Identified hadrons p_T spectra in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV within multiple freeze-out scenario

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in collaboration with

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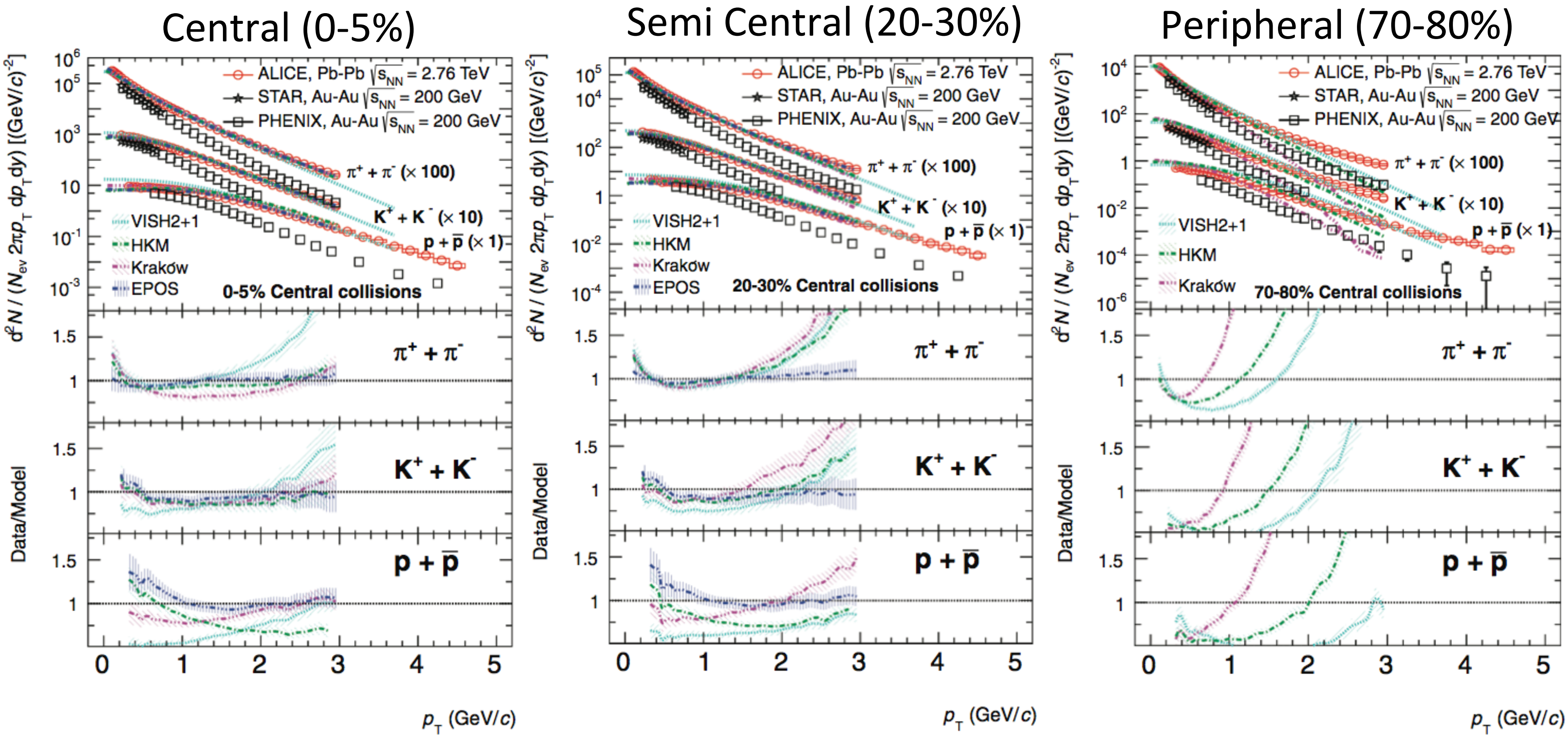
OUTLINE

- Motivation
- MC Event Generator : Therminator
- Results
- Summary

MOTIVATION : Proton anomaly



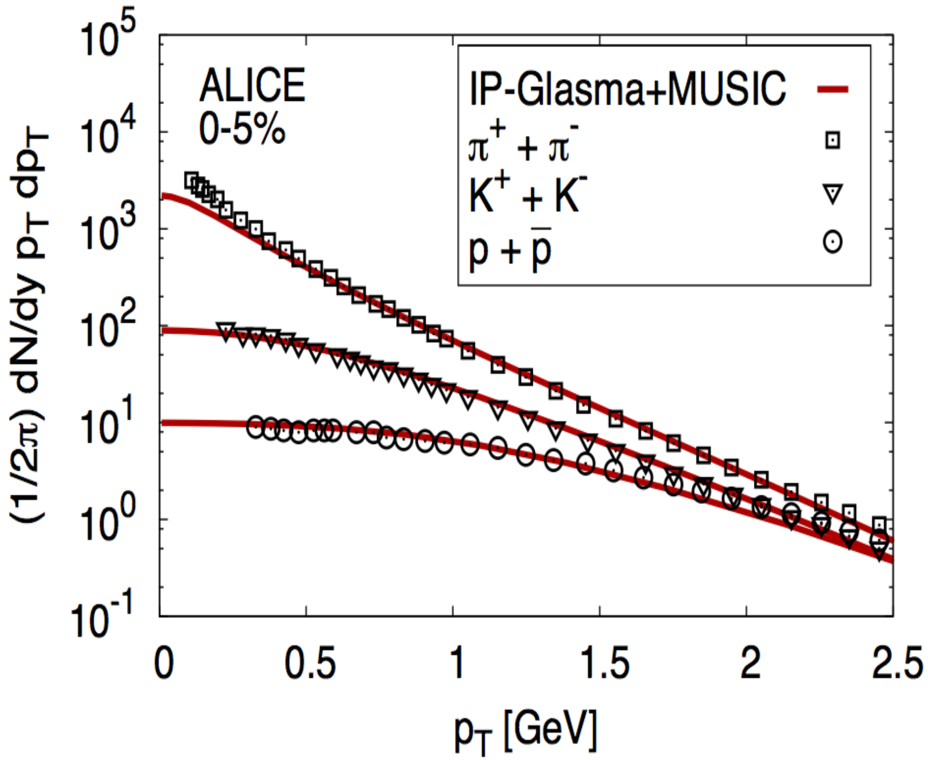
✧ Pion and proton spectra are not explained simultaneously from various thermal and hydro models

✧ Besides proton anomaly, pion spectra show enhancement in low p_T by about 25%–50%

ALICE Collaboration: Phys. Rev. Lett. 109, 252301 (2012), Phys. Rev. C 88, 044910 (2013).

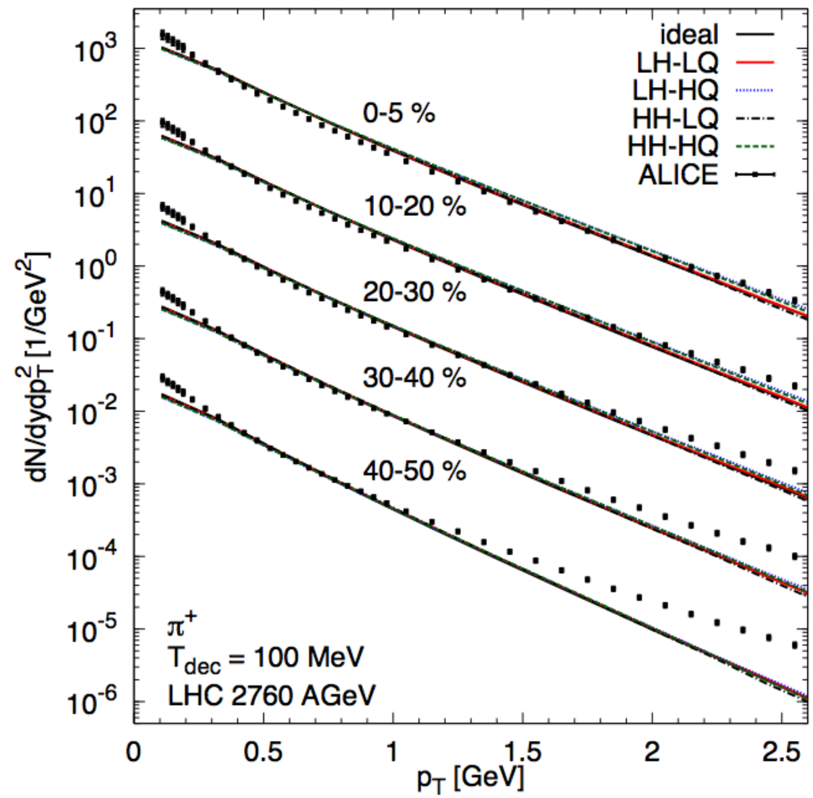
MOTIVATION : Pion enhancement

IP-Glasma + MUSIC



C Gale et al., Phys. Rev. Lett. 110, 012302 (2013).

Hydro with dynamical freeze-out



E. Molnar et al., Phys. Rev. C 90, 044904 (2014).

✧ Pion enhancement at low p_T

Possible explanations :

✧ Flavor hierarchy at freeze-out

S. Chatterjee, R.M. Godbole and S. Gupta, Phys.Lett. B 727, 554 (2013).
K. Bugaev et al., Europhys.Lett. 104, 22002 (2013).

