Knut and Alice Wallenberg Foundation

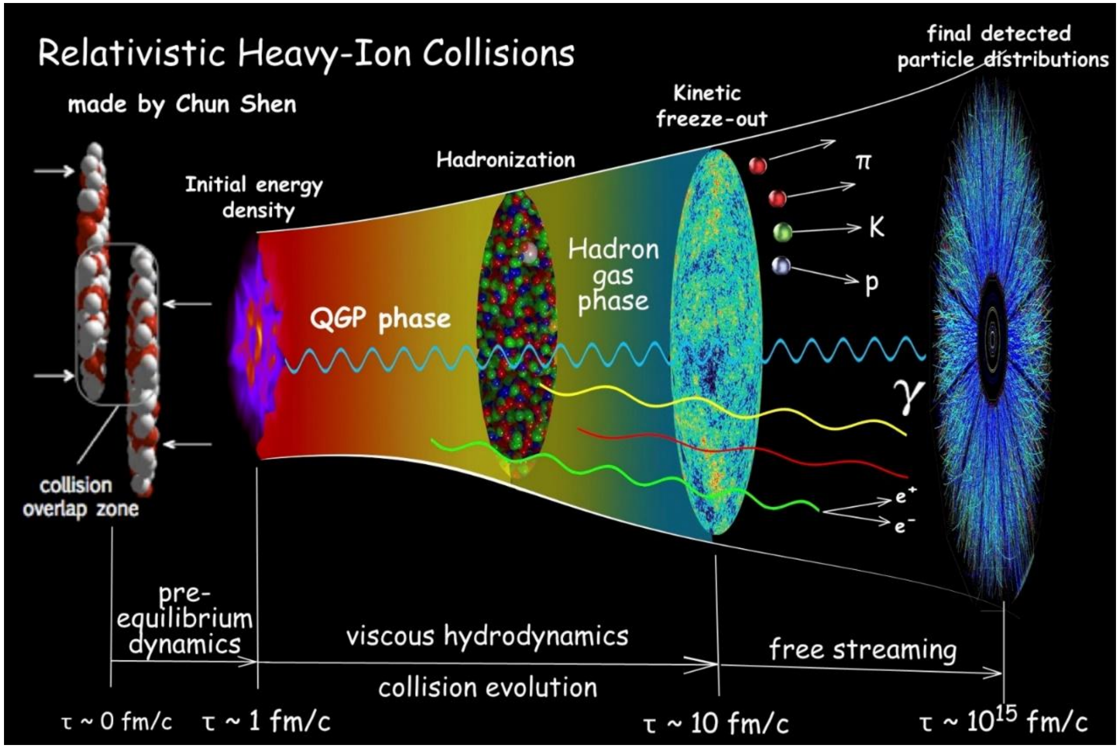
QGP in small systems? Why we CLASH and what we have learned

Peter Christiansen (Lund University, Sweden)

Outline

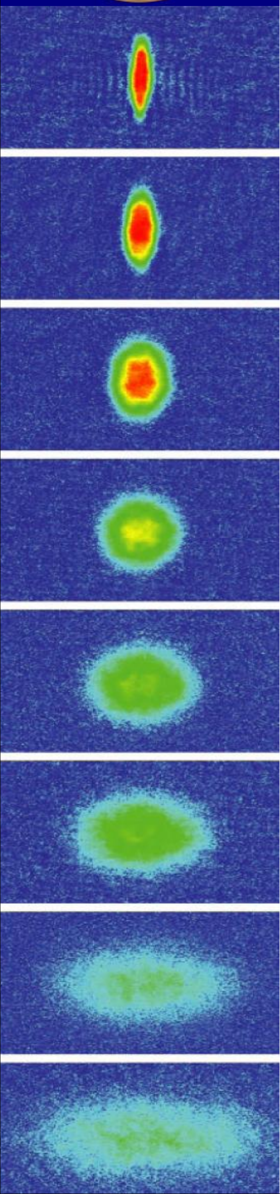
- An introduction to Quark Gluon Plasma (QGP) physics in large and small (?) systems
- The CLASH project and relevant models
- Results from the CLASH project
- Conclusions and how to make further progress

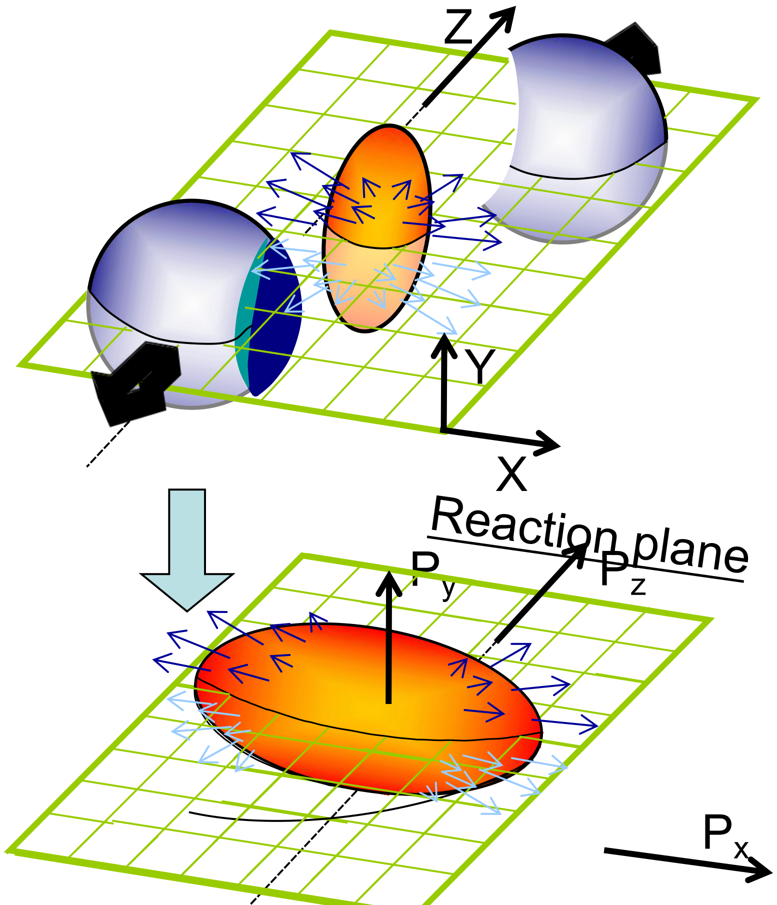
How we create QGP and what the challenges are



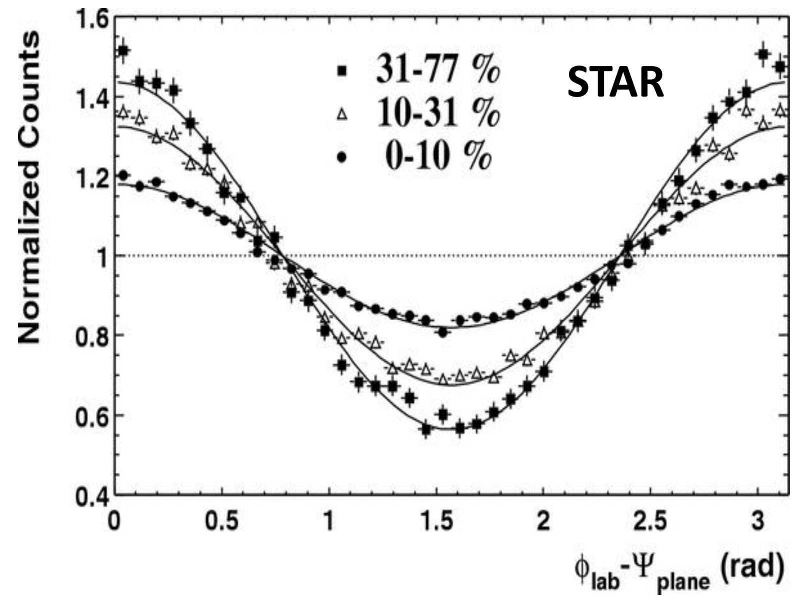
- The QGP is a new phase of matter where quarks and gluons are deconfined
- Challenges
  - We can mainly only observe final state particles (after QGP)
  - We do not know very well from theory what to look for (non-perturbative nature of QGP)

Elliptic flow (v_2)



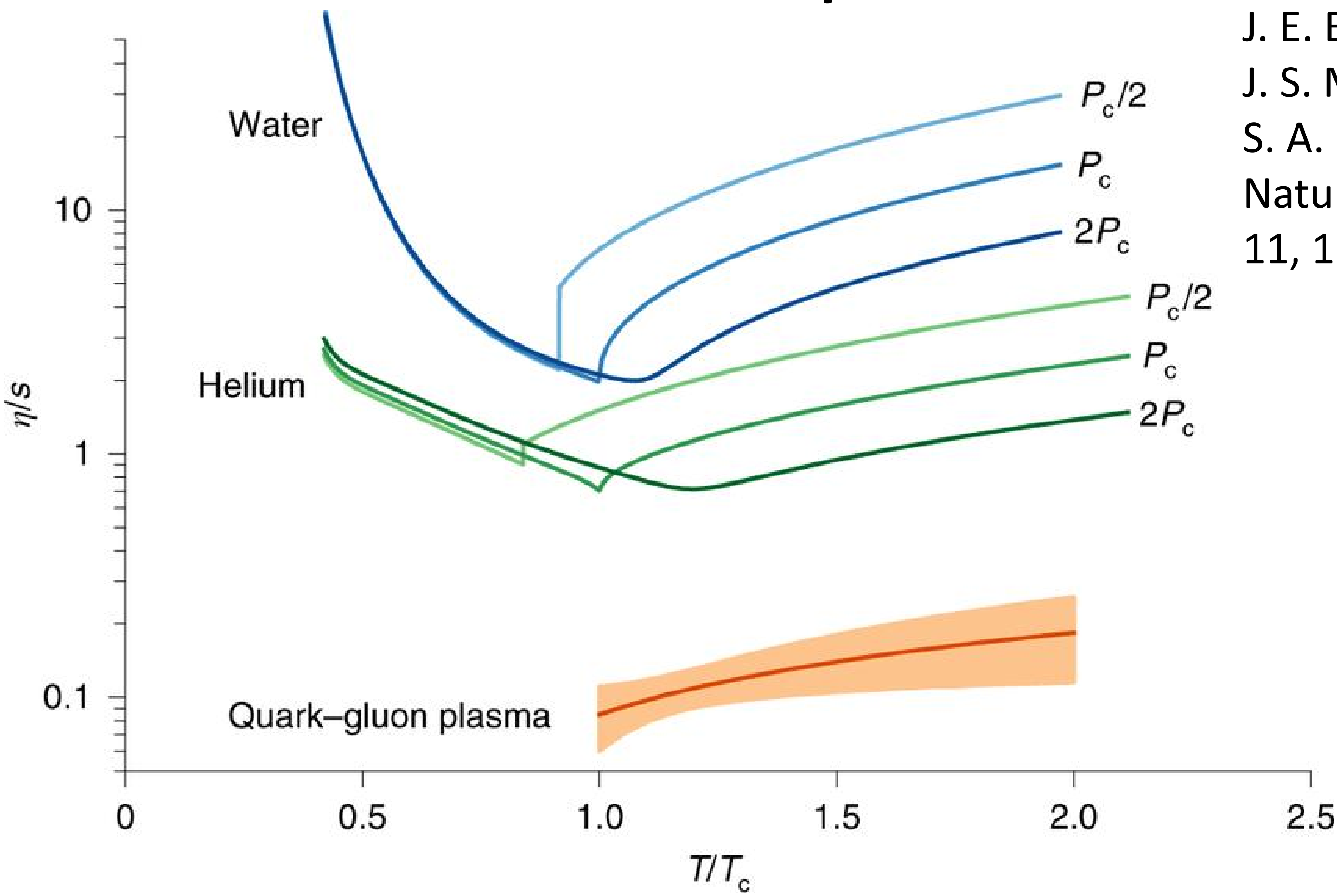


Fourier decomposition:
$dN/d\Delta\phi = 1 + 2\, v_2 \cos(2\, \Delta\phi)$



Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

The QGP liquid compared to other liquids

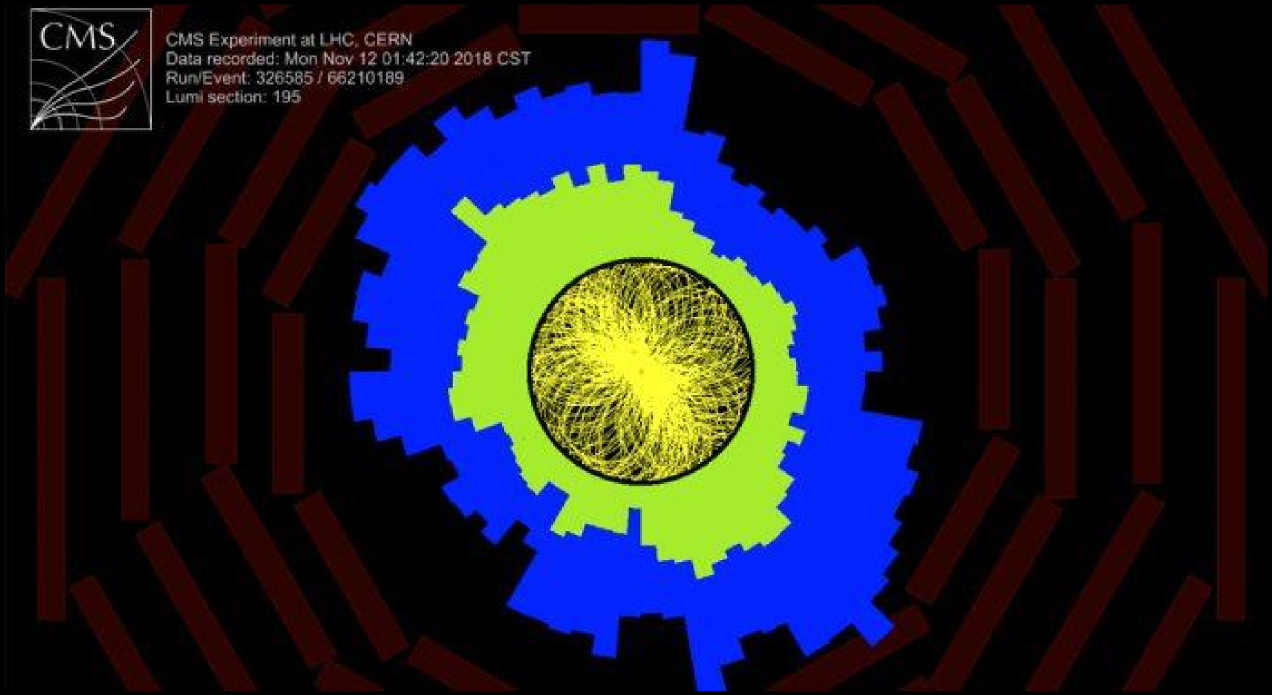


J. E. Bernhard,
J. S. Moreland,
S. A. Bass
Nature Phys. 15 (2019) 11, 1113

Because of the very low η/s (shear viscosity-to-entropy density) we think the QGP is a perfect liquid!

