New Developments of EPOS 2

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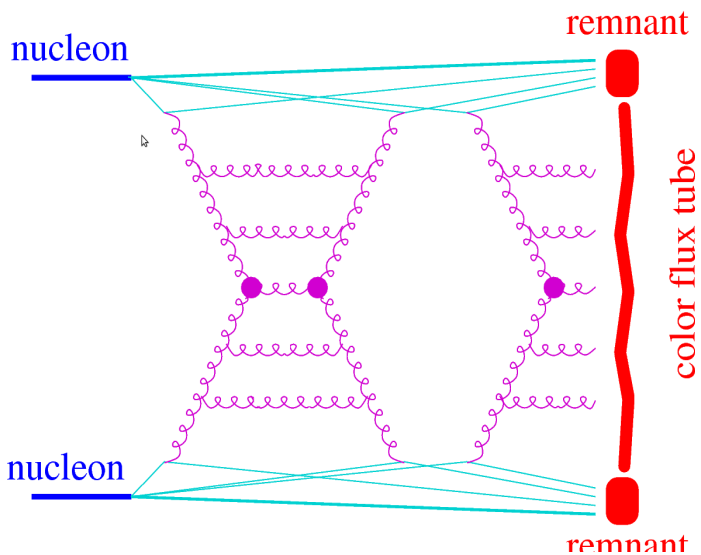
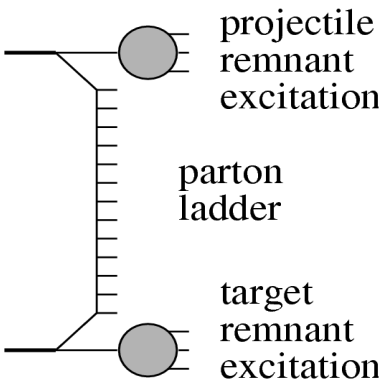
Outline

- **The EPOS model**
  - Baryons and remnants
- **New developments**
  - 3D Hydrodynamical calculation
  - New Parton Distribution Function (PDF)
  - LHC data
- **Preliminary results**
  - LHC
  - Consequences on air shower development

The EPOS Model





EPOS* is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

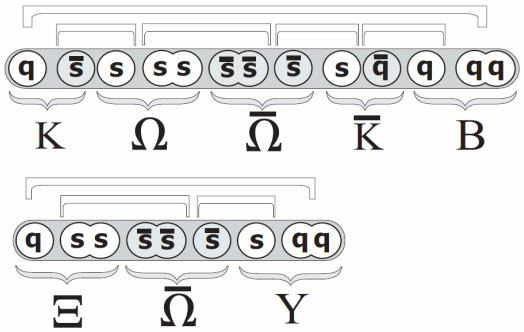
EPOS first designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

*T.Pierog, S. Porteboeuf and K. Werner

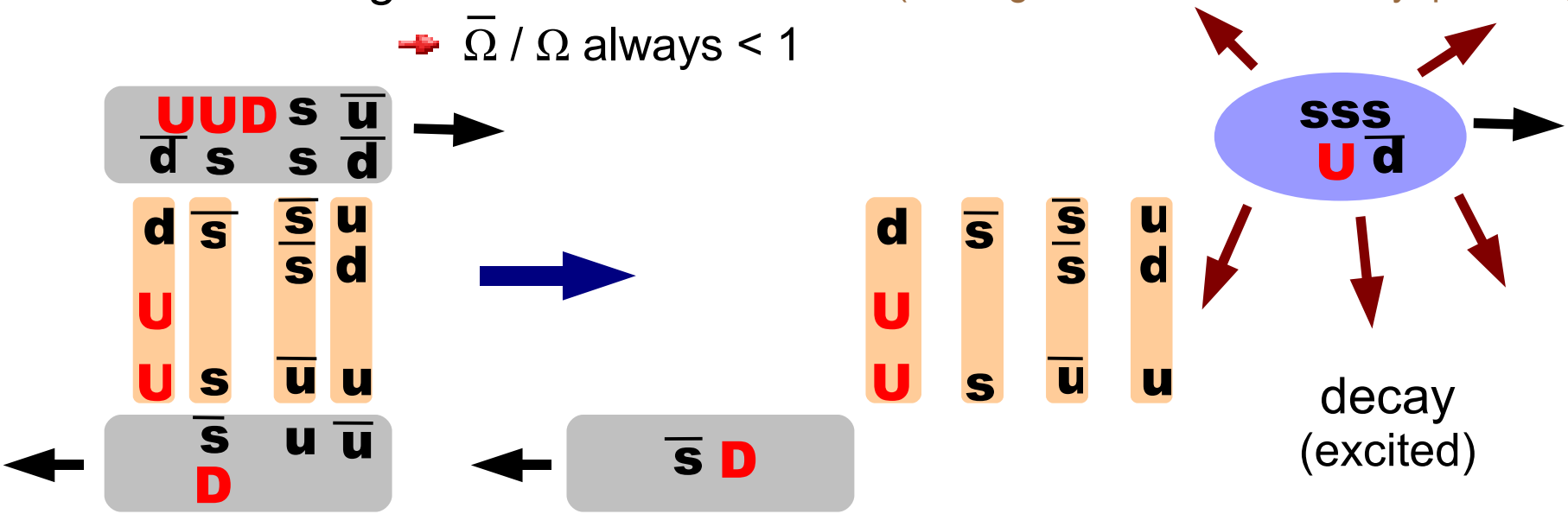
Baryons and Remnants

Parton ladder string ends :

- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega}$ / Ω always < 1



New Developments (1)

EPOS approach : use theory to fix the framework and adapt the details to be as close as possible to all possible data.

- **Collective effects (hydro) needed for heavy ions**
  - Important even for pp and pA
    - explain <pt> vs mult. (flow), strangeness, baryon pt shape, etc …
    - replace former effective treatment needed to describe these data (medium dependent string parameters)
  - In EPOS 2 : detailed 3D hydro calculation
    - For CR same simplified calculation of collective effects as in EPOS 1.x but with flow extrapolation based on calculation instead of low energy data (large uncertainty).

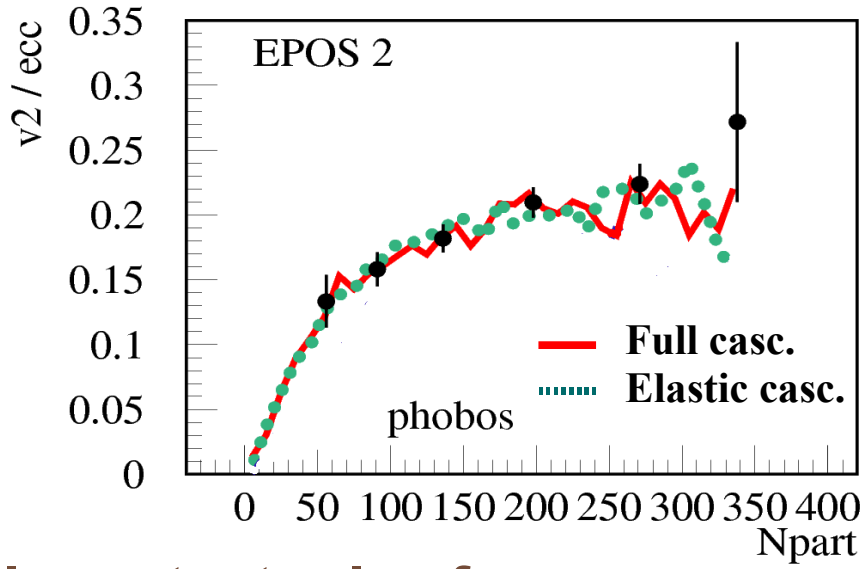
Hydro in EPOS 2

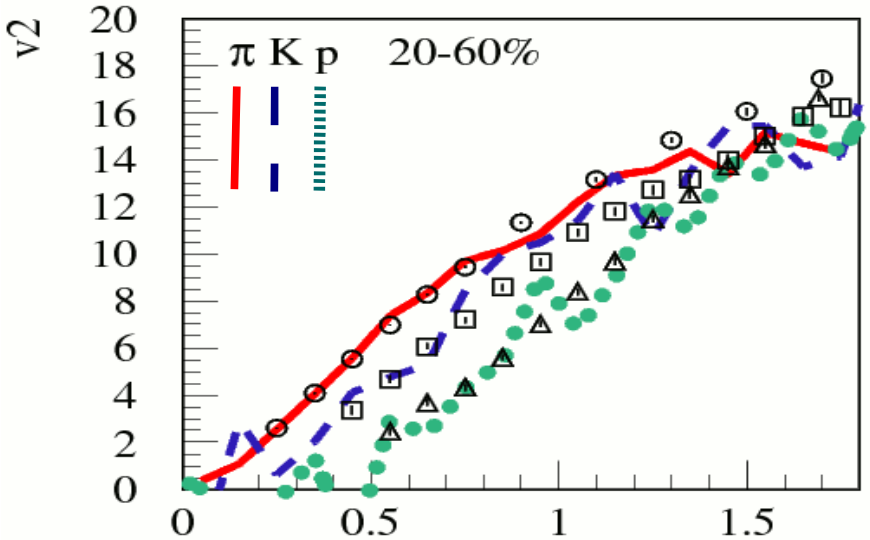
- **Features**
  - Flux-tube initial condition
  - Event-by-event treatment
  - 3D core-corona procedure
  - Tree flavor cross-over EoS (X3F)

    $$p = p_Q + \lambda(p_H - p_Q),\ \lambda = \exp(-\frac{T-Tc}{\delta})\theta(T - T_c) + \theta(T_c - T)$$
  - 3 + 1D hydro
  - Complete hadron set (latest PDG)
  - Hadronic cascade (HC), here UrQMD
- **Checks :** Centrality dependence of
  - Yields and pt spectra of identified particles
  - v2 and pt dependence of v2 of identified particles
  - Particle correlations (eta-phi, HBT (in progress), ...)

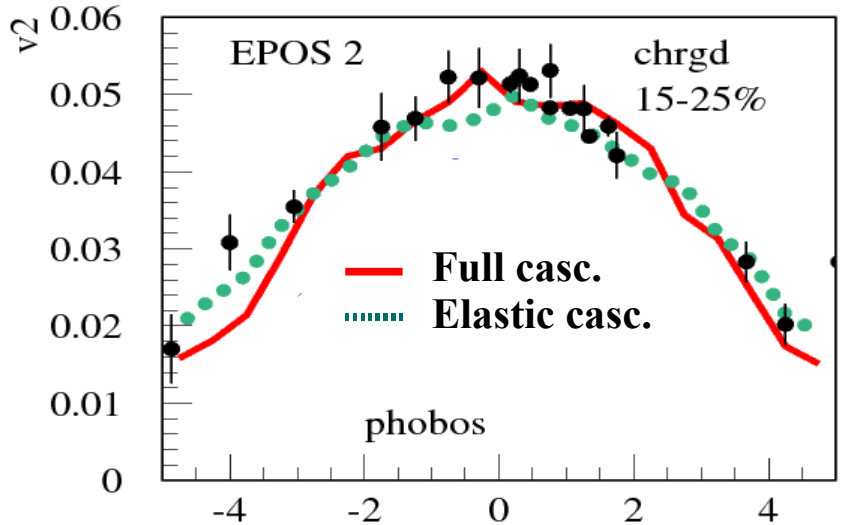
Check with Heavy Ions : AuAu@RHIC

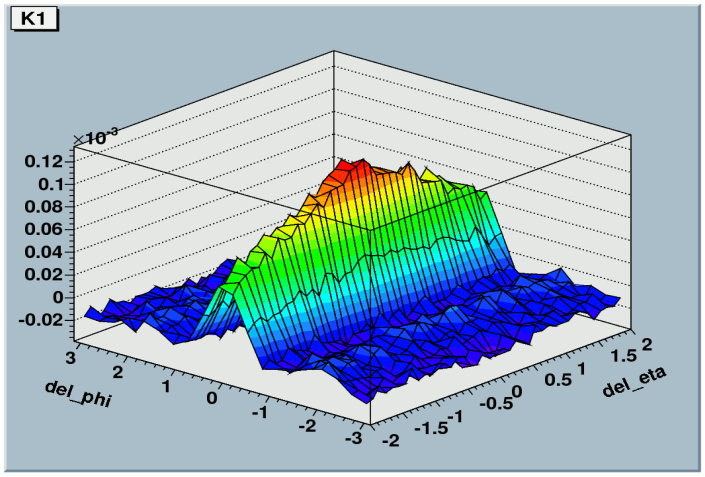
- Early freeze-out (166MeV) + hadr. cascade





Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)

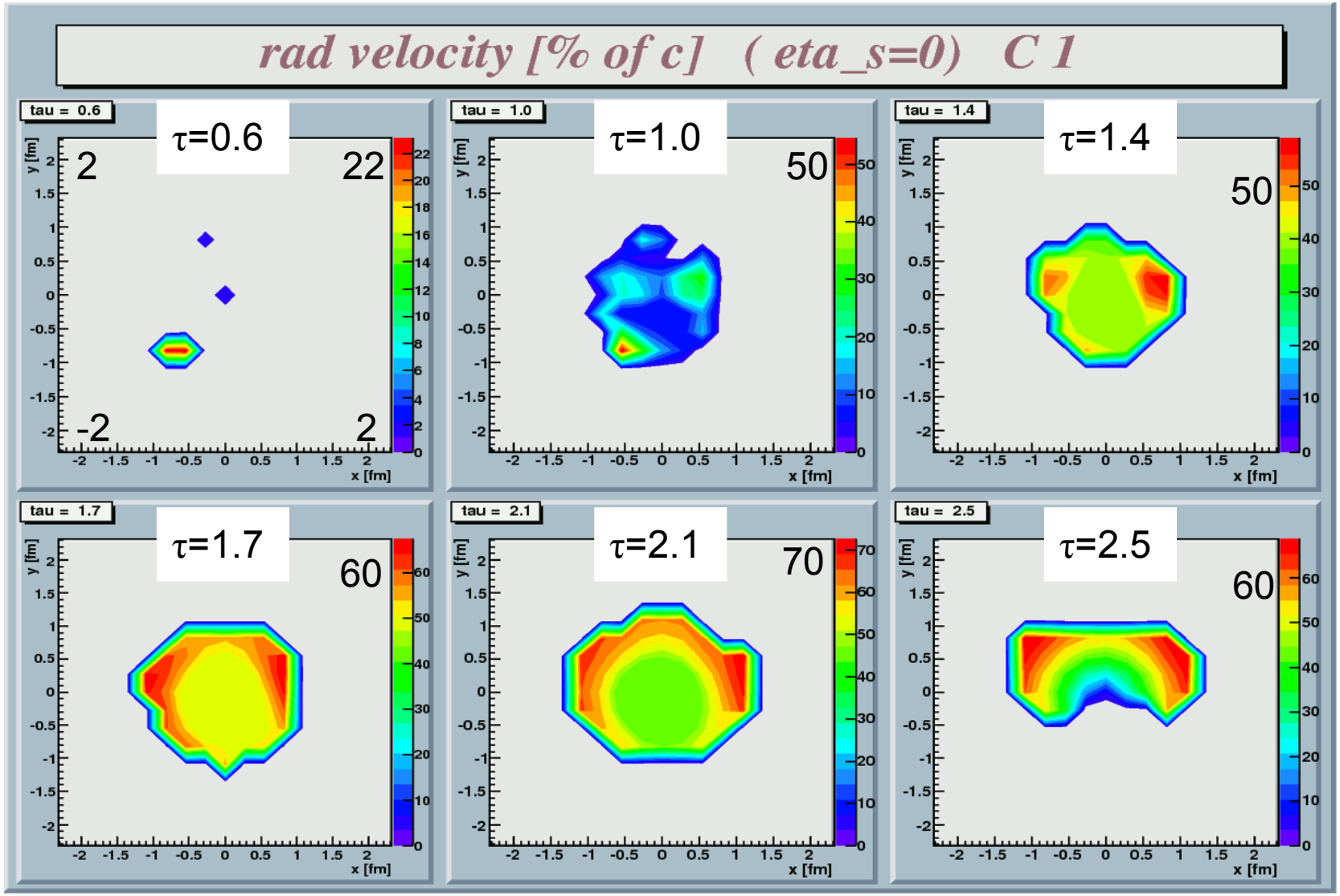




AuAu 0-10%, $3 < p_t^{trig} < 4$ GeV/c $2 < p_t^{assoc} < p_t^{trig}$

First Real Hydro in ap-p@1.8 TeV : Radial Velocity

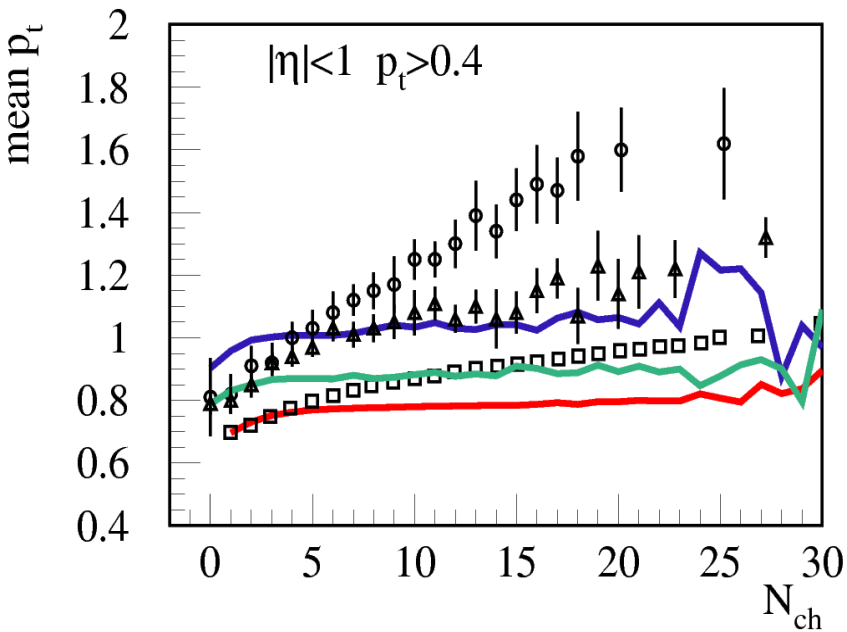
- Apply same parameters as for AuAu@RHIC
  (except flux tube radius = free parameter)



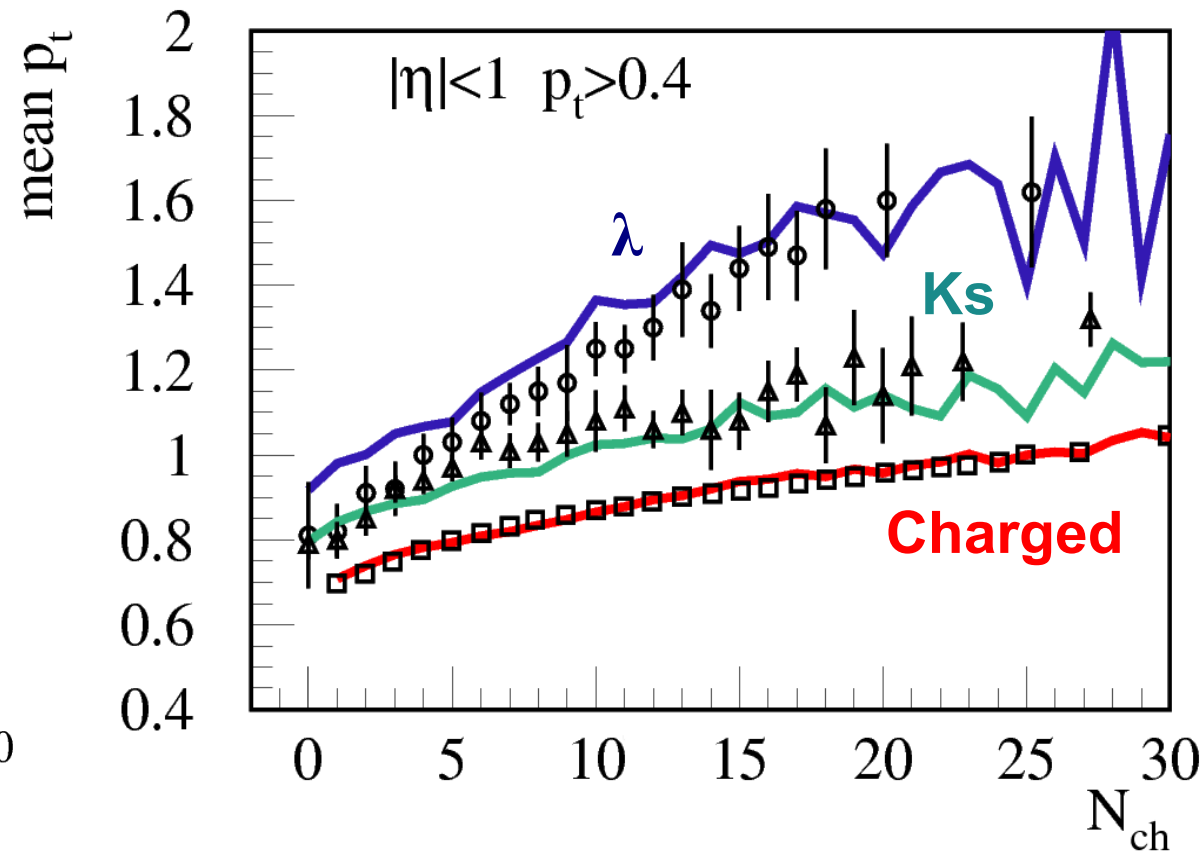
$<p_t>$ vs multiplicity ap-p@1.8 TeV : EPOS 2

- **Using small flux tube size**
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

No collective effects



hydro+hadronic cascade



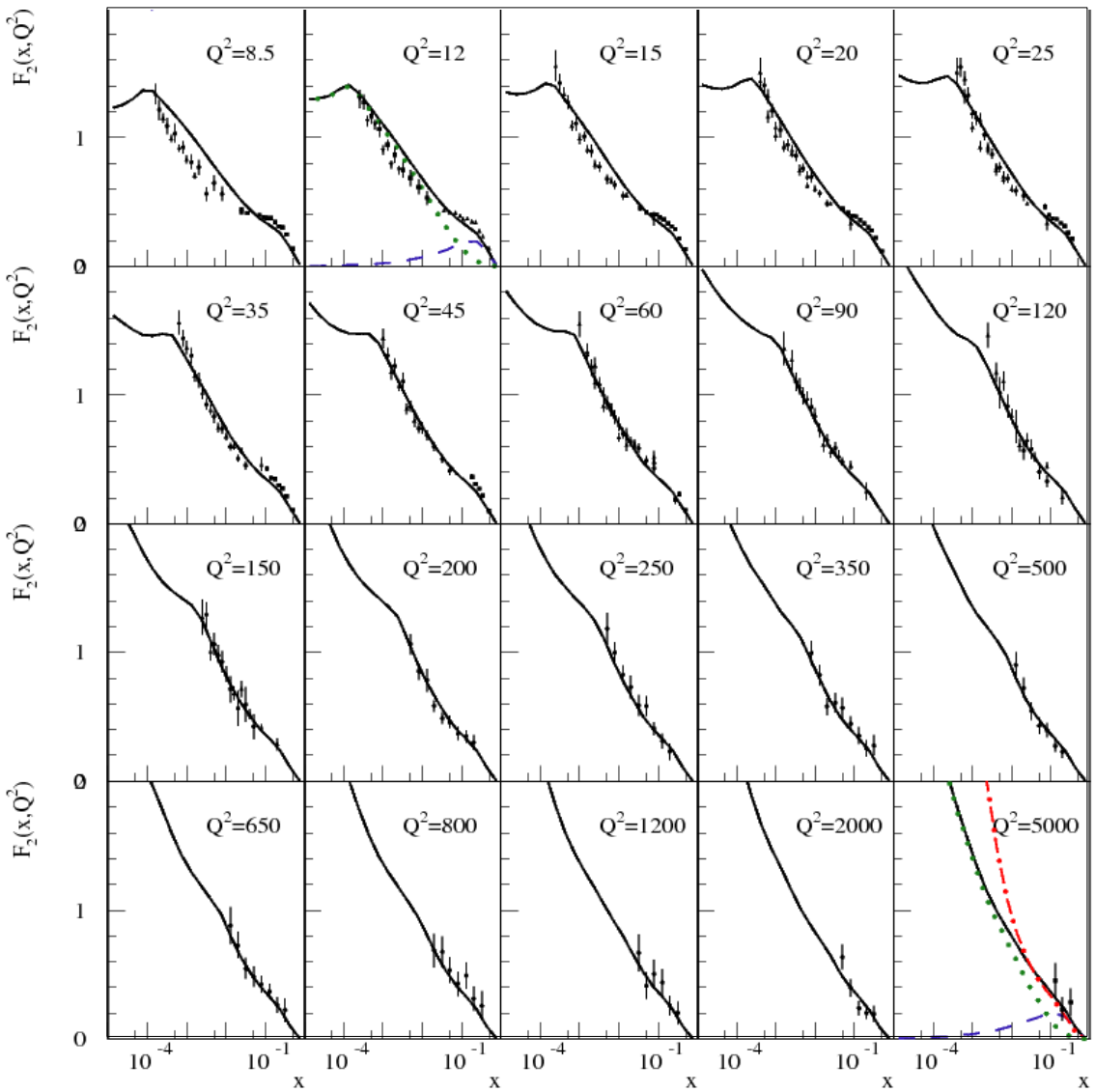
New Developments (2)

EPOS approach : use theory to fix the framework and adapt the details to be as close as possible to all possible data.

