Multidimensional analysis of Bose-Einstein correlations in pp collisiosn at 2.76 and 7 TeV in CMS

Sandra S. Padula

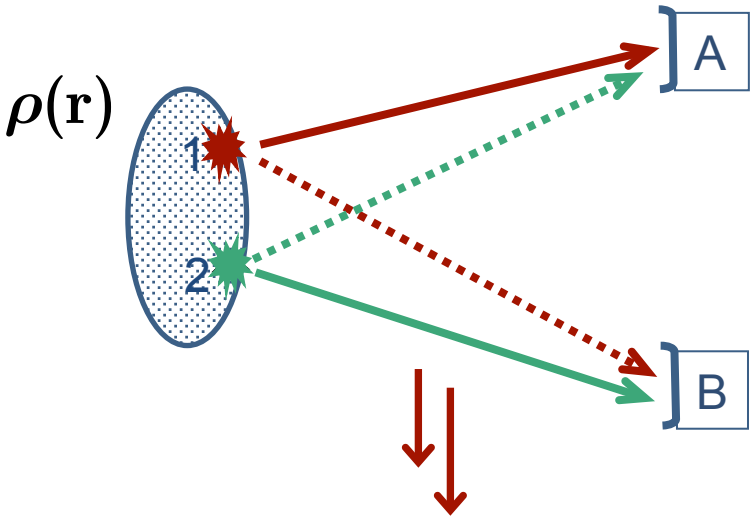
IFT – UNESP

For the CMS Collaboration

WPCF 2014, Gyöngyös, Hungary, 25-28 September, 2014

Briefly revisiting the basic HBT concepts

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



- Two-boson correlation function ⟶ reflects source dimensions

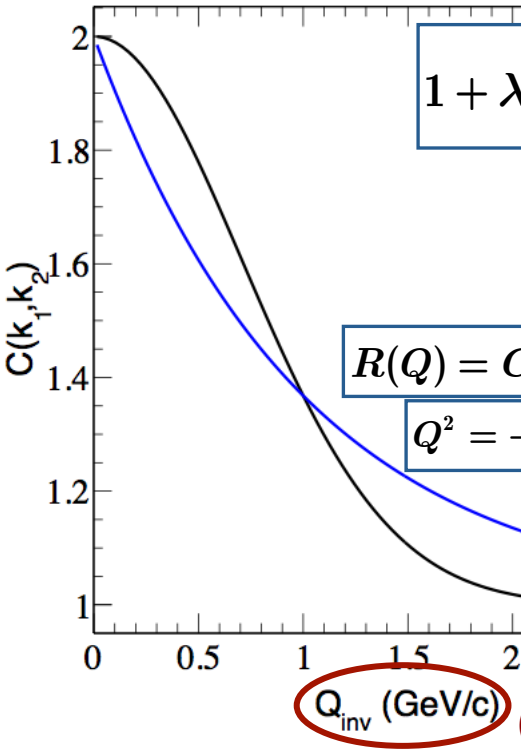
– Correlation Function:

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

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

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

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



(1st two CMS papers)

HBT in 1D @ CMS single & double ratios

First 2 CMS papers on HBT

- Experimentally

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

Same event pairs (with BEC)

Different Reference Samples (no BEC)

  - Background (reference sample) pair selection
    - Same event, ≠ charges (☹ resonances)
    - Rotation of 1 track of the pair
    - Mixed events (☺)

Coulomb FSI
Gamow factor applied to data

$$\Upsilon_{SS}(\eta) = \frac{\eta / Q}{e^{\eta/Q} - 1}$$

$$\eta = 2\pi\alpha_{em} m_{\pi}$$

  - Double ratios → 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	MB Commisssioning Run (23 M)	
7TeV	MB 2010 A (23 M)	Pythia 6 Z – 2 tune (23 M)
7 TeV	MB 2010 B (4 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
  - $\eta < |2.4|$

This analysis:
charged hadrons ($h^{\pm}$)
(assumed to be dominated by π's)

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

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

Fit functions summary: 1D – 2 D – 3D

- 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

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

a = 1 — *Stretched Exponentials*

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

    - 3 D

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

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

Summary of results in 1-dimension

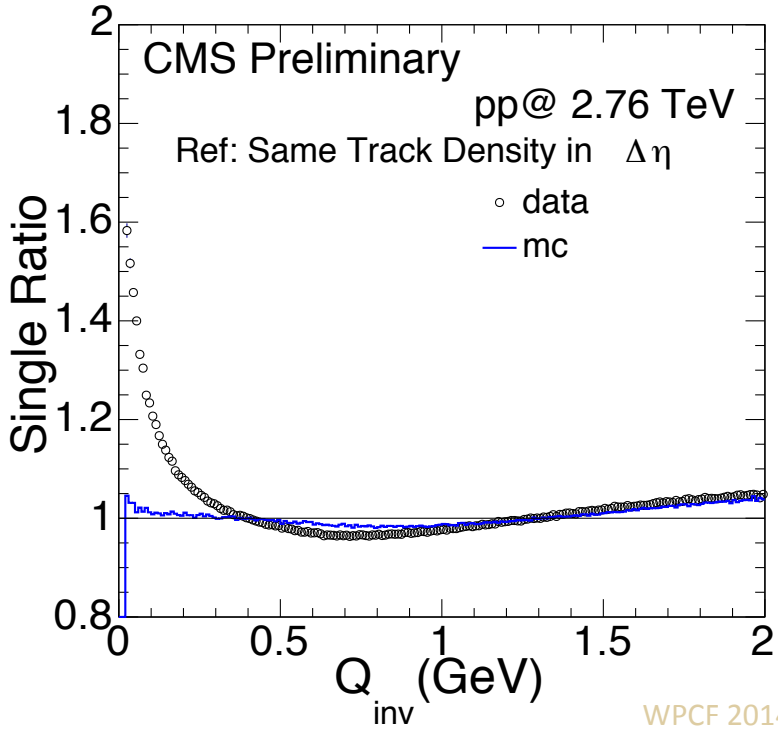
1-D Single and Double Ratios in pp @ 2.76 TeV

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

Signal distribution

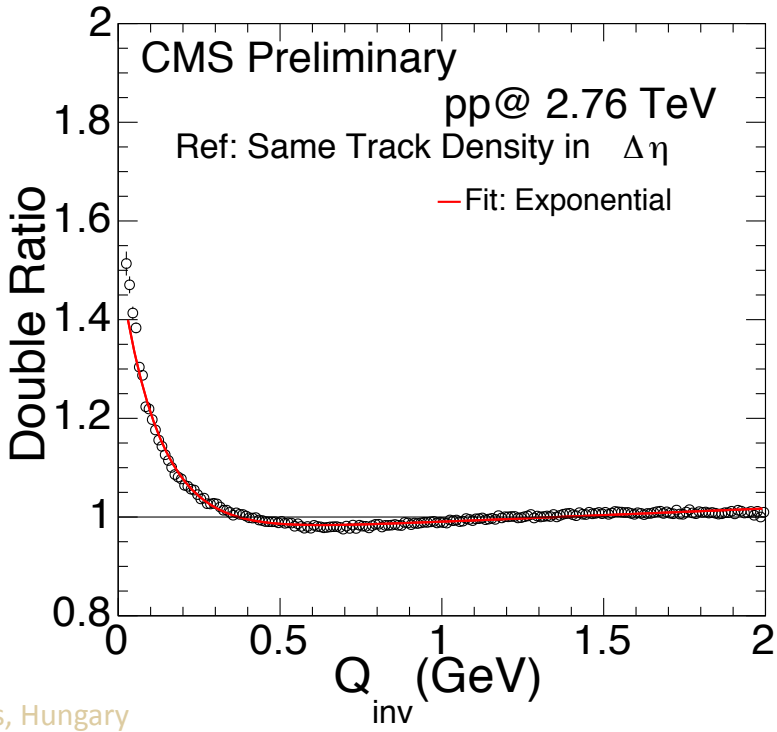
Reference sample (mixed events: similar N_{ch} within same η range)

❑ Single ratios indata and in MC



FSQ-13-002-PAS

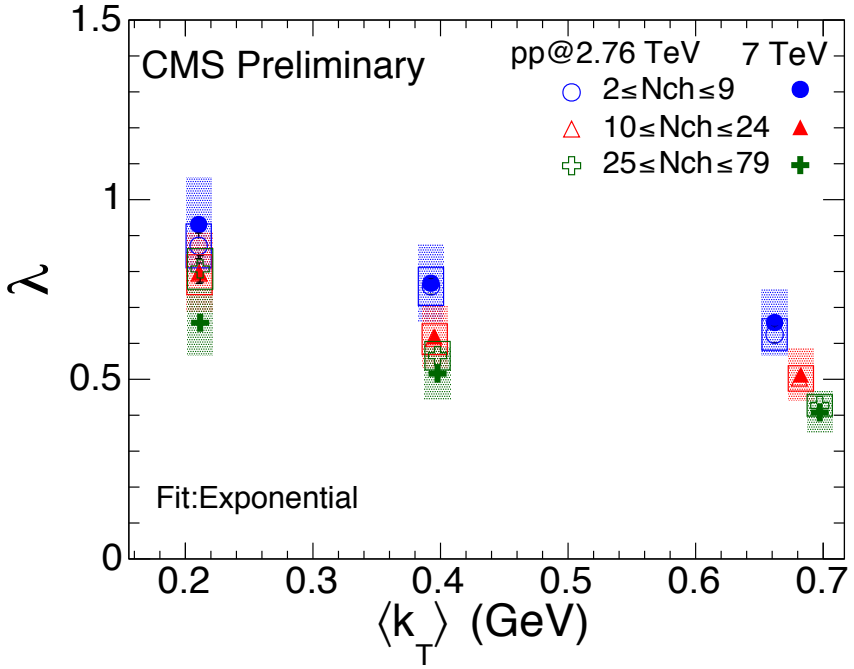
□ Double Ratio

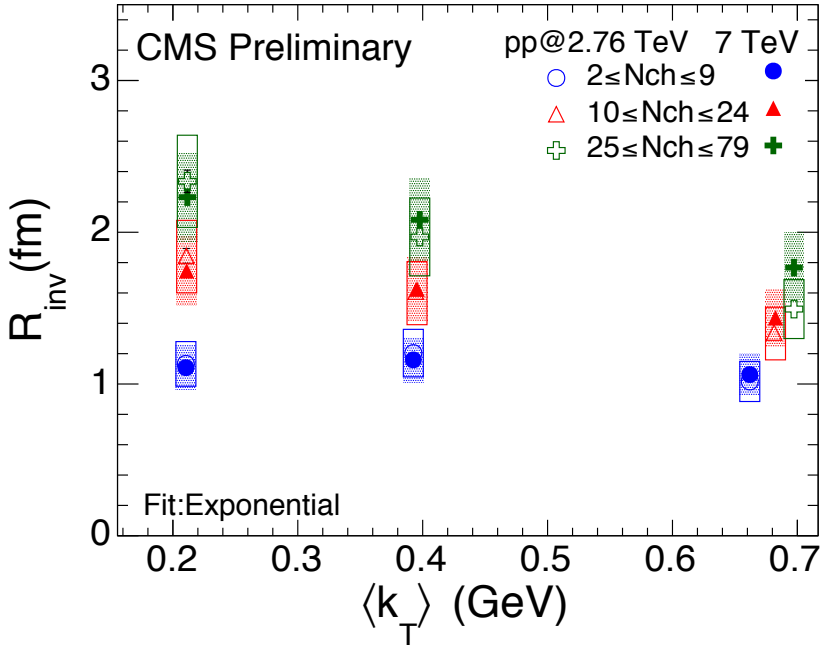


Double ratios and fit parameters R_{inv} and λ

- 1D Double ratios investigated
  - pp collisions at 2.76 and 7 TeV
  - differencially in N_{ch} and k_T bins
  - Fit function: exponential
  - Uncertainties in plots below
    - statistical → error bars
    - systematic → shaded rectangular areas

