$f_0(980)$ production with ALICE

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Status summary for $f_0(980)$ analysis in ALICE

- $f_0(980)$ production in pp at $\sqrt{s} = 5.02$ TeV
  - Preliminary results, which had been approved in QM 2018, were updated
  - Paper proposal was approved by Bologna group: `https://alice-publications.web.cern.ch/node/7410`
- Multiplicity dependent $f_0(980)$ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
  - Analysis Note was approved: `https://alice-notes.web.cern.ch/node/1018`
    - Measurements were fully approved
  - Further preparation on model calculation to support our messages
- Multiplicity dependent $f_0(980)$ production in pp collisions at $\sqrt{s} = 13$ TeV
  - Analysis Note: `https://alice-notes.web.cern.ch/node/884`
- $f_0(980)$ production in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  - A few updates were presented in PAG resonance meeting.
  - Targeting $f_0(980)$ v_2 with the event plane method

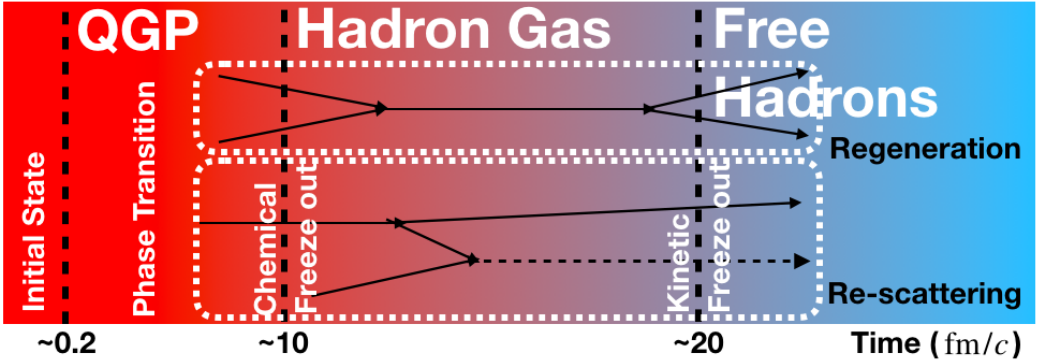
Long-term plan for $f_0(980)$ analysis

- p–Pb@5.02 TeV
  - Particle yield ratios
  - Nuclear modification factor of $f_0(980)$ in p–Pb
- Pb–Pb@5.02 TeV
  - $f_0(980)$ v_2 with the event plane method
  - Test NCQ scaling
- + pp@13 TeV + p–Pb@8.16 TeV + ...
  - Production of $f_0(980)$ with ALICE

JBNU's contribution to $f_0(980)$ analysis

- $f_0(980)$ production in pp at $\sqrt{s} = 5.02$ TeV
  - Cross-checking the preliminary result
    - Preliminary results were found to be wrong by JBNU.
    - Results were updated by Bologna group.
- Multiplicity dependent $f_0(980)$ production in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - ARC and conveners agreed with the measurement itself.
  - Preparation on the model expectation to support physics messages
- $f_0(980)$ production in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - Updates on signal extraction method and finer p_{T} bin definition.

