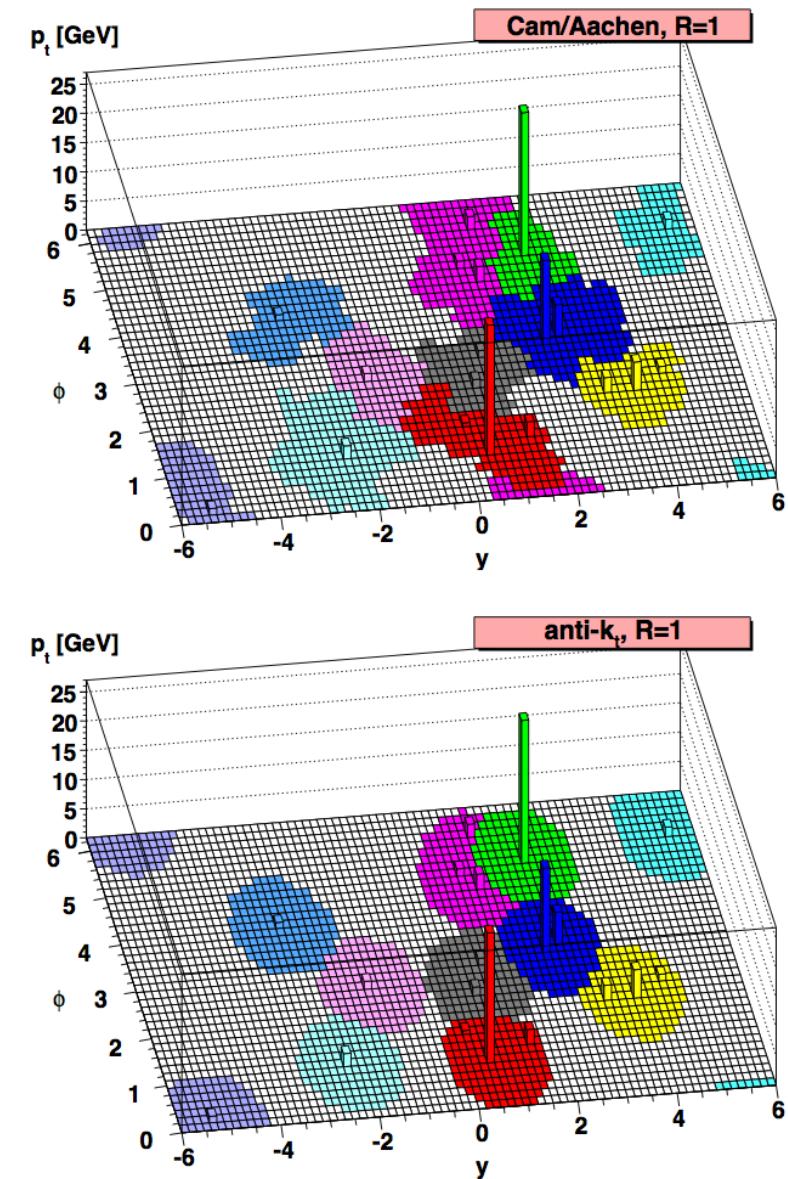
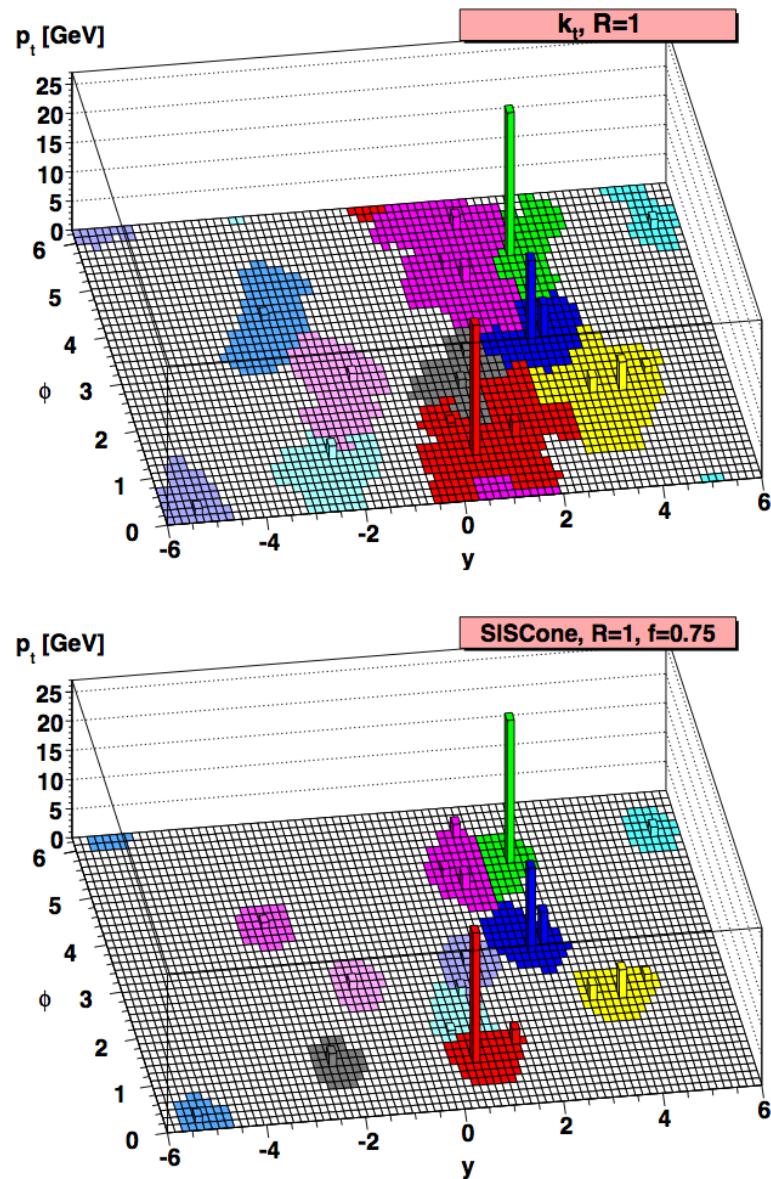
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$gg \rightarrow tbH^+, t \rightarrow Wb \rightarrow scb, H^+ \rightarrow \tau\nu \rightarrow \text{hadrons}$ with a radiative gluon jet

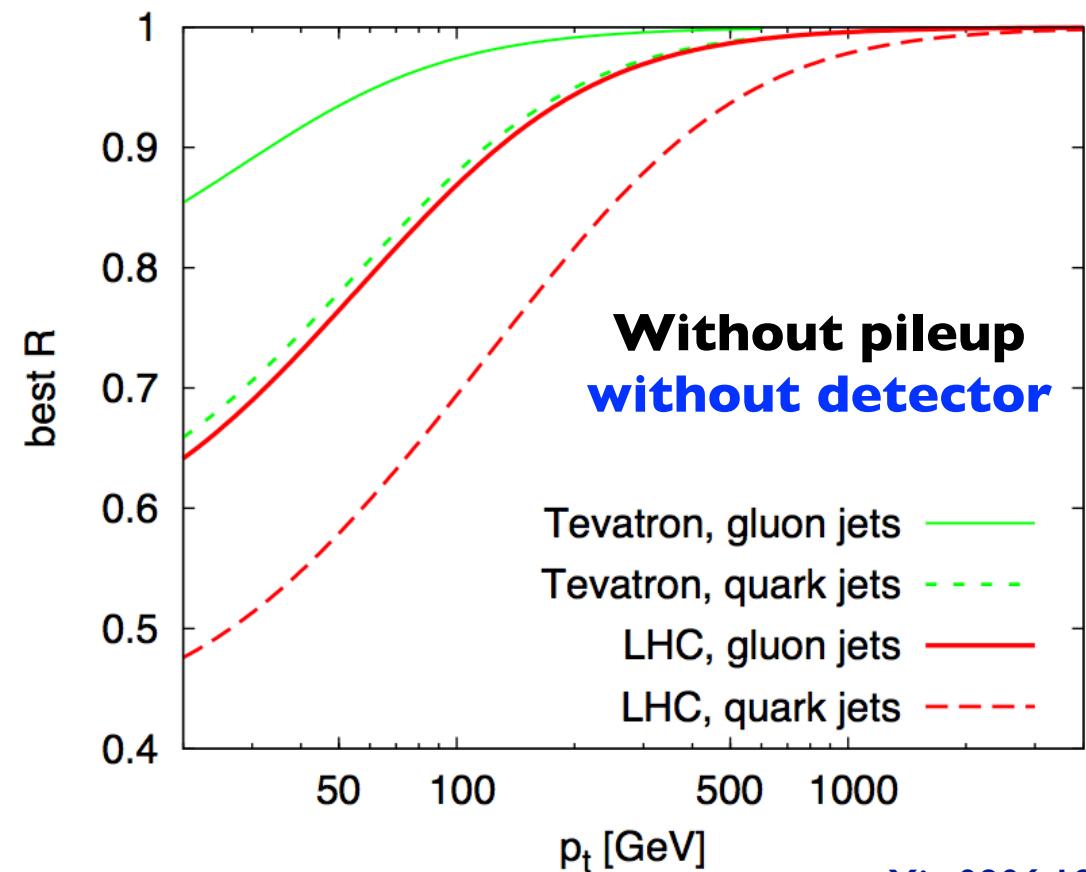
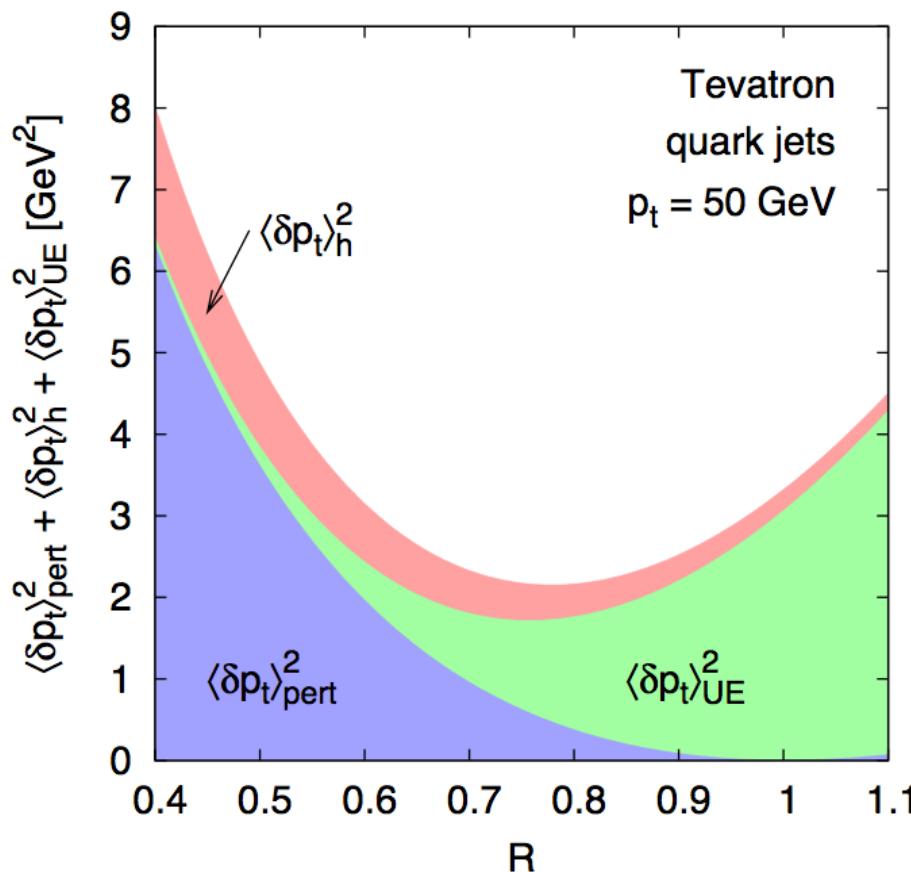
Jet clustering

- Snowmass: infrared and collinear safety
- Sequential recombination: merge particle 4-vectors in pairs
- k_T : softest 1st, invert parton shower
 - ▷ LHC: clusters pileup
 - ▷ favoured at e^+e^-
- **anti- k_T** : hardest 1st, catch early FSR
 - ▷ “cookie-cutter”, favours leading jets
 - ▷ **default at LHC**
- CA: nearest 1st, keep substructure



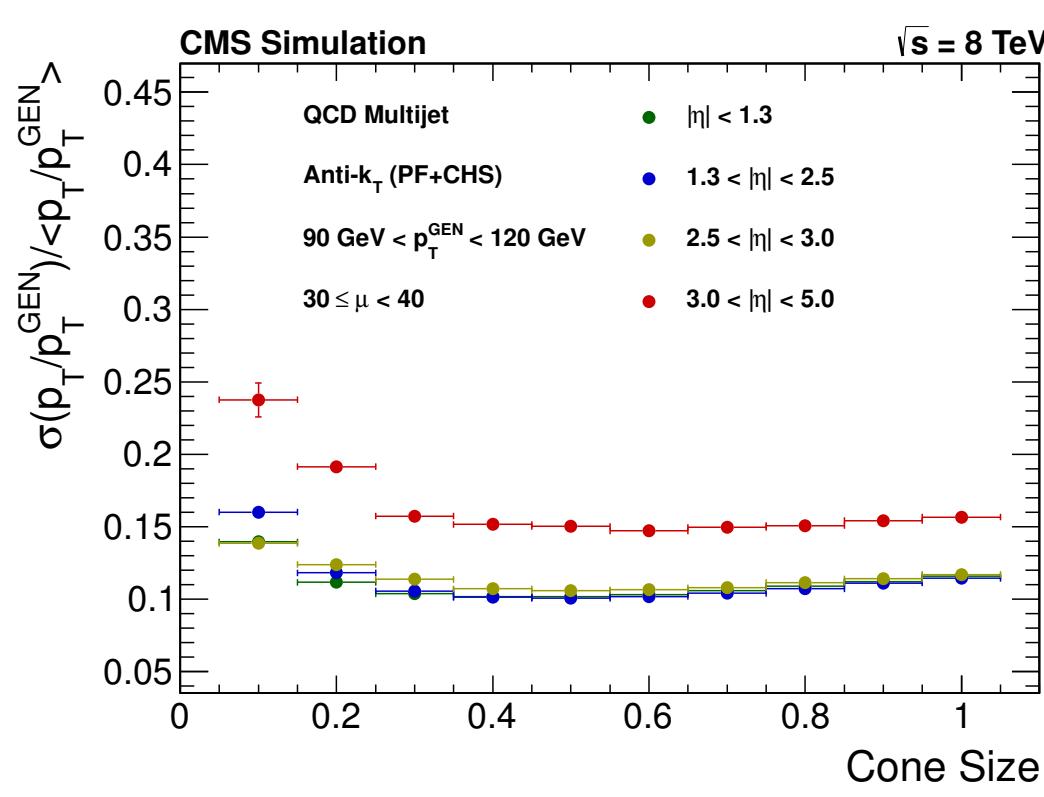
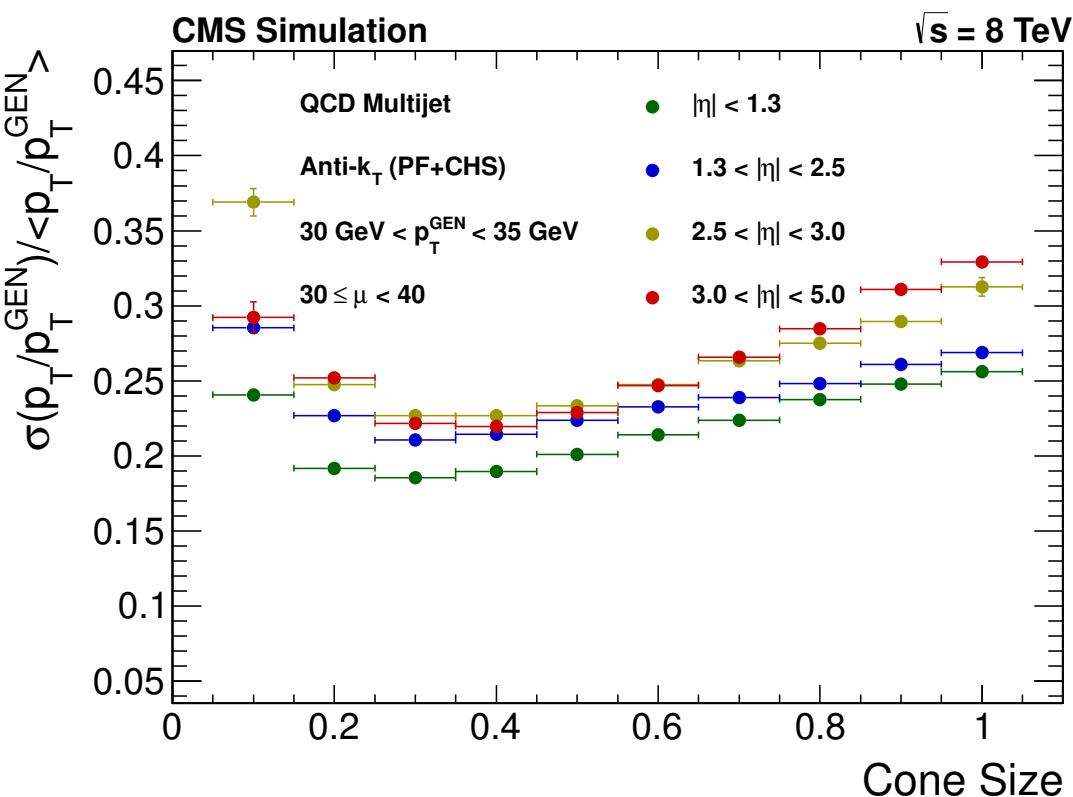
Optimal R - gen

- Optimal jet radius R interplay between out-of-cone (-) and offset (+)
- Out-of-cone: hadronisation, perturbative radiation (FSR), magnetic field and granularity
 - ▷ very approximately proportional to $p_T \times \ln(R)$ for $R < 1$
 - ▷ gluon jets favor larger cones due to FSR
- Offset: underlying event (UE), pileup (PU)
 - ▷ proportional to $R^2 \times \langle N_{PU} \rangle$

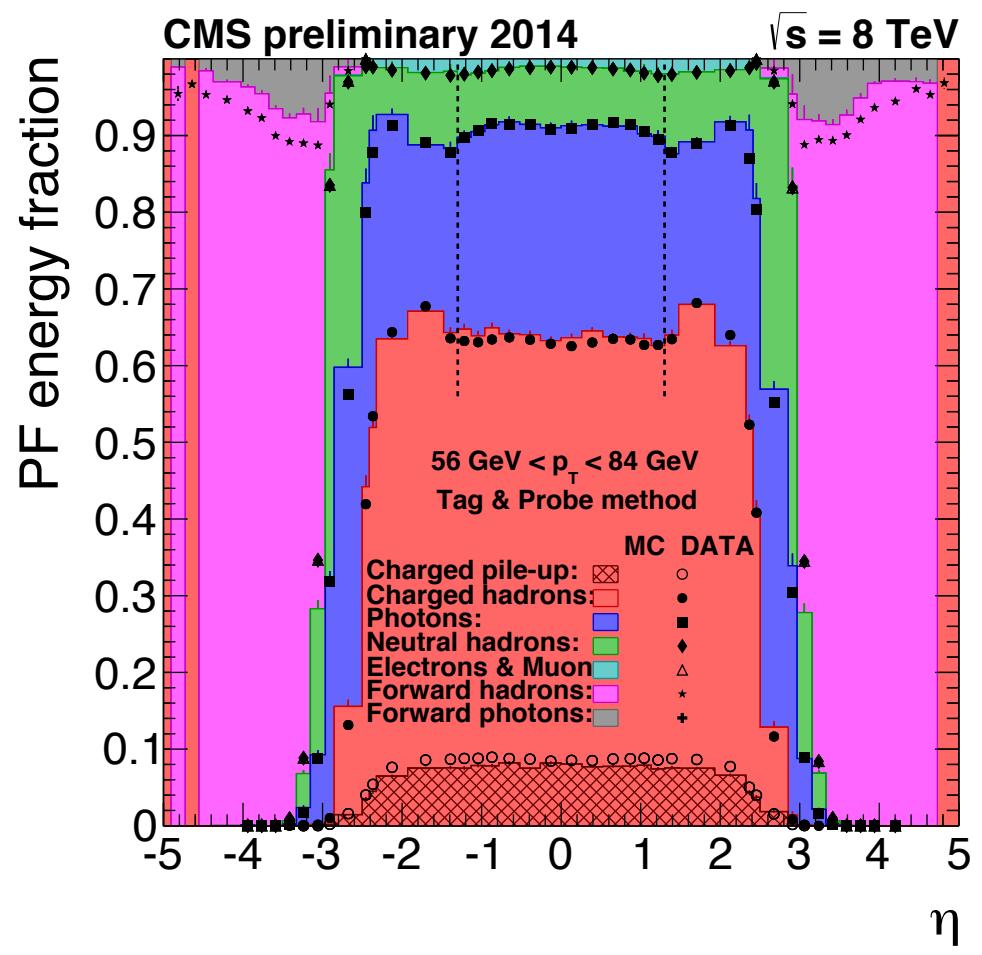
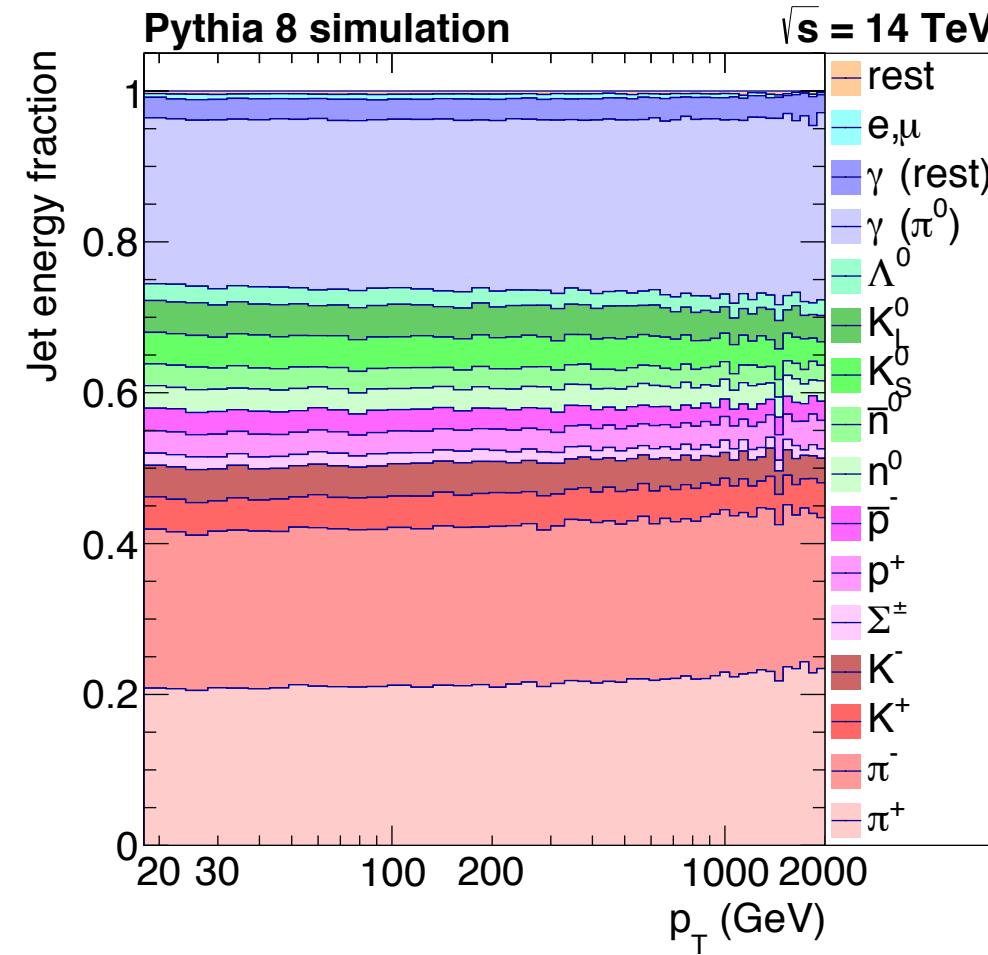
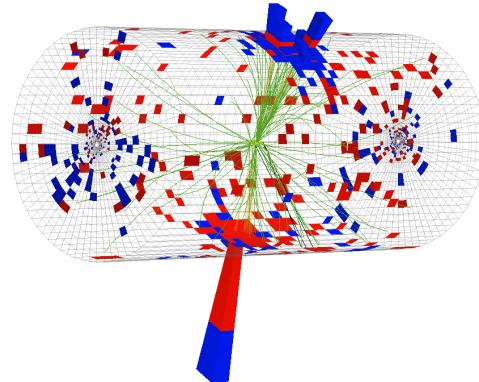


arXiv:0906.1833

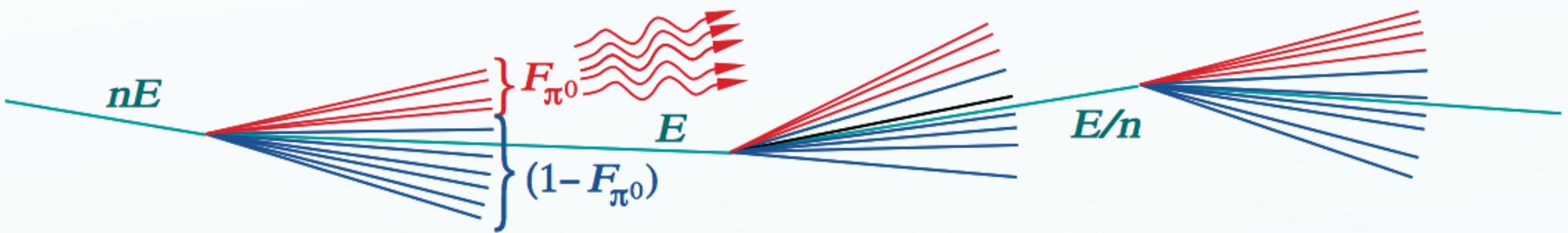
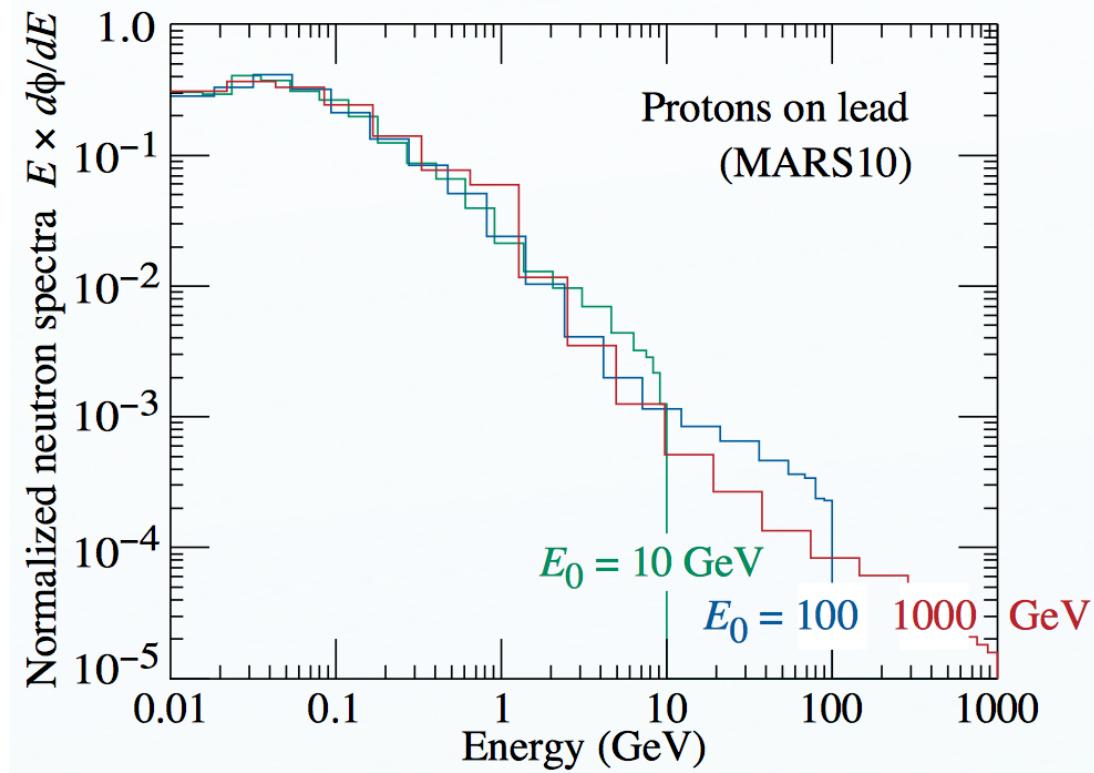
- At the LHC, pileup tips the balance toward small cone sizes
 - ▷ ATLAS: $R=0.4$ and 0.6
 - ▷ CMS: $R=0.5$ and 0.7 (moving to $R=0.4$ and 0.8)
- Larger radii ($R=0.8, 1, 1.2$) used for substructure, with grooming
- Smaller radii ($R=0.2, 0.3$) used in heavy ion collisions with extreme UE



- From MC generator to reconstructed particles
 - charged hadrons** (60-65%): tracks
 - photons** (25%): non-linked (“isolated”) ECAL clusters
 - neutral hadrons** (10-15%): non-linked HCAL clusters
- Neutral hadrons (n, K_L, Λ) the main challenge



- D. E. Groom: A Simplistic View of Hadron Calorimetry [FNAL colloq.] - great talk!
 - ▷ Idea 1: most energy deposited by the final soft particles with universal spectrum
 - $A(nE) = n A(E)$
 - ▷ Idea 2: hadron shower response driven by h/e differences in ionisation efficiency
 - thus, only fractions f_e and f_h matter
 - typically $h(\text{hadronic}) \ll e(\text{electromagnetic})$
 - ▷ Idea 3: each step of nuclear interactions removes 1/3 of hadrons
 - ($\pi^0 \rightarrow \gamma + \gamma$; γ shower detected with 100% eff.)
 - the more steps we have, the lower f_h we get



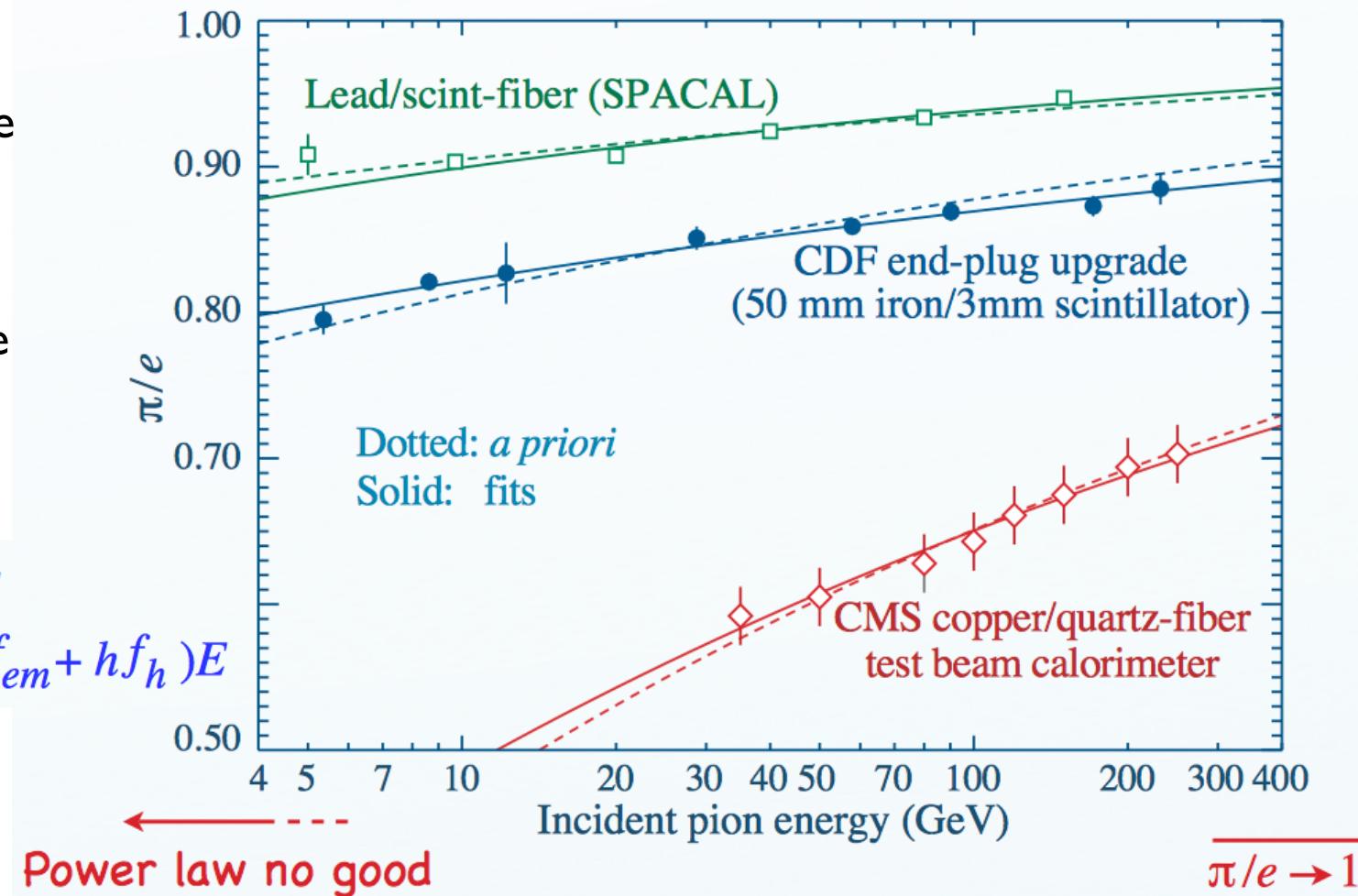
D.E. Groom

Hadron response

- Plugging in I–3 we find a **power law**
- Approaches EM response asymptotically at high p_T
- Different factors in coefficient ‘ a ’ not experimentally accessible
=> fit

electron response (“ e ”) = eE

pion response (“ π ”) = $(ef_{em} + hf_h)E$



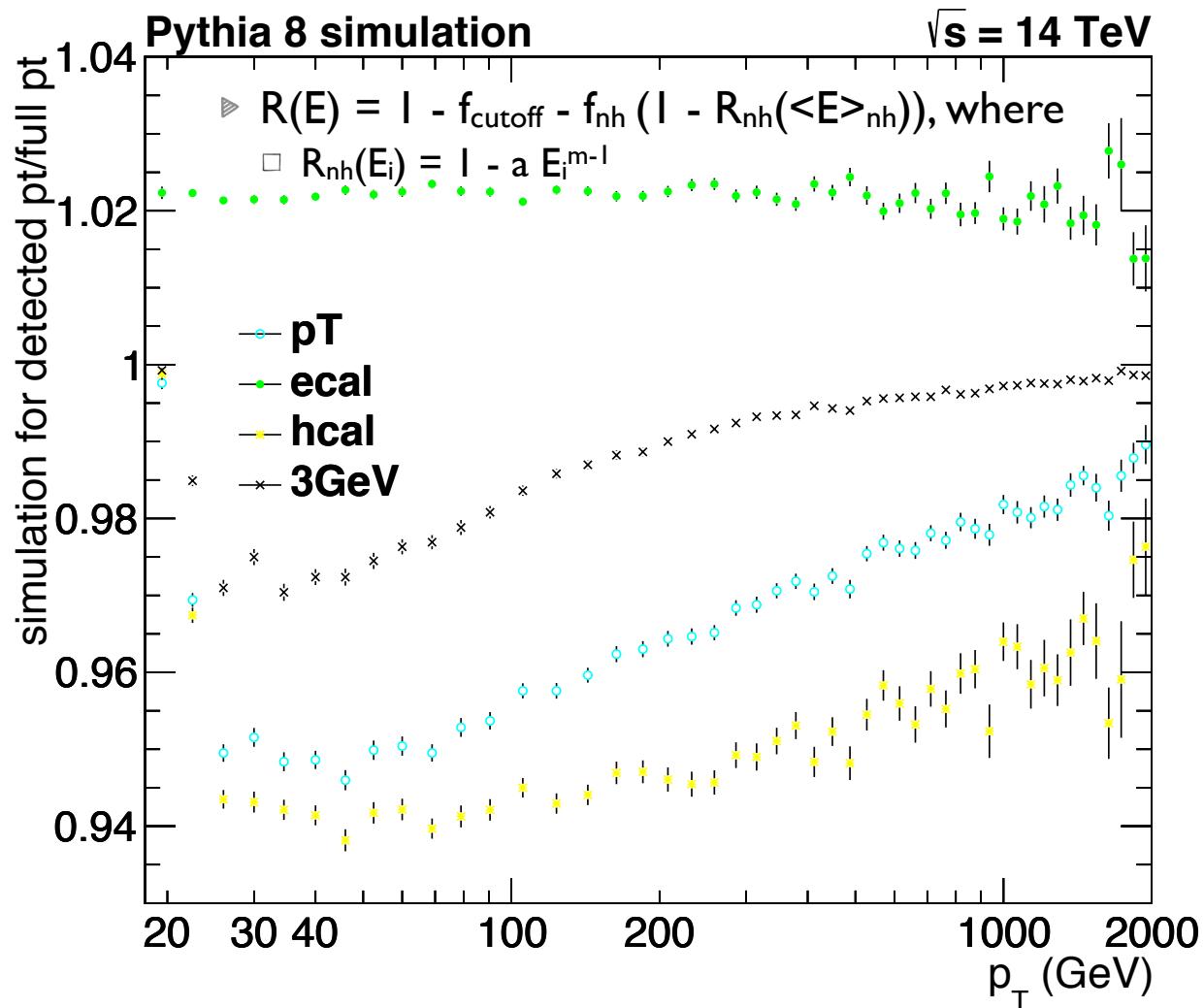
Power law no good

$$\begin{aligned} \text{“}\pi/e\text{”} &= 1 - [(1 - h/e)(1 - f_\gamma)/E_0]^{m-1} E^{m-1} \\ &\equiv 1 - a E^{m-1} \end{aligned}$$

