FANSY 2.0: Monte Carlo tool for "forward physics" interaction simulations. Cosmic ray coplanarity and LHC data

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Content

- Introduction
- FANSY 2.0's brief description
  1. Superhigh ($\sqrt{s} \gtrsim 1$ TeV) energies (*pp* interactions)
     - central region (y & $\eta \lesssim 5$)
     - high y & $\eta \gtrsim 6$, $d\sigma/dx_F$
  2. Lower ($E_0 \lesssim$ 2 ТэВ, $\sqrt{s} \lesssim$ 63 ГэВ) energies ($d\sigma/dx_F$) (*pp*, *πp*, K*p* interactions)
- Cosmic-ray coplanarity and LHC data at superhigh energies

Introduction

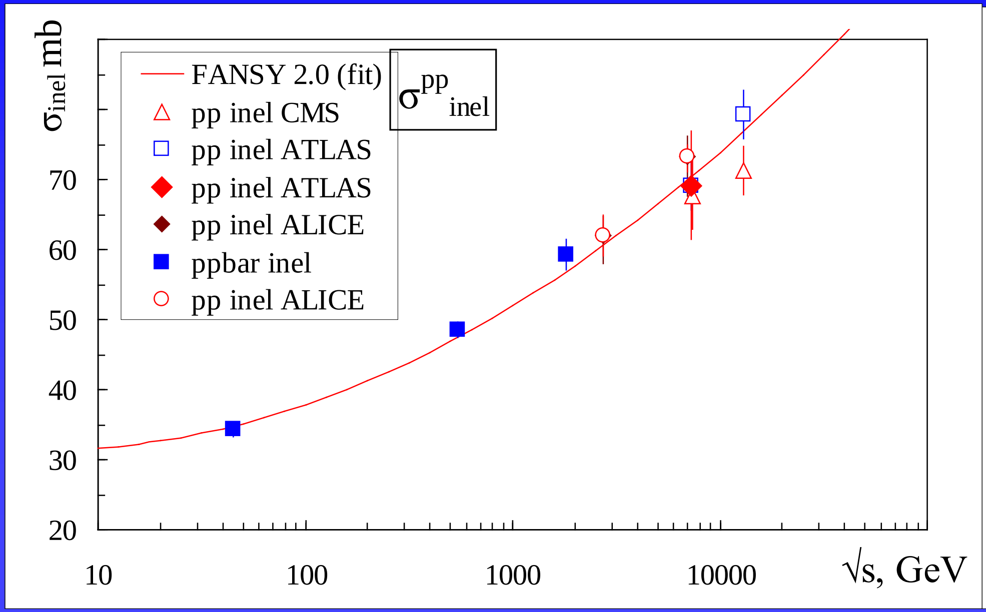
- Interesting cosmic-ray high-precision X-REC experiment results (most sensitive to interaction parameters):
  - coplanarity of most energetic subcores in γ-ray-hadron families (high-energy particles in EAS cores) at $\langle E_0 \rangle \gtrsim 10^{16}$ eV;
  - too intensive generation of forward-range charmed hadrons in hadron-lead nucleus interactions at $\langle E_h \rangle \sim 75$ TeV
- To analyze these results, a new easily-variable model is required, which could reproduce results of
  - cosmic-ray experiments in a wide energy range:
  - LHCf and CMS+TOTEM experiments in the high η & x_F range
  - LHC (ALICE, ATLAS, CMS, LHCb) experiments in the central kinematic range ($dN/d\eta$, $d\sigma/dp_t$, $\sigma_{prod}^{\pi,K,charm...}$ etc) (mainly for greater trust !)

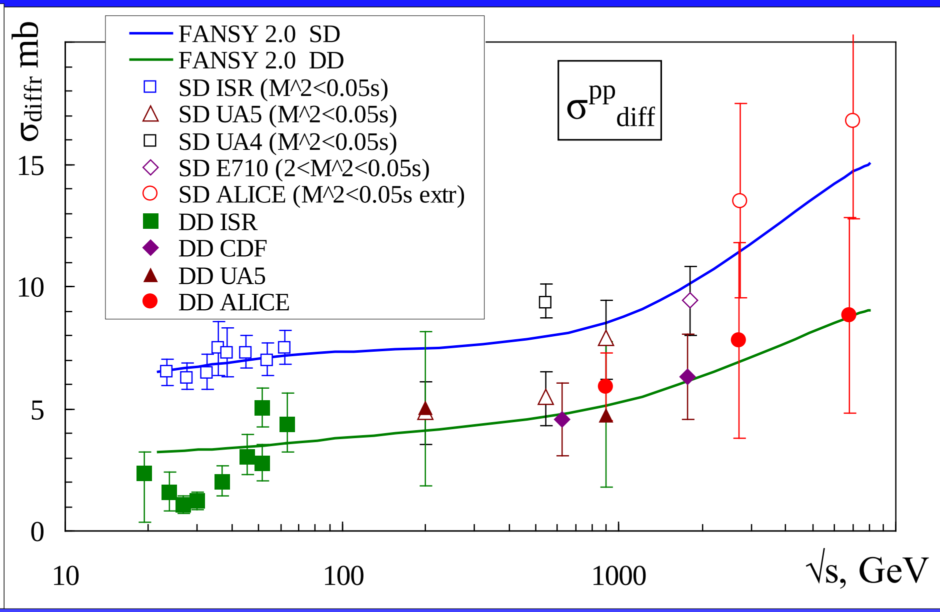
⬇

Phenomenological *FANSY* 2.0 model
(traditional QGSJ version)

p-p high-energy interactions (central range)

