Highlights of Hadronic Physics for HEP

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Outline

- Status of String models
  - FTF
  - QGS
- Status of Intranuclear Cascade models
  - BERT
  - BIC : no development
  - INCLXX
- Status of Precompound/de-excitation
  (plus a few other things)

- Jet energy scale issue for ATLAS and CMS

String models

See talk in Parallel Session ***6A*** *by V. Uzhinsky*

Status of **FTF** (Fritiof) Model

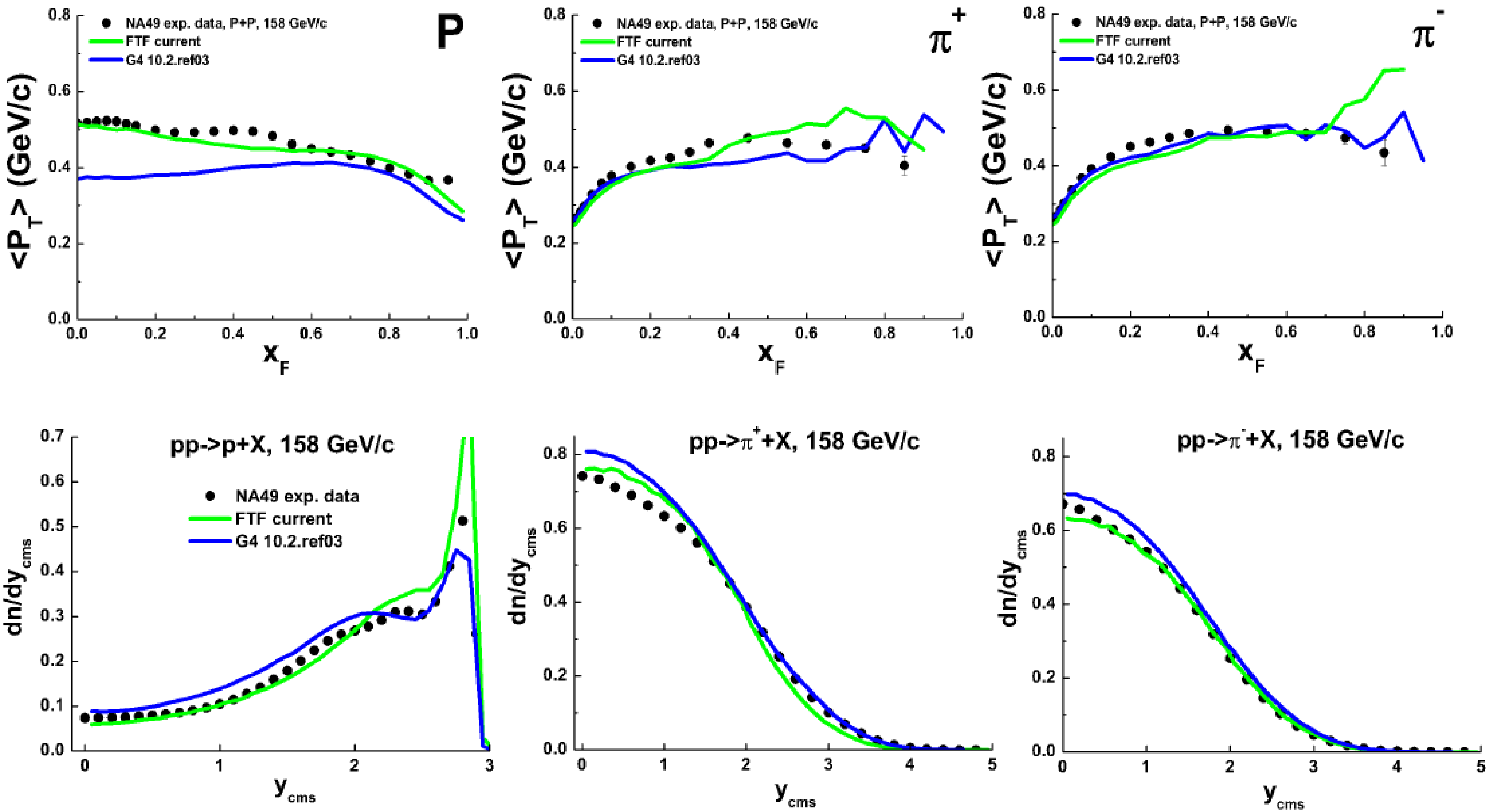
- Bug-fix and improved sampling in **nucleus-nucleus** interactions
- Improved anti-baryon **annihilations** (π^o, η, η' production)
- Improved treatment of Δ-isobars
- Improved parameterization of quark-exchange process with excitation
- Several improvements in string hadronization
- Refined tuning to improve the description of **NA49** and **NA61/SHINE** thin-target data

➡ Impact on hadronic showers :

