Precision QCD Measurements from ATLAS, CMS, ALICE & LHCb

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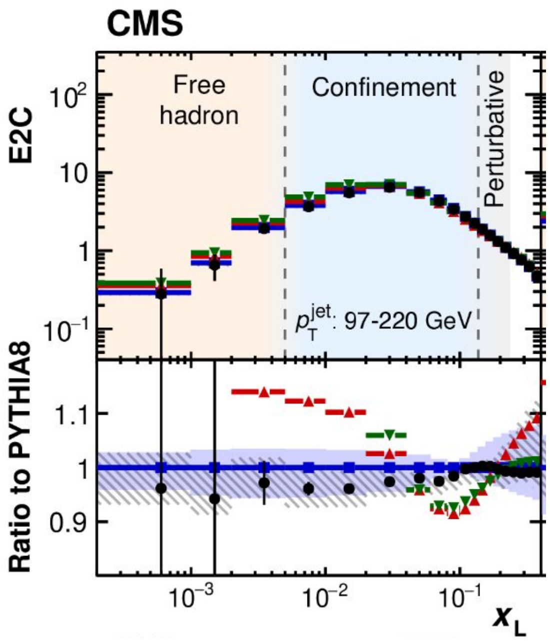
LHCP - Boston

Science and Technology Facilities Council

Introduction

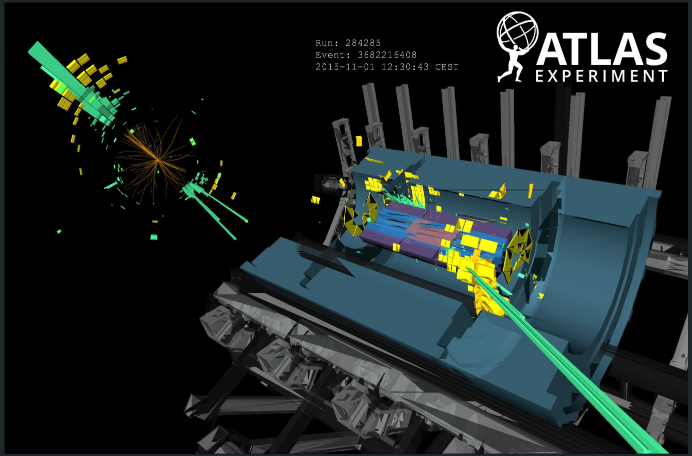
- Focus today on some **select recent results** from LHC experiments with sensitivity to the modelling of QCD.
- Starting at the perturbative energy scale of the **top and the Z**, and then working down to the **non-perturbative** domain.
- **Taster** - focus briefly on one interesting aspect of each analysis, with a recency-bias. Try and compliment the plenary & other more focused presentations.
- Measurements are all unfolded to a particle level definition, unless otherwise specified.



2402.13864

Jet substructure in boosted $t\bar{t}$ events

13 TeV pp, 140 fb^{-1}



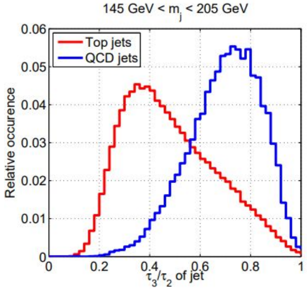
arXiv:2312.03797, submitted to PRL

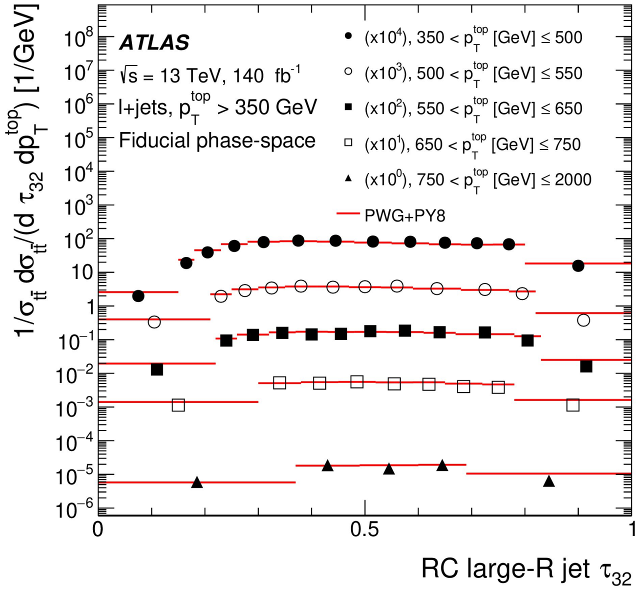
December 2023

ATLAS EXPERIMENT

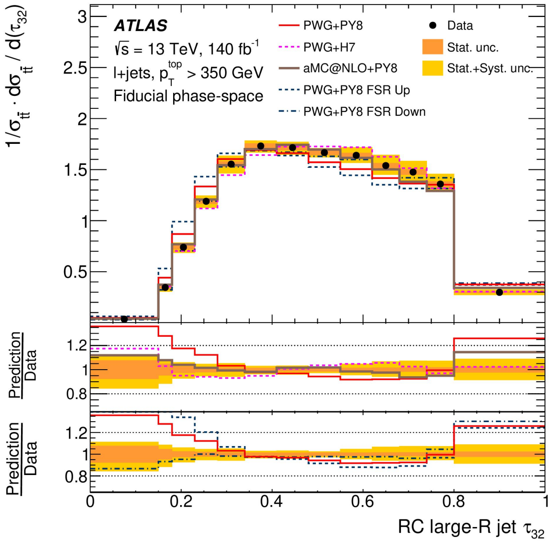
- Single leptonic decay selection events:
    - 83.0k data events vs 97.2∓3.7k expected.
    - 92∓1% signal efficiency
- Fully hadronic decay selection L-R-Jets:
    - 30.5k data vs 36.5∓1.4k expected.
    - 65∓1% signal efficiency.
- Many unfolded 1D (and 2D) correlators
    - τ_{32}: Ratio of 3-to-2 sub-jettiness variable.
- RC = trimmed large-R Re-Clustered jets, from R=0.4 jets within R=1.0 - used in the semi-lep case.