D.E. Groom

Jet response

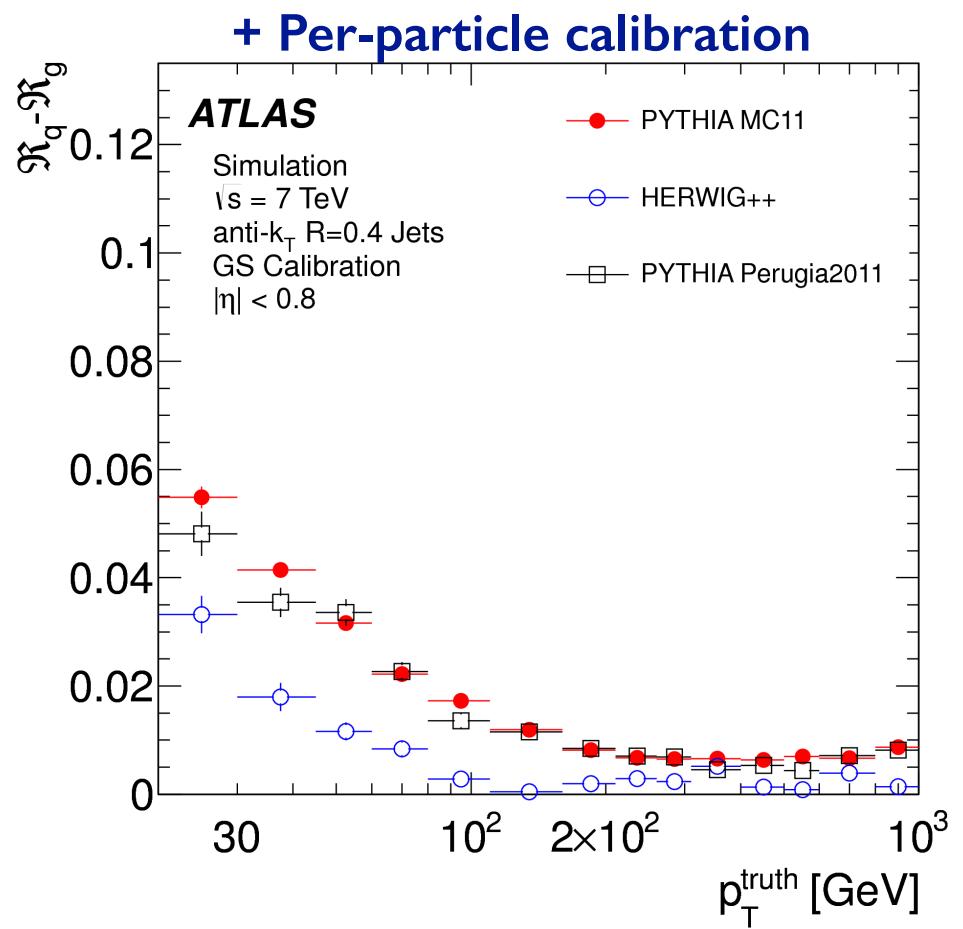
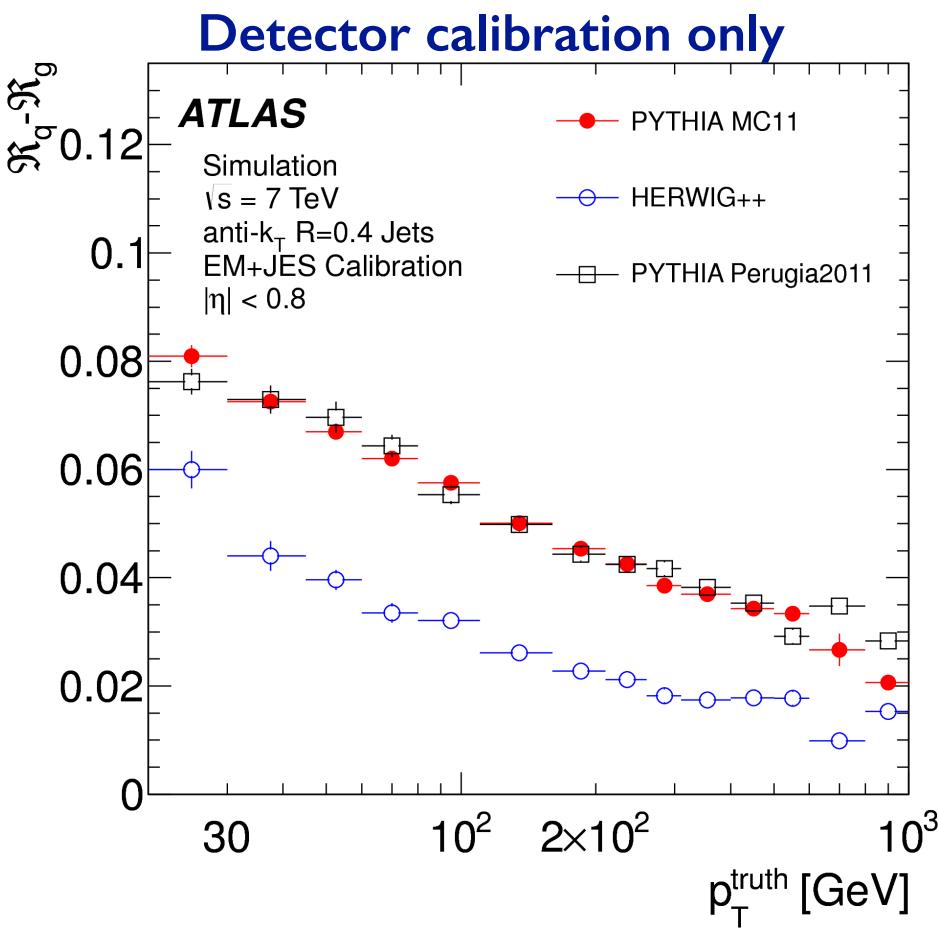
- Jet is a collection of particles, so we get jet response
 - ▷ $R(E_{\text{gen}}) = \langle E_{\text{reco}} \rangle / \langle E_{\text{gen}} \rangle = (\sum_i R_f(E_{\text{gen},i}) E_{\text{gen},i}) / E_{\text{gen}}$, where
 - $R_f(E_i) = 1$ for tracks and EM clusters, (i.e. charged hadrons, muons, and photons, electrons)
 - **$R_f(E_i) < 1$ for (neutral) hadrons => power law**
 - $R_f(E_i) = 0$ for $E_i < E_{\text{cutoff},f}$ (CMS: 0.1 GeV for γ , 0.2 GeV for track, ~3 GeV for neutral hadron)



H. Siikonen

Per particle calibration

- Both CMS and ATLAS try to improve jet resolution by calibrating individual particles
 - ▷ CMS: Particle Flow (neutral) hadron calibration for HCAL clusters
 - ▷ ATLAS: Global Sequential Calibration for 3D clusters of hadrons
- Very important consequence: reduced quark/gluon response difference
 - ▷ Flavor response is one of leading JES systematics, particularly for top quark mass

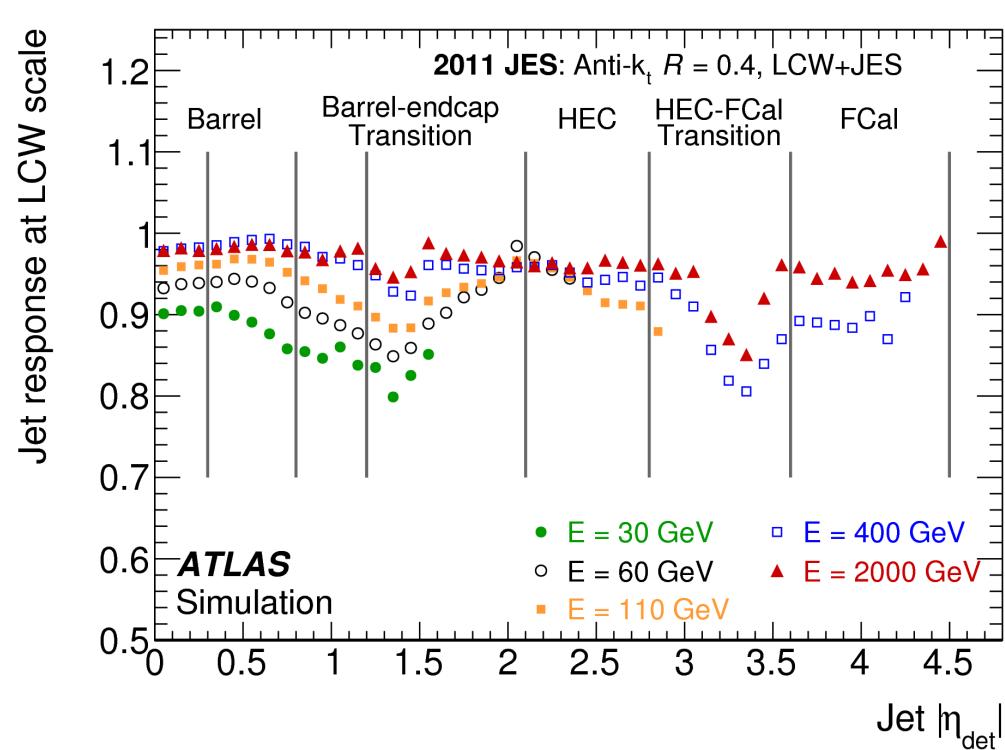


ATLAS PERF-2012-01

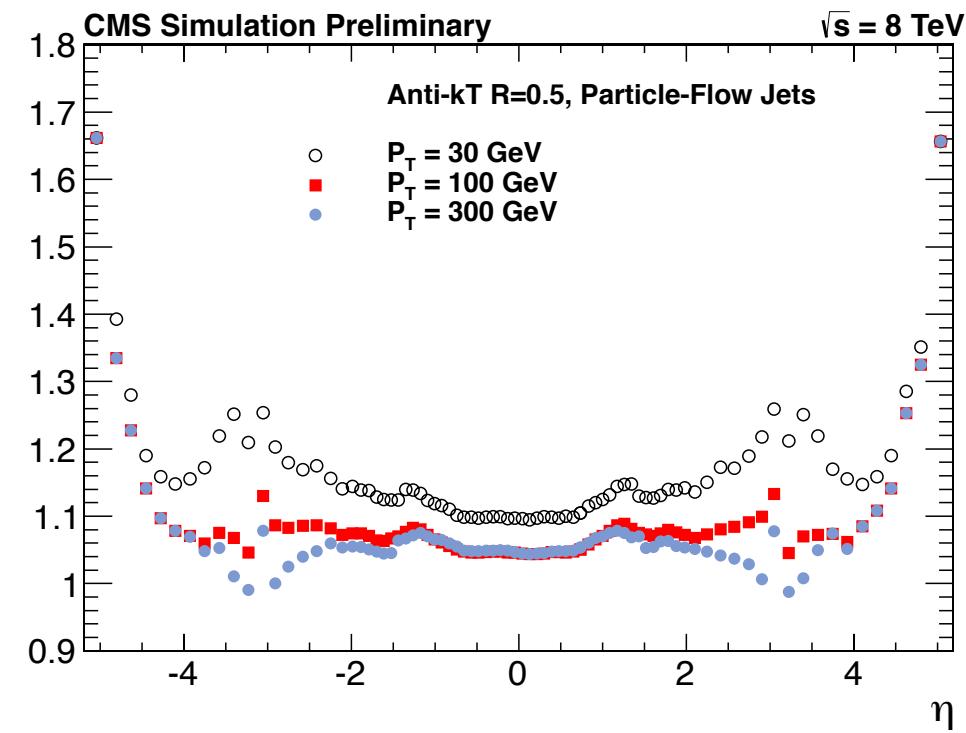
Jet response from MC

- Modern MC generators and detector simulation do a pretty good on predicting response
 - ▷ Response variation less than 20% after per-particle corrections (otherwise up to 50%)
- Both CMS and ATLAS base jet corrections on full detector simulation
 - ▷ only small perturbative corrections applied on top using data-based methods

$$\text{Response} = \langle p_{T,\text{meas}} \rangle / \langle p_{T,\text{ptcl}} \rangle$$

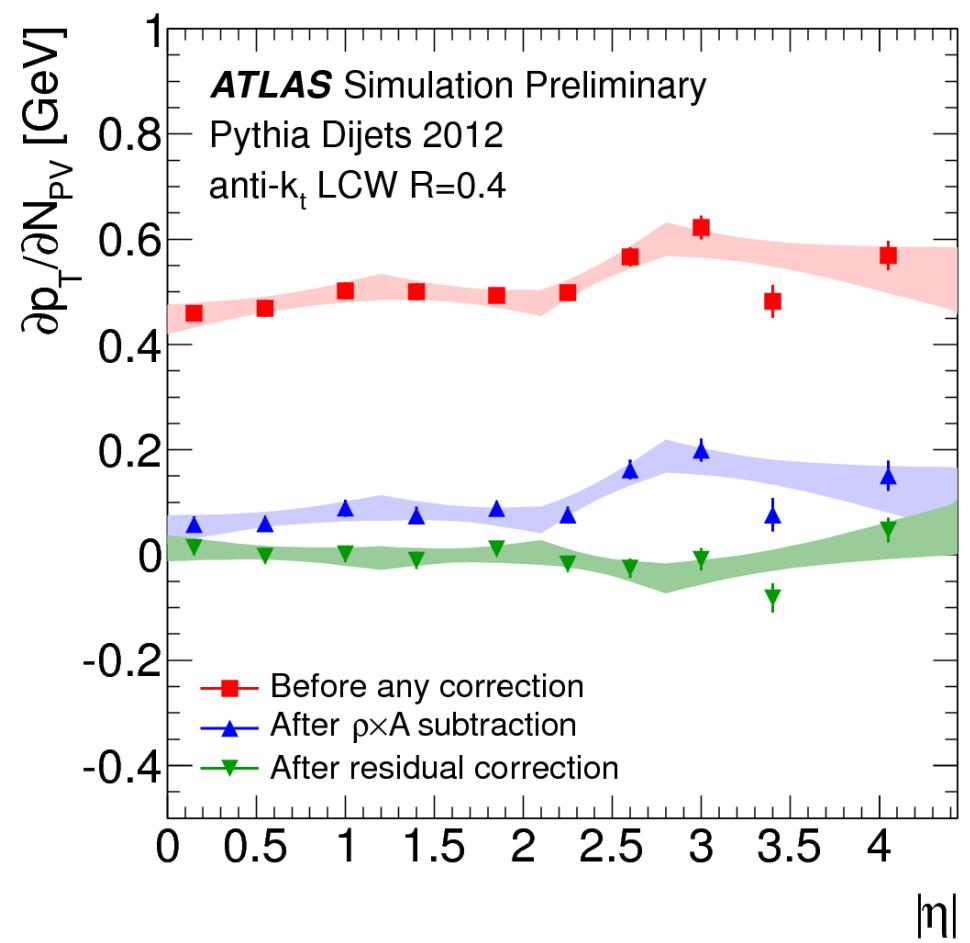
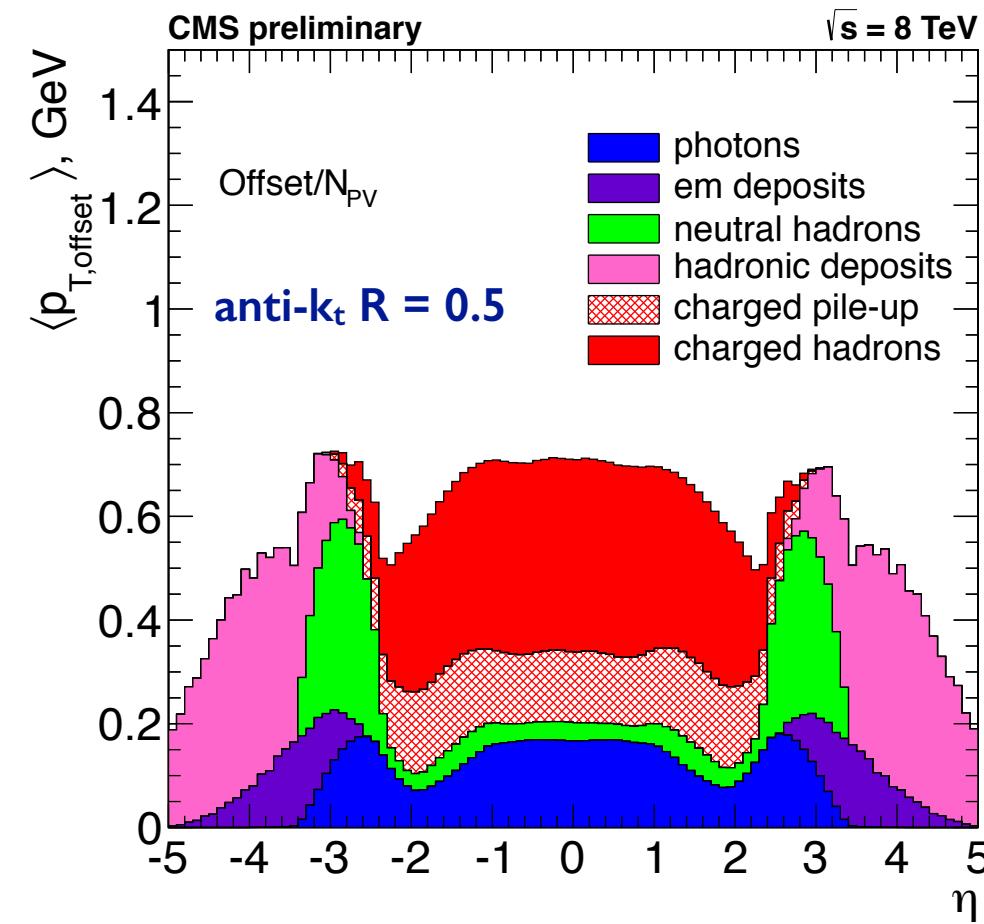


$$\text{Corr} = 1 / \text{response}$$



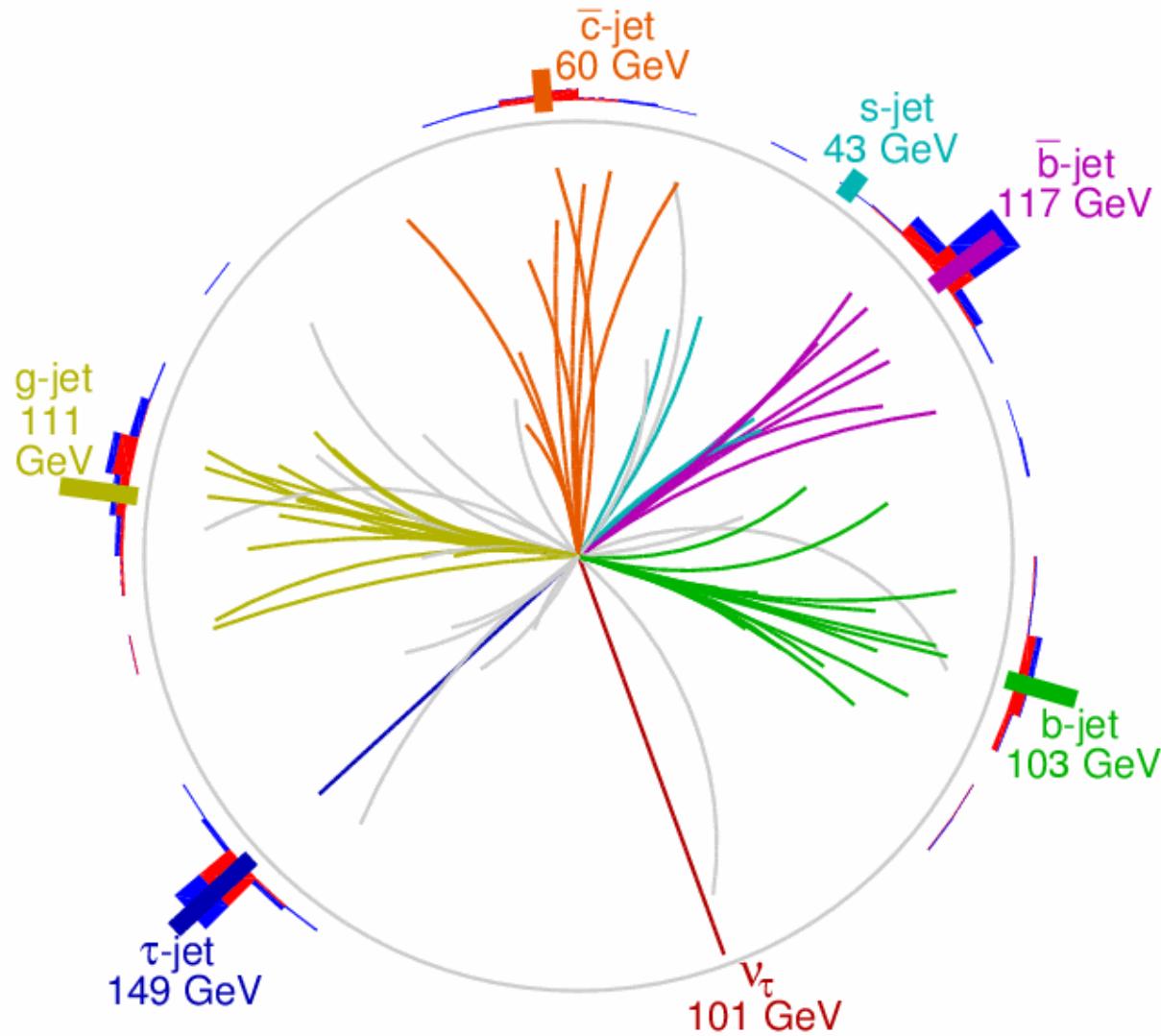
Pileup offset

- Offset = **in-time pileup** + **out-of-time pileup** + noise
 - ▷ in-time pileup estimate with N_{PV} (#vertices) or ρ (offset energy density)
 - ▷ residual out-of-time pileup estimate with $\langle \mu \rangle$ (Poisson mean pileup)
- part of in-time pileup can be removed by matching tracks to PU vertices



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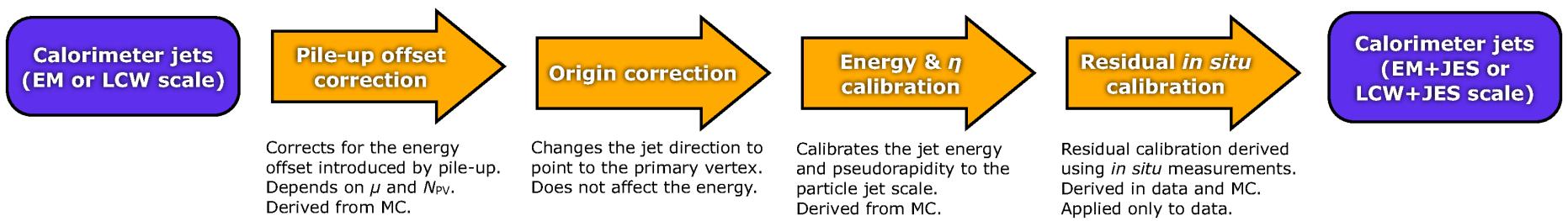
$gg \rightarrow tbH^+, t \rightarrow Wb \rightarrow scb, H^+ \rightarrow \tau\nu \rightarrow \text{hadrons}$ with a radiative gluon jet

Jet energy corrections

- JEC inverts everything we just described, and takes jet back to **particle level**
- Basic tasks of JEC are pileup removal, calibration vs η and p_T , and extrapolation
 - ▷ Data-based flavour inter-correction is a future path
- Details vary across experiments / time, but the basic scheme is the same
 - ▷ Detector simulation with test beam data is used as baseline
 - ▷ In-situ corrections for data as much smaller residual data/MC factors

$$p_{T,\text{corr}} = \frac{p_{T,\text{raw}} - O(\eta, p_T)}{k_{\text{data/MC}} \times R \cdot S(\eta, p_T)}$$

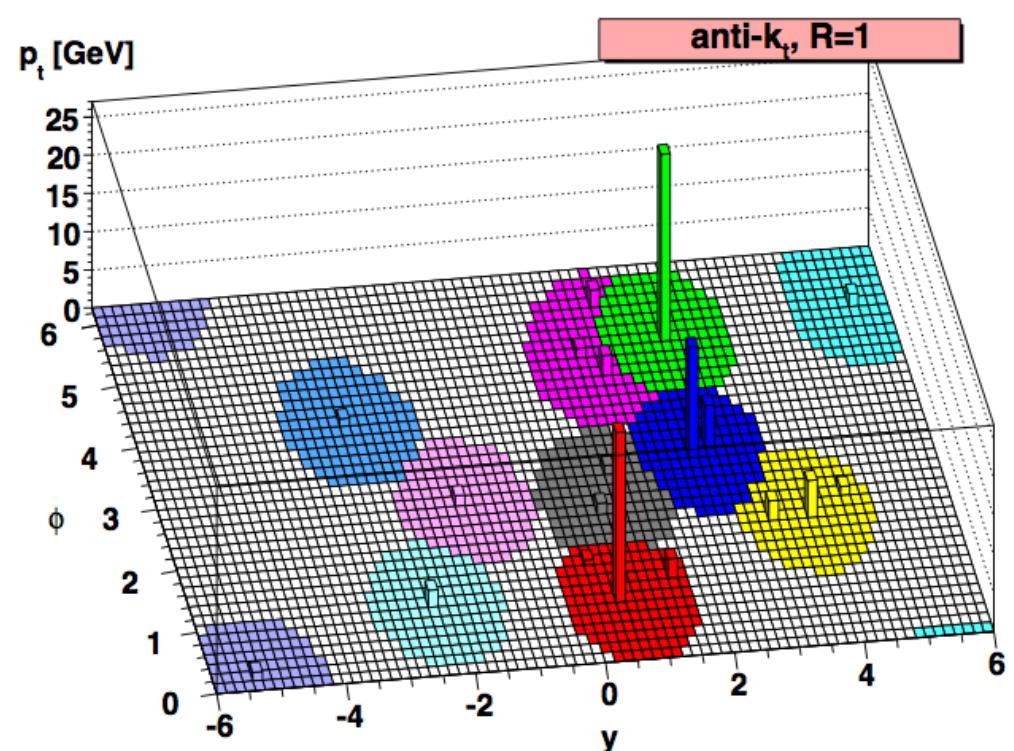
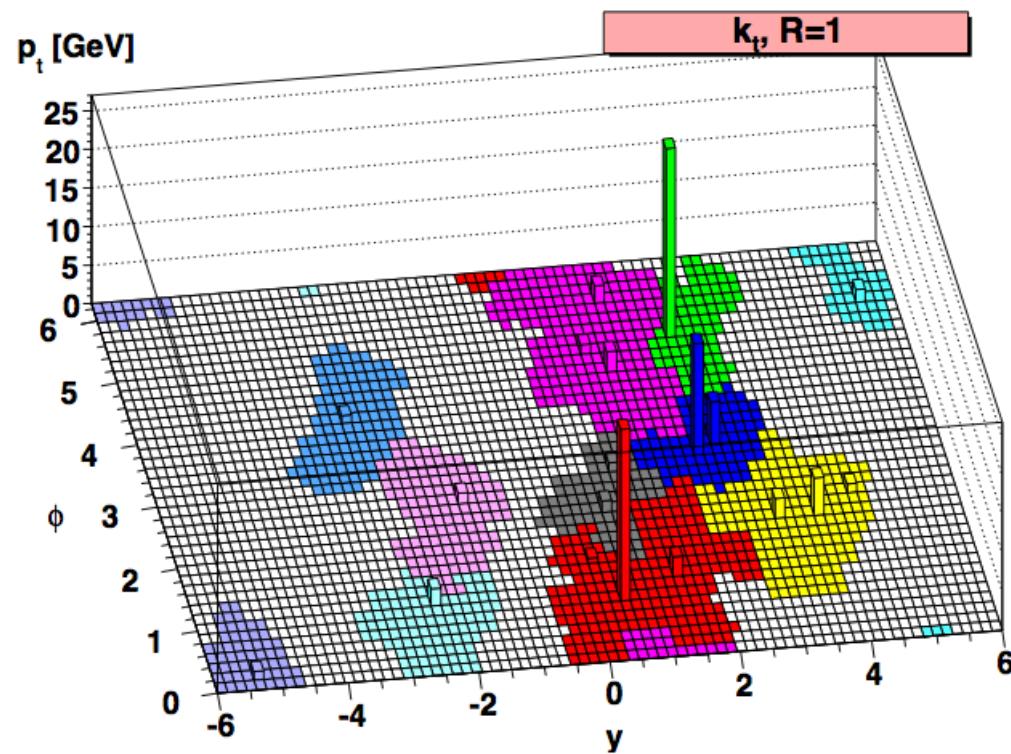
Correction	Pileup offset	η -intercalibration	Absolute JES vs p_T	Very high p_T	Flavour
Samples	Minimum Bias $Z/g+\text{jet}$ vs N_{pv}	Dijet balance	$Z/\gamma+\text{jet}$ balance	Multijet balance, single pion response	Tagged $Z/\gamma+\text{jet}$, dijet



Pileup removal

- Both experiments now use the area-median (ρ -A) method
 - jet area calculated in FastJet by throwing ghosts
 - energy density ρ as $\text{median}\{\rho_{T,i} / A_i\}$ over all k_T jets
- Experimental tweaks to account for η -dependent response, UE, jet p_T dependence etc.
 - easier for anti- k_t with fixed cone shape for leading jets

$$\mathbf{O}(\eta, p_T, \mu) = \rho_{\text{eff}} \times \mathbf{A}_{\text{jet}}$$

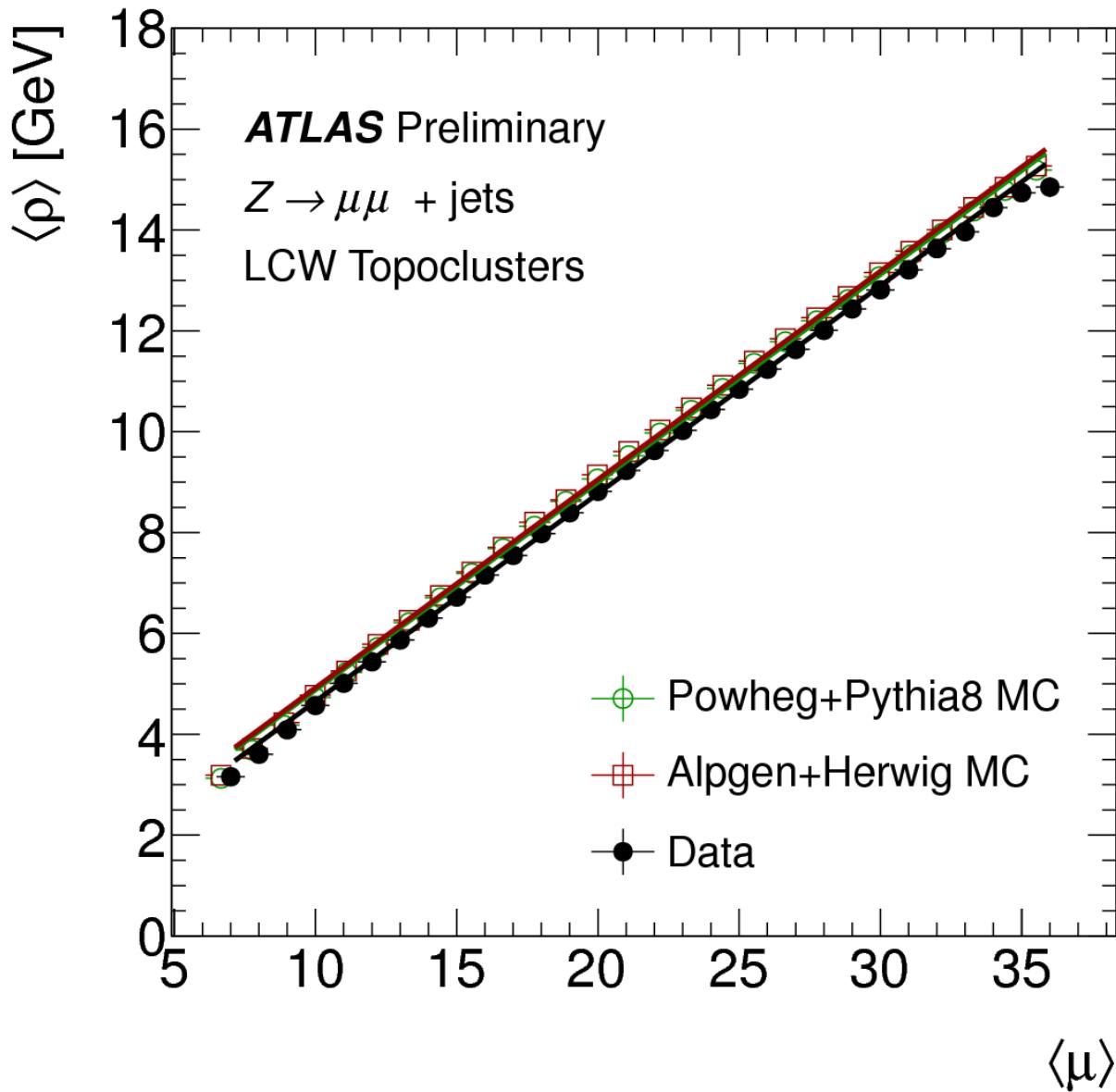


$$\rho_{\text{eff}} = (\rho - \rho_{\text{UE}}) \cdot k_p(\eta, p_T, \mu)$$

arXiv:0906.1833

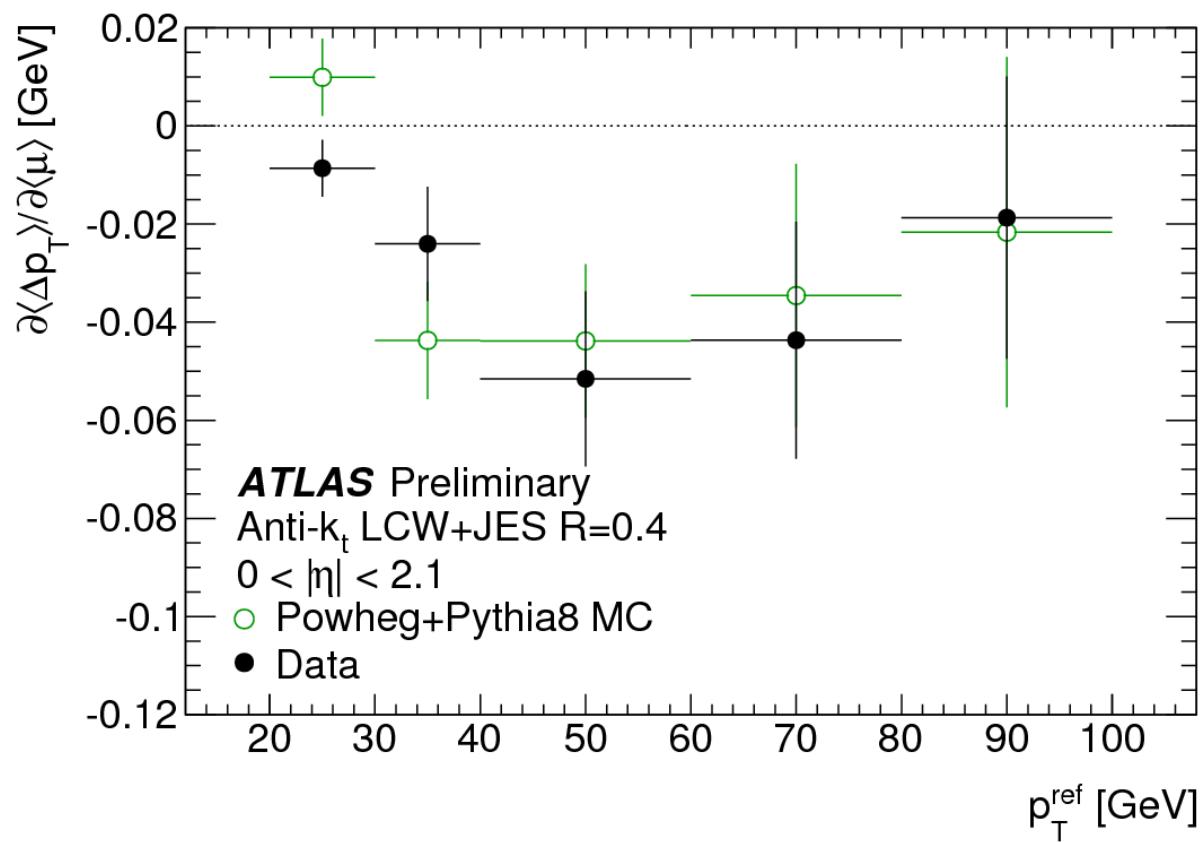
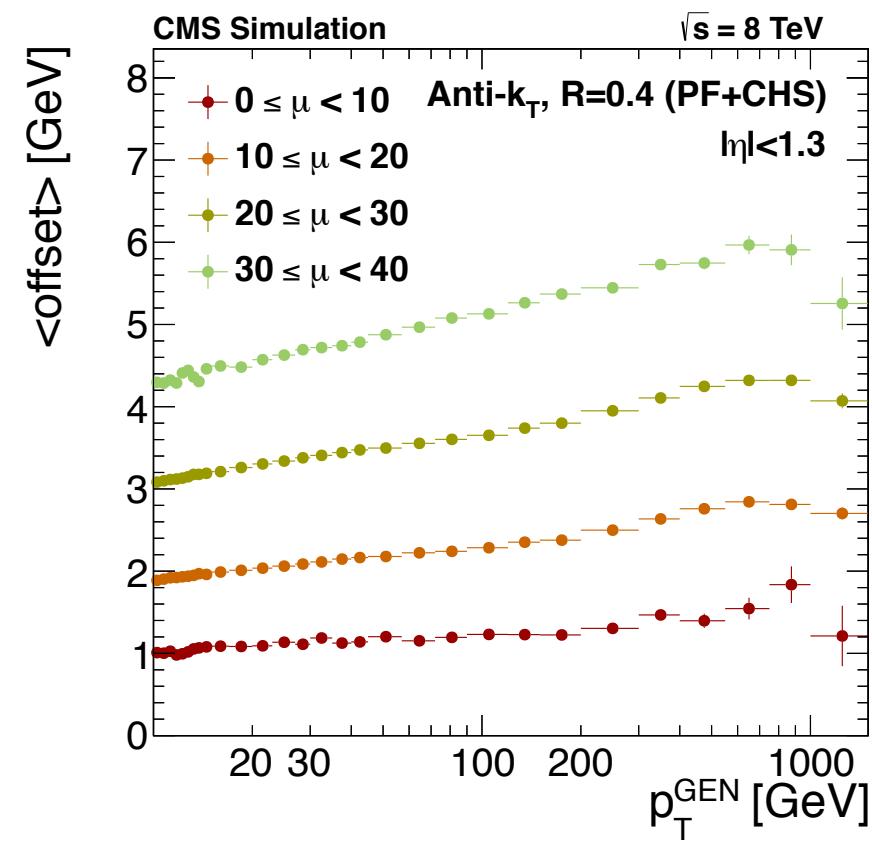
- Pileup scales almost linearly with $\langle \mu \rangle$, and is to first order independent of jet p_T

$$\langle O(\eta, p_T, \mu) \rangle = \langle \rho_{\text{eff}} \times A_{\text{jet}} \rangle = C \times \langle \mu \rangle$$

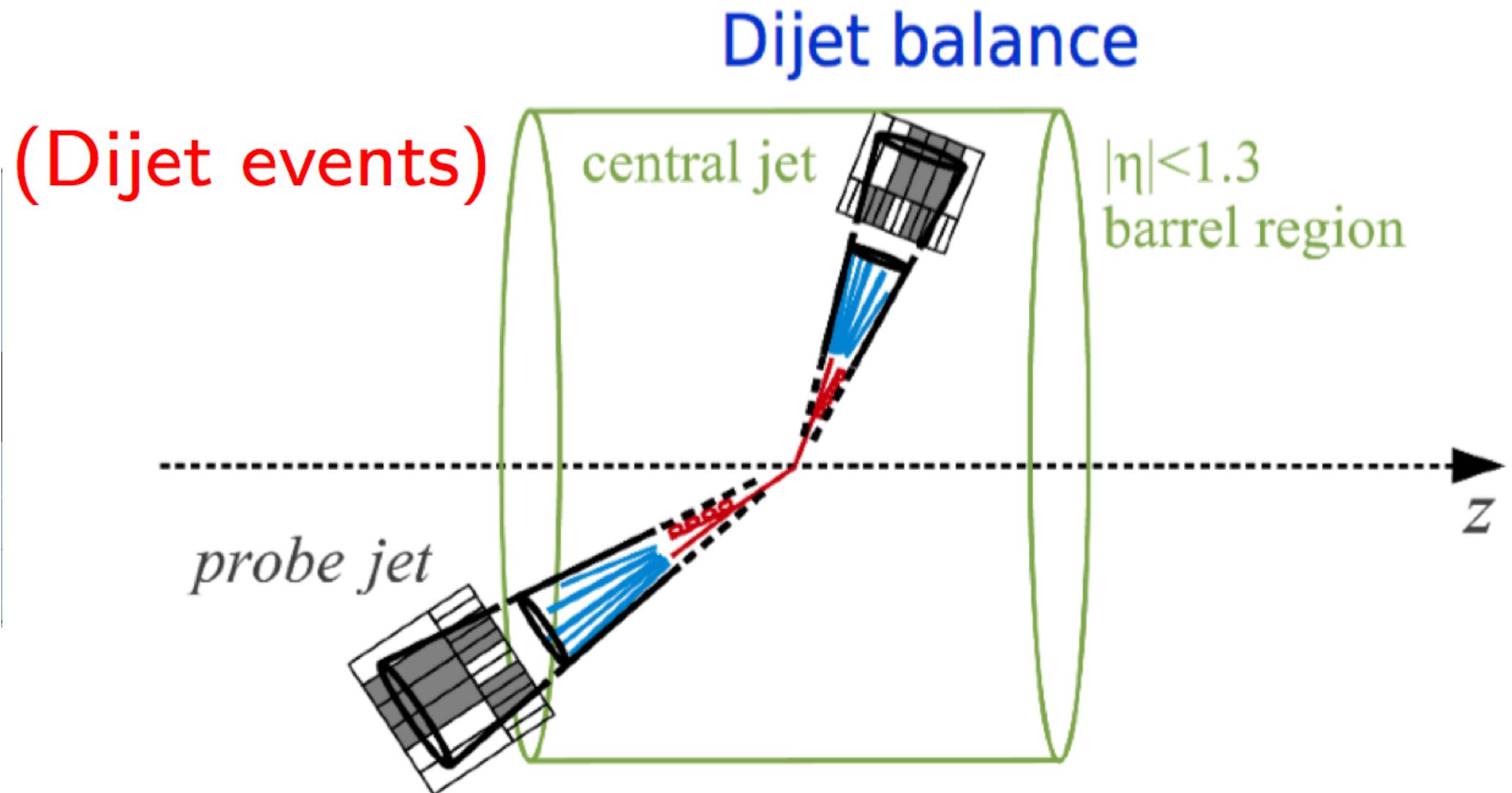


Pileup within jets

- Offset inside and outside jet can be slightly different => $\rho = \rho_{\text{eff}}(p_{T,\text{jet}}, \eta, \Delta R)$
 - ▷ e.g. zero suppression, p_T thresholds, particle correction non-linearities
- MC approach (CMS): same event simulated with and without PU
- Data approach (ATLAS): check Z+jet balance vs $\langle \mu \rangle$ in data

