Neutral meson analysis on LHCf
(π^0, η, K^0s)

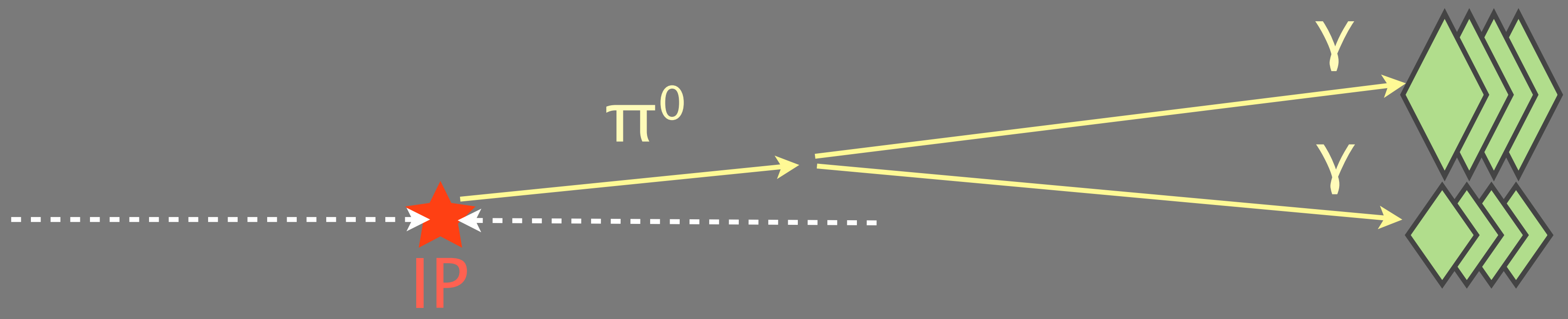
G. Mitsuka (Nagoya University)

Oct. 3-4, 2012, RIKEN

Outline

- Introduction and Physics motivation
- Analysis procedures
- π^0 p_T spectra at $\sqrt{s}$=7TeV (arXiv:1205.4578, accepted by PRD)
- K^0_s analysis
- Summary

π^0 analysis at $\sqrt{s}$=7TeV



Large tower

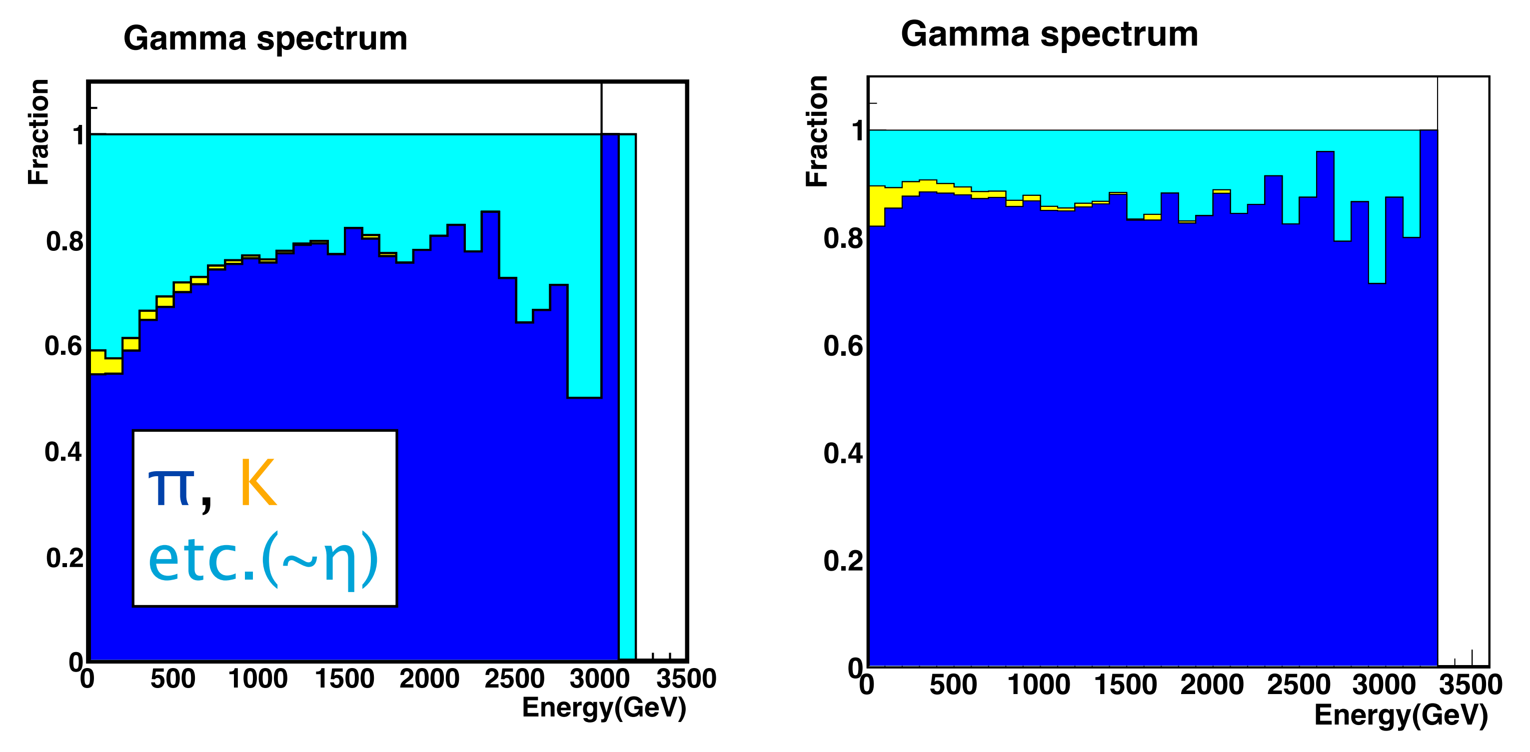
Small tower

(8.9<y<11.0)

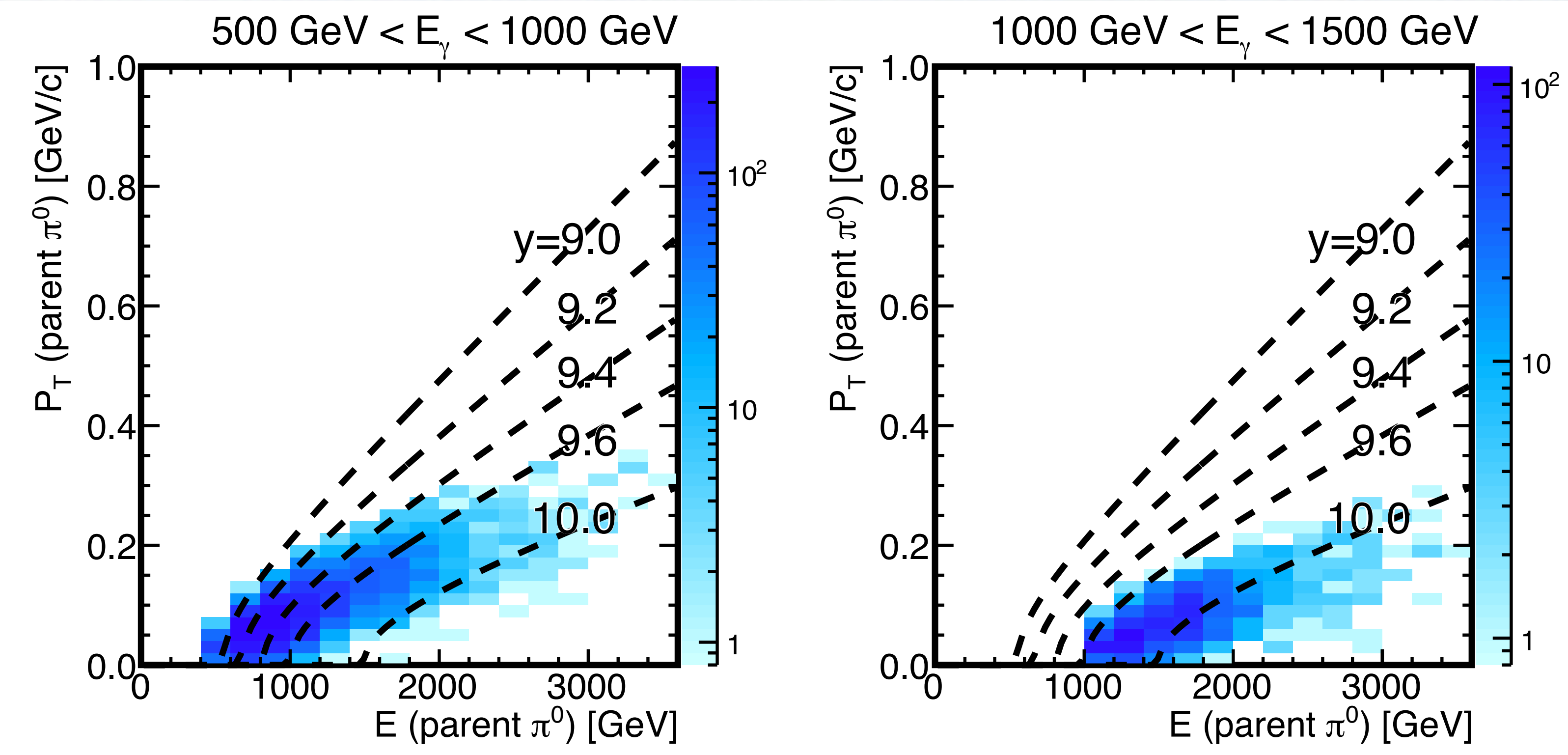
Physics motivation

Parent particle decaying to the detected photon

SIBYLL 2.1 DPMJET 3.04



Contribution of π^0 decay to photons in $\eta>10.94$

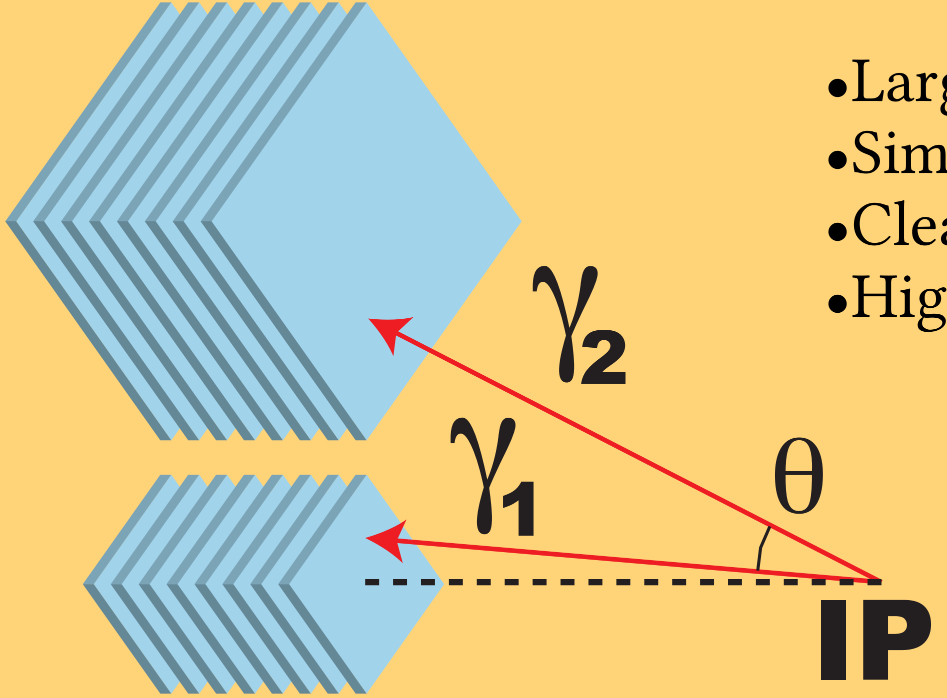


Production of extensive air shower is quite sensitive to forward photon. Forward photon energy spectra are investigated at $\sqrt{s}$=900GeV and 7TeV.

- More detailed discussion needs information at hadron level even for the application to air shower simulation.
- Input of pT and rapidity is necessary.

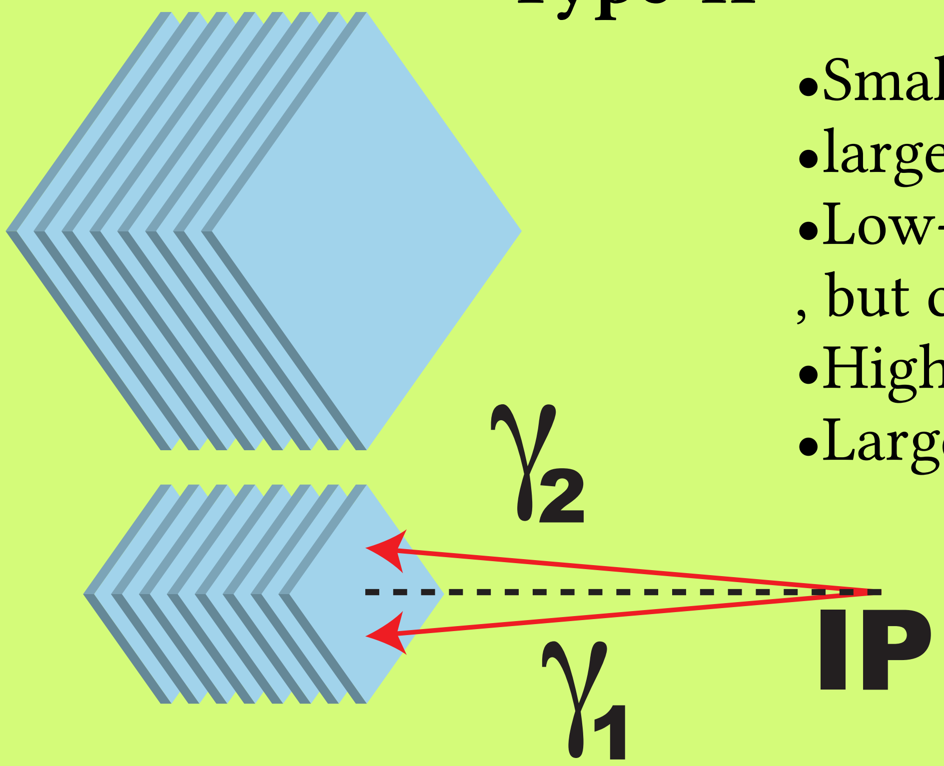
π^0 analysis at $\sqrt{s}$=7TeV

Type-I



- Large angle
- Simple
- Clean
- High-stat.