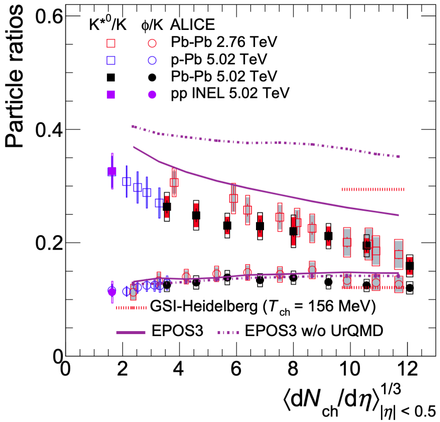
Short-lived Resonances

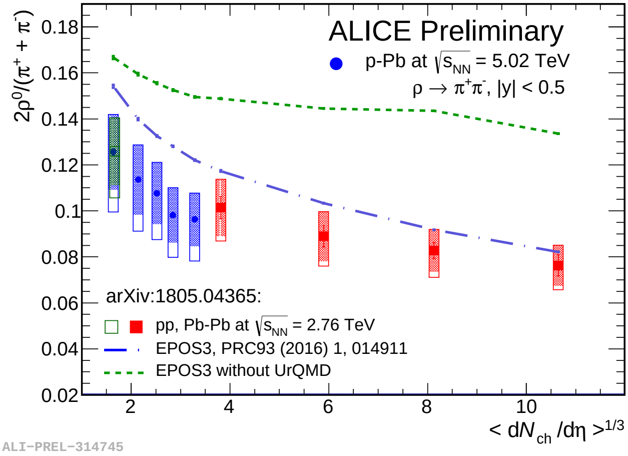


- Measured resonance yields are modified in the hadronic phase via regeneration and re-scattering.
- Short-lived resonances are powerful probes to understand hadronic phase.

Re-scattering effect with UrQMD

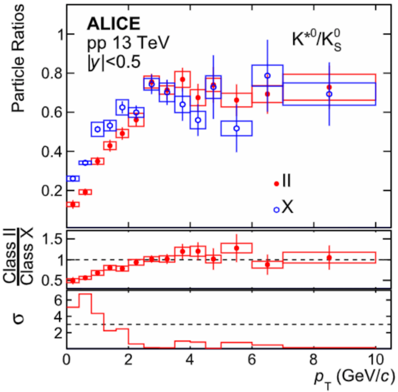
PLB 807 (2020) 135501

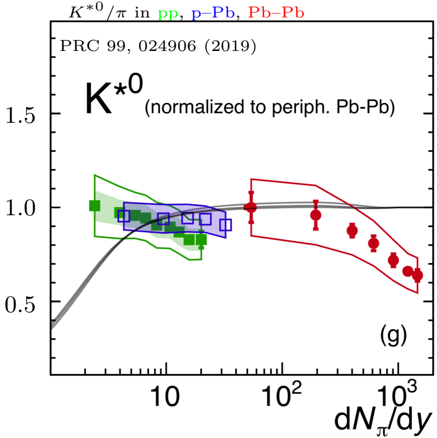




- (K^{*0}/K) and (ρ/π): probes to observe the re-scattering effect.
- With UrQMD, decreasing trends are well described.
  - Multiplicity dependent re-scattering effect.

Particle yield ratio





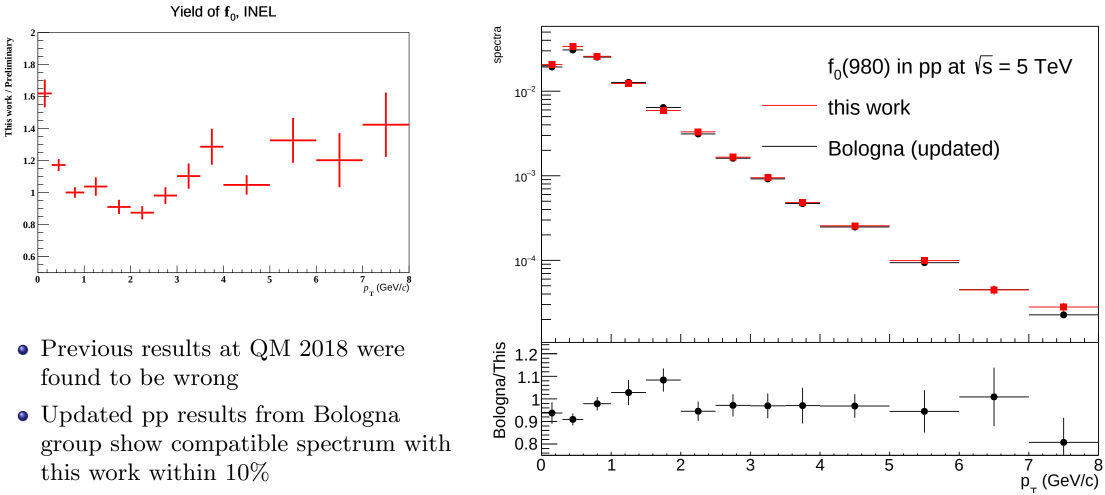
- (K^{*0}/K): cancelling out the strangeness enhancement
  - Re-scattering effect in low p_{T}.
- (K^{*0}/π): flat with increasing multiplicity in p–Pb.
  - Due to two competing effects, strangeness enhancement and re-scattering effect.