- **New fragmentation function based on initial parton type in jets (gluon or quark)**
  - Natural change of baryon and strangeness production with energy
- **Needs for LHC**
  - Proper PDF needed for hard scattering (Jet, etc …)
  - In EPOS 2 :
    - F_2 data from HERA used in global fit (same parameters for cross-section, PDF and multiplicity …)
    - Hard diffraction
    - New parameters taken into account LHC data
      - Preliminary results

Parton Distribution Function

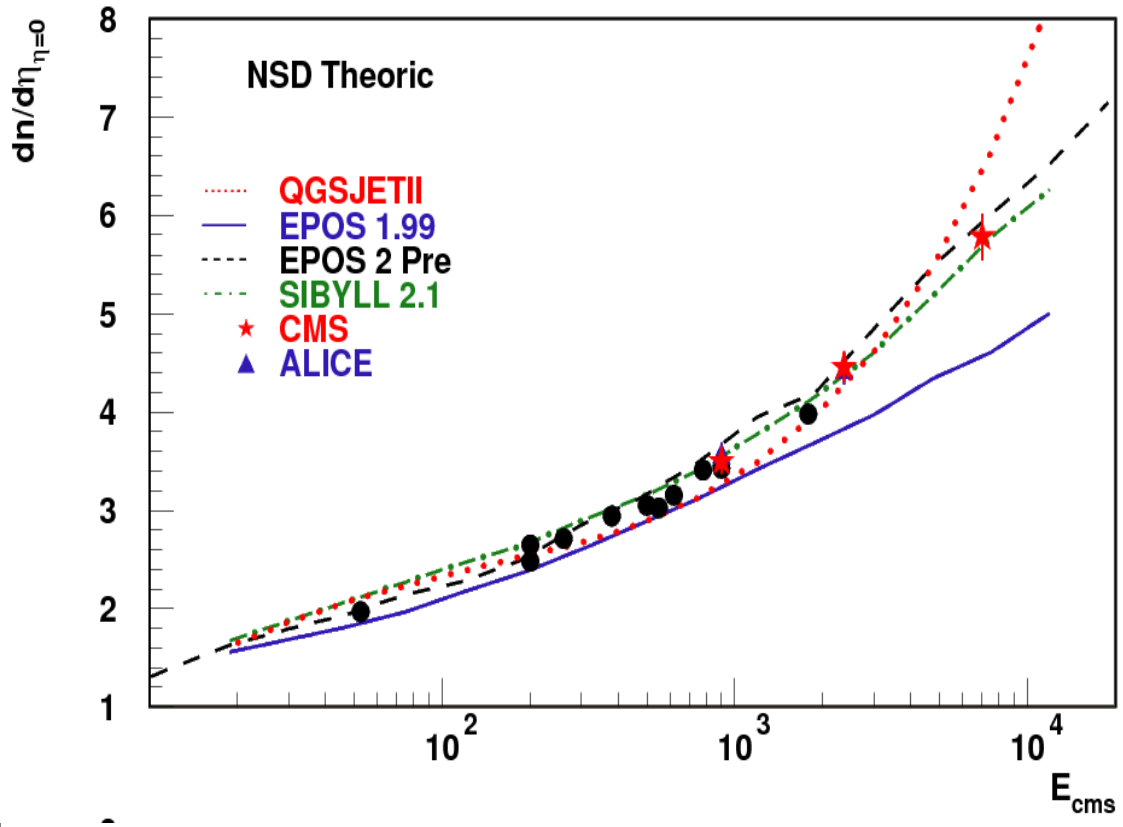
- PDF based and DGLAP and initial soft parametrization

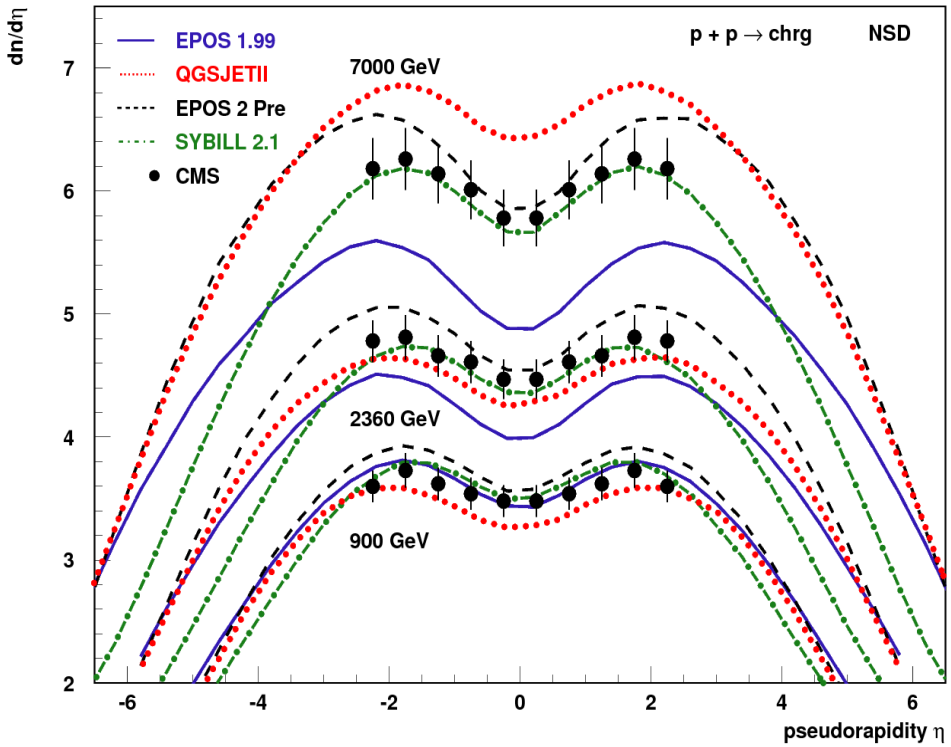


Preliminary

LHC data (1)

- Higher average multiplicity due to reduced screening





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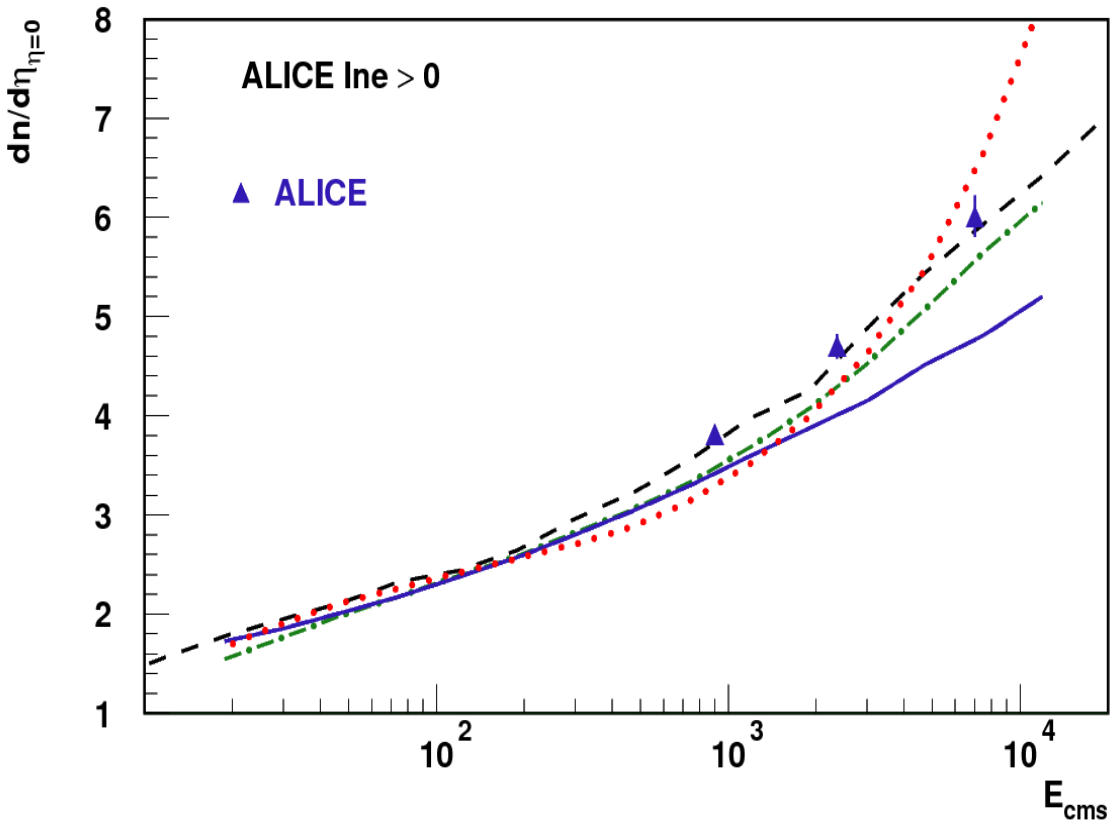
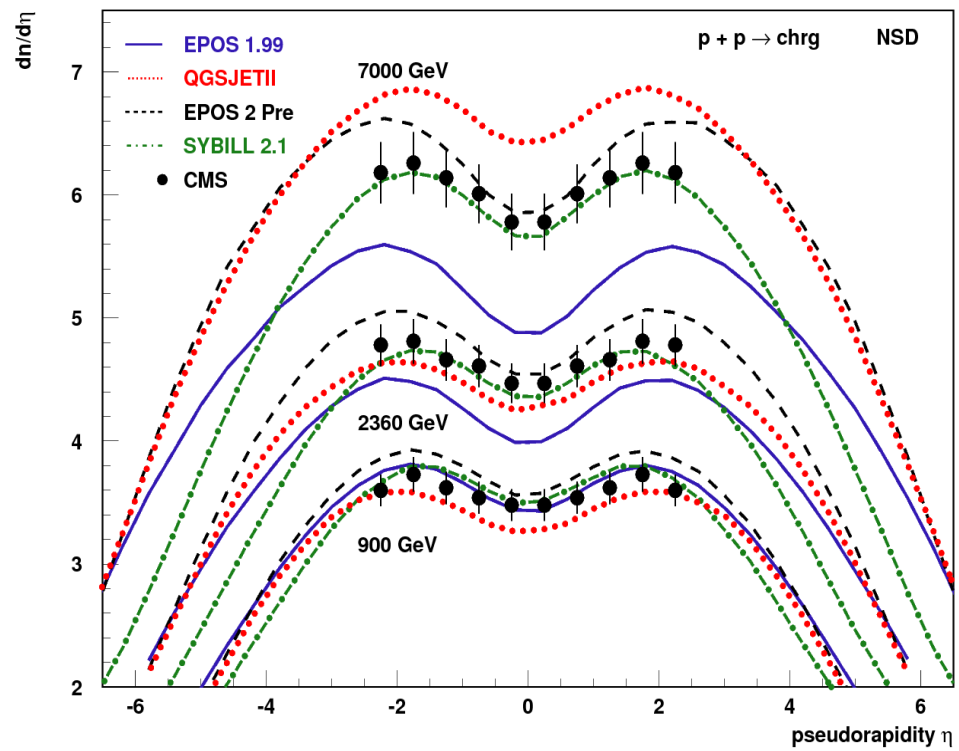
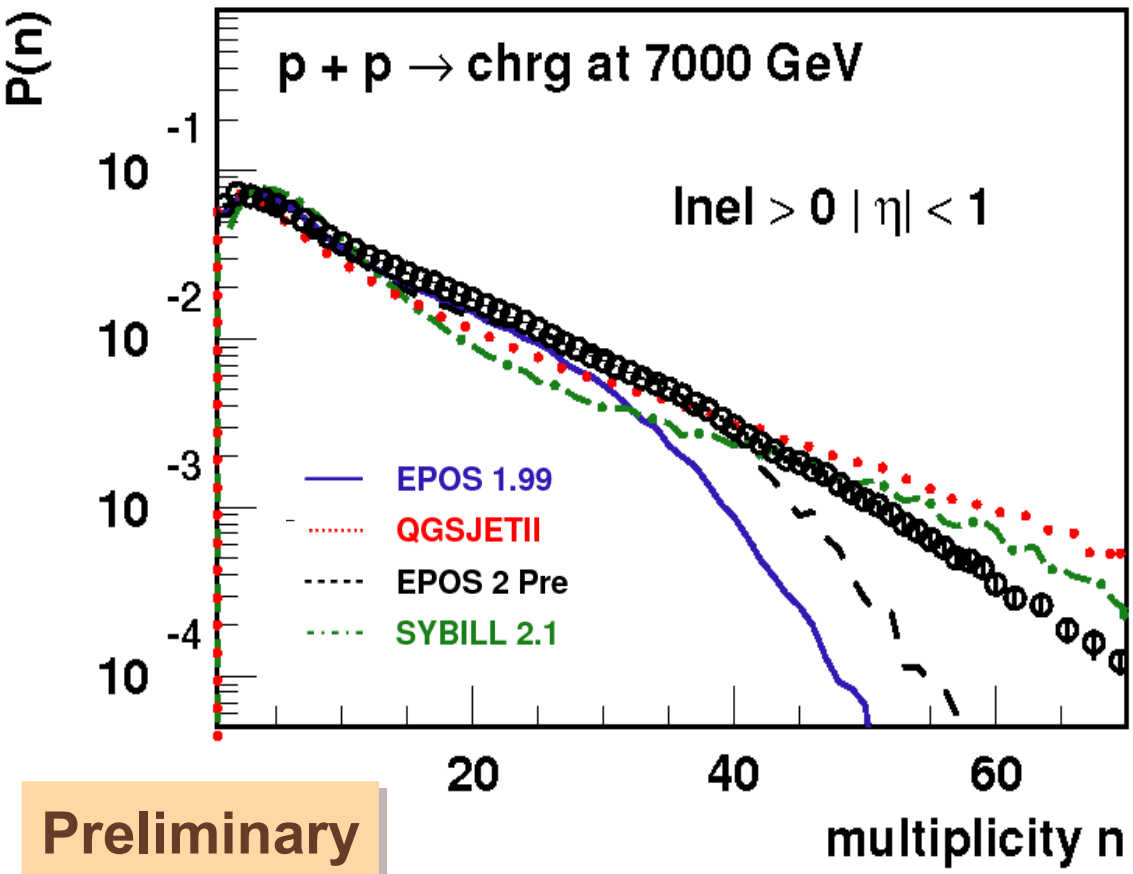


