

30th CONFERENCE ON ULTRA-RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS



Exploring the internal structure of the exotic resonances with ALICE

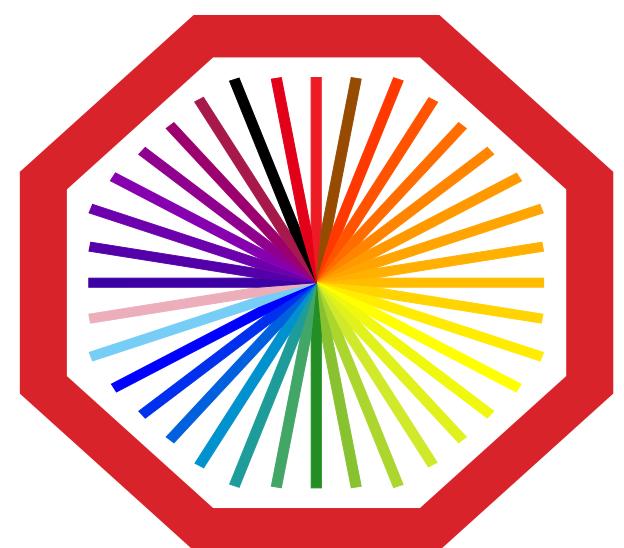


Sonali Padhan

On behalf of the **ALICE** Collaboration

Indian Institute of Technology Bombay

QM-2023, Houston, Texas September 3-9, 2023



ALICE

Introduction - Exotic Hadrons

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

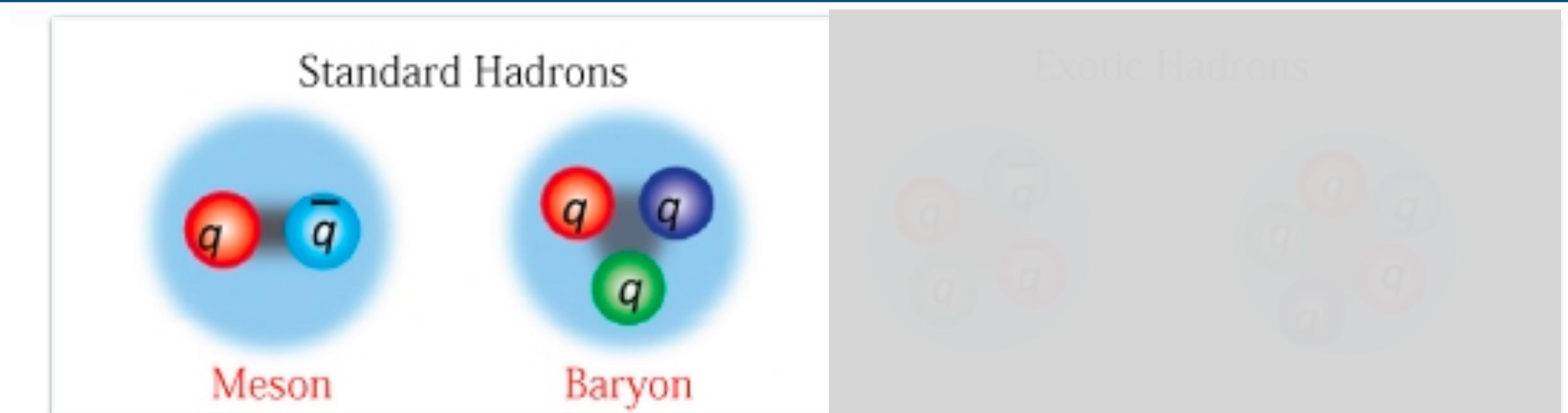
Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^- , s^- , u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) and the members of the anti-triplet as anti-quarks \bar{q} . Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q \bar{q} \bar{q})$, etc., while mesons are made out of $(q \bar{q})$, $(q q \bar{q} \bar{q})$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration $(q \bar{q})$ similarly gives just 1 and 8.



- The classification of Standard Hadrons based on the constituents of quark model- **Baryons (qqq), Mesons ($q\bar{q}$)**

Introduction - Exotic Hadrons

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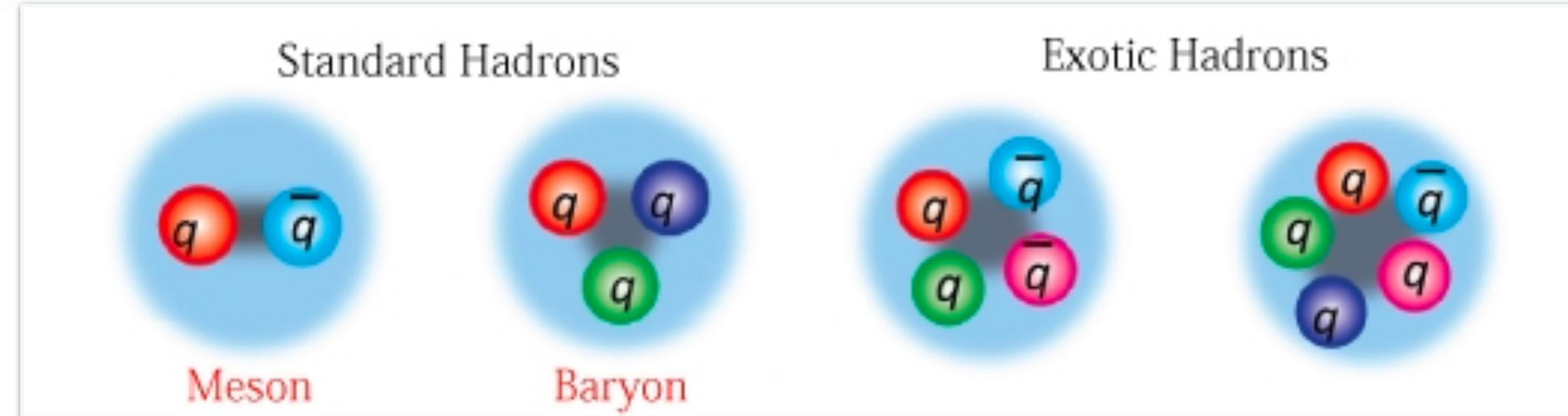
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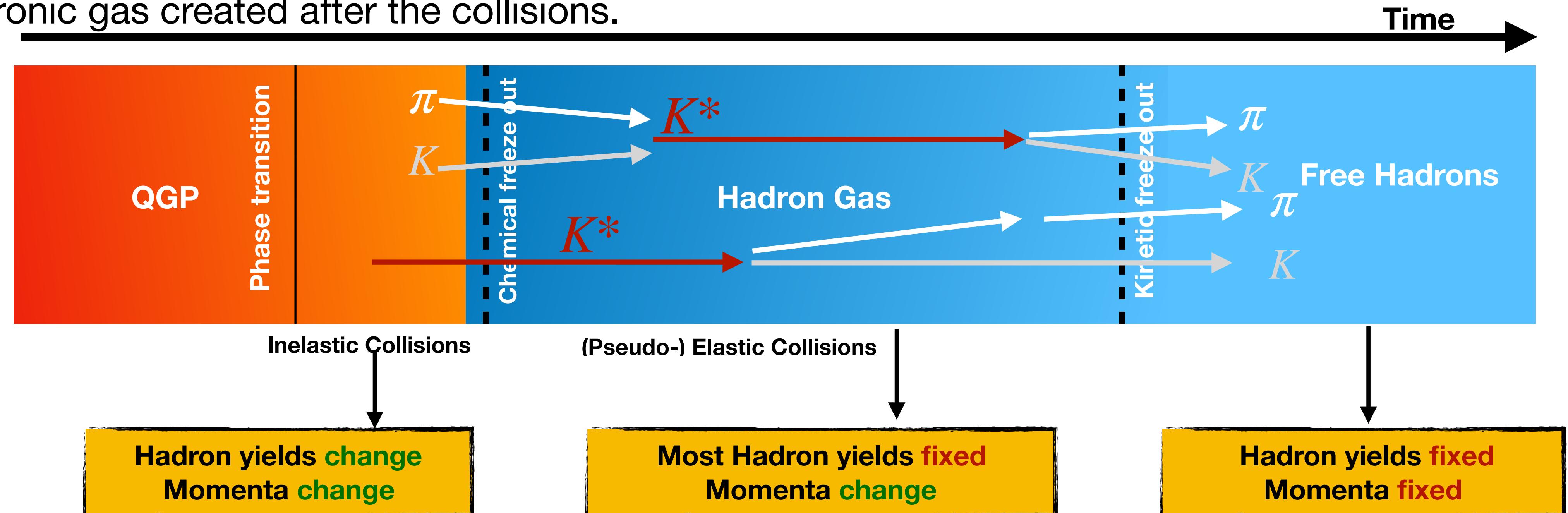
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- The classification of Standard Hadrons based on the constituents of quark model- **Baryons (qqq), Mesons ($q\bar{q}$)**
- Exotic Hadrons: Combinations of quarks and antiquarks with "unusual" configurations- **Tetra quark ($qq\bar{q}\bar{q}$), Penta quark($qqqq\bar{q}$) etc**
- Internal structure not clear : compact multi-quark states? or molecular structure?

Introduction- Resonances

- Hadronic resonances are short-lived particles and their lifetimes are comparable or less than that of the hadronic gas created after the collisions.



More by N.Agrawal on 5th Sept at 12:20

- Rescattering - Rescattering of decay daughters - reduction of the measured resonance yield
- Regeneration - (Pseudo-) elastic scatterings- Increase in resonance yield

Exotic Resonances

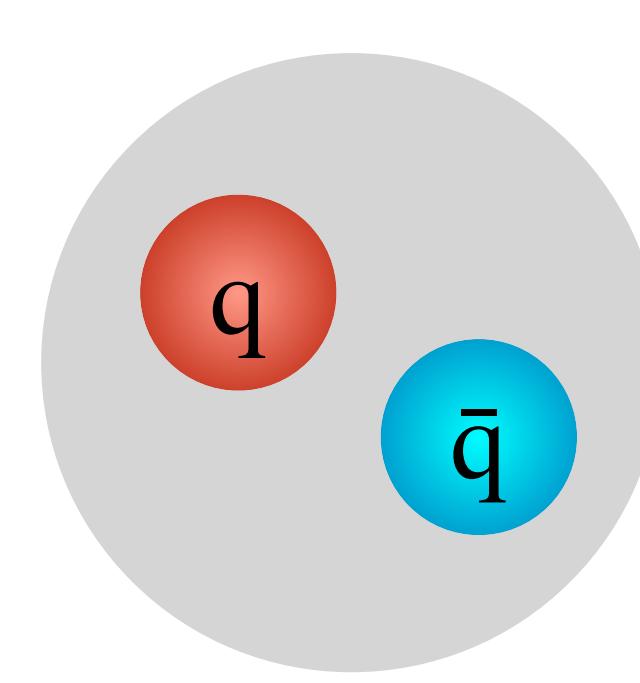
	ρ^0	K*(892)	f ₀ (980)	$\phi(1020)$	f ₁ (1285)	f ₀ (1370)	$\Sigma(1385)$	f ₀ (1500)	$\Lambda(1520)$	$\Xi(1530)$
Mass	775	892	990	1020	1280	1200 -1500	1385	1506	1520	1530
J^P	1-	1-	0 ⁺	1-	1 ⁺	0 ⁺	(3/2) ⁺	0 ⁺	(3/2) ⁻	(3/2) ⁺
Quark Contents	$\frac{u\bar{u} + d\bar{d}}{2}$	d \bar{s}	???	s \bar{s}	???	???	uus, dds	???	uds	dds
Lifetime (fm/c)	1.3	4.2	~5?	46.2			~5		12.6	21.7

Particle Data Group

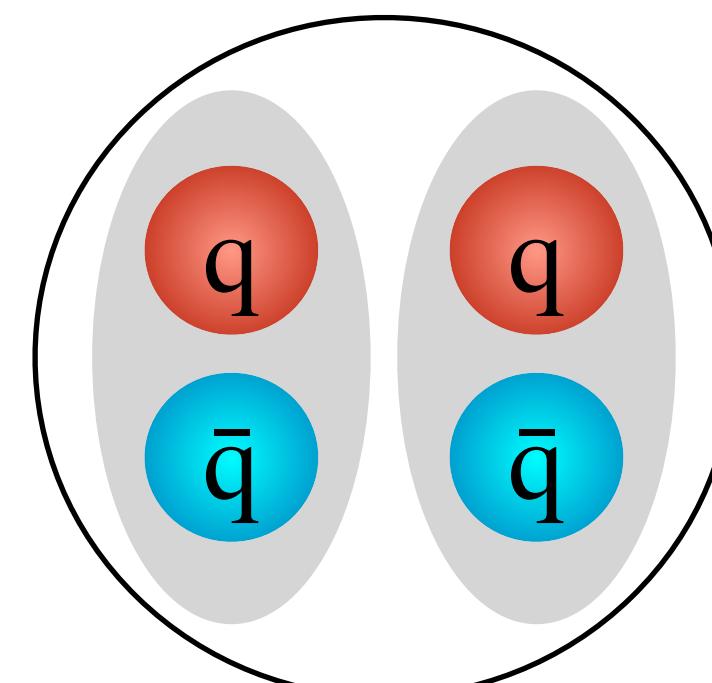
- A list of (exotic) resonances in 1-2 GeV/c² mass range
- Quark contents of these scalar mesons are still controversial.

More by N.Agrawal on 5th Sept at 12:20

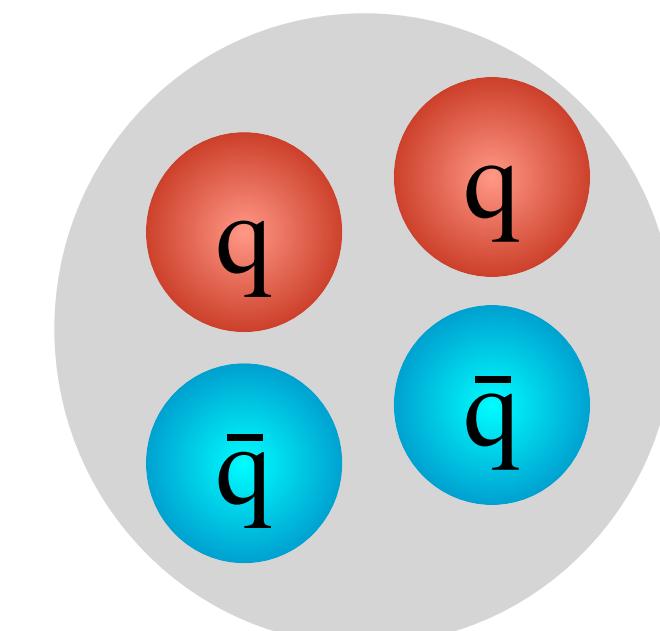
Structure of Exotic Resonances



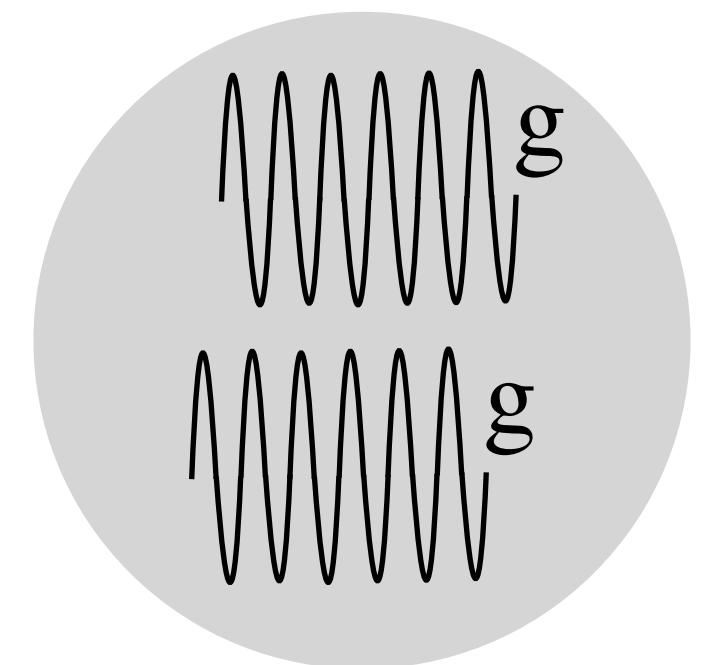
Diquark



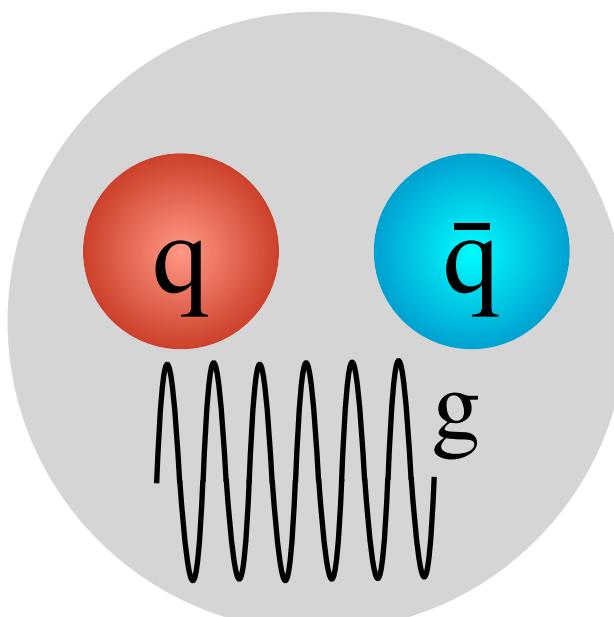
meson-meson
molecule



Tetraquark

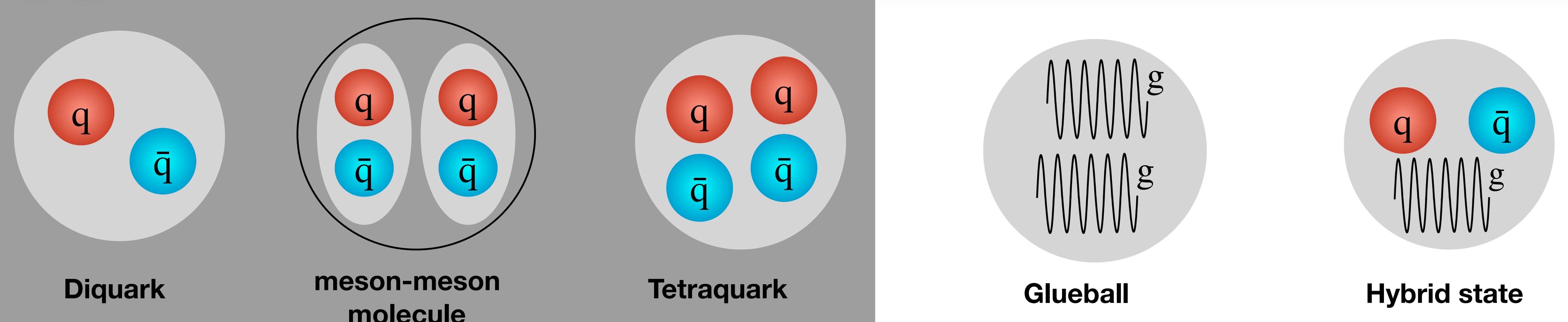


Glueball



Hybrid state

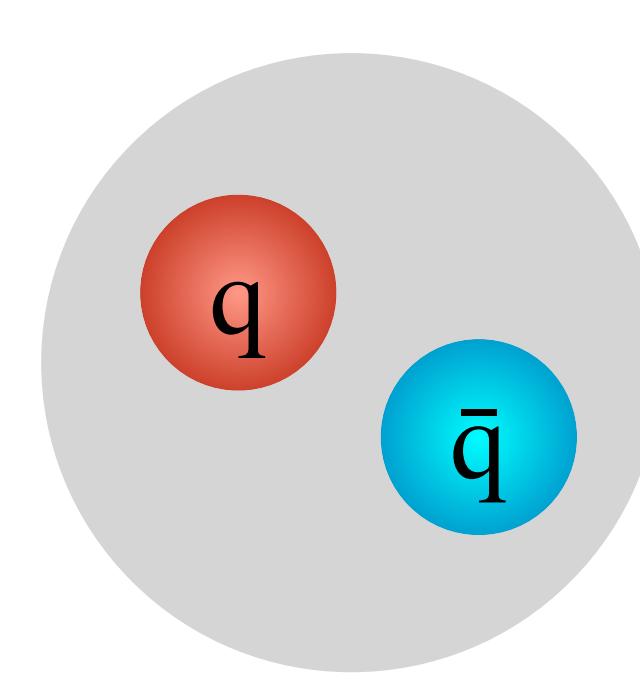
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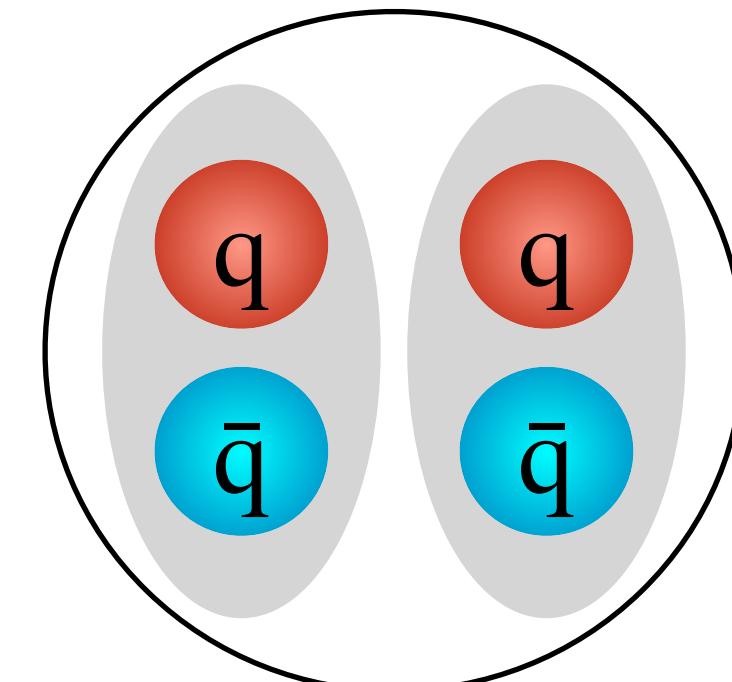
$f_0(980)$

- $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: [Phys.Rev.D 67 \(2003\) 094011](#)
- Molecular state ($KK\bar{\bar{K}}$): [Phys.Rev.D 101 \(2020\) 9, 094034](#)
- Tetraquark: [Phys.Rev.D 103 \(2021\) 1, 014010](#)