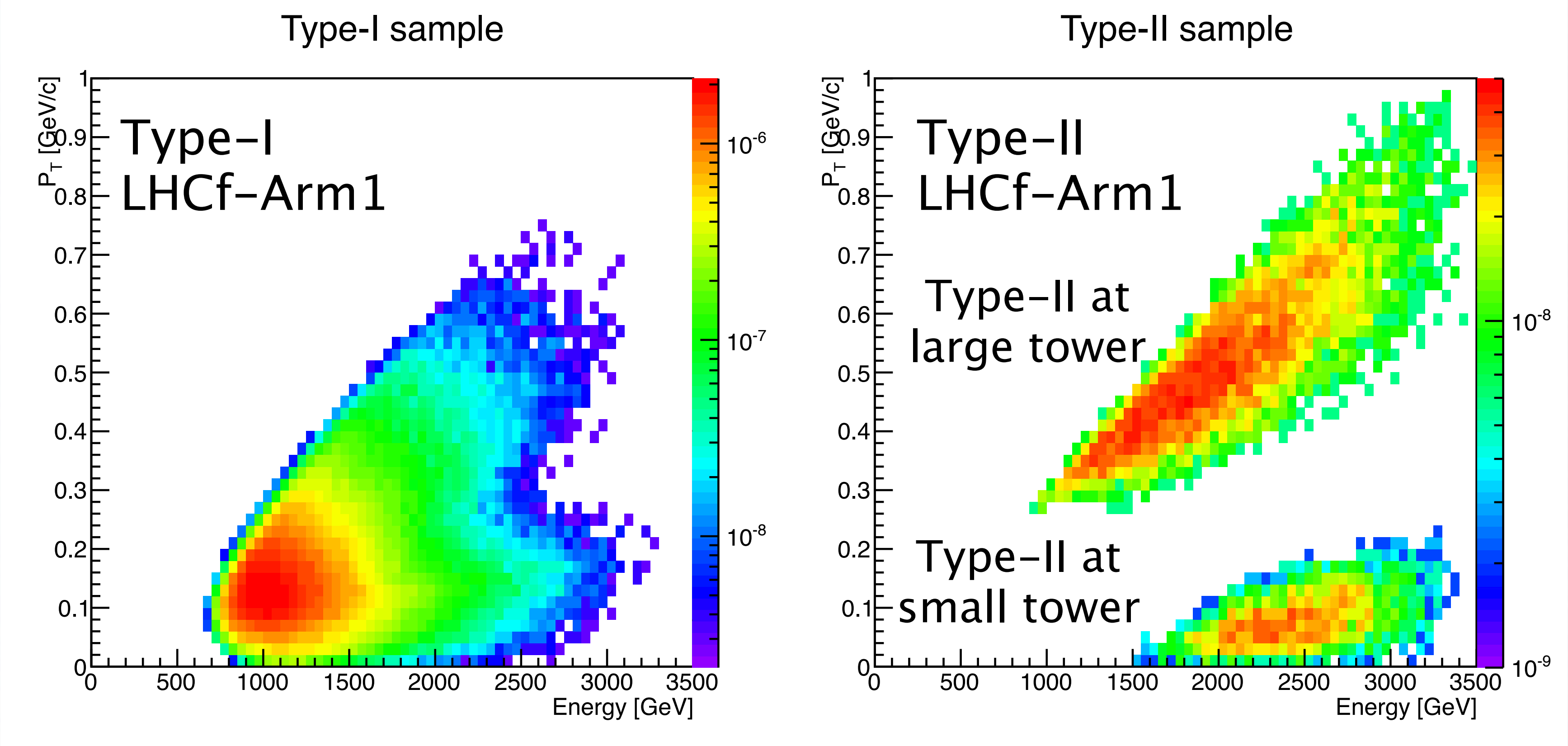
Type-II

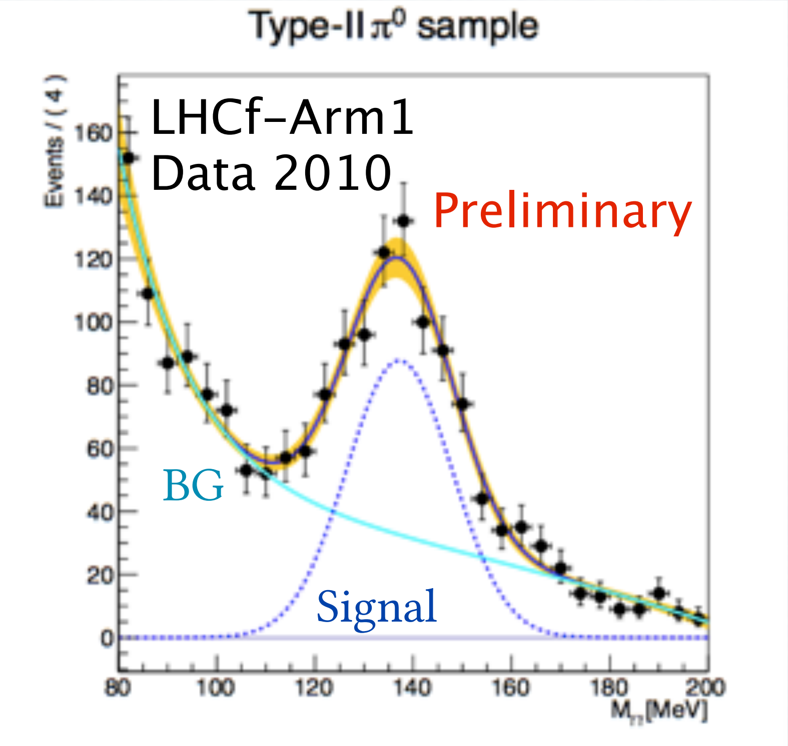


- Small angle
- large BG
- Low-stat.

, but can cover

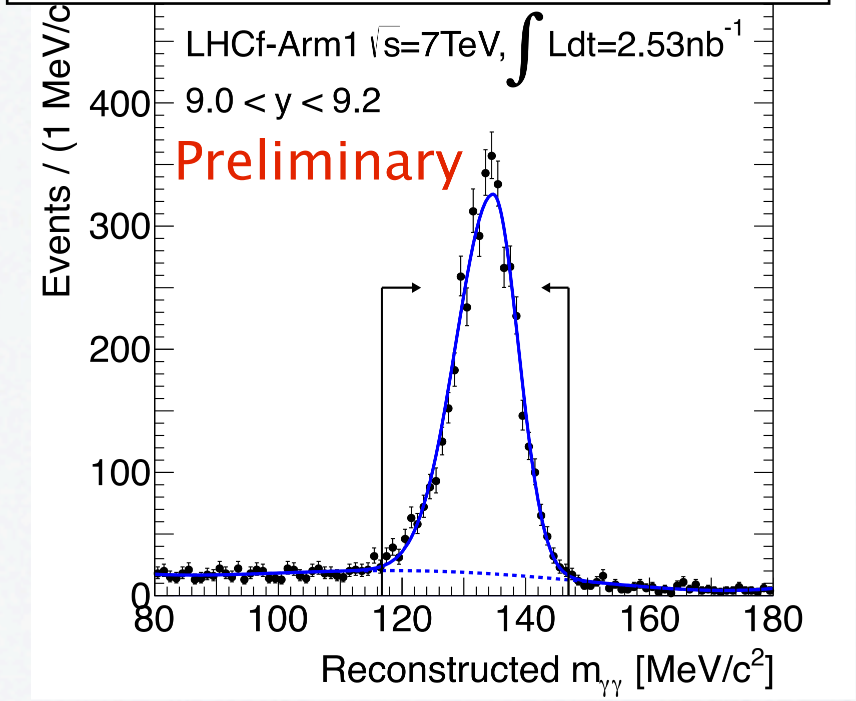
- High-E
- Large-P_T





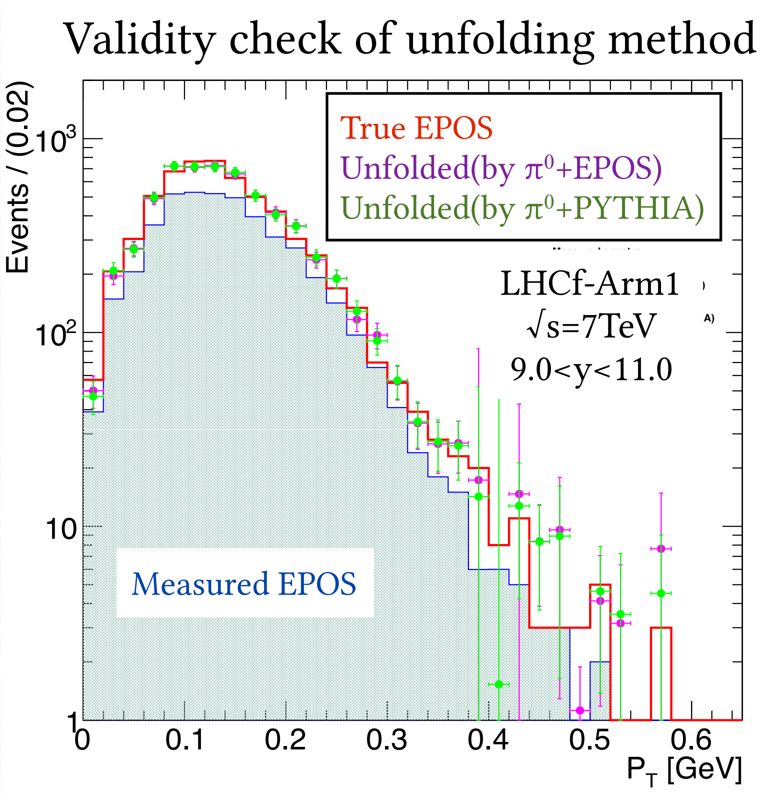
Analysis procedures

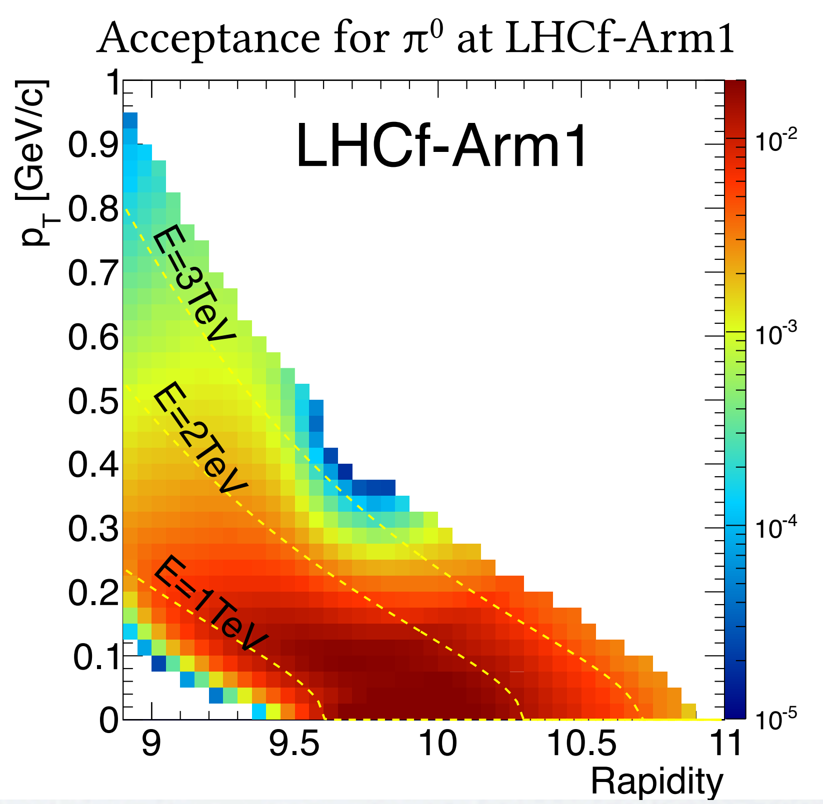
Signal window : [-3σ, +3σ]
Sideband : [-6σ, -3σ] and [+3σ, +6σ]



- Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

$$f(y,p_{\mathrm{T}})^{\mathrm{Sig}} = f(y,p_{\mathrm{T}})^{\mathrm{Sig+BG}} - f(y,p_{\mathrm{T}})^{\mathrm{BG}} \frac{\int_{\hat{m}-3\sigma_l}^{\hat{m}+3\sigma_u} L_{\mathrm{BG}}\,dm}{\int_{\hat{m}-6\sigma_l}^{\hat{m}-3\sigma_l} L_{\mathrm{BG}}\,dm + \int_{\hat{m}+3\sigma_u}^{\hat{m}+6\sigma_u} L_{\mathrm{BG}}\,dm}$$


Validity check of unfolding method


Acceptance for π0 at LHCf-Arm1

- Raw distributions are corrected for detector responses by an unfolding process that is based on the iterative Bayesian method.
  (G. D'Agostini NIM A 362 (1995) 487)

- Detector response corrected spectrum is proceeded to the acceptance correction.

Systematic uncertainties

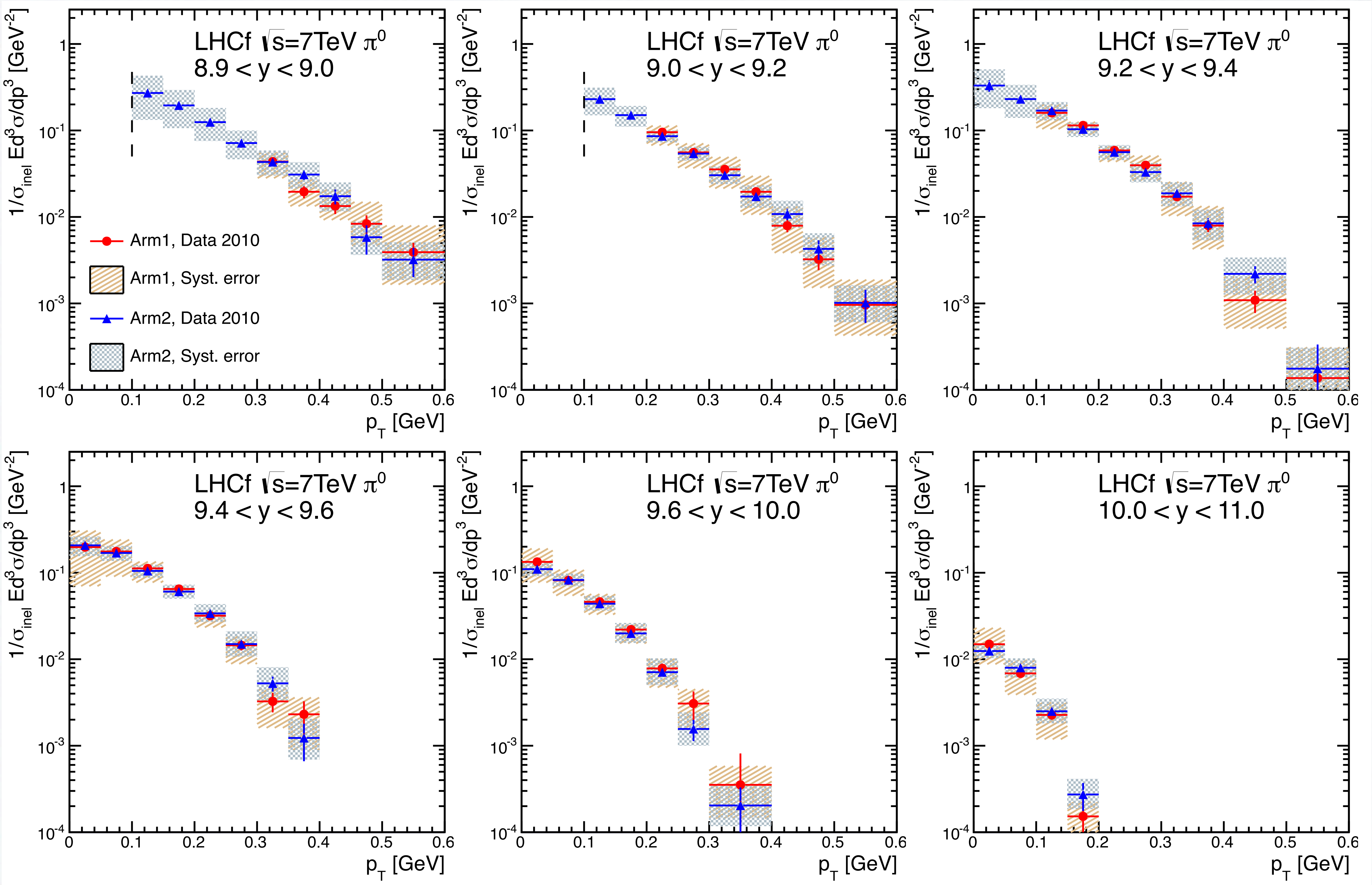
- Energy scale*
  - 3.5% : calibration at SPS and by radiative source
  - 8.1(3.8)& : invariant mass excess to the π^0 mass
- Particle identification
  - Residual in the longitudinal shower development (0-20%)
- Offset of beam axis
  - Offset of the "beam center" position (5-20%)
- Single-hit selection
  - Different performance between data and MC (3%)
- Position dependent correction
  - Shower leakage and light-yield collection efficiency (5-40% for Arm1 & 5-30% for Arm2, due to the light guide geometry)
- Luminosity
  - Calibration factor 2.7% + intensity 5.0% = 6.1%

---

* This uncertainty indicate a shift along the energy axis, not along the vertical axis.

π^0 p_T spectra

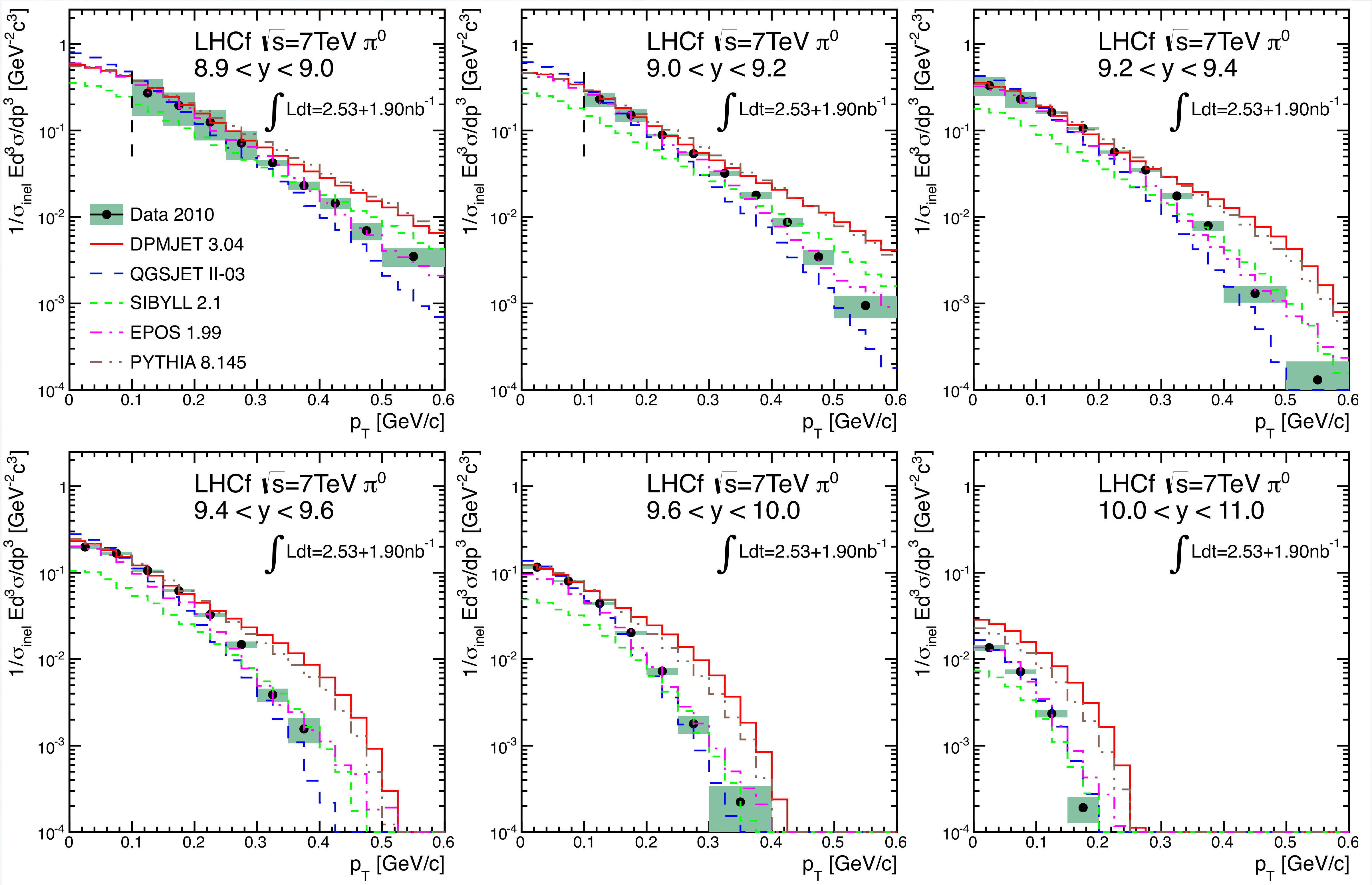
Arm1 data vs Arm2 data



- No energy-scale systematic uncertainty quoted.
- Consistent spectra are obtained between Arm1 and Arm2.

