

Collectivity in Hadronic Collisions from final-state string dynamics



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Collectivity and Strings

- ▶ Heavy Ions in PYTHIA8: Angantyr
- ▶ Strings
 - ▶ in vacuum
 - ▶ in a dense system
- ▶ String interactions: Gleipnir
 - ▶ Colour reconnections
 - ▶ String repulsion
 - ▶ Rope hadronisation



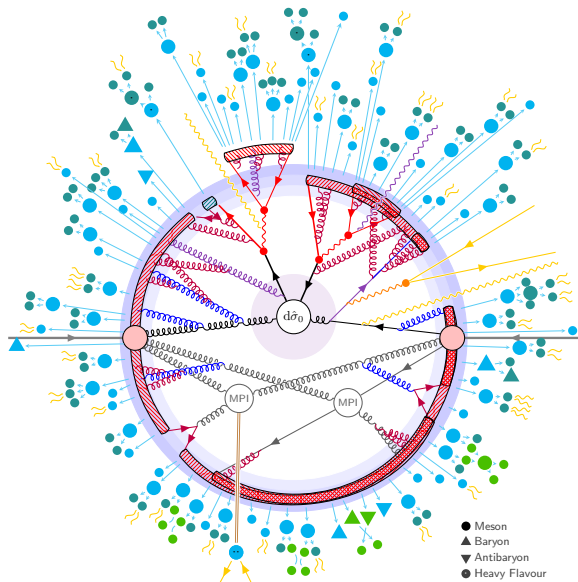
Angantyr: Heavy Ions in PYTHIA8

PYTHIA8 describes a wide range of pp measurements from the LHC and elsewhere.

Can we describe Heavy Ion Collisions by just stacking a bunch of pp events on top of each other?

[arXiv:1607.04434, arXiv:1806.10820]

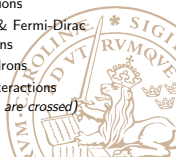




- Hard Interaction
 - Resonance Decays
 - MECs, Matching & Merging
 - FSR
 - ISR*
 - QED
 - Weak Showers
 - Hard Onium
 - Multiparton Interactions
 - Beam Remnants*
 - Strings
 - Ministring / Clusters
 - Colour Reconnections
 - String Interactions
 - Bose-Einstein & Fermi-Dirac
 - Primary Hadrons
 - Secondary Hadrons
 - Hadronic Reinteractions
- (*: incoming lines are crossed)

- Meson
- ▲ Baryon
- ▼ Antibaryon
- Heavy Flavour

[arXiv:2203.11601]

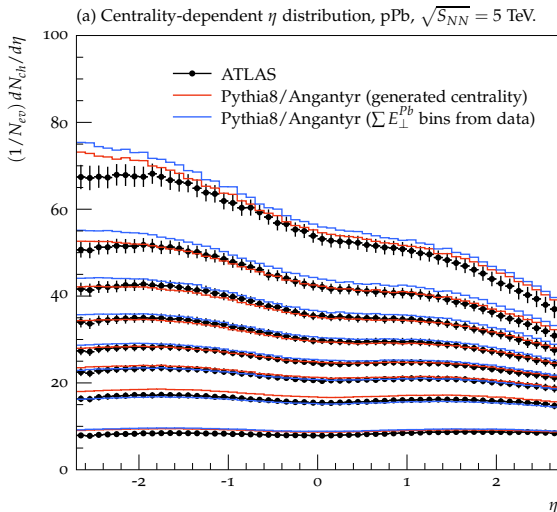




- ▶ Glauber calculation including Glauber–Gribov-like fluctuations
- ▶ Special treatment of multiple inelastic non-diffractive scattering, giving Nuclear shadowing
- ▶ Standard PYTHIA8 Multi-parton interactions (including *saturation*)
- ▶ Standard PYTHIA8 String fragmentation