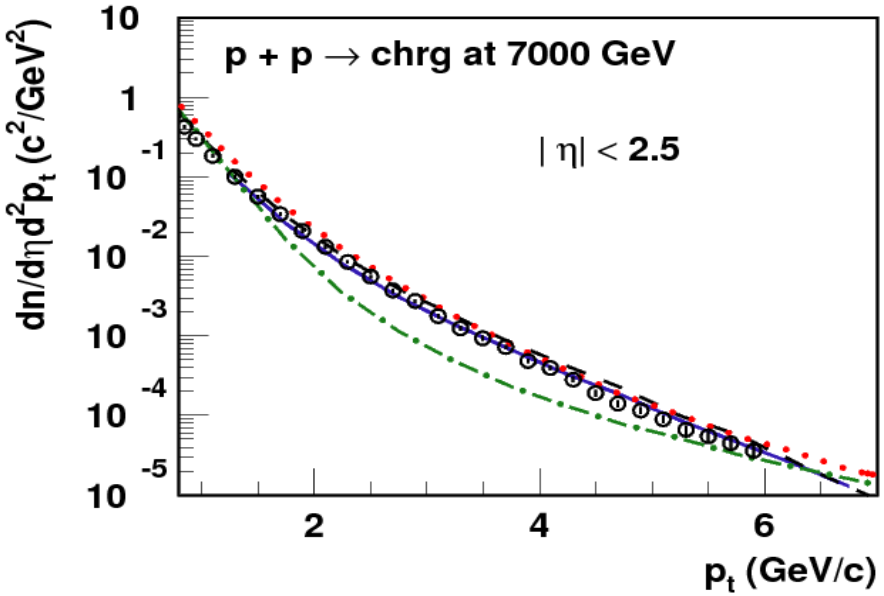


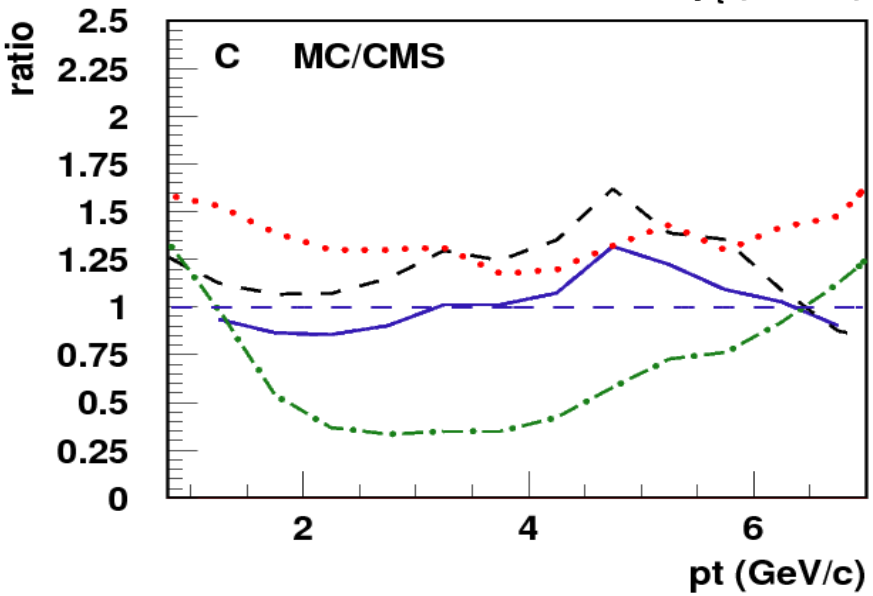
Preliminary

LHC data (2)

- Multiplicity tale still not long enough
- Pt now to high ?
  - Only lack of low pt particles ?



