Experiments with non-convex particles

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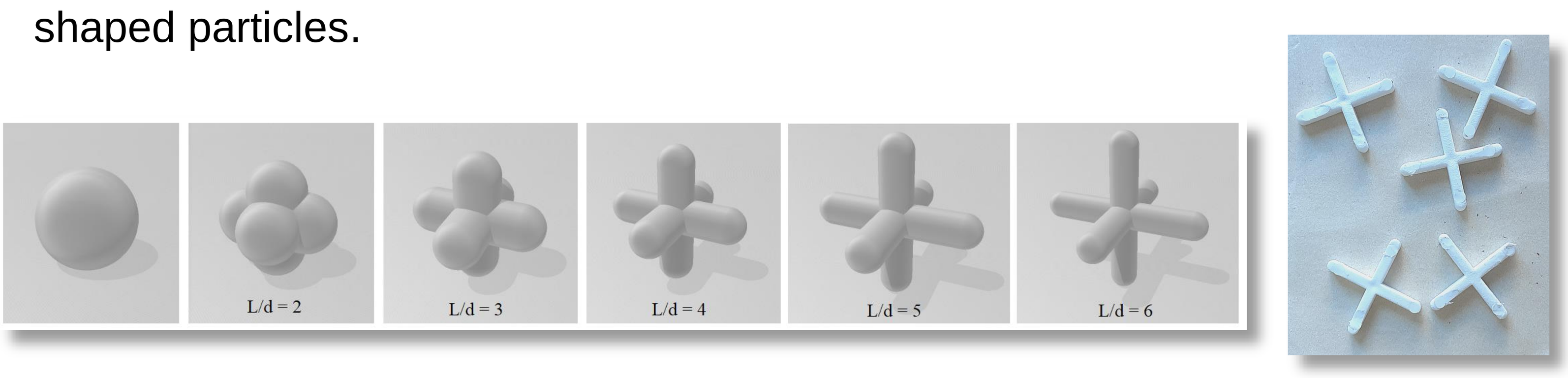
Motivation

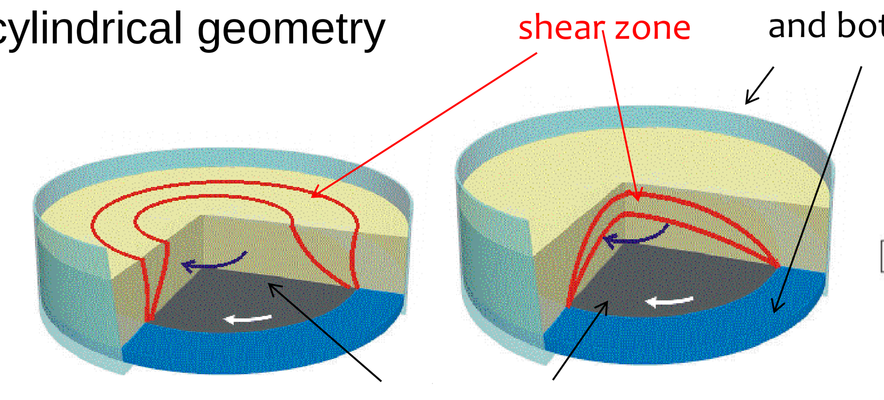
Shape matters

- Most studies deal with the simplest grain shapes: hard, monodisperse spheres.
- Recently, the role of anisotropic grain shape has gained focus, e.g. rice grains, cylinders or lens-shaped ellipsoids. They add the aspect of orientational order.
- Also, soft, elastic grains have been introduced. These materials can exhibit fundamentally new features.
- Non-convex grains received comparably little attention so far. U-shaped particles, flat crosses and even spherical crosses introduce novel features, like catching or entanglement. They may also cause unexpected dynamic effects.
- We present experimental results of packing and shear experiments with cross-shaped particles.