- A bit higher energy response and narrower showers *w.r.t.* G4 10.2

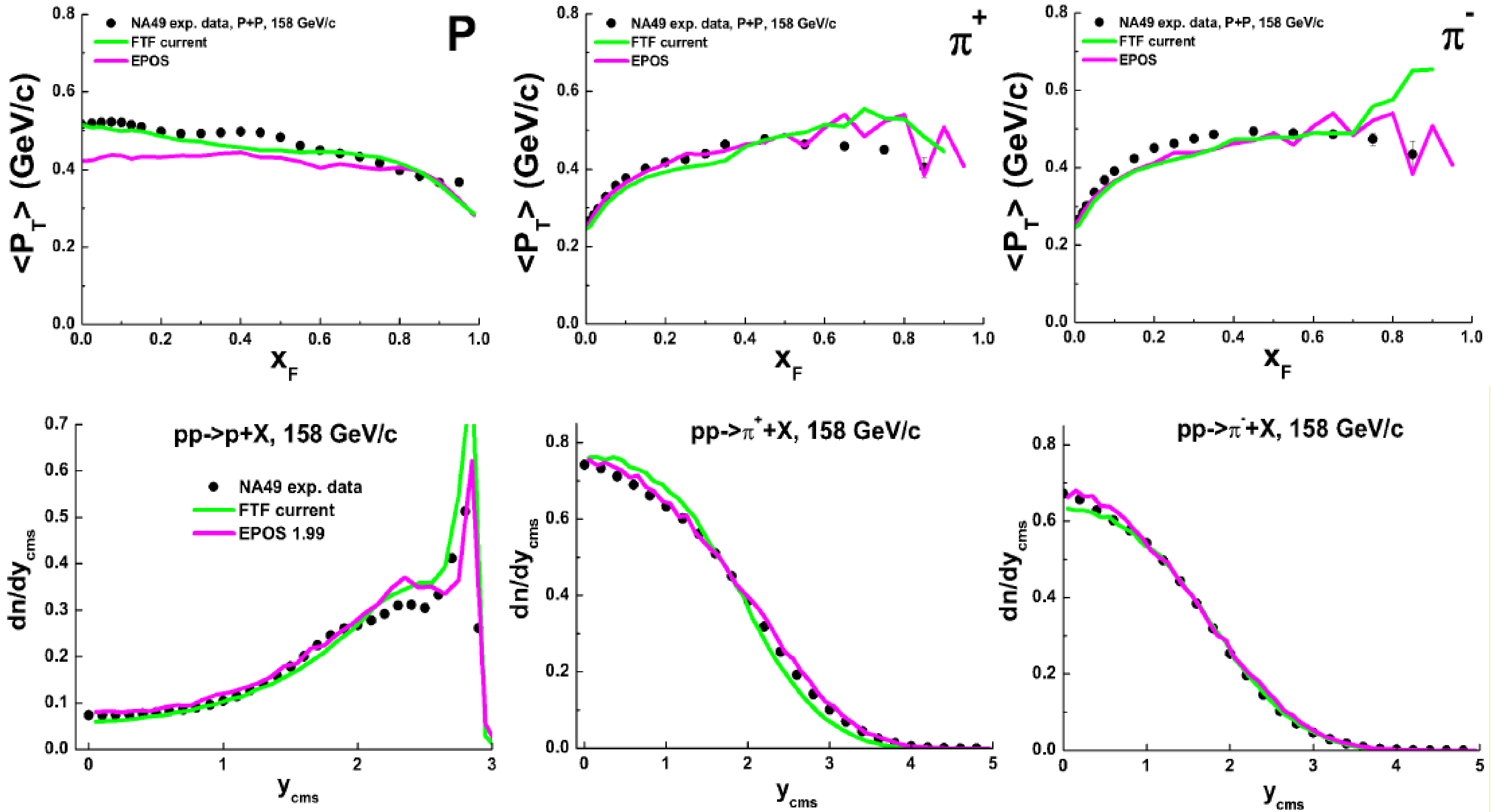
NA49 158 GeV/c p p → **h** + X

G4 10.2.**ref09** vs 10.2.**ref03**

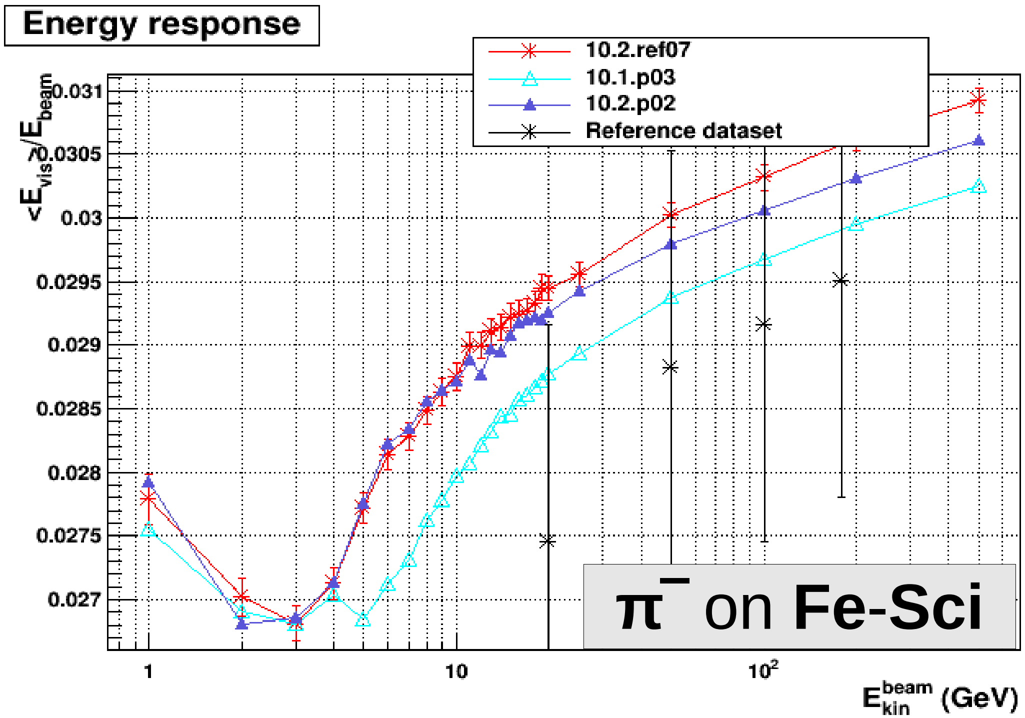


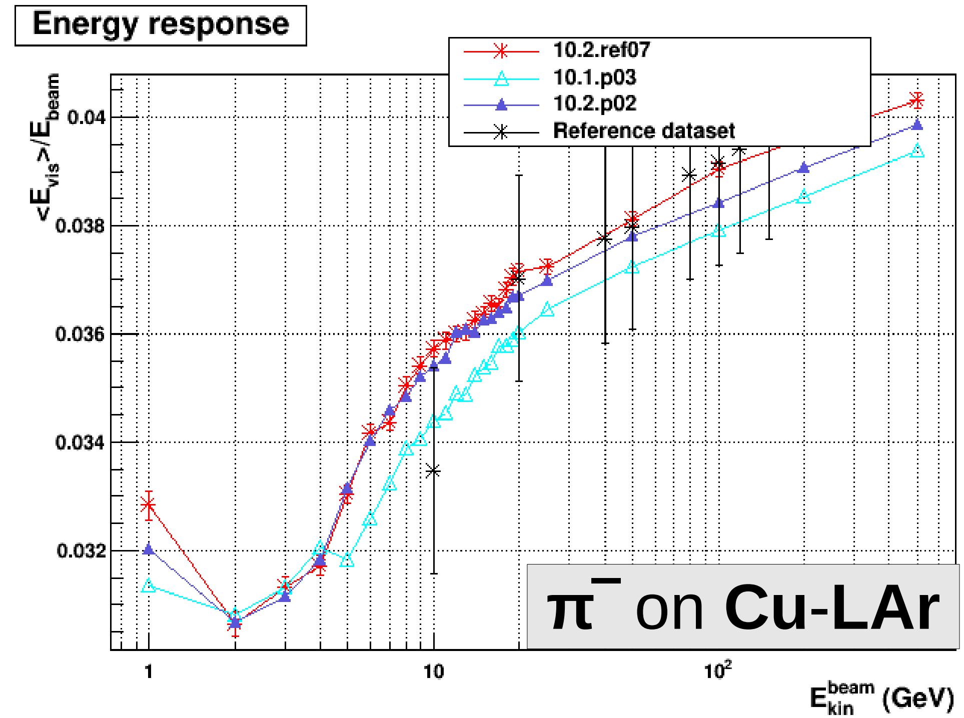
NA49 158 GeV/c p p → h + X

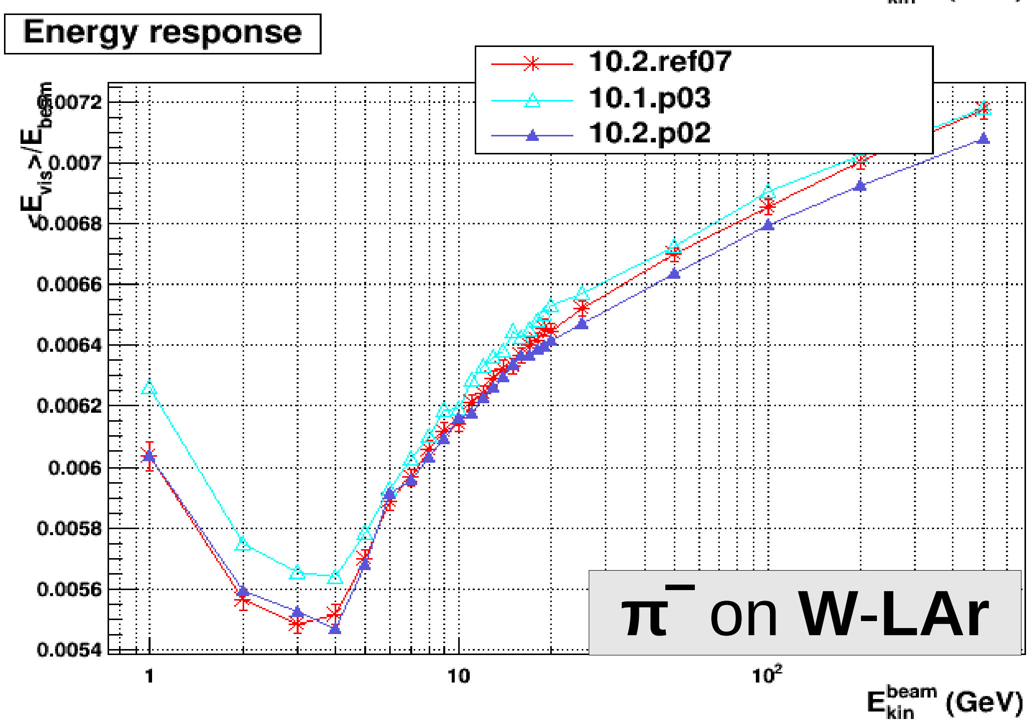
G4 10.2.**ref09** vs EPOS

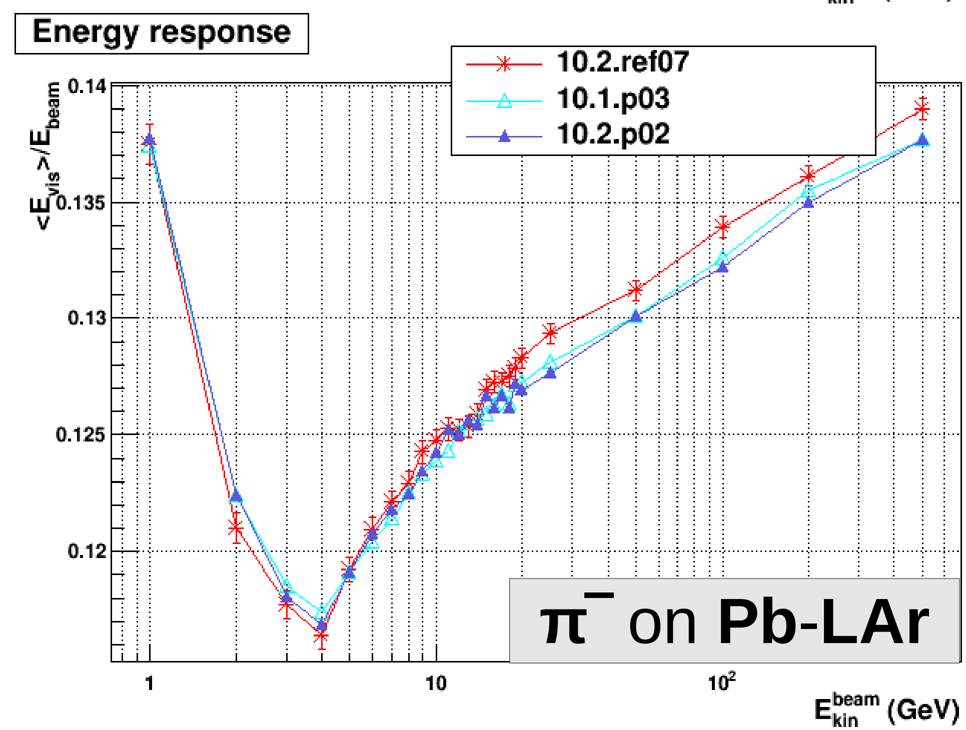


FTFP_BERT : Energy Response

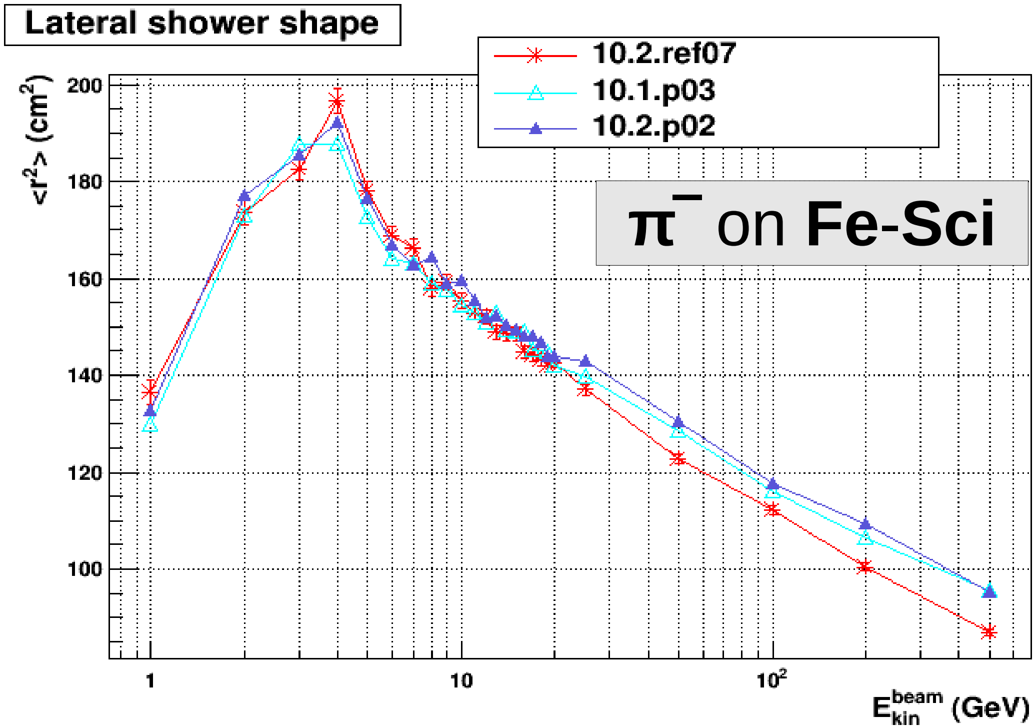


