ICHEP 2024 | PRAGUE

Investigation of charm-quark hadronization in proton-proton collisions with ALICE

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on behalf of the ALICE Collaboration

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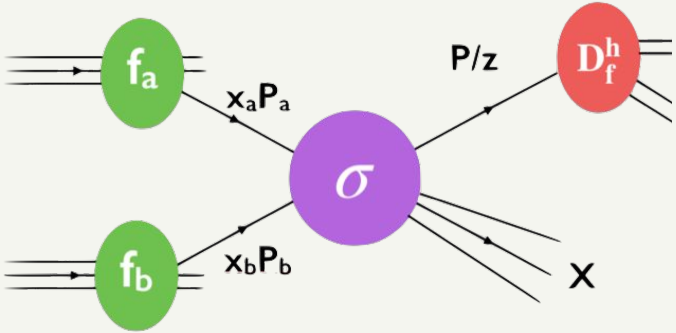
July 19th, 2024

Introduction

- The production of heavy-flavor hadrons in hadronic collisions can be described within QCD factorization:

$$d\sigma_{AB\to h} = f_{i/A}(x_i, Q^2) \otimes f_{j/B}(x_j, Q^2) \otimes d\sigma_{ij\to q\bar{q}}(x_i x_j, Q^2) \otimes D_{q\to h}(z, Q^2)$$

Parton distribution functions (PDFs) — Hard scattering cross section (pQCD) — Fragmentation function (hadronization)



heavy quarks

c $m_c \sim 1.3$ GeV/c^2

b $m_b \sim 4.2$ GeV/c^2

- **Test of perturbative QCD (pQCD)** calculations

July.19th 10AM, M.Zhang

Introduction

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$$d\sigma_{AB\to h} = \mathbf{f_{i/A}(x_i, Q^2)} \otimes \mathbf{f_{j/B}(x_j, Q^2)} \otimes d\sigma_{ij\to q\bar{q}}(\mathbf{x_i x_j}, Q^2) \otimes \mathbf{D_{q\to h}(z}, Q^2)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)

  - PDFs and hadronization are parametrized and extracted from measurements
    - PDFs e.g. deep-inelastic scattering
    - Fragmentation functions & fractions, e^+e^- and ep collisions

  - Test the **universality** of hadronization at the different collider experiments

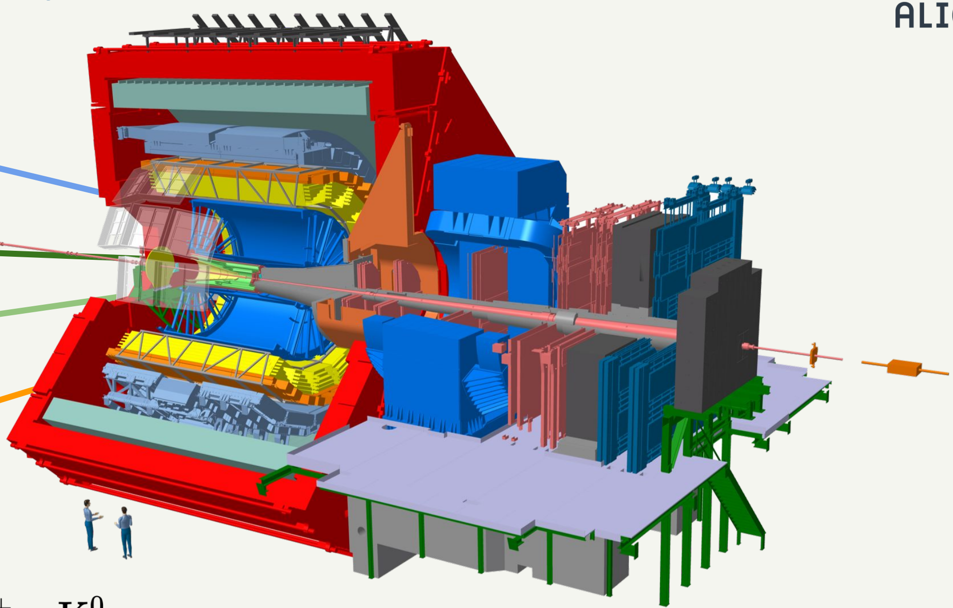
ALICE experiment in Run 2

Time Projection Chamber (TPC)
Tracking, PID via dE/dx

V0 detector
Triggering

Inner Tracking System (ITS):
Tracking and vertexing

Time-of-Flight (TOF)detector:
PID via time of flight



Measured particles
(talk here)

$\Lambda_c^+(\mathrm{udc}) \rightarrow \mathrm{pK}^-\pi^+, \mathrm{pK}_s^0$

$\Sigma_c^{0,++}(\mathrm{ddc}, \mathrm{uuc}) \rightarrow \Lambda_c^+\pi^{-,+}$

$\Xi_c^0(\mathrm{dsc}) \rightarrow \Xi^-\mathrm{e}^+\nu_\mathrm{e}, \Xi^-\pi^+$

$\Xi_c^+(\mathrm{usc}) \rightarrow \Xi^-\pi^+\pi^+$

$\Omega_c^0(\mathrm{ssc}) \rightarrow \Omega^-\pi^+, \Omega^-\mathrm{e}^+\nu_\mathrm{e}$

$\mathrm{D}^0(\bar{\mathrm{u}}\mathrm{c}) \rightarrow \mathrm{K}^-\pi^+$

$\mathrm{D}^+(\bar{\mathrm{d}}\mathrm{c}) \rightarrow \mathrm{K}^-\pi^+\pi^+$

$\mathrm{D}_s^+(\bar{\mathrm{s}}\mathrm{c}) \rightarrow \Phi\pi^+ \rightarrow \mathrm{K}^+\mathrm{K}^-\pi^+$

$\mathrm{D}^{*+}(\bar{\mathrm{d}}\mathrm{c}) \rightarrow \mathrm{D}^0\pi^+ \rightarrow \mathrm{K}^-\pi^+\pi^+$