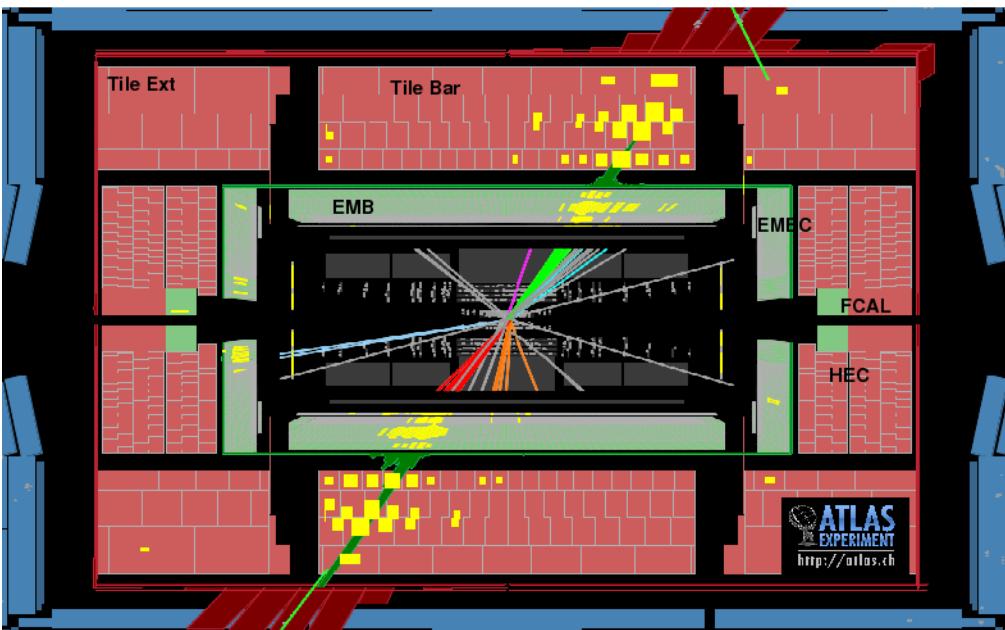


- Dijet balance measures response relative to reference region
 - ▷ $B(\eta_{\text{probe}}, p_{T,\text{ave}}) = \langle R(\eta_{\text{probe}}) * p_{T,\text{probe}} \rangle / \langle R(\eta_{\text{ref}}) * p_{T,\text{ref}} \rangle \sim \langle R(\eta_{\text{probe}}) \rangle / \langle R(\eta_{\text{ref}}) \rangle$

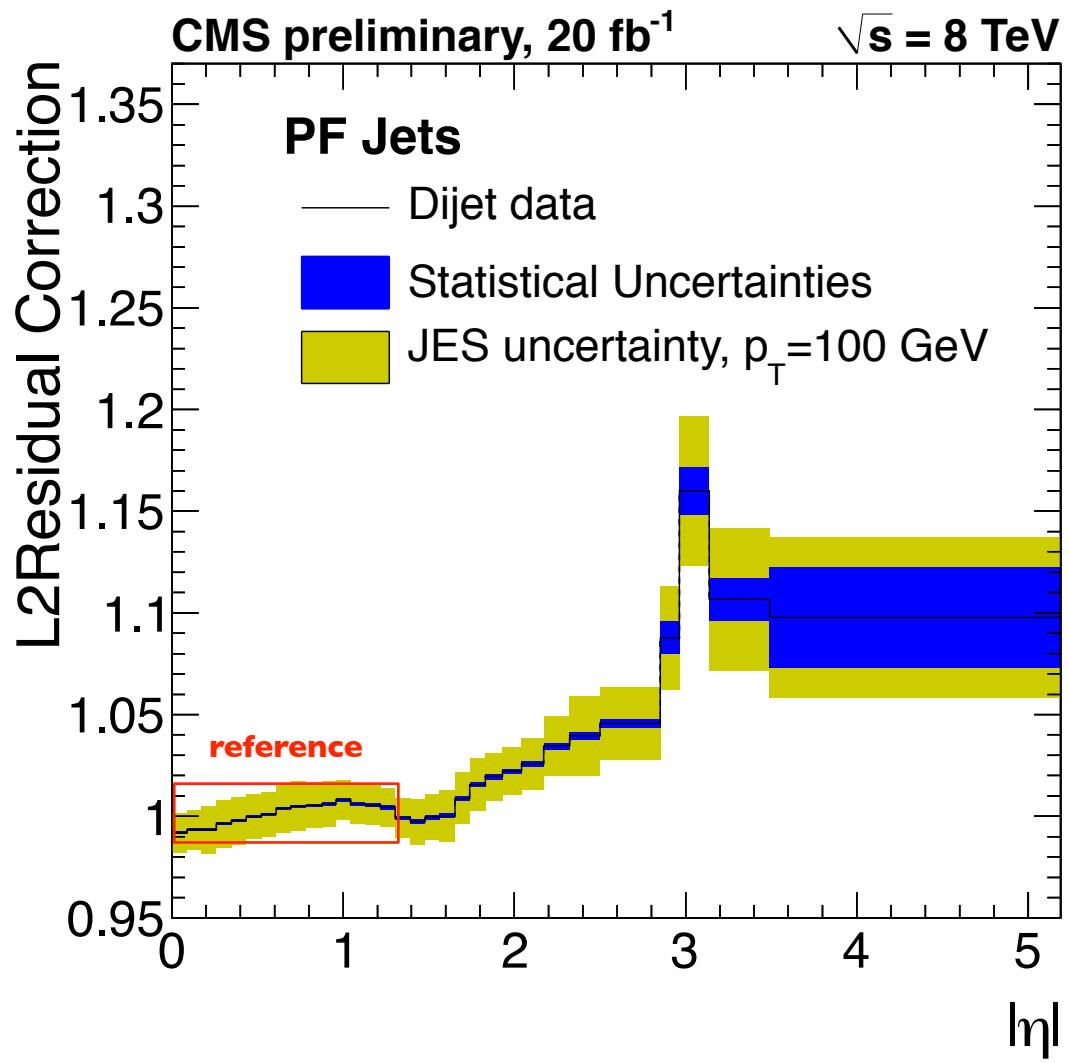


Dijet balance

- Dijet balance measures response relative to reference region
 - ▷ $B(\eta_{\text{probe}}, p_{\text{T,ave}}) = \langle R(\eta_{\text{probe}}) * p_{\text{T,probe}} \rangle / \langle R(\eta_{\text{ref}}) * p_{\text{T,ref}} \rangle \sim \langle R(\eta_{\text{probe}}) \rangle / \langle R(\eta_{\text{ref}}) \rangle$
- Leading biases: ISR+FSR ($\langle p_{\text{T,probe}} \rangle \neq \langle p_{\text{T,ref}} \rangle$), jet p_{T} resolution (JER)
 - ▷ Both minimised with $p_{\text{T,ave}} = (p_{\text{T,probe}} + p_{\text{T,ref}})/2$



- Technical detail:
 - ▷ $B = (1 + 0.5\langle A \rangle) / (1 - 0.5\langle A \rangle)$, where
 - ▷ $A(\eta_{\text{probe}}, p_{\text{T,ave}}) = (p_{\text{T,probe}} - p_{\text{T,ref}}) / p_{\text{T,ave}}$



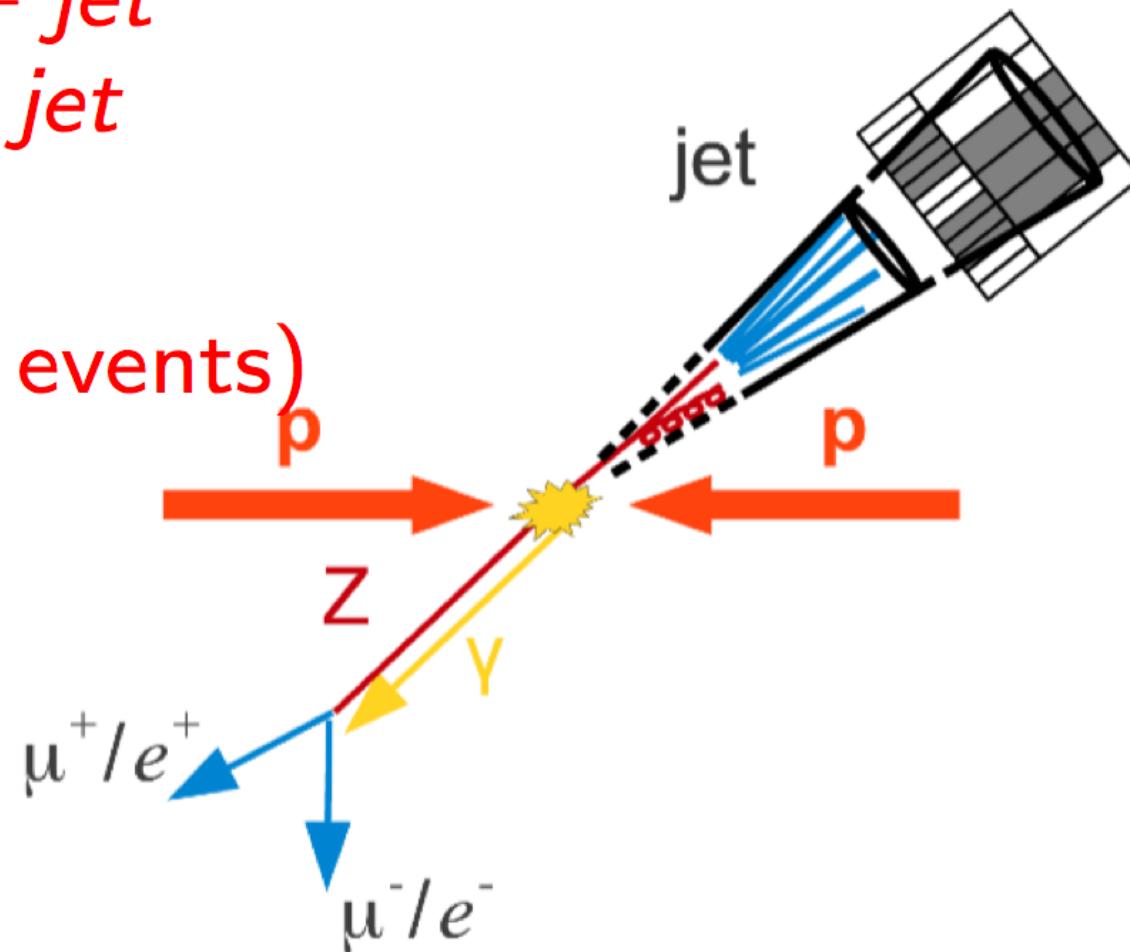
- Muons, electrons and photons measured well ($R_{\text{ref}} = 1$) compared to jets
 - ▷ $B(\eta_{\text{jet}}, p_{T,\text{ref}}) = R(\eta_{\text{jet}}) * p_{T,\text{jet}} / p_{T,\text{ref}} \sim R(\eta_{\text{jet}})$
- JER bias removed by binning in $p_{T,\text{ref}}$
 - ▷ => Bias from ISR+FSR ($p_{T,\text{jet}} \neq p_{T,\text{ref}}$) larger than for dijet balance!

$Z(\mu\mu) + \text{jet}$

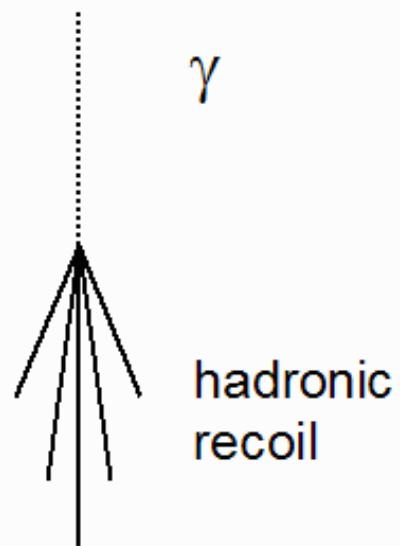
$Z(ee) + \text{jet}$

$\gamma + \text{jet}$

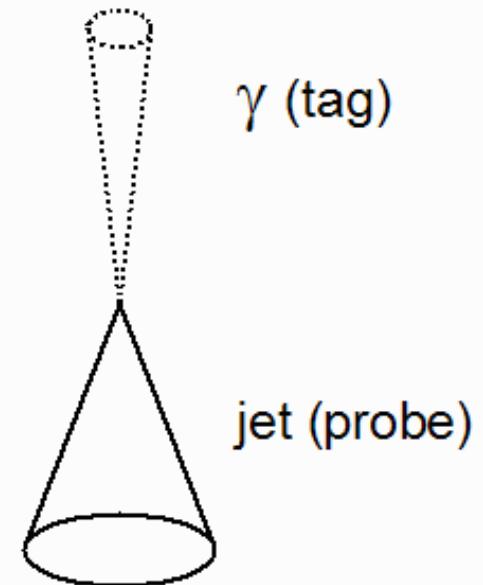
(multijet events)



- Missing E_T projection fraction (MPF) method designed to tackle $\vec{p}_{T,\text{probejet}} \neq \vec{p}_{T,\text{ref}}$
- Basic premises (*underscore denotes vector*):
 - ▷ $\underline{p}_{T,\text{probejet}} + \underline{p}_{T,\text{other}} + \underline{p}_{T,\text{ref}} = \underline{0}$ (no gen-MET)
 - ▷ Detector: $R_{\text{probe}} \underline{p}_{T,\text{probejet}} + R_{\text{other}} \underline{p}_{T,\text{other}} + R_{\text{ref}} \underline{p}_{T,\text{ref}} = -\underline{\text{MET}}$ (MET from mis-measurements, no tilts)
- Solving R_{probe} for $R_{\text{ref}} \sim 1$, $R_{\text{other}} \sim R_{\text{probe}}$:
 - ▷ $R_{\text{probe}} = 1 + \underline{\text{MET}} * \underline{p}_{T,\text{ref}} / |\underline{p}_{T,\text{ref}}|^2 \equiv R_{\text{MPF}}$

Particle Level

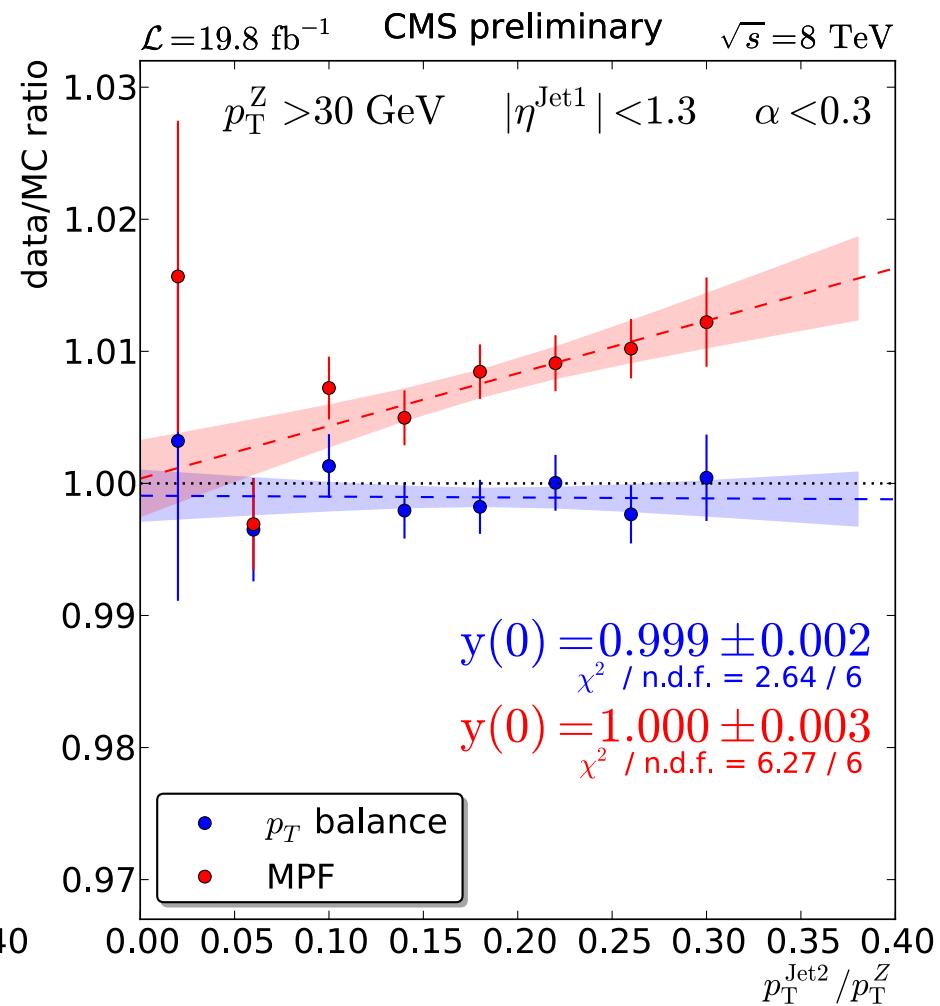
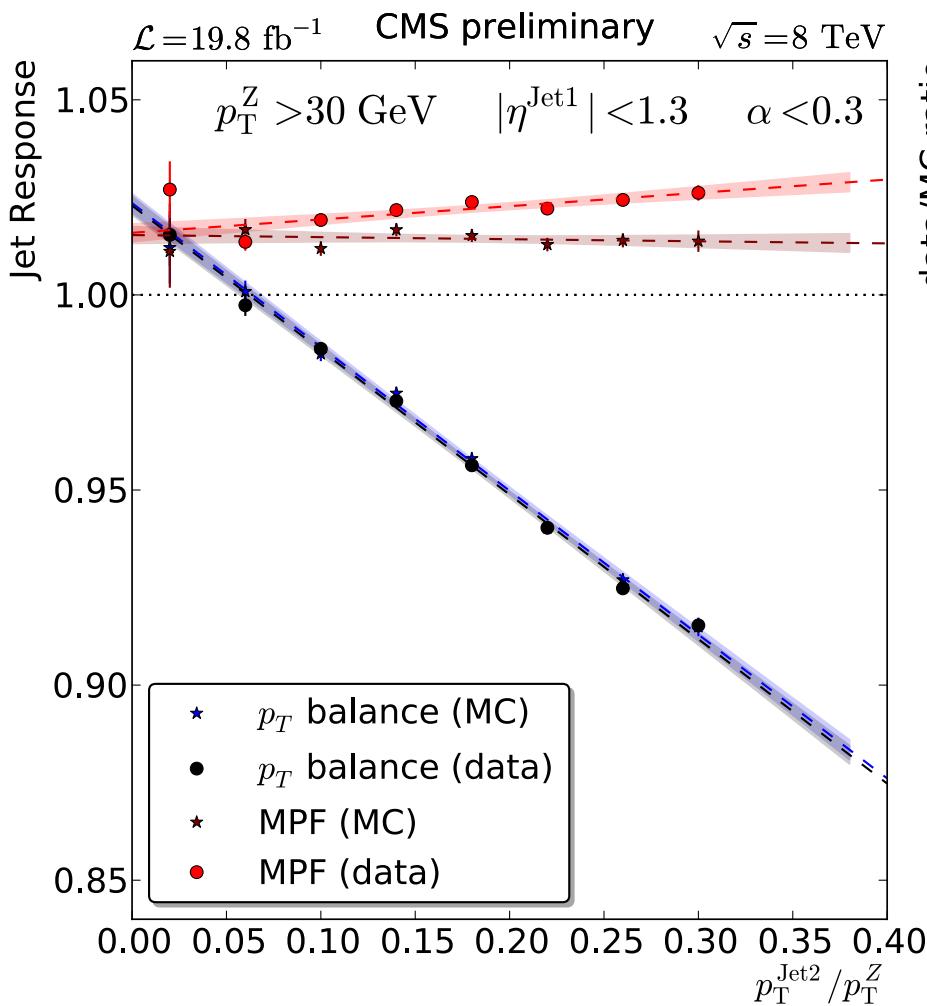
$$\vec{p}_{T,\gamma} + \vec{p}_{T,\text{had}} = \vec{0}$$

Detector Level

$$\vec{p}_{T,\gamma} + R_{\text{had}} \vec{p}_{T,\text{had}} = -\vec{E}_T$$

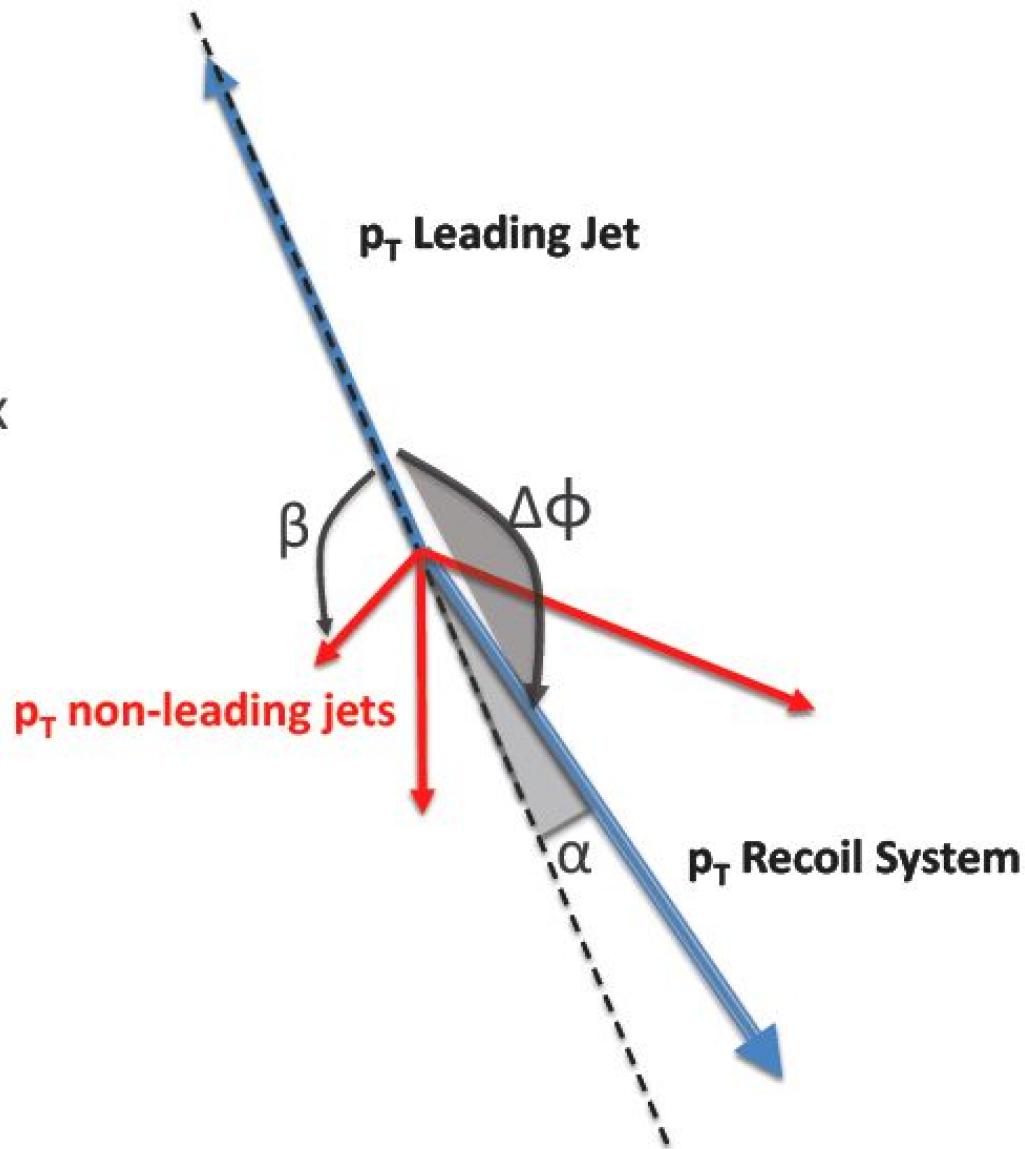
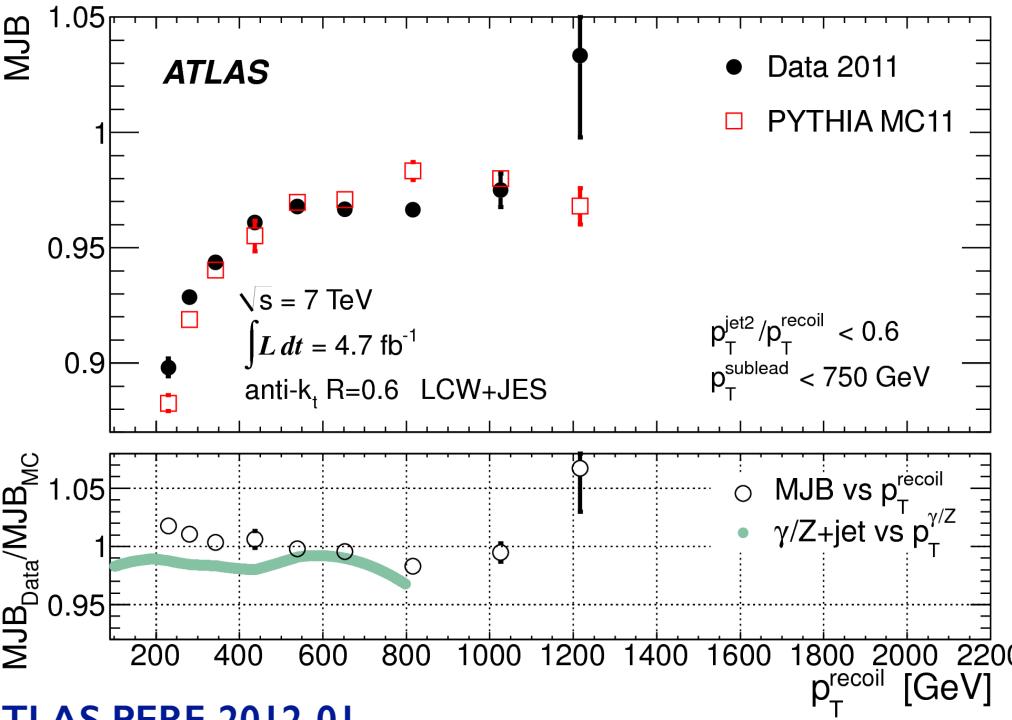
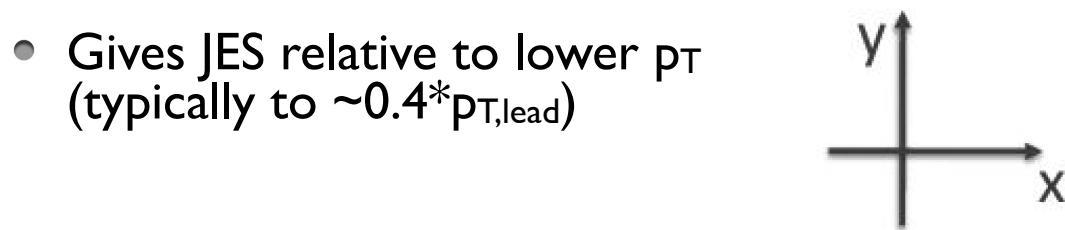
Extrapolation

- Extrapolating additional jet activity to zero forces $p_{T,\text{probe}} \rightarrow p_{T,\text{ref}}$
- Applying this to combine p_T balance and MPF methods ensures ISR+FSR negligible
 - ▷ ISR+FSR second order effect for MPF through $R_{\text{other}} \neq R_{\text{probe}}$ (also true for data/MC)
 - ▷ $\langle p_{T,\text{probe}} \rangle \neq \langle p_{T,\text{ref}} \rangle$ also second order for data/MC of p_T balance



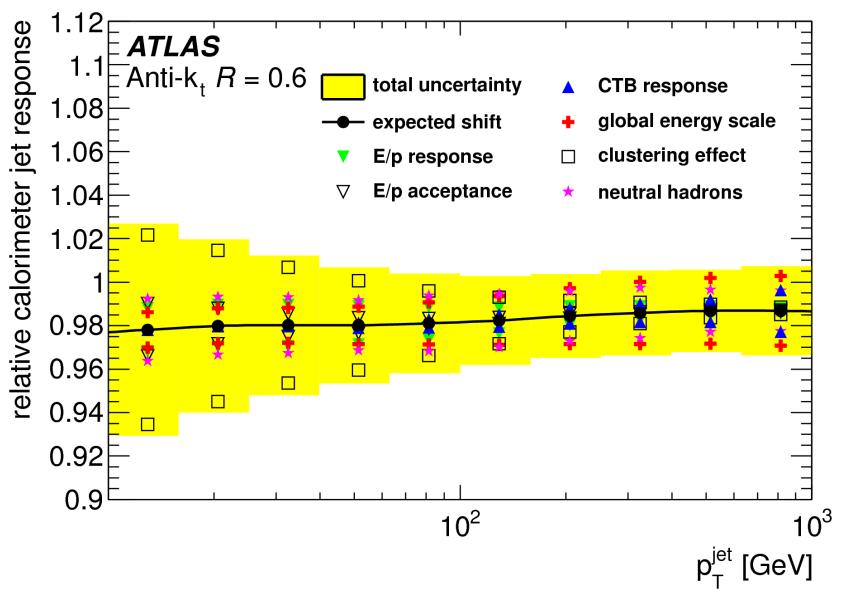
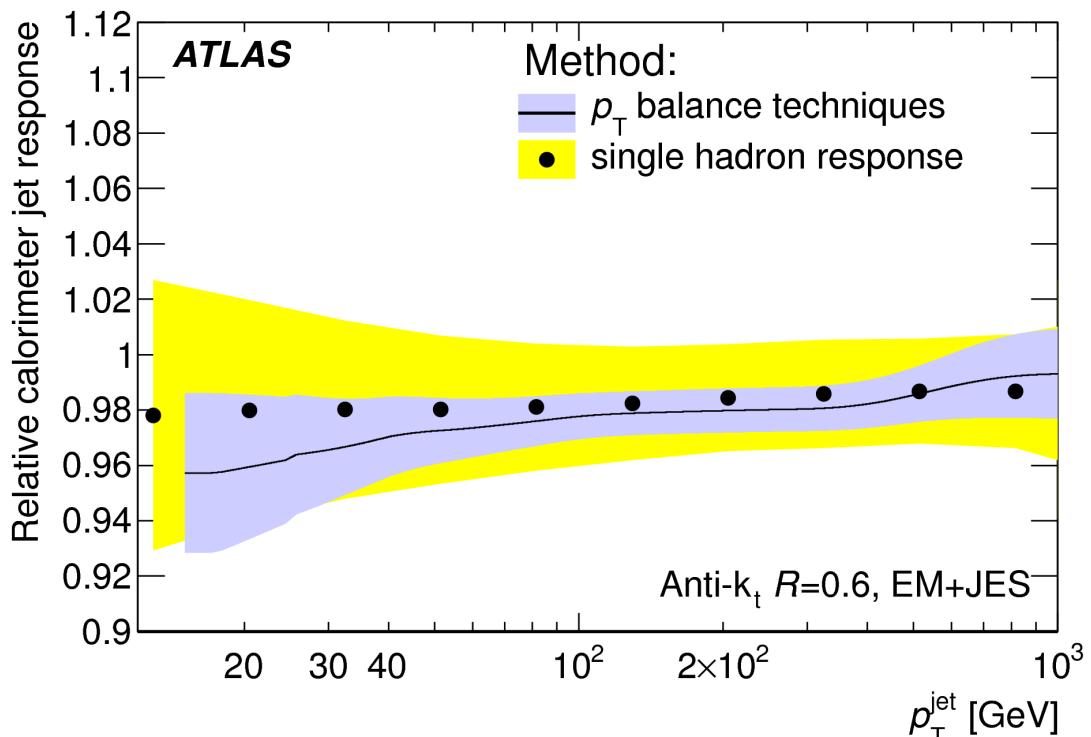
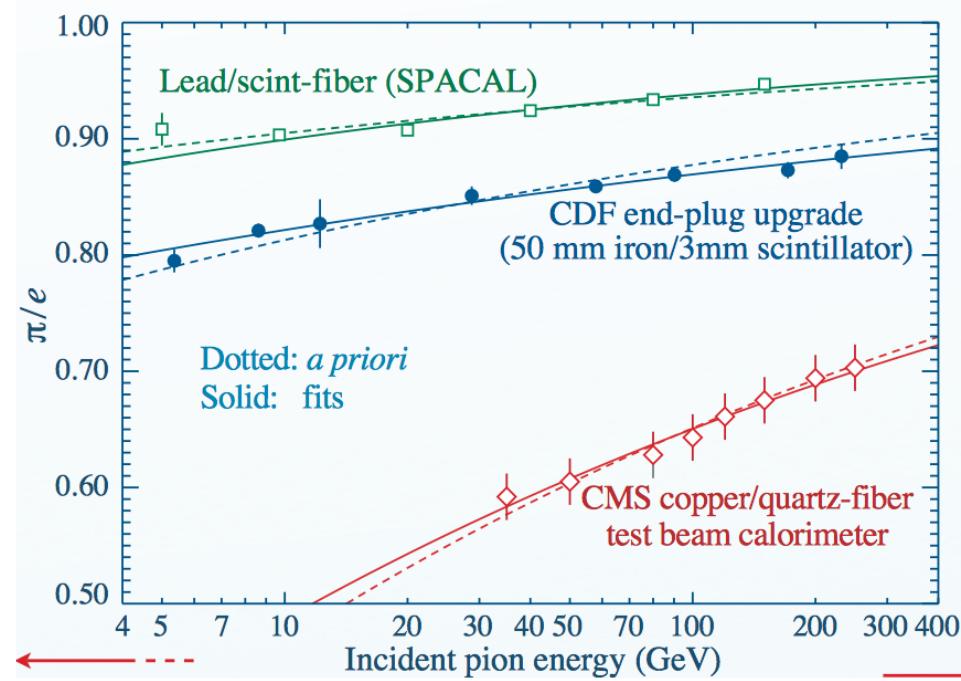
Multijet balance

- Going beyond TeV scale requires using (multi)jet events for sufficient statistics
- Multijet balance has some bias from jets below threshold (ISR+FSR) and JER for p_T^{recoil} binning => use Data/MC
- Gives JES relative to lower p_T (typically to $\sim 0.4 * p_{T,\text{lead}}$)



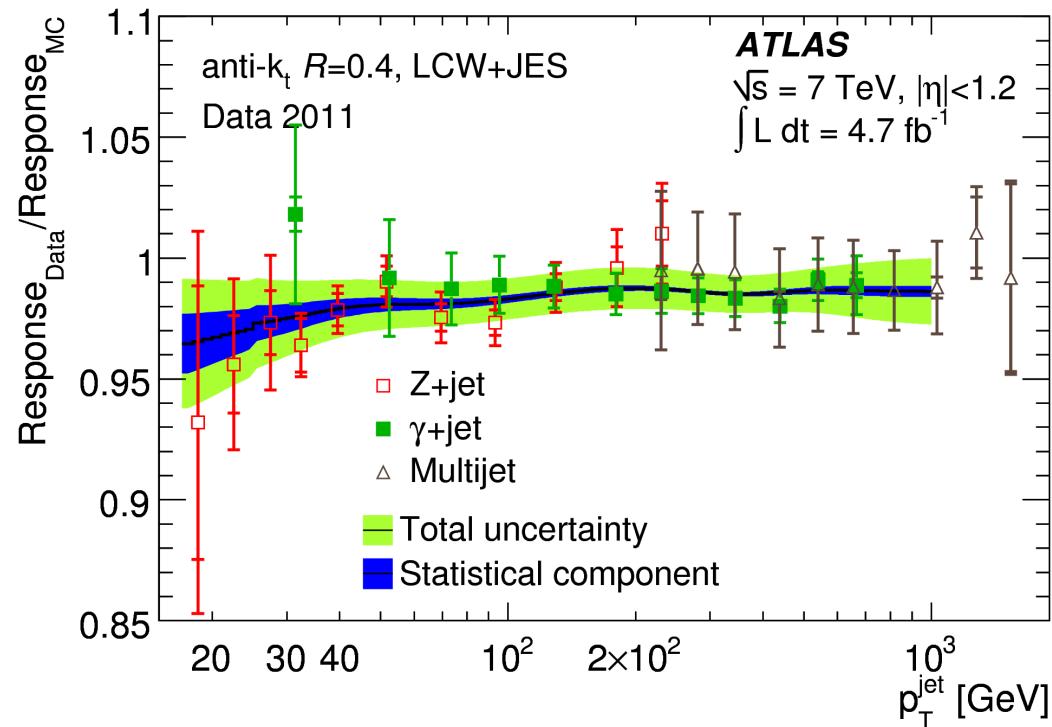
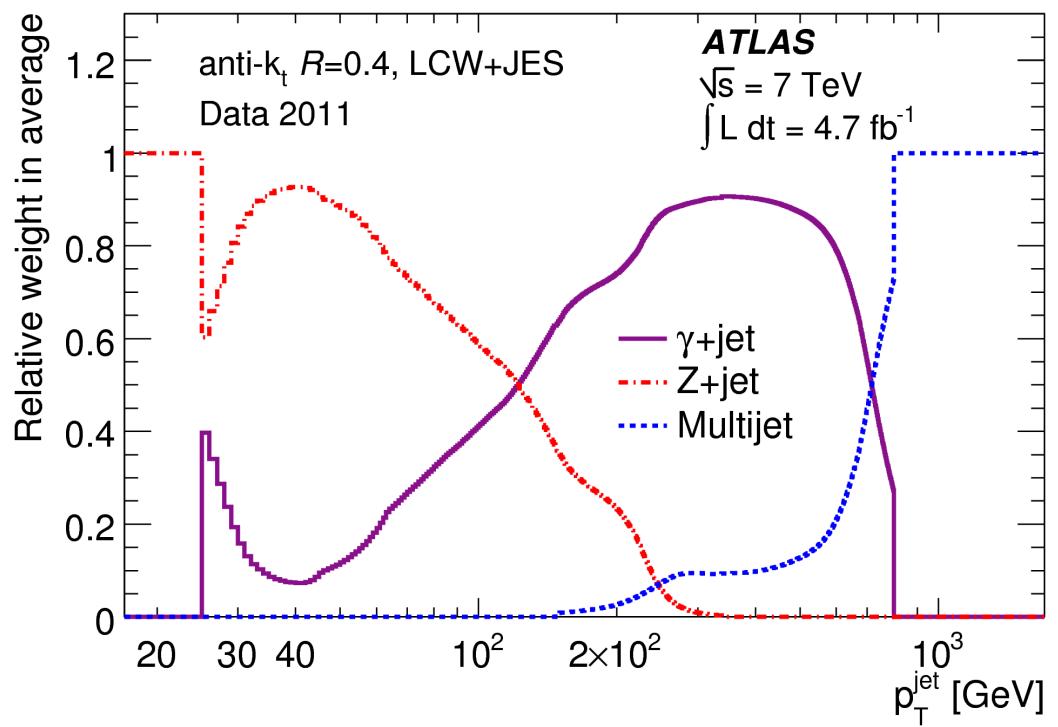
Single pion response

- Alternative approach to high p_T is MC
 - ▷ TeV scale jet response driven by hadrons at $O(100 \text{ GeV})$ and less => test beam
 - ▷ Hadron response plateaus in this p_T range, which limits extrapolation uncertainty



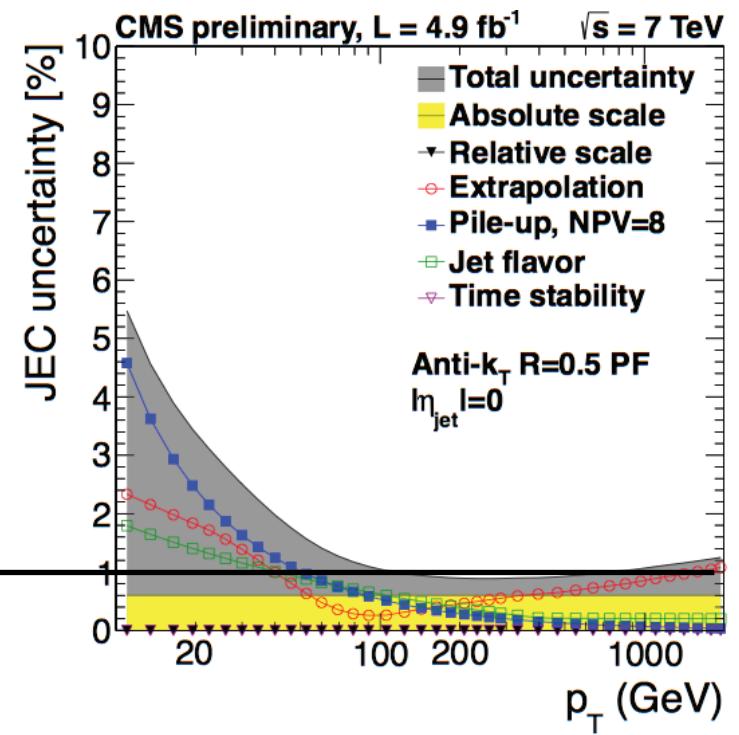
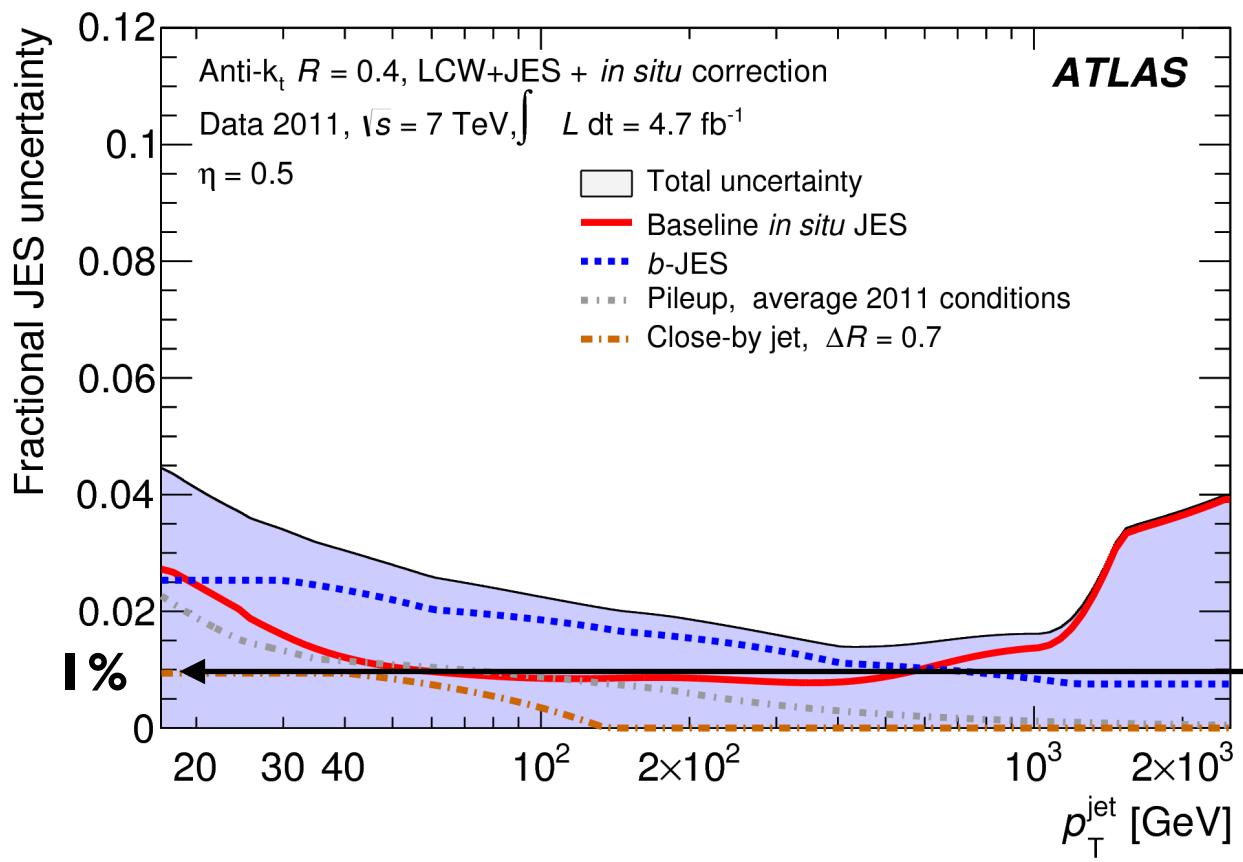
Putting it all together