π^0 p_T spectra

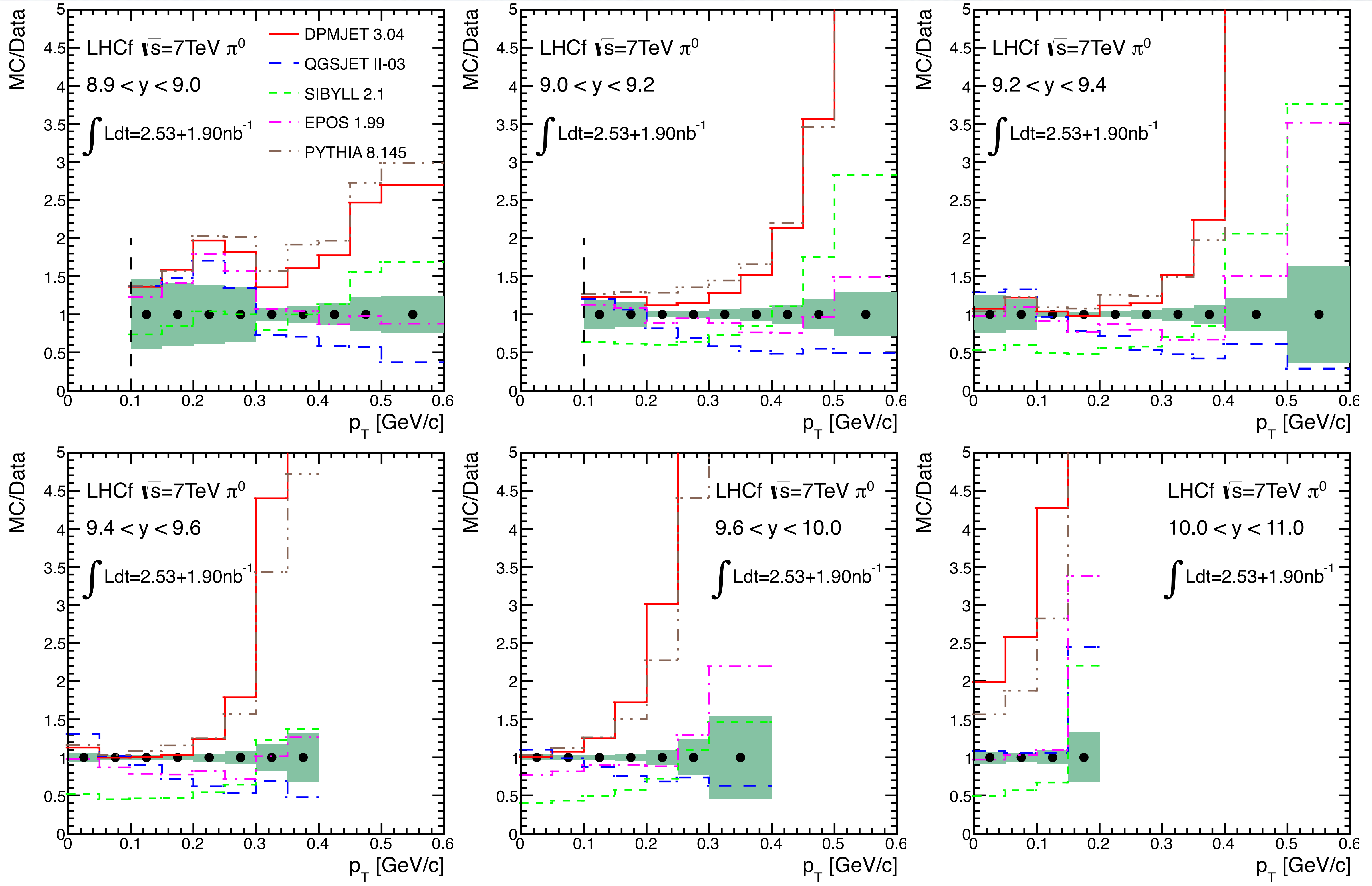
MC simulations vs Combined spectra (Arm1 and Arm2 data)



- LHCf data are mostly bracketed among hadronic interaction models.
- DPMJET, SIBYLL(x2) and PYTHIA are apparently harder, while QGSJET2 is softer.

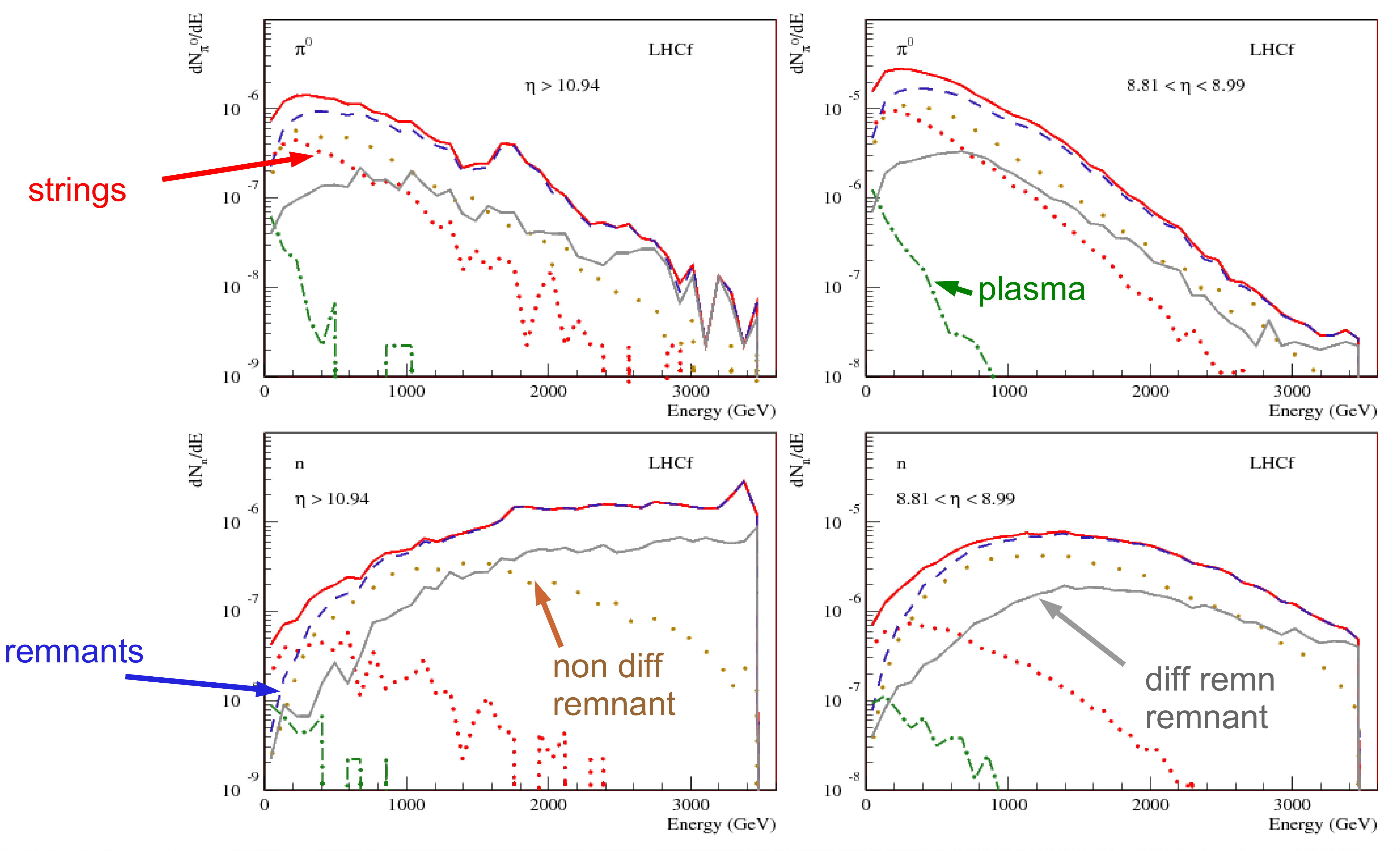
π^0 p_T spectra

MC simulations / Combined spectra (Arm1 and Arm2 data)



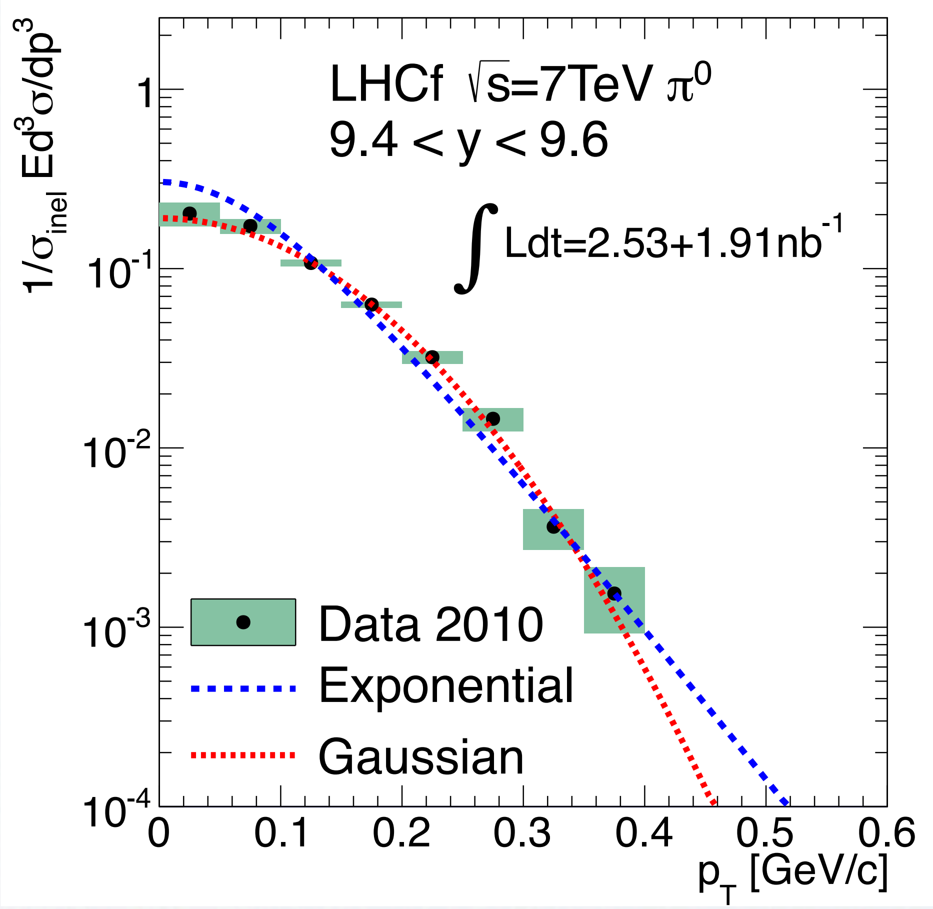
- Harder models use the Lund “popcorn” model → produce hard mesons.
- QGSJET allows only one quark exchange in collision → leading is always baryon.

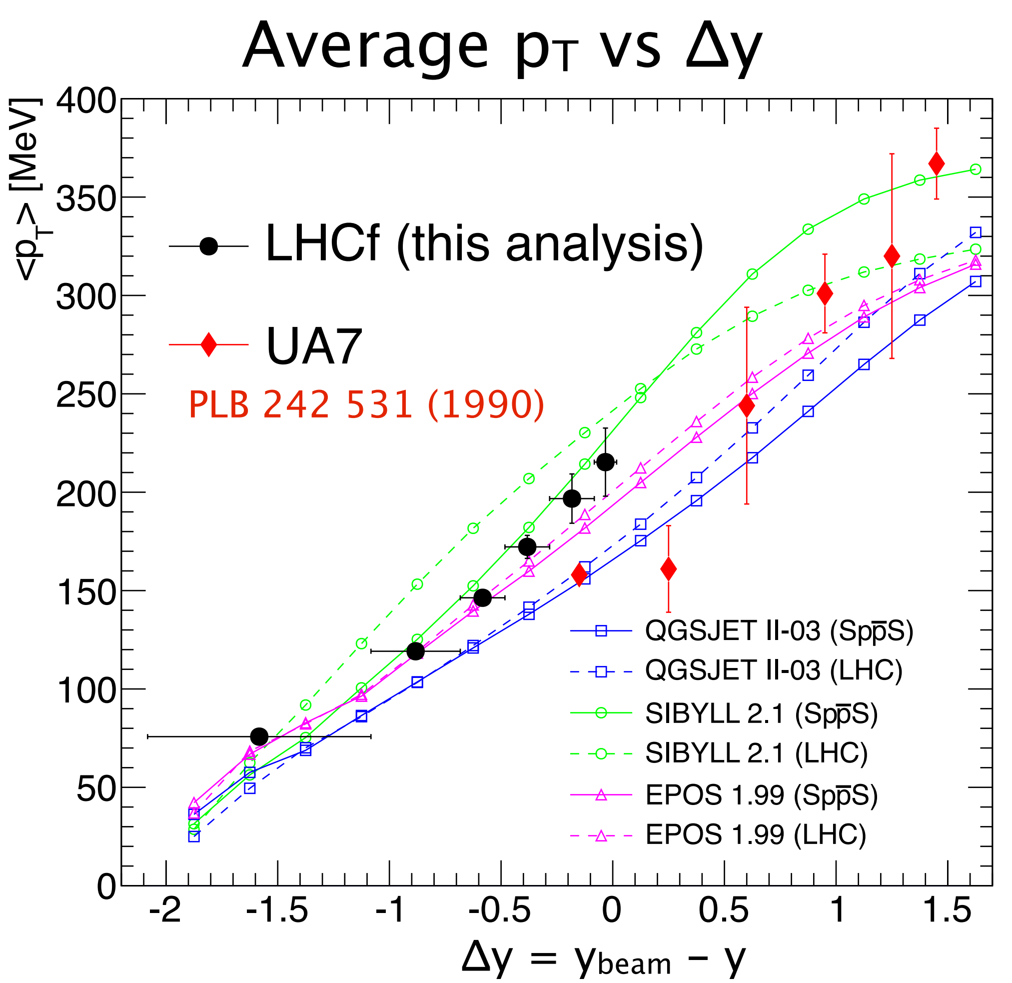
Expected contribution



(courtesy of T. Pierog)

π^0 average p_T





1. Thermodynamics (Hagedron model)

$$\frac{1}{\sigma_{\mathrm{inel}}} E \frac{d^3\sigma}{dp^3} = A \cdot \exp(-\sqrt{p_{\mathrm{T}}{}^2 + m_{\pi^0}^2}/T)$$

$$\langle p_{\mathrm{T}} \rangle = \sqrt{\frac{\pi m_{\pi^0} T}{2}} \frac{K_2(m_{\pi^0}/T)}{K_{3/2}(m_{\pi^0}/T)}$$