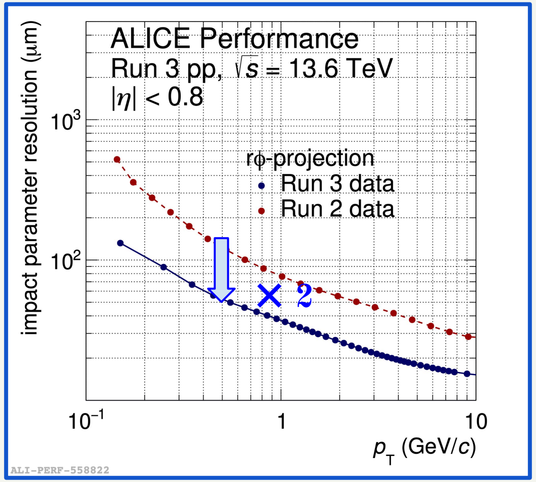
$\mathrm{J}/\psi(\bar{\mathrm{c}}\mathrm{c}) \rightarrow \mathrm{e}^+\mathrm{e}^-$

ALICE experiment in Run 3

ALICE

Run 3 upgrades:

- Upgraded **ITS** detector
  Gas Electron Multipliers (GEMs) in **TPC** readout
- Data acquisition in continuous readout mode
- New Fast Interaction Trigger (**FIT**) trigger
- Muon Forward Tracker(**MFT**) $2.5 < \eta < 3.6$



July 18th, 9:42AM, F.Schlepper
July 18th, 10:45AM, J.Liu
July 18th, 5:36PM, G.Gioachin
July 19th, 8:48 AM, Y.Melikyan
July 20th, 4:45PM, G.Batigne

New entries for the measured particles

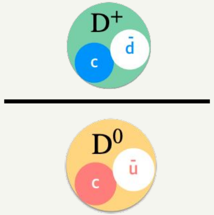
(talk here)

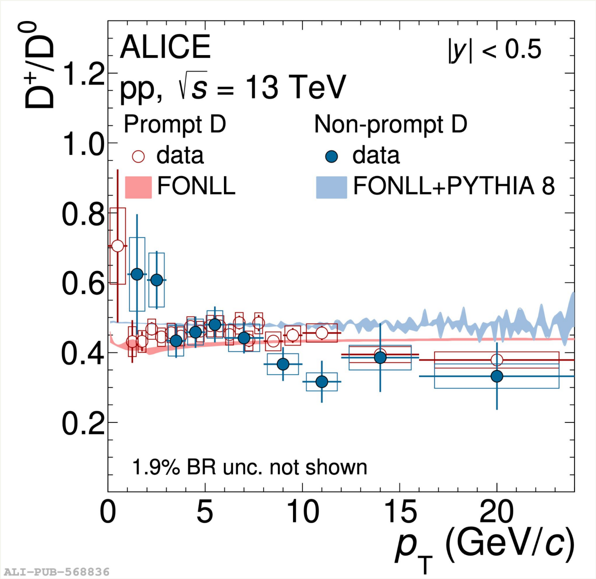
$$\mathrm{D}^+ \rightarrow \phi\pi^+ \rightarrow \mathrm{K}^+\mathrm{K}^-\pi^+$$

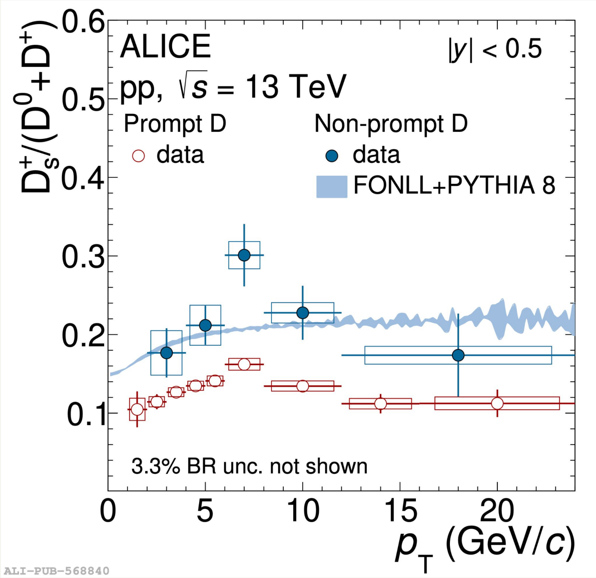
$$\Sigma_c^{0,++}(2520) \rightarrow \Lambda_c^+\pi^{+,-} \rightarrow \mathrm{pK}^-\pi^+\pi^{+,-}$$

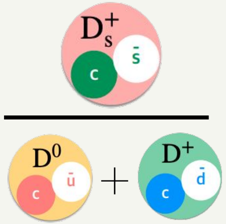
D-meson production in pp collisions

- **Yield ratios are sensitive to the hadronization mechanism**
  - Meson-to-meson ratios in agreement with e^+e^- and ep results and with models









JHEP 10 (2022) 137
JHEP 12 (2023) 086
arxiv:2402.16417

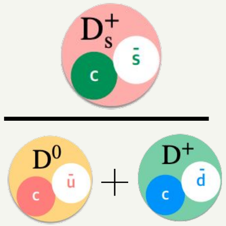
Prompt D meson: from charm-quark fragmentation or the decays of excited open charm states