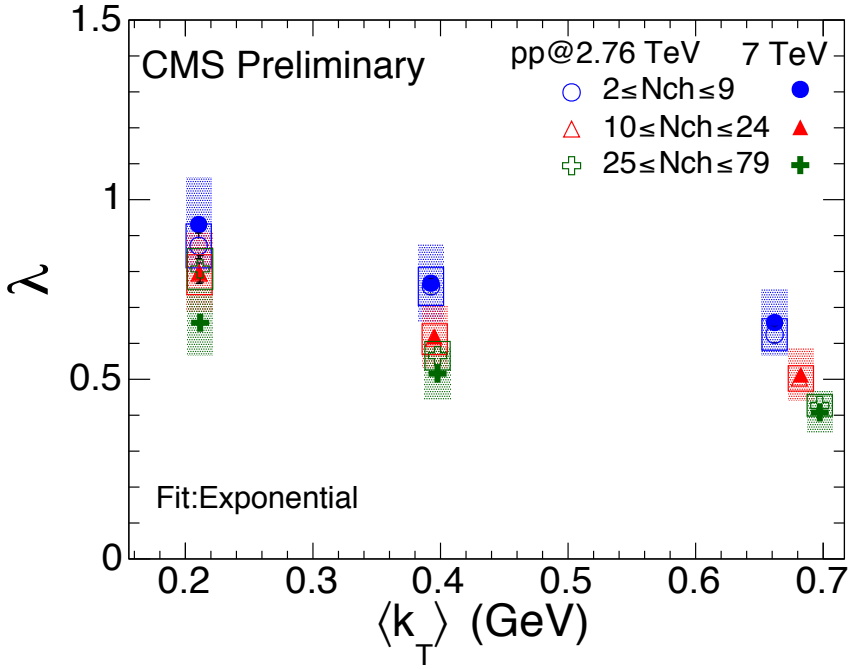
FSQ-13-002-PAS

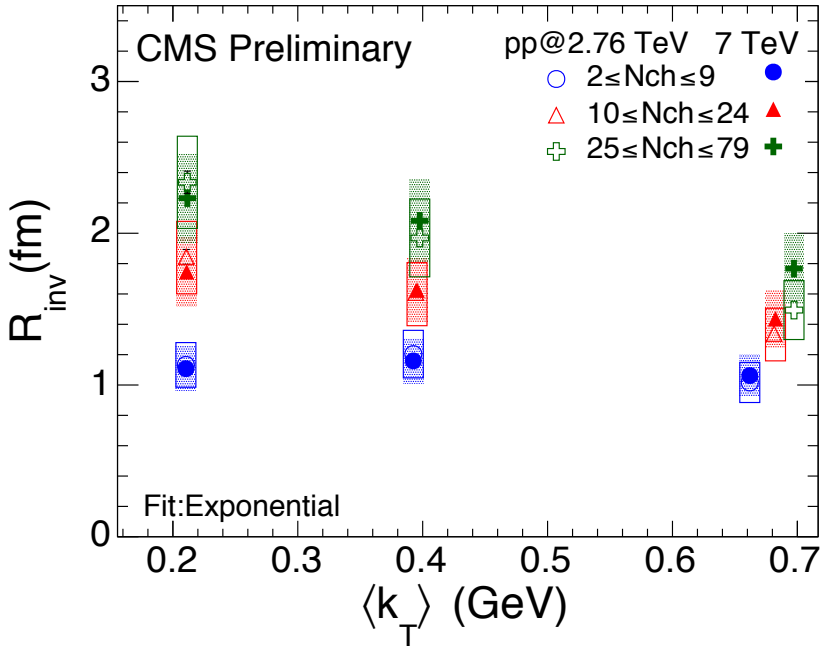




Double ratios and fit parameters R_{inv} and λ

- 1D Double ratios investigated
  - pp collisions at 2.76 and 7 TeV
  - differencially in N_{ch} and k_T bins
  - Fit function: exponential
  - Uncertainties in plots below
    - statistical → error bars
    - systematic → shaded rectangular areas
- Summary of results:
  - Radius fit parameter – R_{inv}
    - increase with N_{ch}
    - decrease with k_T
  - Intercept parameter – λ
    - decreases with N_{ch} (3 bins only)
    - decreases with k_T





FSQ-13-002-PAS

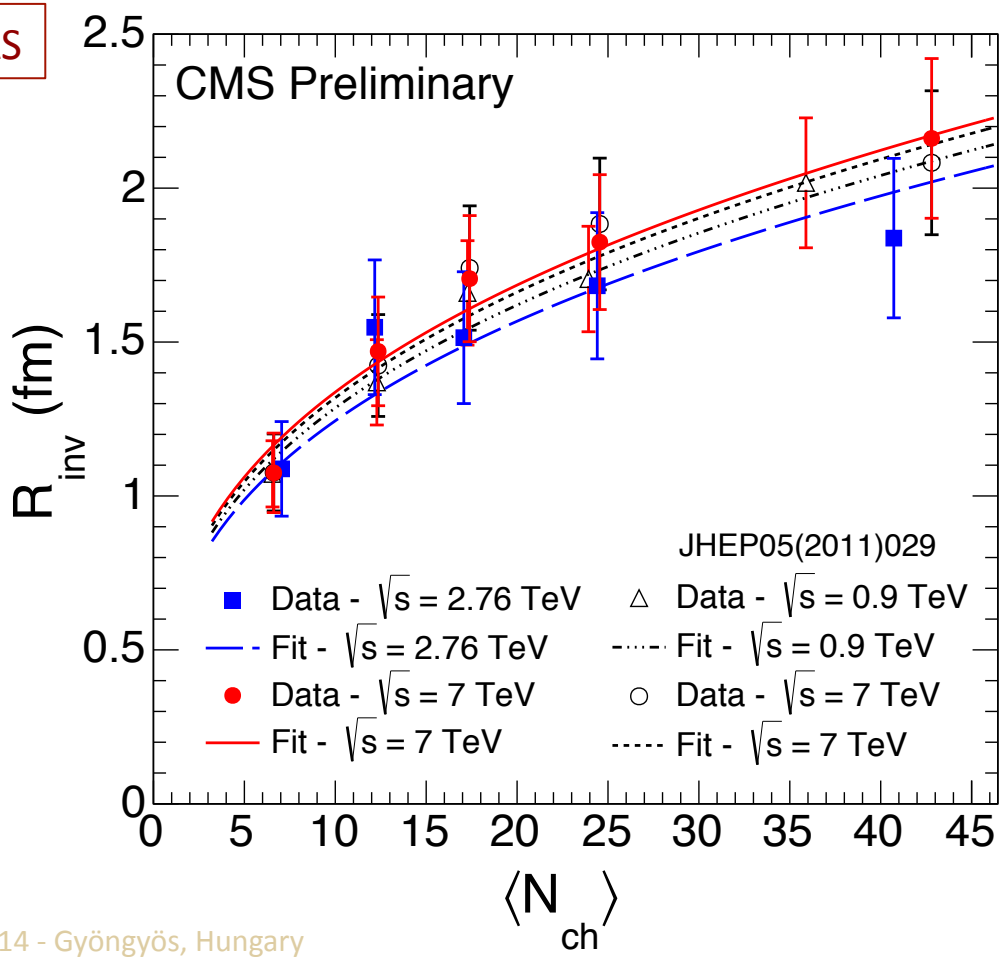
Radius fit (exponential) parameter vs. N_{ch}

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

FSQ-13-002-PAS

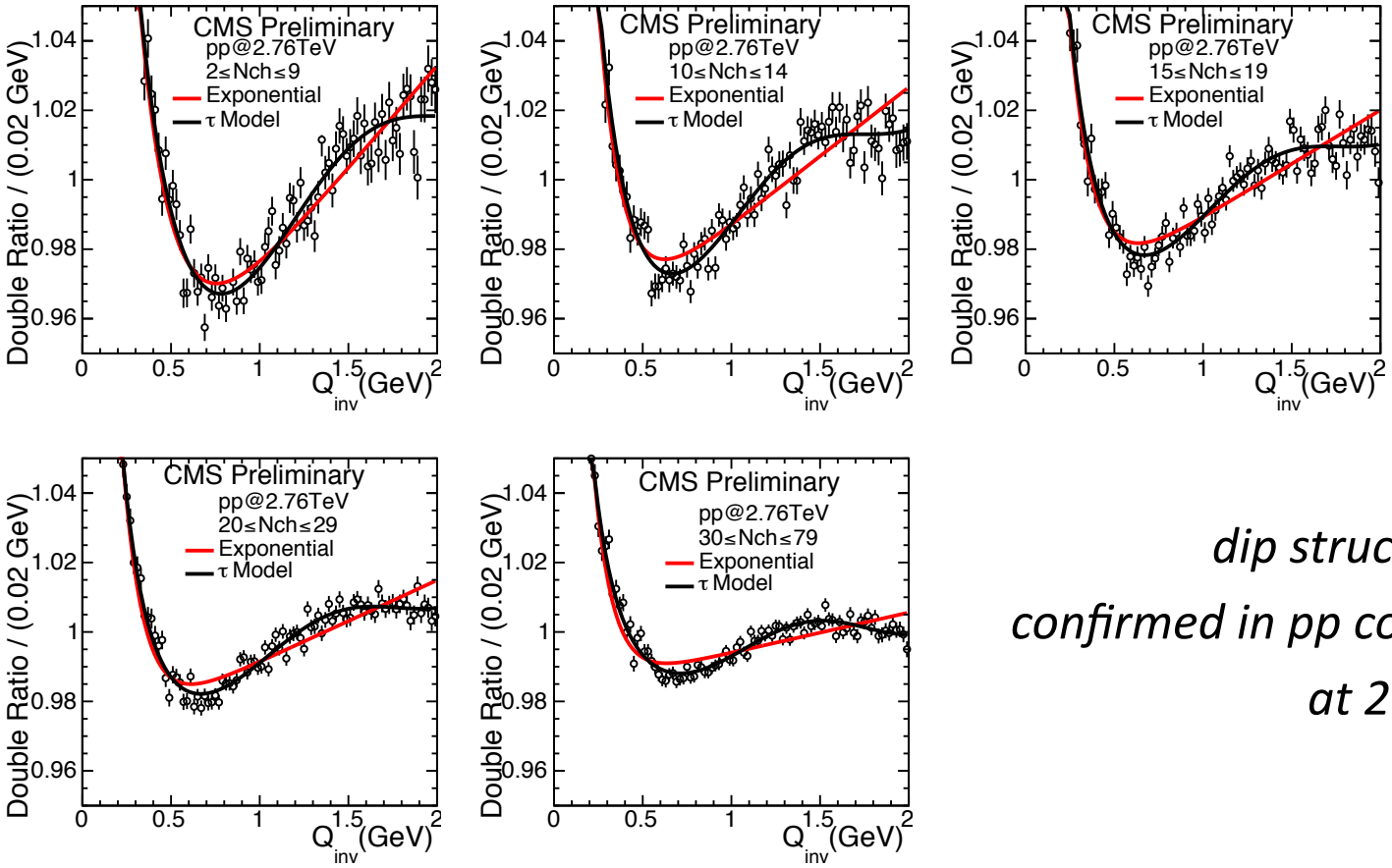
- The proportionality parameter α in of R as a function of $N_{ch}^{1/3}$
  - at 0.9 TeV
    α=[0.597 ± 0.009] (fm)
  - at 7 TeV
    α= [0.612 ± 0.007)] (fm)
  - at 2.76 TeV
    α= [0.578 ± 0.005] (fm)
  - at 7 TeV (new results)
    α= 0. 621 ± 0.001

