Highlights from High-Energy Hadronic Physics

Alberto Ribon
CERN PH/SFT

Geant4 Collaboration Meeting, Wollongong, 28 September 2017

Outline

- Status of String models
  - FTF
  - QGS
- Status of Intranuclear Cascade models
  - BERT
  - BIC : no development
  - INCLXX

- Non-reproducibility AMD *vs.* INTEL

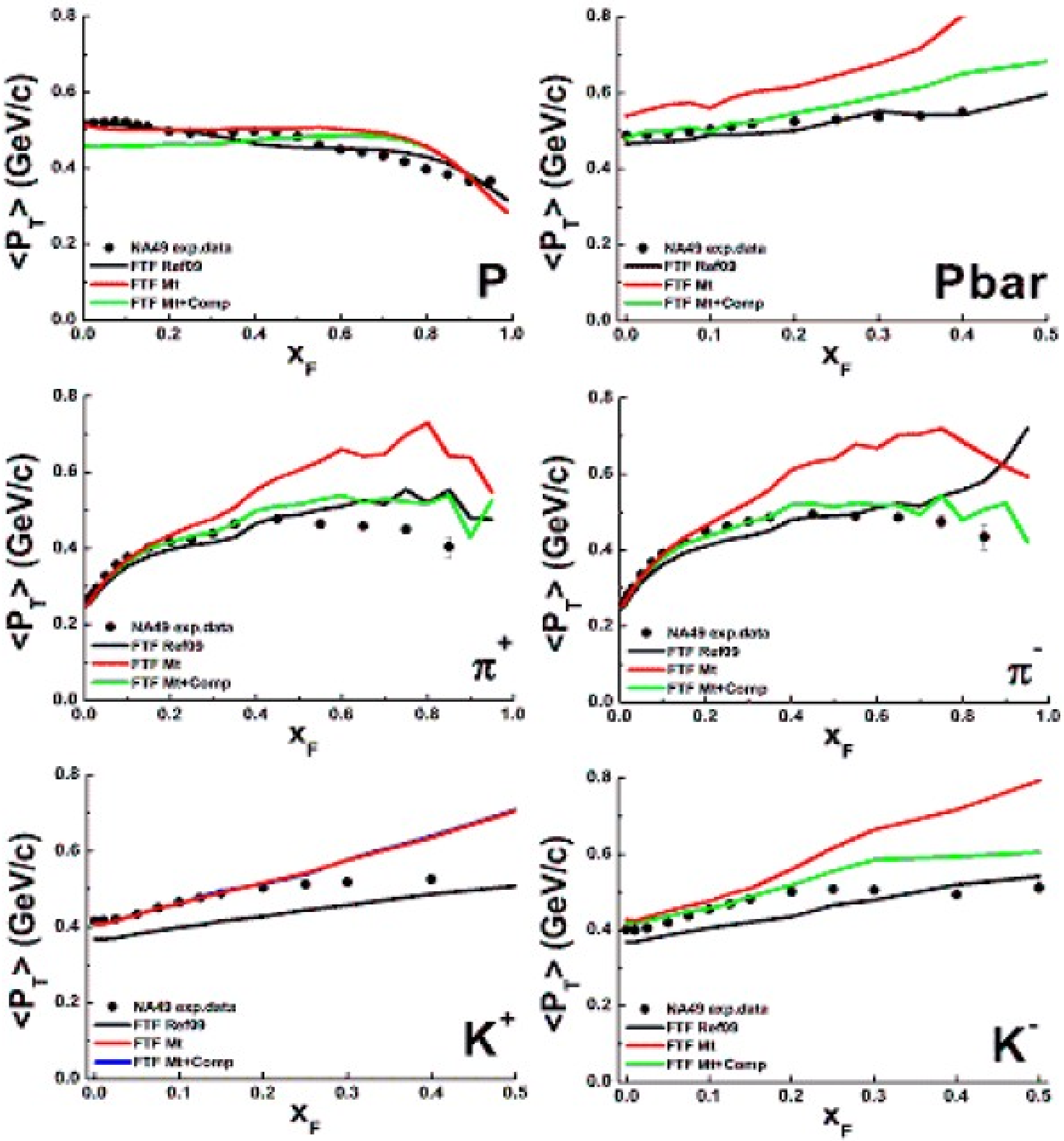
String models

*See talk in Parallel Session **4A** by V. Uzhinsky*

Status of **FTF** (Fritiof) Model

- Introduction of **rotating strings** in the string fragmentation
  - The standard Lund string fragmentation is unable to reproduce the <**Pt**> dependence on hadron type (mass)
  - Various ideas: for FTF, fragmenting strings rotate –> transverse mass distributions of produced hadrons
- Improved description of small-angle HARP data
  - 3-12 GeV p and π± projectiles on Al, Cu, Pb
- Smearing of resonance masses (e.g. Δ and ρ)
  - Requested by Panda Collaboration
- Outcome
  - Thin-target: better at low-energies; not clear at higher energies
  - Hadronic showers: a bit higher energy response and wider showers w.r.t. G4 10.3.p02; but smaller fluctuations of energy response

Rotating Strings and Mt distributions



Black lines – G4-10-02-Ref09
Red lines -- Mt implemented
Green lines – Mt and Pt compen

Before I had
<Pt> = 0.5 (GeV) for mesons
<Pt> = 1 (GeV) for Deltas

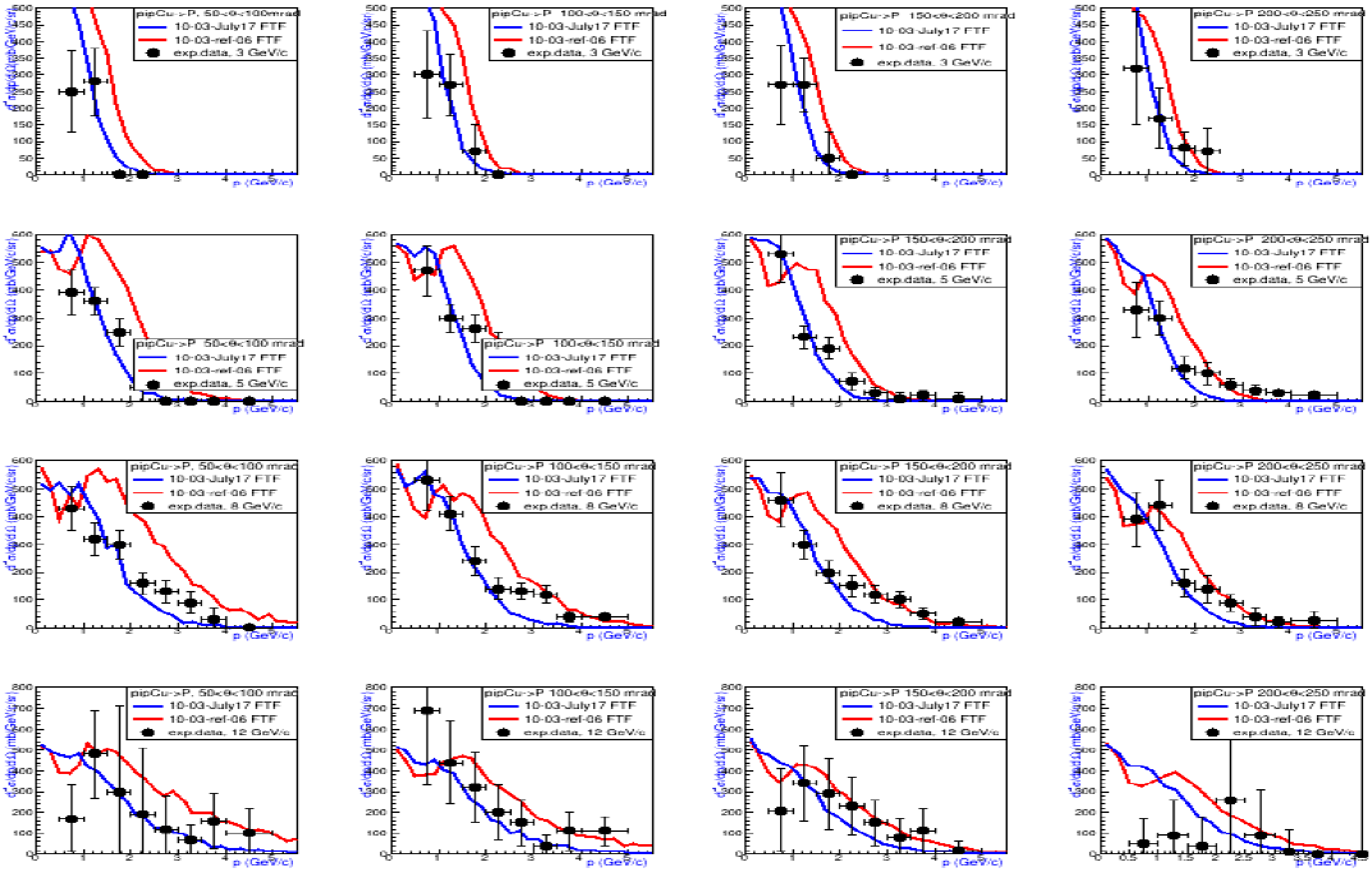
Now I have only 1 parameter:
Slope Mt = 5 (GeV^-1)
for all hadrons!

