# Femtoscopy with Lévy sources in 5.02 TeV PbPb collisions

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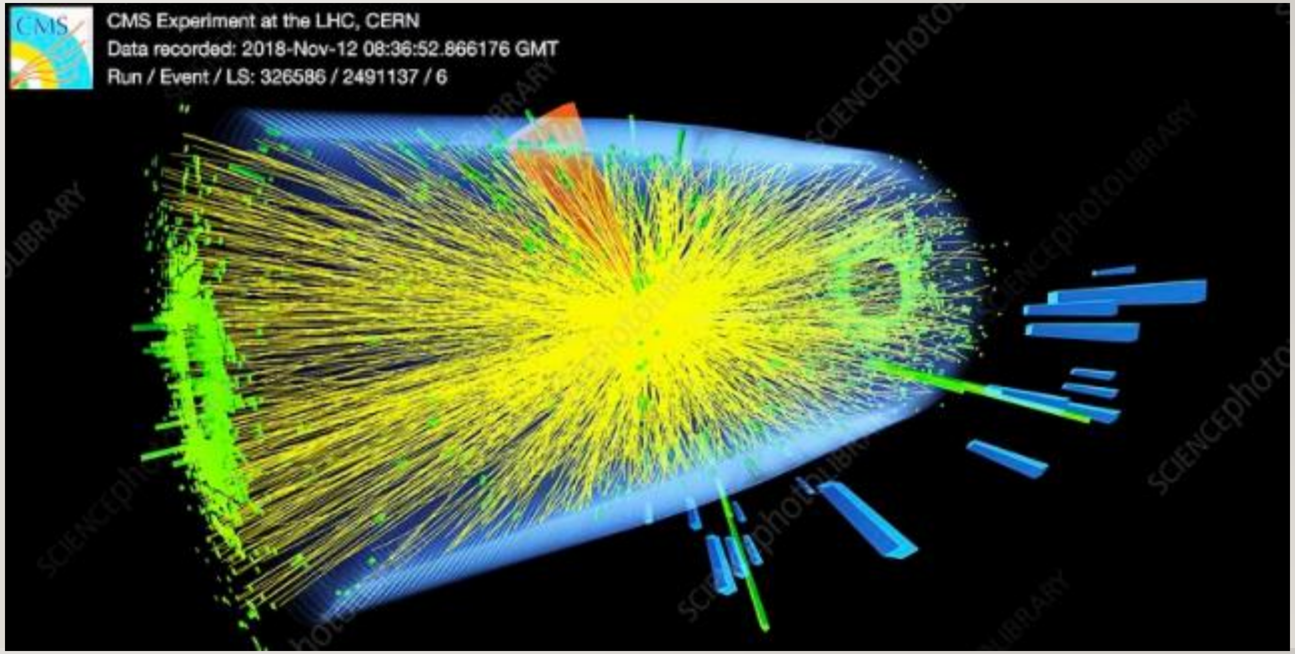
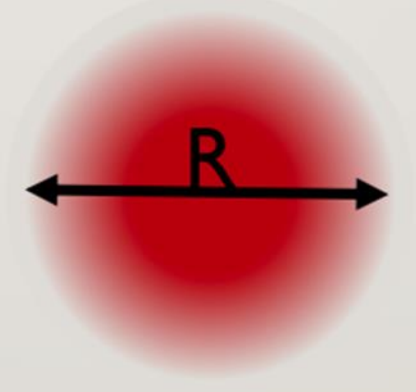
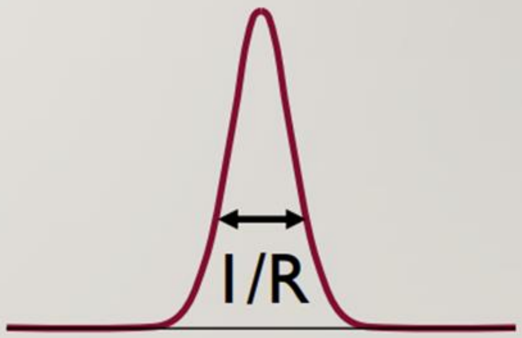


# BASICS OF FEMTOSCOPY

- HBT in high energy physics: *G. Goldhaber, S. Goldhaber, W.Y. Lee, A. Pais, Phys. Rev. 120, 300 (1960)*
  - Momentum correlation of pions
  - Bose-Einstein correlation → C(q), $q \equiv |\boldsymbol{q}_{\mathrm{LCMS}}|, \boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$
  - Relation to the source: $C(q) \approx 1 + |\tilde{S}(q)|^2$
  - Gaussian source: $C(q) = 1 + e^{-|qR|^2}$
  - Lévy-type source + core-halo model: $C(q) = 1 + \lambda e^{-|qR|^\alpha}$
  - Final state interactions → Coulomb correction
- Goals:
  - Measure $C(q)$ in different centrality and $K_T$ classes
  - Obtain the parameters via fitting
  - Study the centrality and $K_T$ dependence of the parameters



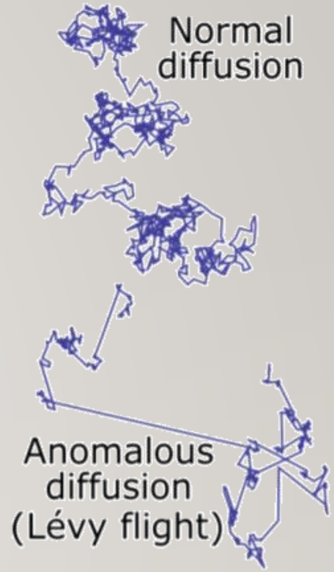

S(r) source

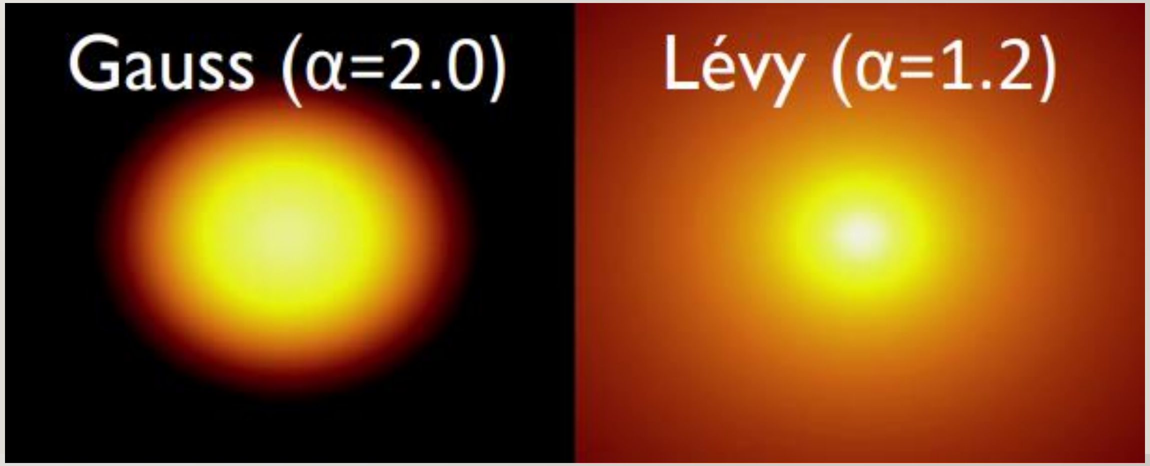



C(q) correlation function

# CONCEPT: LÉVY HBT

- Gaussian assumption not precise enough
- Lévy distribution: $L(\alpha, R; r) = \frac{1}{2\pi} \int dq\, e^{iqr} e^{-\frac{1}{2}|qR|^{\alpha}}$
- Many possible reasons i.e. anomalous diffusion, critical phenomena …
  - *Csörgő, Hegyi, Novák, Zajc, Acta Phys. Polon. B36 (2005) 329-337*
  - *Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) no.1, 525-532;*
  - *Csanád, Csörgő, Nagy, Braz. J. Phys. 37 (2007) 1002*
- Detailed centrality dependent Lévy shape analysis
  - Measurement of:
  - ➢ Lévy stability index $\alpha \rightarrow$ shape
  - ➢ Lévy scale parameter $R \rightarrow$ scale
  - ➢ Correlation strength $\lambda \rightarrow$ core-halo, partial coherence