  (in α: statistical uncert. only)



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

FSQ-13-002-PAS



dip structure →

confirmed in pp collisions

at 2.76 TeV

- 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)]

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

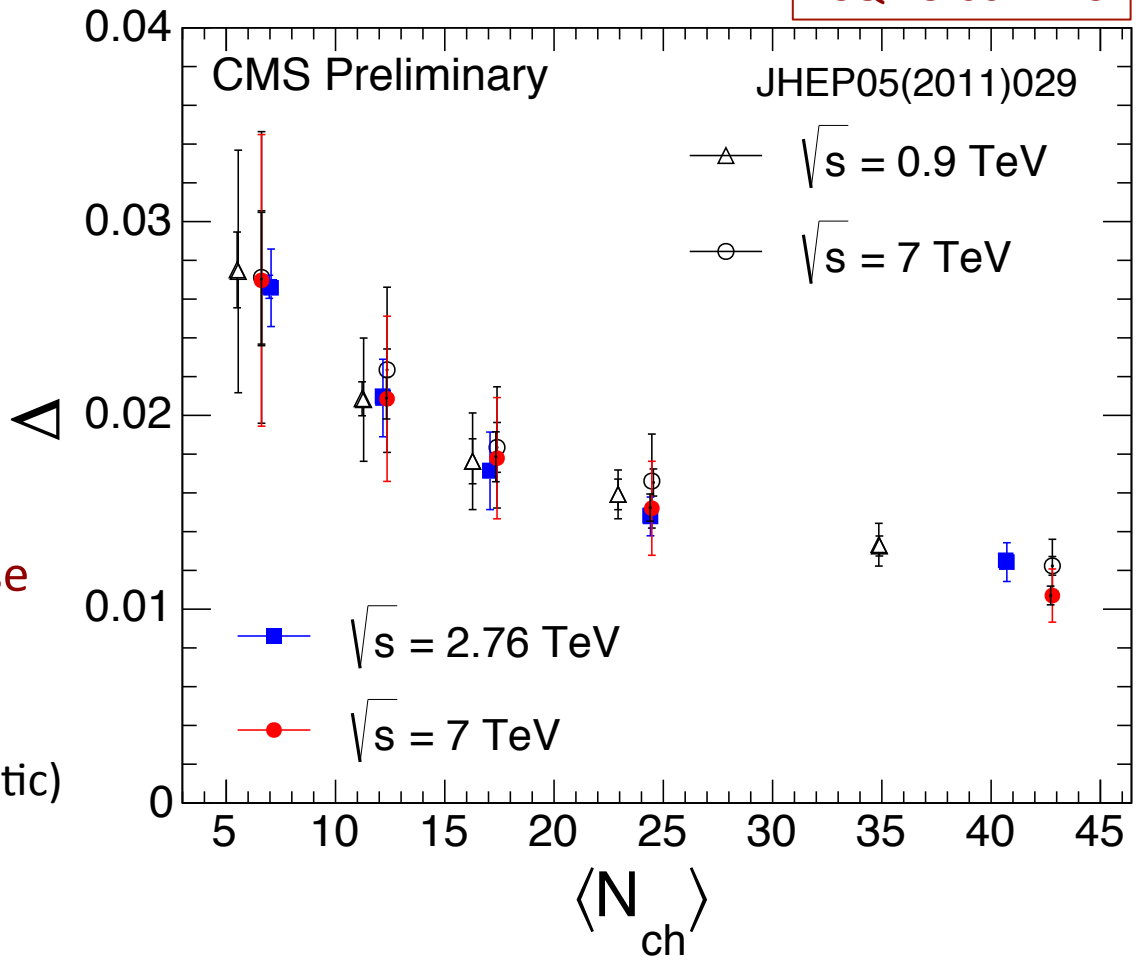
Quantifying the dip's depth

- Dip's depth (integrate in k_T)
  - published results (0.9 & 7 TeV) [JHEP 05(2011)029]
    + new results at 2.76 TeV and at 7 TeV [FSQ-13-002-PAS]

- Summary:
  - ❑ previous and new results → consistent
  - ❑ ≈ scaling with √s
  - ❑ dip's depth → decrease with N_{ch}

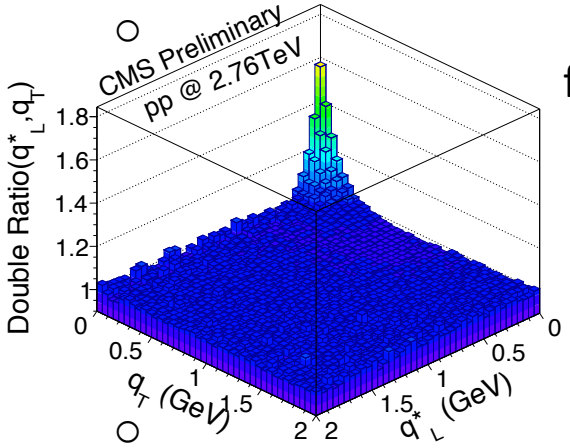
(error bars → systematic)

FSQ-13-002-PAS

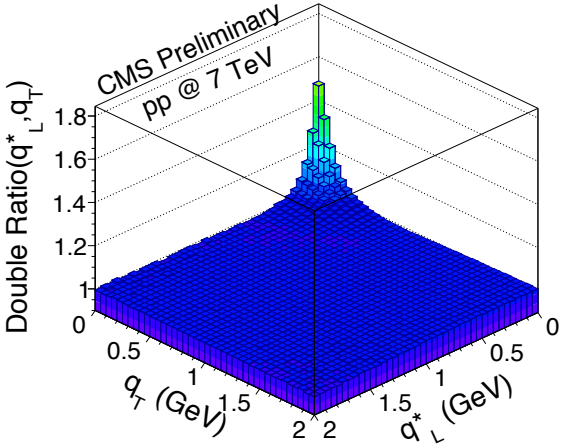


Summary of results in 2-dimensions

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



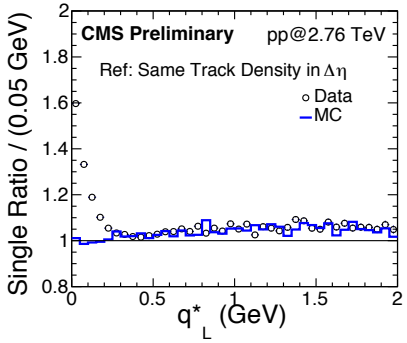
2-D correlation functions (q_T, q_L)

