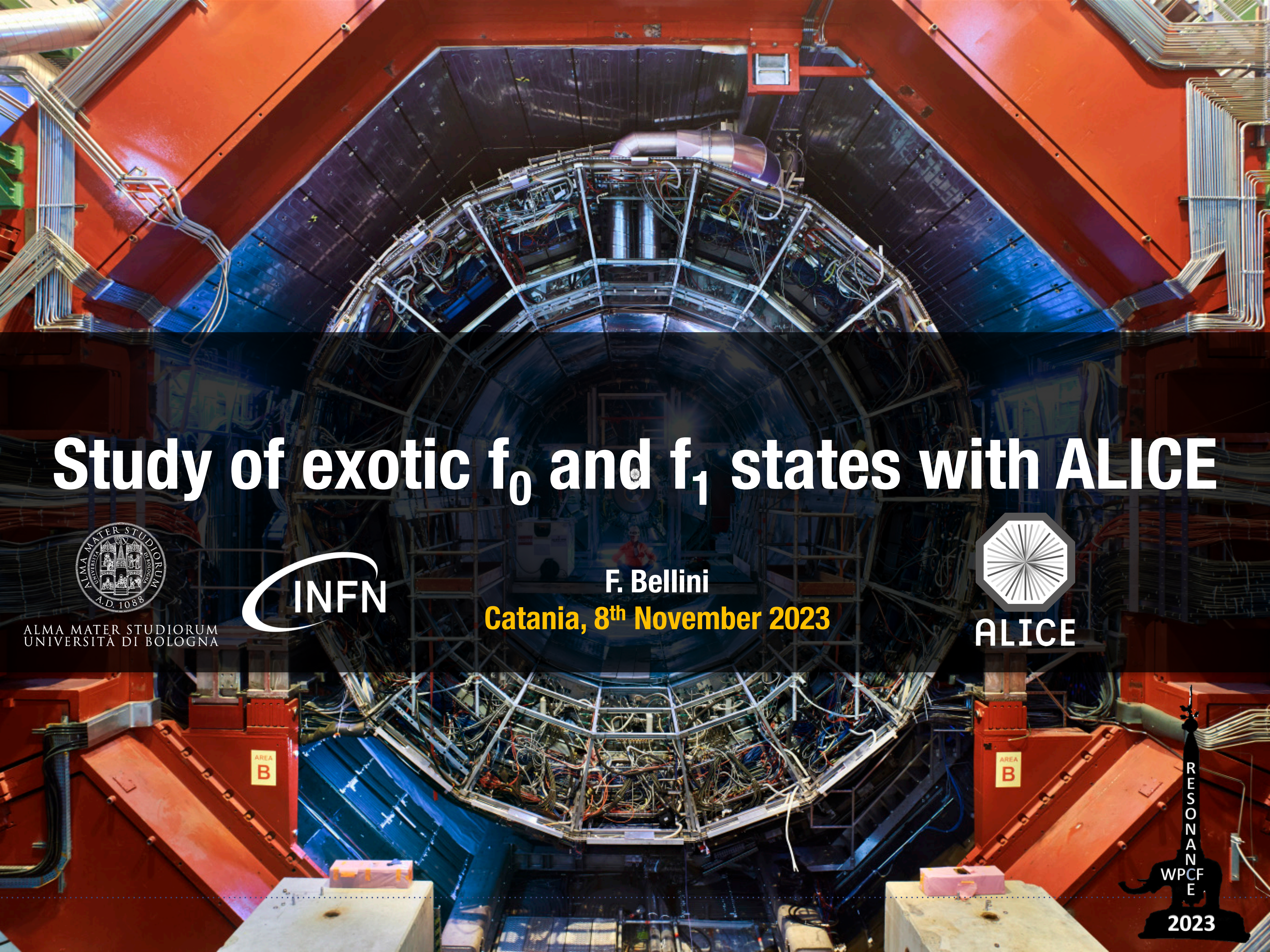


Study of exotic f_0 and f_1 states with ALICE

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN

F. Bellini

Catania, 8th November 2023

ALICE

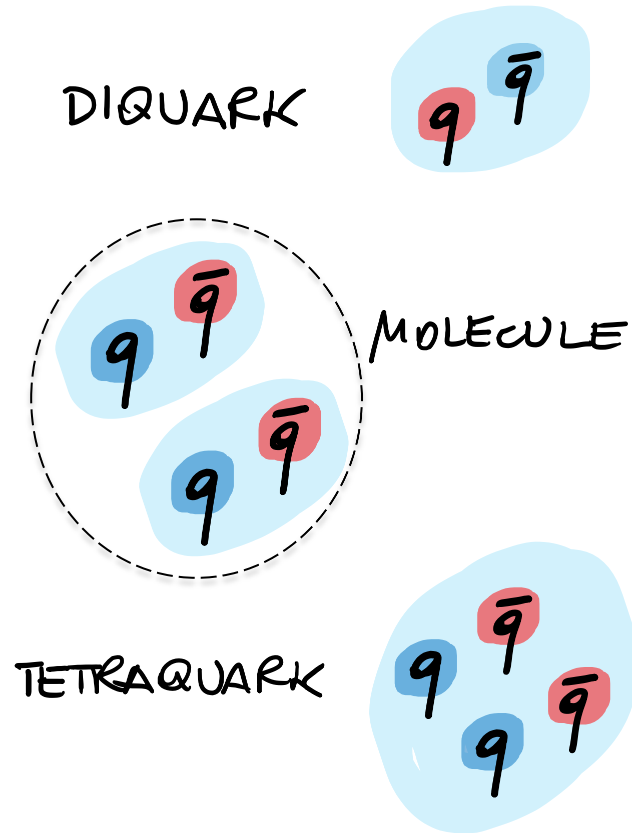
RESONANCE WPCF 2023

Exotic hadrons in the light-flavour sector

Meson = color singlet state of a $q\bar{q}$ pair with u, d, or s grouped into a flavor multiplet of SU(3)
[M. Gell-Mann, 1964]

Exotic = non-conventional

Observed states with
- known quantum numbers but
- debated structure and flavour content



$f_0(980)$

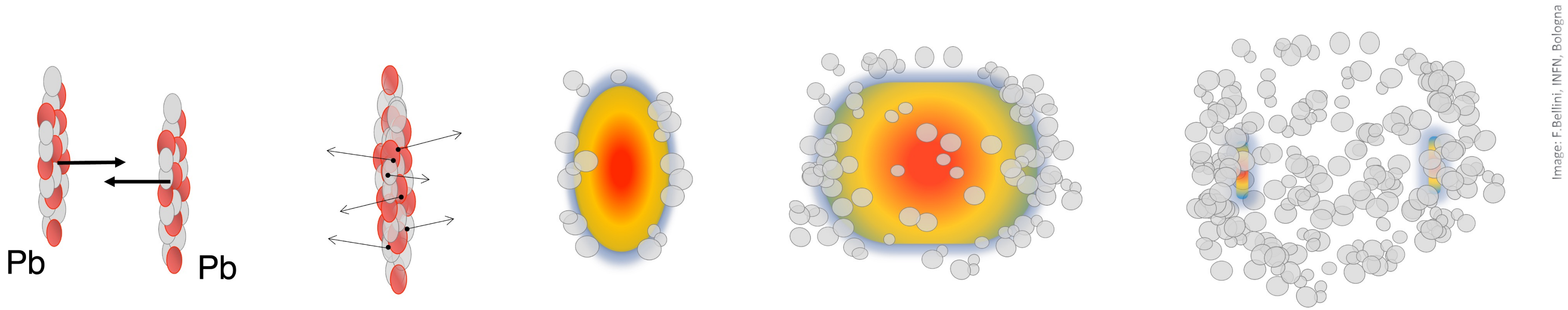
Diquark: PRD 67 (2003) 094011
Tetraquark: PRD 103 (2021) 1, 014010
Molecule ($K\bar{K}$): PRD 101 (2020) 9, 094034

$f_1(1285)$

Tetraquark: Mod.Phys.Lett. A2 (1987) 771
Molecule: Phys. Rev D42 (1990) 874
Diquark: PRD 96 (2017) 5, 054012
Hybrid: Nucl.Phys.A 992 (2019) 121641

Challenging signal extraction:
- Broad widths
- Interference
- Partial-wave analysis (PWA)

Heavy-ion collisions: lessons learnt and inspiration



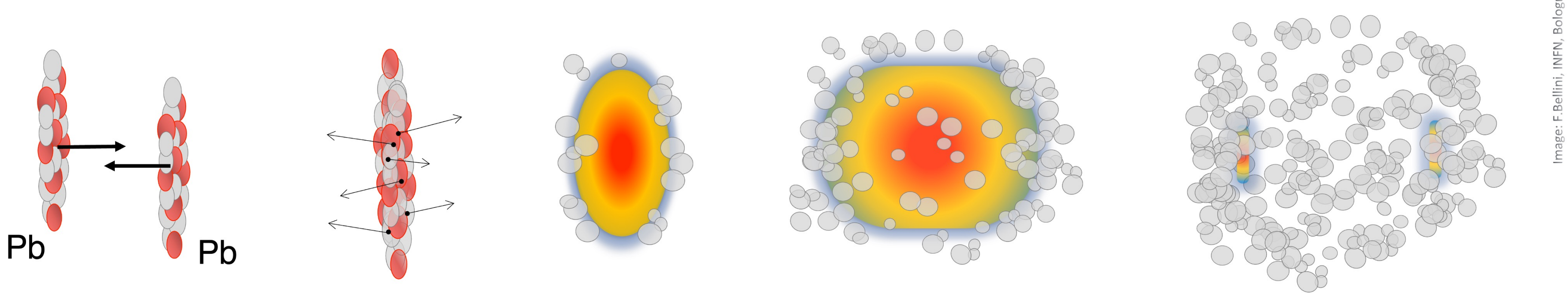
INITIAL STATE

HARD SCATTERINGS

QGP FORMATION AND EXPANSION
$\tau \sim 1\ fm/c$

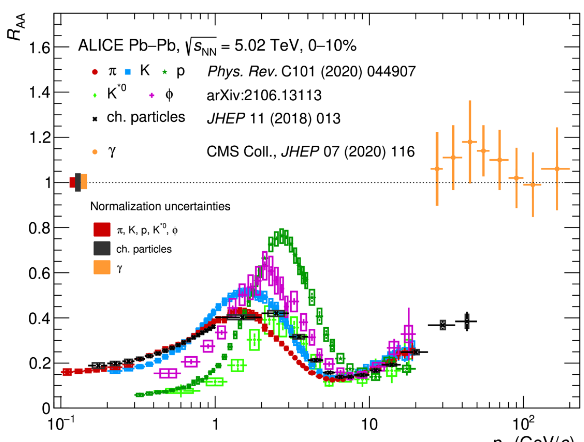
HADRON FORMATION AND FREEZE-OUT
$\tau \sim 10\ fm/c$

Heavy-ion collisions: lessons learnt and inspiration



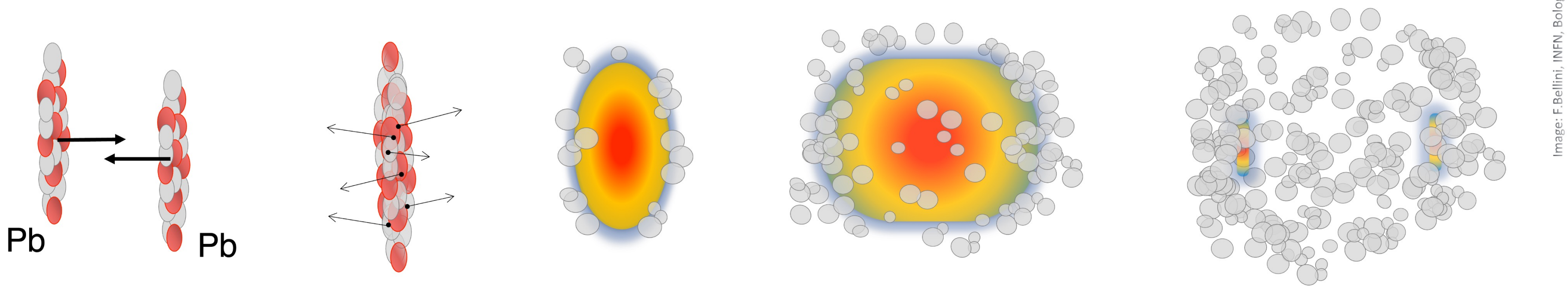
Initial state | **Hard scatterings** | **QGP formation and expansion** $\tau \sim 1\ fm/c$ | **Hadron formation and freeze-out** $\tau \sim 10\ fm/c$

Nuclear modification
> initial (cold nuclear matter) vs final-state (QGP) effects on particle production



arXiv:2211.04384

Heavy-ion collisions: lessons learnt and inspiration



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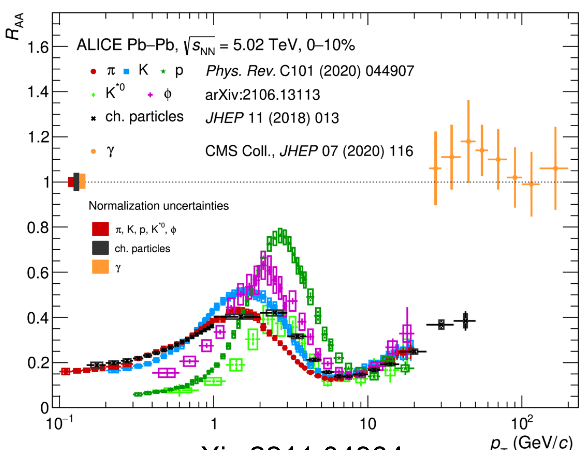
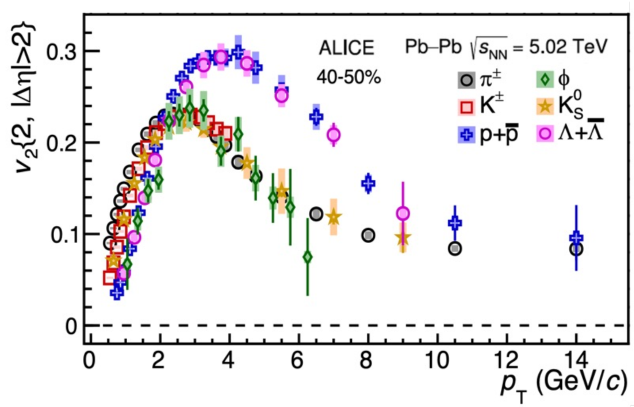
Flow and recombination
> collective dynamics from the QGP phase and impact on hadron formation