But Pt compensation is very
important!

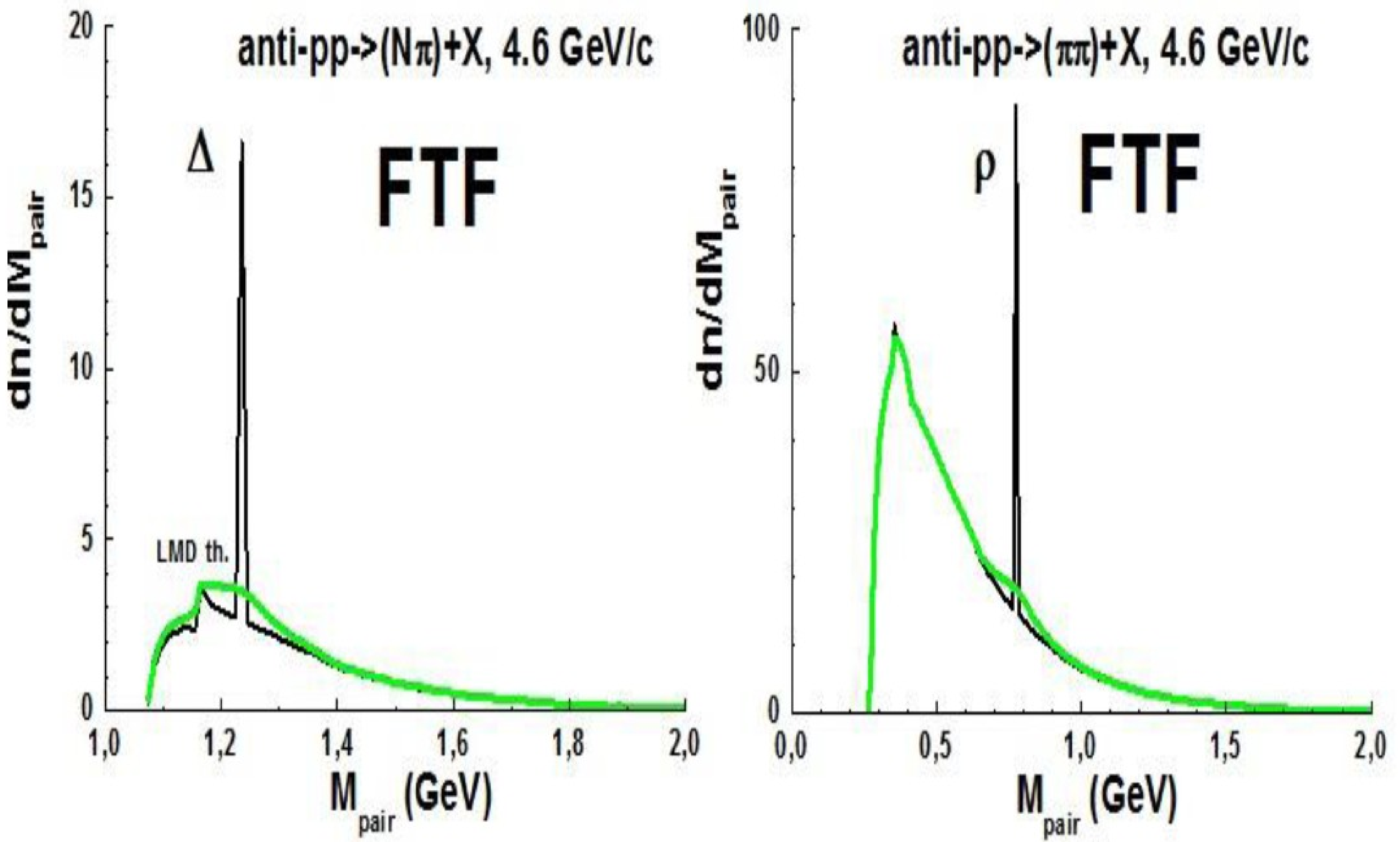
Pt compensation is very important!