JHEP 1103:015,2011





MC: NLO ME + LO PS



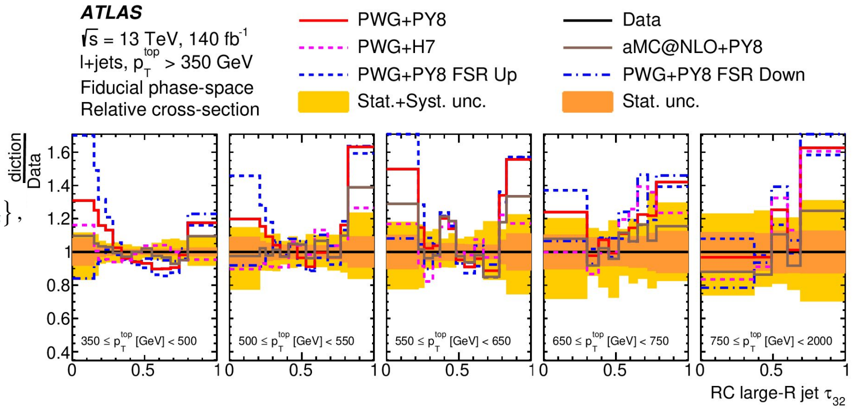
3-body nature of the top decay visible. MC predictions typically above data outside $0.4 < \tau_{32} < 0.7$

