Hadronic Interactions (Hadint)

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Our primary energy interval: **50 GeV – 5 PeV**

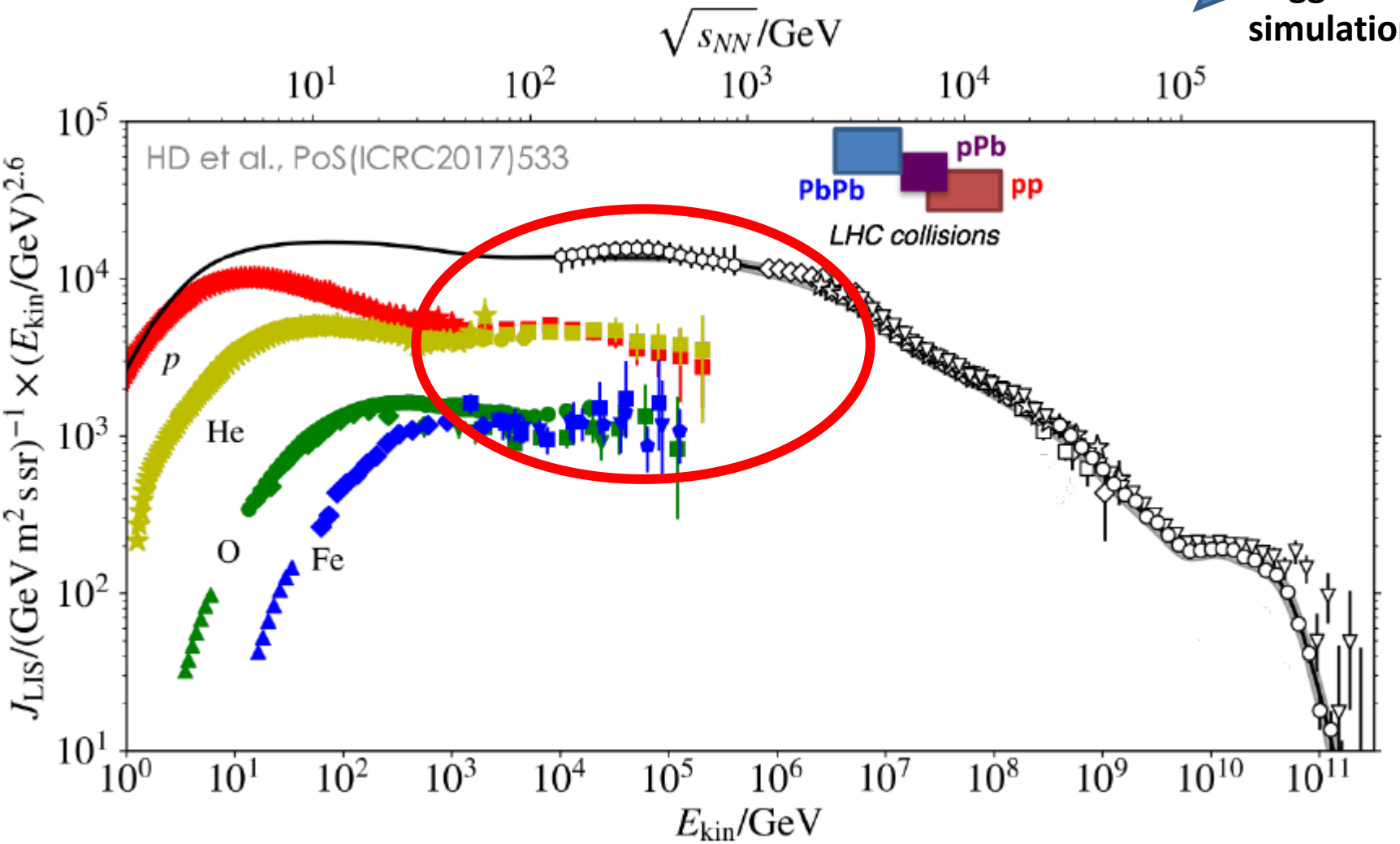
We **need**

Good simulation of **energy deposits** (hadron calorimetry, bck rejection for e/γ analyses)

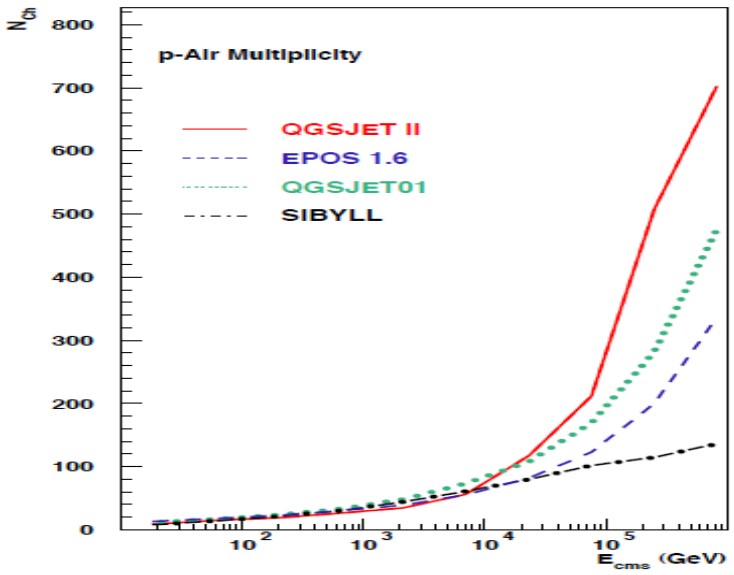
Good simulation of **backscattered particles** (backsplash vs particle ID)