- Z+jet has good statistics at low p_T , γ +jet at higher p_T , multijets at the very highest p_T
- Combination of all channels measures JES from $p_T=30$ GeV to about 1.3 TeV
 - ▷ Both statistical and systematic uncertainties, and their correlations, considered



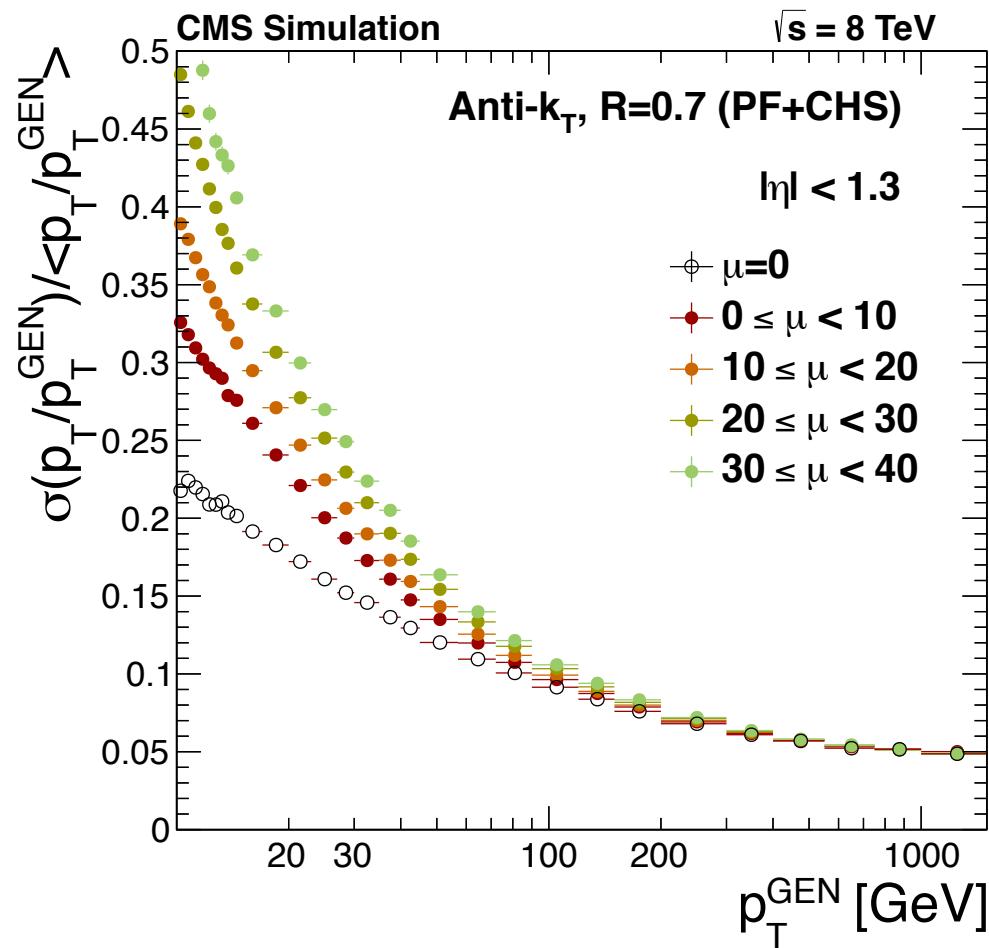
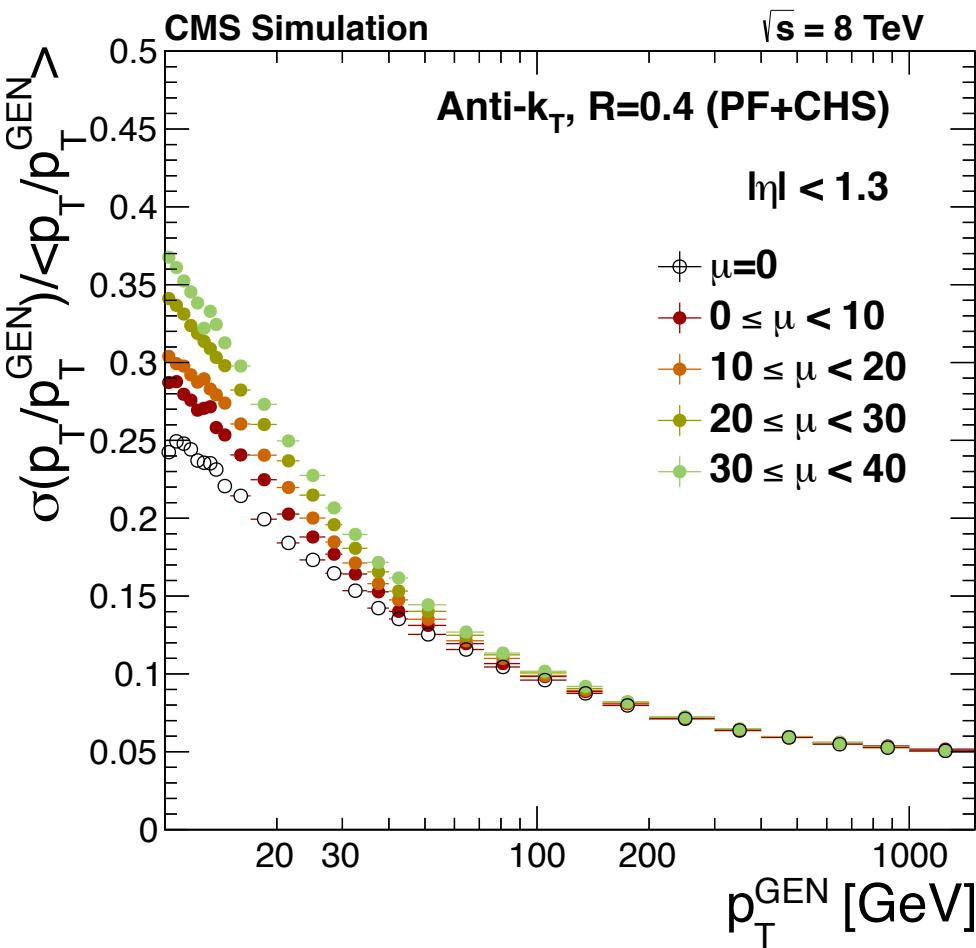
Uncertainties

- Both experiments reached in-situ calibration precision of better than 1% already in 2011
- This will further improve for final 2012 calibrations, despite increasing pileup



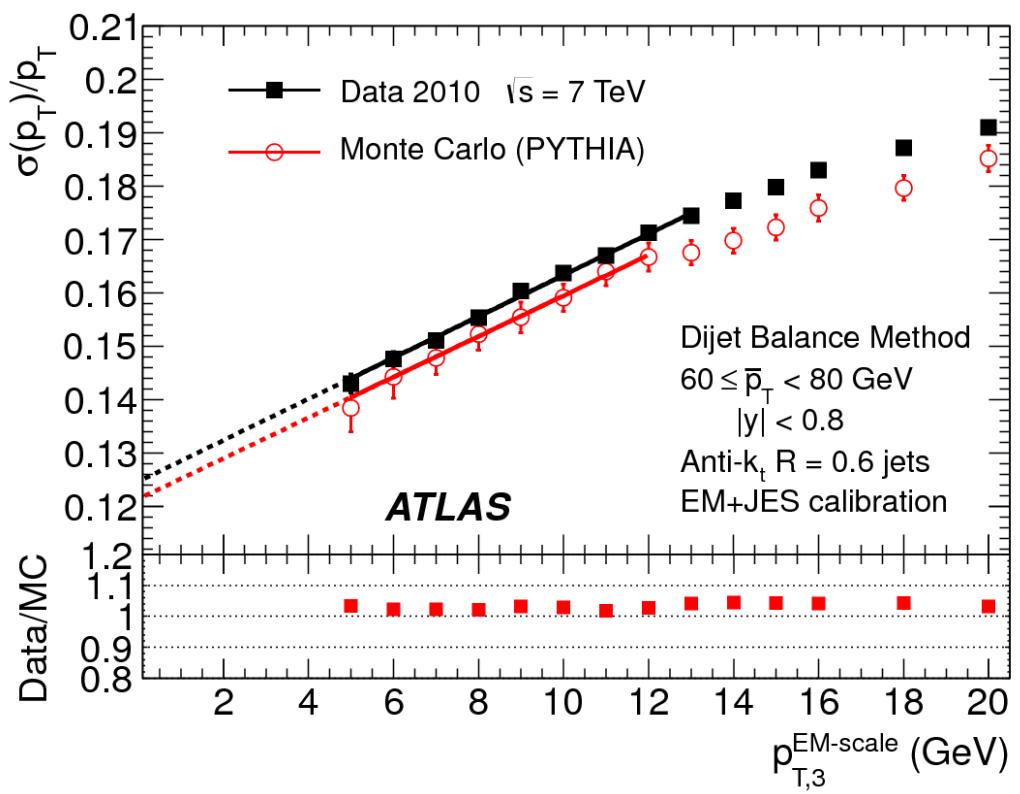
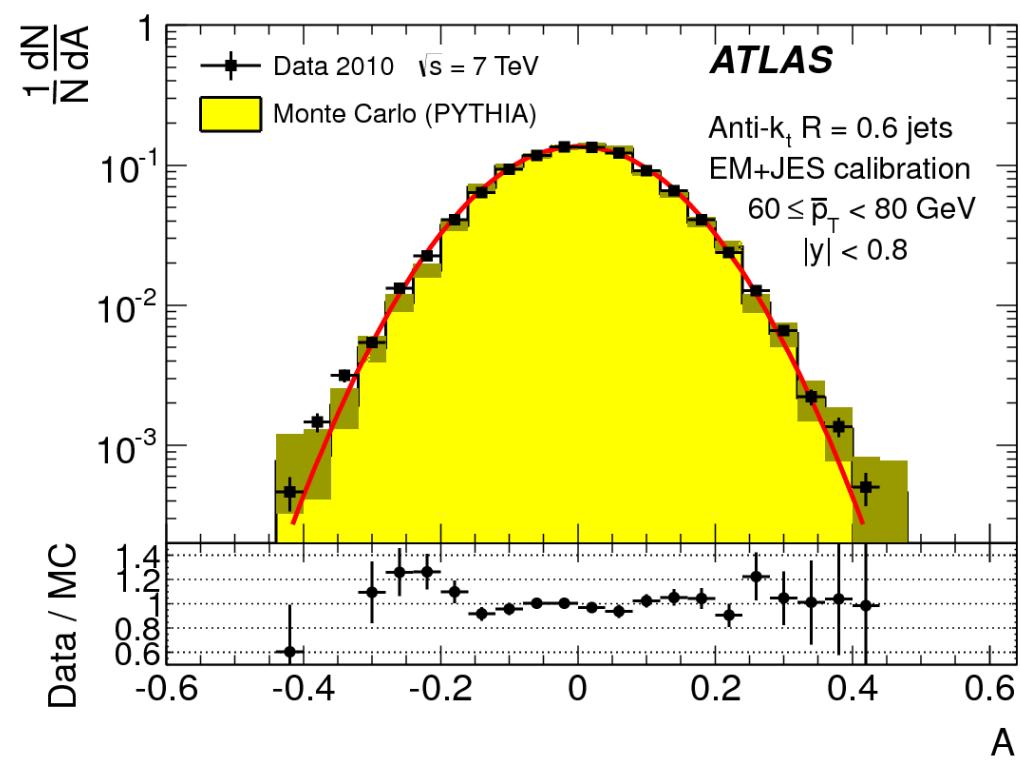
Jet p_T resolution

- Gaussian jet p_T resolution (JER) dominated by three contributions
 - ▷ Noise and pile-up ($N \sim \sqrt{(\mu A_{jet})}$)
 - ▷ Stochastic fluctuations in measured energy ($S \sim 1$)
 - ▷ Constant term ($C \sim 5\%$) e.g. from calorimeter cell inter-calibration
- $\sigma(p_T) / p_T = \sqrt{N^2 / p_T^2 + S^2/p_T + C^2}$

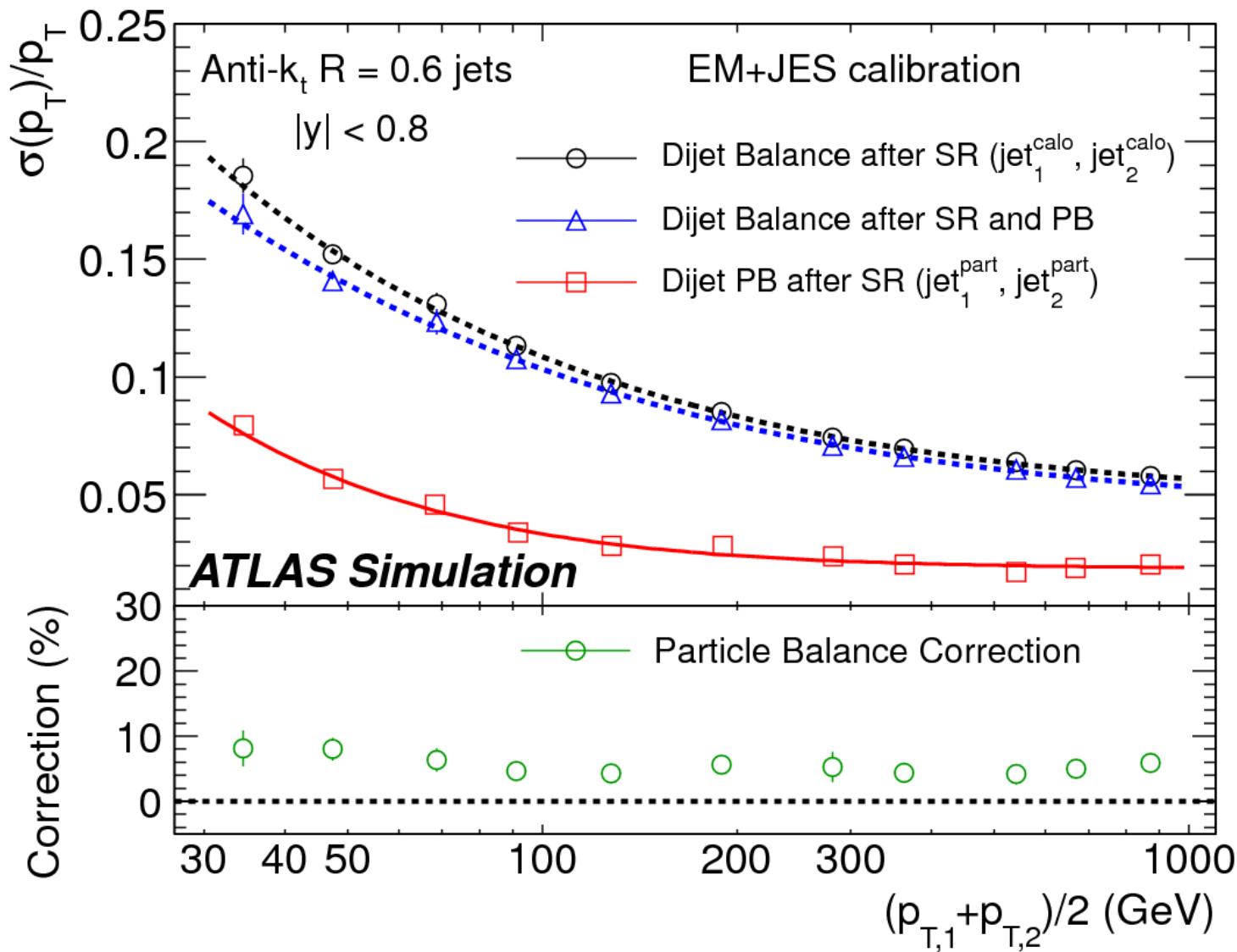


JER from data

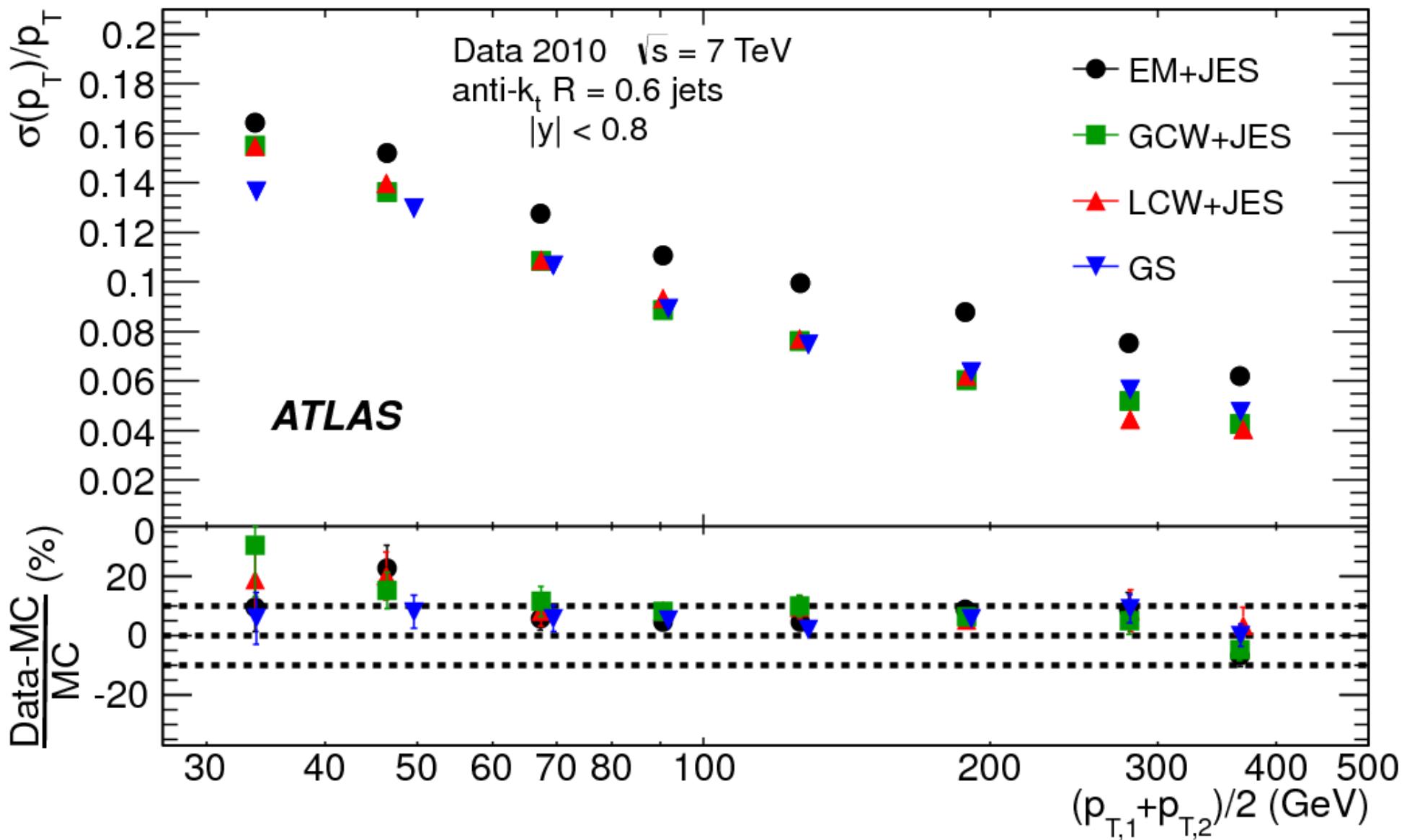
- JER measured from data using dijet asymmetry $A = (\mathbf{p}_{\text{T}2} - \mathbf{p}_{\text{T}1}) / \mathbf{p}_{\text{T,ave}}$
- Asymmetry affected by JER, additional jets, and particle level balance (UE+out-of-cone)
- Additional jet effect removed by extrapolating to zero third jet \mathbf{p}_{T}



- Remaining particle level (im)balance after extrapolating soft radiation to zero is small
- Residual correction, subtracted in quadrature, taken from MC



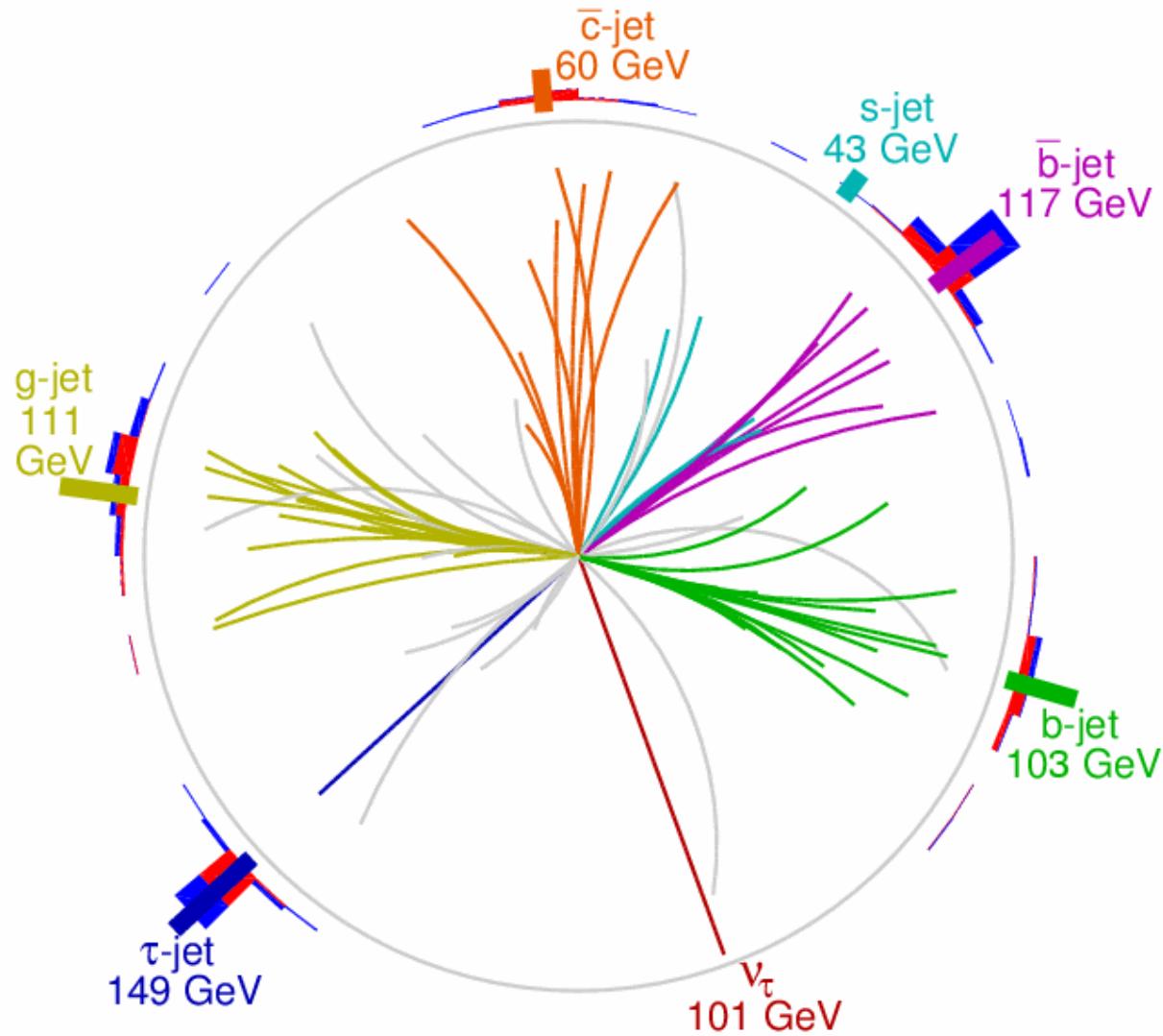
- Final results quoted as data/MC scale factor
 - Typical to see slightly (5–10%) worse resolution in data than MC



Jet reconstruction

- Topics I will cover today:

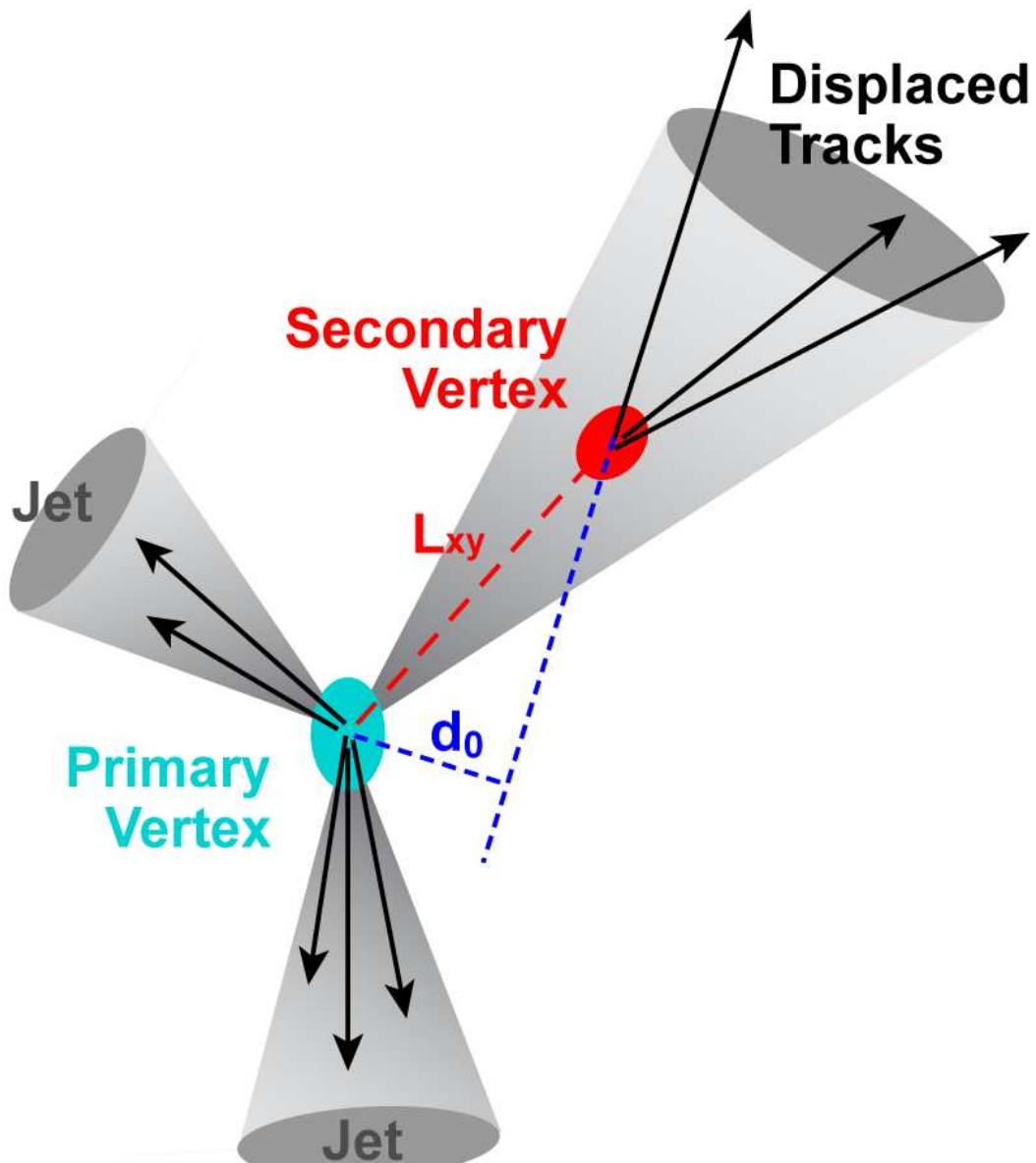
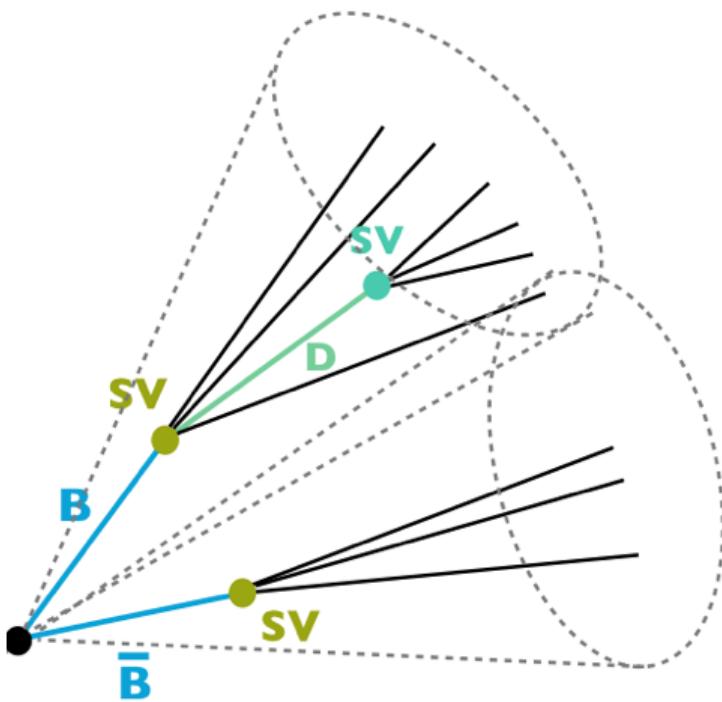
- ▶ Parton shower
- ▶ Hadronization (inlc. jet composition)
- ▶ Jet clustering
- ▶ Particle Flow / Global sequential cal.
- ▶ Jet response and pileup
- ▶ JEC and JER from data
- ▶ **Heavy flavor jets**
- ▶ **Quark/gluon likelihood**
- ▶ Inclusive jet cross section
- ▶ Top mass with lepton+jet



$gg \rightarrow tbH^+, t \rightarrow Wb \rightarrow scb, H^+ \rightarrow \tau\nu \rightarrow \text{hadrons}$ with a radiative gluon jet

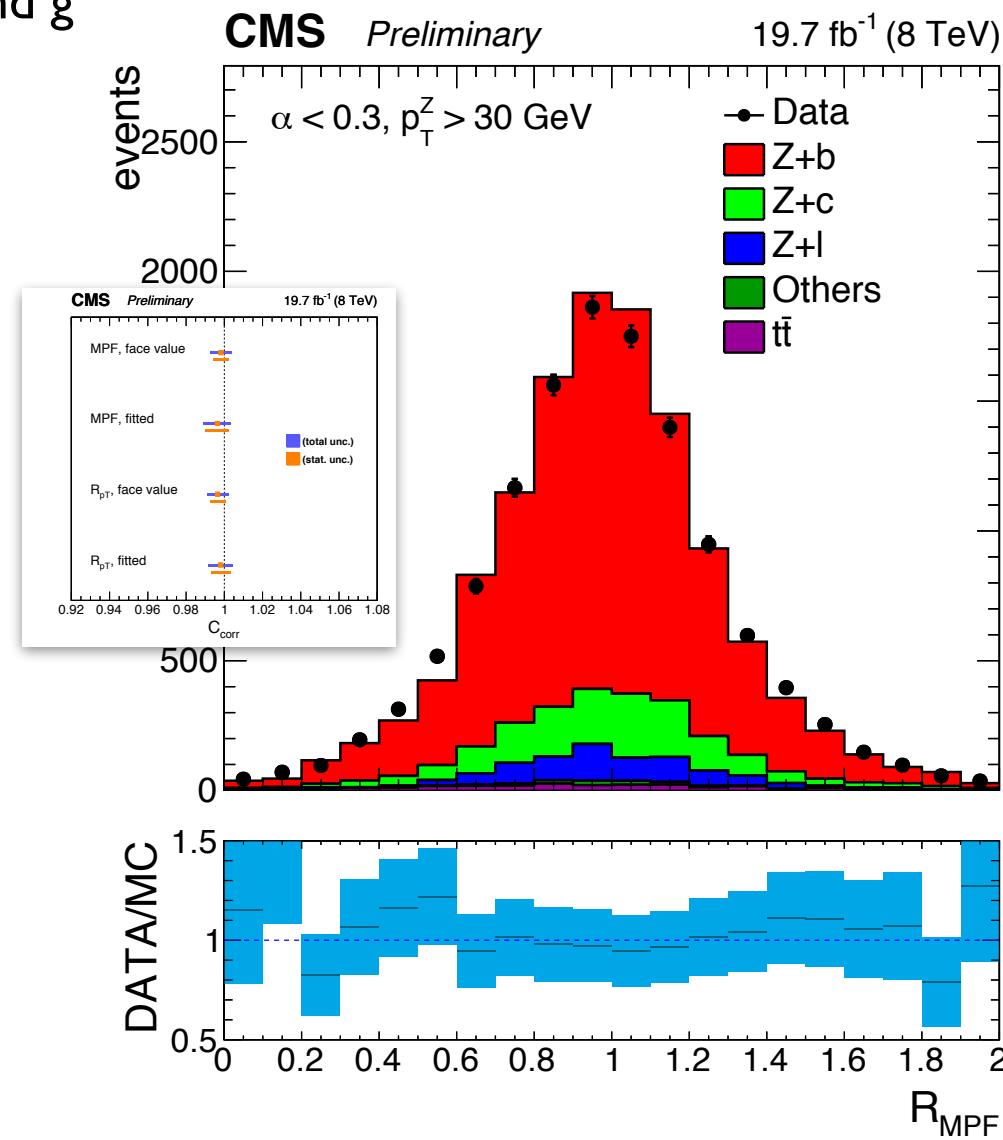
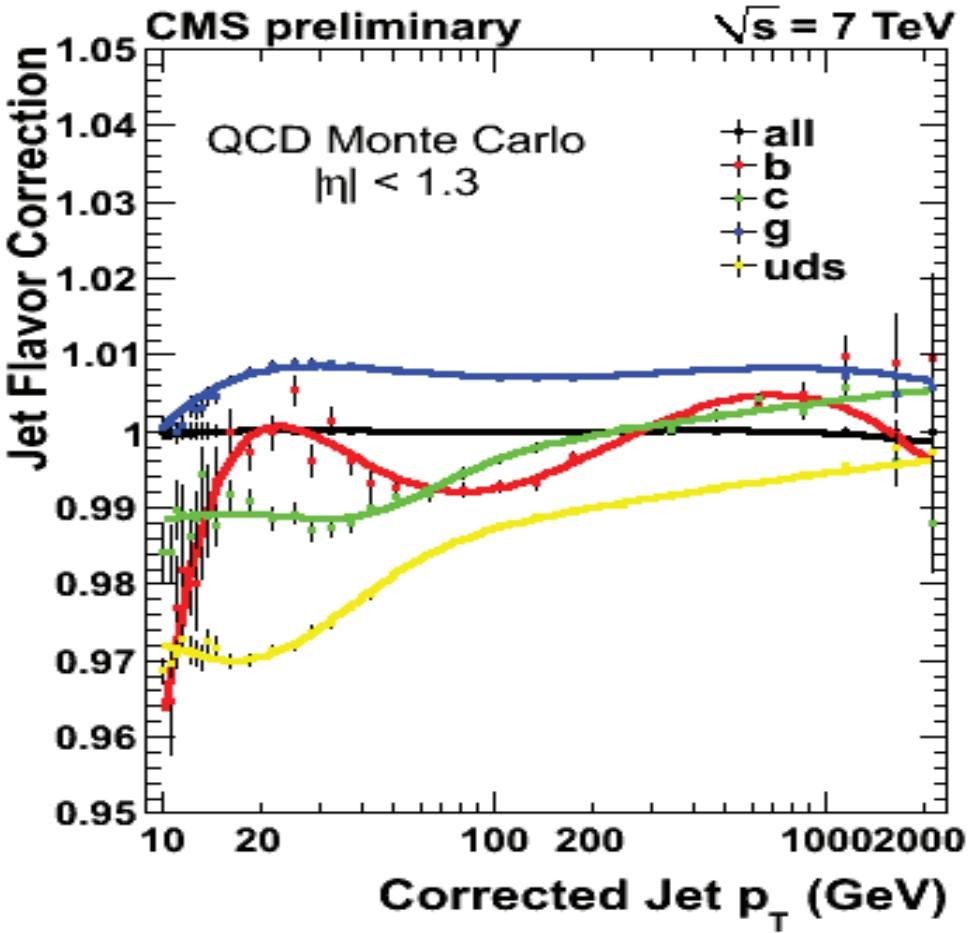
Heavy flavor jets

- Heavy flavor jets are identified by a heavy hadron containing b or c quark
 - ▷ B and D have cT of ~ 0.1 mm and can often be identified by a secondary vertex
 - ▷ Alternative way is to tag semileptonic decays of B and D
- Wide b-jets from gluon-splitting ($g \rightarrow b\bar{b}$) can have two SV for b, and another two for “cascade-c”



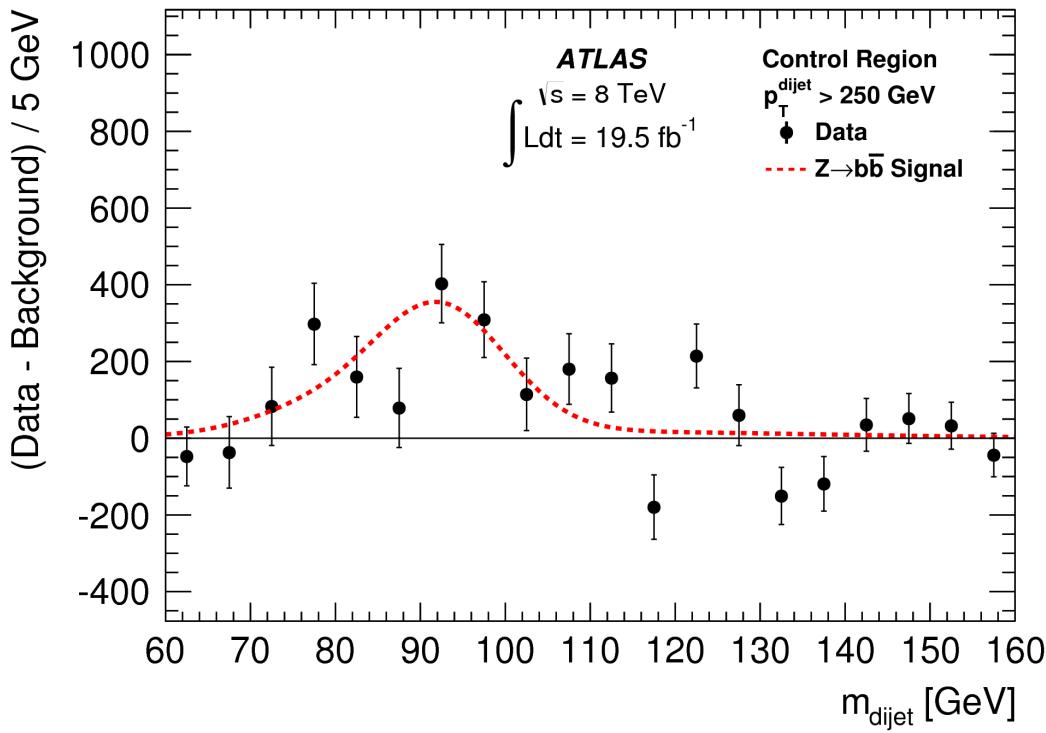
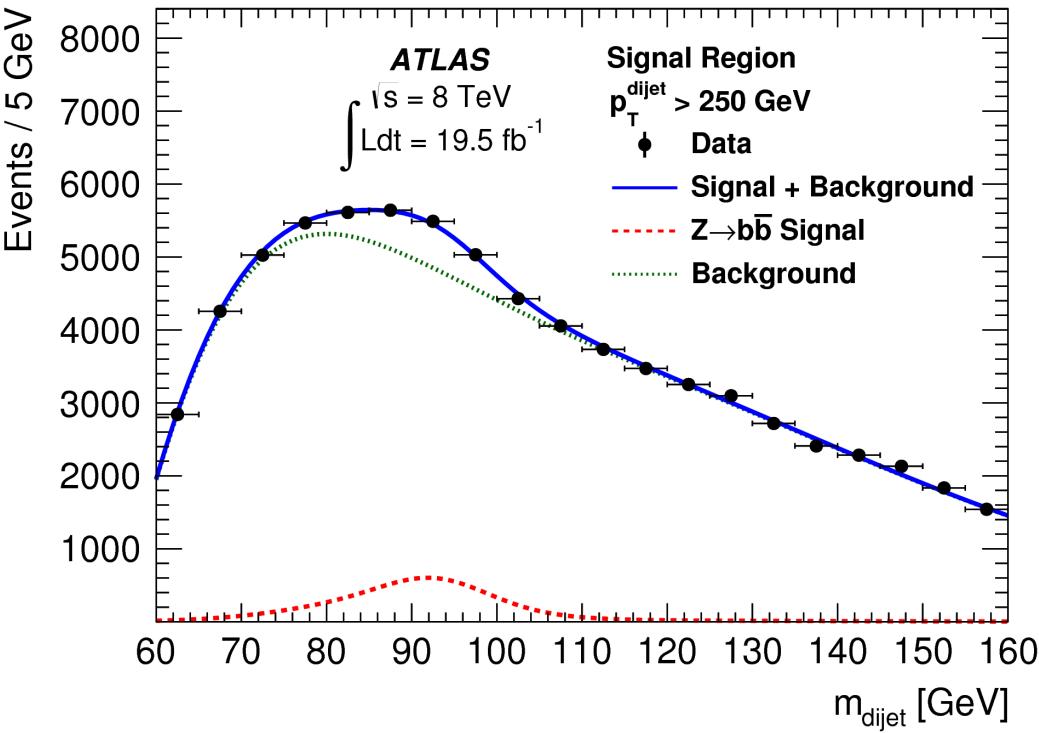
Flavor response