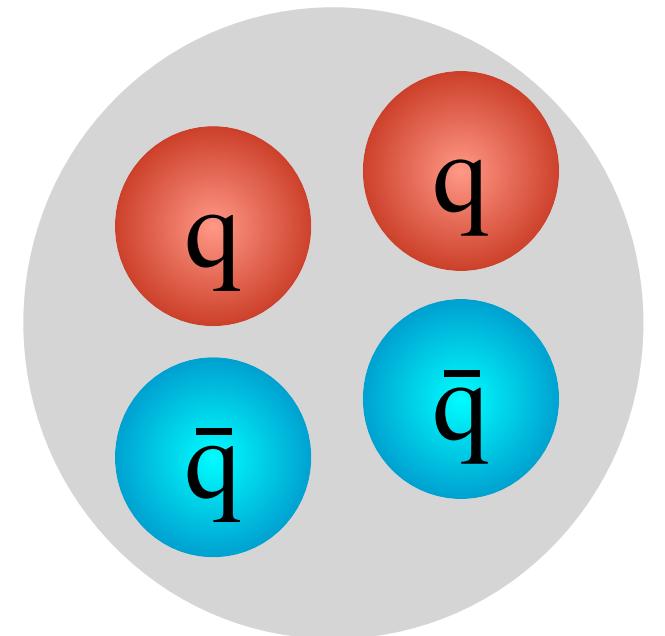
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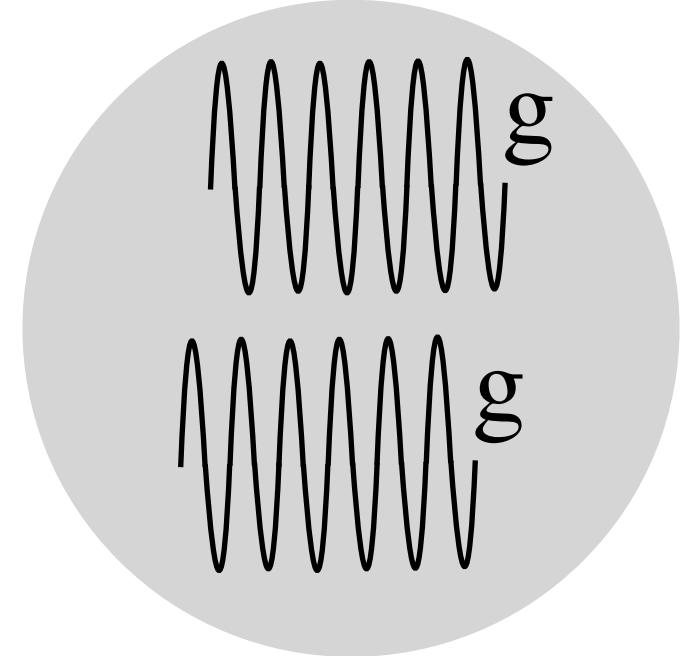
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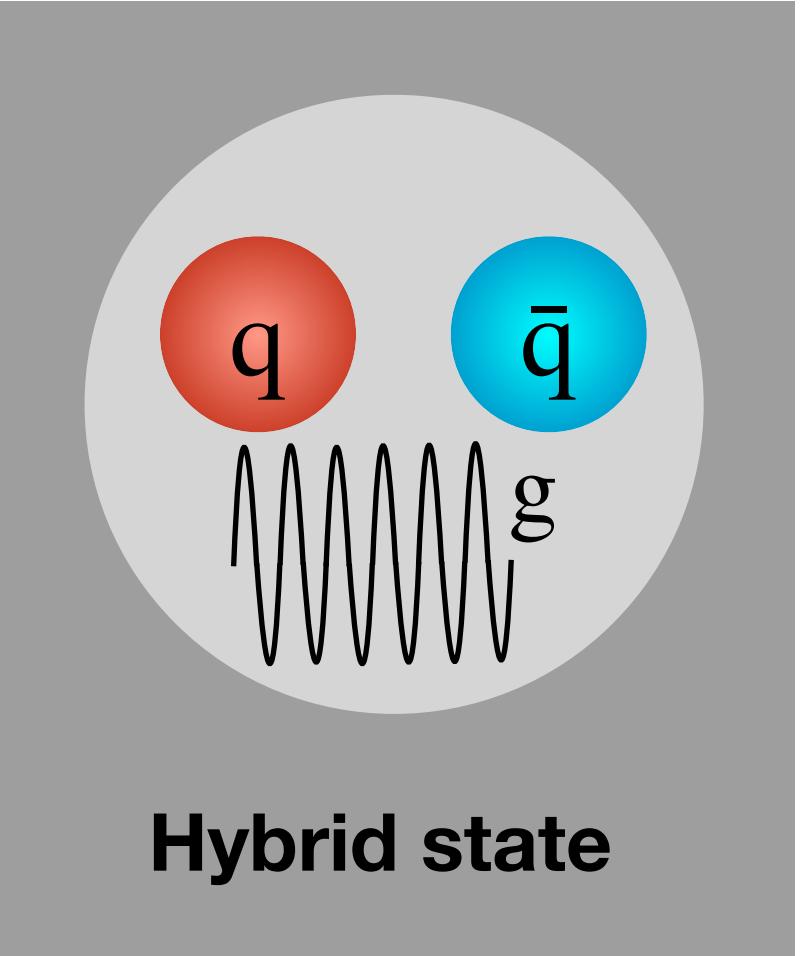
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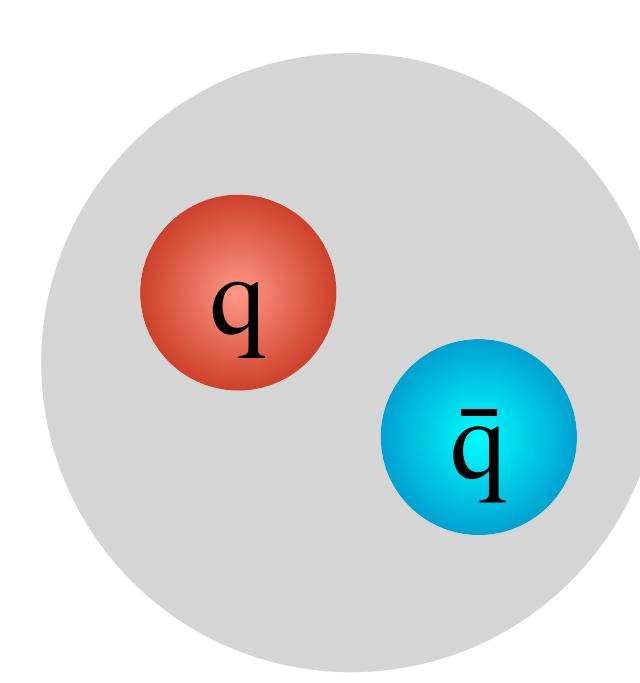
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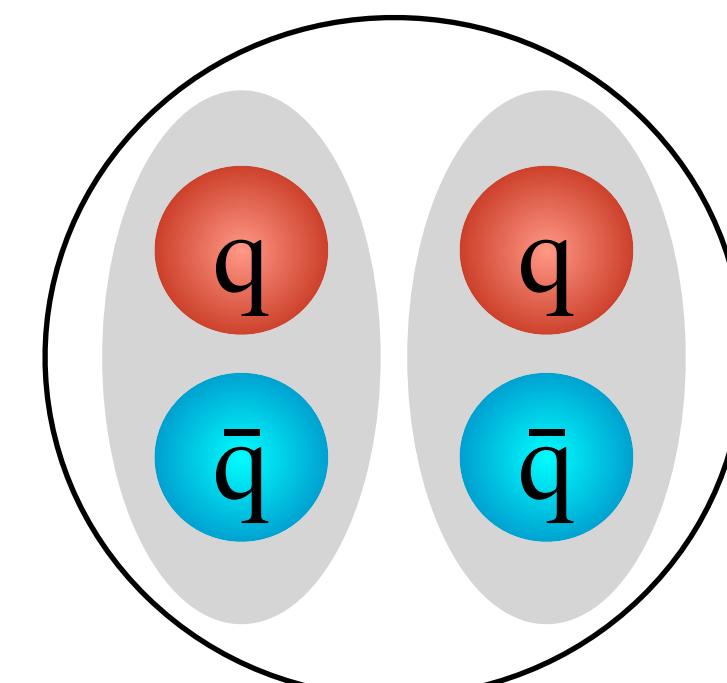
$f_1(1285)$

- $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: [Phys.Rev.D 96 \(2017\) 5, 054012](#)
- Tetraquark: [Mod.Phys.Lett. A2 \(1987\) 771](#)
- Molecular state: [Phys. Rev D42 \(1990\) 874](#)
- Hybrid state: [Nucl.Phys.A 992 \(2019\) 121641](#)

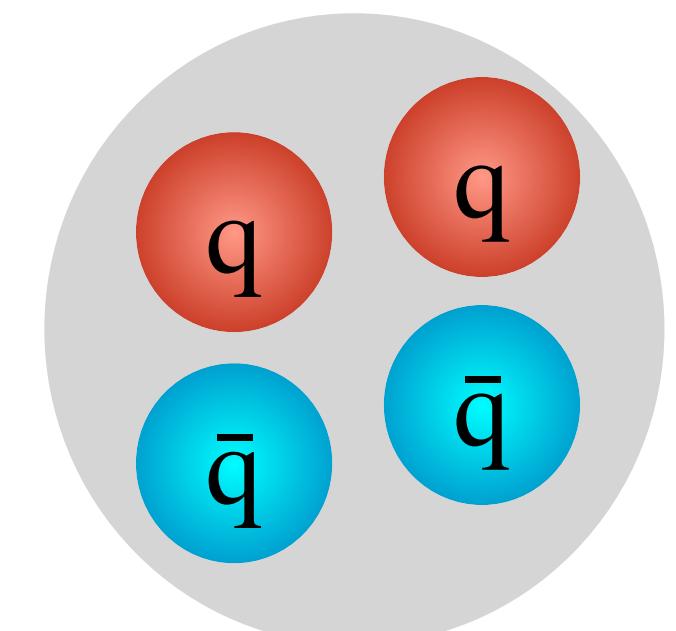
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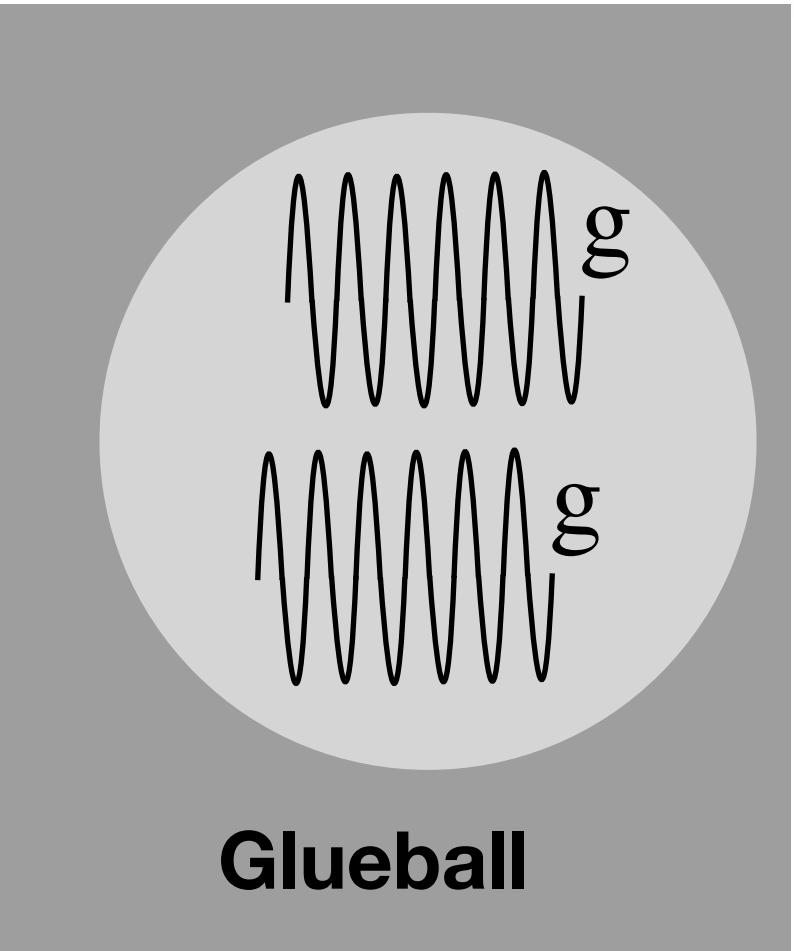
Diquark



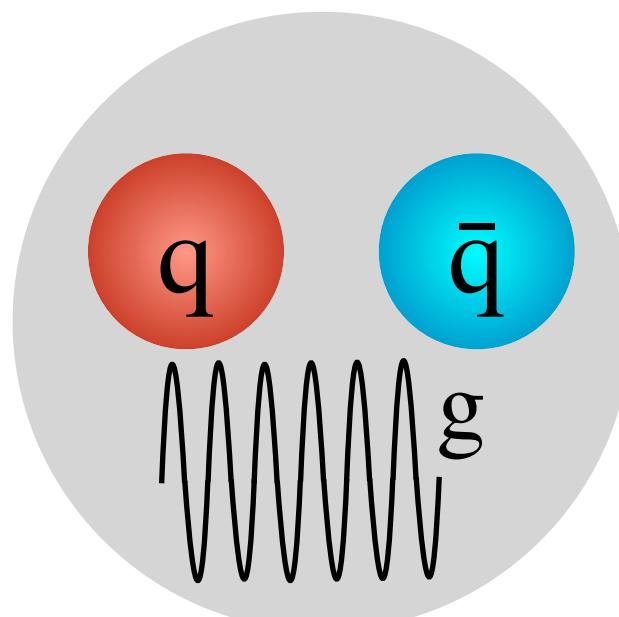
meson-meson
molecule



Tetraquark



Glueball



Hybrid state

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f₀(1710)

- Glueball candidate: [Phys.Rev.Lett. 101 \(2008\) 112003](#), [Review of Particle Physics \(PDG\)](#)

More by Satoshi Yano's poster

f₁(1285)

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Glueball hunting

- Lattice QCD predicts the possible existance of glueballs [1],[2].
- **Glueball:** A particle composed of gluons only, because gluons carry color charge and have bound state without the valence quarks.
- Expected properties: Mass range; $1 \sim 2 \text{ GeV}/c^2$, and total angular momentum, charge and parity $J^{PC} = 0^{++}$ (lightest one)
- Candidates: **f₀(1370), f₀(1500), f₀(1710)** are suitable candidates for searching glueball.

[1] PRL101, 112003 (2008)

[2] P.A. Zyla et al. (Particle Data Group)

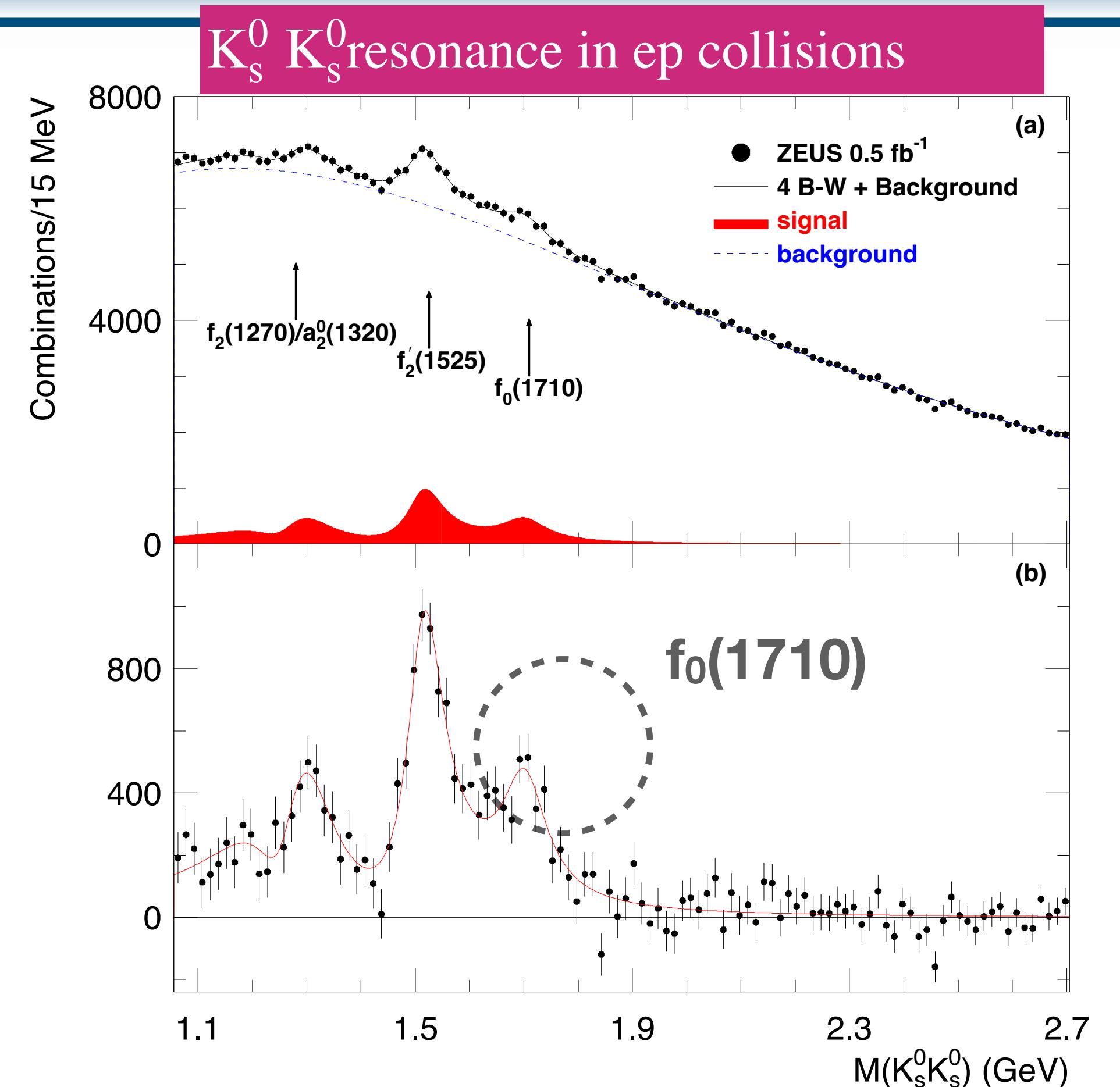
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[3] Phys.Lett.B 413 (1997) 225-231



- WA102 [3], ZEUS have measured the K_S⁰K_S⁰ mass peak
- Various resonances can be found in K_S⁰K_S⁰ channel

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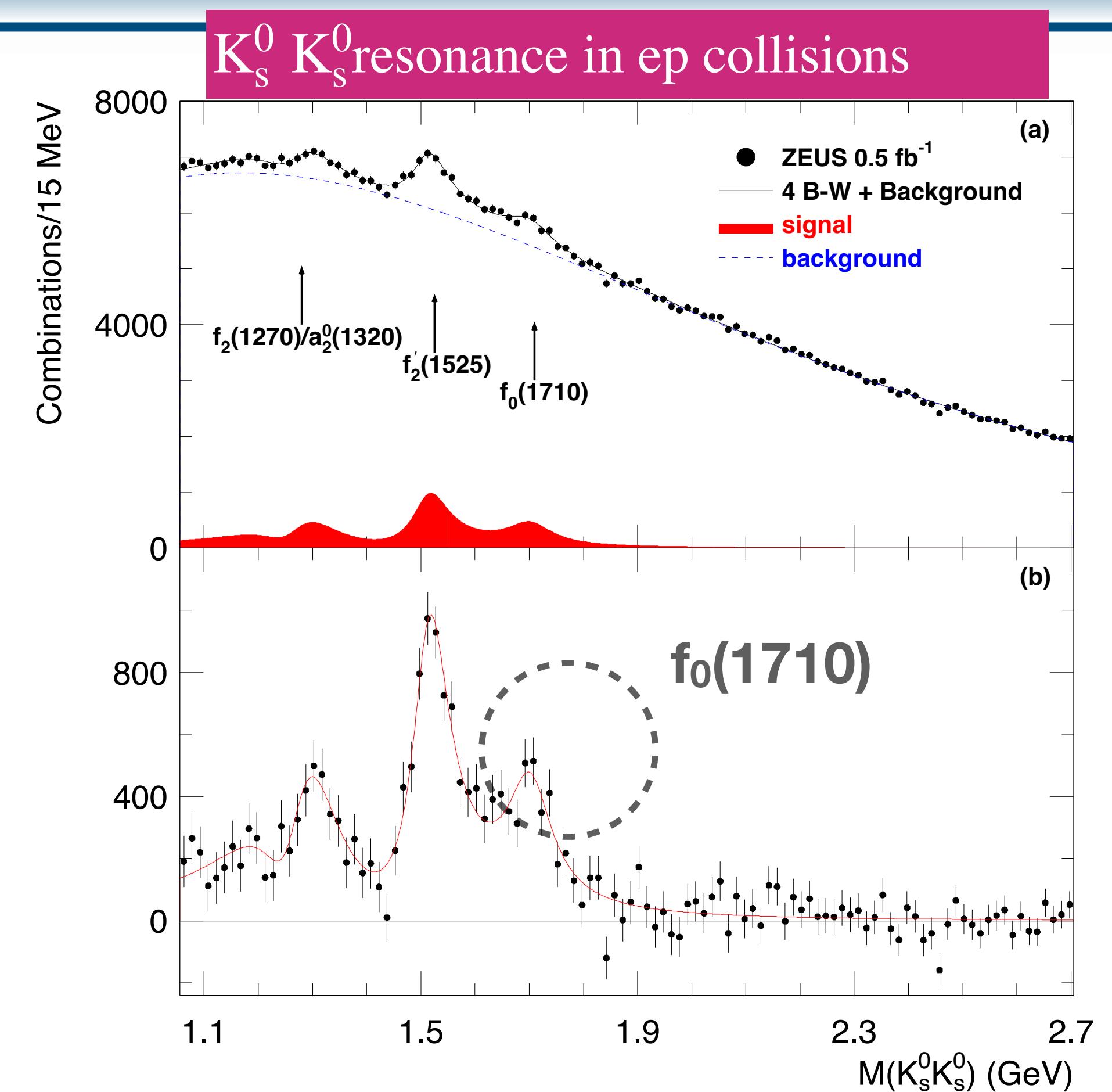
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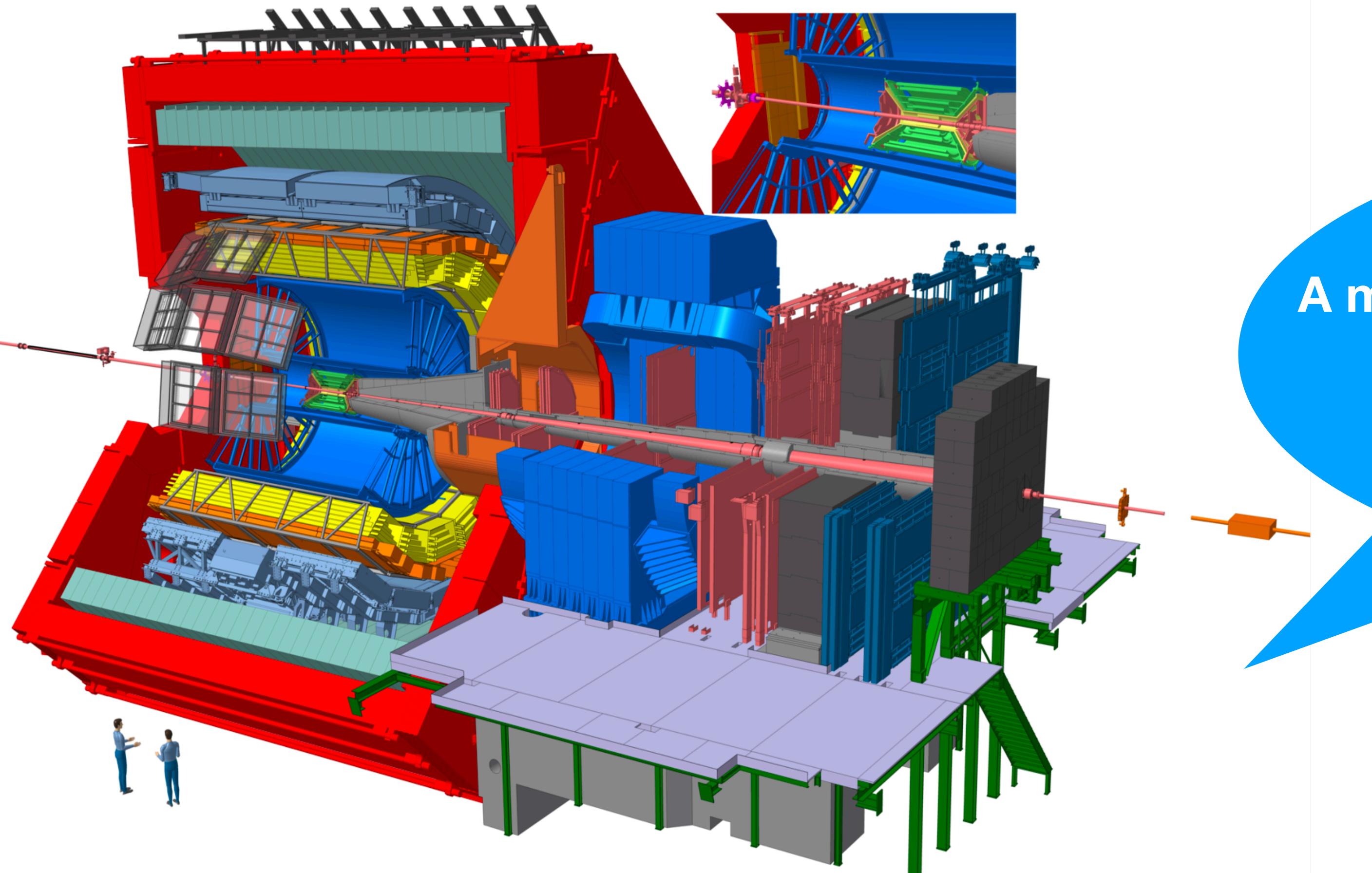
Structure, quark content and nature yet not understood

Can we see these states in pp collisions with the ALICE detector ??