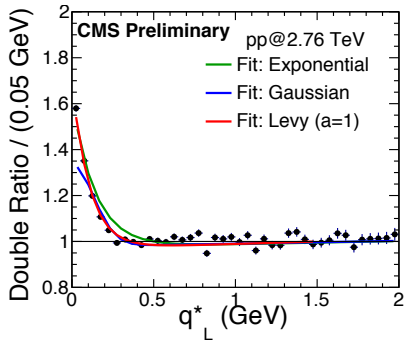


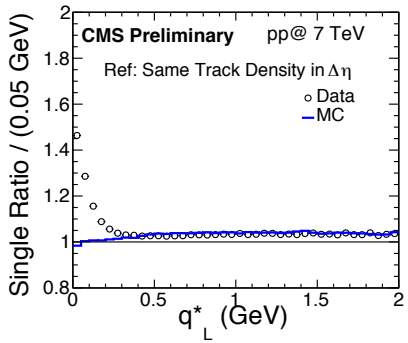
FSQ-13-002-PAS

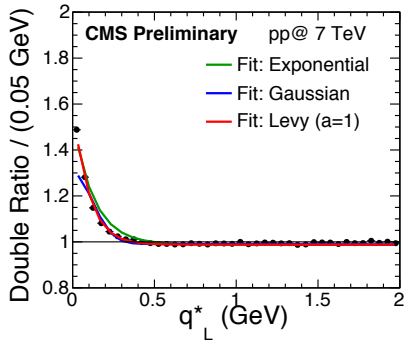
1-D projections

$|q_T| \leq 0.05$ GeV

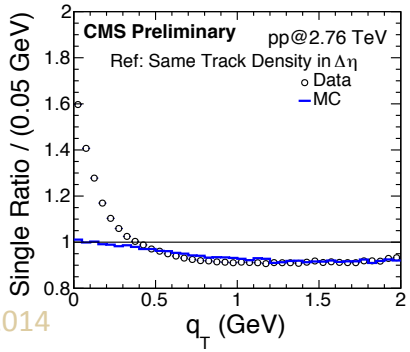


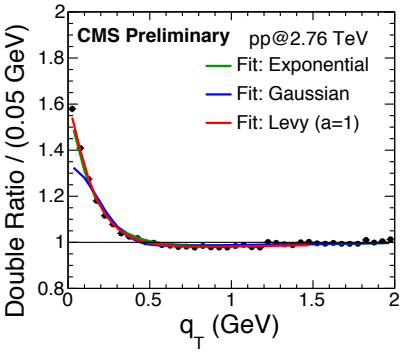


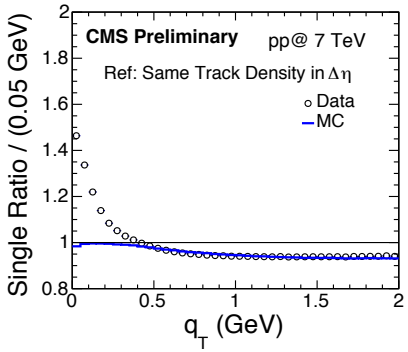


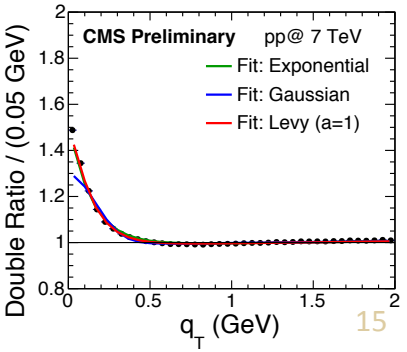


$|q^*_L| \leq 0.05$ GeV



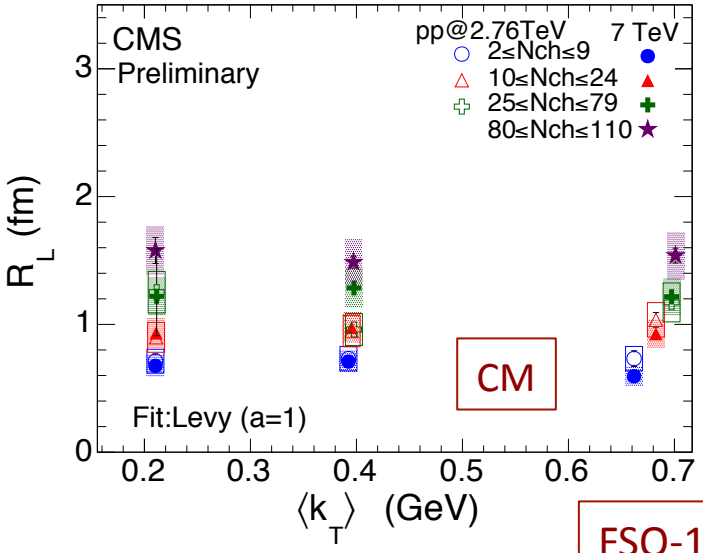


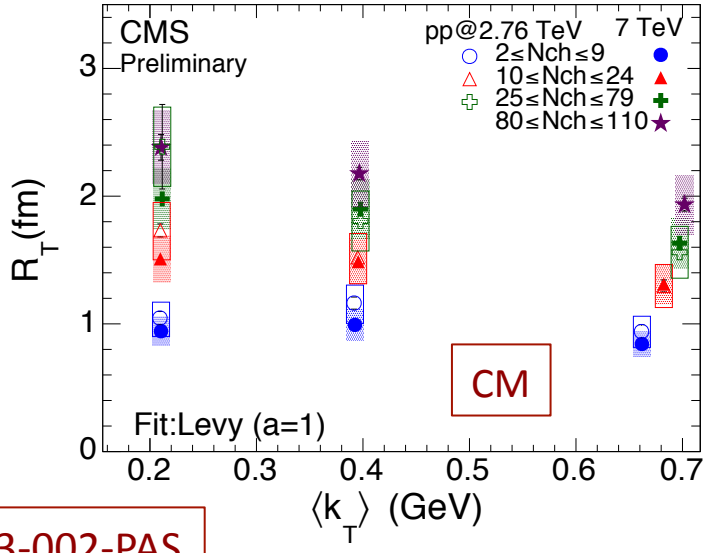




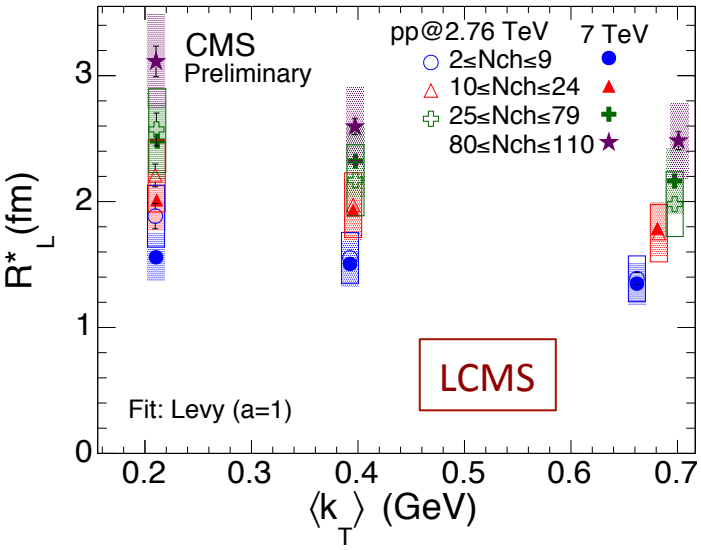
2D results with *stretched exponential* fit function

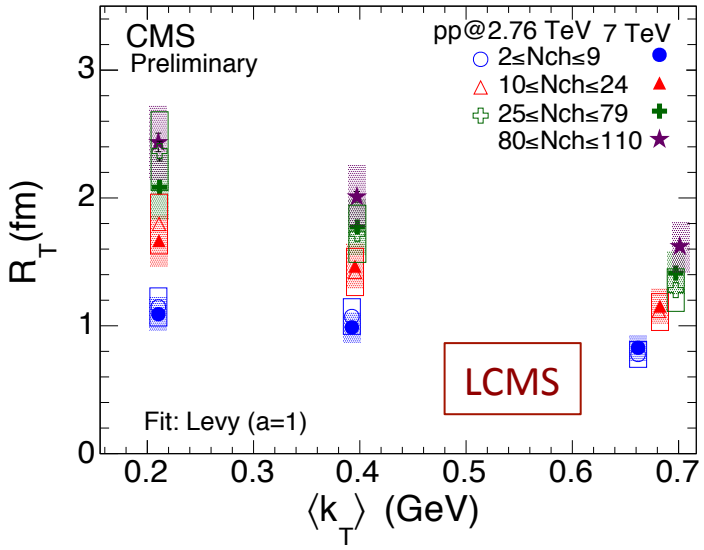
- For $R^{(*)}_L$ & R_T:
- CM frame
  - ↗ as N_{ch} ↗
  - ↘ as k_T ↗ (for large N_{ch})
  - $R_L < R_T$
- LCMS
  - ↗ as N_{ch} ↗
  - ↘ as k_T ↗ (for larger N_{ch})
  - Integrated in k_T , N_{ch}:
  - $R^*_L > R_L$
  - $R^*_L > R_T$ (LCMS)





FSQ-13-002-PAS



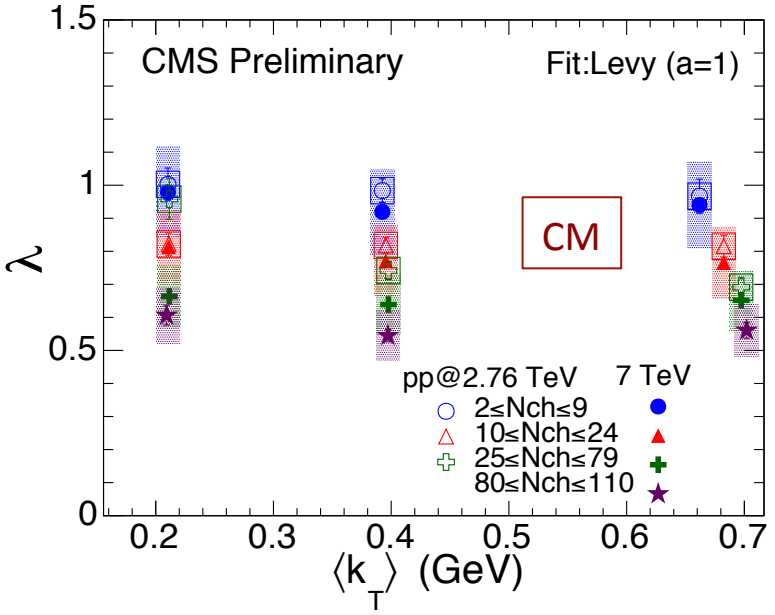


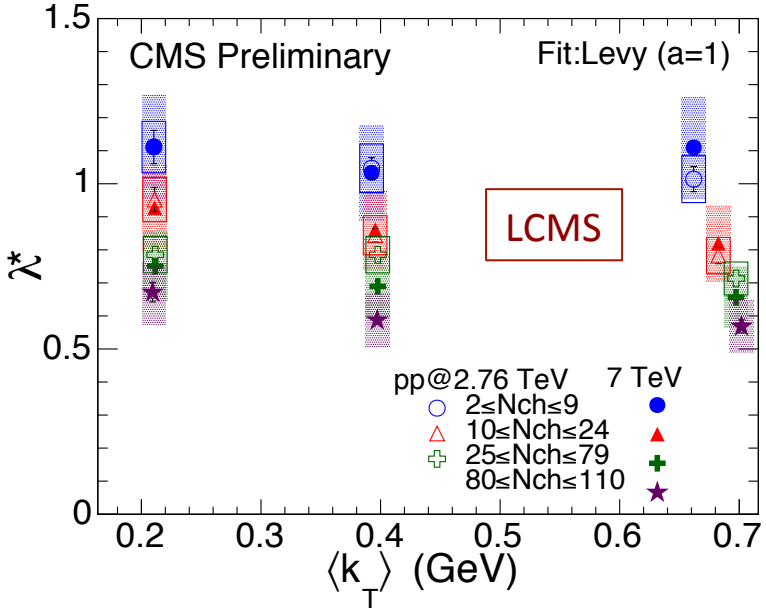
2D results with *stretched exponential* fit function

- For the intercept $\lambda^{(*)}$
- CM frame
  - ↘ as N_{ch} ↗
  - almost flat as k_T ↗

