Forward-backward correlations with strange particles in PYTHIA

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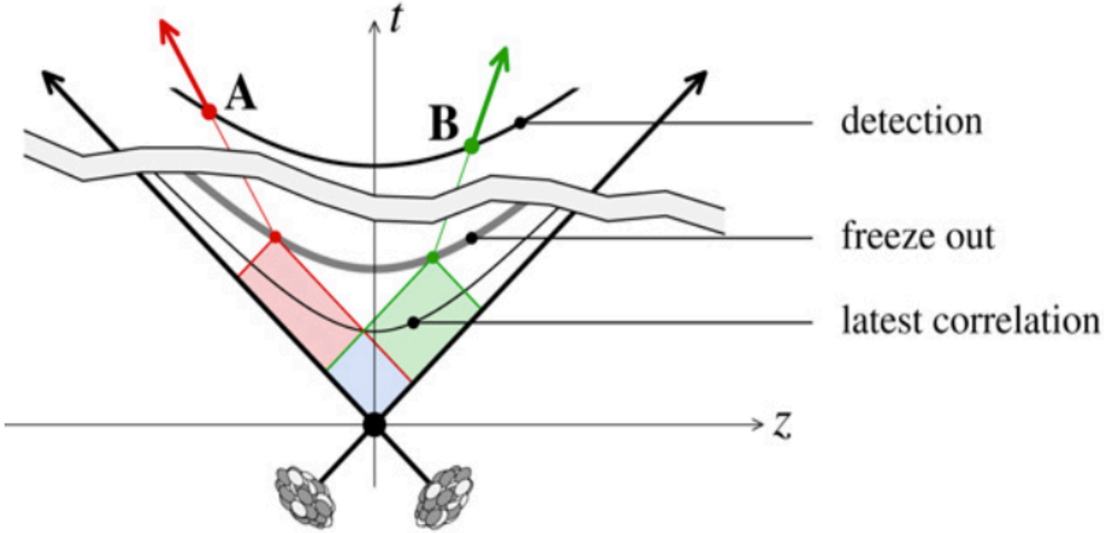
SQM-2015, Dubna

Outline

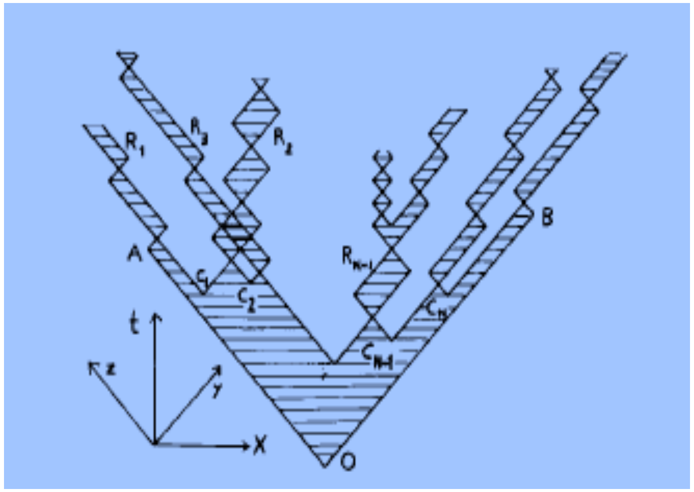
- FB correlations of multiplicities
- Motivation for new types of FB correlations
- PYTHIA: color reconnection as a collective behavior
- FB correlations with strange particles in PYTHIA8

Forward-Backward (*or* Long-Range) correlations

Causality requires appearance of long-range correlations at the very early stages between particles detected in separated rapidity intervals in any type of collisions (pp, pA, AA):



A.Dumitru et al., Nuclear Physics A 810 (2008) 91-108



X. ARTRU and G. MENNESSIER,
"STRING MODEL AND MULTIPRODUCTION",
Nuclear Physics B70 (1974) 93-115

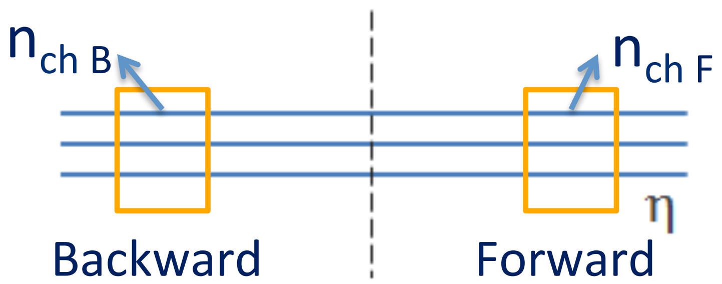
Long-range correlations originate from fluctuations in the number and properties of particle emitting sources (like strings).

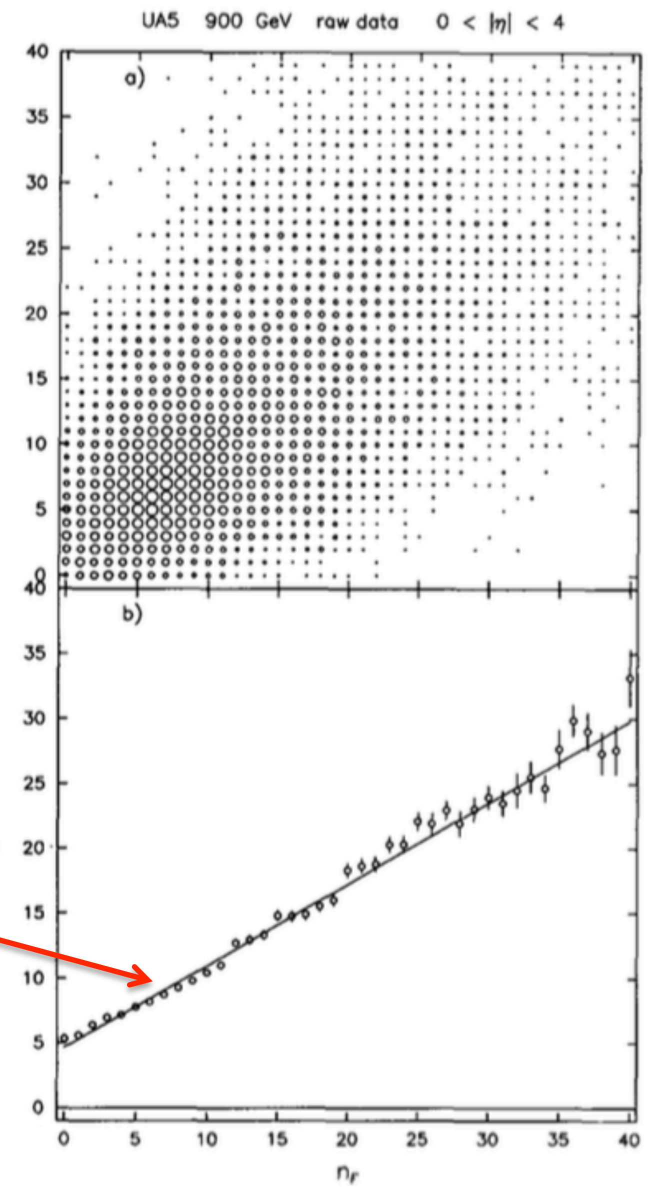
The first early experimental indications of FB multiplicity correlations *(1988)*

Charged particle correlations in $\bar{p}p$ collisions at c.m. energies of 200, 546 and 900 GeV

UA5 Collaboration

Z.Phys. C 37, 191-213 (1988)





Correlation strength is extracted by:

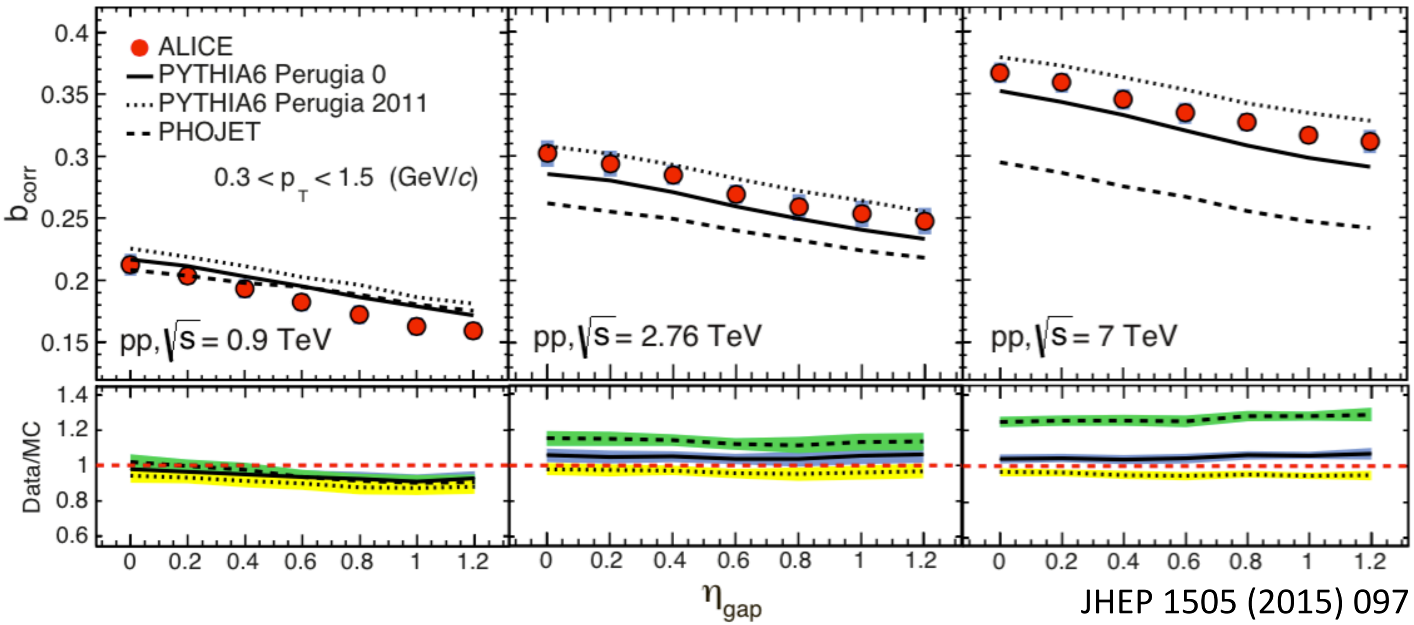
1) linear regression $\langle n_B \rangle_{n_F} = a + b_{corr} \cdot n_F$

2) “correlator”:

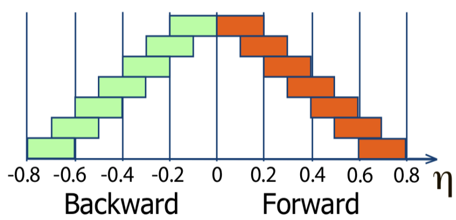
$$b_{corr} = \frac{\langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$

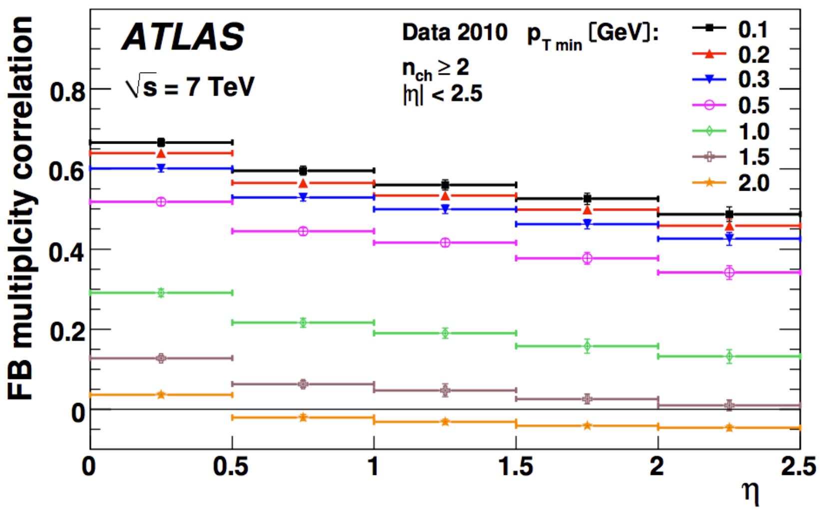
A.Capella et al.,Phys.Rep. 236,225 (1994)

FB multiplicity correlations in pp collisions in separated η windows



JHEP 1505 (2015) 097

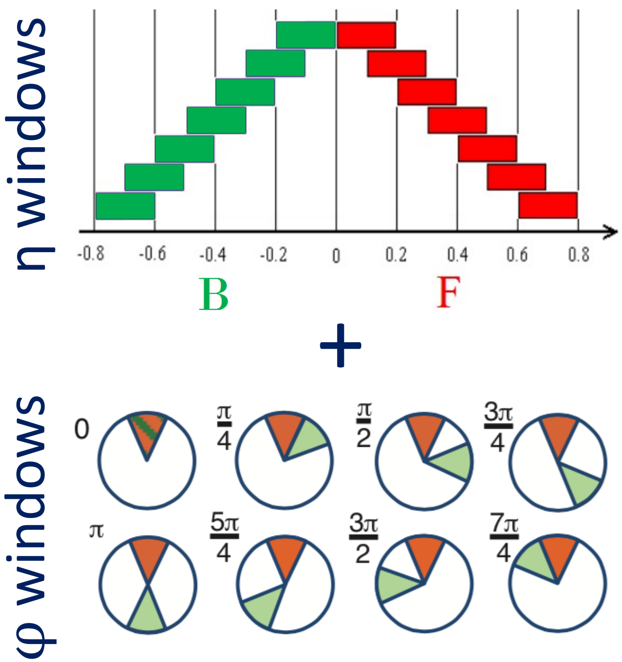


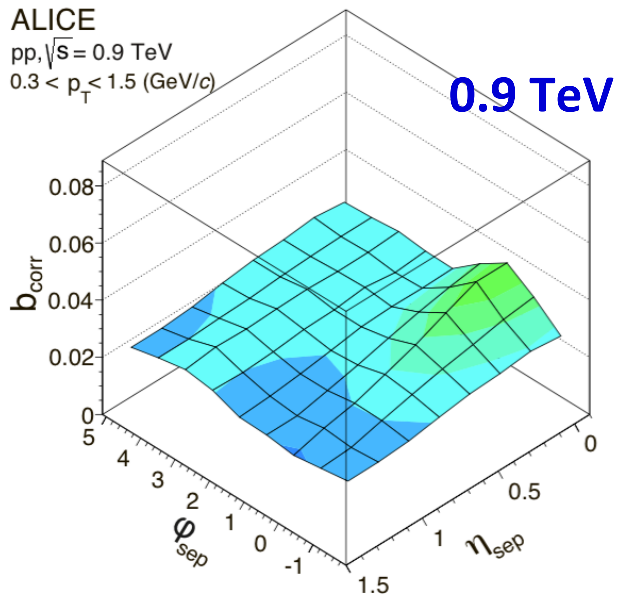


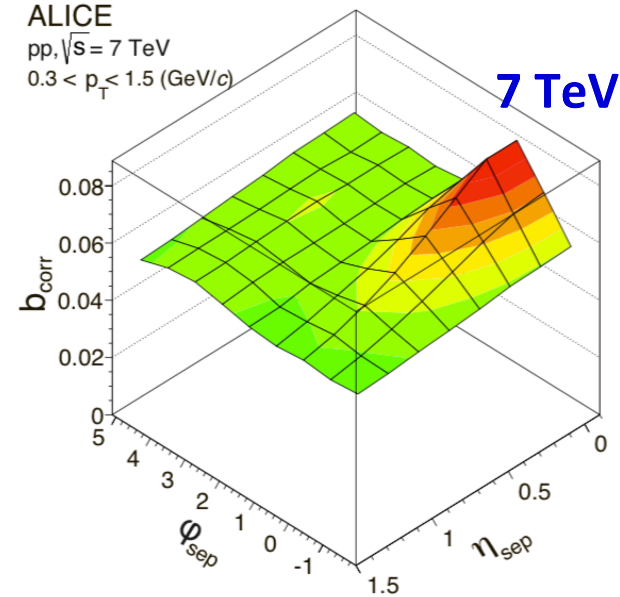
JHEP07(2012)019

- trends are reproduced by MC
- PYTHIA6 reproduce the numbers better than PHOJET

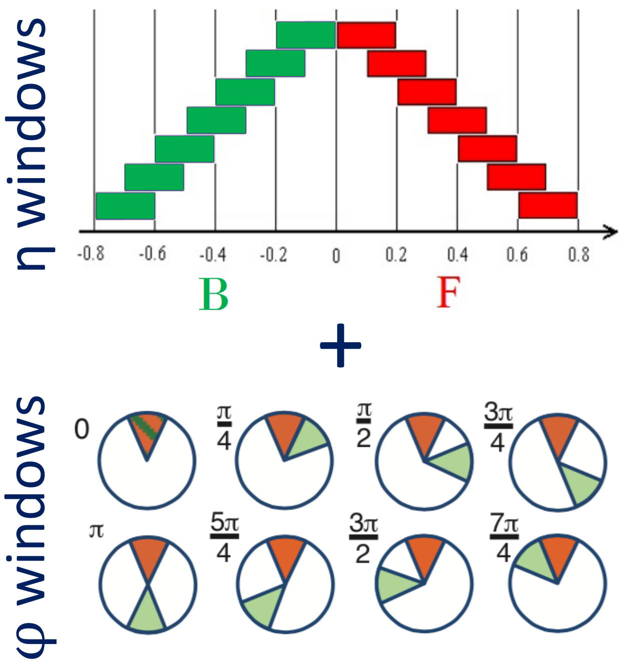
FB multiplicity correlations in separated η and φ windows