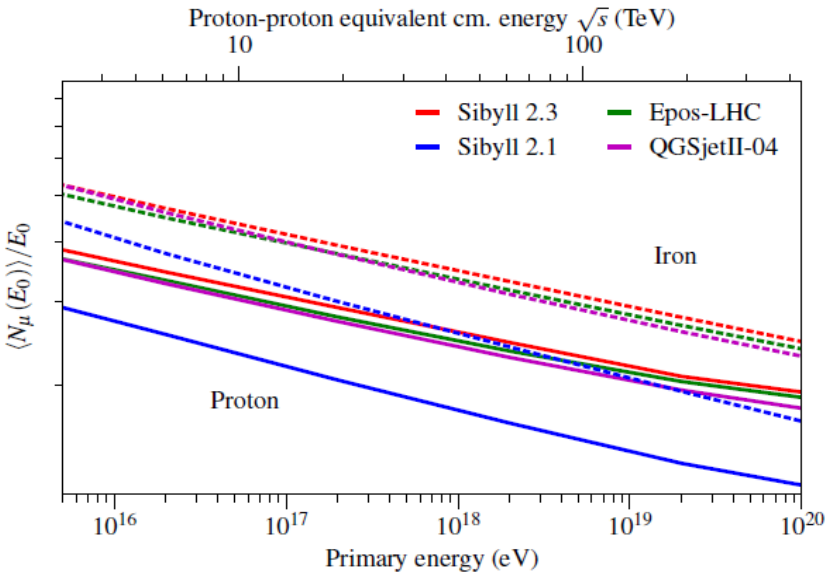
Good simulation of primary **nuclei fragmentation** (nucleus ID)