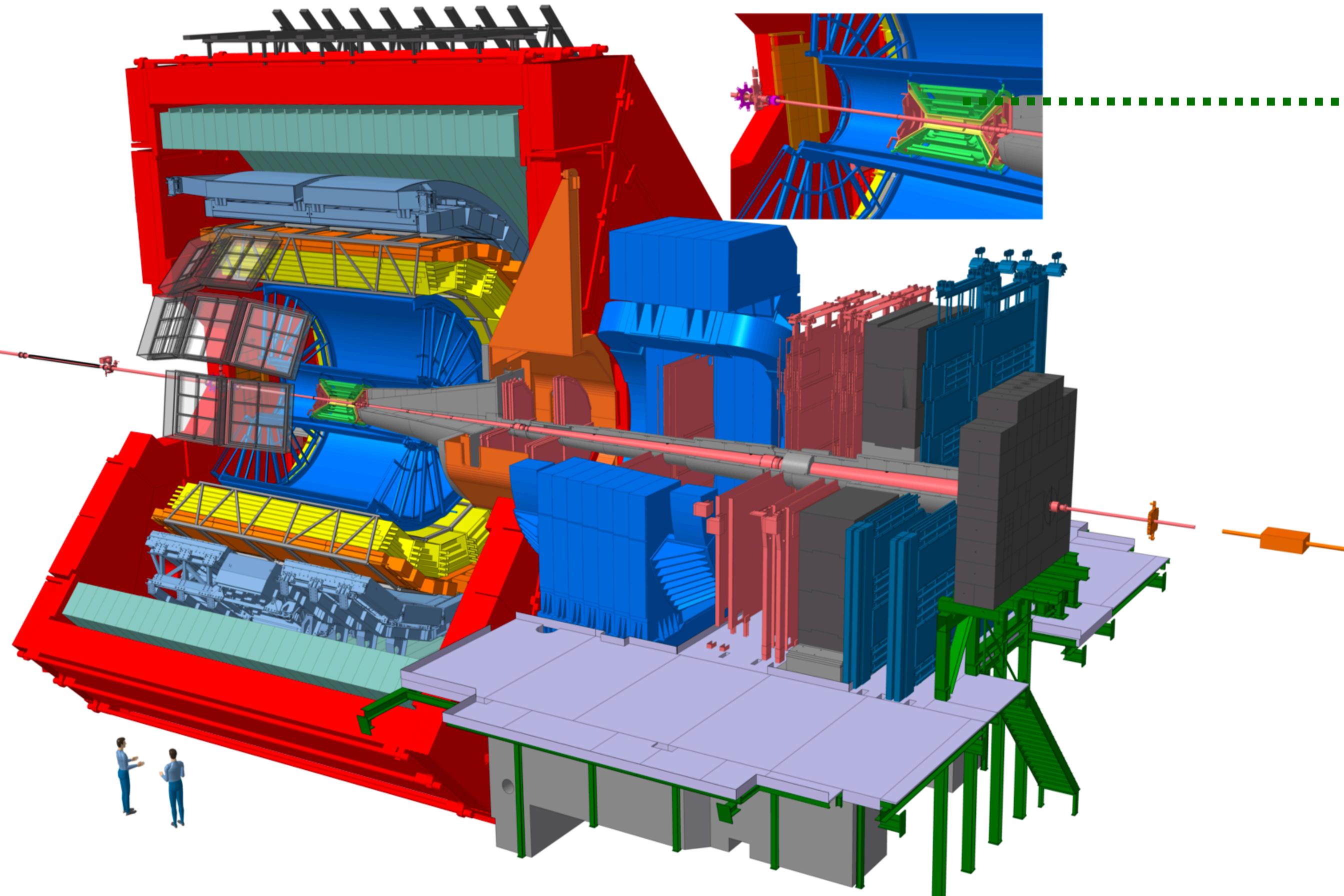
- WA102 [3], ZEUS have measured the $K_S^0 K_S^0$ mass peak
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The ALICE Detector in Run2



A multipurpose detector of LHC with excellent tracking and particle identification capability

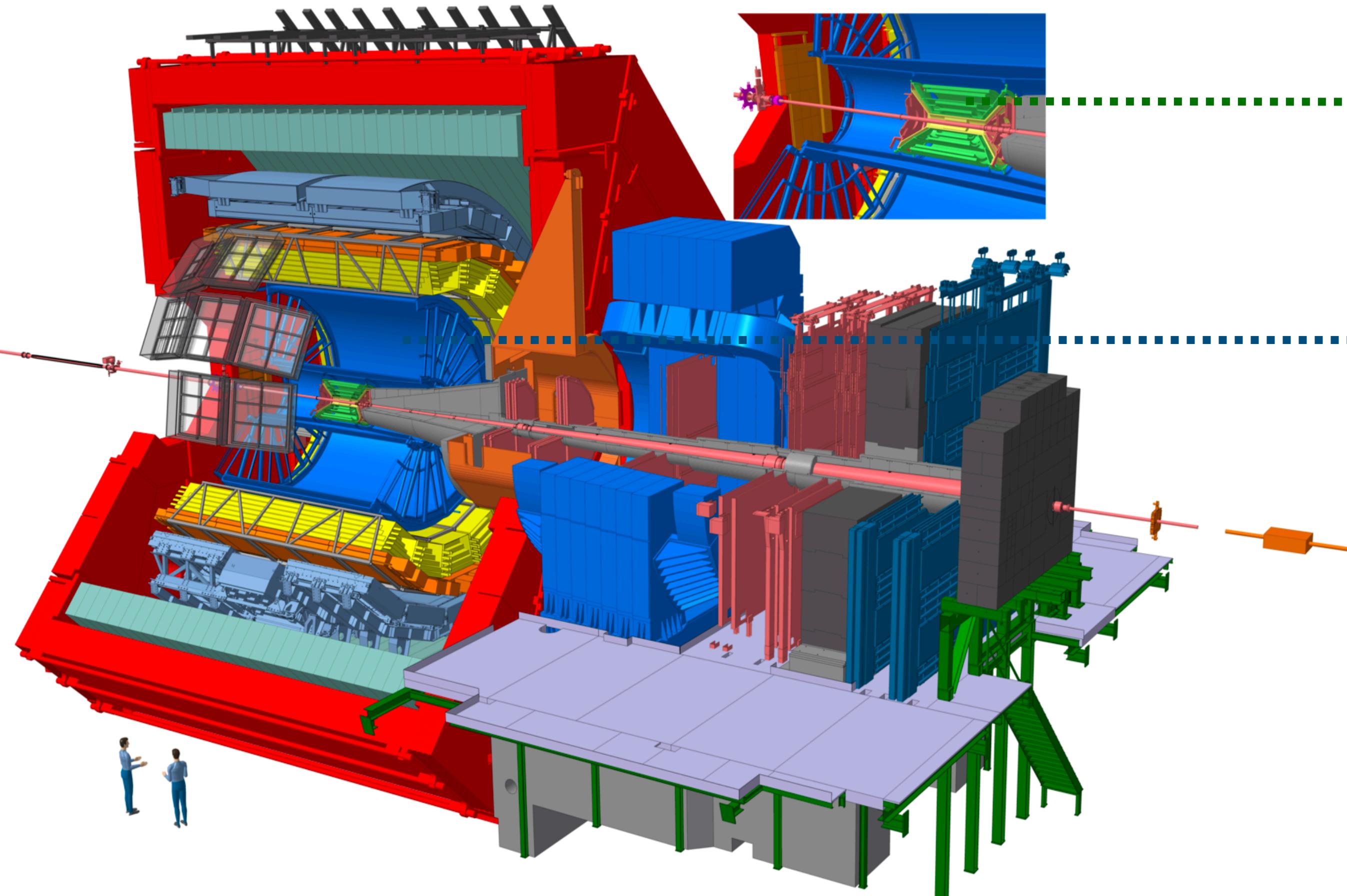
The ALICE Detector in Run2



Inner Tracking System (ITS)

- $|\eta| < 0.9$
- 6 layers of silicon detectors
- Particle identification & tracking

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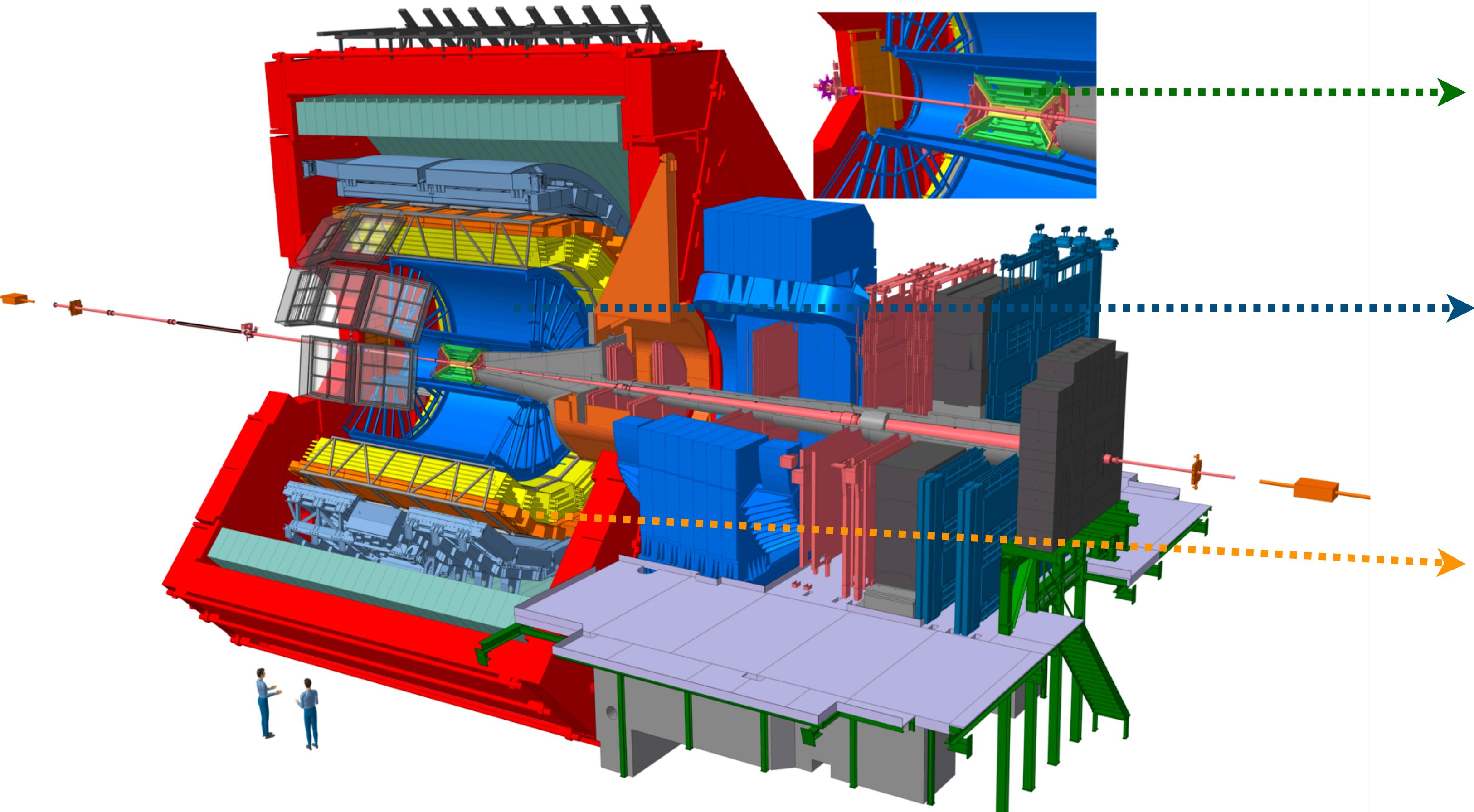
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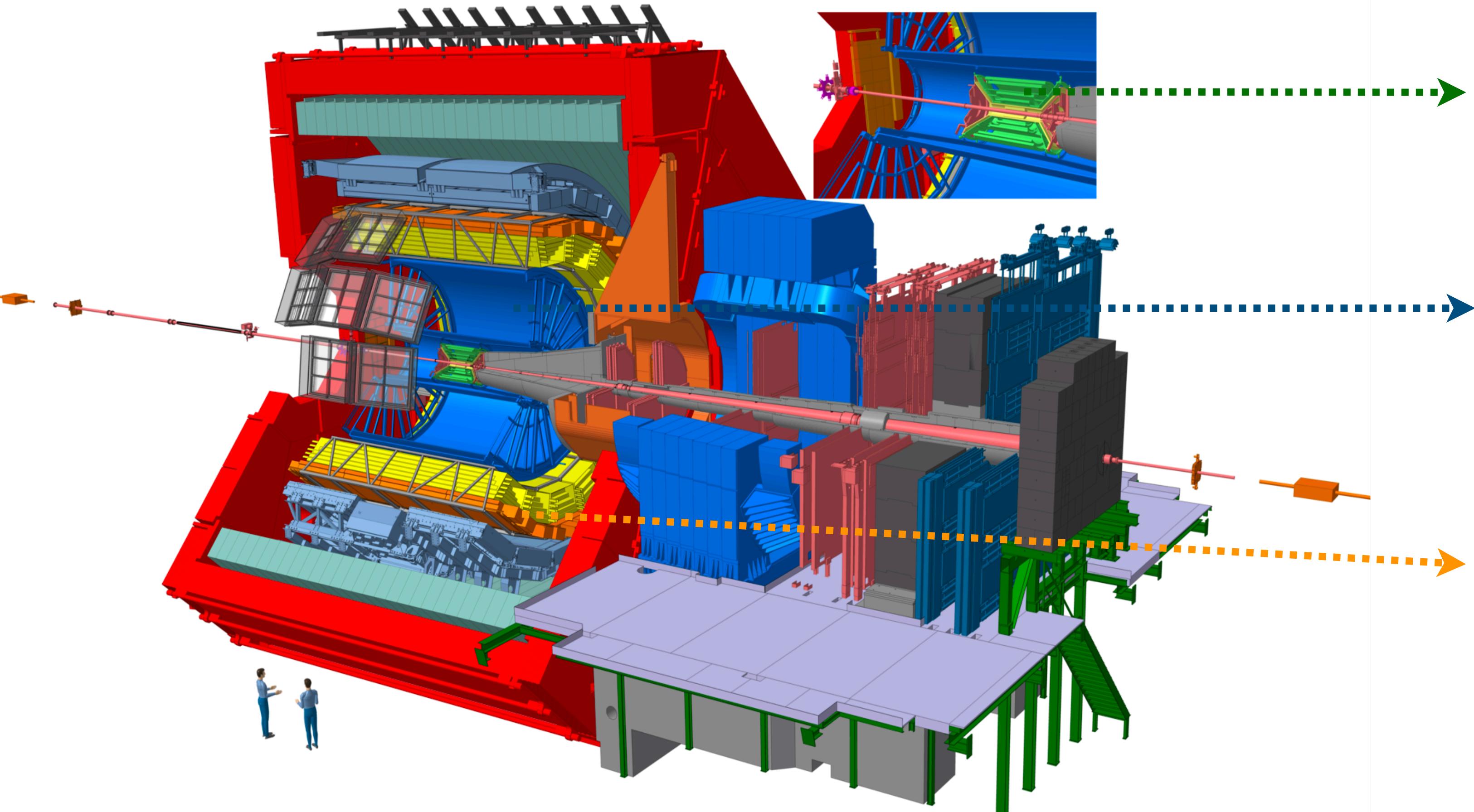
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Time Of Flight (TOF)

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- Multi-gap resistive plate chambers
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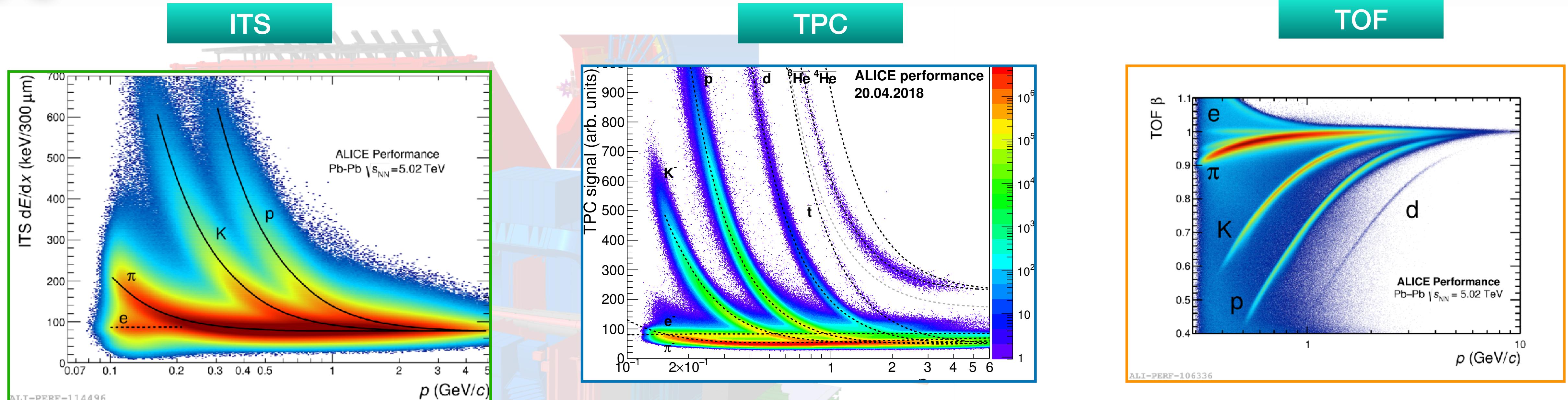
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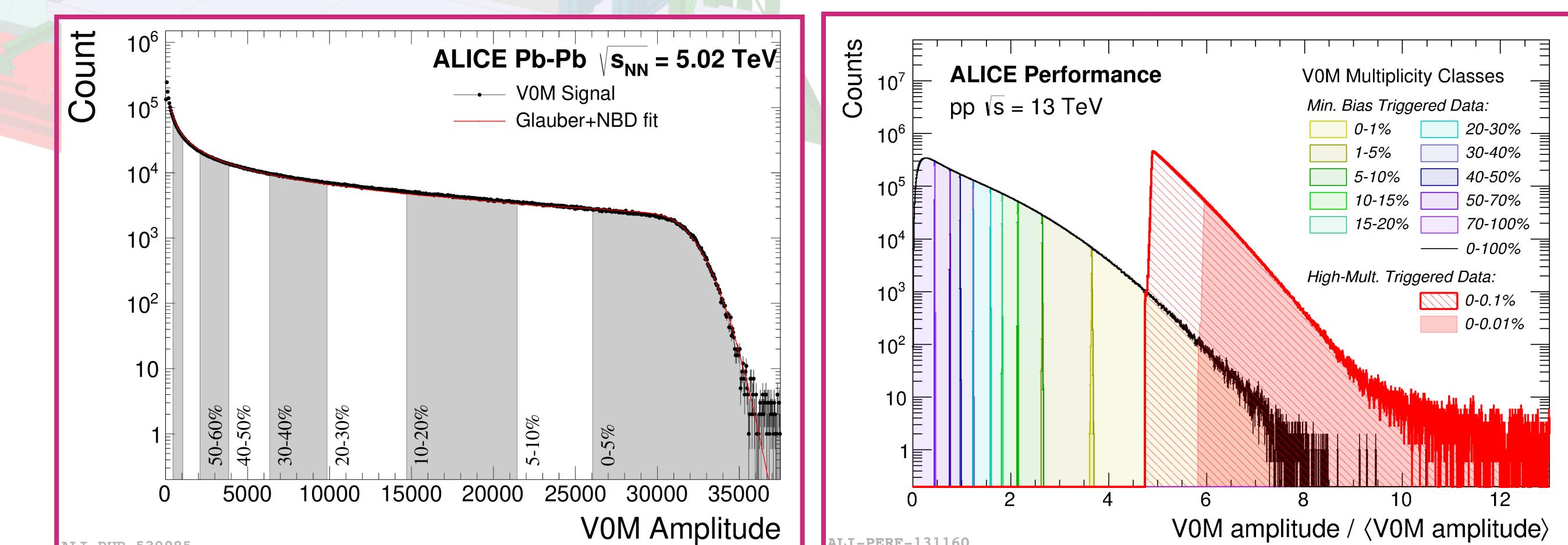
V0A & V0C

- V0A($2.8 < \eta < 5.1$),
V0C($-3.7 < \eta < -1.7$)
- Array of scintillators
- Trigger and multiplicity estimator

