# Validation of Geant4 hadronic physics with LHC data

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# Outline

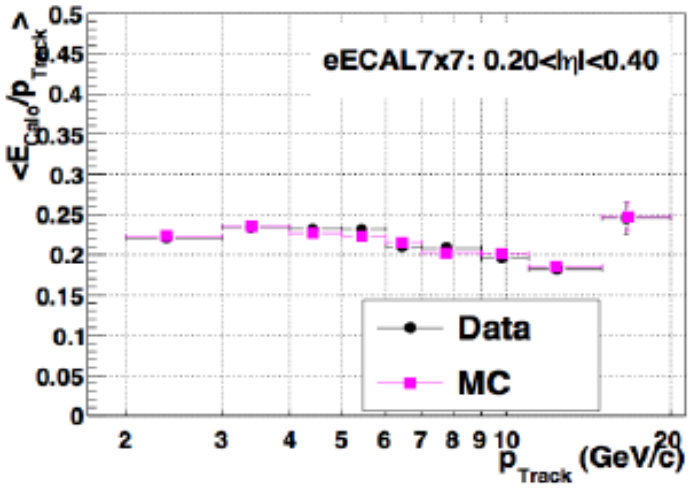
- Energy response
- Energy resolution
- Longitudinal shower profile
- Lateral shower profile
- Antiprotons
- Summary & conclusions

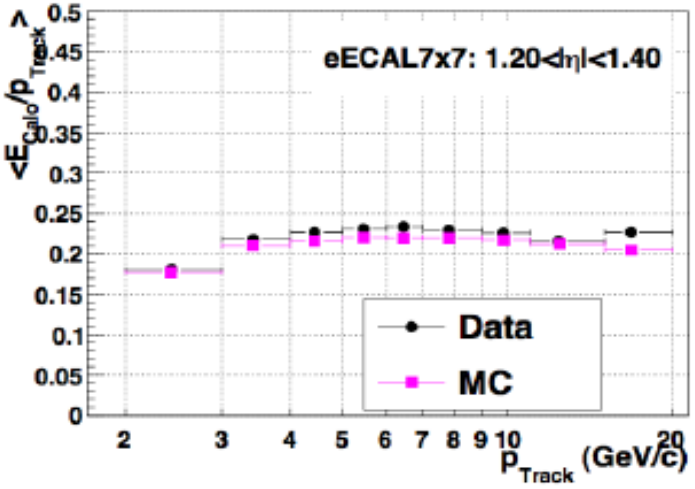
# Energy response

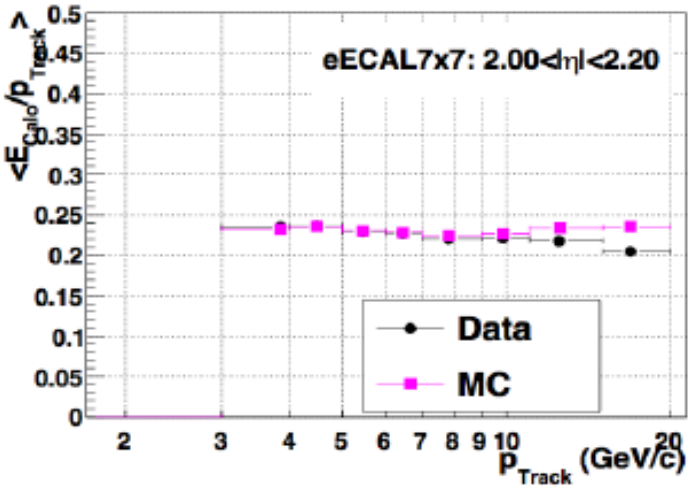
- Very important for the jet energy scale
- Geant4 **QGSP_BERT**, **FTFP_BERT**, and **QGSP_FTFP_BERT** describe the energy response in calorimeters reasonably well, **within few %**
- For CMS, **QGSP_FTFP_BERT** (default in 2011) gives the best agreement with test-beam data, and it is smoother than QGSP_BERT (default until 2010)
- For ATLAS, **QGSP_BERT** (default) gives the best agreement with test-beam data, with **few % higher response** especially in the **TileCal** . Fritiof-based variants (QGSP_FTFP_BERT and FTFP_BERT) are smoother, but have an even higher response

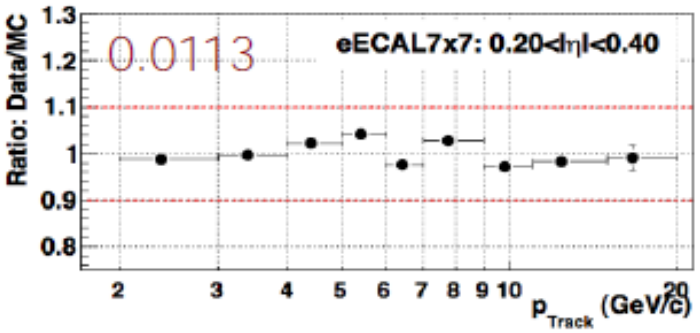
# CMS E/p collision data: ECAL

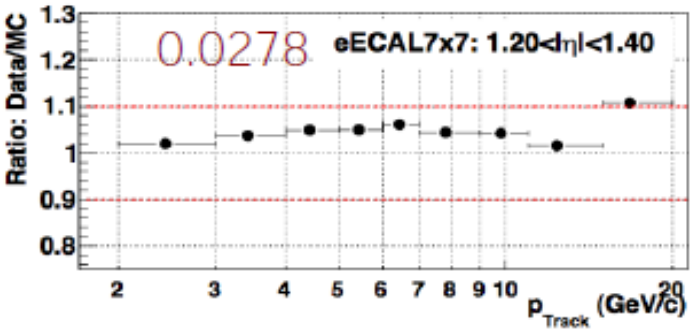
Measure energy in a 7x7 crystal matrix around the impact point.

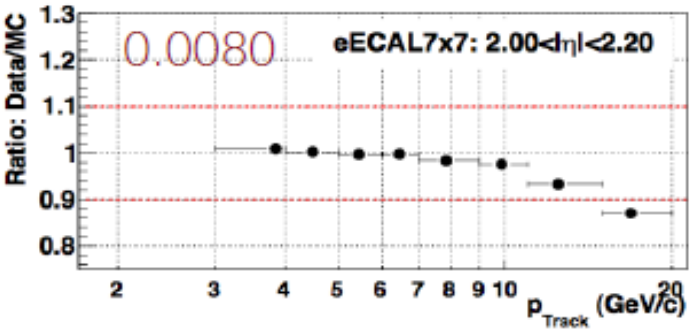


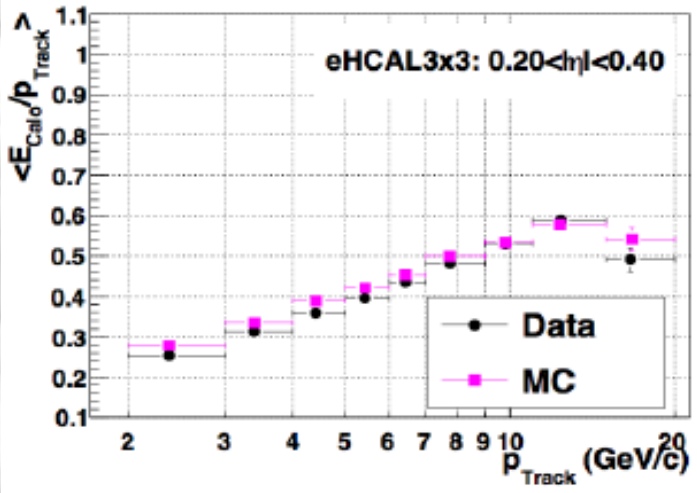



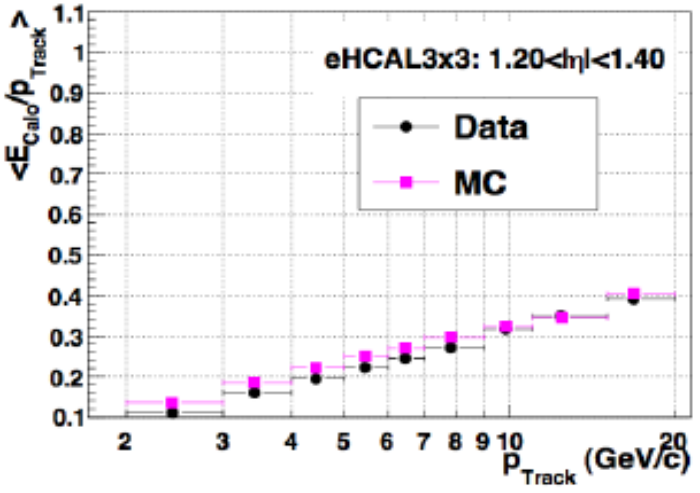



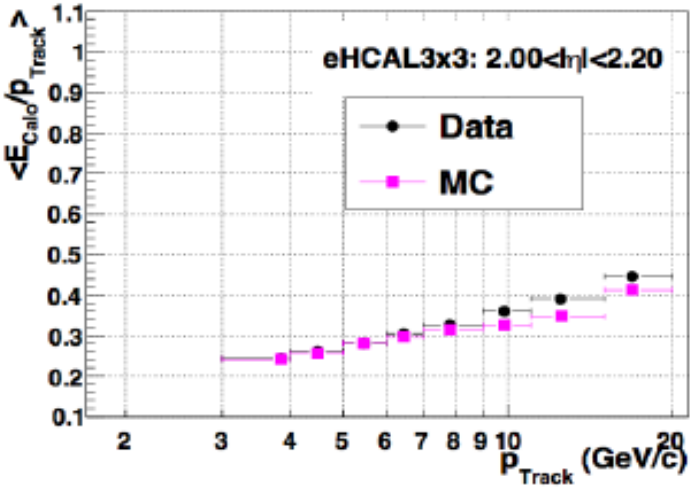

Data and MC are in good agreement in barrel and in endcap.

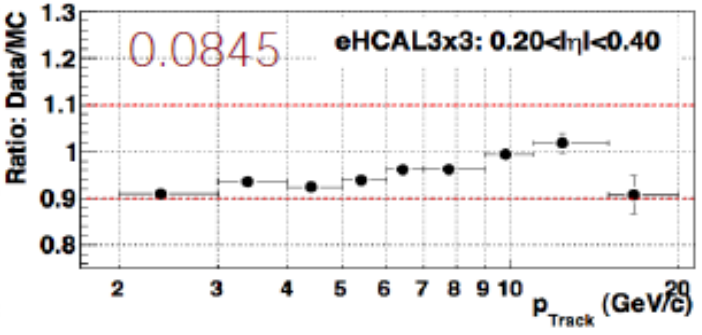
# CMS E/p collision data: HCAL

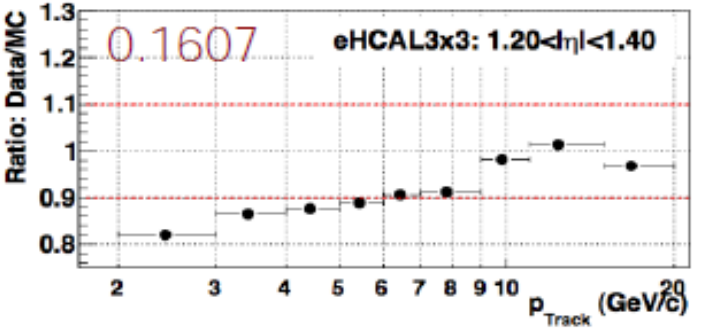
Measure energy in a 3x3 matrix around the impact point.

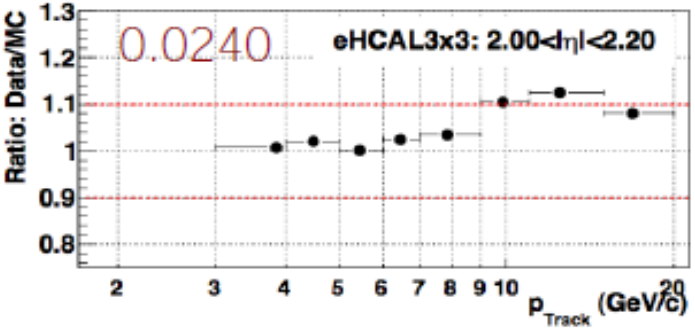


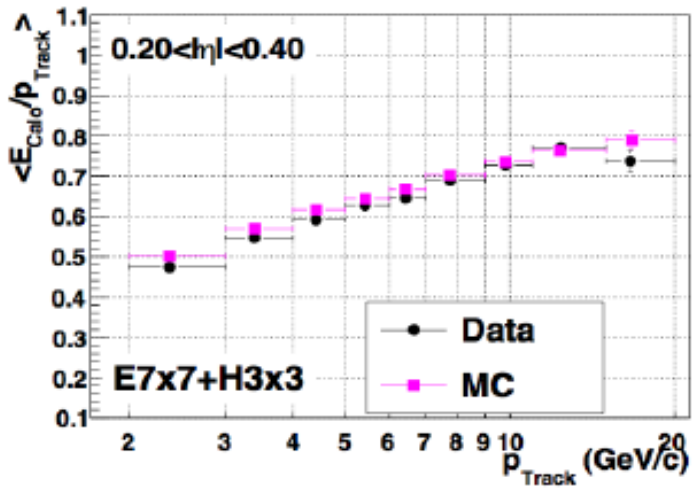



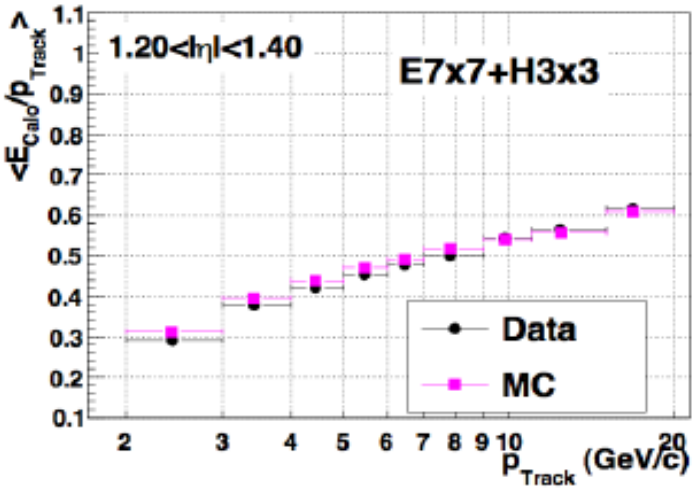



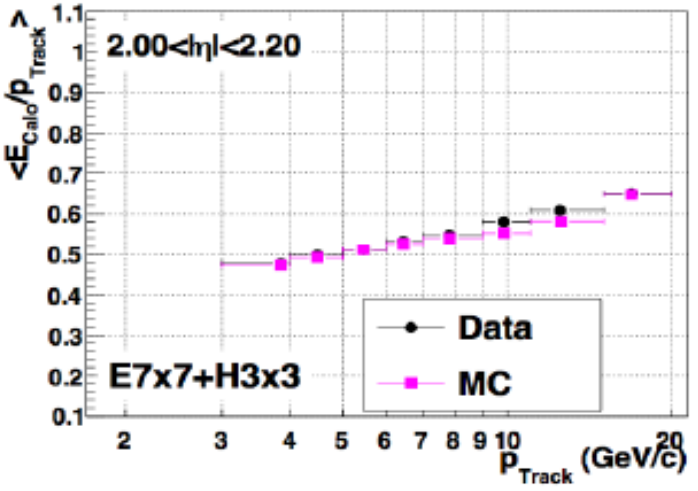



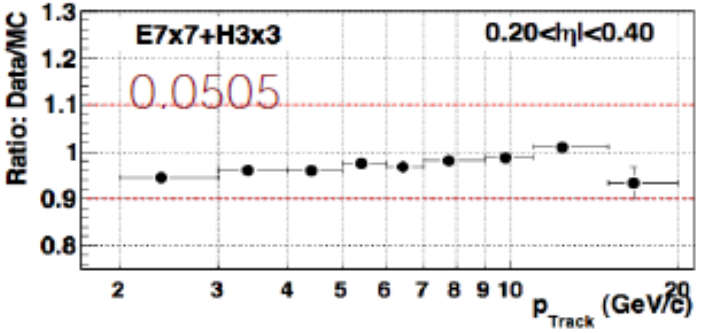
# CMS E/p collision data: ECAL+HCAL

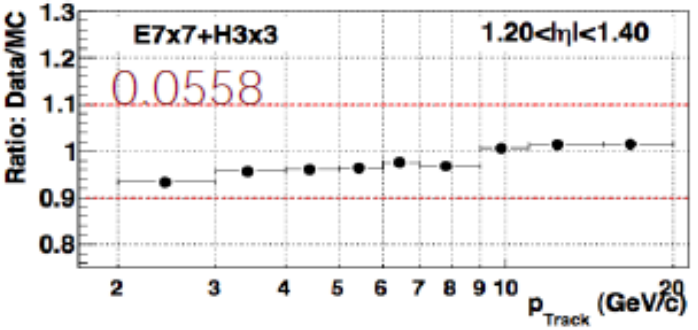
Energy measured in (E7x7+H3x3)