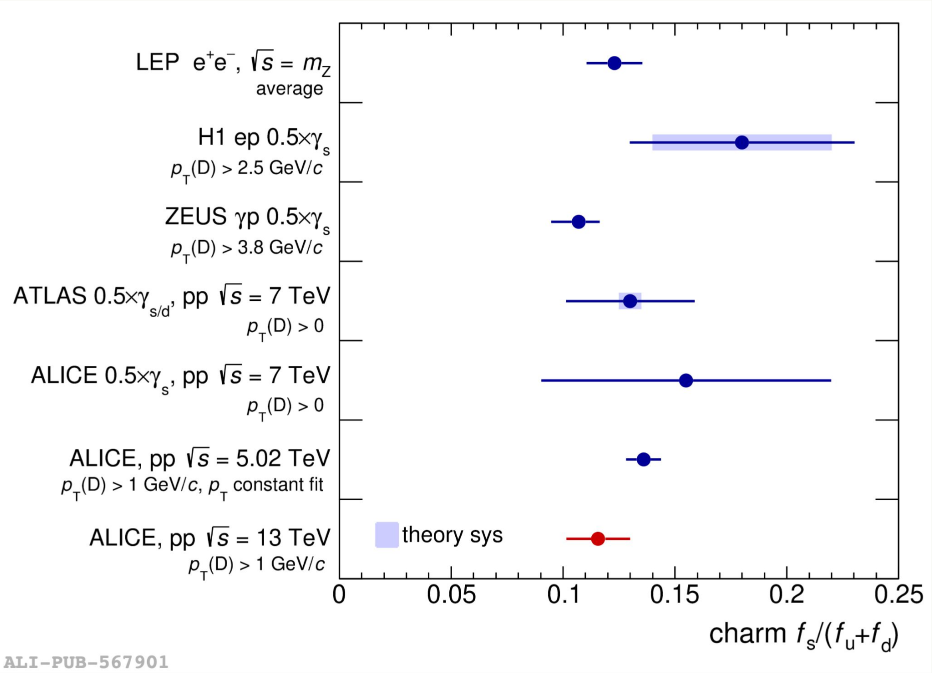
Non-prompt D meson: coming from beauty-hadron decays

Run 2 results

D-meson production in pp collisions

- Results are **compatible** with the values measured in e^+e^- collisions





- No significant collision system and energy dependence of charm quark fragmentation fraction ratios into strange and non-strange D mesons

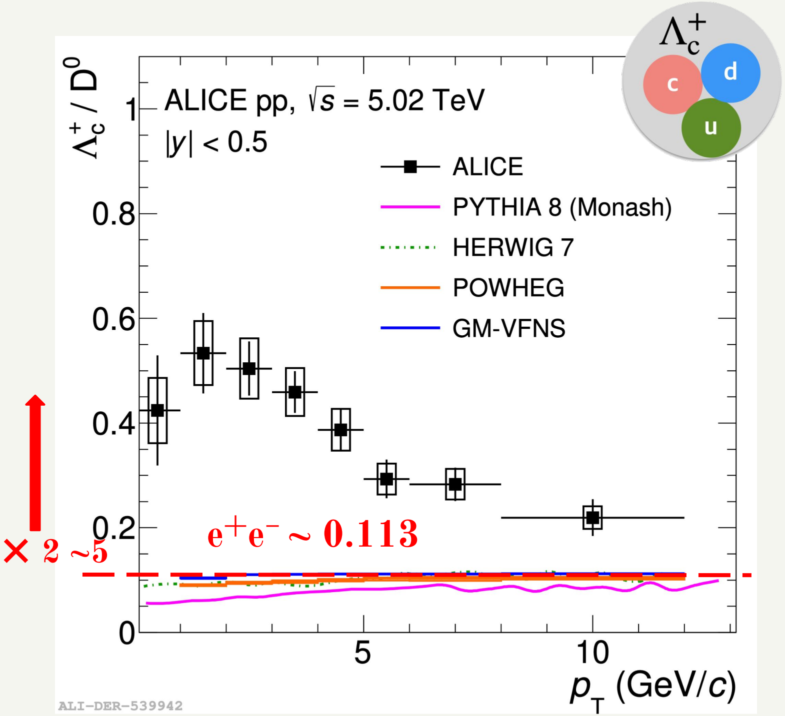
Indicates no modification of the hadronization of charm quarks into mesons!

JHEP 12 (2023) 086
arxiv:2402.16417

Run 2 results

Story for charm baryons

- **HF-baryon puzzle** at the LHC
  - Disagreement from the results of the $e^{+}e^{-}$ collisions

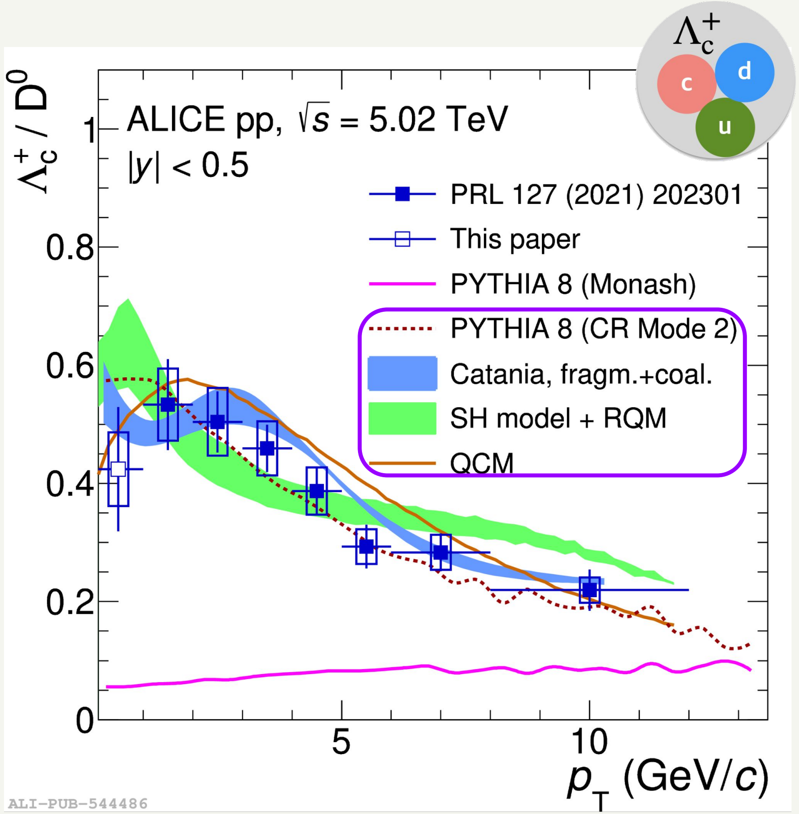


- Strong p_T dependence
- **Underestimated** by PYTHIA 8 Monash
  - standard Lund fragmentation models with fragmentation functions tuned on $e^{+}e^{-}$ data