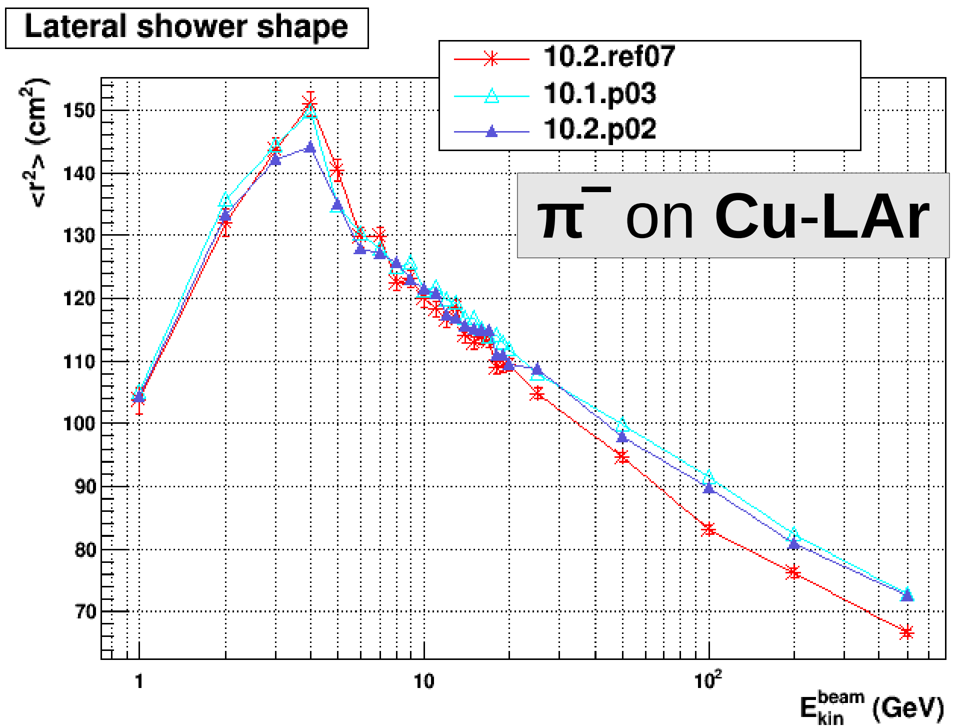


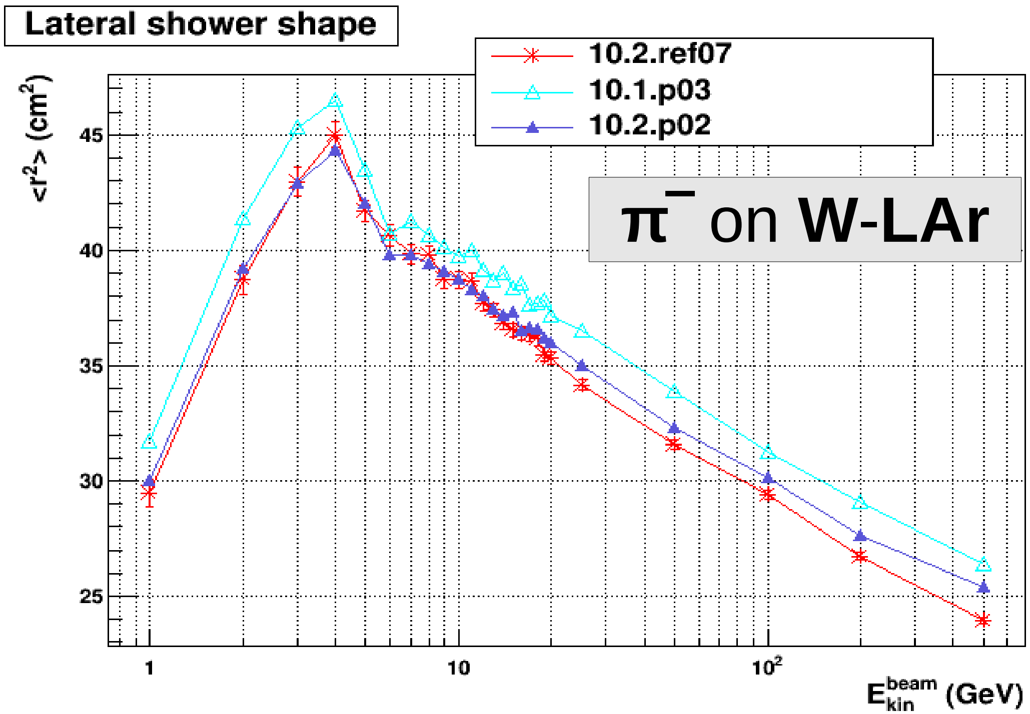


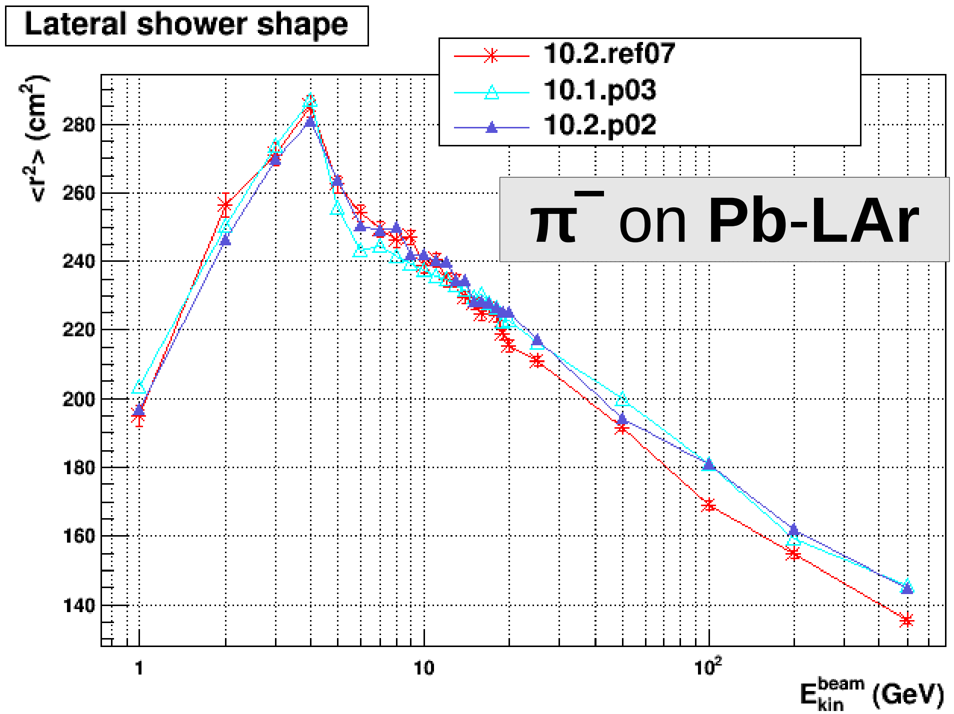


FTFP_BERT : Lateral Shape









FTF : Thin-target *vs.* Calorimeters

- Improvement of the model at the level of clean thin-target hadron-nucleon and hadron-light nucleus data
- For hadronic showers, the current FTF development (ref08)
  - has slightly higher energy response than in G4 10.2, with the latter already higher than in G4 10.1, hence in the wrong direction (more on this in the last part of this talk)
  - has narrower showers, hence in the wrong direction

  so, we expect **worse** hadronic showers than in G4 10.2 !
- The problem is that for calorimeters, medium and heavy nuclei are important, but, for these nuclei, the existing thin-target experimental data are fewer and less precise, and therefore the models cannot be constrained quite well...