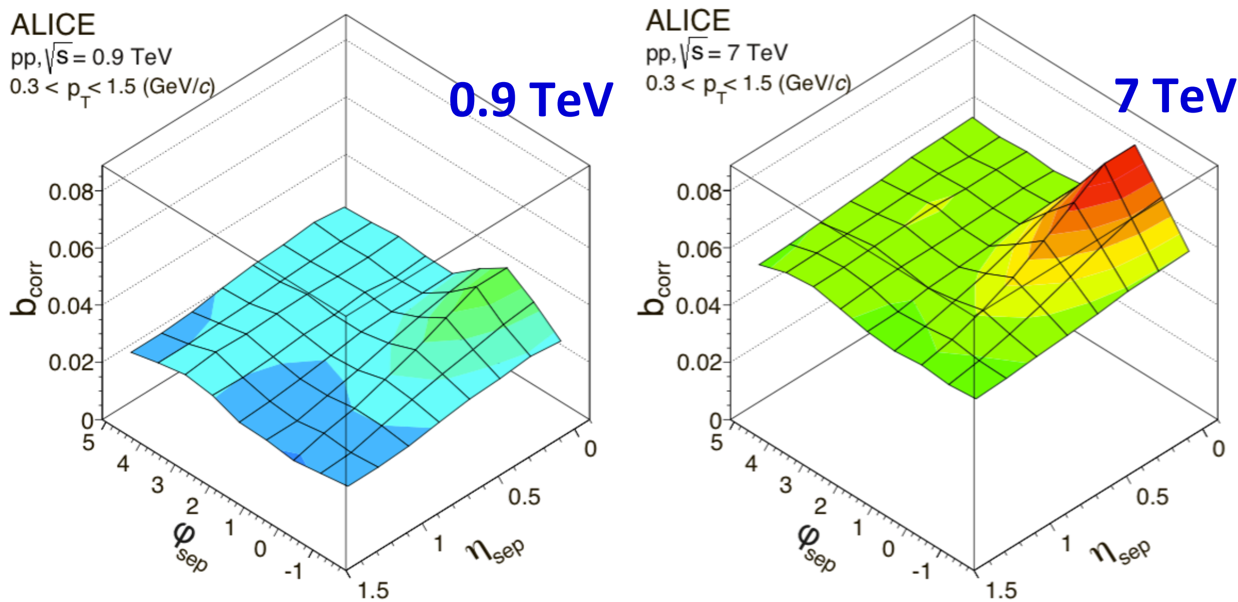


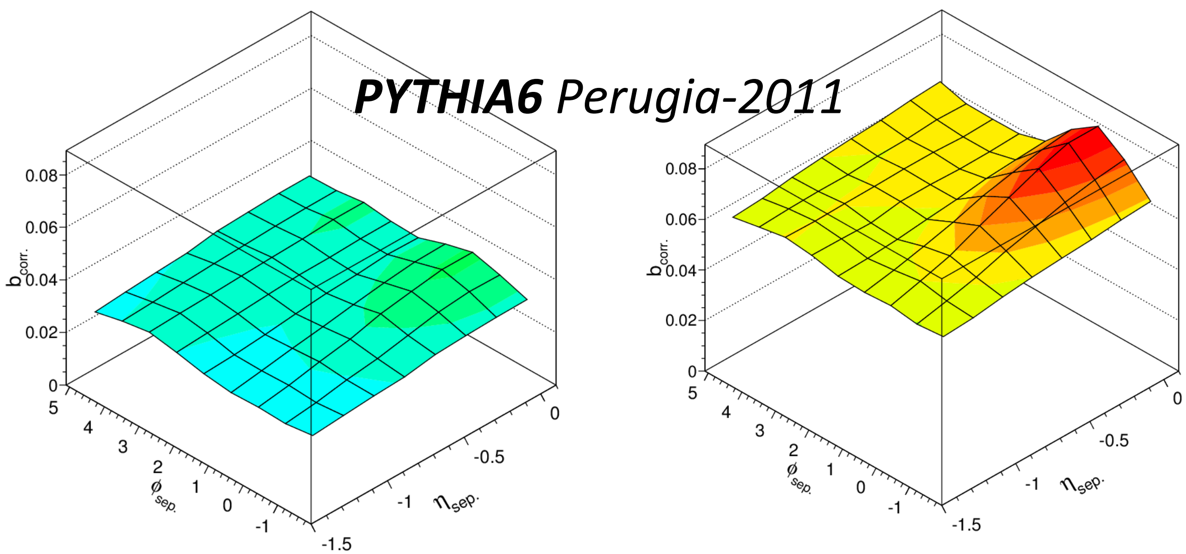




FB multiplicity correlations in separated η and φ windows

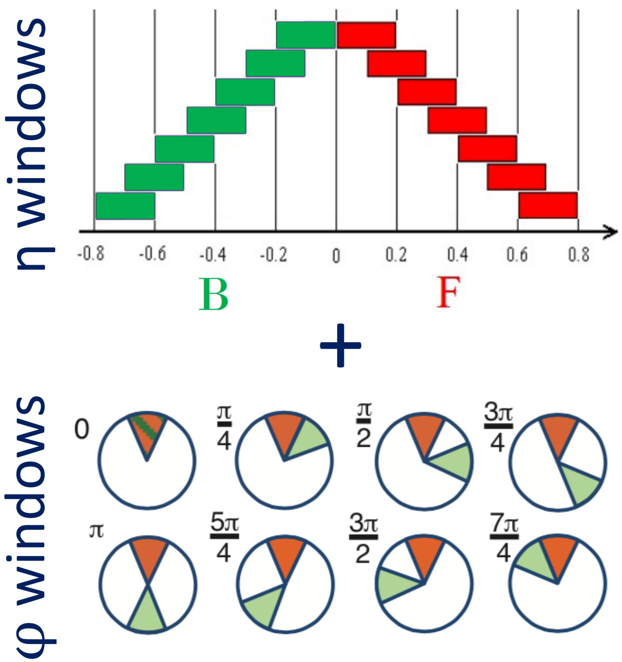


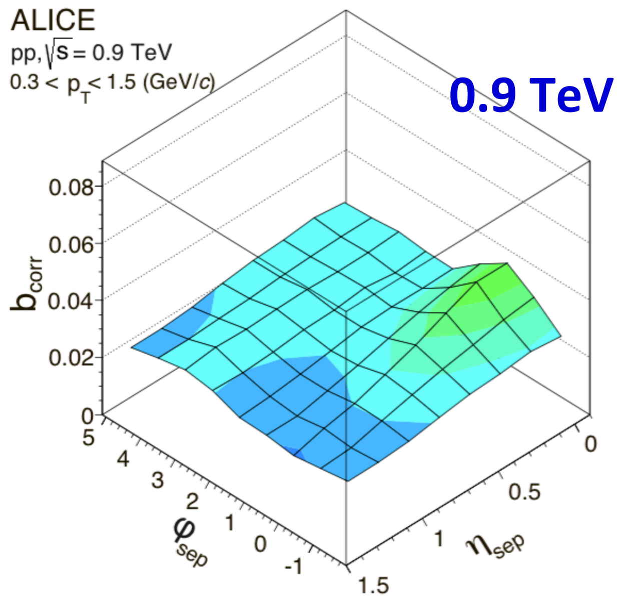


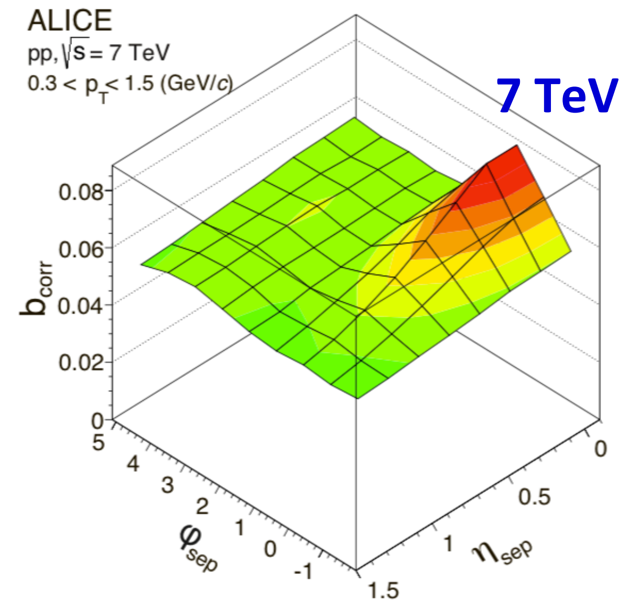


- PYTHIA reproduces the behavior of the data

FB multiplicity correlations in separated η and φ windows



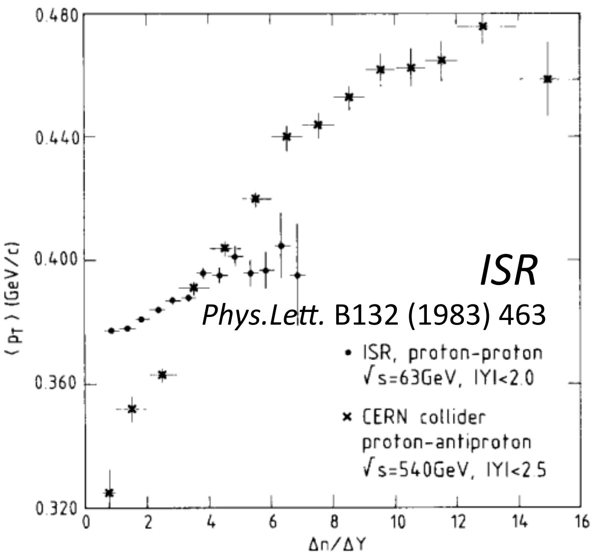


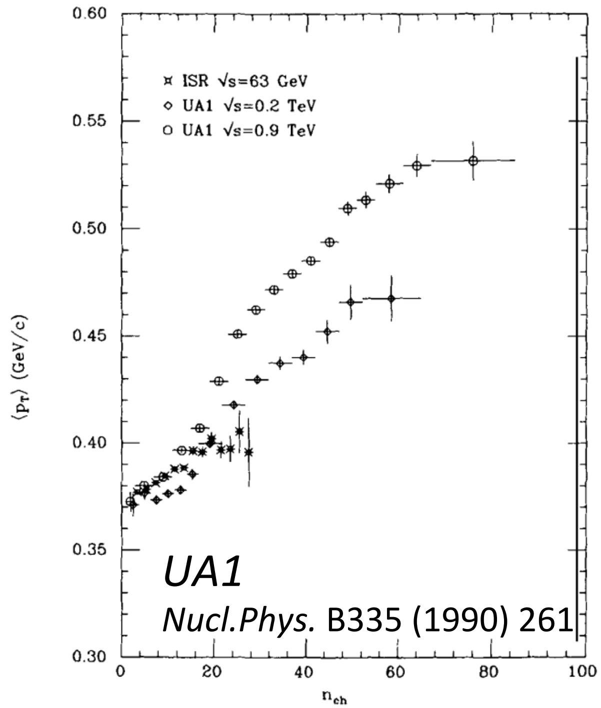


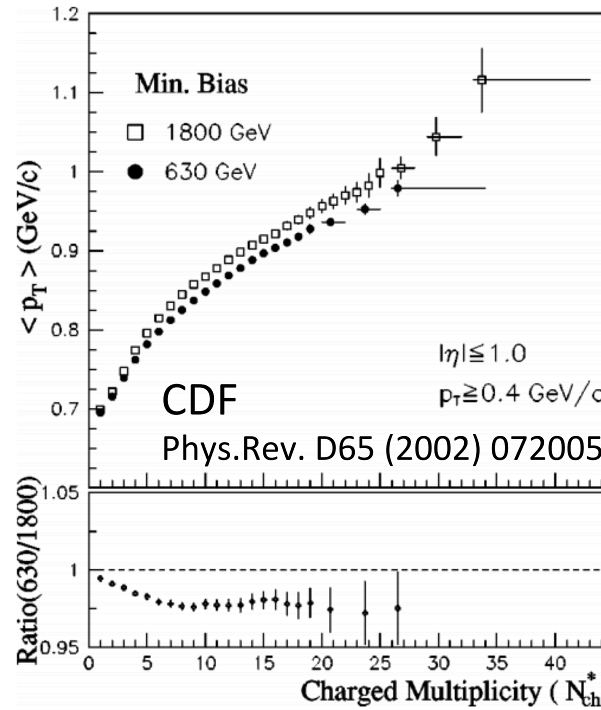
- short-range and long-range contributions are distinguishable
- non-zero plateau is observed and increases with the energy
- can be interpret by simple model of independent particle emitters

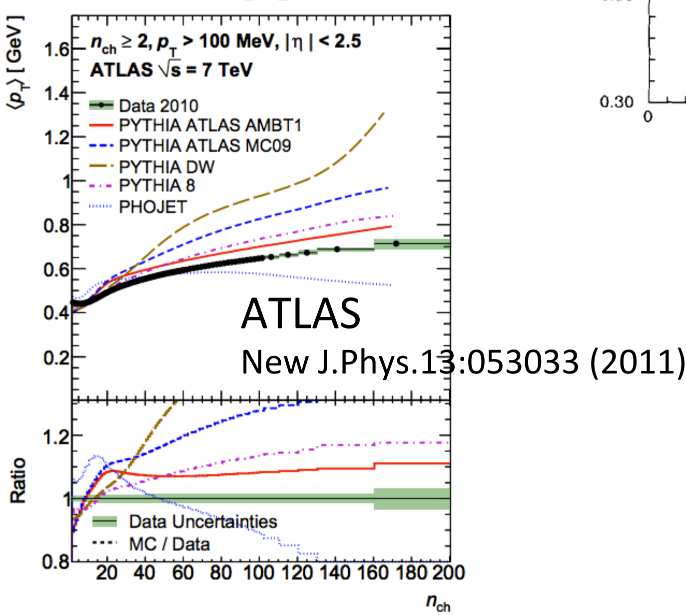
V.V. Vechernin, *Nucl.Phys. A939 (2015) 21*,
arXiv:1210.7588 [hep-ph]

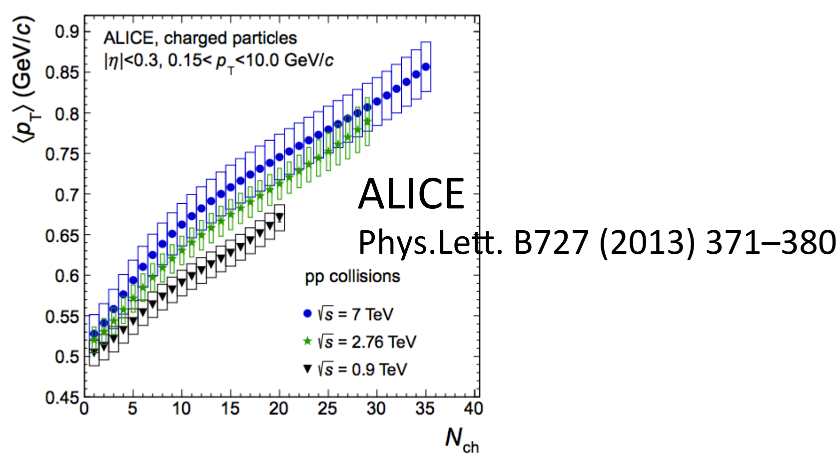
$\langle p_T \rangle$-N_{ch} correlation in same η-window:
hard to interpret it by independent particle emitters











How to explain <p_T>-N_{ch} and other obsevations?
High string densities → overlapping strings should interact!

production of a quark pair with opposite transverse momenta p_T:

$$\propto \exp\left(-\frac{\pi\left(\mu^2+p_\perp^2\right)}{\kappa}\right)$$

J. Schwinger, 1951
T.S.Biro et. al, 1984

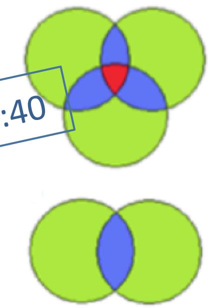
→ Modifications of strings (string tension κ, etc.):

- String fusion model (SFM) M. A. Braun, C. Pajares, Nucl. Phys. B 390 (1993) 542

Fused strings decay faster and produce relatively more baryons, especially strange ones.

$$\langle\mu\rangle_k = \mu_0\sqrt{k}\frac{S_k}{\sigma_0} \qquad \langle p_t^2\rangle_k = p_0^2\sqrt{k} \qquad \langle p_t\rangle_k = p_0\sqrt[4]{k}$$

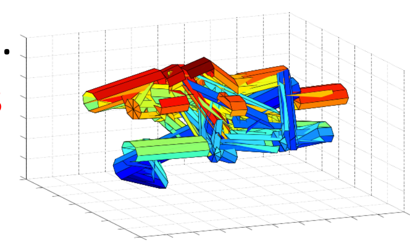
V.Kovalenko, Tue 17:40



- "Colour ropes" Bierlich et. Al, arXiv:1412.6259v3 [hep-ph] Feb 2015

In nucleus collisions, strings close in space can fuse to form "colour ropes".

The stronger field in a rope is expected to give larger rates for strangeness and baryons.



Overlapping strings can also be expected in pp collisions
(especially at the high LHC energies the expected density of strings is quite high).