- B-jet parton-to-particle response dominated by neutrinos from semileptonic decays
 - ▷ Neutrinos excluded from particle jets so this is **not** part of JES
- B-fragmentation and response between uds and g
- Precise b-JES from data using $Z(\ell\ell) + b$ events
 - ▷ (CDF also used $Z \rightarrow b\bar{b}$)

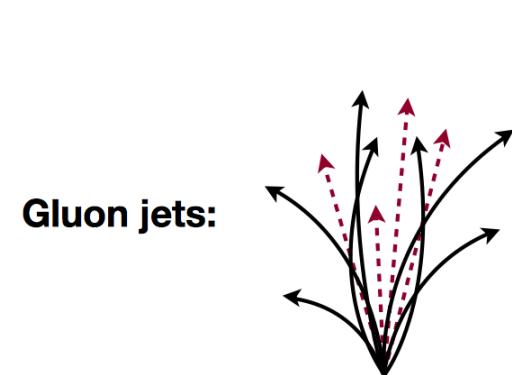
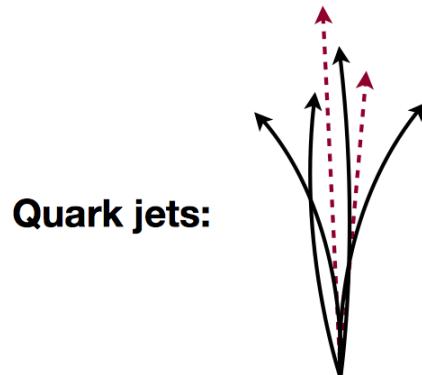


- Semileptonic decays are a major effect for b-jets
 - ▷ about 25% (+1.3%/-1.1%) of B hadrons decay semileptonically
 - ▷ on average about 12% of original b-parton p_T lost to neutrinos in semileptonic decays
 - ▷ introduces large smearing e.g. for boosted $Z(bb)$ and $H(bb)$ reconstruction
- Regression corrections can recover some of the resolution
 - ▷ neutrino p_T correlated with observable lepton (muon, electron) p_T

Boosted $Z(bb)$ decay

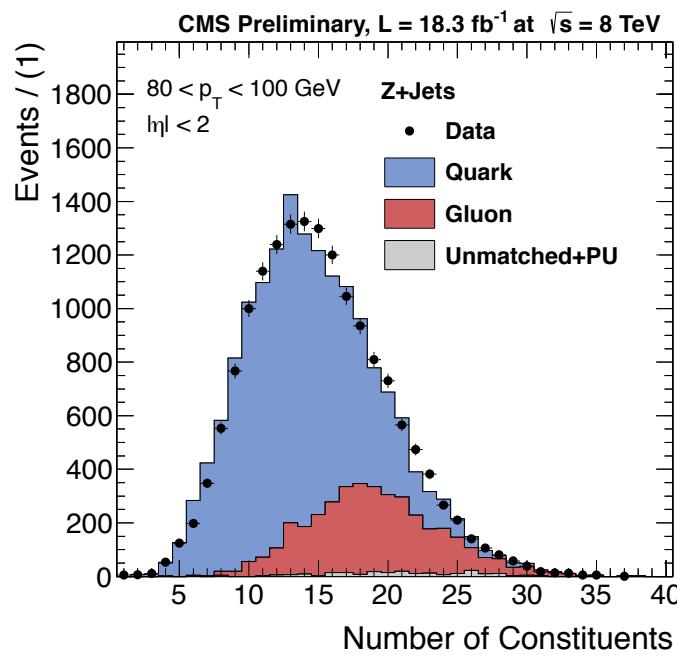


- Gluon jets differ from quarks: more particles, softer leading particle, wider jet
 - These derive from high colour factor ($C_A=3$ for gluons vs $C_F=4/3$ for quarks vs $T_F=1/2$ for $g \rightarrow q\bar{q}$)

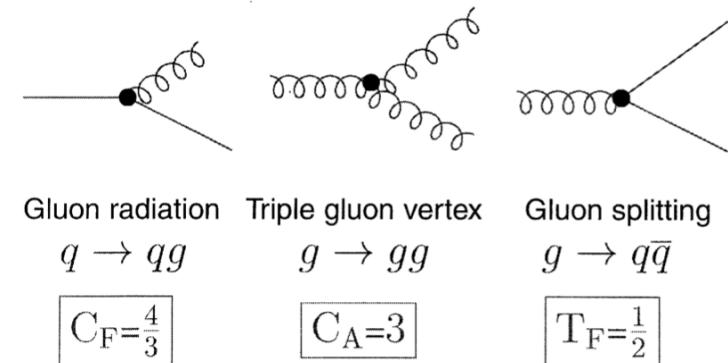
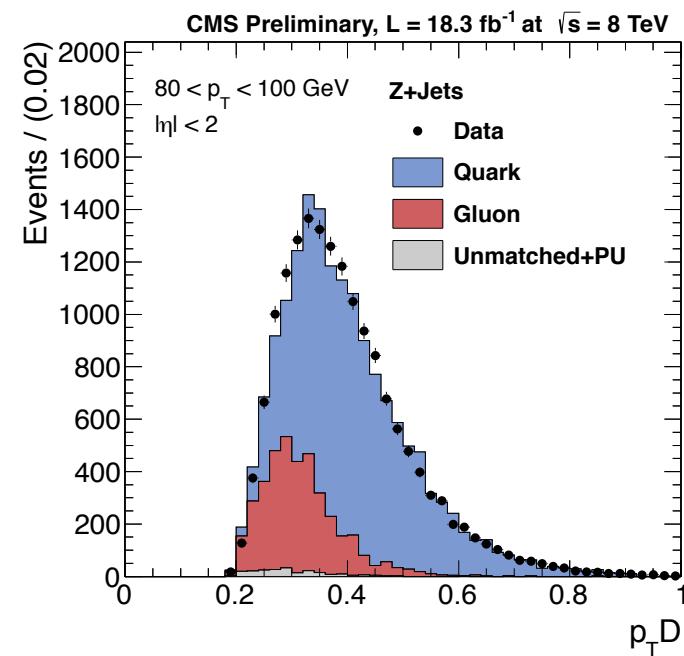


F. Pandolfi

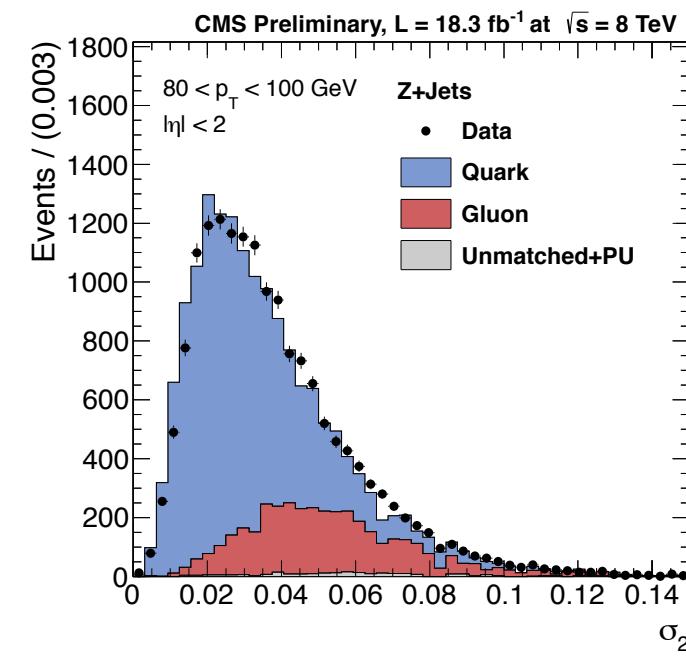
particles



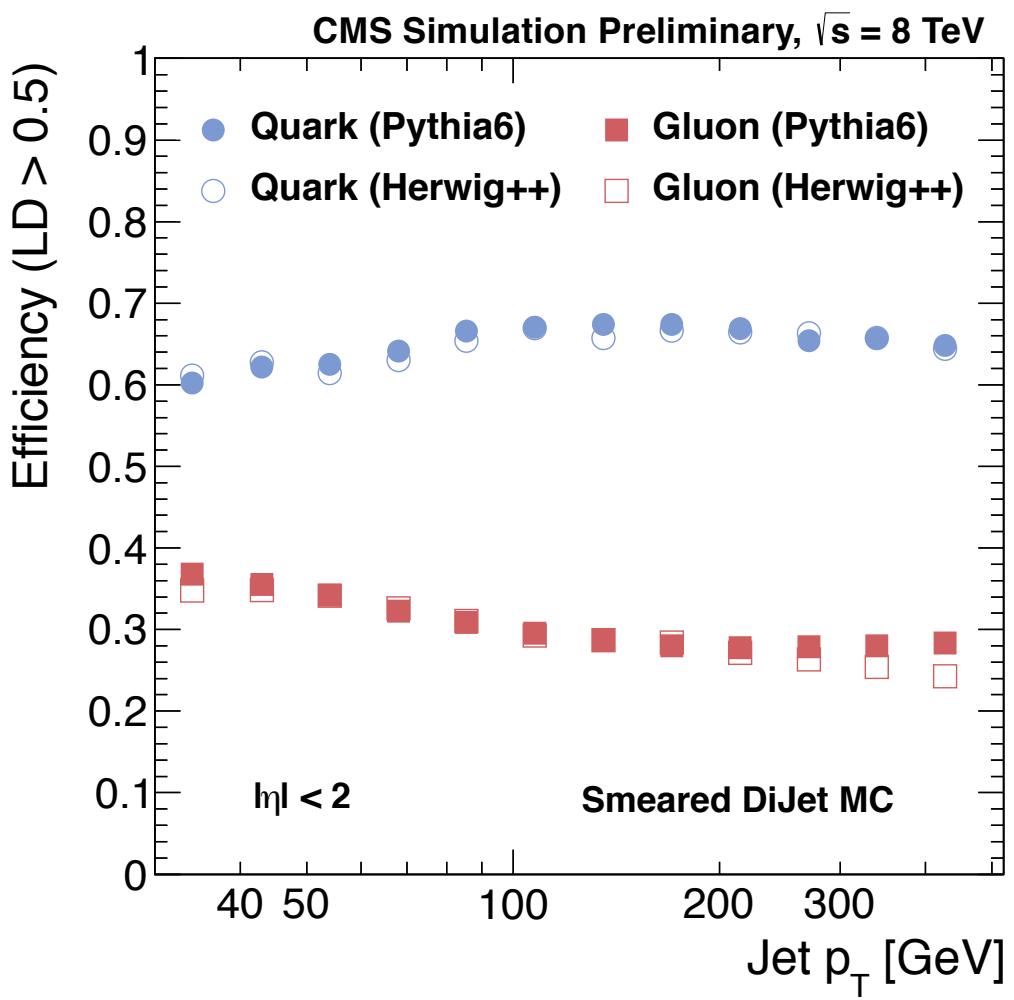
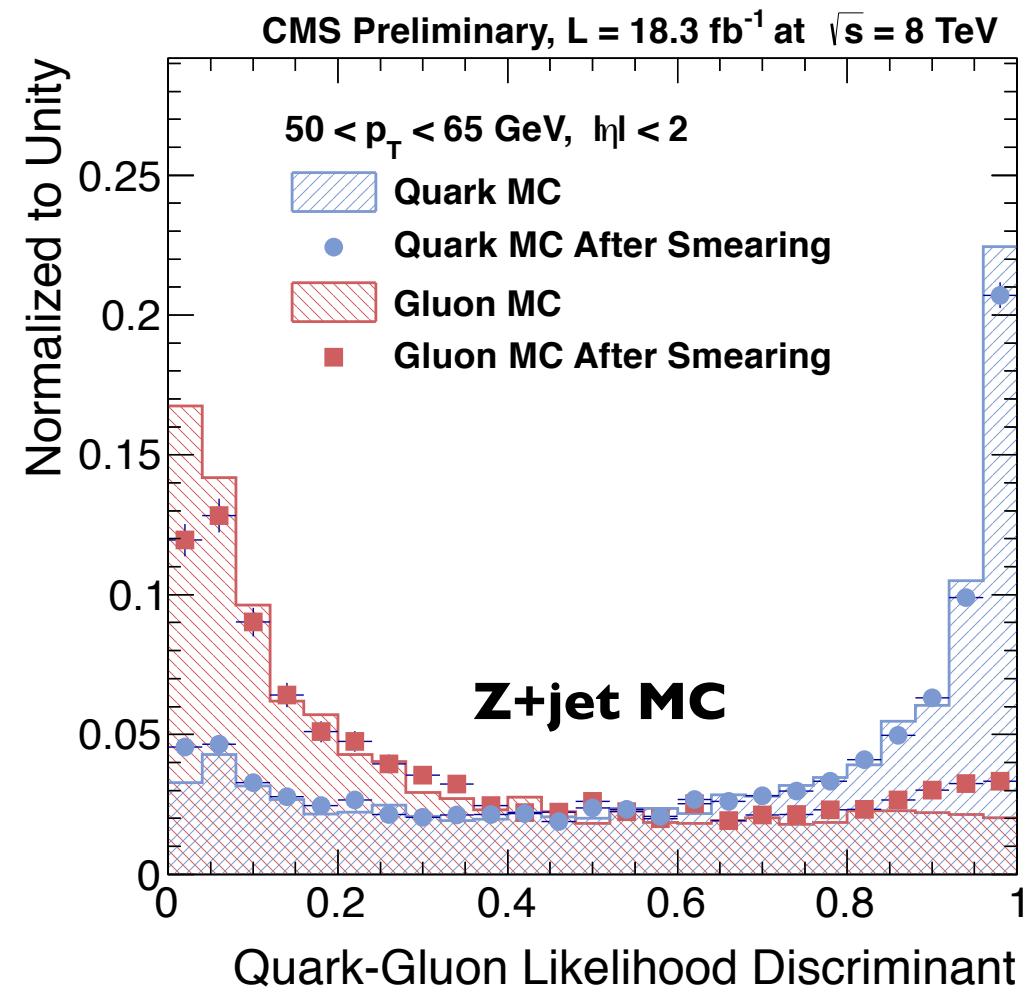
“hardness” of jet



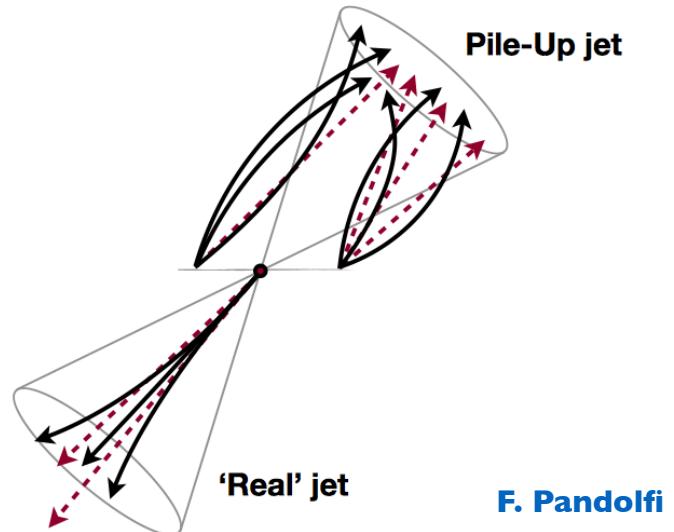
jet width



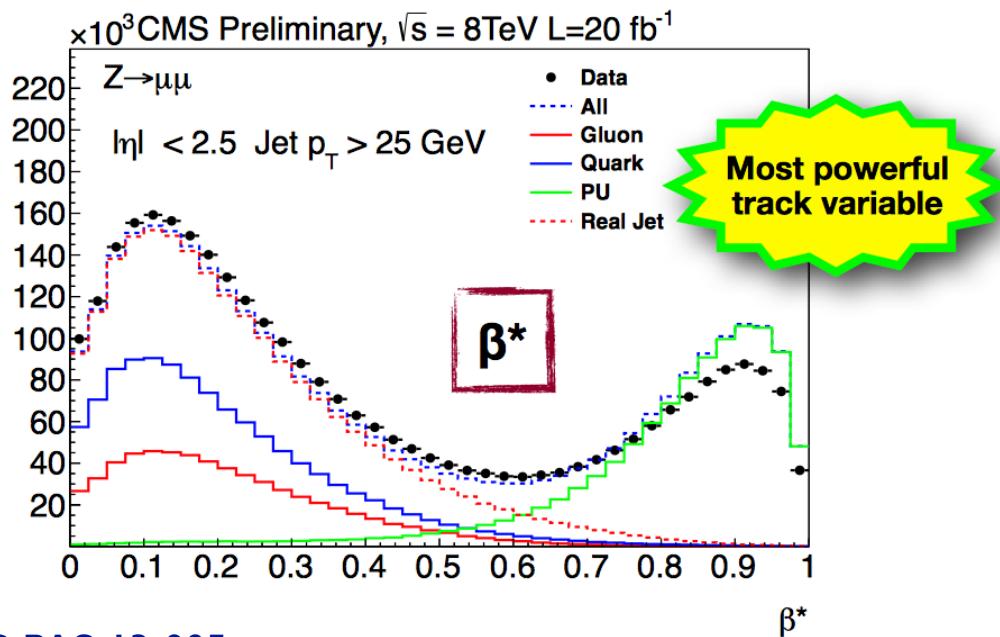
- Likelihood discriminant for quark vs gluon is not as powerful as for b-jet tagging, but ok
- Pythia6 overestimates gluon efficiency, Herwig++ underestimates
 - ▶ good agreement in Dijet MC after smearing to match Z+jet LD distributions in data



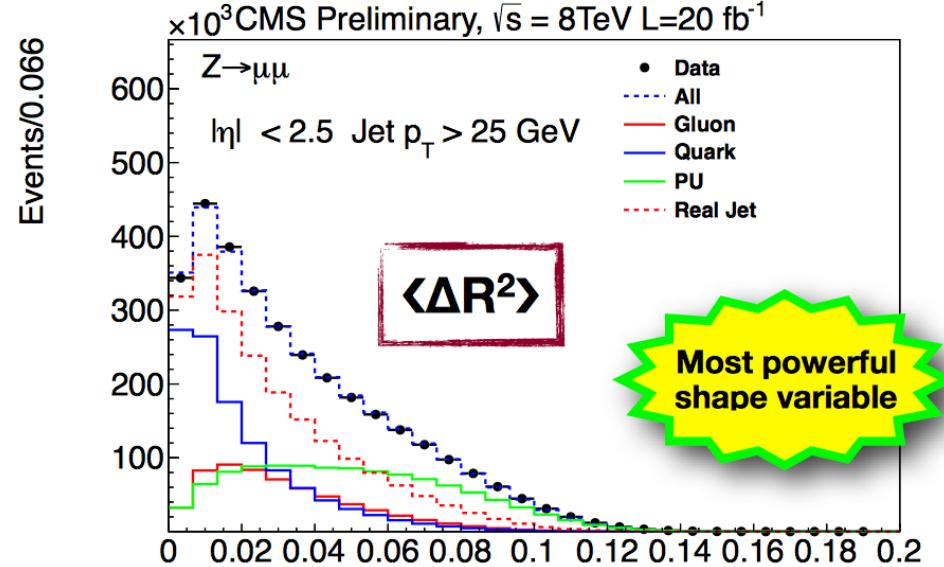
- Jets from pileup interactions are an issue at LHC
 - single gluon jets from non-leading vertex
 - overlapping pileup jets from non-leading vertices
- Tracking information and shape to identify pileup jets



fraction of tracks from PU vertices

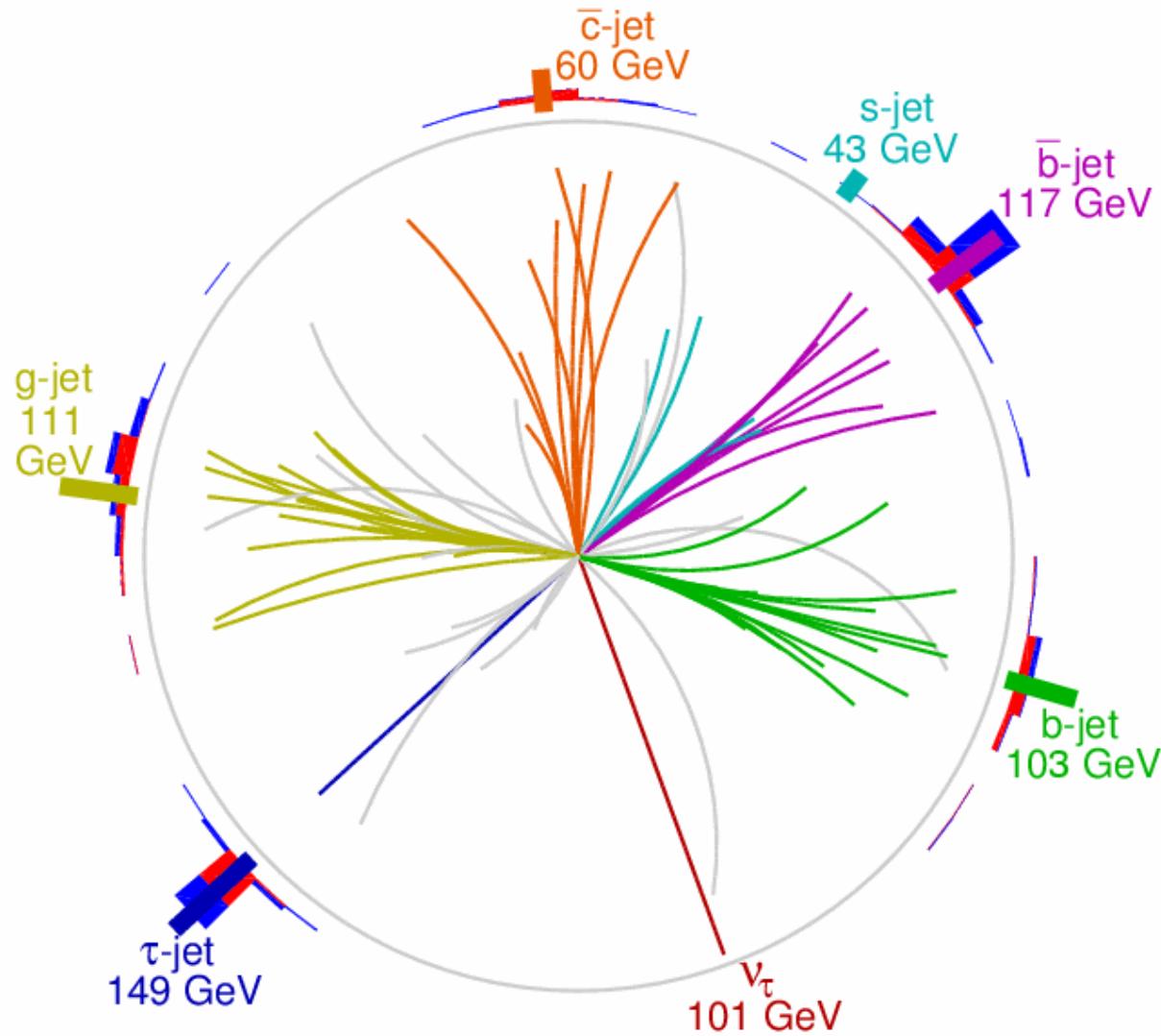


RMS width of the jet (squared)



- Topics I will cover today:

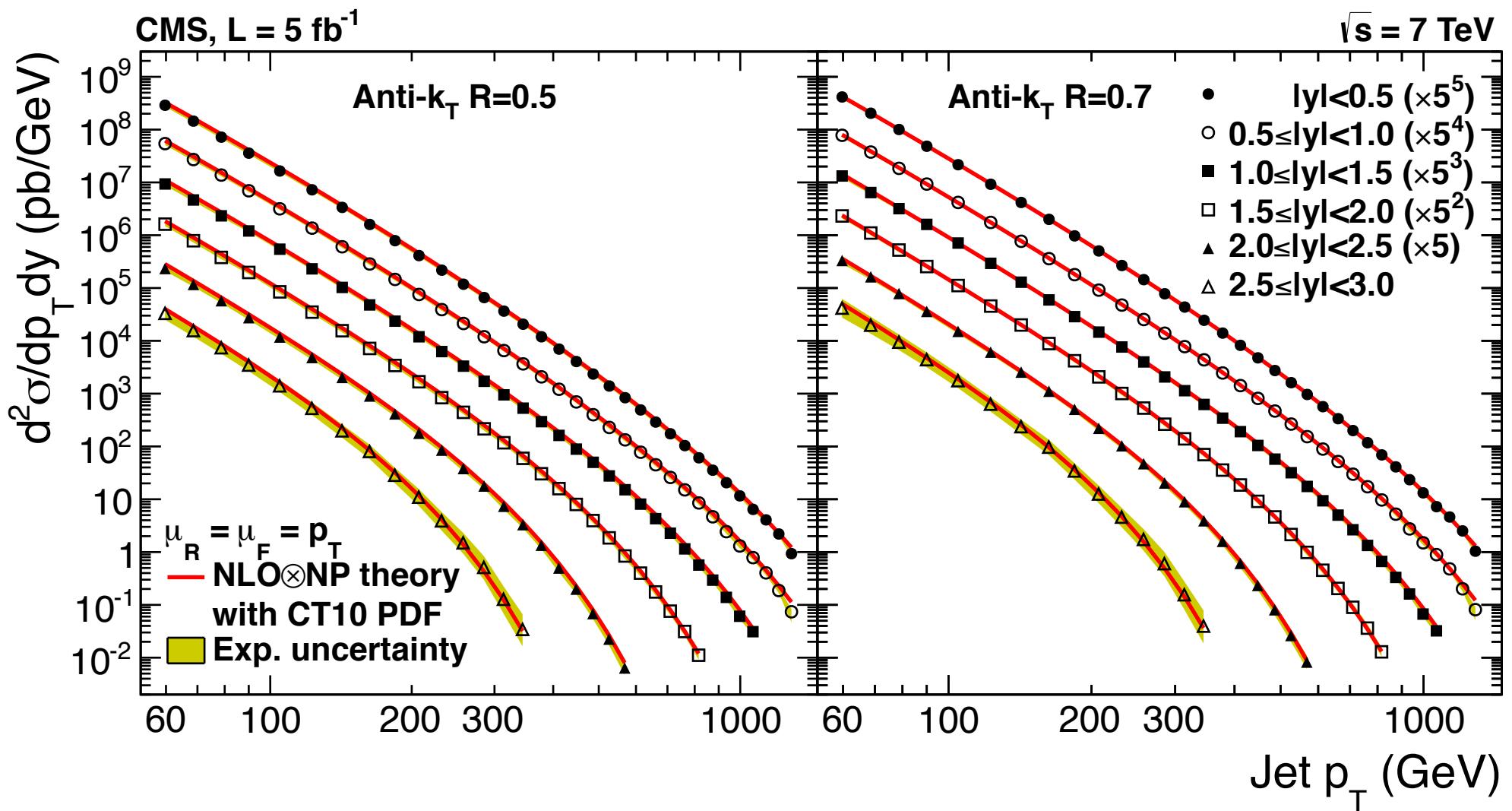
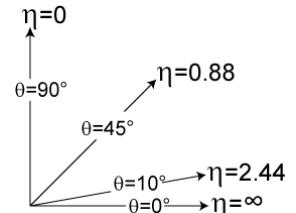
- ▷ Parton shower
- ▷ Hadronization (inlc. jet composition)
- ▷ Jet clustering
- ▷ Particle Flow / Global sequential cal.
- ▷ Jet response and pileup
- ▷ JEC and JER from data
- ▷ Heavy flavor jets
- ▷ Quark/gluon likelihood
- ▷ **Inclusive jet cross section**
- ▷ **Top mass with lepton+jet**



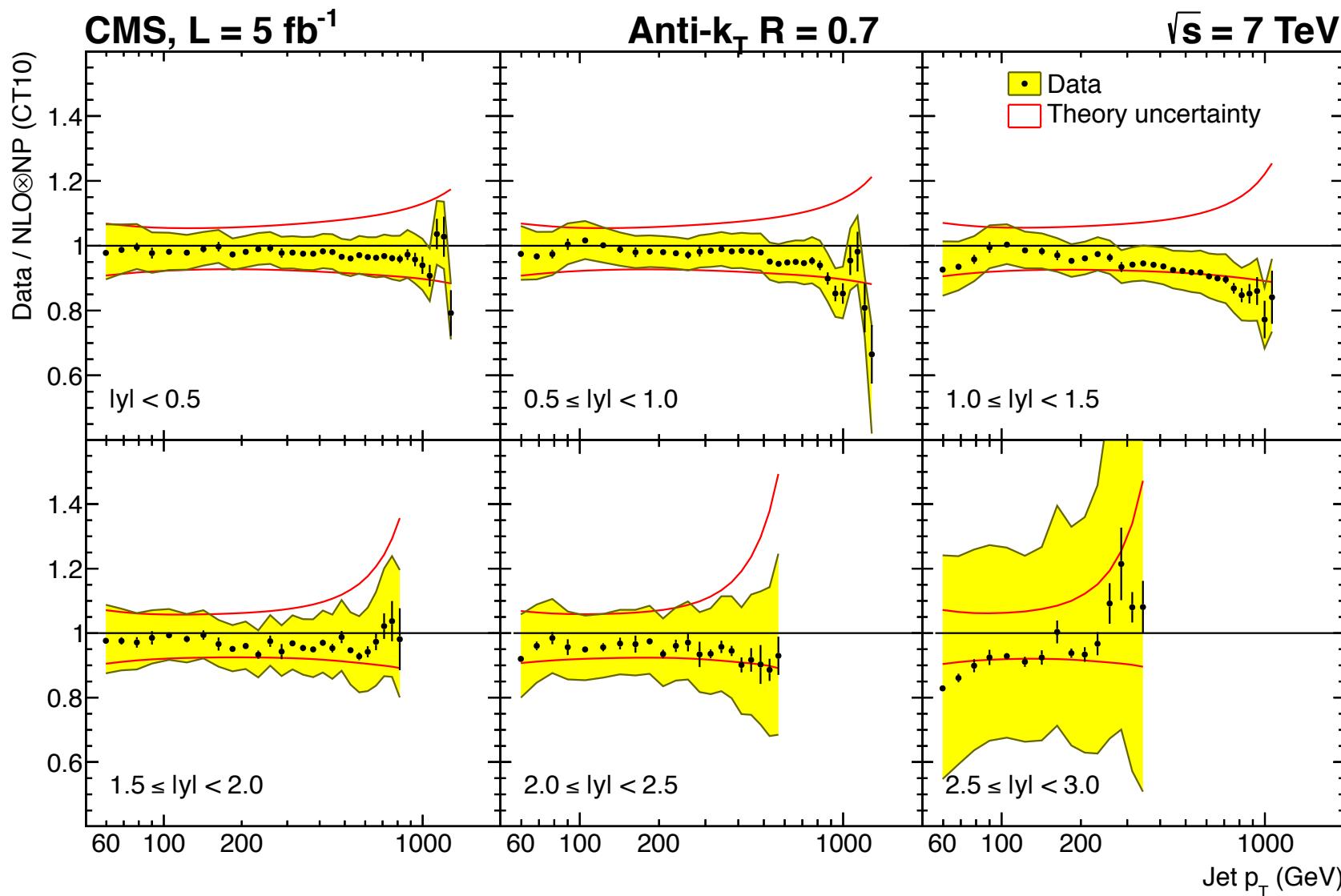
$gg \rightarrow tbH^+, t \rightarrow Wb \rightarrow scb, H^+ \rightarrow \tau\nu \rightarrow \text{hadrons}$ with a radiative gluon jet

Inclusive jet cross section

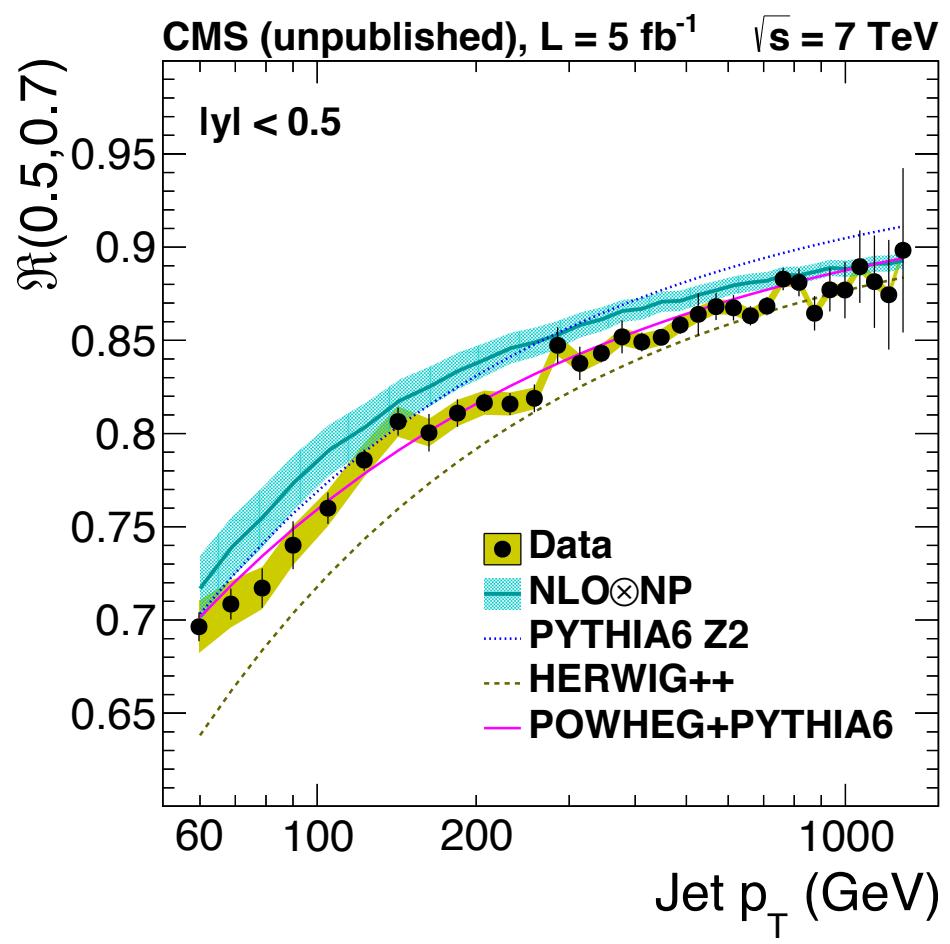
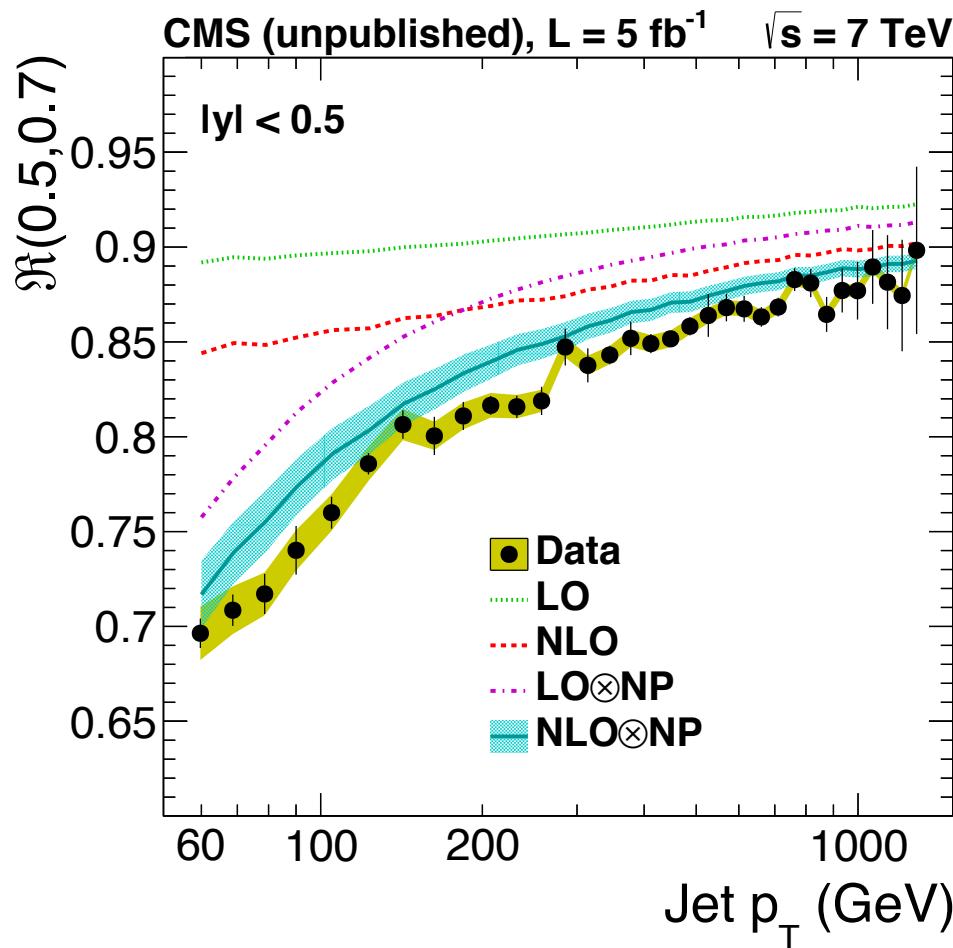
- Inclusive jet production one of most fundamental probes of QCD
 - ▷ = rate of jets versus p_T and scattering angle ($y \sim \eta = \ln[\tan(\theta/2)]$)
- Fundamental parameter is jet radius R



- Perturbative QCD predictions for large R quite accurate at next-to-leading-order (NLO)

