Jets at LHC

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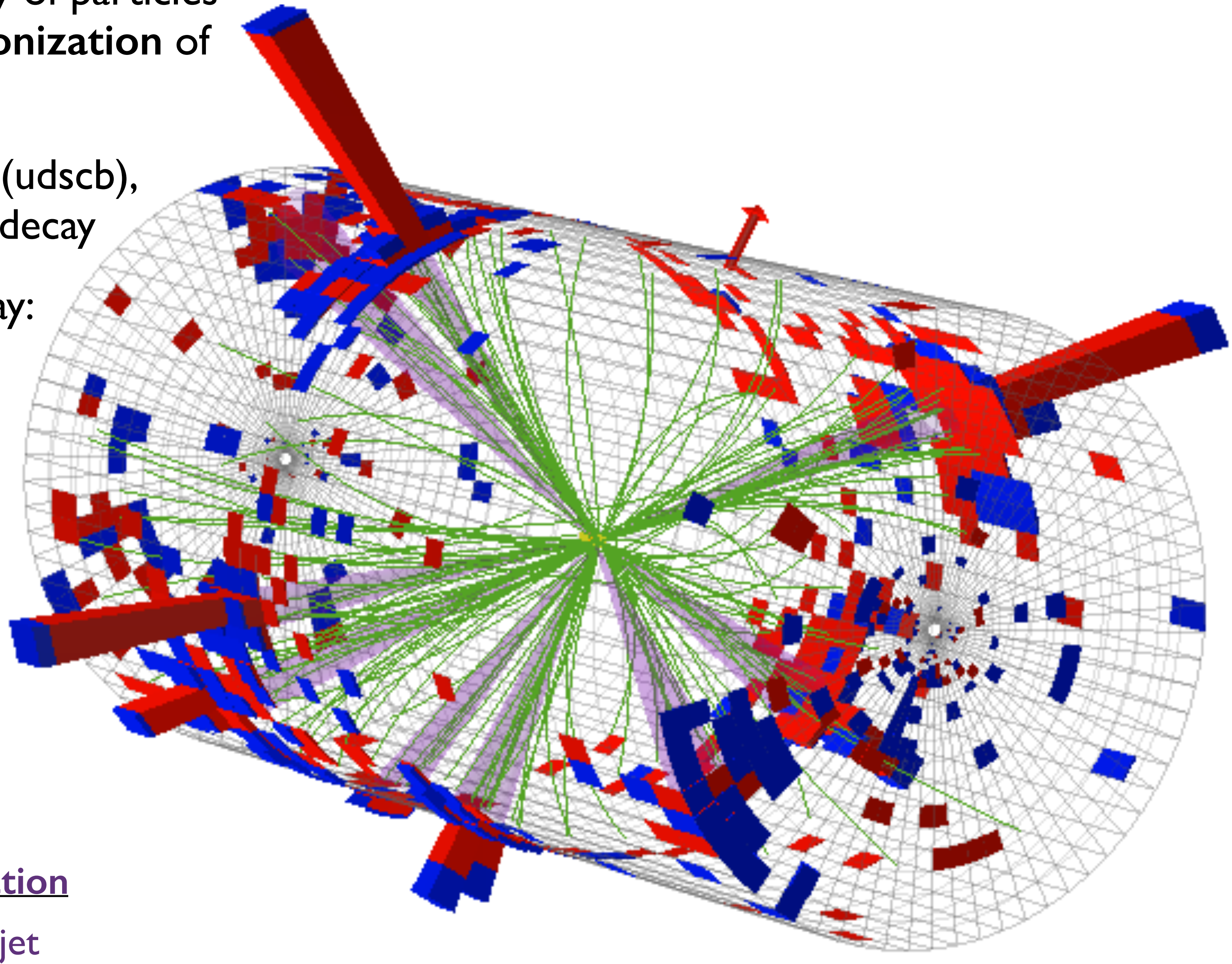
What is a jet?

- Jet is a collimated spray of particles produced by the **hadronization** of a coloured **parton**
- Parton can be a quark (udscb), gluon, or hadronic tau decay
- Topics I will cover today:
  - Parton shower
  - Hadronization
  - Jet clustering
  - **Particle Flow,** GS
  - Pileup offset
  - **JEC from data**
  - **Heavy flavor jets**
  - Quark/gluon likelihood
  - **Inclusive jet cross section**
  - Top mass with lepton+jet

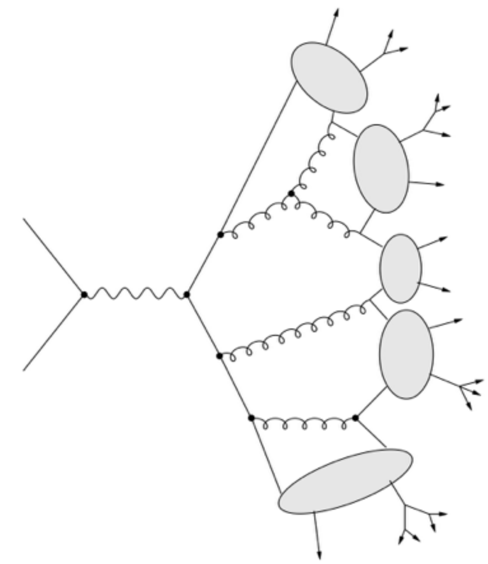


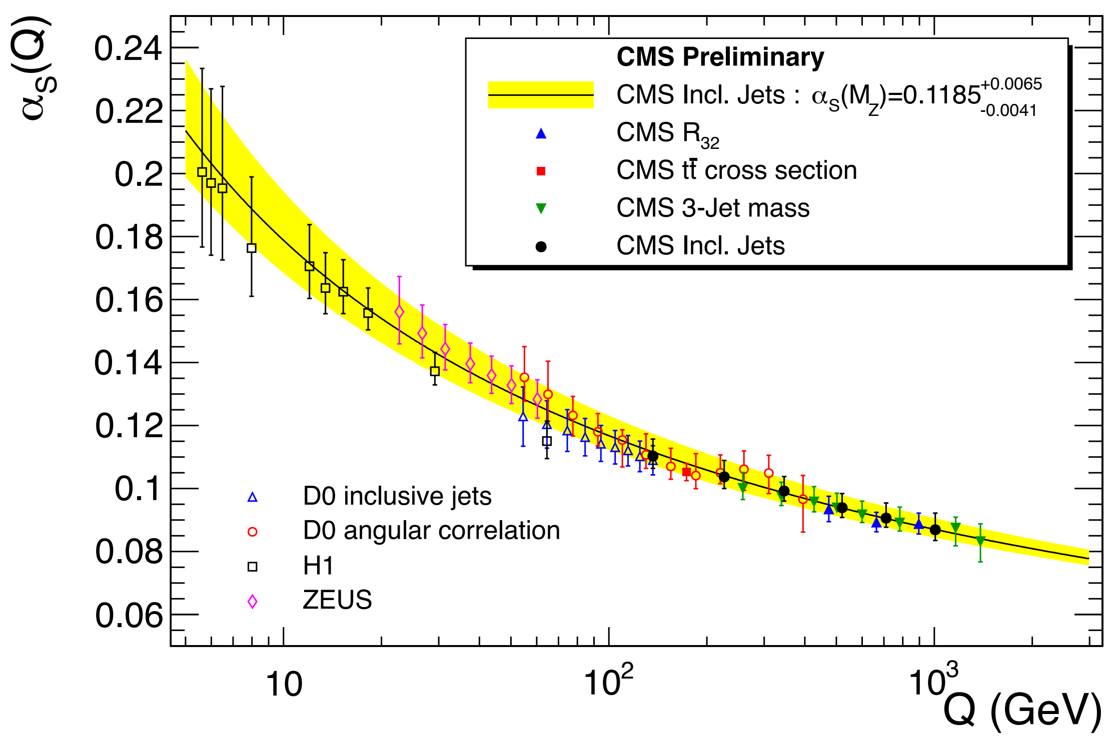
But first, anatomy of a jet

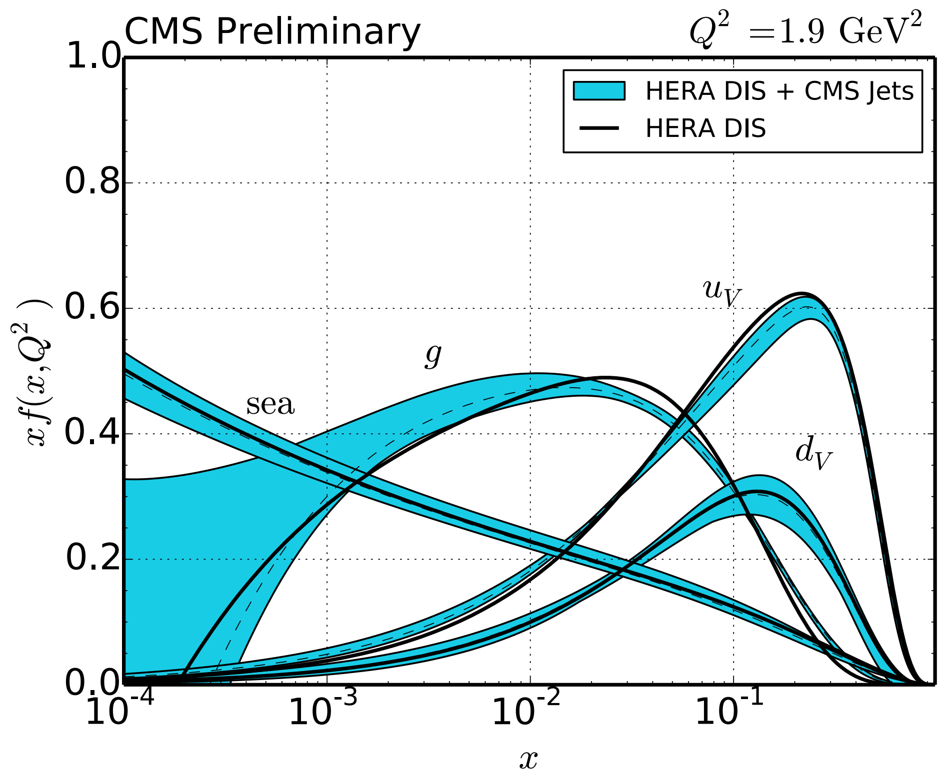
- Click here for an in-depth anatomy tour

Uses of jet measurements

- Jets useful for studies of **strong coupling (α_s)** and **proton structure (PDFs)** at high energy
- They are also needed for understanding effective models based on **Quantum Chromodynamics (QCD)**
- (more on these plots later)







Uses of jets

- Jets are omnipresent at LHC (="gluon-gluon collider")
  - testament to their importance, CMS jet calibration paper is top-5 with >700 citations
  - (new reference paper now ready for submission)
- Of particular importance are jets used to reconstruct top quark mass in tt events
  - hints of vacuum metastability (more in this later)

HEP — 6 records found — Search took 0.57 seconds.

1. **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**
(6086) CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 32 pp.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to PRESSRELEASE; Interactions.org article
Detailed record - Cited by 6086 records 1000+

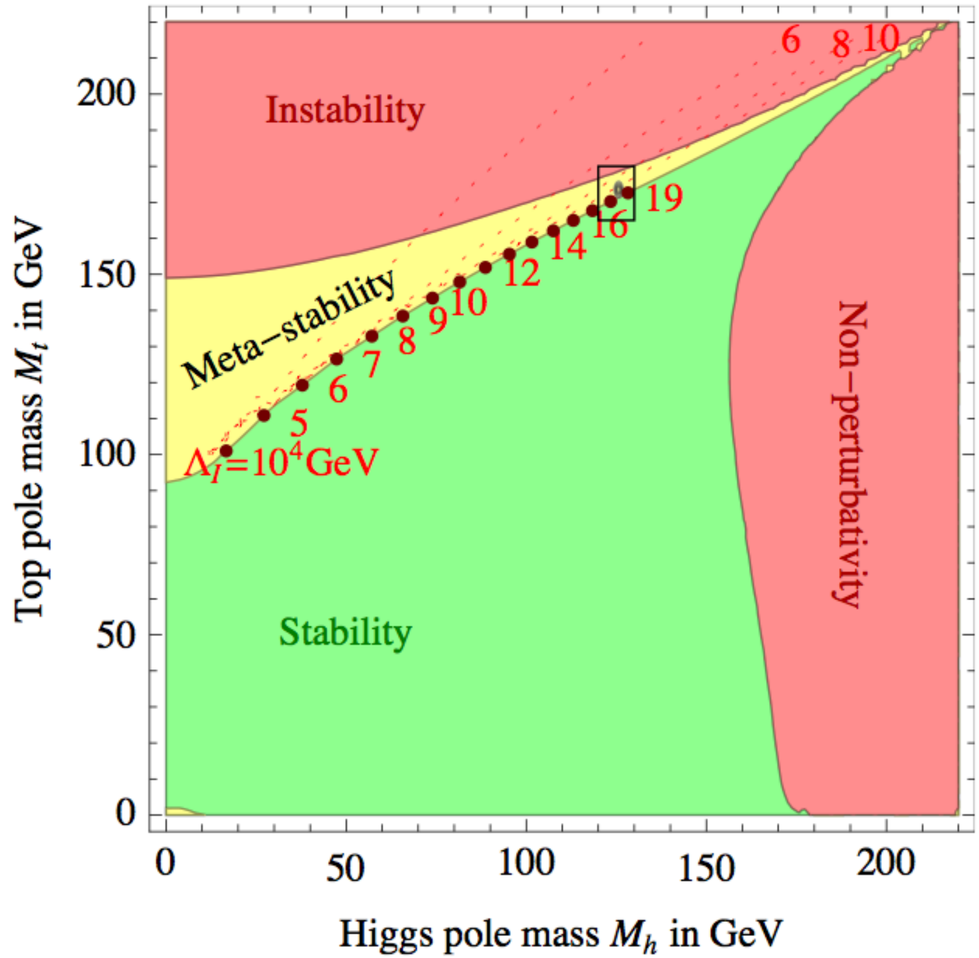
2. **The CMS experiment at the CERN LHC**
(3642) CMS Collaboration (S. Chatrchyan (Yerevan Phys. Inst.) *et al.*). Aug 2008. 361 pp.
Published in **JINST 3 (2008) S08004**
DOI: 10.1088/1748-0221/3/08/S08004
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 3642 records 1000+

3. **CMS technical design report, volume II: Physics performance**
(1288) CMS Collaboration (G.L. Bayatian (Yerevan Phys. Inst.) *et al.*). 2007. 585 pp.
Published in **J.Phys. G34 (2007) 995-1579**
CERN-LHCC-2006-021, CMS-TDR-008-2
DOI: 10.1088/0954-3899/34/6/S01
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service ; CERN Document Server ; Link to Fulltext
Detailed record - Cited by 1288 records 1000+

4. **Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV**
(784) CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Feb 2012. 23 pp.
Published in **Phys.Lett. B710 (2012) 26-48**
CMS-HIG-11-032, CERN-PH-EP-2012-023
DOI: 10.1016/j.physletb.2012.02.064
e-Print: **arXiv:1202.1488 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI Information Bridge Server; Fermilab Today Result of the Week; Fermilab Library Server (fulltext available)
Detailed record - Cited by 784 records 500+

5. **Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS**
(759) CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2011.
Published in **JINST 6 (2011) P11002**
CERN-PH-EP-2011-102, CMS-JME-10-011
DOI: 10.1088/1748-0221/6/11/P11002
e-Print: **arXiv:1107.4277 [physics.ins-det]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 759 records 500+

10.1007/JHEP12(2013)089



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  - **Hadronization**
  - Jet clustering
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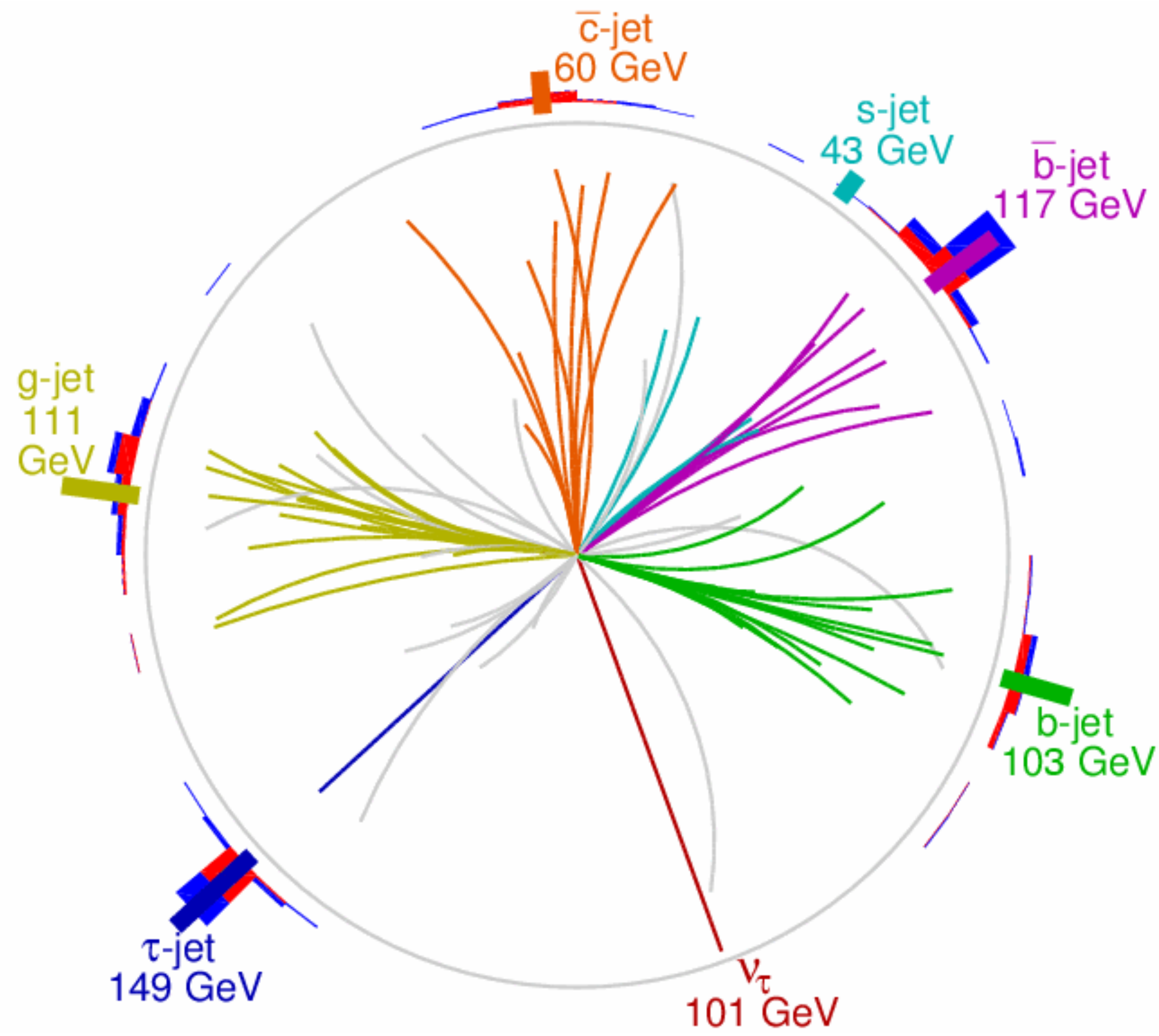
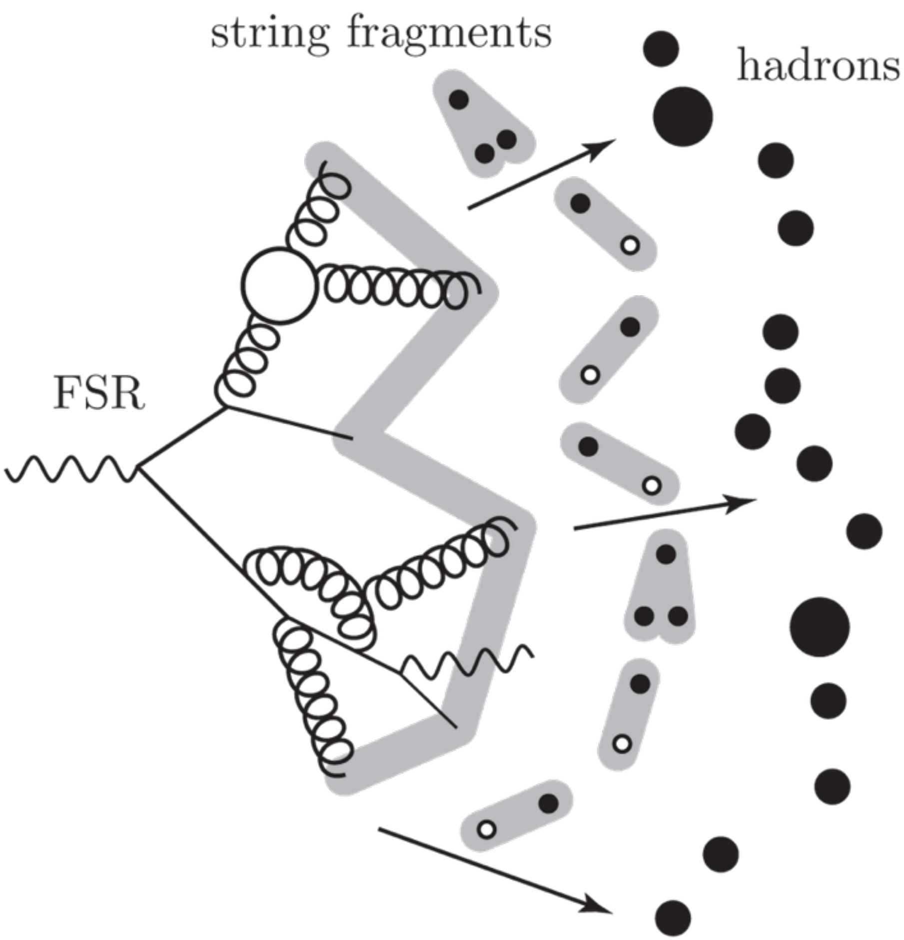
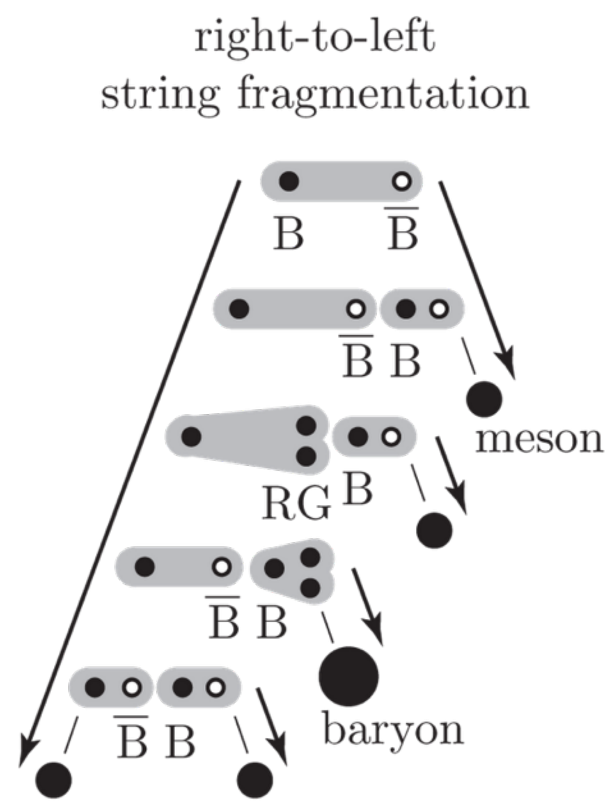


$gg \to tbH^+$, $t \to Wb \to scb$, $H^+ \to \tau\nu \to$ hadrons with a radiative gluon jet

Parton shower, hadronization

- Parton shower approximates missing perturbative orders of matrix element (often LO)
  - missing orders by generating a shower of gluon emissions and g->qqbar
  - 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)



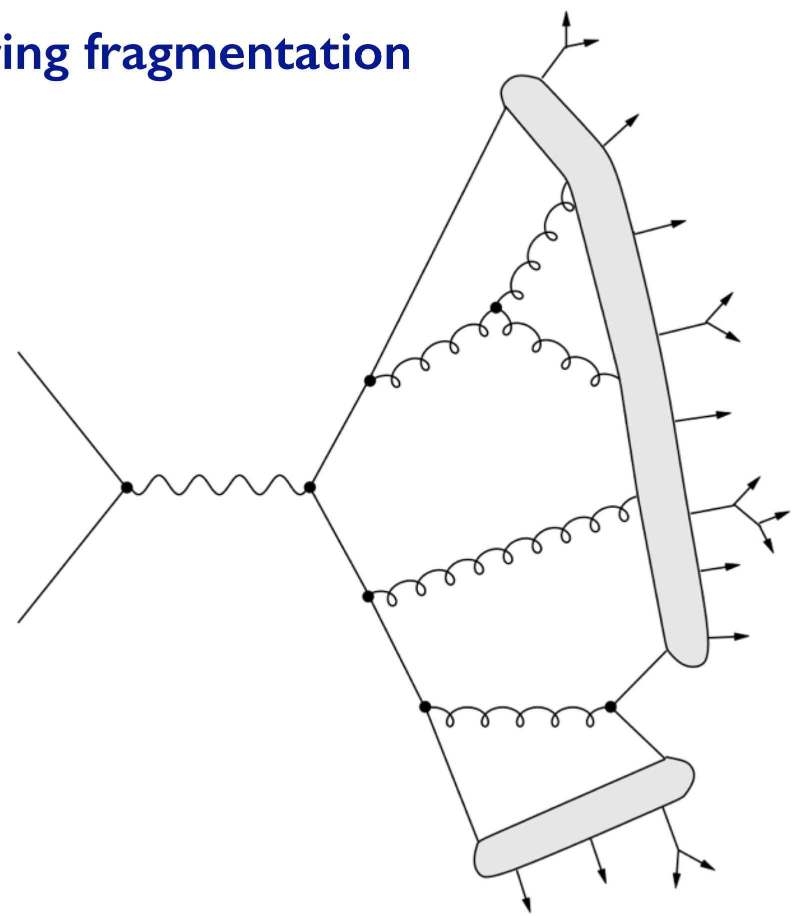


www.imperialhep.blogspot.com

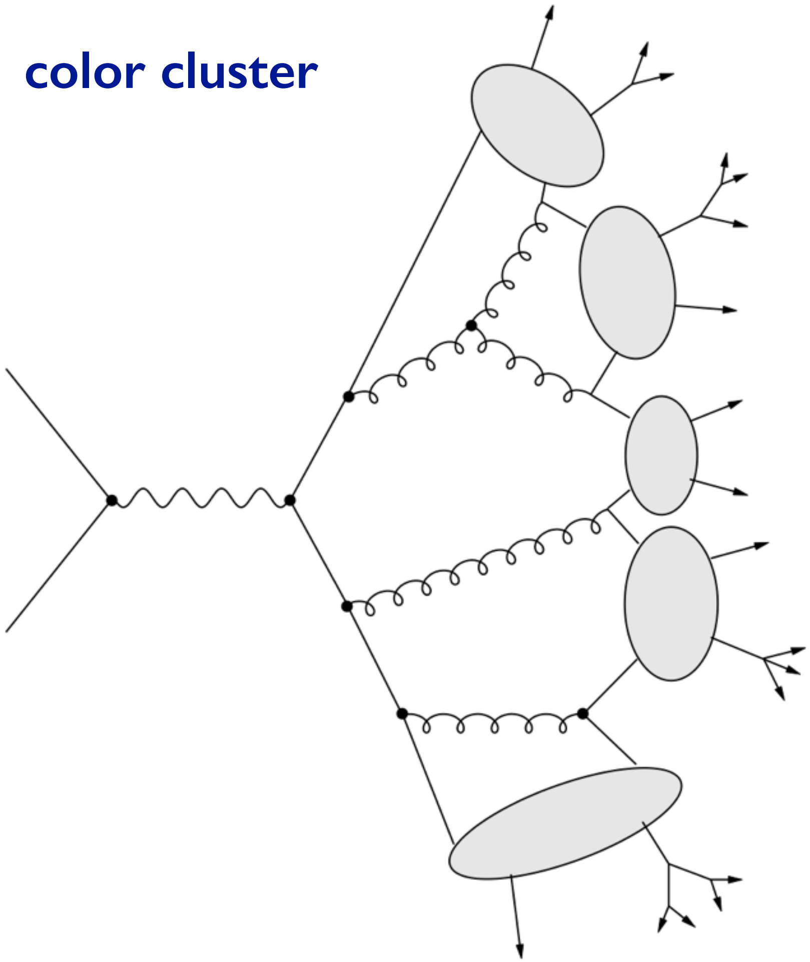
Hadronization models

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

string fragmentation

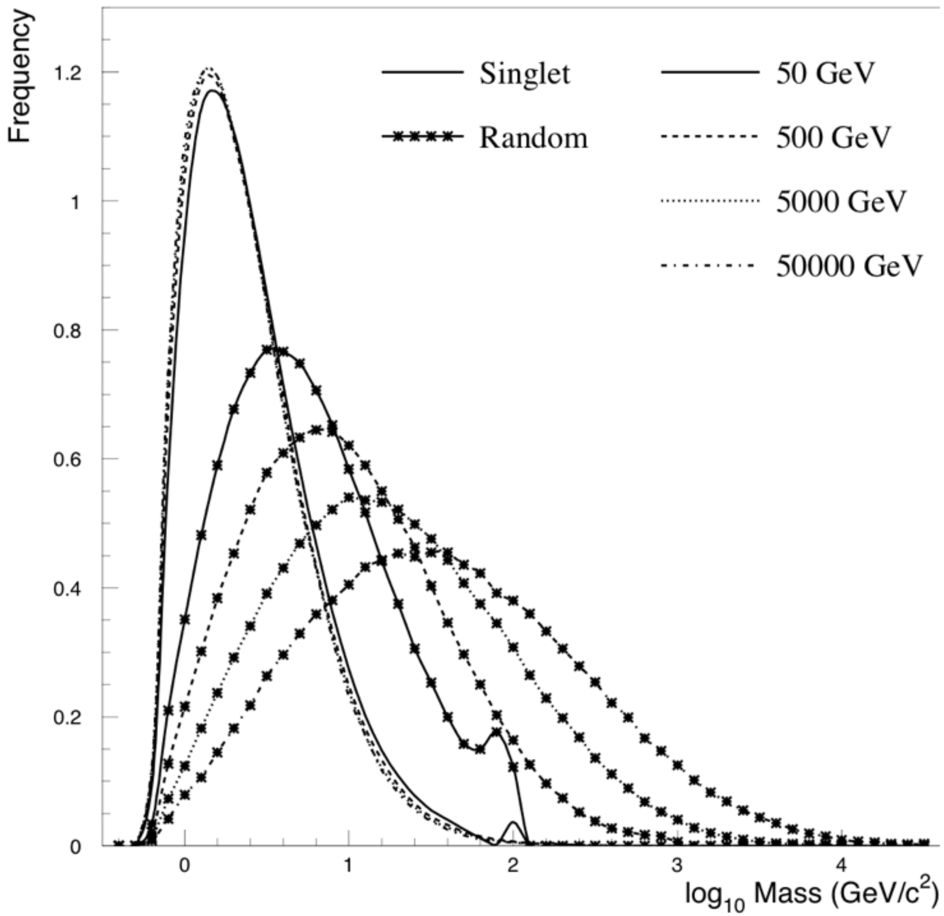


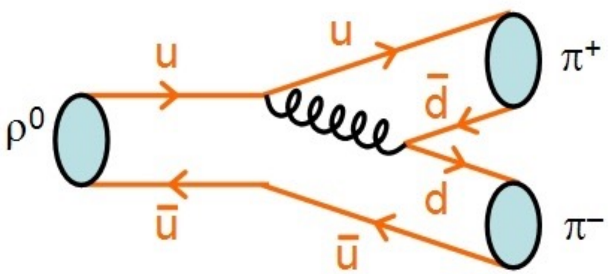
color cluster

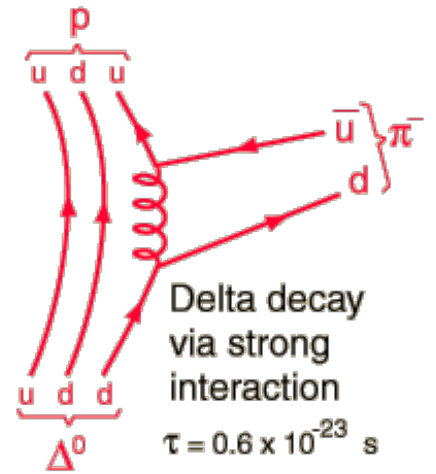


Hadron decays

- 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

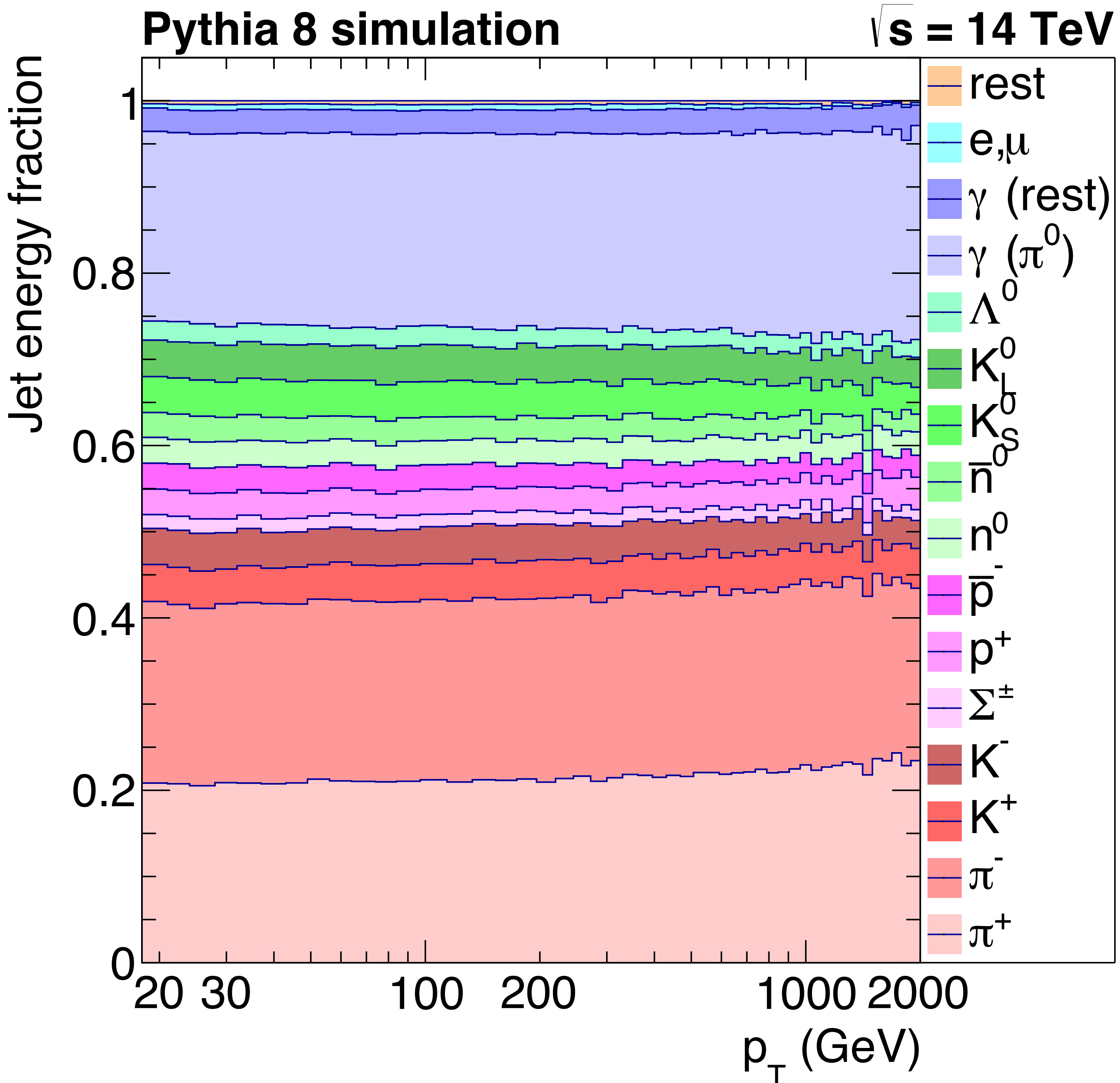






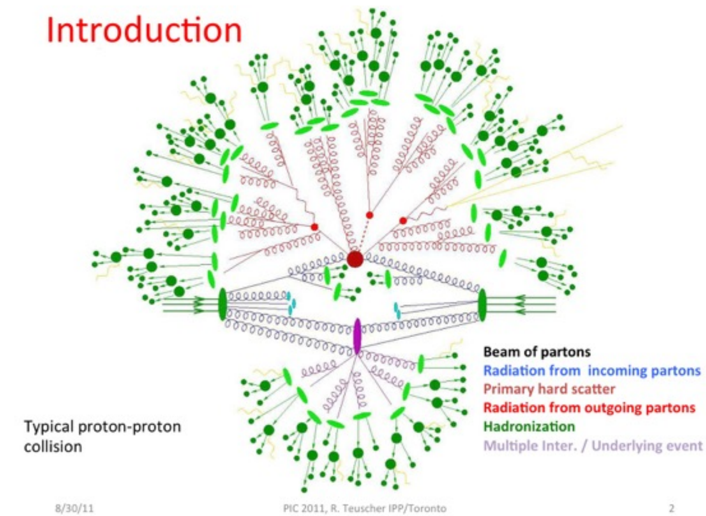
Jet composition

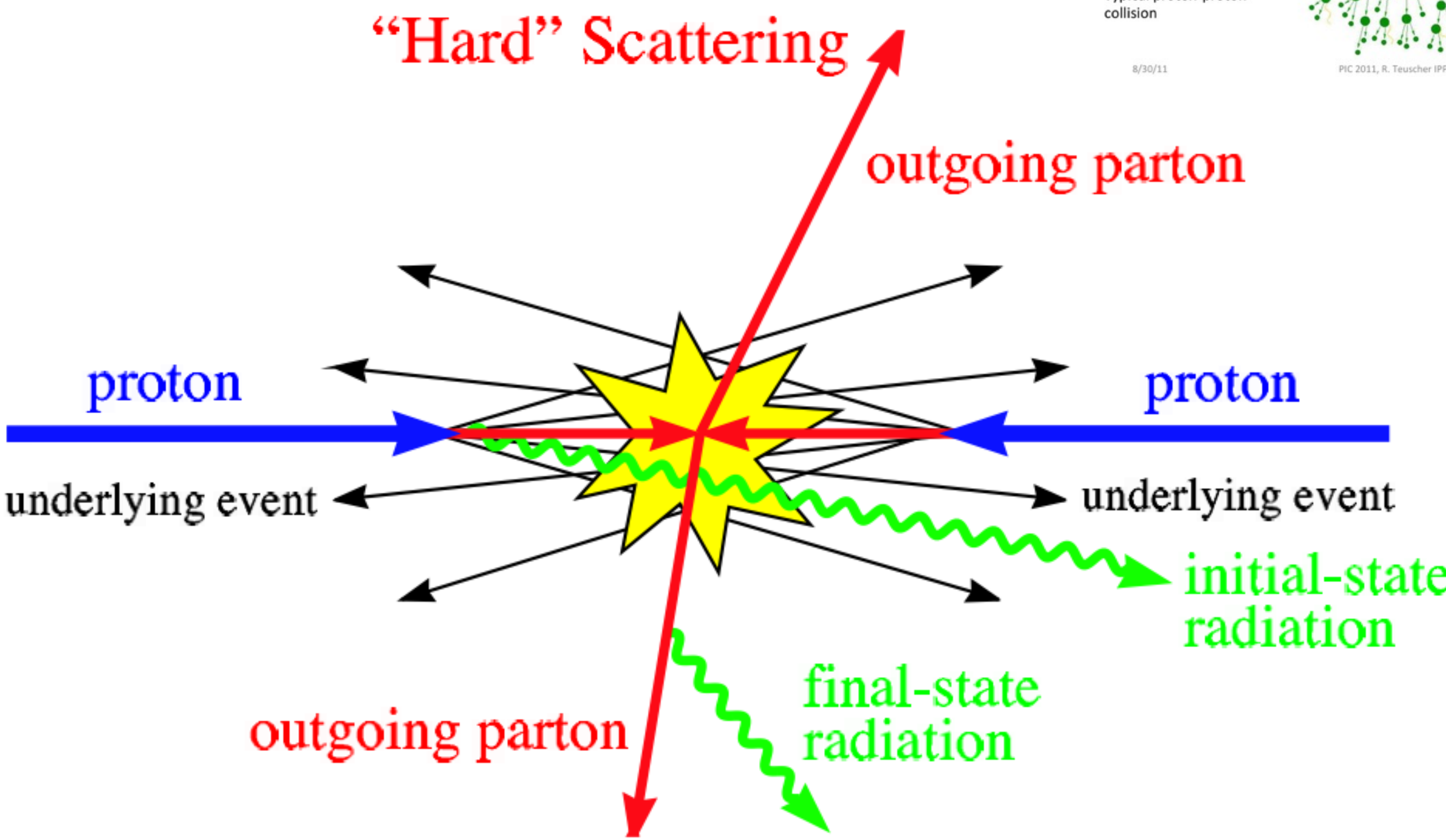
- As a result of decays of excited states, most of the jet is composed of familiar pions, kaons and nucleons
  - neutral pions immediately decay to photon pair
- Rough proportions:
  - pions: 65%
  - kaons: 15%
  - nucleons: 12%
  - rest (Λ^0,$\Sigma^\pm$,e,μ,..): 8%
- Neutral-to-charge ratios in proportion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



Hannu Siikonen

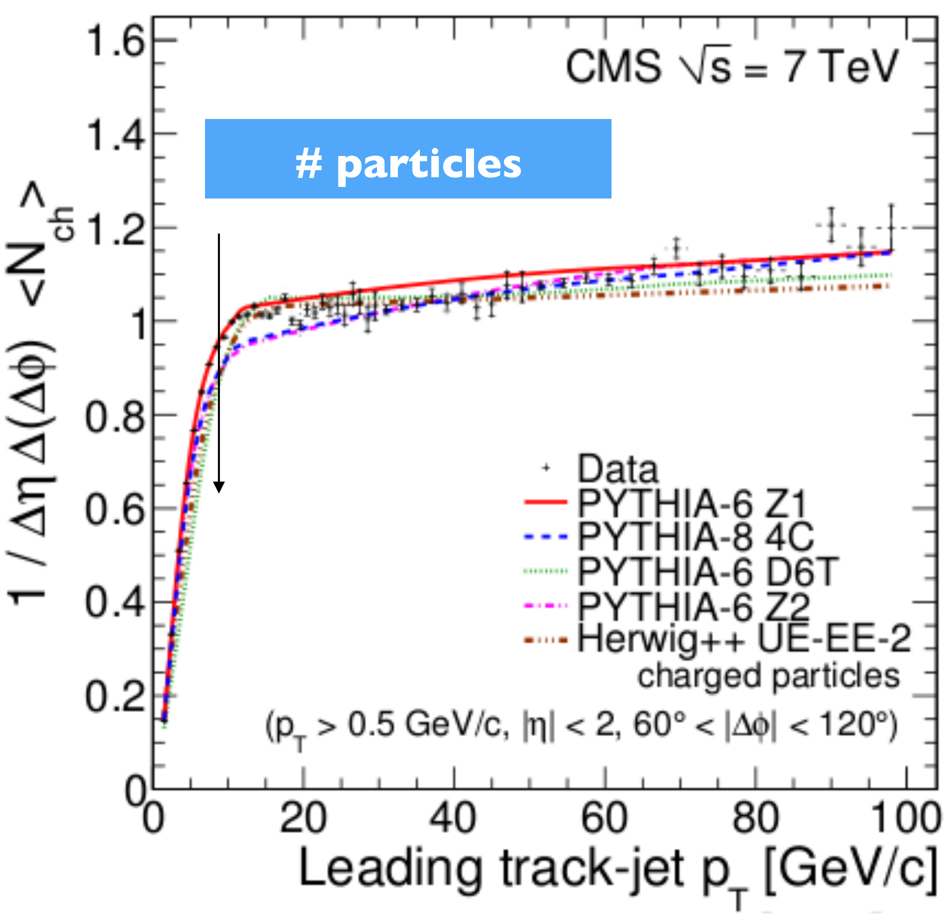
- Proton-proton collisions are messy, and jets also contain particles from additional soft parton interactions
  - aka **"Underlying event" (UE)**
- Adds a diffuse, fairly homogeneous offset to jets
  - **"pileup" (PU)** is tens of low-scale UE on top of each other

