Results of femtoscopic correlations at CMS

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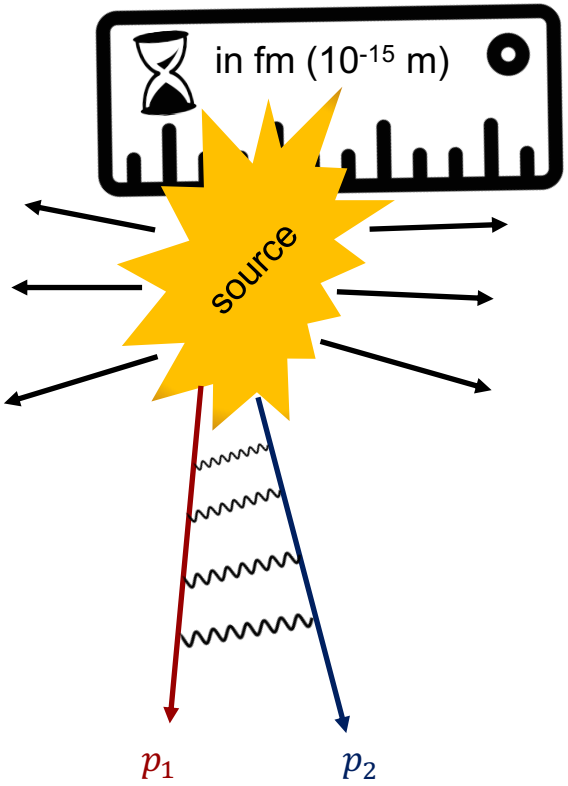
Introduction and motivation

- Femtoscopy: particle correlations at low-q
  - $q^2 = q_{\mathrm{inv}}^2 = -(p_1 - p_2)^2$
- Powerful tool to probe space-time dimensions of the particle emitting source
- Sensitive to
  - quantum statistics
  - final-state interactions
  - backgrounds
- In this talk, charged hadron ($h^{\pm}$) correlations
  - pp collisions at 13 TeV: measurements of multiplicity and pair transverse momentum dependence
  - PbPb collisions at 5.02 TeV: study of correlation function shape



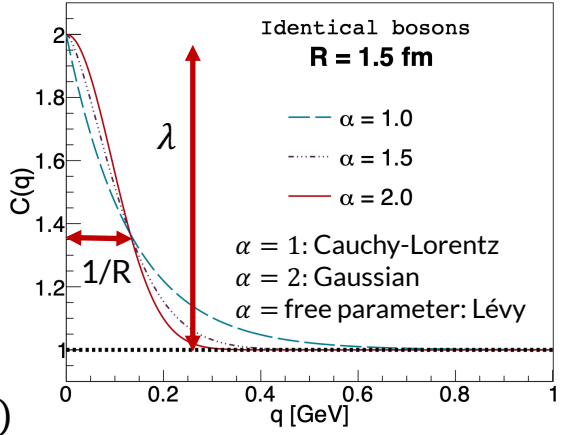
Femtoscopic correlation function

- Theoretically

$$C(q) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)}$$

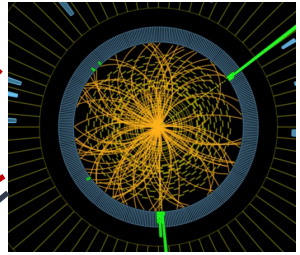
$$C(q) \sim 1 \pm \lambda |F[\tilde{\rho}(q)]|^2$$

$$C(q) = N(1 \pm \lambda e^{-|qR|^\alpha})$$



- Experimentally
  - single ratio (SR)

$$C(q) = N\frac{A(q)}{B(q)}$$



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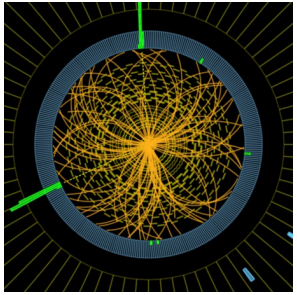
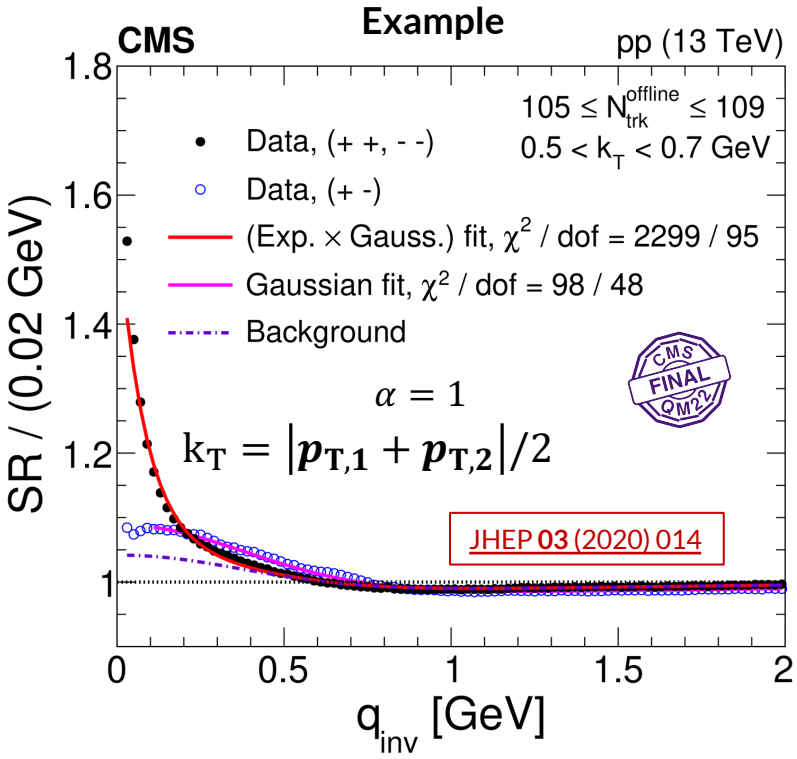


One-dimensional fit to correlation function for charged hadrons (Lévy-type)

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

Coulomb correction | Quantum Statistics | Background (bkg)

Fitting the correlation function



One-dimensional fit to correlation function for charged hadrons (Lévy-type)

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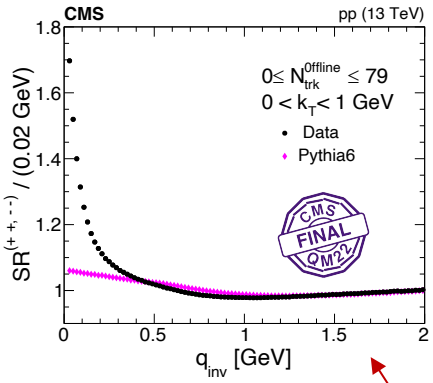
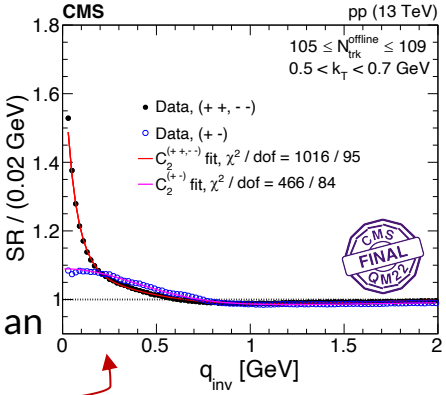
Background estimate

- **Double Ratios**
  - ratio of SR
    - $DR = SR^{DATA}/SR^{MC}$
  - strong MC dependence



- **Cluster Subtraction**
  - fully data-driven
  - bkg estimated from fit of (+ −) SR
  - translate (+ −) to (± ±) SR estimating an amplitude factor



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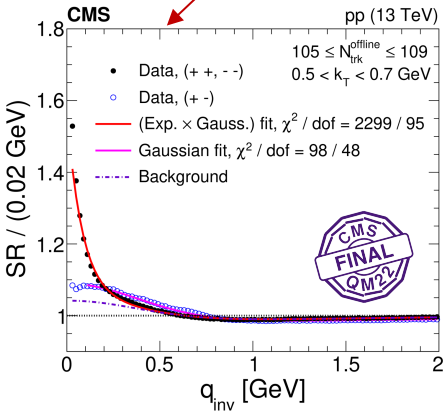
- **Hybrid Cluster Subtraction**
  - fit SR from MC for both (+ −) and (± ±) bkg
    - find a conversion function (parameters)
  - fit (+ −) in data and use the conversion to (± ±) SR



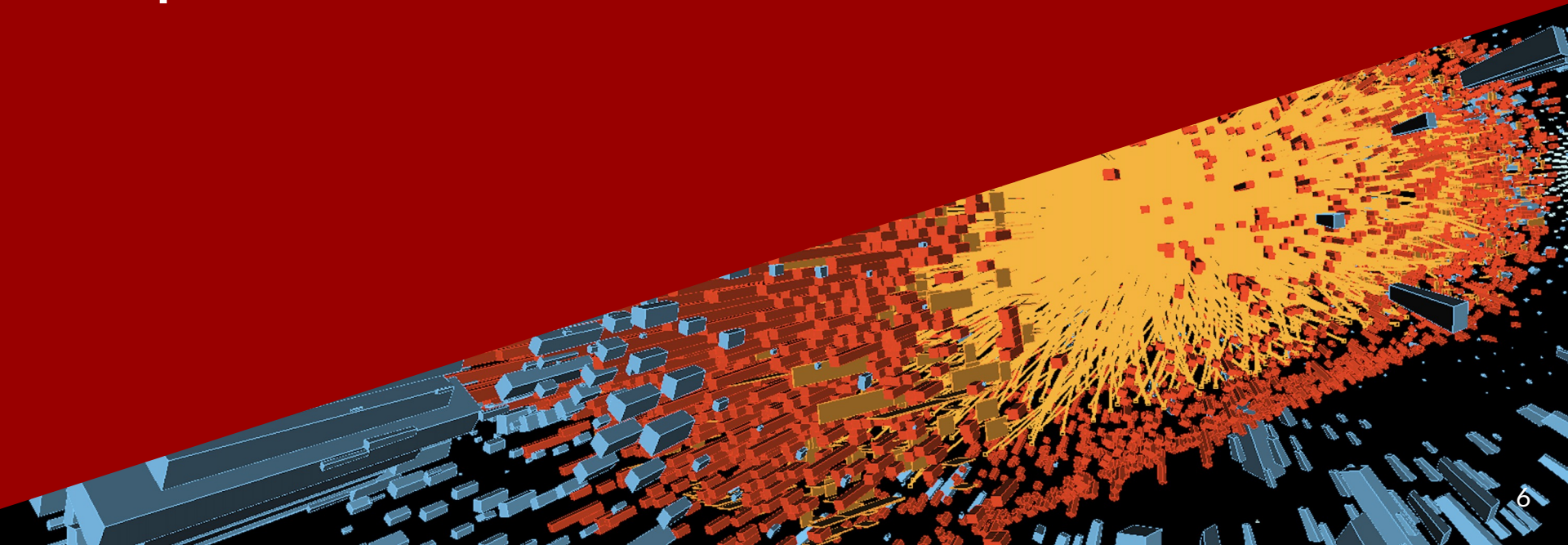
- CMS PAS HIN-21-011 → New method!
  - similar to double ratios