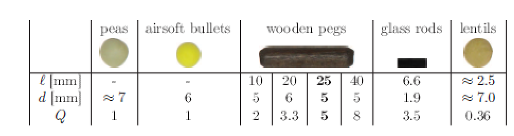


Split-bottom shear experiment

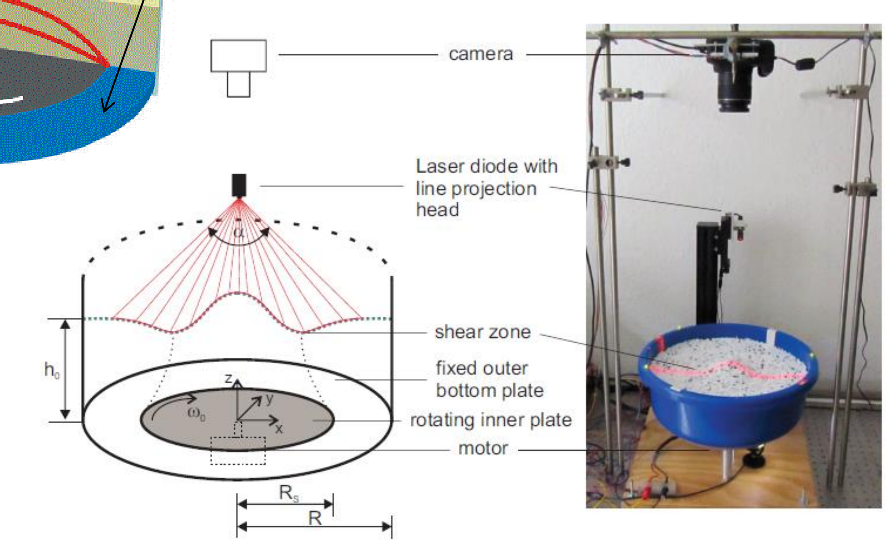
Continuous shear in cylindrical geometry



Materials studied in earlier experiments



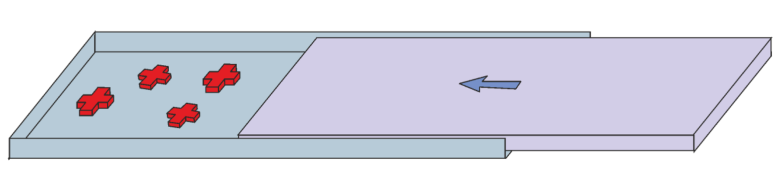
1. Projection of an obliquely incident Laser sheet recorded with camera. The displacement of the line reflects the height profile.
2. 3D camera for a complete 2D surface profile determination. Simultaneous optical recording of surface images.

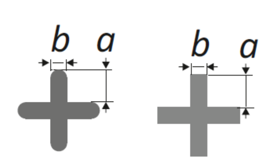


Granular "Weissenberg effect"?

Random packing of flat crosses

Setup



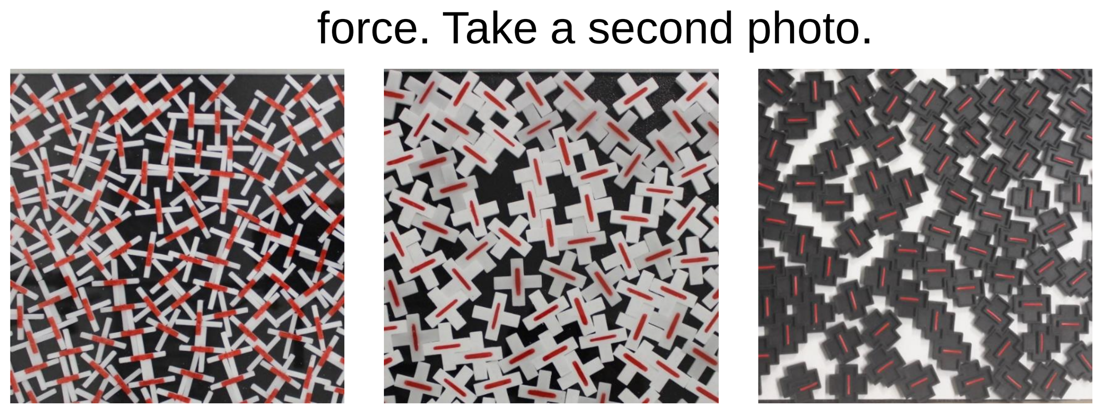


Random packings for aspect ratios ρ = a/b.