Improved Description of HARP Data

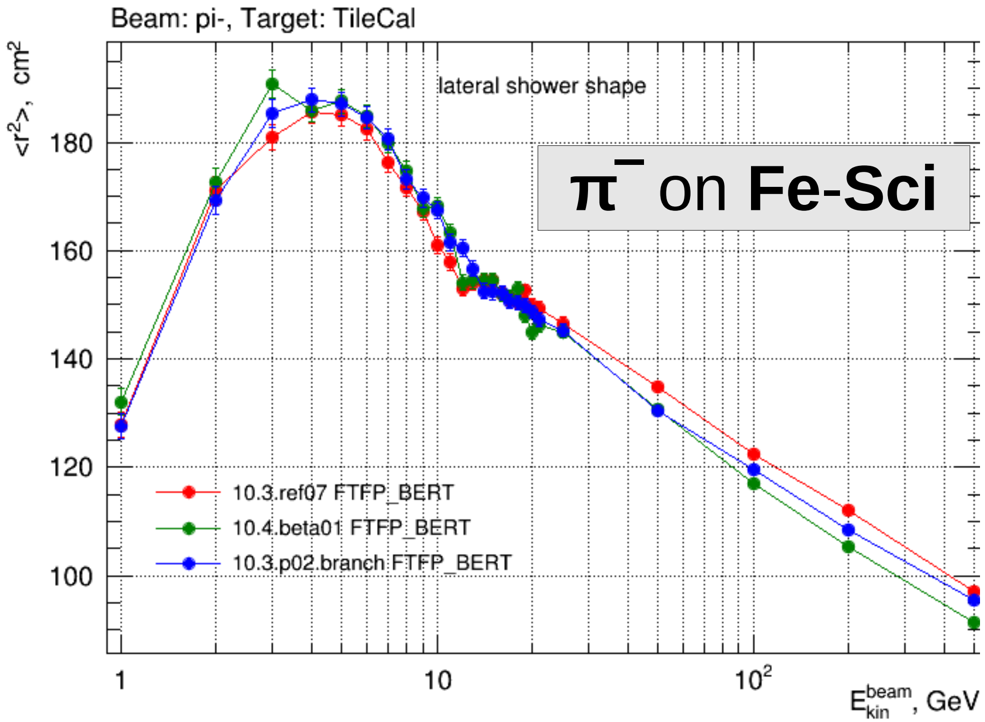
π+ Cu → p : G4 10.3.ref07 vs 10.3.ref06

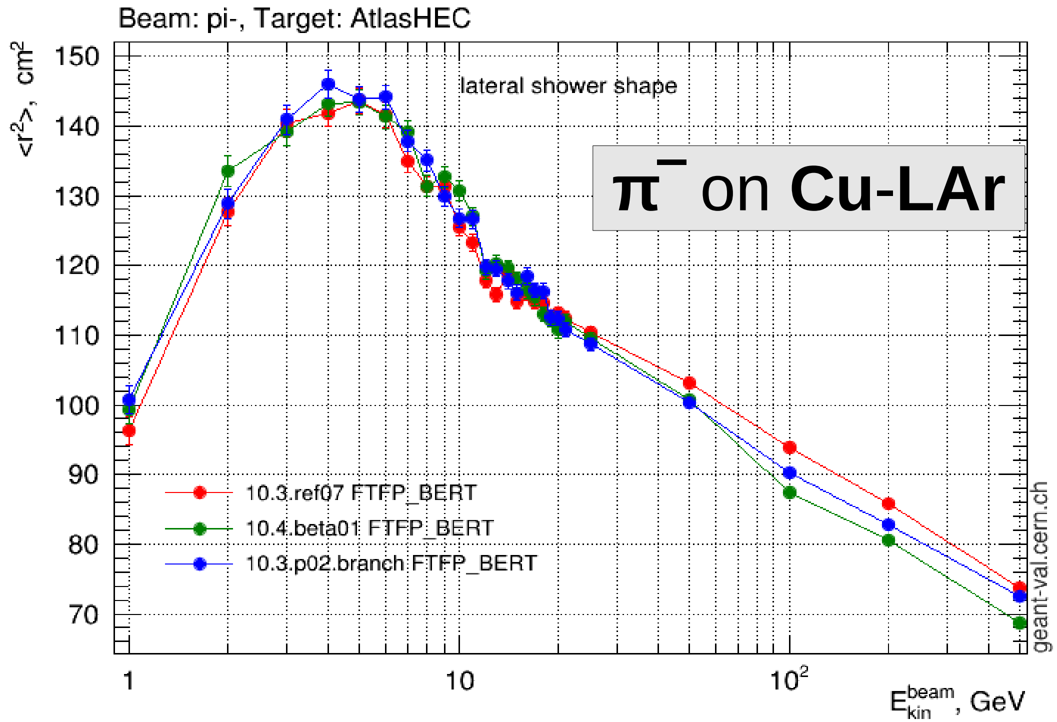


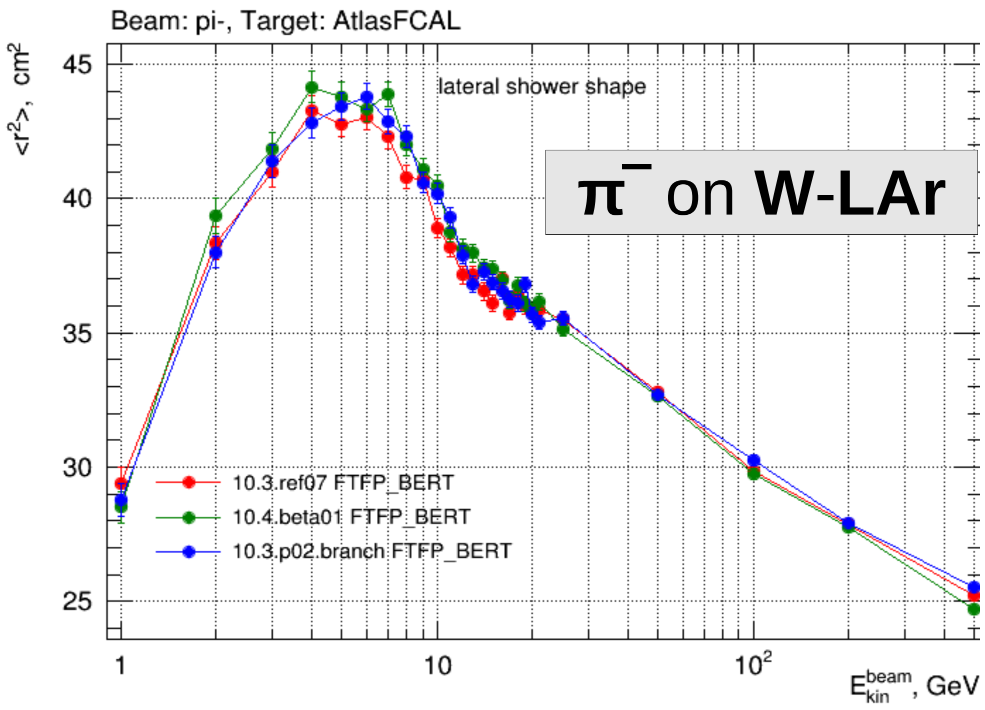
Smearing of Resonance Masses

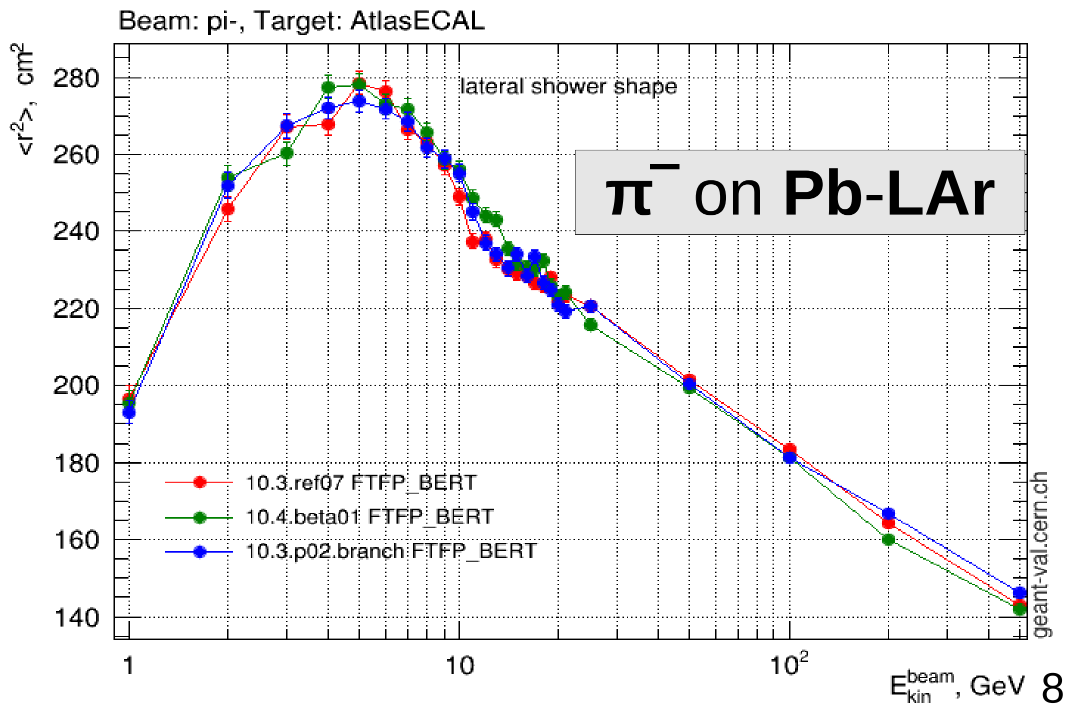


FTFP_BERT : Lateral Shape

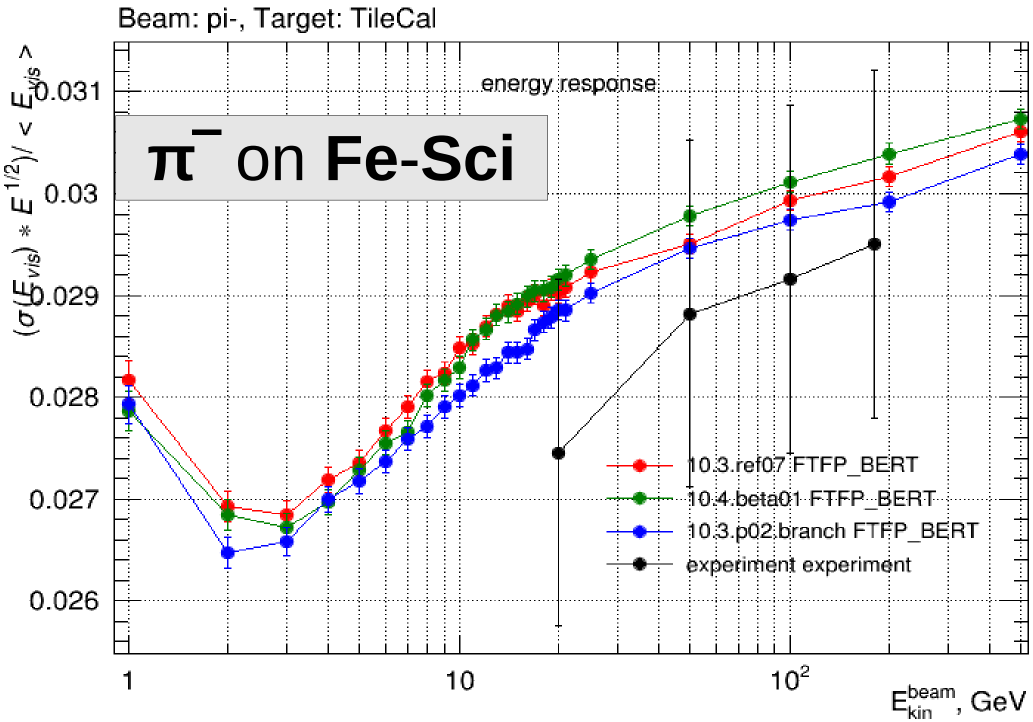


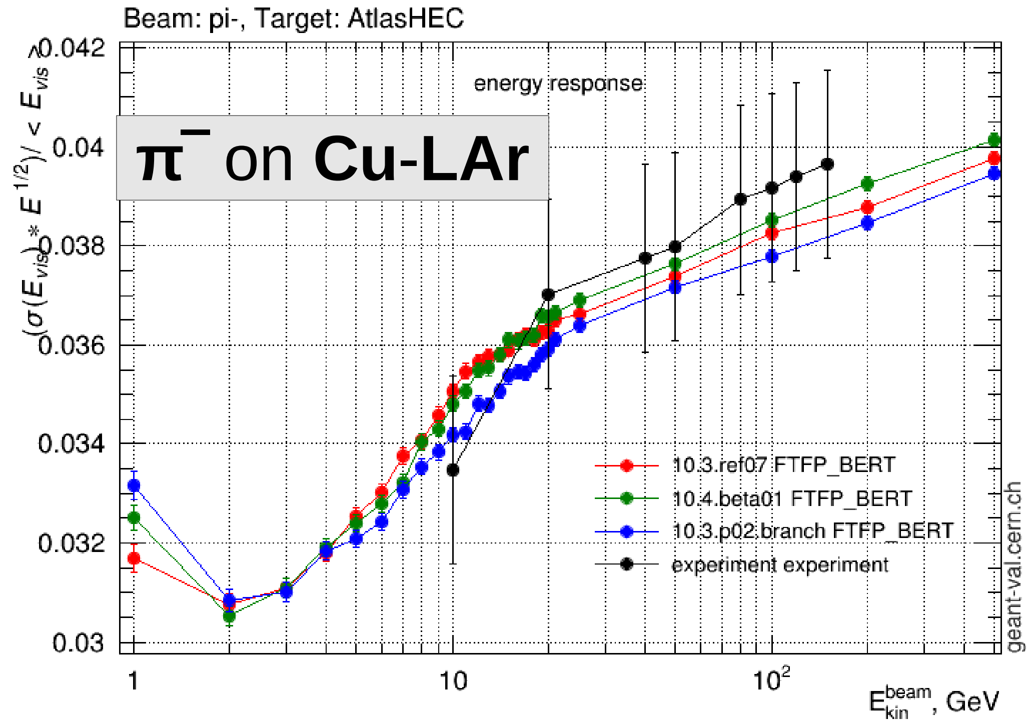


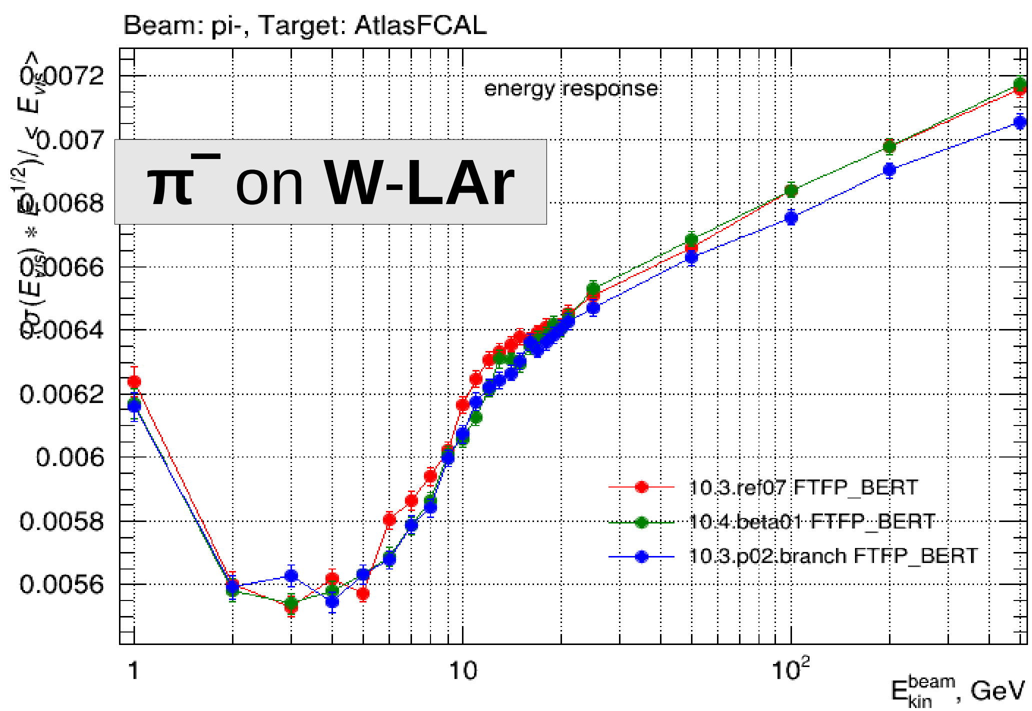


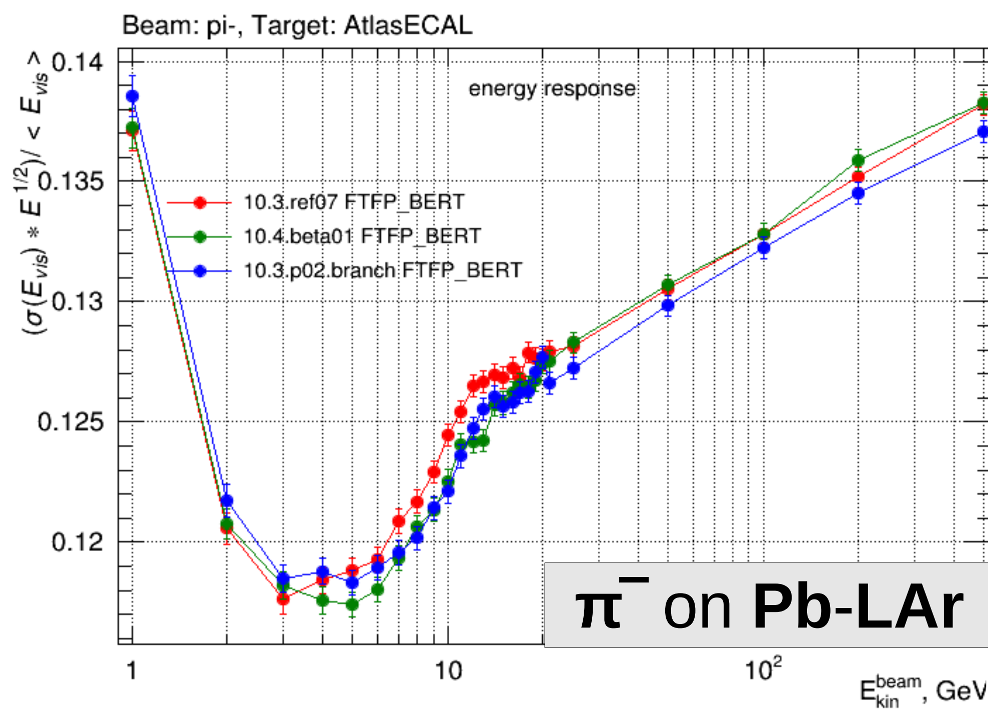


FTFP_BERT : Energy Response

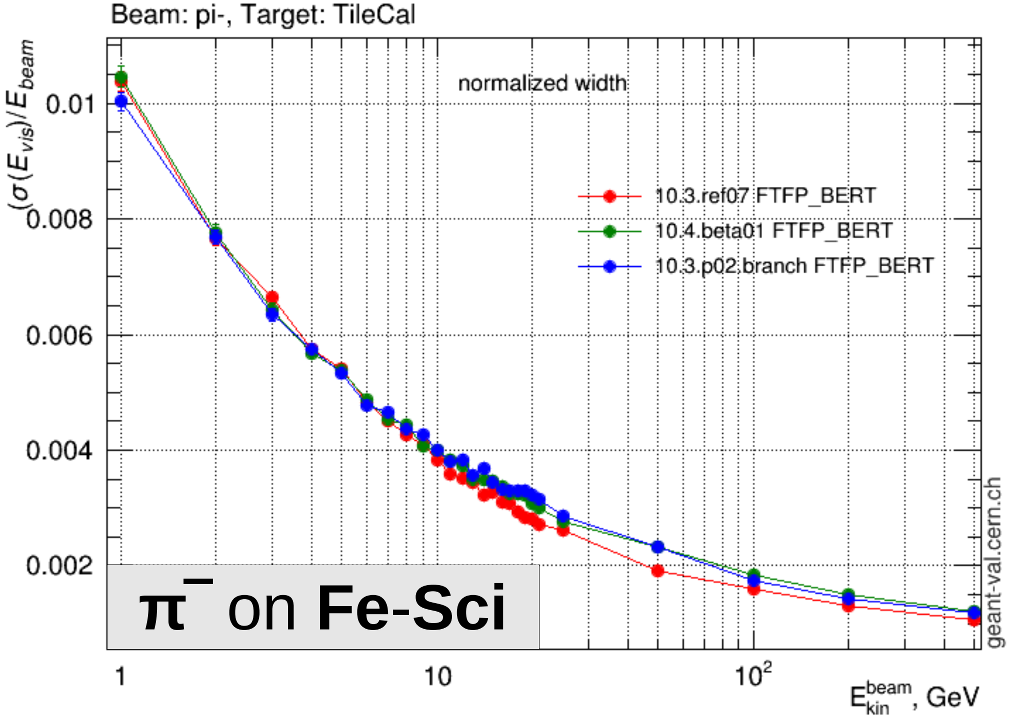


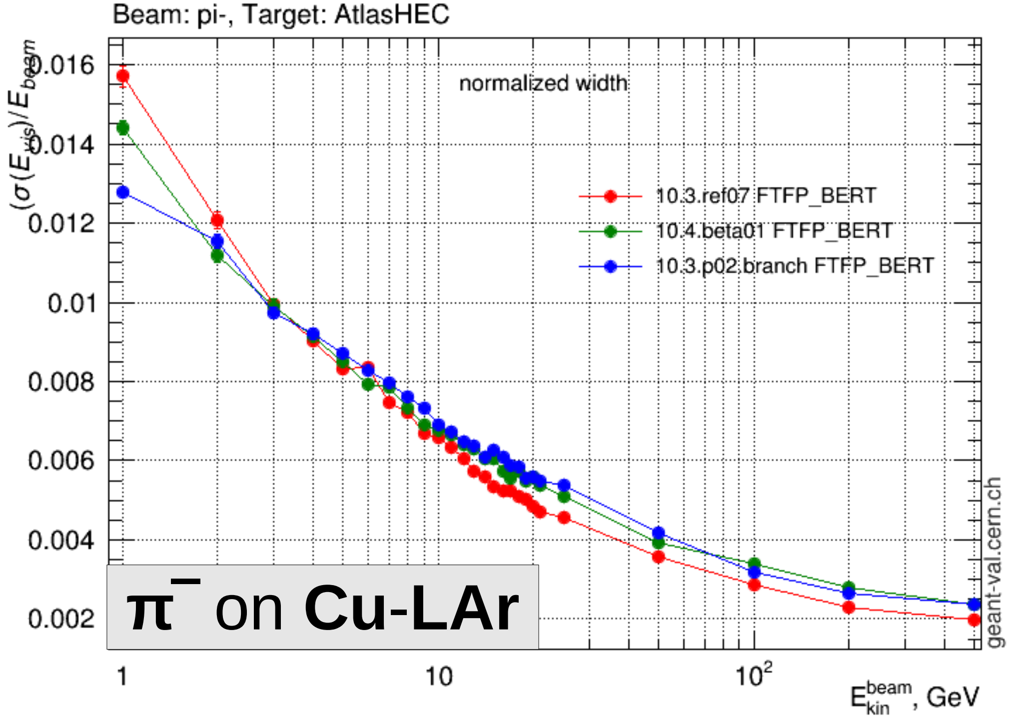


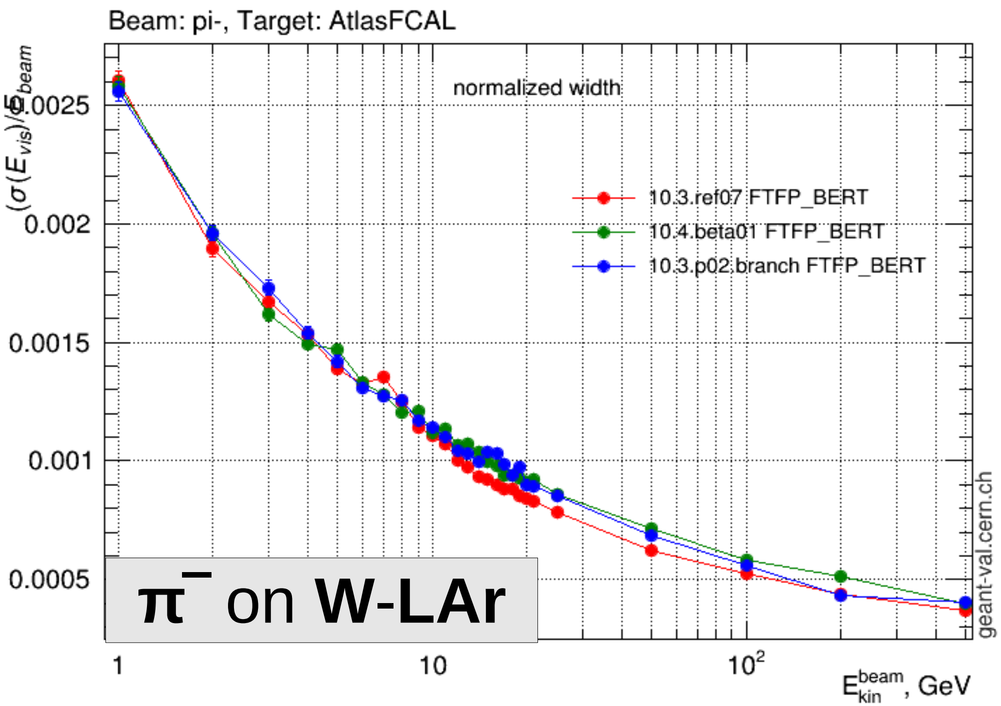


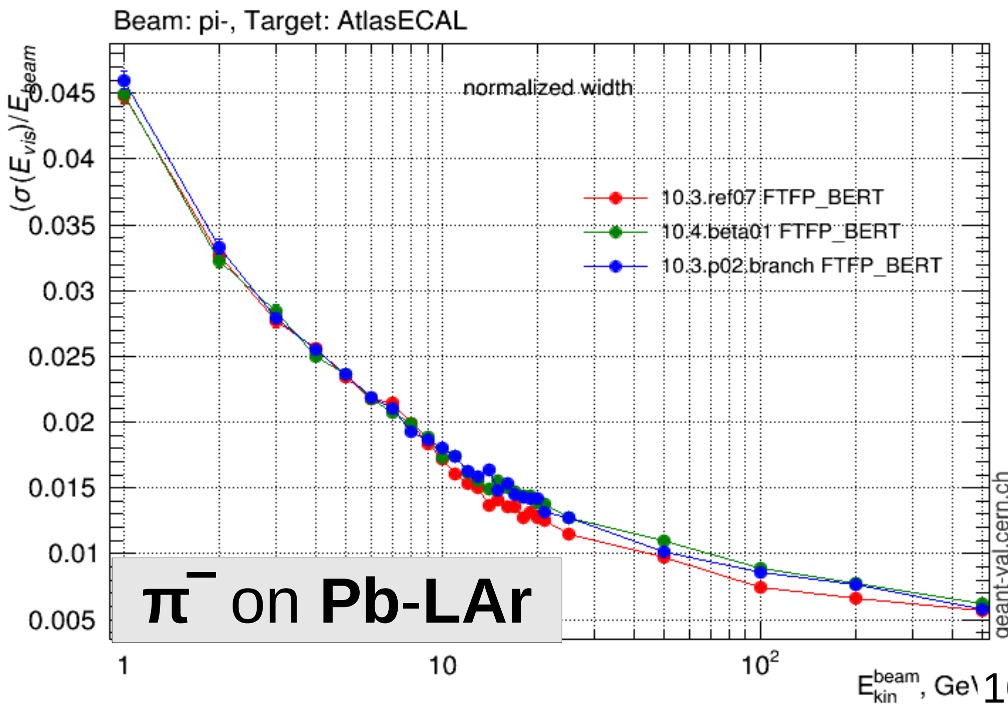


FTFP_BERT : Energy Width



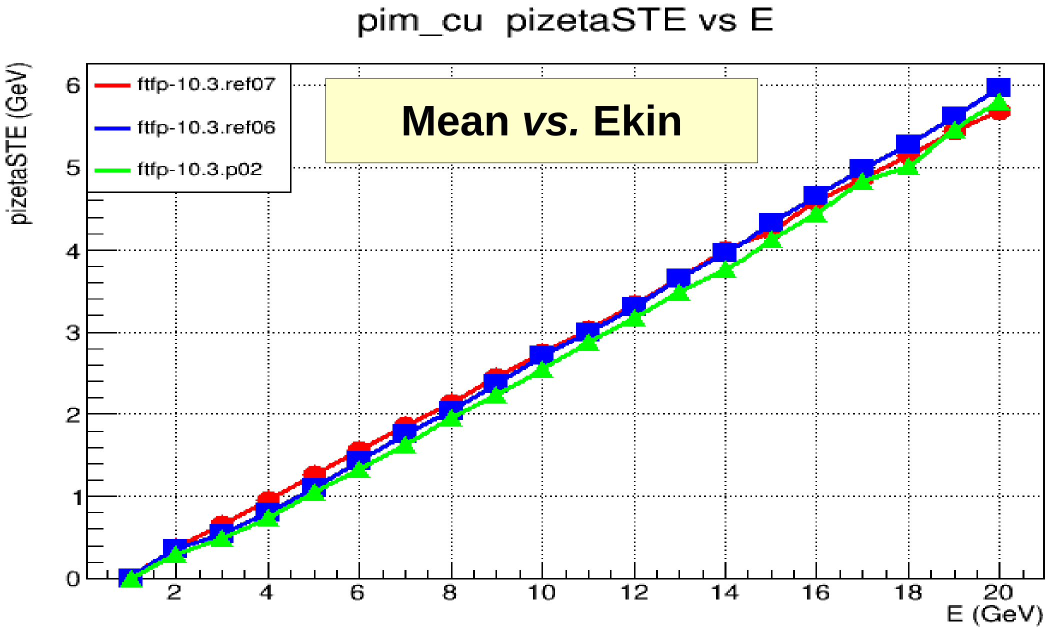


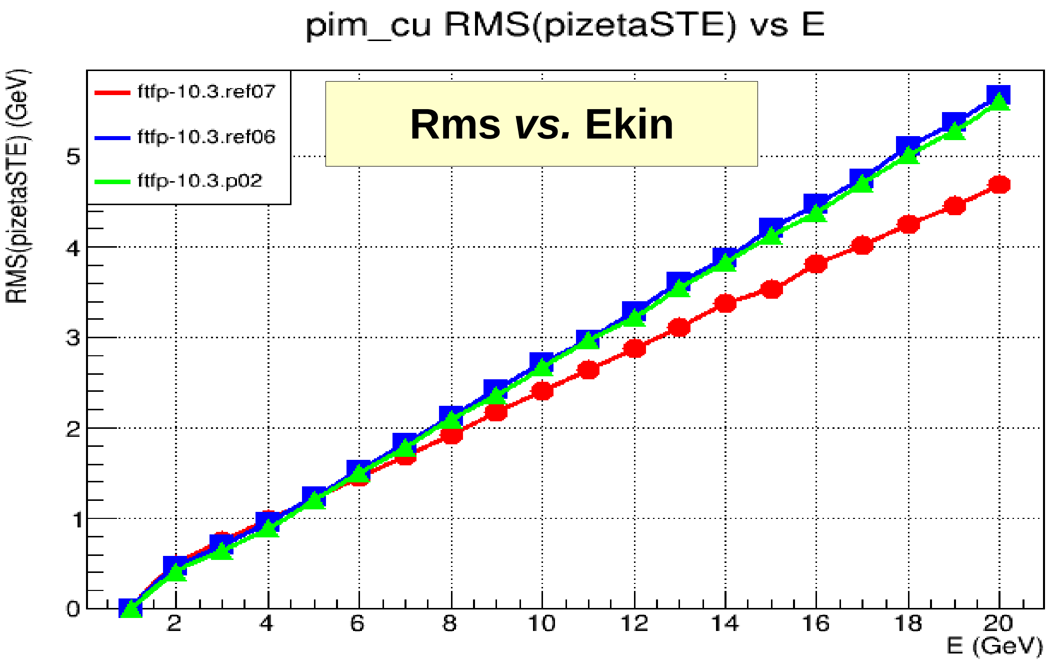




π° + η + η' Energy Flow

π⁻ on Cu





- The higher the **mean** value of the energy flow in **π° + η + η'** in hadron-nucleus collisions, the higher the EM component of hadronic showers, so the higher the mean energy response in calorimeters (under-compensating)