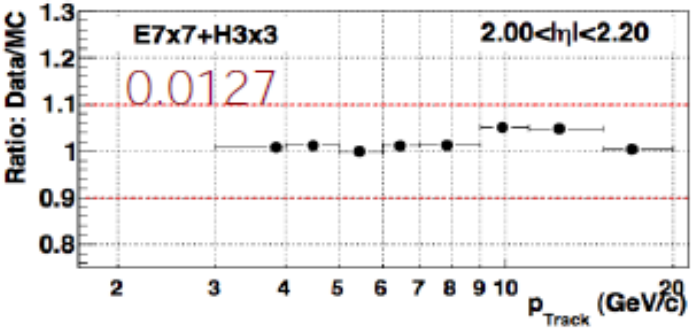


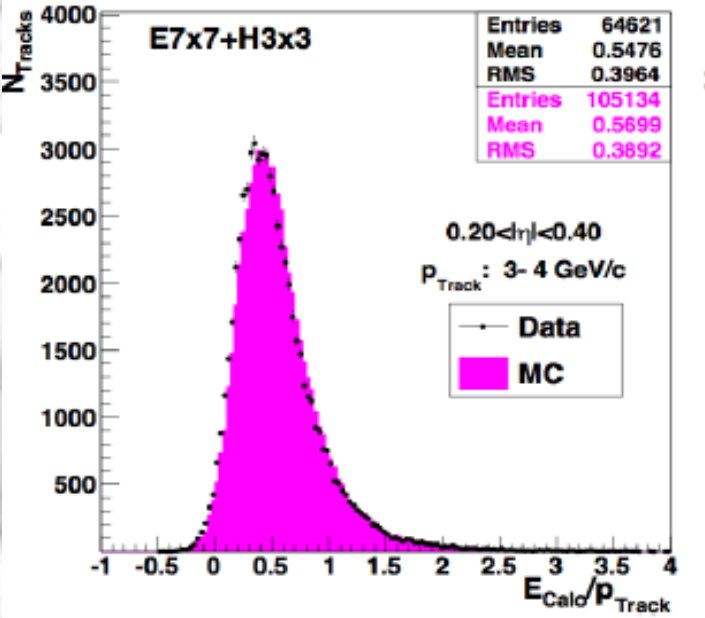



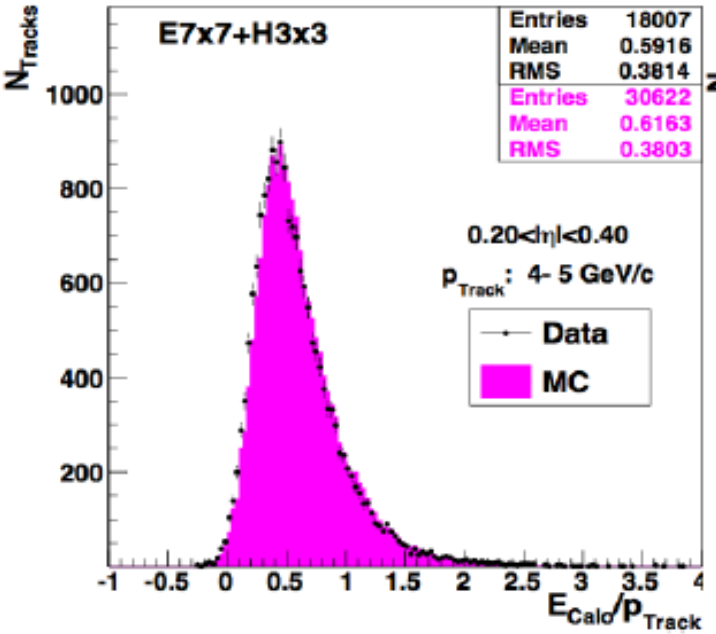



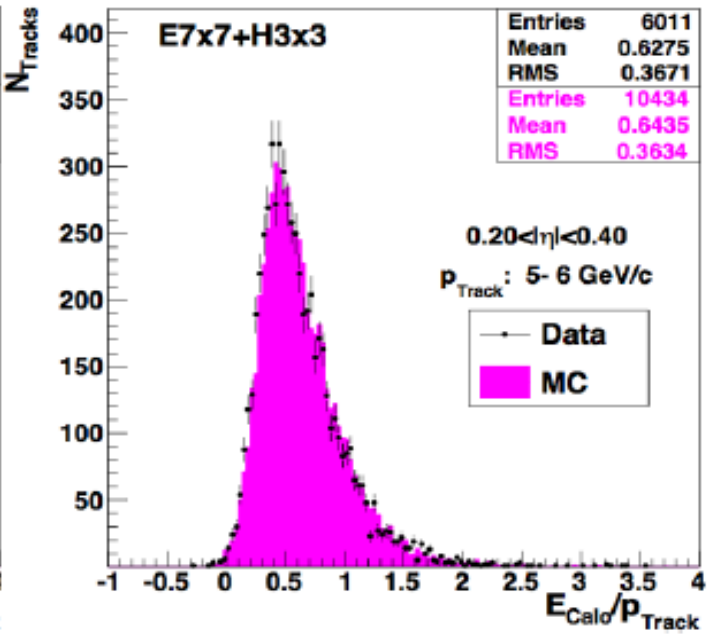



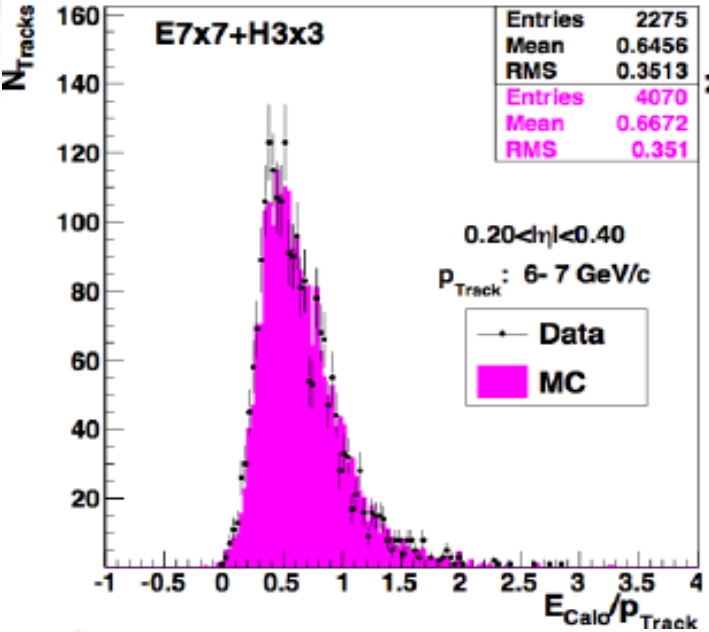



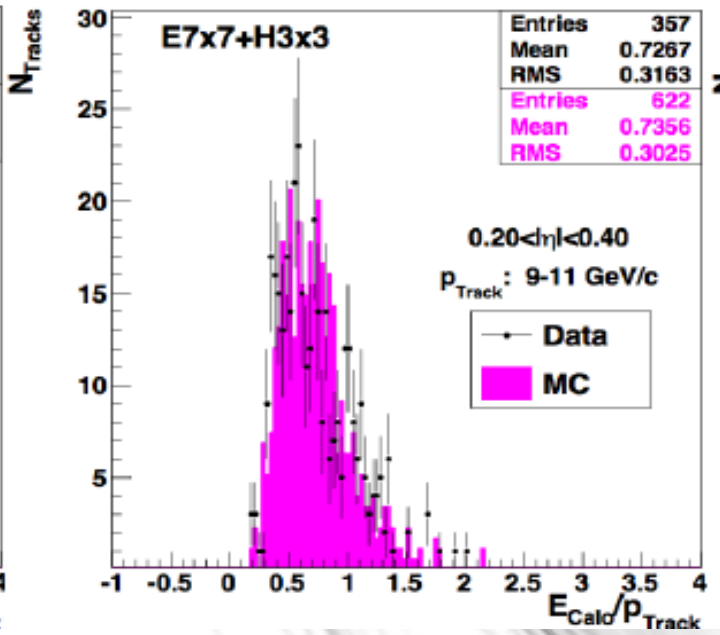
# CMS E/p collision data

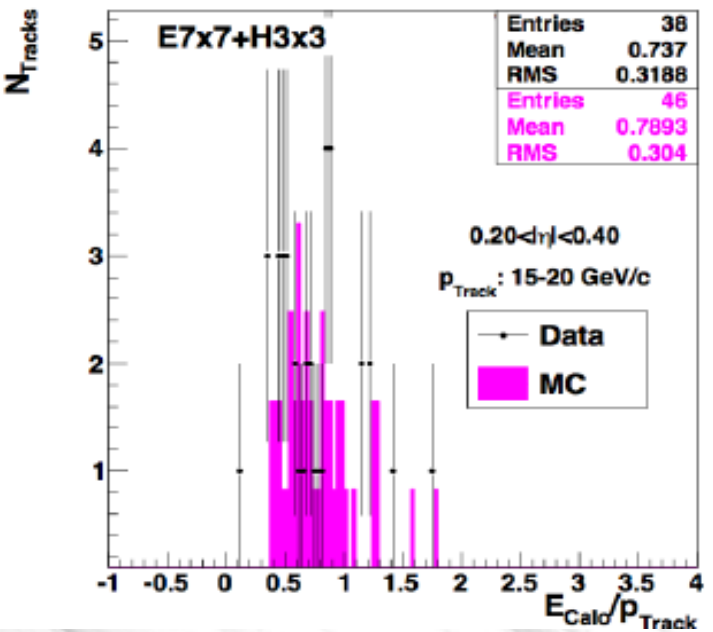


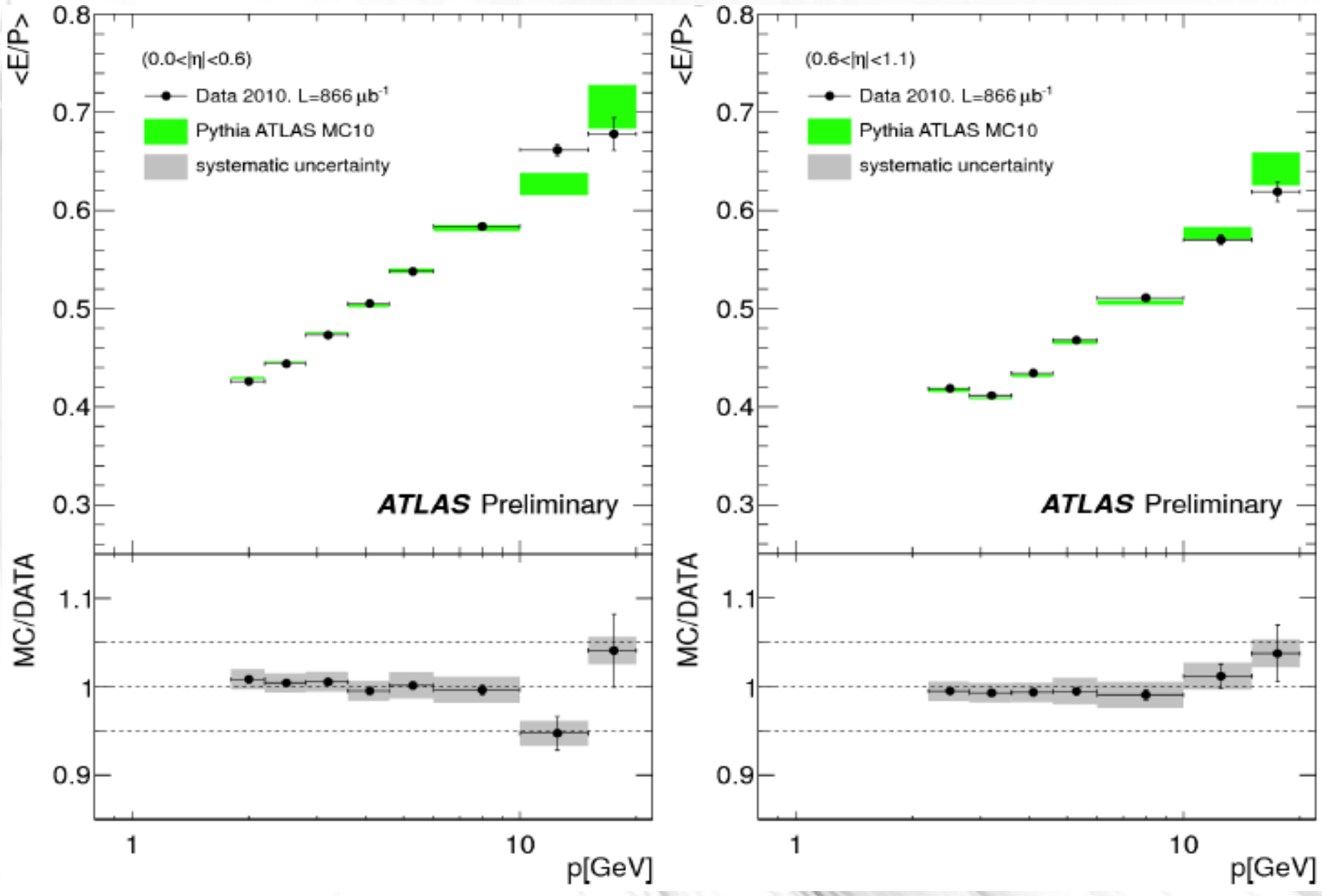



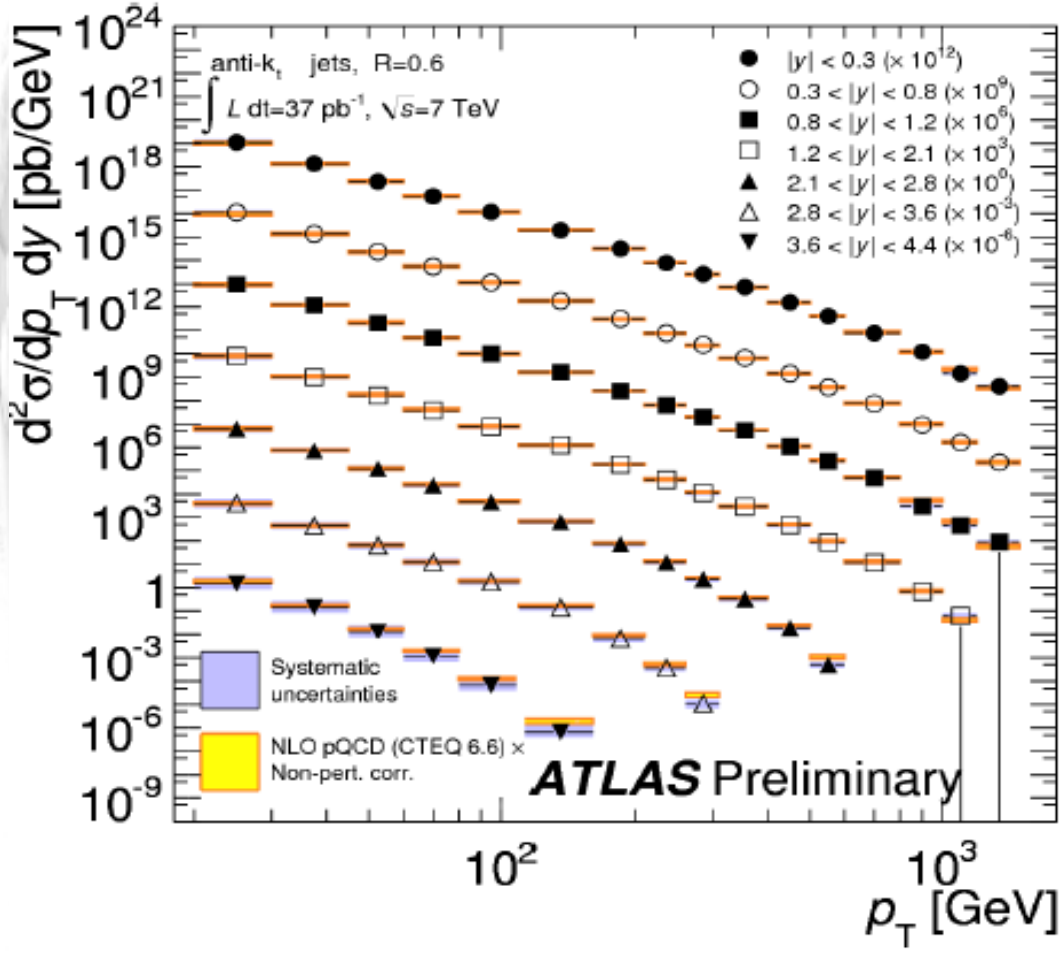