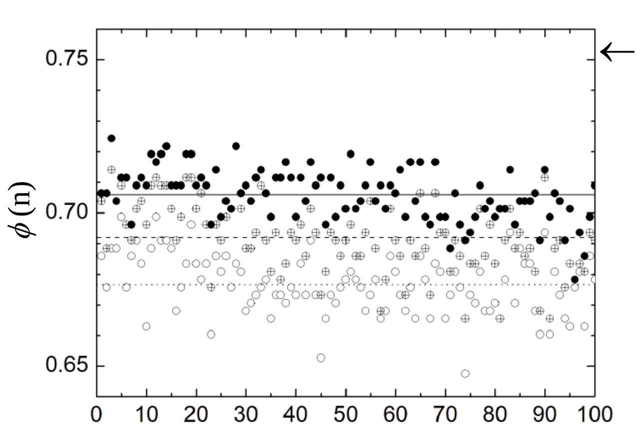
20 cm x 20 cm clips of photos after compaction

Preparation of random 2D packings:

- Place crosses loosely on a flat table, compactify the arrangement with a slider until the crosses give resistance.
- Take a photo and compress further with force. Take a second photo.

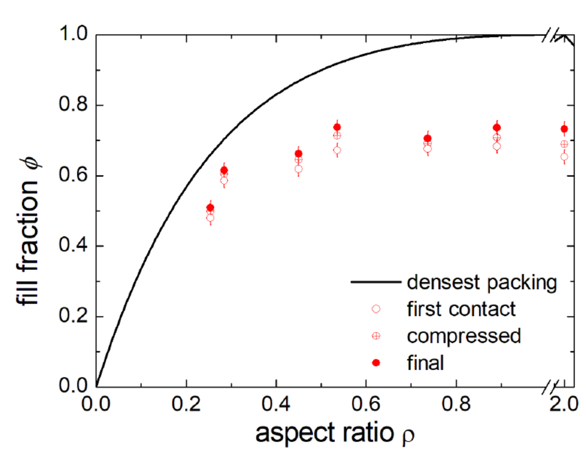


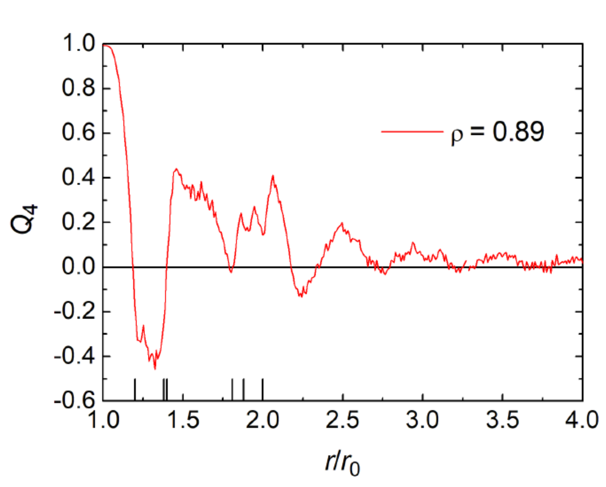
ρ = 0.25 ρ = 0.73 ρ = 2.0



← Packing fraction ϕ in 100 independent experiments, ρ = 0.73. o: first blockage, and •: fully compacted.

ϕ for different aspect → ratios. The solid line is the optimum crystalline packing.

