# Selected Results on Correlations from CMS (and phenomenology)

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# Preamble

## Kind invitations to attend Zimanyi School since always!...

- ❑ Different impediments every year…
- ❑ Organizers about to give up this invitation…
- ❑ Unexpectedly, the 2020 pandemic finally made it possible (online)!

## Reports on SPRACE HI team analyses: 10 years of delay

- ❑ Trying to reduce this wide gap ➔
  - Panoramic view of some results obtained in this period from SPRACE HI team (some in collaboration with the Hungarian team!)
- ❑ Expectation: inspire future collaborations!

# Outline of this talk

## Introducing the SPRACE HI team


Sunil M. Dogra
Research Professor
Kyungpook National U.
Korea


César A. Bernardes
Associate Professor
Univ. Federal do RS
UFRGS


Dener S. Lemos
Ph.D. Student
UNESP/SPRACE & IFT

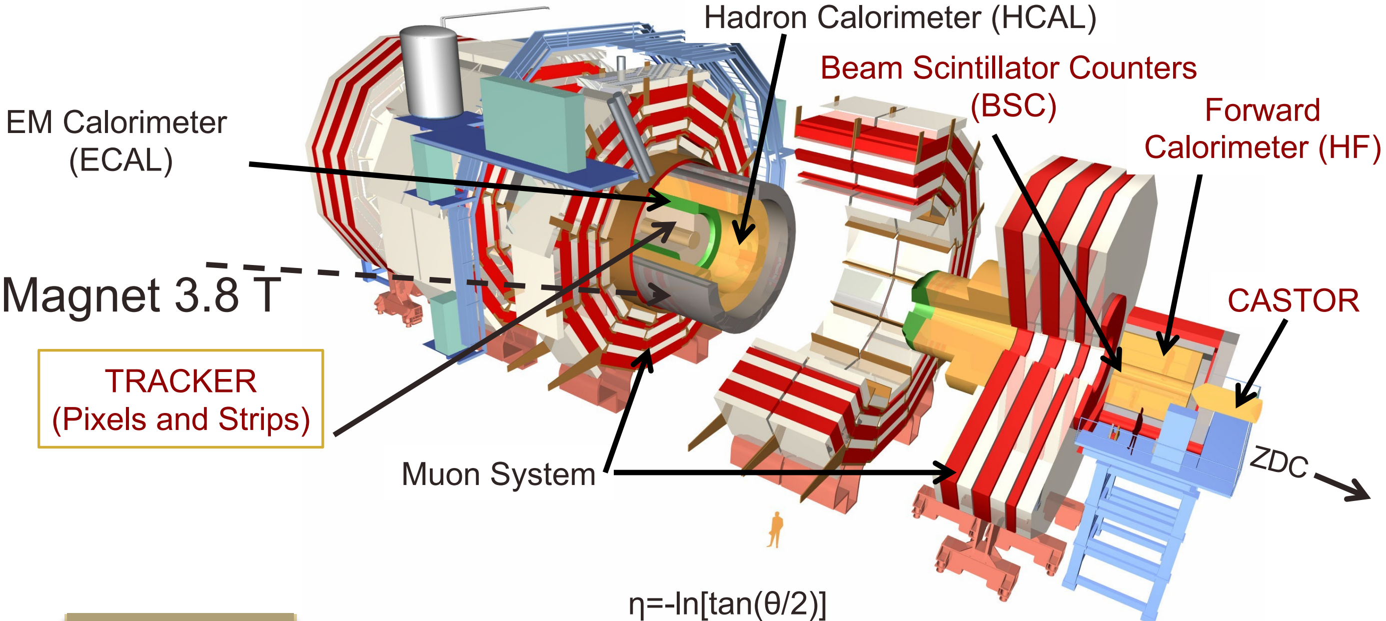

Isabela M. Silvério
M. Sc. Student
UNESP/SPRACE & IFT

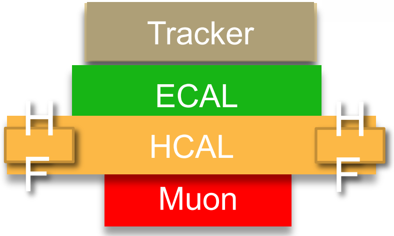

Sandra S. Padula
UNESP/SPRACE & IFT

## Results on correlations in pp, pPb and PbPb collisions at the LHC energies involving the team

- ❑ Femtoscopic correlations
- ❑ Anisotropic azimuthal correlations (one example)

# CMS Detector



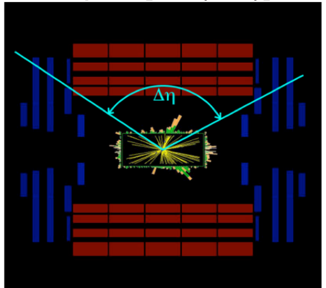

$|\eta| < 2.5$

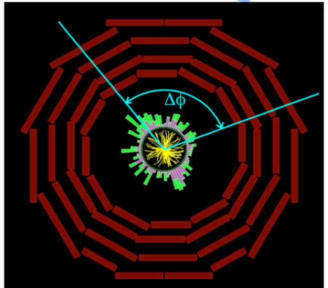
$|\eta| < 3.0$

$|\eta| < 5.2$

$|\eta| < 2.4$

$\eta = -\ln[\tan(\theta/2)]$




$|\Delta\varphi| \leq 2\pi$

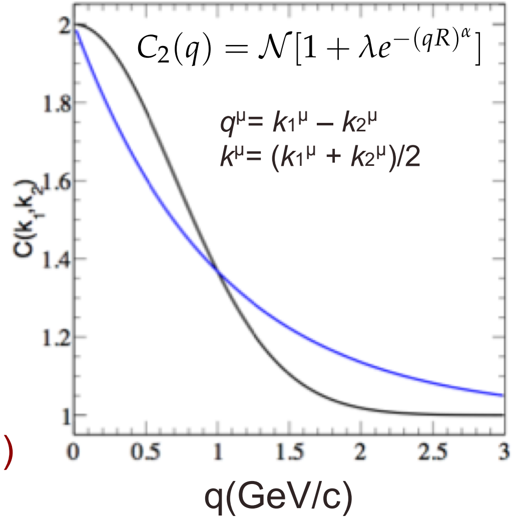
# Femtoscopic analyses
# SPRACE HI team

# Bose - Einstein Correlations

Identical boson correlations can be used to determine the effective size of the emission source

- by measuring a correlation function vs. $q_{inv}$ in 1-D:

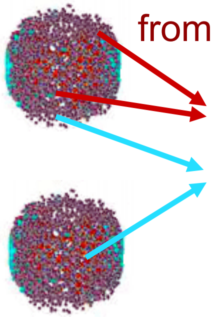
$$C(q=k_1-k_2)=\frac{P_2(k_1,k_2)}{P_1(k_1)P_1(k_2)} \longrightarrow 1+\lambda|\mathcal{F}[\tilde{\rho}(q)]|^2$$




- Single Ratios (SR)

Event 1

Pairs of same charge from the same event (with BEC)



$$\frac{\mathcal{S}(k_1,k_2)}{\mathcal{B}(k_1,k_2)}=C(q=k_1-k_2)$$

Event 2

Different events (no BEC); reference samples

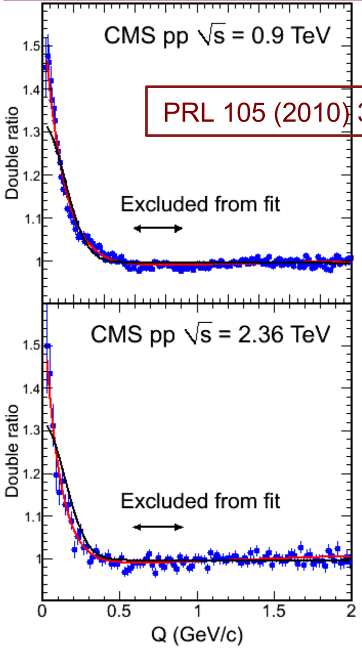
# First BEC results from LHC: 1-D (CMS)

pp collisions at 0.9 and 2.36 TeV

- early 2010 (⌘)