✧ Final stage hadronic re-scattering effects

F. Becattini et al. Phys.Rev.Lett. 111, 082302 (2013).

✧ Incomplete list of hadrons

arXiv:1405.7298 [nucl-th]; arXiv:1408.0761 [nucl-th].

✧ Non-equilibrium hadronization

M. Petran et al., Phys.Rev. C88, 021901 (2013); Phys.Rev. C 88, 034907 (2013).

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Therminator

- ✓ Therminator (THERMal heavy IoN generATOR) : implements thermal models of particle production -- perform the hadronic freeze-out on simple boost-invariant hypersurfaces

- ✓ Input of any shape of the freeze-out hyper surface (FH) and the expansion velocity field

- ✓ Include the complete list of hadronic resonances
  -- which at the rather high temperature at freeze-out, 145-160 MeV, contribute very significantly

- ✓ Two- and three-body decays of resonances are taken into account, proceed in cascades, ultimately producing the stable particles

- ✓ Provides full information on the space-time positions and momenta of the produced particles.

Adam Kisiel et al., Comput.Phys.Commun. 174, 669-687.

Therminator : contd.....

✓ Cracow Single-freeze out model

-- includes all well established resonances from the PDG

W. Broniowski et al., Phys. Rev. Lett. 87, 272302 (2001); Phys.Rev. C 85, 054907 (2012).

The transverse momentum spectra and the freeze-out hyper surface is calculated using the Cooper-Frye formula

$$\frac{d^2N}{p_T dp_T dy} = \int d\Sigma_\mu . p^\mu f(p.u, T, \mu_B, \mu_Q, \mu_S), \quad (\tau^f)^2 = t^2 - x^2 - y^2 - z^2, \quad x^2 + y^2 \le \rho^2_{\max}$$

Where, $d\Sigma^\mu$ is a differential element and $u^\mu = x^\mu / \tau_f$ is the hydrodynamic 4-velocity of the fire-ball at FH

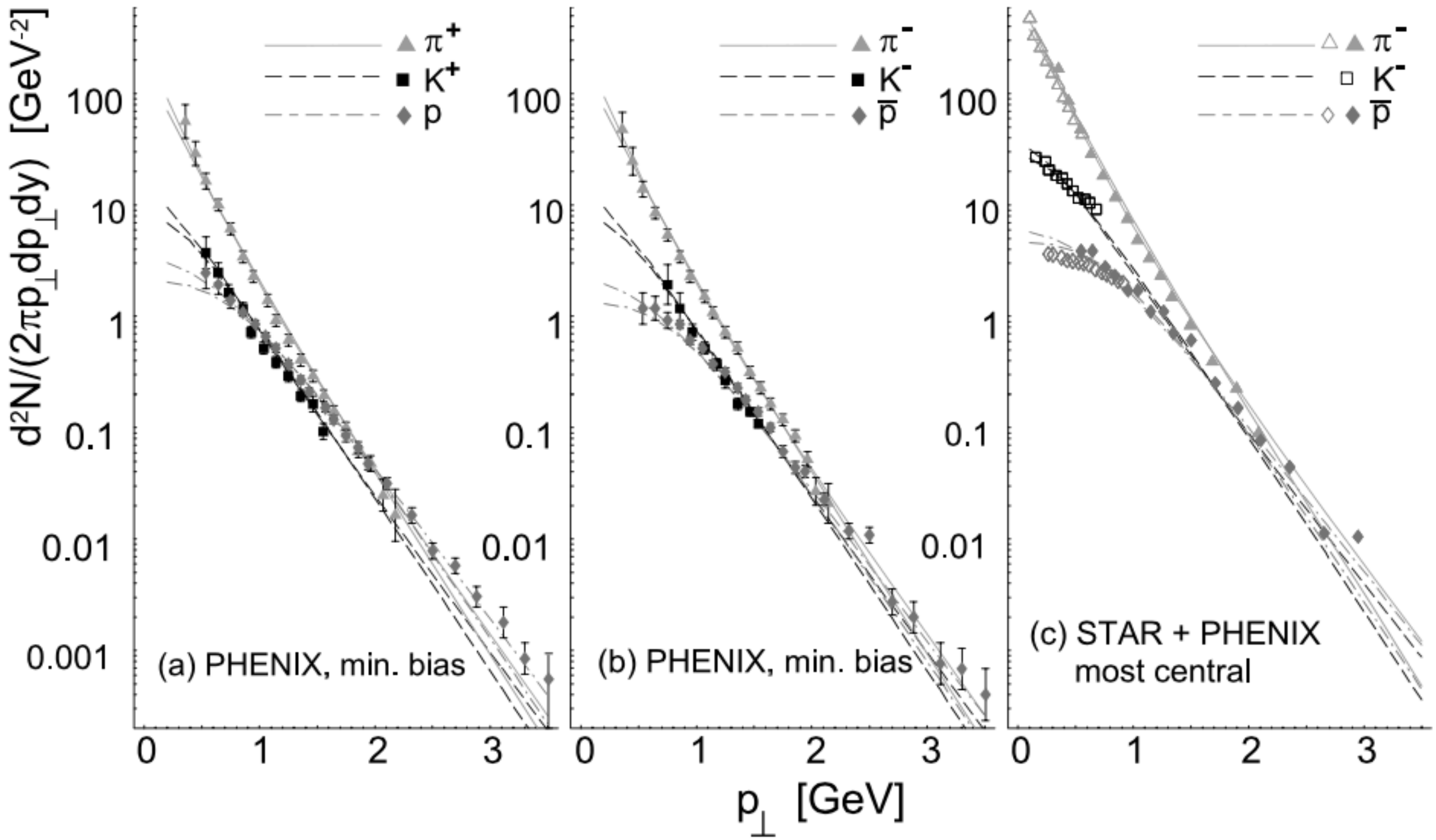
✓ The distribution function 'f' comprise of primary hadrons as well as the decay products of all well established resonances from PDG.

The primordial distribution of the i^{th} in the local rest frame has the form

$$f_p^i(p, T, \mu_B, \mu_Q, \mu_S) = \frac{g_i}{\exp\left[\left(\sqrt{m_i^2 + p^2} - B_i\mu_B - S_i\mu_S - Q_i\mu_Q\right)/T\right] + a_i}$$

Thermінator : Reproduces RHIC results

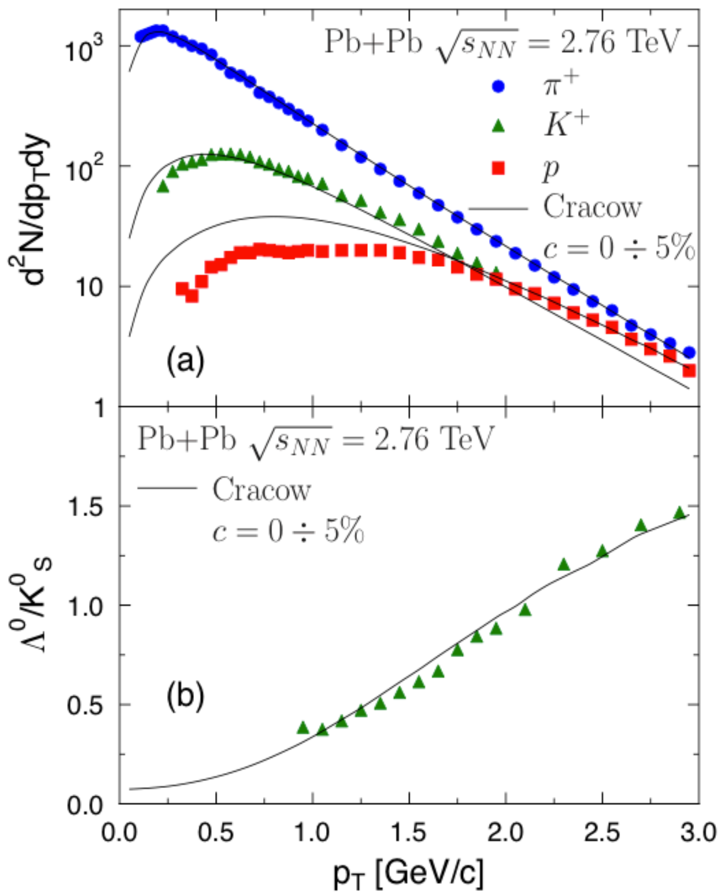
- ✓ ***π, K, p*** spectra at RHIC energies is in a good agreement with Therminator