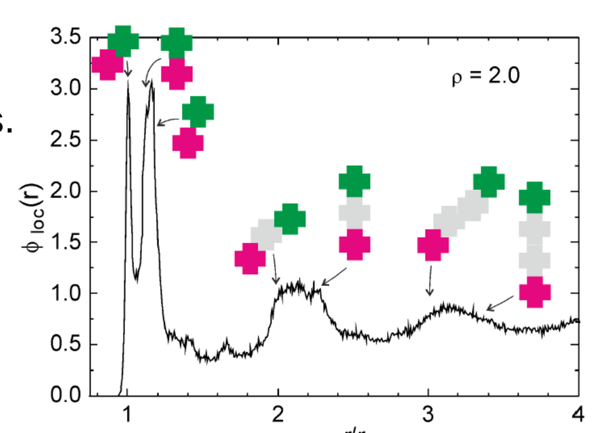




Short range positional order. Peaks reflect typical short-range ordered configurations. r_0 is the shortest possible distance of crosses →

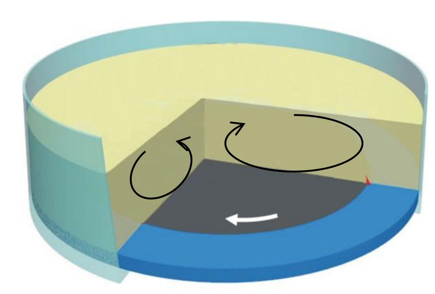
← Short range tetradic orientational order

$Q_4 = \langle \cos 4\varphi \rangle$.

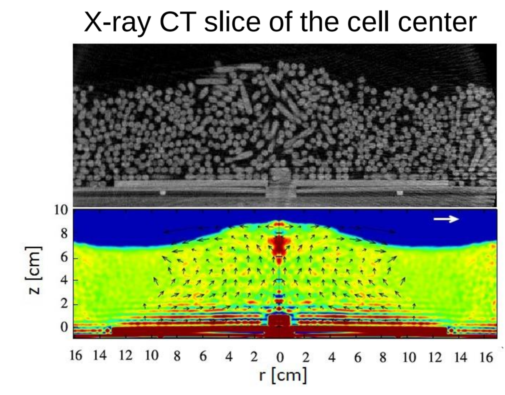


- Stannarius and Schulze, *Granular Matter* **24**, 25 (2022)

Earlier findings for convex particles



X-ray CT slice of the cell center



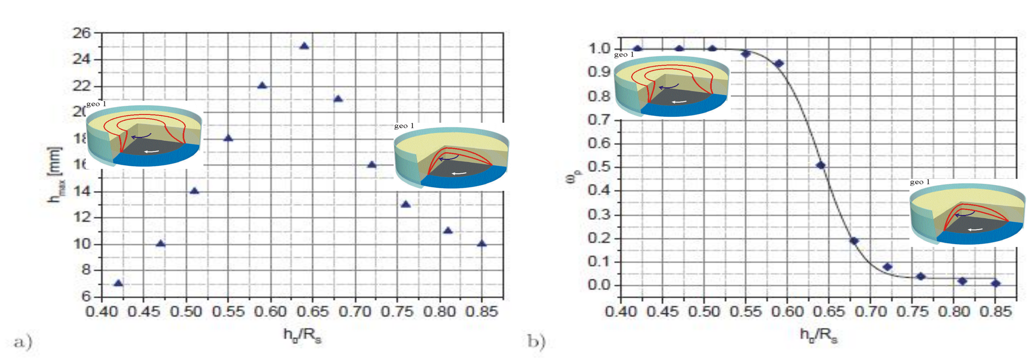
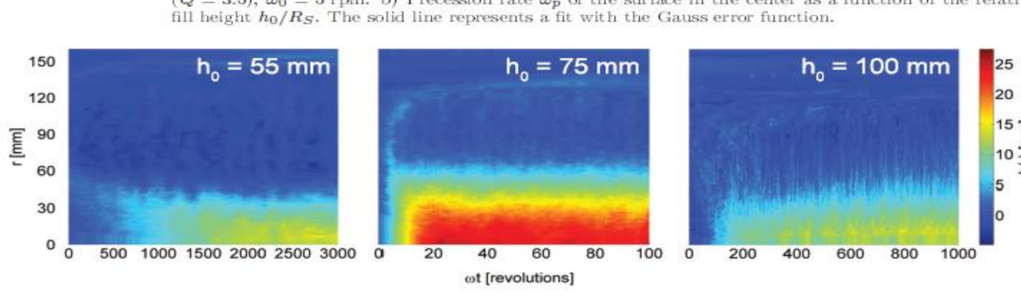


