
بسم الله الرحمن الرحيم

Bose-Einstein Correlations in Proton-Proton Collisions at LHC

By

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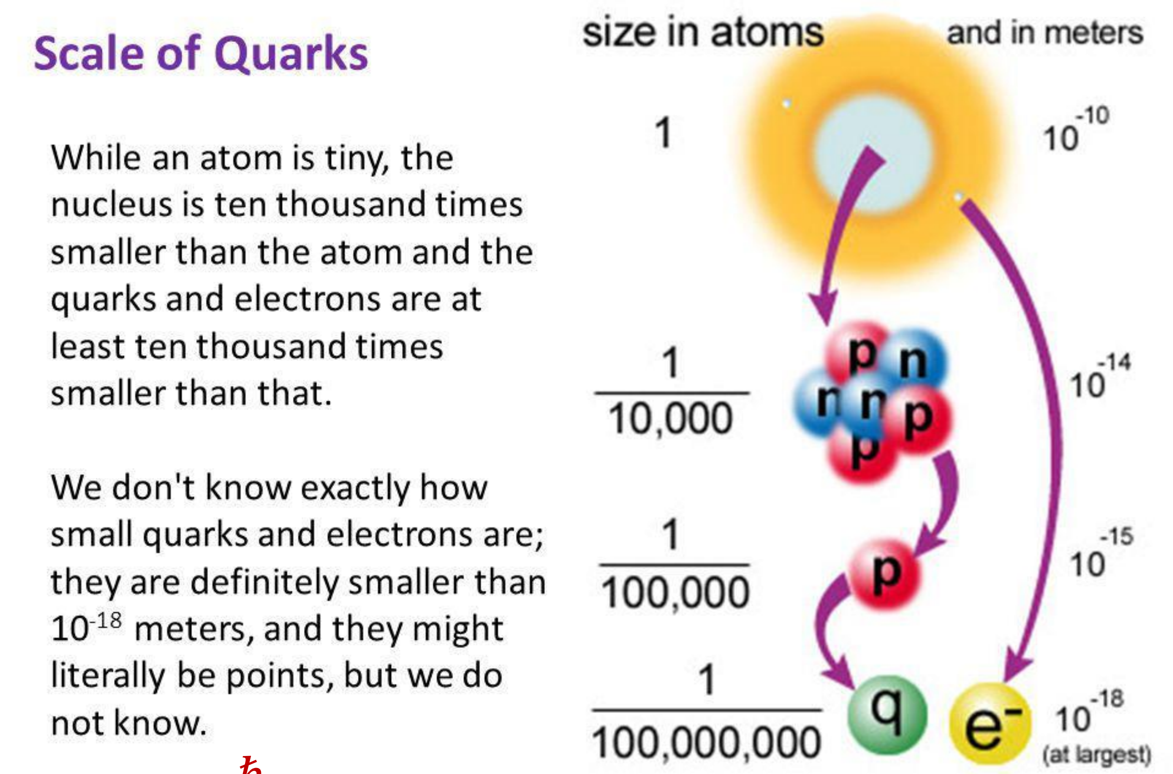
Outline

- The **L**arge **H**adron **C**ollider (**LHC**) at **CERN**.
- The **C**ompact **M**uon **S**olenoid Experiment (**CMS**).
- **B**ose **E**instein **C**orrelations (**BEC**).
- Main Results.
- Conclusions.

Eternal Questions

- What principles govern energy, matter, space and time at the most elementary level?
- What is the world made up of?
- How does it work?

High Energy Physics tries to answer them all!

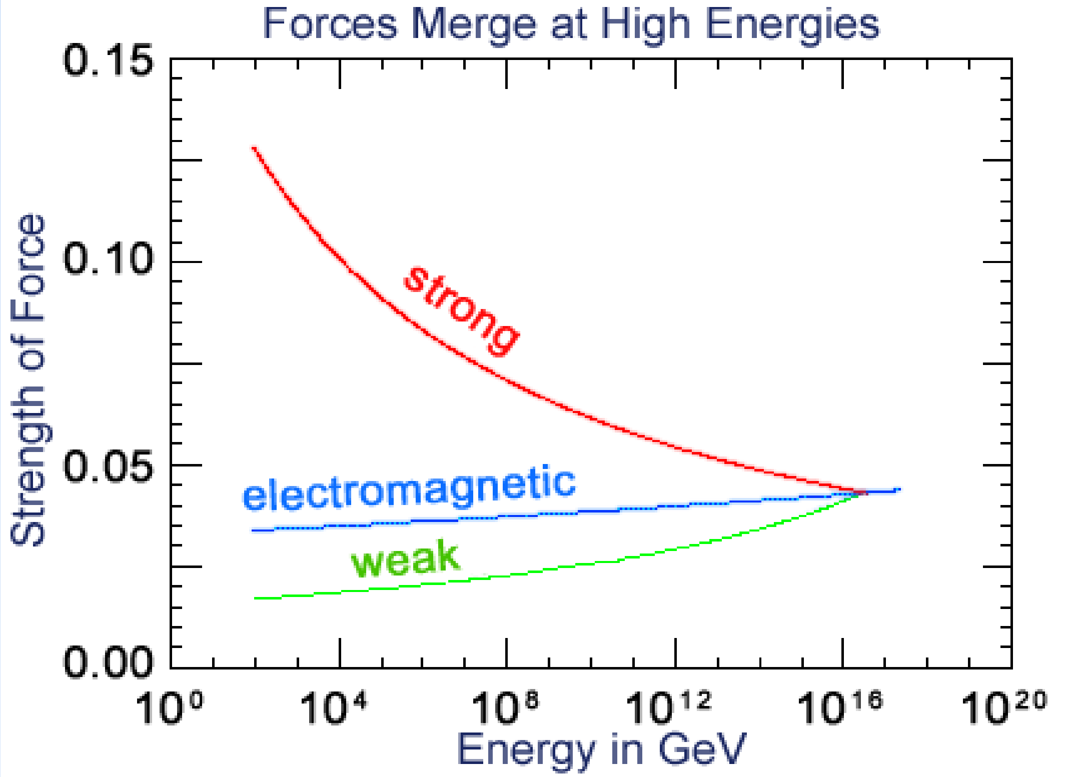


$$\Delta x \approx \frac{\hbar}{E} \longrightarrow 10^{-20}\, m \approx 10^{+13}\ \mathrm{eV} = 10\ \mathrm{TeV}$$