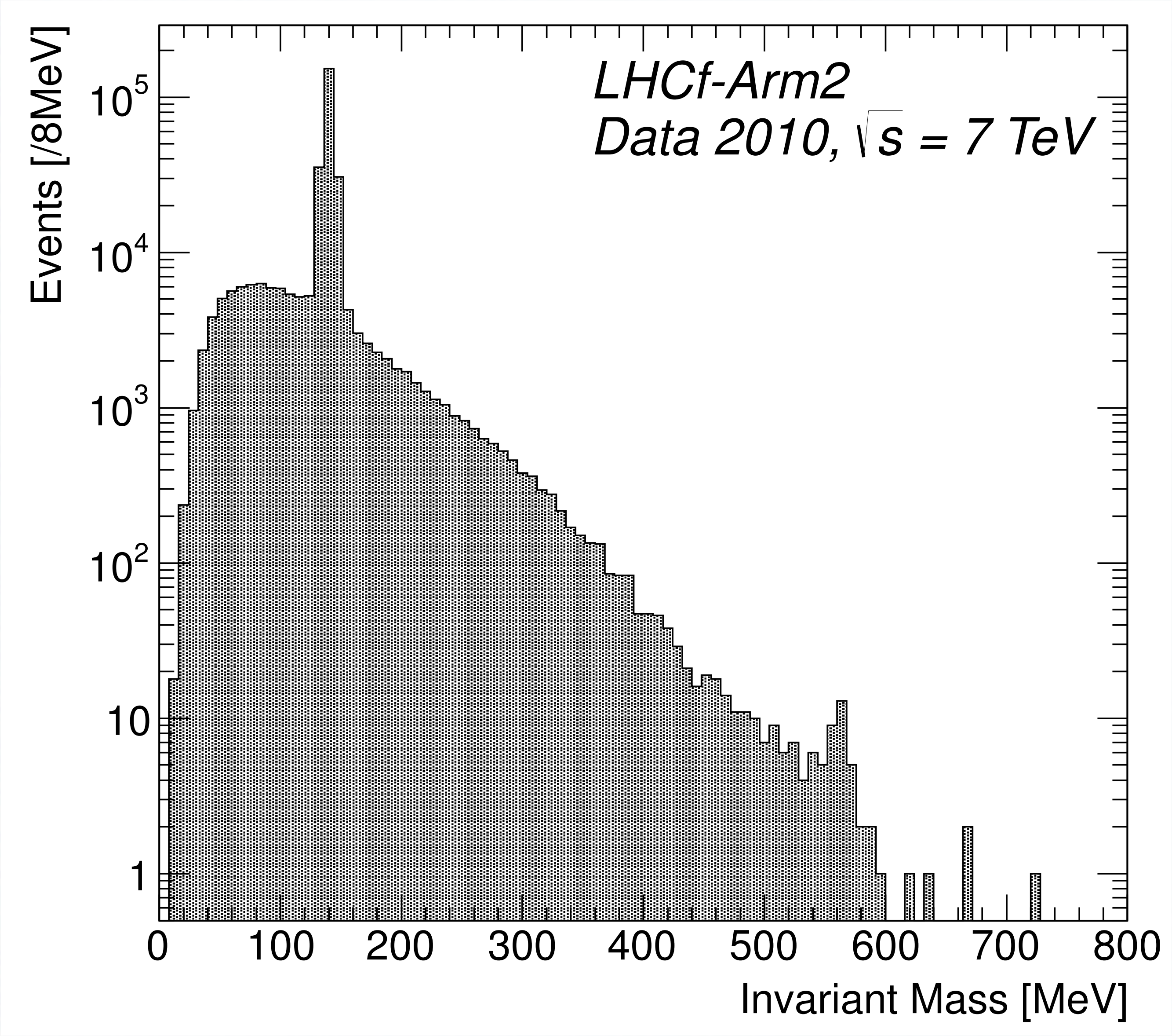
2. Gauss distribution

$$\frac{1}{\sigma_{\mathrm{inel}}} E \frac{d^3\sigma}{dp^3} = A \cdot \frac{\exp(-p_{\mathrm{T}}^2/\sigma_{\mathrm{Gauss}}^2)}{\pi \sigma_{\mathrm{Gauss}}^2}$$

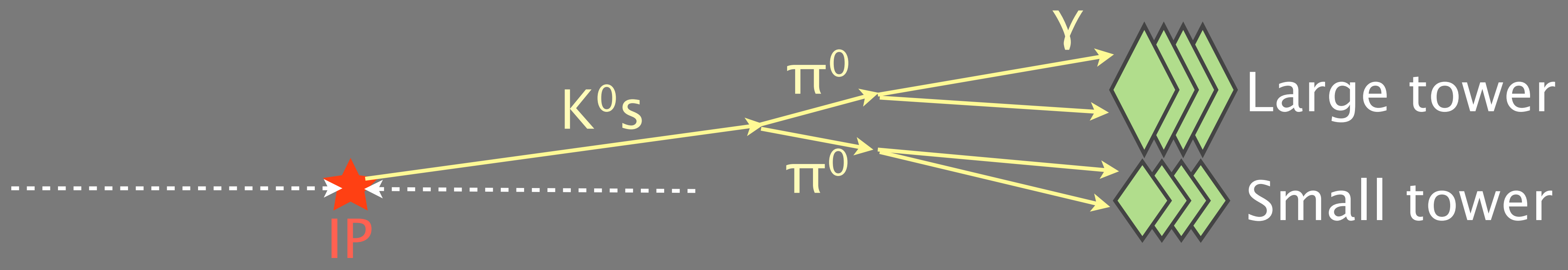
$$\langle p_{\mathrm{T}} \rangle = \frac{\sqrt{\pi}}{2} \sigma_{\mathrm{Gauss}}$$

- Systematic uncertainty of LHCf data is <10%.
- Compared with the UA7 data (√s=630GeV) and MC simulations (QGSJET, SIBYLL, EPOS).
- Smallest dependence on E_{CMS} is found in EPOS and it is consistent with LHCf and UA7.
- Large E_{CMS} dependence is found in SIBYLL → this indicates the prediction at UHE region may differ from at the LHC energy region.

η analysis at √s=7TeV

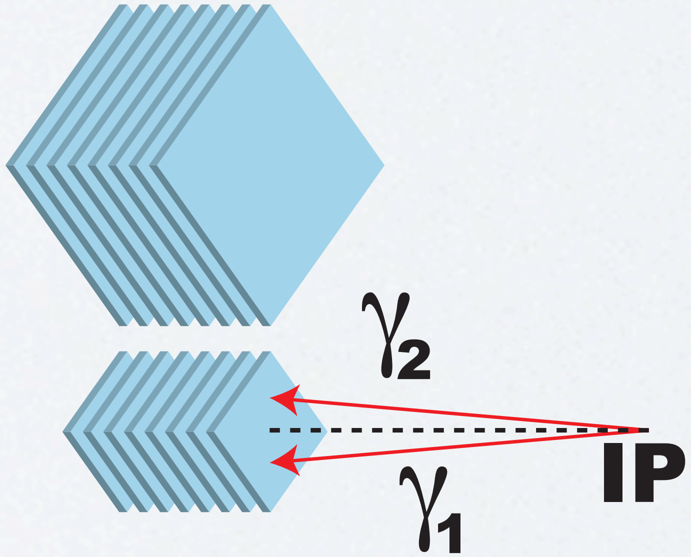


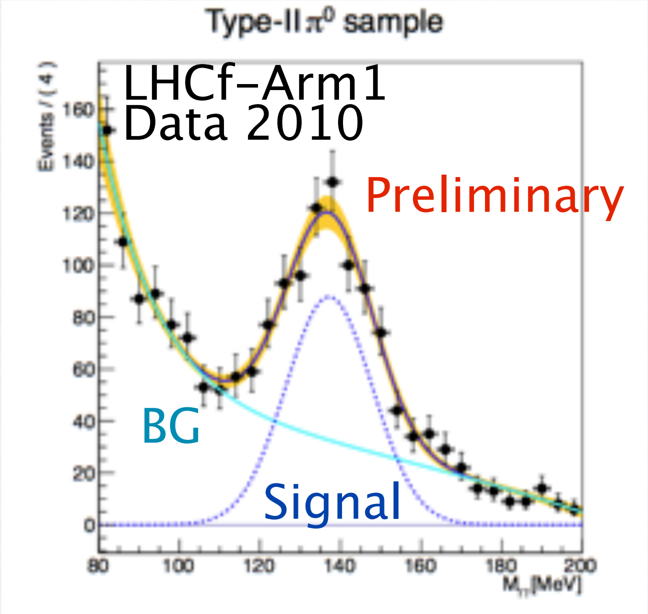
K^0_s analysis at $\sqrt{s}$=7TeV



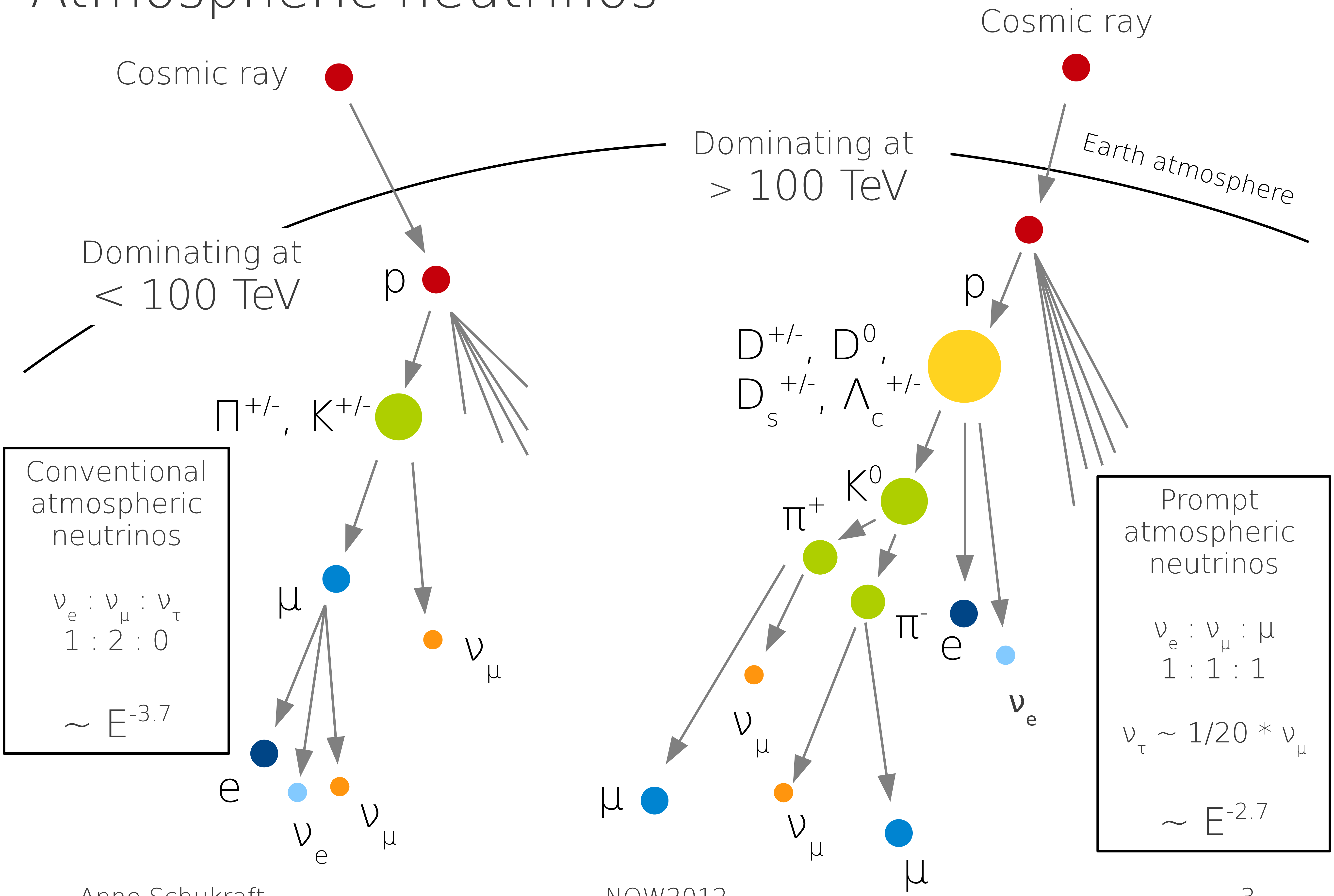
K^0_s analysis at √s=7TeV

- Analysis of K^0s has following motivations:
  - Poor understanding of forward s-quark.
  - Forward K/π ratio is important for estimating the ν_e/ν_μ ratio in atmospheric ν.
- Vertex of a $K^0s \rightarrow 2\pi^0$ decay is unknown due to the longer flight path of K^0s:
  - Vertex must be estimated using likelihood of $K^0s \rightarrow 2\pi^0$ decay with the rest mass constraints.
- Precise understanding of so called Type-II π^0 events is crucial for the reconstruction of K^0s.





