Chasing the holy Grail – the quark gluon plasma in pp: a personal view on the history and present

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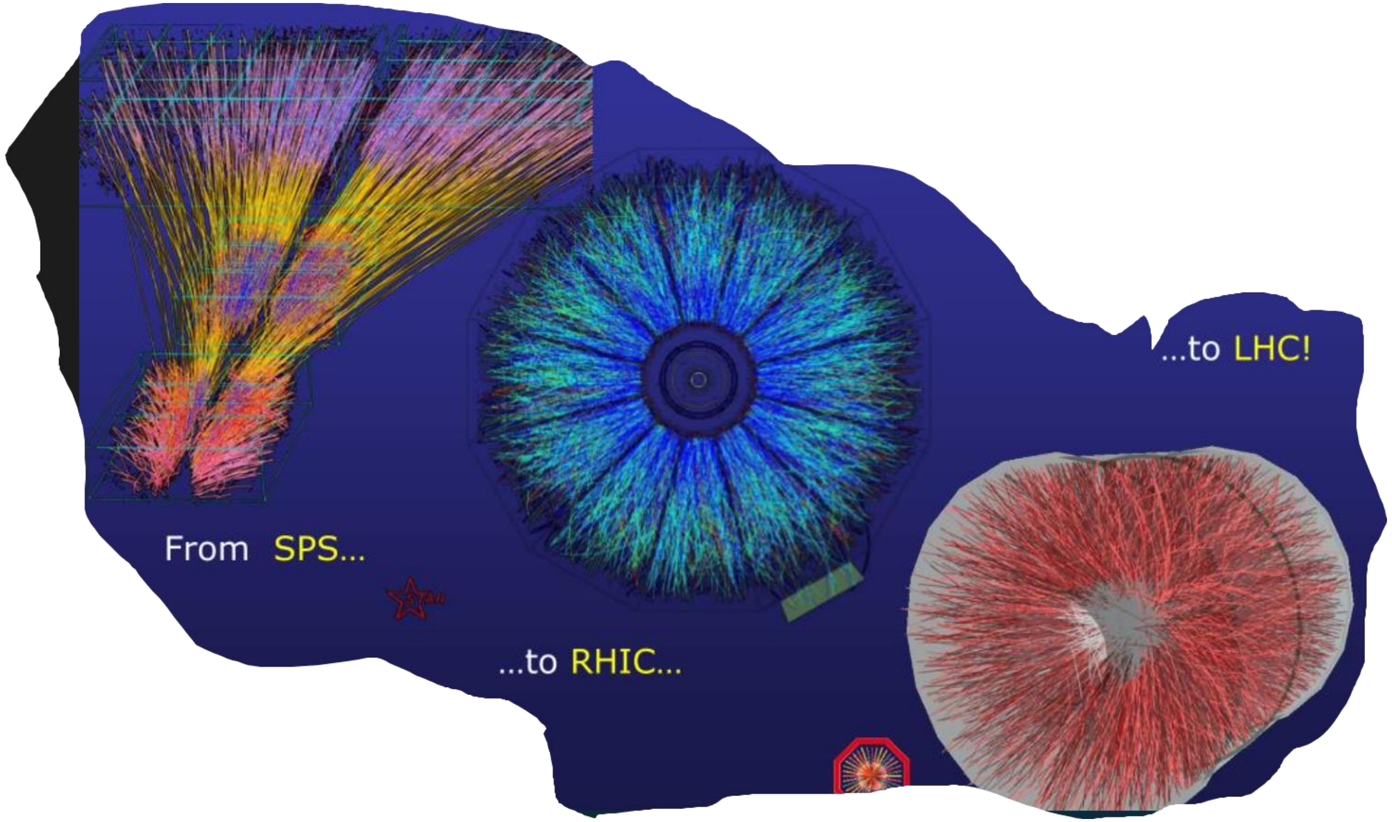
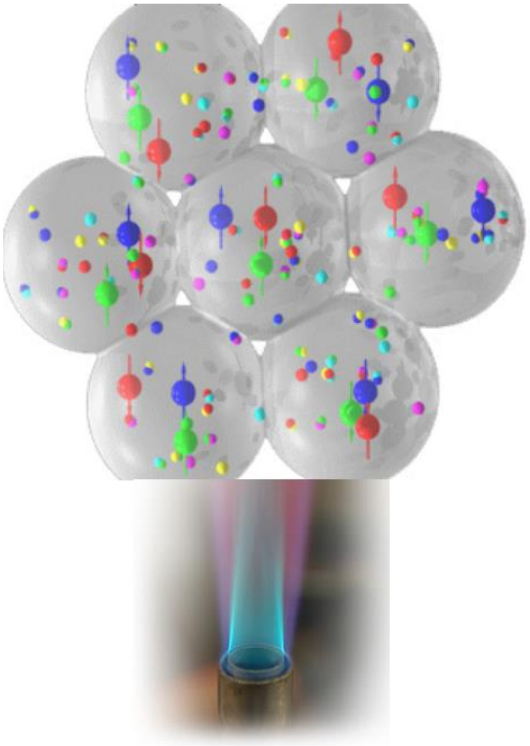
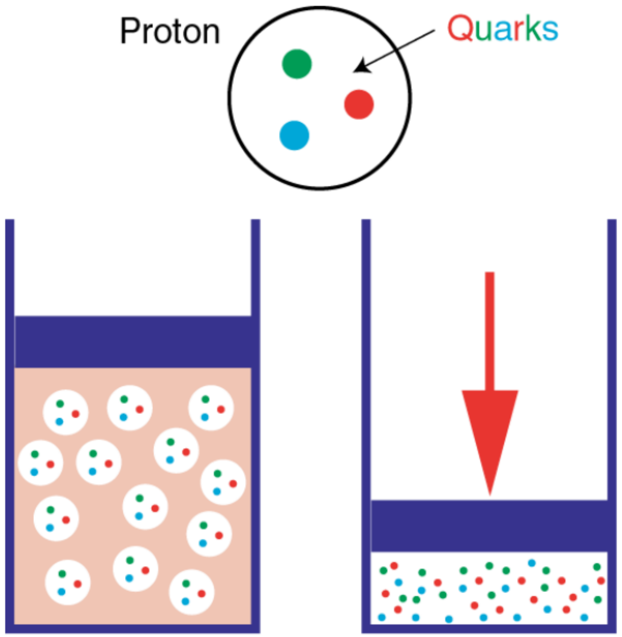


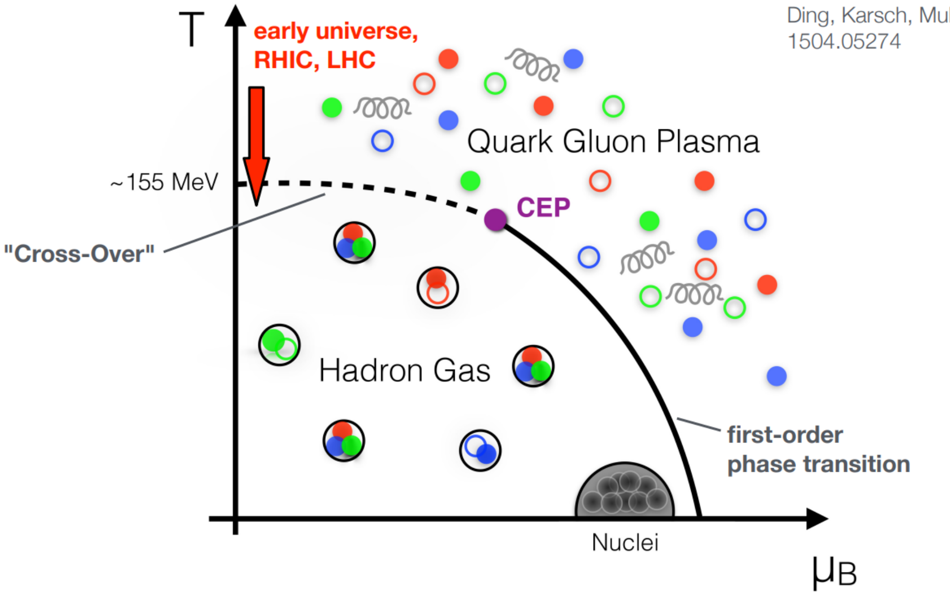
A small introduction to the facts about quark gluon plasma

What happens to matter if you make it hotter or denser

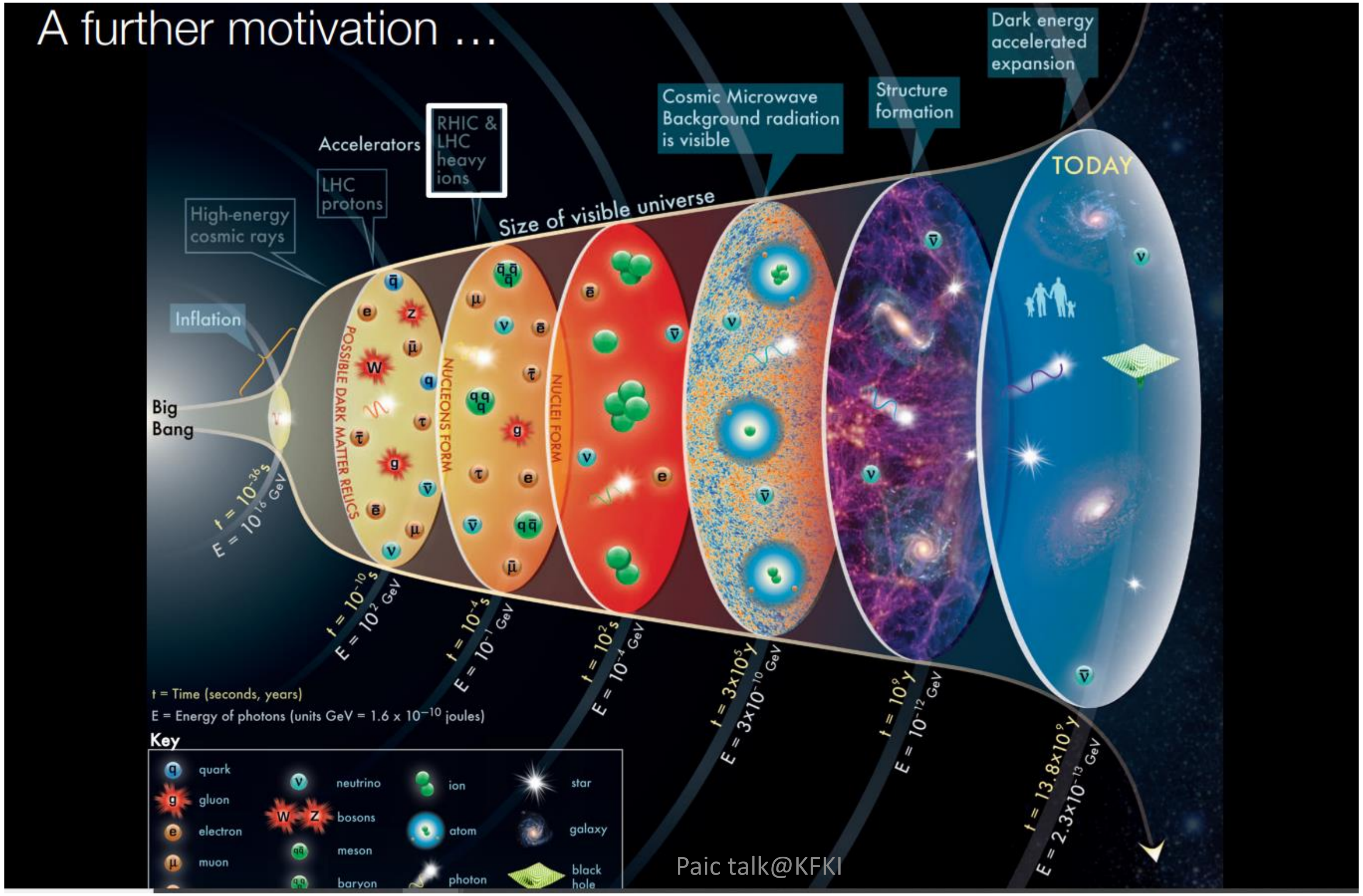
- Solid → liquid →gas → plasma → hadron gas →QGP







A tentative view of the evolution



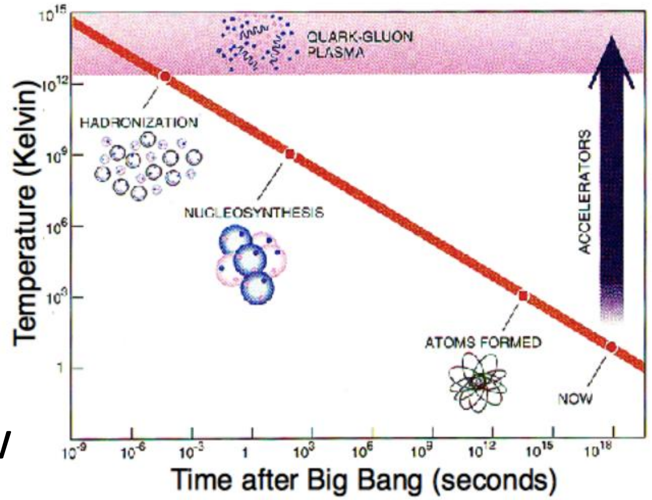
The QGP was at the beginning !

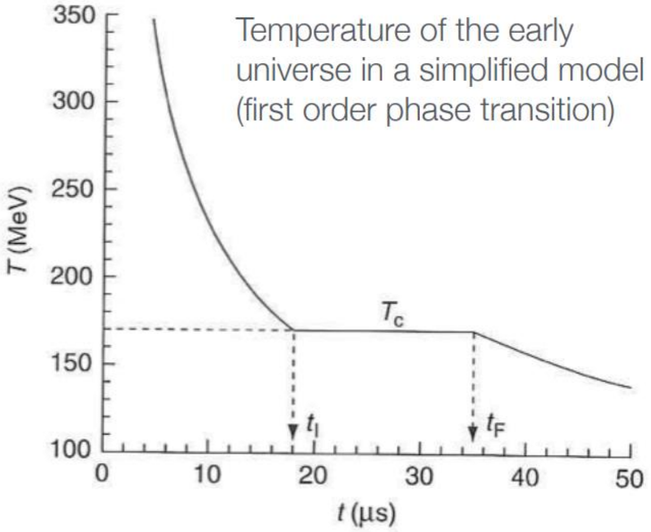
- A good reason to study!
- Although many caveats!