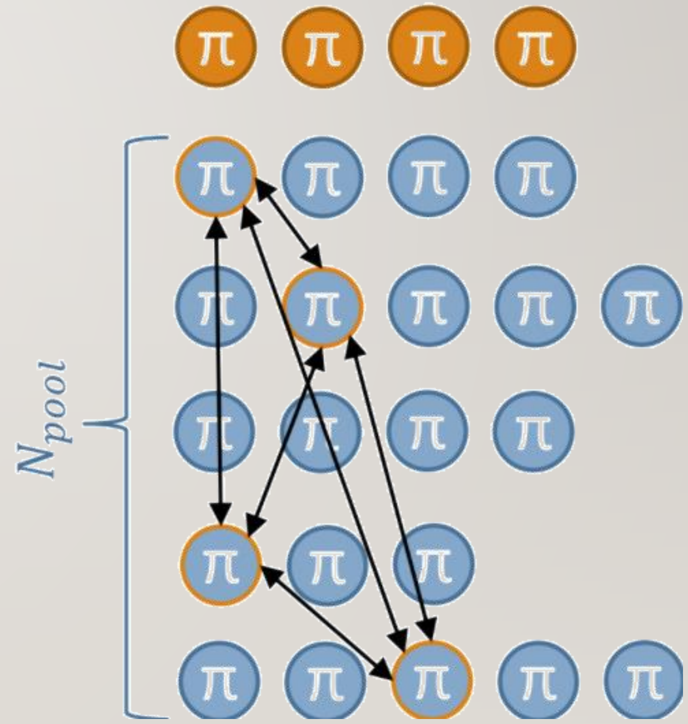
# DATA SELECTION

- 2018 5.02 TeV PbPb data
- Event selection → ≈2.65 billion events
- Track selection → ≈662 billion tracks
- Pair selection
- No particle identification
  - ≈ 80-90% pion, ≈10-20% kaon+proton
  - $K_T$ dependent ratios
  - Only influences λ

| Variable | Default | Tight | Loose |
|---|---|---|---|
| Zvertex | <15 cm | <12 cm | <18 cm |
| $p_T$ | >0.5 GeV/c | >0.55 GeV/c | >0.5 GeV/c |
| $\delta p_T$ | <10% | <5% | <15% |
| $X^2/N_{dof}/N_{layer}$ | <0.18 | <0.15 | <0.18 |
| $\|\eta\|$ | <0.95 | <0.9 | <1.0 |
| $N_{pixel\ hit}$ | >1 | >2 | >0 |
| $\|d_{xy}/\sigma(d_{xy})\|$ | <3 | <2 | <5 |
| $\|d_z/\sigma(d_z)\|$ | <3 | <2 | <5 |
| Δη, Δϕ pair cut | $\Delta\eta_{cut} = 0.014$ $\Delta\phi_{cut} = 0.022$ | $\Delta\eta_{cut} = 0.017$ $\Delta\phi_{cut} = 0.028$ | $\Delta\eta_{cut} = 0.011$ $\Delta\phi_{cut} = 0.016$ |

# 5/14 CALCULATING THE CORRELATION FUNCTION

- Pair distributions: quantum statistics + acceptance + kinematics + … → background sample needed
- Calculating the correlation function: $C(q) = \frac{A(q)}{B(q)} \cdot \frac{\int B}{\int A}$
  - A(q) actual pair distribution: all same charged pairs of a given event
  - B(q) background pair distribution: obtained by event mixing
  - Calculate $C(q)$ for different $K_T$ and centrality classes
- Event mixing:
  - A pool of events in classes (zvertex, centrality) is kept
  - For an actual event, we create a mixed event:
    - Random selection of N particles
    - Two particles can't come from the same event
  - Minimally correlated mixed event
  - Background pairs from mixed event
- Remove remaining long-range background → $DR(q)$



# FITTING THE CORRELATION FUNCTION

- ROOT MINUIT2 $\chi^2$ fit; errors: MINOS
- 6 centrality (0-60%) and 24 $K_T$ classes (0.5-1.9 GeV/c)
- Fit limits different in each class
- Small q: not reliable because of pair resolution
  - Checked using MC simulations
- Fitted function: Bowler-Sinyukov method

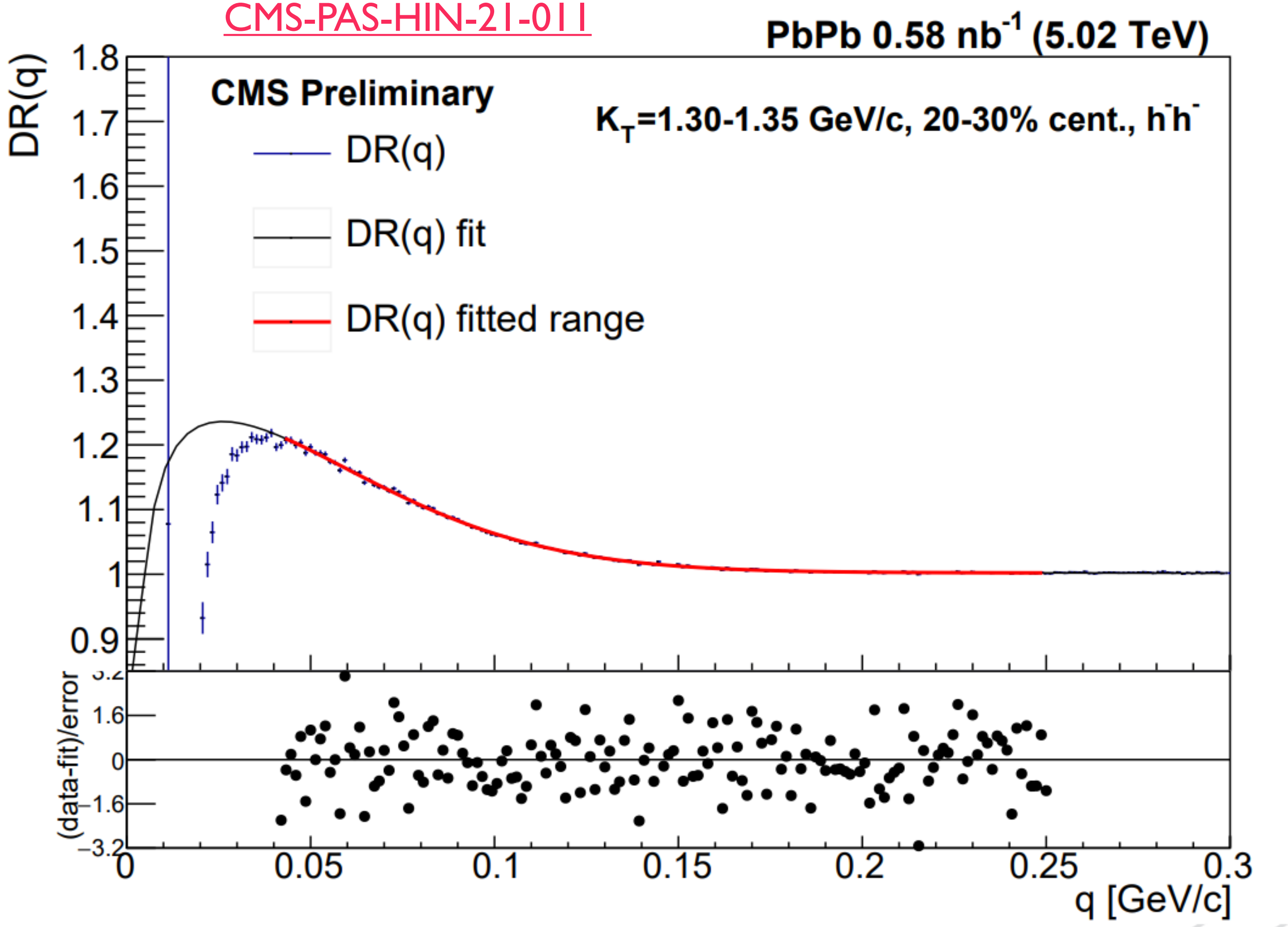
$$DR(q) = N(1+\varepsilon q)\left[1-\lambda+\lambda\left(1+e^{-|qR|^{\alpha}}\right)K_C(q;\alpha,R)\right]$$

