BOSE-EINSTEIN CORRELATIONS IN PP COLLISIONS AT 13 TEV

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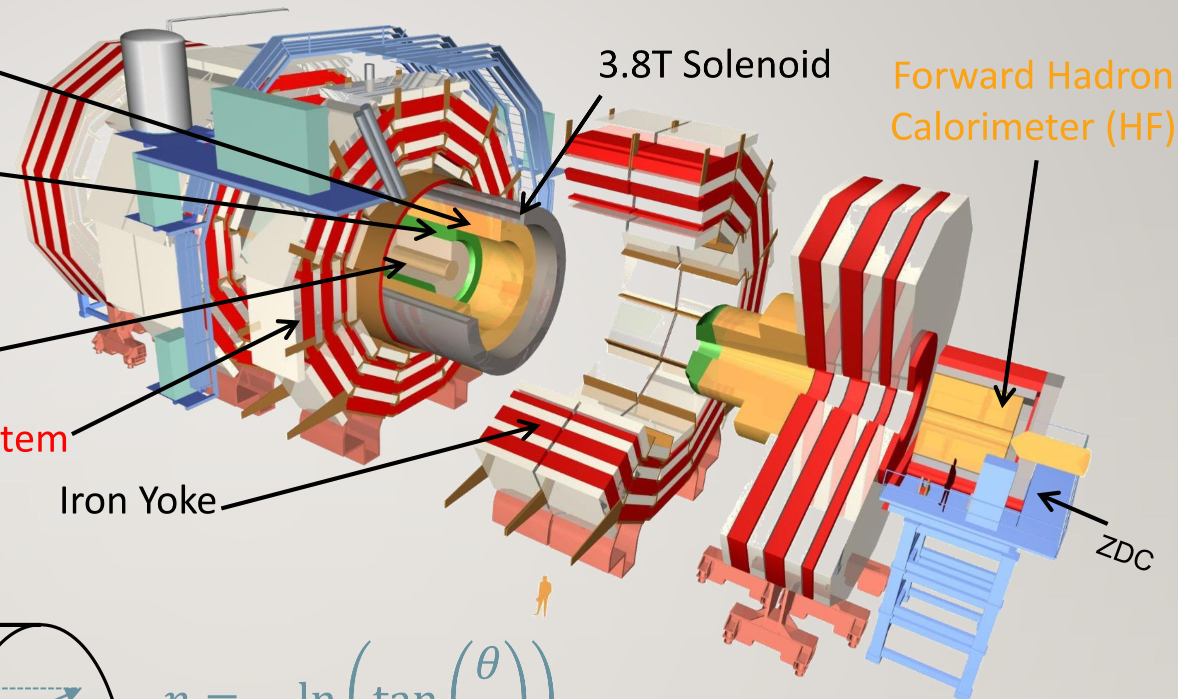
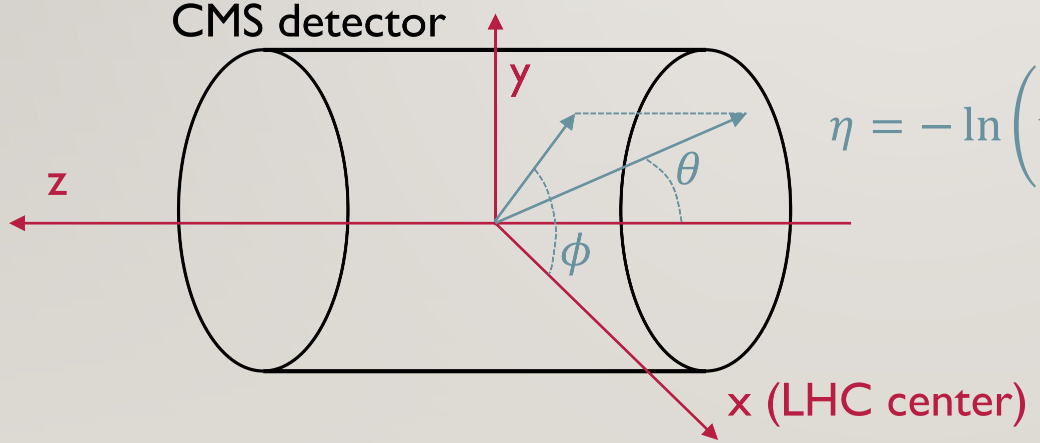
ZIMÁNYI SCHOOL WINTER WORKSHOP 2019

THE CMS DETECTOR

Hadron Calorimeter (HCAL)
EM Calorimeter (ECAL)
TRACKER (Pixels and Strips)
Muon System
Iron Yoke
3.8T Solenoid
Forward Hadron Calorimeter (HF)



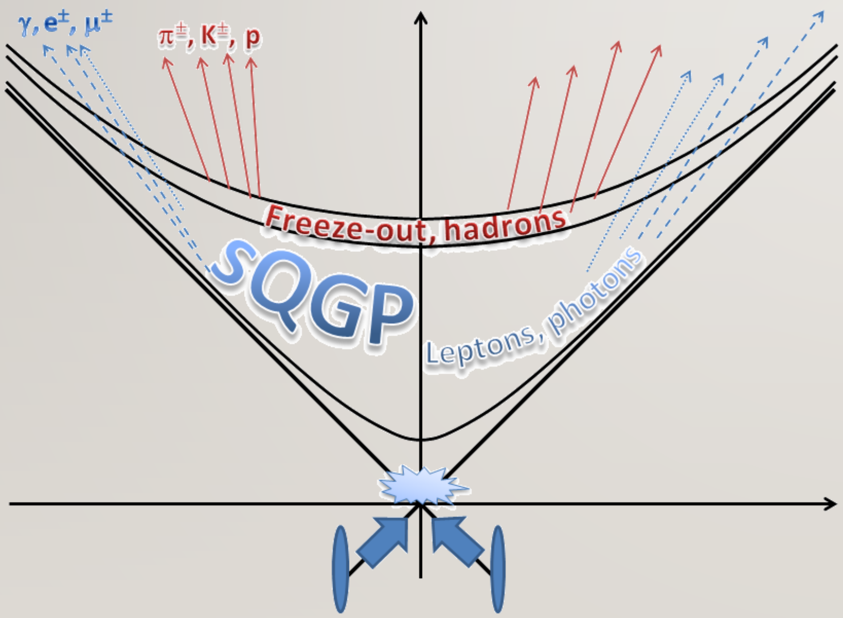


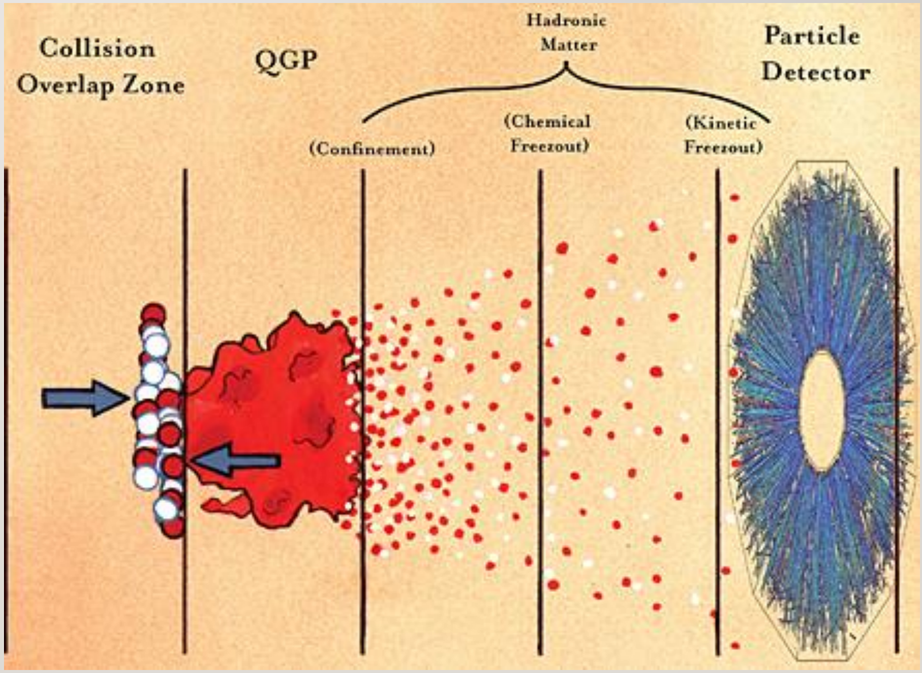
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Muon	$\lvert\eta\rvert < 2.4$
HF, HCAL, HF	$\lvert\eta\rvert < 5.2$
ECAL	$\lvert\eta\rvert < 3.0$
Tracker	$\lvert\eta\rvert < 2.5$

3/16 SPACE-TIME STRUCTURE OF A COLLISION

- $5 \cdot 10^{12}$ Kelvin, strongly interacting Quark Gluon Plasma (sQGP) is created
- Expands and cools down, forms a hadron gas in 10^{-22} s
- We observe the "frozen" particles: hadrons
- How to access space-time geometry when only momenta are measured?