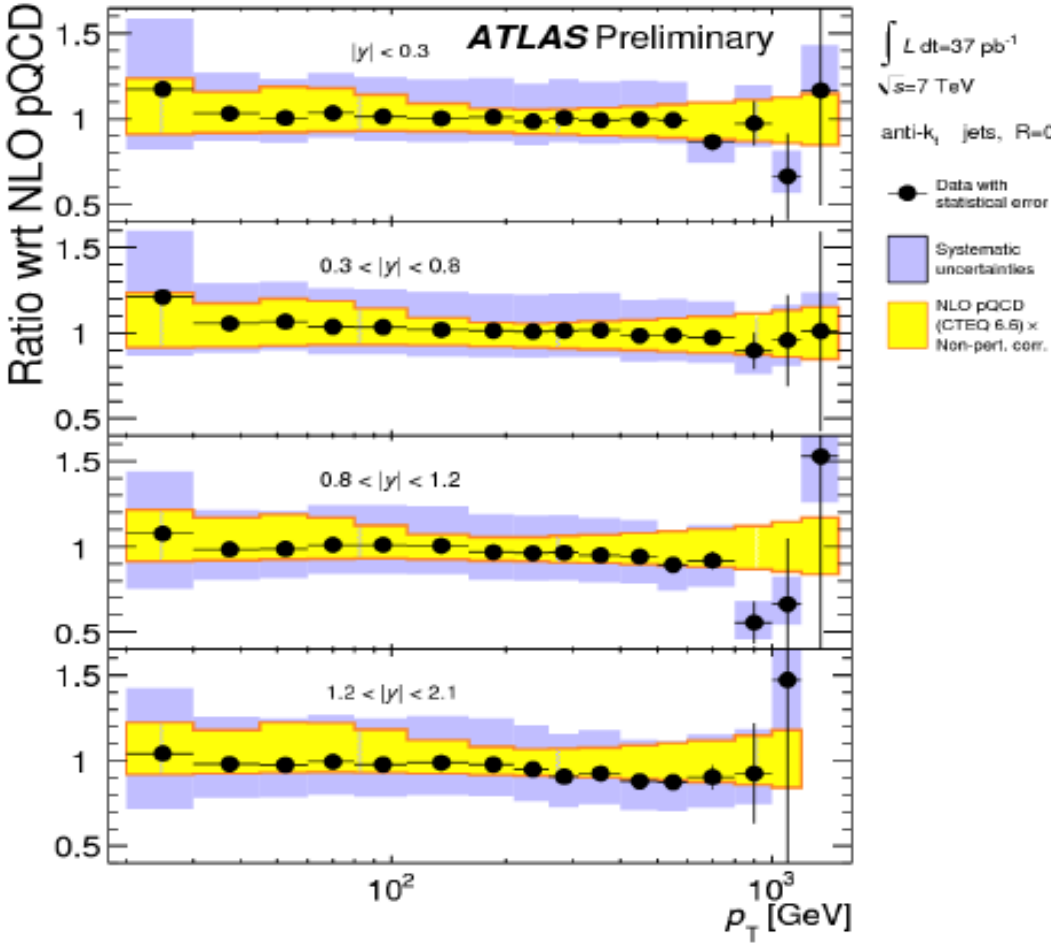



# ATLAS E/p collision data



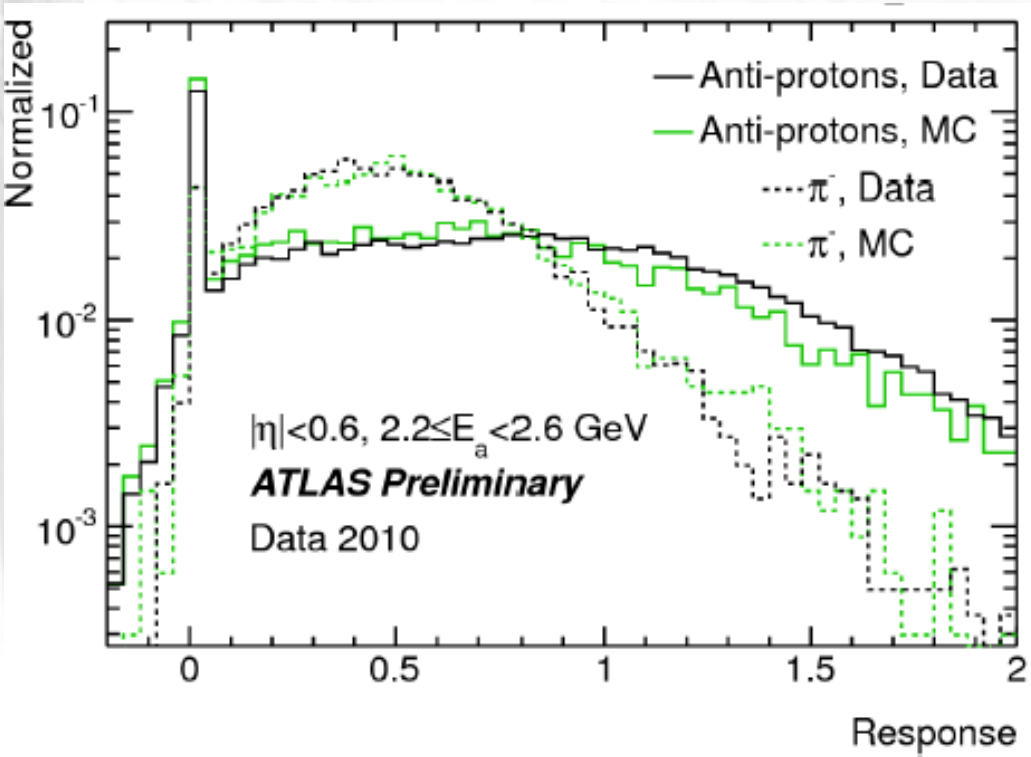
# ATLAS collision data: inclusive jets

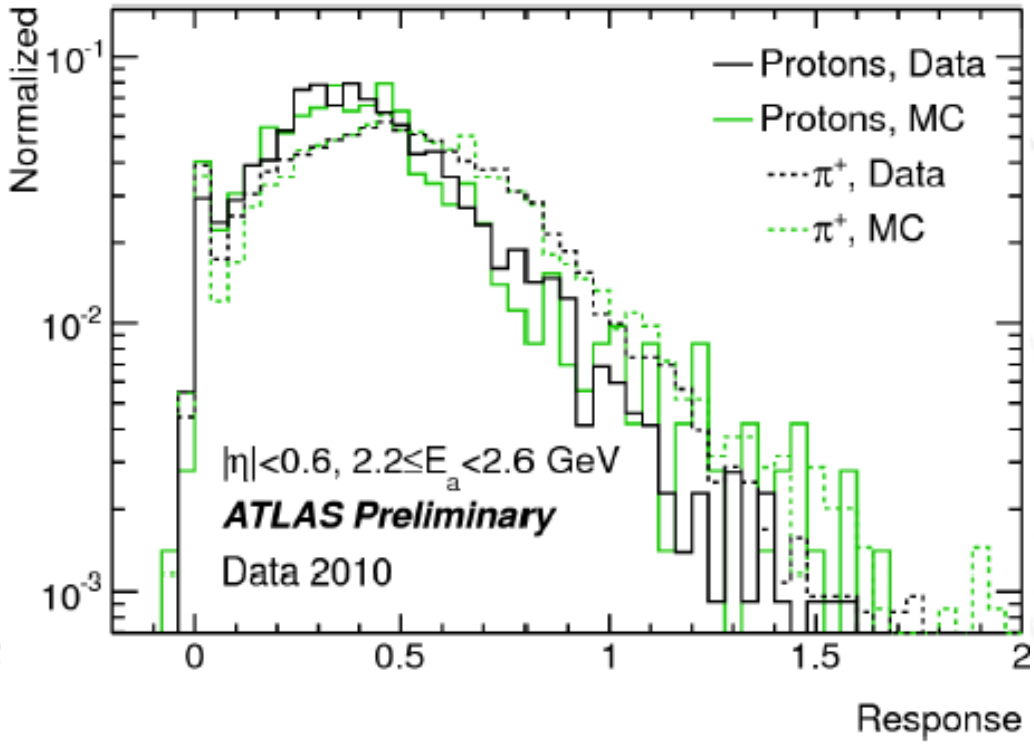


# ATLAS collision data

π+ and proton look similar, whereas
π- and antiproton look different



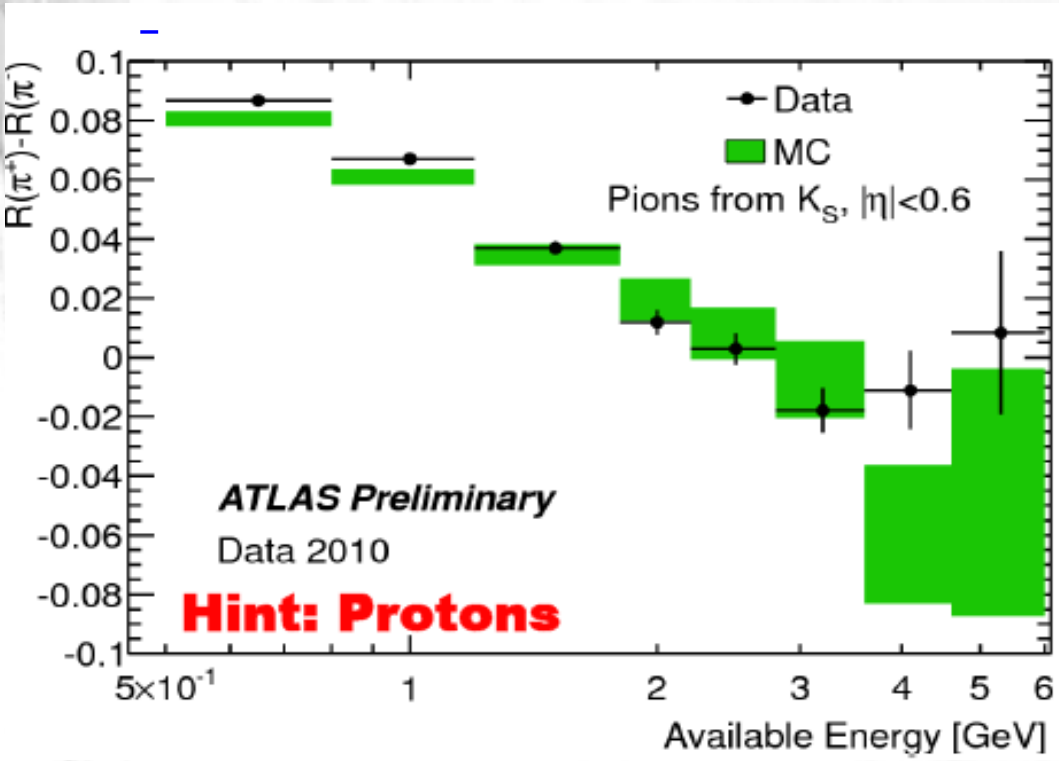
# ATLAS collision data

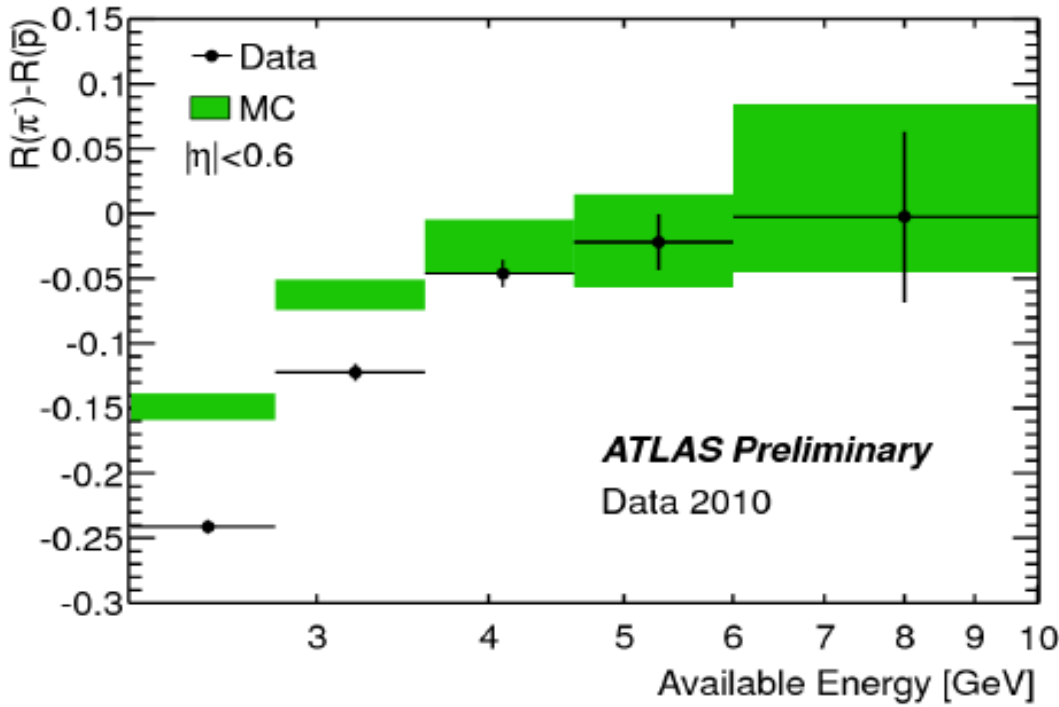
Use differences to avoid background issues:

π+ - π- and π- - p̄

π+ and π- are different

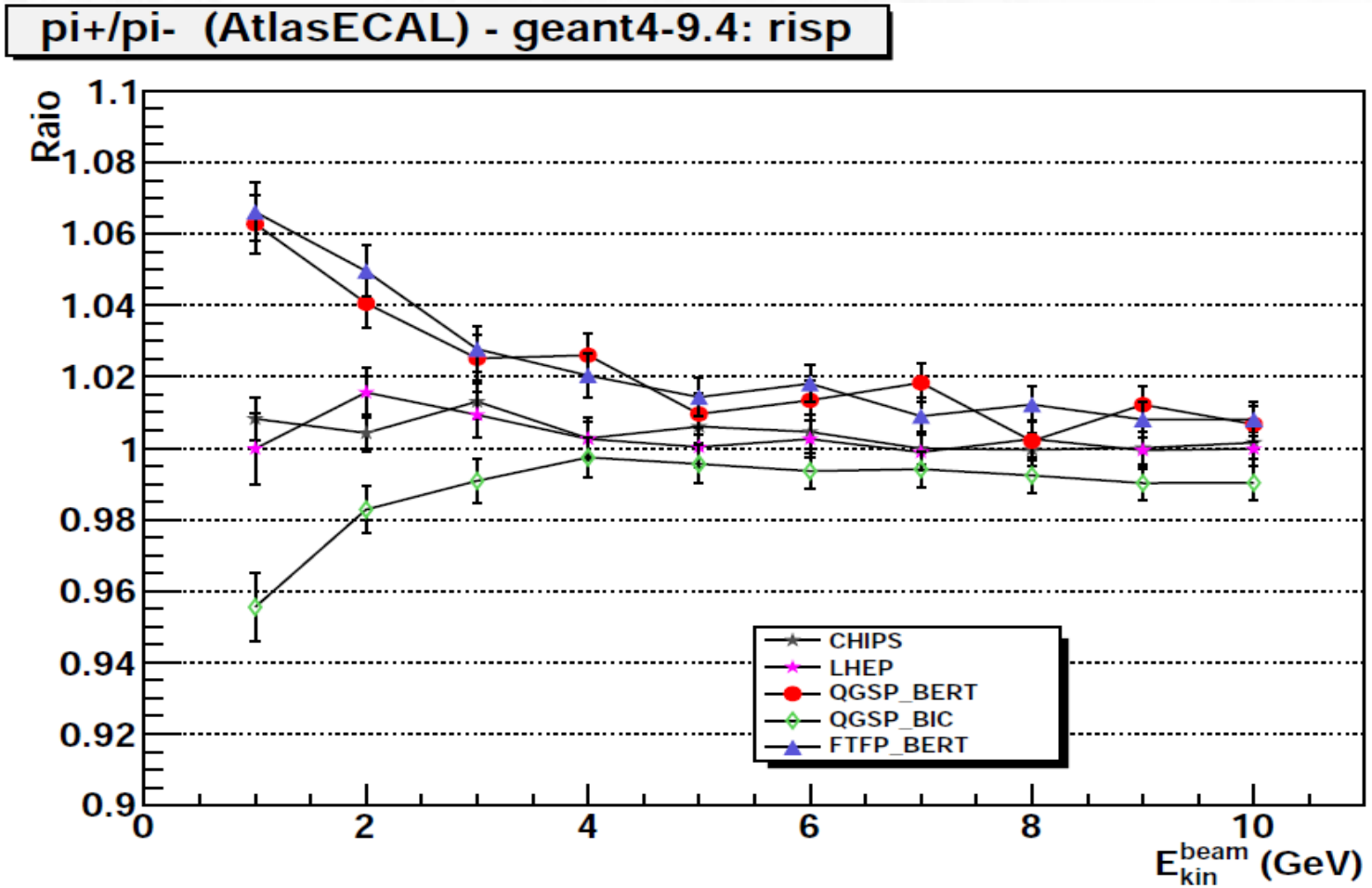
QGSP_BERT does poorly with p̄



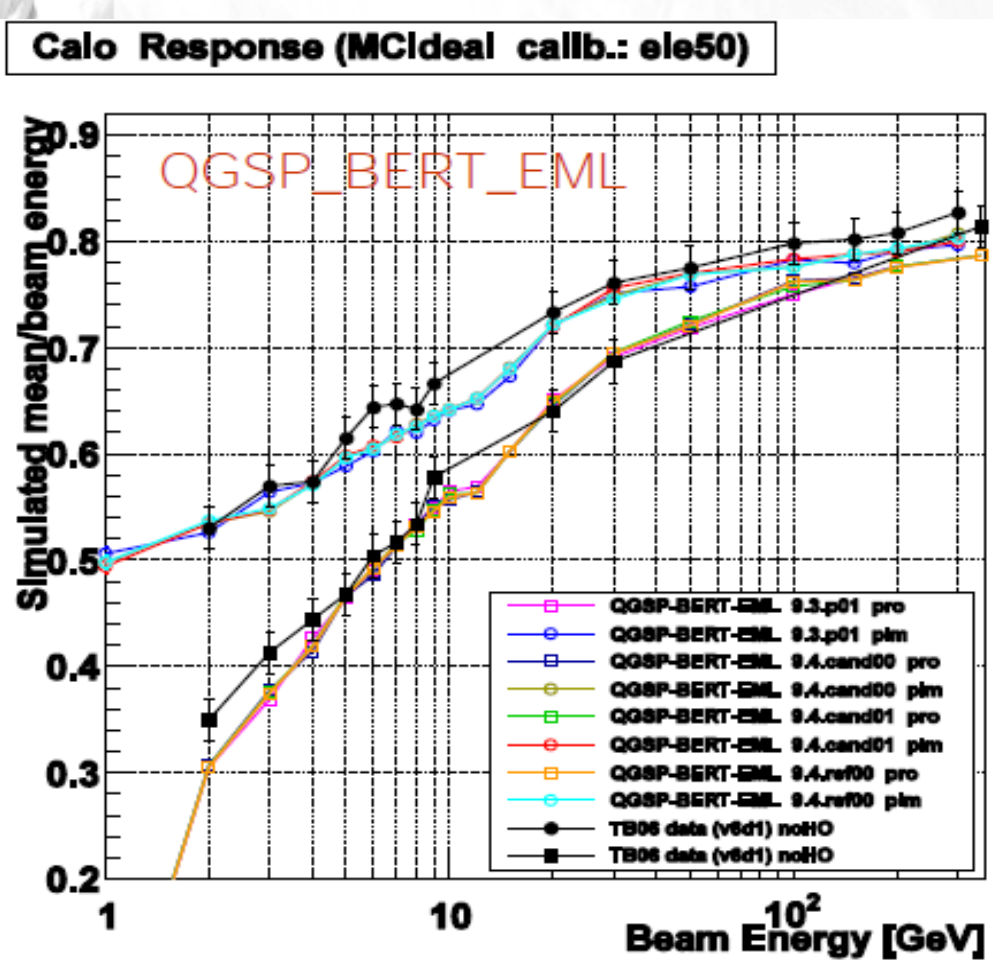



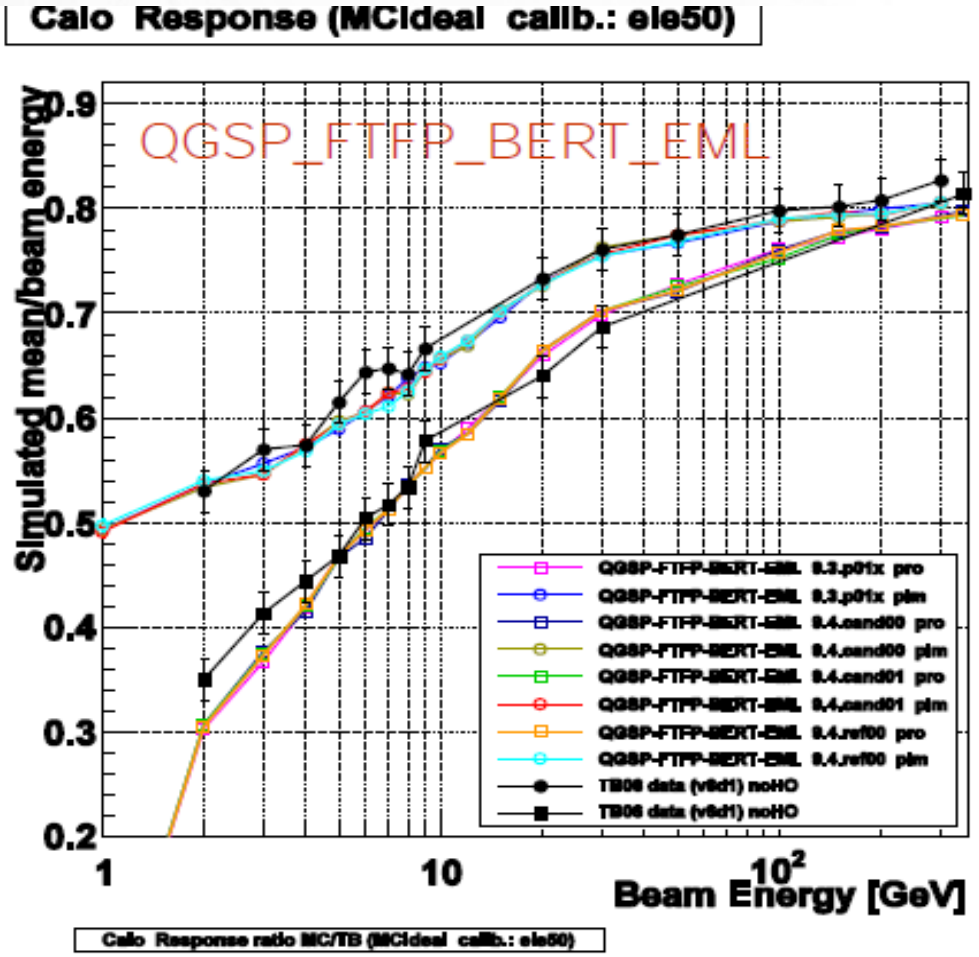
# Simplified calorimeter study: π+/π-

Difference between π+ and π- is better modeled by QGSP_BERT and FTFP_BERT

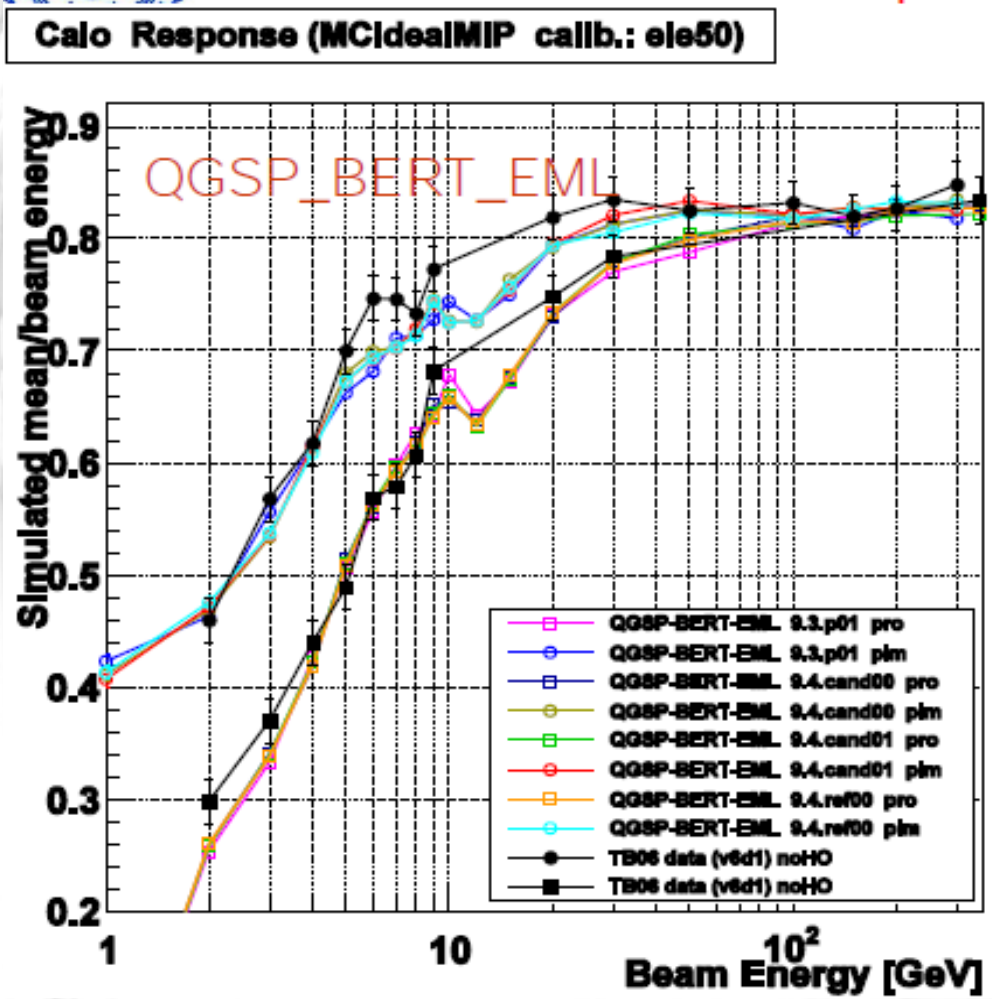


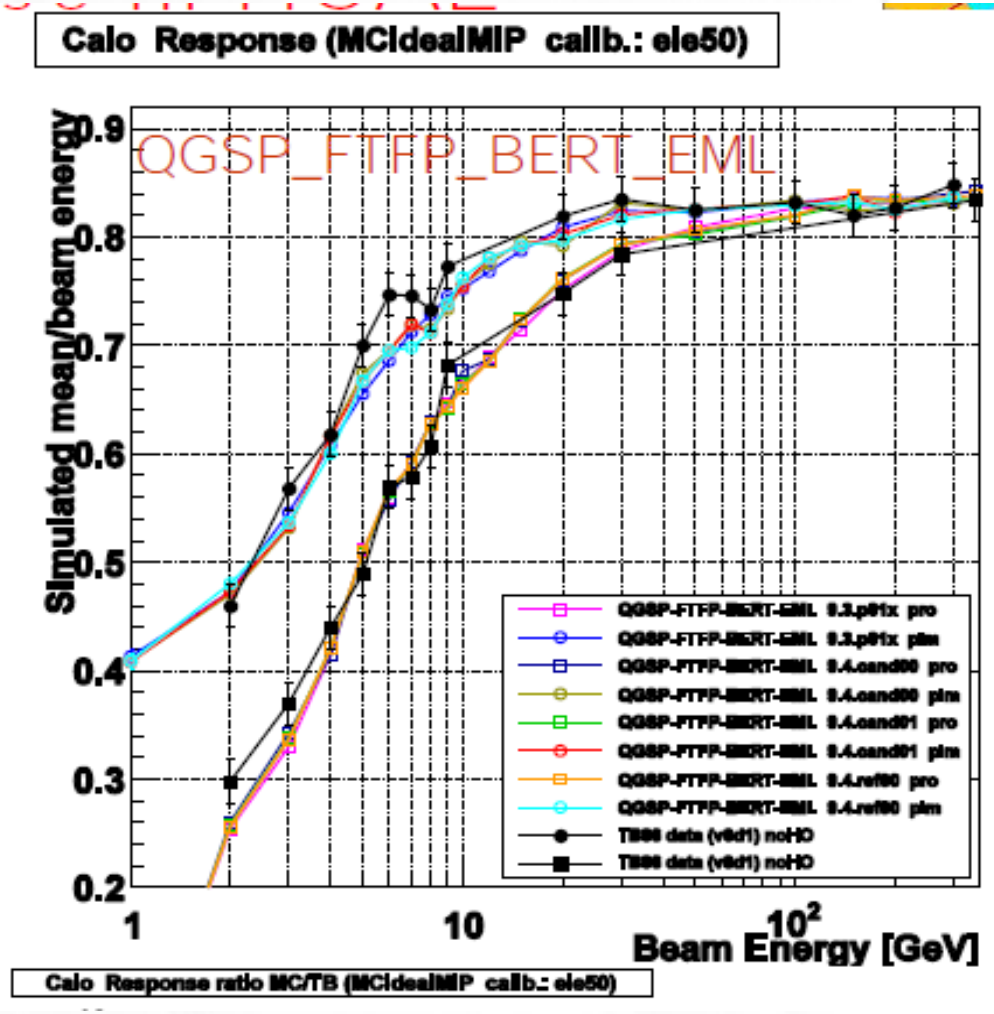
# CMS combined test-beam G4 9.4



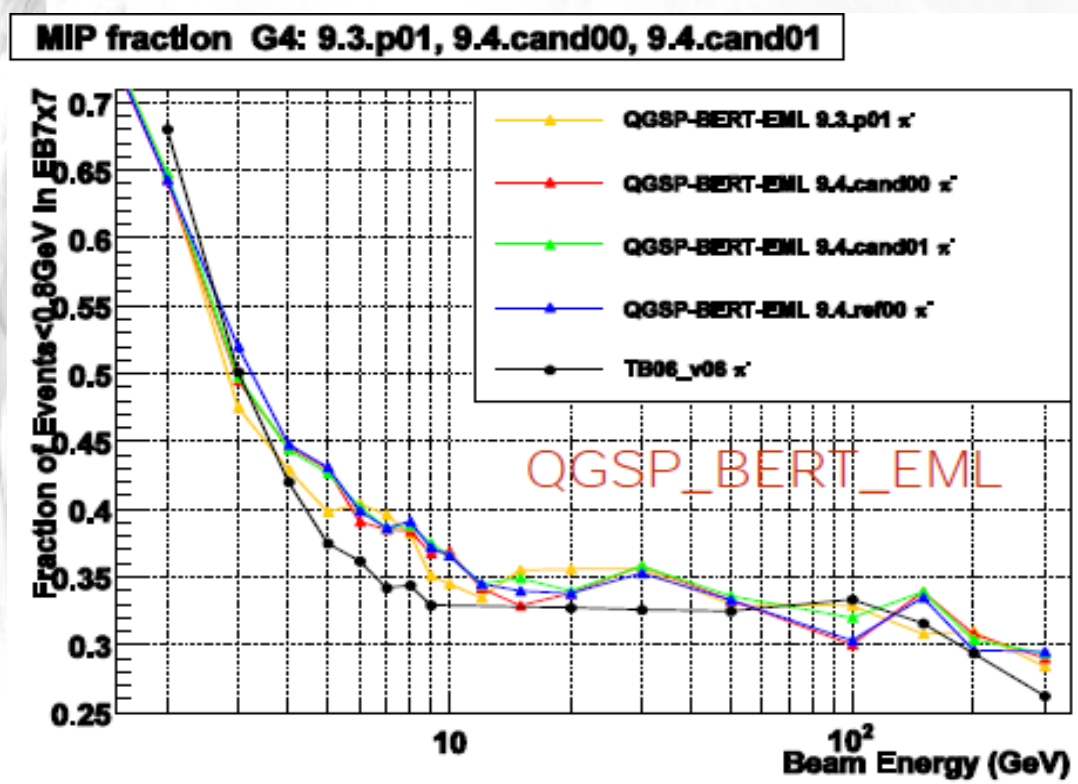



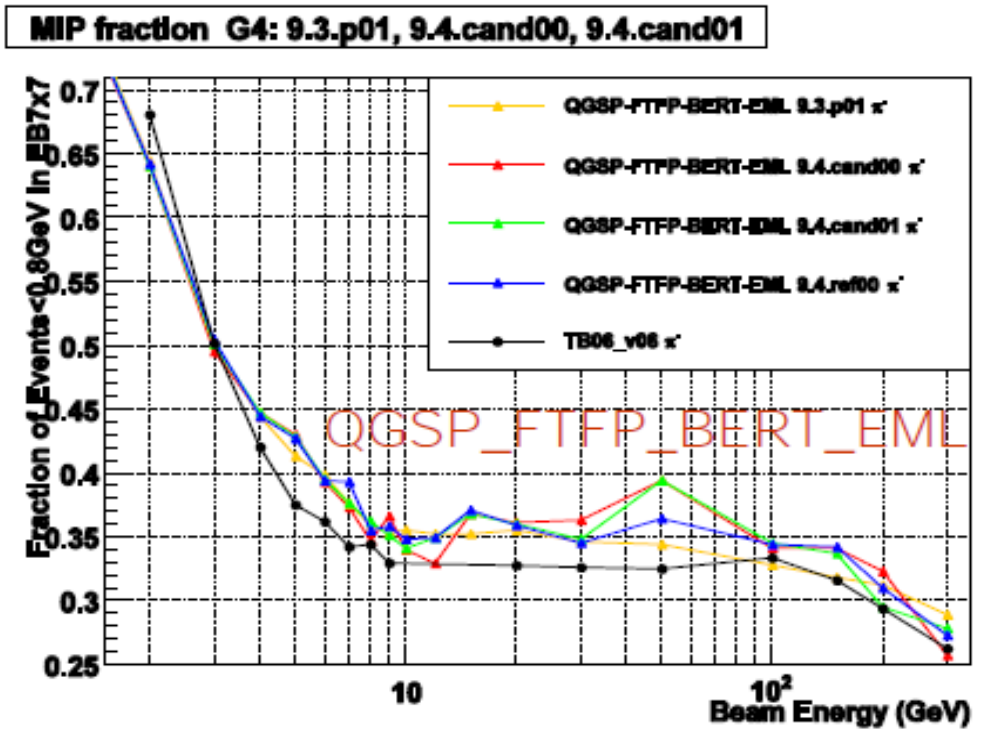
# CMS HCAL test-beam G4 9.4



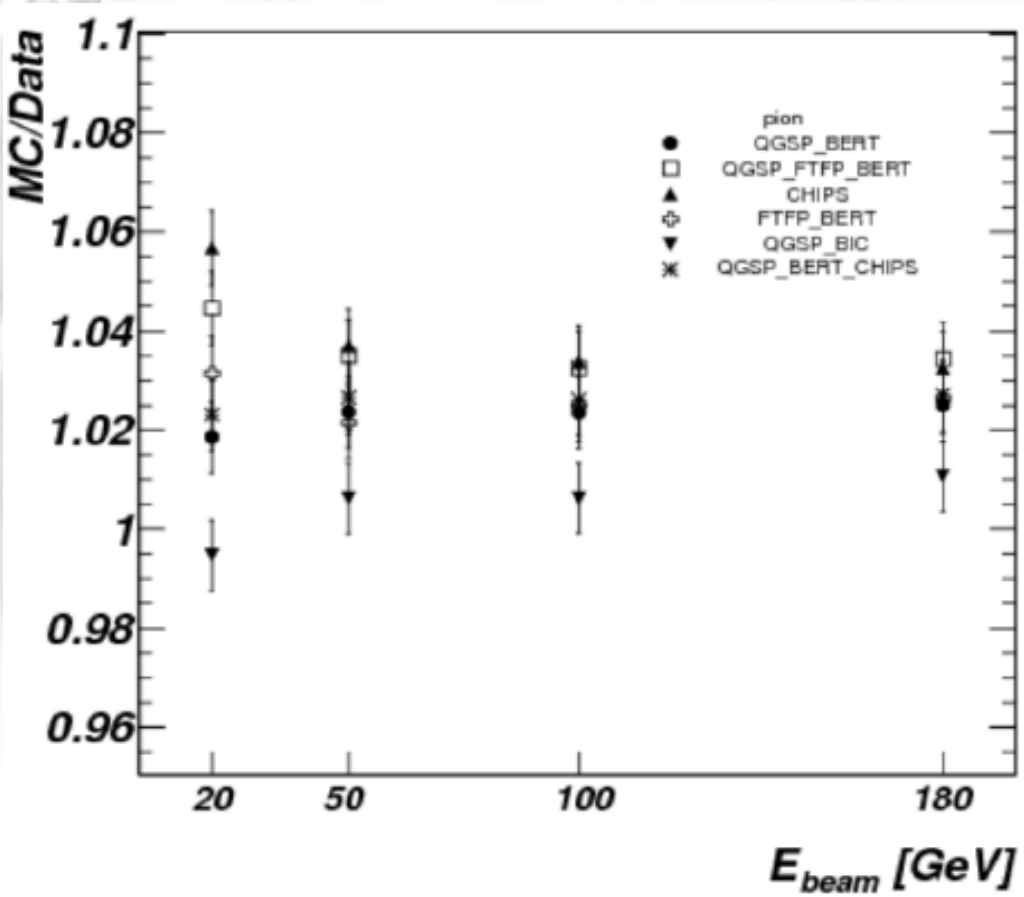



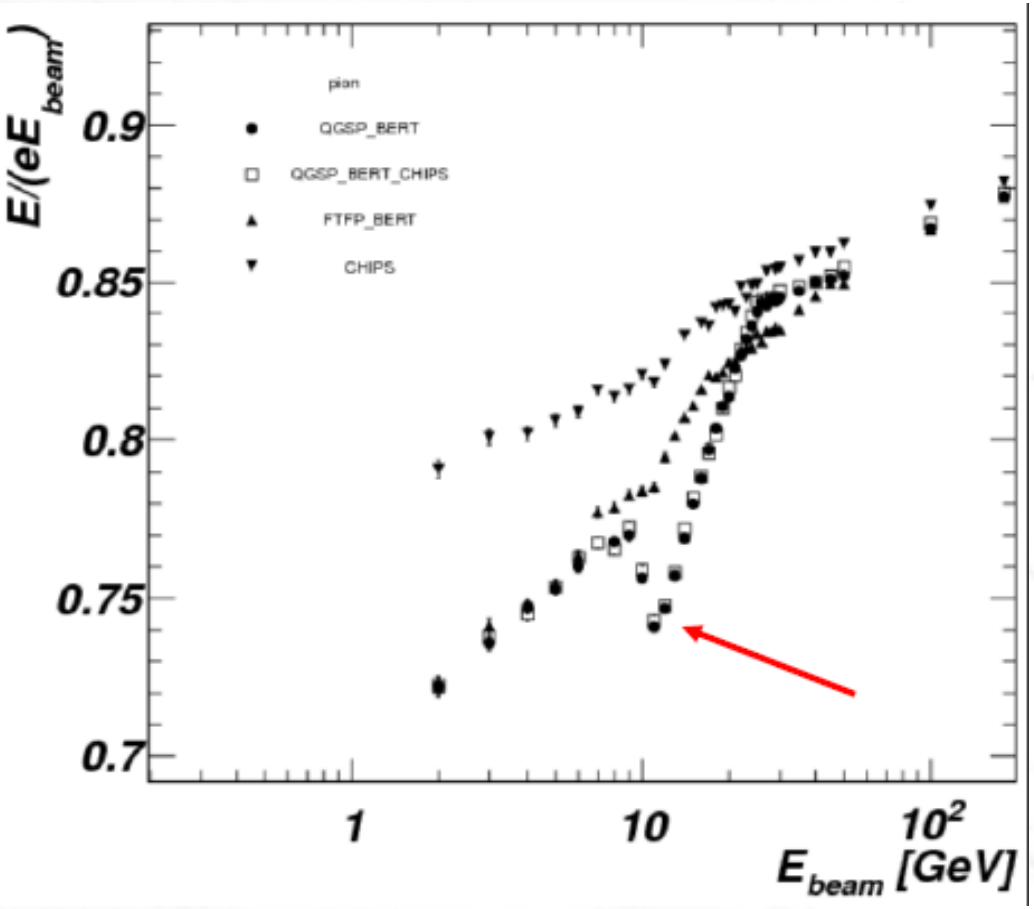
