First measurement and investigation of the ρ^0p final-state interaction with ALICE

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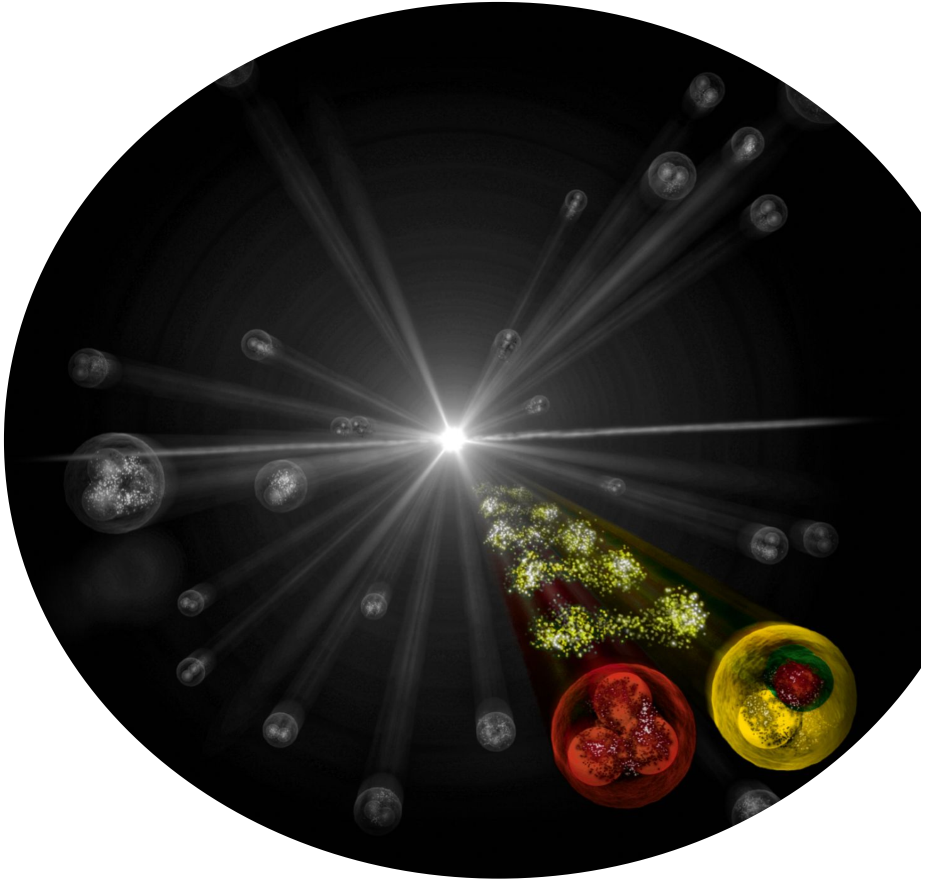
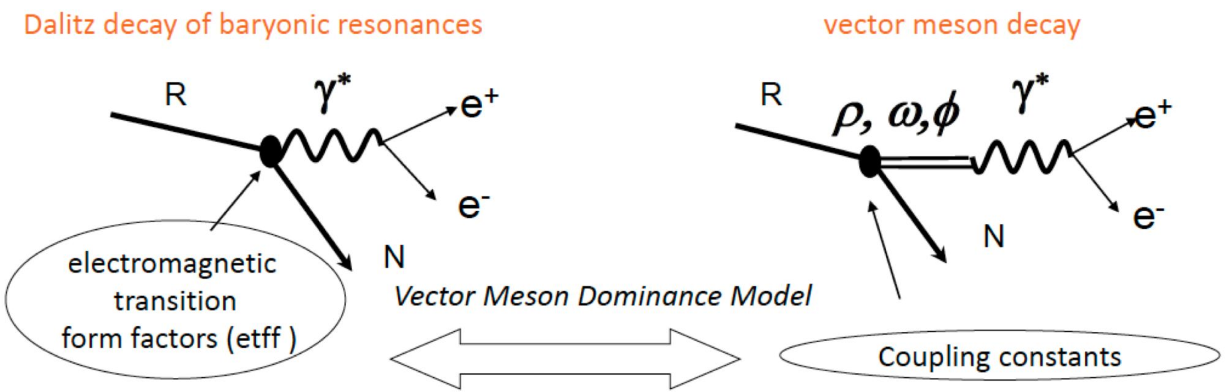


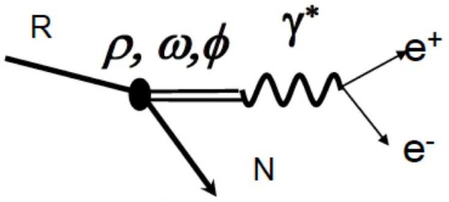
Vector meson nucleon interaction



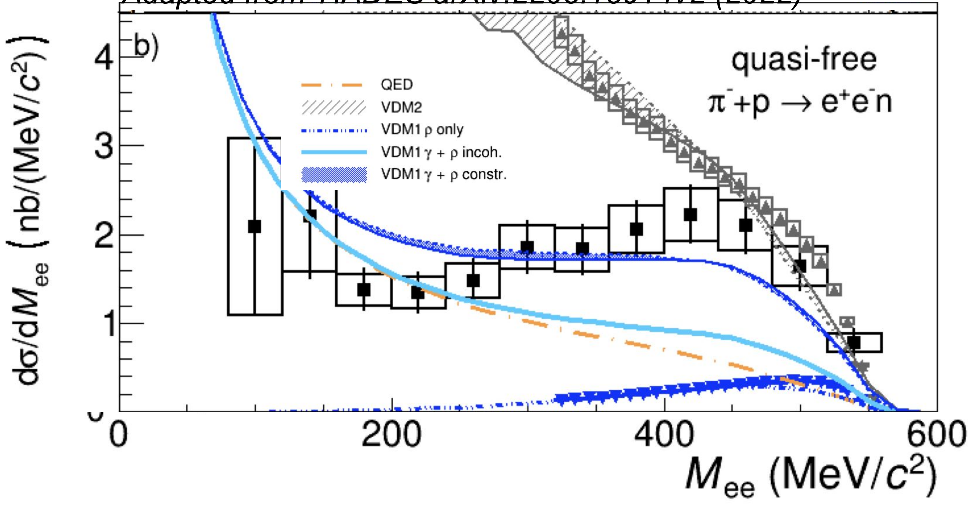
- Usually probed by Vector Meson Dominance (VMD[1]) Models
  1: J. J. Sakurai, Phys. Rev. Lett. 22, 981 (1969)
  - Hadronic contribution to the photon propagator
  - Off-shell vector mesons

- Important to understand…
  - … in-medium dilepton production
  - … dynamically generated states N* and Δ* (pole positions) from unitarised chiral perturbation theory (UChPT[2])
    2: N. Kaiser, P. B. Siegel and W. Weise, Phys. Lett. B 362, 23 (1995)

Vector meson nucleon interaction



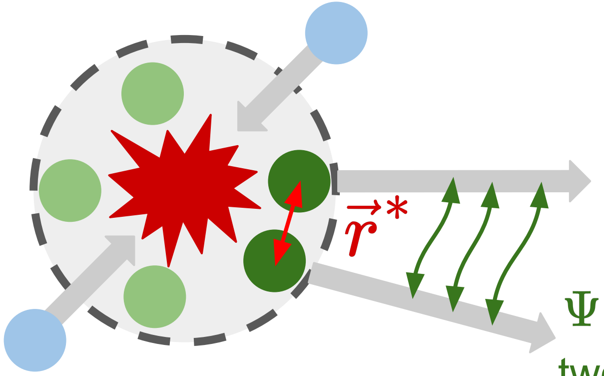
Adapted from HADES arXiv:2205.15914v2 (2022)



- Test of VMD at HADES
  - Low-energy beams (π)
  - M_{ee} excess compared to QED reference
- Excess modeled
  - With low-lying intermediate resonances (R) (N(1440), N(1520), N(1535) in a Rγ*N vertex)
- But how can one access the interaction between the ρ^0 and nucleon directly?

Femtoscopy in a nutshell

L. Fabbietti and V. Mantovani Sarti and O. Vazquez Doce, Ann.Rev.Nucl.Part.Sci.55:357-402, 2005



Measure the correlation function *C(k*)*

$\Psi(\vec{k}^*, \vec{r}^*)$

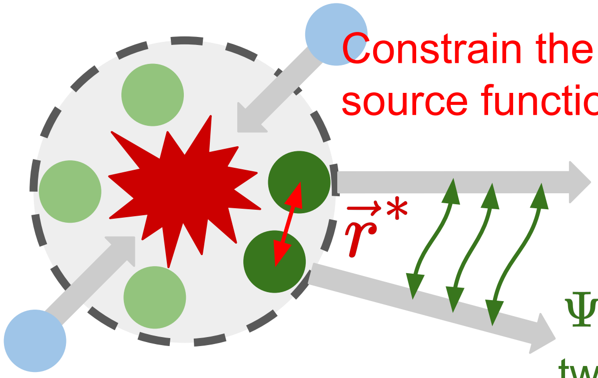
two-particle wave function

$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)}$$

Particle pair observed in the same event

Particle pair constructed from different events

Femtoscopy in a nutshell



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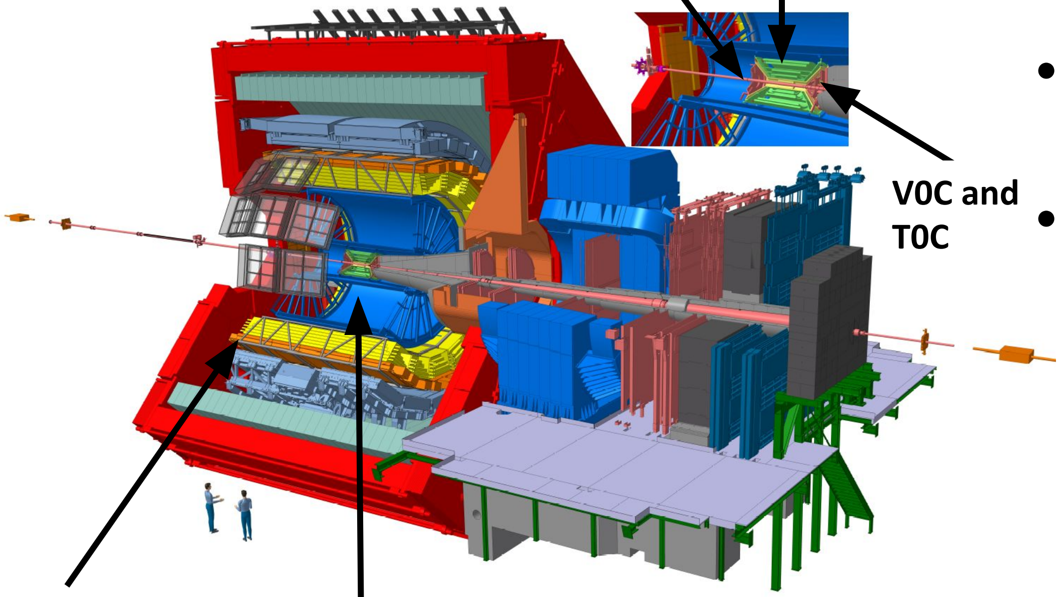
$$C(k^*) = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