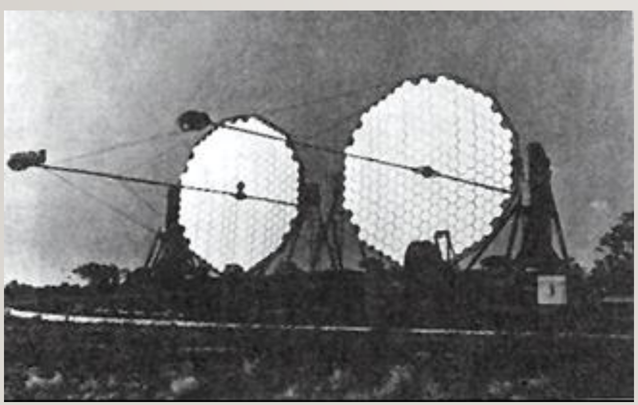


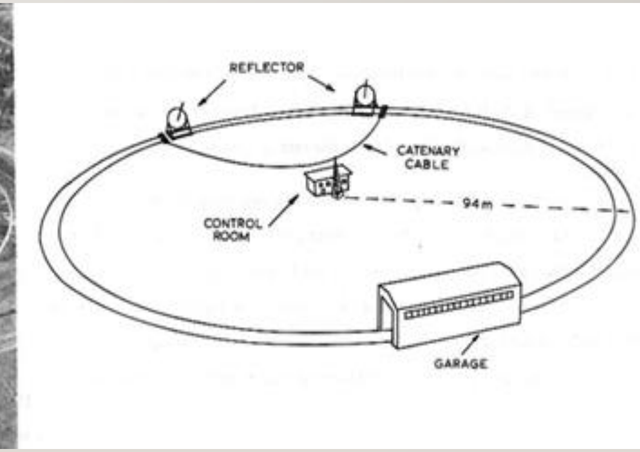


A SUPRISING DISCOVERY: HBT-CORRELATIONS

- Radio astronomy: Jansky, 1933, weird 24 hour oscillation; stars emit radio frequency waves as well
- R. H. Brown: radio astronomy measurements at Jordell bank
- Strange correlations observed: diameter of a star can be measured
- R. Q. Twiss helps to work out the details

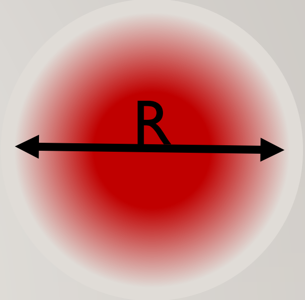
  Nature 170, 1061; Nature 177, 27; Nature 180, 324; Nature 178, 1046; Mon. Notices Royal Astron. Soc. 137, 375; Nature 201, 1111; Mon. Notices Royal Astron. Soc. 137, 393



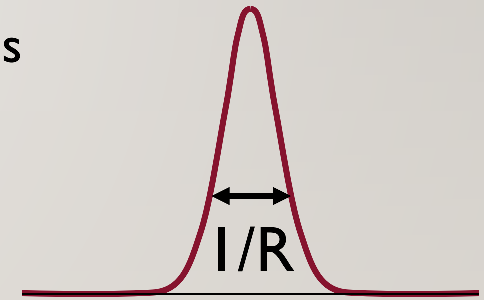


HBT IN PARTICLE PHYSICS: FEMTOSCOPY

- Goldhaber, Goldhaber, Lee & Pais: pion pairs in p+p̄ collisions, HBT-effect
  Phys.Rev. 120 (1960) 300, Phys.Rev.Lett. 3 (1959) 181
- Departure from conventional statistics:
  Bose-Einstein statistics
- Understanding: Glauber, Fano, Baym, …
  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …
- Birth of femtoscopy: reconstructing femtometer sources
  - Momentum correlation $C(q)$ related to source $S(r)$
  - $C(q) \cong 1 + \left|\int S(r) e^{iqr} dr\right|^2$ (under some assumptions)
  - Or the distance distribution $D(r)$:
    $C(q) \cong 1 + \int D(r) e^{iqr} dr$
- Measure C(q): map out source space-time geometry on femtometer scale!



source function S(r)



correlation function C(q)

6/16 EVENT&TRACK SELECTION, CORRELATIONS

- Event selection to reduce beam background & diffractive events
  - At least 1 reconstructed Primary Vertex: $|V_z|< 15$ cm, $|V_r|< 0.15$ cm (vertex distance to beam)
  - HighPurity track fraction > 25% [see details in: CMS Collab., JINST 9 (2014) P10009]
  - At least one tower with E > 3 GeV in both HadronForward calorimenters
- Track selection:
  - HighPurity tracks only, $p_T > 0.2$ GeV, $|\eta|< 2.4$
  - $|\sigma_{pT}/p_T|< 0.1$, $|d_z/\sigma_{dz}| < 3$, $|d_{xy}/\sigma_{dxy}| < 3$ (d: distance to Primary Vertex)
  - At least one pixel layer
- $N_{\mathrm{track}}^{\mathrm{offline}}$ definition: same except $p_T > 0.4$ GeV and no pixelLayer cut
- Pair distribution as a function of $q_{\mathrm{inv}} = \sqrt{-(p_1 - p_2)^2}$
- In several intervals of $N_{\mathrm{track}}^{\mathrm{offline}}$ and $k_T = |p_{1T} + p_{2T}|/2$
- Non-femtoscopic background removed with different methods (see next slides)
- Correlation function fitted with $C(q) = N(1 + \lambda e^{-q_{\mathrm{inv}} R_{\mathrm{inv}}})(1 + q_{\mathrm{inv}}\epsilon)$

PAIR DISTRIBUTION, CORRELATION FUNCTION

- Theoretical definition of Bose-Einstein (femtoscopic) correlation function:

$$C_2(q,K) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}, \text{ where } q = p_1 - p_2 \text{ and } K = \frac{1}{2}(p_1 - p_2)$$

