Measurement of strange particle femtoscopic correlations at the CMS experiment

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for the CMS collaboration

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SQM Strasbourg 2024

Introduction: femtoscopy

- **Femtoscopy:** Powerful tool to probe space-time dimensions of the particle emitting source region on the femtometer scale
  - Use final state particle correlations

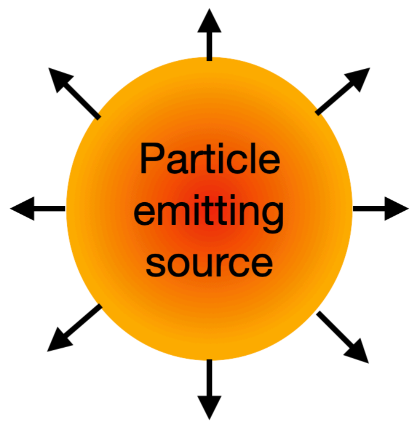
Femtoscopic correlation

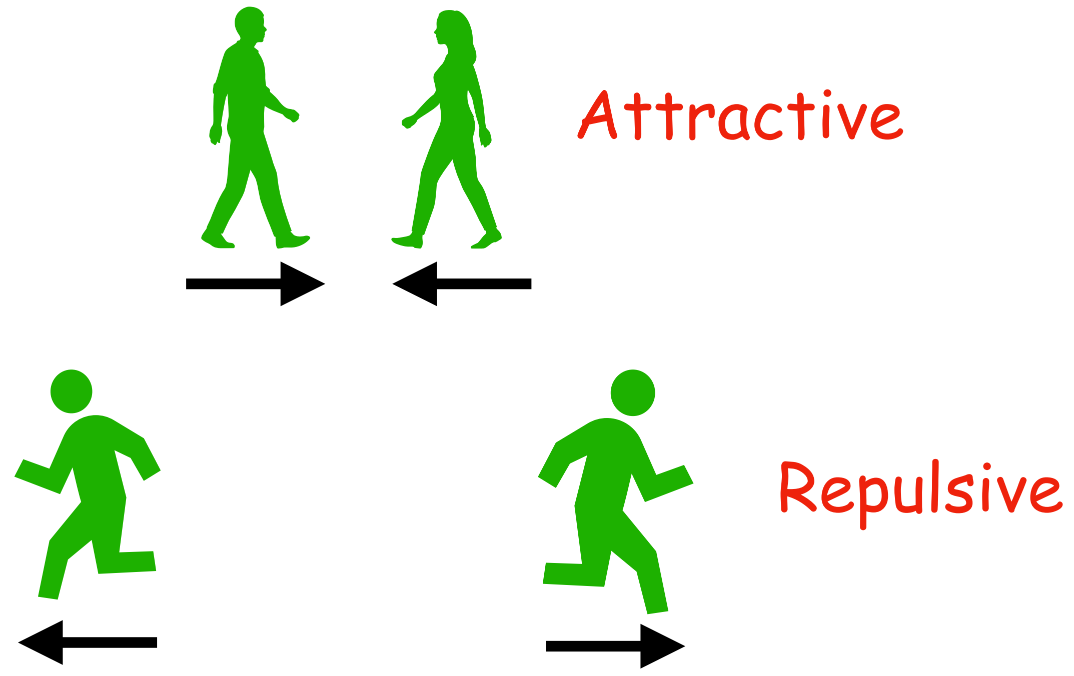
Sensitive to:

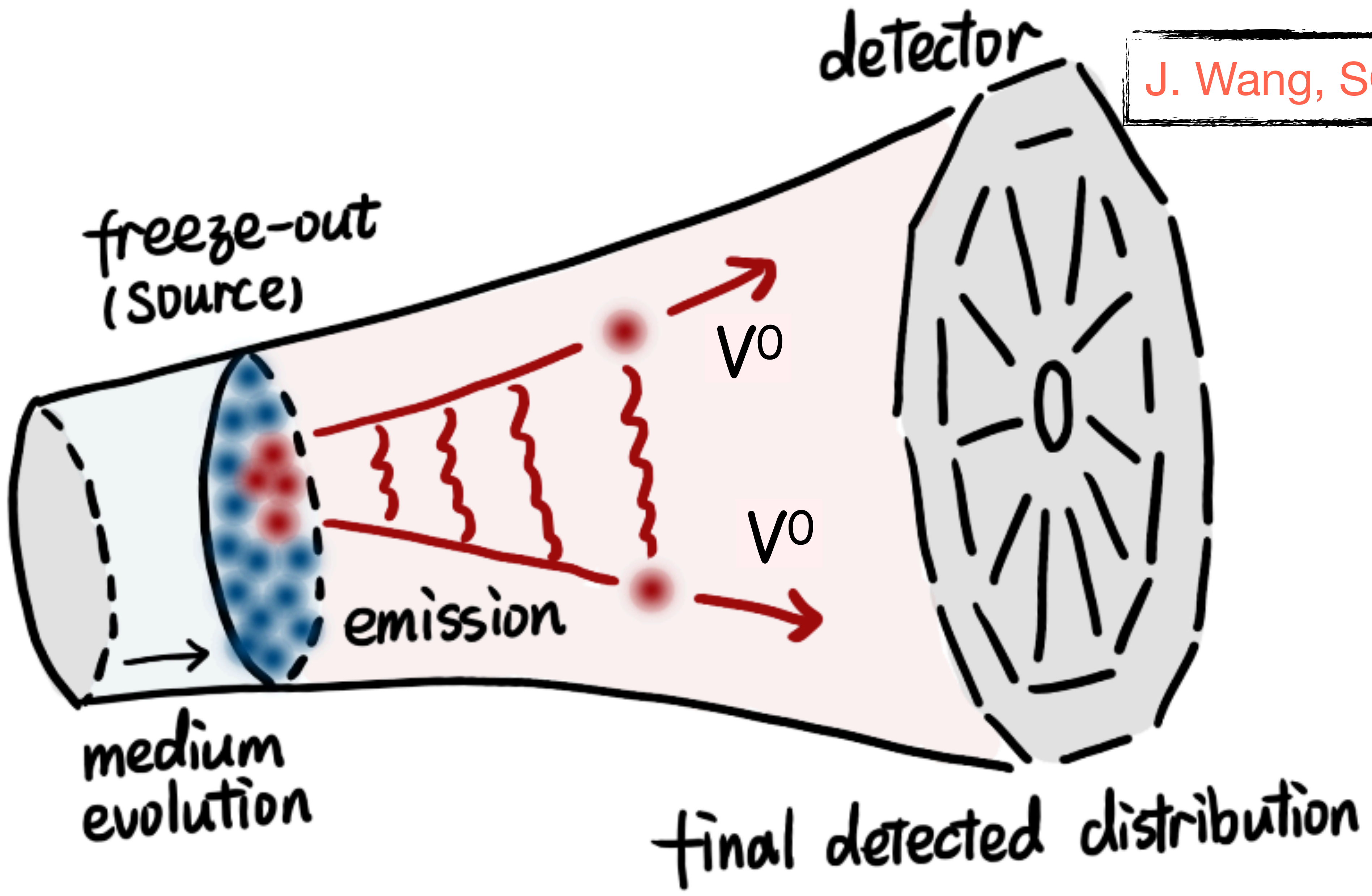
- Quantum statistical effect (QS) : Bose - Einstein or Fermi - Dirac
- Possible final state interaction (FSI) : Strong, Coulomb,..

Help us to measure:

- Size and shape of the particles emitting source at kinetic freeze-out
- Which type of interaction? Attractive or repulsive?



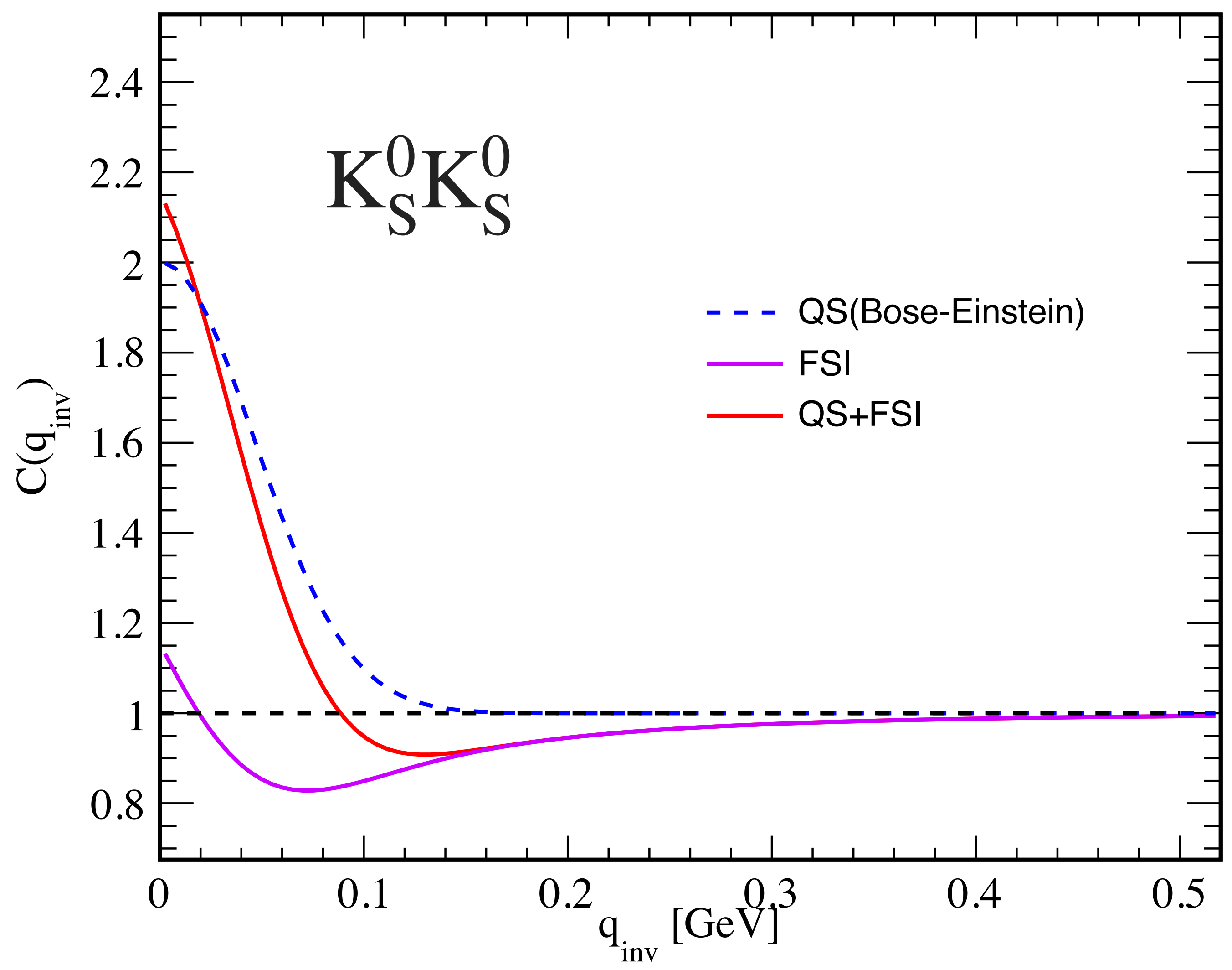




J. Wang, SQM 2022

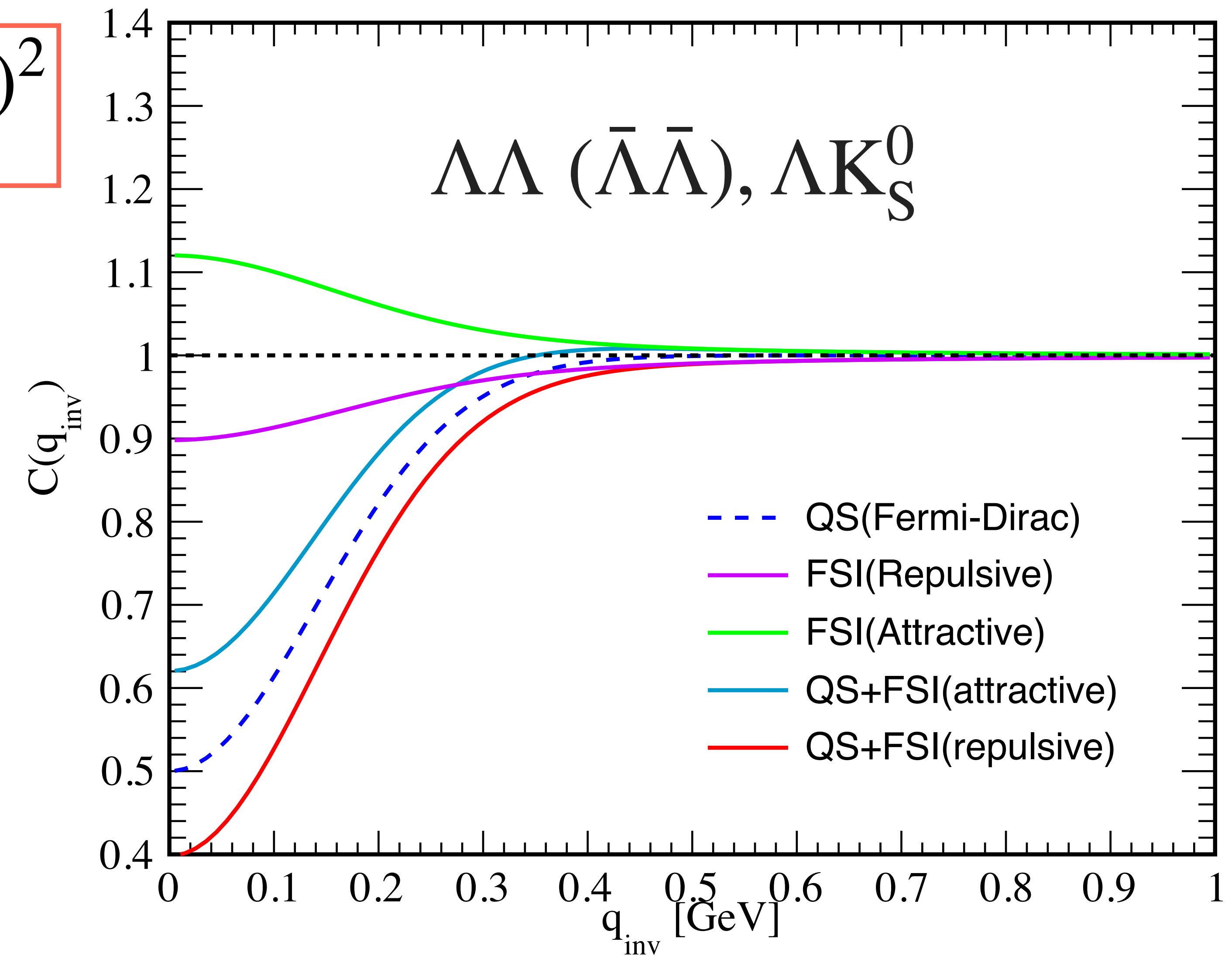
- **Why study V^0 particles ($\Lambda(\bar{\Lambda})$ & K^0_S) femtoscopic correlation?**
  - No coulomb interaction
  - Quantum statistical (QS) effect and strong final state interaction (FSI)
  - Less resonance contribution (less feed down contribution)
  - Size of the particles emitting source
  - Interaction between baryons and mesons
    - Strong interaction scattering parameters
      - ➡ Scattering length and effective range
  - $\Lambda\Lambda(\bar{\Lambda}\bar{\Lambda})$ correlation is relevant for searching bound H-dibaryon