FTF in G4 10.3

We have 3 practical possibilities:

1. Release FTF as it is – with bad hadronic showers – but prepare internal tags to apply on top of it for the LHC experiments to improve the hadronic showers "by hand"
   - Need to test them and keep them in sync. with patches
2. Release FTF including these tags to improve the hadronic showers "by hand"
   - Special tags for thin-target applications & model developm.
3. Release FTF as it is – with bad hadronic showers – but with special physics lists for the LHC experiments to get better hadronic showers "by hand"
   - Need to be able to steer FTF parameters from a physics list

Status of **QGS** (Quark Gluon String) Model

- The QGS model of Geant4 has been successfully used in production for several years by ATLAS and CMS simulations
  - In particular for all Run 1 analyses, including the Higgs discovery
- After the improvements and low-energy extensions of FTF model made by V. Uzhinsky, FTF became the recommended string model in Geant4 for high-energy applications
  - It is used for Run 2 analyses by all LHC experiments
- Still, there are two main reasons to keep developing QGS

1. For evaluation of systematic errors, to compare against FTF
2. For its potential applicability up to slightly higher energy than FTF

   - QGS is more theoretically motivated than the phenomenological FTF model
   - Might be relevant for the increased LHC energy: 7-8 TeV --> 13-14 TeV, and even more for FCC @100 TeV
   - But QGS cannot be applied to much higher energies than few TeV : it does not included hard scattering (*i.e.* jet production) (the same applies for FTF as well)

QGS String Fragmentation

- In 2014, V. Uzhinsky made the first step in the revision of the Geant4 QGS model: the string fragmentation
  - The quark and diquark fragmentation functions (in G4 10.0) were significantly different with respect to Kaidalov's prescription
  - Kaidalov argued that the use of fragmentation functions extracted from e+ e- annihilation or in deep inelastic scattering is not justified in soft processes, and inconsistent with Reggeon theory
  - Vladimir changed the fragmentation functions of Geant4 QGS to bring them consistent with those recommended by Kaidalov
  - This development was included in G4 **10.1**
  - Although not driven by experimental data, the new QGS string fragmentation improved the description of some thin-target data
- Significant impact on hadronic showers
  - lower energy response, bigger (longer and wider) showers
  - closer to the hadronic showers of FTF model

QGS String Formation

- In 2015, V. Uzhinsky has improved and extended the QGS model regarding the formation of quark strings
  - Inclusion of the Reggeon Cascade, as in FTF
  - Rewriting of the sampling of parton momenta
  - Improvement of the Fermi motions of target nucleons
  - Inclusion of the multi-pomeron exchange
  - More accurate preparation of the excited nuclear remnant
  - These developments have been included in G4 **10**.{**2**,**3**}.**beta**
- A very important thing which is still **missing** – planned for 2016 – is the **tuning of the parameters**
  - Currently the parameters are left as they were, often quite different from the values used in other modern QGS implementations
  - Consequently, the thin-target data were not well described, and therefore we did **not** include it in the public release G4 **10.2**

QGS in G4 10.3

- V. Uzhinsky is currently working on the re-tuning of the parameters of QGS, based on thin-target data
  - A bit behind schedule due to bug-fixes and improvements in FTF
- If we get good results in time for the release, then the new QGS will be included in G4 10.3
- Else, the old QGS final-state model will be released
  - as we did for G4 10.2

Intranuclear Cascade models

*See talk in Parallel Session **6A** by J.C. David*

Bertini-like (BERT) model

- For G4 **10.3**
  - Complete extension of kaon interactions from ~5 to ~15 GeV
    - Required addition of 8- and 9-body final-state partial cross sections, and inclusion of data up to 32 GeV to get correct behaviour
    - Reactions enabled: K+ , K- , K0 , K0bar on p , n
  - No longer do filtering of low-energy gamma-nuclear final-states by default: too time consuming
- For G4 **10.4**
  - Re-tune for gamma-nuclear interactions with larger data set
  - Examine de-excitation code for bug: may be the cause of over-production of neutrons

INCLXX model

- A reaction code in Geant4
  - 10 MeV → 10÷15 GeV

  followed by a de-excitation code
- Until 2010-2011, up to 2÷3 GeV ;
  then, with multi-pion channels: up to 10÷15 GeV
- But other particles are produced as well
  - eta , omega …   (2016)
  - kaons , hyperons (2017)

  which have minor roles, but could be useful to probe New Physics

INCLXX : why **η** , **ω** ?

- A necessary step towards kaons and hyperons
- To understand the role in pion production (decay product)
- Source of di-leptons (useful for studying nuclear matter)
- To study rare decays violating a conservation law

INCLXX : Ingredients

- Cross sections
  - Production : $\pi N \rightarrow \eta(\omega)N$; $NN \rightarrow NN\eta(\omega)+X$
  - Elastic scattering : $\eta(\omega)N \rightarrow \eta(\omega)N$
  - Absorption : $\eta(\omega)N \rightarrow \pi N$; $\eta(\omega)N \rightarrow \pi\pi N$

Parameterization from:
- Fit on experimental data
- Fit on models
- Previous parameterizations

- Features of the reaction products
  - particles, energies, angles

Parameterization from:
- Fit on experimental data
- Fit on models
- Isotropy
- Phase Space

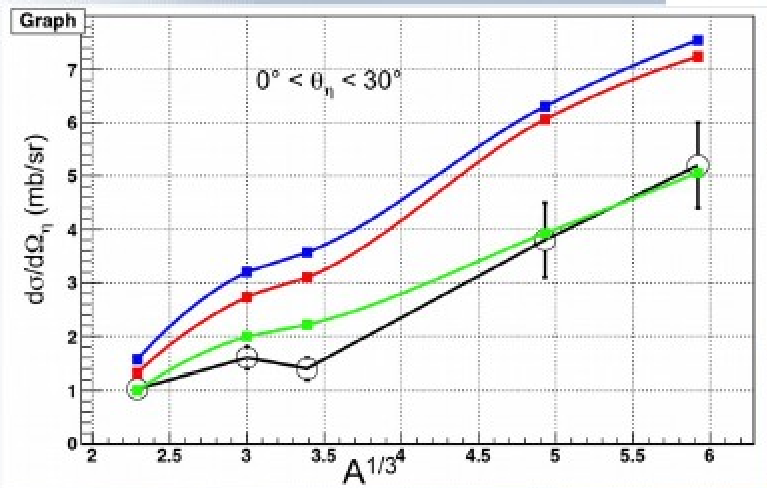
- In-medium potential (few information)

