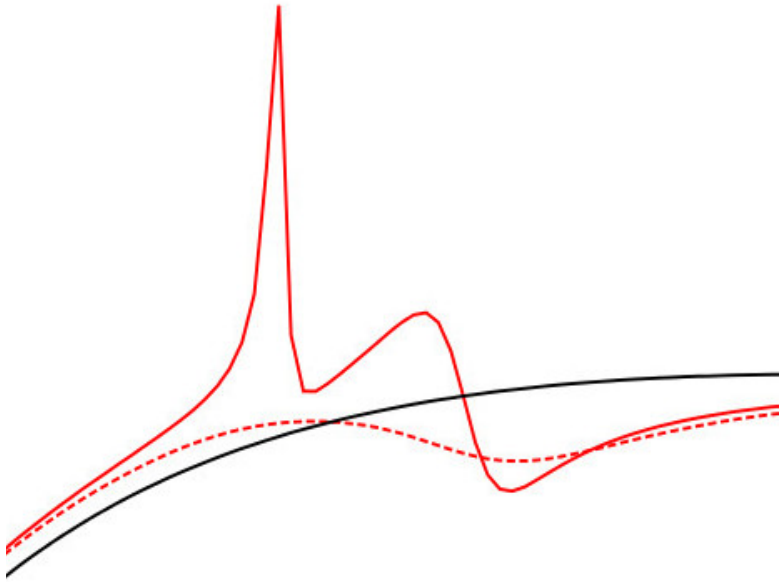
# Tops for PoF-V.

## ATLAS data analysis plans



**Dr. Katharina Behr**

PoF-V MU-FPF Retreat

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

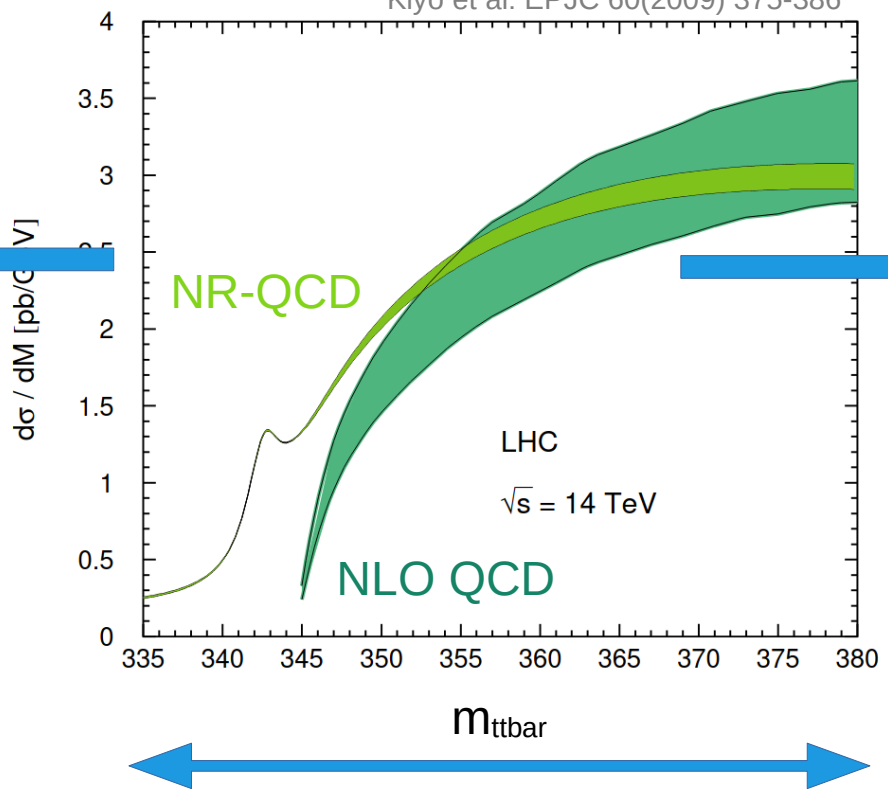
ATLAS EXPERIMENT

DESY.

# In a nutshell

> Leverage strong synergies between searches and measurements in ttbar* final states

Kiyo et al: EPJC 60(2009) 375-386




Production threshold

- Quantum tops: entanglement
- Quasi-bound-state effects

Extreme Lorentz boosts

- Quantum Tops: Bell's inequalities
- High-mass BSM resonances (DM, EFT, ...)