$$DR(q) = \frac{SR(q)}{BG(q)}$$

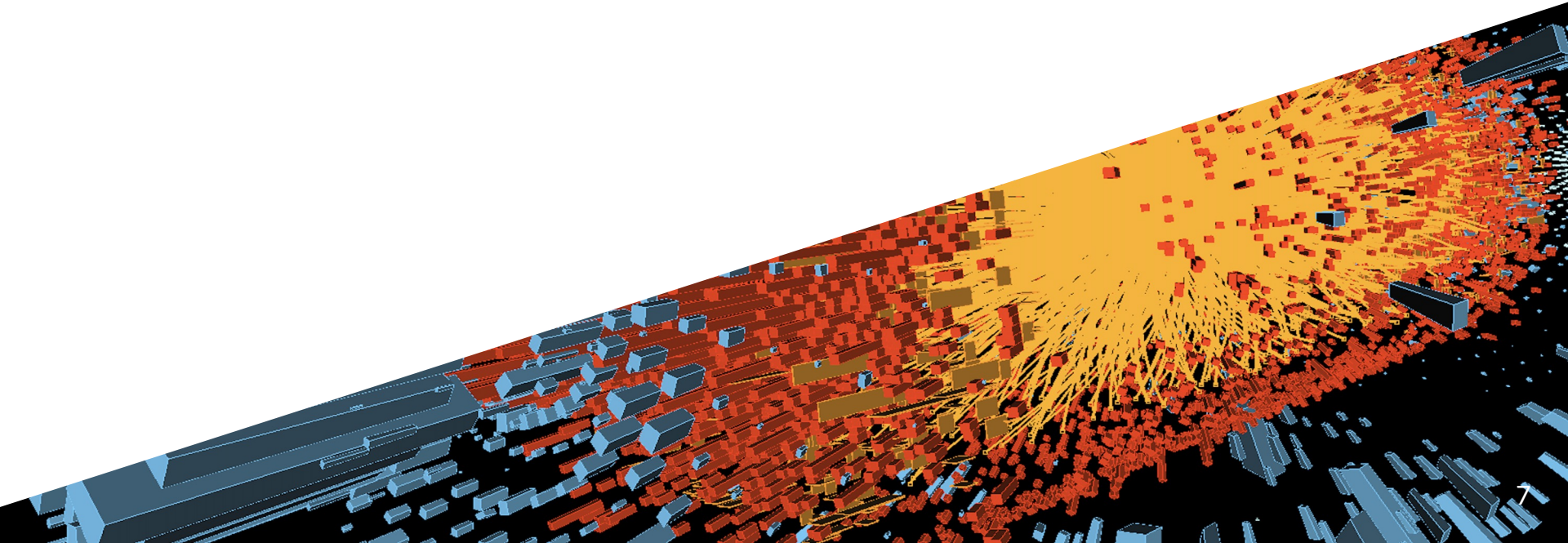
  - $BG(q)$ is fitted using data with

$$BG(q) = N(1 + \alpha_1 e^{-(qR_1)^2})(1 - \alpha_2 e^{-(qR_2)^2})$$

Experimental results

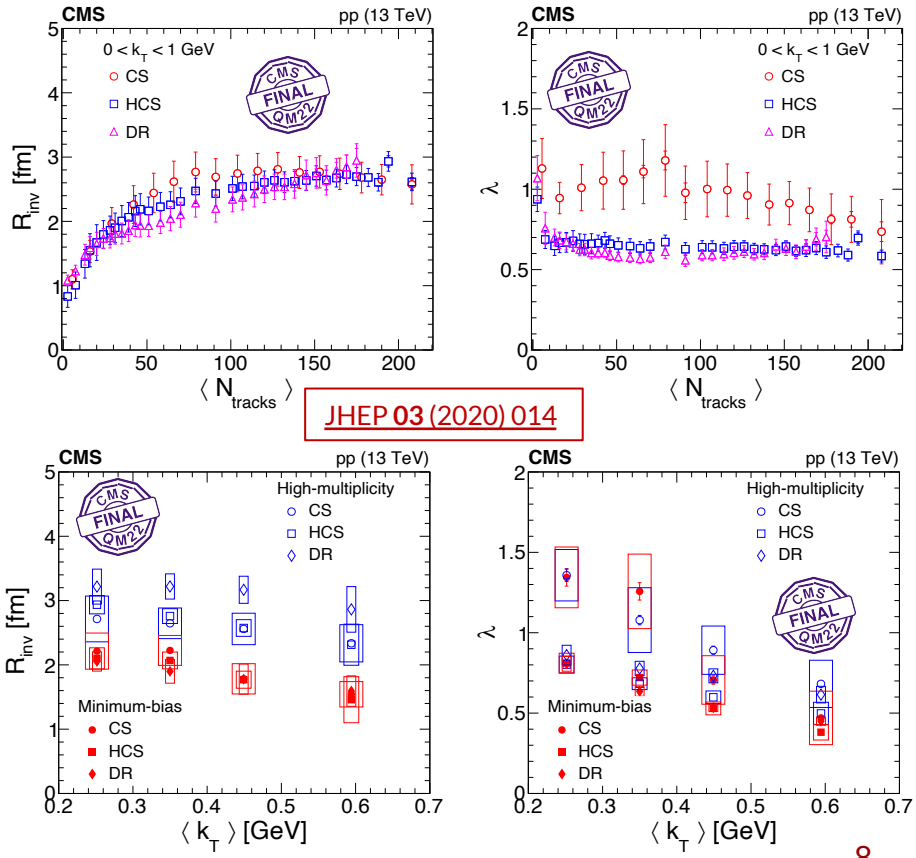


pp collisions at 13 TeV



Comparing different background removal methods

- Similar behavior for all the methods
  - in agreement for R_{inv} (or R)
    - R_{inv} increases with N_{tracks}
  - λ shows small dependence with N_{tracks}
    - except the first bin
  - deviations in λ using CS method
    - less constrained by the fit
  - R_{inv} and λ decrease with k_T
    - source expansion in pp collisions?



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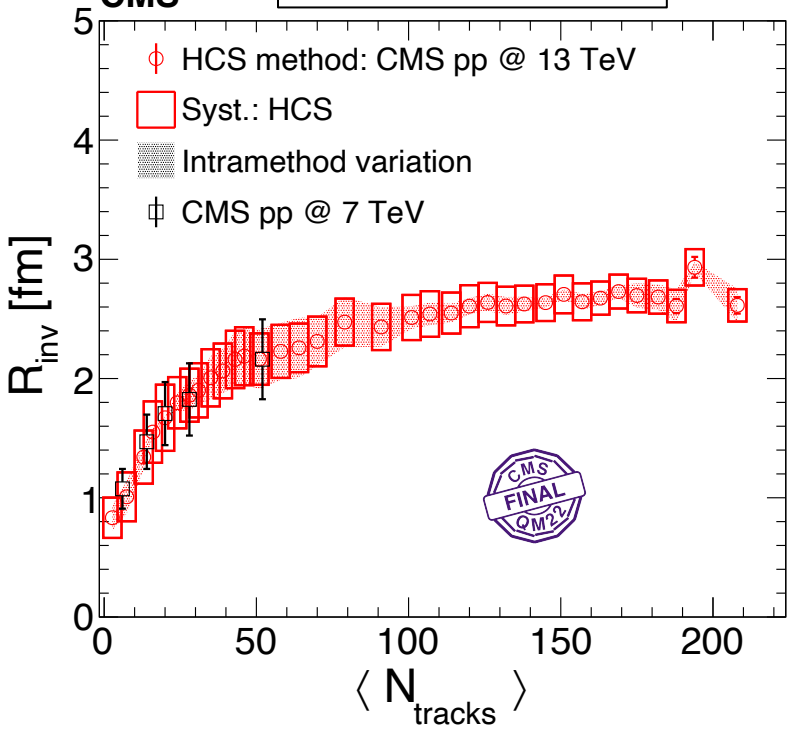
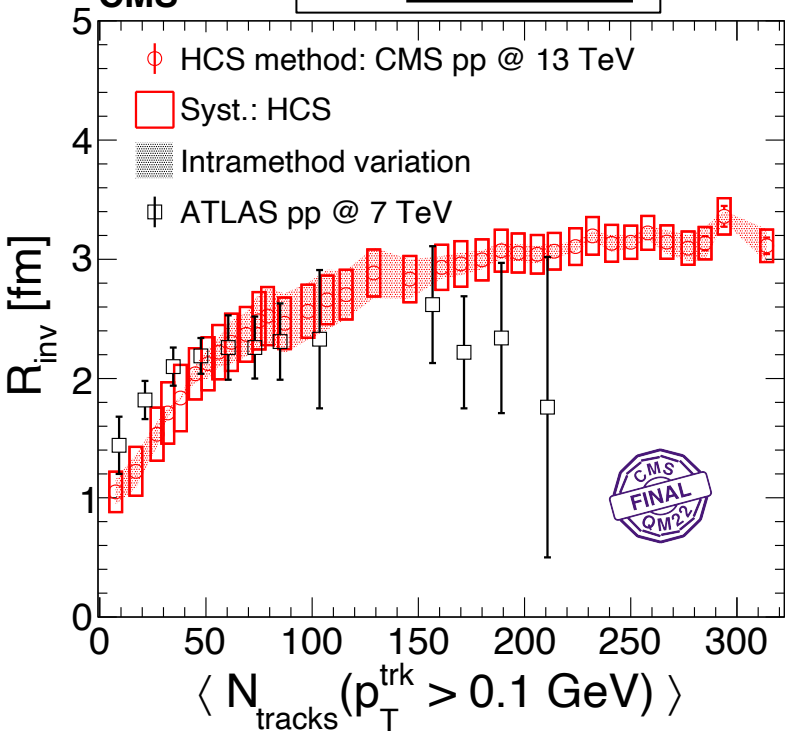
Comparison with CMS and ATLAS results at 7 TeV

CMS at 13 TeV: JHEP **03** (2020) 014

7 TeV: PRC 97 (2018) 064912



ATLAS: EPJC **75** (2015) 466

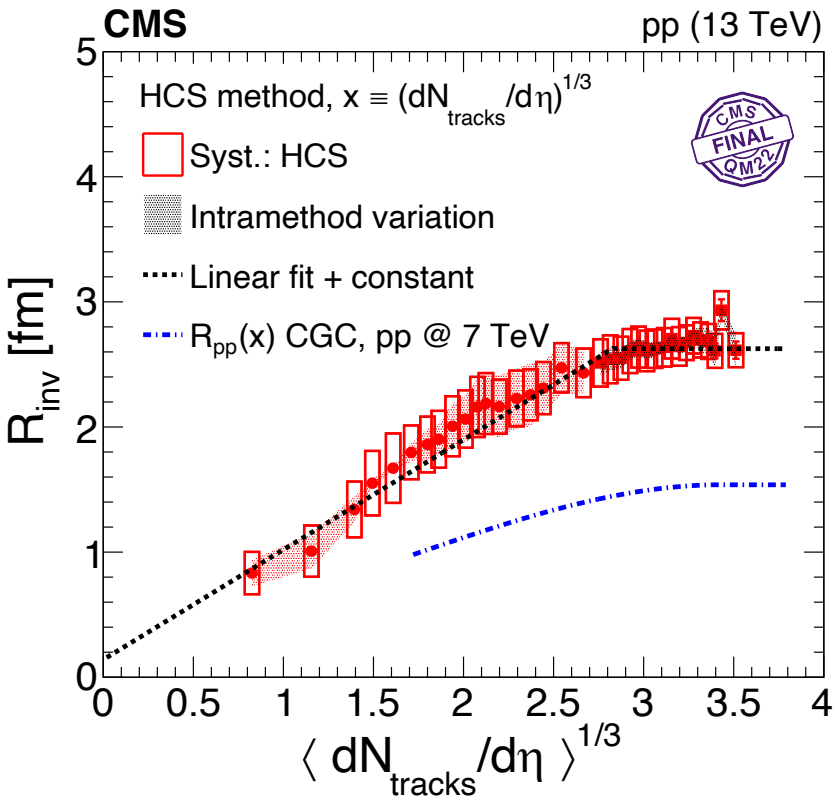


Good agreement with previous measurements!

Comparison with Color Glass Condensate (CGC) predictions

- CGC calculation for pp at 7 TeV
  - without system evolution
    - *L. McLerran et al.*
      - *NPA* **916** (2013) 210
    - *A. Bzdak et al.*
      - *PRC* **87** (2013) 064906

- Similar shape, but large difference in magnitude
  - hydrodynamic evolution?
  - cold nuclear matter effects?
  - need more phenomenological studies!