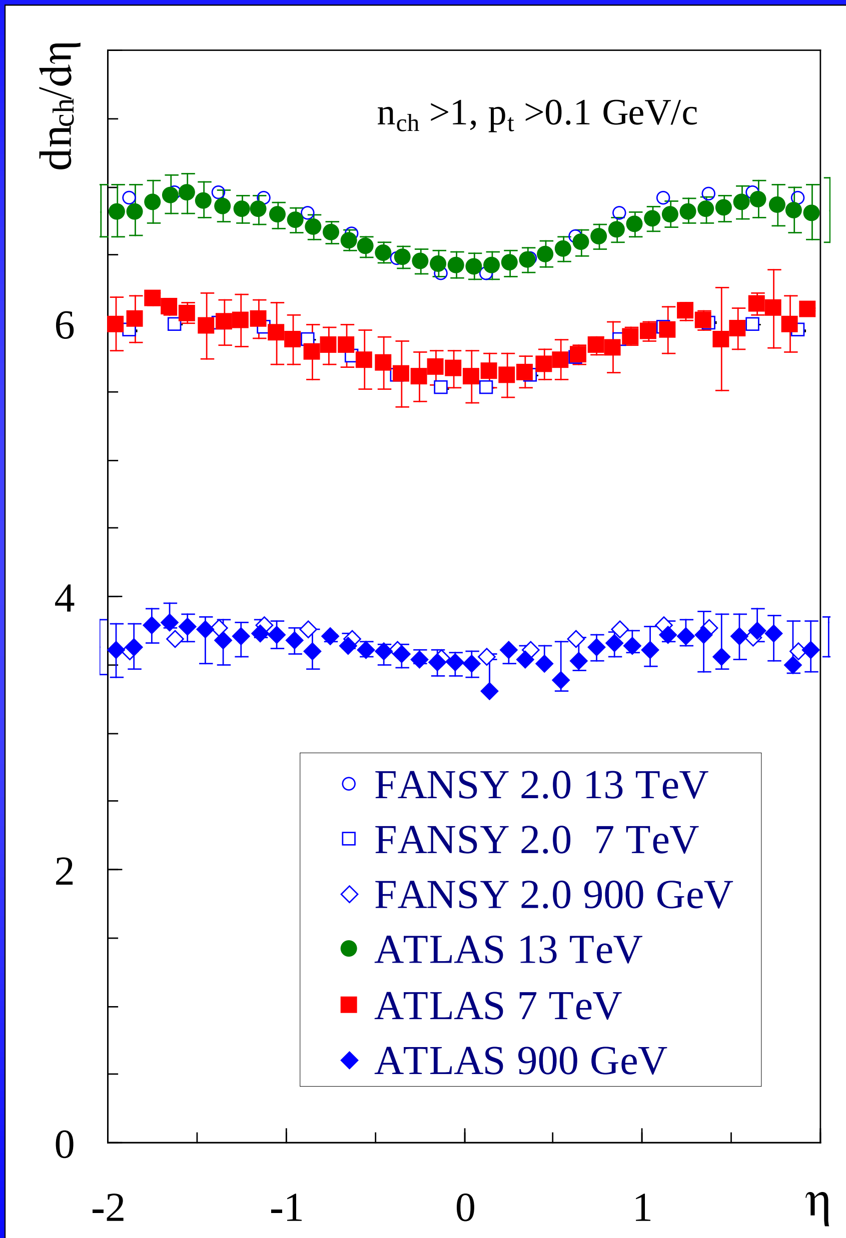
Cross sections

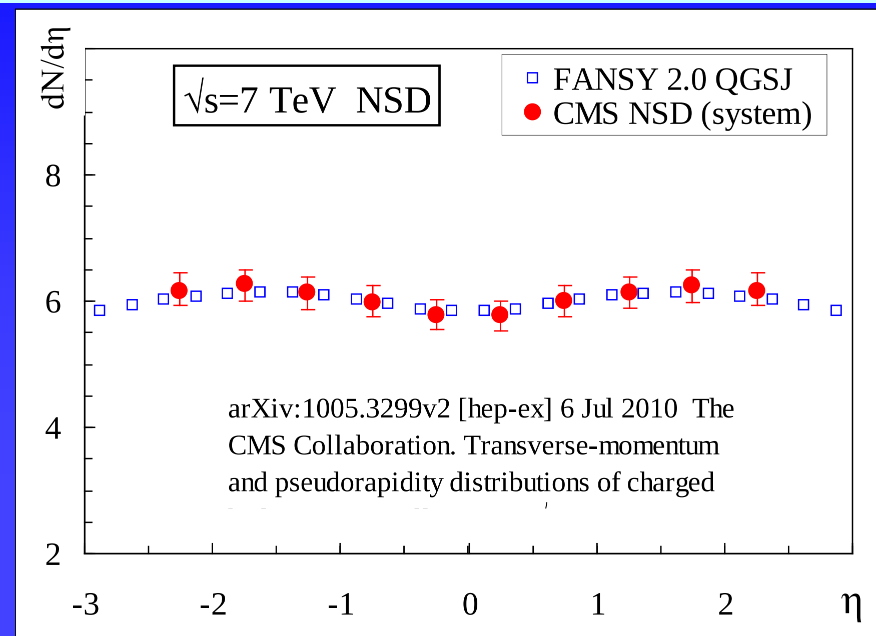


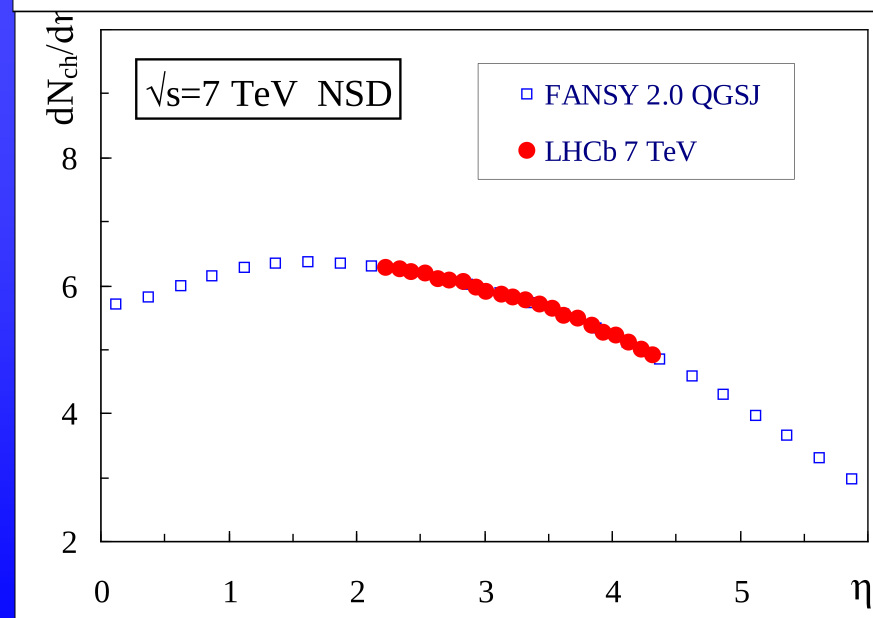


p-p interactions (central range) FANSY 2.0 / QGSJ

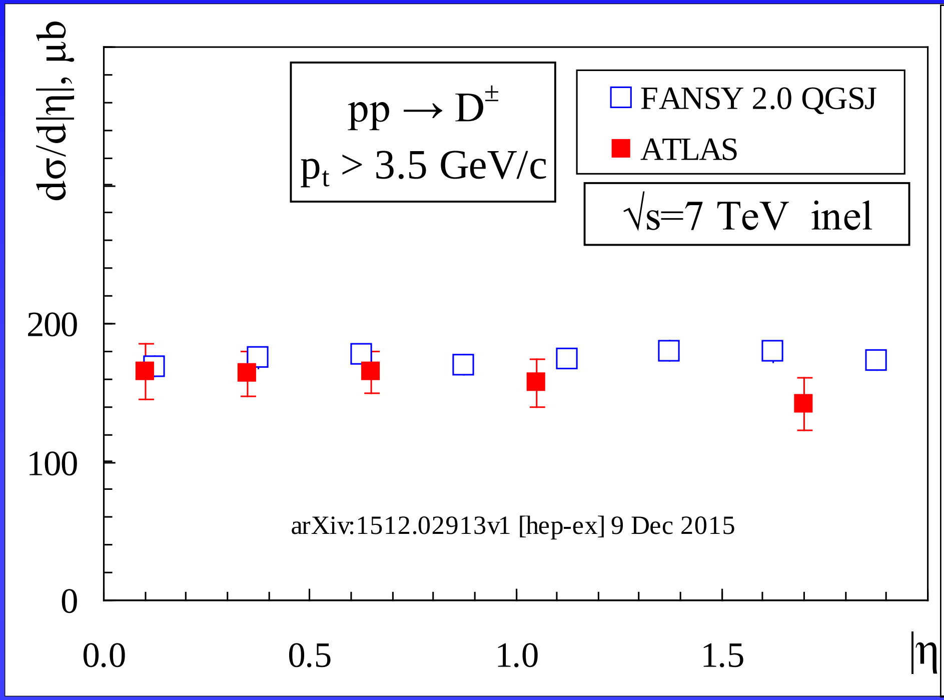
$dN/d\eta_{ch}$ distributions

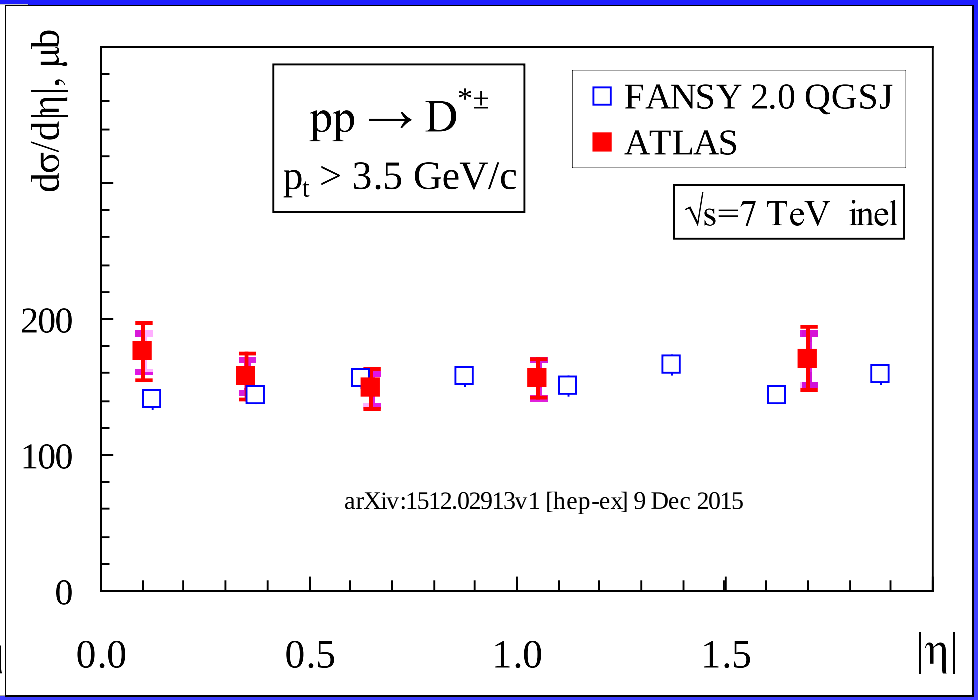




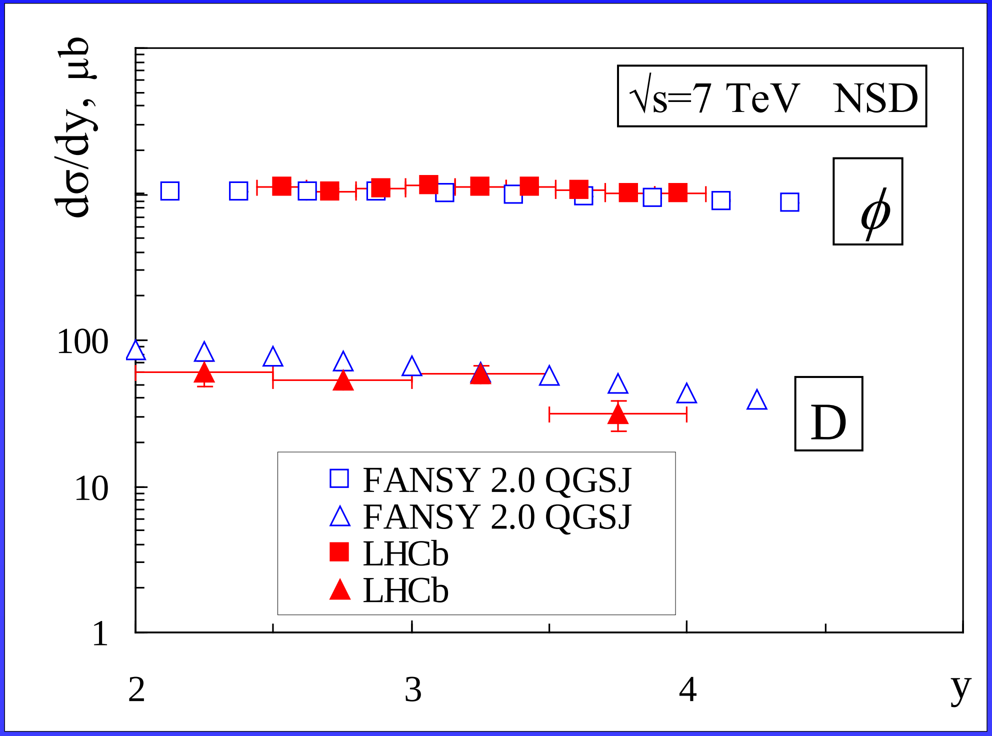


Charmed $D^{\pm}$ & $D^{*\pm}$ meson dN/dη distributions

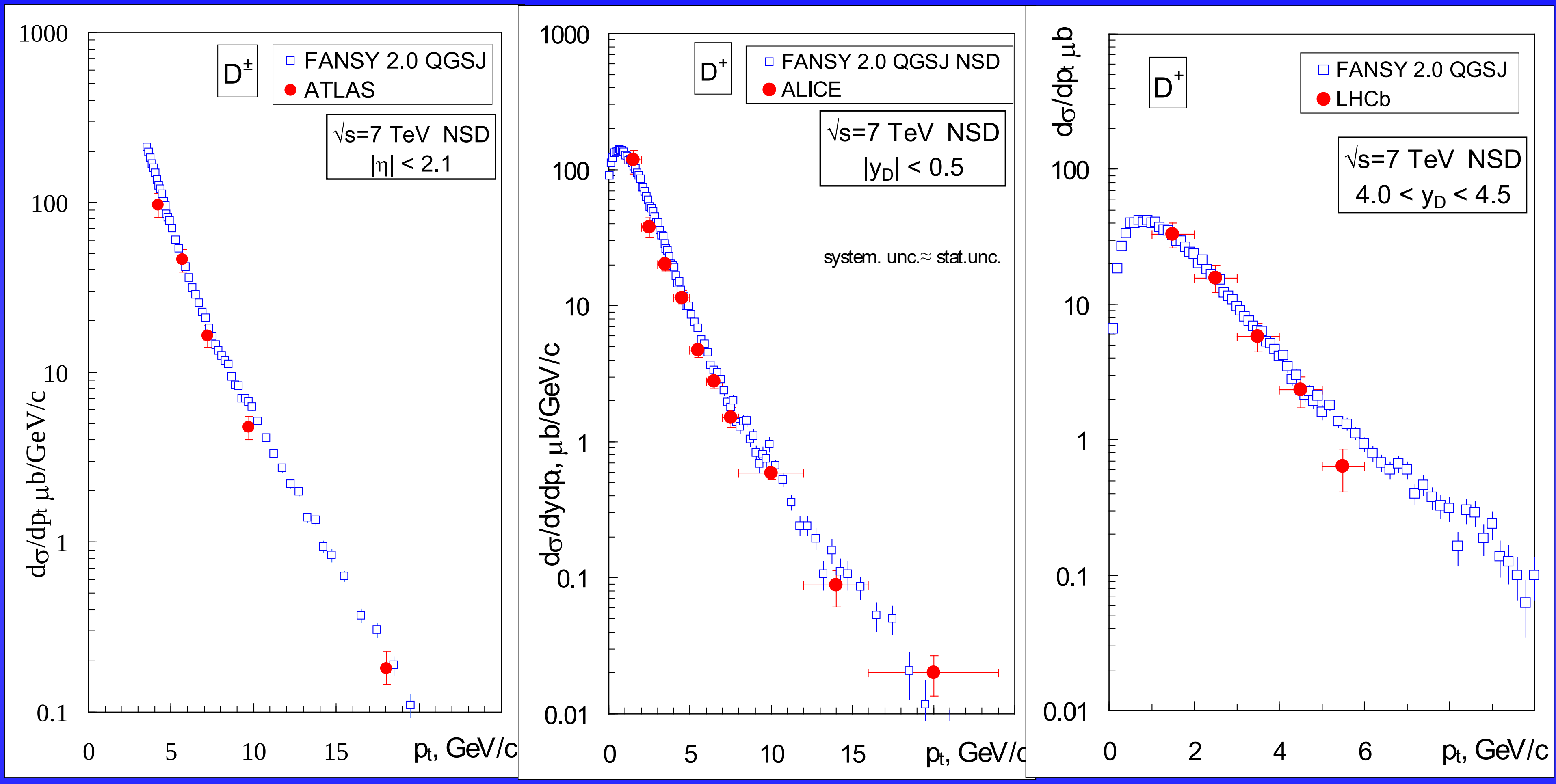




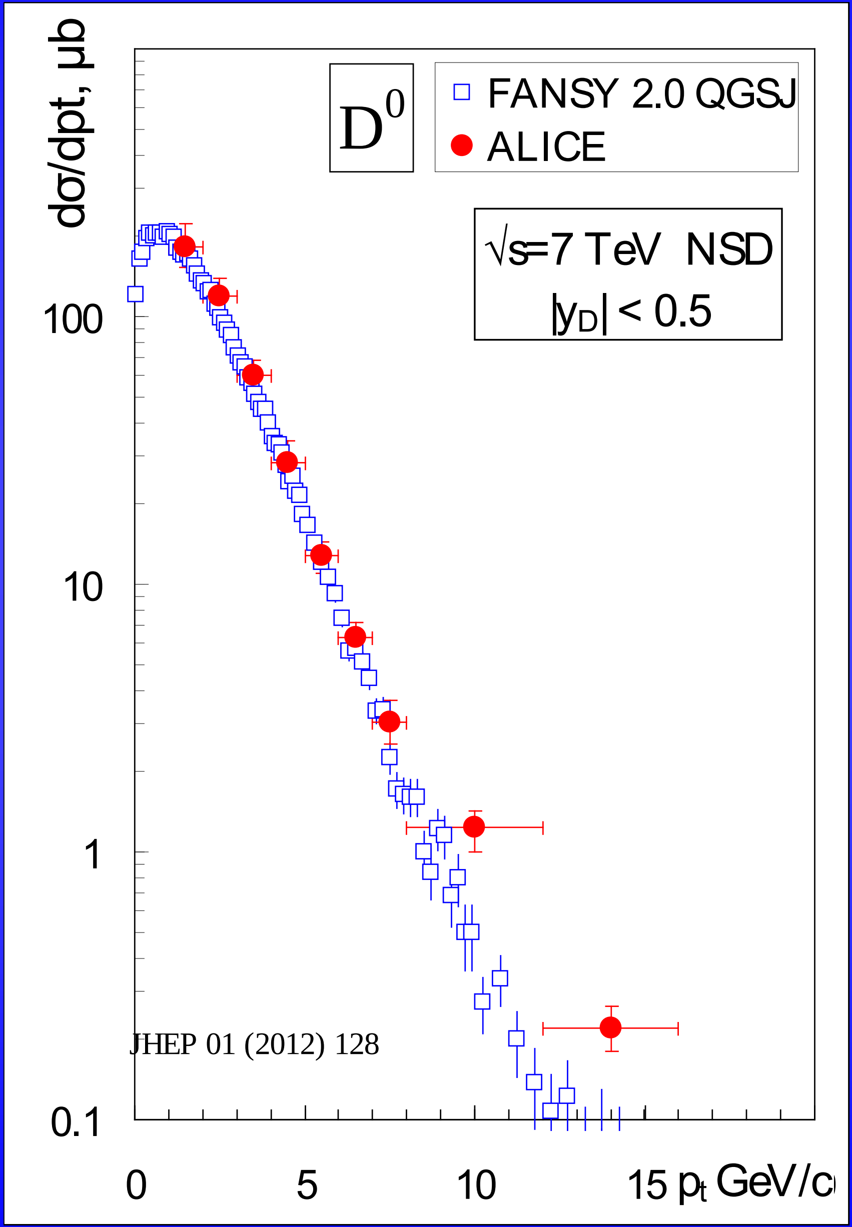
ϕ & $D_s^{\pm}$ meson $d\sigma/dy$ distributions

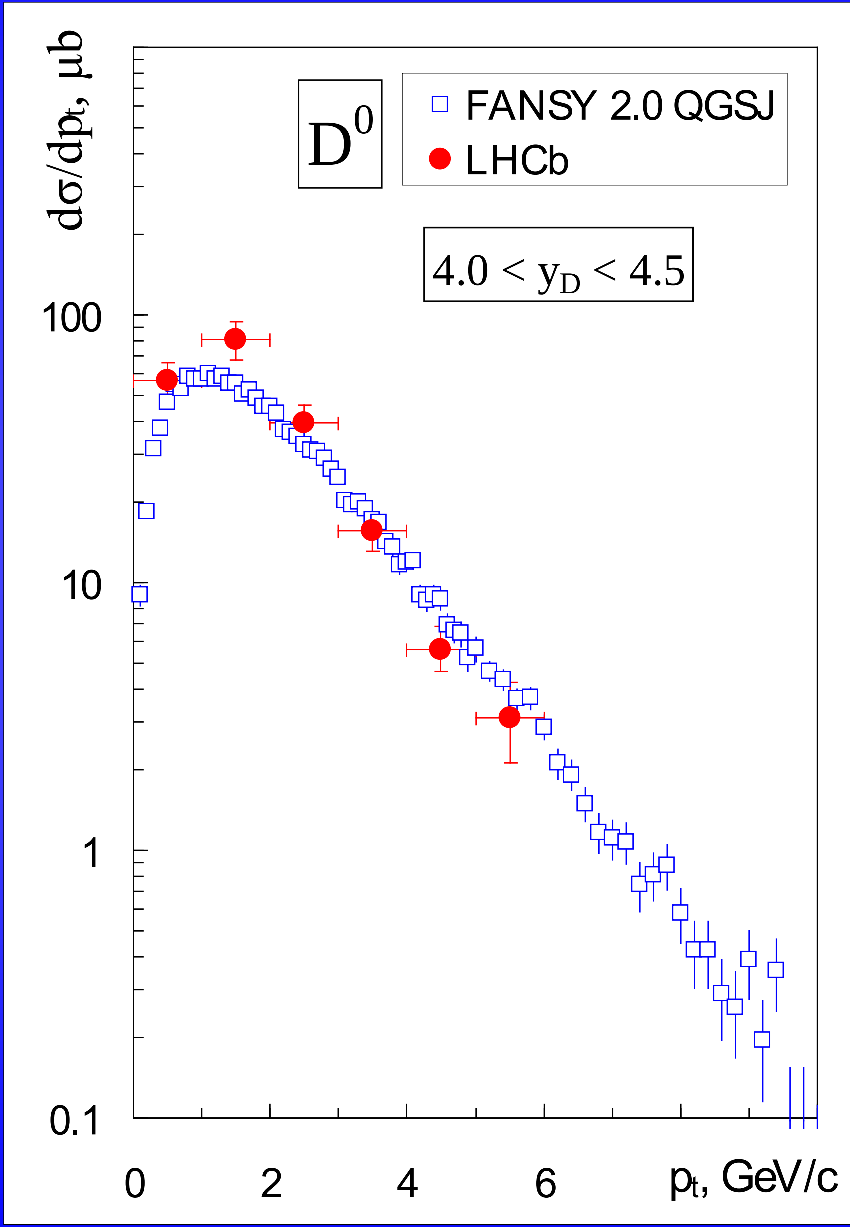


Charmed $D^{\pm}$ meson $d\sigma/dp_t$ distributions

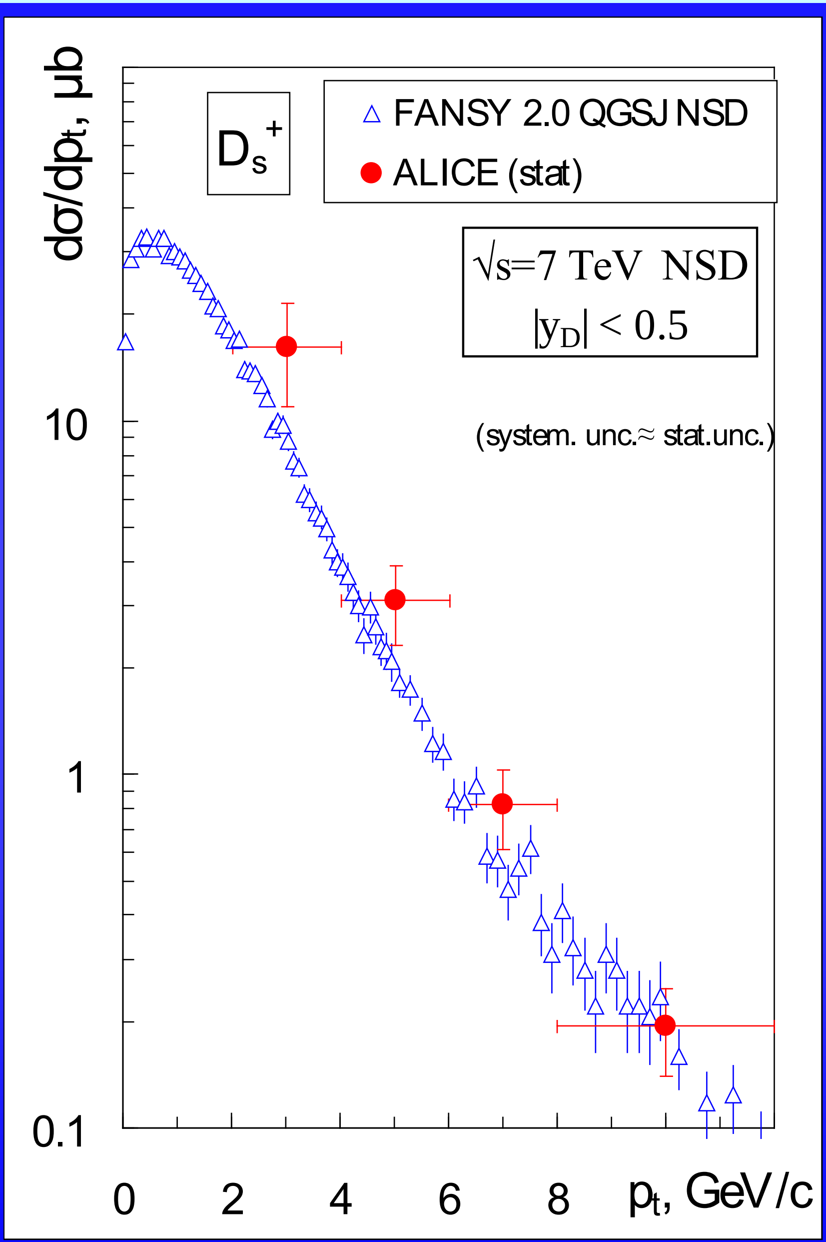


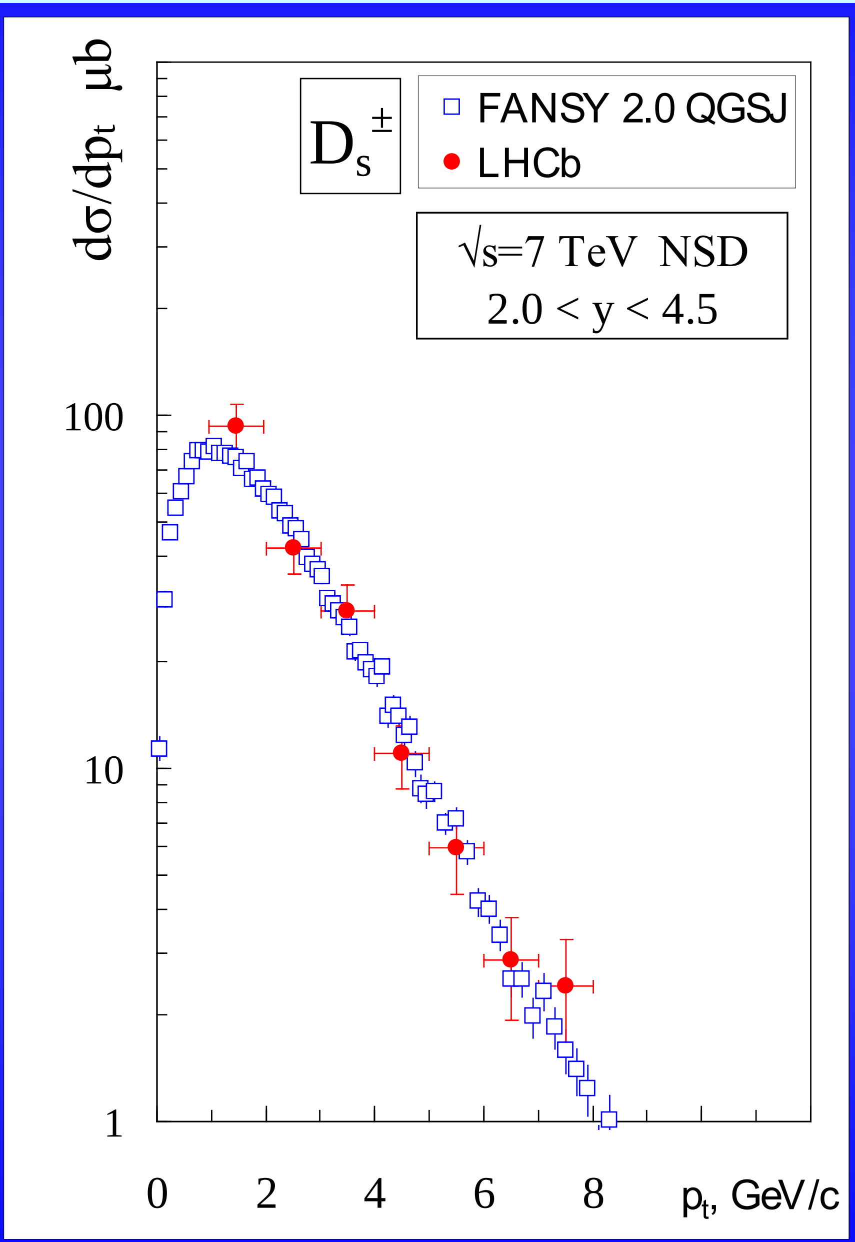
Charmed D^0 meson $d\sigma/dp_t$ distributions



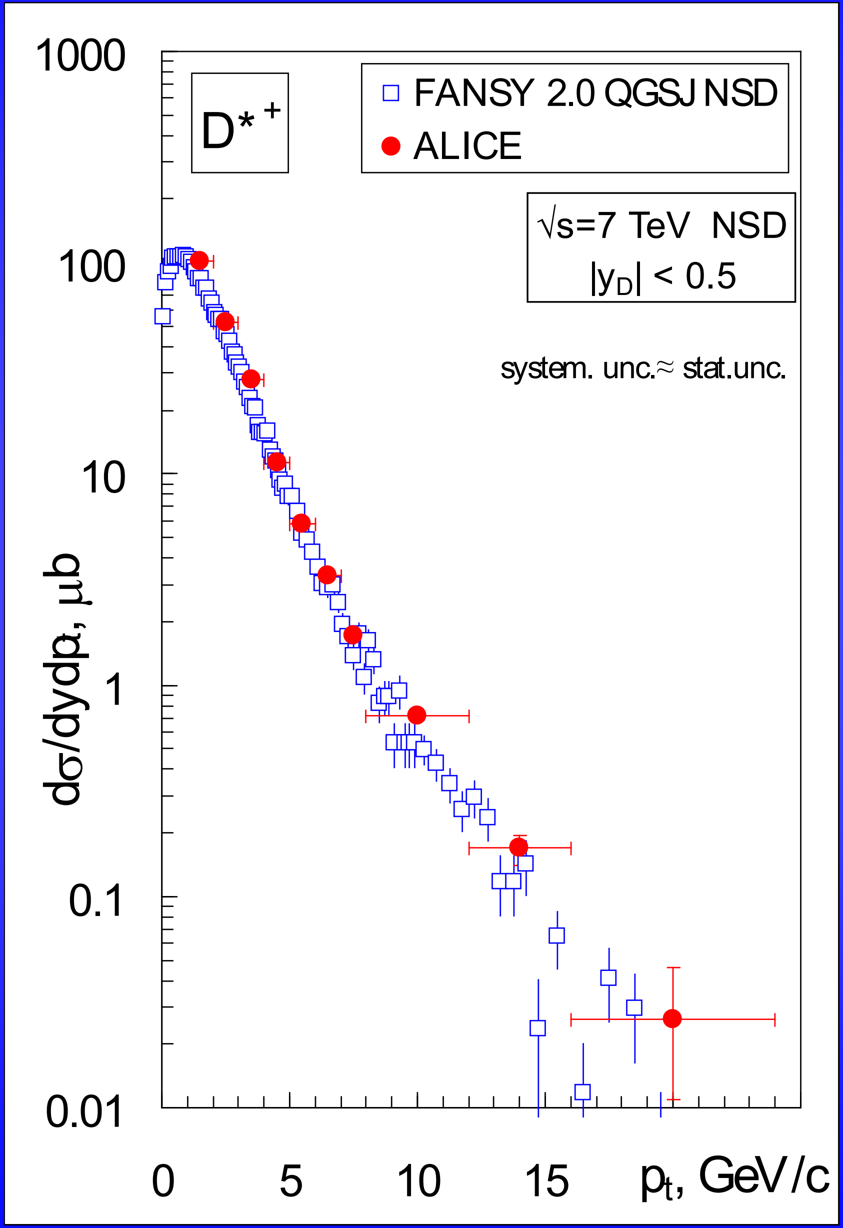


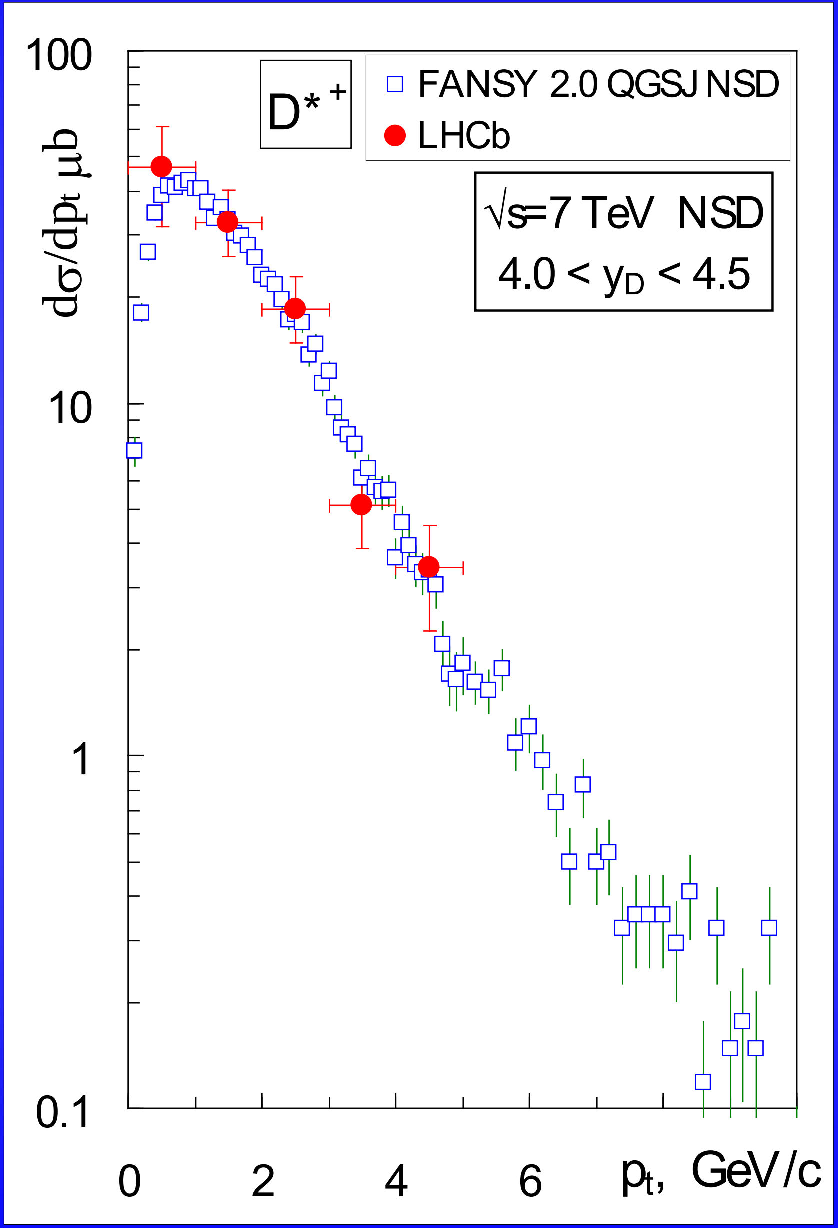
Charmed $D_s^{\pm}$ meson $d\sigma/dp_t$ distributions



