Investigating the hidden strangeness content of exotic resonances with ALICE

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Exotic resonances

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https://pdg.lbl.gov

$f_0(980)$ [j] $I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 10$ to 100 MeV

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	476
$K\overline{K}$	seen	36
$\gamma\gamma$	seen	495

$f_1(1285)$ $I^G(J^{PC}) = 0^+(1^{++})$

$f_1(1285)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1281.9 ± 0.5	**OUR AVERAGE**	Error includes scale factor of 1.8. See the ideogram		

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Only experiments giving width error less than 20 MeV are kept for averaging.

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- $f_0(980)$, a scalar meson, is an interesting particle due to its debated nature

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Branching ratio of f_0 (980) $\rightarrow \pi^+ + \pi^-$ channel: 46 ± 6 %

S. Stone *et. al.*, PRL 111, 062001 (2013)
LHCb Collaboration, Phys. Rev. D 89, (2014) 092006

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$f_0(980)$: 4q(?)

With dominat $s\bar{s}$ contribution

- tetra-quark candidate in the LF sector (?)
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  - N. N. Achasov, Nucl. Phys. A728 (2003) 425: based on SND [2], CMD-2 [3] and KLOE [4] data (ϕ meson radiative decay)

1. BESIII Collaboration, Phys. Rev. D92, (2015) 052003.
2. M. N. Achasov et al., Phys. Lett. B479 (2000) 53.
3. CMD-2 Collaboration, Phys. Lett. B462 (1999) 371.
4. KLOE Collaboration, Phys. Lett. B536 (2002) 209.

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- mix of di-quark and tetra-quark (?)
  C. H. Sen, Phys. Rev. D67, 094011 (2003),
  PDG collaboration, PTEP 2020, (2020) 083C01:
  - ☑ based on E791 data [1] (D_s^+ decays)
  - ☑ based on LHCb data [2] (B_s^+ decays)

1. E791 collaboration, Phys. Rev. Lett. 86 (2001) 765
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- K^+K^- molecule (?):
  H. Ahmed *et. al.*, Phys. Rev. D101 094034 (2020),
  C. Xiao *et. al.*, Eur. Phys. J. A56, (2020) 23:
  - ☑ based on the study of pion–pion and kaon–kaon scattering

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	ρ^0	K^*	$f_0(980)$	ϕ
Mass (MeV/c^2)	775	892	990	1020
J^P	1^-	1^-	0^+	1^-
Contents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	???	$s\bar{s}$
lifetime (fm/c)	1.3	4.2	~ 5	46.2

- $f_0(980)$ is a short-lived resonance (similar lifetime as K^{*0}) and it contributes to the study of the hadronic phase in AA collisions

ALICE

What do we know about $f_1(1285)$?

- $f_1(1285)$, a scalar meson, is an interesting particle due to its debated nature
- $f_1(1285)$ is also a chiral partner of $\omega(782)$ particle makes it an interesting particle to study in heavy-ion collisions

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  - ☑ Y. Kanada-En'yo et al., Phys.Rev.D71 (2005), 094005

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  A.A. Osipov et al., Phys.Rev.D 96 (2017), 054012

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  Phys.Rev.D 96 (2017), 054012
- molecule:
  F. Aceti et al., Phys.Lett. B750(2015) 609.

Motivation

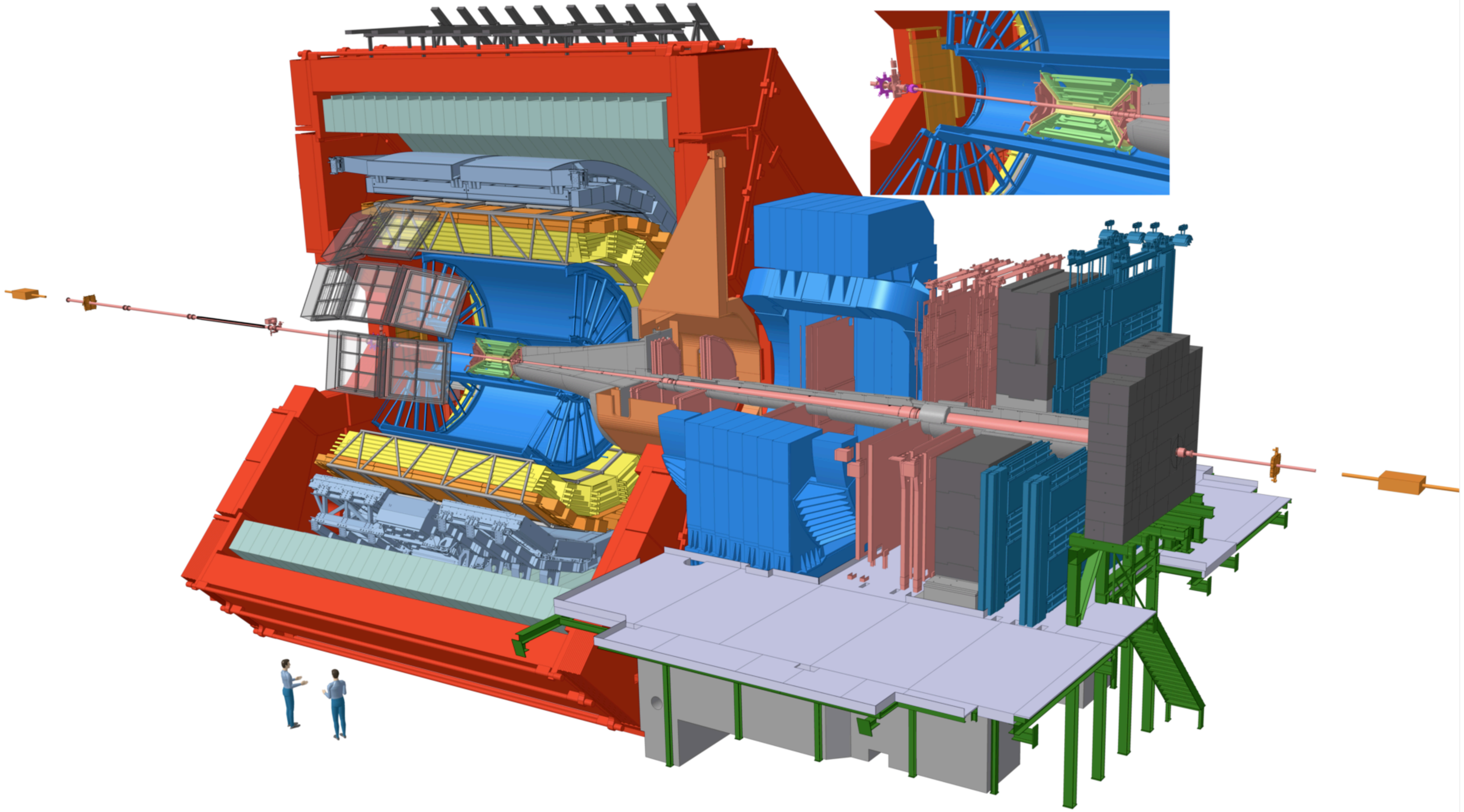
- Production yields/ratios, nuclear modification factors and elliptic flow have been proposed as observables to learn about the elusive nature of these particles

Objective for study in pp and p-Pb collisions:

- First measurement of production yield at the LHC in inelastic pp collisions
- Proof of feasibility
- Provide a fundamental baseline for measurements in Pb-Pb collisions at the same energy to probe hadronic phase
- Investigation of strangeness content

A Large Ion Collider Experiment

Run 2 configuration

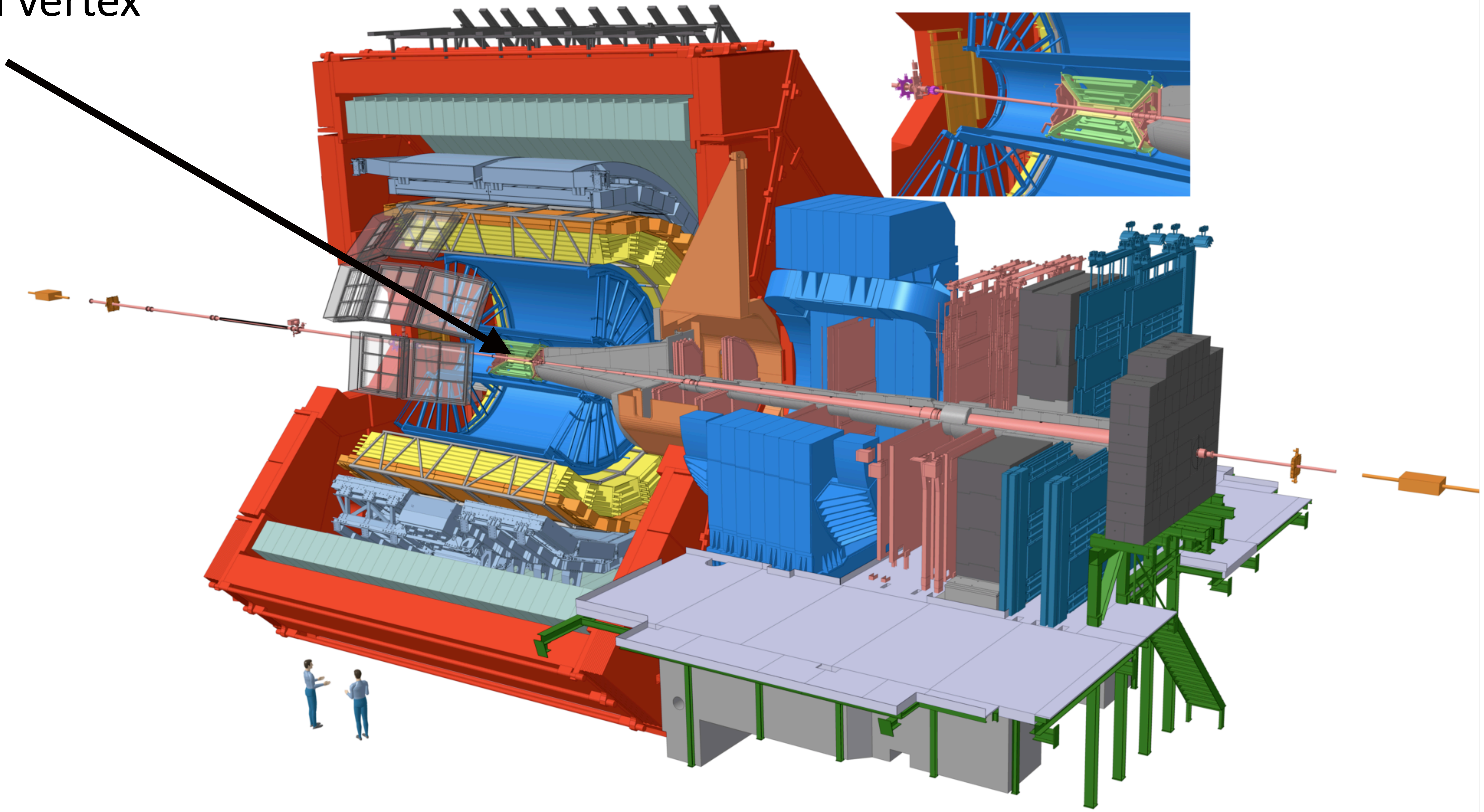


A Large Ion Collider Experiment

Run 2 configuration

Inner Tracking System (ITS)

Tracking and vertex



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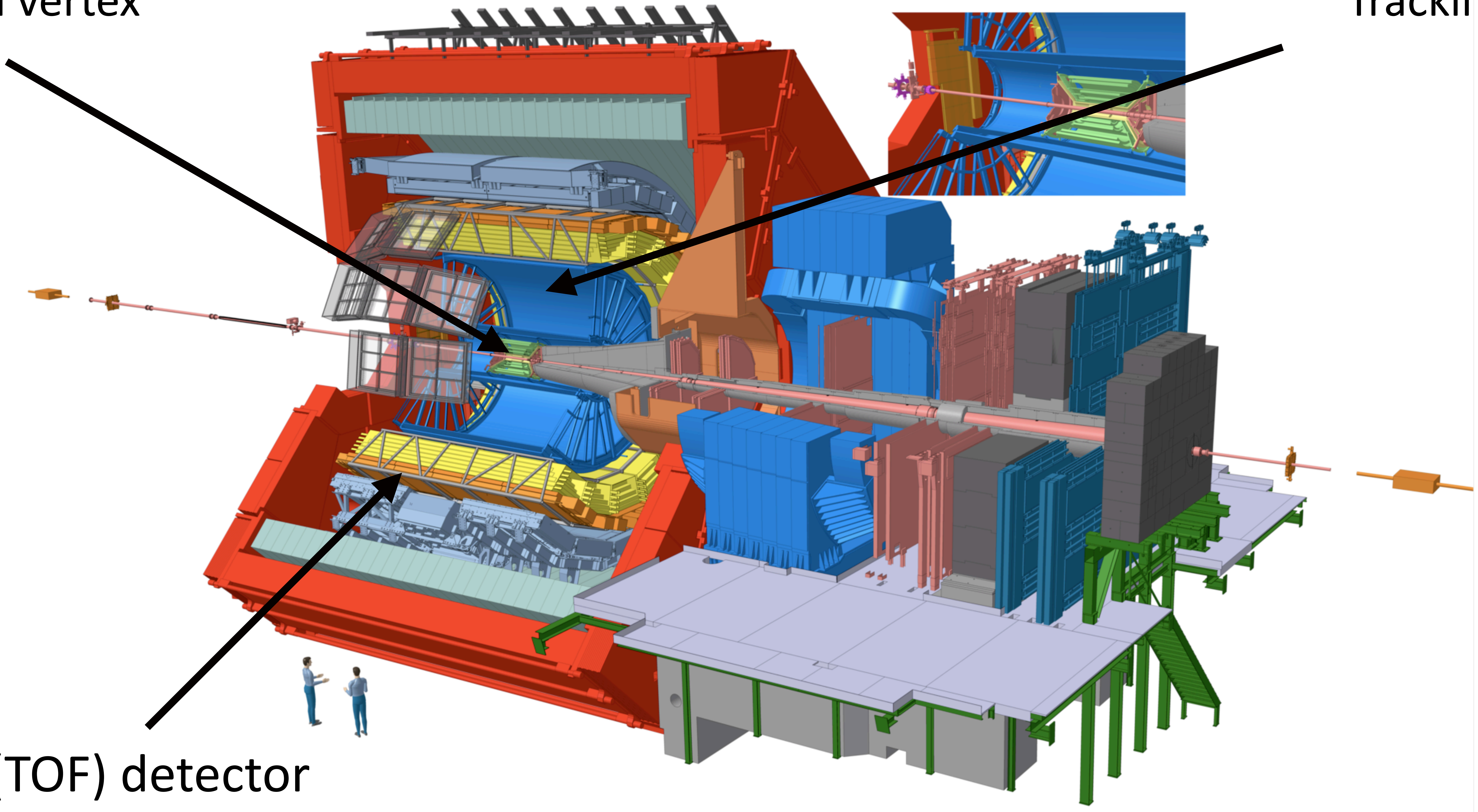
Time Projection Chamber (TPC)
Tracking and PID (dE/dx)



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

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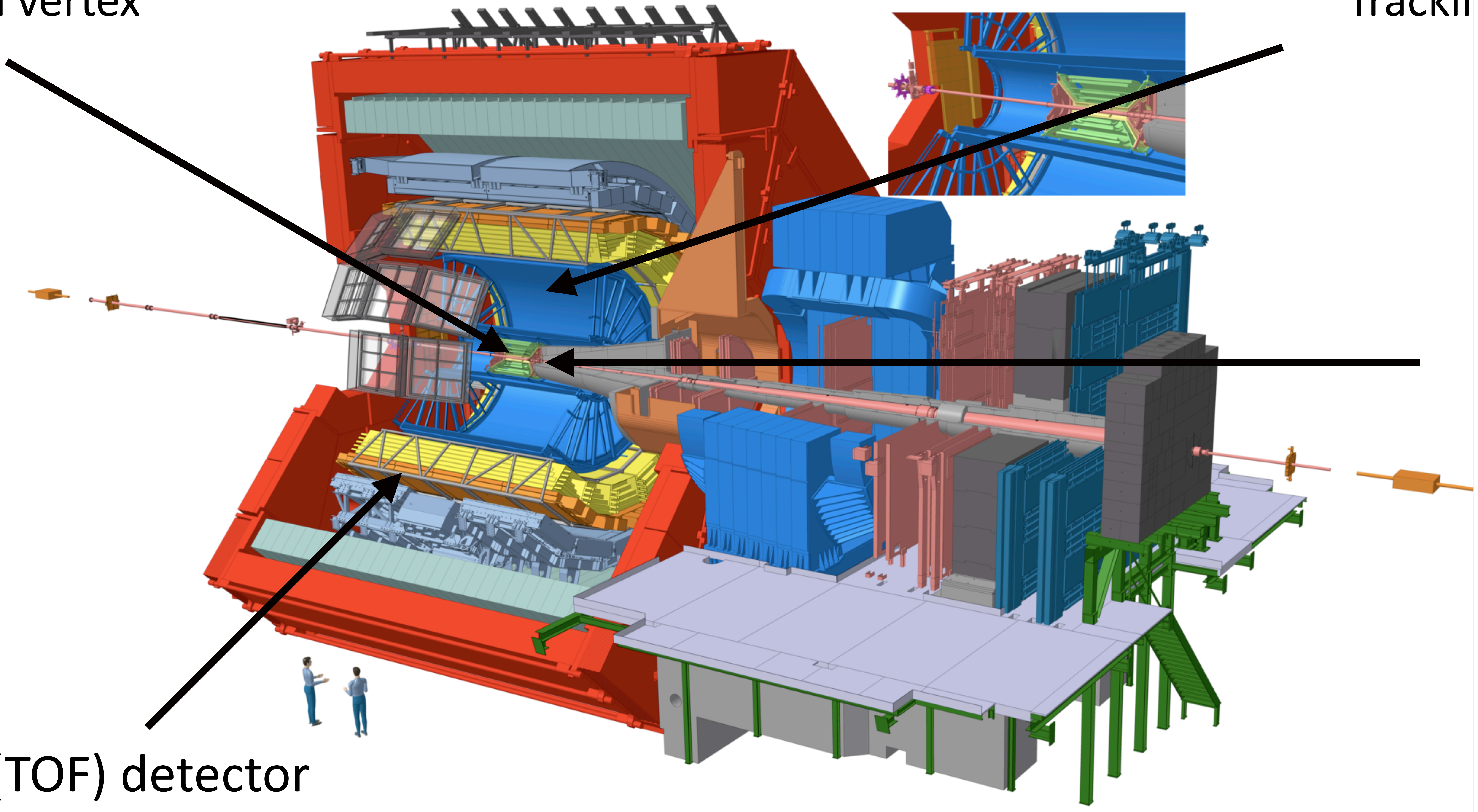
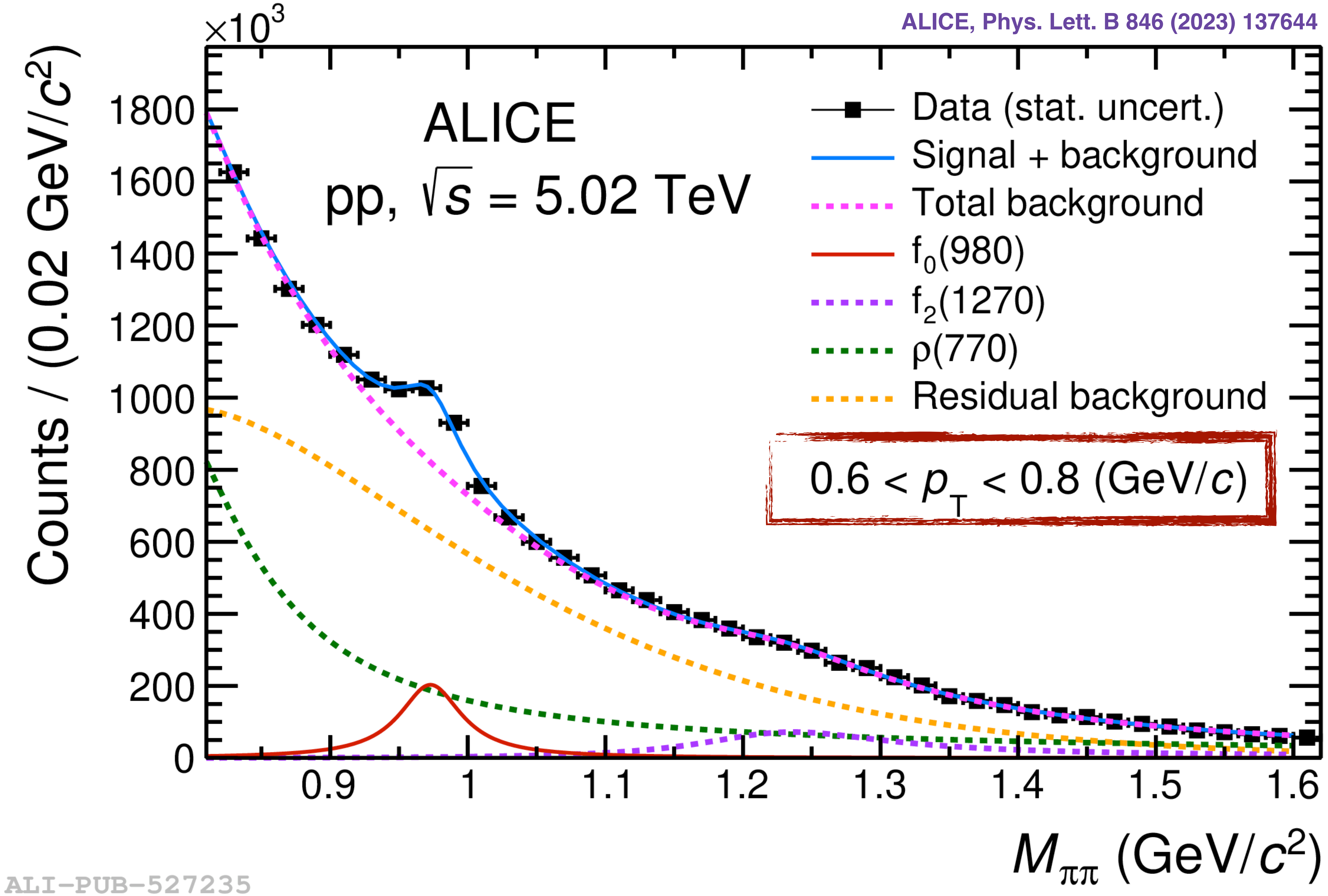