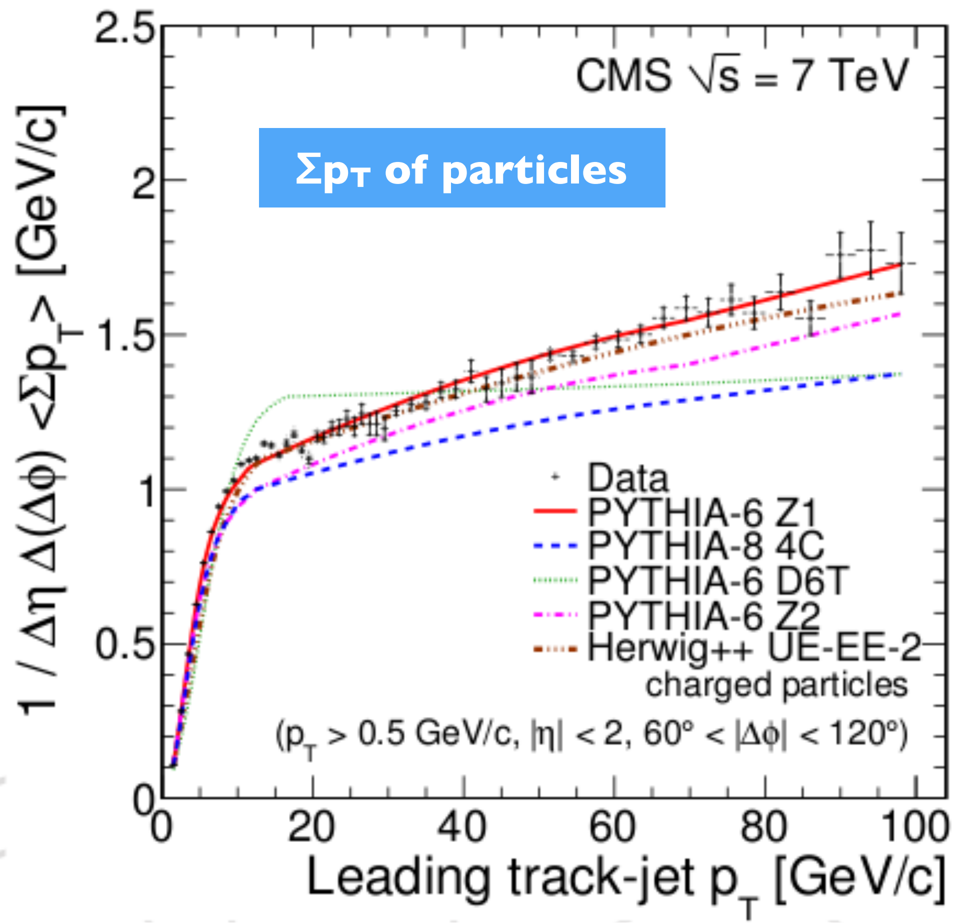




Underlying event -> pileup

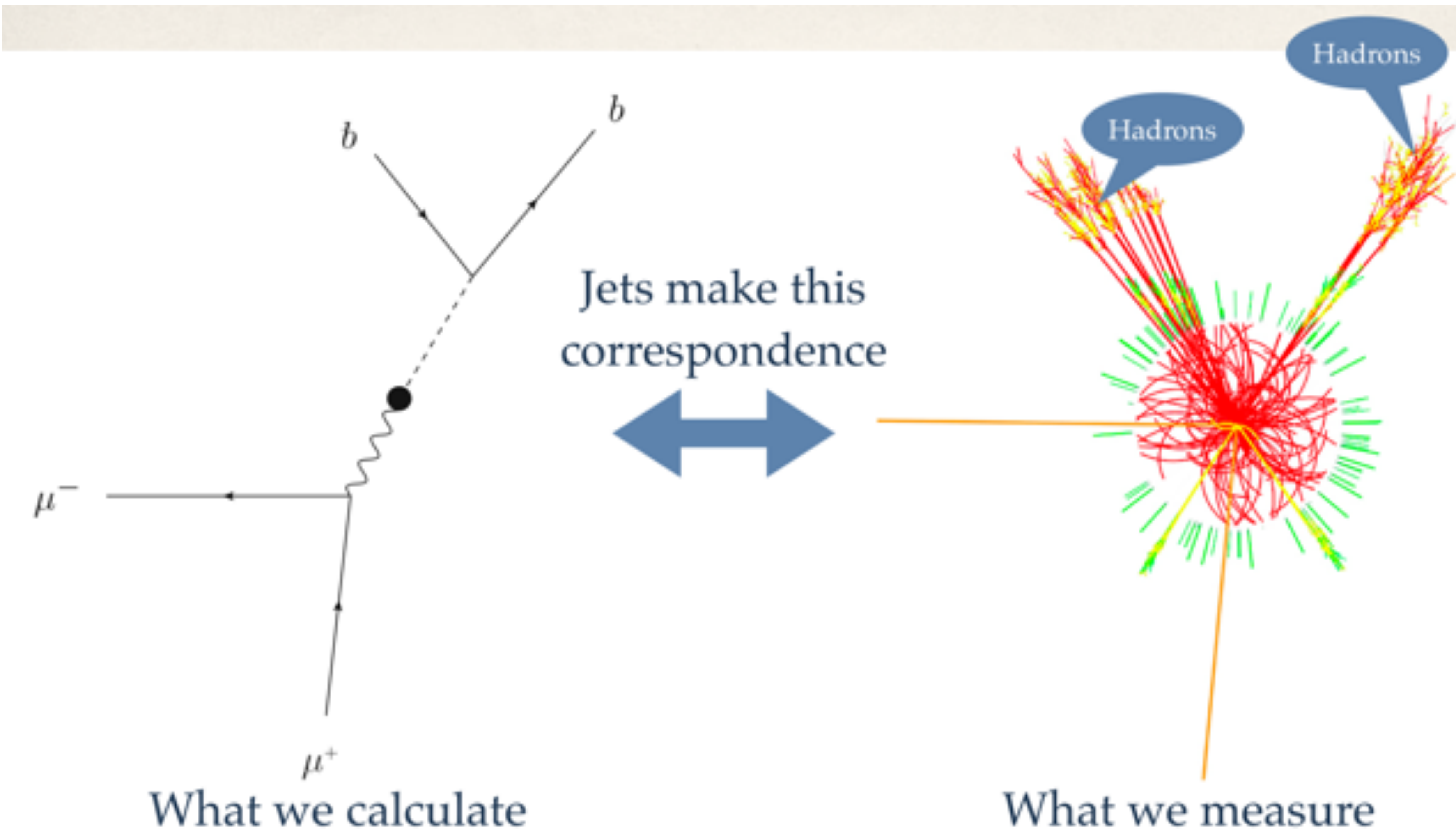
- Underlying event (UE) for soft Minimum Bias events is the basis of simulating pileup
  - Pythia6, Pythia8 and Herwig++ have tunes based on LHC data (e.g. Z1, Z2*, AMBT, CUETM1…)
- UE quickly saturates for hard collisions ($p_{T,ch\text{-}jet}$ > 10 GeV, or $p_{T,jet}$ > 15 GeV)
  - slow rise on the plateau is due to additional jets in transverse region





JHEP 9 (2011) 109 / QCD-10-010

- 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 clustering

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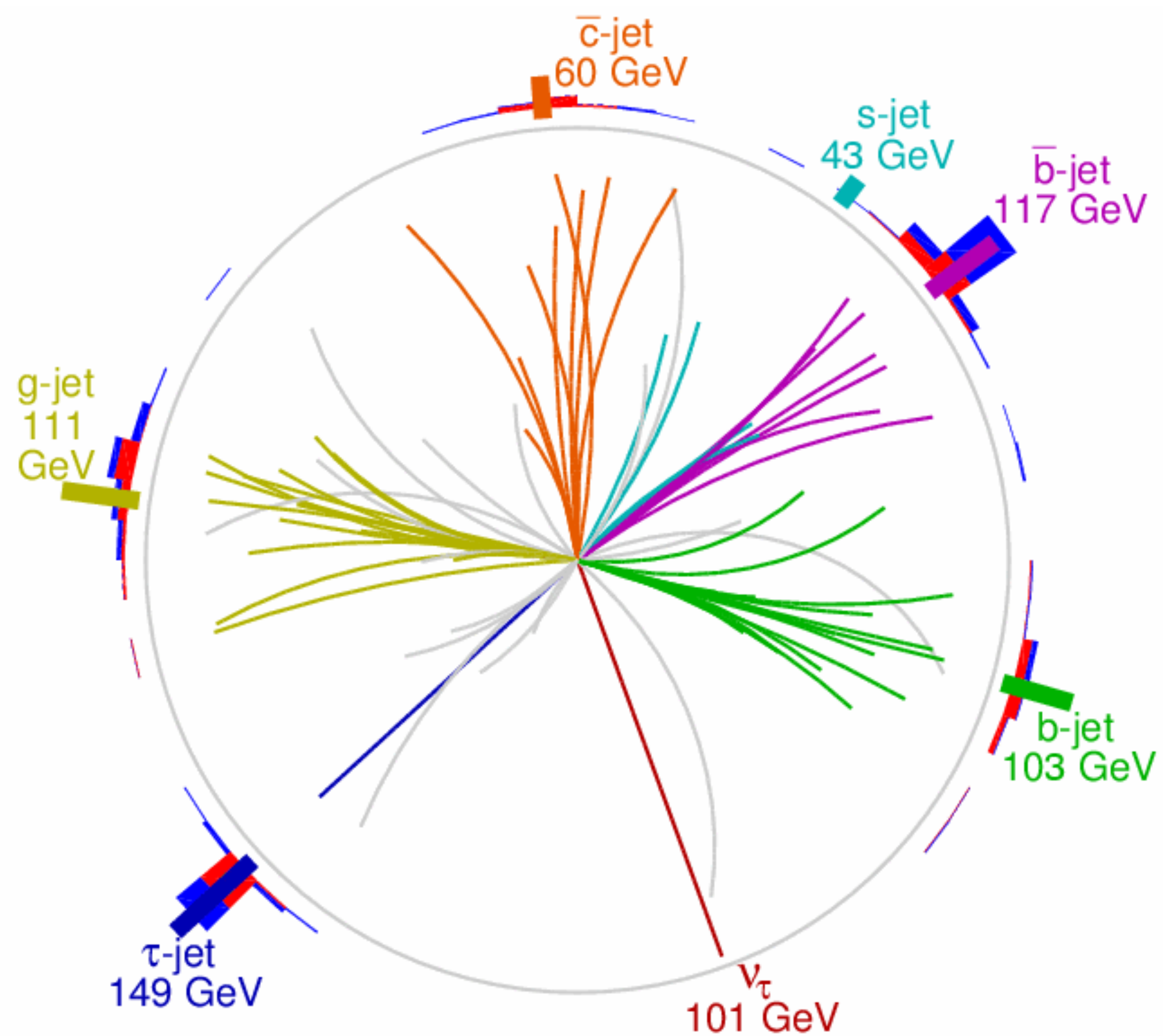
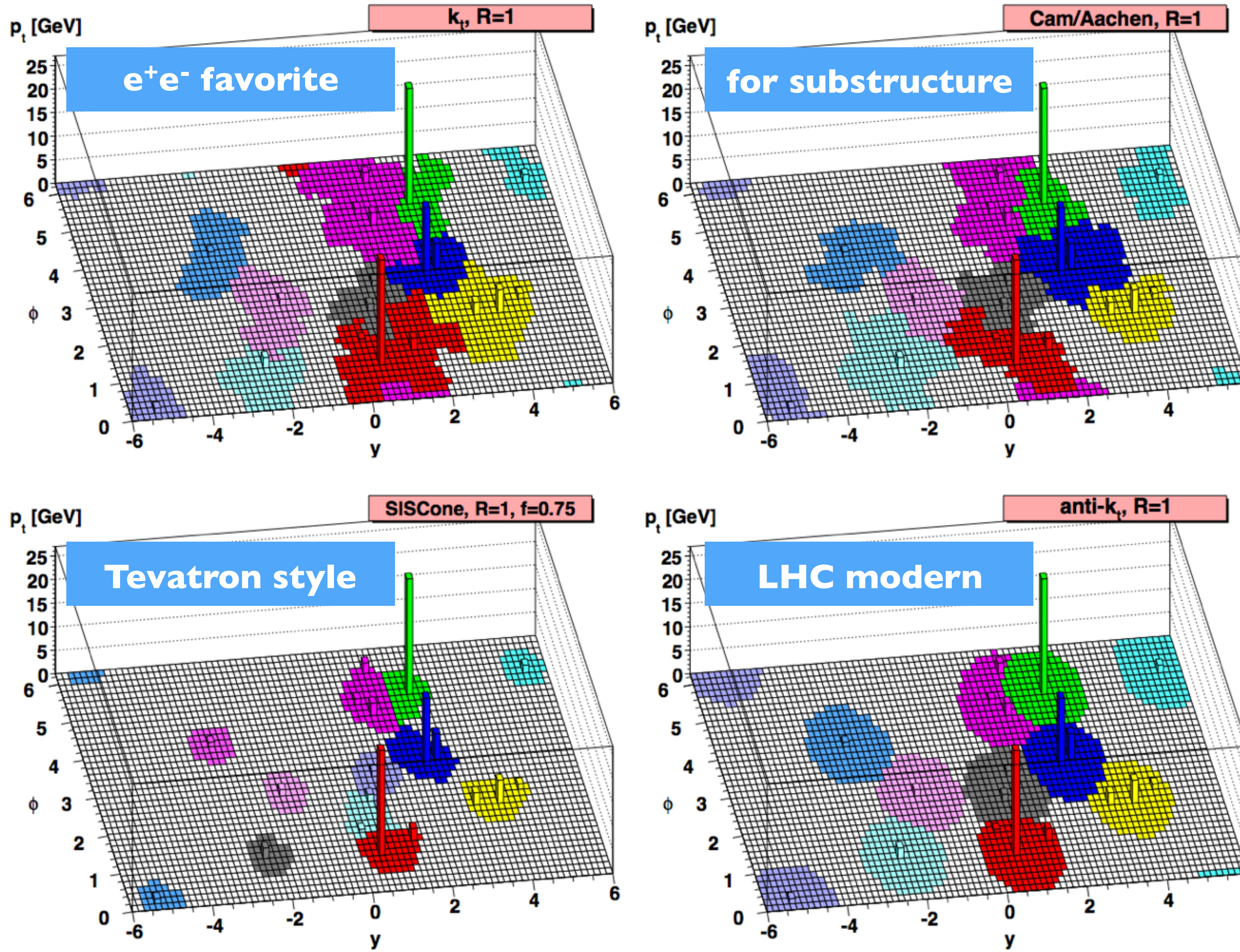


$gg \to tbH^+$, $t \to Wb \to scb$, $H^+ \to \tau\nu \to$ hadrons with a radiative gluon jet

Jet clustering

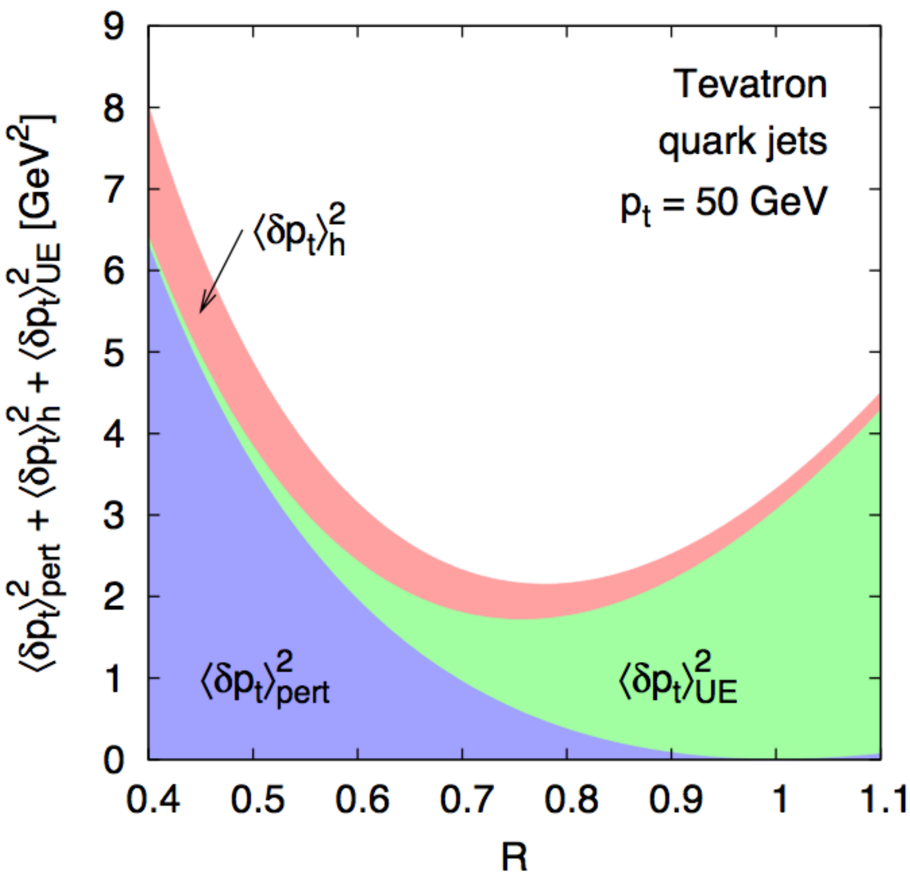
- Snowmass: infrared and collinear safety
- Sequential recombination: merge particle 4-vectors in pairs
- k_T: softest 1st, invert parton shower
  - LHC: clusters pileup
  - favoured at e^+e^-
- **anti-k_T**: hardest 1st, catch early FSR
  - "cookie-cutter", favours leading jets
  - **default at LHC**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

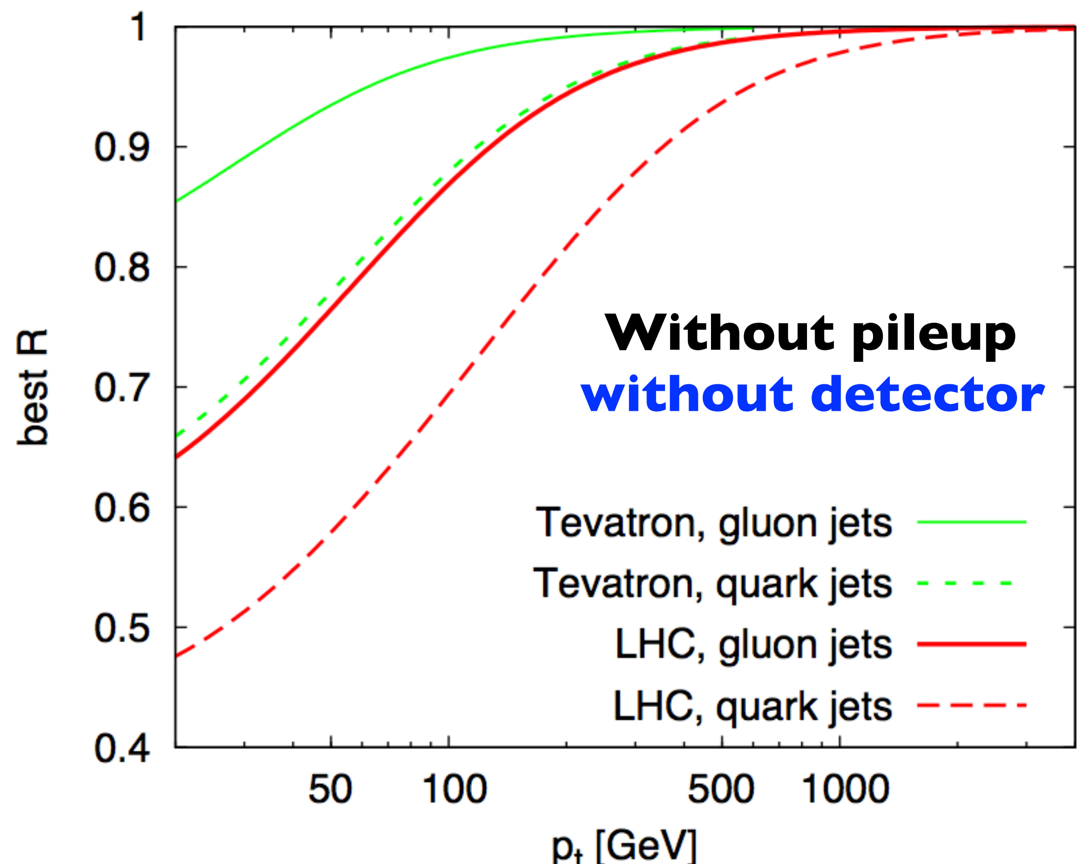


arXiv:0906.1833

Optimal R — gen

- Optimal jet radius *R* is an 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

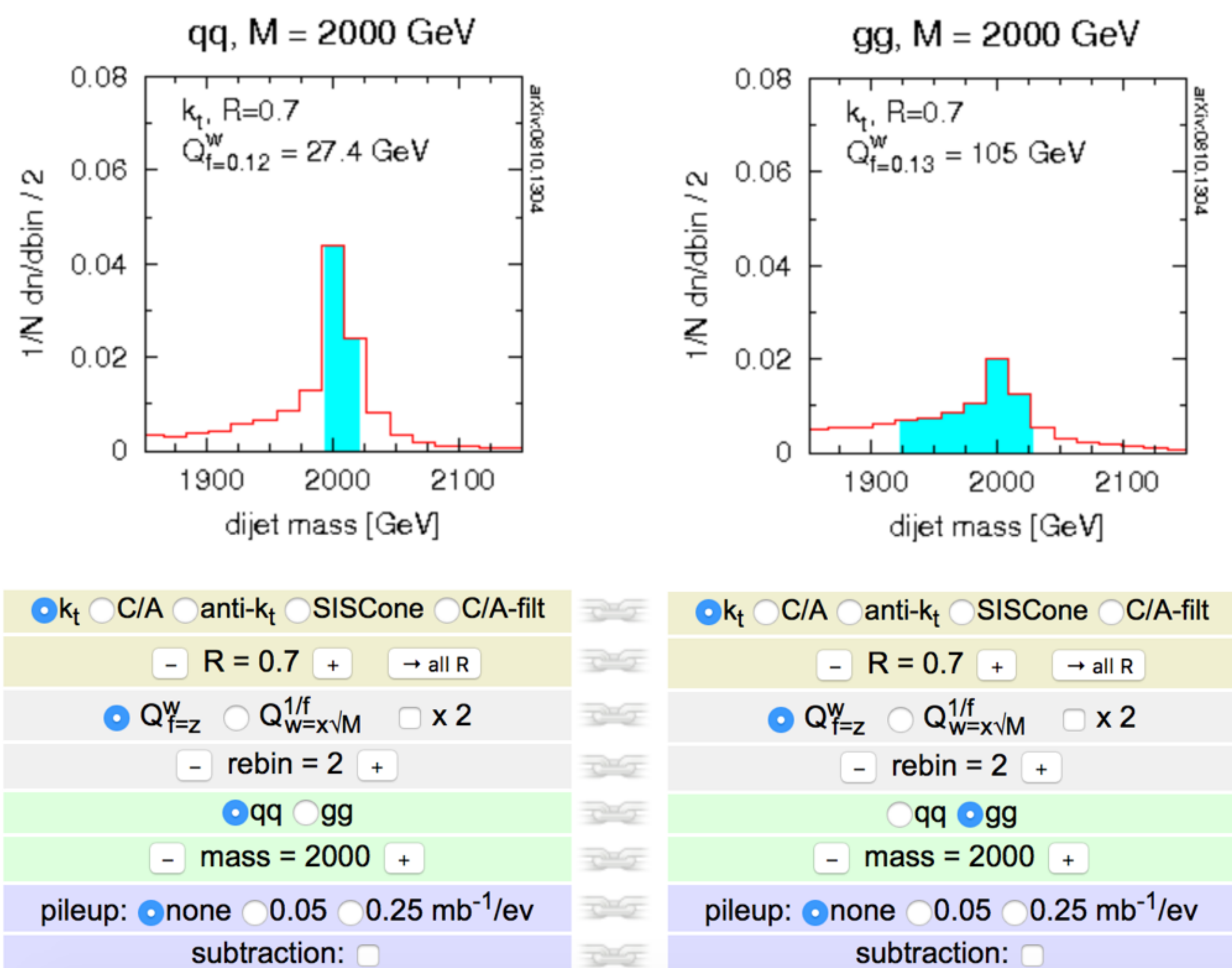
Optimal R — bumps

- Typical use case is a **bump hunt** of new particles decaying to qq or gg pair; optimum R depends on…

Try it yourself: Gavin Salam's jet-quality

Testing jet definitions: qq & gg cases

by M. Cacciari, J. Rojo, G.P. Salam and G. Soyez,



This page is intended to help visualize how the choice of jet definition impacts a dijet invariant mass reconstruction at LHC.

The controls fall into 4 groups:

- *the jet definition*
- *the binning and quality measures*
- *the jet-type (quark, gluon) and mass scale*
- *pileup and subtraction*

The events were simulated with Pythia 6.4 (DWT tune) and reconstructed with FastJet 2.3.

*For more information, view and listen to the **flash demo**, or click on individual terms.*

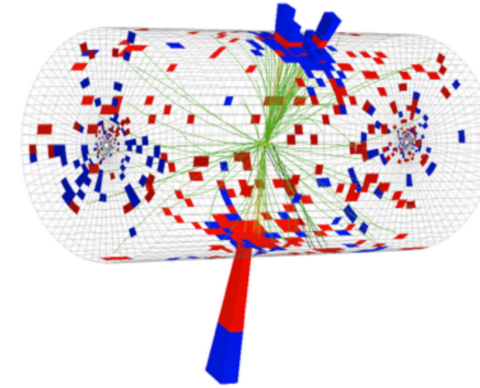
This page has been tested with Firefox v2 and v3, IE7, Safari v3, Opera v9.5, Chrome 0.2.

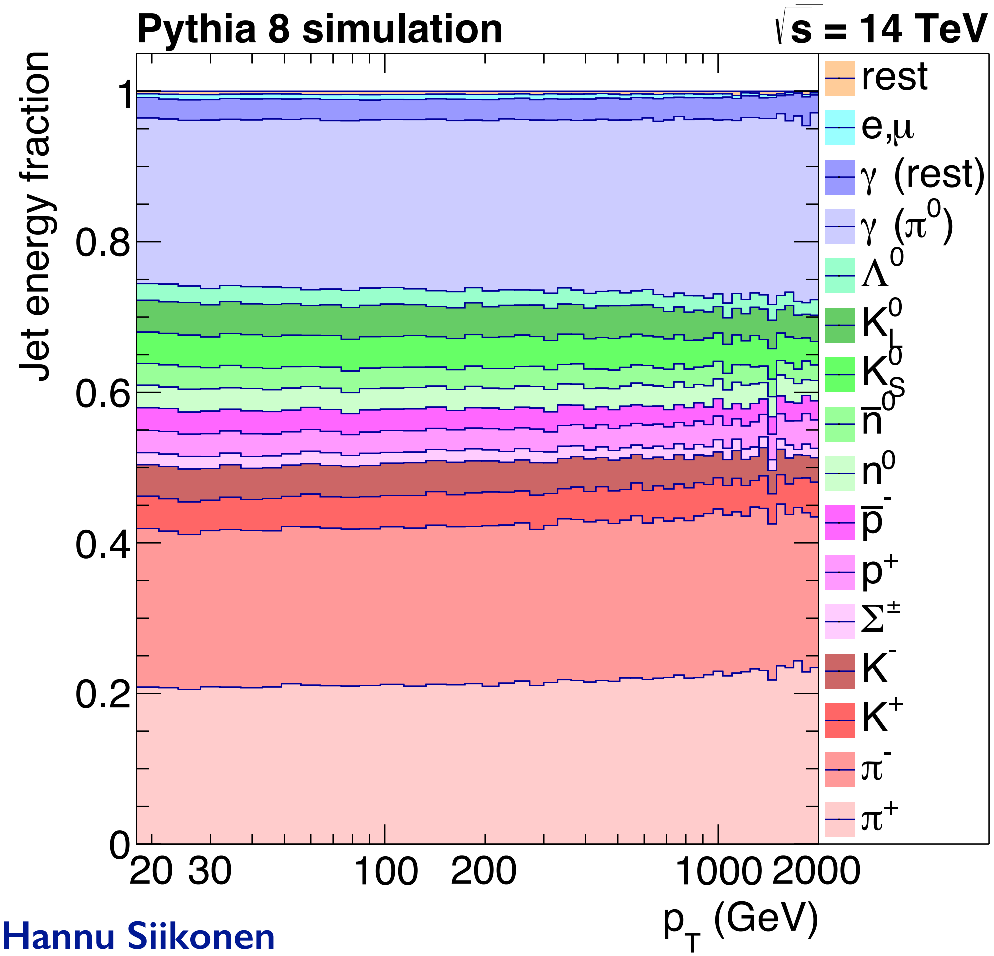
Reset

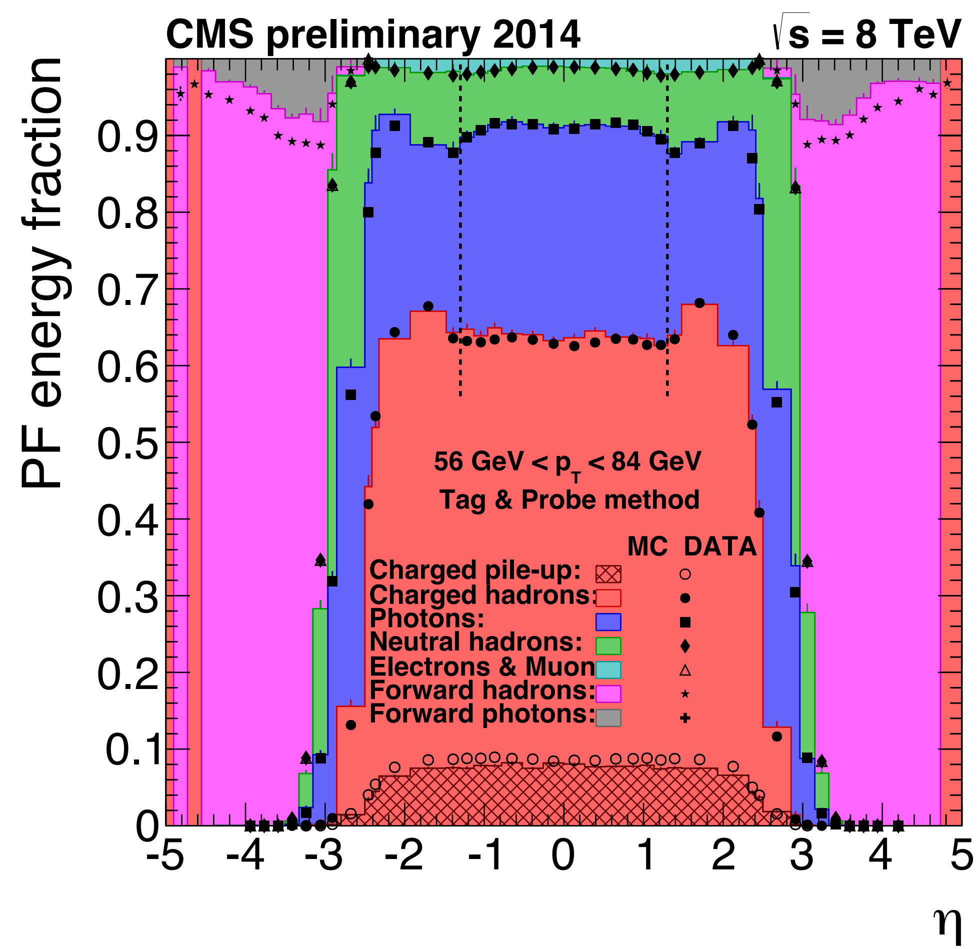
arXiv:0810.1304

Particle flow

- 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

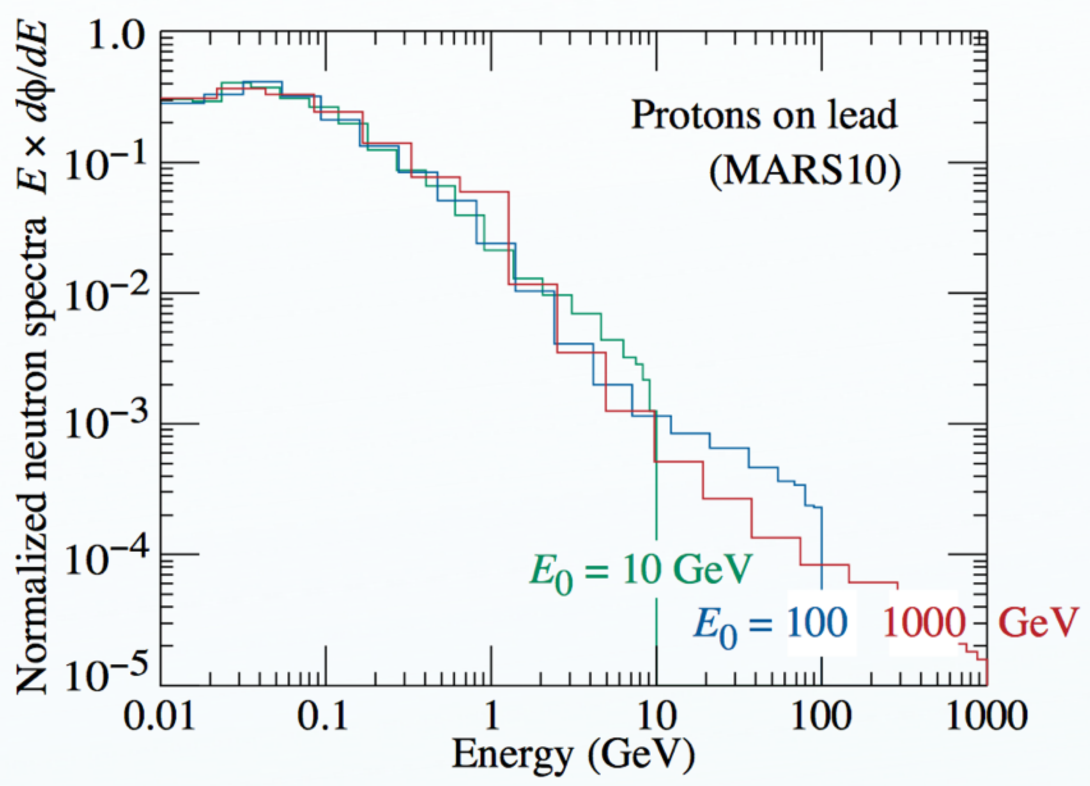






Hannu Siikonen

- 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*(adronic) << e(lectromagnetic)
  - 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

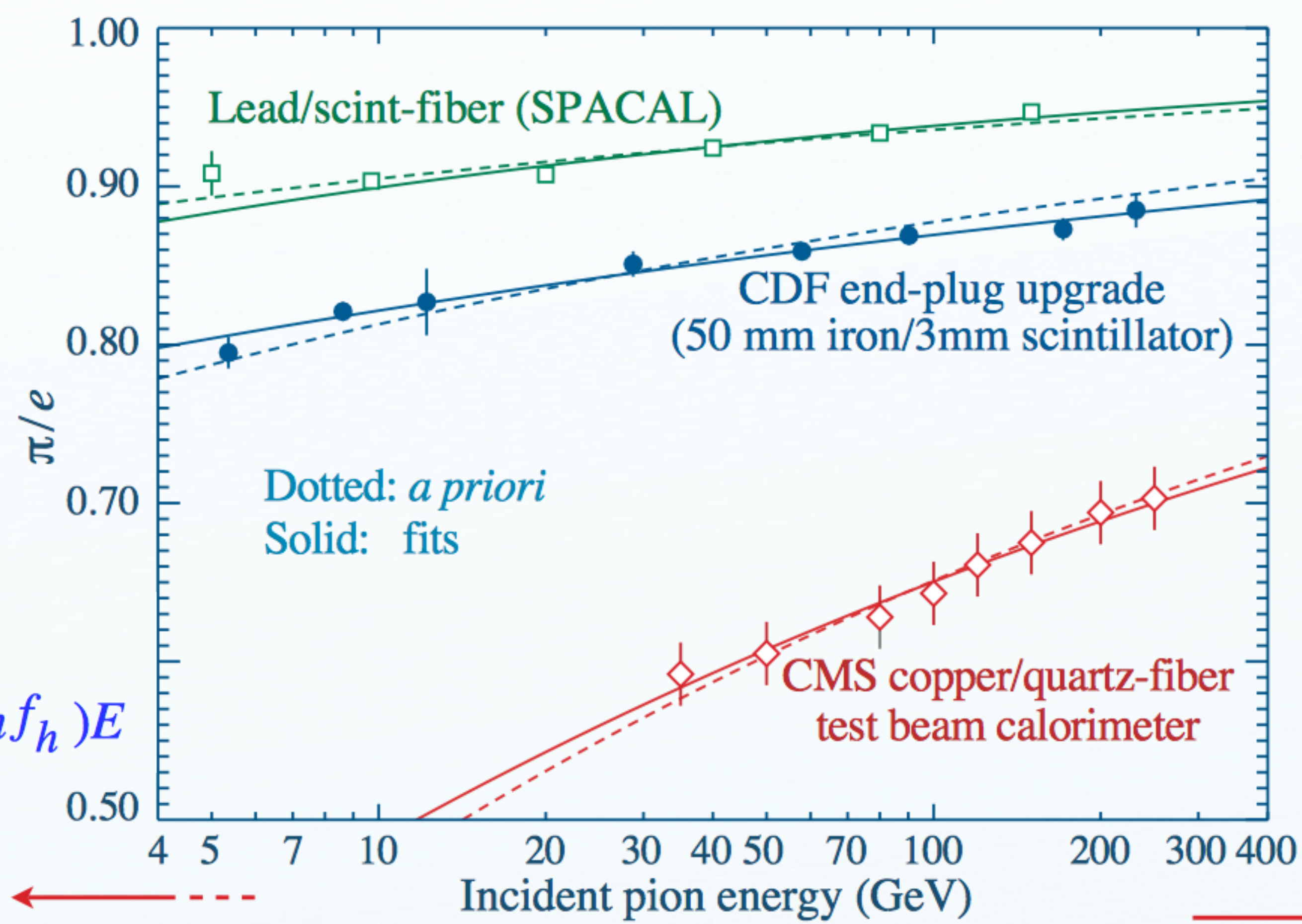


D.E. Groom

- Plugging in #1-#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

$\pi/e \to 1$

$$\text{“}\pi/e\text{”} = 1 - [(1 - h/e)(1 - f_\gamma)/E_0^{\,m-1}]\,E^{\,m-1}$$

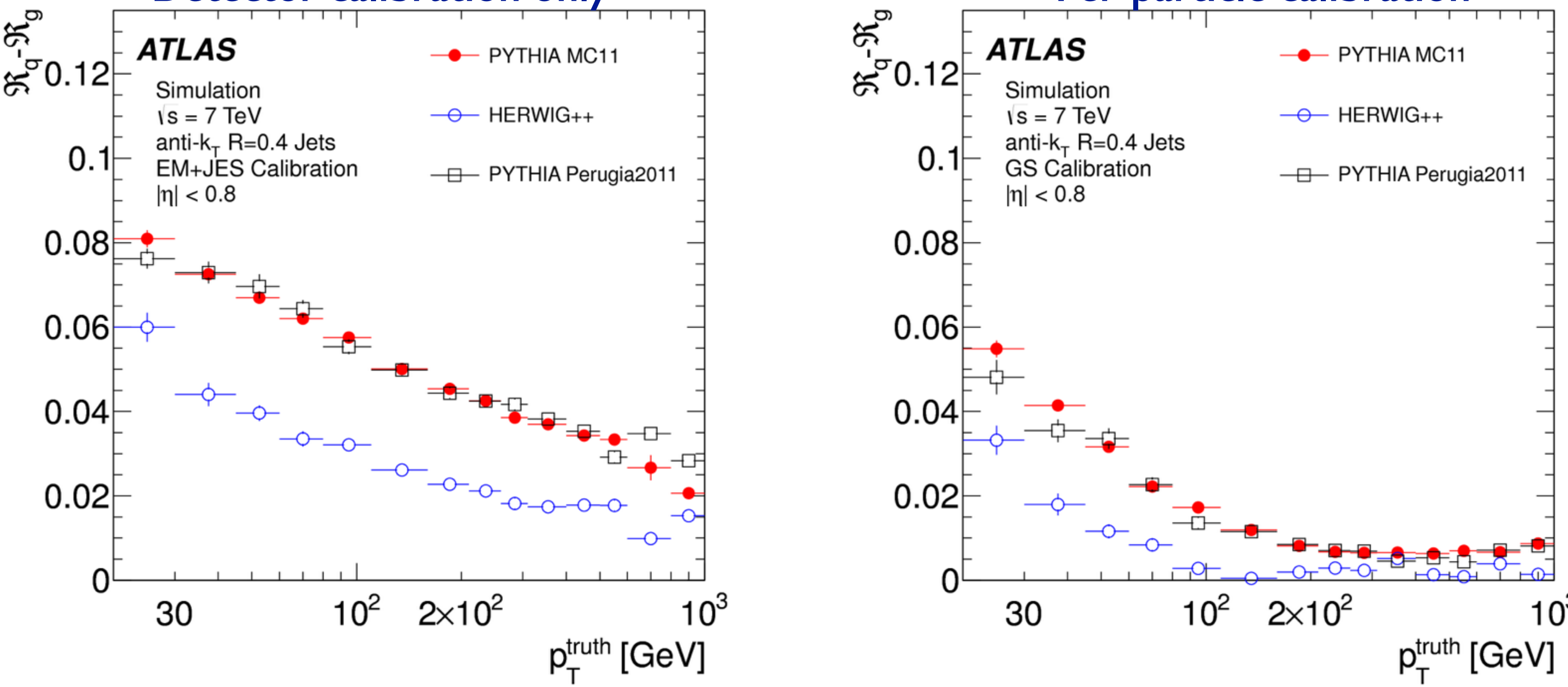
$$\equiv 1 - a\,E^{\,m-1}$$

D.E. Groom

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

Detector calibration only | **+ Per-particle calibration**

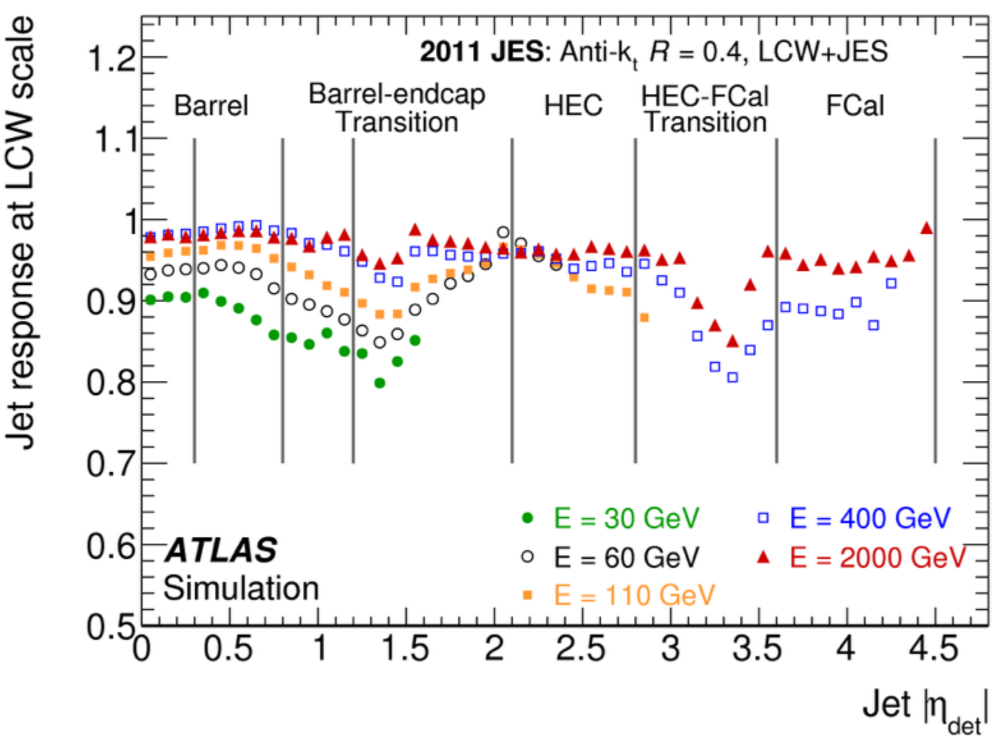


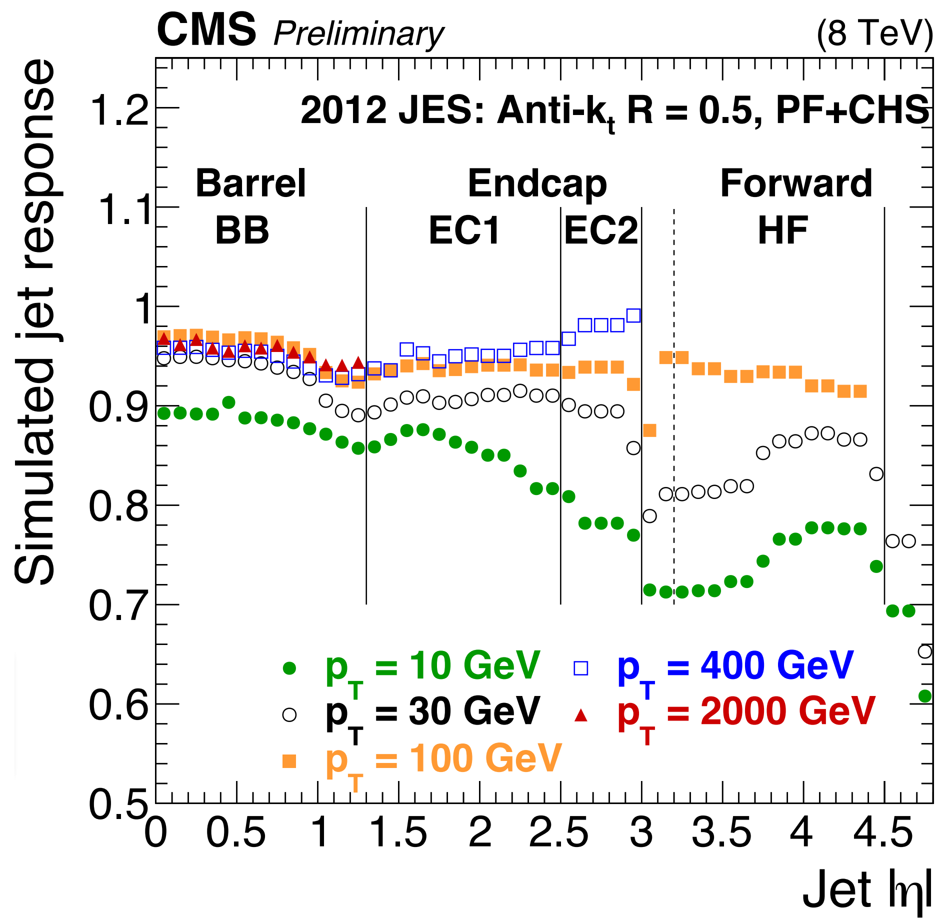
ATLAS PERF-2012-01

Jet response from MC

- Modern MC generators and detector simulation do quite well 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

