Recent improvements on the description of hadronic interactions in Geant4

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Overview

- Introduction
- Status of the simulation of hadronic interactions for HEP experiments
- Recent developments
  - FTF based physics lists improvements
  - CHIPS one model physics list
- Results: comparison of different physics lists of calorimetric quantities

Introduction

"Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science"

NIM A506 (2003) 250-303, IEEE TNS 53 No.1 (2006) 270-278

http://www.cern.ch/geant4

- Hadronic physics in Geant4:
  - cross sections and models for hadron-nucleus interaction up to TeV
  - For neutrons from thermal energies to TeV
- Models are tuned with thin target data (not calorimeters test-beam)
- Models are assembled in physics lists: stable configurations (few billions of events simulated)
  - Example: QGSP_BERT (used at LHC since 3-4 years)
- Experiments compare physics lists with test-beam data
- We use simplified calorimeters to study the impact of hadronic models on calorimeter observables

Models Summary

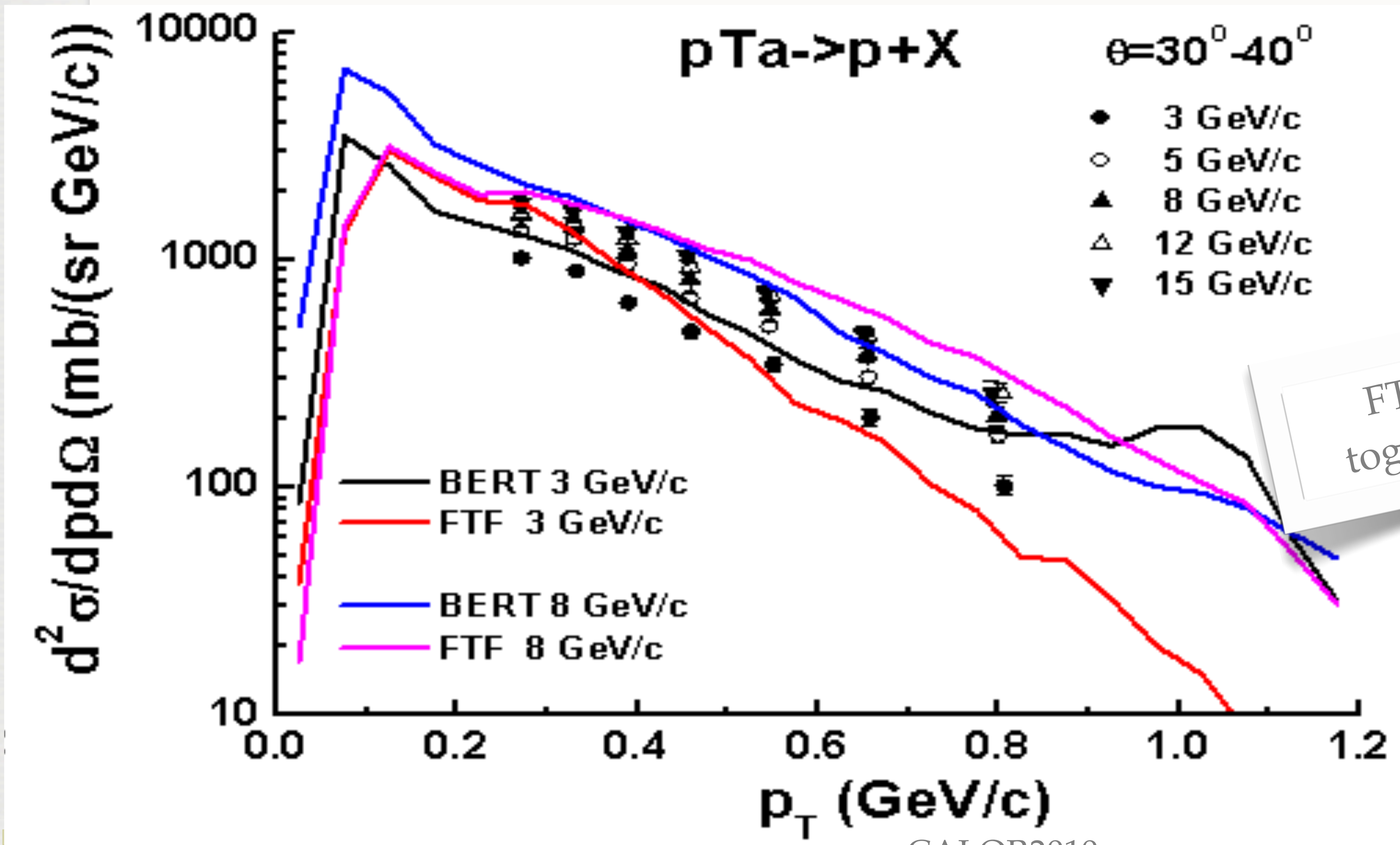
Recent Improvements

- Bertini cascade: low energy intra-nuclear cascade (best agreement with data up to $E_{kin} \approx 5$ GeV) Nucl. Instr. Meth, 66, 1968, 29 ; Physical Review Letters 17, (1966), 478-481
- Quark-Gluon-String, “QGS”: p,n,k,π of high energy (agreement with data from $E_{kin} \approx 10$-15 GeV) See Sec. IV, Chap. 22 of Geant4 Physics Reference Manual and bibliography within
- Parameterized models (derived from GHEISHA as first hadronic model mid-90): all E and particles. Goal: replace with more accurate models. Still used in most physics lists for hyperons and antibaryons
- Chiral Invariant Phase Space Decay,“CHIPS” (new developments): all E and particles. Eur. Phys. J. A 8, 217-222 (2000) ; Eur. Phys. J. A 9, (2001) ; Eur. Phys. J. A 9, (2001)
- Fritjof, “FTF” (new developments): p,n,k,π of high energy (valid from $E_{kin} \approx 4$-5 GeV) Nucl. Phys. 281 289 (1987)

Thin Target Tuning: Example

- Tuning is done at model level:
- Thin target data
- Several tests are run routinely to follow evolution of model code

- BERT and FTF predictions for HARP-CDP data: double differential cross sections in pA interactions
- BERT and FTF describe data reasonably well

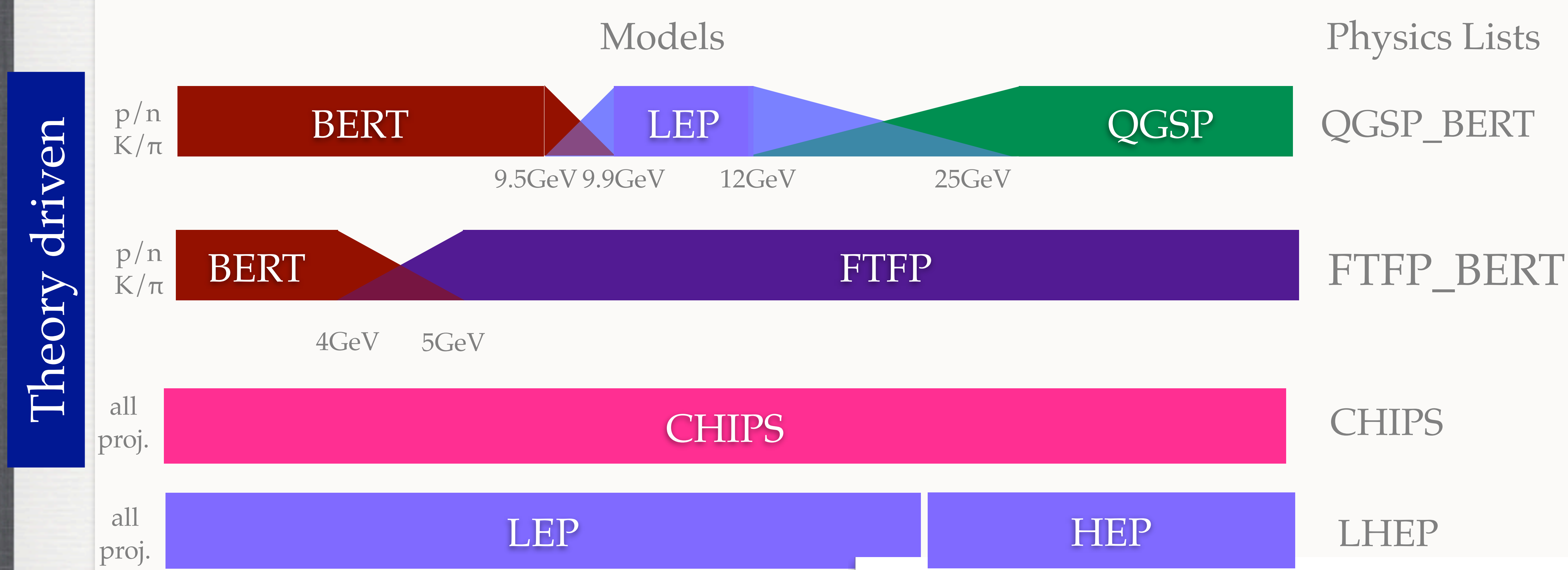


FTF and BERT can be used together in the 4-5 GeV region

Physics Lists In This Talk

http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/physicsLists.shtml

- A Physics List is a set of consistent physics models for each particle in application
- LHC tested several options: most challenging requirements on hadronic interactions come from ATLAS and CMS calorimeters
    - After detailed validation with test-beam: QGSP_BERT (2007)
- For a given physics list when a hadronic interaction occurs a model, depending on primary type and energy, is sampled



CHIPS components used by other PL
for capture of negative hadrons at rest
and γ-Nuclear and Lepto-Nuclear interactions