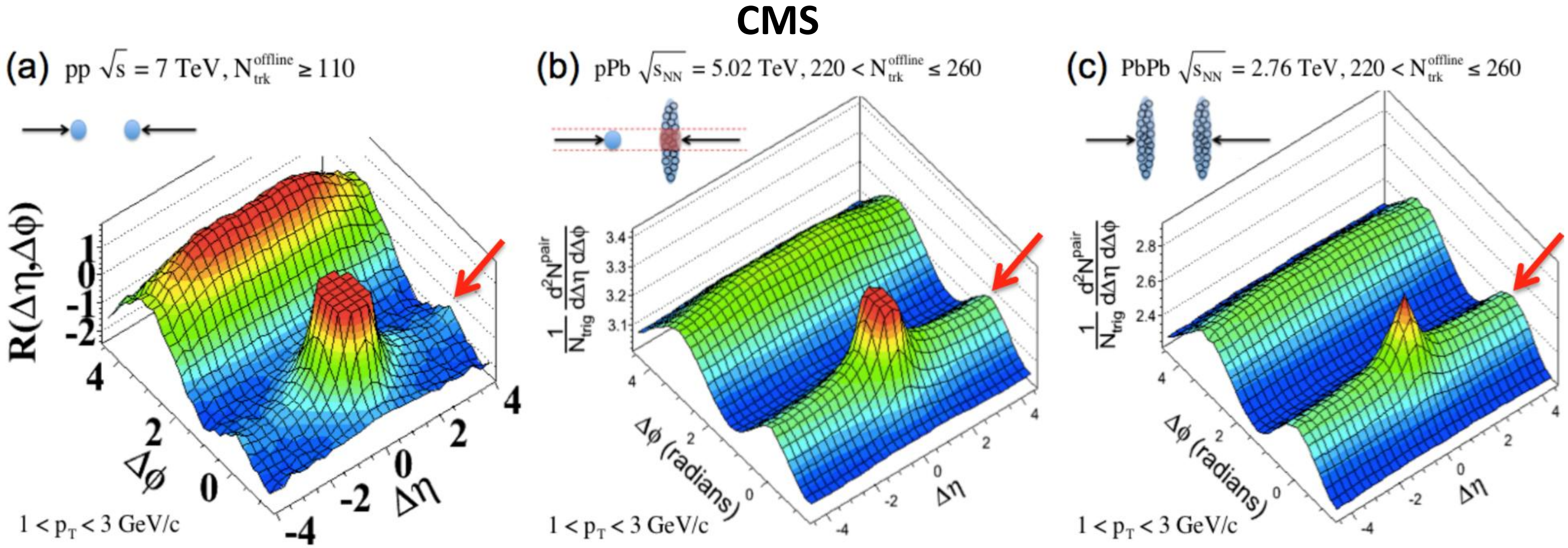
Perfect liquid has become a workhorse

Perfect liquid expansion is almost reversible
➔Almost no entropy production!?
➔We can “photograph” the initial overlap



And we can even measure nuclear shapes in this way: arXiv:2209.11042

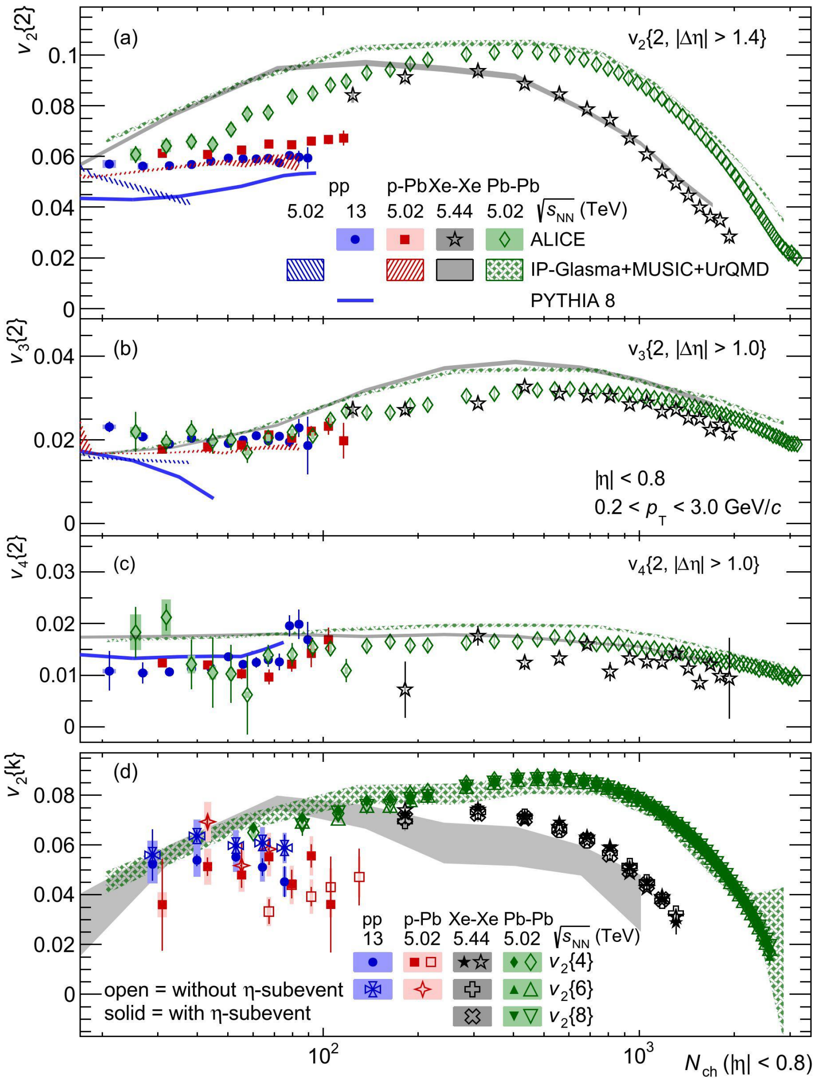
Ridges in all systems



The perfect liquid is produced in all systems suggesting that small QCD systems produce "macroscopic" matter

Is it the same flow mechanism in small and large systems?

ALICE, PRL 123, 142301 (2019)

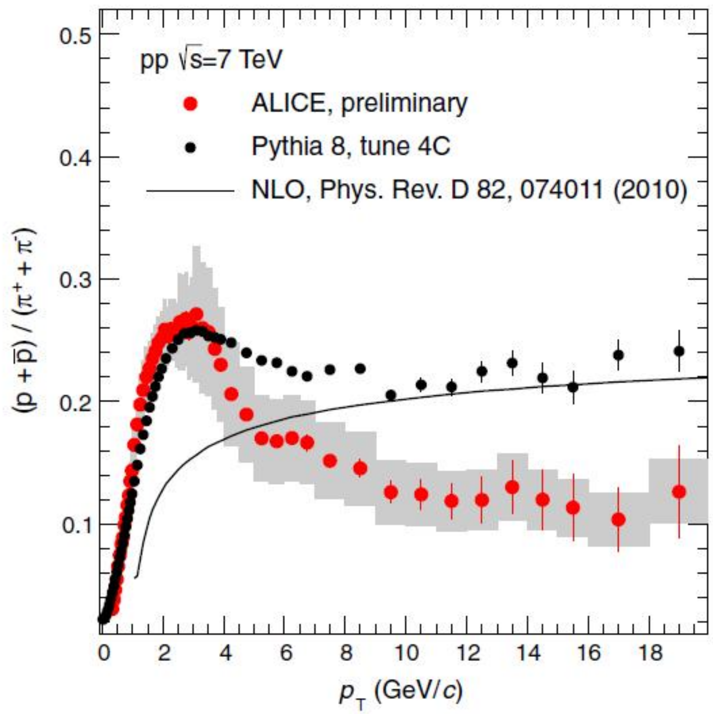


- v_2 driven by geometry in large system $\rightarrow$ larger than in small systems as expected
- v_3 driven by fluctuations $\rightarrow$ same in small systems as expected
- What is the microscopic mechanism?

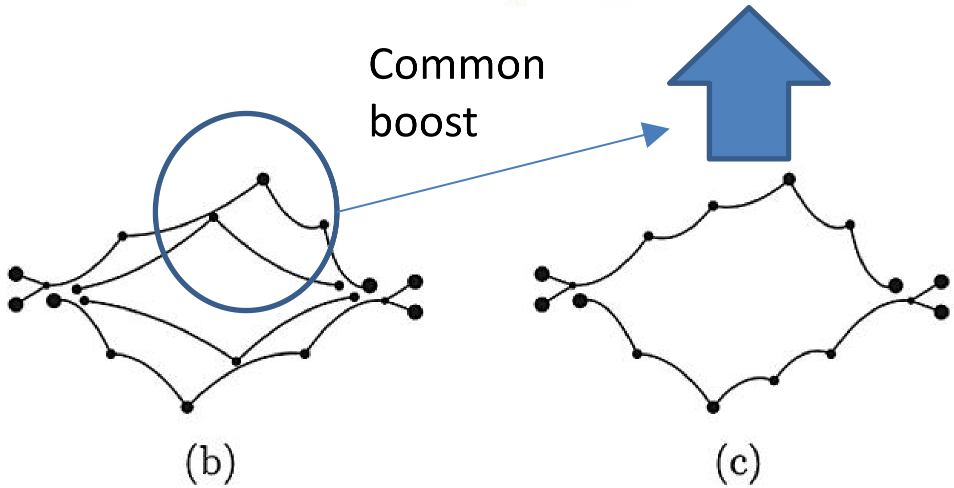
The Mexican angle

- Visited UNAM 1 month in 2011 (EPLANET)
  - Ongoing collaboration since then
  - Common workshops: QCD challenges from pp to AA collisions, Taxco (2016), Puebla (2017), Lund (2019), Padova (2023), Muenster (2024)

The "flow peak" in pp



Realized that Color Reconnection (CR) in PYTHIA gives rise to flow like boosts
Antonio Ortiz Velasquez, Peter Christiansen, Eleazar Cuautle Flores, Ivonne Maldonado Cervantes, Guy Paić, PRL 111, 042001 (2013).
For details, see T. Sjöstrand, arXiv:1310.8073.

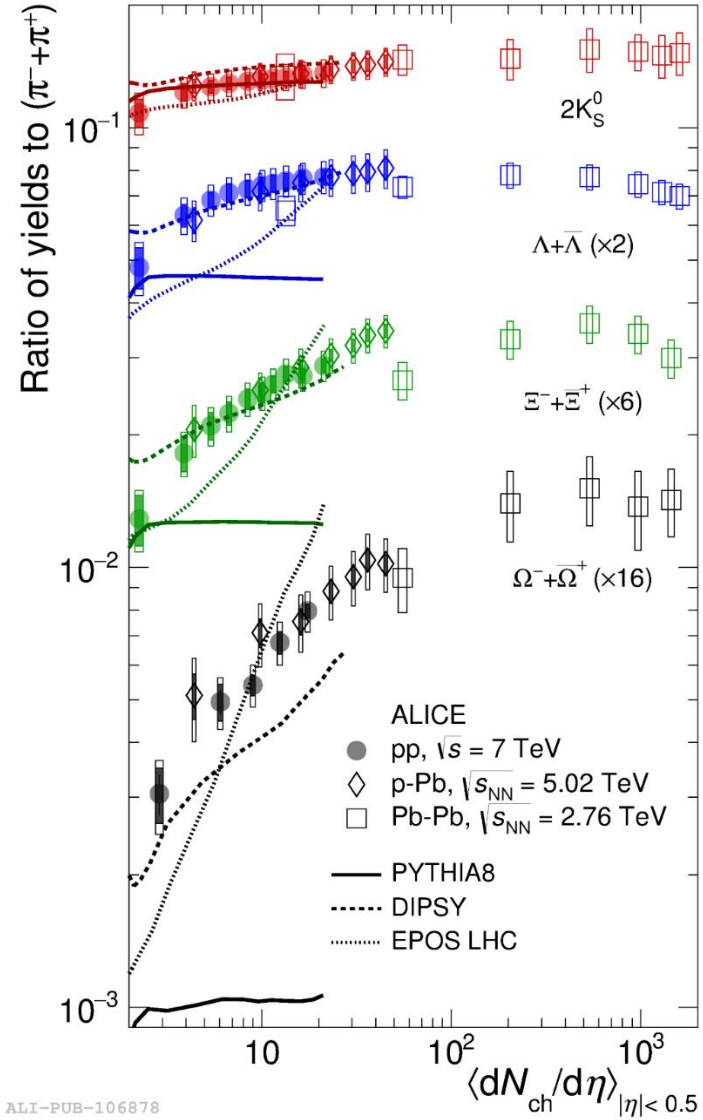


CR can be a microscopic model of flow
$\rightarrow$ Renewed interest in CR

Alternative to hydrodynamics

Integrated particle ratios

ALICE, Nature Physics 13 (2017) 535



(sud)

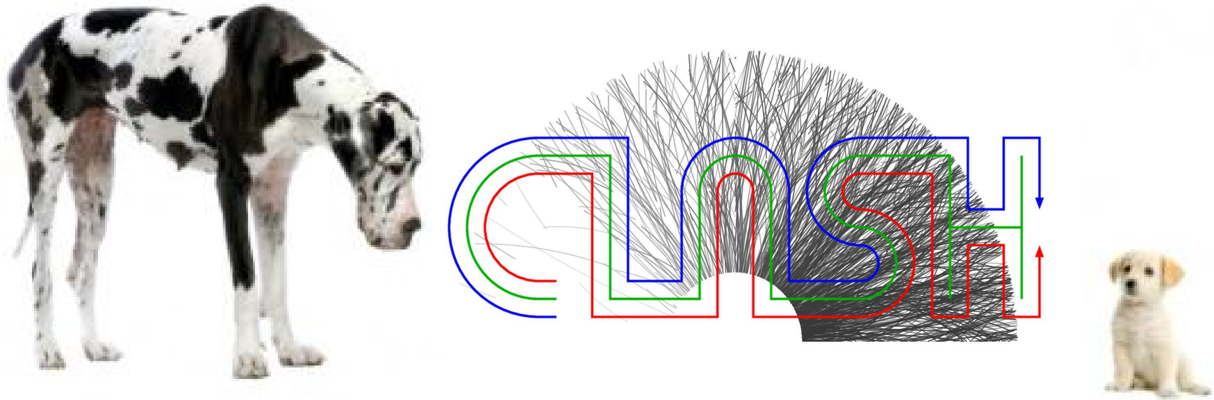
(ssd)

(sss)

DIPSY Color rope model:
C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov (Jefferson Lab), JHEP 1503 (2015) 148

Later implemented in Pythia (see later).

