cherenkov
telescope
array

CTA 報告 187:
ハドロン相互作用モデルとCTA

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Contents of this talk based on
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Outline

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- Simulation without detector response
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- Simulation with detector response (CTA prod3b, baseline configuration)
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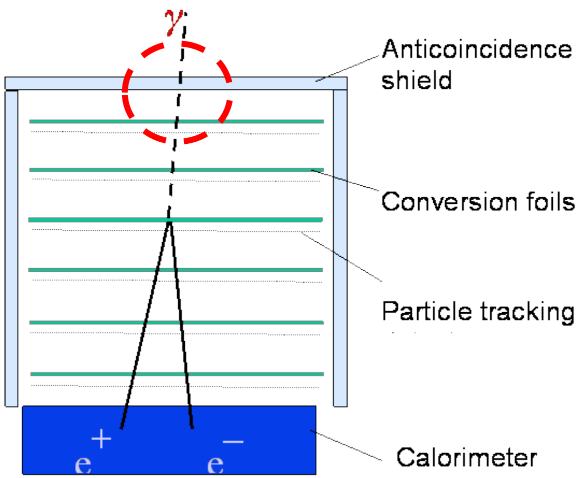
  - Basic shower parameters
  - Multivariate Analysis (MVA) parameter
  - γ-ray sensitivity
- Possibility of the interaction model verification with CTA
- Conclusion

Introduction: indirect/direct γ-ray observations

Direct

primary charge
→ most important info for the screening of charged cosmic rays

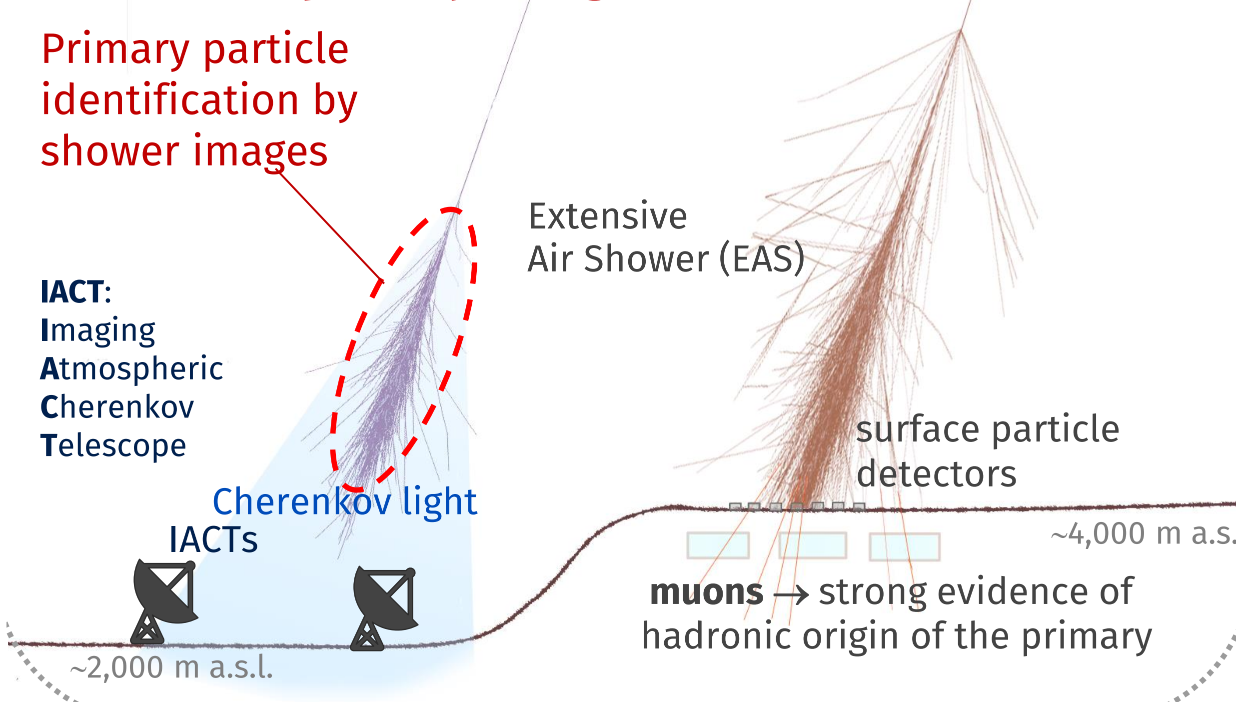


(figure from NASA GSFC website)

Indirect

primary charge → cannot be measured*

Primary particle identification by shower images



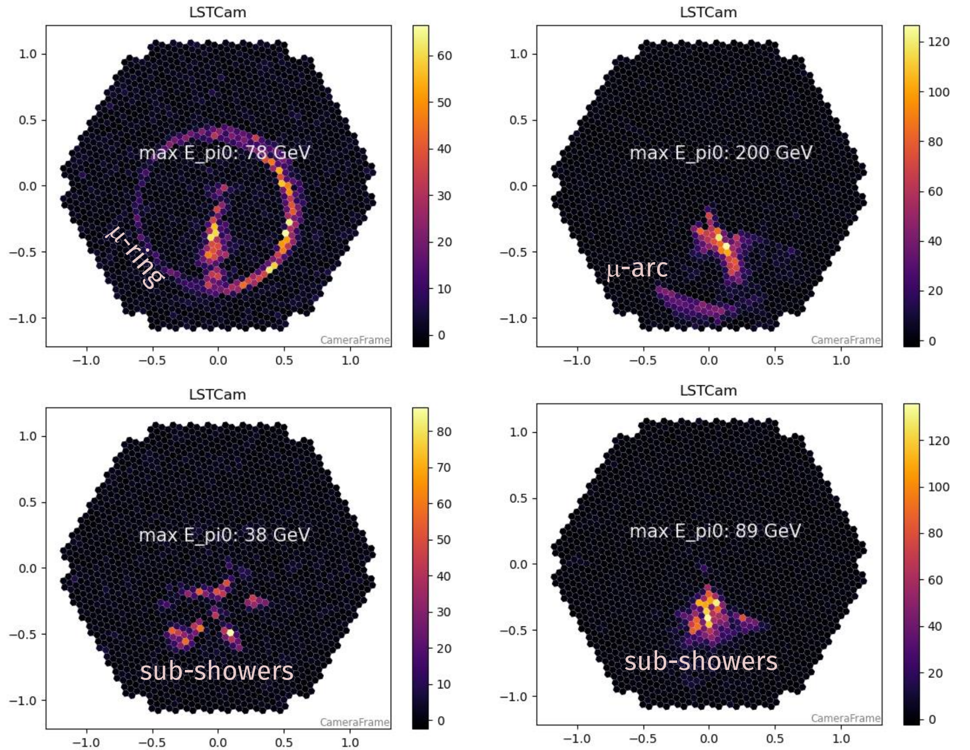
✓ Particle identification (γ or not) is more difficult in indirect observations
→ higher background level due to charged cosmic rays