→ ideas are implemented in the DIPSY MC event generator JHEP08(2011)103

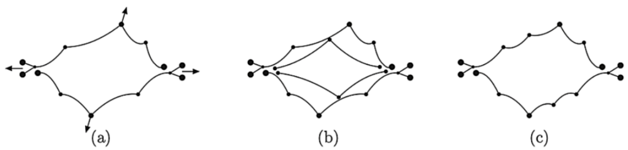
- Colour reconnection (CR) in PYTHIA event generator (next slides)

- alternative argumentation to explain <p_T>(N_{Ch}) etc. – hydrodynamic collective flow (EPOS, …)

Colour Reconnection in PYTHIA8

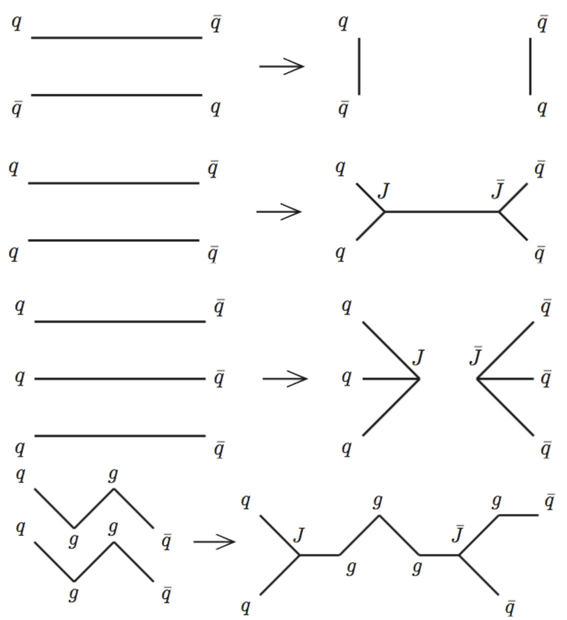
http://home.thep.lu.se/~torbjorn/pythia82html/ColourReconnection.html

The MPI-based scheme



In this scheme partons are classified by which MPI system they belong to. The colour flow of two such systems can be fused, and if so the partons of the lower-pT system are added to the strings defined by the higher-pT system in such a way as to give the smallest total string length. The bulk of these lower-pT partons are gluons, and this is what the scheme is optimized to handle.

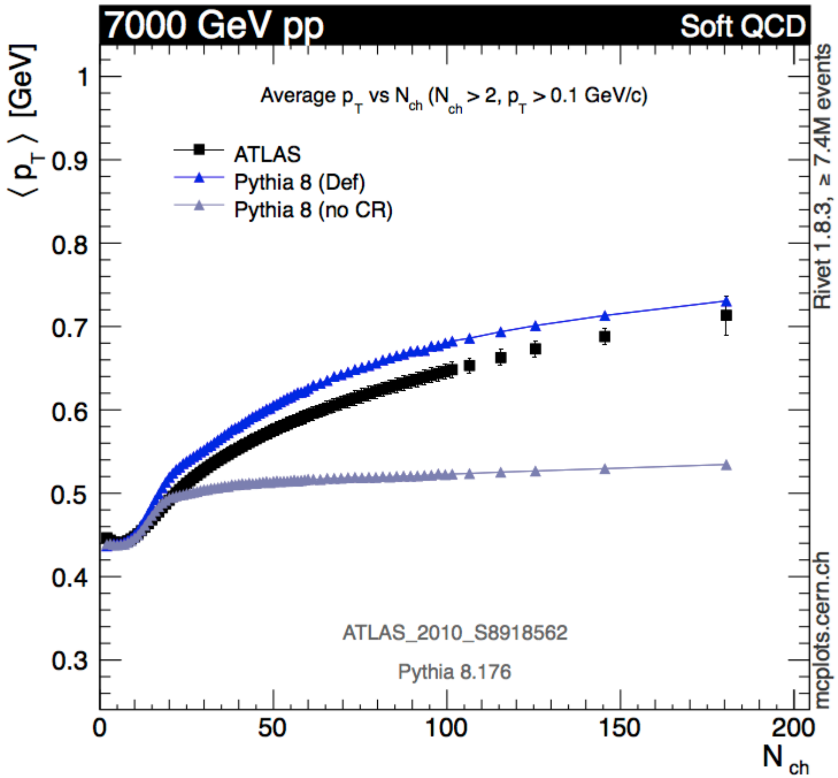
The newer scheme

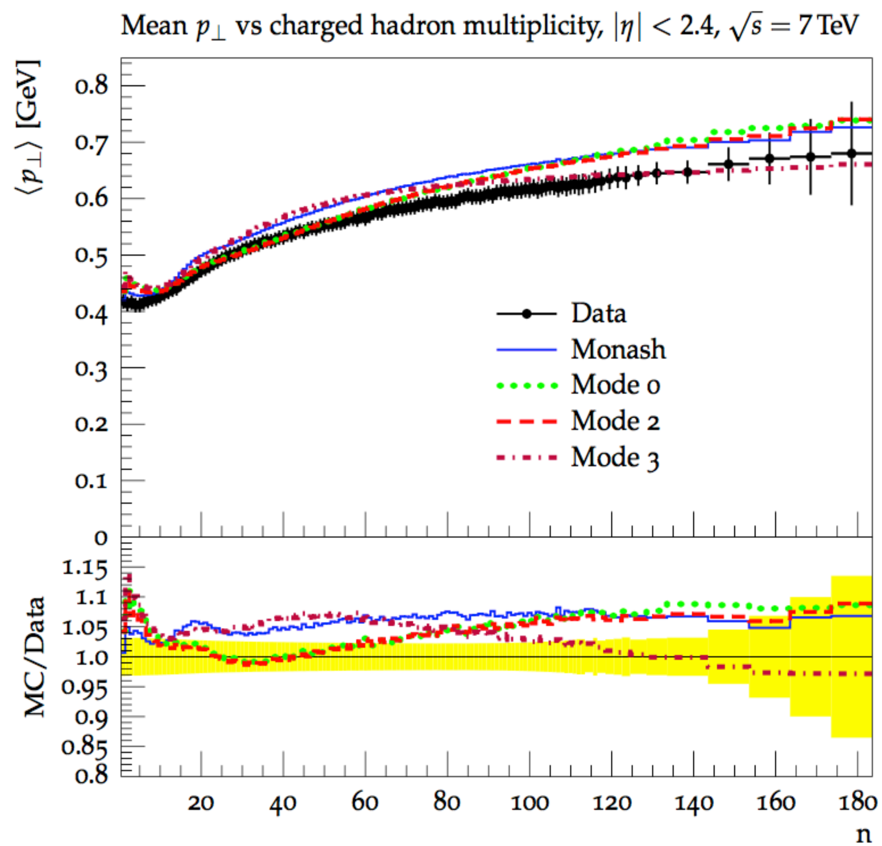


The newer CR scheme builds on the minimization of the string length as well as the colour rules from QCD. A main feature of the new model is the introduction of junction structures. These are possible outcomes of the reconnection in addition to the more common string-string reconnections.

String Formation Beyond Leading Colour
arXiv:1505.01681v1 [hep-ph] May 2015

$\langle p_T \rangle$-N_{ch} correlation: Data VS PYTHIA8 (CR on/off)

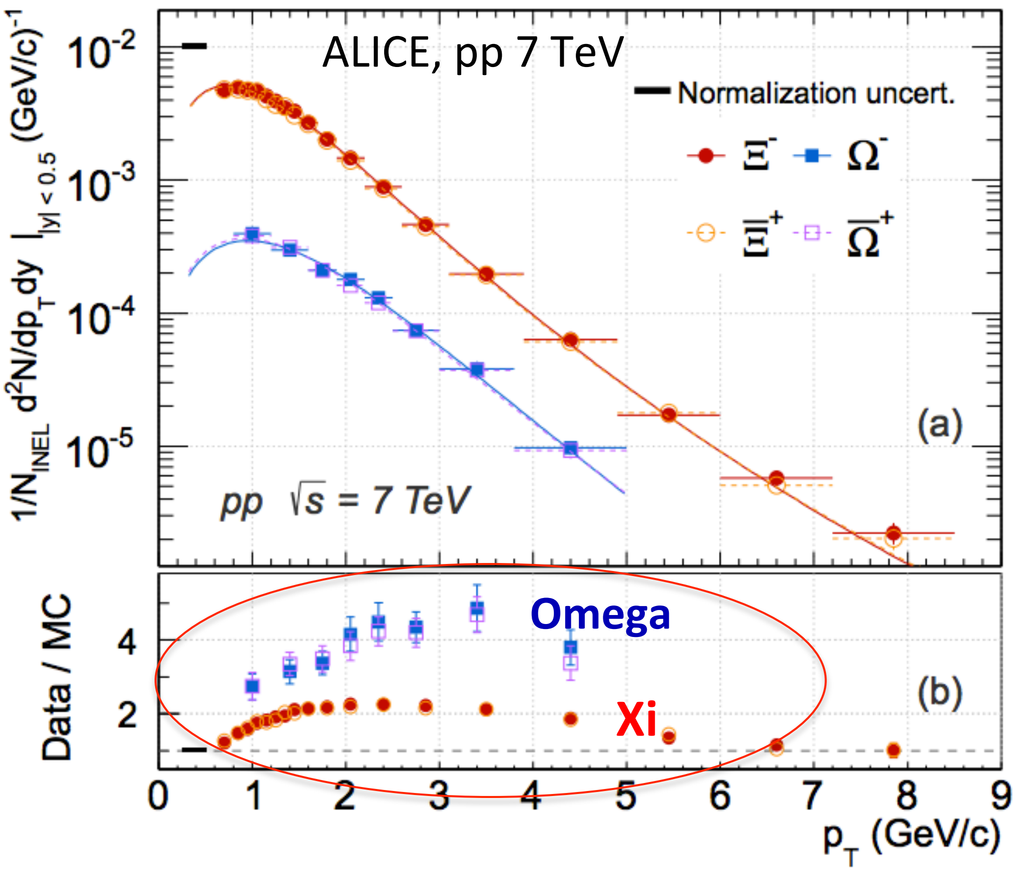




- Implementation of the CR mechanism in PYTHIA6 and PYTHIA8 allowed to describe this correlation

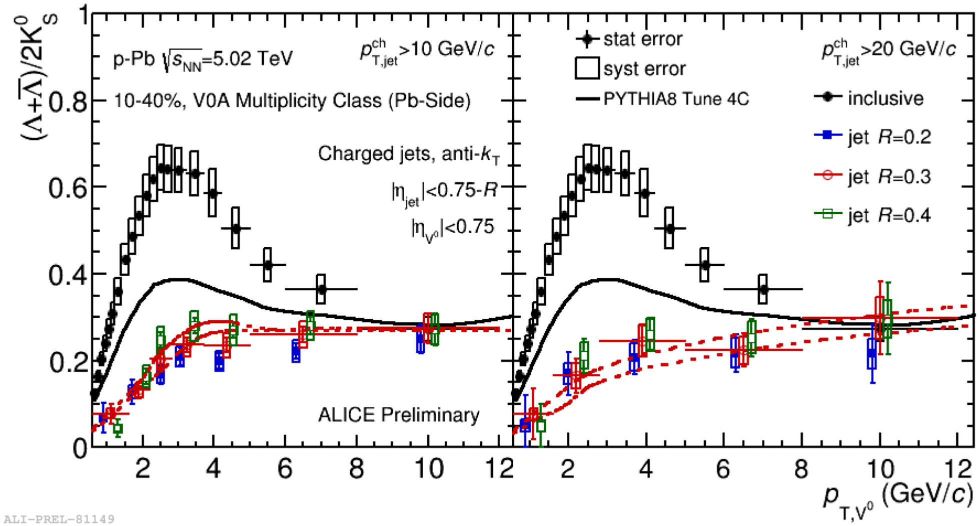
Multi-strange baryon production: Data vs MC

arxiv:1204.0282 , Eur. Phys. J. C74



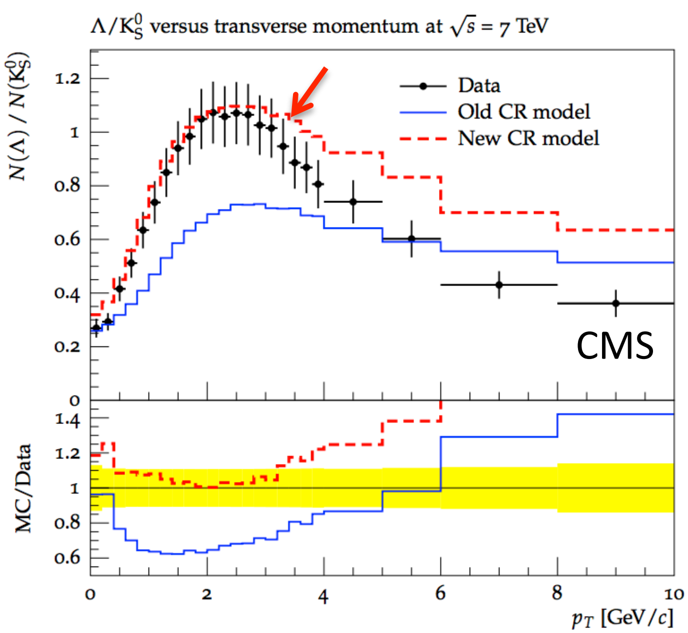
- insufficient multi-strange baryon yields in PYTHIA6 (Perugia 2011)

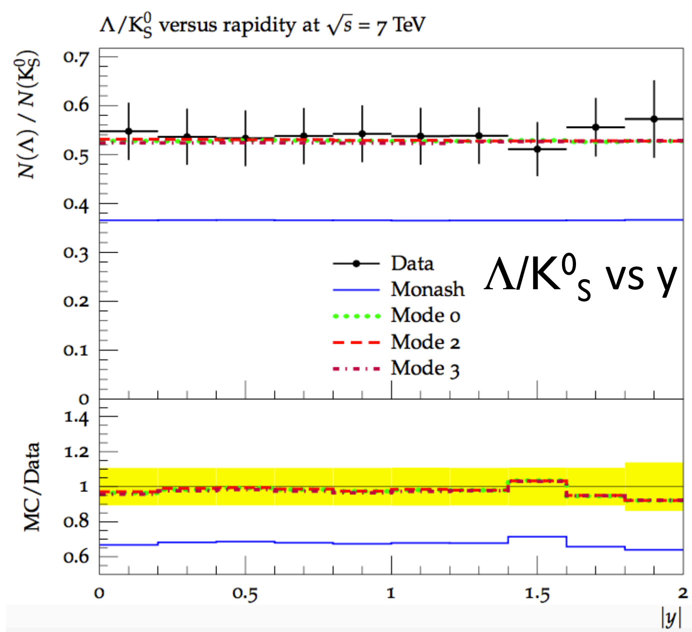
Λ/K^0_S ratio



Pythia8 tune 4C is known not to be best for reproducing strangeness (Pythia8 2013 Monash is not better)

New PYTHIA CR model Christiansen, Skands, arXiv:1505.01681 (**May 2015**)





PYTHIA8 setup

- PYTHIA8 (8210, June 2015)
- Monash 2013 tune *(tune to both e^+e^- and pp data, the starting point for many later tunes)*
- pp 7 TeV, inelastic collisions
- Event and track selection:
  ≥ 1 charged particle in $|\eta|<2.4$ (=CMS acceptance)
  no p_T cuts

- Variations:
  1) run with new CR model
  2) run with CR switched off

⇨ 10^6 events with each setup

Newer CR model parameters:
from arXiv:1505.01681 (**May 2015**)

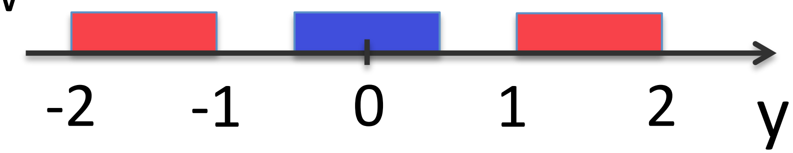
A Model parameters

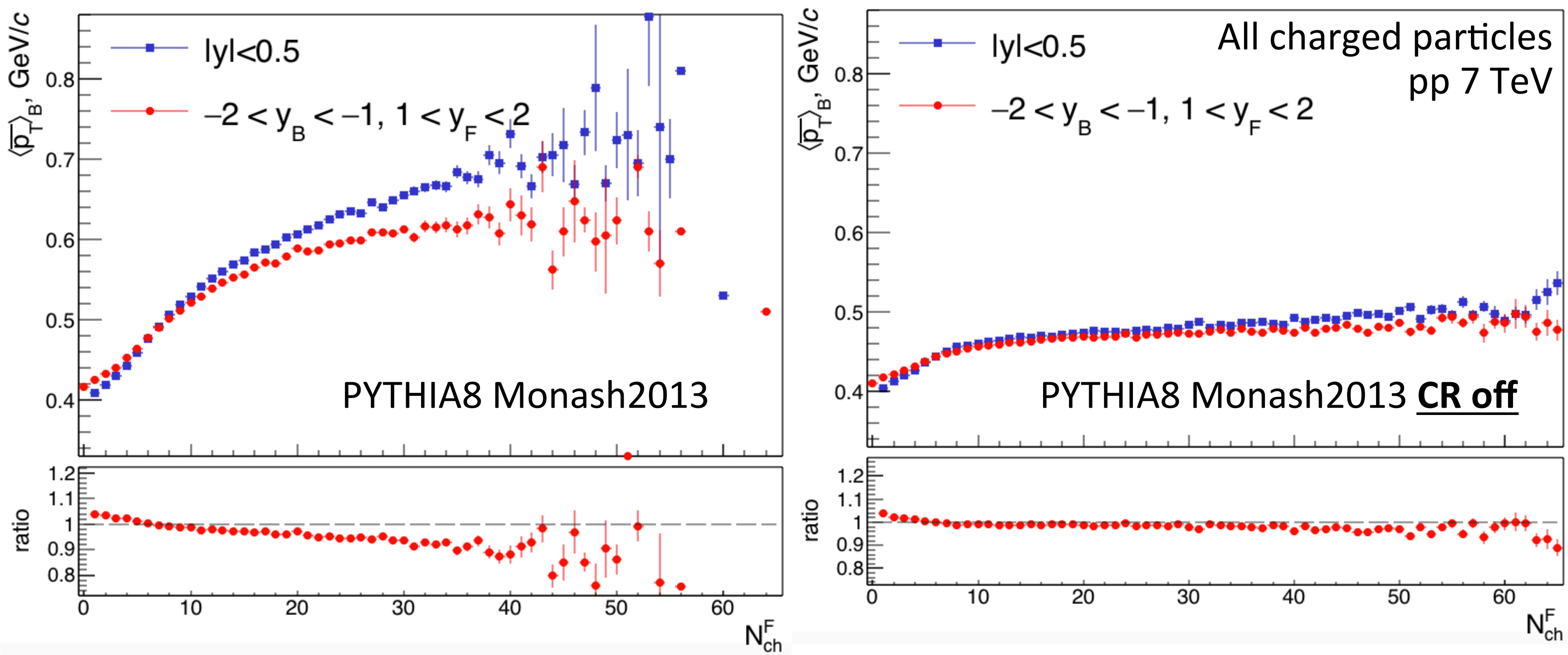
A complete list of all the parameters that differ from the Monash tune for the three different models are listed in the table below.