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

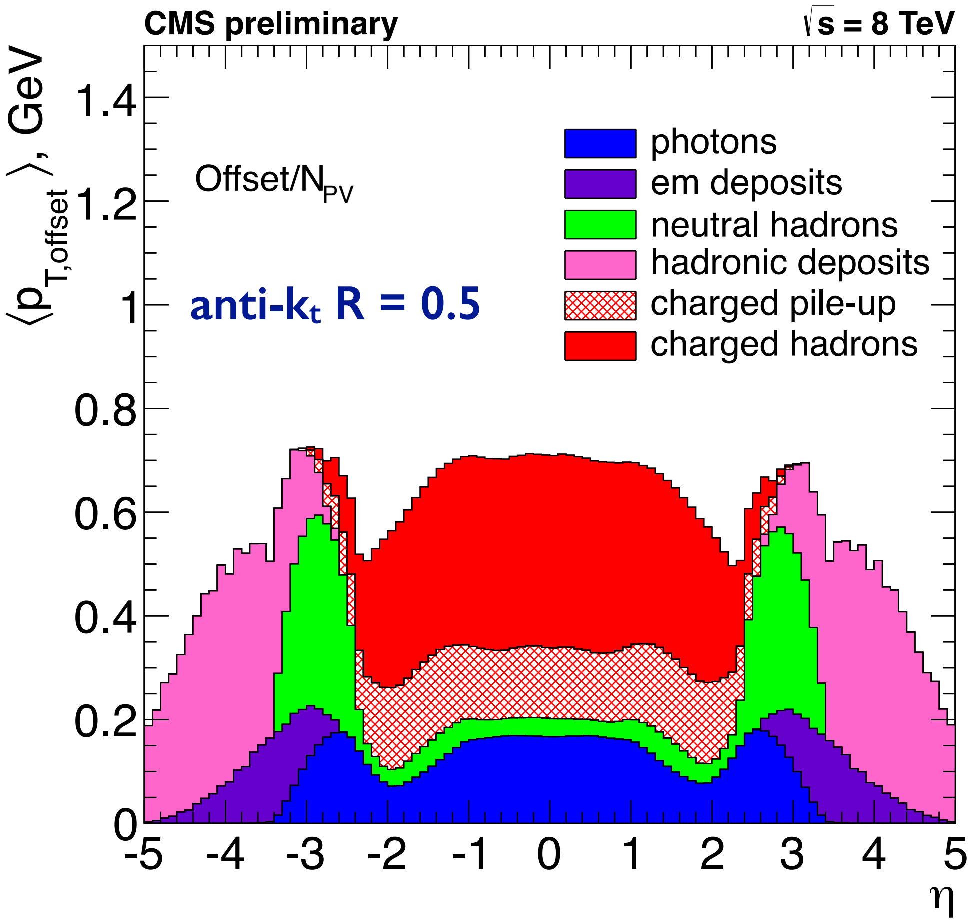


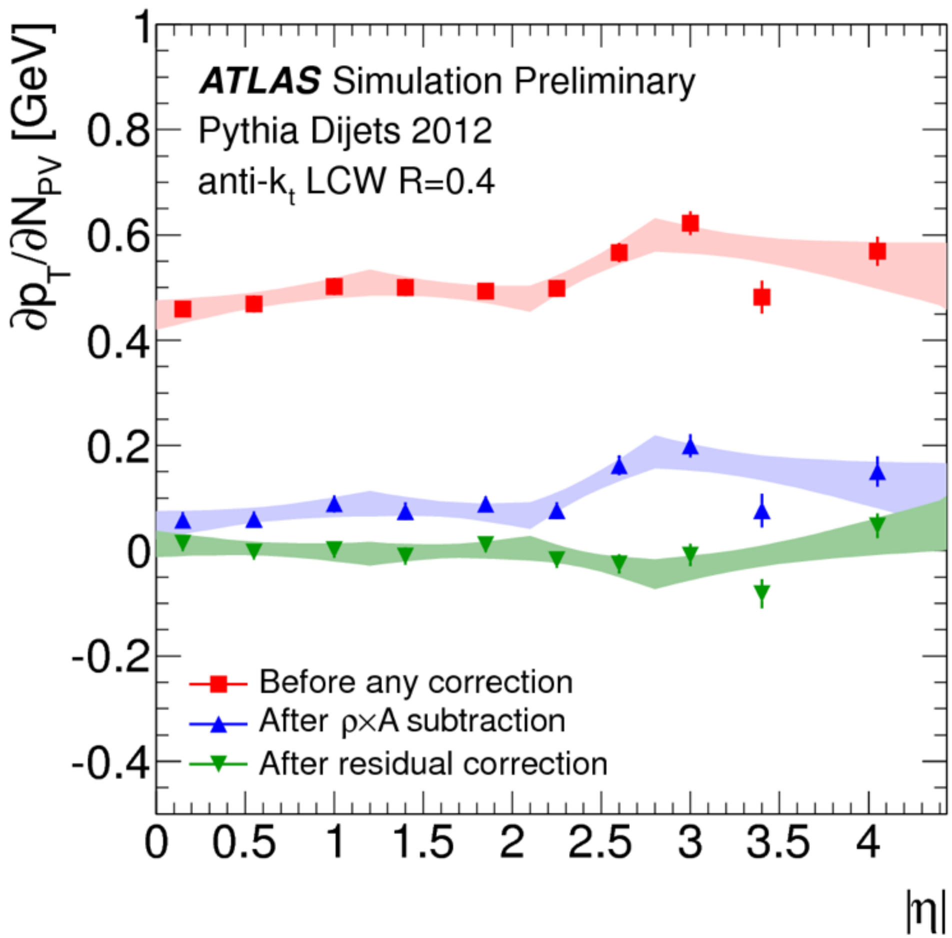


ATLAS PERF-2012-01

CMS DP-2015-044

- 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 <μ> (Poisson mean pileup)
- part of in-time pileup can be identified by matching tracks to PU vertices





CMS-DP-2012-012

ATLAS-CONF-2013-083

Jet corrections

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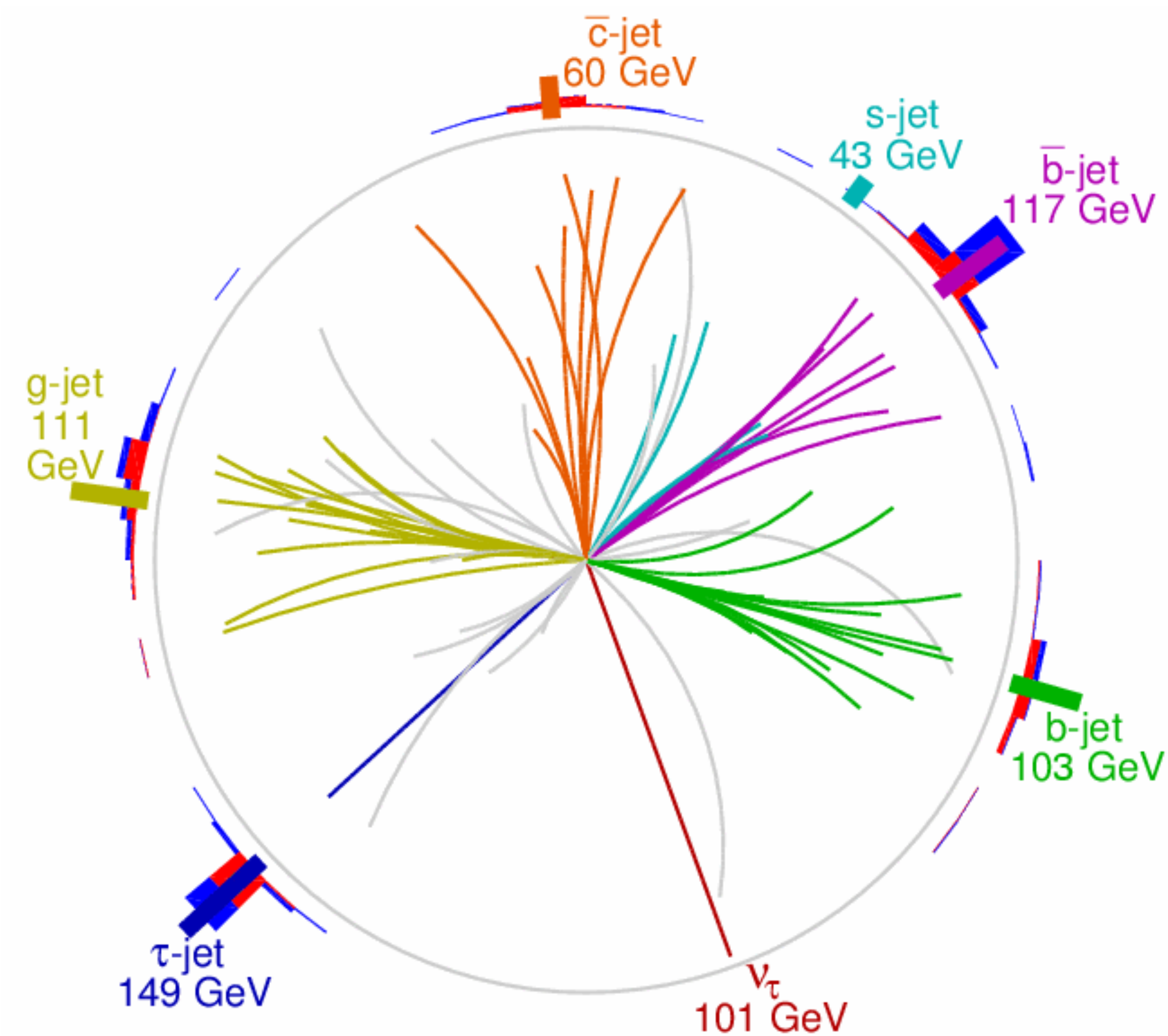


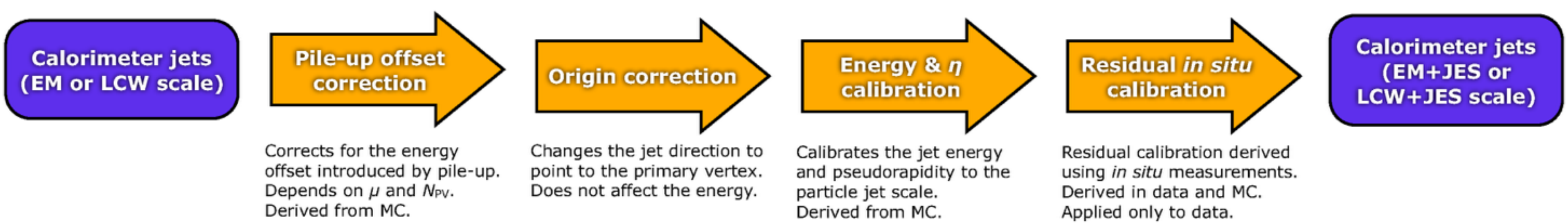
$gg \to tbH^+, t \to Wb \to scb, H^+ \to \tau\nu \to$ *hadrons with a radiative gluon jet*

Jet energy corrections

- JEC inverts everything we just described, and takes jet p_T 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 preferentially as much smaller residual data/MC factors

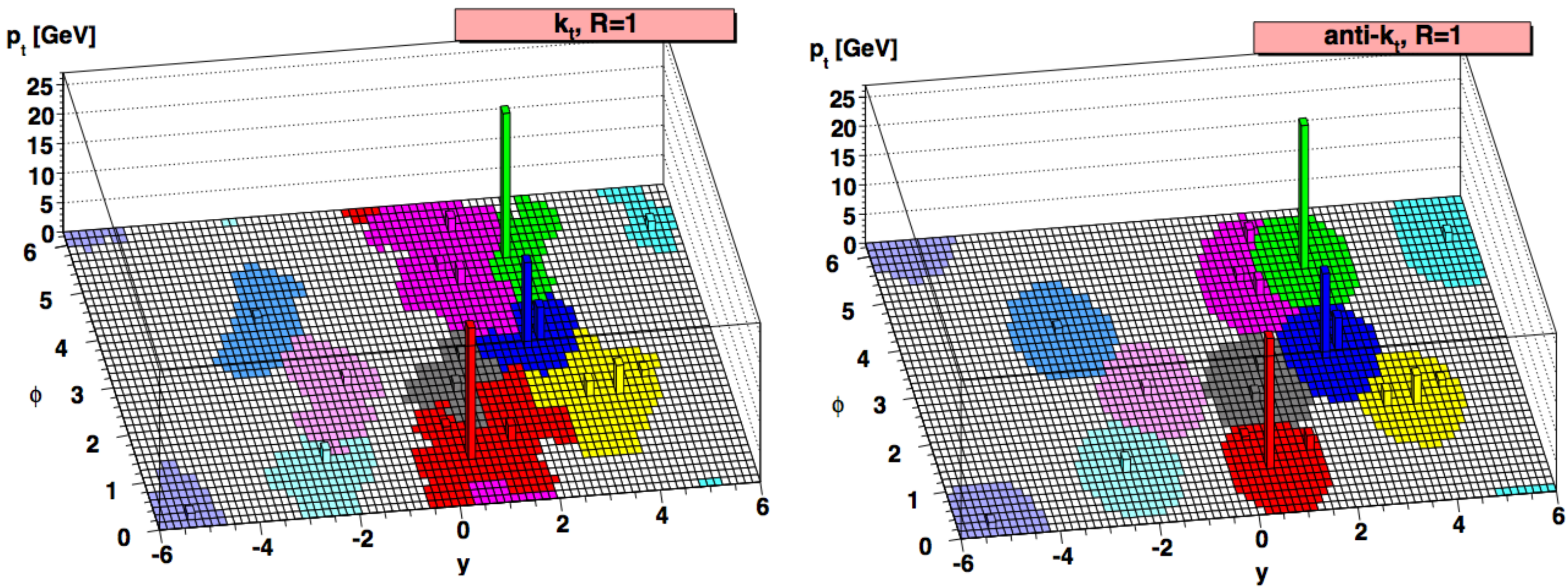
$$p_{T,corr} = \frac{p_{T,raw} - O(\eta,p_T)}{k_{data/MC} \times R \cdot S\,(\eta,p_T)}$$

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



- Both experiments now use the area-median (ρ-A) method
  - jet area calculated in FastJet by throwing ghosts
  - energy density ρ as median{ $p_{T,i}$ / 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

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

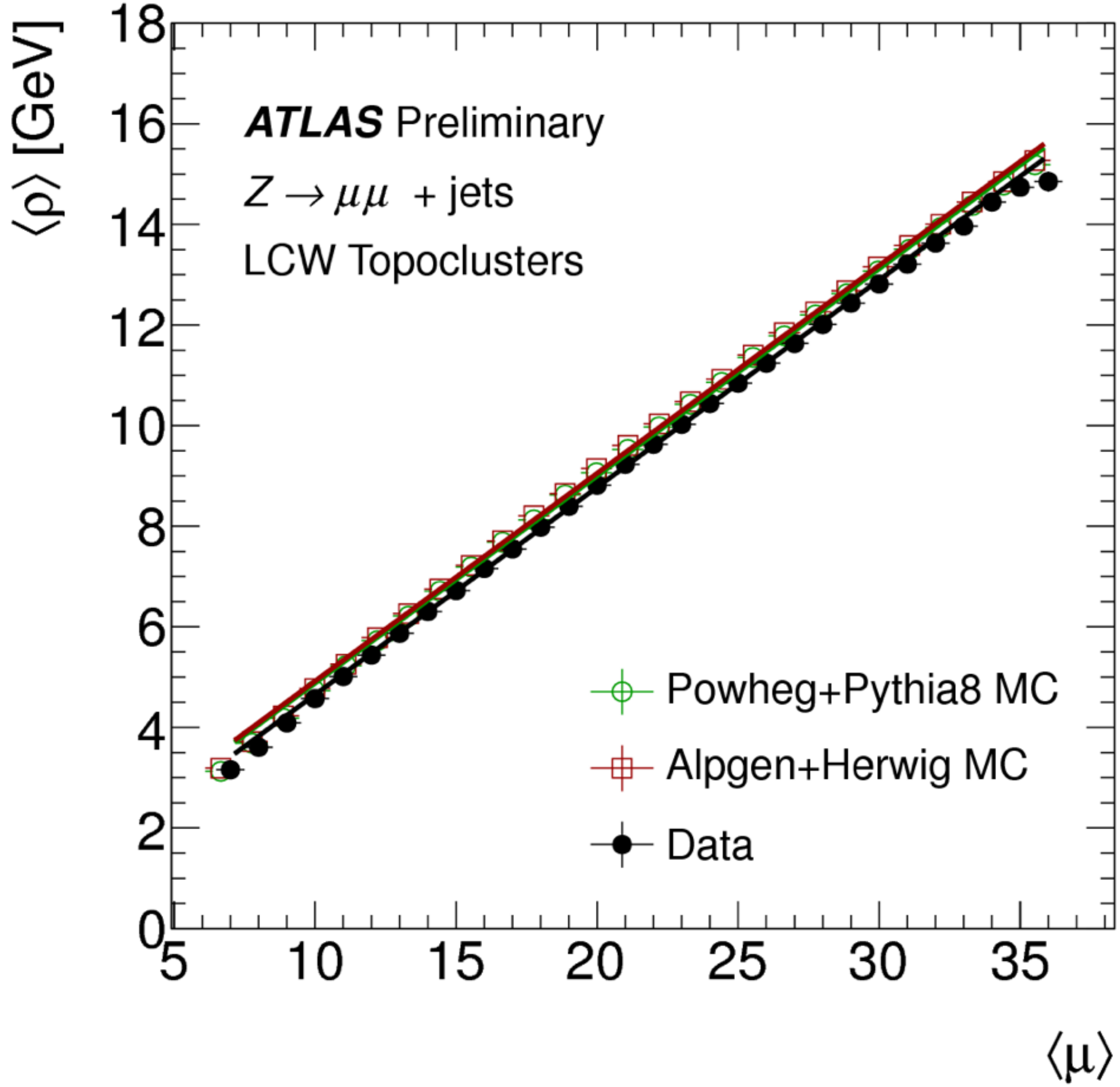


$$\rho_{eff} = (\rho - \rho_{UE}) \cdot k_\rho(\eta, p_T, \mu)$$

arXiv:0906.1833

- Pileup scales almost linearly with <μ>, and is to first order independent of jet p_T

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

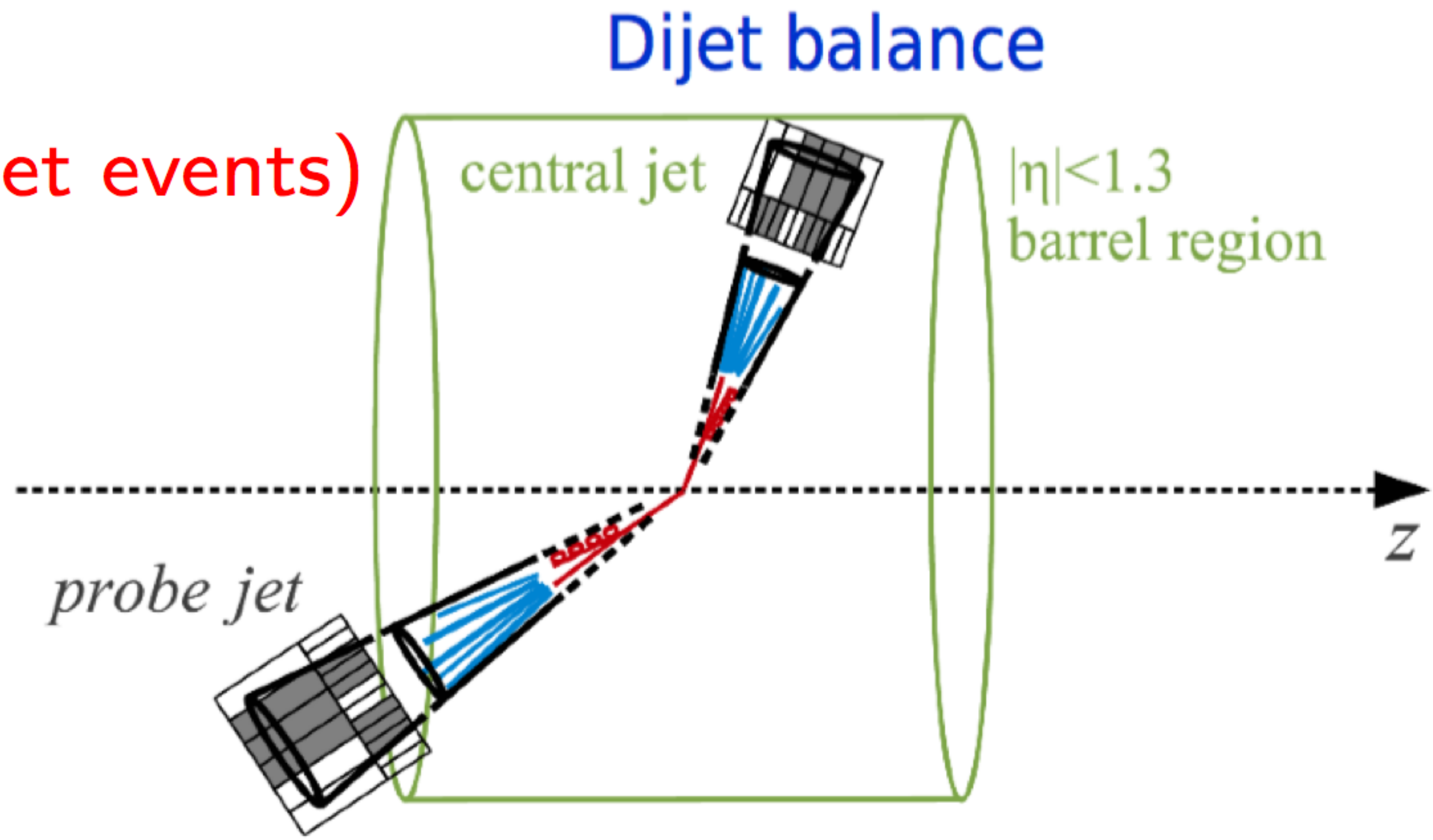


ATLAS-CONF-2013-083

Dijet balance

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

(Dijet events)



Dijet balance

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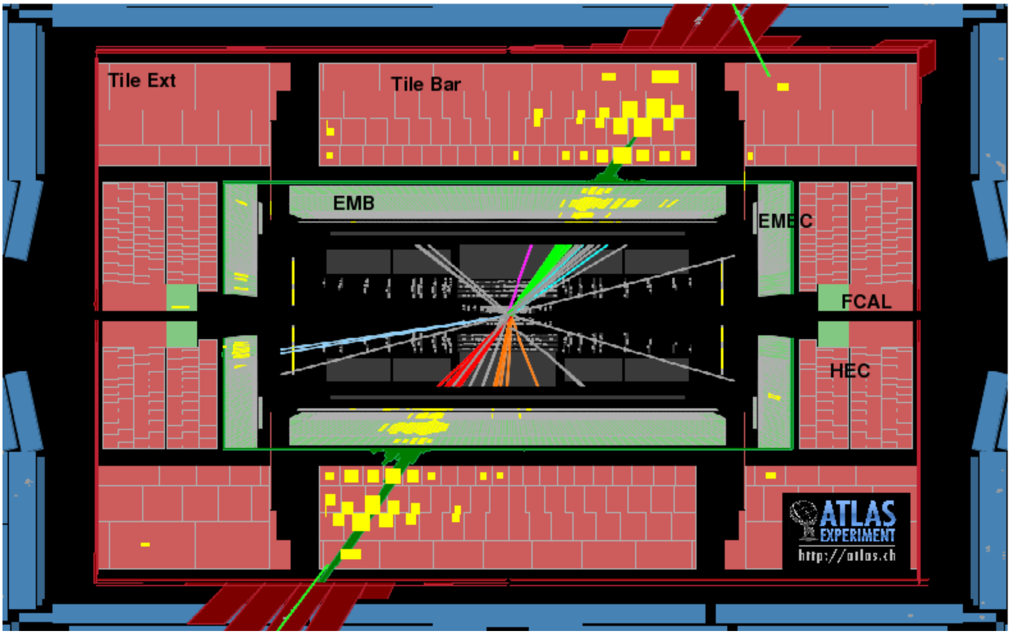
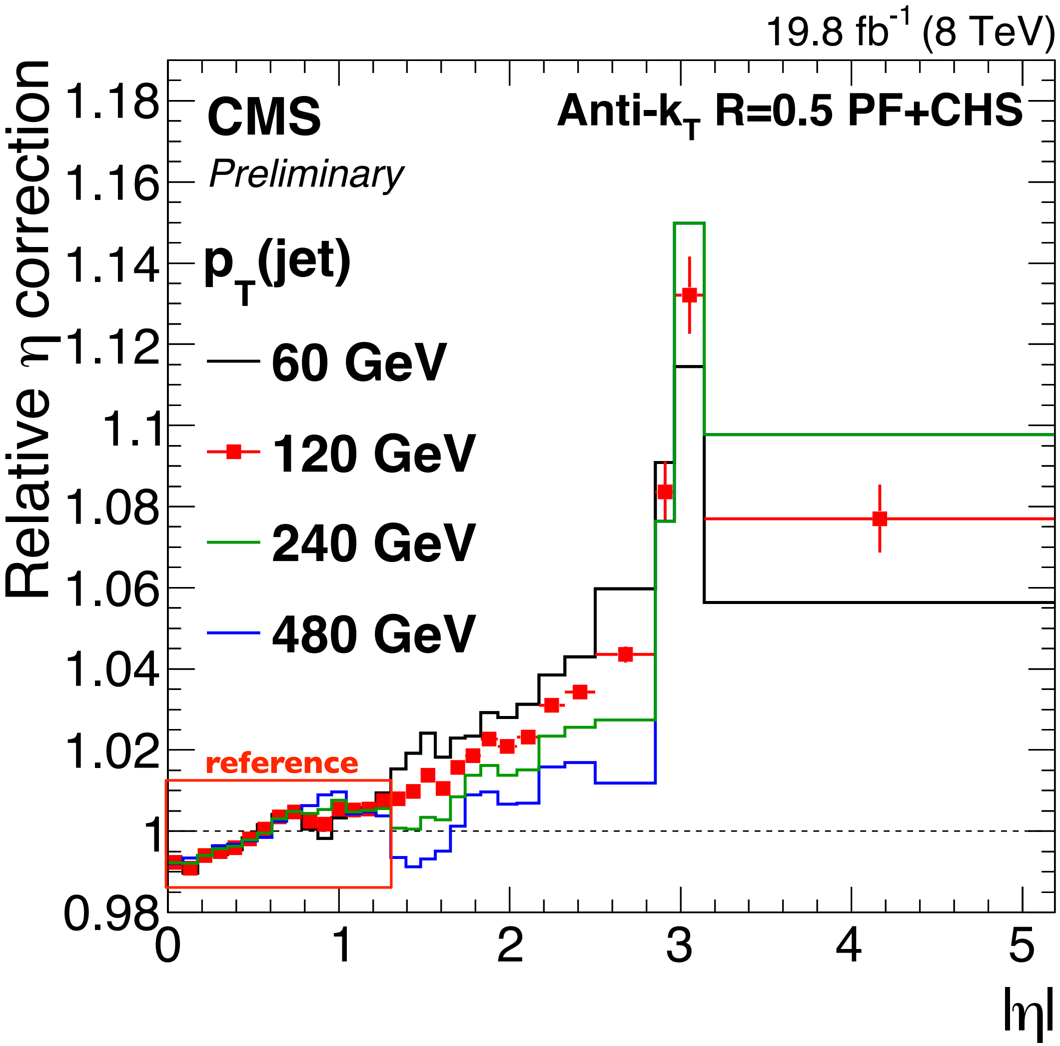
- Leading biases: ISR+FSR ($\langle p_{T,probe} \rangle \neq \langle p_{T,ref} \rangle$), jet p_T resolution (JER)
  - Both minimised with $p_{T,ave} = (p_{T,probe} + p_{T,ref})/2$





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

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CMS DP-2015-044

Z/γ+jet balance

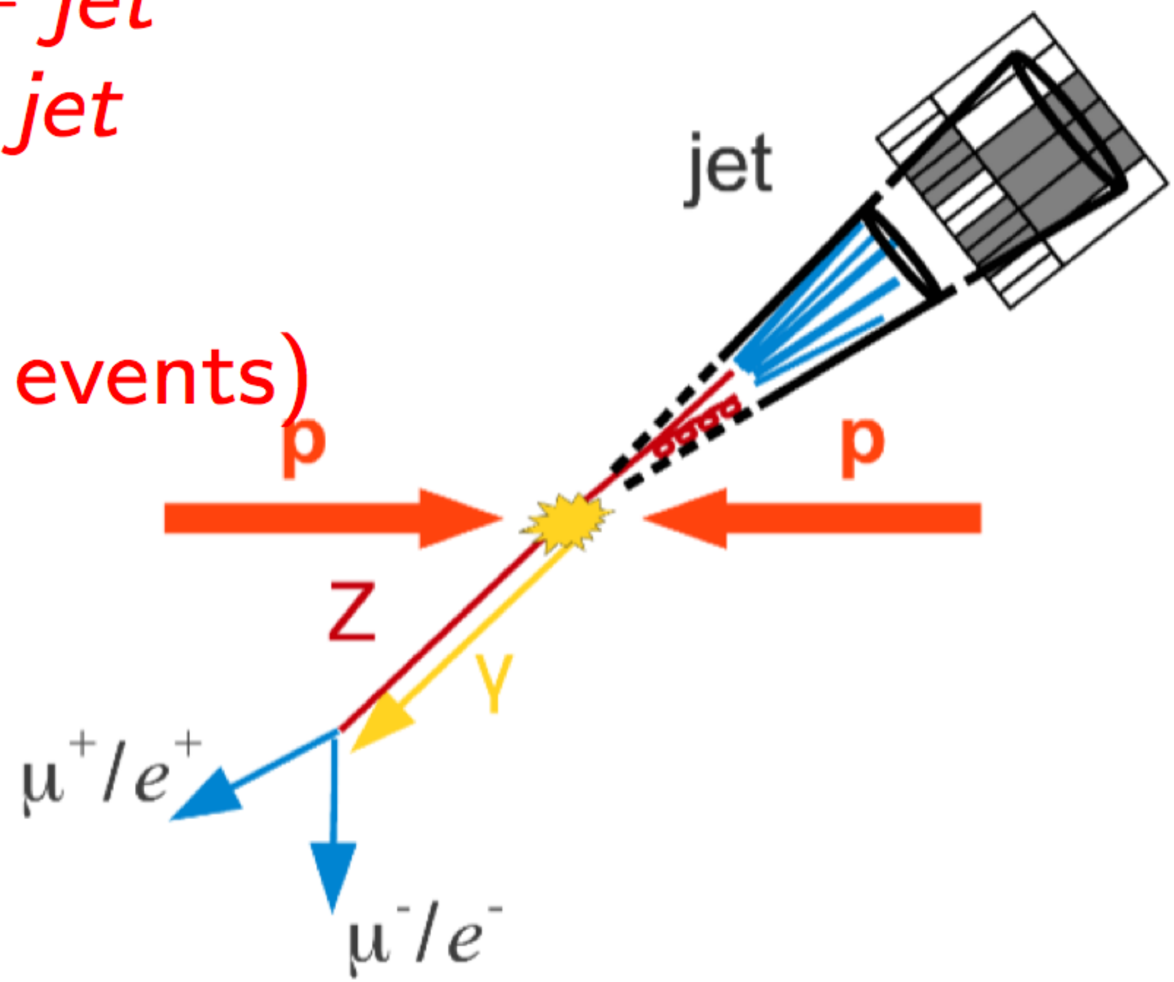
- Muons, electrons and photons measured well ($R_{ref} = 1$) compared to jets
  - $B(\eta_{jet}, p_{T,ref}) = R(\eta_{jet}) * p_{T,jet} / p_{T,ref} \sim R(\eta_{jet})$
- JER bias removed by binning in $p_{T,ref}$
  - => Bias from ISR+FSR ($p_{T,jet} \neq p_{T,ref}$) larger than for dijet balance!

$Z\,(\mu\mu) + jet$

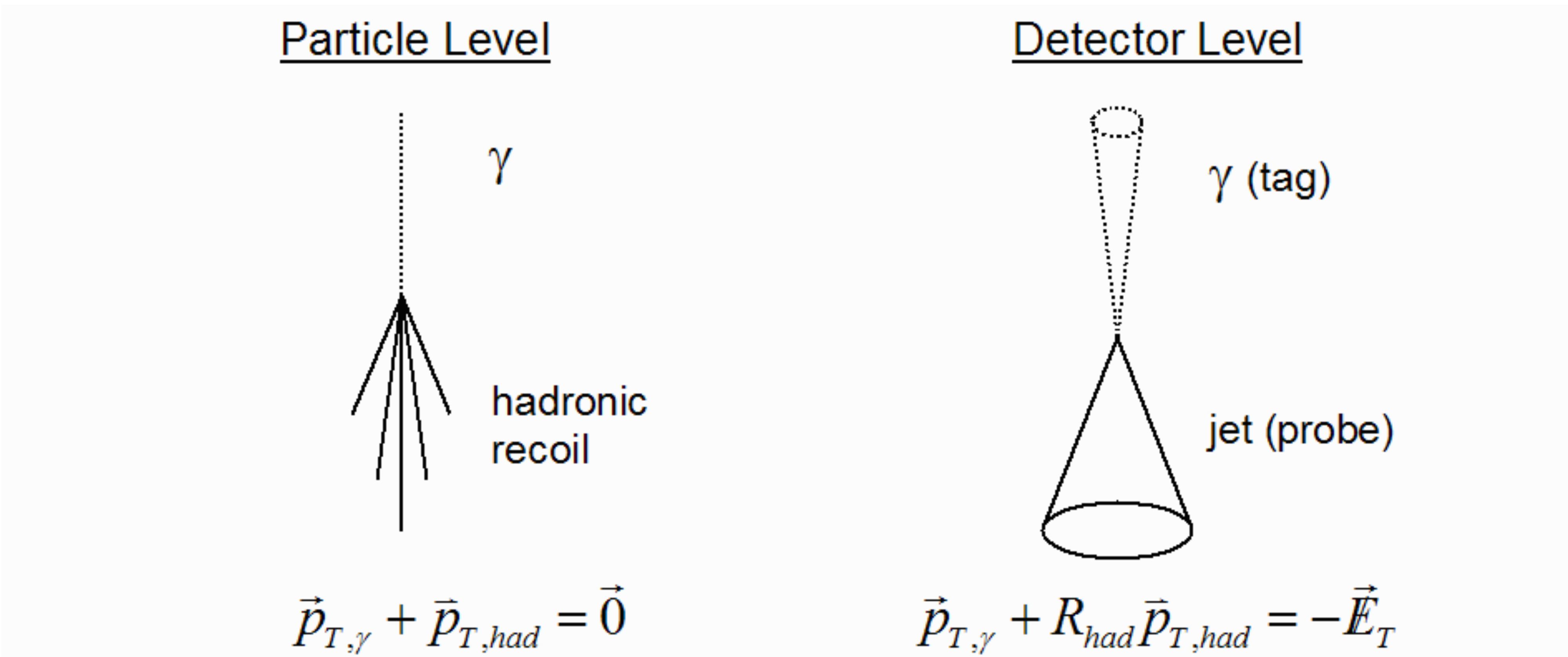
$Z\,(ee) + jet$

$\gamma + jet$

(multijet events)

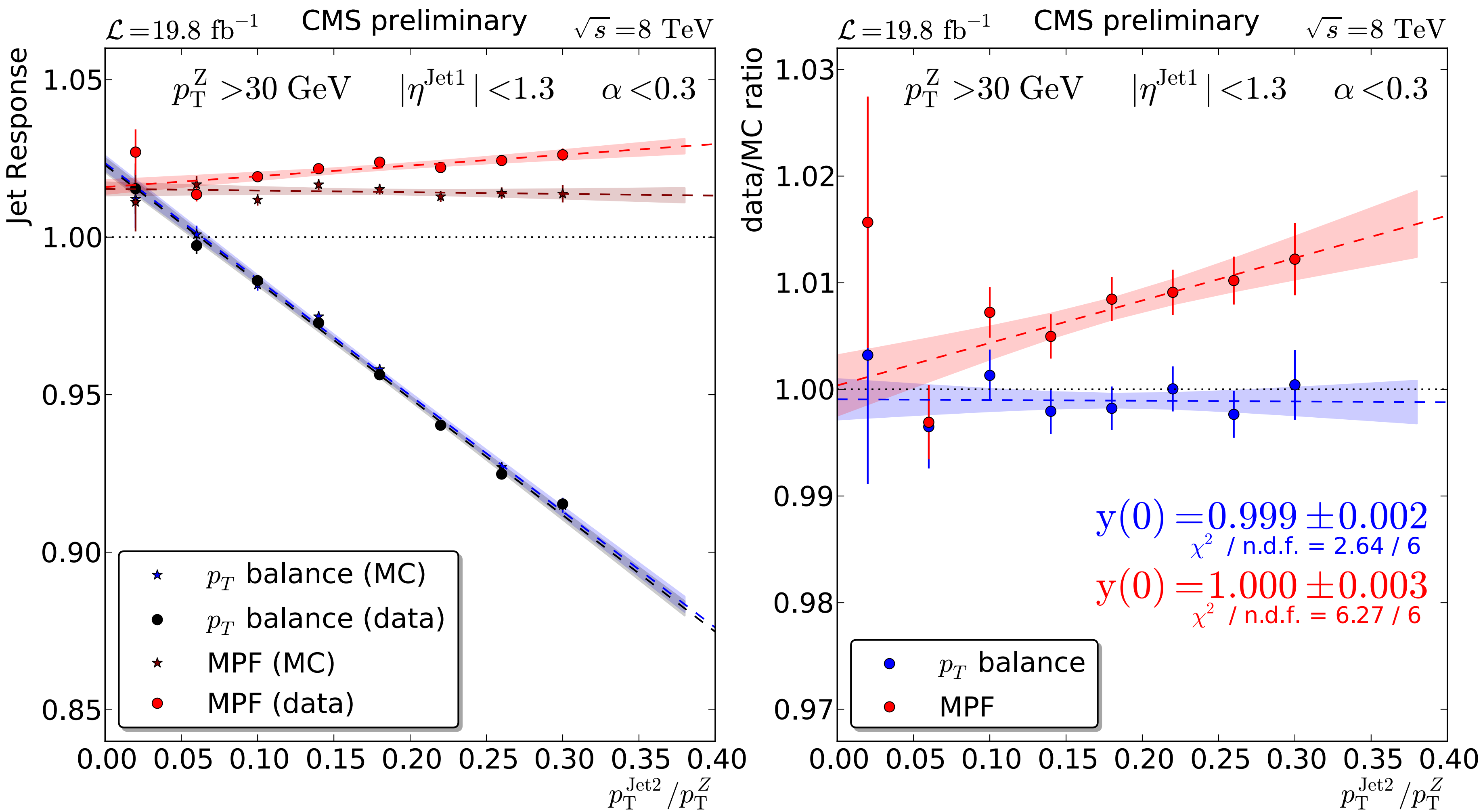


- **Missing E_T projection fraction (MPF)** method designed to tackle $p_{T,probejet}$!= $p_{T,ref}$
- Basic premises *(underscore denotes vector)*:
  - $\underline{p}_{T,probejet} + \underline{p}_{T,other} + \underline{p}_{T,ref} = \underline{0}$ (no true MET)
  - Detector: $R_{probe}\, \underline{p}_{T,probejet}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



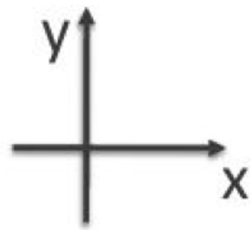
Extrapolation

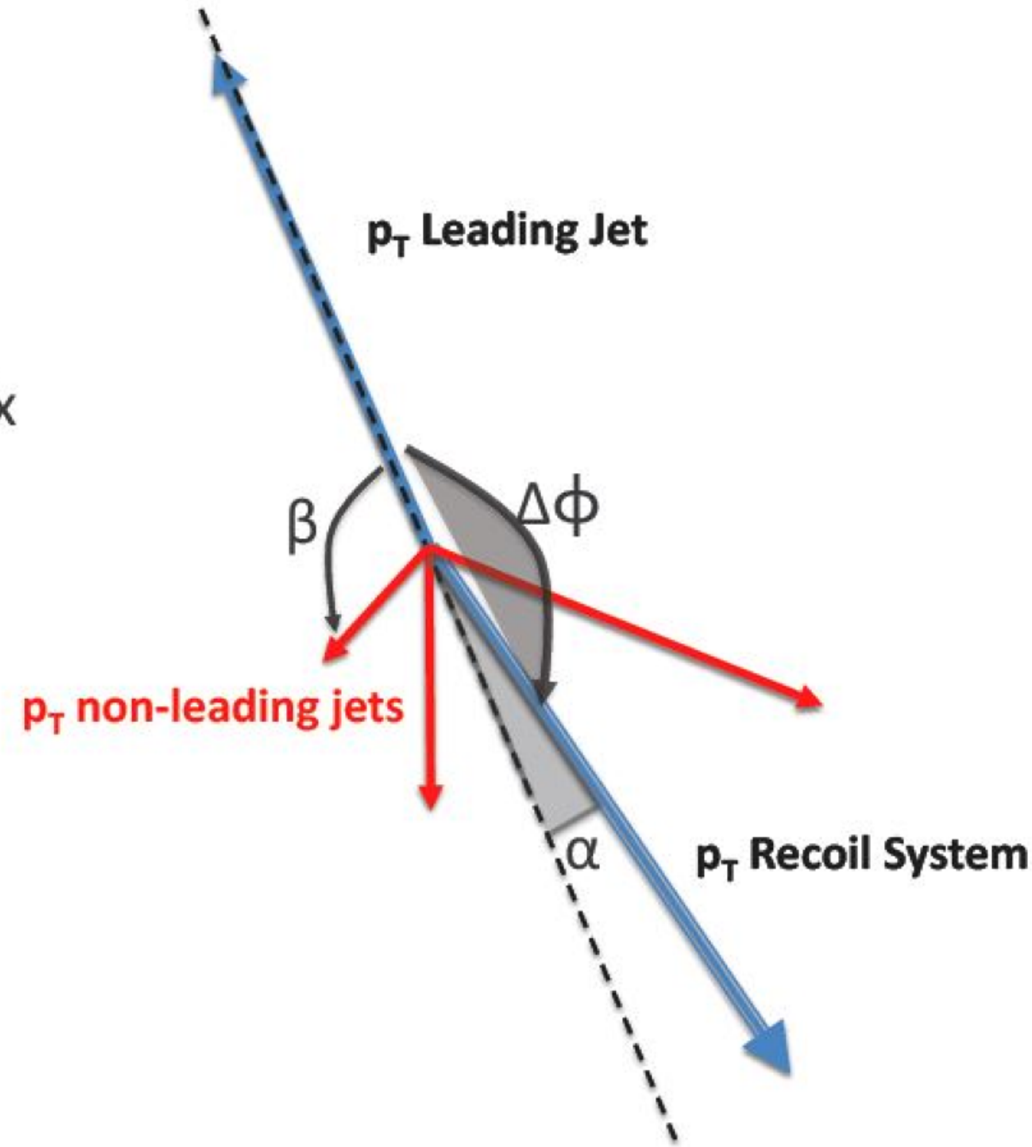
- Extrapolating additional jet activity to zero ensures $p_{T,probe} = p_{T,ref}$
- Applying this to combined p_T balance and MPF methods makes ISR+FSR negligible
  - ISR+FSR second order effect for MPF through R_{other} != R_{probe} (also true for data/MC)
  - $\langle p_{T,probe}\rangle$!=$\langle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