* Except for IACT observations of heavy nuclei in limited situations

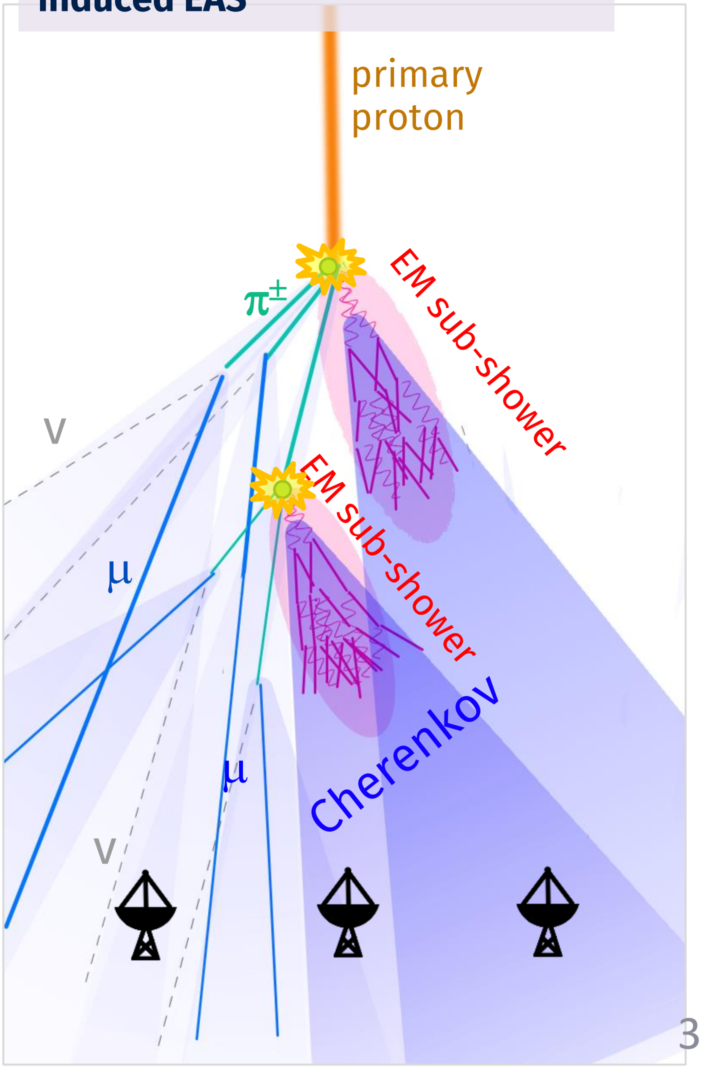
Proton-induced shower images in IACTs

- EASs from cosmic-ray protons : sub-structures
  - **EM sub-showers** from π^0
  - **Muons** from $\pi^{\pm}$
- Wide variation in observed images

Cherenkov Image samples for 1 TeV proton
z : 0 deg, Impact Parameter : 120 m,
first interaction height : 20km, target nucleus: Nitrogen (all fixed)



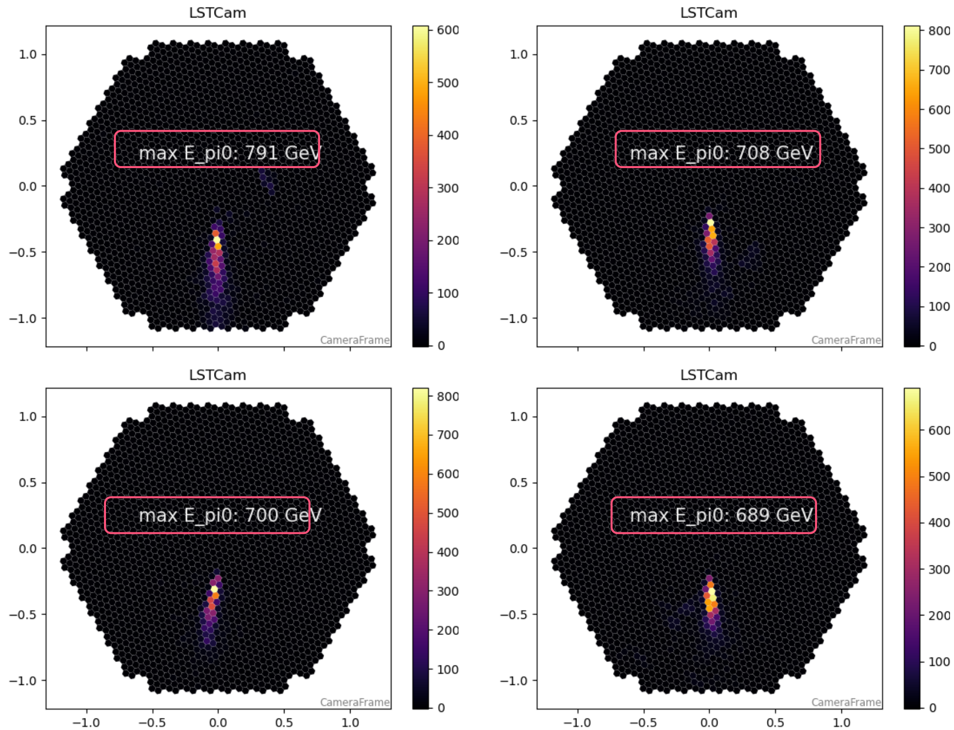
Schematic diagram of a proton-induced EAS