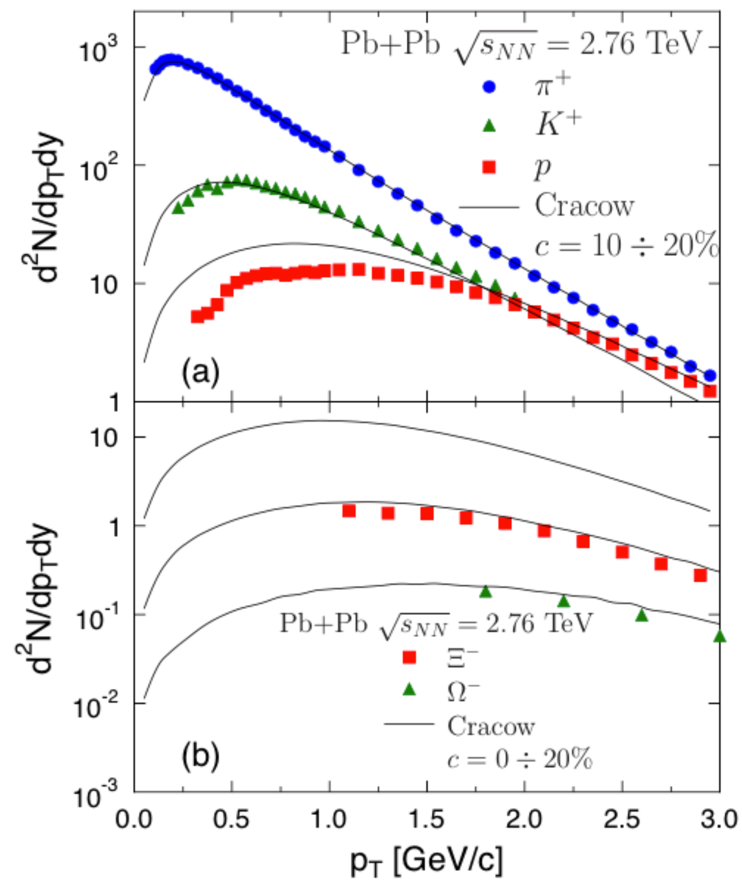


W. Broniowski and W. Florkowski, Phys. Rev. Lett. 87, 272302 (2001).

Thermintor : proton anomaly at LHC

- ✓ ***π, K*** spectra is in good agreement with Therminator model
- ✓ Proton spectra is over predicted by the model
  – leads to proton anomaly





Maciej Rybczynsky et al., Phys.Rev. C 85, 054907 (2012).

Freeze-out scheme : 1FO to 2FO

1FO - All hadrons freeze-out together

2FO - Hadrons with non zero strangeness content freeze-out earlier compared to the rest

Now we have two FHs
$$(\tau_s^f)^2 = t_s^2 - x_s^2 - y_s^2 - z_s^2,$$
$$(\tau_{ns}^f)^2 = t_{ns}^2 - x_{ns}^2 - y_{ns}^2 - z_{ns}^2$$

where the subscripts 's' and 'ns' stand for the strange and non-strange FHs respectively.

The expression for u^μ and f_p^i modify accordingly.

The parameters T_s, T_{ns} are extracted from fits to multiplicity and τ_s^f, τ_{ns}^f, $\rho_s^{\max}$, $\rho_{ns}^{\max}$ are extracted from fits to spectra.

Parameters : FHs

centrality %	T (MeV)	T_s (MeV)	T_{ns} (MeV)	ρ^{max} (fm)	ρ_s^{max} (fm)	ρ_{ns}^{max} (fm)	τ^{f} (fm)	τ_s^{f} (fm)	τ_{ns}^{f} (fm)
00-05	155(2)	164(7)	149(4)	13.4	11.4	14.5	9.5	7.7	10.2
05-10	155(2)	166(6)	149(4)	12.2	10.5	13.8	8.6	7.4	9.6
10-20	156(2)	162(2)	146(4)	11.0	10.1	13.3	7.9	7.0	9.2
20-40	162(3)	163(4)	147(5)	8.3	8.1	10.9	6.1	6.0	7.8
40-60	160(3)	162(4)	150(5)	6.1	6.0	7.3	4.8	4.7	5.6
60-80	154(3)	158(3)	151(6)	4.2	4.0	4.5	3.9	3.4	3.9

Parameters : FHs

centrality %	T (MeV)	T_s (MeV)	T_{ns} (MeV)	ρ^{max} (fm)	ρ_s^{max} (fm)	ρ_{ns}^{max} (fm)	τ^f (fm)	τ_s^f (fm)	τ_{ns}^f (fm)
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60-80	154(3)	158(3)	151(6)	4.2	4.0	4.5	3.9	3.4	3.9

- ✓ Thermal parameter 'T' is extracted from the fit to yields
- ✓ Geometric parameters τ, ρ are extracted from fits to spectra

S. Chatterjee, R.M. Godbole and S. Gupta, Phys.Lett. B 727, 554 (2013).

Parameters : FHs

centrality %	T (MeV)	T_s (MeV)	T_{ns} (MeV)	ρ^{max} (fm)	ρ_s^{max} (fm)	ρ_{ns}^{max} (fm)	τ^f (fm)	τ_s^f (fm)	τ_{ns}^f (fm)
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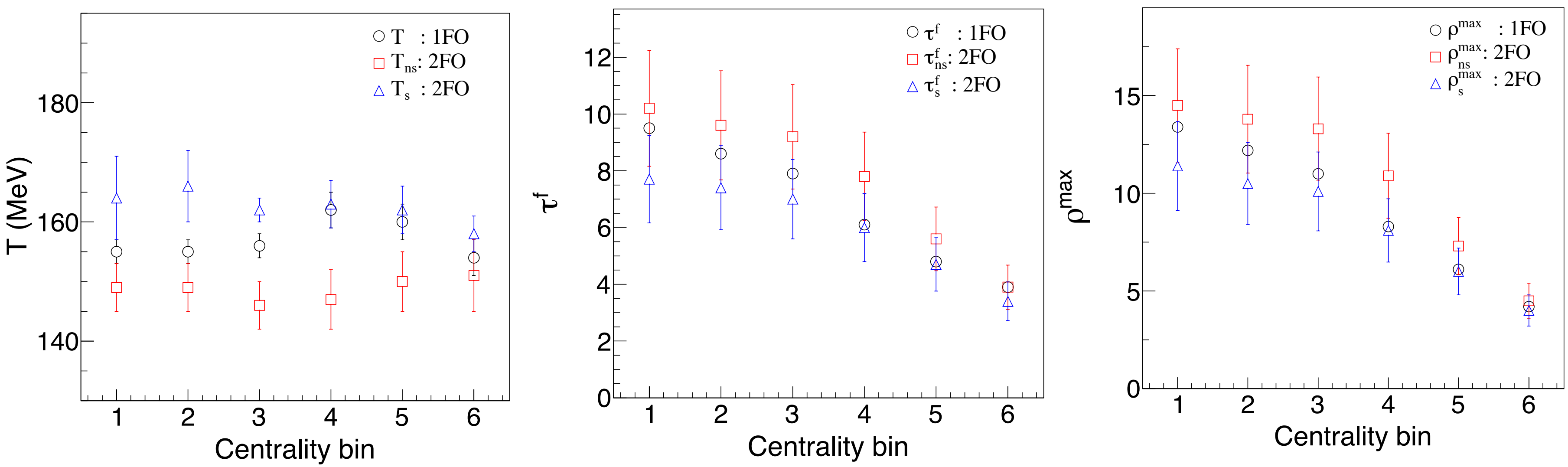


RS, SC and BM, arXiv:1411.1718v1

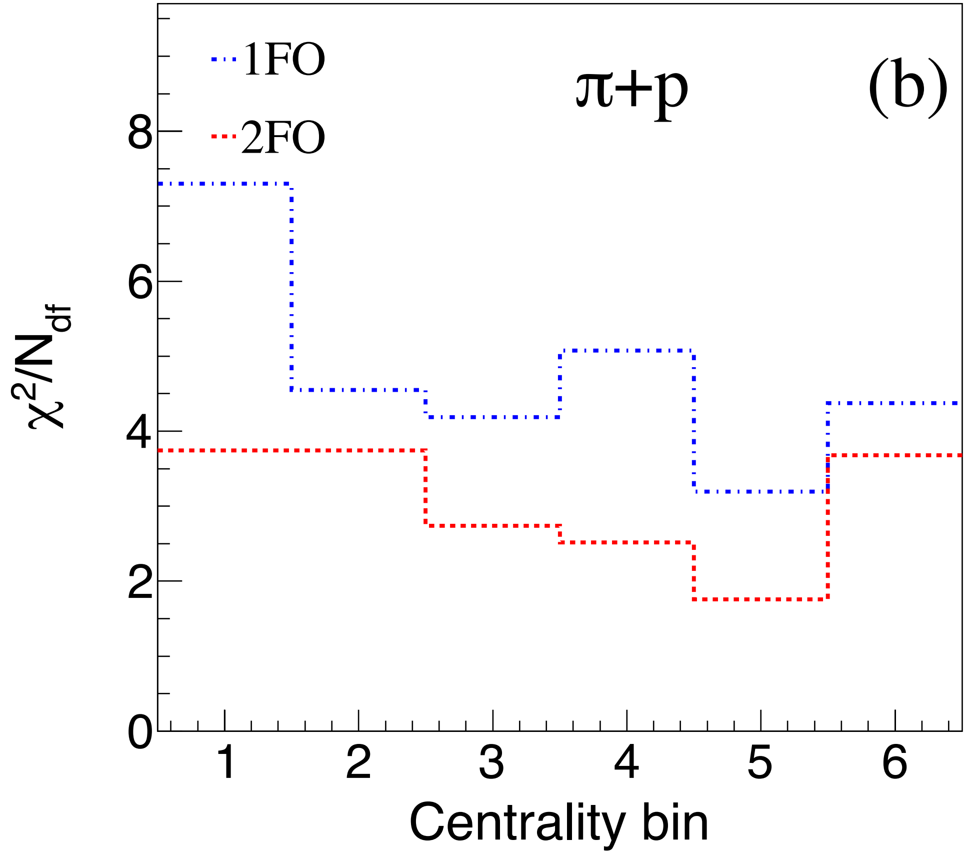
- Temperatures of the two FHs are almost constant within errors
- τ, ρ decrease monotonically from central to peripheral collisions