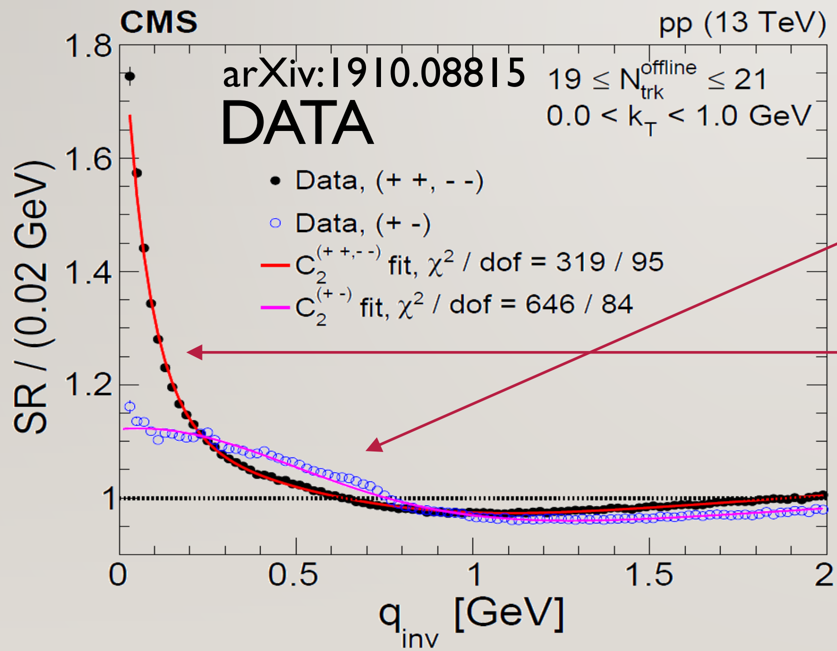
- If assuming Cauchy source, then correlation function: $\boldsymbol{C_2 = 1 + \lambda e^{-q_{\text{inv}} R_{\text{inv}}}}$
- How to realize in experiment? Creating non-femtoscopic background
  - Opposite charge sample (c.f. resonances, Coulomb interaction)
  - Rotation or opposite hemisphere (c.f. residual same-event effects)
  - Event mixing!
- Femtoscopic correlation function: signal / background (Single Ratio, SR)

$$C_2(q,K) = \frac{A(q,K)}{B(q,K)}, \text{ where } A(q,K)\text{: same event pairs, } B(q,K)\text{: mixed event pairs}$$

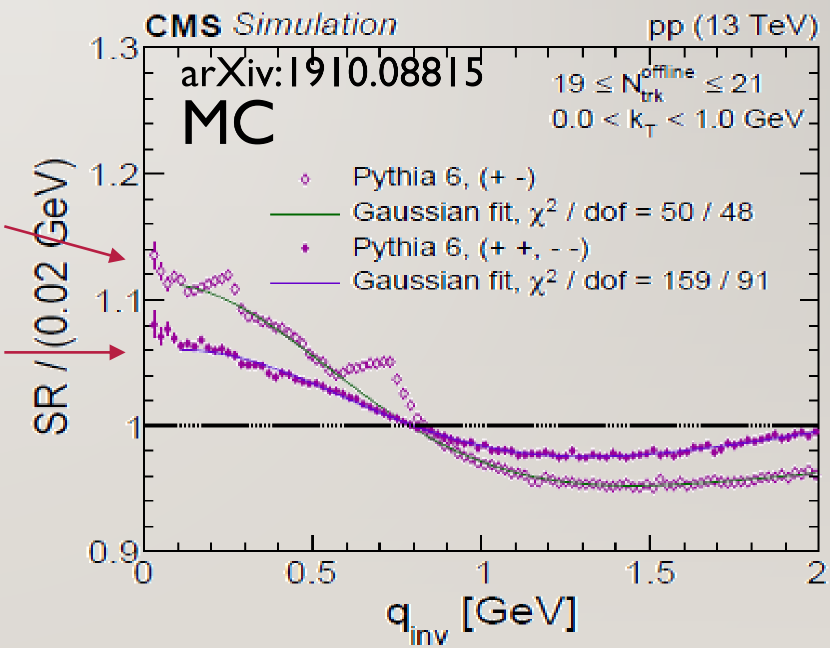
- Background pair distribution $B(q,K)$ removes some non-femtoscopic effects
  - Single particle momentum distribution, tracking, efficiency, acceptance, …
  - How to remove these?

8/16 SINGLE RATIOS AND NON-FEMTOSCOPIC BKG

- Single Ratio $C_2(q, K)$ still contains non-femtoscopic effects
  - Final-state effects (Coulomb, strong interaction): handled by corrections
  - Pair reconstruction: handled by cuts in q-space
  - Residual correlations due to minijets, clusters, mom. conservation: long range background
  - High-multiplicity collisions: dominant contribution is femtoscopy (scales with multiplicity^2)
- In pp, cluster contribution important, estimation via $(+,-)$ pairs or MC

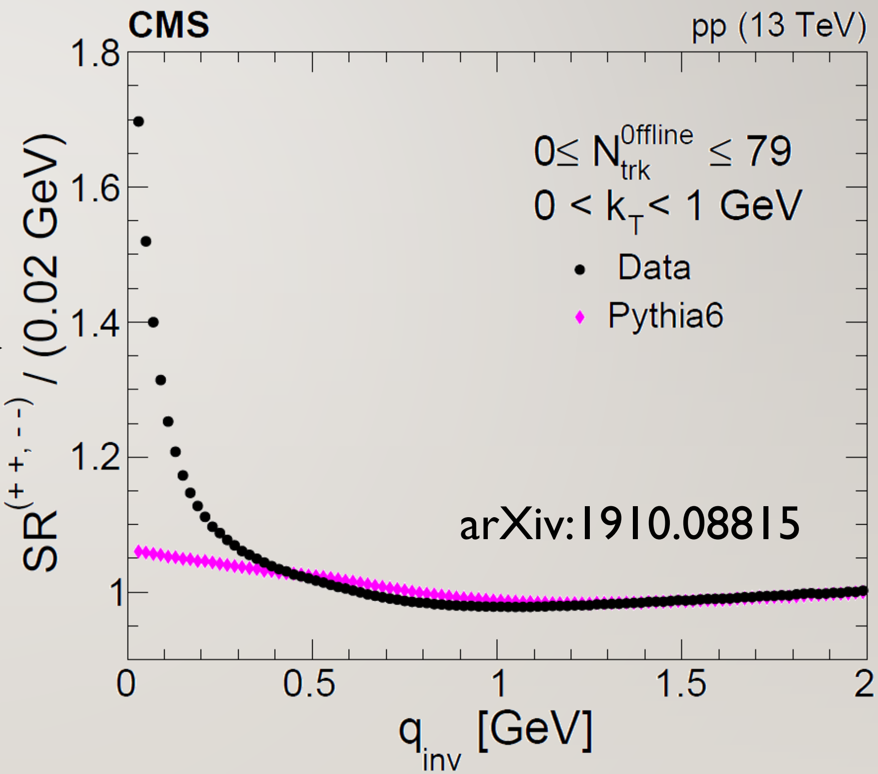


(+, −)
(±, ±)



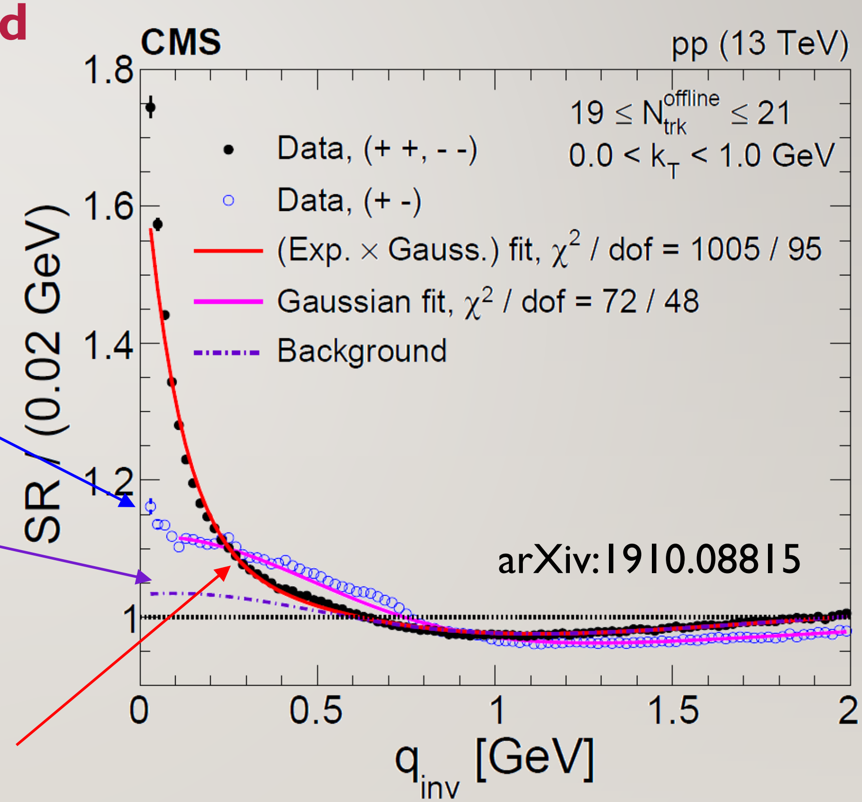
9/16 ANALYSIS METHODS: DOUBLE RATIO

- How to remove residual non-femtoscopic background?
  - Due to minijets, momentum conservation, pair acceptance, …
- **Double Ratio (DR) method**
  PRC 97 (2018) 064912 [CMS]
  PRL 105 (2010), JHEP 05 (2011) [CMS]
- Single Ratio (SR) from event mixing
  - Both in Data and MonteCarlo
- Data over MonteCarlo:
  removes non-femtoscopic effects
- Fit Double Ratio with
  femtoscopic fit function
- Significant dependence on MonteCarlo choice