  - $K_C(q;\alpha,R)$: Coulomb correction

*Csanád, Lökös, Nagy: Phys. Part. Nuclei 51, 238-242 (2020)*

- 5 fit parameters:
  - N : normalisation factor
  - $\varepsilon$ : neccesary because of still remaining background
  - $R, \alpha, \lambda$ : physical meaning

CMS-PAS-HIN-21-011



# 7/14 THE LÉVY SCALE PARAMETER: $R$ VS $m_T$

- $m_T = \sqrt{m^2 + (K_T/c)^2}$
- Generalized homogeneity length of the source
- Smooth $m_T$ dependence
- Centrality dependent
- Boxes: uncorrelated systematic uncertainties
- Error bars: statistical uncertainties

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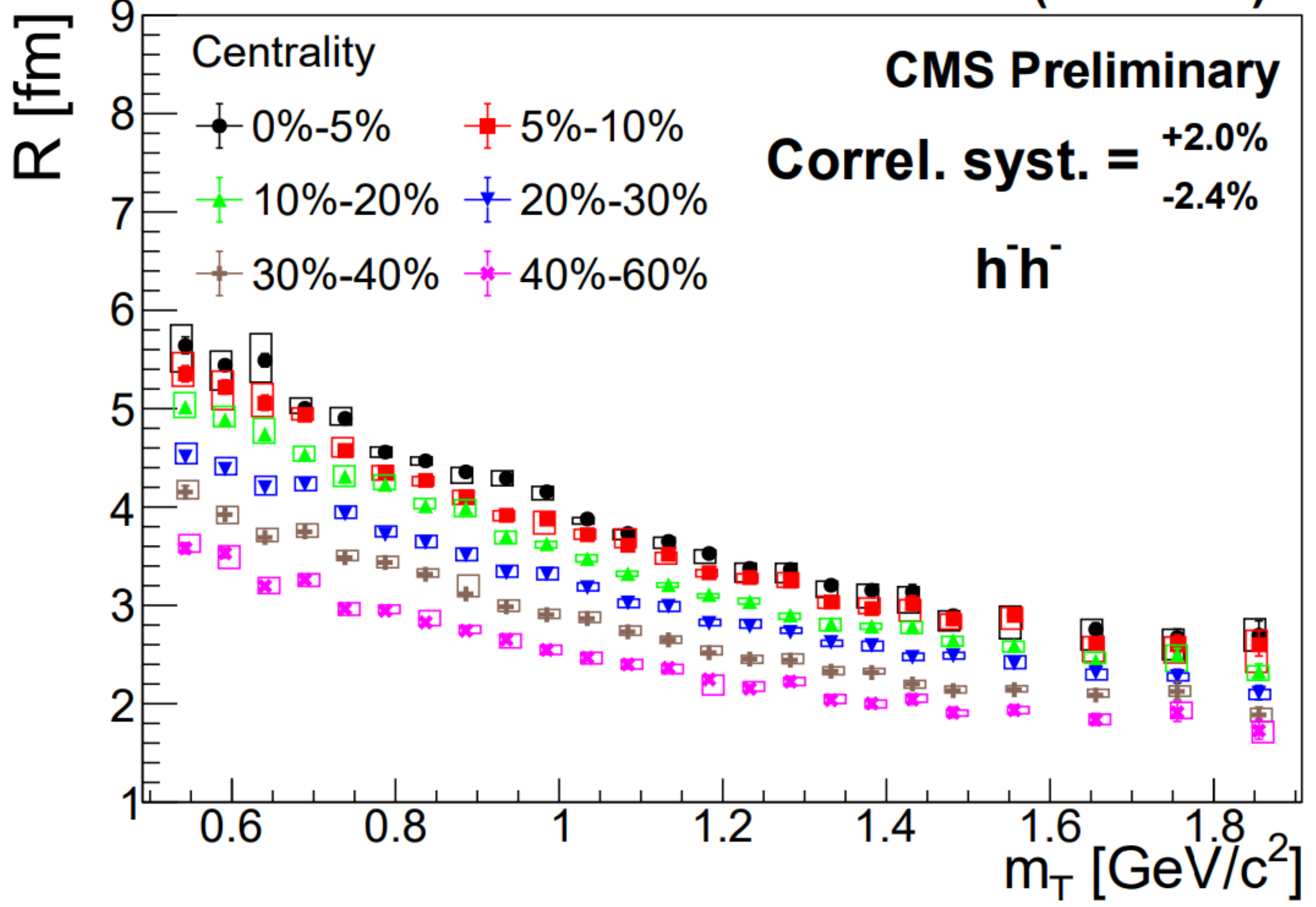
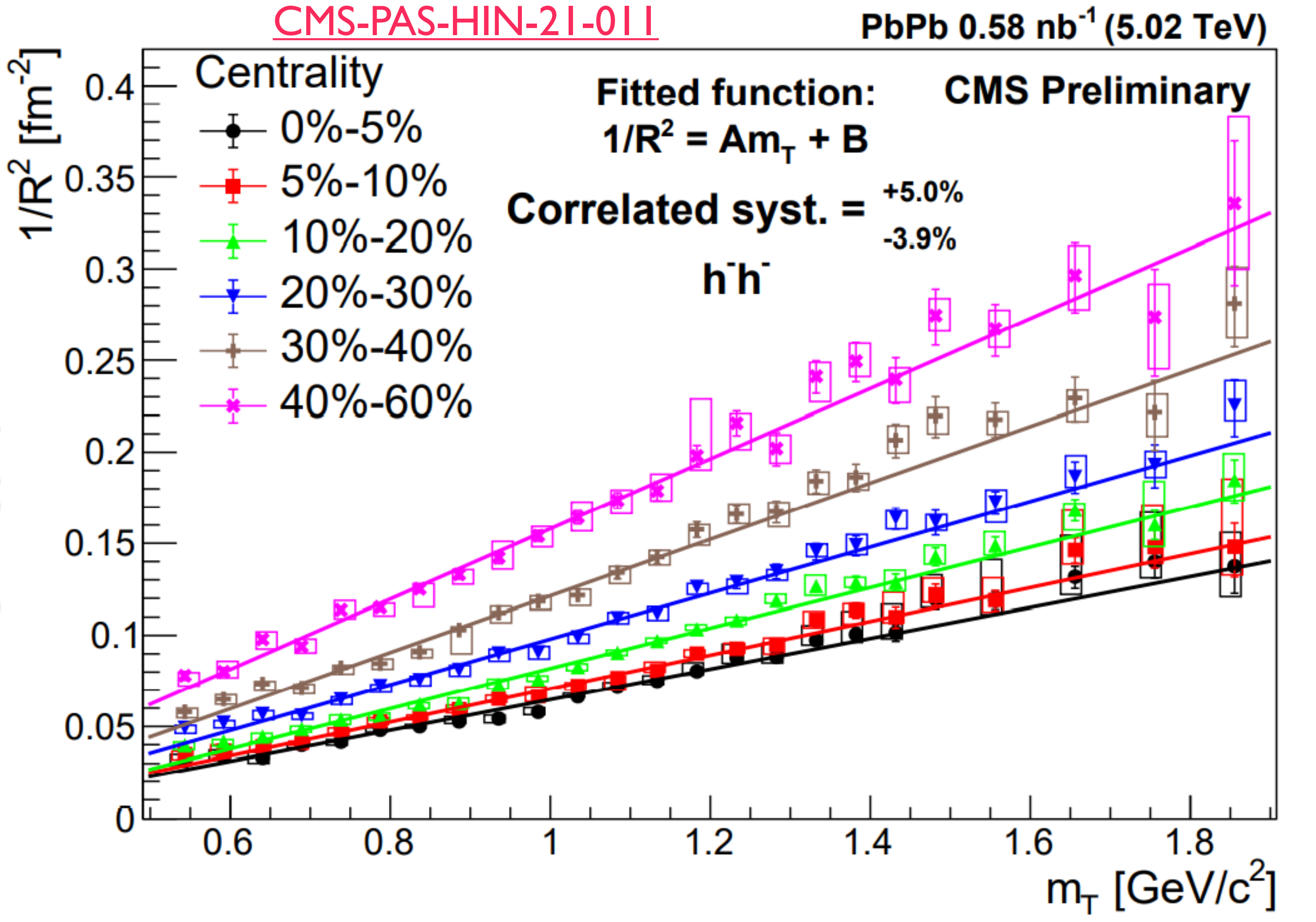
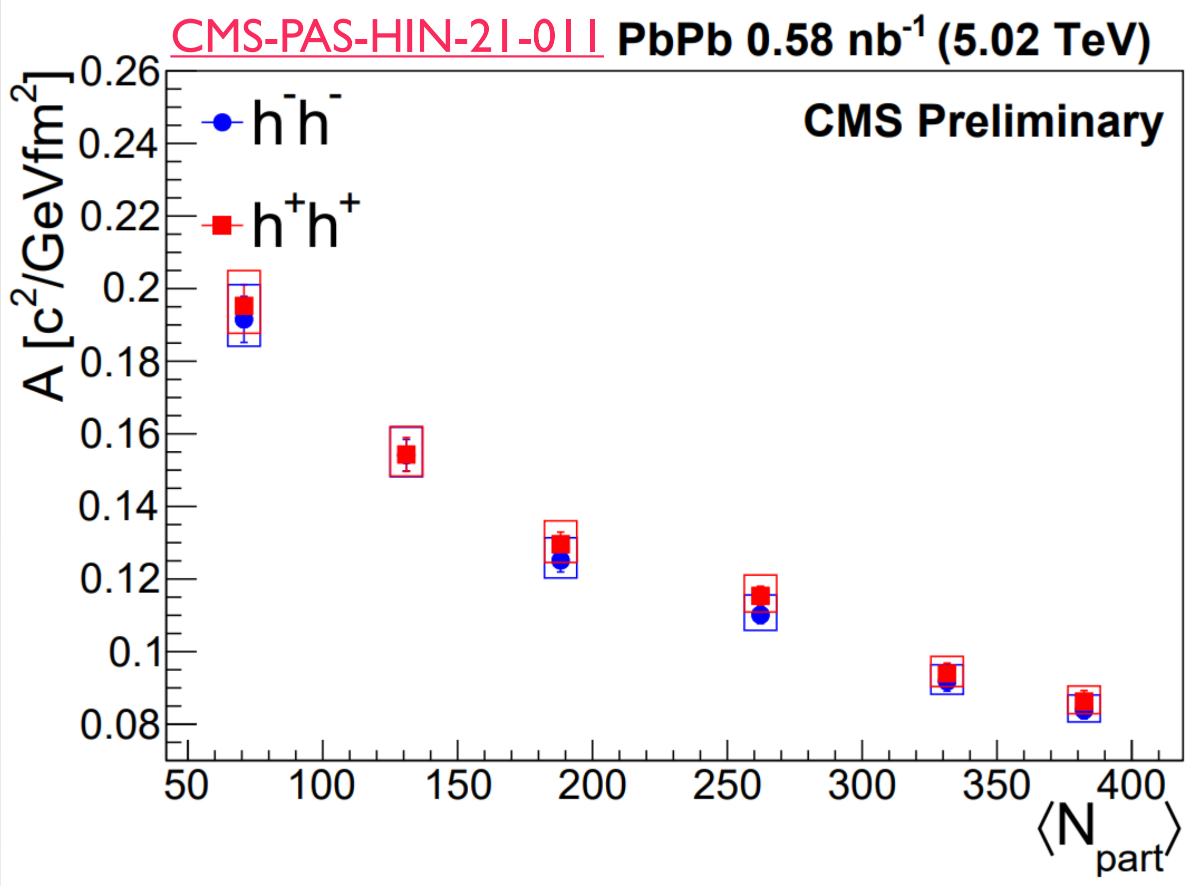


