

Soft QCD

Into the realm of the non-perturbative



Nikhef

Lecture Nikhef

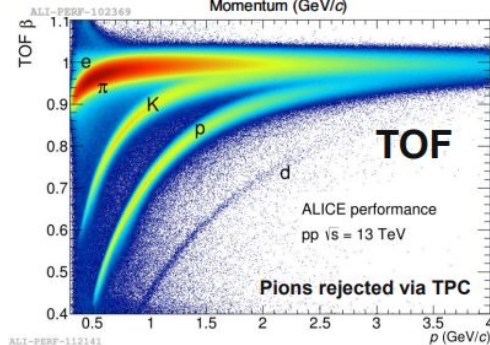
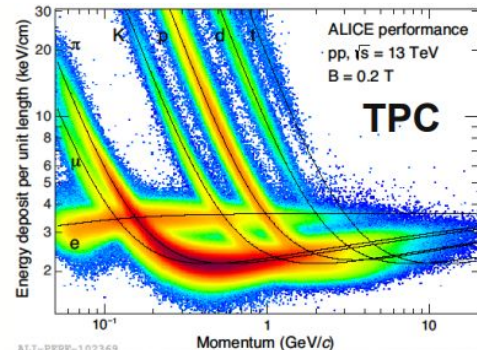
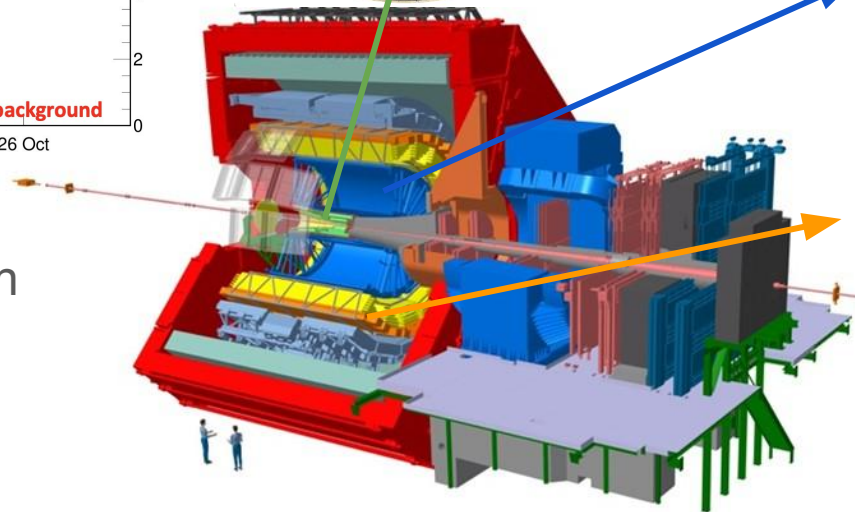
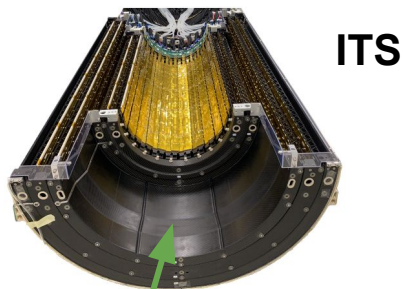
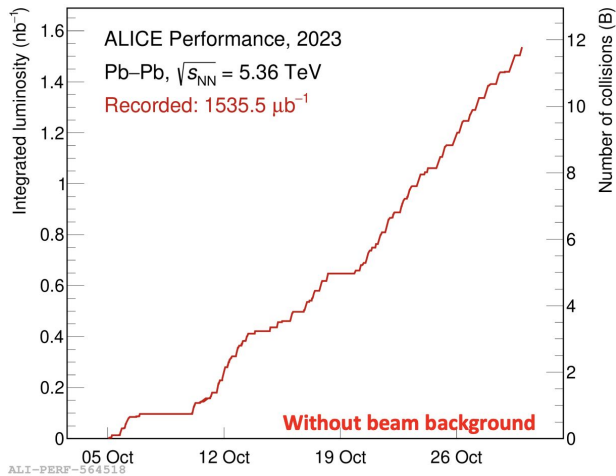
March 12, 2025

Mike Sas



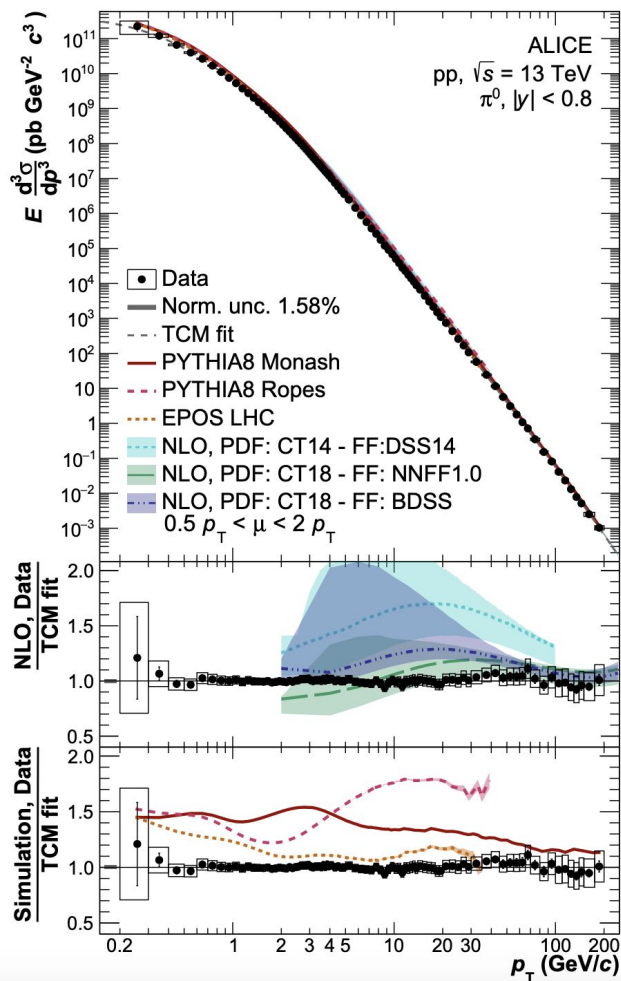
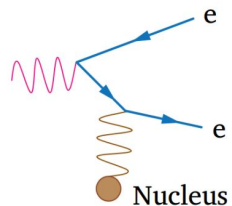
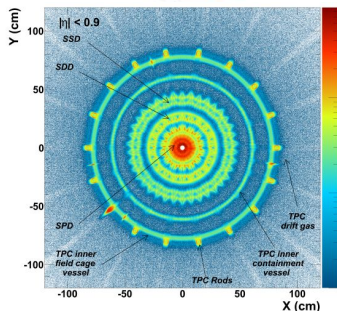
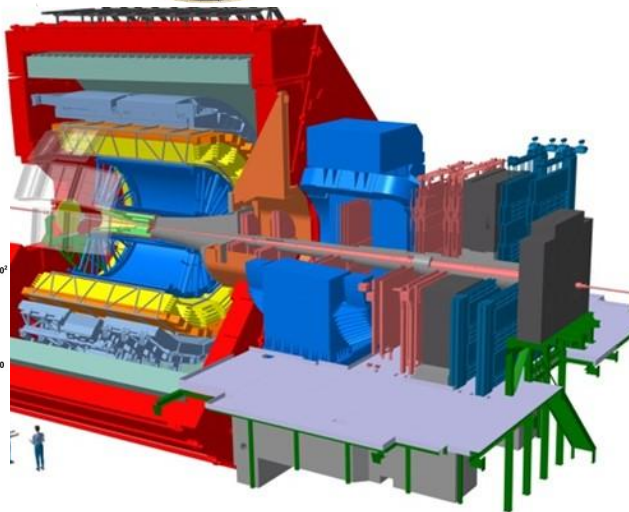
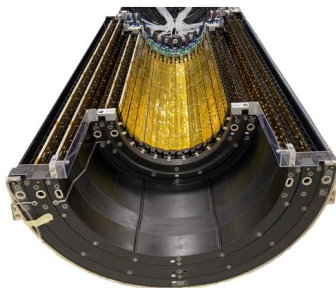
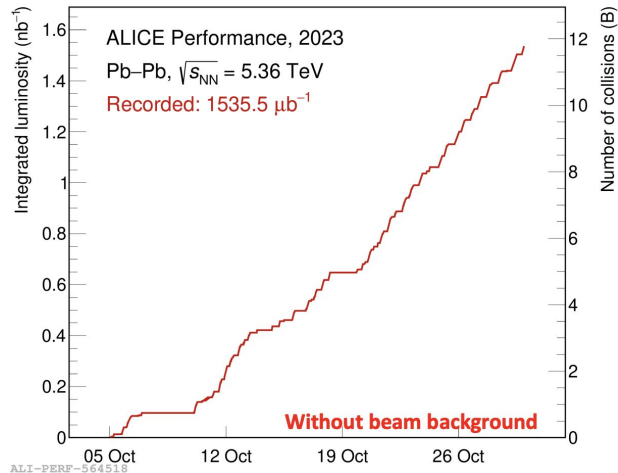
ALICE