Parameter	Monash	Mode 0	Mode 2	Mode 3
StringPT:sigma	= 0.335	= 0.335	= 0.335	= 0.335
StringZ:aLund	= 0.68	= 0.36	= 0.36	= 0.36
StringZ:bLund	= 0.98	= 0.56	= 0.56	= 0.56
StringFlav:probQQtoQ	= 0.081	= 0.078	= 0.078	= 0.078
StringFlav:ProbStoUD	= 0.217	= 0.2	= 0.2	= 0.2
StringFlav:probQQ1toQQ0join	= 0.5, 0.7, 0.9, 1.0	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275	= 0.0275, 0.0275, 0.0275, 0.0275
MultiPartonInteractions:pT0Ref	= 2.28	= 2.12	= 2.15	= 2.05
BeamRemnants:remnantMode	= 0	= 1	= 1	= 1
BeamRemnants:saturation	-	= 5	= 5	= 5
ColourReconnection:mode	= 0	= 1	= 1	= 1
ColourReconnection:allowDoubleJunRem	= on	= off	= off	= off
ColourReconnection:m0	-	= 2.9	= 0.3	= 0.3
ColourReconnection:allowJunctions	-	= on	= on	= on
ColourReconnection:junctionCorrection	-	= 1.43	= 1.20	= 1.15
ColourReconnection:timeDilationMode	-	= 0	= 2	= 3
ColourReconnection:timeDilationPar	-	-	= 0.18	= 0.073

$\langle p_T \rangle$-N_{ch} Forward-Backward correlation, check CR on/off

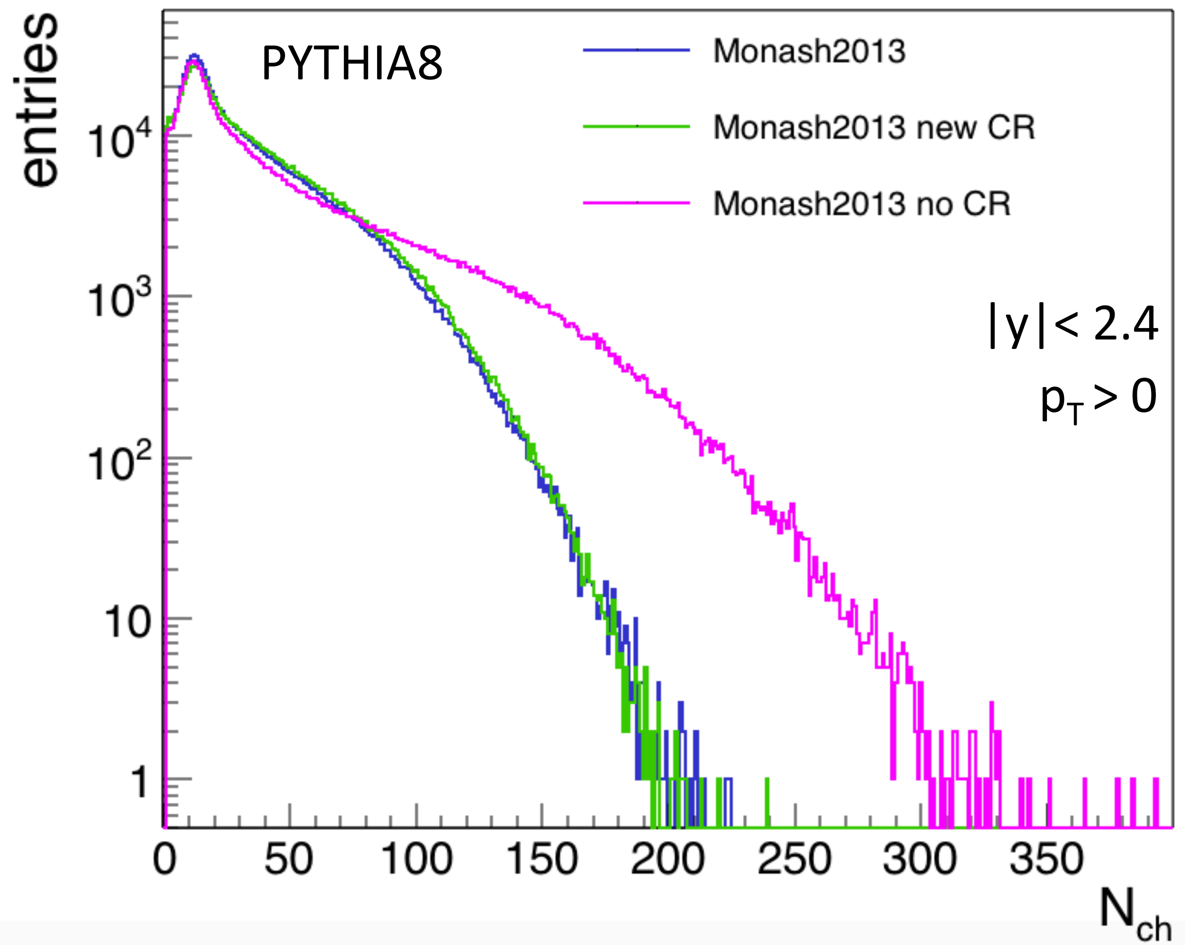
conventionally is measured in the same window
→ look in separated y-windows





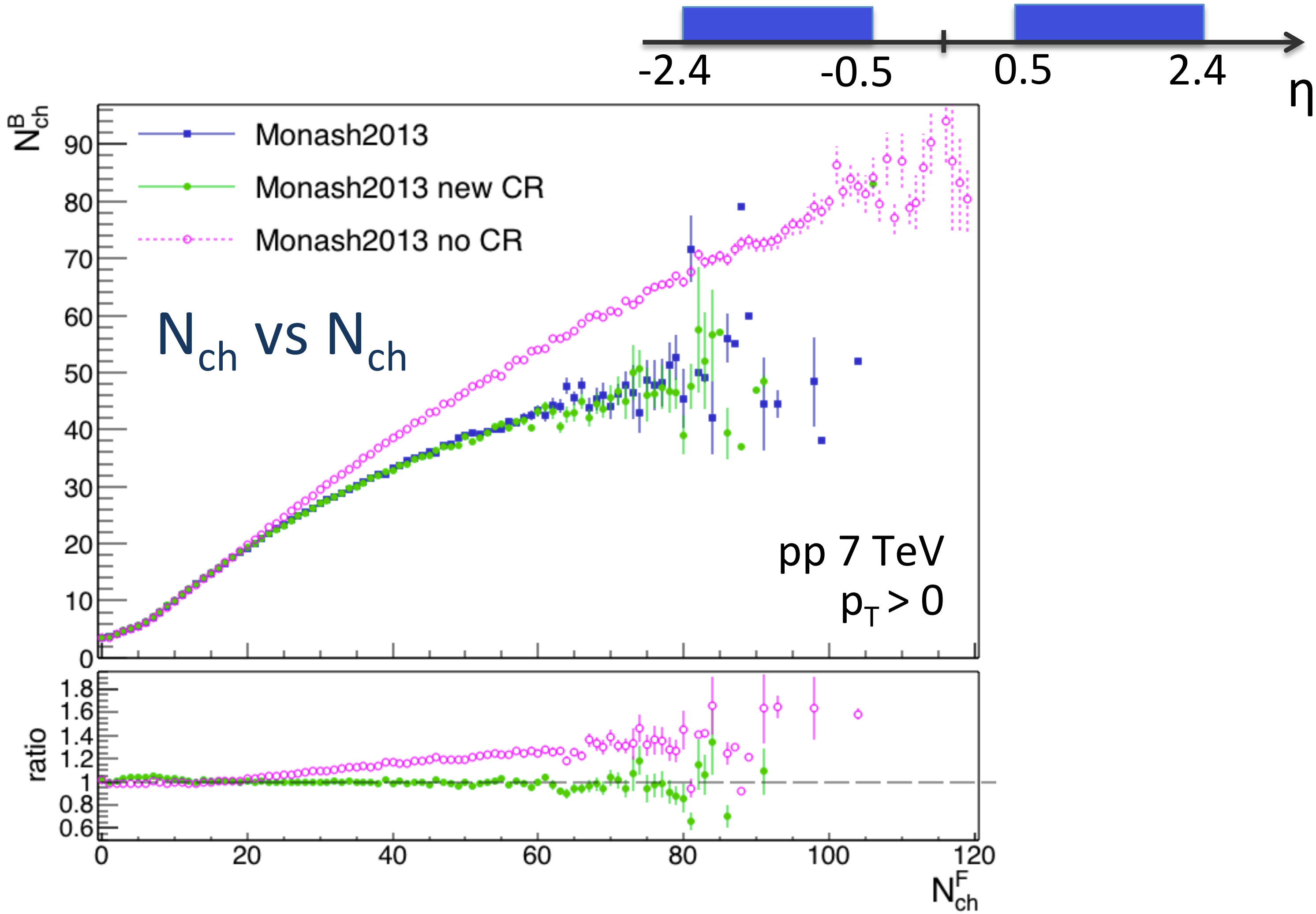
- reveals $\langle p_T \rangle$-N_{ch} correlation with "CR on" and its absence with "CR off"
- also in long-range!

Multiplicity distribution in PYTHIA8 for different scenarios



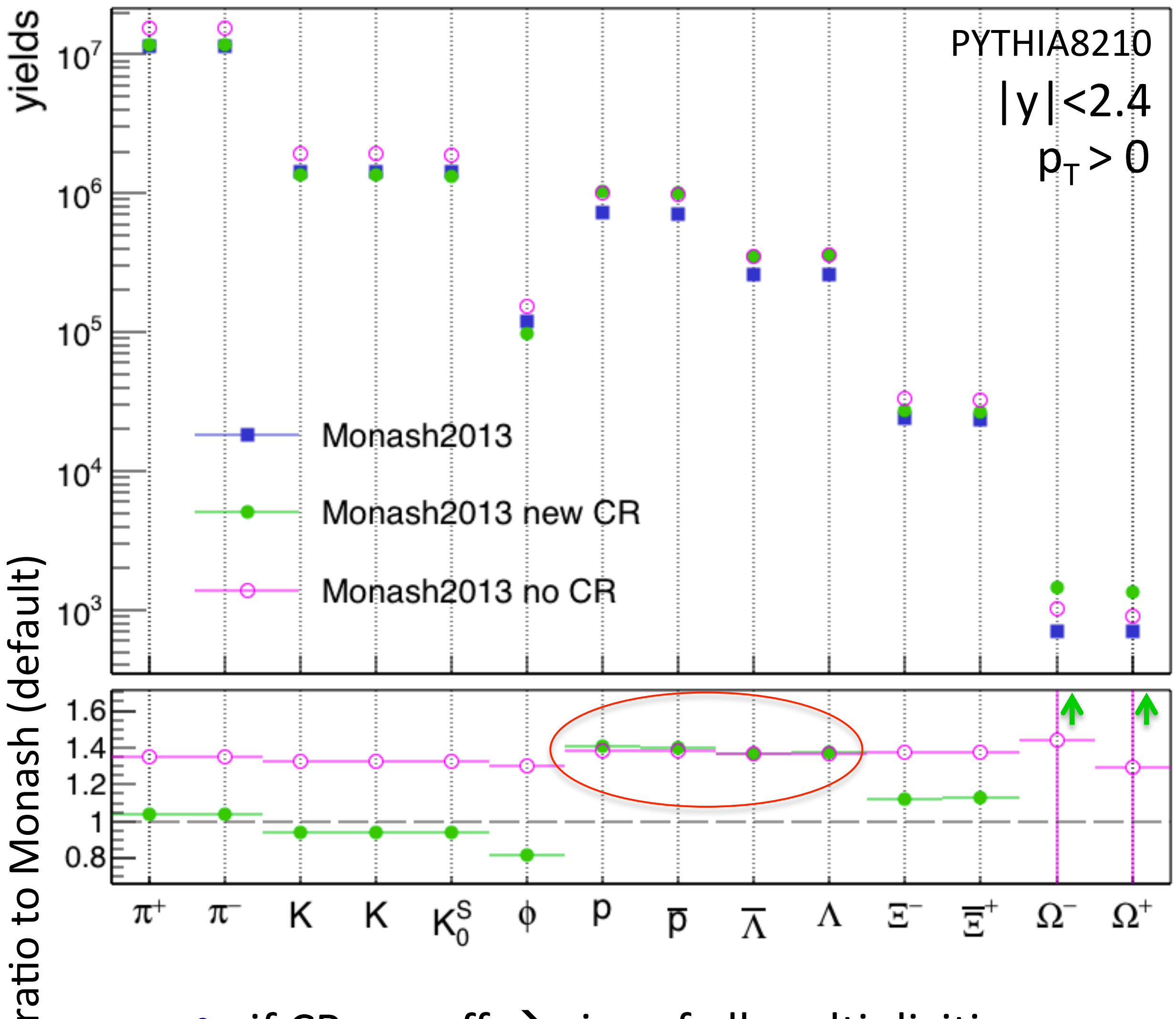
- in "CR on" scenario multiplicity drops down
- for in "new CR" scenario – same as default Monash tune

FB correlations between multiplicities



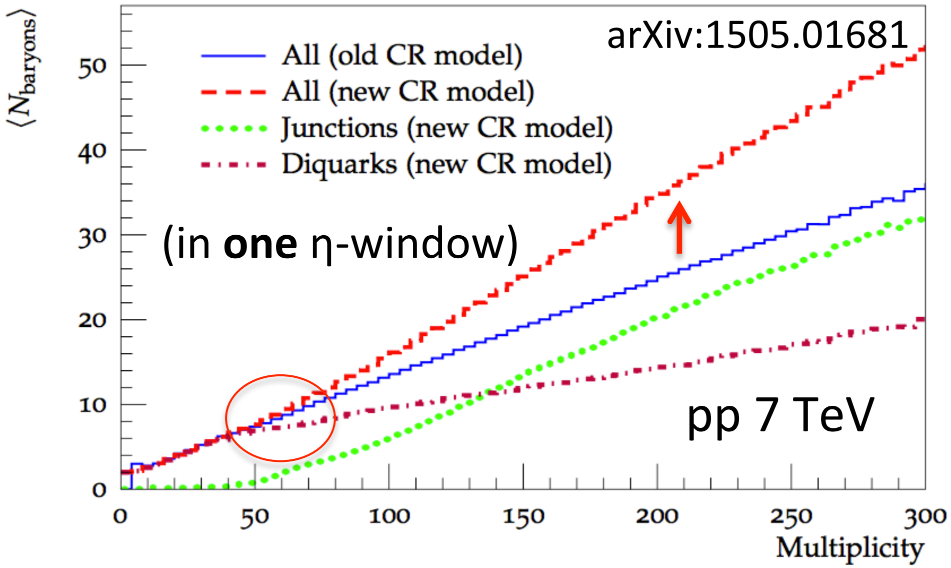
- Same for old and new CR
- "no CR" scenario deviates due to higher multiplicities

Yields of particles in PYTHIA8 for different CR modes



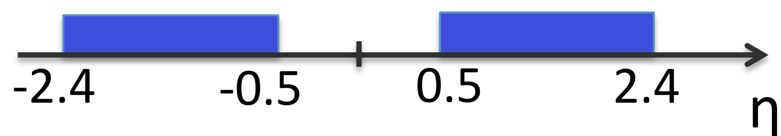
- if CR are off → rise of all multiplicities
- new CR model enhances baryon yields

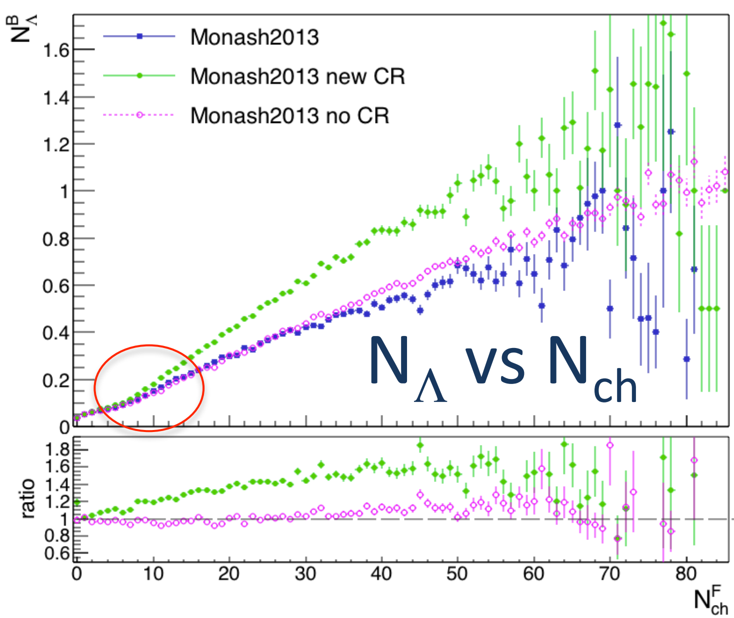
Baryon production as a function of multiplicity