Atmospheric neutrinos



Dominating at
< 100 TeV

Dominating at
> 100 TeV

Conventional
atmospheric
neutrinos

$\nu_e : \nu_\mu : \nu_\tau$
1 : 2 : 0

$\sim E^{-3.7}$

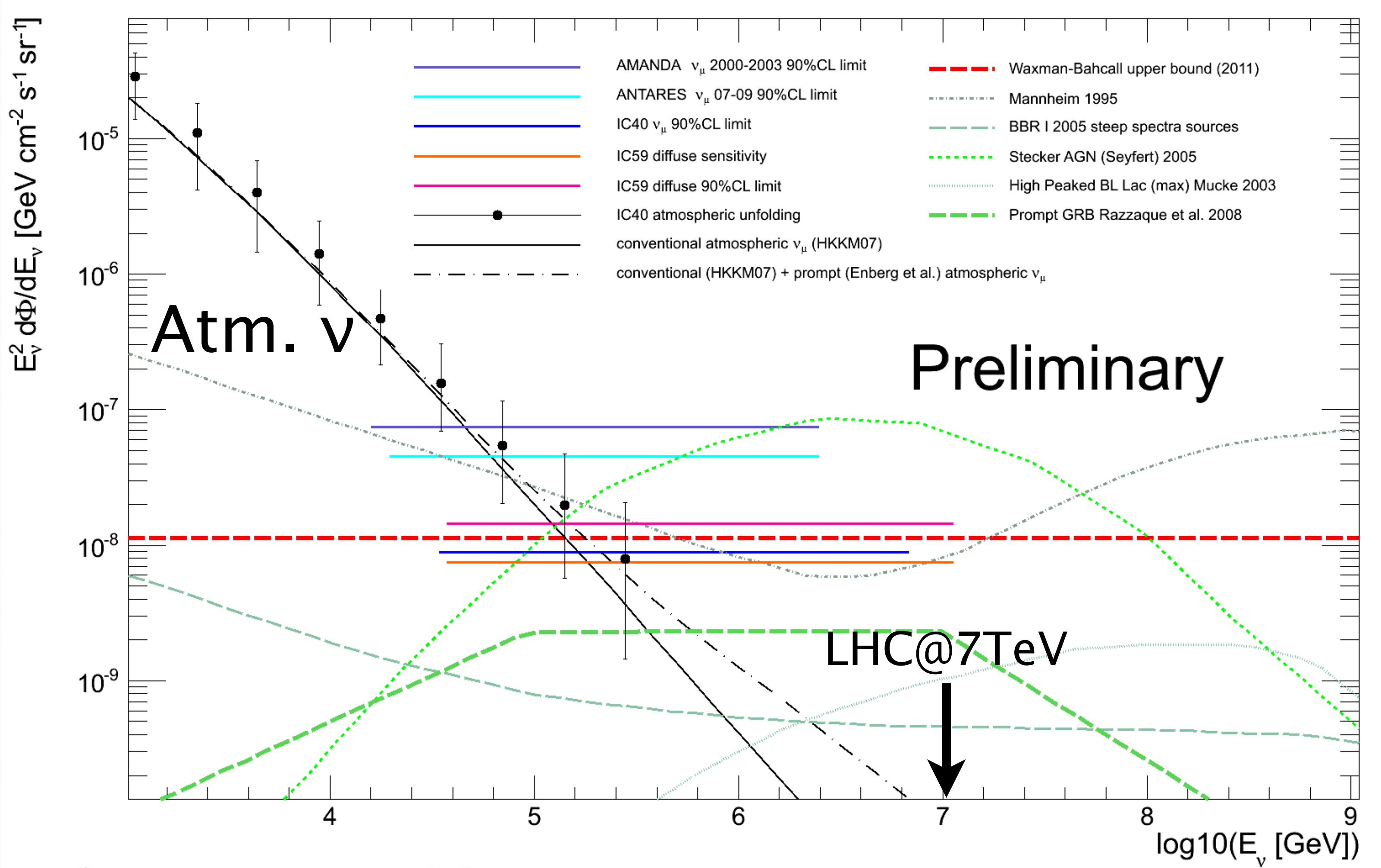
Prompt
atmospheric
neutrinos

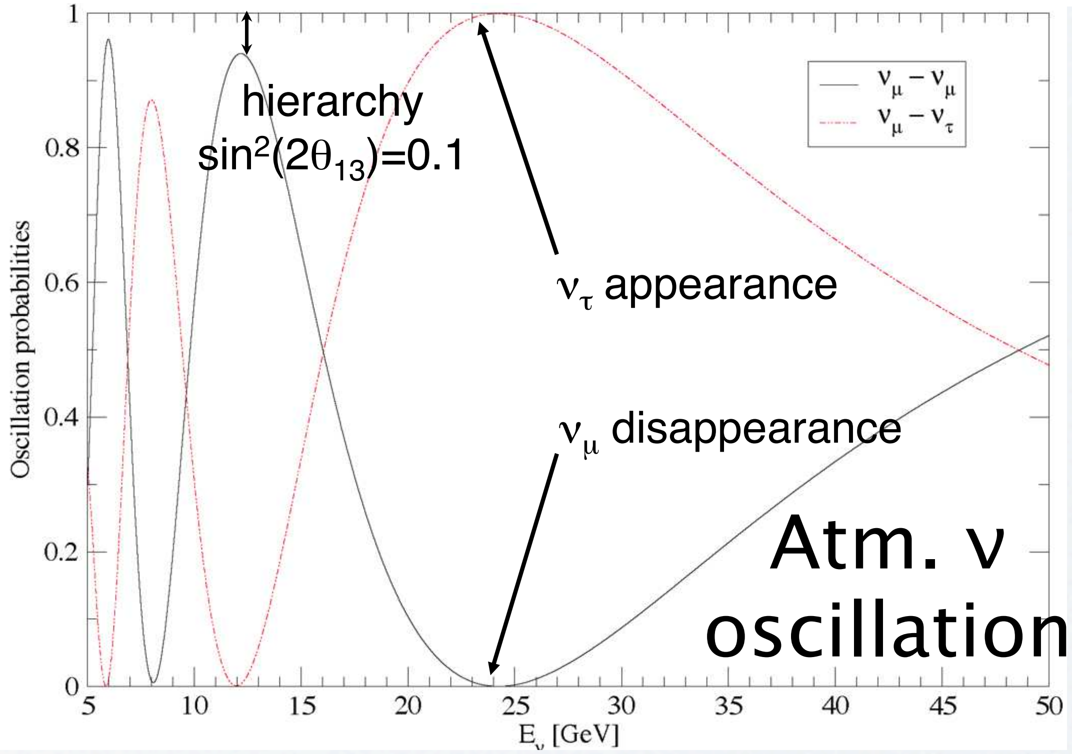
$\nu_e : \nu_\mu : \mu$
1 : 1 : 1

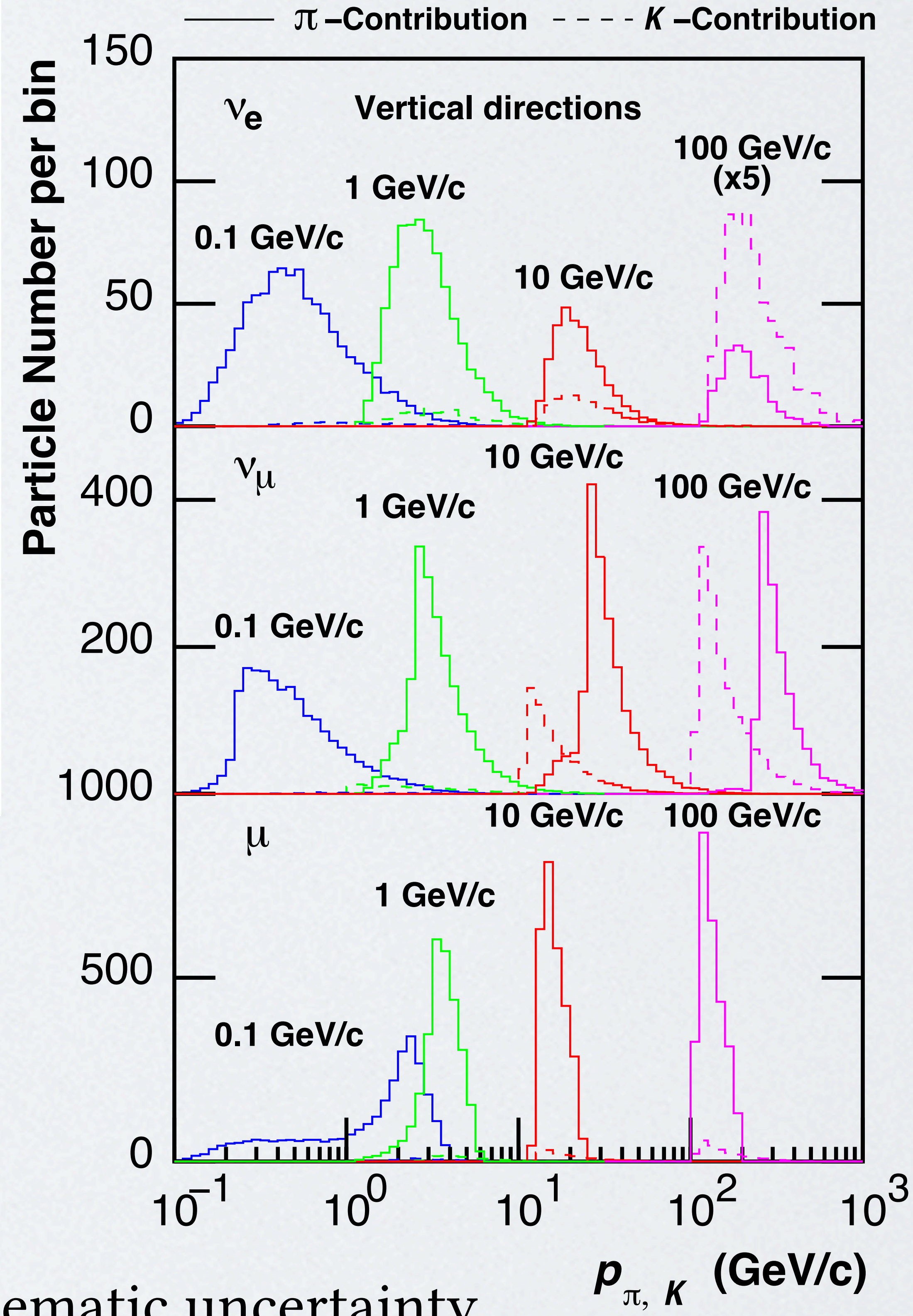
$\nu_\tau \sim 1/20 * \nu_\mu$

$\sim E^{-2.7}$

K^0_s analysis at $\sqrt{s}$=7TeV







Largest systematic uncertainty
~ K/π ratio@high energy

Mass-constraint kinematic fit

Likelihood function for reproducing the π^0 and K^0s rest masses.

$$\mathcal{L} = \frac{1}{\sqrt{2\pi}^{2\cdot 4}} \exp^{-\frac{1}{2}\Delta y_s^T W_s^{-1} \Delta y_s} \cdot \frac{1}{\sqrt{2\pi}^{2\cdot 4}} \exp^{-\frac{1}{2}\Delta y_l^T W_l^{-1} \Delta y_l} \cdot \exp^{-\sum_i \lambda_i f_i}$$

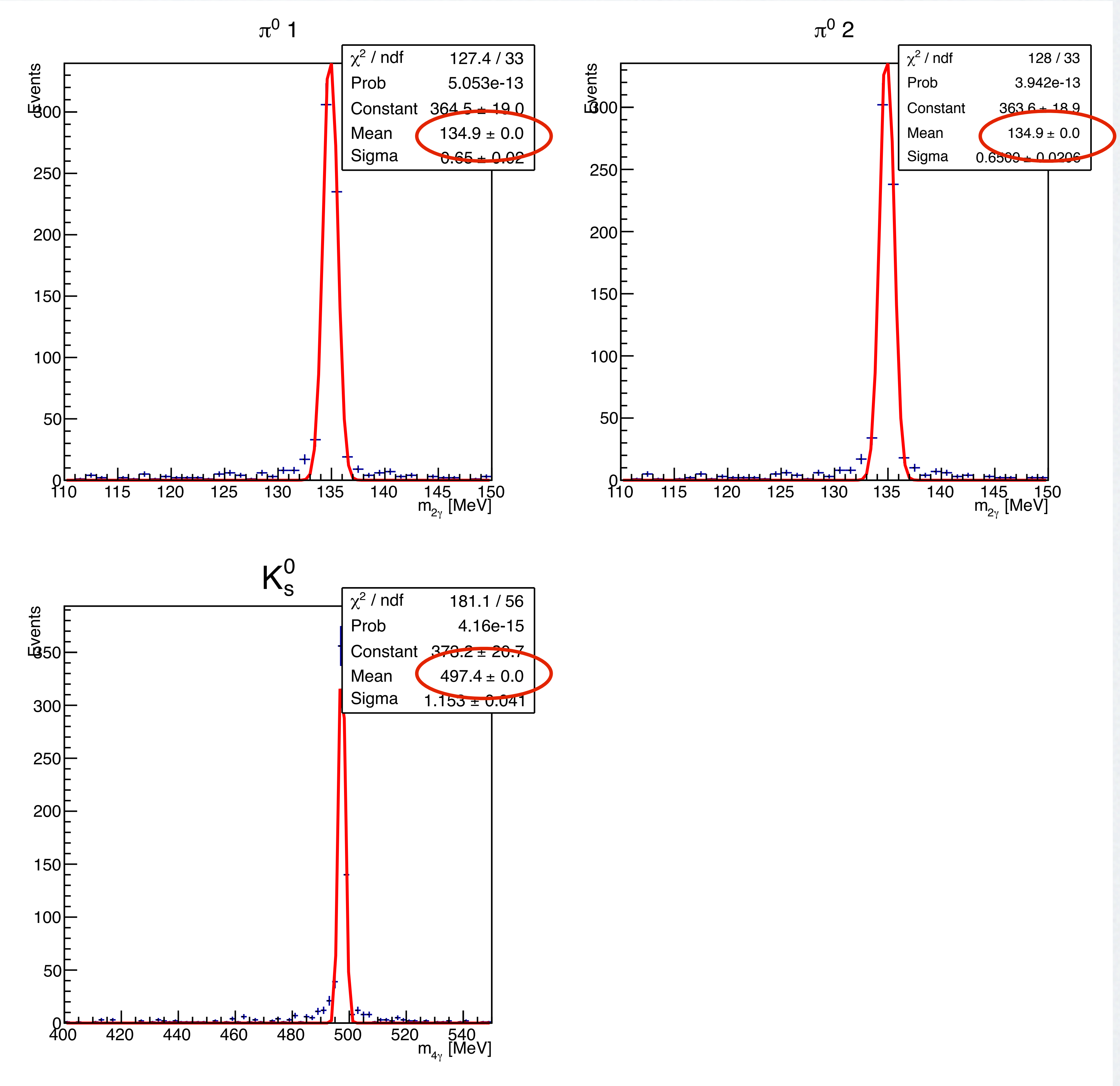
y_s (y_l) : 4-vectors of two photons in small (large) tower,
Δy_s (Δy_l) : Correction factors for the 4-vectors y_s (y_l),
then the best-fit “corrected” measurements should be $y' = y + \Delta y$.

W_s (W_l) : Covariance matrix of measured variables.

f_i : Constraint term concerning the “i”-th invariant parameter, i.e. $m_{\gamma\gamma} - m_{\pi 0} = 0$ etc…
λ_i : Lagrange multiplier for f_i.

- Minimizing -logL leads to the best-fit 4-vectors of four photons allowed within the variation of covariance matrix.
- In the real data analysis, some criteria should be defined to cut the poor quality fit events. Of course selected production rates must be corrected for inefficiencies.

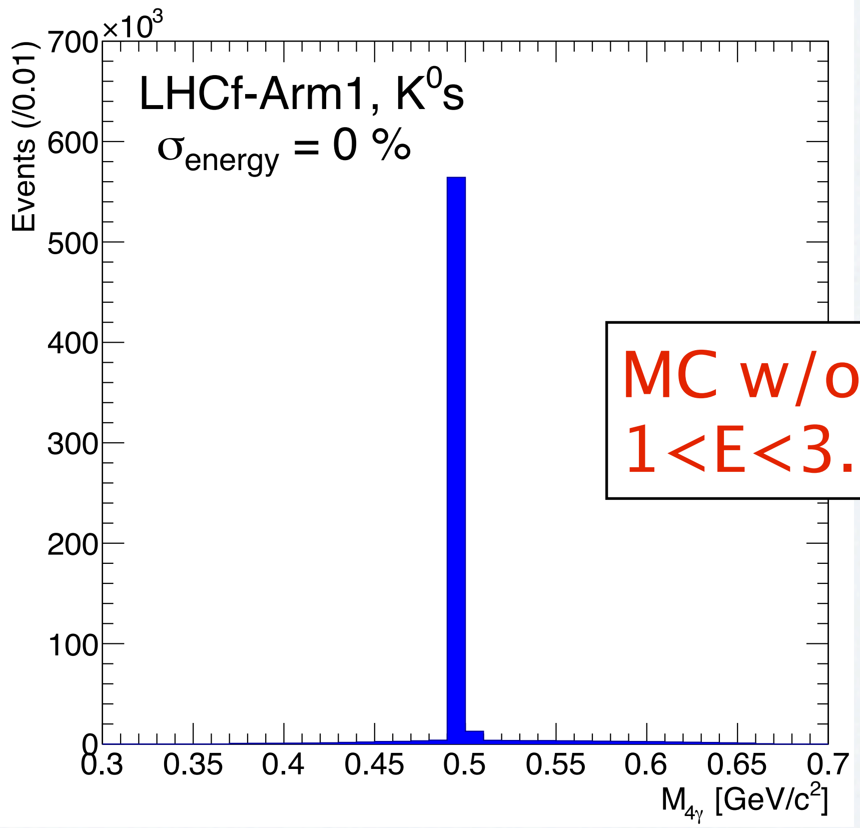
Fitted results (true single K^0_s)

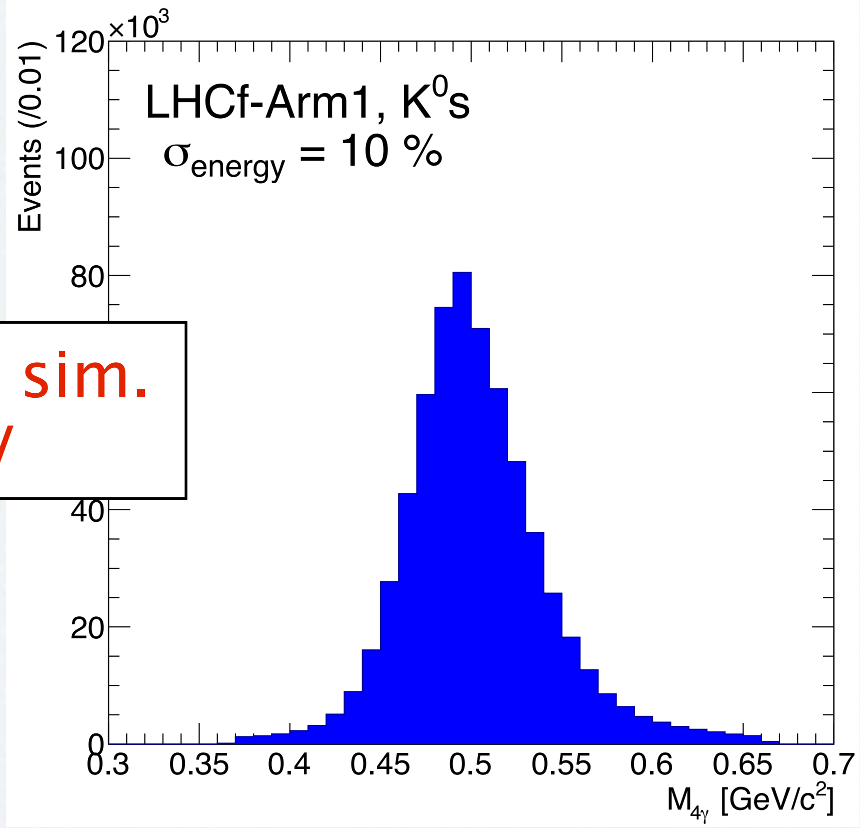


- True information of four photons are artificially smeared by 3% (should be much larger in real case).
- Covariance matrix is assumed to be a diagonal matrix with 10MeV error.
- Minimization of -log L is done by the MINUIT2 library in ROOT.

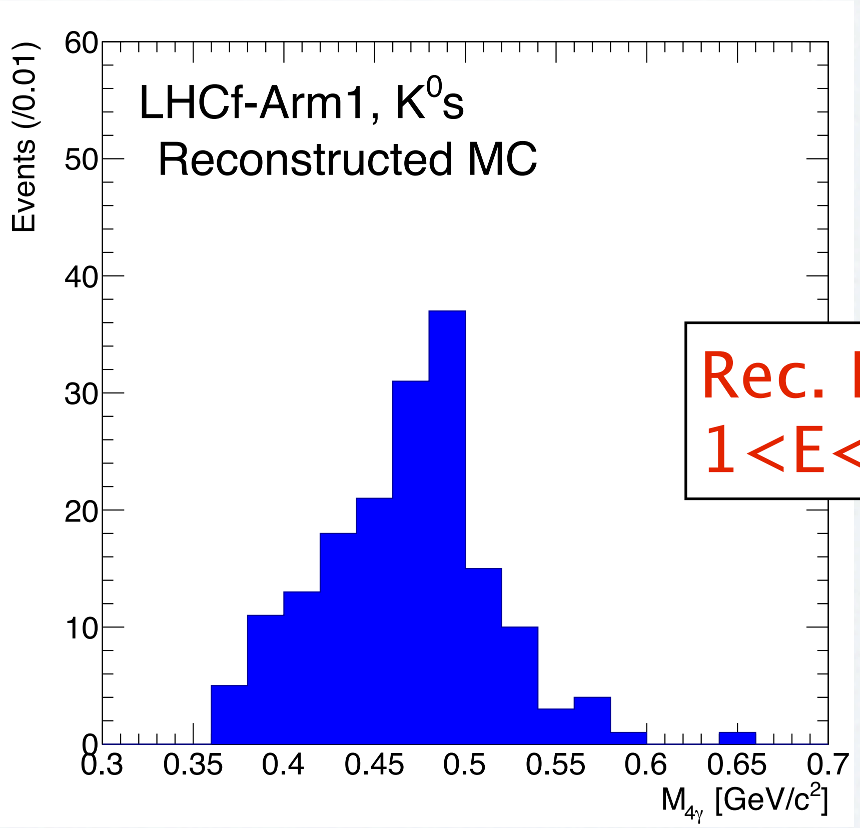
- Invariant masses successfully reproduce the rest mass of K^0_s and intermediate π^0s.