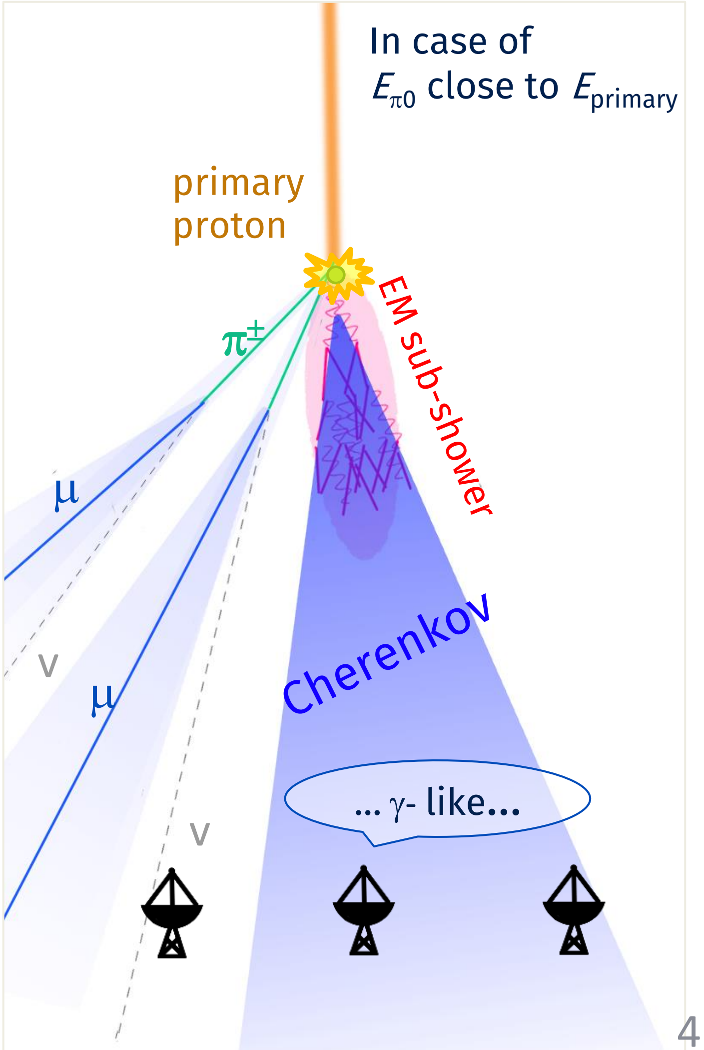
Proton-induced shower images in IACTs

- Previous studies on nature of γ-like proton events: Maier+ (2007), Sitarek+ (2018), Sobczyńska (2008, 2015) etc.
- Emission of **energetic π^0** $\rightarrow$ γ -like shower
- Rate of γ-like events depends on π^0 spectrum

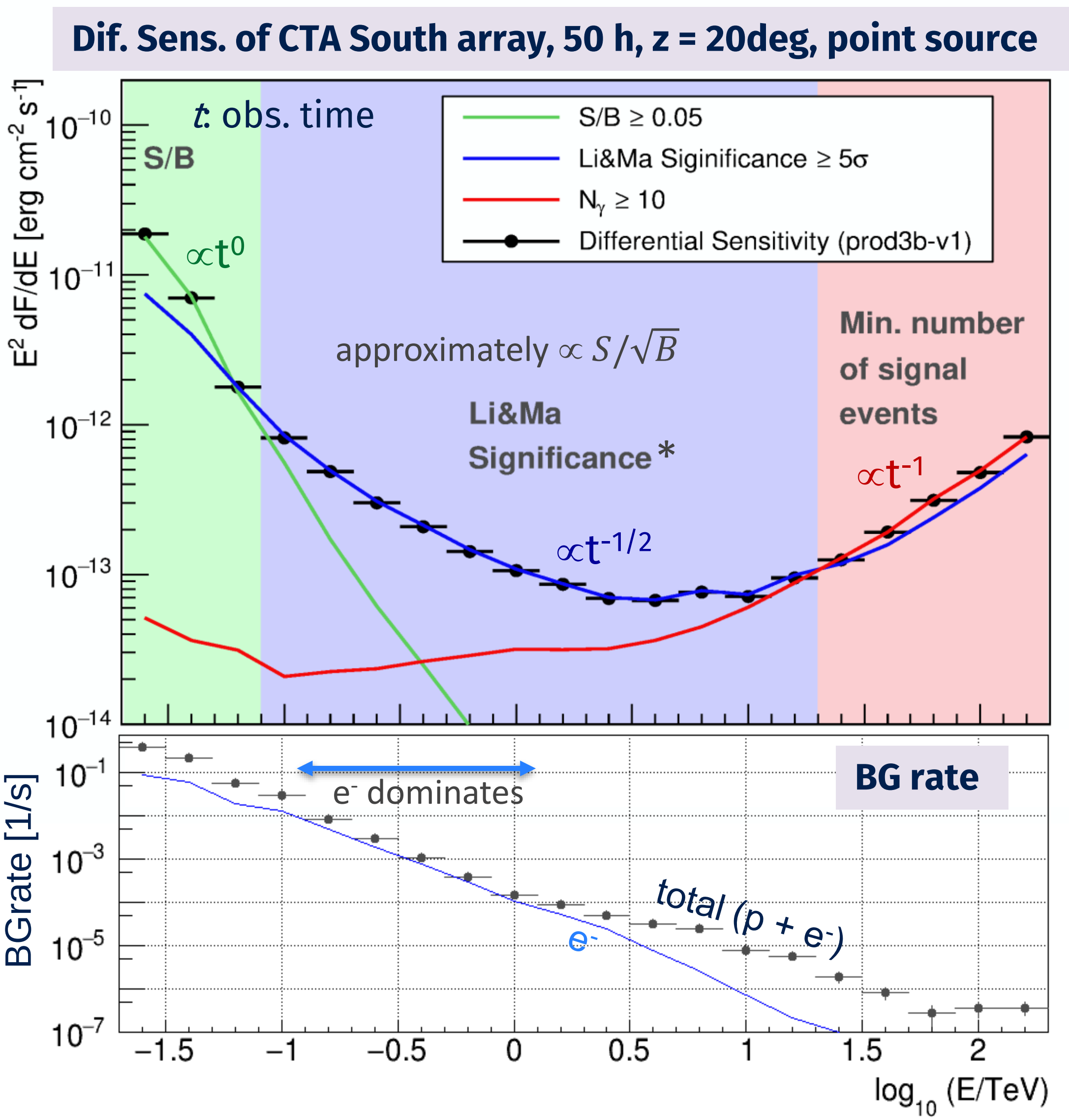
High max $E_{\pi 0}$ image samples for 1 TeV proton
z : 0 deg, Impact Parameter : 120 m,
first interaction height : 20km, target nucleus: Nitrogen (all fixed)



Schematic diagram of a γ-like EAS



γ-ray sensitivity (CTA case)



- At the trigger level, γ-ray events account for only <1 % (even for bright sources)
- Background ≈ misidentified cosmic-ray **protons** and **electrons**

- Efficiency of BG rejection in the analysis affects the sensitivity
- Event selection is optimized considering a balance of BG rejection and signal loss