The CLASH: Macroscopic (top-down) vs microscopic (bottom up) models

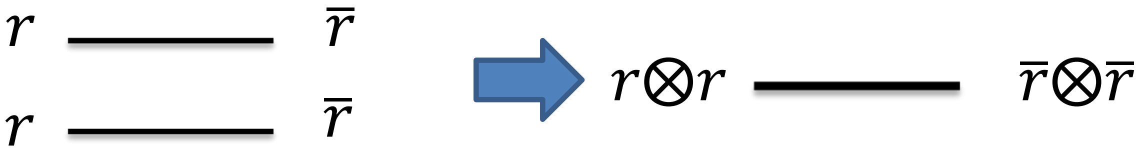


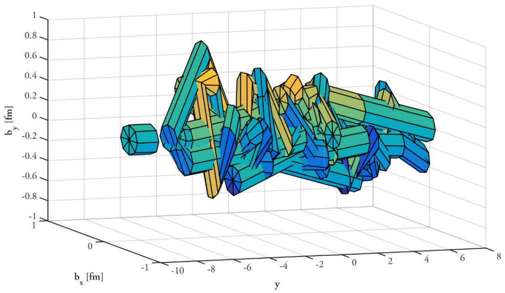
- Stat. thermal model
  - Canonical
  - Grand-canonical
- Hydrodynamics
  - Radial flow
  - Azimuthal anisotropic
- Tunneling of $q\bar{q}$-pairs
  - Strings
  - Ropes and junctions
- String interactions
  - Color reconnection
  - Shoving

Strangeness enhancement: Pythia explanation

C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov, JHEP 03 (2015) 148

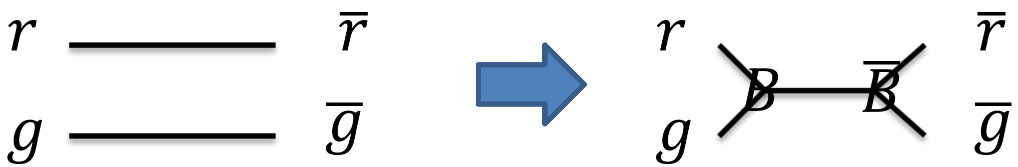
String interactions: rope formation





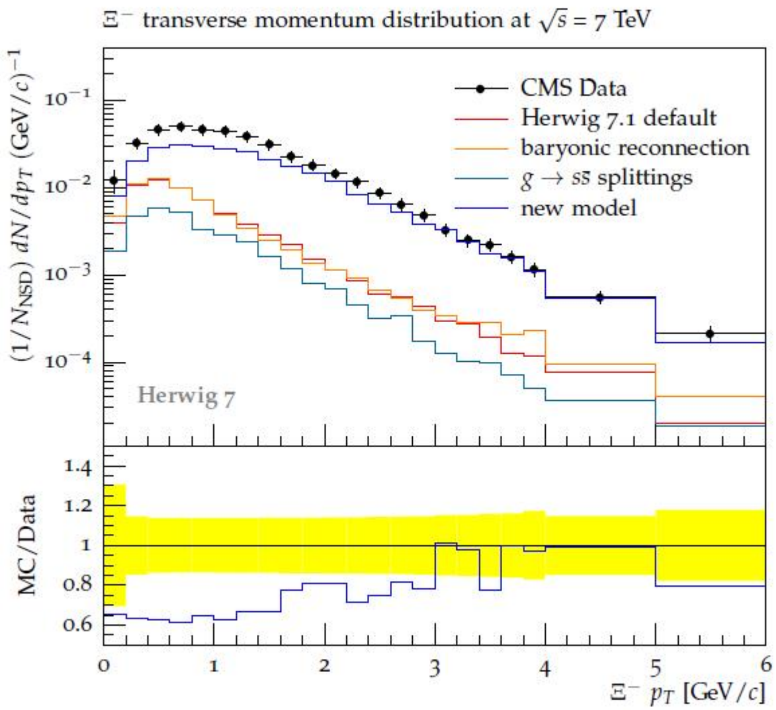
Picture from C. Bierlich
(string radii ~3.5 times too small!)

String interactions: junction formation

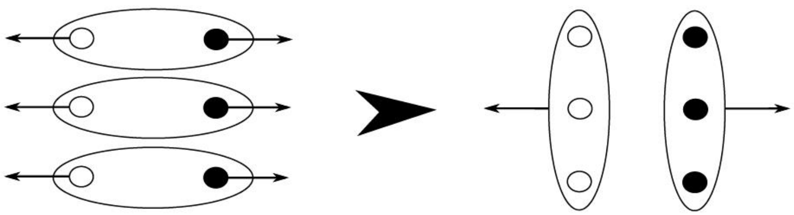


- Increase strangeness and/or baryon production
  – Ropes have increased string tension $\rightarrow$ Produce more strangeness
  – Junctions produce more baryons

Strangeness enhancement: Herwig explanation



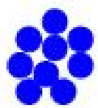
S. Gieseke, P. Kirchgaeßer, S. Plätzer
Eur.Phys.J.C 78 (2018) 2, 99



- Non-QGP model like Pythia that uses cluster hadronization
- New additions to Herwig:
  - Improved description of strangeness by baryon reconnection and allowing $g \to s\bar{s}$ splittings

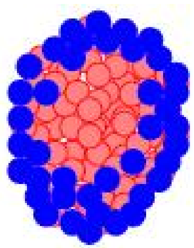
Strangeness enhancement: EPOS explanation

Figure from "QCD Challenges, ECT, Feb 2017, Klaus Werner"



Low mult pp

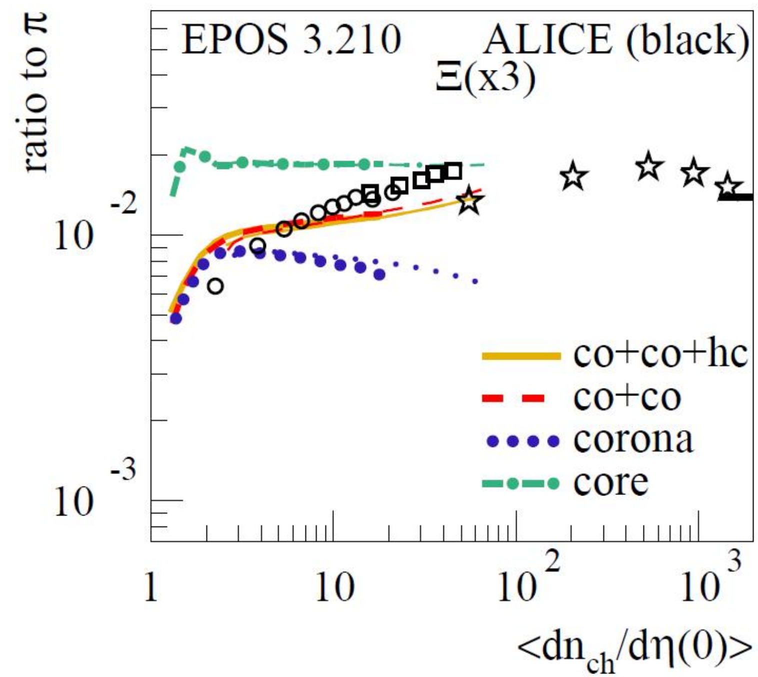
High mult



corona

core

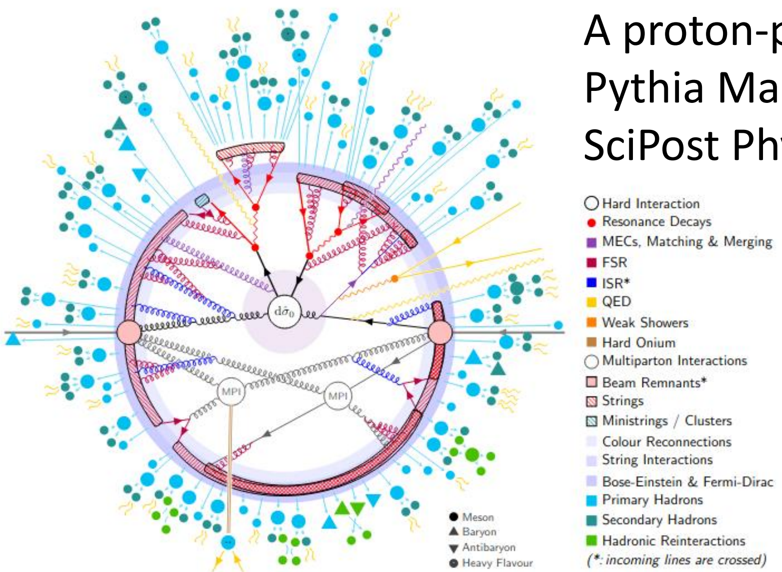
Pictures from K. Werner



thick lines = pp (7TeV)
thin lines = pPb (5TeV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

- Corona is more or less like basic PYTHIA
- Core is modelled as a QGP where particle production is described by grand canonical ensemble
  - Strangeness is produced thermally and only conserved globally

CLASH experimental angle: "Event Engineering"



A proton-proton collision in Pythia
Pythia Manual,
SciPost Phys.Codeb. 2022 (2022) 8

Figure 1: Schematic of the structure of a pp $\rightarrow t\bar{t}$ event, as modelled by PYTHIA.

- Discovery $\rightarrow$ Control/Isolation
- Question: can we control strangeness enhancement? E.g., switch on and off strangeness enhancement for a fixed multiplicity

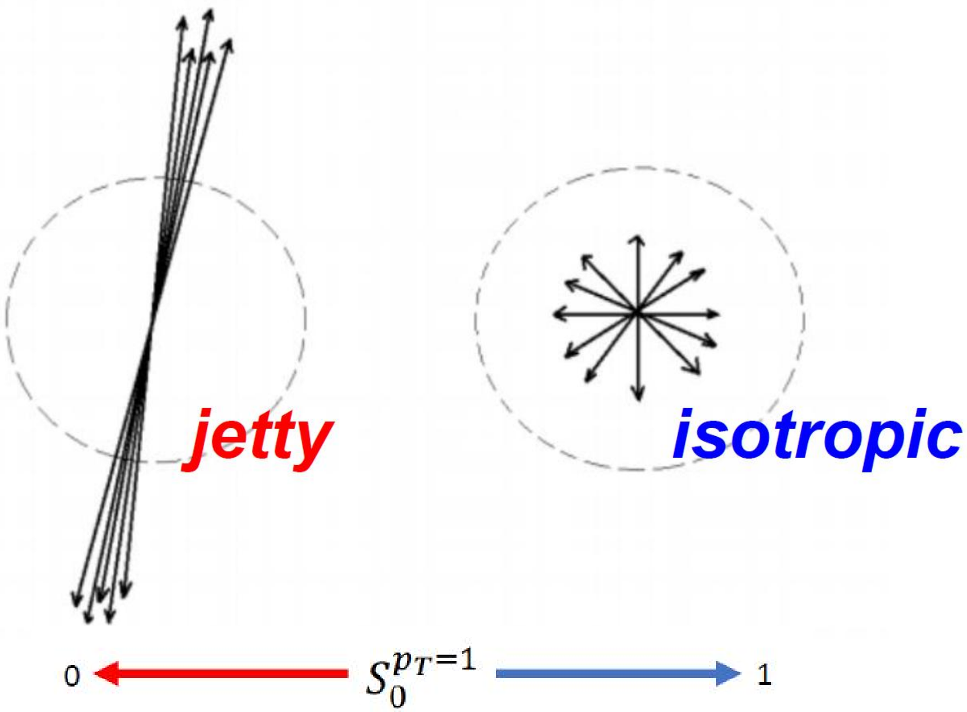
Two ideas tested in CLASH

- No time to show: Relative Transverse Activity (R_T)
  - PhD thesis: Omar Vazquez Rueda (UNAM $\rightarrow$ Lund $\rightarrow$ University of Houston)
    - ALICE, JHEP 06 (2023) 027 (π, K, p)
  - PhD thesis: Oliver Matonoha
    - To be published (K_s^0, ϕ, Λ, Ξ)

- Transverse Spherocity (S_O)
  - Extension ($N_{ch} \rightarrow$ Particle identification) of ideas and work proposed by Antonio Ortiz (see later)
  - PhD thesis: Adrian Nassirpour
    - ALICE, JHEP 05 (2024) 184

Transverse Spherocity S_O

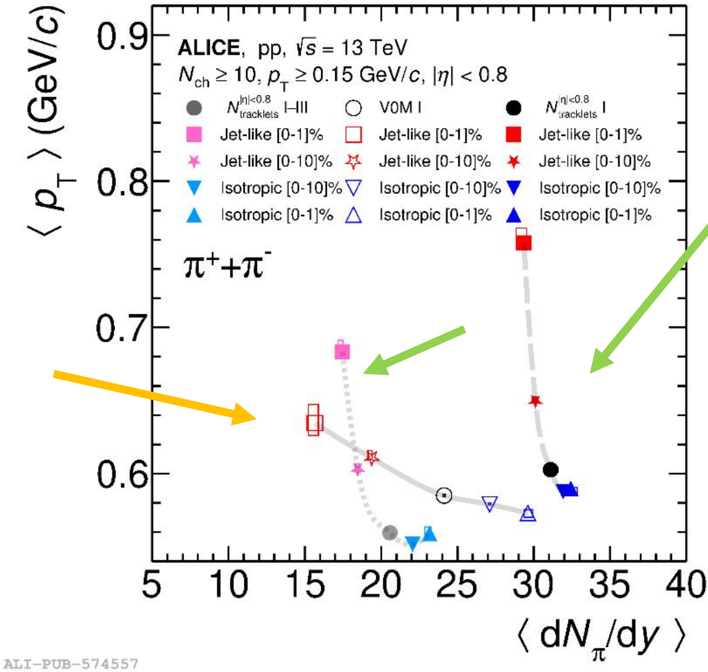
Define the unweighted transverse spherocity:
$S_O^{p_T=1} =$
$\frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\sum_{tracks} |\hat{p}_T \times \hat{n}|}{N_{tracks}} \right)^2$