V0
Trigger, multiplicity estimator

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

$f_0(980)$ signal extraction

ALICE, Phys. Lett. B 846 (2023) 137644



ALI-PUB-527235

Signal is extracted via invariant mass analysis

f_0 (980) → $\pi^+ + \pi^-$ channel

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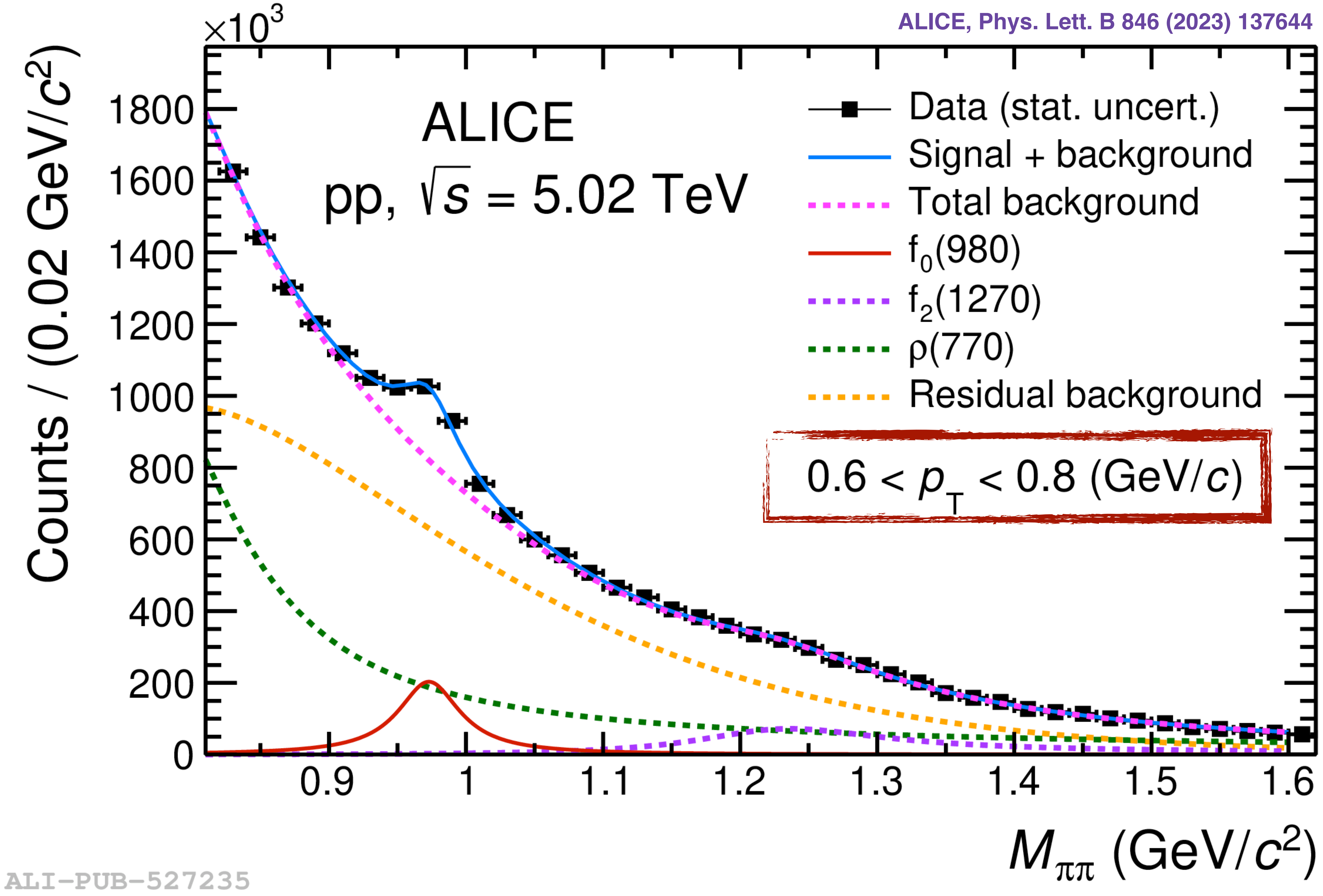

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Contribution from three resonances: f_0(980), ρ(770) and f_2(1270): described by Relativistic Breit-Wigner distribution

$$f(M_{\pi\pi}) = \frac{M_{\pi\pi}\Gamma M_0}{(M_{\pi\pi}^2 - M_0^2)^2 + M_0^2\Gamma^2}$$

$$\Gamma = \Gamma_0 \times (M_0/M_{\pi\pi}) \times \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_0^2 - 4m_\pi^2}\right)^{(2J+1)/2}$$

M_0 and Γ_0 are the mass and width of the resonance, respectively. J is the spin of the particle.

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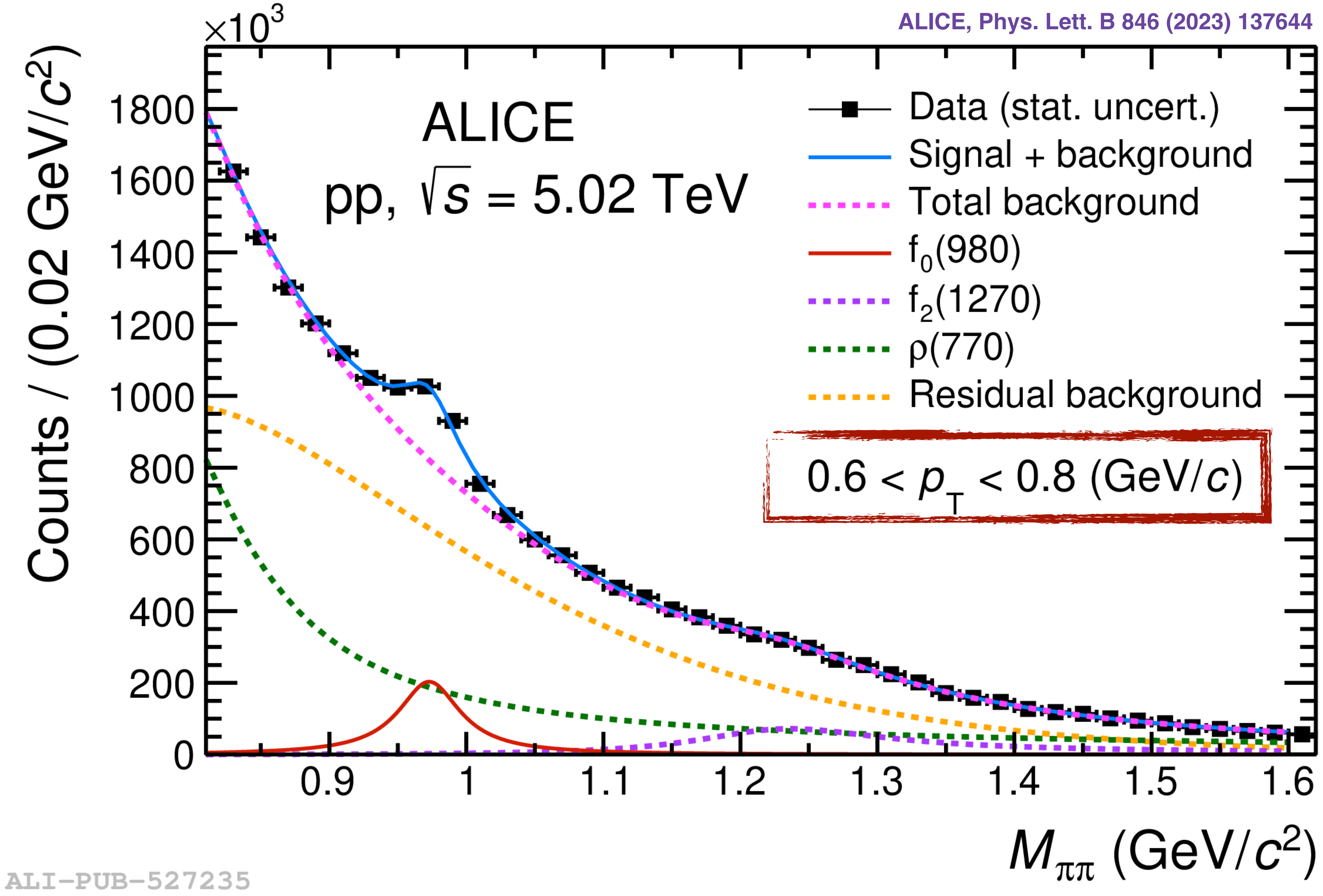

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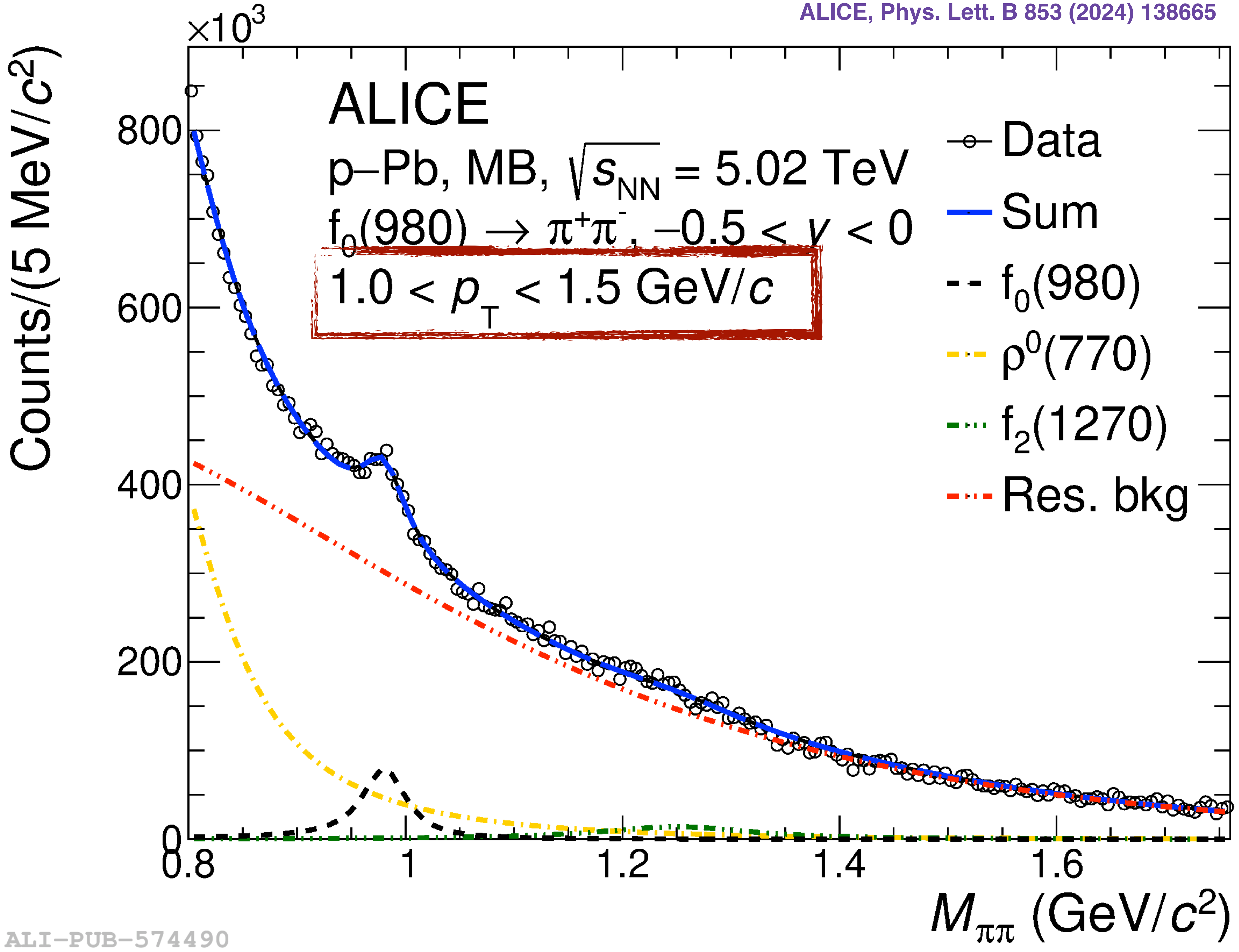

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Insight into quark content with particle ratios

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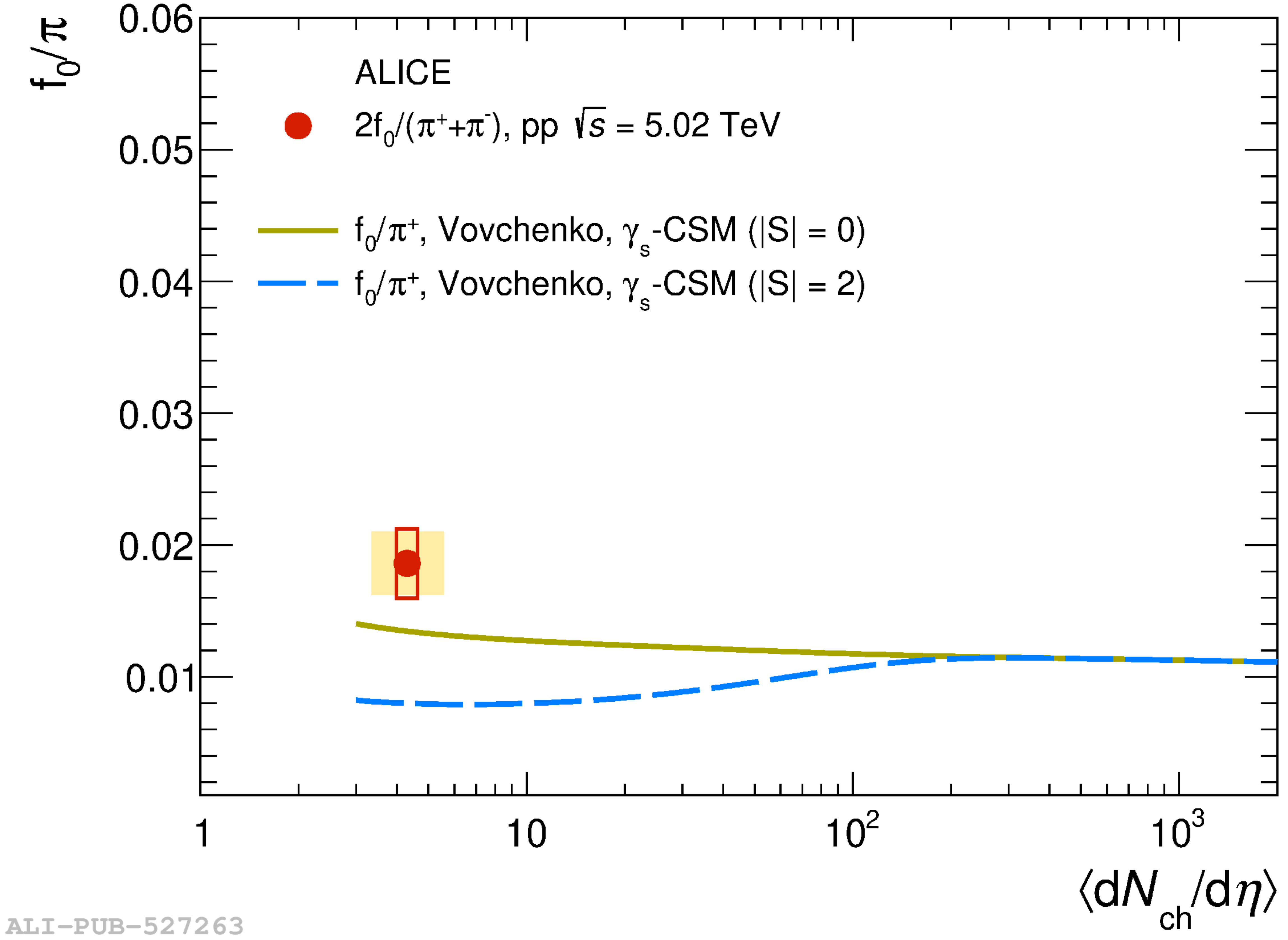

ALI-PUB-527263

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|S|: Total number of strange/anti-strange quarks inside the hadron

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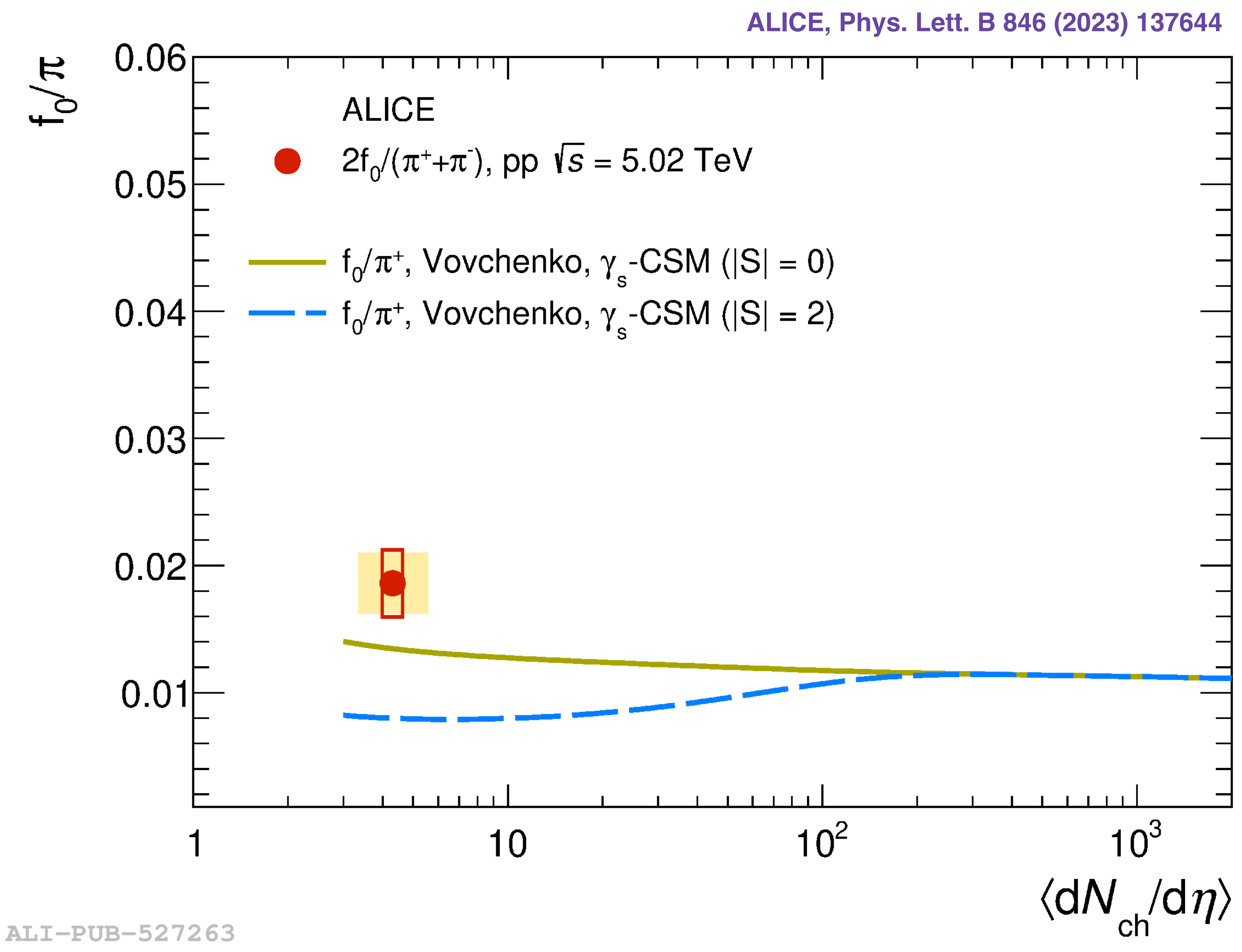