The ALICE detector

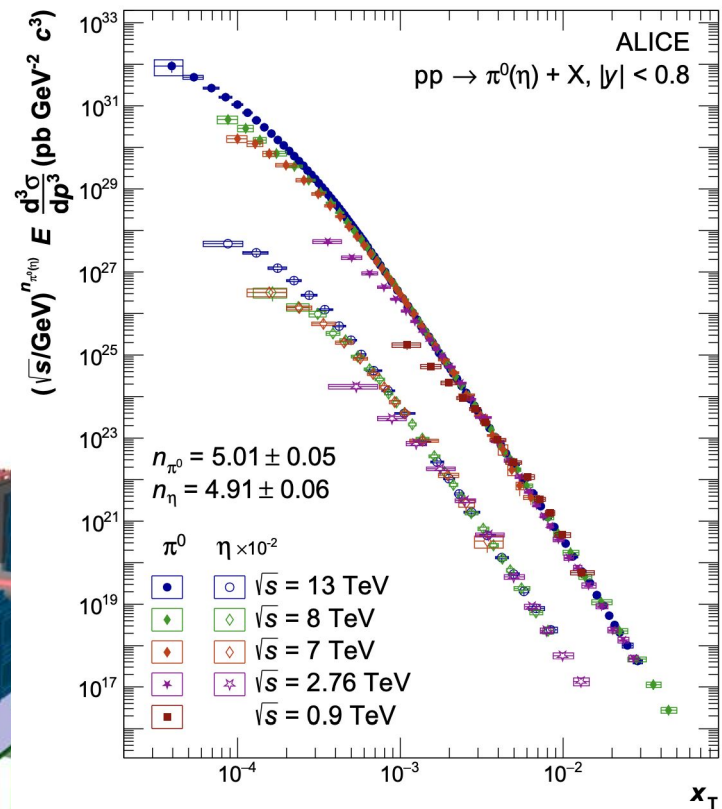
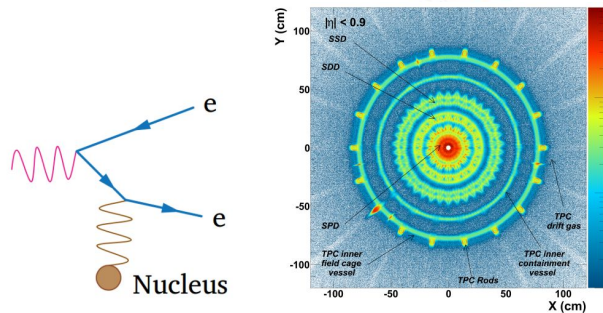
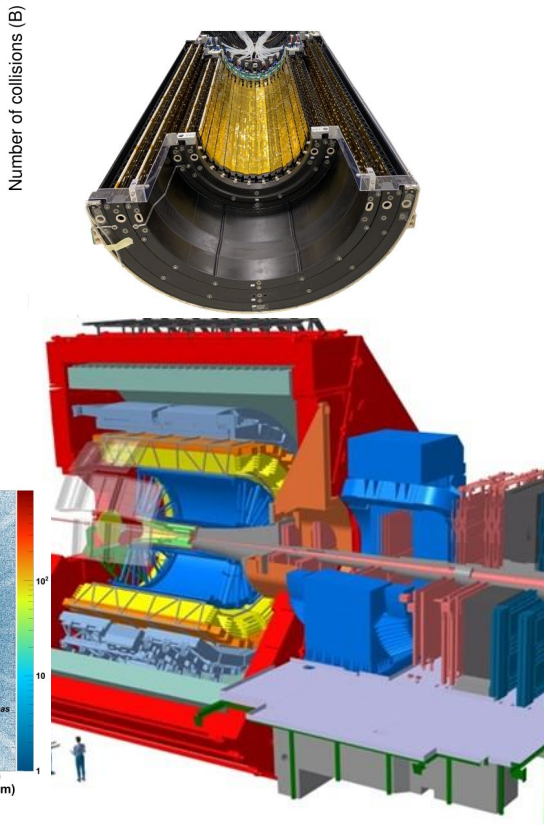
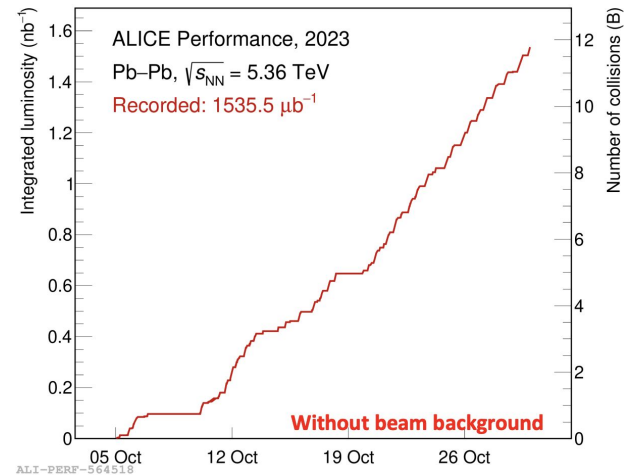


What is the main difference?

A (very?) impressive spectrum



A (very?) impressive spectrum

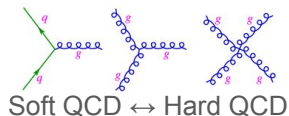


What is soft QCD?



What is soft QCD?

QCD describes interactions between quarks and gluons.



Can't calculate (perturbatively)? **Soft QCD !**

Why? → understand the full richness of particle physics at (relatively) low energy/momenta & describing the total cross section.

How? → implement phenomenological models into event generators.

Typical contents of soft QCD:

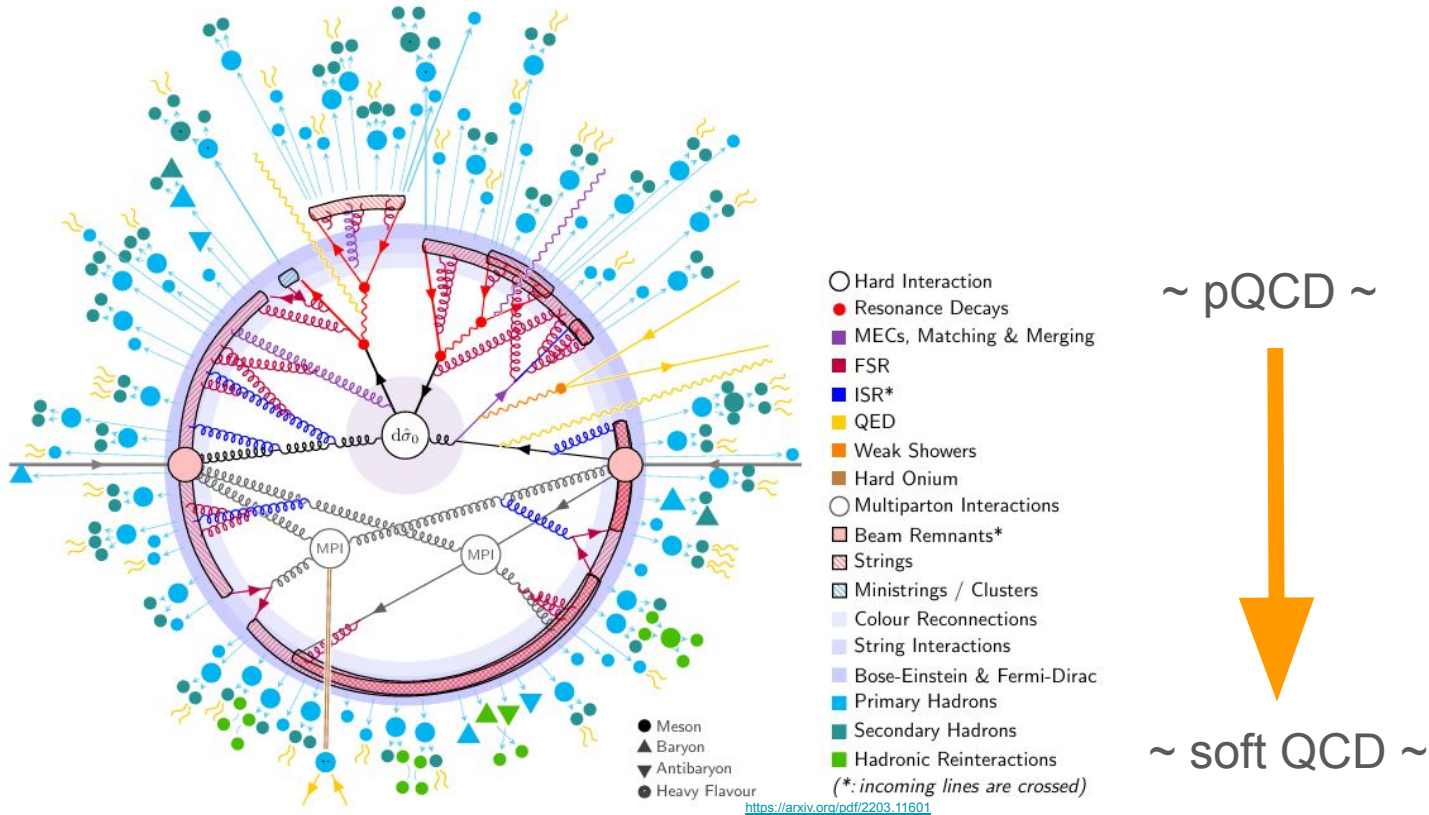
- hadronisation
- multiparton interactions (MPI)
- The unexpected?!

Disclaimer: experimentalist!

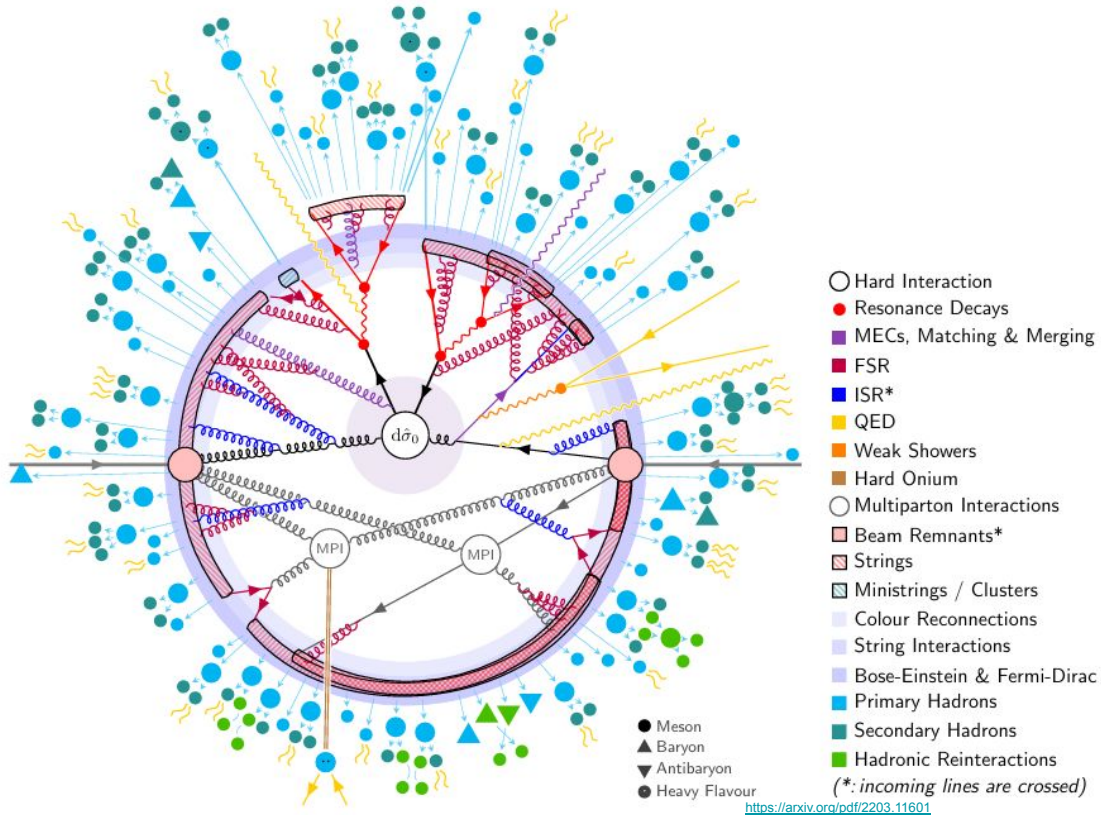
Not covered: non-perturbative QCD (like lattice-QCD)