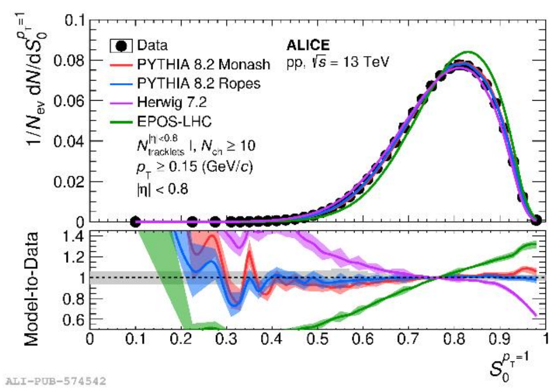
- Most other ALICE results were for the p_T-weighted S_O
  - We need this change because we study shortlived and neutral particles
  - Will call it S_O in the following

The effect of S_O selection for different multiplicity estimators

Forward estimator
Different region than where we measure S_O
Shown for top 10%.
(typically used in ALICE to avoid autocorrelations)



Mid-rapidity estimator
Same region where we measure S_O

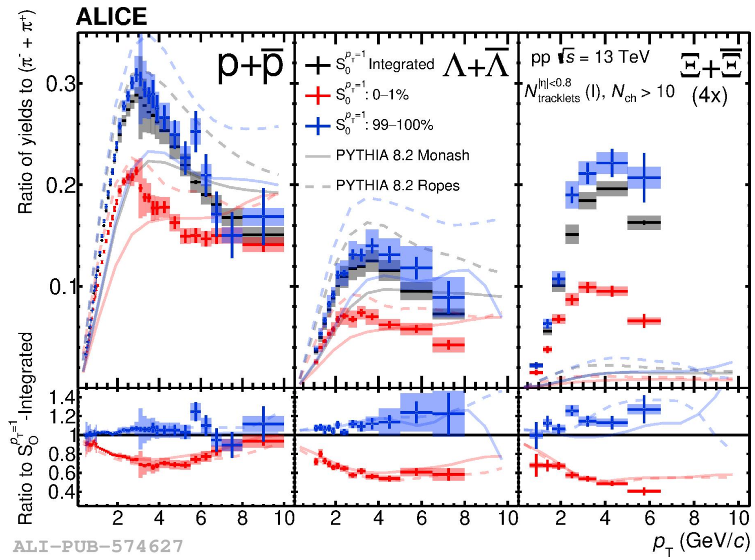


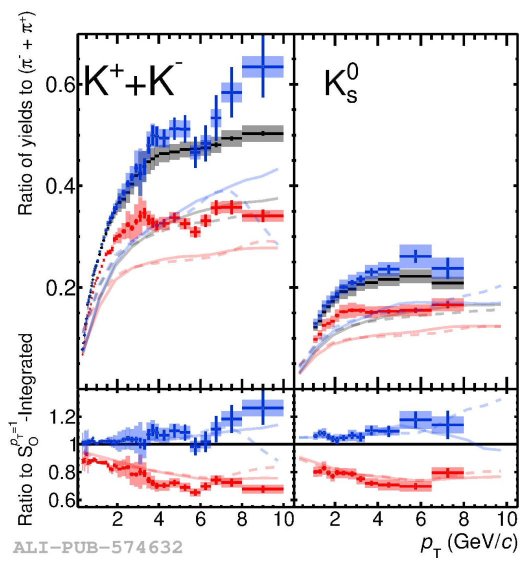
- Physics we can address with S_O depends on where we select the multiplicity
- The following results are all done with the mid-rapidity estimator
  - This ensures that multiplicity is almost constant so that we mainly select harder or softer events

Results top 1% multiplicity and top 1% S_O (0.01% of events)

- Large differences between jetty and isotropic ratios ✓
- Events without S_O selection are similar to isotropic
  - QGP-like effects dominates
    - Perfect liquid?
  - Hard physics is outlier

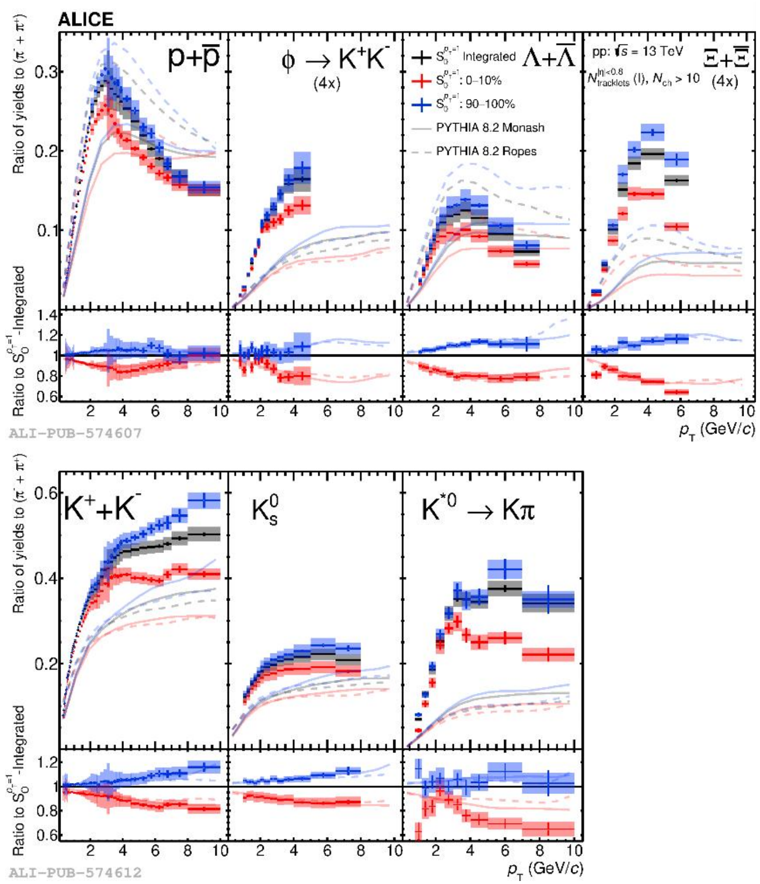
- Jet-like events
  - Radial-flow "peaks" are reduced
  - Strangeness is significantly reduced at high p_T





ALICE, JHEP 05 (2024) 184

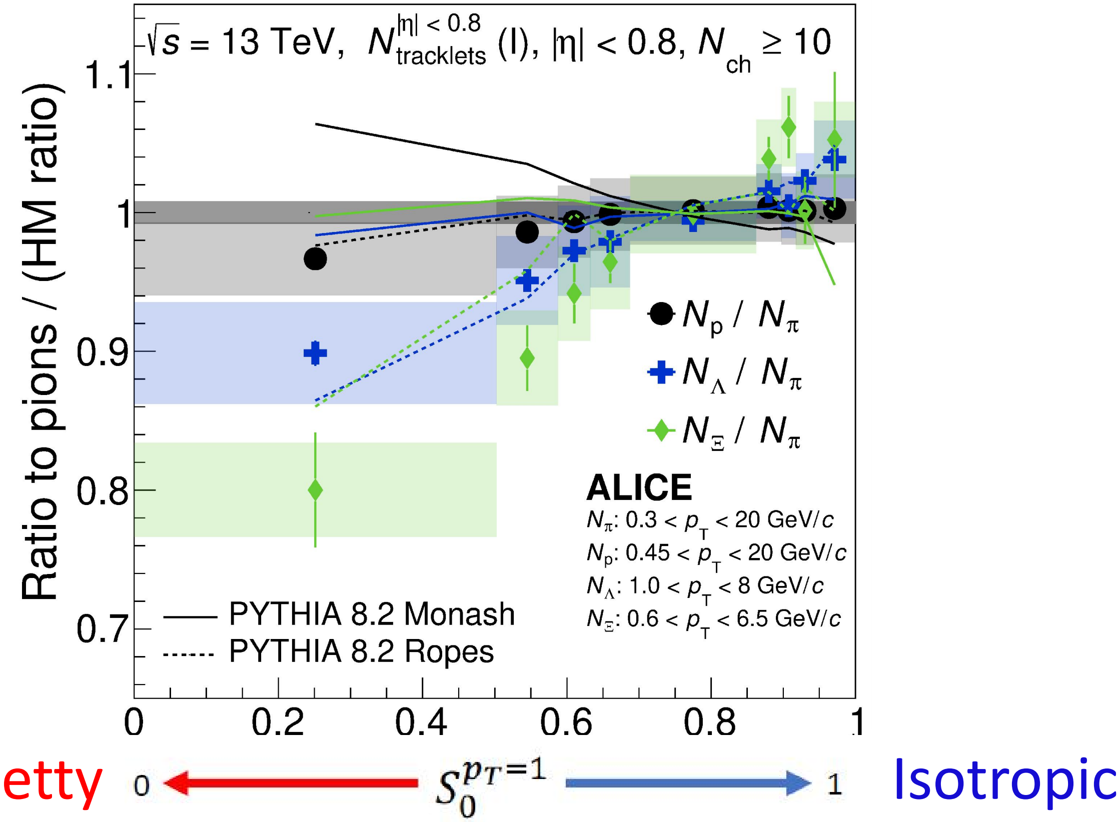
Results top 1% multiplicity and top 10% S_O (0.1% of events)



ALICE,
JHEP 05 (2024) 184

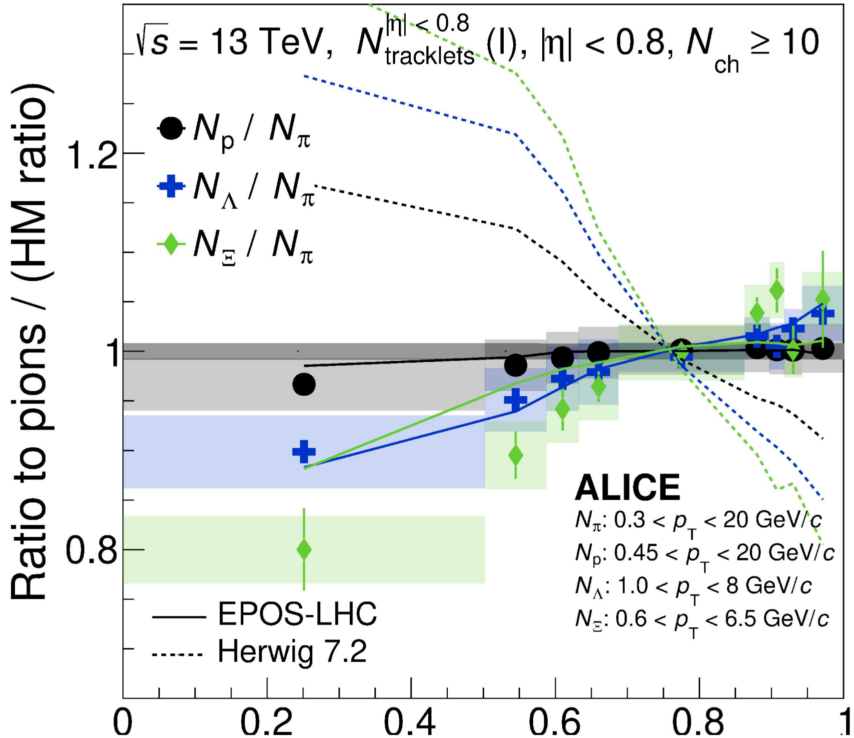
- For top 10% we also have resonances (ϕ and K^{*0})
  - Require more statistics due to event mixing background
- Vs top 1%: effects are reduced but trends are the same

Strangeness enhancement vs S_0 (top 1% multiplicity)



- We can control the strangeness enhancement with S_0 ✓
  - The effect is bigger for Ξ (S=2) than for Λ (S=1)
- Pythia ropes can describe the enhancement qualitatively

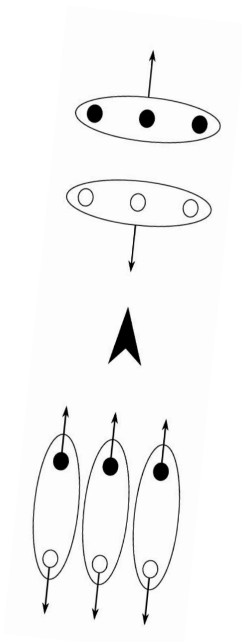
Strangeness enhancement vs S_O (top 1% multiplicity)

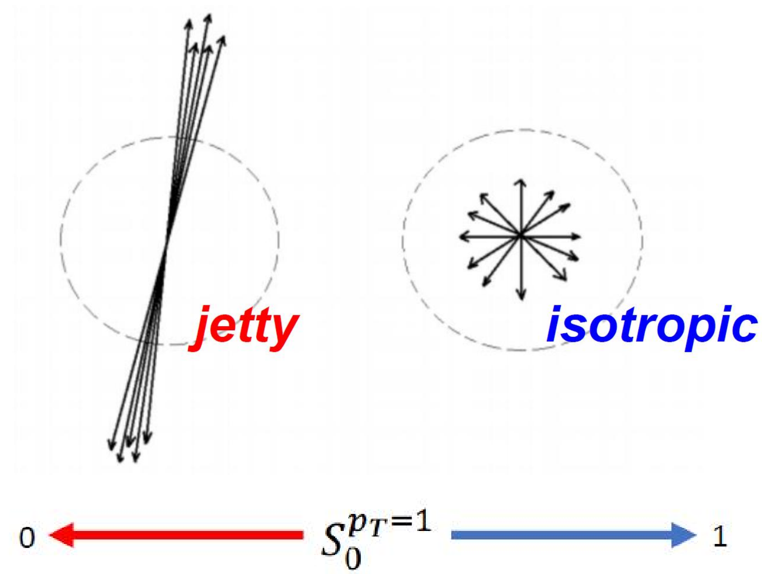


Jetty 0 ← $S_0^{p_T=1}$ → 1 Isotropic

- EPOS LHC captures the trend
  - The QGP core is reduced in jetty events
- HERWIG has opposite trend?! (next slide)

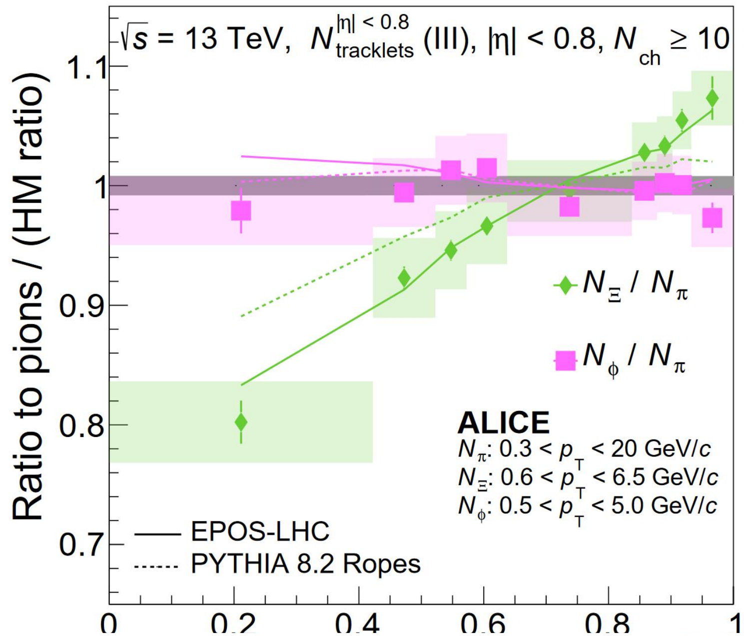
Why Herwig is wrong





- Herwig produces a baryon enhancement by allowing 3 mesons close in phase space to form a baryon-antibaryon pair
  - But this will be more likely to happen in pencil-like events!
  - What about quark coalescence models?