- **Measure $C(k^*)$, use constrained $S(r^*)$, study interaction**
  ALICE, PLB 811:135849 (2020); ALICE, EPJC 85 (2025) 2, 198; ALICE, arXiv:2502.20200 (2025)

- For evaluation of integral and $S(r^*)$ use CATS framework
  D. L. Mihaylov et al. Eur.Phys.J.C 78 (2018) 5, 394

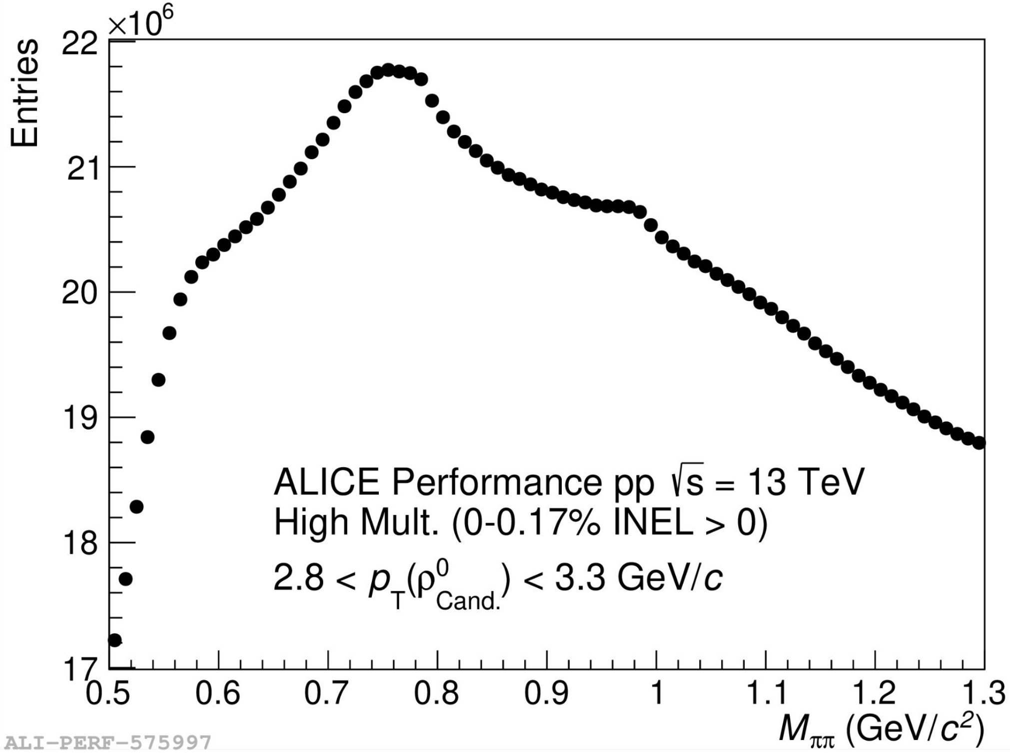
ALICE Run 2

ALICE Coll. Int.J.Mod.Phys. A29(2014)
Run 2 configuration



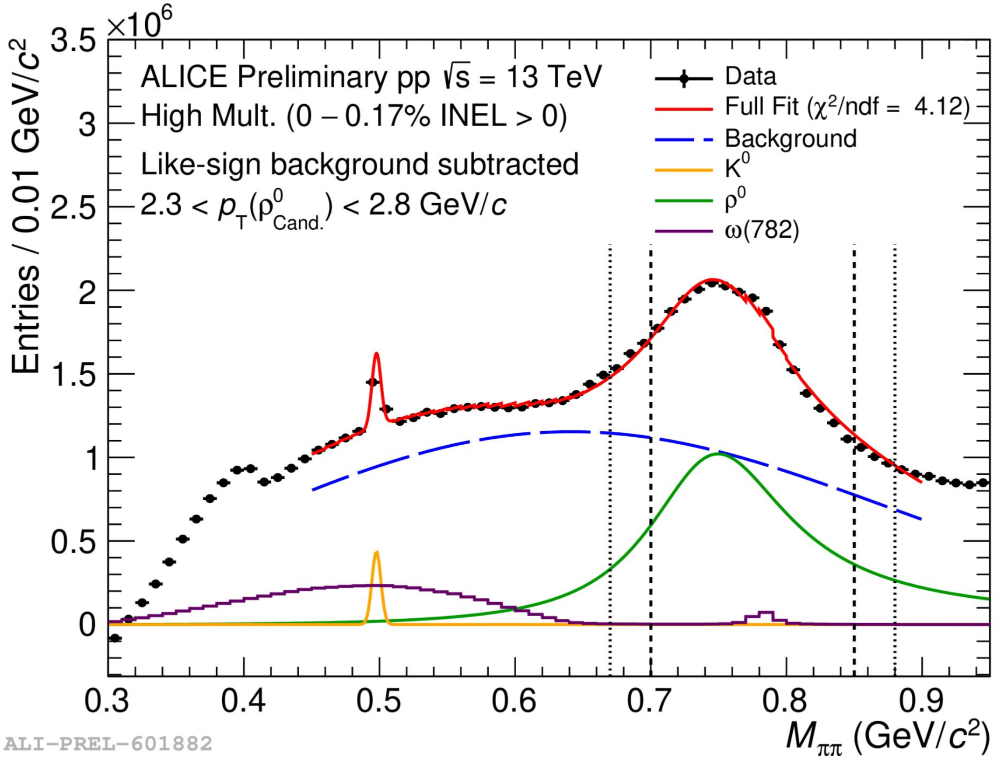
- High multiplicity (HM) pp collisions @ 13 TeV
  - 1 Billion events in Run 2
- Direct detection of charged particles (π, K, p) by TPC and TOF
- Particle identification
  - Mean energy loss in TPC
  - Momentum reconstruction by TOF
  - Purity of about 99% for π, K, p due to excellent PID capabilities

Reconstruction of ρ^0



- Access to ρ^0 ($c\tau$ = 1.2 fm/c)
  - Pair all π in an event $\rho^0 \rightarrow \pi^+\pi^-$ (B.R. ≅ 100%)
- Purity of the ρ^0 around **3.26%**
  - Obtained by fit
- Two types of background
  - Combinatorial due to $(\pi\pi)_{Comb.}$
  - Mini-jet correlations

Model $M_{\pi\pi}$ to access purity of ρ^0



Assess purity of ρ^0

- Pair all π in an event
- Record $M_{\pi\pi}$ vs p_T
- Fit projections

Method follows established procedures[1,2]

- Use LSB subtraction
- Model states with rBW/MC temp.
- Gaussian for K^0
- **Purity 3.26%**

For p_T > 1.8 GeV/c ρ^0-peak is visible

- translates to high m_T pairs
- **1.64 < m_T < 3.77 (GeV/c^2)**

1: STAR, PRL. 92 (2004) 092301
2: ALICE, PRC 99 (2019) 064901

Extraction of the genuine ρ^0–p correlation

$$C_{\text{measured}}(k^*) = C_{\text{minijet}}(k^*)\left[\lambda_{\rho^0-\text{p}} \cdot C_{\rho^0-\text{p}}(k^*)\right] + (1-\lambda_{\rho^0-\text{p}}) \cdot \left(\omega_{\text{left}} C_{\text{SB}}^{\text{left}}(k^*) + (1-\omega_{\text{left}}) C_{\text{SB}}^{\text{right}}(k^*)\right).$$

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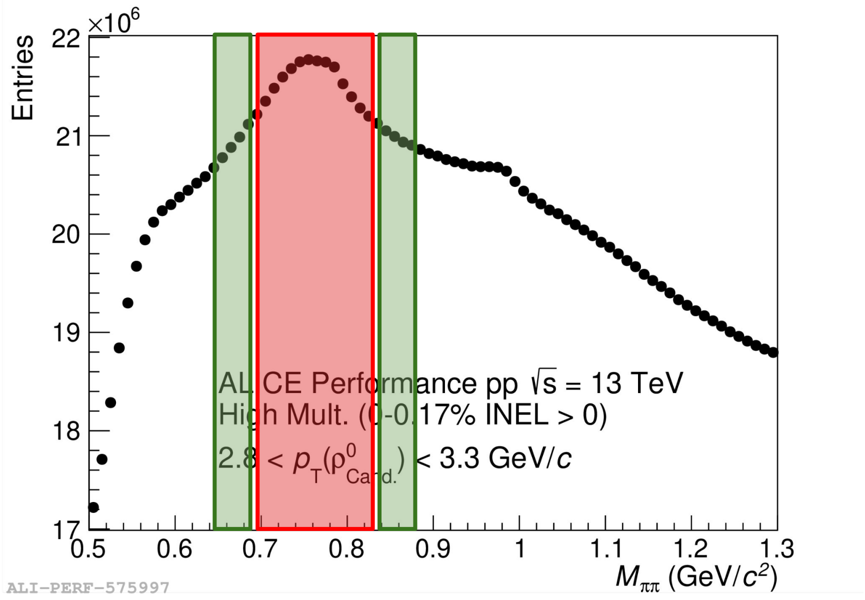
- Account for correlation of $(\pi\pi)_{\mathrm{Comb.}}$ underneath ρ^0 signal
- Employ sideband (SB) analysis
  - Compute correlation function selecting $\rho^0_{\mathrm{Cand.}}$ from left and right sideband region