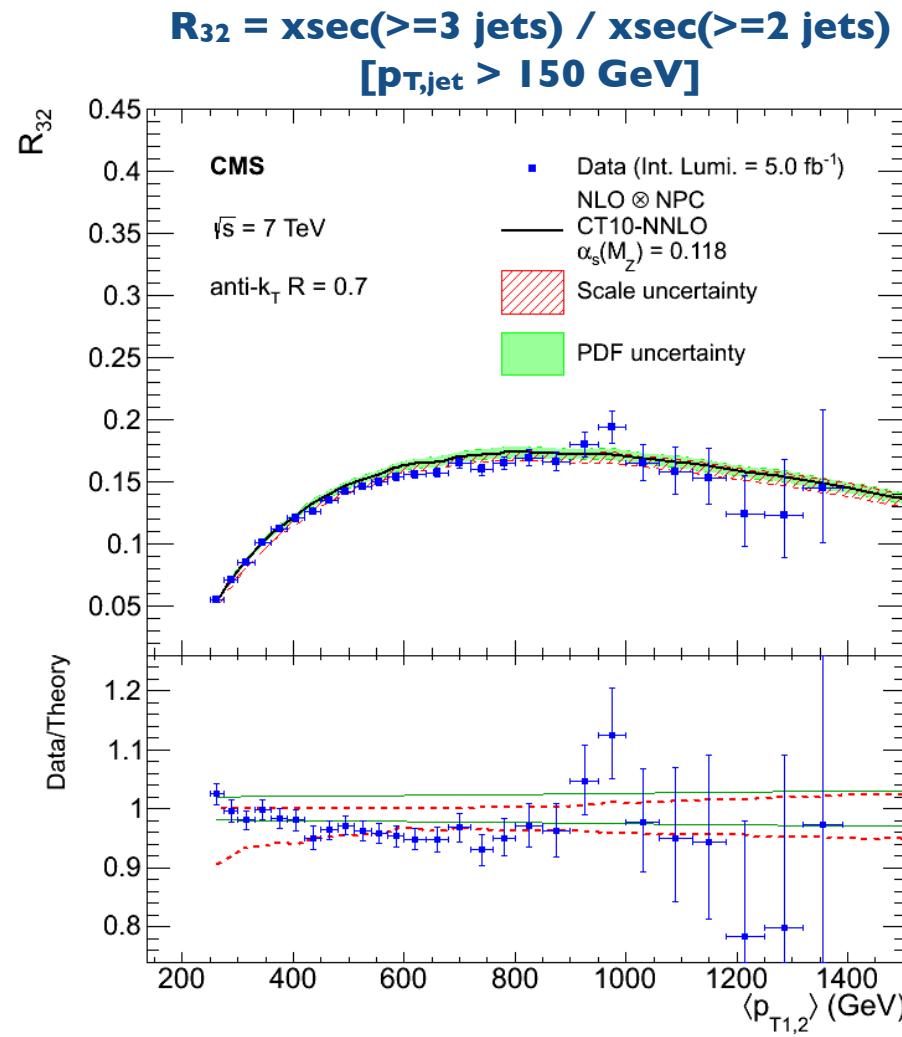
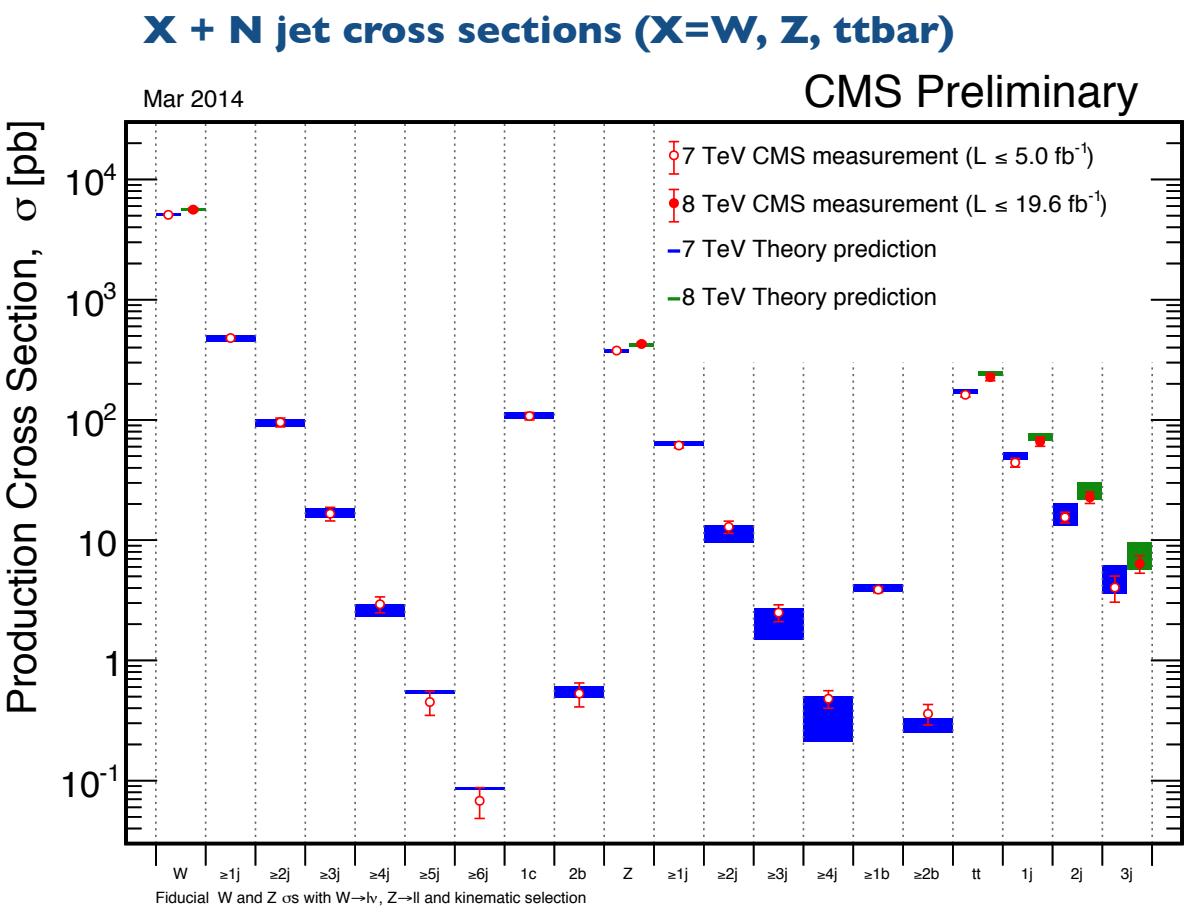


- For smaller R, generally need higher order pQCD to model larger jet multiplicities
 - ▷ alternatively, NLO matched to parton shower (e.g. POWHEG) does well
- Ratio of jet cross sections with R=0.5/R=0.7 sensitive to pQCD one order higher
 - ▷ e.g. NLO for ratio means NNLO for cross sections



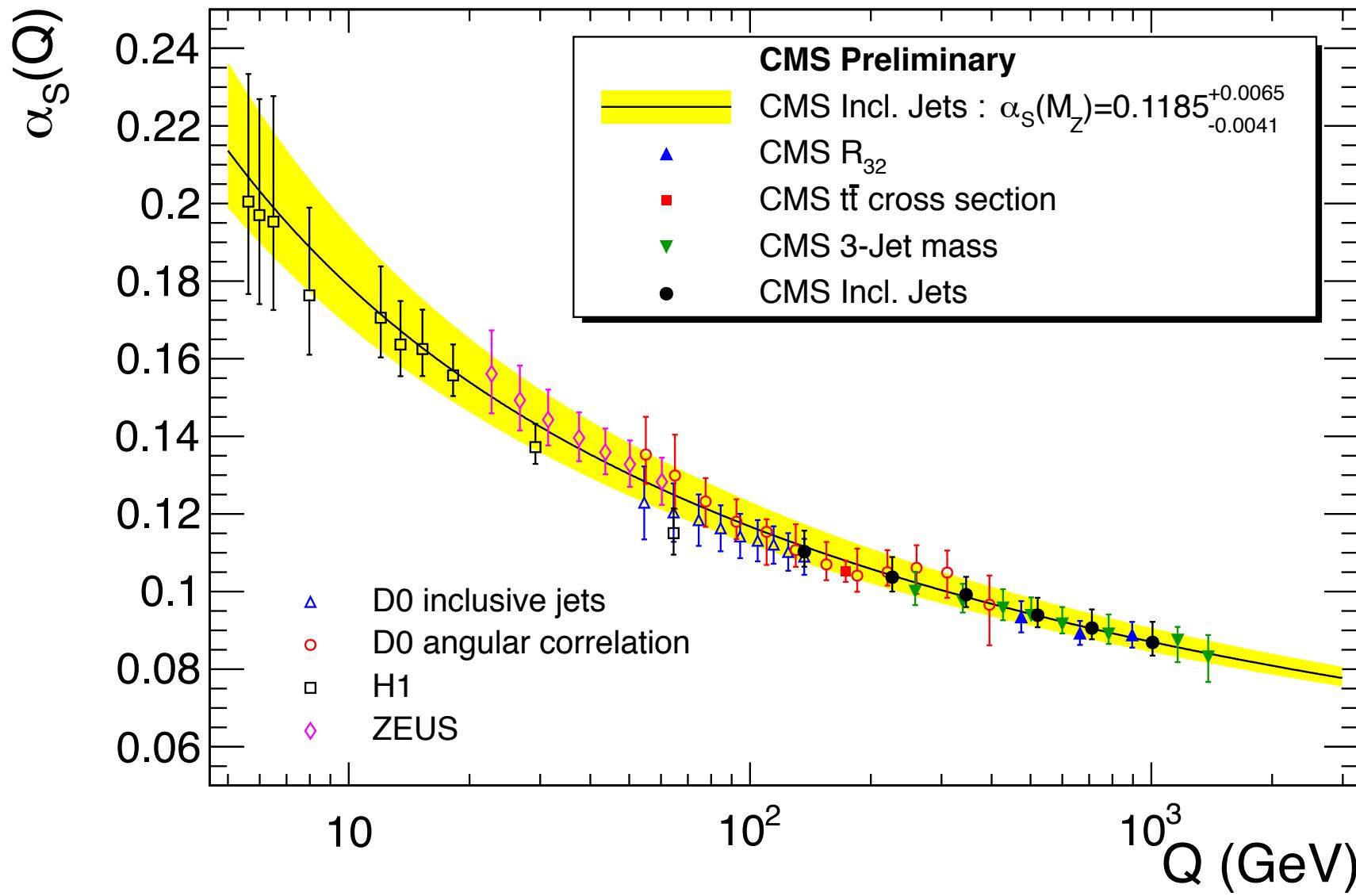
When 2 become 3

- What's the difference between a 2-jet and a 3-jet event: α_s and radius parameter R
 - ▷ each additional jet “costs” a multiple of α_s
 - ▷ “price per jet” depends on R (and minimum p_T required, if too high)
 - soft’ish collinear’ish gluon radiation promoted to a jet with small R parameter

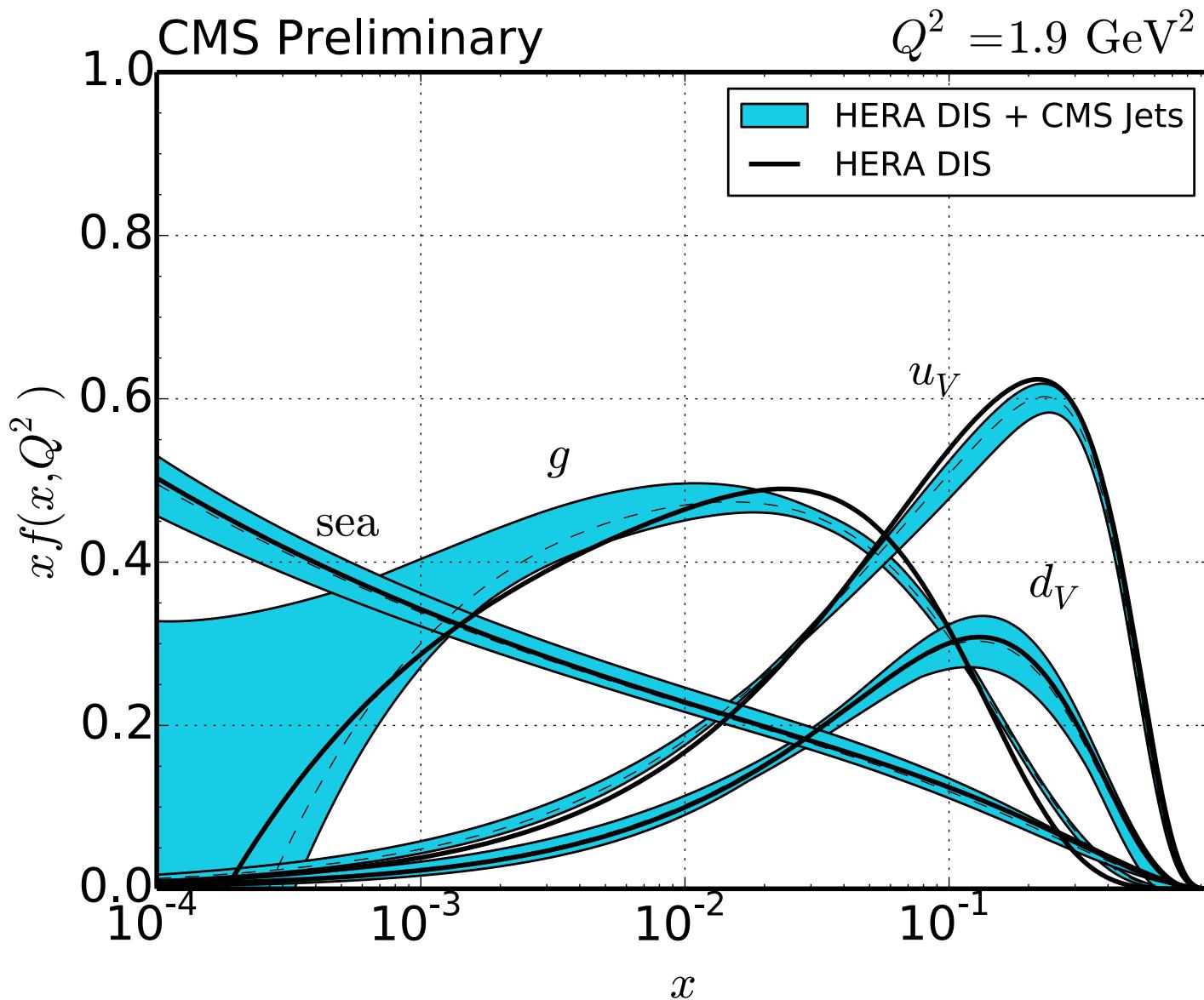


Strong coupling from jets

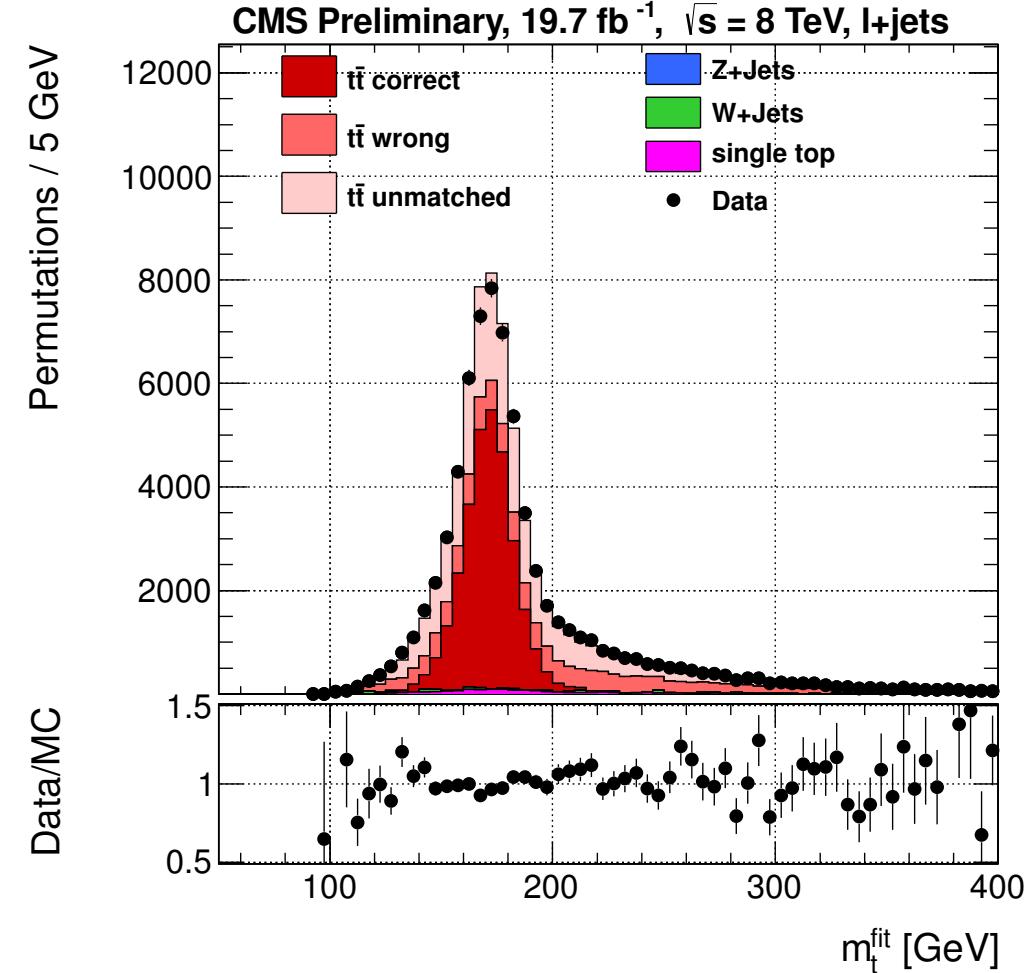
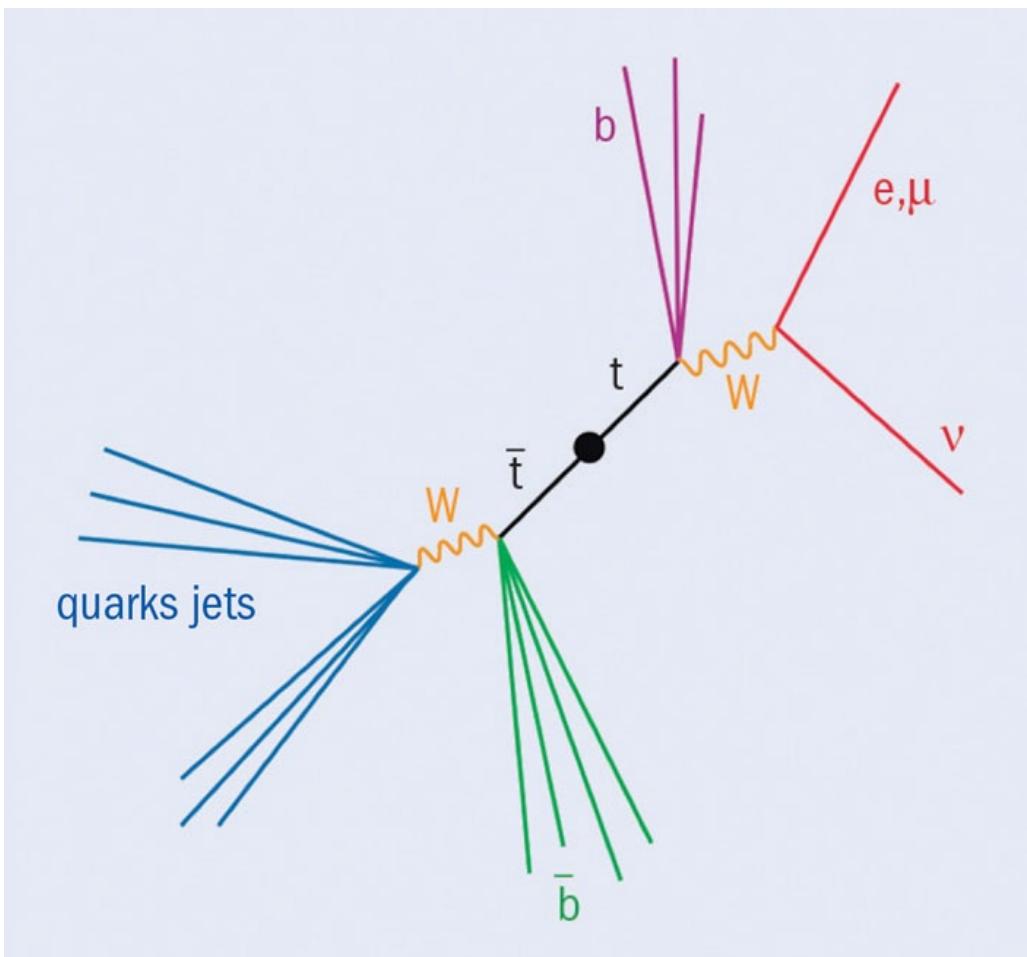
- Strong coupling α_s controls probability of (gluon) jet radiation
 - ▷ Running coupling can be extracted from jet data (inclusive, 3-jet/2-jet, 3-jet mass etc.)



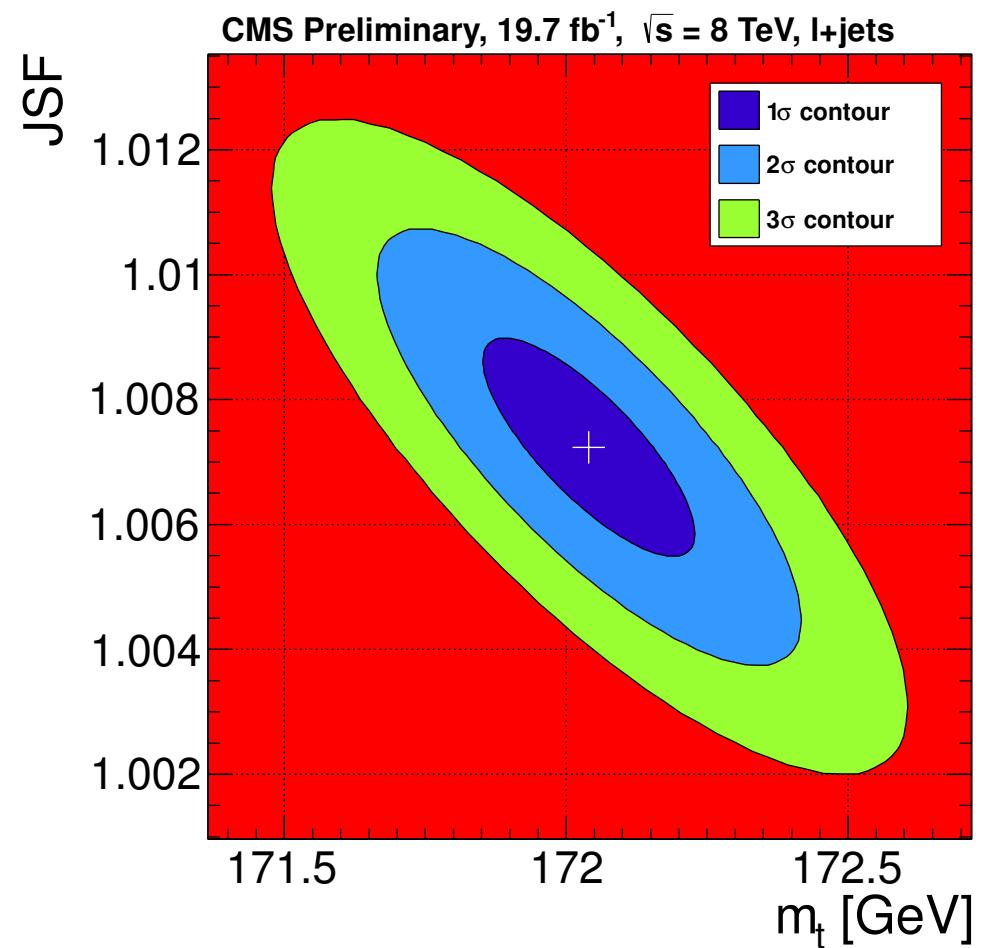
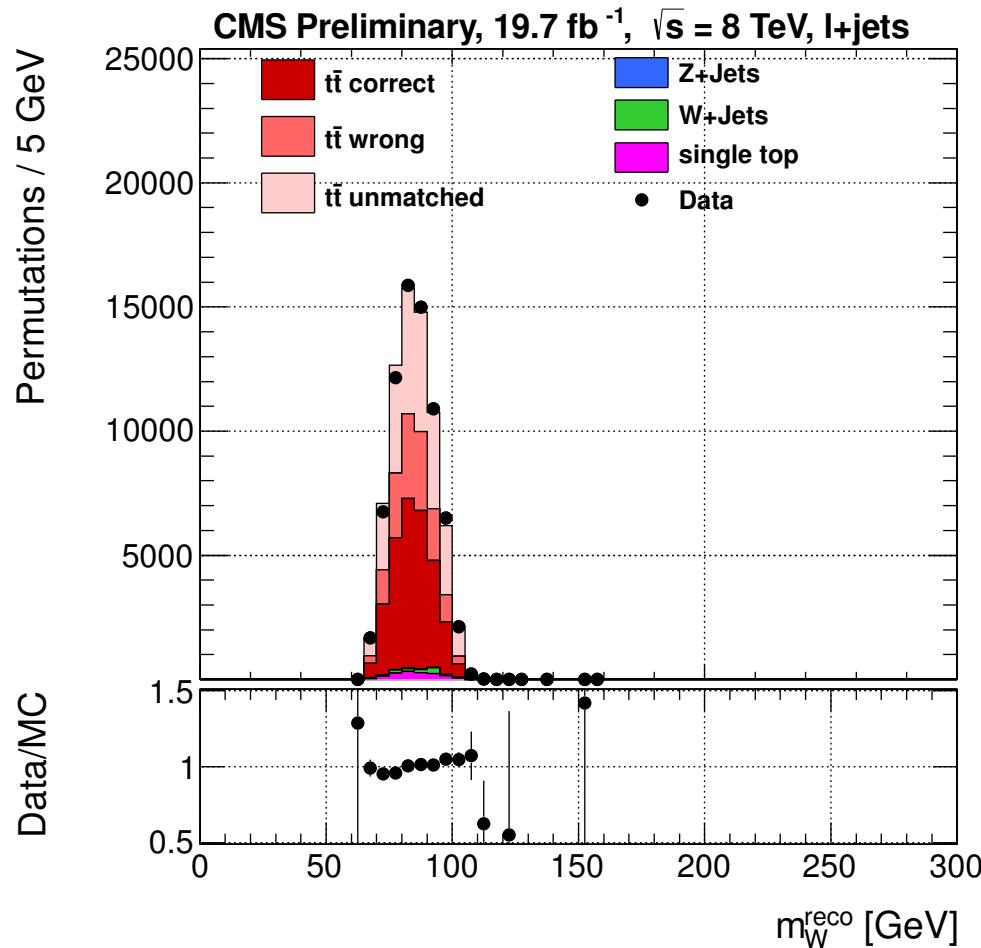
- Jet data useful for complementing HERA measurements of proton parton distributions



- Most precise determinations of top quark mass m_t to date with lepton+jet channel
 - ▷ “golden channel” with reduced systematics compared to dileptonic and fully hadronic channels
 - ▷ dileptonic: two neutrinos => cannot reconstruct individual neutrinos p_T
 - ▷ fully hadronic => large combinatoric background (wrong jet combinations)

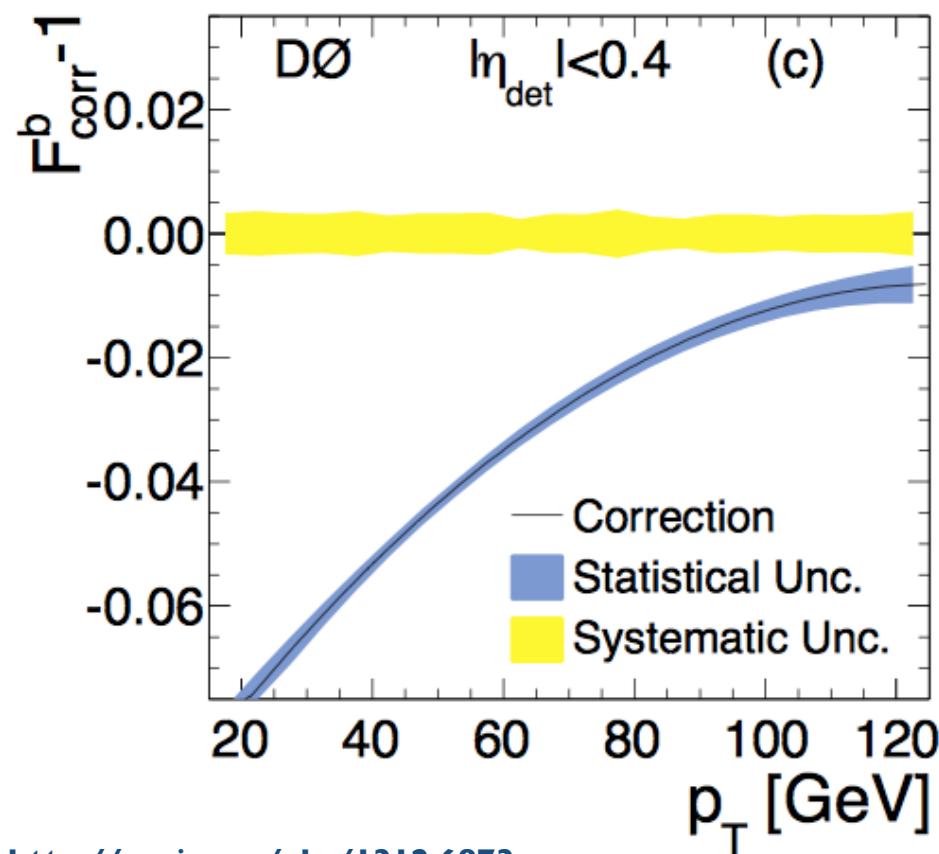


- Hadronic W mass can be reconstructed from light jets
 - Offers a way to fit leading JES uncertainty *in-situ* from data
 - Top mass from $W(q\bar{q}) + b$
- With jet energy scale factor (JSF) in 2D method b-jet to light jet scale dominant systematic



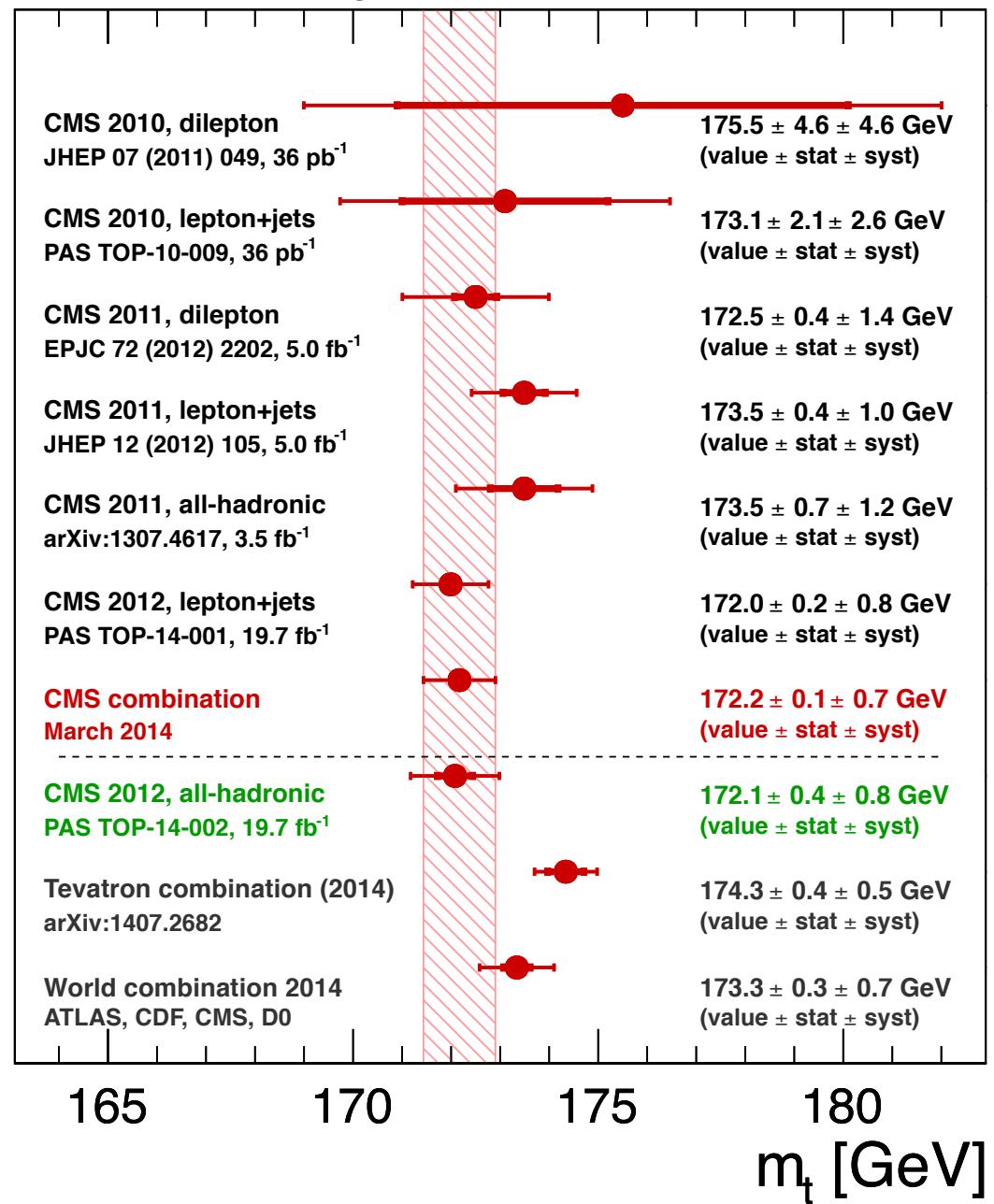
Top mass combinations

- The two most precise top mass measurements from CMS and D0 currently differ by about 3σ
- Key is the b-jet scale relative to light
 - CMS: MC with Z+b check in data
 - D0: single-particle response in data



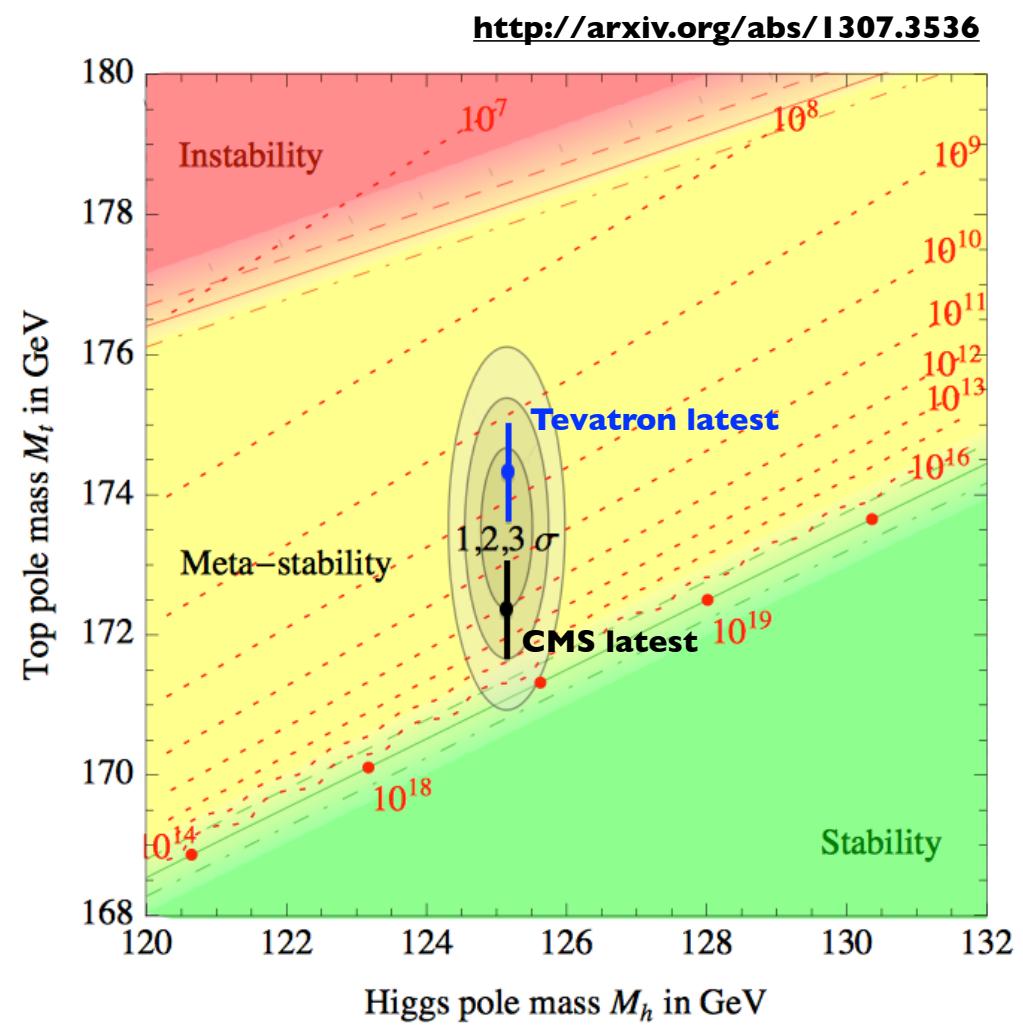
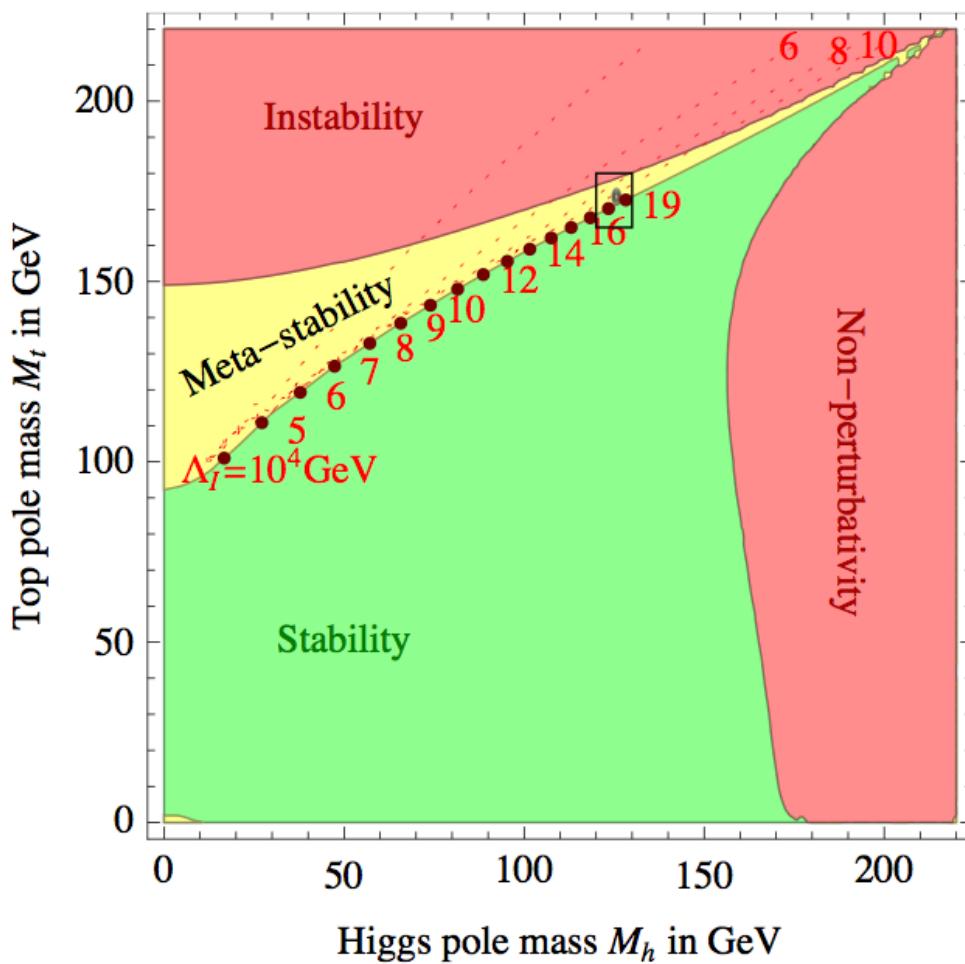
<http://arxiv.org/abs/1312.6873>