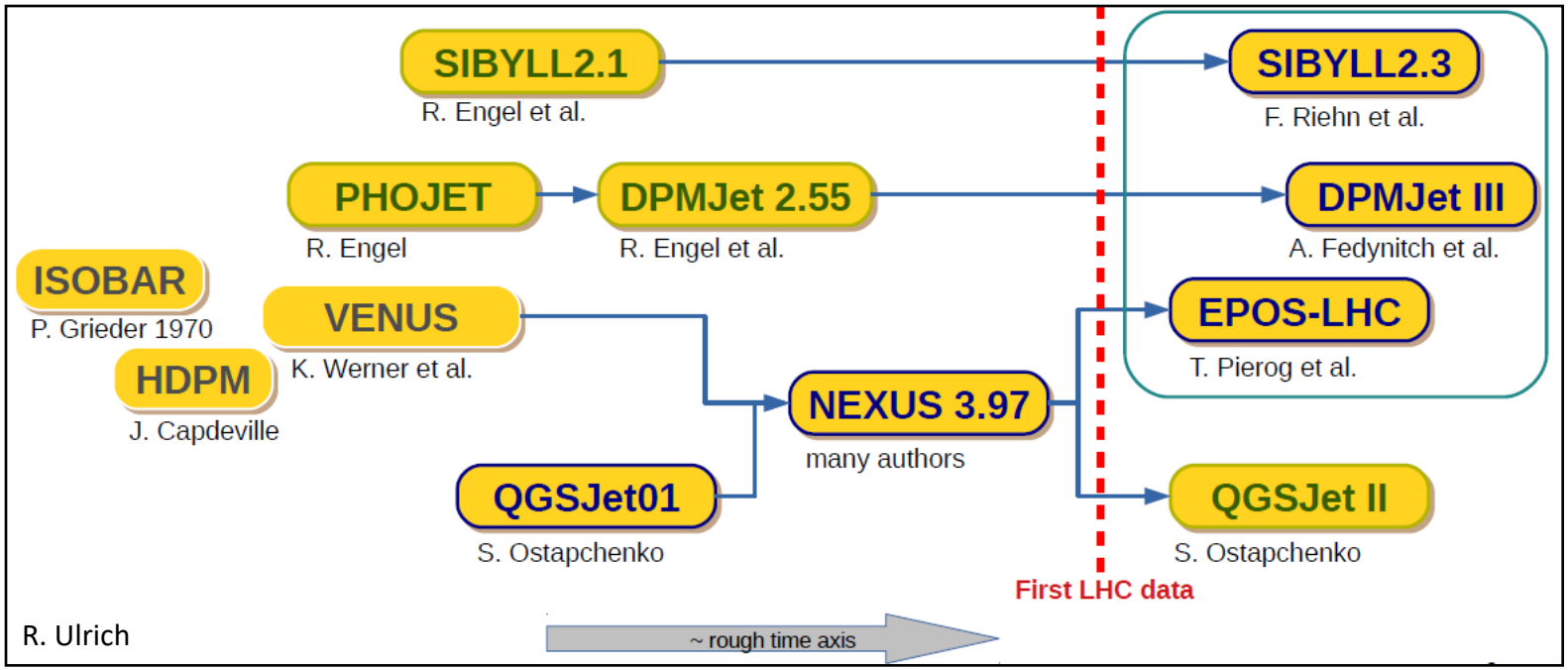
Trigger simulation



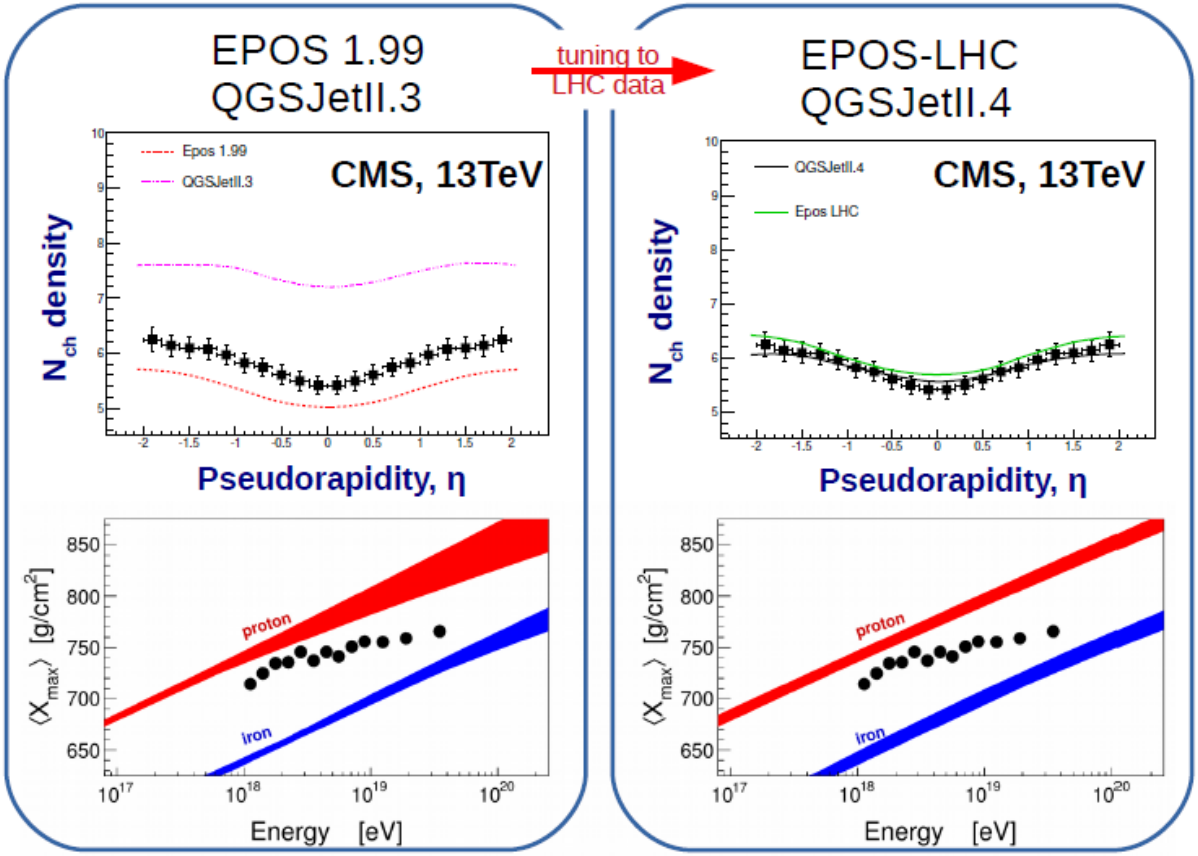
An old problem for indirect CR measurements