- Decay

INCLXX : Results on η Production

π⁺(680 MeV) + X

NPA 562 (1993) 389

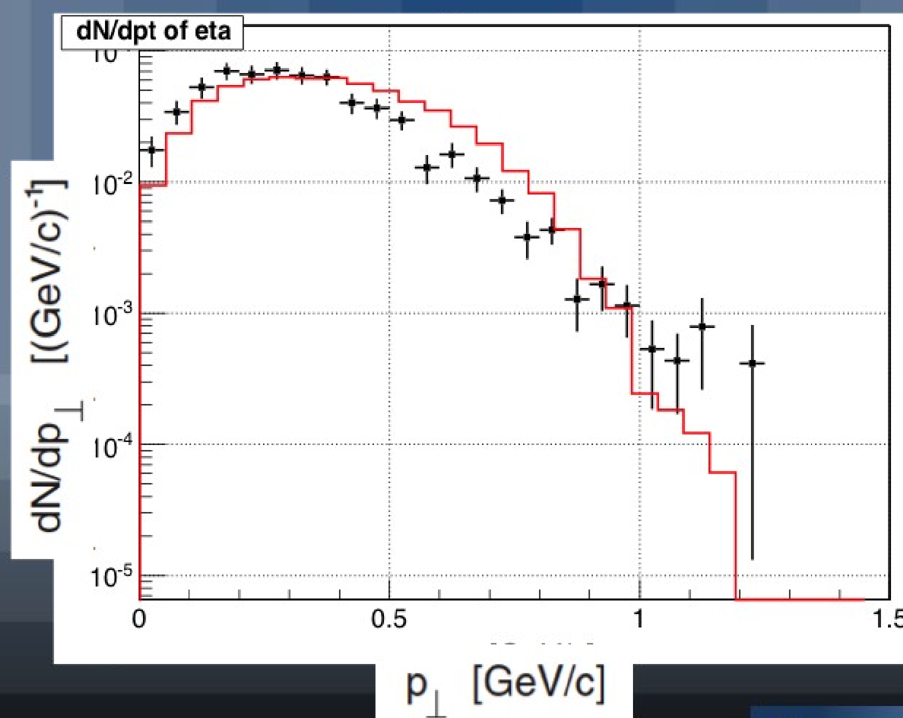


Good results with V_η=0

p(3.5 GeV) + Nb

HADES collaboration

PRC 88, 024904 (2013)



Pretty good!

Geant 4
21st Collaboration Meeting
12-16 September 2016

Precompound/de-excitations
+
a few other things

*See talk in Parallel Session **6A** by V. Ivanchenko*

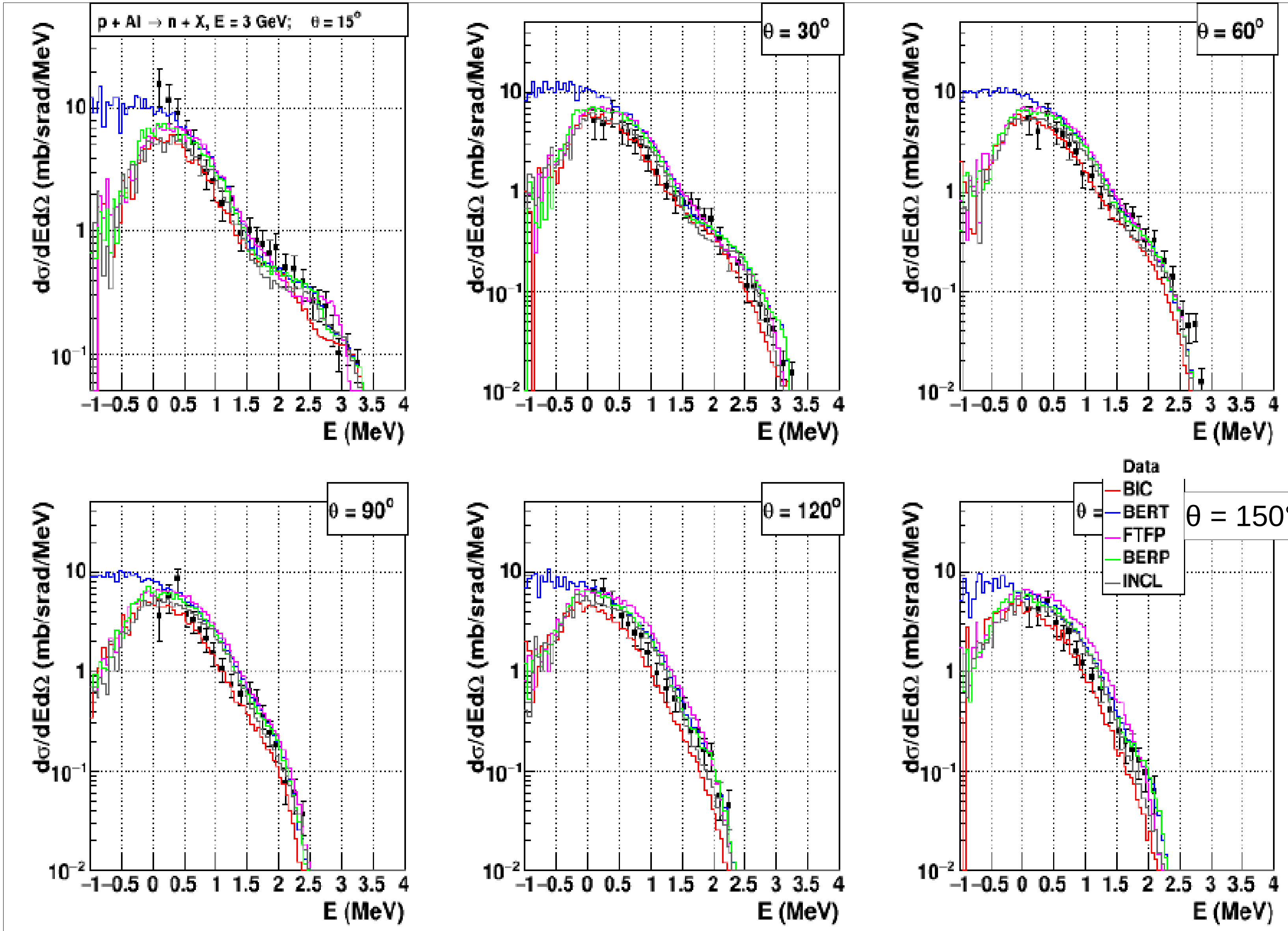
Status of Precompound/de-excitation

- Available interface to change Precompound/de-excitation parameters
  (only from the master thread)
- Reduced number (8) of default evaporation channels
  (no GEM channels by default → better CPU performance for HEP applications)
- Coulomb barrier classes now shared and available to all sub-models
- New, validated class **G4FermiBreakUpVI** is the current default
  (based on the nuclear level structure from G4LEVELGAMMADATA; no hardcoded energies or other parameters any longer, which is important for reproducibility)
- New class **G4GEMChannelVI** ready but not yet validated
  (expected for G4 10.3)
- Improved and extended class **G4PhotonEvaporation**
  (most radioactive decay transitions are now correct;
  possibility to have correlated gammas: not yet tested, but expected for G4 10.3)
- CPU and memory performance of the de-excitation module has improved, allowing to be used also by the Bertini cascade model