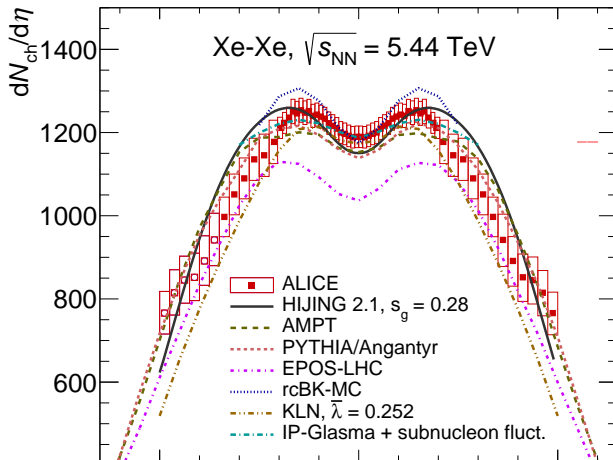
It works!



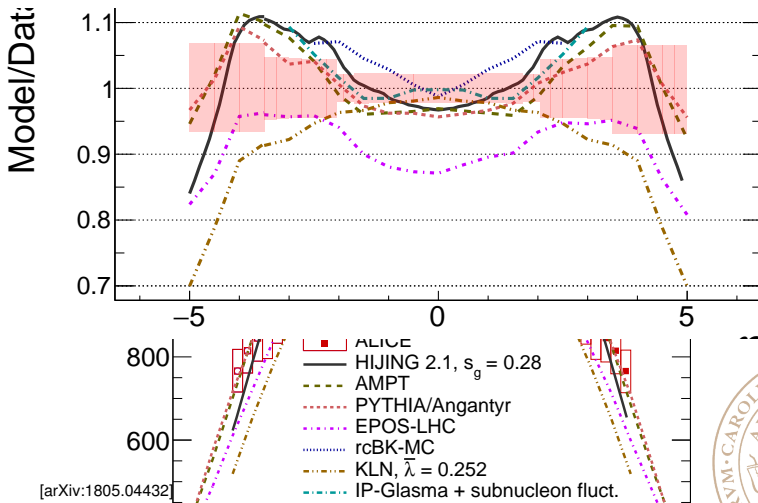
[arXiv:1508.00848]



It works even in AA!



It works even in AA!



Where is the Quark-Gluon Plasma?



There is **NO** Quark-Gluon Plasma!



There is **NO** Quark-Gluon Plasma!

There is only

- ▶ Multi-parton interaction with (semi-)hard scattering
- ▶ parton showers
- ▶ and string fragmentation



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But where is the collectivity?



String fragmentation

Formally based on one-dimensional, massless, relativistic strings.

- ▶ $V(r) \propto r$ gives a constant string tension
 $\kappa \sim 1 \text{ GeV/fm}$
- ▶ The string breaks by $q\bar{q}$ pairs tunnelling out of the vacuum
 $P \propto \exp(\pi(m_q^2 + k_{\perp}^2)/\kappa)$
- ▶ Strings are stretched between a quark and an anti-quark with gluons in between acting as kinks.
- ▶ Hadrons are chopped off from the ends with the Lund symmetric fragmentation function

$$f(z) \propto \frac{(1-z)^a}{z} e^{-bm_{\perp}^2/z}$$

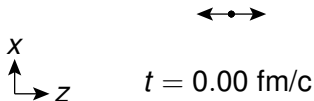


But strings are not one-dimensional. We can estimate both the tension and the radius of a QCD string on the lattice:

$$R = 0.25 - 1.0 \text{ fm.}$$

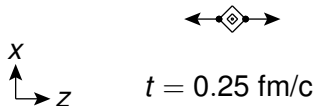


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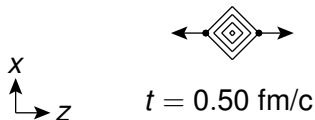
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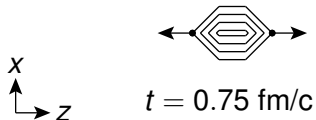
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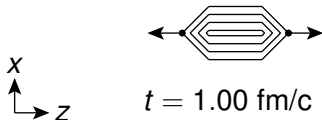