# CMS combined test-beam G4 9.4 : MIP fraction in ECAL



# ATLAS TileCal test-beam energy response, G4 9.4

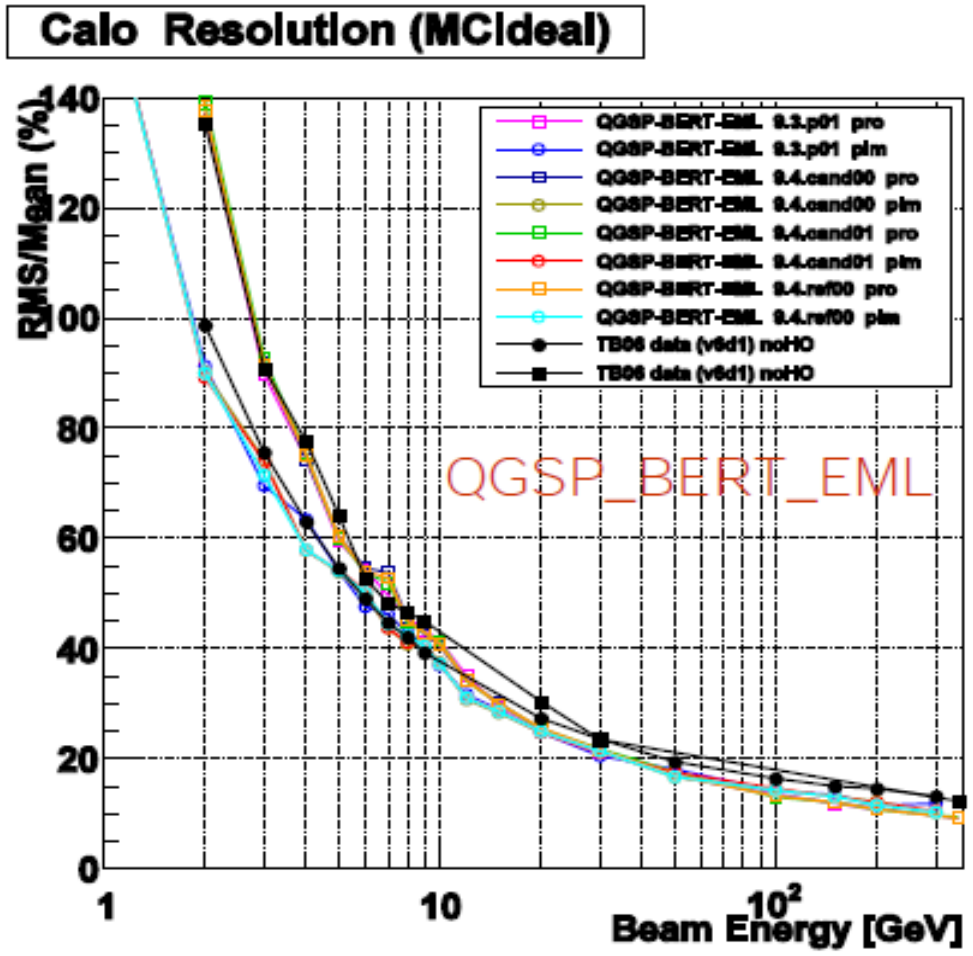


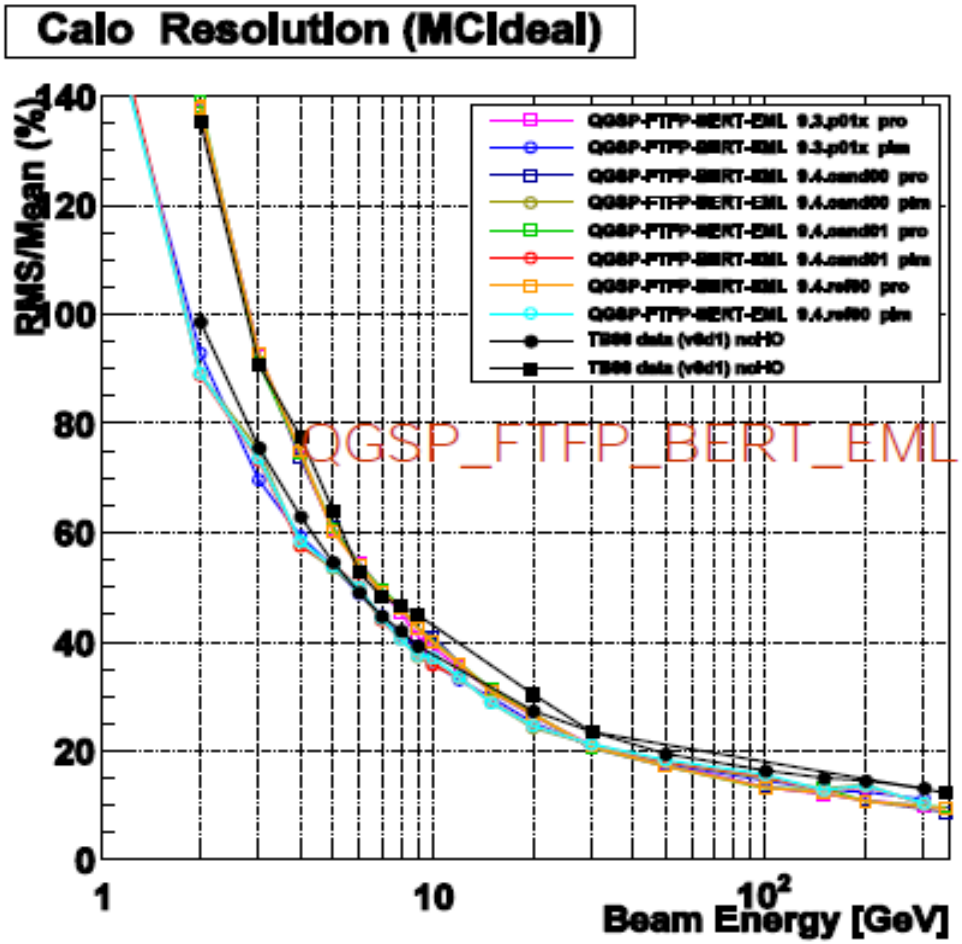



# Energy resolution

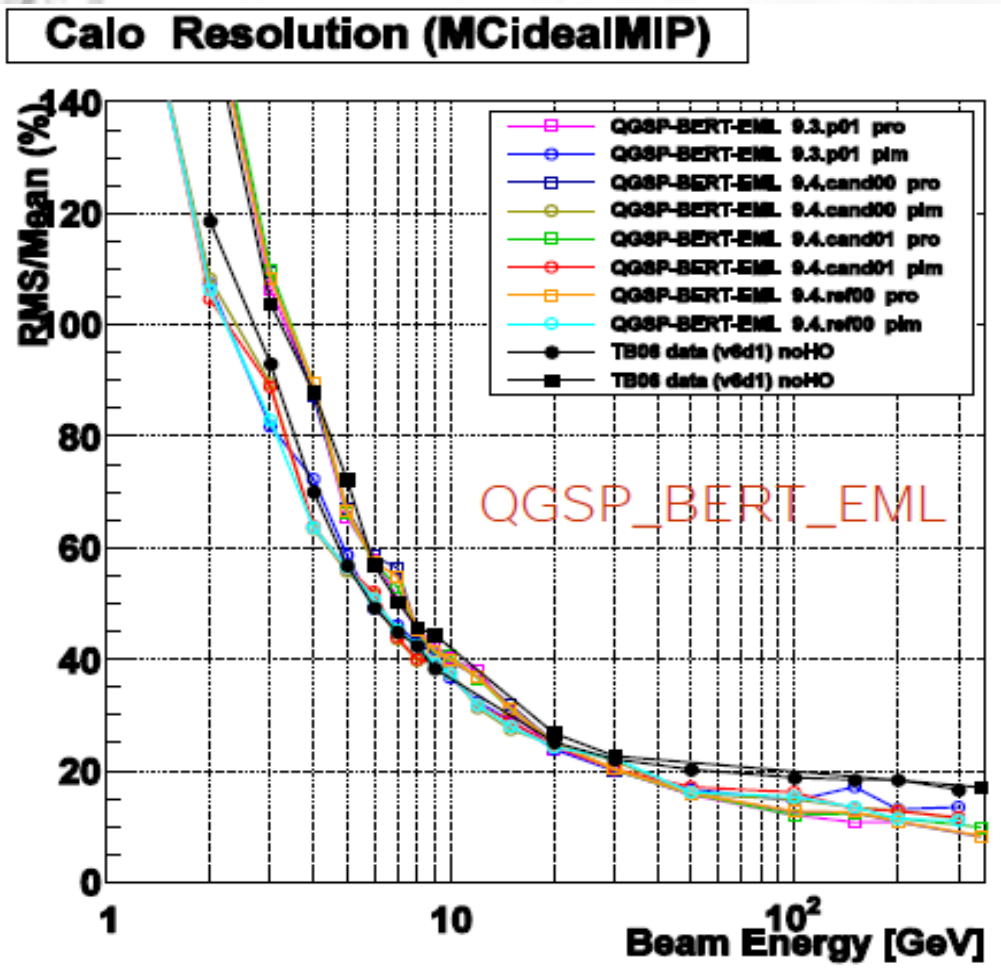
- Very important for di-jet invariant masses
- All Geant4 physics lists of interest for LHC (QGSP_BERT, FTFP_BERT, QGSP_FTFP_BERT) are producing **too optimistic (narrower) energy resolutions**, by **~ 10%** with respect to test-beam data, for both ATLAS and CMS
- Recent versions of FTFP_BERT are producing energy resolutions in better agreement with ATLAS HEC (Cu-LAr) test beam...