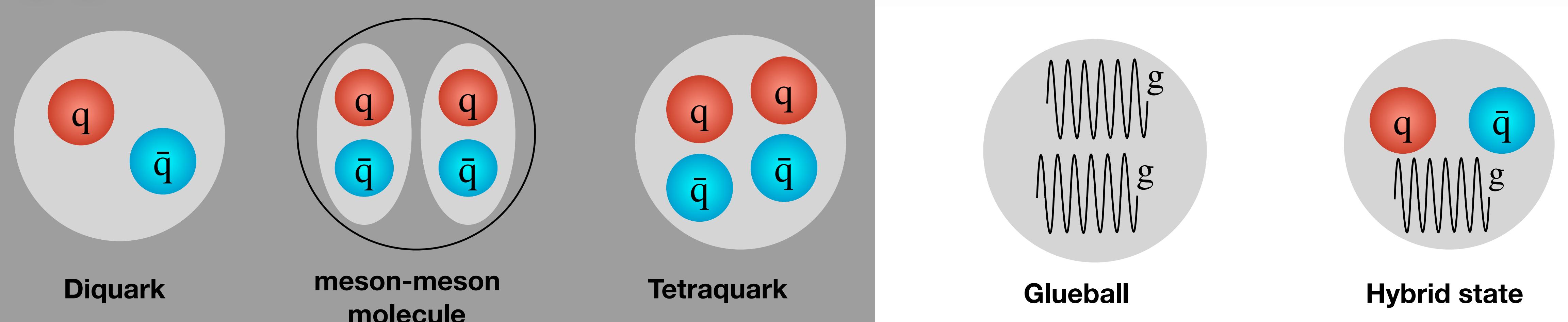
The ALICE Detector in Run2 - PID



VOM Multiplicity



Measurement of $f_0(980)$

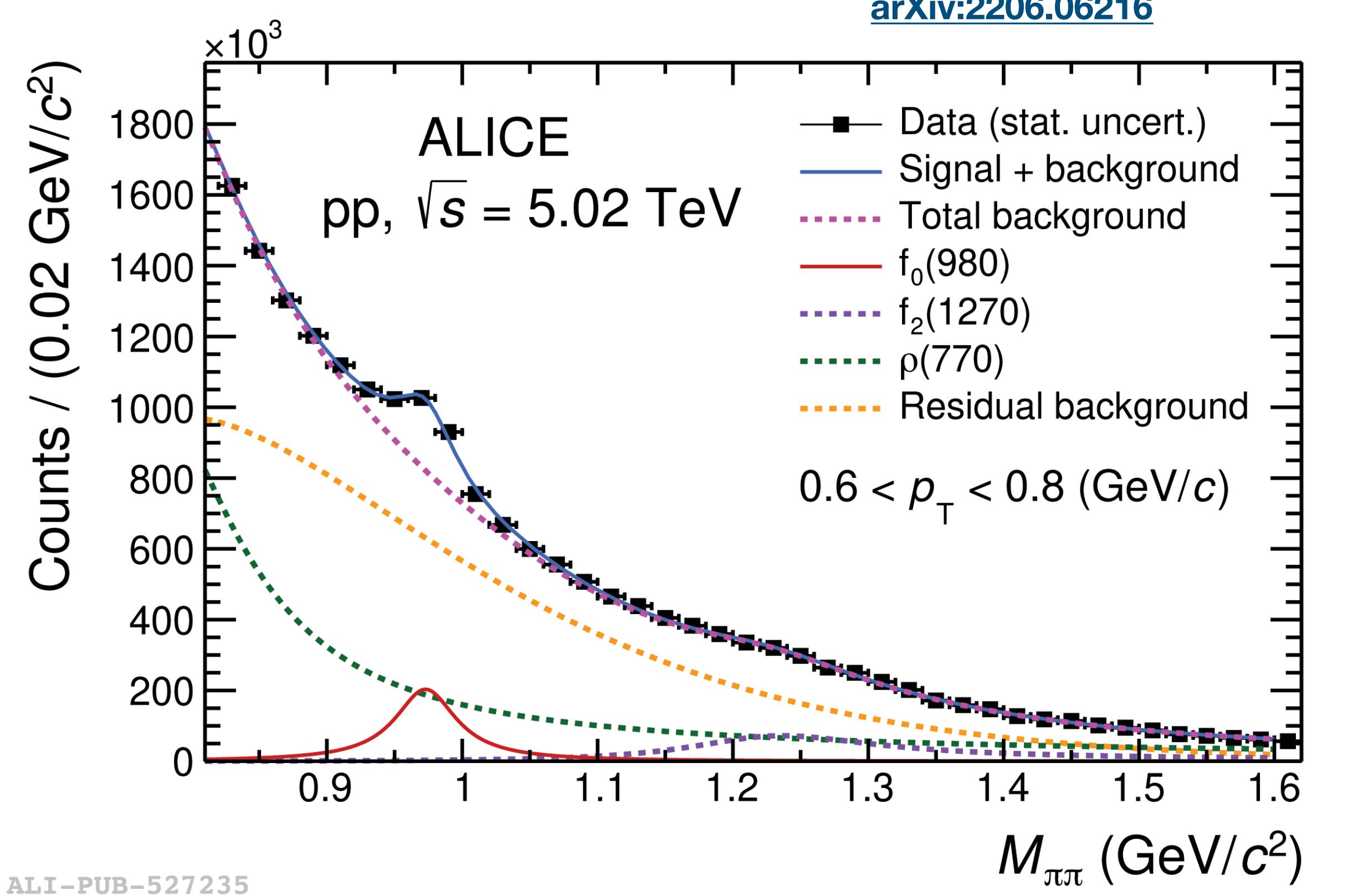


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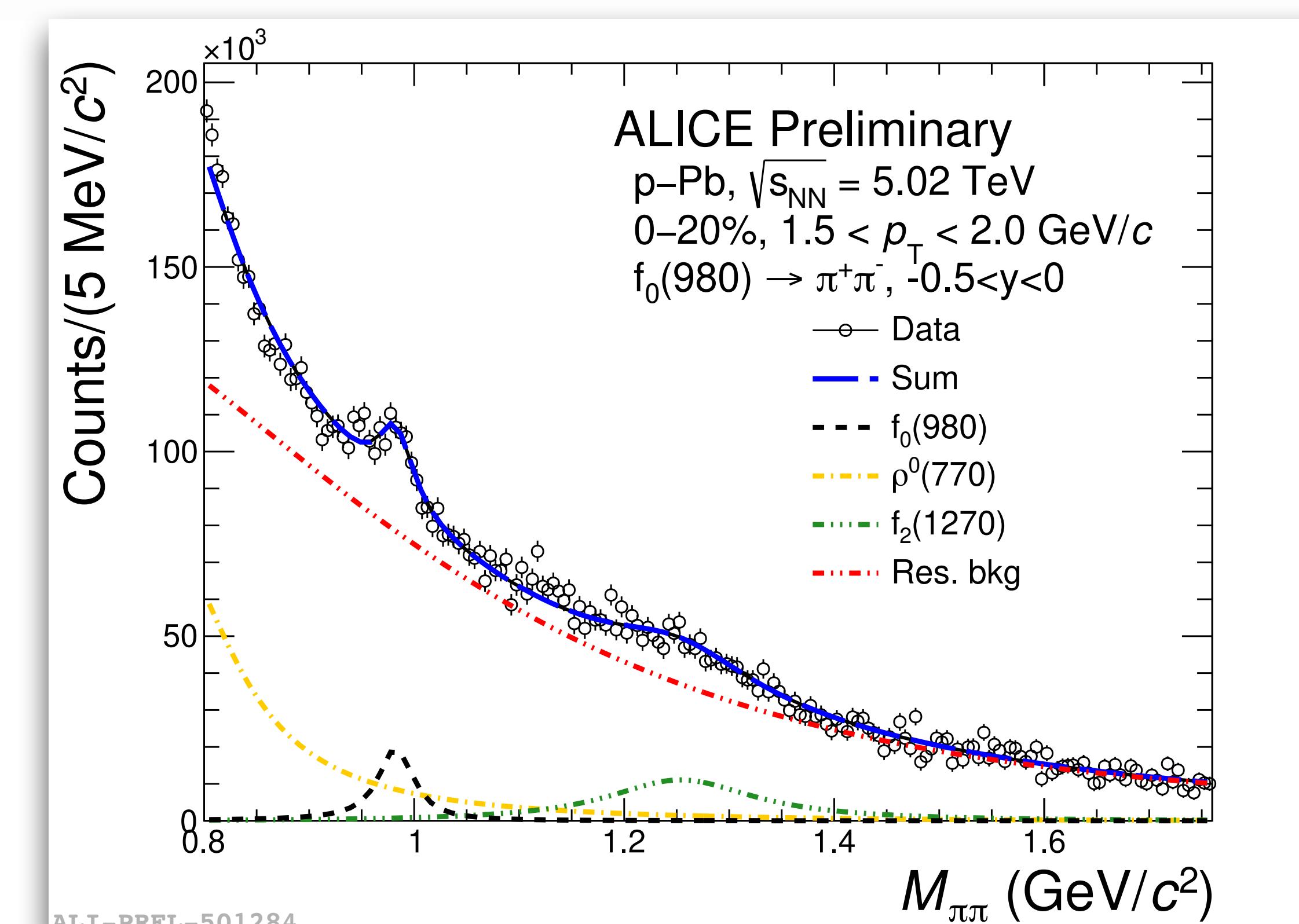
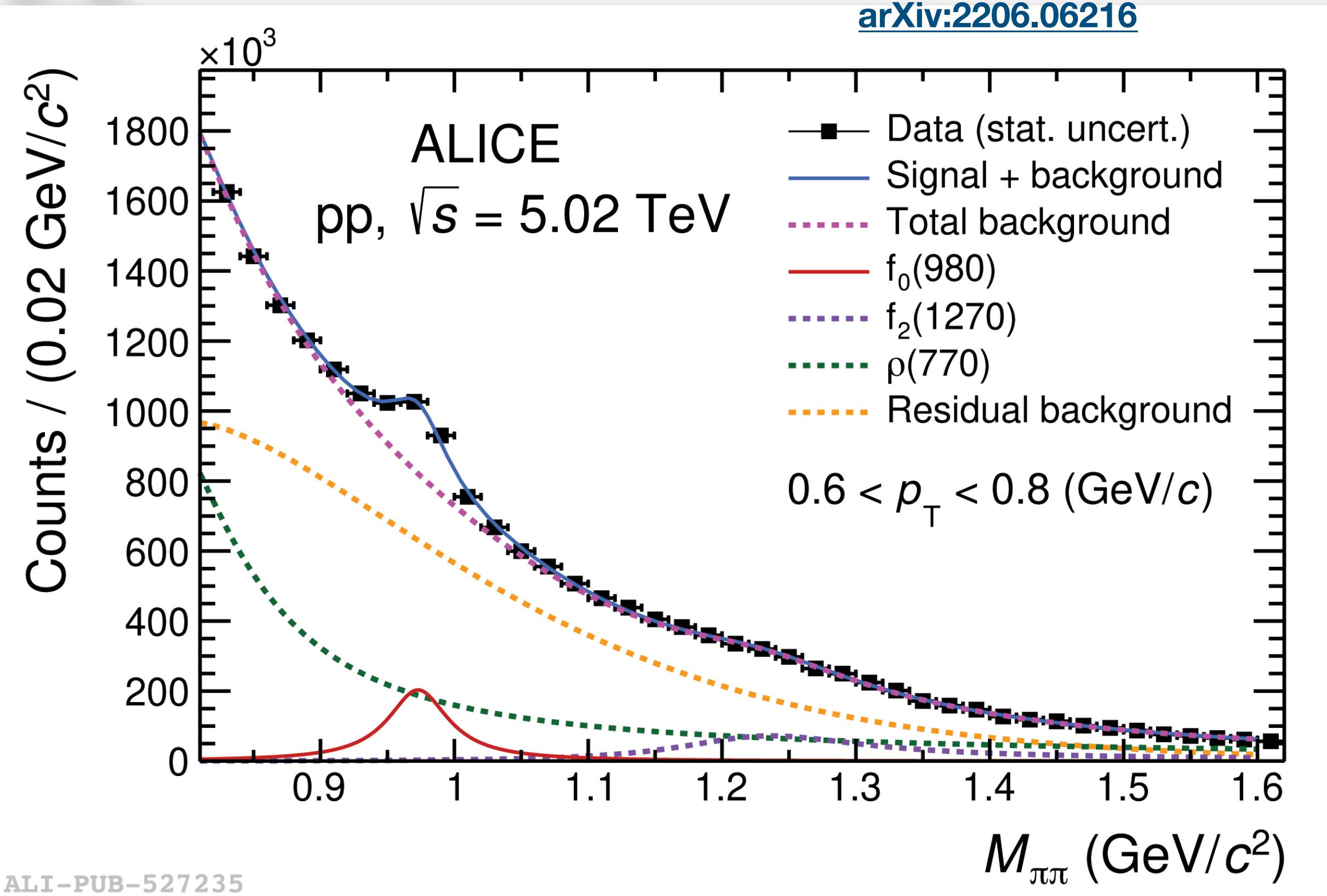
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Measurement of $f_0(980)$

[arXiv:2206.06216](https://arxiv.org/abs/2206.06216)



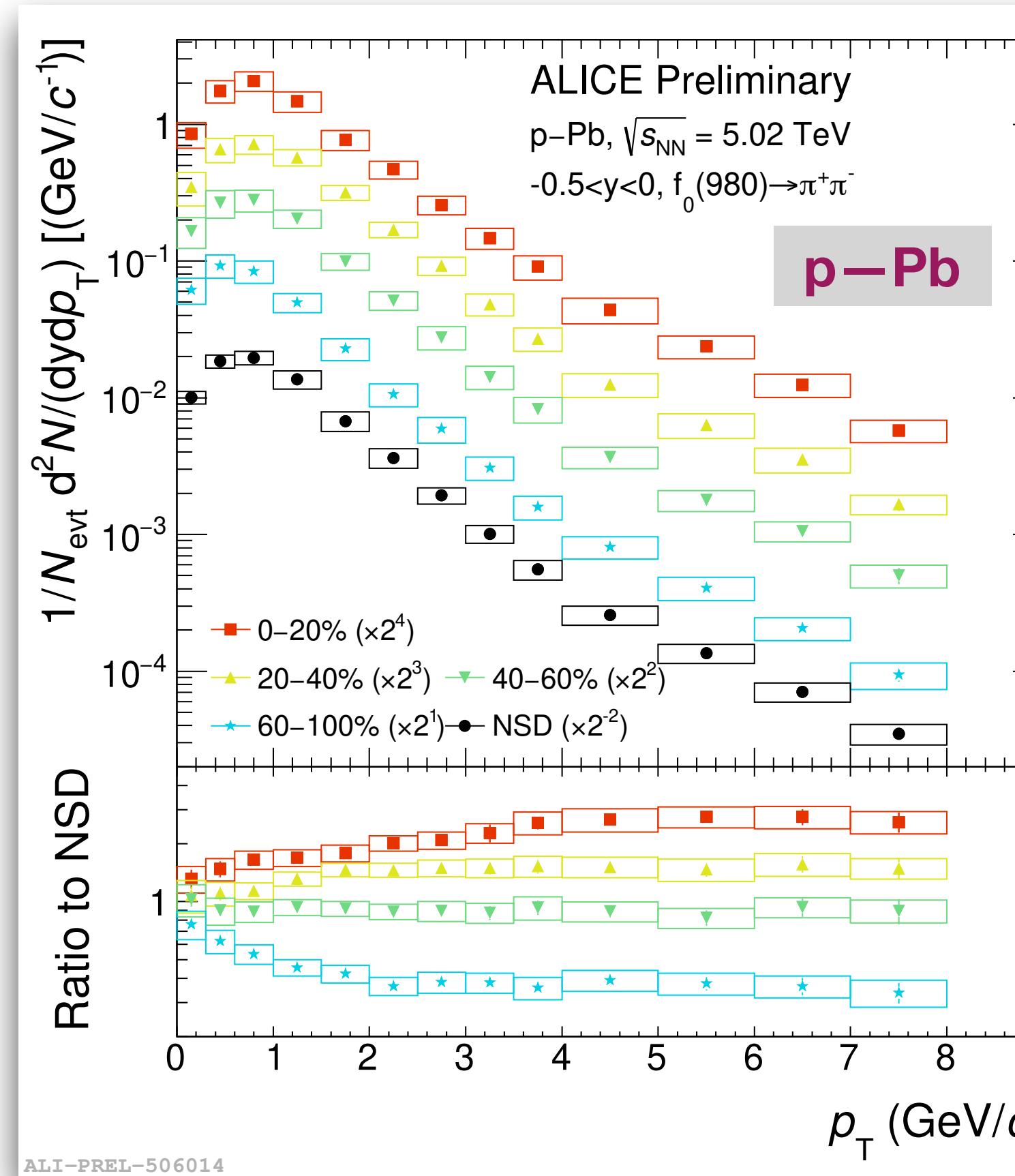
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- Signal extraction: Invariant mass analysis via $f_0(980) \rightarrow \pi^+\pi^-$ decay channel in pp and p-Pb collisions at $\sqrt{s} = 5.02 \text{ TeV}$
- Contributions from three resonances, $f_0(980)$, $\rho^0(770)$, and $f_2(1270)$: fitted with relativistic Breit-Wigner functions
- p_T -differential yields** are obtained with the combined fit of signal description and corrected for the detector acceptance and reconstruction efficiency

$f_0(980)$ spectra , yield and mean p_T

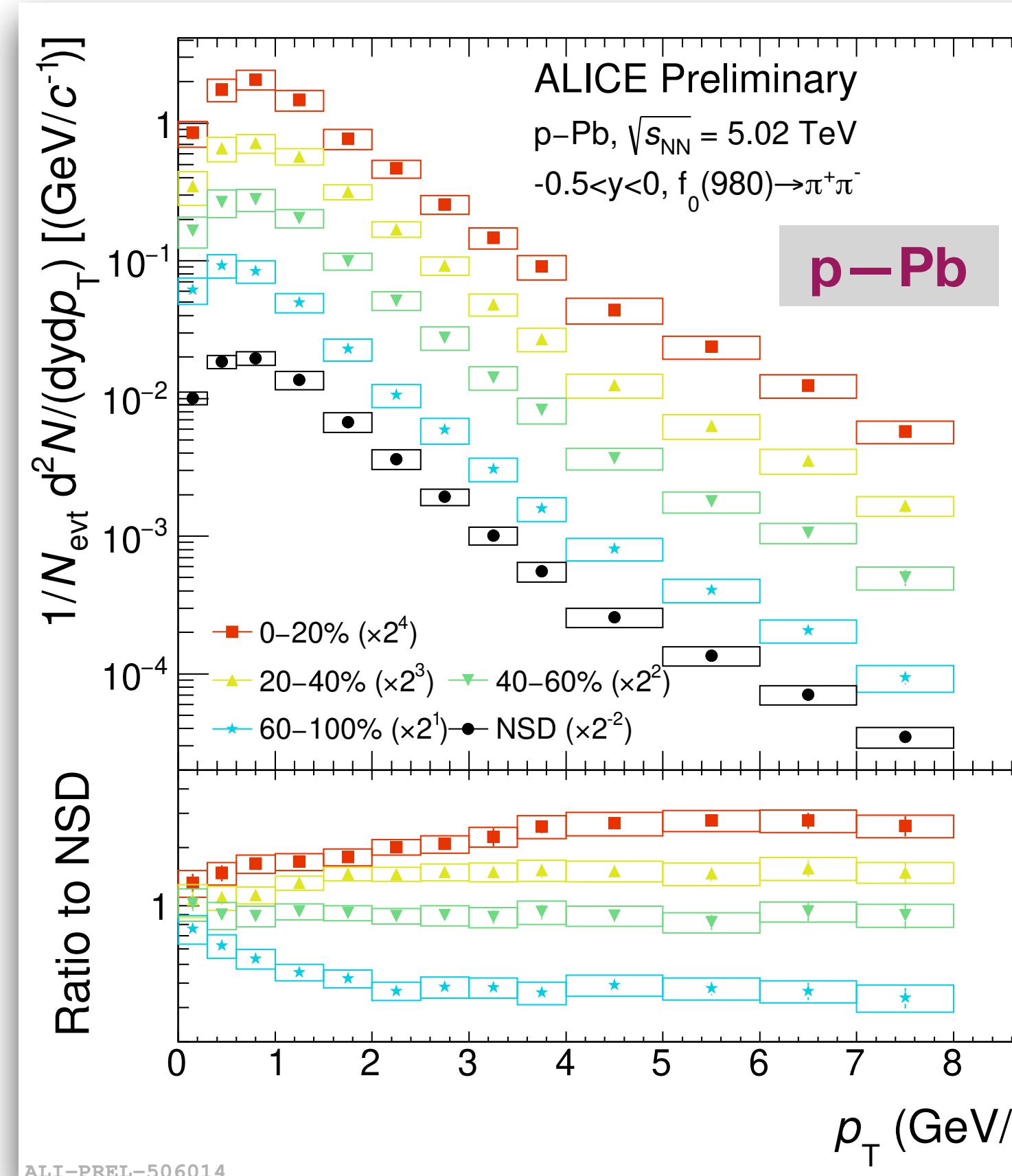
p_T Spectra



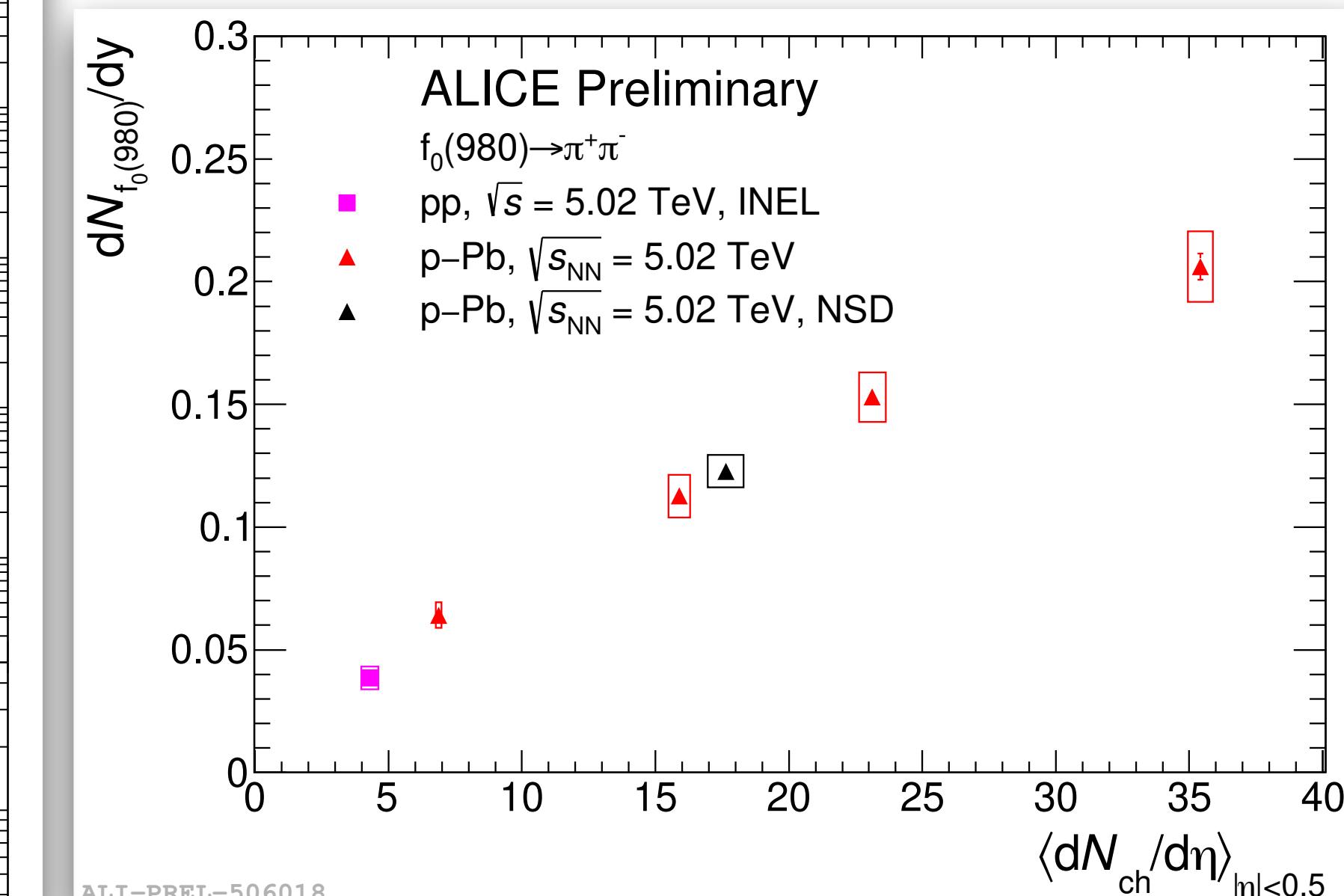
- Spectra are measured in four multiplicity classes & inelastic/non-single diffractive collisions.