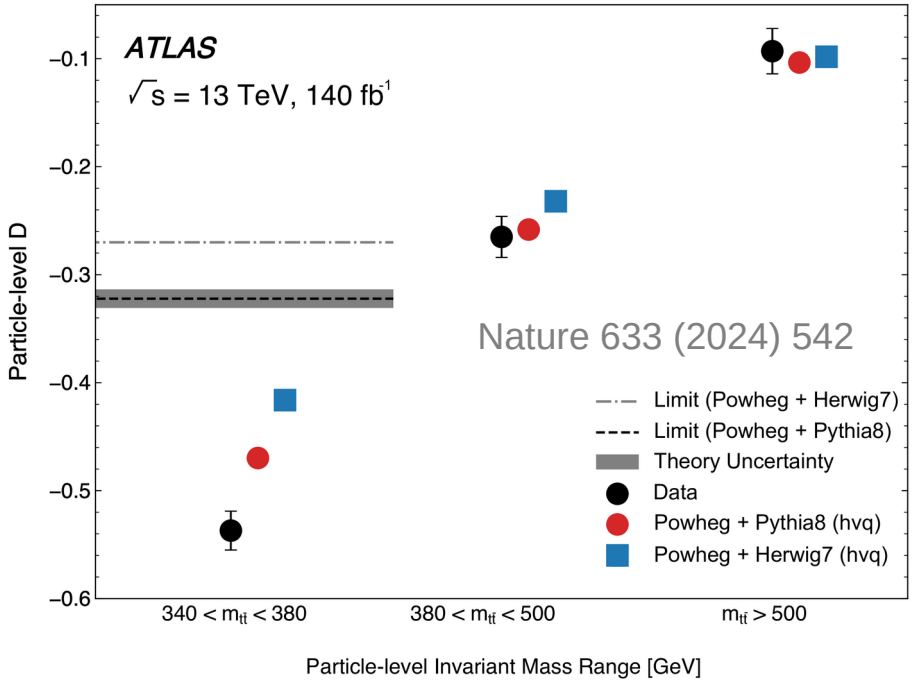
Full kinematic range

- Interference searches (BSM Higgs, ALPs, ...)

*Rare top processes (tW, ttZ, ttH, tZ, tH, 4tops) targeted in BSM searches (Federico's talk)

# Quantum tops

- Exciting experimental opportunity to study quantum effects in a top-antitop quark system
  - Decay before hadronisation or spin de-correlation ($\tau_{life} = 0.5\times10^{-25}$ s $< \tau_{had} \sim 10^{-24}$ s $< \tau_{spin\text{-}dec.} \sim 10^{-21}$ s)
  - Spin state accessible from decay products
- Top – antitop system = two qubit system
- Unique opportunity to test quantum effects in fundamental quarks and at the TeV scale
- Recent observation of quantum entanglement by ATLAS and CMS… only the beginning!