What we can study from $f_0(980)$

- One of scalar mesons, whose quark contents are still controversial
  - $n(u,d)\bar{n}$ state: PRD 67, 094011 (2003)
  - 4 quarks state: PRD 103, 014010 (2021)
  - Molecule state: PRD 101 094034 (2020)
- $f_0(980)$ yield can be largely affected by the hadronic re-scattering effect due to the short lifetime of $f_0(980)$ ($\tau_{f_0} \sim 5$ fm/c).
- Particle yield ratios of $f_0(980)$ enable to
  - Observe the hadronic phase
  - Explore internal structures of $f_0(980)$
- Cronin peak, which came from radially boosted quarks, could suggest the number of quarks for $f_0(980)$
  - Tetra-quark state: May expect similar (or larger) Cronin peak with baryons in the intermediate or higher p_T
  - $q\bar{q}$: Small Cronin peak.

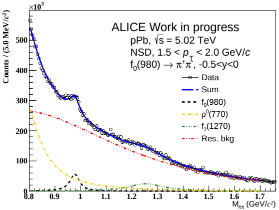
	ρ^0	K^*	$f_0(980)$	ϕ
Mass (MeV/c^2)	775	892	990	1020
J^P	1^-	1^-	0^+	1^-
Contents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	???	$s\bar{s}$
lifetime (fm/c)	1.3	4.2	~ 5	46.2

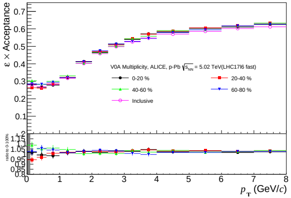
This work / QM 2018

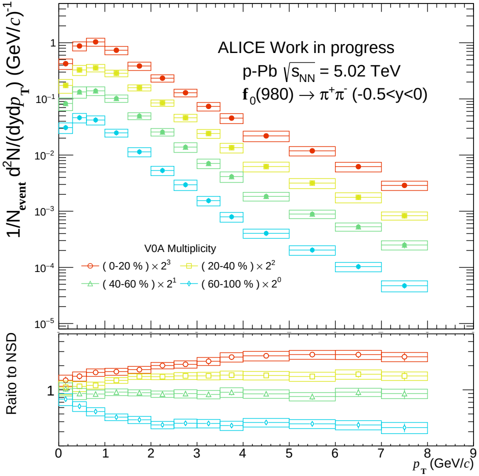


- Previous results at QM 2018 were found to be wrong
- Updated pp results from Bologna group show compatible spectrum with this work within 10%

Signal extraction and p_{T} spectrum of $\mathrm{f}_0(980)$ in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