V. Vovchenko et. al., Phys. Rev. C100, (2019) 054906

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- In CSM, the hadron production is subjected to canonical suppression, namely the exact conservation of baryon number, charge, and strangeness over the correlation volume.
- γ_s-CSM incorporates incomplete equilibration of strangeness by introducing a strangeness saturation factor (γ_s)
- Predictions based on the γ_s-CSM are calculated assuming two scenarios:
  - |S| = 0 —> meson with no strange quark (differ by 1.9σ)
  - |S| = 2 —> meson with $s\bar{s}$ quark (differ by 4σ)
  - The two predictions match each other for $\langle dN_{ch}/d\eta \rangle \geq 100$

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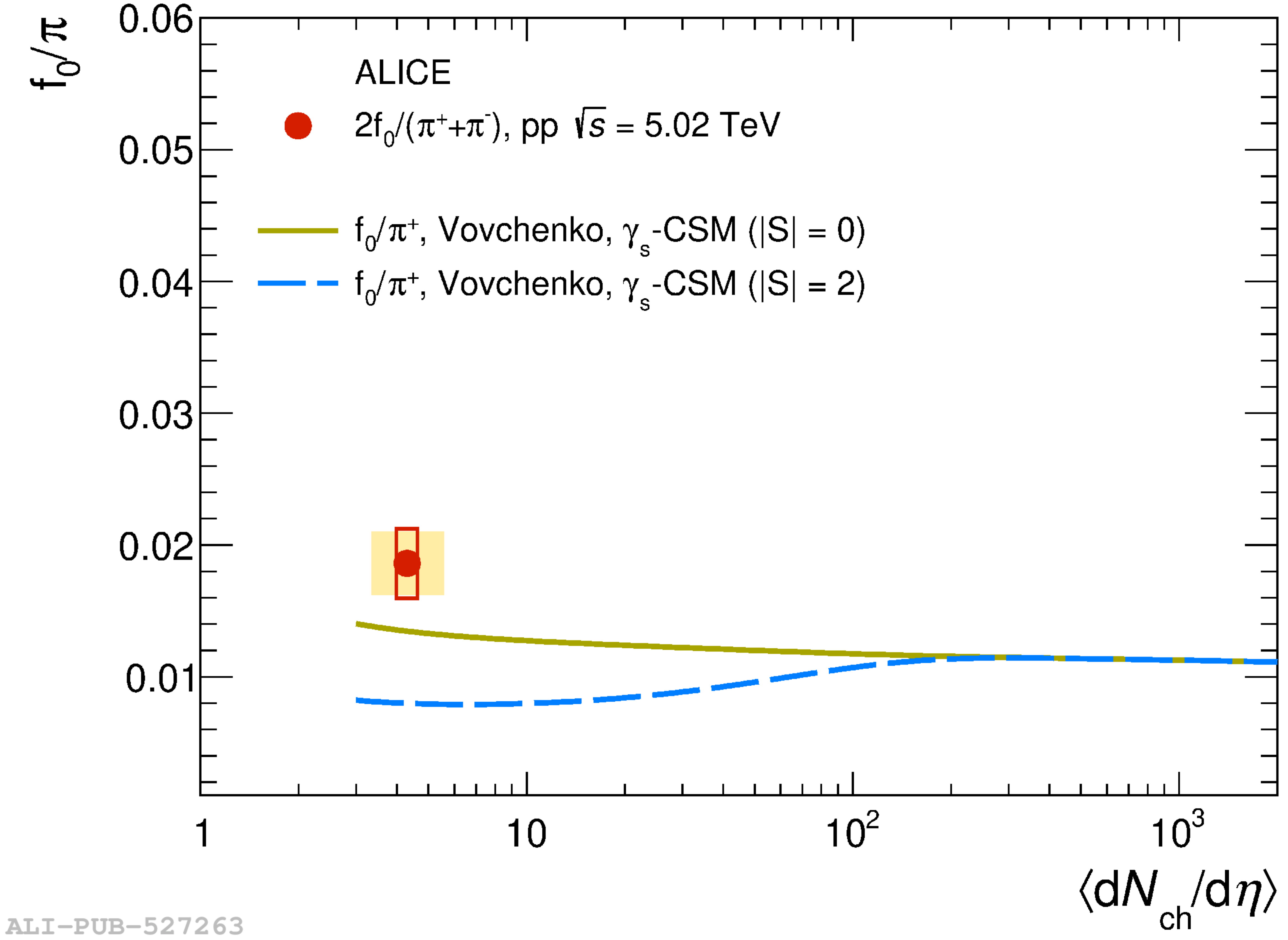

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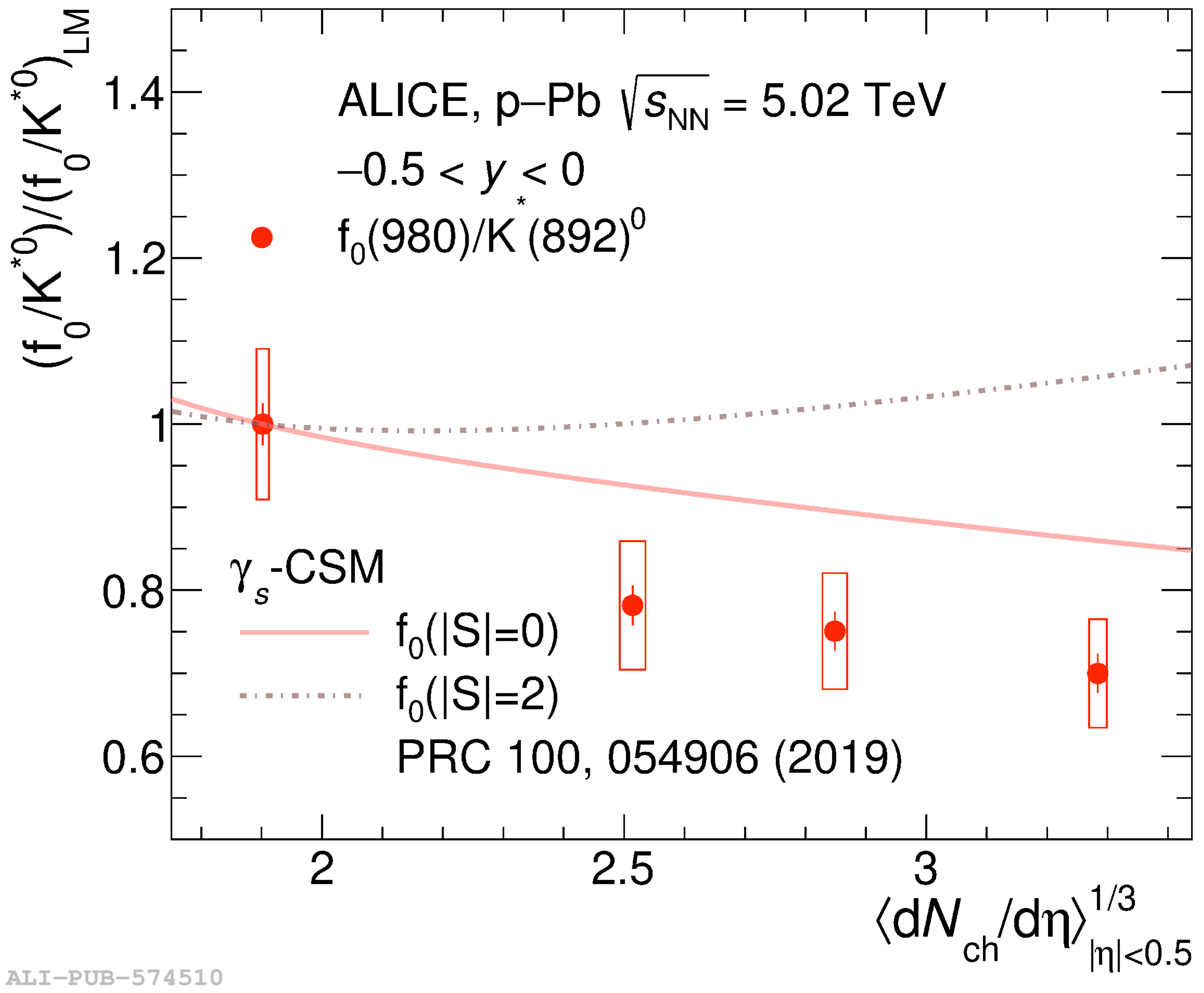

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- Measurements disfavor |S| = 2 quark configuration

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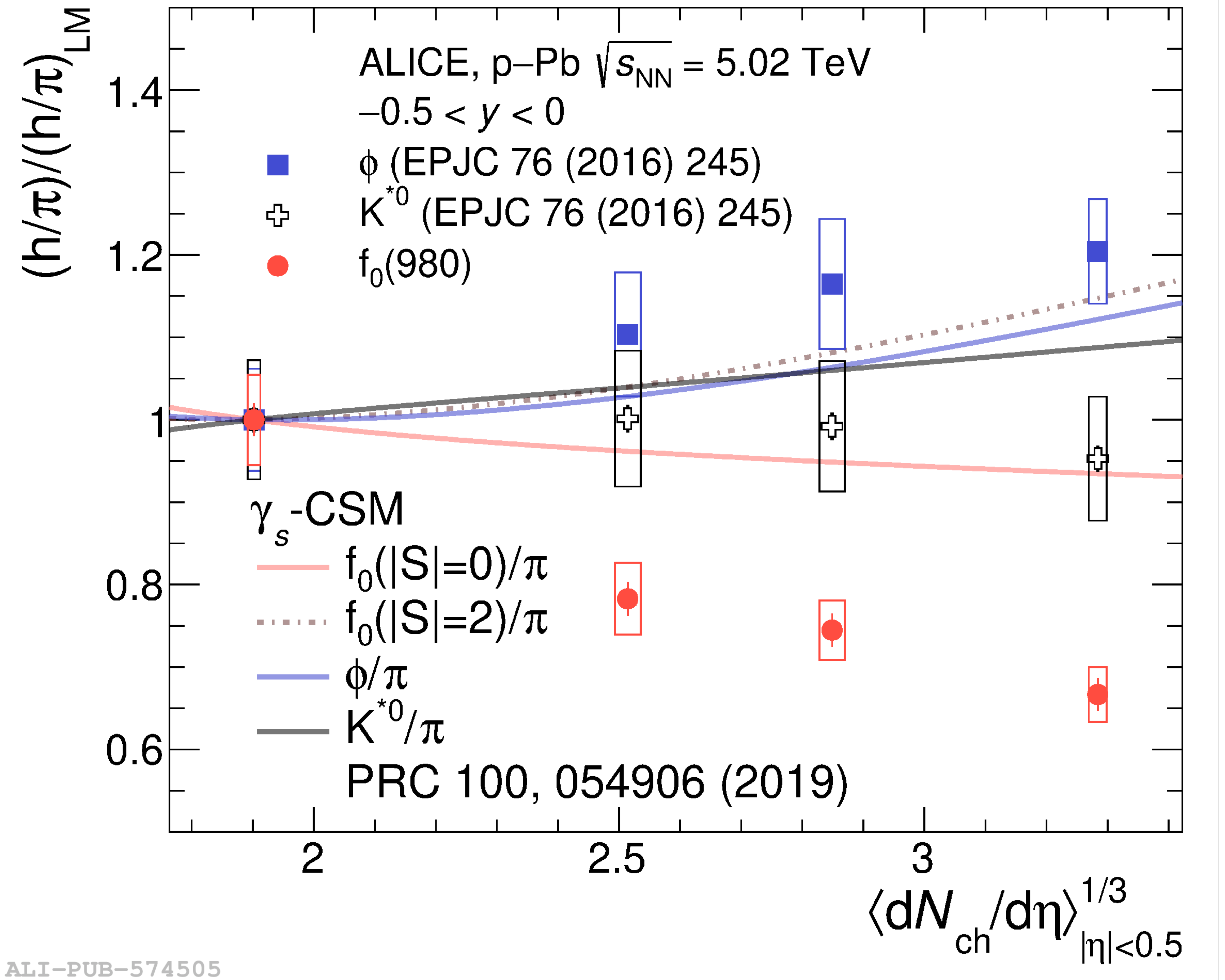

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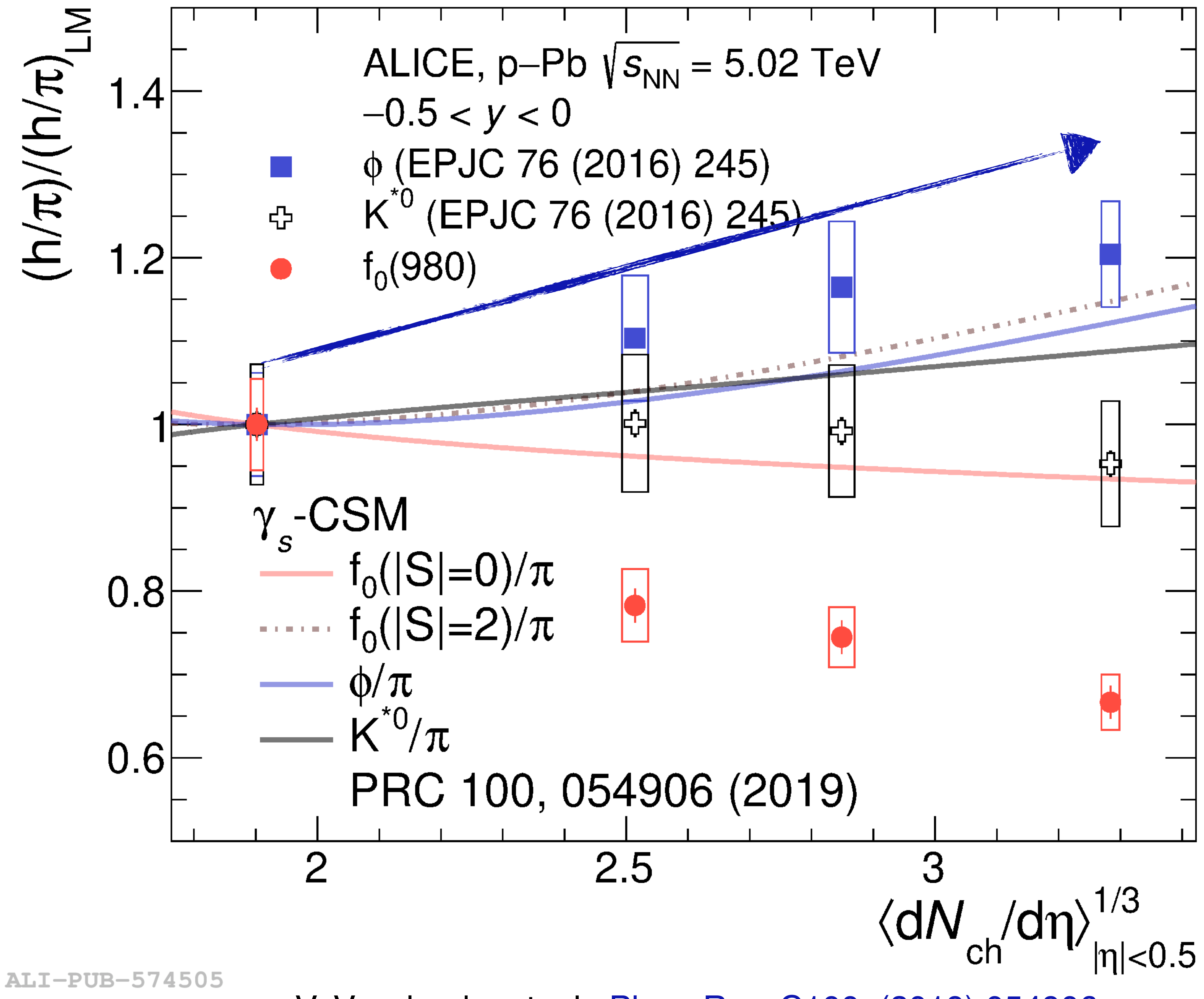

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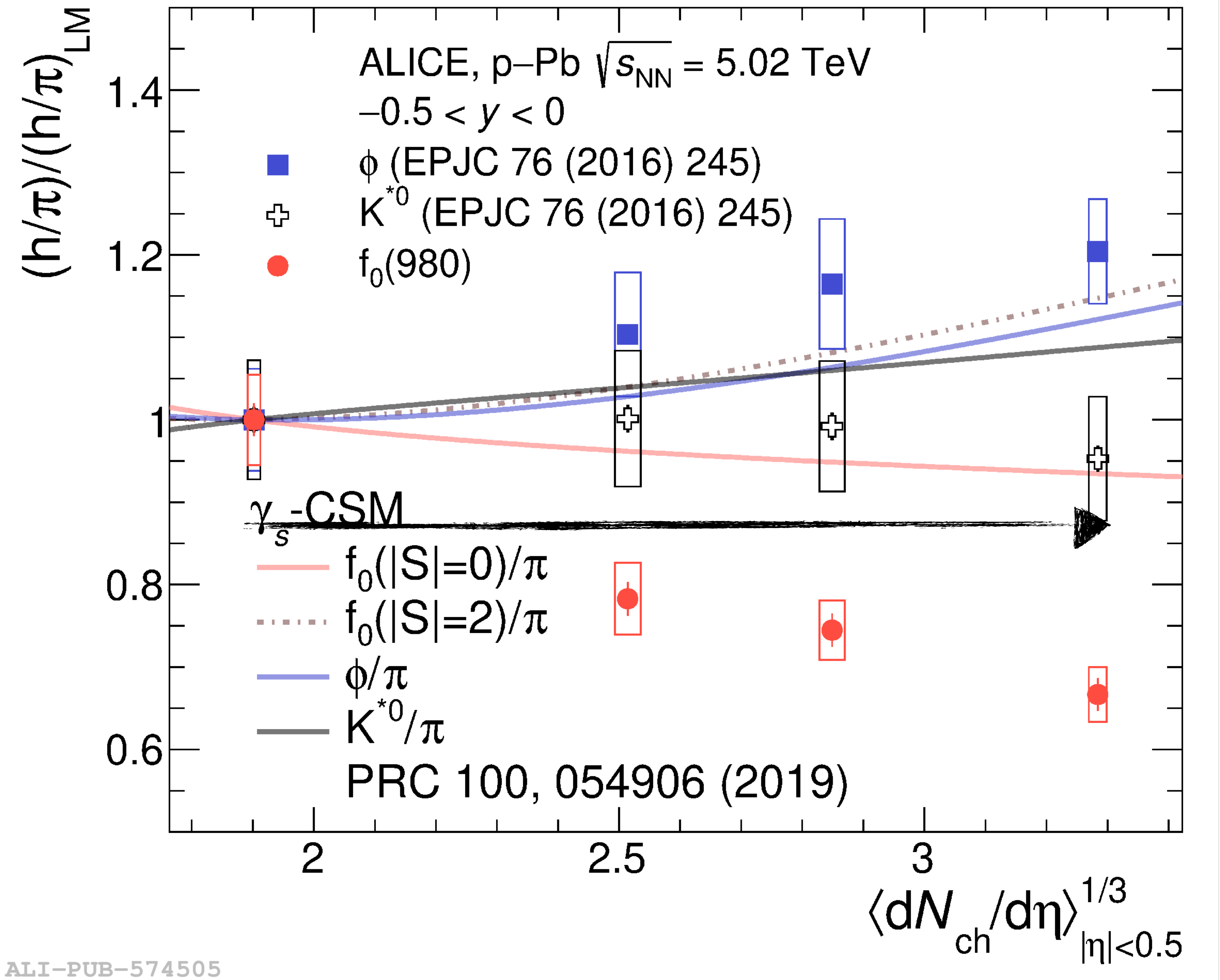