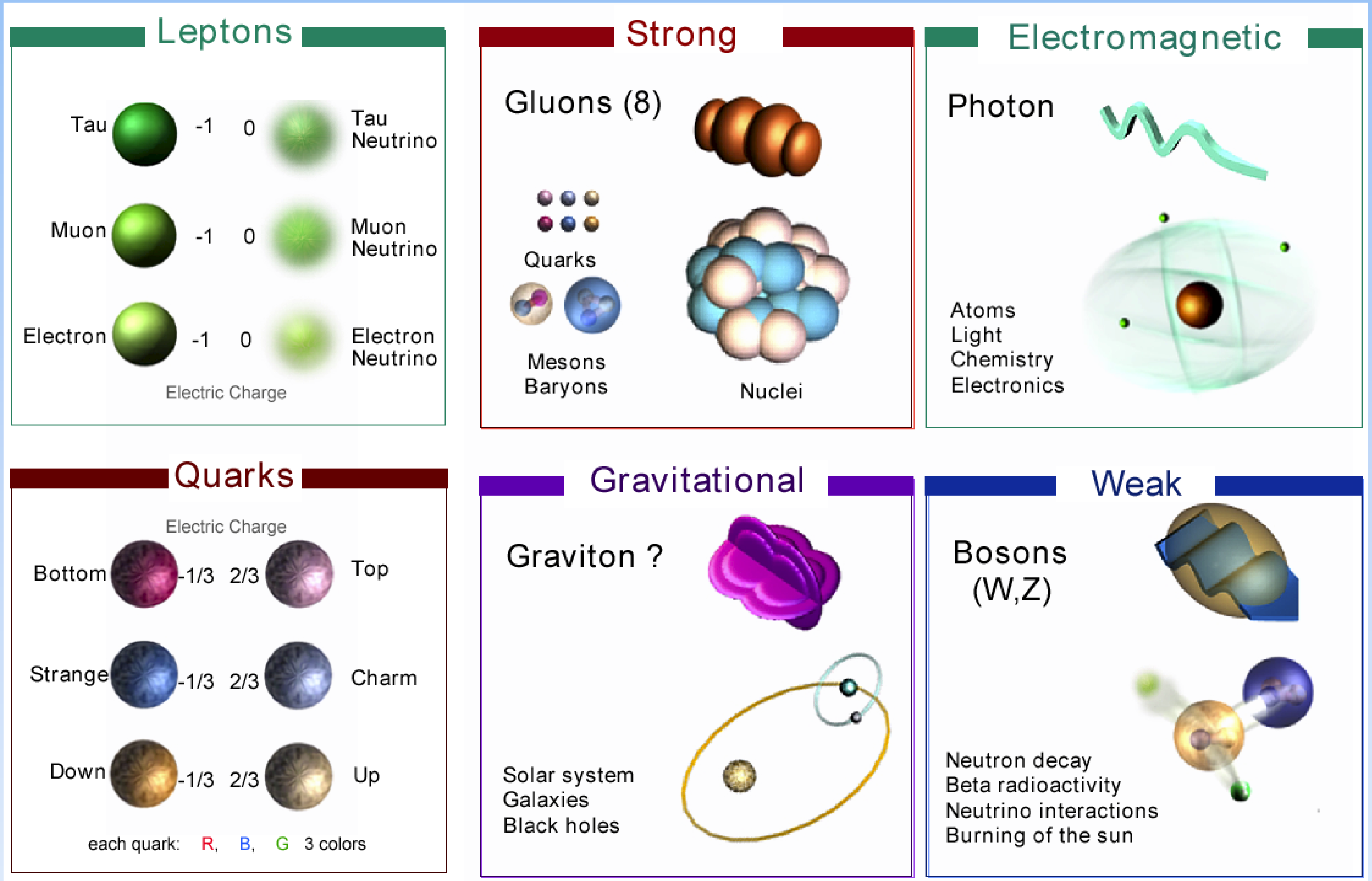
What lies within…?

$$\lambda = \frac{h}{P}$$

The probe wavelength should be smaller than the distance scale to be probed.



Accelerators can answer


Leptons
Tau
-1
0
Tau Neutrino
Muon
-1
0
Muon Neutrino
Electron
-1
0
Electron Neutrino
Electric Charge
Strong
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
Electromagnetic
Photon
Atoms
Light
Chemistry
Electronics
Quarks
Electric Charge
Bottom
-1/3
2/3
Top
Strange
-1/3
2/3
Charm
Down
-1/3
2/3
Up
each quark: R, B, G 3 colors
Gravitational
Graviton ?
Solar system
Galaxies
Black holes
Weak
Bosons (W,Z)
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

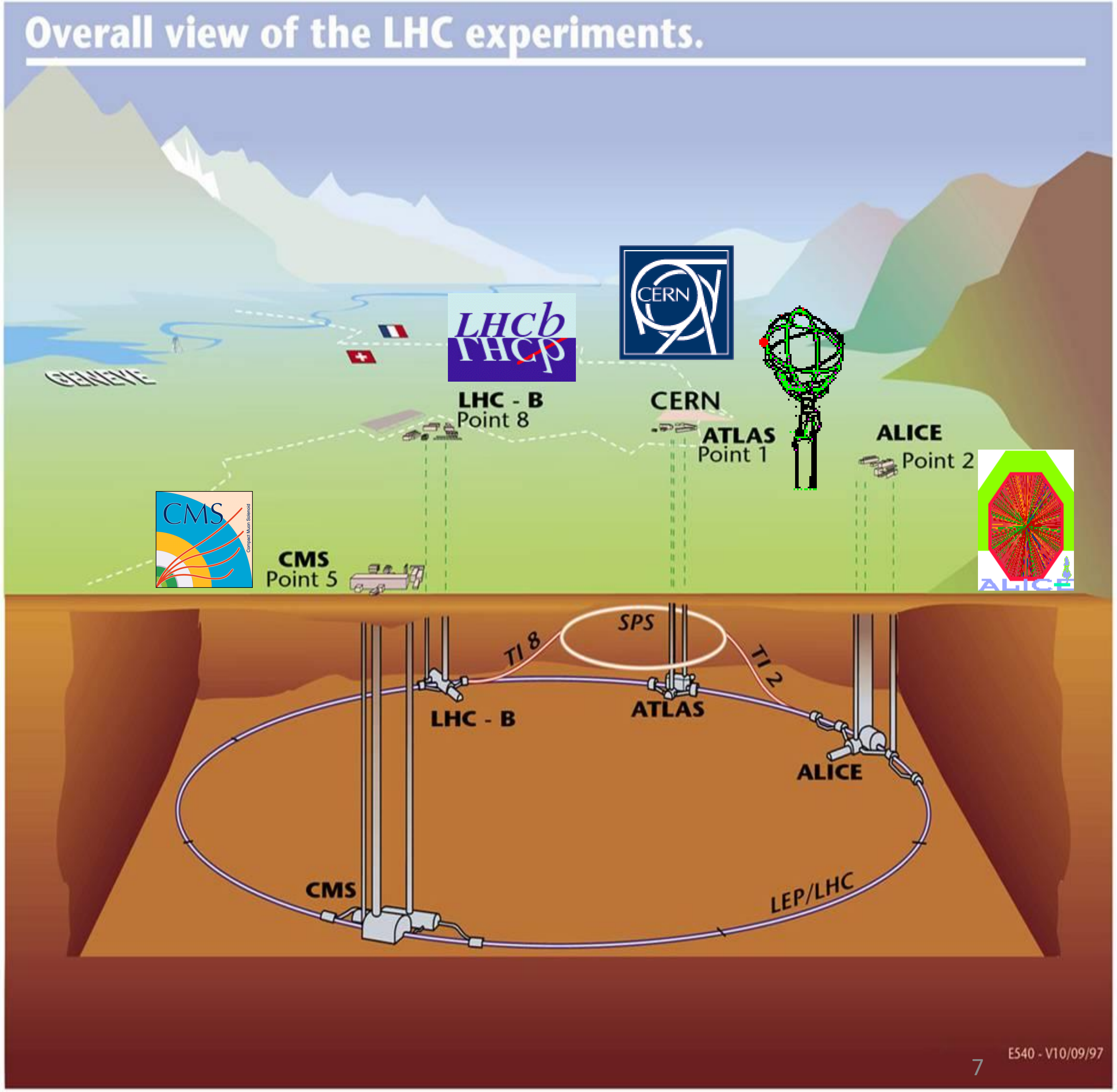
Will address some of the most fundamental questions in modern physics