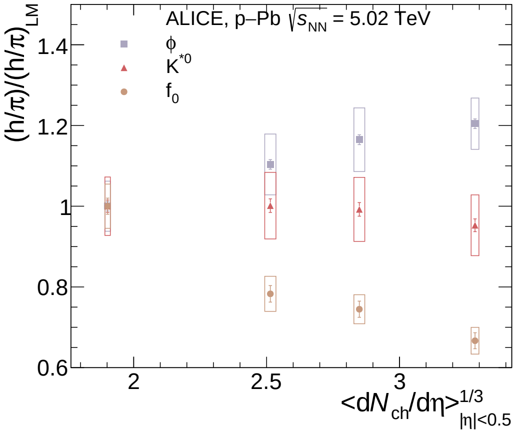






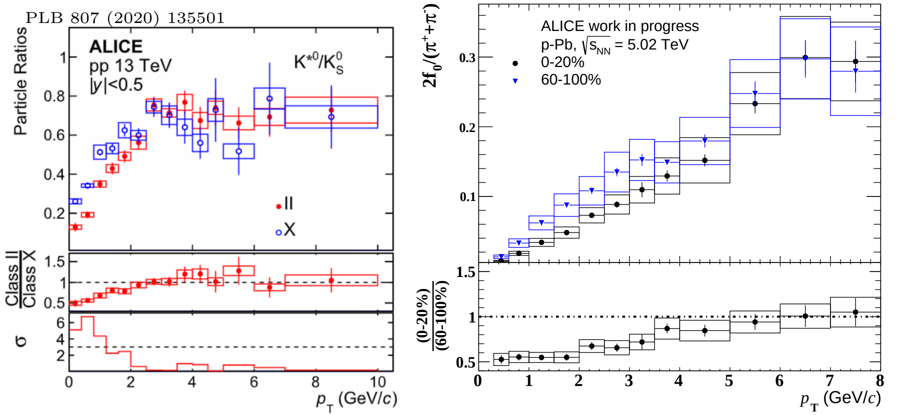
- Each resonance is corrected by Phase space correction,
  $$PS(M_{\pi\pi}) = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi}^2 + p_{\mathrm{T}}^2}} \exp(-\sqrt{M_{\pi\pi}^2 + p_{\mathrm{T}}^2}/T)$$
- Residuals are described by $f_{\mathrm{BG}}(M_{\pi\pi}) = (M_{\pi\pi} - 2m_{\pi})^n A\exp(BM_{\pi\pi} + CM_{\pi\pi}^2)$
- In total, $f(M_{\pi\pi}) = (N_{\rho}\mathrm{rBW}_{\rho^0}(M_{\pi\pi}) + N_{\mathrm{f}_0}\mathrm{rBW}_{\mathrm{f}_0}(M_{\pi\pi}) + N_{\mathrm{f}_2}\mathrm{rBW}_{\mathrm{f}_2}(M_{\pi\pi})) \times PS(M_{\pi\pi}) + f_{\mathrm{BG}}(M_{\pi\pi})$
- Fully corrected with $\varepsilon \times A$ and normalized to NSD class

Particle yield ratios to π

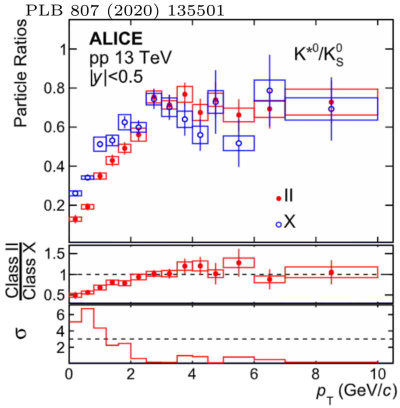


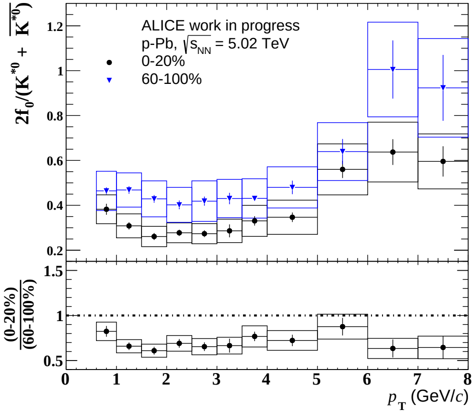
- Clear strangeness enhancement from (ϕ/π)
- Strangeness enhancement and re-scattering effect are competing (K^{*0}/π)
- Decreasing (f_0/π) was observed, why?