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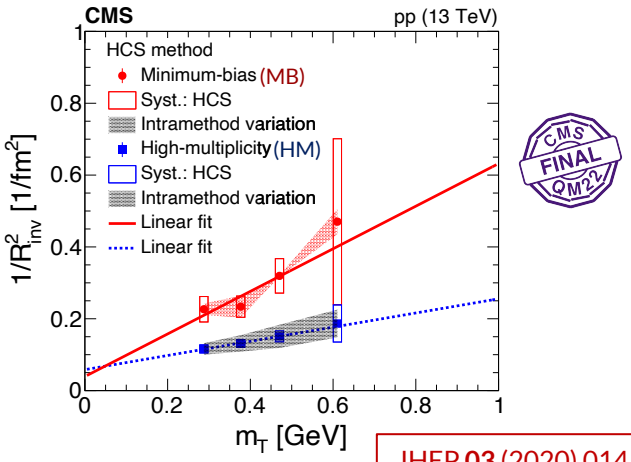
m_T dependence

$$1/R^2_{inv} \text{ vs } m_T = \sqrt{m_\pi^2 + k_T^2}$$

- From hydrodynamics (NPA **946** (2016) 227)
  - intercept: reflects the source geometrical size (at freeze-out)
  - slope: reflects the flow component
    - larger slope (larger flow) → lower multiplicities (similar to peripheral AA collisions)
    - smaller slope (lower flow) → higher multiplicities (similar to more central AA collisions)
  - similar behavior for multiplicity > 40



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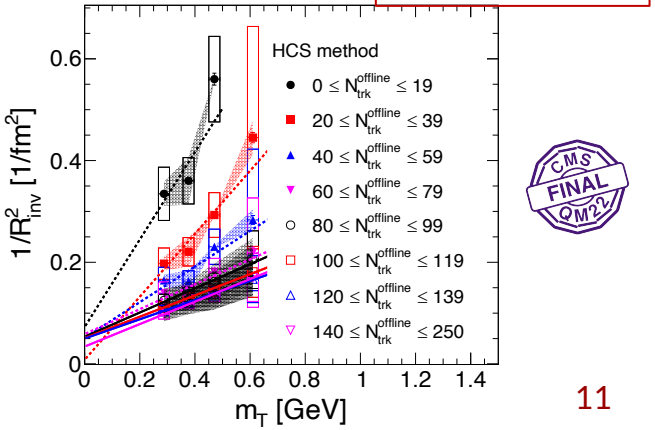
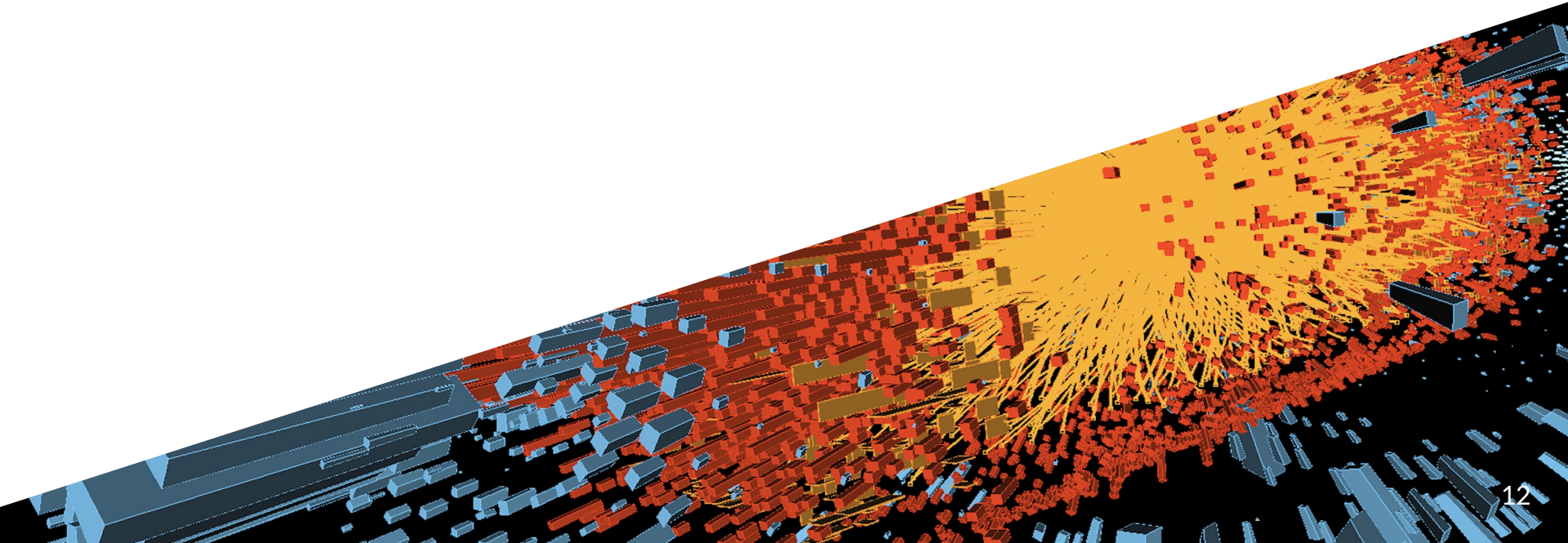


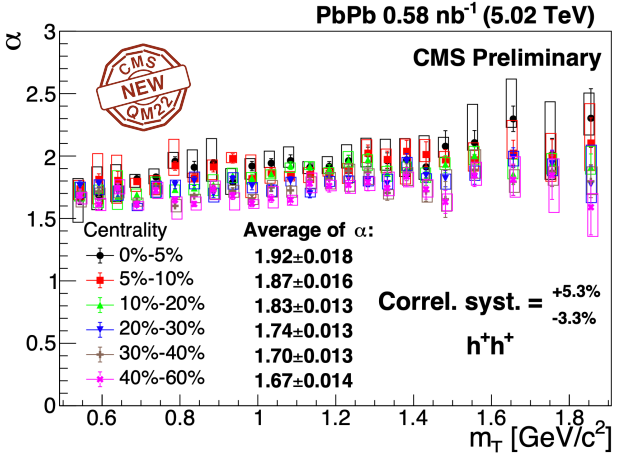
For more details see Sandra Padula poster (April 6th at Section 1 – T07_1)

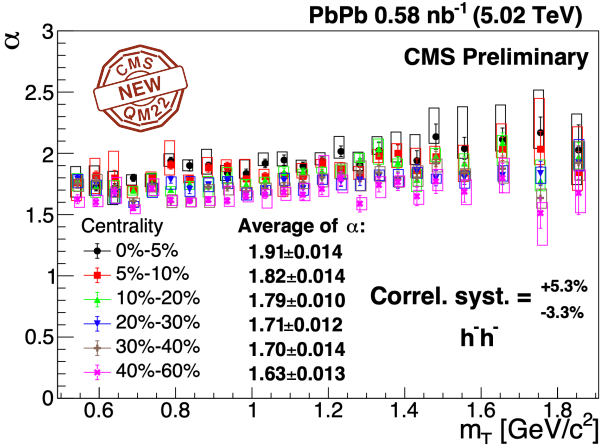
PbPb collisions at 5.02 TeV

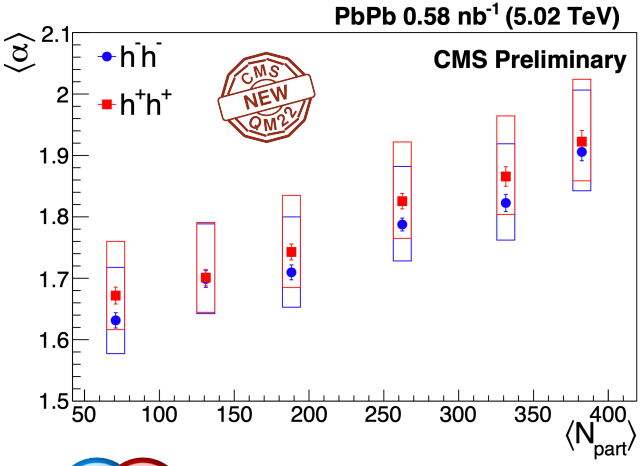


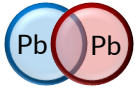
Dependence of Lévy stability index α in m_T and multiplicity

CMS PAS HIN-21-011









First measurement of α at LHC energies

Does not strongly depend on m_T

Between 1.6 and 2.0 from semi-peripheral to central collisions

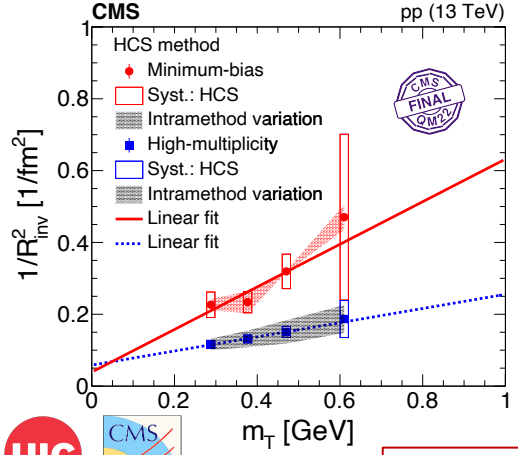
Centrality dependence not modeled so far → challenge for phenomenology

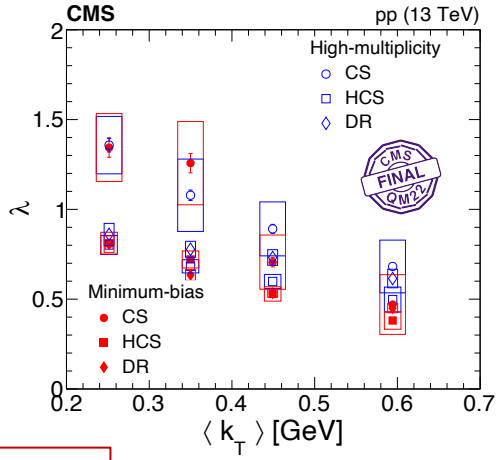
Shape is important in femtoscopic measurements!

For more details see Balázs Kórodi poster (April 6th at Section 1 – T07_1)

Centrality and m_T dependence

- Similar behavior as observed in pp collisions
  - λ decreases with m_T (k_T)
    - small centrality dependence
  - R_{inv} (or R) increases with centrality and decreases with m_T





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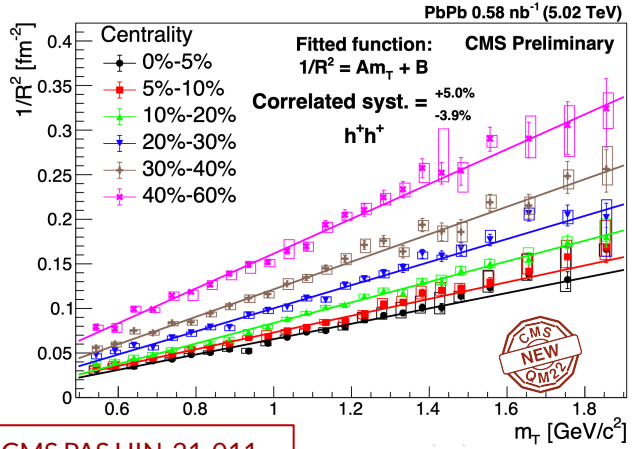

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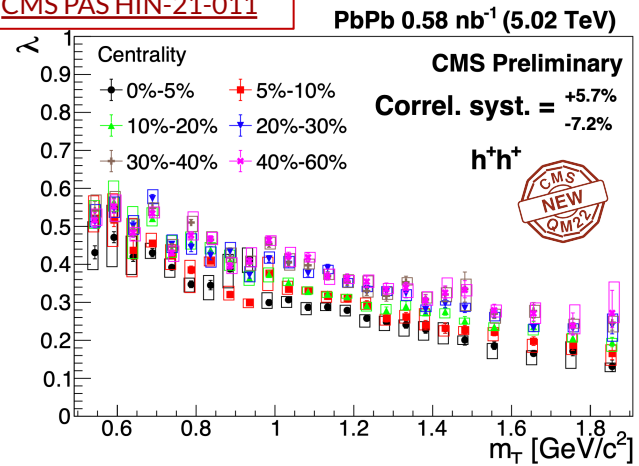
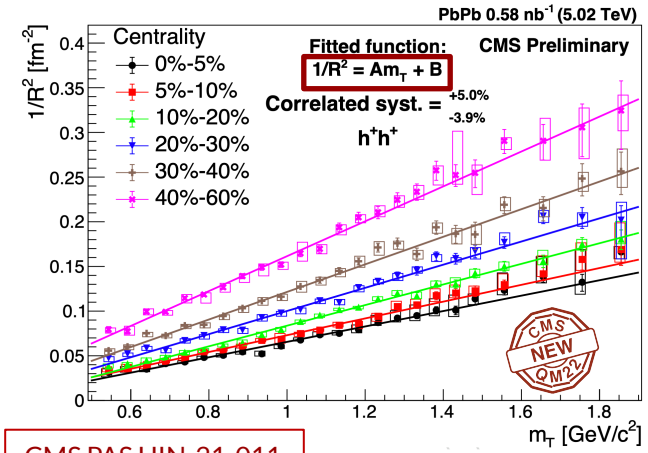