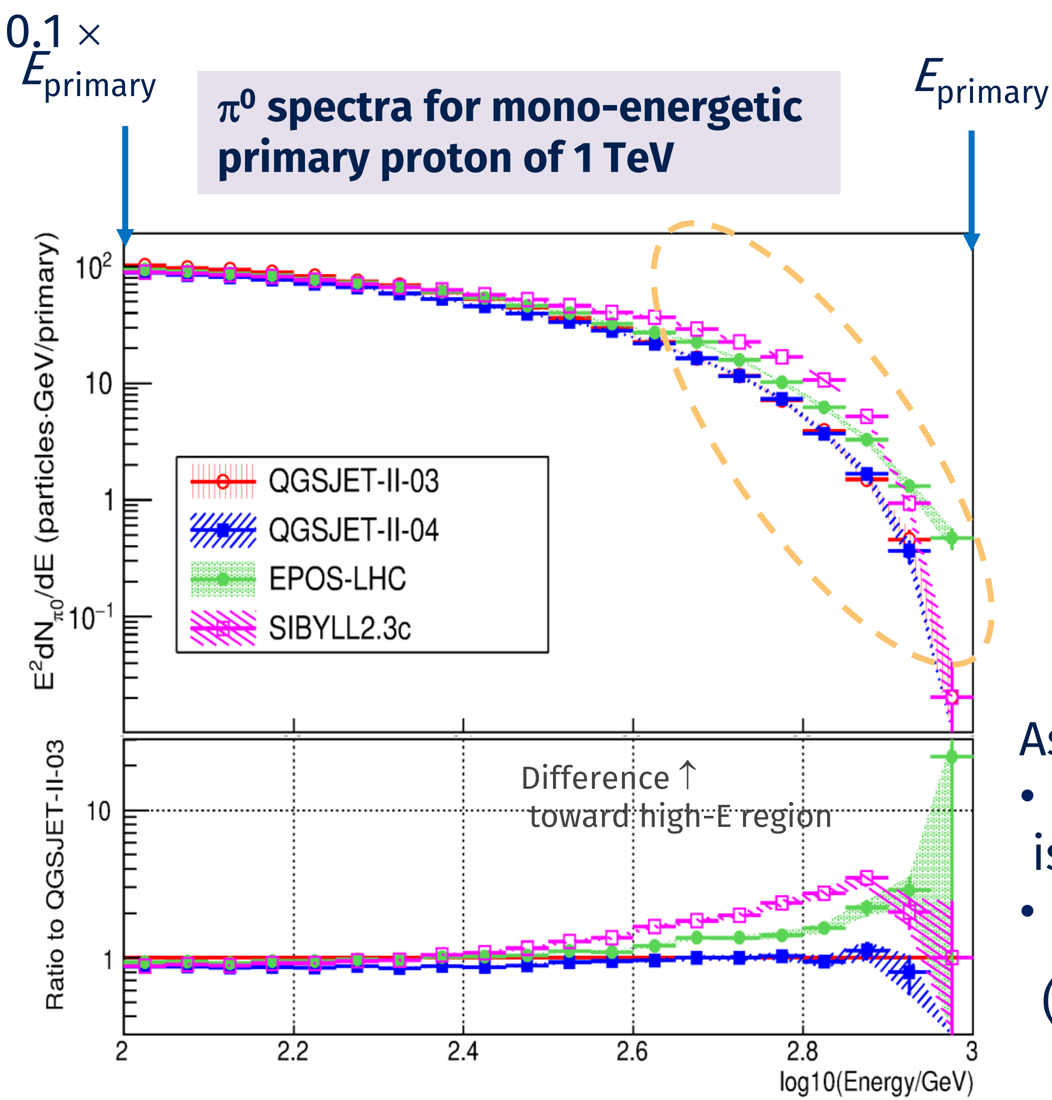
* Li &Ma (1983) Eq. (17) with α = 0.2, for CTA case

Monte Carlo Simulations

- **Tested hadronic interaction models**
  - **QGSJET-II-03** (pre-LHC) in CORSIKA 6.99
  - **QGSJET-II-04**, **SIBYLIL2.3c**, **EPOS-LHC** (post-LHC) in CORSIKA 7.69
- **Simulation w/o detector response**
  - π^0 spectra, energy fraction consumed in EM components
- **Simulation w/ detector (CTA) response**
  - **prod3b baseline** configuration (“**Omega** configuration”), South site array
  - Reconstructed energy, collection area, basic shower parameters, MVA parameter, γ-ray sensitivity

Current public CTA performance plot: ”**Alpha configuration**" is used as the first construction phase

Simulation w/o det. response: π^0 spectrum



- π^0 spectrum at the high energy edge affects γ–**like** event rate
- Tested models **show different features**
- **Harder** spectrum → **higher BG rate** is expected

EPOS-LHC → SIBYLL2.3c → QGSJET-II-03 ≈ QGSJET-II-04

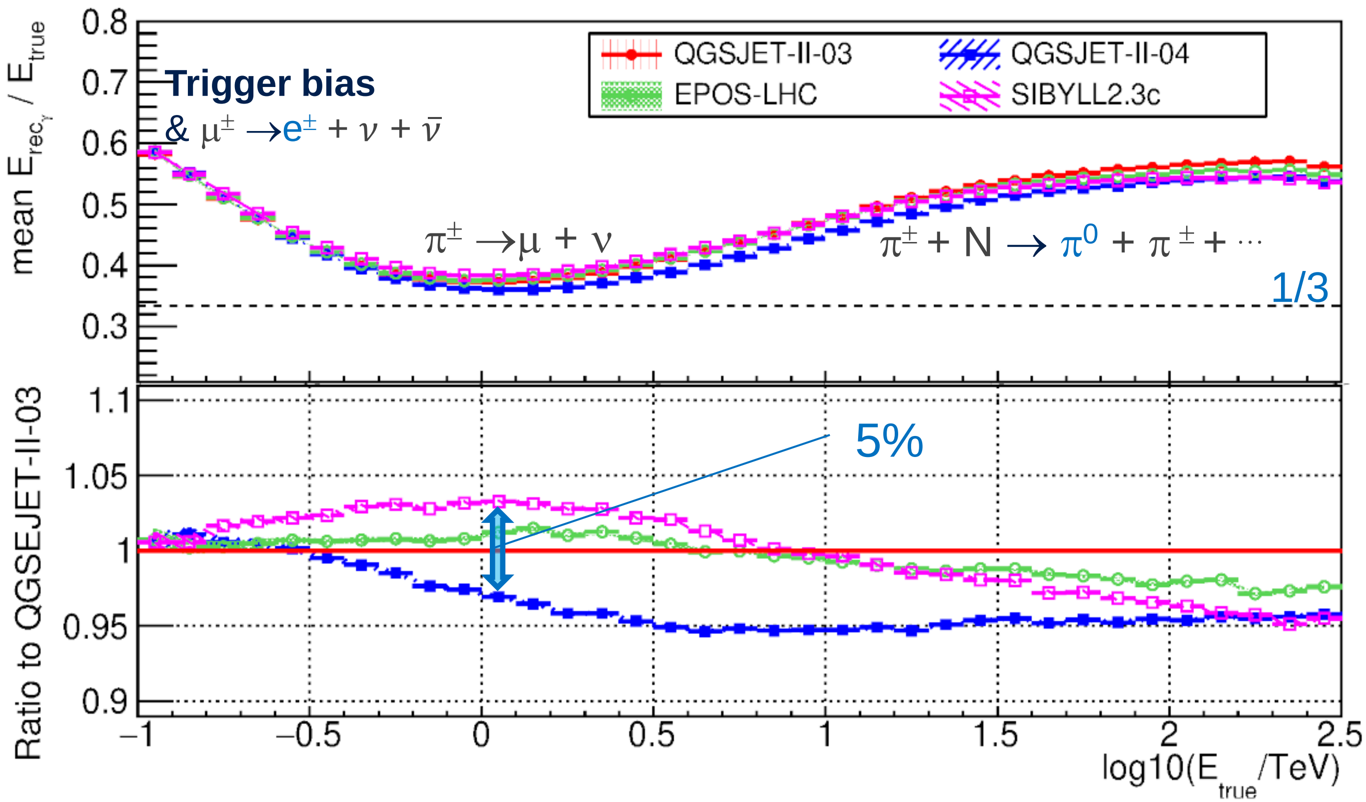
As for γ-like event rate, effect of
- different model **characteristics**