- GALAXY baryon content:
  - Solar mass is MSun = 2 × 10^30kg = 1.2 × 10^57 protons.
  - Galactic mass is Mgalaxy = 5 × 10^11MSun, Therefore, assuming 1/4 is visible matter the galaxy has about N Milky Way B = (6/4) × 10^68 proton masses. To make a galaxy we need a QGP in the Universe of the magnitude V = 0.5 × 10^78fm3 , that is R = 0.5 10^11meter
- UNIVERSE baryon content:
  - The baryon content of the Universe requires estimated of ‘unseen’ galaxies, leading to Ngalaxie = 5X10^11, thus the total baryon number bound in stars within the current horizon of the Universe is given as B(all stars)¬ 0.5X10^80.
- Size of QGP Universe:
  - at time hadronization V(QGP) ¬ (10^15meter^3) , light needs to travel a month across this domain. However, the Universe is only about 30µs old; we see the need for a gigantic inflation prior to QGP era, factor: 10X11 Keep in mind the big differences to RHI: time and size scale ⇒ equilibrium
  - Rafelski:140429NotreDame_Universe.pdf (arizona.edu)

`Temperature evolution – the QGP'

- Transition from the quark-gluon plasma to a gas of hadrons at a temperature of Tc ≈ 1.8 x 1012 K ■ 100 000 hotter than the core of the sun ■ Early universe: QGP → hadron gas a few microseconds after the Big Bang

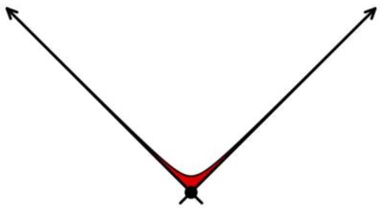




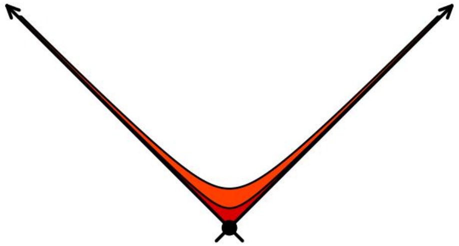
The study of the QGP in the lab?

- Colliding two heavy ions and measuring the resulting particles
- And compare to pp in the first naïve approach

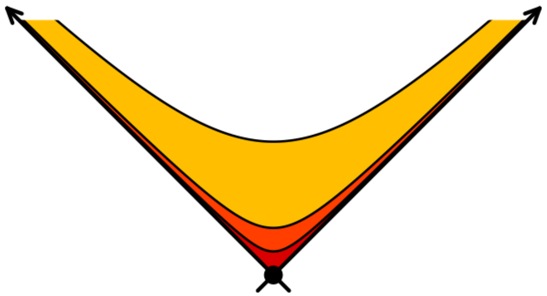
The way to the real world after collisions in the QGP picture



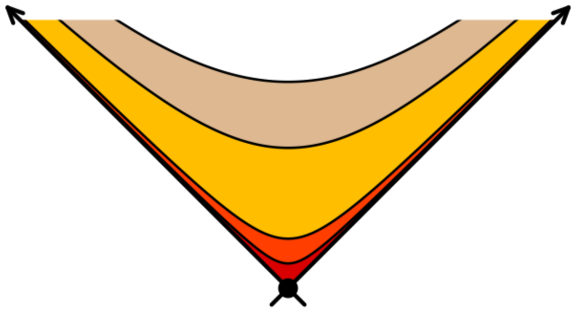
- $\tau \sim 0.2$ fm/c
- Production of semi-hard particles :
  - gluons, light quarks
- relatively small momentum : $p_\perp \lesssim 1\text{–}2$ GeV
- make up for most of the multiplicity



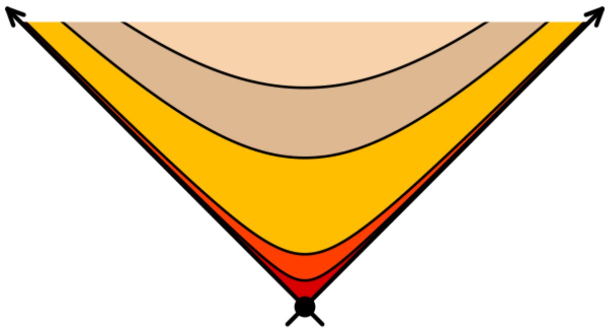
- $\tau \sim 1\text{–}2$ fm/c
- Thermalization
  - experiments suggest a fast thermalizati
  - but this is still not understood from QCD



- $2 \leq \tau \lesssim 10$ fm/c
- Quark gluon plasma

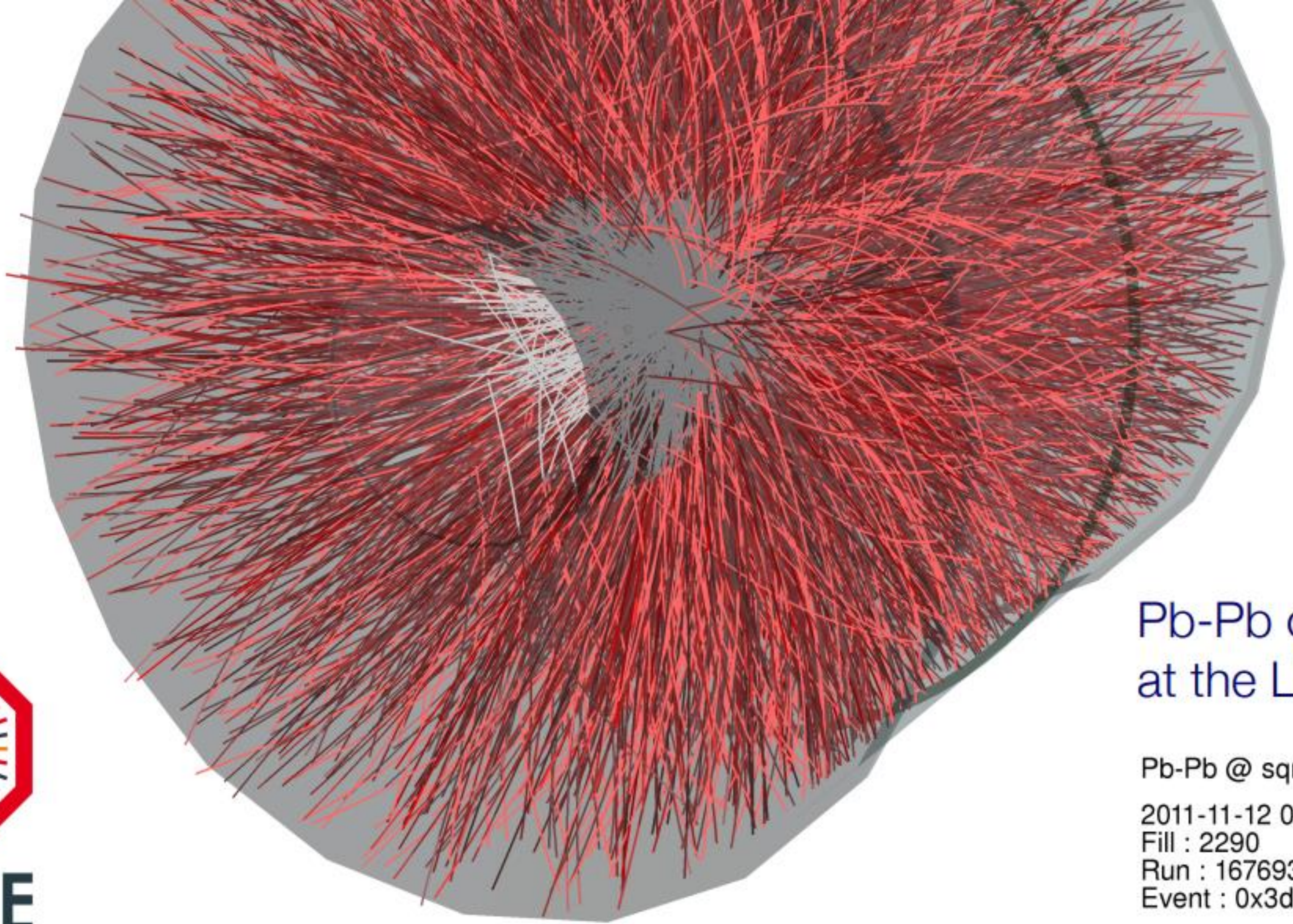


- $10 \lesssim \tau \lesssim 20$ fm/c
- Hot hadron gas



- $\tau \to +\infty$
- Chemical freeze-out :
  density too small to have inelastic interactions

And in the lab we come very late!



Pb-Pb collision at the LHC

Pb-Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

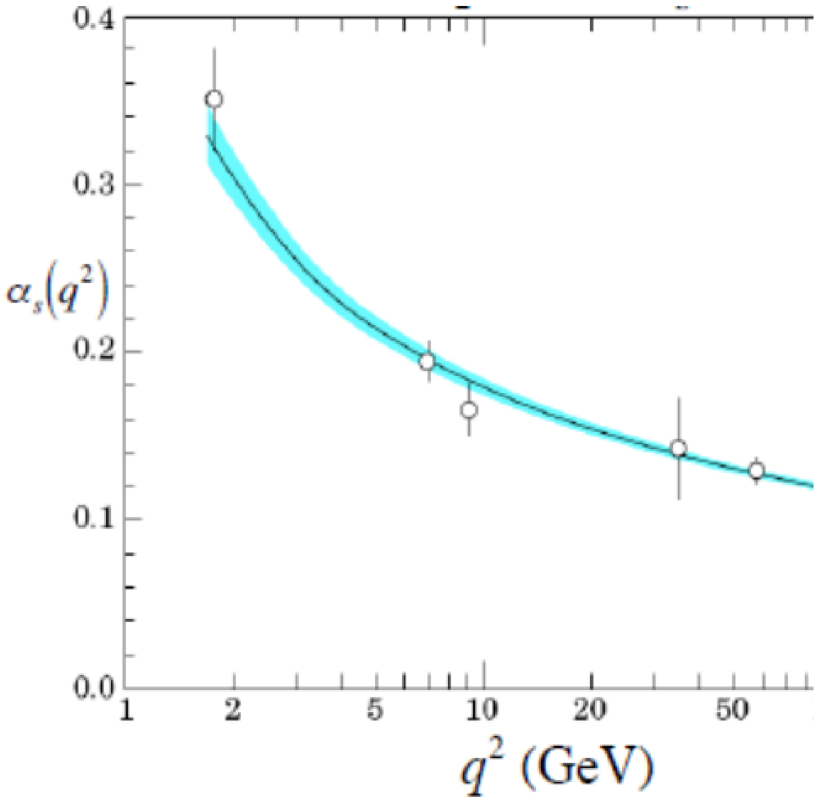
ALICE
A JOURNEY OF DISCOVERY

The first crack in the story: QGP is not a gas but a liquid!

The truth in science is of a temporary nature!

`gas or liquid the early question

- Contrary to QED, in QCD the coupling constant decreases when the momentum transferred in the interaction increases or, in other words, at short distances BUT:
  - The naive picture of the quark-gluon plasma belongs to such asymptotic idealizations: as a natural consequence of the QCD asymptotic freedom
- **However**
  - Experiments conspired to a shift in paradigm as Valentin*Telegdi* would say: turned the pages of the bible!. The RHIC data did not provide any evidence for ideal gas behavior. They are currently interpreted by assuming that the produced matter behaves as a liquid with low viscosity, the "perfect liquid".
  - perturbation theory is notoriously unable to describe the quark-gluon plasma unless the temperature is extremely high.
  - new techniques have emerged that allow calculations to be done in some strongly coupled gauge theories (that differ however in essential aspects from QCD). Blaizot
  - Blaizot 0703150.pdf (arxiv



The next question:
can we reach QGP in pp collisions?

A long history - tempting for theorists and experimentalists

Van Hove 1982

Alexopoulos et alhttps://doi.org/10.1016/S0370-2693(02)01213-3,

CERN-Heidelberg-Lund Collaboration Charged Particle Spectra in ~ and ~p Collisions at the CERN ISR . W. Bell et al

Presently, it is widely believed that in pp collisions in the studied energy range a hot QCD matter is not produced in the typical inelastic minimum bias events due to small energy density. But in high multiplicity (HM) pp events the energy density may be comparable to that in AA collisions at RHIC and LHC energies. And if the thermalization time, $\tau 0$, is small enough, say $\tau 0 \sim < 0.5$ fm, the mini-QGP with size of $\sim 2 - 3$ fm should be formed quite likely to the large-size plasma in AA collisions

B.G Zakharov https://doi.org/10.48550/arXiv.1311.1159
Parton energy loss in the mini quark-gluon plasma and jet quenching in proton-proton collisions - We evaluate the medium suppression of light hadron spectra in pp collisions at RHIC and LHC energies in the scenario with formation of a mini quark-gluon plasma