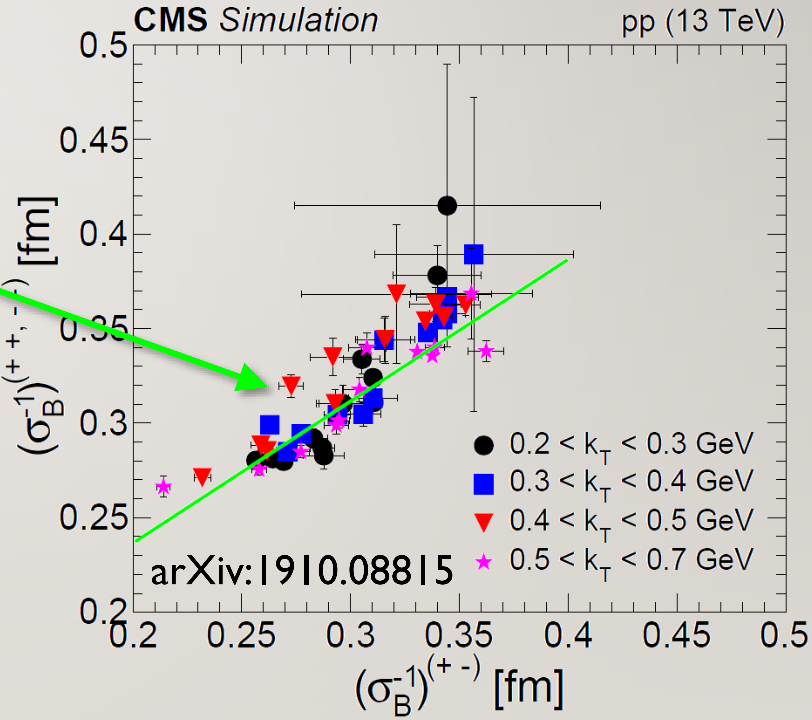
ANALYSIS METHOD: CLUSTER SUBSTRACTION

- Remove MonteCarlo dependence: estimate non-femtoscopic effects based on data
- **Cluster Substraction (CS) method**
  PRC 97 (2018) 064912 [CMS]
- Non-femtoscopic clusters: shape estimated via $(+,-)$ pairs
- Cluster strength directly estimated in $(\pm,\pm)$ data
- Fit SR with functional form combining signal+cluster component: exponential (BEC) x Gauss (non-BEC)



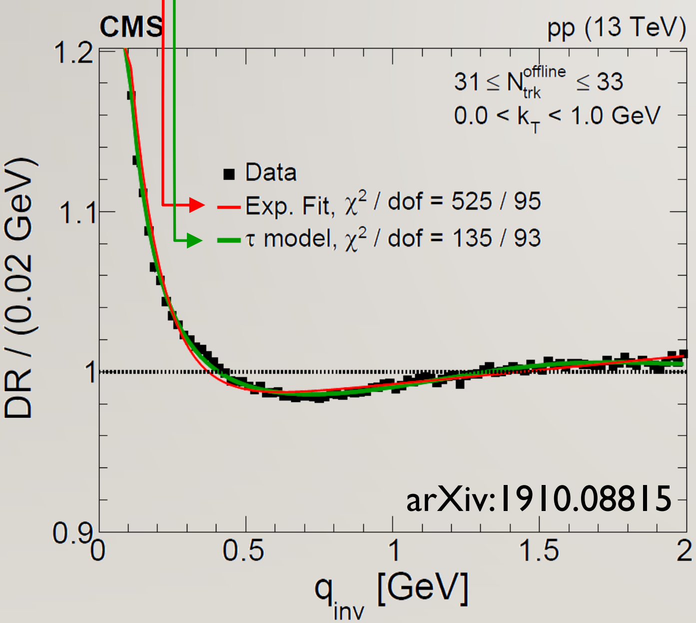
ANALYSIS METHOD: HYBRID CLUSTER SUBSTR.

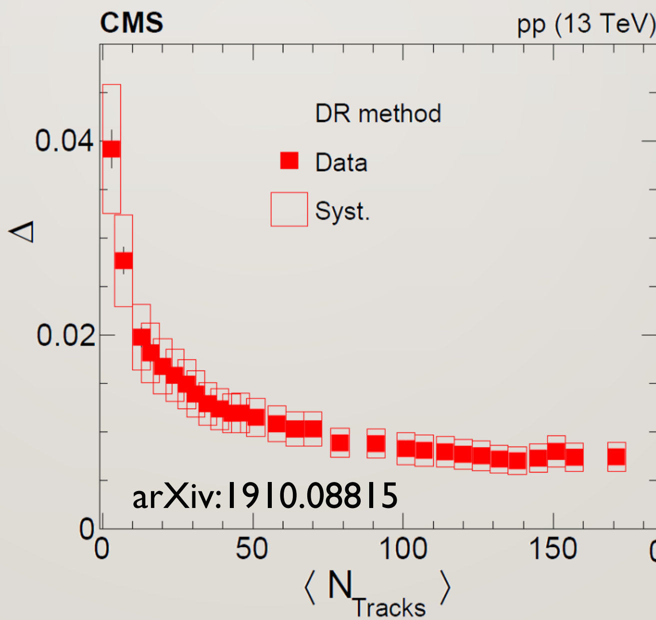
- A further possibility: estimate non-BEC clusters via MonteCarlo
- **Hybrid Cluster Substraction (HCS) method**
  PRC 96 (2017) 064908 [ATLAS]
- Non-BEC clusters fitted in data and MC, for both $(\pm,\pm)$ and $(+,-)$
- Determine $(\pm,\pm)$ to $(+,-)$ relation in MonteCarlo (Pythia 6 – Z2*)
- Use this to convert $(\pm,\pm)$ to $(+,-)$ in data
- Fit SR with functional form combining BEC+cluster components

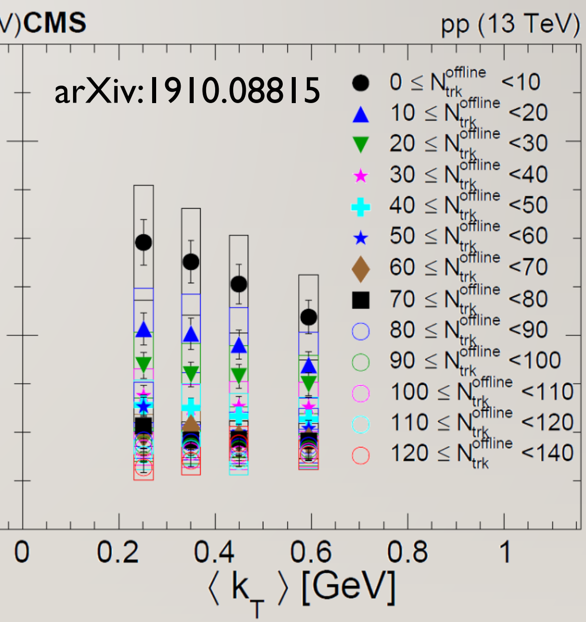


SHAPE ANALYSIS: ANTICORRELATION/DIP

- Small region of anticorrelation (aka „dip”) at intermediate q
  - Fitted with slope times exponential: statistically not acceptable description
  - Fitted with form based on τ-model [Csörgő, Zimányi NPA 517 (1990) 588]
- Dip depth (Δ) analyzed as a function of multiplicity & transverse momentum
  - Maybe related to DoubleRatio method itself, maybe intrinsic property?

