Bose-Einstein correlations in various collision systems and energies measured with the CMS experiment

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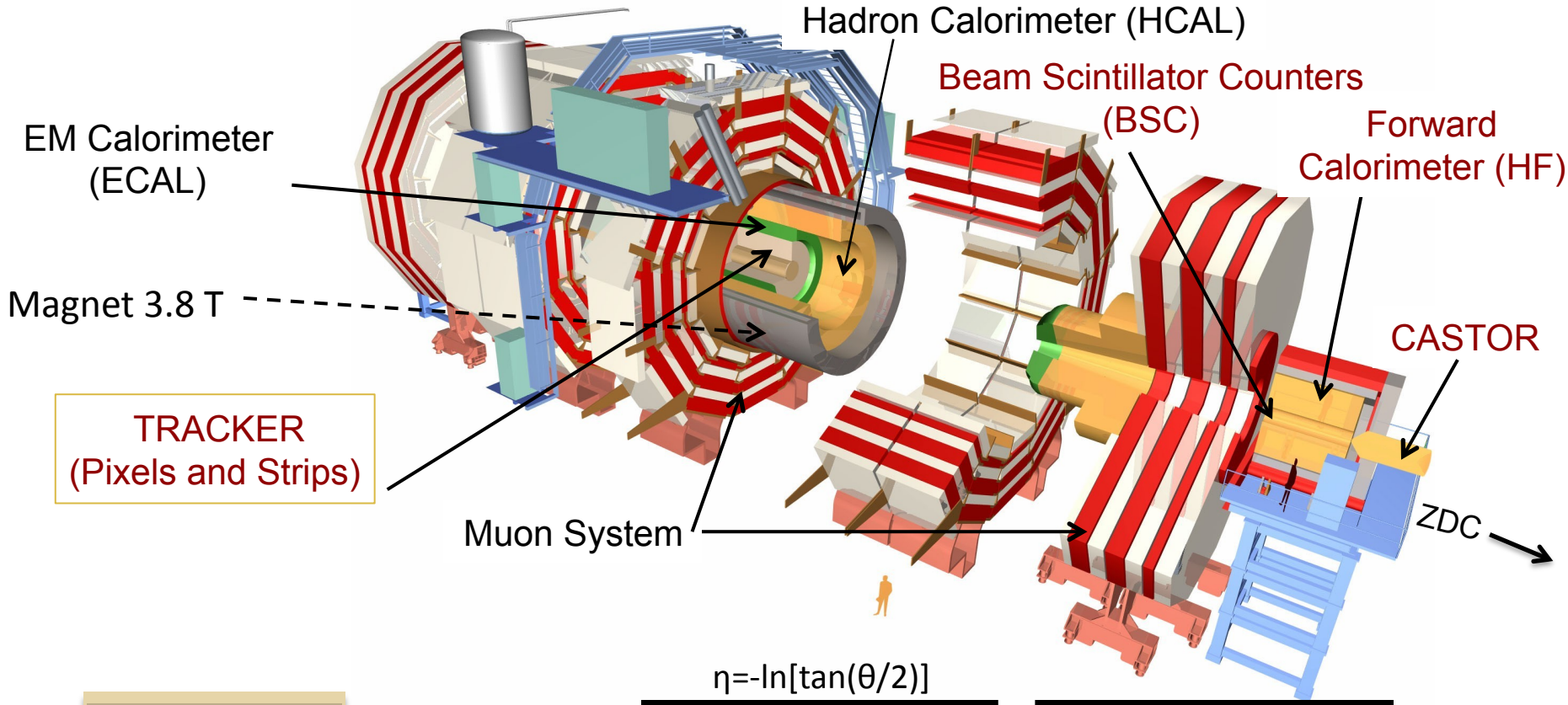
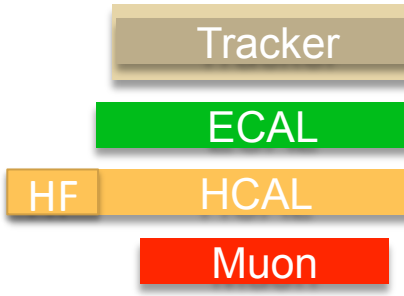
For the CMS Collaboration

DIS2015, Dallas, TX, USA, 04/27-05/01

CMS Detector





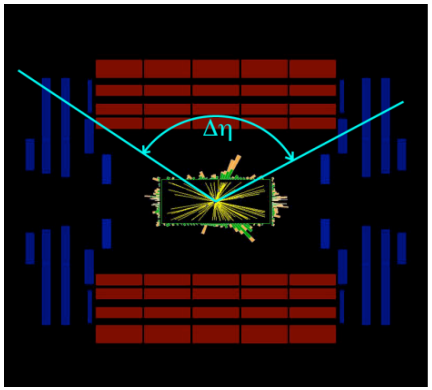
$|\eta| < 2.5$

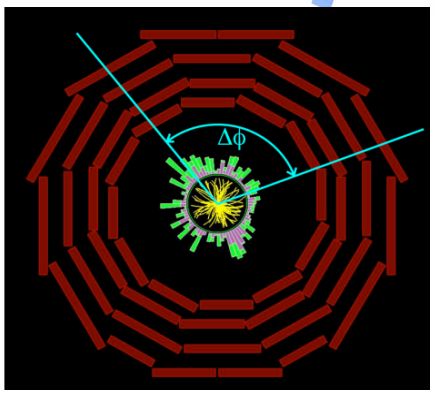
$|\eta| < 3.0$

$|\eta| < 5.2$

$|\eta| < 2.4$

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

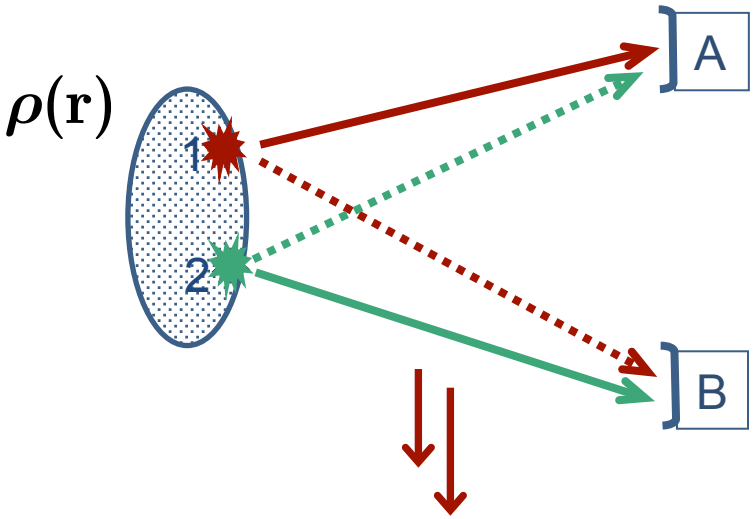




$|\Delta\varphi| \leq 2\pi$

BEC basic concepts

- Detecting two identical bosons emitted from sources 1 & 2 at A & B



- Two-boson correlation function ⟶ reflects source dimensions

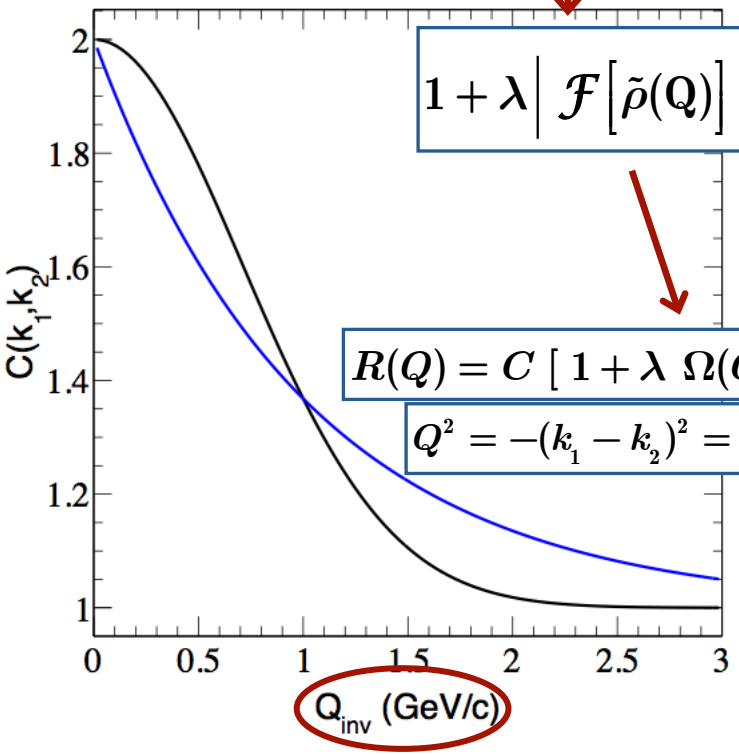
– Correlation Function:

$$R\left(Q = k_1 - k_2\right) = \frac{P_2(k_1, k_2)}{P_1(k_1)P_1(k_2)}$$

$$1 + \lambda \left| \mathcal{F}\left[\tilde{\rho}(\mathbf{Q})\right] \right|^2$$ (ideal)

$$R(Q) = C\ [\ 1 + \lambda\ \Omega(Qr)\ ]\ (1 + \delta Q)$$

$$Q^2 = -(k_1 - k_2)^2 = M_{inv}^2 - 4m_\pi^2$$



(two previous CMS papers)

Overview on multi-dimensional BEC

- Part I
  - Min Bias pp collisions at $\sqrt{s}$=2.76 TeV and 7 TeV → scrutinized by
    - ❑ extending previous BEC measurements to 2-D and 3-D (also 1-D)
      - unidentified charged hadrons → technique as in (CMS) PRL 105, 032001 (2010) JHEP05(2011)29
    - ❑ investigating the behavior of the correlation functions
      - three parameterizations of the source and in two reference frames
      - dependence on different multiplicity (N_{ch}) and average pair momentum (k_T)
- Part II
  - Various systems: Min Bias pp ($\sqrt{s}$=0.9, 2.76, 7 TeV), pPb ($\sqrt{s}$=5.02 TeV) and (peripheral) PbPb ($\sqrt{s}$=2.76 TeV) collisions
    - ❑ investigate similarities and differences in the three systems
      - identified pions and kaons with data-driven technique
      - stretched exponential fit in 1-D, 2-D and 3-D
      - dependence on different multiplicity (N_{ch}) and average pair momentum (k_T)

Part I: BEC with Double Ratio technique

- Single Ratios (SR)

$$R^{\exp}\left(Q = k_1 - k_2\right) = \frac{S(k_1, k_2)}{\mathcal{B}(k_1, k_2)}$$

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

Different reference samples (no BEC)

CMS Collab., PRL 105, 032001 (2010)
CMS Collab., JHEP05(2011)29

– Background pair selection
  - ❑ Same event, ≠ charges (☹ resonances)
  - ❑ Rotation of 1 track of the pair
  - ❑ Mixed events (☺) → (similar N_{ch} within same η range)

Coulomb Final State Interact.
Gamow factor applied to data

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

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

Double Ratios (DR) ⟶ reduce bias:

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \frac{\left(\frac{dN_{signal}/dQ}{dN_{ref}/dQ}\right)}{\left(\frac{dN_{MC,\,like}/dQ}{dN_{MC,\,ref}/dQ}\right)}$$

(No BEC in MC)

Data and MC samples – Track selection

√s	pp collisions	
	Data Sample	Monte Carlo
2.76 TeV	Minimum bias/2013 (3.4 M)	Pythia 6 Z–2 tune (2 M)
7 TeV	Full Minimum bias sample (23 M+16M+4M)	Pythia 6 Z–2 tune (33 M)

- Track selection cuts
  - Tracks associated with most populated vertex
  - $\chi^2 < 5$
  - $d_{xy} < 0.15$ cm
  - $R_{min} > 20$ cm
  - $p_T > 0.2$ GeV/c
  - $\eta < |2.4|$