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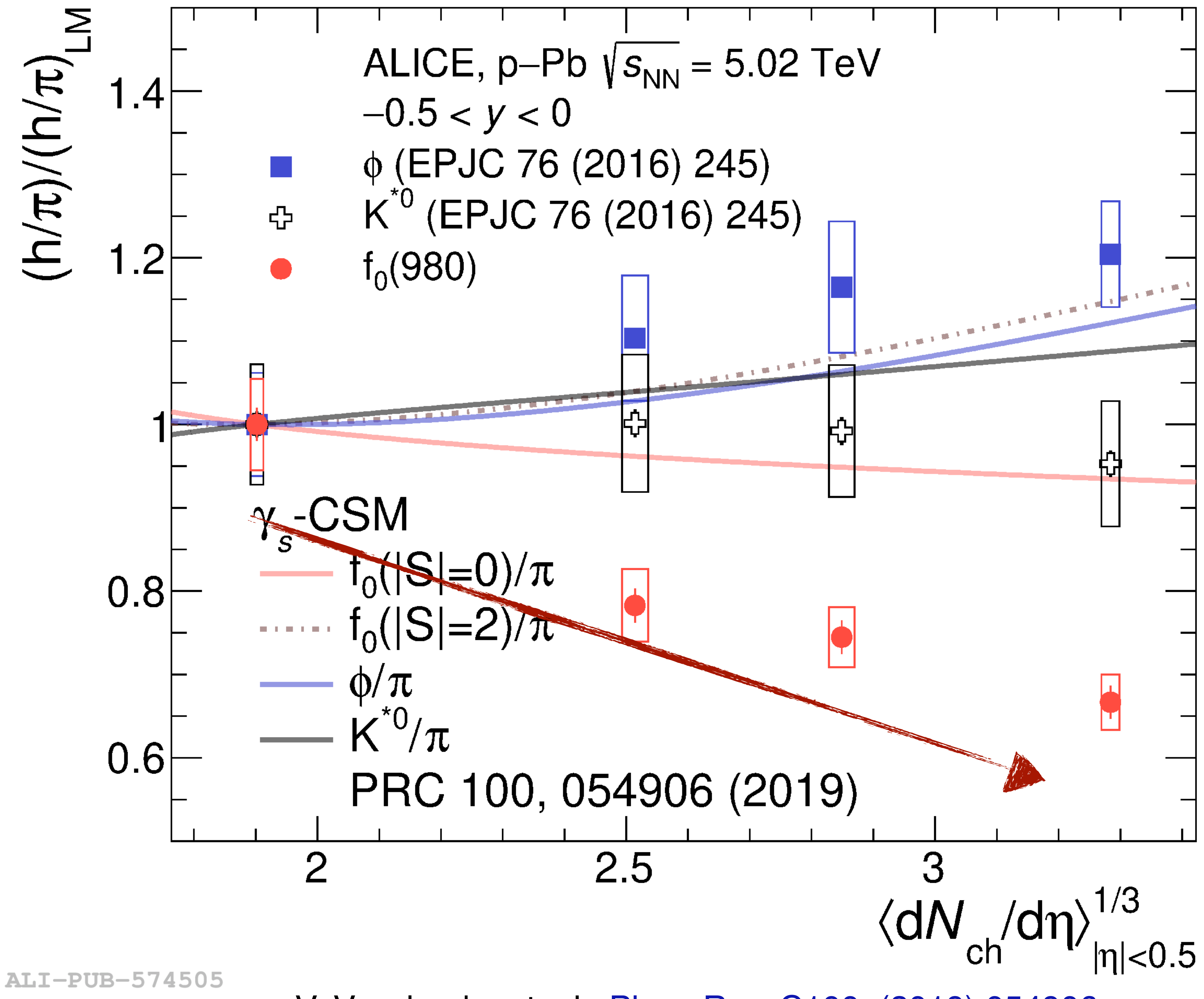

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- ϕ/π: data suggests a strangeness enhancement but γ_S-CSM that incorporate incomplete thermal equilibrium, explains the data
- K^{*0}/π: Competition between strangeness enhancement and rescattering effect is observed
- $f_0(980)/\pi$: Significant suppression of $f_0(980)/\pi$ is seen: larger rescattering effect of decay daughters of $f_0(980)$ than K^{*0}

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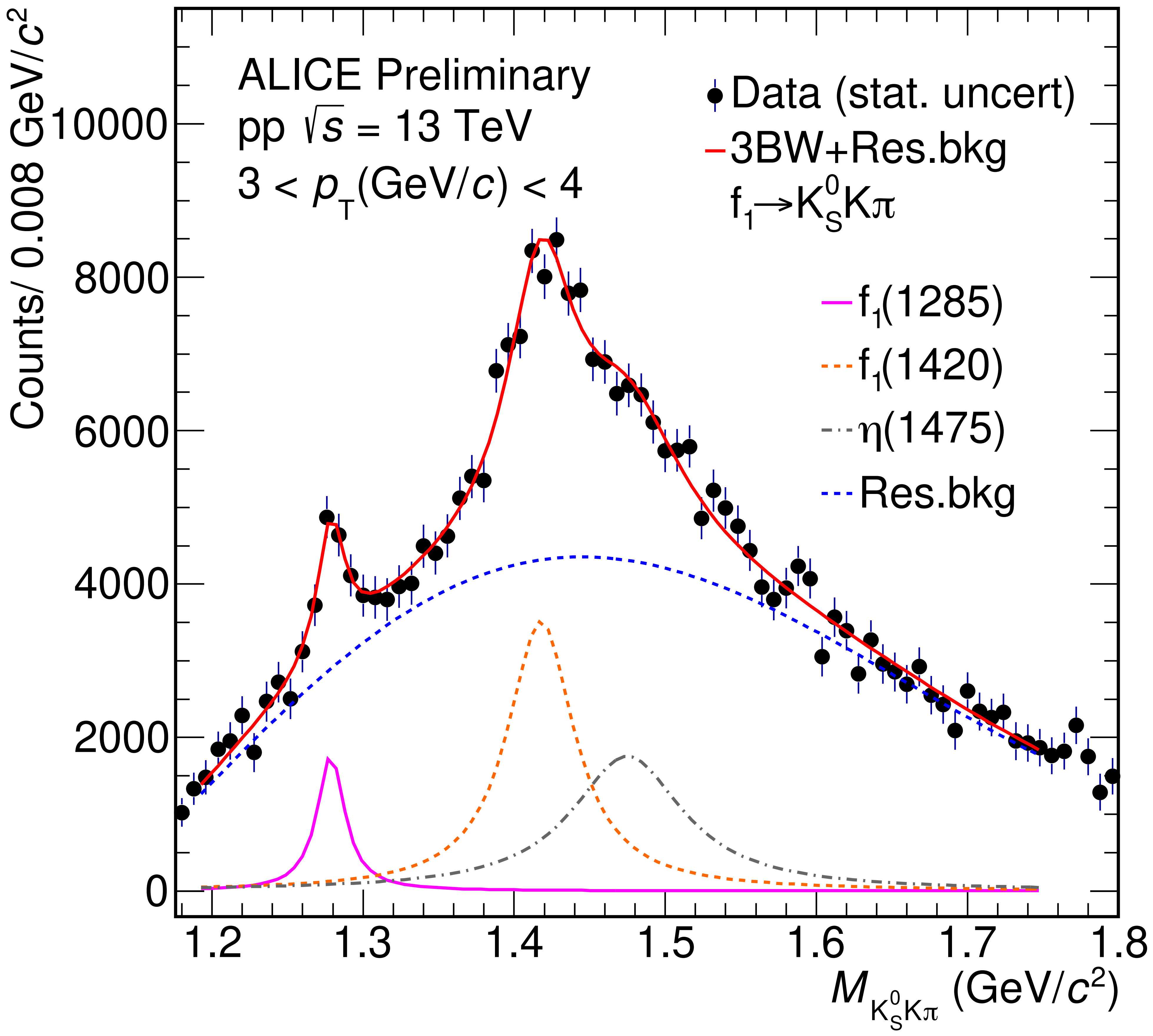
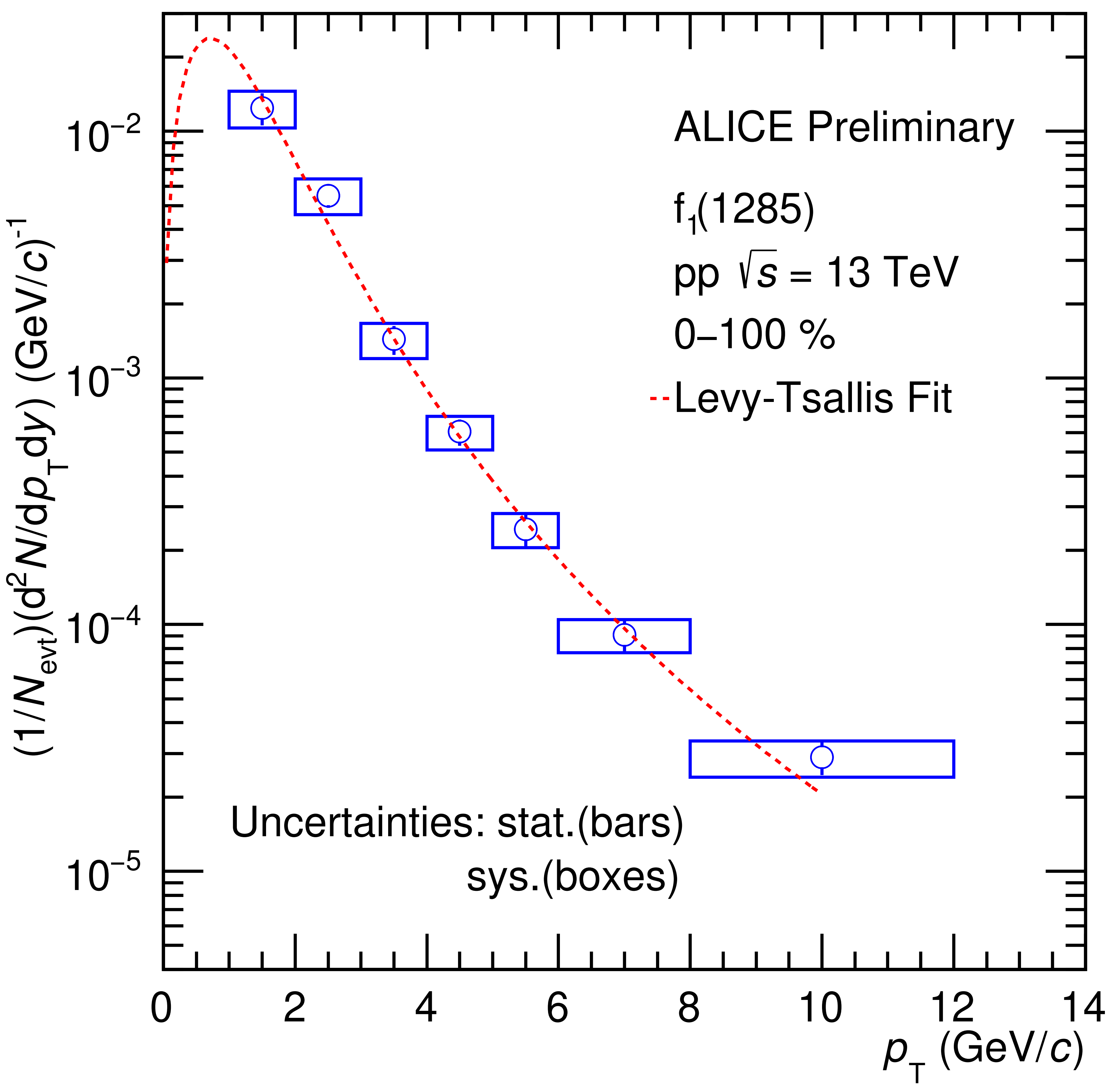
Measurement of $f_1(1285)$



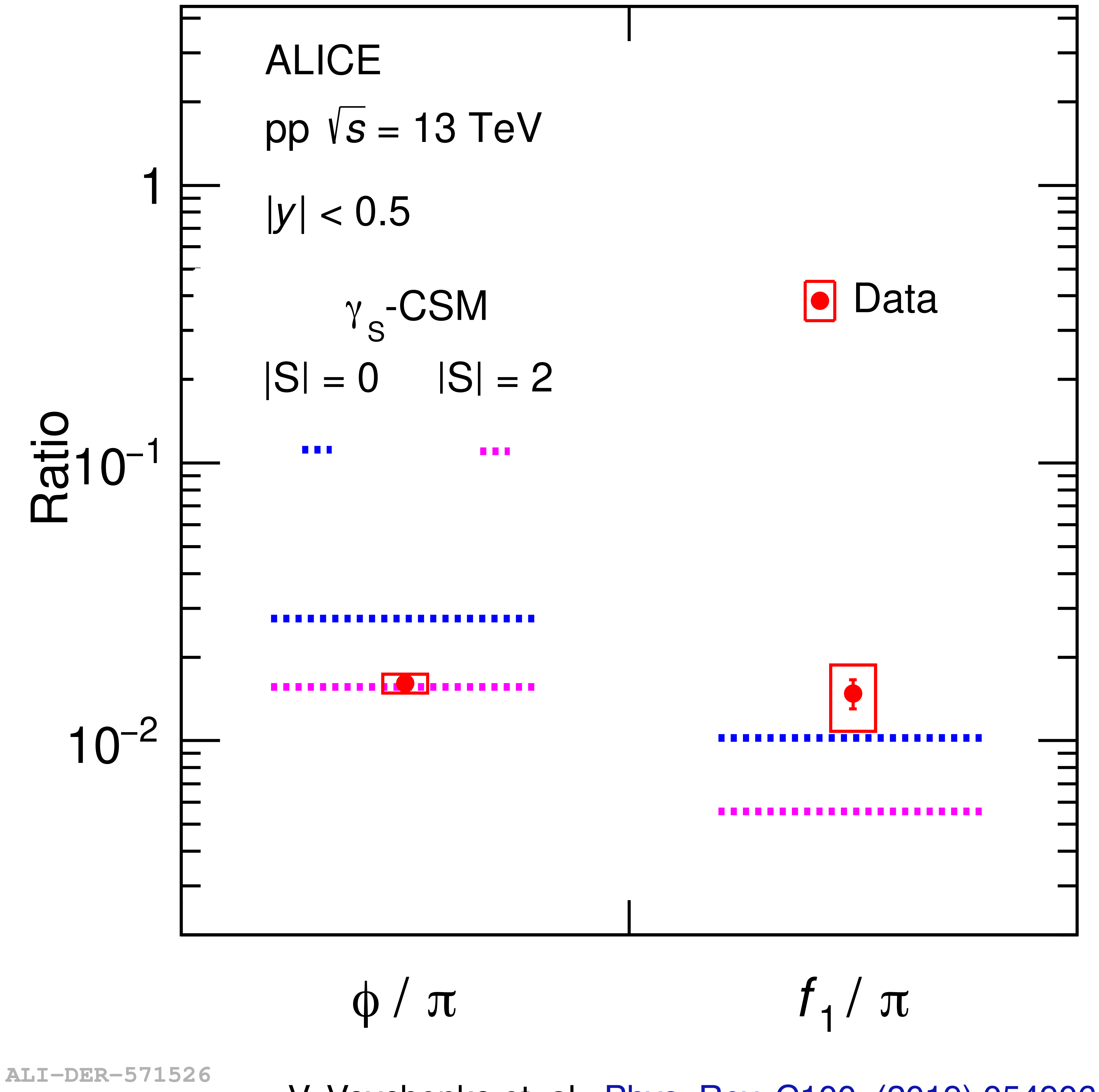
ALI-PREL-548632



ALI-PREL-548654

- First observation of $f_1(1285)$ in ALICE
- Invariant mass distribution modelled using 3 Breit-Wigner + Residual function

Insight into quark content with particle ratios

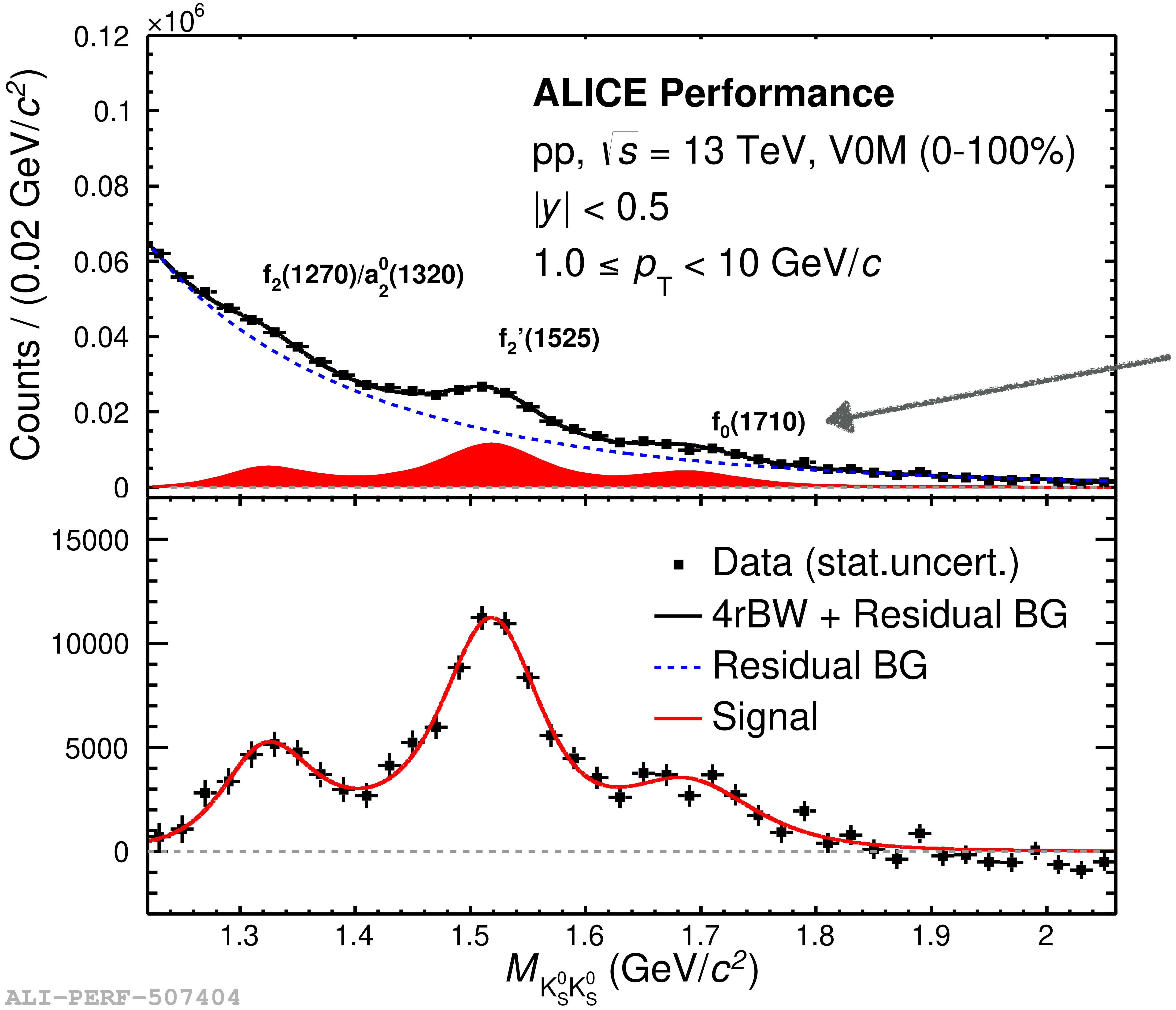


V. Vovchenko et. al., Phys. Rev. C100, (2019) 054906

- ϕ is composed of $s\bar{s}$ in γ_s-CSM
- ϕ/π is consistent with ISI = 2

- f_1/π is consistent with ISI = 0 within 1σ
- f_1/π differ ISI = 2 by 2.1σ

Glueball hunt



- Particles composed entirely of gluons
- f0(1710) in $K^0_S K^0_S$ decay channel could be a glueball candidate

  ZEUS collaboration, Phys.Rev.Lett.101 (2008) 112003

- Invariant mass distribution modelled using Relativistic Breit-Wigner + Maxwell Boltzmann distribution

Summary and outlook

- The first measurements of the production cross-section of $f_0(980)$ and $f_1(1285)$ production in inelastic pp collisions at the LHC are presented
- The predictions based on the γ_S-canonical statistical hadronisation model assuming net strangeness equal to zero seem to be favoured for both particles
- These results provide the necessary baseline for the future measurements of the production and the nuclear modification factor in Pb–Pb collisions at the LHC
- Promising signals of glueball candidates in ALICE
- Stay tuned for more exciting results with large statistics Run 3 data