Probing late hadronic phase with $f_0(980)$: Re-scattering effect



- Significant suppression in high-multiplicity events atlow p_T (< 3 GeV/c)
- Little modification at high p_T (> 4 GeV/c)
- **Re-scattering effect with f_0(980) in p–Pb collisions is clearly observed!**

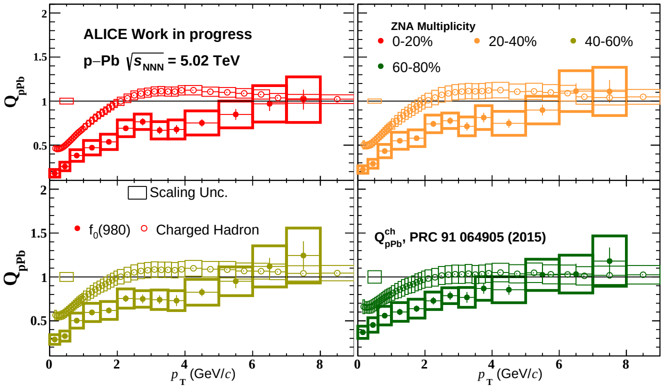




- Re-scattering effect would be compatible between f_0 and K^{*0} as they have compatible lifetime and mass.
- **Suppression in the entire p_T, which is different dependence from (f_0/π)**
- **Can be explained by a weak strangeness enhancement for $f_0(980)$!**

Nuclear modification factor, Q_{pPb}

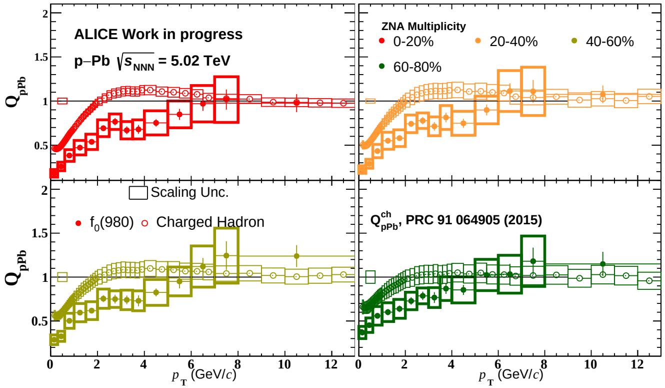
pp spectrum from `https://alice-publications.web.cern.ch/node/7410`

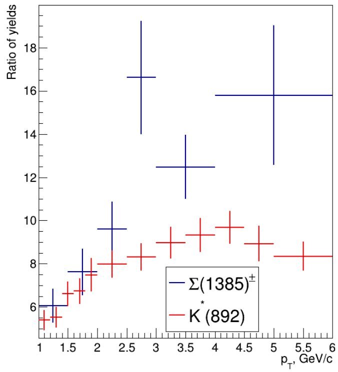


- Stronger multiplicity dependence (suppression) for $f_0(980)$ in low p_{T} (< 4 GeV/c).
- Suppression disappears with increasing p_{T}
- **Confirmation of the re-scattering effect**
- No Cronin peak in the intermediate p_{T}

Nuclear modification factor, Q_{pPb}

pp spectrum from https://alice-publications.web.cern.ch/node/7410





- Stronger multiplicity dependence (suppression) for $f_0(980)$ in low p_T (< 4 GeV/c).
- Suppression disappears with increasing p_T
- **Confirmation of the re-scattering effect**
- No Cronin peak even in the **high** p_T $\leftrightarrow$ Different from baryons

Multi-quark particle yield

- STAR measured f_0/ρ to be 0.2 (**STAR Collaboration, Nucl.Phys.A 715 (2003) 462-465**)
- ρ yield is estimated to be 42 from statistical model $\rightarrow$ f_0 yield is estimated to be $42 \times 0.2 \sim 8$
- Not to be pure and compact tetra-quark
- Scaling the f_0 yield with the multiplicity:

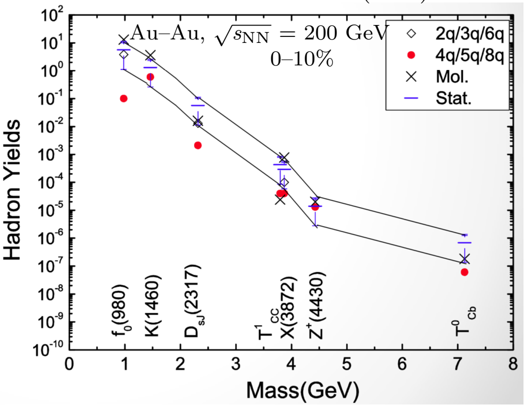
$$Y_{f_0}^{pPb} = Y_{f_0}^{PbPb} \frac{dN^{ch}/d\eta_{pPb}}{dN^{ch}/d\eta_{PbPb}}$$

  - $(dN^{ch}/d\eta_{pPb})/(dN^{ch}/d\eta_{PbPb}) = 0.01$, $(dN^{ch}/d\eta_{pp})/(dN^{ch}/d\eta_{PbPb}) = 0.0025$
  - $Y_{f_0}^{pPb} = 10 \times 0.01 = 0.1$ (0.12 is measured by this work) $Y_{f_0}^{pp} = 10 \times 0.0025 = 0.025$ (0.0385 is measured)
  - Favors $q\bar{q}$ assumption

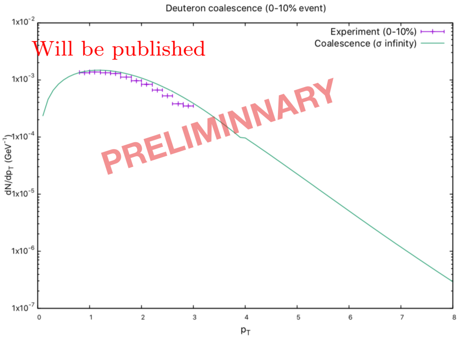
	RHIC, Au–Au, $\sqrt{s_{NN}}$ = 200 GeV	LHC, Pb–Pb, $\sqrt{s_{NN}}$ = 5.5 TeV
$q\bar{q}$	3.8	10
$s\bar{s}$	0.73	2.0
$q\bar{q}s\bar{s}$	0.1	0.28

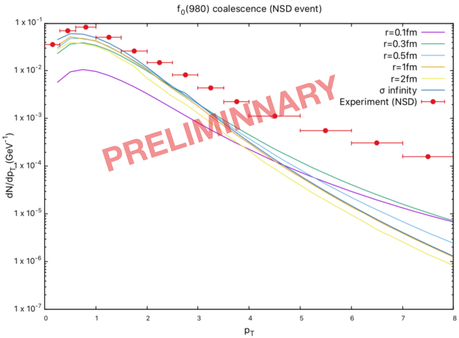
Centrality for both collisions: 0–10%

S. Cho *et. al* PRL 106 212001 (2011)



Coalescence model in p–Pb collisions



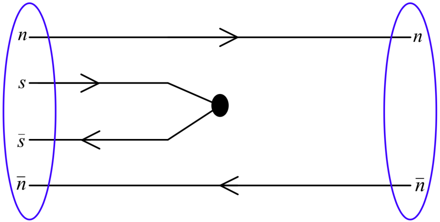


- Hadronic volume size was scaled down with the charged-particle multiplicity:

$$A_{\mathrm{pPb}} = A_{\mathrm{PbPb}} \frac{\mathrm{d}N^{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{pPb}}}{\mathrm{d}N^{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{PbPb}}}$$

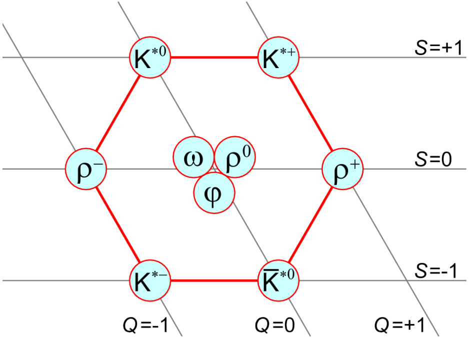
- Finite size effect due to compatibility between volume size and deuteron size
  - C.M. Ko et al. Physics Letters B 792 (2019) 132-137
- Simple coalescence model is nicely working in p–Pb collisions as well.
- The same approach was also applied to K^+K^- coalescence calculation → The same approach is not applicable for f_0