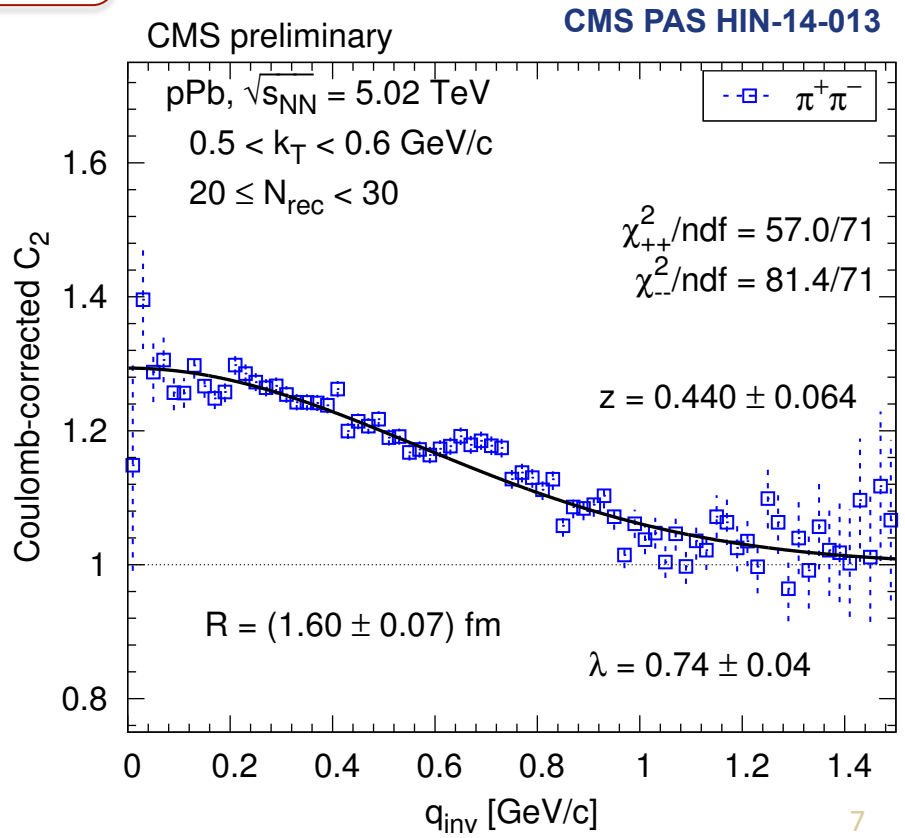
First part of the talk:
charged hadrons ($h^{\pm}$)
(assumed to be dominated by π's)

Part II:Data-driven technique (cluster removal)

- Correlation function $R^{\mathrm{exp}} \rightarrow C_2(q_{\mathrm{inv}}) = \frac{\mathcal{S}(k_1,k_2)}{\mathcal{B}(k_1,k_2)}$
- Coulomb (kaons)→ full correction:

$$\Upsilon(\eta_\omega) \rightarrow K(q_{\mathrm{inv}}) \approx 1 + \pi\eta_\omega \frac{q_{\mathrm{inv}} R}{1.26 + q_{\mathrm{inv}} R}$$

- Cluster contributions
  - Mini-jets
  - Multi-body resonance decays
- Use (+−) pairs → estimate cluster contribution in (±±) pairs
- Systematics
  - Mixed Events
  - Cluster contributions
  - Fitting range



Data Sample and Particle Identification

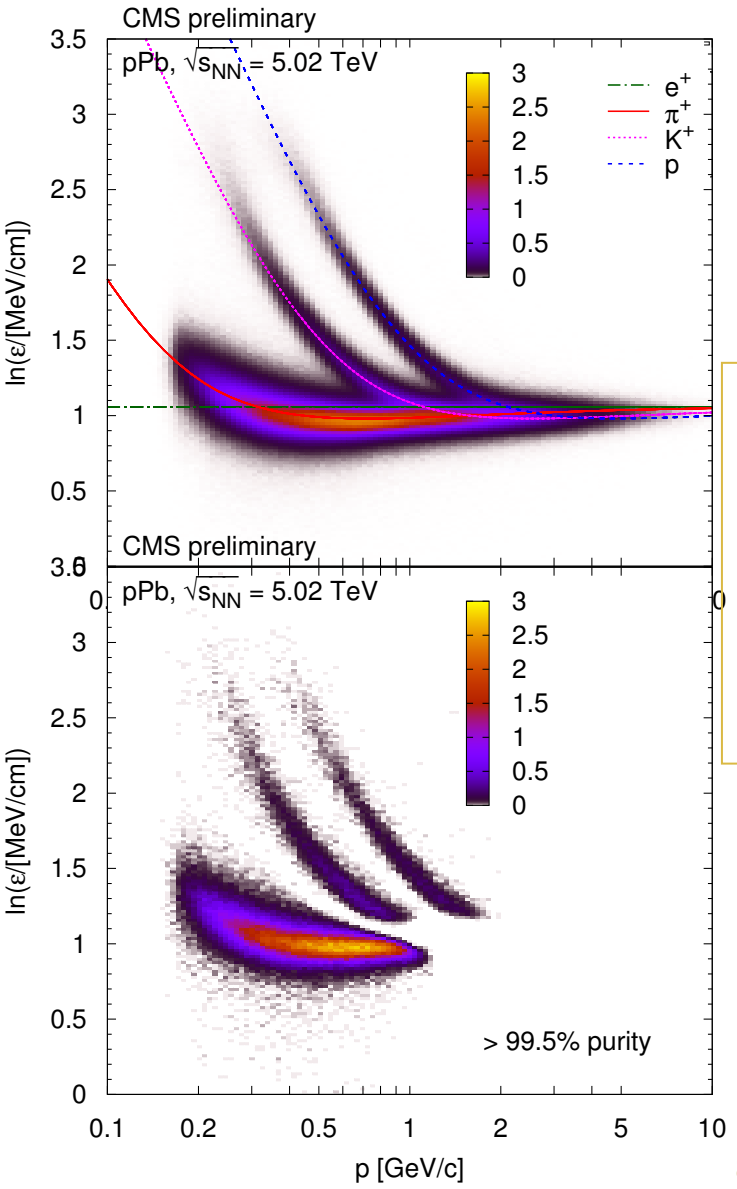
– Datasets used

$\sqrt{s_{NN}}$	Minimum Bias Events
pp @ 0.9 TeV	8.97 M
pp @ 2.76 TeV	9.62 M
pp @ 7 TeV	6.20 M
pPb @ 5.02 TeV	8.95 M
PbPb @ 2.76 TeV – Peripheral (60-100%)	3.07 M

– Tracking : Very low bias tracking (pT > 0.1 GeV/c, at least two tracks)

– PID : Ionization energy loss rate (lnε)
  - ❑ Momentum range p < 1.15 GeV/c (π's,K's)
  - ❑ p < 2 GeV/c (protons)
  - ❑ Determine probability of being a charged π,K, p or e
  - ❑ Used particles with |η| <1

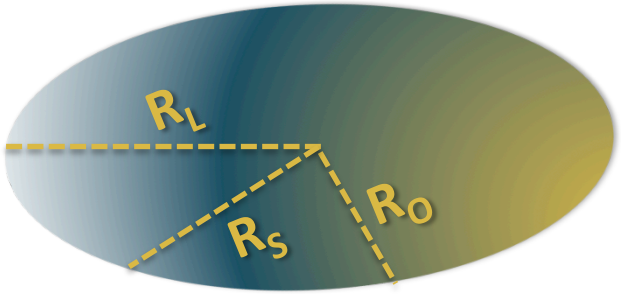
– High purity identified particles (> 99.5%)

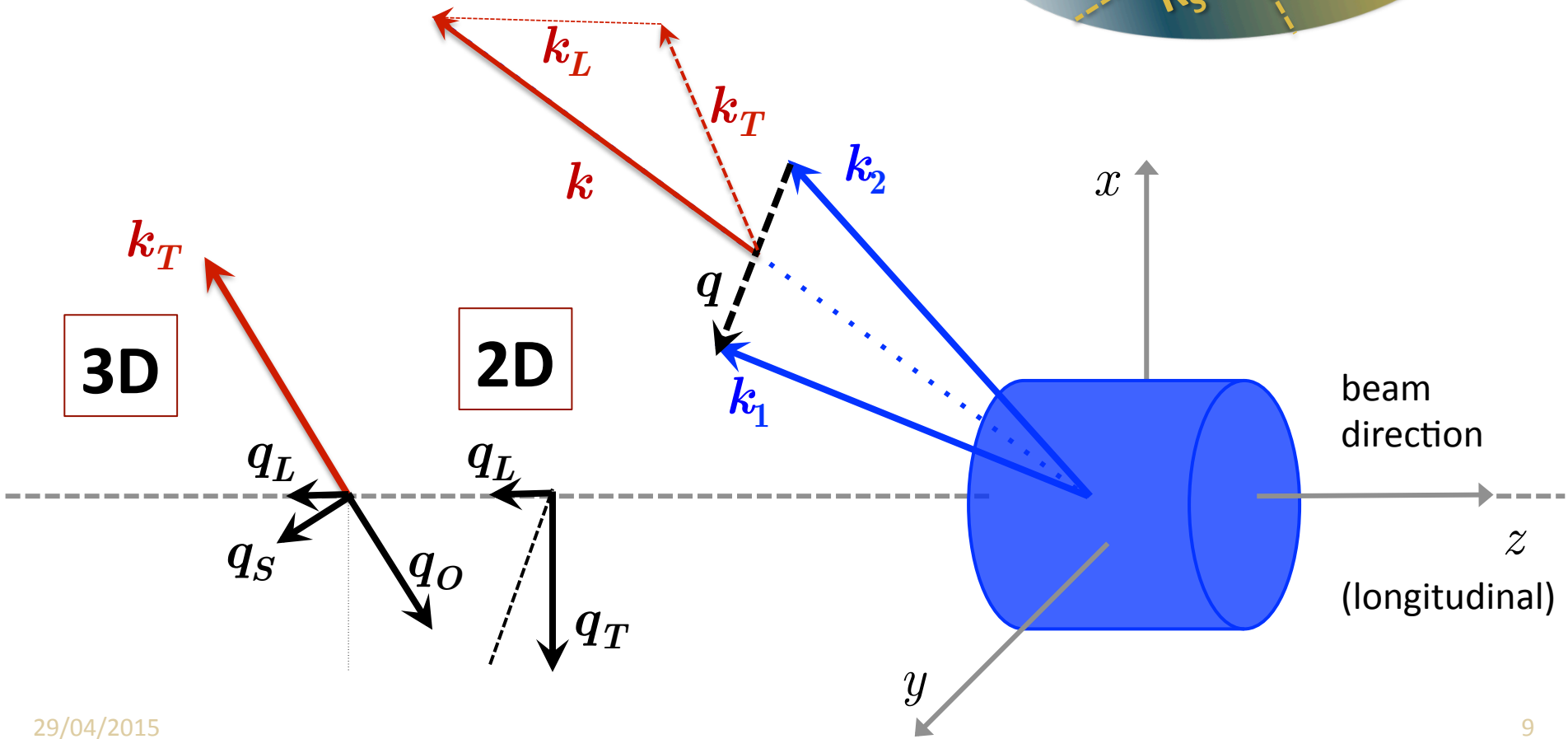


CMS PAS HIN-14-013

Decomposition: (q_L, q_T) in 2-D and (q_L, q_O, q_S) in 3-D

- $q^\mu = k_1{}^\mu - k_2{}^\mu$
- $k^\mu = (k_1{}^\mu + k_2{}^\mu)/2$





Part I and II – Fit functions summary

- Lévy distribution with index of stability a
  - $a = 1$ → *exponential* ; $a = 2$ → *Gaussian*
  - 1D

$$\mathcal{R}(Q_{\rm inv}) = C[1 + \lambda e^{-(Q_{\rm inv}R_{\rm inv})^a}]\,(1 + \delta\, Q_{\rm inv})$$

  - 2-D

$$\mathcal{R}(q_T, q_L) = C\left\{1 + \lambda \exp\left[-\left|q_T^2 R_T^2 + q_L^2 R_L^2 + 2q_T q_L R_{LT}^2\right|^{\frac{a}{2}}\right]\right\} \times (1 + \alpha q_T + \beta q_L)$$

$a = 1$ *Stretched Exponentials*

T. Csörgö, Hegyi, W. A. Zajc, Eur. Phys. J. **C36** (2004) 67

  - 3 D

$$\mathcal{R}(q_S, q_L, q_O) = C\left\{1 + \lambda \exp\left[-\left|q_S^2 R_S^2 + q_L^2 R_L^2 + q_O^2 R_O^2 + 2q_O q_L R_{LO}^2\right|^{\frac{a}{2}}\right]\right\} (1 + \alpha q_S + \beta q_L + \gamma q_O)$$

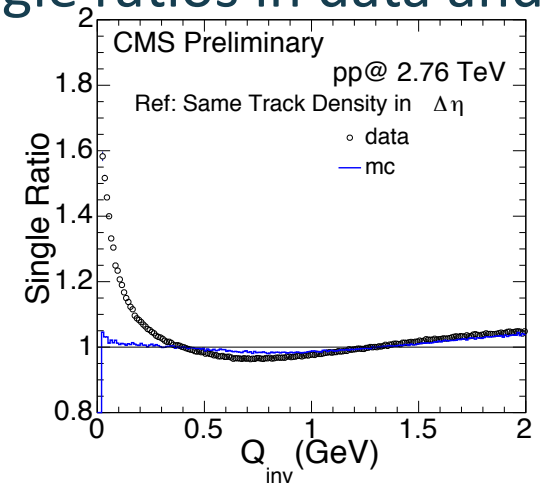
    - (in the **LCMS** → $k_L=(k_{1L}+k_{2L})/2=0$ and cross-term disappears for sources symmetric in longitudinal direction; (*) added to variables in this frame)