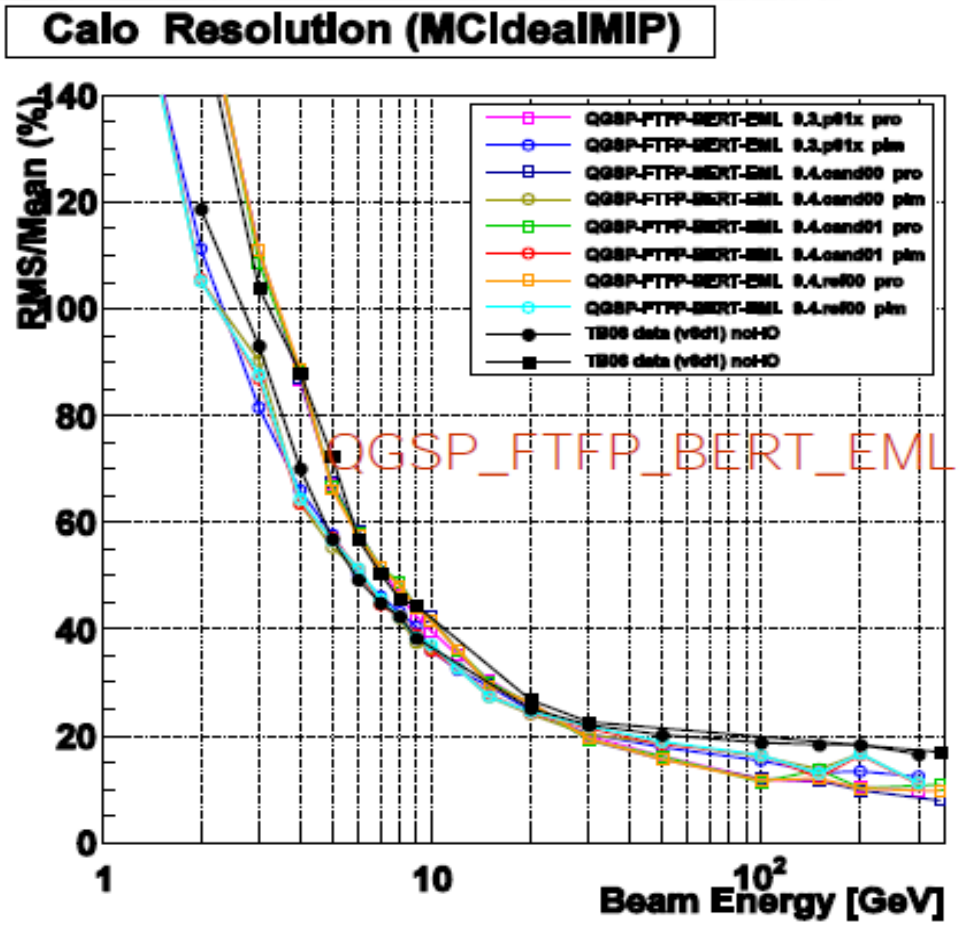
# CMS combined test-beam: G4 9.4



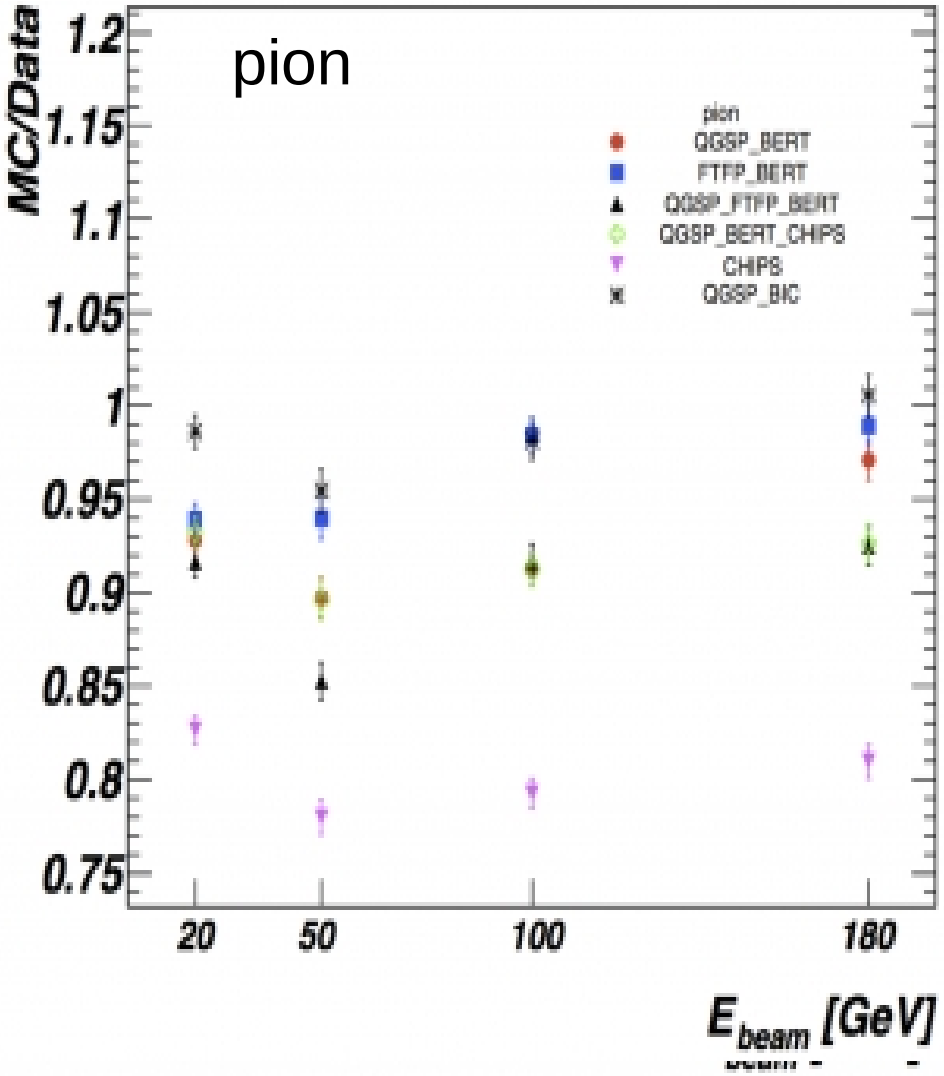



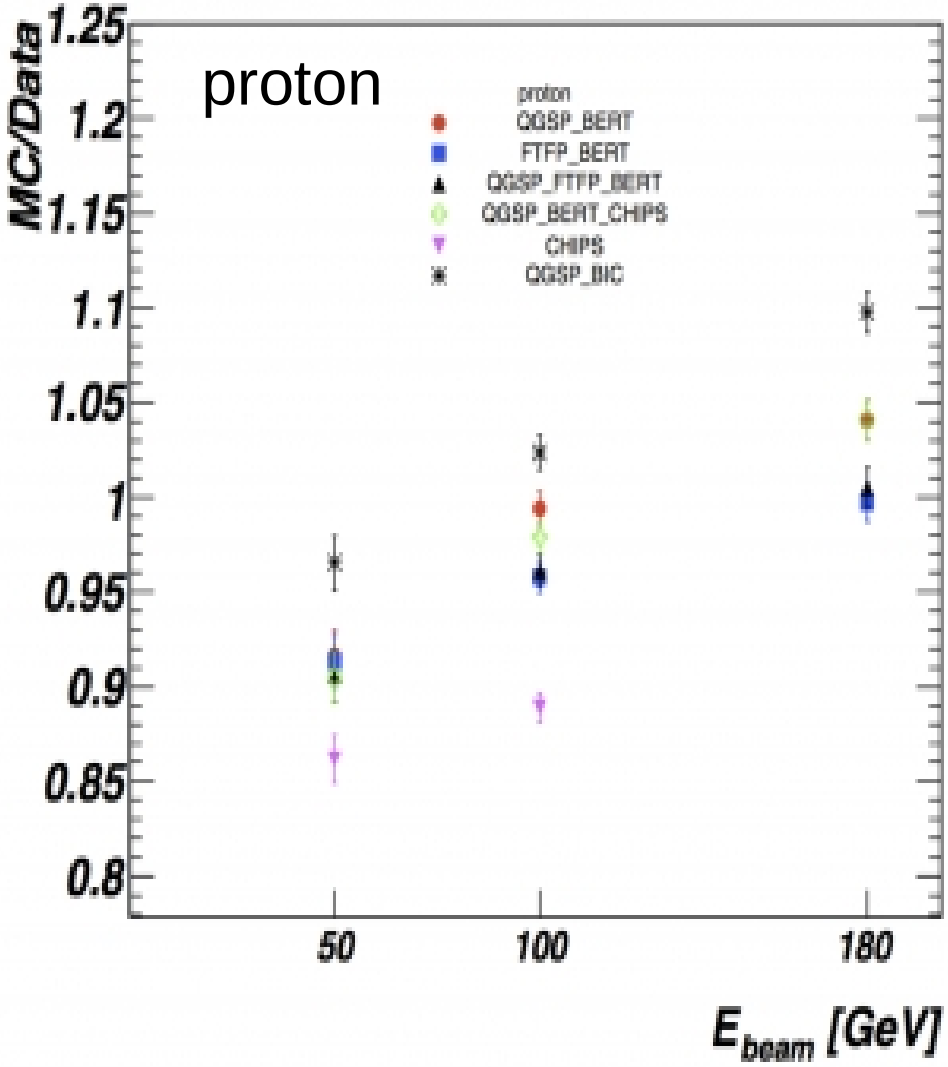
# CMS HCAL test-beam, G4 9.4



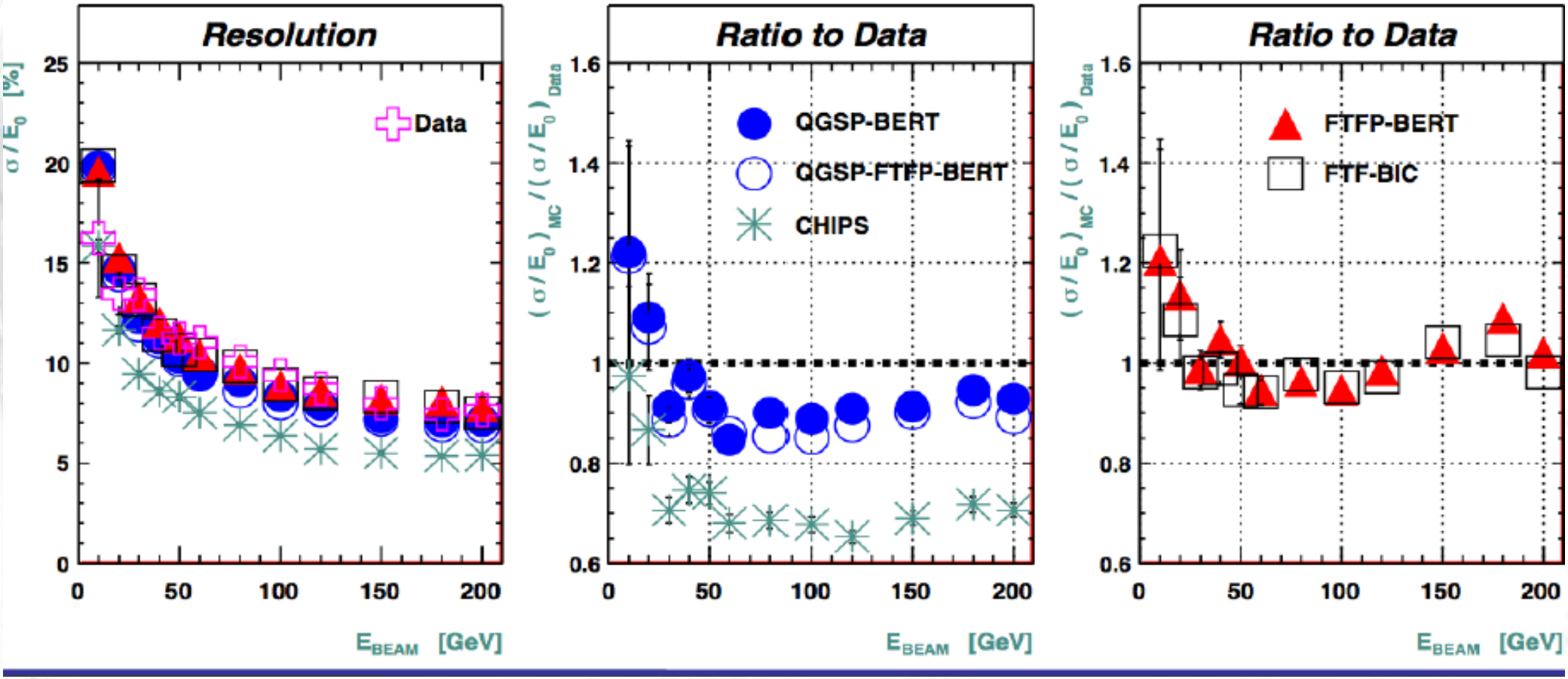



# ATLAS TileCal test-beam energy resolution, G4 9.4



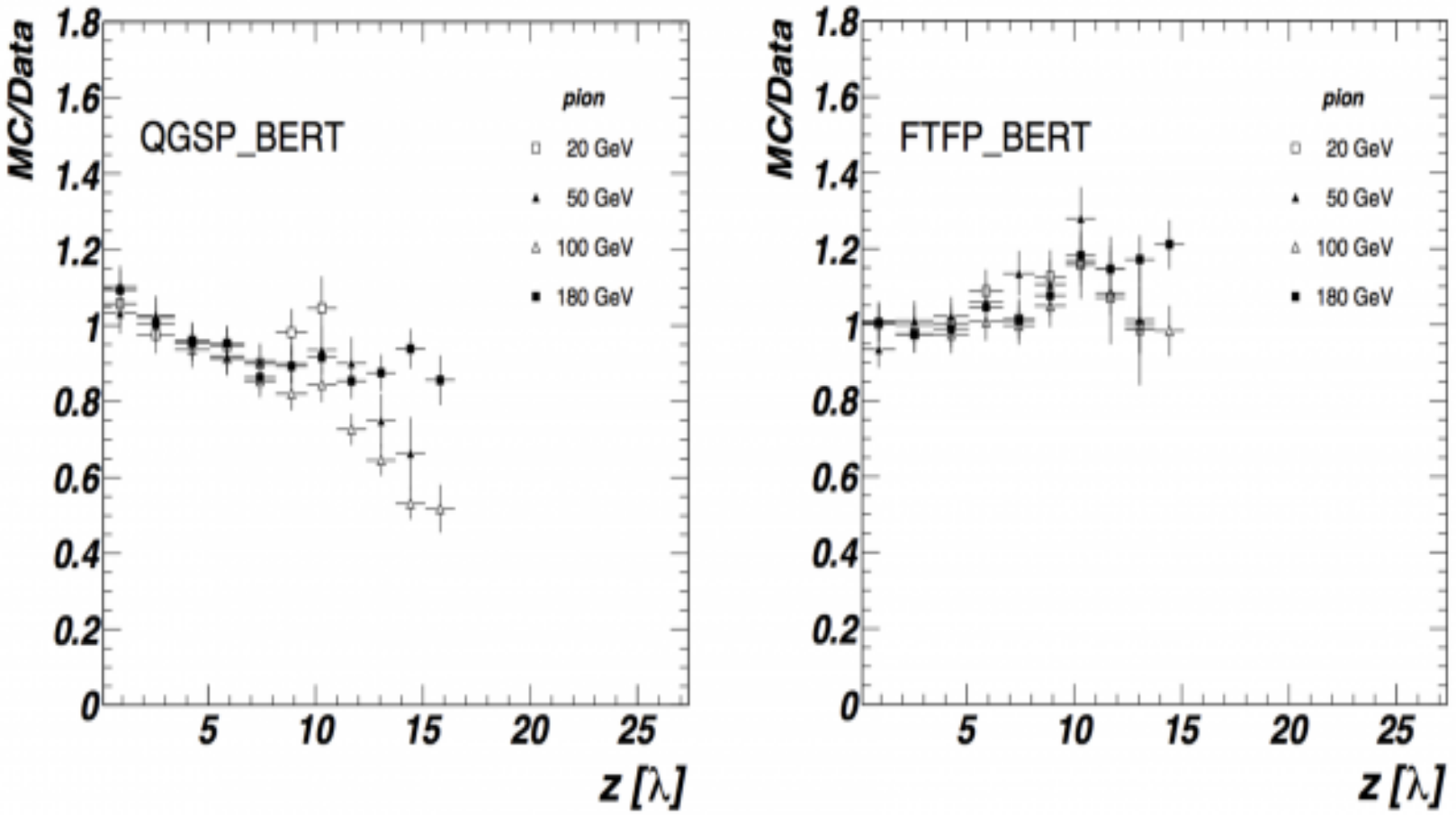
# ATLAS HEC test-beam pion energy resolution, G4 9.4