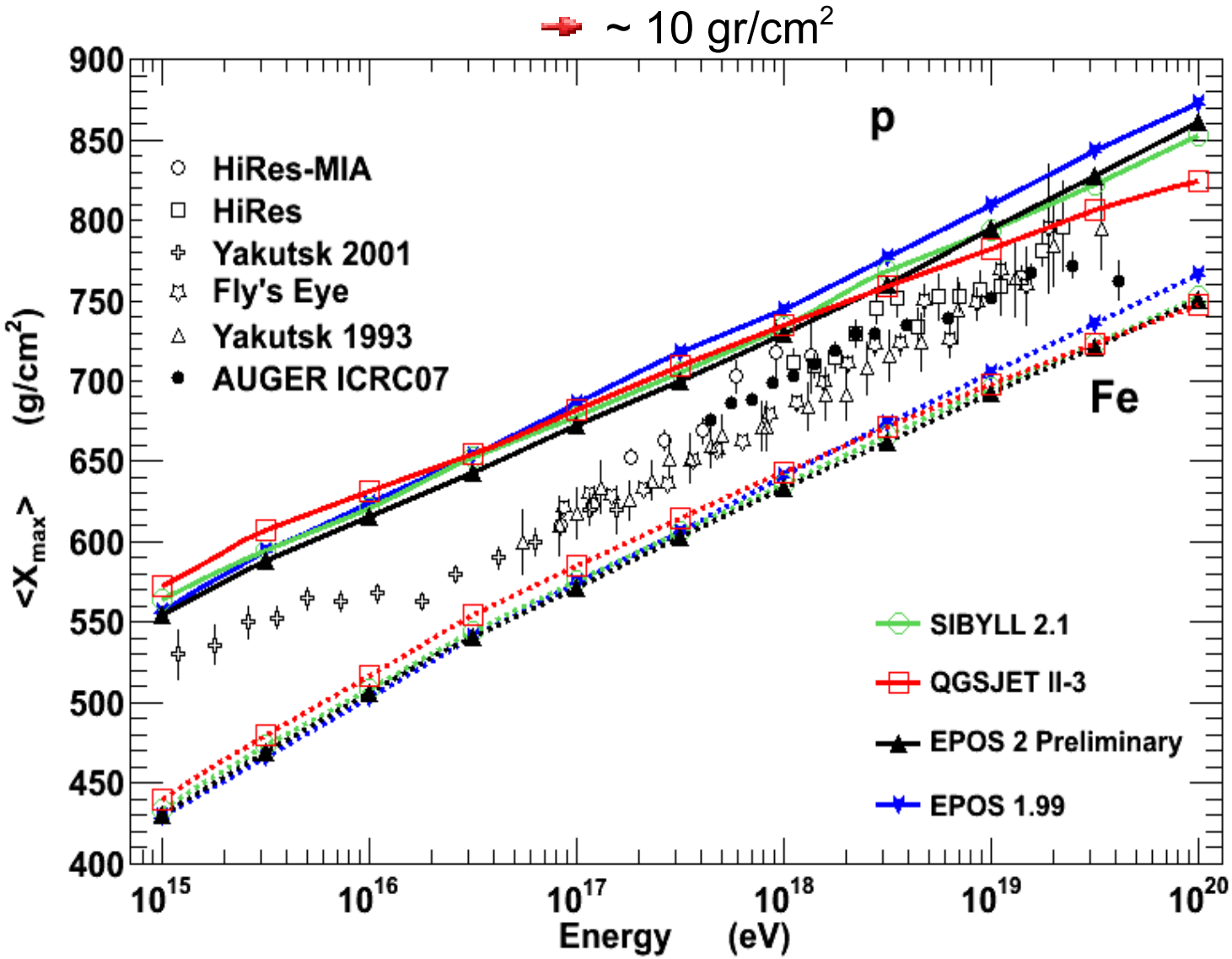




Preliminary

Air Shower Development

- Change in multiplicity seen in $\langle X_{max} \rangle$



Summary

On-going developments : EPOS 2

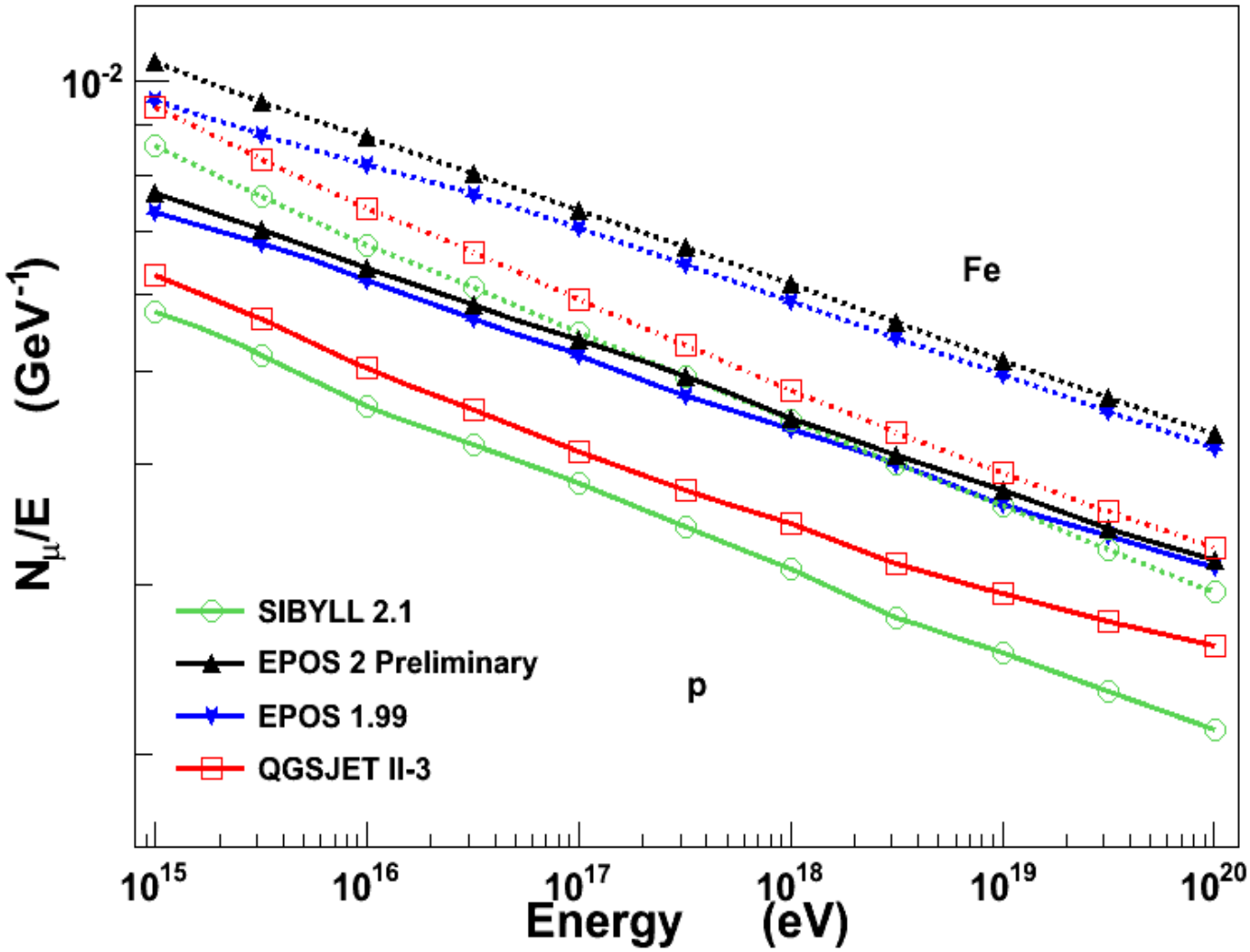
- Real hydrodynamical evolution
- Hard scattering (PDF and Jets) correctly described
- First test with LHC data
  - Good in average
  - Inconsistency pt/multiplicity : more checks needed
- No dramatic change for air shower development

Next step :

- Selection of hard processes
- Both at the same time : underlaying events

Air Shower Development

- Muons affected by baryon production

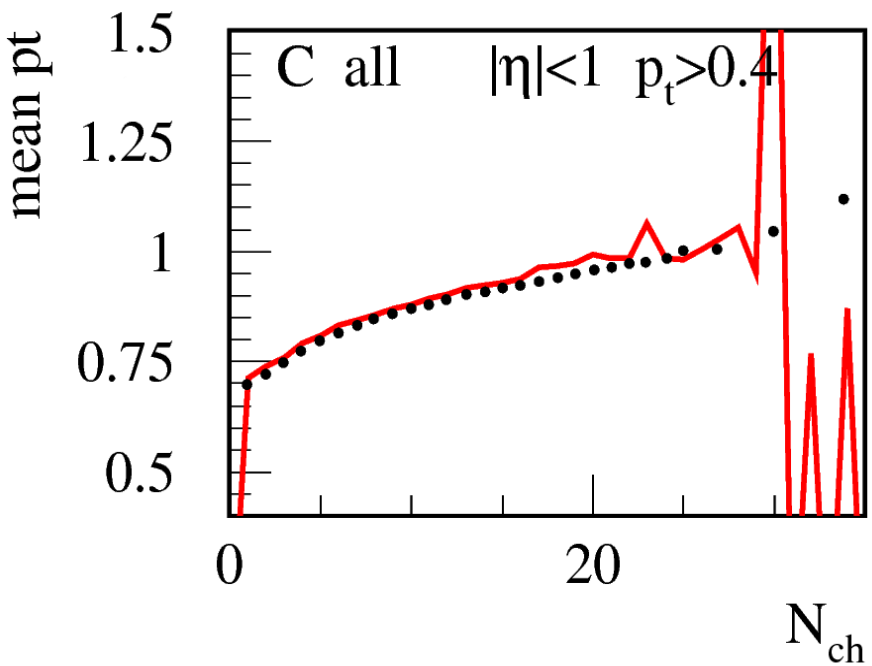


$\langle p_t \rangle$ vs multiplicity : EPOS 1.61 (2007)

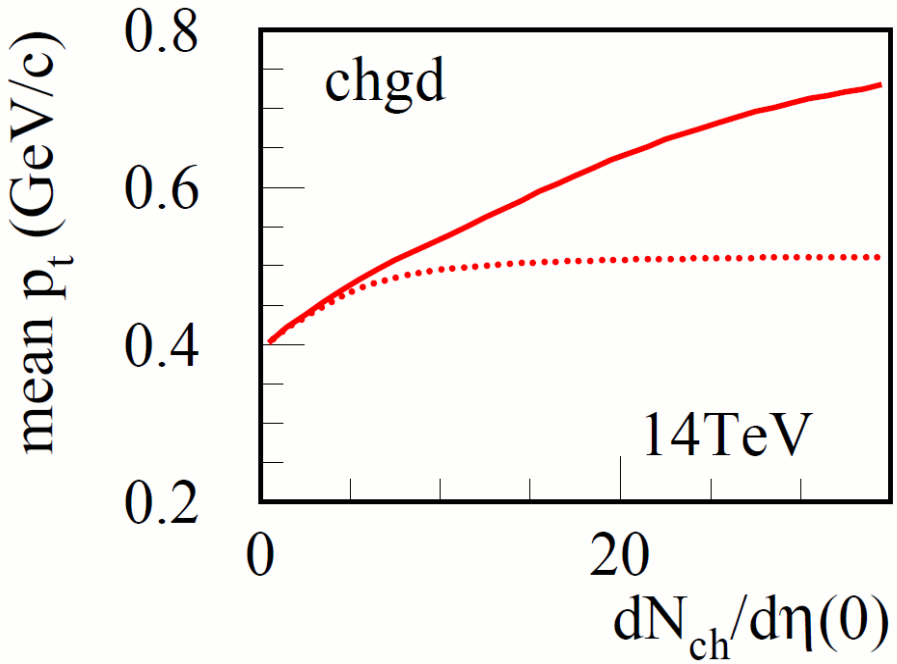
- **Since 2007 collective effects in EPOS for any system :**
  - Minimum energy density needed to start formation of "core clusters"
  - Microcanonical decay with additional flow
  - Flow parametrized from SPS HI, RHIC HI and Tevatron ap-p

K. Werner
Phys.Rev.Lett.98:152301,2007.

ap-p 1.8 TeV (fit)



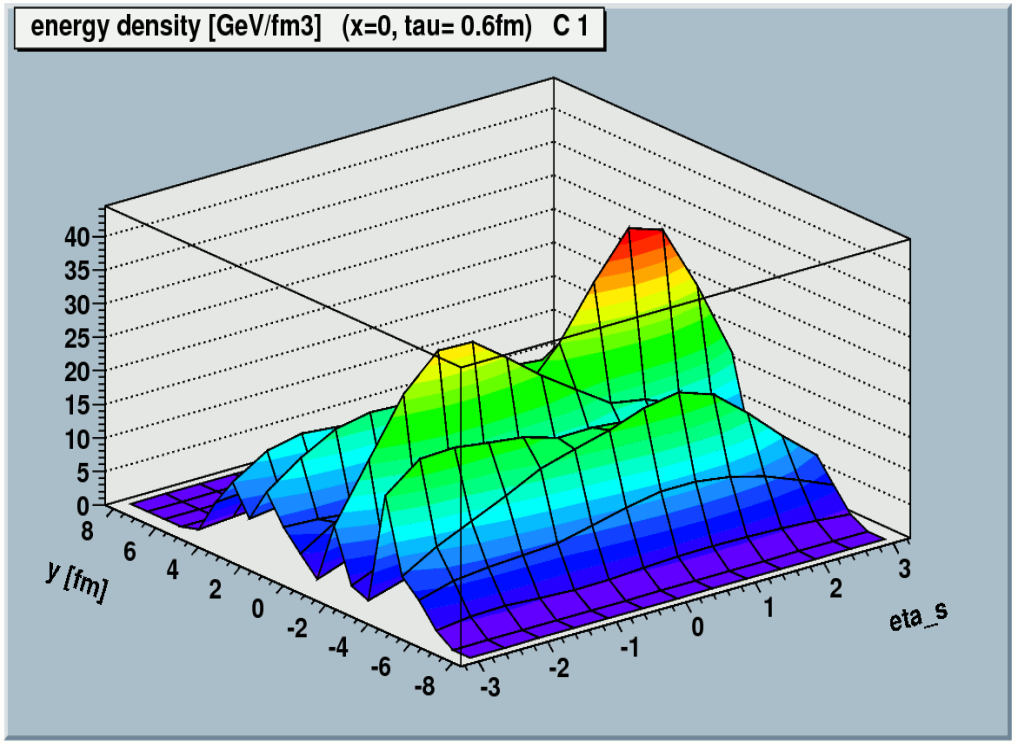
p-p 14 TeV (prediction)
"HI at LHC : Last Call for Predictions" Armesto et al.

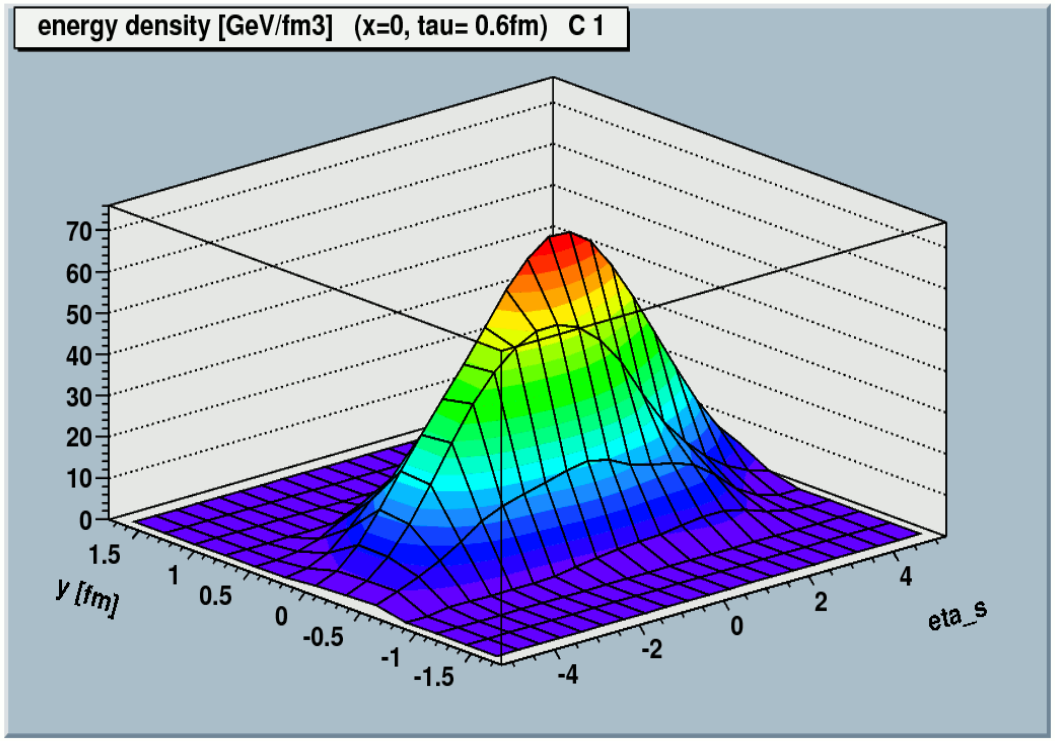


- **More development on collective effects in pp from other groups :**
  D'Enterria et al. (arXiv:0910.3029), Solana et al. (arXiv:0911.4400), Chaudhuri (arXiv:0912.2578), ...