P. Jacobs Search for jet quenching effects in high multiplicity pp collisions at $\sqrt{\mathrm{s}}$=13 Tev

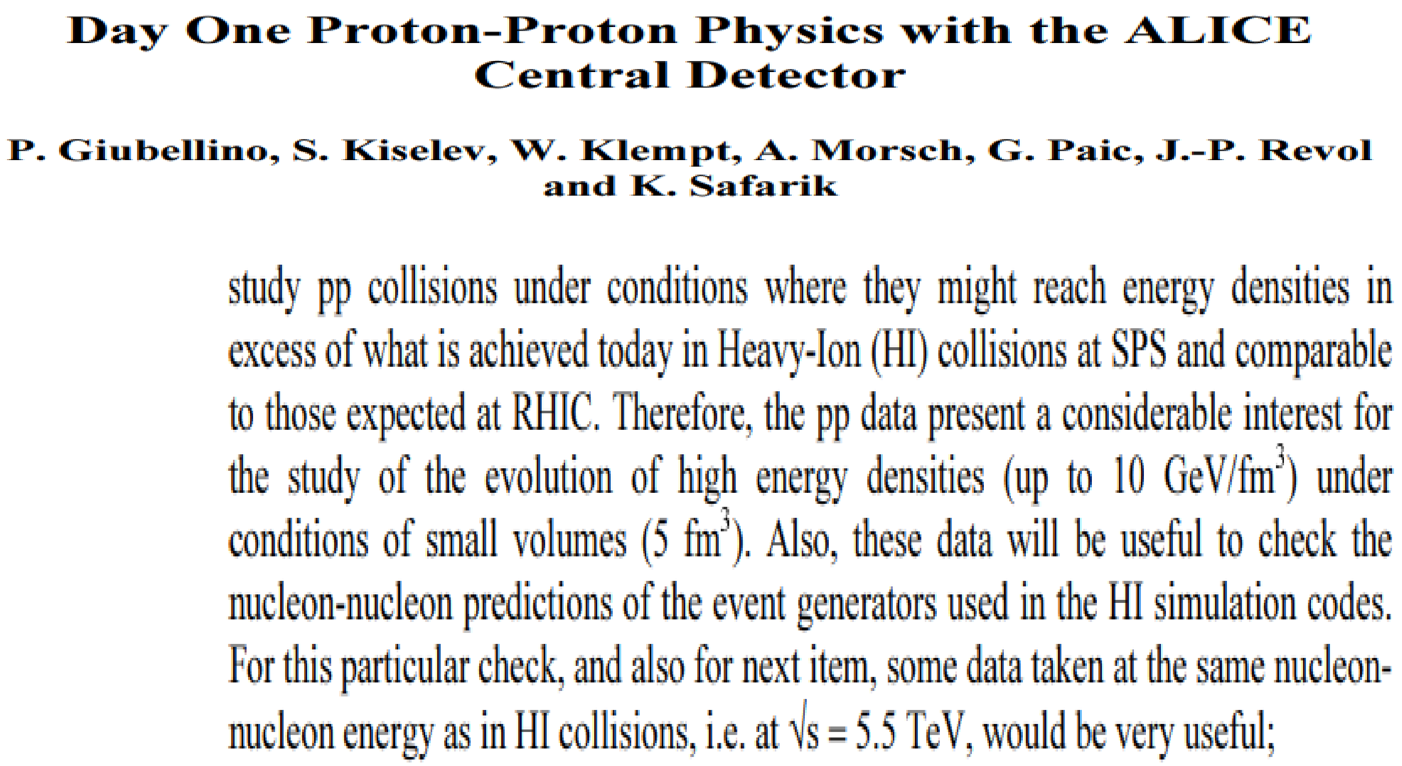
arXiv:2001.09517 [nucl-ex]

M. Mangano and B Nachman Observables for possible QGP signatures in central pp collisions
https://doi.org/10.48550/arXiv.1708.08369

We consider observables such as jet energy loss and jet shapes, which could point to the possible existence of an underlying quark-gluon plasma, or other new dynamical effects related to the presence of large hadronic densities. Eur. Phys. J. C 78 (2018) 343

And ALICE also!

Alice note 2000-28!!


Day One Proton-Proton Physics with the ALICE Central Detector

P. Giubellino, S. Kiselev, W. Klempt, A. Morsch, G. Paic, J.-P. Revol and K. Safarik

study pp collisions under conditions where they might reach energy densities in excess of what is achieved today in Heavy-Ion (HI) collisions at SPS and comparable to those expected at RHIC. Therefore, the pp data present a considerable interest for the study of the evolution of high energy densities (up to 10 GeV/fm^3) under conditions of small volumes (5 fm^3). Also, these data will be useful to check the nucleon-nucleon predictions of the event generators used in the HI simulation codes. For this particular check, and also for next item, some data taken at the same nucleon-nucleon energy as in HI collisions, i.e. at $\sqrt{s} = 5.5$ TeV, would be very useful;

the second crack

The next crack: the pp collisions exhibit the same behavior as heavy ions` (around 2010)!

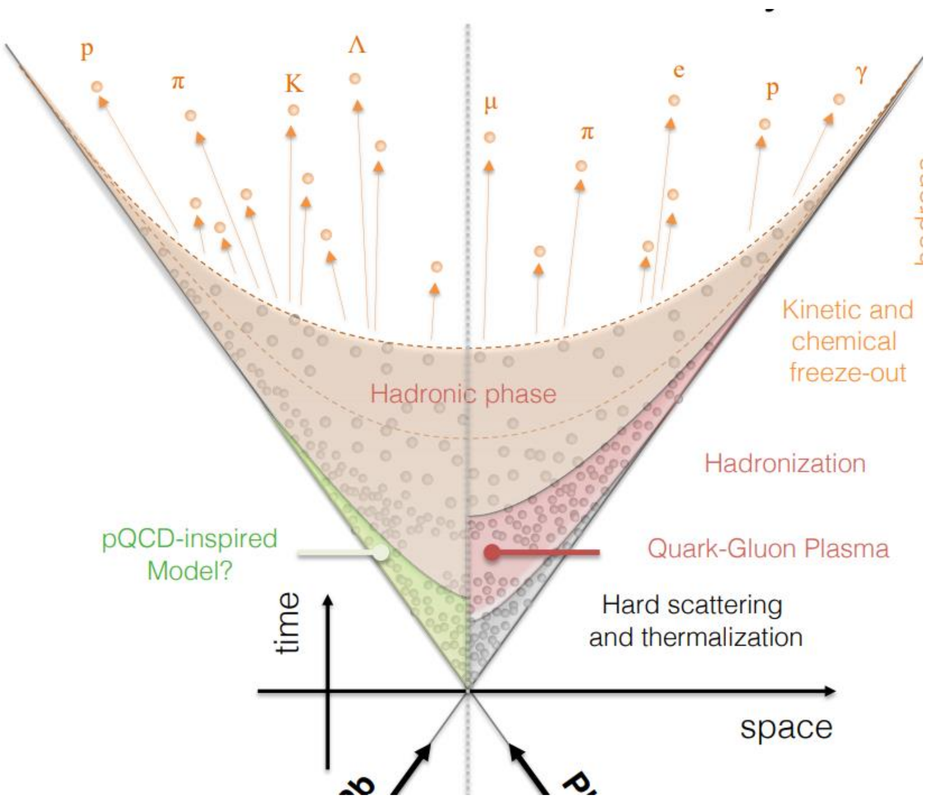
- Actually the idea of a mini QP is old: both the theorists and experementalists have tackled the question of it existence
- So far all the observables indicating the QGP in heavy ion collisions have been observed in pp collisions **except for one** – the energy loss of partons in the QGP environment.

QGP or strings?

- The experimental facts especially those on pp collisions are also at the heart of an important debate:
  - The models based on strings (Pythia etc), and the hydro models (CGC etc) are about equally successful in describing the experimental results!
  - The question has also political overtones - dangerous in science!

The clash of models & not only!

- My personal view is that we should find more experimental facts (outliers) that may decide on the controversy or on the possibility of @ grand Unification!
- There are several steps that should be followed to clarify.

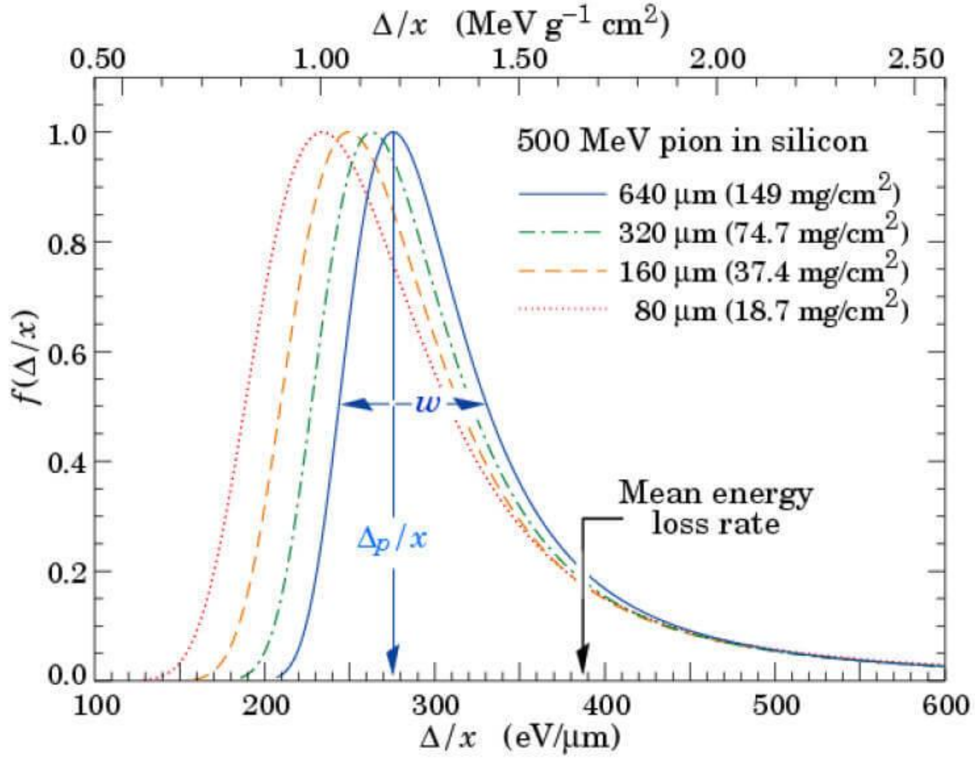


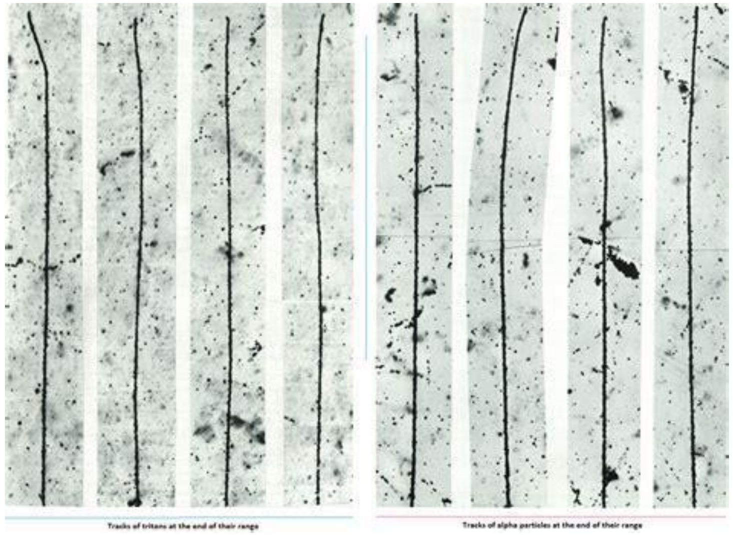
From David Chinellato

Where to look - are the "means"sufficient?

- For different reasons the observations we are doing and the accompanying theories are based on "means" – mean multiplicity, transverse momentum, anisotropy, strangeness…
- The means are the result of many contributions – like the Landau distribution for the energy loss – several effects contribute.
- The models can get the most prominent features but never all the details of the interactions if there multiple sources that contribute
- IMHO they serve to compare models and measurements in a very crude manner.

The meaning of the "means"