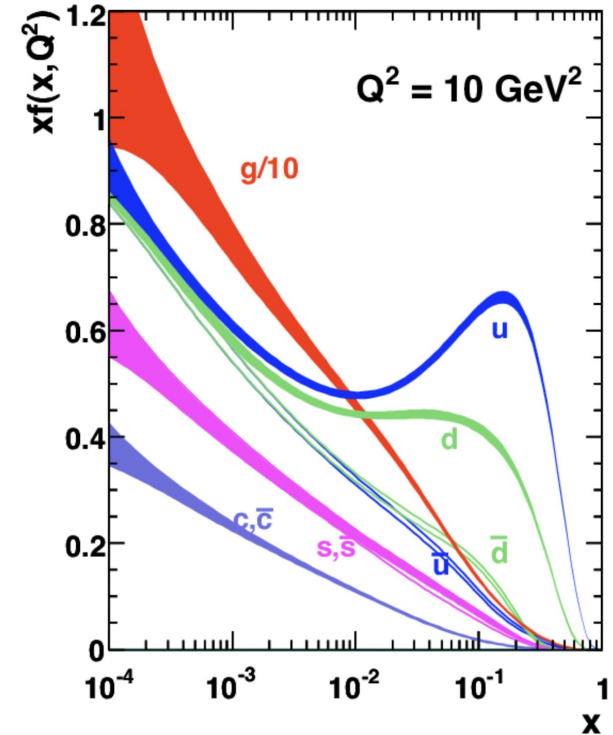
Overview of a pp collision



Overview of a pp collision

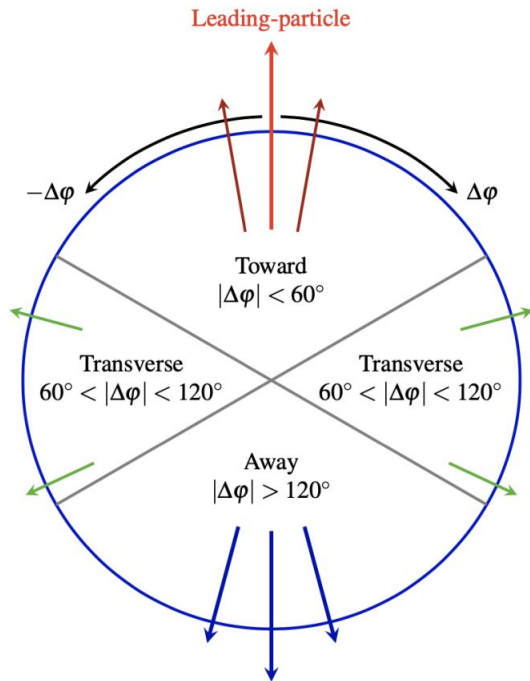


The proton PDF



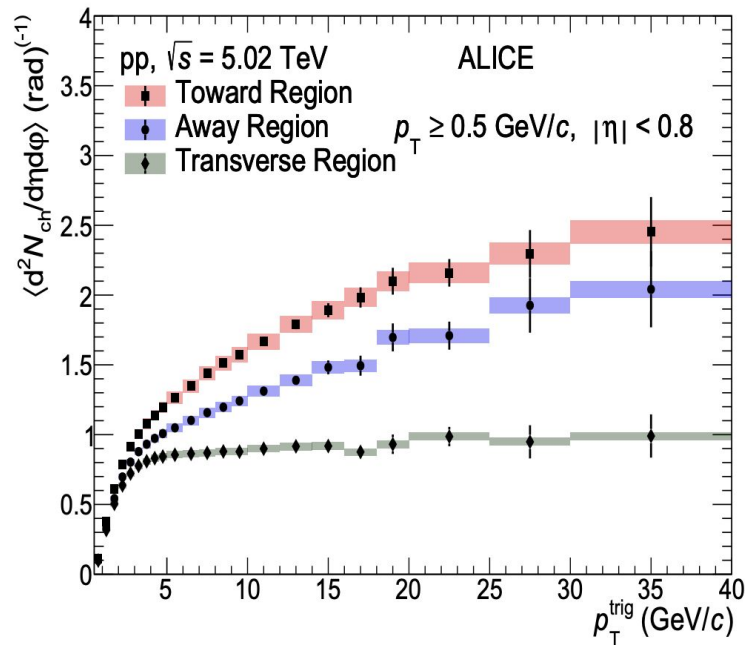
Underlying event properties

Define regions w.r.t. a leading particle



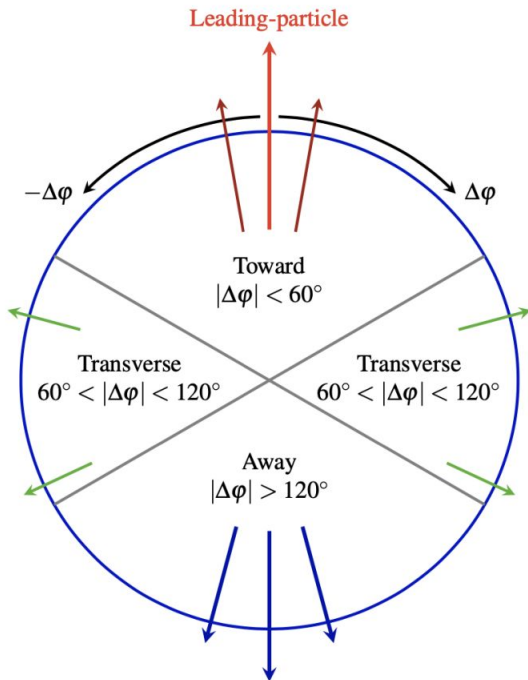
$$\left\langle \frac{d^2 N_{ch}}{d\eta d\phi} \right\rangle (p_T^{trig}) = \frac{1}{\Delta\eta \Delta\phi} \frac{1}{N_{ev}(p_T^{trig})} N_{ch}(p_T^{trig})$$

<https://arxiv.org/abs/2204.10389>



Underlying event properties

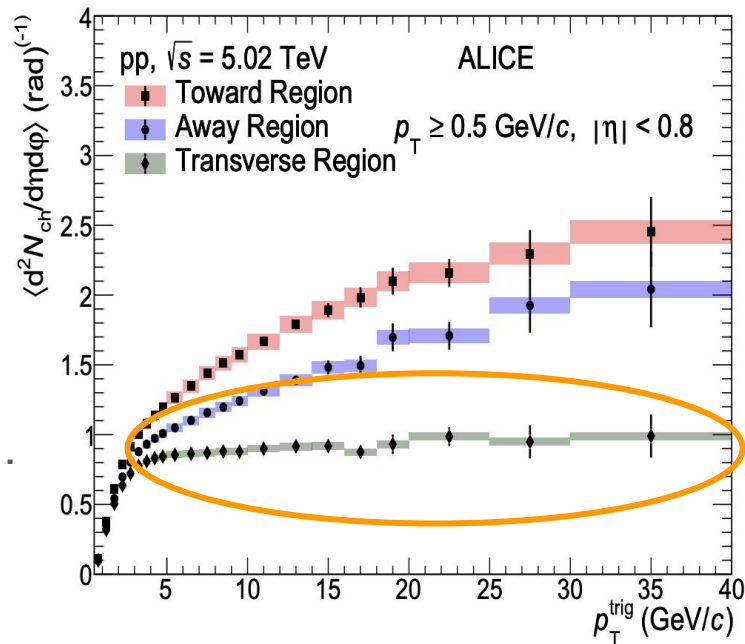
Define regions w.r.t. a leading particle



Interestingly..
very flat !

$$\left\langle \frac{d^2 N_{\text{ch}}}{d\eta d\phi} \right\rangle (p_{\text{T}}^{\text{trig}}) = \frac{1}{\Delta\eta \Delta\phi} \frac{1}{N_{\text{ev}}(p_{\text{T}}^{\text{trig}})} N_{\text{ch}}(p_{\text{T}}^{\text{trig}})$$

<https://arxiv.org/abs/2204.10389>



Event shapes

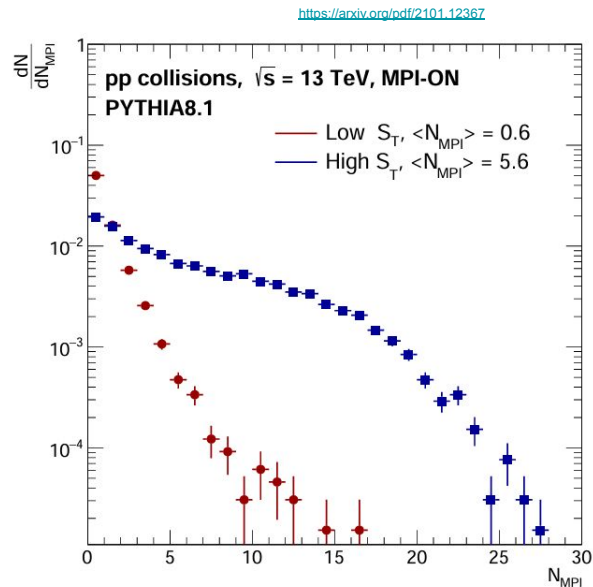
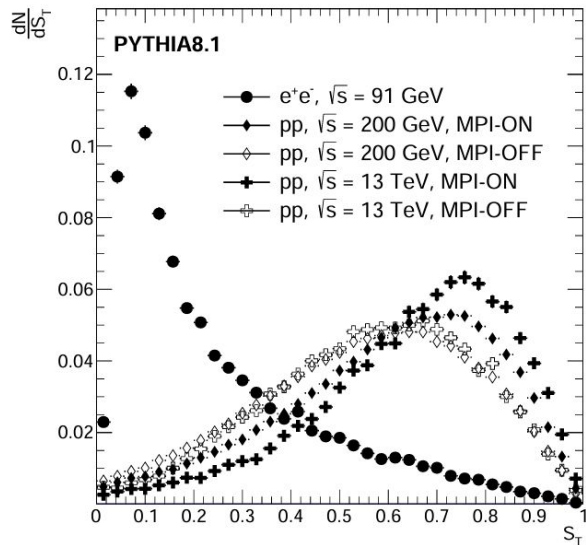
A tool to expose MPI?

Definition of **sphericity**:

$$S_{xy}^L = \frac{1}{\sum_i p_{T,i}} \sum_i \frac{1}{p_{T,i}} \begin{bmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{bmatrix}$$

$$S_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

Analogous to Thrust / Sphericity.