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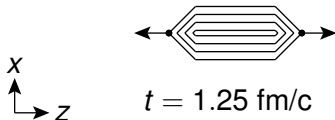
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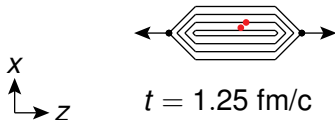
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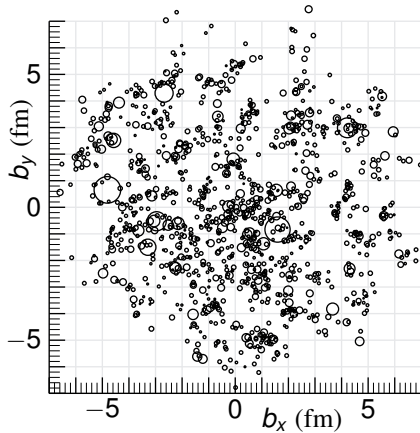
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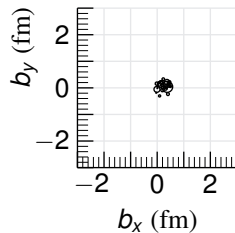
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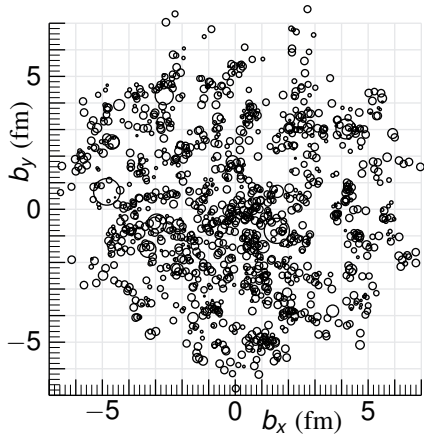
PbPb. $t = 0.1 \text{ fm}/c$



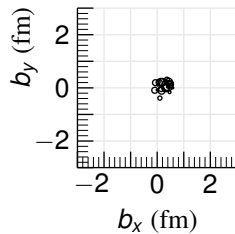
pp, $t = 0.1 \text{ fm}/c$

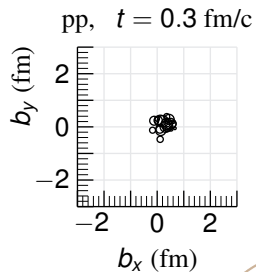
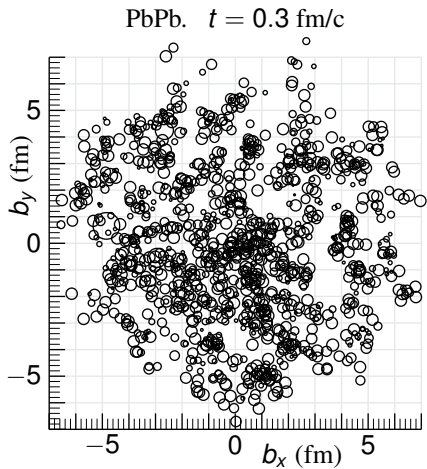


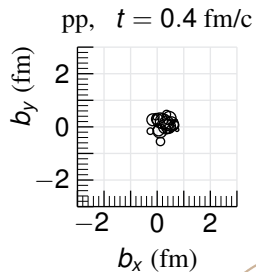
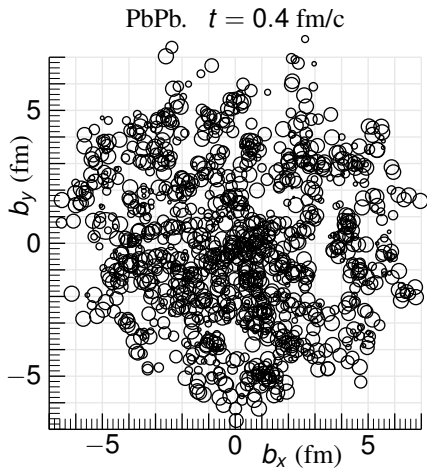
PbPb. $t = 0.2 \text{ fm}/c$