FSQ-13-002-PAS

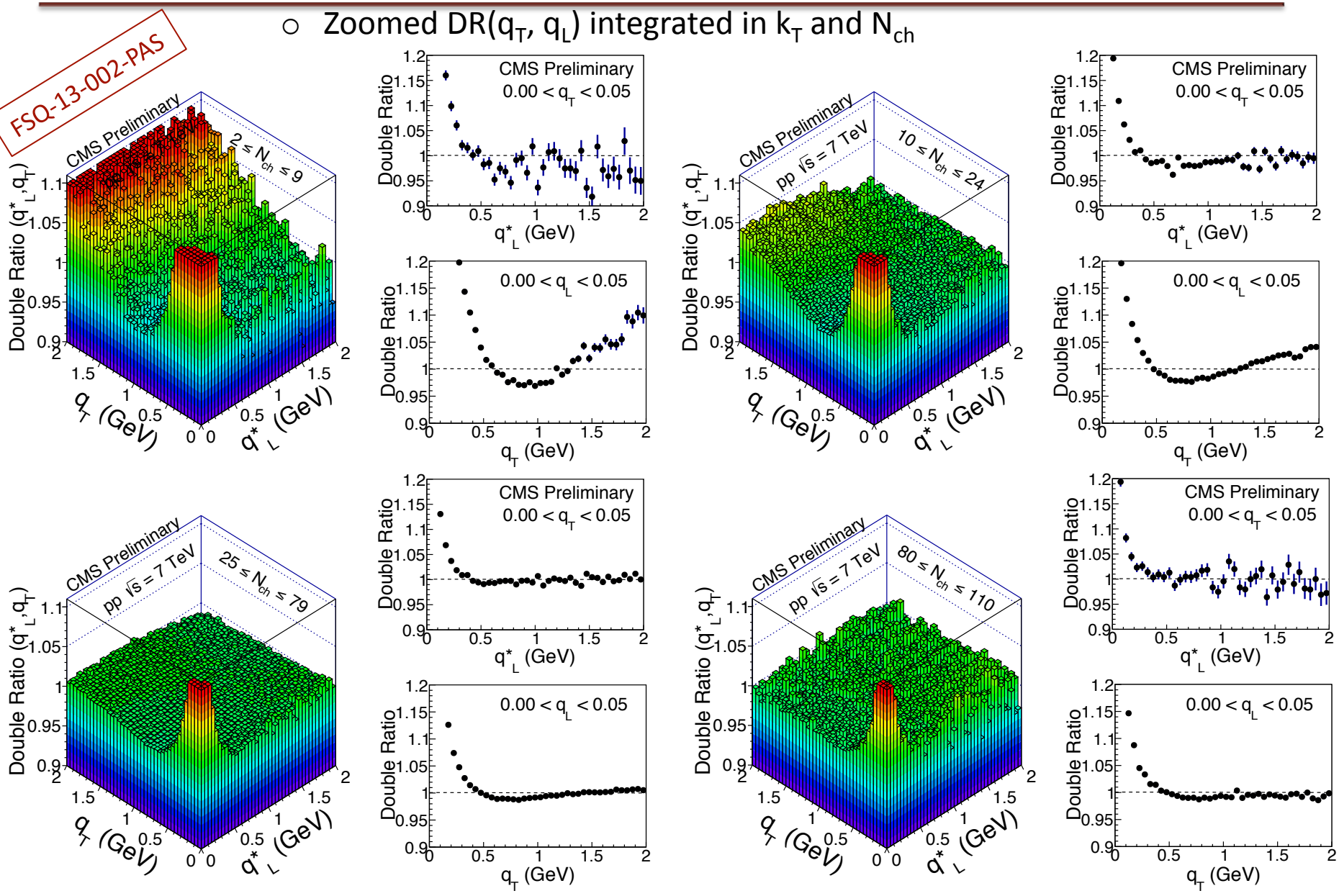
- LCMS
  - ↘ as N_{ch} ↗
  - slight decrease as k_T ↗ (for larger N_{ch})





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

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

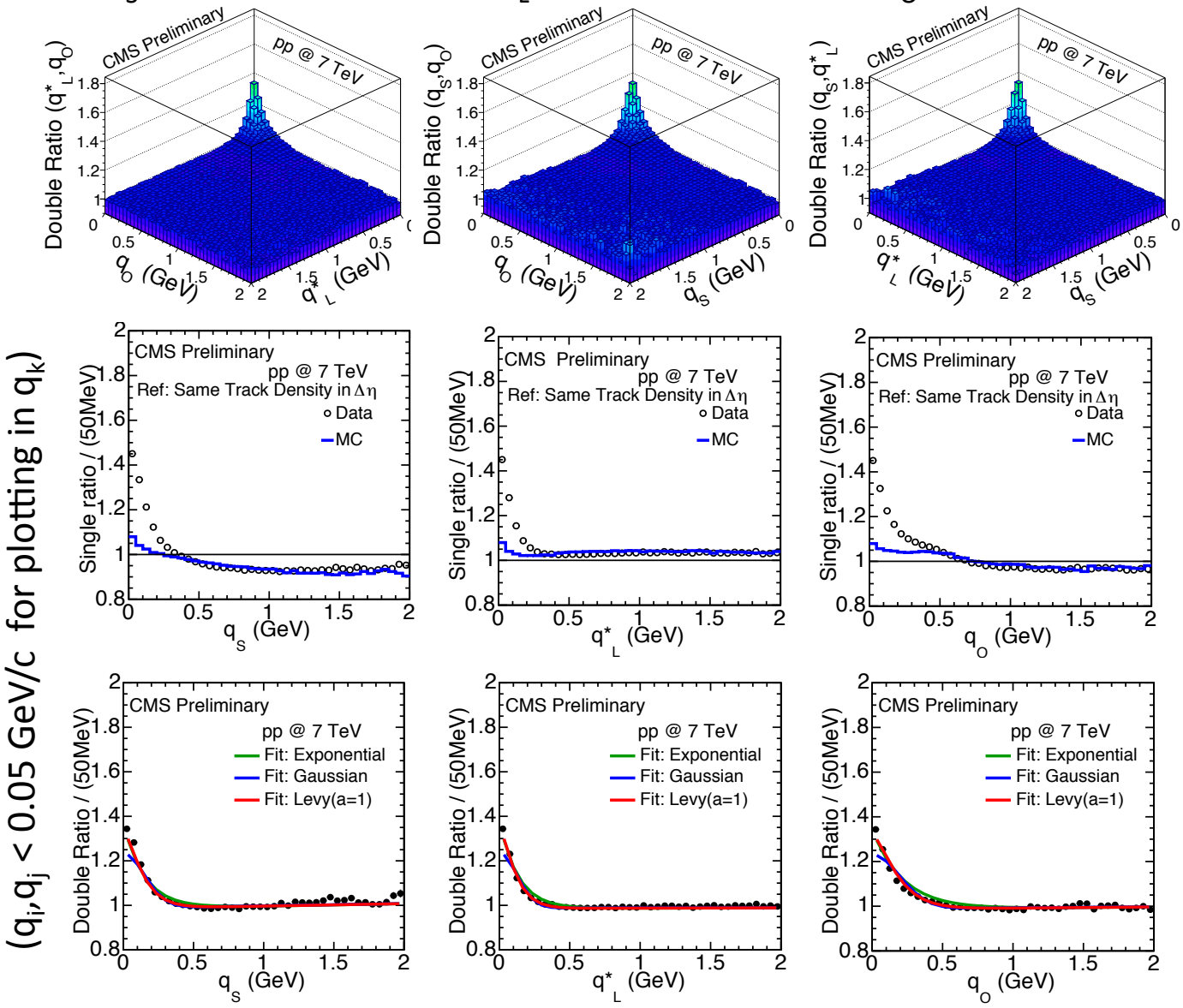


Summary of results in 3-dimensions

3-D Double Ratios (q_O, q_S, q_L) – in LCMS at 7 TeV

FSQ-13-002-PAS

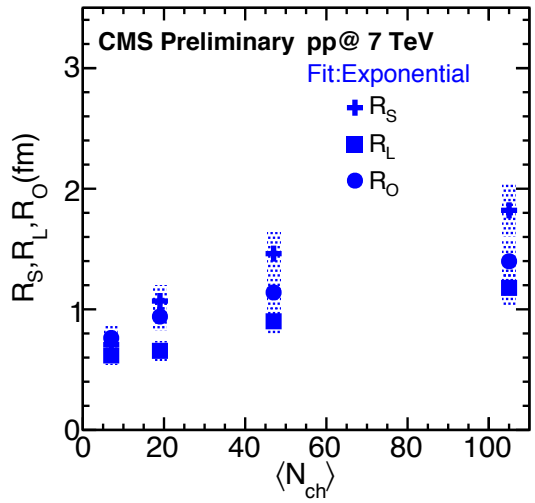
- (q_S < 0.05 GeV/c) (q_L < 0.05 GeV/c) (q_O < 0.05 GeV/c)

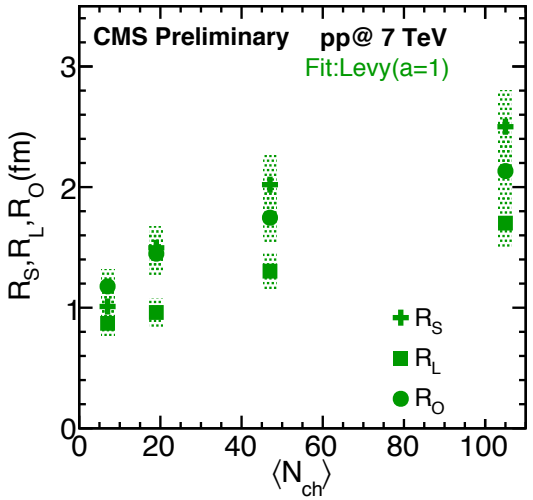


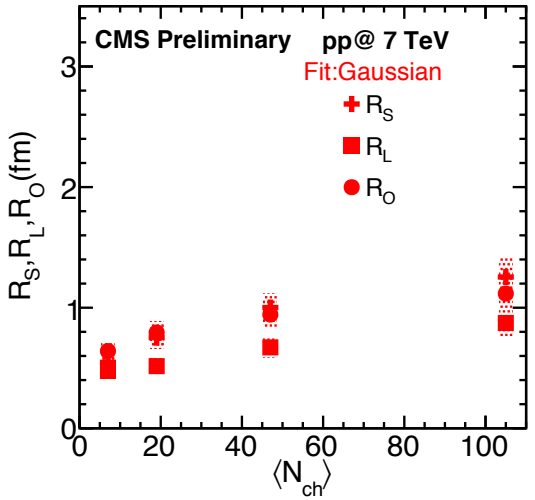
Results: R_S, R_L, R_O from different fit functions

FSQ-13-002-PAS

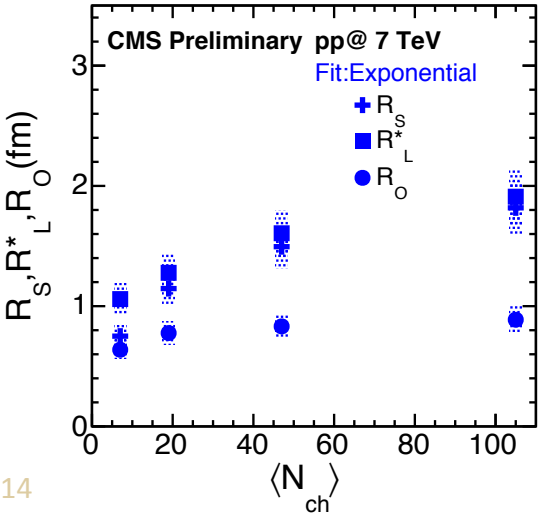
❑ In the CM frame (integrated in k_T bins)