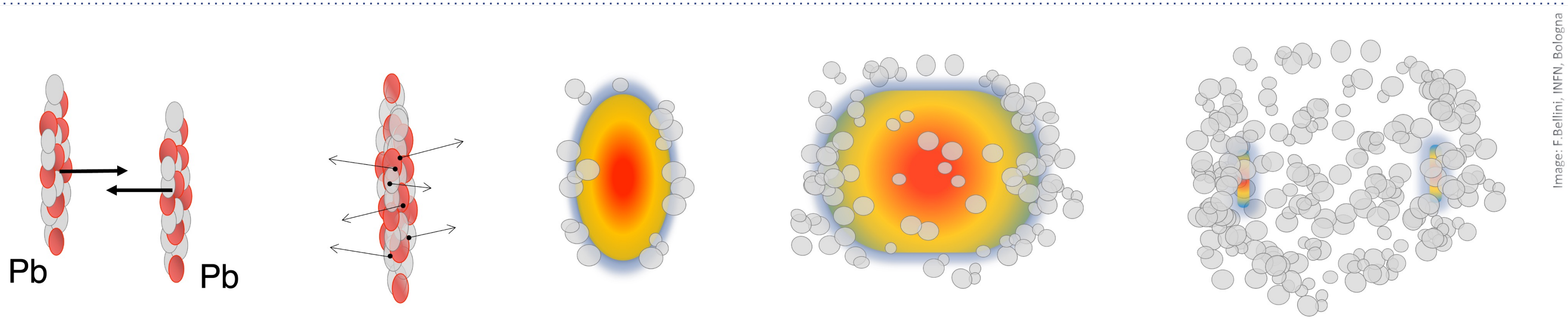


arXiv:2211.04384



JHEP 09 (2018) 006

Heavy-ion collisions: lessons learnt and inspiration

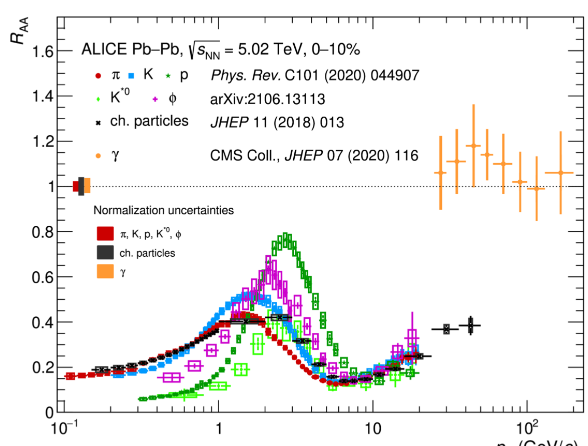


Initial state | **Hard scatterings** | **QGP formation and expansion** $\tau \sim 1\ fm/c$ | **Hadron formation and freeze-out** $\tau \sim 10\ fm/c$

Nuclear modification
> initial (cold nuclear matter) vs final-state (QGP) effects on particle production

Flow and recombination
> collective dynamics from the QGP phase and impact on hadron formation

Hadrochemistry
> hadronization, equilibration and hadronic interactions in the late stage



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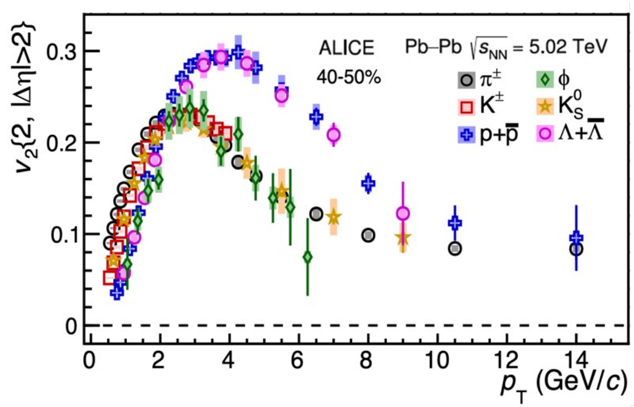
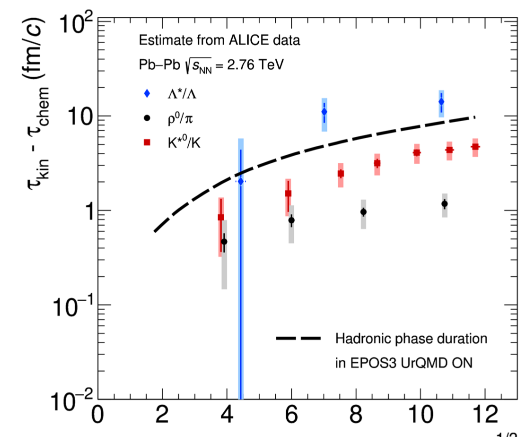


JHEP 09 (2018) 006



arXiv:2211.04384

The ALICE detector [LHC Runs 1+2: 2009-2018]

Central barrel:

- B = 0.5 T, $|\eta| < 0.9$
- robust PID up to $p_{\mathrm{T}} \sim 20$ GeV/c
- very low momentum cut-off, $p_{\mathrm{T}} \sim 0.15$ GeV/c

Inner Tracking System

- tracking
- vertex reconstruction

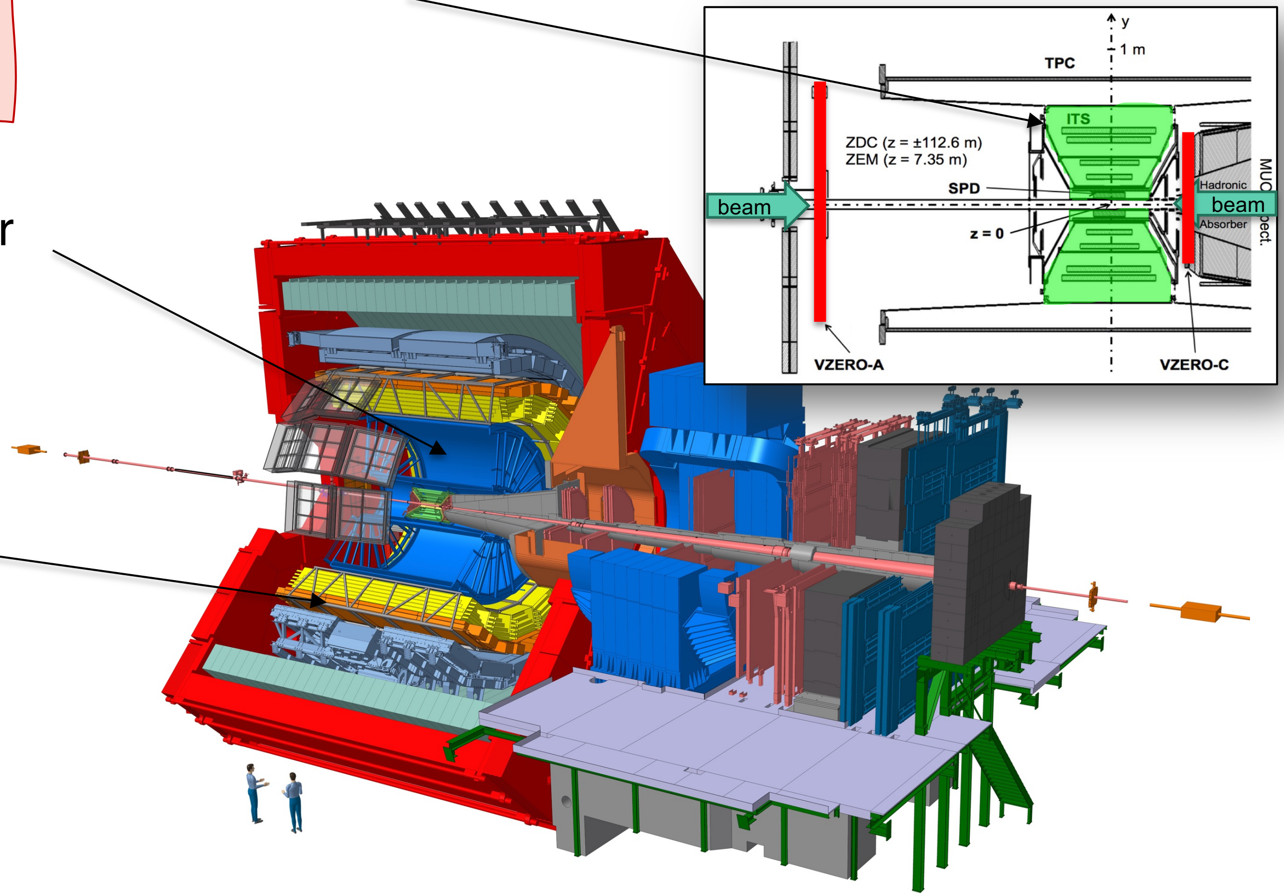
[replaced with ITS2 for Run3]

Time Projection Chamber

- tracking
- vertex reconstruction
- particle identification (dE/dx)

Time Of Flight

- particle identification (t)



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Inner Tracking System
- tracking
- vertex reconstruction

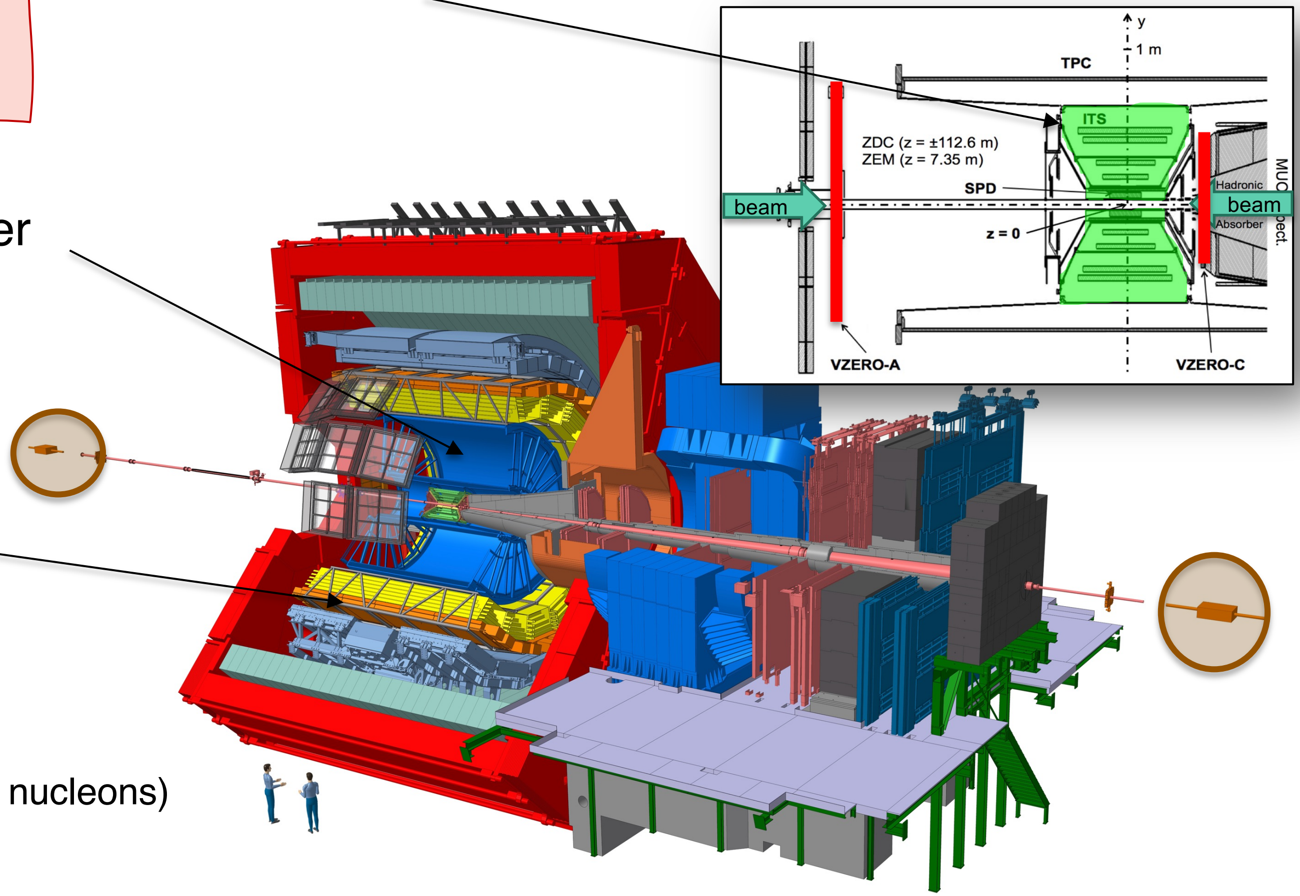
[replaced with ITS2 for Run3]