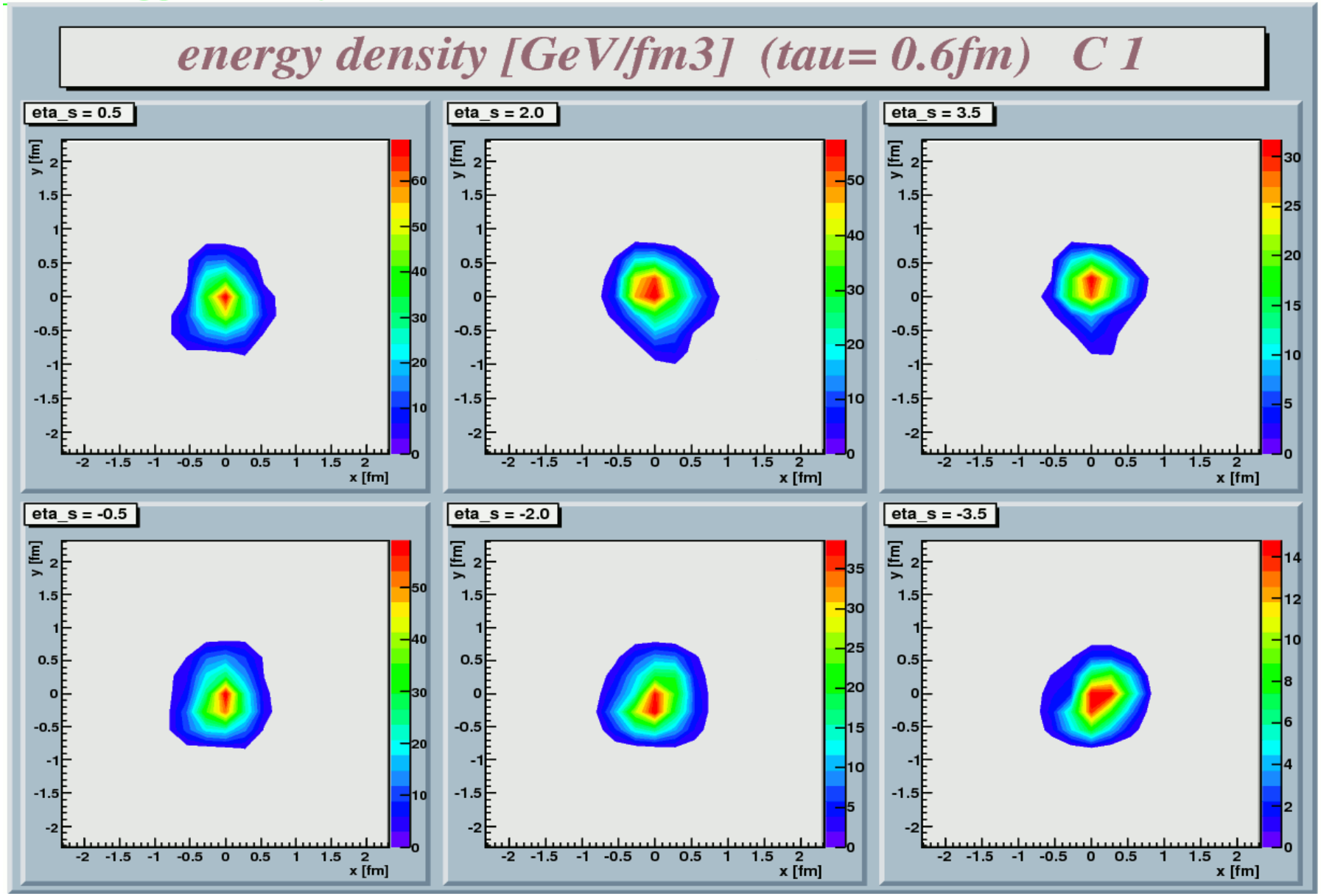
Hydro in pp : Initial Conditions

- **Initial conditions from multiple interactions :**
  - Energy density comparable to AuAu@RHIC
  - Size comparable to size of fluctuations in AuAu@RHIC
- **We propose (and we do) for pp :**
  - Hydrodynamical expansion + statistical decay based on EPOS flux tube initial conditions (event-by-event)



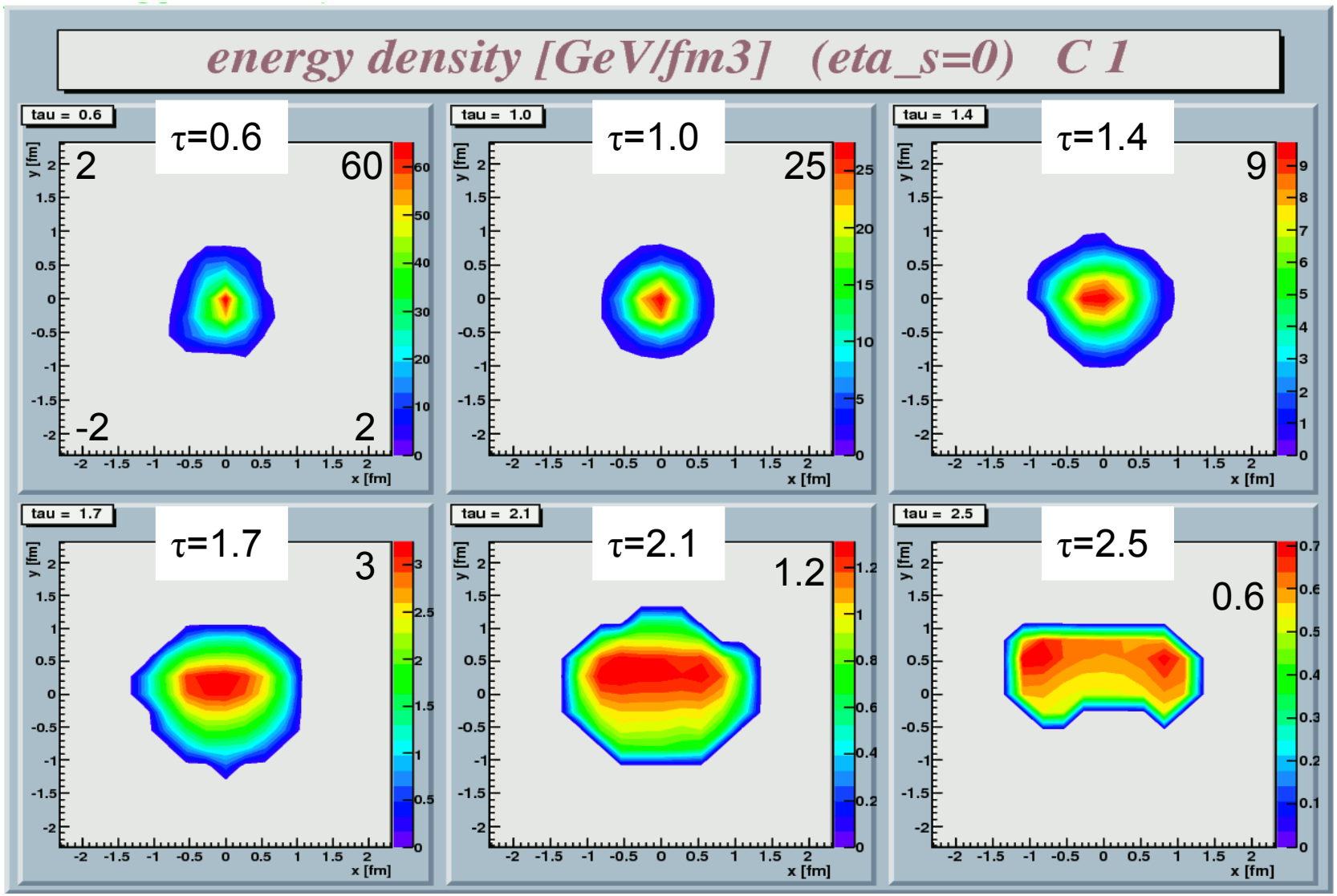


Initial Conditions ap-p@Tevatron

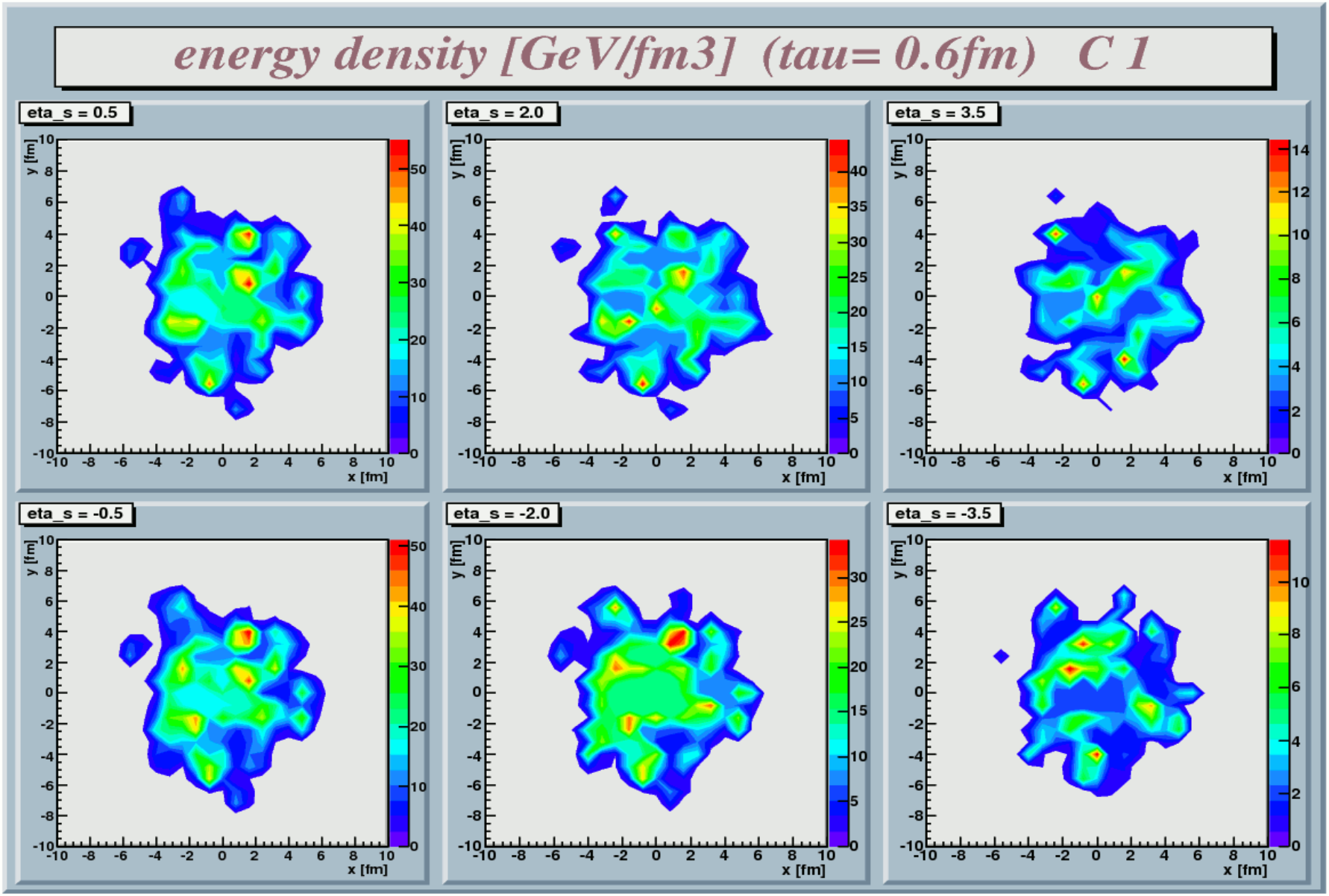


First Real Hydro in ap-p@1.8 TeV : Tau

- Apply same parameters as for AuAu@RHIC
  (except flux tube radius = free parameter)