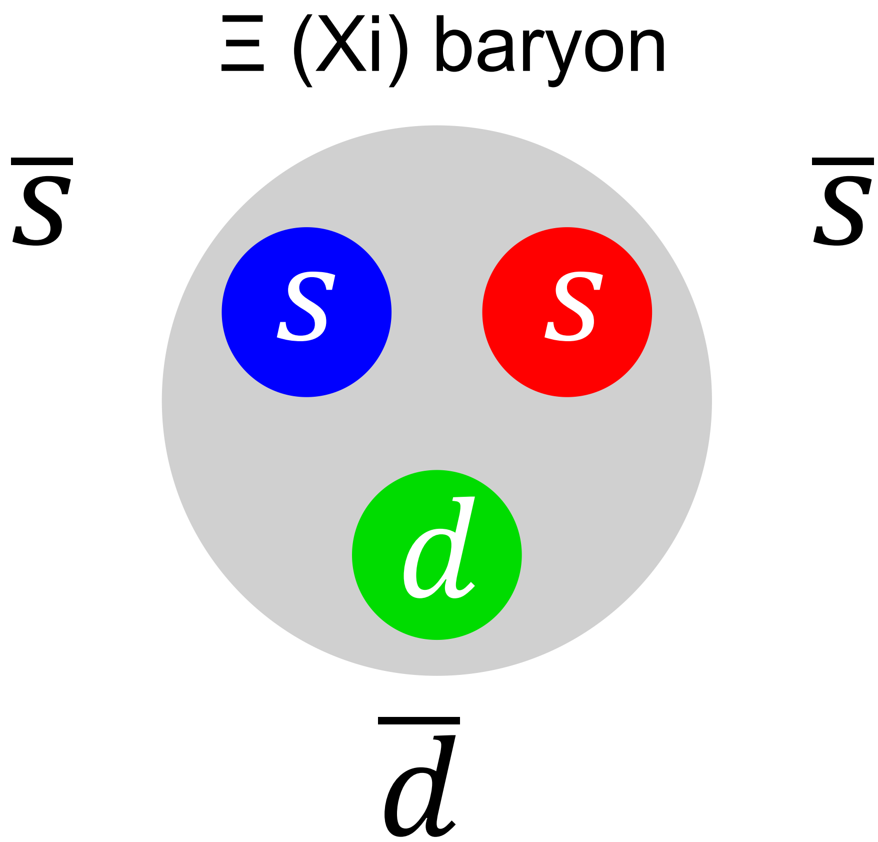
Strangeness enhancement vs S_O (top 10% multiplicity)



Jetty 0 ← $S_0^{p_T=1}$ → 1 Isotropic

- ϕ ($\approx s\bar{s}$) and Ξ (ssd) follows different trends
- Data and models agree
  - Surprising for Pythia where ϕ is produced via 2 $s\bar{s}$ breakings
    - Suggests that the effect is mostly due to junctions
- How can we differentiate between EPOS and Pythia Ropes?

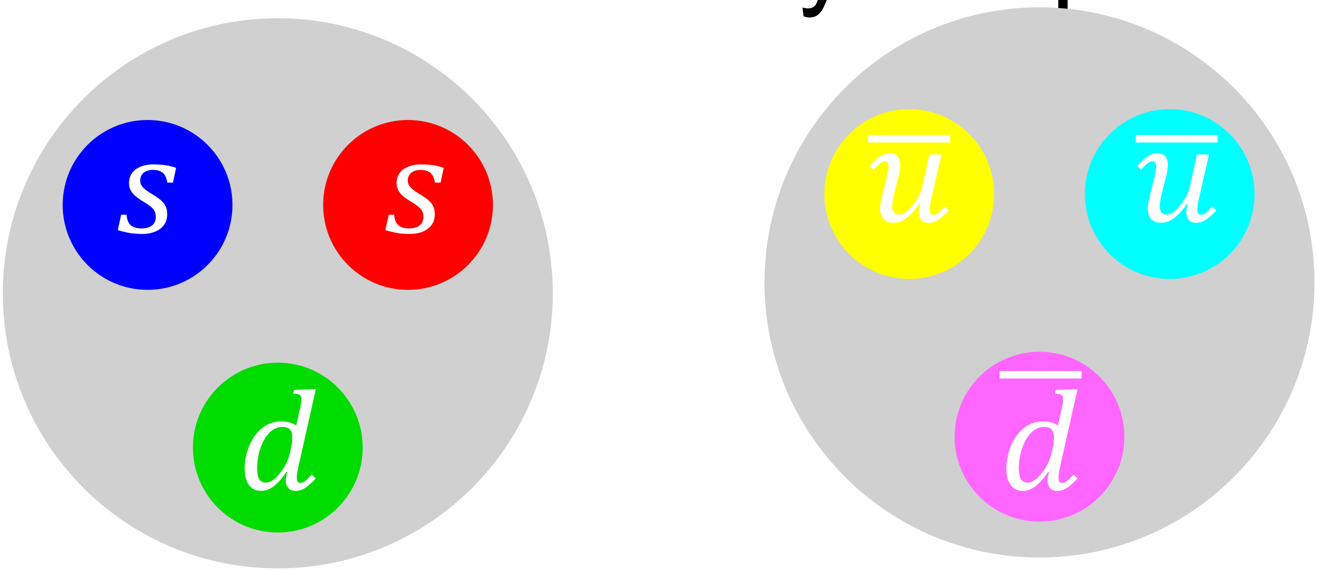
Answer: look at the how the strange quarks are balanced



QGP:
We naively expect that in a QGP the quarks will be deconfined and so eventually the quark pairs will drift apart in phase space.

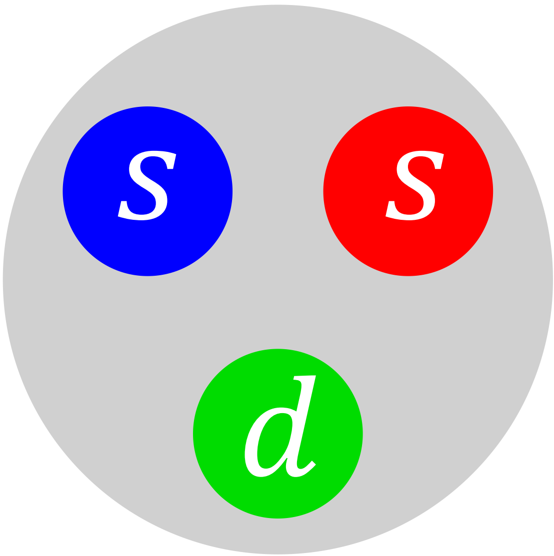
Lund string:
Most quarks and antiquarks are produced together during hadronization.

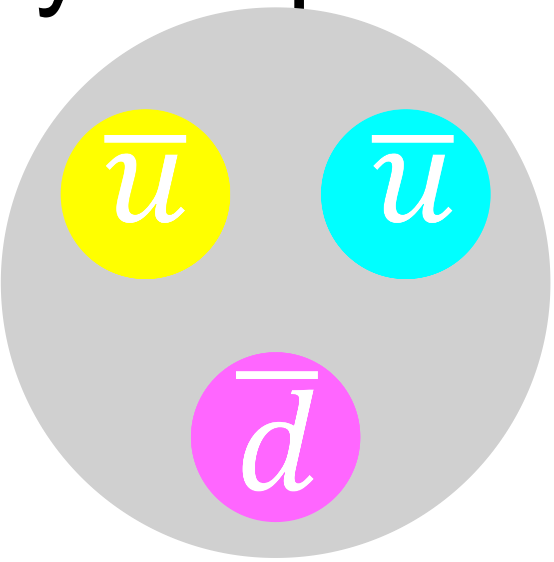
The easiest case:
Ξ balanced by antiproton

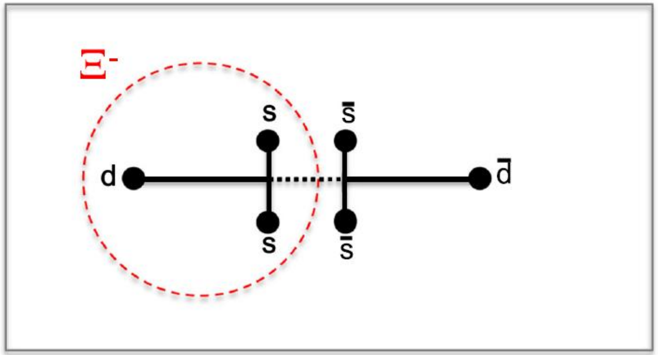


QGP:
We expect that the balancing occurs on a statistical basis so this can happen.

The easiest case:
Ξ balanced by antiproton



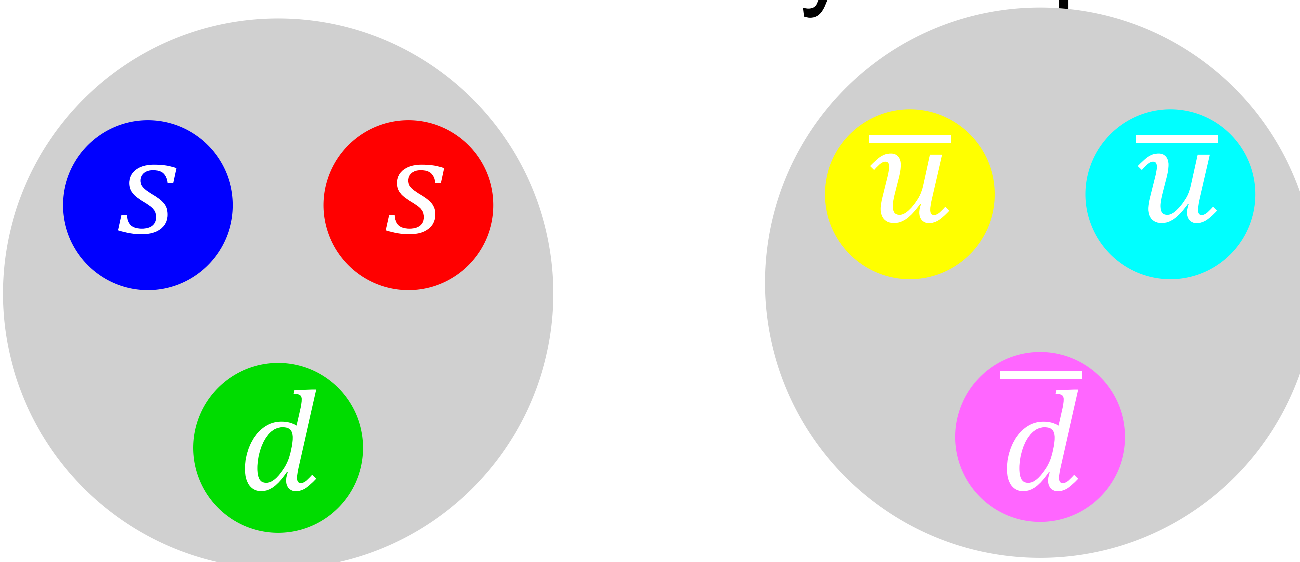


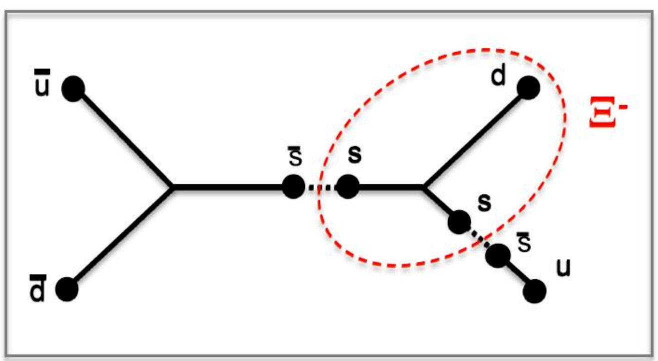


Normal Lund string and ropes:
Ξ almost never balanced by antiproton but instead typically by antistrange baryons and even anti-Ξ!