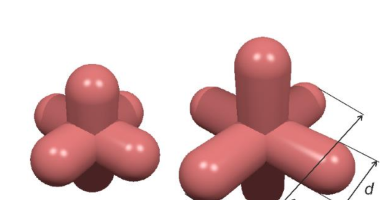
Figure 7. a) Maximum heap height h_{max} as a function of the relative fill height h_0/R_S for glass rods. b) Precession rate of the surface in the center as a function of the relative fill height h_0/R_S. The solid line represents a fit with the Gauss error function.

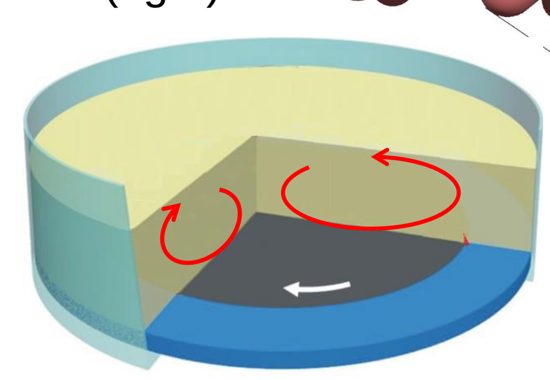


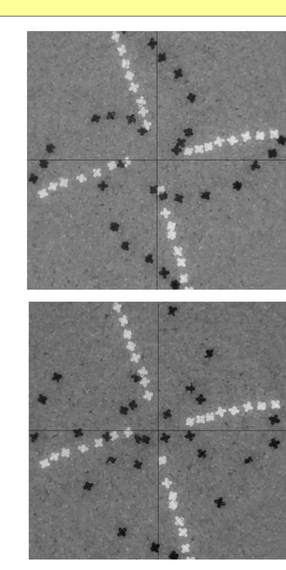
- Secondary flow: convection between shear zone and center
- Heap formation in the center of the split-bottom container
- Effect exists for oblate and prolate grains, NOT for spherical particles
- Heaping sensitively depends on container fill height, at optimum fill height it is fastest and most efficient
- Upon reversal of the rotation sense, the heap collapses and reappears in the same way as before

Spatial crosses under shear

Spatial crosses with aspect ratios 3 (left) and 4 (right)







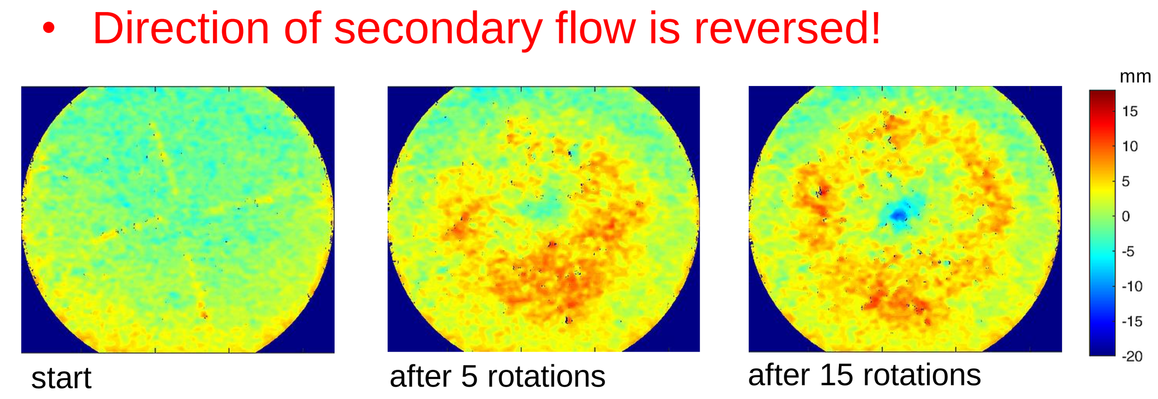
Top view of the rotation center:

Colored crosses are placed at the surface as markers before the rotation starts. Overlay of initial marker positions in white and positions after 5 (top) and 15 (bottom) full rotations of the bottom disk in black.