Phys. Rev. Lett. 38, 195

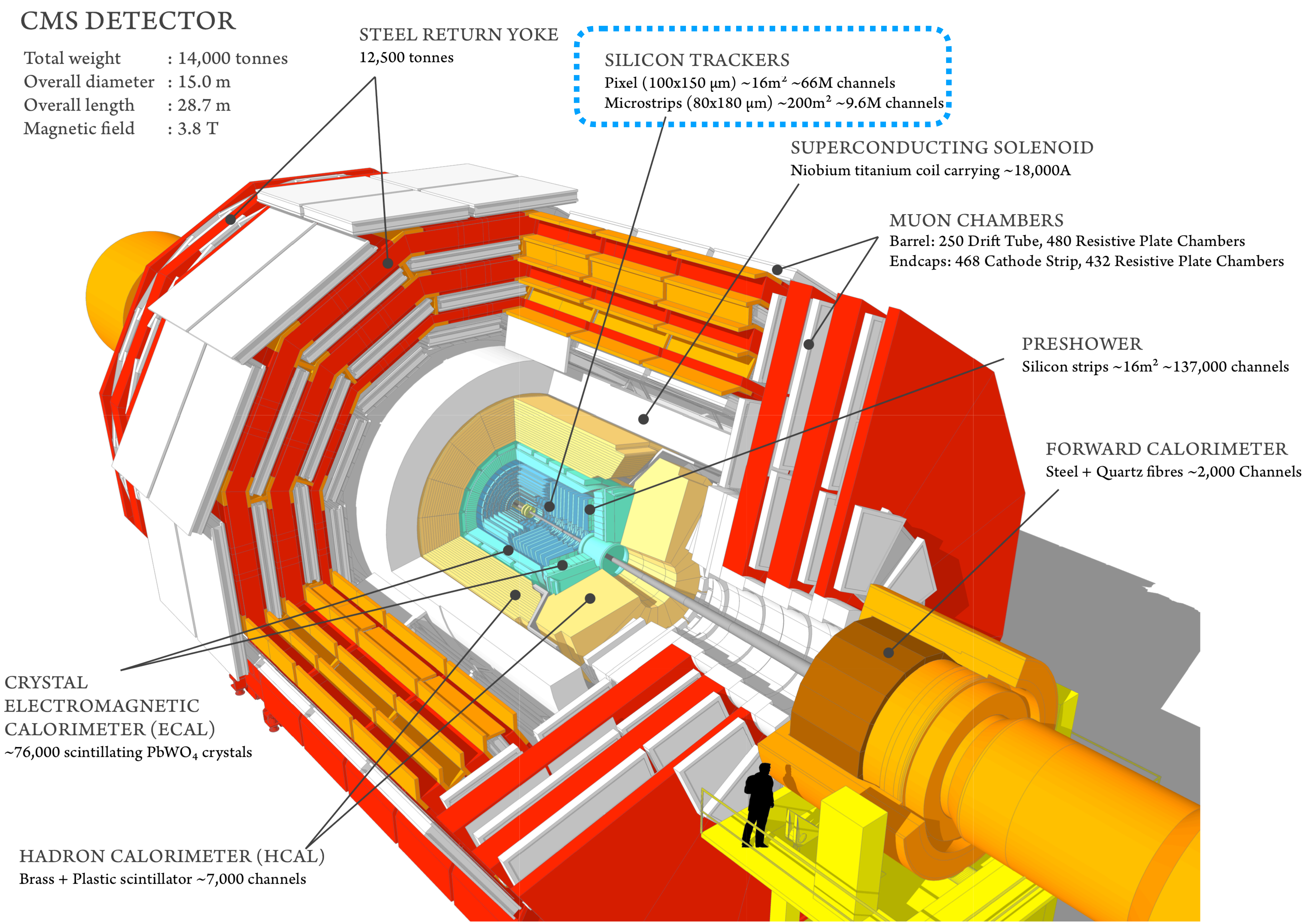


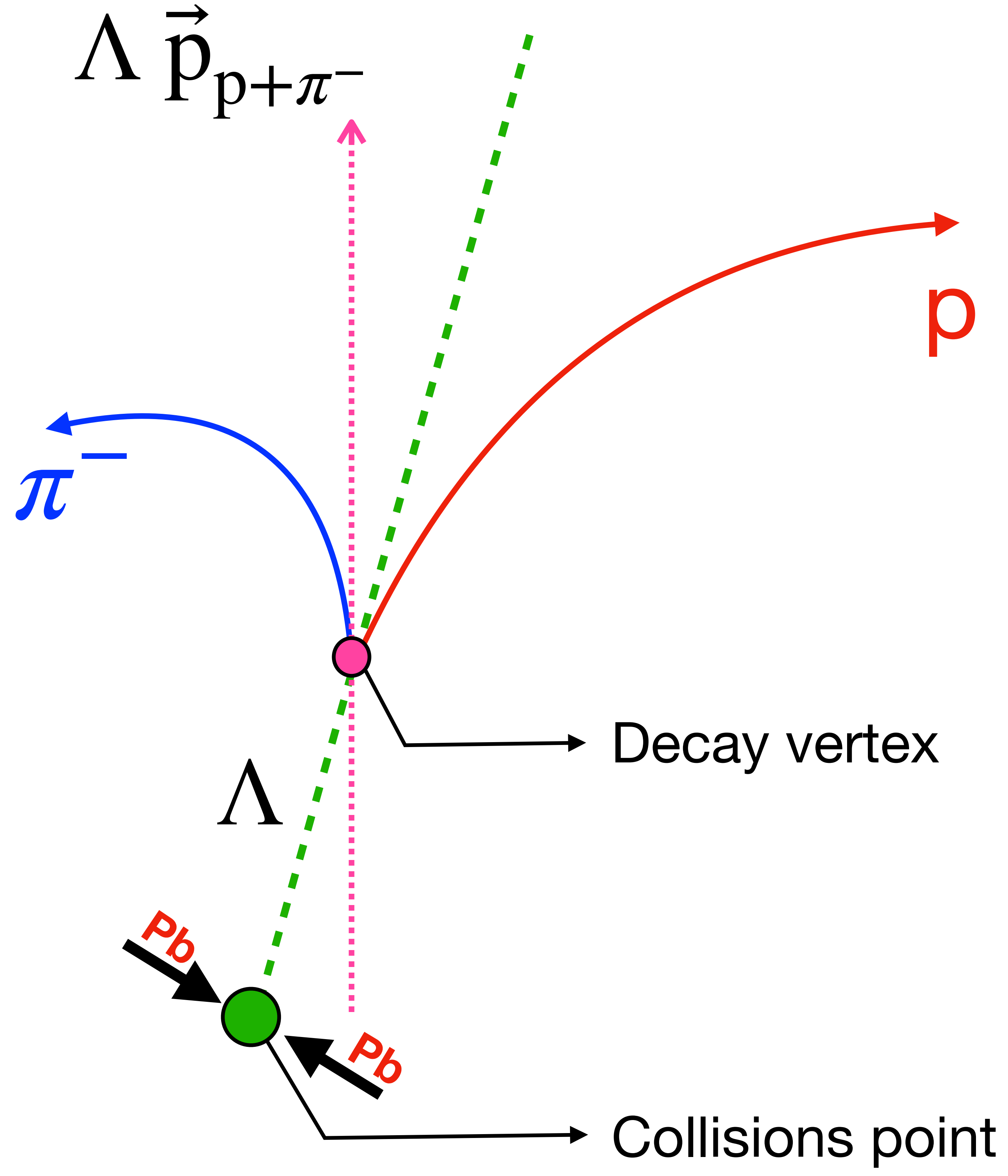
Assumed Gaussian source

$$S(r) \sim e^{-(r/R)^2}$$



CMS detector and V⁰ decay





- $\Lambda \to p + \pi^-$ [(63.9 ± 0.5)%]
- $K^0_S \to \pi^+ + \pi^-$ [(69.20 ± 0.05)%]

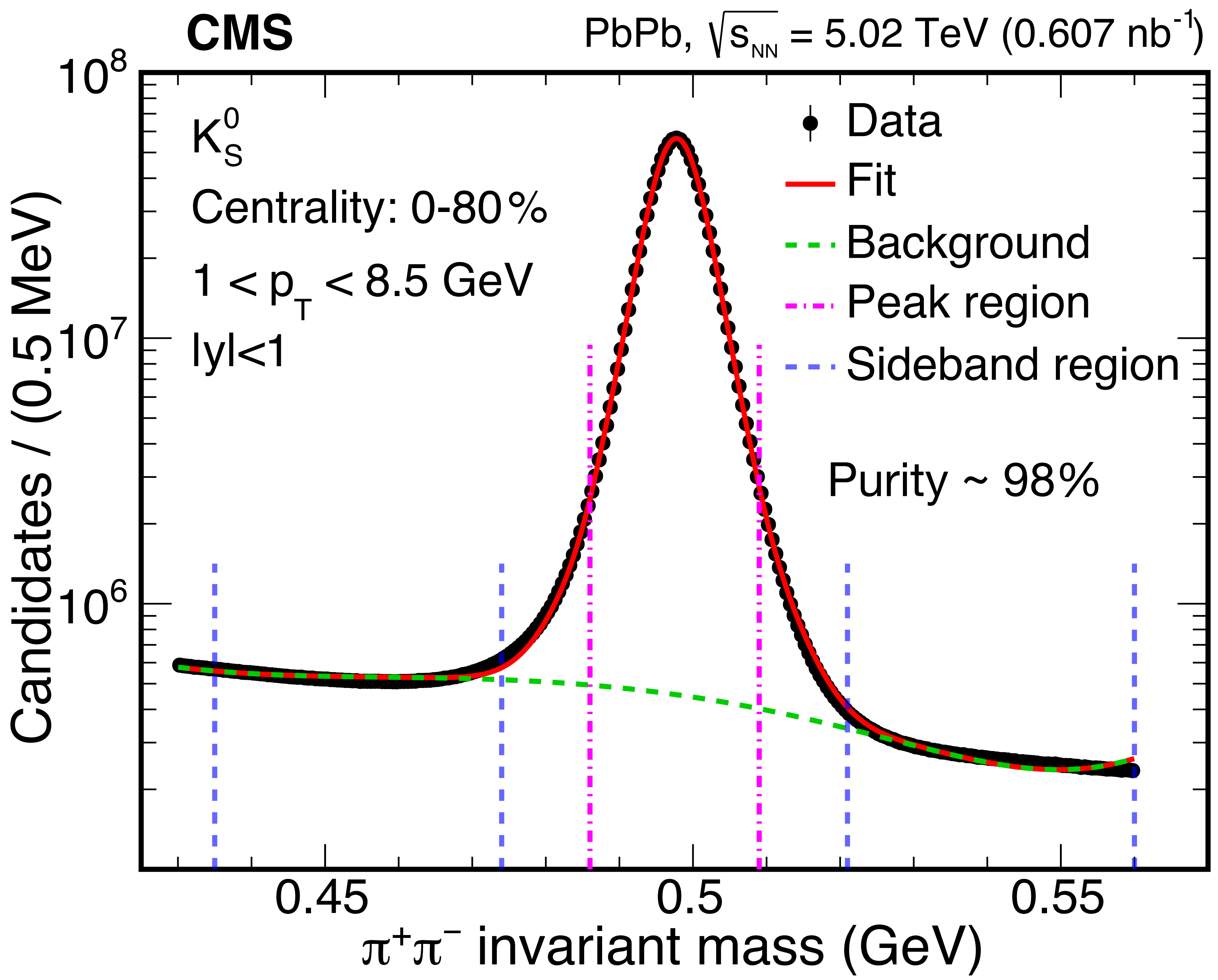
V^0 particles reconstruction

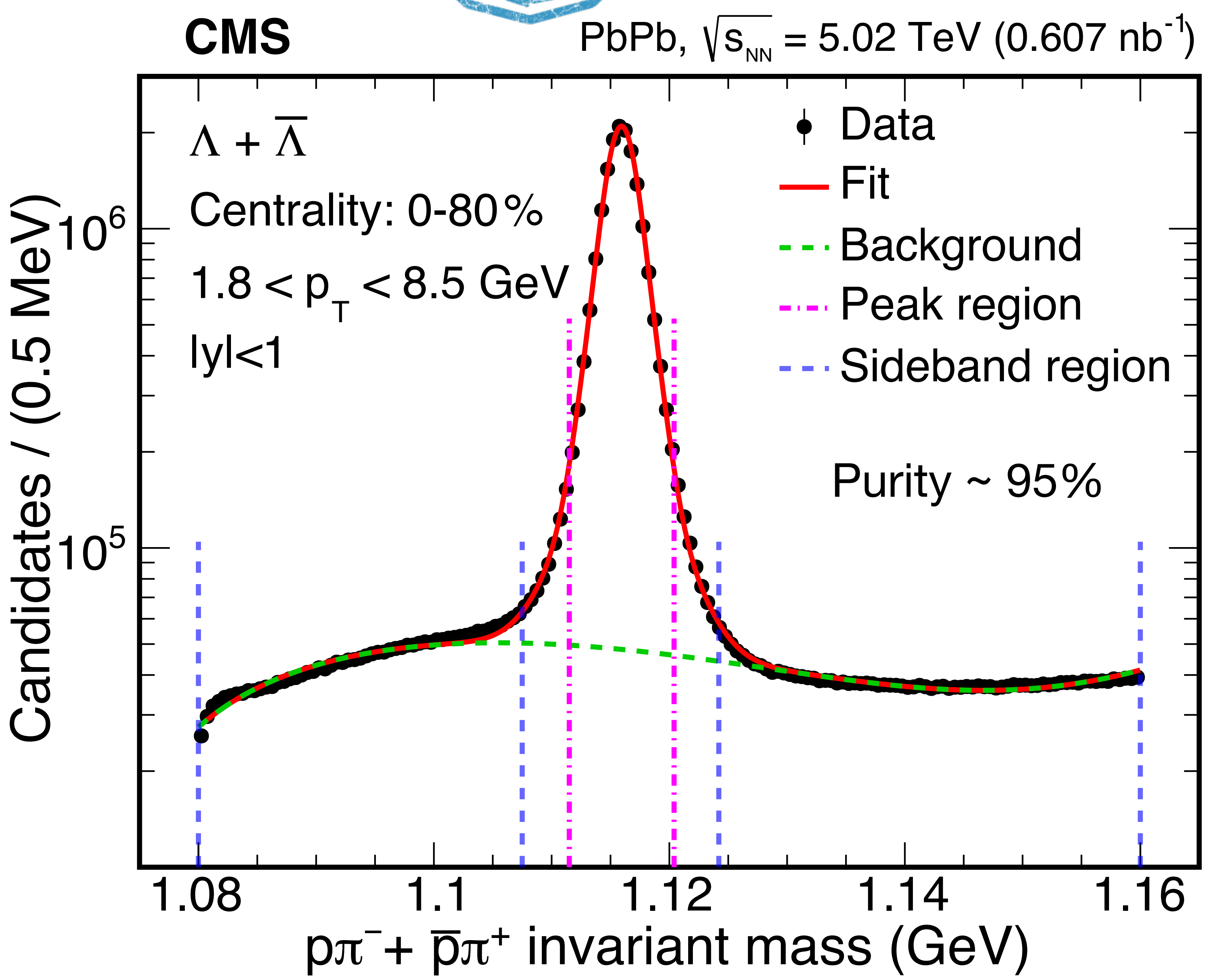
- 2018 PbPb collisions @ 5.02 TeV
  - Minimum Bias
  - ~ 4 B events