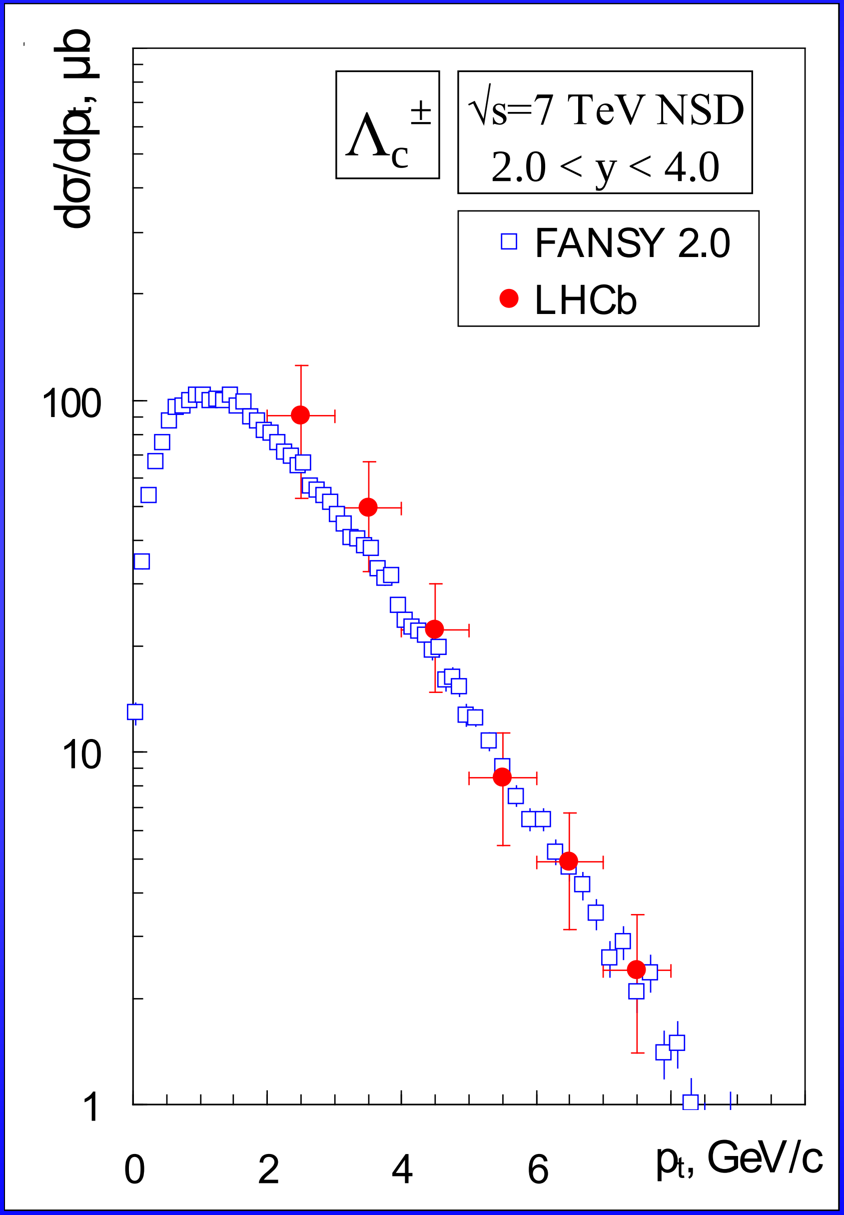


Charmed vector D^{*+} meson $d\sigma/dp_t$ distributions

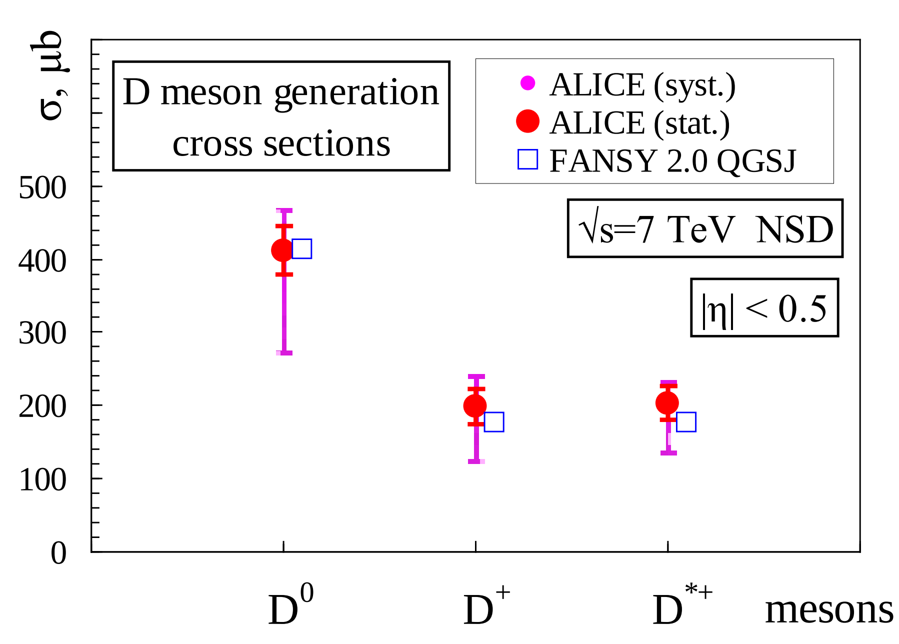


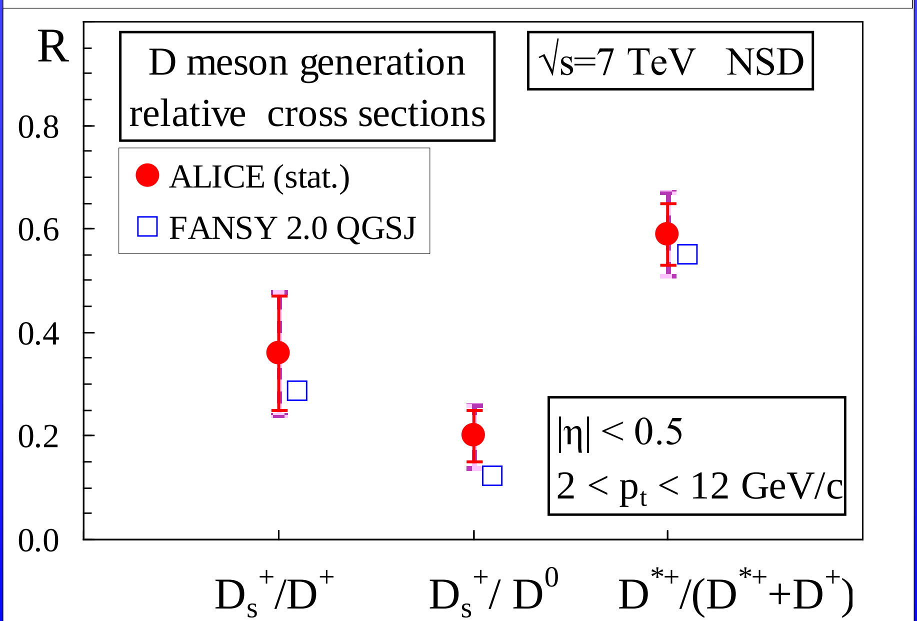


Charmed $\Lambda_c^{\pm}$ baryon $d\sigma/dp_t$ distribution



Charmed D meson generation cross sections

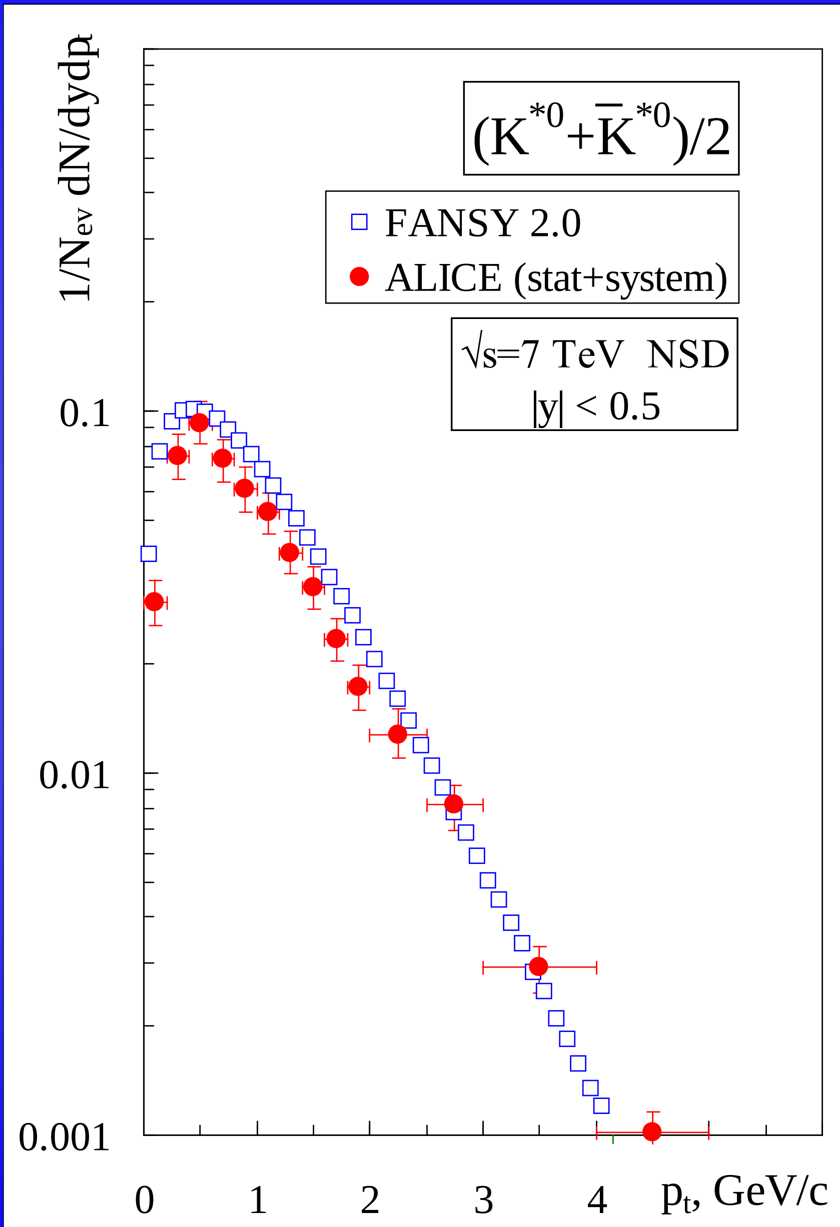


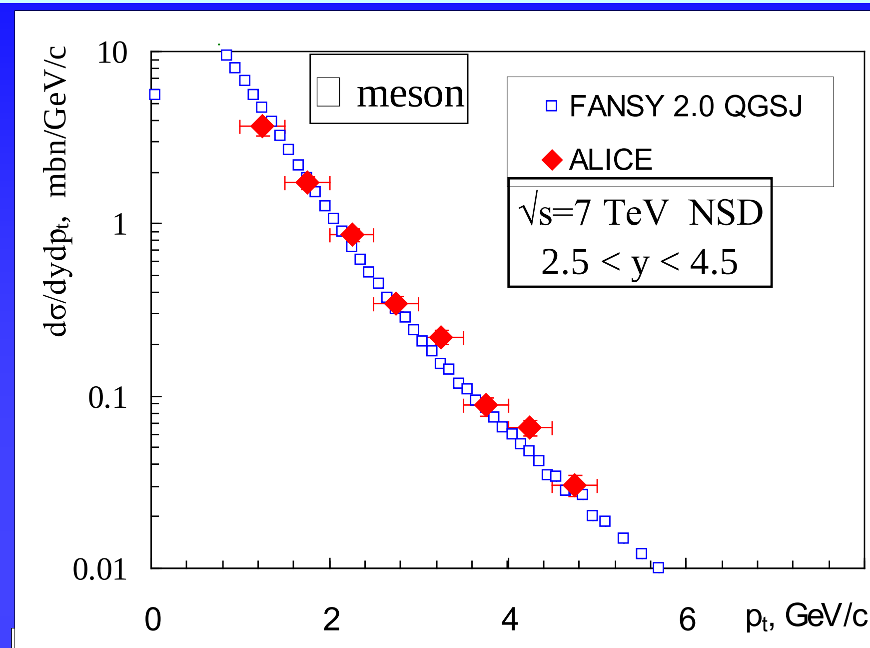


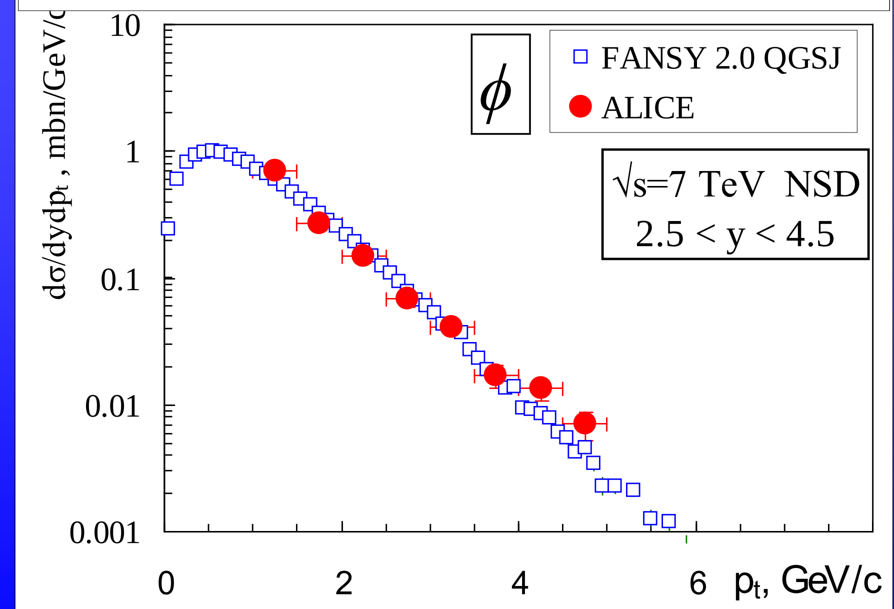
$\|\eta\|<0.5$				
Mesons	p_t GeV/c	A L I C E		FANSY 2.0
		σ ± stat	± system	σ ± stat
D^0	1 – 16	412 ± 33	+55 -140	432 ± 2
D^+	1 – 24	198 ± 24	+42 -73	182 ± 4
D^{*+}	1 – 24	203 ± 23	+30 -67	177 ± 1
Generation ratio of D^+_s to D^+ & D^0				
D^+_s / D^+	2 – 12	0.36 ± 0.11	± 0.12	0.29 ± 0.01
D^+_s / D^0	2 – 12	0.20 ± 0.05	± 0.06	0.17 ± 0.01
Ratio $P_v = D^{*+}/(D^{*+} + D^+)$				
P_v	1 – 24	0.59 ± 0.06	± 0.08	0.55 ± 0.01

Experimental & simulated cross sections of $D/D^*/\Lambda^{\pm}_c$ generation agree in general within statistical & systematic errors

Heavy vector neutral K, ω, ϕ meson $d\sigma/dp_t$ distributions







This is all very interesting,

but not too important for cosmic-ray experiments …

- PCR spectrum falls off rapidly with energy $I(>E)\sim E^{-\beta}$ ($\beta\sim1.6$–2.2)
- Strong fluctuations in EAS development

↓

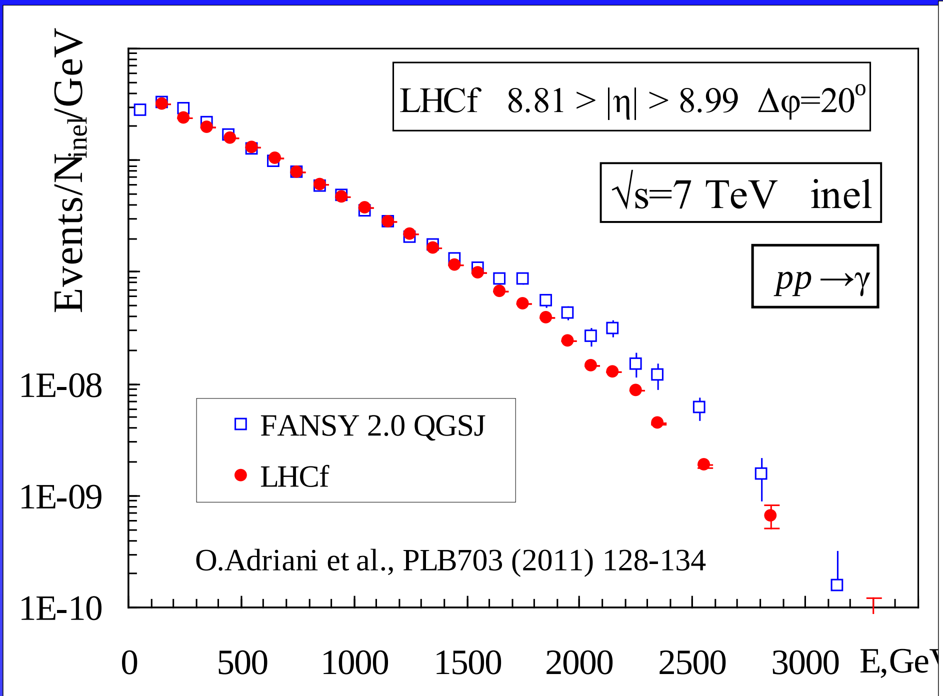
Important !