Centrality and m_T dependence

- Similar behavior as observed in pp collisions
  - λ decreases with m_T (k_T)
    - small centrality dependence
  - R_{inv} (or R) increases with centrality and decreases with m_T
  - $^1/_{R^2_{inv}}$ vs m_T : shows linear scaling
    - $^1/_{R^2_{inv}} = Am_T + B$
    - hydrodynamic prediction
      - working also for Lévy sources



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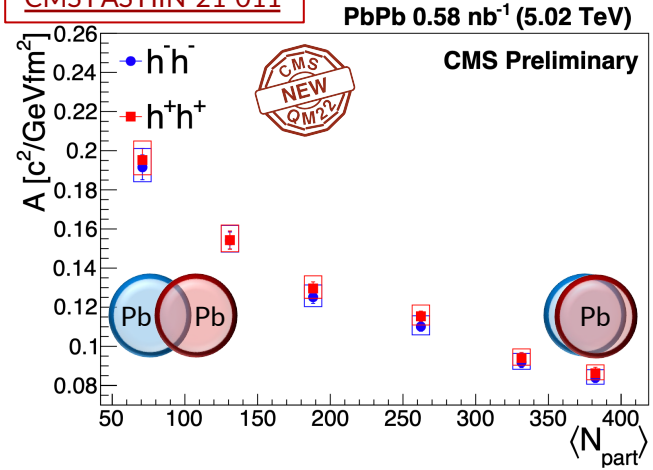
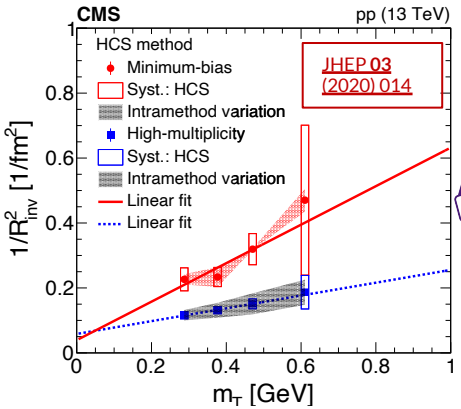
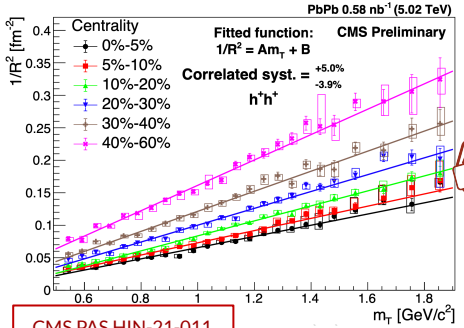


Summary and outlook

- In general, the results show
  - R_{inv} ↗ with N_{trk}/centrality and ↘ with k_T
  - λ ↘ with N_{trk} and k_T (m_T)
- First measurement using MB and HM pp collisions at 13 TeV
  - different background methods studied
  - consistent with previous measurements at 7 TeV
  - qualitative comparison CGC and hydro models
- First measurement of α dependency (centrality and m_T) at LHC energies
  - non-Gaussian behavior observed
    - centrality dependent
  - R_{inv} results show hydro scaling for Lévy sources
- Measurement of correlations with V^0's coming soon





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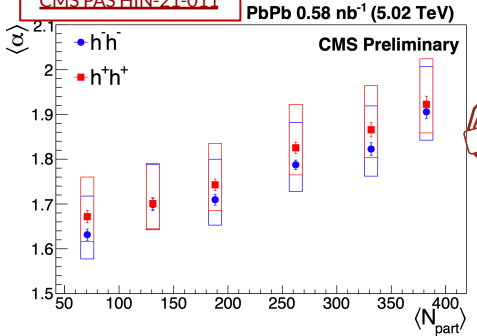
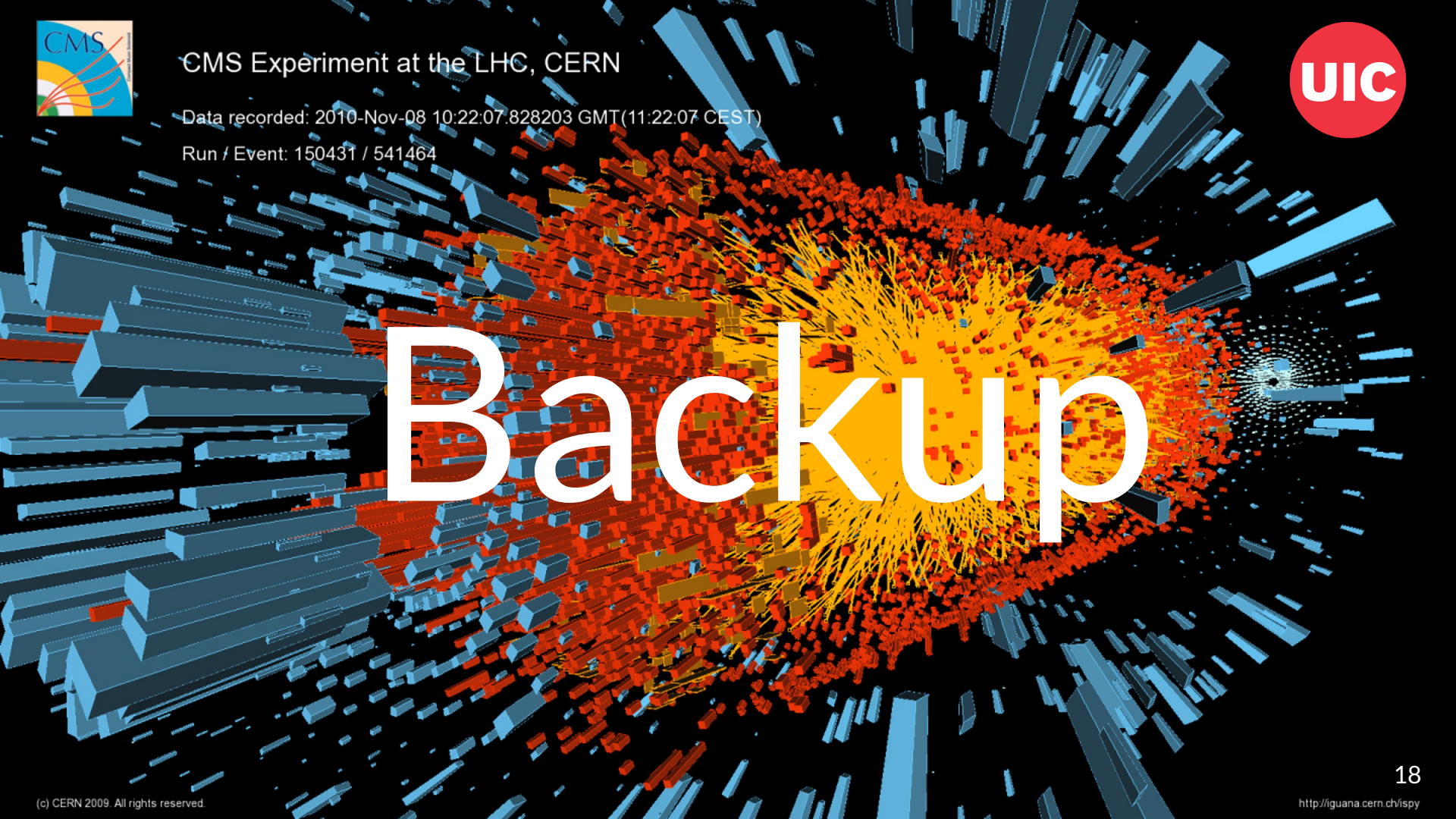


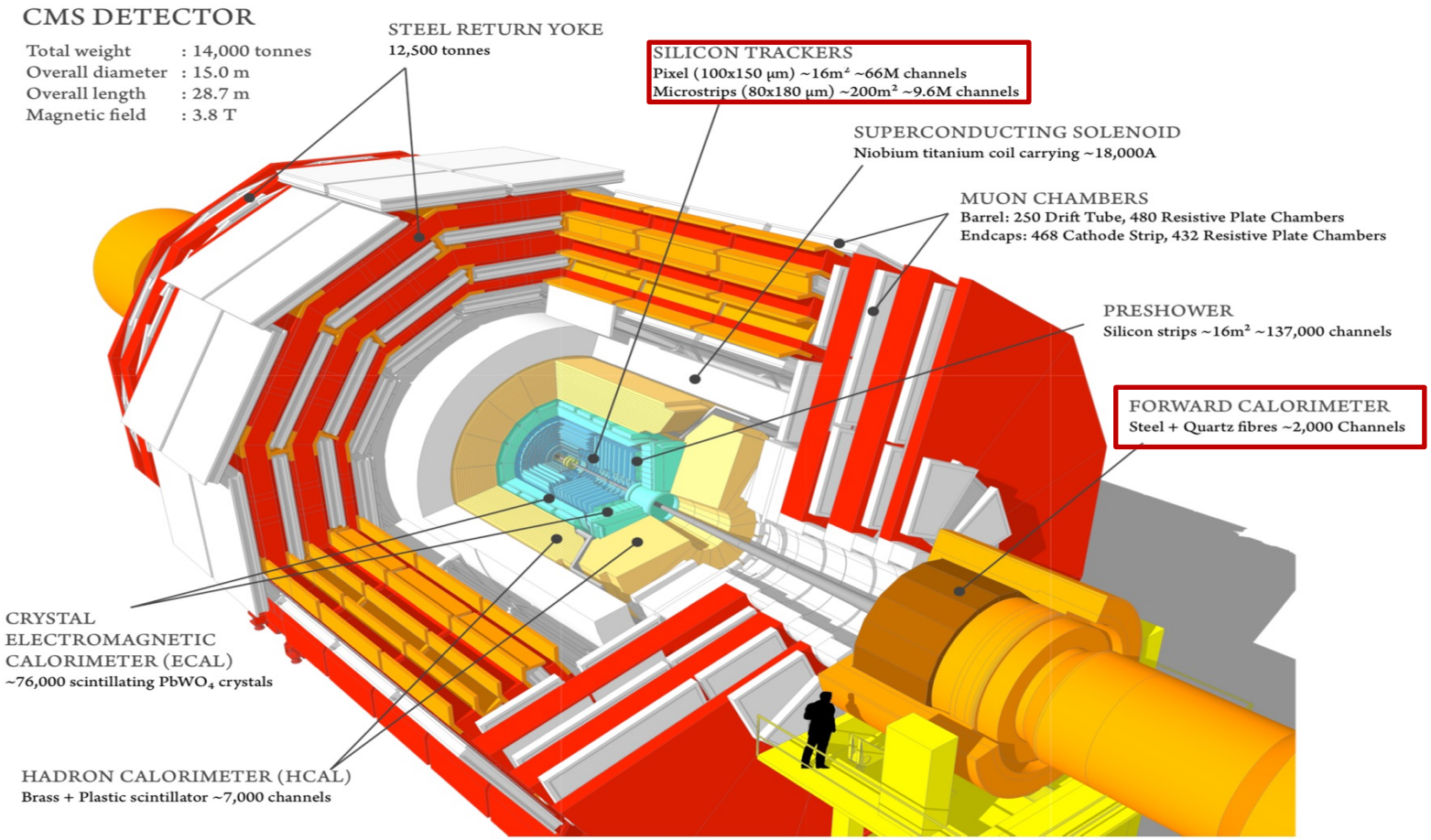
Thank You

The work of the UIC HINP group is supported by the DOE-NP grant

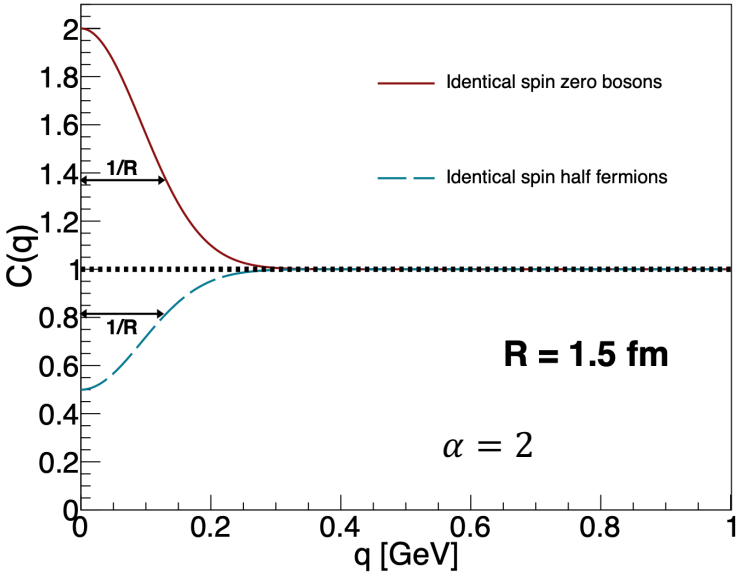

CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-08 10:22:07.828203 GMT(11:22:07 CEST)
Run / Event: 150431 / 541464
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy