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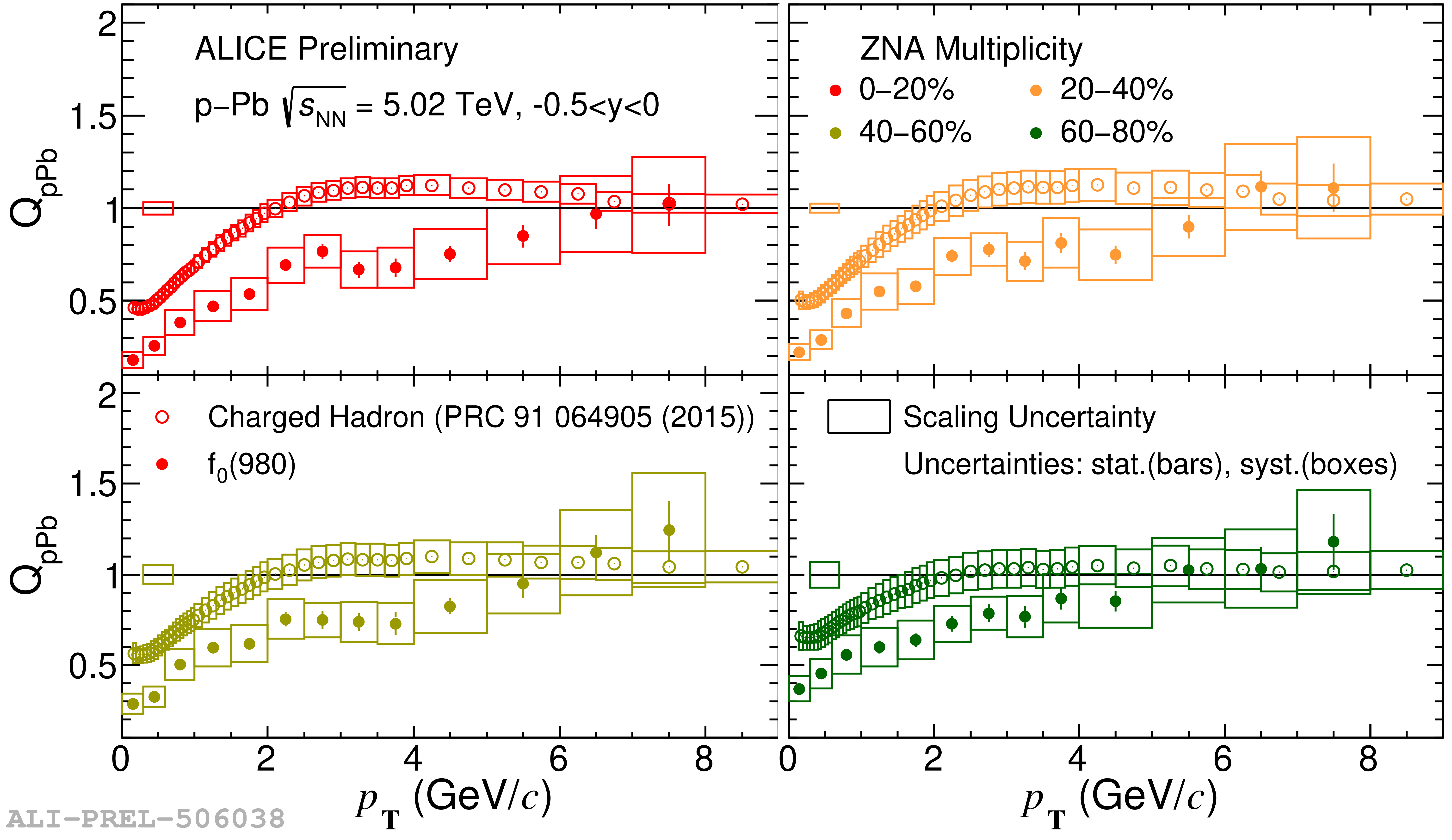
Thank you for your attention!

Backup

Nuclear modification factor, Q_{pPb}

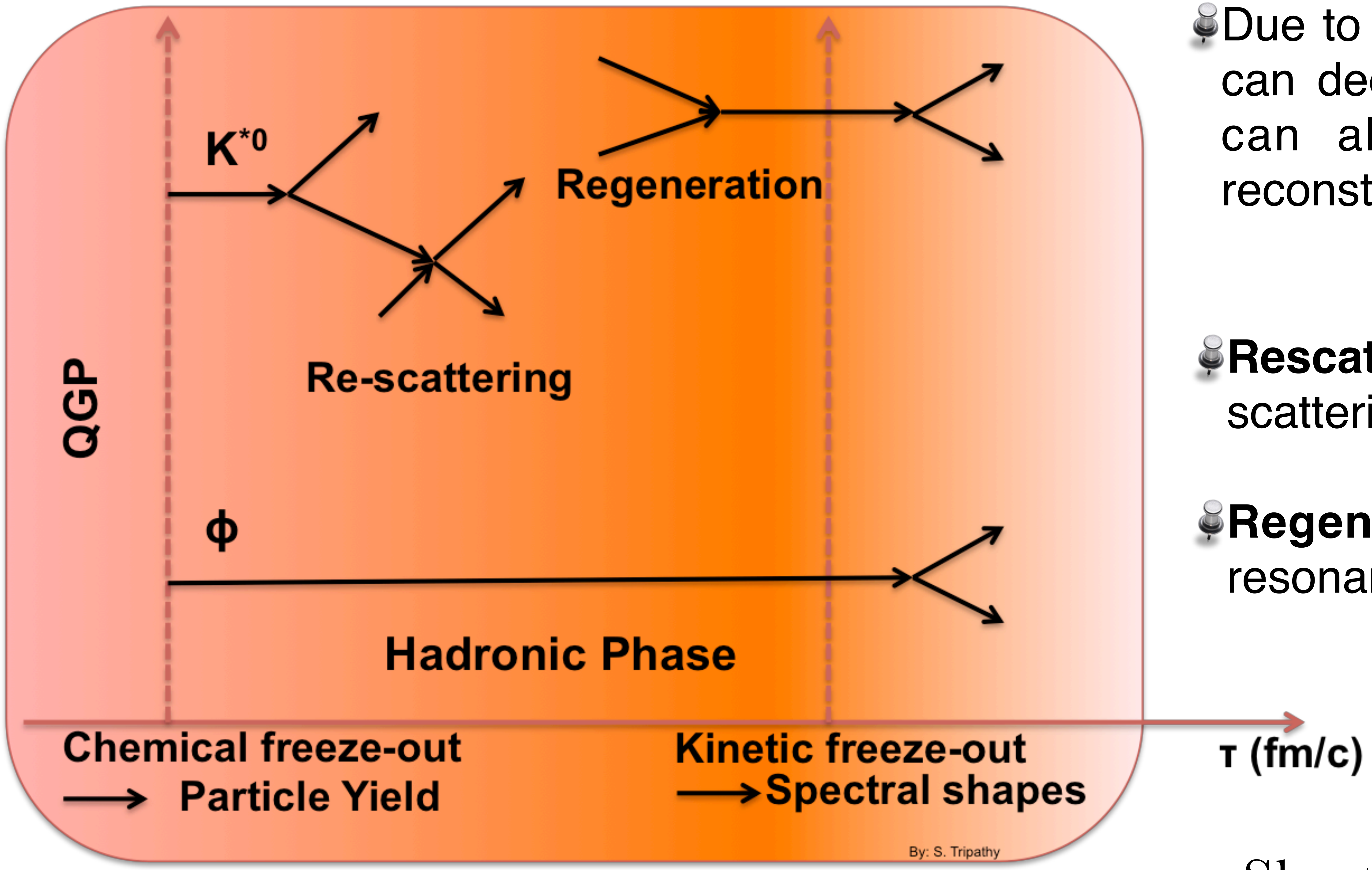


$$Q_{pPb}(p_T, \text{cent}) = \frac{d^2N^{cent}_{pPb}/dydp_T}{\langle T^{cent}_{pPb}\rangle \times d^2\sigma^{INEL}_{pp}/dydp_T}$$

$$\langle T^{cent}_{pPb}\rangle = N^{cent}_{coll}/\sigma_{NN},\ \sigma_{NN} = 70 \pm 5 \text{ mb}$$

- A strong centrality dependent suppression of $f_0(980)$ in low-p_T is observed with respect to charged hadrons
  - possible explanation could be due to larger re-scattering effect of decay daughters of $f_0(980)$ in more central collisions

Introduction



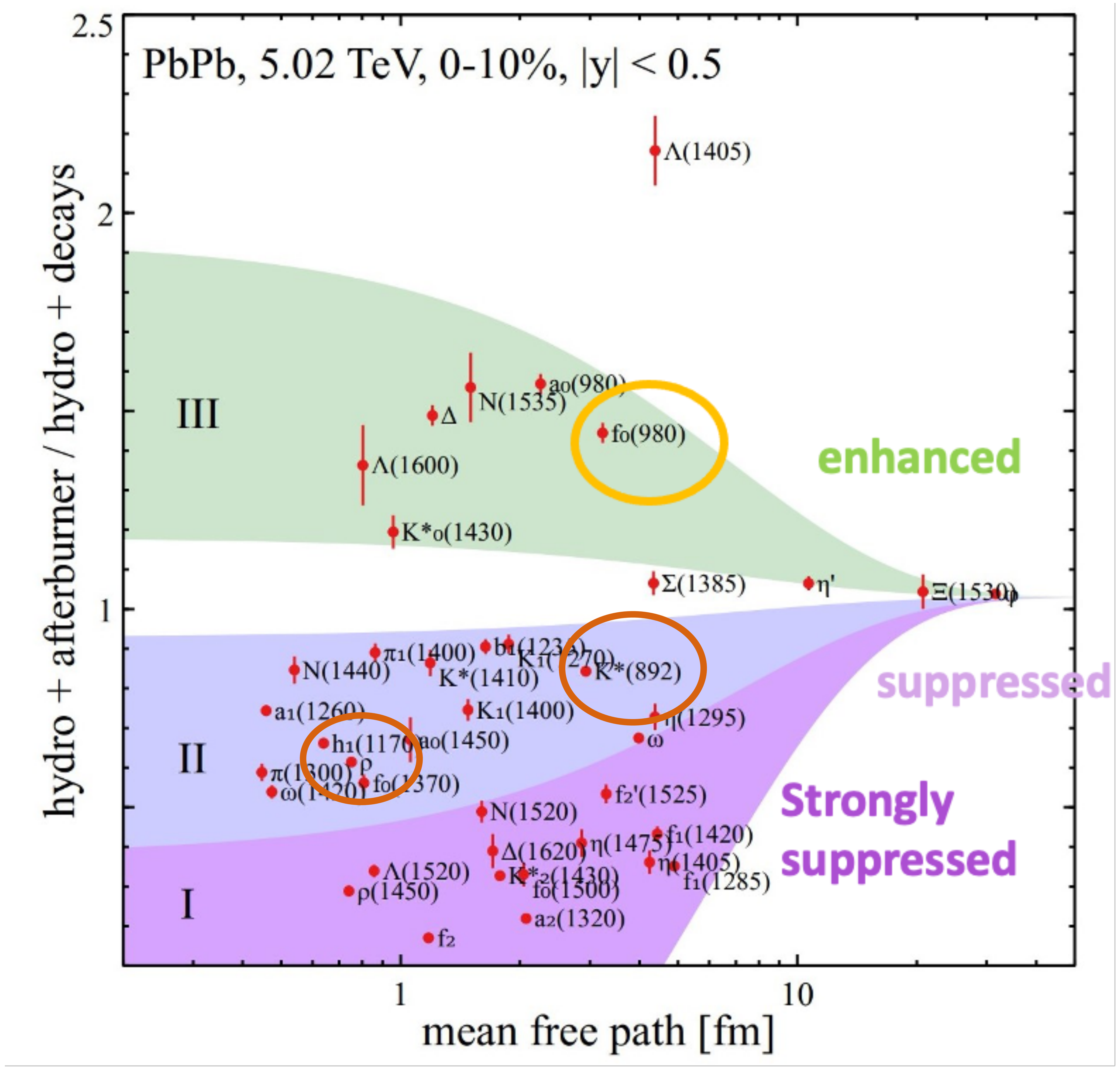
- Due to their short lifetimes (τ ~ few fm/c), resonances can decay within the hadronic medium which in turn can alter their final yields via invariant mass reconstruction

- **Rescattering:** Decay products may undergo elastic scattering - Suppression of resonance yields

- **Regeneration:** Pseudo-elastic scattering through resonance state - Enhancement of resonance yields

Short lifetimes ⟶ Probing the hadronic phase

Introduction and motivation



D. Oliinychenko et. al., arXiv:2105.07539

- $f_0(980)$, a scalar meson, is an interesting particle due to its debated nature:
  - tetra-quark candidate in the LF sector (?)
    Phys. Rev. D103, 014010 (2021), Nucl. Phys. A728 (2003) 425
  - mix of di-quark and tetra-quark (?)
    Phys. Rev. D67, 094011 (2003), PTEP 2020, (2020) 083C01
  - K^+K^- molecule (?): Phys. Rev. D101, 094034 (2020), Eur. Phys. J. A56, (2020) 23

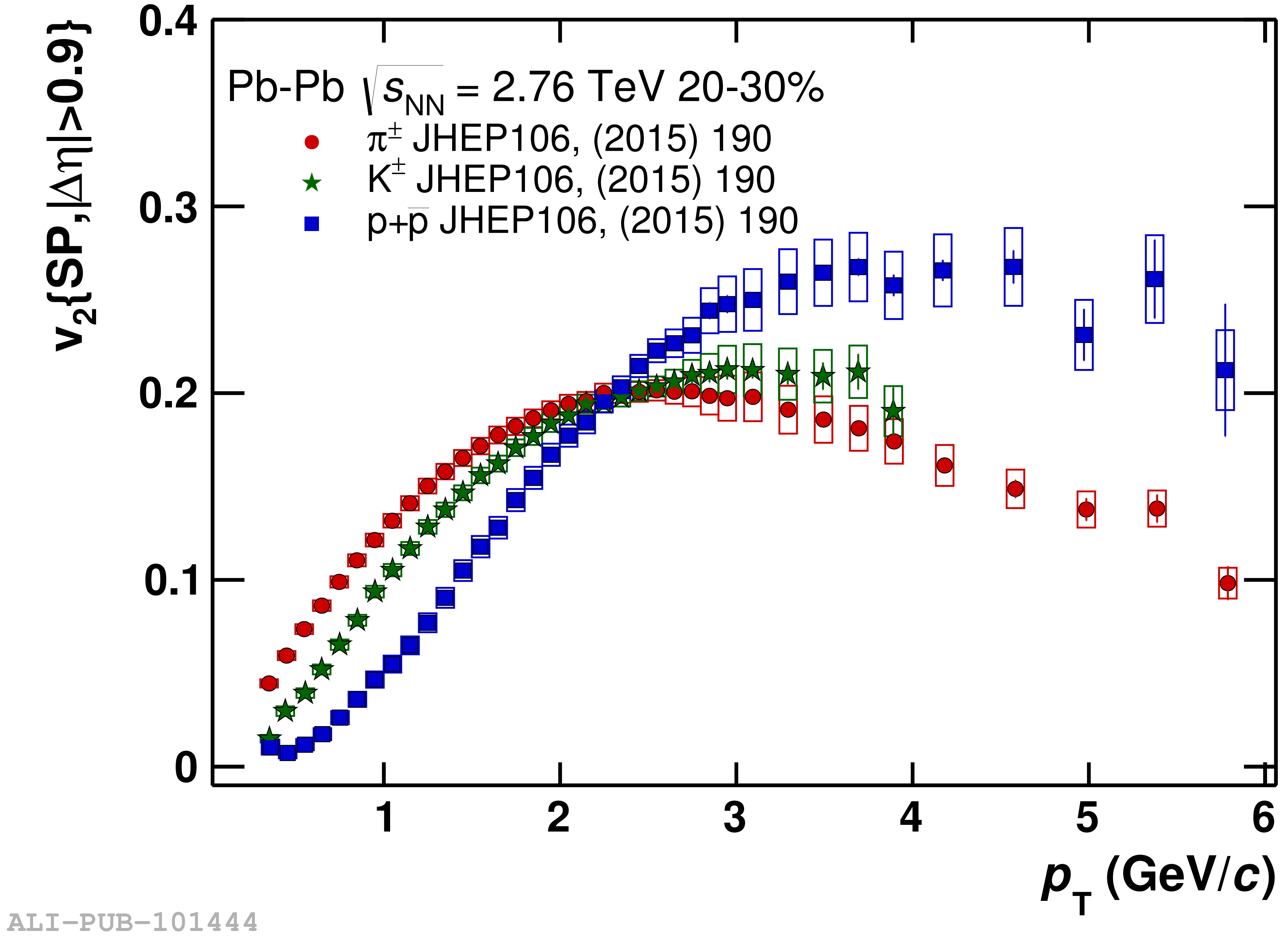
- $f_0(980)$ is a short-lived resonance (similar lifetime as K^{*0}) and it contributes to the study of the hadronic phase in AA collisions

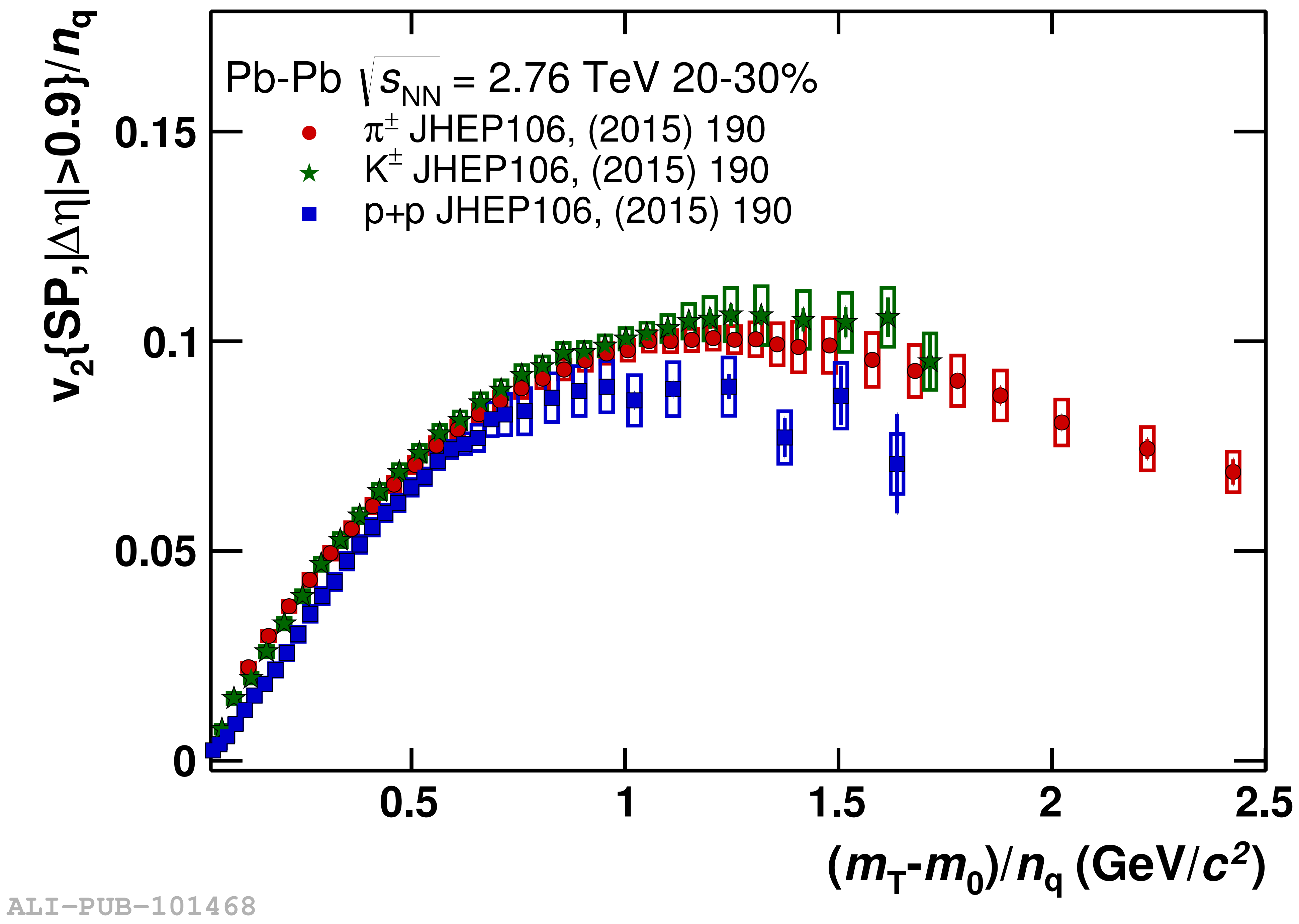
- Recent simulation results from hydro + hadronic afterburner (SMASH) suggest f_0 yield might get enhanced in the hadronic phase, contrary to K^{*0}.