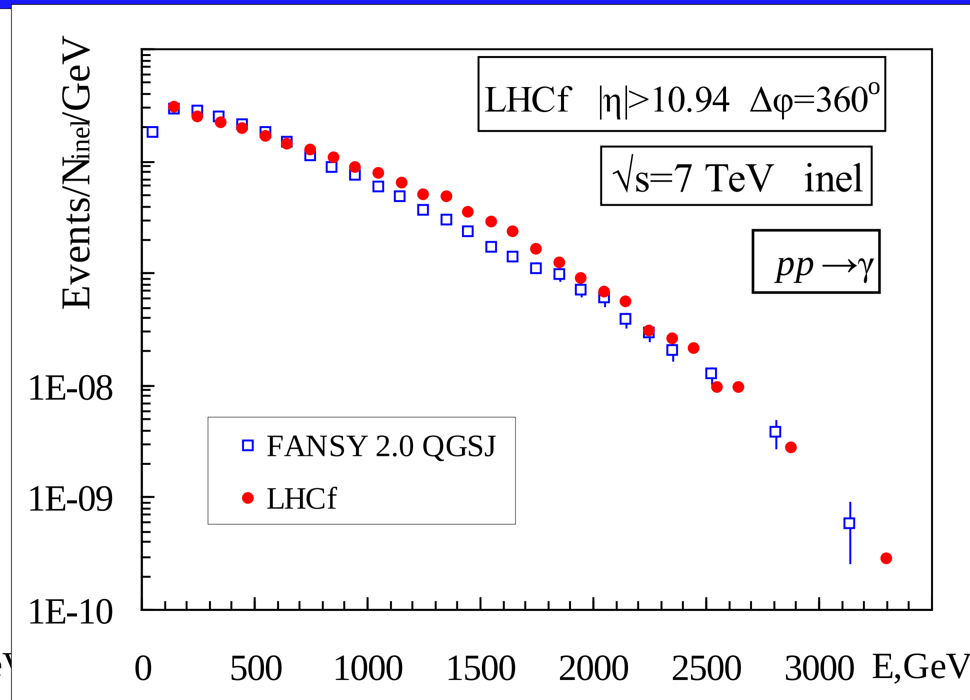
1) $d\sigma/dX_F$ spectrum at $X_F \gtrsim 0.05$

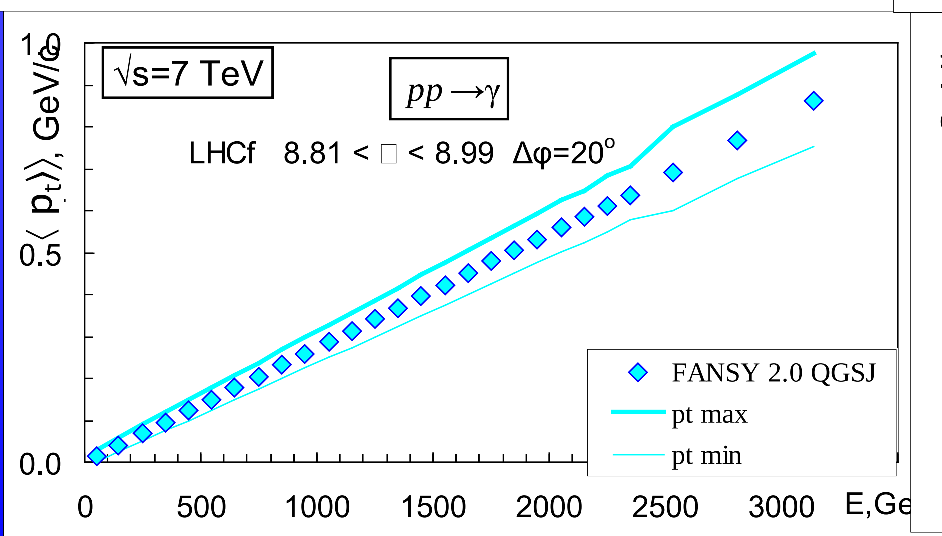
2) $\langle X_F^{\beta}\rangle$ (not $\langle X_F\rangle$!) $\Rightarrow$ the role of particles rises with increasing X_F

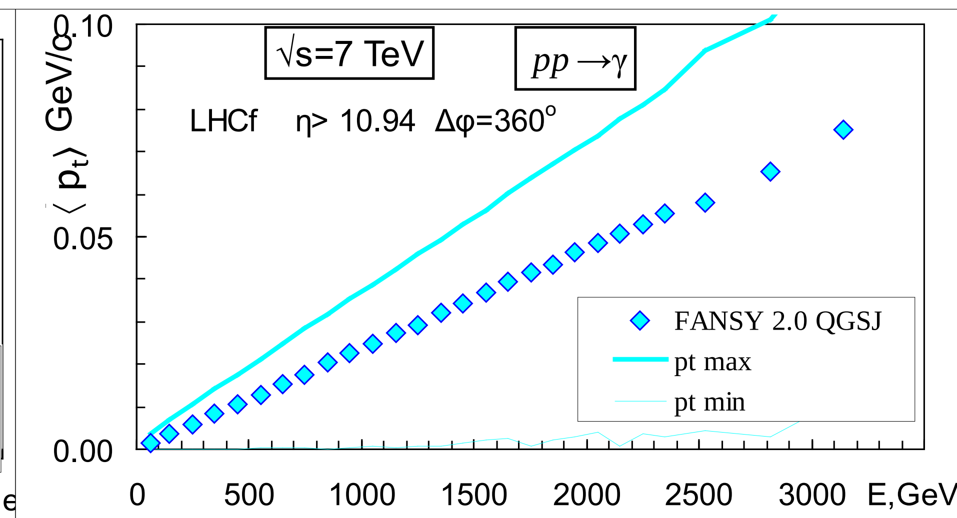
p-p interactions
& "forward physics"
(large X_F and, particlally, η)

LHCf: spectra and observable p_t of γ-rays

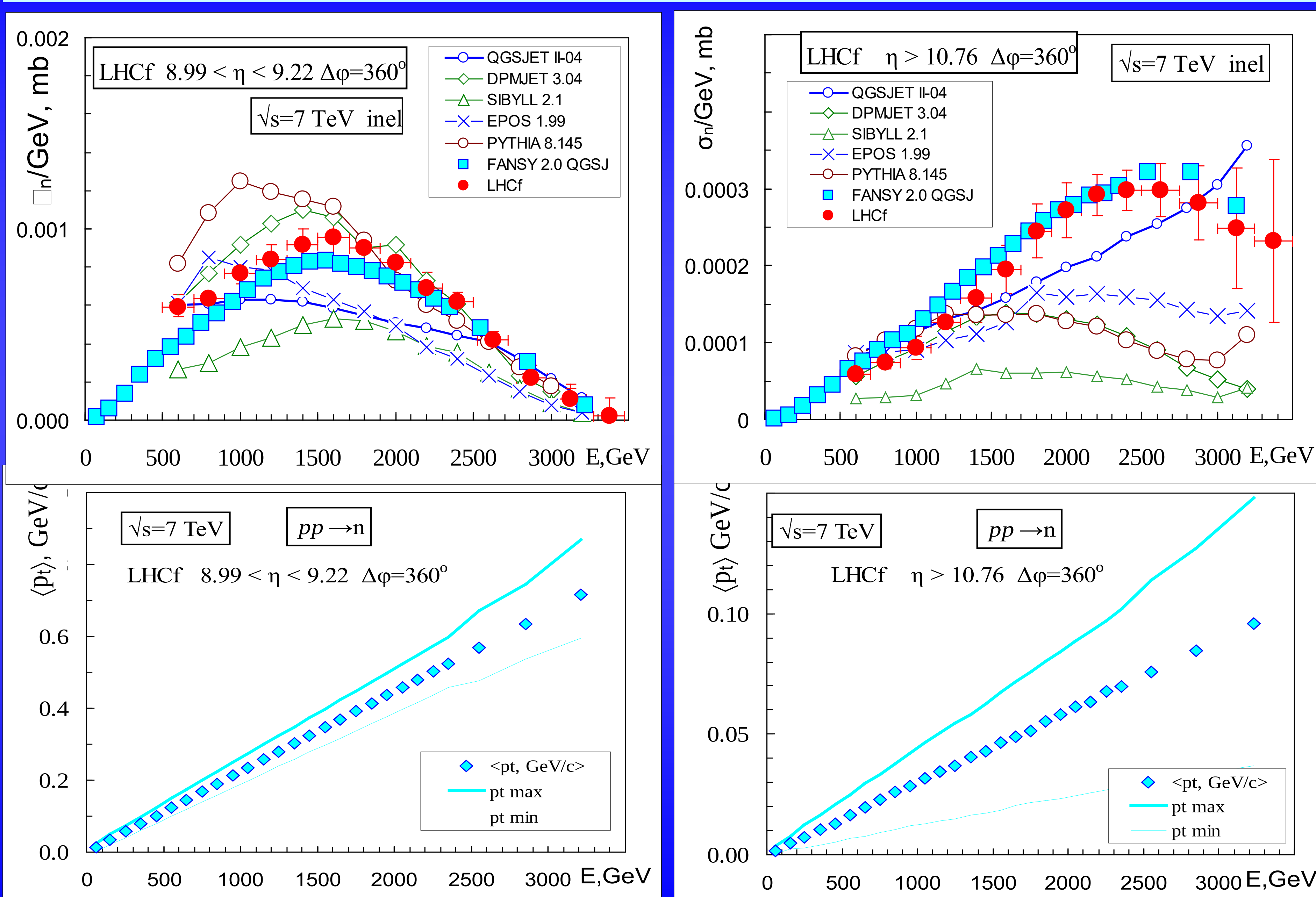




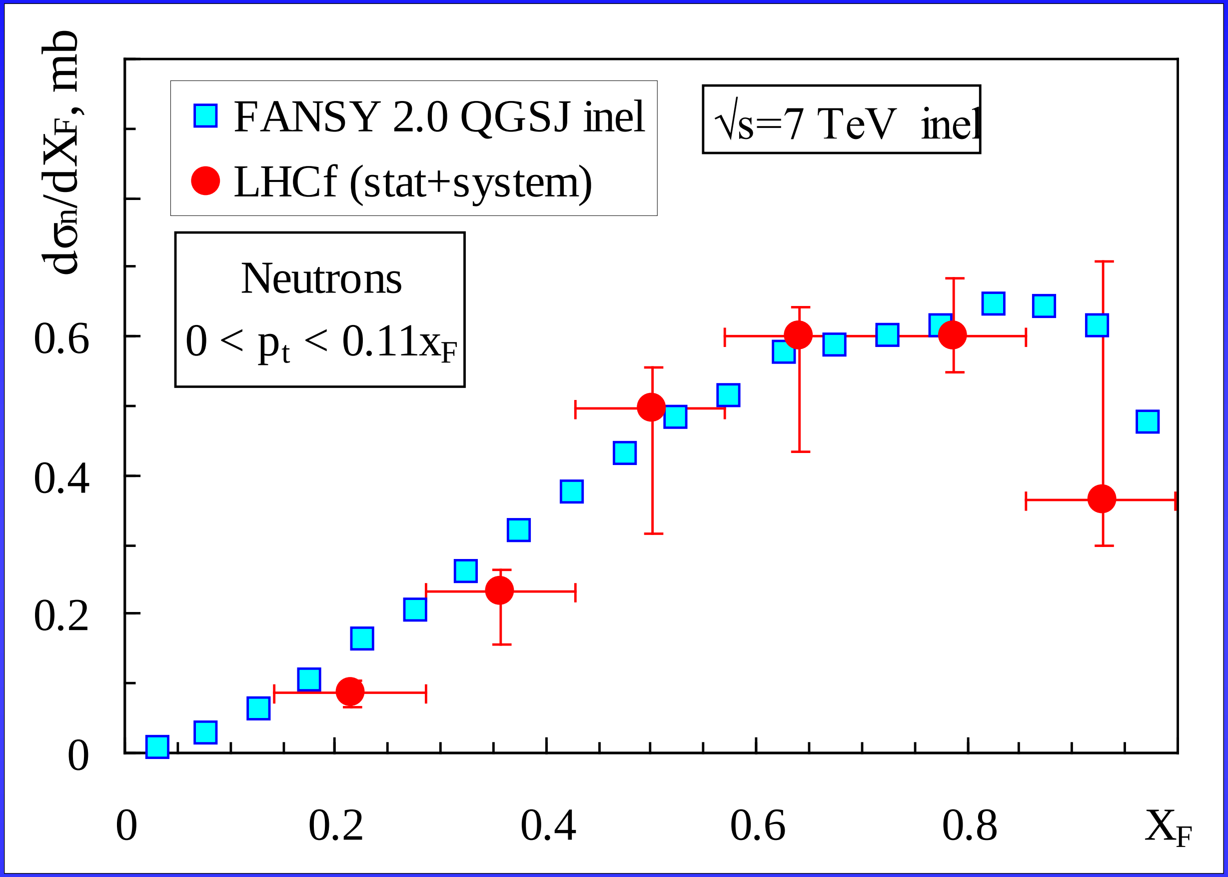




LHCf: neutrons

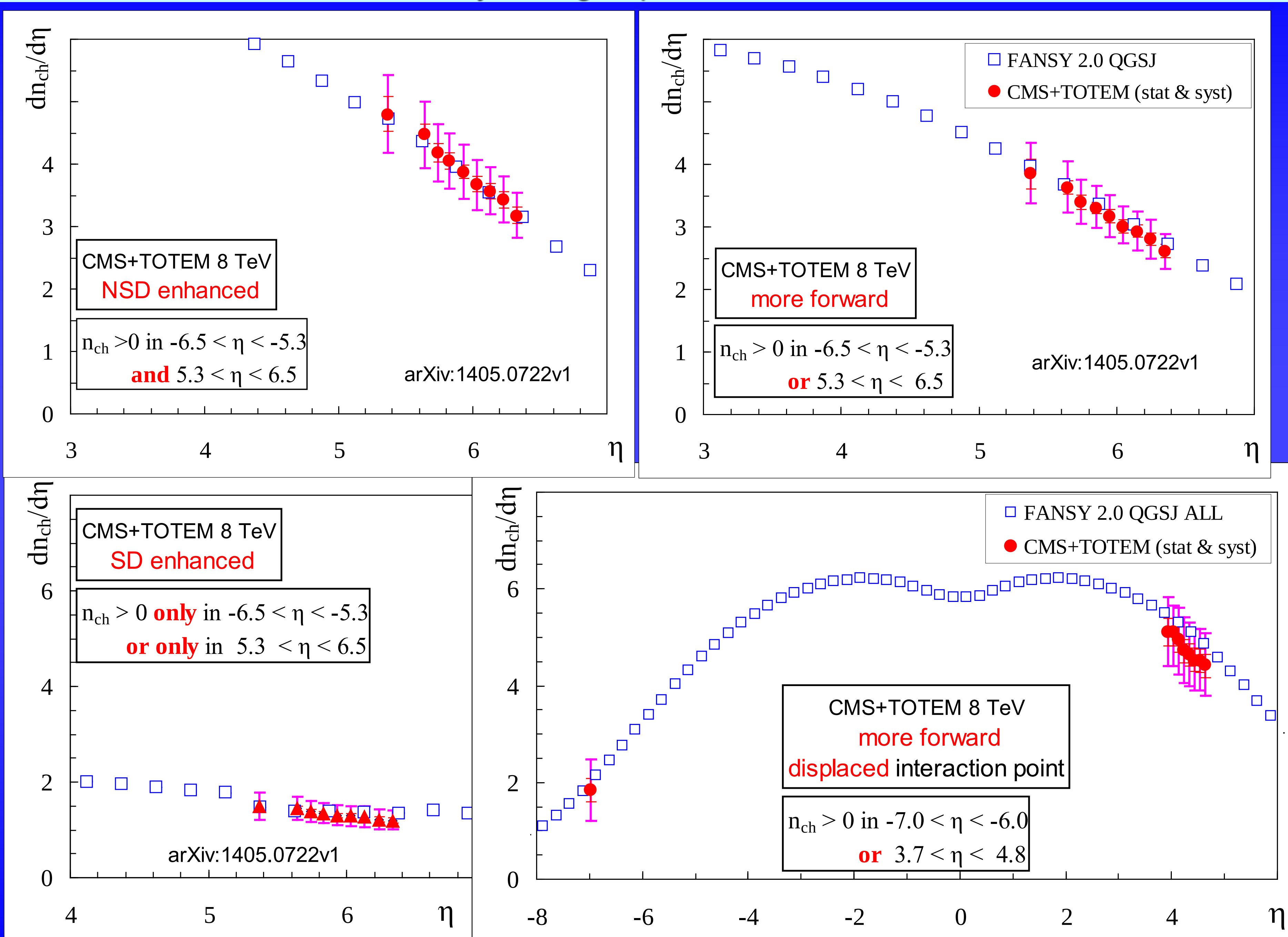


LHCf: neutrons



Very narrow p_t ranges of γ-ray and neutron data!

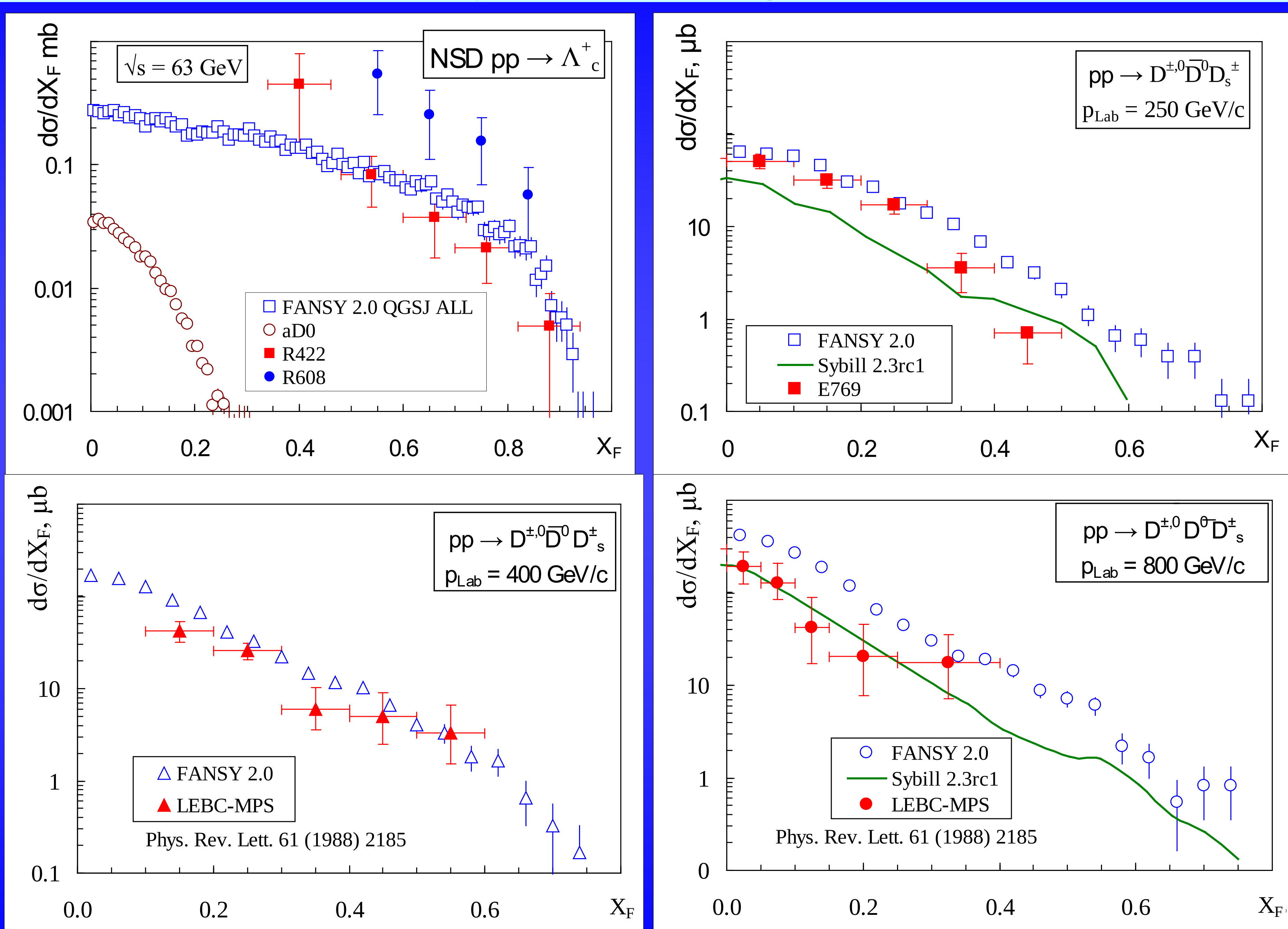
CMS + TOTEM: very strong dependence on selection criteria!