Ratio significantly higher w.r.t. $e^{+}e^{-}$ and ep collisions

Run 2 results

Λ_c^+/D^0 in pp collisions



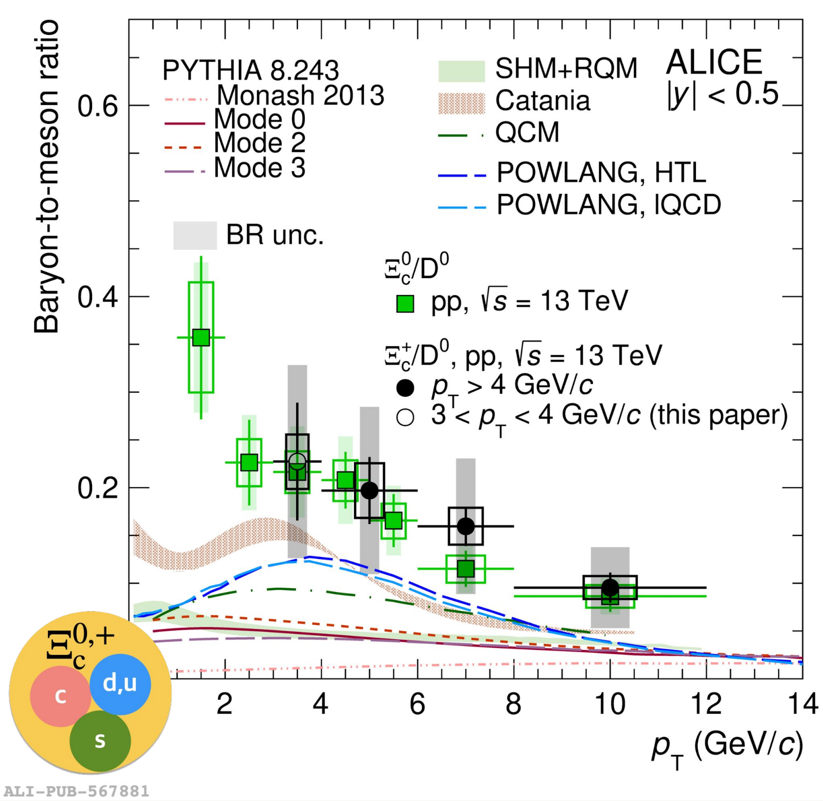
Statistical hadronization model (SHM)
Relativistic quark model (RQM)

PRC 107 (2023) 064901

- Strong p_T dependence
- **Underestimated** by PYTHIA 8 Monash
  - standard Lund fragmentation models with fragmentation functions tuned on e^+e^- data
- **Qualitatively described** by models
  - PYTHIA 8 CR Mode 2
    - Include additional junctions, increase baryon production
  - Catania
    - Hadronization via fragmentation and coalescence
  - SHM + RQM
    - Feed-down from higher-mass charm baryons
  - Quark-recombination model (QCM)
    - Recombination of charm and light quarks with same velocity

Run 2 results

$\Xi_c^{0,+}/D^0$ in pp collisions



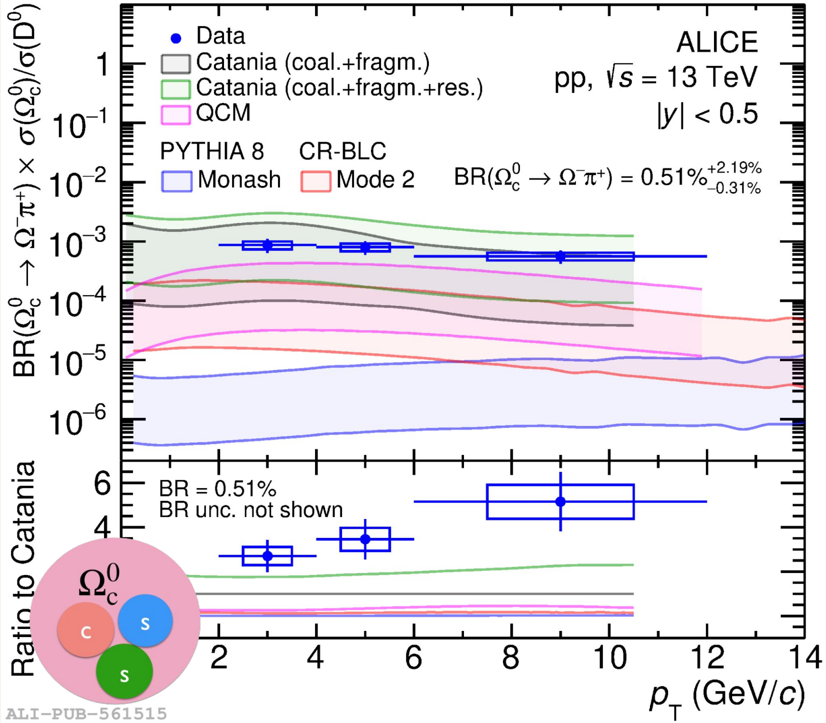
JEHP 12 (2023) 086

Charm-strange baryon puzzle at the LHC

- All models **underestimate** the data
  - Much larger enhancement than for non-strange baryons?
- Catania model describes best the data
  - Related to the QGP in small systems?