RESULTS : χ^2/N_{df} for π, p

$$\chi^2 = \sum_i \left(\left(Data(p_{Ti}) - Model(p_{Ti})\right) / Error(p_{Ti})\right)^2$$

N_{df} = No. of data points – No. of free parameters

Sum is performed over all available data points upto p_T = 3 GeV/c



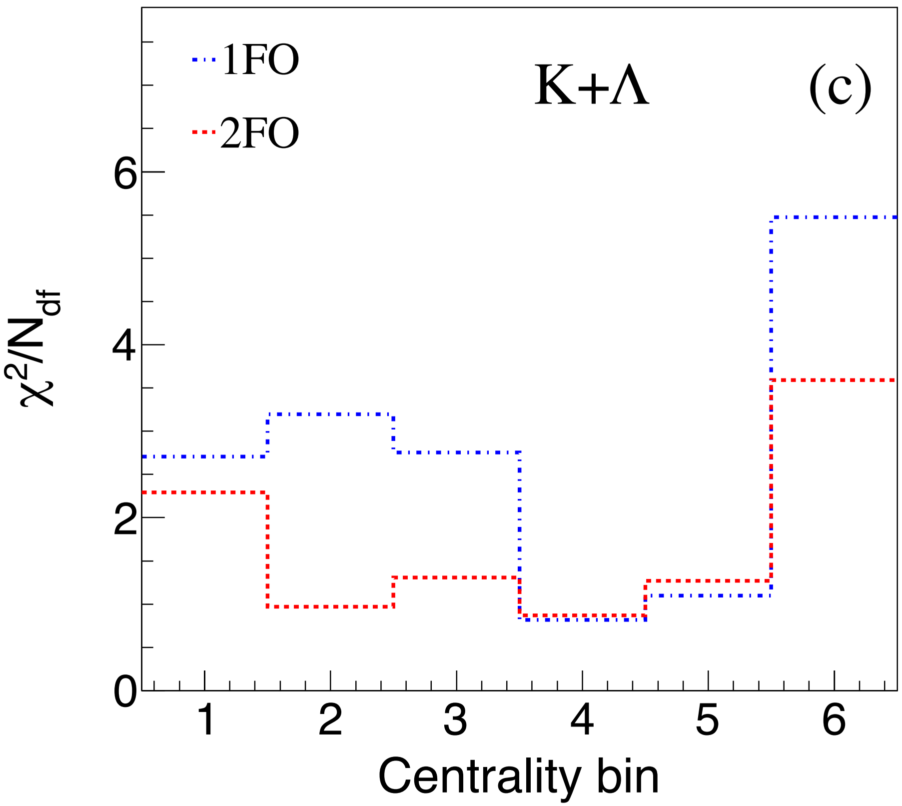
RS, SC and BM, arXiv:1411.1718v1

RESULTS : χ^2/N_{df} for *K, Λ*

$$\chi^2 = \sum_i \left(\left(Data(p_{Ti}) - Model(p_{Ti}) \right) / Error(p_{Ti}) \right)^2$$

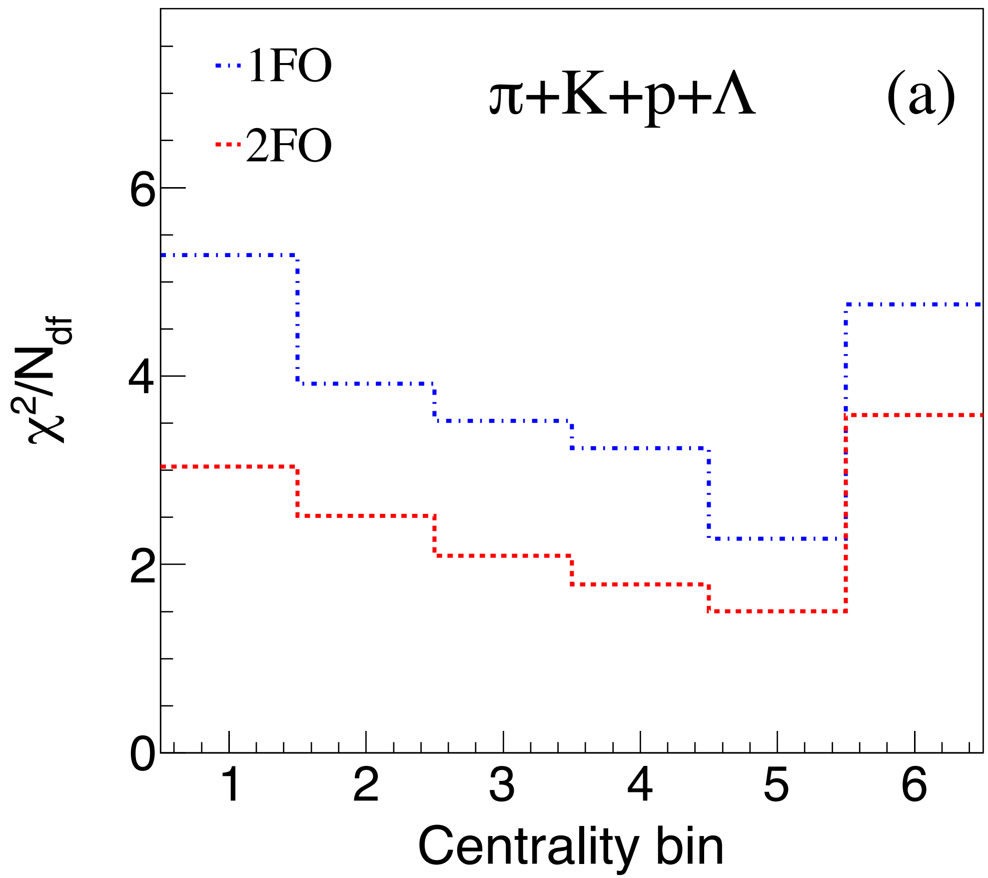
N_{df} = No. of data points – No. of free parameters