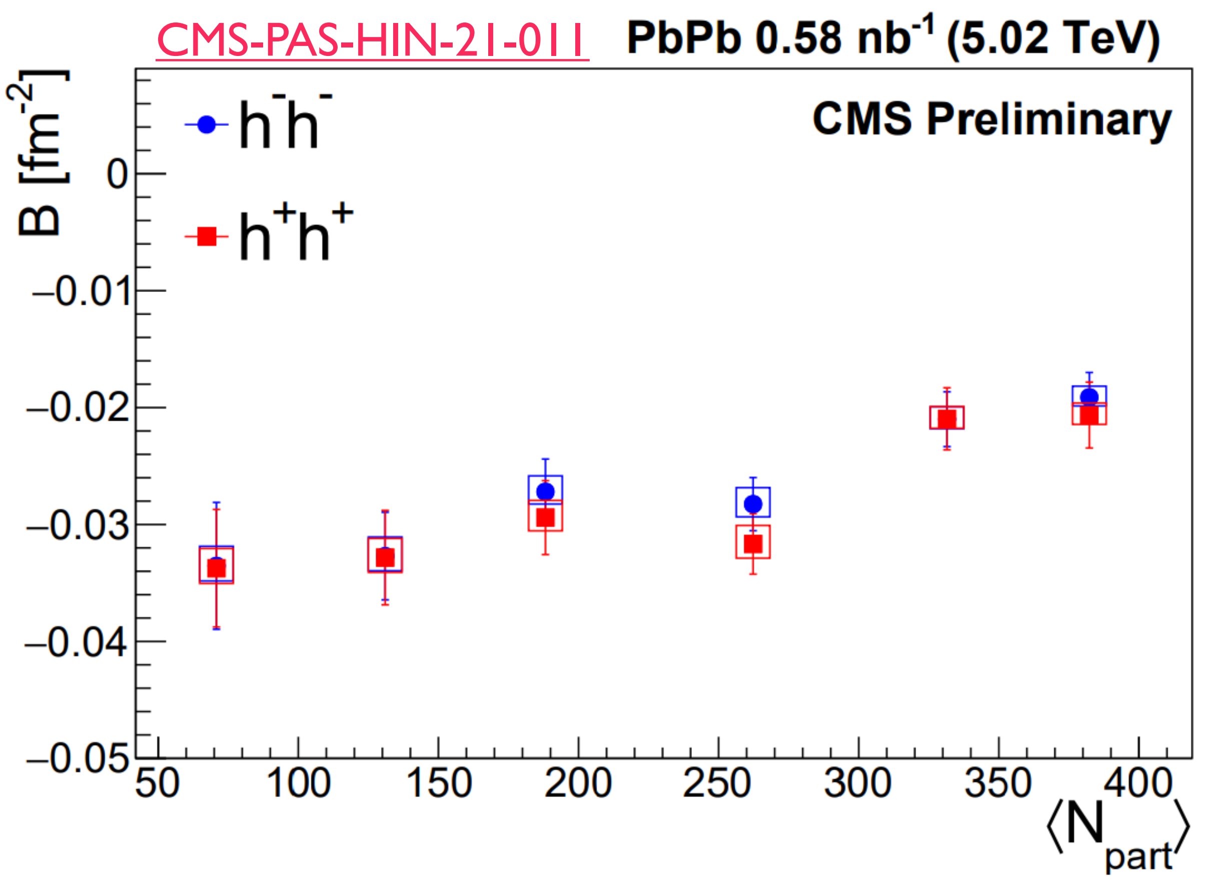
# 8/14 HYDRO SCALING OF $1/R^2$ VS $m_T$