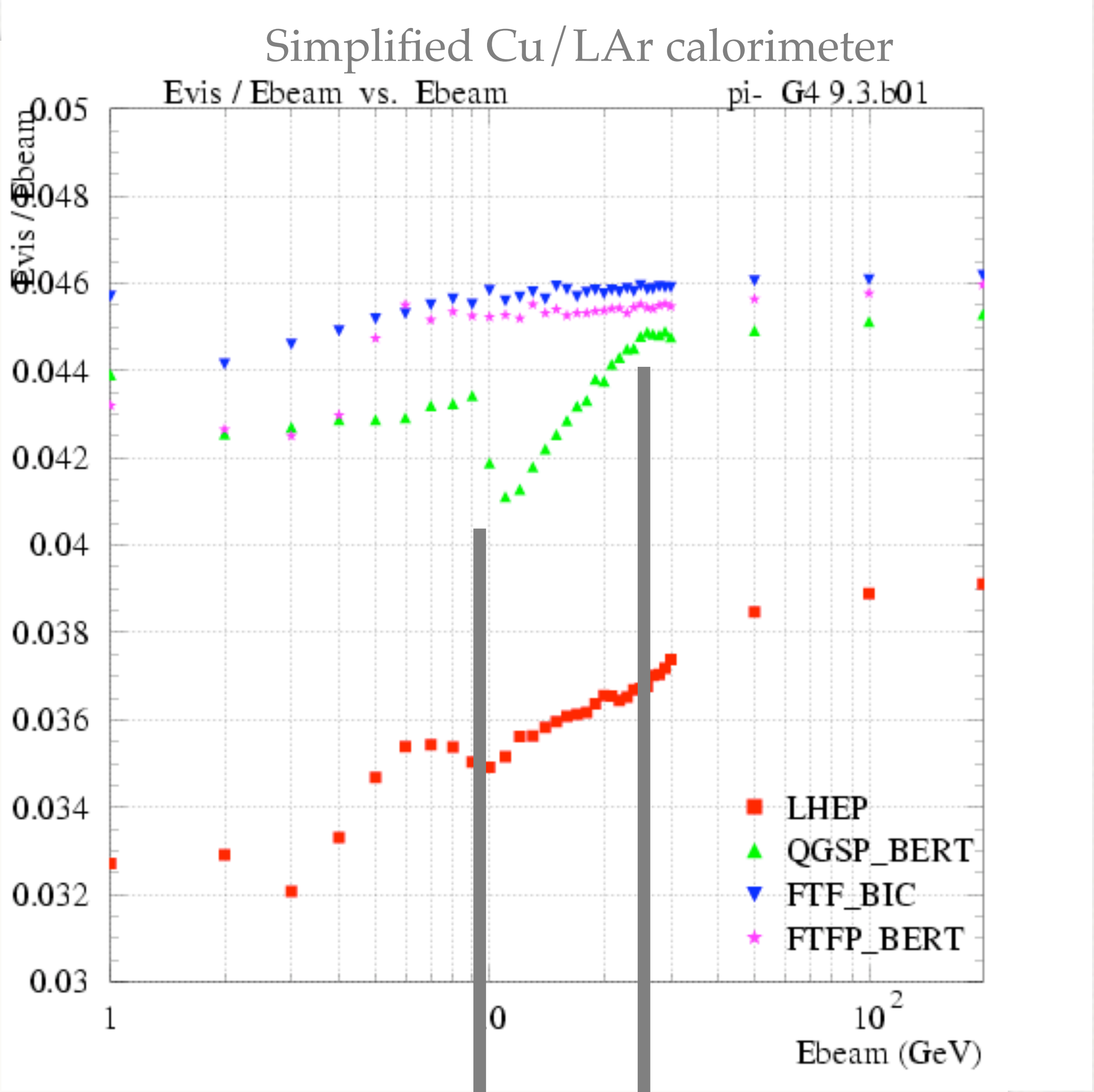
Status Of Simulation

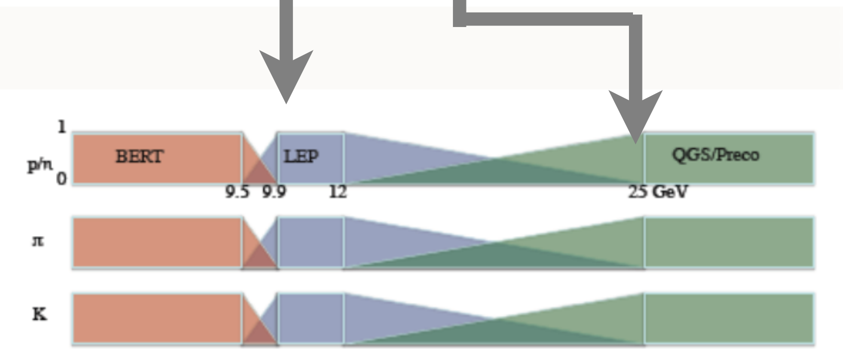
- Need for precise simulation of observables for LHC (CERN-LCGAPP-2004-02):
  - Response (e/pi), resolution, shower shapes
- Results from ATLAS & CMS test beam:
  - best description obtained with QGSP_BERT physics list
    - G4 9.3 under validation by experiments
  - Response: good agreement, within 3%
  - Resolution: simulation is a bit too narrow, within 10%
  - Showers still a bit shorter and narrower than data:
    - pions within 10% up to 10λ
    - protons within **30%** up to 10λ

See: JoP Conf. Series 160 (2009) 012073 ; CALOR08 Contribution by G. Folger

Transition Between Models

- CMS, and then ATLAS, observed unphysical steps in response as a function of beam energy
    - Confirmed with simplified setups
- We have investigated in detail the source of this:
    - Related to transitions between models
    - Use of parametrized models (LEP) in medium (10-25GeV) energy range
- This has been one of the main area of activity in Geant4 hadronic

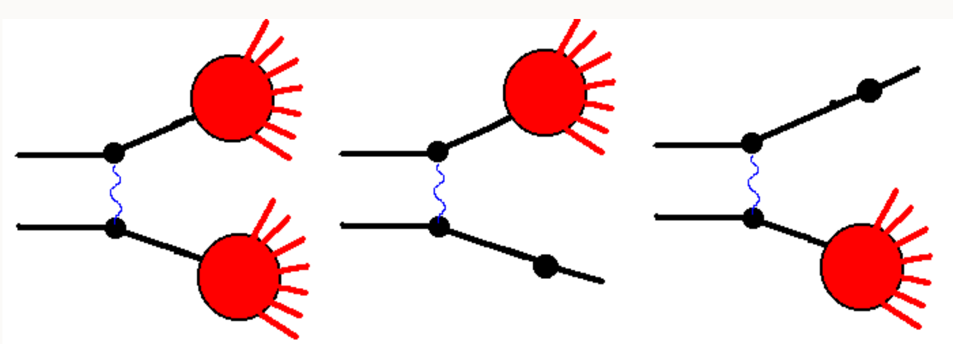




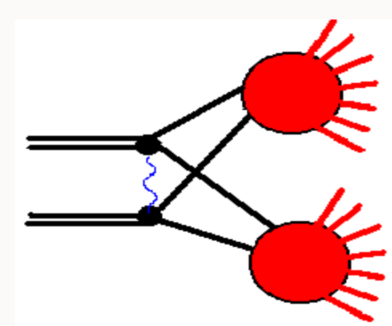
Details presented at IEEE NSS/MIC 2009 - 25-31 October 2009 - A. Ribon's contribution. Proceedings under publication

FTF Physics Lists Improvement

- Based on Fritiof model: string model with LUND fragmentation
- Why FTF? Geant4 QGS is valid from $E_{kin} \approx$ 10-15 GeV, FTF is promising alternative: valid from $E_{kin} \approx$4-5 GeV
- Hadron-hadron interactions are modeled as binary reactions:
$$a + b \rightarrow a' + b' \;;\; m_{a'} > m_a ,\; m_{b'} > m_b$$
    - a′ and b′ are excited states of the initial hadrons a and b
- FTF model in Geant4: simulation of single diffraction, simulation of binary reactions, Reggeon cascading
- Recent improvements (quark exchange introduction, Reggeon cascading) allow for a smooth coupling with Bertini cascade models at 4-5 GeV: removing discontinuities
- FTF is also implemented in HIJING, UrQMD, ART, HSD codes



Original FTF

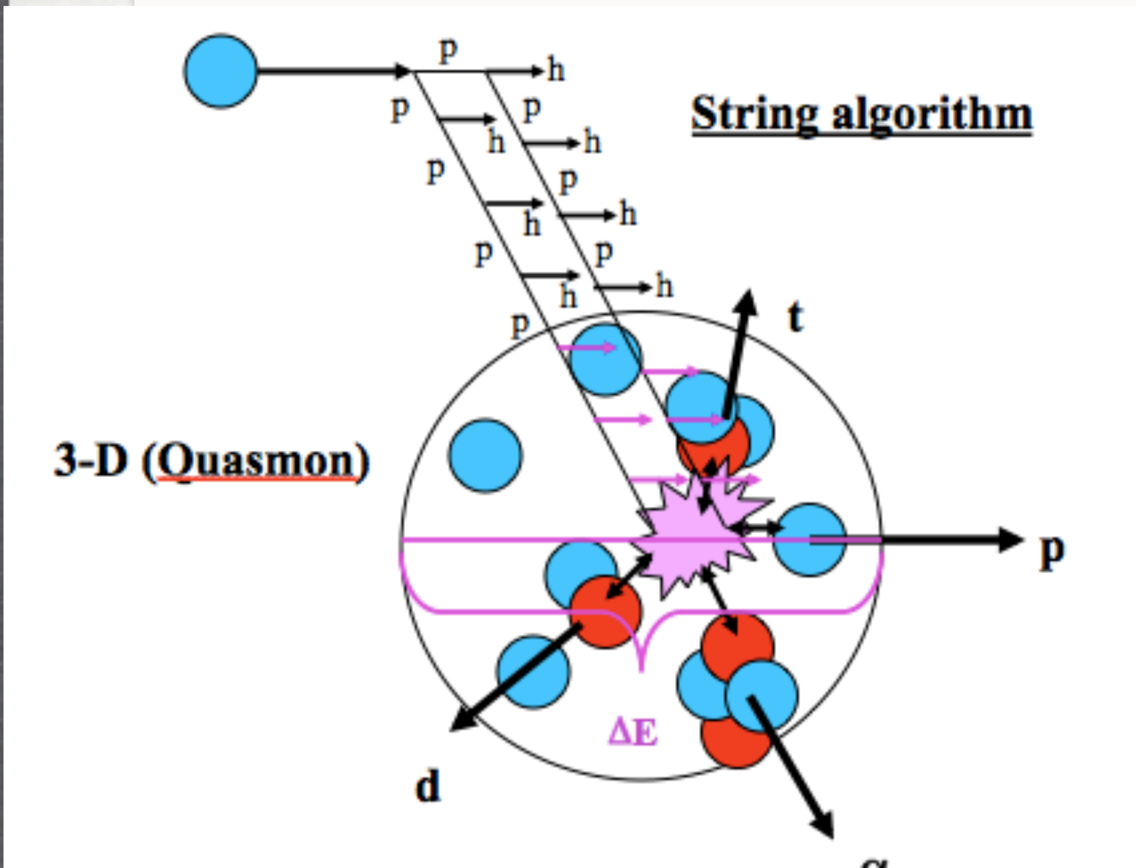


Quark-exchange (new)

Nucl. Phys. **B** 281 (1987) 289
Comp. Phys. Comm. 43 (1987) 387

New CHIPS Physics List

- CHIPS model of inelastic nuclear interactions:
  - High energy: 1-D Parton Multi String (PMS), soft part of it absorbed by target nucleus creating quasmons
  - Low energy: 3-D decay of a quasmon (parton plasma) with final CHIPS evaporation
- CHIPS physics list (released as experimental PL in Dec. 2009) very smooth: melds the HE and LE approaches
- CHIPS can be used for all particles (including kaons, anti-baryons, hyperons)

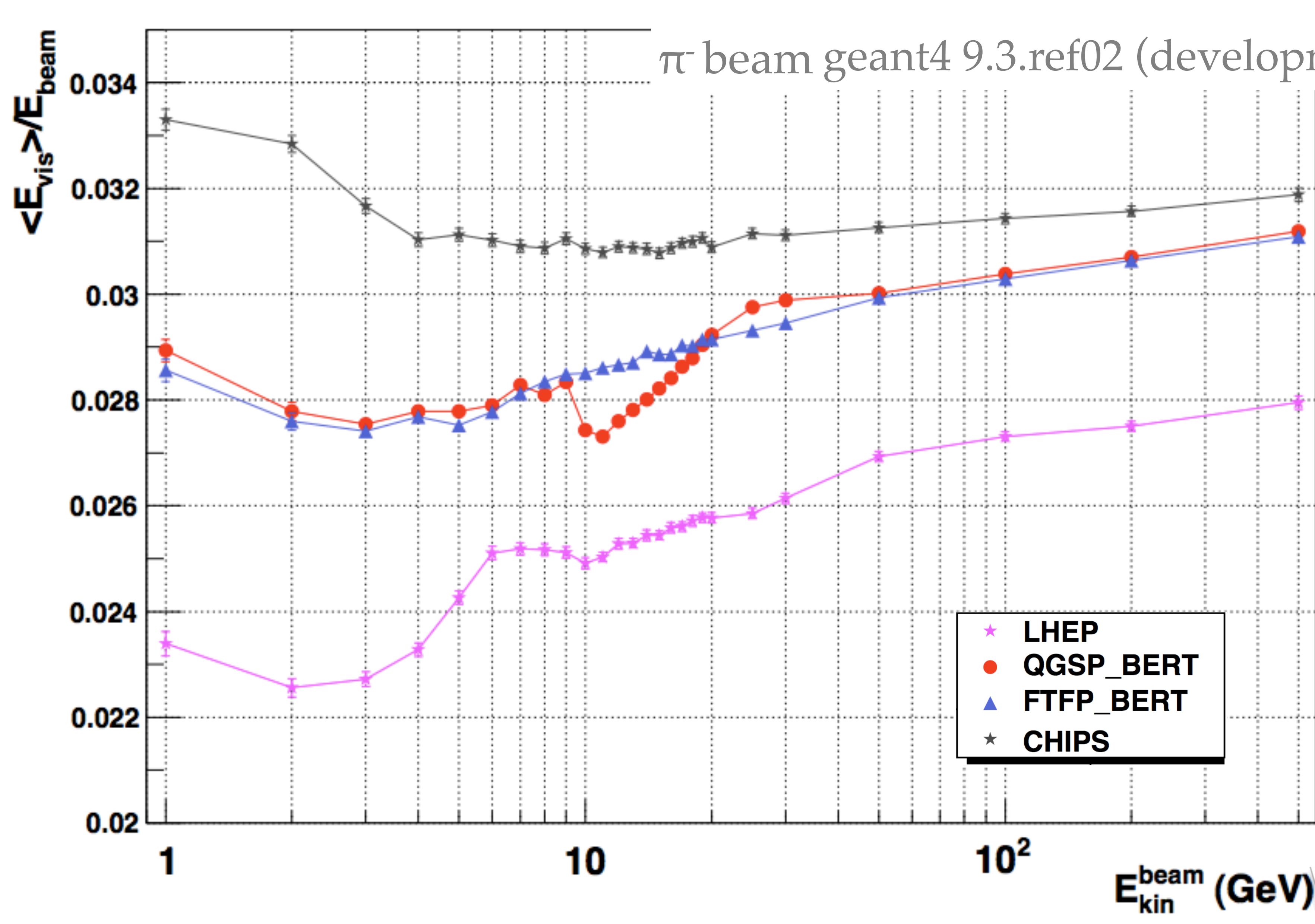


CHIPS provides also:

- Revised cross sections for all hadrons
- At rest nuclear capture processes for negative hadrons
- Neutrino-nuclear, electron-, muon-, tau-nuclear and photo-nuclear reactions
- Elastic scattering for all hadrons
- Quasi-elastic scattering

EPJ **A** 8 (2000), 217
EPJ **A** 9 (2000), 411
EPJ **A** 9 (2000), 421

Simplified Fe/Sci Calorimeter



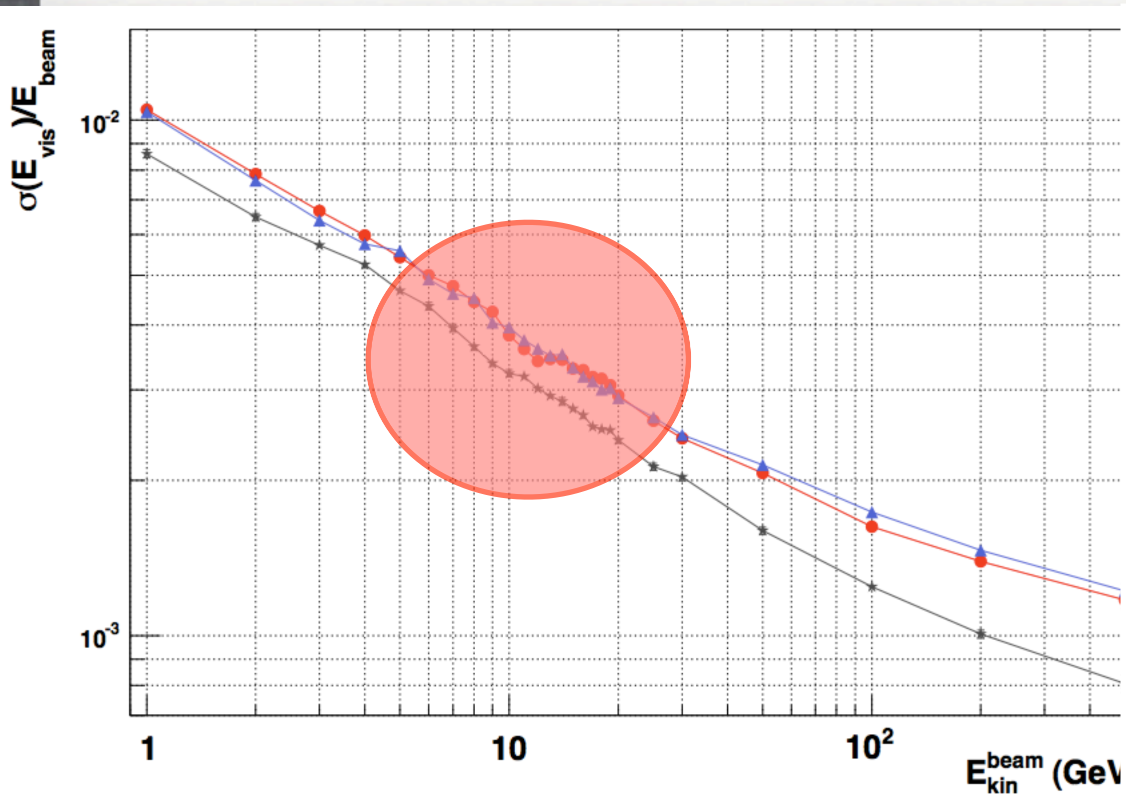
- QGSP_BERT stable since G4 8.3 (May 2007)
- FTFP_BERT smooth response (improved in G4 9.3)
- CHIPS (new in G4 9.3) higher response

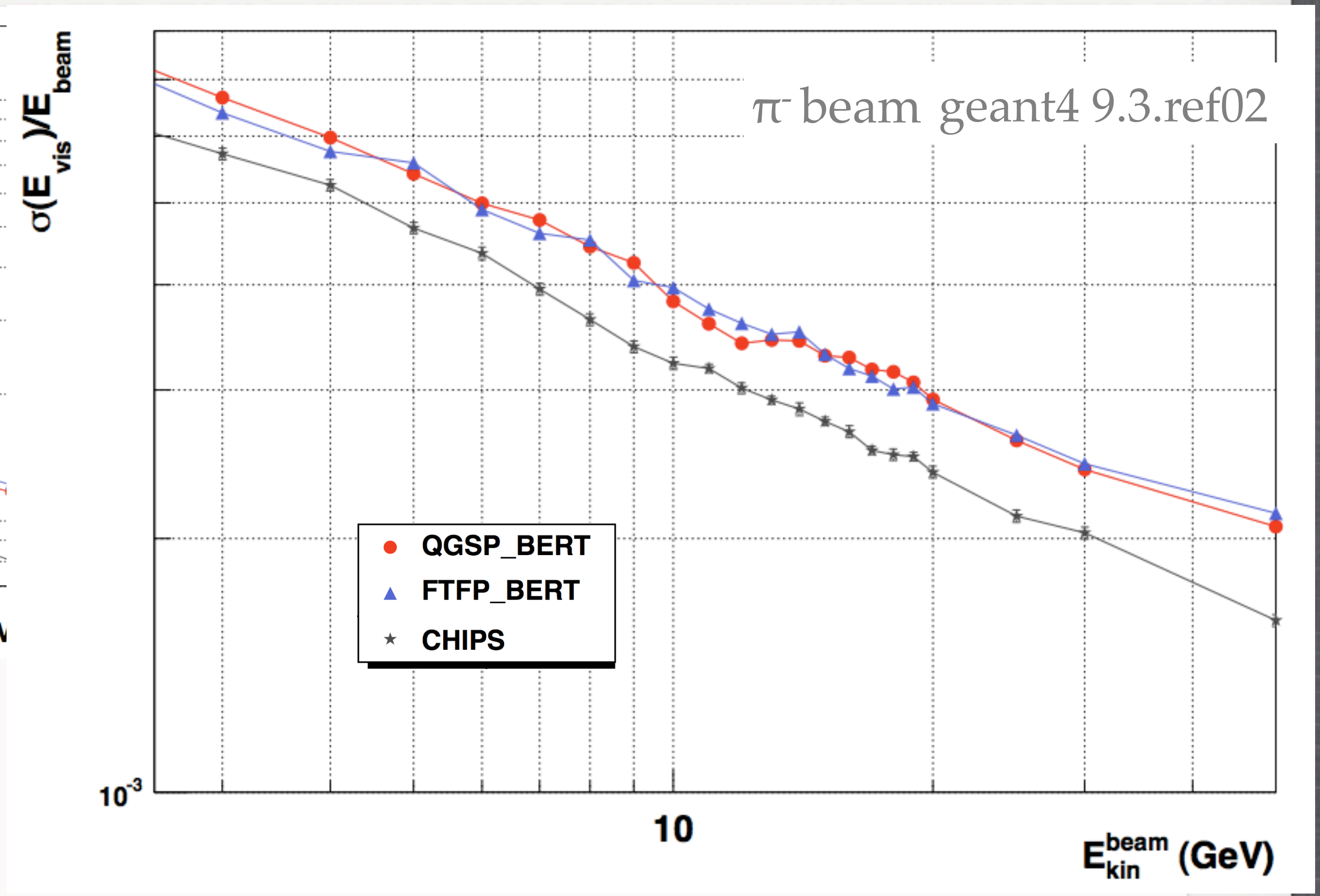
CHIPS still under tuning

FTFP_BERT and CHIPS: smooth response. FTFP_BERT agrees with QGSP_BERT, where this one agrees with data

What about other observables (resolution, shower shapes)?

Standard Deviation

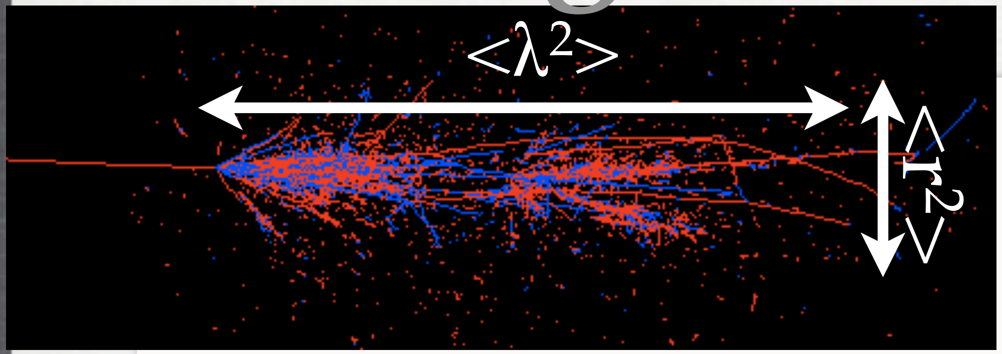




- Resolution (σ(Evis)/<Evis>) is not a good observable: <Evis> has steps, prefer to show σ(Evis)/Ebeam
- CHIPS smaller width
- QGSP_BERT: step at 10 GeV

FTFP_BERT and CHIPS: smooth.

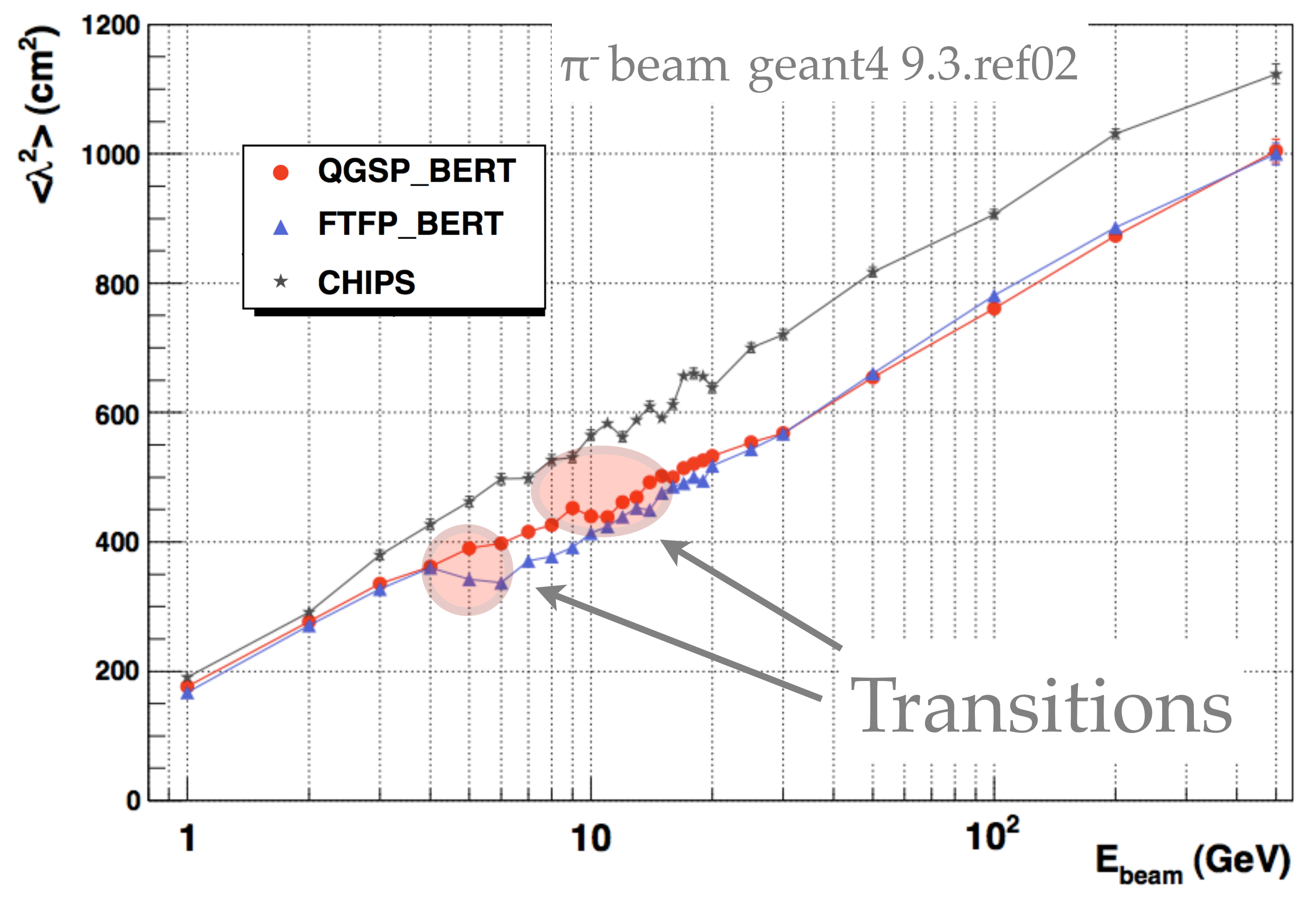
Longitudinal Shower Shapes



Shower shapes: weighted average of read-out cells position with respect to shower axis and shower center

$$< \lambda^2 >= \frac{\sum_{cell} E_{cell}\lambda^2_{cell}}{\sum_{cell} E_{cell}}$$