$f_0(980)$ spectra , yield and mean p_T

p_T Spectra



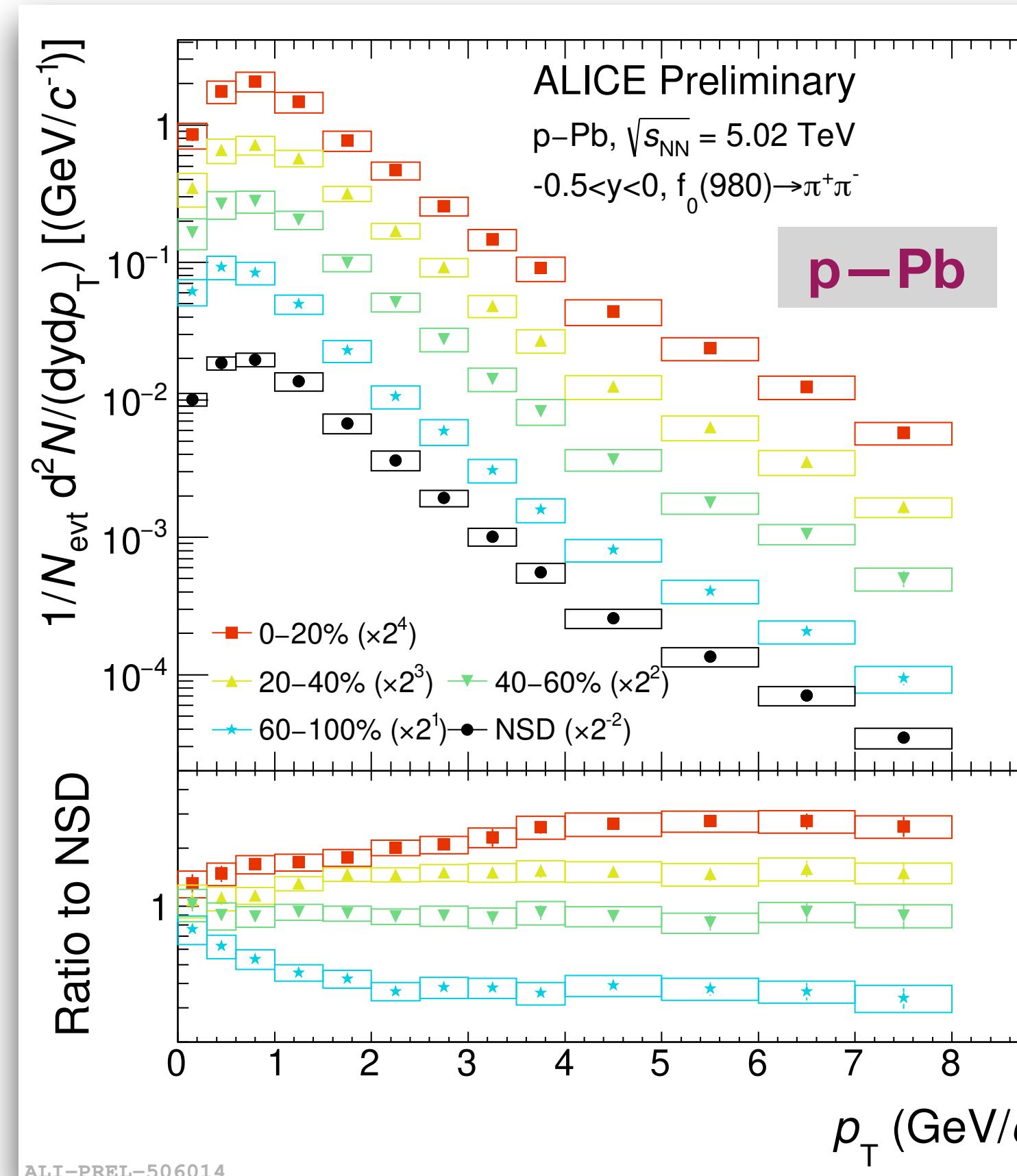
p_T - Integrated yield



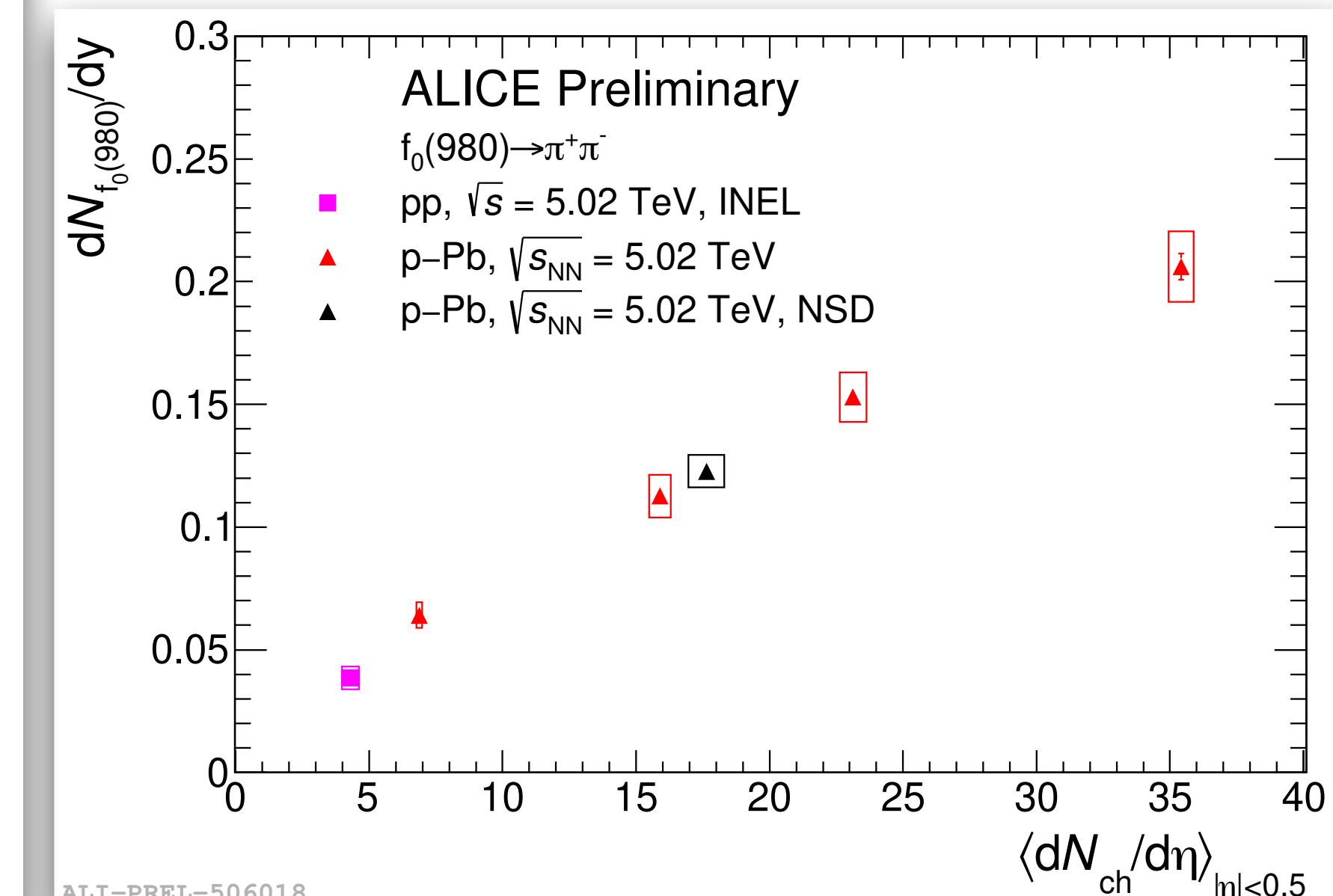
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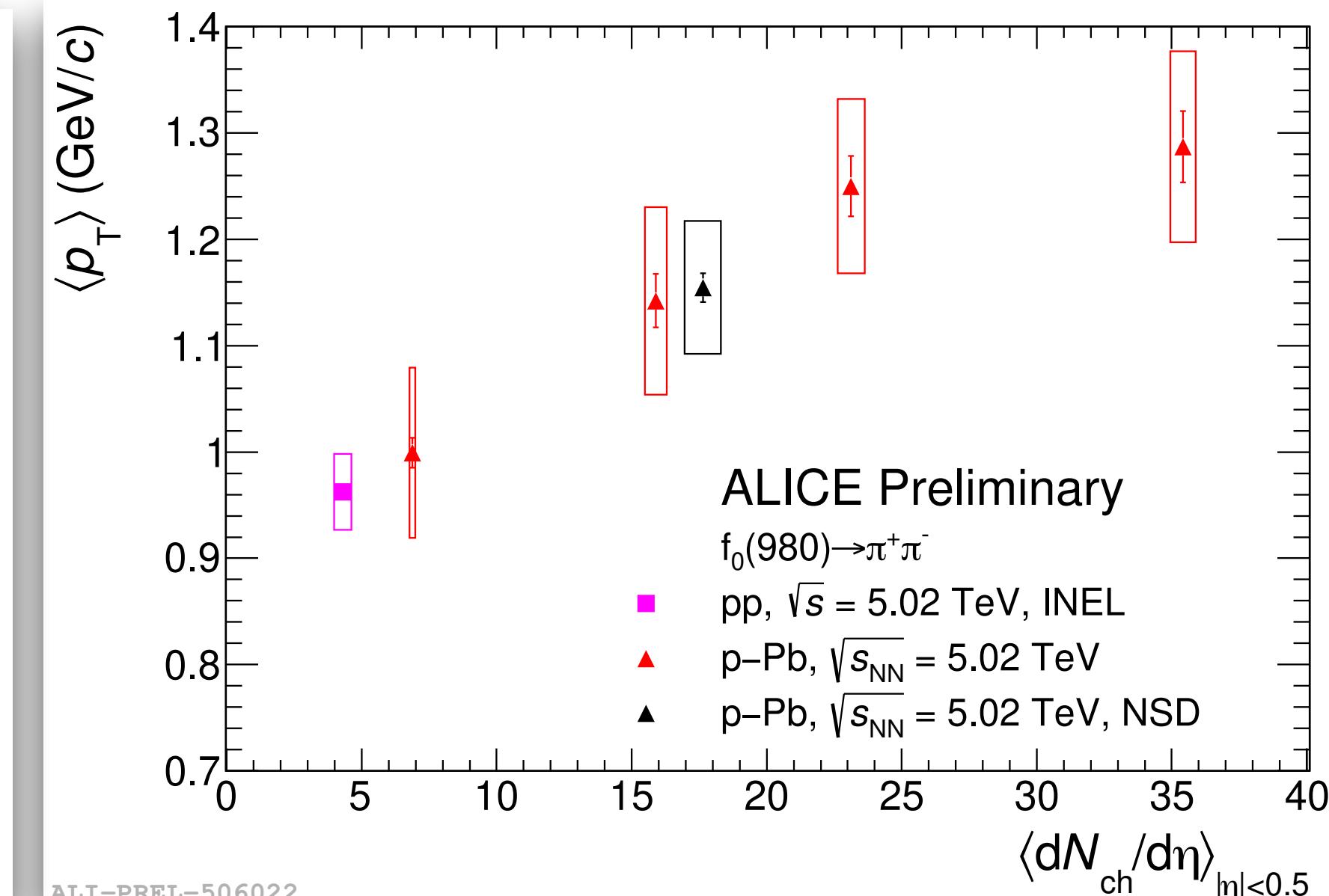
p_T Spectra



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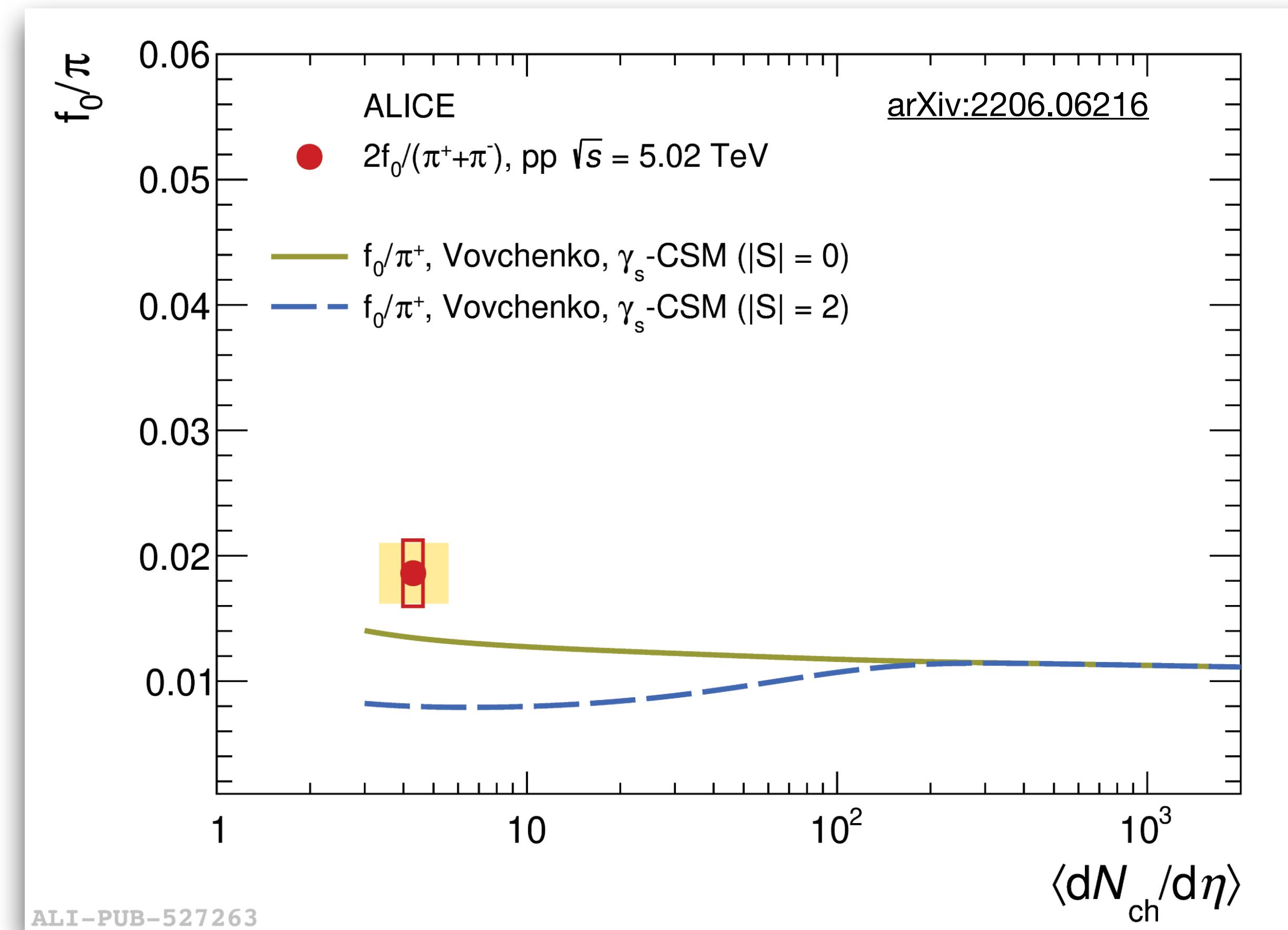


Mean p_T



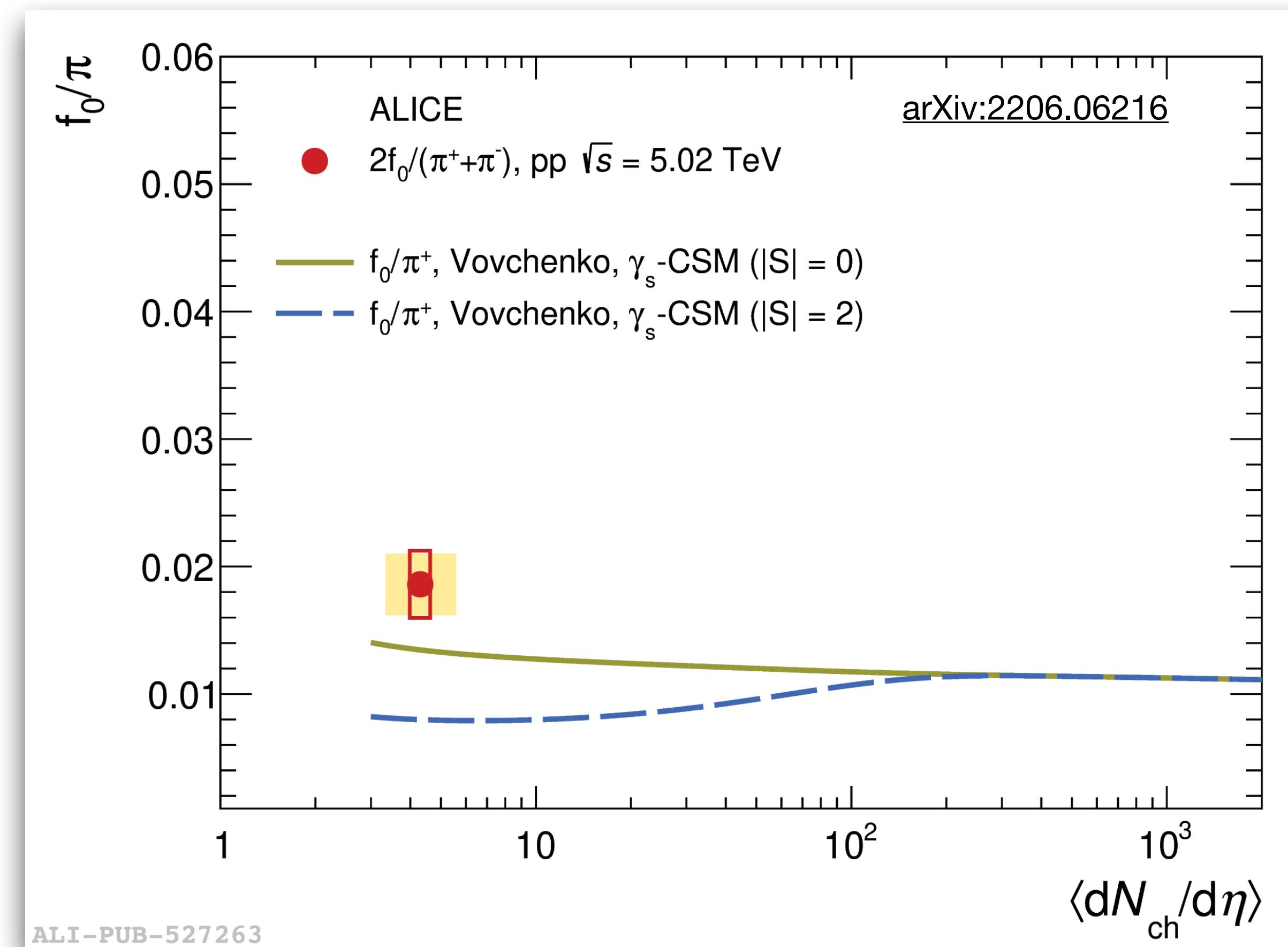
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- p_T -Integrated yield and mean- p_T increase with the multiplicity in pp and p-Pb collisions

Internal quark structure of $f_0(980)$



$\langle dN_{\text{ch}} / d\eta \rangle$ - Average pseudo-rapidity density of charged particles

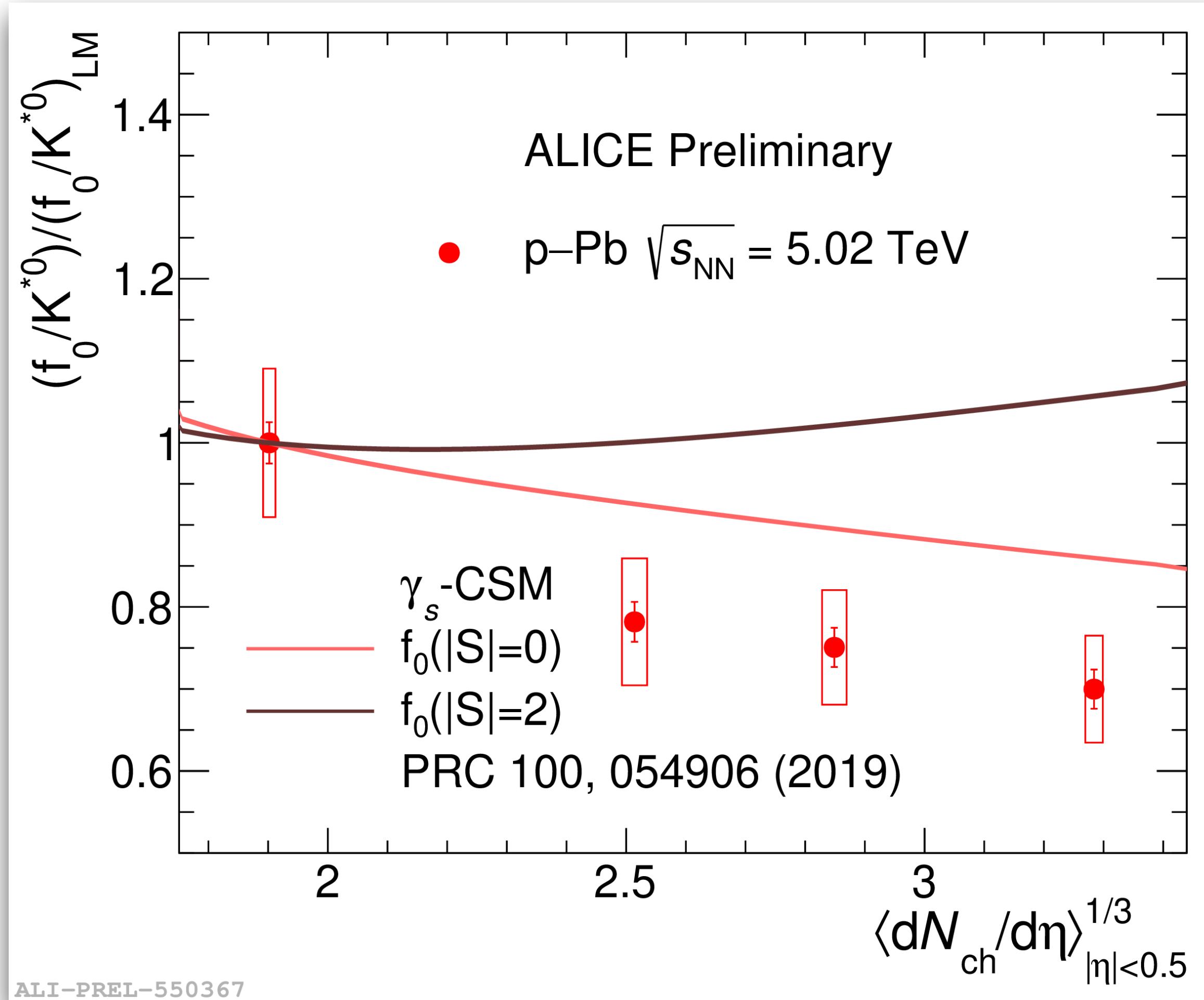
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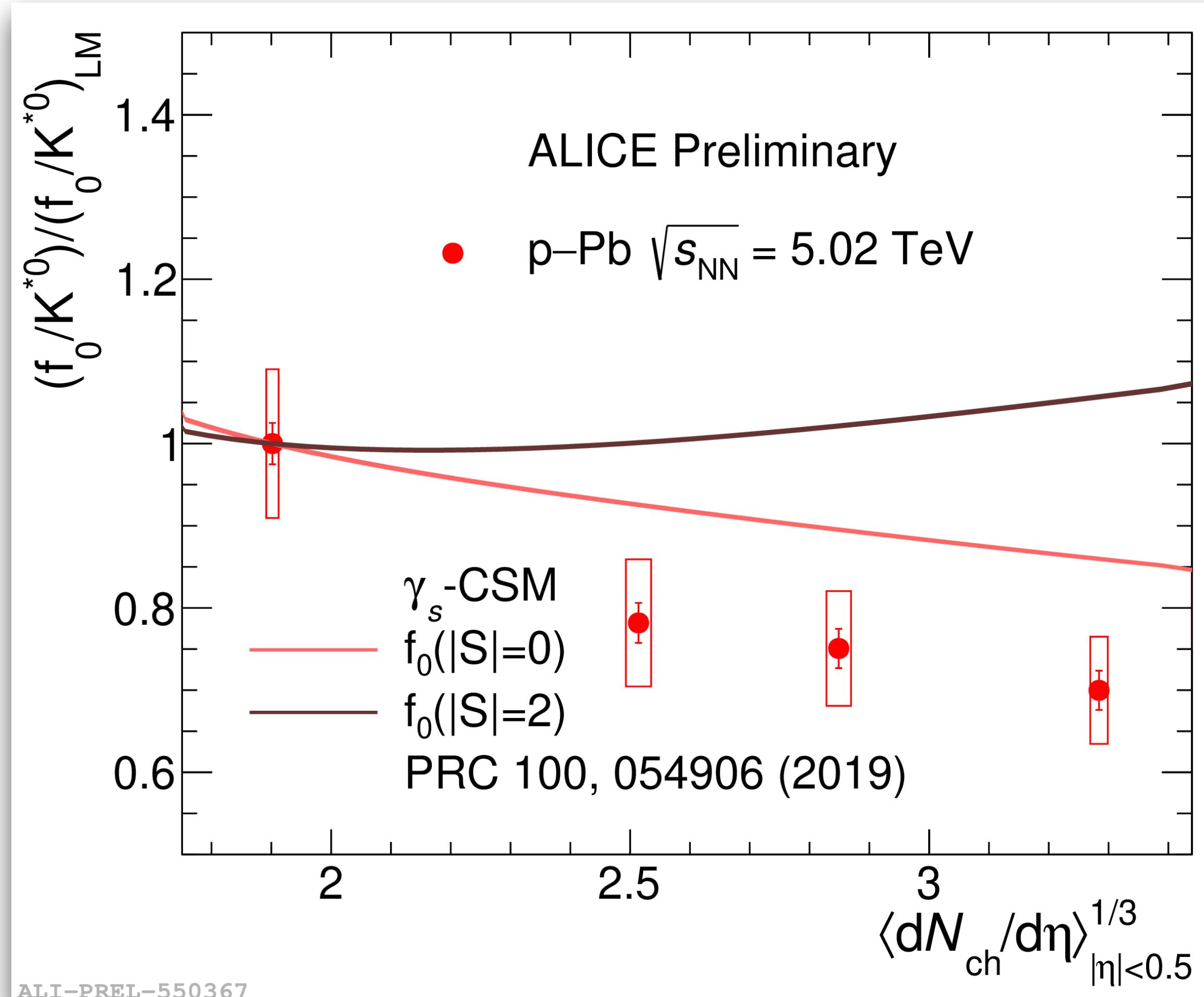
$\langle dN_{ch}/d\eta \rangle$ - Average pseudo-rapidity density of charged particles