Introduction and motivation

The azimuthal anisotropy in the $f_0(980)$ momentum distributions in heavy-ion collisions, quantified by the elliptic flow coefficient (v_2), could be sensitive to the number of constituent quarks (NCQ)

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]$$





ALICE, JHEP 06 (2015) 190

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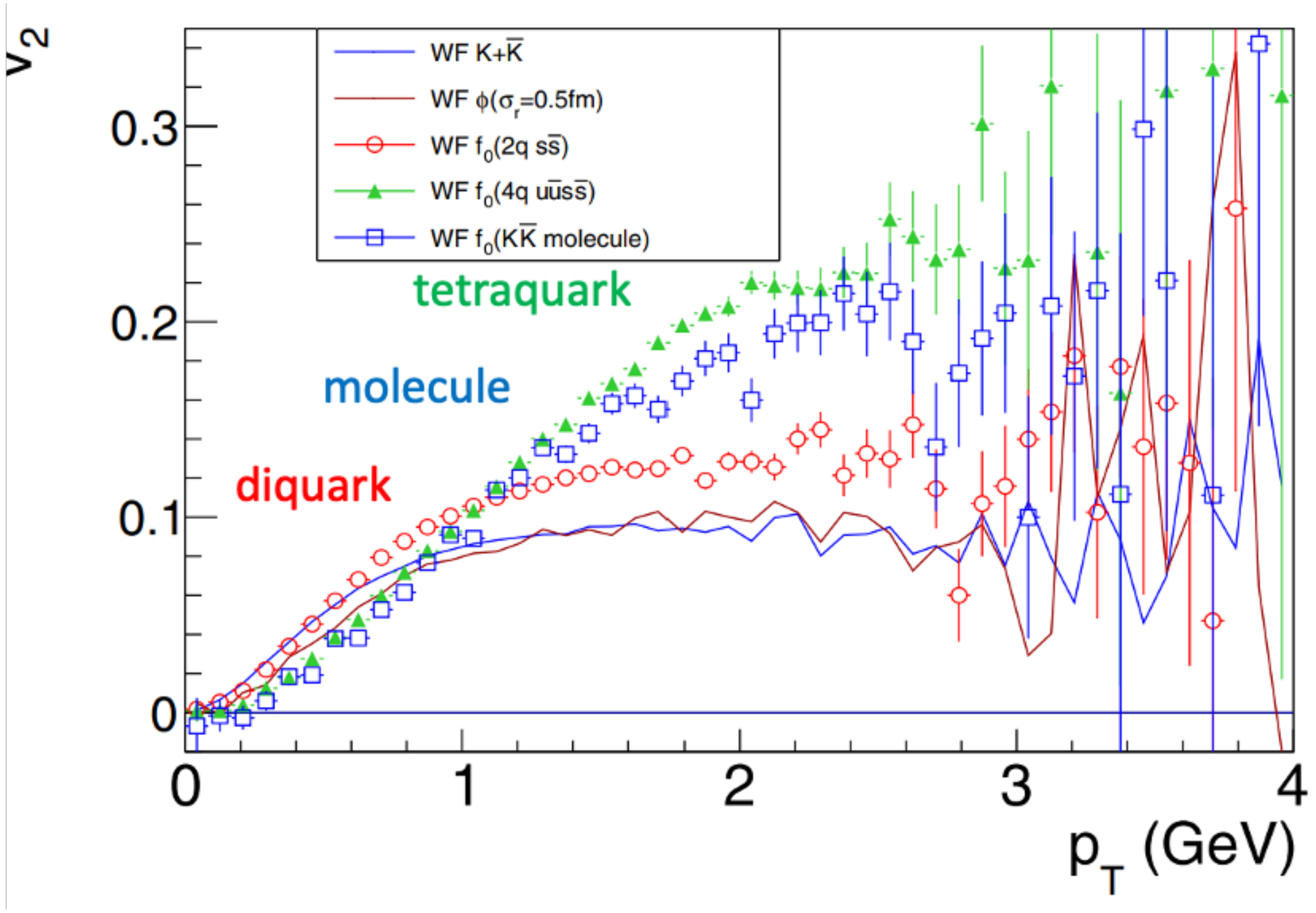


AMPT* model coupled with a coalescence afterburner with Gaussian Wigner function

An Gu et. al., Phys. Rev. D103, 014010 (2021)

*AMPT stands for A Multi-Phase Transport model that contains four main components namely initial conditions, partonic interactions, conversion from partonic to hadronic matter, and interactions among hadrons based on a relativistic transport model

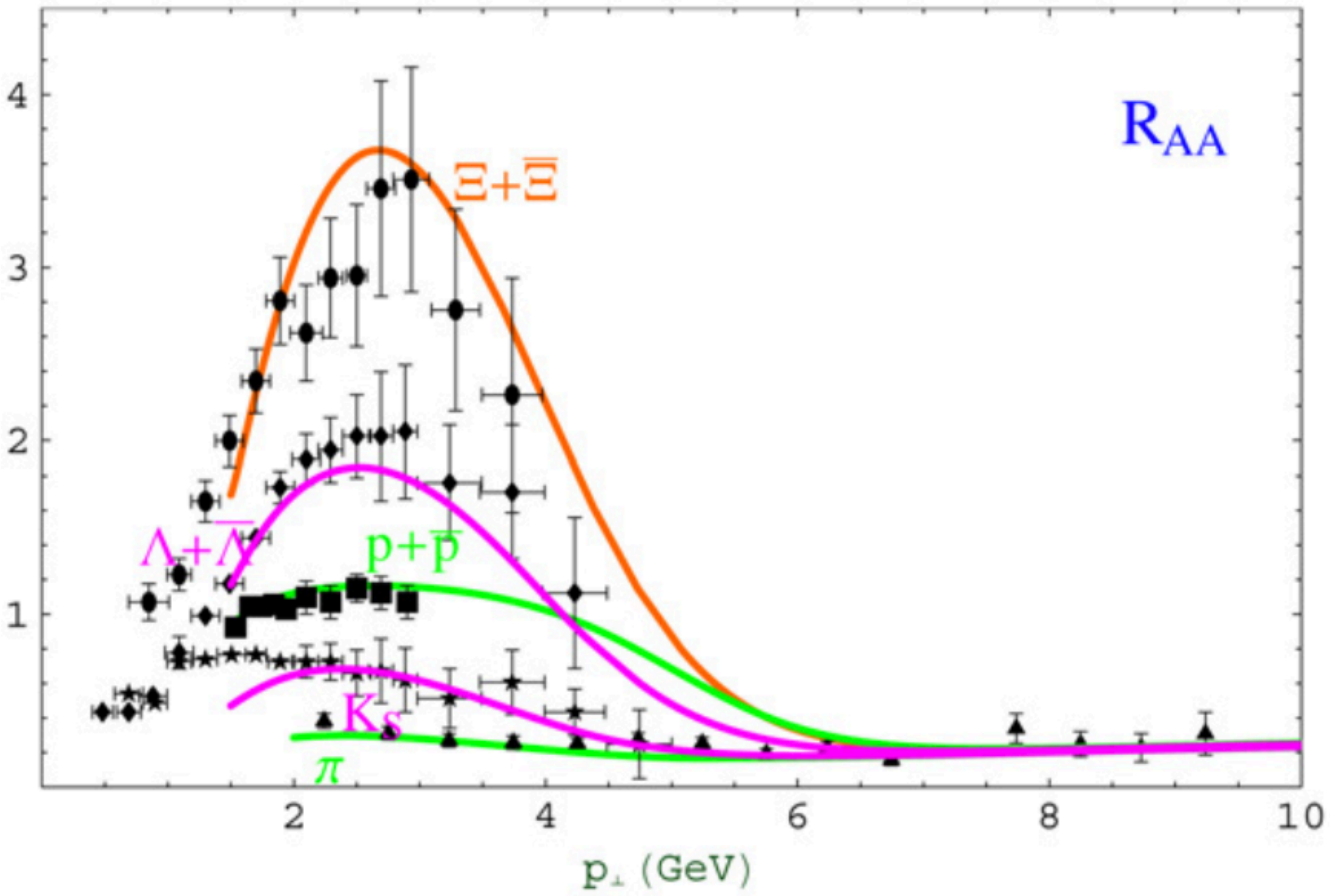
Introduction and motivation

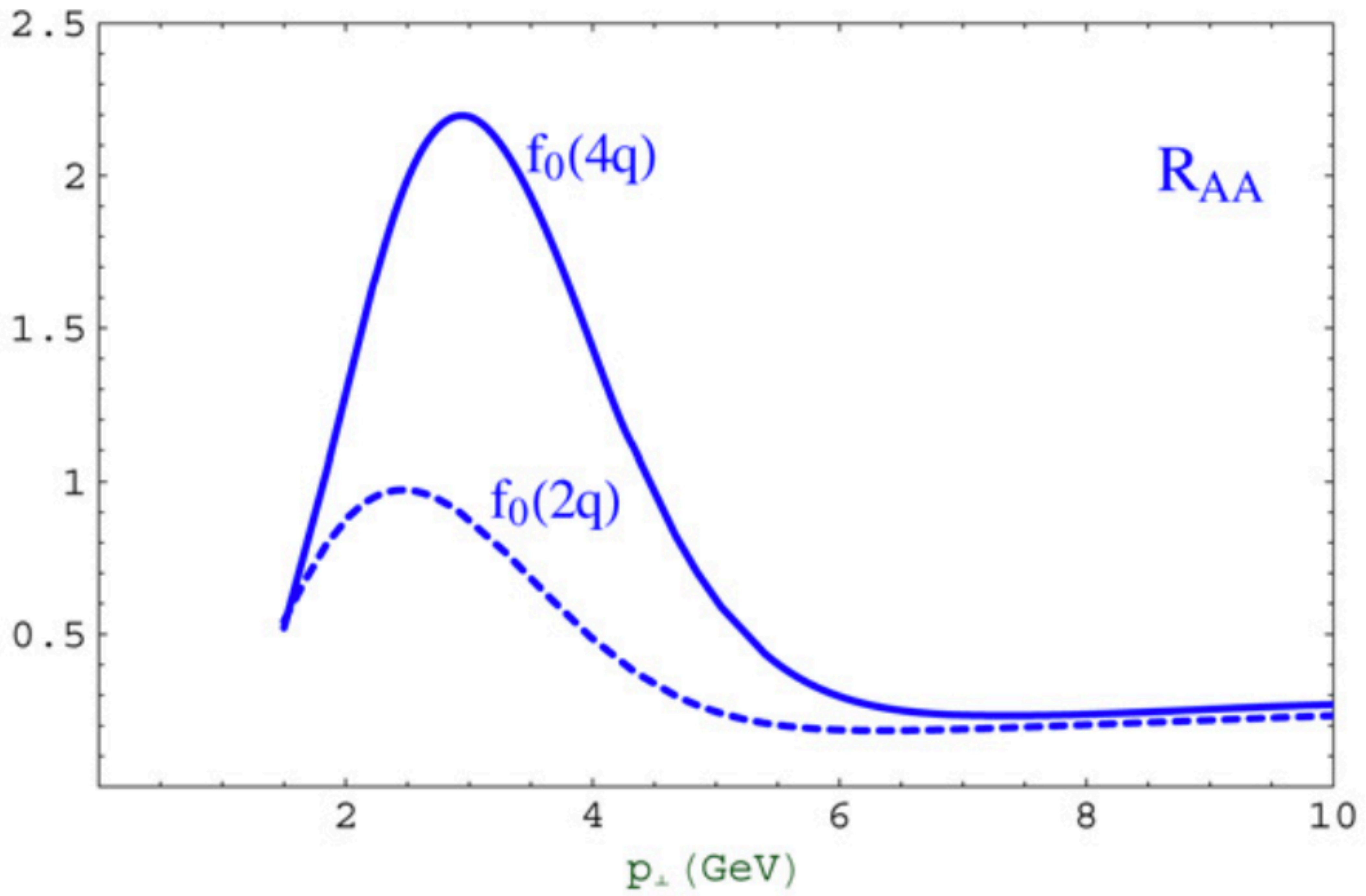
It has been proposed that the $f_0(980)$ with different configurations would have significantly different value of production yield and nuclear modification factor in heavy-ion collisions.

$$R_{AA} = \frac{d^2 N_{\mathrm{Au+Au}}(b=0)/dP_\perp^2}{N_{\mathrm{coll}}(b=0)\, d^2 N_{p+p}/dP_\perp^2}.$$

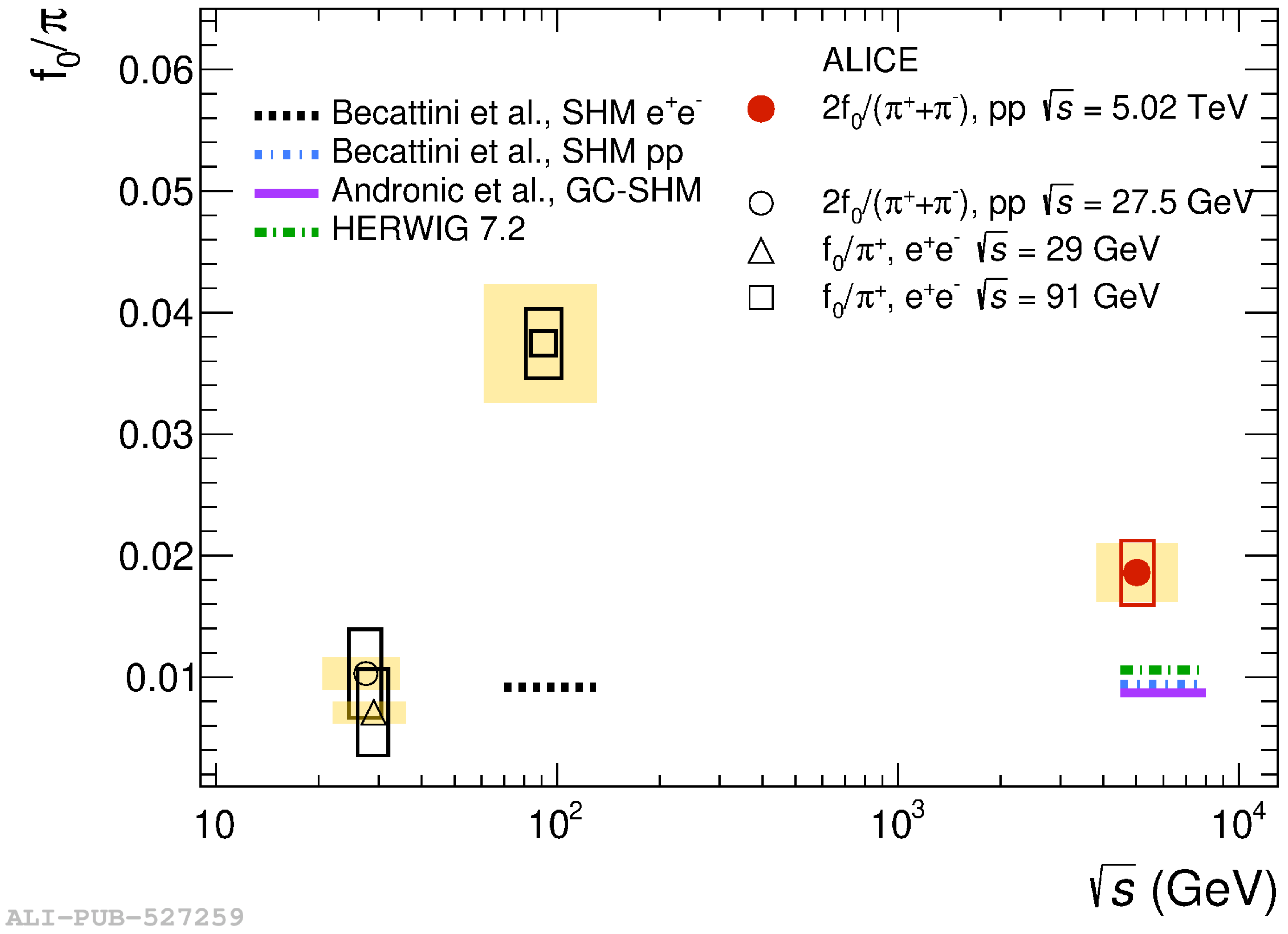
L. Maiani et. al., Phys. Lett. B645 (2007) 138

Based on a two component recombination/fragmentation model.





p_T-integrated ratio to pions

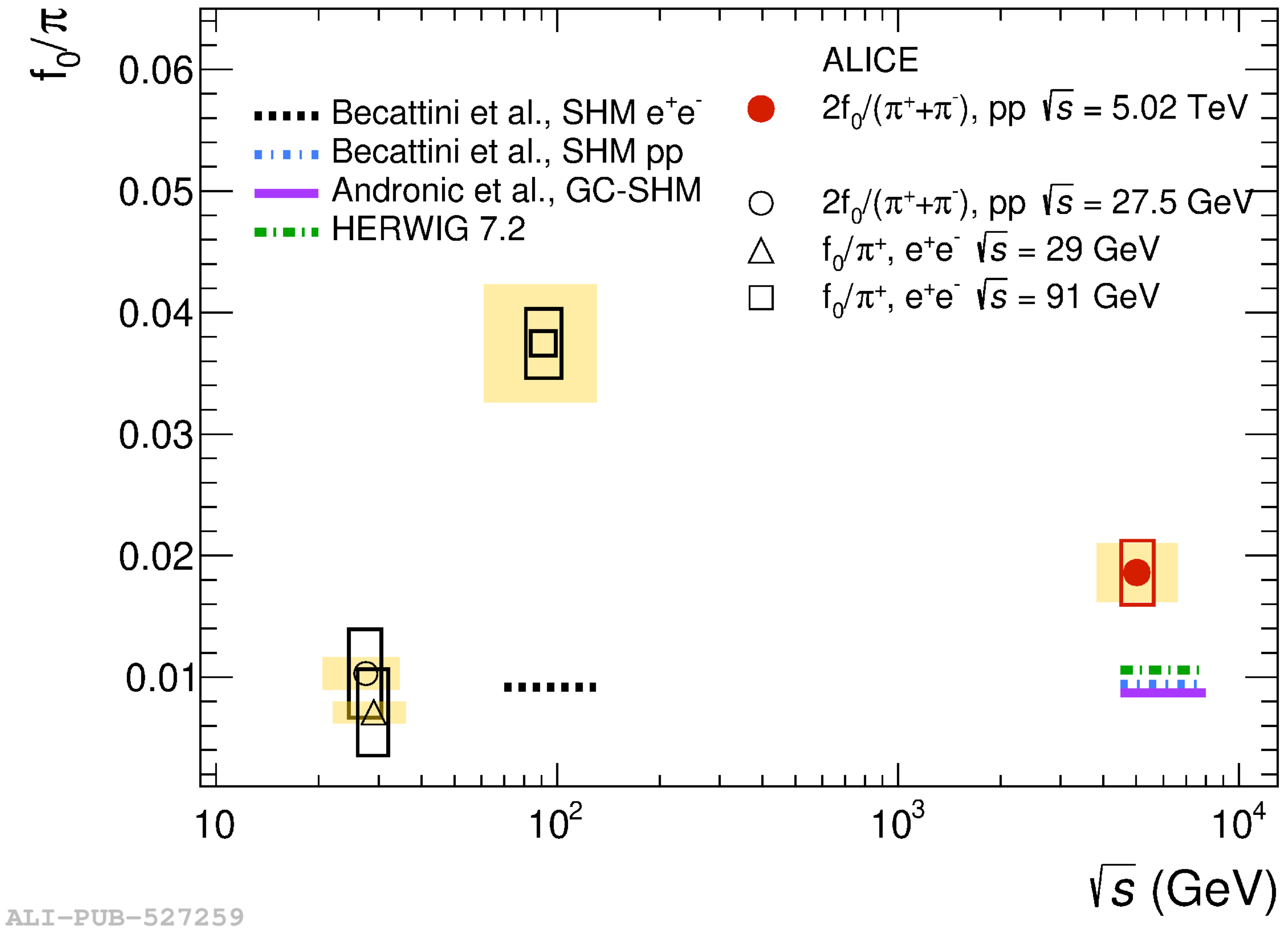


- Particle ratio value from the fixed-target NA27 experiment at the CERN SPS*, measured in pp collisions at 27.5 GeV [1] is lower by 44.5%
- Particle ratios from e^+e^- collisions* at 29[2] and 91[3] GeV are lower by 61% and higher by a factor of two, respectively

1. M. Aguilar-Benitez *et. al.*, Z. Phys. C50 (1991) 405.
2. W. Hofmann, Ann. Rev. Nucl. Part. Sci. 38 (1988) 279.
3. P. V. Chliapnikov, Phys. Lett. B462 (1999) 341.