Initial Conditions AuAu@RHIC



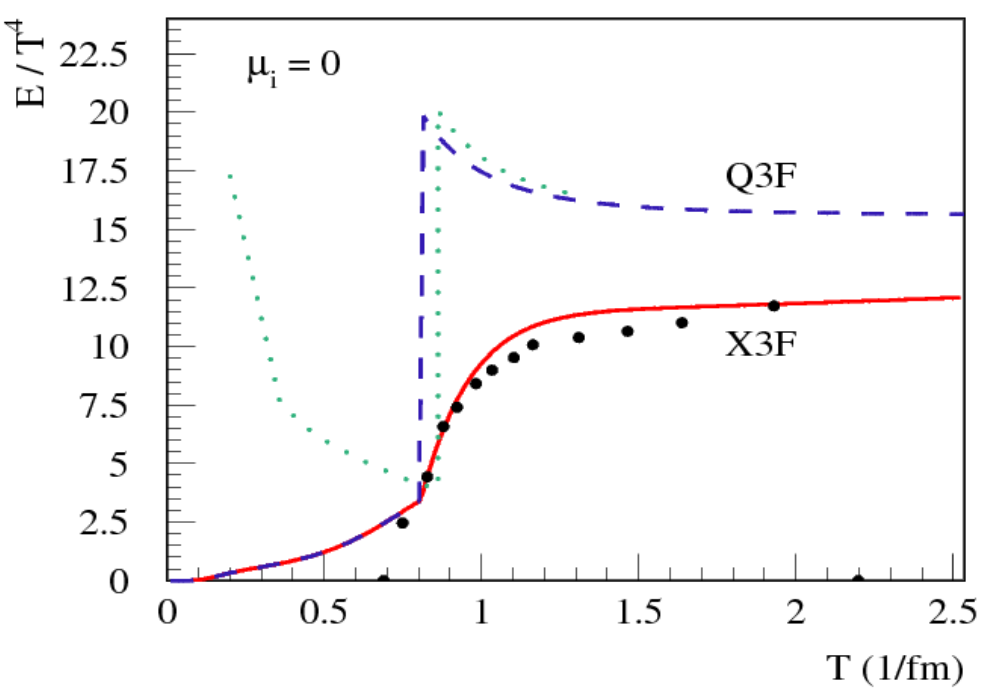
EoS

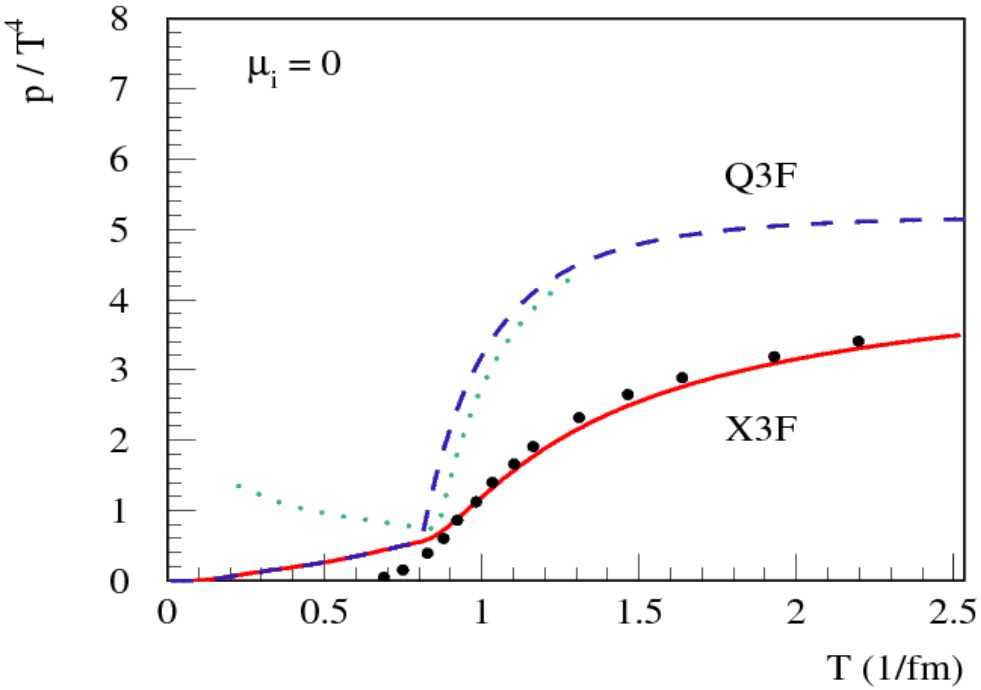
Hirano: QG & resonance gas => 1st order PT, PCE, $\mu_B = \mu_S = \mu_Q = 0$

Q3F: QG & "complete" resonance gas => 1st order PT, excl volume correction, μ_B, μ_S, μ_Q considered, parameters as in Spherio

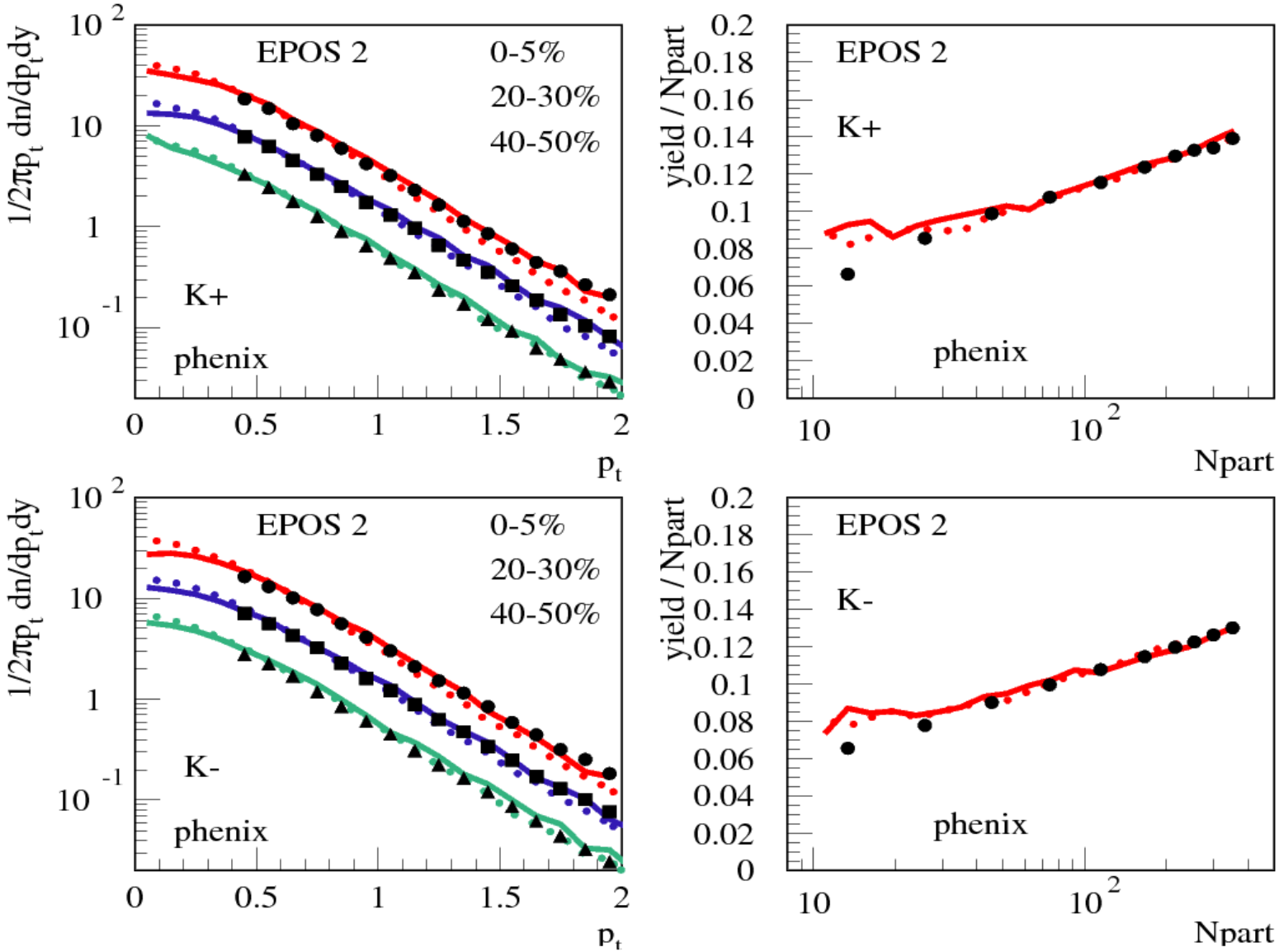
X3F: crossover : $p = p_Q + \lambda(p_H - p_Q)$, $\lambda = \exp(-\frac{T-T_c}{\delta})\theta(T-T_c) + \theta(T_c - T)$