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, "QCD challenges from pp to A–A collisions"

The easiest case: Ξ balanced by antiproton

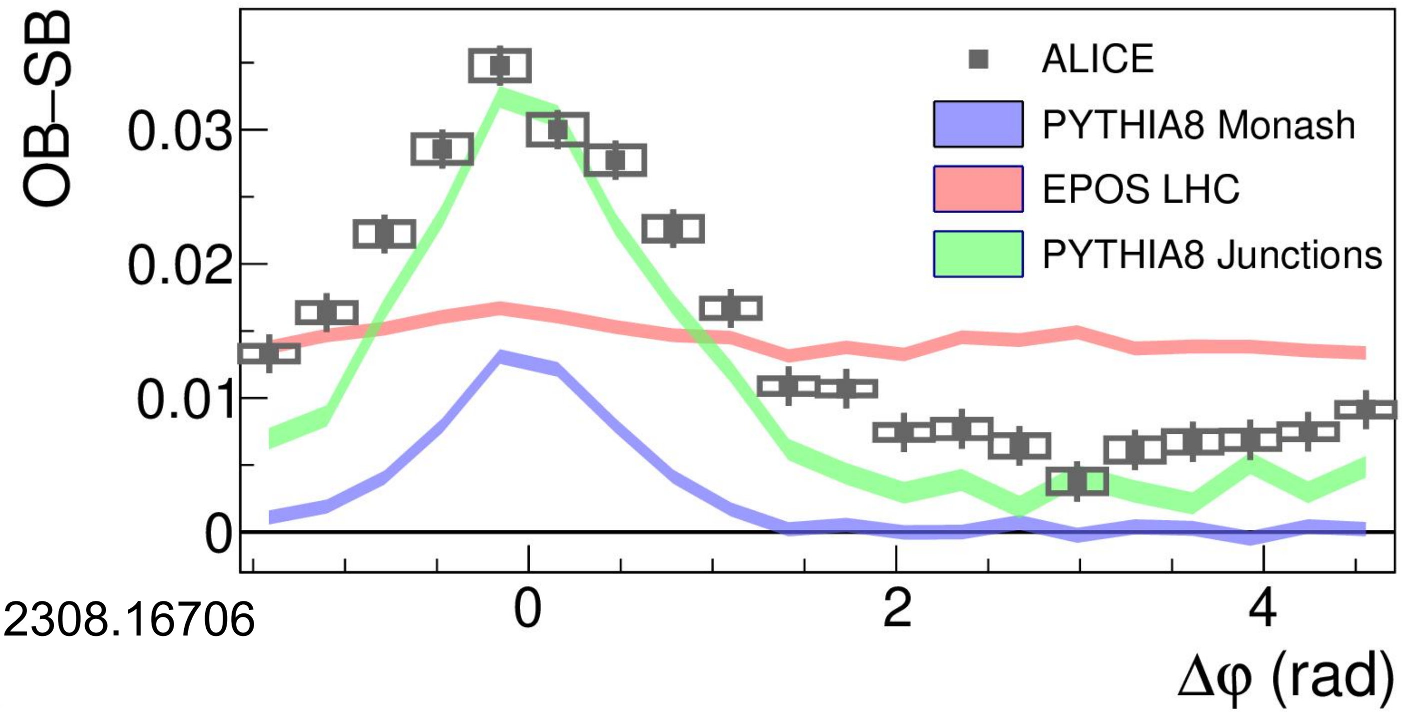




Junction:
Ξ balanced more by kaons and less by antistrange baryons.
Broader correlations in rapidity.

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, “QCD challenges from pp to A–A collisions”

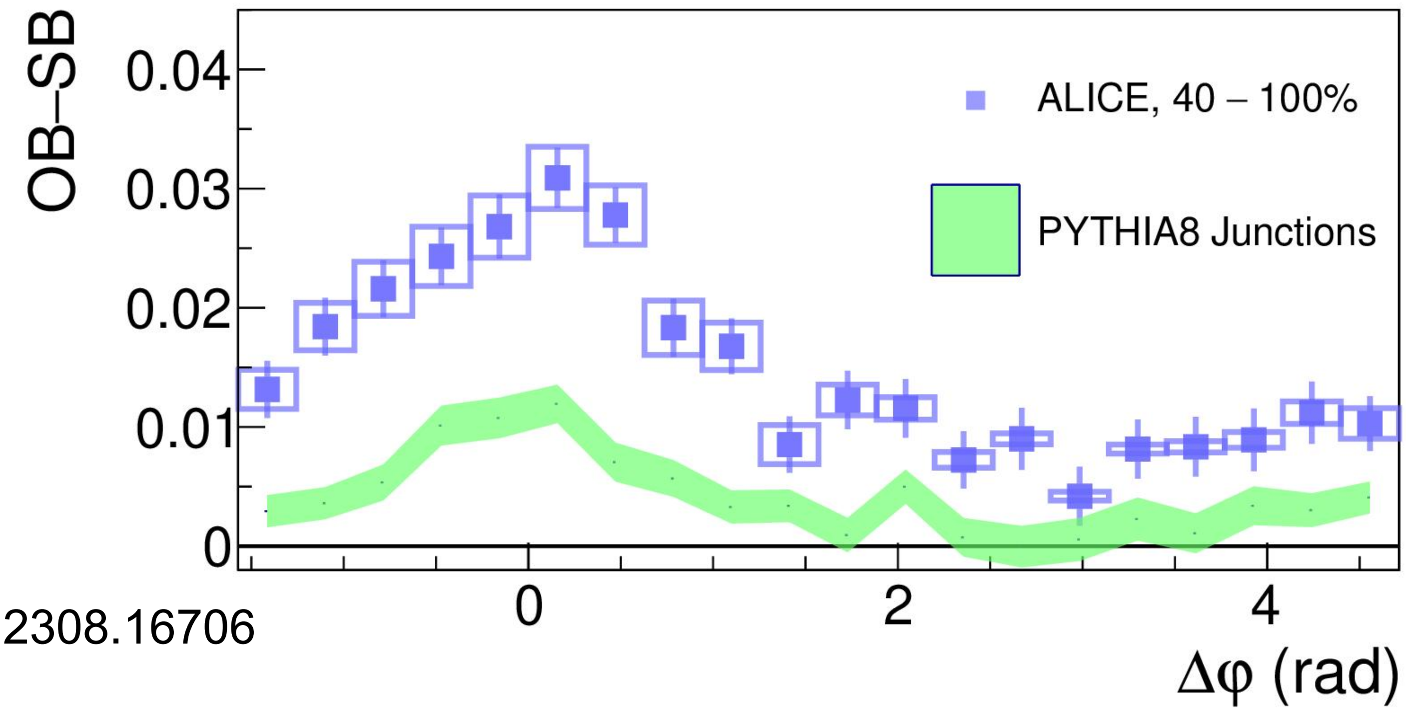
Microscopic balance of Ξ by antiprotons: MB results



arXiv:2308.16706

- EPOS (QGP) model: no structure due to extreme assumption of grand-canonical ensemble
- Pythia8 Monash: fails since this almost never happens
- Pythia8 Junctions: describes well the data

Microscopic balance of Ξ by antiprotons: low mult results



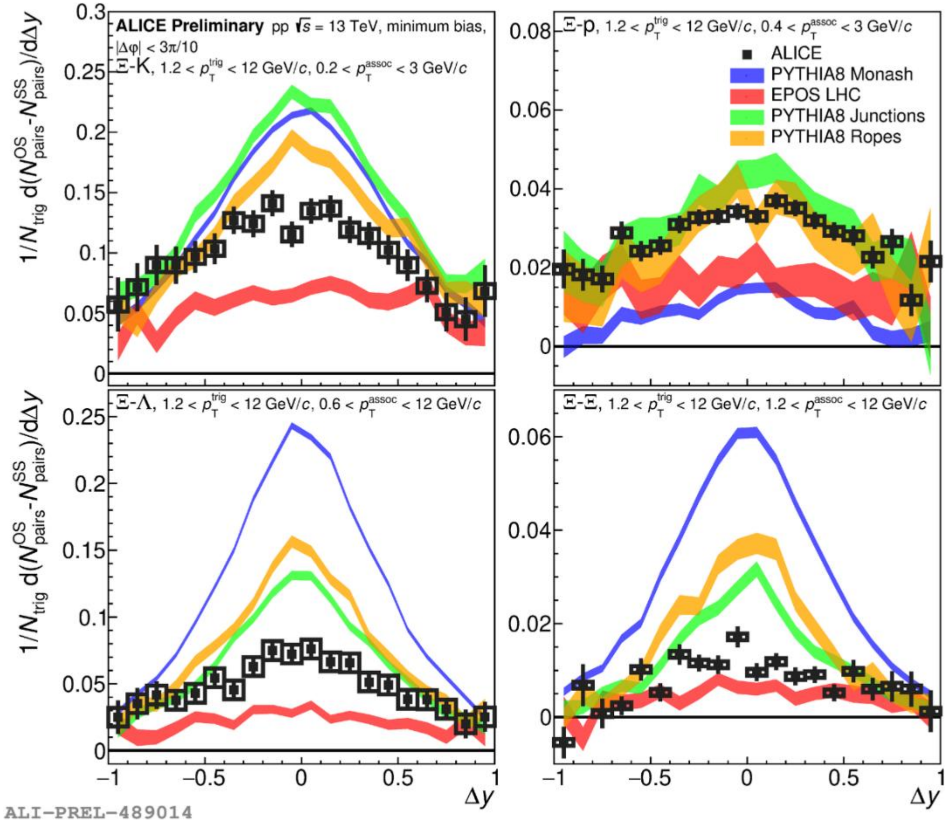
arXiv:2308.16706

- Pythia8 Junctions: fails to describe the data since in the low multiplicity limit it must agree with Monash (no CR)
- But why does nature prefer such a complicated process where strangeness is balanced by two mesons?

Part of the work of Jonatan Adolfsson's PhD Thesis

Ξ-K

Ξ-Λ



Ξ-p

ALICE congratulates its PhD thesis award winner

2 JULY, 2021

Jonatan Adolfsson (LU)

ALICE Spokesperson Luciano Musa (left) awards the prize to Jonatan Adolfsson (right) in the virtual presence of Collaboration Board Chair Silvia Masciocchi and the Chairs of the Thesis Award Committee, Giuseppe Bruno and Philippe Crochet (Image: CERN)

https://home.cern/news/news/cern/alice-congratulates-its-phd-thesis-award-winner

Ξ-Ξ

- He studied many more combinations, see arXiv:2308.16706

Conclusions and how to make further progress

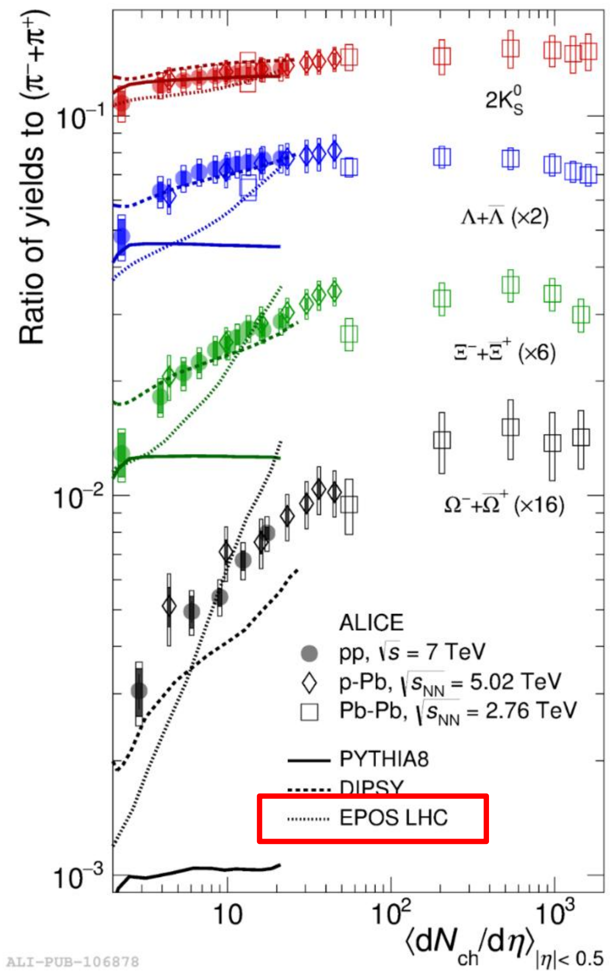
- Focus less on measuring "more of the same" and more about **new observables**
  - In CLASH, we could in this way point to fundamental issues that needs to be addressed in Herwig and for Pythia ropes/junctions
  - And point out an EPOS limit: we need QGP-based generators that tries to implement microscopic models
- Alternative descriptions such as Angantyr/Ropes/shoving offer unique opportunities to look at our field from a different perspective
  - **We should welcome this!**

Thank You!