Fitted results (true single K^0_s)





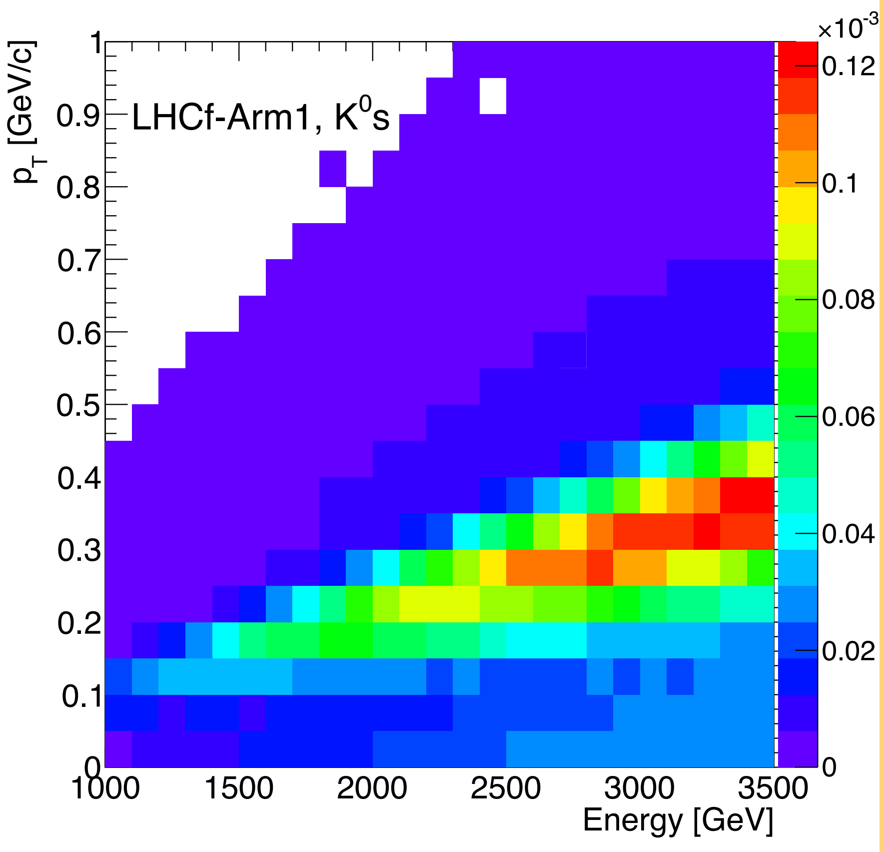
MC w/o det. sim.
1<E<3.5TeV

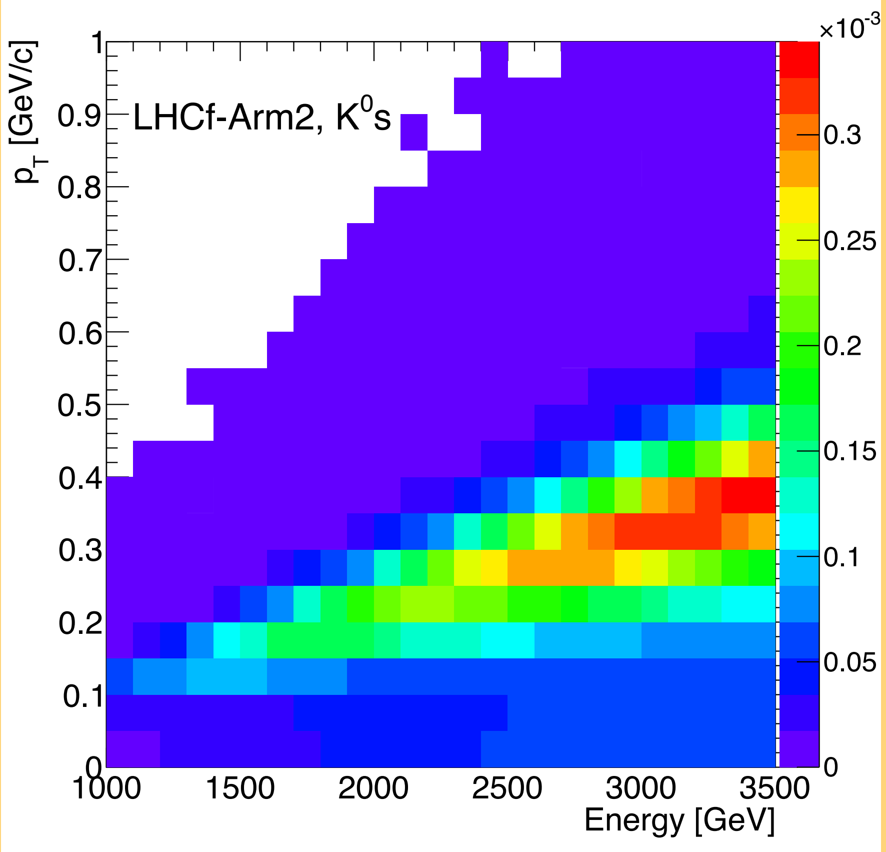


Rec. MC
1<E<3.5TeV

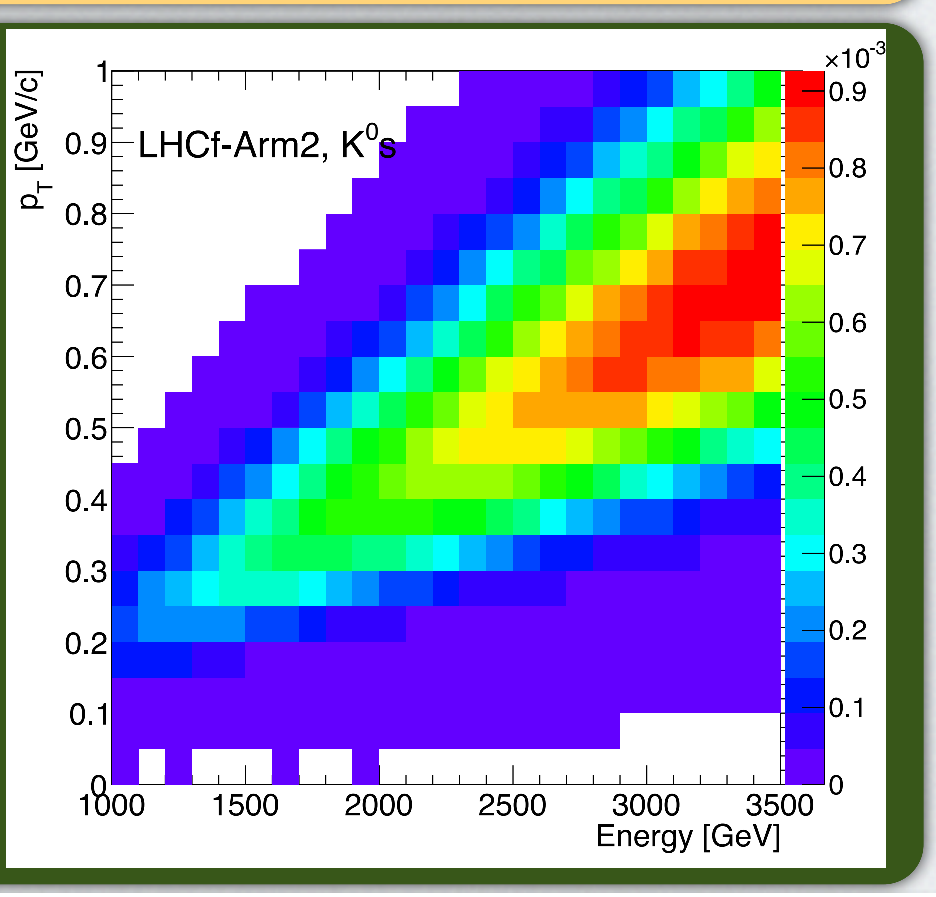
Acceptance efficiency (E vs. p_T)

- Two photons both on small & large tower.
- Eγ > 100GeV.
- Position of Arm1 is supposed to be “–14mm”.





- One photon on small tower & three photons on large tower → challenging !
  (Arm2‘s high pos.res. is needed.)
- E_γ > 100GeV.



Both towers cover pT<0.5GeV/c.

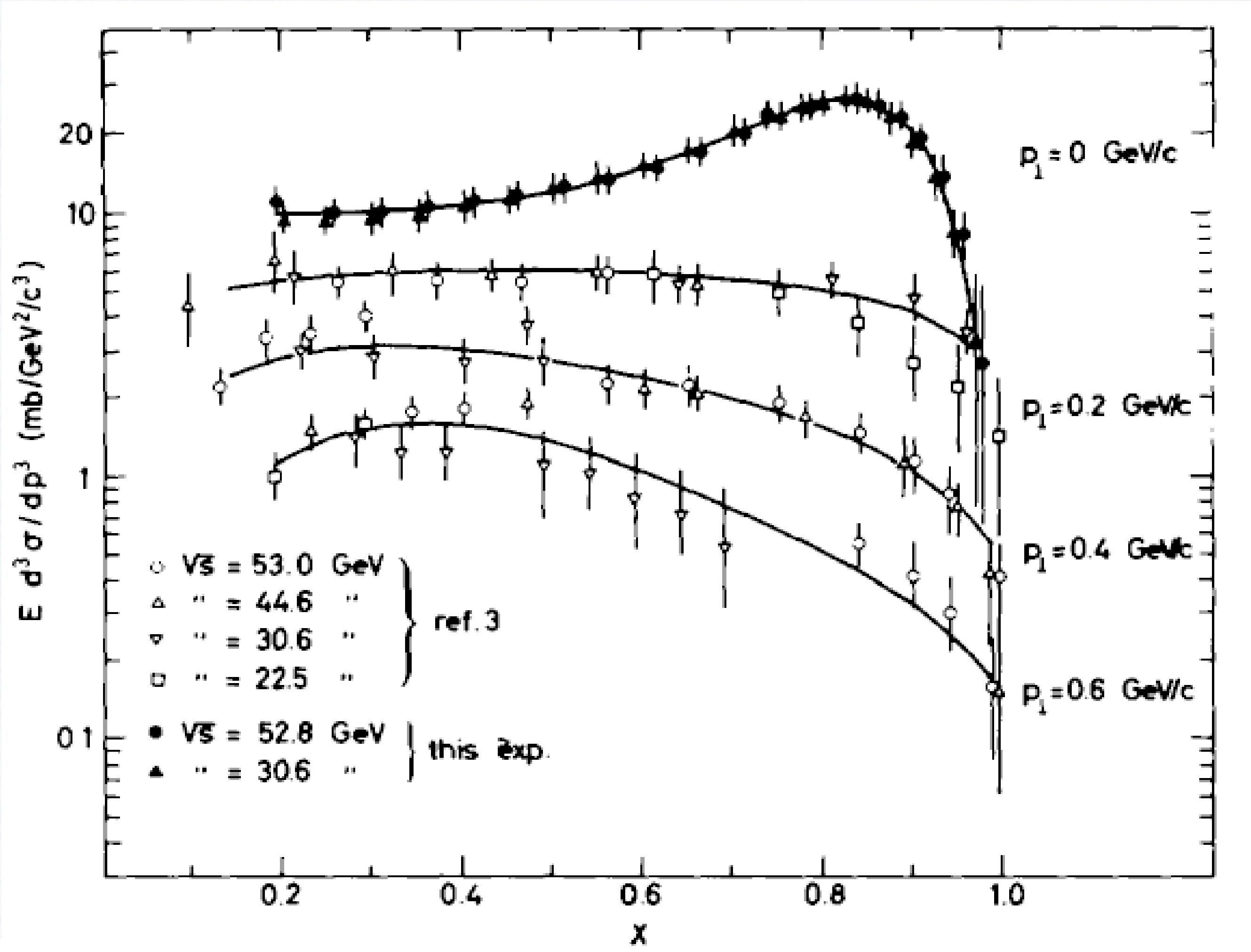
Phase space possibly extends to 1GeV/c.

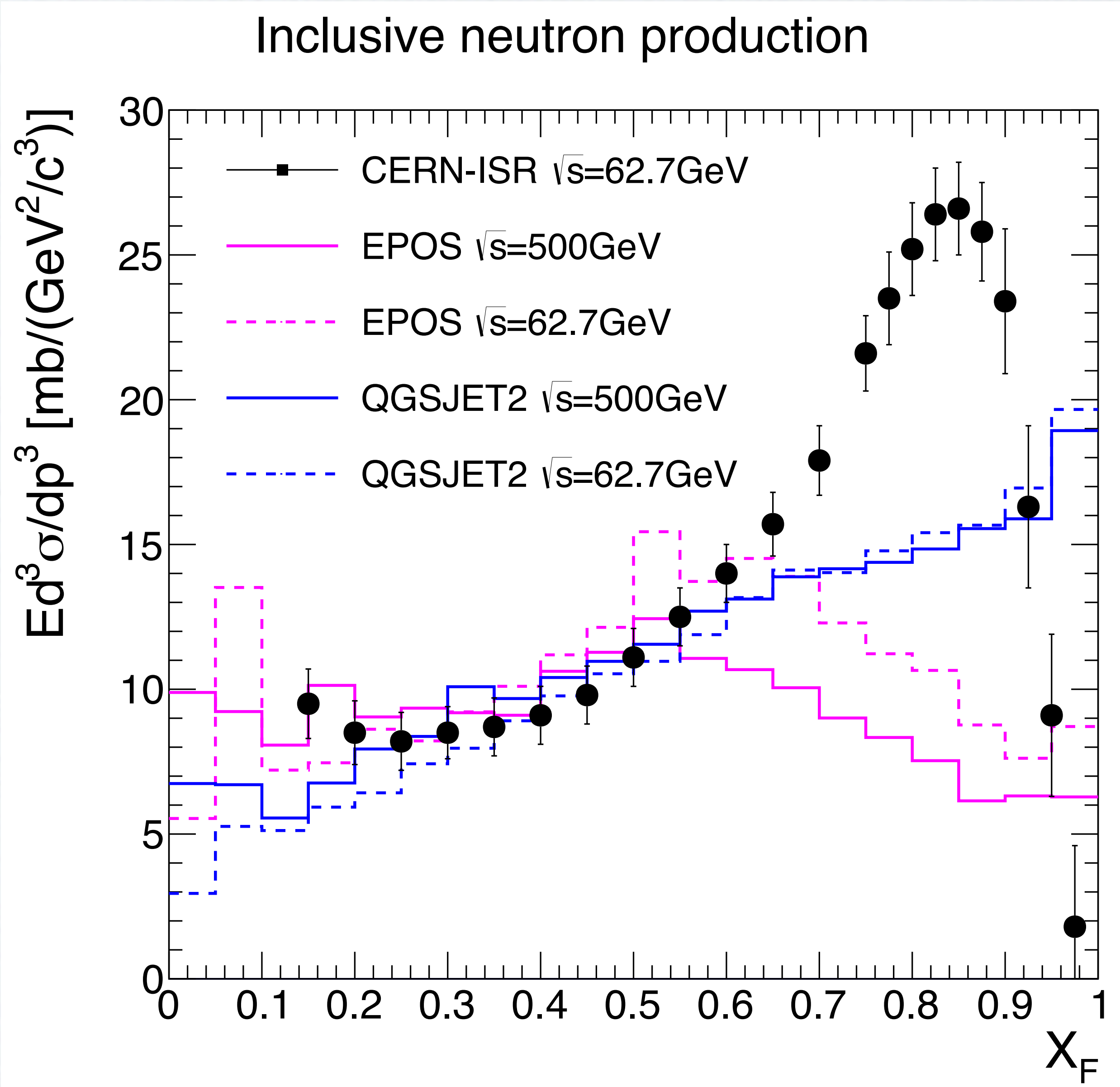
Summary

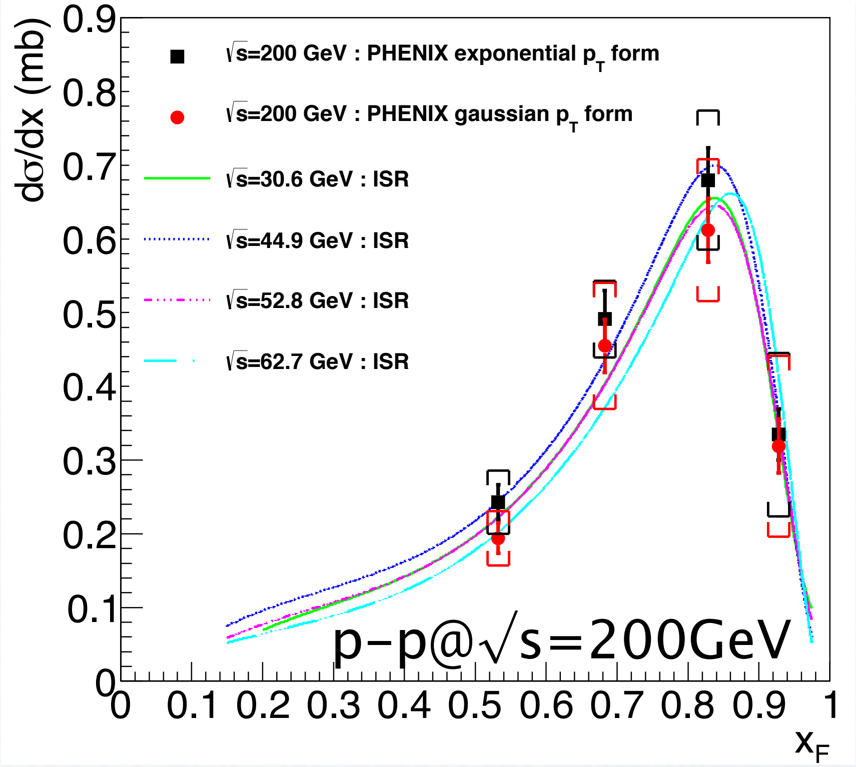
- Consistent π^0 spectra are obtained between the Arm1 and Arm2 detector. Combined spectra agree with the prediction by EPOS for the p_T spectra and $<p_T>$.