The Large Hadron Collider (LHC) is located in a circular tunnel 27 km in circumference. The tunnel is buried around 100 m underground.

It straddles the Swiss and French borders on the outskirts of Geneva.

Four main experiments (detectors) around circumference that collect and analyze data:

- CMS
- ATLAS
- ALICE
- LHCb



How Do We Get 13 TeV for Protons?

Charged particles are accelerated, guided and confined by **electromagnetic fields**.

- Bending: Dipole magnets
- Focusing: Quadrupole magnets
- Acceleration: RF cavities

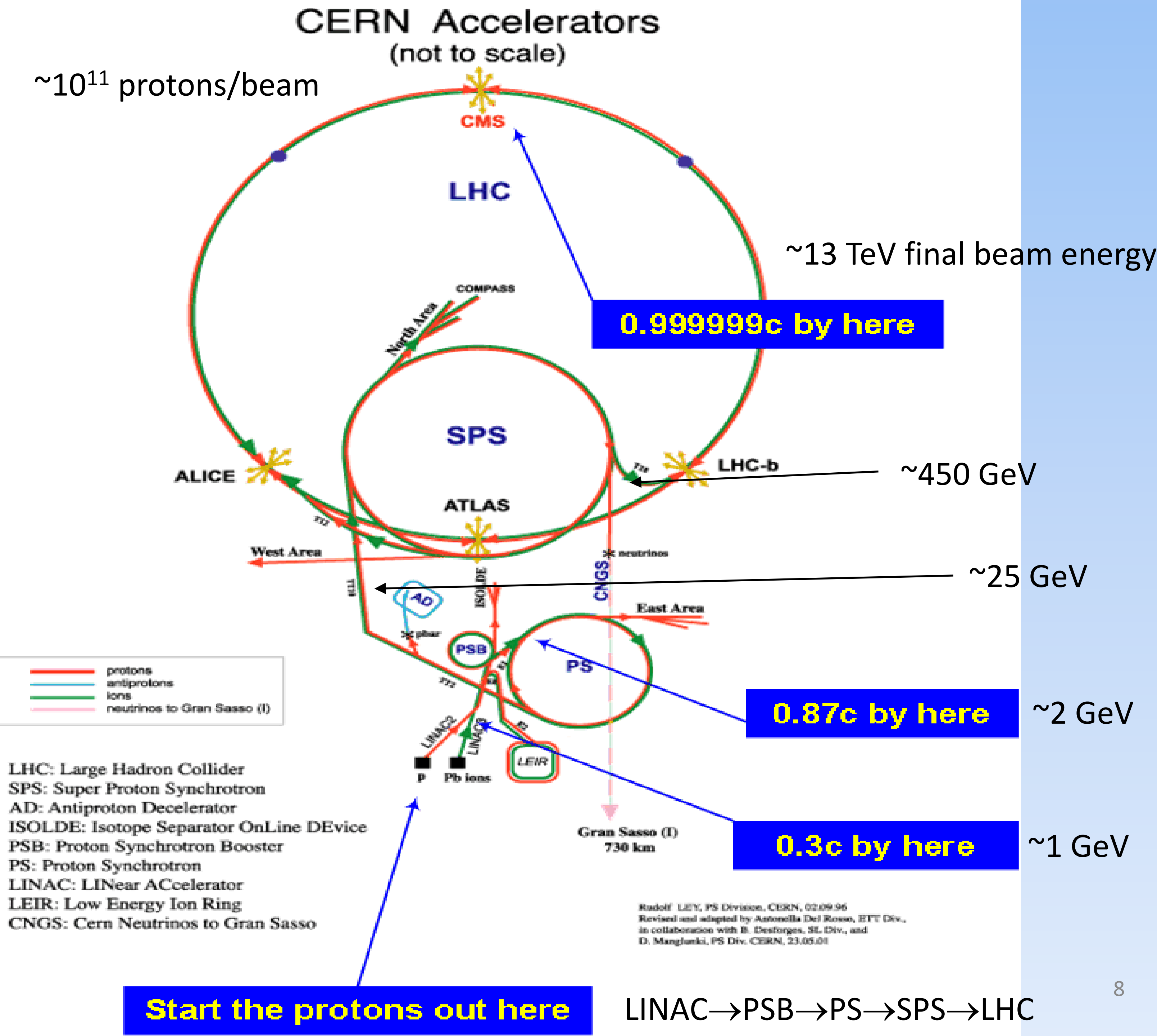
Vacuum: 10^{-10} Torr or 3 million molecules/cm^3 (sea level-760 Torr).

Protons must avoid collisions with other gas molecules.

2808 bunches of protons in routine beam

Stored energy of 350 MJ .

Beams are focused by magnets into a 40-μm -cross-section.