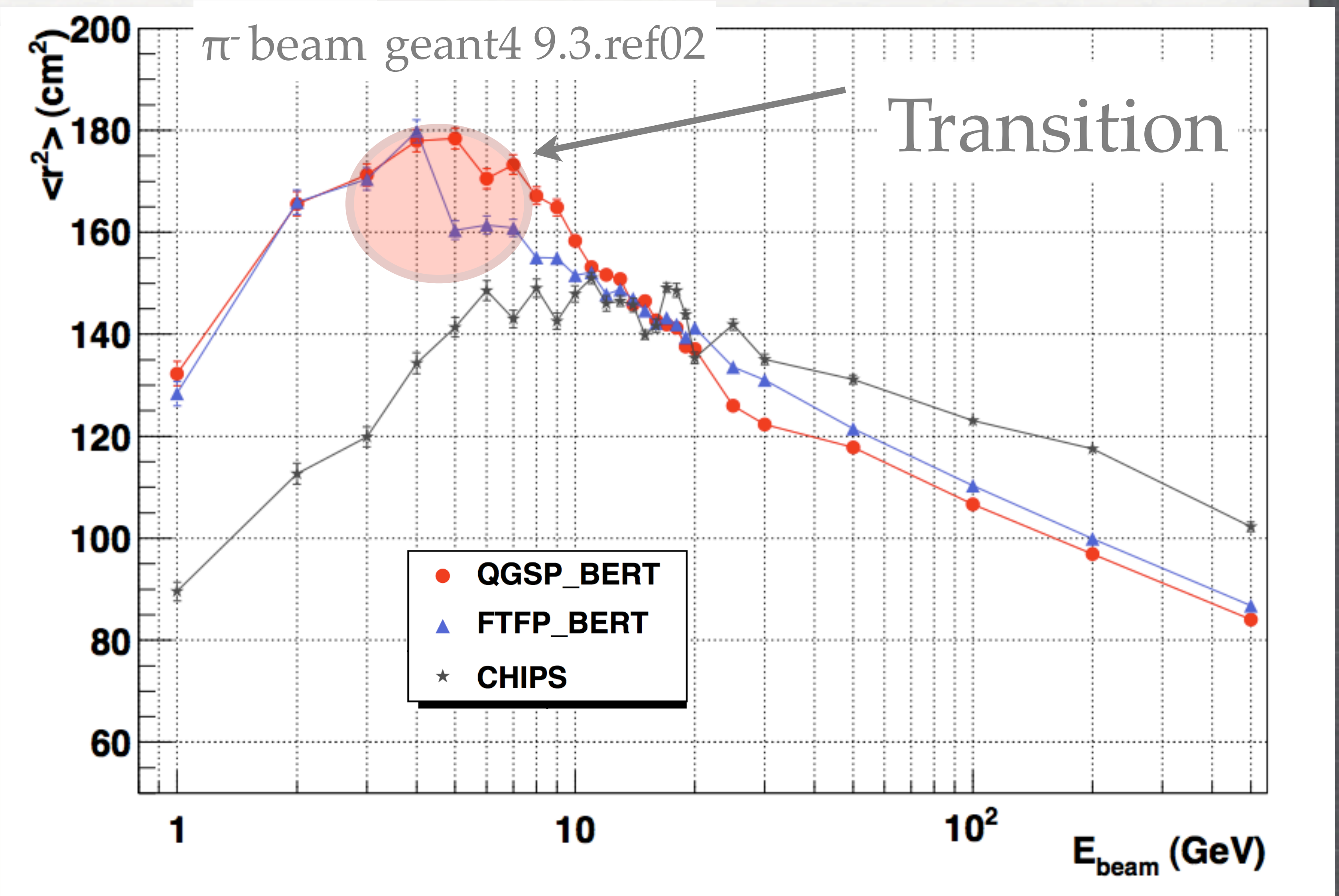
$$< r^2 >= \frac{\sum_{cell} E_{cell}r^2_{cell}}{\sum_{cell} E_{cell}}$$



- Bertini model (low energy) increases dimensions of showers
- Small steps at 10 GeV (QGSP_BERT) and at 5 GeV (FTFP_BERT) are visible
- CHIPS predicts longer showers at high energy
- Feedback from experiments: agreement (QGS_BERT) with test-beam data has improved in the last years, models predicting longer and wider showers should be preferred (G4 still 10-30% shorter)

Lateral Shower Shape

- QGSP_BERT is smooth
- FTFP_BERT has a step at 4-5 GeV (transition between BERT and FTFP): can be improved increasing transition region (under investigation)



- Compared with data (E>20GeV): FTFP_BERT and CHIPS better agreement with data
- FTF and CHIPS predicts wider showers at high energy and more compact at low energy
- Cascading is a fundamental ingredient to increase shower size and thus improve agreement with test-beam data

Conclusions

- Thin target experiments are the primary source of data for tuning models
- Agreement with test-beam data for response and resolution is O(few %)
- Agreement for shower shapes have much improved but still a bit shorter and narrower with respect to test-beam data (worst case: shower length for protons -30% at 10λ),
- Recent major improvements:
  - Fritiof model (available in FTFP_BERT physics list)
  - Extension of CHIPS components (available in CHIPS physics list)
- Main concern is discontinuities in response
  - Studied in detail during 2009, origin tracked down to use of parametrized model (LEP) in intermediate region: now providing option with reduced or no dependence on this (FTFP_BERT, CHIPS)
  - FTFP_BERT is smooth and agrees with QGSP_BERT for E_{kin}<9 GeV and E_{kin}>25 GeV

Challenges And Future Work

- At the moment two physics lists show the most promising results to solve these issues:
  - FTFP_BERT physics list (Bert < 5 GeV ; FTF > 4 GeV). Transition effect to be corrected in shower dimension. Very similar results to QGSP_BERT at high and low energies
  - CHIPS physics list: very smooth. Response is too high, results should be considered preliminary: still “experimental” physics list, ongoing validation and tuning with thin target data
- Expect further improvements in next months thanks to new data:
  - First comparison with LHC collisions
  - CALICE test-beams
- Other challenges: improve simulation of hadronic interactions for kaons, anti-p, hyperons
- Other possibilities being explored: example QGSP_FTFP_BERT (use of FTF instead of LEP)


Thank you!

BACKUP SLIDES

Geant4 Hadronic Working Group

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- Gunter Folger (CERN) - Working group deputy coordinator
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- G. A. Pablo Cirrone (INFN LNS)
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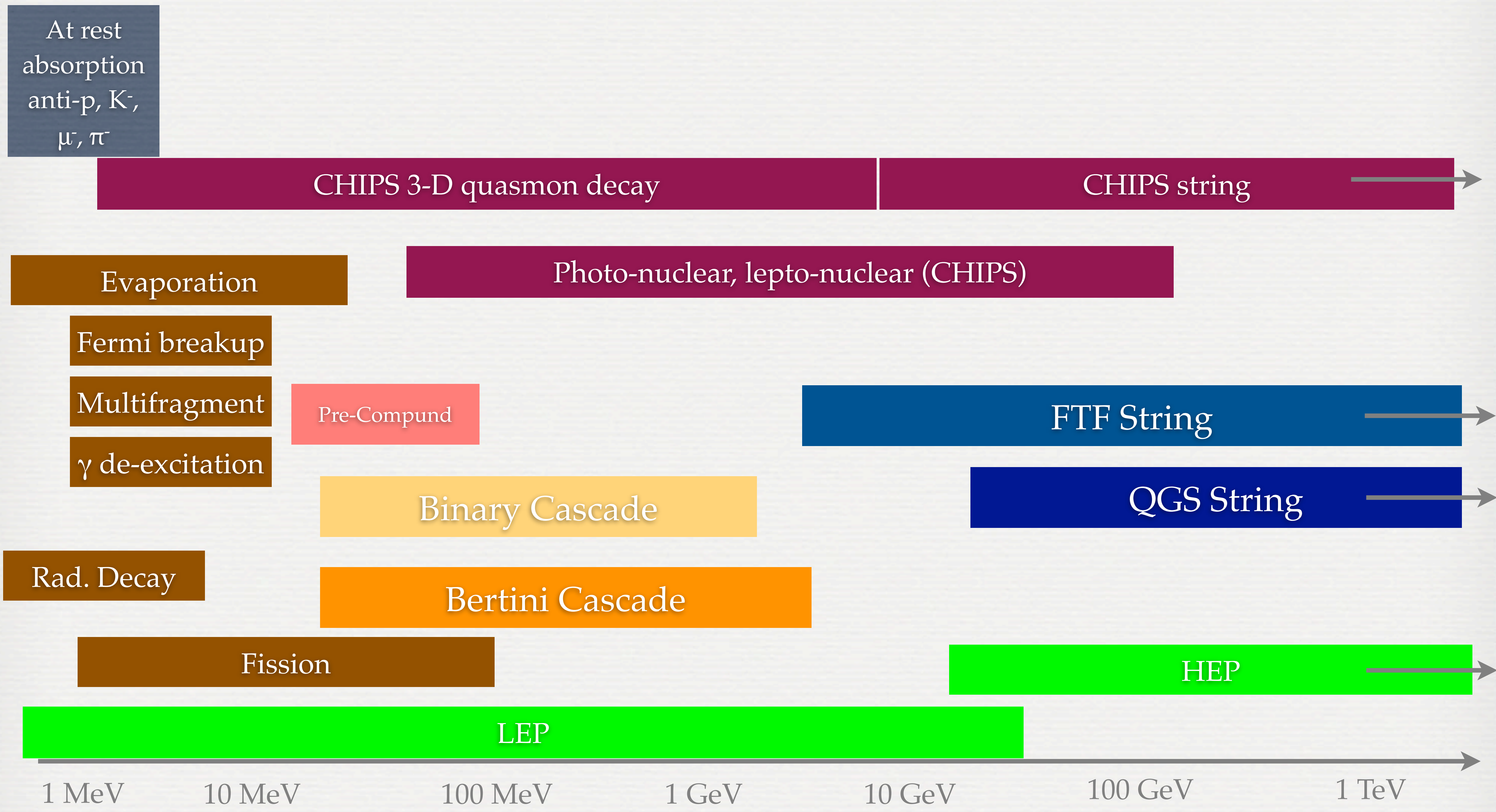
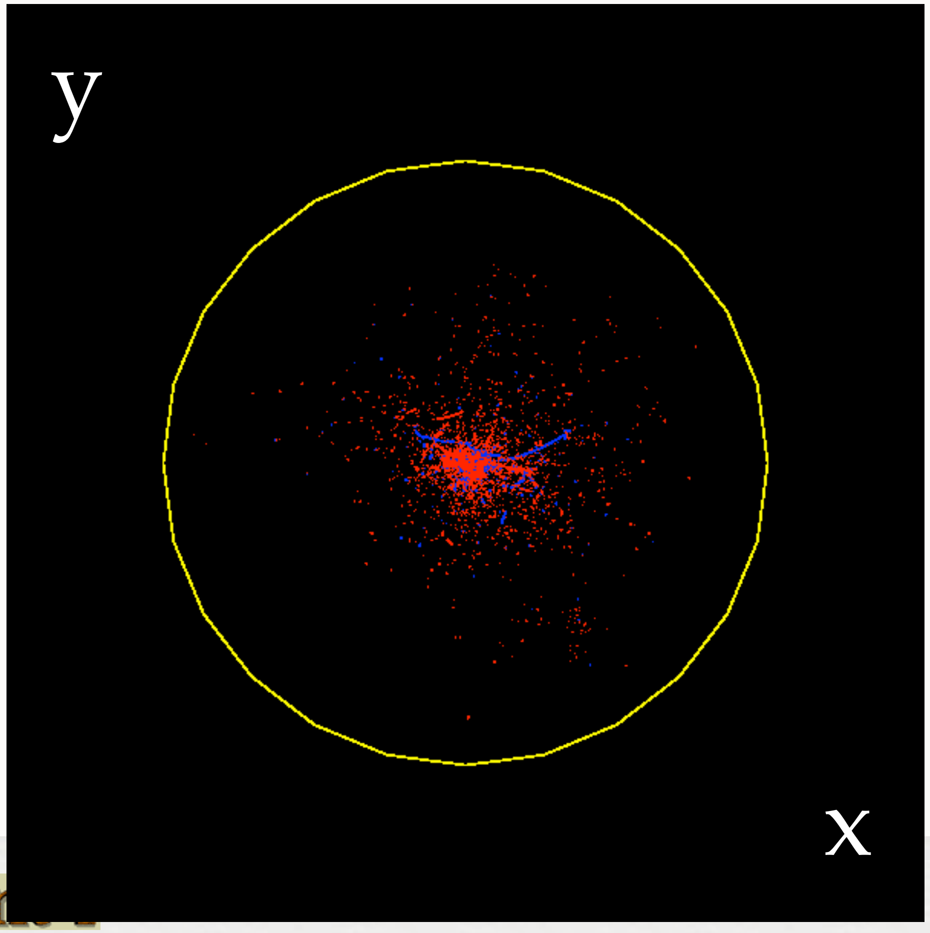
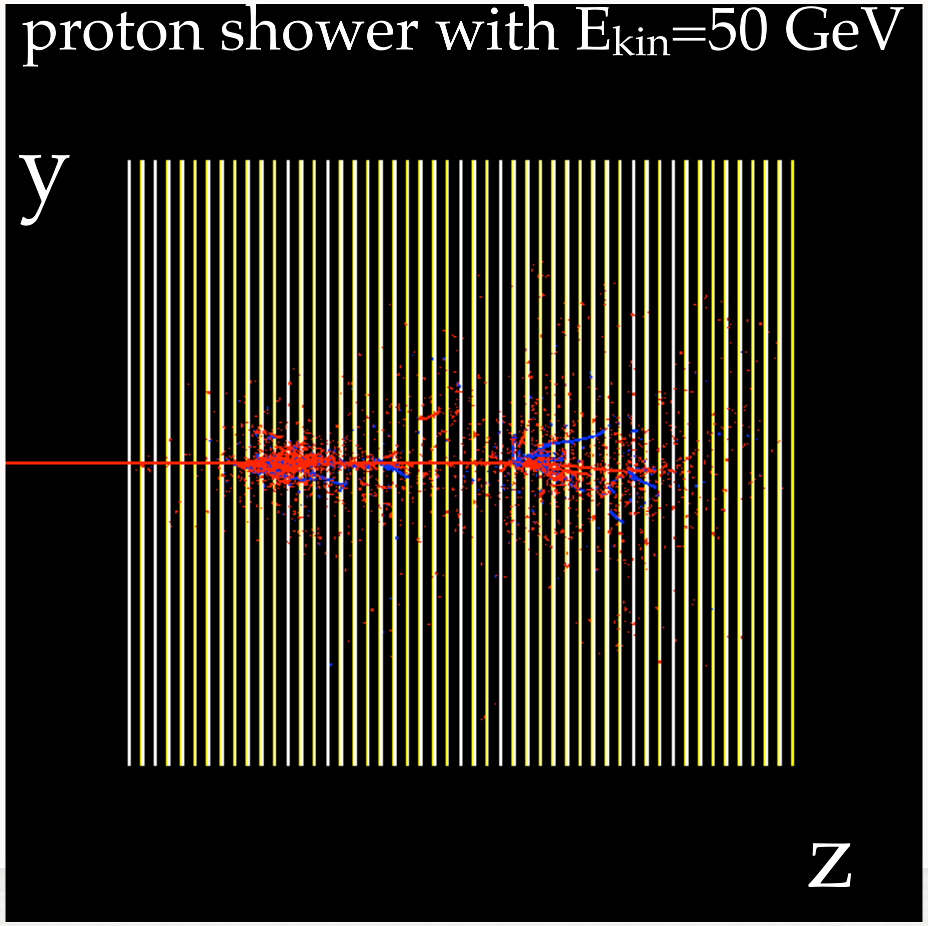
Hadronic Inelastic Interactions Models