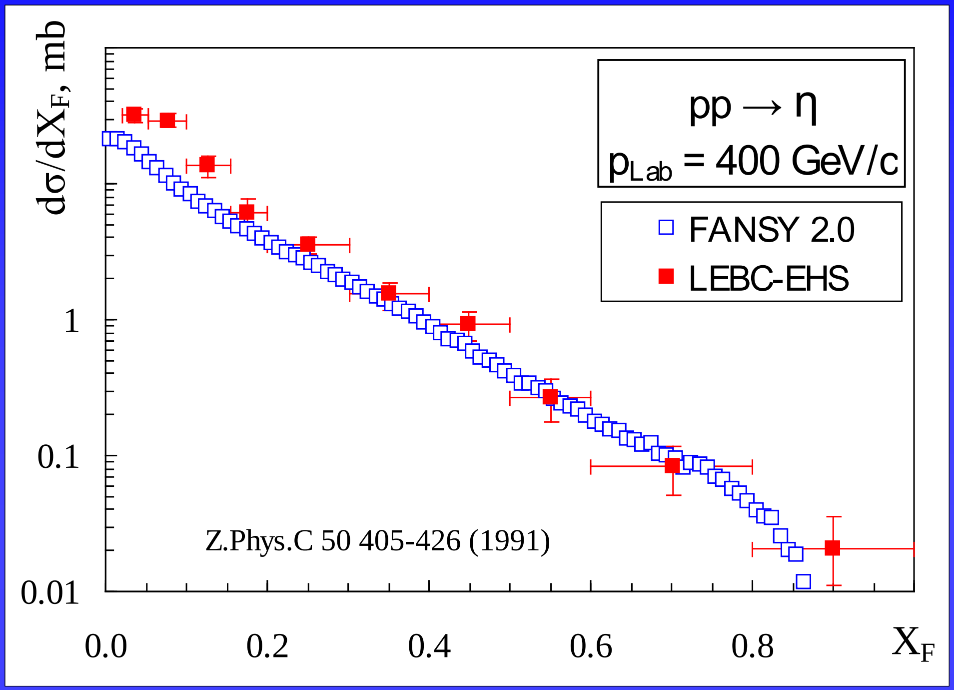
Low energies (“forward physics”)

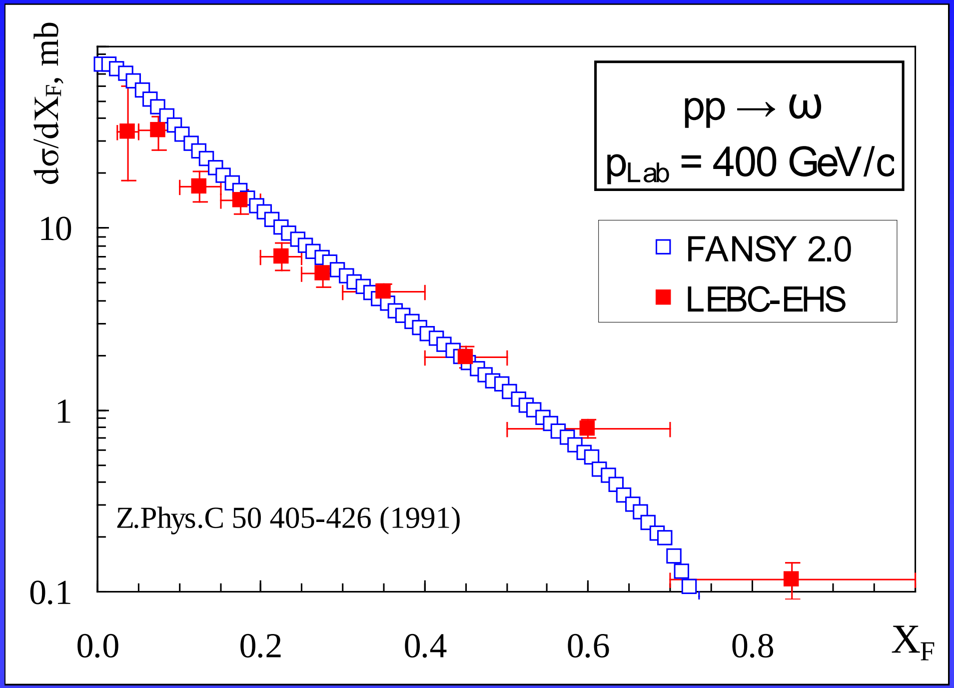
p-*p* interactions

dσ/dx$_F$ spectra (pp → Λ_c^+, $D^{\pm,0,s}$)

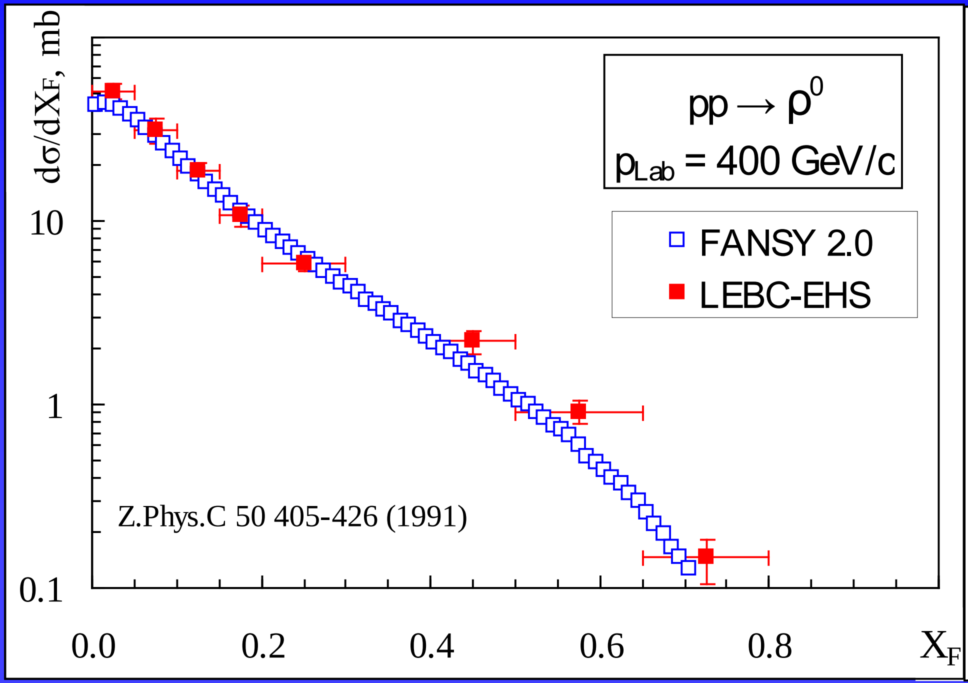


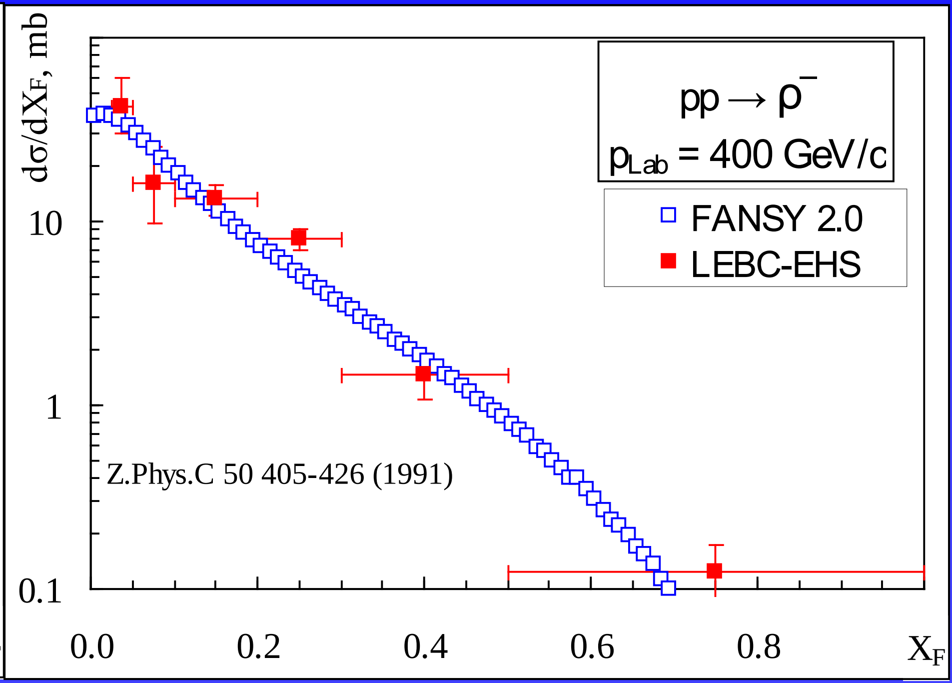
$d\sigma/dx_F$ spectra of η and ω mesons



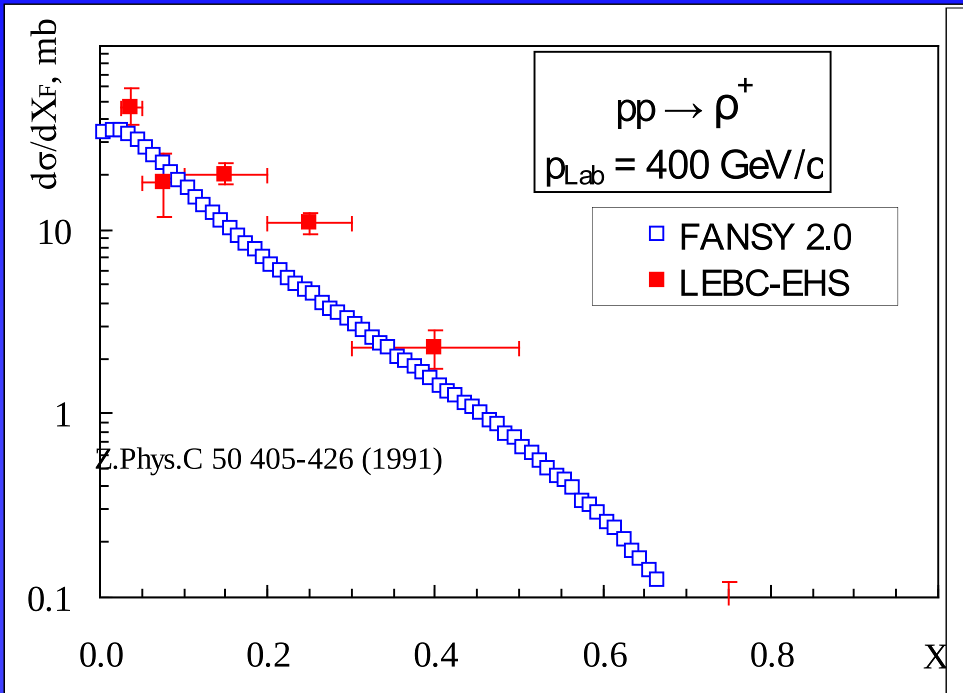


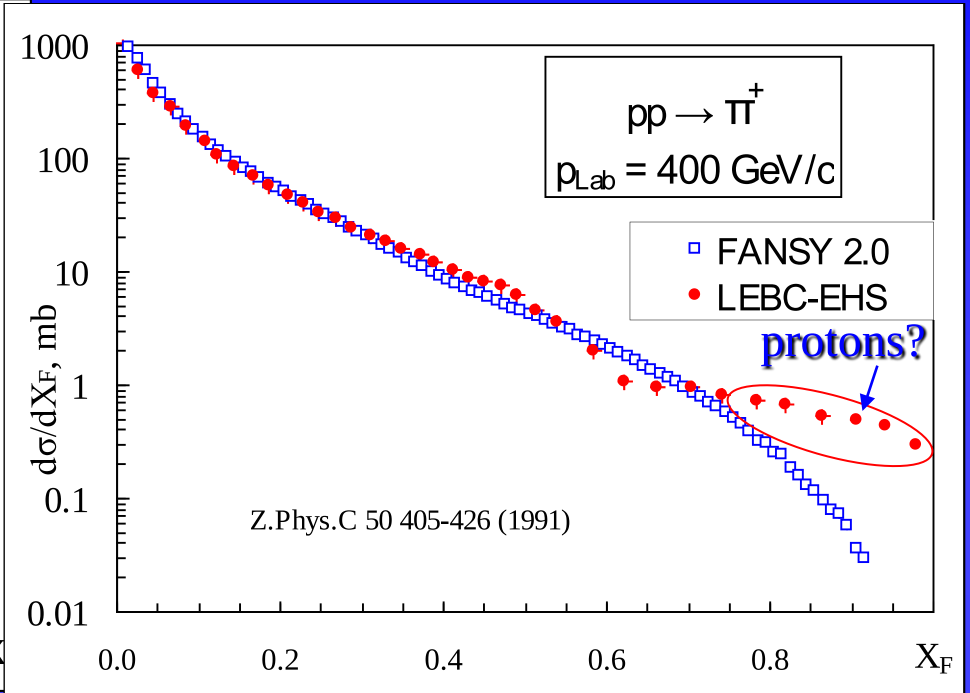
dσ/dx_F spectra of ρ^0/ρ^- mesons





$d\sigma/dx_F$ spectra of ρ^+ и π^+ mesons



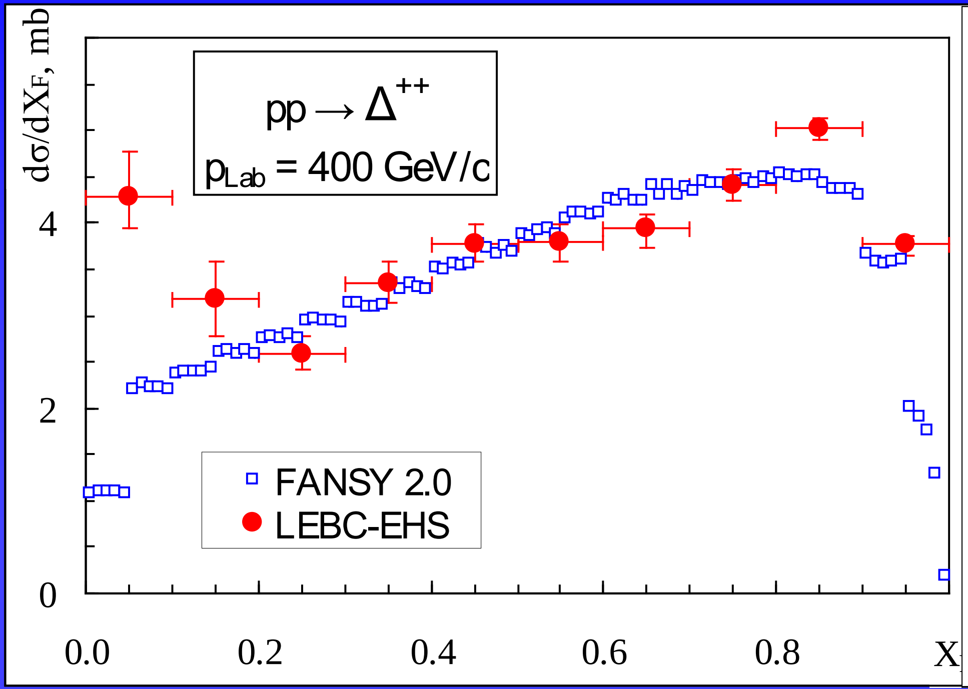


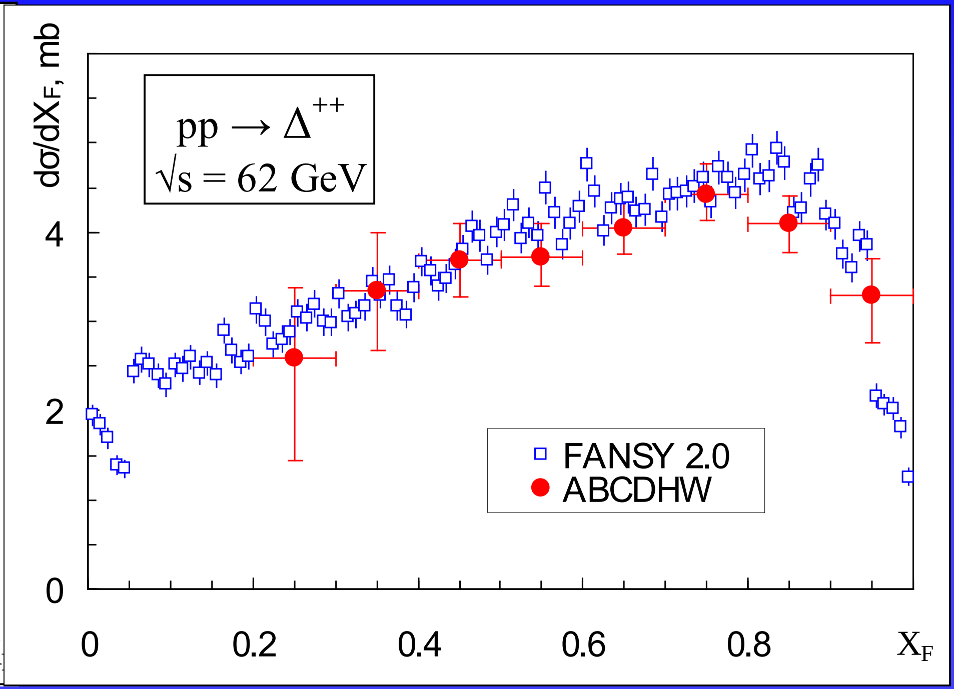
Experimental & simulated spectra of η, ω, $\rho^{0,+,-}$ mesons agree in general within statistical & systematic errors

LEBC-EHS spectrum of π^+ mesons at $X_F > 0.7$

- contradicts the ICR results on π^+ spectra
- is difficult to explain using known processes (Δ^{++} generation, e.g.)

dσ/dx$_F$ Δ^{++} spectra

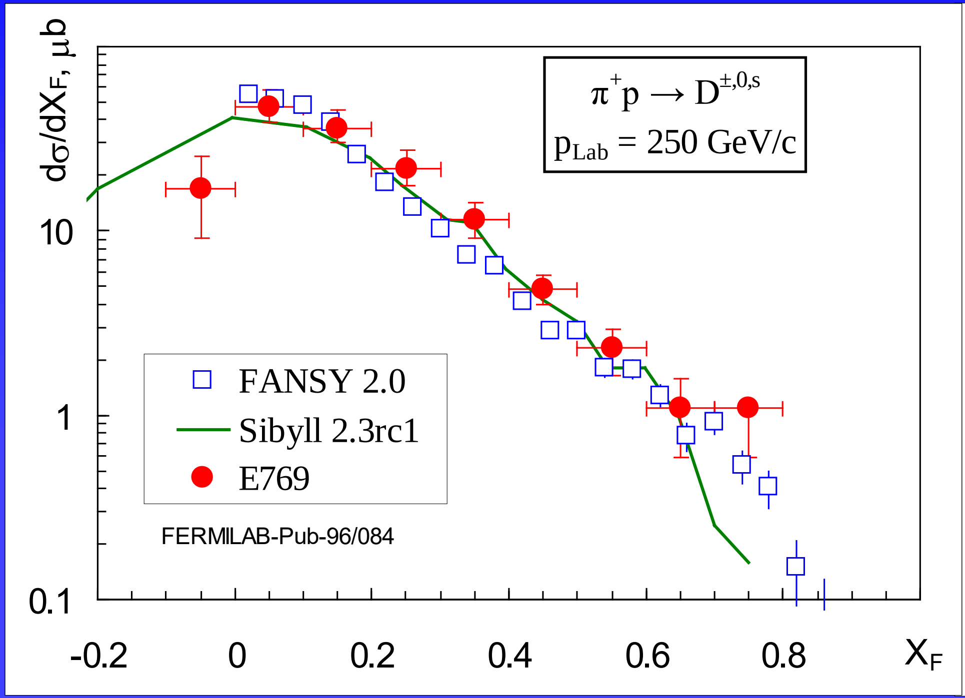


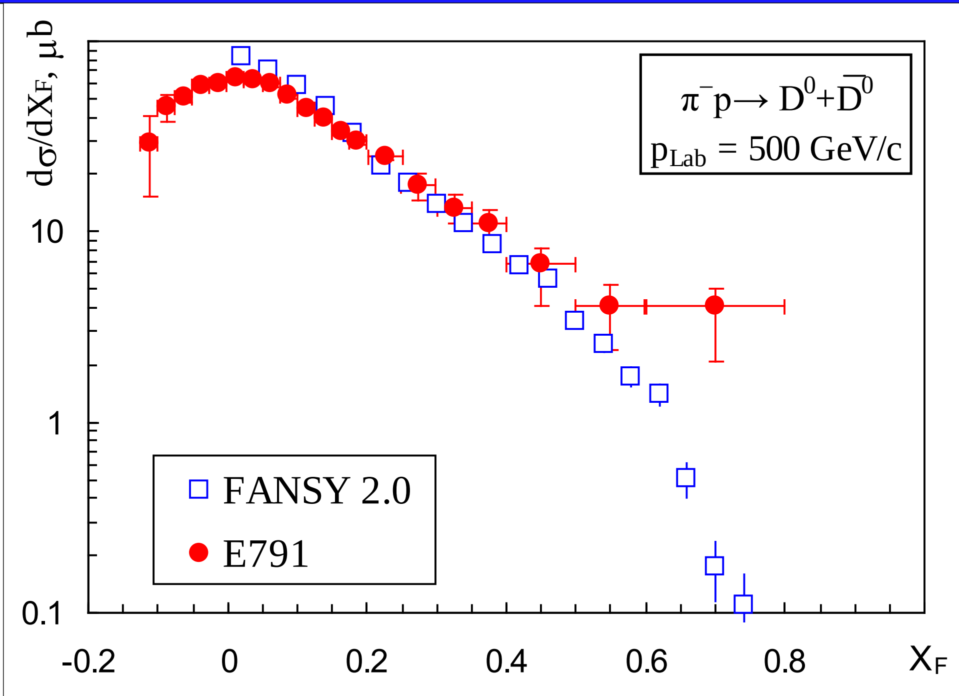


Low energies (“forward physics”)