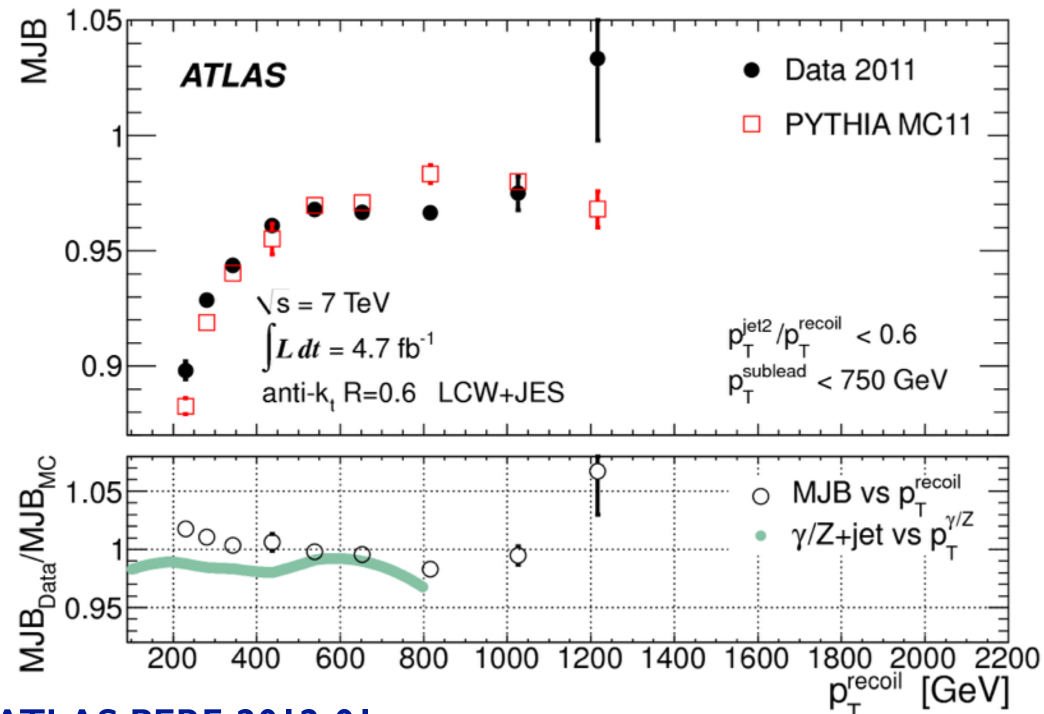


Multijet balance

- 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 ~$0.4*p_{T,lead}$)







ATLAS PERF-2012-01

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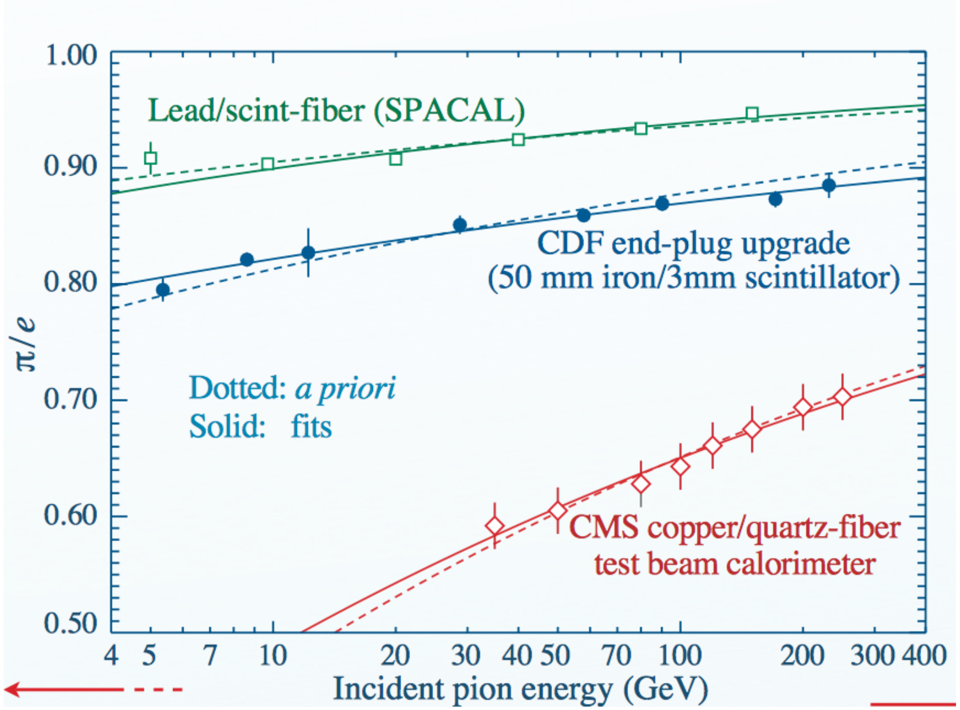
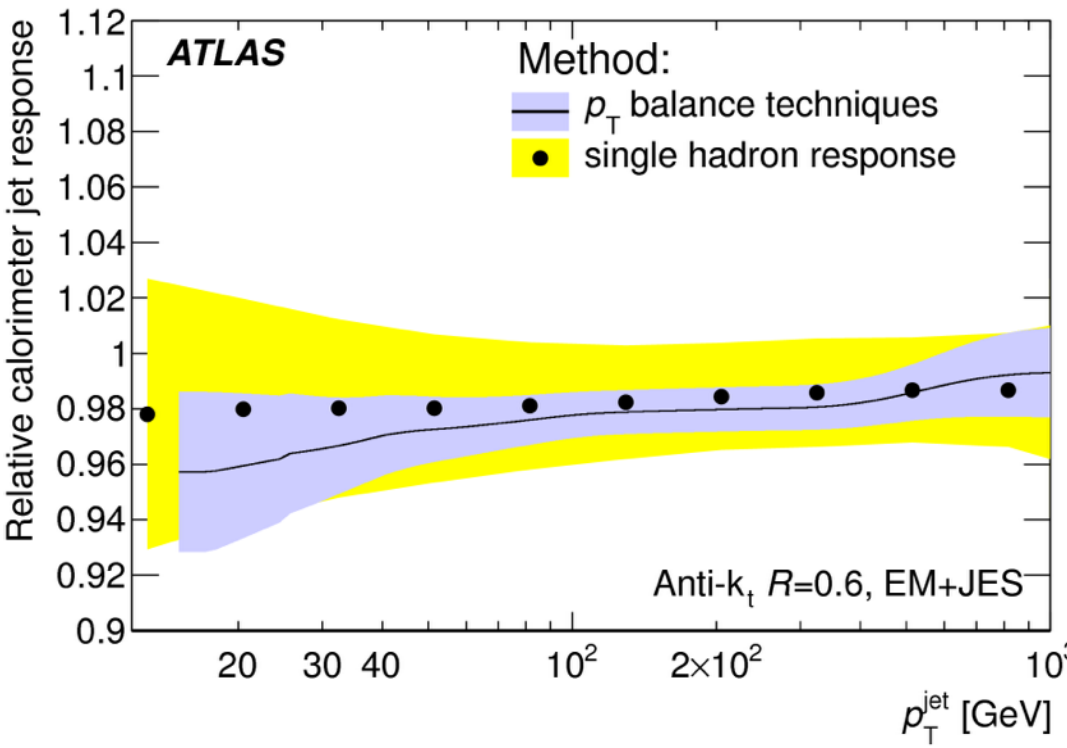
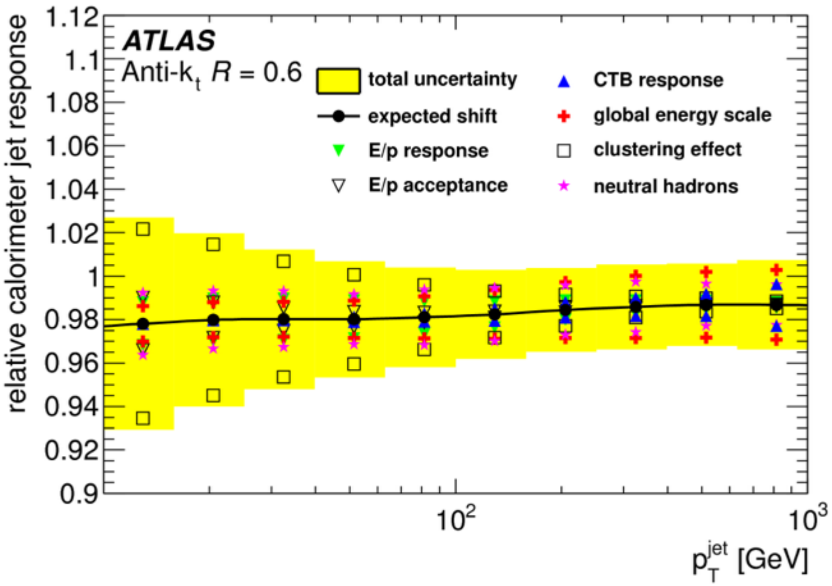
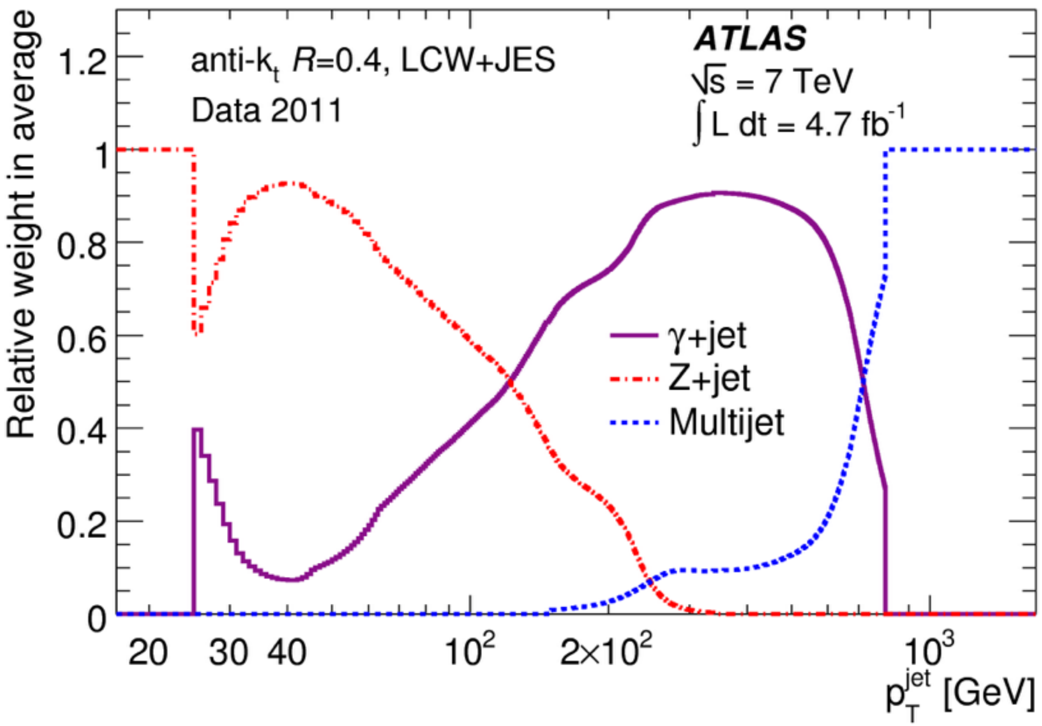
- Alternative approach to high p_T is MC
  - TeV scale jet response driven by hadrons at O(100 GeV) and less => test beam
  - Hadron response plateaus in this p_T range, which limits extrapolation uncertainty

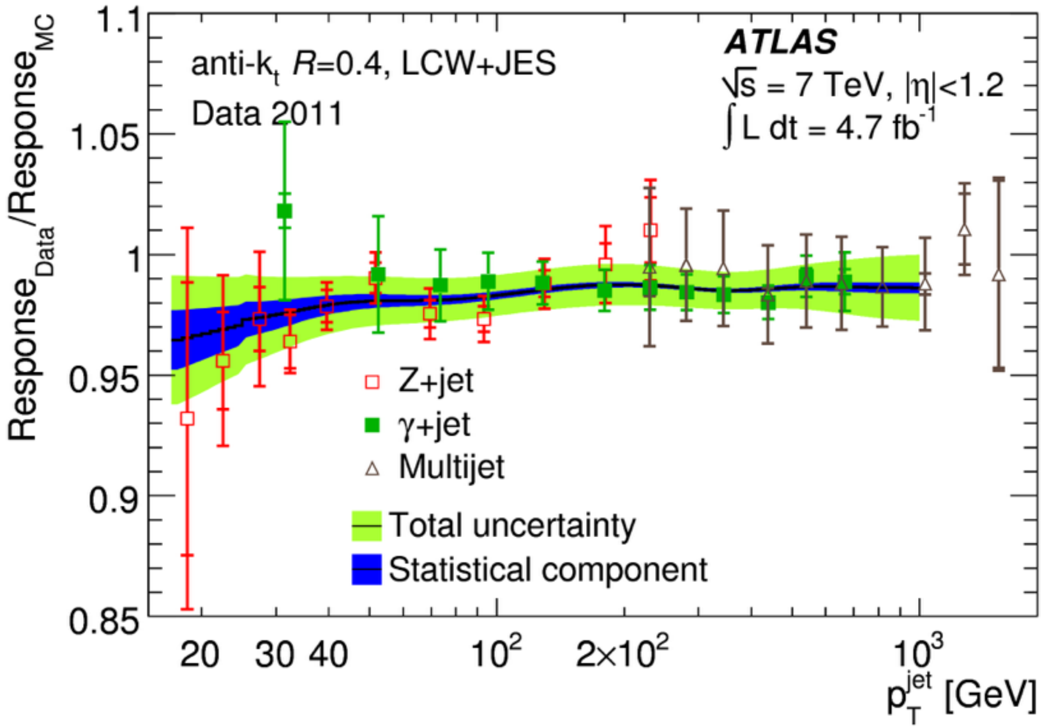




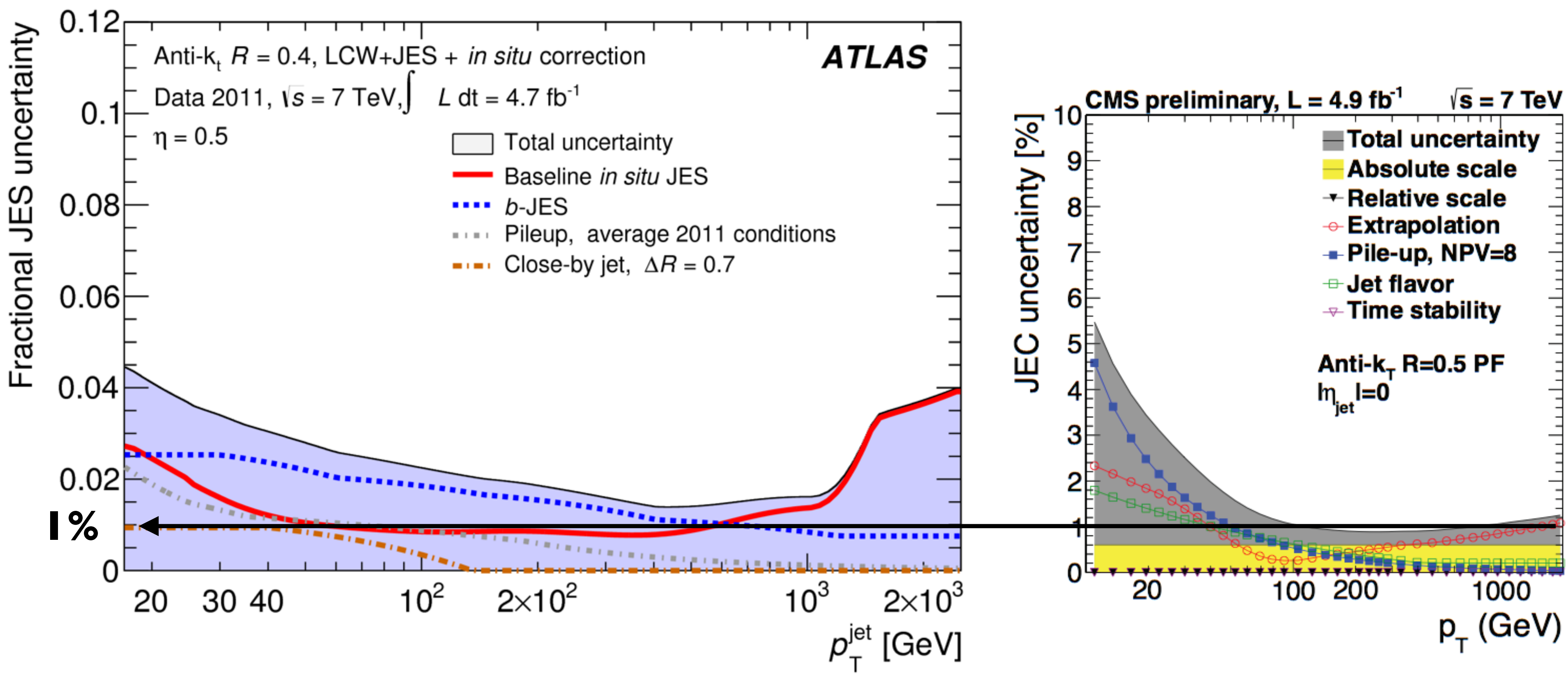


- Z+jet has good statistics at low p_T, γ+jet at higher p_T, multijets at the very highest
- Combination of all channels measures JES from p_T=30 GeV to about 1.3 TeV
  - Both statistical and systematic uncertainties, and their correlations, considered

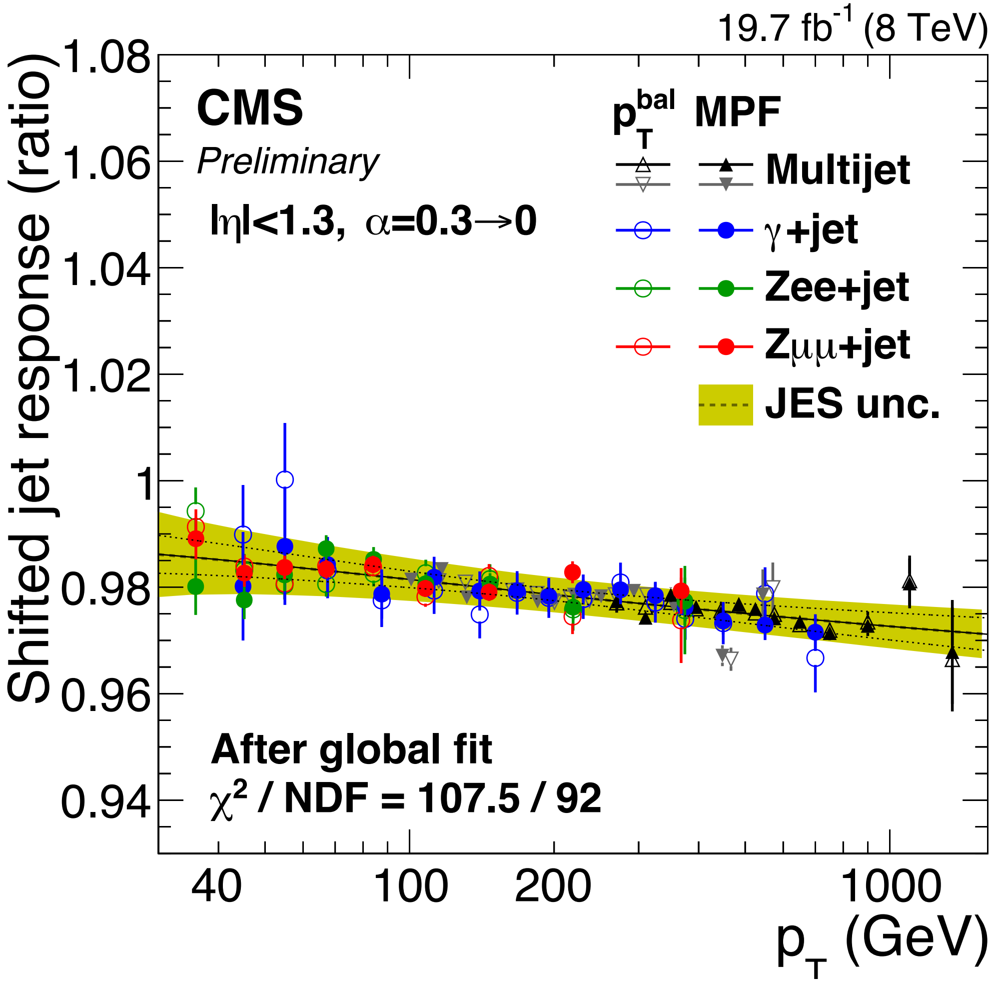


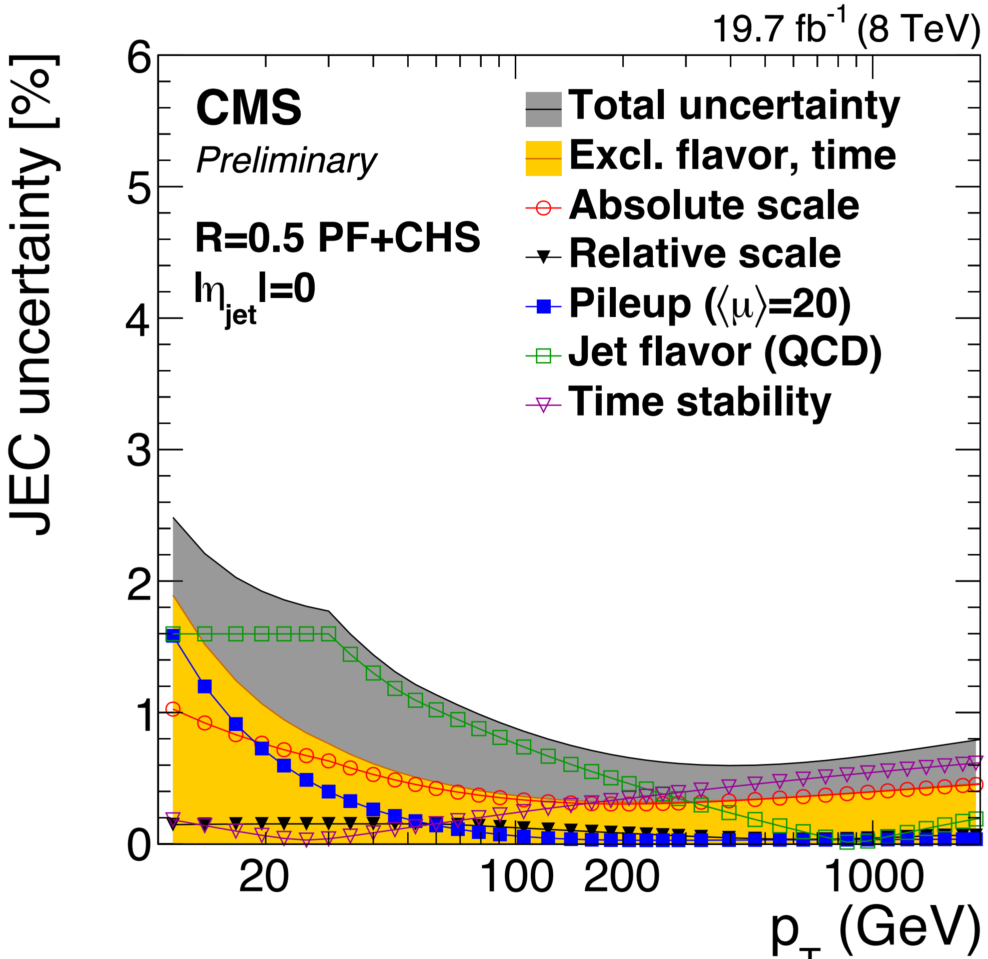


- Both experiments reached in-situ calibration precision of better than 1% already in 2011
- This has further improved for final 2012 calibrations, despite increasing pileup



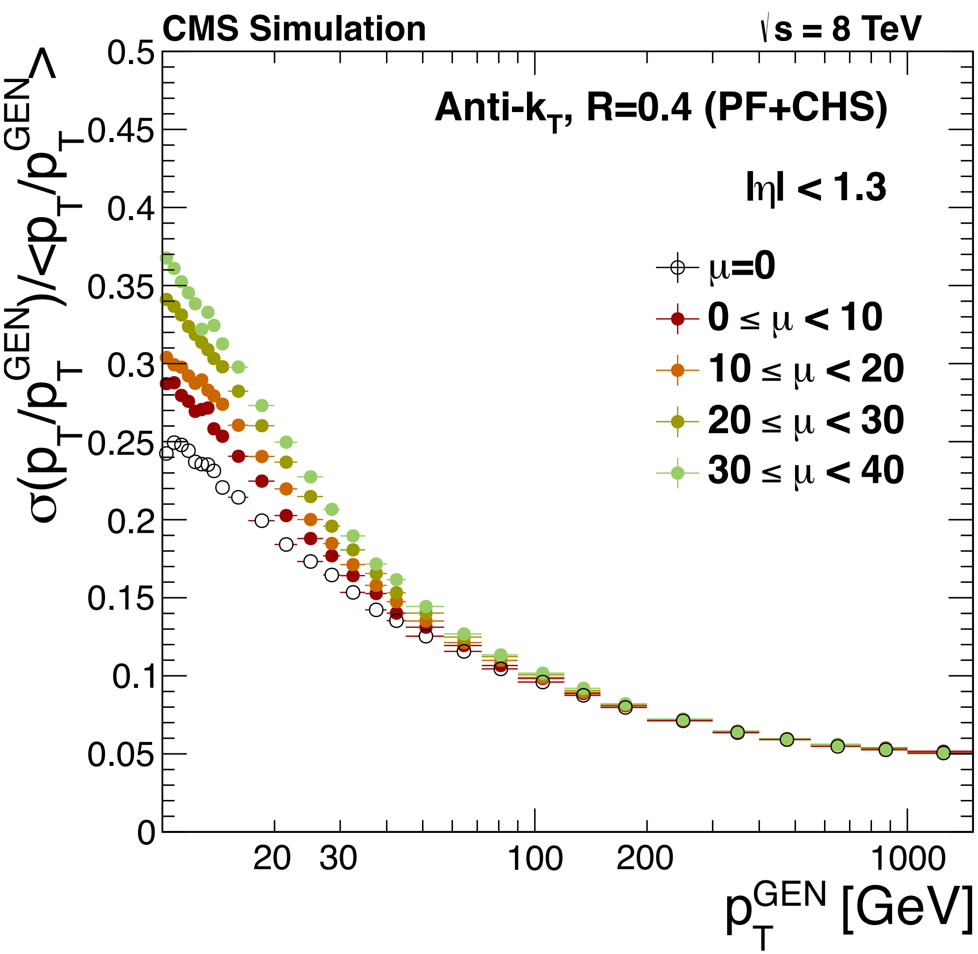
- Best precision 0.32% without time dependence and flavor uncertainty
  - detector performance [cds link], full paper ready for submission
- Develops ATLAS-style combination of channels one step further into a full global fit
  - limiting factor now jet flavor response (of gluon jets in particular)

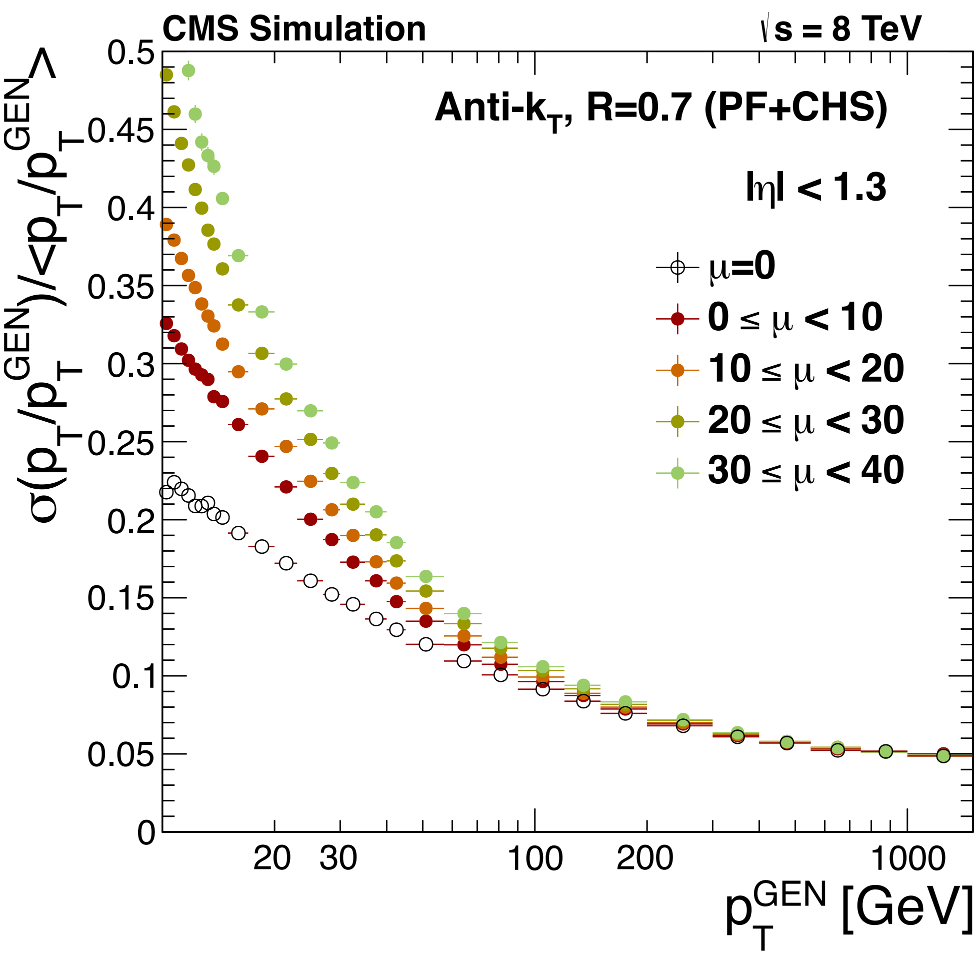




Jet energy resolution

- While JEC is accurate to 1%, individual jets have resolution of ~10%
- Typical **jet p_T resolution (JER)** is 15% at 30 GeV, 5% at 3 TeV
- $\boldsymbol{\sigma(p_T) / p_T = \sqrt{(N^2/p_T^2 + S^2/p_T + C^2)}}$
  - **N**=noise (and pileup), **S**=stochastic ($\sqrt{E}$), **C**=constant (intercalibration)





- Topics I will cover today:
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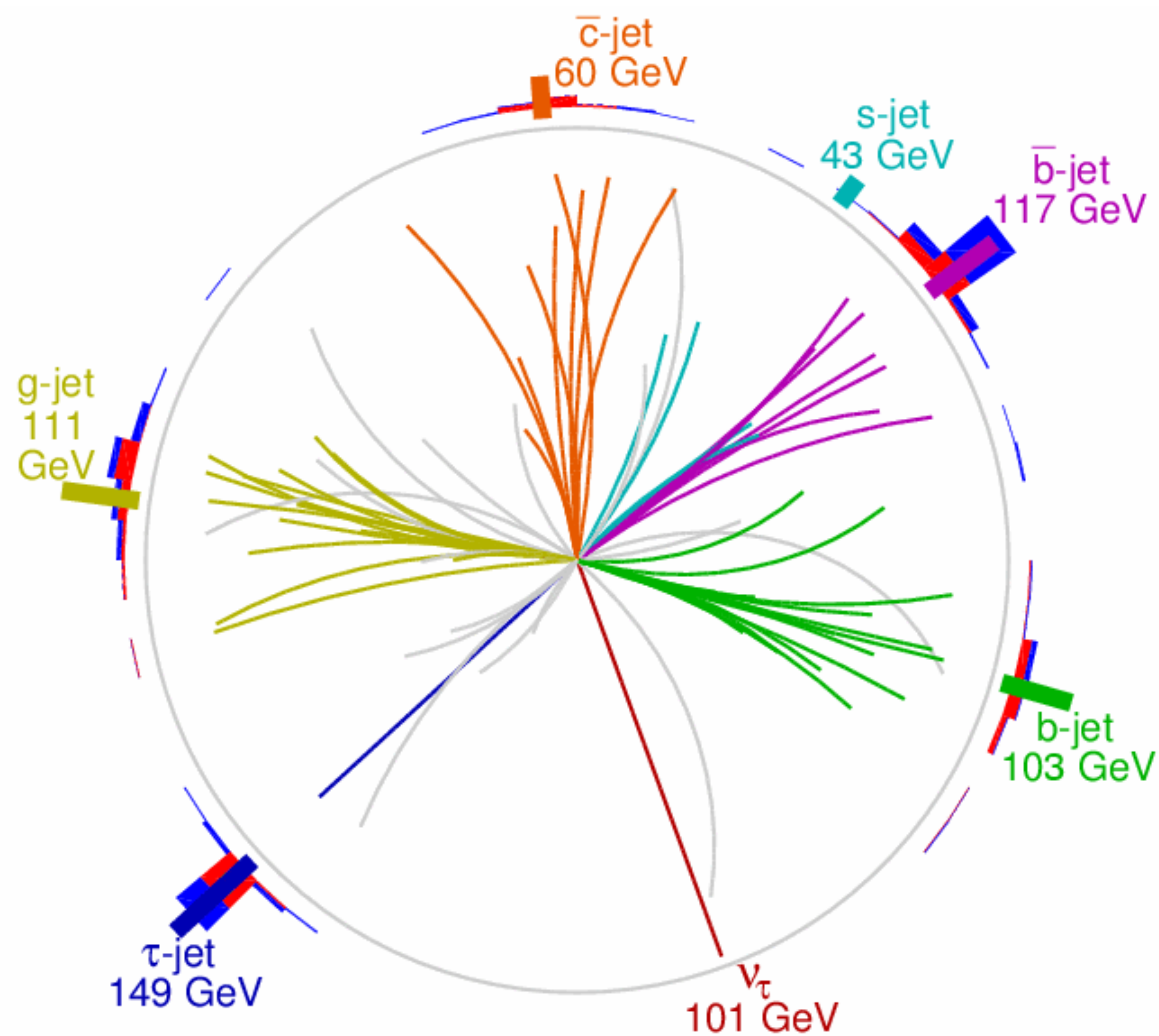
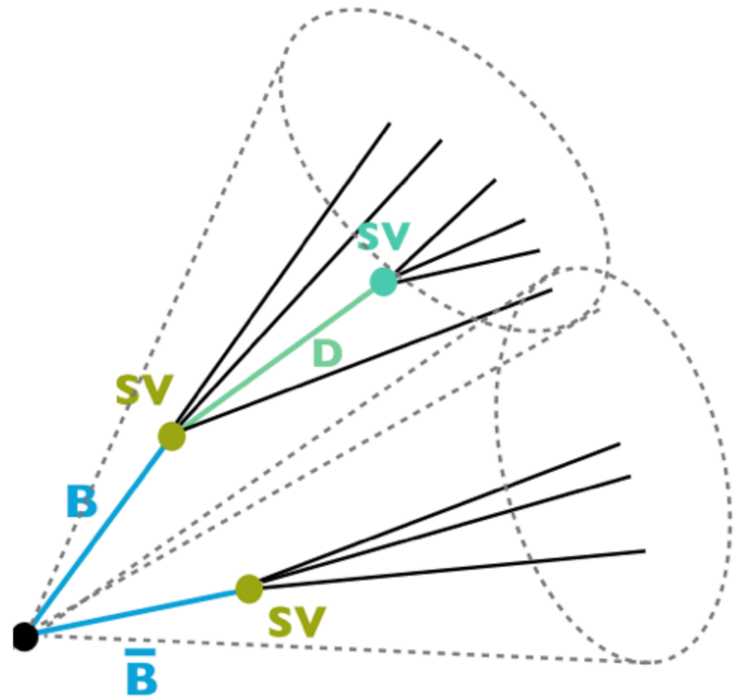
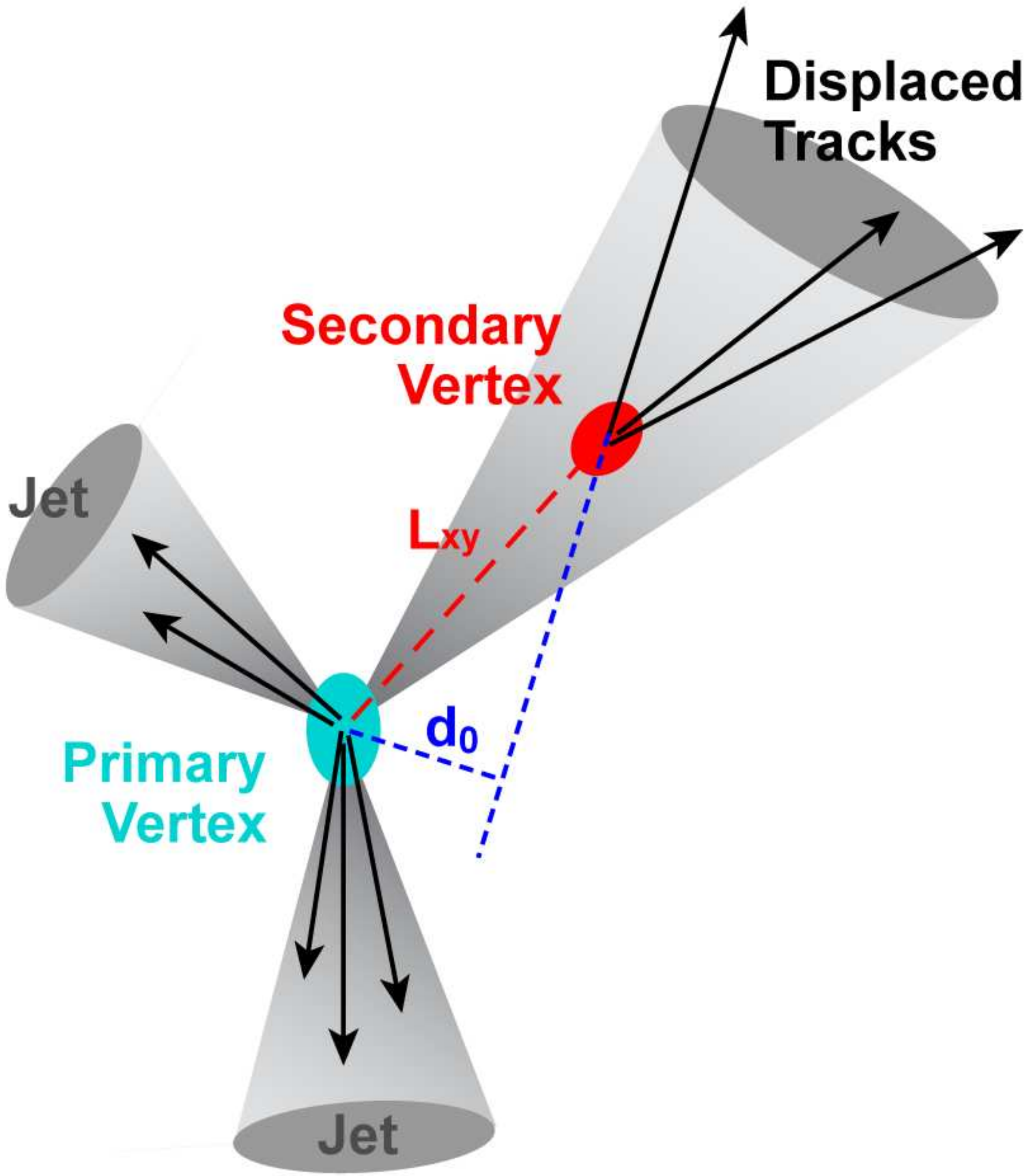
  - Hadronization
  - Jet clustering
  - Particle Flow, GS
  - Pileup offset
  - JEC from data
  - Heavy flavor jets
  - Quark/gluon likelihood
  - Inclusive jet cross section
  - Top mass with lepton+jet



$gg \to tbH^+$, $t \to Wb \to scb$, $H^+ \to \tau\nu \to$ hadrons with a radiative gluon jet

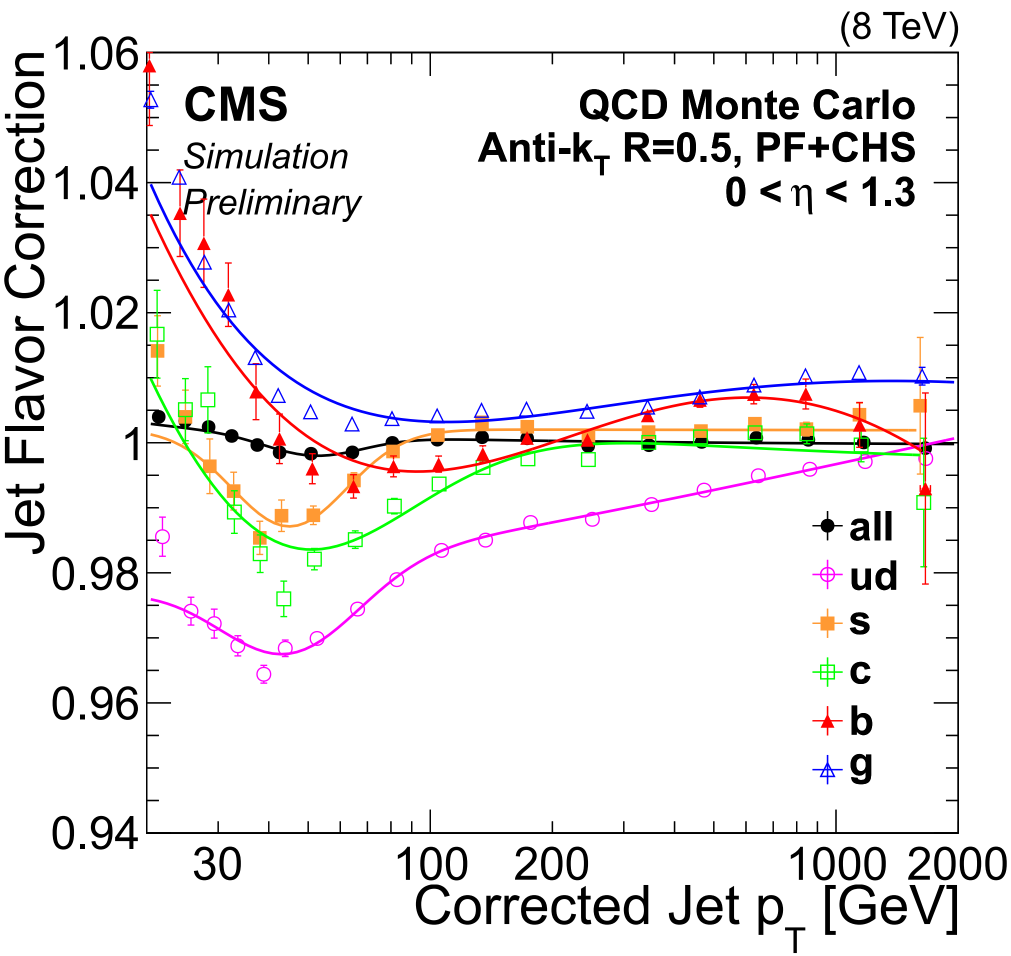
- Heavy flavor jets are identified by a heavy hadron containing b or c quark
  - B and D have cτ of ~1 mm and can often be identified by a secondary vertex
  - Alternative way is to tag semileptonic decays of B and D
- Wide b-jets from gluon-splitting (g->bbar) can have two SV for b, and another two for "cascade-c"