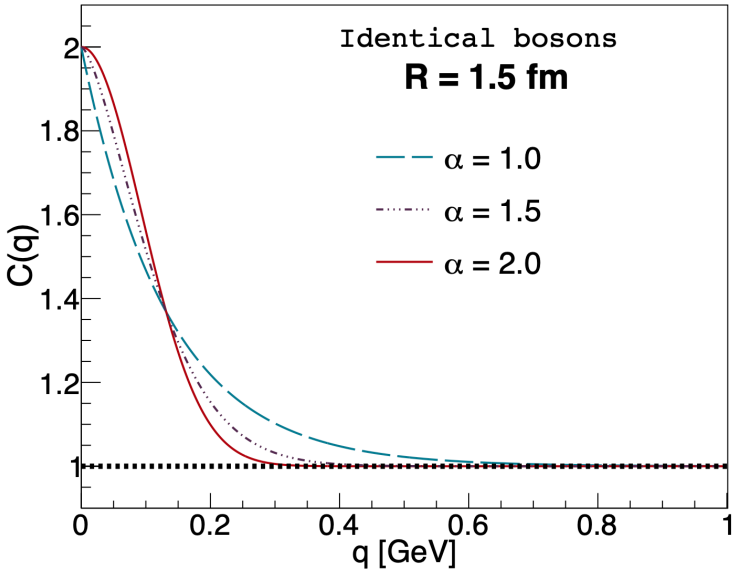
Backup

CMS detector



Quantum statistics effect



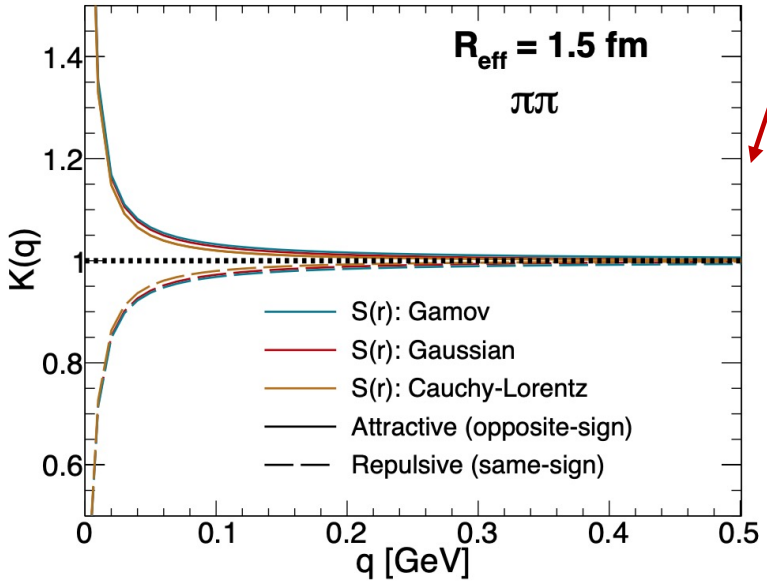


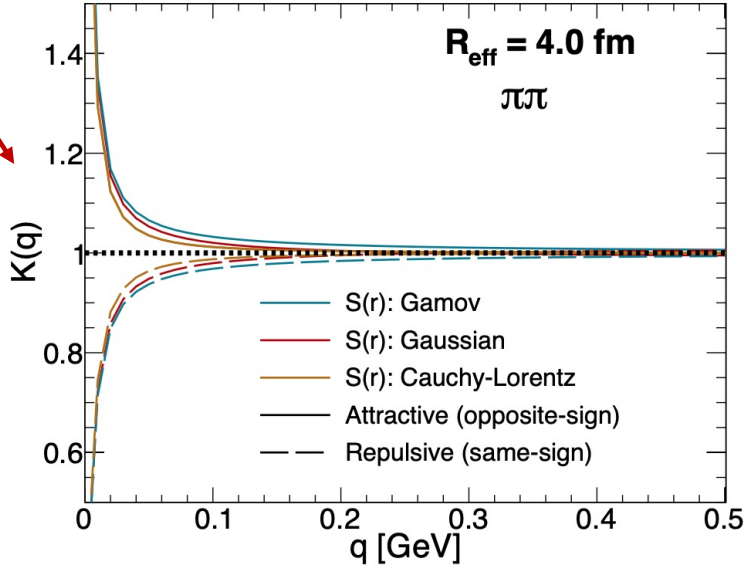
$$C(q) = 1 + \beta e^{-|qR|^{\alpha}}$$

β = 1 for identical bosons, -½ for identical fermions and 0 for non-identical

Coulomb final-state interactions

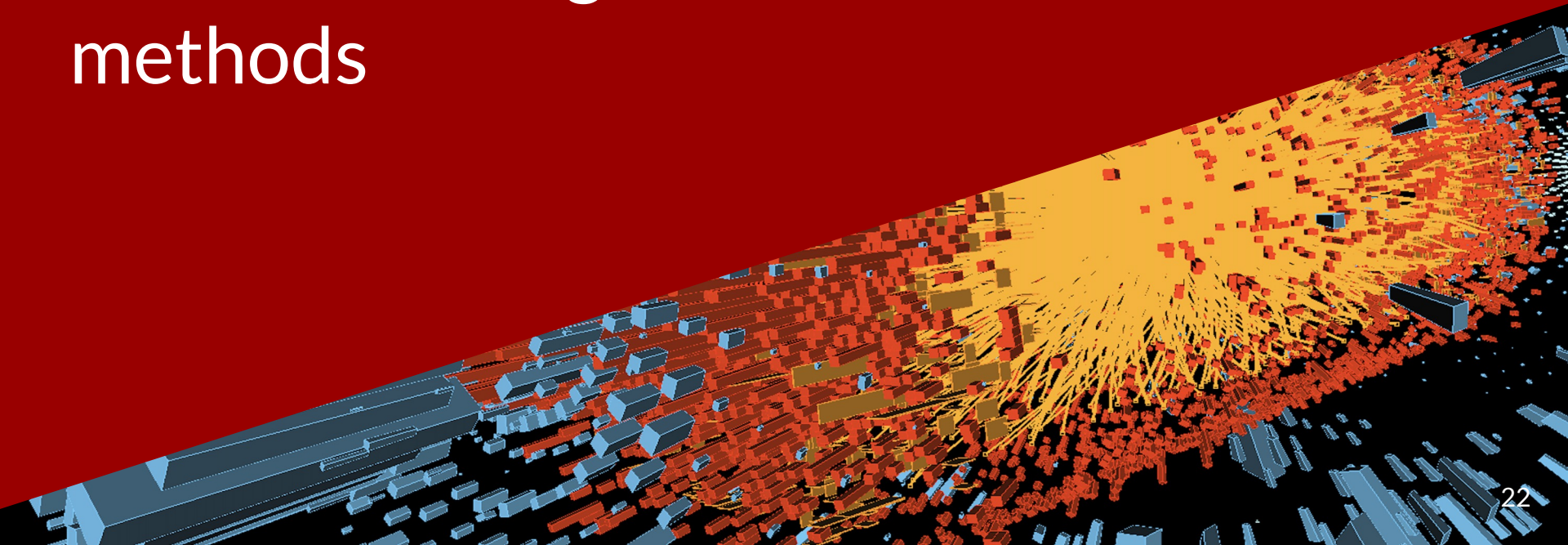
$$C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)[1 + \lambda e^{-|qR|^\alpha}]\}\Omega(q)$$





For Gaussian (hypergeometric) and Gamov: see PRC 80 (2009) 034907
For Cauchy-Lorentz (alpha = 1), see : PRC 97 (2018) 064912
For Lévy-type source (alpha dependency): see PPN 51 (2020) 238

Different background subtraction methods

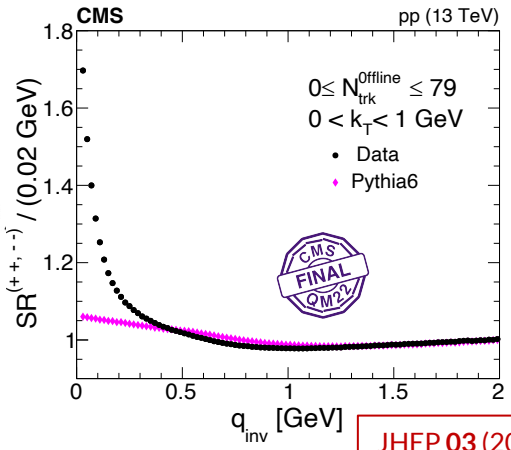


Double ratios

- Ratio of single ratios

$$\mathrm{DR}(q_{\mathrm{inv}}) \equiv C_{2,\mathrm{BE}}(q_{\mathrm{inv}}) = \frac{\mathrm{SR}(q_{\mathrm{inv}})}{\mathrm{SR}(q_{\mathrm{inv}})_{\mathrm{MC}}} = \frac{\left[\left(\frac{\mathcal{N}_{\mathrm{ref}}}{\mathcal{N}_{\mathrm{sig}}}\right)\left(\frac{\mathrm{d}N_{\mathrm{sig}}/\mathrm{d}q_{\mathrm{inv}}}{\mathrm{d}N_{\mathrm{ref}}/\mathrm{d}q_{\mathrm{inv}}}\right)\right]}{\left[\left(\frac{\mathcal{N}_{\mathrm{ref}}}{\mathcal{N}_{\mathrm{sig}}}\right)_{\mathrm{MC}}\left(\frac{\mathrm{d}N_{\mathrm{MC}}/\mathrm{d}q_{\mathrm{inv}}}{\mathrm{d}N_{\mathrm{MC,\,ref}}/\mathrm{d}q_{\mathrm{inv}}}\right)\right]}$$

  - need MC simulations without femtoscopic signal
    - ideally should remove all background
    - strong MC dependence



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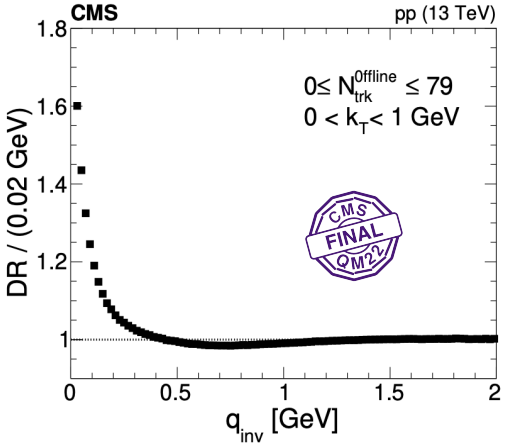

Cluster subtraction (CS) method - I

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- Fully data-driven technique
  - effect of resonances: decreases with increasing multiplicity
  - modulation of bkg effect from $h^{\pm}$ SR in data