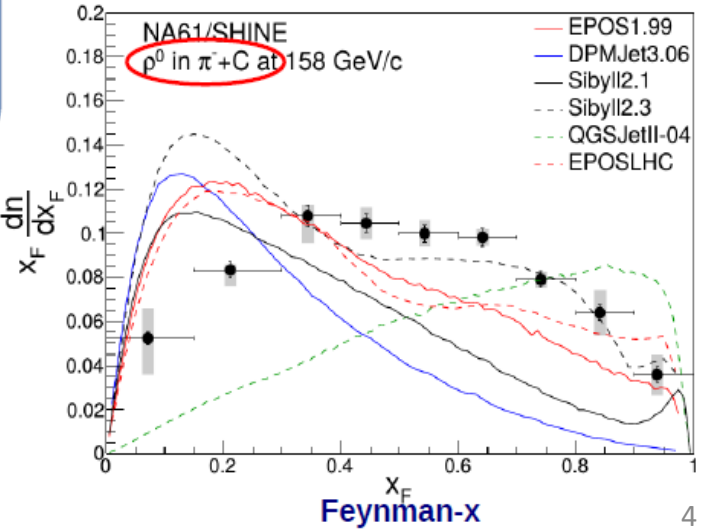




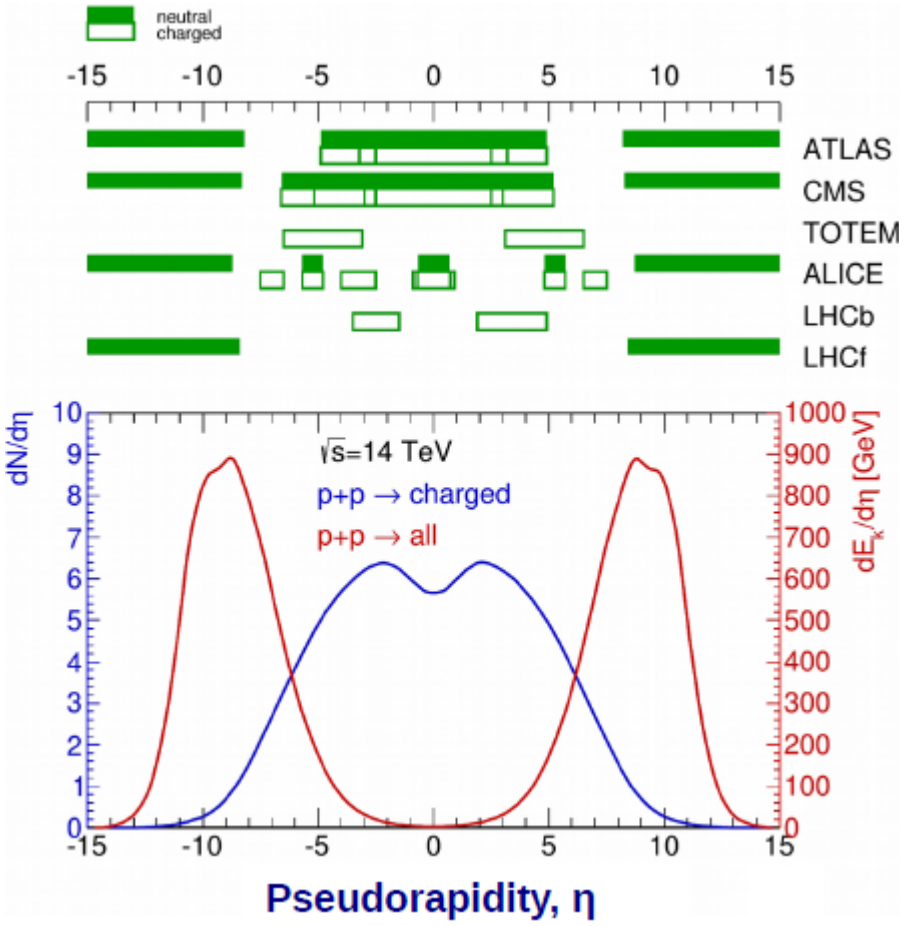
Important inputs from LHC…



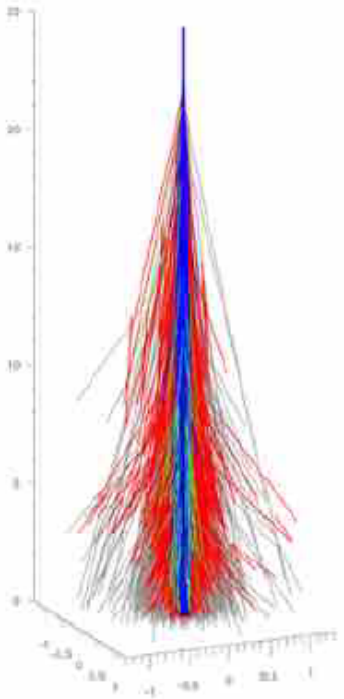
…but many topics still to be understood



Moreover..
not only a problem of C.M. energy:

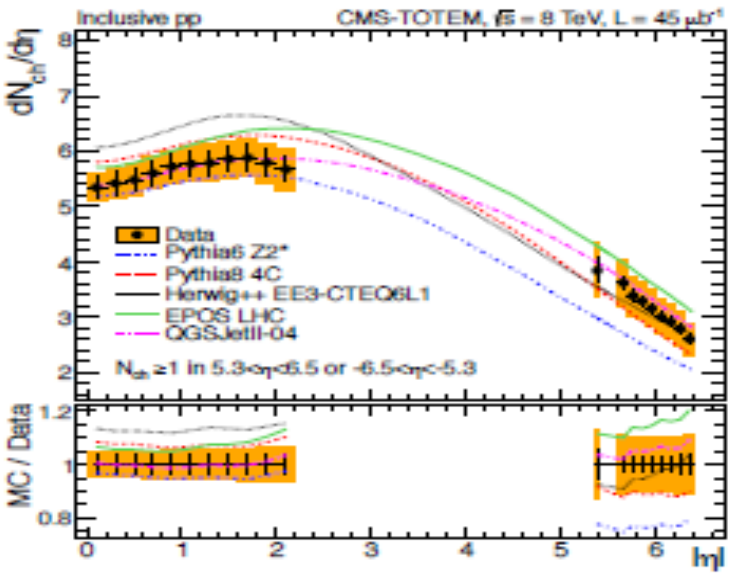


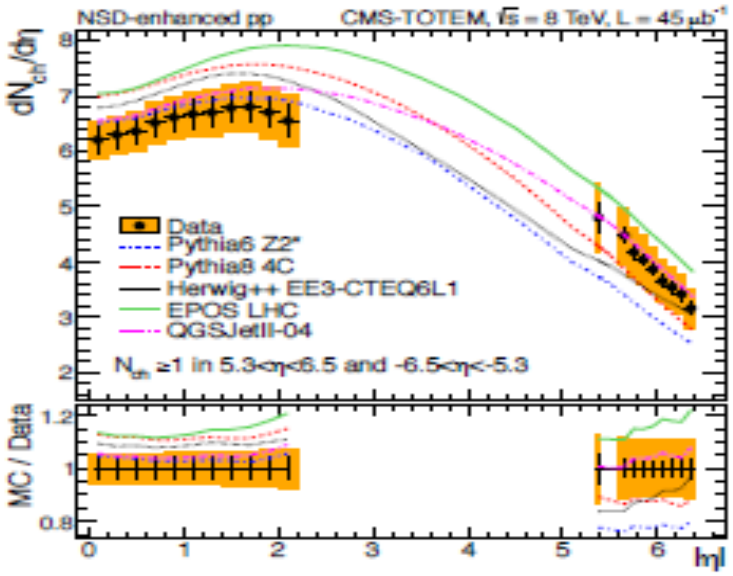
η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009