Simplified Calorimeter

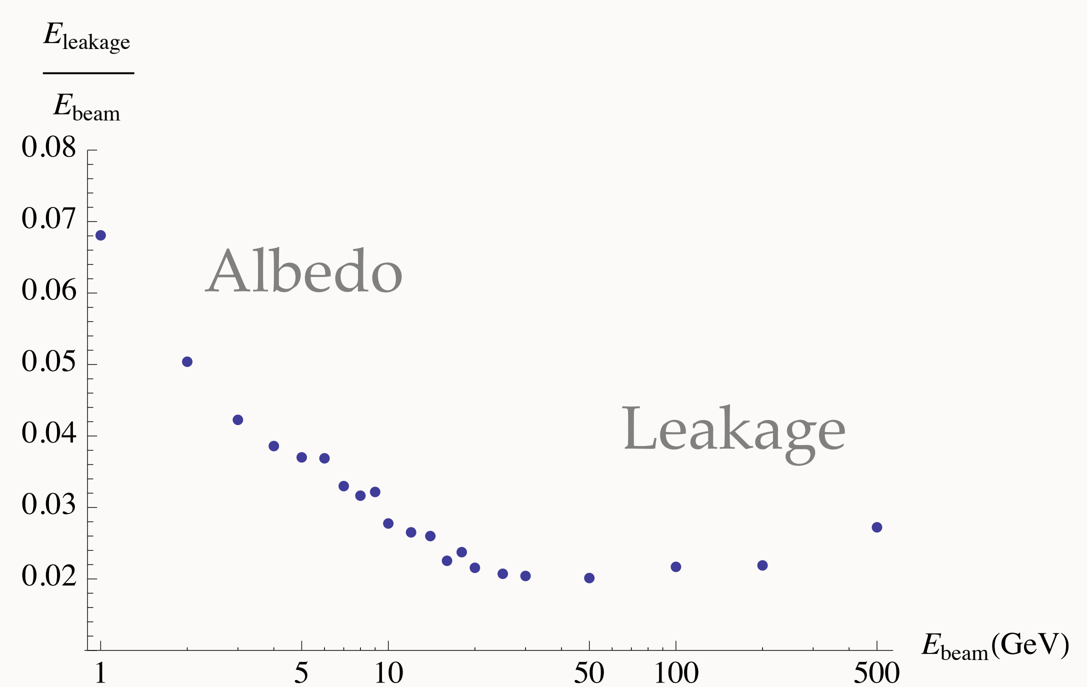
- Simulation of a cylindrical calorimeter 10 λ_I long
- All LHC calorimeters technologies are implemented: Pb/Sci, Fe/Sci, Cu/LAr, PbWO4
- Energy in active material is collected





Corrections And Systematics

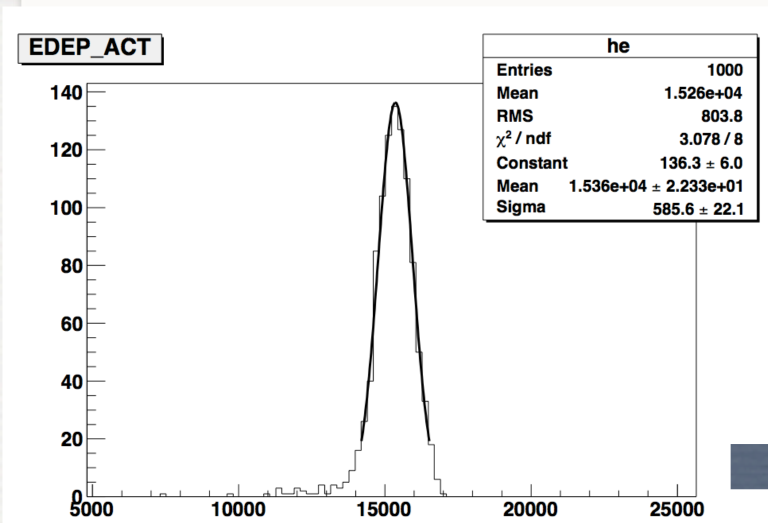
- There are two effects introducing a systematic error in the simulation of energy response: late energy deposits (slow neutrons) and finite dimension of simplified calorimeter
- A time cut at 50 ns (typical read-out timing of scintillator calorimeters) have been introduced: deposited energy depends softly from this cut (3% varying from 20 to 200 ns)
- Most important correction is leakage (front and longitudinal): O(1%), error on leakage is a fraction of stat error
- At low energy correction for (front)leakage becomes important