V0A: $-3.7 < \eta < -1.7$
V0C: $-2.8 < \eta < -5.1$
- trigger for min. bias collisions
- event classification (multiplicity)

Time Projection Chamber
- tracking
- vertex reconstruction
- particle identification (dE/dx)

Time Of Flight
- particle identification (t)

Zero Degree Calorimeters:
- at ±112.5 m from the IP
- beam background rejection
- event classification (spectator nucleons)



Signal extraction: $f_0(980)$

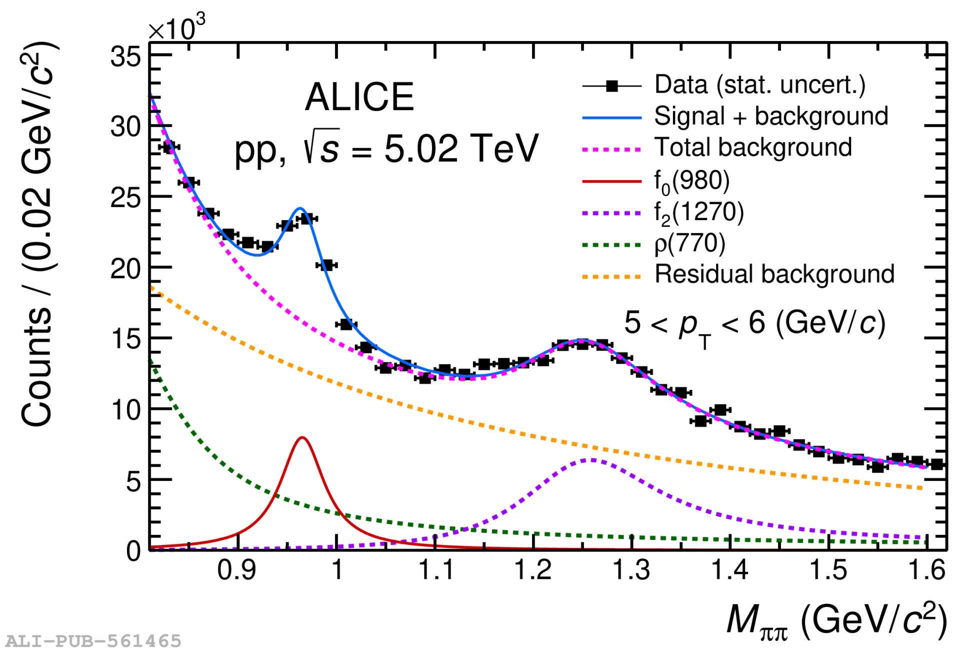
$f_0(980) \rightarrow \pi^+\pi^-$

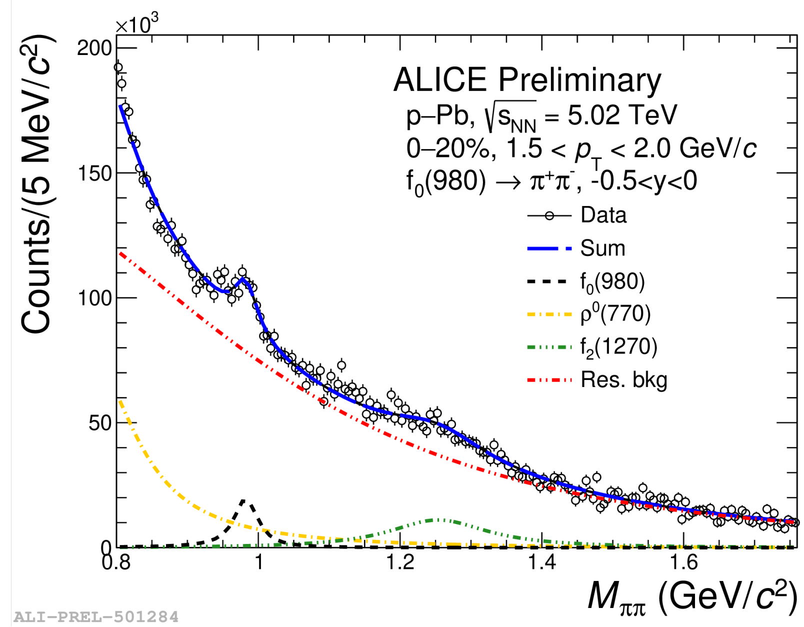
B.R. = (46 ± 6)%

[Stone and Zhang, PRL 111 (2013) 062001]

Technique:

- pion ID by TPC and TOF
- invariant mass analysis
- fit with relativistic Breit-Wigner for $\rho(770), f_0(980)$ and $f_2(1270)$





Data:

pp √*s* = 5.02 TeV: Phys. Lett. B 846 (2023) 137644

p-Pb √*s*$_{NN}$ = 5.02 TeV: paper in preparation

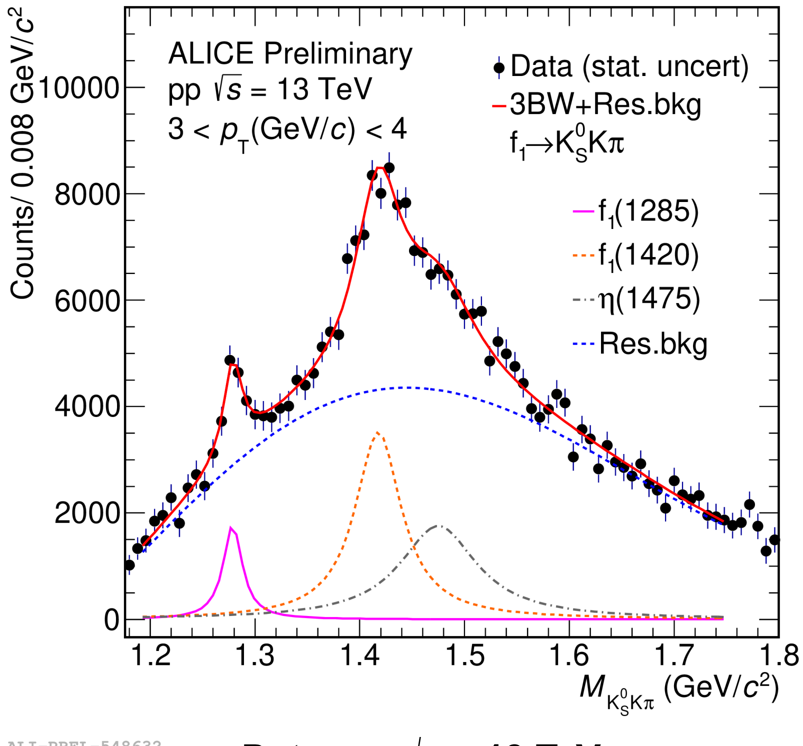
pp √*s* = 13 TeV: in progress

Signal extraction: $f_1(1285)$

$f_1(1285) \rightarrow K^0_S K\pi$

B.R. = 2.25 % *[PDG]*

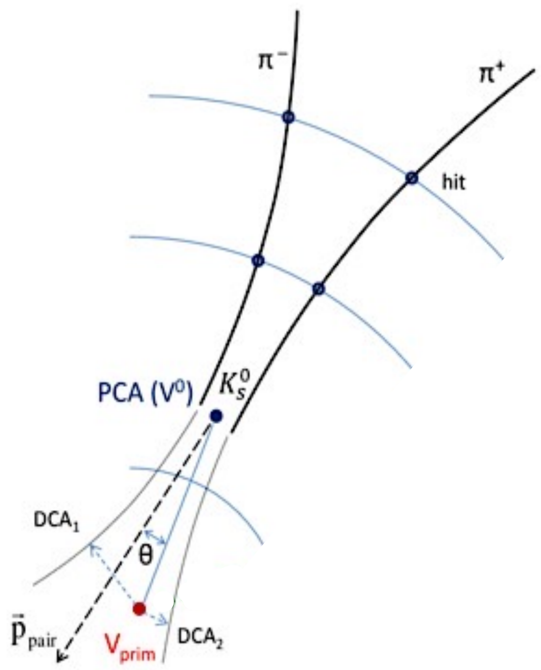
First measurement in ALICE
in pp collisions at $\sqrt{s}$ = 13 TeV



Data: pp $\sqrt{s}$ = 13 TeV

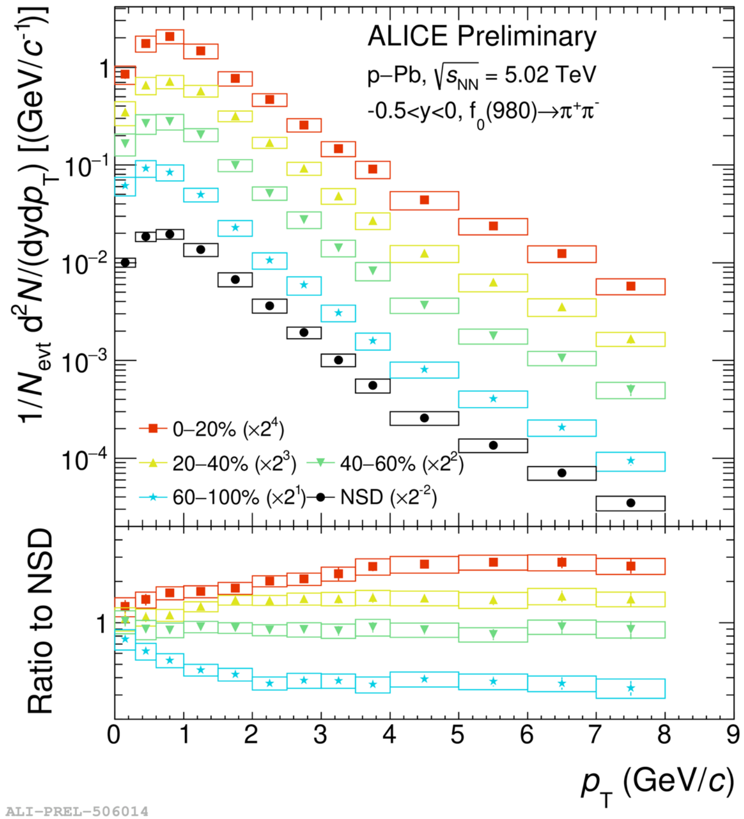
Technique:

- Kaon and pion ID by TPC and TOF
- Topological reconstruction of K^0_S
- invariant mass analysis
- fit with relativistic Breit-Wigner for $f_1(1285), f_1(1420)$ and $\eta(1475)$