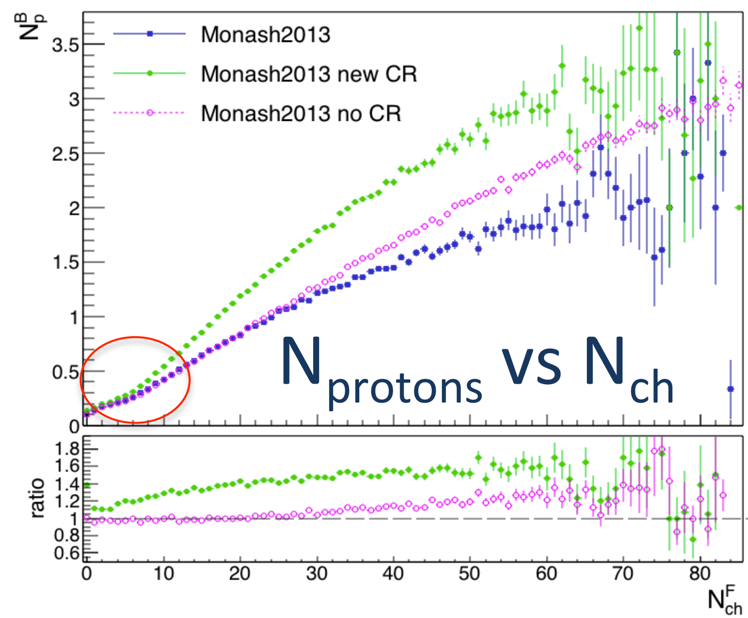


- baryon yield is enhanced with new CR model

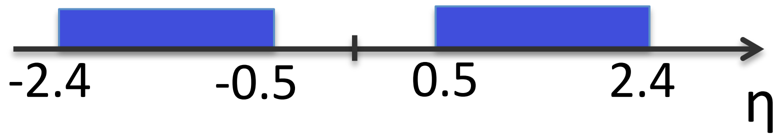
→ check correlation between baryons and N_{ch} in FB windows:



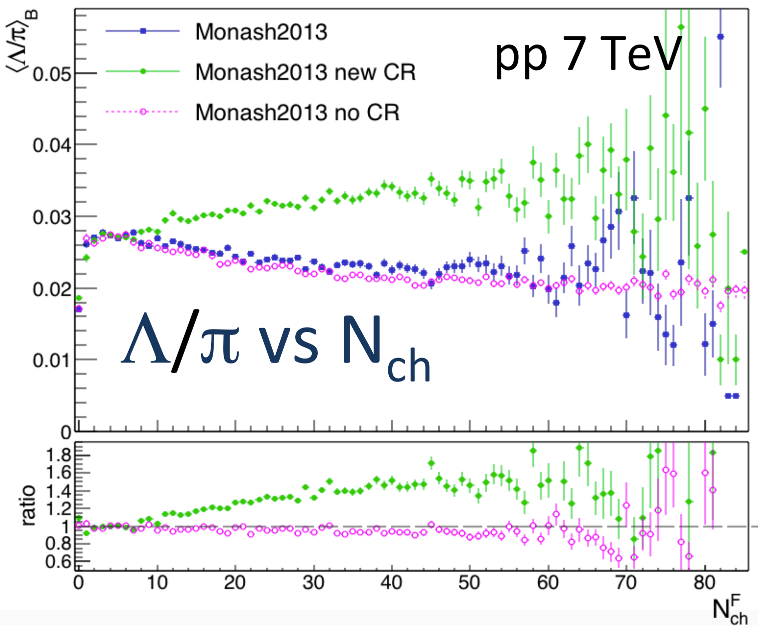


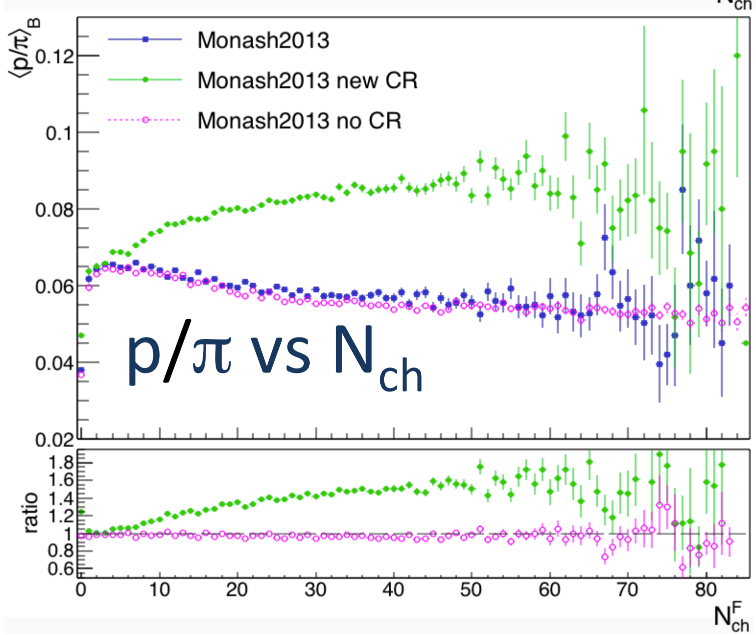


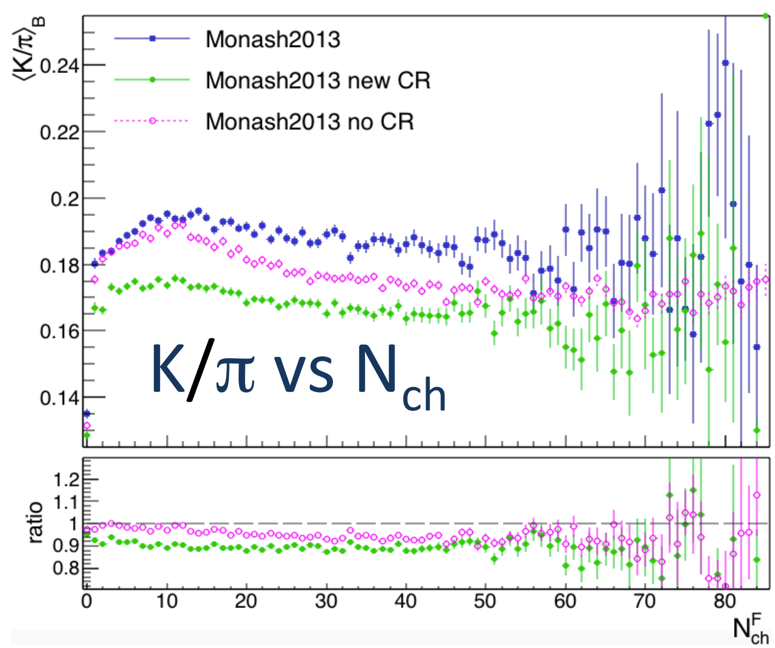
More observables for FB correlations



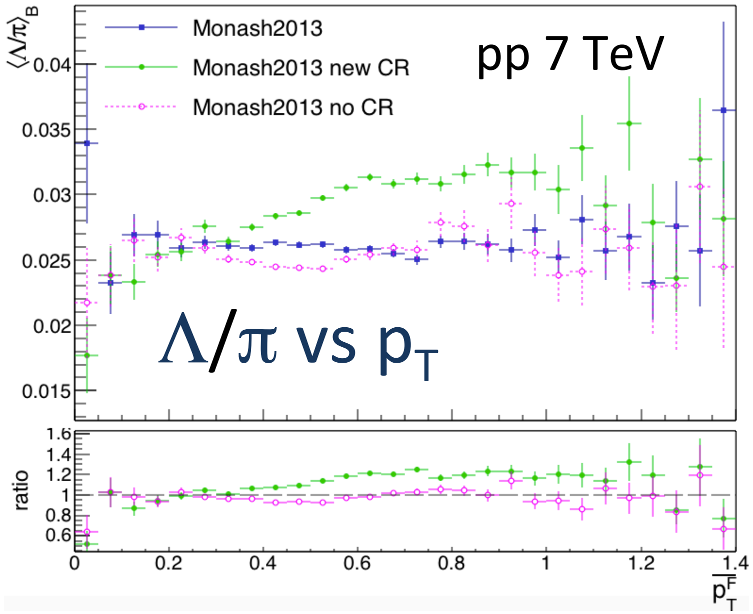
- **ratio** of particle species in one window vs $\mathbf{N_{ch}}$ in another

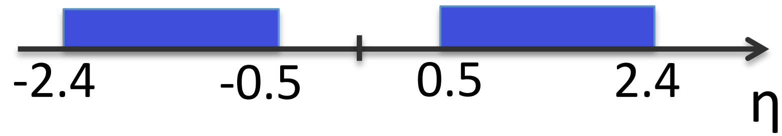




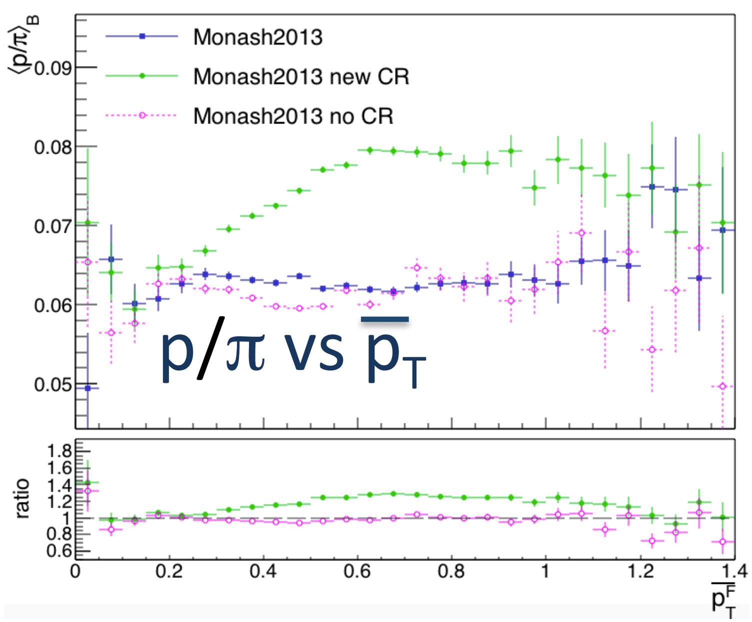


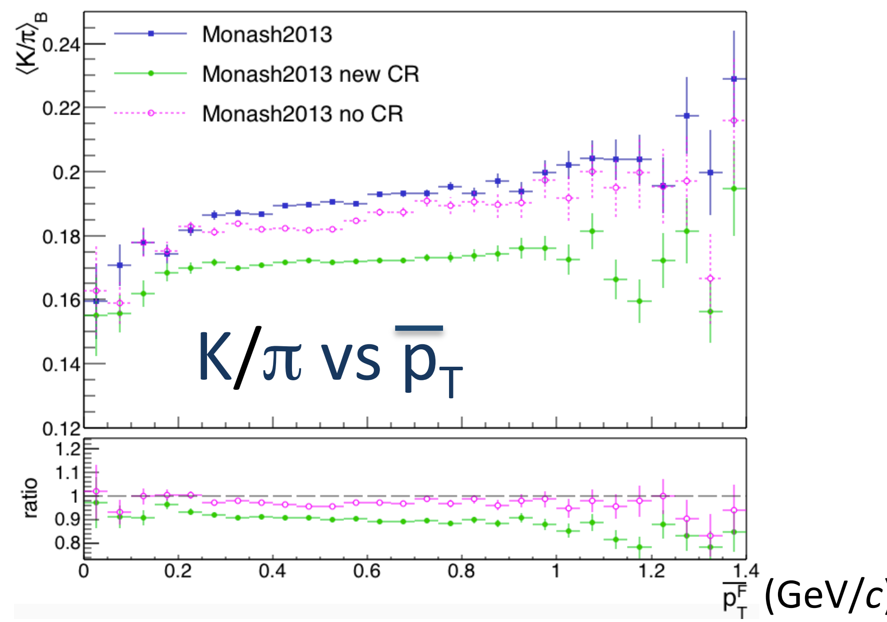
More observables for FB correlations





- **ratio** of particle species in one window vs $\overline{p_T}$ in another



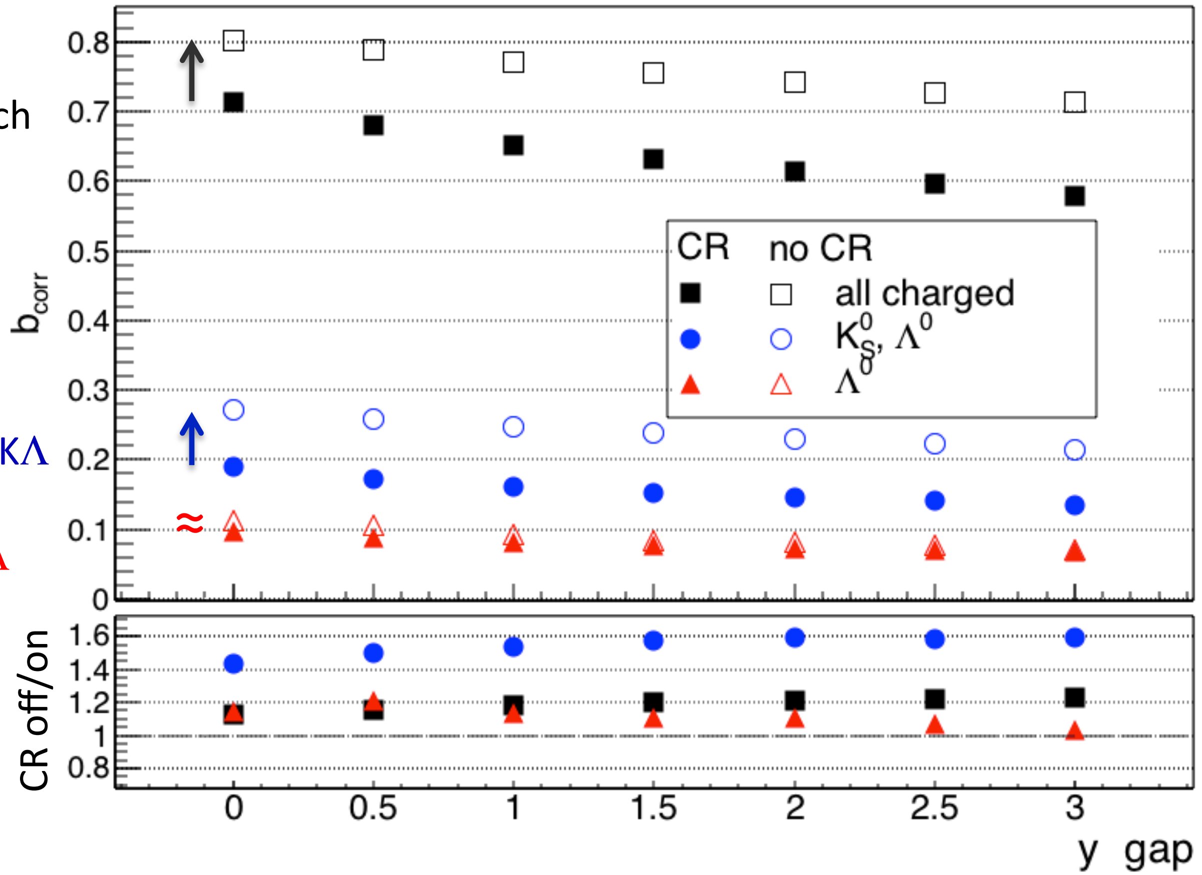


FB correlations in PYTHIA8 for CR and no-CR scenario

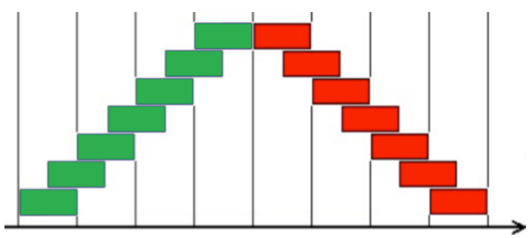
N_{ch} vs N_{ch}

$N_{K\Lambda}$ vs $N_{K\Lambda}$

N_{Λ} vs N_{Λ}

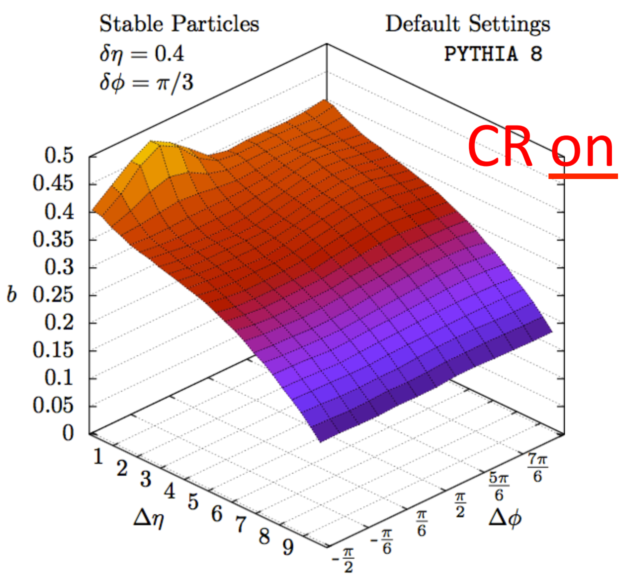


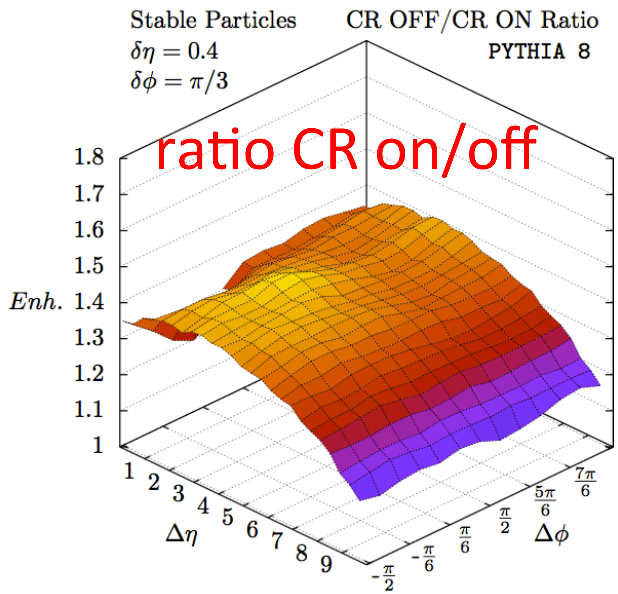
N vs N

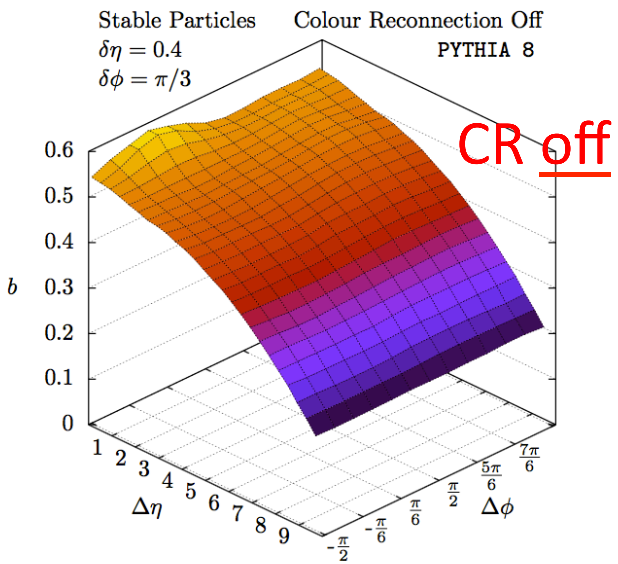


- due to different multiplicities and baryon yields in these scenarios – different behavior of NN correlations for mesons and baryons (i.e. K, Λ)