PART I

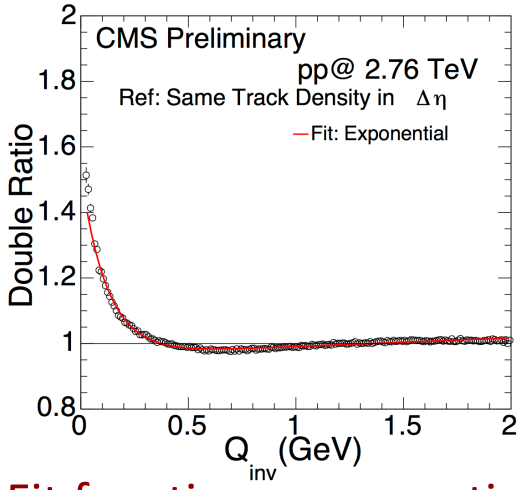
Results in pp collisions with DR technique

1D Single and Double Ratios in pp @ 2.76, 7 TeV

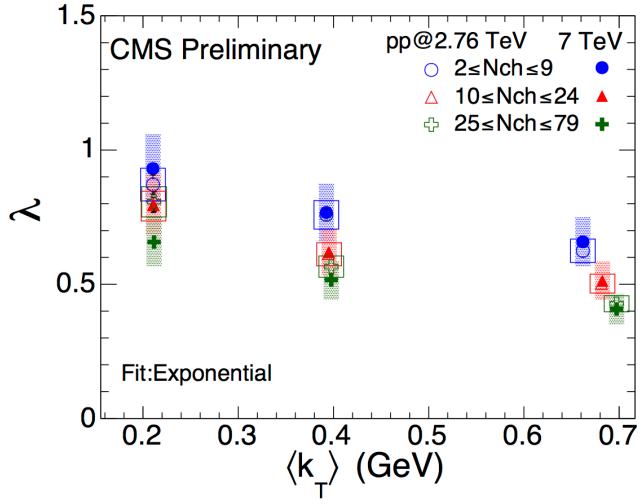
– Single ratios in data and in MC

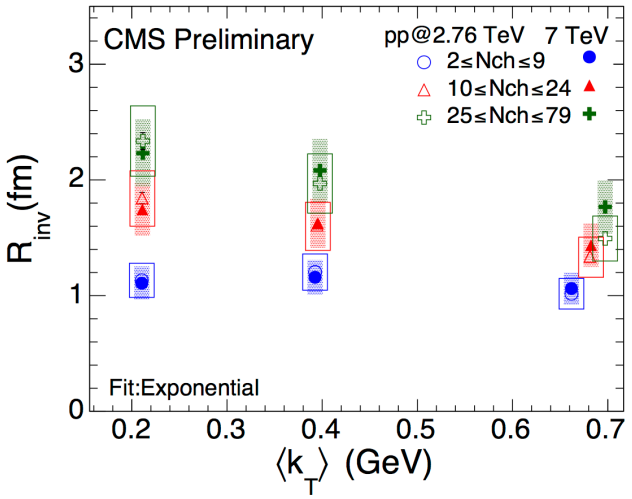


– Double Ratio



- ❑ Differentially in N_{ch} and k_T bins
- ☐ Fit function: exponential
- ❑ Uncertainties in plots below
  - statistical → error bars; systematic → shaded and empty boxes





FSQ-13-002-PAS

Radius fit (exponential) parameter vs. N_{ch}

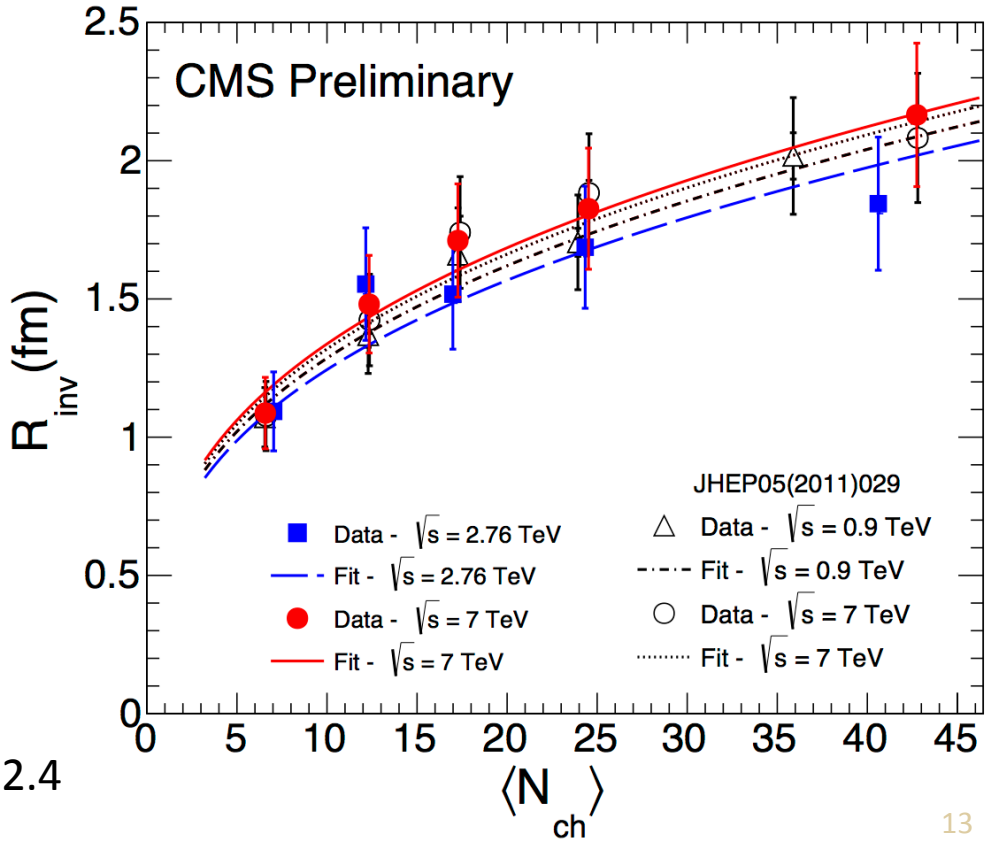
- Curves: $R_{inv} = \xi N_{ch}^{1/3}$ – comparing results at 0.9 TeV, 2.76 TeV and 7 TeV
  - k_T integrated results (error bars: statistical and systematic)
  - R_{inv} ←→ increase particle production with increasing collision energy (≈ scaling w/ √s)

- The proportionality parameter ξ of R as a function of $N_{ch}^{1/3}$

FSQ-13-002-PAS

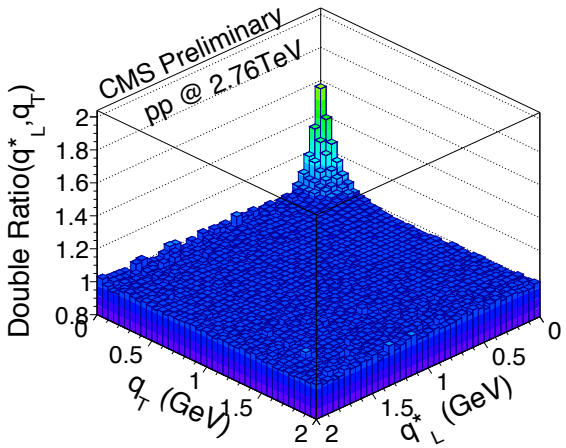
  - at 0.9 TeV
    ξ =[0.597 ± 0.009] (fm)
  - at 7 TeV
    ξ = [0.612 ± 0.007)] (fm)
  - at 2.76 TeV
    ξ = [0.578 ± 0.005] (fm)
  - at 7 TeV (full dataset)
    ξ = 0. 621 ± 0.001

(in ξ: statistical uncertainties only)

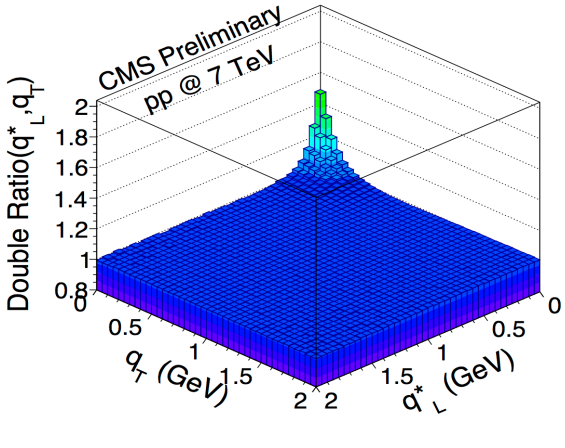


  - $\langle N_{ch} \rangle$ is the number of charged tracks integrated in p_T and within $|\eta| < 2.4$

2-D DR(q_T,q_L): k_T and N_{ch} integrated



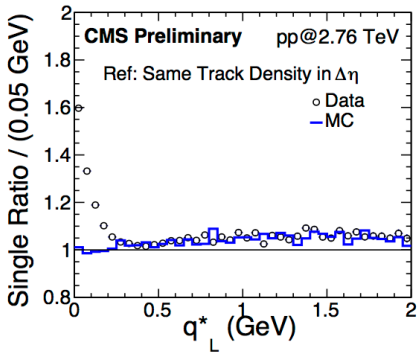
2-D correlation functions (q_T, q_L)