Run 2 results

Ω_c^0/D^0 in pp collisions



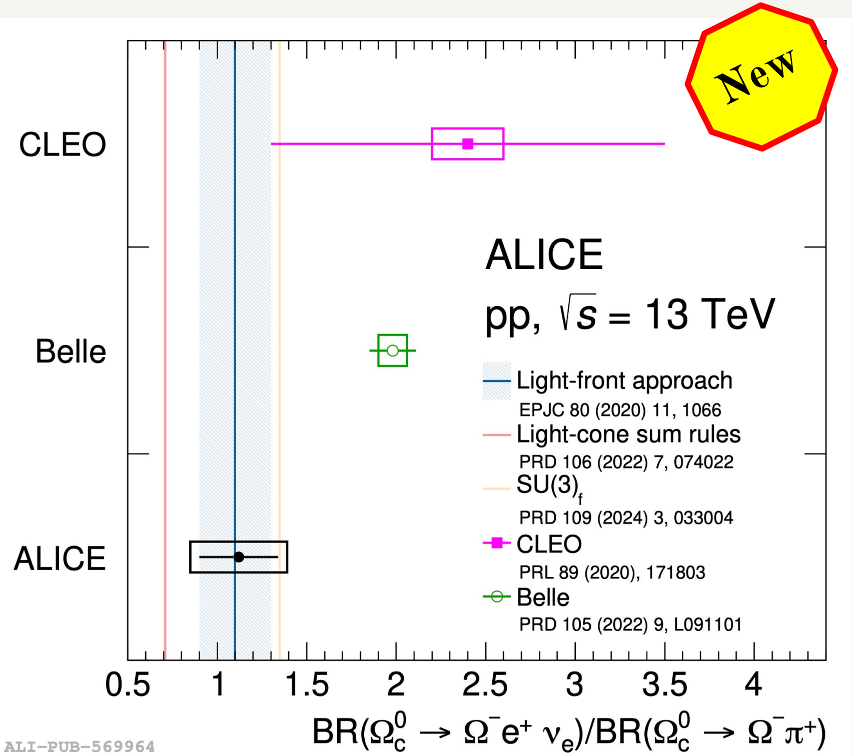
- No absolute branching fraction for $\Omega_c^0 \to \Omega^-\pi^+$
- The p_T trend of baryon-to-meson ratio is similar as other baryon results
- Theoretical value $BR(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\%$ used, which limits the conclusions

Branching fraction constraints needed !
→ Input to understand charm baryon production

PLB 846 (2023) 137625
EPJC 80 (2022) 1066

Run 2 results

Ω_c^0 branching ratios

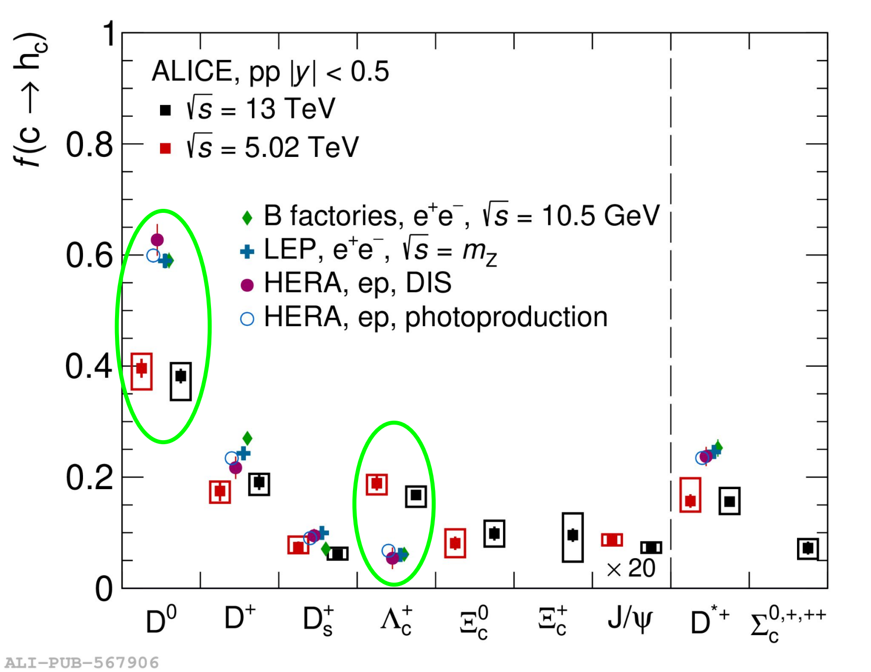


- Our new result for the BR:
  - **1.12 ± 0.22(stat.) ± 0.27(syst.)**
- Within 2.3σ of Belle measurement
- **Belle**
  - 1.98 ± 0.13(stat.) ± 0.08(syst.)
- In agreement with theory predictions

arxiv: 2404.17272, accepted by PRD

Run 2 results

Charm-quark $f(c \rightarrow h_c)$ in pp collisions



Sum of prompt D^0, D^+, D_s^+, Λ_c^+, $\Xi_c^{0,+}$, J/Ψ production cross section

- $f(c\rightarrow \Lambda_c^+)$ larger than e^+e^-, e^-p by $\times\sim 3$
- $f(c\rightarrow D^0)$ lower than e^+e^-, e^-p by $\times\sim 1.5$
- **No significant energy dependence in pp collisions**

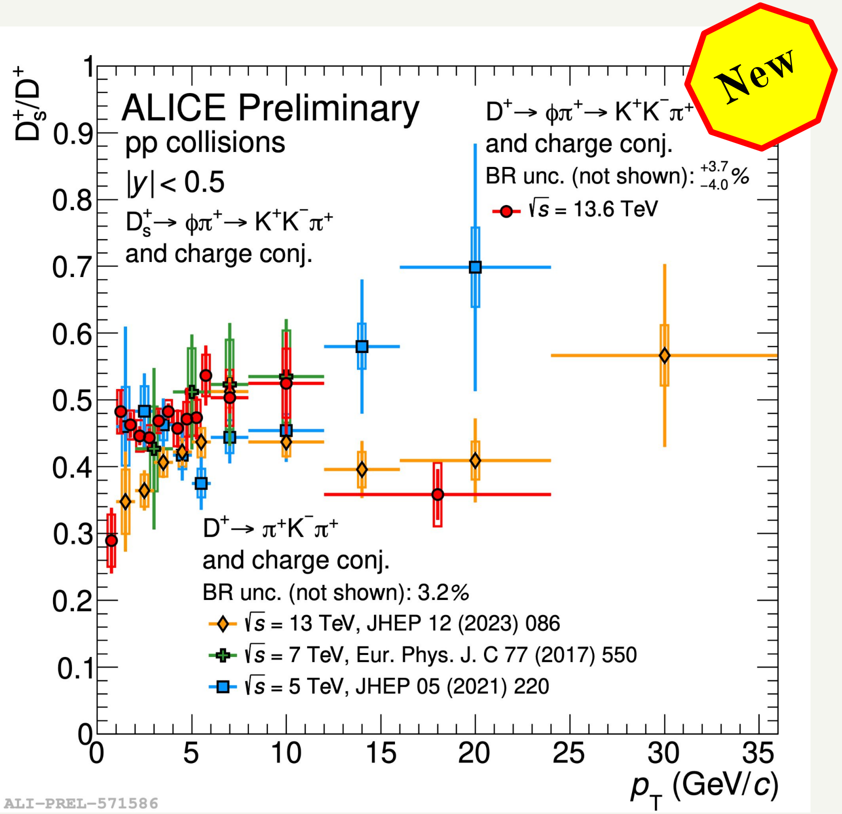
Baryon enhancement at the LHC

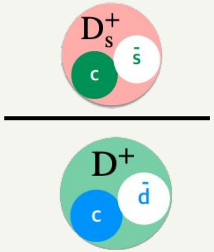
- Observation of different fragmentation fractions at the LHC with respect to e^+e^-, e^-p
- Modification of hadronization is needed !