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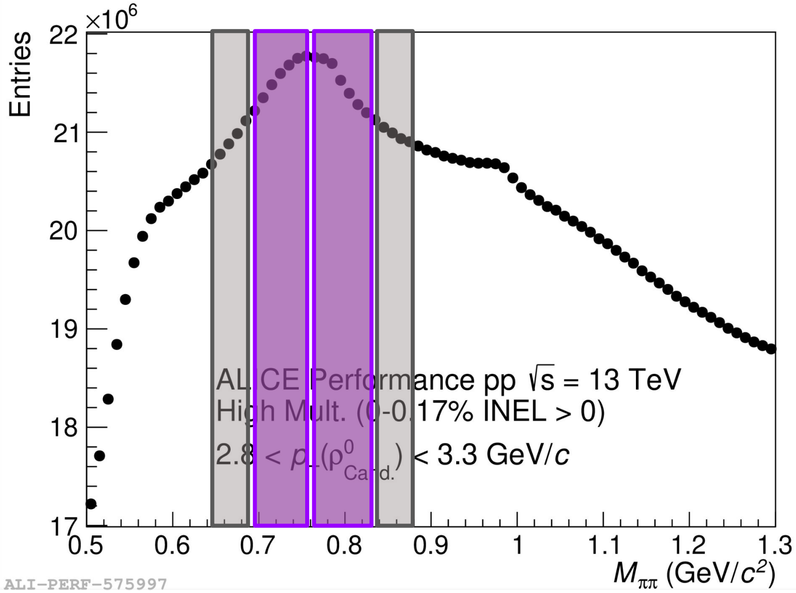
- Account for correlation of $(\pi\pi)_{\mathrm{Comb.}}$ underneath ρ^0 signal
- Employ sideband (SB) analysis
  - Compute correlation function selecting $\rho^0_{\mathrm{Cand.}}$ from left and right sideband region
  - Calculate weights by integration
  - Obtain SB correlation by a weighted average



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$$C_{\rho^0\text{—p}}(k^*) = \frac{1}{C_{\text{minijet}}}\left\{\frac{1}{\lambda_{\rho^0\text{—p}}}\left[C_{\text{measured}}(k^*) - (1 - \lambda_{\rho^0\text{—p}}) C_{\text{SB}}(k^*)\right]\right\}.$$

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- Account for correlation of …
  - fake ρ^0-p by **SB subtraction**
    - SB left and right weighted (ω) with integral under ρ^0 peak
    - Take genuine ρ^0-p in SB into account
  - **Minijets** in ρ^0-p by dividing by SB (assume SB is dominated by Minijet)

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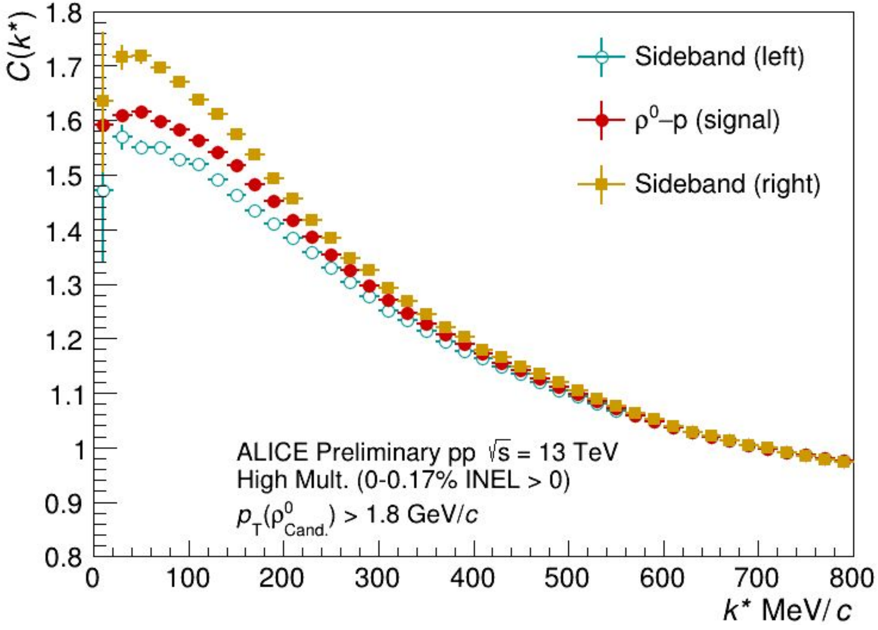
- Properly scaled by the **λ parameter**
  - Depends on the single-particle properties (purity and fractions)
  - dominated by the purity of ρ^0

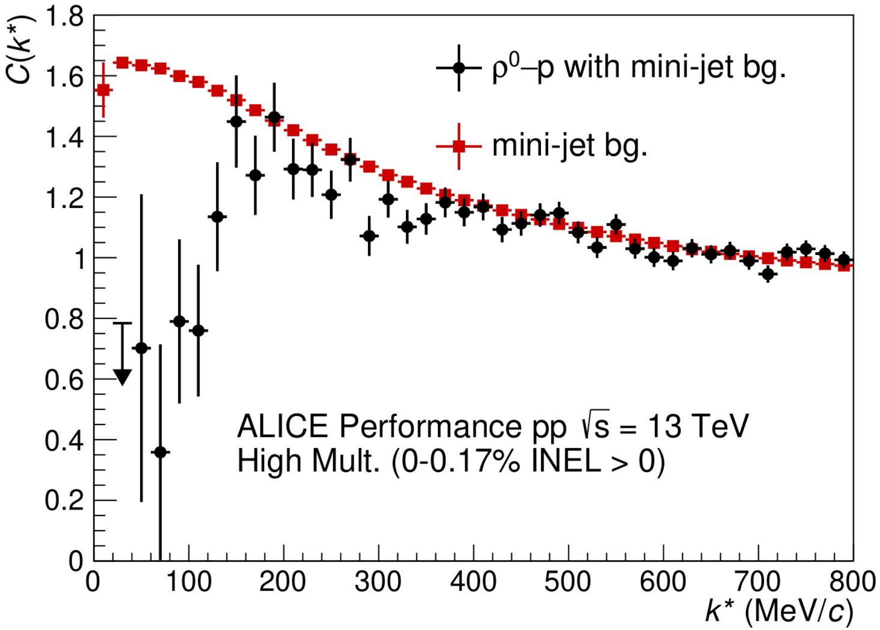
Correlation function of signal and sidebands



- Normalisation 600 - 800 MeV/*c*
- Correlation in signal region
  - ρ^0-p final-state interaction
  - Minijet contribution
  - correlation from SB
- Corrections
  - Take ρ^0-p in SB into account
  - Subtract λ scaled SB

$$C_{\rho^0\text{–p}}(k^*) = \frac{1}{C_{\text{minijet}}}\left\{\frac{1}{\lambda_{\rho^0\text{–p}}}\left[C_{\text{measured}}(k^*) - (1-\lambda_{\rho^0\text{–p}})C_{\text{SB}}(k^*)\right]\right\}.$$

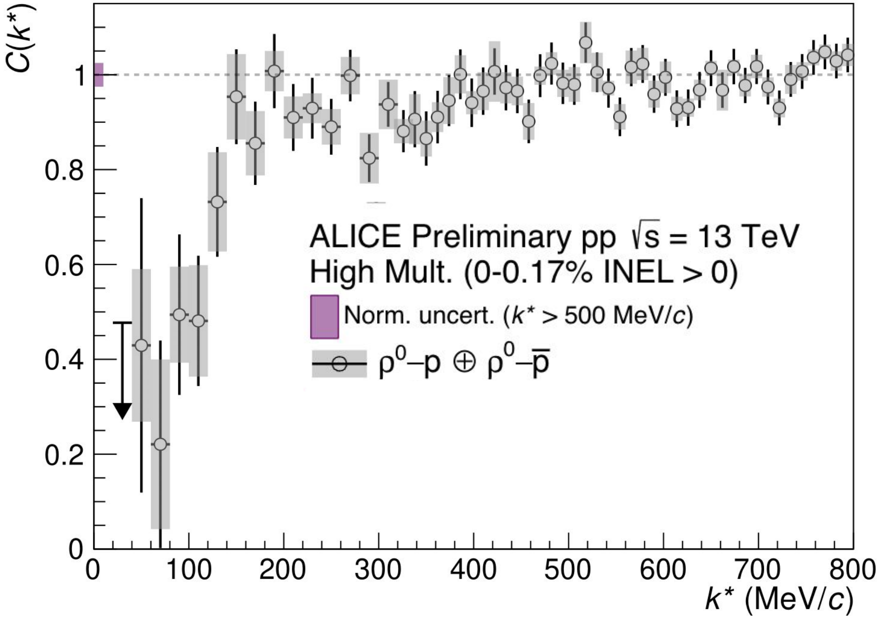
ρ^0-p correlation after SB subtraction



- Normalization region in 600–800 MeV/*c*
- **λ(= 2.7%)** dominated by ρ^0 purity
- Minijet contribution still present
- Corrections
  - Assumption: Minijet equals SB
  - Divide by SB as proxy for Minijet

$$C_{\rho^0-\mathrm{p}}(k^*) = \frac{1}{C_{\mathrm{minijet}}} \left\{ \boxed{\frac{1}{\lambda_{\rho^0-\mathrm{p}}} \left[C_{\mathrm{measured}}(k^*) - (1-\lambda_{\rho^0-\mathrm{p}}) C_{\mathrm{SB}}(k^*) \right]} \right\}.$$

First direct observation of the ρ^0N coupling



- Systematics obtained by varying selections
- nσ values w.r.t to unity (no interaction) for…
  - < 100 MeV/c: 3.6
  - < 120 MeV/c: 4.3
  - < 200 MeV/c: 4.0
- Coupled channels: ρ^+n, ωp, ϕp, K*Λ, K*Σ
- Other N* and Δ* states (4* in PDG)
  - N*(1700) below ρN threshold (1713 MeV)

$$\boxed{C_{\rho^0-\mathrm{p}}(k^*)} = \frac{1}{C_{\mathrm{minijet}}}\left\{\frac{1}{\lambda_{\rho^0-\mathrm{p}}}\left[C_{\mathrm{measured}}(k^*) - (1-\lambda_{\rho^0-\mathrm{p}})C_{\mathrm{SB}}(k^*)\right]\right\}.$$