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\},$$

with $d_0 = \sum_k p_{\mathrm{T},k} R_0.$

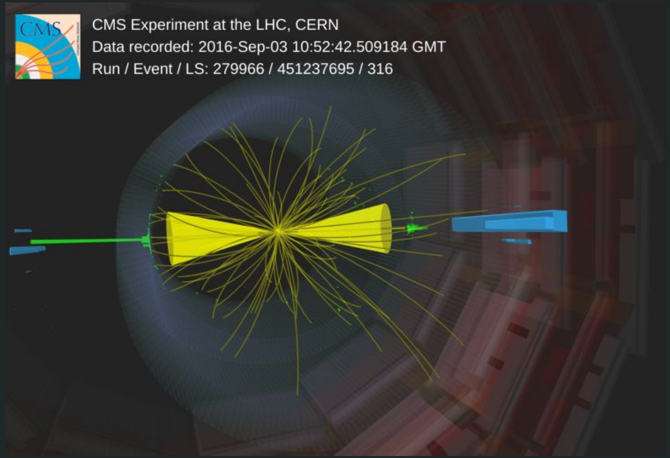
2-prong: $\tau_2 \simeq 0$

3-prong: $\tau_3 \simeq 0$



Energy correlators inside jets & determination of $\alpha_s(m_Z)$

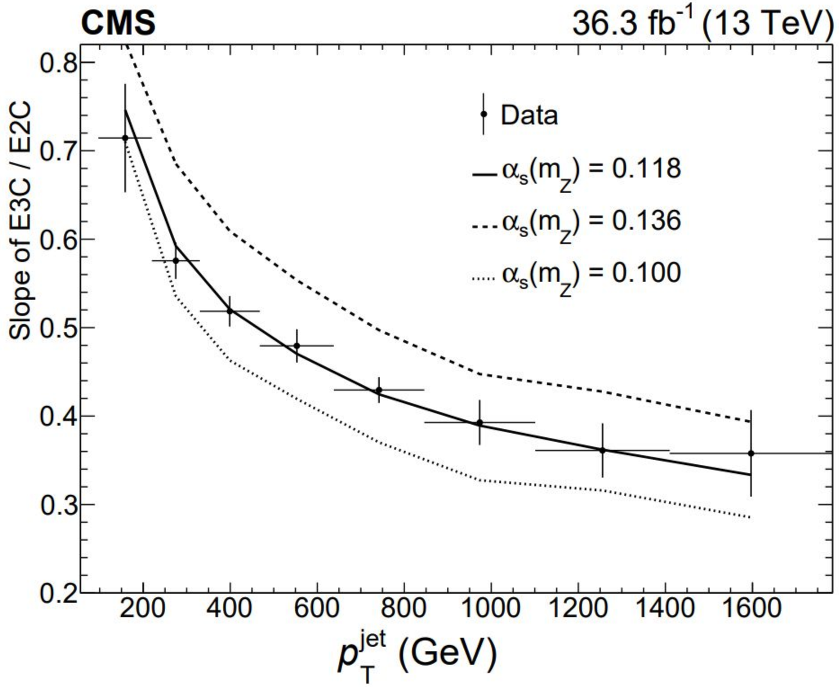
13 TeV pp, 36.3 fb^{-1}

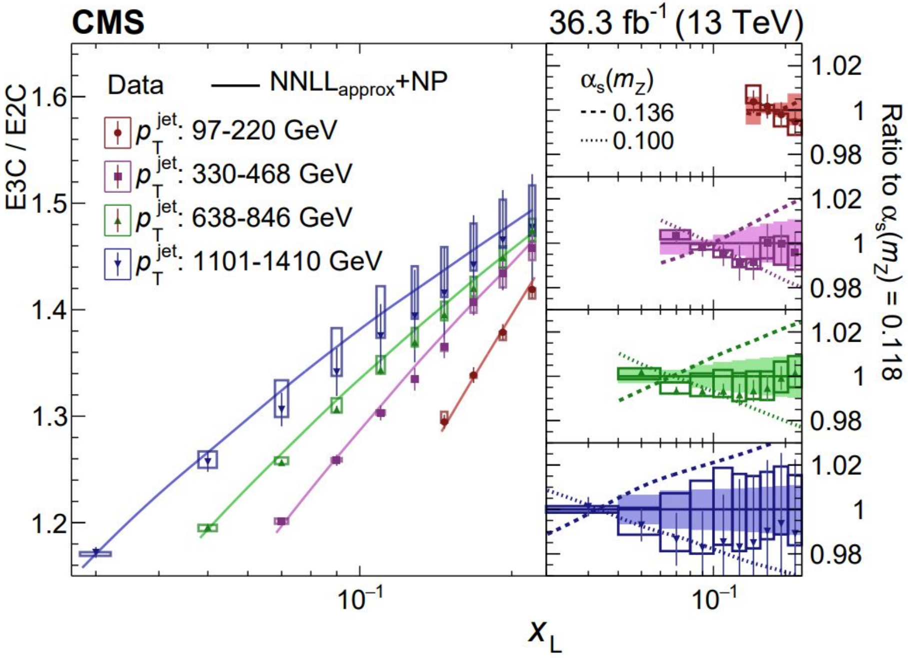


arXiv:2402.13864, submitted to PRL

February 2024

- **Two-** and **three-particle** correlators EC2, EC3 have **different dependencies on α_s** and its higher order expansion terms.
- x_L: Largest angular distance between pair (pairs from triplet) in EC2 (EC3)
- **LL approximation: EC3/EC2 ≃ linear in α_s ln x_L**





- **PDF dependence on α_s largely suppressed**!
- Shape of the ratio fitted vs jet p_T. Dominant systematics theory renormalisation scale (2.4%), jet energy scale (2.3%). Overall, $^{+3}_{-4}$% uncertainty.

Most precise α_s from jet substructure

$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$$

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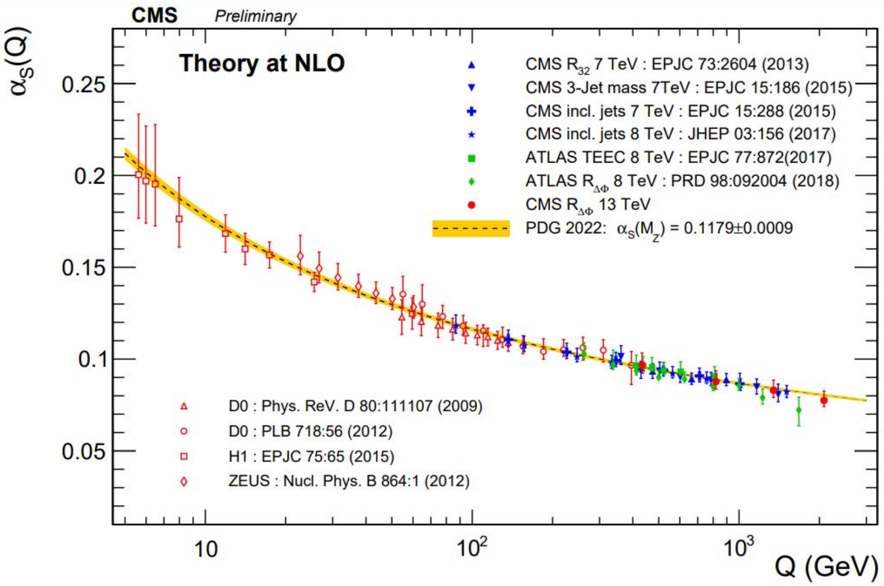
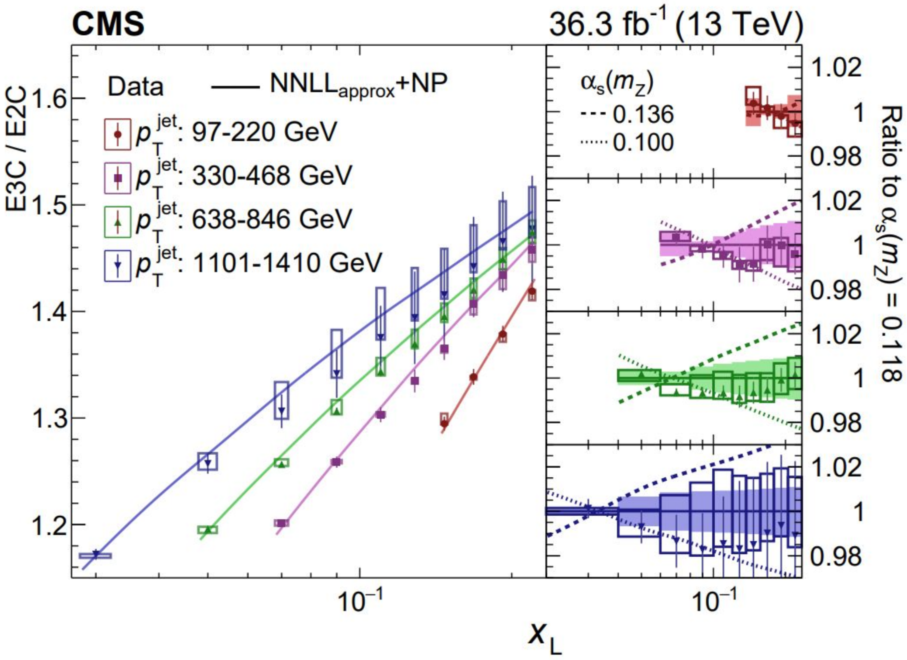