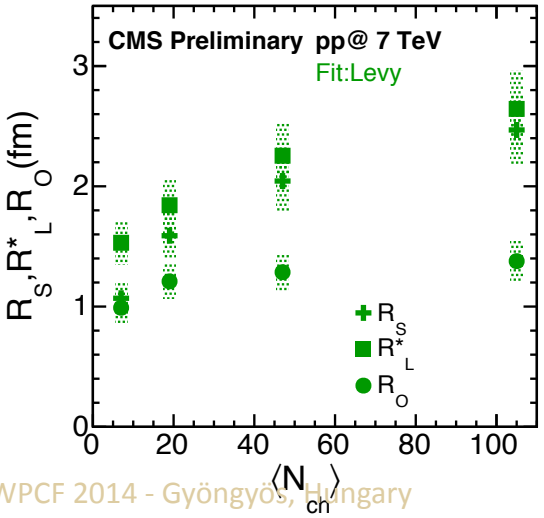


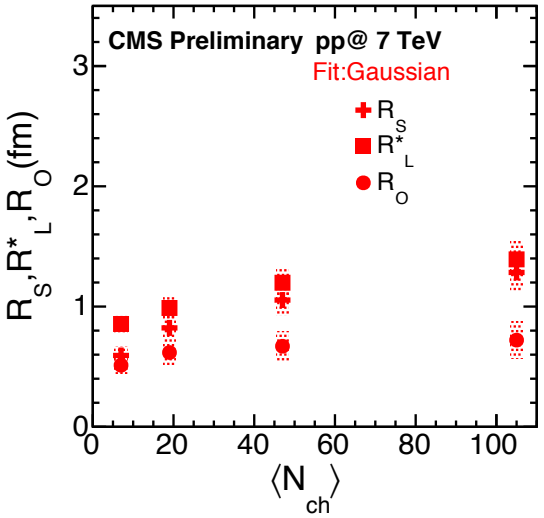




❑ In the LCMS frame (integrated in k_T bins)





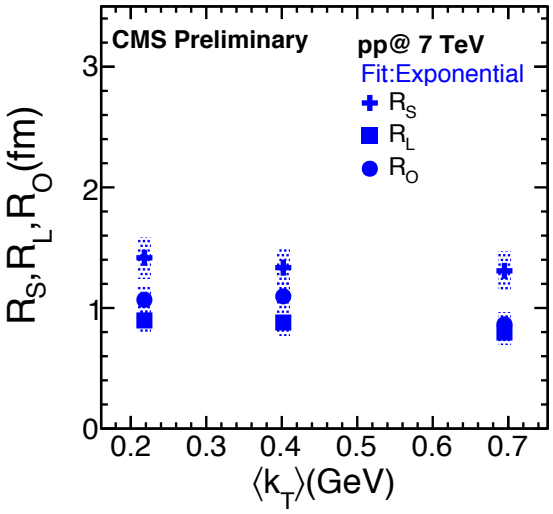


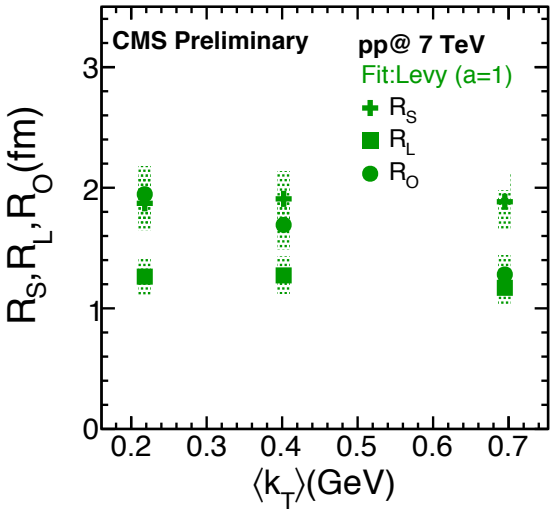
Stat. and syst. uncertainties included, vs. corrected N_{ch}

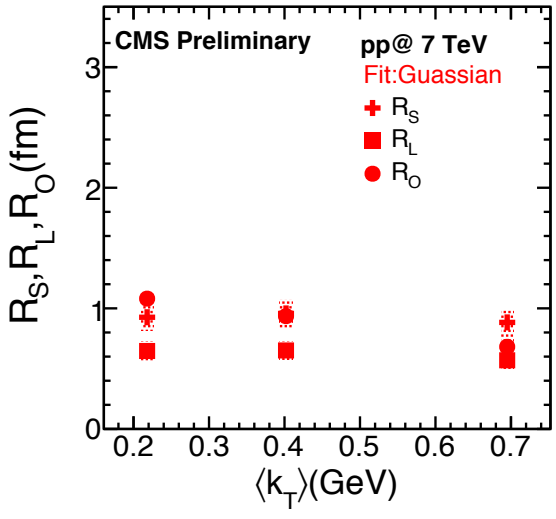
Results: R_S, R_L, R_O from different fit functions

FSQ-13-002-PAS

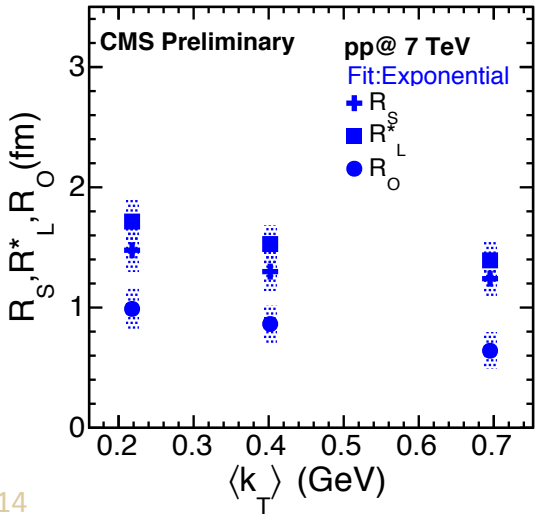
❑ In the CM frame (integrated in N_{ch} bins)

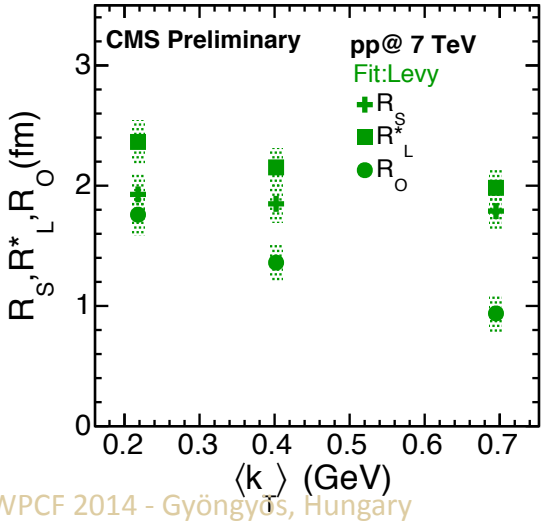


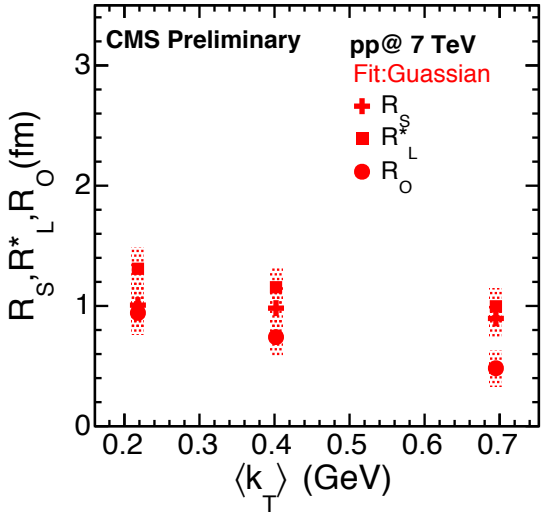




❑ In the LCMS frame (integrated in N_{ch} bins)





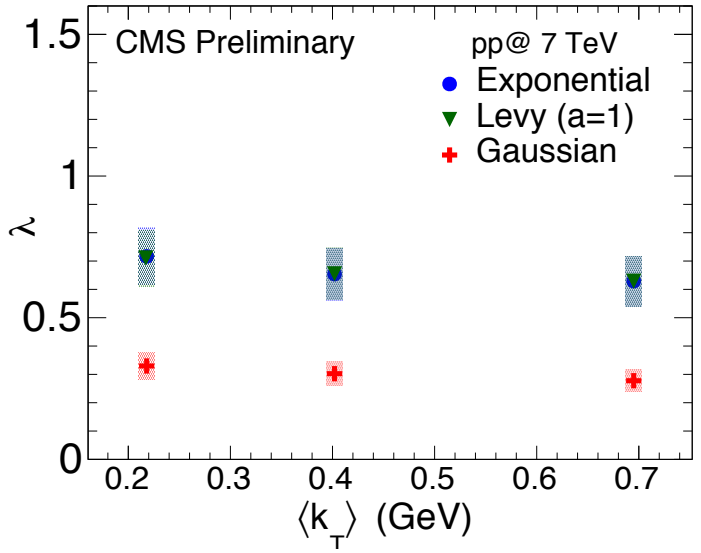


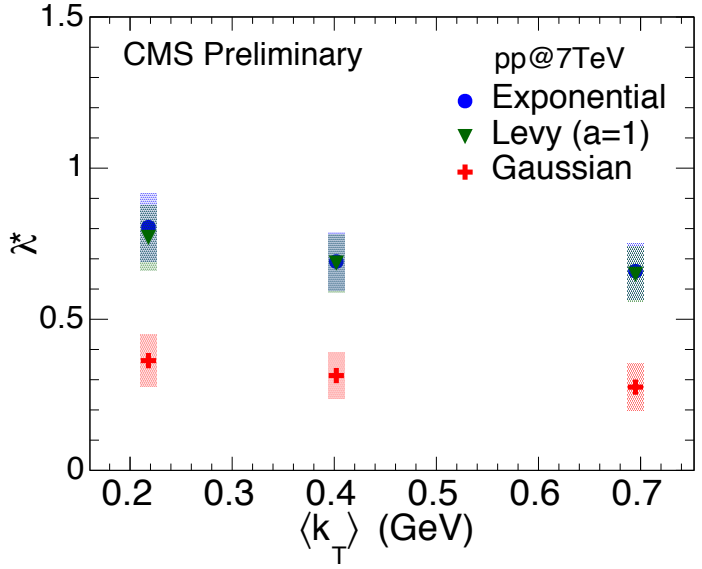
Stat. and syst. uncertainties included, vs. corrected N_{ch}