$r$=1.59 ± 0.05 (stat) ± 0.19 (syst)
λ=0.625 ± 0.021 (stat) ± 0 .046 (syst)

PRL 105 (2010) 32001




(exponential fit)

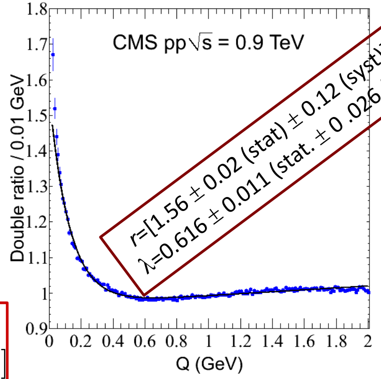
$$R(Q) = C[1 + \lambda e^{-qr}] \times (1 + \delta q)$$

$r$=1.99 ± 0.18 (stat) ± 0.24 (syst)
λ=0.662 ± 0.073 (sta.) ± 0.048 (syst)

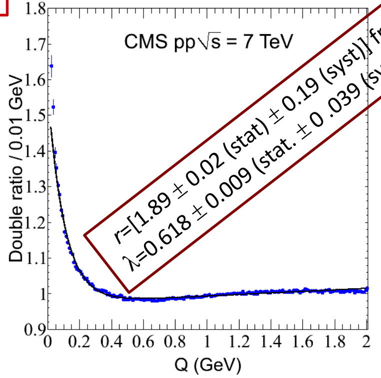
pp collisions at 0.9 and 7 TeV

- early 2011

JHEP05(2011)029

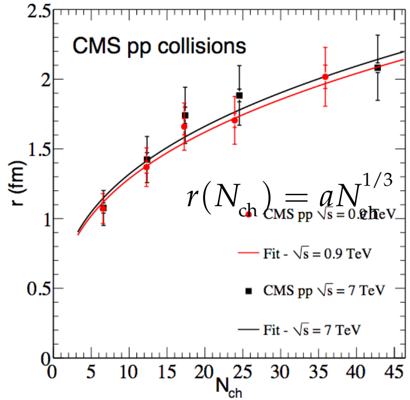



r=[1.56 ± 0.02 (stat) ± 0.12 (syst)] fm
λ=0.616 ± 0.011 (stat. ± 0 .026 (syst)

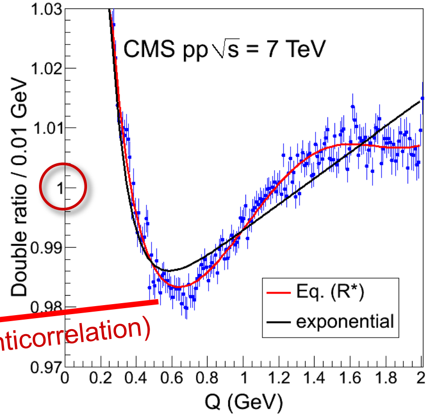



r=[1.89 ± 0.02 (stat) ± 0.19 (syst)] fm
λ=0.618 ± 0.009 (stat. ± 0 .039 (syst)

[ **τ-model** → Csörgő & Zimányi, N.P. A 517, 588 (1990); Metzger et al., P. L. B663, 114 (2008) ]




$$r(N_{ch}) = aN_{ch}^{1/3}$$




(anticorrelation)

# BEC in 1D, 2D & 3D in pp collisions at 2.76 & 7 TeV

Data from pp collisions

– LHC run I

- Minimum bias data
- BEC – charged hadrons
  - 1D: $q_{inv}$
  - Extended to
    - 2D: ($q_L$, $q_T$)
    - 3D: ($q_{Long}$, $q_{Out}$, $q_{Side}$)
    - source sizes in different directions

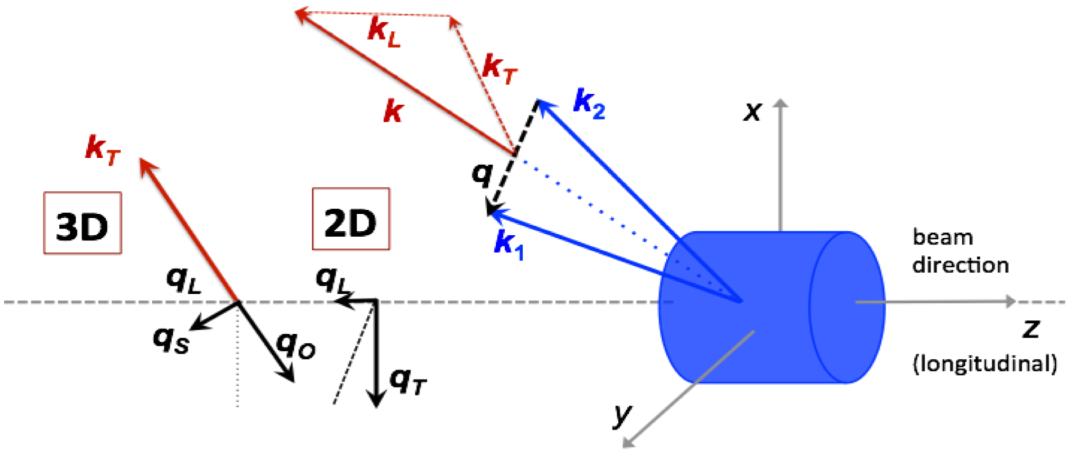
Fits to data:

- 1D: exponential source

$$C_2(q) = \mathcal{N}[1 + \lambda e^{-q_{\rm inv} R_{\rm inv}}][1 + \epsilon q]$$

- In 2D & 3D: “stretched exponential}

$$C_2(q_S, q_L, q_O) = \mathcal{N}\left\{1 + \lambda \exp\left[-\{q_S^2 R_S^2 + q_L^2 q R_L^2 + q_O^2 R_O^2 + 2 q_O q_L R_{LO}^2|^{1/2}\right]\right\} \times (1 + \alpha q_S + \beta q_L + \gamma q_O)$$



# Two experimental BEC techniques in CMS: Double Ratios

Double ratio technique (DR): uses MC simulations

- ❑ Signal and reference (++ , −−) → Single Ratios (SR)

$$\mathrm{SR}\,(q = k_1 - k_2) = \frac{S(q)}{B(q)} = \frac{dN_{\mathrm{signal}}/dq}{dN_{\mathrm{ref}}/dq}$$

  - ❑ Reference sample (*ref*) pair selection
    - – several possibilities → used:
    - ○ mixed events w/ ≈ $N_{ch}$ and $\eta$ range
- ❑ Double ratios (DR)
  - ○ eliminates bias due to *ref*
  - ○ tries to correct for non-BEC effects

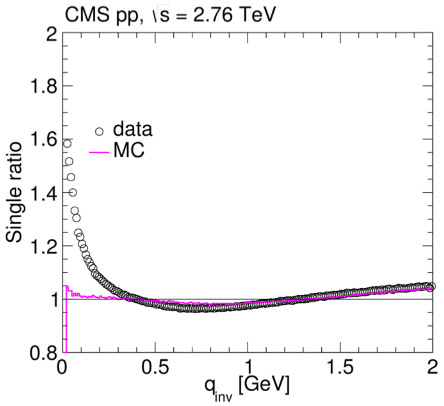
$$\mathrm{DR}\,(q = k_1 - k_2) = \frac{SR(q)}{SR(q)_{\mathrm{MC}}} = \frac{\left[\frac{dN_{\mathrm{signal}}/dq}{dN_{\mathrm{ref}}/dq}\right]}{\left[\frac{dN_{\mathrm{MC,\,like}}/dq}{dN_{\mathrm{MC,\,ref}}/dq}\right]}$$