- Hydrodynamic model: $1/R^2 \sim m_T$ $(\alpha = 2)$
  - Slope (A) → QGP Hubble constant : $A = \frac{H^2}{T_f}$
  - Intercept (B) → Size at freeze-out : $B = \frac{1}{R_f^2}$
- Uncorrelated syst. + stat. uncertainties for fitting
- Verifies hydrodynamic scaling
- Hubble constant between $0.12\ \mathrm{fm}^{-1}$ and $0.18\ \mathrm{fm}^{-1}$
- Centrality dependence



# 9/14 PARAMETERS OF THE HYDRO FIT



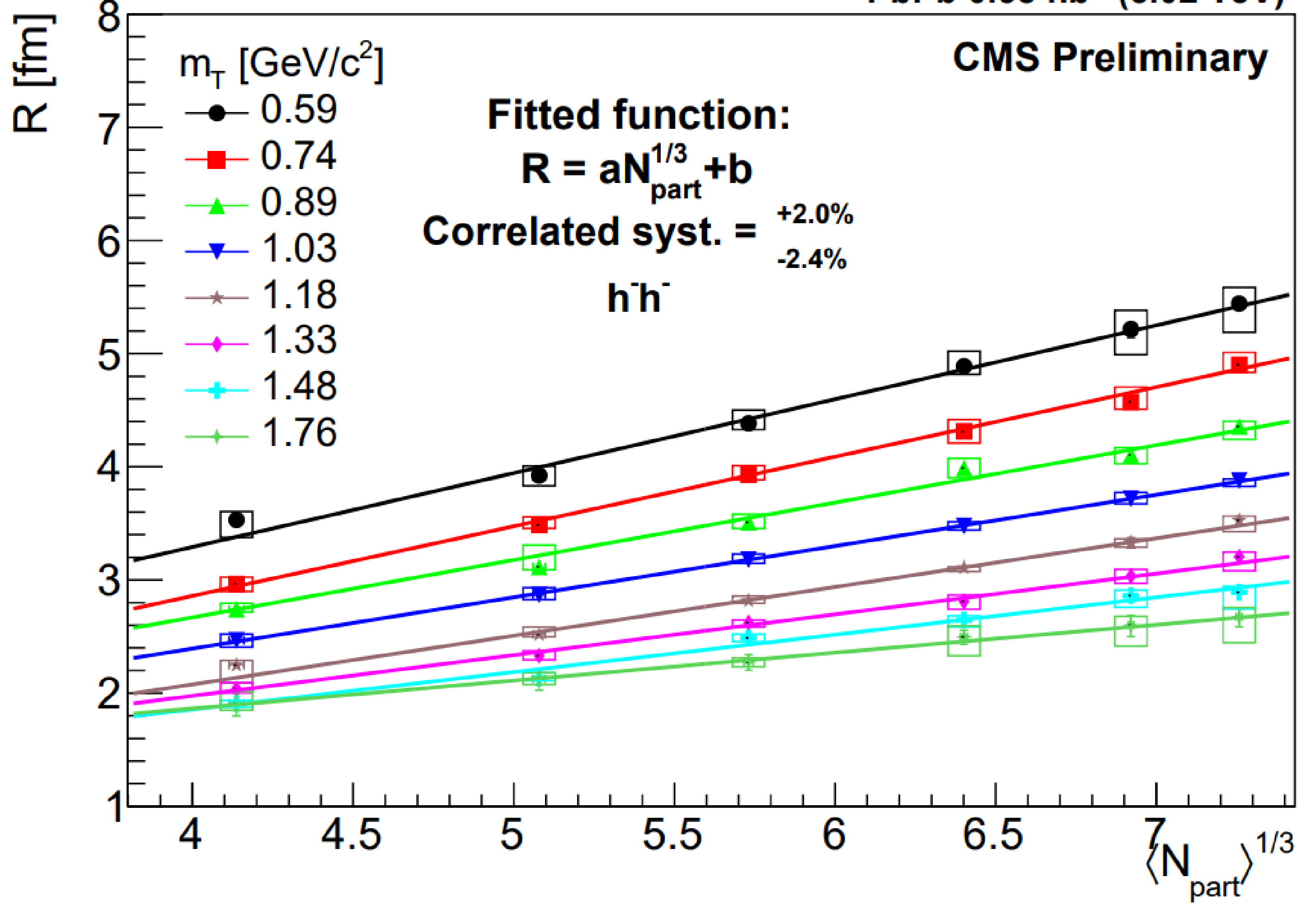

- A decreasing monotonically with $\langle N_{\text{part}} \rangle$
- Centrality dependent expansion speed

- B negative, close to constant
- Caused by Lévy source?

# 10/14 THE LÉVY SCALE PARAMETER: R VS $N_{\text{part}}$

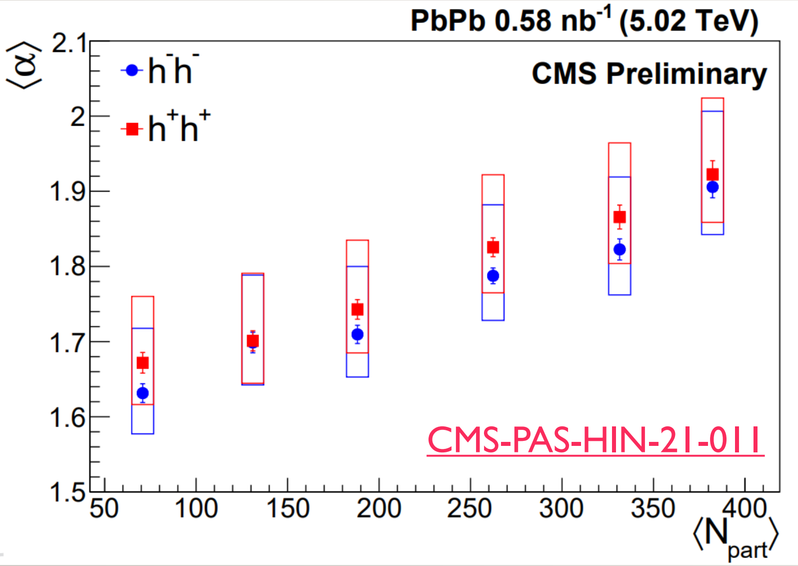
- $\langle N_{\text{part}} \rangle^{1/3} \sim$ one-dimensional size
- If $R \sim \langle N_{\text{part}} \rangle^{1/3} \rightarrow$ geometrical meaning of $R$
- Linear scaling verified