World average: 0.8%



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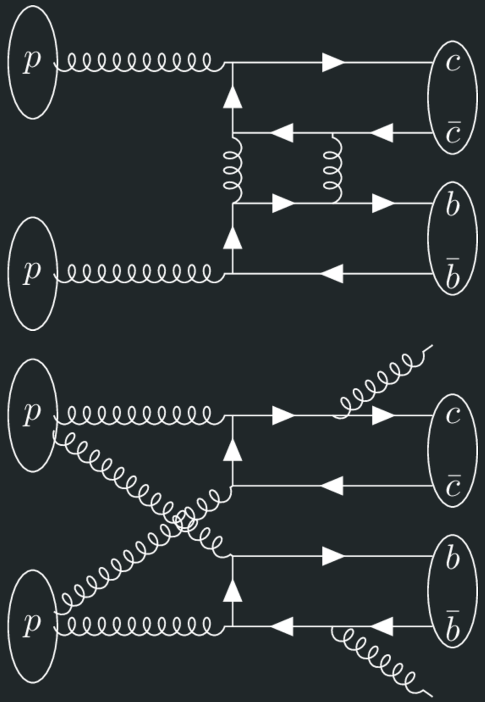
Associated J/ψ and Υ Prod & J/ψ-Pair Prod.

13 TeV pp, 4 fb^{-1} - 4.2 fb^{-1}

(*Not unfolded to particle level*)

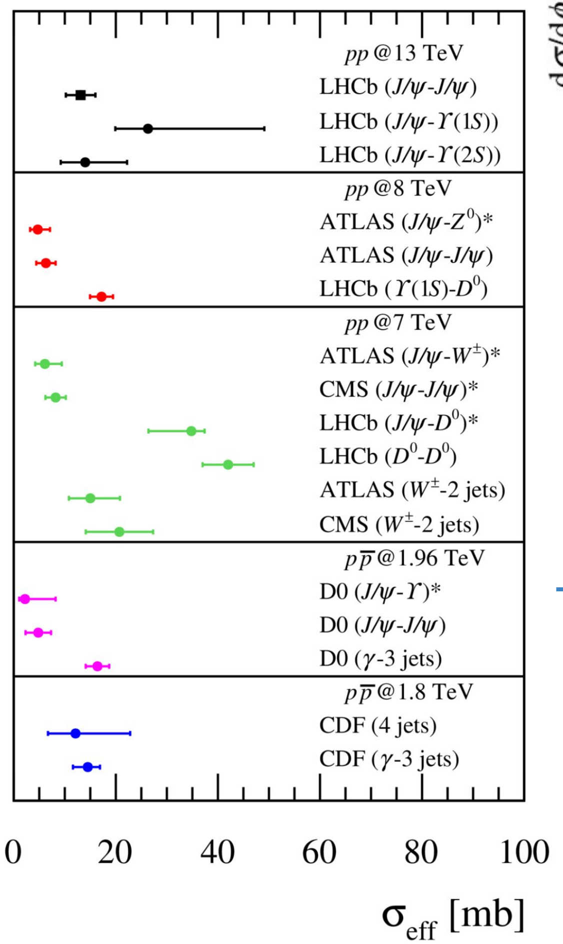


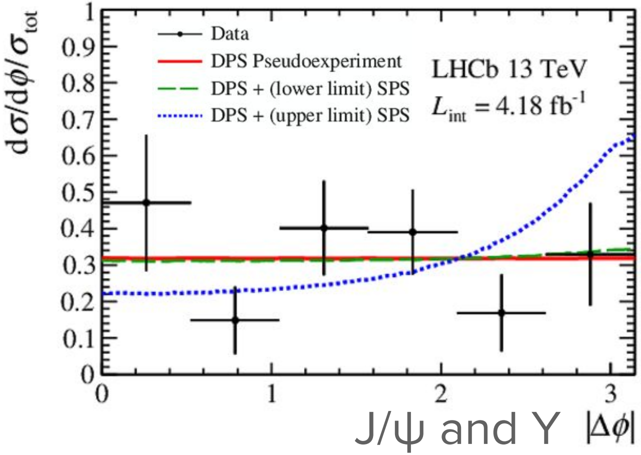
[JHEP 08 (2023) 093](#)

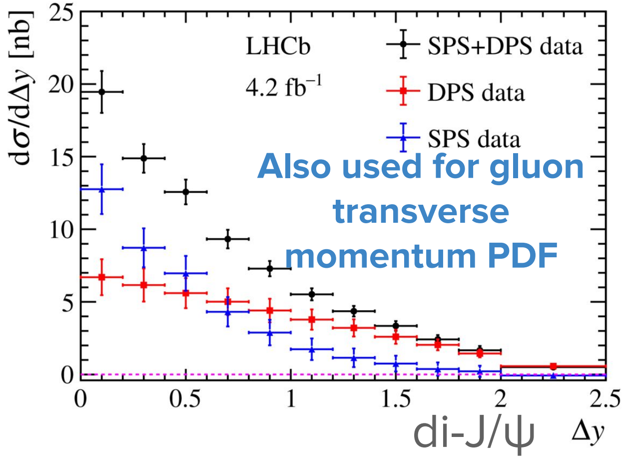
May 2023

[JHEP 03 (2024) 088](#)

November 2023







- Extraction of supposed universal σ_{eff} e.g. via: $$\sigma^{\text{DPS}}_{\text{di-}J/\psi} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma_{\text{eff}}}$$
- Data-templates for DPS from uncorrelated J/ψ
- J/ψ DPS **normalised at Δy > 1.8 where SPS probability is small**.