Sum is performed over all available data points upto p_T = 3 GeV/c



RS, SC and BM, arXiv:1411.1718v1

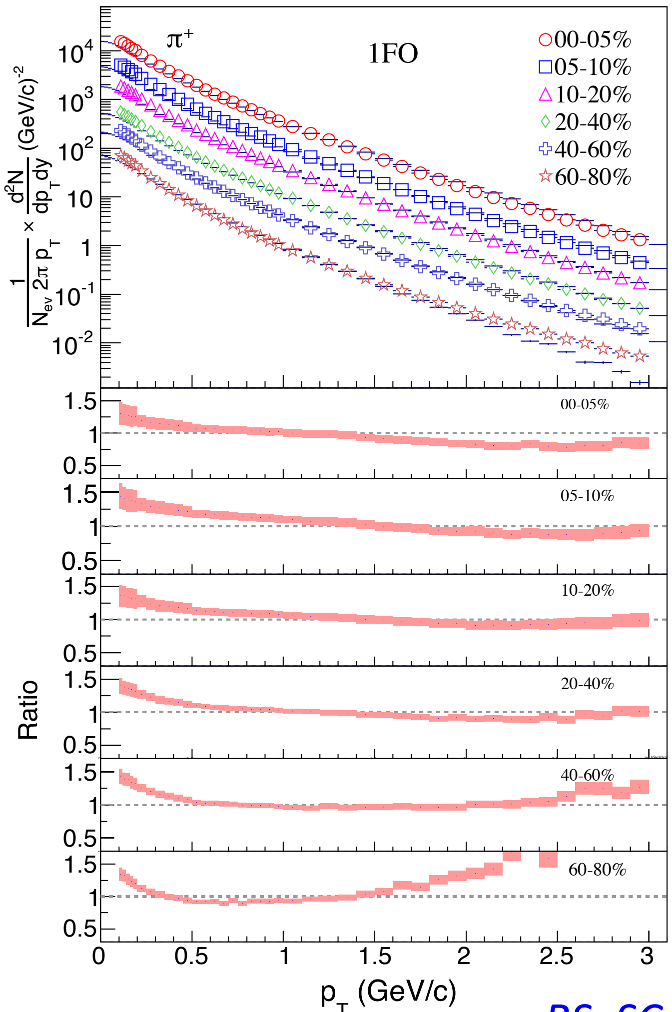
RESULTS : χ^2/N_{df} for π, p, K, Λ

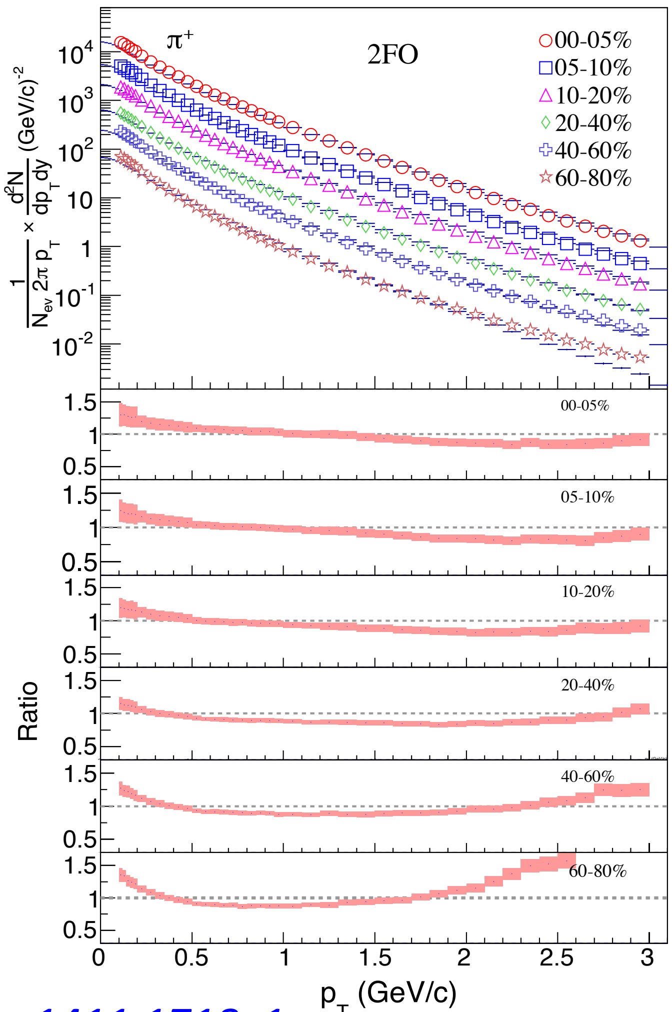


RS, SC and BM, arXiv:1411.1718v1

RESULTS : π^+ spectra

1FO **2FO**



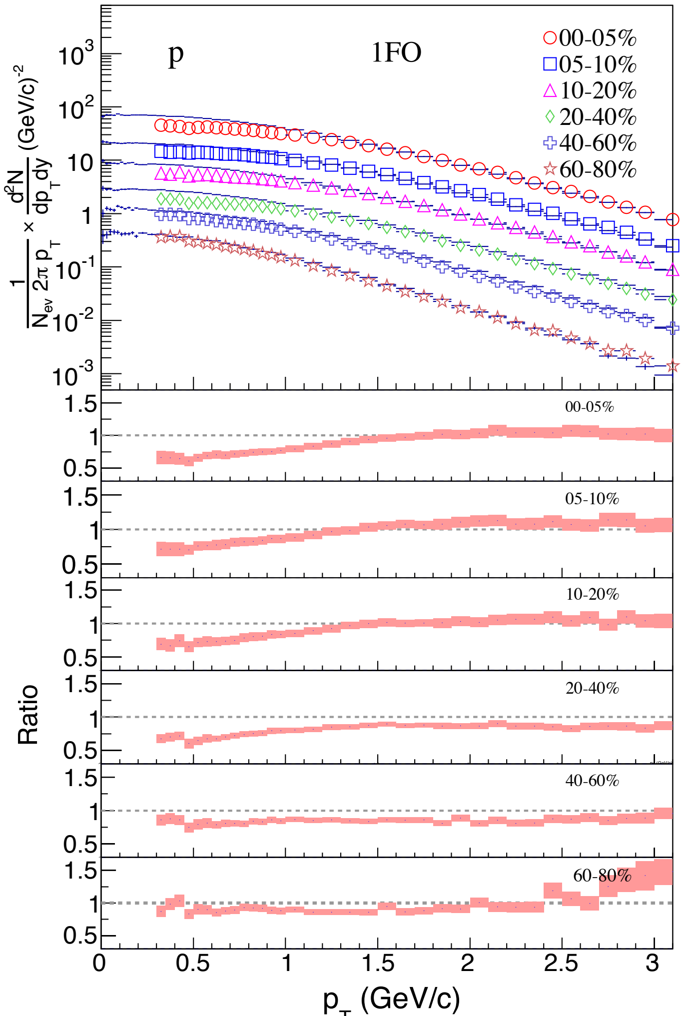


RS, SC and BM, arXiv:1411.1718v1

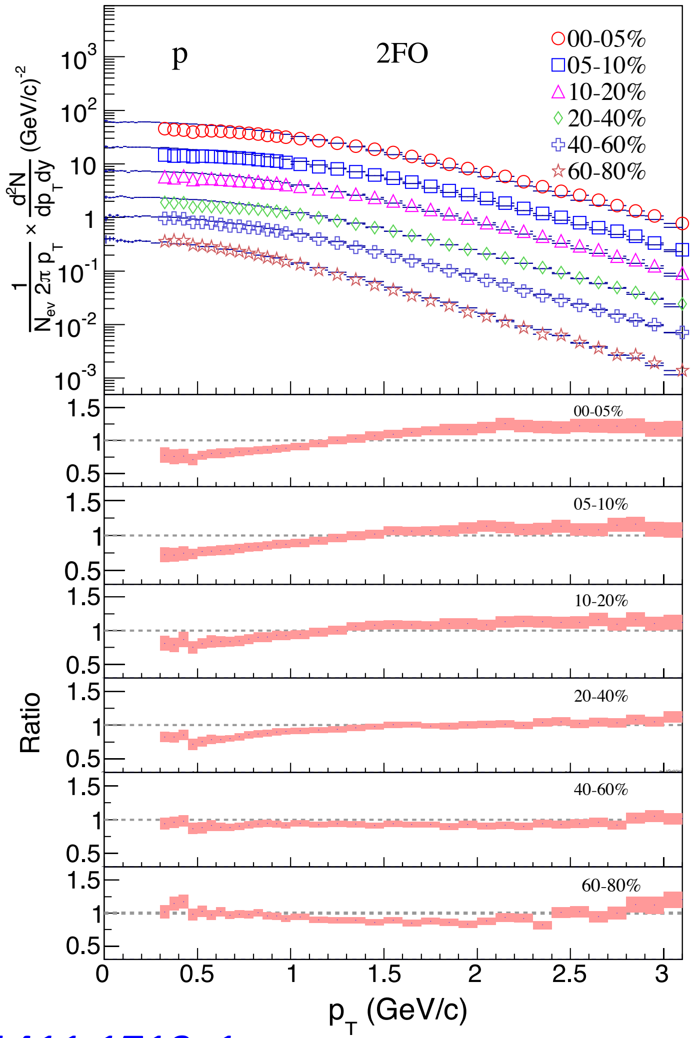
- Significant reduction in pion enhancement at low pT in 2FO