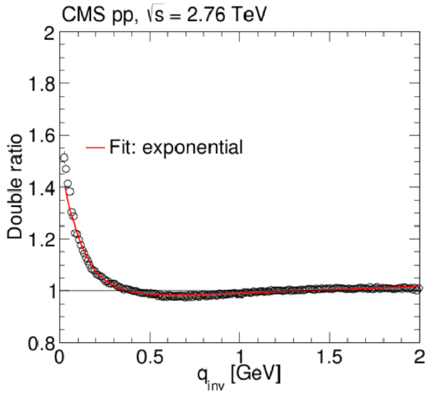
- ❑ Correct for Coulomb FSI (Gamow)

$$\Upsilon(\eta_\omega) = \frac{\eta_\omega/Q}{\exp(\eta_\omega/Q) - 1}$$

$$\eta_\omega = \pm 2\pi\alpha_{\mathrm{em}} m_\pi$$

Phys. Rev. C 97, 064912

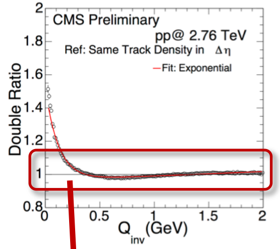


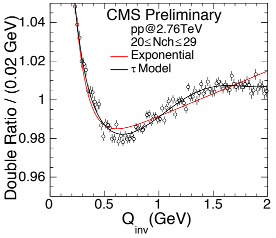

$$DR(q_{\mathrm{inv}}) = \mathcal{N}[1 + \lambda e^{-q_{\mathrm{inv}} R_{\mathrm{inv}}}][1 + \epsilon q_{\mathrm{inv}}]$$

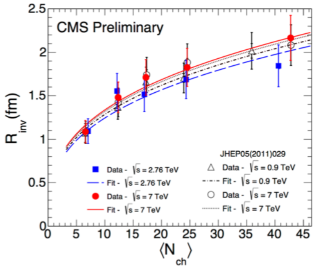
# BEC in 1-D, 2-D and 3-D in pp collisions at 2.76 and 7 TeV

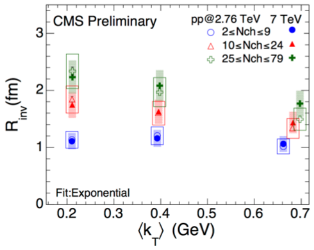
1-D

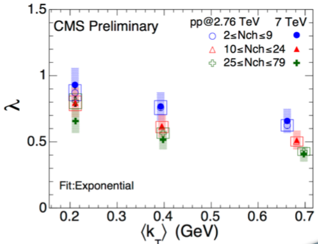



zoom

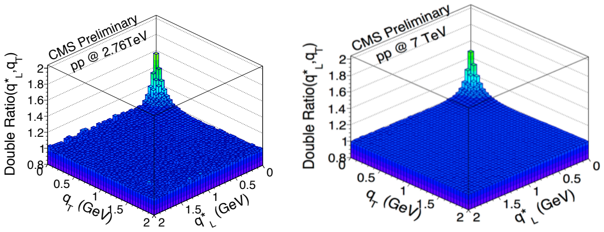


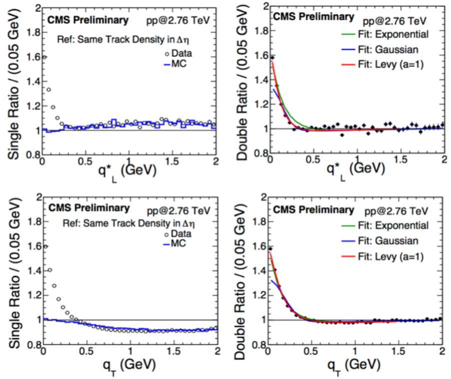



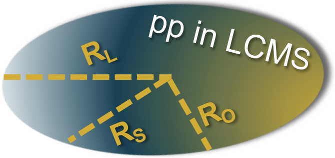




2-D

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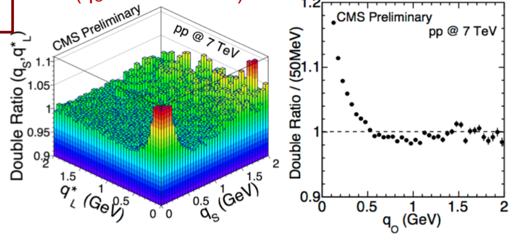
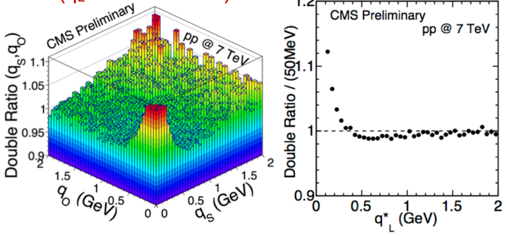
3-D

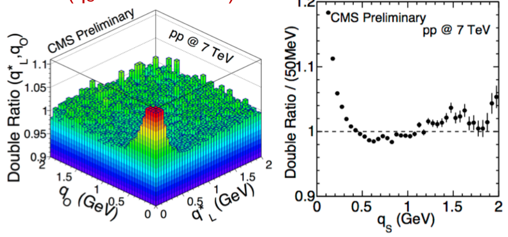
($q_O$ < 0.05 GeV/c)




($q_L$ < 0.05 GeV/c)



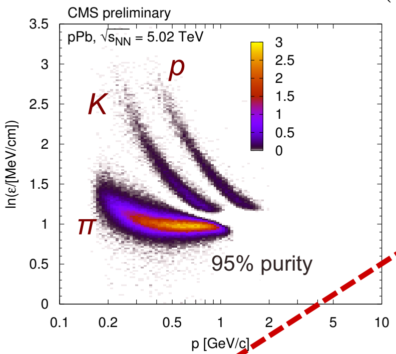

($q_S$ < 0.05 GeV/c)

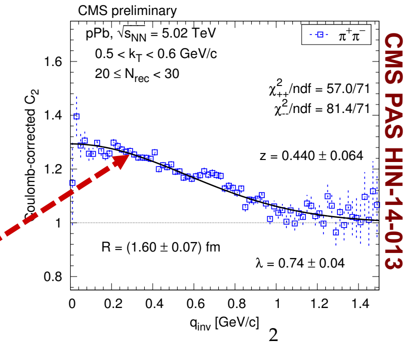


# Two experimental BEC techniques in CMS: Cluster Subtraction

CS method: data-driven [Ferenc Sicklér]

- SR only → for identified $\pi$, $K$, $p$
- uses (+ −) → correct for non-BEC effect (cluster)
  - mini-jets
  - multibody resonances
  - Coubom FSI: $\Upsilon(\eta_\omega) \to K(q_{\rm inv}) \approx 1 + \pi\eta_\omega \frac{q_{\rm inv}R}{1.26+q_{\rm inv}R}$




$$C^{+-}(q_{\rm inv}) = cK^{+-}(q_{\rm inv})\left\{1 + \frac{b}{\sigma_b\sqrt{2\pi}}\exp\left[-\left(\frac{q_{\rm inv}^2}{2\sigma_b^2}\right)\right]\right\}$$

- $b$ → cluster amplitude:

$$b(N_{\rm trk}^{\rm offline}, k_T) = \frac{b_0}{N_{\rm trk}^{\rm offline}}\exp\left[-\left(\frac{k_T}{k_0}\right)\right]$$

- $\sigma_b$ → cluster width:

$$\sigma_b(N_{\rm trk}^{\rm offline}, k_T) = \left[\sigma_0 + \sigma_1\exp\left(-\frac{N_{\rm trk}^{\rm offline}}{N_0}\right)\right]k^{n_T}$$