<https://arxiv.org/pdf/2101.12367>

Event shapes

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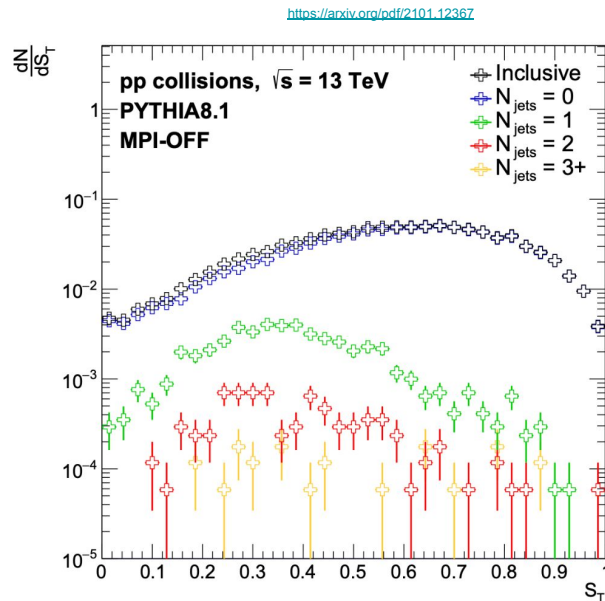
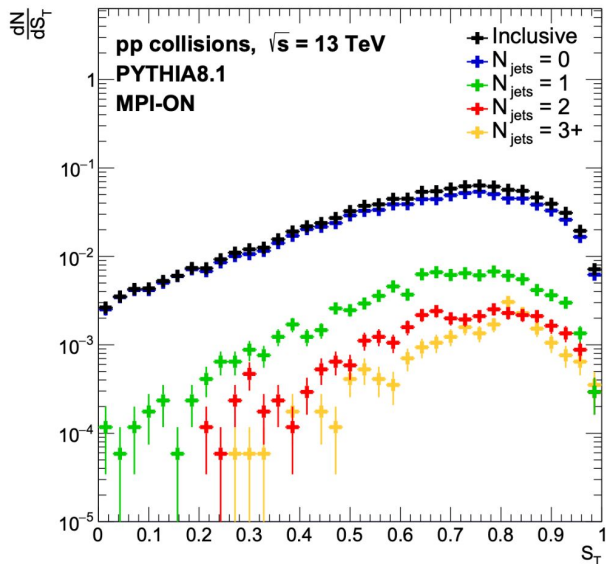
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$$S_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

Analogous to Thrust / Sphericity.

Counter-intuitive: e.g. we find more jets in spherical pp collisions, why is this?

More MPI, typically spherical, more jets!



<https://arxiv.org/pdf/2101.12367>

Hadronisation

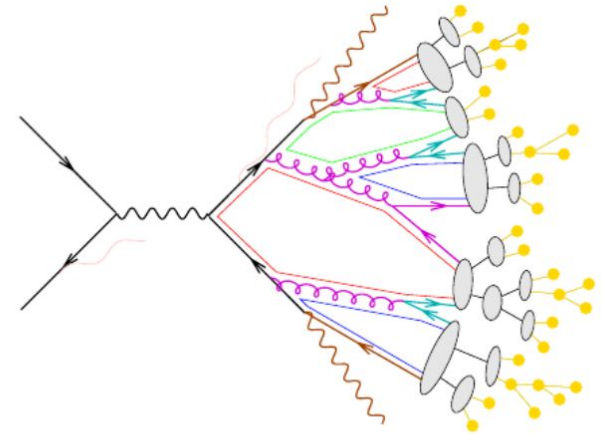
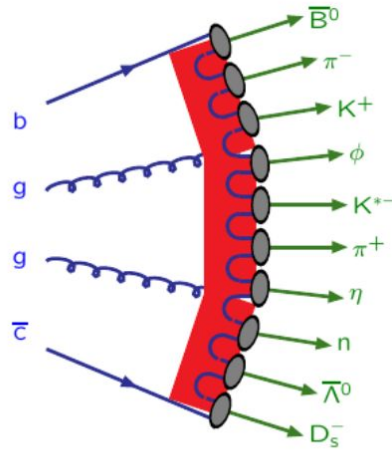
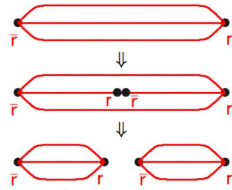
Hadrons



Partons



Hadrons



Model considerations for grouping up the parton shower .. how to choose what becomes a meson / baryon ?

program
model

energy-momentum picture

parameters

flavour composition

parameters

PYTHIA
string

powerful

predictive

few

messy

unpredictive

many

HERWIG
cluster

simple

unpredictive

many

simple

in-between

few

Hadronisation

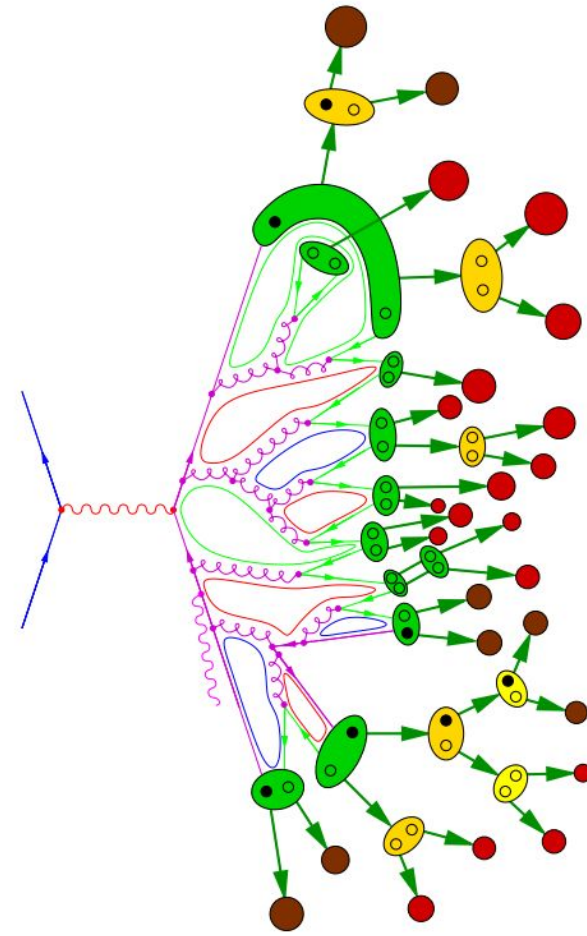
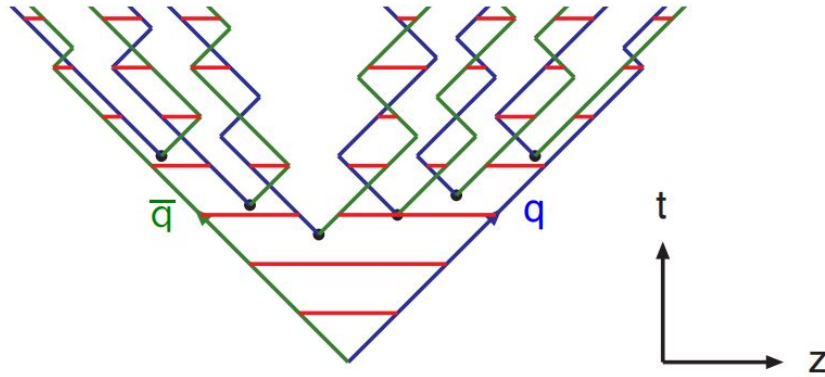
Hadrons



Partons



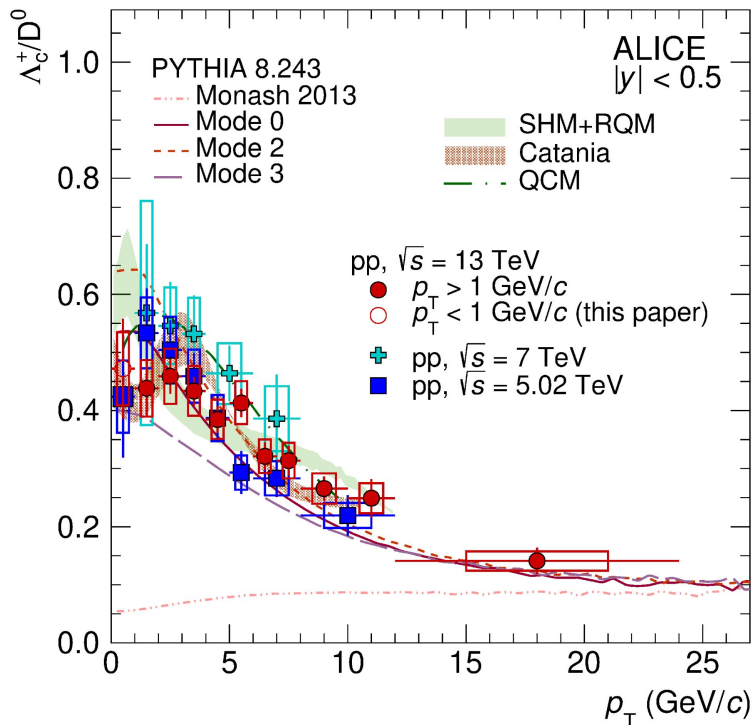
Hadrons



Model considerations for grouping up the parton shower .. how to choose what becomes a meson / baryon ?

Hadronisation - baryon to meson ratio

[arXiv:2308.04877](https://arxiv.org/abs/2308.04877)



Λ_c^+/D^0 ratio is not only described by PYTHIA with CR-BLC but also by other models based on different principles

SHM+RQM

- statistical hadronisation model with feed-down from an augmented set of charm-baryon states

Catania

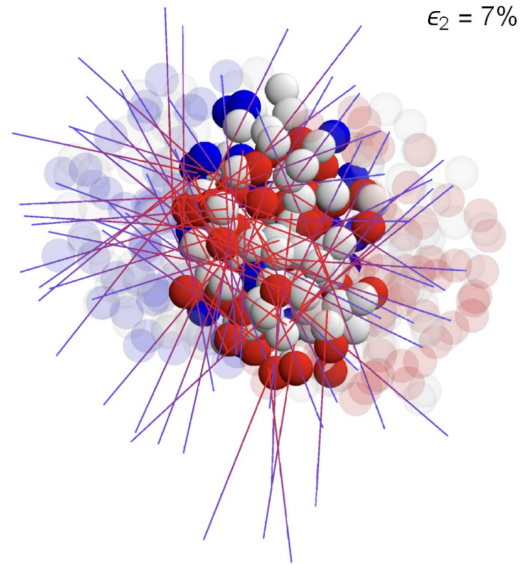
- coalescence and fragmentation processes in a thermalised QGP-like system

QCM

- charm quarks combined with surrounding equal-velocity light quarks

Caveat: only Catania seems to work for $\Xi_c^{0,+}$ and Ω_c^0

Switching gears to heavy-ion collisions ...



... Just to come back to pp again later!