Image sizes 24 cm x 24 cm.

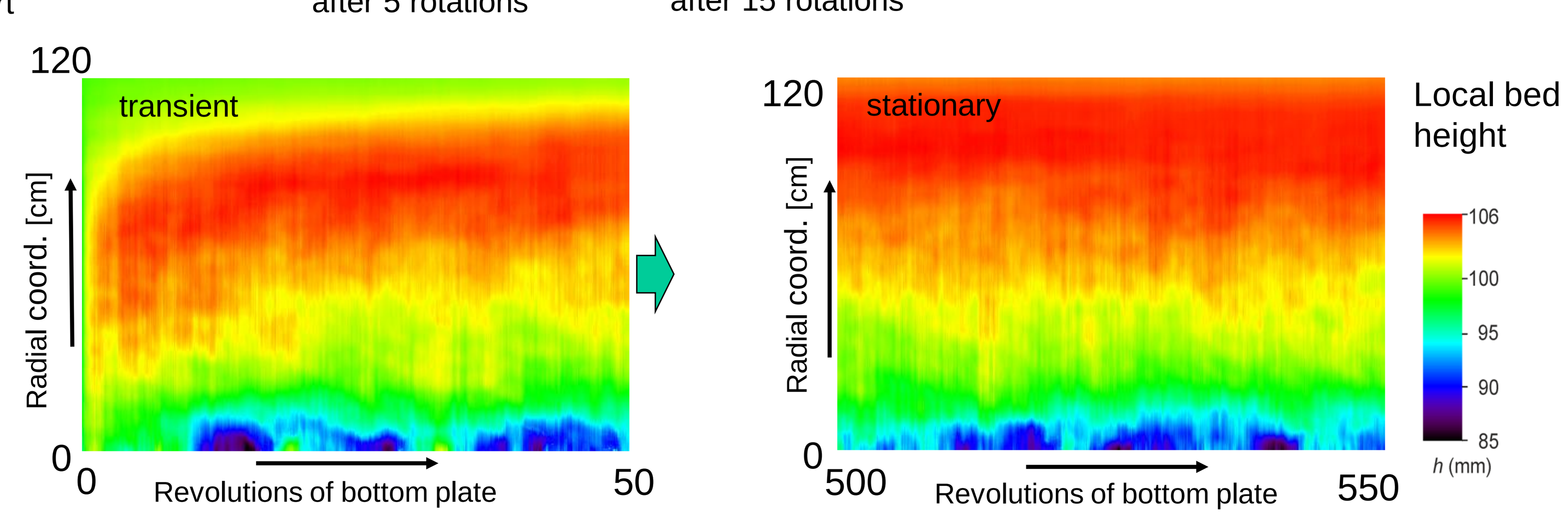
- Crosses at the surface within the sheared ring zone migrate inward.

- Direction of secondary flow is reversed!



Top views of the bed of 3D crosses in the split-bottom container, recorded with a stereoscopic camera.

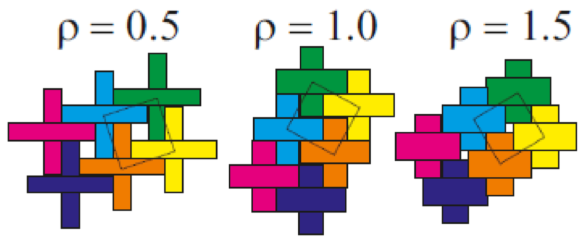
color-coded surface profile (blue: low, red:high)