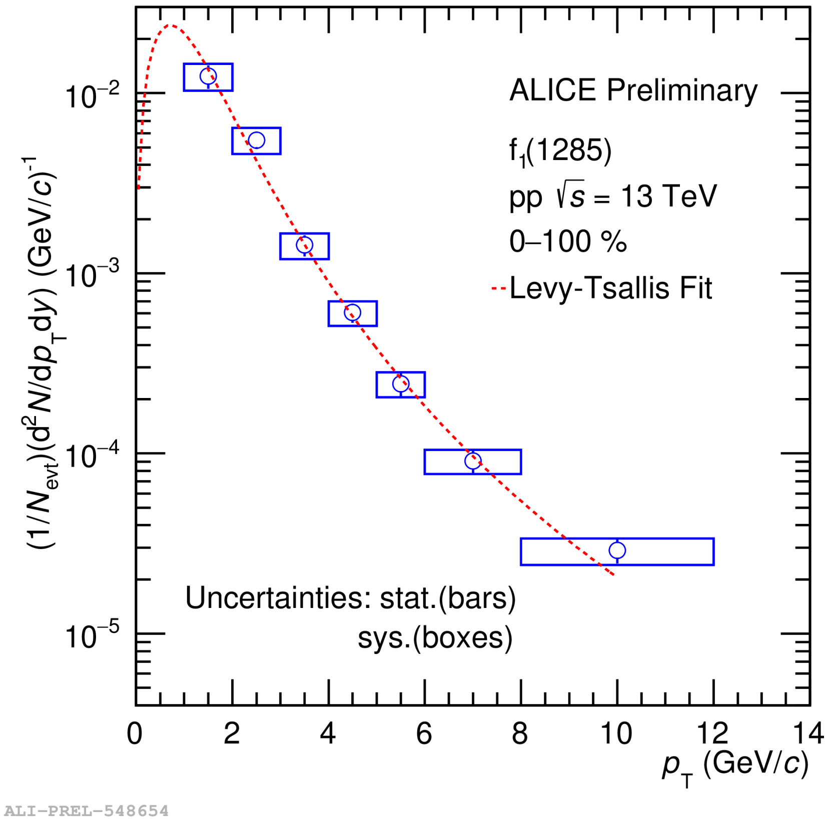


p_T-spectra in pp and p-Pb collisions

$f_0(980) \rightarrow \pi^+\pi^-$



$f_1(1285) \rightarrow K^0_S K\pi$

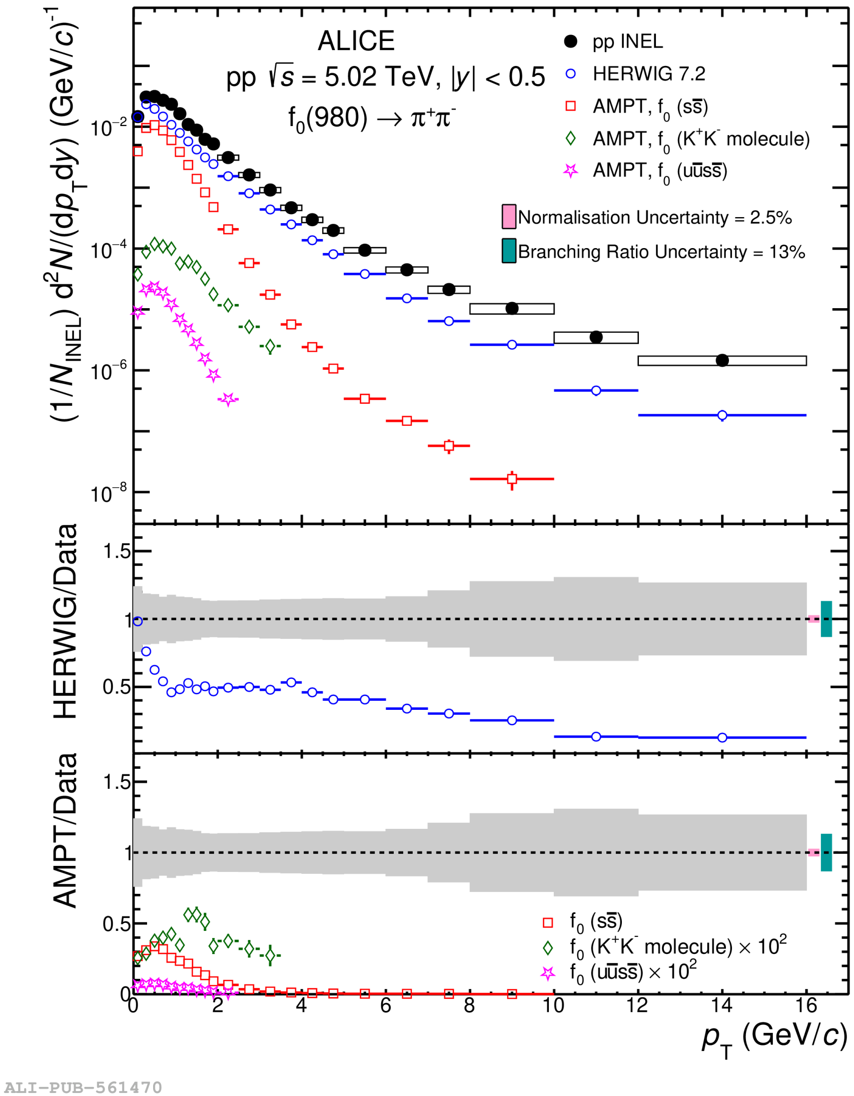


Main observables:

- p_T-dependent yields in INEL/NSD events and vs charged-particle multiplicity
- dN/dy obtained by integrating spectra over p_T and fit function for low-p_T extrapolation

$f_0(980)$ production in MC generators

pp



Phys. Lett. B 846 (2023) 137644

Few MC generators foresee the generation of $f_0(980)$ and none is able to fully reproduce the data

HERWIG 7.2

J. Bellm et al., Eur. Phys. J. C 76(4) (2016) 196

- cluster hadronisation model

AMPT + coalescence

An Gu et. al., Phys. Rev. C 101 (2020) 024908

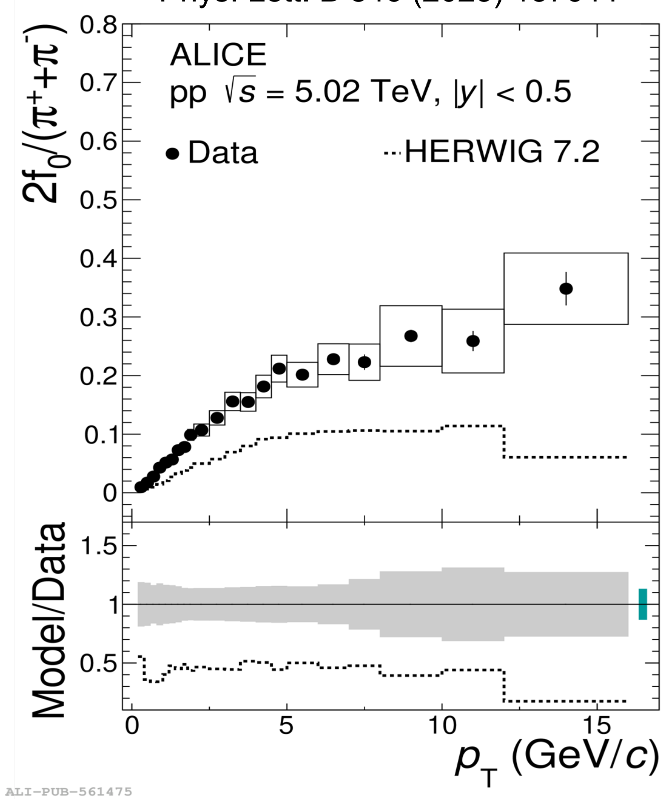
- $s\bar{s}$, $u\bar{u}d\bar{d}$ by quark coalescence
- KK molecule by K coalescence

Note: PYTHIA and EPOS in default configurations do not produce $f_0(980)$

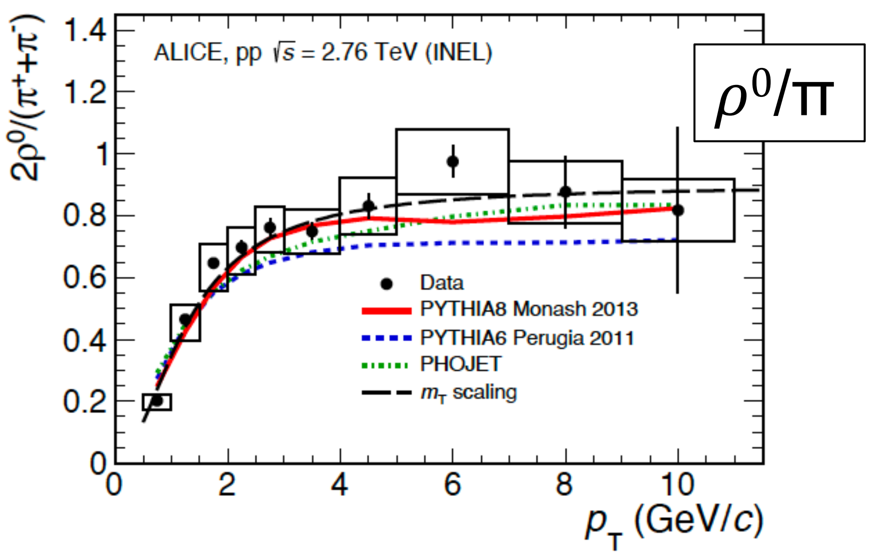
$f_0(980)/\pi$ compared to $\rho(770)/\pi^{\pm}$ and η/π^0

pp

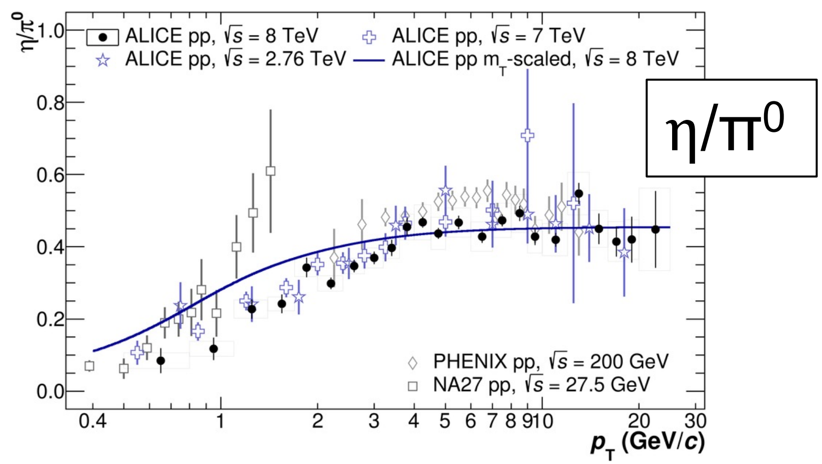
Phys. Lett. B 846 (2023) 137644



Phys. Rev. C 99, 064901 (2019)



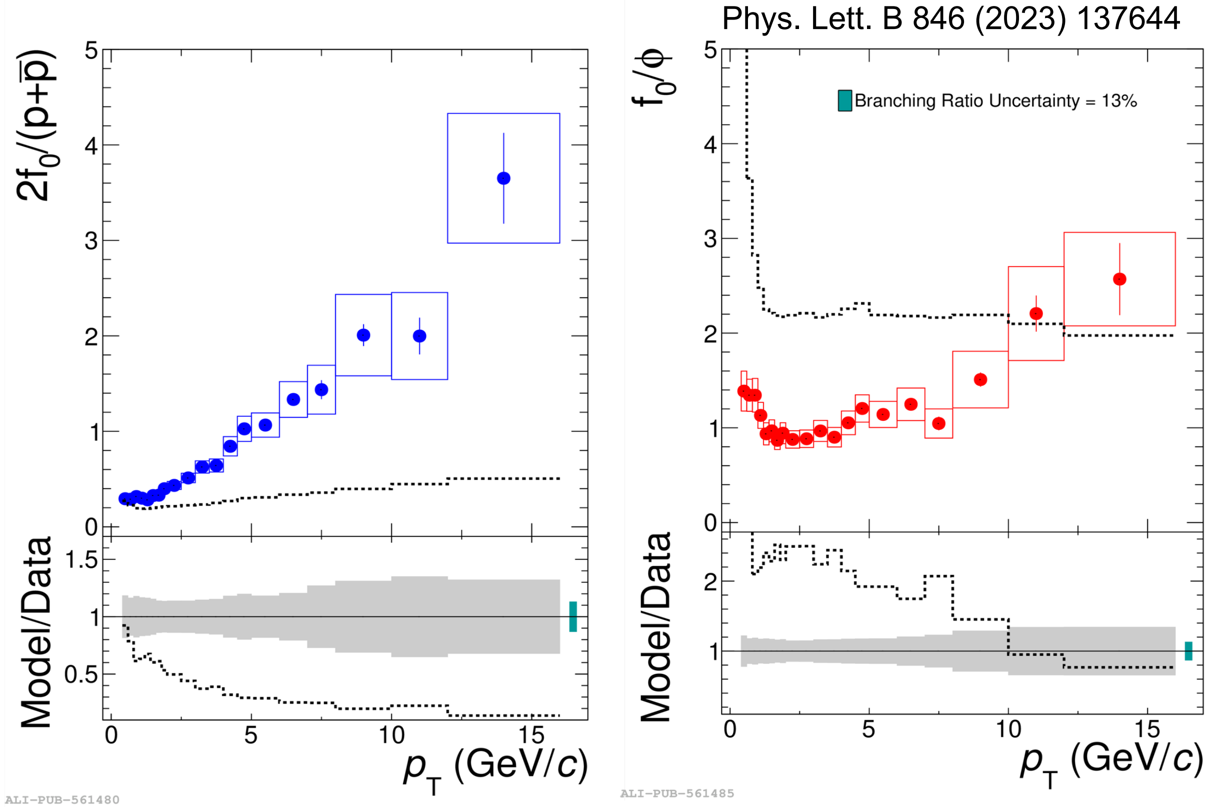
Eur. Phys. J. C 78 (2018) 263



Increasing p_T-dependent f_0/π ratio: qualitatively similar to $\rho(770)/\pi$ and η/π

f_0(980) production compared to p and ϕ(1020)

pp



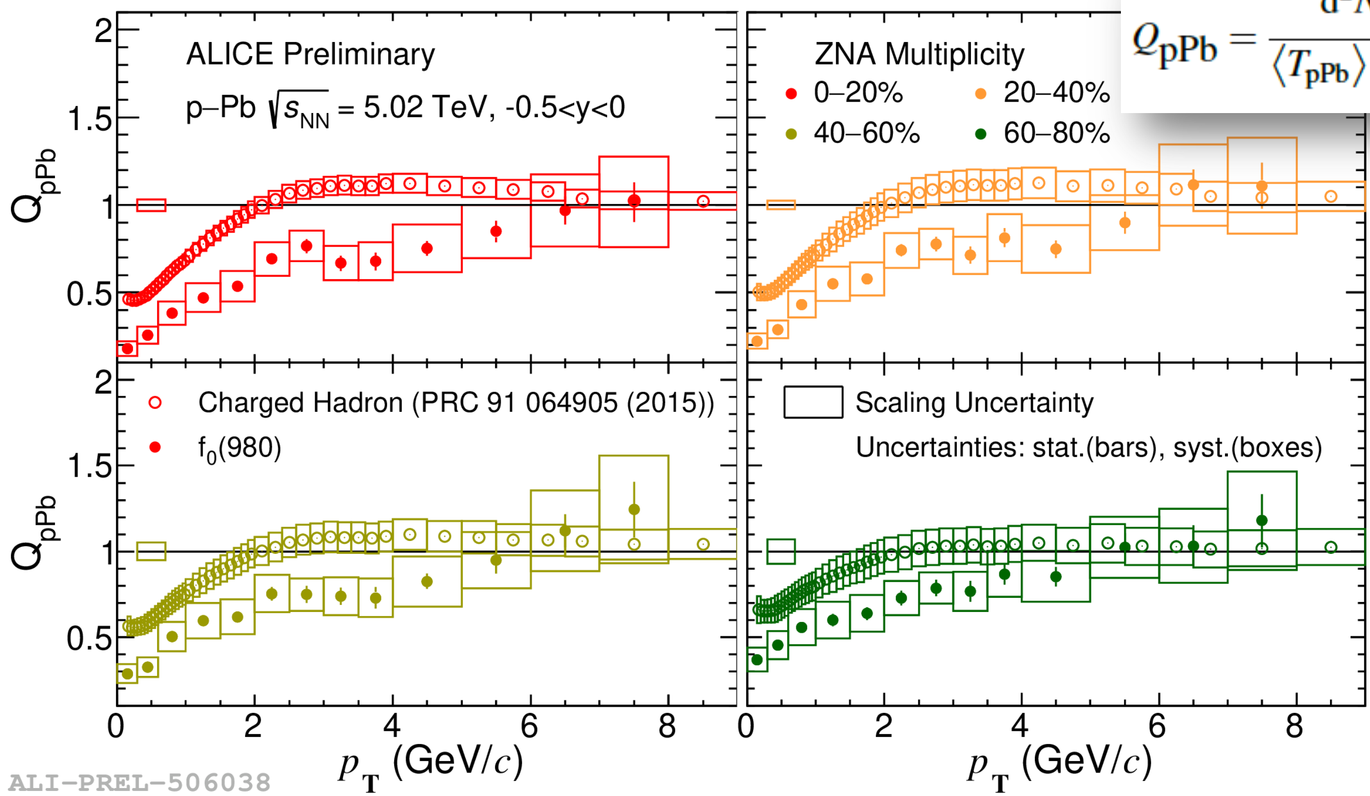
- f_0/p ratio increasing with p_T → decreasing baryon-to-meson ratio
- Similar production of f_0 and ϕ(1020) in $1.5 \lesssim p_T \lesssim 8$ GeV/c