Overview of a heavy-ion collision

Initial state



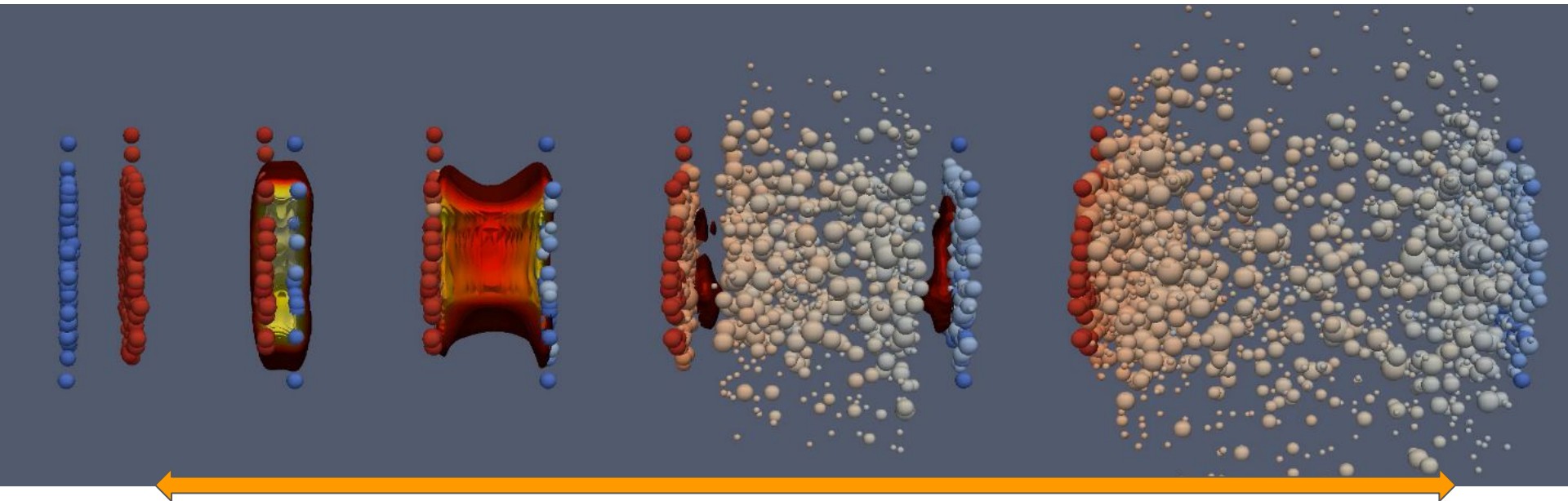
QGP



hadronization



hadron cascades



time

Overview of a heavy-ion collision



Initial state



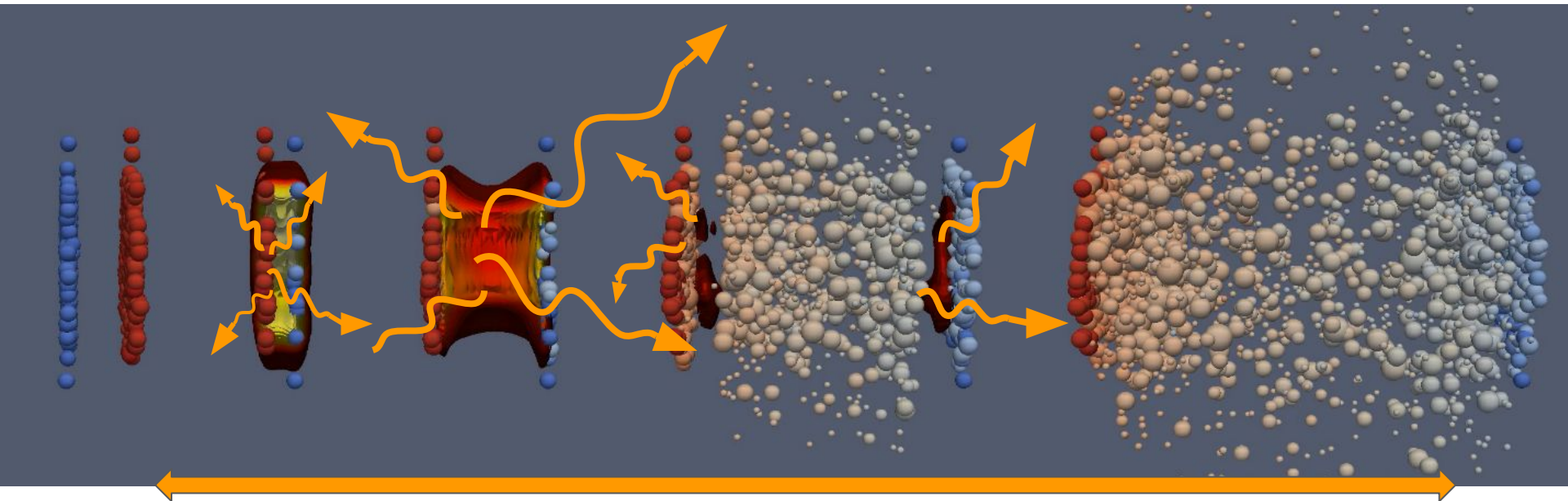
QGP



hadronization



hadron cascades



time

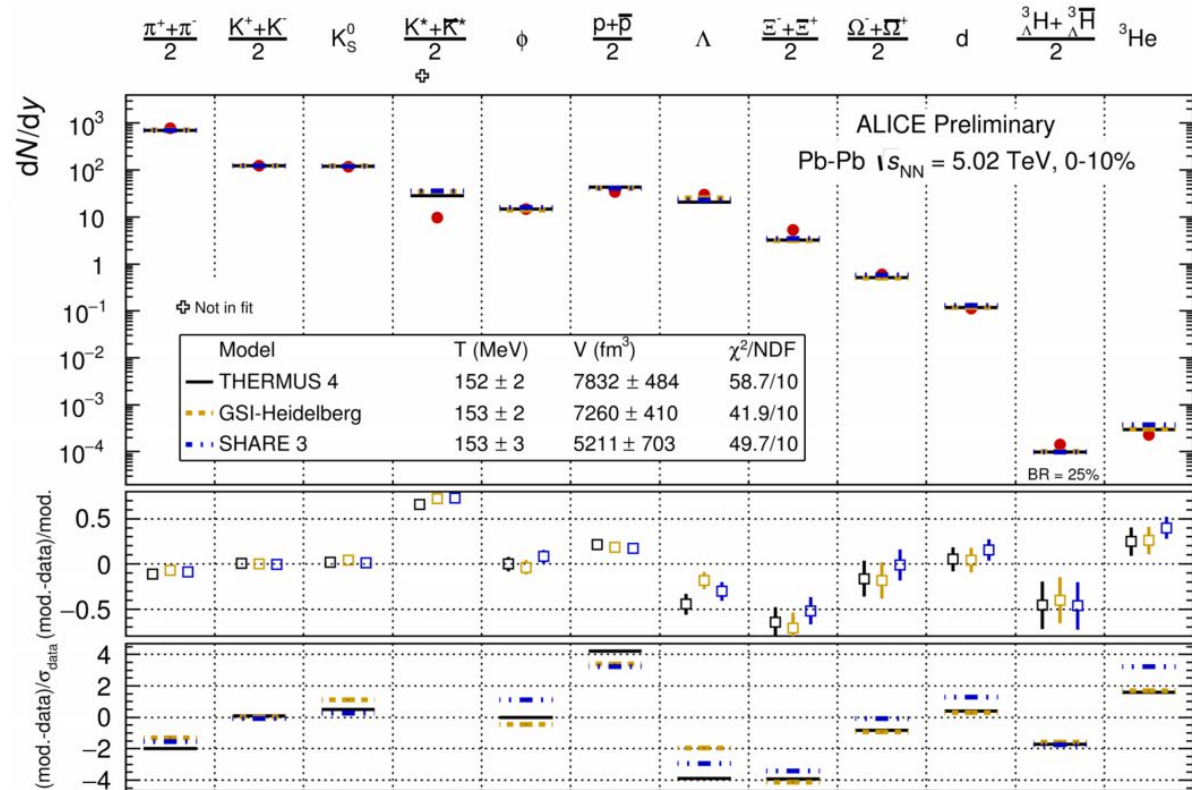
Statistical hadronisation model for heavy-ions

From statistical physics:

$$\frac{p}{T^4} = \frac{1}{T^3} \frac{\partial \ln Z(V, T, \mu)}{\partial V}$$

$$\ln Z(T, V, \mu) \approx \sum_{i \in \text{mesons}} \ln Z_{M_i}^M(T, V, \mu_Q, \mu_S) + \sum_{i \in \text{baryons}} \ln Z_{M_i}^B(T, V, \mu_B, \mu_Q, \mu_S)$$

Very accurate yield predictions for mesons, baryons, light nuclei!



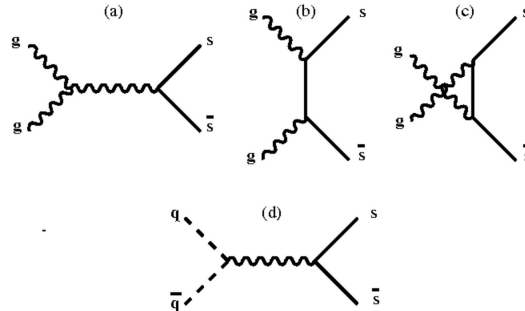
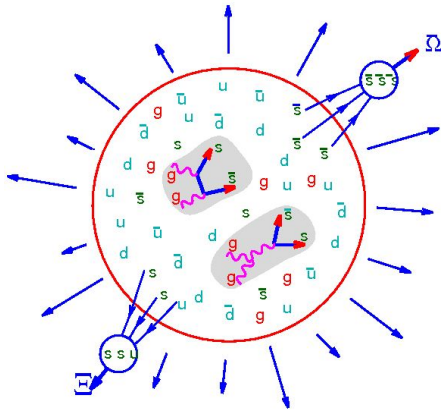
ALI-PREL-148739

Particle production in heavy-ion collisions

General picture: prompt & jet \rightarrow thermal \rightarrow bulk

Early prediction for heavy-ion collisions: Enhancement of strange particle production. (Rafelski, Hagedorn 1980s)

QGP \rightarrow large amount of gluons \rightarrow enable gluon fusion to create strange quarks \rightarrow signal for QGP formation