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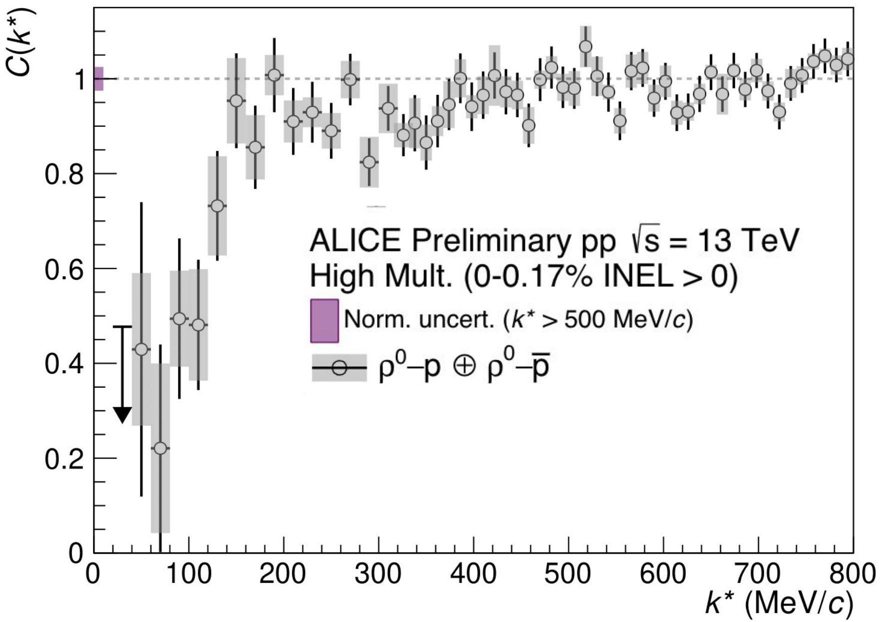


1: *A. Feijoo, MK, L. Fabbietti PRD 111 (2025) 1, 014009*
2: *ALICE PRL 127 (2021)*

- Prediction obtained within UChPT[1] for S=0
  - Coupled channels: ρ^+n, ωp, ϕp, K*Λ, K*Σ
  - Includes dynamical states N*(1700) and N*(2000)
- Additional constraint for ρ^0–p
  - Use ϕ–p CF result[2] for simultaneous fit

Unitarised chiral perturbation theory for ρ^0–p

Interaction kernel V

$$T_{ij} = (1 - V_{il}G_l)^{-1} V_{lj}$$

Scattering Matrix T i to j

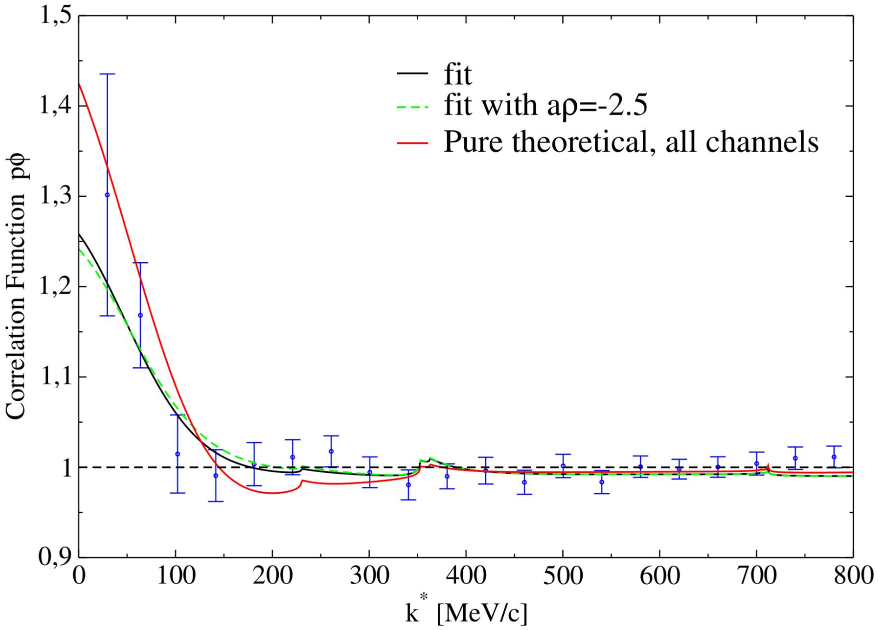
Loop-function G

- *Core Idea*
  - Extract LO interaction form **Chiral *L* + Hidden Gauge Symmetry**
  - Solve **Bethe–Salpeter Equation** in **coupled channels** ansatz[1]
- *Outcome*
  - Resonances as poles in *T*-Matrix
  - Extract scattering parameters from wavefunction

$$\psi_{ji}(k^*, r^*) = \delta_{ij} j_0(k^* r^*) + \int_{q \leq q_{\text{cut}}} d^3q\, j_0(qr^*) G_j(\sqrt{s}, q) T_{ji}(\sqrt{s}, k^*, q)$$

1: A. Feijoo, MK, L. Fabbietti PRD 111 (2025) 1, 014009

Unitarised chiral perturbation theory for ρ^0–p



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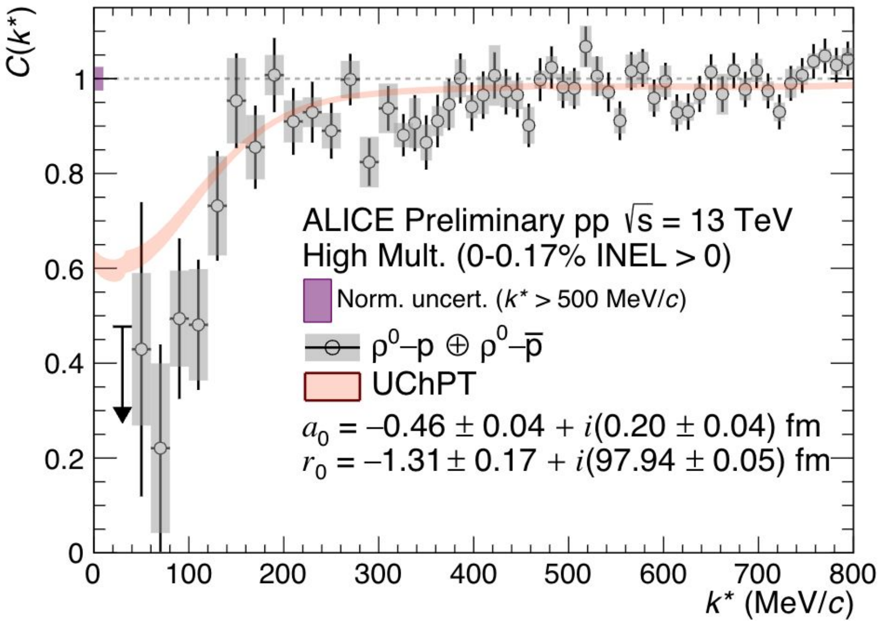
  - Solve **Bethe–Salpeter Equation** in **coupled channels** ansatz[1]
- *Outcome*
  - Resonances as poles in *T*-Matrix
  - Extract scattering parameters from wavefunction
- *Advantages over VMD*
  - *Naturally* accounts for int. dynamics coupled channels + resonances
    - Use ϕ–p CF result[2]
  - Based on gauge principle

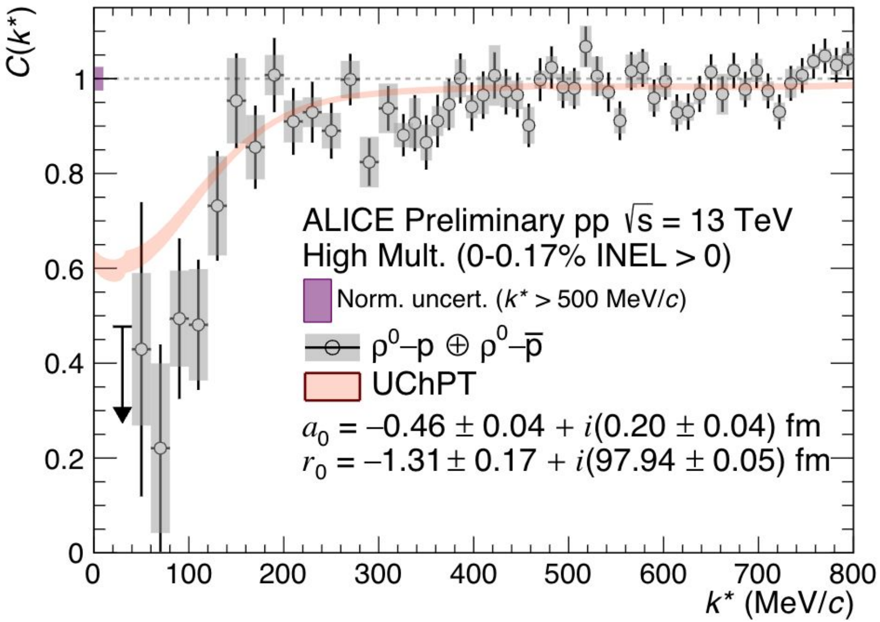
Prediction from UChPT for ρ^0–p



1: A. Feijoo, MK, L. Fabbietti PRD 111 (2025) 1, 014009
2: ALICE PRL 127 (2021)
3: Y Koike and A. Hayashigaki, PTP. 98412 (1997) 631−652

- Prediction obtained within UChPT[1] for S=0
  - Coupled channels: ρ^+n, ωp, ϕp, K*Λ, K*Σ
  - Includes dynamical states N*(1700) and N*(2000)
- Additional constraint for ρ^0–p
  - Use ϕ–p CF result[2] for simultaneous fit
- Results
  - Data provide unique constraint on pole position of N*(1700)
  - Extract scattering parameters consistent with QCD sum rule calc.[3]

Take away



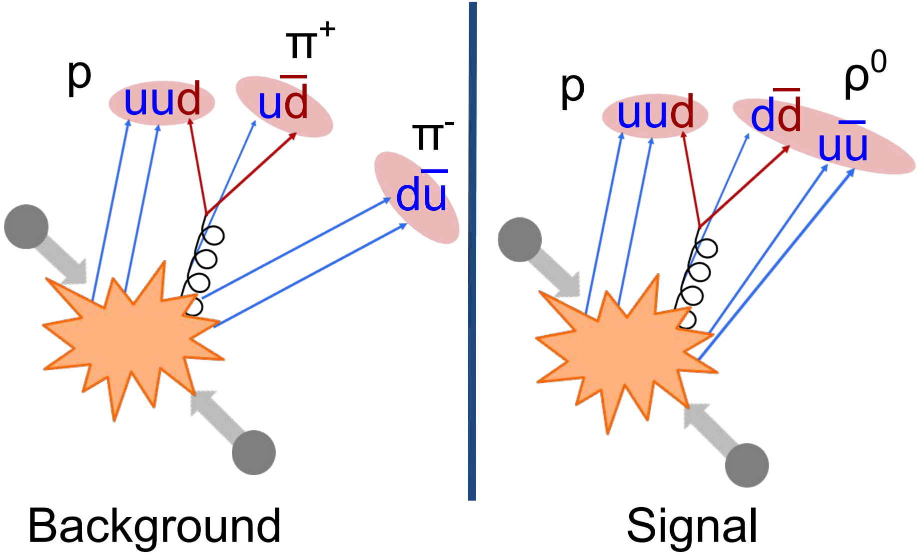
- Access to the interaction of the shortest-lived QCD state
- First direct measurement of the $\rho^0 p$ interaction with full phase information
- Implications
  - Benchmark VMD implementations
  - Basis for Chiral symmetry restoration studies
  - Collider based insight into QCD spectrum
- Paper in preparation!