  → p_T dependence of f_0/ϕ reproduced by HERWIG, larger by ~2x

Centrality-dependent suppression of $f_0(980)$

p-Pb

$$Q_{pPb} = \frac{d^2N^{pPb}_{f_0(980)}/dp_T dy}{\langle T_{pPb}\rangle d^2\sigma^{pp}_{f_0(980)}/dp_T dy}$$



Significant anomalous centrality-dependent suppression observed at p_T< 4 GeV/c
→ **rescattering**

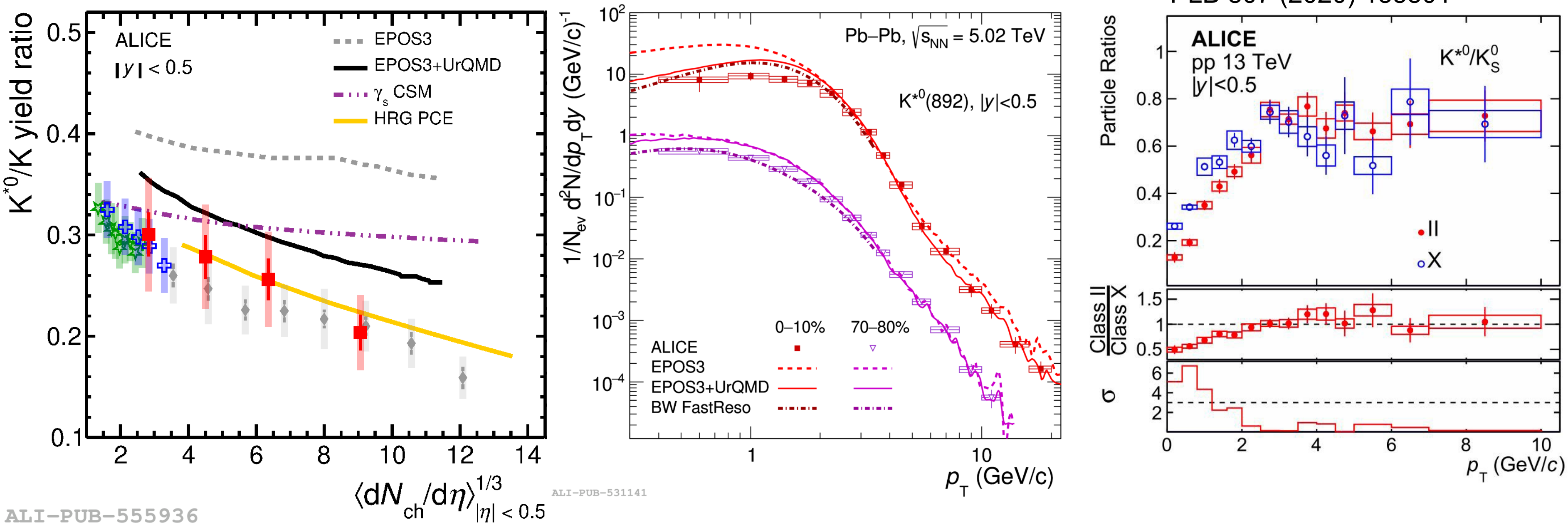
No Cronin peak in the intermediate p_T region, as for π and K (PLB 760 (2016) 720-735)
→ **di-quark** structure of $f_0(980)$

Reminder - Rescattering in the hadronic phase

- Centrality-dependent suppression of resonant-to-ground-state particle ratio
- Suppression at low p_T compared to models with no rescattering, enhanced in more central collisions

+ indication for a short but finite hadronic phase in high multiplicity pp/p-Pb collisions

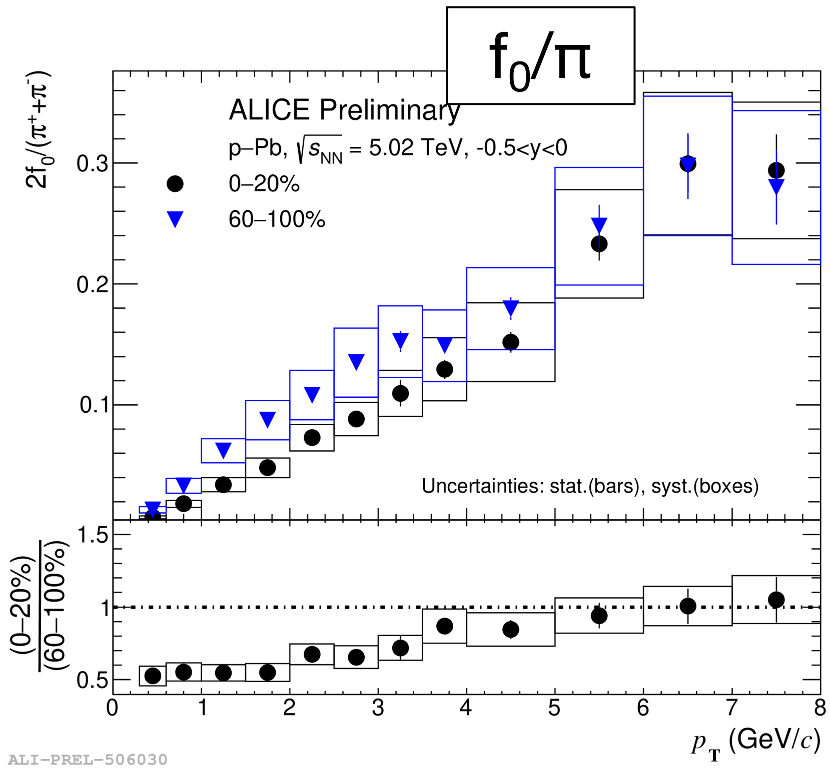
PLB 807 (2020) 135501

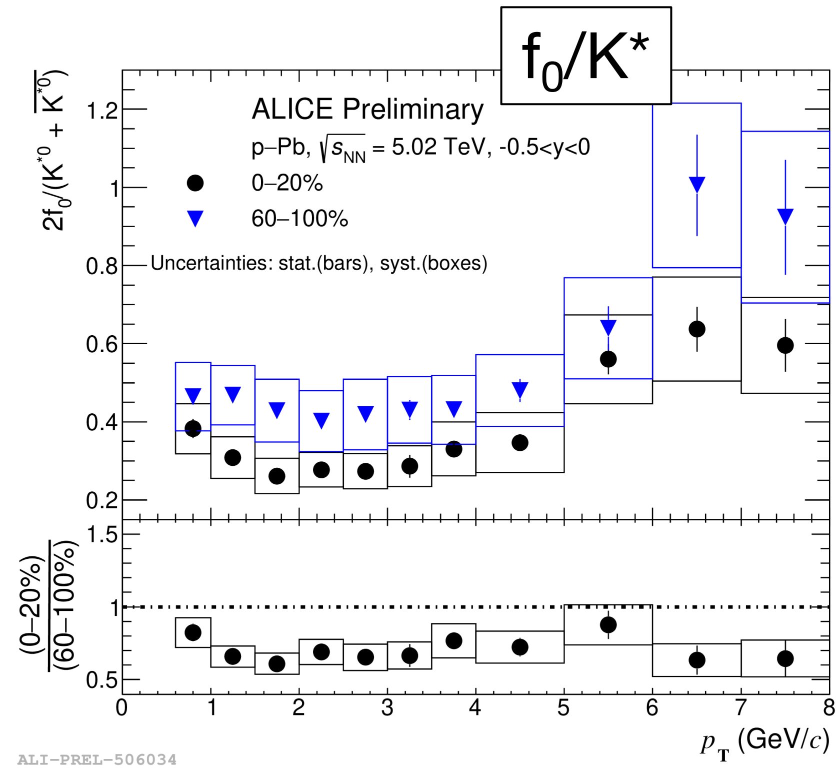


Bong-Hwi Lim, Nov. 6th

Particle ratios probe hadron interaction effects

p-Pb



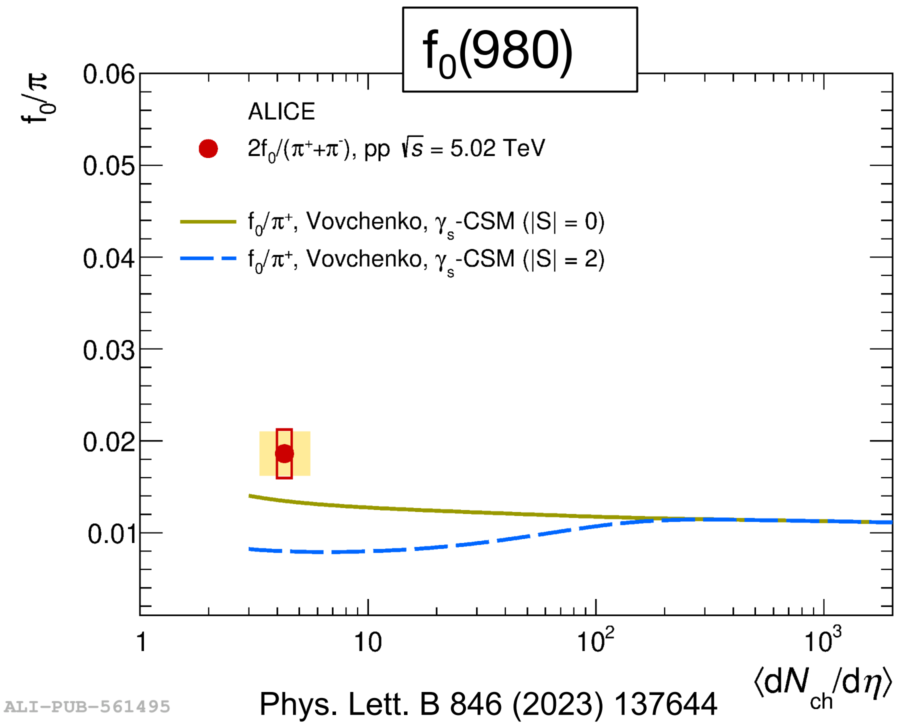


Significant centrality-dependent suppression of f_0/π observed at p_T< 3 GeV/c
Similar behaviour as for K*/K, with comparable lifetime (~4.5 fm)
→ **rescattering**