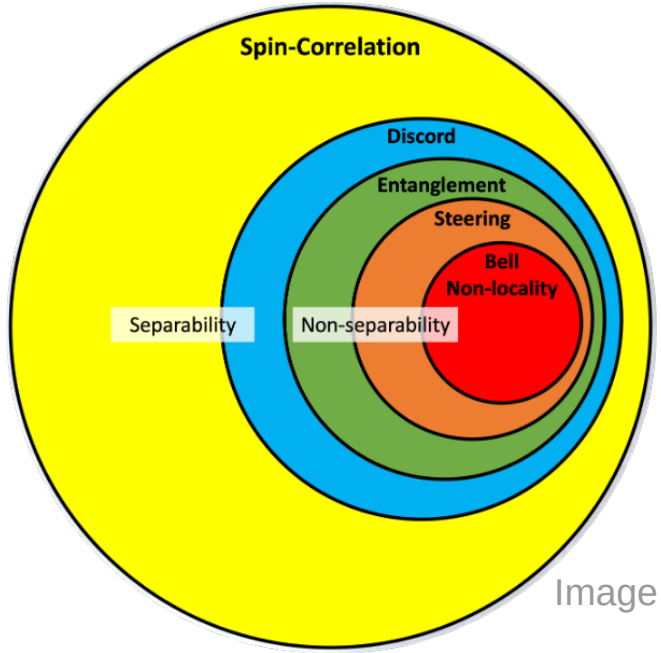
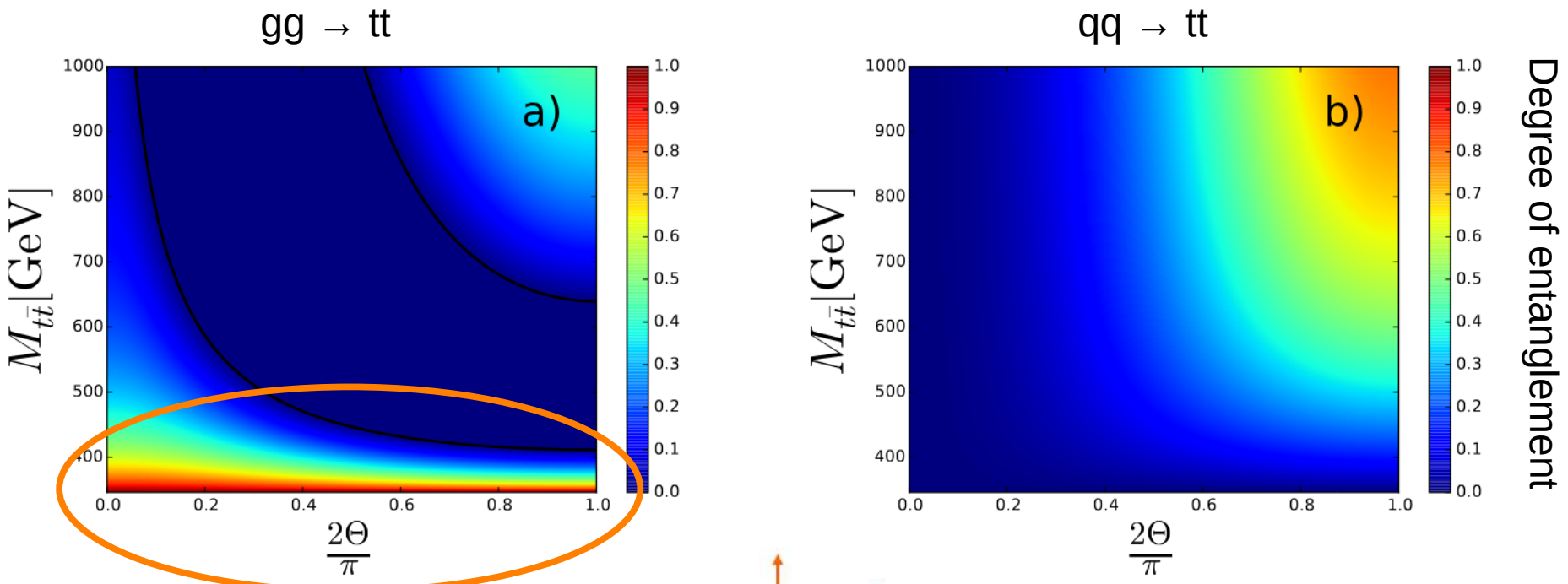




Image credit: Y. Afik

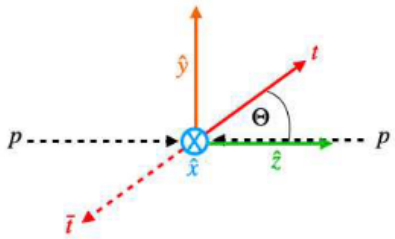
# Quantum tops

> Quantum effects from spin correlation variables in very limited regions of phase space