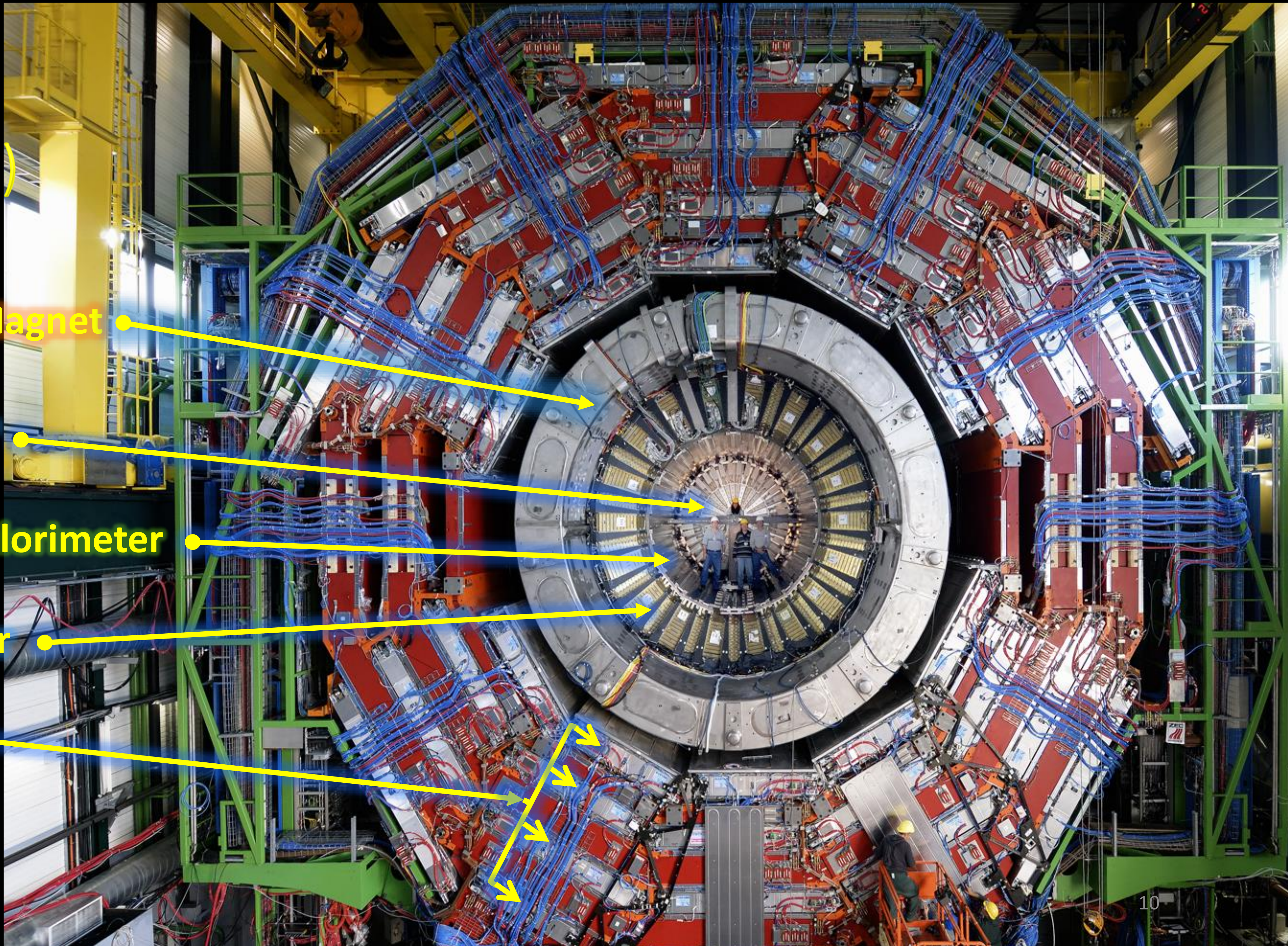
LINAC→PSB→PS→SPS→LHC

The Compact Muon Solenoid (CMS) detector

CMS is a particle detector that is designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC. Like a cylindrical onion, different layers of detectors measure the different particles, and use this key data to build up a picture of events at the heart of the collision.

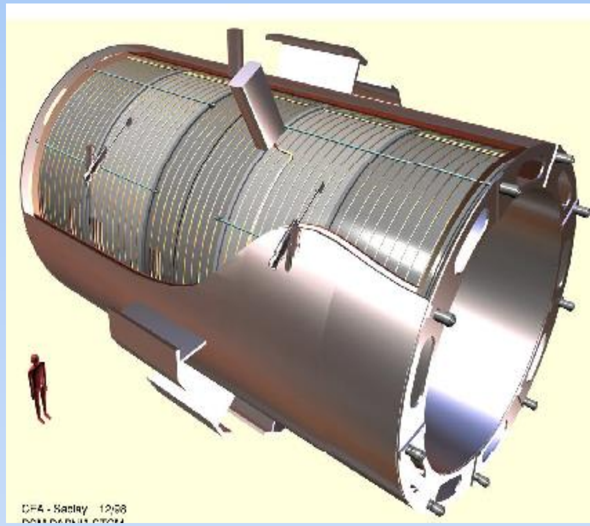
The first essential feature of the CMS is the very strong magnet. The higher a charged particle's momentum, the less its path is curved in the magnetic field, so when we know its path we can measure its momentum. A strong superconducting solenoid magnet was therefore needed to allow us to accurately measure even the very high momentum particles, such as muons. This large magnet also allowed for a number of layers of muon detectors within the magnetic field, so momentum could be measured both inside the coil (by the tracking devices) and outside of the coil (by the muon chambers). (compact)

CMS Layers: (Subdetectors)



- Superconducting Magnet
- Tracker detector
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Muon Detectors