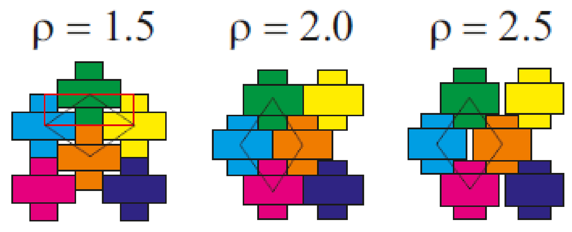
Mohammadi et al. Phys. Rev. E 106 L052901 (2022)

Crystalline Packing

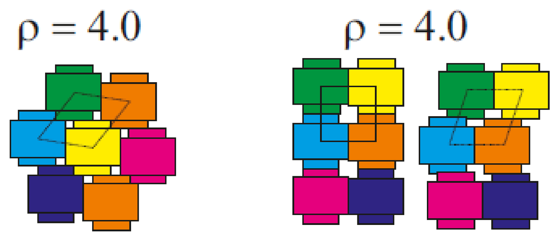
One cross per unit cell



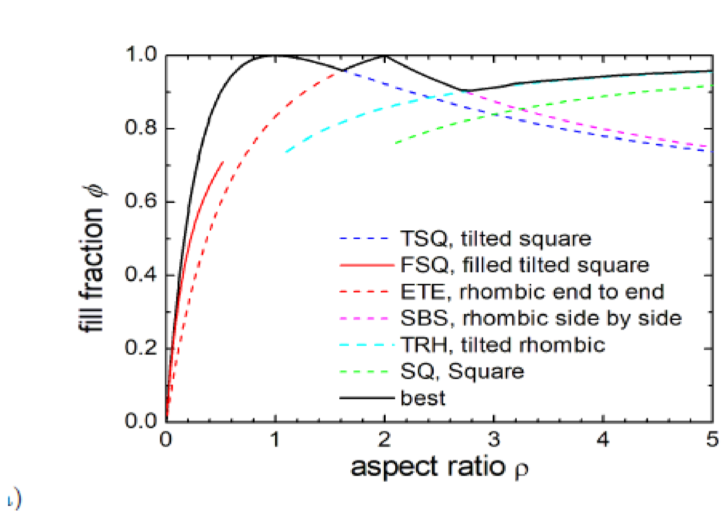
tilted square, TSQ



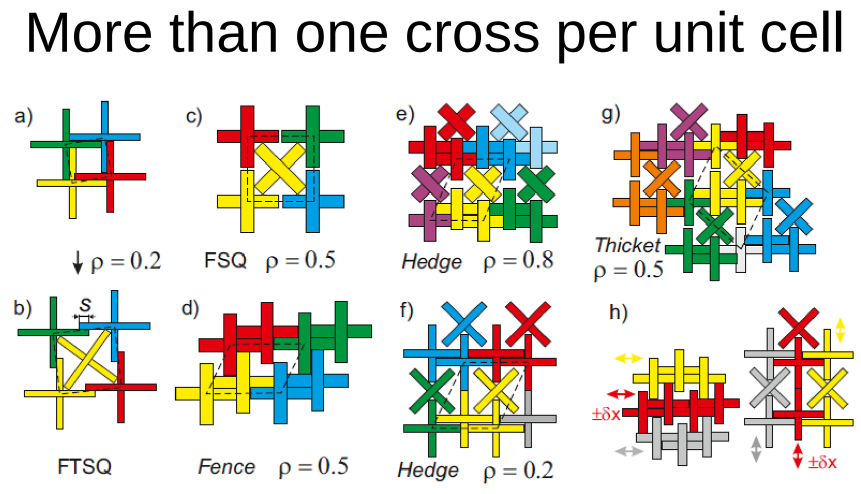
ETE ← rhombic → SBS



tilted rhomboid, TRH square,SQ



More than one cross per unit cell



Packing is less efficient!

- See also: Atkinson et al., Phys. Rev. E , 86 031302 (2012)

Results

Packing of 2D crosses

- **Packing fractions in dependence of aspect ratios**
- **Local positional and orientational correlations**

Shearing of 3D crosses (hexapods)

- **Dimple formation in the center of sheared granular bed**
- **Flow reversed with respect to convex (rodlike and lentil-shaped) particles**