- Predictions based on the γ_s -CSM are calculated by assuming two scenarios:
 - $|S| = 0$ (Data differ by 1.9σ)
 - $|S| = 2$ (Data differ by 4.0σ)
- f_0/π vs $\langle dN_{ch}/d\eta \rangle$: Canonical Statistical Model (arXiv:1906.03145) underestimates the ratio
- γ_s -CSM predicts higher values for yield ratio when assuming net strangeness 0 ($|S| = 0$) compared to $|S| = 2$ in the low $\langle dN_{ch}/d\eta \rangle$
- The two predictions match each other for $\langle dN_{ch}/d\eta \rangle \geq 100$

Internal quark structure of $f_0(980)$

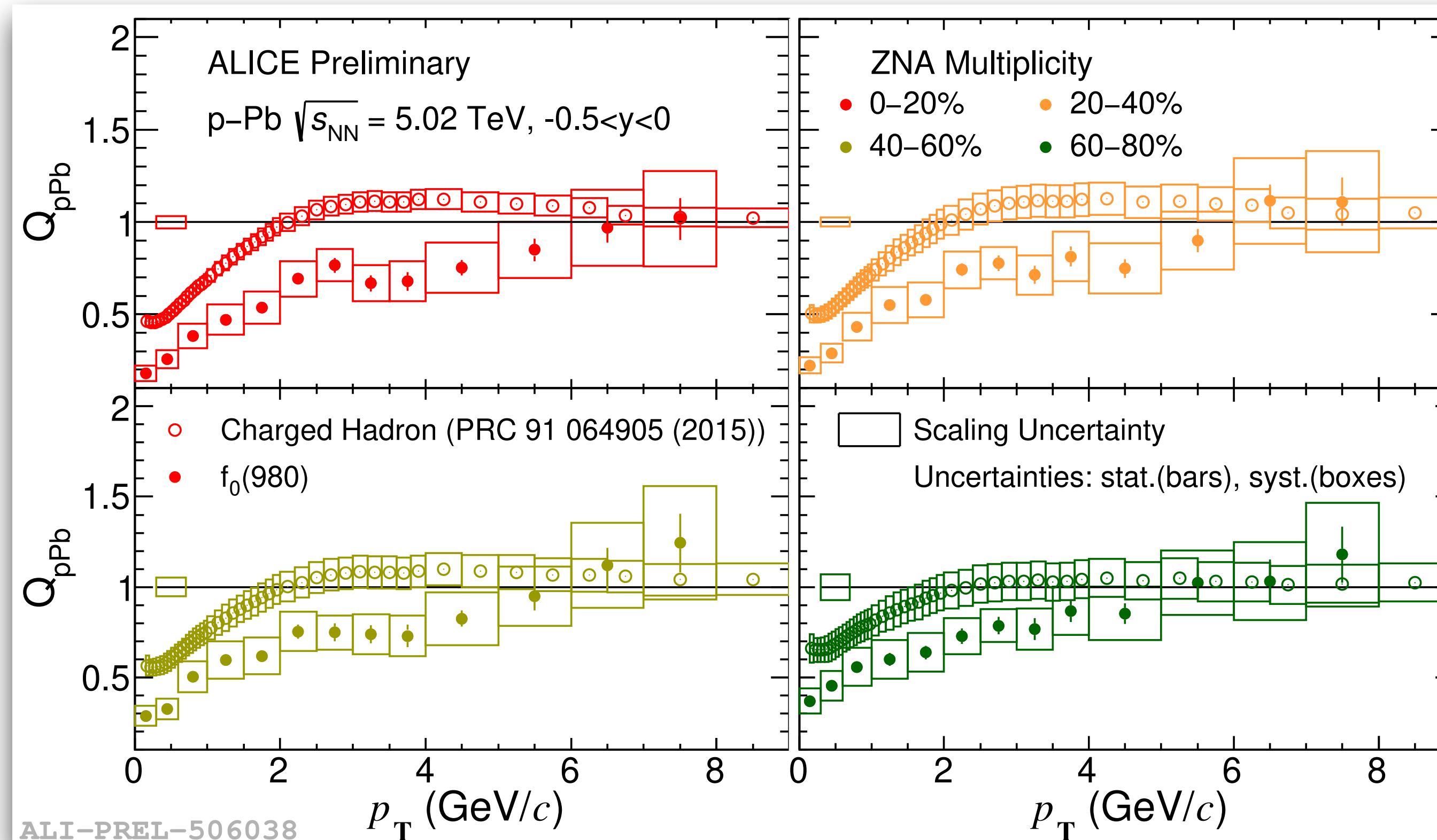


Internal quark structure of $f_0(980)$



- $f_0(980)/K^0$ is calculated with two assumptions i.e strange and anti-strange quark ($|S|=2$) or not?
- Double ratio of $f_0(980)$ to K^*0 yields compared with γ_s -CSM model.
 - $|S|=2$ (Increasing trend)
 - $|S|=0$ (Declining trend)
- If strangeness content exists ($|S|=2$), we should observe a rising trend as K^* possesses ($S=1$), and the model suggests a **mild increasing trend**
- The data's behaviour aligns qualitatively with the second scenario

Nuclear modification factor, Q_{pPb}

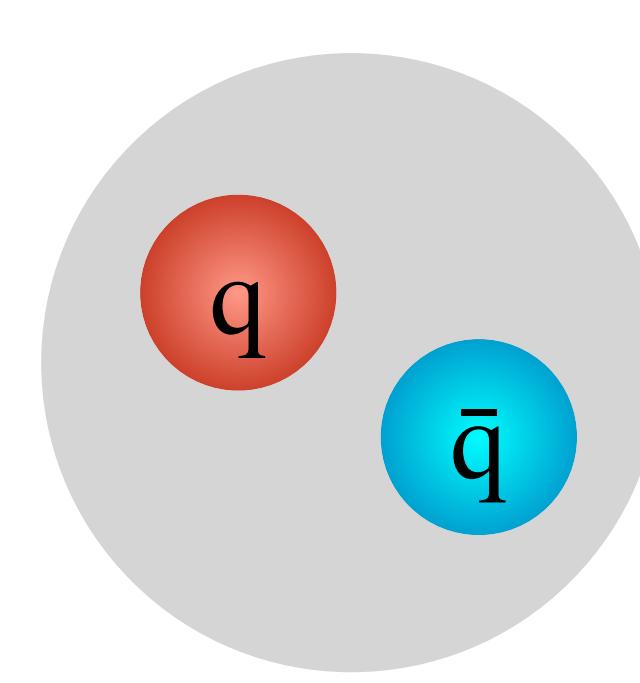


- $Q_{\text{pPb}}(p_T, \text{cent}) = \frac{d^2N_{\text{pPb}}^{\text{cent}}/dydp_T}{\langle T_{\text{pPb}}^{\text{cent}} \rangle \cdot d^2\sigma_{\text{pp}}^{\text{INEL}}/dydp_T}$
- $\langle T_{\text{pPb}}^{\text{cent}} \rangle = N_{\text{coll}}^{\text{cent}}/\sigma_{\text{NN}}$
- $\sigma_{\text{NN}} = 70 \pm 5 \text{ mb}$

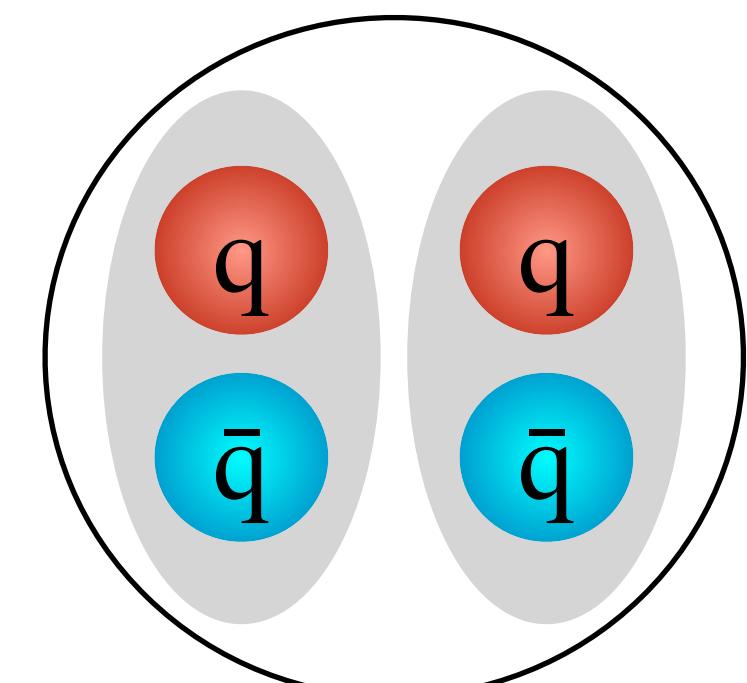
PHYSICAL REVIEW C 91, 064905 (2015)

- A significant **centrality dependent suppression** observed for the $f_0(980)$ yield at **low p_T** : may be the presence of **rescattering effects**
- More suppression in central collisions
- No Cronin peak is observed in the intermediate region : may suggest an **ordinary meson structure** of $f_0(980)$

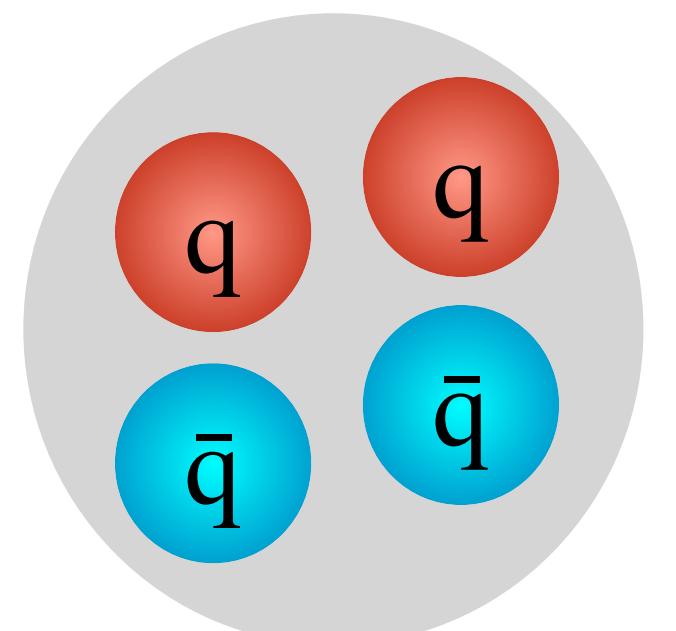
Measurement of $f_1(1285)$



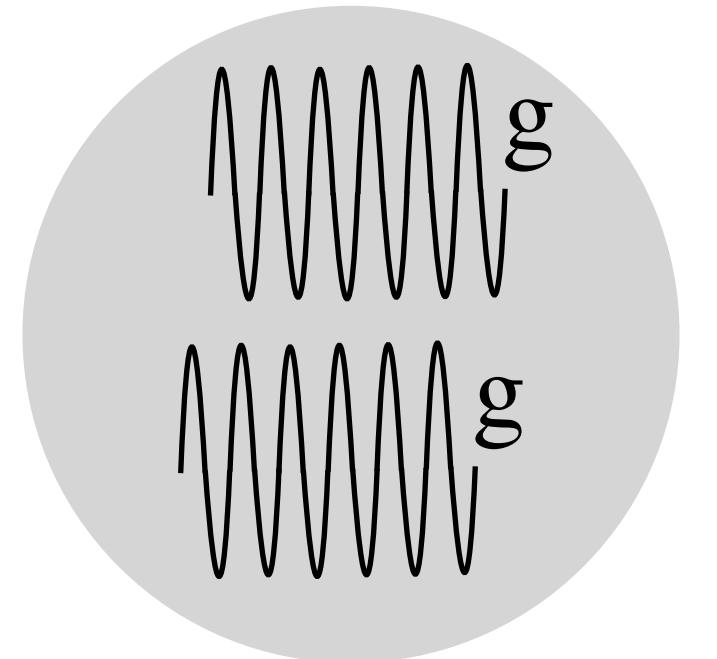
Diquark



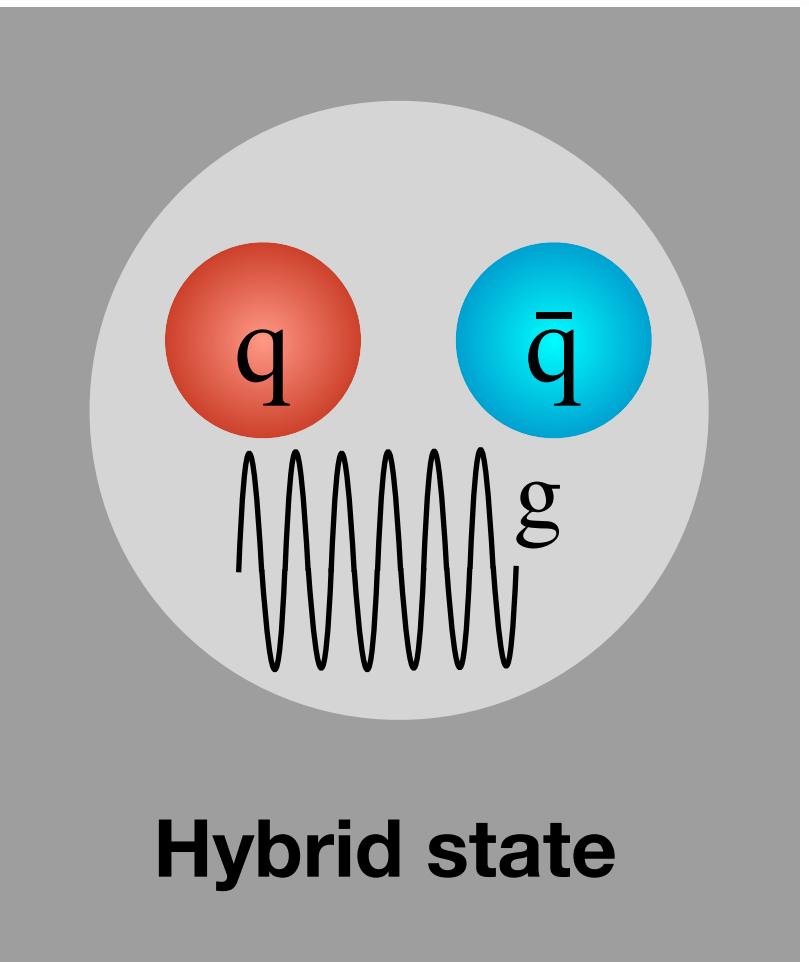
meson-meson
molecule



Tetraquark



Glueball



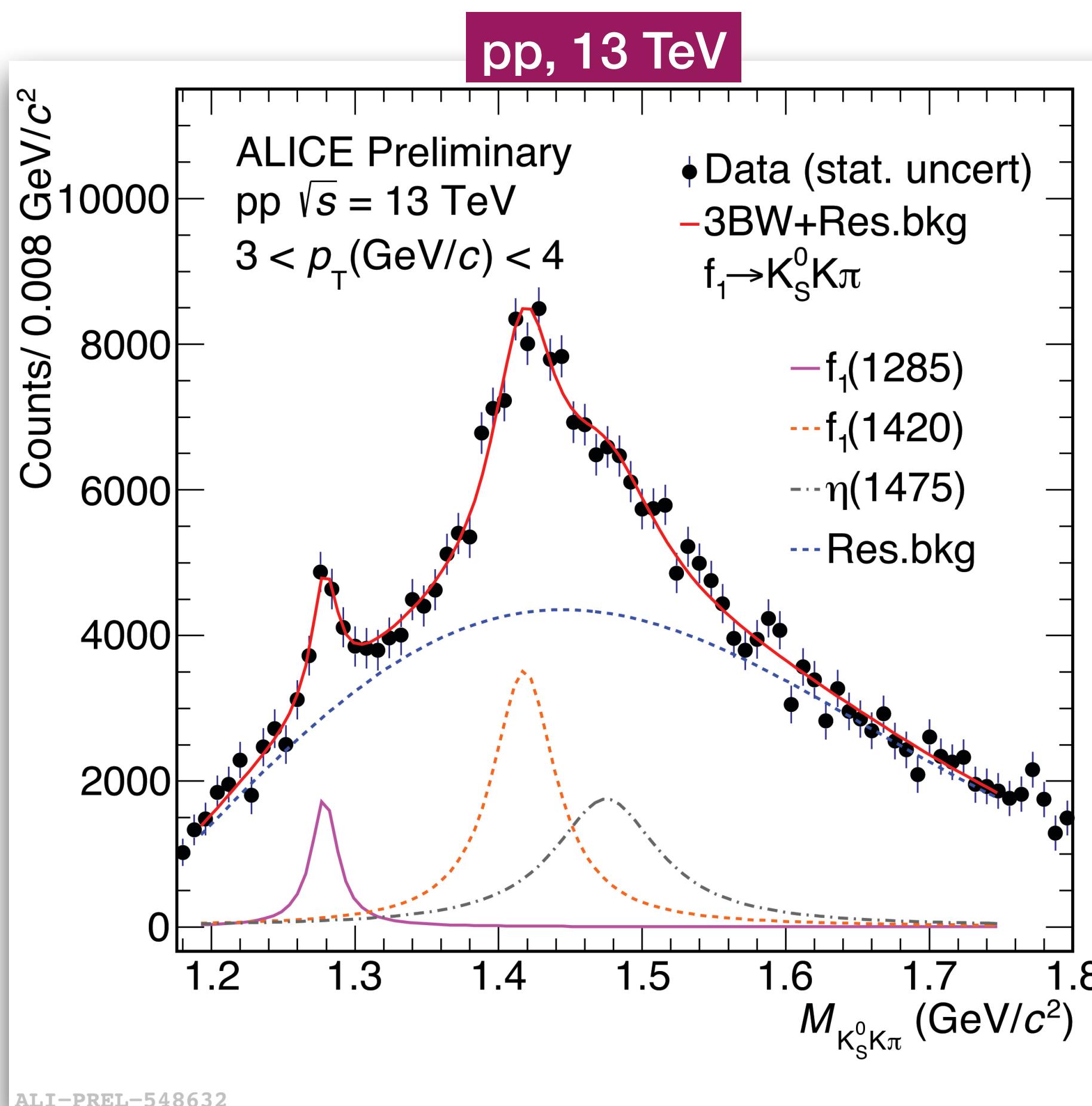
Hybrid state

$f_1(1285)$

- $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: [Phys.Rev.D 96 \(2017\) 5, 054012](#)
- Tetraquark: [Mod.Phys.Lett. A2 \(1987\) 771](#)
- Molecular state: [Phys. Rev D42 \(1990\) 874](#)
- Hybrid state: [Nucl.Phys.A 992 \(2019\) 121641](#)

Measurement of $f_1(1285)$ in pp collisions

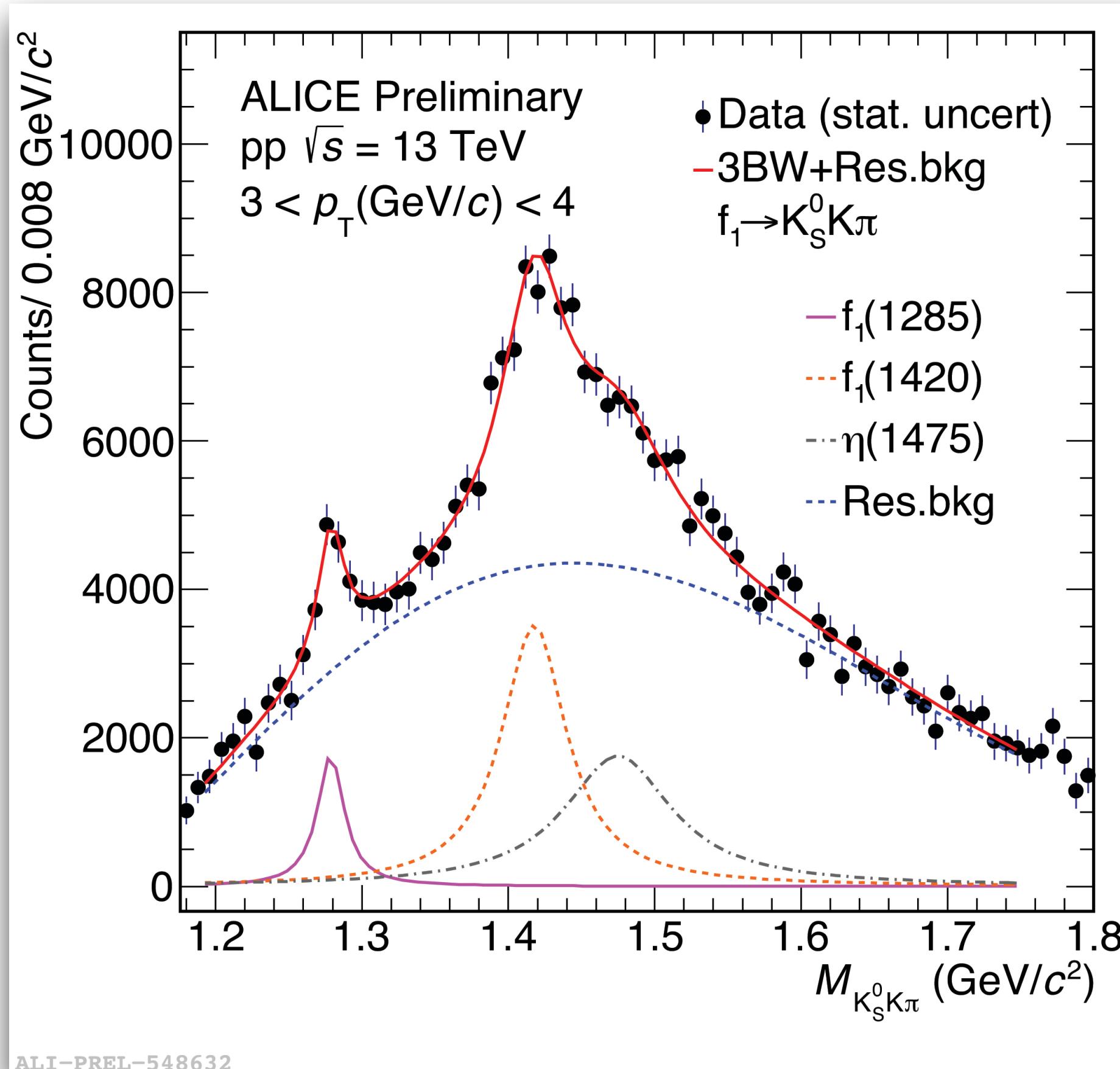
NEW in QM 2023



First measurement of $f_1(1285)$ at ALICE

Measurement of $f_1(1285)$ in pp collisions

NEW in QM 2023

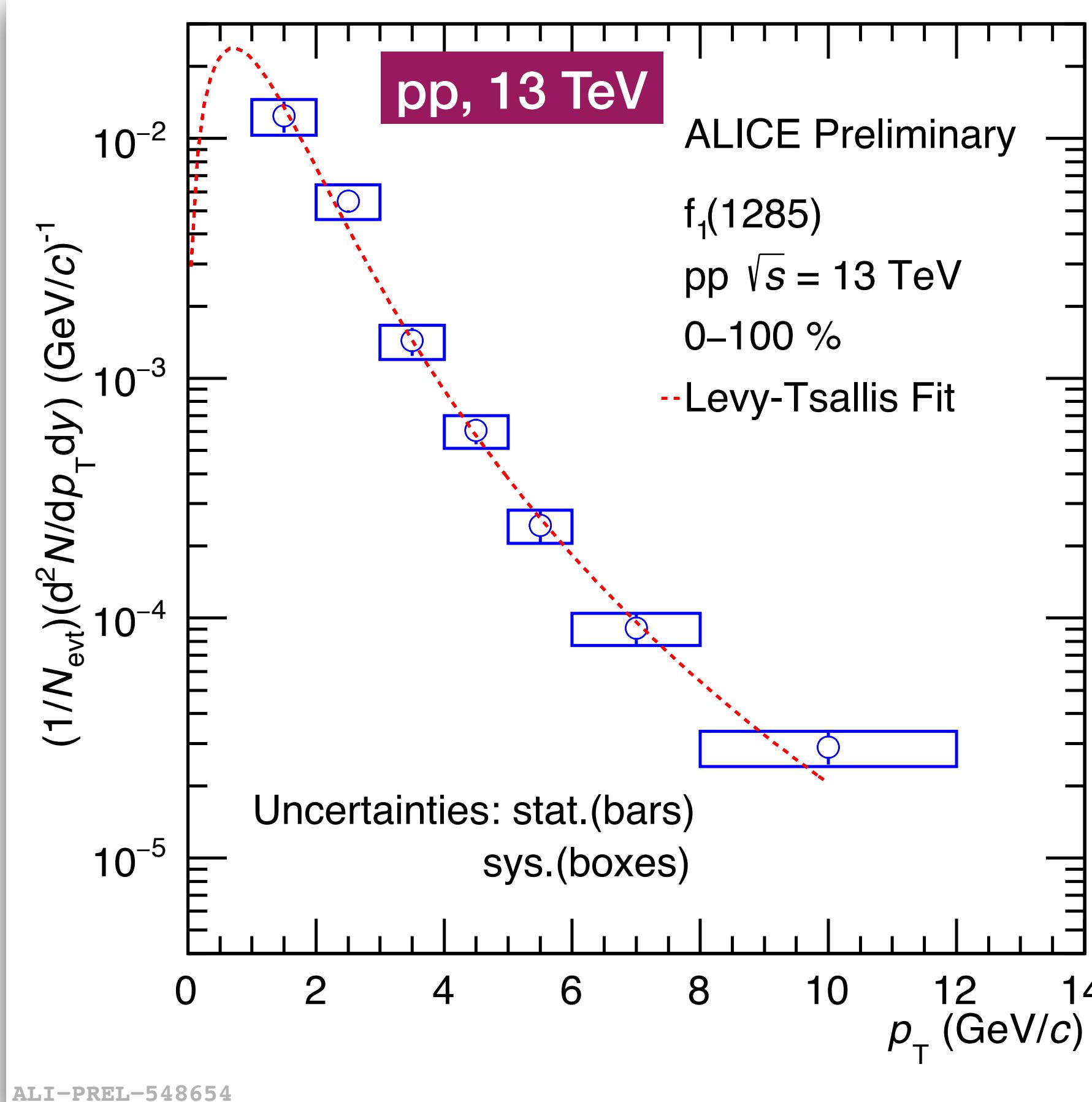


First measurement of $f_1(1285)$ at ALICE

- Signal extraction: Invariant mass analysis via $f_1(1285) \rightarrow K_S^0 K\pi$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV
- Contributions from three resonances $f_1(1285)$, $f_1(1420)$, and $\eta(1475)$ are fitted with Breit-Wigner functions