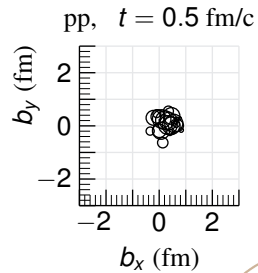
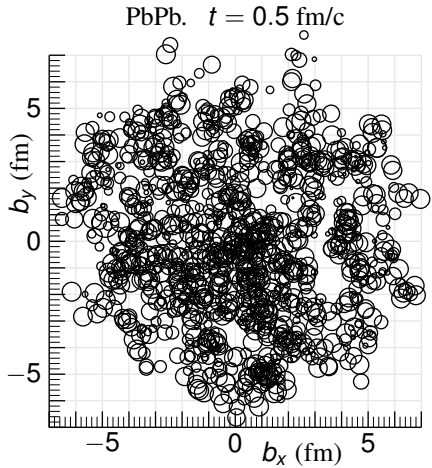


pp, $t = 0.2 \text{ fm}/c$









String Interactions: GLEIPNIR (X \uparrow MIC \downarrow IR)

- ▶ Overlapping anti-parallel strings may attenuate each other.
- ▶ Overlapping strings may repel each other
- ▶ Overlapping strings will have an increased string tension, making it easier to produce eg. strange hadrons.

[work in progress]



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Swing, Colour reconnections \Rightarrow ?
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String Shoving \Rightarrow ridges and flow
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[arXiv:1710.09725, arXiv:2010.07595]



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Rope Hadronisation \Rightarrow strangeness enhancement

[work in progress]

[arXiv:1710.09725, arXiv:2010.07595]

[arXiv:1412.6259, arXiv:2202.12783, arXiv:2205.11170]



String repulsion: Shoving

The string endpoints (quarks and gluons) carry longitudinal momentum, but the string itself cannot.

The shoving between parallel gives a transverse push according to a

$$\frac{dp_{\perp}}{dt dz} = \frac{g_{\kappa} \delta_{\perp}(t)}{R^2} \exp\left(-\frac{\delta_{\perp}^2(t)}{4R^2}\right).$$

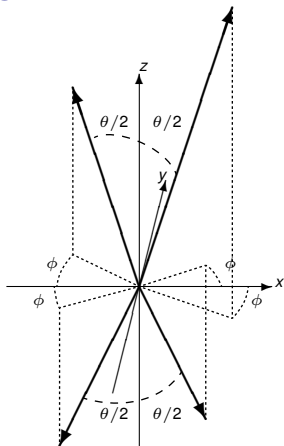
This push must be parallel to both string pieces.

There is no frame where two random string pieces are parallel.

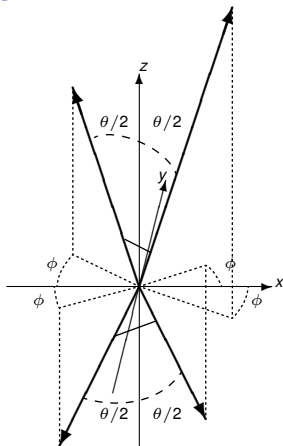
But there is always a frame where they lie in parallel planes at any given time.