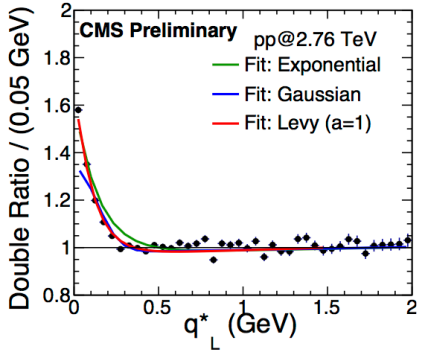


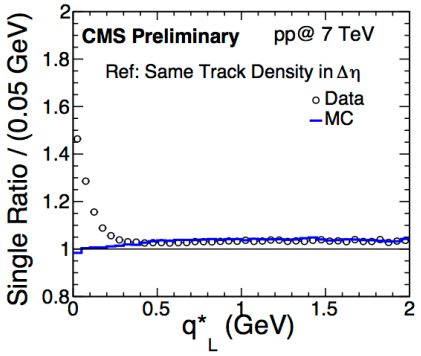
FSQ-13-002-PAS

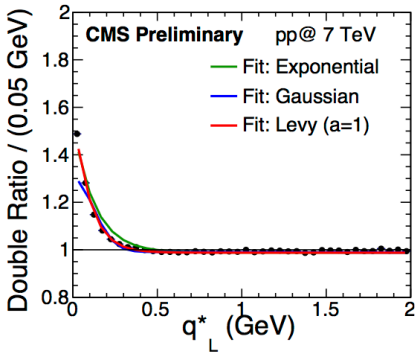
1-D projections

$|q_T| \leq 0.05$ GeV

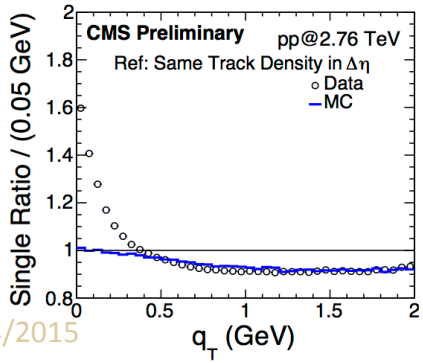


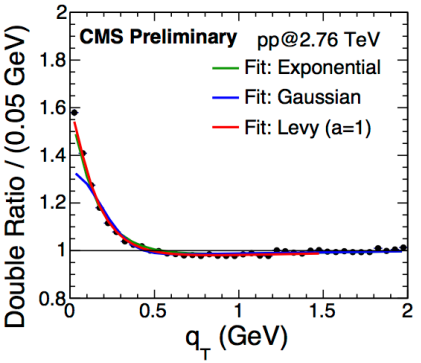


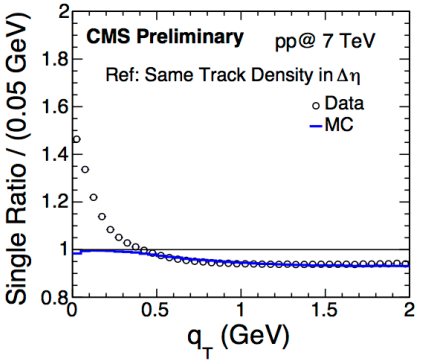


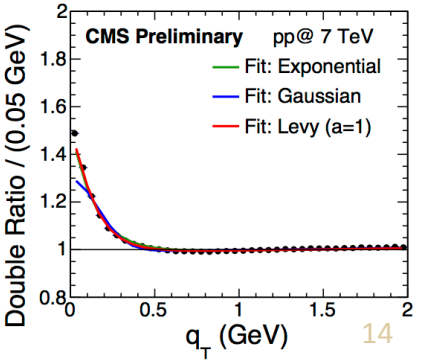


$|q^*_L| \leq 0.05$ GeV



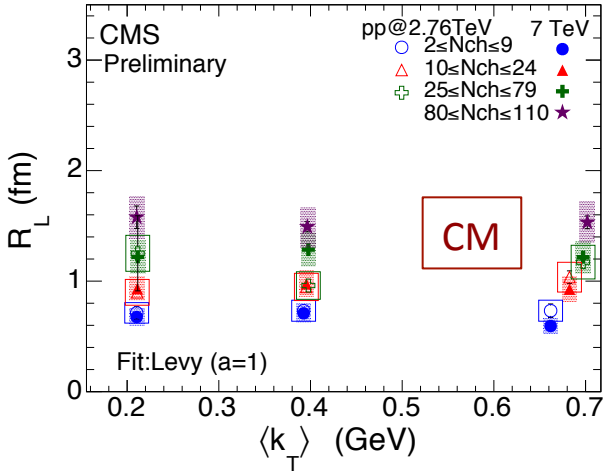




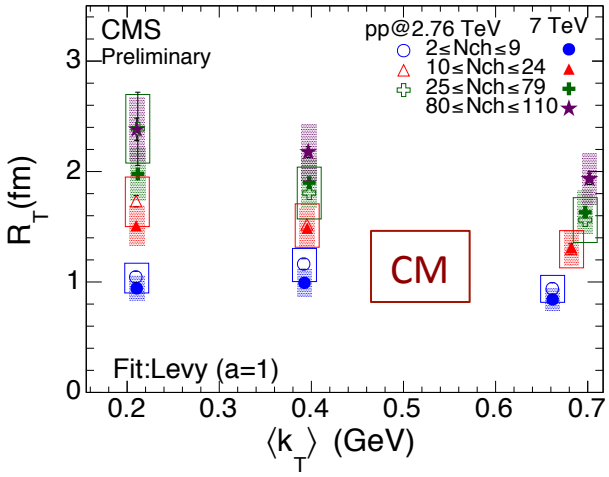


2D results with *stretched exponential* fit function

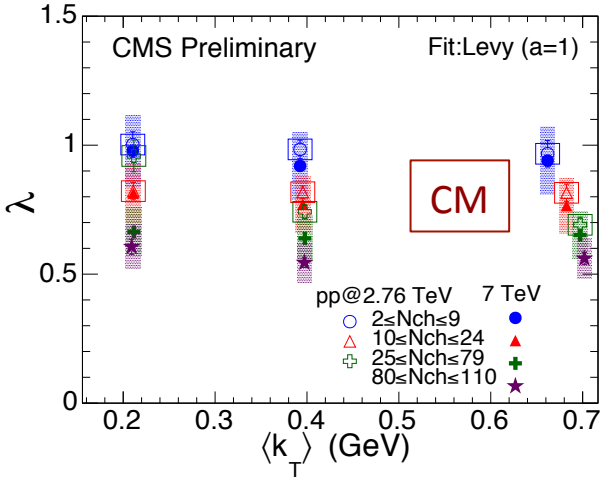
❑ R_L (R^*_L)



□ R_T



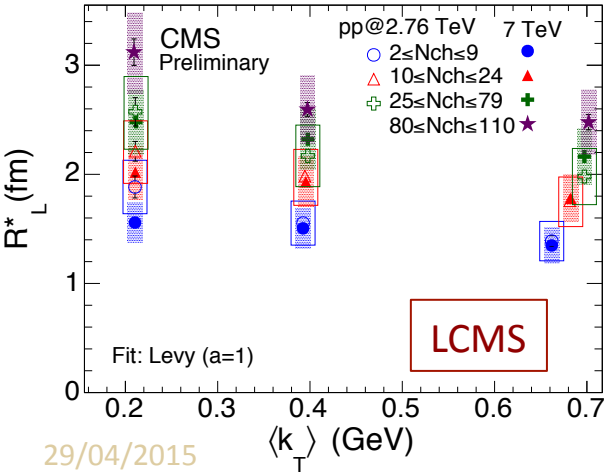
□ λ (λ*)

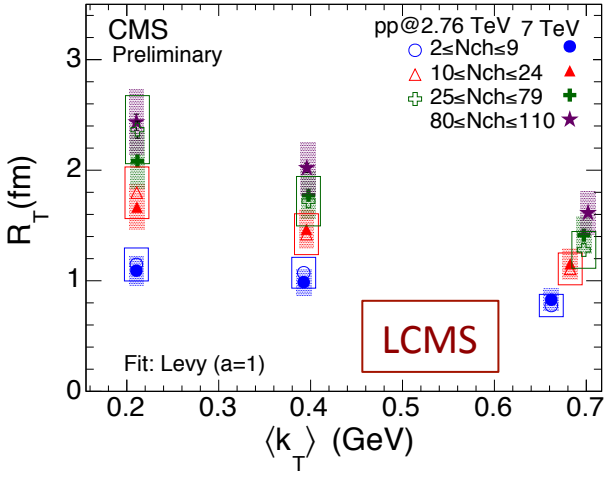


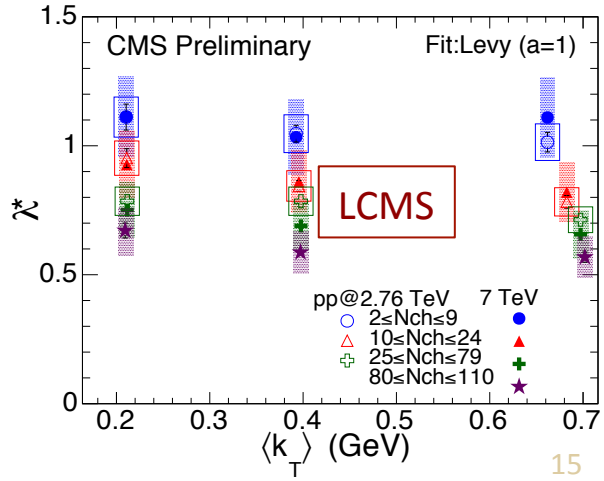
(R_L, λ, R_T in CM frame)

FSQ-13-002-PAS

(R^*_L, λ*, R_T → LCMS)

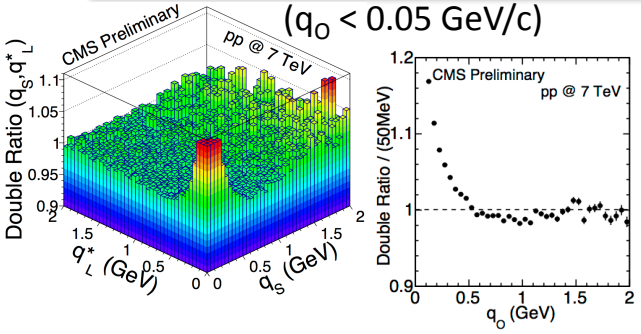




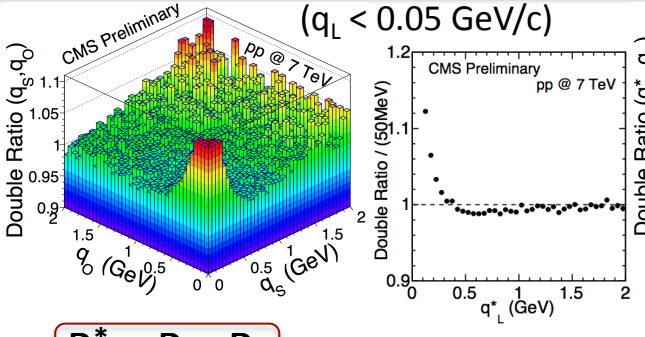


3-D Double Ratios(q_O, q_S, q_L) - LCMS

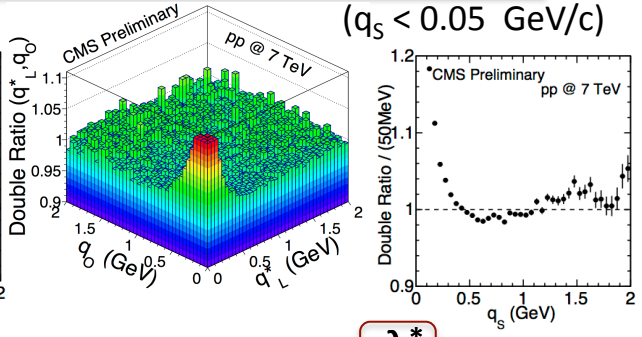
(q_O < 0.05 GeV/c)



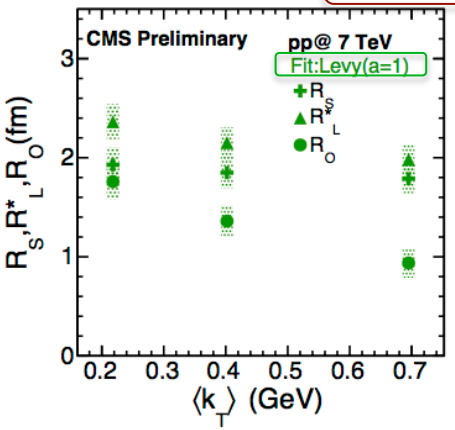
(q_L < 0.05 GeV/c)

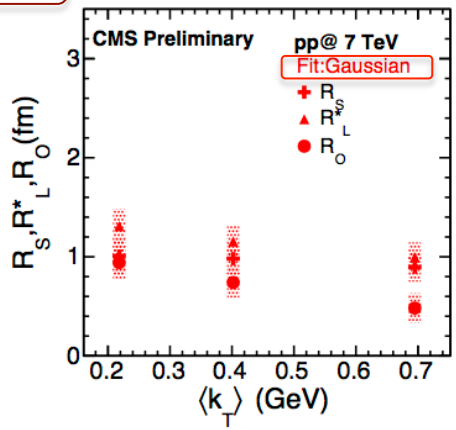


(q_S < 0.05 GeV/c)

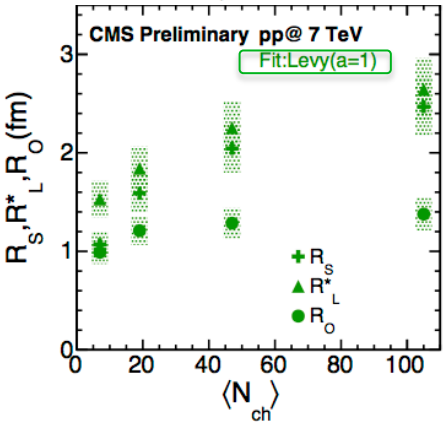


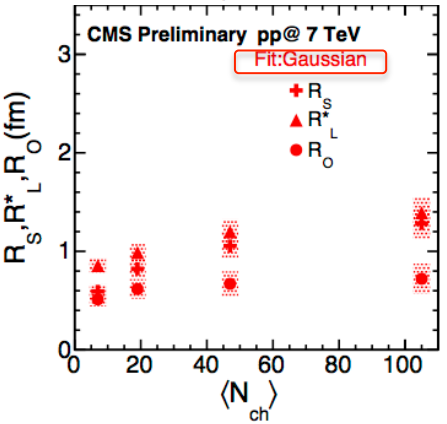
R^*_L ; R_O; R_S





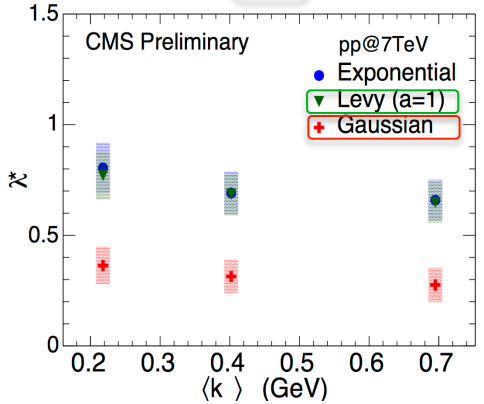
(integrated in N_{ch} bins)

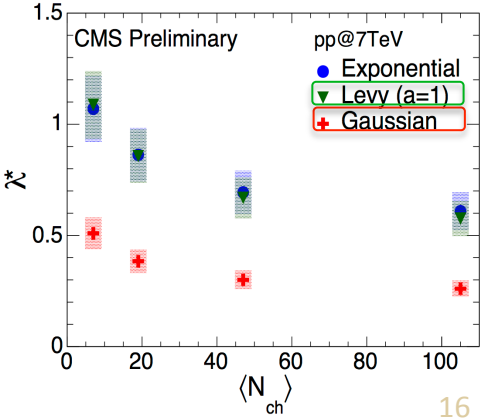




(integrated in k_T bins)