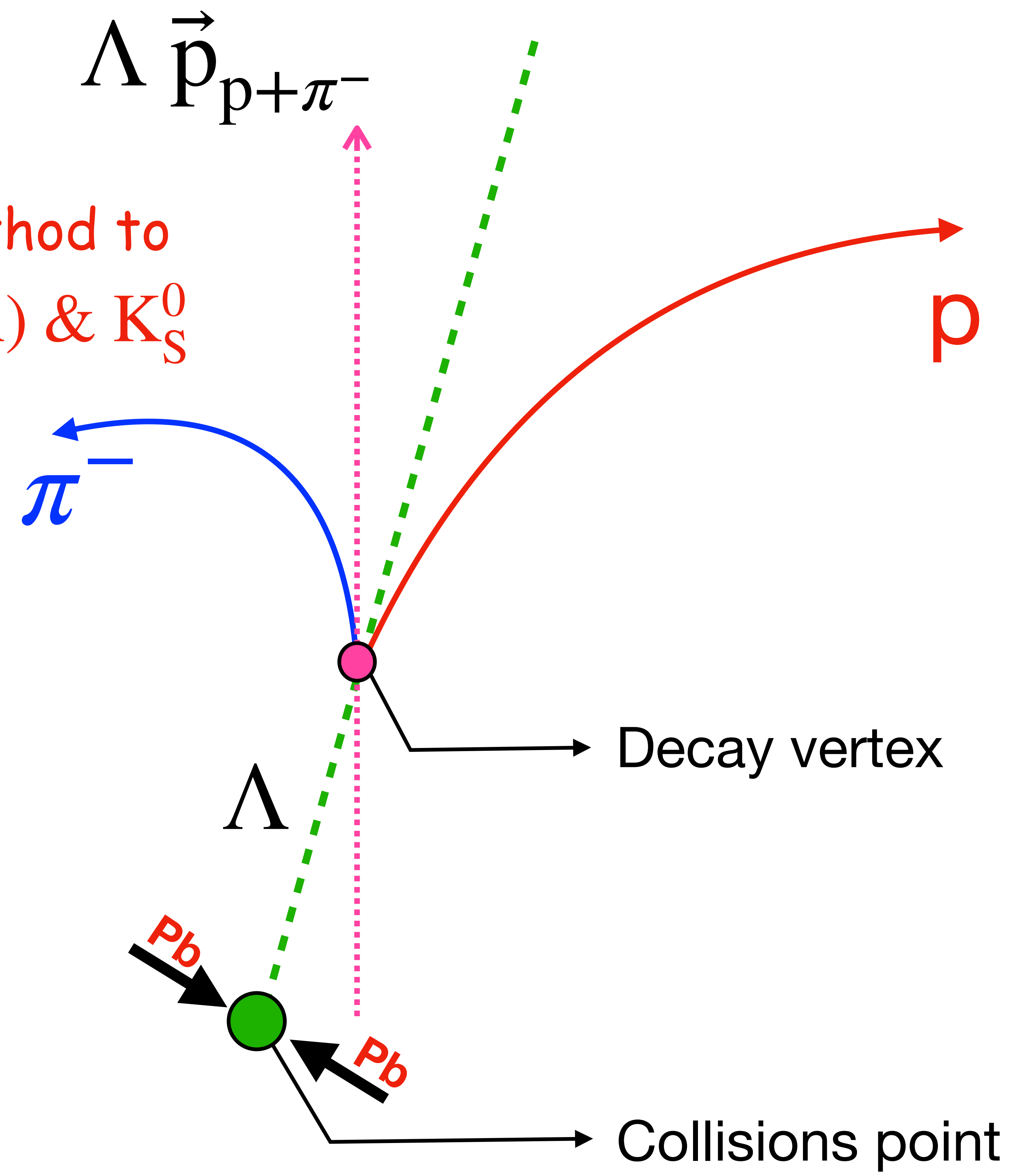
arXiv:2301.05290

CMS FINAL RESULT SQM24

Applied BDT method to reconstruct $\Lambda(\bar{\Lambda})$ & K^0_S



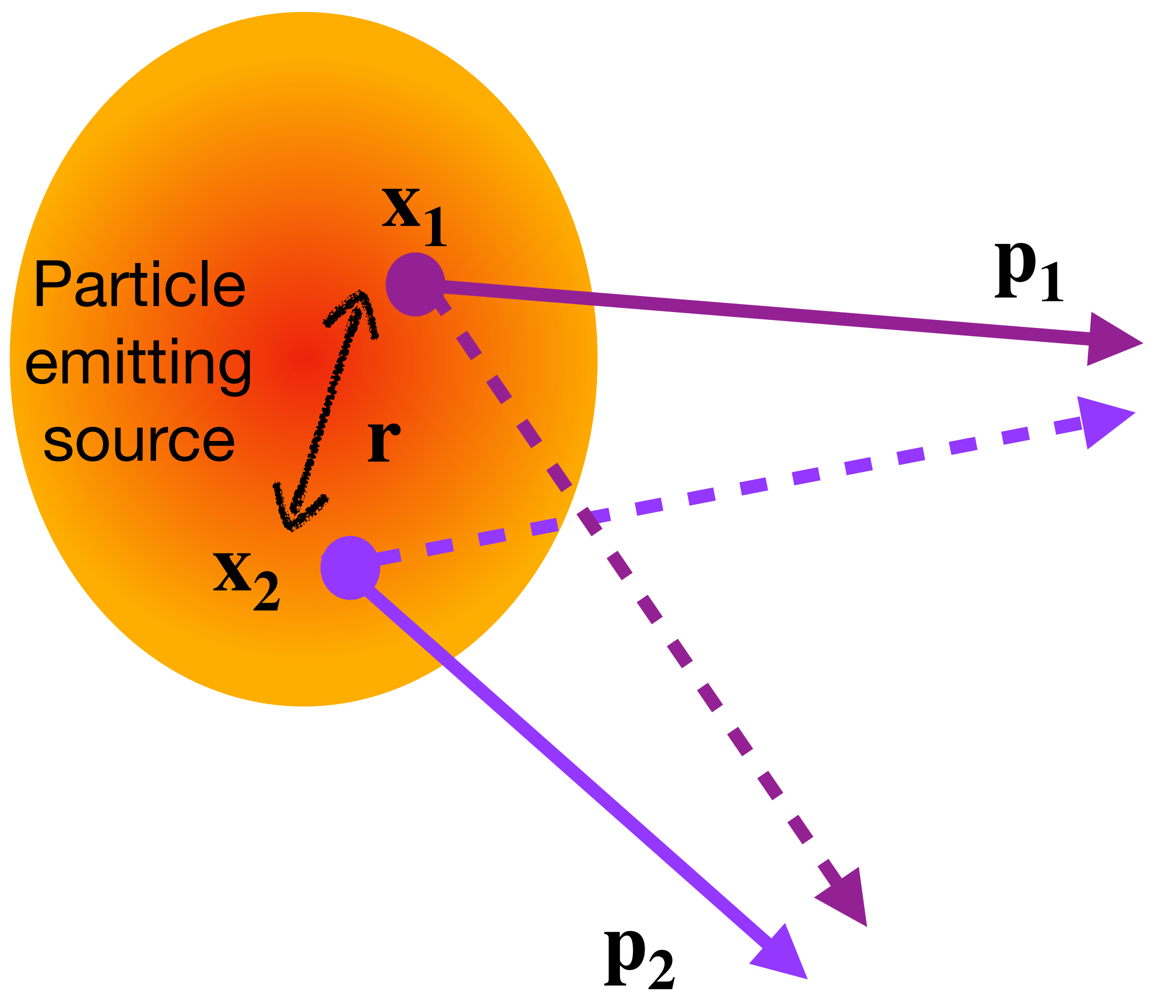




- Signal : triple Gaussian
- Combinatorial background : 4^{th} order polynomial

- $\Lambda \rightarrow p + \pi^-$ [(63.9 ± 0.5)%]
- $K^0_S \rightarrow \pi^+ + \pi^-$ [(69.20 ± 0.05)%]

Correlation function



- **In theory :**

$$C_K(q) = \int S(r)\,|\Psi_{1,2}(q,r)|^2 d^3r = 1 \pm C_{QS}(q) + C_{FSI}(q)$$

$q = p_1 - p_2$

$K = \frac{p_1 + p_2}{2}$

$r = x_1 - x_2$

$C_K(q)$: Theoretical correlation

$S(r)$: source function → Not known

$\Psi_{1,2}(q,r)$: Two-particle wave function → Known

$\pm$: + for identical bosons; − for identical fermions

Generally we assume Gaussian source function

$$S(r) \sim e^{-(r/R)^2}$$

- **In the experiment :**

$$C(q_{inv}) = N\left[\frac{A(q_{inv})}{B(q_{inv})}\right],\quad q_{inv} = |q^\mu|,\ q^\mu = k^\mu - \frac{k\cdot P}{P^2}P^\mu,$$

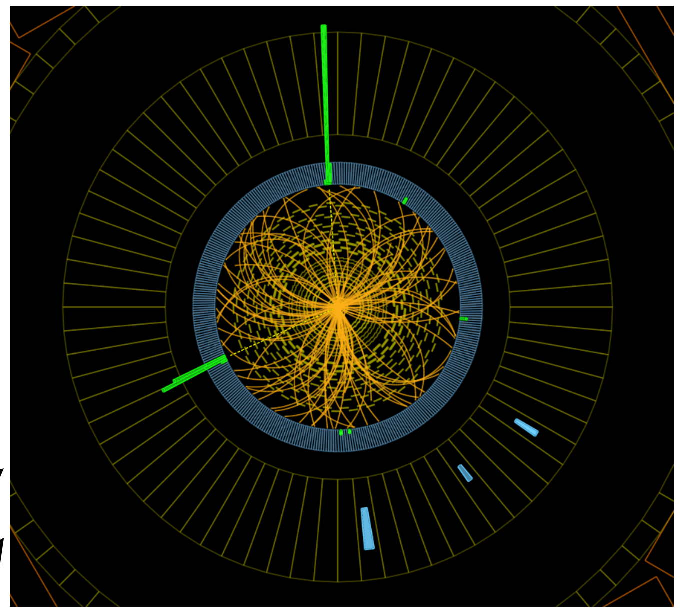
Ann.Rev.Nucl.Part.Sci.55:357-402,2005

$k = p_1 - p_2,\ P = p_1 + p_2$

$A(q_{inv})$: Signal distribution of pair from same event

$B(q_{inv})$: Reference distribution of pair from mixed events

N: Normalization constant



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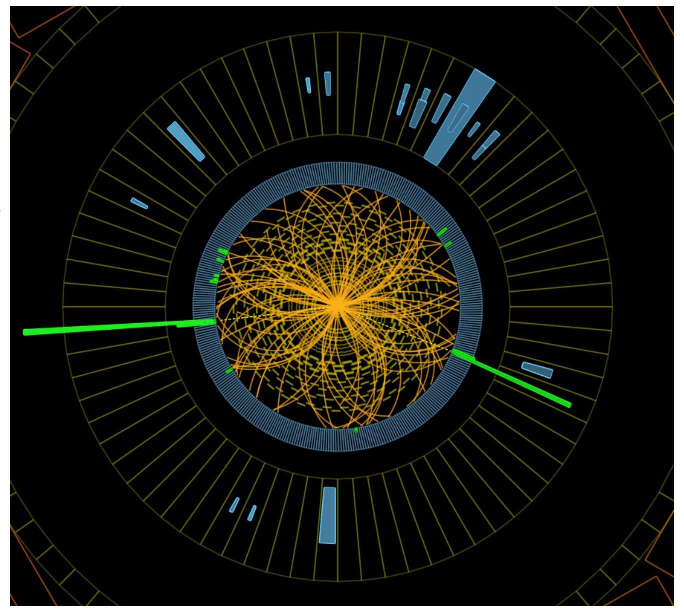

Results: correlation and fitting

arXiv:2301.05290

$K^0_S K^0_S$

QS (Bose-Einstein)
+ strong FSI

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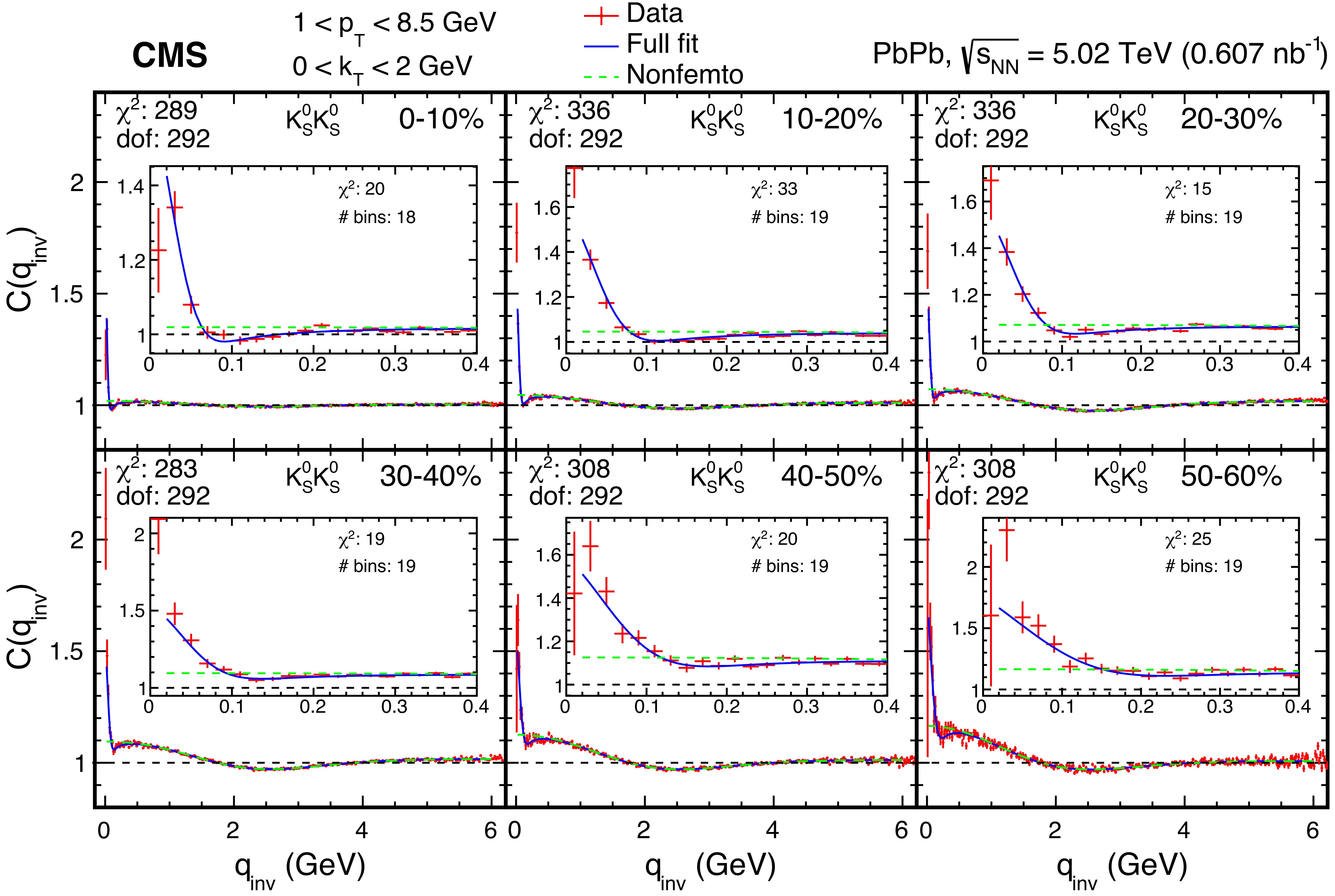