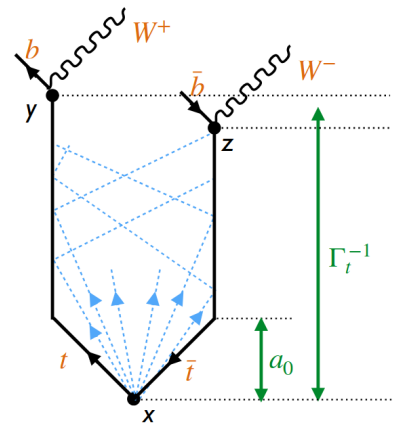

Pure spin singlet state, maximally entangled, time-like separation

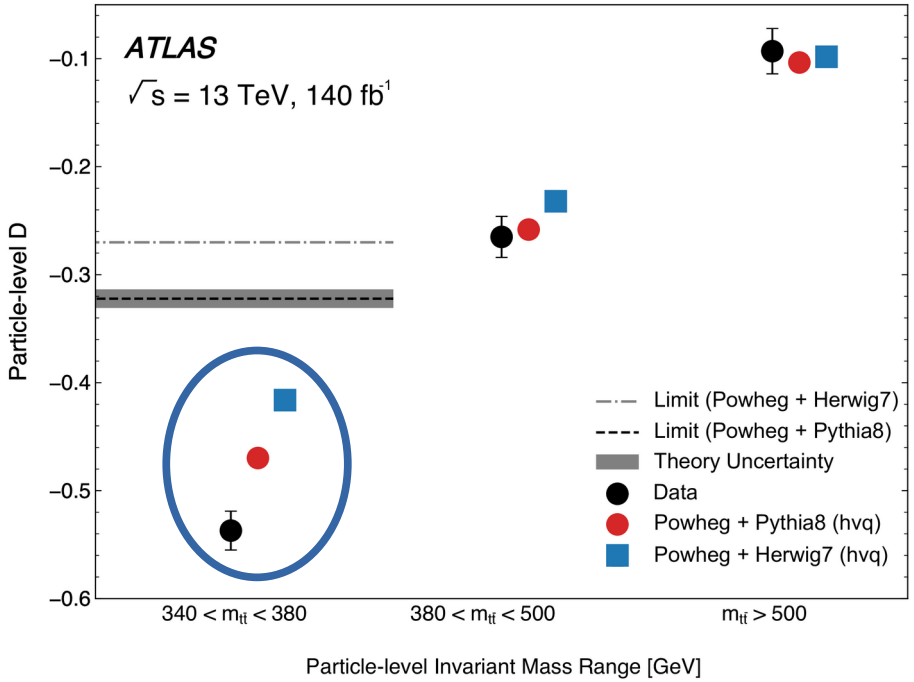
$$\frac{|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle + |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle}{\sqrt{2}}$$

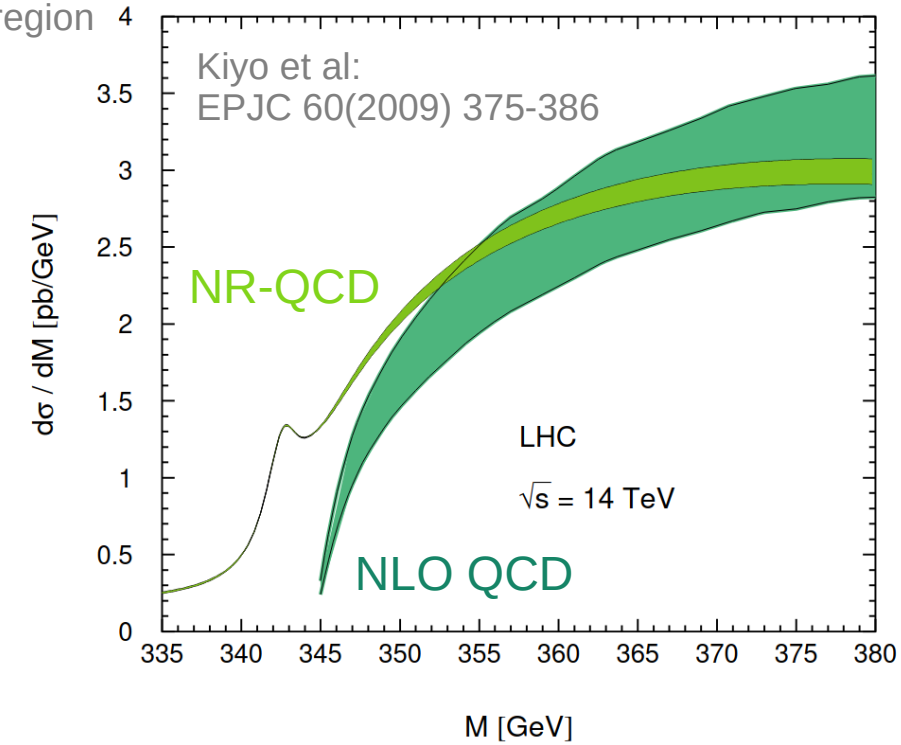


# Threshold region

- First observation of entanglement at the LHC
- Tension observed between data and predictions:
  - Incomplete ttbar model (resummation, off-shell effects)? BSM physics?
- Observation of pseudo-scalar excess by CMS: consistent with quasi-bound-state formation
- Threshold region expected to remain a key focus of LHC physics!
- Side note: exciting to have a future lepton collider that can scan threshold region