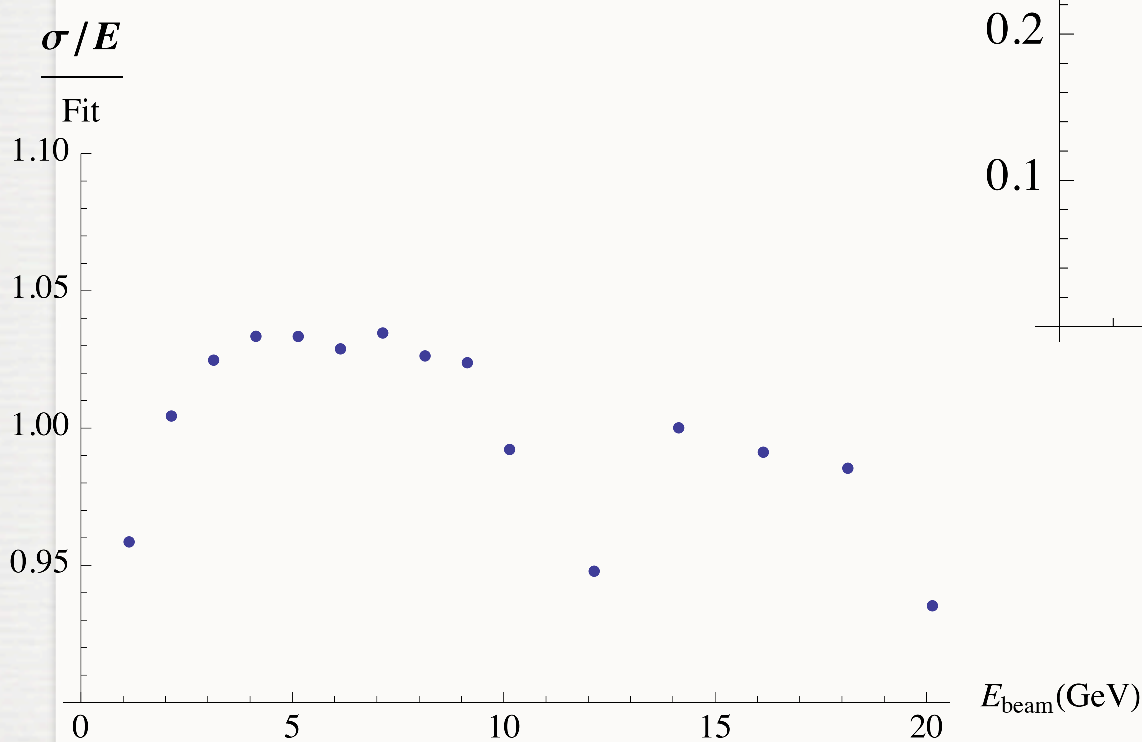


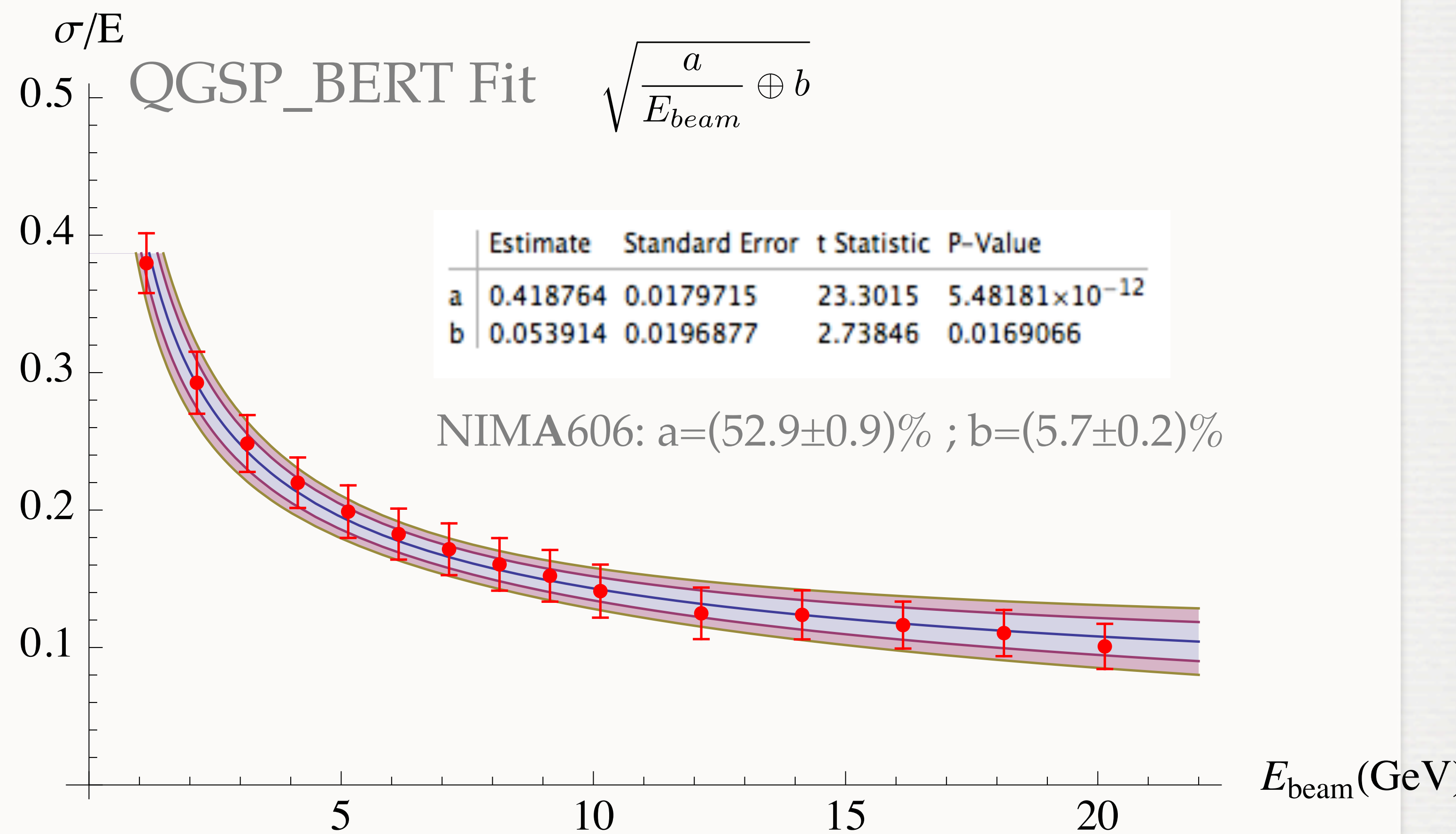
Neutrino and muon included! Effect on visible energy is reduced to less than half

Resolution Vs Width

- Response and width extracted from iterative gaussian fit around response peak of visible energy







	Estimate	Standard Error	t Statistic	P-Value
a	0.418764	0.0179715	23.3015	5.48181×10^{-12}
b	0.053914	0.0196877	2.73846	0.0169066

Modulation of residuals following transition regions: is this a problem in σ or in <E>? Need to look at both independently

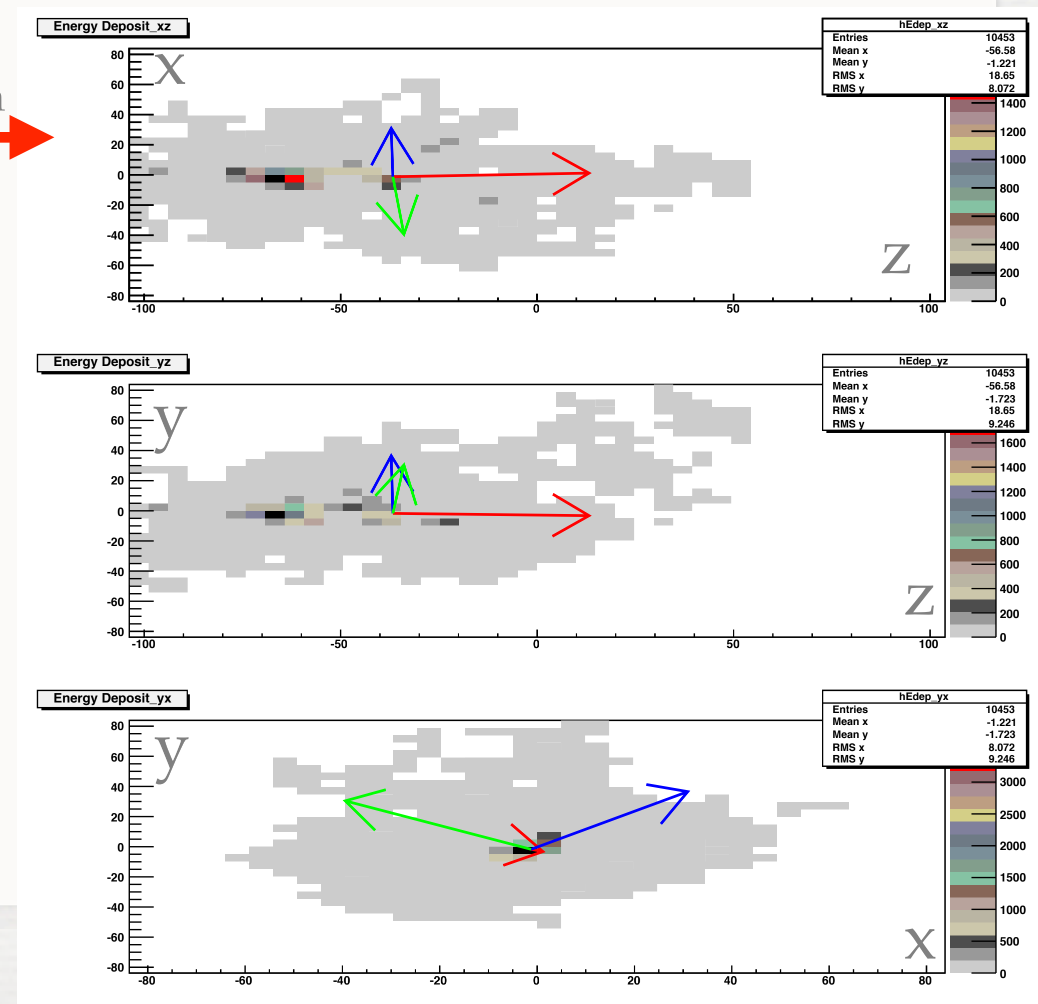
Shower Shape

1. Define "mesh" of voxels: pseudo-cells
2. Accumulate quantity for each voxel (energy deposit, energy density)
3. If an observable O can be defined for each voxel (e.g. energy, density, position) the n-th moment in O can be calculated:

$$< O^n >= \frac{\sum_v E_v \cdot O_v^n}{\sum_v E_v}, v \in voxels$$

4. Moments are often calculated w.r.t. shower center (<x>,<y>,<z>) and shower axis (principal component analysis)

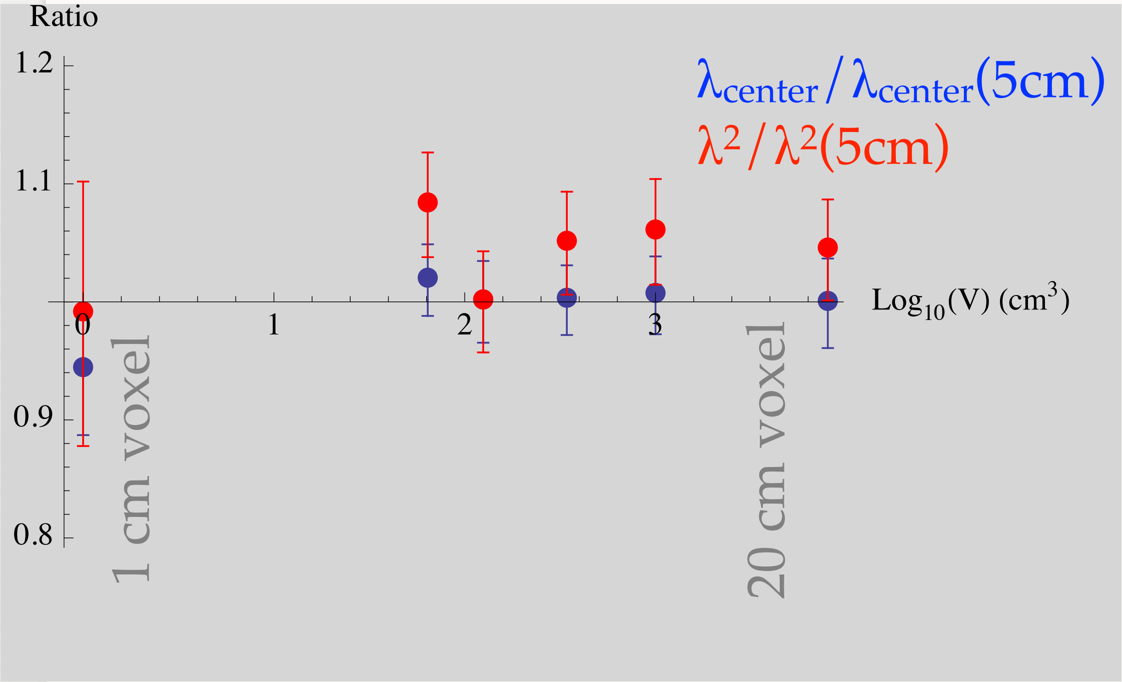
beam direction



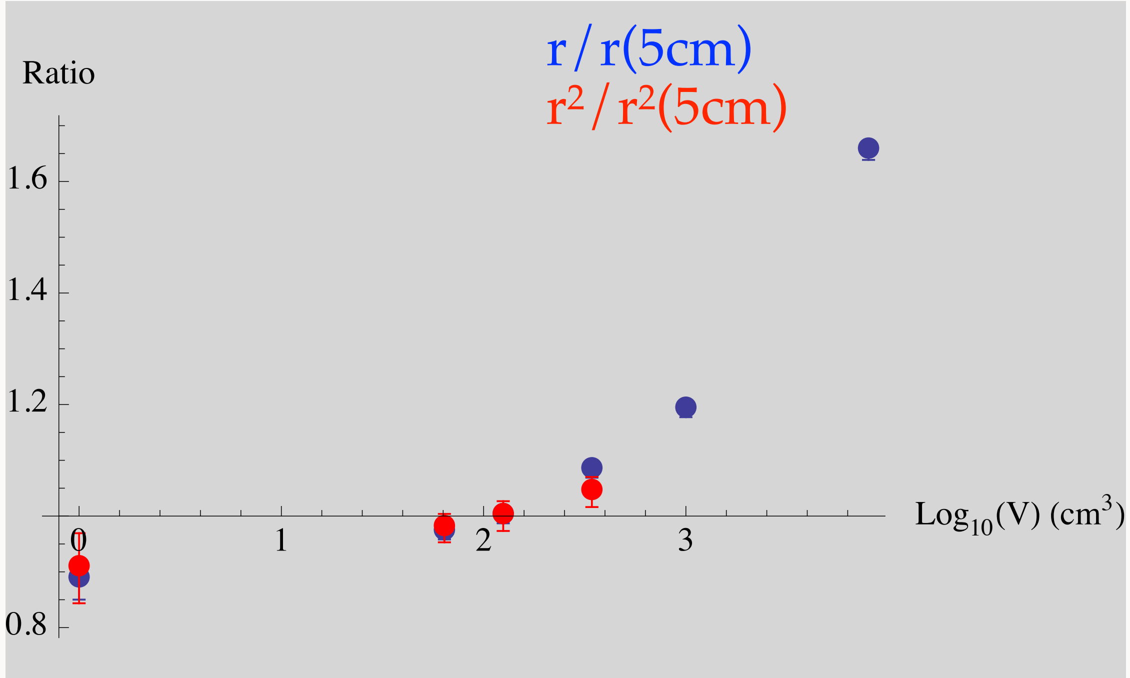
Original Idea from:
T. Barillari et al. ; Local Hadron Calibration; 2008 (CERN); ATL-LARG-PUB-2009-001