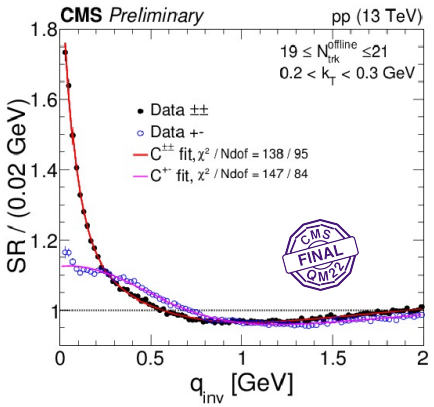
$$C_2^{(+-)}(q_{\mathrm{inv}}) = c\left[1 + \frac{b}{\sigma_b\sqrt{2\pi}}\exp\left(-\frac{q_{\mathrm{inv}}^2}{2\sigma_b^2}\right)\right](1 + \epsilon q_{\mathrm{inv}})$$

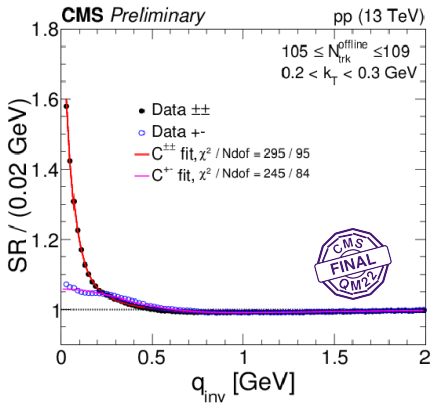
- b and σ_b can be parametrized as
  - b → bkg amplitude:

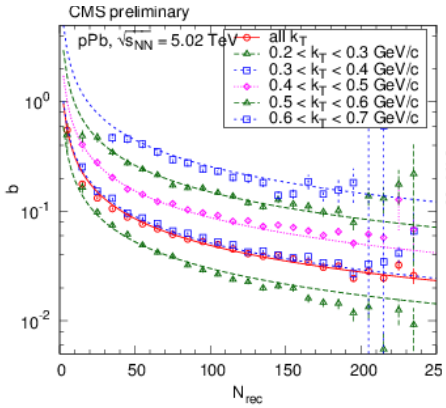
$$b(N_{\mathrm{trk}}^{\mathrm{offline}}, k_{\mathrm{T}}) = \frac{b_0}{(N_{\mathrm{trk}}^{\mathrm{offline}})^{n_b}}\exp\left(\frac{k_{\mathrm{T}}}{k_0}\right)$$

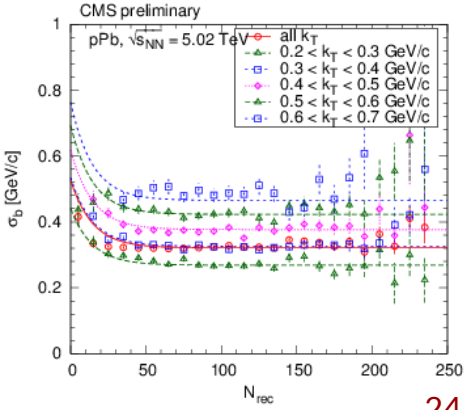
  - σ_b → cluster width:

$$\sigma_b(N_{\mathrm{trk}}^{\mathrm{offline}}, k_{\mathrm{T}}) = \left[\sigma_0 + \sigma_1\exp\left(-\frac{N_{\mathrm{trk}}^{\mathrm{offline}}}{N_0}\right)\right]k_{\mathrm{T}}^{n_{\mathrm{T}}}$$









https://cds.cern.ch/record/2318575

Cluster Subtraction (CS) method – II

- Modulation of background effect in charged hadron correlations:
  - also present in $h^{\pm}$ pairs, with similar shape but a smaller amplitude
  - use the form of the contribution obtained from $h^{\pm}$ pairs: b and σ_b fixed
  - assume the width is the same and determine the (±±) bkg amplitude $z(N_{trk}^{offline})$

$$C_2^{(++,--)}(q_{inv}) = c\left[1 + z(N_{trk}^{offline}, k_T)\frac{b}{\sigma_b\sqrt{2\pi}}\exp\left(-\frac{q_{inv}^2}{2\sigma_b^2}\right)\right]C_{2,BE}(q_{inv})$$

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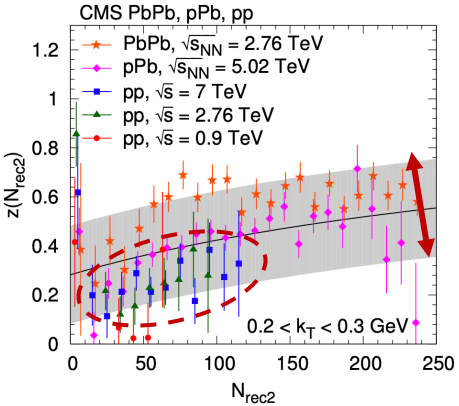
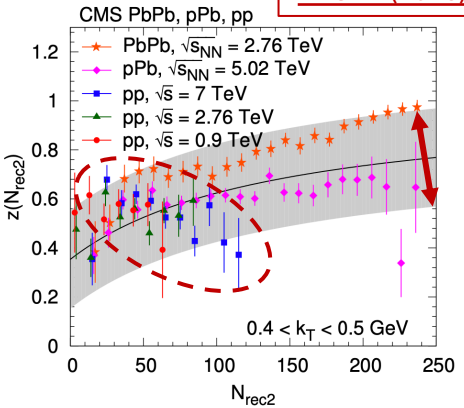
$$z(N_{trk}^{offline}) = \left(\frac{aN_{trk}^{offline}+b}{1+N_{trk}^{offline}+b}\right)$$

$$C_{BE}(q_{inv}) = [1 + \lambda\exp(-q_{inv}R_{inv})]$$





Hybrid Cluster Subtraction (HCS) Method – I

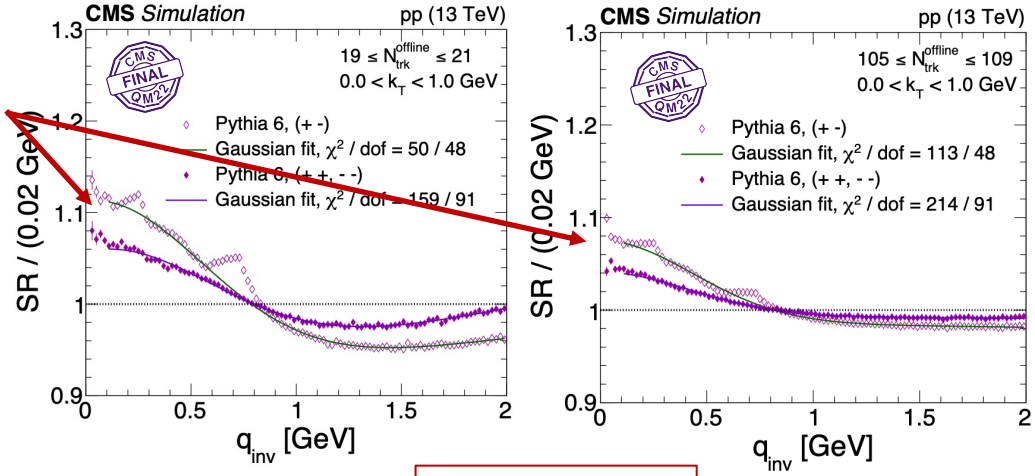
- Technique first used by ATLAS (PRC 96 (2017) 064908) in pPb collisions at 5.02 TeV
- Fitting (±±) and (+ –) SR in MC
  - in Monte Carlo: no femtoscopic effects → bkg can be modeled by fitting parameters
  - in data: Bose-Einstein correlations not present in (+ –) component – Bkg only
    - use the relations from MC to estimate the bkg component in (±±) SR
- Fit Functions

$$\Omega(q_{\mathrm{inv}}) = \mathcal{N}\left(1 + B\exp\left[-\left|\frac{q_{\mathrm{inv}}}{\sigma_B}\right|^{\alpha_B}\right]\right)$$

  - Parameters relation ($\alpha_B = 2$)

$$\left[(\sigma_B)^{-1}\right]^{\pm\pm} = \rho\left[(\sigma_B)^{-1}\right]^{+-} + \beta$$

$$B^{\pm\pm} = \mu(k_T)\left[B^{+-}\right]^{\nu(k_T)}$$



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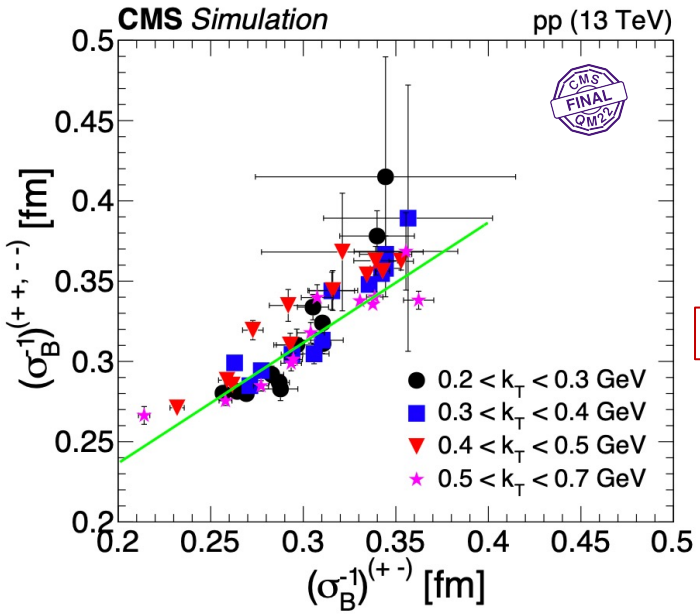
Hybrid Cluster Subtraction (HCS) Method – II

- Relation $[(\sigma_B)^{-1}]^{\pm\pm}$ vs. $[(\sigma_B)^{-1}]^{+-}$



Pythia6 Z2*

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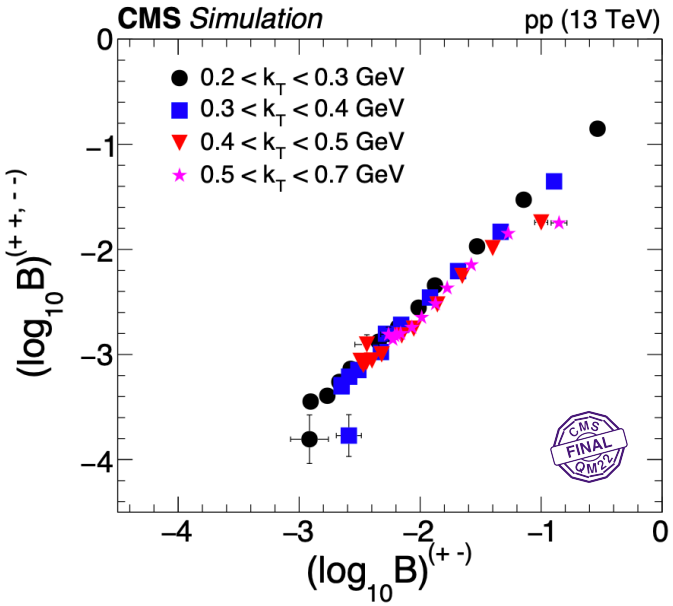
- Relation $(B)^{\pm\pm}$ vs. $(B)^{+-}$



$$[(\sigma_B)^{-1}]^{\pm\pm} = \rho[(\sigma_B)^{-1}]^{+-} + \beta$$

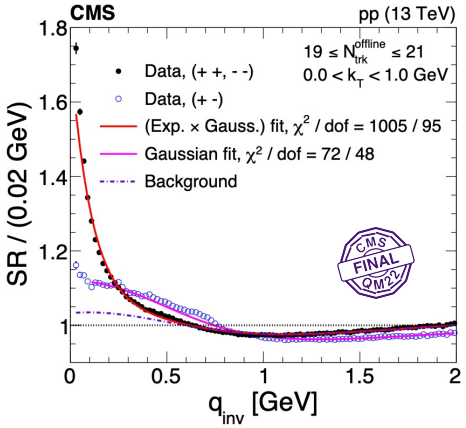
$$B^{(++,--)} = \mu(k_T)\,[B^{+-}]^{\nu(k_T)}$$

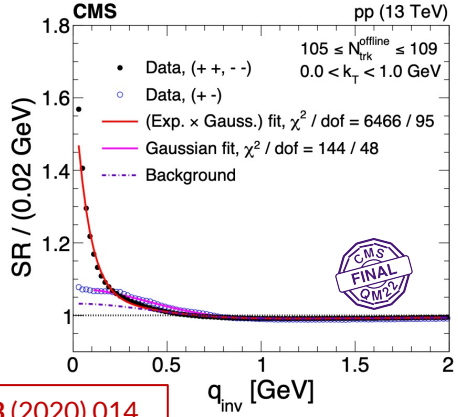
ρ = 0.82 ± 0.04 (stat.); β = 0.077 ± 0.013 (stat.)