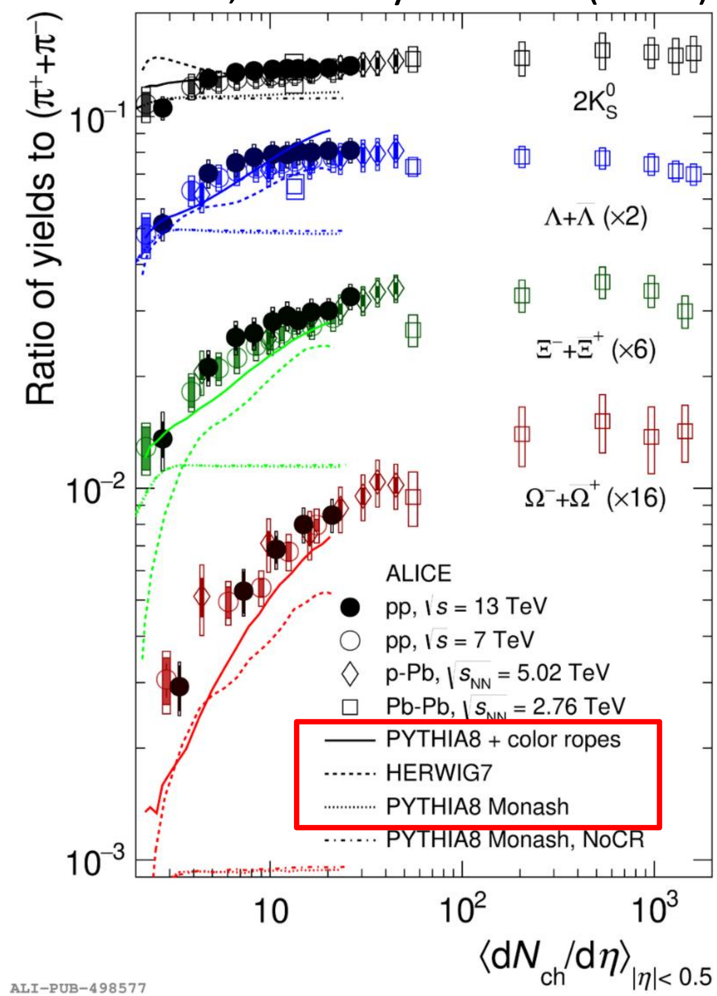
Backup

Focus on models that address strangeness enhancement

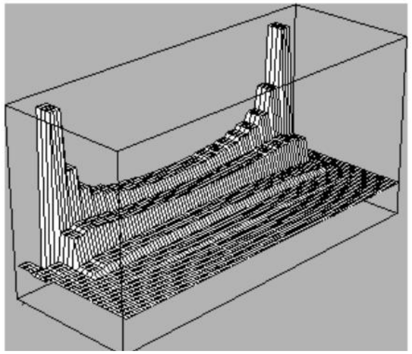
ALICE, Nature Physics 13 (2017) 535



ALICE, Eur. Phys. J. C 80 (2020) 693



Pythia and Lund string-model in one slide



Pythia Manual, SciPost Phys.Codeb. 2022 (2022) 8

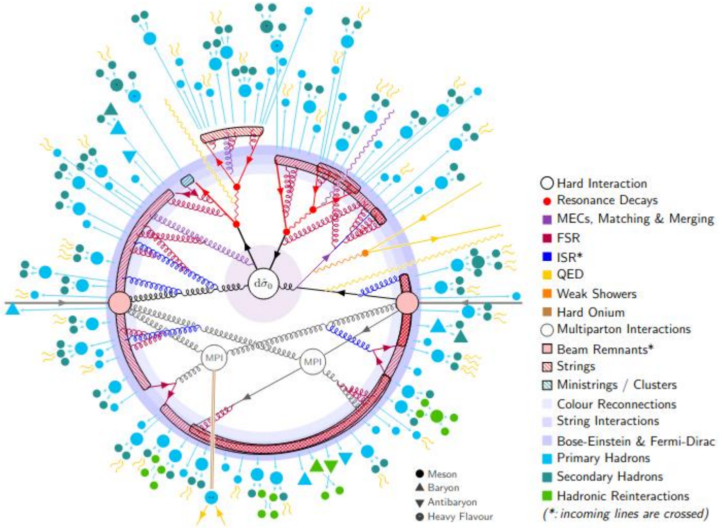
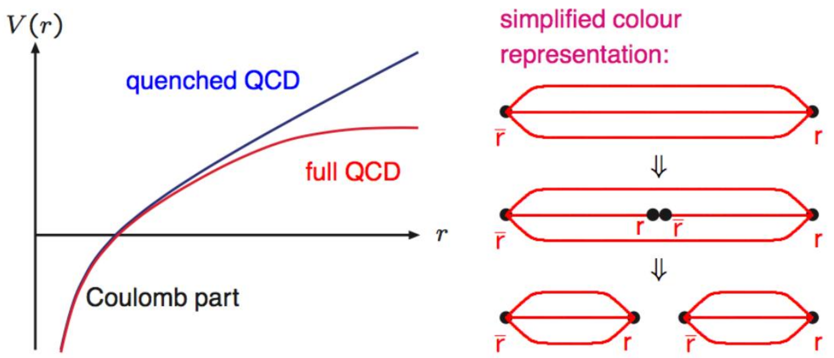


Figure 1: Schematic of the structure of a pp → $t\bar{t}$ event, as modelled by PYTHIA.



Pythia simulates inelastic non-diffractive proton-proton collisions as a sum of parton-parton collisions

Lund string model hadronizes the final partons. Motivated from LQCD / confinement, simple picture.
String breaks into q-qbar pairs (mesons) and q+q-qbar+qbar pairs (baryons)

- More details: https://www.hep.lu.se/staff/christiansen/teaching/spring_2013/lundString.pdf

Introduction to R_T

Idea: Martin, Skands, Farrington, Eur. Phys. J. C76 (2016), 1

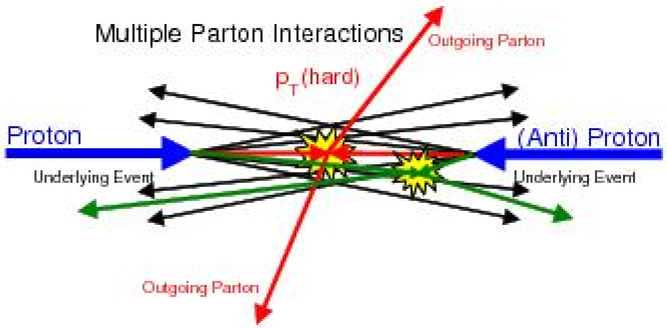
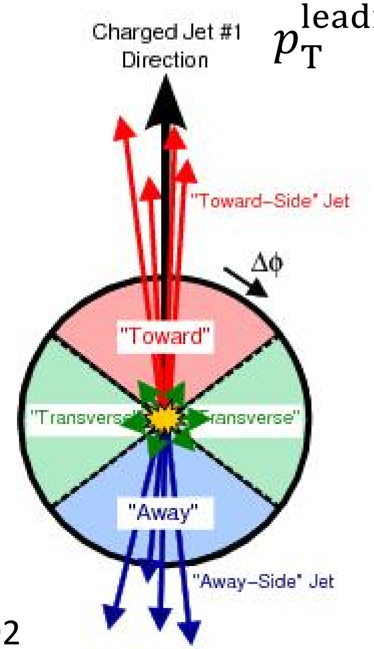
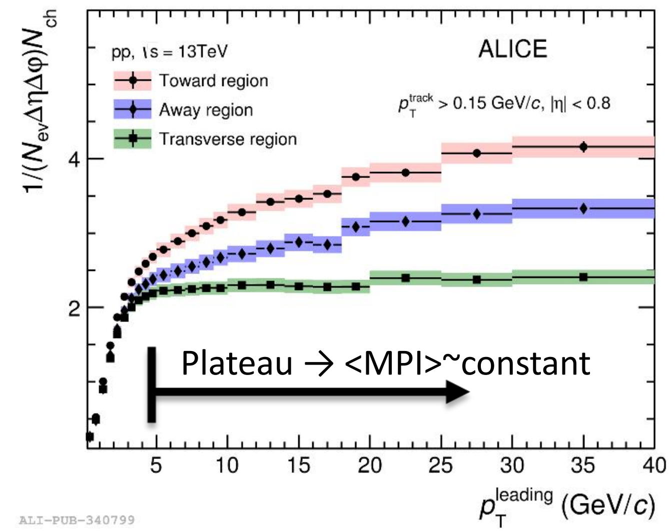


Figure from Eur. Phys. J. C62 (2009), 237

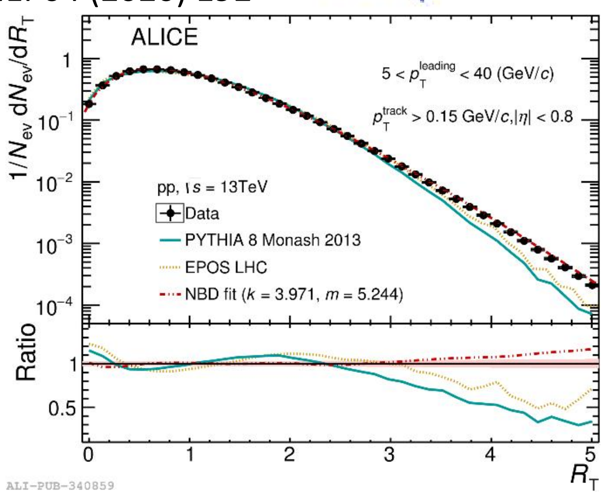


$p_{\mathrm{T}}^{\mathrm{leading}} \,/\, p_{\mathrm{T}}^{\mathrm{trigg}}$

arXiv:1910.14400



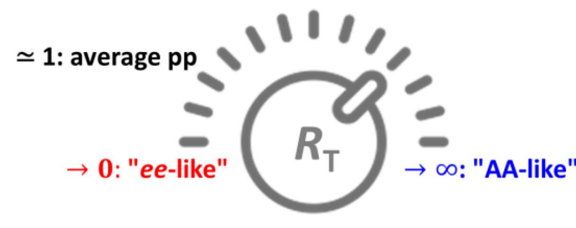
JHEP04 (2020) 192



Define:

$$R_T = \frac{N_{ch}^{Transverse}}{\langle N_{ch}^{Transverse} \rangle}$$

Gives some control over the UE

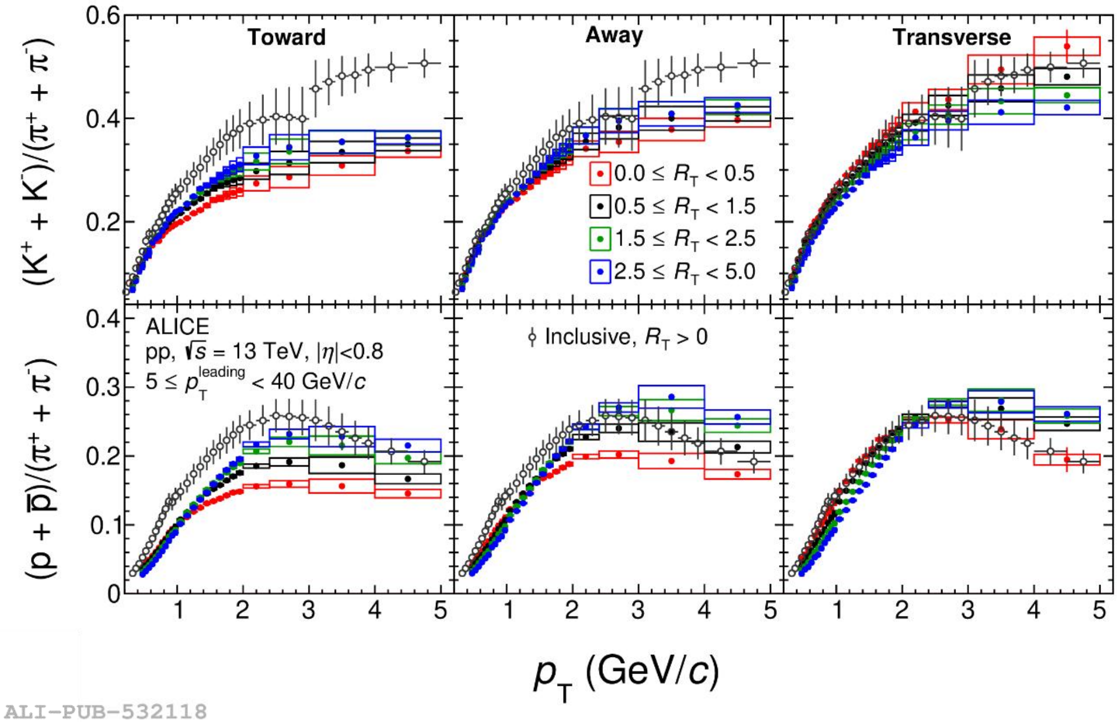


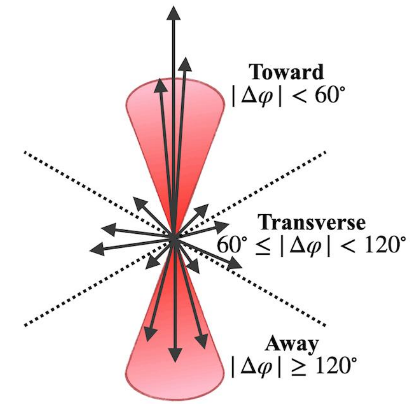
In particular tries to control N_{MPI}

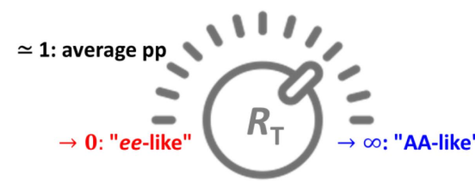
Particle ratios vs p_T

kaon/ pion

proton/ pion





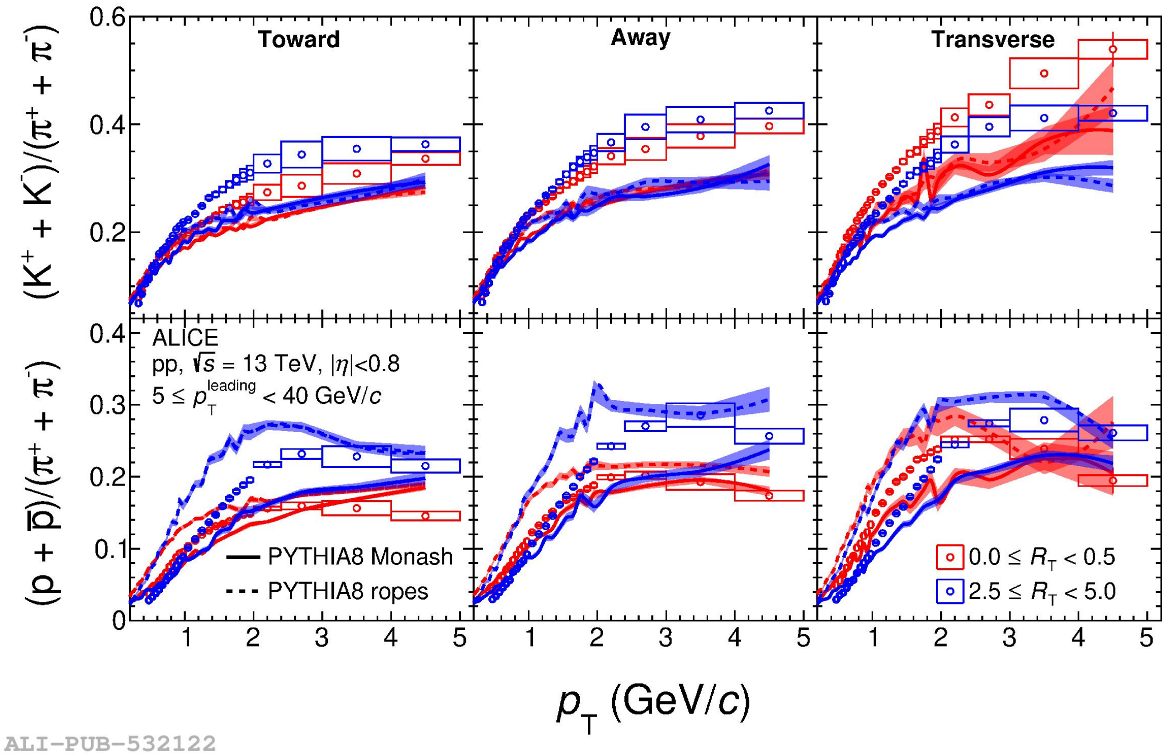


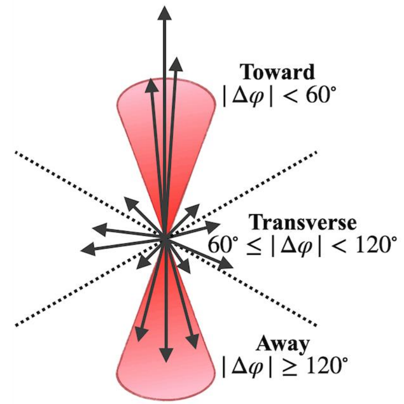
- Opposite behaviour of kaons and protons
  - Protons: Little change in Transverse region, MB is like Transverse
  - Kaons: largest change in Transverse region
- Protons: ratios grow in Toward and Away regions with RT
  - Jet is diluted → Approach transverse region