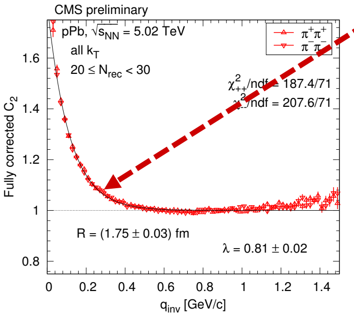
- The cluster contribution: also present in $\pi^+\pi^-$ pairs, with similar shape but a smaller amplitude
- Use the form of the contribution obtained from $\pi^{+-}$ pairs: $b$ and $\sigma_b$ fixed
- Assume the width is the same and determine the $(\pm\pm)$ cluster relative amplitude $z(N_{\rm trk}^{\rm offline})$

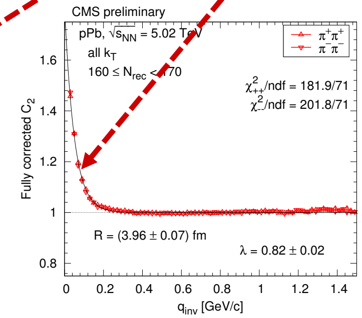
$$C^{\pm\pm}(q_{\rm inv}) = cK^{\pm\pm}(q_{\rm inv})\left[1 + z(N_{\rm trk}^{\rm offline})\frac{b}{\sigma_b\sqrt{2\pi}}\exp\left(-\frac{q_{\rm inv}^2}{2\sigma_b^2}\right)\right]C_{BE}(q_{\rm inv})$$

Phys. Rev. C 97, 064912

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

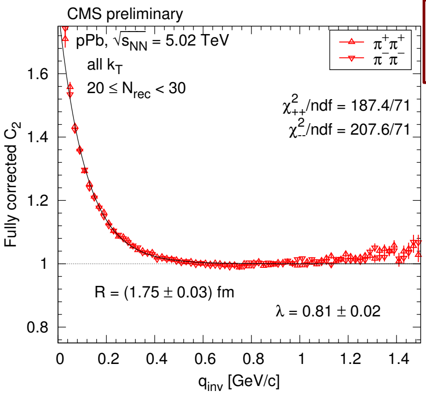
$$C_{BE}(q_{\rm inv}) = [1 + \lambda\exp(-q_{\rm inv}R_{\rm inv})]$$

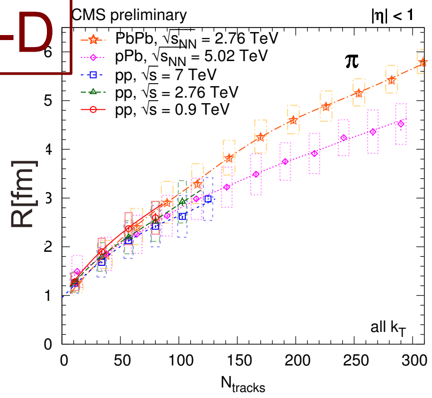


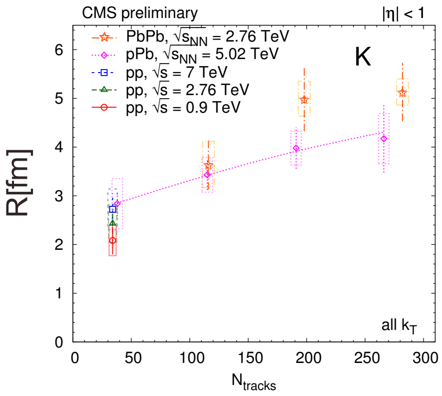



# BEC in 1-D, 2-D and 3-D using CS technique in pp, pPb & PbPb

**1-D**



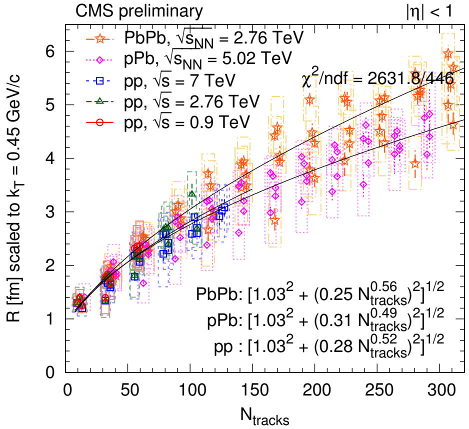



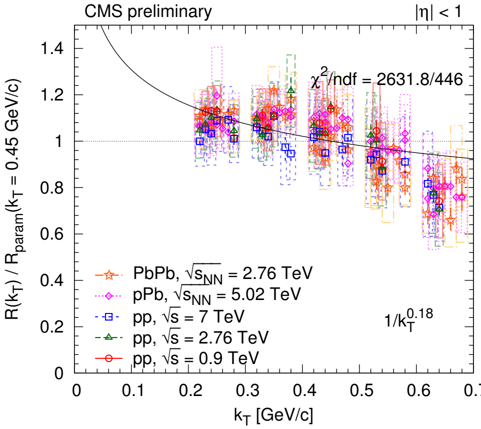

CMS PAS HIN-14-013

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

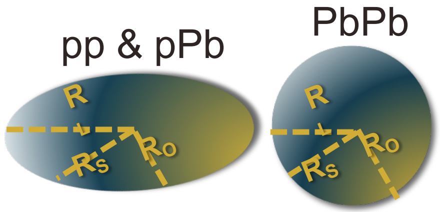
$C_{BE}(q_l, q_t) = 1 + \lambda \exp[-\sqrt{(q_l R_l)^2 + (q_t R_t)^2}]$

$C_{BE}(q_l, q_s, q_o) = 1 + \lambda \exp[-\sqrt{(q_l R_l)^2 + (q_s R_s)^2 + (q_o R_o)^2}]$




**2-D & 3-D**




Phys. Rev. C 97, 064912

# BEC in pp collisions at 13 TeV: assumptions

Two-particle BEC in pp at 13 TeV

- Radius of particle emitting region ($R_{inv}$) as function of charged particle multipicity ($N_{tracks}$)
- Large multiplicity range: from minimum bias (MB) to high multiplicity (HM) ($2 \leq N_{tracks} < 250$ particles)
- $R_{inv}$ and $\lambda$ as functions of multiplicity and $k_T$

Three different analysis technique:

(first results with high multiplicity data)

- Double Ratios method (depends on Monte Carlo simulations for removing non-BE effects
- Cluster Subtraction (CS): data driven
- Hybrid Cluster Subtraction (HCS): less dependent on MC
- All three methods return similar results!

# Outline of analysis methods

Double Ratio (DR), as in (*) & PRC 97 (2018) 064912

- ❑ Ratio of Single Ratios (SR)
  - Data SR divided by MC SR
  - Non-BEC contributions: removed by directly performing the ratio of data to MC
- ❑ Fit double ratio with a function representing the BEC signal alone

Cluster Subtraction (CS) – fully data-driven, as in PRC 97 (2018) 064912

- ❑ Employs Single Ratios only
- ❑ Non-BEC cluster is estimated direcly from data (+ –) SR
  - Estimates the amplitude (``height'') of the cluster using (±±) SR in data
- ❑ Fit SR with functional form combining signal+cluster components

$\neq$

Hybrid Cluster Subtraction (HCS) partially data-driven, as in ATLAS [PRC 96 (2017) 064908]

- ❑ Employs Single Ratios only
- ❑ Uses MC SR to correlate (+ –) and (±±) background
- ❑ Non-BEC effects: estimated from data (+ –) SR
  - Uses MC estimate to convert this contribution into the cluster in the data (±±) SR
- ❑ Fit SR data with combined function for signal + cluster