- The lower the **r.m.s.** value of the energy flow in **π° + η + η'** in hadron-nucleus collisions, the smaller the fluctuations in the EM component of hadronic showers, which is the dominant component in the energy response **fluctuations**

FTF in G4 10.4

- The goal for this year was to get back to a single version of the string models (FTF & QGS) instead of the current two (production and development) as introduced in G4 10.3. We managed to reduced the gap between the two versions, but the production is still better for hadronic showers...
- As discussed at the last Hadronic Physics Working group meeting on September 13, there are two options:

1. Try to release the latest, development version of FTF

  - If we manage to improve (in the next few weeks) the hadronic shower energy width, while keeping good thin-target results

2. Else release the stable, production version of FTF

  - As we did for G4 10.3 : good and stable hadronic showers, with reasonable thin-target description (although not as good as with the development)
  - Development version of FTF will be brought back in 10.4.ref01

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

- V. Uzhinsky improvements in 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**}.**β**
  - Constituent quark masses have been introduced
  - Pomeron and reggeon parameters are set as prescribed by A. Kaidalov and M. Poghosyan
  - Interpretation of cutted (non-vacuum) reggeons as quark exchange processes
  - All these improved the description of thin-target data, but came too late to be included in G4 10.4, but they are in G4 **10.4.β**

QGS in G4 10.4

- V. Uzhinsky is starting now (after the work he did on FTF) to continue improving QGS
  - Further tuning of parameters and thin-target validation
  - Diffraction Dissociation
- If we get good results in time for the release, then the new QGS will be included in G4 10.4