Results: correlation and fitting

arXiv:2301.05290

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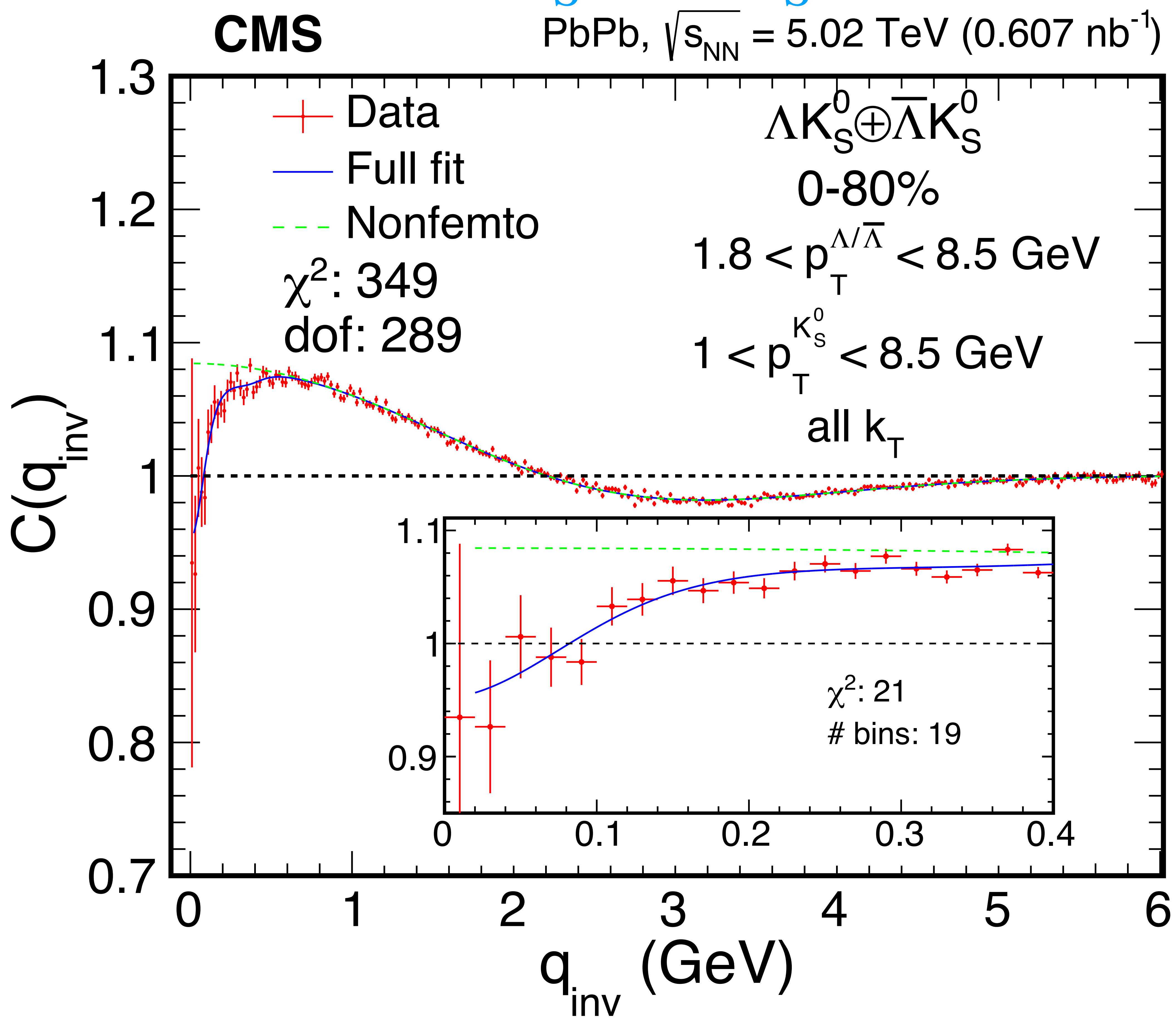
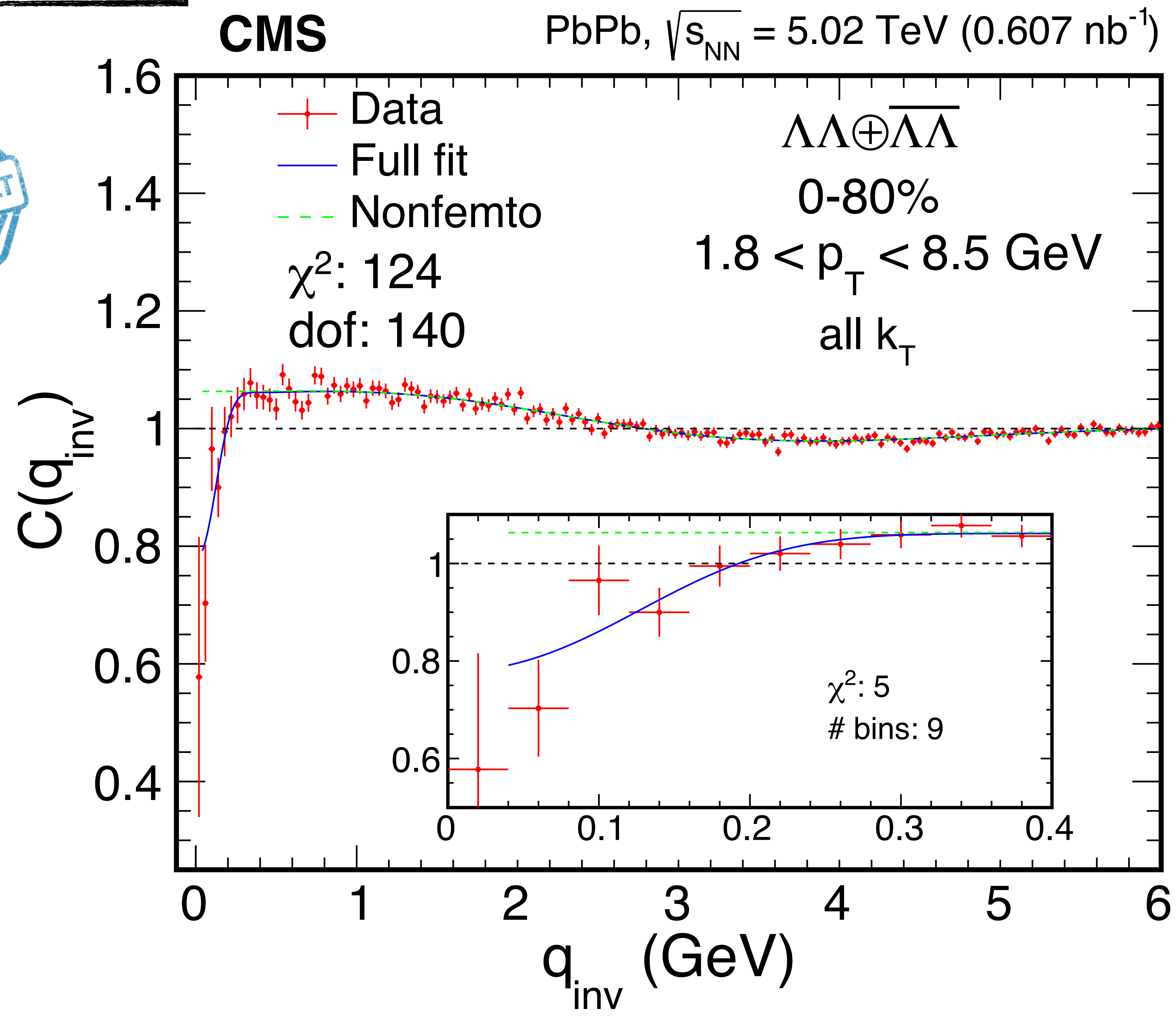
$\Lambda K^0_S \oplus \bar{\Lambda} K^0_S$



QS + strong FSI [non-identical]

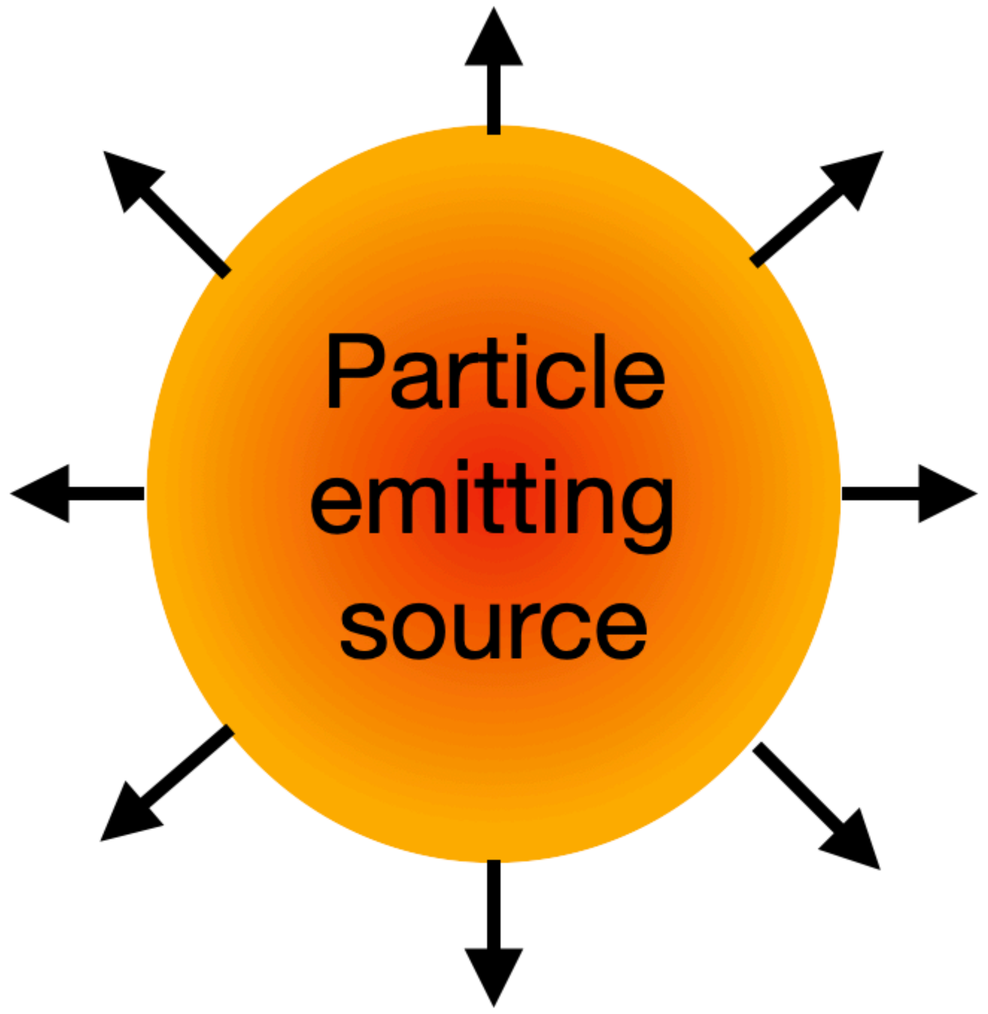
$\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$



QS (Fermi-Dirac) + strong FSI

- Different pairs have different shape depending on their correlation features.