f_0/K* ratio < 1 in full p_T range
→ different **strangeness content**

Yield ratios depend on strangeness content

pp



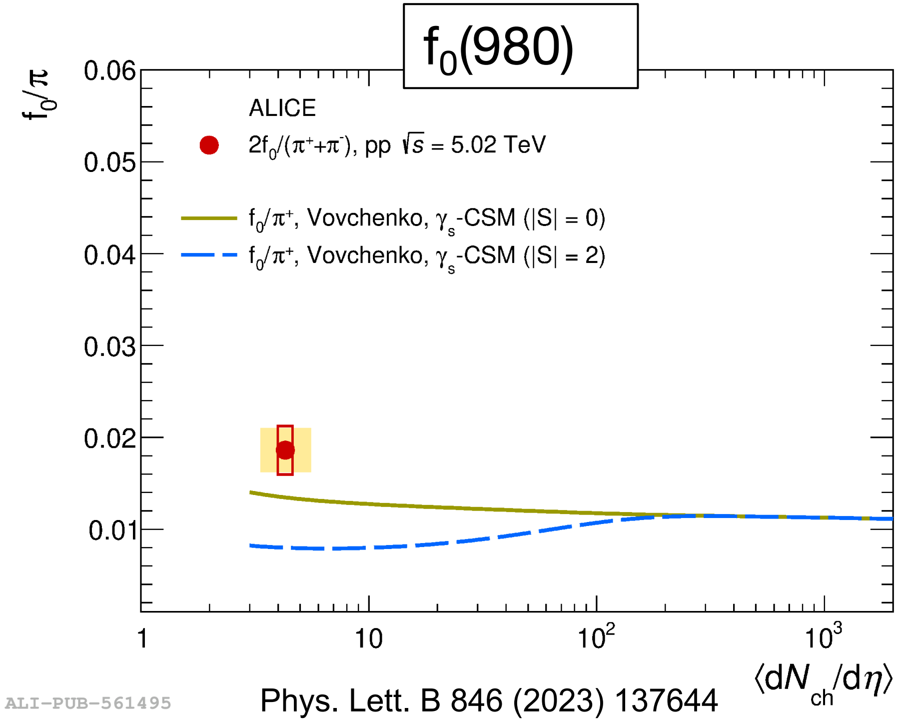
Phys. Lett. B 846 (2023) 137644

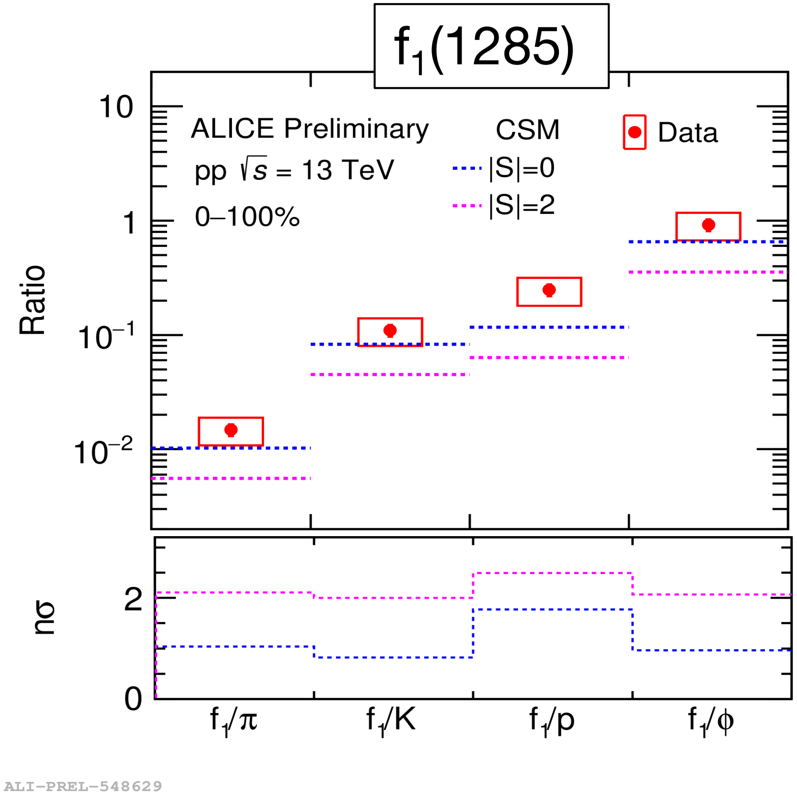
Comparison to γ_s- CSM predictions favours no hidden strangeness scenario
Vovchencko et al., PRC 100, 054906 (2019)

|S| = 0 → f_0/π data differ by 1.9σ
|S| = 2 → f_0/π data differ by 4.0σ
predictions converge in the high-multiplicity limit

Yield ratios depend on strangeness content

pp





Comparison to γ_s- CSM predictions favours no hidden strangeness scenario

Vovchencko et al., PRC 100, 054906 (2019)

$|S| = 0 \rightarrow f_0/\pi$ data differ by 1.9σ

$|S| = 2 \rightarrow f_0/\pi$ data differ by 4.0σ

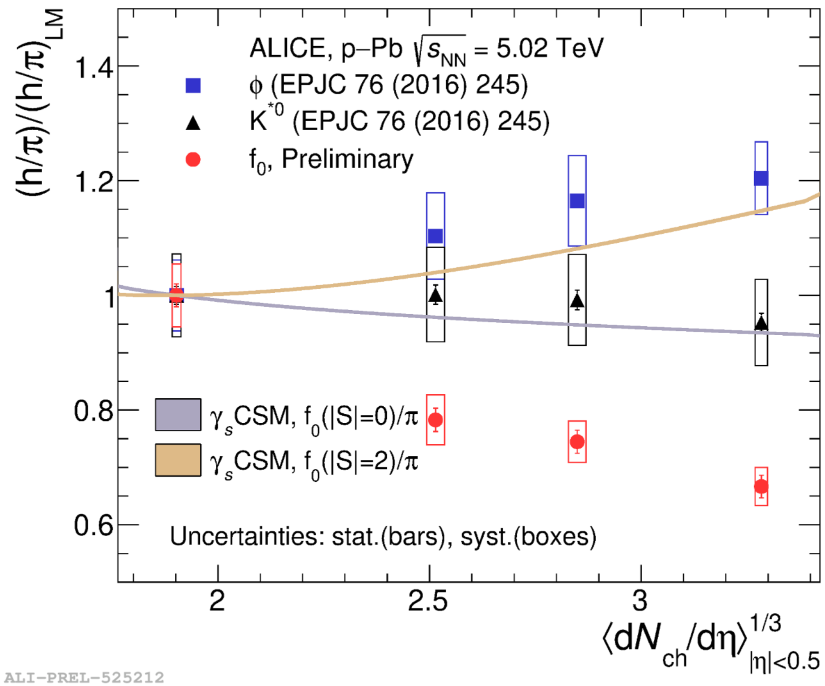
predictions converge in the high-multiplicity limit

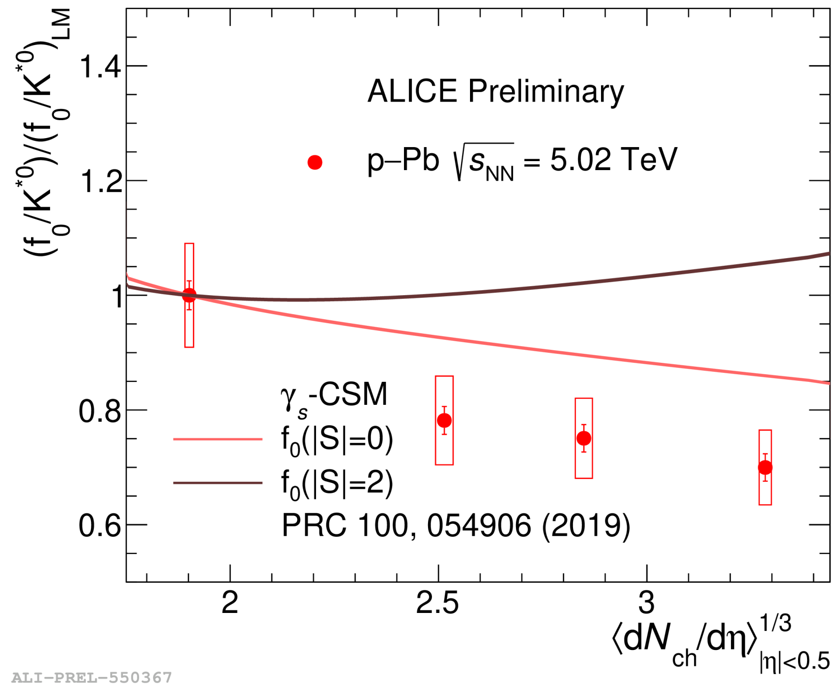
$|S| = 0 \rightarrow f_1/h$ data differ by ~1σ

$|S| = 2 \rightarrow f_1/h$ data differ by ~2σ

Yield ratios depend on strangeness content

p-Pb





Comparison to γ_s- CSM predictions favours no hidden strangeness scenario
Vovchencko et al., PRC 100, 054906 (2019)

If f_0 contains strangeness, |S|=2 (as $\phi = s\bar{s}$), a mild increase due to strangeness enhancement is expected with multiplicity

- f_0/π double-ratio decreases with multiplicity
- f_0/π and f_0/K^* multiplicity dependence closer to |S|=0 ($K^* = d\bar{s}$) predictions

The hunt for glueballs

Glueball: particle composed of bound gluons only
Lattice QCD: PRL101, 112003 (2008)

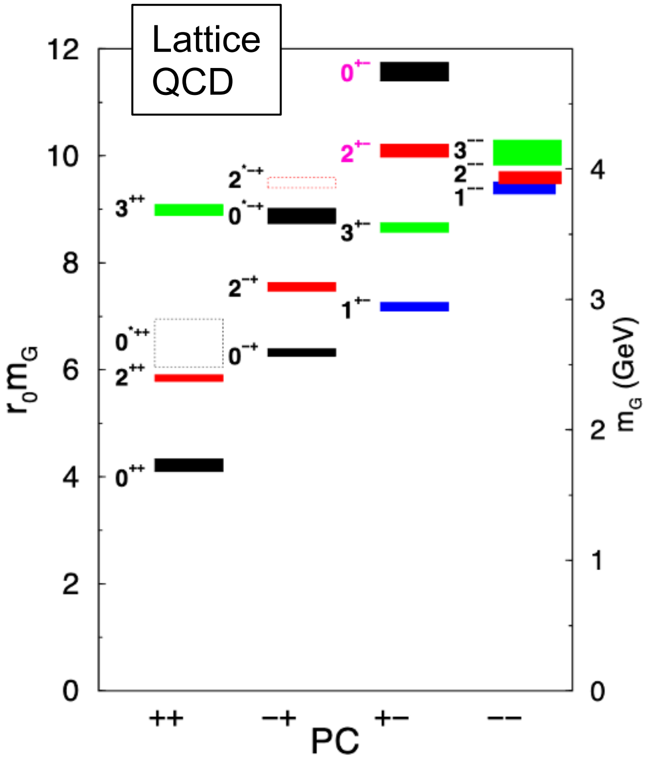
Expected properties:

- $J^{PC} = 0^{++}, 0^{-+}, 2^{++}$
- Mass range: 1~2 GeV/c^2
- All candidates decay into ππ, KK, ηη

Candidates for scalar glueball:
$f_0(1370), f_0(1500), f_0(1710)$

- Observed
- Different structure and hidden flavour content assignments according to different models

	M_{PDG} (GeV/c^2)	M_{BESIII} (GeV/c^2)	Γ_{PDG} (GeV/c^2)	$\Gamma_{BESSIII}$ (GeV/c^2)
f_0 (1370)	1.2 to 1.5	1.350±0.009	0.2 to 0,3	0.231±0.021
f_0 (1500)	1.506±0.006	1.505±0.000	0.112±0.009	0.109±0.000
f_0 (1710)	1.704±0.012	1.765±0.002	0.123±0.018	0.146±0.003



Morningstar, Peardon, PRD 60, 034509 (1999)

Signal extraction: $K^0_S K^0_S$ and KK mass spectrum

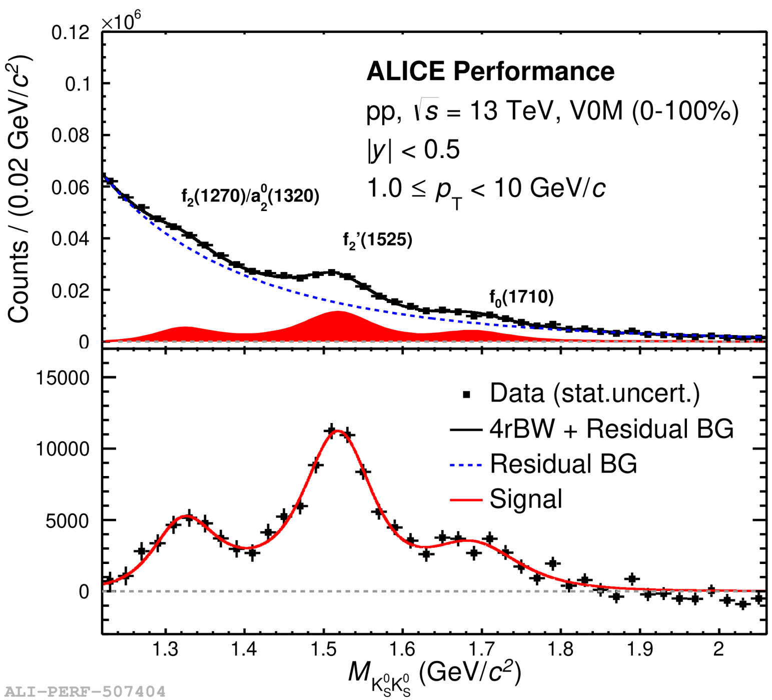
Many resonances below 2 GeV/c^2:

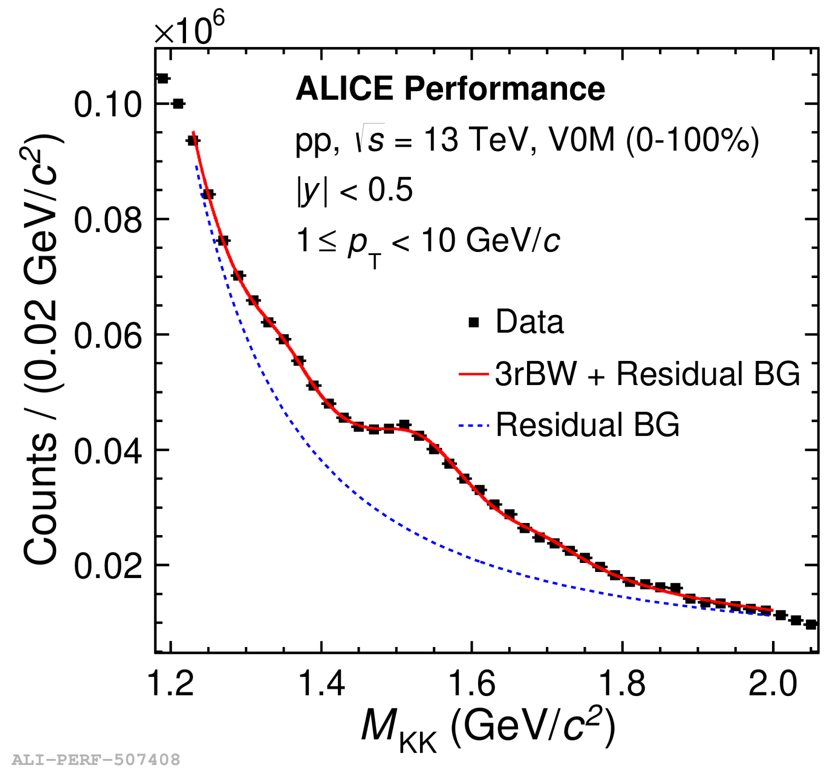
$J^{CP} = 0^{++}$: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