- Else, the old QGS final-state model will be released
  - as we did for G4 10.2 & 10.3

Intranuclear Cascade models

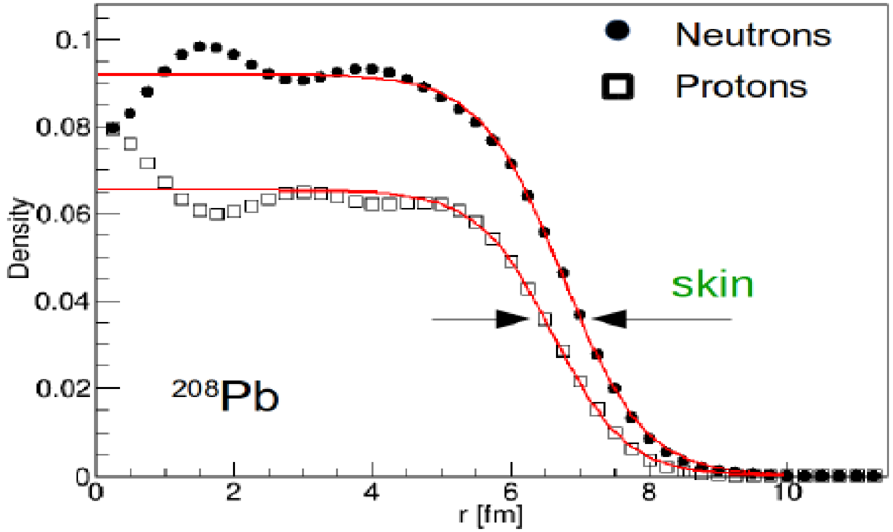
*See talk in Parallel Session **4A** by J. Hirtz*

Bertini-like (BERT) model

- In G4 **10.3** (after Ferrara) : improved the evaporation spectrum, reducing the overproduction of low-energy neutrons and protons
- In G4 **10.4.β** , important bug-fix on coalescence
  - Eliminates significant memory usage observed with high-energy applications of BERT
  - More fragments (d, t, He3, α) are created, which travel less than nucleons, therefore more compact hadronic showers are observed in particular for heavy absorbers (W & Pb)
- On-going, to be included in G4 **10.4**
  - Re-tune for gamma-nuclear interactions above 20 MeV with larger data set
    - Below 20 MeV, a new, data-driven approach based on LEND is under development by T. Koi (see Parallel Session 6A)