JHEP 12 (2023) 086

Run 2 results

New results from Run 3

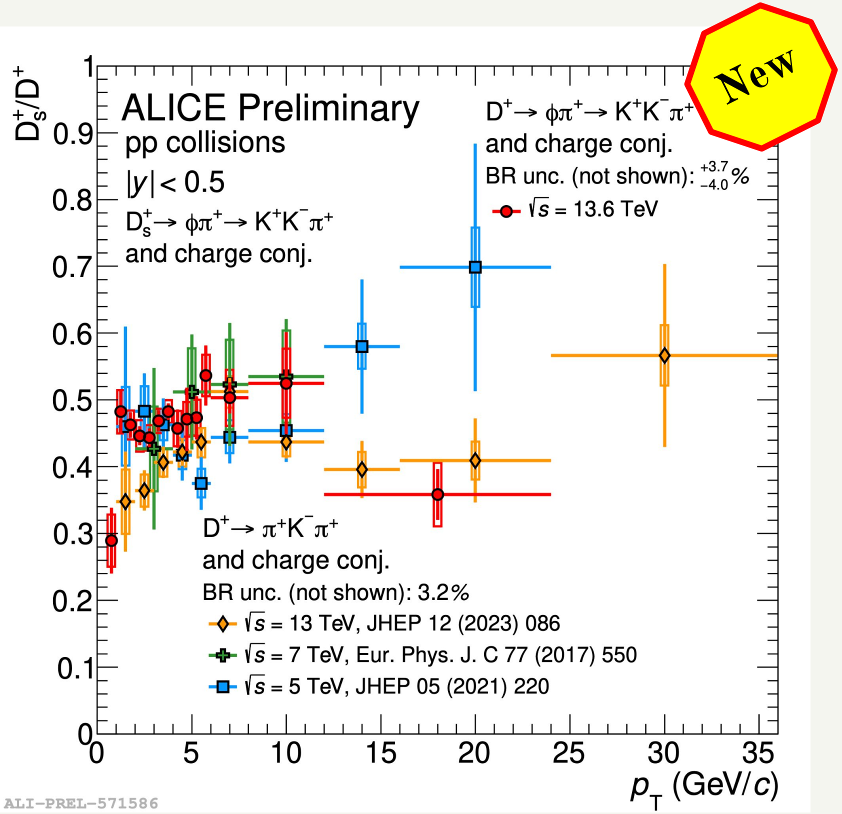


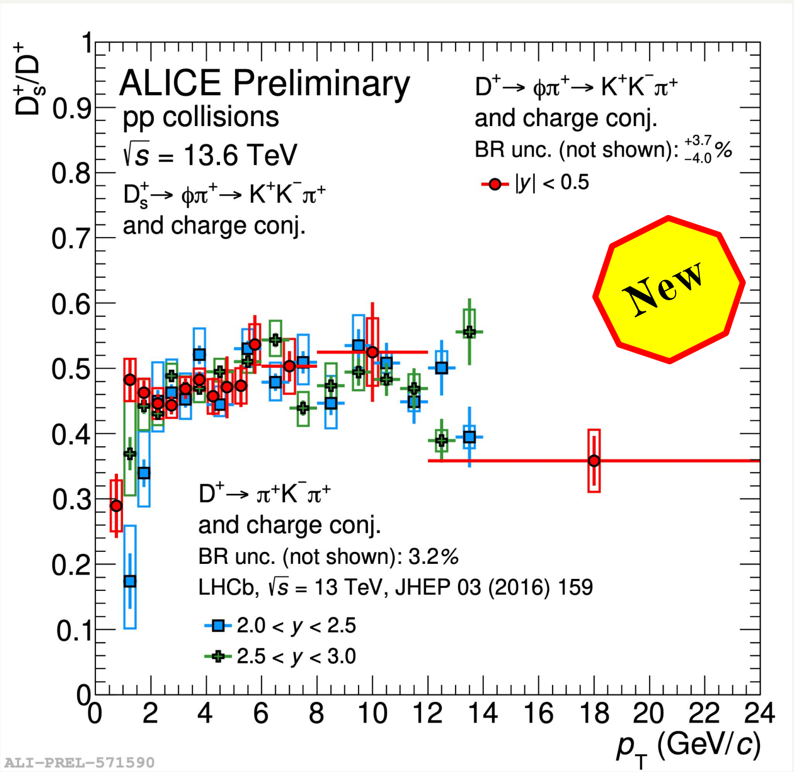


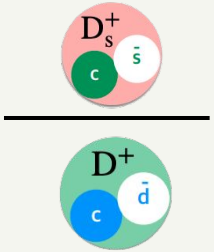
- **First** measurement of prompt D_s^+/D^+ ratio in **pp** collisions at **13.6 TeV**
  - An improvement in granularity by a factor of 2 for $1 < p_T < 6$ GeV/c
  - Down to $p_T = 0.5$ GeV/c