Results: source size



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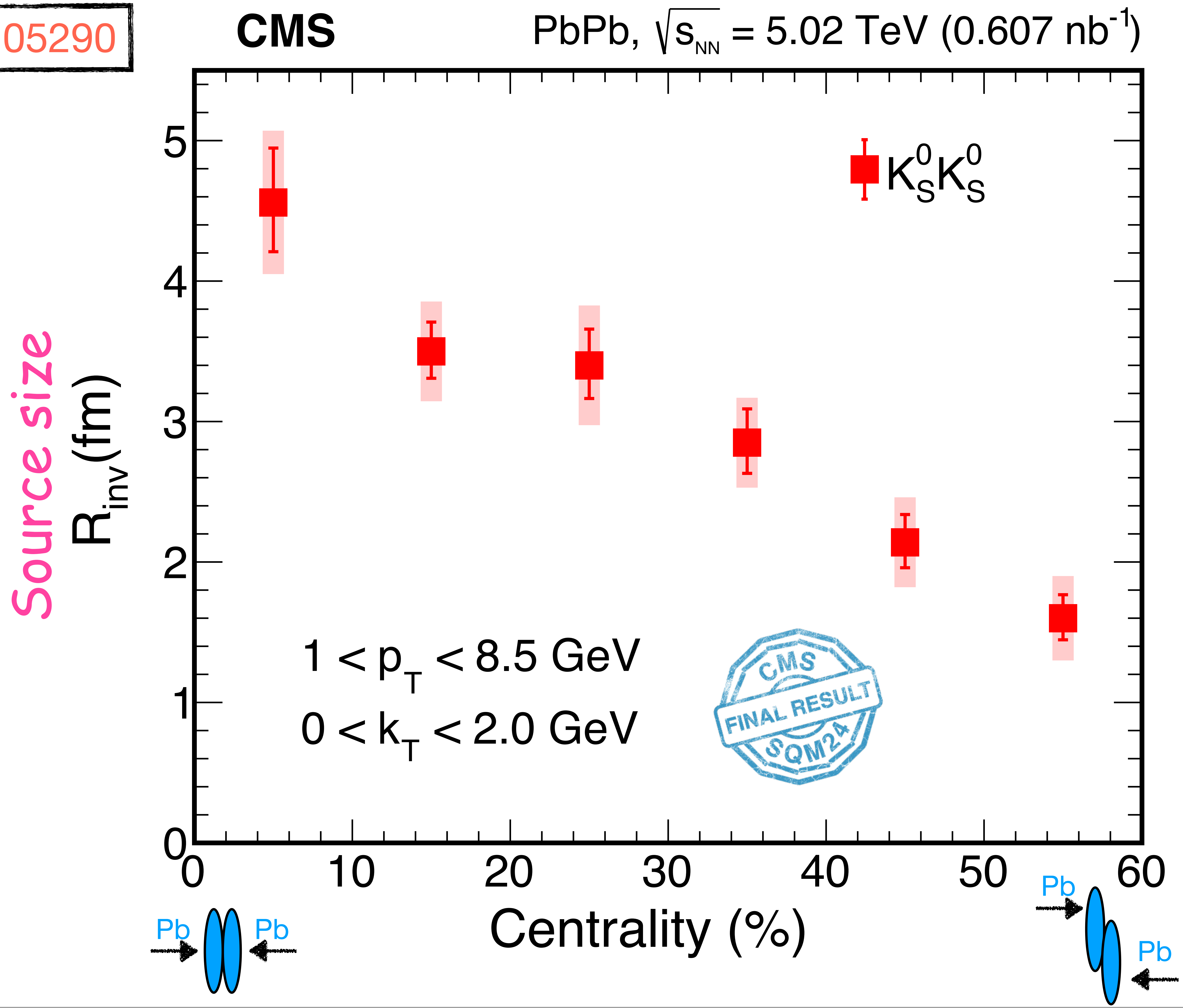
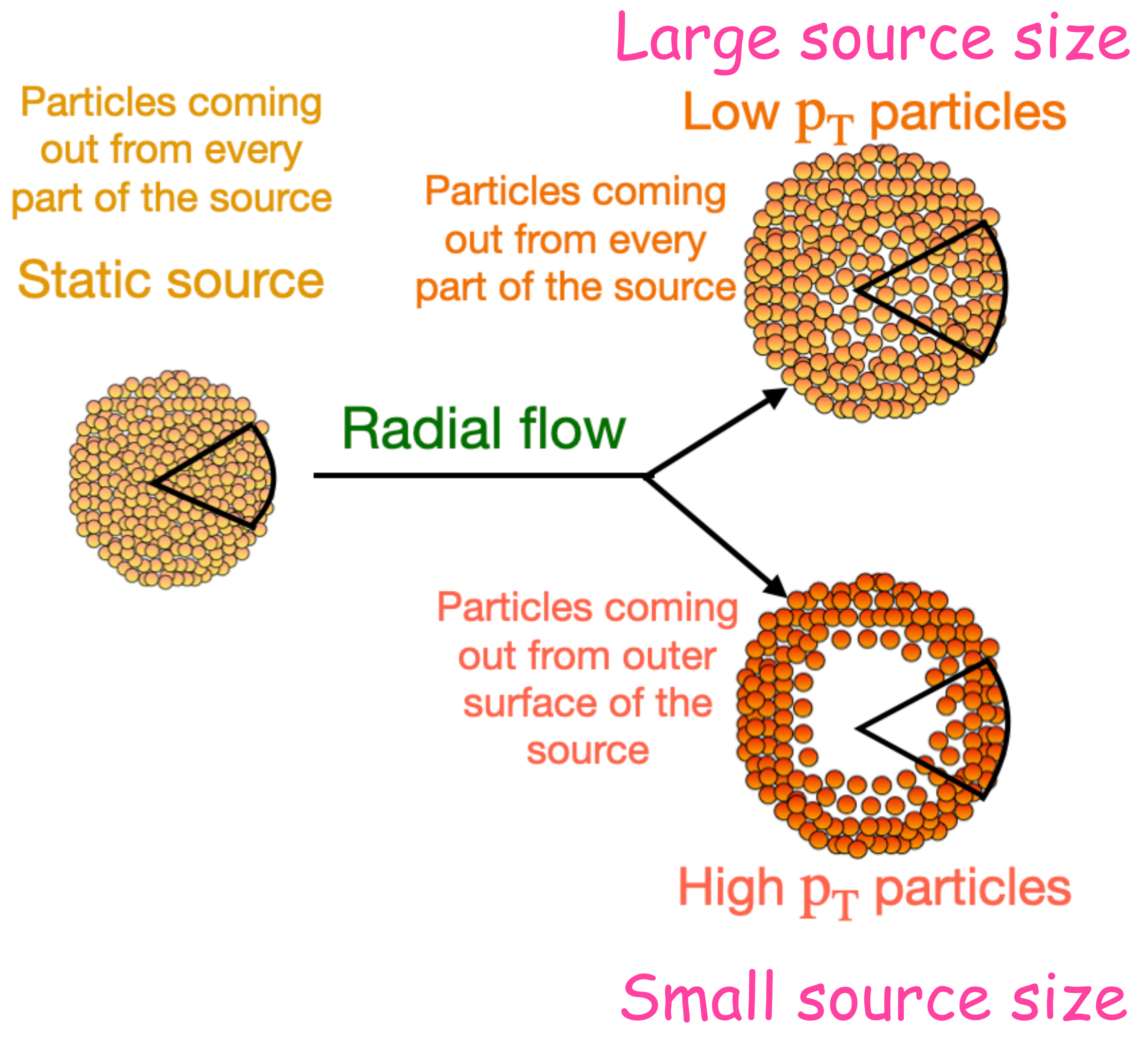


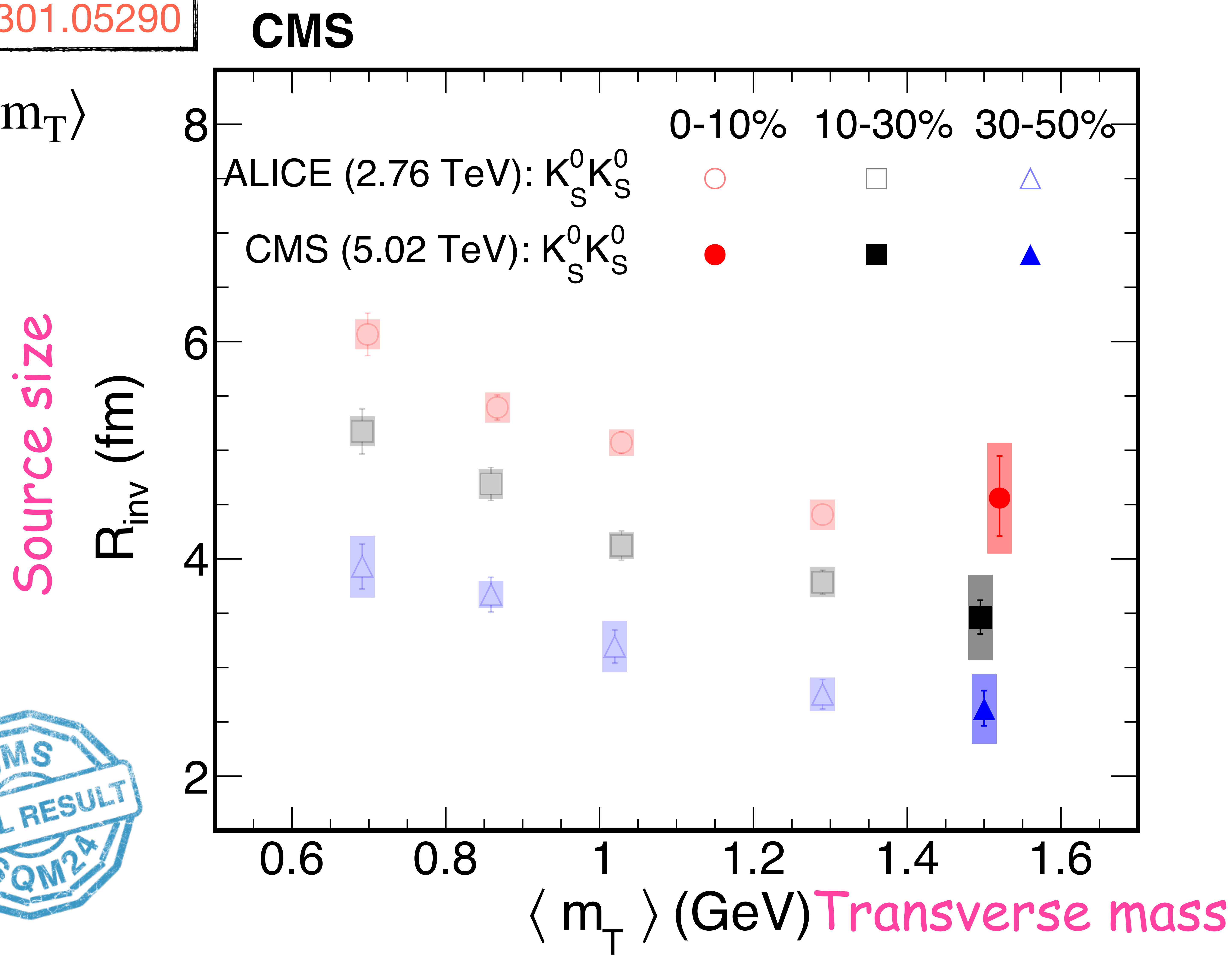
- Source size (R_{inv}) decreases from central to peripheral collisions
  - expected from a simple geometric picture

Results: comparison with ALICE

arXiv:2301.05290

- Source size is decreasing with increasing $\langle m_T \rangle$
- Following the trend measured by ALICE





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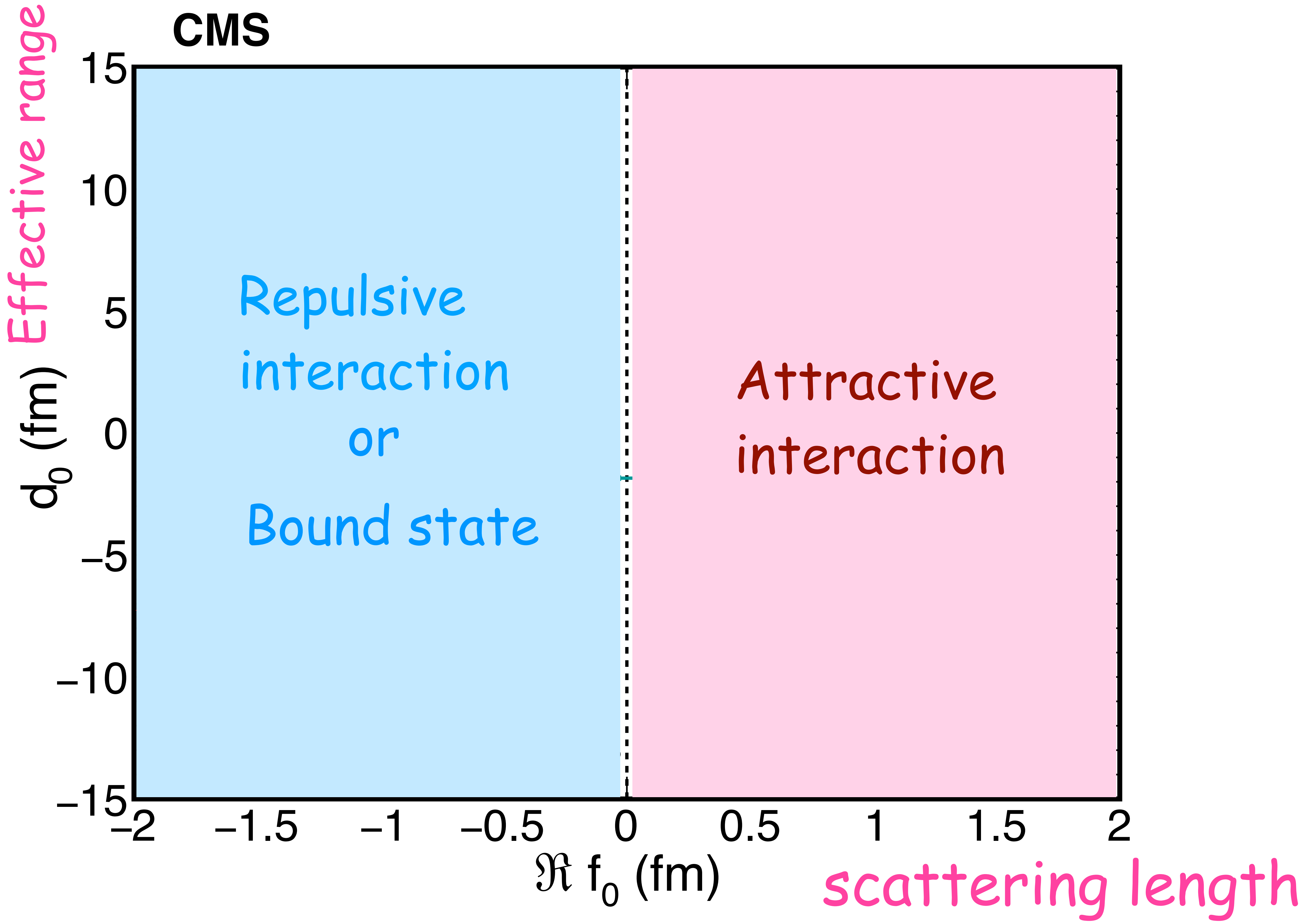
Results: scattering parameters