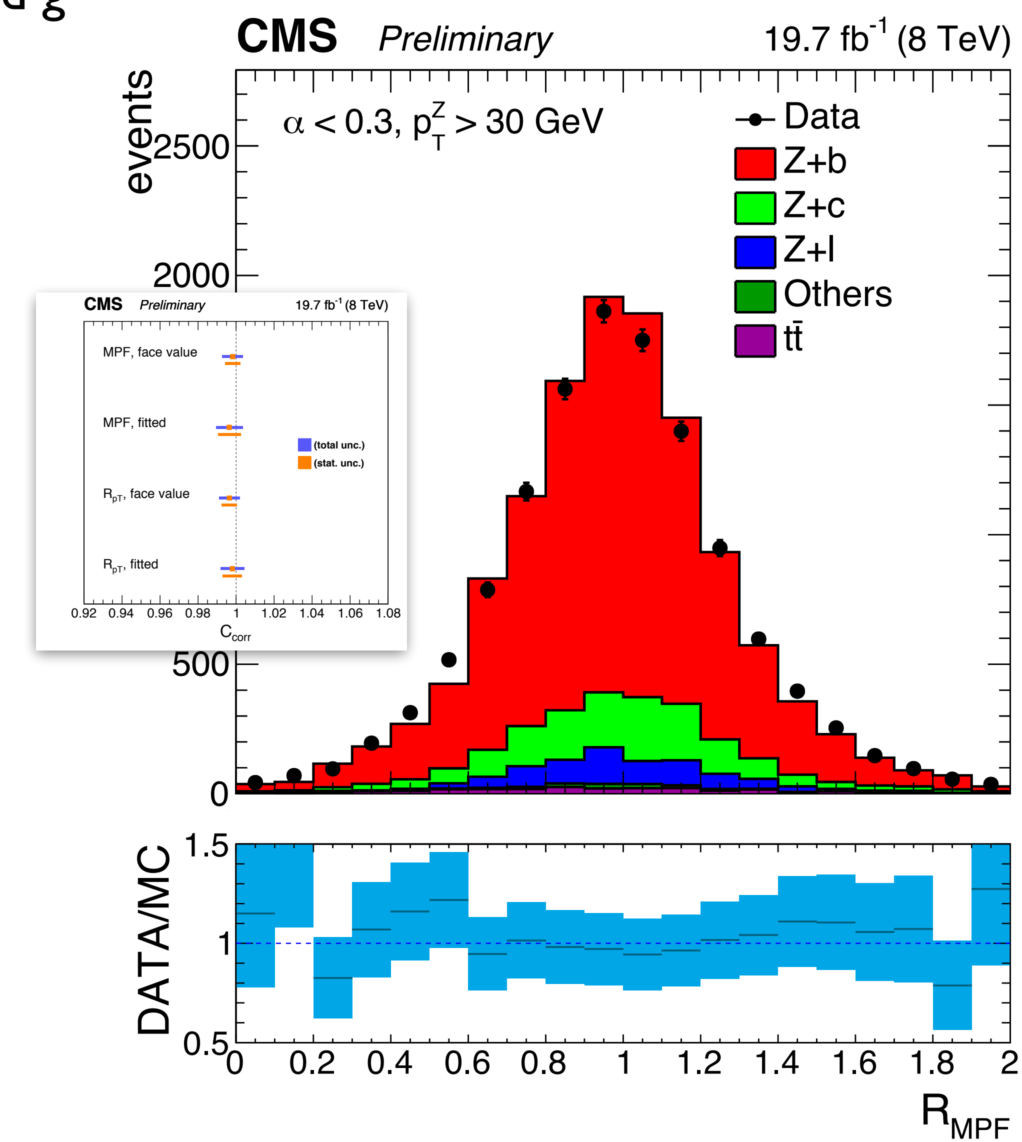




Flavor response

- 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 ud and g
- Precise b-JES from data using Z(ll)+b events
  - (CDF also used Z->bbar)

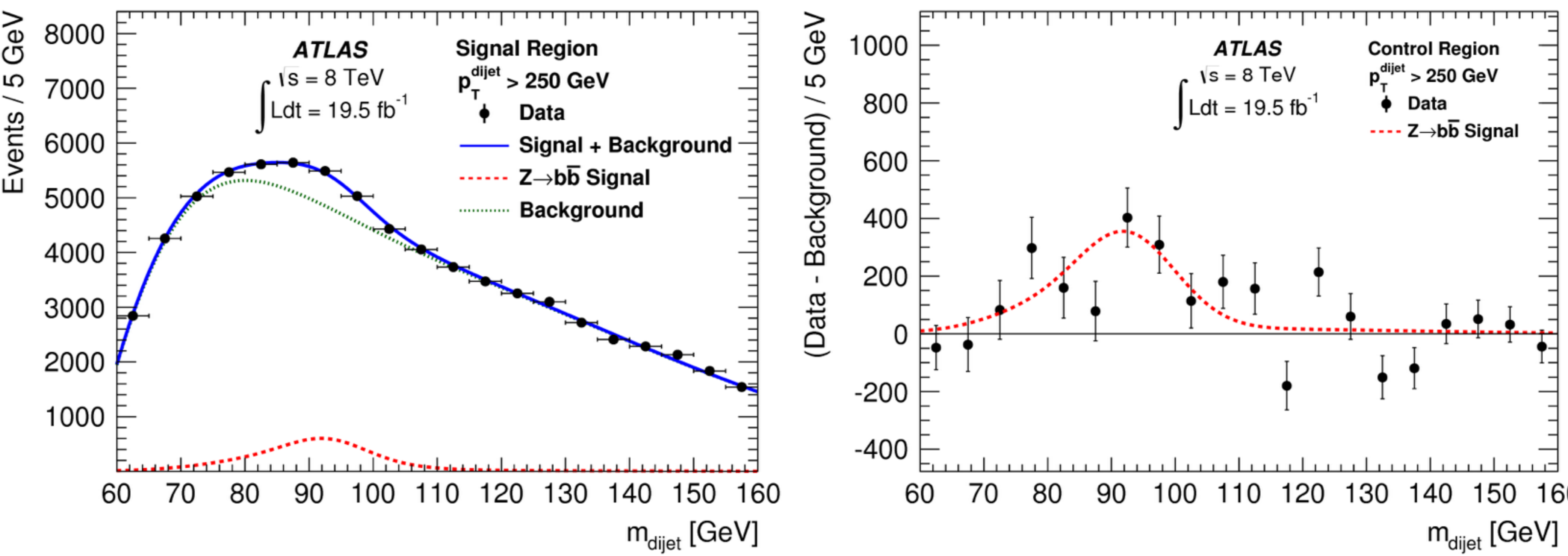




Semileptonic b decays

- 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

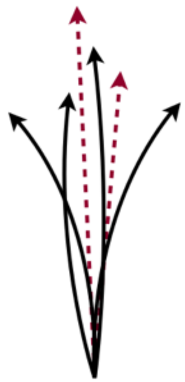
Boosted Z(bb) decay



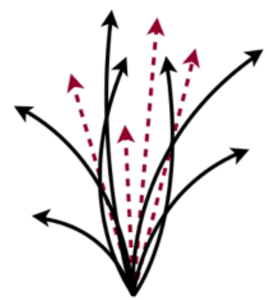
Quark/gluon discrimination

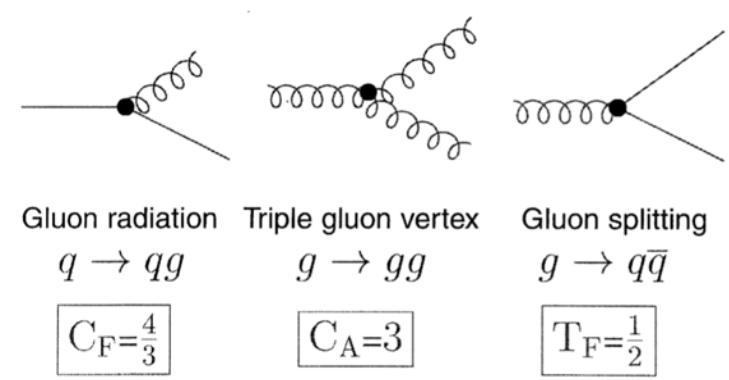
- Gluon jets differ from quarks: more particles, softer leading particle, wider jet
  - These derive from high colour factor (C_A=3 for gluons vs C_F=4/3 for quarks vs T_F=1/2 for g->q$\bar{q}$)

Quark jets:



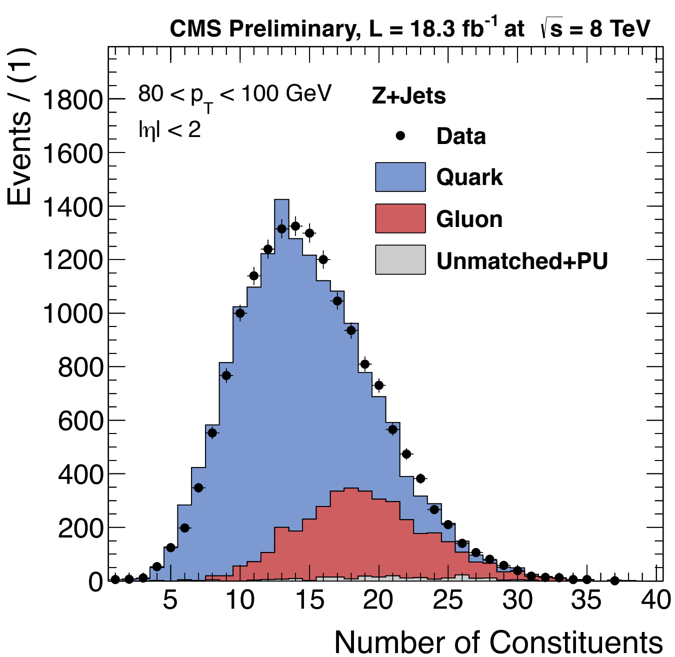
Gluon jets:



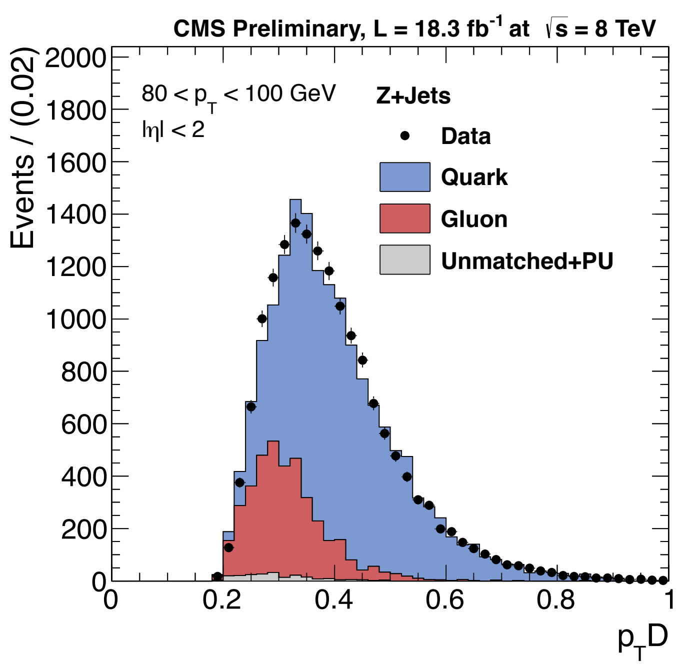


F. Pandolfi

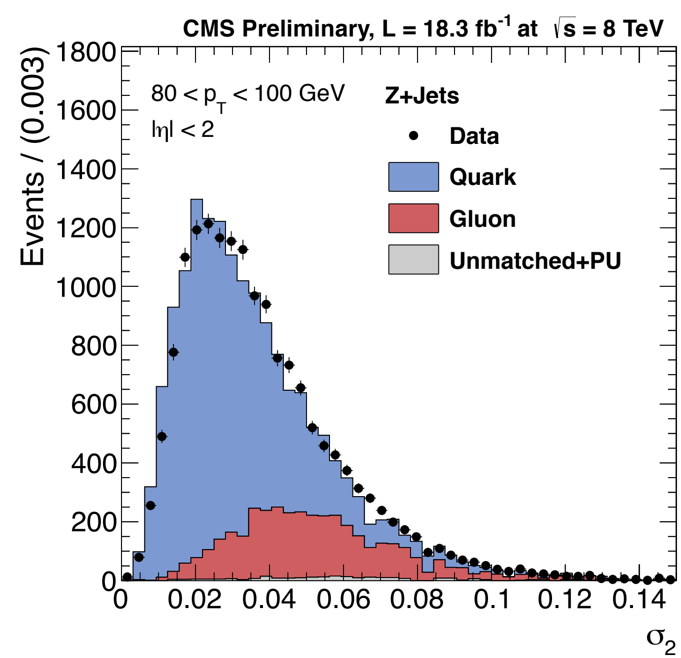
particles



"hardness" of jet

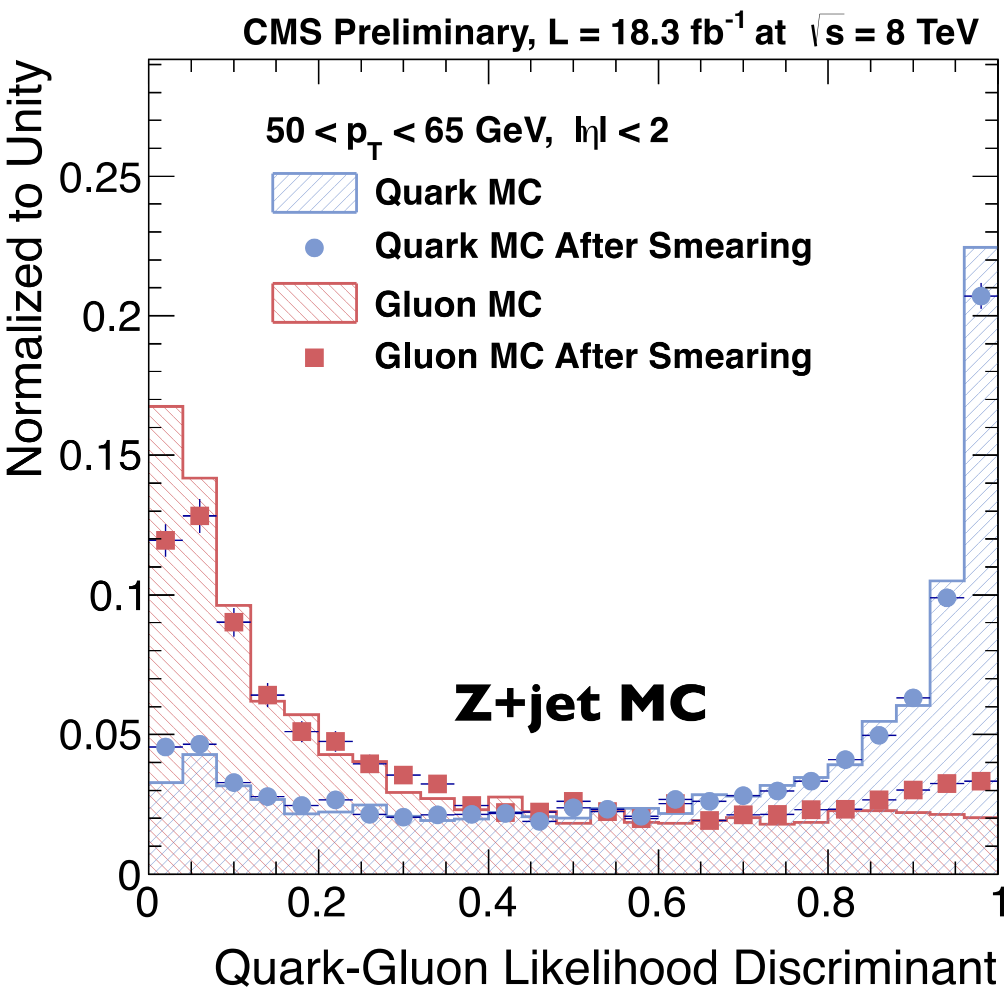


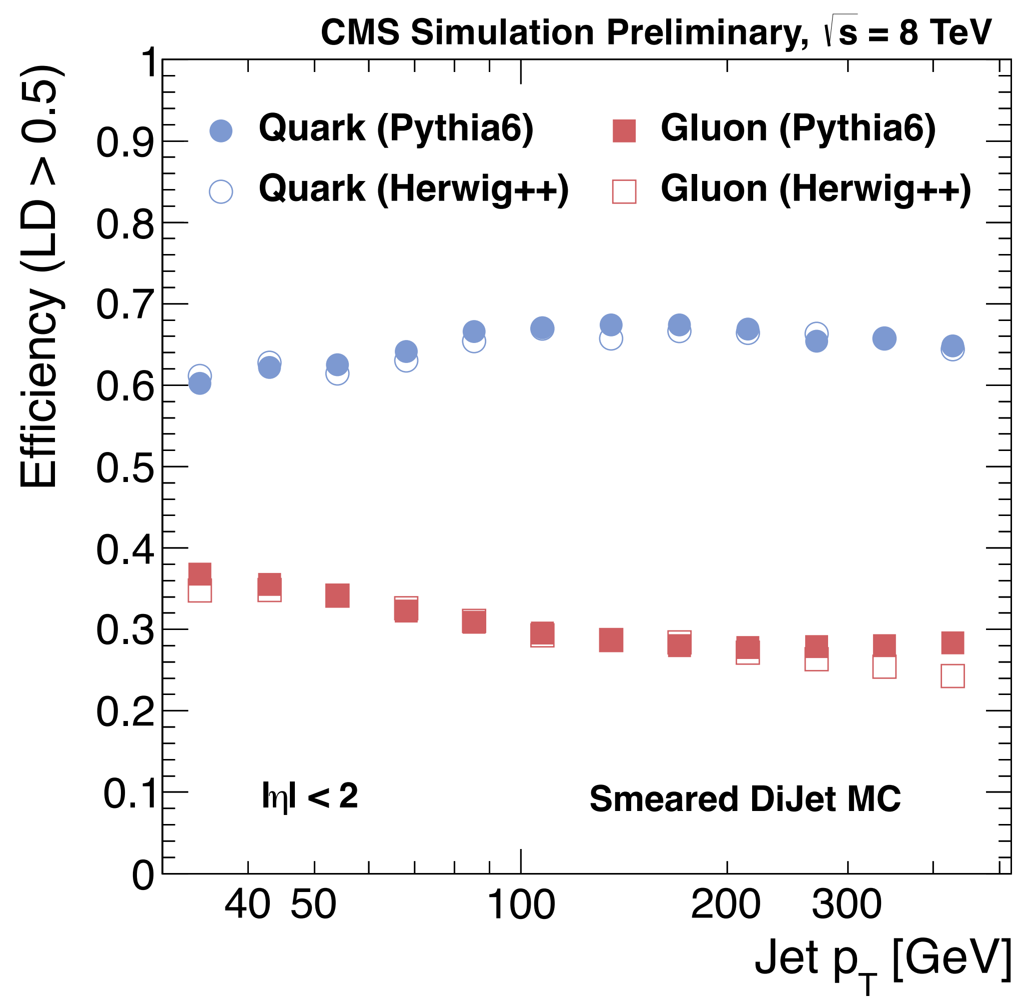
jet width



Quark/gluon discrimination

- 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





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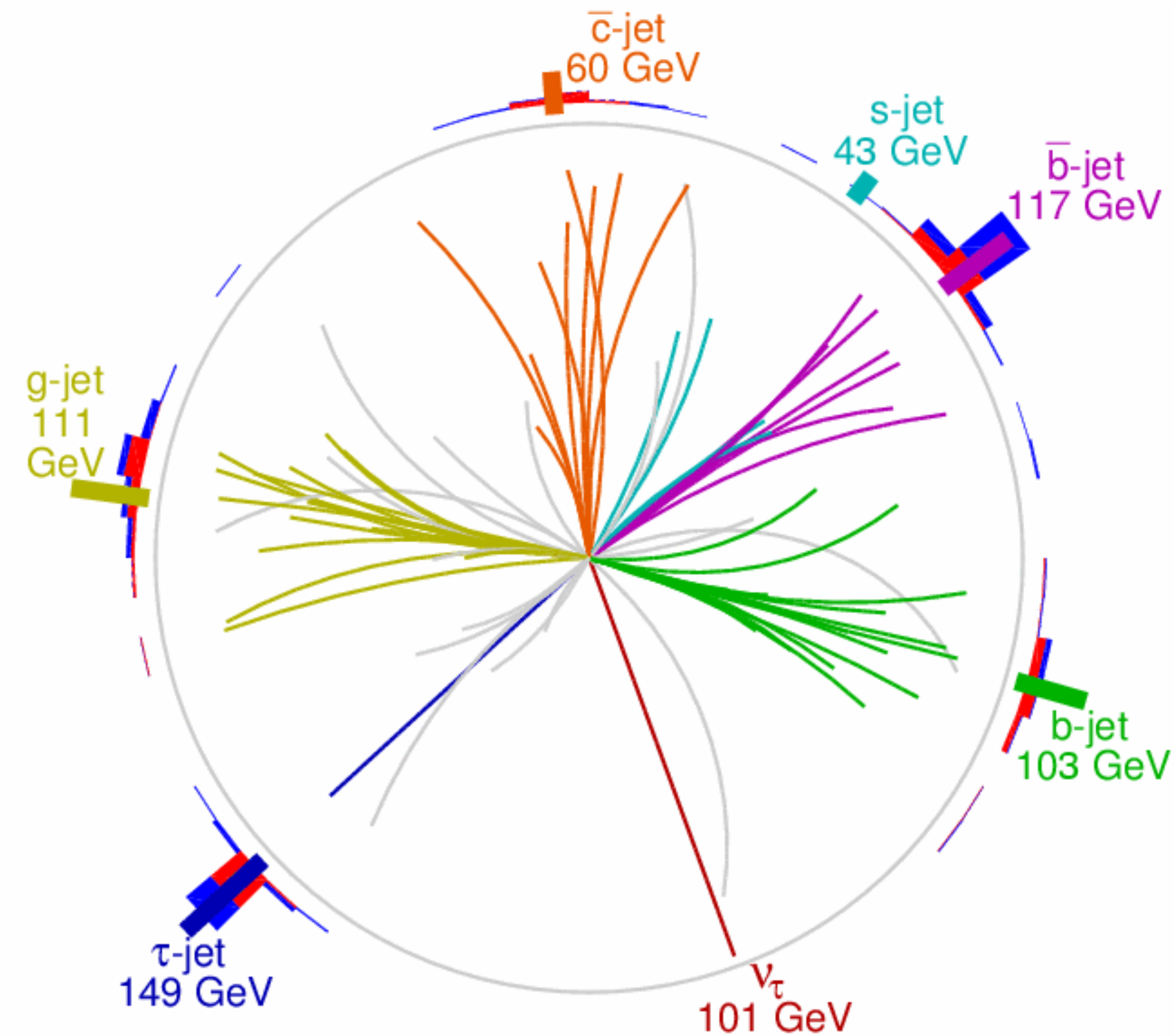
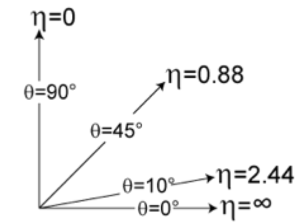
  - **Inclusive jet cross section**
  - Top mass with lepton+jet

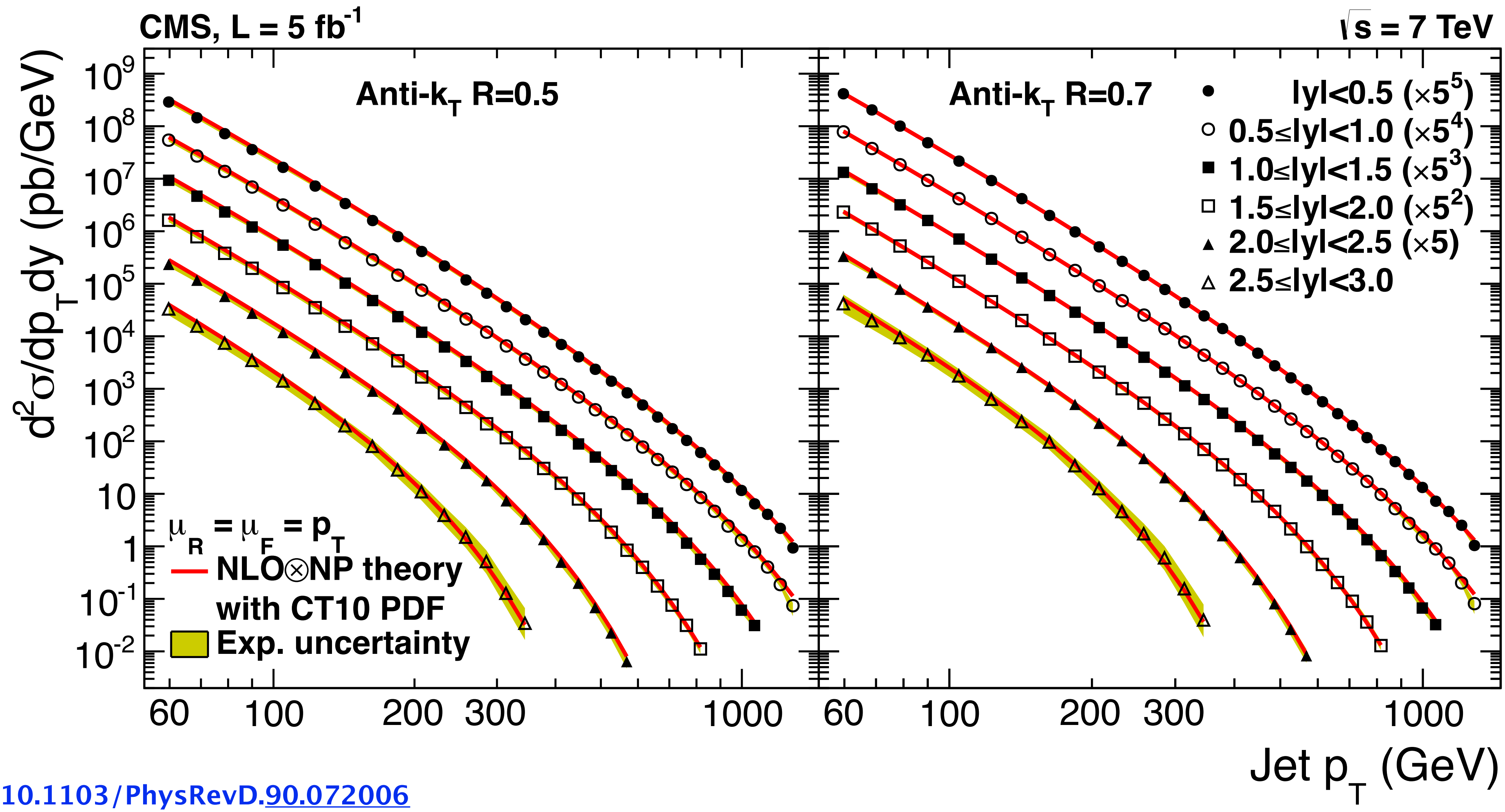


$gg \to tbH^+$, $t \to Wb \to scb$, $H^+ \to \tau\nu \to$ hadrons with a radiative gluon jet

Inclusive jet cross section

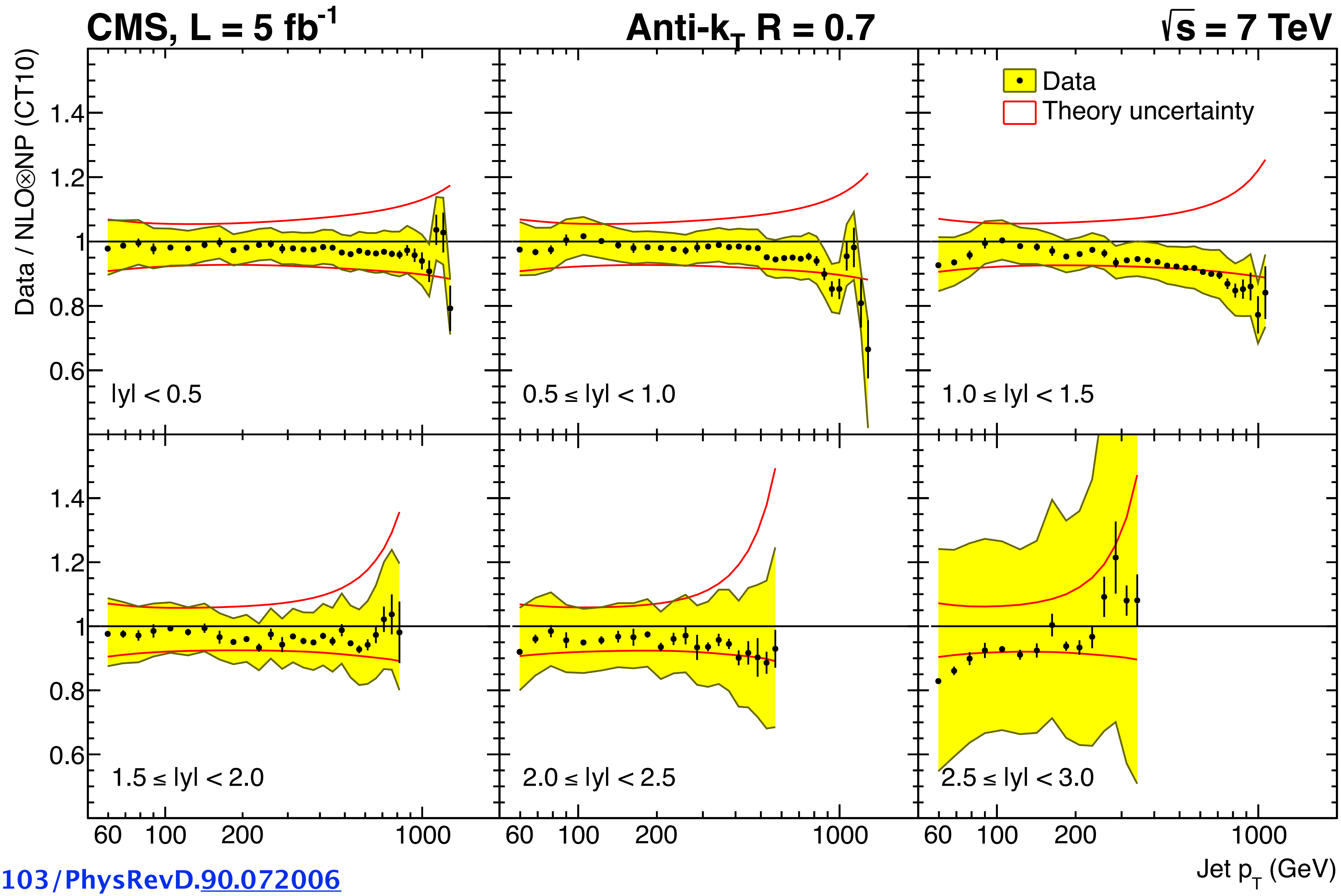
- Inclusive jet production one of most fundamental probes of QCD
  - = rate of jets versus p_T and scattering angle ($y \sim \eta = \ln[\tan(\theta/2)]$)
- Fundamental parameter is jet radius R





10.1103/PhysRevD.90.072006

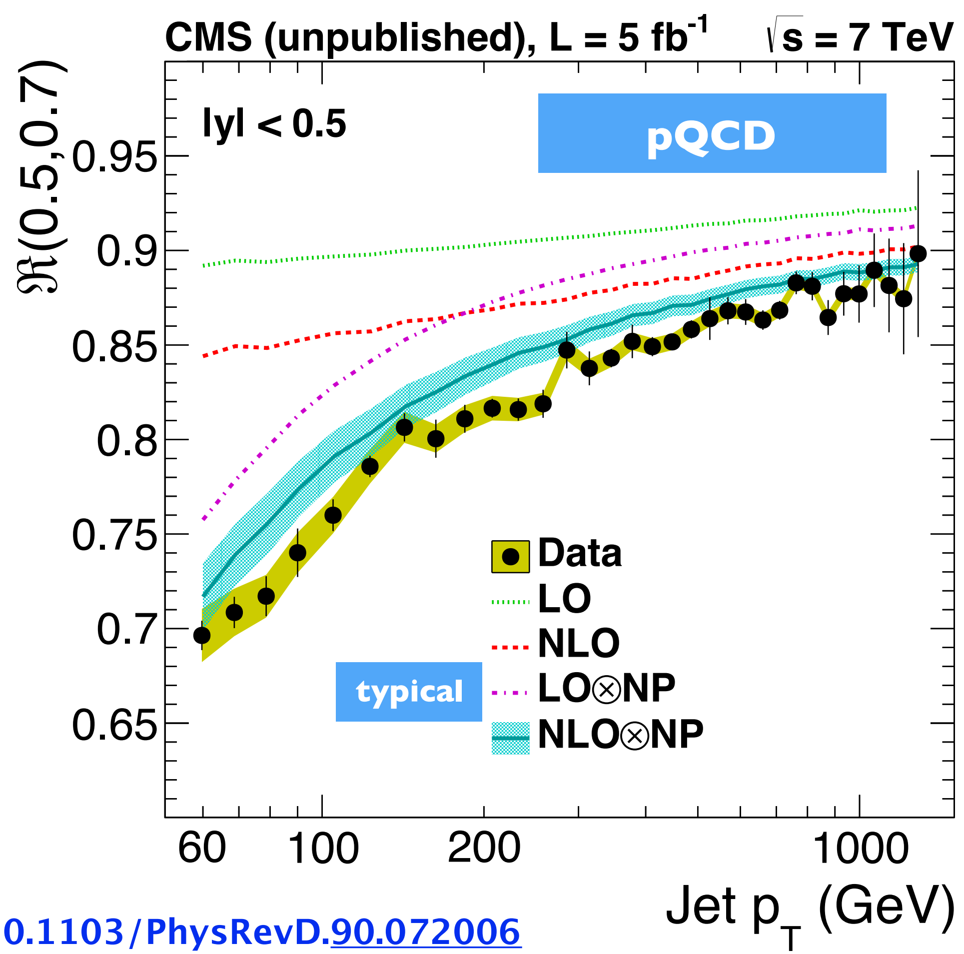
- Perturbative QCD predictions for large R quite accurate at next-to-leading-order (NLO)

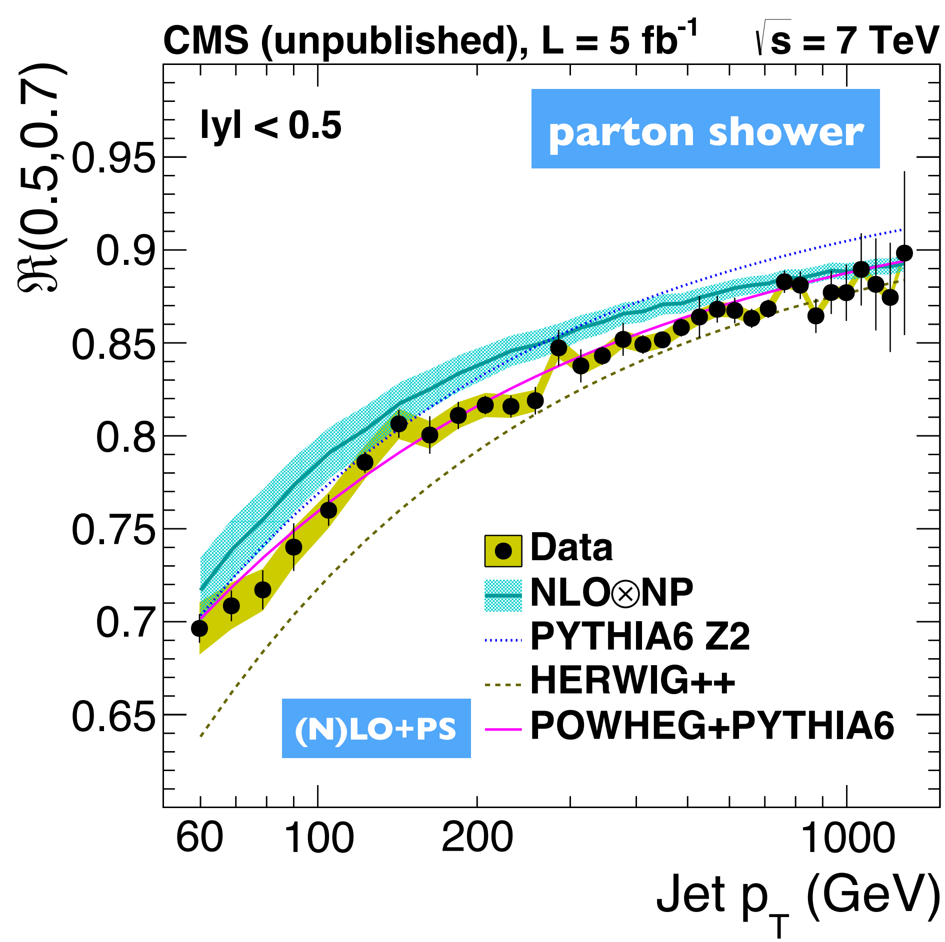


10.1103/PhysRevD.90.072006

Smaller R

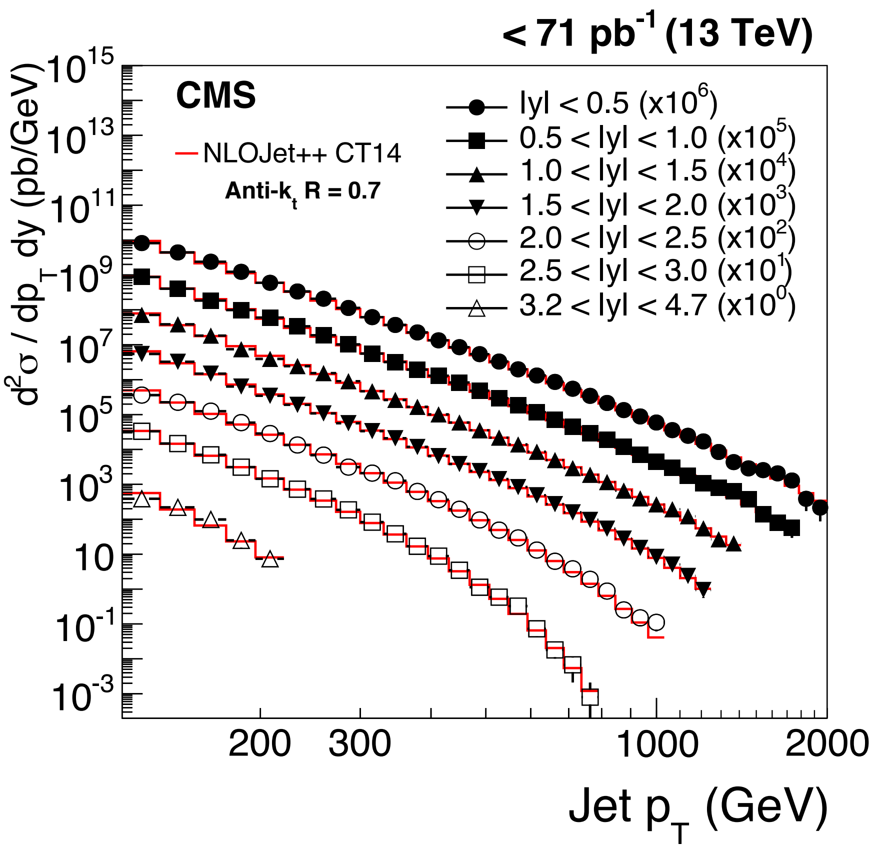
- For smaller R (=0.4,0.5), need higher order pQCD to model larger jet multiplicities
  - alternatively, (N)LO matched to parton shower (e.g. POWHEG) does well
- Ratio of jet cross sections with R=0.5/R=0.7 sensitive to pQCD one order higher
  - e.g. NLO for ratio means NNLO for separate cross sections

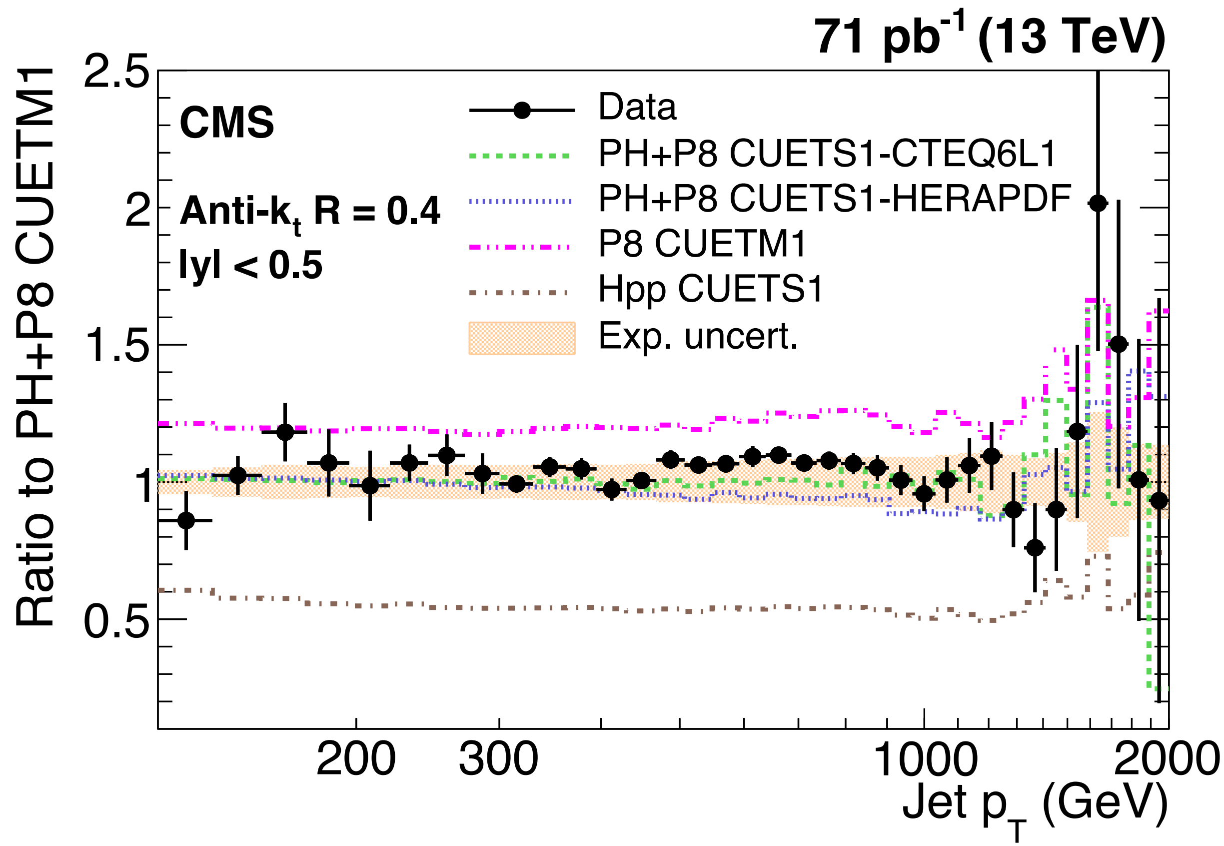




10.1103/PhysRevD.90.072006

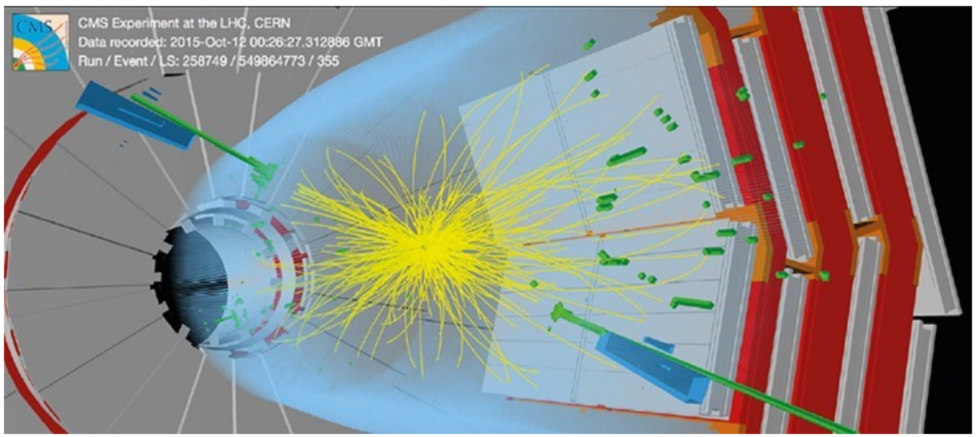
- Good agreement still holds at 13 TeV LHC — by DESY group (Paolo, Engin, Hannes)
  - LO+PS (Pythia8, Herwig++) are off, but mostly by a constant k-factor
  - NLO+PS (PowHeg+Pythia8) works well for R=0.4 and R=0.7
  - NLOxNP works well for R=0.7