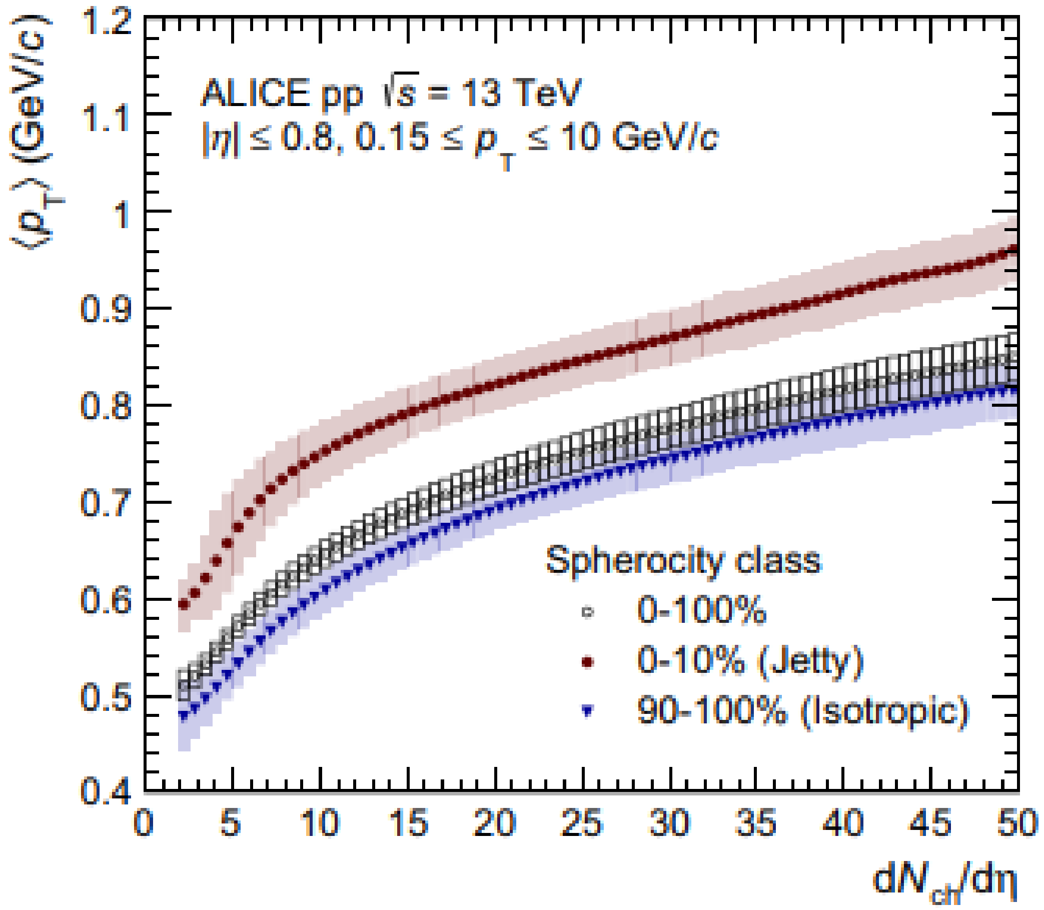
Deta rays around a track@

- **Take the example of the "landau"curve for energy loss in a medium!**

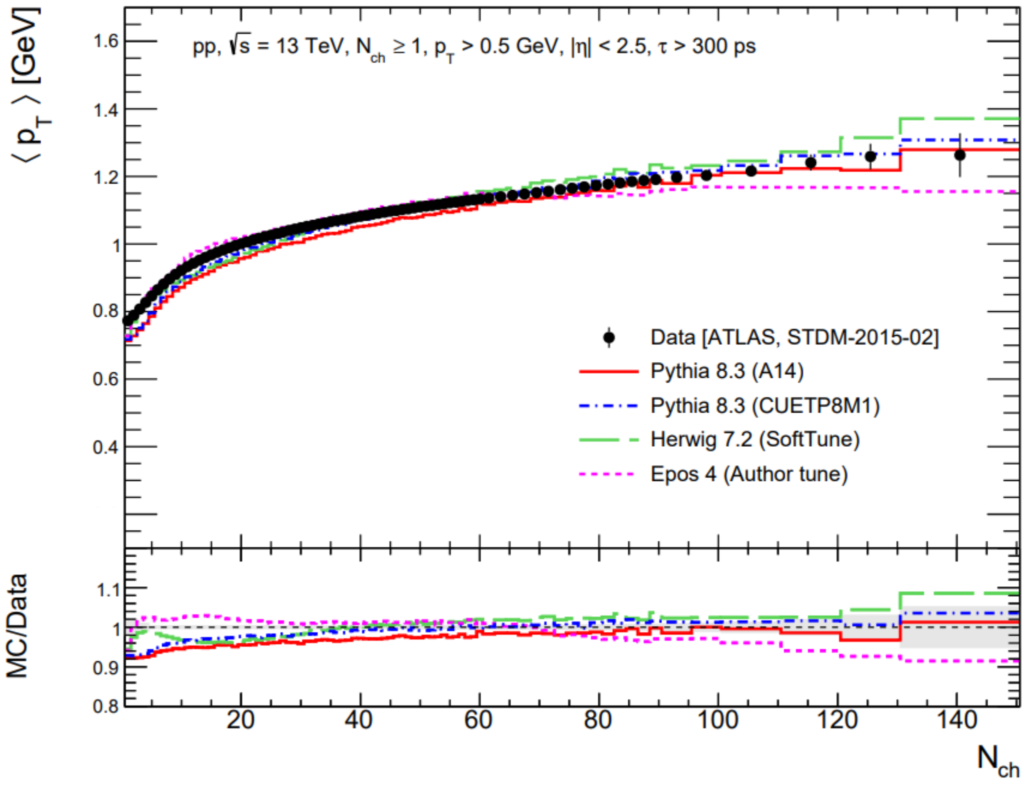
The usual way of presenting the <pt>evolution

Even applying event shape criteria: jetty and isotropic the mean pt does not go beyond 1 GeV

Lets see how do the spectra evolve in multiplicity bins…



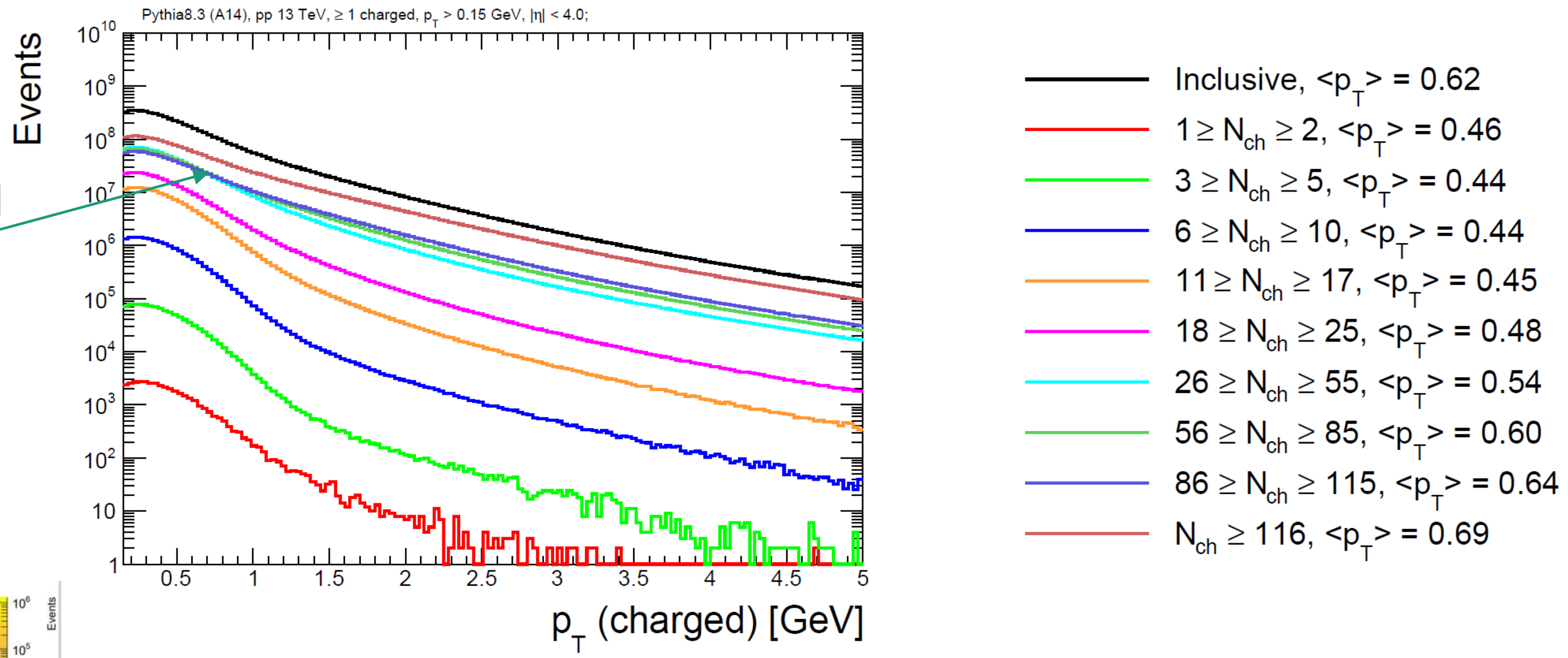
Different models can give similar mean values and yet have very different behavior

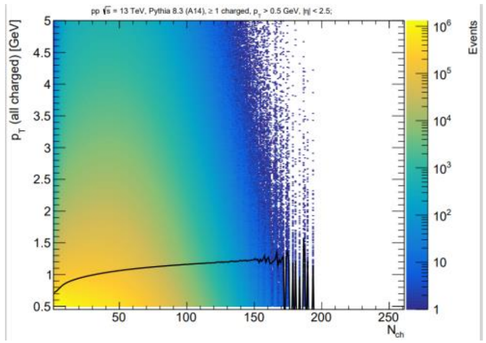


Pythia8.3, pT > 0.15 GeV, |η| < 4.0

Instead of plotting the mean pt in function of multiplicity we compare the pt spectra for each multiplicity bin! The simulation shows interesting behavior

Note the evolution in shape of the spectra and the crossing at ~ 1.5 GeV/c





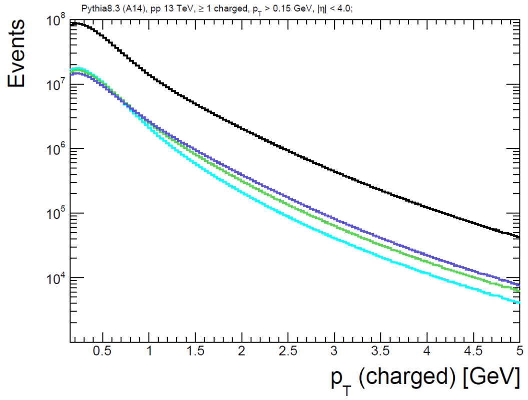
The 3D plot of Pythia pt vs multiplicity

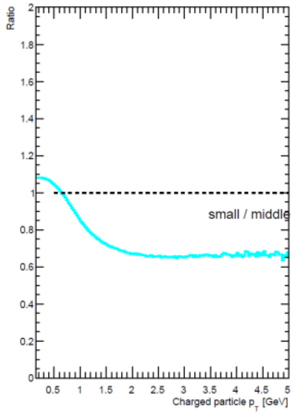
The mean reflects only a small part of the real situation – outliers are out hiding there?

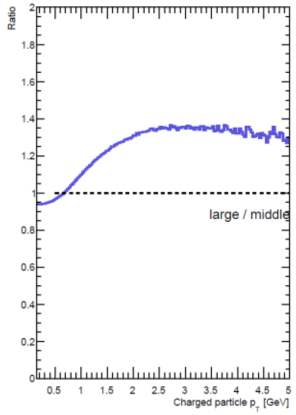
The model comparison much more sensitive than with the "total" approach!

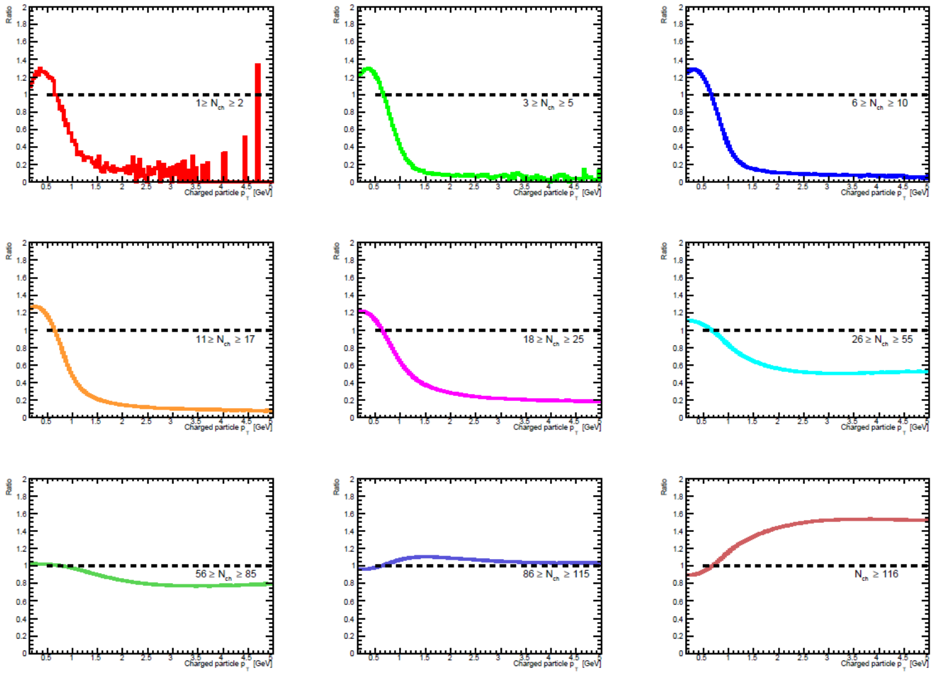
Pythia8.3, pT > 0.15 GeV, |η| < 4.0

Ratio to inclusive in 9 bins of Nch – rapid changes and zoom on the crossing spercra