Results: λ, λ* from different fit functions

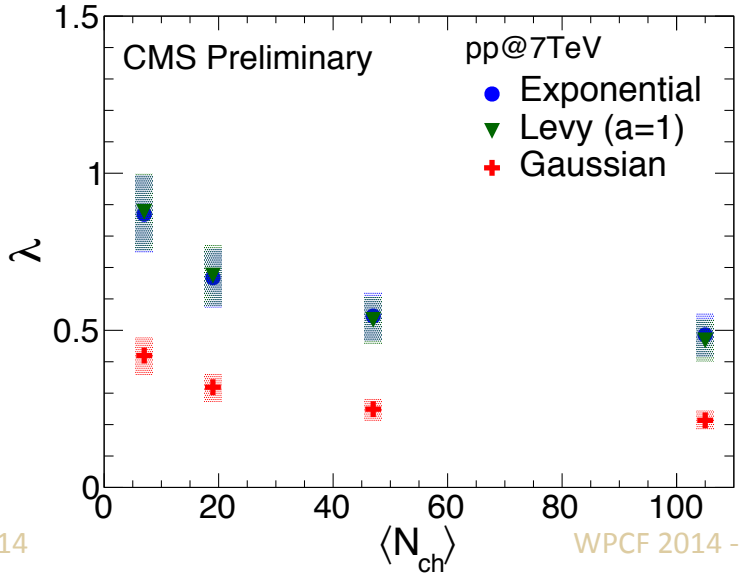
- In the CM frame
- In the LCMS frame

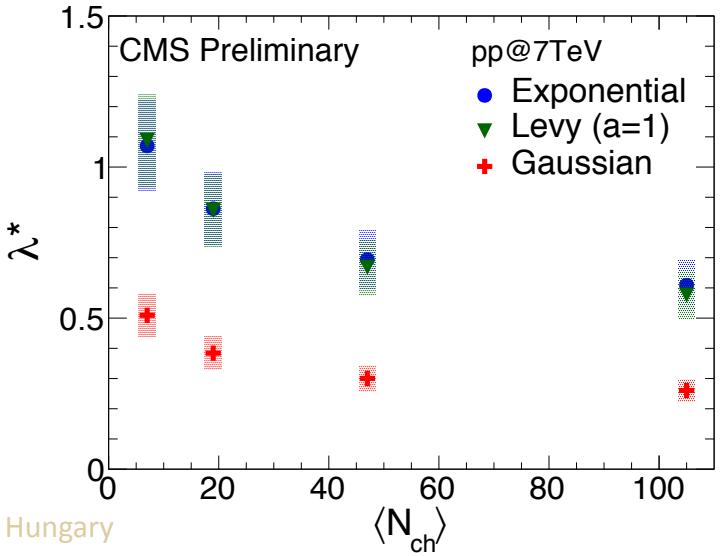
(N_{ch} integrate)





(k_T integrate)





FSQ-13-002-PAS

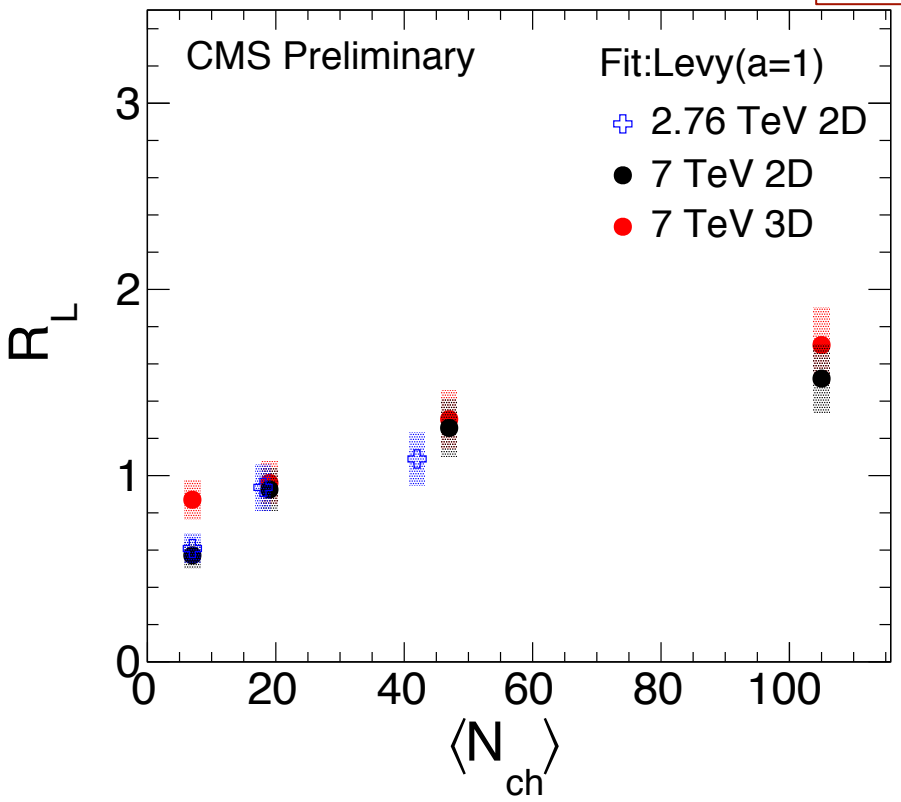
Compilation of the 3-D results

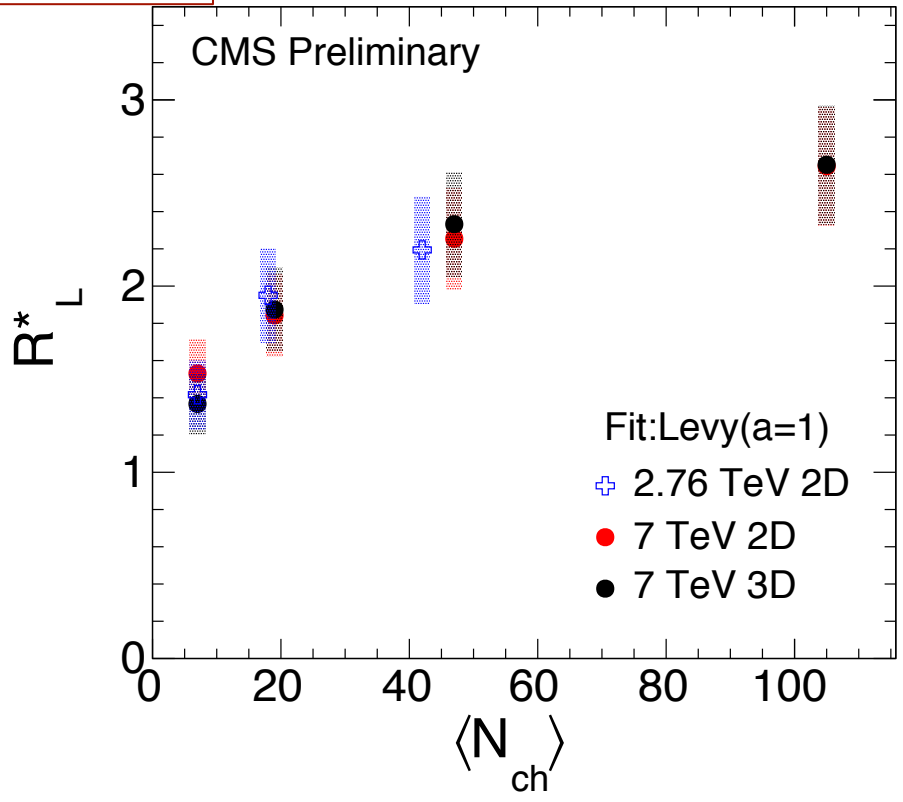
- Fits: Gaussian, *stretched* (Lévy: α=1) and simple exponential
  - Radius parameters R_O, R_S, $R^{(*)}_L$ in CM frame and LCMS (streched exp.)
    - R_O, R_S, R_L (k_T integrate) ↗ as N_{ch} ↗ in both frames and all three fit functions
    - R_O, R_S, R_L (N_{ch} integrate) vs. k_T:
      - R_S → almost insensitive to N_{ch}
      - R_O , R_L → decreases moderately with k_T (more easily seen in LCMS)
      - $R^*_L > R_L$ and $R^*_O < R_O$ → consistent with Lorentz boost from LCMS to CM frame
    - Integrated values in k_T and N_{ch}:
      - $R_S > R_O > R_L$ (in CM frame) and $R_L > R_S > R_O$ (in LCMS)
  - $\lambda^{(*)}$ intercept parameter in CM frame and LCMS (streched exp.)
    - k_T integrated: decreases with N_{ch} for lower bins and seems to flatten out for higher N_{ch} (4 bins only)
    - N_{ch} integrated: practically insensitive to k_T

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

FSQ-13-002-PAS

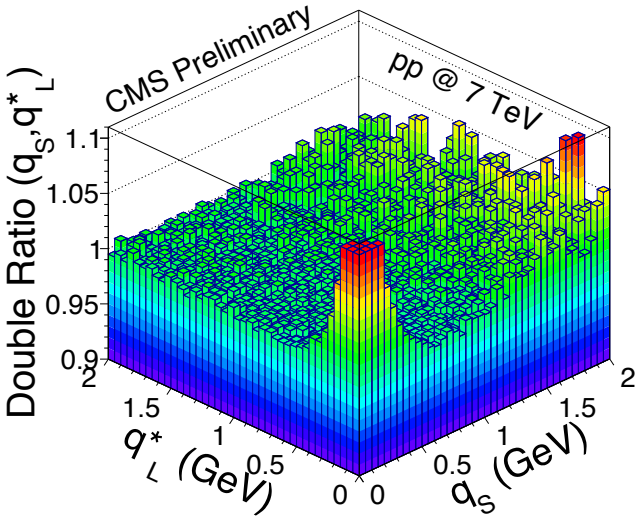


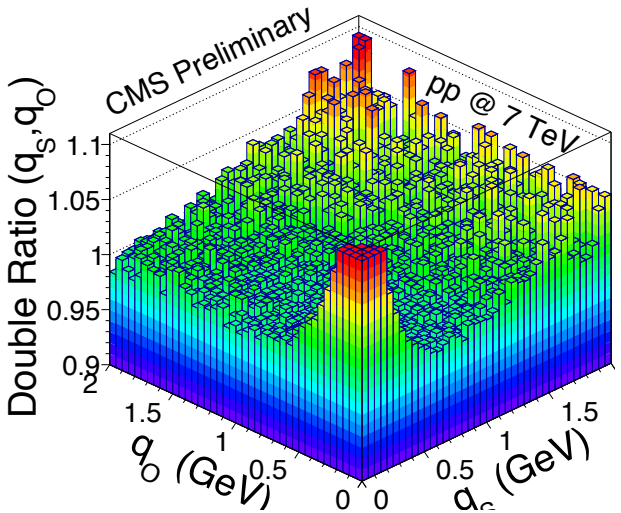


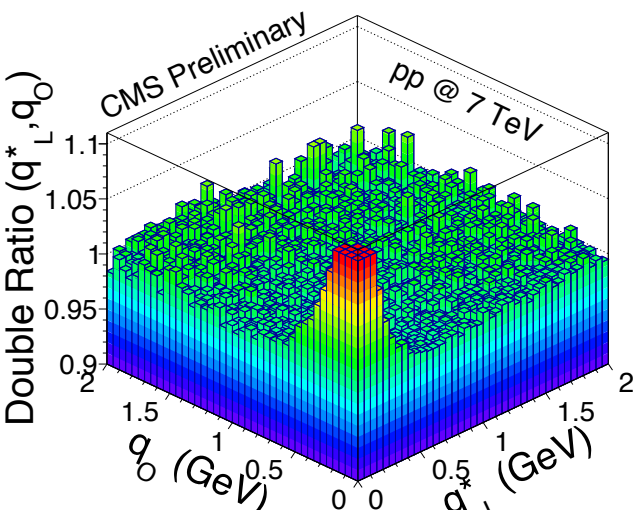
The anticorrelation in 3-D $DR(q_O, q_S, q_L)$ - LCMS