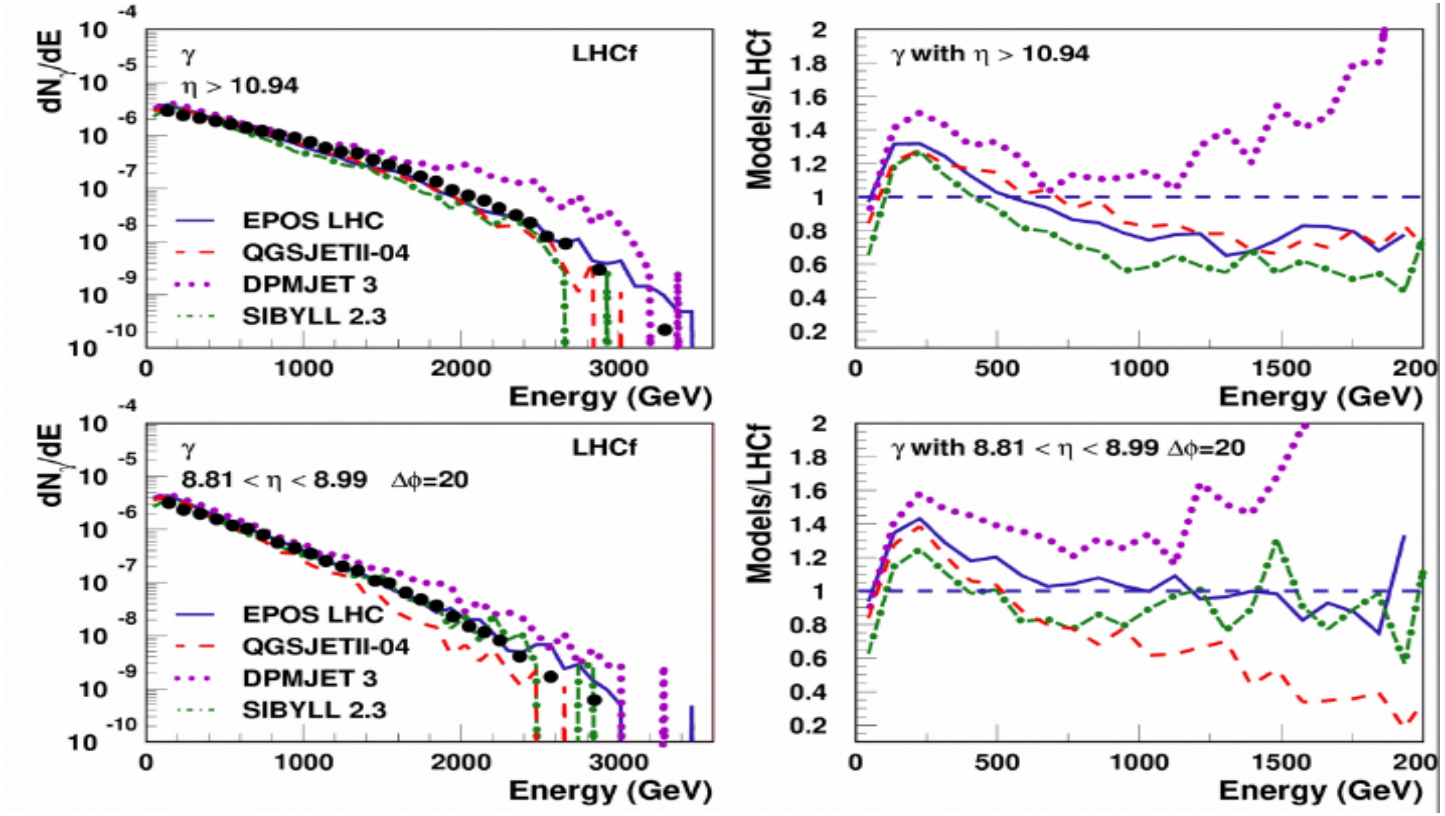


$$\eta = -\ln\tan\frac{\theta}{2}$$

Indirect (EAS) measurements are dominated by particles "close" to the shower axis


Inclusive pp
CMS-TOTEM, $\sqrt{s}$ = 8 TeV, L = 45 μb^{-1}
$dN_{ch}/d\eta$
Data
Pythia6 Z2*
Pythia8 4C
Herwig++ EE3-CTEQ6L1
EPOS LHC
QGSJetII-04
$N_{ch} \geq 1$ in 5.3<|η|<6.5 or -6.5<η<-5.3
MC / Data
|η|


NSD-enhanced pp
CMS-TOTEM, $\sqrt{s}$ = 8 TeV, L = 45 μb^{-1}
$dN_{ch}/d\eta$
Data
Pythia6 Z2*
Pythia8 4C
Herwig++ EE3-CTEQ6L1
EPOS LHC
QGSJetII-04
$N_{ch} \geq 1$ in 5.3<|η|<6.5 and -6.5<η<-5.3
MC / Data
|η|


dN_γ/dE
γ
η > 10.94
LHCf
EPOS LHC
QGSJETII-04
DPMJET 3
SIBYLL 2.3
Energy (GeV)
Models/LHCf
γ with η > 10.94
γ
8.81 < η < 8.99 Δφ=20
γ with 8.81 < η < 8.99 Δφ=20

We are not in the worst situation…

Collider experiments

- Sqrt(s) < 15 TeV
- Low pseudorapidity

(p-p collisions)

Indirect CR measurements

- Sqrt(s) up to ~500 TeV
- High pseudorapidity

Direct (high energy) CR measurements

- Sqrt(s) up to few TeV
- Mostly Low pseudorapidity (to be checked)

In our case:
Most of the CR models might properly work for energy deposit at our energies.
Backsplash and fragmentation to be checked.

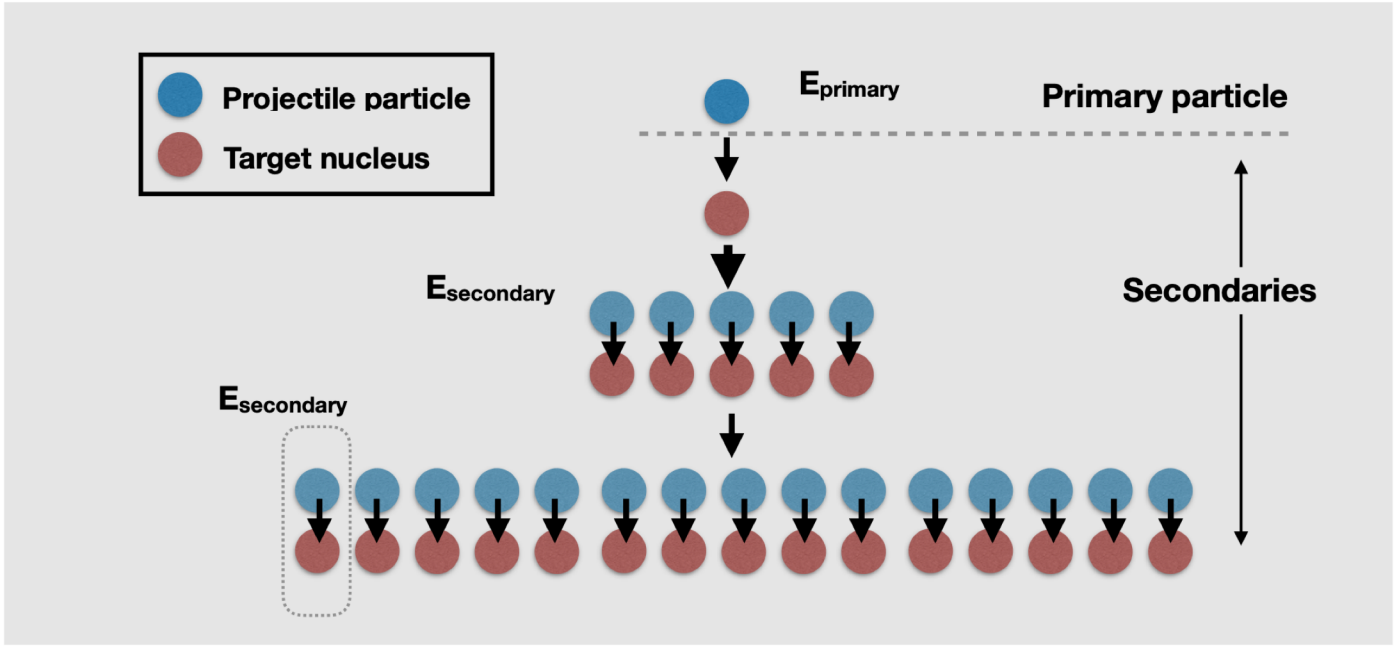
Our main goals now:
- Build a SW framework that use those models and correctly run up to 10PeV.
- Crosscheck with EAS simulation tools
-Investigate calorimetry, backsplash, fragmentation,… vs detector design
-Validation with CR direct calorimetric easurements (DAMPE, CALET, …)