(*) PRL **105** (2010) 03200 & JHEP **05** (2011) 029

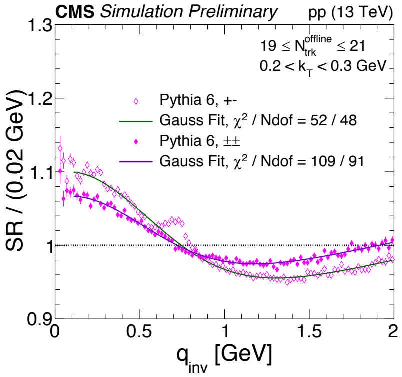
# Hybrid Cluster Subtraction (HCS) Method – I

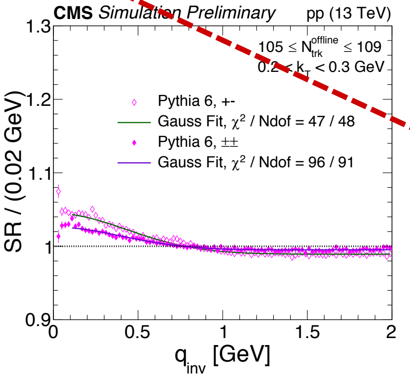
## Fitting Same-Sign and Opp-Sign **SR in MC**

- In MC (no BEC effects) → Bkg modeled by fit par
- In data: BE effect **not** present in [(+ −)] pairs – Bkg only
  - Use the relations from MC to estimate the Bkg in (±±) SR

## Fit functions:

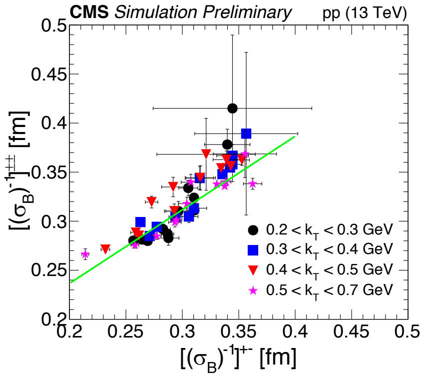
$$\Omega(q_{\mathrm{inv}}) = \mathcal{N}\left(1 + B\exp\left[-\left|\frac{q_{\mathrm{inv}}}{\sigma_B}\right|^{\alpha_B}\right]\right)$$



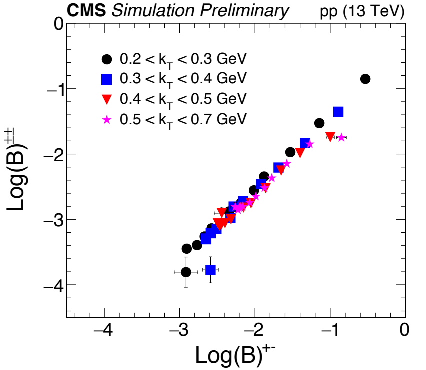

## Relation $[(\sigma_B)^{-1}]^{\pm\pm}$ vs. $[(\sigma_B)^{-1}]^{+-}$ (Pythia6 Z2*):

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




## Relation $(B)^{\pm\pm}$ vs. $(B)^{+-}$ (Pythia6 Z2*):

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

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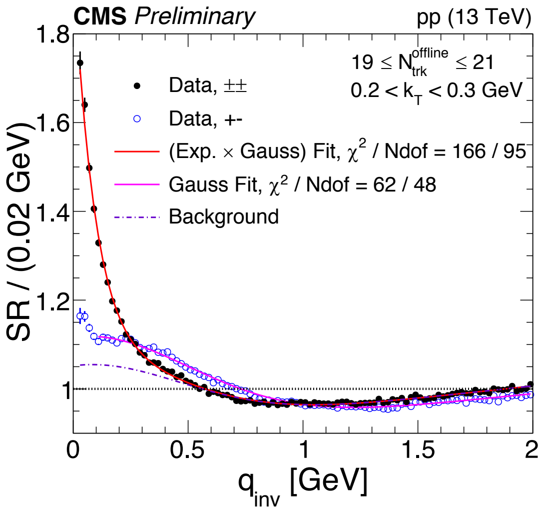
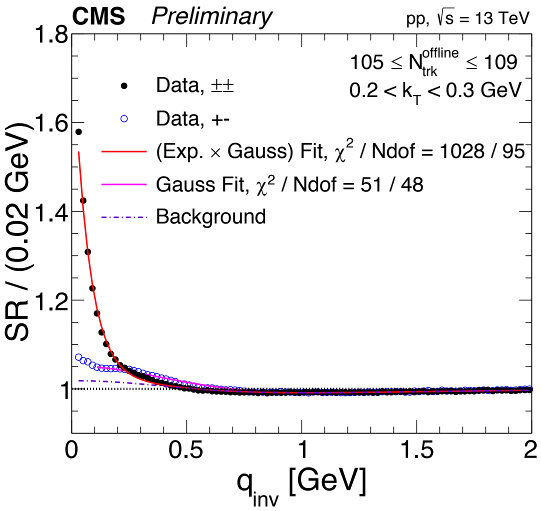
# Hybrid Cluster Subtraction (HCS) Method – II

After getting relations for ``Bkg'' fit parameters in 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: $C(q_{\rm inv}) = \Omega(q_{\rm inv}) \times C_{\rm BEC}(q_{\rm inv})$

JHEP 03 (2020) 014

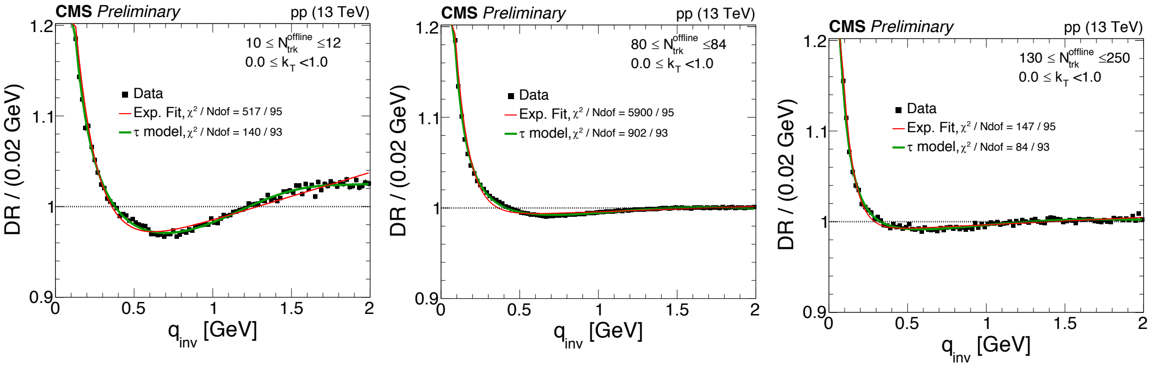



https://cds.cern.ch/record/2318575

# Results: discussion about anticorrelation (I)

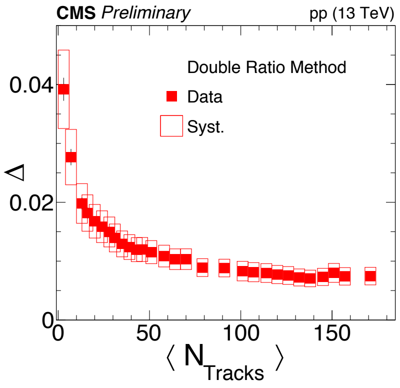
Zoomed (along the y-axis) correlation functions from DR method