$f_1(1285)$ Spectra and yield

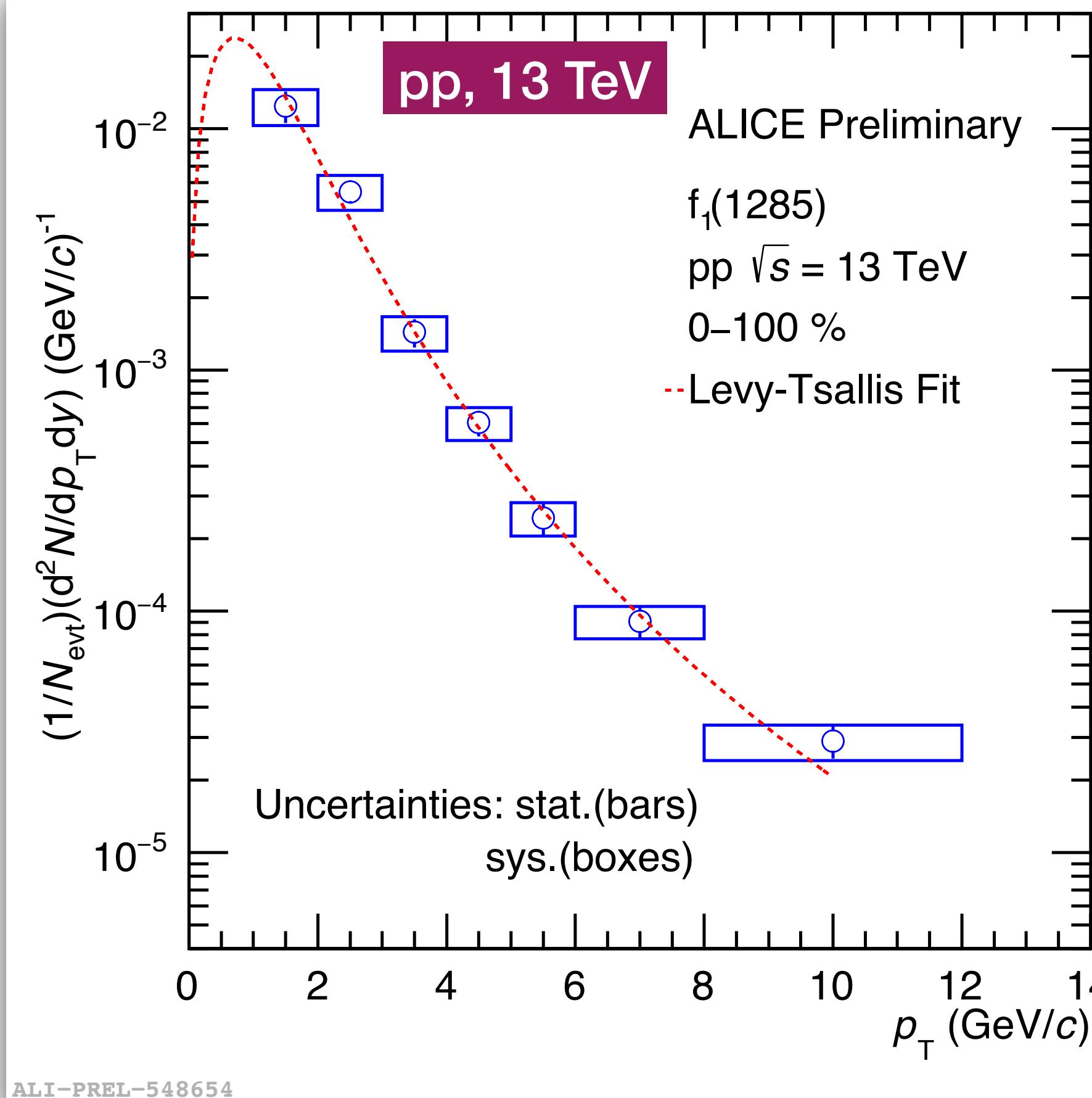
NEW in QM 2023



- p_T spectrum is obtained from 1 GeV/c to 12 GeV/c in pp collisions at $\sqrt{s} = 13$ TeV
- Spectrum is fitted with Levy-Tsallis fit

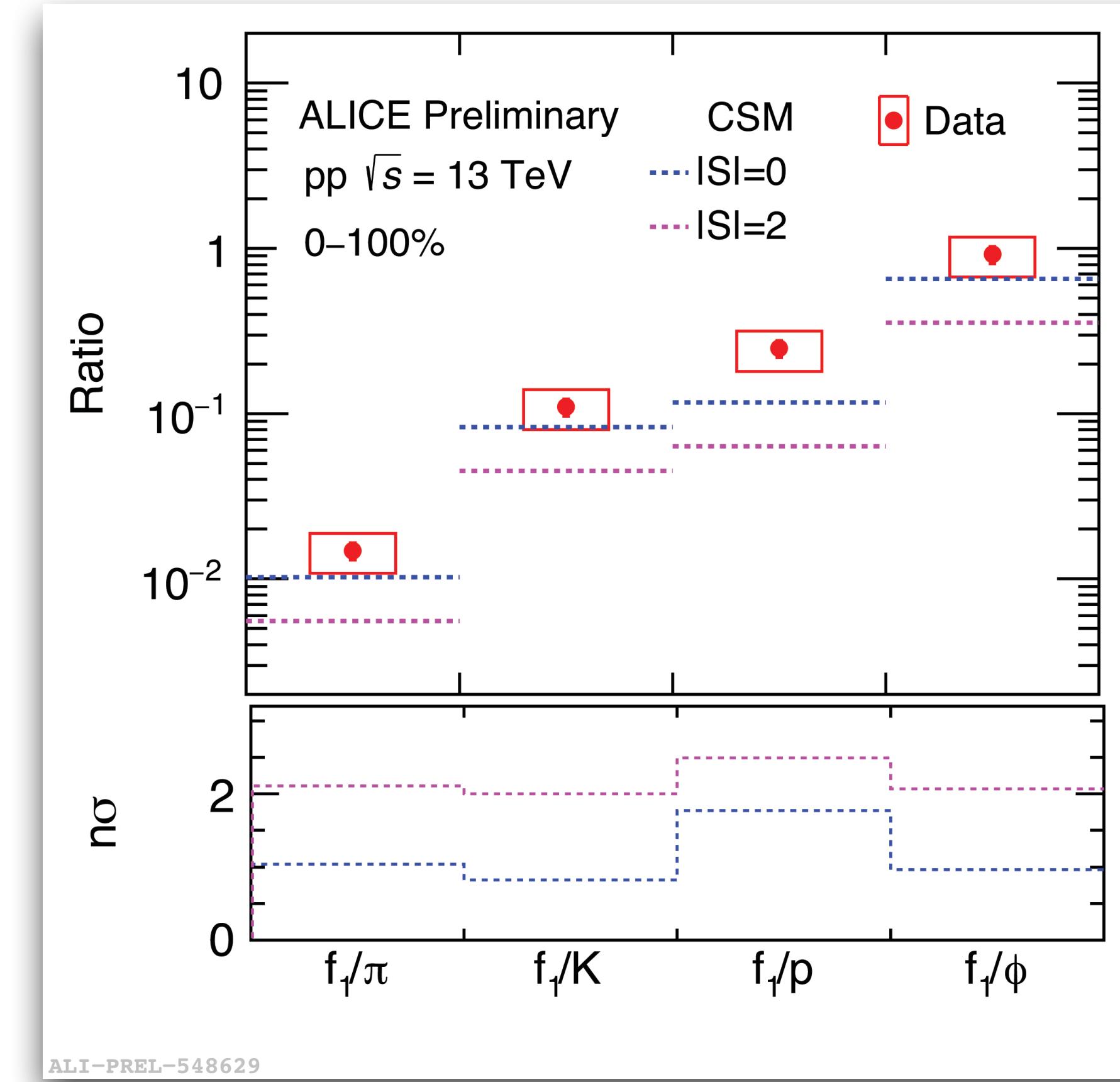
$f_1(1285)$ Spectra and yield

NEW in QM 2023



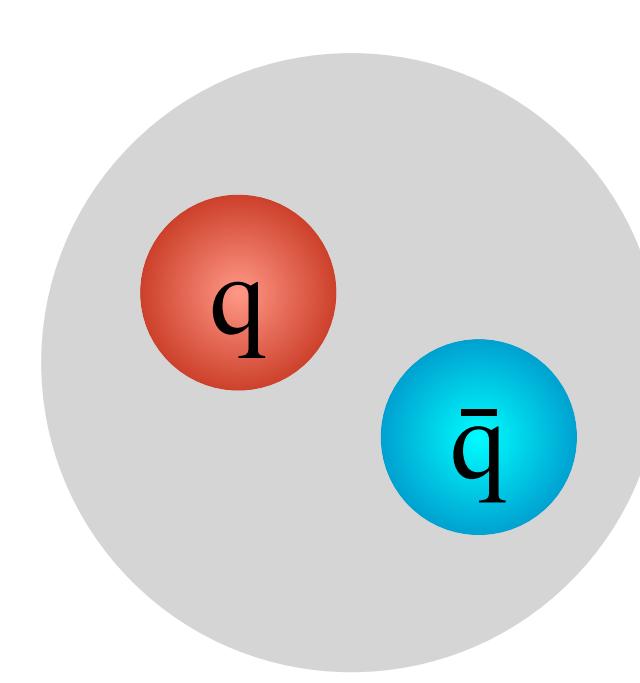
- p_T spectrum is obtained from 1 GeV/c to 12 GeV/c in pp collisions at $\sqrt{s} = 13 \text{ TeV}$
- Spectrum is fitted with Levy-Tsallis fit

$$\sigma = \frac{\text{Ratio}_{\text{data}} - \text{Ratio}_{\text{model}}}{\text{Error}_{\text{data}}}$$

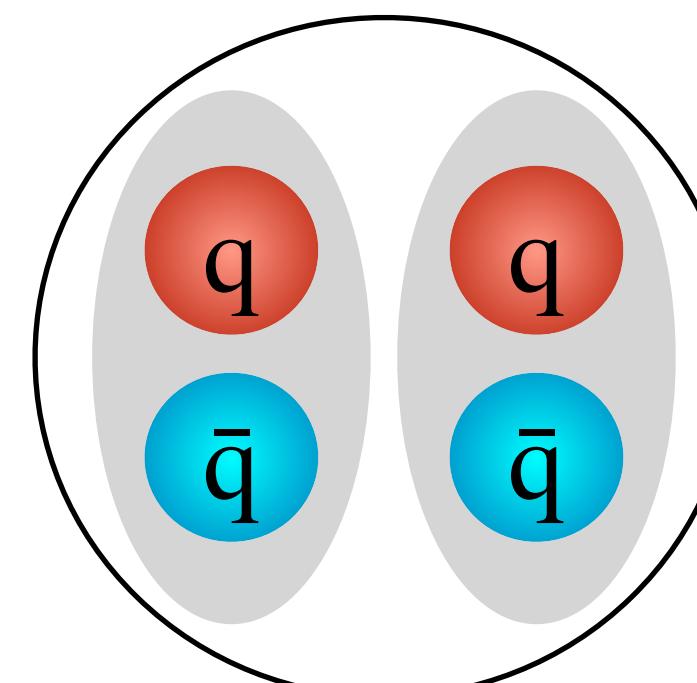


- Thermal model predictions of particle ratios with $f_1(1285)$ having strange quark content $|S|=0$ are closer to the experimental measurements than $|S|=2$

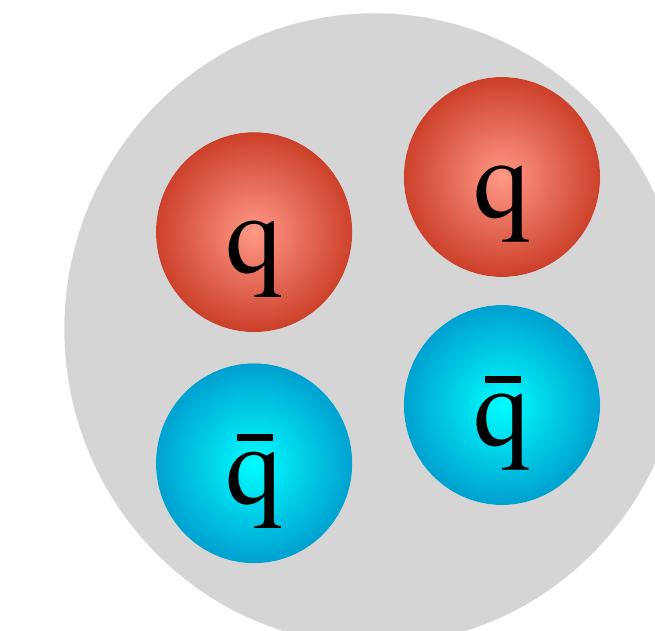
Glueball search



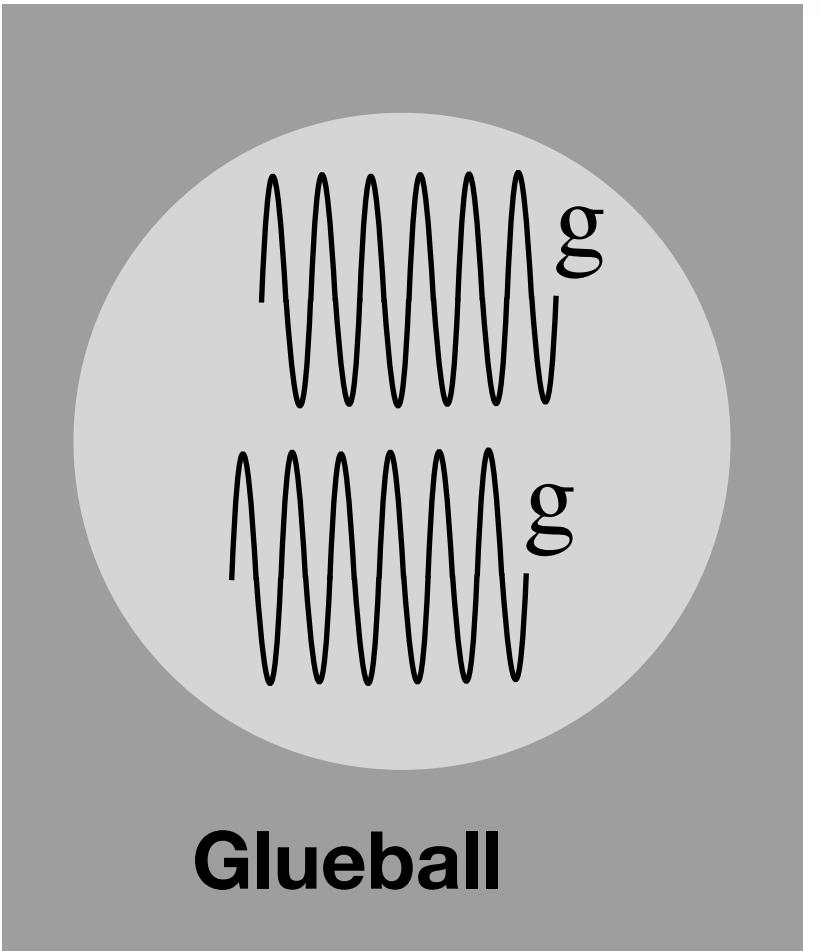
Diquark



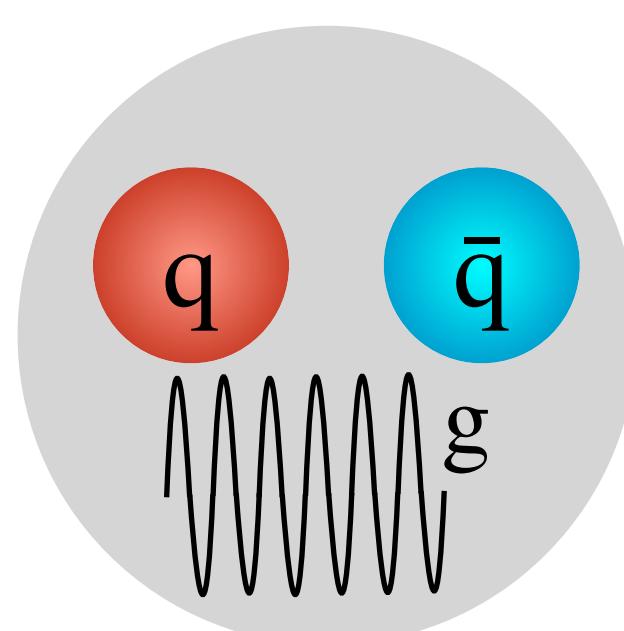
meson-meson
molecule



Tetraquark



Glueball



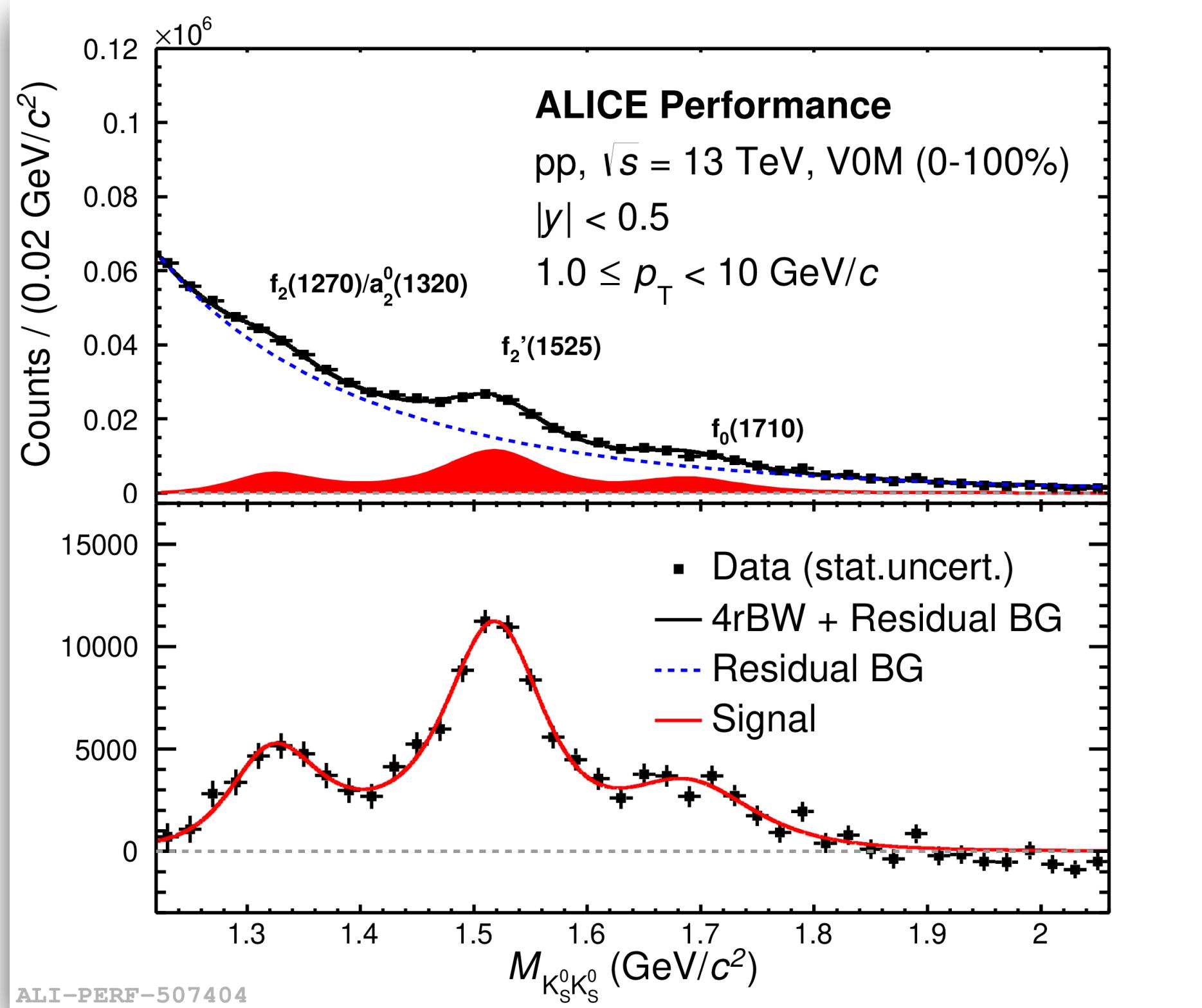
Hybrid state

f₀(1710)

- Glueball candidate:
[Phys.Rev.Lett. 101 \(2008\) 112003](#)
, [Review of Particle Physics \(PDG\)](#)

Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

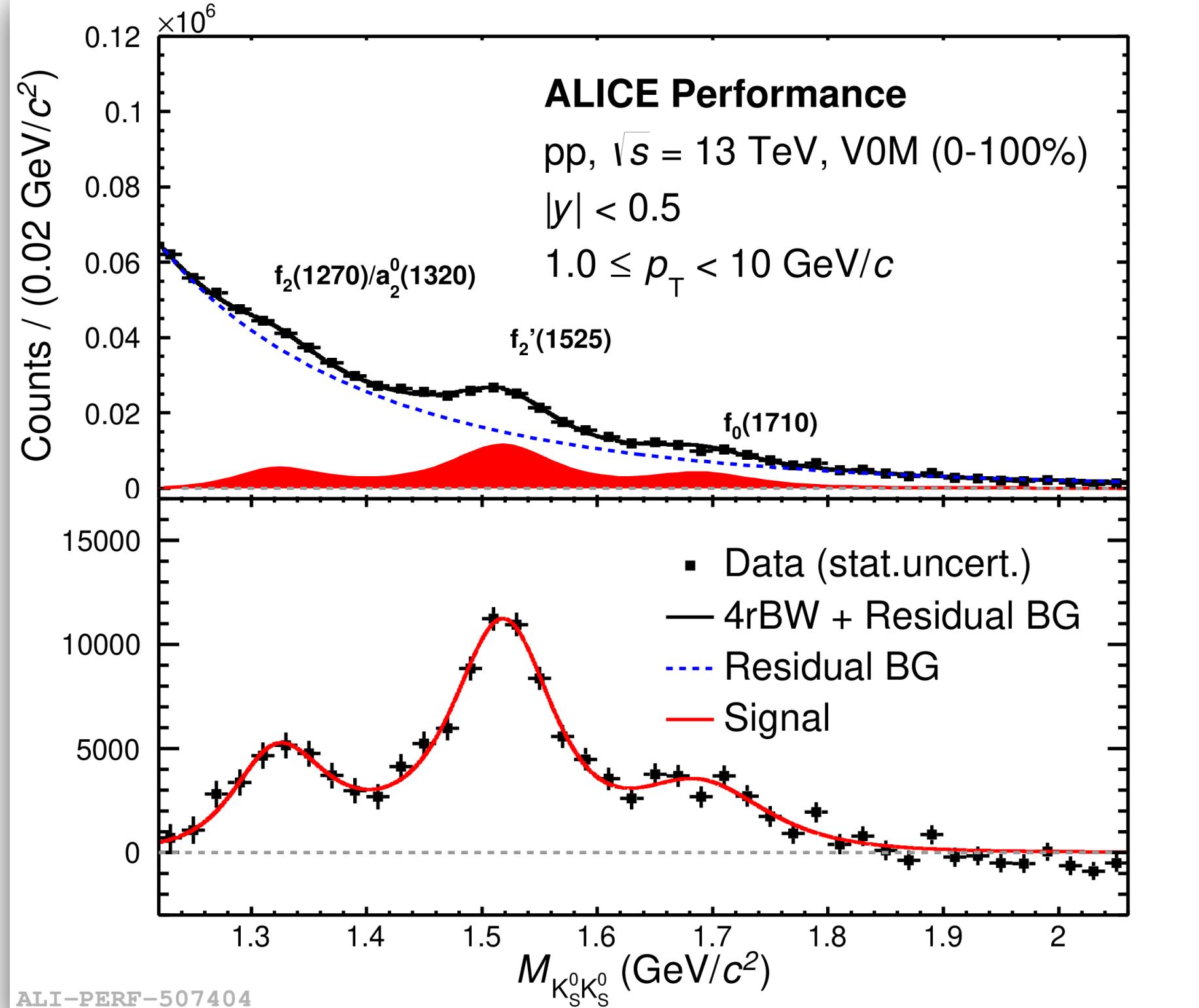
pp, 13 TeV



- Signal extraction: Invariant mass distribution from $K_S^0 K_S^0$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV
- Signal extraction has been performed and $f_0(1270)$, $f_2(1525)$, $f_0(1710)$ are fitted with Breit-Wigner functions

Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

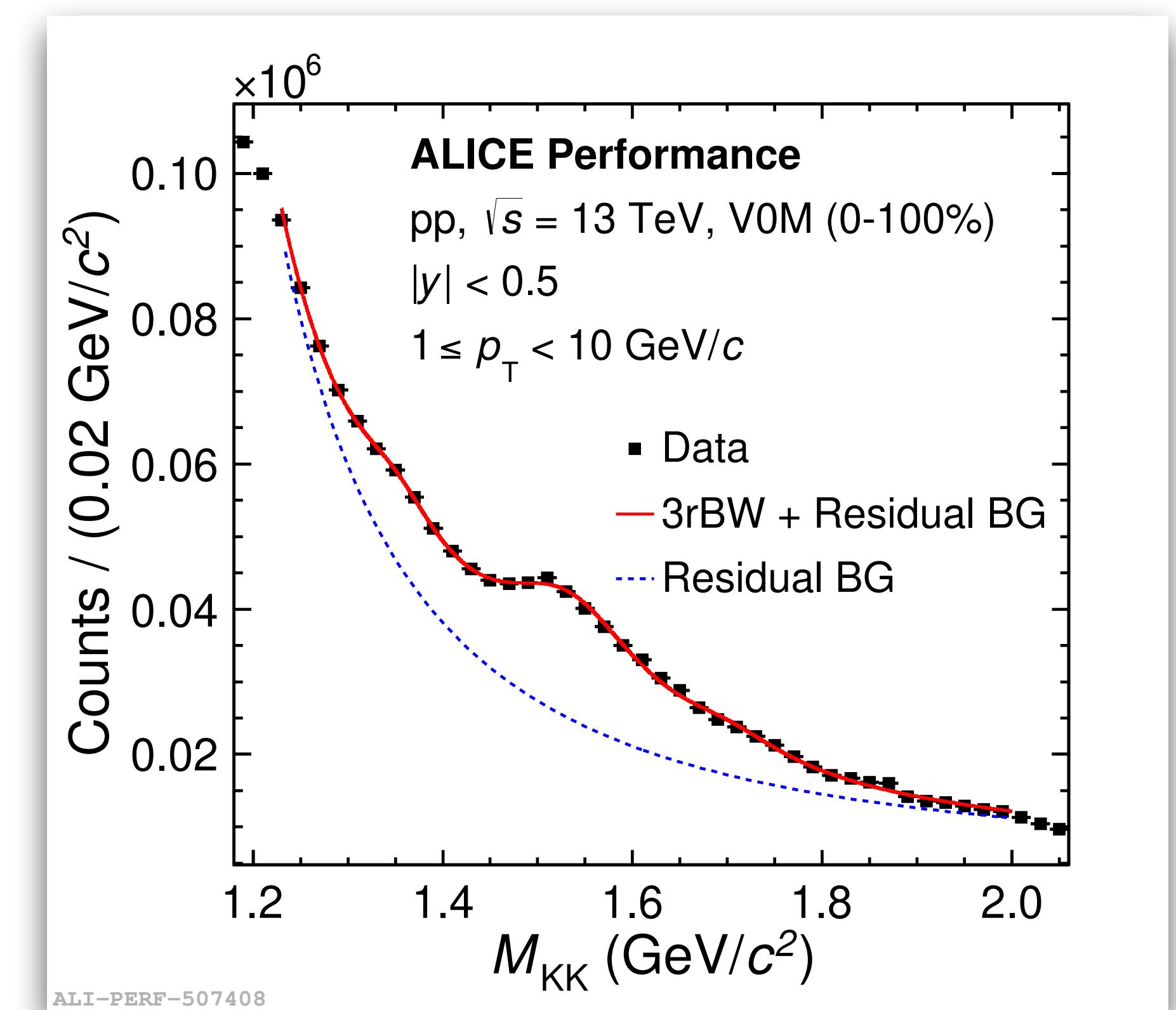
pp, 13 TeV



- Signal extraction: Invariant mass distribution from $K_s^0 K_s^0$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV
- Signal extraction has been performed and $f_0(1270)$, $f_2(1525)$, $f_0(1710)$ are fitted with Breit-Wigner functions

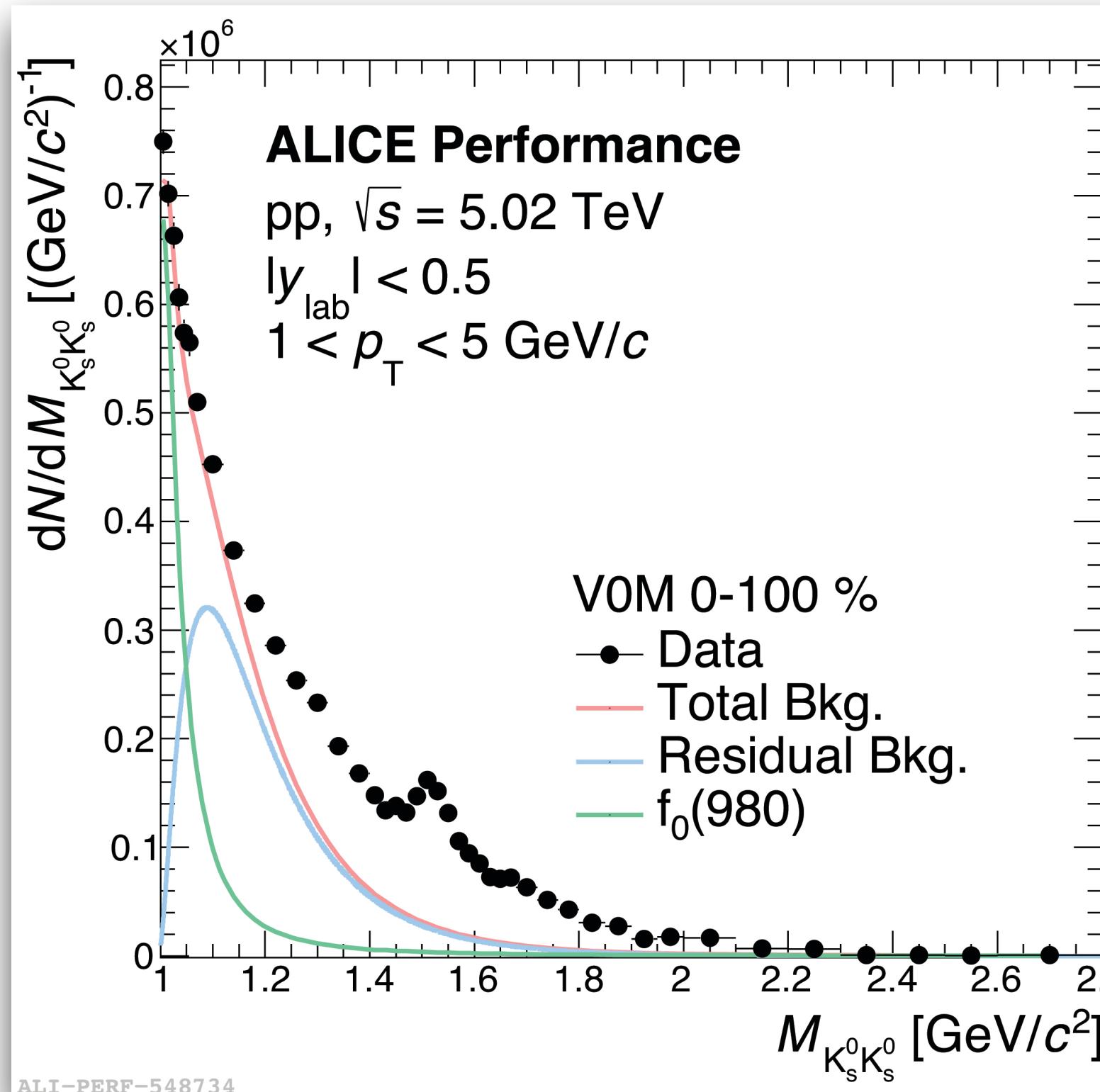
- $K_s^0 K_s^0$ channel: 3 peaks are seen -> consistent with the observation in ep collisions at HERA[1].
- $K K$ channel: 2 peaks are visible.

[1] PRL101, 112003 (2008)

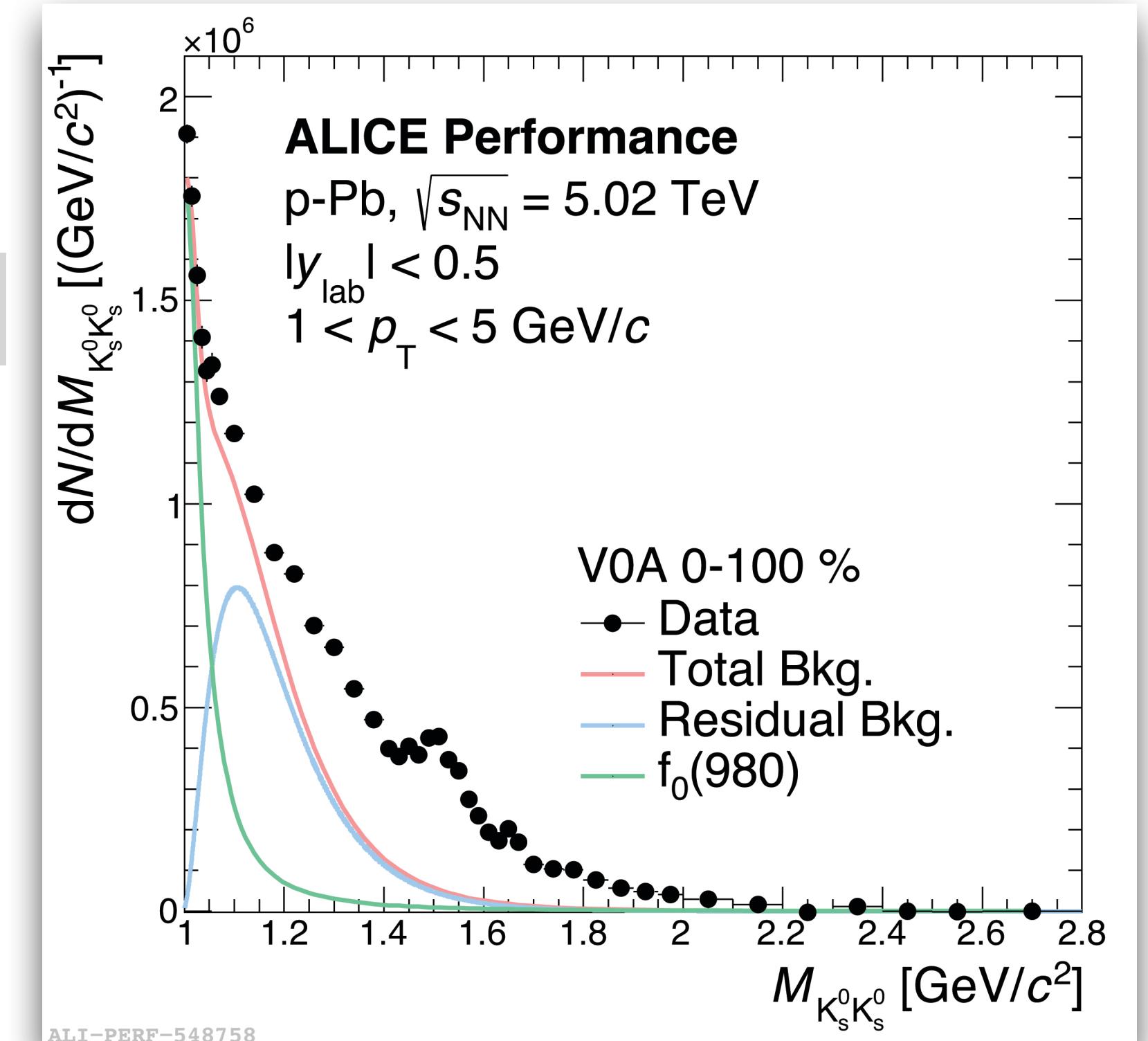


Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

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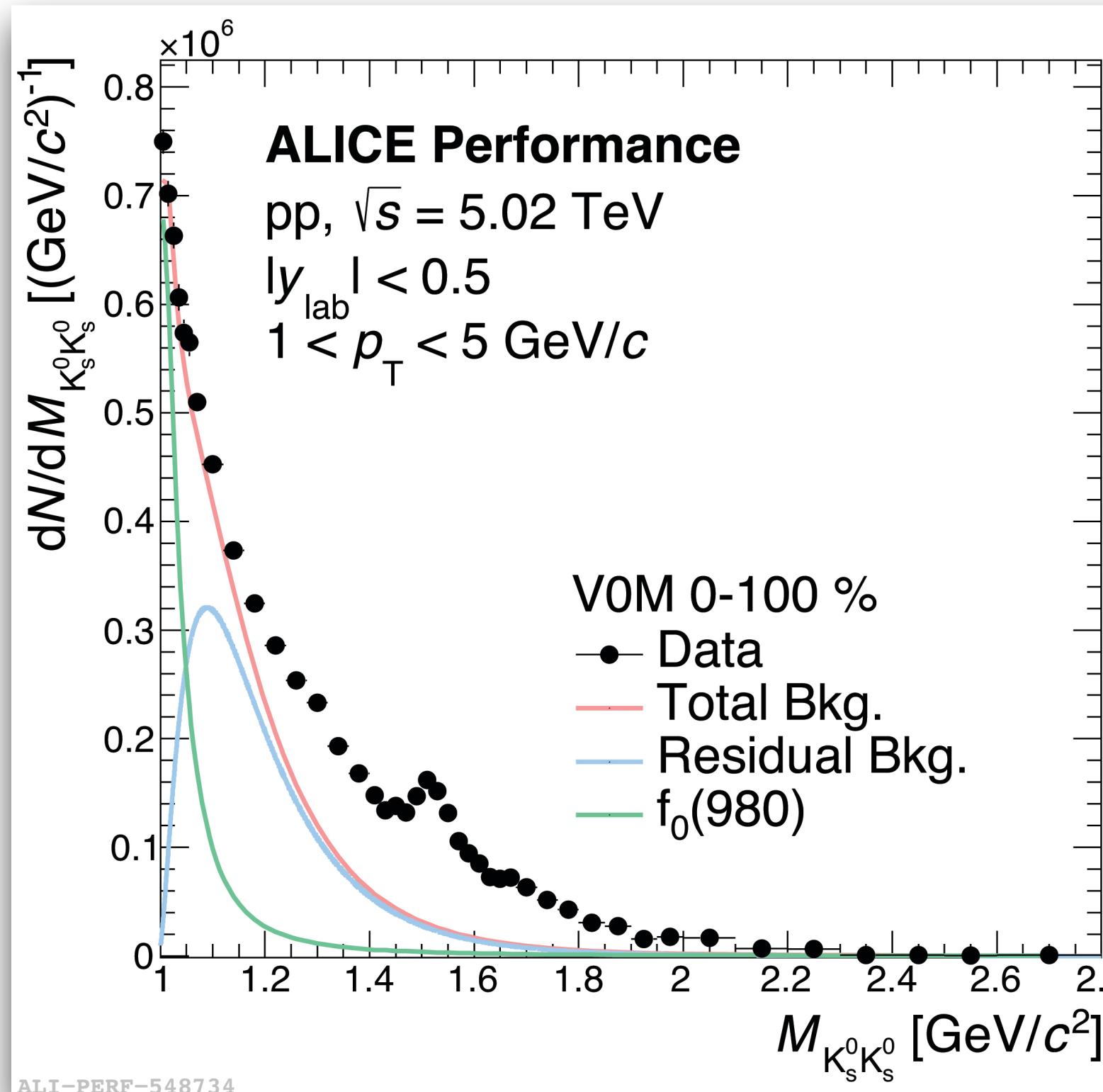
More by Satoshi Yano's poster



- Signal extraction: Invariant mass distribution from $K_s^0 K_s^0$ decay channel in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV).
- Signal extraction has been performed, $f_0(1370)$, $f_2(1525)$, $f_0(1710)$.
- Target: R_{pA} measurement of $f_0(1710)$ - enhancement expected due to large gluon density

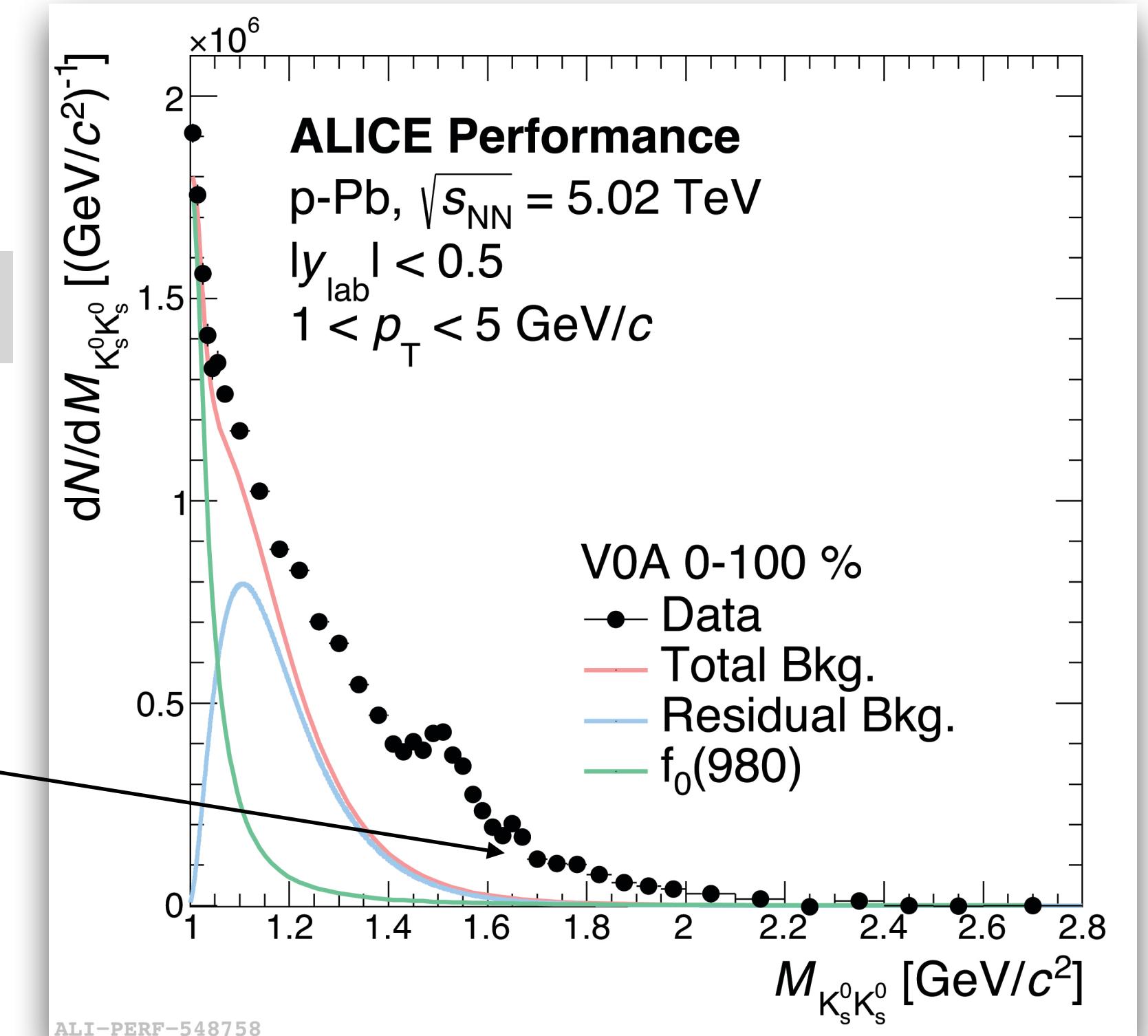
Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

NEW in QM 2023



More by Satoshi Yano's poster

$f_0(1710)$



- Signal extraction: Invariant mass distribution from $K_s^0 K_s^0$ decay channel in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV
- Signal extraction has been performed, $f_0(1370)$, $f_2(1525)$, $f_0(1710)$
- Target: R_{pA} measurement of $f_0(1710)$ - enhancement expected due to large gluon density

Summary

- Exotic resonances like f_0 , f_1 and f_2 have stirred debates over their quark compositions
(e.g- diquarks, tetraquarks, molecules, hybrid, glueball?)
- No Cronin peak is observed in the intermediate p_T region. This may suggest an ordinary meson structure of $f_0(980)$
- First measurement of f_1 production in pp collisions
- Comparison to CSM(canonical statistical model): close to scenario $|S|=0$. This may suggests that most likely f_1 resonance is made of up and down quarks only
- First measurement of f_0 , f_2 production in pp and p–Pb collisions
- More results will come with Run 3 data collected by ALICE



Canonical Statistical Model

- In CSM, the multiplicity dependence of 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)