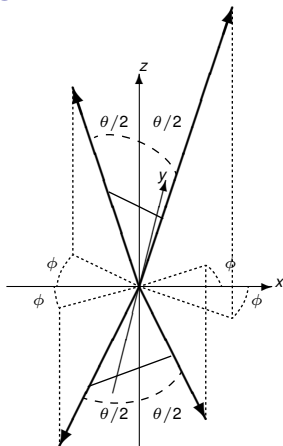
The parallel string frame



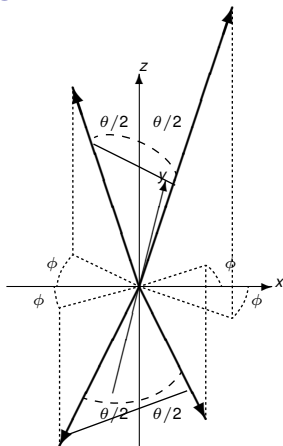
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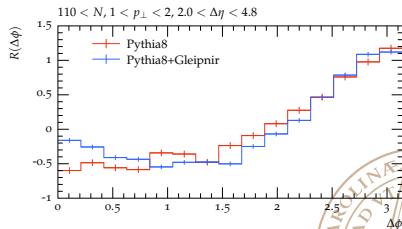
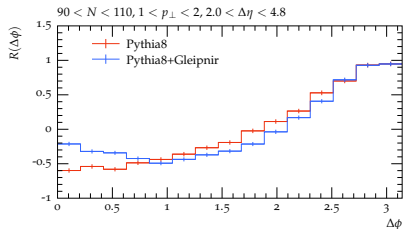
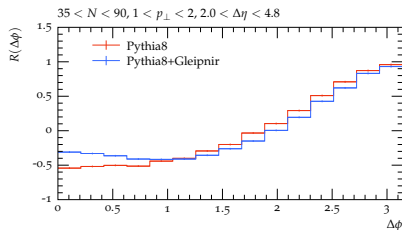
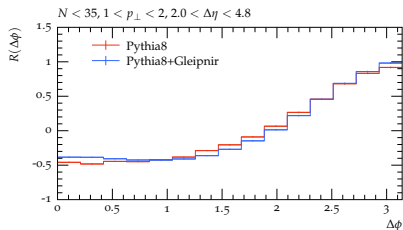
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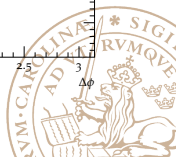
- ▶ Use (simplified) space-time information of all partons.
- ▶ Transform to parallel frame for every pair of string pieces.
- ▶ Calculate and collect small nudges, ordered in time.
- ▶ Apply the nudges to the produced primary hadrons (both position and momenta).

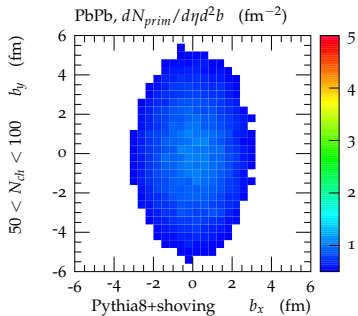
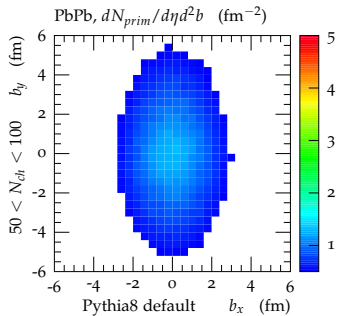


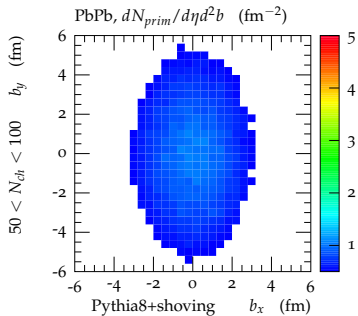
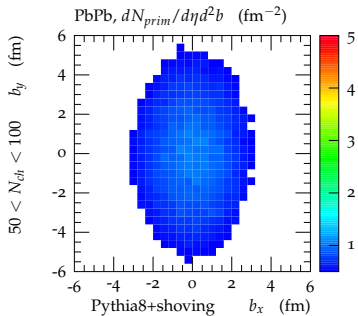
We have a ridge!