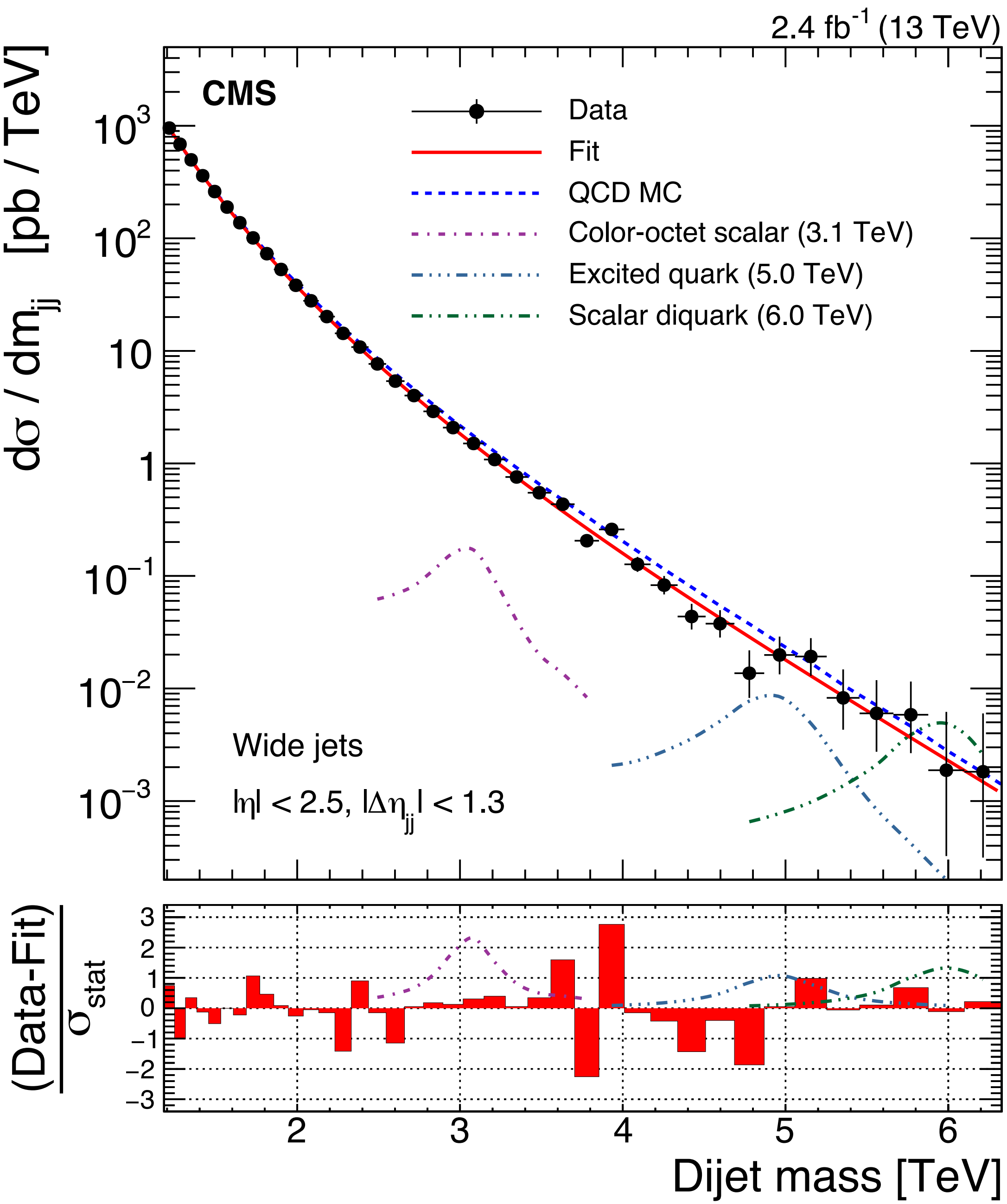


At highest masses

- Dijet mass spectra agree well with the smooth power law predicted by QCD



- No sign of deviations in the form of bumps caused by exotic particles



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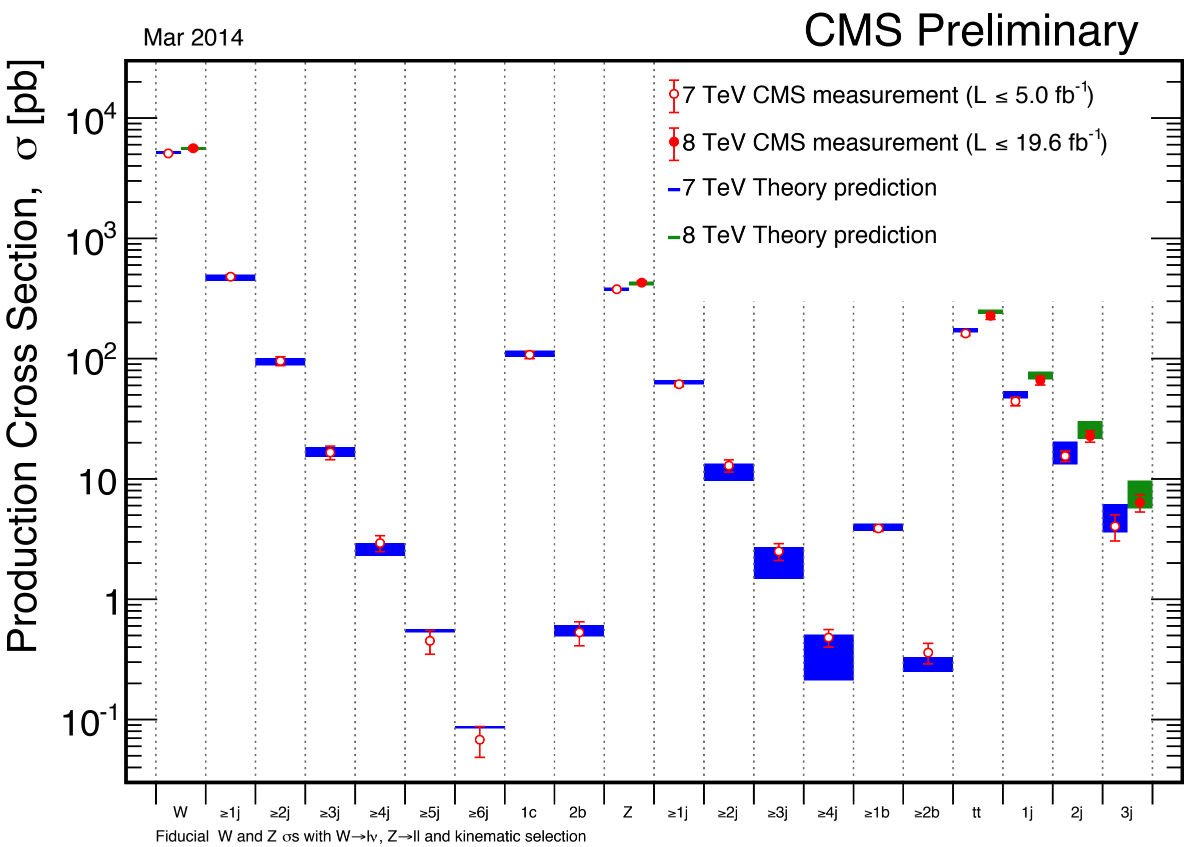
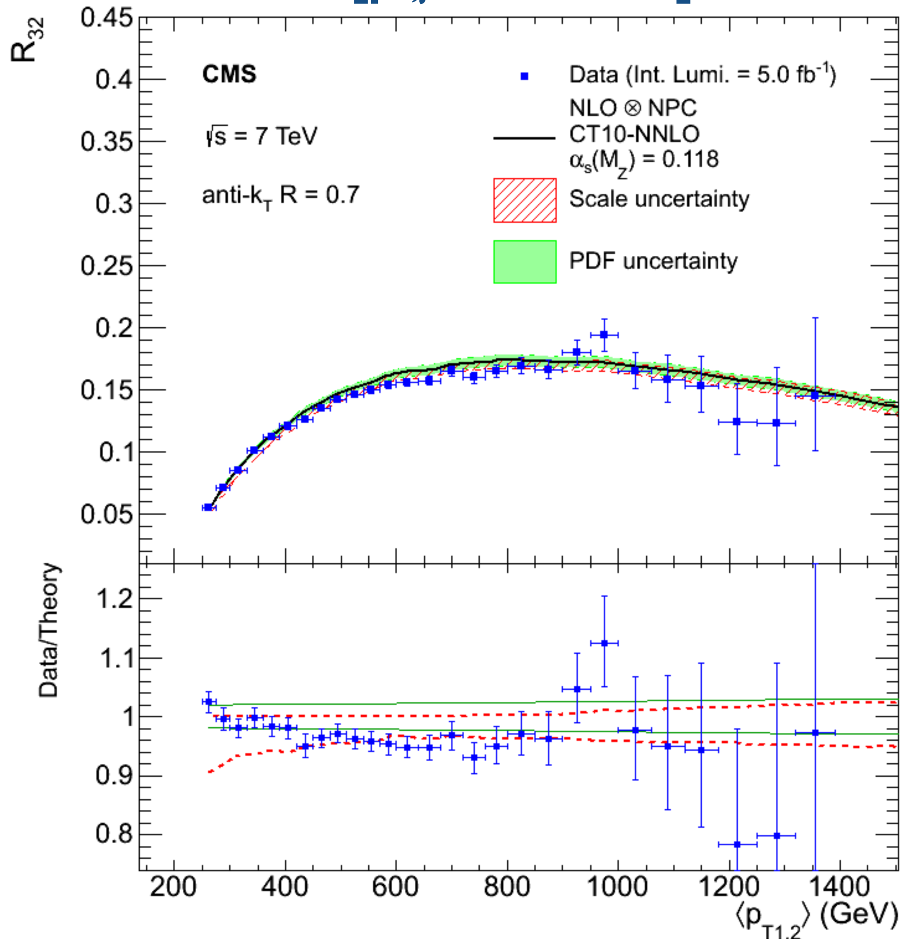
- What's the difference between a 2-jet and a 3-jet event: α_s and radius parameter R
  - each additional jet "costs" a multiple of α_s
  - "price per jet" depends on R (and minimum p_T required, if too high)
    - soft'ish collinear'ish gluon radiation promoted to a jet with small R parameter

X + N jet cross sections (X=W, Z, ttbar)

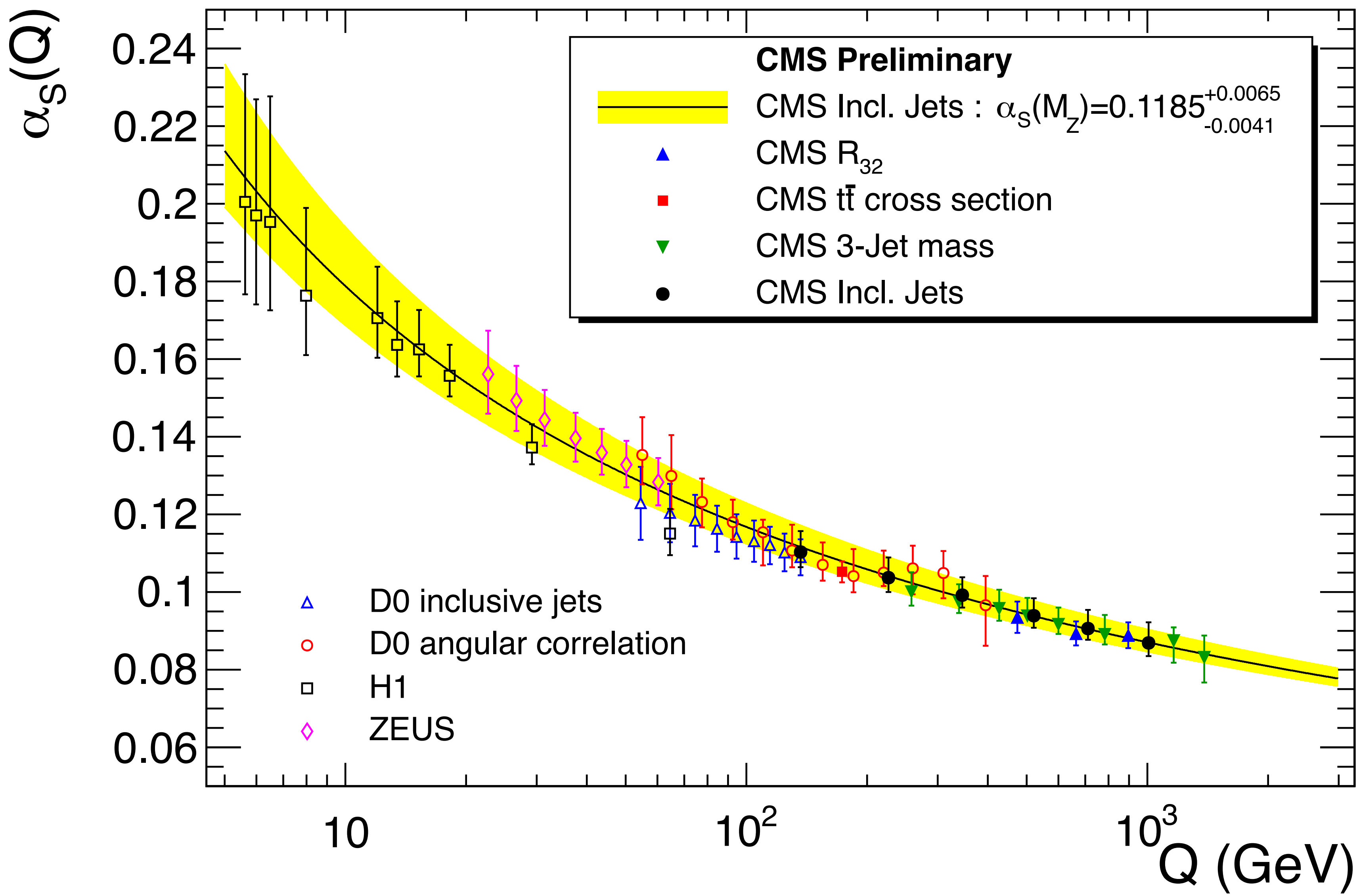


R_{32} = xsec(>=3 jets) / xsec(>=2 jets) [$p_{T,jet}$ > 150 GeV]

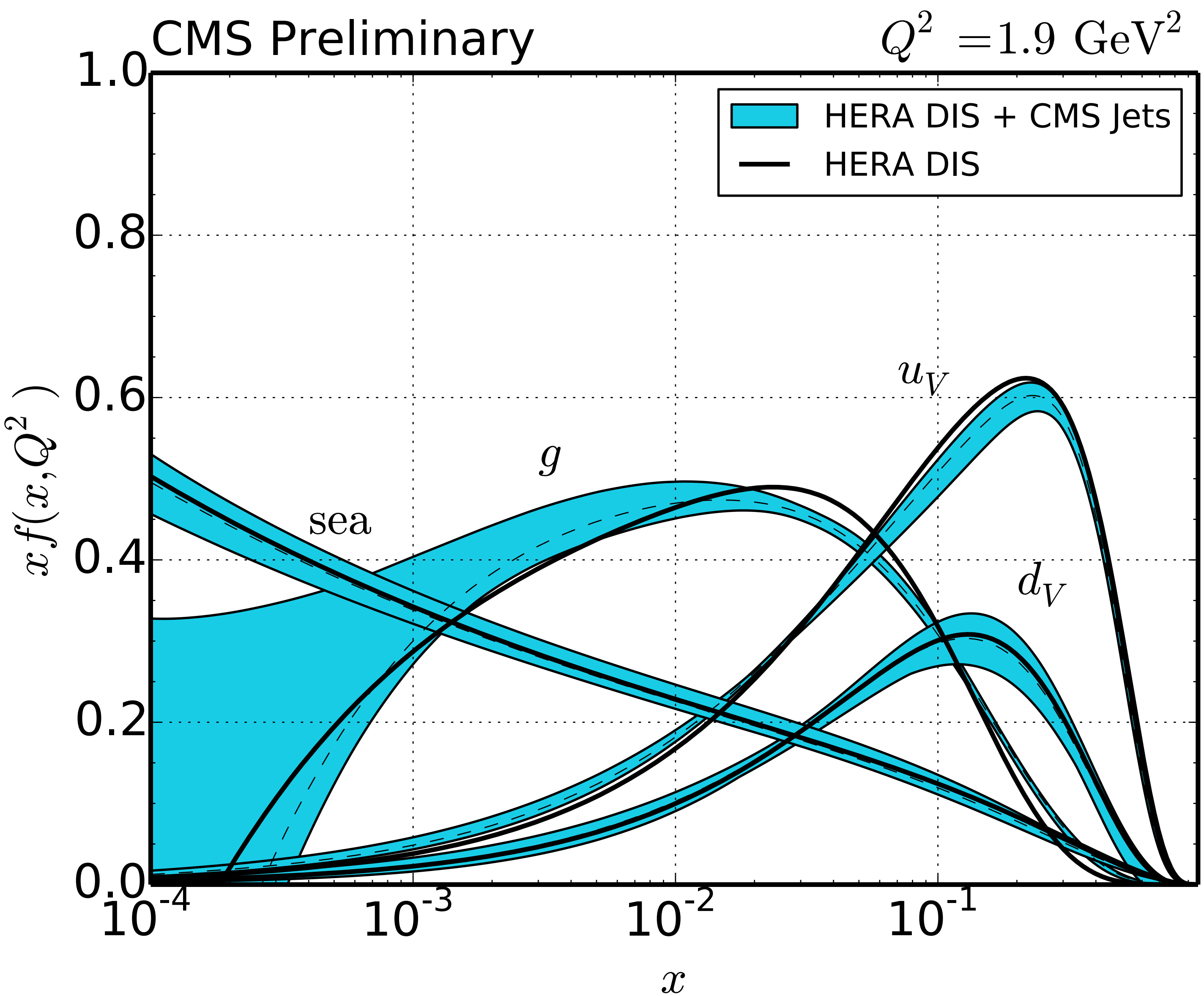


Strong coupling constant

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

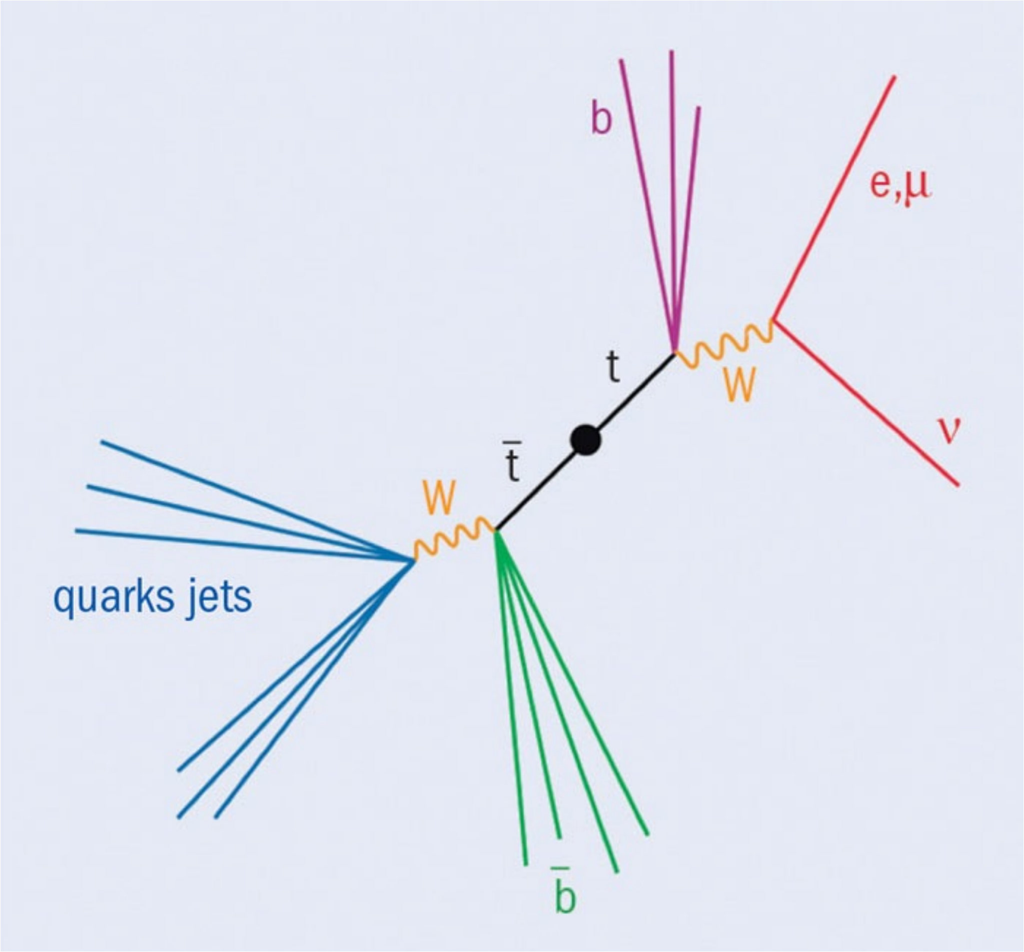


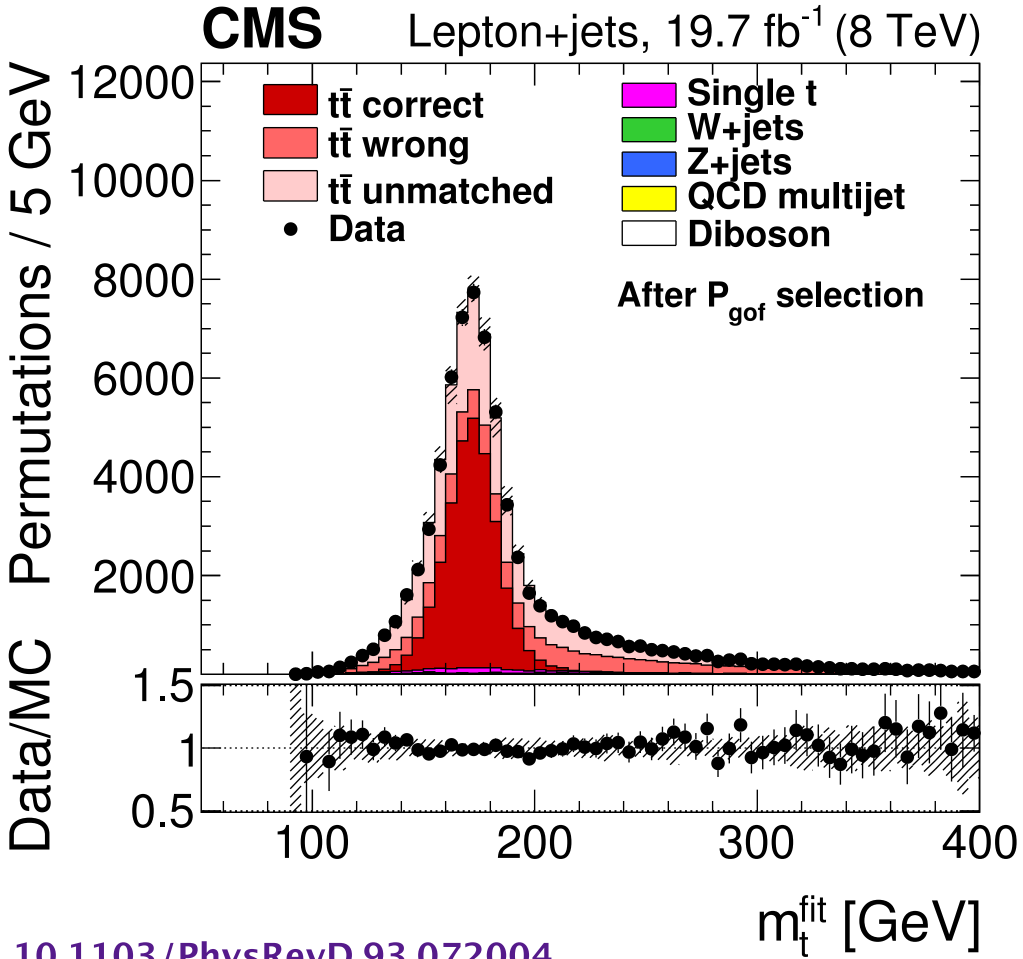
- Jet data useful for complementing **HERA** measurements of proton PDFs for high-x gluons
  - (we're at the "Mecca" of PDFs here in DESY-Hamburg)



Top quark mass

- Most precise determinations of **top quark mass m_t** to date with lepton+jets channel
  - "golden channel" with reduced systematics compared to dileptonic and fully hadronic channels
    - Markus Seidel (U. Hamburg, now CERN); Hartmut Stadie (U. Hamburg)
  - dilepton channel: two neutrinos => cannot reconstruct individual neutrinos p_T
  - fully hadronic channel => large combinatoric background (wrong jet combinations)

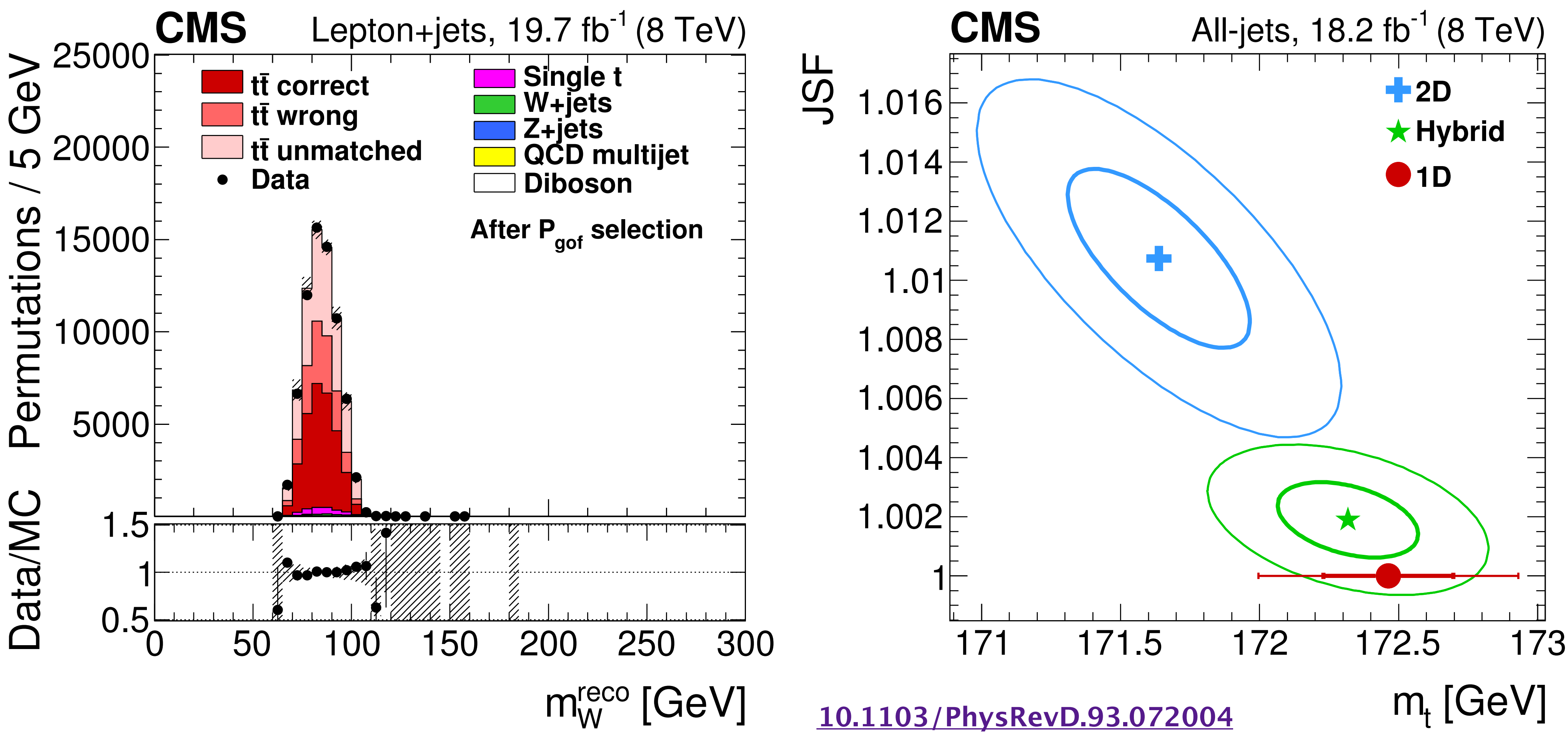




10.1103/PhysRevD.93.072004

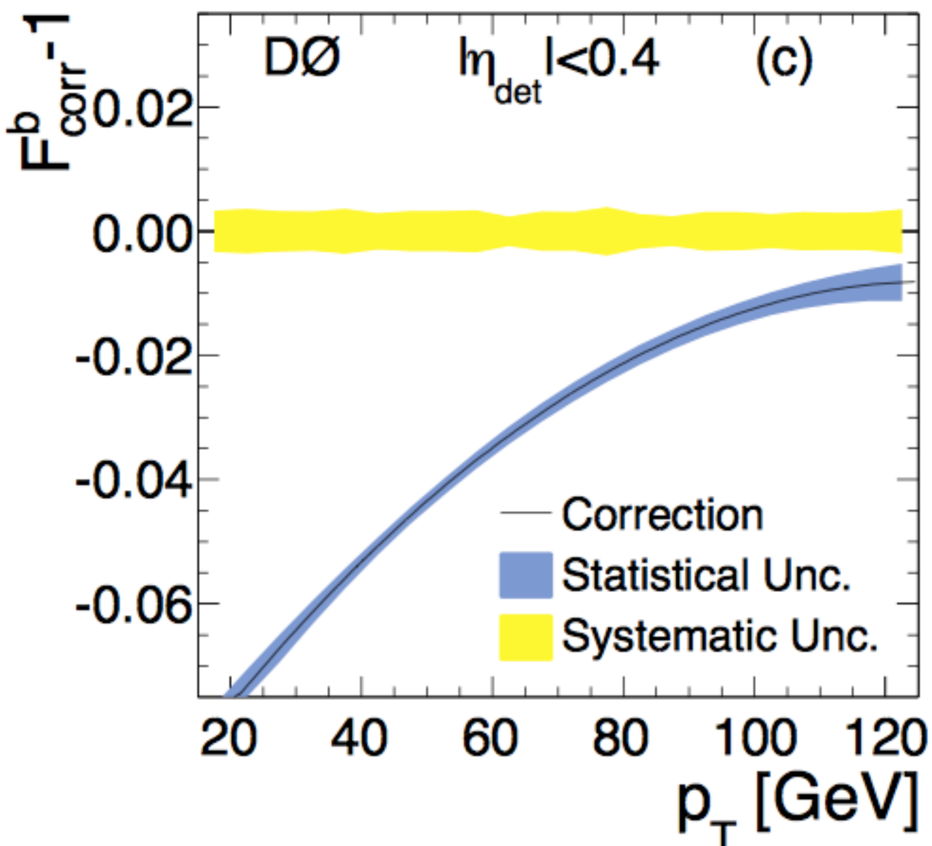
W mass constraint

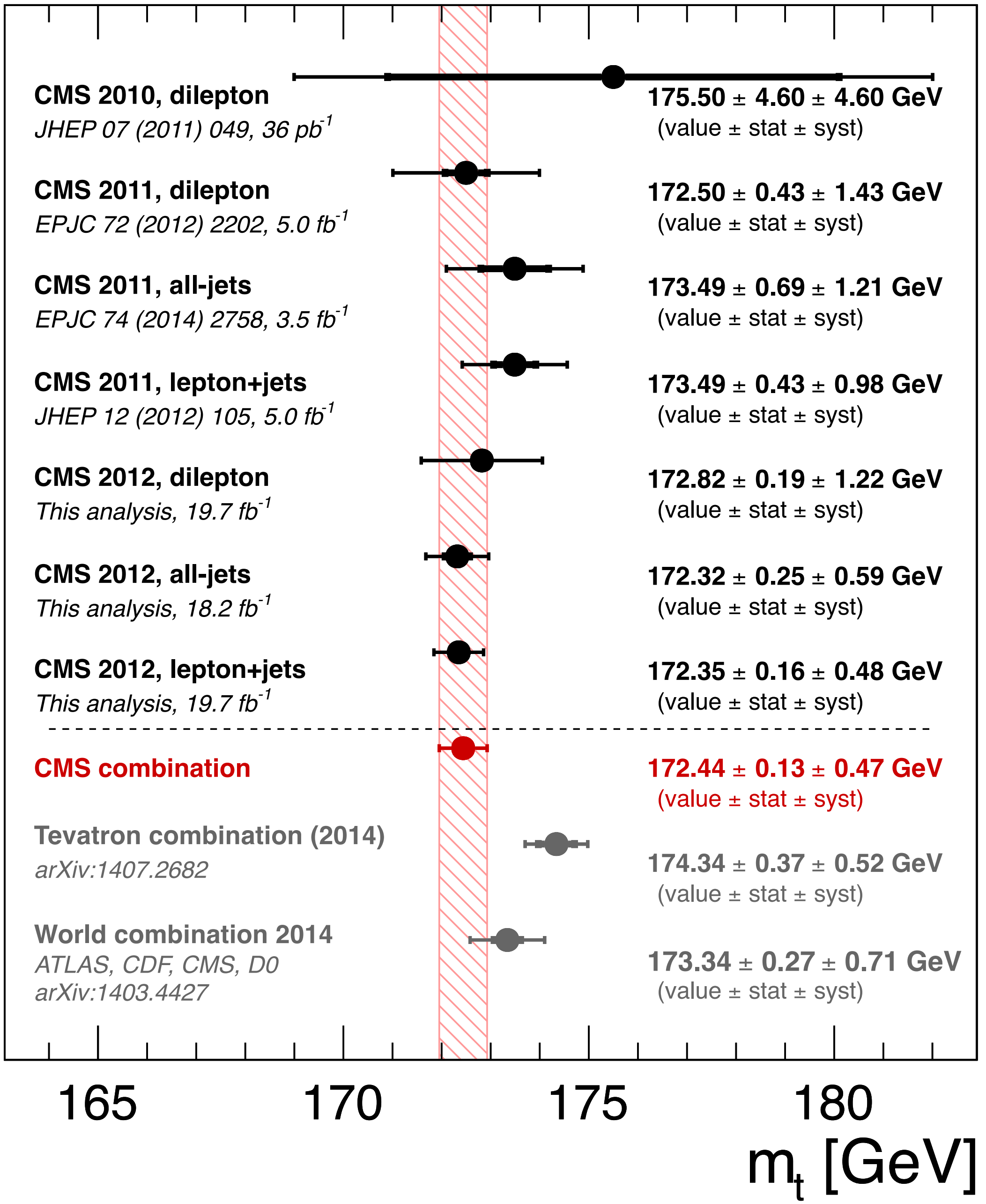
- Hadronic W mass (W->qq') reconstructed in tt events constrains JEC with m_t (W+b)
  - dominant systematic then b-jet to light-jet scale; addressable in Run II e.g. with Z+b events
- Current state-of-the art is hybrid combining "2D" (JEC+m_t) with "1D" (m_T only)
  - in-situ W mass versus reference Z+jet p_T balance: similar precision, different systematics



10.1103/PhysRevD.93.072004

- The two most precise top mass measurements from CMS and D0 currently differ by about 3 σ
- Key is b-jet scale relative to light?
  - CMS: MC with Z+b check in data
  - D0: single-particle response in data
- Or e.g. modeling of FSR in "2D"?

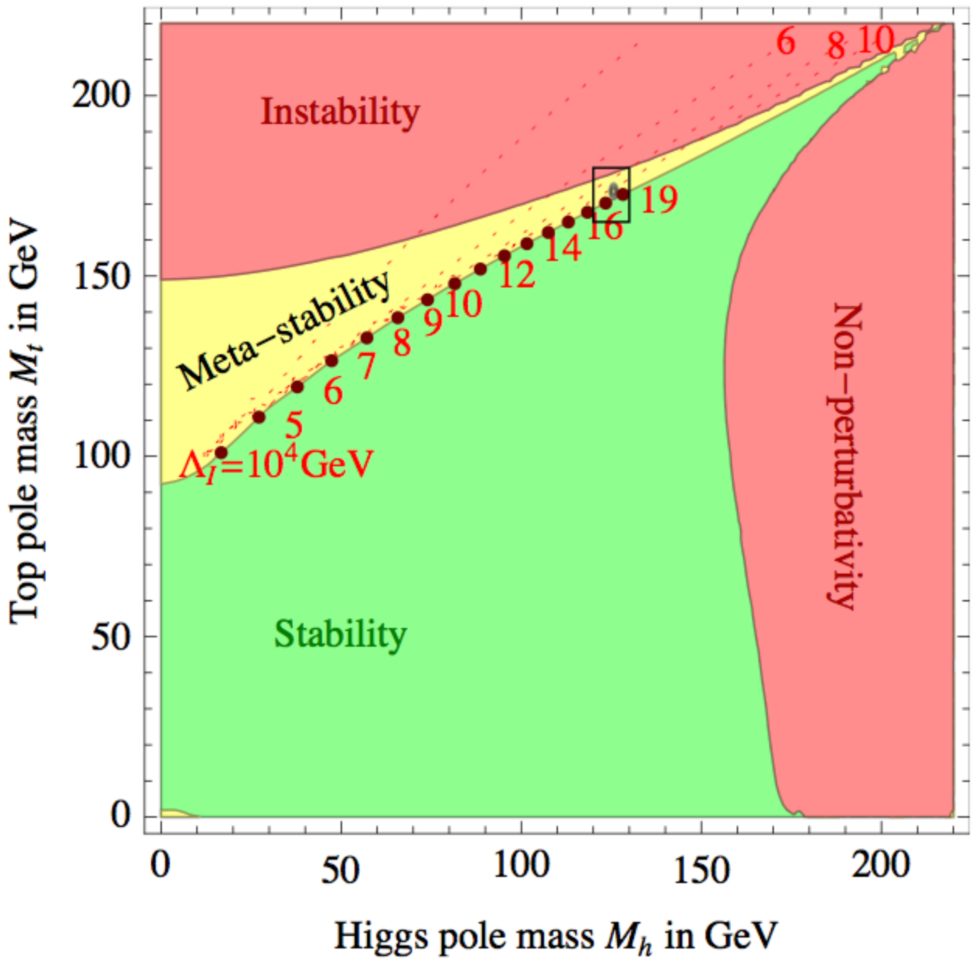


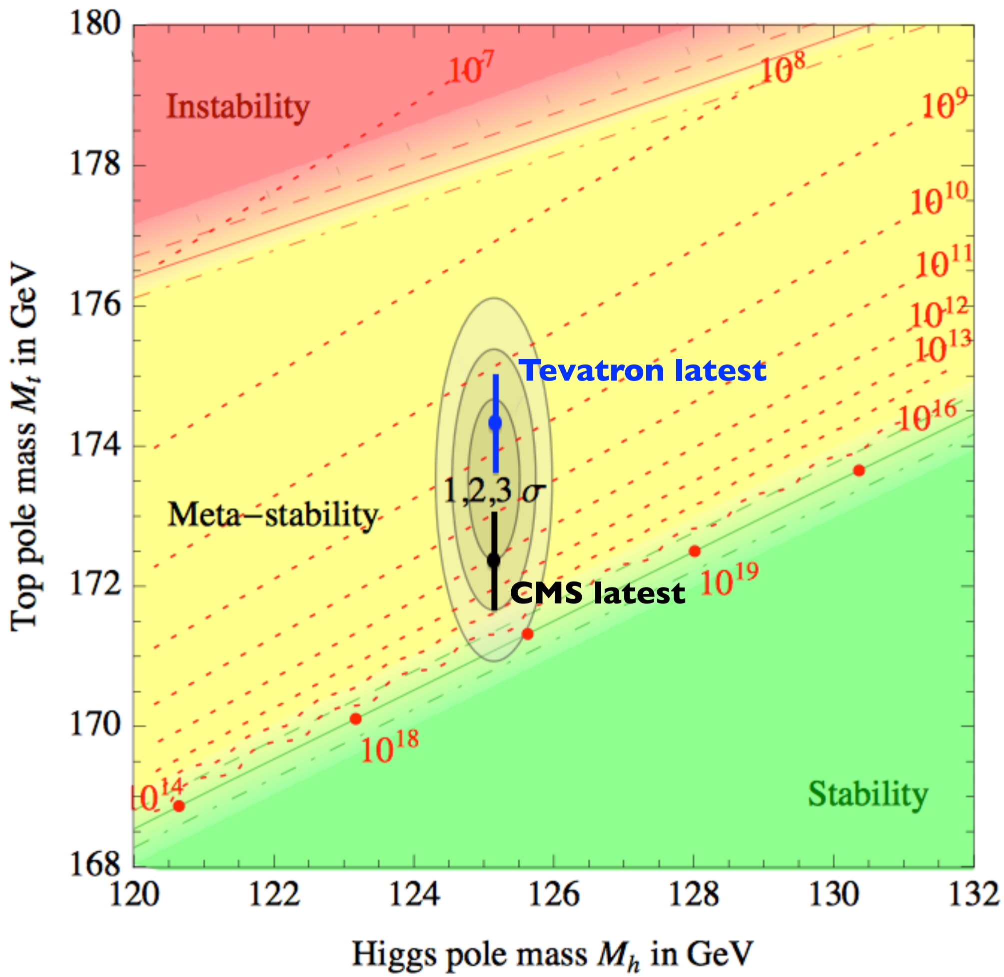


http://arxiv.org/abs/1312.6873

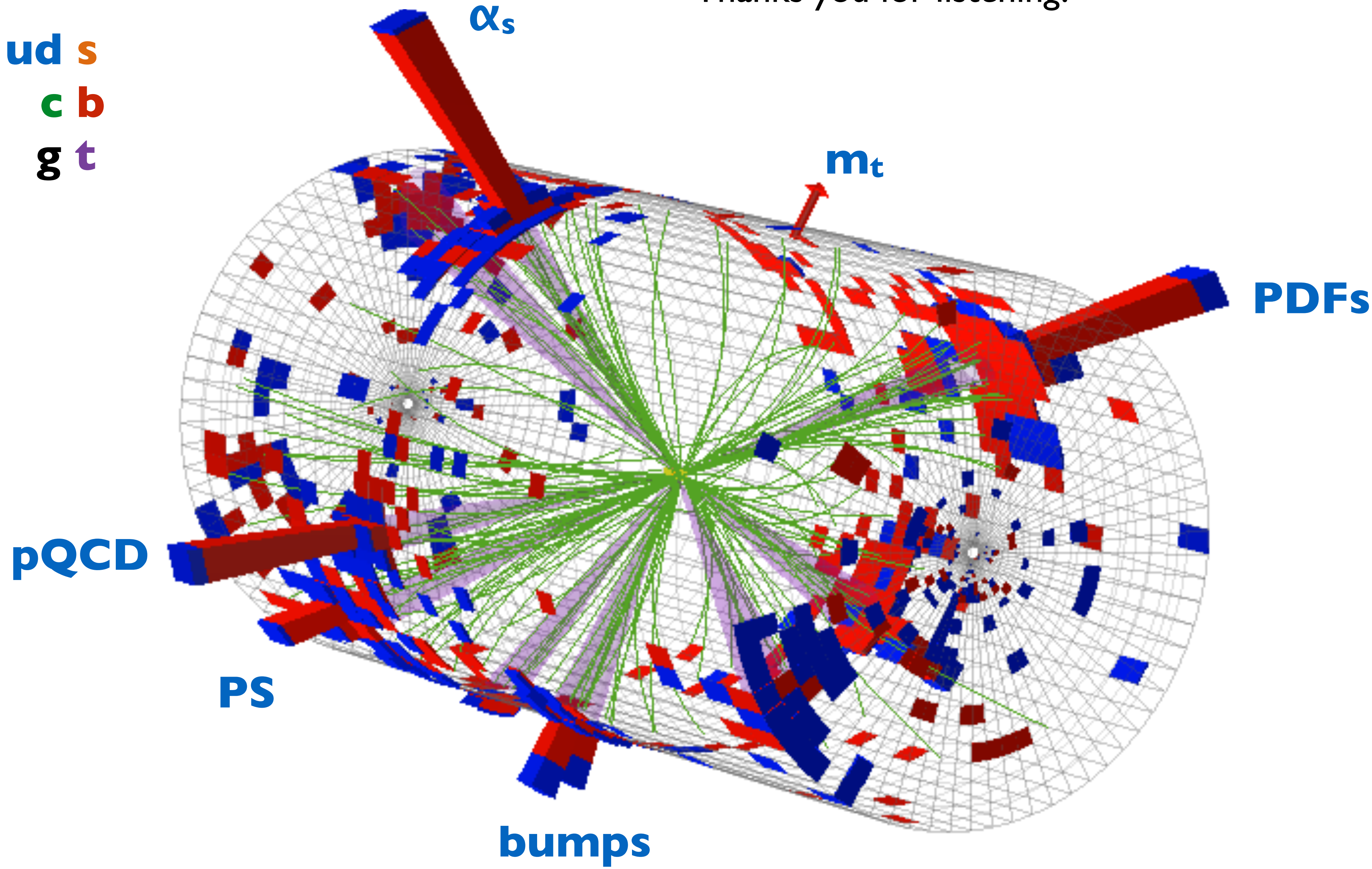
Massive constraints

- Metastability of SM vacuum (in absence of new particles) could be a hint of something
- If Run II finds no new particles, maybe precise m_t helps to constrain dynamics at high scale
  - but, Tevatron vs LHC?
  - but, MC mass vs pole mass?