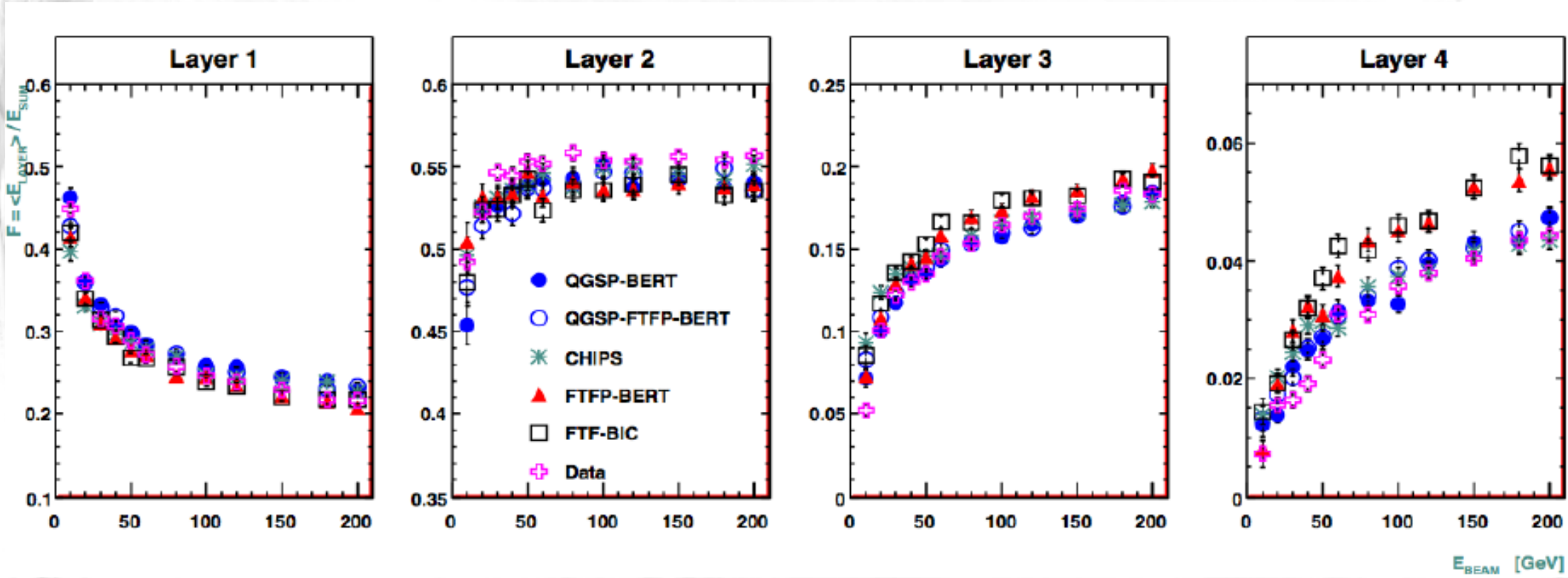
# Longitudinal shower profile

- Important for jet corrections and particle identification
- QGSP_BERT longitudinal pion shower profiles are **~ 10% shorter** than test-beam data
- FTFP_BERT longitudinal pion shower profiles are **~ 10% longer** than test-beam data
- Proton shower longitudinal profiles are not so well simulated: QGSP_BERT is **shorter** by **$\gtrsim$ 20%** , FTFP_BERT is **longer** by **$\lesssim$ 20%** than test-beam data
- Progress in the past has been obtained thanks to better modeling of **quasi-elastic**. Further improvements on longitudinal shower profiles will likely need refinement in the **diffraction**, especially for QGS

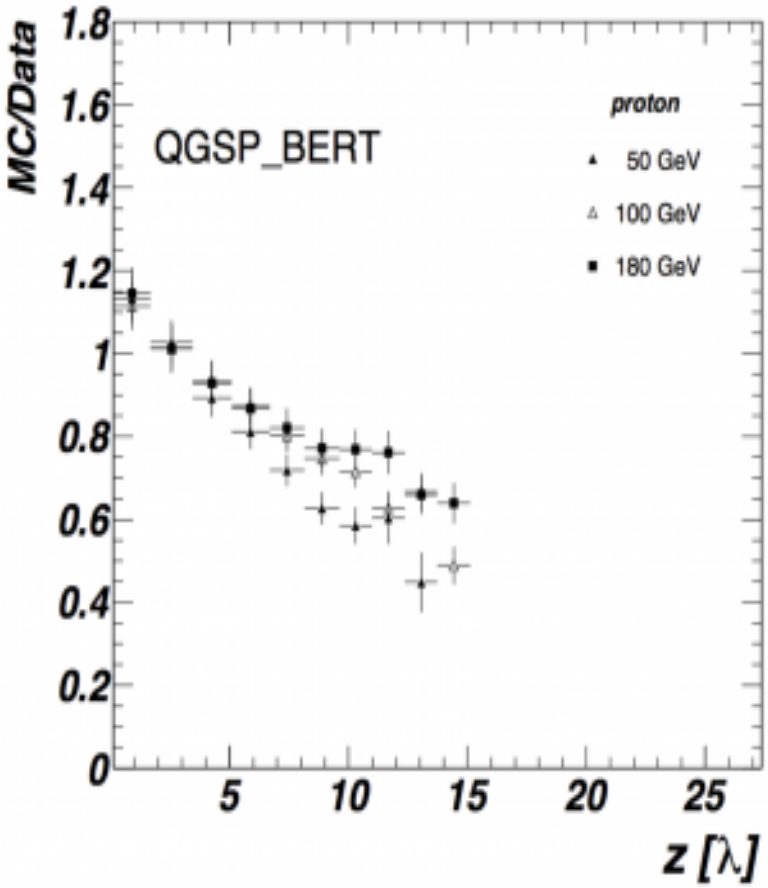
# ATLAS TileCal test-beam pion longitudinal shower profile, G4 9.4

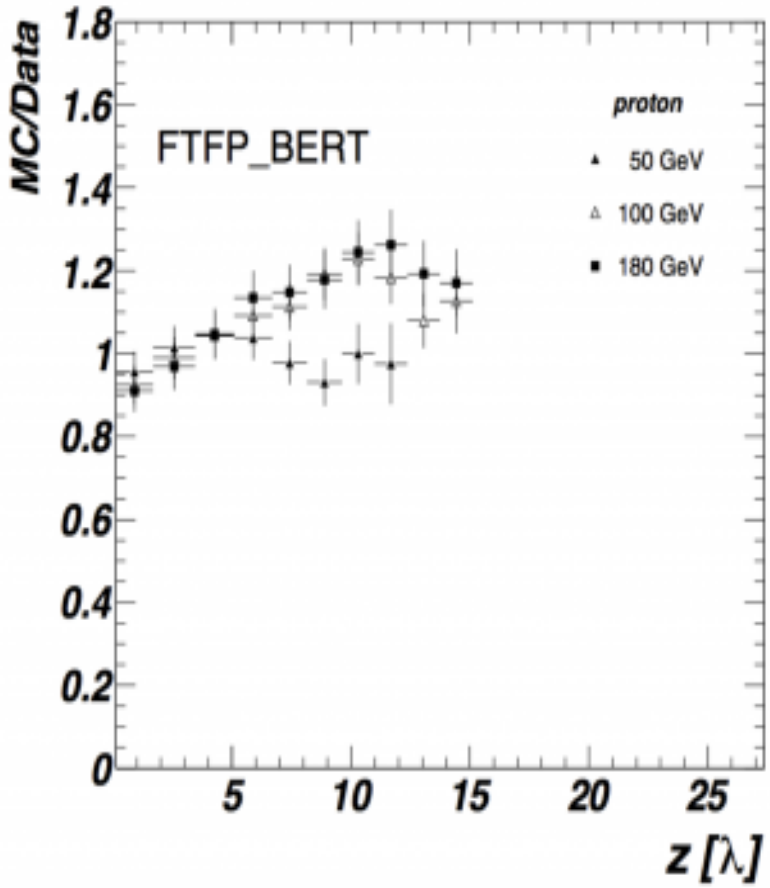


# ATLAS HEC test-beam pion longitudinal shower profile, G4 9.4



# ATLAS TileCal test-beam proton longitudinal shower profile, G4 9.4

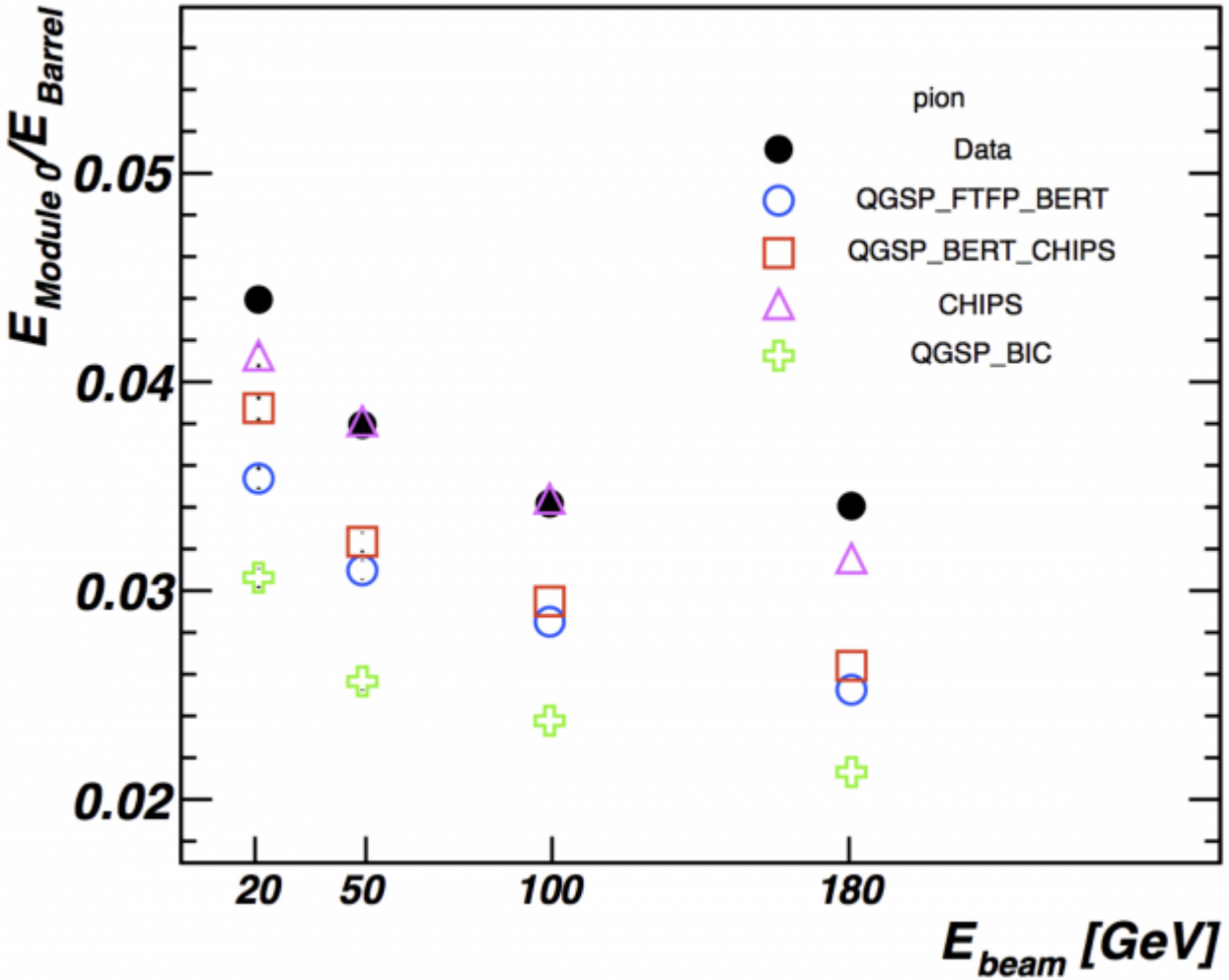


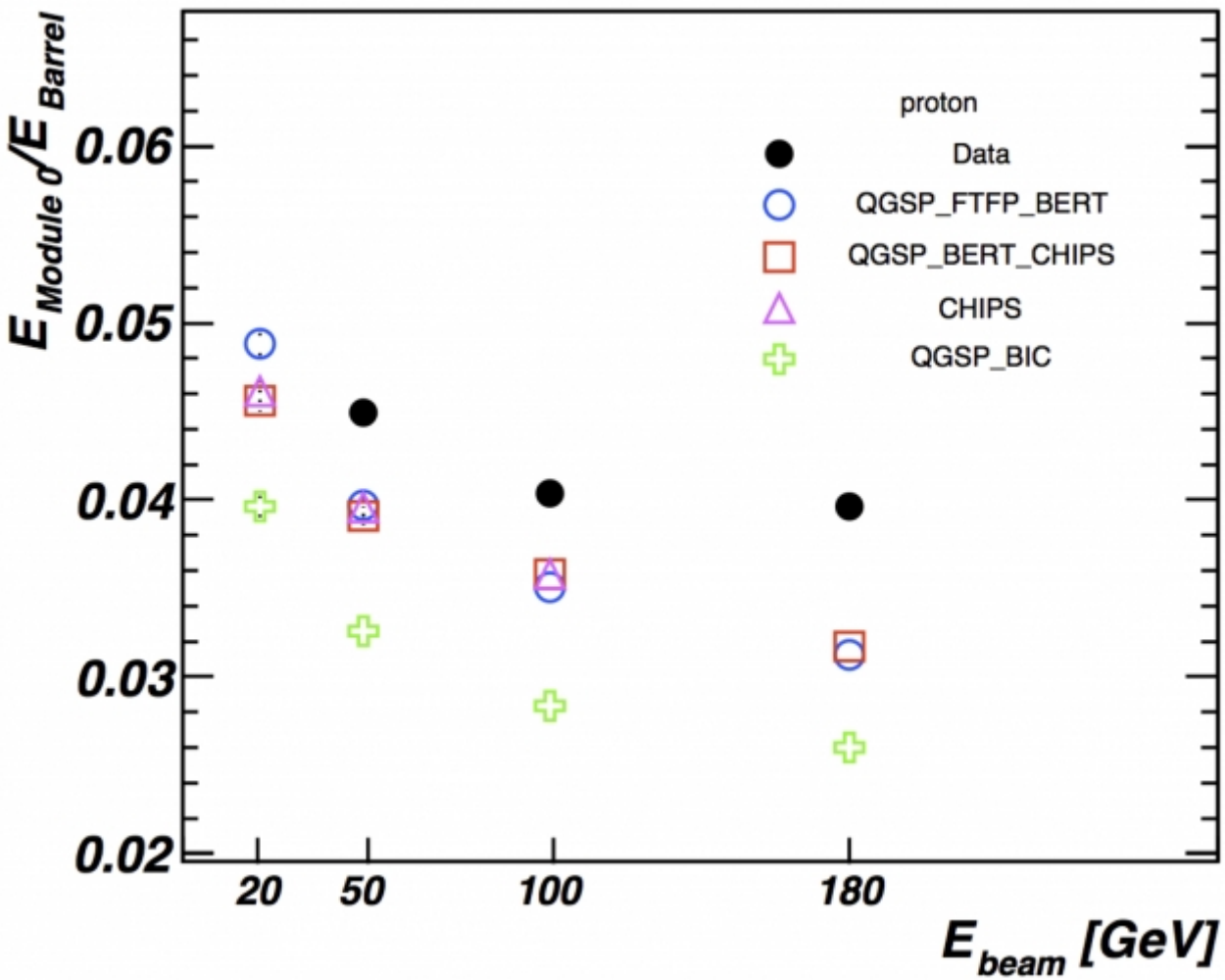
# Lateral shower profile

- Relevant for isolation and separations between jets
- Results from LHC test-beam setup (ATLAS TileCal) and CALICE show that all Geant4 physics lists are producing pion and proton showers that are **narrower** than data by **10 ÷ 20 %**
- Improvements on this observable is very important for highly granular calorimeters under design for ILC, but likely not critical for the coarse LHC calorimeters
- Electromagnetic showers: CALICE and ATLAS have recently observed that Geant4 electromagnetic showers are a few % **narrower** than data. This is a critical issue (present also in Geant3). Work is undergoing to improve it, with already some partial promising results...