$J^{CP} = 2^{++}$: $f_2(1270)$, $f_2(1525)$

Technique:

- V0 reconstruction of K^0_S ($c\tau = 2.68$ cm)
- K ID with TPC and TOF
- invariant mass analysis
- Breit-Wigner fit of known states





Data: pp $\sqrt{s}$ = 5.02 and 13 TeV, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Signal extraction: $K^0_S K^0_S$ mass spectrum

Several signal peaks, including $f_0(1370)$, $f_2(1270)$, $f_2(1525)$, and $f_0(1710)$, are visible after background subtraction

Technique:
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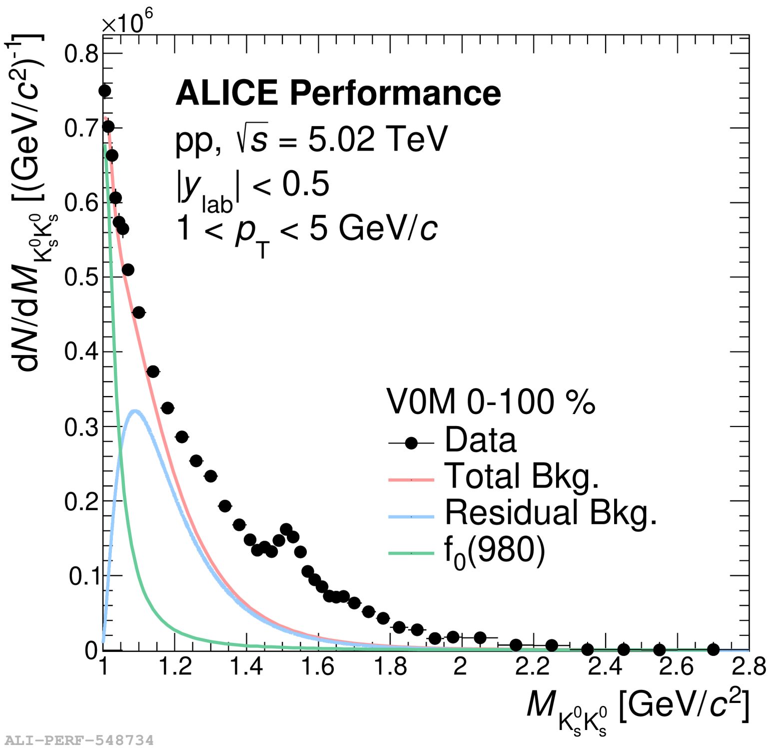

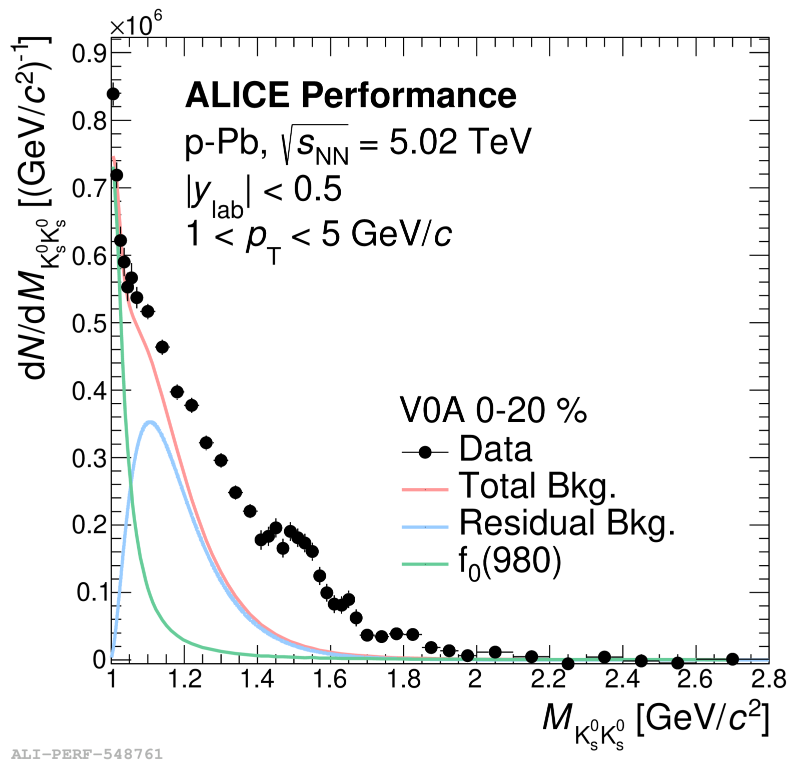

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Signal extraction: $K_S^0 K_S^0$ mass spectrum

Several signal peaks, including $f_0(1370)$, $f_2(1270)$, $f_2(1525)$, and $f_0(1710)$, are visible after background subtraction

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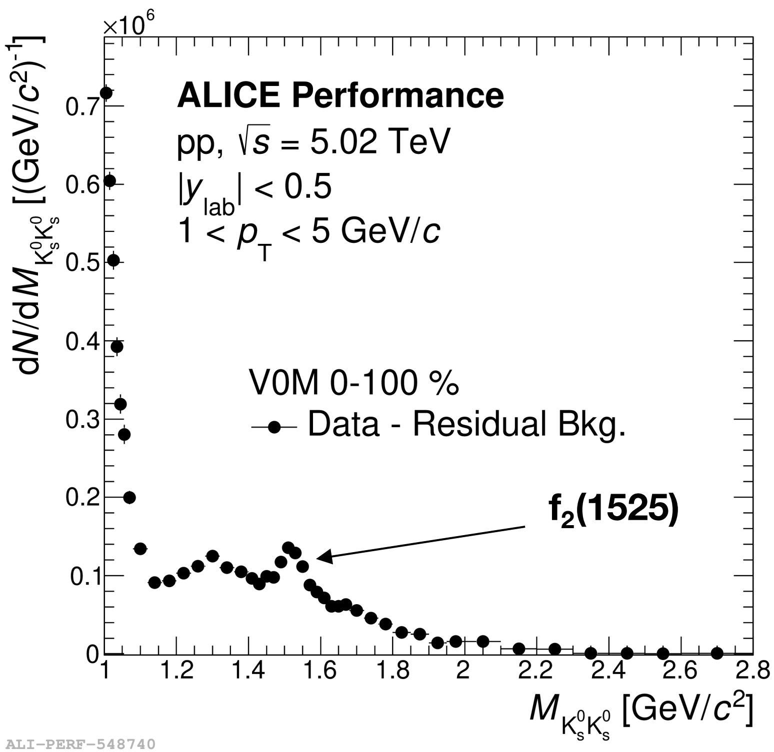
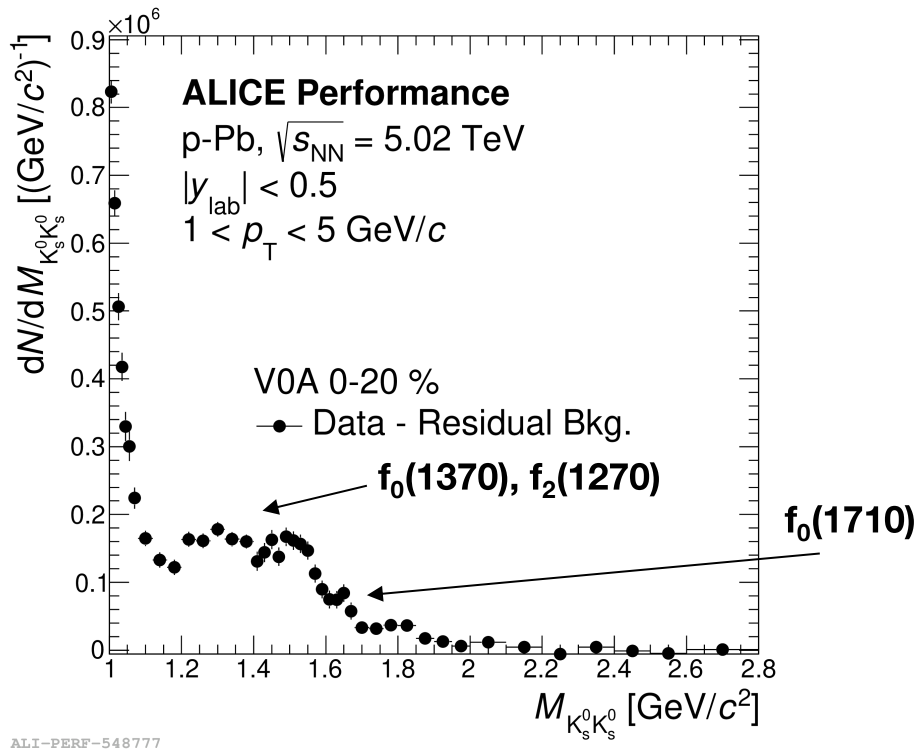




Data: pp $\sqrt{s}$ = 5.02 and 13 TeV, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Summary and outlook

$f_0(980)$

- Centrality-dependent suppression in p-Pb at low $p_T \rightarrow$ hadron rescattering
- Particle ratios and absence of Cronin peak → conventional meson with no hidden strange quarks

$f_1(1285)$ production in pp collisions

- First measurement in ALICE
- Particle ratios compared to CSM → no strange content

Search for glueballs in the KK mass spectrum

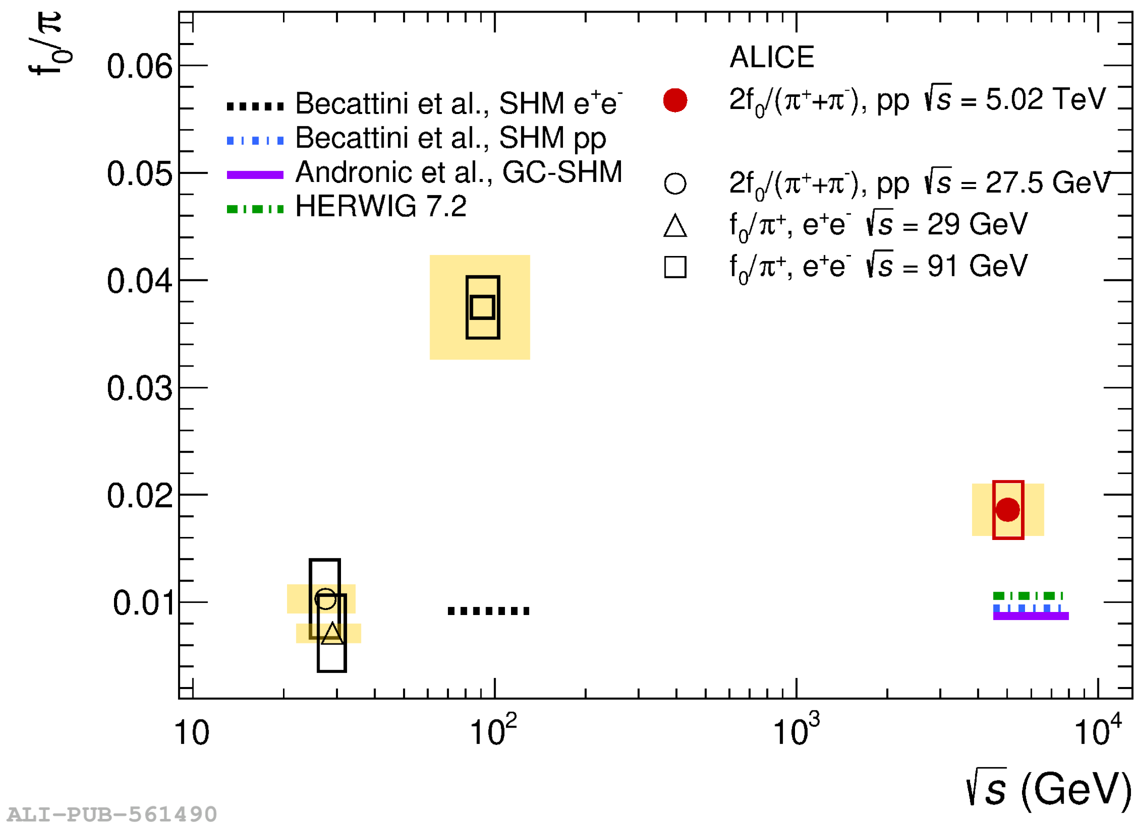
- Promising first signals of $f_0(1370), f_0(1500), f_0(1710)$
→ measure nuclear modification to test glueball hypothesis (enhancement expected due to large gluon density)

Measurements in pp provide essential reference and input to models.

Heavy-ion physics provides observables to investigate the internal structure and debated nature of exotic states.