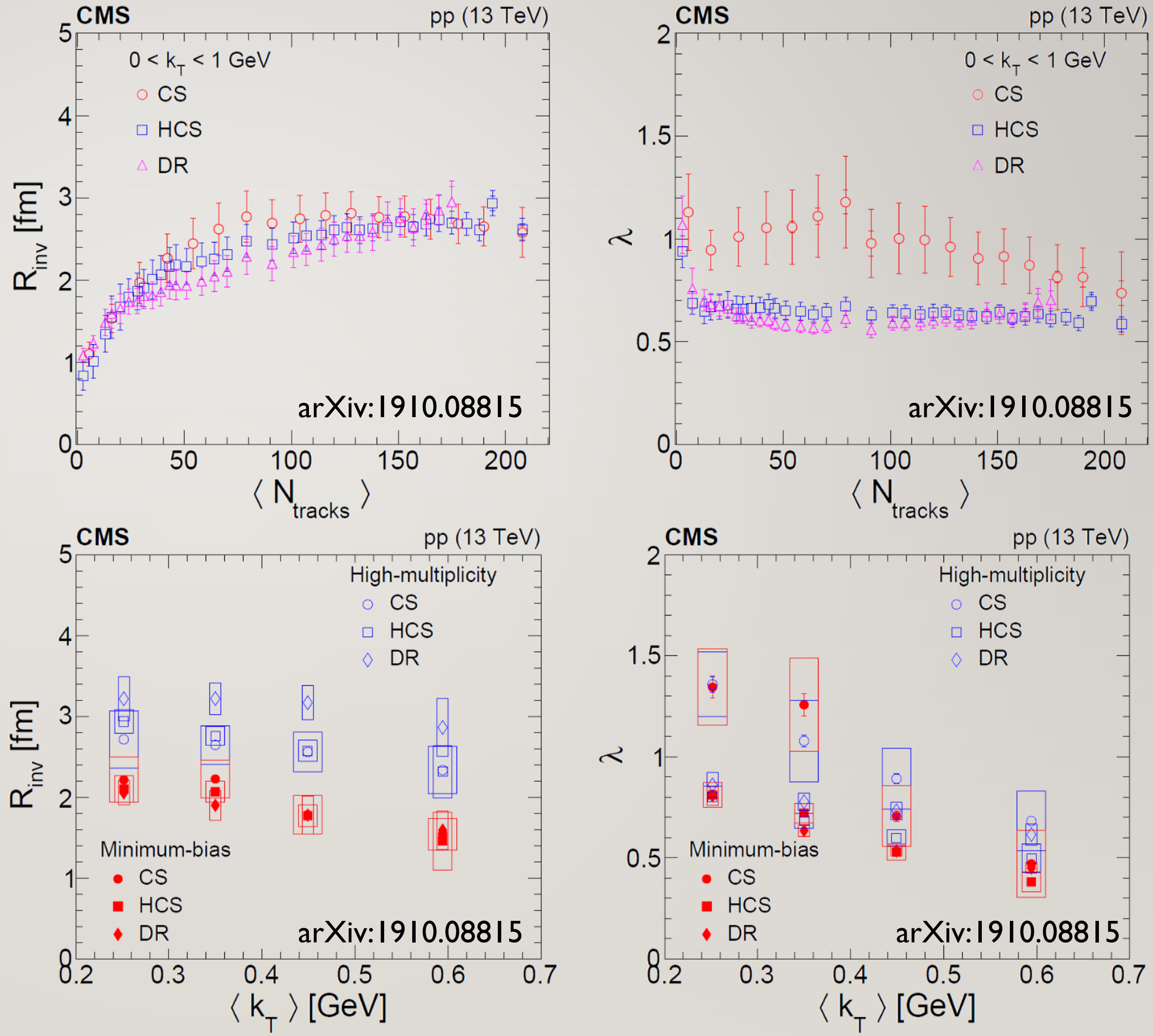






RESULTS: METHOD DEPENDENCE

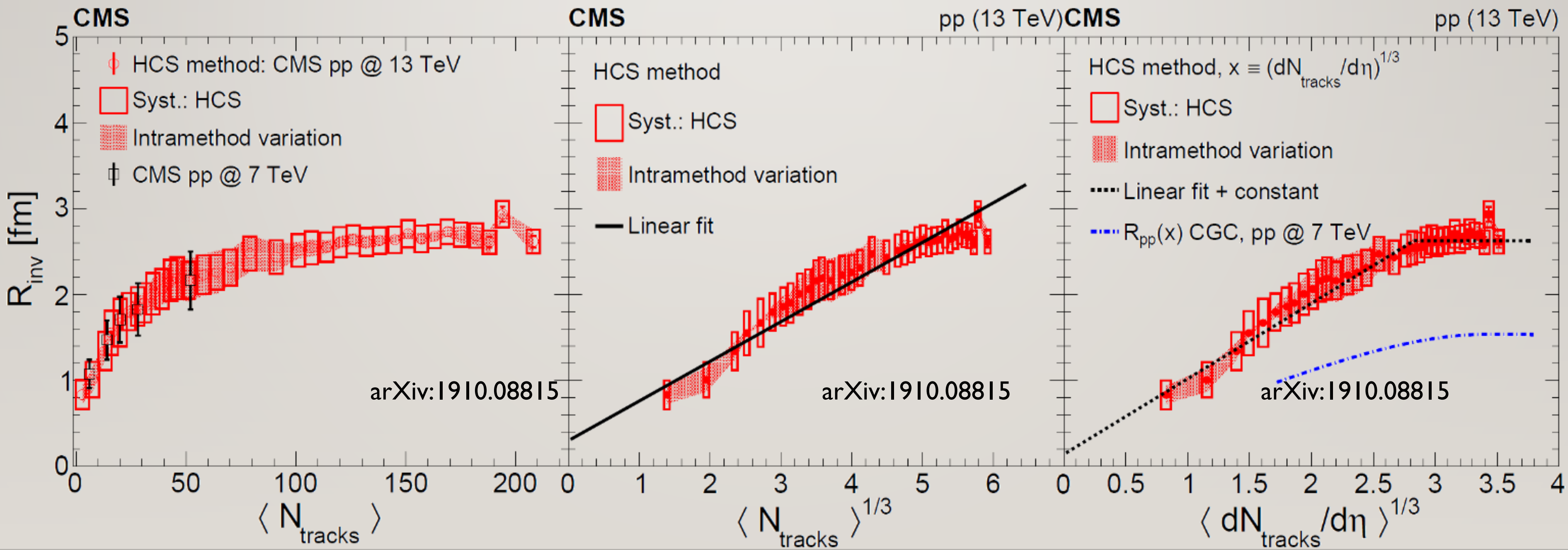
- Recall three methods:
  - Double Ratio
  - Cluster Substraction
  - Hybrid Cluster Substr.
- Fit parameters:
  - HBT radius R_{inv}
  - Correlation strength λ
- As a function of:
  - Multiplicity $\langle N_{\text{tracks}} \rangle$
  - Transverse mom $\langle k_T \rangle$
- Methods yield compatible results