Back-up

Extraction of the genuine ρ^0–p correlation

$$C_{\text{measured}}(k^*) = \boxed{C_{\text{minijet}}(k^*)}\left[\lambda_{\rho^0\text{–p}} \cdot C_{\rho^0\text{–p}}(k^*)\right] + (1 - \lambda_{\rho^0\text{–p}}) \cdot \left(\omega_{\text{left}} C_{\text{SB}}^{\text{left}}(k^*) + (1 - \omega_{\text{left}}) C_{\text{SB}}^{\text{right}}(k^*)\right).$$

- Mini-jets
  - Partons share a common production (i.e. via gluon splitting)
  - Introduces momentum correlations
  - Contained in signal and SB regions
  - Use sideband correlation functions



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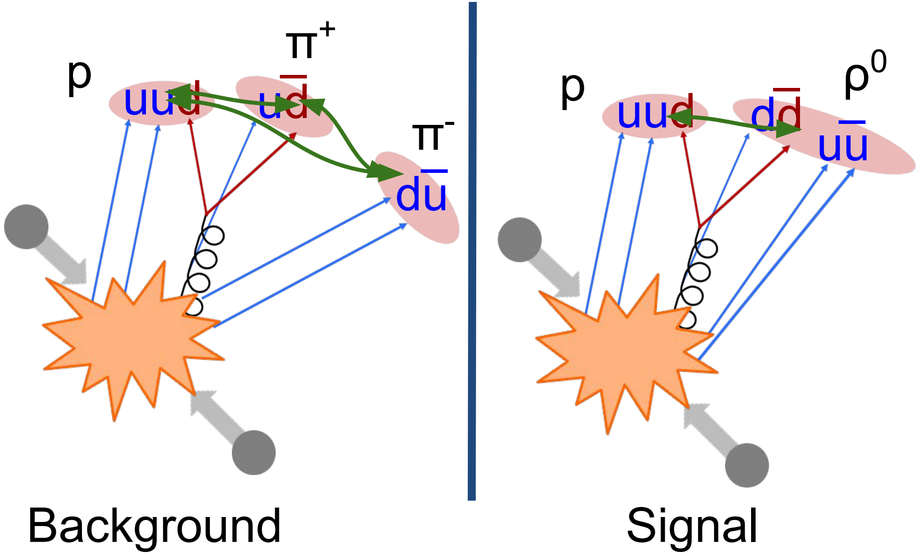

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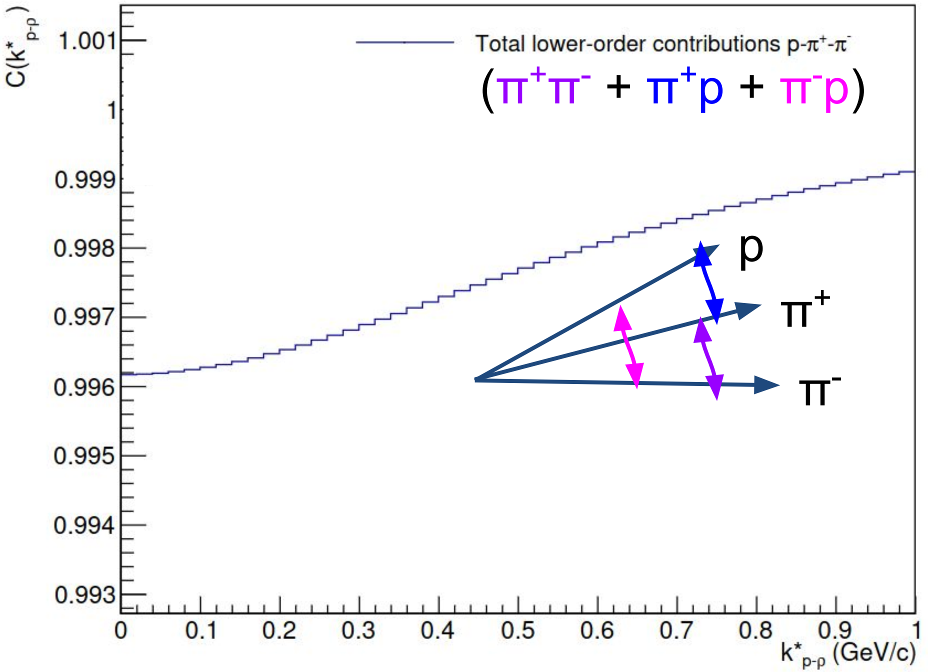
  - Use sideband correlation functions

- Residual 2-Body correlations
  - Analytical projection in ρ^0–p system
  - Projected[1] 2-Body correlations flat in ρ^0–p kinematic system

➔ SB dominated by mini-jets

1: R. Del Grande et. al. EPJC 82 (2022)



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- Weight each contribution with corresponding λ
  - Depends on the single-particle properties (purity and fractions)
  - Dominated by ρ^0 purity amounts to 5%

- Due to small purity extract the genuine ρ^0–p correlation from data

Extraction of the genuine ρ^0–p correlation

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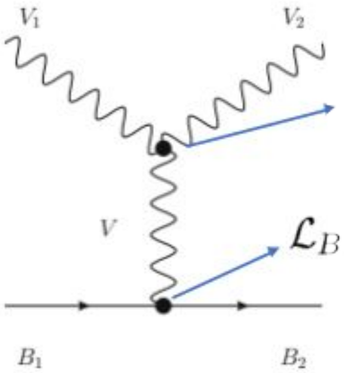
UChPT - Plots

Theory - Plots

Unitarised chiral perturbation theory (UChPT) 1/2

Formalism: Interaction

Hidden gauge formalism



$$\mathcal{L}_{VVV} = ig\,\langle (V^{\nu}\partial_{\mu}V_{\nu} - \partial_{\mu}V^{\nu}V_{\nu})V^{\mu}\rangle$$

$$\mathcal{L}_{BBV} = g\left(\langle \bar{B}\gamma_{\mu}[V^{\mu}, B]\rangle + \langle \bar{B}\gamma_{\mu}B\rangle\langle V^{\mu}\rangle\right)$$

$$V_{\mu} = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_{\mu}$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

Relativistic Interaction kernel projected onto s-wave

$$V_{ij} = -\frac{1}{4f^2}C_{ij}\sqrt{\frac{M_i+E_i}{2M_i}}\sqrt{\frac{M_j+E_j}{2M_j}}\left(2\sqrt{s}-M_i-M_j\right)$$

S=0, Q=+1 sector: 7 channels

C_{ij}	$\rho^0 p$	$\rho^+ n$	ωp	ϕp	$K^{*+}\Lambda$	$K^{*0}\Sigma^+$	$K^{*+}\Sigma^0$
$\rho^0 p$	0	$\sqrt{2}$	0	0	$-\sqrt{3}/2$	$1/\sqrt{2}$	$-1/2$
$\rho^+ n$		1	0	0	$-\sqrt{3}/\sqrt{2}$	0	$1/\sqrt{2}$
ωp			0	0	$-\sqrt{3}/2$	$-1/\sqrt{2}$	$-1/2$
ϕp				0	$\sqrt{3}/\sqrt{2}$	1	$1/\sqrt{2}$
$K^{*+}\Lambda$					0	0	0
$K^{*0}\Sigma^+$						1	$\sqrt{2}$
$K^{*+}\Sigma^0$							0

Unitarised chiral perturbation theory (UChPT) 1/2

Formalism: T-matrix

The Bethe-Salpether equation is solved to calculate the scattering matrix

$$T_{ij} = (1 - V_{il} G_l)^{-1} V_{lj}$$

The vector meson – baryon loop after dimensional regularization:

$$G_l = \frac{2M_l}{(4\pi)^2} \left\{ a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln \frac{m_l^2}{M_l^2} + \frac{q_{\rm cm}}{\sqrt{s}} \ln \left[\frac{(s+2\sqrt{s}q_{\rm cm})^2 - (M_l^2 - m_l^2)^2}{(s-2\sqrt{s}q_{\rm cm})^2 - (M_l^2 - m_l^2)^2} \right] \right\}$$

subtraction constants for the dimensional regularization scale in all the "l" channels.

isospin symmetry

$$a_{\rho^0 p} = a_{\rho^+ n} = a_{\rho N}$$

$$a_{\omega p} = a_{\omega N}$$

$$a_{\phi p} = a_{\phi N}$$

$$a_{K^{*+}\Lambda} = a_{K^*\Lambda}$$

$$a_{K^{*+}\Sigma^0} = a_{K^{*0}\Sigma^+} = a_{K^*\Sigma}$$

In principle, all vector mesons are assumed to be stable particles but…

Unitarised chiral perturbation theory (UChPT) 2/2

Formalism: T-matrix

The Bethe-Salpether equation is solved to calculate the scattering matrix

$$T_{ij} = (1 - V_{il} G_l)^{-1} V_{lj}$$

The vec[...]rization:

$$\psi_{ji}(k^*, r^*) = \delta_{ij} j_0(k^* r^*) + \int_{q \le q_{\mathrm{cut}}} d^3 q \, j_0(q r^*) G_j(\sqrt{s}, q) T_{ji}(\sqrt{s}, k^*, q)$$

$$G_l = \frac{2M_l}{(4\pi)^2} \Big\{ a_l \ldots \mu^2 \ldots 2s \ldots M_l^2 \ldots \sqrt{s} \ldots \frac{\ldots \sqrt{s} q_{\mathrm{cm}})^2 - (M_l^2 - m_l^2)^2}{\left[(s - 2\sqrt{s} q_{\mathrm{cm}})^2 - (M_l^2 - m_l^2)^2 \right]} \Big\}$$

subtraction constants for the dimensional regularization scale in all the "l" channels.