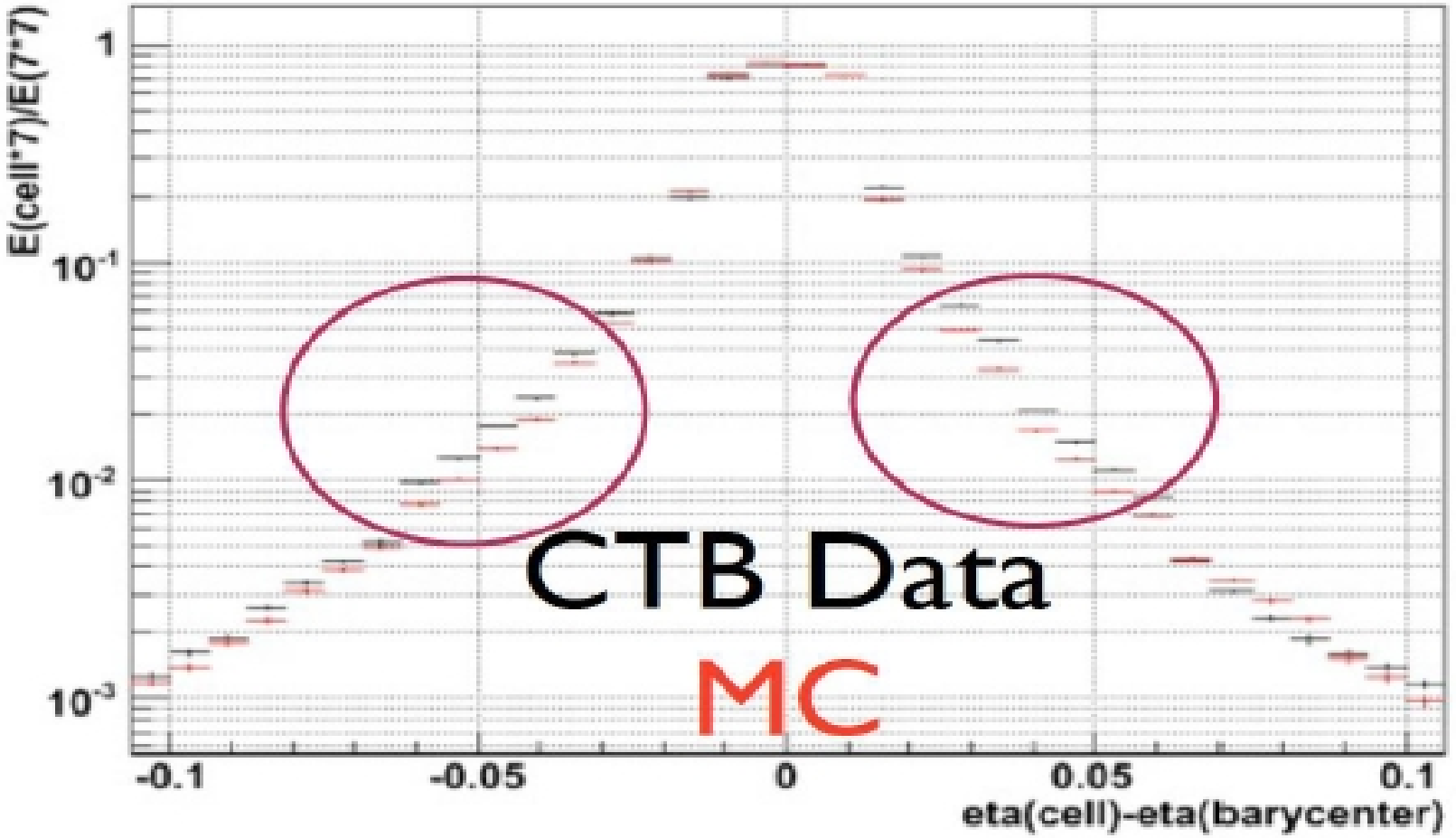
# ATLAS TileCal test-beam pion lateral shower shape, G4 9.4



# ATLAS TileCal test-beam proton lateral shower shape, G4 9.4



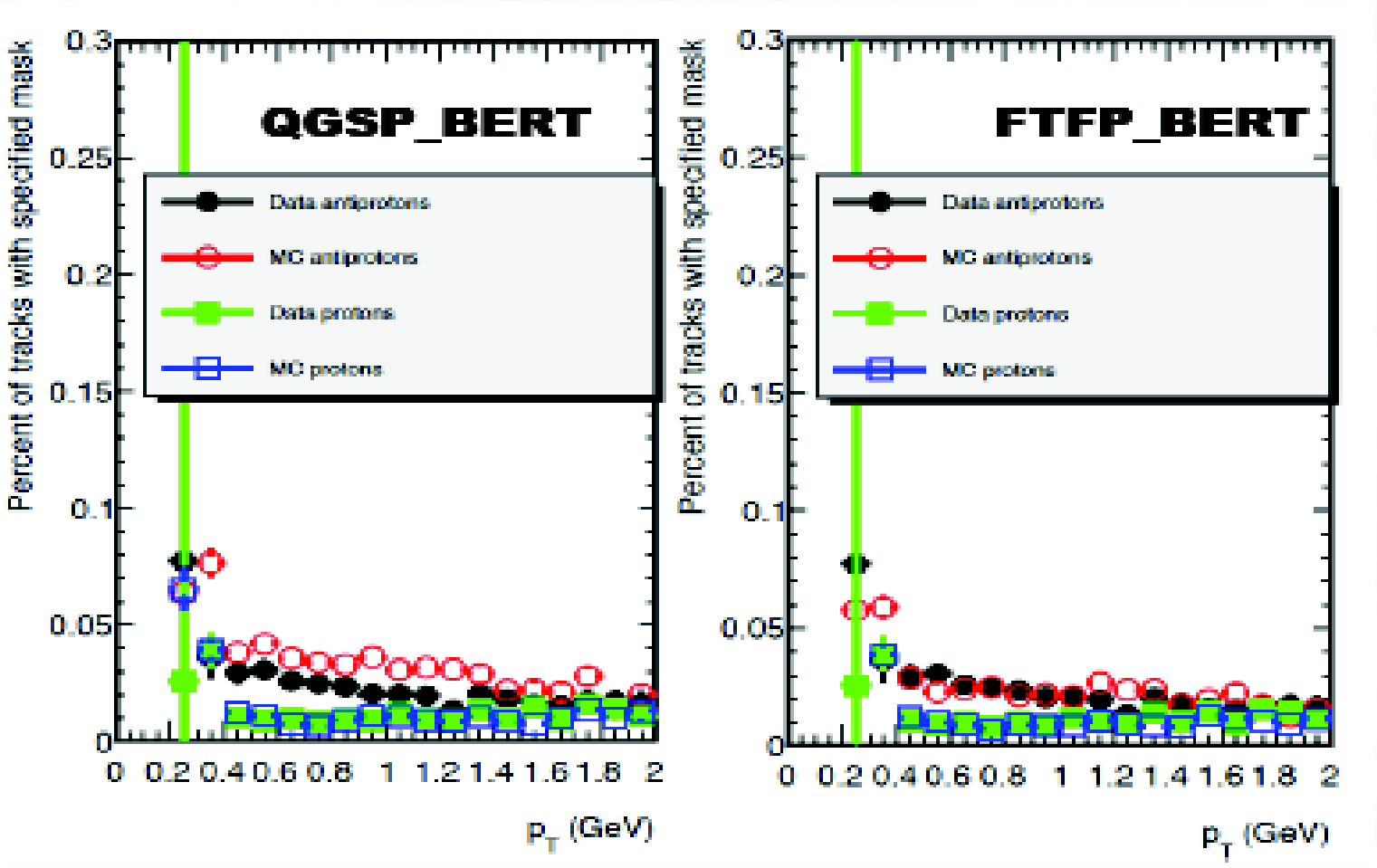
# ATLAS EM lateral shape



# Kaons and antiprotons

- Kaons and antiprotons are non negligible jet components
- For **LHCb**, the modeling of hadronics interactions (both cross section and final state) in thin layers is very important including Ks , Λ . The differences in interactions for particle and antiparticles, particularly for K± , are also vital
- Much less data available to test these particles
- For kaons, **CHIPS** provides the best current simulation in Geant4, available in QGSP_BERT_CHIPS and in all Fritiof-based physics lists (FTFP_BERT, QGSP_FTFP_BERT,...)
- For antiprotons, **Fritiof**-based physics lists provide the best simulation currently available in Geant4

# ATLAS hadronic interactions in the inner detector



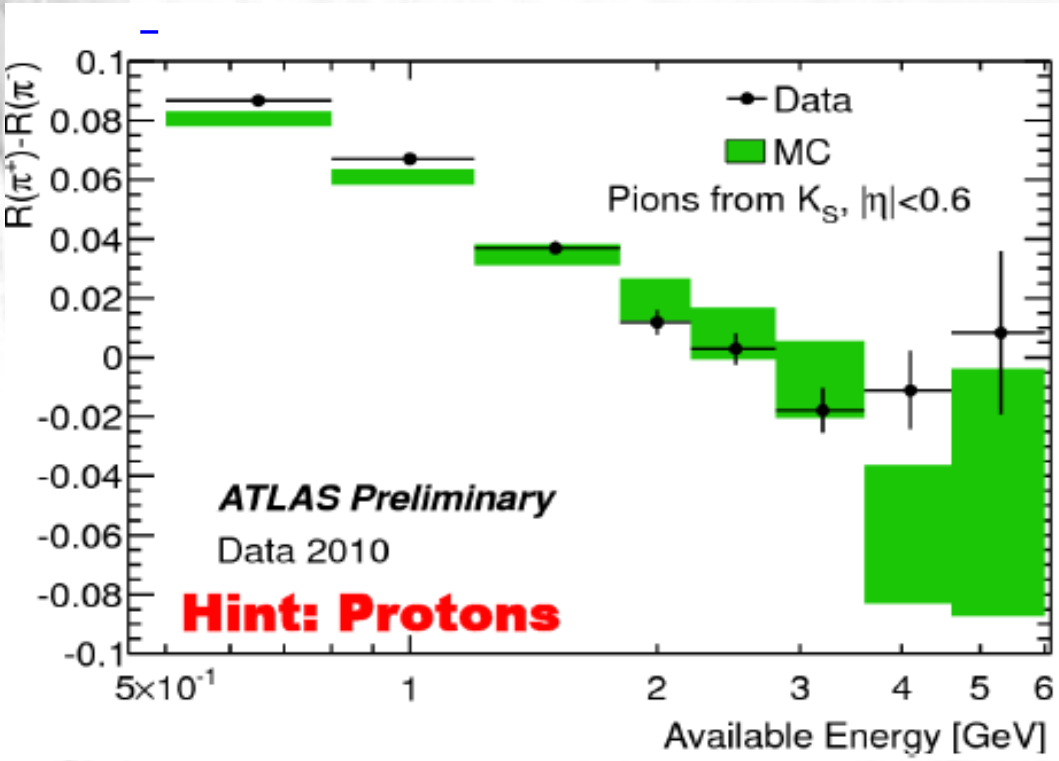
# ATLAS collision data

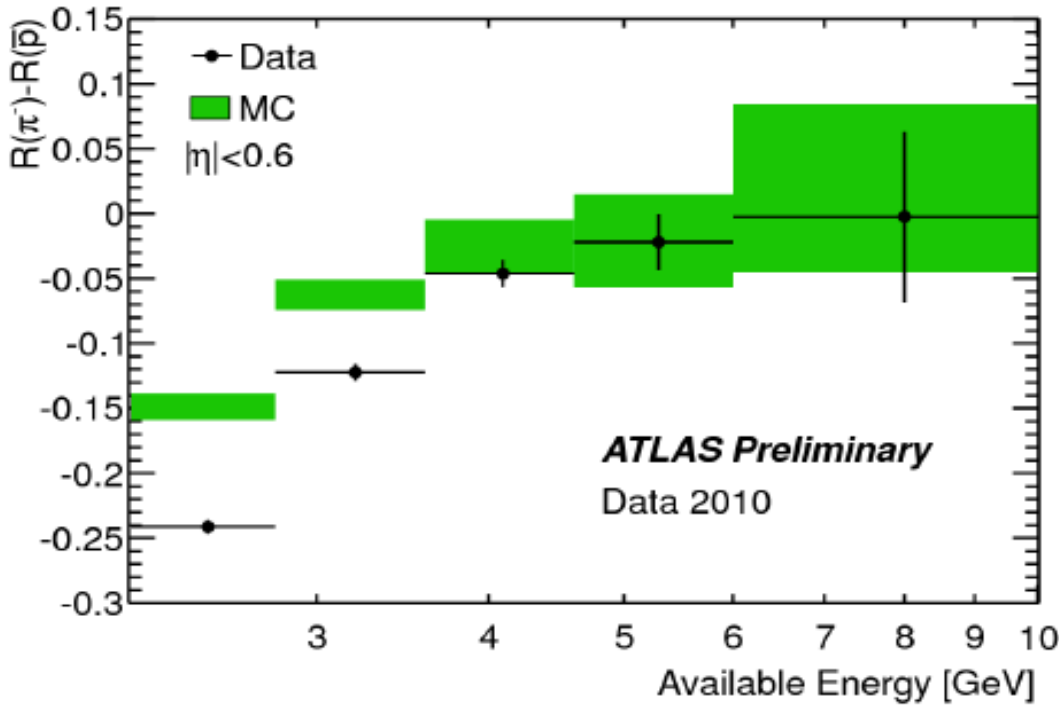
Use differences to avoid background issues:

π+ - π- and π- - p̄

π+ and π- are different

QGSP_BERT does poorly with p̄



# Validation summary table for G4 9.4.p01

Table made by A. Dotti

| | Response | Resolution | Smoothness | Lateral Shape | Longitudinal Shape @10λ | Notes |
|---|---|---|---|---|---|---|
| QGSP_BERT | +(1-3)% | -(10-5)% | Bad | -(20-10)% | π: -10%<br>p: -20% | anti-nucleons, hyperons via LHEP |
| FTFP_BERT | +(3-5)% | -(7-3)% | Good | π: -(20-10)%<br>p: -(10-3)% | π: +10%<br>p: +(10-20)% | anti-nucleons, hyperons via CHIPS(*) |
| CHIPS | +(10-5)% | -(20-10)% | Very Good | π: -(10-3)%<br>p: -(20-10)% | π: -10%<br>p: -20% | native anti-nucleons, hyperons |
| FTF_BIC(**) | +(3-5)% | -(6-2)% | Bad | - | π: +10% | Implements re-scattering at high E |

# Summary & conclusions

- Up to now, overall satisfactory behavior of Geant4 simulations with respect to **LHC collision data**. **Test-beams data** are still providing more stringent validation for Geant4 simulations, especially for hadronic showers
- Need to keep a balance between **stability** and **new features/improvements** between Geant4 releases
- Focus on a **few physics lists**, relying on a **few key models**
- Energy response and energy resolution are the two most important observables for LHC physics, followed by longitudinal and lateral shower profiles. For ILC/CALICE the top observable is the lateral shower profile
- Growing attention to “other particles”, besides the traditional pions and protons

# Thanks

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