- $\Re f_0 < 0$ for $\Lambda K^0_S \oplus \overline{\Lambda} K^0_S$

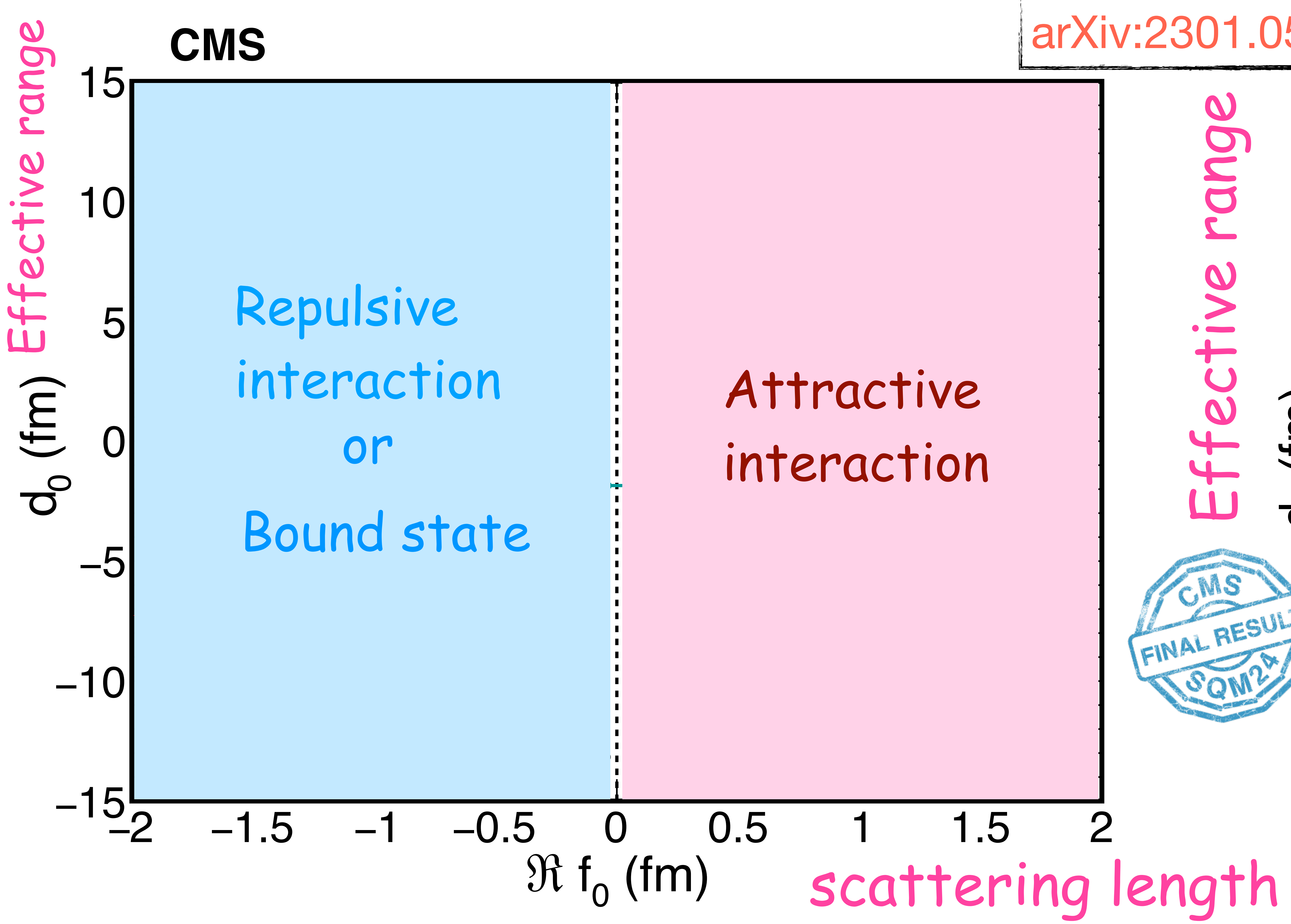
  Repulsive

- $\Re f_0 > 0$ for $\Lambda\Lambda \oplus \overline{\Lambda}\overline{\Lambda}$

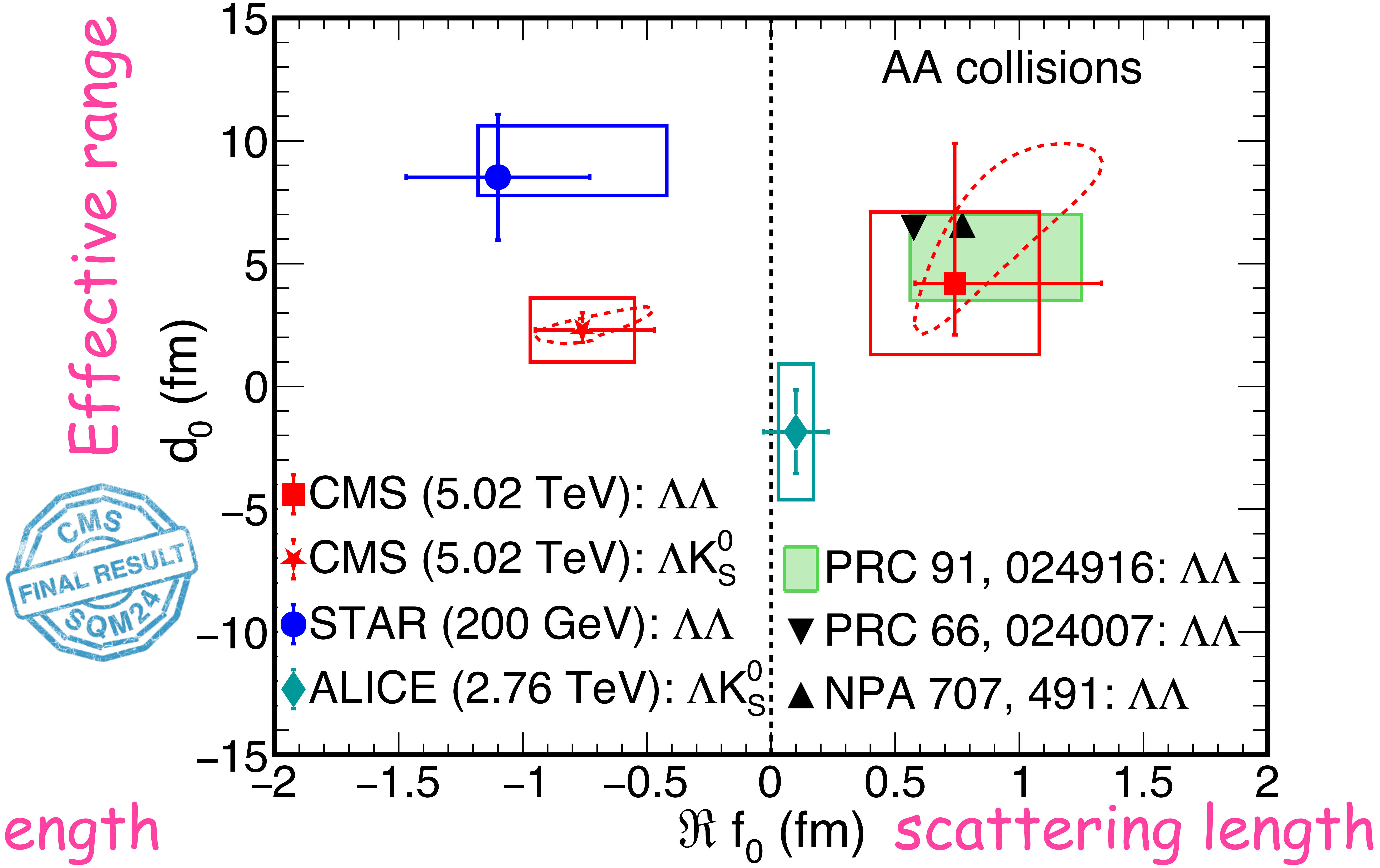
  Attractive

Results: scattering parameters

arXiv:2301.05290



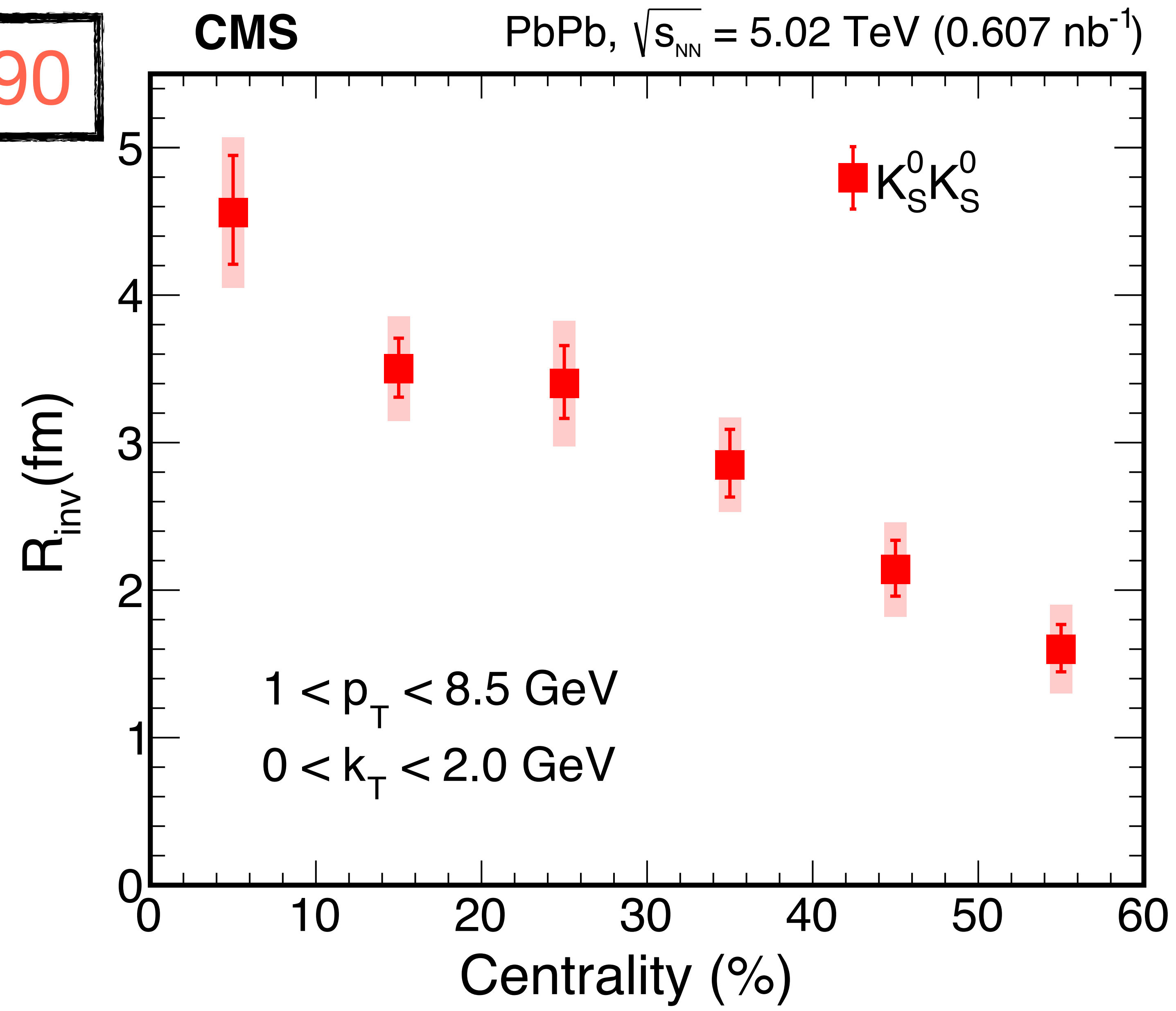
Without feed-down correction explicitly



- $\Re f_0 < 0$ for $\Lambda K^0_S \oplus \overline{\Lambda} K^0_S$ ★ — Repulsive
- $\Re f_0 > 0$ for $\Lambda\Lambda \oplus \overline{\Lambda}\overline{\Lambda}$ ■ — Attractive → Indicating no bound state between two $\Lambda(\overline{\Lambda})$

Summary

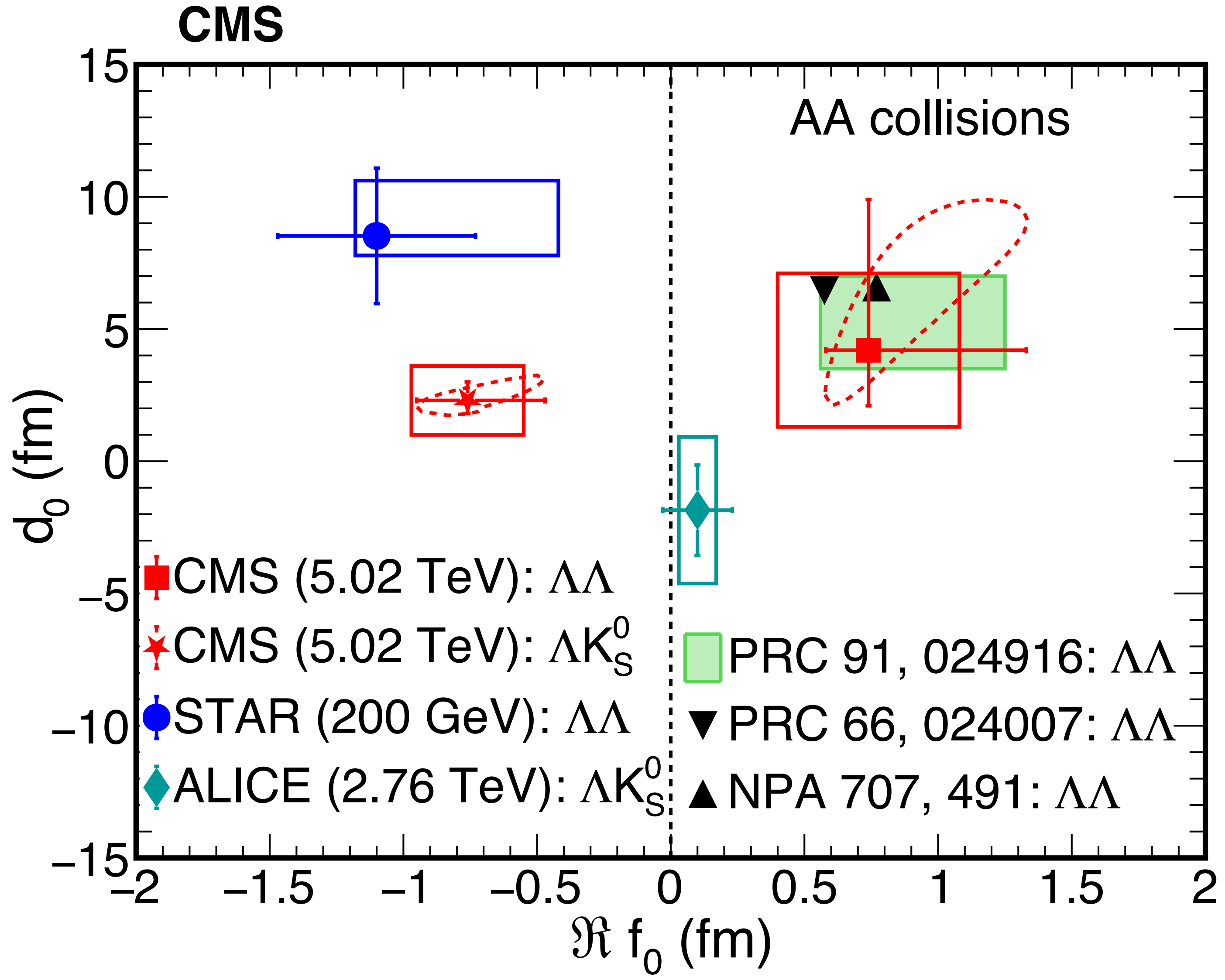
arXiv:2301.05290



- Source size is extracted from $K^0_S K^0_S$ correlation and it increases from peripheral to central collisions as expected.

- First measurement of $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ correlation in PbPb collisions at LHC
  - $\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$ interaction : Attractive
    - ➡ Indicating non-existence of bound H-dibaryon of two $\Lambda(\bar{\Lambda})$

- $\Lambda K^0_S \oplus \bar{\Lambda} K^0_S$ interaction : Repulsive

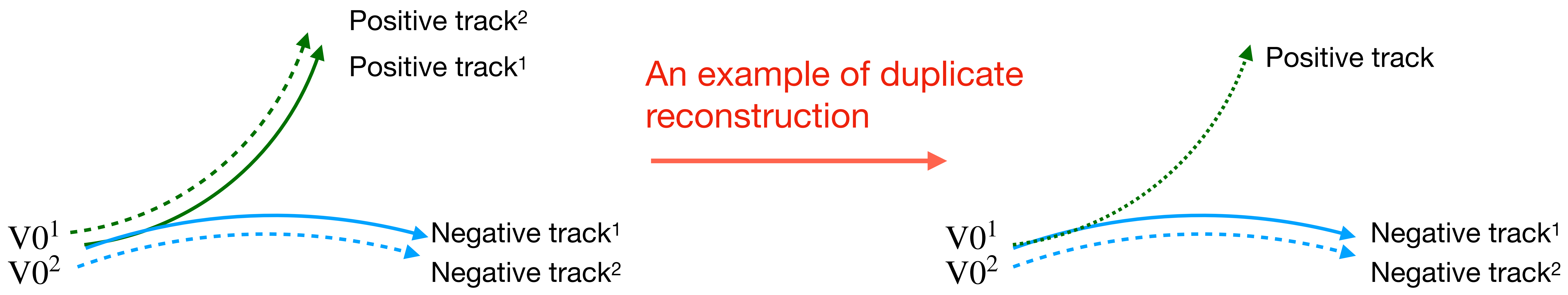


Thank you for your kind attention !