isospin symmetry

$$a_{\rho^0 p} = a_{\rho^+ n} = a_{\rho N}$$

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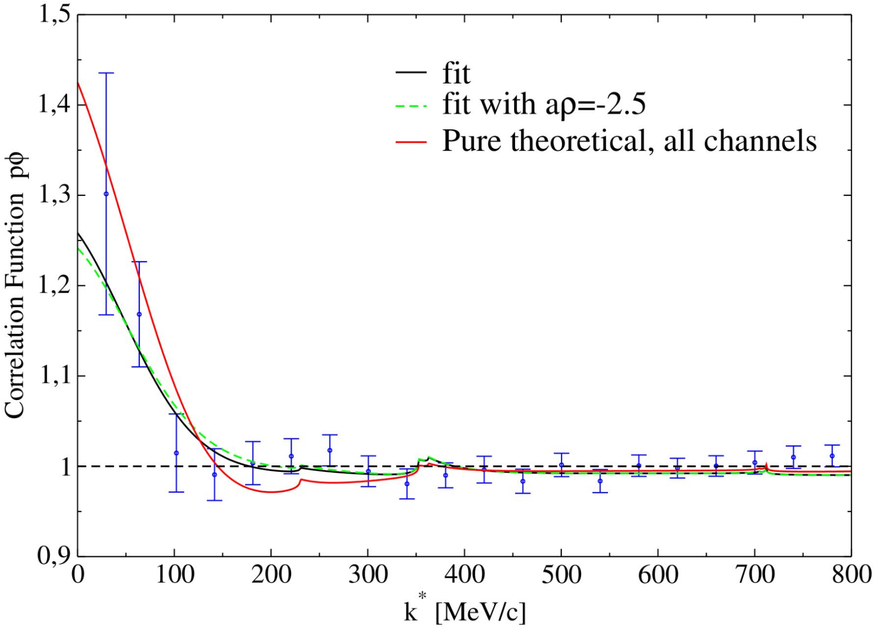
In principle, all vector mesons are assumed to be stable particles but…

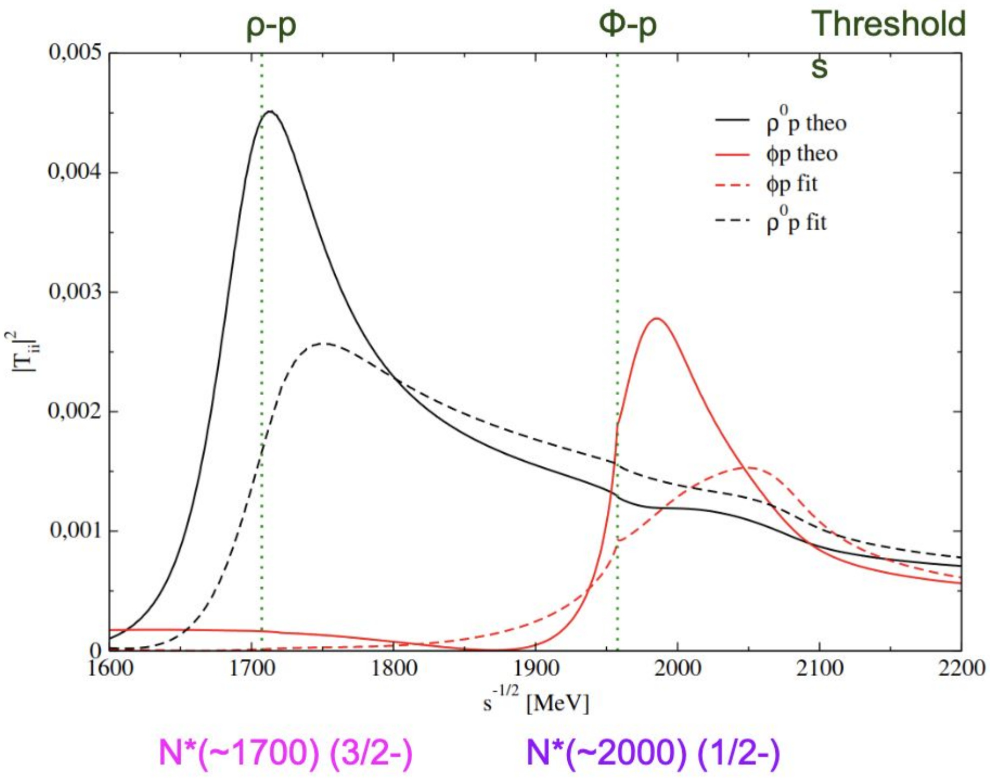
Comparison with model (courtesy of A. Feijoo)



- Use ϕ-p result to fit parameters of UChPT
  - employs coupled channel approach
  - Weights obtained using
    - Thermal model
    - kinematic toy model (Kp)

- Obtain estimate for aρ

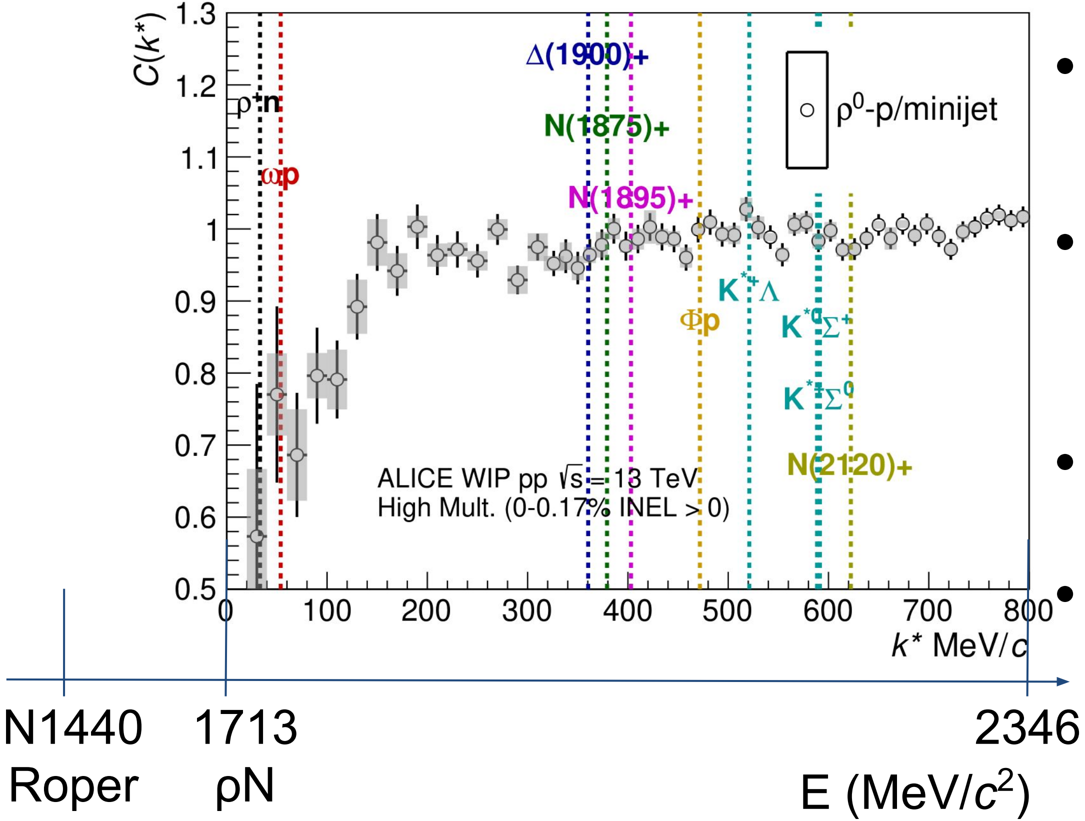
Comparison with model (courtesy of A. Feijoo)



- Use ϕ-p result to fit parameters of UChPT
- Modification of dynamically generated states
  - PDG links:
    - N*(~1700) (3/2-) (3*)
    - N*(~2000) (1/2-) (4*) (not clear if this is the correct state 1895, formerly 2090)

Threshold - Plots

First direct observation of the ρ^0N coupling



- **First direct measurement** of ρ^0N coupling
  - Far above low lying resonance states traditionally used
- nσ values for
  - < 100 MeV/*c*: 3.4σ
  - < 120 MeV/*c*: 4.2σ
  - < 200 MeV/*c*: 3.9σ
- Coupled channels:
  ρ+n, ωp, ϕp, K*Λ, K*Σ
- Other N* and Δ* states (4* in PDG)
  - N*(1700) below threshold (1713 MeV)

Resonances < 1700 MeV

Resonance	B.R. (%)	k* (MeV)
N(1440)+	0.0133	-
N(1520)+	0.0667	-
N(1535)+	0.0067	-
N(1650)+	0.0267	-
N(1675)+	0.0067	-
N(1680)+	0.03	-