λ^*





FSQ-13-002-PAS

Summary and Conclusions – pp with DR technique

- Fits: Gaussian, simple and *stretched* (Lévy: a = 1) exponentials
- Measurements in two reference frames

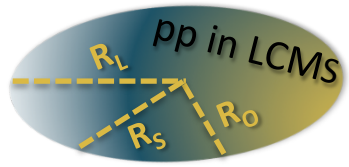
pp collisions (LCMS)

  - CM frame → closer to previous two BEC from CMS, for extending to 2-D and 3D
    - requires additional cross-term (in $q_T q_L$ and in $q_O q_L$)
  - LCMS frame → $k_L=(k_1+k_2)/2=0$ (no cross-term) → comparisons
    - interesting observations when comparing results to those in the CM frame
- Results in 1-D, 2-D, 3D in pp collisions at 2.76 and 7 TeV:
  - $\lambda^{(*)}$ vs N_{ch}: ↘ as N_{ch} ↗ in 1-D, 2-D and 3-D (lower q_O, q_S,q_L then flattens down);

    $\lambda^{(*)}$ vs k_T: ↘ as k_T ↗ in 1-D; almost flat in k_T in 2-D; almost insensitive to k_T in 3-D
  - Radii fit parameters[#] increase with multiplicity, decrease with k_T (1D, 2D, 3D)
    - Integrated values in (k_T , N_{ch}): $R^*_L > R_L$; $R^*_L > R_T$ (in LCMS) in 2D;

      in 3-D: $R_S > R_O > R_L$ (in CM frame) and $R_L > R_S > R_O$ (in LCMS)

      ([#]lengths of homogeneity $1 \le R_i < 3$ fm in LCMS)

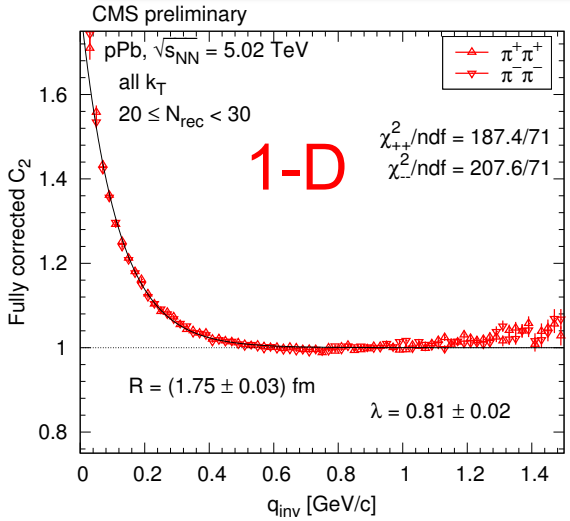


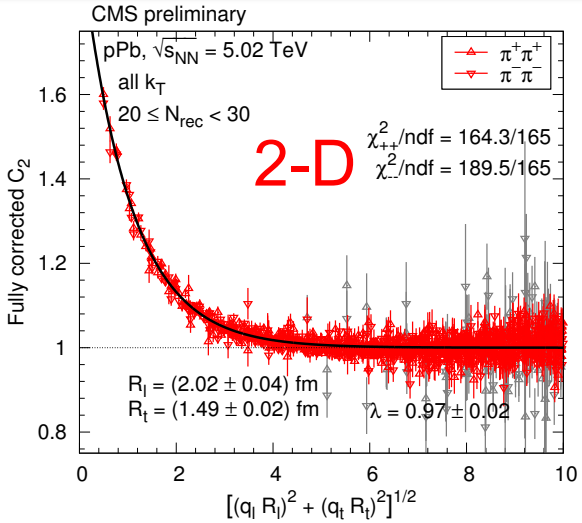
    - CMS-PAS-FSQ-13-002 (http://cds.cern.ch/record/1754947?ln=en)
    - Figures: : https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ13002

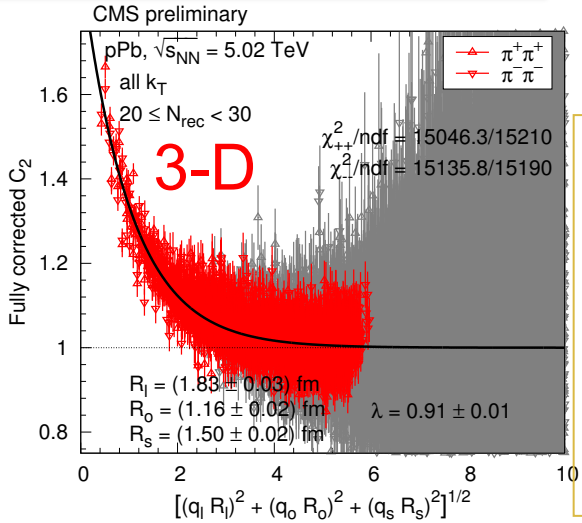
PART II

Multi-systems with data-driven technique

Fully Corrected Correlation Functions







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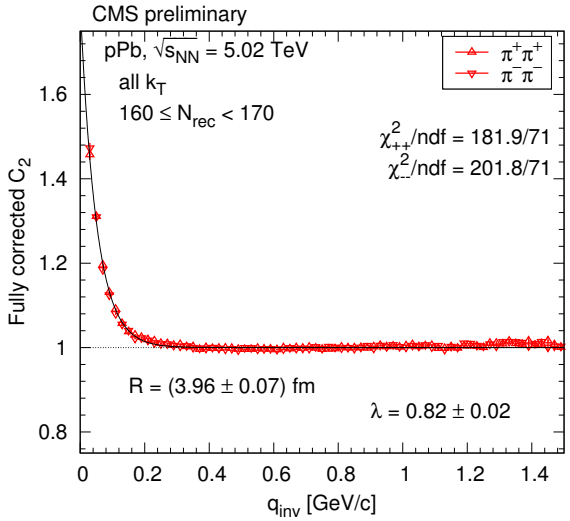
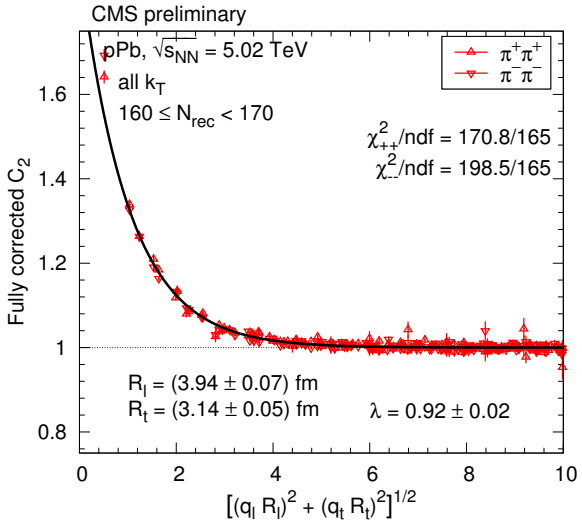
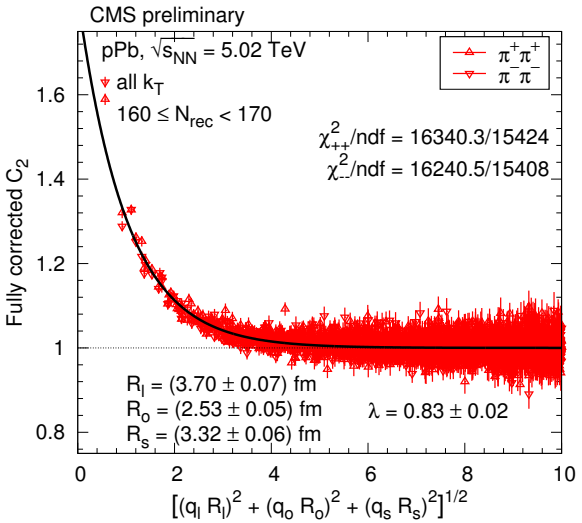
$C_{BE}(q_{\rm inv}) = 1 + \lambda \exp[-q_{\rm inv} R]$

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

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







1-D BEC results: Pions & Kaons

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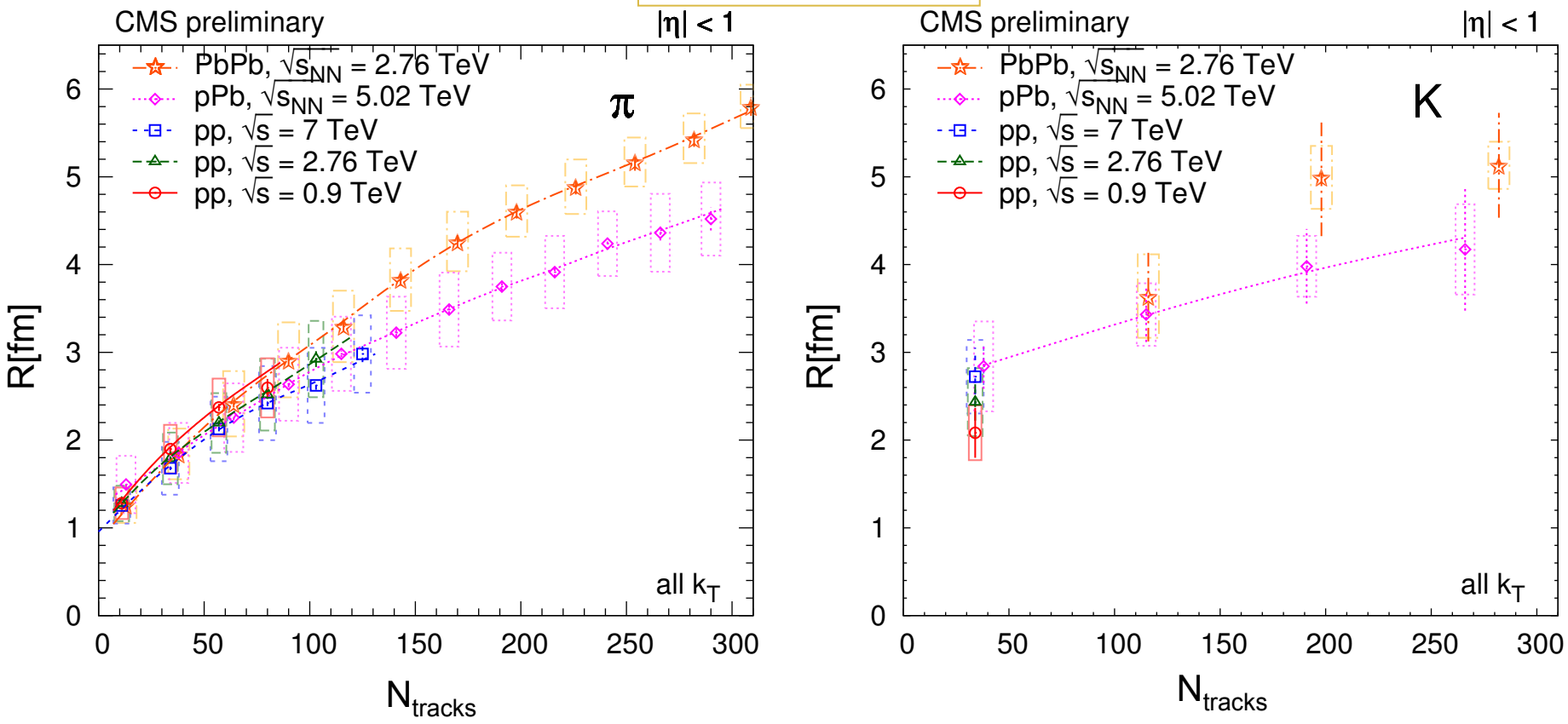

- One-dimension $C_{BE}(q_{inv})$ – exponential fit
  - R for pions and kaons → increase with N_{tracks} for all systems and center-of-mass energies
  - Small increase for kaons compared to pions: long lived resonances + rescattering