CMS Preliminary

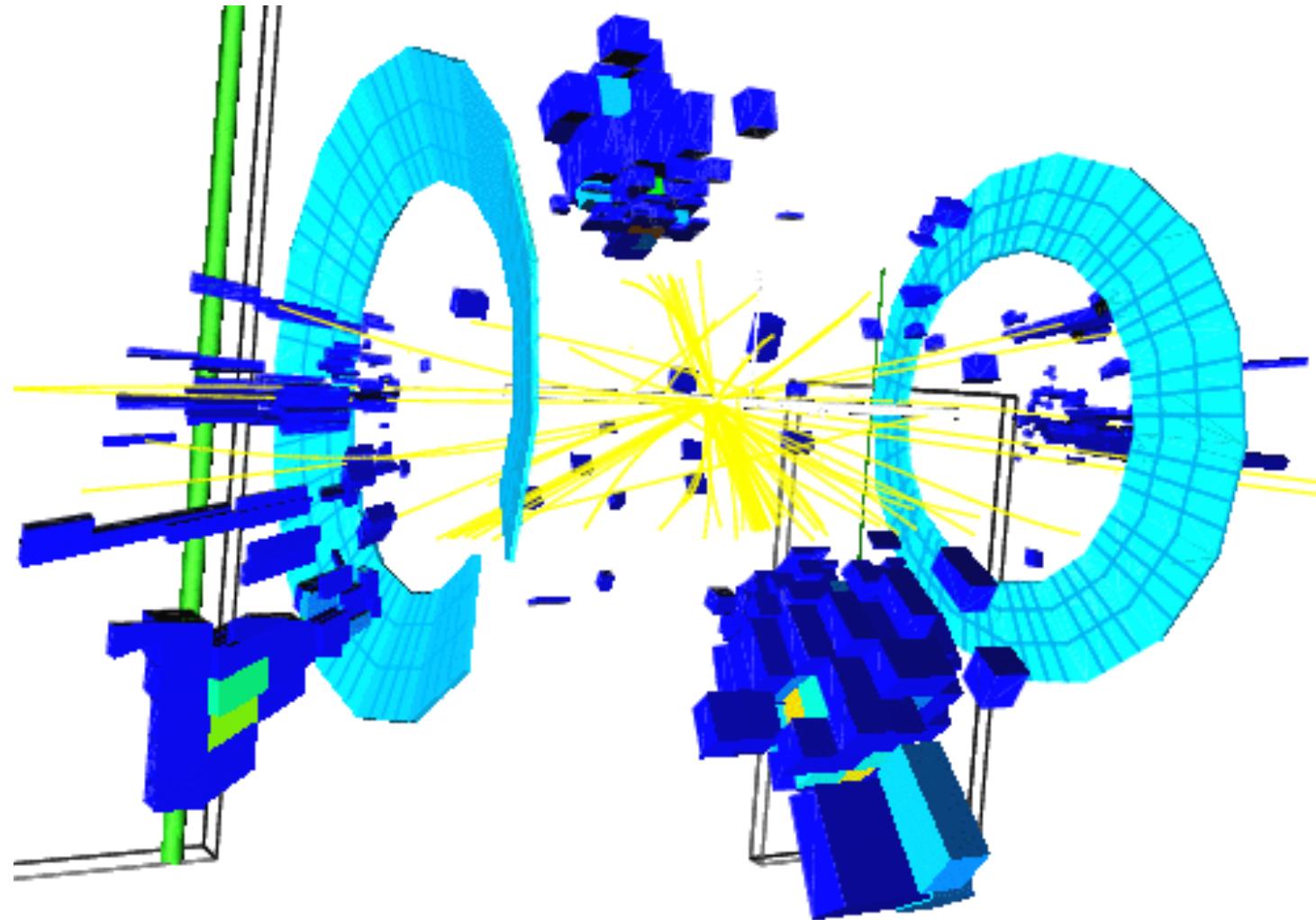


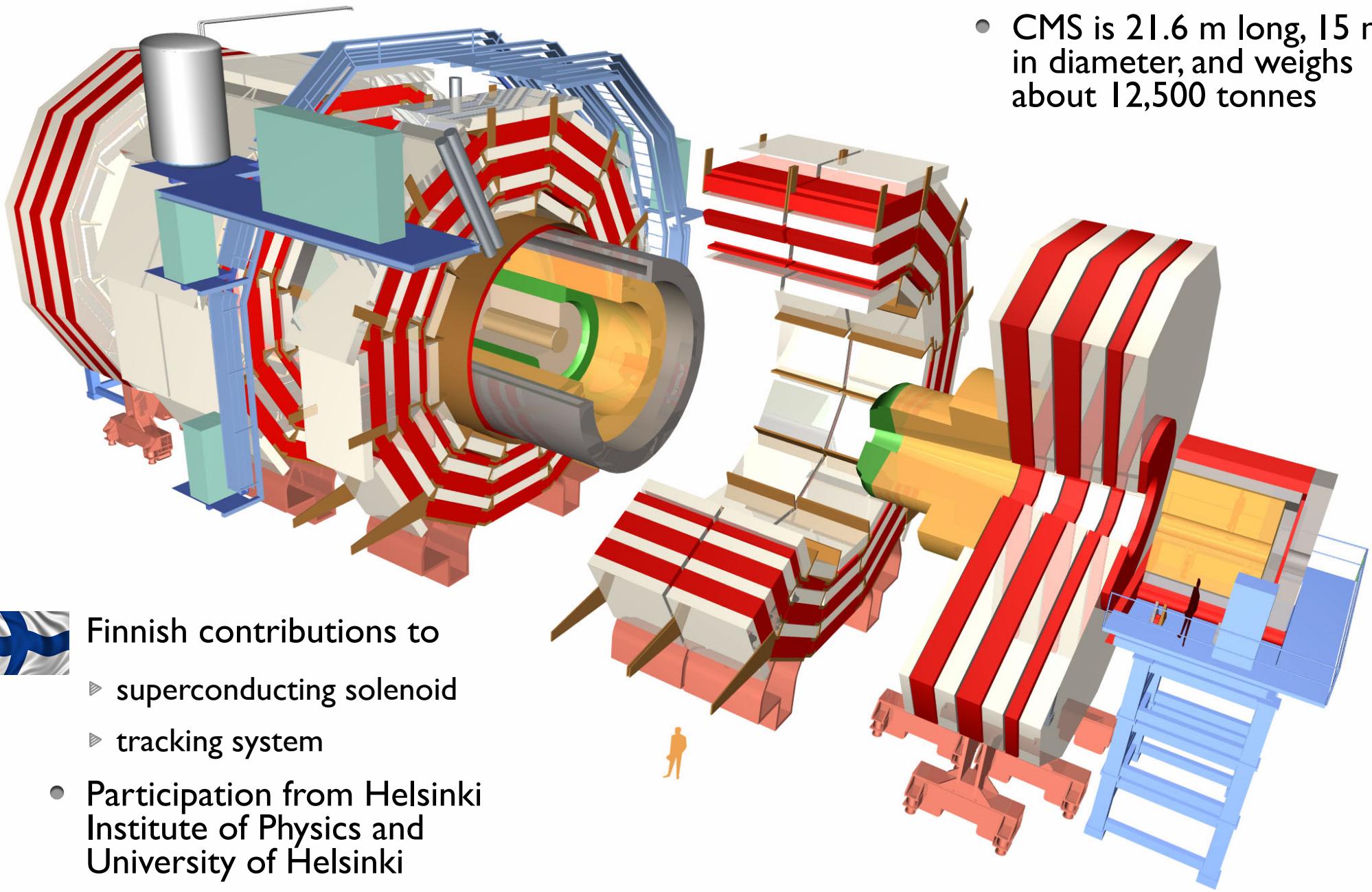
Why Top mass matters

- If only standard model up to Planck scale, we seem to live in semi-stable universe
 - ▷ Top quark mass needed to confirm this
 - ▷ Leading experimental systematic: b-jet JES
- Alternatively, there are new particles that could also be responsible for dark matter
 - ▷ We may find the answer in Run II



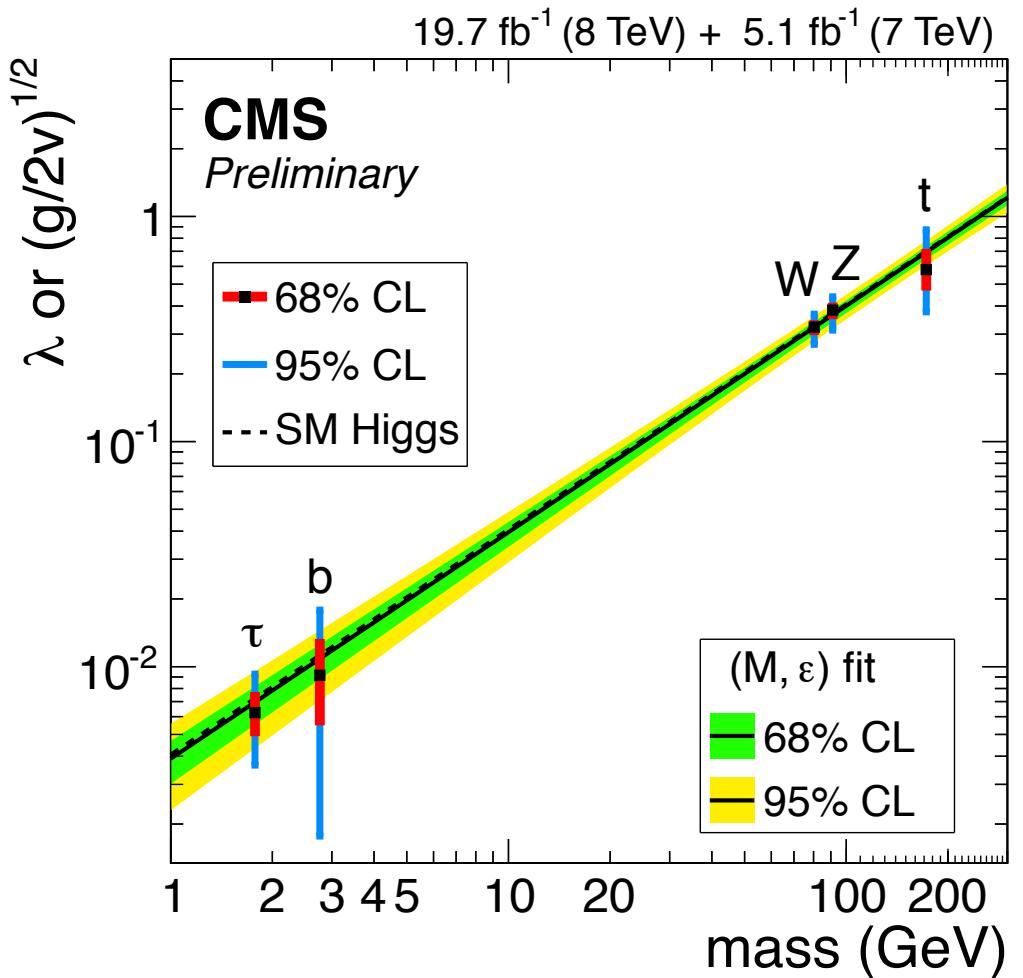
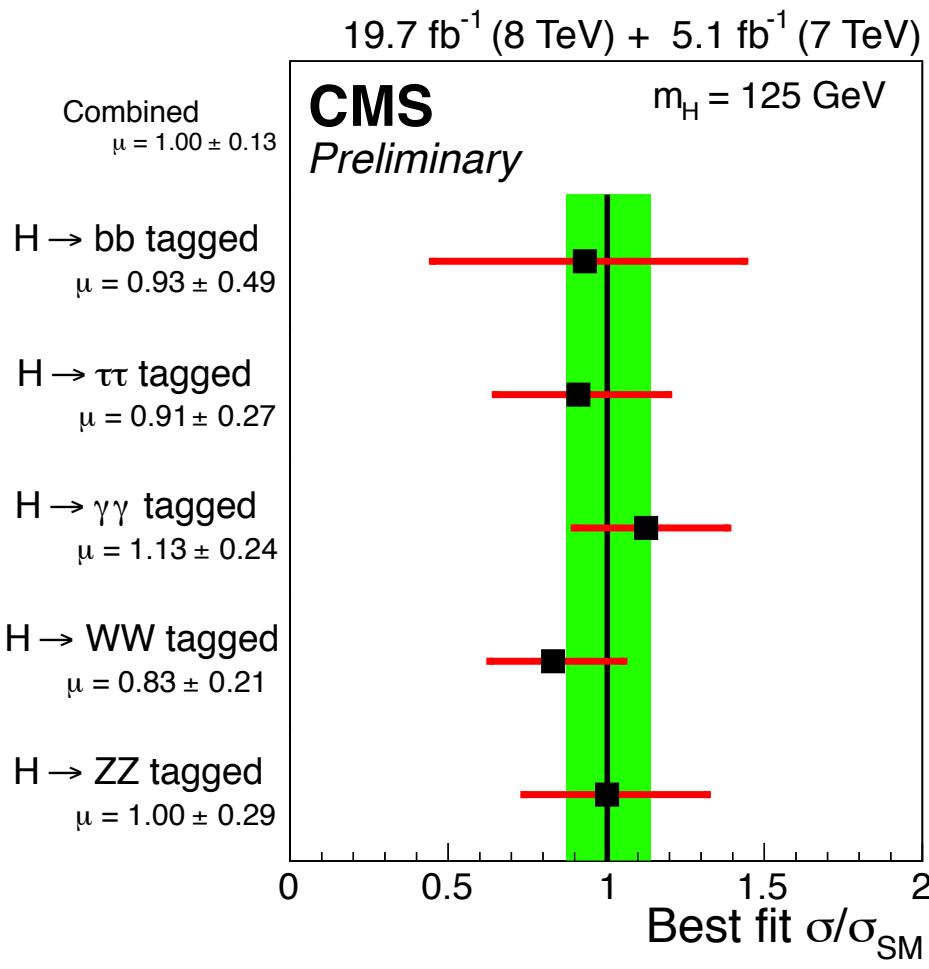
Backup slides





'a' Higgs boson

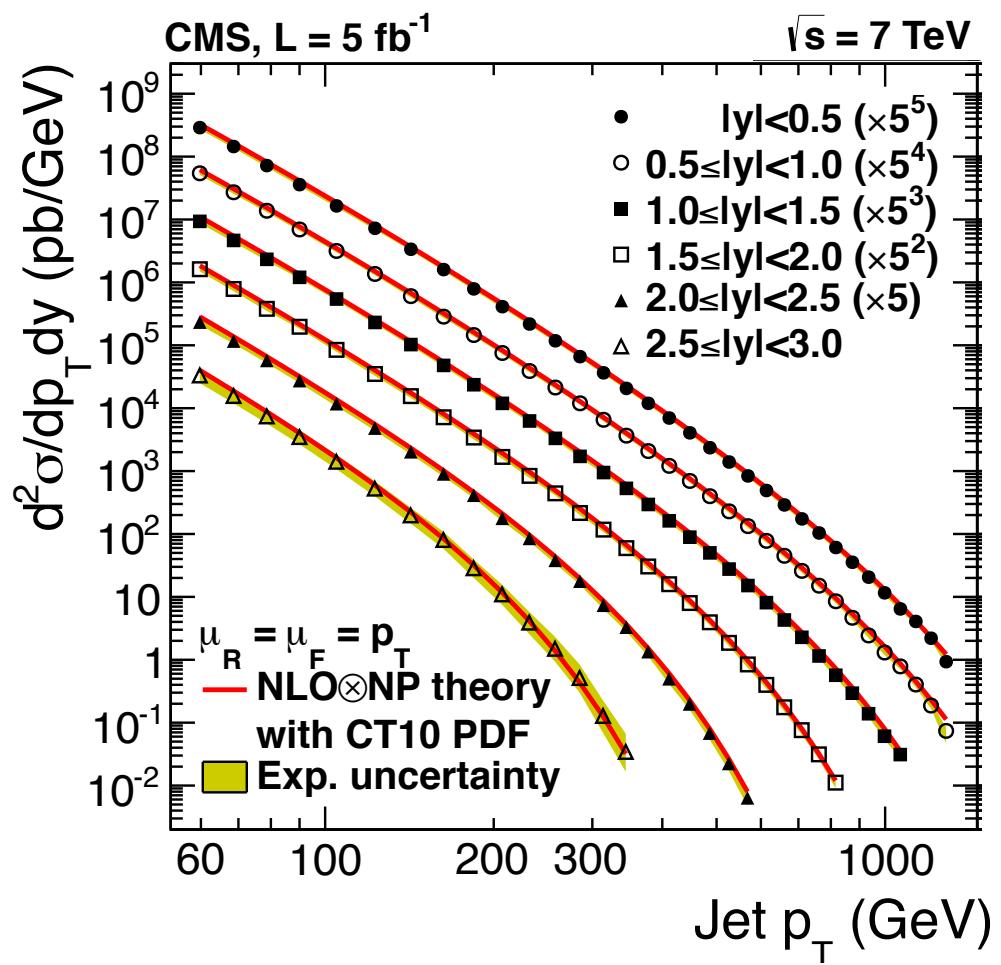
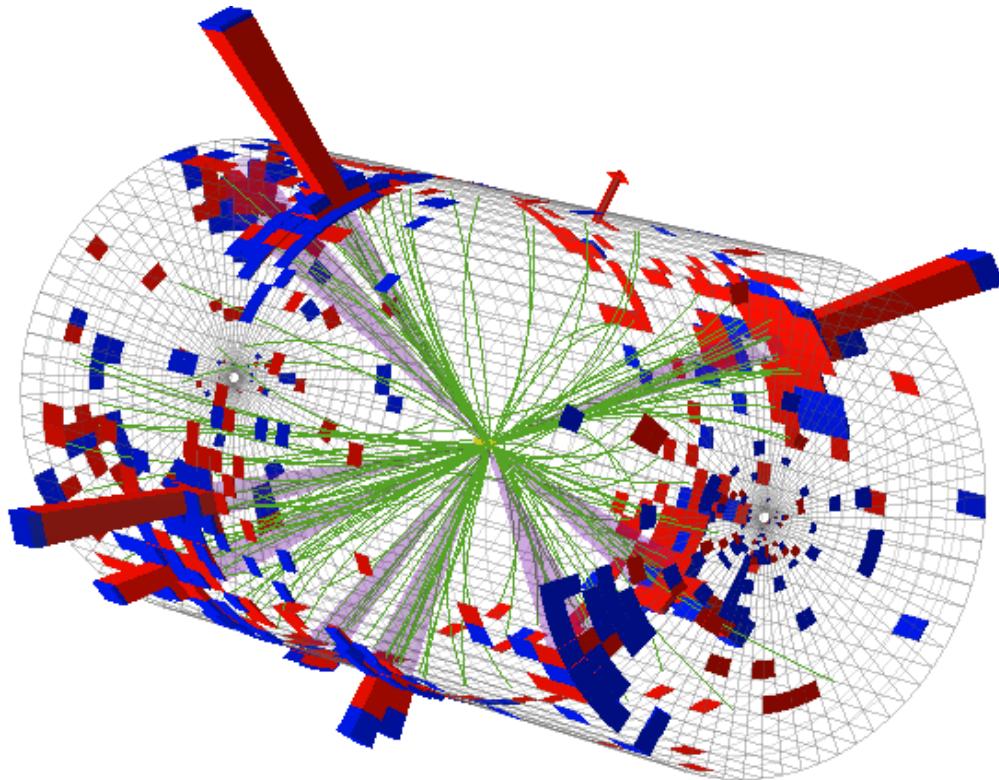
- Big discovery of CMS was a boson with mass of 125 GeV on 4th July, 2012
- Now identified as 'a' Higgs boson, fully consistent with the standard model (SM)
- Detailed studies of properties: couplings, spin, parity



Number of H decaying to each particle pair, over SM prediction

Couplings to Higgs are proportional to particle masses

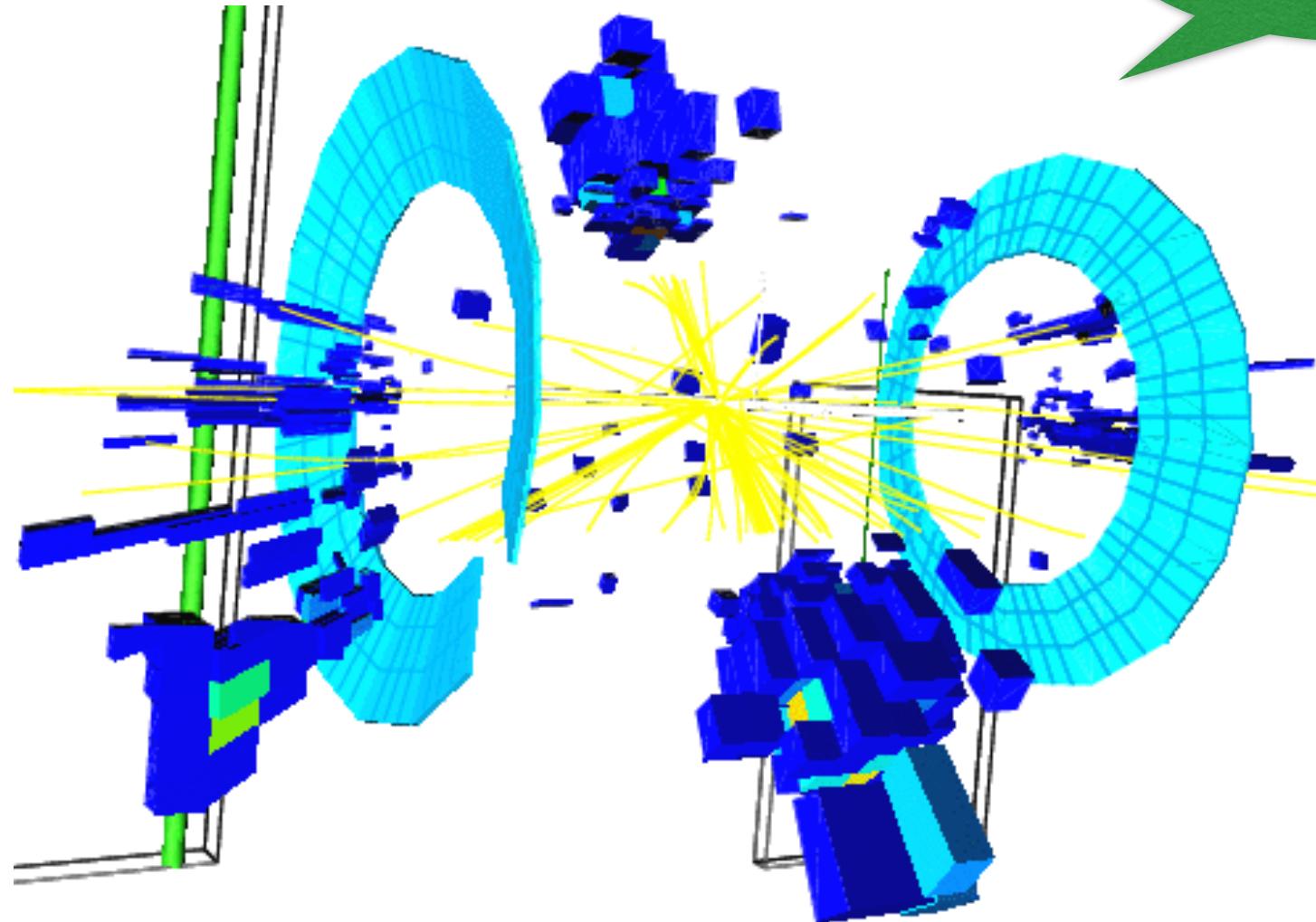
- The most abundant particles produced at the LHC are quarks and gluons
- Never seen alone, these quickly turn into sprays of particles, jets
- Production rate vs energy and scattering angle predicted by Quantum Chromodynamics
- Helps us understand proton structure and jets in other, rarer processes



Anatomy of a jet in CMS

- [Click here to return to main talk](#)

16 slides of
pretty pictures!

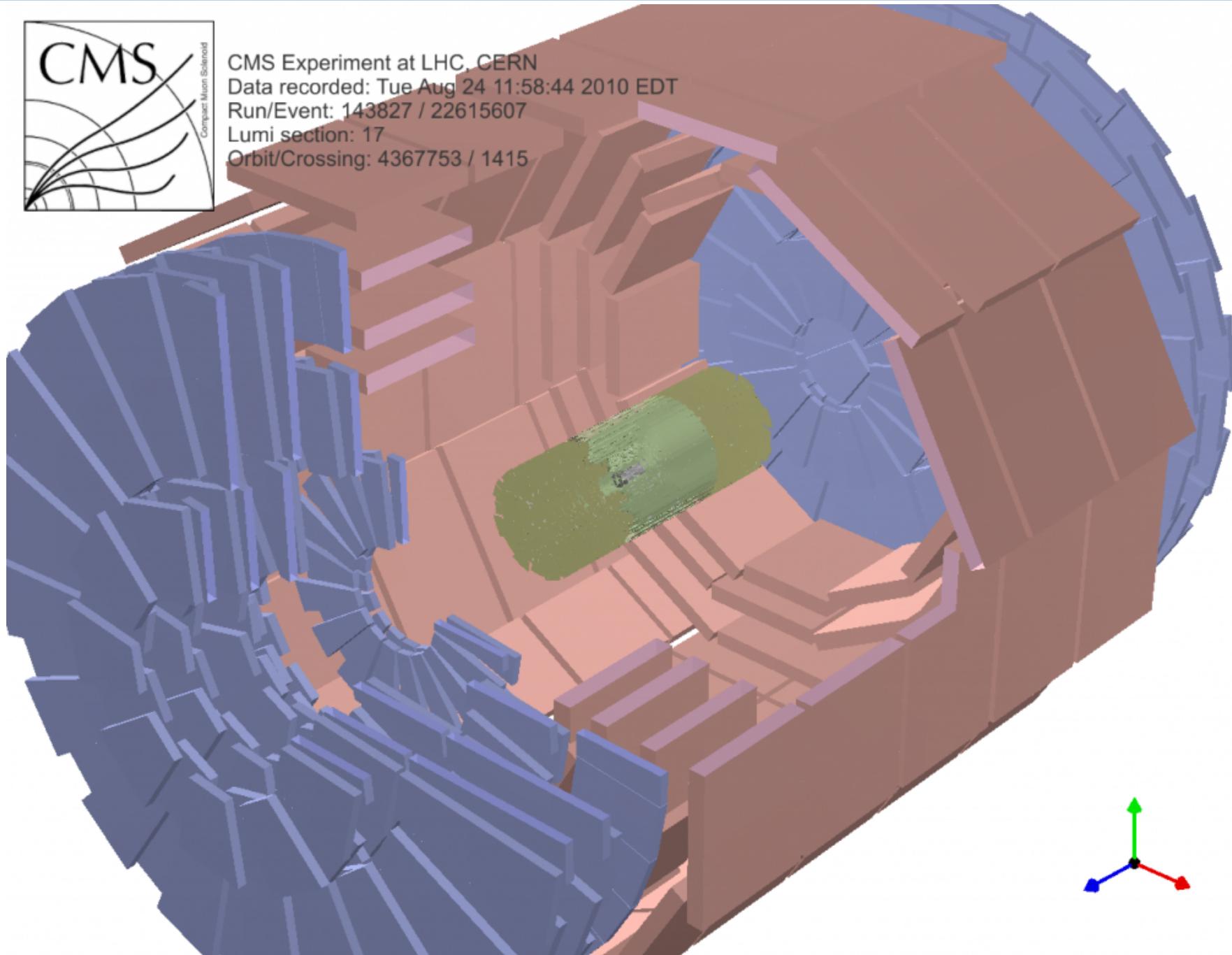


- Credits: [Brian Dorney, US LHC blogger](#)

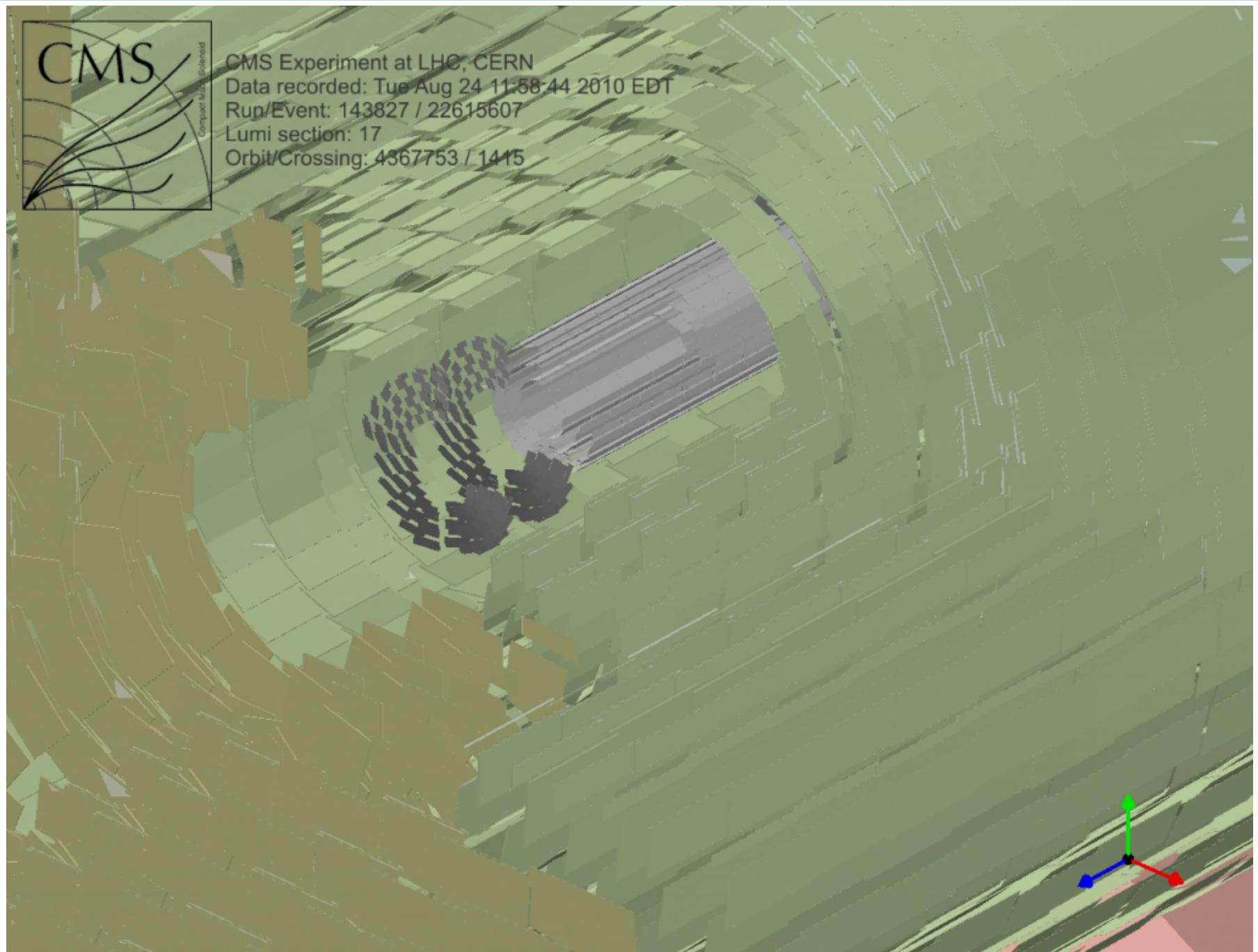
Cutaway view of CMS



CMS Experiment at LHC, CERN
Data recorded: Tue Aug 24 11:58:44 2010 EDT
Run/Event: 143827 / 22615607
Lumi section: 17
Orbit/Crossing: 4367753 / 1415