Resonances > 1700 MeV

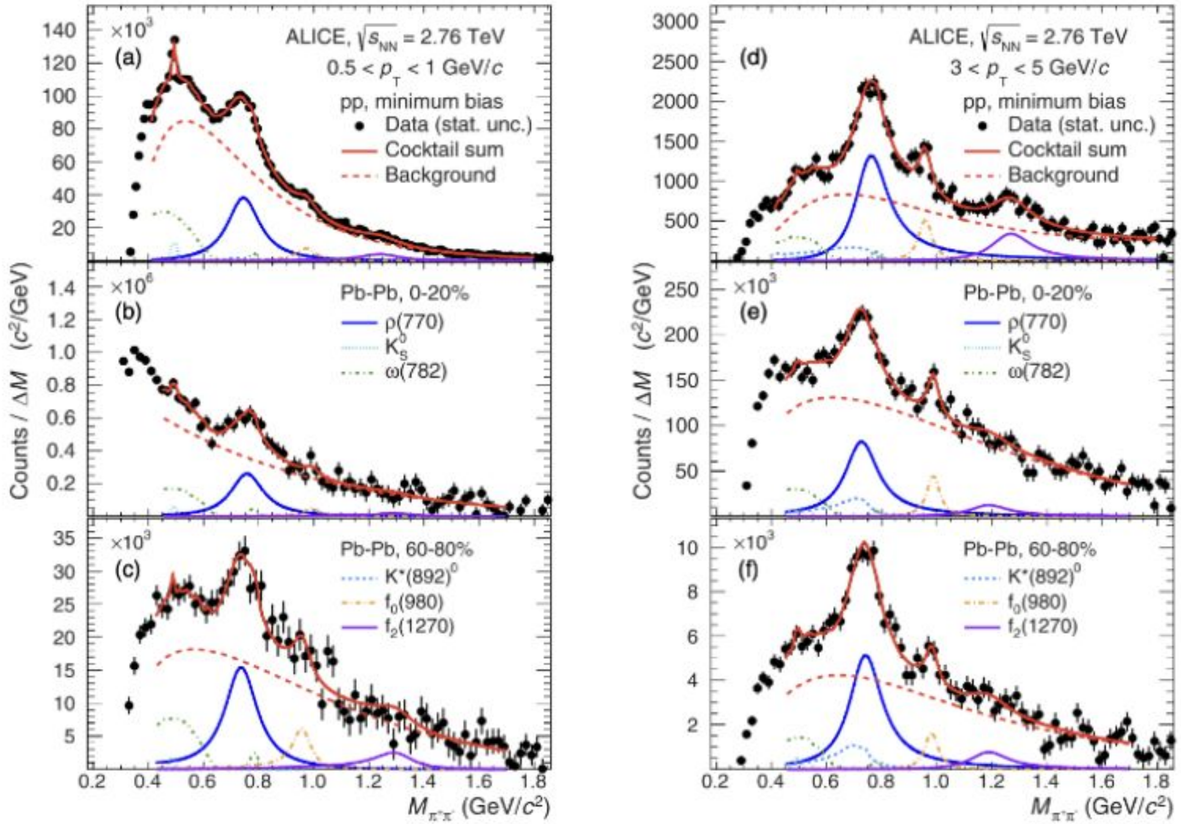
rho-p
1713

Resonance	B.R. (%)	k* (MeV)
Delta(1700)+	0.2	-
N(1710)+	0.05	-
N(1720)+	0.255	77.16
N(1875)+	0.02	379.76
Delta(1930)+	0.22	442.97
N(2190)+	0.0333	680.33
N(2250)+	0.0533	727.49
N(2600)+	0.0533	976.04

Old measurement - Plots

Motivation

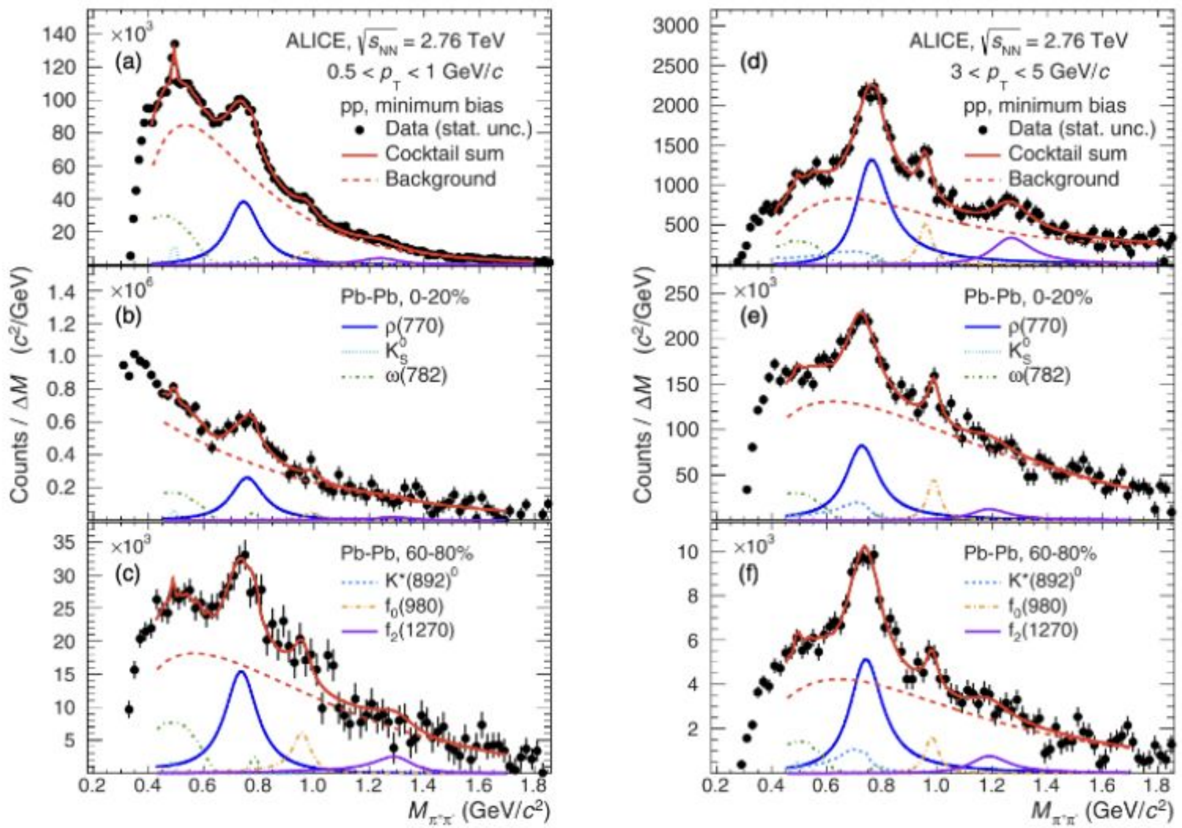
PHYSICAL REVIEW C **99**, 064901 (2019)



- ALICE measurements of ρ^0
  - Γ = 150 MeV
  - m = 775 MeV

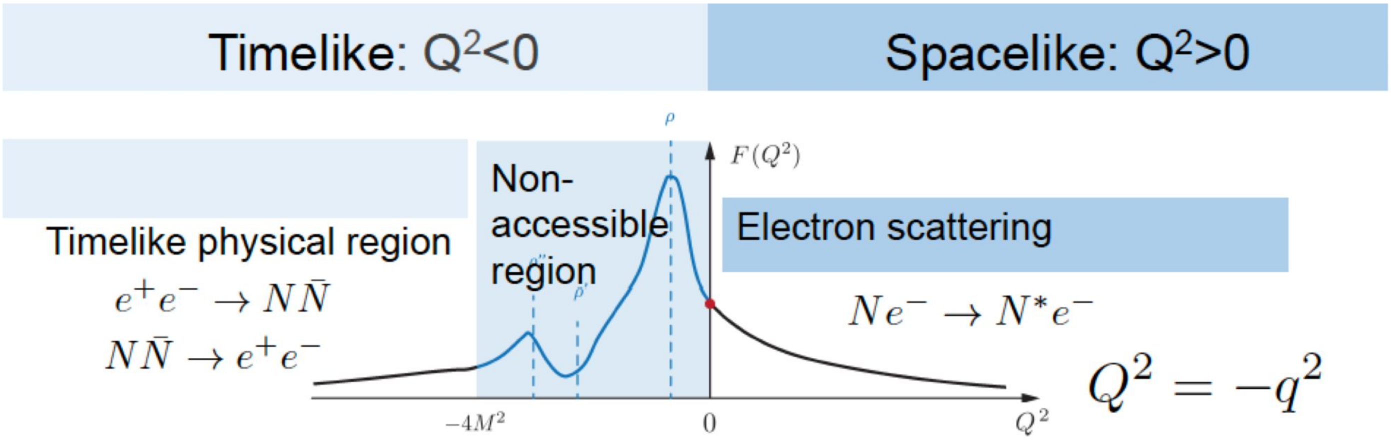
Motivation

PHYSICAL REVIEW C **99**, 064901 (2019)



- ALICE measurements of ρ^0
  - Γ = 150 MeV
  - m = 775 MeV
- Important to constrain Vector Meson Dominance Models/ Vector Meson-Baryon interactions
  - couplings; scattering param.
  - validating theoretical approaches
  - First time direct measurement
- Further the understanding of dynamically generated states N* and Δ* (pole positions) from UChPT
- Good candidate to search for signatures of chiral symmetry restoration

Vector meson nucleon coupling



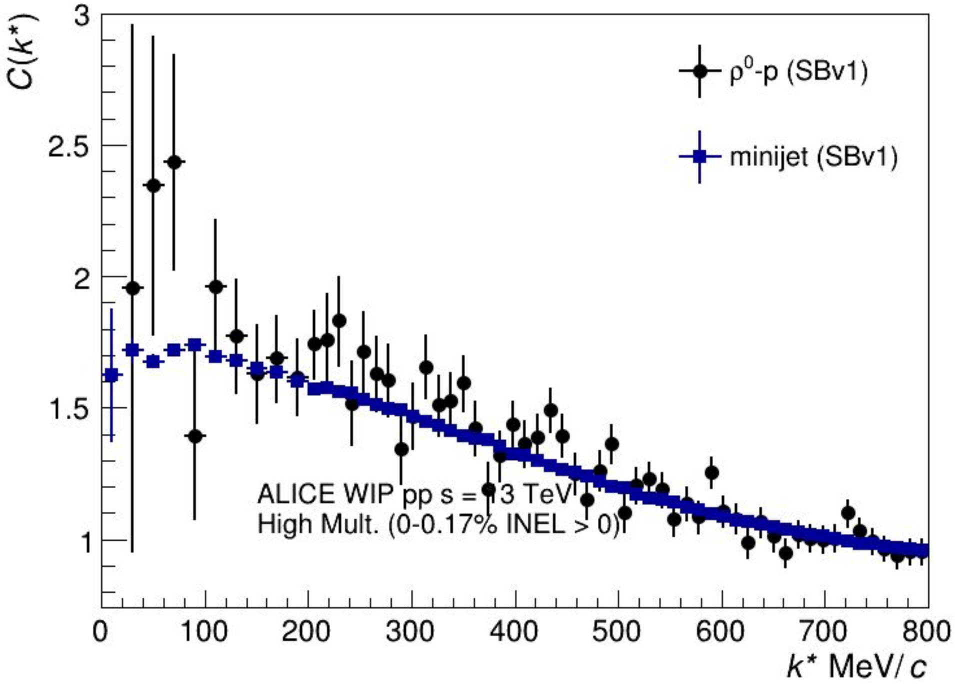
- Important to constrain Vector Meson Dominance Models/Vector Meson-Baryon interactions