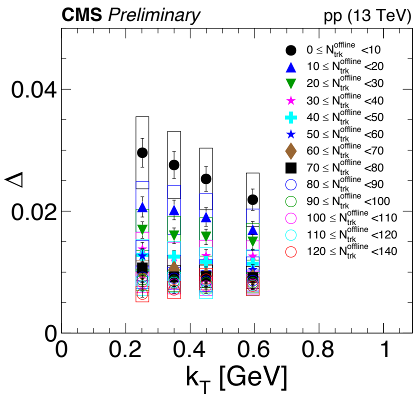



- ❑ Fits with exponential (red) and τ-model [Csörgö, Zimányi NPA **517** (1990) 588] (green)
- ❑ τ-model explains better the overall behavior of data
- ❑ Dip's depth (Δ):
  - distance of the τ-model fit at its minimum and the baseline C(1+ε $q_{inv}$,
- ❑ Integrated in $k_T$
  - Decreases with <$N_{tracks}$>, tend to ≈ const. above 100
- ❑ and differential in $k_T$
  - Decrease with $k_T$ for lower <$N_{tracks}$> ranges
  - For <$N_{tracks}$> > 30 → ≈ const. with increasing $k_T$

$$C_{CZ}(q_{inv}) = C\left[1+\lambda\left(\cos\left[(r_0 q_{inv})^2+\tan(\alpha\pi/4)\,(q_{inv}r_\alpha)^\alpha\right]e^{-(q_{inv}r_\alpha)^\alpha}\right)\right]\cdot(1+\delta q_{inv})$$

JHEP 03 (2020) 014



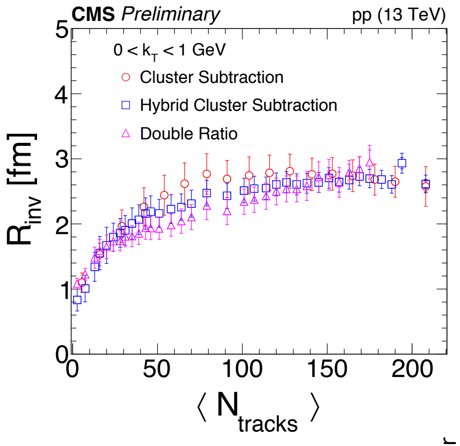

Dip's depth at the highest multiplicities ──> const. value

- ❑ Possible consequence of the DR method
- ❑ or an intrinsic characteristic of the collision system
  - keep memory of its initially small size, even at the highest track multiplicities produced in pp collisions

# BEC in pp collisions at 13 TeV: results

3 analysis methods: comparing results

- ❑ Double ratios
- ❑ Cluster subtraction
- ❑ Hybrid CS → Consistent results

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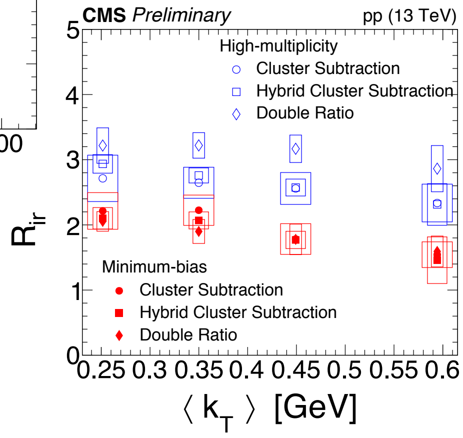
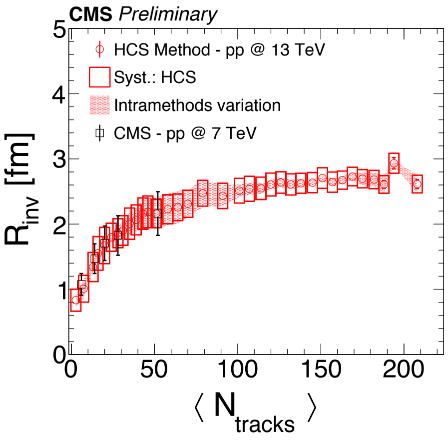
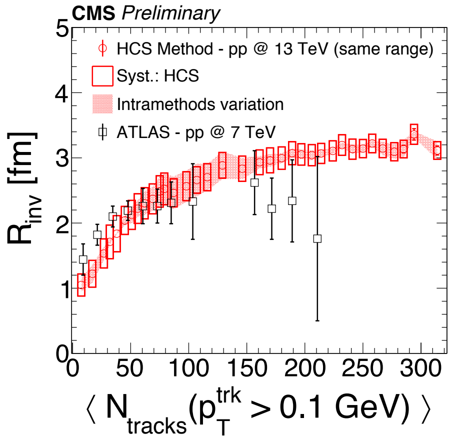



Results from HCS → consistent with

- ❑ CMS for pp@7 TeV [PRC 97 (2018) 064912] using Double Ratio method (η-mixing reference sample)




- ❑ ATLAS for pp@7 TeV [EPJC **75** (2015) 466]
  - using Double Ratio method (opposite sign reference sample)



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

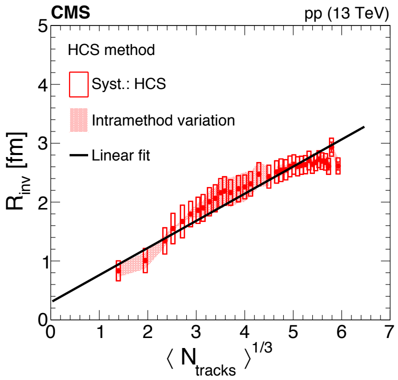
# BEC up to high multiplicity (pp @ 13 TeV)

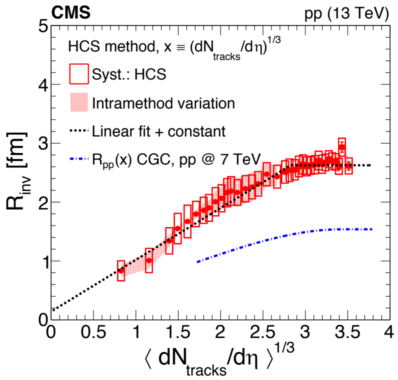
Data vs. CGC and vs. Hydro

- ❑ Color Glass Condensate
  - $R_{inv}$ saturates at high multiplicity
- ❑ Above 1.7 : fit with same function obtained from CGC prediction (dashed black curve; stat. uncert. only)
  - [*McLerran, Schenke, NPA* **916** (2013) 210; P. T. A. Bzdak et al, *PRC* **87** (2013) 064906]

$$R_{pp}(x) = \begin{cases} (1\,\text{fm}) \times [a + b\,x + c\,x^2 + d\,x^3], & \text{for } x < 3.4 \\ e\,(\text{fm}), & \text{for } x \geq 3.4 \end{cases}$$

  - $x = \left({}^{dN_{tracks}}/_{d\eta}\right)^{1/3}$
- ❑ Hydrodynamics
  - $R_{inv}$ continuously grow w/ $\langle N_{tracks} \rangle$

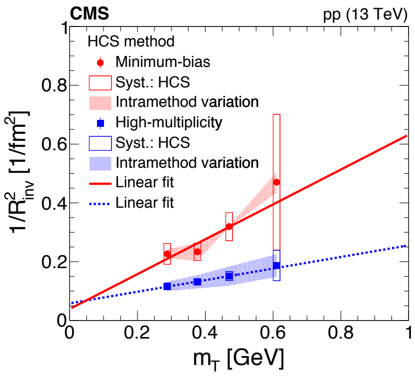


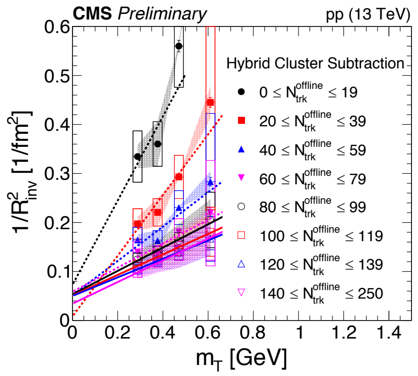




→ Results compatible with expectations from both, within uncertainties

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

- ❑ In hydrodynamic models [Sinyukov et al., NPA 946 (2016) 227]
  - Intercept <—> source geometrical size (at freeze-out)
  - Slope: reflects the flow component …
    - ○ Larger slope (faster expansion) → MB (low $N_{tracks}$) (similar to peripheral AA collisions)
    - ○ Lower slope → higher multiplicities (similar to more central AA collisions)