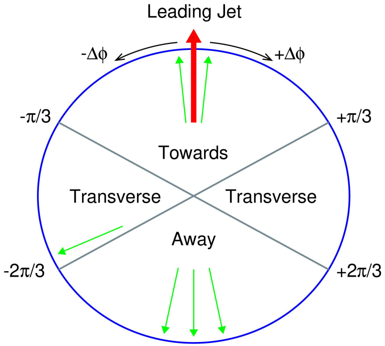
- For J/ψ-Y, extract DPS J/ψ-Y(1s) and J/ψ-Y,(2s) by subtraction of SPS 20^{+52}_{-15} and 8^{+22}_{-6} pb from the measured 113±14 and 76±22 pb.
- SPS cross-sections are adapted from the calculations with the NRQCD framework with data from other LHCb analyses.

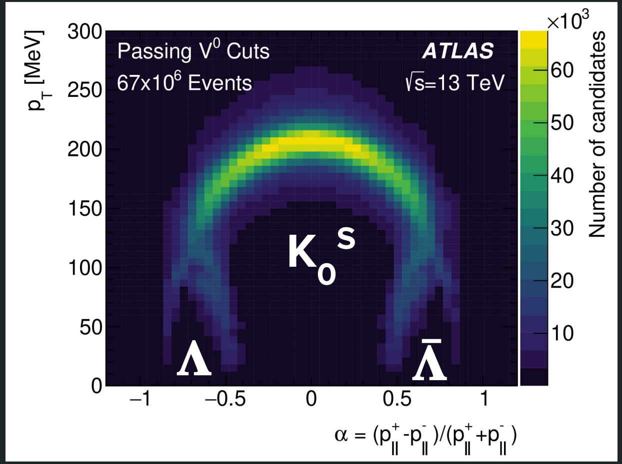
$$\sigma_{\text{eff}}(J/\psi\text{–}\Upsilon(1S)) = 26 \pm 5 \pm 2^{+22}_{-3}\,\text{mb},$$
$$\sigma_{\text{eff}}(J/\psi\text{–}\Upsilon(2S)) = 14 \pm 5 \pm 1^{+7}_{-1}\,\text{mb},$$

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{\text{DPS}}_{\text{di-}J/\psi}} = 13.1 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst})\,\text{mb},$$