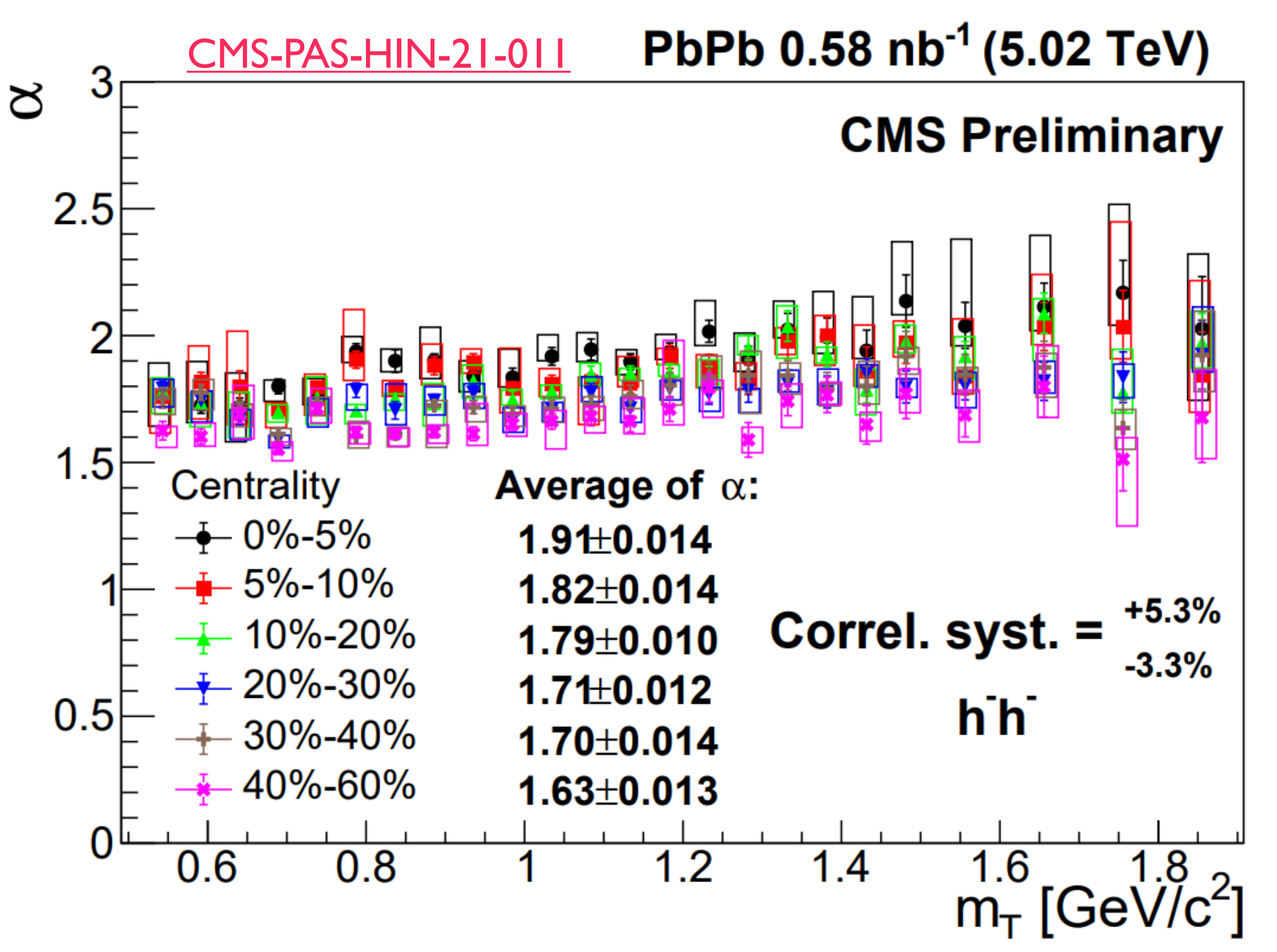
CMS-PAS-HIN-21-011



# 11/14 THE LÉVY STABILITY INDEX: α

- Source deviation from Gaussian ($\alpha = 2$)
- Almost constant at each centrality
- Centrality dependent source
- Avareage value between 1.6 and 2.0
  - $\langle\alpha\rangle$ increasing with $\langle N_{\mathrm{part}}\rangle$
  - Systematically larger for positive pairs
- Lévy assumption correct



# 12/14 THE CORRELATION STRENGTH: λ

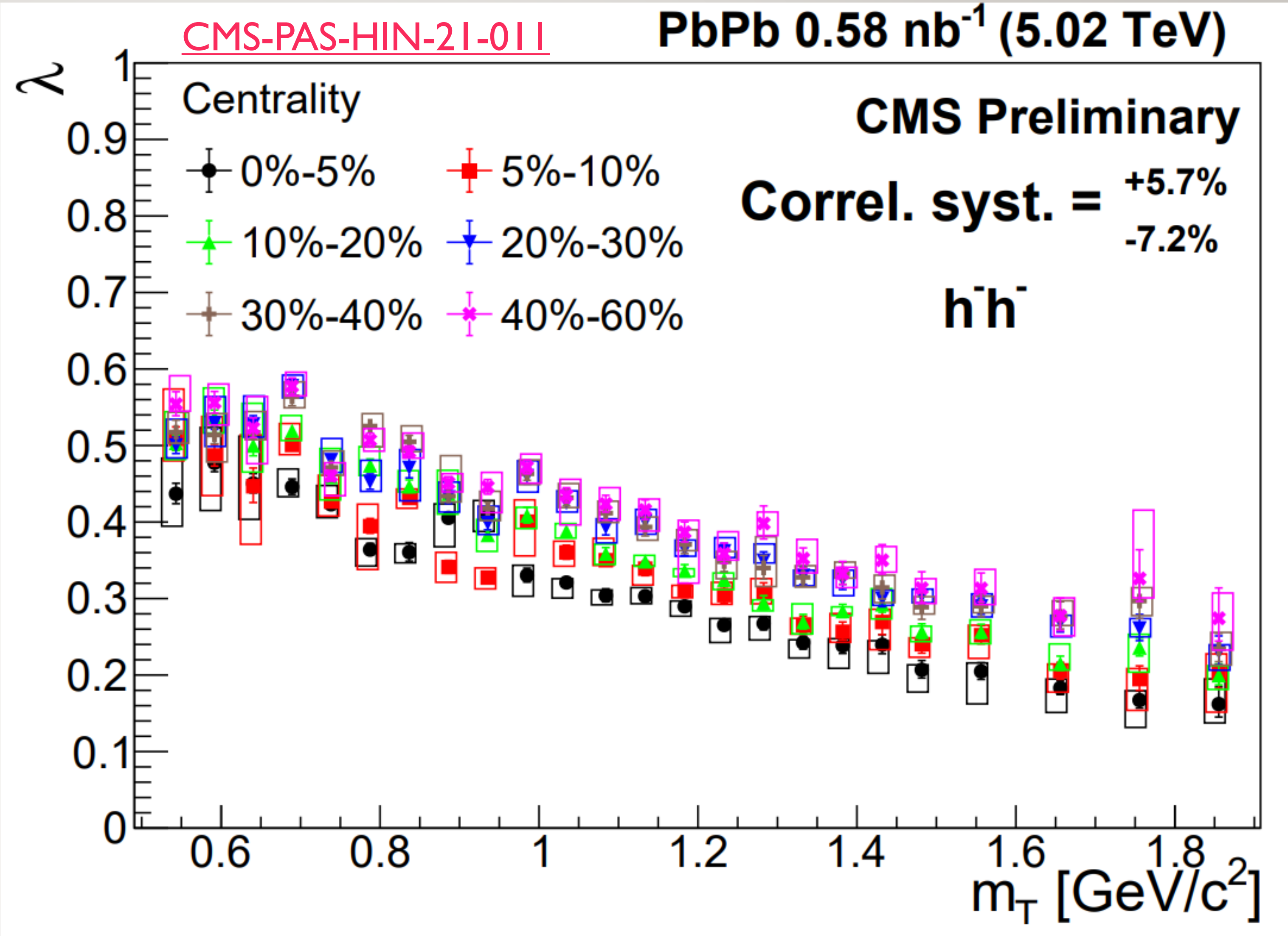
- Value of λ determined by:
  - Core-halo model:

$$\lambda = \left(\frac{N_{core}}{N_{core} + N_{halo}}\right)^2$$

  - Lack of particle identification:

$$\lambda \leq \left(\frac{N_{pion}}{N_{hadron}}\right)^2$$

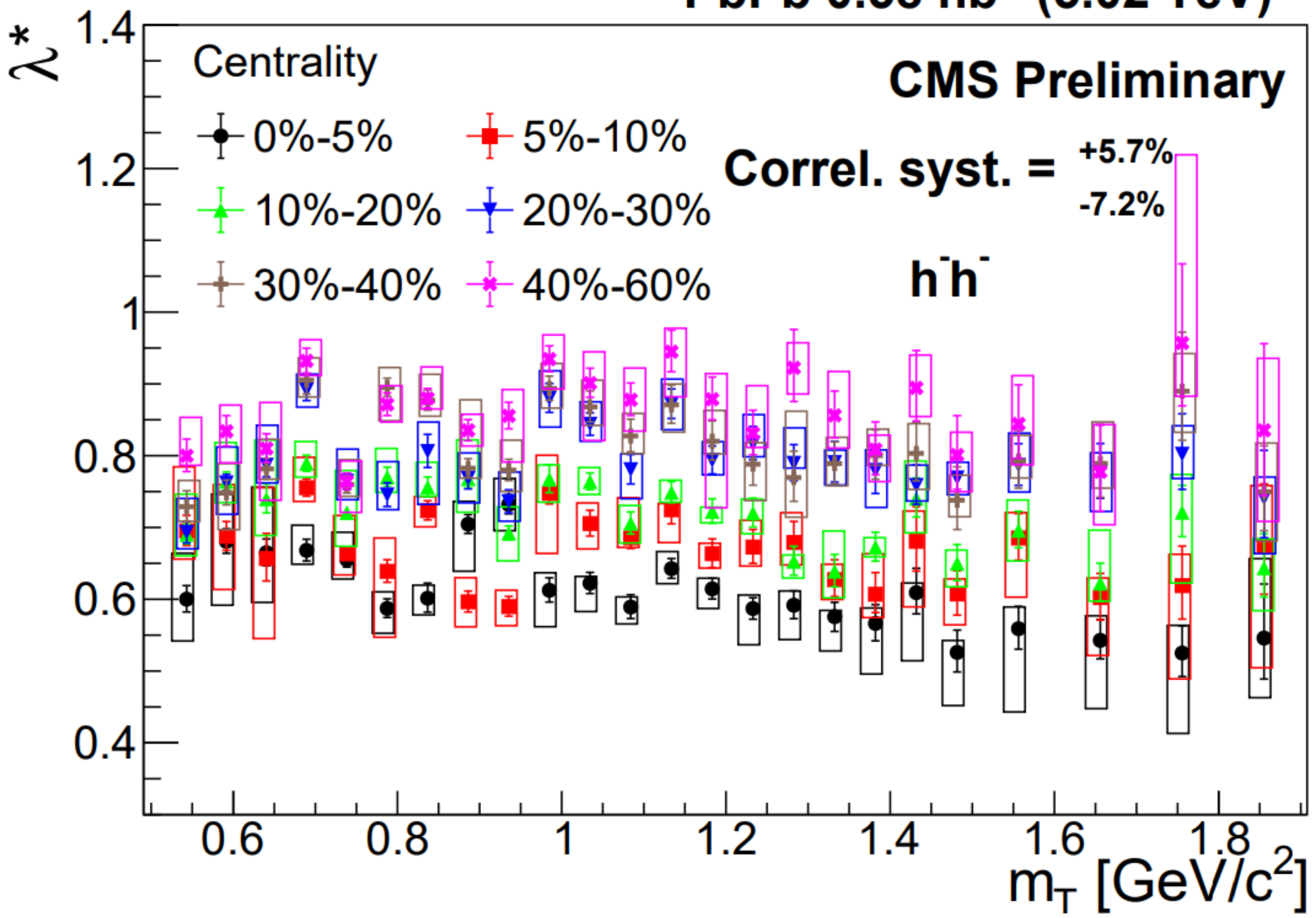
  - Coherent pion production …
- Decreasing trend
  - Caused by increasing kaon, proton ratio?
- Minimal centrality dependence



# THE CORRELATION STRENGTH: λ

- $m_T$ and centrality dependent $K/\pi$ and $p/\pi$ ratios
- Rescaling with the pion ratio:
  - $\lambda^* = \dfrac{\lambda}{(N_{pion}/N_{hadron})^2}$
  - $K/\pi$ and $p/\pi$ from ALICE: *Phys.Rev.C 101 (2020) 4, 044907*
- Almost constant trend at each centrality
- Centrality dependent core-halo ratio

CMS-PAS-HIN-21-011



# 14/14 SUMMARY

- Bose-Einstein correlations CMS 5.02 TeV PbPb
- Centrality dependent Lévy HBT analysis
  - PAS: CMS-PAS-HIN-21-011
- Results:
  - $1/R^2$ linear scaling in $m_T \rightarrow$ hydrodynamic model verified
    - Hubble constant between $0.12\ \mathrm{fm}^{-1}$ and $0.18\ \mathrm{fm}^{-1}$ and centrality dependent
  - $R$ linear scaling in $\langle N_{\mathrm{part}} \rangle^{1/3} \rightarrow$ generalized homogeneity length of the source
  - $\alpha$ between 1.6 and 2.0 $\rightarrow$ Lévy source
    - Centrality dependent
    - Almost constant at each centrality
  - Decreasing $\lambda$
    - Caused by the lack of PID
    - Centrality dependent

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# Thank you for your attention!

# Backup slides

# 17 SYSTEMATIC UNCERTAINTIES

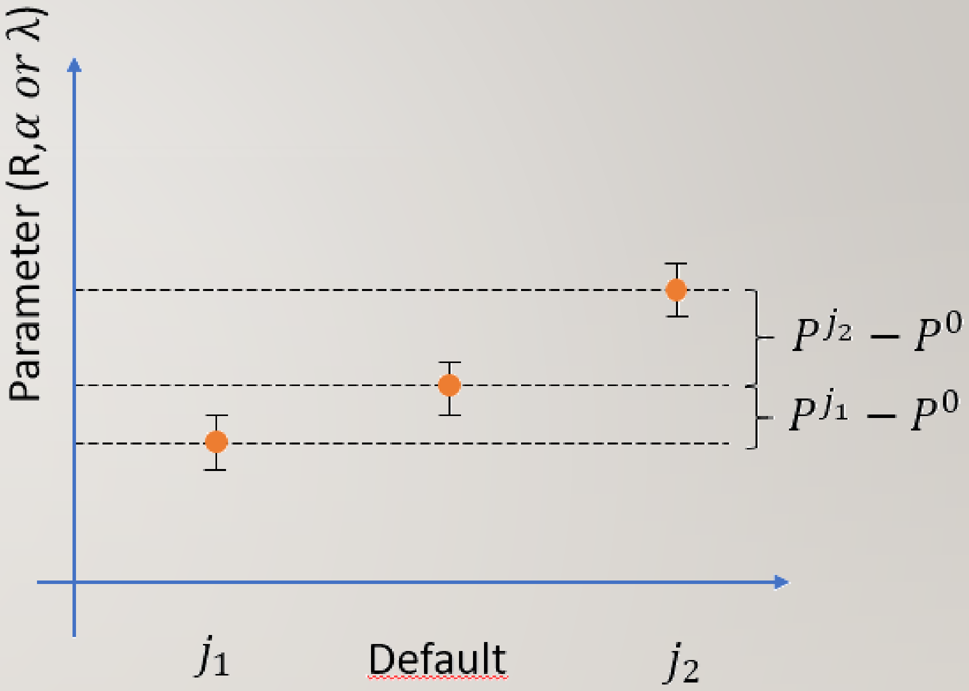
- Zvertex cut
- All particle selection cuts
- Pair cut
- Limits of the fits → biggest effect
- Centrality calibration
- Loose, default, tight settings in all cases
- Separated into "correlated" and "uncorrelated" parts