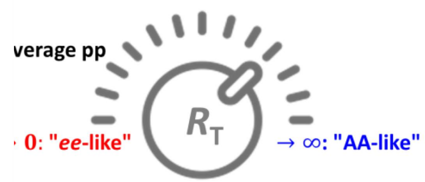
Comparison with Pythia

kaon/ pion

proton/ pion





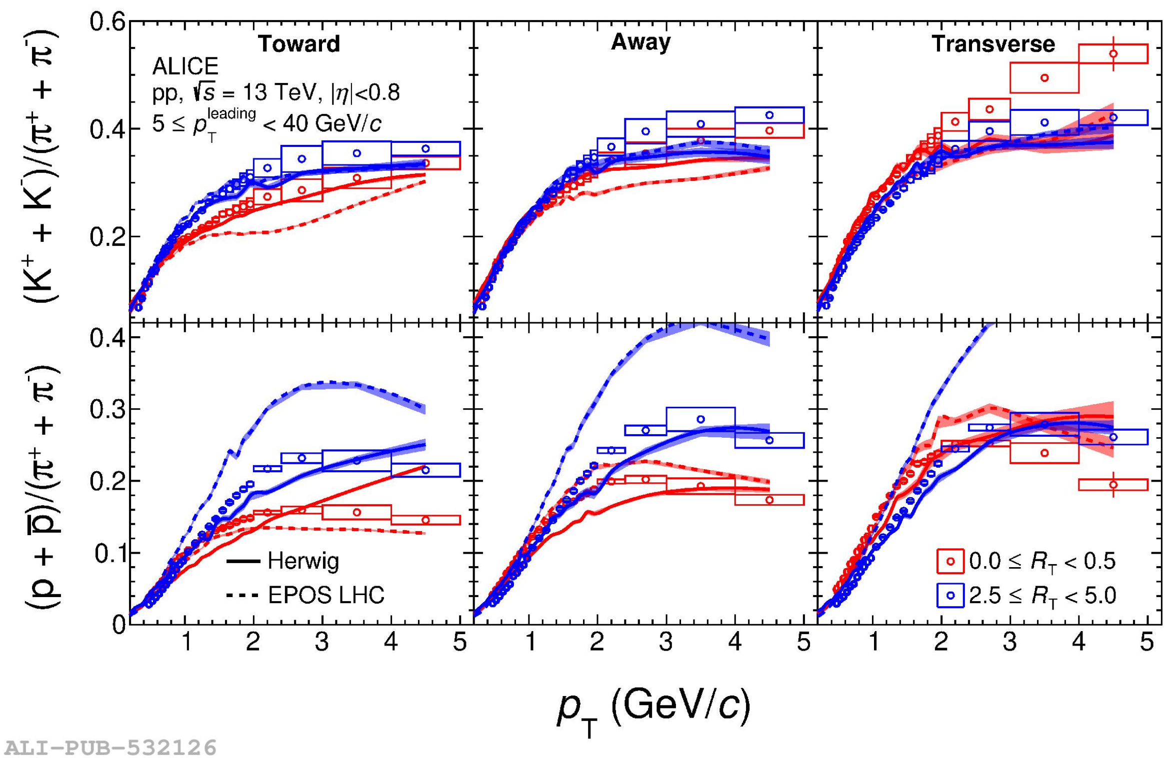


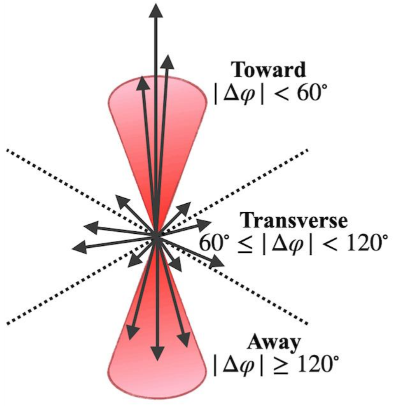
- Pythia Monash has little R_T dependence
  - More of the same without new CR schemes → we need the new physics!
- Pythia Ropes qualitatively captures the trends. Quantitatively overestimates effect on protons
  - Too many protons in general (seems to be a junction problem, see later)

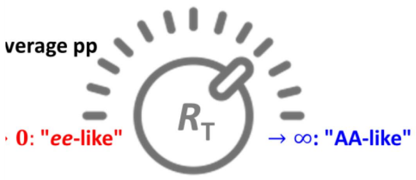
Comparison with Pythia

kaon/
pion

proton/
pion





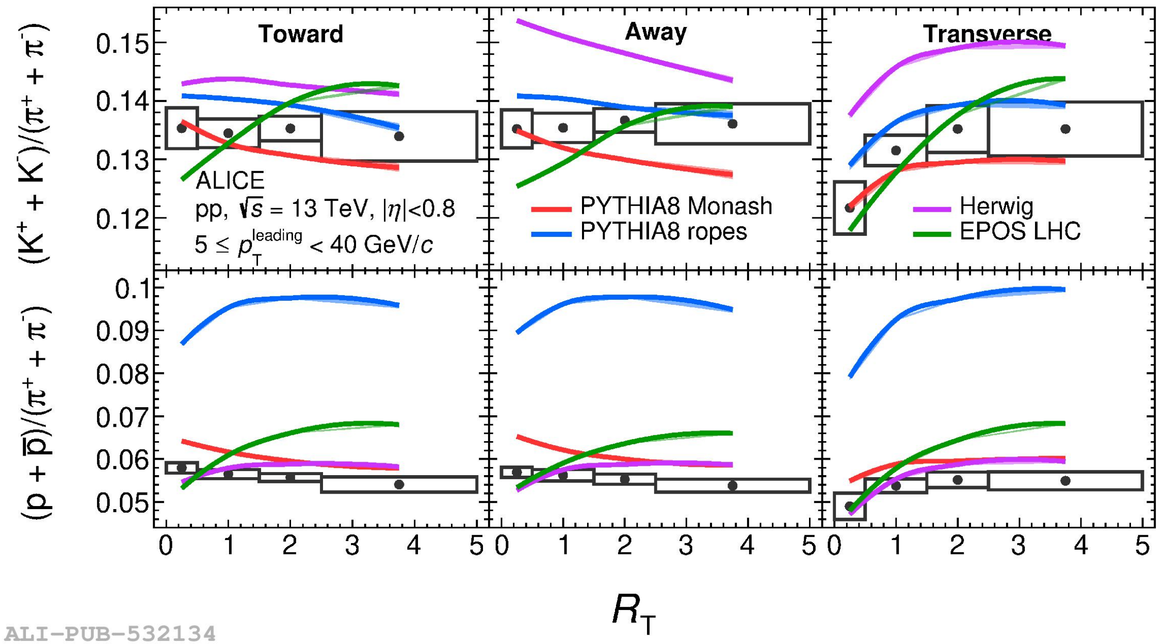


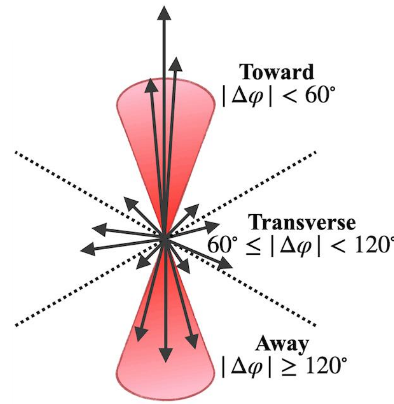
- EPOS and Herwig both qualitatively captures the trends
- EPOS overestimates proton production. In particular in Transverse region.

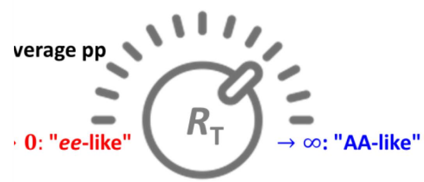
p_T integrated ratios compared with models

kaon/ pion

proton/ pion



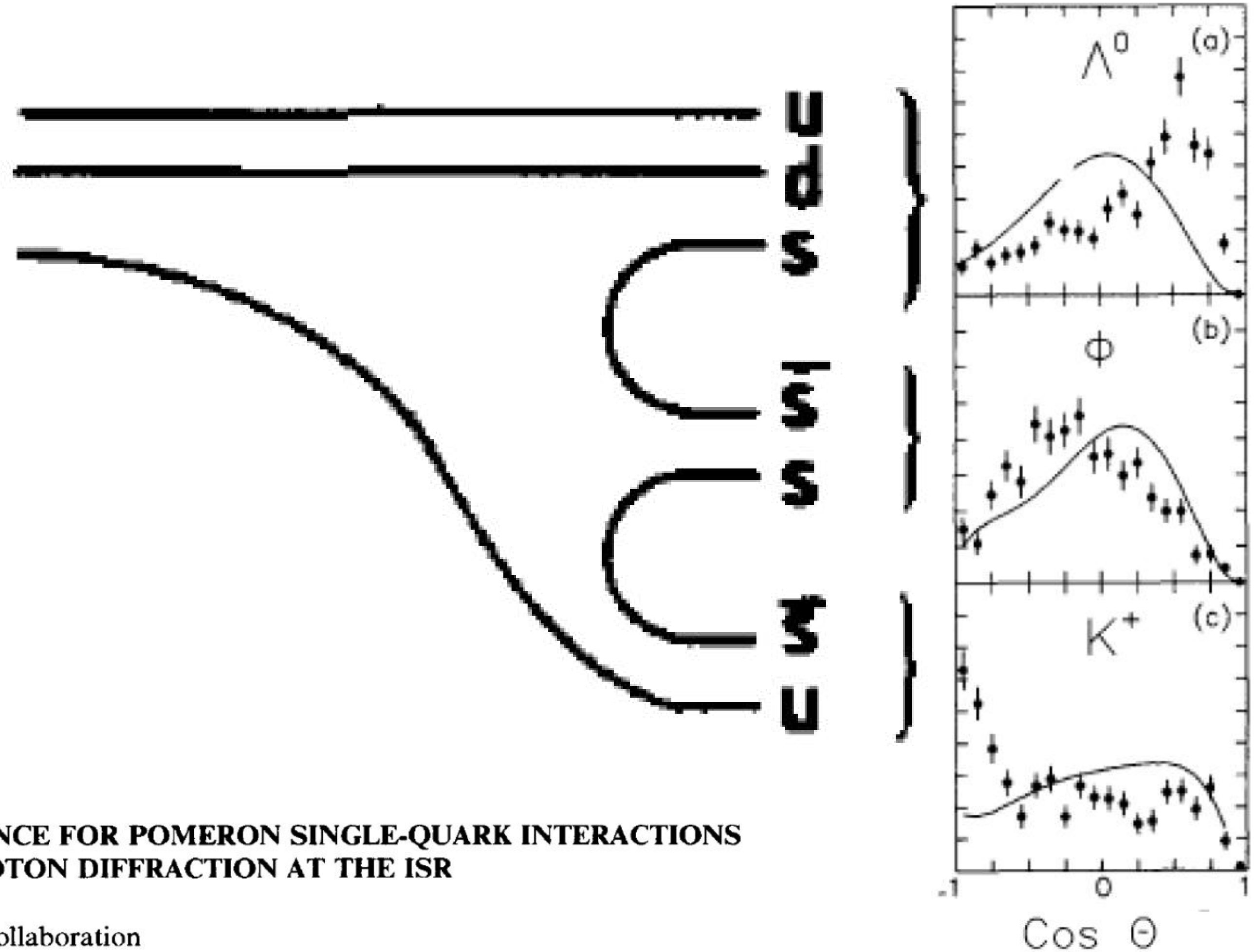




- It is clear that all models have issues
  - E.g. wrong trends for the proton-to-pion ratio vs RT
- Pythia Ropes produces too many protons – more of a baryon enhancement (junctions) than a strangeness enhancement (ropes)
- In general for all models: the data provides opportunity to tune and test!

Quantum number balance is an old idea that was also used to validate string model

Phys.Lett. 163B (1985), 267



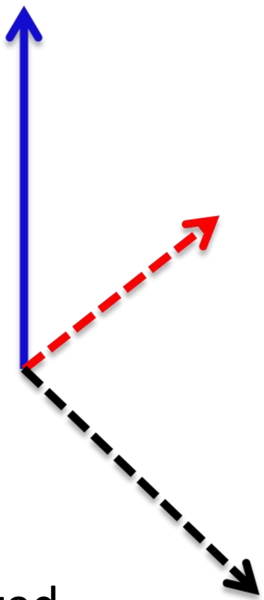
EVIDENCE FOR POMERON SINGLE-QUARK INTERACTIONS IN PROTON DIFFRACTION AT THE ISR

R608 Collaboration

Solid lines are calculations for isotropic phasespace

Example:
Ξ-K correlation functions

Trigger on : $\Xi\ (ssd)$



Measure where balancing QN ends up:
$K^{+}\ (u\bar{s}), \bar{p}\ (\bar{u}\bar{u}\bar{d}),$
$\bar{\Lambda}\ (\bar{u}\bar{d}\bar{s}), \bar{\Xi}\ (\bar{s}\bar{s}\bar{d})$

Subtract the uncorrelated production via the same QN correlations:
$K^{-}\ (s\bar{u}),\ \ p\ (uud), \Lambda\ (uds),\ \ \Xi\ (ssd)$