Backup

Duplicate V0 removal

- Removed duplicate V0 (sharing common daughters):
  - If $|\Delta\chi 2/ndf| = 0$ between V0 daughters with same charge, remove one V0 randomly



Correction to the correlation

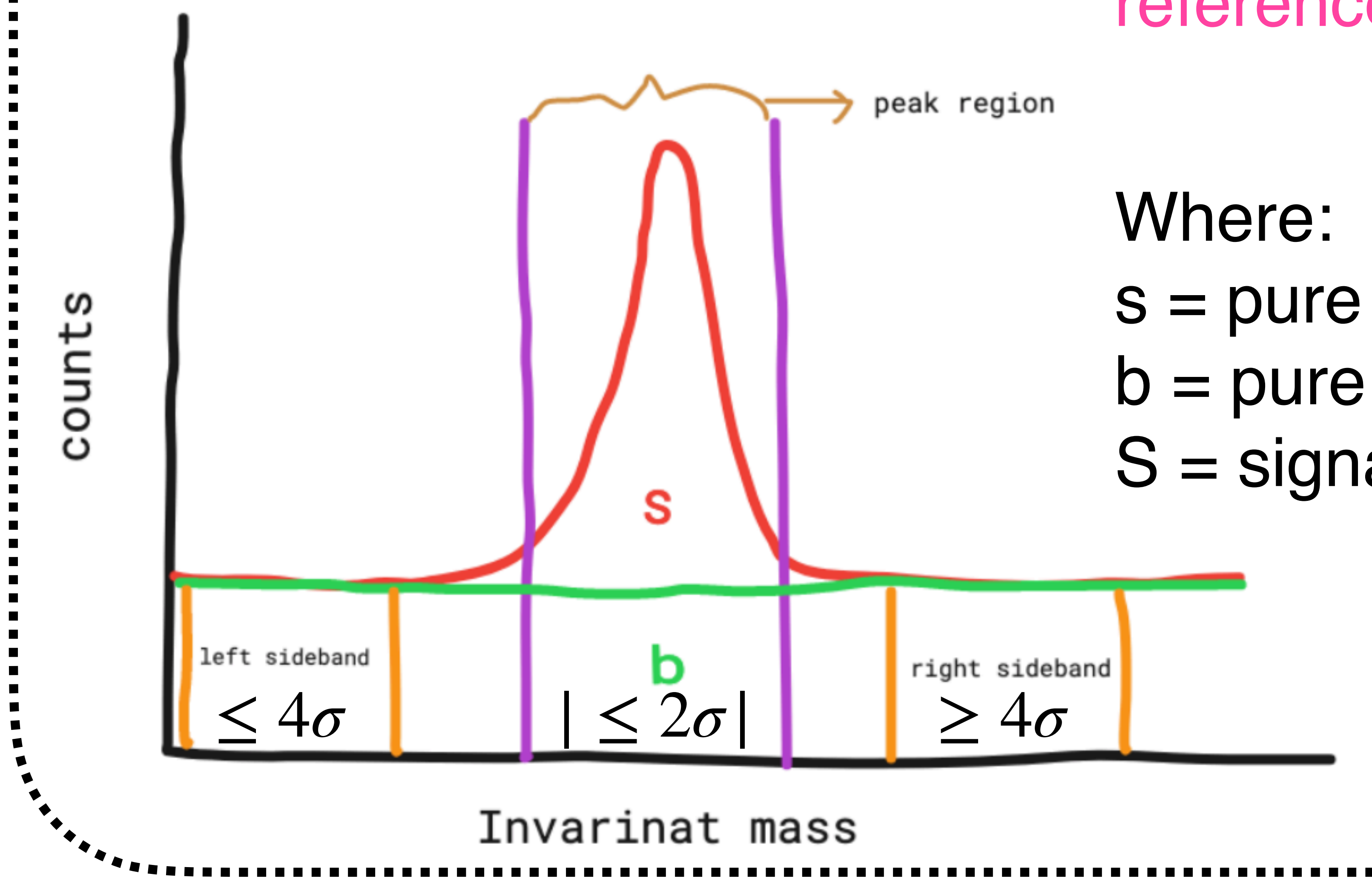
Pair purity

$$A^{measured}(q_{inv}) = f^{ss}A^{ss}(q_{inv}) + f^{bb}A^{bb}(q_{inv}) + f^{Sb}A^{Sb}(q_{inv})$$

$$A^{ss}(q_{inv}) = \left[A^{mesured}(q_{inv}) - f^{bb}A^{bb}(q_{inv}) - f^{Sb}A^{Sb}(q_{inv})\right]/f^{ss}$$

$$f^{ss} = \frac{\binom{s}{2}}{\binom{s+b}{2}},\ f^{bb} = \frac{\binom{b}{2}}{\binom{s+b}{2}},\ f^{Sb} = 1 - f^{ss} - f^{bb}$$

Applied on signal and reference samples



Where:
s = pure signal,
b = pure background
S = signal + background (s+b)

Non-femtoscopic background

$$\Omega(q_{inv}) = \mathcal{N}(1 + \alpha_1 e^{-(q_{inv}R_1)^2})(1 - \alpha_2 e^{-(q_{inv}R_2)^2})$$

arXiv:2301.05290

Total correlation function will be:

$$C_{Fit}(q_{inv}) = \Omega(q_{inv}) \times C'_{Fit}(q_{inv})$$

Theoretical fitted function

Sov. J. Nucl. Phys. 35 (1982) 770.

- All the non-femto parameters, $\mathcal{N}$, α_1, α_2, R_1, and R_2, were treated as free parameters during fitting

Fitting function: Lednicky model

$K^0_S K^0_S \longrightarrow$

$$C'_{Fit}(q_{inv}) = N\left[1 + \lambda\left(\exp(-q_{inv}^2 R_{inv}^2) + \frac{1}{2}\left|\frac{f(q_{inv}/2)}{R_{inv}}\right|^2 + \frac{2\Re f(q_{inv}/2)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{qinv}) - \frac{\Im f(q_{inv}/2)}{R_{inv}} F_2(Q_{inv}R_{inv})\right)\right]$$

R_{inv}, λ and N are the free parameters

$$F_1(q_{inv}R_{inv}) = \int_0^{q_{inv}R_{inv}} dx \frac{e^{x^2 - q_{inv}^2 R_{inv}^2}}{q_{inv}R_{inv}} \qquad F_2(q_{inv}R_{inv}) = \frac{1 - e^{-q_{inv}^2 R_{inv}^2}}{q_{inv}R_{inv}}$$

QS

FSI

$$f(q_{inv}/2) = \frac{f_{f_0} + f_{a_0}}{2} \qquad f_{f_0,a_0}(q_{inv}/2) = \gamma_{f_0,a_0}/[m_{f_0,a_0}^2 - s - i\gamma_{f_0,a_0}q_{inv}/2 - i\gamma'_{f_0,a_0}k'_{f_0,a_0}]$$

$\Lambda K^0_S \oplus \bar{\Lambda} K^0_S \longrightarrow$

$$C'_{Fit}(q_{inv}) = N\left[1 + \lambda\left(\frac{1}{2}\left|\frac{f(q_{inv}/2)}{R_{inv}}\right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi}R_{inv}}\right) + \frac{2\Re f(q_{inv}/2)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{qinv}) - \frac{\Im f(q_{inv}/2)}{R_{inv}} F_2(Q_{inv}R_{inv})\right)\right]$$

R_{inv}, d_0, $\Re f_0$, $\Im f_0$, λ and N are the free parameters

$$f(q_{inv}/2) = \left(\frac{1}{f_0} + \frac{1}{8}d_0 q_{inv}^2 - i\frac{q_{inv}}{2}\right)^{-1}$$

$\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda} \longrightarrow$

$$C'_{Fit}(q_{inv}) = N\left[1 + \lambda\left(-\frac{1}{2}\exp(-q_{inv}^2 R_{inv}^2) + \frac{1}{4}\left|\frac{f(q_{inv}/2)}{R_{inv}}\right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi}R_{inv}}\right) + \frac{\Re f(q_{inv}/2)}{\sqrt{\pi}R_{inv}} F_1(q_{inv}R_{qinv}) - \frac{\Im f(q_{inv}/2)}{2R_{inv}} F_2(Q_{inv}R_{inv})\right)\right]$$

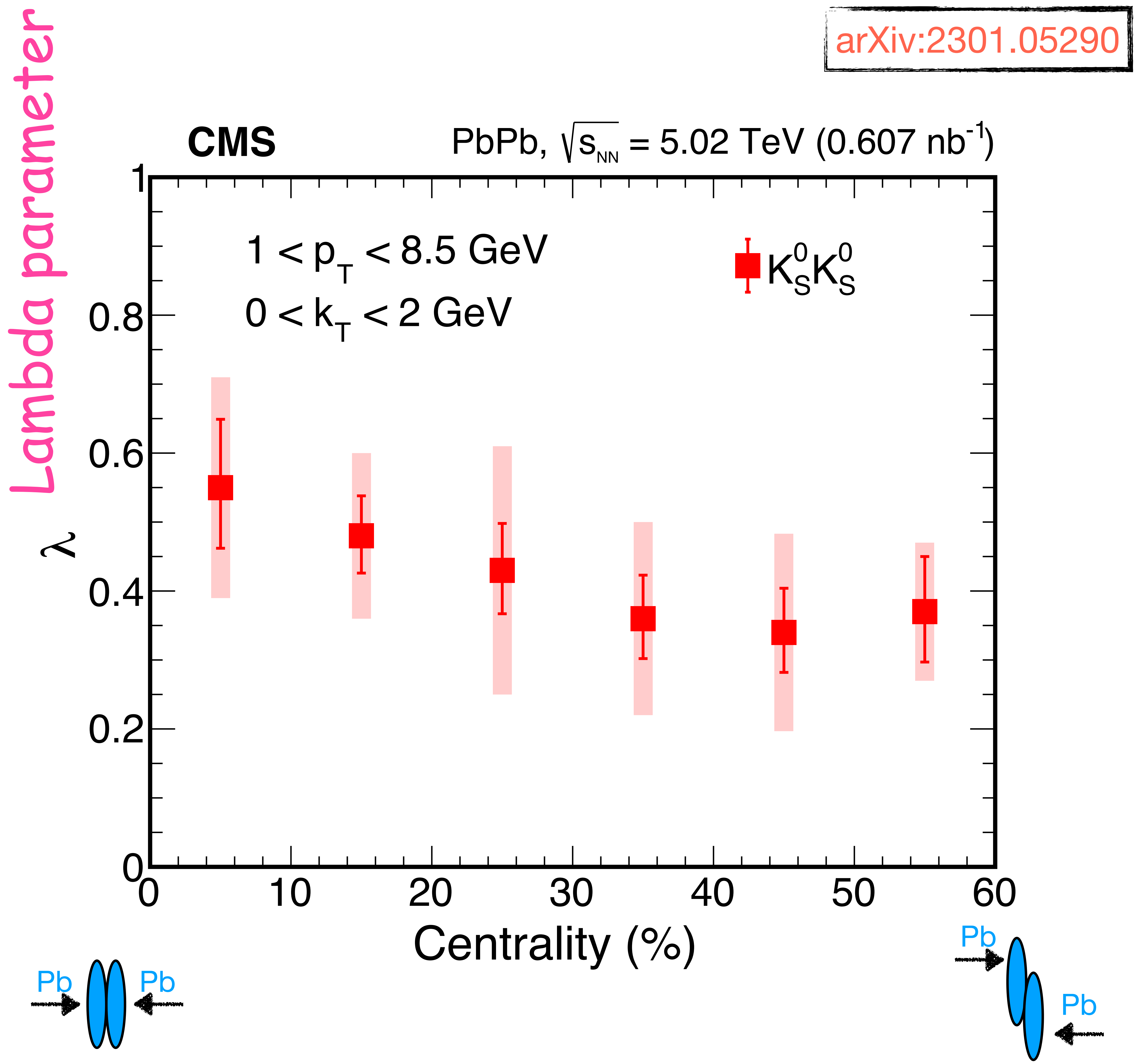
R_{inv}, d_0, $\Re f_0$, λ and N are the free parameters

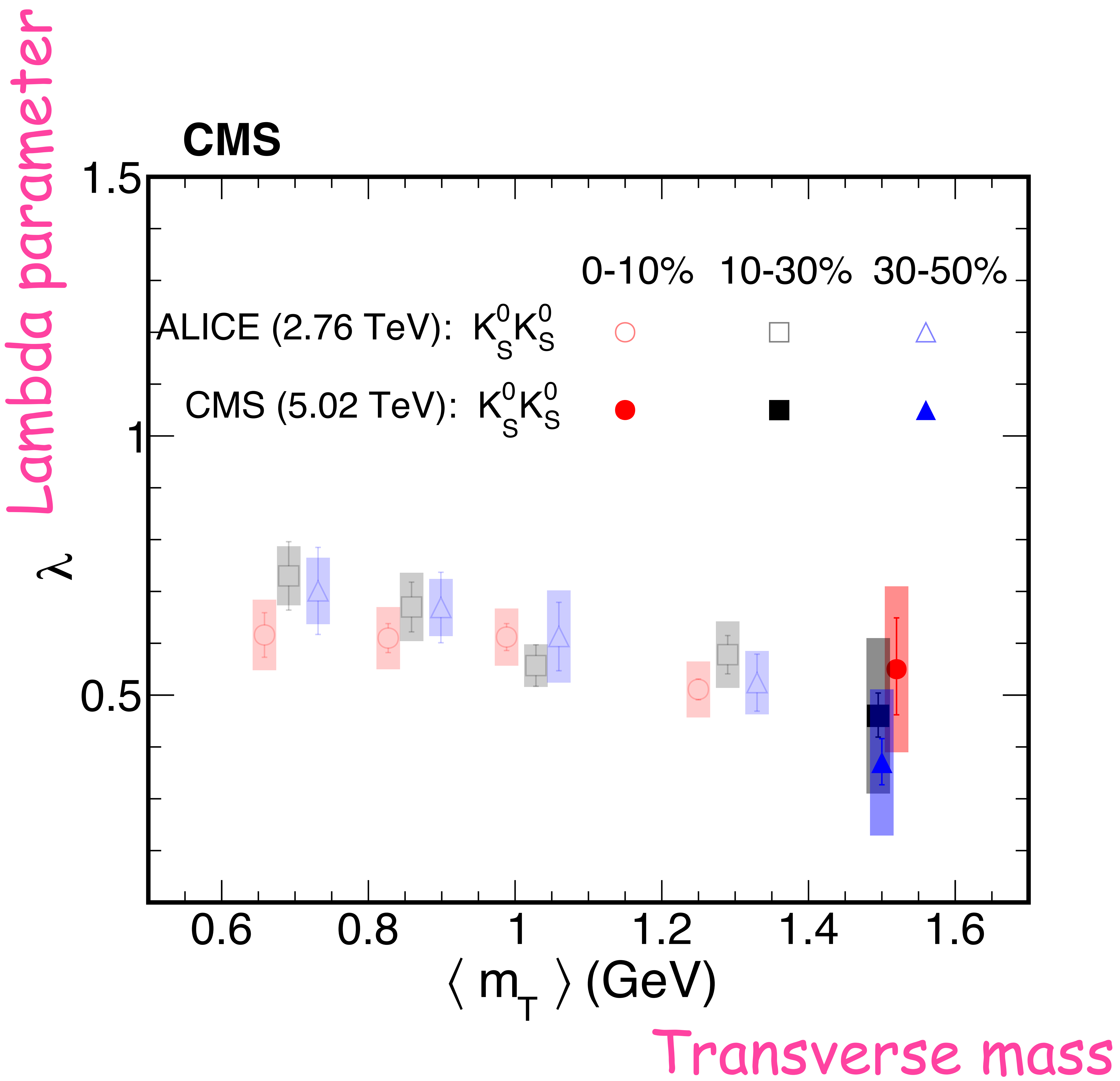
$$f(q_{inv}/2) = \left(\frac{1}{f_0} + \frac{1}{8}d_0 q_{inv}^2 - i\frac{q_{inv}}{2}\right)^{-1}$$

Sov. J. Nucl. Phys. 35 (1982) 770.