Integral Approach

- Added the so-called "Integral Approach" in the sampling of hadronic interactions, in the base class G4HadronProcess of hadronic processes
- Integral approach is used since a long time in EM
  - Published in *Radiation Physics and Chemistry 78 (2009) 859*
- The idea of the method is to take into account the eventual change of cross section between the pre-step point and the post-step point, due to the energy loss of a charged hadron along the step
  - In EM, this is implemented for all cross sections
  - In HAD, the current implementation applies only for cross sections that decrease with energy
    - The main application is for low-energy threshold effects, e.g. for **ParticleHP**

3 GeV p + Al → **n** + X

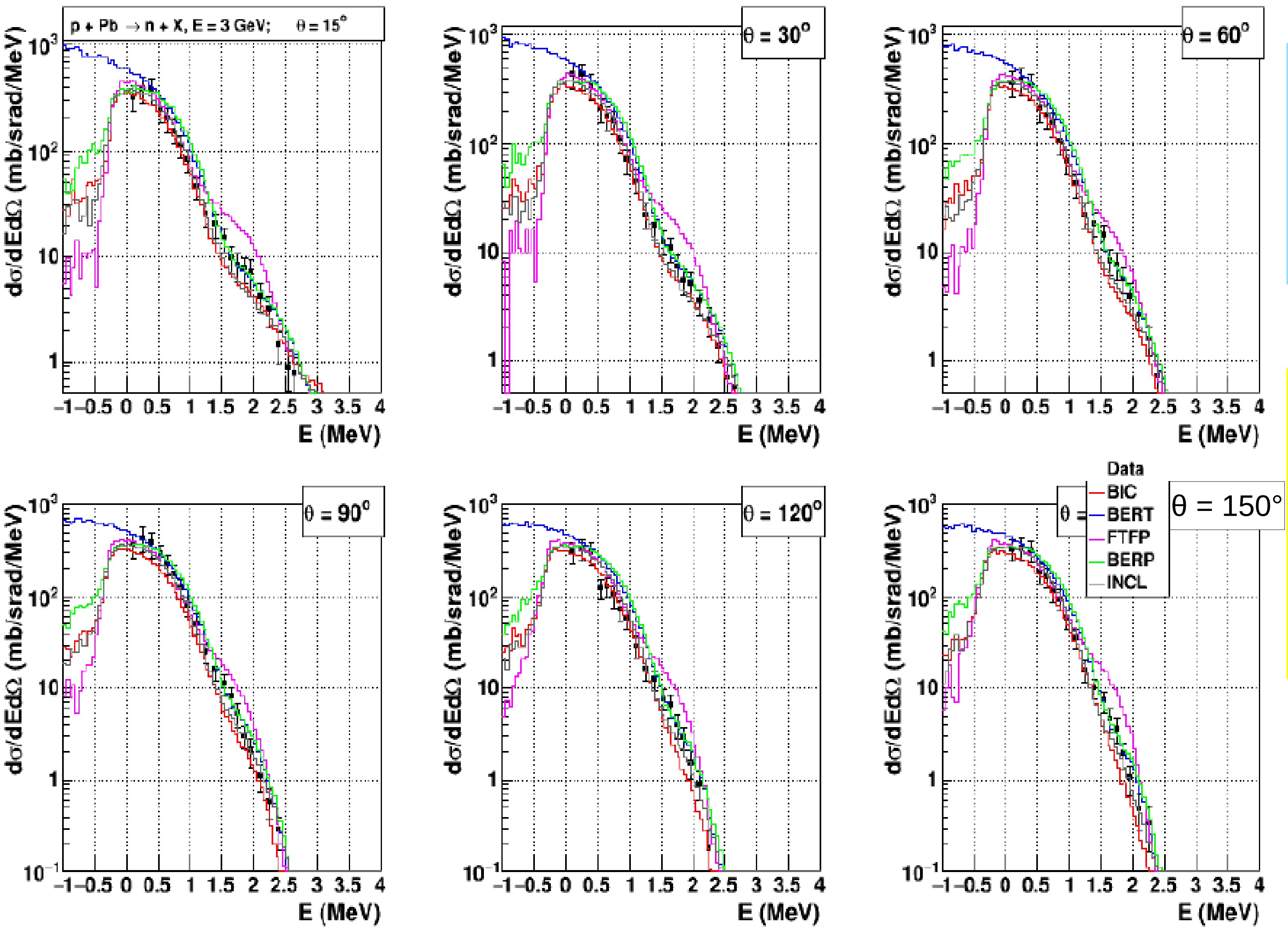


Double differential cross section of Neutron production Geant4 10.3beta

FTFP systematically overestimates backward hemisphere

BERT overestimates neutron yield below 1MeV

3 GeV p + Pb → **n** + X



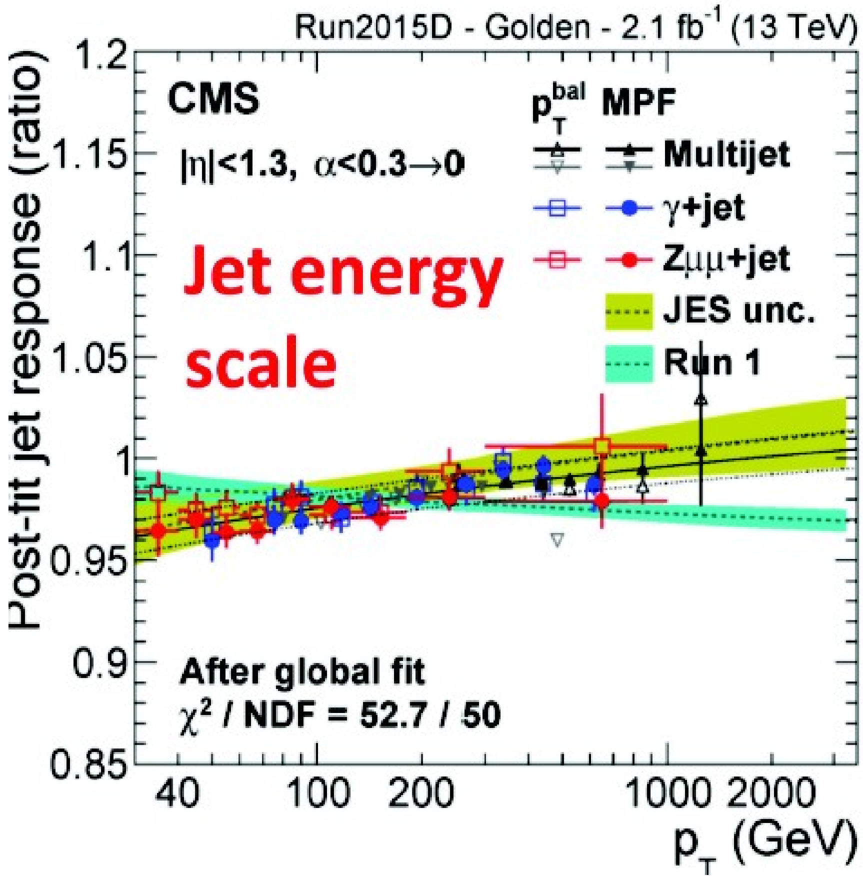
Double differential
cross section of
Neutron production
Geant4 10.3beta