Run 3 results

New results from Run 3



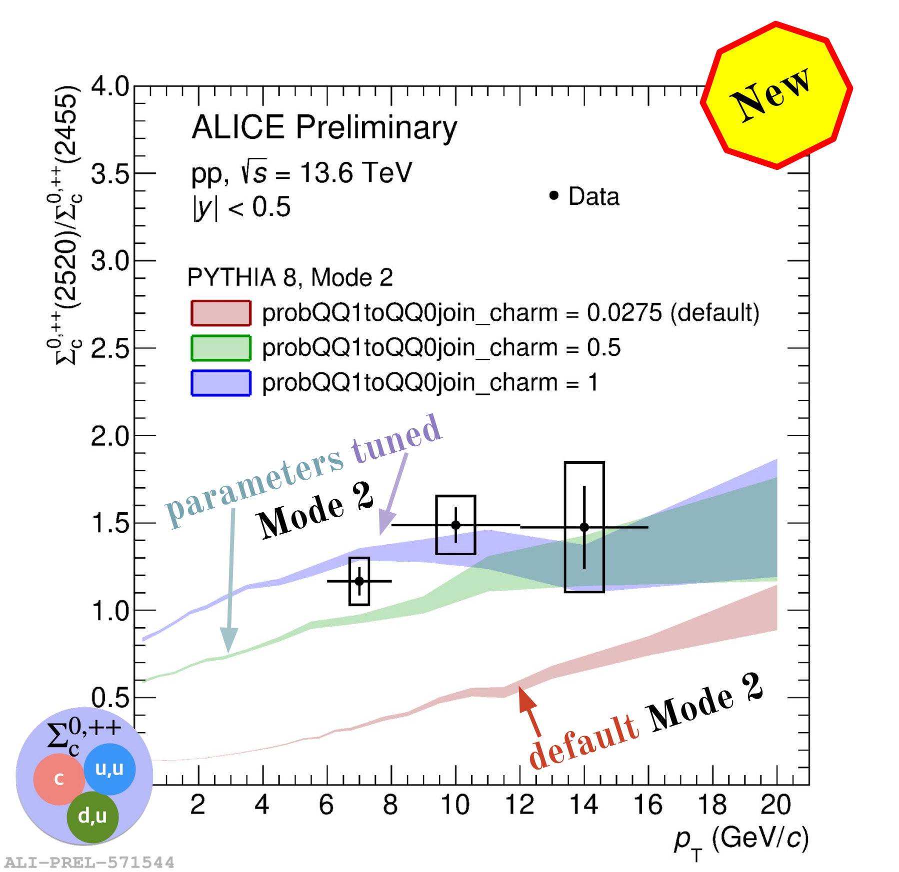




- **No** significant energy and rapidity dependence observed

Run 3 results

New results from Run 3



- **First time for the baryon resonance** $\Sigma_c^{0,++}$ **(2520)** measurement at the LHC
  - Add further inputs to constraint hadronization
- **New models** with tuned parameters on PYTHIA 8 Mode 2 **can catch the data**
  - Modified parameters related to amount of suppression for heavy diquark spin 1 state w.r.t spin 0

Constraint power for model !

Run 3 results

Summary and outlook

- Charm-hadron measurements with **Run 2** data
  - Charm meson: in agreement with model calculations
  - Charm baryon: significantly enhanced production in pp collisions wrt leptonic collisions
- **Charm-quark hadronization is not universal across colliding systems**

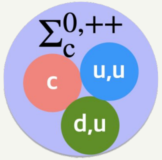
Stay Tuned!

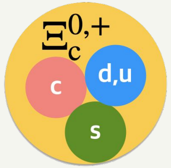
- Charm-hadron measurements with **Run 3** data
  - More precise studies with an extended observables in Run 2
  - More differential measurement and extended p_{T} reach
- **Better constraints** to theoretical models implementing different hadronization mechanisms