Lambda parameter

arXiv:2301.05290

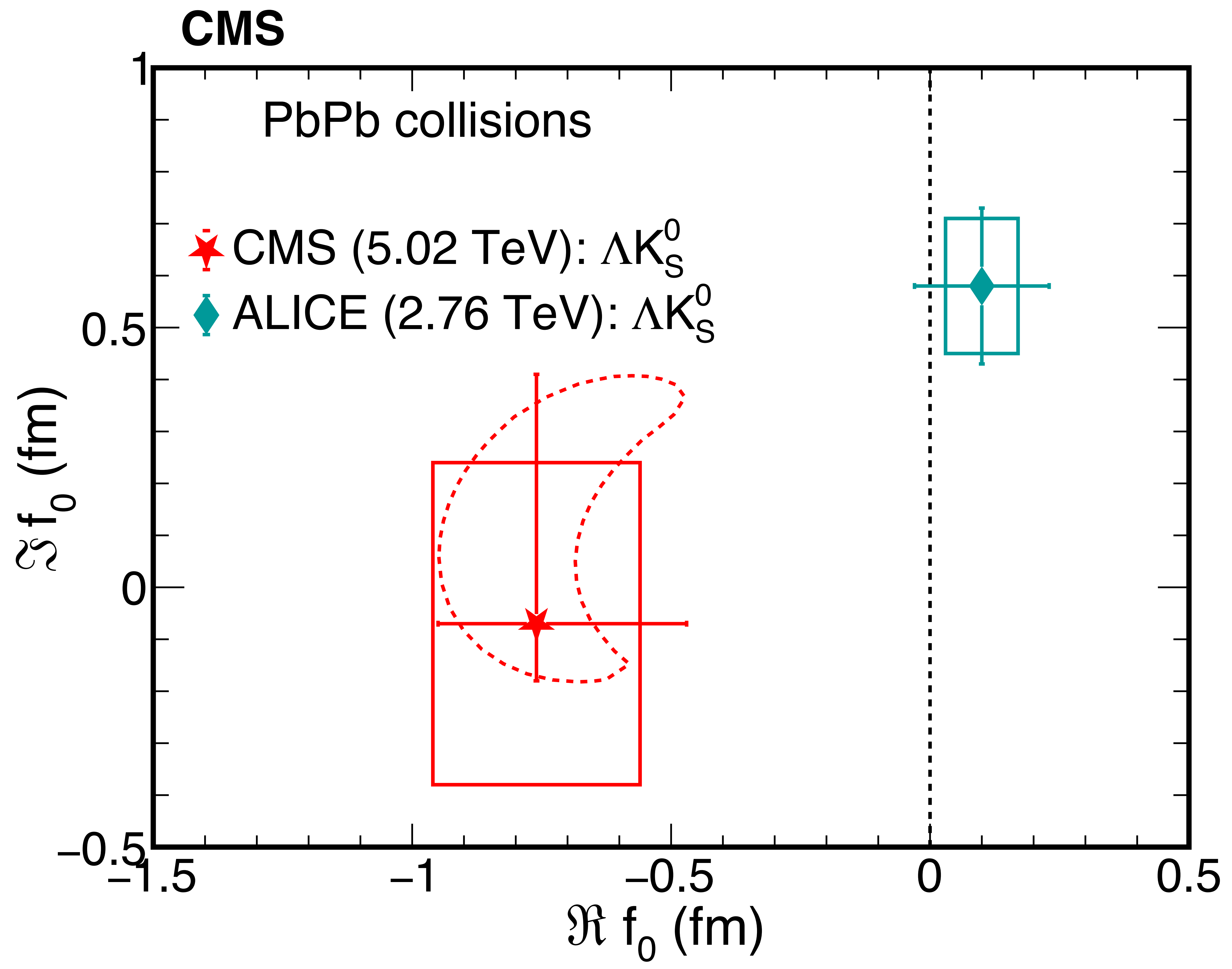




Results: Scattering parameters

arXiv:2301.05290

Imaginary scattering length



Real scattering length

Fitted parameters

arXiv:2301.05290

Table 3: Extracted values of the R_{inv}, $\Re f_0$, $\Im f_0$, d_0, λ, and $\langle m_{\mathrm{T}} \rangle$ parameters from the $K^0_S K^0_S$, ΛK^0_S, and $\Lambda\Lambda$ combinations in the 0–80% centrality range. The first and second uncertainties are statistical and systematic, respectively.

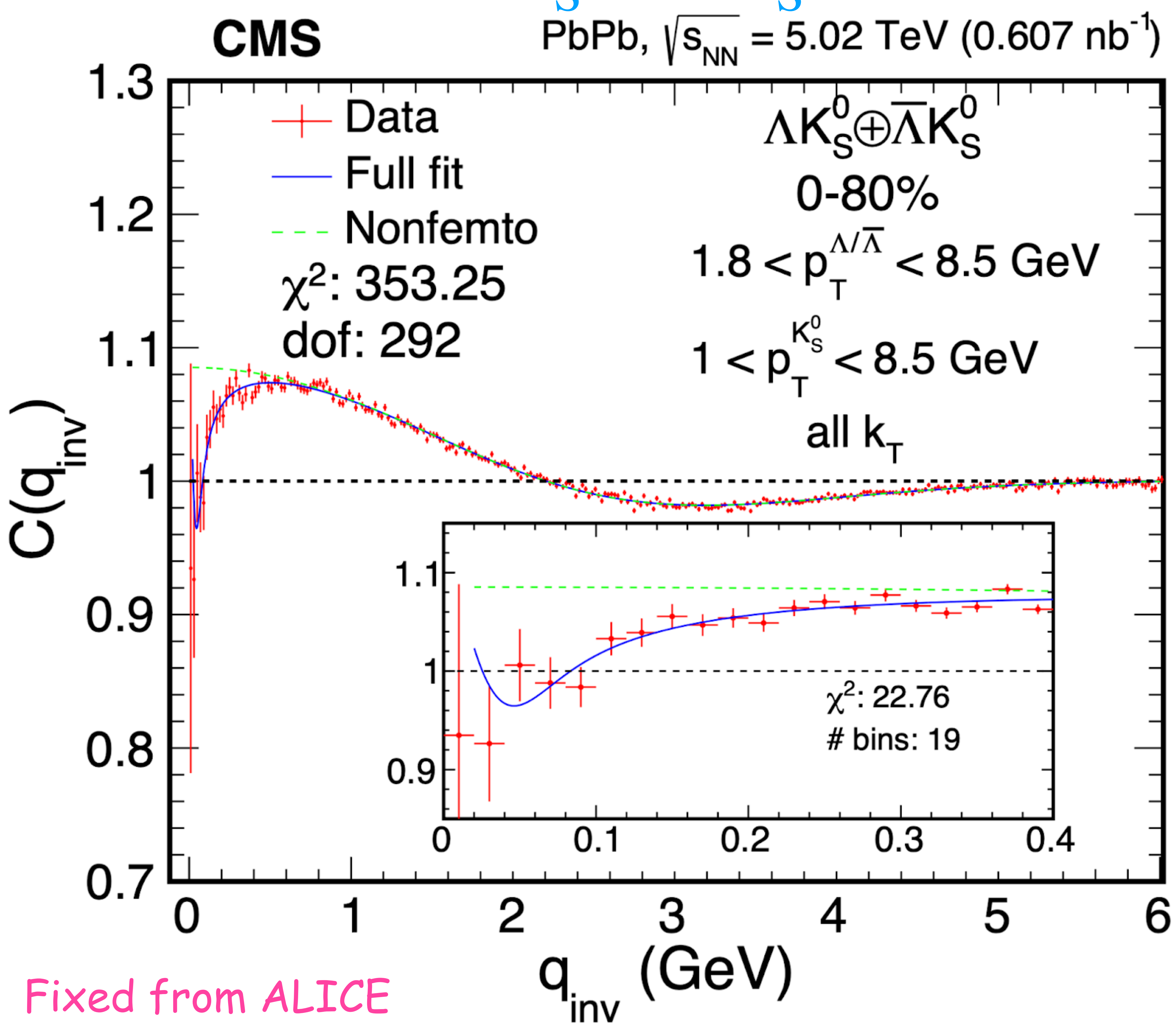
Parameter	$K^0_S K^0_S$	ΛK^0_S	$\Lambda\Lambda$
R_{inv} (fm)	$3.40 \pm 0.11 \pm 0.37$	$2.1^{+1.4}_{-0.5} \pm 0.8$	$1.3^{+0.4}_{-0.2} \pm 0.3$
$\Re f_0$ (fm)	—	$-0.76^{+0.29}_{-0.19} \pm 0.20$	$0.74^{+0.59}_{-0.16} \pm 0.33$
$\Im f_0$ (fm)	—	$-0.07^{+0.48}_{-0.11} \pm 0.32$	—
d_0 (fm)	—	$2.3^{+0.7}_{-0.5} \pm 1.3$	$4.2^{+5.7}_{-2.1} \pm 2.9$
λ	$0.43 \pm 0.03 \pm 0.13$	$0.34^{+0.41}_{-0.12} \pm 0.17$	$1.5^{+1.2}_{-1.1} \pm 1.4$
$\langle m_{\mathrm{T}} \rangle$ (GeV)	1.50	2.09	2.60

Non-prompt fraction

- HYDJET: 85% $\Lambda(\overline{\Lambda})$ produce directly and 15% $\Lambda(\overline{\Lambda})$ from secondary decay
- HIJING: 39% $\Lambda(\overline{\Lambda})$ produce directly and 61% $\Lambda(\overline{\Lambda})$ from secondary decay

Strong parameters fixed

$\Lambda K^0_S \oplus \bar{\Lambda} K^0_S$

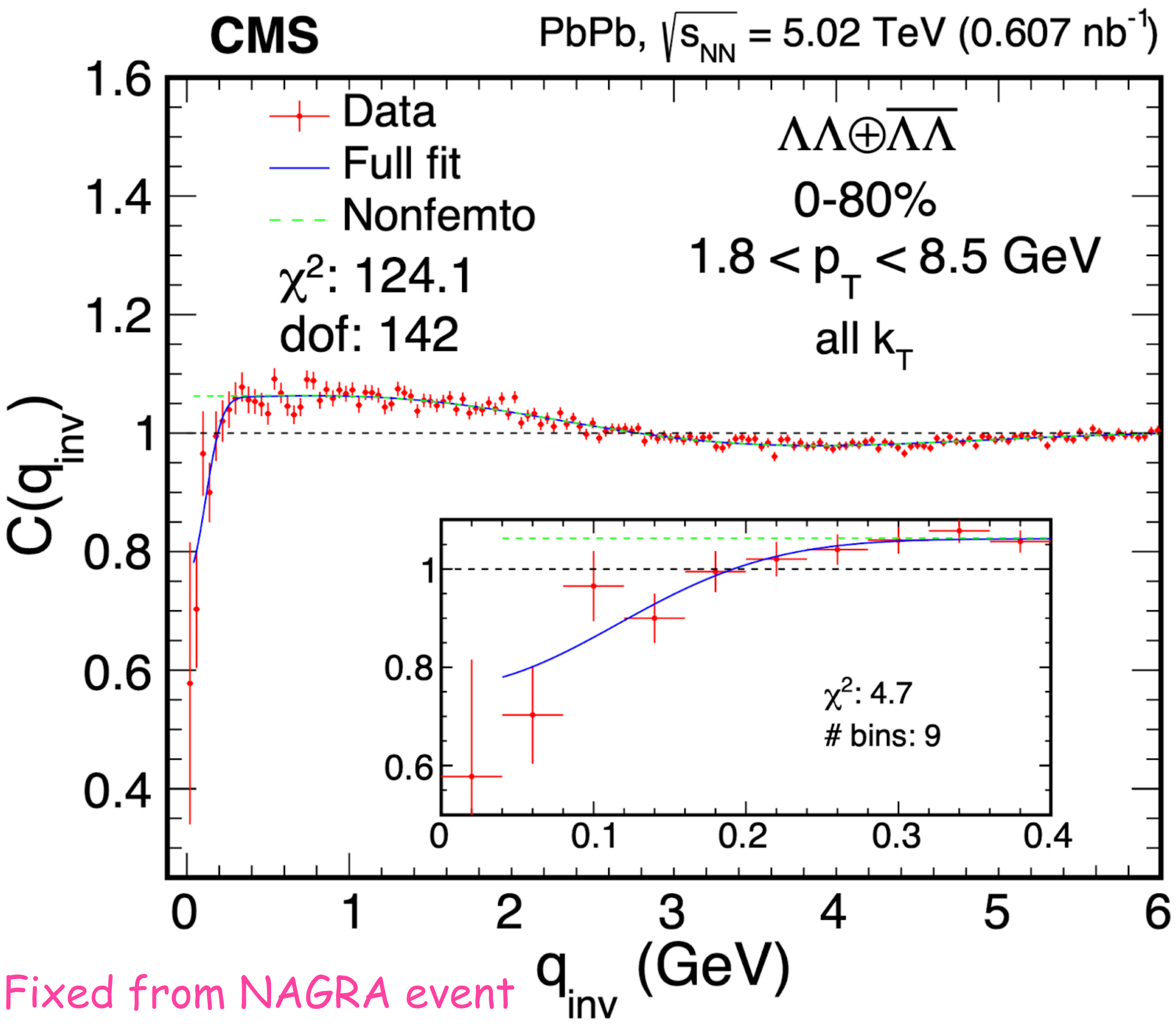


Fixed from ALICE

R_{inv} = 5.27 +2.209 -1.146

λ = 2.13 +1.893 -0.766

$\Lambda\Lambda \oplus \bar{\Lambda}\bar{\Lambda}$



Fixed from NAGRA event

R_{inv} = 1.34 +0.208 -0.173

λ = 1.03 +0.289 -0.261

Armenteros-Podolanski plot

$$\alpha = (p_{1L} - p_{2L})/(p_{1L} + p_{1L})$$

$$p_{iL} = (\vec{p}_{V^0} \cdot \vec{p}_i)/|\vec{p}_{V^0}|$$

$$Q_T = |\vec{p}_1 \times \vec{p}_2|/|\vec{p}_{V^0}|$$