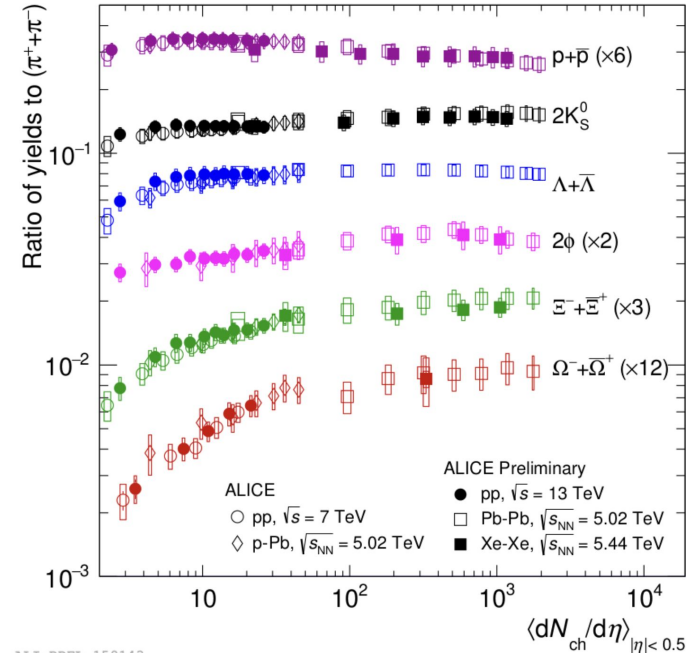
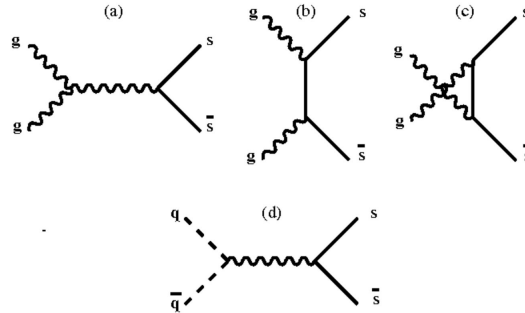
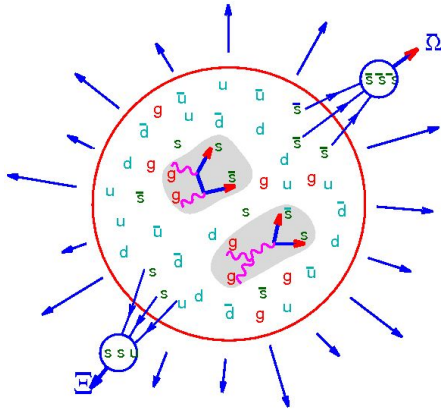


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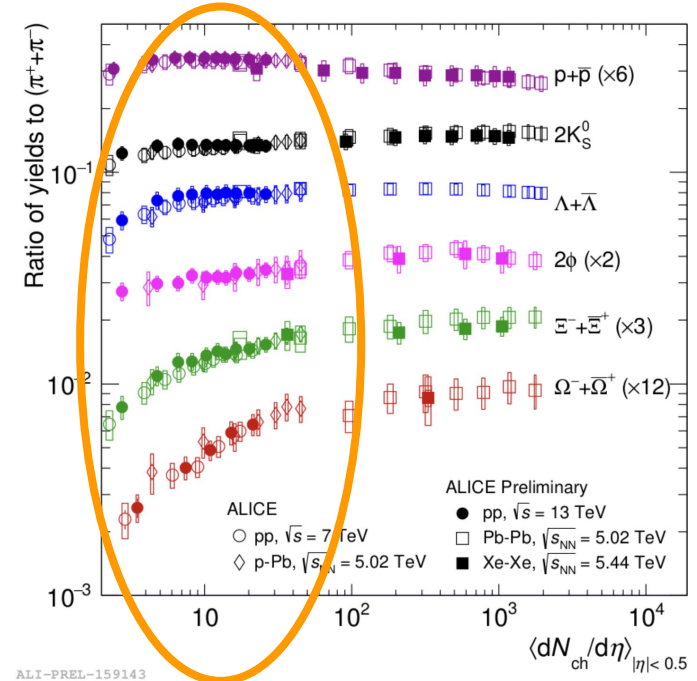
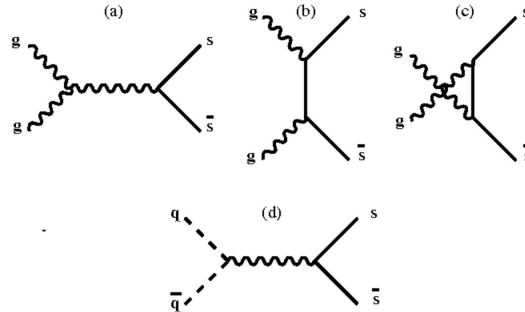
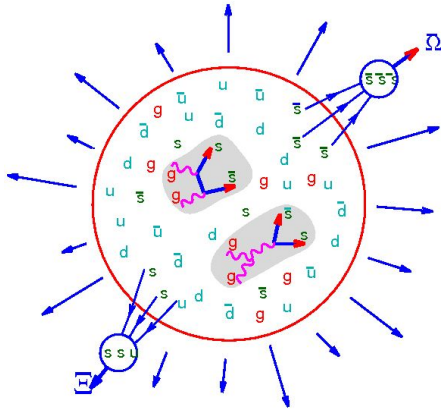


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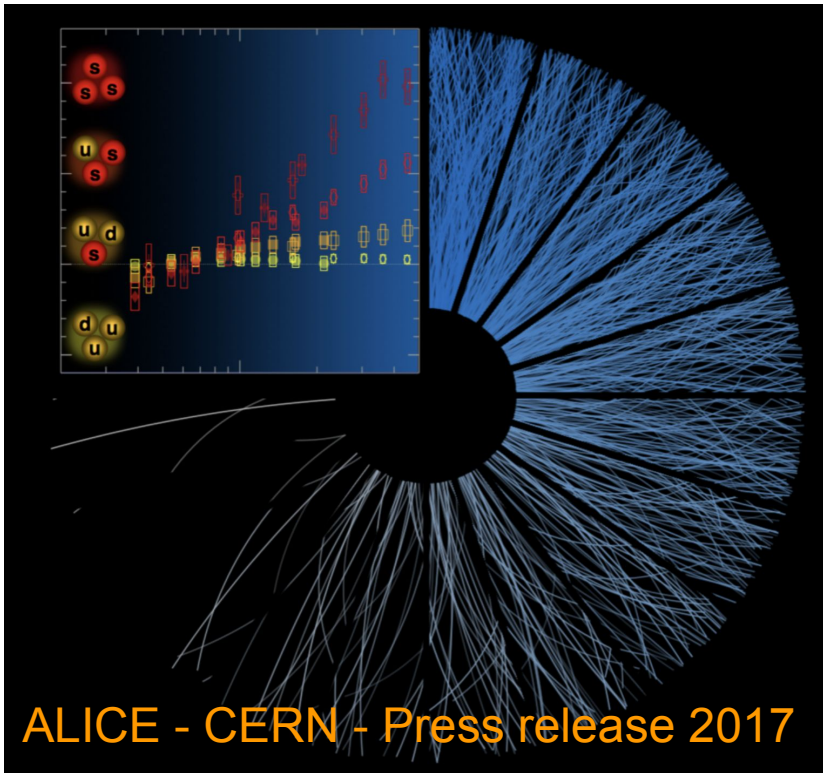
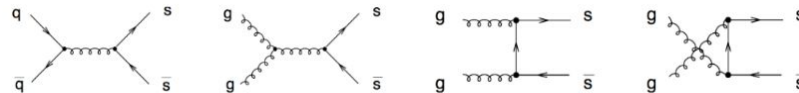
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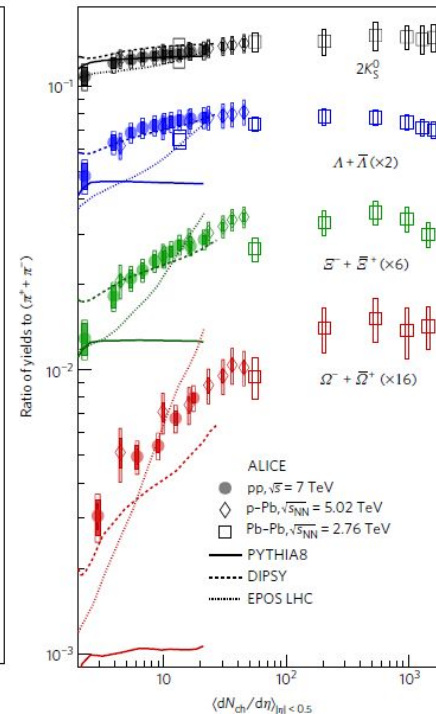
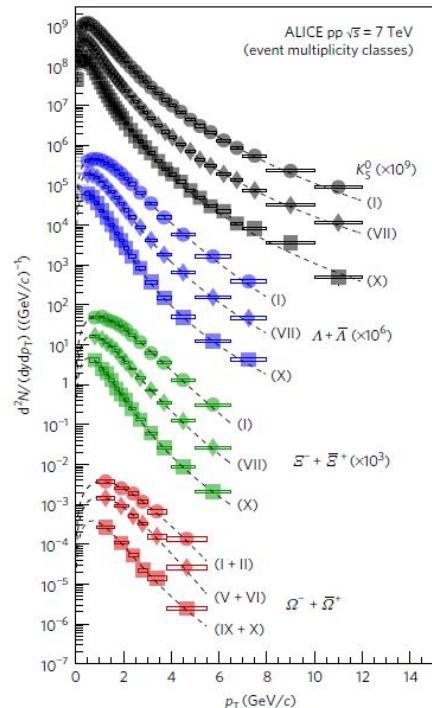


Surprise !