Shower Shape

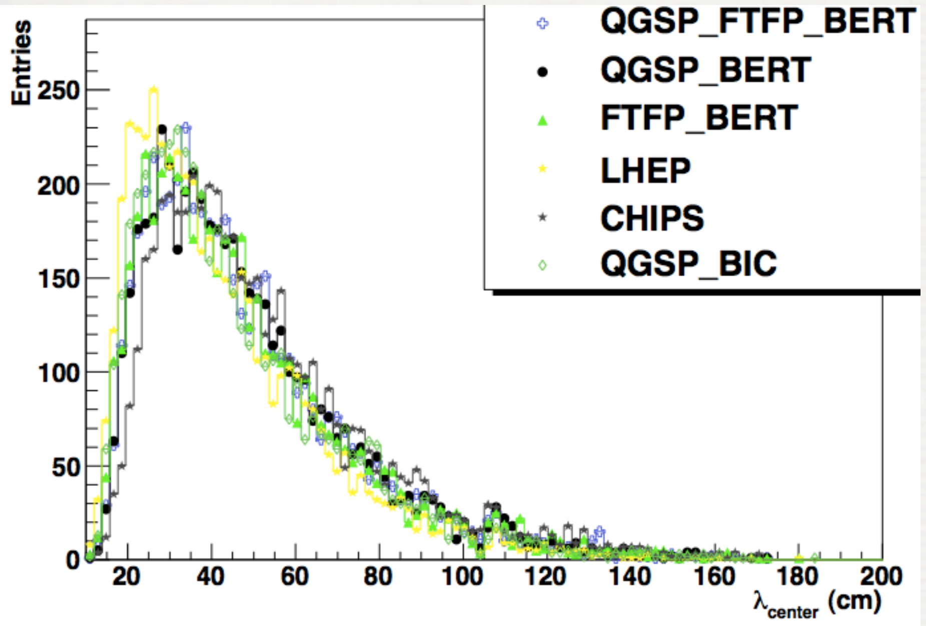
- Shower moments can be used to “summarize” the shower shape in few numbers:
  - λ_{center} : depth of the shower “maximum” w.r.t. calorimeter front-face
  - λ^2 : shower dimension along shower axis
  - r ,r^2: shower dimension in plane ortogonal to shower axis
- Long. shapes depend weakly from mesh size (<10%)
- Lateral shower shape depends weakly (<10%) from mesh size only for 1cm<size<10 cm. Prefer r^2 over r: less dependency on mesh size



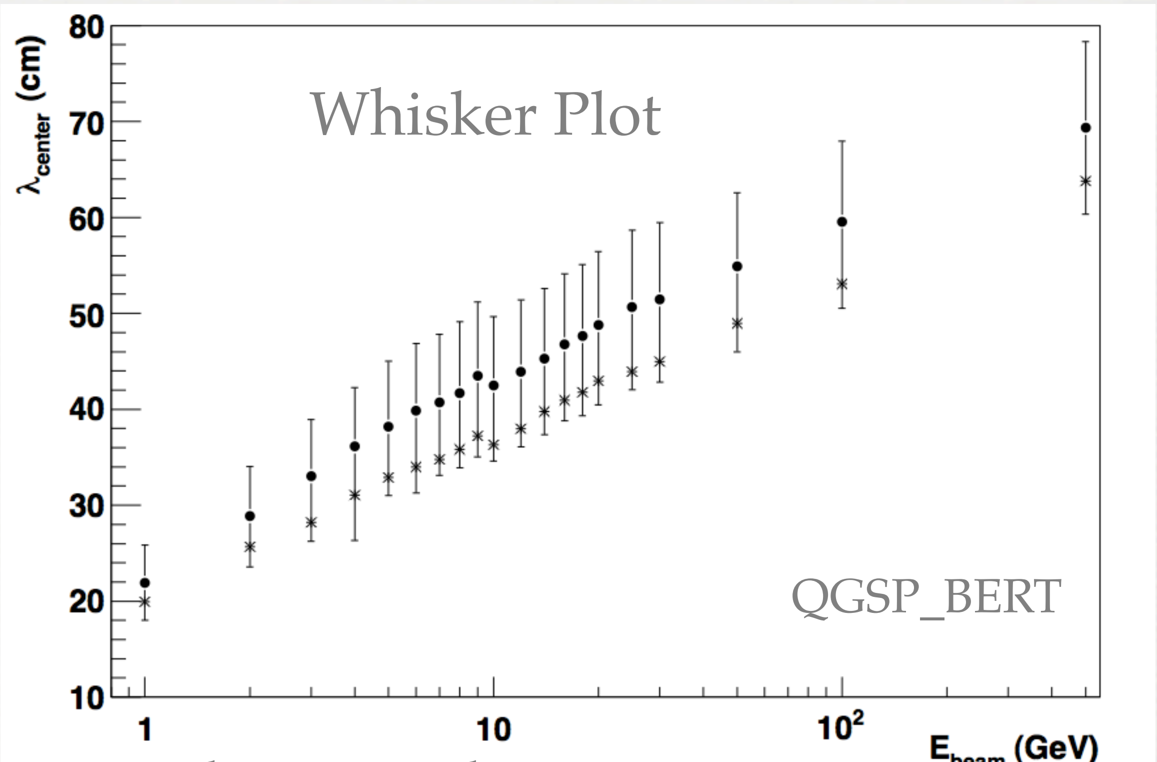
Systematic error O(5%) on shower shapes due to choice of a particular mesh size



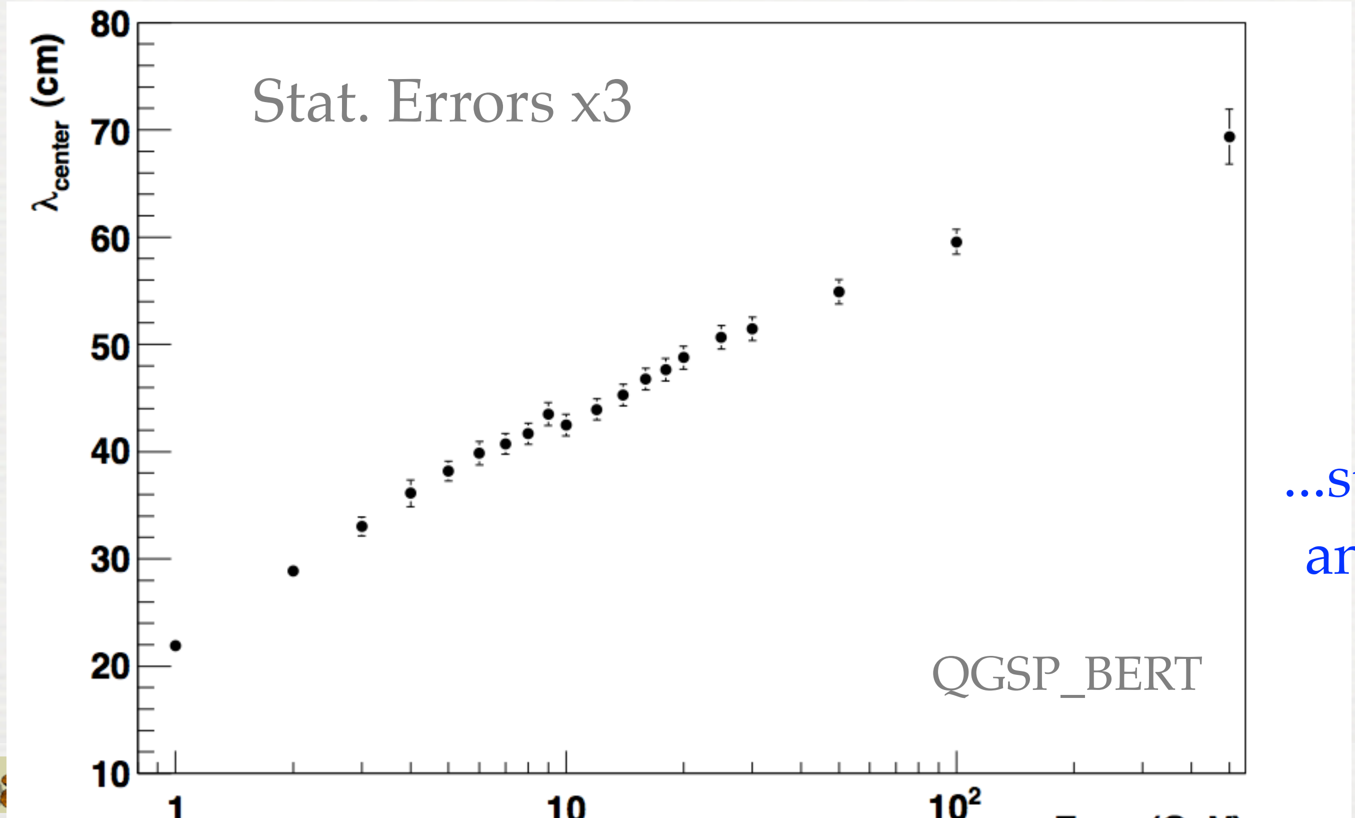
Shower Shape



Shower moments distributions present a long tail...

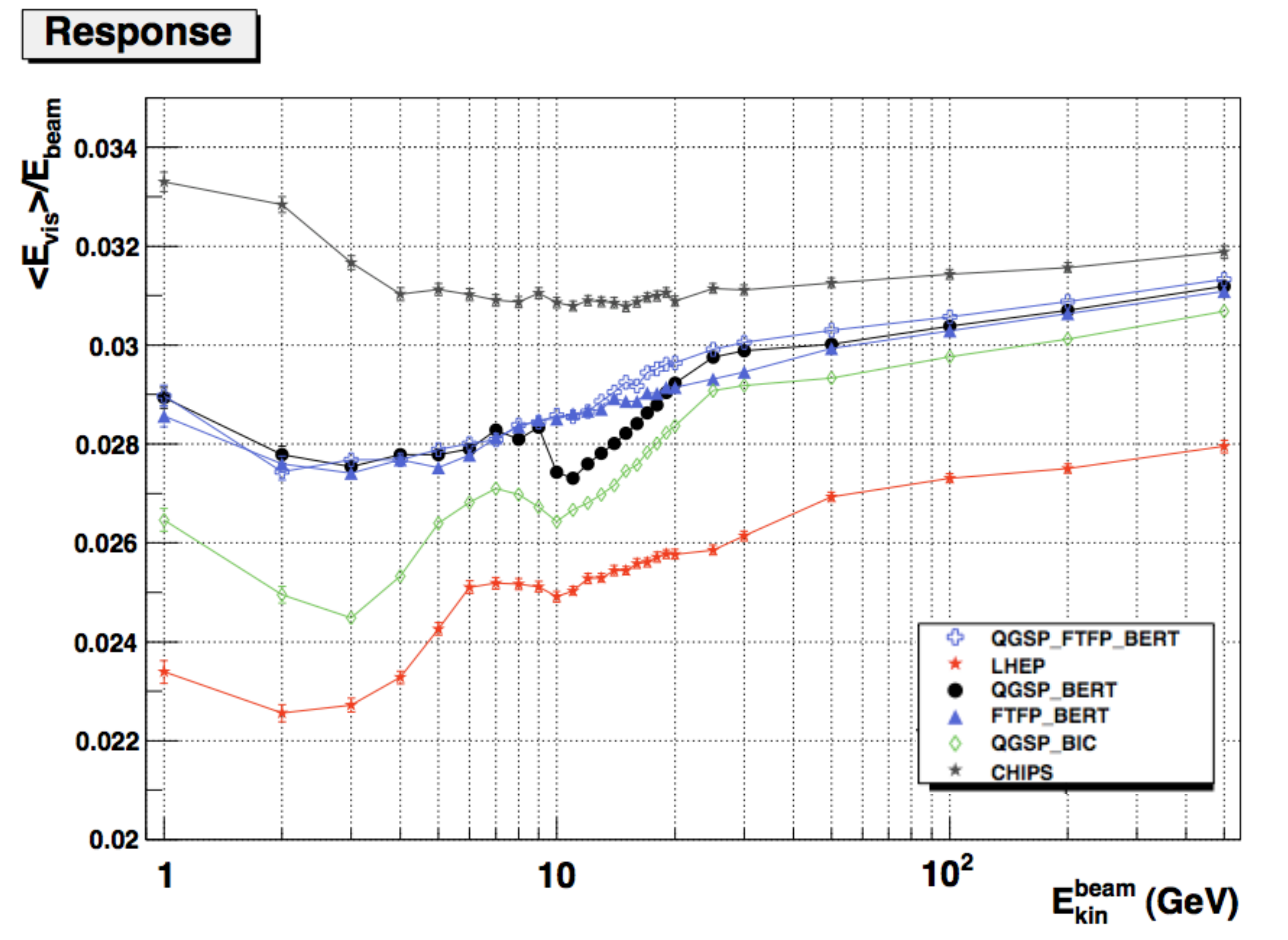


...however they are regular w.r.t. beam energy...