"data": Y. Aoki, Z. Fodor, S.D. Katz , K.K. Szabo, JHEP 0601:089,2006





AuAu : Kaon



solid lines: with hadronic cascade

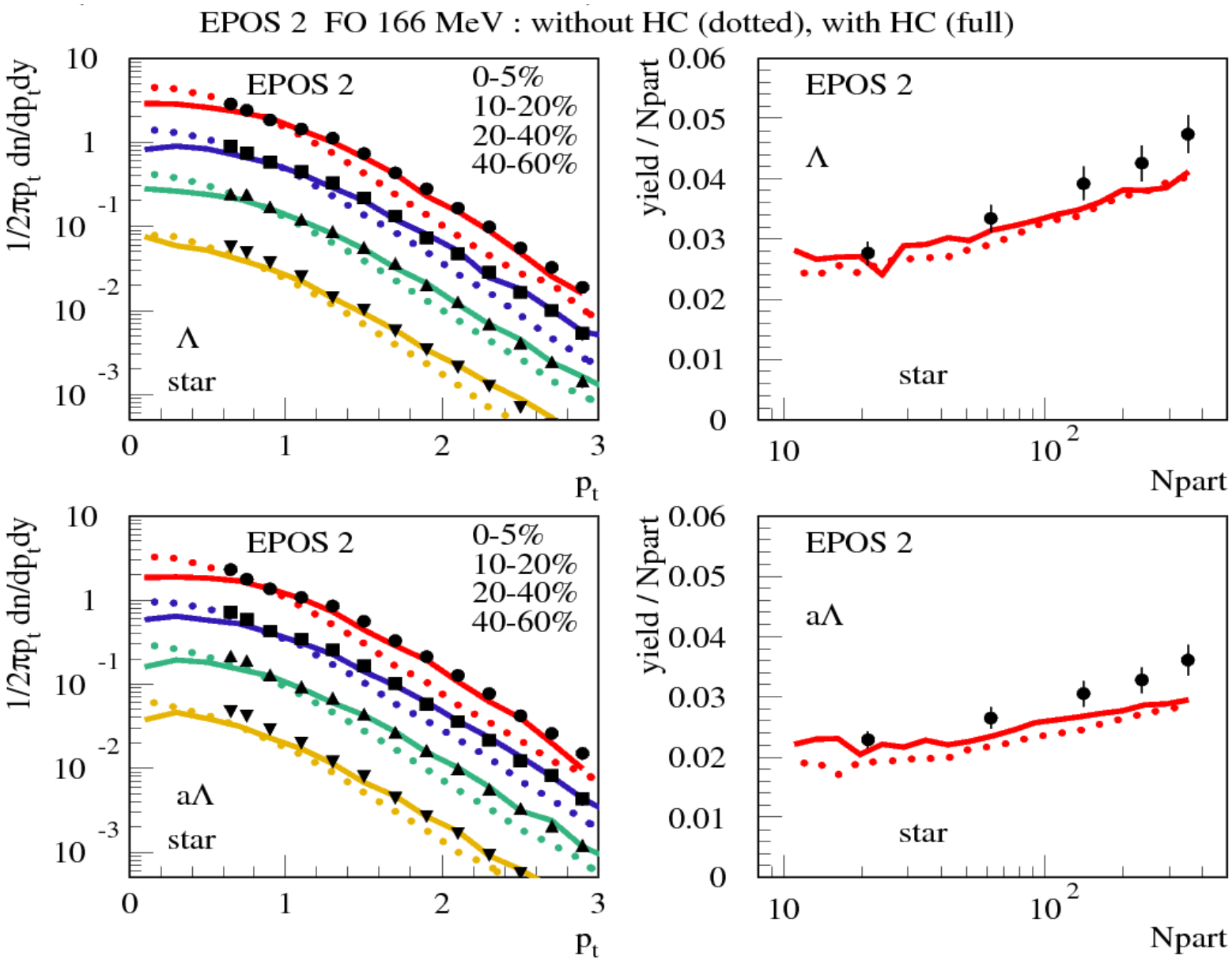
dotted lines: w/o cascade

AuAu : Lambda

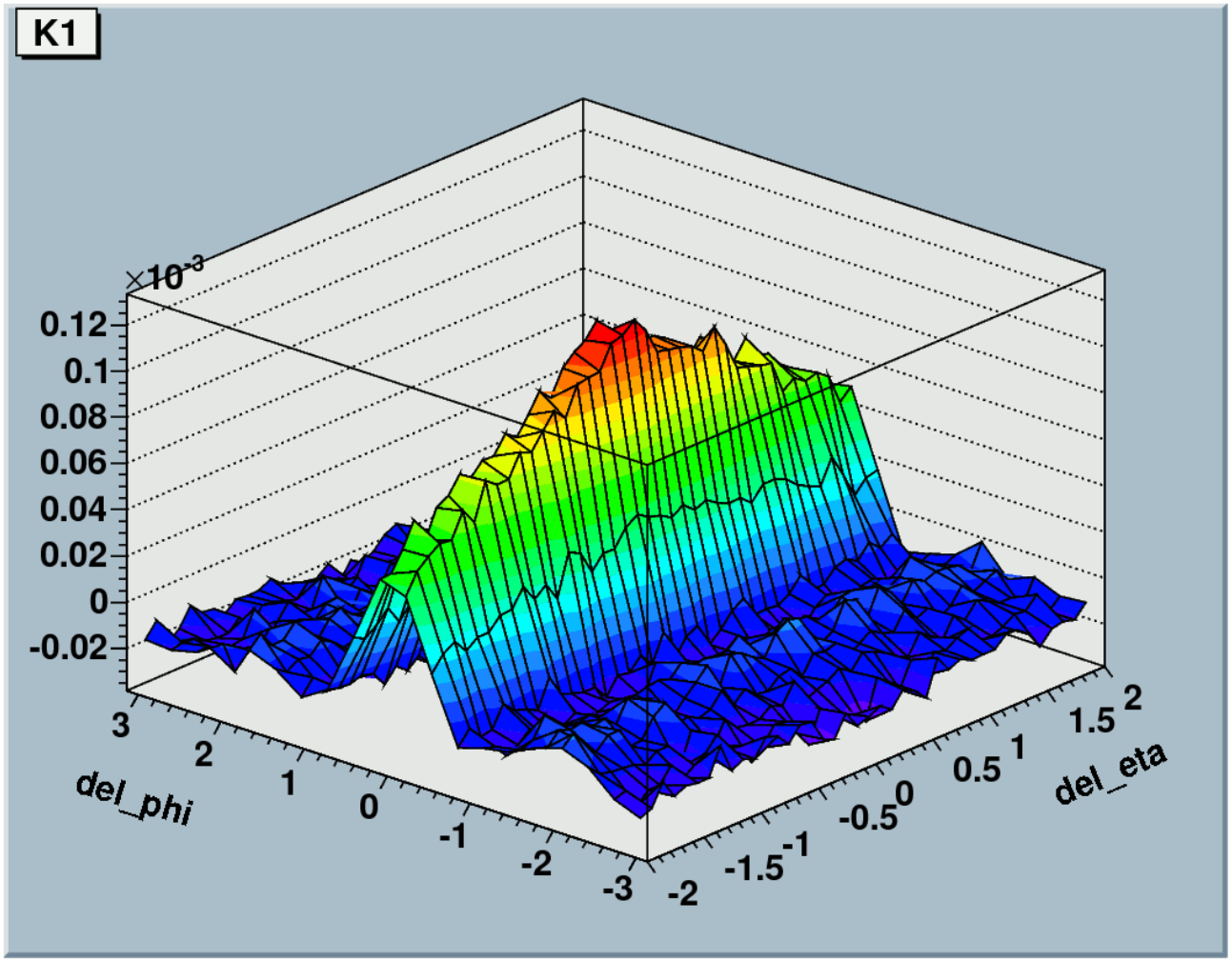
for better visibility:

pt spectra scaled by

1/2 (10-20%)
1/4 (20-40%)
1/8 (40-60%)

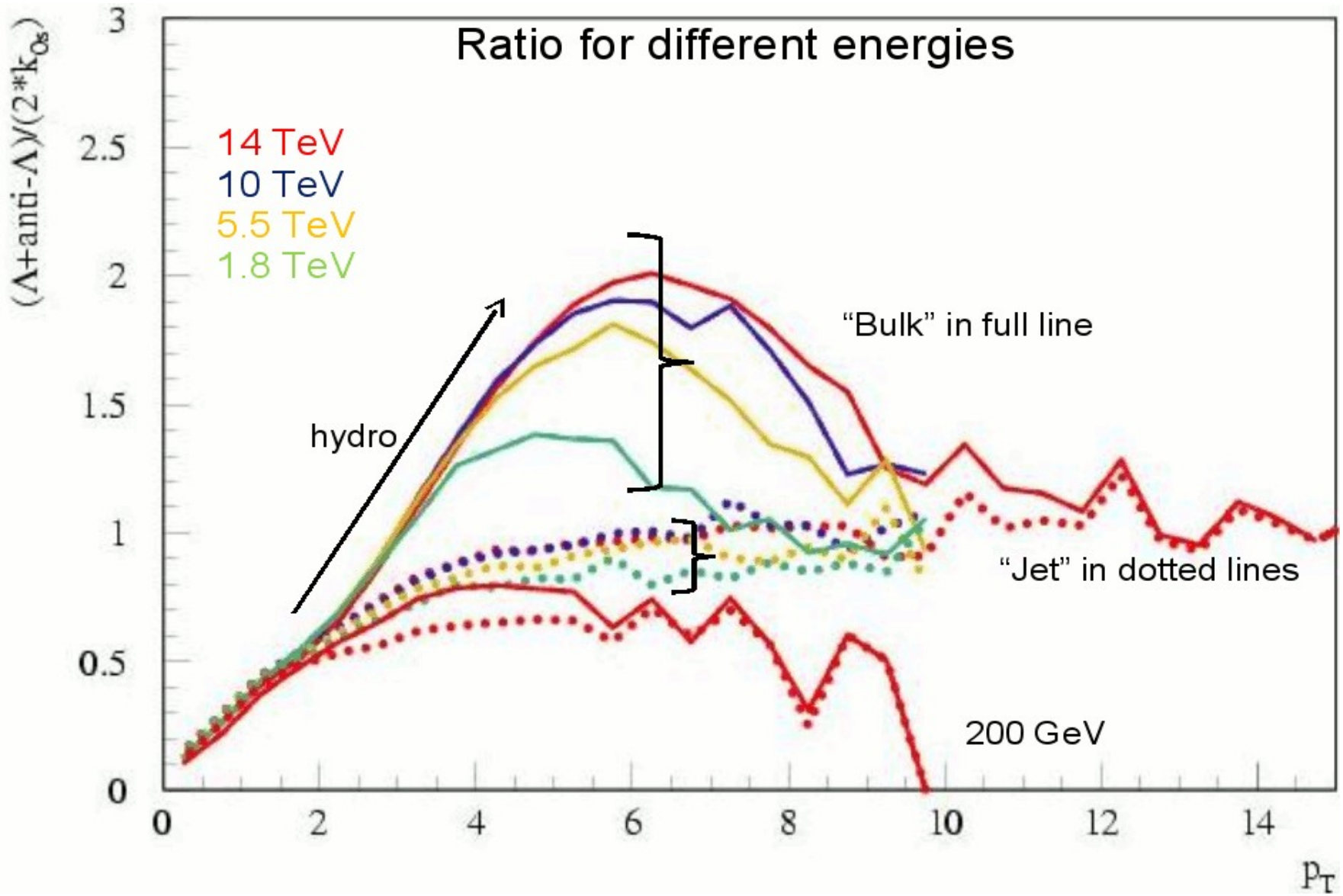


AuAu : Di-hadron correlation

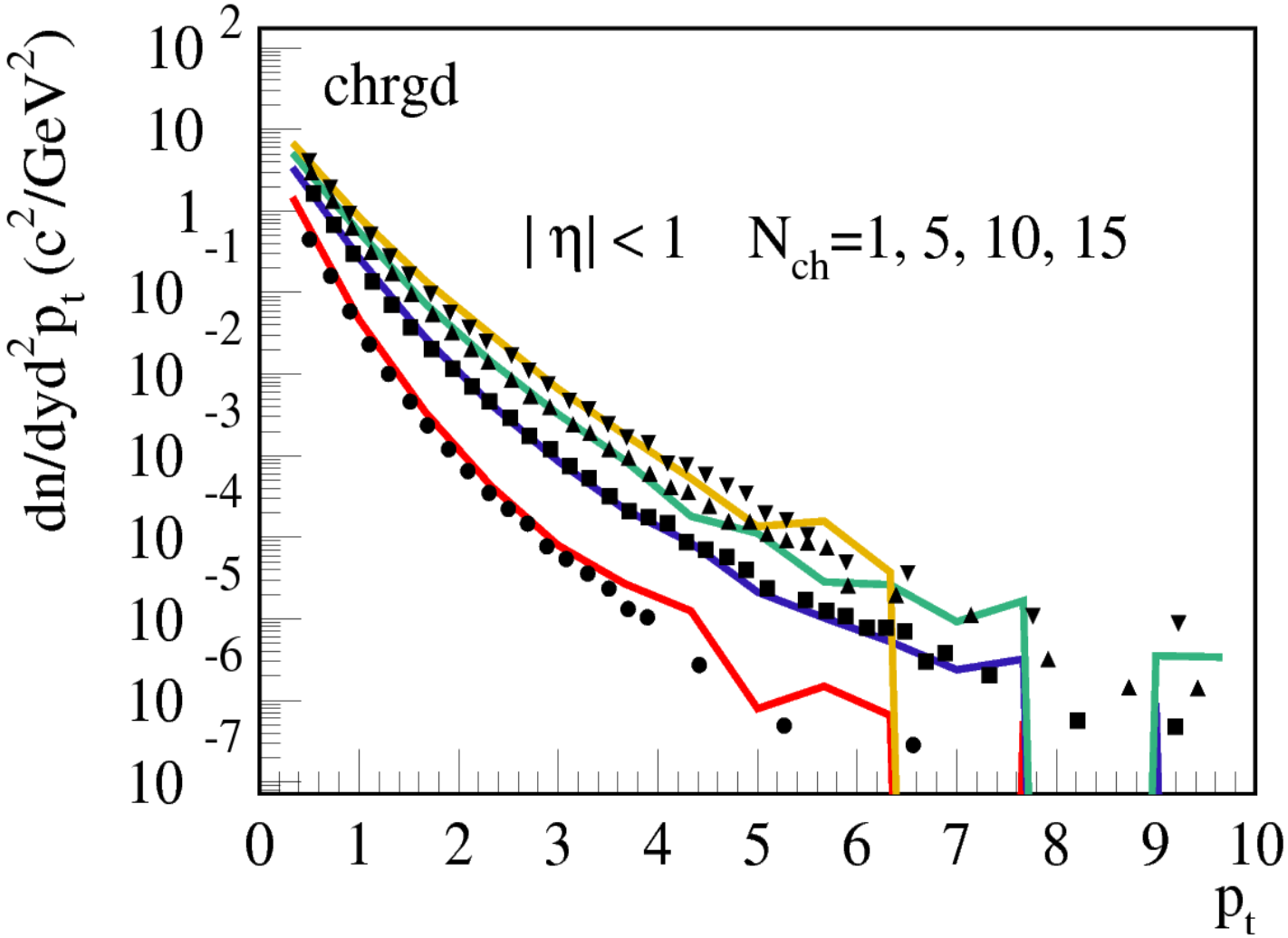


AuAu 0-10%, $3 < p_t^{\mathrm{trig}} < 4\,\mathrm{GeV/c}$ $2 < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trig}}$

p-p : Other Possible Observable



Pt distribution CDF ap-p@1.8 TeV with Hydro



Pt distribution CDF ap-p@1.8 TeV without Hydro