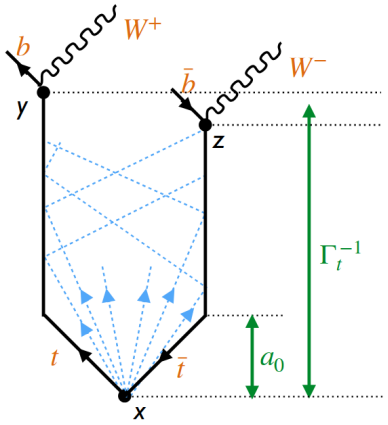


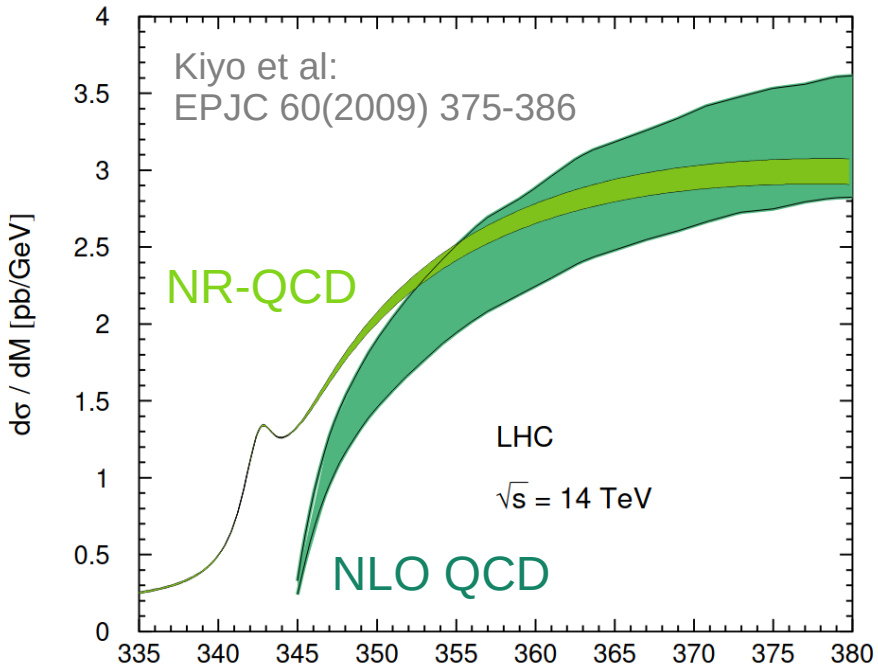



# Threshold region

- Main experimental challenge: improve resolution of kinematic variables
  - Including spin-sensitive variables
- ML-based reconstruction methods (both dilepton and l+jets channel)
- Improved b-, c-, … tagging crucial for l+jets channel
  - Down-type jet from hadronic W decay with highest spin-analysing power