*In order to compare the new measurement of the p_T-integrated f_0(980) to pion ratio with low energy data, the low energy points were updated with the latest branching ratio [more details in the backup]

p_T-integrated ratio to pions



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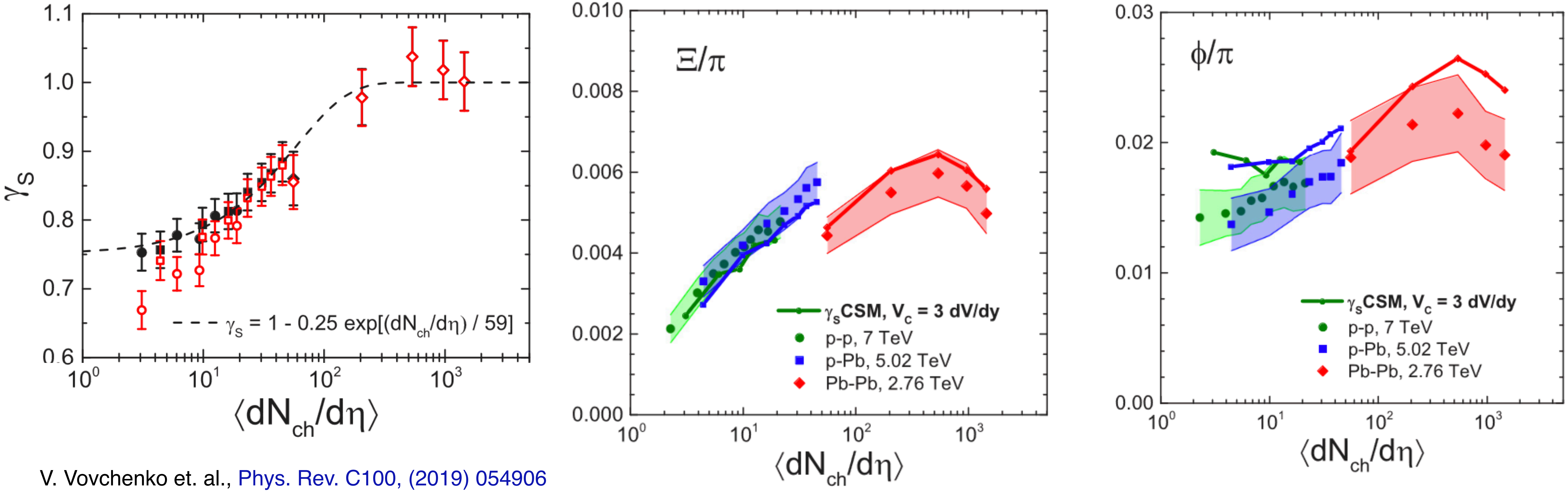
- Particle ratios from e^+e^- collisions* at 29 and 91 GeV are lower by 61% and higher by a factor of two, respectively
- The statistical hadronisation models [1-3] and HERWIG predictions underestimate the measurement in pp collisions by about a factor two

1. F. Becattini *et. al.*, Eur. Phys. J. C 56 (2008) 493.
2. F. Becattini *et. al.*, Z. Phys. C 76 (1997) 269.
3. A. Andronic *et. al.*, Nature 561 no. 7723, (2018) 321.

Canonical statistical model (CSM)

- In CSM, the hadron production is driven by the canonical suppression, namely the exact conservation of baryon number, electric charge, and strangeness over the correlation volume.

- γ_S-CSM incorporates incomplete equilibration of strangeness by introducing a strangeness saturation factor (γ_S)



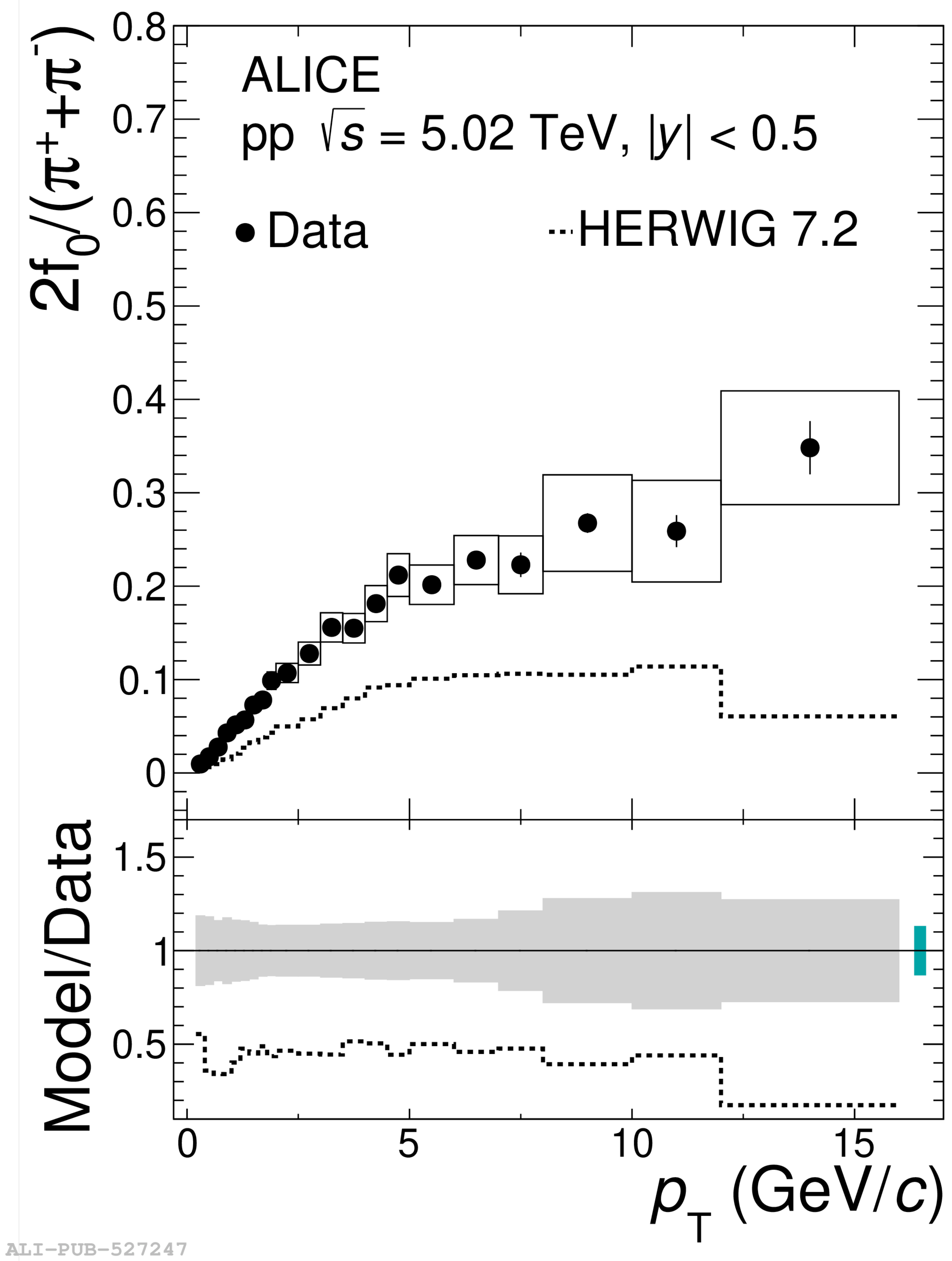
V. Vovchenko et. al., Phys. Rev. C100, (2019) 054906

$\langle dN_{ch}/d\eta \rangle$: average pseudorapidity density of charged particles

p_T-differential ratio

- The shape of the measured $2f_0(980)/(\pi^+ + \pi^-)$ ratio is well reproduced by HERWIG 7.2 over almost the entire measured p_T range.

- However, the yield is underestimated by about a factor of two by the model.

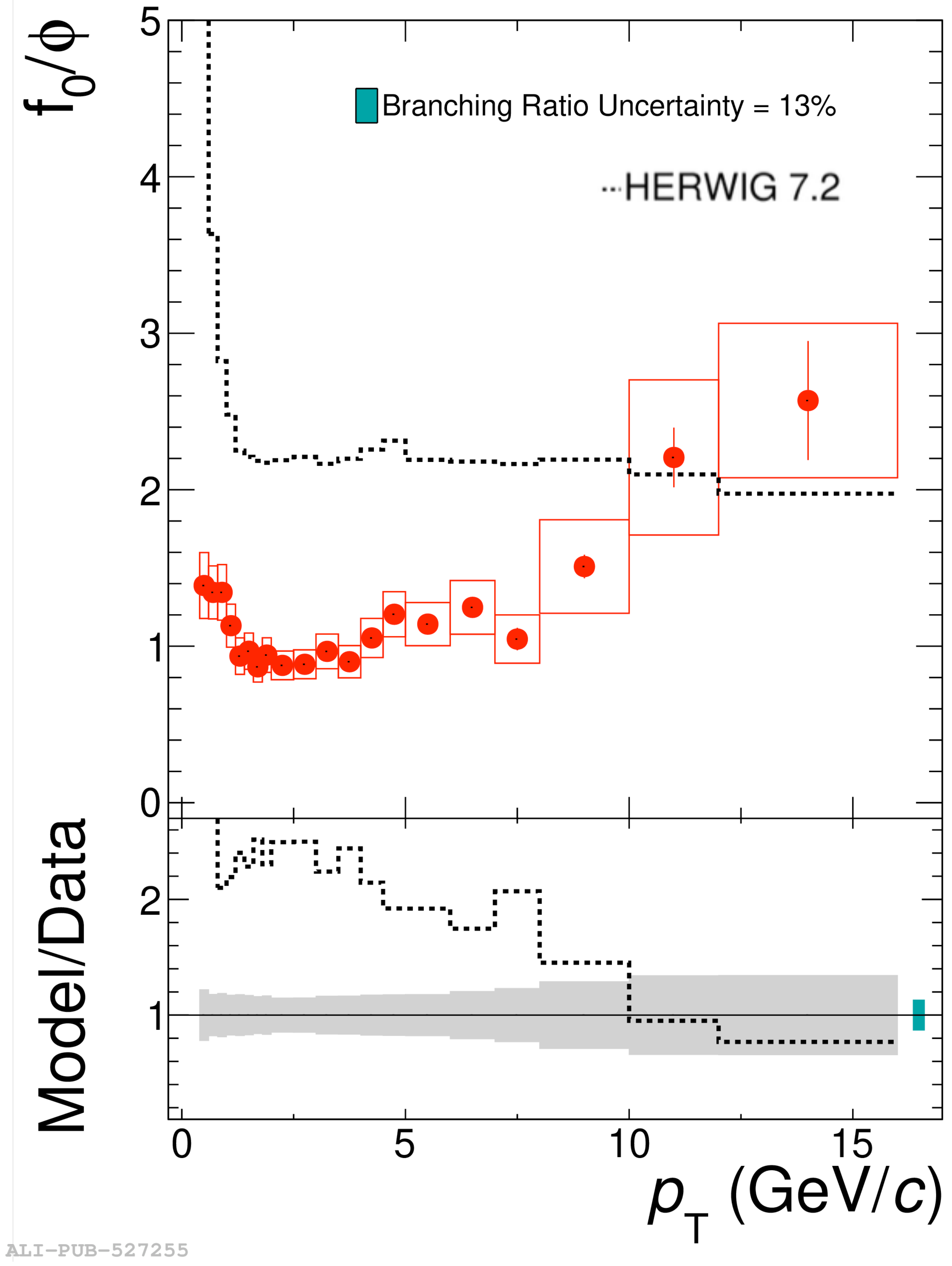


p_T-differential ratio

- For $p_T < 1$ GeV/c, the $f_0(980)/\phi$ ratio exhibits a steeply decreasing trend, that is qualitatively present also in the model prediction

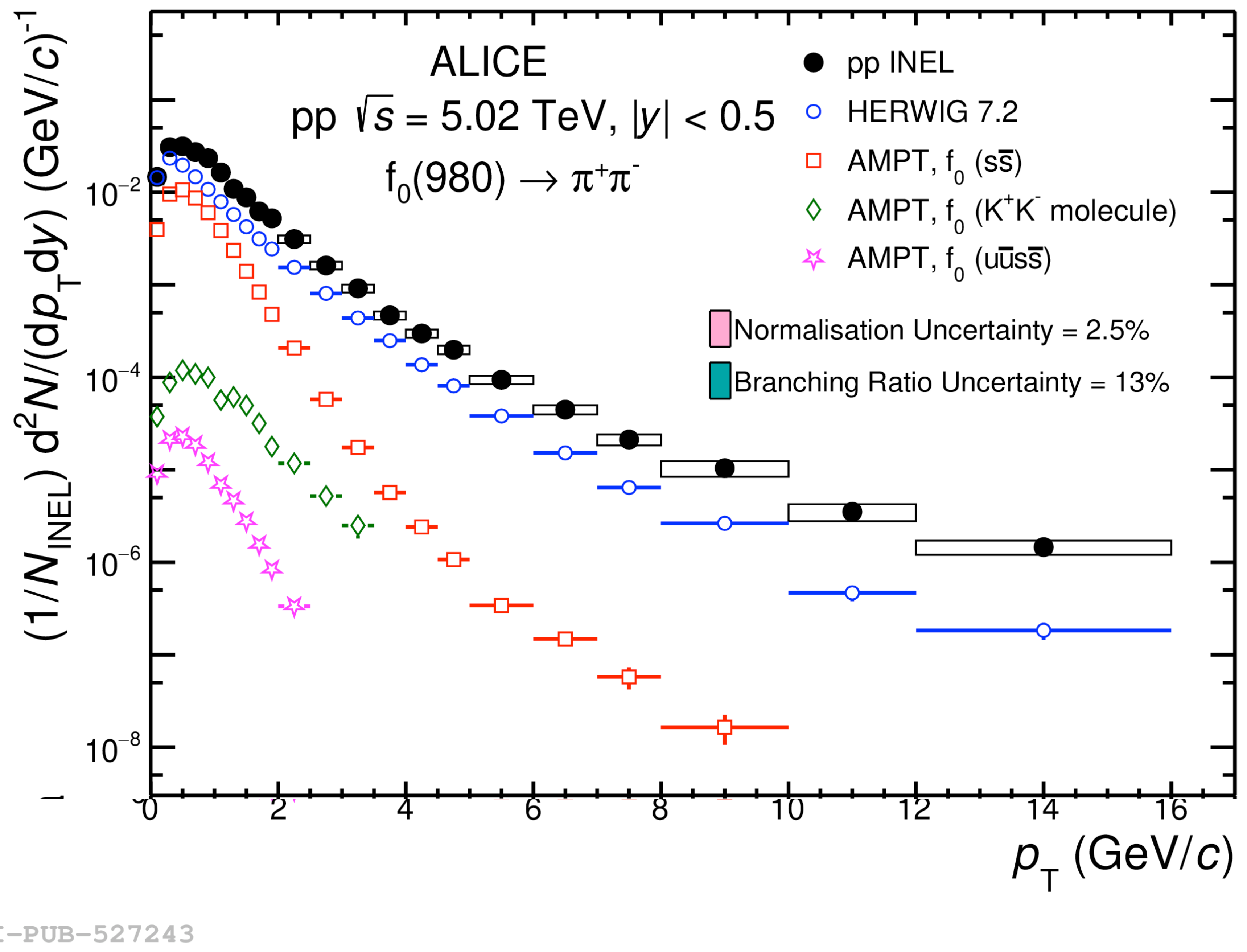
- The trend of $f_0(980)/\phi$ ratio is flat for $1 < p_T < 10$ GeV/c, indicating the spectral shape of $f_0(980)$ and ϕ are similar in this p_T range. This feature is qualitatively well reproduced by HERWIG

- The HERWIG predictions improves with increasing p_T with the $f_0(980)/\phi$ data within the uncertainties