JHEP 03 (2020) 014

# Anisotropic Flow and the search for strong magnetic field

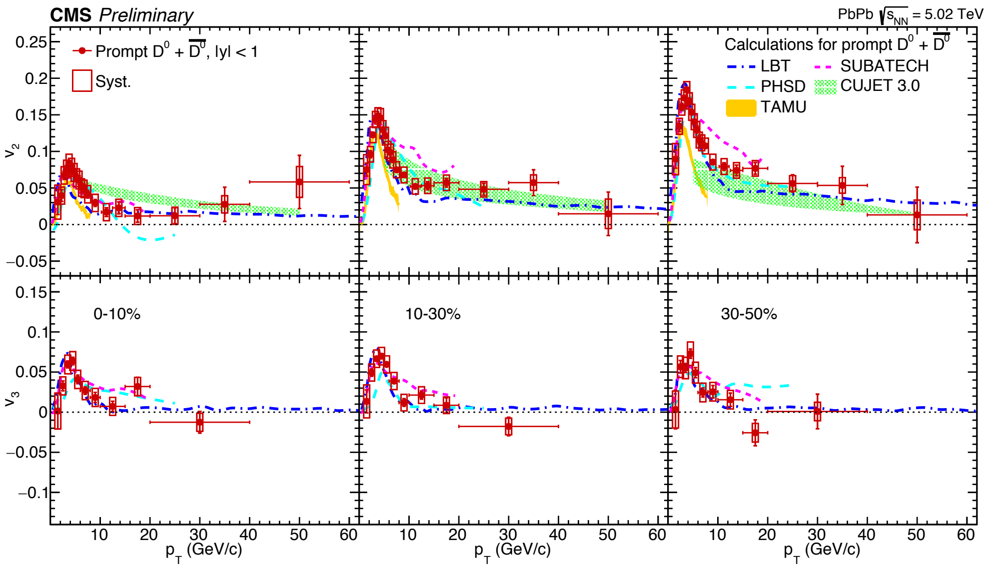
SPRACE

# Electromagnetic Fields in PbPb Collisions

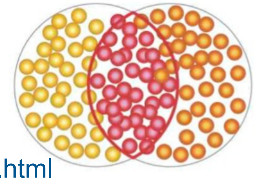
## Strong and short lived EM fields in PbPb collisions at LHC

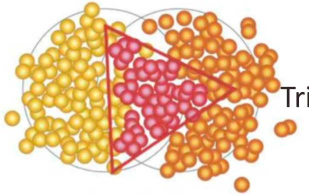
- ❑ Generated by spectators and participants
- ❑ Charge-odd contributions to flow coefficients ($v_n$)
  - Non-zero $\Delta v_n$ for opposite-charge
- ❑ Measurements constrain medium parameters
  - E.g. electric conductivity

## $D^0$ Mesons Azimuthal Anisotropy




Elliptic Flow





Triangular Flow

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN-19-008/index.html

# $\Delta v_2(D^0 - \overline{D^0})$ as Function of Rapidity

Electric field can generate non-zero $\Delta v_2$

- ❑ Currently, no theoretical predictions for $D^0$
    - Predictions for charged hadrons at LHC energies: $|\Delta v_2| \sim 0.001$ [Phys. Rev. C **98**, 055201 (2018)]
    - Expected bigger values for $D^0$ [Phys. Rev. C **98**, 055201 (2018)]

Average value extracted with a fit to data

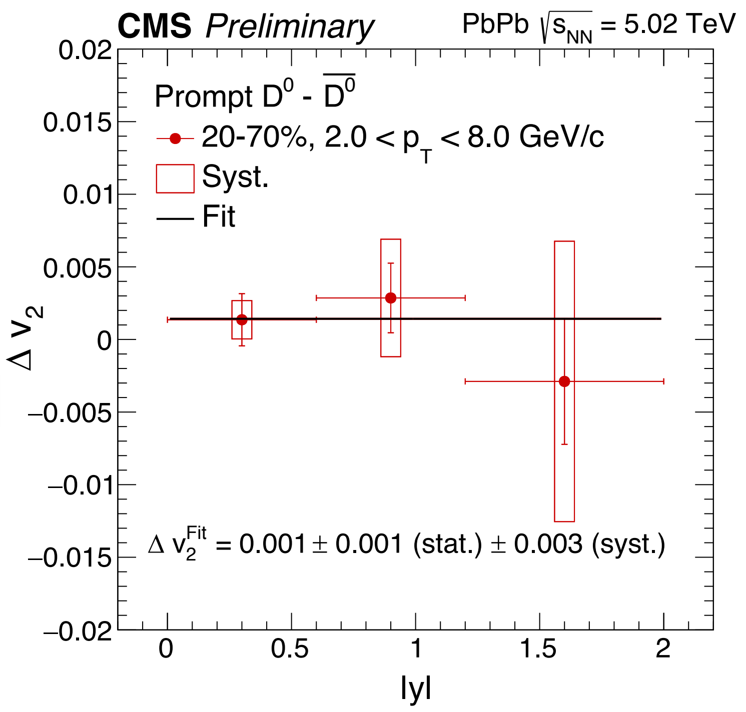
- ❑ $\Delta v_2^{Fit} = 0.001 \pm 0.001\ (stat) \pm 0.003\ (syst)$

Comparable to the values for charged hadrons

- ❑ Constrain medium properties: electric conductivity

(see talk by César A. Bernardes – Thu/10 – 16h20)

CMS-PAS-HIN-19-008




http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN-19-008/index.html

# Results on phenomenology

# Study of D mesons with Femtoscopy

Femtoscopy: correlation function of two particles vs. their relative momentum

- quantum statistics
- sensitive to the effects of the final-state interaction:
  - Coulomb, strong interaction, etc.

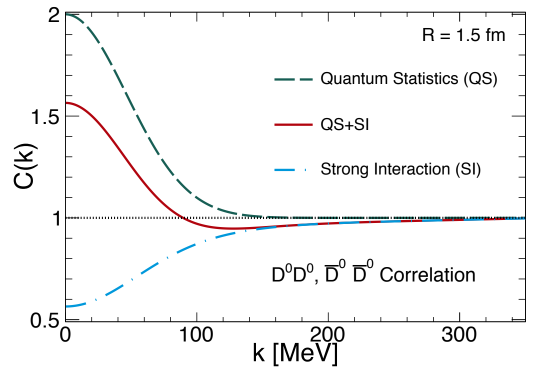
Correlation Function between two identical bosons:

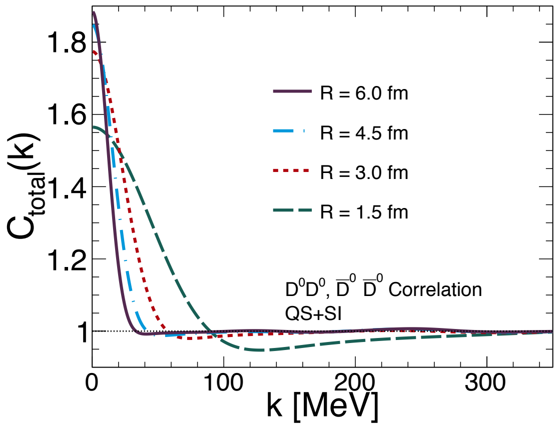
$$C(k) = \int d^3r S(r) |\psi(r,k)|^2$$
$$= 1 + e^{-4k^2R^2} + 2\int d^3r S(r) \left[ |\psi_0(r)|^2 - j_0^2(kr) \right]$$

Scattered wave function and the Correlation Function → from:

- the Schrödinger Equation (Schr. Eq.) for Local Potential
- the Lippmann-Schwinger Equation (LS Eq.), for Non-Local Potential (the D meson case).