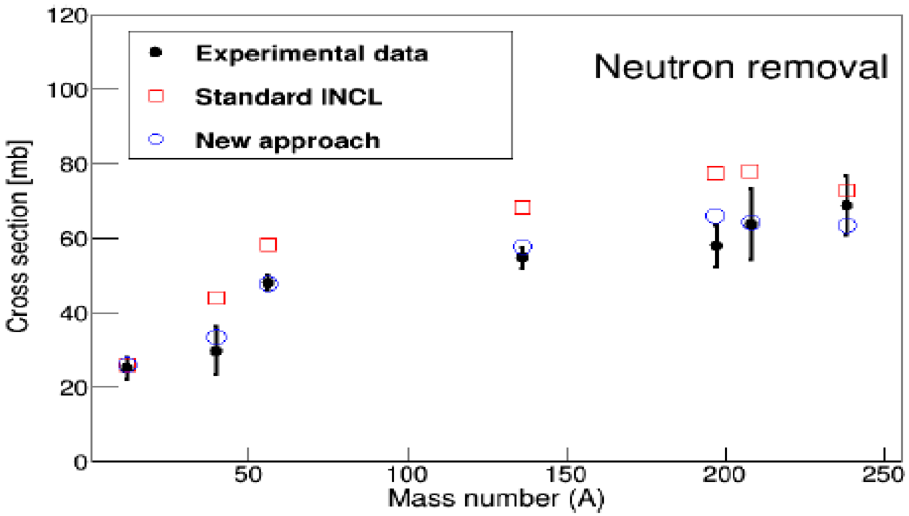
INCLXX model – Slides from Jason Hirtz (1/3)

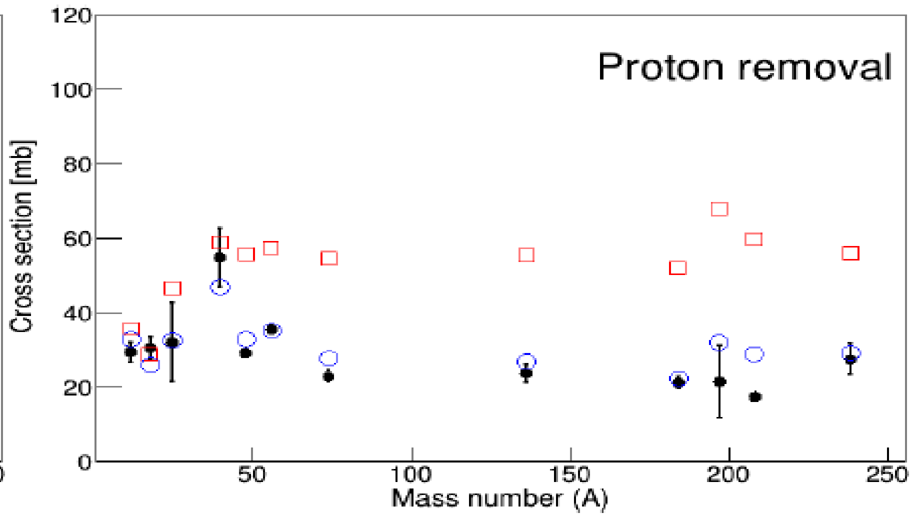
Jose-Luis Rodriguez Sanchez



Hartree-Fock-Bogoliubov calculations are used to shape the surface of the nucleus (skin and halo) and to determine the excitation-energy uncorrelations

1-proton and 1-neutron removal highly improved.
New approach provides a satisfactory description of the experimental data covering a large number of nuclei, from ^{12}C to ^{238}U



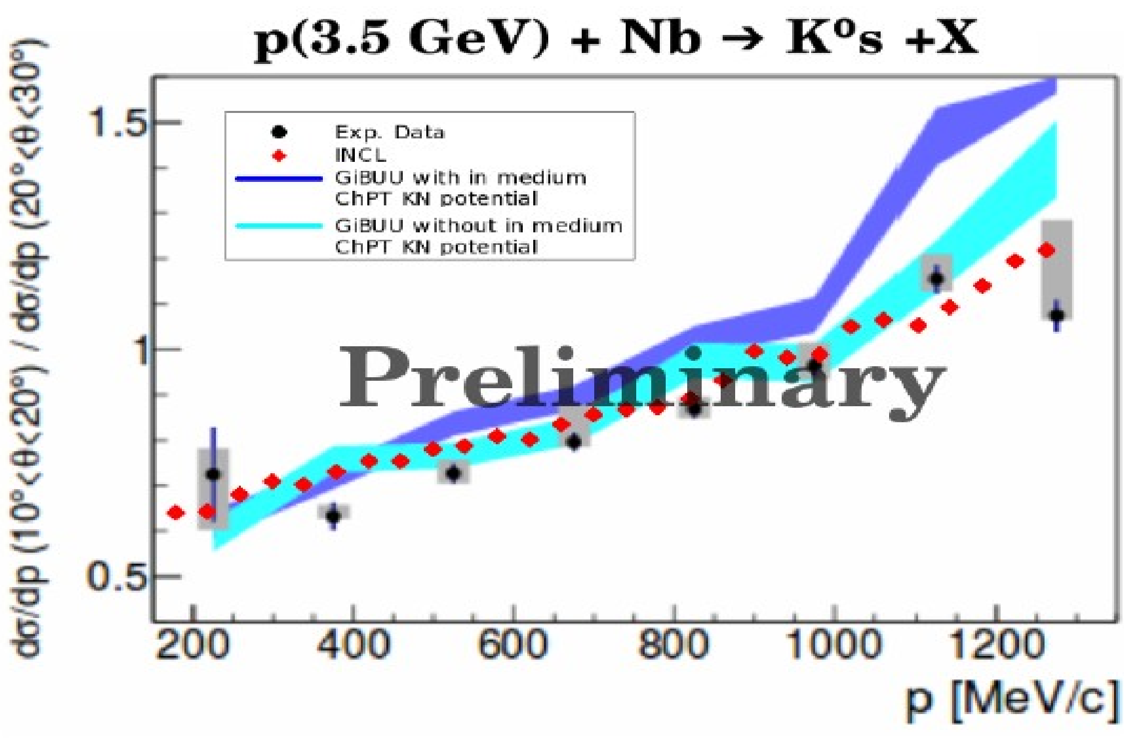


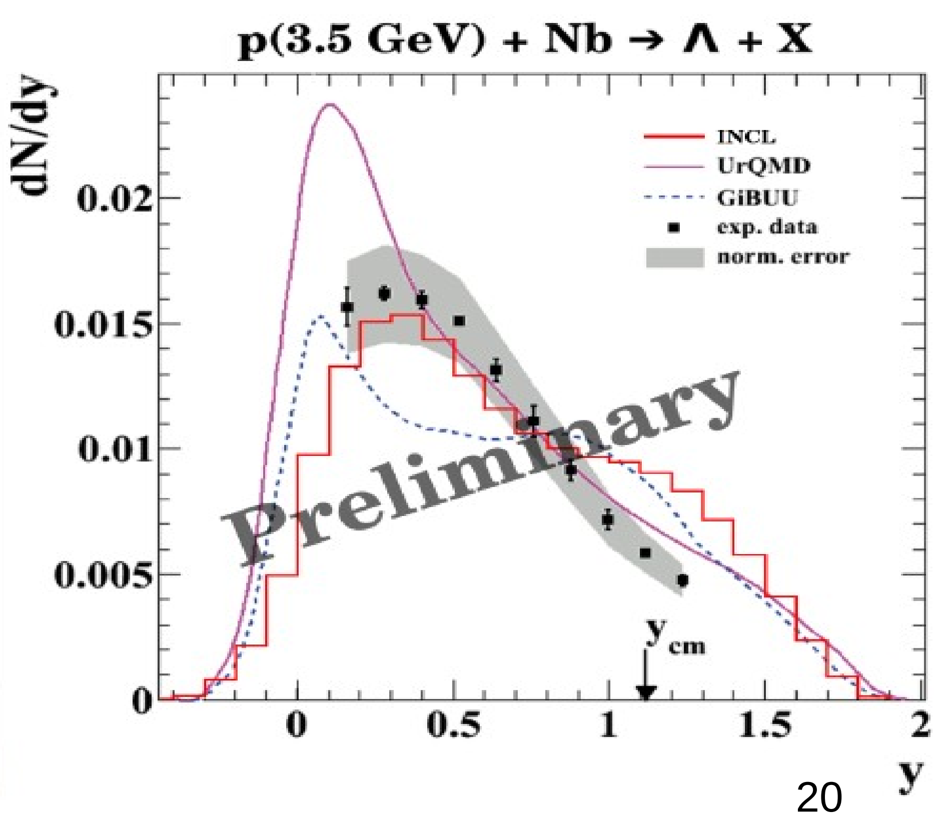
INCLXX model – Slides from Jason Hirtz (2/3)

Jason Hirtz

INCL initially designed up to 3 GeV. Recent extension up to 15 GeV. New physics contribute: e.g. Multiple pions emission and new type of particle (η, ω, K, $\overline{K}$, Λ, Σ...)