2- and 3-D BEC results: Pions

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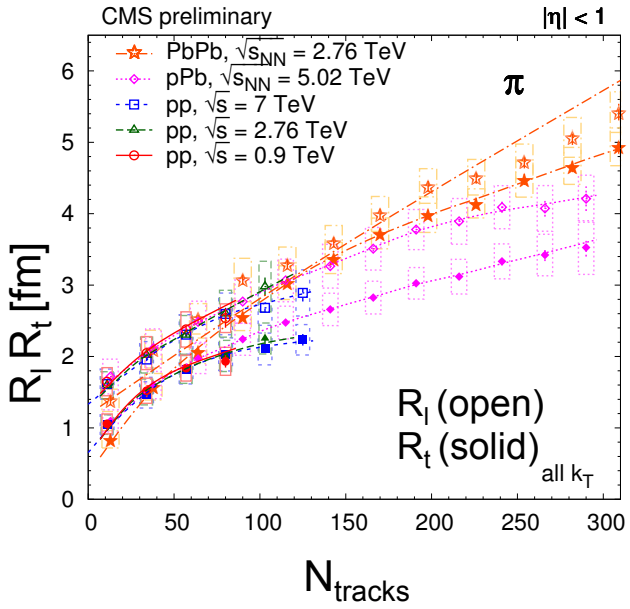
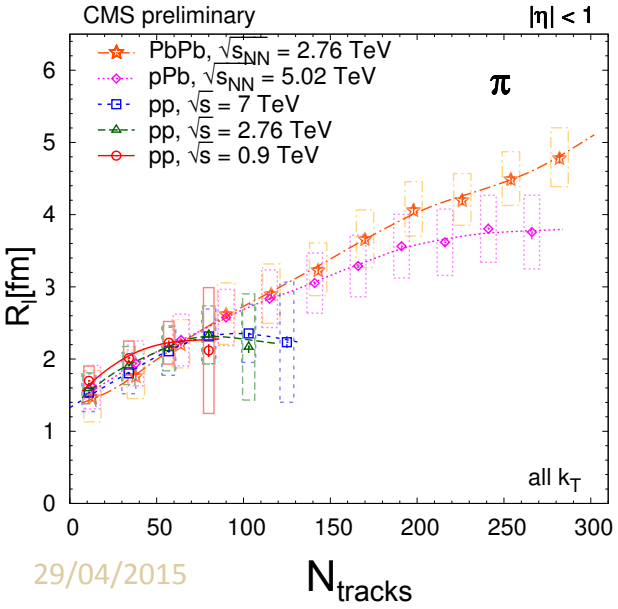
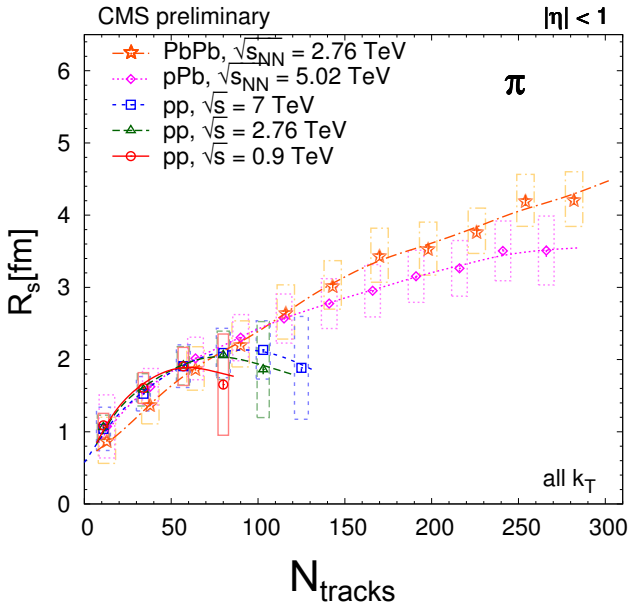
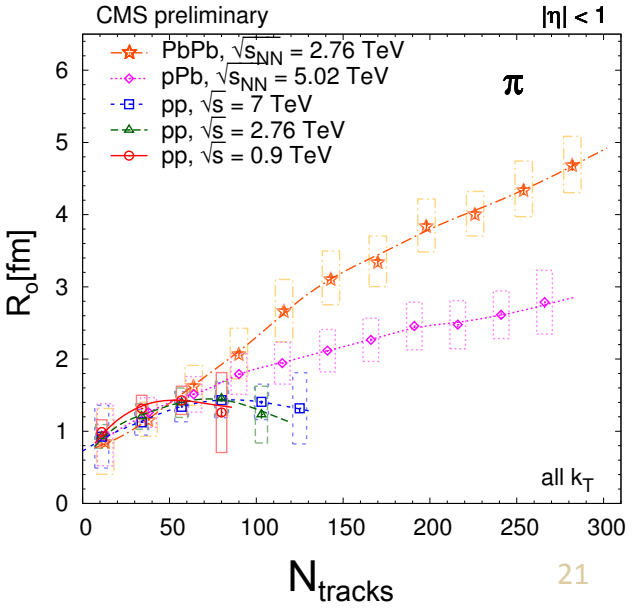


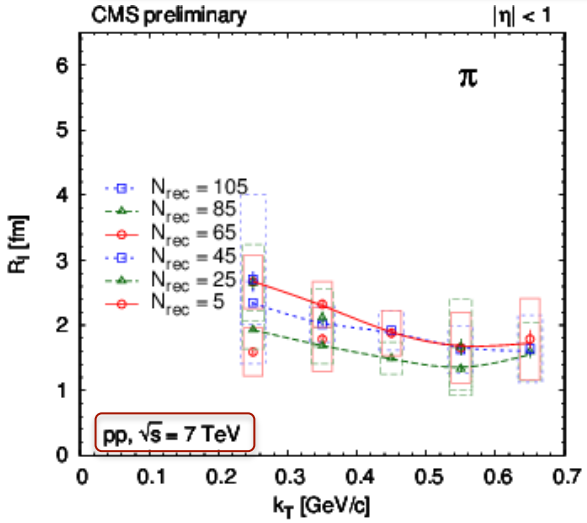
- 2-D $C_{BE}(R_l, R_t)$ (*stretched exponential* fit)
  - For pp and pPb: $R_l > R_t$ → elongated source along beam
  - For peripheral PbPb: $R_l \approx R_t$ → spherical source
- 3-D $C_{BE}(R_l,R_s,R_o)$ (*stretched exponential* fit)
  - For pp and pPb: $R_l > R_s > R_o$ → elongated source in beam direction
  - For peripheral PbPb: $R_l \approx R_s \approx R_o$ → ≈ spherical source
  - Large difference in R_o in PbPb and pPb → possibly due to lifetime of the source

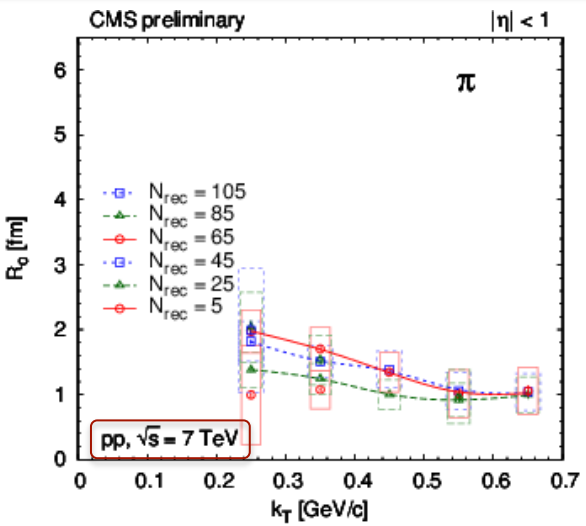


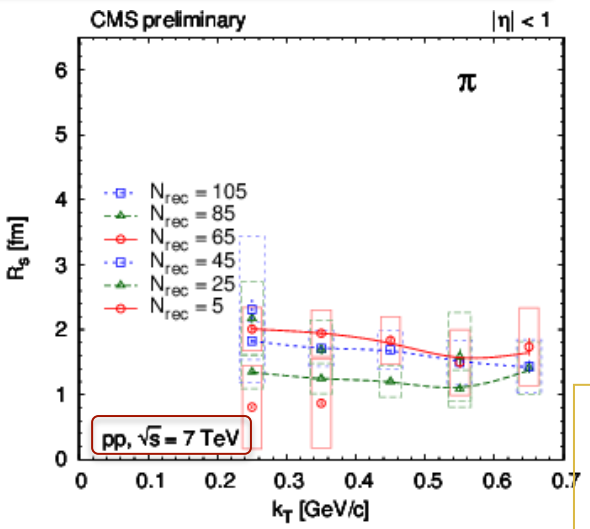




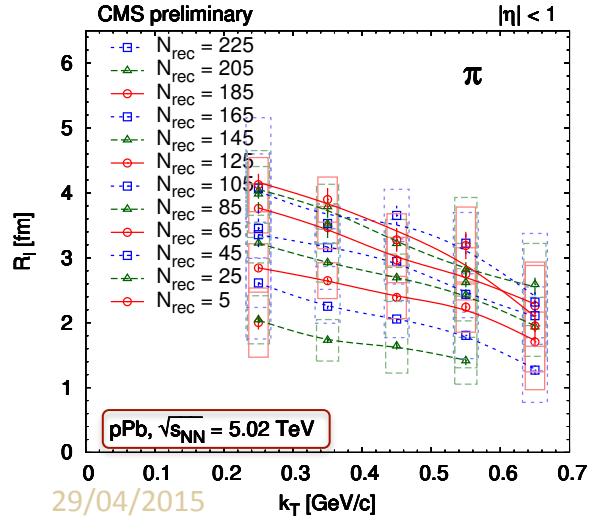
The k_T-dependence in pp and pPb

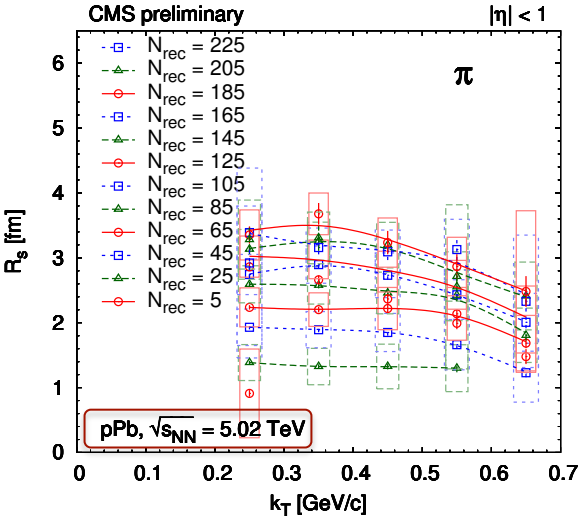


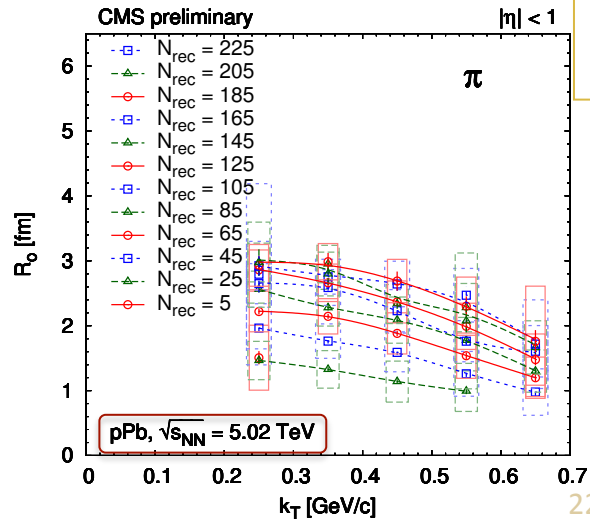




- R_l, R_s, R_o → decrease with increase in k_T (stretched exponential fit)
- Similar behavior for all system and at all center of mass energies







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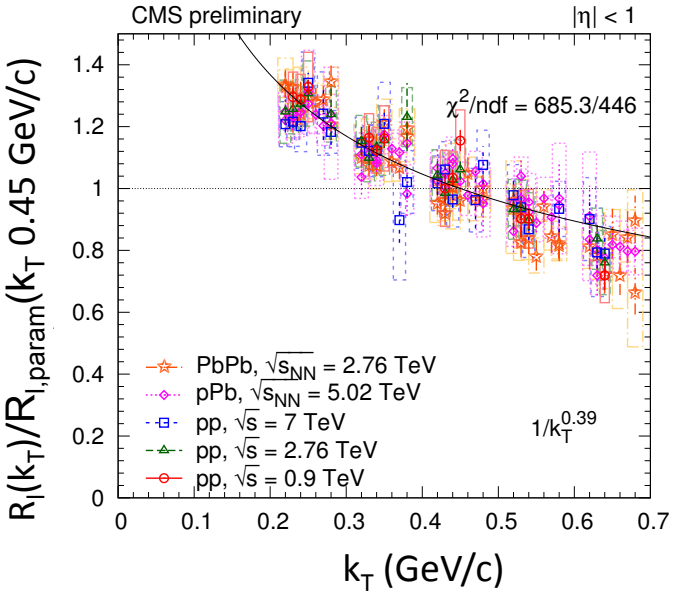
Scaling Properties in N_{tracks} and k_T