RESULTS: MULTIPLICITY DEPENDENCE

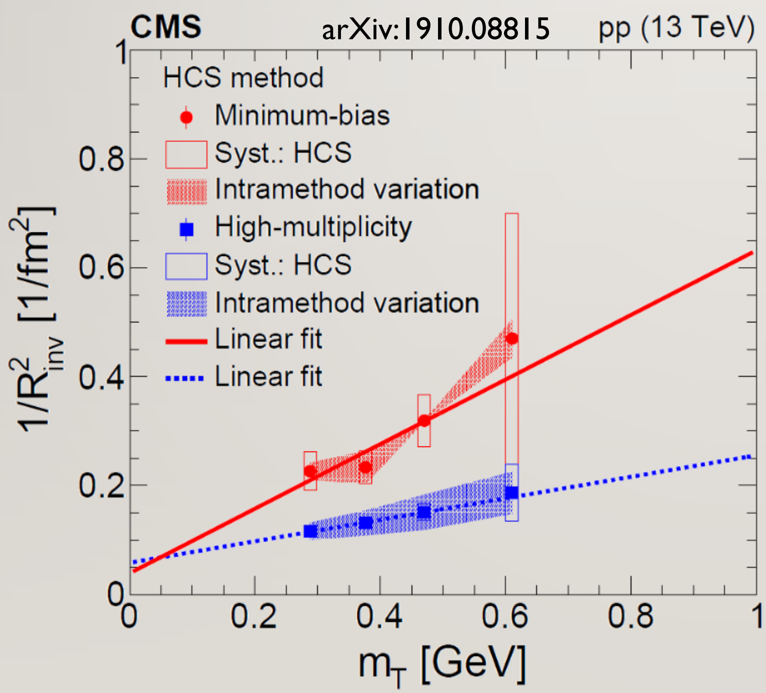
- Results compatible with 7 TeV (ATLAS also), much higher multiplicities avail.
- R_{inv} increasing with multiplicity: geometrical understanding of HBT radius
  - $N_{\mathrm{tracks}}^{1/3}$: ~ final state size; R_{inv}: length of homogeneity; two related in hydro (especially R_{long})
- CGC predicts specific dependence, qualitatively confirmed

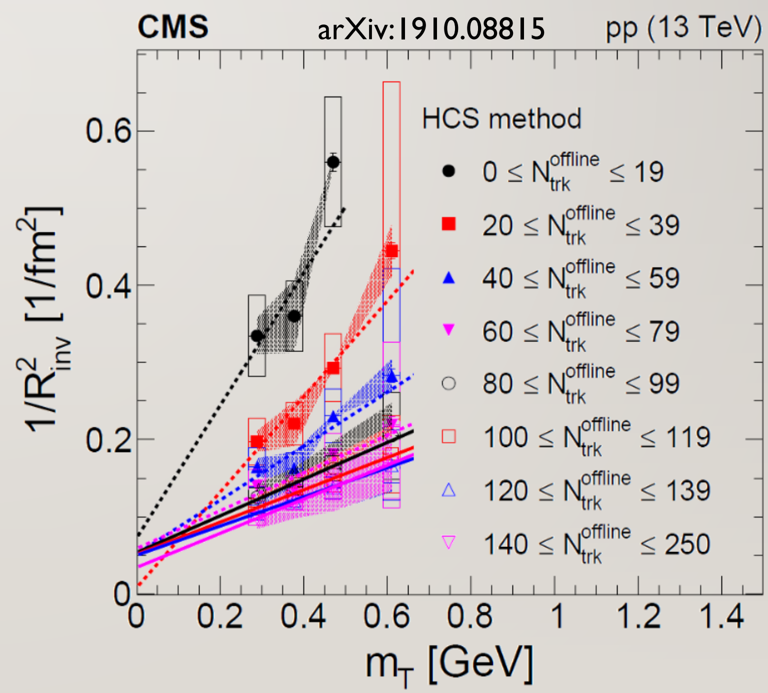
Campanini et al., PLB 703 (2011) 237; McLerran et al., NPA 916 (2013) 210; A. Bzdak, et al. PRC 87 (2013) 064906



RESULTS: TRANSVERSE MOMENTUM DEPENDENCE

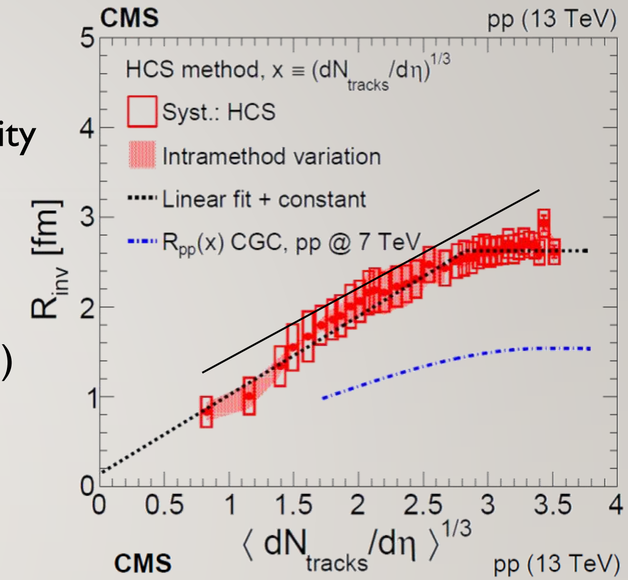
- Universally observed $R^{-2} \sim a + b \cdot m_T$ dependence, based on Hubble flow
  - Transverse flow, also temperature gradient
- Simple estimate of Hubble-coefficient (if $T_{\text{freeze-out}} = 150$ MeV assumed)
  - $H_{\text{HighMultiplicity}} = 0.17 \pm 0.04\ c$/fm, $H_{\text{MinimumBias}} = 0.298 \pm 0.004\ c$/fm
  - Similar to results in heavy ion collisions (also multiplicity dependence of slope)

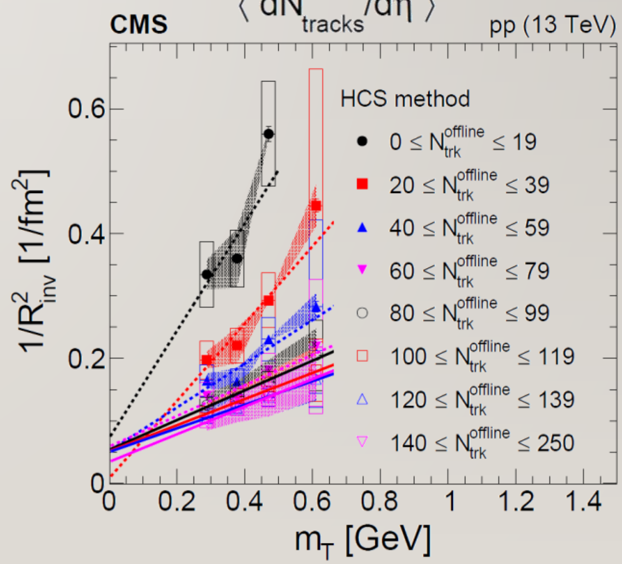


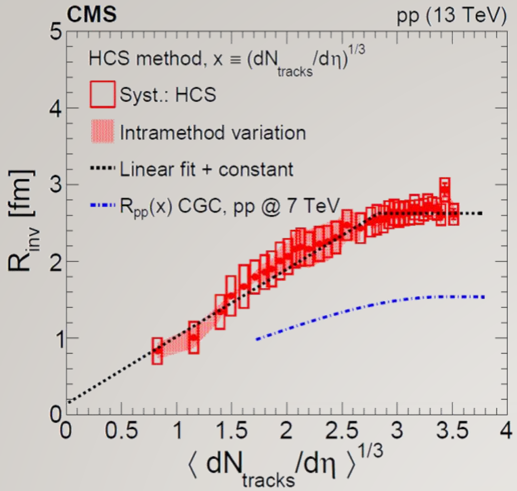


SUMMARY

- BEC measured in pp collisions at 13 TeV
  - First investigation with both Minimum Bias and High Multiplicity
- Three different techniques employed:
  - Double Ratios with MC (as in earlier CMS BEC)
  - Fully data-driven Cluster Substraction (as in earlier CMS BEC)
  - Hybrid Cluster Substraction (as in ATLAS BEC)
- 1-D BEC (exponential fit): R_{inv} (and λ)
  - As a function of multiplicity and momentum
  - Slope change, saturation with N_{tracks} → compatible with data
  - Continuous growth with $(N_{tracks})^{1/3}$ → compatible with data
  - m_T scaling works: Hubble-flow stronger in MB than in HM
- Complete results:
  - CMS-PAS-FSQ-15-009
  - arXiv:1910.08815