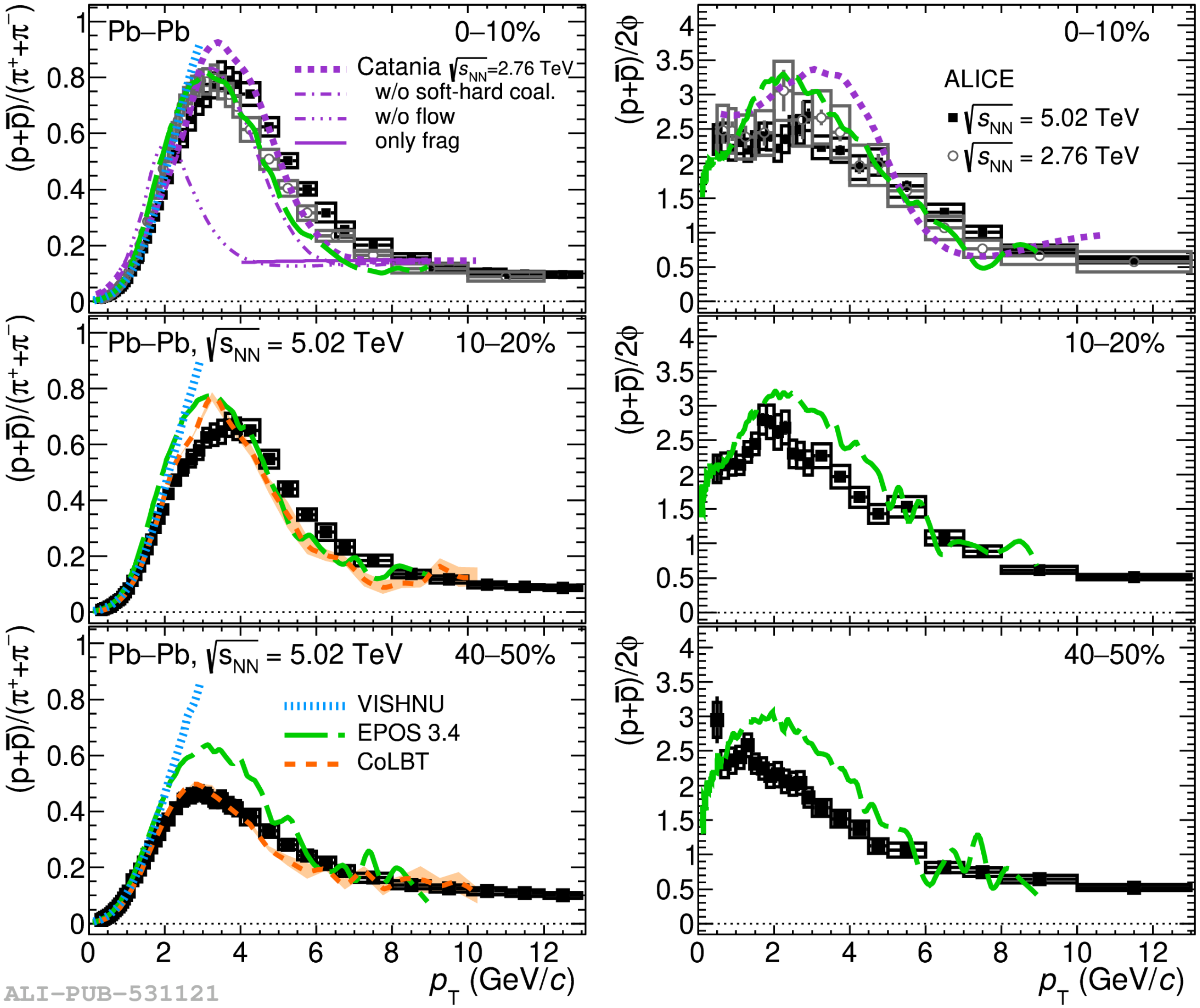
Thank you!

√s dependence of f0/π



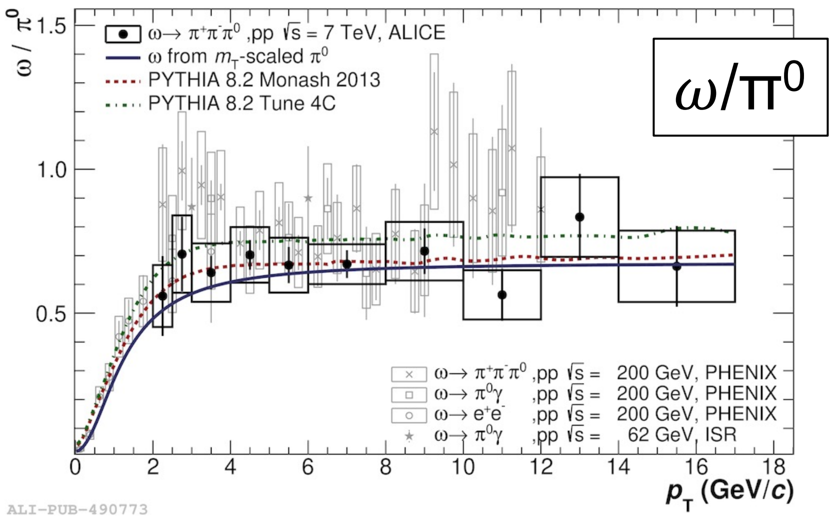
Baryon/meson ratios

ALICE review, arXiv:2211.04384

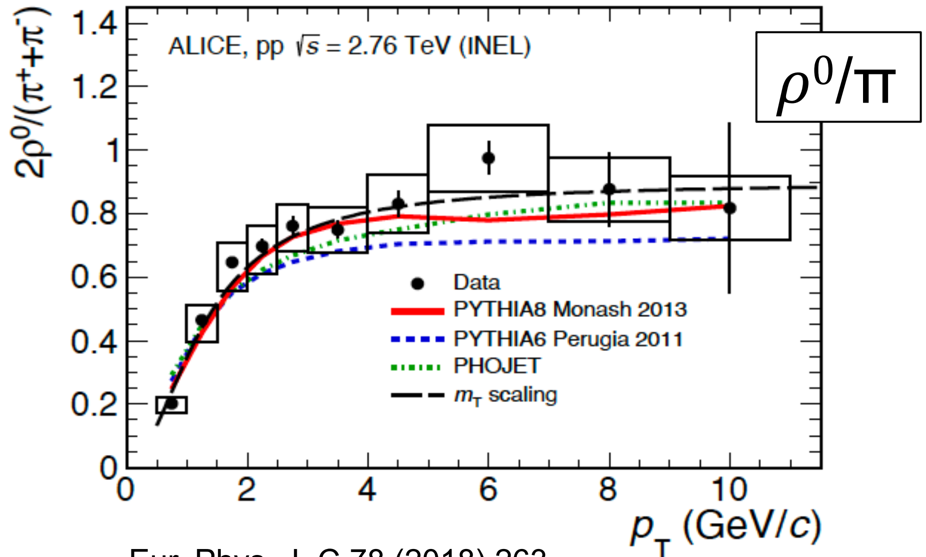


$f_0(980)/\pi$ in pp compared to $\rho(770)/\pi^{\pm}$, ω/π^0, η/π^0

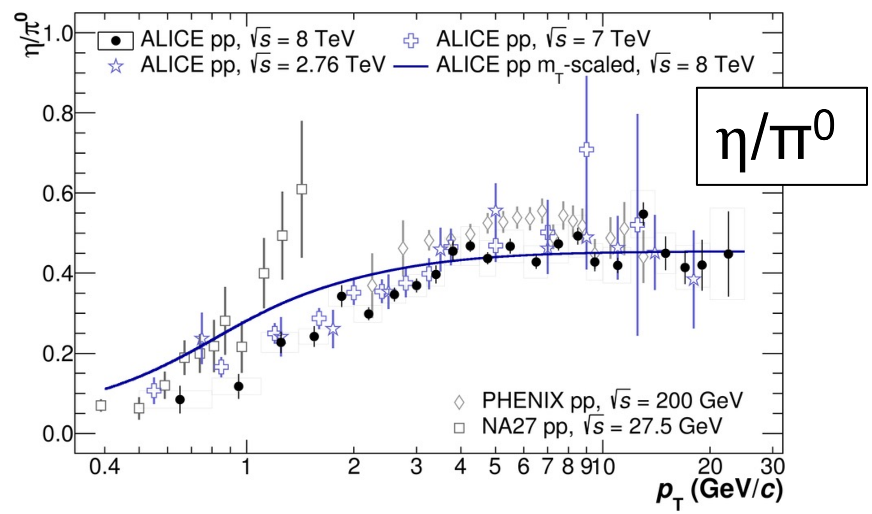
Eur. Phys. J. C 80 (2020) 1130



Phys. Rev. C 99, 064901



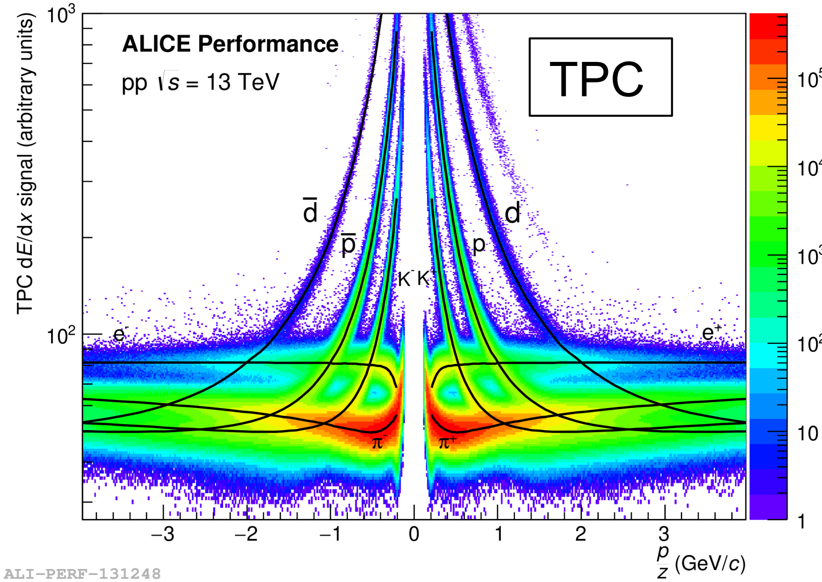
Eur. Phys. J. C 78 (2018) 263



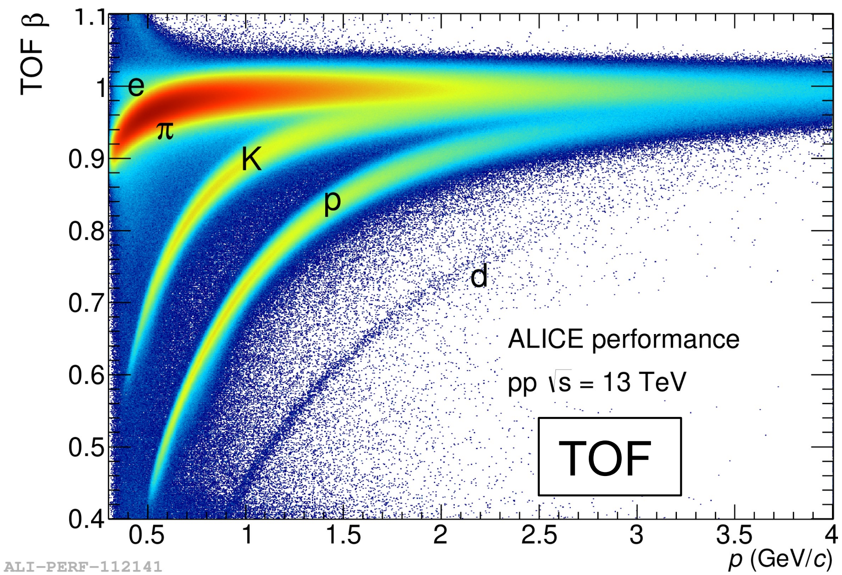
Note: transverse mass scaling with π as reference does not work in the full p_T range at LHC energies, scaling is better with K

Altenkämper et al., Phys. Rev. C 96, 064907

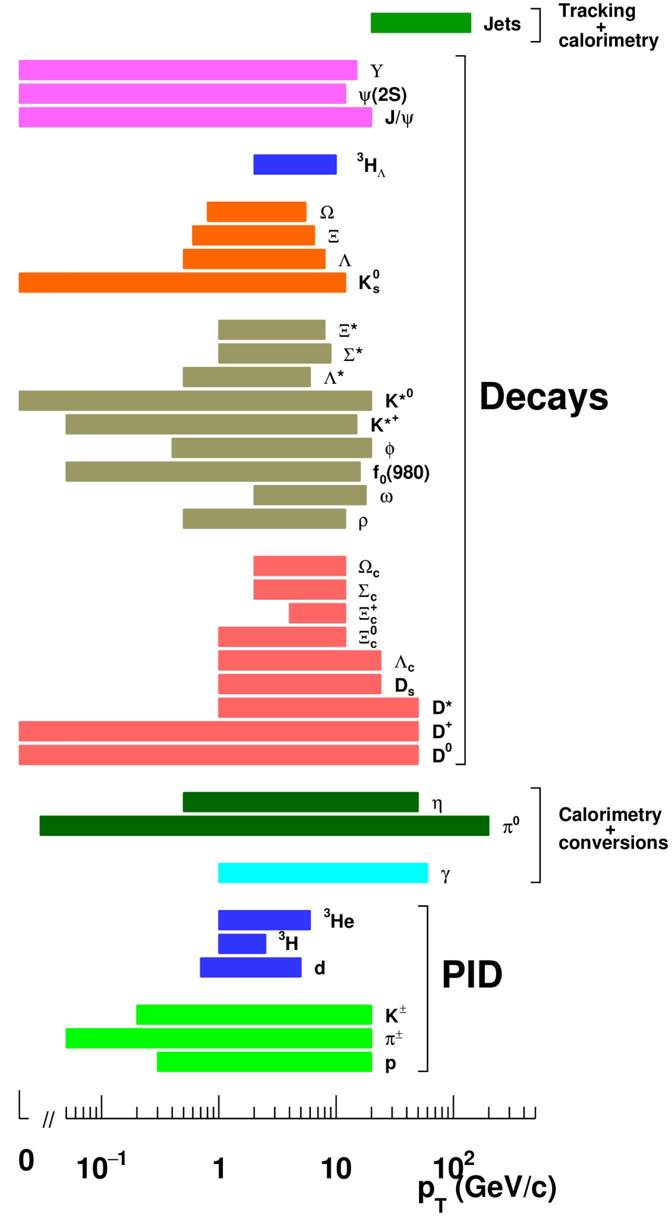
ALICE PID capabilities



ALI-PERF-131248



ALI-PERF-112141



ALI-PUB-530977