RESULTS : *p* spectra

1FO



2FO

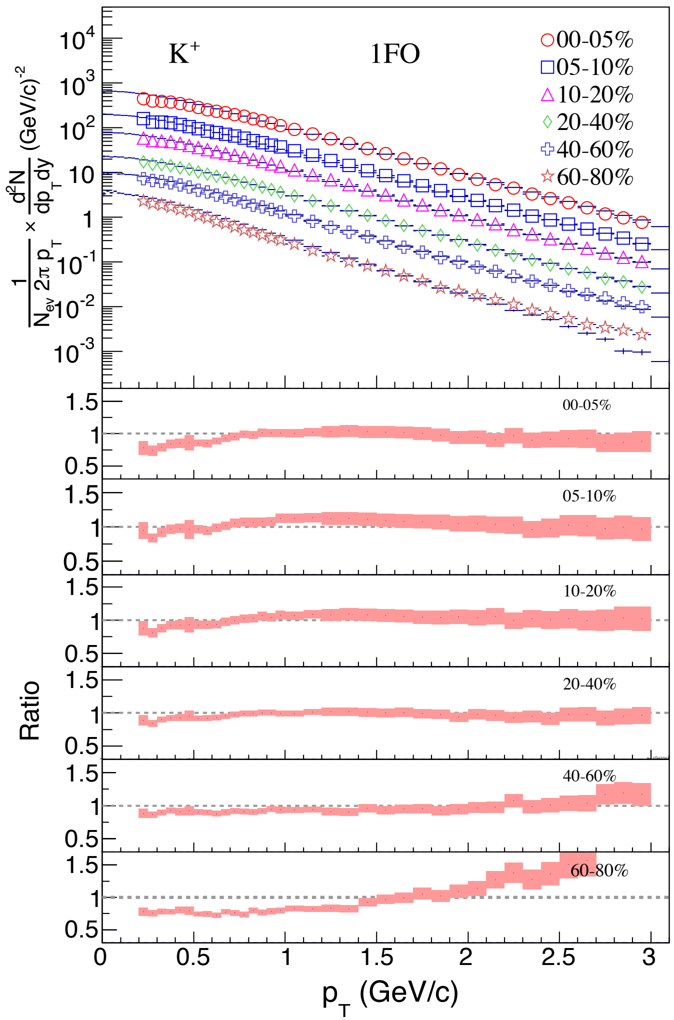


RS, SC and BM, arXiv:1411.1718v1

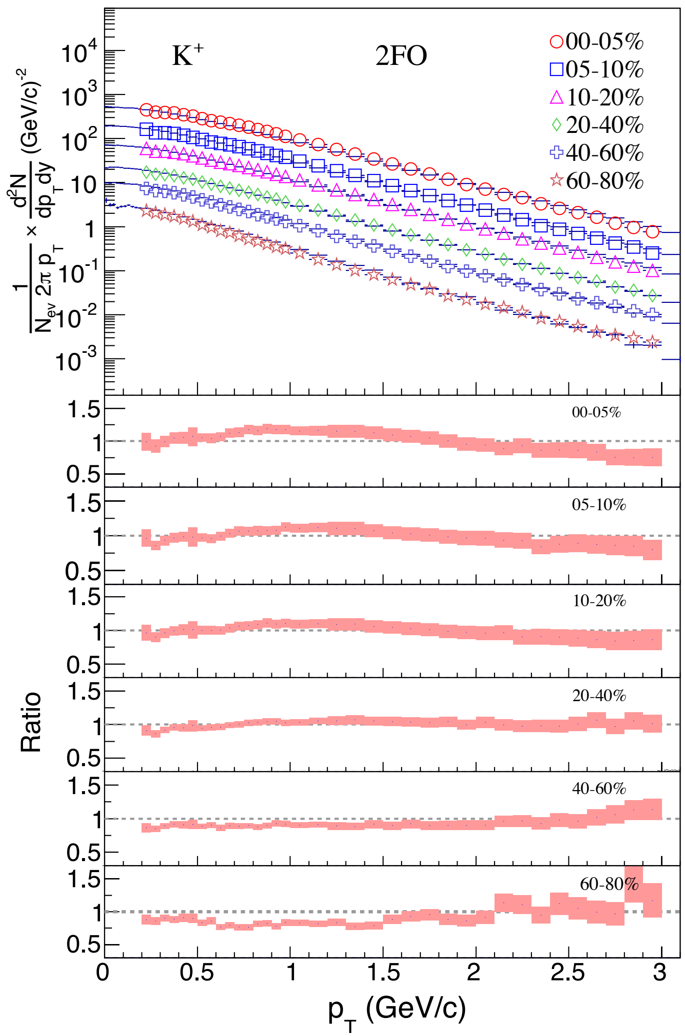
- In 2FO significant improvement in *p* spectra
- Also the π and *p* tension is reduced considerably