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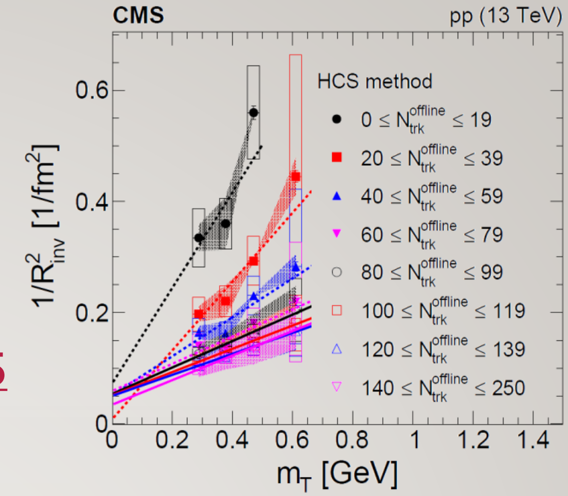

THANK YOU FOR YOUR ATTENTION

This talk was in part supported by NKHIF grant K128713

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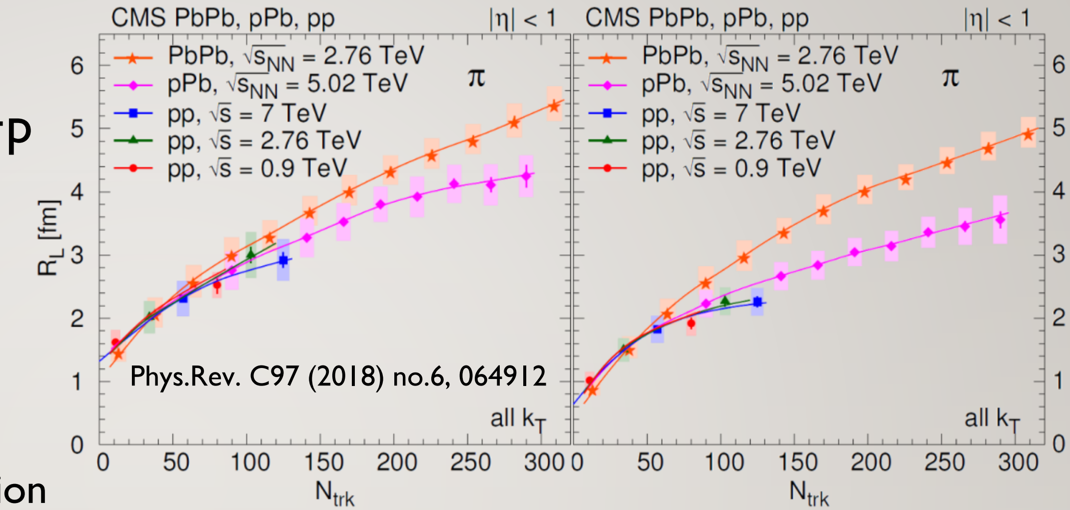
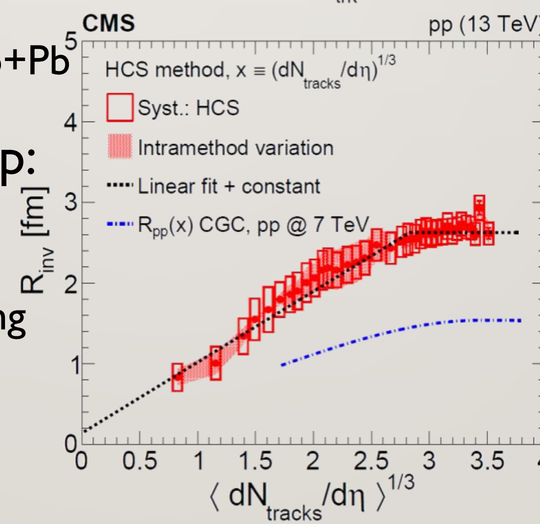
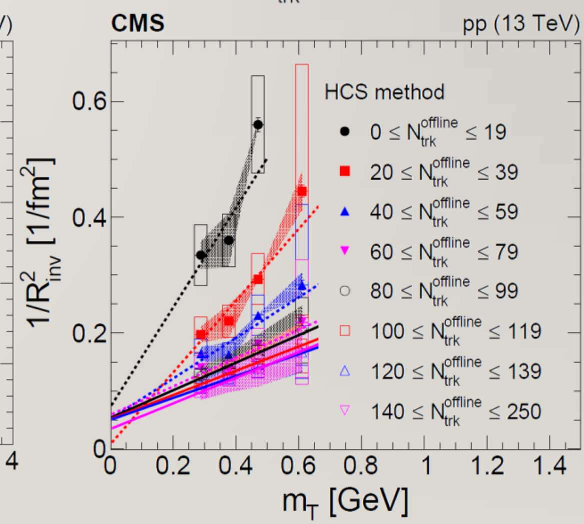
BACKUP

RESULTS AT CMS

- Analysis performed at 0.9-13 TeV, Pb+Pb, p+Pb, p+p
- Using $\alpha = 1$ fixed
- 3D analysis for 0.9-7 TeV
  - Analysis: Wigner (F. Siklér)
  - Detailed geometry exploration
  - Elongated source: p+p and p+Pb
- High multiplicity 13 TeV p+p: similar results as ion-ion
  - Geometric multiplicity scaling
  - Hydro type of mT scaling?
  - Analysis: USP+ELTE







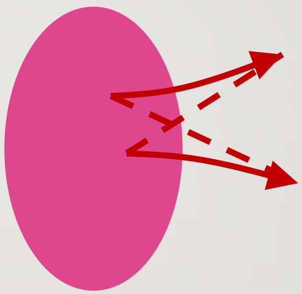
INTERACTIONS: THE COULOMB-EFFECT

- Plane-wave result, based on $\left|\Psi_2^{(0)}(r)\right|^2 = 1 + e^{iqr}$:

$$C_2(q,K) \cong \int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- If there is interaction:

$$\Psi_2^{(0)}(r) \to \Psi_2^{(\text{int})}(r_1, r_2)$$



- For Coulomb:

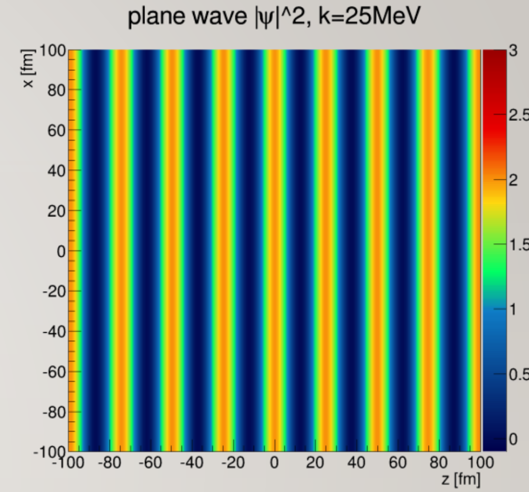
$$\left|\Psi_2^{(C)}(r)\right|^2 = \frac{2\pi\zeta}{e^{2\pi\zeta}-1} \cdot \text{(complicated hypergeometric expression)}$$