| Systematic source | Default | Low | High |
|---|---|---|---|
| Zvertex cut | $< 15$ cm | $< 12$ cm | $< 18$ cm |
| $p_T$ cut | $> 0.5$ GeV/c | $> 0.55$ GeV/c | $> 0.5$ GeV/c |
| $\delta p_T$ cut | $< 10\%$ | $< 5\%$ | $< 15\%$ |
| $\|\eta\|$ cut | $< 0.95$ | $< 0.9$ | $< 1$ |
| $N_{\text{pixel hit}}$ cut | $> 1$ | $> 2$ | $> 0$ |
| $\chi^2/N_{\text{dof}}/N_{\text{layer}}$ cut | $< 0.18$ | $< 0.15$ | $< 0.18$ |
| $\|d_{xy}/\sigma(d_{xy})\|$ cut | $< 3$ | $< 2$ | $< 5$ |
| $\|d_z/\sigma(d_z)\|$ cut | $< 3$ | $< 2$ | $< 5$ |
| $\Delta\eta, \Delta\phi$ pair cut | $\Delta\eta_{\text{cut}}$=0.014<br>$\Delta\phi_{\text{cut}}$=0.022 | $\eta_{\text{cut}}$=0.017<br>$\Delta\phi_{\text{cut}}$=0.028 | $\eta_{\text{cut}}$=0.011<br>$\Delta\phi_{\text{cut}}$=0.016 |
| $q_{\text{min}}$ lower fit limit | $q^0_{\text{min}}(K_T,\text{cent})$ | $q^0_{\text{min}}$-0.004 | $q^0_{\text{min}}$+0.004 |
| $q_{\text{max}}$ upper fit limit | $q^0_{\text{max}}(K_T,\text{cent})$ | $0.85 \cdot q^0_{\text{max}}$ | $1.15 \cdot q^0_{\text{max}}$ |
| Cent. edges | Default values | Lower values | Higher values |

# 18 CALCULATION OF THE SYSTEMATIC UNCERTAINTY

$$\delta P^{\uparrow}(i) = \sqrt{\sum_{n=\mathrm{cuts}} \frac{1}{N_n^{j\uparrow}} \sum_{j\in J_n^{\uparrow}} (P_n^j(i) - P^0(i))^2}$$

$$\delta P^{\downarrow}(i) = \sqrt{\sum_{n=\mathrm{cuts}} \frac{1}{N_n^{j\downarrow}} \sum_{j\in J_n^{\downarrow}} (P_n^j(i) - P^0(i))^2}$$




- n : different cuts i.e. $p_T$ cut, $N_{hit}$cut, pair cut, lower fit limit …
- j : loose or tight setting

# 19 UNCORRELATED AND CORRELATED SYSTEMATICS

- Calculate the average effect of a cut on a parameter
  - Average of all centrality, $K_T$ and charge classes
- Uncorrelated systematic error:
  - Calculate using the differences from the averages
  - Different for every centrality, $K_T$ and charge classes
- Correlated systematic error:
  - Calculate using the difference between the average and the default
  - Same for every centrality, $K_T$ and charge classes
- Use $\sqrt{uncorrelated^2 + statistical^2}$ for fitting

# 20 AVERAGE SYSTEMATIC EFFECTS

| $\delta R$[%] | Track and event cuts | | Pair cut | | Fit limits | | Overall | |
|---|---|---|---|---|---|---|---|---|
| Cent.[%] | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ |
| 0-5 | 1.0 | 0.4 | 0.0 | 2.9 | 2.5 | 3.2 | 2.7 | 4.3 |
| 5-10 | 0.7 | 0.5 | 0.0 | 2.1 | 2.0 | 2.3 | 2.1 | 3.2 |
| 10-20 | 0.6 | 0.4 | 0.0 | 1.4 | 1.8 | 2.3 | 1.9 | 2.7 |
| 20-30 | 0.6 | 0.3 | 0.2 | 1.6 | 1.8 | 1.9 | 1.9 | 2.5 |
| 30-40 | 0.5 | 0.2 | 0.6 | 1.5 | 1.9 | 1.7 | 2.1 | 2.3 |
| 40-60 | 0.5 | 0.5 | 0.7 | 1.4 | 1.9 | 1.7 | 2.1 | 2.3 |

| $\delta\alpha$[%] | Track and event cuts | | Pair cut | | Fit limits | | Overall | |
|---|---|---|---|---|---|---|---|---|
| Cent.[%] | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ |
| 0-5 | 0.6 | 0.7 | 4.8 | 0.0 | 6.9 | 3.8 | 8.4 | 3.9 |
| 5-10 | 1.1 | 0.6 | 3.2 | 0.0 | 5.2 | 3.0 | 6.2 | 3.1 |
| 10-20 | 0.3 | 0.4 | 1.9 | 0.0 | 4.9 | 3.0 | 5.3 | 3.0 |
| 20-30 | 0.1 | 0.5 | 2.0 | 0.1 | 5.1 | 2.8 | 5.5 | 2.8 |
| 30-40 | 0.2 | 0.7 | 2.0 | 0.7 | 4.5 | 3.5 | 4.9 | 3.6 |
| 40-60 | 0.4 | 0.4 | 1.7 | 0.7 | 4.4 | 4.0 | 4.7 | 4.1 |

| $\delta\lambda$[%] | Track and event cuts | | Pair cut | | Fit limits | | Overall | |
|---|---|---|---|---|---|---|---|---|
| Cent.[%] | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ | ↓ |
| 0-5 | 4.7 | 2.0 | 0.0 | 6.8 | 6.1 | 8.9 | 7.7 | 11.4 |
| 5-10 | 3.7 | 1.7 | 0.0 | 5.5 | 4.9 | 6.9 | 6.1 | 9.0 |
| 10-20 | 2.6 | 1.3 | 0.0 | 4.3 | 4.7 | 6.5 | 5.4 | 7.9 |
| 20-30 | 2.4 | 1.0 | 1.1 | 4.4 | 4.2 | 6.4 | 5.0 | 7.8 |
| 30-40 | 2.4 | 0.9 | 1.7 | 4.0 | 4.9 | 5.6 | 5.7 | 6.9 |
| 40-60 | 2.0 | 0.9 | 1.7 | 3.3 | 5.6 | 5.1 | 6.2 | 6.1 |

# 21 THE PHYSICAL MEANING OF THE FIT PARAMETERS

- Usually plot them vs transverse mass: $m_T = \sqrt{m^2 + (K_T/c)^2}$
- Lévy scale parameter *R* :
  - Generalised homogeneity length of the source
  - Hydrodynamic model: $1/R^2 \sim m_T$ (if $\alpha = 2$)
    - Slope of the line (A) → QGP's Hubble constant: $A = \frac{H^2}{T_f}$
    - Intercept of the line (B) → geometrical size at freeze-out
- Lévy stability index $\alpha$ :
  - Difference compared to Gaussian distribution ($\alpha = 2$)
    - Anomalous diffusion, fragmentation of jets …
  - Sign of the QCD critical point (not at LHC energies)
- Correlation strength λ :
  - Core-halo model: $C(q \to 0) = 1 + \lambda$
  - Other possible causes i.e. coherent pion production, restoration of the chiral symmetry …