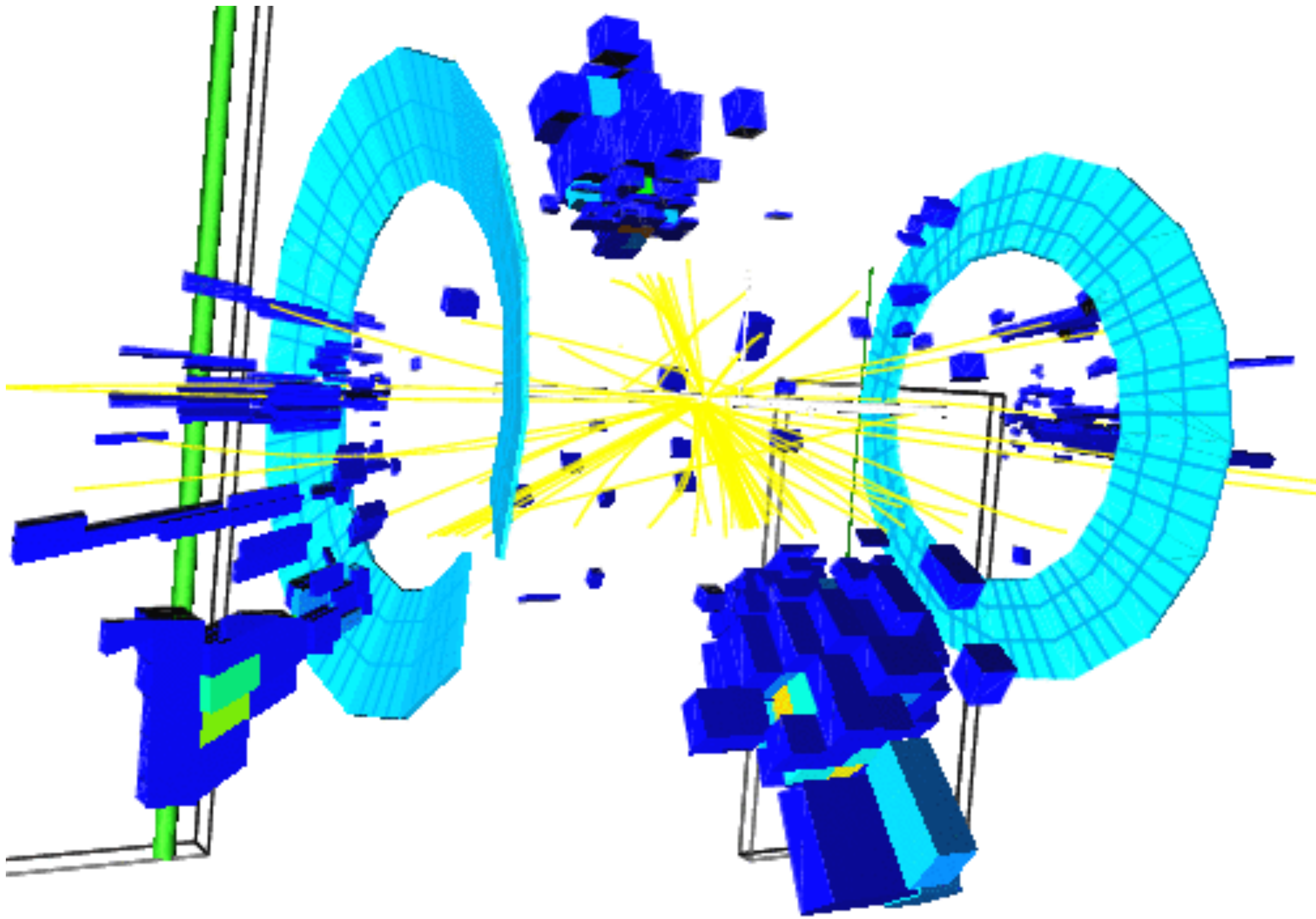




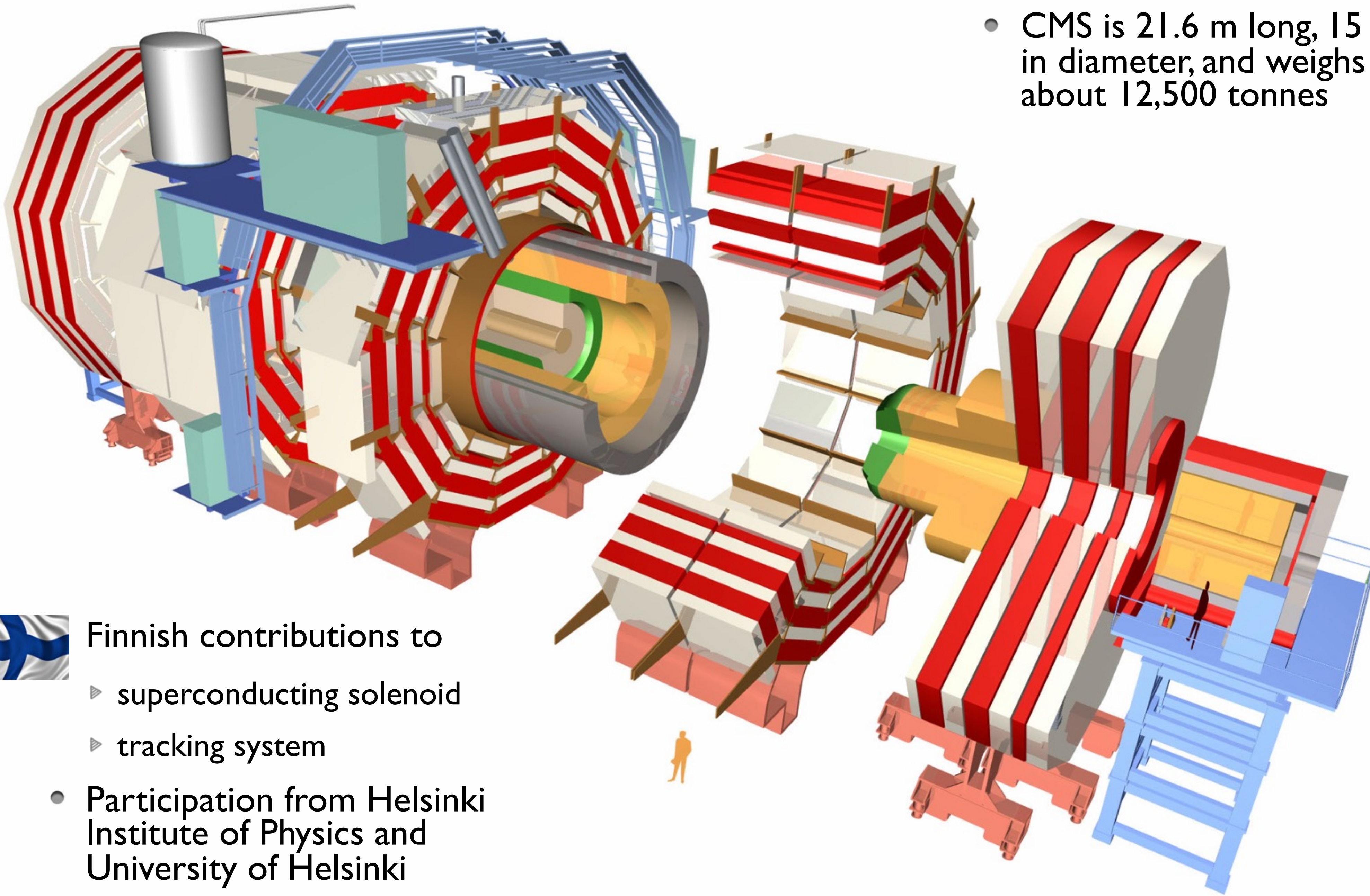
- Thanks you for listening!



Backup slides



CMS detector

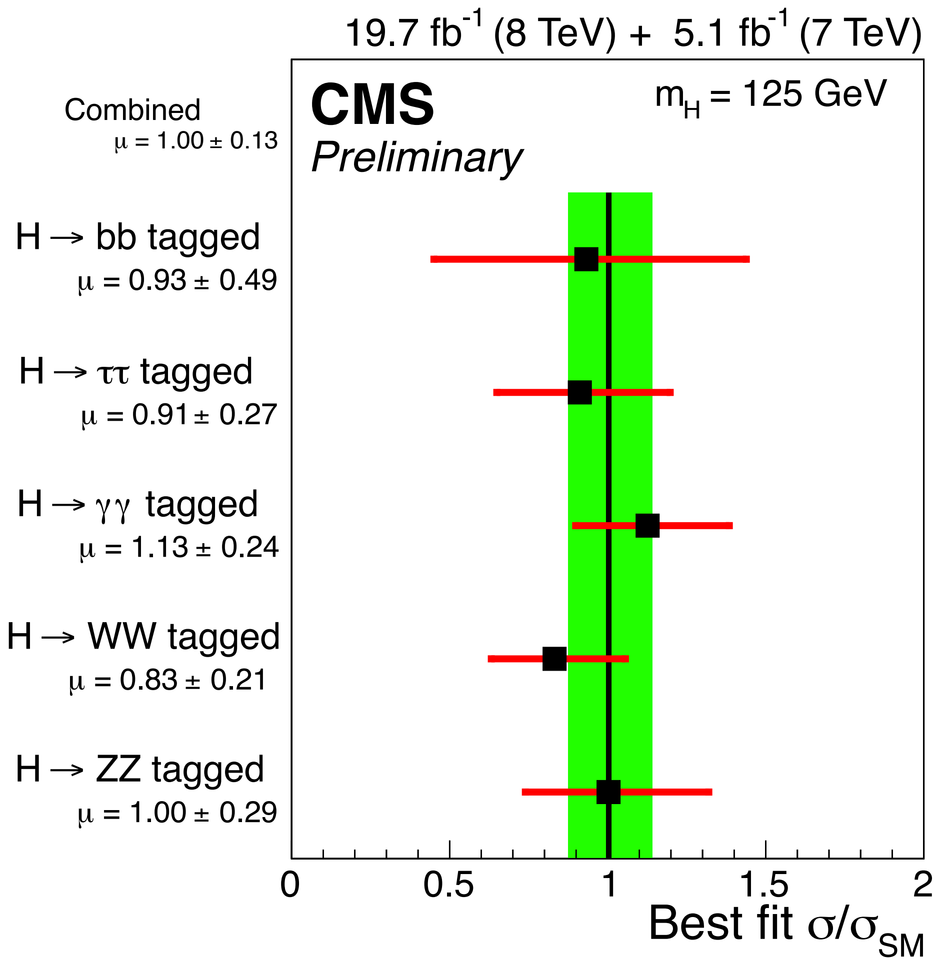


- CMS is 21.6 m long, 15 m in diameter, and weighs about 12,500 tonnes

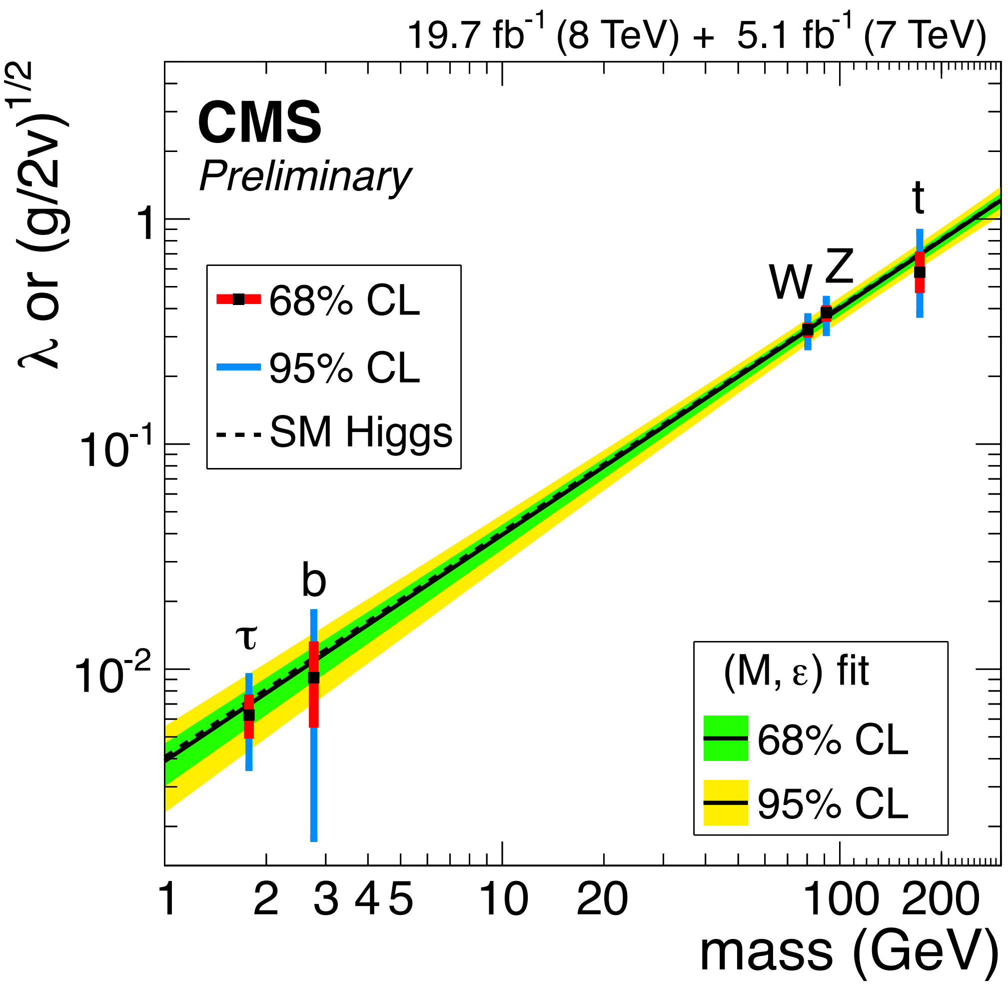
Finnish contributions to
  - superconducting solenoid
  - tracking system
- Participation from Helsinki Institute of Physics and University of Helsinki

'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

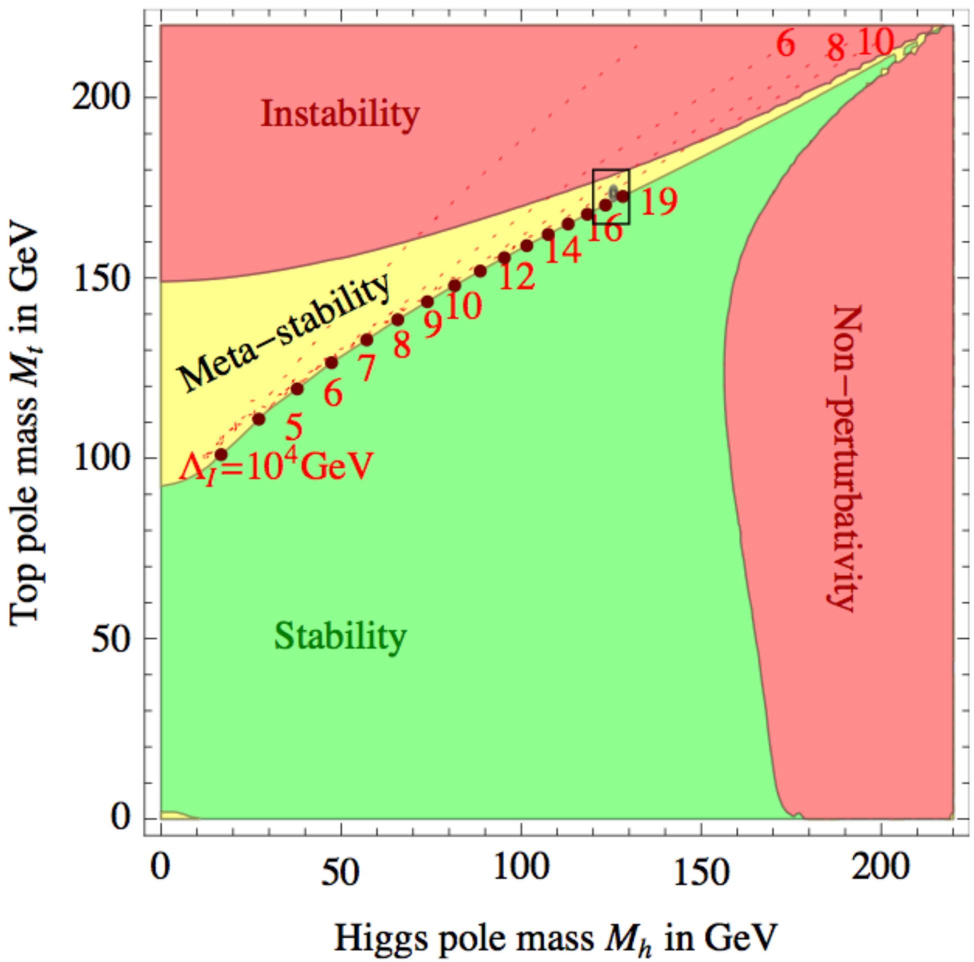


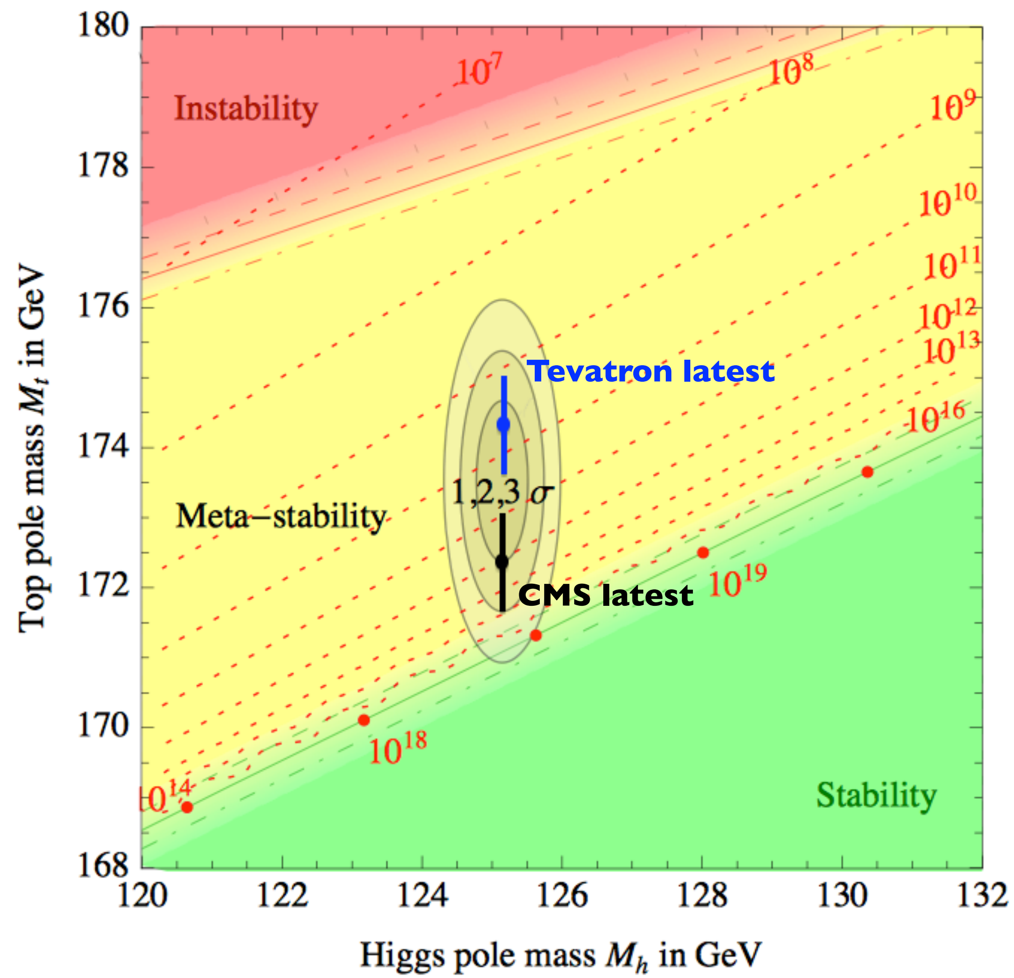
Couplings to Higgs are proportional to particle masses

Towards LHC Run II

- If only standard model up to Planck scale, we seem to live in semi-stable universe
  - Top quark mass (relying on **Jet Energy Scale**) to confirm this
- Alternatively, there are new particles that could also be responsible for dark matter
  - If SUSY, **Charged Higgs search** could make the discovery
- We may find the answer in Run II starting next Spring!

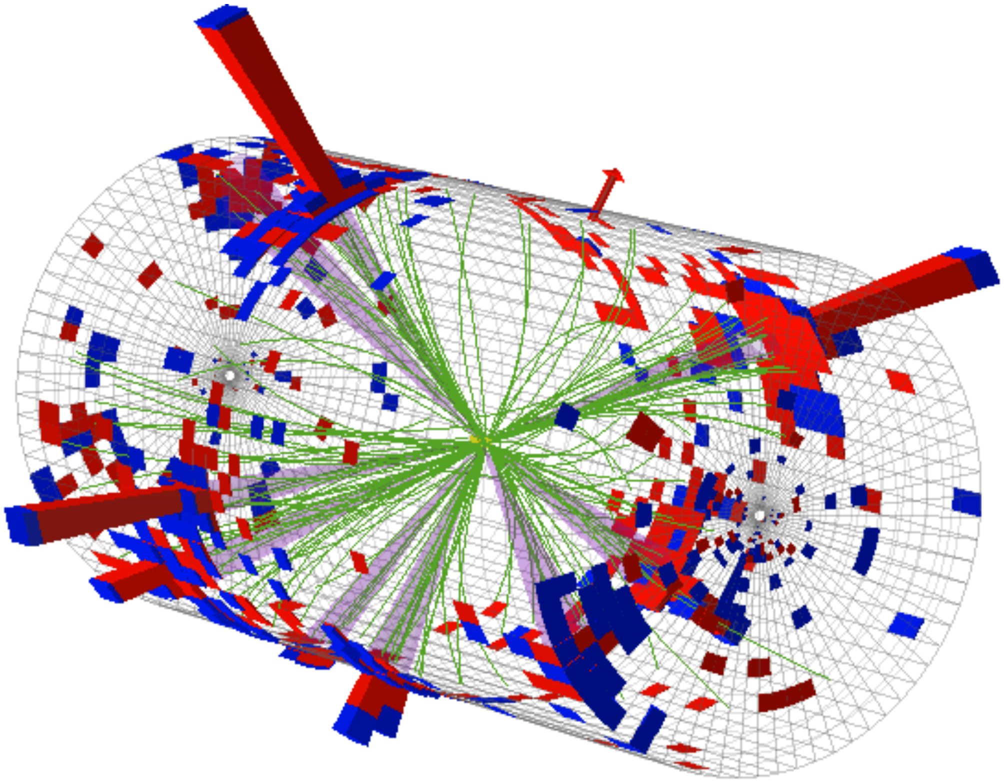
http://arxiv.org/abs/1307.3536

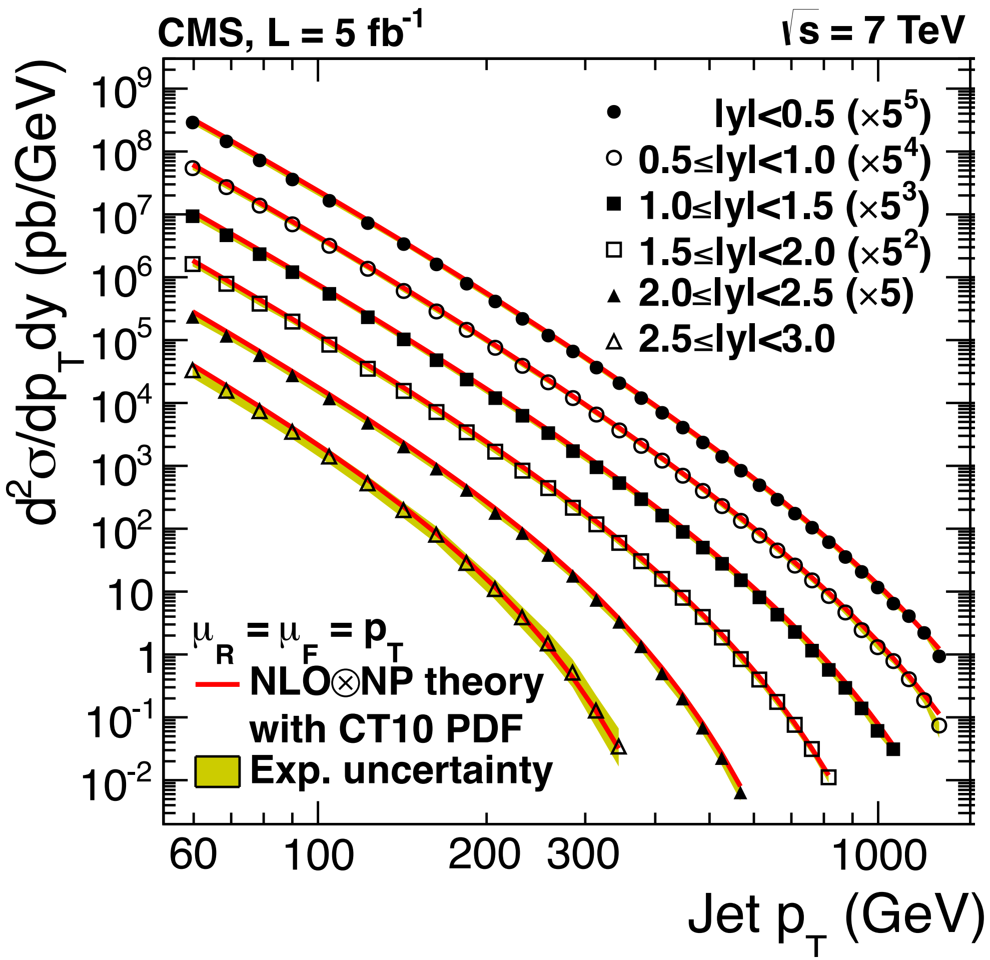


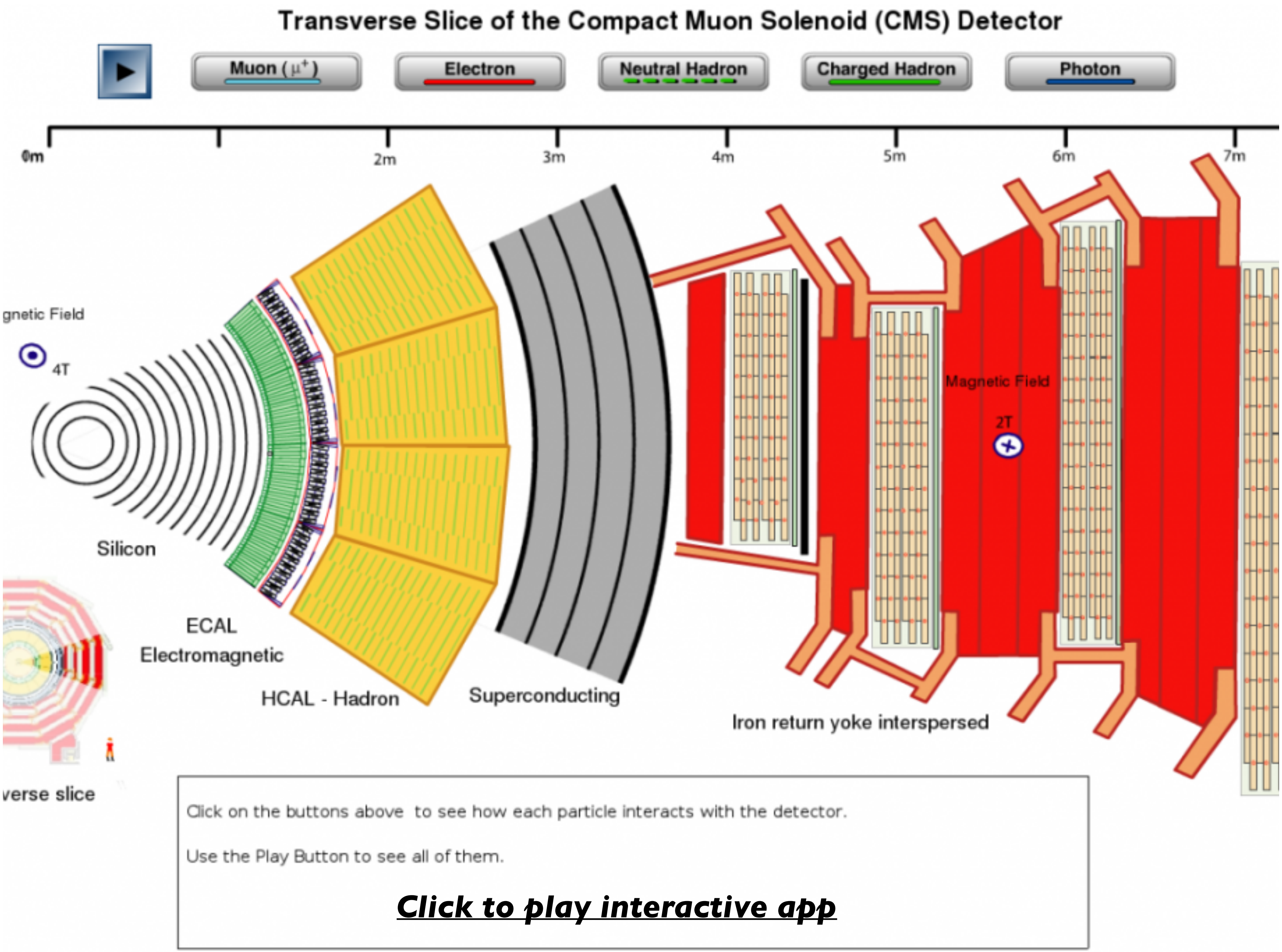


Jet physics

- 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





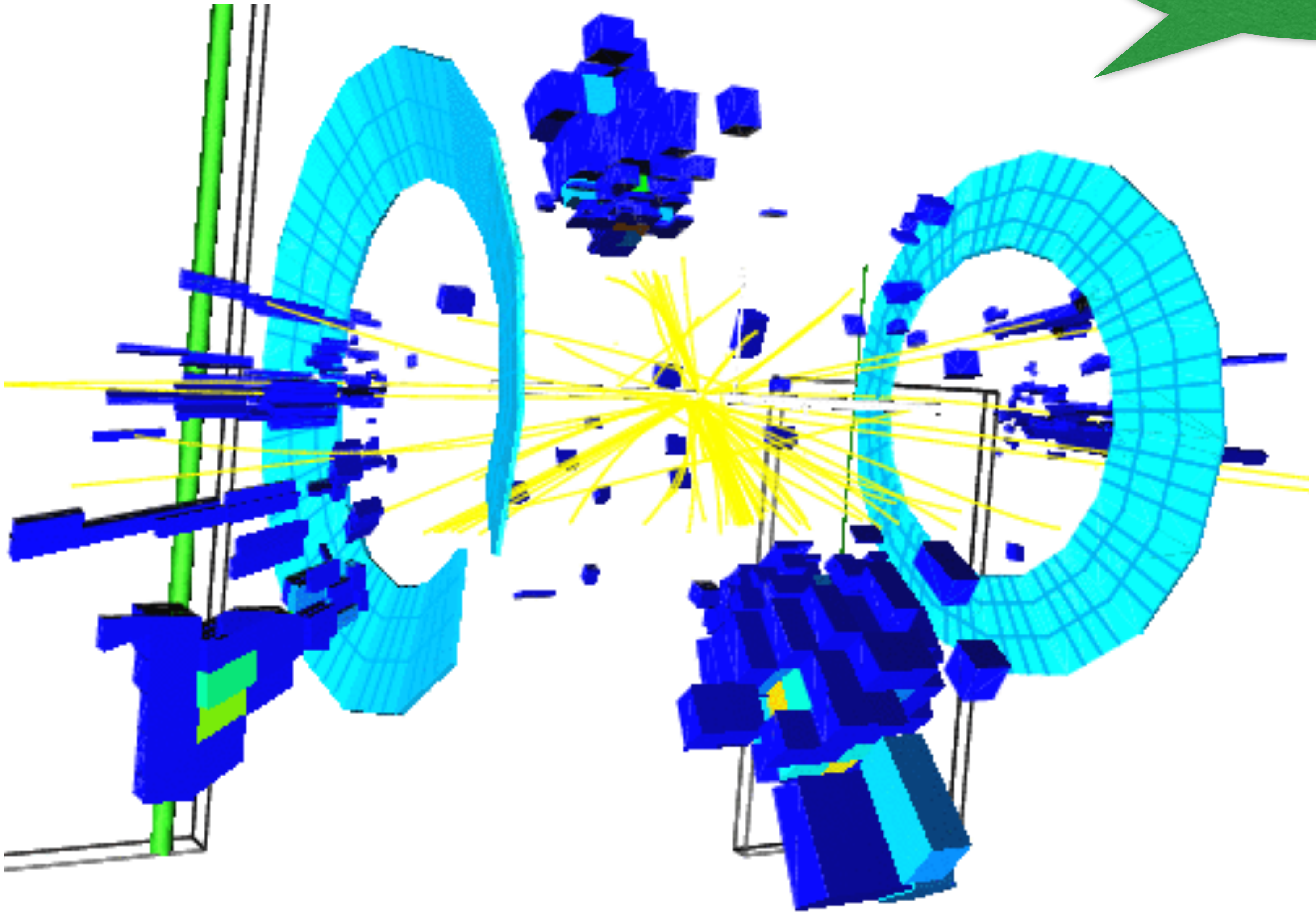


<u>Click to play interactive app</u>

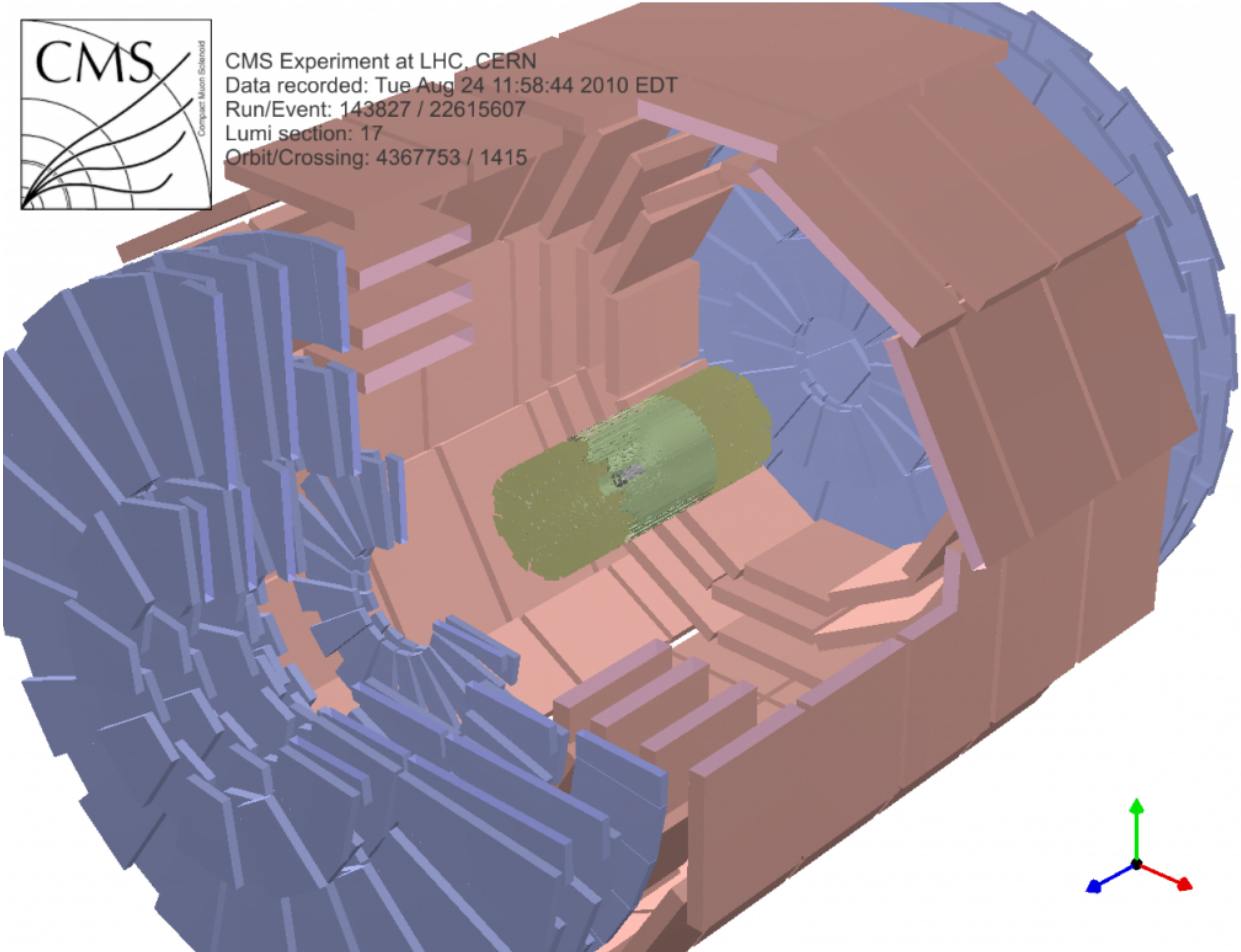
Derived from CMS Detector Slice from CERN

- <u>Click here to return to main talk</u>

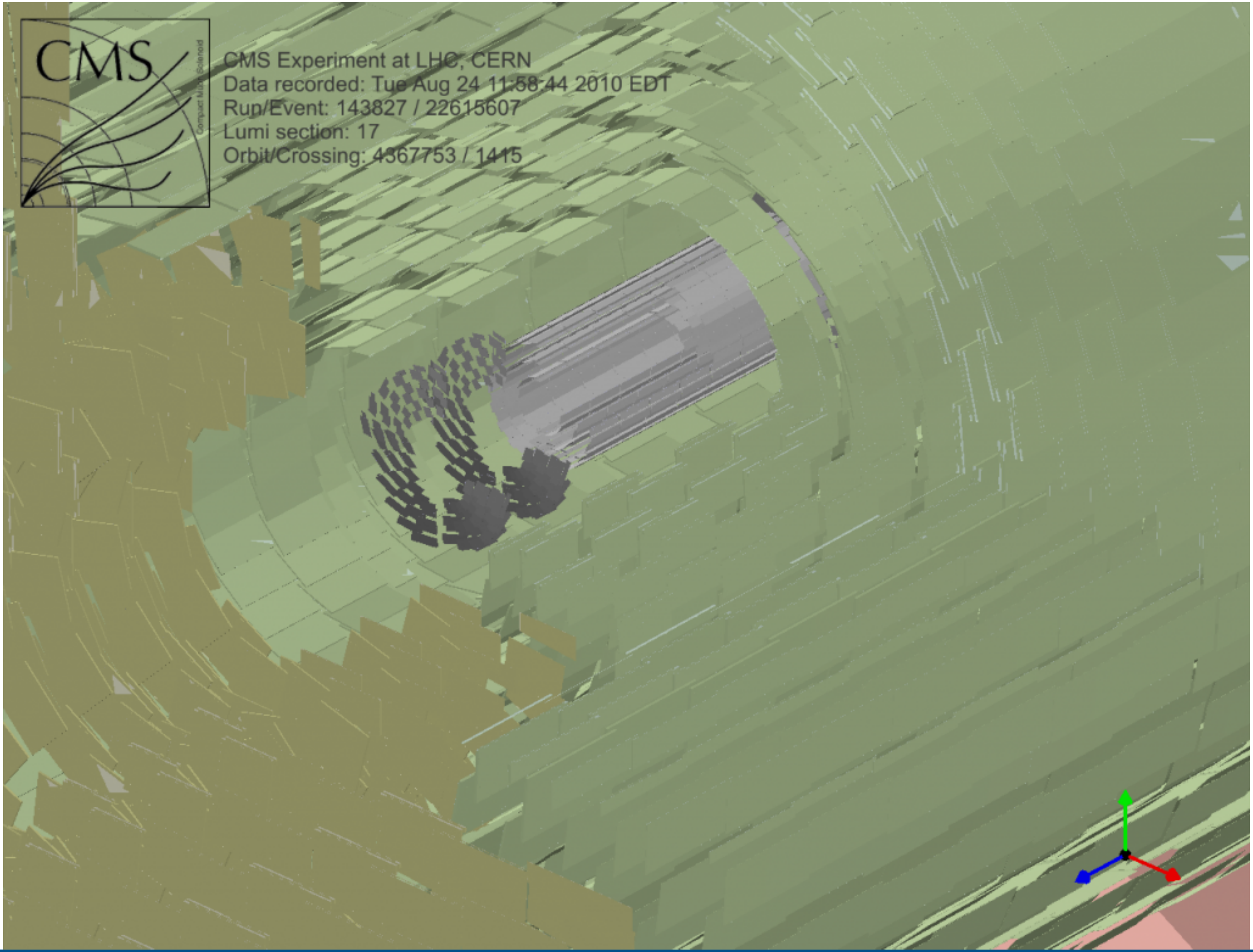
15 slides of pretty pictures!