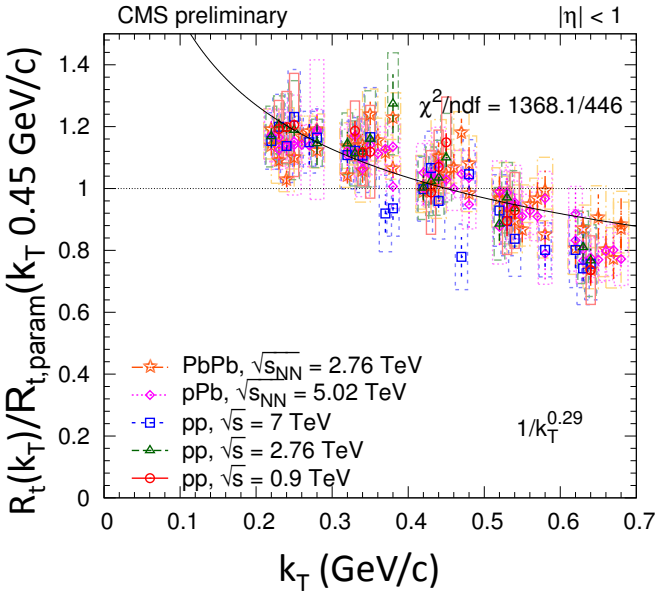
- Pion radius fit parameters (lengths of homogeneity)
  - Increase with increasing N_{tracks}
  - Decrease with increasing k_T
  - Dependence on N_{tracks} and k_T factorizes:

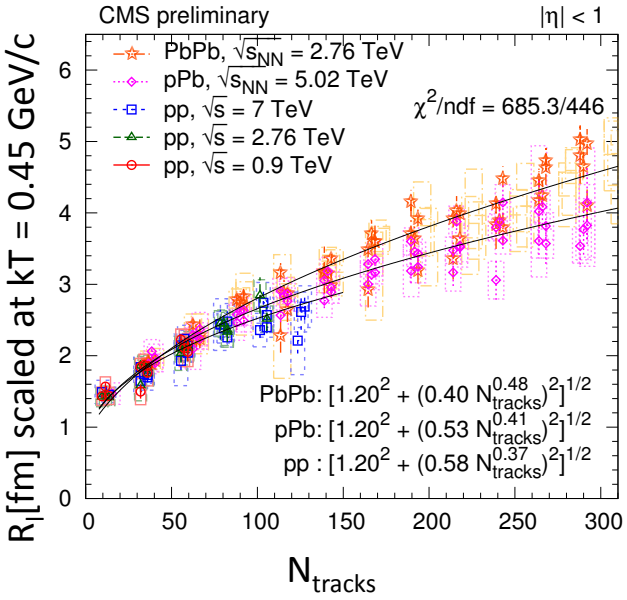
$$R_{param}\ (N_{tracks},\ k_T) = [a^2 + (bN_{tracks}^{\beta})^2]^{1/2}\ .\ (0.2GeV/c/k_T)^{\gamma}$$

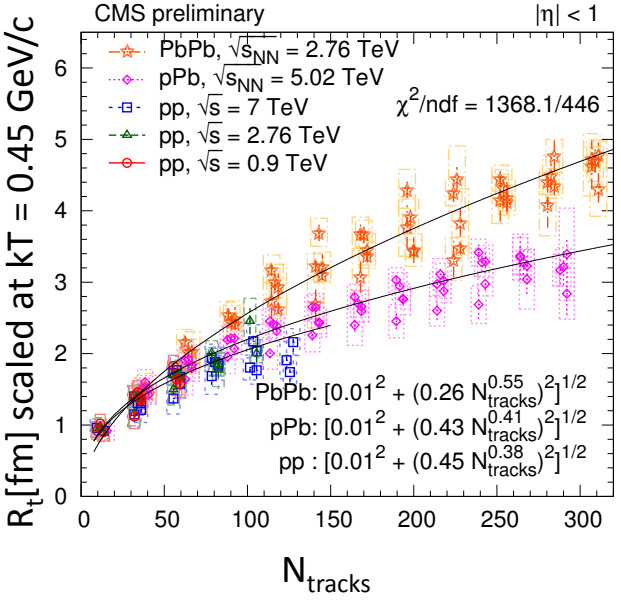
    - For a given R component → a (minimal radius) and γ are kept the same for all collision systems
    - Identical parameters used for the three proton-proton energies
    - All five systems are fit simultaneously
  - Plotting as a function of N_{tracks}
    - Radius is scaled to $R_{measured} * (1/0.45^{\gamma}) / (1/k_T^{\gamma})$
  - Plotting as a function of k_T
    - $R_{measured}/(R_{param}$ at the same N_{tracks} but at $k_T=0.45)$

Scaling properties in N_{tracks} and k_T: 2-D illustration







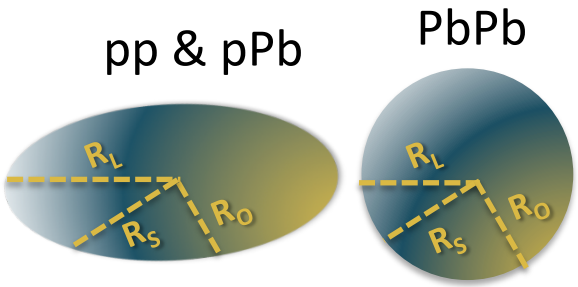


CMS PAS HIN-14-013

Summary & Conclusions – multi-systems (data-driven technique)

- Measured BEC → best described by stretched exponential function
- Radius parameters → from 1-5 fm
  - All the radii increase smoothly with N_{tracks}
  - Highest values for pPb and peripheral PbPb (large system)
  - Small increase for kaons compared to pions
  - Radius parameter (lengths of homogeneity) decrease with increasing k_T
  - Radius parameters for pp and pPb are similar the same for N_{tracks}
- For two- and three-dimensions in pp and pPb
  - $R_l > R_t$
  - $R_l > R_s > R_o$

  } source elongated along beam direction in pp and pPb collisions



  - In peripheral PbPb collisions: R_o different than in pp, pPb → possibly indicating different life-time of the source created in such collisions

    - CMS-PAS-HIN-14-013 (https://cds.cern.ch/record/1703272/files/HIN-14-013-pas.pdf)
    - Figures: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN14013

EXTRA SLIDES

Systematic Uncertainties – Summary

Systematical Uncertainties				
$\sqrt{s}$	2.76 TeV		7 TeV	
Origin of Systematics	λ	R_{inv} (fm)	λ	R_{inv} (fm)
Monte Carlo tune	0.032	0.160	0.032	0.160
Reference Sample	0.009	0.047	0.051	0.188
Coulomb Corrections	0.016	0.009	0.018	0.020
Charge Dependence	0.006	0.012	0.007	0.006
Pileup filter	5.0 e-4	0.011	0.001	0.0025
Track Cuts	0.014	0.119	0.014	0.119
Total	0.040	0.206	0.065	0.275

Comparing $R_L^{(*)}$ fit parameter in 2-D and 3-D

- Longitudinal fit parameters should be the similar in 2-D and 3-D
  - indeed, R_L and R^*_L lengths of homogeneity → close values
  - increase with N_{ch} and scales in energy, similar to the 1-D case

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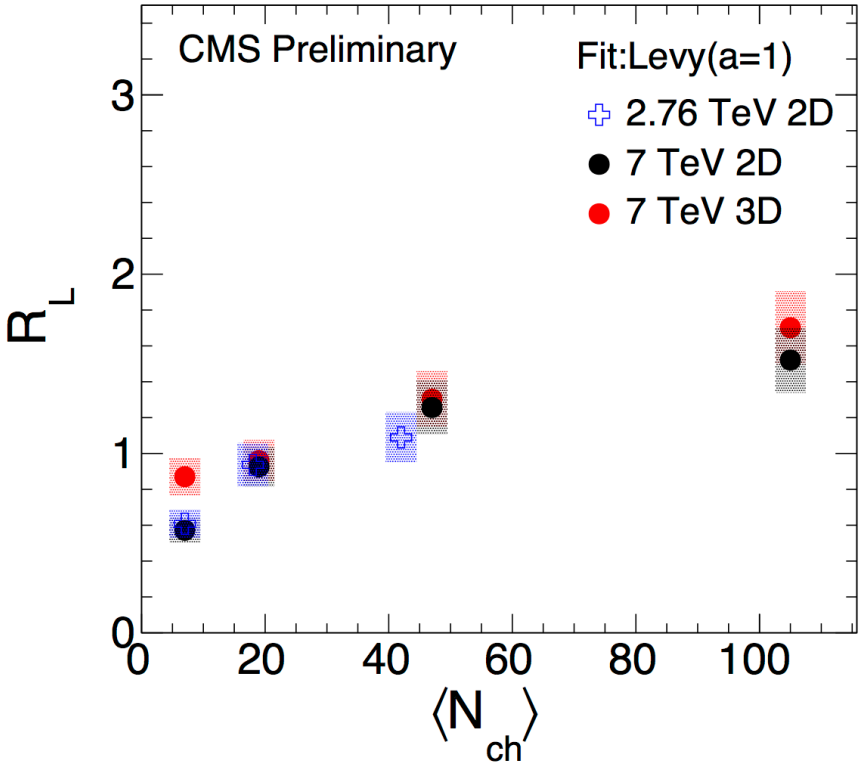
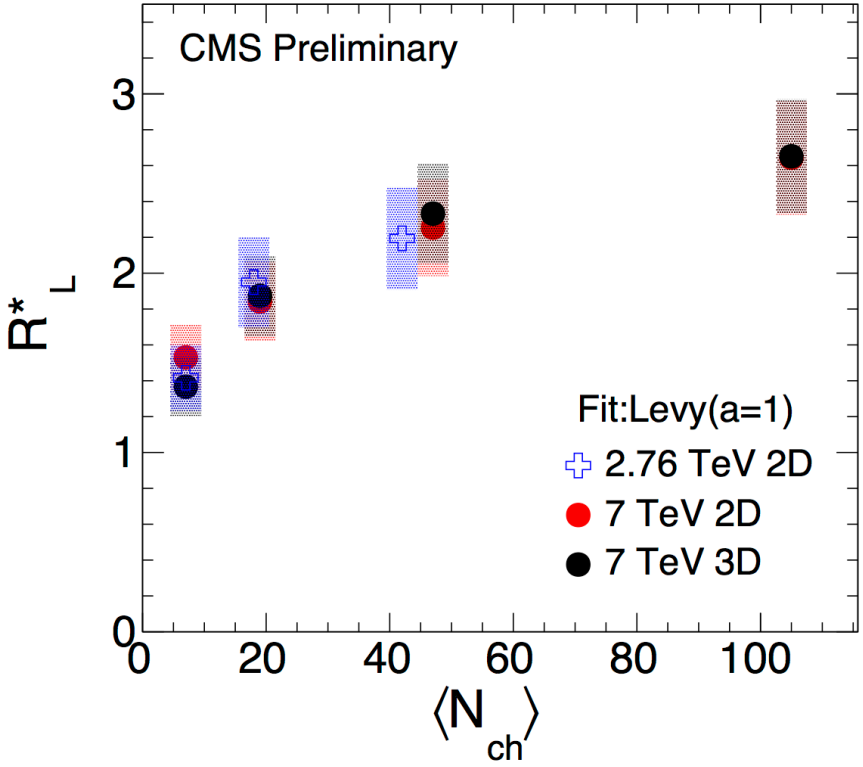
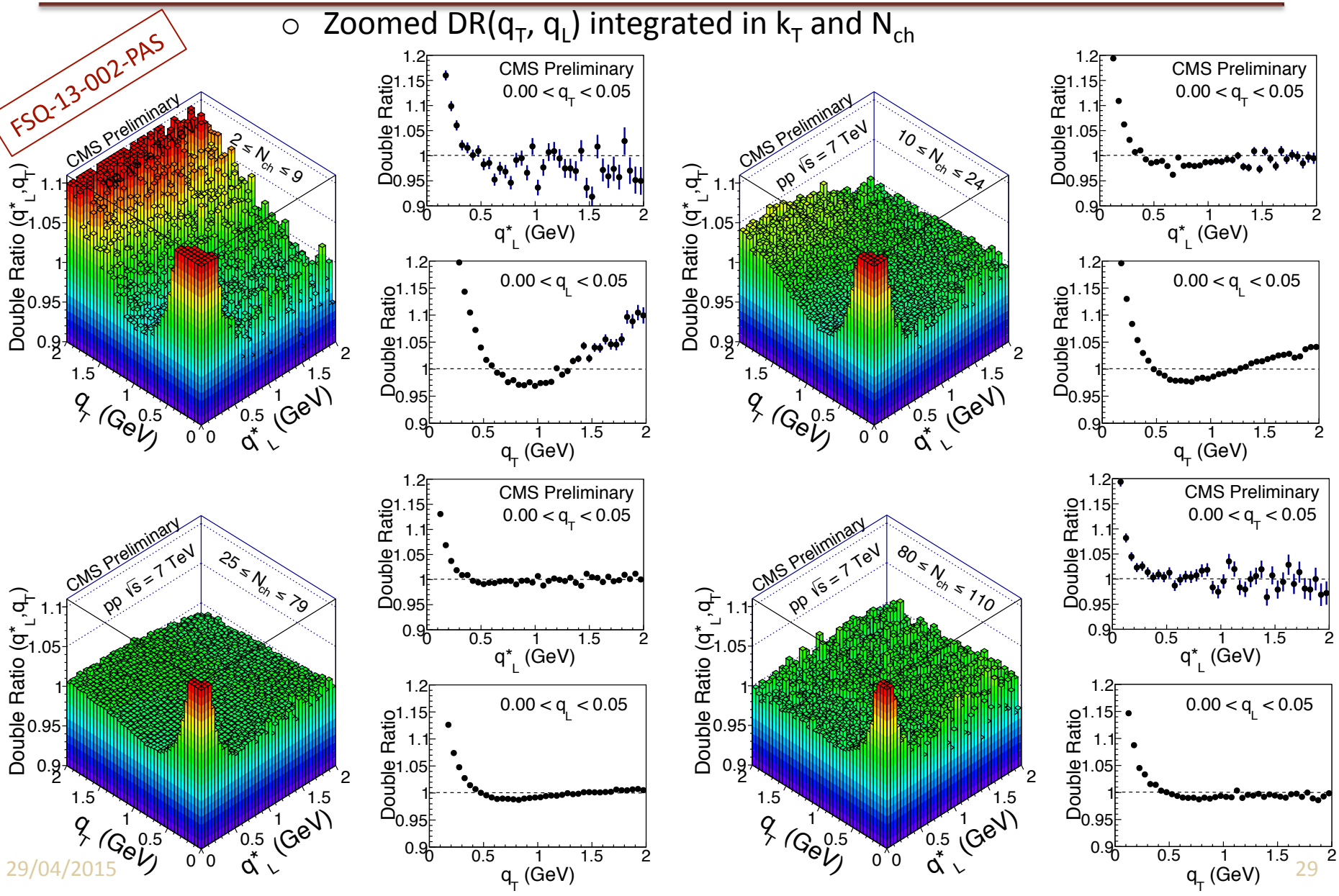