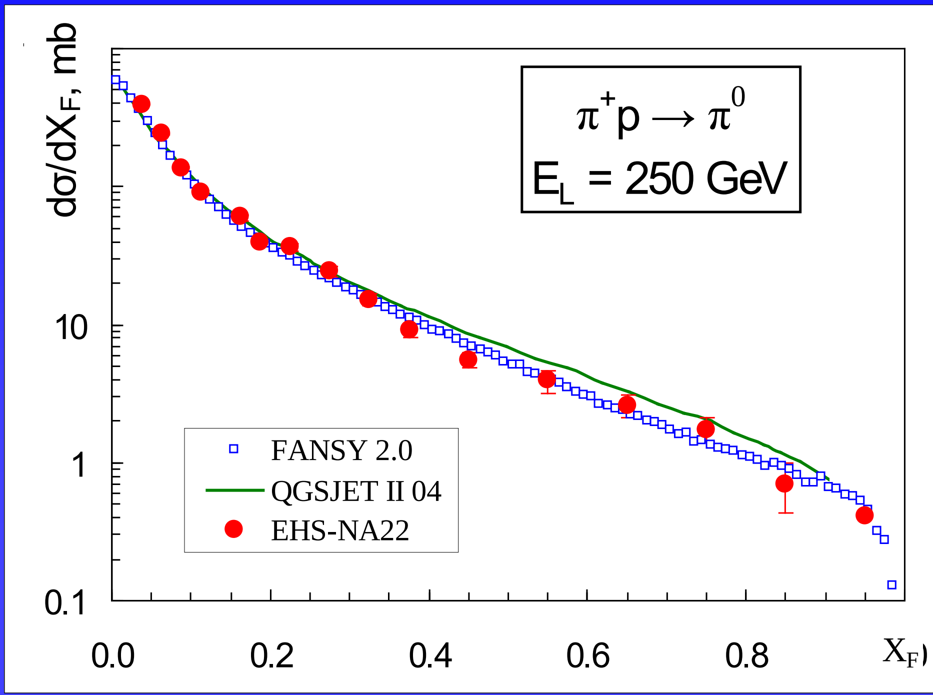
π-p interactions

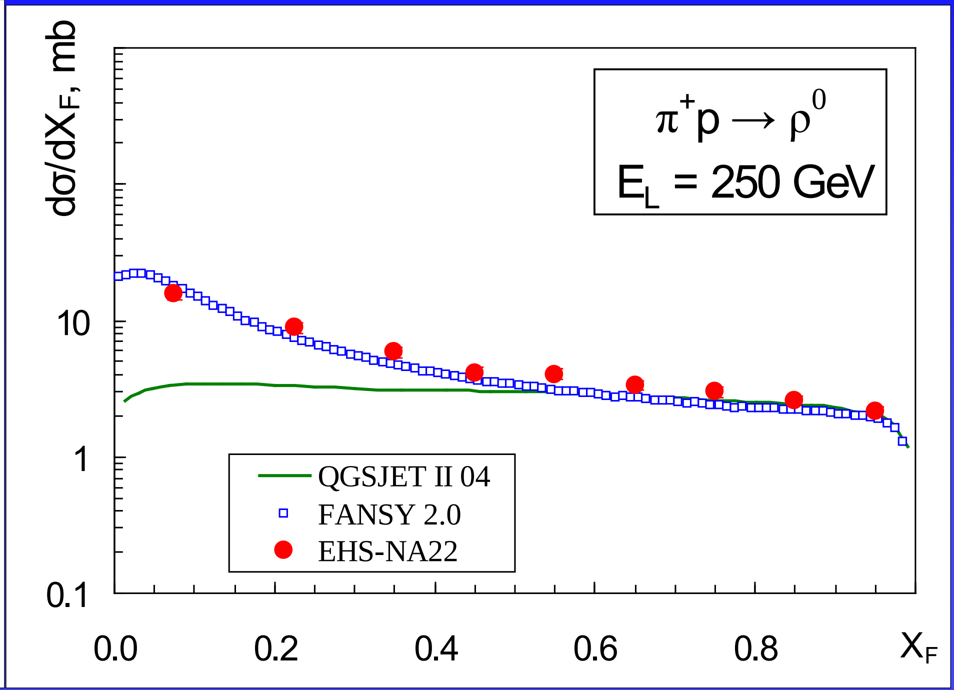
Charmed D meson dσ/dx$_F$ spectra





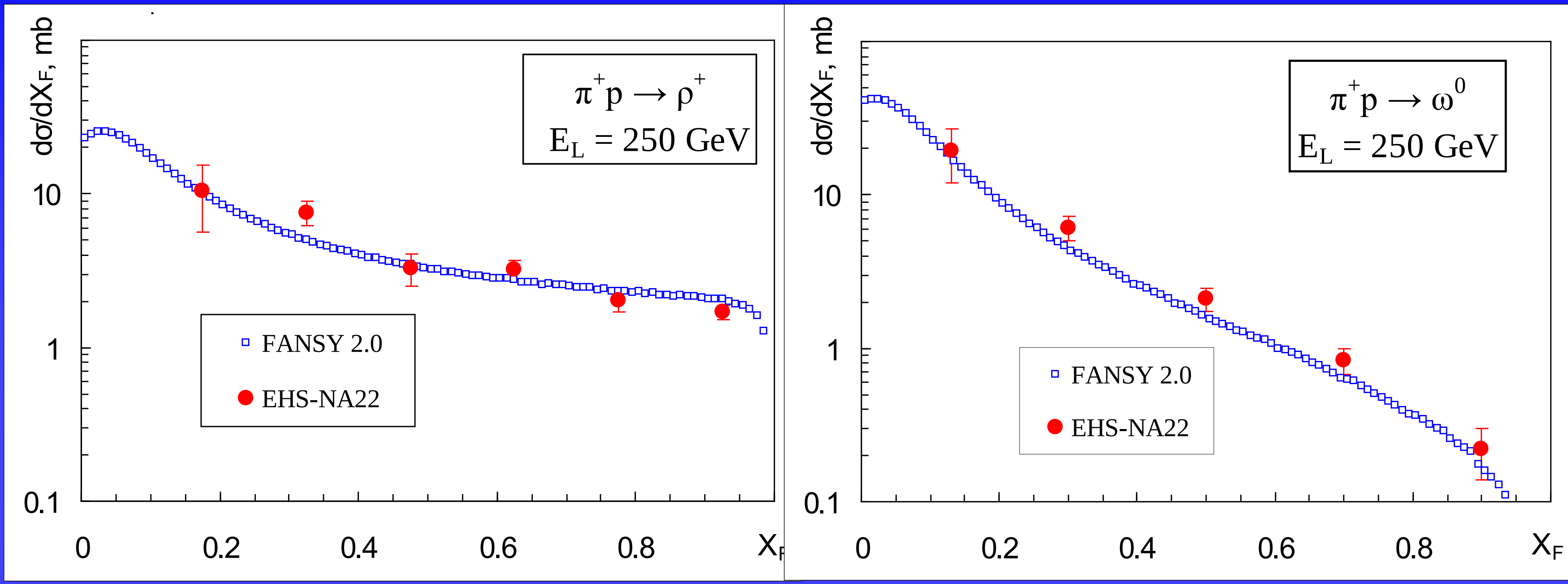
$d\sigma/dX_F$ spectra of π^0 & ρ^0 mesons





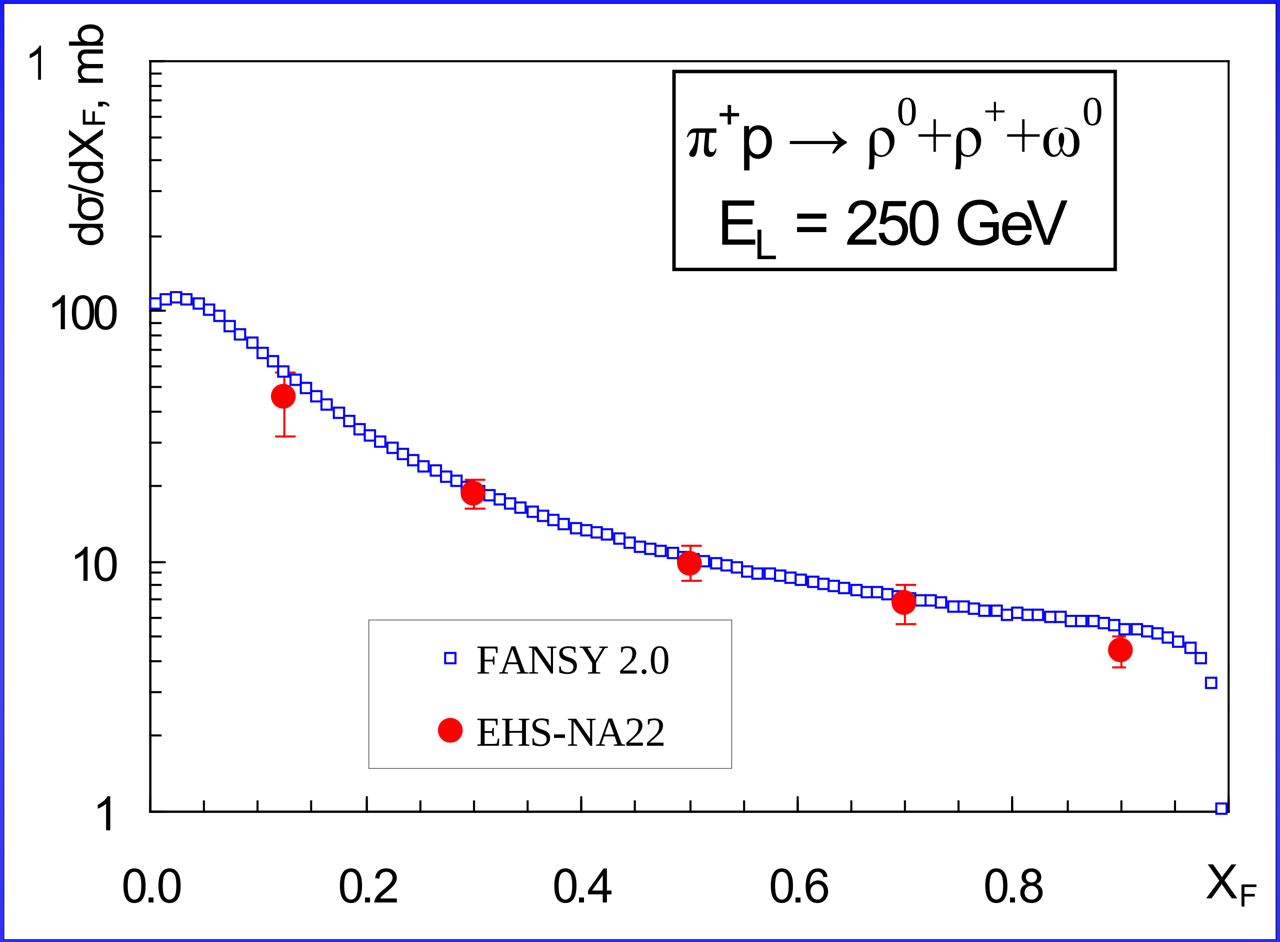
- Spectrum of π^0 is softer than spectrum of ρ^0
- Experimental & simulated spectra of π^0 and ρ^0 mesons agree within statistical & systematic errors

$d\sigma/dX_F$ spectra of ω^0 & ρ^+ mesons

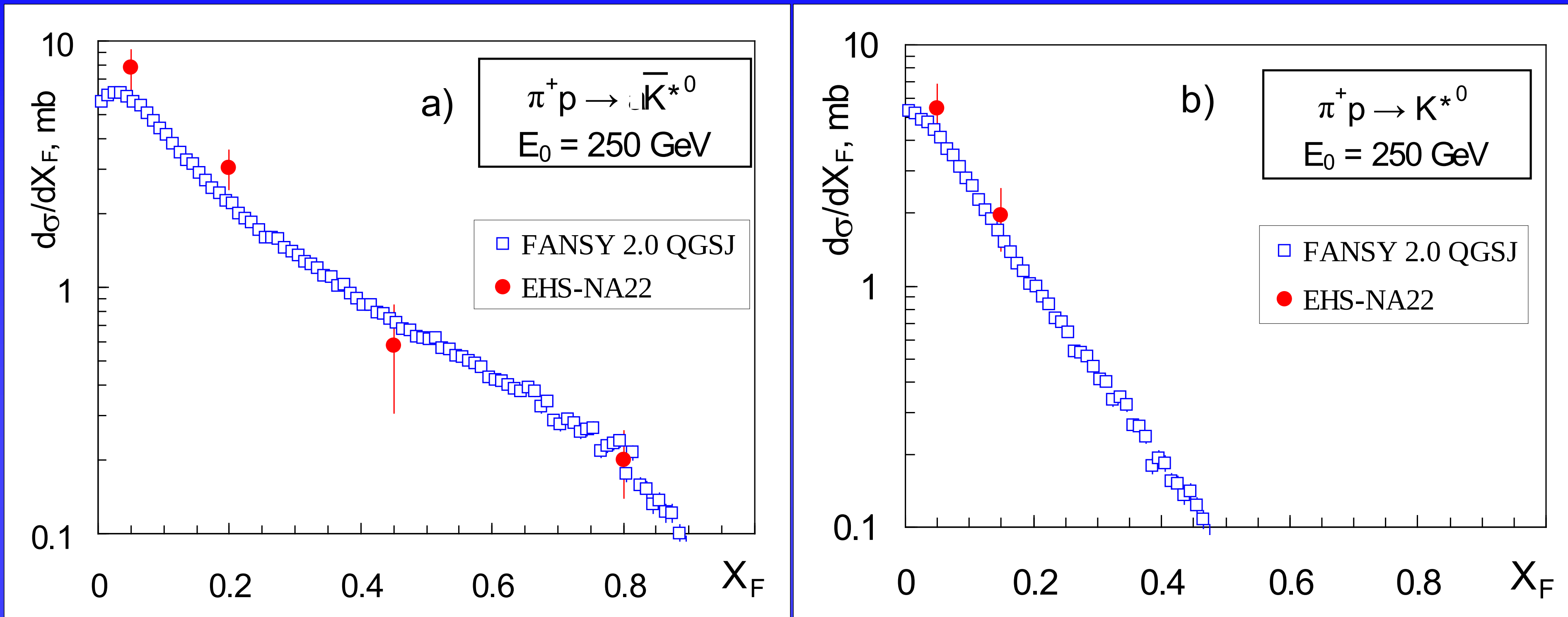


- Spectrum of ω^0 is softer than spectrum of ρ^+ (due to generation of leading ρ mesons)

Summary $d\sigma/dX_F$ spectrum of ω^0 & $\rho^{\pm,0}$ mesons



$d\sigma/dX_F$ spectra of strange vector K*(892) mesons



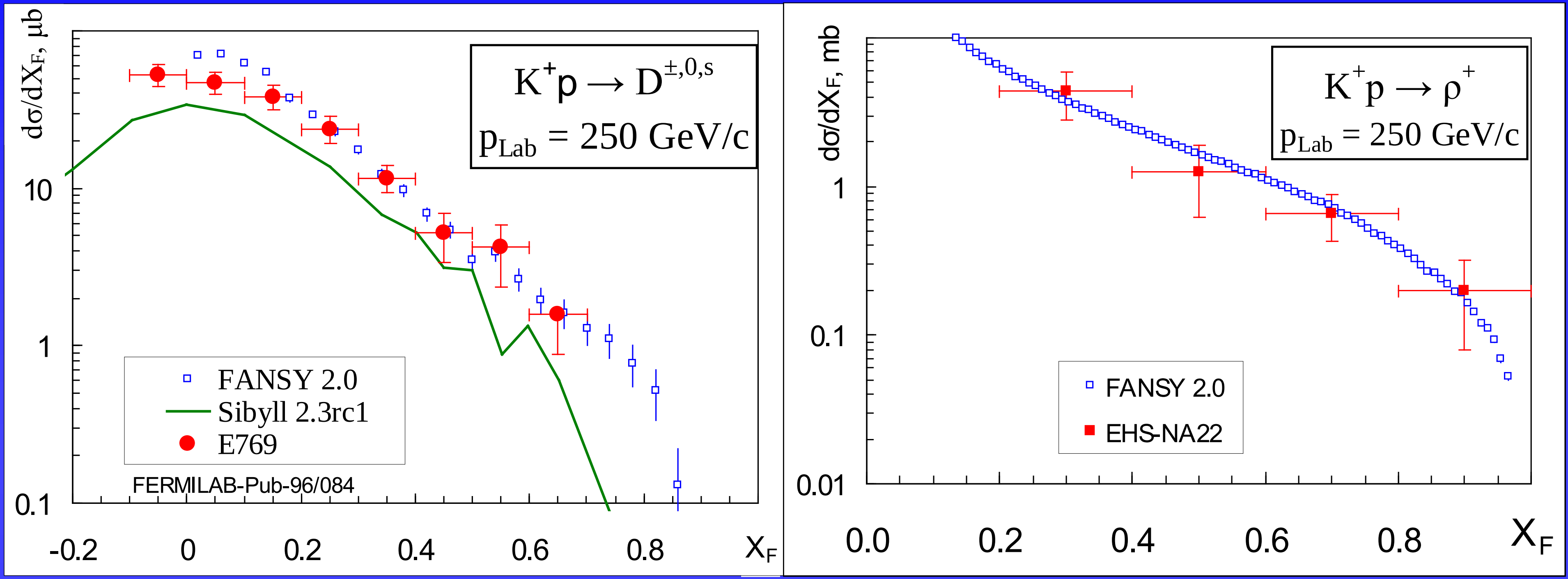
- Experimental & simulated spectra agree within error limits
- Spectrum of leading $\bar{K}^{*0}$(892) mesons is harder than K*0 (892) spectrum

- Experimental & simulated spectra of resonances and charmed mesons at low energies agree within statistical & systematic errors
- Spectra of ρ mesons are most hard
- Spectra of neutral ρ^0 meson is harder than spectra of charged $\rho^\pm$ mesons

Low energies (“forward physics”)

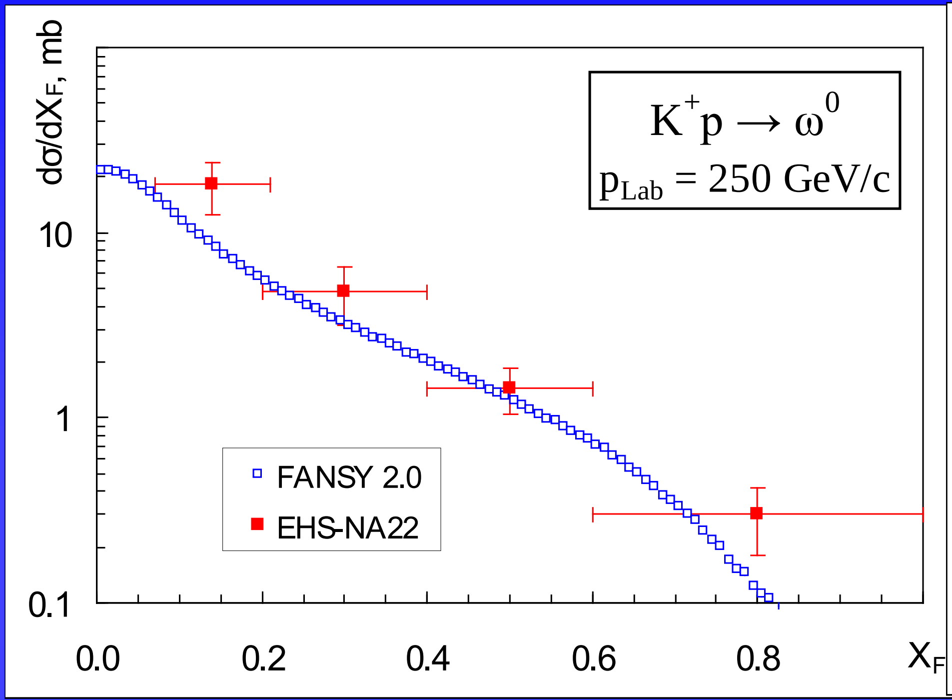
K-*p* interactions

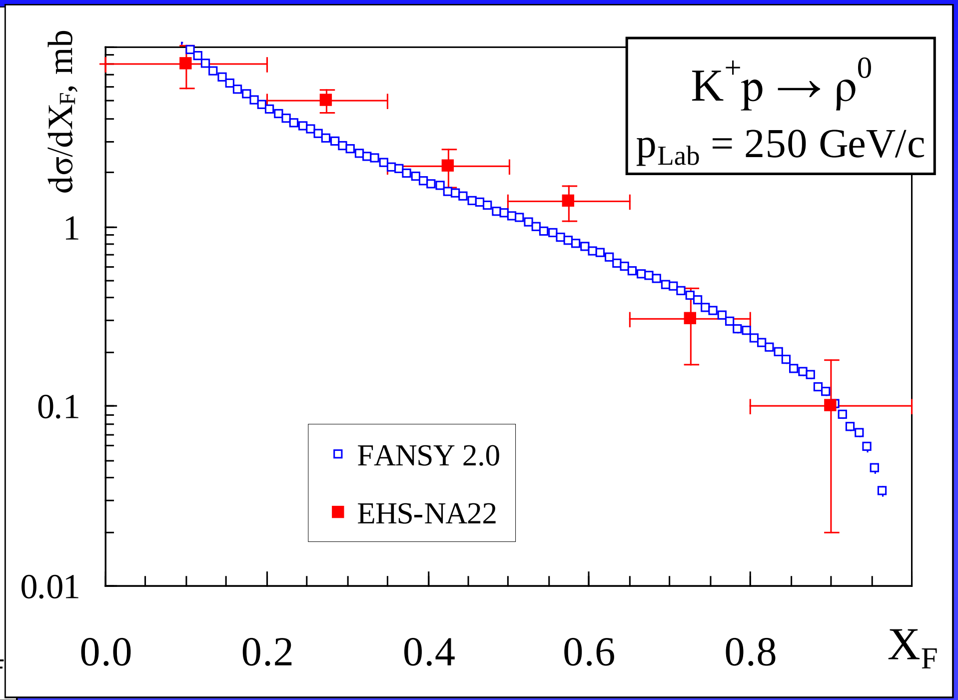
dσ/dX_F spectra of D & ρ^+ mesons



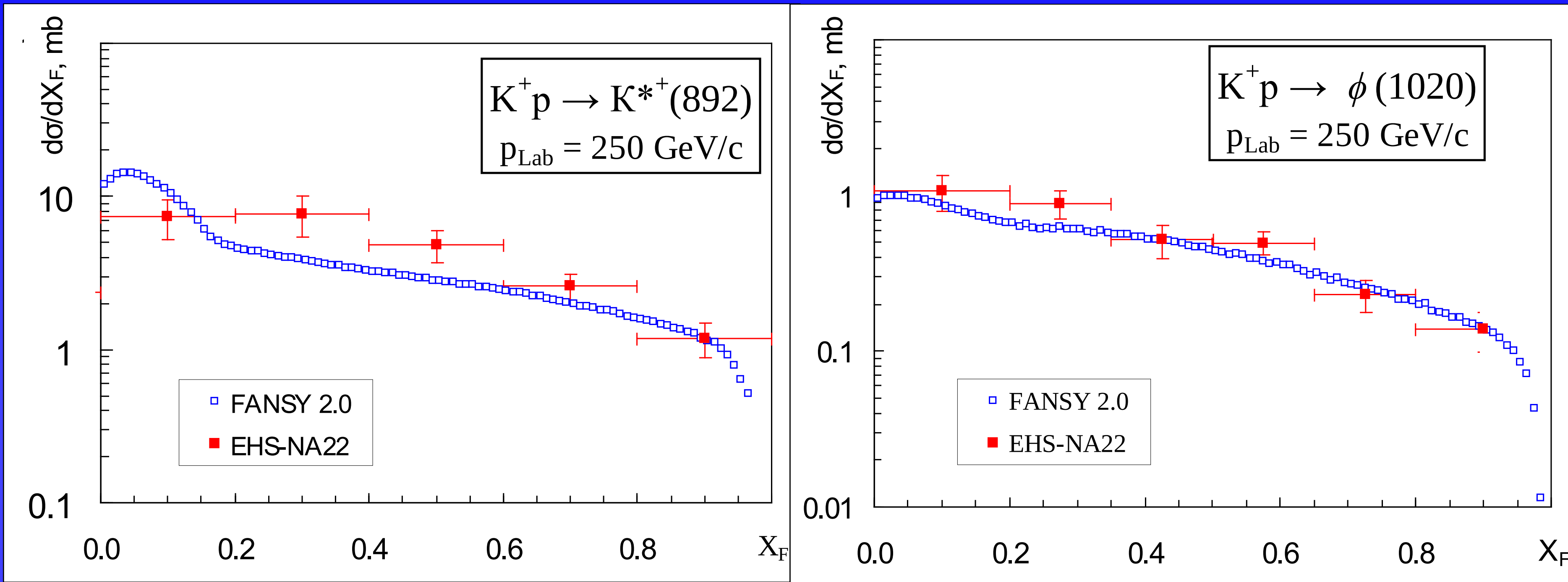
- Experimental & simulated spectra agree within error limits