[arXiv:1009.4122]







Rope hadronisation

Overlapping strings will give a higher string tension.

From lattice calculations $\kappa \propto C_2$.

In a rope with p parallel and q anti-parallel, completely overlapping strings we have

$$\kappa_{\{p,q\}} = \frac{1}{4} (p^2 + pq + q^2 + 3p + 3q) \kappa_{\{1,0\}}$$

The relative probability to produce a strange quark in a break-up, compared to a light quark is

$$P \propto \exp(\pi(m_s^2 - m_d^2)/\kappa_{\text{eff}}), \text{ where}$$

$$\kappa_{\text{eff}} = \kappa_{\{p,q\}} - \kappa_{\{p-1,q\}}$$

is the *reduction* of the string tension.

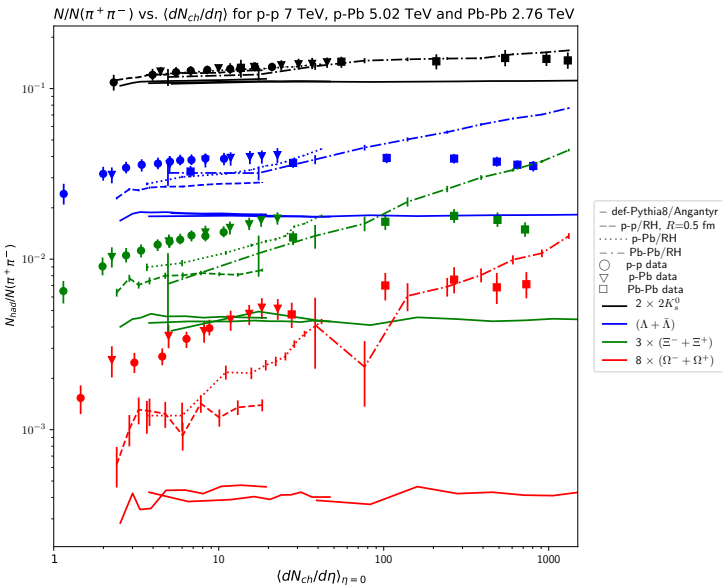


- ▶ Strings are not parallel \Rightarrow the parallel frame
- ▶ Strings are not completely overlapping

$$\begin{aligned} \mathcal{I}(\delta_y, \delta_z, \phi) &= \int d^2\rho \mathbf{E}_1(\rho) \cdot \mathbf{E}_2(\rho) \\ &= 2\pi E_0^2 R^2 \frac{\cos \phi}{\cos \frac{\phi}{2}} \exp\left(-\frac{\delta_y^2 \cos \frac{\phi}{2} + \delta_z^2}{4R^2}\right). \end{aligned}$$

- ▶ Again use pairwise interactions, and sum up (fractional) p and q .
- ▶ Adjust the hadronisation parameters in PYTHIA8 in each break-up.





Outlook

- ▶ **Angantyr** gives a reasonable description of inclusive particle production of (pp), pA and AA.
- ▶ Successfully extrapolates the pp dynamics of PYTHIA8 via pA to AA without introducing QGP dynamics.
- ▶ PYTHIA8/Angantyr brings general purpose event generators to heavy ion physics.
- ▶ Collective behaviour can be introduced via the **Gleipnir** models (Swing, Shoving, Ropes) as well as from hadronic rescattering.
- ▶ So far we have a qualitative description, more work is needed to get things properly working together and to compare to data.



Thanks!