Underlying Event with Strange Hadrons

13 TeV pp, 67×10^{6} Events

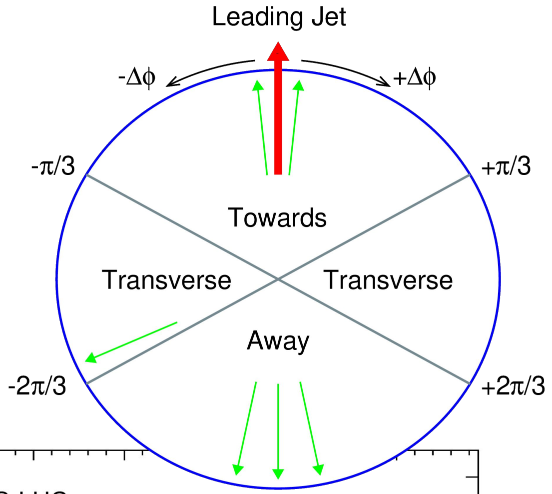


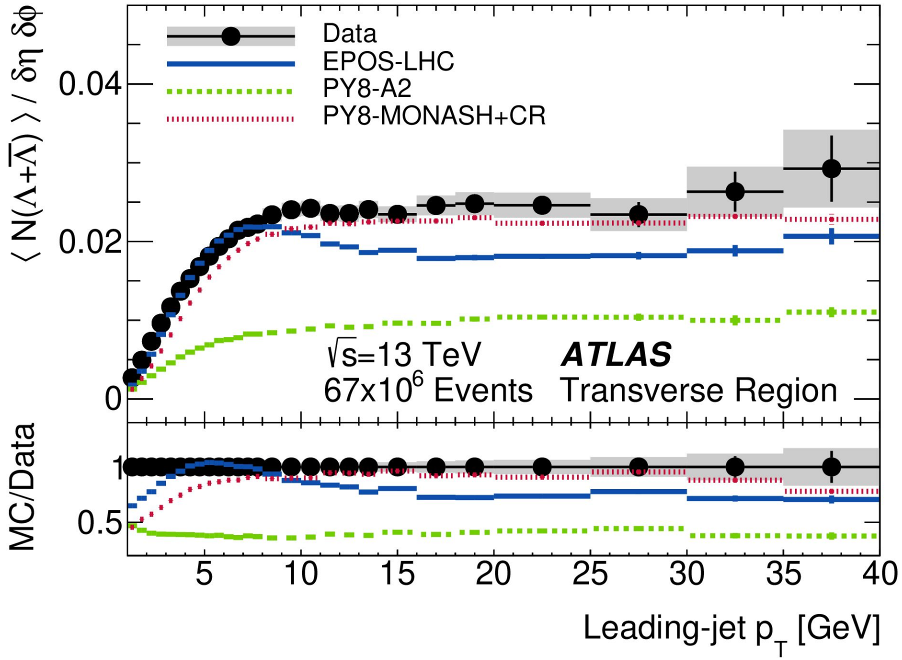


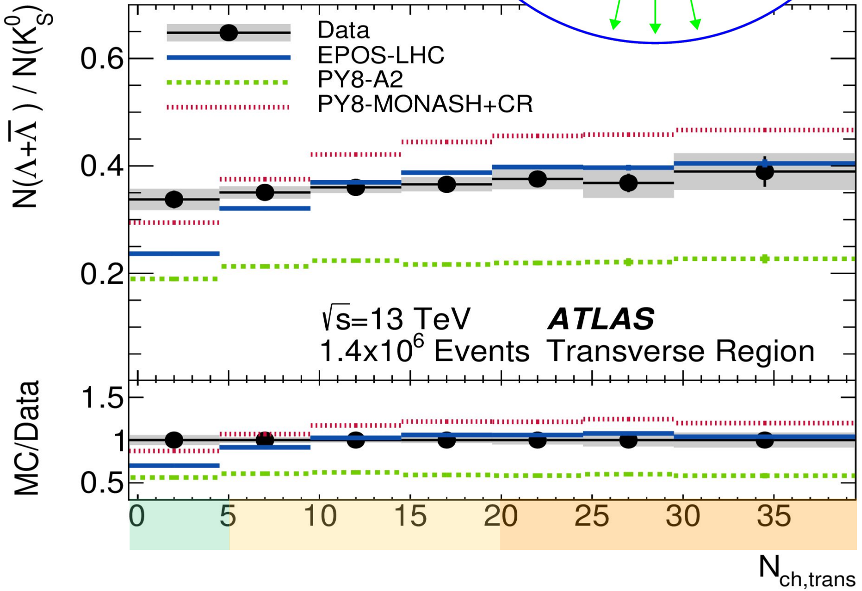
arXiv:2405.05048, submitted to EPJC

May 2024

- Underlying event in **strange hadrons (Λ^0 and K^0_S)** via displaced vertices, as a test of hadronisation.
- Mean per-event or strange-baryon to strange-meson yields.
- Harder region **10 < p_T jet < 40 GeV** investigated vs. the **number of prompt particles in the transverse region** - MPI proxy.
- Large degree of modelling variability between MCs.

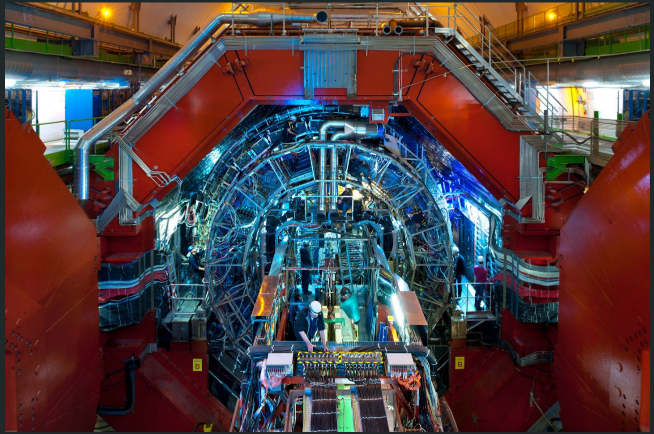






Light Flavour Production as a Function of Transverse Spherocity

13 TeV pp



arXiv:2310.10236, submitted to JHEP

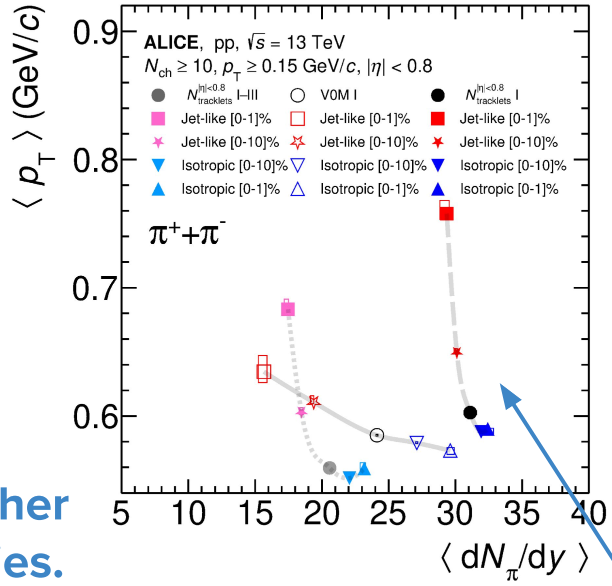
October 2023

ALICE

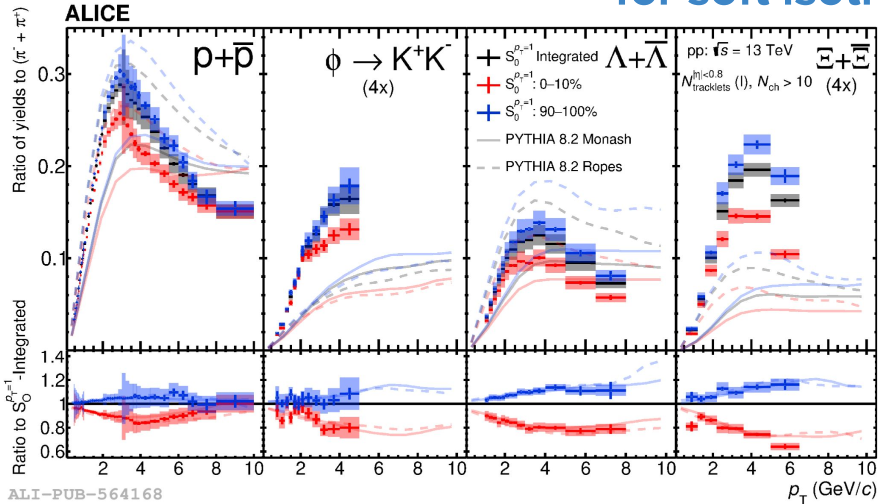
- Unweighted transverse spherocity (track p_T normalised to unity) to give similar sensitivity to charged & neutrals.