- Photon and π^0 analysis can be extended to other channels:
  - η, K0s, and Λ
  - Correction to π^0 spectra by nuclear effects (pA@LHC, next talk by Sako)

Comment on neutron analysis





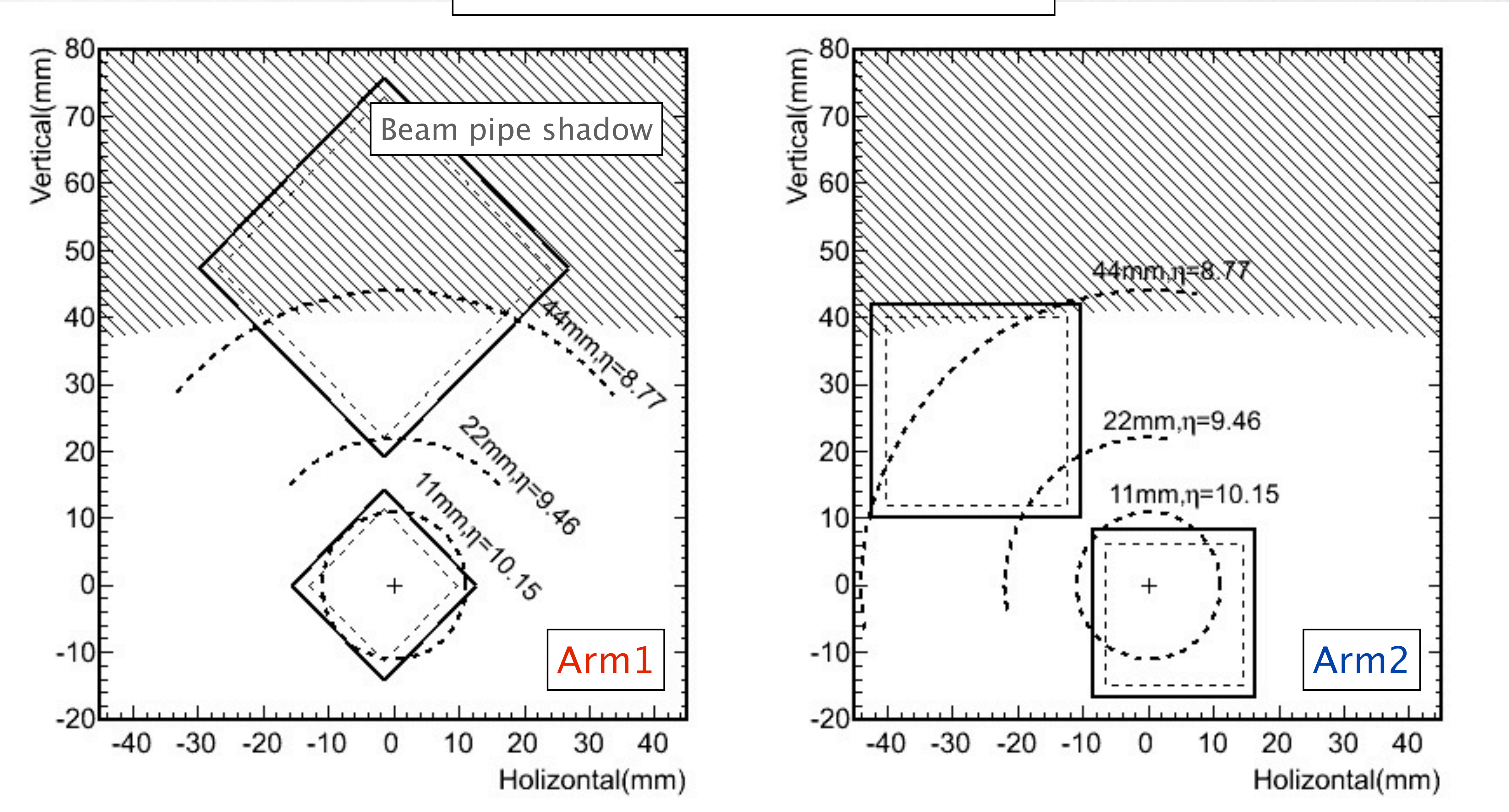


(arXiv:1209.3283)

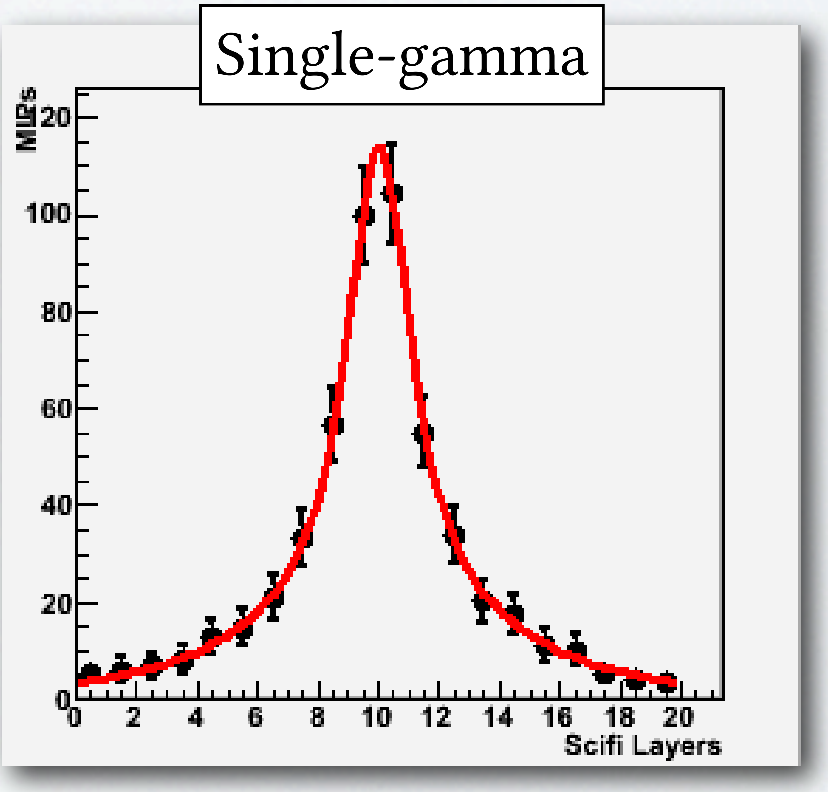
Backup

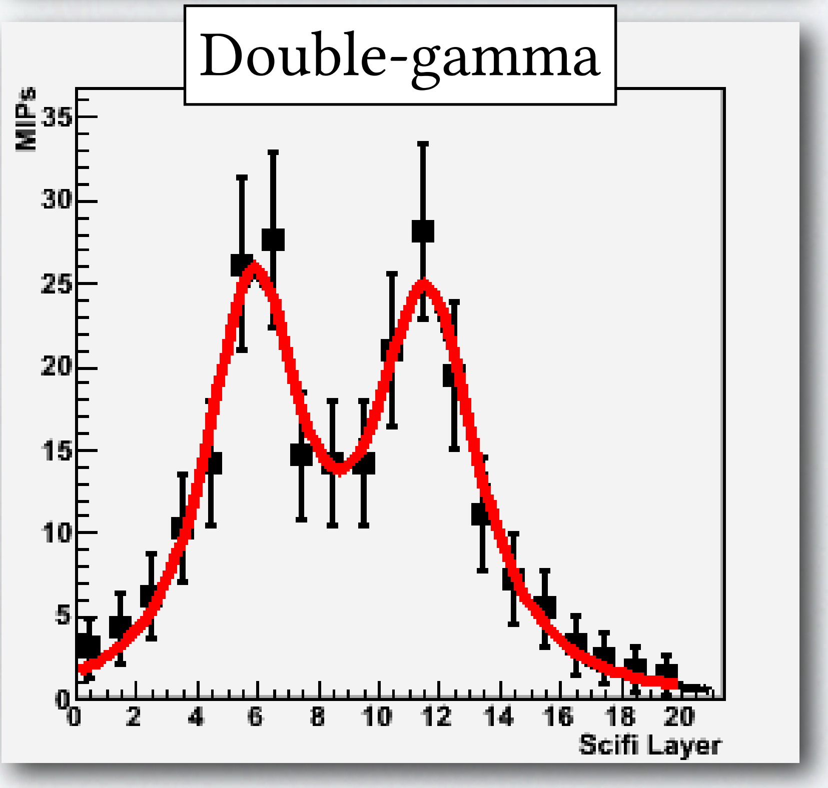
Photon analysis at √s=900GeV

Cross section of the LHCf detectors

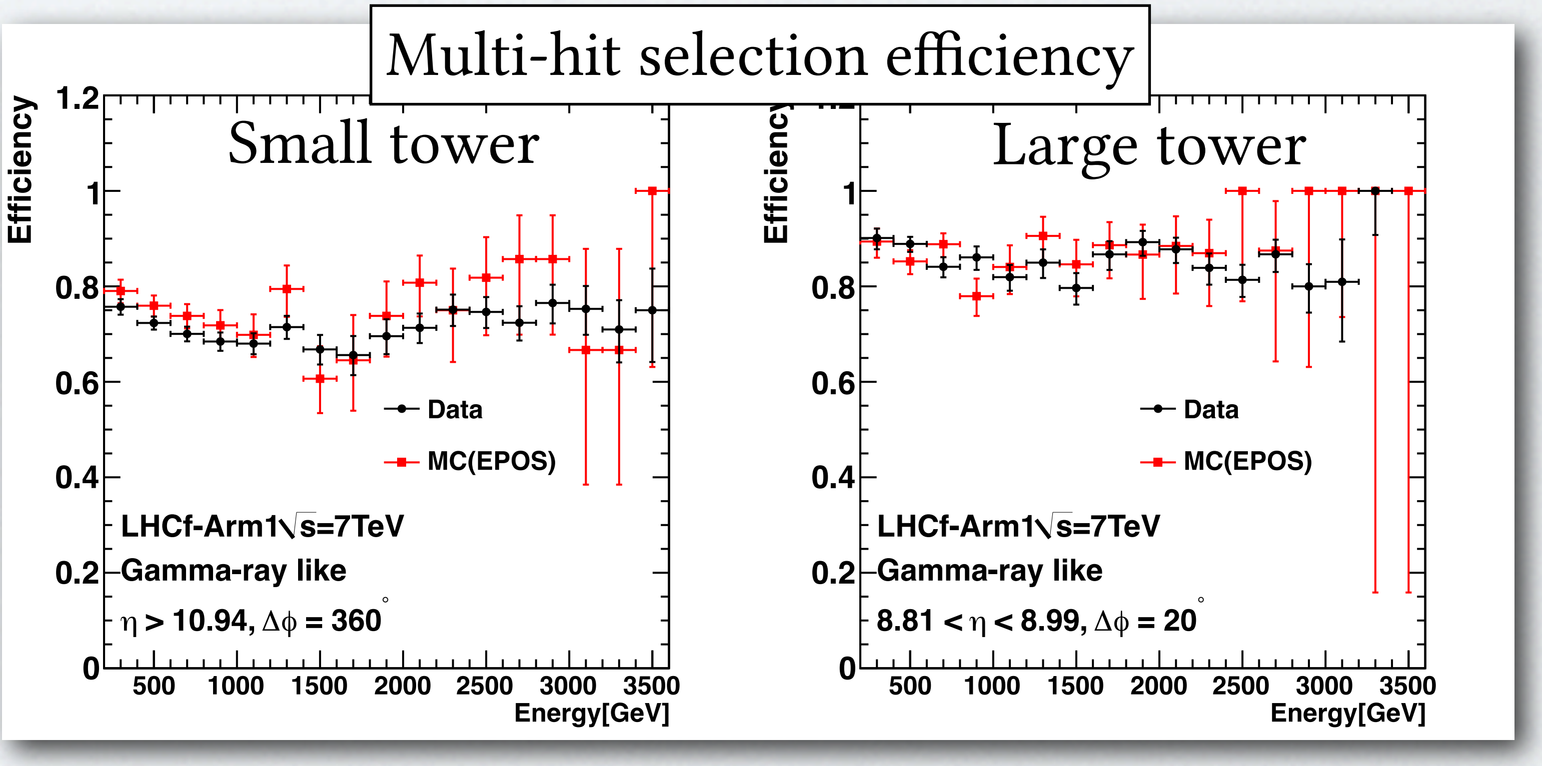


Single-hit selection


Single-gamma


Double-gamma

- SIngle-hit/Multi-hit separation by the number of showers.
- Transverse shower development is fitted by a superimpose of a Lorentzian spectra.
- Incident position(X, Y) of neutral particle is used to estimate an amount of shower leakage and to cut events by the fiducial volume.
- Deviation of “multi-hit selection” efficiency btw. data and MC is assigned to a systematic uncertainty.