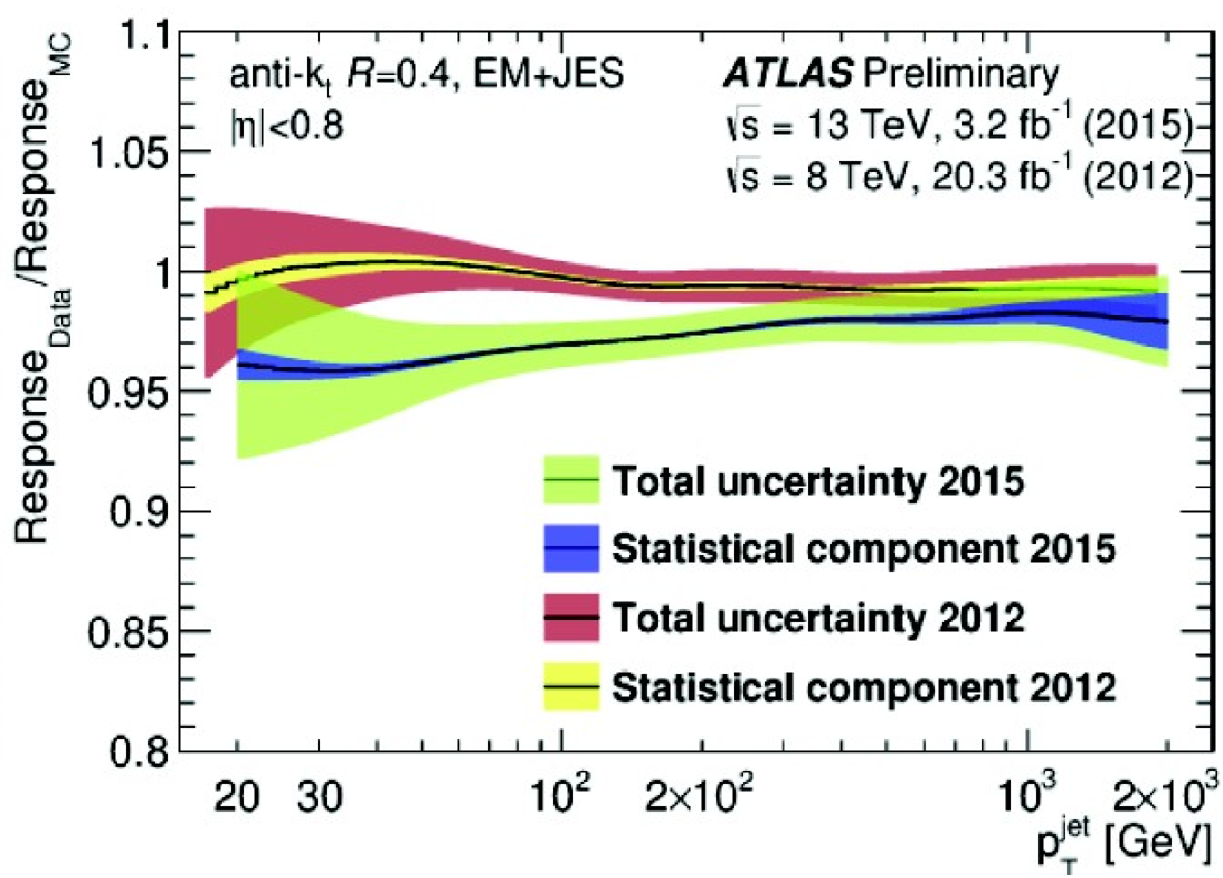
FTFP has biased shape
in backward hemisphere

Bertini overestimate
production of
low-energy neutrons
below 1 MeV

Jet Energy Scale

JES Issues





- There is a low-P_T scale change between Run 1 and Run 2 simulations for both ATLAS and CMS
  - ATLAS : from G4 **9.4** with **QGSP_BERT** to G4 **9.6** with **FTFP_BERT**
  - CMS : from G4 **9.4** to G4 **10.0** , same physics list **QGSP_FTFP_BERT**_EML

Conclusions for ATLAS (1/2)

- No "surprises" for showers started by different types of hadrons (π-, π+, K-, K+, K°_L, K°_S, p, n, pbar)
- BERT has changed significantly from G4 9.4 to 9.6, but its impact on the ATLAS JES change seems small
- A more important contribution is the use of FTFP instead of BERT in the region ~4.5 – ~9.5 GeV
  - **QGSP_BERT** : transition **BERT – LEP [9.5, 9.9] GeV**
  - **FTFP_BERT** : transition **BERT – FTFP [4.0, 5.0] GeV**
- Created a new, special physics list for ATLAS, **FTFP_BERT_ATL**, which is as FTFP_BERT, except for the transition **BERT – FTFP** in **[9, 12] GeV**

Conclusions for ATLAS (2/2)

- FTFP_BERT(_ATL) hadronic showers in G4 10.1 are similar to 9.6
- **FTFP_BERT_ATL** should be used for both G4 **9.6** & **10.1**
- For G4 **10.2**, stable response in ECAL, while in TileCal the energy response has increased by a few %
  - Due to tuning of the nuclear remnant excitation energy in FTF, based on thin-target data
  - Likely not doing good for the jet energy scale
    - negative slope expected, with more energetic jets being more affected (i.e. relative higher response) than lower energy ones; moreover, the more energetic jets have more visible energy in the TileCal...
    - FTFP_BERT_ATL is expected to push away the problem to slightly higher jet energies with respect to FTFP_BERT

Conclusions for CMS

- Reminder about QGSP_FTFP_BERT
  - BERT – FTFP **[6, 8]** GeV ; FTFP – QGSP **[12, 25]** GeV
- There are some changes – in the energy response of hadronic showers with QGSP_FTFP_BERT between G4 9.4 and 10.0 – which are consistent with the shift in jet energy scale of CMS
  - Due to FTFP model which, for proton and neutron projectiles, produces more energy in mesons and less in baryons in G4 version 10.0 than in 9.4
- For G4 **10.2** : use a **modified version of FTF** that has the same treatment of the excited nuclear remnant as in G4 10.1
  - To lower down the energy response
  - On top of G4 10.2.p02, use the (internal) tag:
    - **cms_hadr-string-diff-V10-01-17**

Looking at G4 10.3 and beyond

- Our strategy in Geant4 has always been to improve the models to better describe thin-target data, hoping that this improves thick-target data – e.g. hadronic showers in calorimeters – as well
  - This was indeed the case for several years

  - But in the two most recent versions
    - G4 10.1 : great improvements in thin-target, but stable hadronic showers
    - G4 10.2 : small improvements in thin-target, worse hadronic showers

  this is not happening any longer !

- Why and what to do ?
  - Models reaching their limits? Tuning driven by too few distributions?
  - Give different weights to thin-target of light vs heavy materials?
  - Have different set of tunings for each experiment, based on all data available from that experiment (e.g. test-beam and collider data)? This could be risky, given the complexity of these observables...