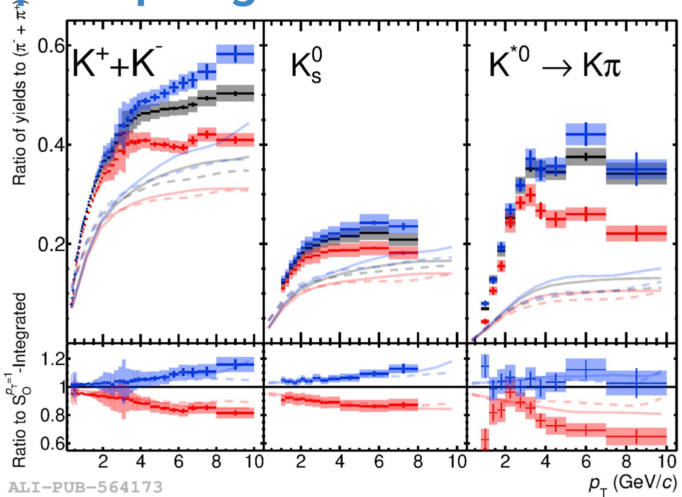
$$S_{\mathrm{O}}^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{\mathrm{T},i}} \times \hat{n}|}{N_{\mathrm{trks}}} \right)^2$$

- $\hat{n}$: unit vector which minimises S_O.
- $S_O \simeq 0$ → pencil-like. $S_O \simeq 1$ → isotropic.
- Multiplicity percentiles, 0% is the highest multiplicity
  - $N_{\mathrm{tracklets}}$ I = 0-1%, $N_{\mathrm{tracklets}}$ I-III = 0-10%.
  - V0M charge I = 0-1%



Strange particle rates higher for soft isotropic topologies.





Best hardness separator

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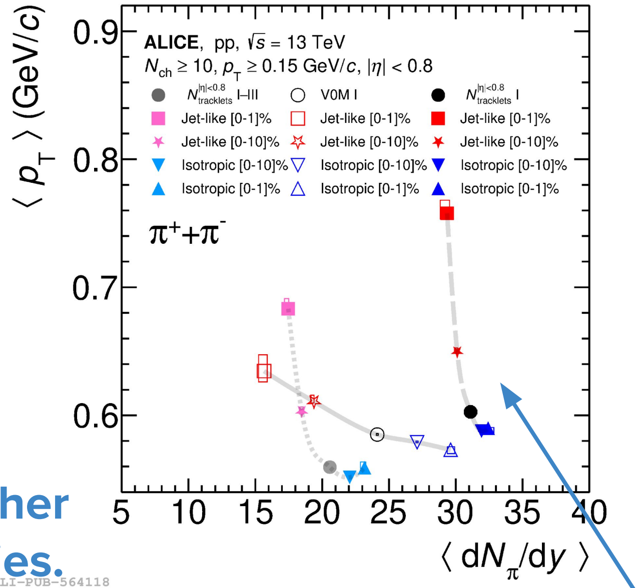

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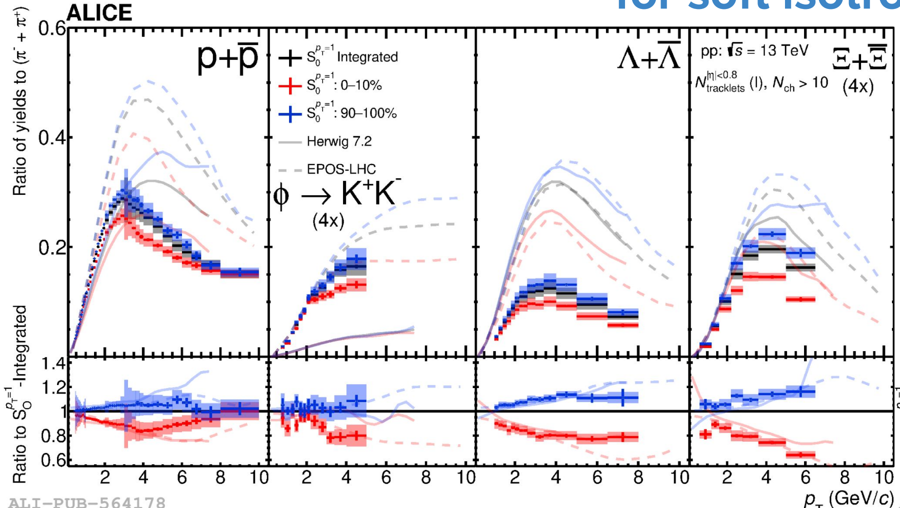
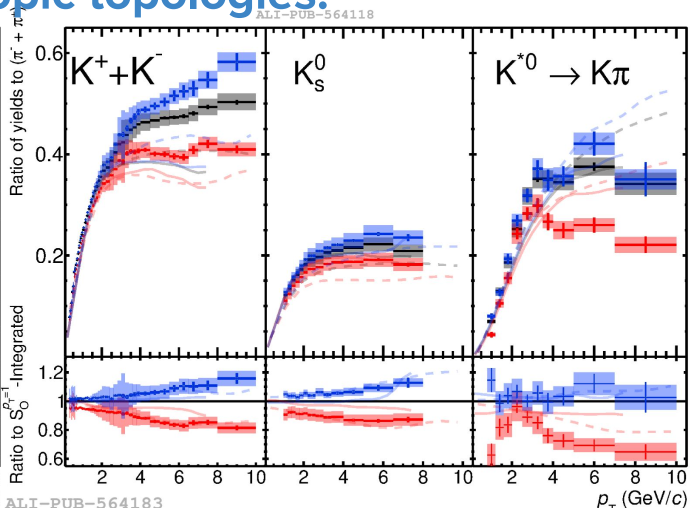