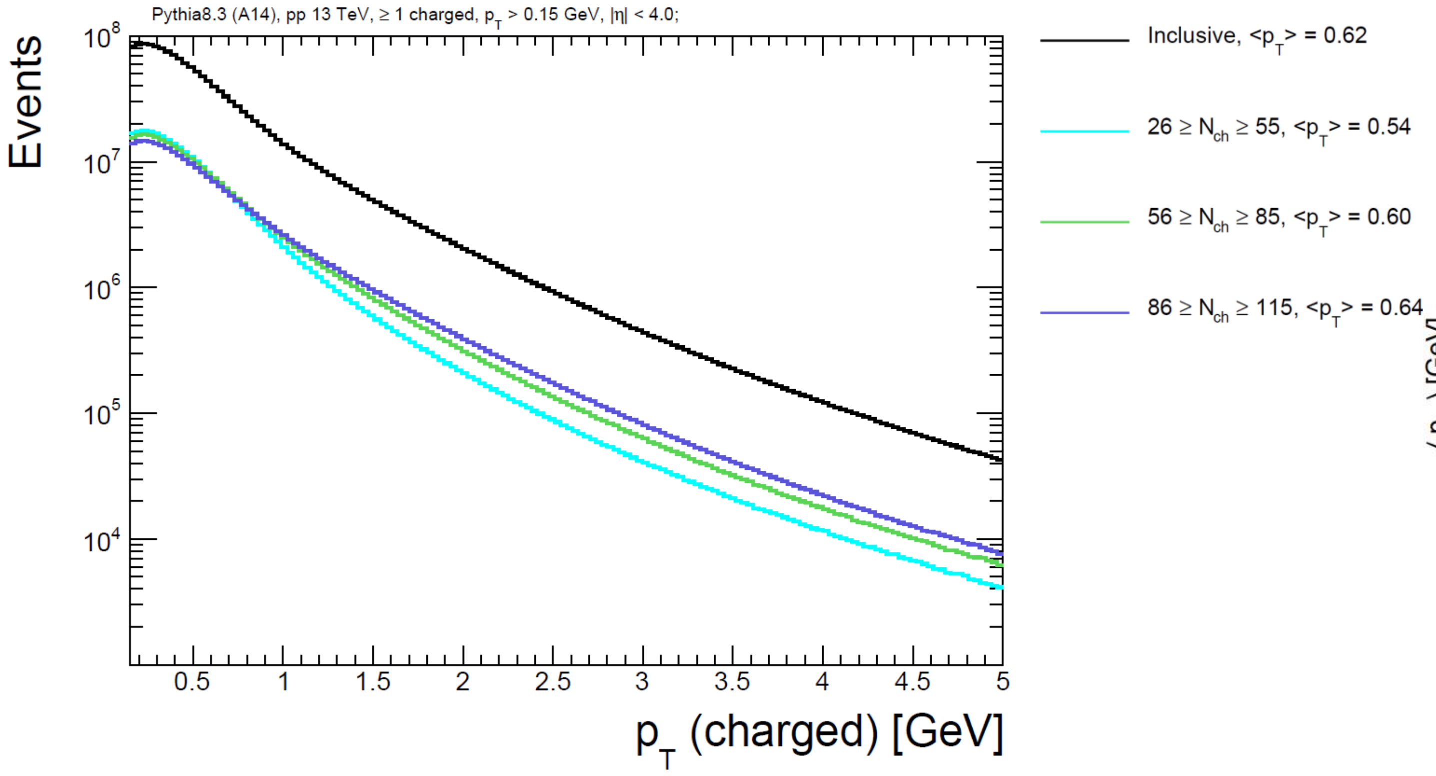


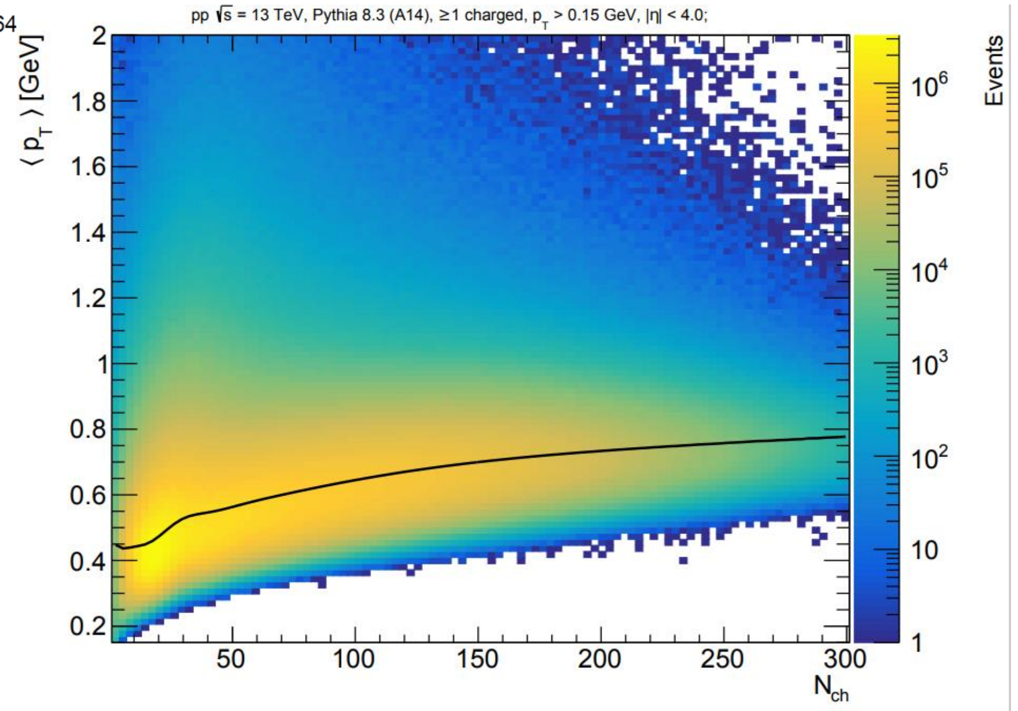


Within a small multiplicity range important change of shape!

Pythia8.3, pT > 0.15 GeV, |η| < 4.0

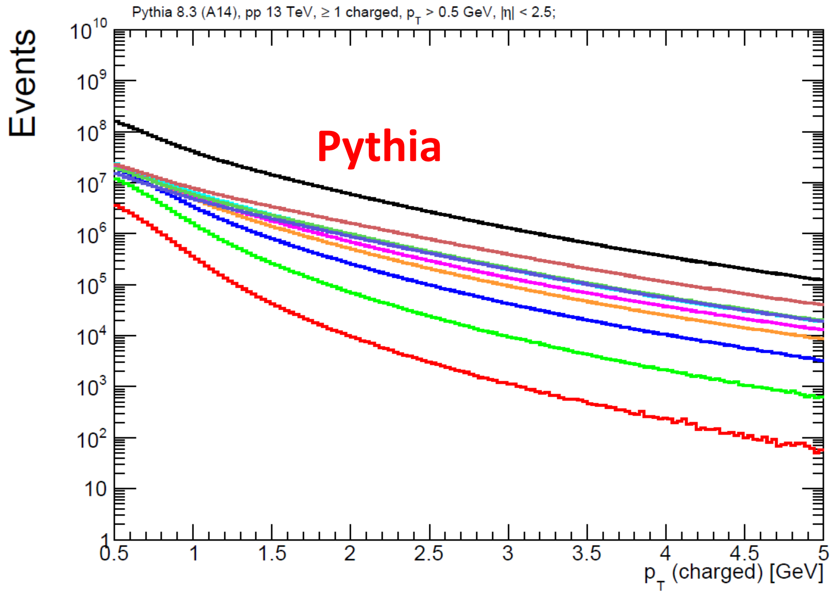
Zooming:

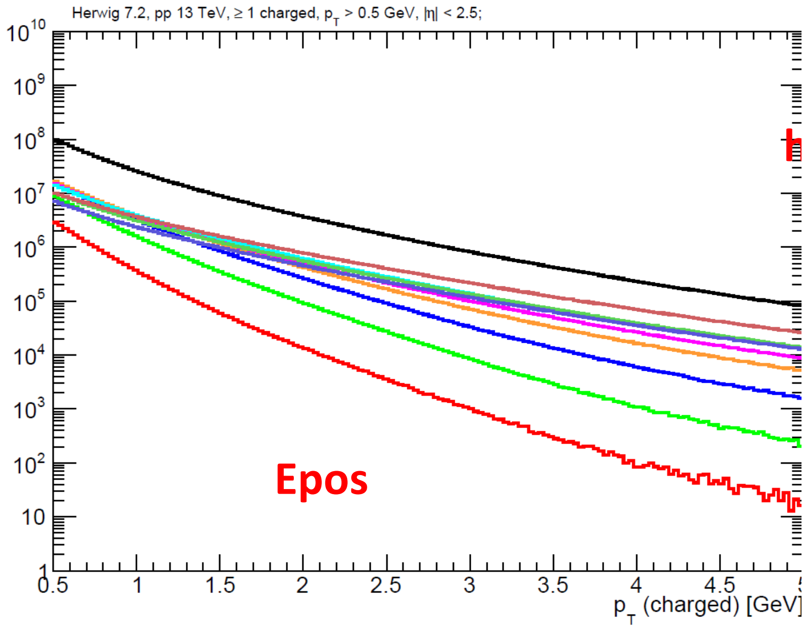


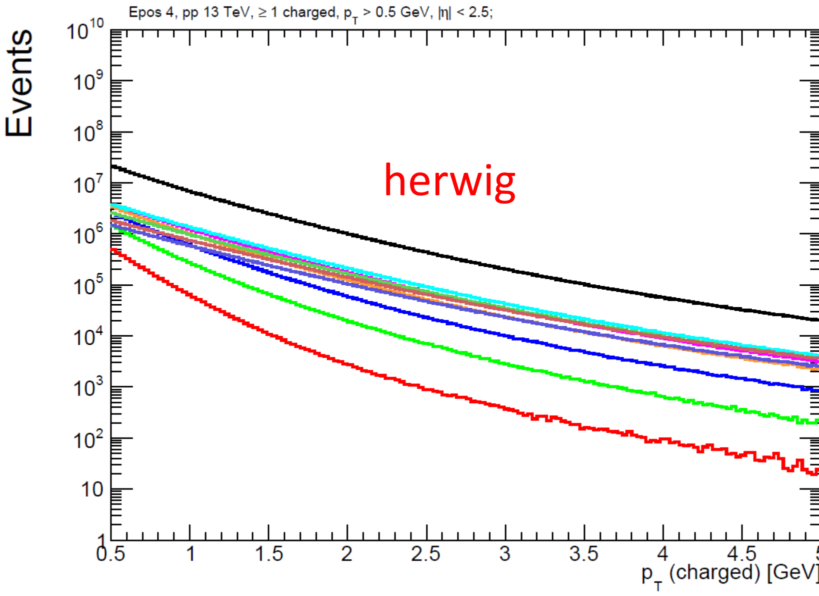


Note the crossing at ~ .8 Gev/c!

Pythia vs Herwig vs Epos in the pT distribution







Small differences in the mean pt's but important differences in the spectra!

Pythia	Herwig	Epos
Inclusive, $\langle p_T \rangle$ = 0.98	Inclusive, $\langle p_T \rangle$ = 0.99	Inclusive, $\langle p_T \rangle$ = 1.02
$1 \geq N_{ch} \geq 2$, $\langle p_T \rangle$ = 0.72	$1 \geq N_{ch} \geq 2$, $\langle p_T \rangle$ = 0.76	$1 \geq N_{ch} \geq 2$, $\langle p_T \rangle$ = 0.77
$3 \geq N_{ch} \geq 5$, $\langle p_T \rangle$ = 0.77	$3 \geq N_{ch} \geq 5$, $\langle p_T \rangle$ = 0.82	$3 \geq N_{ch} \geq 5$, $\langle p_T \rangle$ = 0.85
$6 \geq N_{ch} \geq 10$, $\langle p_T \rangle$ = 0.84	$6 \geq N_{ch} \geq 10$, $\langle p_T \rangle$ = 0.87	$6 \geq N_{ch} \geq 10$, $\langle p_T \rangle$ = 0.91
$11 \geq N_{ch} \geq 17$, $\langle p_T \rangle$ = 0.90	$11 \geq N_{ch} \geq 17$, $\langle p_T \rangle$ = 0.92	$11 \geq N_{ch} \geq 17$, $\langle p_T \rangle$ = 0.98
$18 \geq N_{ch} \geq 25$, $\langle p_T \rangle$ = 0.95	$18 \geq N_{ch} \geq 25$, $\langle p_T \rangle$ = 0.97	$18 \geq N_{ch} \geq 25$, $\langle p_T \rangle$ = 1.01
$26 \geq N_{ch} \geq 35$, $\langle p_T \rangle$ = 1.00	$26 \geq N_{ch} \geq 35$, $\langle p_T \rangle$ = 1.02	$26 \geq N_{ch} \geq 35$, $\langle p_T \rangle$ = 1.05
$36 \geq N_{ch} \geq 45$, $\langle p_T \rangle$ = 1.03	$36 \geq N_{ch} \geq 45$, $\langle p_T \rangle$ = 1.06	$36 \geq N_{ch} \geq 45$, $\langle p_T \rangle$ = 1.07
$46 \geq N_{ch} \geq 55$, $\langle p_T \rangle$ = 1.07	$46 \geq N_{ch} \geq 55$, $\langle p_T \rangle$ = 1.10	$46 \geq N_{ch} \geq 55$, $\langle p_T \rangle$ = 1.09
$N_{ch} \geq 56$, $\langle p_T \rangle$ = 1.11	$N_{ch} \geq 56$, $\langle p_T \rangle$ = 1.15	$N_{ch} \geq 56$, $\langle p_T \rangle$ = 1.11

Conclusion 1

- The detailed investigation of the spectra in function of pt has a larger sensitivity than the mere means.
- The means do not reflect completely the situation!
- We should try to push for more details!

And now something completely different

- The hedgehogs

If all the earlier works were focused to low multiplicities reported feature by UA1 and CDF That occurs at the othe multiplicity spectrum

Always with the idea to study rare evnts which may give insights

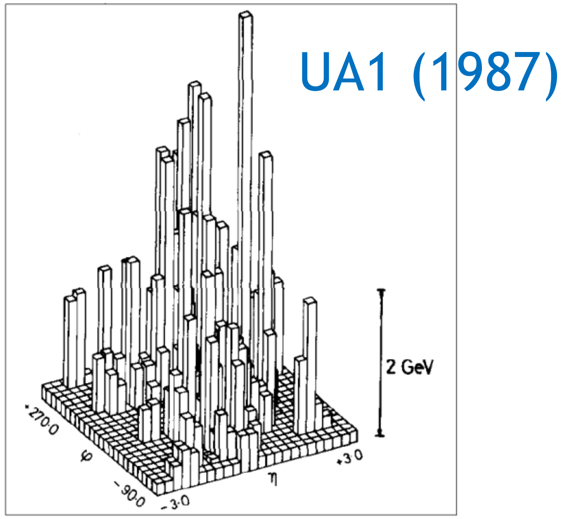
"hedgehog" events

- The UA1 and CDF collaborations have reported the presence of events with a very extended structure of low momentum tracks filling in a uniform way the pseudorapidity-azimuth (η-φ) phase space.

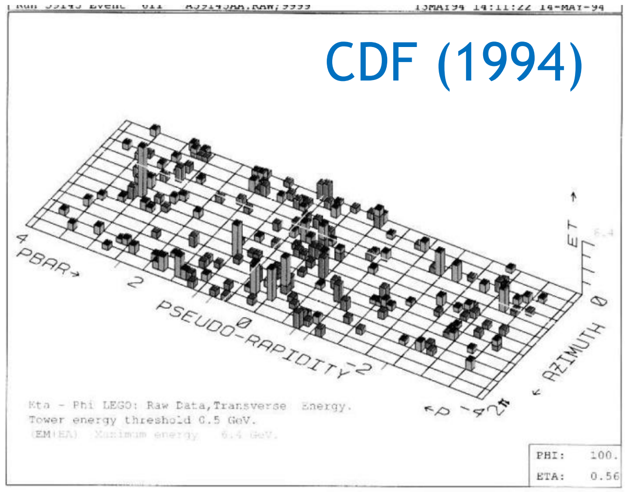
- First dedicated analysis of highest E_T events seen in the UA1 detector at √s = 630 GeV (with isotropic events with E_T ~ 210 GeV) – no evidence for non-QCD mechanism for these events.

- Unusual events observed in ppbar collisions at √s = 1.8 TeV by CDF's Run 1 detector with more than 60 charged particles and ~320 GeV of transverse energy (E_T) – called "**hedgehog**" events by C. Quigg.

- Taken for granted that in these events with high E_T perturbative aspects of QCD dominate the event properties: multi-jet events.



UA1 Collaboration, Zeit. für Phys. C, V. 36, p. 33 (1987)



C. Quigg, Il Nuovo Cimento, V. 33C, N. 5 p. 327 (2010)

Event structures – key to understanding!

- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using transverse sphericity:

$$S_{\perp} = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}, \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an **under-estimation** of isotropic events by MC generators at high charged multiplicity

  ✓ Suggests that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

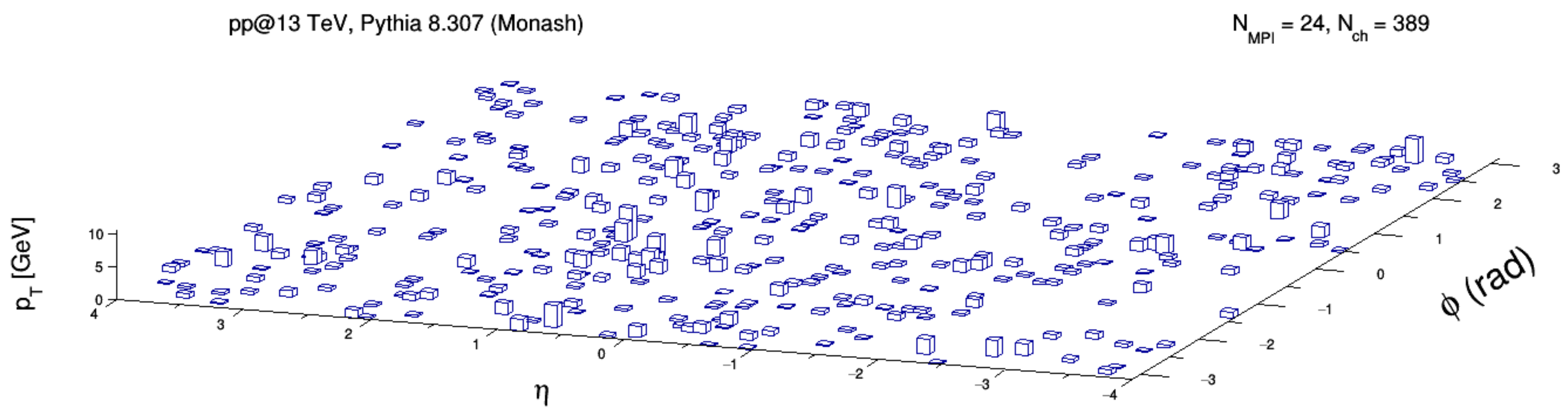
- ALICE measurement shows that $<p_T>$ as a function of N_{ch} in isotropic events was found to be **smaller** than that measured in jet-like events, and that for jet-like events, the $<p_T>$ is **over-estimated** by PYTHIA 6 and 8 models.

- **Recently, a new event shape parameter, flattenicity**, was proposed [A. Ortiz, G. Paic, Rev. Mex. Fis. Suppl. 3 (2022) 4, 040911] that allows one to identify and characterise high-multiplicity events with a quasi-isotropic distribution in a wide pseudorapidity range in proton-proton collisions.

- MC event generators reproduce “hedgehog” events, which opens the possibility to study their properties and find a way to experimentally trigger these events.

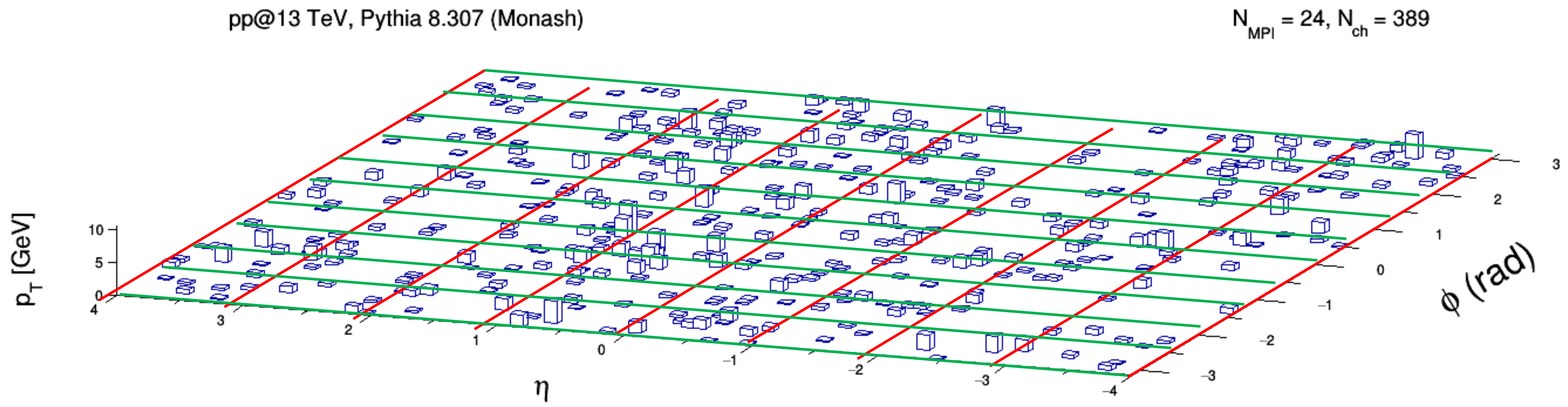
Calculating flattenicity

- The idea: find out how uniform the p_T of tracks is distributed in a given event!



Calculating flattenicity

- Build **8** x **10** grid in (η-φ) space:



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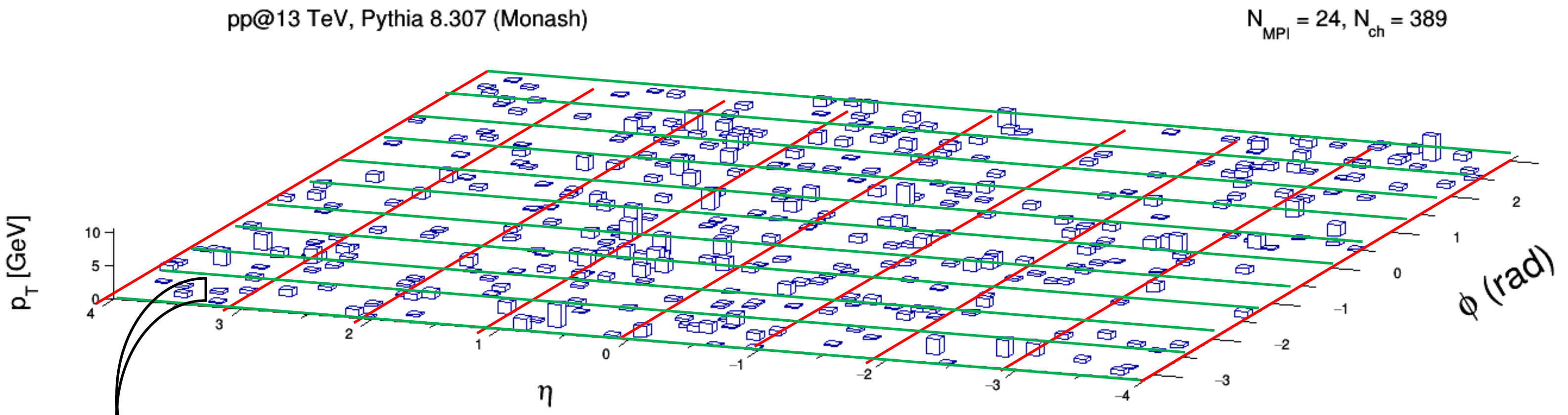
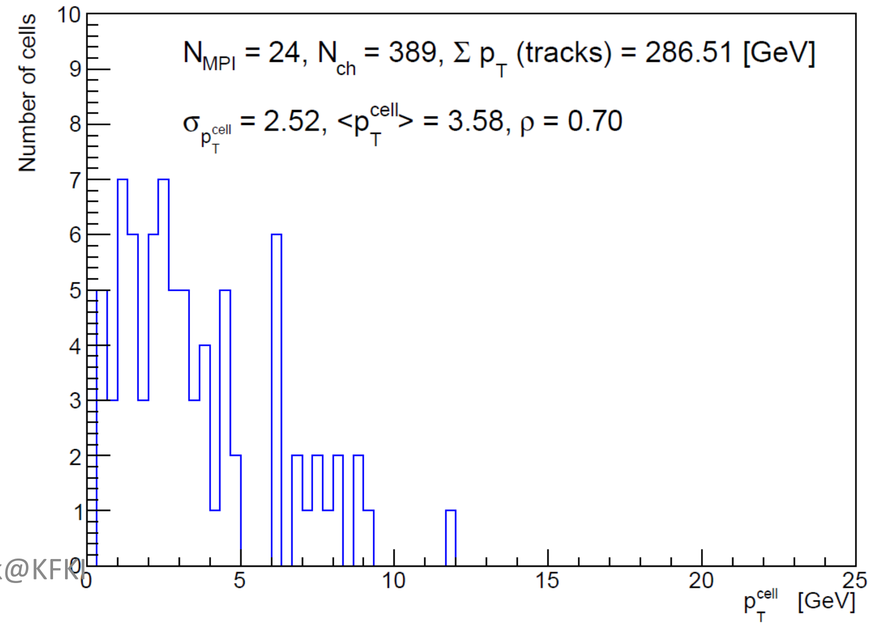


In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$



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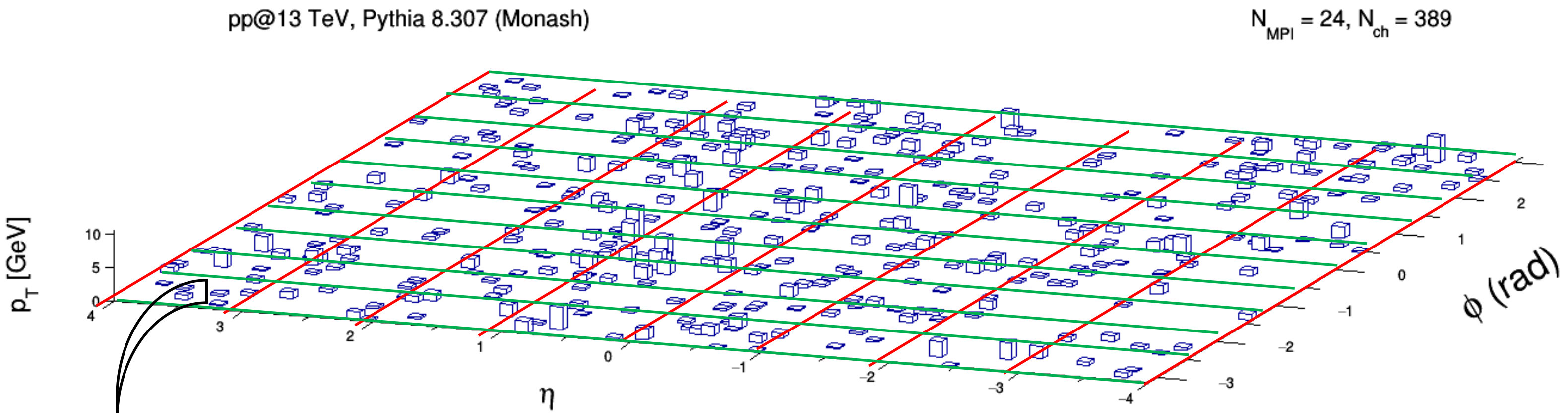
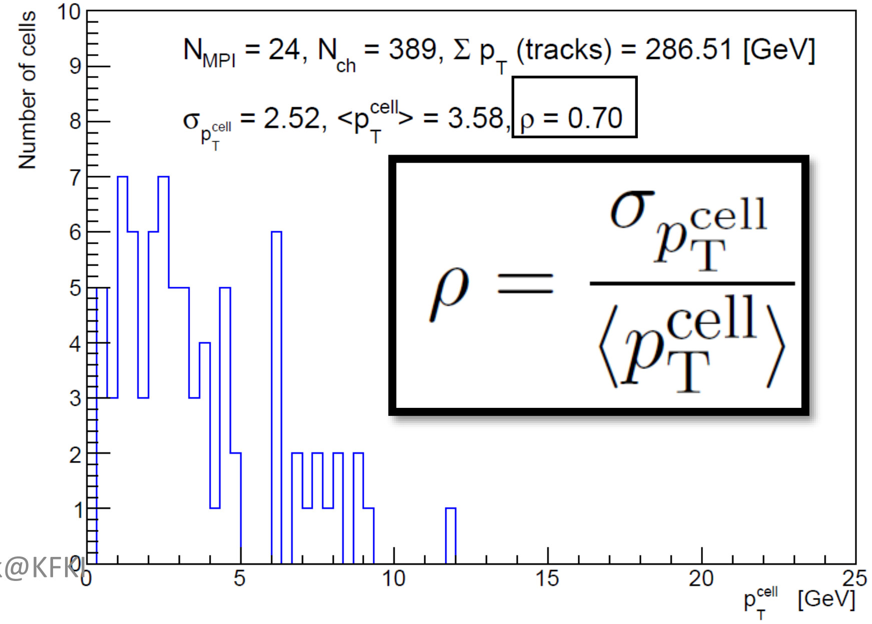


In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.

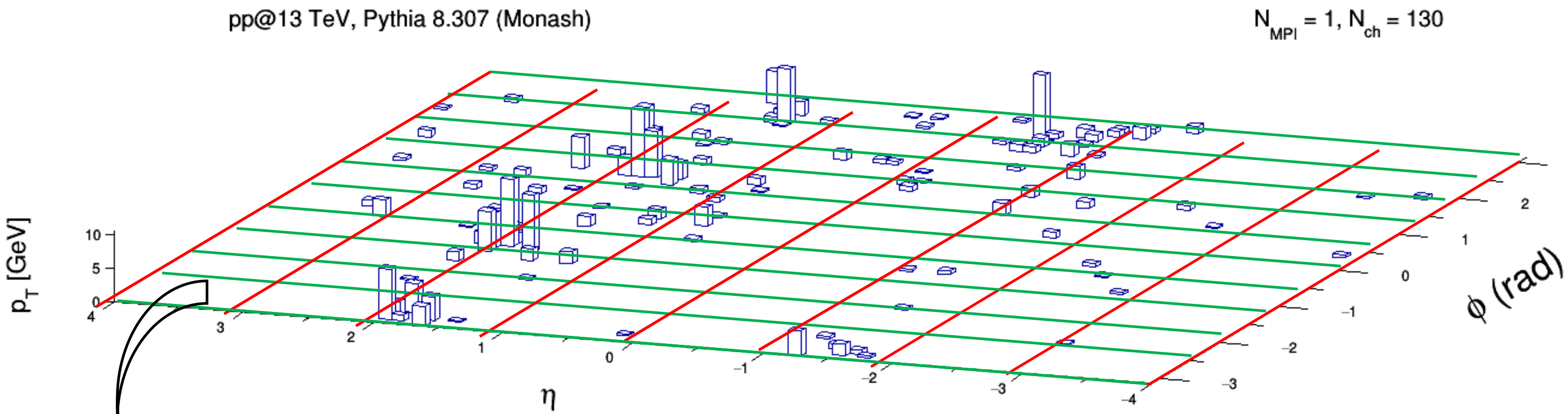
- Events with isotropic distribution of particles (“**hedgehogs**”) are expected to have **a small value of flattenicity** (ρ < 1).