- Usually probed by low energy experiments (HADES)
  - Access the time like form factor ($q^2 > 0$!)
  - Test of VDM (Rγ*N vertex) with low lying intermediate resonances N(1440), N(1520), N(1535)

- Important to understand
  - In-medium dilepton production
  - Dynamically generated states N* and Δ* (pole positions) from UChPT

MC - Plots

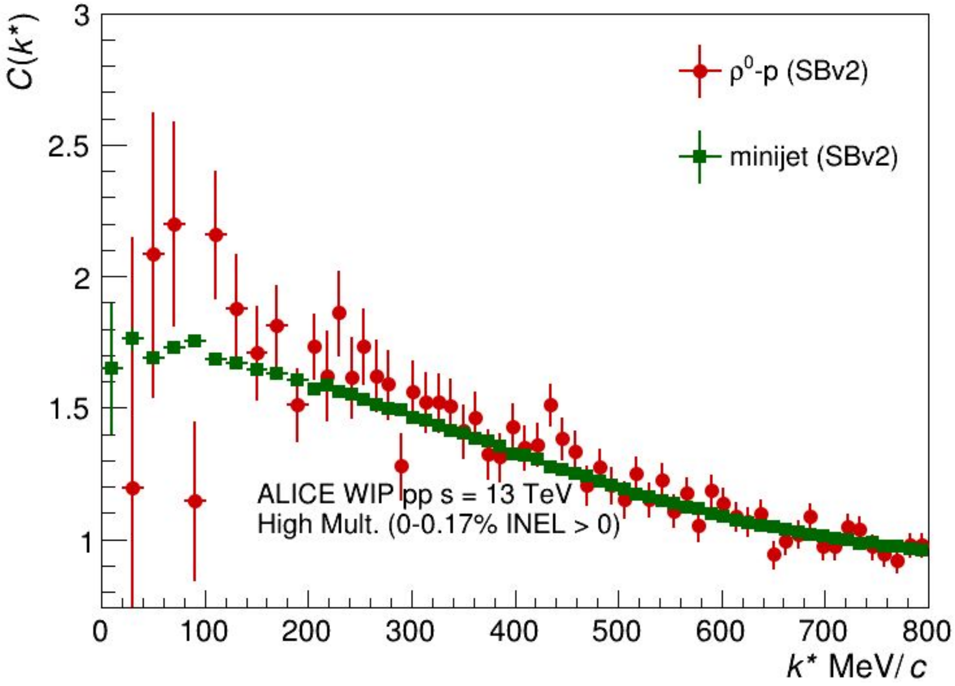
Constraining the minijet MC



- Minijet describe data for all k^*
- Divide ρ^0-p by Minijet

v1 = close
v2 = overlap

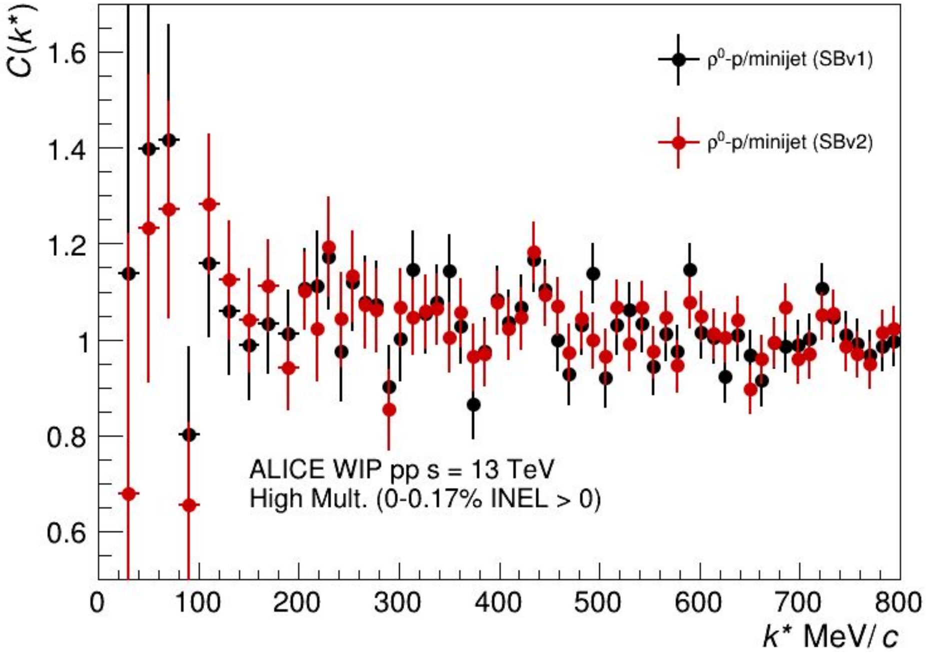
Constraining the minijet MC



- Minijet describe data for all *k**
- Divide ρ^0-p by Minijet

v1 = close
v2 = overlap

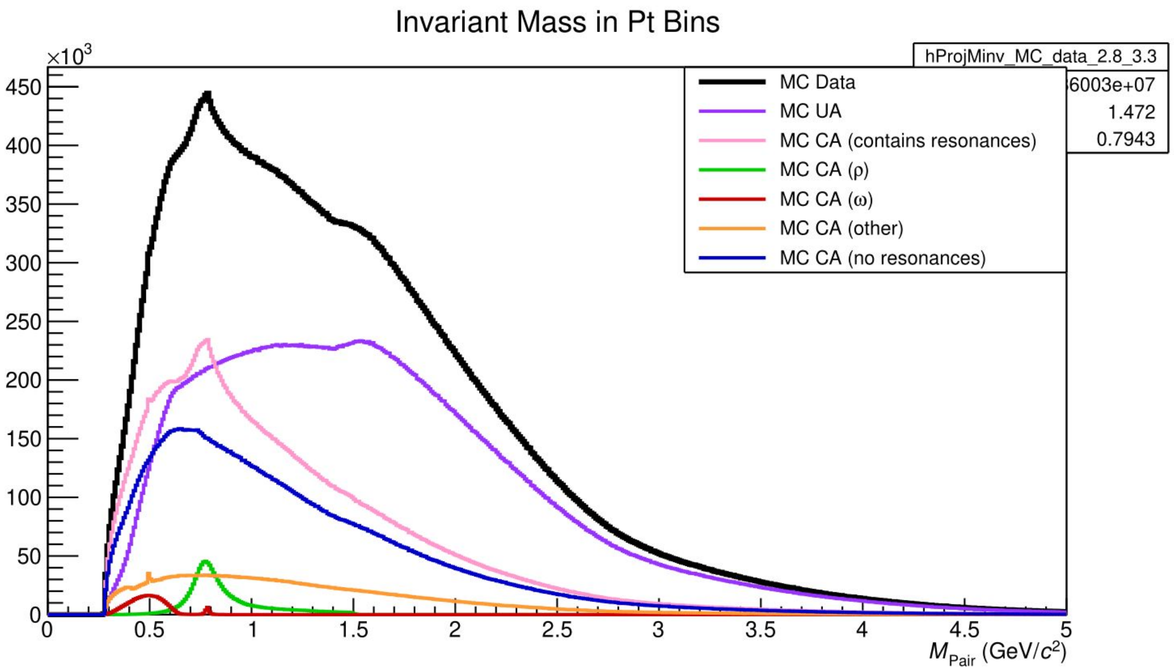
ρ^0-p without SB and divided for Minijet MC



- Consistent with unity
- No structures
- Re-run whole chain now that trains are available again (anchored to META_17)
  - include META_16 and META_18

v1 = close
v2 = overlap

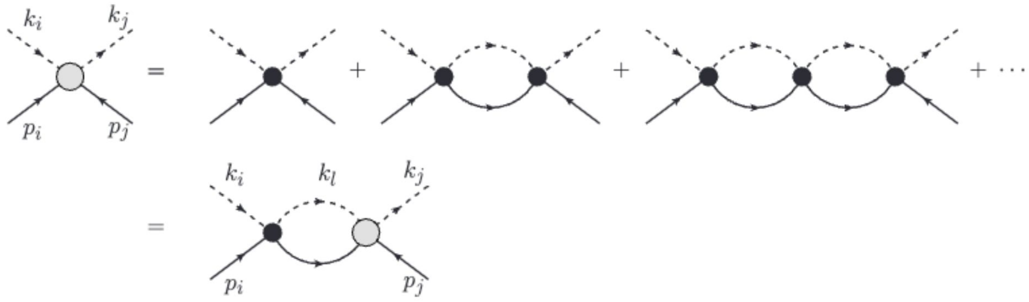
Ancestor Method for ρ (MC only)



- For the fit to data MC UA and MC CA (no reso.) will be used
- In MC no f0 and f2

Unitarised chiral perturbation theory for ρ^0–p

$$T_{ij} = (1 - V_{il}G_l)^{-1} V_{lj}$$



- *Core Idea*
  - Extract LO interaction form **Chiral *L* + Hidden Gauge Symmetry**
  - Solve **Bethe–Salpeter Equation** in **coupled channels** ansatz[1]

C_{ij}	$\rho^0 p$	$\rho^+ n$	ωp	ϕp	$K^{*+}\Lambda$	$K^{*o}\Sigma^+$	$K^{*+}\Sigma^0$
$\rho^0 p$	0	$\sqrt{2}$	0	0	$-\sqrt{3}/2$	$1/\sqrt{2}$	$-1/2$
$\rho^+ n$		1	0	0	$-\sqrt{3}/\sqrt{2}$	0	$1/\sqrt{2}$
ωp			0	0	$-\sqrt{3}/2$	$-1/\sqrt{2}$	$-1/2$
ϕp				0	$\sqrt{3}/\sqrt{2}$	1	$1/\sqrt{2}$
$K^{*+}\Lambda$					0	0	0
$K^{*o}\Sigma^+$						1	$\sqrt{2}$
$K^{*+}\Sigma^0$							0

1: A. Feijoo, MK, L. Fabbietti PRD 111 (2025) 1, 014009