Conclusion

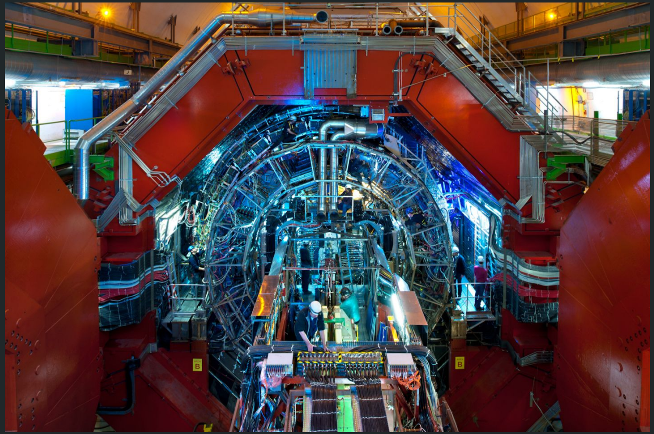
Work continues in earnest on LHC experiments to measure novel QCD observables at world-record precisions.

Sophistication of analysis methods is continuing to advance with time as the LHC experiments mature in their physics programmes.

QCD probes are investigated at all energy-scales of perturbative and non-perturbative coupling strengths.

Multiplicity Dependence of Charged Particle Intra-Jet Properties

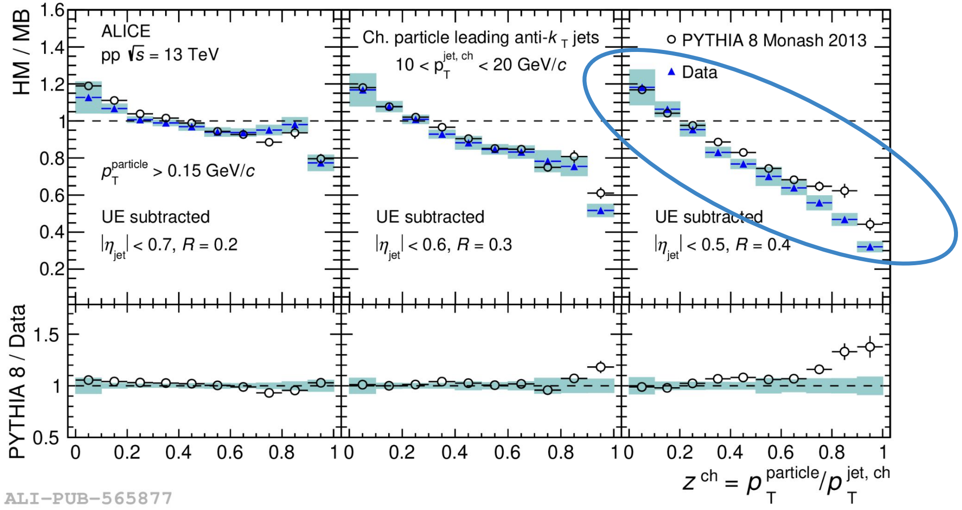
13 TeV pp, 32 nb^{-1} - 10 pb^{-1}



arXiv:2311.13322, submitted to EPJC

November 2023

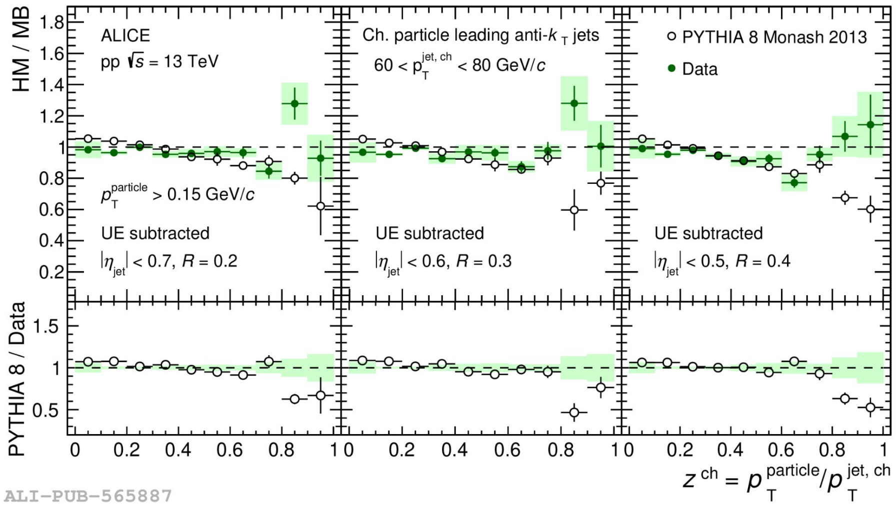
ALICE



- Intra-jet properties of charged-particle jets

$$z^{\mathrm{ch}} = \frac{p_{\mathrm{T}}^{\mathrm{particle}}}{p_{\mathrm{T}}^{\mathrm{jet,ch}}} \qquad \xi^{\mathrm{ch}} = \ln\left(\frac{1}{z^{\mathrm{ch}}}\right)$$

- For Anti-k_t jets R = 0.2, 0.3, 0.4, differential in jet p_T from 10 to 80 GeV
- Minimum-Bias (MB) and High-Multiplicity (HM) event categorisation - with V0M charge greater than 5 times the mean for the latter.



Pythia 8 qualitativly reproducing MinBias and HighMulti. for z^{ch}, ξ^{ch}. Fragmentation prob. suppressed in high z^{ch} in HighMulti. w.r.t MinBias. Most pronounced at low jet p_T and for jet radius.