Part 2 – towards implementation …

CRMC-Geant4 interface status and plans

- The CRMC-Geant4 interface is developed in cooperation with KIT experts to allow the integration of Ultra-High-Energy hadronic interaction model (EPOS, DPMJET, SYBILL,..) in Geant4
- First (alpha) version of CRMC-Geant4 interface is available for use in HERD — a dedicated “mirror” of the code repository will be created at HERD software Gitlab
- Physics not yet validated — next steps …

CRMC-Geant4 rationale (reminder)




```
If E < Ether
     use FTFP (GEANT4)
else
     use CRMC (EPOS/DPMJET/..)
```

CRMC-Geant4 interface: status and plans

- Plans for physics validation of CRMC-Geant4:
  - Investigating possible energy non-conservation issues
  - Validating with the existing TeV—PeV data of other experiments (mostly DAMPE)
  - Research aimed at “tuning” the hadronic simulations with the existing data at TeV—PeV energies

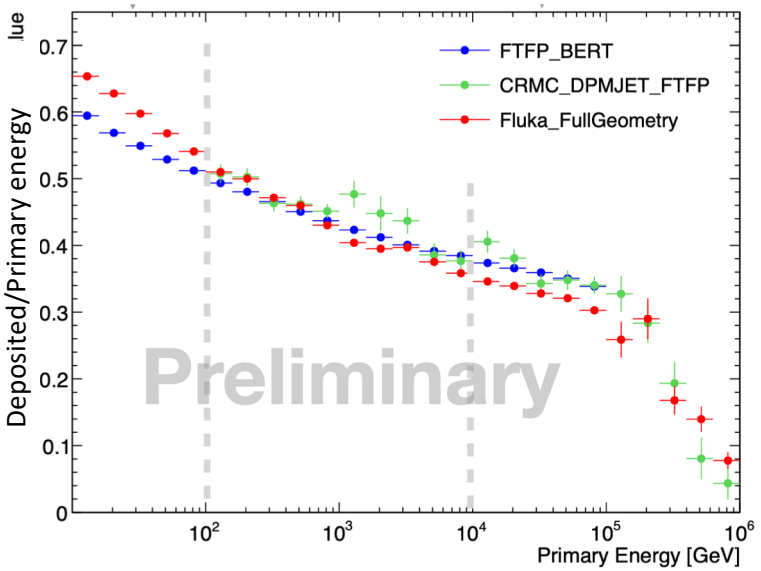
- Task force:
  - PhD student (A. Tykhonov’s group) — anticipated start : Summer 2020 (was delayed due to COVID)
  - PhD student (Prof. I. De Mitri’s group)
- Interested to join the task force are very welcome! (please contact Ivan De Mitri and Andrii Tykhonov)

CRMC-Geant4 interface: known issues

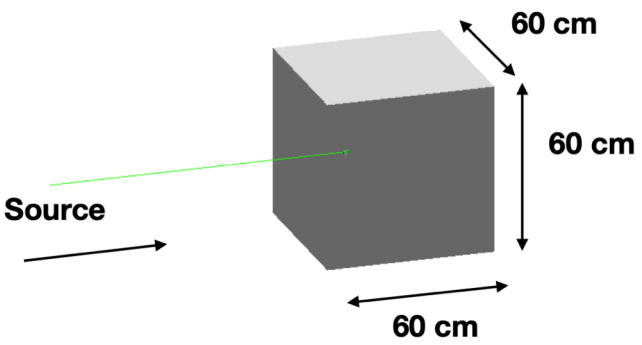
~ 1-2% energy non-conservation errors in CRMC- generated collisions:

```
-------- WWWW ------- G4Exception-START -------- WWWW -------
*** G4Exception : had012
      issued by : G4HadronicProcess:CheckResult()
Warning: Bad energy non-conservation detected, will re-sample.
the interaction
 Process / Model: alphaInelastic / HadronicModel
 Primary: alpha (1000020040),  E= 1.00264e+06, target nucleus
(83, 209)
 E(initial - final) = 20340.7 MeV.
*** This is just a warning message. ***
-------- WWWW -------- G4Exception-END --------- WWWW -------
```