RESULTS : K^+ spectra

1FO

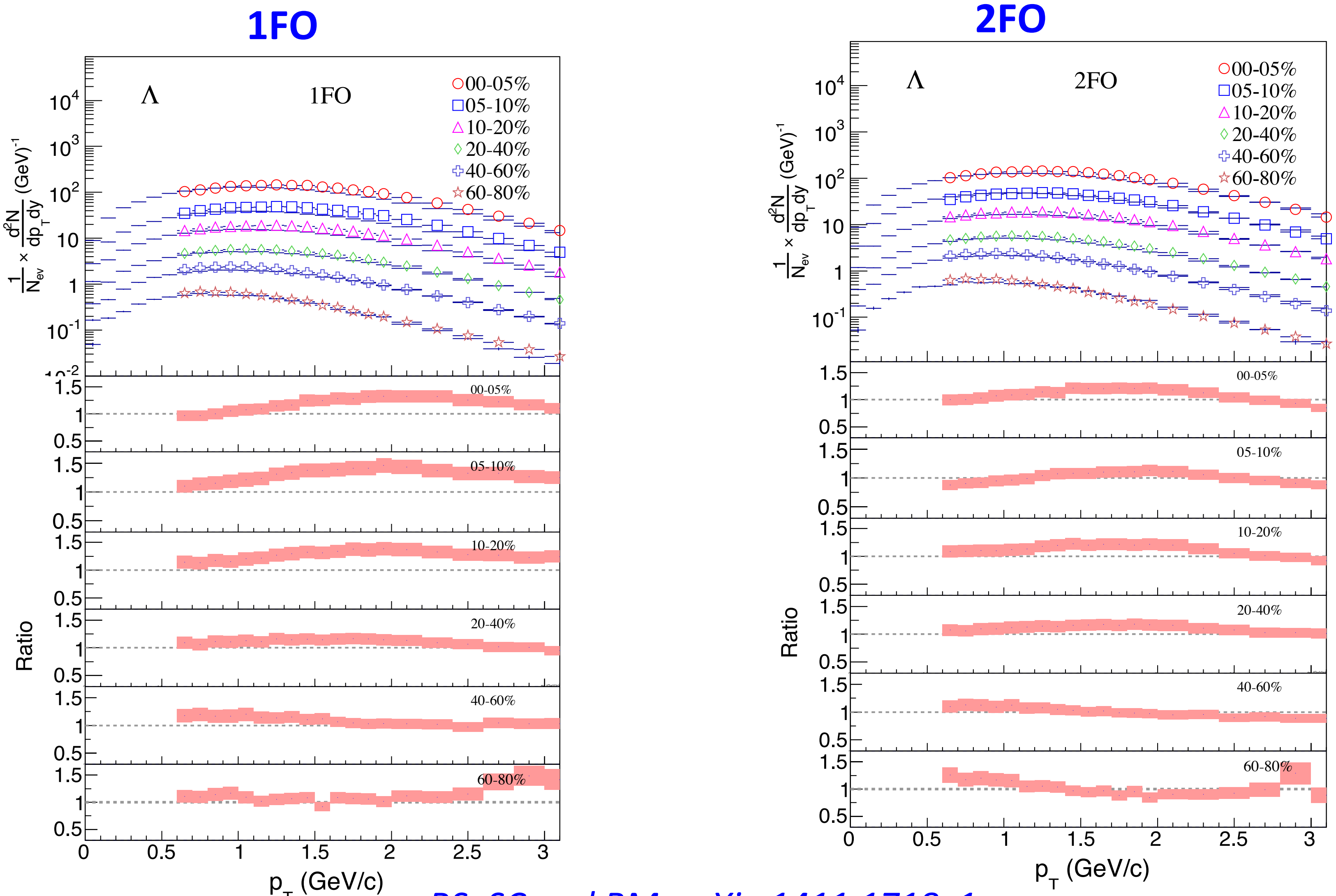


2FO



RS, SC and BM, arXiv:1411.1718v1

RESULTS : Λ spectra

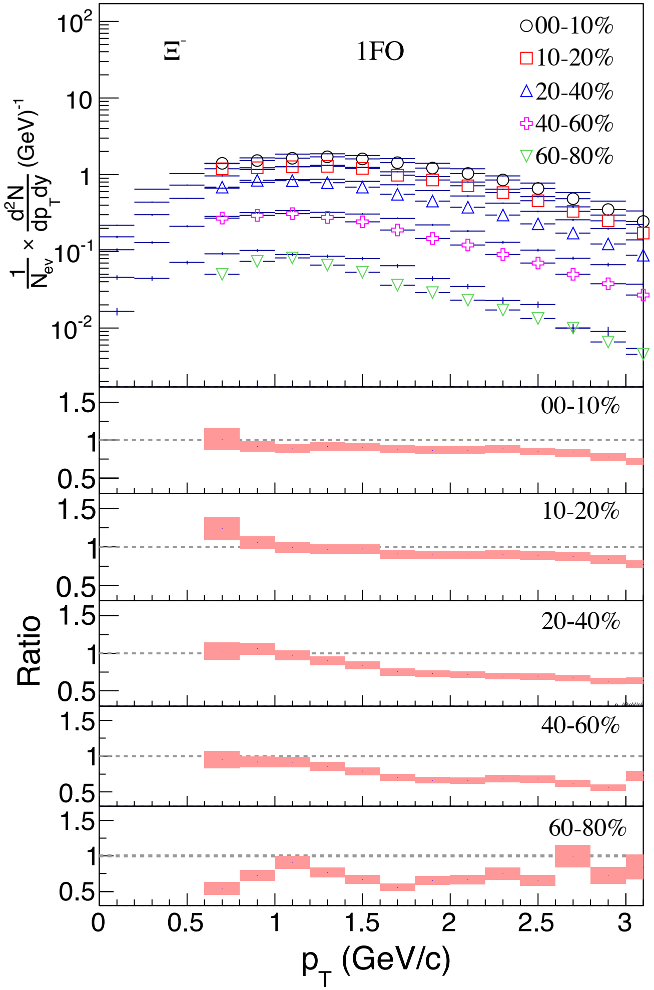


RS, SC and BM, arXiv:1411.1718v1

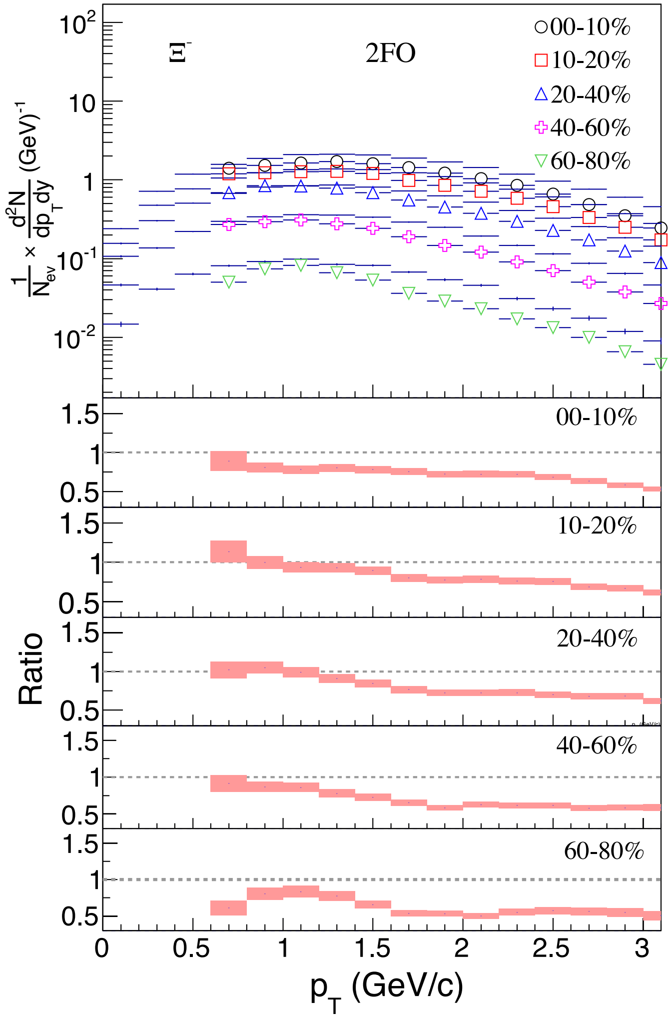
- For K^+ and Λ the agreement between model and data is better compared to π^+ and p

RESULTS : Ξ^- spectra

1FO

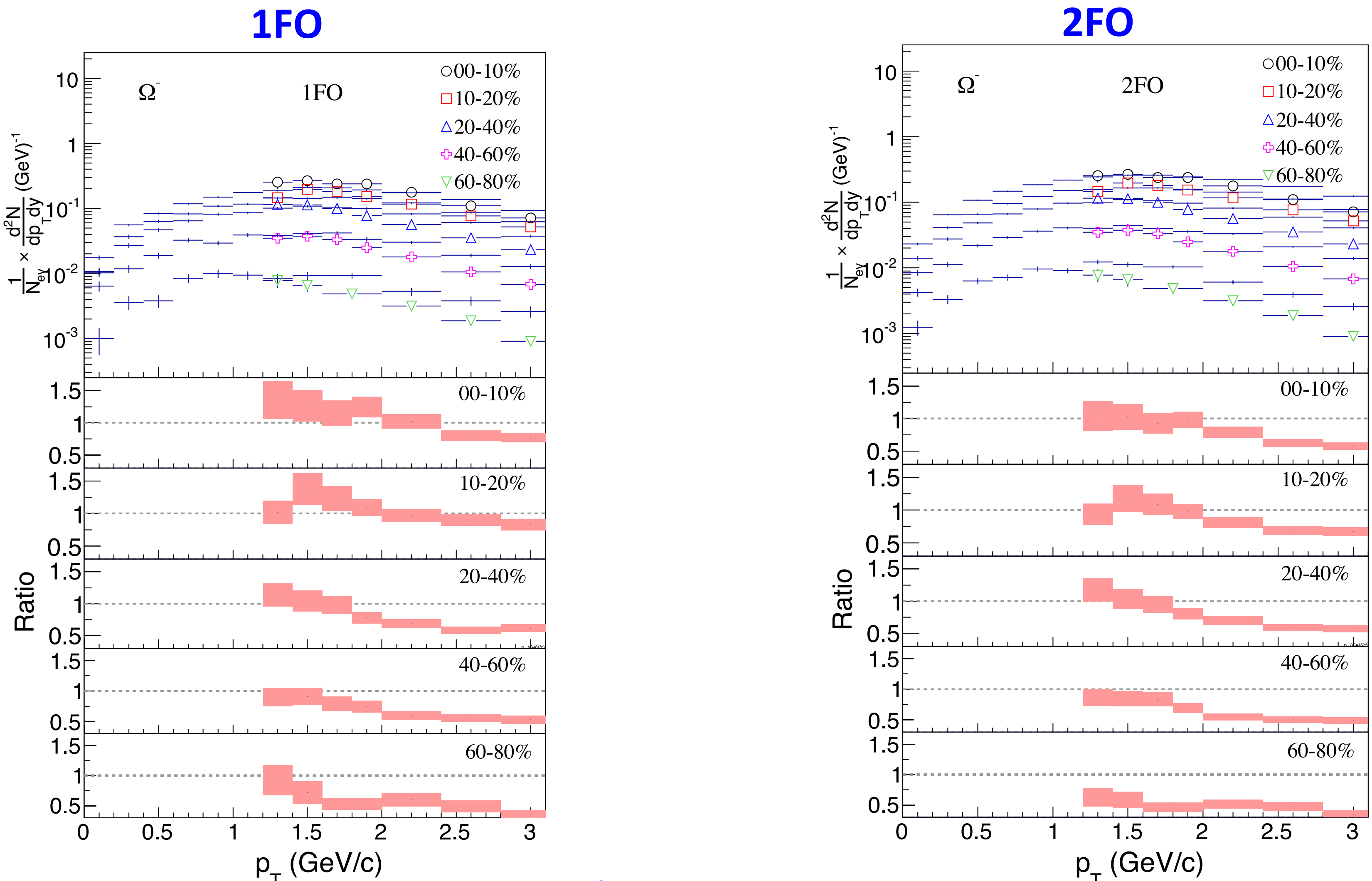


2FO



RS, SC and BM, arXiv:1411.1718v1

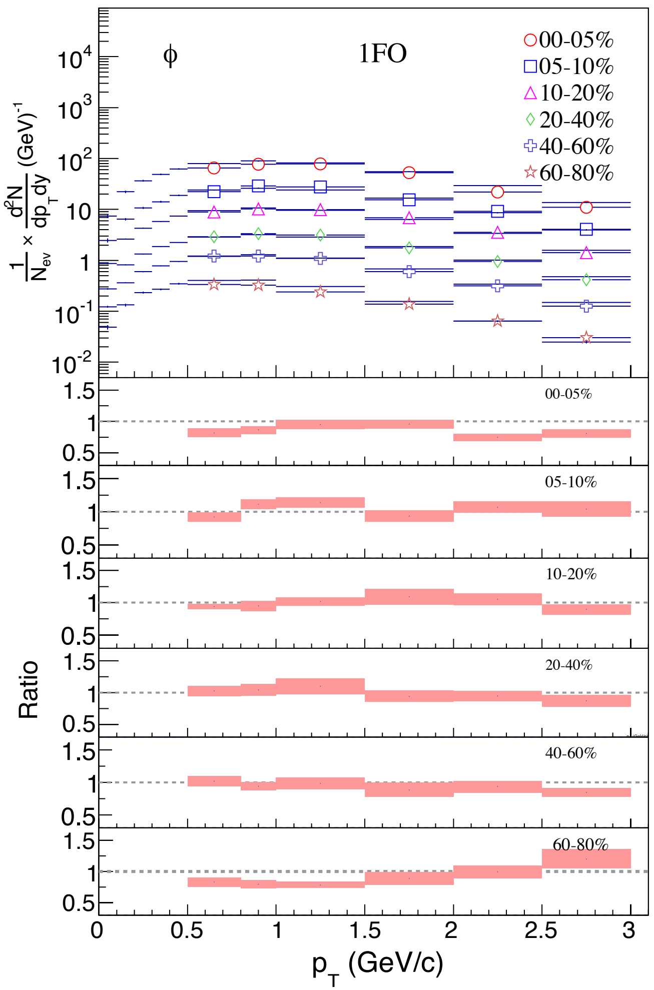
RESULTS : Ω^- spectra



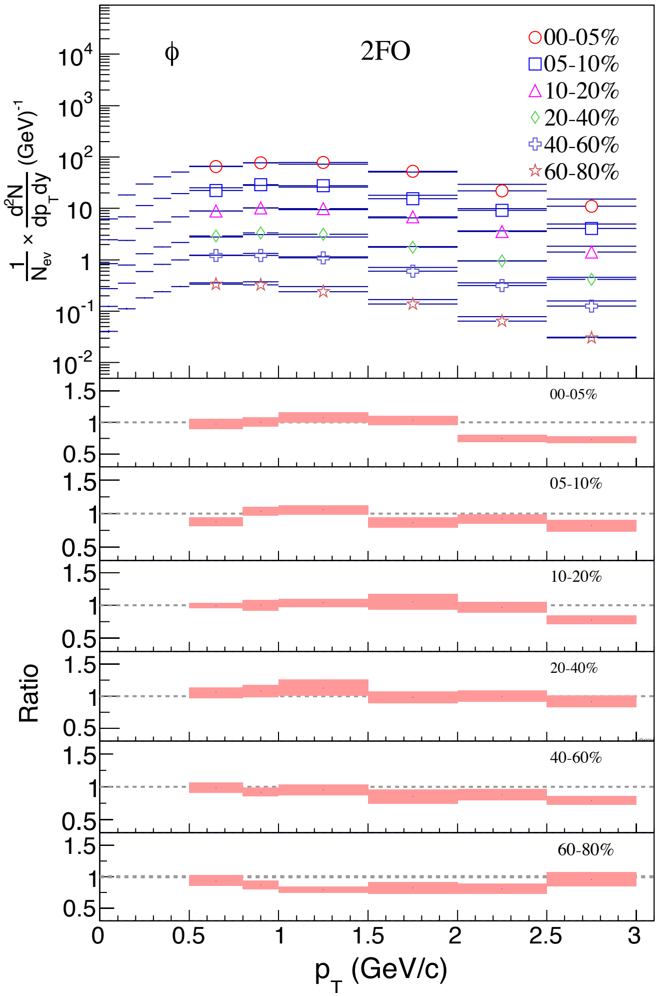
RS, SC and BM, arXiv:1411.1718v1

- For Ξ^- and Ω^- the agreement between data and model for p_T upto 1.5 to 2.0 GeV/c is within 25% for all centralities except 60-80%