$d\sigma/dX_F$ spectra of ω and ρ^0 mesons

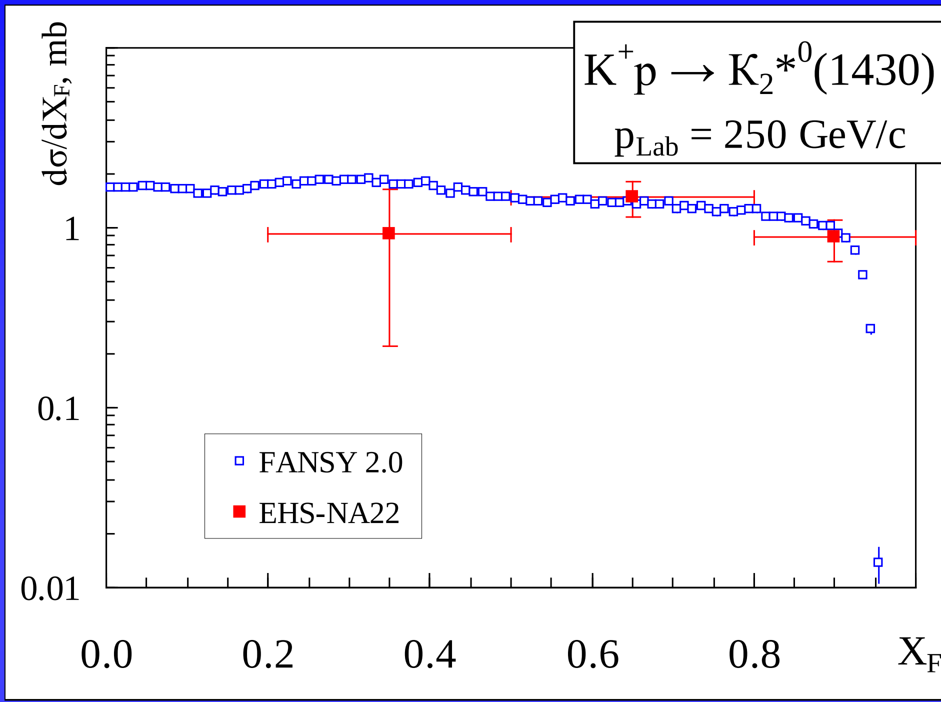


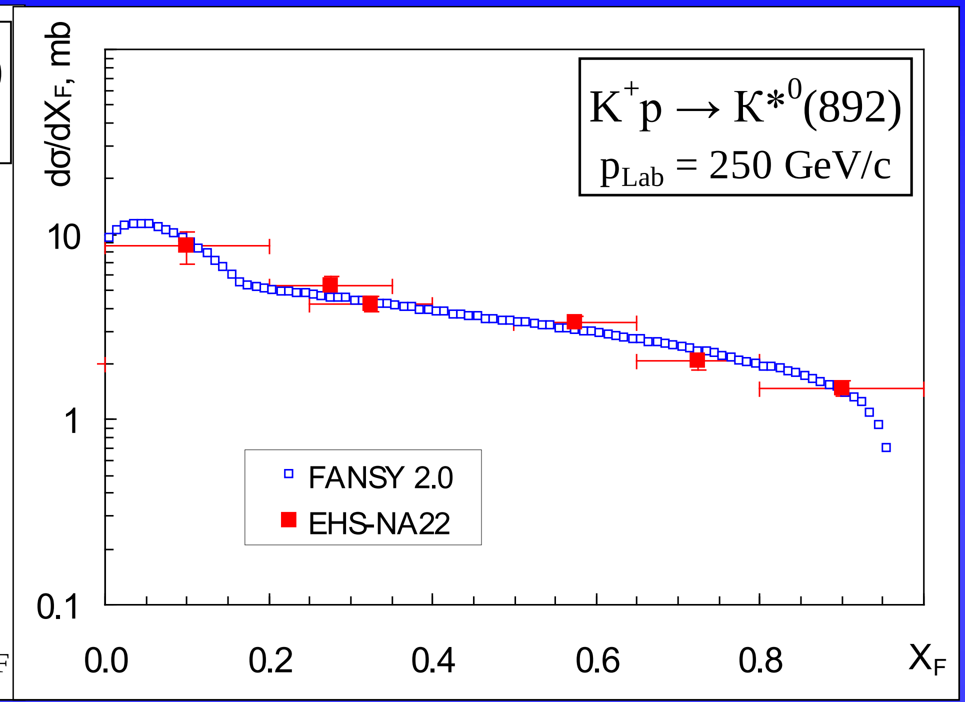


$d\sigma/dX_F$ spectra of $K^{*+}(892)$ & ϕ mesons



dσ/dX$_F$ spectra of K_2^{*0} (1430) & K^{*0} (892) mesons





- Experimental & simulated spectra agree within error limits
- Spectrum of $K_2^{*0}(1430)$ is harder than $K^{*0}(892)$ spectrum; the spectra are comparable at $X_F \rightarrow 1$

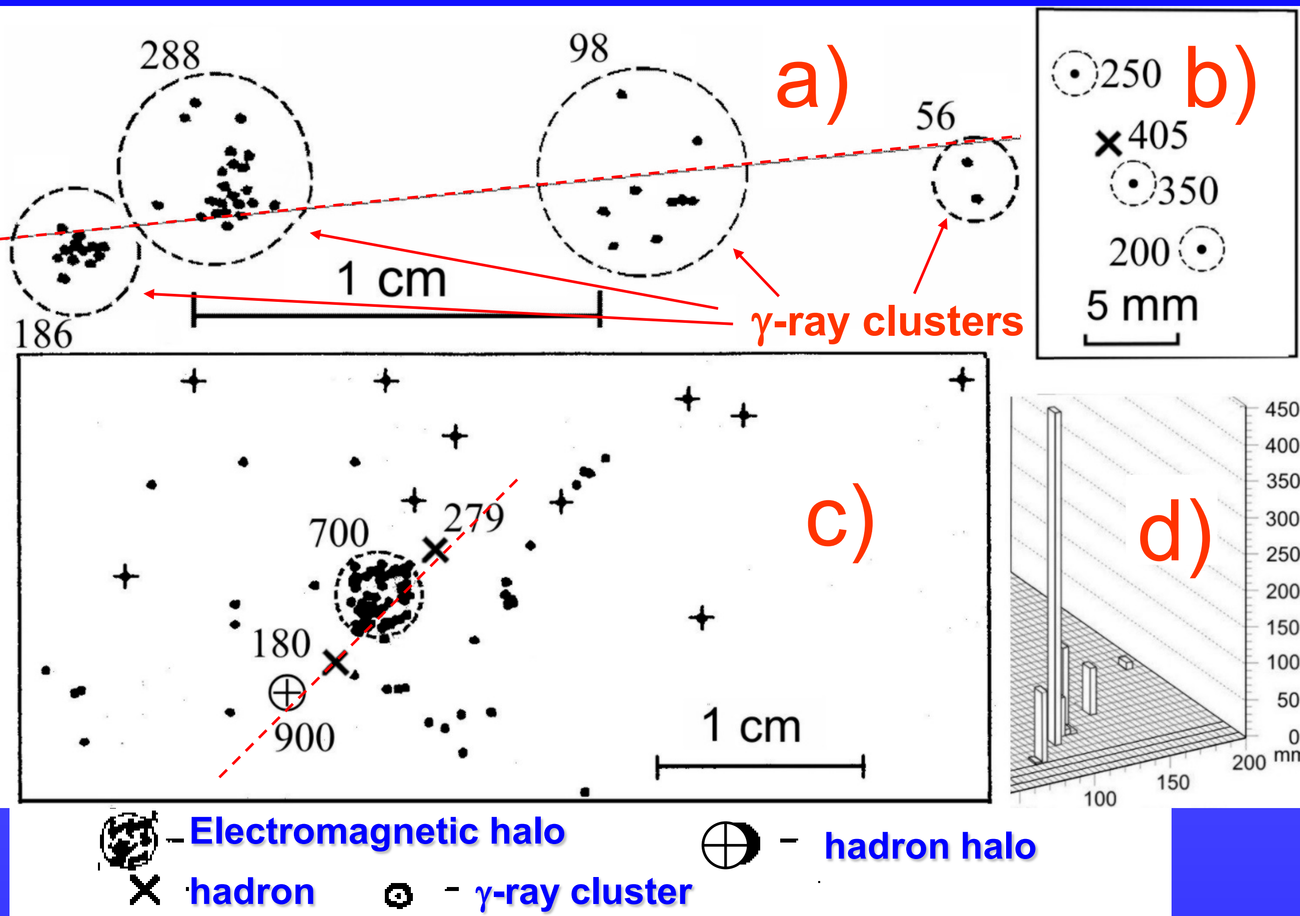
Coplanarity at superhigh energies

"Forward-physics" coplanarity at superhigh energies

Coplanarity of most energetic subcores of young air showers

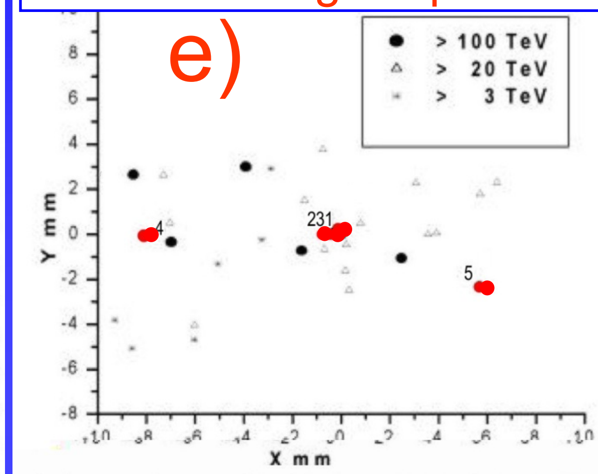
- is found in γ-*h* families ($E_{\gamma,h} > n\cdot 1$ TeV) in:
  - high-mountain *Pamir* & *Kanbala* experiments;
  - stratospheric events «*JF2af2*» & «*Strana*»
- corresponds to hadron interaction energies $E_0 \gtrsim 10^{16}$ eV

"Forward-physics" coplanarity at superhigh energies



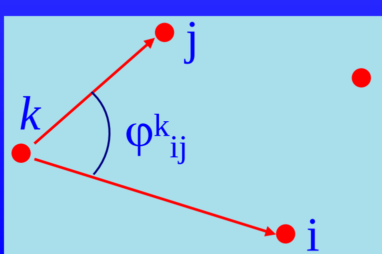
Examples of coplanar events

• 5 most energetic particles



$\langle P_t \rangle \approx$ **10 ÷ 100** GeV/c

"Pamir" : **a)** 4- γ-ray cluster family; **b)** Pb-6: λ_4=0.95; **c)** Pb-28: λ_4=0.85.
d) *JF2af2* ("*Concorde*"); **e)** "*Strana*" (balloon). Numbers show energy (TeV)



$-1/(N-1) \le \lambda_N \le 1{,}0$

Aligned event: $\lambda_N \ge \lambda_{fix}$

Usually: $\lambda_4 \ge 0{,}8$

$$\lambda_N = \frac{\sum\limits_{i \ne j \ne k}^{N} cos2\varphi^k_{ij}}{N(N-1)(N-2)}$$

"Forward-physics" coplanarity at superhigh energies

Coplanarity

- is not explained with
  - fluctuations in the framework of KGS models ($w_{fluct} \ll 10^{-10}$)
  - magnetic field of Earth & electric thunderstorm fields
  - QCD jet generation;
- has a large cross section: $\sigma^{p}_{copl} \sim a \cdot \sigma^{p}_{inel}$ ($a \approx 0.1 - 0.5$);
- is produced by hadron interactions at $E_0 \gtrsim \cdot 10^{16}$ eV
- was explained long time with growth of p_t of most energetic particles in the coplanarity plane

Theoretical status:

- The mechanism of coplanar particle generation (CPG) is unknown
- Different hypothesis are proposed

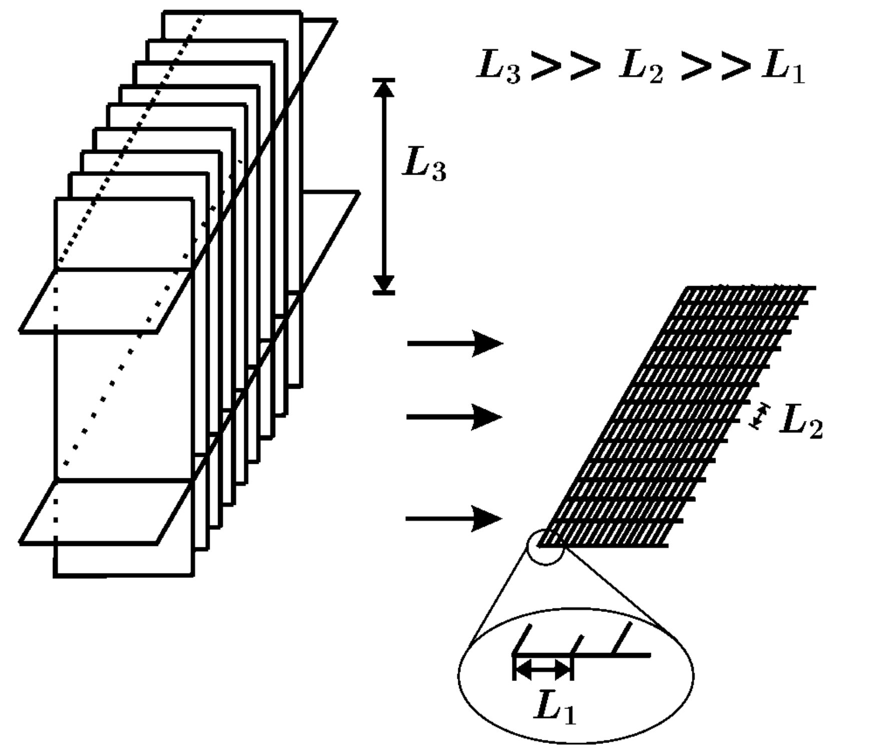
"Forward-physics" coplanarity at superhigh energies

Acceptable (phenomenologically!) ideas:

a) Wibig 2004: Conservation of QGS angular momentum transforming to a growth of particle p_t in a coplanarity plane

b) Roizen, 1994: *SHDID* – rupture of stretched quark-gluon string in Double Diffraction clusters

c) Luis A. Anchordoqui *et al.* 2010: Most exotic idea on connection of coplanarity with the recently proposed "crystal world" with latticized and anisotropic spatial dimensions. Planar events are expected to dominate in particle collisions at a hard-scattering energy exceeding the scale 3 at which space transitions from 3D ⇋ 2D



Ordered lattice. The fundamental quantization scale of space is indicated by L1. Space structure is 1D on scales much shorter than L2, while it appears effectively 2D on scales much larger than L2 but much shorter than L3. At scales much larger than L3, the structure appears effectively 3D.

In this work
coplanar generation of most energetic particles through the rupture of the quark-gluon string stretched between the interacting hadrons
is analyzed

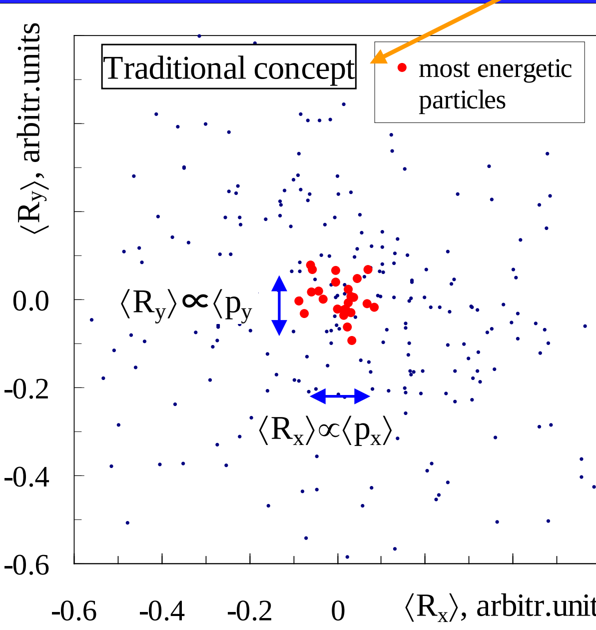
Simulation of coplanar particle generation

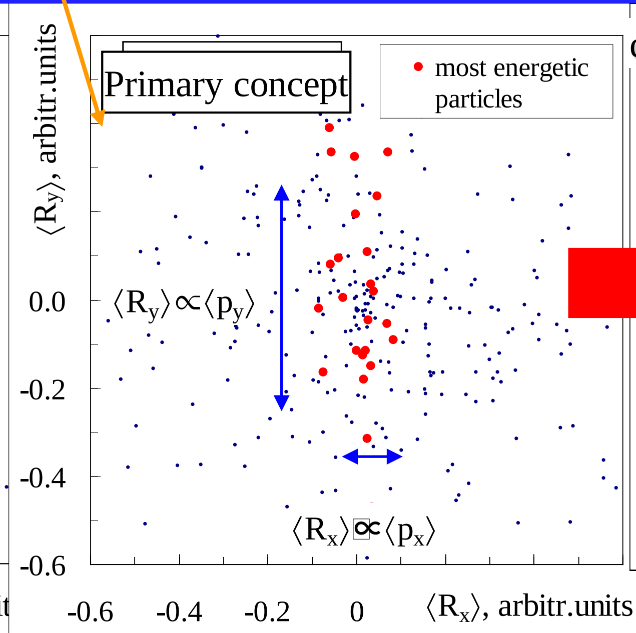
"Forward-physics" coplanarity at superhigh energies

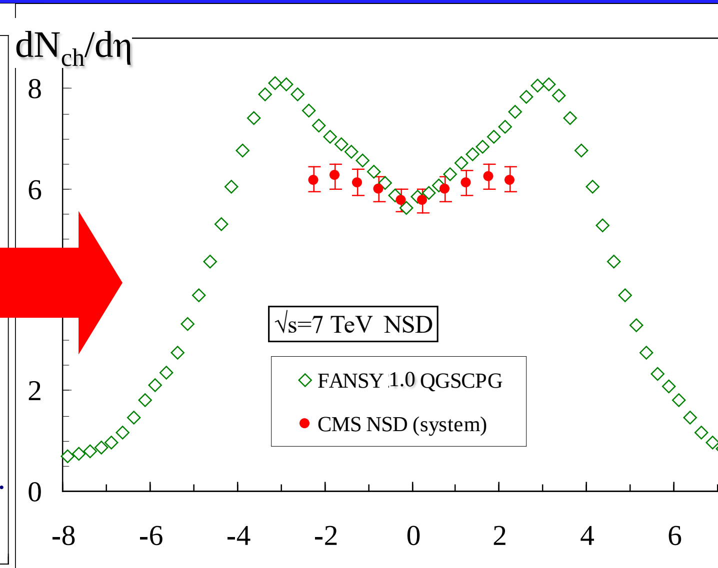
View of particle tracks on the target plane

Target plane (view from interaction point)

⟨R⟩ = average distance of tracks from the centre







Traditional concept:
axial symmetry
$\langle R\rangle_{trad} \sim \langle p_x\rangle = \langle p_y\rangle$

Primary concept :
axial asymmetry
$\langle R\rangle_{copl\ prim} > \langle R\rangle_{trad}$
$\langle p_x\rangle < \langle p_y\rangle$

Growth of p_t due to coplanar particle generation suppresses hadron $d\sigma/dy$ & $d\sigma/d\eta$ distributions at $|\eta,y| >> 1$ and creates peaks at $2 \lesssim |\eta| \lesssim 5$

On the one hand, LHC data contradict the primary-concept simulation results
On the other hand, coplanarity in cosmic rays is observed!