More detailed picture using η and φ windows

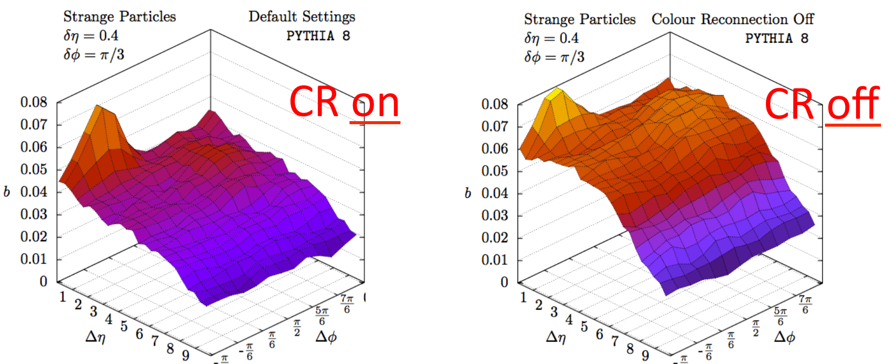






(charged particles)

- η-φ "topology" reveals finer details (for instance, dip in short-range area)
- similar can be done for strange particles:



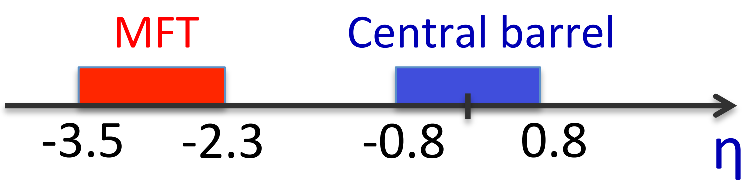
! warning: η, not y !

Notes

- Use intensive variables for FB correlations, like <p_T>, <E_T>, K/π, Λ/π, etc.
- Is the b_{corr} enough to understand underlying physics?
  → closer look at correlation function itself
- Proper treatment of b_{corr} due to difference between rapidity and pseudorapidity, also to be careful with p_T range
- Disentangling of different mechanisms of string interactions and other scenarios of collective behavior is desired!
- Similar studies of FB correlations can be performed in h-h, h-A and AA systems

- Prospects of long-range correlations with upgraded *ALICE* detector (2018):
  - central barrel with **PID** in $|\eta|<0.9$
  - N_{ch} by Muon Forward Tracker (MFT) within $-3.5 \leq \eta \leq -2.3$

ALICE-TDR-018 (2015)



Conclusions

- need good observables to study interactions between particle emitting sources (strings)
- FB correlations with strange particles are sensitive to the scenario of string formation and interactions

- Colour Reconnection mechanism in PYTHIA event generator implements string interactions and provides forward-backward (long-range) correlations
- Newer Color Reconnection scheme in PYTHIA8 gives more baryons and demonstrates different behavior of FB correlation functions

- Thank you!

Backup

Fragmentation of a single string

"tunneling": production of a pair with opposite transverse momenta p_T

$$\propto \exp\left(-\frac{\pi\left(\mu^2+p_\perp^2\right)}{\kappa}\right) \qquad (1)$$

where $\sqrt{\mu^2+p_\perp^2}$ is a transverse mass

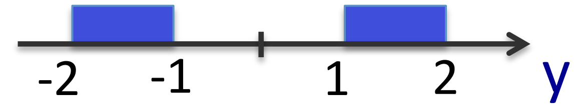
The strange quark fraction and the p_T-distribution are governed by the tunneling mechanism

The result in eq. (1) can be used to estimate the relative production of quarks with different flavour, and the distribution in p_T

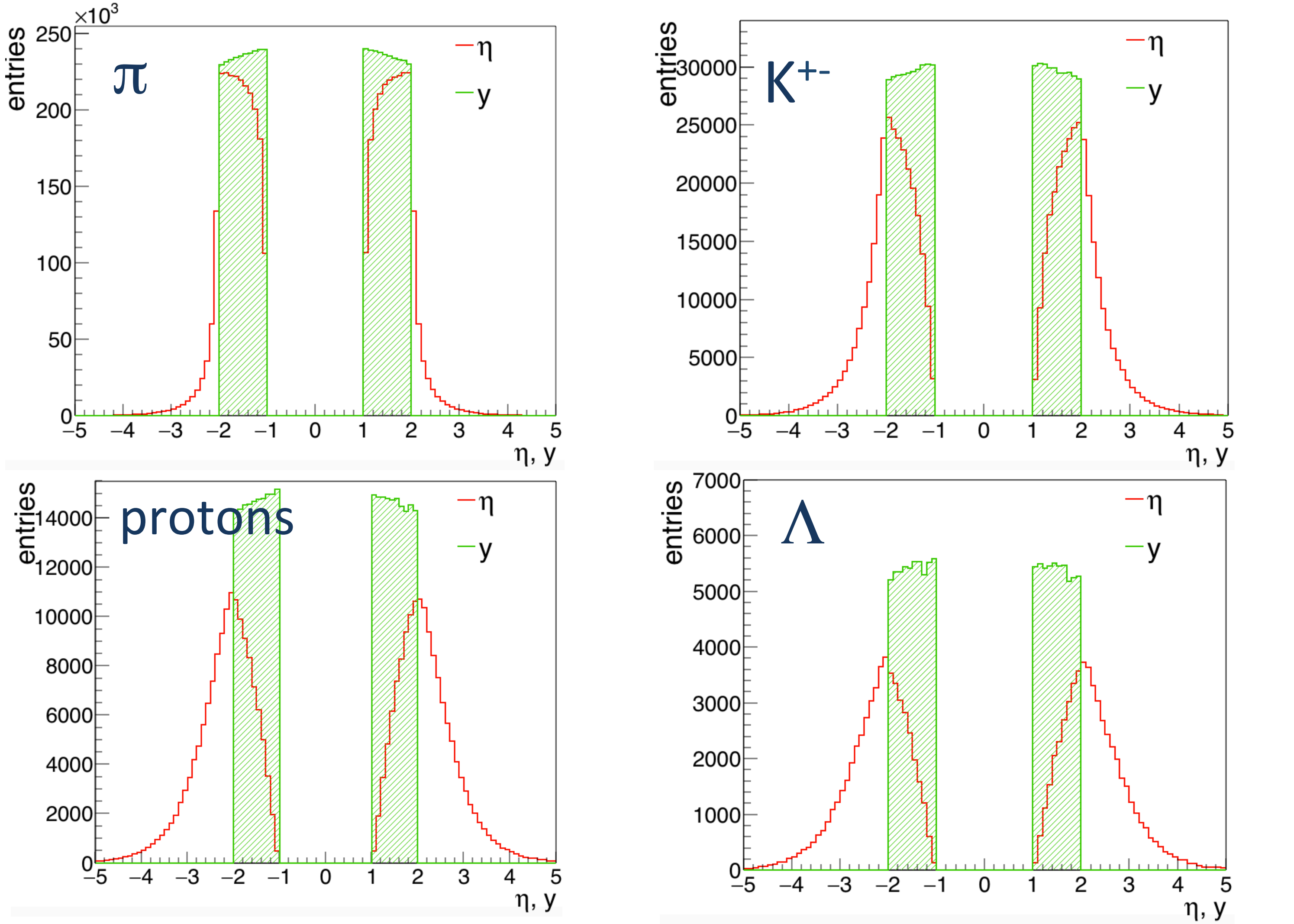
effective quark masses in (1) unknown → tune s/u ratio to experimental data

Fits to LEP data give s/u ≈ 0.2

Windows in rapidity vs η



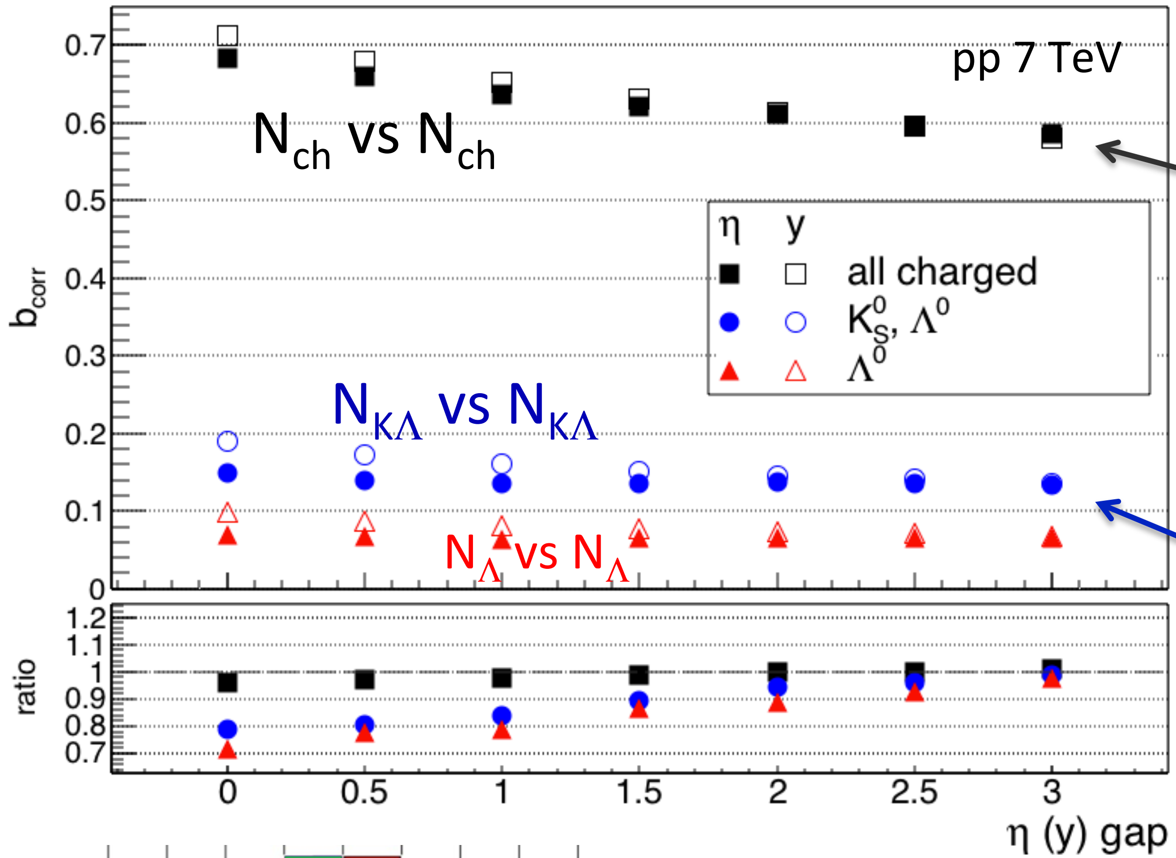
$p_T>0$

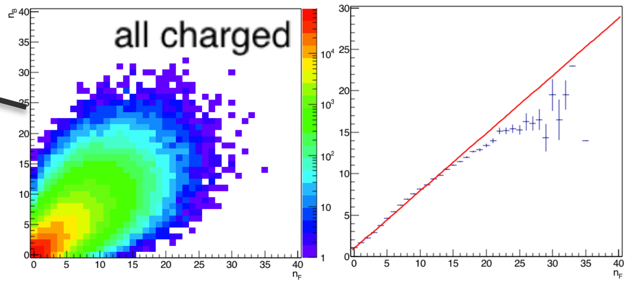


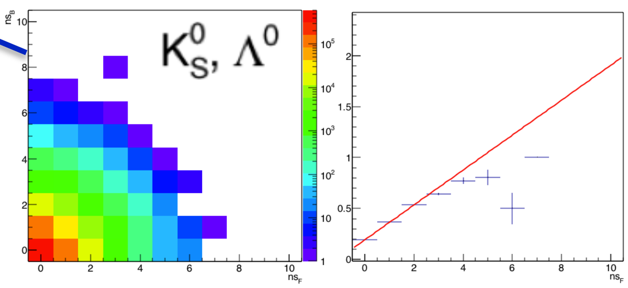
- for FB correlations, choose **y** instead of **η**, especially for heavy particles
- to be careful in experiment with the corrections on acceptance

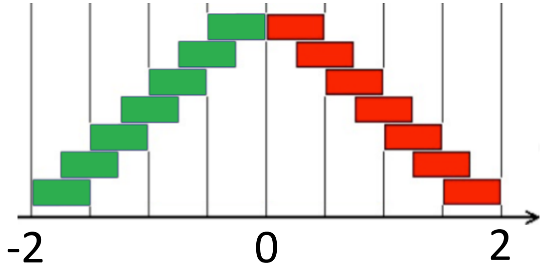
Windows in rapidity vs η

FB correlation dependence on the gap between windows





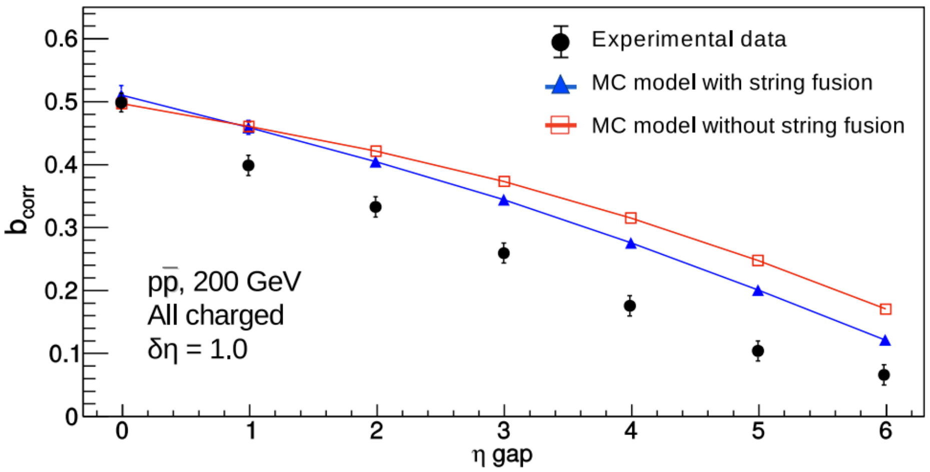


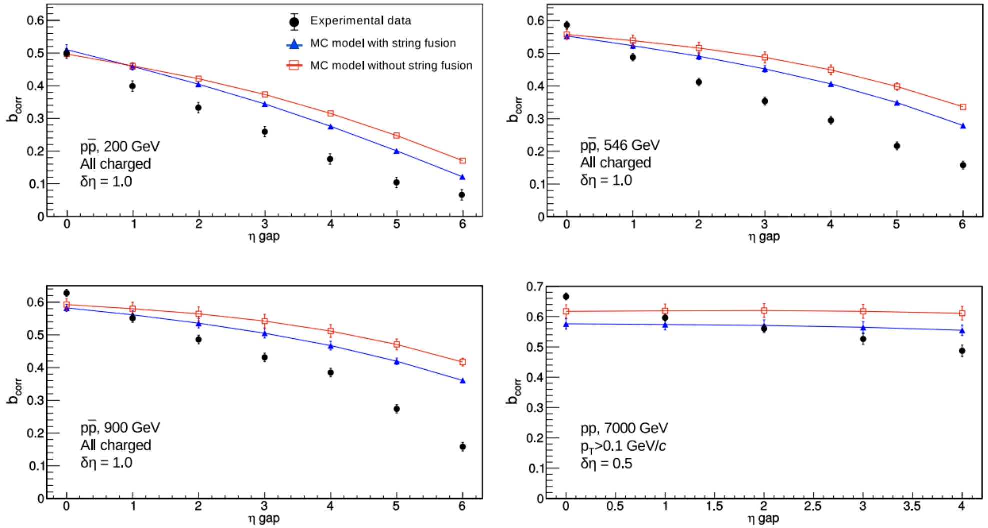


- results for y and η differ more for heavier particles, especially at central y

Note: hard to see collective effects in NN correlations – Motivation for other kind of correlations