is stronger than
- parameter **tuning by LHC data**

(since QGSJET-II-03 ≈ QGSJET-II-04)

Simulation w/ detector response: Reconstructed energy

Mean Reconstructed Energy $E_{rec\gamma}$/True Energy VS True Energy

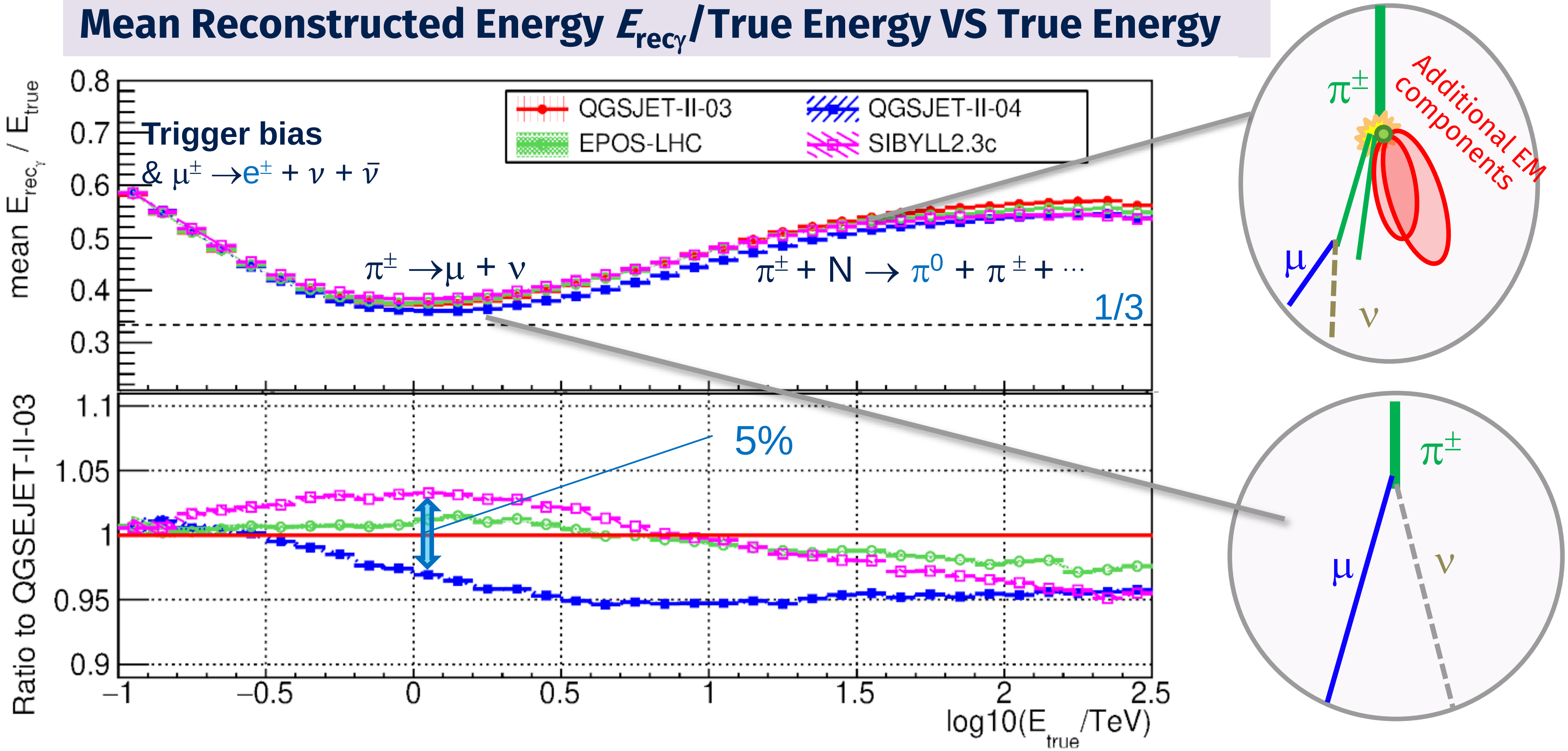


- Proton events, **before** γ-like event selection
- $E_{rec\gamma}$ is estimated assuming all the events are γ-rays
- Mean $E_{rec\gamma}$ approaches to **1/3** (= energy consumed in π^0) in moderately low-E region

- In mean $E_{rec\gamma}$, a difference of **5-7 %** between models is seen
- Difference in $E_{rec\gamma}$ propagates to a difference of **8-12%** in proton shower rate at a certain $E_{rec\gamma}$, assuming spectral index of -2.62