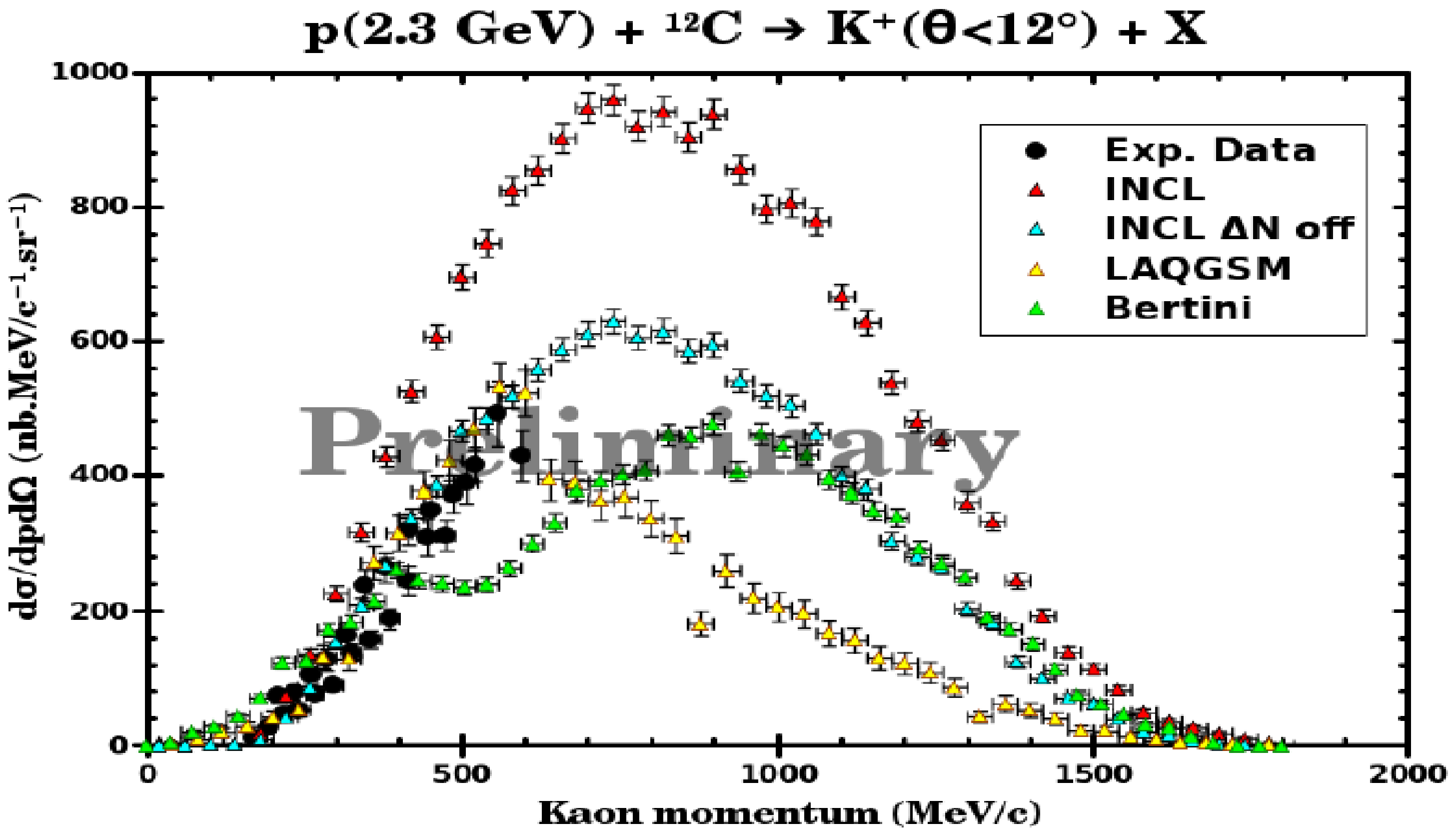
2017: Implementation of Strangeness.
New possibilities of simulation: Kaons, Hyperons and Hypernuclei physics.





INCLXX model – Slides from Jason Hirtz (3/3)

Problem with strange particle production through Δ induced reaction: important estimate contribution but shape and amplitude unknown.



Available in the future Geant4 release

Future work: Deexitation of hypernuclei and study of Δ induced reactions.

AMD *vs.* INTEL non-reproduciblity

Findings

- Frequent cases of non-reproducibility AMD *vs.* INTEL seen with Geant4 simulations
  - With all 3 types of math libraries: **libm**.so , **VDT** , **libimf**.so (with the latter producing about 4 times more violations)
  - With **libm**.so or **VDT** math libraries these differences are due to compiler's optimizations, and disappear when Geant4 is built without optimization, i.e. with the flag **-O0** .
    This is **not** the case with **libimf**.so !
  - The non-reproducibilities are due to (tiny) differences of **sine** or **cosine** functions between AMD and INTEL with the same argument
  - Seen (in practice) only with **hadronic physics**
    - Not optimal use of rotations in current G4 hadronic physics (whereas it is optimal in G4 electromagnetic physics).
      This could be improved, reducing the number of violations
      - Use only rotateUz and only on the final-states
    - Cannot be completely eliminated due to **longer paths and richer physics of low-energy neutrons with respect to low-energy electrons**

Why for EM reproducibility is fine ? (1/2)

- Because of 2 reasons:

1. Minimal (i.e. optimal) use of **sine** and **cosine** functions, together with the fact that most single electron Coulomb scatterings occur at low-angles (θ below a few degrees)

- Only use the method Hep3Vector::**rotateUz** and only for final-state particles (not for projectile !)
- Still, sometimes tiny differences in **sin(φ)** or **cos(φ)** between AMD and INTEL do appear, but most of them disappear when **rotateUz** is applied to the final-state particles (i.e. deflected projectile and nuclear recoil) because of low-angle (θ below a few degrees) electron Coulomb scattering

```
Hep3Vector& Hep3Vector::rotateUz( const Hep3Vector& dir ) {
   double u1 = dir.x(), u2 = dir.y(), u3 = dir.z();   // dir must be normalized !
   double up = sqrt( u1*u1 + u2*u2 );
   double px = dx,  py = dy,  pz = dz;              //  Differences in sin or cos appear as differences in px or py
   dx = (u1*u3*px - u2*py)/up +  u1*pz;            //  1st term  <<  2nd term
   dy = (u2*u3*px + u1*py)/up + u2*pz;             //  1st term  <<  2nd term
   dz =      -up*px                     +  u3*pz;  //  1st term  <<  2nd term
   return *this;
}
```

- Note: if multiple scattering is used (instead of single scattering), much fewer rotations would occur! (I use G4 10.3.p02, with a modified version of FTFP_BERT without hadronic physics and with G4eSingleCoulombScatteringModel)

Why for EM reproducibility is fine ? (2/2)

2. Short paths and local energy deposits for low-energy electrons that can have large-angle elastic Coulomb scatterings

- Tiny differences in **sin(φ)** or **cos(φ)** between AMD and INTEL that appear sometimes in Coulomb elastic scattering survive after **rotateUz** is applied to the final-state particles (i.e. deflected electron and nuclear recoil) only for large-angle scatterings ($\theta \geq 10 - 20°$), which can happen only for **low-energy** ($E_{kin} \leq 1$ MeV) **electrons**
- Low-energy electrons **stop shortly and deposit their energy locally**; if they manage to produce secondaries (electron delta-rays or bremssthralung gammas), these have even lower energies and therefore stop also shortly and deposit their energy locally
- Hence, although the little differences between AMD and INTEL persist, they cannot grow up too much and produce different event histories: in other words, the **event remains essentially the same** (a part, eventually, some very small differences in energy deposits), i.e. reproducibility is preserved!

Why for HAD irreproducibilities occur ?

- Because of 2 reasons

1. Inefficient (non-optimal) use of **sine** and **cosine** functions, together with the fact that many neutron elastic scatterings can occur at relatively large angles ($\theta \geq 10° - 20°$)

- Rotate, even more than once, the projectile along the z-axis
- Isotropic φ-rotation applied sometimes more than once
- Use different variants of rotation methods, not only **rotateUz**
- When **rotateUz** is applied to the final-state particles (i.e. scattered neutron and recoil nucleus), eventual tiny differences in **sin(φ)** or **cos(φ)** between AMD and INTEL survive

2. Long flights and production of secondaries for low-energy neutrons

- Neutrons are neutral and with long lifetimes, so they can travel long distances and produce secondaries, like gamms, neutrons and protons in nuclear capture
- Therefore the tiny differences between AMD and INTEL can grow up and produce **different event histories**, i.e. irreproducibilities can occur!