Vetenskapsrådet



Marie Curie Actions
HUMAN RESOURCES and mobility

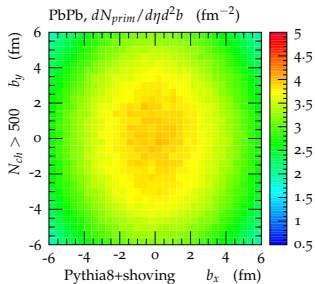
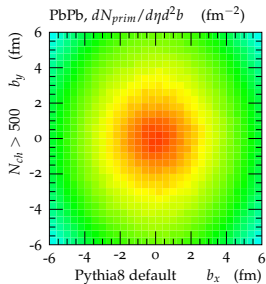
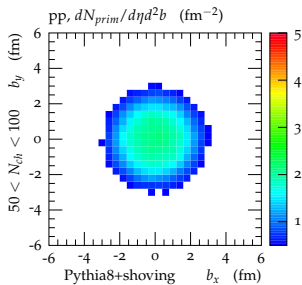
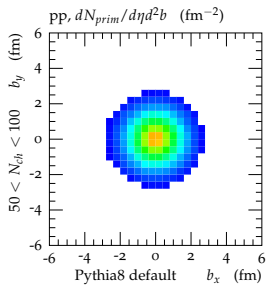


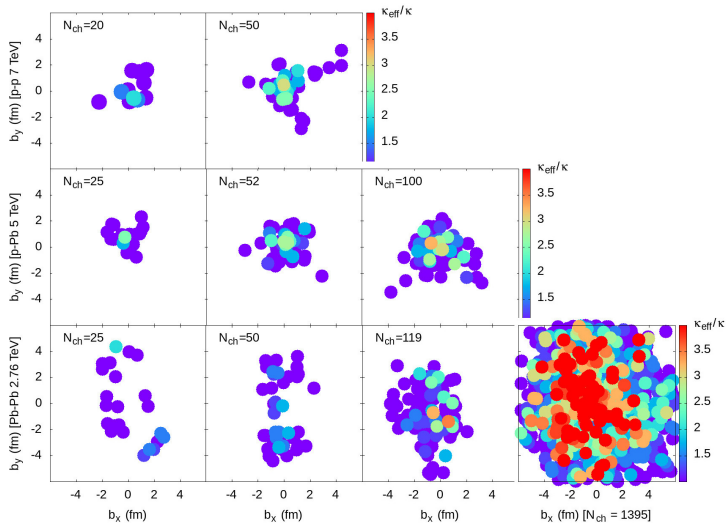
European Research Council

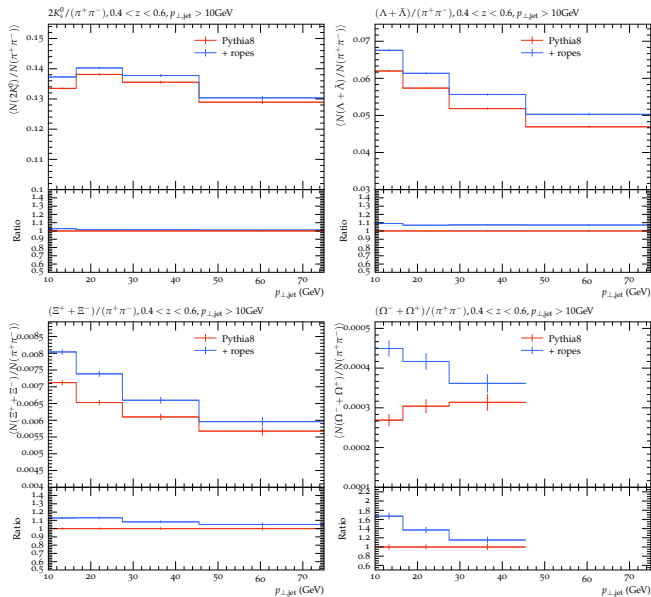
Established by the European Commission



backup slides







$$\hat{\sigma}_{2 \rightarrow 2} \longrightarrow \hat{\sigma}_{2 \rightarrow 2} \times \frac{\alpha_S(p_{\perp}^2 + p_{\perp 0}^2(s))}{\alpha_S(p_{\perp}^2)} \times \frac{p_{\perp}^4}{(p_{\perp}^2 + p_{\perp 0}^2(s))^2}$$