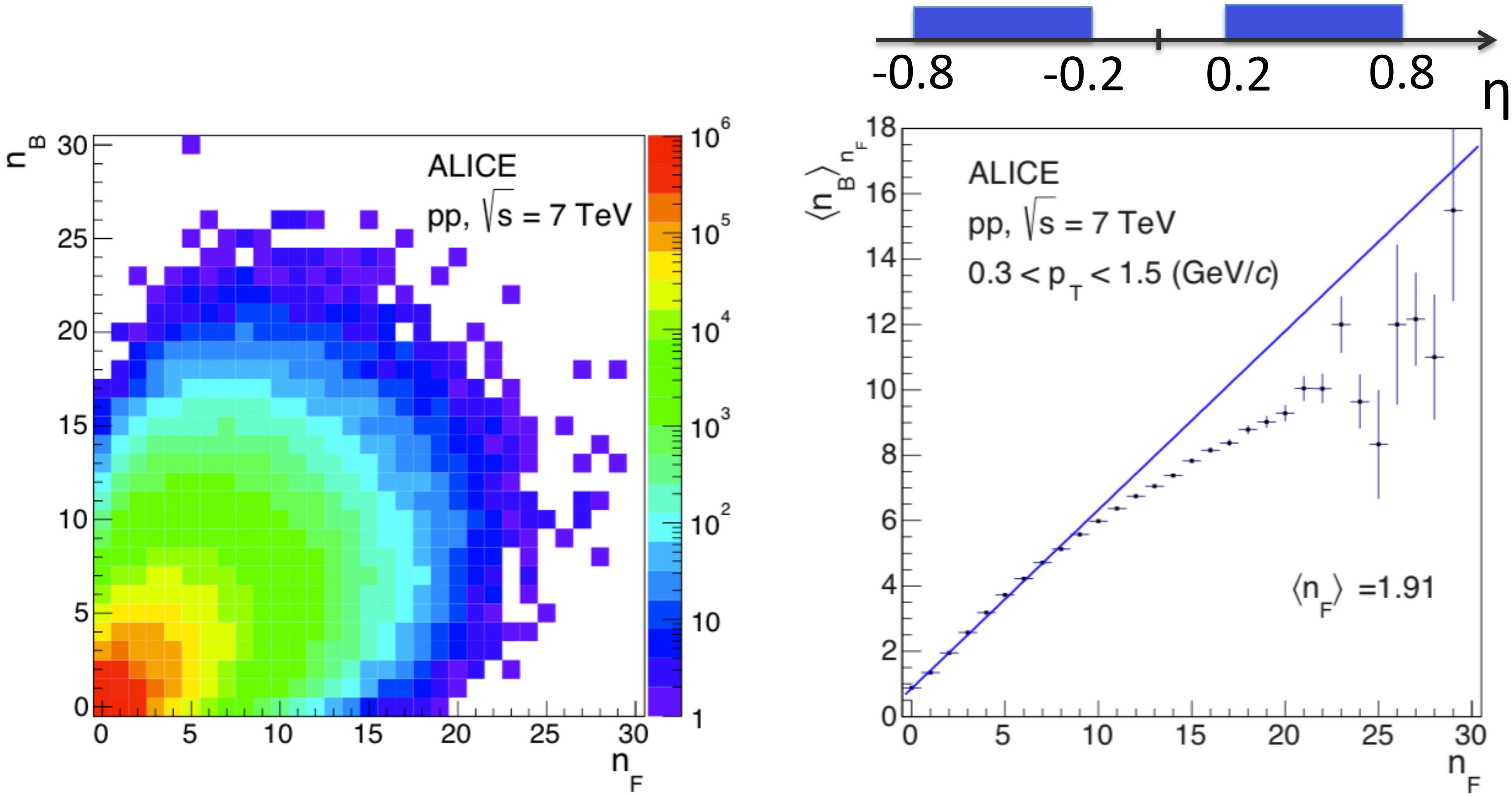
Example:
NN correlations in pp with string fusion on/off





arxiv:1410.3884
DESY Conf. Proc. 2014-04, 82 (pp. 691-694)

Forward vs backward *raw multiplicity distribution* and corresponding correlation function



JHEP 1505 (2015) 097

Which processes have influence on multiplicity correlations?

try to look into generator:

Forward-Backward multiplicity correlations in **PYTHIA8**

FB multiplicity correlations: *pp*, look at Pythia8

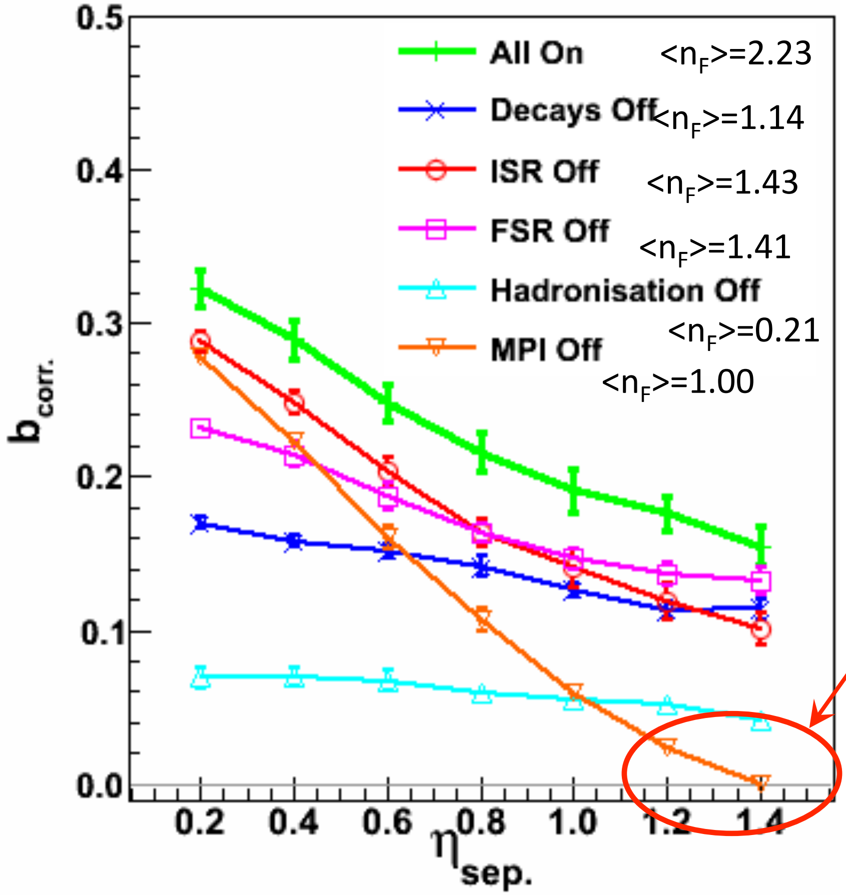
samples:
Pythia8 (8170)
Tune 4Cx
Beams:eCM = 7000 ! CM energy of collision

Can switch on/off the key event generation steps:
#PartonLevel:MPI = off ! no multiparton interactions
#PartonLevel:ISR = off ! no initial-state radiation
#PartonLevel:FSR = off ! no final-state radiation
#HadronLevel:Hadronize = off ! no hadronization
#HadronLevel:Decay = off ! no decays

⇨ 100k events were generated for each option set "off"

FB multiplicity correlations, *pp*, 7 TeV: look at Pythia8

Take separated in η windows (φ size is 2π):



($\langle n_F \rangle$ is the mean multiplicity in Forward rapidity window)

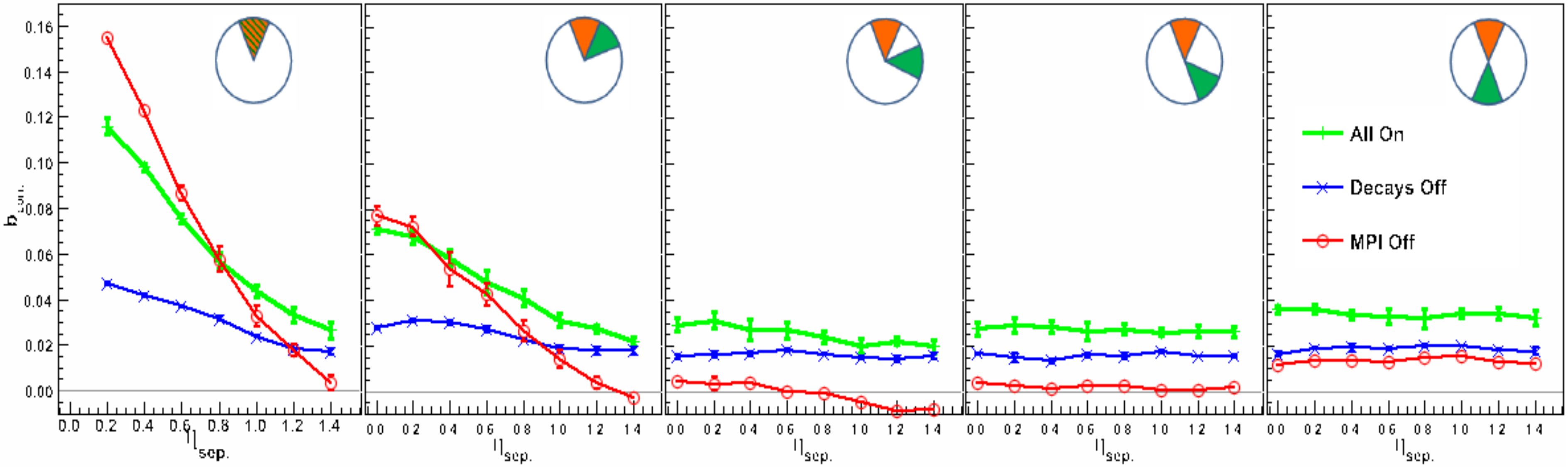
Switching off MPI removes fluctuations in number of emitting sources (in Pythia way of implementation).

That causes absence of correlations in distant η windows

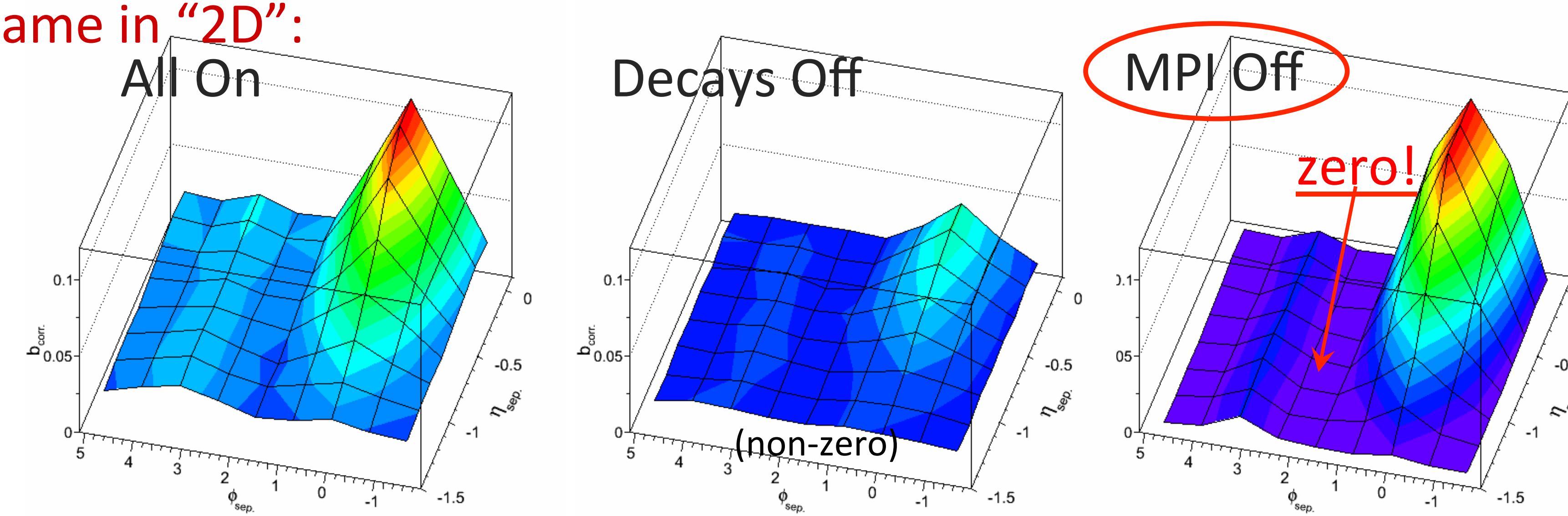
, while switching off the other processes leads mainly to multiplicity reduction.

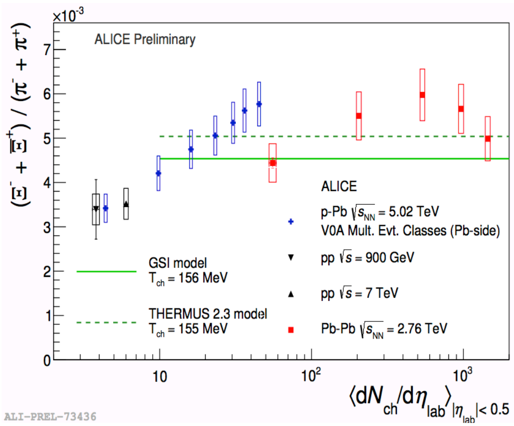
FB multiplicity correlations, *pp*, 7 TeV: look at Pythia8

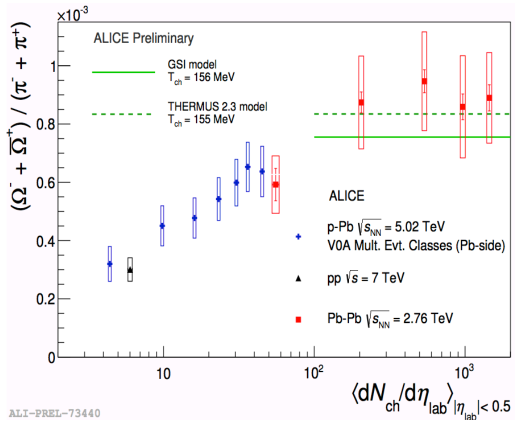
Take separated windows in both η and φ:



Same in “2D”:







PRL 111, 222301 (2013), K0S andLambda Production in Pb-Pb Collisions

TABLE I. Integrated yields, dN/dy, for Λ and K^0_S with uncertainties which are dominantly systematic. A blast-wave fit is used to extrapolate to zero p_T. Fractions of extrapolated yield are specified. Ratios of integrated yields, Λ/K^0_S, for each centrality bin with the total uncertainty, mainly from systematic sources, are shown.

		0%–5%	5%–10%	10%–20%	20%–40%	40%–60%	60%–80%	80%–90%
Λ	dN/dy	26 ± 3	22 ± 2	17 ± 2	10 ± 1	3.8 ± 0.4	1.0 ± 0.1	0.21 ± 0.03
	$p_T < 0.6$ GeV/c frac.	10%	11%	12%	14%	18%	24%	32%
K^0_S	dN/dy	110 ± 10	90 ± 6	68 ± 5	39 ± 3	14 ± 1	3.9 ± 0.2	0.85 ± 0.09
	$p_T < 0.4$ GeV/c frac.	20%	21%	21%	23%	25%	31%	33%
	Ratio dN/dy Λ/K^0_S	0.24 ± 0.02	0.24 ± 0.02	0.25 ± 0.02	0.25 ± 0.02	0.26 ± 0.03	0.25 ± 0.02	0.25 ± 0.02

Multi-strange baryon production at mid-rapidity in Pb–Pb collisions at √sNN = 2.76 TeV

Phys. Lett. B 728 (2014) 216

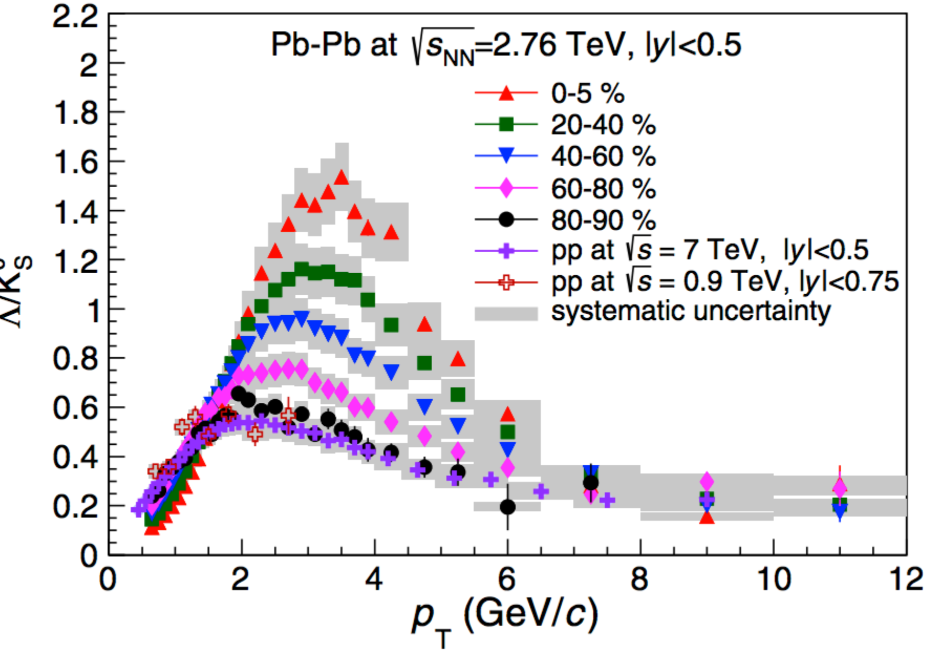
Table 1
Total integrated mid-rapidity yields, dN/dy, for multi-strange baryons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, for different centrality intervals. Both statistical (first) and systematic (second) errors are shown. For each centrality interval the average number of participants, $\langle N_{part} \rangle$, is also reported [26].