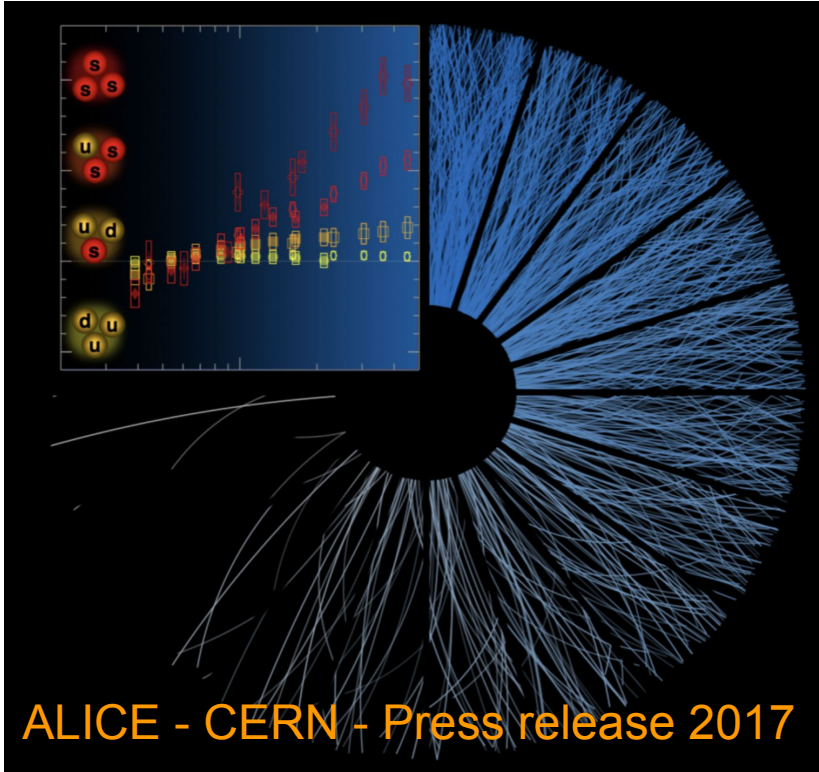
Strangeness enhancement



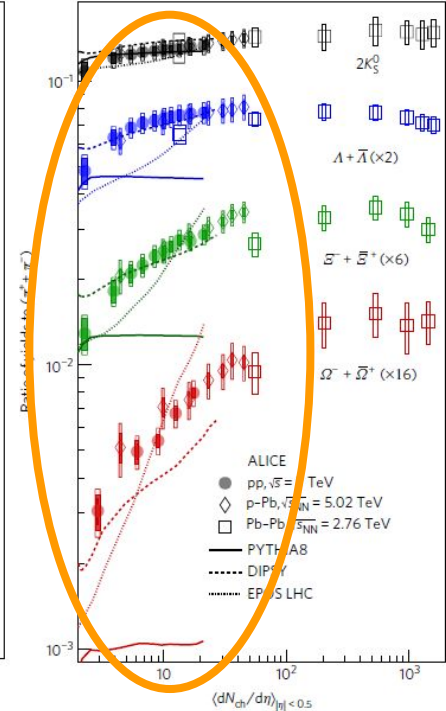
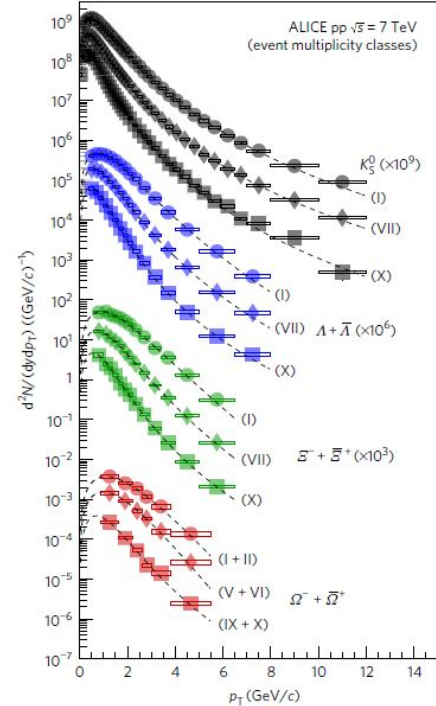
<https://www.nature.com/articles/nphys4111>



Strangeness enhancement



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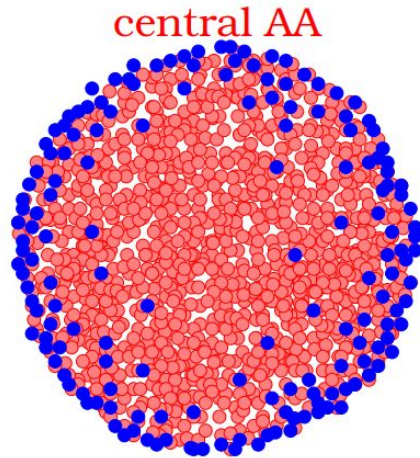


Something truly unexpected is happening!

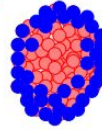
Is there a coherent picture of particle production using both pp and heavy-ion phenomena?

The hybrid approach: The core corona solution

The most “complete” approach:



peripheral AA
high mult pp



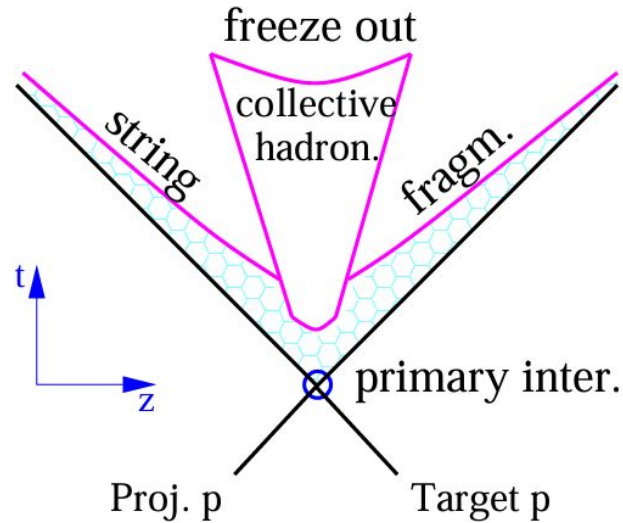
low mult pp



K. Werner, Lund 2017:

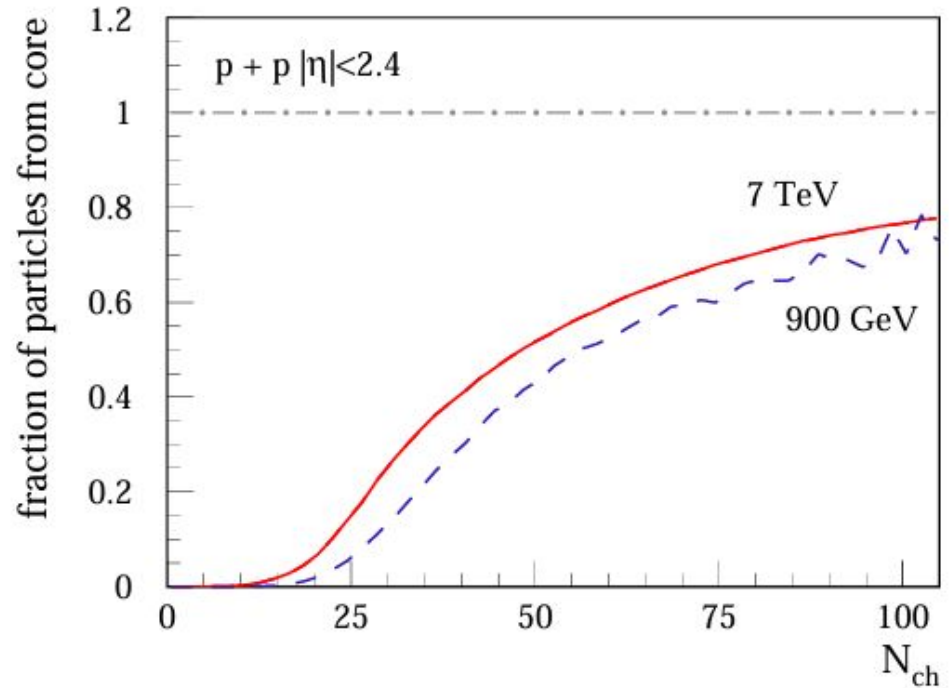
core => hydro => statistical decay ($\mu = 0$)
corona => string decay

The hybrid approach: The core corona solution

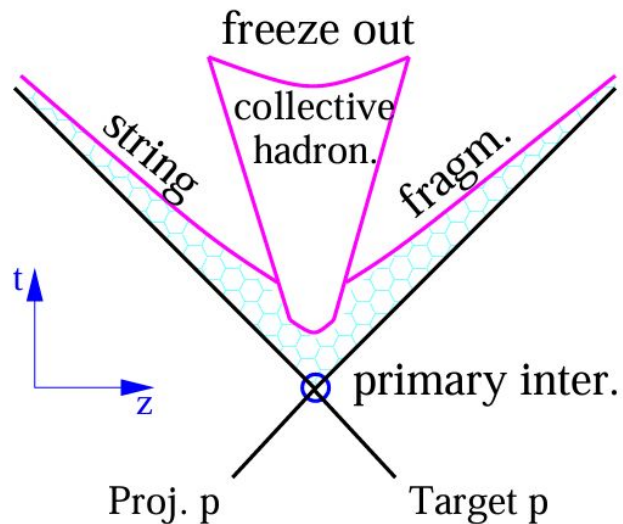


<https://arxiv.org/pdf/1306.0121>

pp collisions with a core that expands
“hydrodynamically”..!

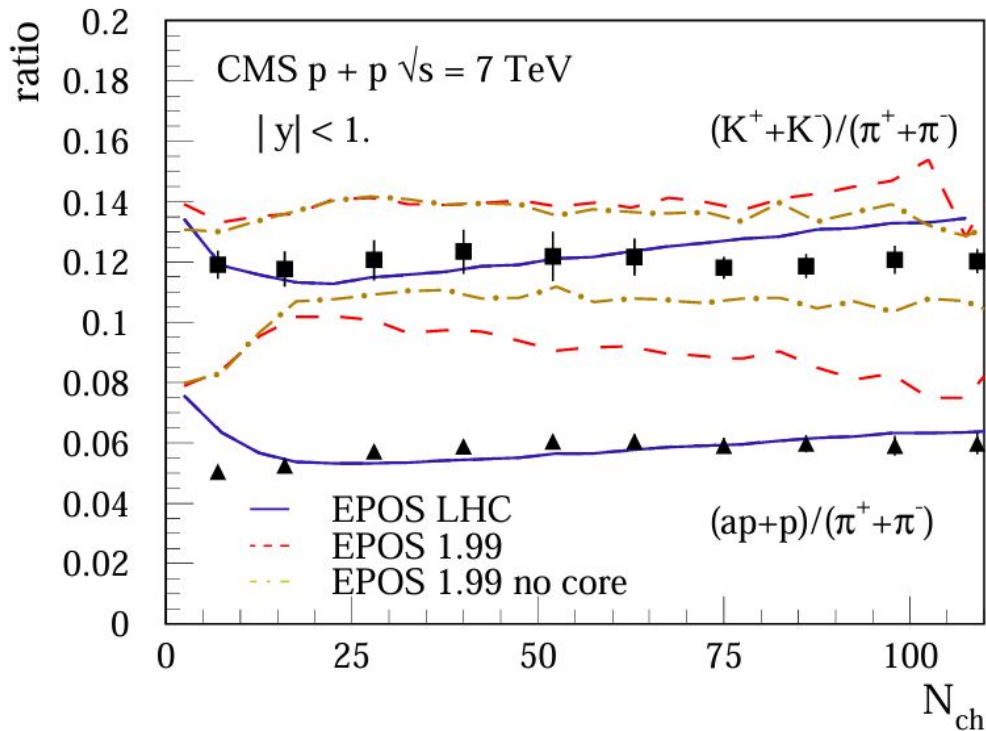


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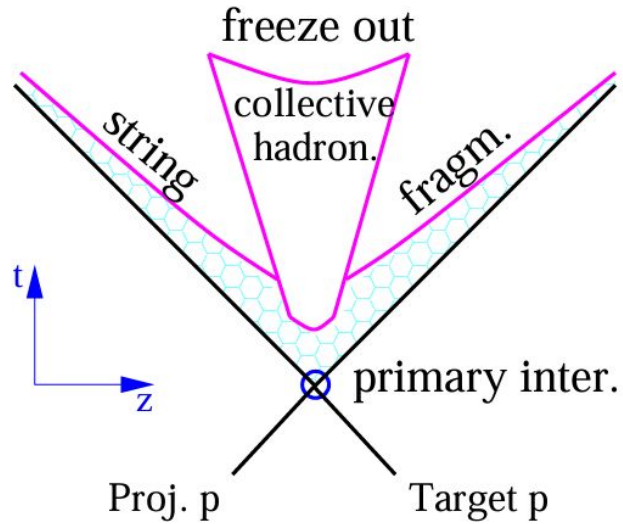


<https://arxiv.org/pdf/1306.0121>

pp collisions with a core that expands "hydrodynamically" ..!