Superconducting Magnet

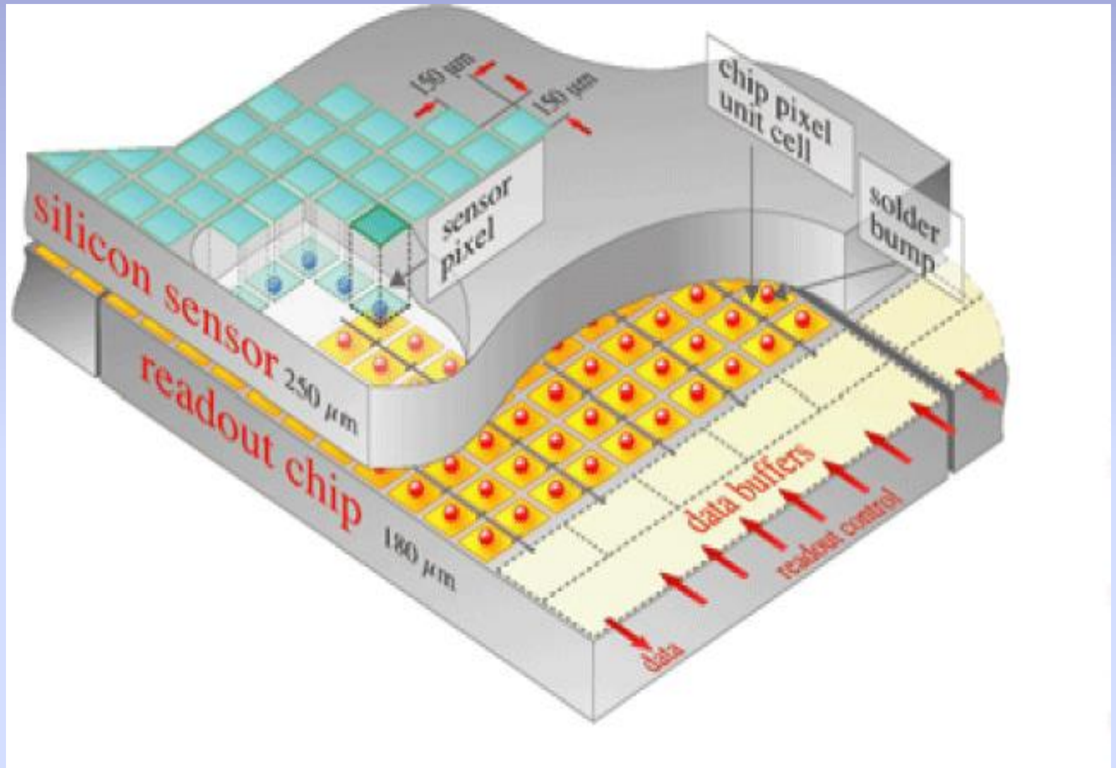


- The CMS magnet is the central device around which the experiment is built, with a 4 Tesla magnetic field that is 100,000 times stronger than the Earth's.
- The Tracker and calorimeter detectors (ECAL *and* HCAL) fit snugly inside the magnet coil whilst the muon detectors are interleaved with a 12-sided iron structure (return yoke) that surrounds the magnet coils and contains and guides the field.
- Made up of three layers, this "return yoke" reaches out 14 meters in diameter and also acts as a filter, allowing through only muons and weakly interacting particles such as neutrinos.
- Is the largest superconducting magnet ever built.
- Weighs 12,000 tonnes.
- Carries bout 20,000 A of current . Has enough energy to melt 18 tonnes of gold.
- Is cooled down with Liquid He to -268.5 C˚, a degree warmer than outer space.
- Uses almost twice much iron as the Eiffel Tower.

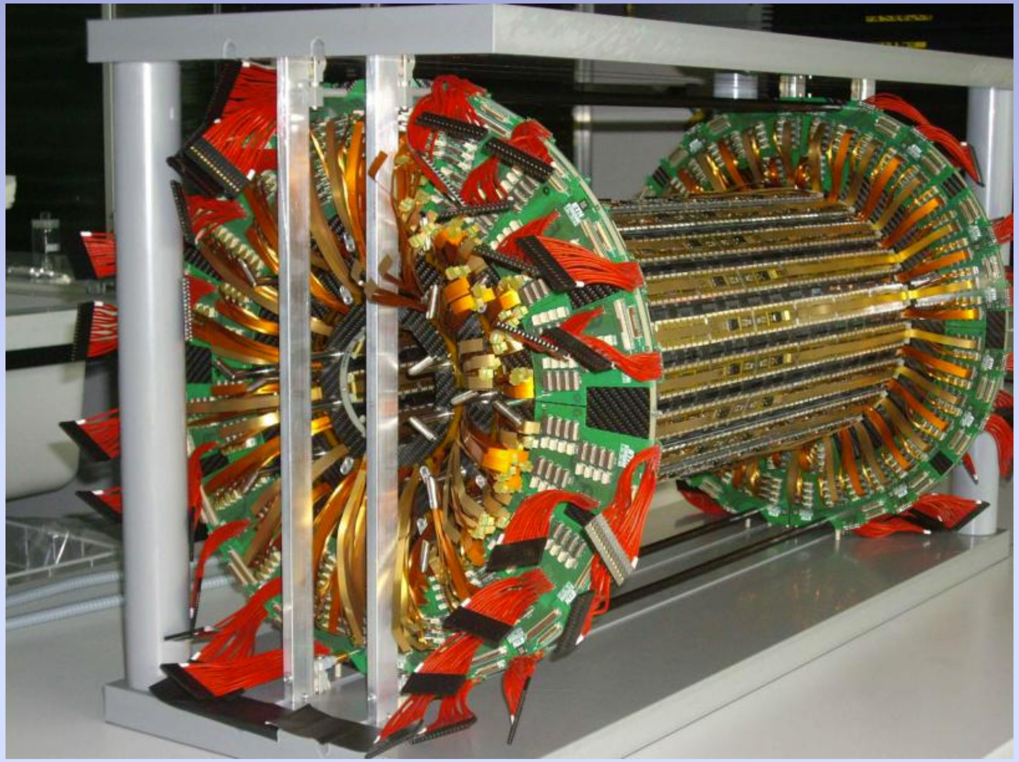
Tracker Detector

- Momentum / charge of tracks and secondary vertices are measured in the central tracker (Silicon layers).
- Tracker records the paths taken by charged particles by finding their positions at a number of key points with accurate such that tracks can be reliably reconstructed using just a few measurement points.
- Each position measurement is accurate to 10 µm, a fraction of the width of a human hair.
- Tracker is the inner most layer of the CMS detector and so receives the highest volume of particles: the construction materials were therefore carefully chosen to resist radiation.
- The final design consists of a tracker made entirely of silicon: the silicon pixels, at the very core of the detector, and the silicon microstrip detectors that surround pixels.
- When a charged particles travels through the pixels and microstrips it gives enough energy for electrons to be ejected from the silicon atoms, creating electron-hole pairs which produce tiny electric signals that are amplified and detected.