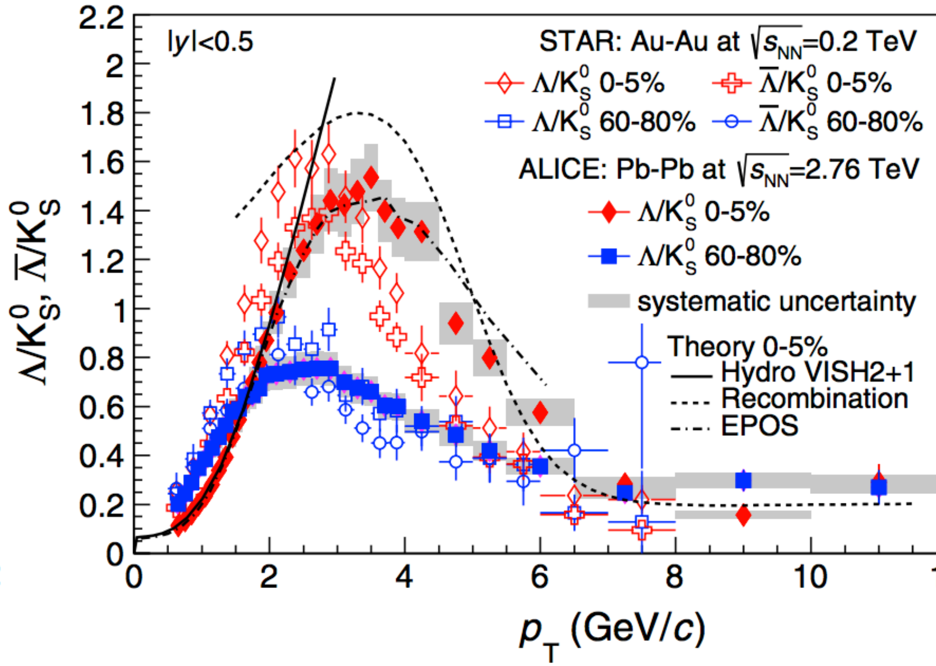
Centrality	0–10%	10–20%	20–40%	40–60%	60–80%
$\langle N_{part} \rangle$	356.1 ± 3.6	260.1 ± 3.9	157.2 ± 3.1	68.6 ± 2.0	22.5 ± 0.8
Ξ^-	3.34 ± 0.06 ± 0.24	2.53 ± 0.04 ± 0.18	1.49 ± 0.02 ± 0.11	0.53 ± 0.01 ± 0.04	0.124 ± 0.003 ± 0.009
$\bar{\Xi}^+$	3.28 ± 0.06 ± 0.23	2.51 ± 0.05 ± 0.18	1.53 ± 0.02 ± 0.11	0.54 ± 0.01 ± 0.04	0.120 ± 0.003 ± 0.008
$\Xi^- + \bar{\Xi}^+$	6.67 ± 0.08 ± 0.47	5.14 ± 0.06 ± 0.36	3.03 ± 0.03 ± 0.22	1.07 ± 0.01 ± 0.08	0.240 ± 0.006 ± 0.019
Ω^-	0.58 ± 0.04 ± 0.09	0.37 ± 0.03 ± 0.06	0.23 ± 0.01 ± 0.03	0.087 ± 0.005 ± 0.014	0.015 ± 0.002 ± 0.003
$\bar{\Omega}^+$	0.60 ± 0.05 ± 0.09	0.40 ± 0.03 ± 0.06	0.25 ± 0.01 ± 0.03	0.082 ± 0.005 ± 0.013	0.017 ± 0.002 ± 0.003
$\Omega^- + \bar{\Omega}^+$	1.19 ± 0.06 ± 0.19	0.78 ± 0.04 ± 0.15	0.48 ± 0.02 ± 0.08	0.170 ± 0.007 ± 0.029	0.032 ± 0.003 ± 0.005

Lambda/K^0_S

ALICE Results

DOI: 10.1103/PhysRevLett.111.222301





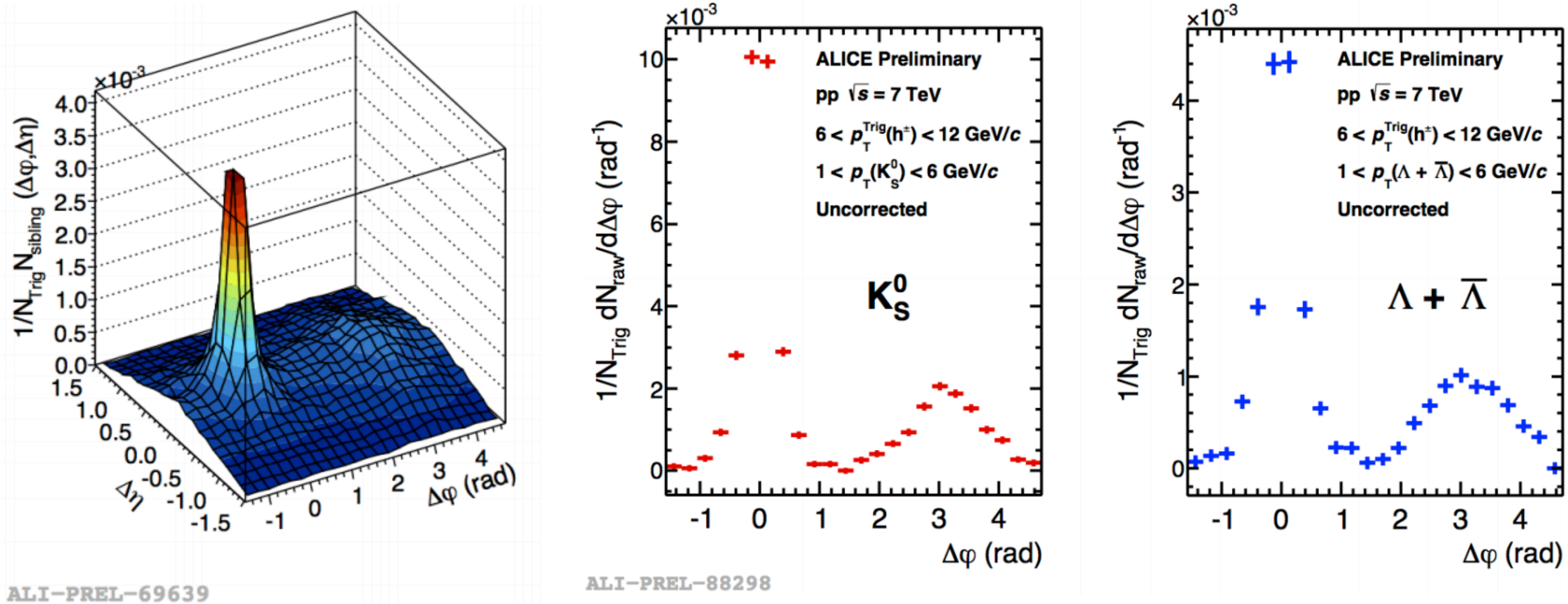
*) The ratio of integrated and K0S yields does not, within uncertainties, change with centrality and is equal to that measured in pp collisions at 0.9 and 7 TeV. Tbaryon enhancement at intermediate pT is predominantly due to a redistribution of baryons and mesons over the momentum range rather than due to an additional baryon production channel progressively opening up in more central heavy-ion collisions.

Correlations with strange particles

- so far: do people measure such correlations?
- some results from ALICE:

Strangeness production in two-particle azimuthal correlations on the near and away side measured with ALICE in pp collisions at √s=7 TeV

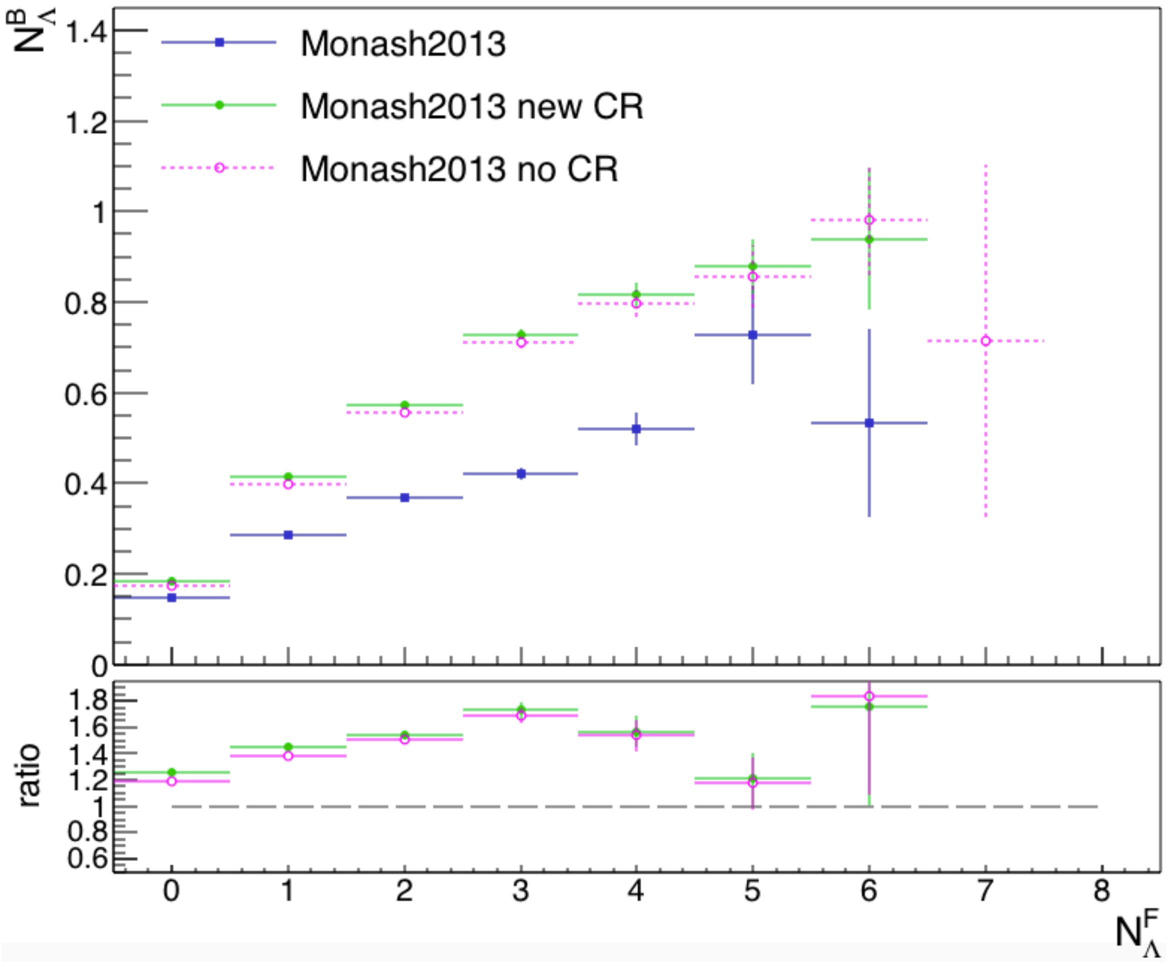
arxiv:1409.3498



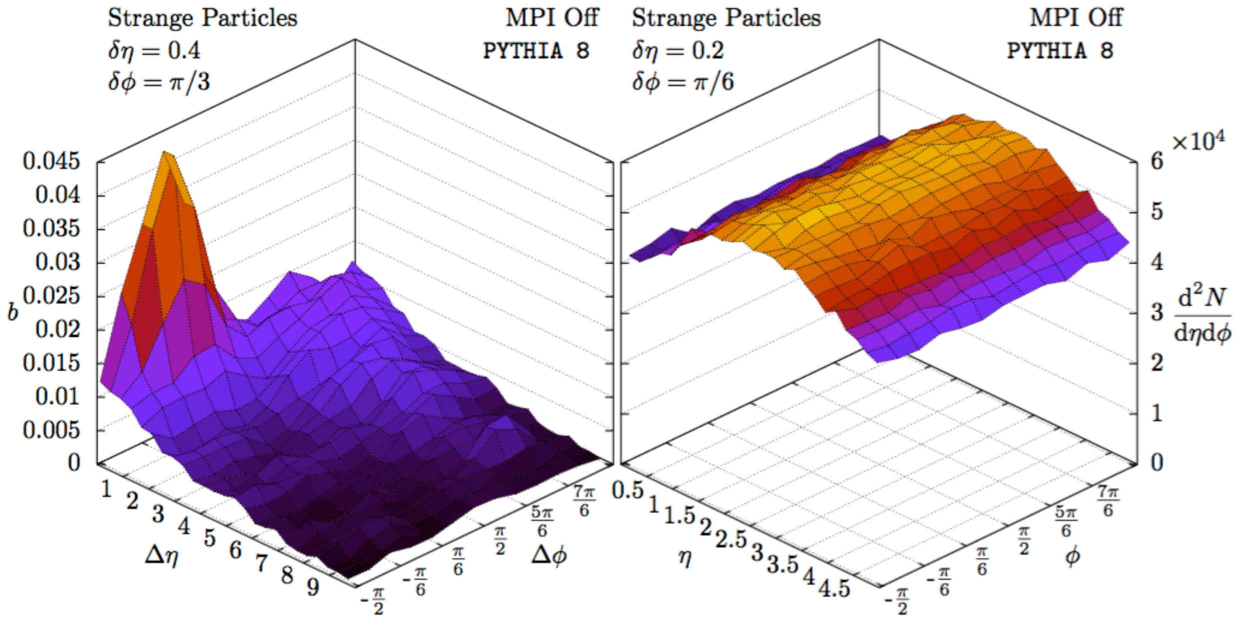
h±−K0S correlation for same event.

Two-particle correlation functions for h±−K0S and h±−(Λ + Λ) pairs at pp √s = 7 TeV after the baseline subtraction.

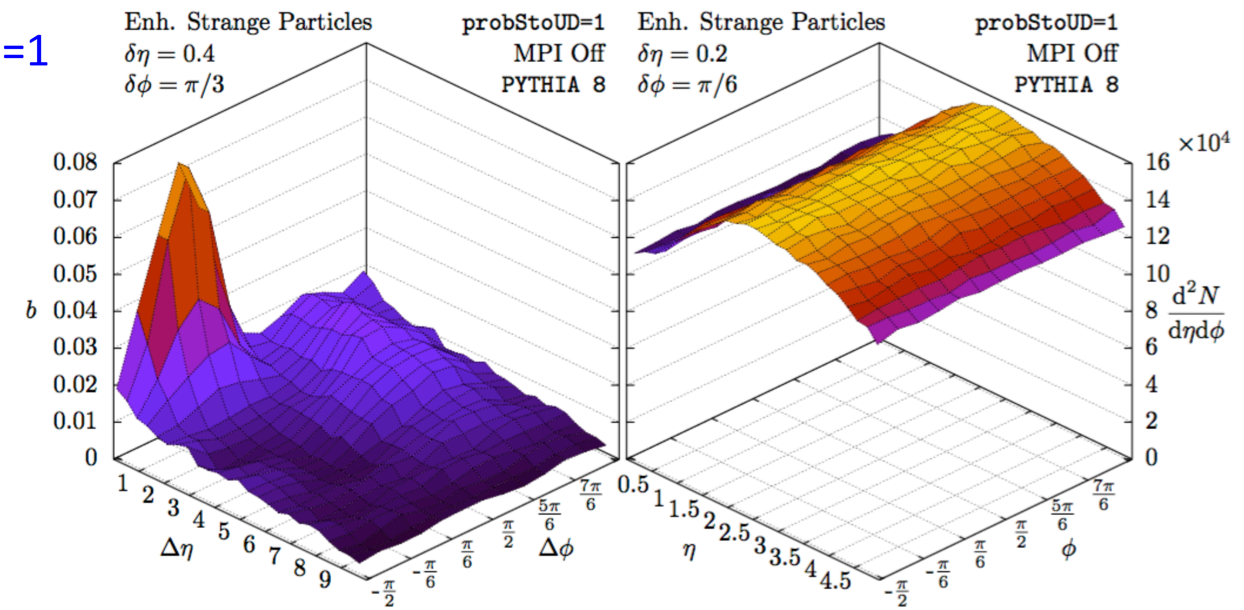
FB correlations for N_{Lambda}-N_{Lambda}



MPI off + explicit strangeness enhancement



probStoUD=1



Mean p_T correlations in string fusion model

- Mean p_T provides a better selection of events: a higher mean p_T means an event with higher degree of string overlap
- Contrary to Nch-Nch and pt-Nch correlations, mean pt-pt correlations are not so strongly influenced by centrality selection issues

$$b_{\text{corr}} = \frac{\langle FB\rangle - \langle F\rangle\langle B\rangle}{\langle F^2\rangle - \langle F\rangle^2}$$

$$B \equiv \overline{p_{\text{T}}}_B = \frac{\sum_{i=1}^{n_B} p_{\text{T}}^{(i)}}{n_B} \qquad F \equiv \overline{p_{\text{T}}}_F = \frac{\sum_{j=1}^{n_F} p_{\text{T}}^{(j)}}{n_F}$$