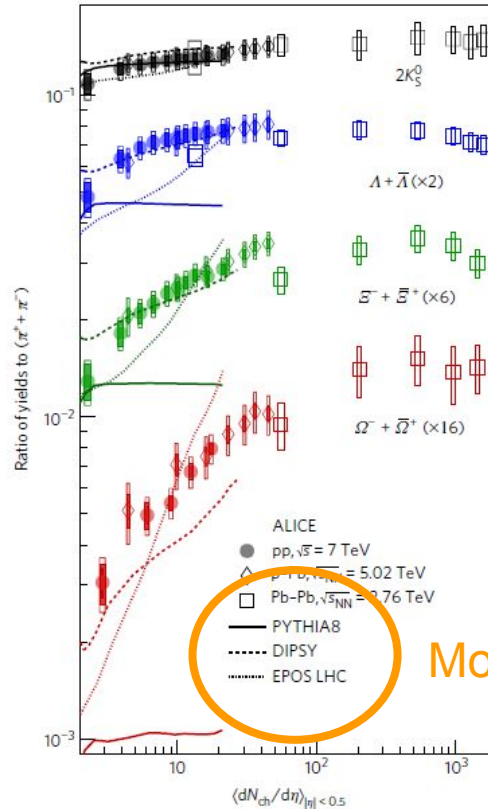


The hybrid approach: The core corona solution



<https://arxiv.org/pdf/1306.0121>

pp collisions with a core that expands “hydrodynamically”..!



The hunt for a QGP in small systems

Requirements for a QGP:

- Deconfined state of quarks and gluons
- Chiral symmetry restored

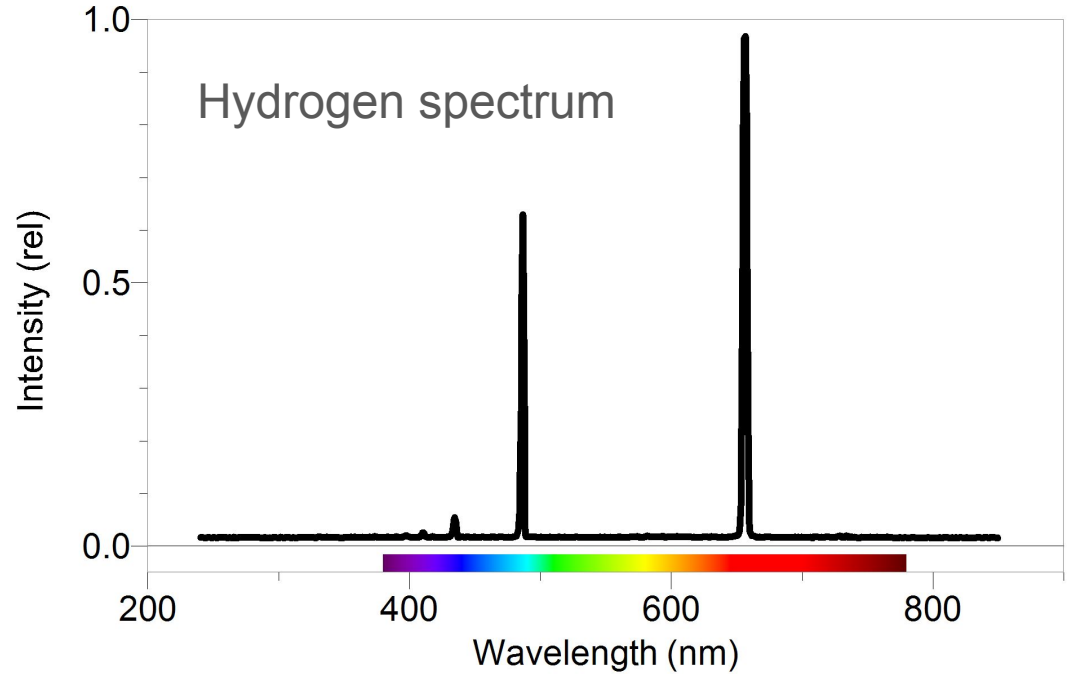
Do we create a QGP at LHC?

- in PbPb collisions?
- in pp collisions?

The hunt for a QGP in small systems

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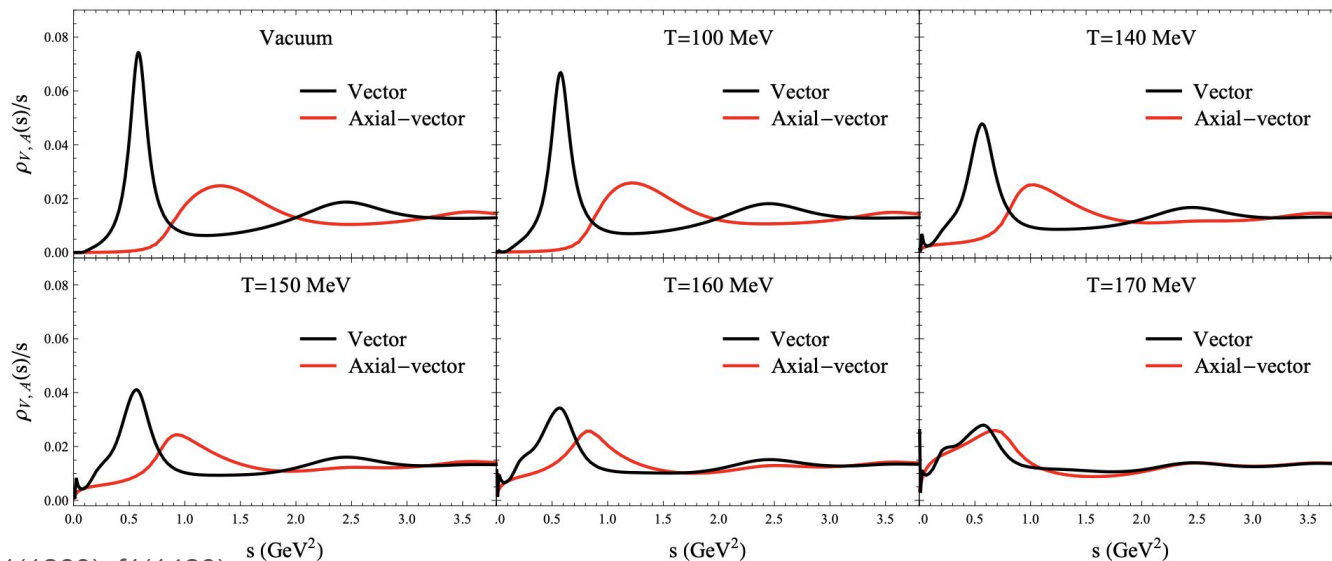


The hunt for a QGP in small systems

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QCD spectral functions



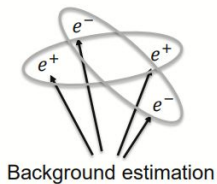
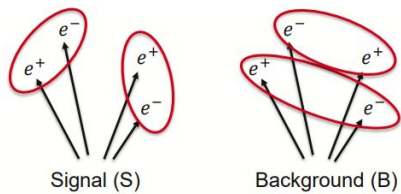
vector ($J^P = 1^-$): ρ , ω , ϕ

axial vector ($J^P = 1^+$): $f_1(1285)$, $a_1(1260)$, $f_1(1420)$

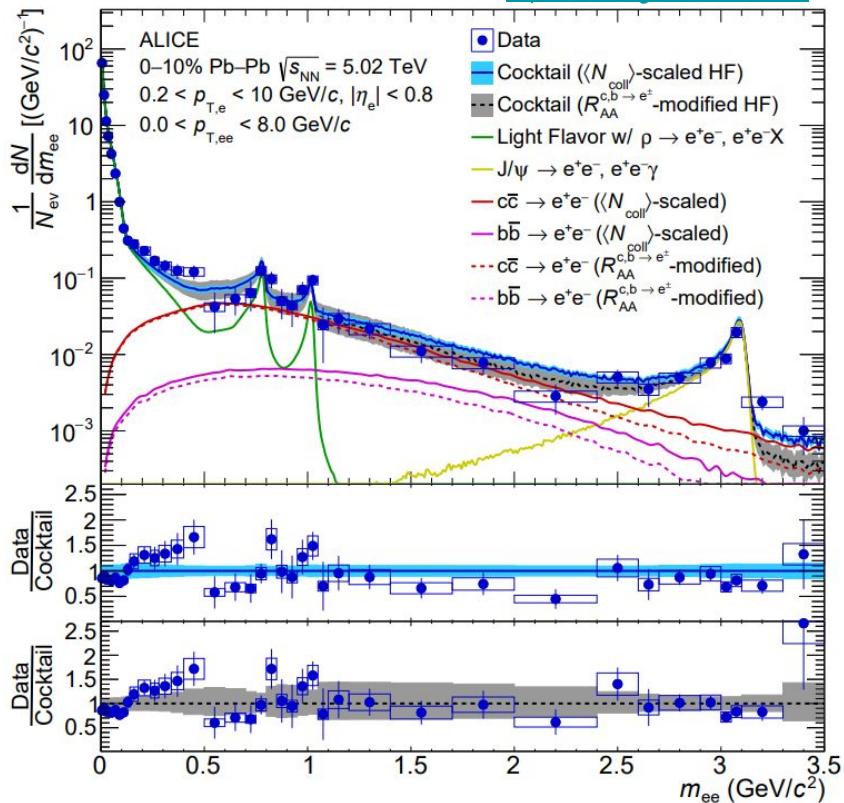
<https://arxiv.org/pdf/1509.05466>

The hunt for a QGP in small systems

<https://arxiv.org/abs/2308.16704>



$$\gamma^* \rightarrow e^+e^-$$



Final remarks

- Understanding physics beyond (below) pQCD is challenging!
- Proton structure on its own is already very rich in phenomenology
- Heavy-ion collisions have their own clear way of particle production, pp collisions as well
- Gluon density in pp collisions high enough for QGP formation / phenomenology?
- Do we need to combine both worlds for an accurate description?



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Soft QCD: many puzzles to investigate!