(see poster by Isabela M. Silvério – Wed/09 – 18h30)

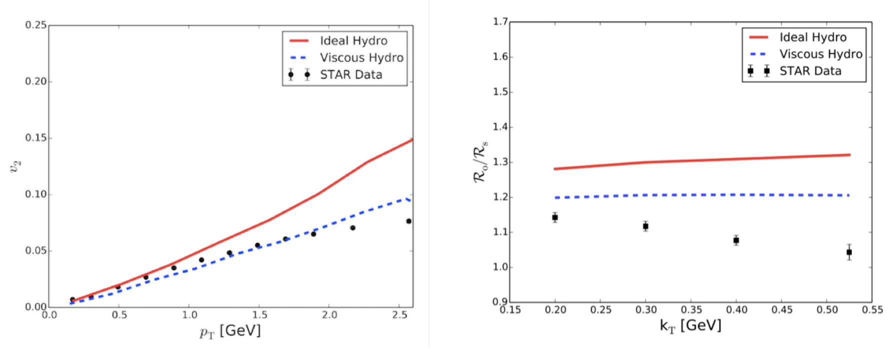


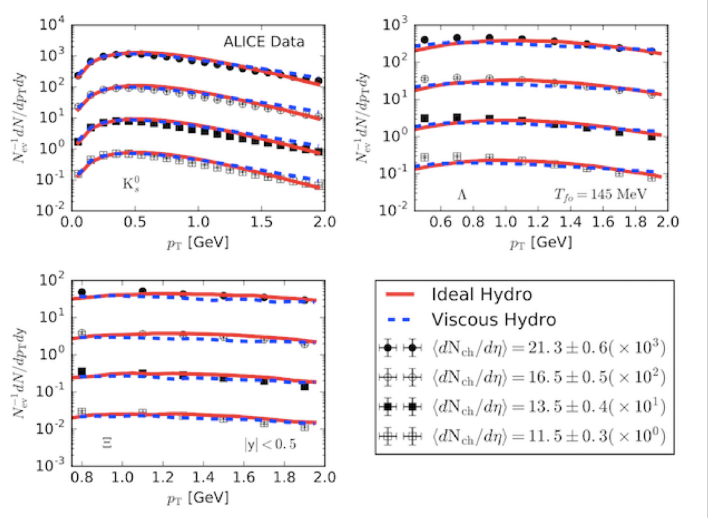



# Phenomenology in Heavy Ions Physics

"CHESS - Complete Hydrodynamical Evolution SyStem"

- Describes the entire evolution of QGP using hydrodynamical model
- Can be applied to investigate small systems or heavy-ion collisions
- Possibility to study viscous or ideal fluid
- Multiple observables can be calculated
- Open Source project available soon




(see poster by Dener S. Lemos – Wed/09 – 18h30)

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| 3. | Antonio Carlos Oliveira Santos | |
| 4. | Jadir Marra Silva | UNESP |
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| 6. | Lord Flaubert Steve Ataucuri Cruz | UNESP |
| 7. | Márcio Costa | UNESP |
| 8. | Ricardo Schinaider de Aguiar | UNESP |
| 9. | Sidney Santos | UNESP |

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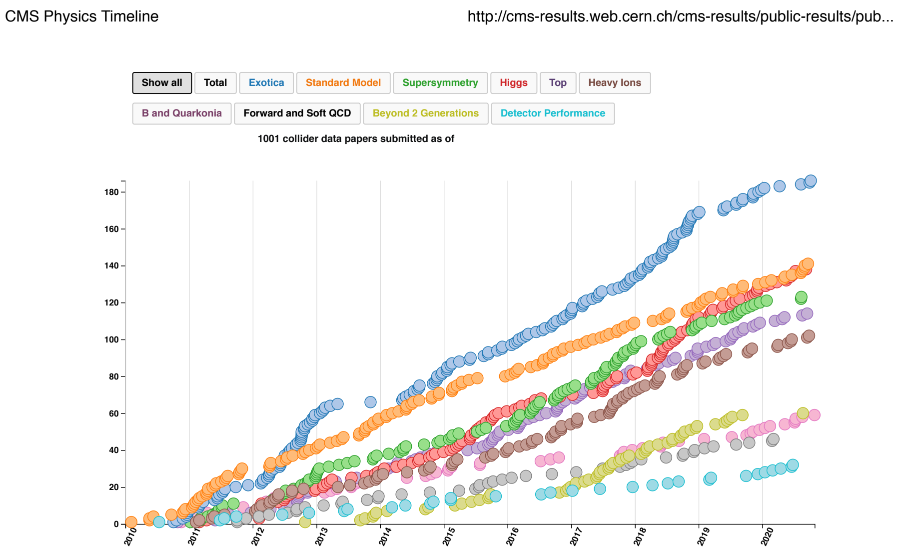
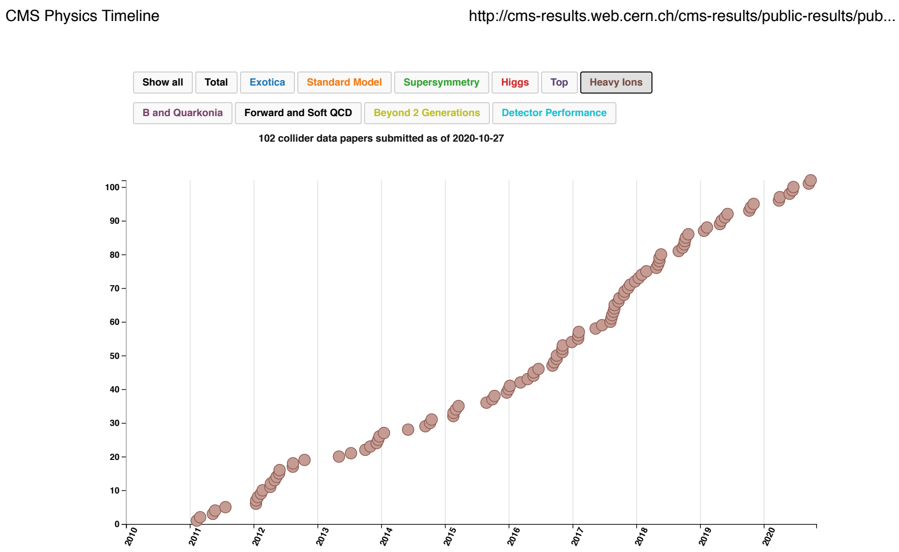
# Thank you!

# Plethora of CMS-HI results



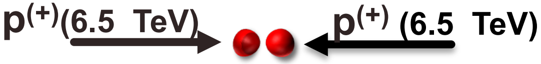

http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

Results can be found in
http://cms-results.web.cern.ch/cms-results/public-results/publications/

# pp, pPb and PbPb collisions @ LHC

Start: 2010 → pp at CMS energies ($\sqrt{s}$):

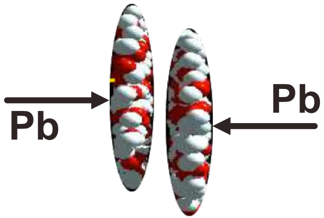
- 900 GeV, 2.36 and 7 TeV
- In 2011: pp at CMS energyies $\sqrt{s}$ = 7 TeV
- In 2013: pp at CMS energyies $\sqrt{s}$ = 8 TeV
- In 2015 : pp at CMS energyies $\sqrt{s}$ = 5 and 13 TeV
- In 2016-2018 : pp at CMS energyies $\sqrt{s}$ = 13 TeV




Nov/2010 → first PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

- ($\sqrt{s_{NN}}$ = 2.76 TeV [ 2 x 3.5 x 82 ($p^+$)/208= 2.76 TeV ] )

- In 2011 → PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- In 2015 → PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- In 2018 → PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV




Jan–Feb/ 2013 → first pPb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- In 2016 → pPb collisions at $\sqrt{s_{NN}}$ =8.16 TeV