Simulation w/ detector response: Reconstructed energy

Mean Reconstructed Energy $E_{rec\gamma}$/True Energy VS True Energy



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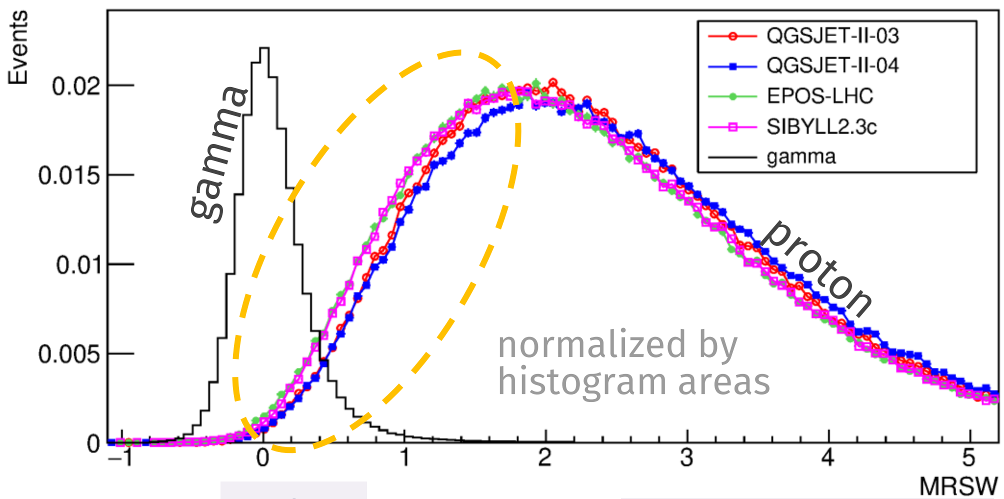
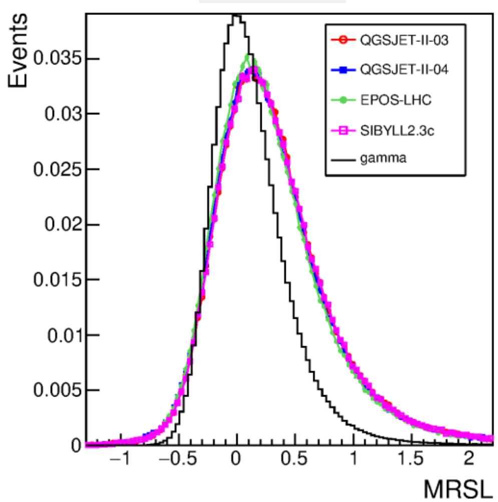
Basic shower parameters

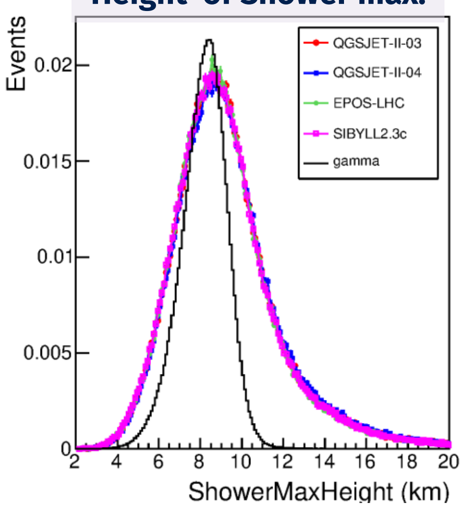
MRSW, $E_{rec\gamma}$: 1 -10 TeV



MRSL



Height of Shower max.



Width : lateral size of an EAS
Length : longitudinal size of an EAS

MRSW/L: Mean Reduced Scaled Width/Length (Aharonian+ 2006)

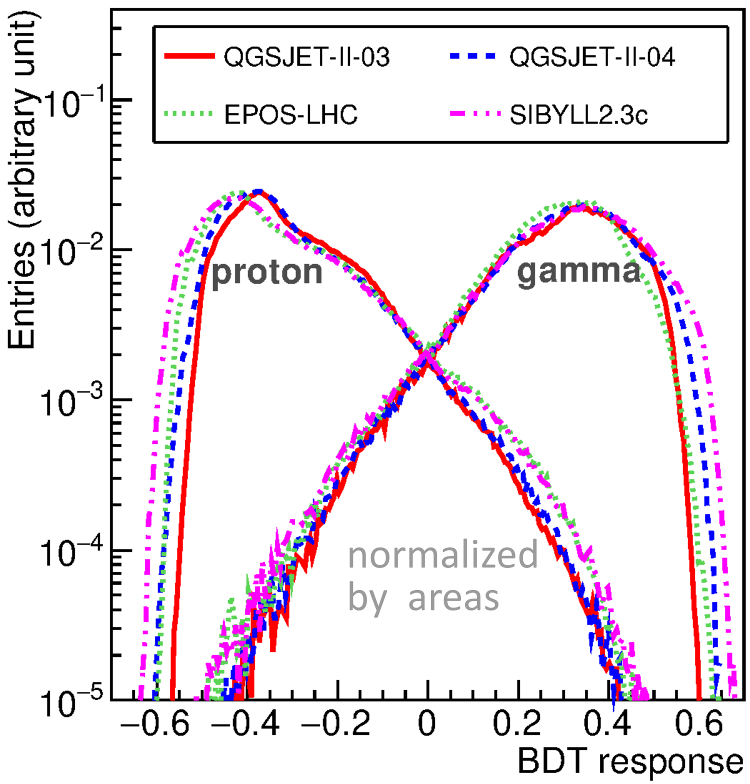
E> 1 TeV : lateral size is the most important for γ/h separation

- **EPOS-LHC** & **SIBYLL2.3c** have more events in γ-like regions
- **QGSJET-II-03 ≈ QGSJET-II-04** in γ-like region, but they are different in large MRSW (proton-like) region