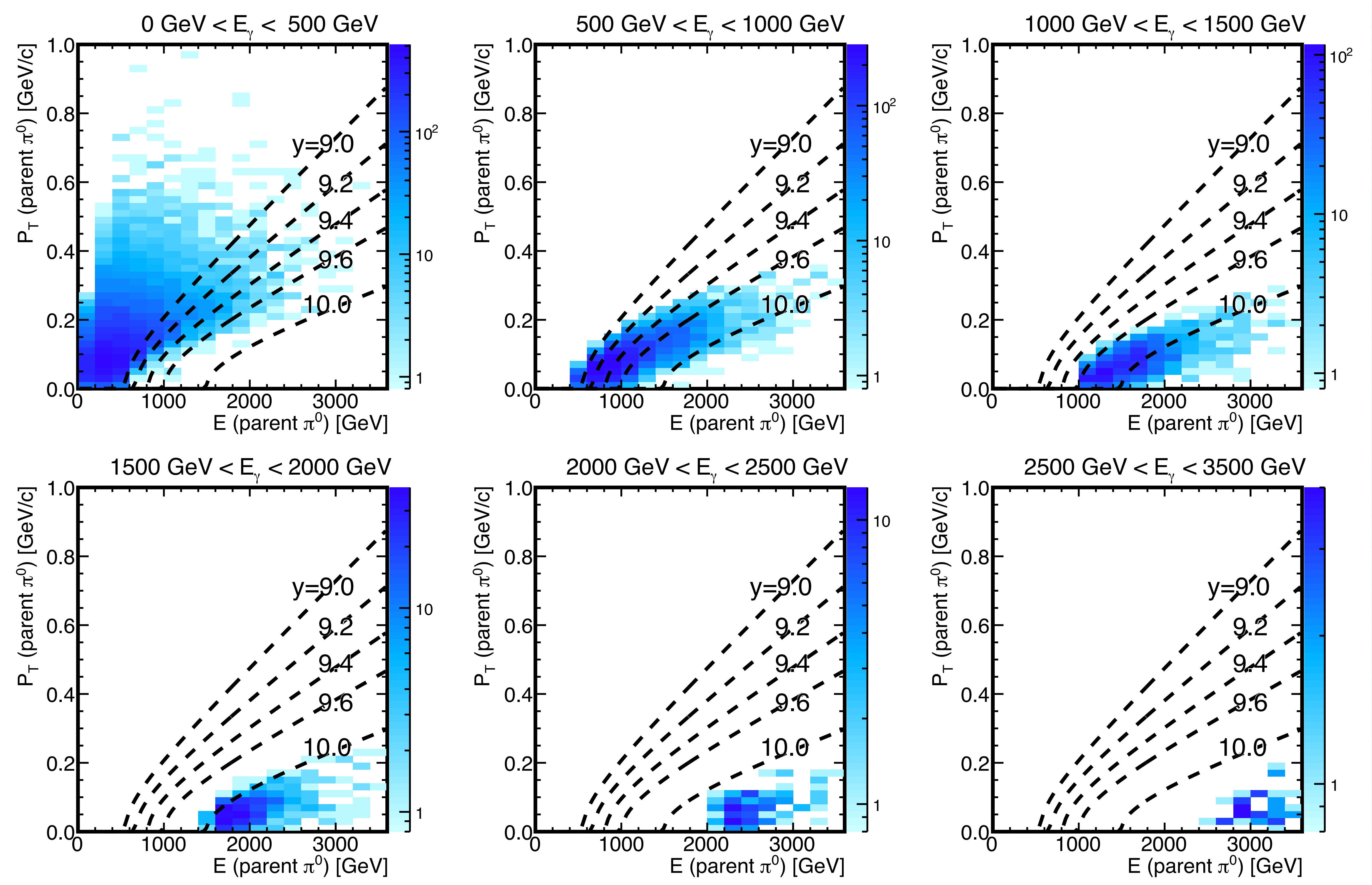

Multi-hit selection efficiency

Small tower

Large tower

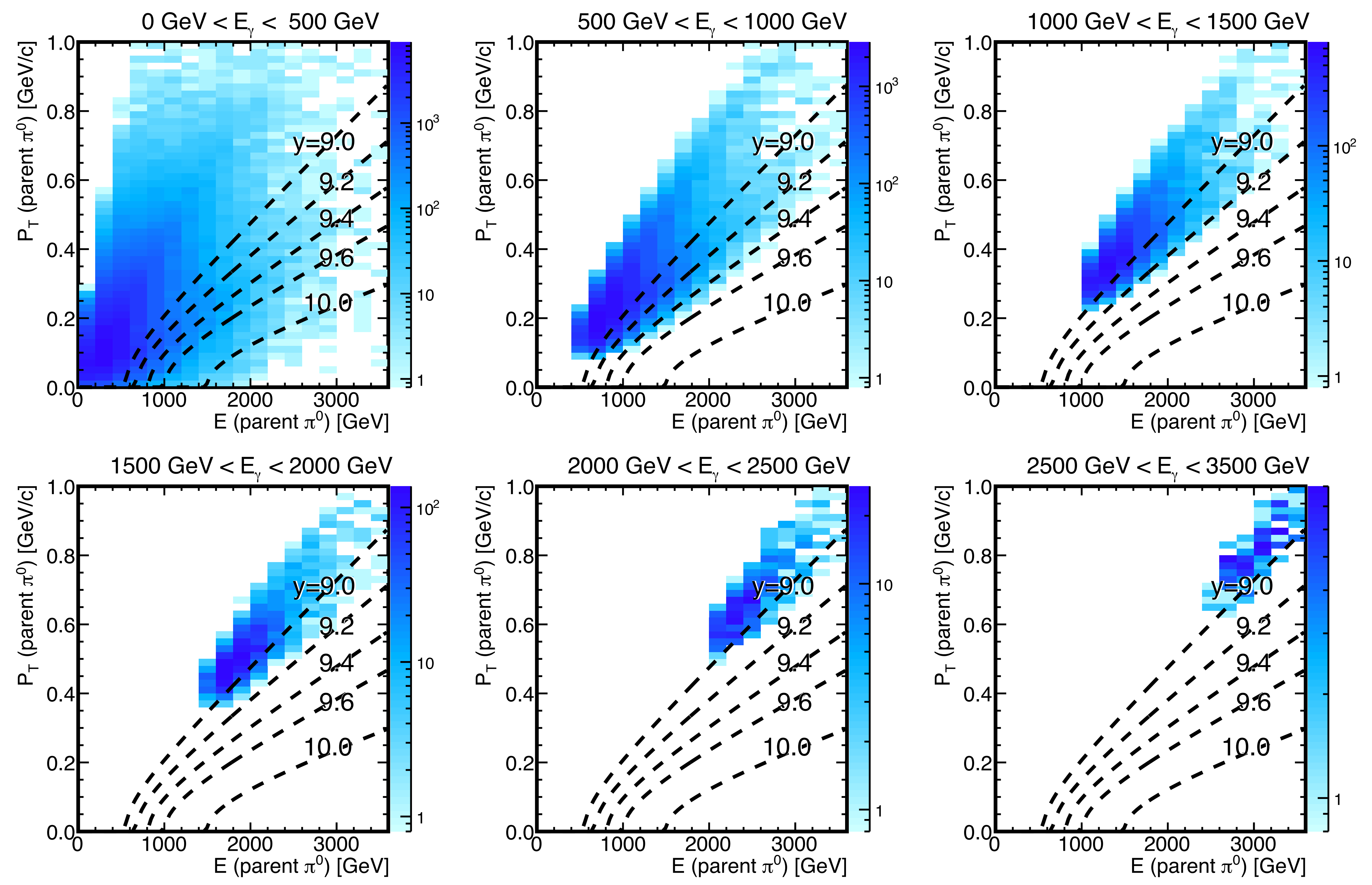
Phase space of photon and π^0

η>10.94 (small tower)

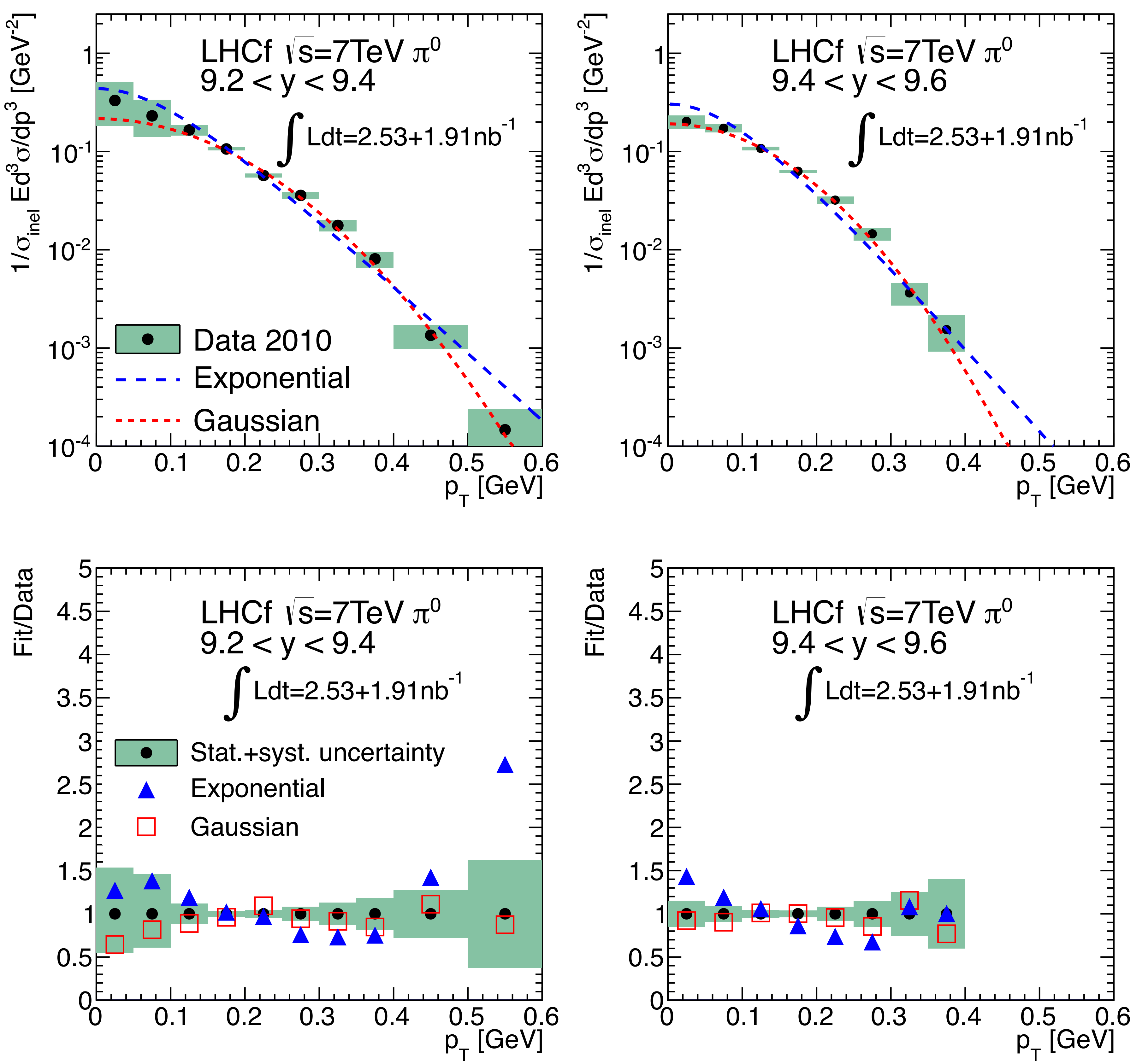


Phase space of photon and π^0

8.81<η<8.99 (large tower)



Fit ansatz to pT spectra



Fit ansatz to pT spectra

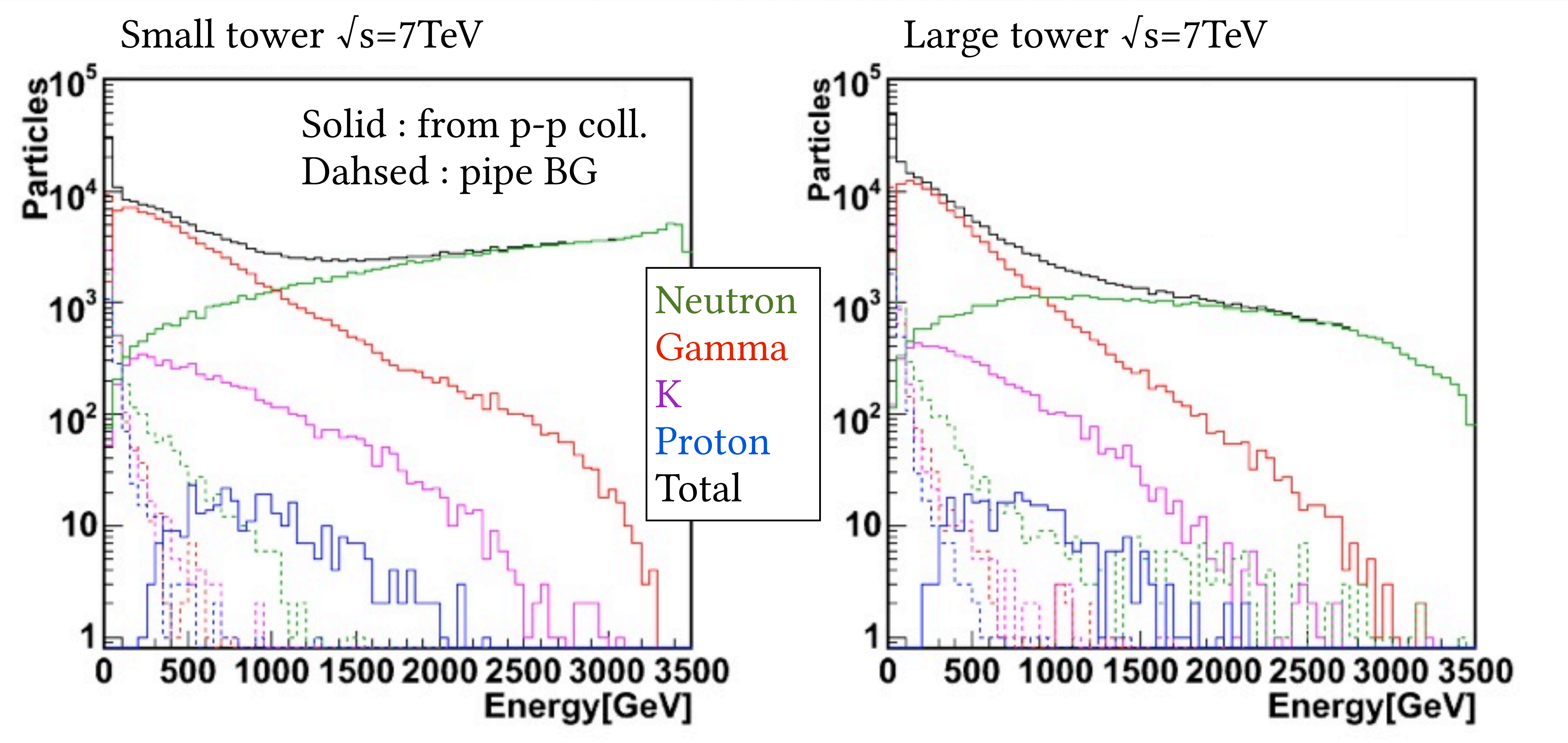
	Exponential fit				Gaussian fit				Numerical integration		
Rapidity	χ^2 (dof)	T [MeV]	$\langle p_\mathrm{T} \rangle$ [MeV]	Stat. error [MeV]	χ^2 (dof)	σ_Gauss [MeV]	$\langle p_\mathrm{T} \rangle$ [MeV]	Stat. error [MeV]	$p_\mathrm{T}^\mathrm{upper}$ [GeV]	$\langle p_\mathrm{T} \rangle$ [MeV]	Stat. error [MeV]
[8.9, 9.0]	0.6 (7)	83.8	201.4	13.5	2.0 (7)	259.0	229.6	13.1			
[9.0, 9.2]	8.2 (7)	75.2	184.1	5.0	0.9 (7)	234.7	208.0	4.6			
[9.2, 9.4]	28.7 (8)	61.7	164.0	2.8	6.9 (8)	201.8	178.9	3.4	0.6	167.7	9.6
[9.4, 9.6]	66.3 (6)	52.8	140.3	1.9	3.3 (6)	166.3	147.4	2.7	0.4	144.8	3.2
[9.6, 10.0]	14.0 (5)	43.3	123.5	2.2	0.3 (5)	139.2	123.3	3.0	0.4	117.0	2.1
[10.0, 11.0]	9.0 (2)	21.3	77.7	2.3	2.1 (2)	84.8	75.1	2.9	0.2	76.9	2.6

Rapidity	$\langle p_\mathrm{T} \rangle$ [MeV]	Total uncertainty [MeV]
[8.9, 9.0]	215.3	17.3
[9.0, 9.2]	196.8	12.5
[9.2, 9.4]	172.2	5.9
[9.4, 9.6]	146.3	3.9
[9.6, 10.0]	119.2	3.4
[10.0, 11.0]	75.8	2.9

Component at √s=7TeV

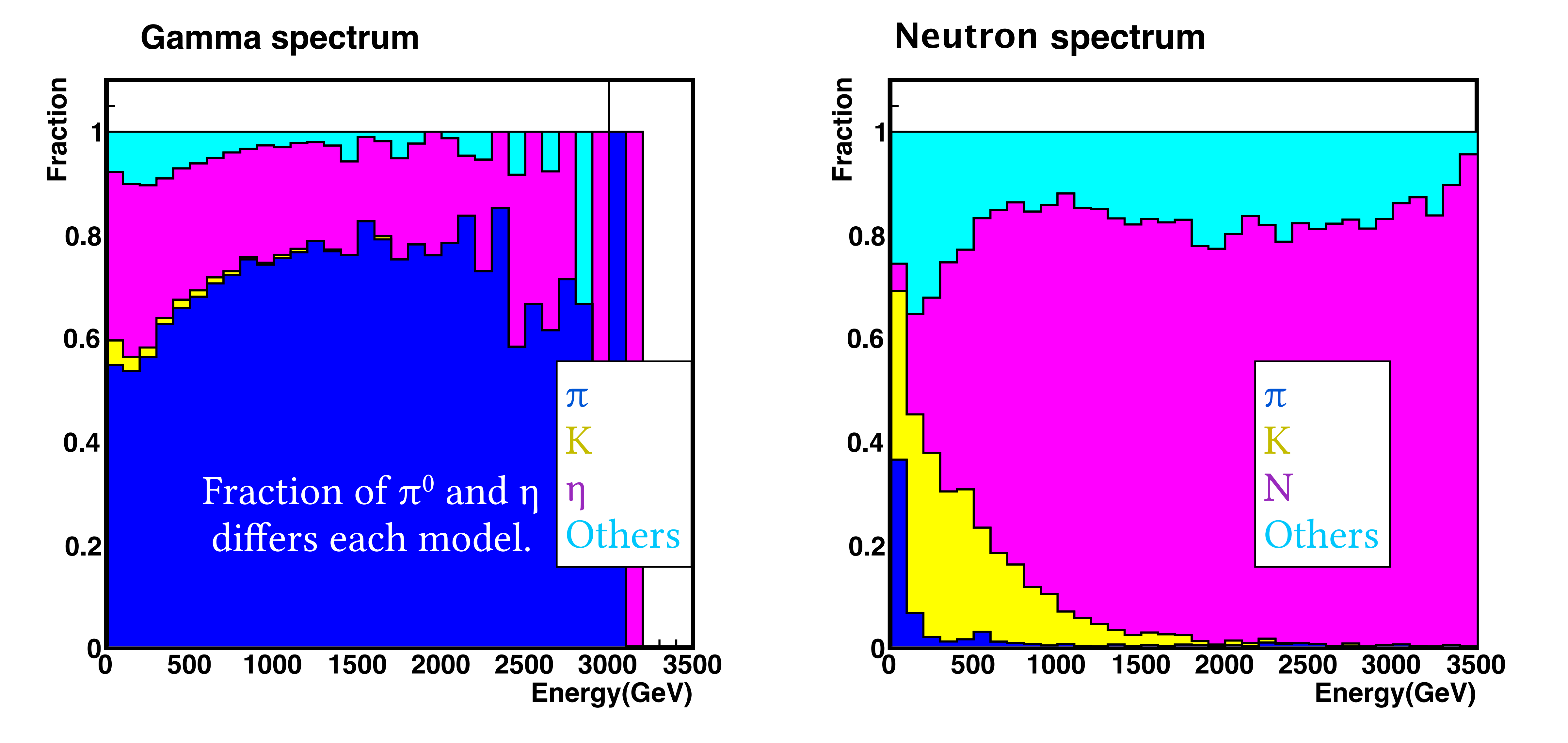
All figures assume
10^7 collisions@√s=7TeV

- Spectrum in the forward region at 140m away from IP1 (i.e. LHCf site).
- No detector simulation is applied.
- Neutron/Gamma ratio is also important from the cosmic-ray point of view.



Description in Sibyll

Fraction of parent particles



Fraction of π^0 and η differs each model.