Silicon Pixels



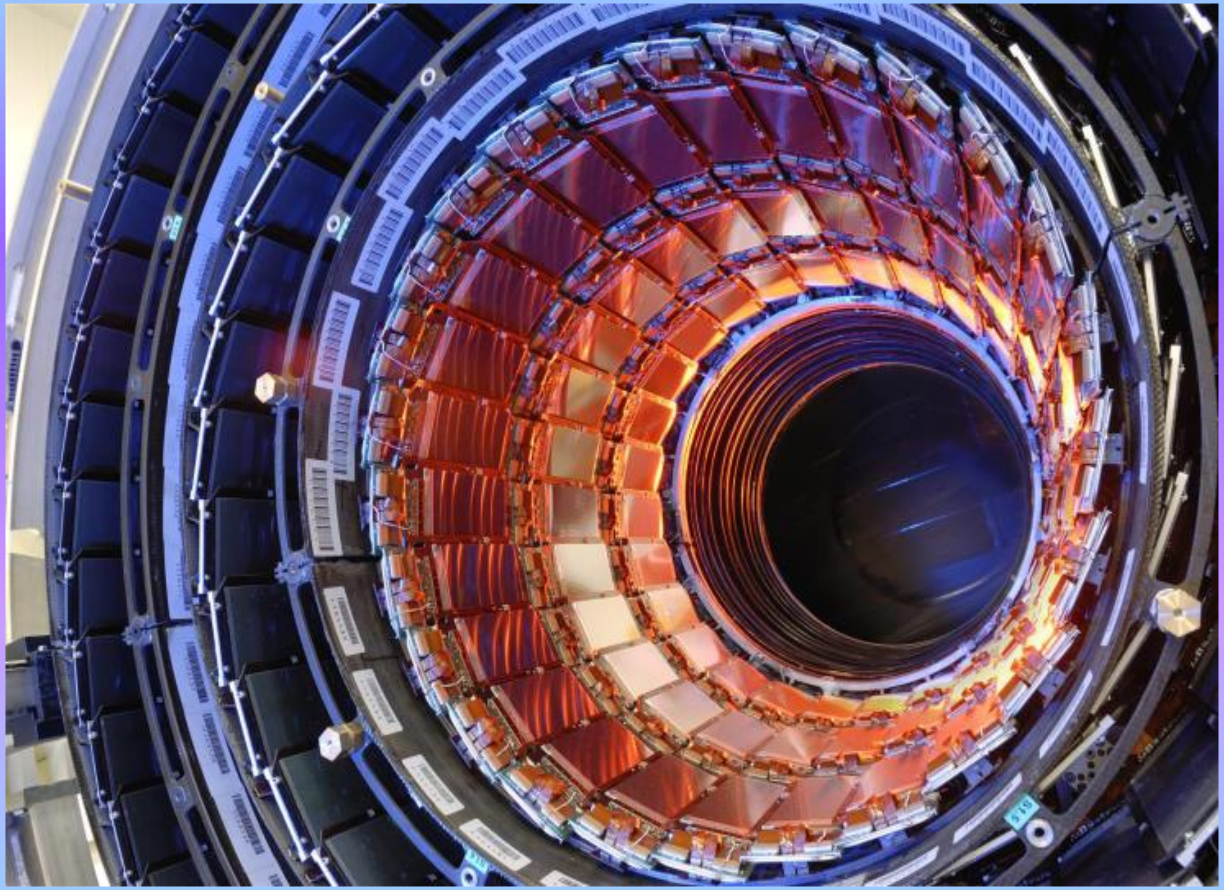
The silicon pixel detector contains 65 million pixels.



Three layers of silicon pixels.