Hybrid Cluster Subtraction (HCS) Method – III

- After getting relations from Monte Carlo
  - bkg in data is estimated in (+ –) SR
  - assume relation of (+ –) SR and (±±) in data is the same as in MC
  - use conversion function to estimate bkg in (±±) SR in data
  - fit with:

$$C(q_{\mathrm{inv}}) = \Omega(q_{\mathrm{inv}}) \times C_{\mathrm{BEC}}(q_{\mathrm{inv}})$$





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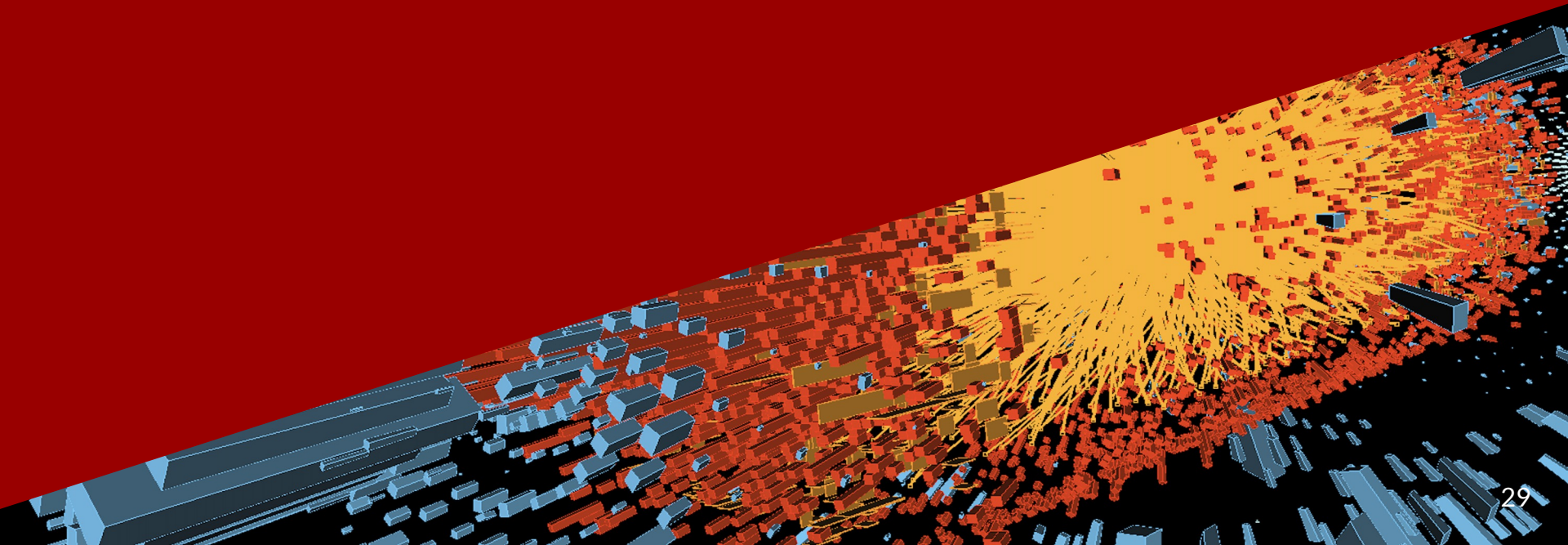
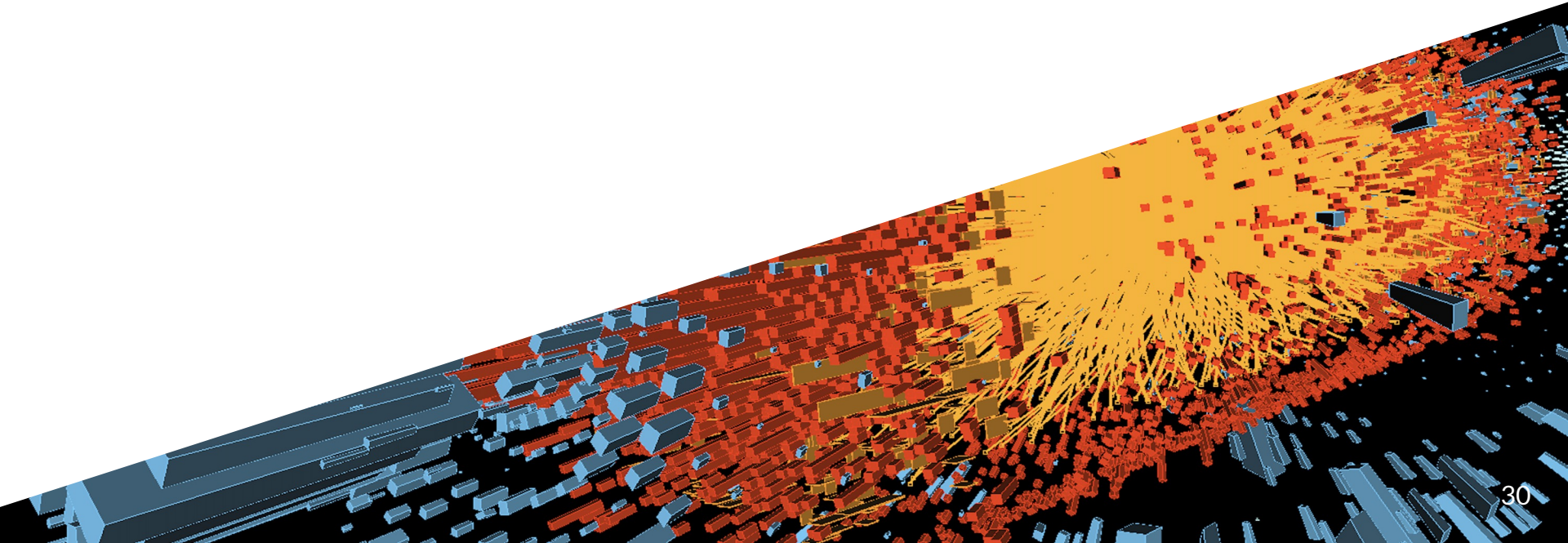
Previous measurements

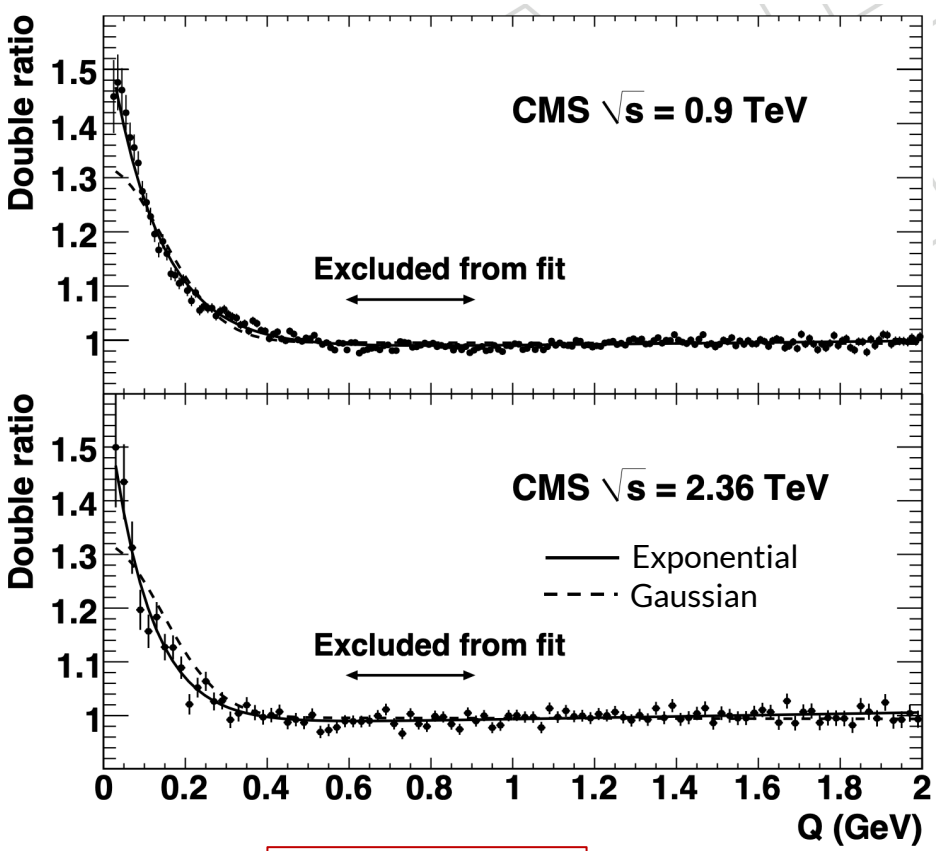


Charged hadrons



First femtoscopic measurement at LHC – pp colisions

- Performed in pp at 0.9 and 2.36 TeV
- Double ratio technique applied
- Coulomb corrected using Gamov
- Exponential fit shows a better agreement with data
  - Observed in higher energies
  - $R^{Gauss} \approx \sqrt{\pi}\, R^{Expo}$



PRL **105** (2010) 032001

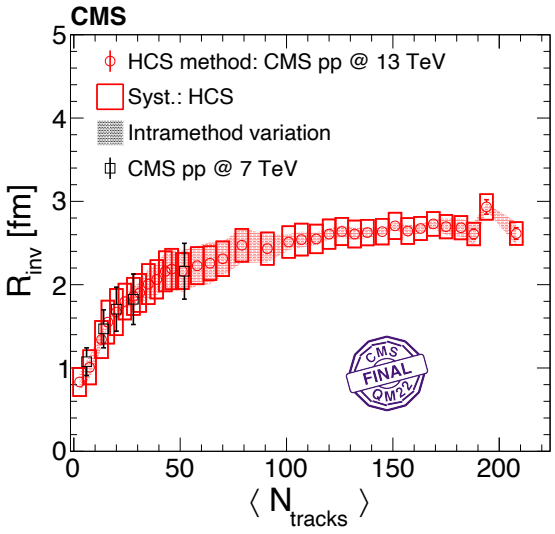
Comparison with CMS and ATLAS results at 7 and 13 TeV