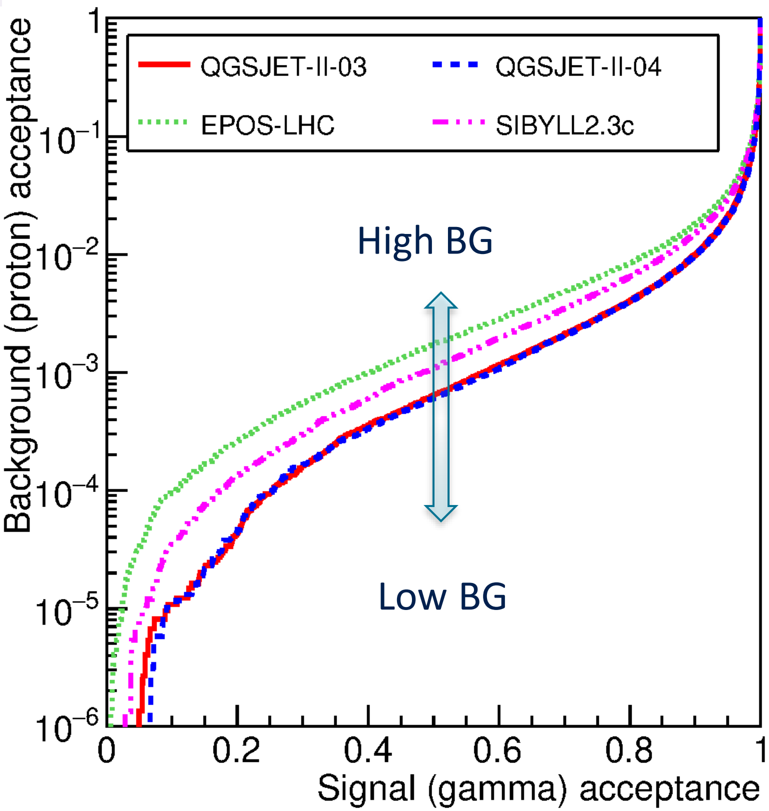
Multivariate analysis (MVA) parameters

- A single index for γ/h separation
- Boosted Decision Tree (BDT) in this work with 11 input parameters
- **EPOS-LHC** and **SIBYLL2.3c** show higher residual BG rate than the two **QGSJET-II** models at a same signal acceptance

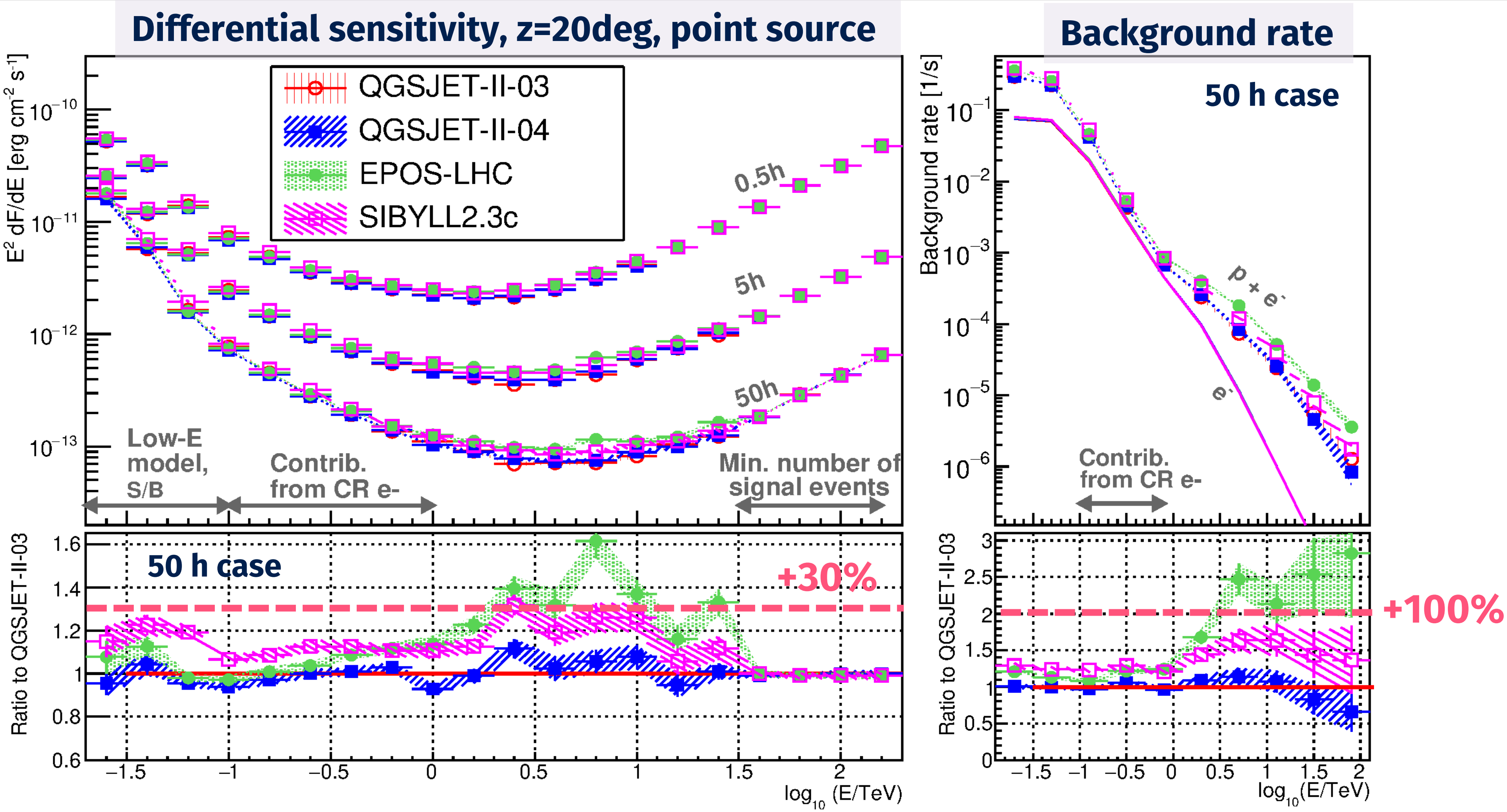
BDT distribution, $0 \leq \log_{10}(E_{rec}/\mathrm{TeV}) \leq 0.75$