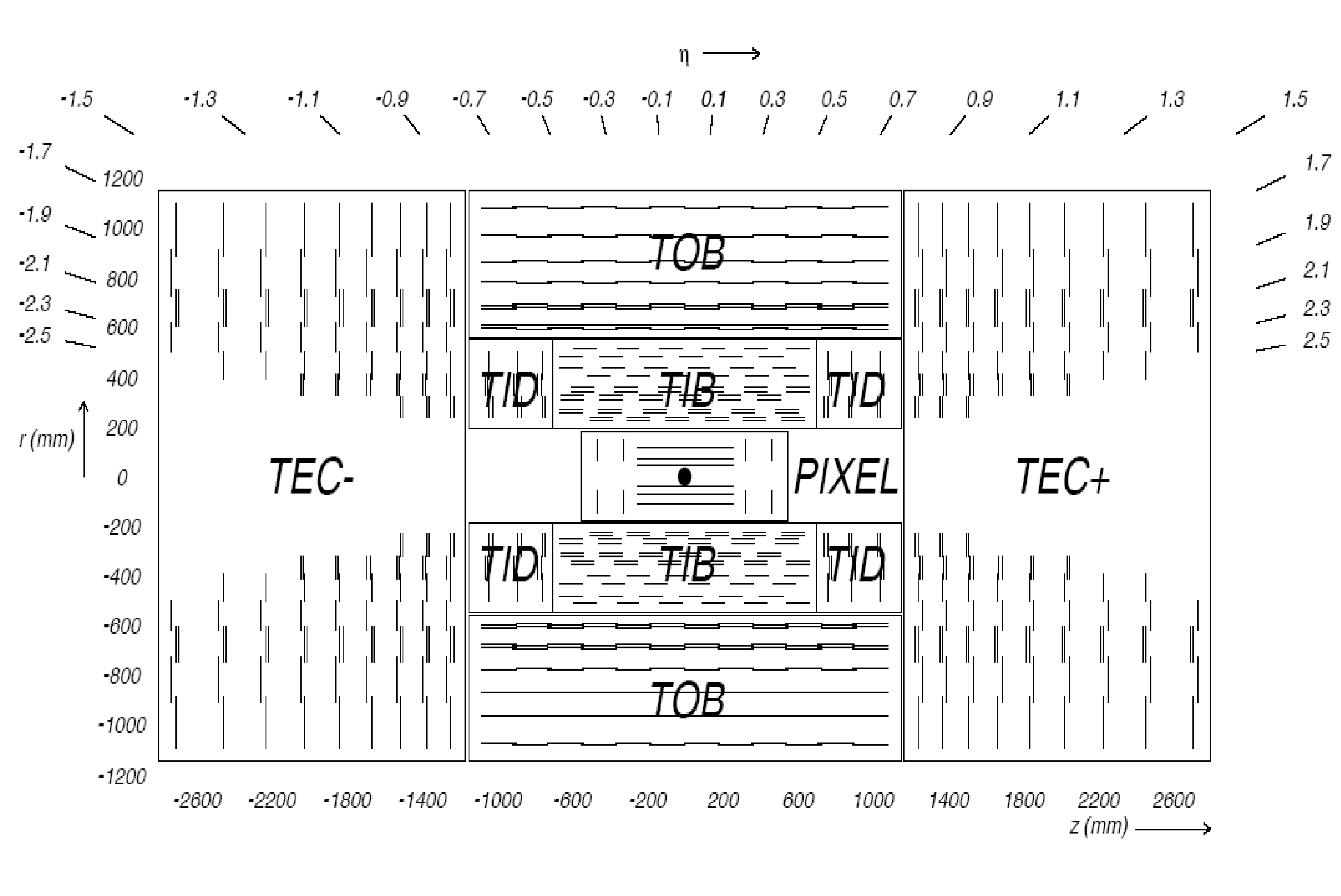
Silicon Microstrips

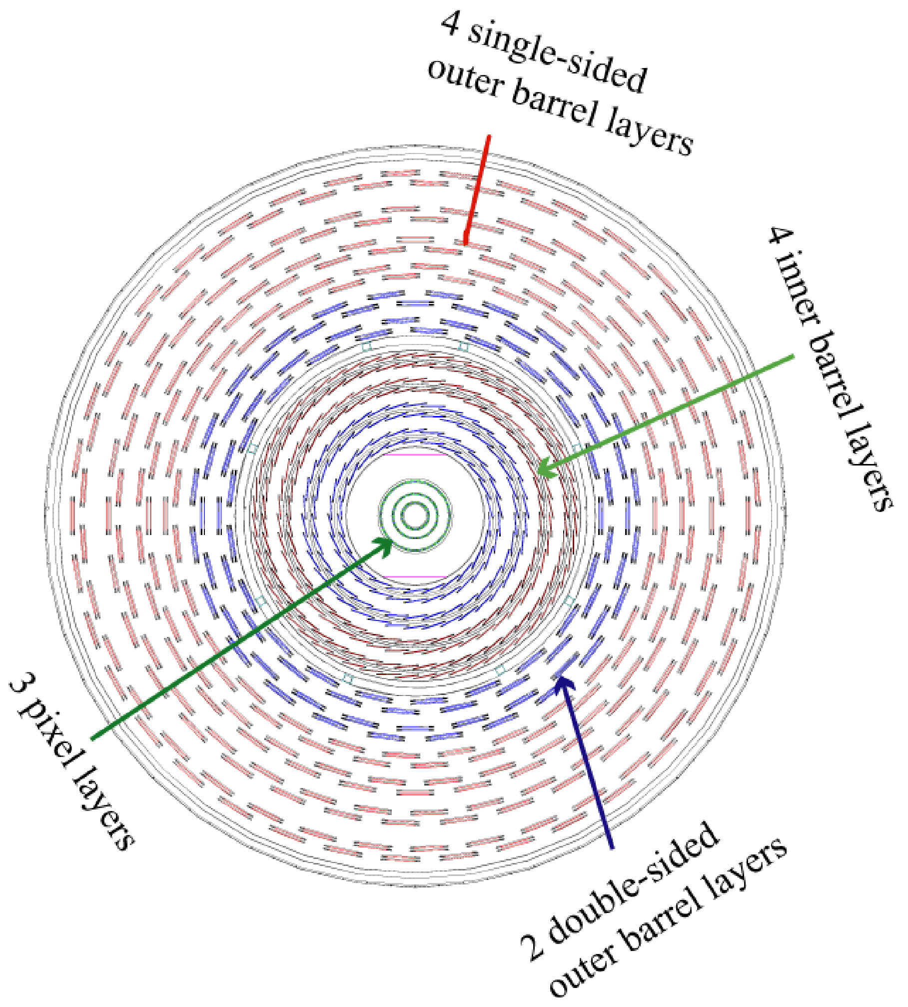
Silicon Microstrip Detector



Silicon Microstrips Barrel

Tracker Overview





All the 13 layers of Tracker plus 9 layers of end caps, 207 m^2, 10.6 milion microstrips and 65.9 milion pixels

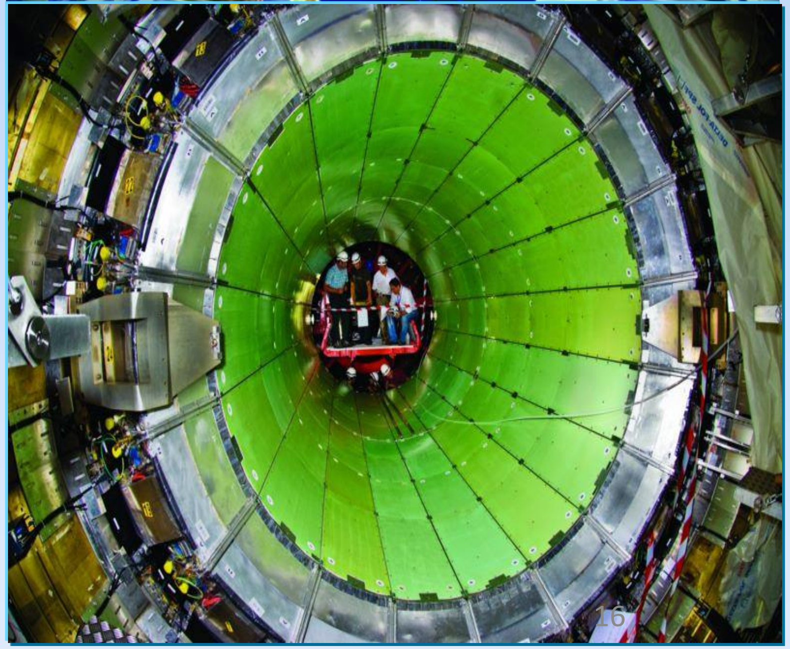
Electromagnetic Calorimeter (ECAL)

Particles interacting with matter produce cascades of secondary particles that releasing their energy to special materials (scintillators) release tine light pulse that can be detected/amplified. The light is proportional to the energy released in the detectors (calorimeters).

ECAL consists of Lead-tungstate (PbWO4) scintillating crystals which are highly transparent and " scintillates " when electrons and photons pass through it. This means it produces light in proportion to the particle's energy.