...stat. errors are small: plot mean and error on the mean Vs beam energy

Additional Physics Lists



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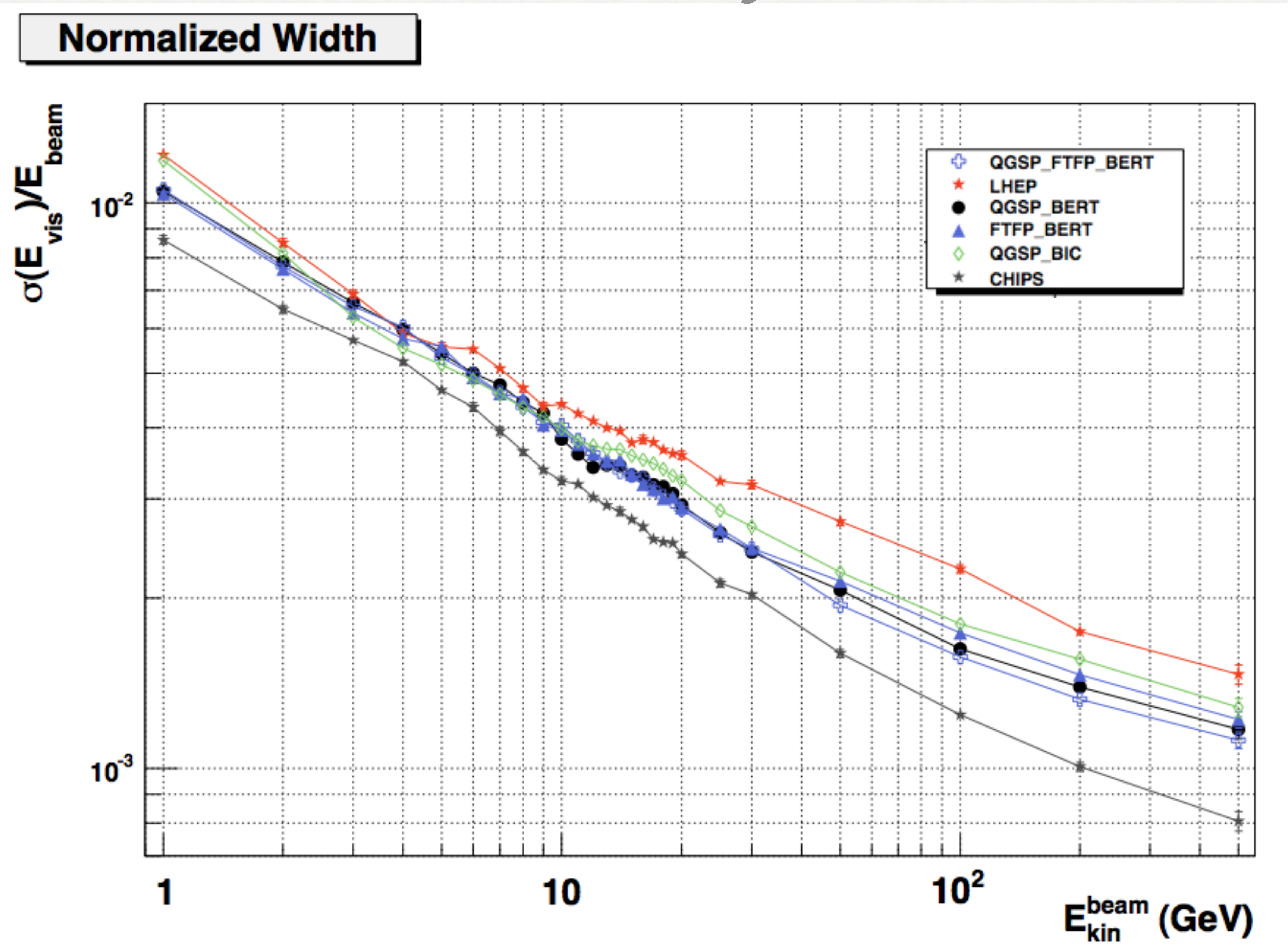

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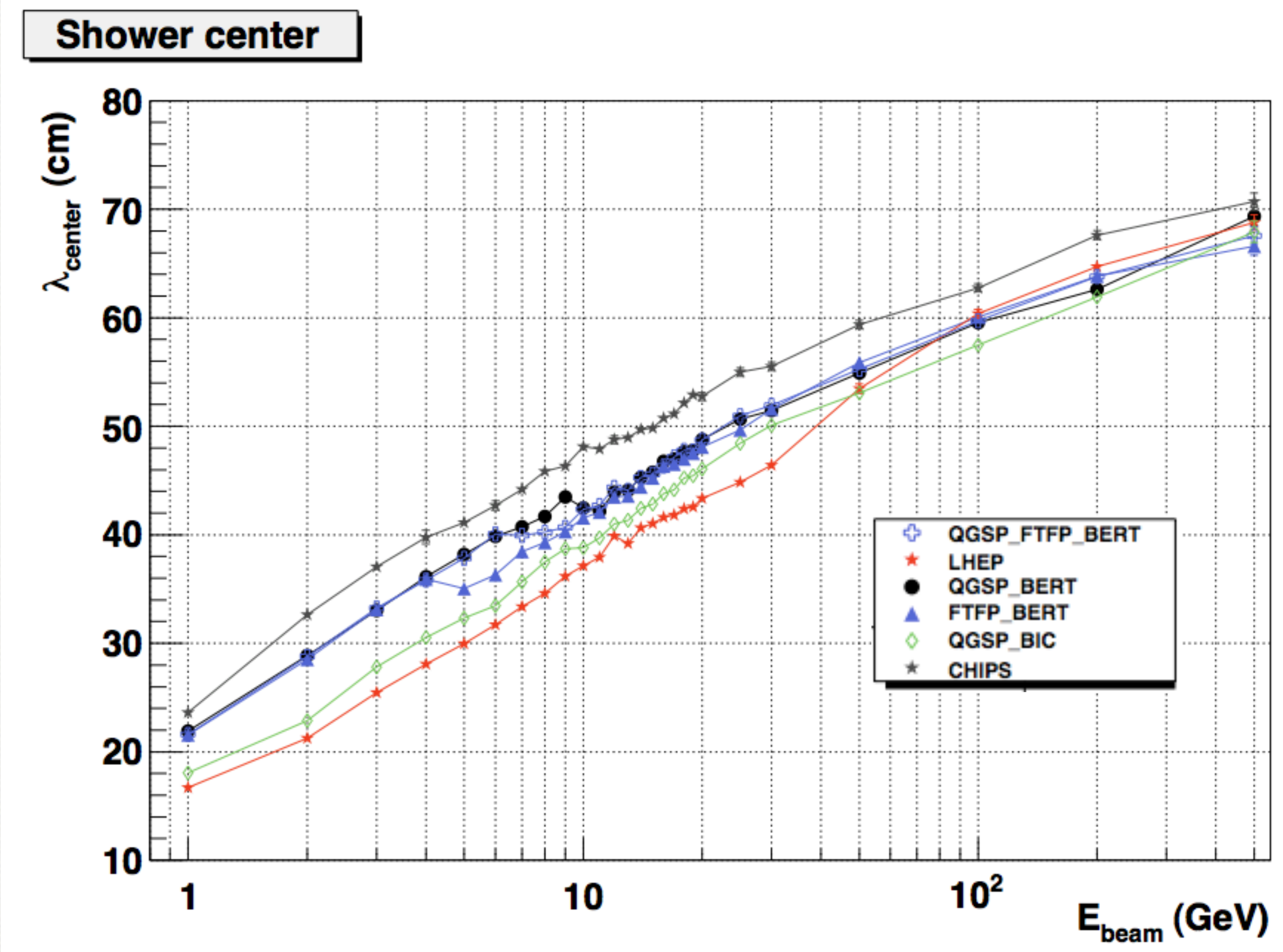

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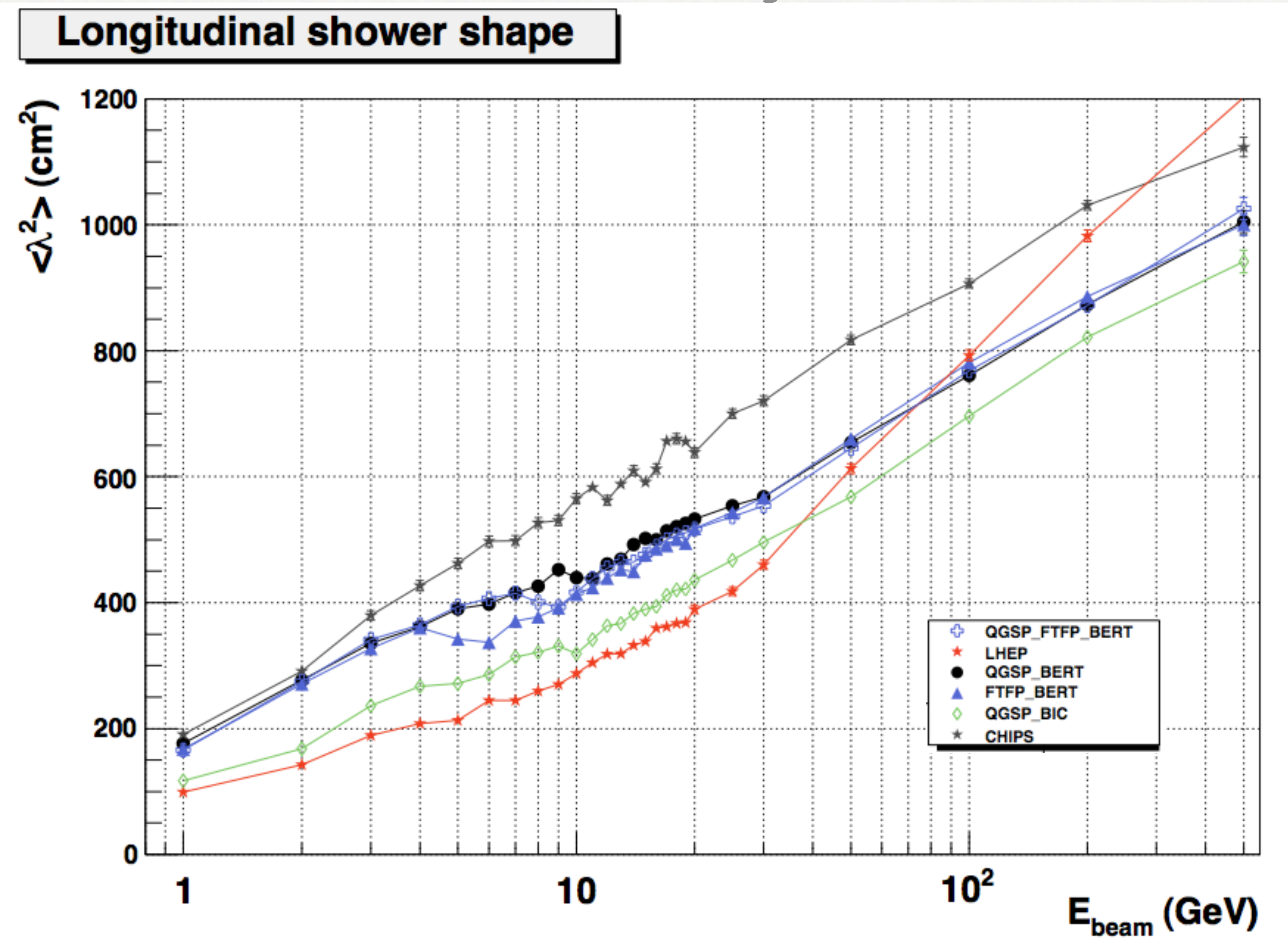

Additional Physics Lists