1FO



2FO

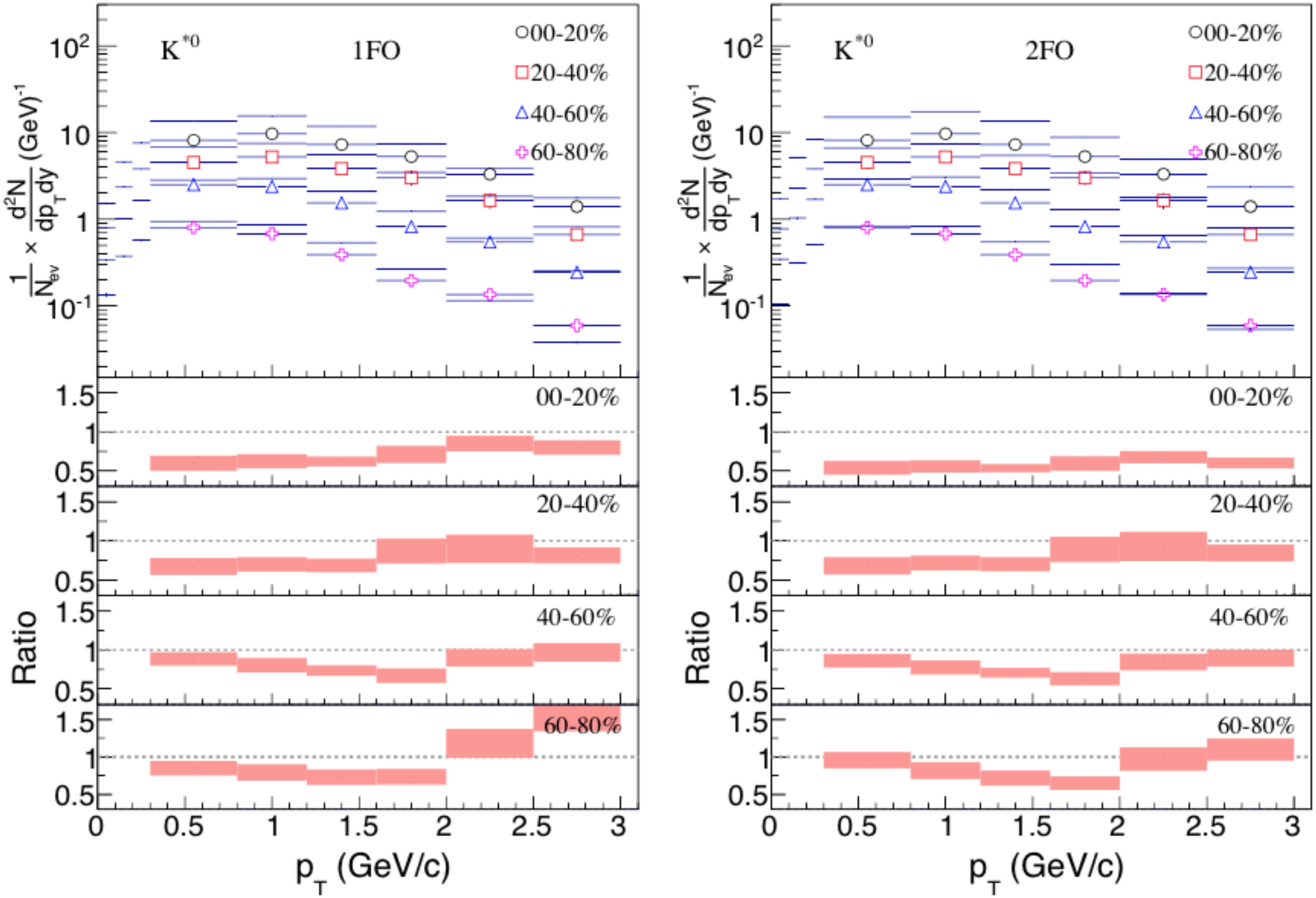


RS, SC and BM, arXiv:1411.1718v1

- both 1FO and 2FO provide good description of the spectra of ϕ

RESONANCES : K^{*0} spectra

1FO **2FO**

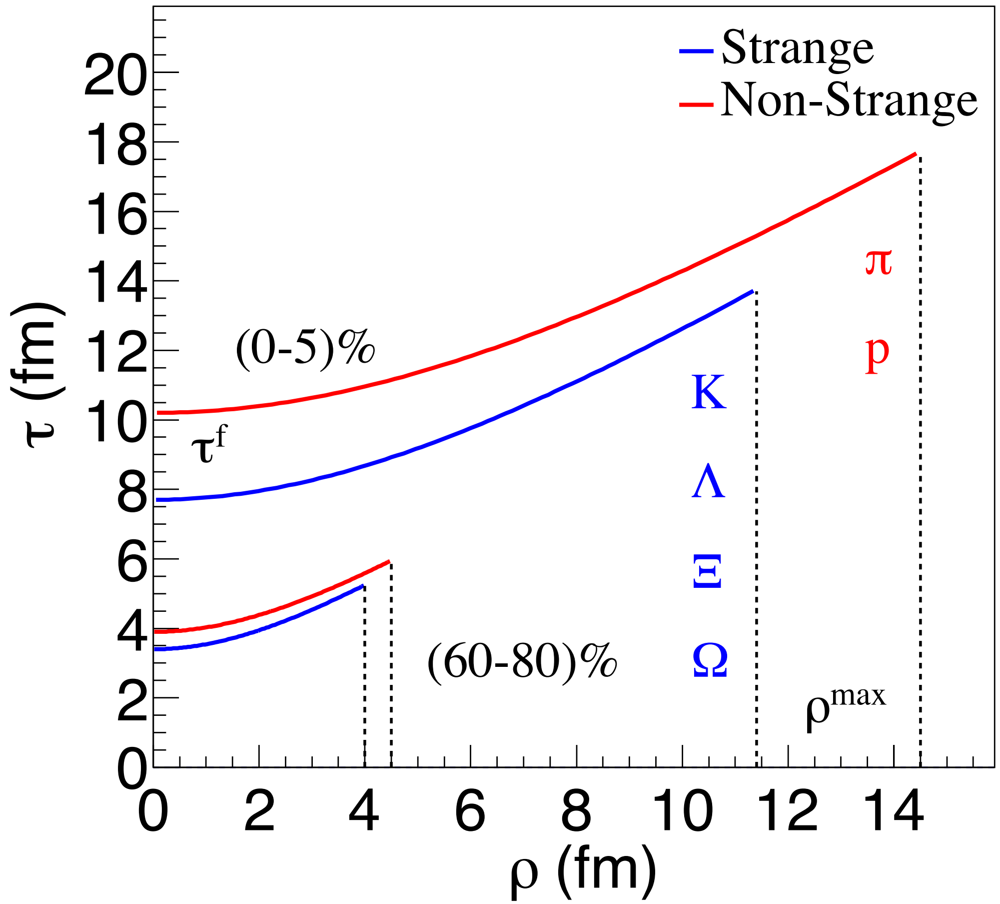


❖ Model over predict the data – Re-sacttering effect in data

RS, SC and BM, arXiv:1411.1718v1

FHs : 1FO and 2FO

RS, SC and BM, arXiv:1411.1718v1



- The separation between strange and non-strange FHs are more in the (0 – 5) % centrality bin than in the (60 – 80) %

SUMMARY :

- ✓ We have presented the p_T spectra of π^+, K^+, p, Λ, Ξ^-, Ω^- and ϕ within two schemes of freeze-out : 1FO and 2FO
- ✓ A significant improvement in 2FO as compared to 1FO with a reduction in χ^2/N_{df} by around 40%
- ✓ A wide gap between non-strange and strange FHs hint for further substructures in the simple 2FO scheme
- ✓ The tension between model spectra and data of π, p is not completely gone in most central collisions
- ✓ Over prediction of the spectra in the case of multi-strange baryons hints of separate freeze-out
- ✓ Before drawing final conclusion it will be important to account for the contribution from the heavier resonances which are yet unobserved