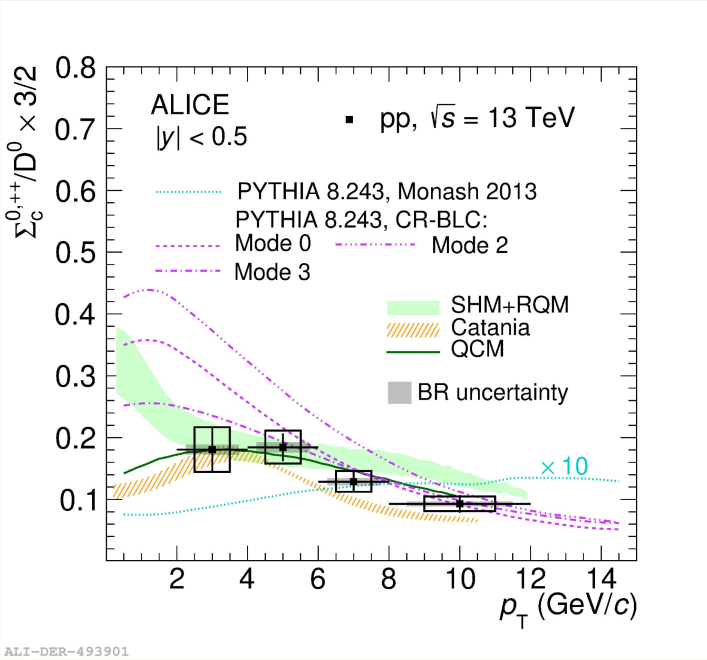
Thanks for your attention 😊

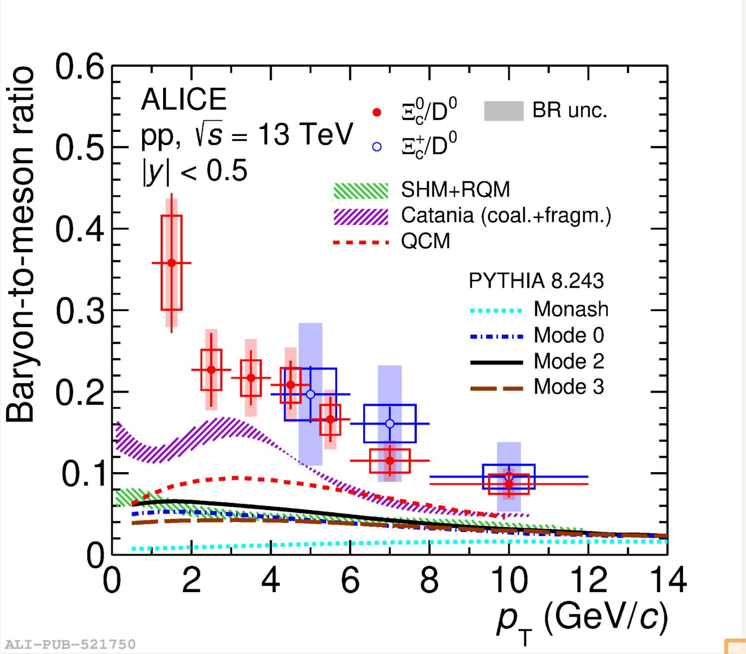
ADDITIONAL SLIDES

Charm baryon-to-meson yield ratios





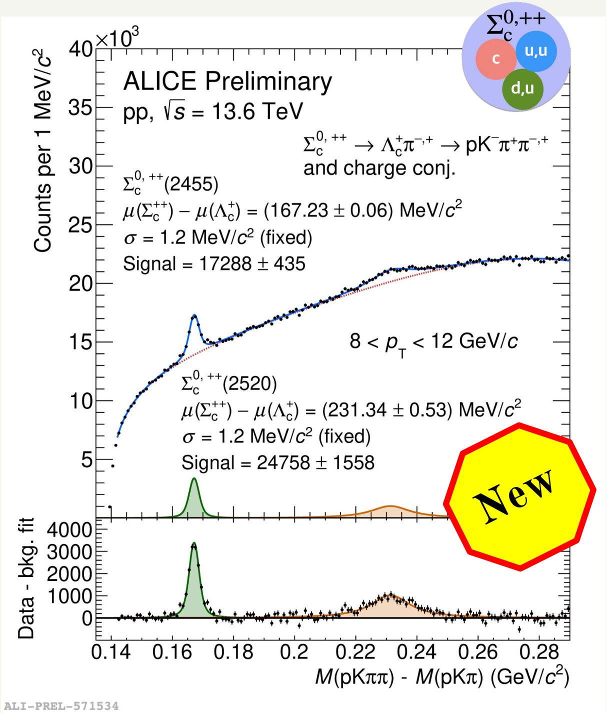


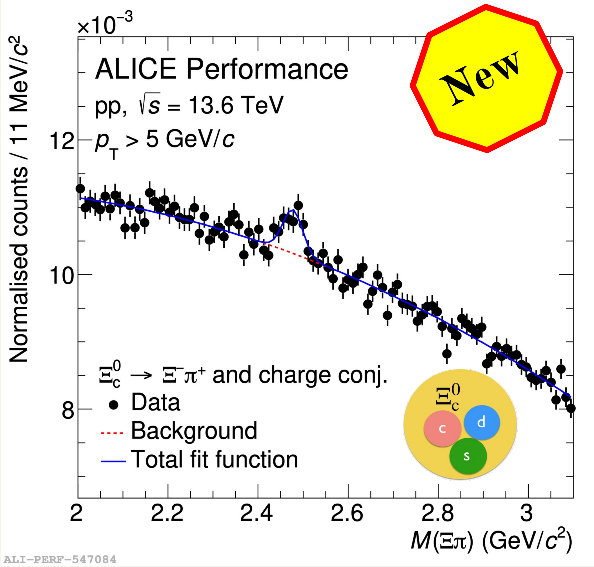


Run 2 results

ALICE experiment in Run 3

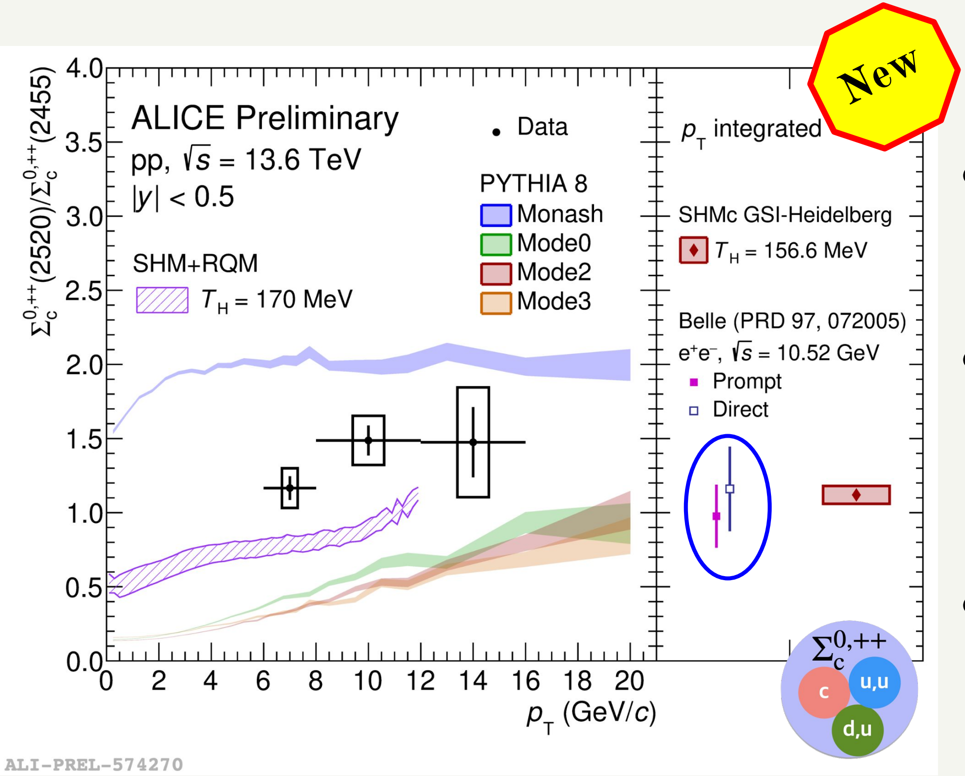
- Large data samples thanks to TPC continuous readout
- Improved impact parameter resolution





Run 3 results

New results from Run 3



- **First time for the baryon resonance** $\Sigma_c^{0,++}$ (2520) measurement at the LHC
- The two $\Sigma_c^{0,++}$ states ratios are consistent between **e+e-** collisions and **pp** collisions within uncertainties
- Models fail to describe the p_T-differential results

Run 3 results