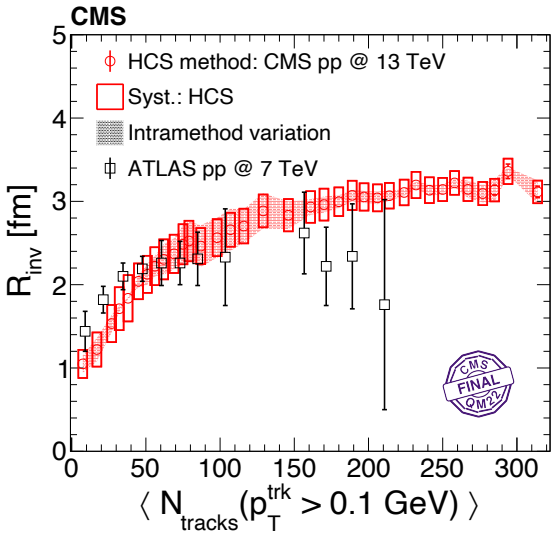
CMS at 13 TeV: JHEP **03** (2020) 014

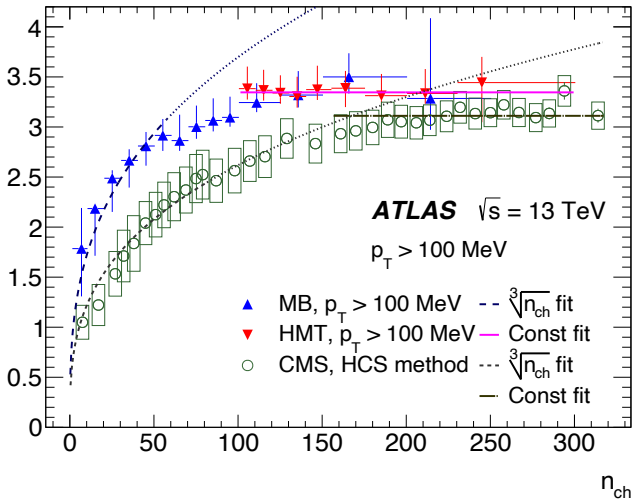
7 TeV: PRC 97 (2018) 064912

ATLAS: EPJC **75** (2015) 466

e-print arXiv:2202.02218



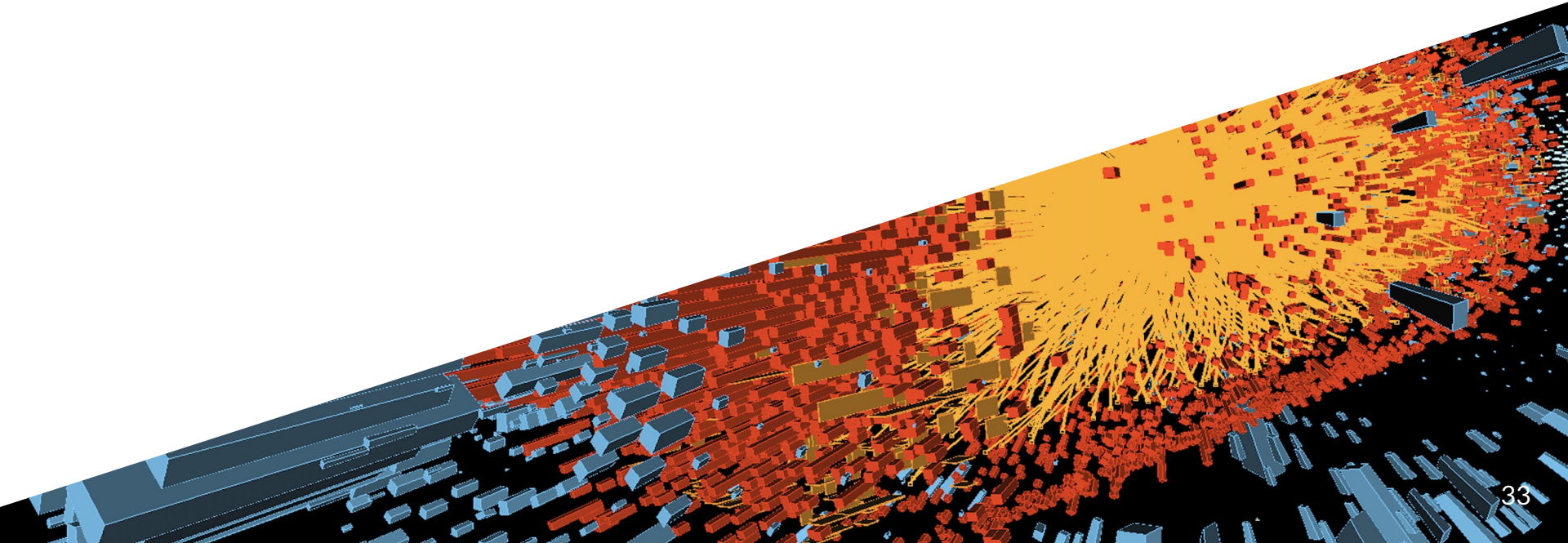




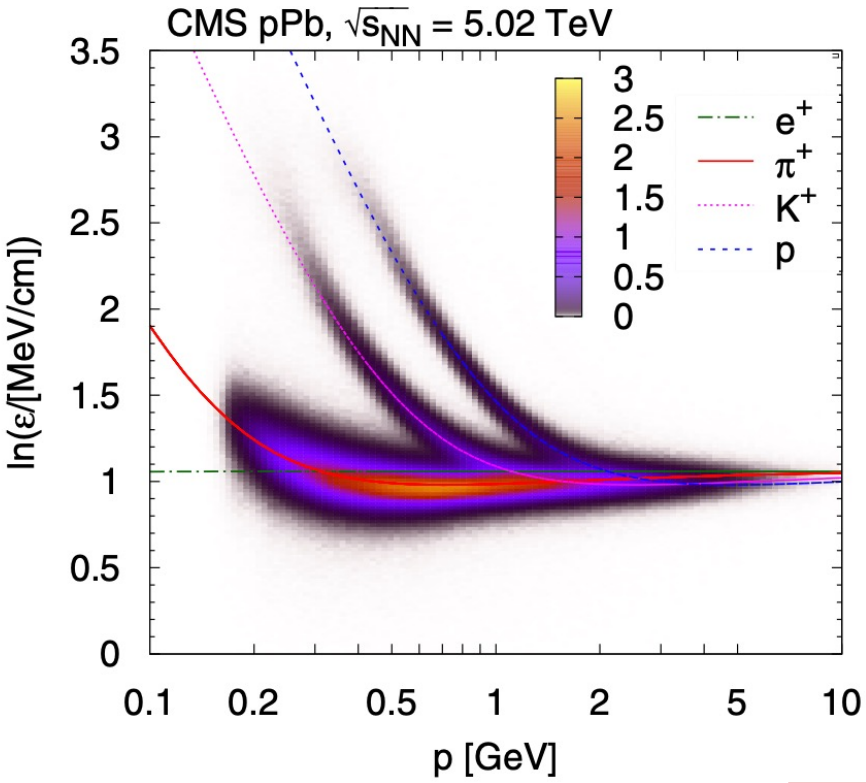
Good agreement with previous results!

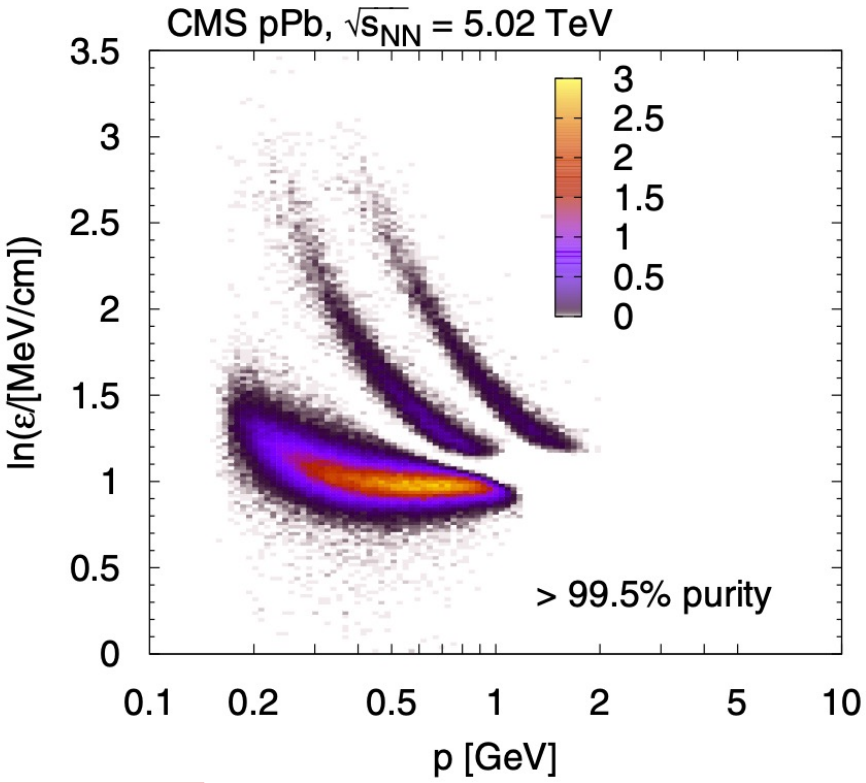
Differences observed when compared with ATLAS results at 13 TeV

Identified particles



Particle identification





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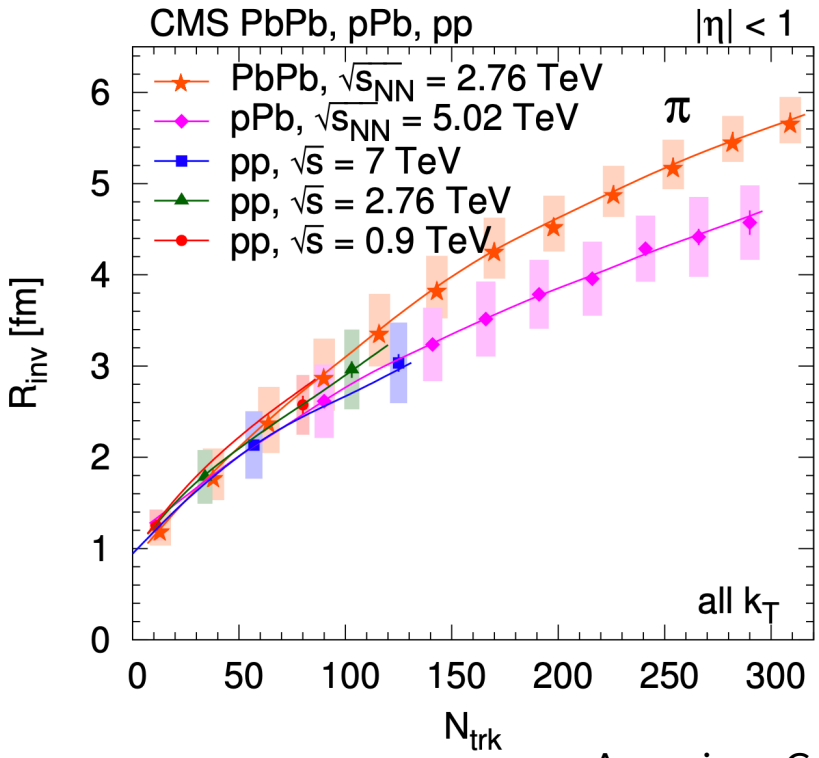
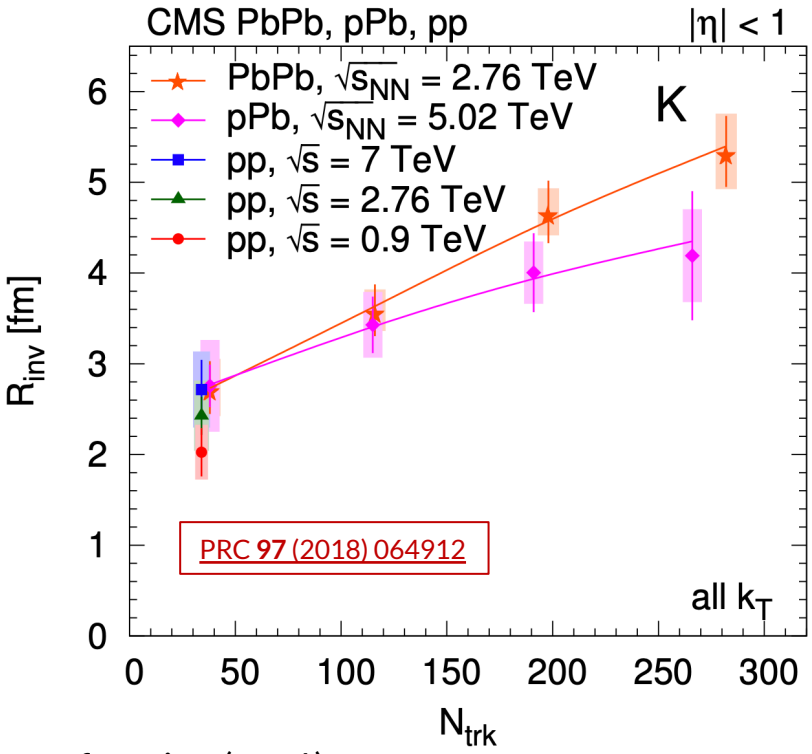
Charged pions and kaons in pp, pPb and PbPb





Assuming a Cauchy source function (α = 1)

Cluster subtraction method used for background determination

Coulomb correction for α = 1 applied