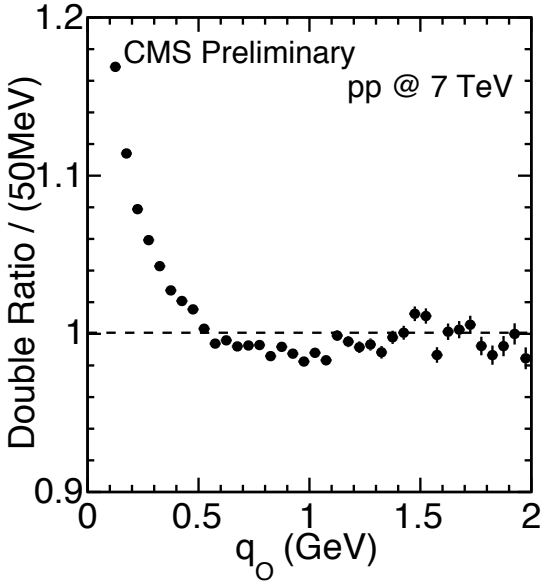
- Zoomed $DR(q_O, q_S, q_L)$ integrated in k_T and N_{ch}

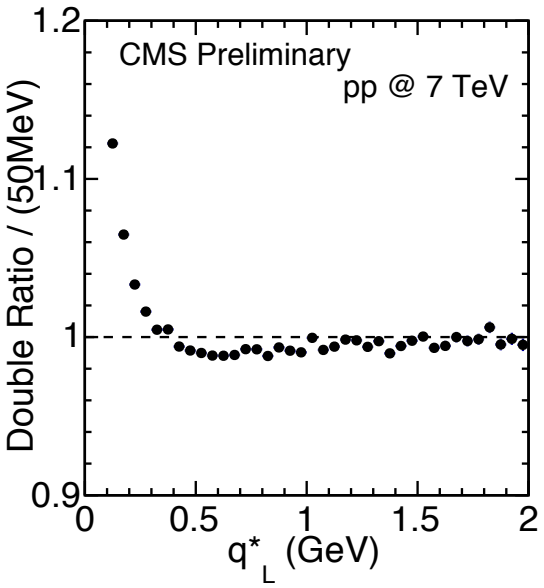
FSQ-13-002-PAS

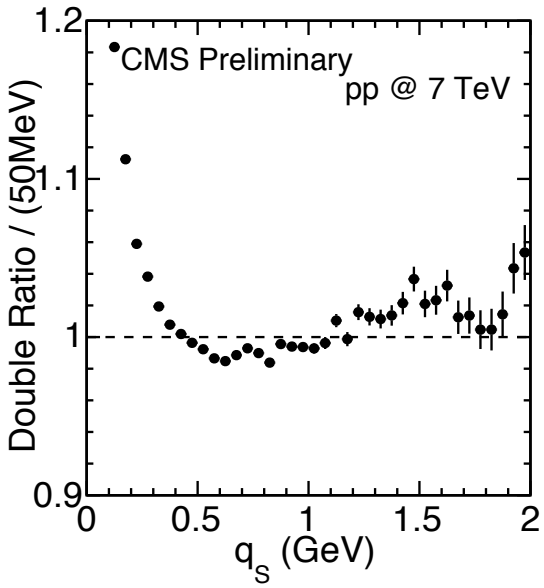












Summary and Conclusions

Summary and Conclusions

- Fits: Gaussian, *stretched* (Lévy: *a*=1) and simple exponential

- Measurements in two reference frames
  - 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 $q_O q_L$)
    - interesting observations when comparing results to those in the LCMS
  - LCMS frame → $k_L=(k_1+k_2)/2=0$ (no cross-term) → comparisons

- Interesting results in 1-D, 2-D, 3D:
  - Radii fit parameters increase with multiplicity, decrease with k_T (1D, 2D, 3D)
  - $\lambda^{(*)}$: 1D → ↘ as N_{ch} , k_T ↗; 2D: ↘ as N_{ch} ↗, almost flat as k_T; 3D: ↘ as N_{ch} ↗ (lower q_O, q_S,q_L) then flattens donw; almost insensitive to k_T
  - 2D: integrated values in k_T , N_{ch}: $R^*_L > R_L$; $R^*_L > R_T$ (in LCMS)
  - $R_S > R_O > R_L$ (in CM frame) and $R_L > R_S > R_O$ (in LCMS)

Summary and Conclusions

- Anticorrelation (dip structure) [already reported in JHEP05, 029 (2011)]
  - confirmed in 1-D in pp collisions at 2.76 TeV (and higher statist. results at 7TeV)
  - present in 2-D (q_T,q_L) and 3-D (q_S,q_L,q_O) and seems sensitive to N_{ch} and k_T
  - (speculation) interesting to quantify: could be related to small system behavior of the protons?
  - (speculation) comparisons to models in 1D, 2D and 3D (τ model, finite size π, …) → result ?

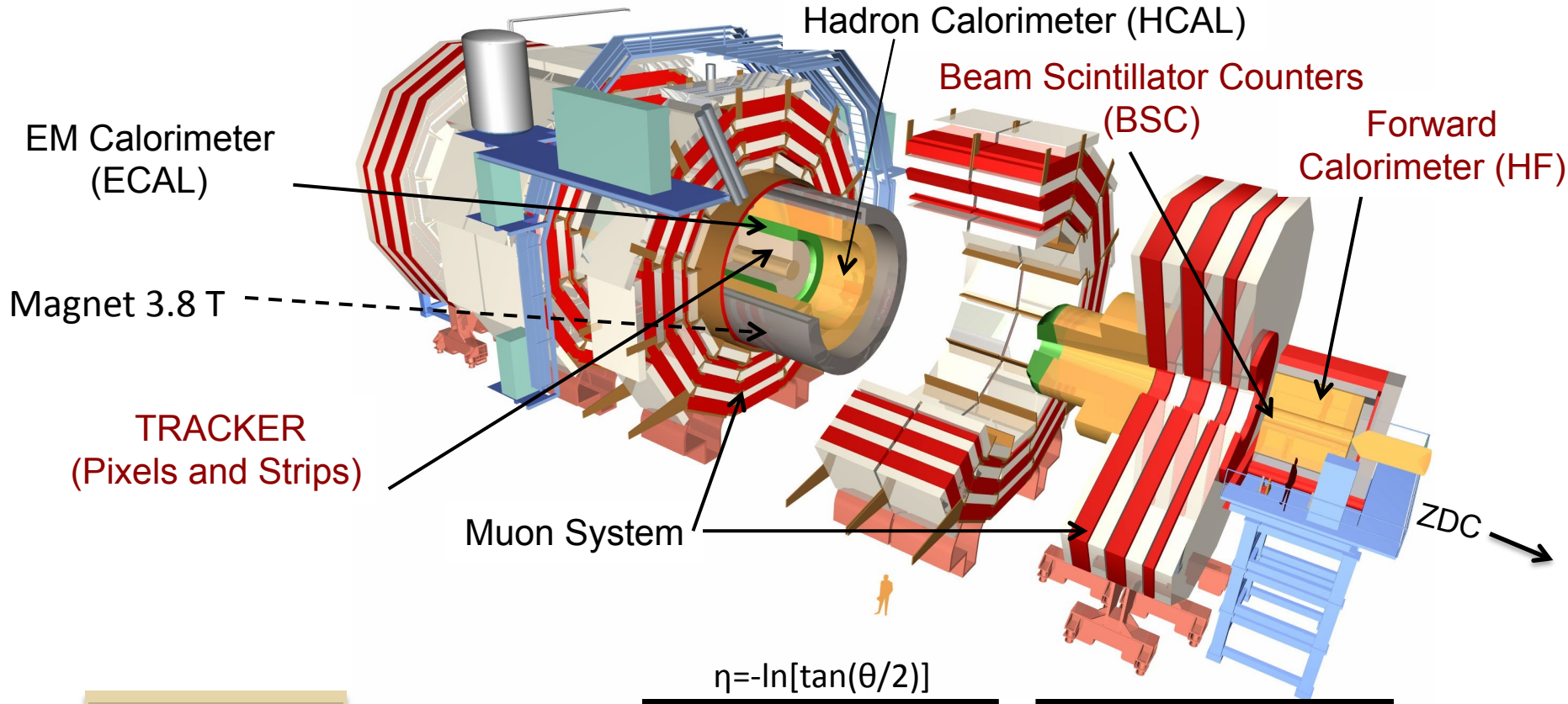
– Thank you!

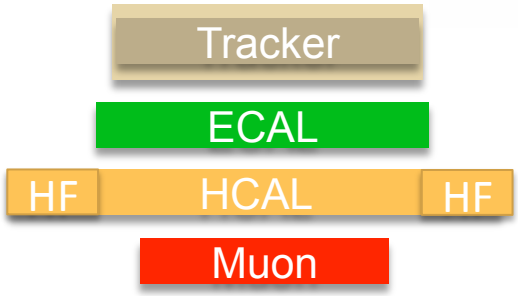
Extras

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

CMS Detector





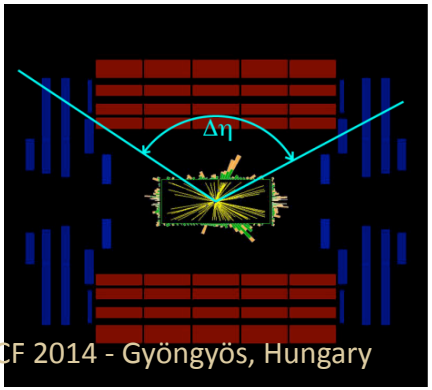
$|\eta| < 2.5$

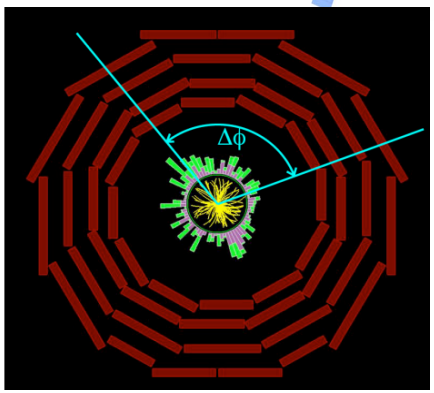
$|\eta| < 3.0$

$|\eta| < 5.2$

$|\eta| < 2.4$

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





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