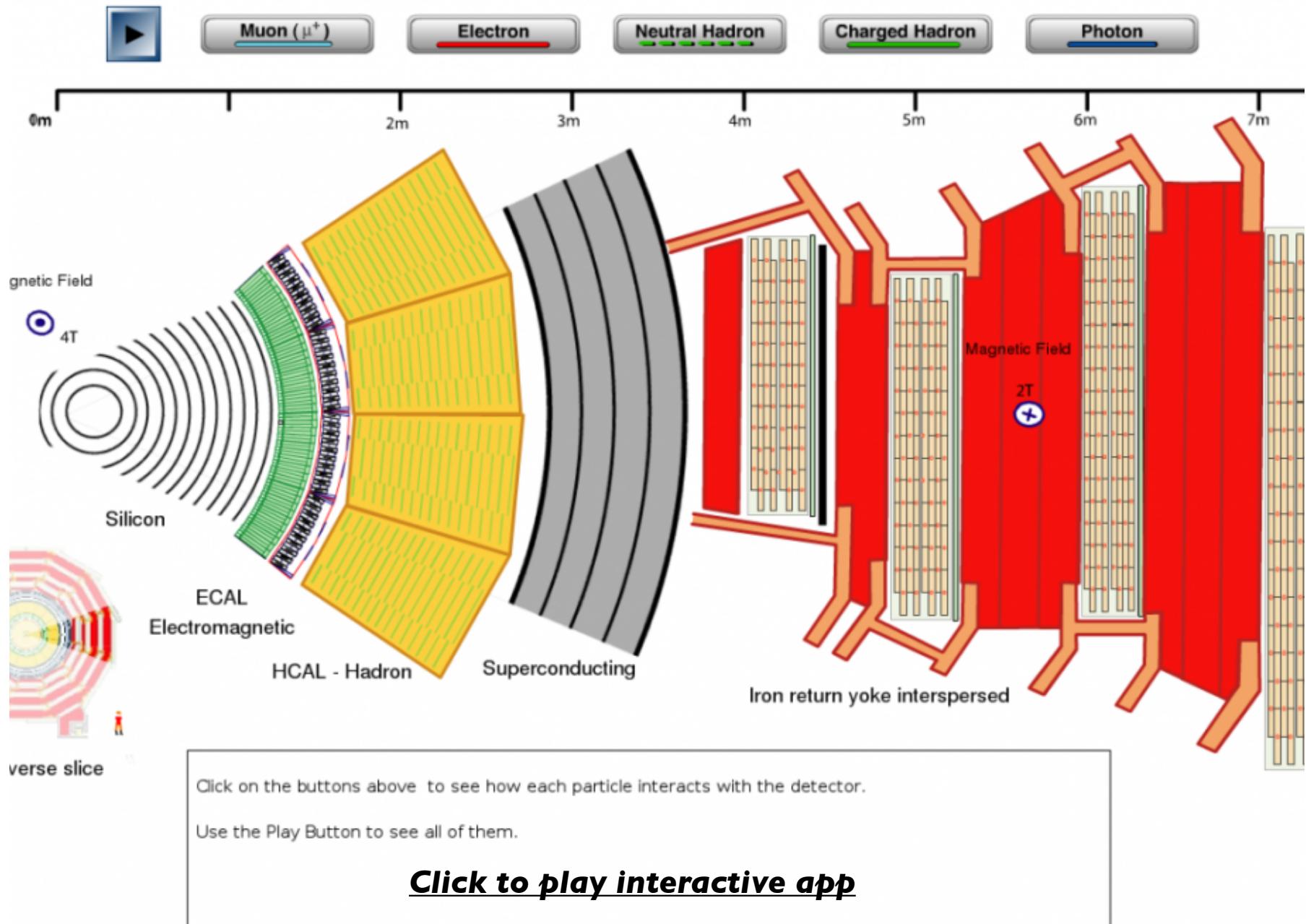


Close-up of silicon tracker



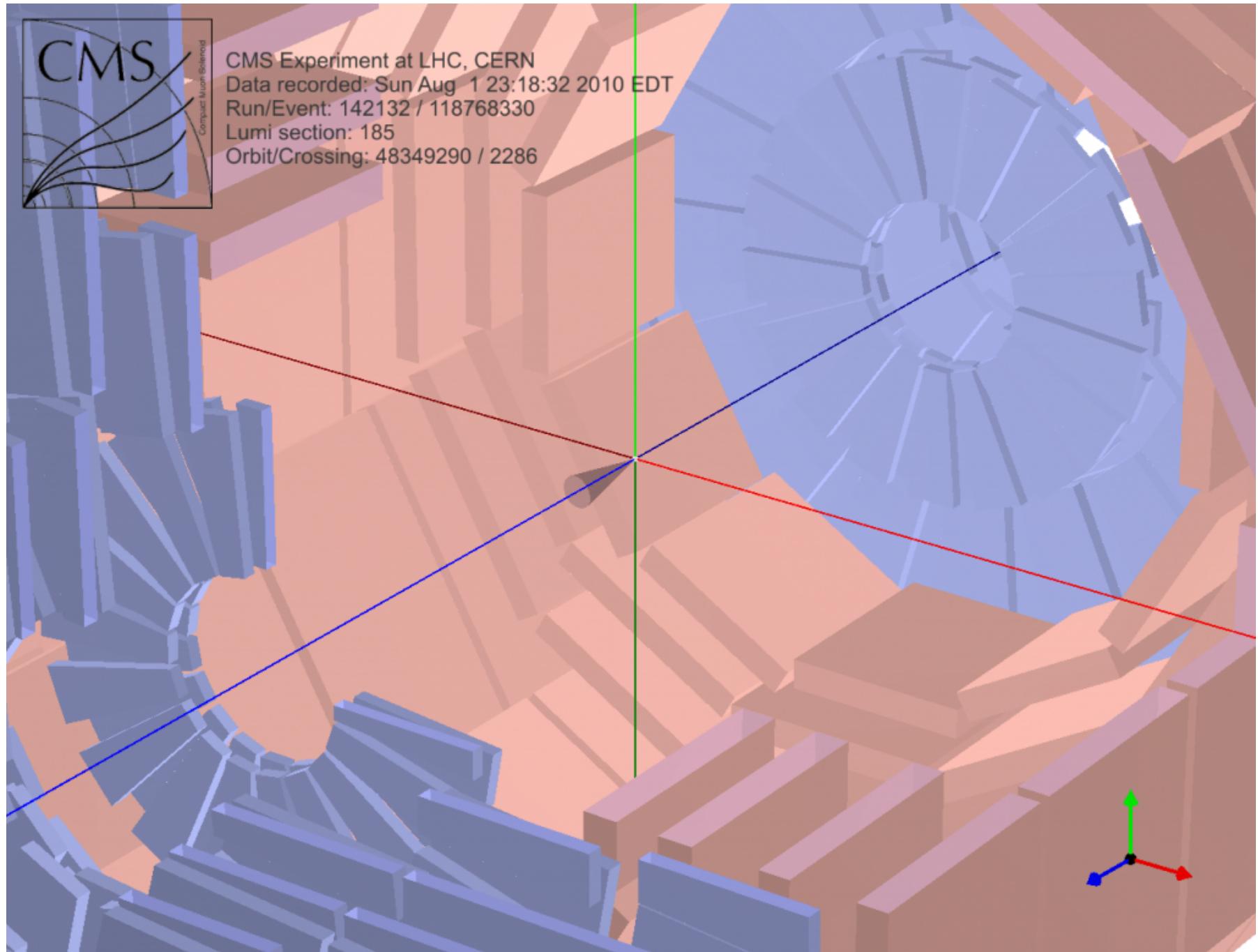
Slice: Calorimeters+magnet

Transverse Slice of the Compact Muon Solenoid (CMS) Detector

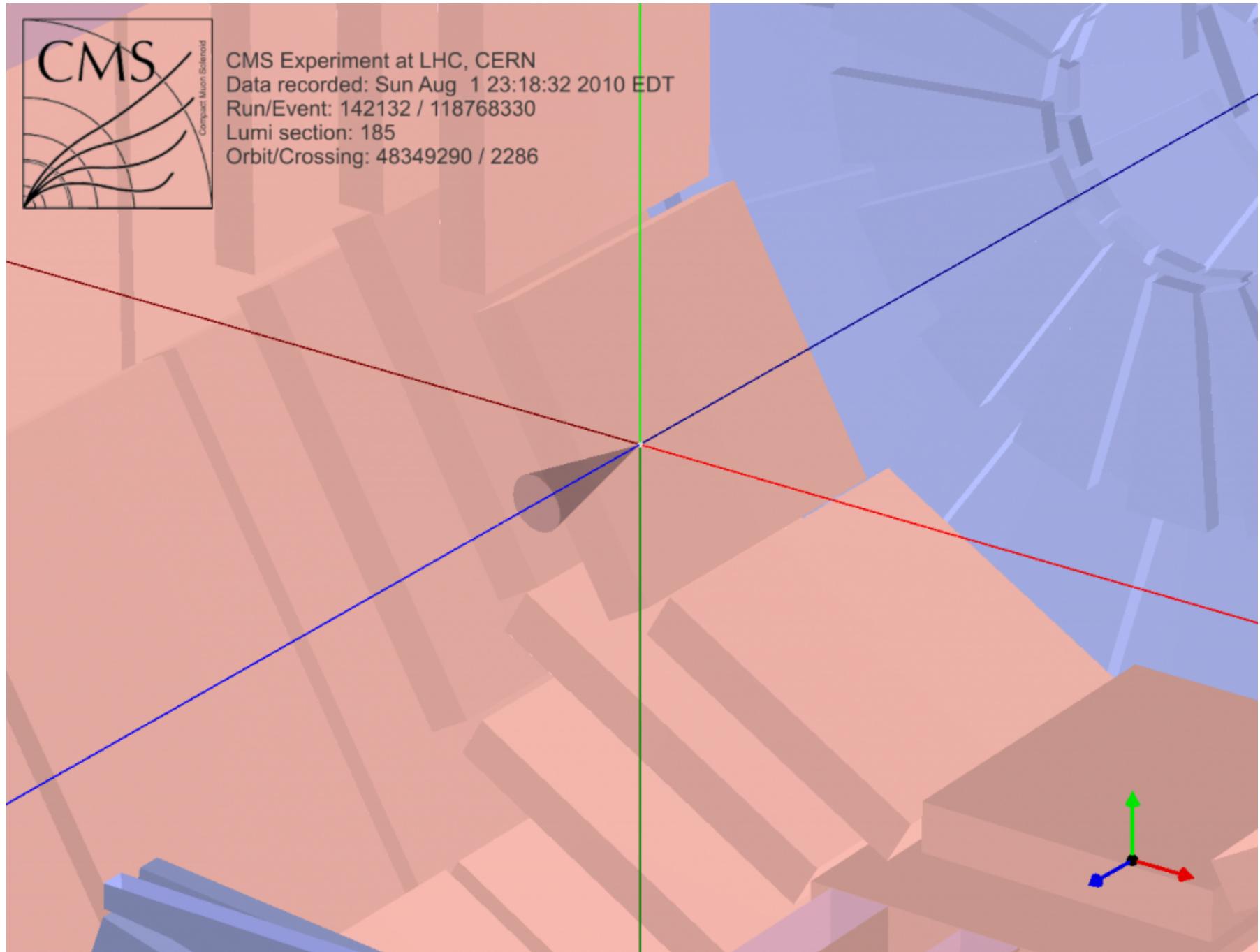


Derived from CMS Detector Slice from CERN

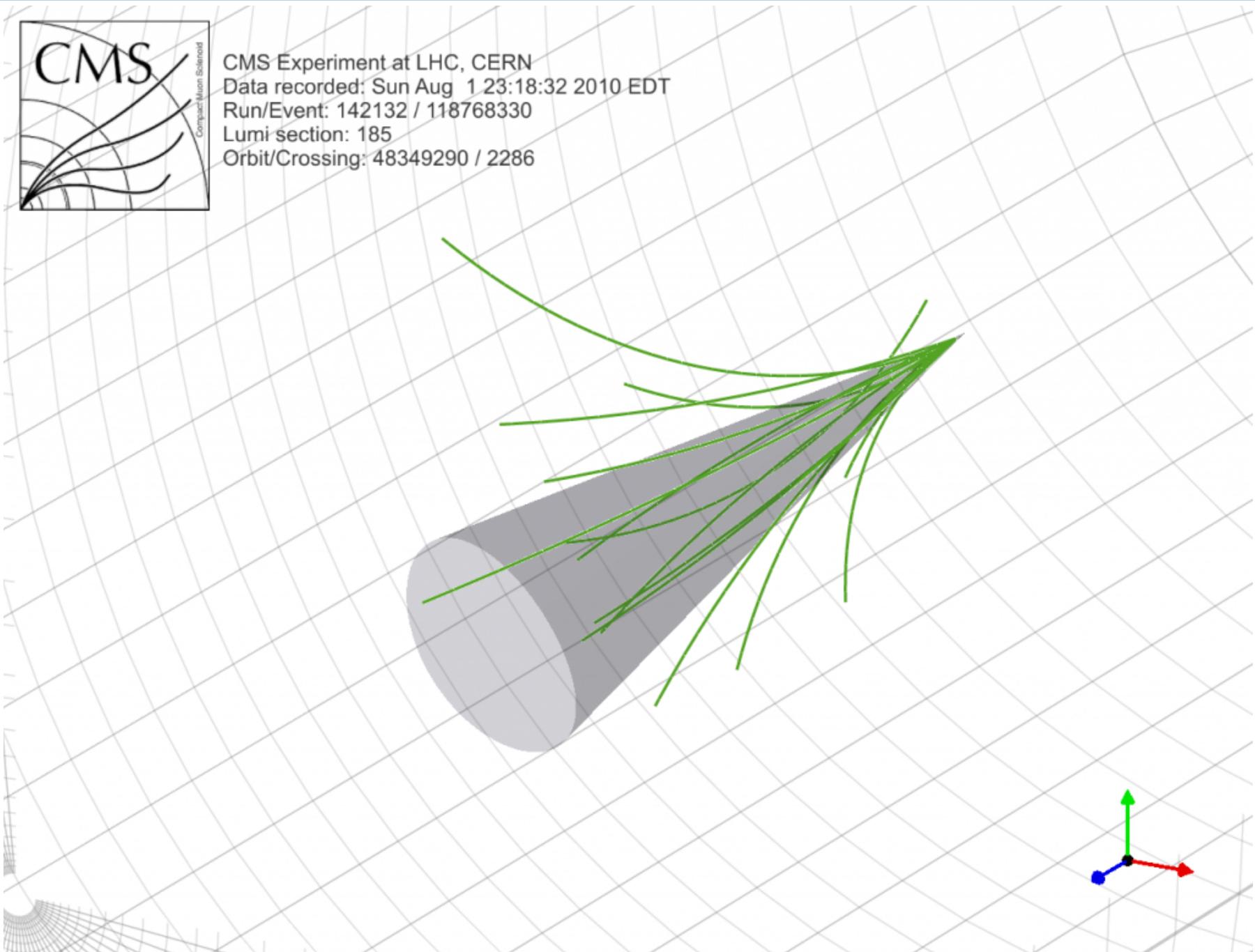
A jet cone in CMS



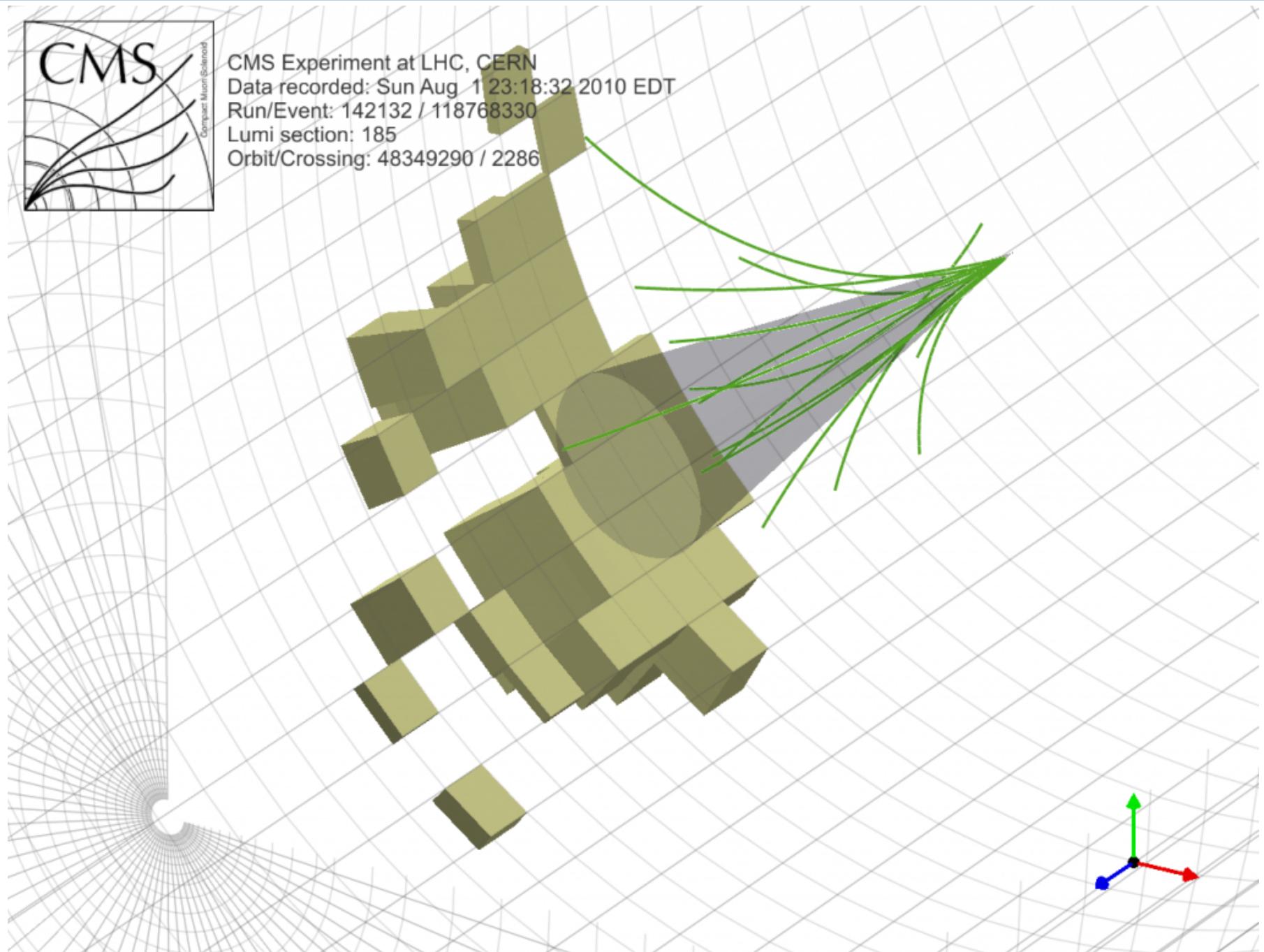
Zoom in the jet cone



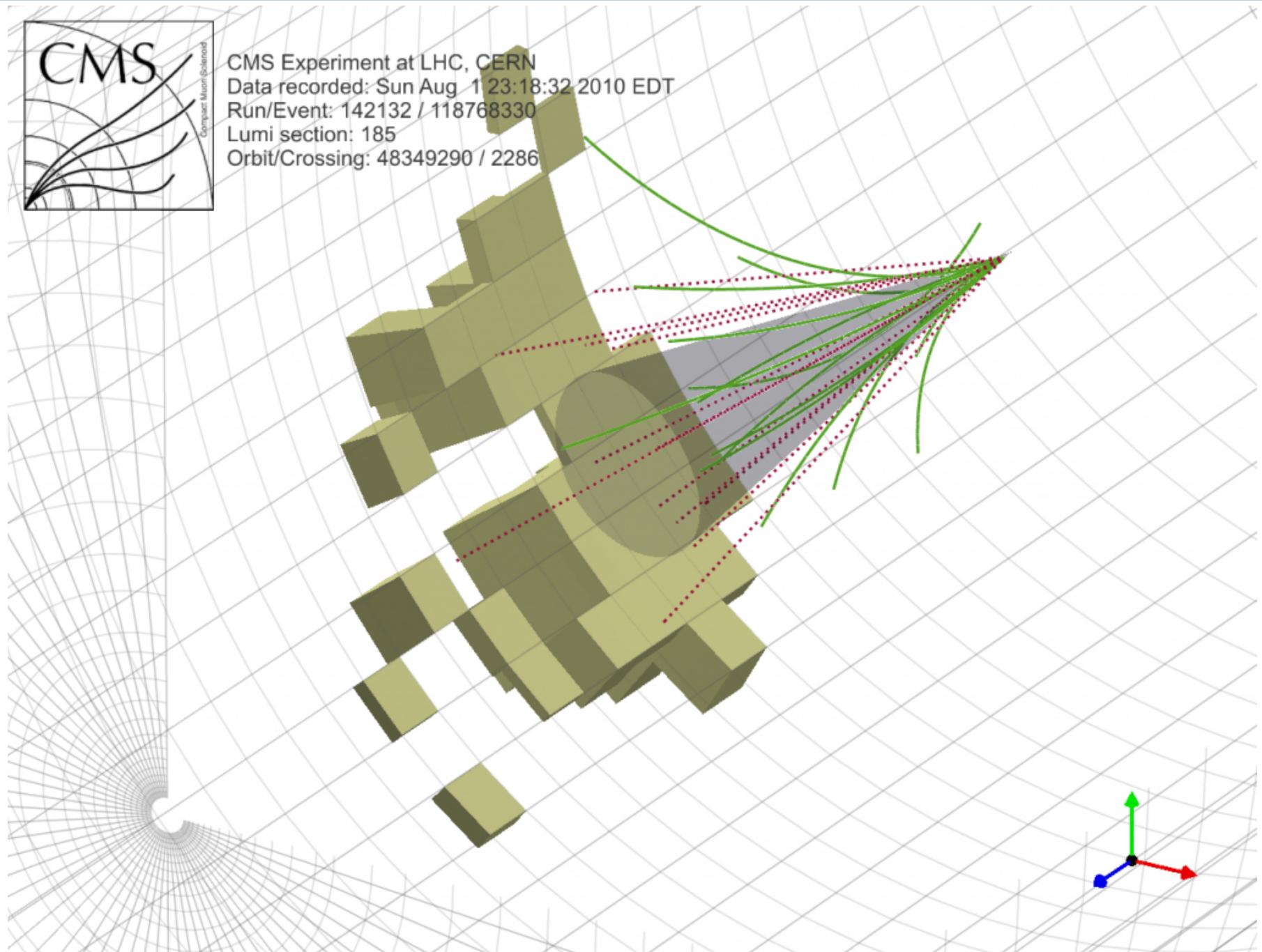
Jet and it's tracks



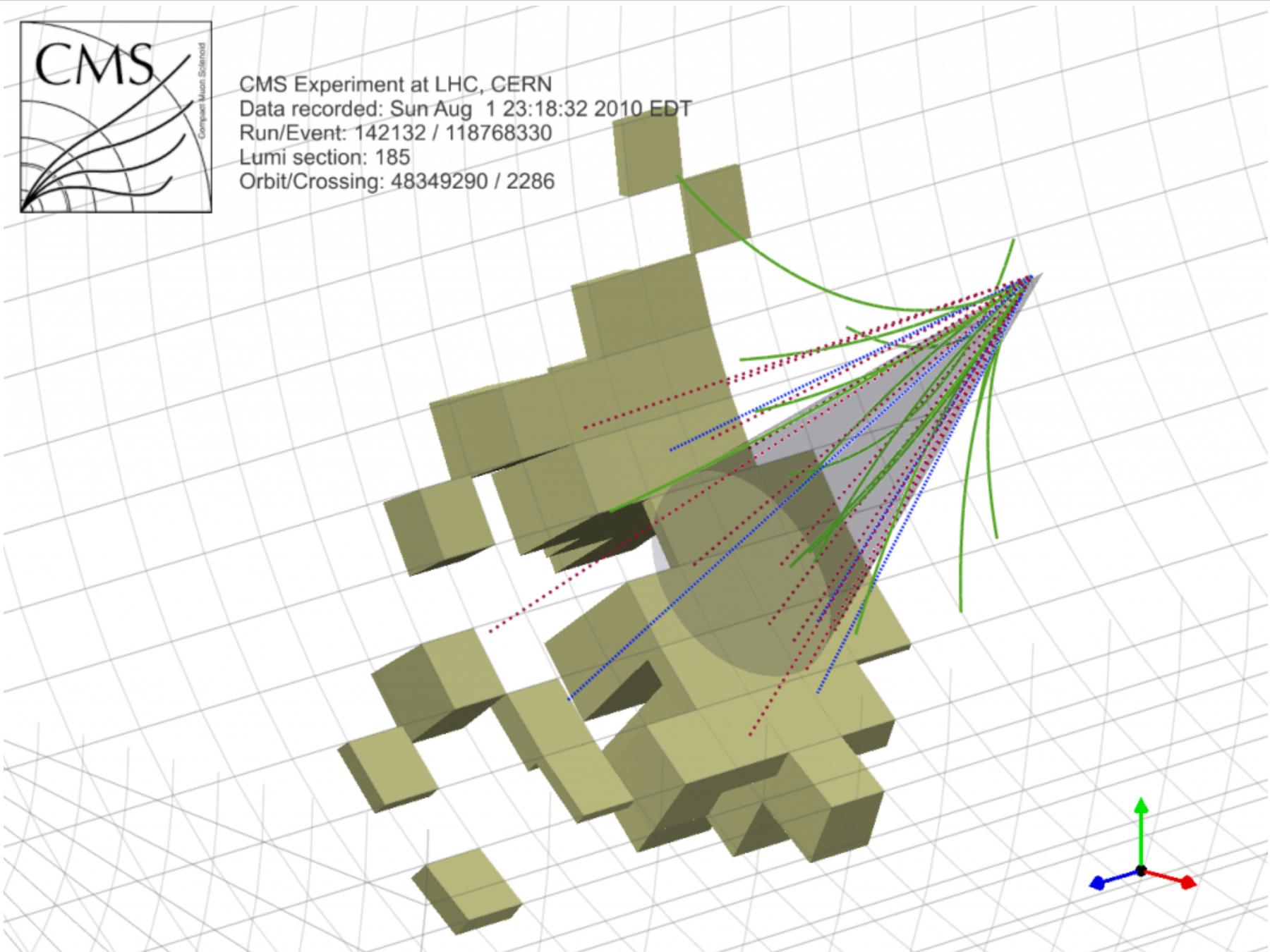
Jet, tracks, ECAL deposits



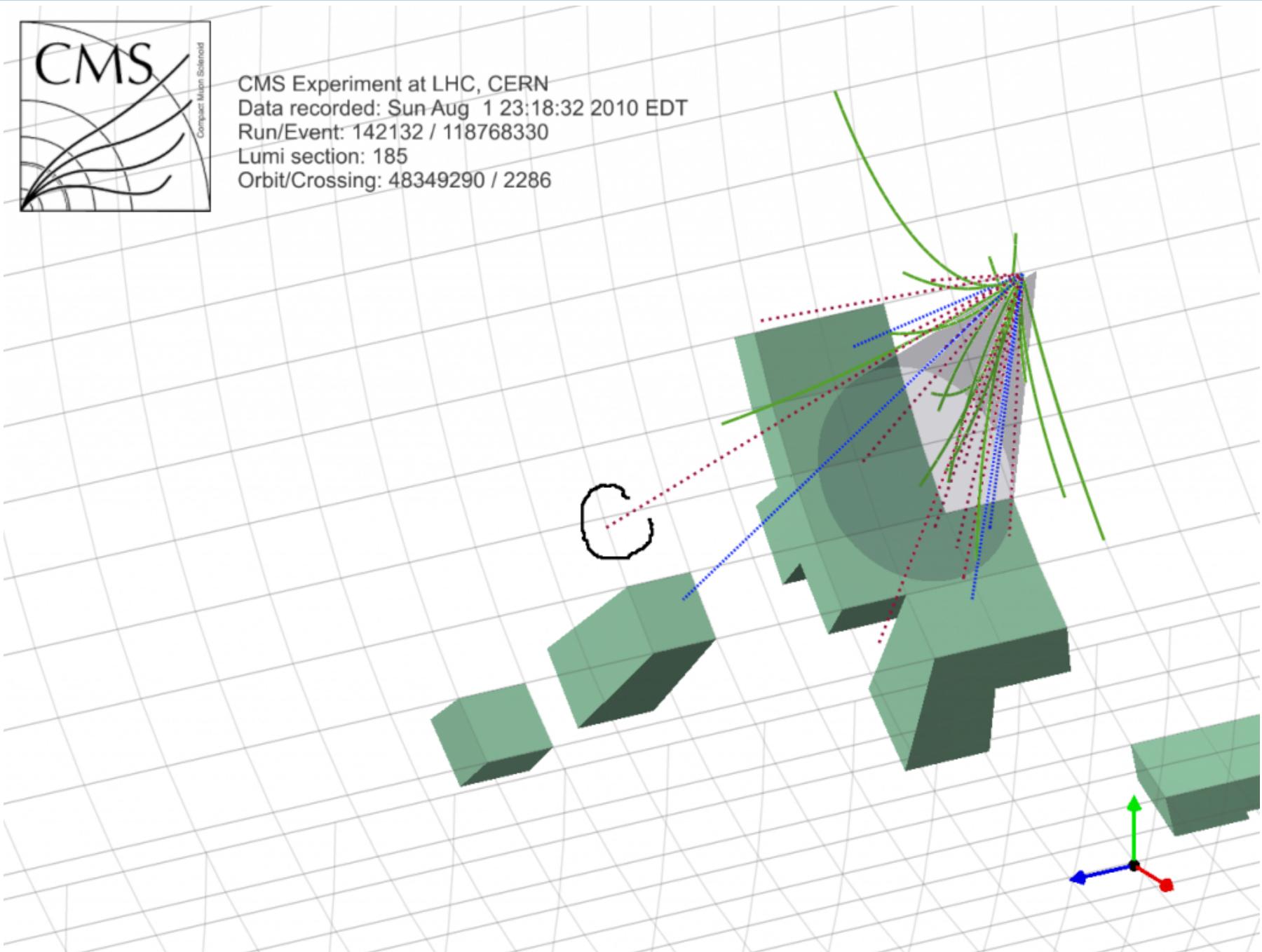
...photon candidates...



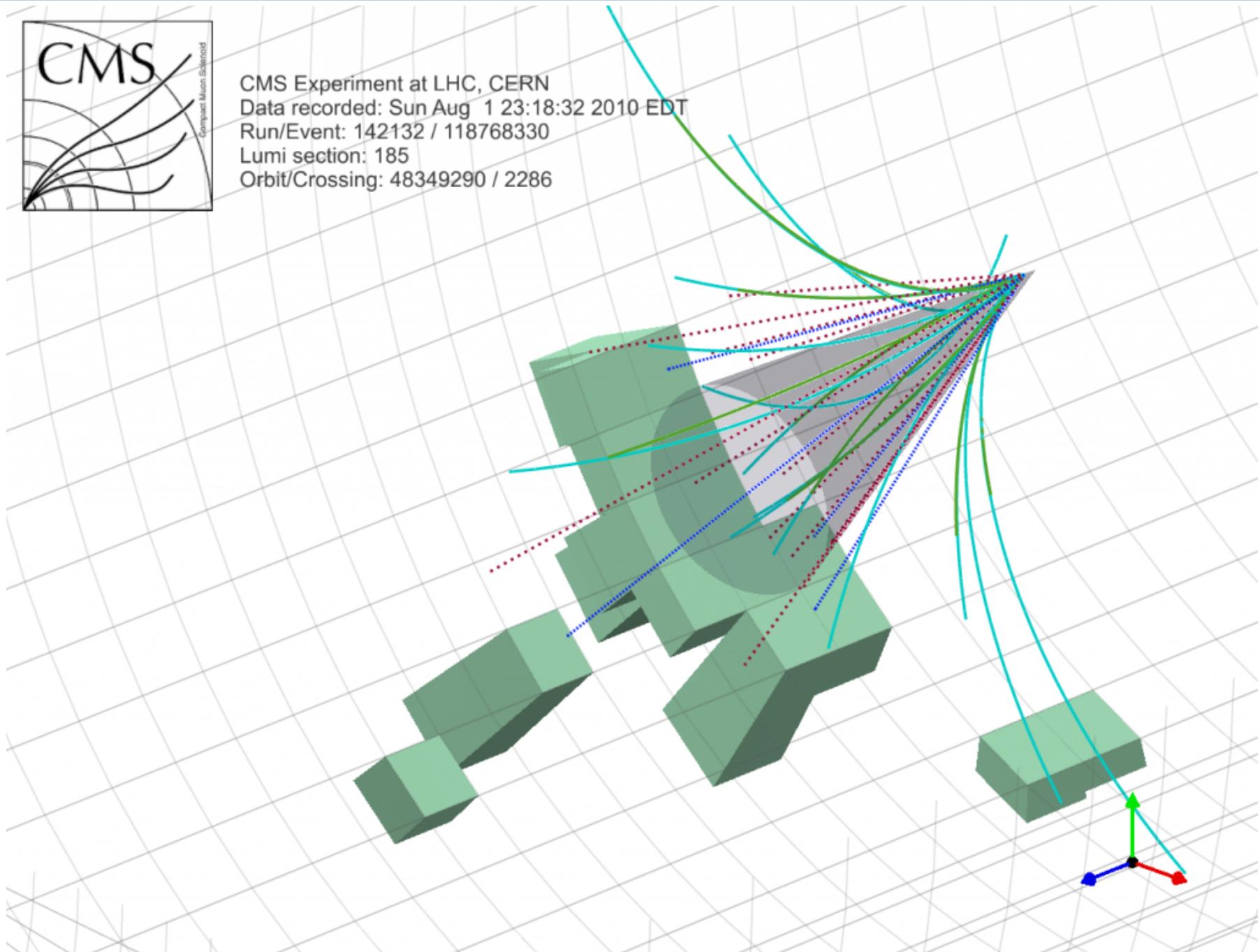
...neutral hadrons...



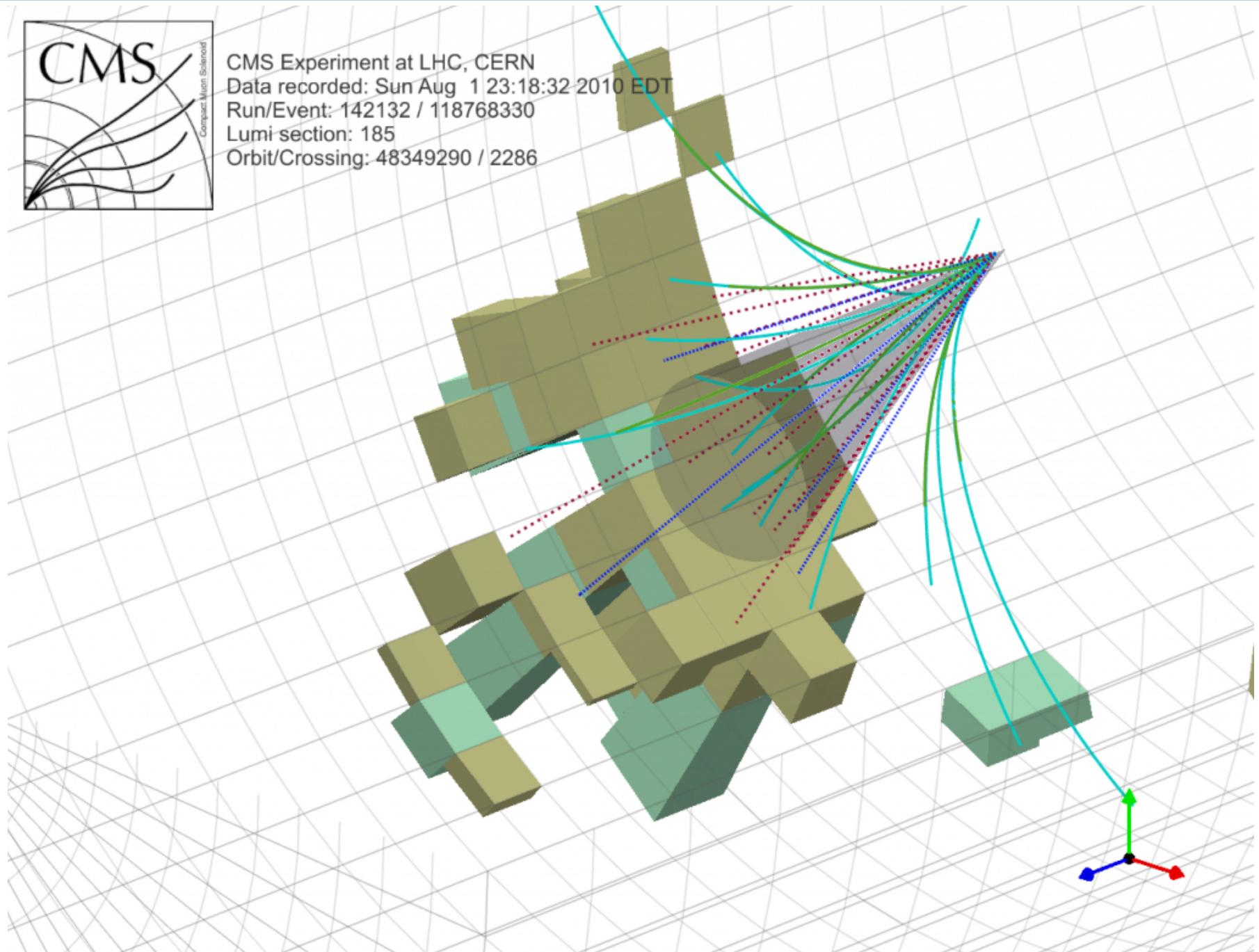
...HCAL deposits...



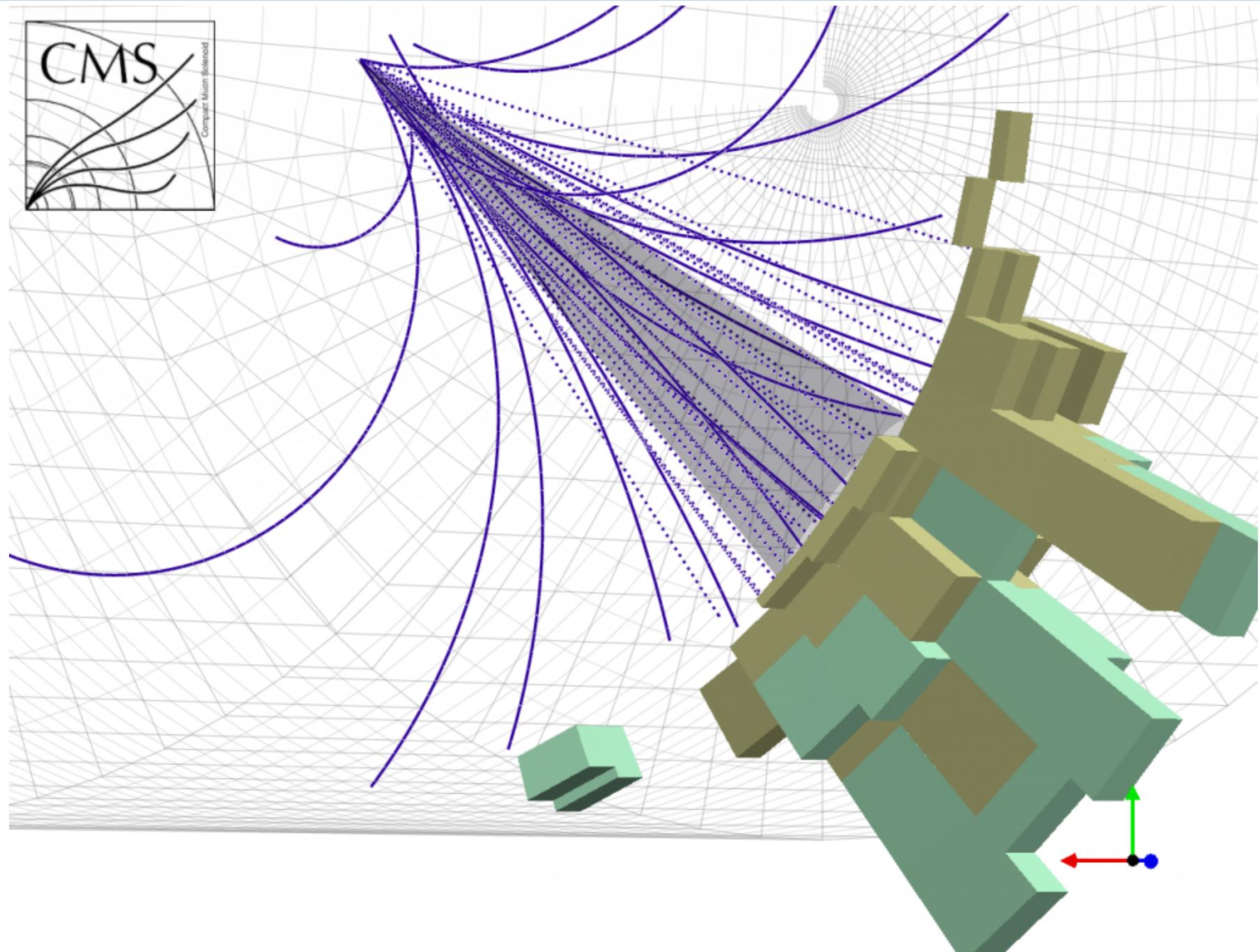
...charged hadrons=tracks...



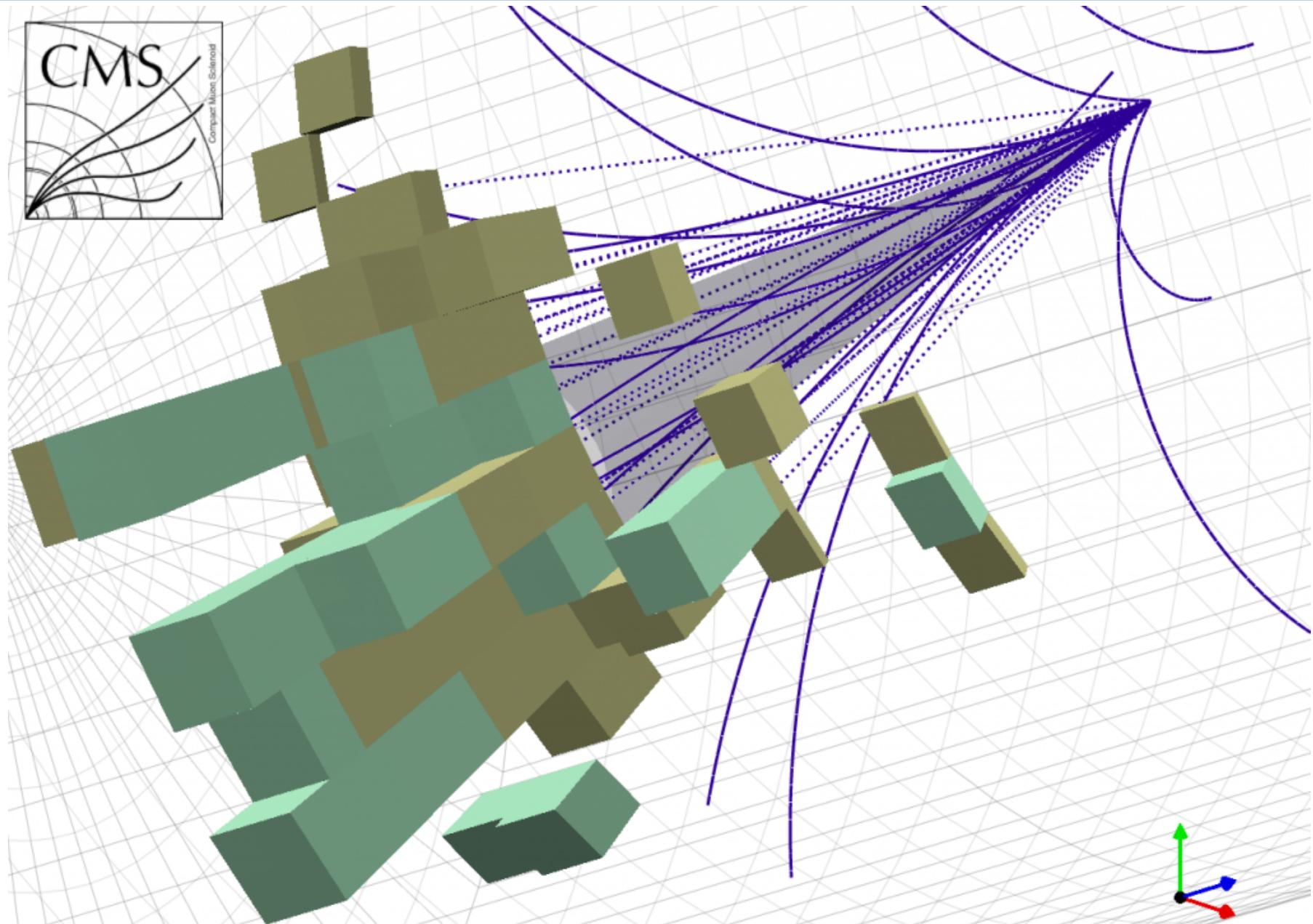
Jet and all its components



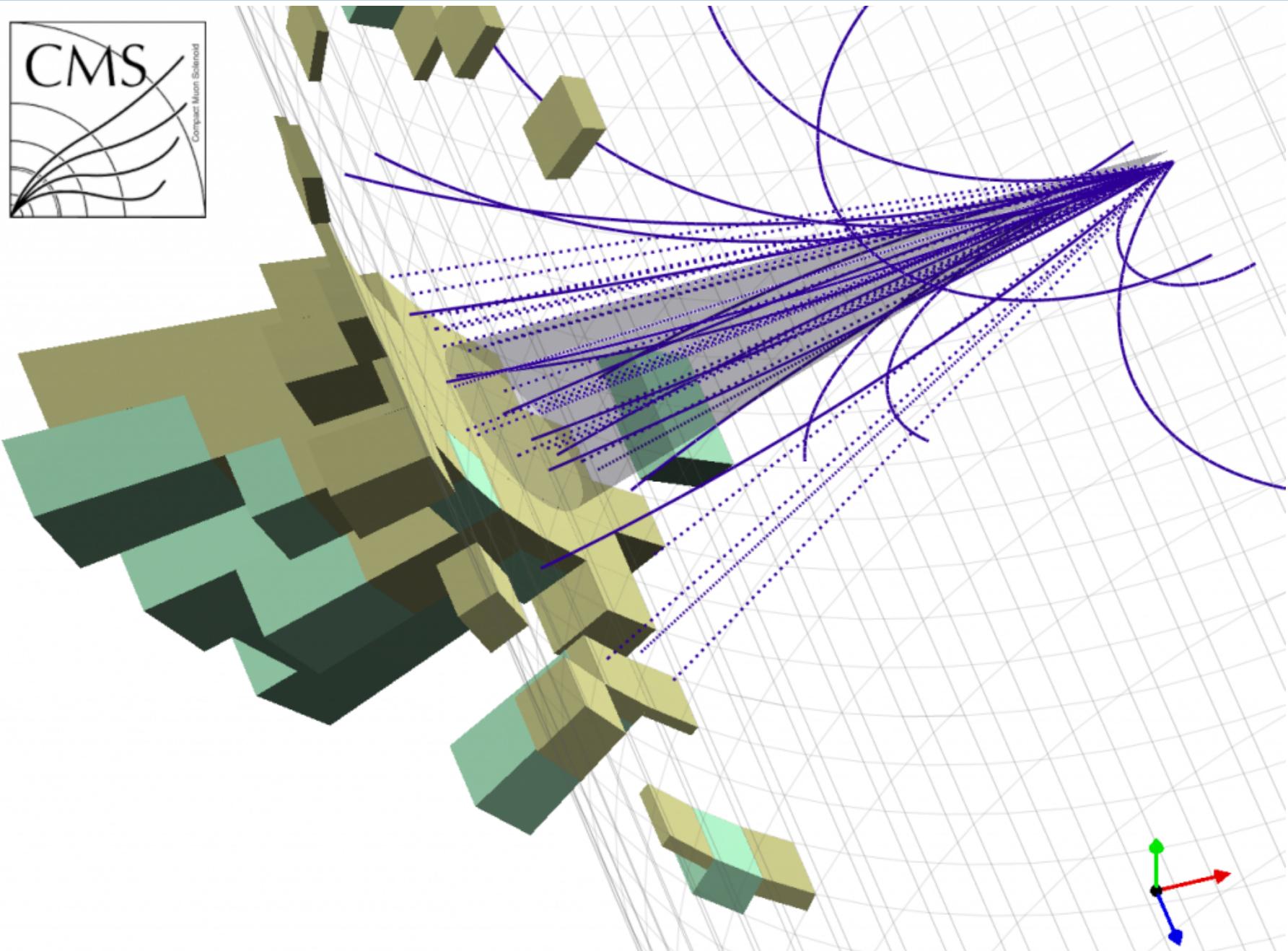
Jet's calorimeter deposits



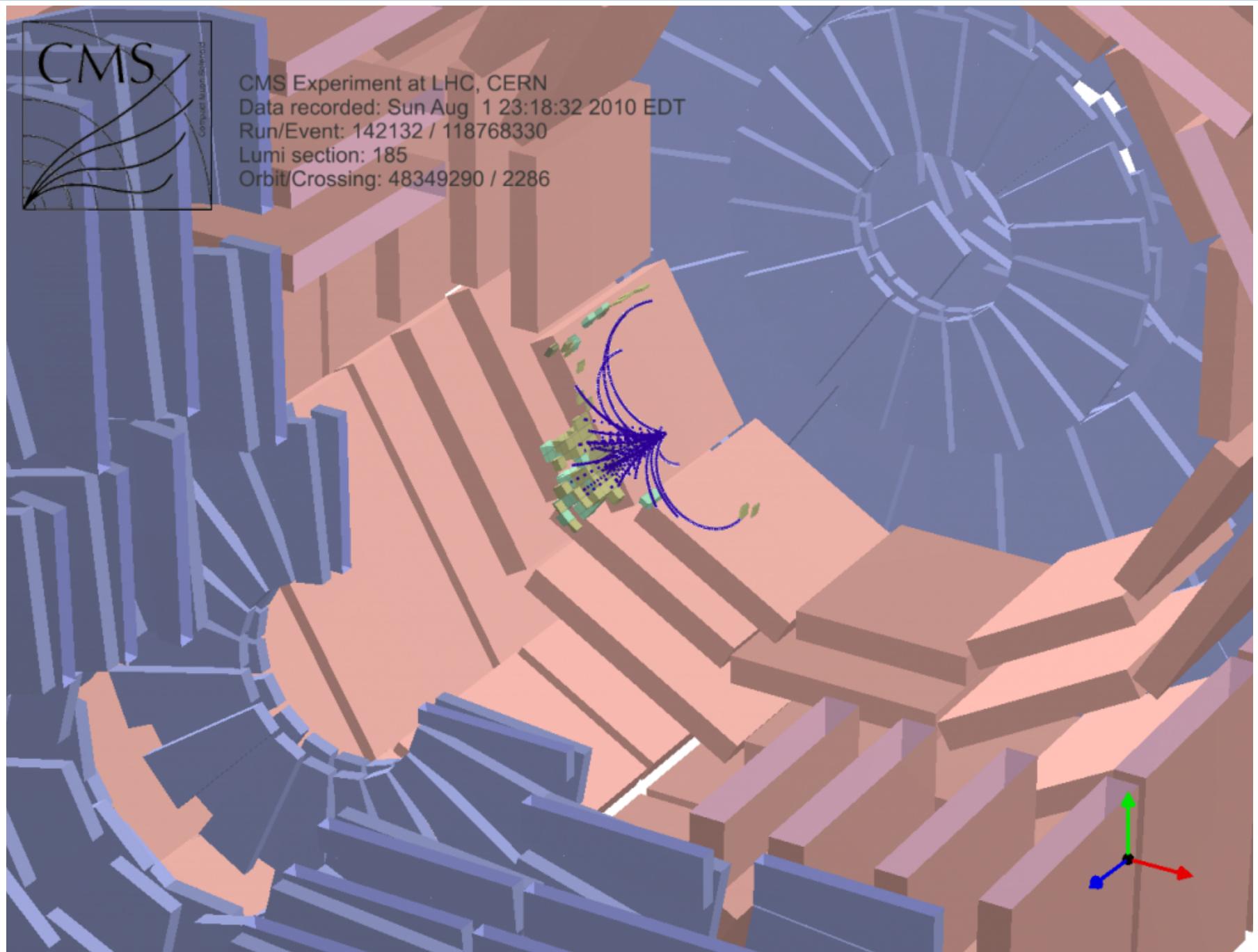
Rotated view



One more



Jet in CMS context



End of the tour

- Now, get me back