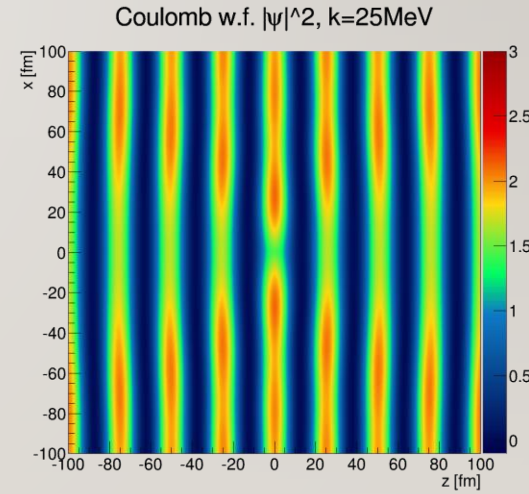
- Direct fit with this, or the usual iterative Coulomb-correction:

$$C_{\text{Bose-Einstein}}(q)K(q), \text{ where } K(q) = \frac{\int D(r,K)\left|\Psi_2^{(C)}(r)\right|^2 dr}{\int D(r,K)\left|\Psi_2^{(0)}(r)\right|^2 dr}$$

- In this analyis: assuming point-like (Dirac-delta) source

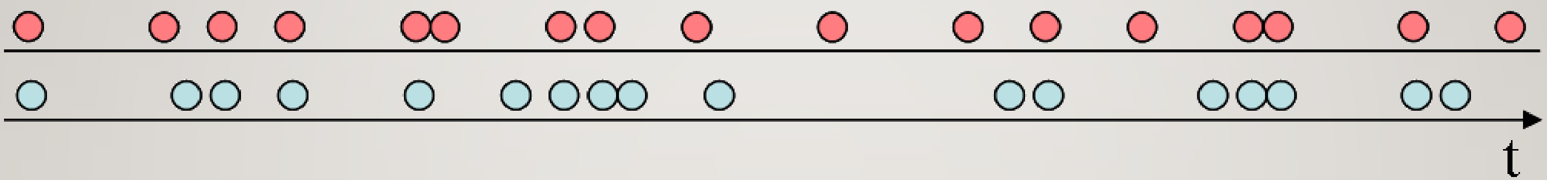
$$K(q) = 2\pi\zeta/(\exp(2\pi\zeta) - 1), \qquad \zeta = m\alpha_{QED}/q$$



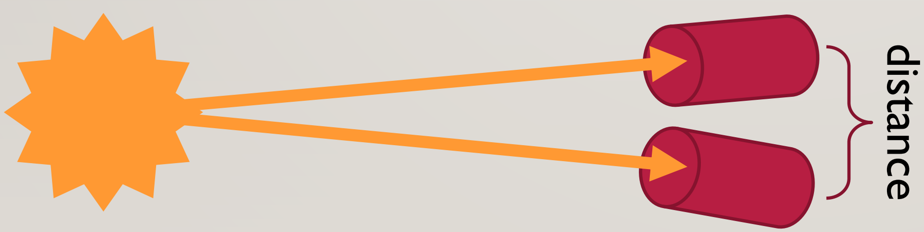


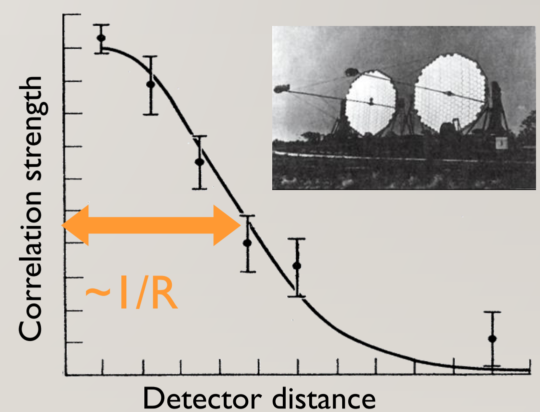
THE HBT CORRELATION

- Observation of Hanbury Brown & Twiss:
  at small detector distances, large correlation between the two detectors
- Joint intensity „too frequent”: $I(A,B) > I(A)I(B) = 1 + \text{correlation}$



- What is the reason for it? Interference?
- „Interference between different photons never occurs”
  P.A. M. Dirac, Quantum Mechanics
- Why does the correlation reduce with distance?





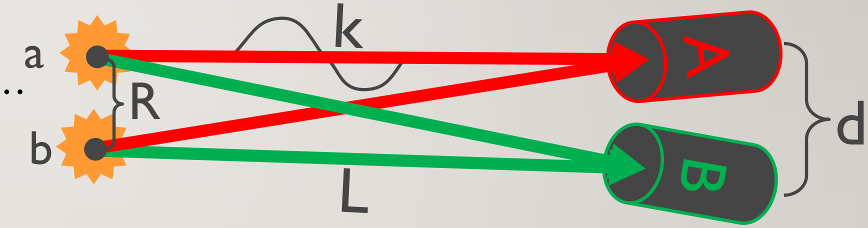
HBT IN HEAVY ION AND PARTICLE PHYSICS

- Goldhaber, Goldhaber, Lee & Pais: pion pairs in p+p̄ collisions

  Phys.Rev. 120 (1960) 300, Phys.Rev.Lett. 3 (1959) 181

- Departure from conventional statistics: Bose-Einstein statistics
  - N pion final states: symmetrized wave functions needed
- Understanding: Glauber, Fano, Baym, …

  Phys. Rev. Lett. 10, 84; Rev. Mod. Phys. 78 1267, …



- Wavefunction:

  1-particle: $\Psi_a(r), \Psi_b(r)$ plane/spherical wave

  2-particle: $\Psi_{A,B} = \Psi(R_A, R_B) = \frac{1}{\sqrt{2}}\left(\Psi_a(R_A)\Psi_b(R_B) + \Psi_a(R_B)\Psi_b(R_A)\right)$

- Two-particle probability: $\left\langle\left|\Psi_{A,B}\right|^2\right\rangle \sim 1 + \cos\frac{kRd}{L} = 1 + \cos R\Delta k$
- Correlation function: $C_{AB} - 1 = \left\langle\left|\Psi_{A,B}\right|^2\right\rangle - 1 = \cos R\Delta k$

HBT EFFECT FOR EXTENDED SOURCES

- What happens for an $S(r)$ source distribution?
- Similarly to the previous description:

$$\Psi(r) = e^{ikr}, \Psi_2(r_1, r_2) = \frac{1}{\sqrt{2}}\left(e^{ik_1r_1}e^{ik_2r_2} + e^{ik_1r_2}e^{ik_2r_1}\right)$$

$$N_1(k) = \int S(r,k)|\Psi(r)|^2 d^4r$$

$$N_2(k_1, k_2) = \int S(r_1, k_1)S(r_2, k_2)|\Psi_2(r_1, r_2)|^2 d^4r_1 d^4r_2$$

$$C_2(k_1, k_2) = \frac{N_2(k_1,k_2)}{N_1(k_1)N_1(k_2)} \cong 1 + \left|\frac{\tilde{S}(q,K)}{\tilde{S}(0,K)}\right|^2$$

where $q = k_1 - k_2, K = (k_1+k_2)/2$

- Simply $C(q) = 1 + \left|\tilde{S}(q)\right|^2$, where $\tilde{S}(q) = \int S(r)e^{iqr}$
- Invertable (sort of), $S(r)$ can be reconstructed from $C(q)$
- Approximations: no interaction, no multiparticle correlation, thermal emission …

SOURCE OR PAIR DISTRIBUTION?

- Under some circumstances (thermal emission, no interactions, …):

$$C_2(q,K) = \int S\left(r_1, K+\frac{q}{2}\right) S\left(r_2, K-\frac{q}{2}\right) |\Psi_2(r_1,r_2)|^2 dr_1 dr_2$$
$$\cong 1 + \left|\int S(r,K)e^{iqr}dr\right|^2$$

- Let us introduce the spatial pair distribution:

$$D(r,K) = \int S\left(\rho+\frac{r}{2}, K\right) S\left(\rho-\frac{r}{2}, K\right) d\rho$$

- Then the Bose-Einstein correlation function becomes:

$$C_2(q,K) \cong \int D(r,K)|\Psi_2(r)|^2 dr = 1 + \int D(r,K)e^{iqr}dr$$

- **Bose-Einstein correlations measure spatial pair distributions!**