Is it possible to resolve this contradiction ?

“Forward-physics” coplanarity at superhigh energies

Phenomenological FANSY 2.0

FANSY = FAN-like Secondary particle Yield

- FANSY QGSJ = traditional version
- FANSY *QGSCPG* = QGSJ + CPG

FANSY QGSCPG:

Two competing channels:

1) traditional qurk-gluon string (QGS) model (i.e. FANSY QGSJ);

2) coplanar QGS particle generation (CPG) (appears at $\sqrt{s} \gtrsim 2$ TeV; probability rises with increasing energy) in soft interactions

Models FANSY QGSJ и QGSCPG are

- different in azimuthal characteristics
- identical in longitudinal characteristics (y, η, x_F, x_{Lab})

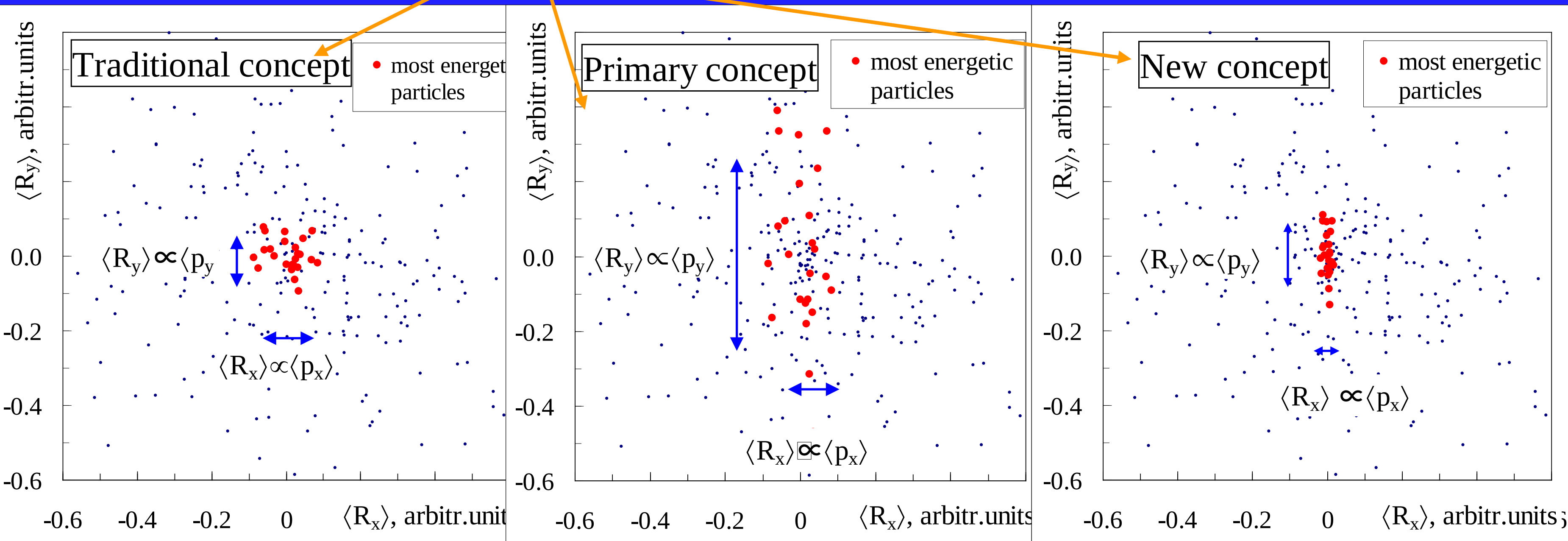
Do model predictions contradict to experimental data?

"Forward-physics" coplanarity at superhigh energies

View of particle tracks on the target plane

Target plane (view from interaction point)

⟨R⟩ = average distance of tracks from the centre



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Primary concept :
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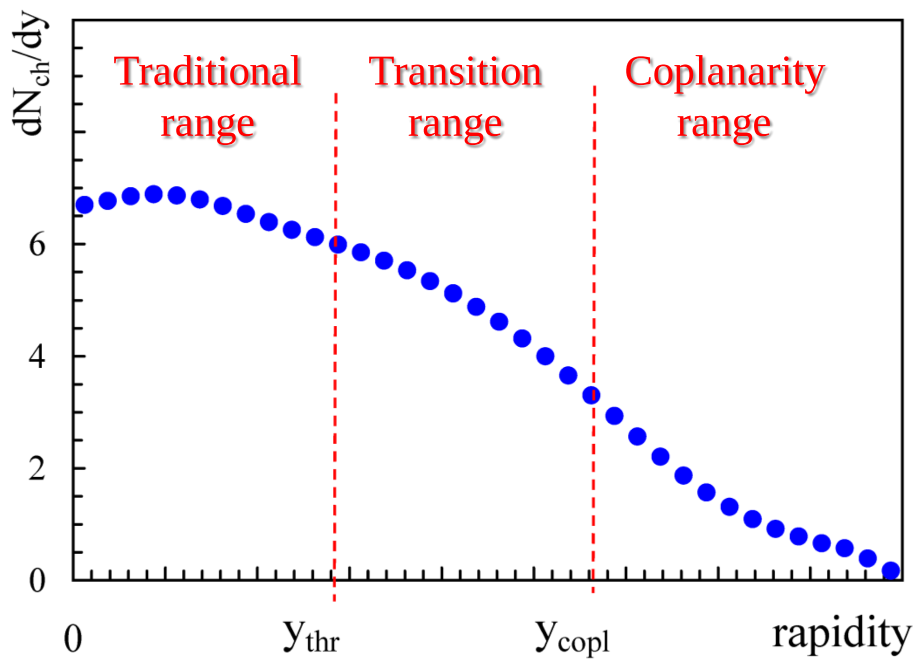
$\langle R\rangle_{copl\ prim} > \langle R\rangle_{trad}$
$\langle p_x\rangle < \langle p_y\rangle$

New concept :
axial asymmetry
$\langle R\rangle_{copl\ new} \approx \langle R\rangle_{trad}$
$\langle p_y\rangle_{copl\ new} \sim \sqrt{2}\ \langle p_y\rangle_{trad}$
$\langle p_x\rangle_{copl\ new} << \langle p_x\rangle_{trad}$

You need to get away from the concept which links coplanarity with increasing p_t !

"Forward-physics" coplanarity at superhigh energies

CPG realization



- Traditional partical generation: $|y| < y_{thr} \approx 2 - 3$
- Transition range: $y_{thr} < |y| < y_{copl}$
- Coplanar particle generation: $|y| > y_{copl} \approx 5 - 6$

- Coplanarity plane is determined by moments of colliding protons and transverse momenta of leading hadrons after interaction
- In the CPG range the algorithm turns transverse moments of particles to the plane (in the direction of the initial minimum angle to the plane)
- In the transition region a tendency to coplanarity decreases with decreasing $|y|$ and disappears at $|y| < y_{thr}$
- Direction of transverse momenta $\vec{p}_t$ near the plane is described with Gaussian distribution at $\sigma \approx 0.1$ rad

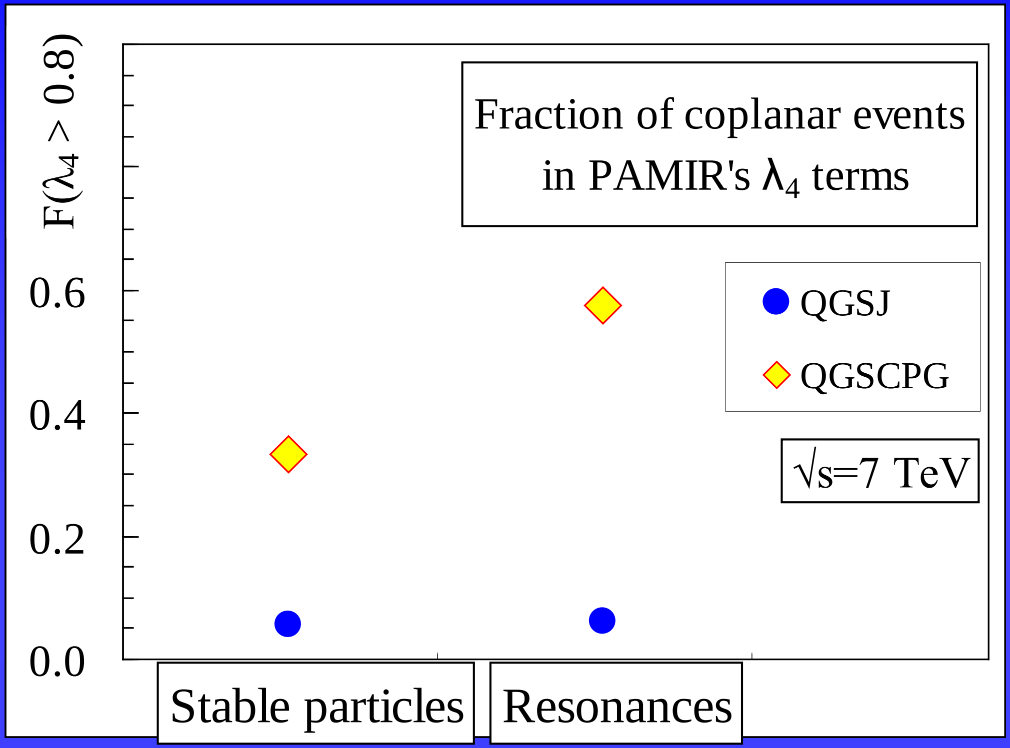
Coplanarity and LHC data

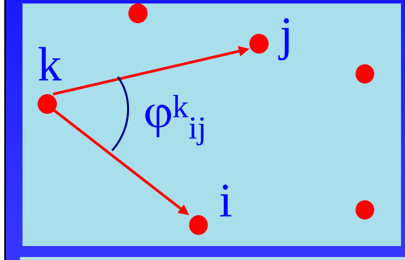
FANSY 2.0 QGSCPG & LHC data

- ALL results of
  traditional QGSJ and
  coplanar QGSCPG
  on rapidity, pseudorapidity, X_F are identical
- Azimuthal properties of most energetic
  secondary particles are different

"Forward-physics" coplanarity at superhigh energies

FANSY 2.0 QGSCPG coplanar-event fraction (in PAMIR's λ_4 terms)





$-1/(N-1) \leq \lambda_N \leq 1{,}0$

Aligned event: $\lambda_N \geq \lambda_{fix}$

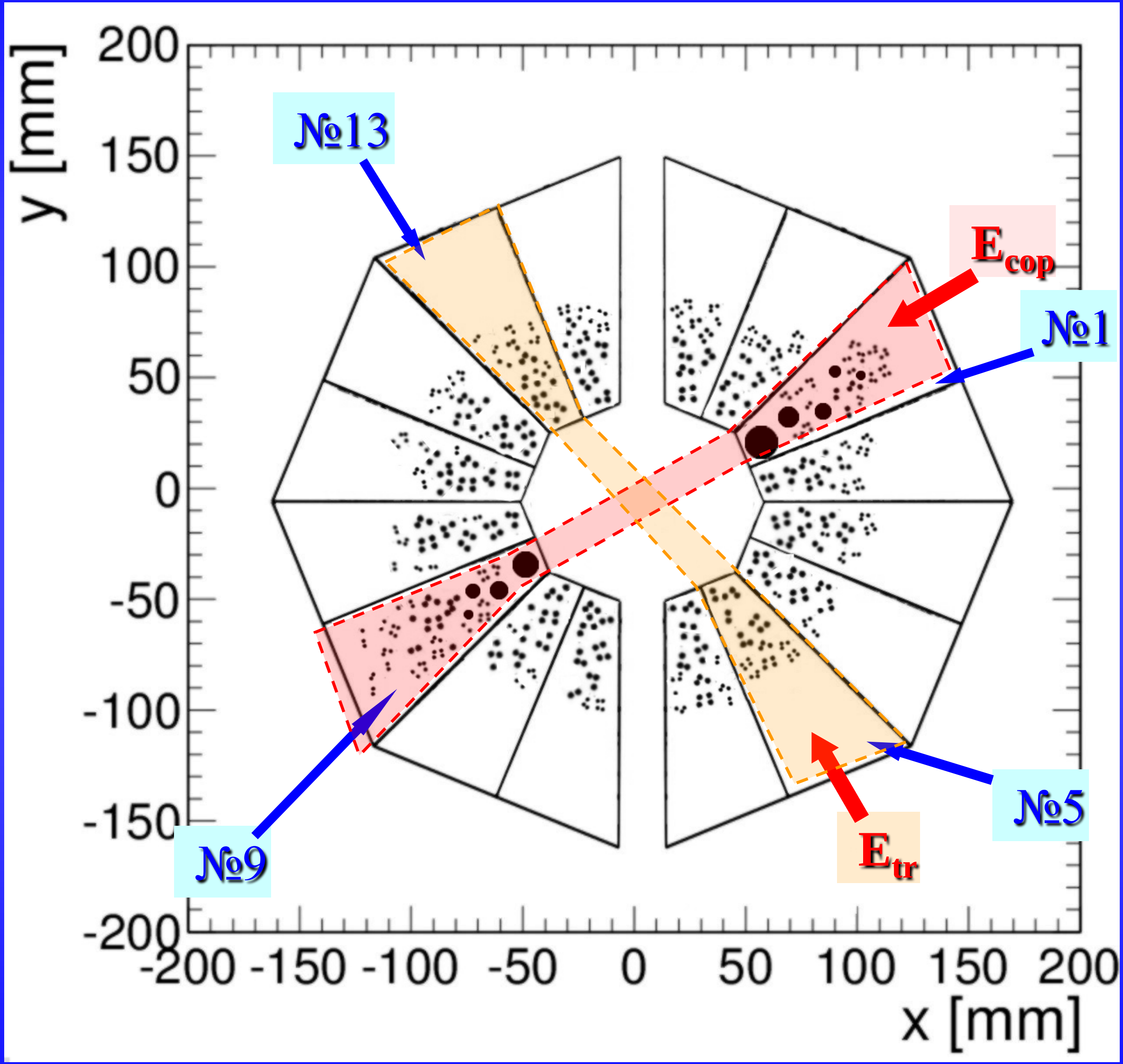
Usually: $\lambda_4 \geq 0{,}8$

$$\lambda_N = \frac{\sum_{i \neq j \neq k}^{N} \cos 2\varphi_{ij}^{k}}{N(N-1)(N-2)}$$

- FANSY QGSCPG: high fraction of "aligned" events
- alignment of resonances is higher, but their decay extends the effect on range of lower η ("ridge" effect ?)

Can we study coplanarity at LHC ?

Coplanarity of energy flows in CASTOR’s 16 segments



$5.3 < \eta < 6.5$

E_{max} = maximum energy flow in i-th segment ($i \to$ no. 1)

E_{cop} = energy in segments 1+9

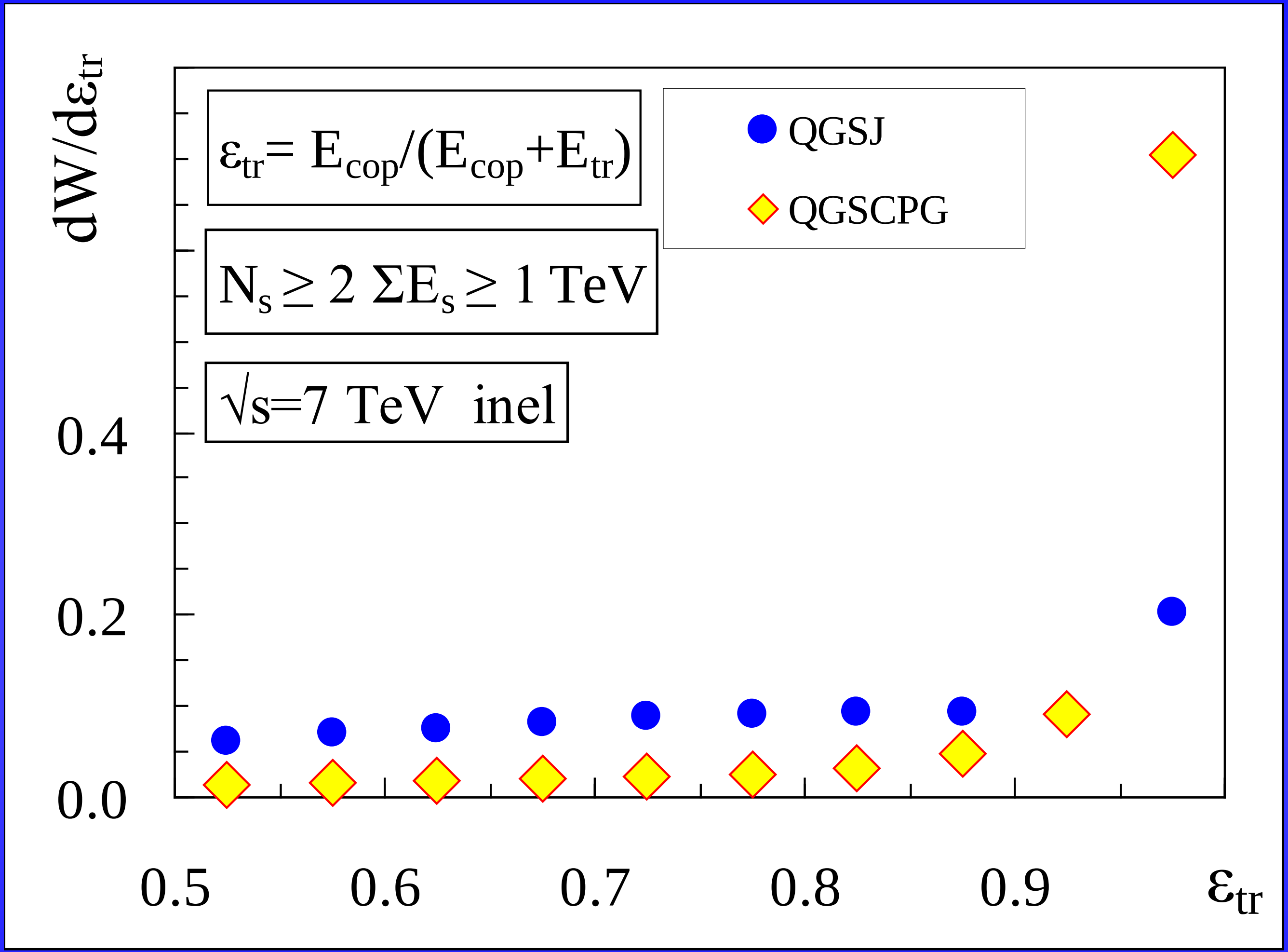
E_{tr} = energy in segments 5+13 (transversal to 1+9)

$\varepsilon_{tr} = E_{cop} / (E_{cop} + E_{tr})$

The larger is circle size, the larger is energy of particle

"Forward-physics" coplanarity at superhigh energies

Energy flows in CASTOR segments



$\varepsilon_{tr} = E_{cop}/(E_{cop}+E_{tr})$

$E_{cop} = E_1 + E_9$

$E_{tr} = E_5 + E_{13}$

- Different CPG versions could be tested by CASTOR
- promising parameter ε_{tr}
- low luminosity and event-by-event measurements are required

Conclusion

- Model *FANSY 2.0* for hadron-hadron interactions is developed:
  - traditional *QGSJ* version
  - *QGSCPG* version with coplanar particle generation:
- All versions are identical at $\sqrt{s} \lesssim 2$ TeV
- All versions reproduce LHC's
  - general central kinematic range data at $|y|$ & $|\eta| \lesssim 7$: $d\sigma/d\eta$, $d\sigma/dy$, $d\sigma/dp_t$ spectra of charged particles, kaons, charmed stable particles and a number of resonances
  - LHCf data for γ–rays and neutrons
- $d\sigma/dx_F$ spectra of stable π, K, D mesons and a number of resonances in *pp*, *πp*, K*p* interactions are reproduced at low energies ($\sqrt{s}$ ~ 17 – 63 GeV)

Conclusion

QGSCPG:

- The concept of coplanarity with *large p_t* of most energetic KGS particles in the plane of coplanarity is contrary to the LHC data
- Agreement between LHC data and complanarity is possible in the concept of *decreasing* of transverse moments perpendicular to the coplanarity plane
- Coplanar particle generation (FANSY 2.0 QGSCPG) can be tested at LHC (CASTOR)

Thank you!