$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

Calculating flattenicity

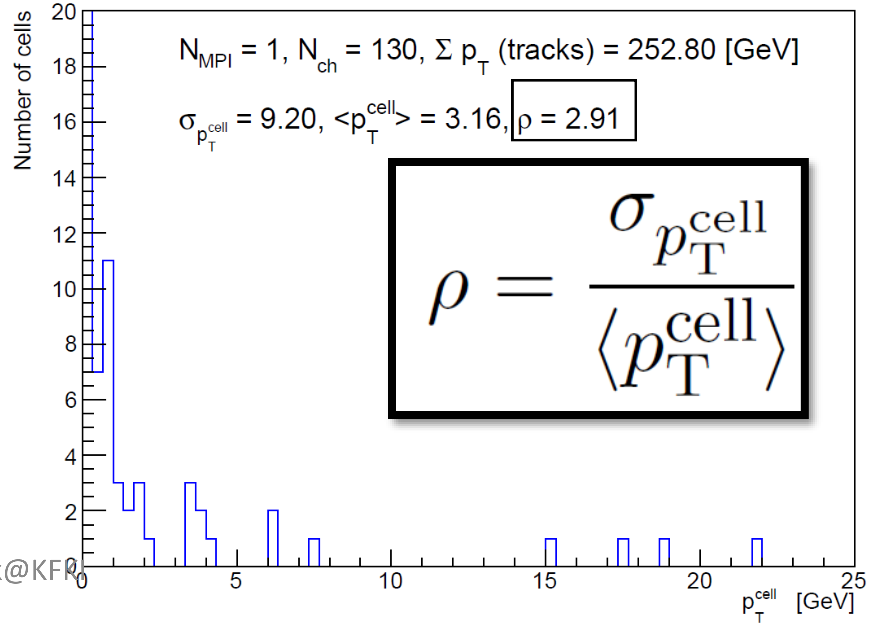
- Build **8** x **10** grid in (η-φ) space:



In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.

- Events with **jet-like** structures are expected to have **larger values** of ρ.



$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

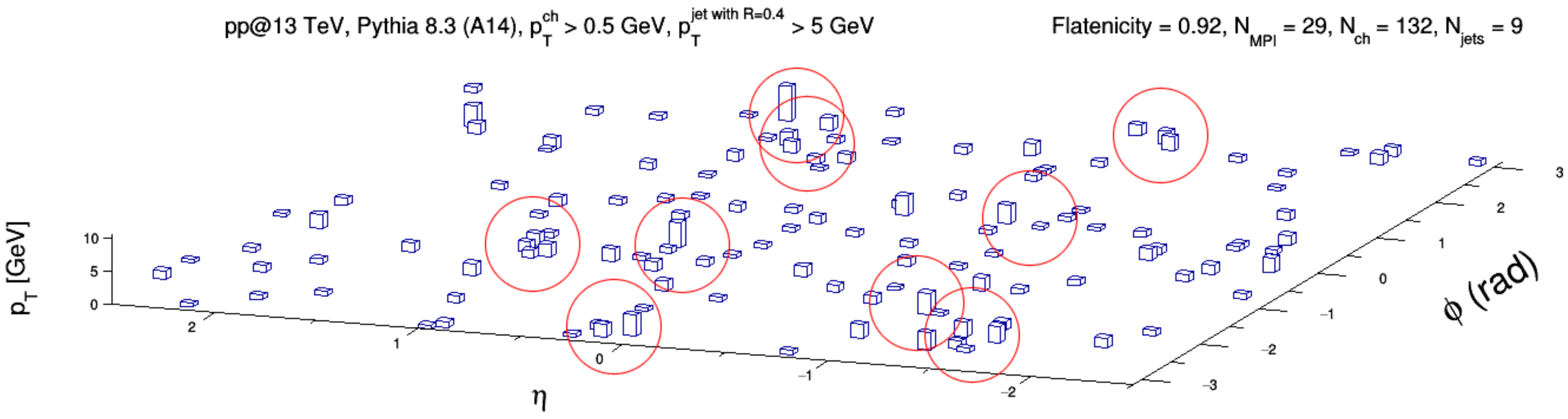
A more recent redefinition of flattenicity

- Flattenicity: $$\rho = 1 - \frac{\sqrt{\sum_i \left(p_T^{cell,i} - < p_T^{cell} >\right)^2 / N_{cell}^2}}{< p_T^{cell} >}$$

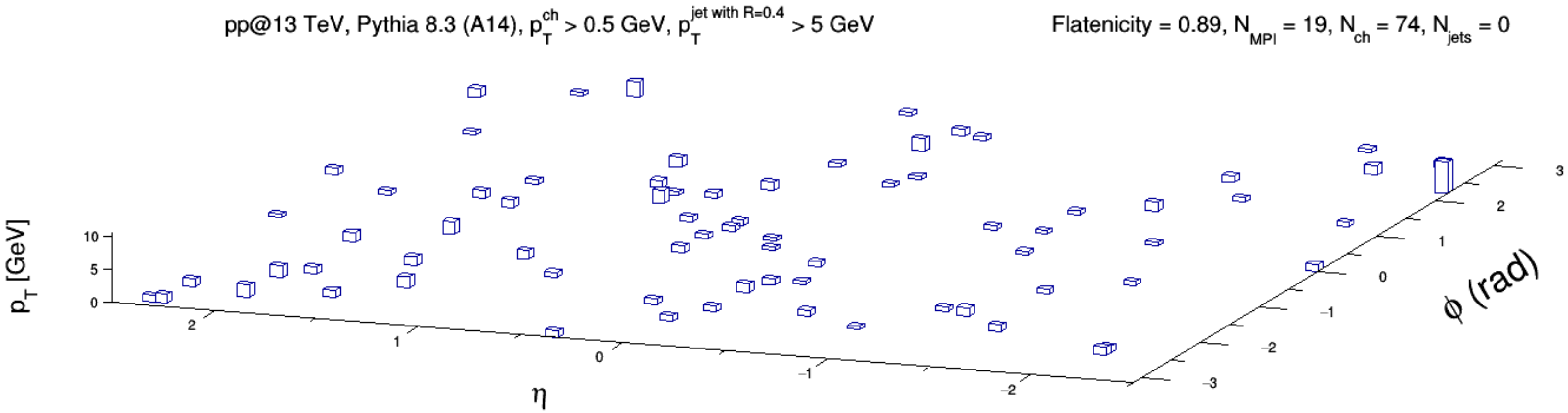
- By using this definition, the values of ρ go from 0 to 1 (as other event shapes).
- Events with **values close to 1** are associated with the **hedgehog** topologies.
- Events with **jet-like** structures are expected to have **smaller values** of ρ.
- A total of 120 cells (stability of flattenicity against variations in the size of the cells was studies anf found consistent within a few percent) allows the area of each cell (Δη = 0.50, Δφ ~ 0.52) to be closely related to a jet area defined with ΔR = 0.4.

Analysing flattenicity vs N_{ch}

- With the **0 - 1% flattenicity percentile selection**, we can clearly see **hedgehogs**:
  - with high N(charged) and jet production:

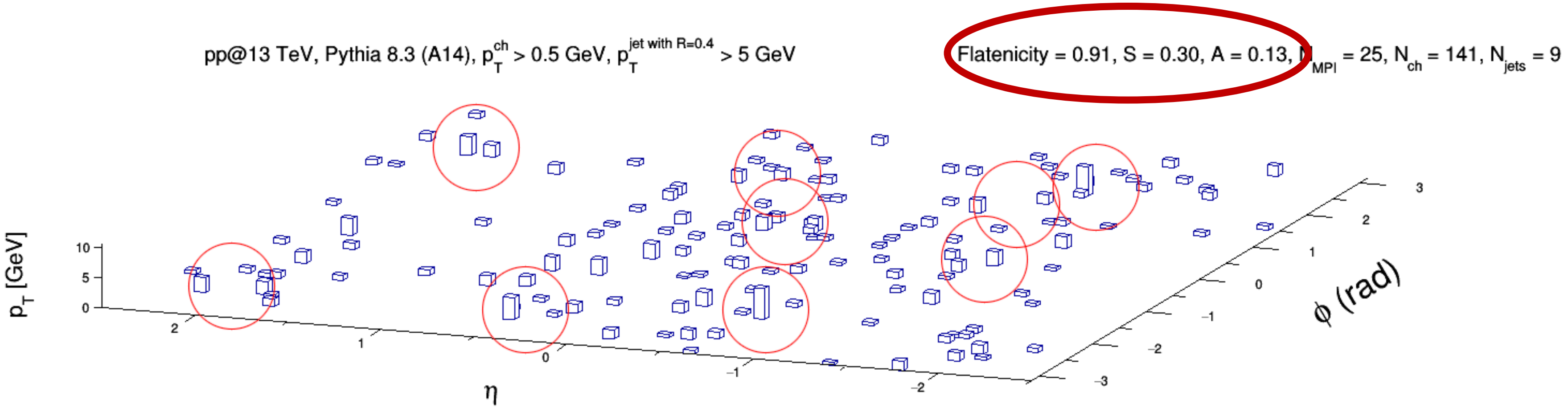


  - with lower N(charged) and **no jet production**:

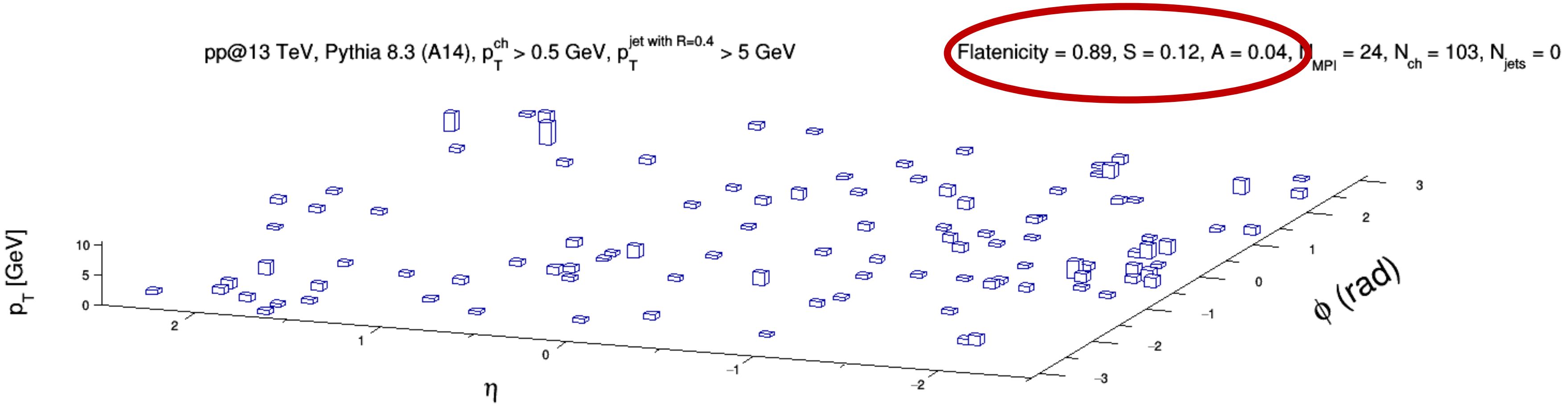


Two sorts of hedgehogs with and without jets – to be studied

ρ > 0.88 and Nch > 140

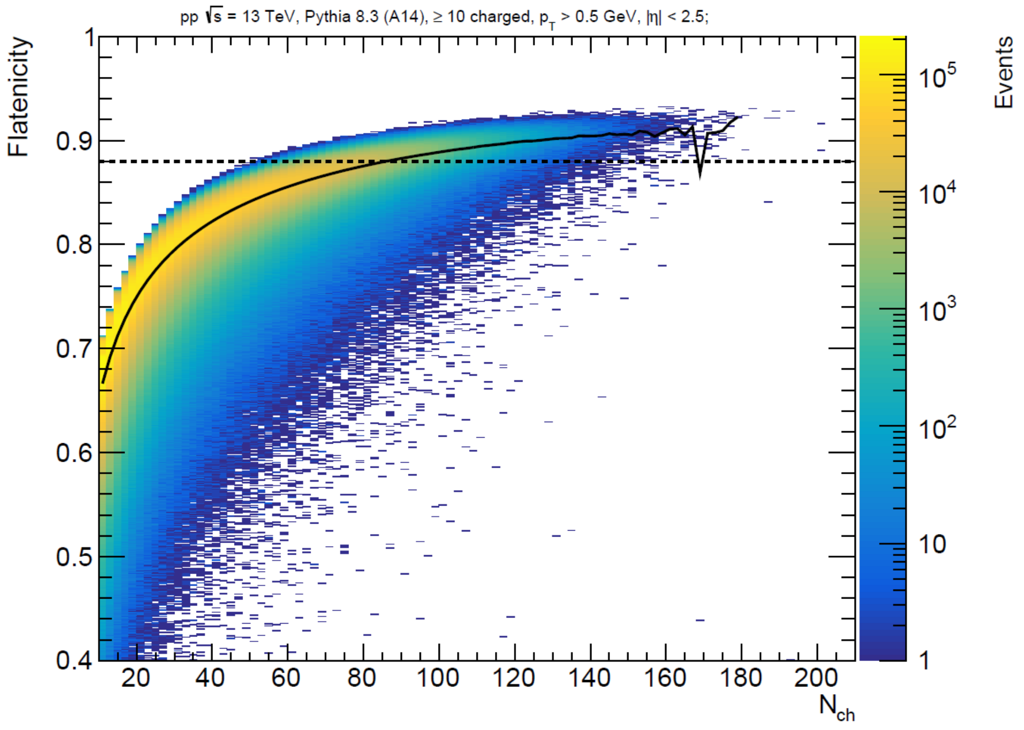


ρ > 0.88 and Nch > 100 and no jets



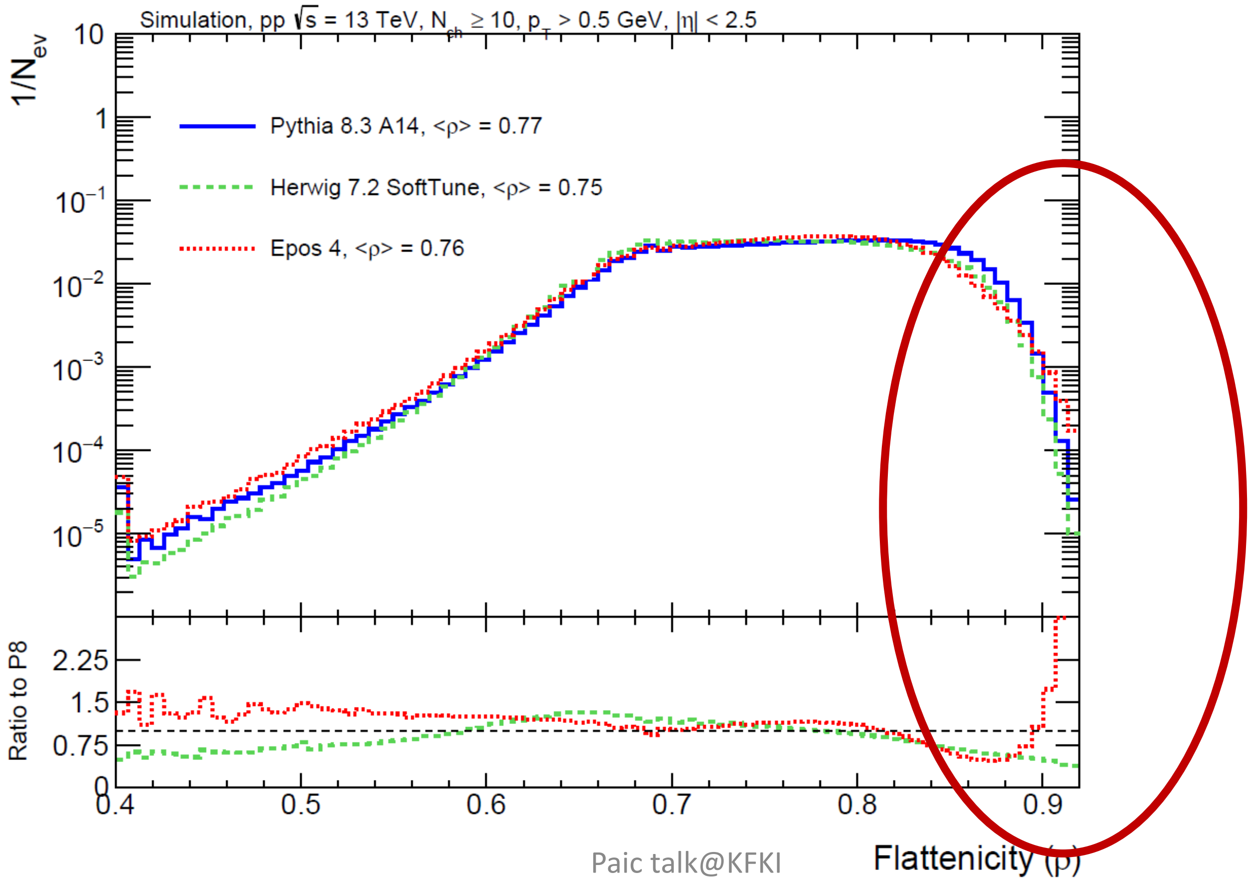
Are hedgehogs rare animals?

- We can select the 0 – 1% percentile event class based on the flattenicity value of ρ > 0.88, denoted with dashed line in the N(charged) vs ρ map:



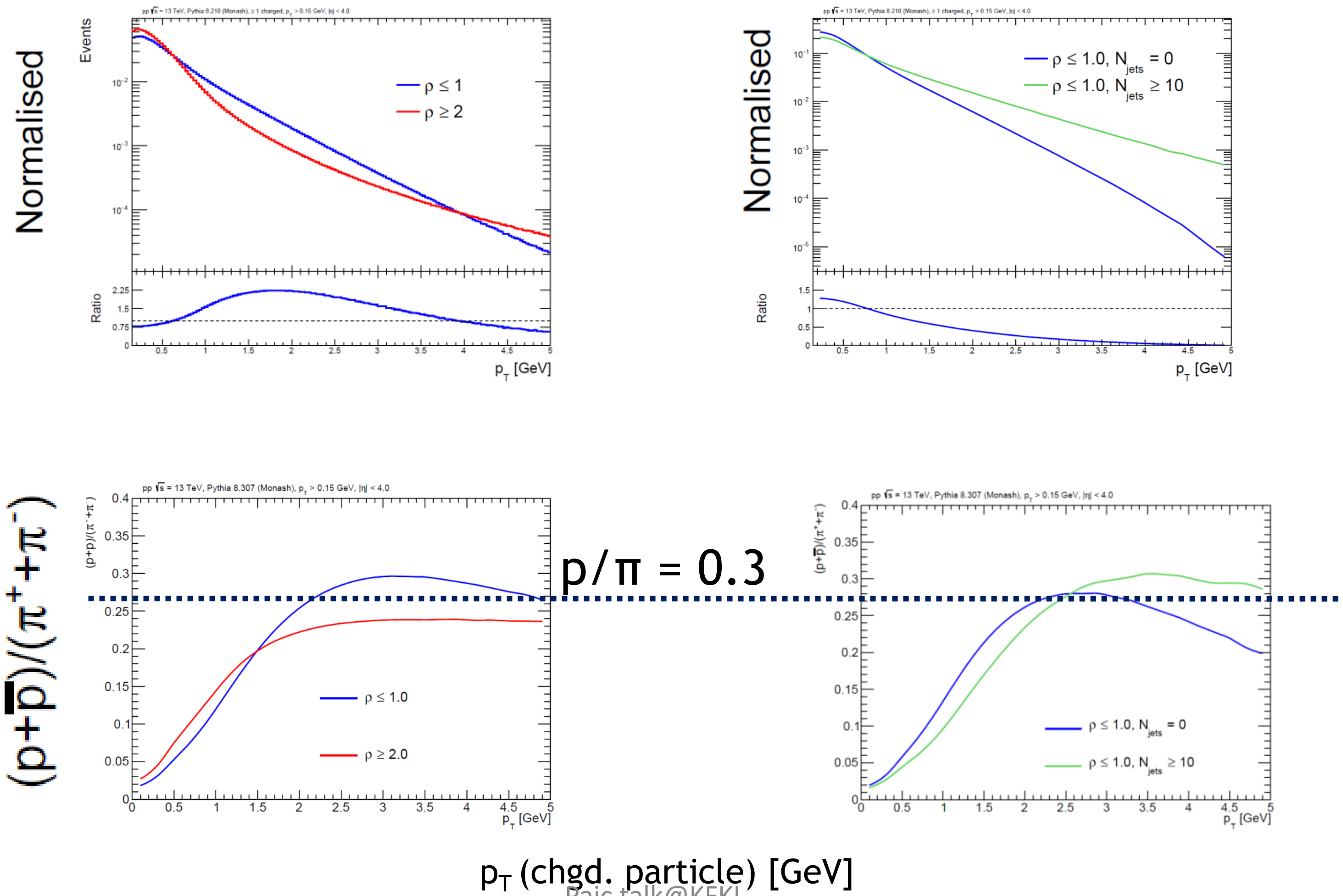
~500M events

Comparing flatenicity with different generators



Analysing flattenicity vs chgd. particle p_T and p/π ratio

- We study the p_T (particle) as well as the proton-to-pion ratio in 0.15 to 5 GeV interval by selecting events with ρ < 1 and ρ > 2. For events with ρ < 1, we also select jetty events (≥10 jets with min p_T(jet) = 5 GeV) and events with no jets at all.

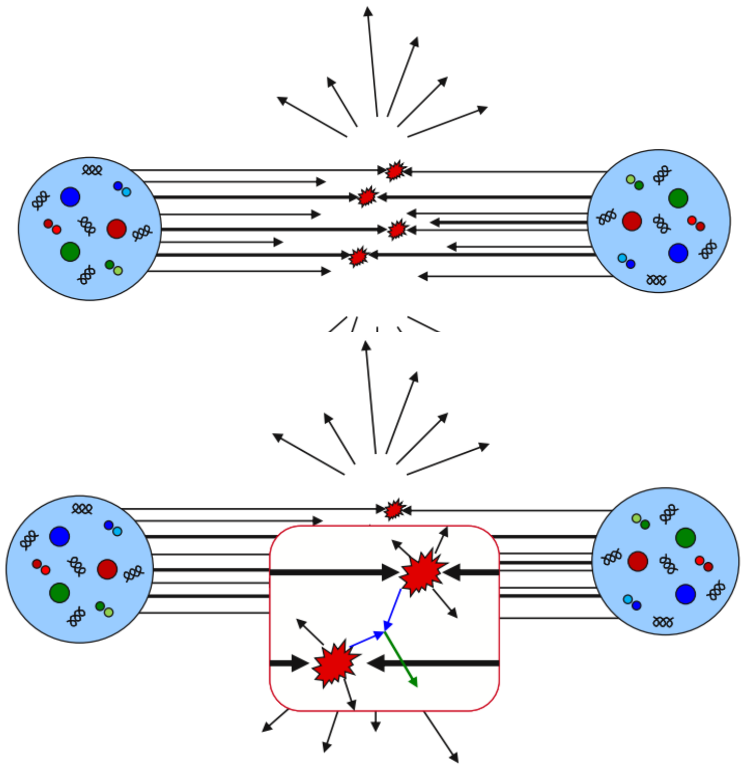


conclusion

- We found two regions that to my knowledge have never been truly studied
  - The low multiplicity behavior of the “mean pt”
  - Hedgehog events – the important baryo chemistry
- plenty of possibilities to study these events and it even may shed light on the “energy re-distribution” effect in pp collisions.
- Was the early universe in a hedgehog state?

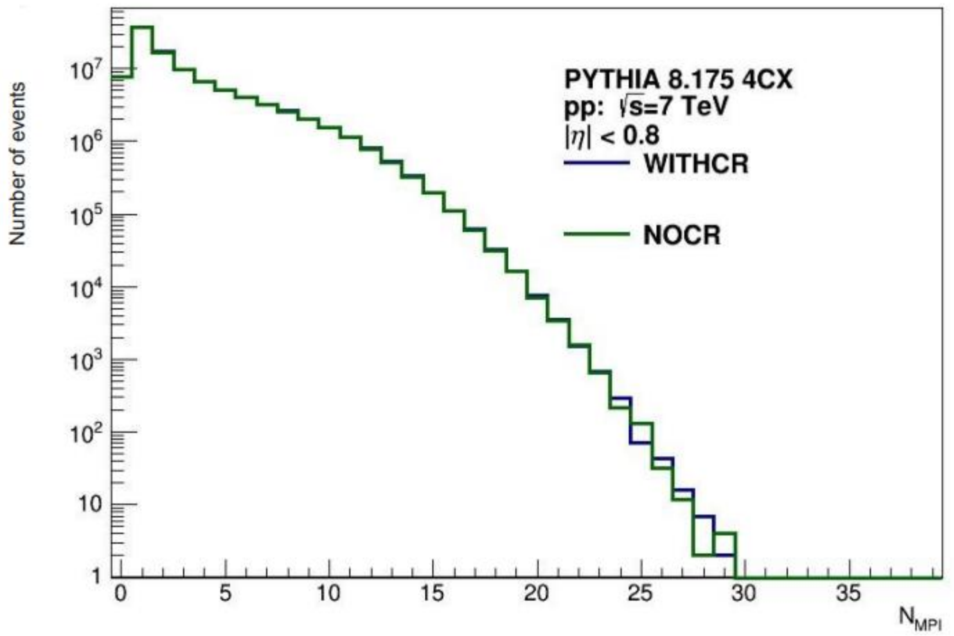
Thanks!

Multiparton interactions and color reconnection in a simple way



From StefanHeckel

Number of events versus number of parton-parton interactions

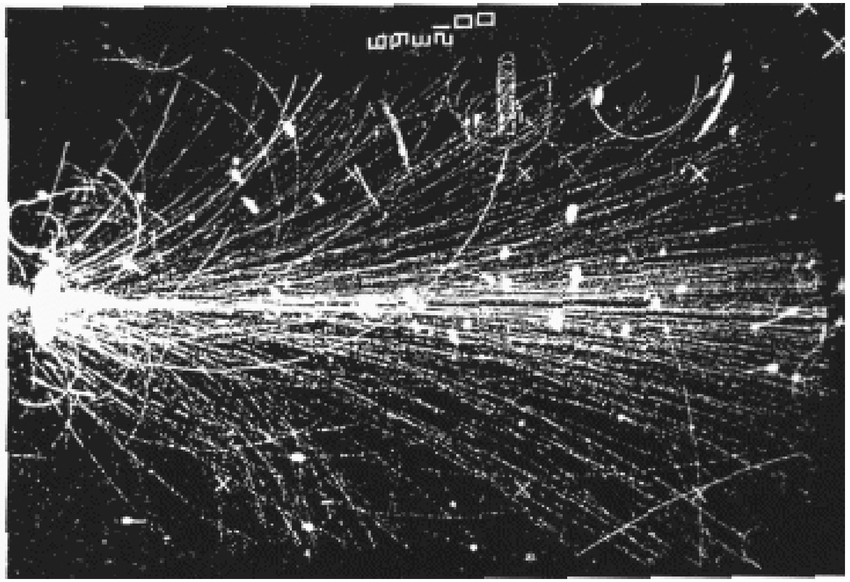


- N_{MPI} = Number of Multi-Parton Interactions
- Peak at N_{MPI} = 1 (about 35%), maximum at $N_{MPI} \approx 30$

Event structure analysis in pp minimum bias events

or the truth is in the details

Guy Paic and A.Ortiz



Prague – 2011!!

Final remarks

- We have seen the wealth of event shapes that Pythia offers in pp collisions.
- Unfortunately, the question has also semi political implications since

A lot of work and publicity has been made around the QGP