The anticorrelation in 2-D DR (q_T,q_L) - LCMS

- Zoomed DR(q_T, q_L) integrated in k_T and N_{ch}



Extracting results: fit functions – 1D

– Symmetric Lévy stable distribution with index of stability *a*

$$\mathcal{R}(Q_{\rm inv}) = C[1 + \lambda e^{-(Q_{\rm inv}R_{\rm inv})^a}]\,(1 + \delta\, Q_{\rm inv})$$

- relative and average momenta of the pair

$$Q^2_{\rm inv} = -(k^\mu_1 - k^\mu_2).(k_{1_\mu} - k_{2_\mu}) = m^2_{\rm inv} - 4m_{\pi^2}$$

$$k_\mu = \frac{k_{1_\mu} + k_{2_\mu}}{2}$$

- Limit *a* =1 → exponential function

Fourier transform of Cauchy-Lorentz source

$$\mathcal{R}(q) = C[1 + \lambda e^{-QR}]\,(1 + \delta Q) \qquad S(r) = \frac{1}{2\pi^2}\frac{R}{r^2 + (\frac{1}{2}R)^2}$$

- Limit *a* =2 → Gaussian distribution

Fourier transform of Gaussian source

$$\mathcal{R}(q) = C[1 + \lambda e^{-Q^2R^2}]\,(1 + \delta Q) \qquad \frac{1}{(\sqrt{2\pi}R)^3}e^{r^2/(2R^2)}$$

Double Ratios (Q_{inv}): study of the anticorrelation

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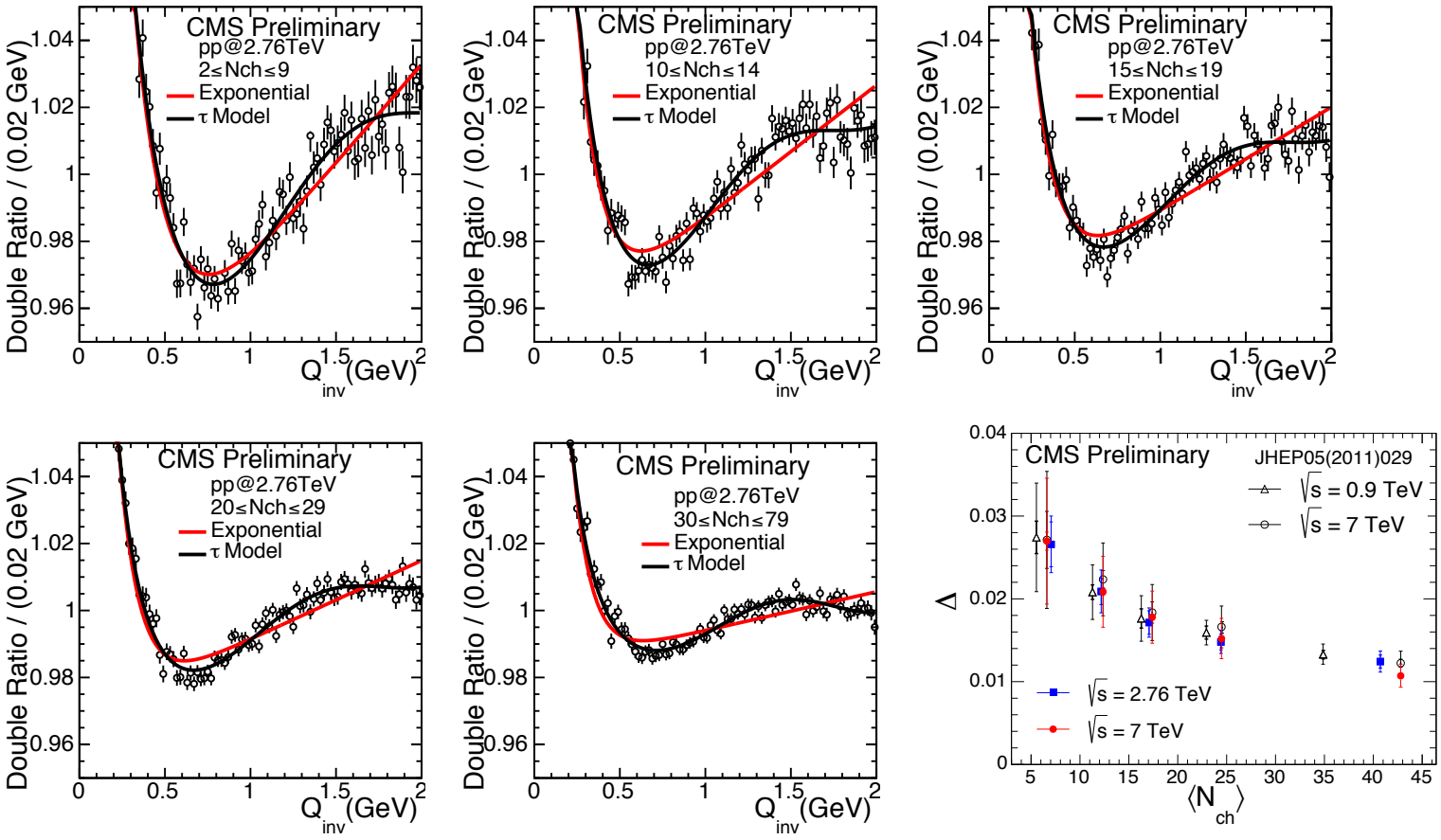
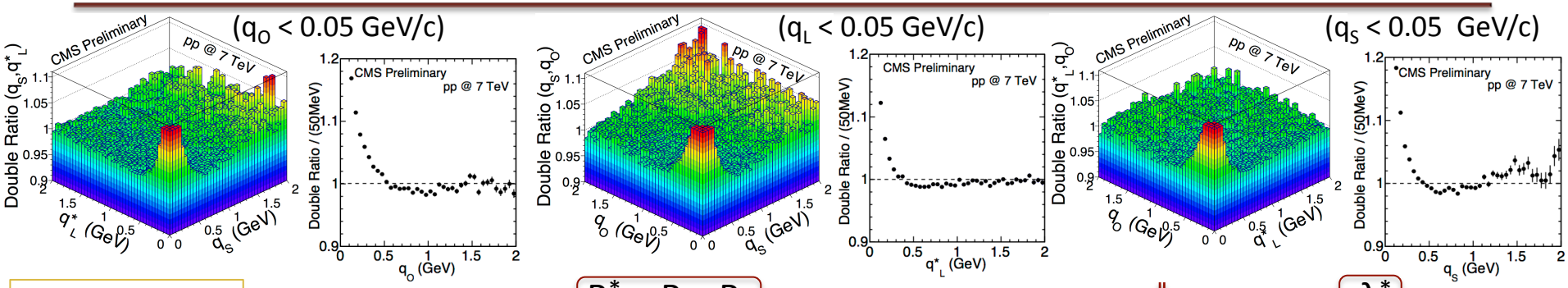


- exponential fit (with long-range term) → red; τ-model → **black**
- Csörgő & Zimányi, N.P. A 517, 588 (1990); Metzger et al., P. L. B663, 114 (2008)]

$$R^*(Q) = C\left[1 + \lambda\left(\cos\left[(r_0 Q)^2 + \tan(\alpha\pi/4)(Qr_\alpha)^\alpha\right]e^{-(Qr_\alpha)^\alpha}\right)\right]\cdot(1+\delta Q)$$

3-D Double Ratios(q_O, q_S, q_L) – LCMS (pp@7TeV)



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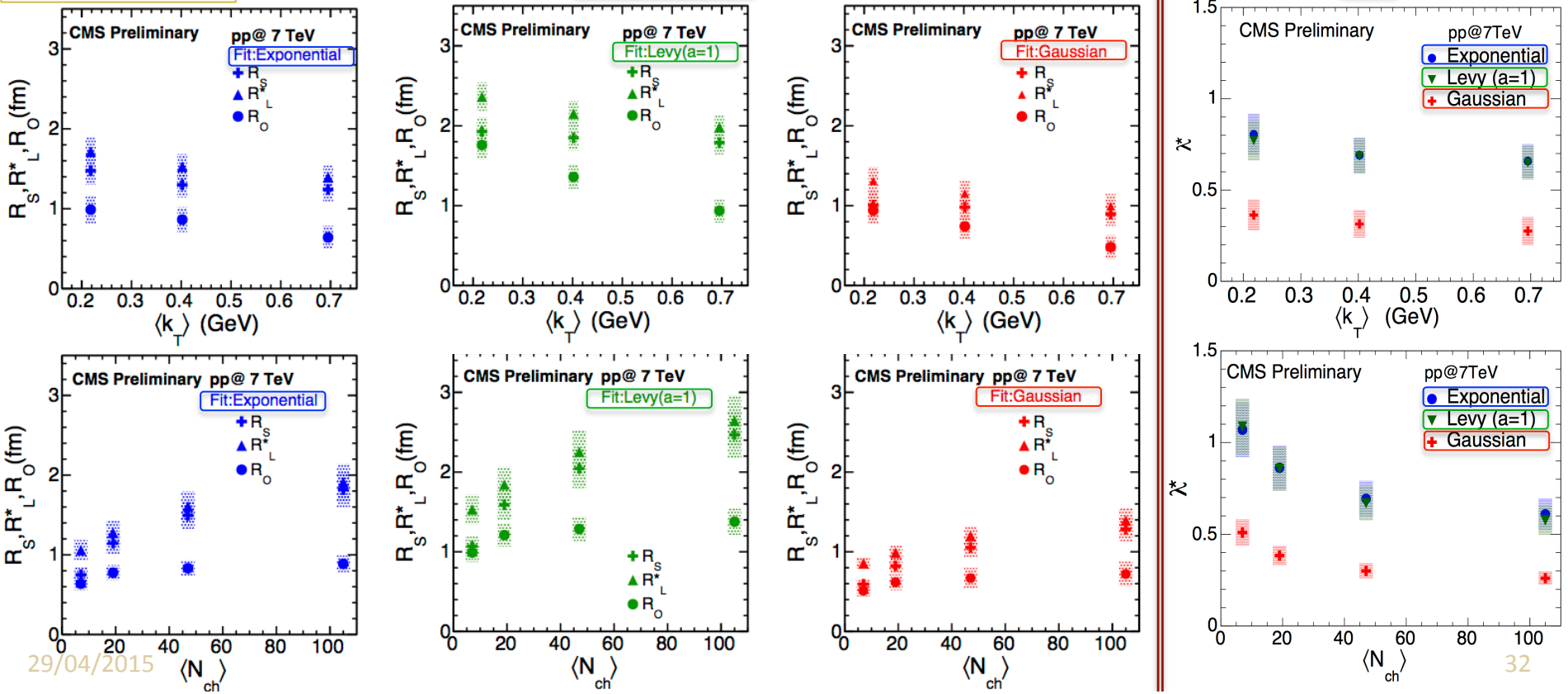
R^*_L ; R_O; R_S

λ^*