BG acceptance VS signal acceptance



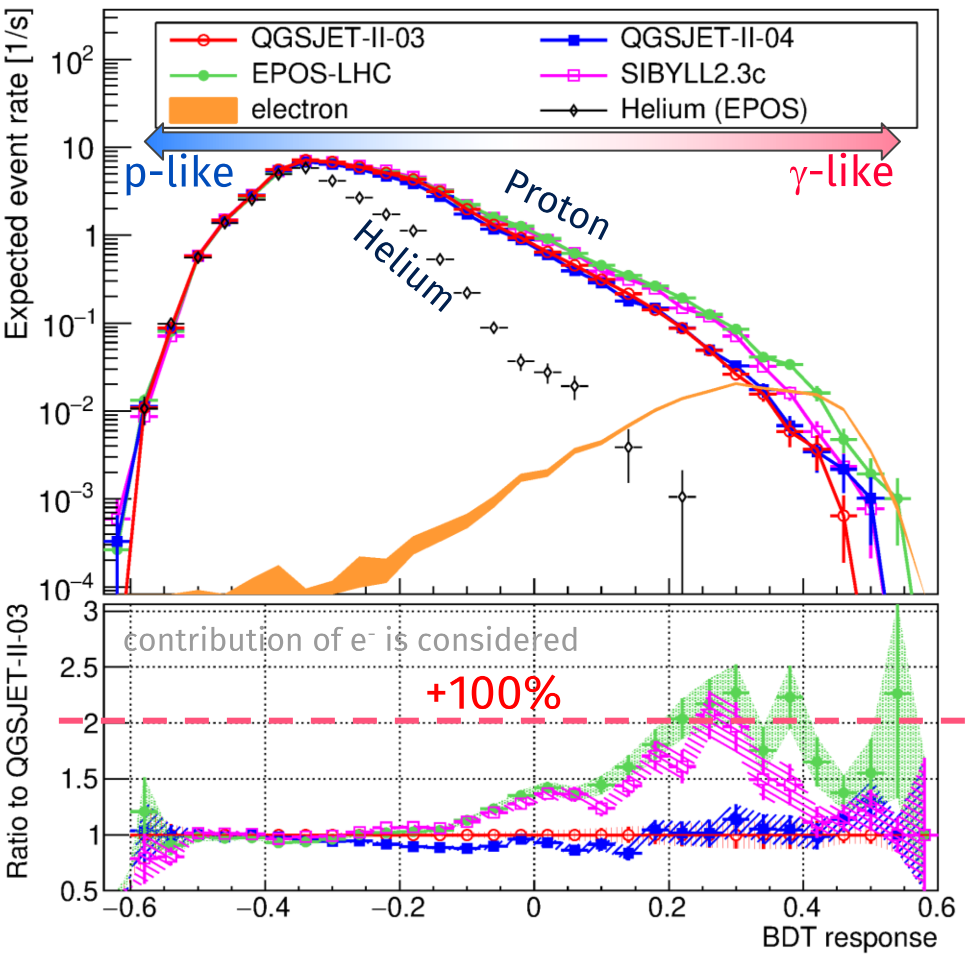
γ-ray sensitivity (prod3b, South site array)



- Differences of factor 2 (+100%) in BG rate, ~30% in γ-ray sensitivity between models
- Relation between models and its energy dependence is consistent with the expectations from simulations without detector response

Possibility of the interaction model verification with CTA

MVA (BDT) parameter, $E_{rec\gamma}$: 1- 10 TeV

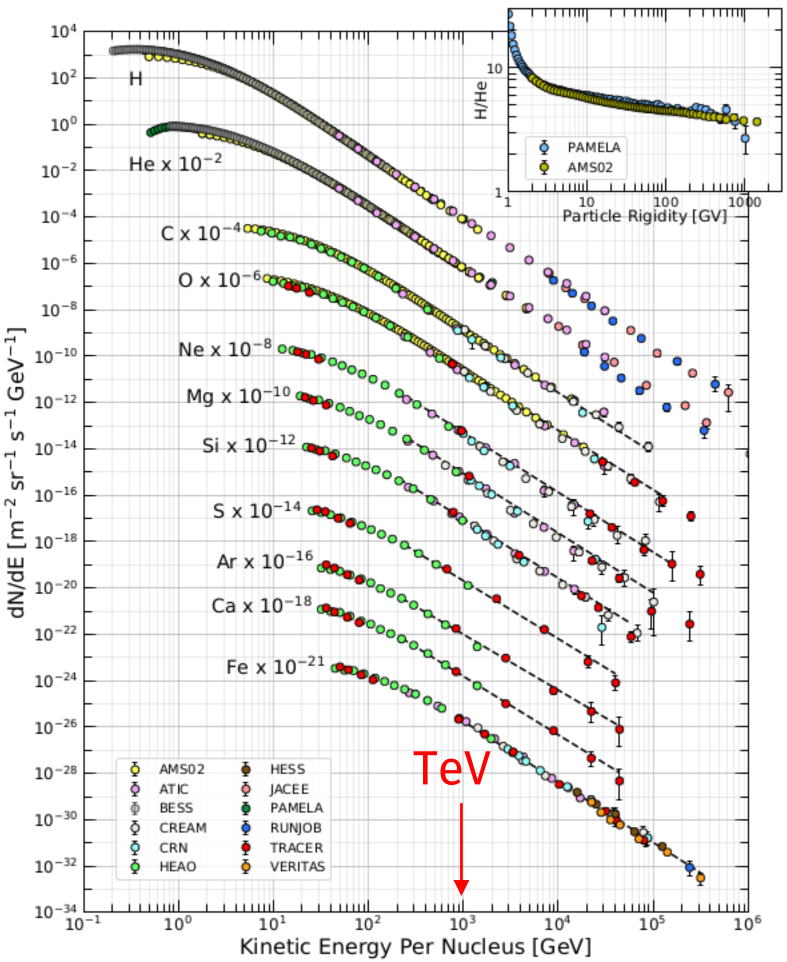


An identical BDT (trained with QGSJET-II-03 proton and γ) is used to evaluate BDT response

- CTA → expected to have a significant capability of model verification with various observables:
  - cosmic ray rate
  - shower shape parameters
  - muon numbers
  - γ-like event rate

  etc.
- Merit of using **γ-like event rate**:
  - Difference between models becomes **large** (due to π^0 spectral feature)
  - Verification with almost **pure proton** (among CR nuclei) is possible
- **No dedicated observation data** is needed

Possibility of the interaction model verification with CTA



Zyla et al. (Particle Data Group, 2020)

- One of the problems in the verification of interaction models with **air shower experiments:**

Composition? Interaction?

e.g. muon production depends on both of primary nuclei type and hadronic interaction.....

- Recent direct measurements at **very-high energy** limit uncertainty in cosmic ray composition
- Feedback from the **current IACTs on** the interaction model verification is **encouraged**!
  (*VERITAS, H.E.S.S., MAGIC....)*

Conclusion

- Effect of the uncertainty in the hadronic interaction models on the estimation of the γ-ray sensitivity of CTA was investigated
- Regarding the South site array of prod3b baseline configuration, differences of
  - factor 2 in background rate
  - ~30% in differential γ-ray sensitivity (in 1 – 30 TeV)

  are seen between the tested four interaction models (**QGSJET-II-03**, **QGSJET-II-04**, **EPOS-LHC**, **SIBYLL2.3c**)
- These results are consistent with the features of the secondary particles in EASs, especially π^0 **spectrum**
- CTA will have a significant capability for verification of interaction models, without requiring any dedicated observation time
- Feedback from current IACTs is also encouraged!

For more detail, see:
Ohishi M *et al.*, *J. Phys. G: Nucl. Part. Phys.* **48** 075201 (2021)