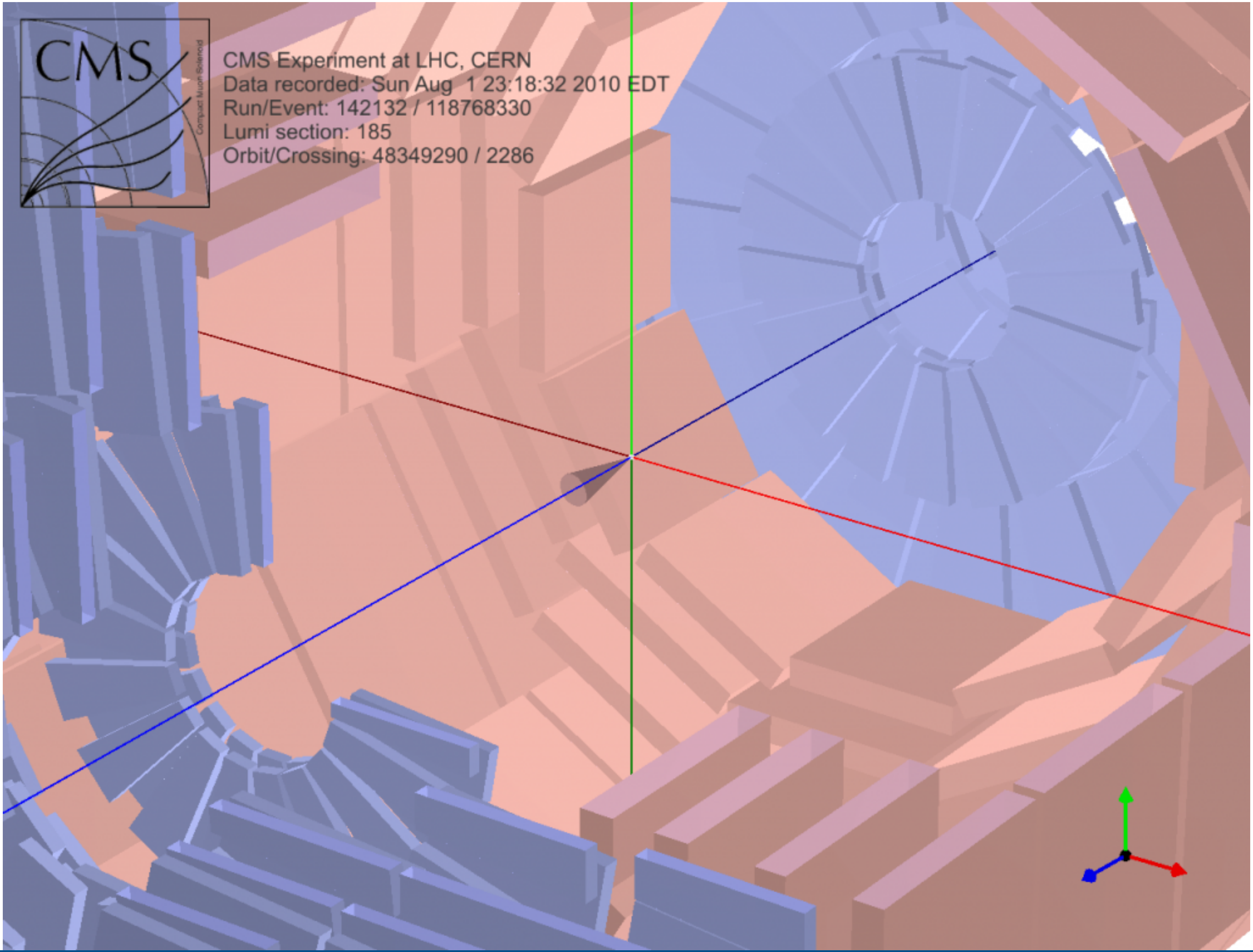
- Credits: <u>Brian Dorney, US LHC blogger</u>


CMS
Compact Muon Solenoid
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

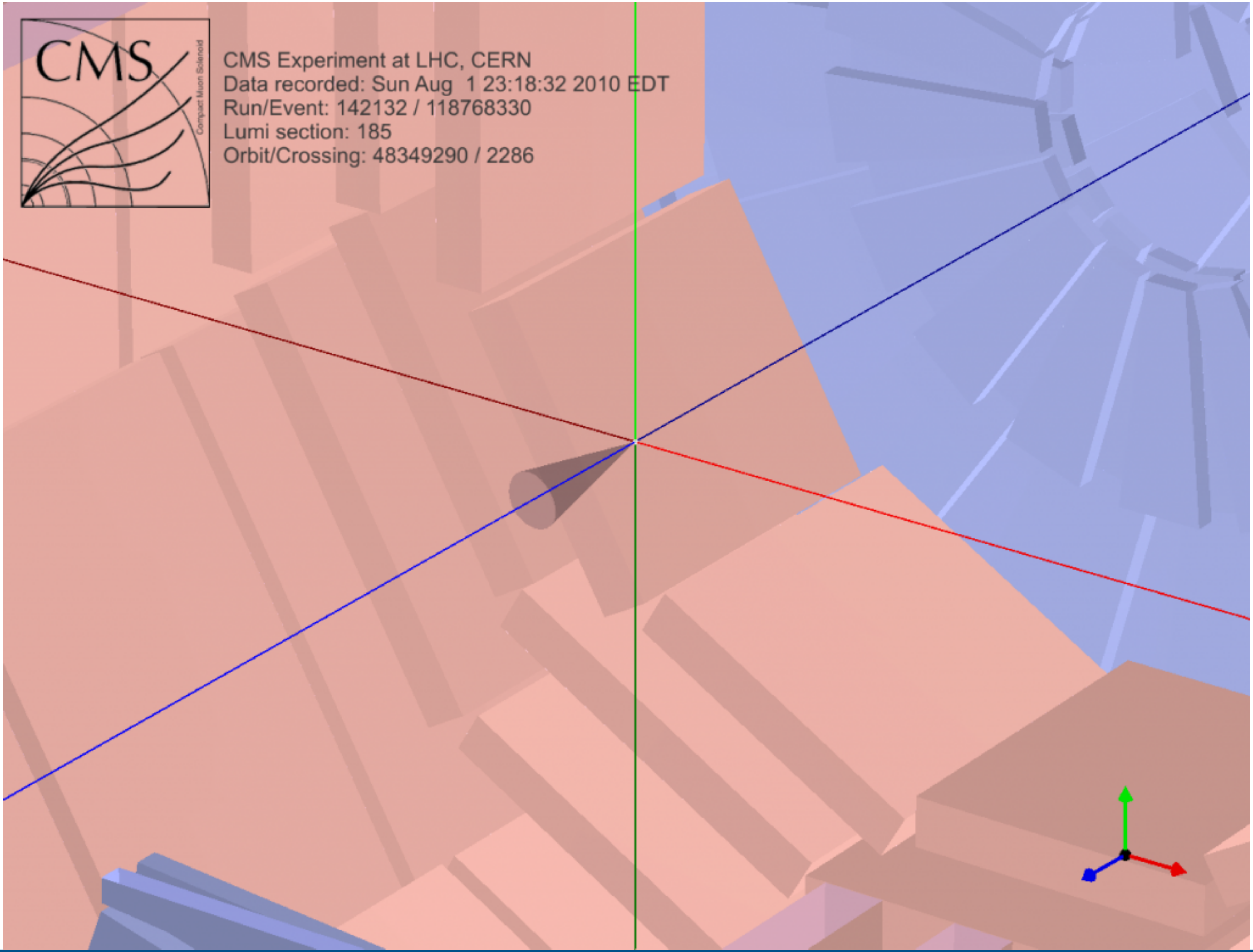
Close-up of silicon tracker



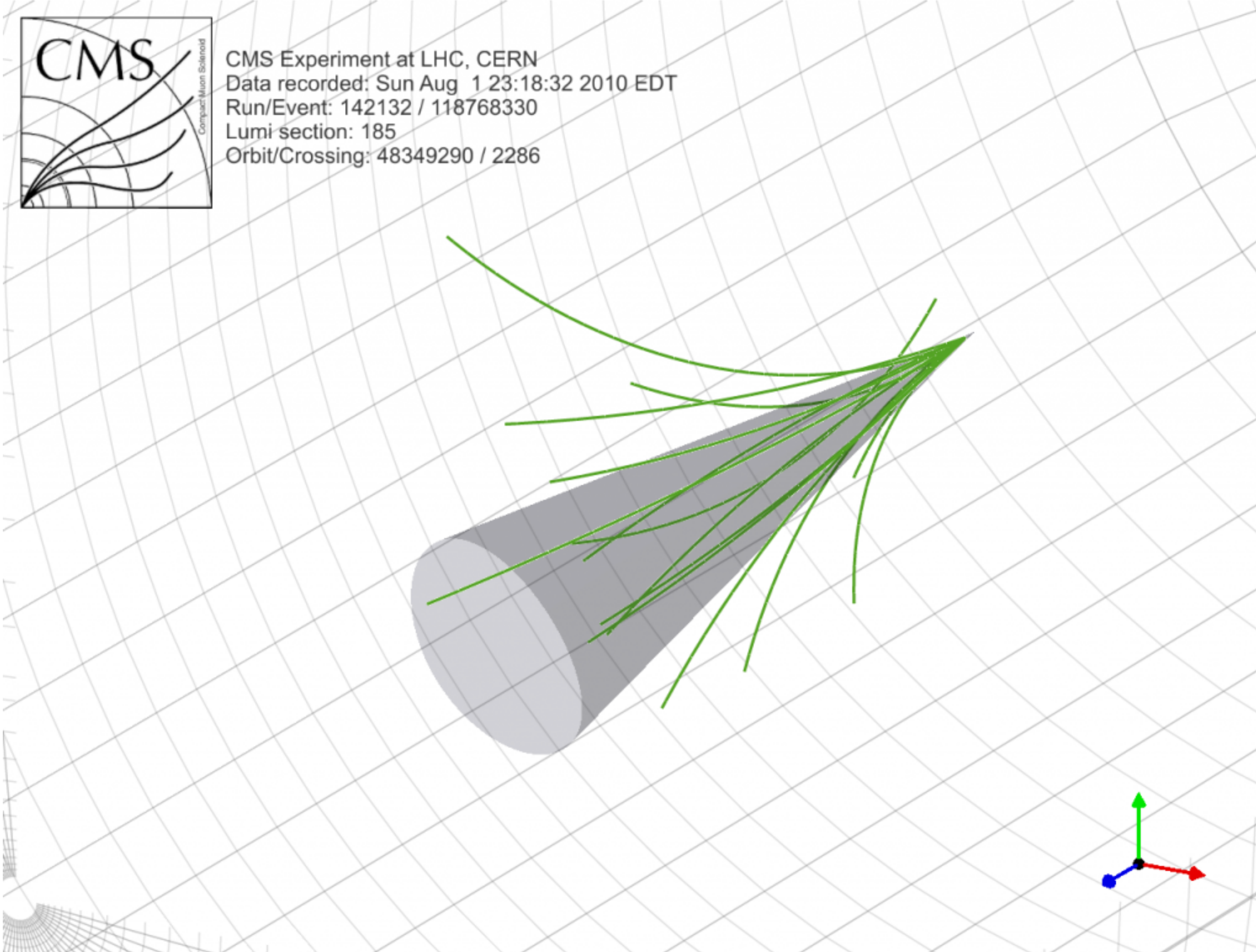
A jet cone in CMS



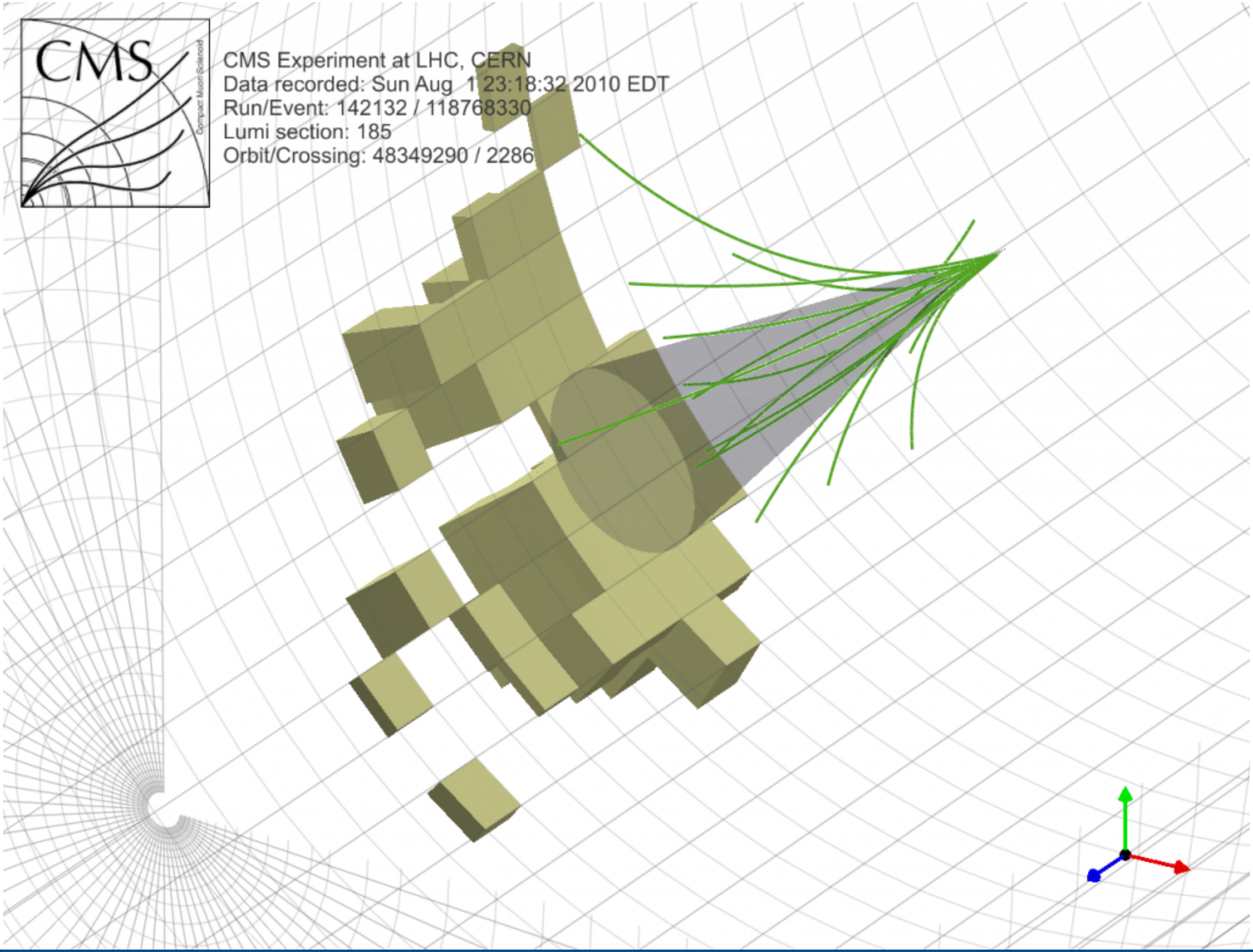
Zoom in the jet cone



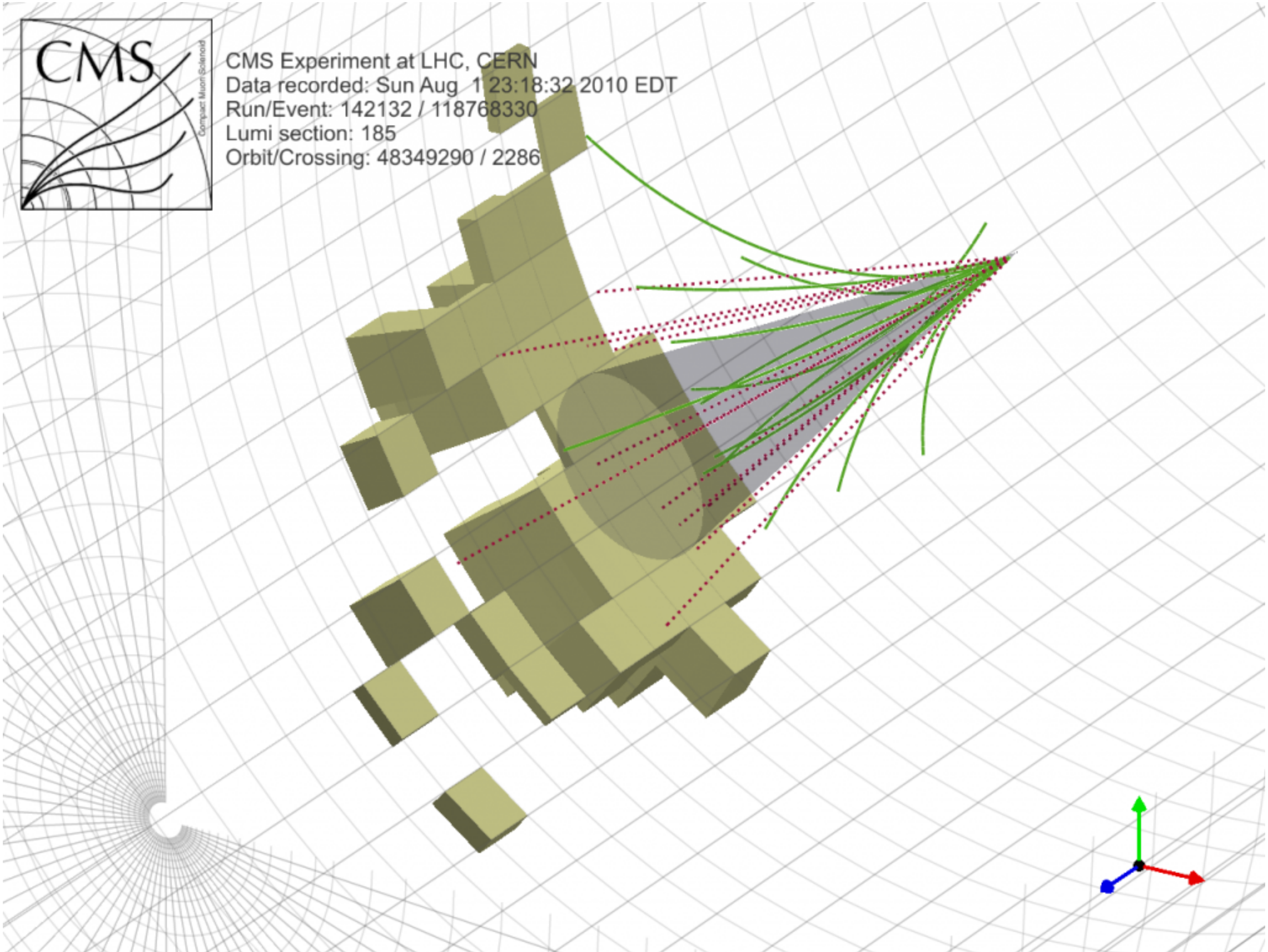
Jet and it's tracks



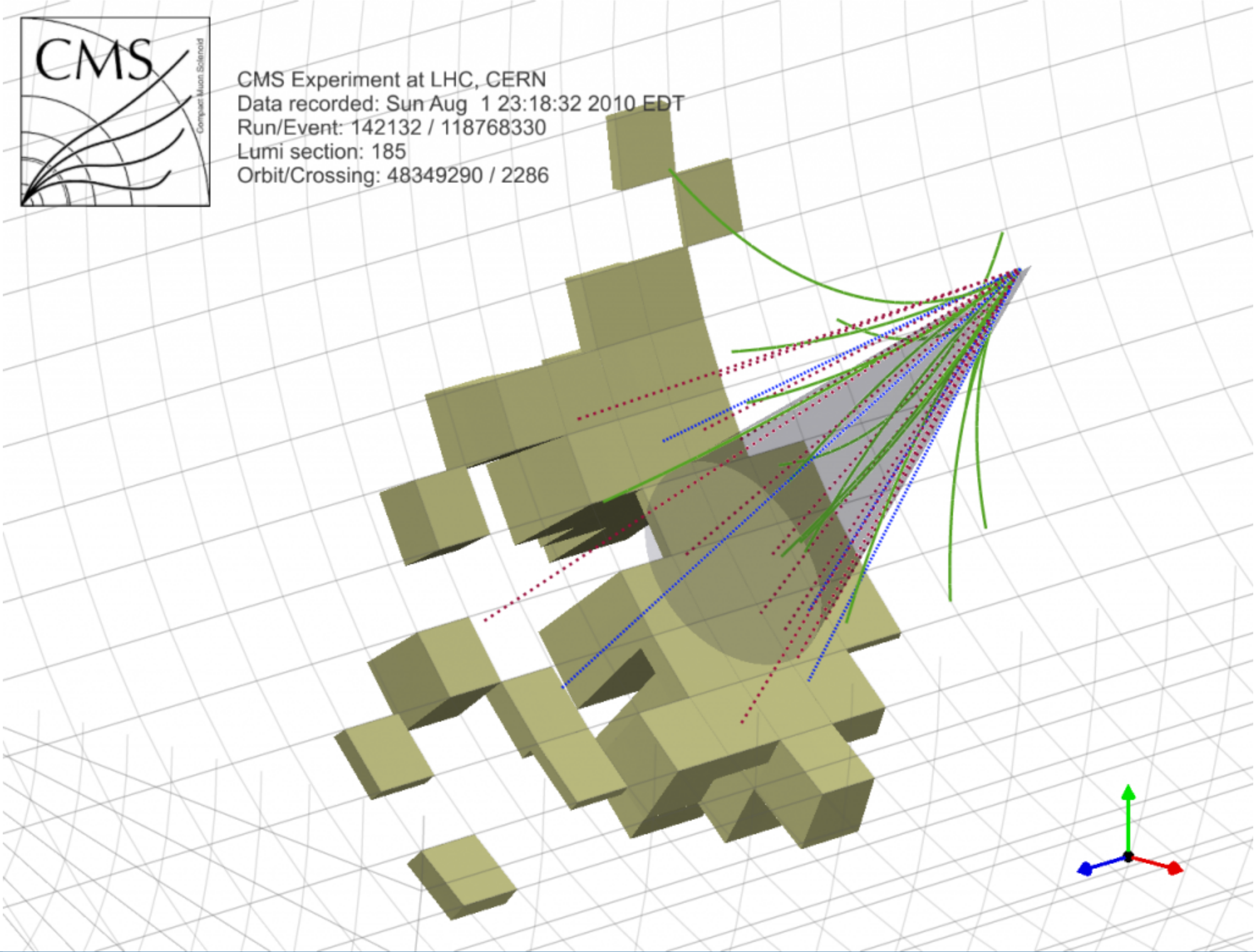
Jet, tracks, ECAL deposits



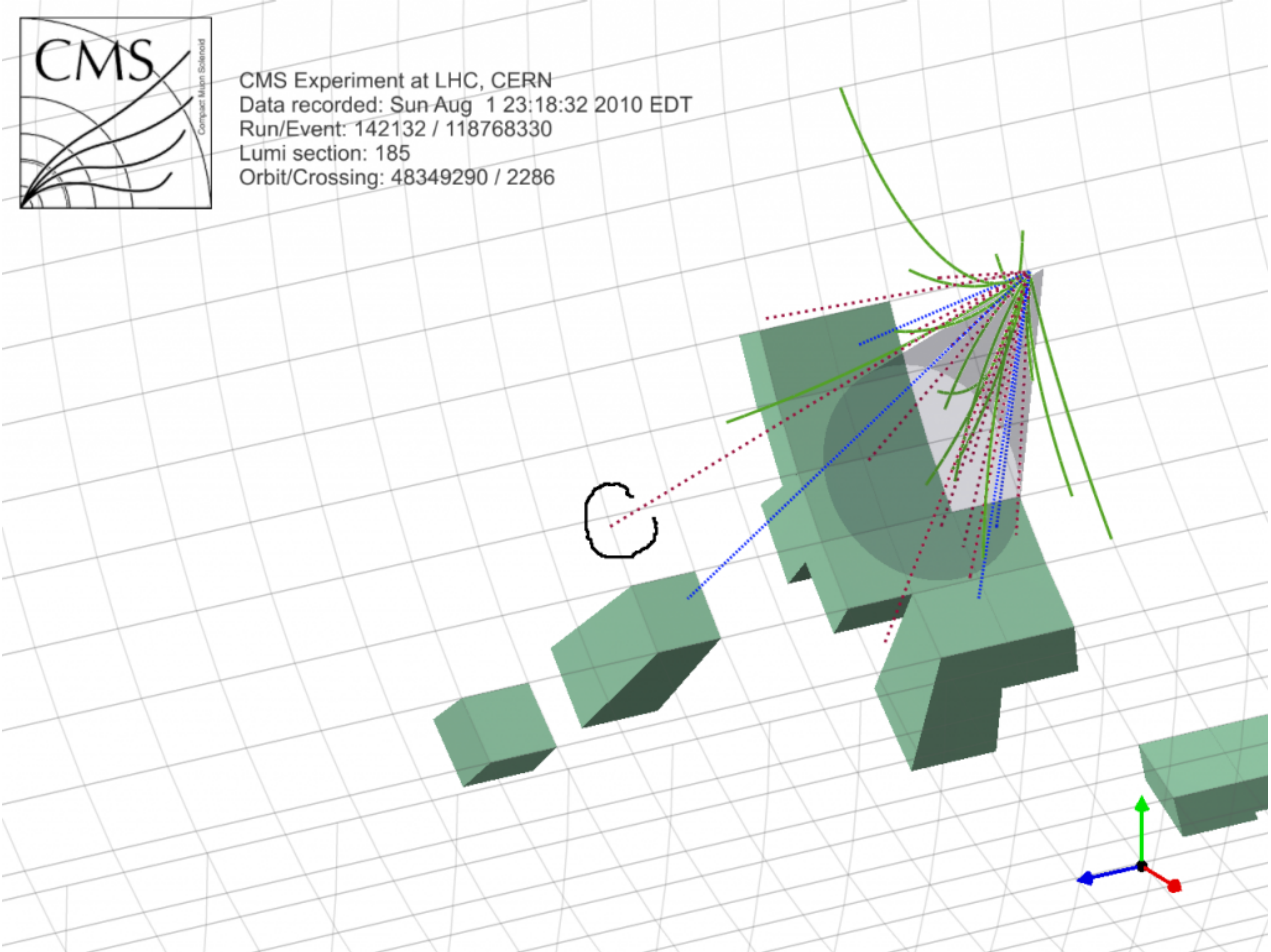
...photon candidates...



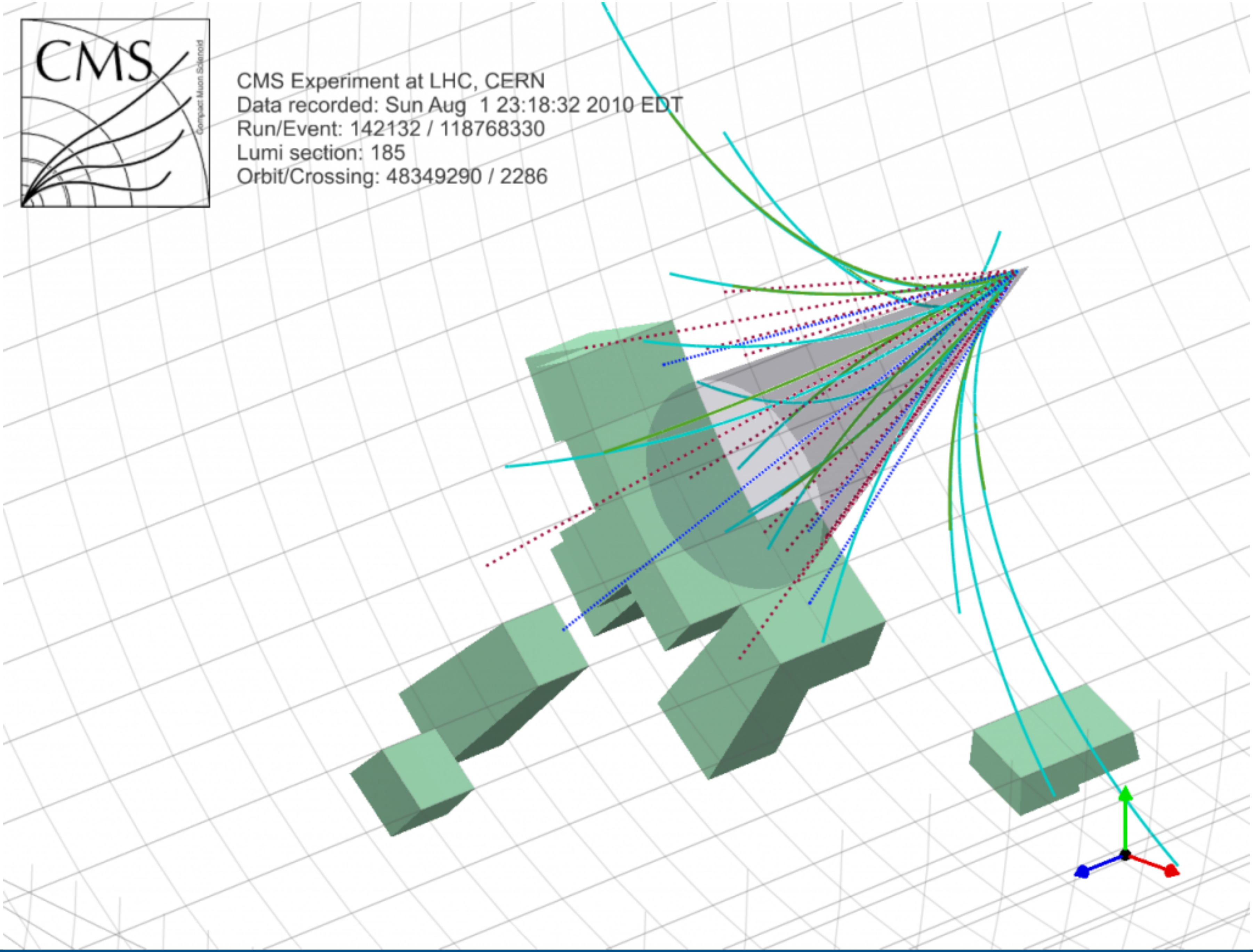
...neutral hadrons...



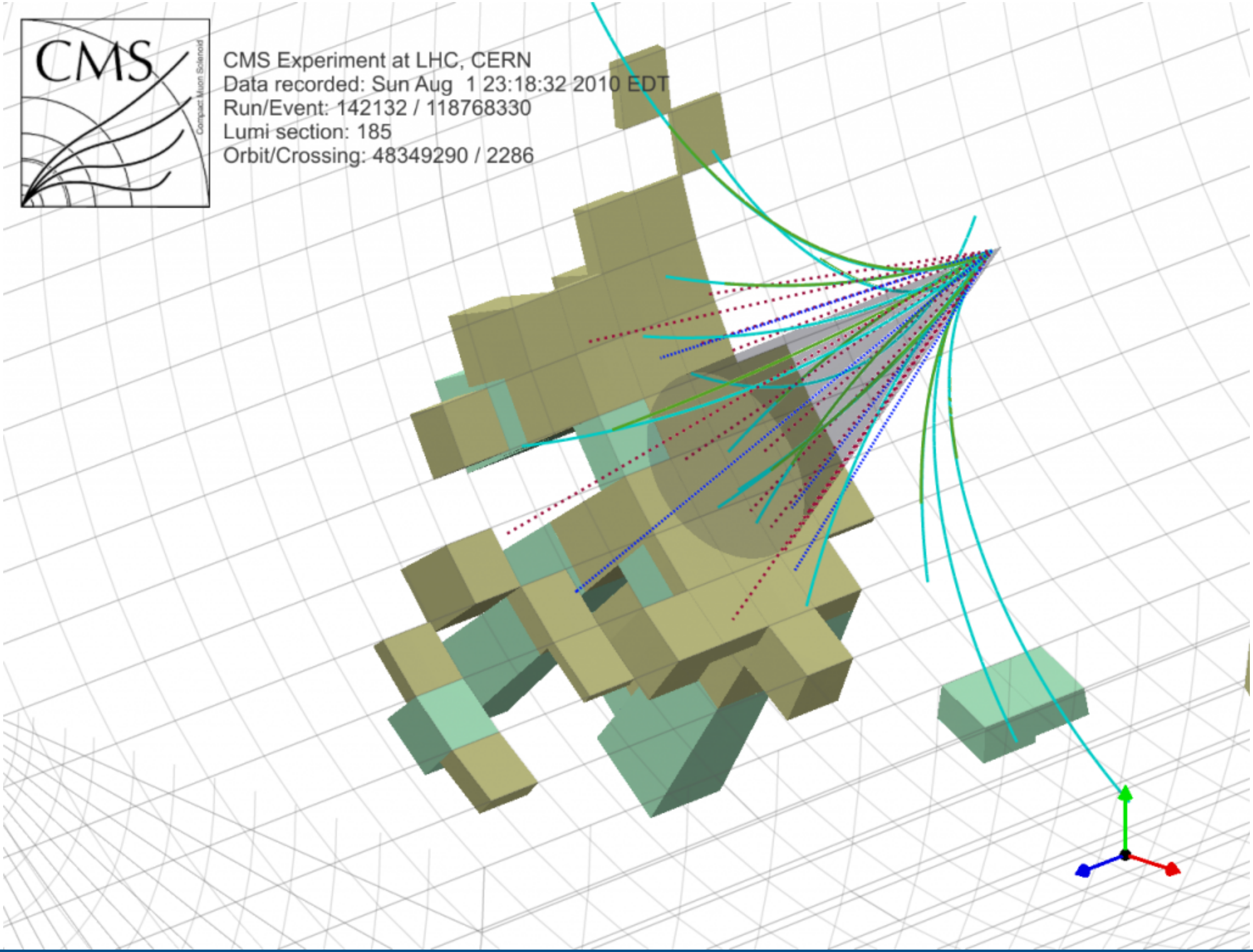
...HCAL deposits...



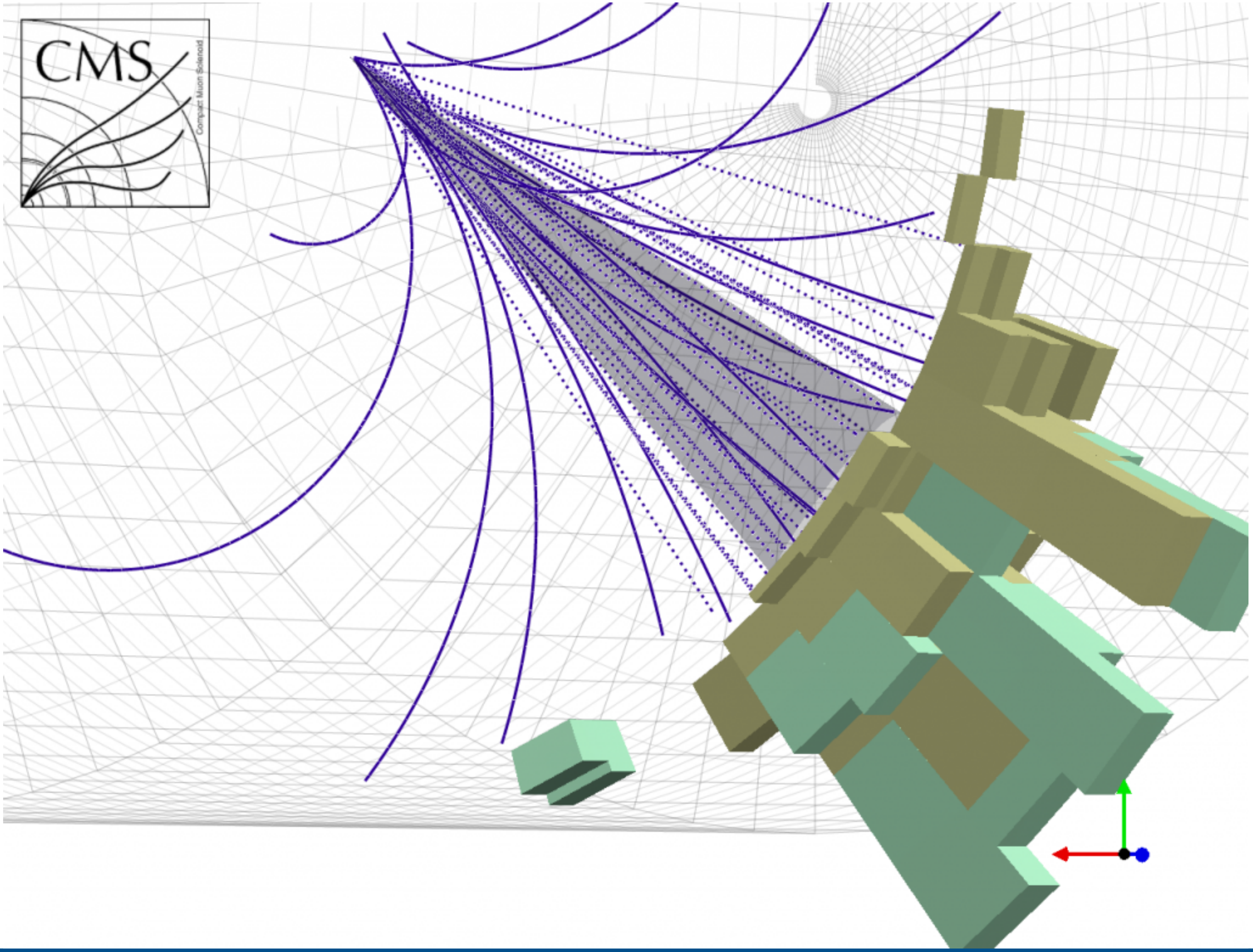
...charged hadrons=tracks...



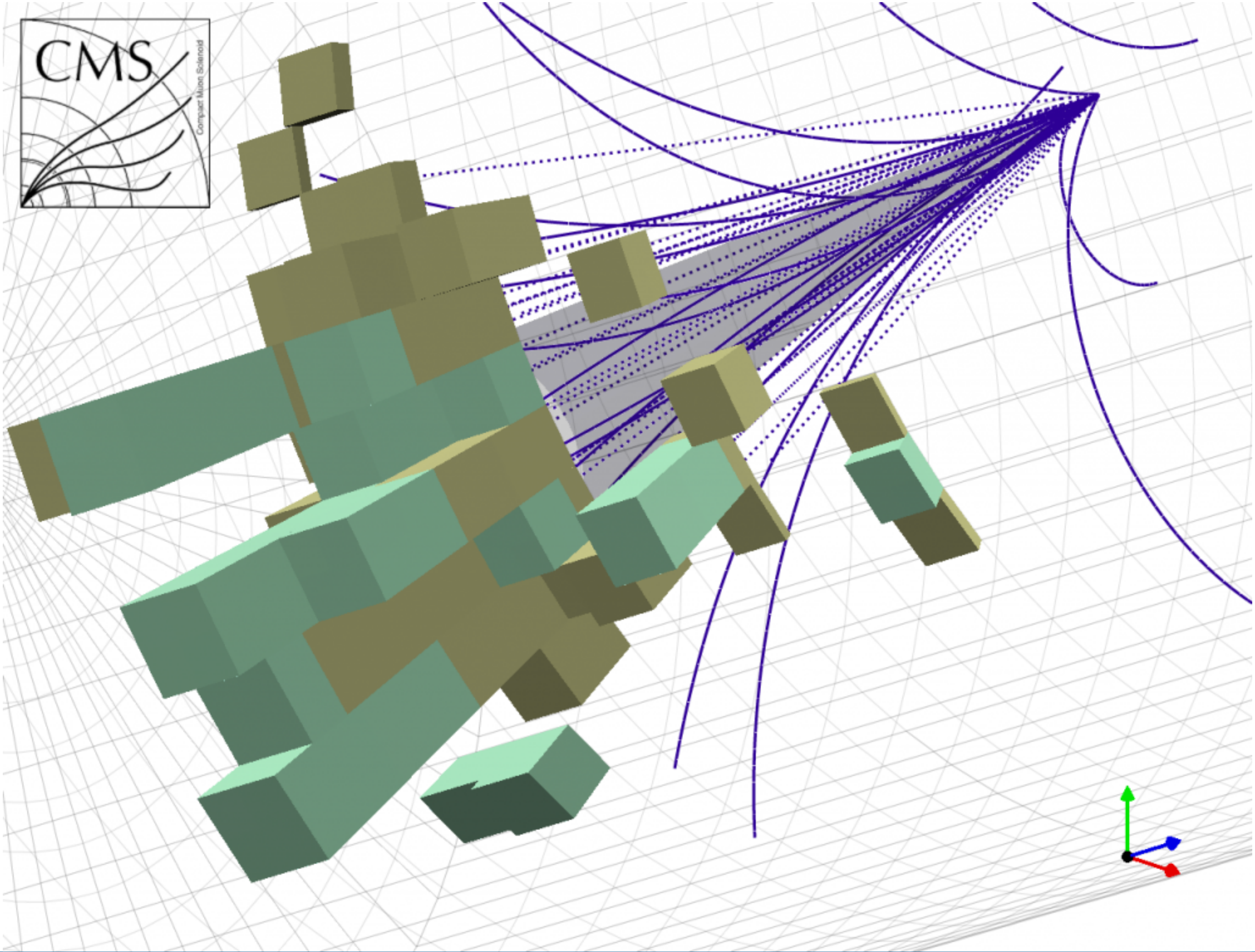
Jet and all its components



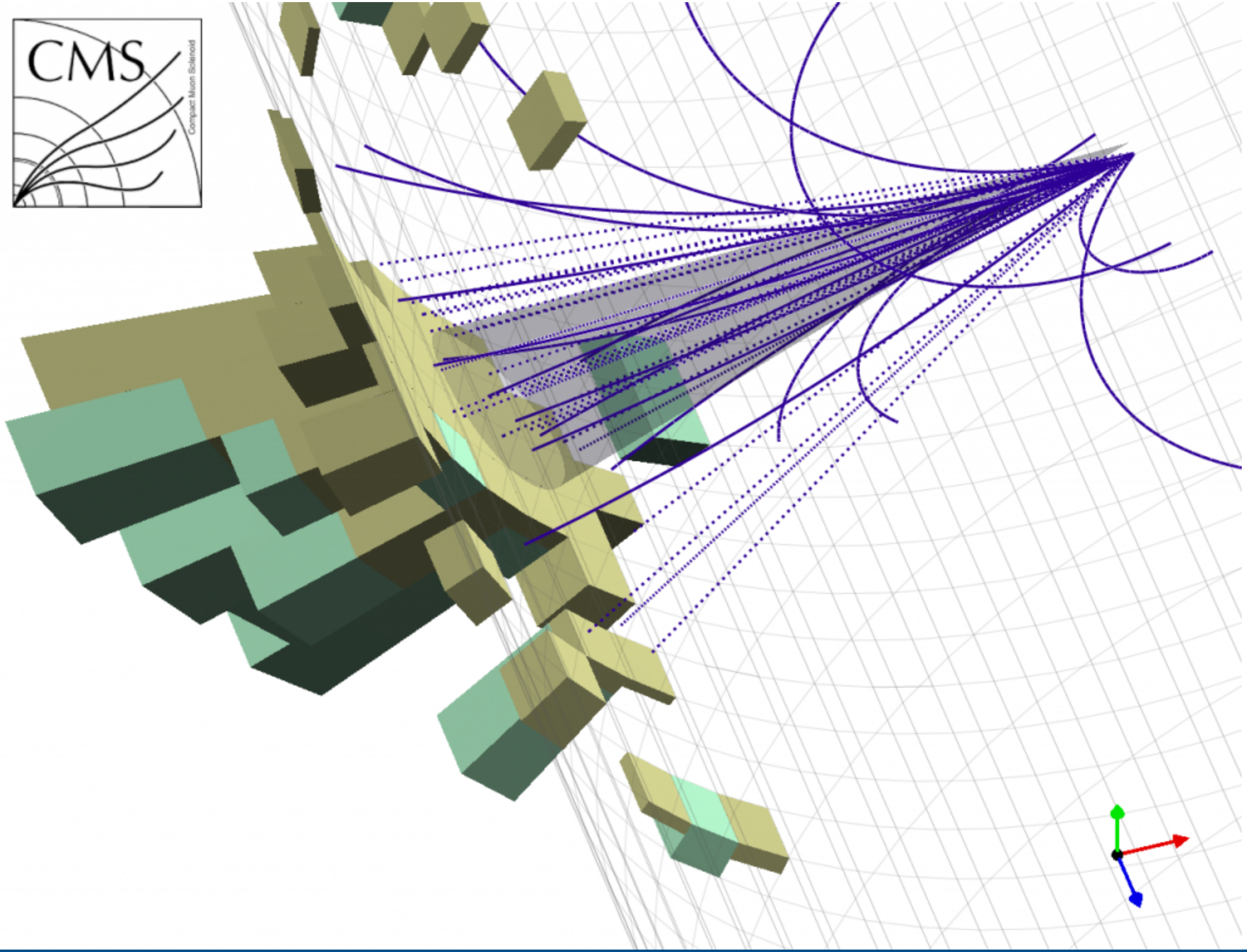
Jet’s calorimeter deposits



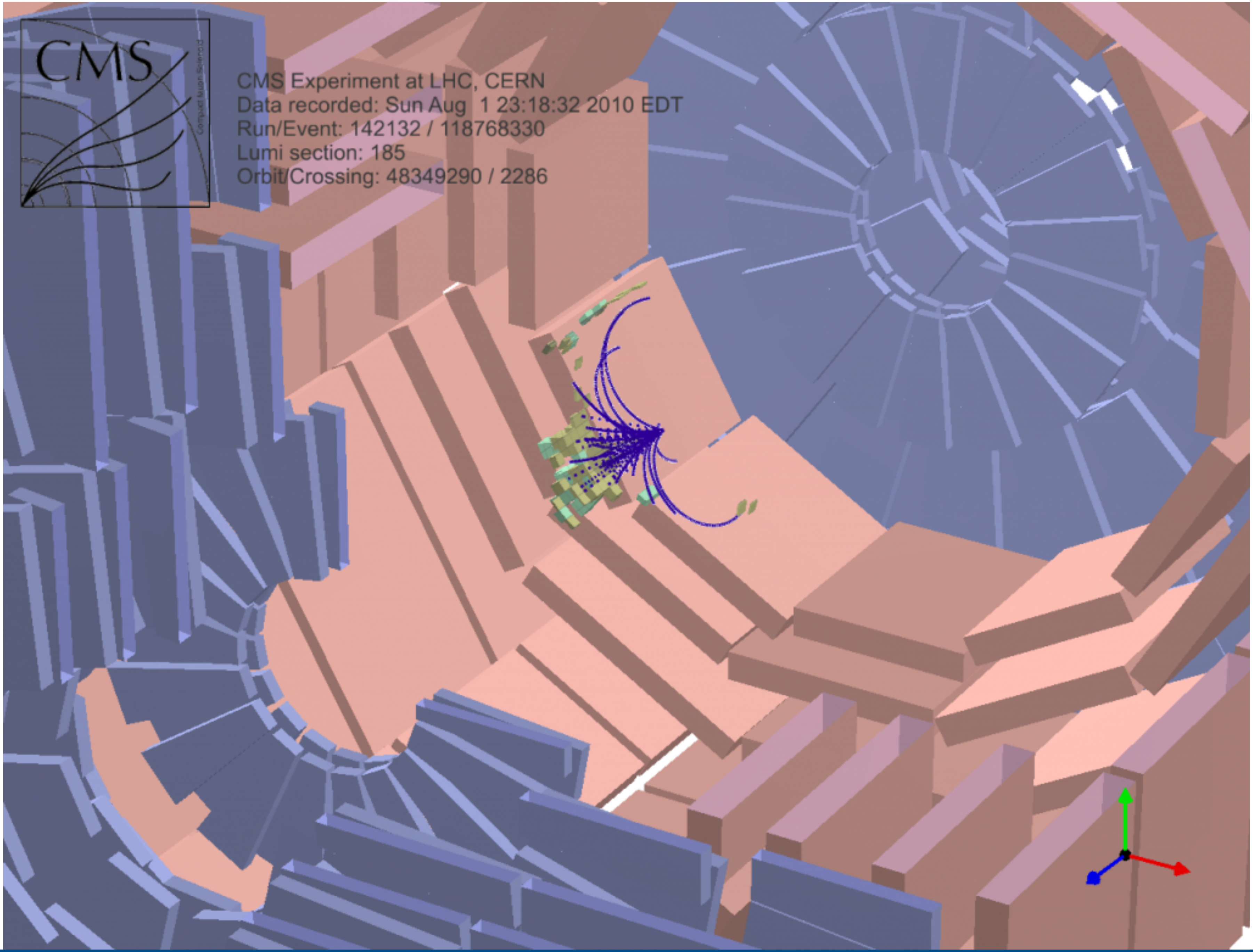
Rotated view



One more



Jet in CMS context



End of the tour

- **Now, get me back**