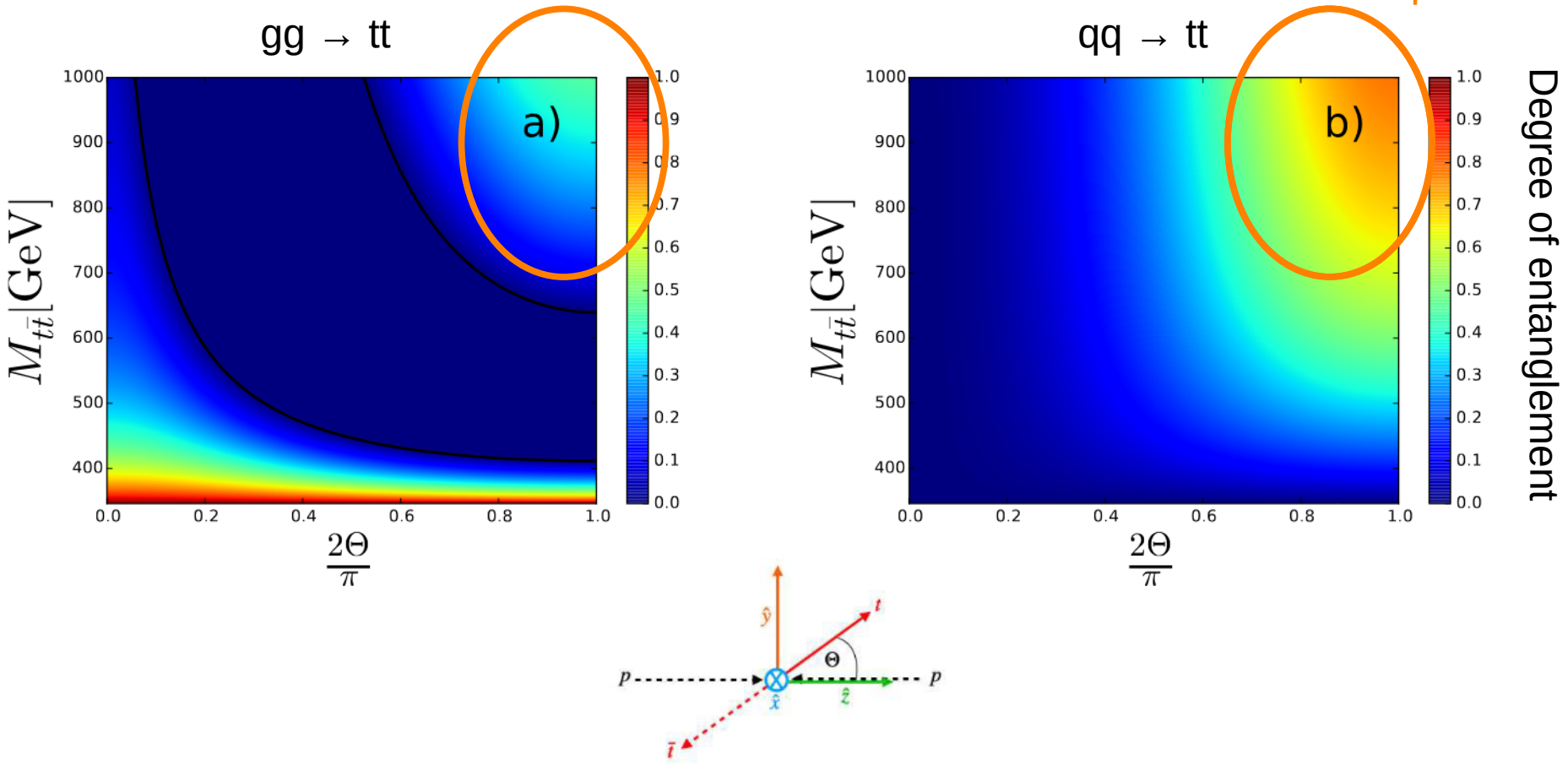


# Measurements of quantum effects in ttbar systems

> Quantum effects from spin correlation variables in very limited regions of phase space

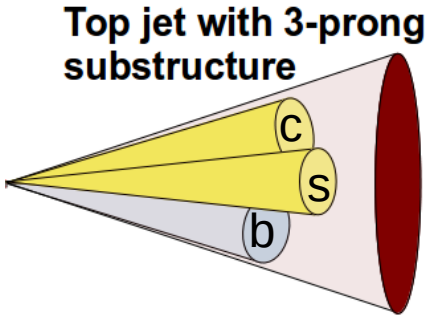
Maximally entangled, space-like separation



# Test of Bell's inequalities

> Strategic significance:

- Paving the ground for very first test of Bell's inequalities at the LHC
- Evidence could already be found in Run-3 data

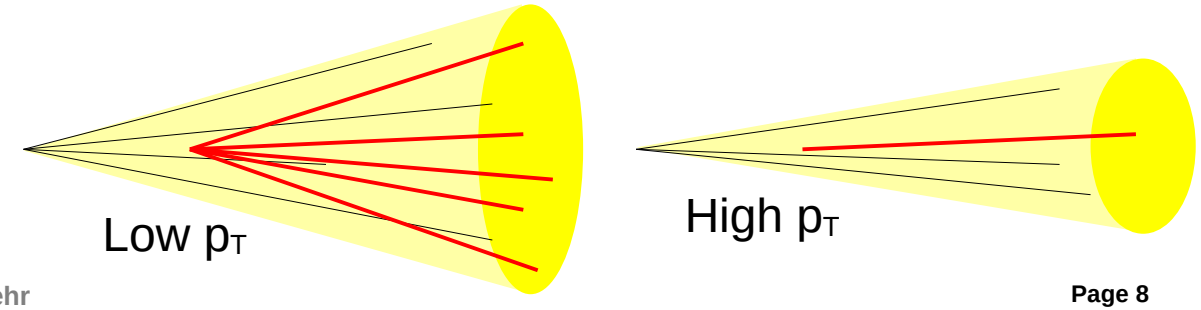



> Key challenges:

- Requires region enriched in space-like separate top quarks
- Statistically limited
  - → Sensitivity boost from full Run-3 dataset and HL-LHC
  - → Main sensitivity from l+jets channel
- Identification of hadronic polarimeter (down-type jet from *W*) in merged top-quark decays

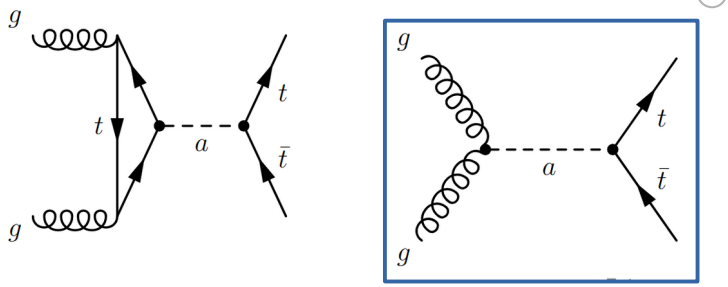
> Relevance of ITk

- Improved flavour tagging at high $p_T$ due to better tracking performance:
  - Higher IP resolution
  - Higher efficiency in dense environments due to reduced rate of cluster merging

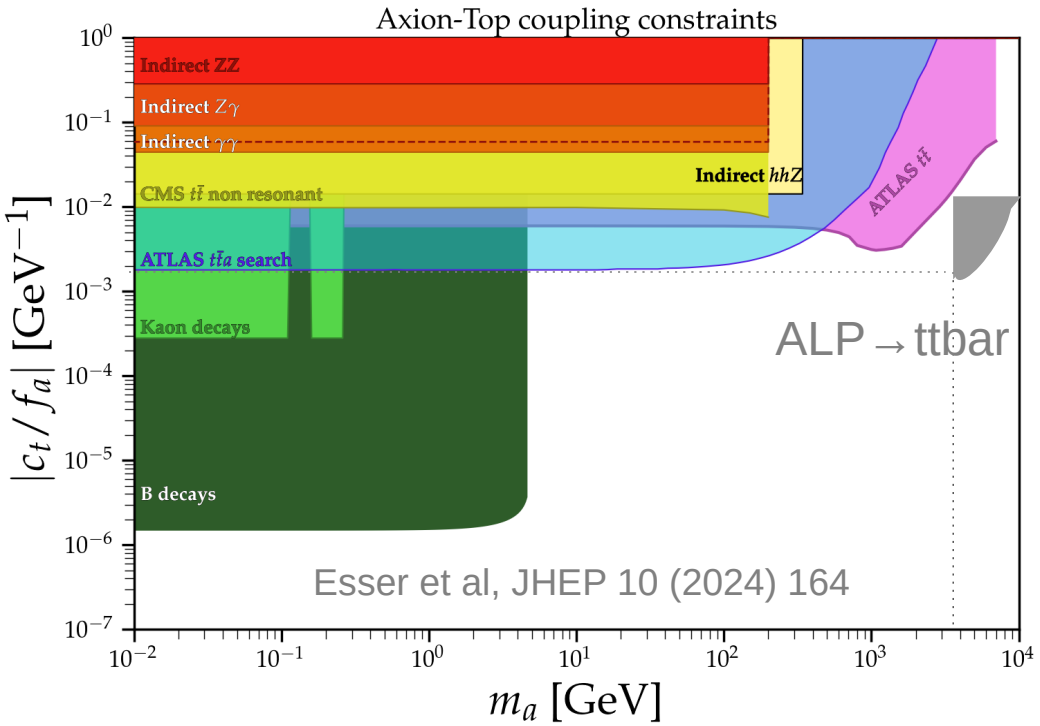


# Interference searches

- Pioneered interference searches in ATLAS
- Unique sensitivity to BSM Higgs at high masses
- **New**: explore sensitivity to axion-like particles (ALPs) at the GeV scale
  - Key difference compared to heavy Higgs bosons: direct gluon coupling!
  - Partially supported by QU-II programme
- Strong synergies with measurements
  - Need accurate ttbar modelling across full kinematic ran
  - Sensitivity enhancement from quantum variables
  - Common frameworks, CP tools, ...




Unique for ALPs!



# Thank you!