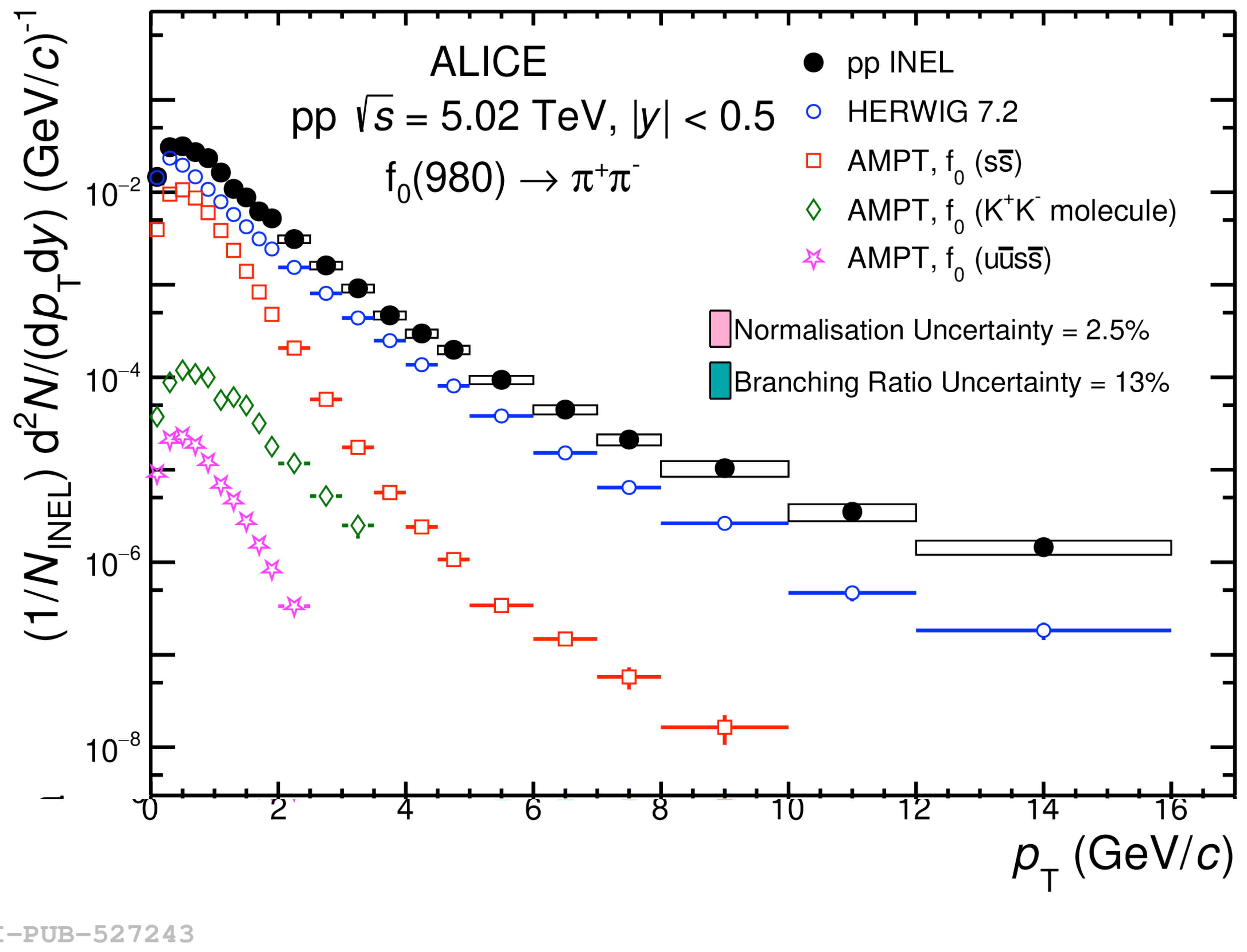
$f_0(980)$ p_T spectrum

- p_T spectrum is measured in wide p_T range up to 16 GeV/c



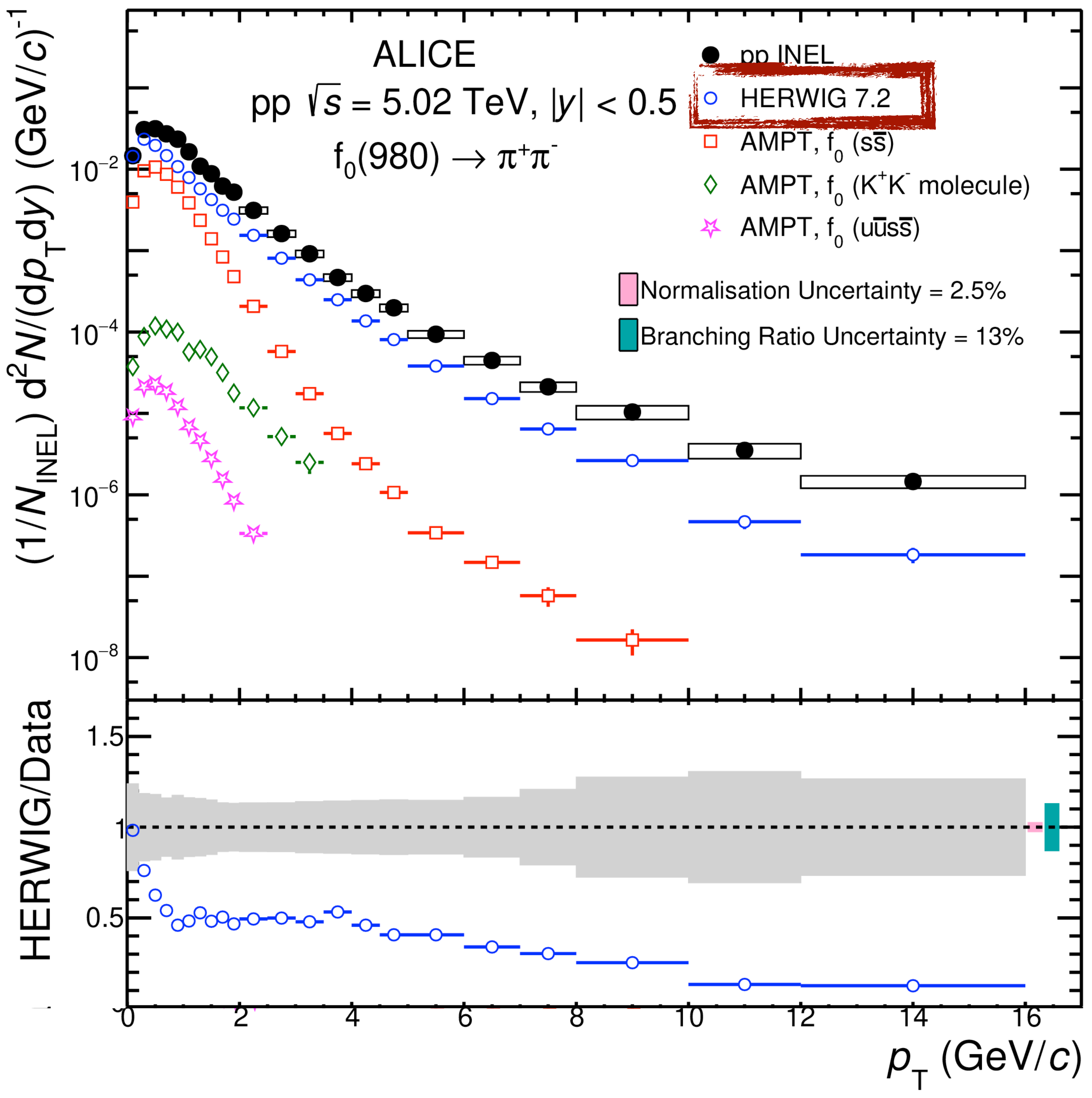
$f_0(980)$ p_T spectrum

- p_T spectrum is measured in wide p_T range up to 16 GeV/*c*
- At present, most MC generators do not implement the generation of $f_0(980)$ in their default configurations



$f_0(980)$ p_T spectrum

- p_T spectrum is measured in wide p_T range up to 16 GeV/*c*
- At present, most MC generators do not implement the generation of $f_0(980)$ in their default configurations
- HERWIG 7.2* under-predicts the spectrum by a factor of 2 and reproduces the spectral shape in the $1 < p_T < 5$ GeV/*c*

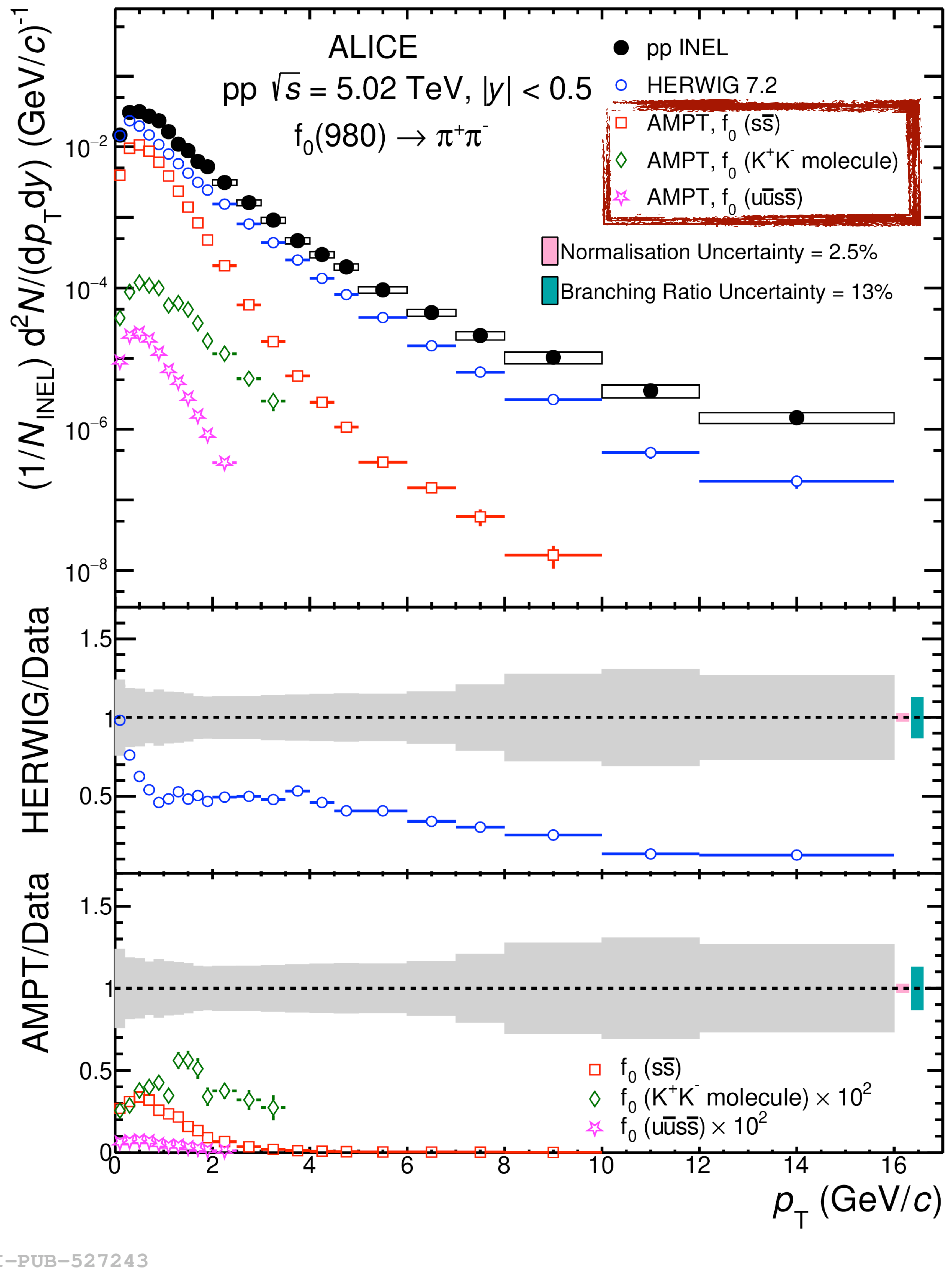


ALI-PUB-527243

*HERWIG 7.2 is a QCD-inspired MC generator includes processes like initial and final state QCD radiation, a description of the underlying event via an eikonal multiple parton–parton interaction model, and a cluster hadronisation model for the formation of hadrons from the quarks and gluons produced in the parton shower

$f_0(980)$ p_T spectrum

- p_T spectrum is measured in wide p_T range up to 16 GeV/c
- Comparison with a coalescence calculation that uses the **AMPT*** model coupled with a coalescence afterburner with Gaussian Wigner function in three configurations:
  - as a $s\bar{s}$ meson (differ by a factor 3)
  - as a $u\bar{u}s\bar{s}$ meson (differ by ~10^3)
  - as a K^+K^- molecule (differ by ~10^2)



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An Gu et. al., Phys. Rev. D103, 014010 (2021)

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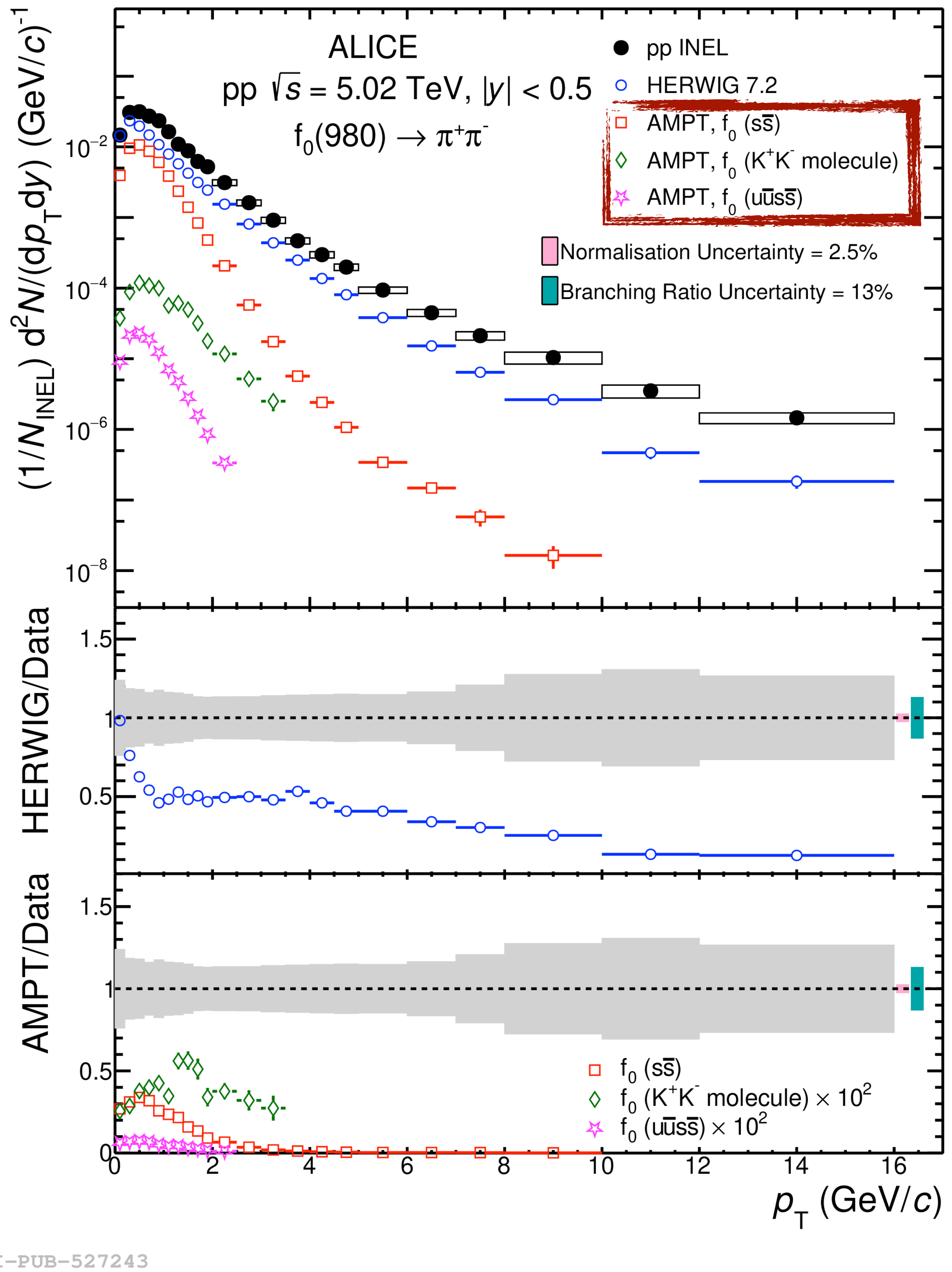
  - as a $u\bar{u}s\bar{s}$ meson (differ by ~10^3)
  - as a K^+K^- molecule (differ by ~10^2)
- the shape of p_T spectra from $s\bar{s}$ and $u\bar{u}s\bar{s}$ configurations are significantly steeper than the data
- ratio of K^+K^- molecule configuration to data show a milder p_T dependence

An Gu et. al., Phys. Rev. D103, 014010 (2021)



f_0 width

https://pdg.lbl.gov/2020/listings/rpp2020-list-f0-980.pdf

$f_0(980)$ WIDTH

Width determination very model dependent. Peak width in $\pi\pi$ is about 50 MeV, but decay width can be much larger.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
10 to 100 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15.3 ± 4.7	424	ABLIKIM 15P	BES3	$J/\psi \to K^+K^-3\pi$
9.5 ± 1.1	706	ABLIKIM 12E	BES3	$J/\psi \to \gamma 3\pi$
$42 ^{+20}_{-16}$		[1,2] GARCIA-MAR..11	RVUE	Compilation
$50 ^{+20}_{-12}$		[2,3] GARCIA-MAR..11	RVUE	Compilation
$48 ^{+22}_{-6}$		[4] MOUSSALLAM11	RVUE	Compilation
36 ± 22		[5] MENNESSIER 10	RVUE	Compilation
$70 ^{+20}_{-32}$		[6] ANISOVICH 09	RVUE	$0.0\ \bar{p}p,\ \pi N$
$91 ^{+30}_{-22} \pm 3$	44	[7] ECKLUND 09	CLEO	$4.17\ e^+e^- \to D_s^- D_s^{*+}$ + c.c.
$66.9 \pm 2.2 ^{+17.6}_{-12.5}$		[8] UEHARA 08A	BELL	$10.6\ e^+e^- \to e^+e^-\pi^0\pi^0$
65 ± 13	262 ± 30	[9] AUBERT 07AK	BABR	$10.6\ e^+e^- \to \phi\pi^+\pi^-\gamma$
81 ± 21	54 ± 9	[9] AUBERT 07AK	BABR	$10.6\ e^+e^- \to \phi\pi^0\pi^0\gamma$
$51.3 ^{+20.8}_{-17.7} {}^{+13.2}_{-3.8}$		[10] MORI 07	BELL	$10.6\ e^+e^- \to e^+e^-\pi^+\pi^-$
$61 \pm 9 ^{+14}_{-8}$	2584	[11] GARMASH 05	BELL	$B^+ \to K^+\pi^+\pi^-$
64 ± 16		[12] ANISOVICH 03	RVUE	
121 ± 23		TIKHOMIROV 03	SPEC	$40.0\ \pi^- C \to K_S^0 K_S^0 K_L^0 X$
~ 70		[13] BRAMON 02	RVUE	$1.02\ e^+e^- \to \pi^0\pi^0\gamma$
$44 \pm 2 \pm 2$	848	[14] AITALA 01A	E791	$D_s^+ \to \pi^-\pi^+\pi^+$
201 ± 28	419	[15] ACHASOV 00H	SND	$e^+e^- \to \pi^0\pi^0\gamma$
122 ± 13	419	[16,17] ACHASOV 00H	SND	$e^+e^- \to \pi^0\pi^0\gamma$
56 ± 20		[18] AKHMETSHIN 99C	CMD2	$e^+e^- \to \pi^0\pi^0\gamma$
65 ± 20		BARBERIS 99	OMEG	$450\ pp \to p_s p_f K^+K^-$
80 ± 10		BARBERIS 99B	OMEG	$450\ pp \to p_s p_f \pi^+\pi^-$
80 ± 10		BARBERIS 99C	OMEG	$450\ pp \to p_s p_f \pi^0\pi^0$
$48 \pm 12 \pm 8$		[19] BARBERIS 99D	OMEG	$450\ pp \to K^+K^-, \pi^+\pi^-$
65 ± 25		BELLAZZINI 99	GAM4	$450\ pp \to pp\pi^0\pi^0$
71 ± 14		[20] KAMINSKI 99	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, \sigma\sigma$
~ 28		[20] OLLER 99	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
~ 25		OLLER 99B	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
~ 14		[20] OLLER 99C	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, \eta\eta$
70 ± 20		ALDE 98	GAM4	
86 ± 16		[20] ANISOVICH 98B	RVUE	Compilation
54		[21] LOCHER 98	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
69 ± 15		[22] ALDE 97	GAM2	$450\ pp \to pp\pi^0\pi^0$
38 ± 20		[23] BERTIN 97C	OBLX	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
~ 100		[24] ISHIDA 96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
34		TORNQVIST 96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
48 ± 10	3k	[25] ALDE 95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
95 ± 20	10k	[26] ALDE 95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
26 ± 10		AMSLER 95B	CBAR	$0.0\ \bar{p}p \to 3\pi^0$
~ 112		[27] AMSLER 95D	CBAR	$0.0\ \bar{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
80 ± 12		[28] ANISOVICH 95	RVUE	
30		JANSSEN 95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
74		[29] BUGG 94	RVUE	$\bar{p}p \to \eta 2\pi^0$
29 ± 2		[30] KAMINSKI 94	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
46		[31] ZOU 94B	RVUE	
48 ± 12		[32] MORGAN 93	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K}), J/\psi \to \phi\pi\pi(K\overline{K}), D_s \to \pi(\pi\pi)$
37.4 ± 10.6		[22] AGUILAR-... 91	EHS	$400\ pp$
72 ± 8		[33] ARMSTRONG 91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
110 ± 30		BREAKSTONE 90	SFM	$pp \to pp\pi^+\pi^-$
29 ± 13		[22] ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^- X$
$120 \pm 281 \pm 20$		ETKIN 82B	MPS	$23\ \pi^- p \to n 2K_S^0$
28 ± 10		[33] GIDAL 81	MRK2	$J/\psi \to \pi^+\pi^- X$
70 to 300		[34] ACHASOV 80	RVUE	
100 ± 80		[35] AGUILAR-... 78	HBC	$0.7\ \bar{p}p \to K_S^0 K_S^0$
30 ± 8		[33] LEEPER 77	ASPK	$2\text{–}2.4\ \pi^- p \to \pi^+\pi^- n, K^+K^- n$
48 ± 14		[33] BINNIE 73	CNTR	$\pi^- p \to n MM$
32 ± 10		[36] GRAYER 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$

Width for $f_0(980)$ is not defined in PDG as several experiments report wide range of values

f_0 branching ratio

To determine the $\pi^+\pi^-$ branching fraction it is assumed that the $\pi\pi$ and KK decays are dominant, and that the ratios of $\pi^0\pi^0$ to $\pi^+\pi^-$ and $K^0\bar{K}^0$ to K^+K^- are given by isospin conservation as 1/2 and 1, respectively, leading to [7]

$$\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (46 \pm 6)\%. \quad (5)$$

S. Stone *et. al.*, PRL 111, 062001 (2013)

Assuming that the $\pi\pi$ and KK decays are dominant, we can also extract

$$\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (46 \pm 6)\%, \quad (30)$$

where we have assumed that the only other decays are to $\pi^0\pi^0$, $\frac{1}{2}$ of the $\pi^+\pi^-$ rate, and to neutral kaons, equal to charged kaons. We use $\mathcal{B}(f_0(500) \to \pi^+\pi^-) = \frac{2}{3}$,

LHCb Collaboration, Phys. Rev. D 89, (2014) 092006

Introduction

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq(L)$	Multiquark	Mol. (L)	ω_{Mol} [MeV]
$f_0(980)$	980	$(0, 0^+)$	$q\bar{q}(P)$ $(s\bar{s}$ $(P))$	$qs\bar{q}\bar{s}$	$\bar{K}K(S)$	67.8(B)
$a_0(980)$	980	$(1, 0^+)$	$q\bar{q}(P)$	$qs\bar{q}\bar{s}$	$\bar{K}K(S)$	67.8(B)

The oscillator frequency for f0(980) is obtained from its binding energy of $B_{f0} = M_{K+}+M_{K-}-M_{f0(980)} = 11.3$ MeV as $\omega_{f0(980)} = 6B_{f0} = 67.8$ MeV.

Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
LHC (5.02 TeV)						
$f_0(980)$	4.3 (1.2)	5.4×10^{-2}	4.1 (1.2)	6.0×10^{-2}	3.2	6.6
$a_0(980)$	13	1.6×10^{-1}	12	1.8×10^{-1}	9.5	20

S. Cho et al., ExHIC Coll. / Progress in Particle and Nuclear Physics 95 (2017) 279–322

The quark coalescence model predicts a yield of f0 in Pb-Pb collisions at 5 TeV
- ~2/3x that predicted by the statistical hadronization (which ignores internal structure)
- about a factor 100 smaller for a 4q state with respect to a 2q state
- ~4/3 larger for a 2q than that of a molecule