$q\bar{q}$ with orbital angular momentum



- HADRON PROPERTIES FROM QCD SUM RULE,
  PHYSICS REPORTS 127, No. 1(1985) 1-97
- In quark model, scalar meson can be expressed as $q\bar{q}$ with $L = 1$ to make parity positive.
- In equation (4.50) of the physics report cited above, $m_{n\bar{n}} = 1.00$ GeV and $m_{s\bar{s}} = 1.35$ GeV
- 500 MeV easily came from $L = 1$
  - $a_1(1260)$ - $\rho(770) = 484$ MeV, $\chi_{c1}(3511)$ - $J/\Phi(3097) = 414$ MeV
- Could be mixed states of tetra-quark and $q\bar{q}$

Suggestion of tetra-quark structure



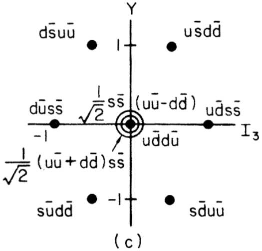
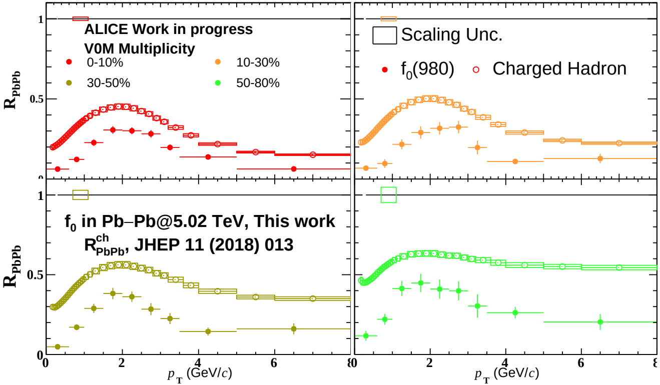


FIG. 9. The quark content of the cryptoexotic nonet. (a) the $\overline{3}$ formed from two quarks; (b) the 3 formed from two antiquarks; (c) the (magically mixed) nonet formed from the direct product of (a) and (b).

- Tetra-quark picture was firstly suggested by:
  `Phys. Rev. D 15, 267 (1977)`
- Introduced to explain inverted masses compared with vector meson.
  - Vector meson: $m_{\text{nonet}} > m_{|S|=1} > m_{|S|=0}$ (same for pseudoscalar)
  - Scalar meson: $m_{|S|=0} > m_{|S|=1} > m_{\text{nonet}}$,

Nuclear modification factor in Pb–Pb collisions



- p_{T} bins and signal extraction were updated
- `https://indico.cern.ch/event/1058961/`

Summary

- $f_0(980)$ in pp
  - Preliminary results, which had been approved in QM 2018, were updated.
- $f_0(980)$ in p–Pb
  - Particle yield ratio of $f_0(980)$ to charged pions is decreasing with the multiplicity at low p_T
    - **Measurement of the re-scattering effect from the scalar meson for the first time**
  - Particle yield ratio of $f_0(980)$ to K^{*0} is decreasing with the multiplicity at the entire p_T
    - **Weak p_T dependence: The re-scattering effect would be compatible between f_0 and K^{*0}**
    - **Suppression at the entire p_T: Weak strangeness enhancement for f_0(980)**
  - Nuclear modification factor (Q_{pPb}) of $f_0(980)$ is measured in different multiplicity classes.
    - **Q_{pPb} of f_0(980) is much suppressed than Q_{pPb} of charged hadrons with the multiplicity at low p_T: Re-scattering effect**
    - **Q_{pPb} of f_0(980) does not exhibit Cronin peak in high-multiplicity events: The number of (boosted) constituent quarks is less than baryons**
- $f_0(980)$ in Pb–Pb
  - p_T bins and signal extraction were updated and reported.
  - Further analysis for $f_0(980)$ v_2 is ongoing.

BACKUP