Fast “drop” of CALO energy deposit at hundreds TeV

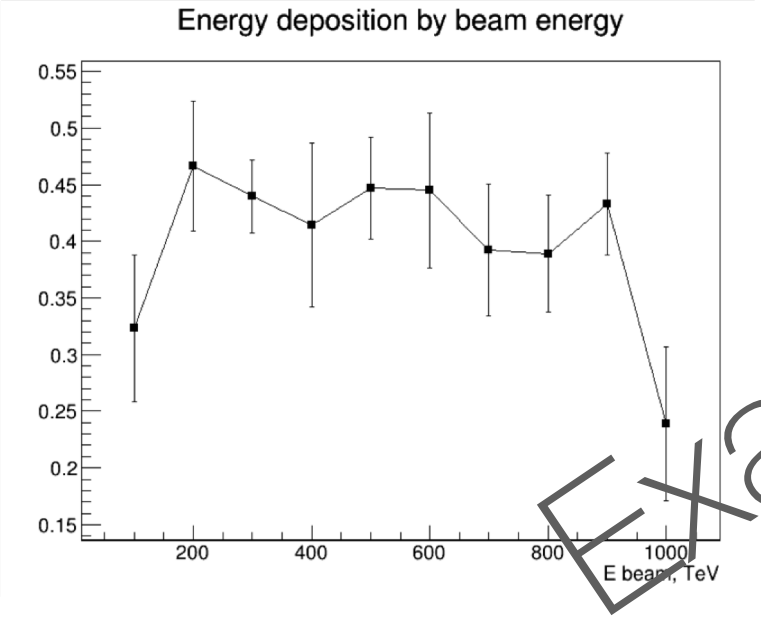


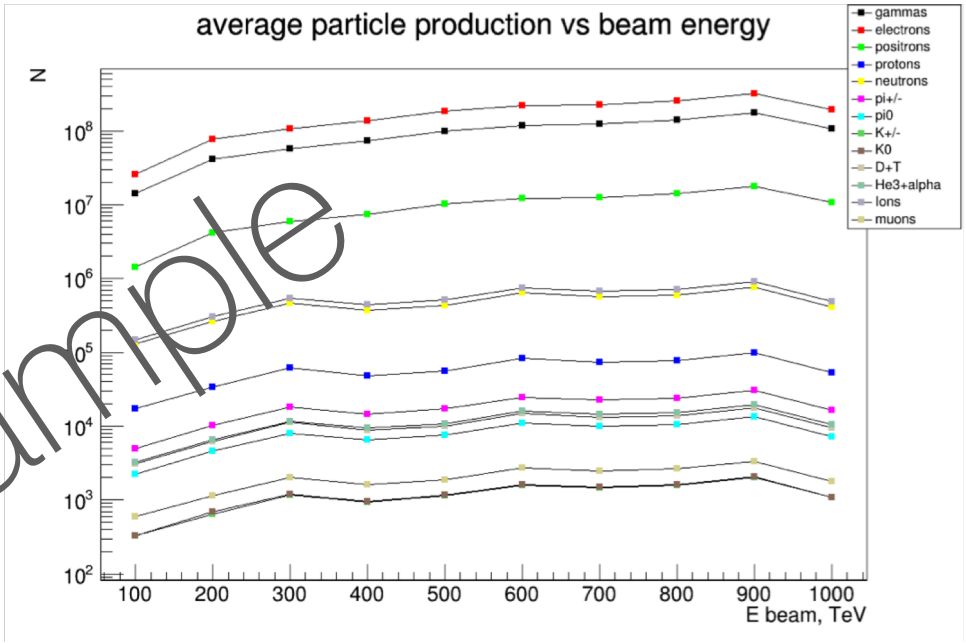
First steps to investigate — simulate simple detector geometry (LYSO/BGO cube) and check particle production / energies (e.g. if there is any “disappearing” energy)



CRMC-Geant4 interface: known issues

Investigating the CRMC-Geant4 issues – first steps





Example

… first preliminary studies performed by PhD candidate (ERC PeVSPACE project)

CRMC-Geant4 interface: known issues

- Validation/improvement of CRMC-Geant4 using the connection to **Cosmic-Ray ground experiments**?
- **FLUKA HERD simulation?**
  - Vey useful as an alternative / cross-check to Geant4 (CRMC)
  - Aim to work with the same geometry model as Geant4
  - Development would require nearly O(100%) commitment (a lot of coding work) in the initial phase

Conclusions

- Hadronic simulations crucial for HERD physics (trigger, energy deposit, particle ID, backscattering …)
- Roadmap:
  - CRCM-Geant4 interface as tool for hadronic model integration in Geant4 – first implementation done, extensive validation on the way …
  - Improving/validating hadronic models up to 10 PeV energies:
    - Using DAMPE data (PeVSPACE project)
    - Connection with EAS experiments
    - FLUKA (?) – open question …