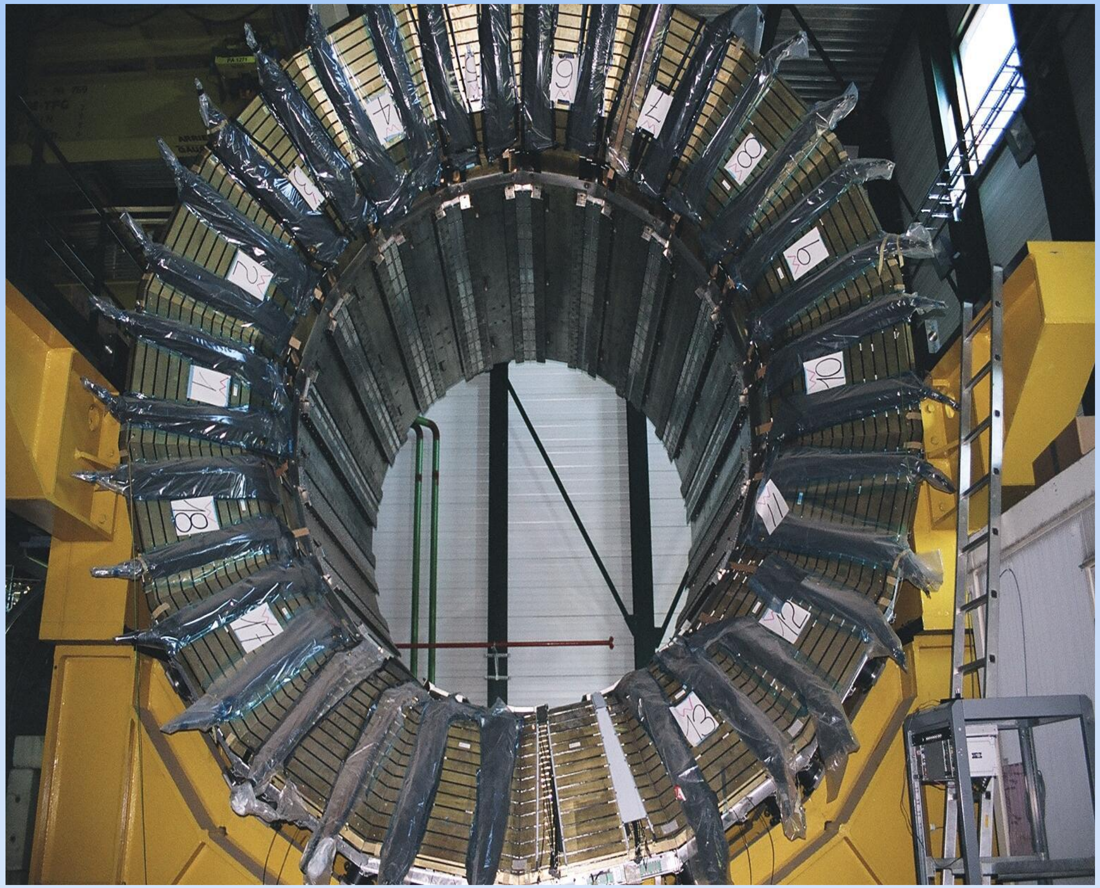
Photodetectors that have been especially designed to work within the high magnetic field, are also glued onto the back of each of the crystals to detect the scintillation light and convert it to an electrical signal that is amplified and sent for analysis.

The cylindrical "barrel" consists of 61,200 crystals. The flat ECAL endcaps seal off the barrel at either end and are made up of almost 15,000 further crystals.



Hadronic Calorimeter (HCAL)

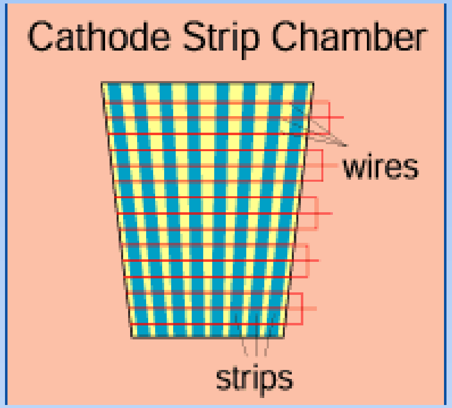
The HCAL is a sampling calorimeter, it finds a particle's **position, energy and arrival time** using alternating layers of "**absorber**" and **fluorescent plastic "scintillator**" materials that produce a rapid light pulse when the hadronic particle passes through and an interaction can occur producing numerous secondary particles. As these secondary particles flow through successive layers of absorber they too can interact and a cascade or "**shower**" of particles results. Special optic fibres collect up this light and feed it into readout boxes where **photodetectors** amplify the signal. When the amount of light in a given region is summed up over many layers of tiles in depth, called a "tower", this total amount of light is a measure of a particle's energy.

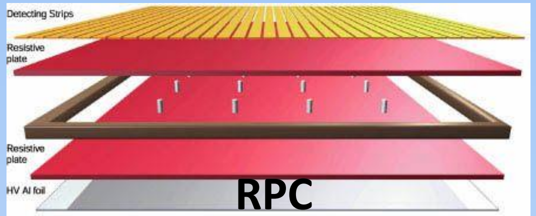


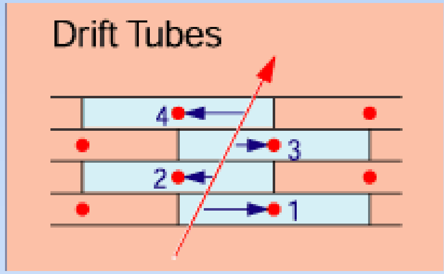
Muon Detectors

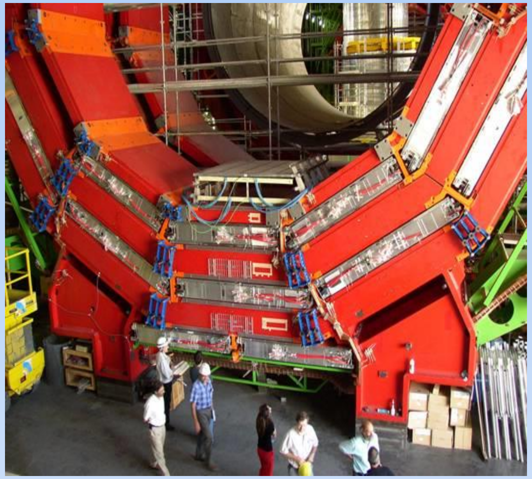
As the name “Compact Muon Solenoid” suggests, detecting muons is one of CMS’s most important tasks. Muons are charged particles that are just like electrons and positrons, but are 200 times heavier. We expect them to be produced in the decay of a number of potential new particles; for instance, one of the clearest "signatures" of the Higgs Boson is its decay into four muons.

Drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC) : gas volumes with wires and/or segmented electrodes kept at very high voltage. Charged particles, interacting with the gas volumes release electrons/ions whose movement under the action of the high electric fields induce signals that can be detected and amplified. RPCs form a redundant trigger system, which quickly decides to keep the acquired muon data or not.

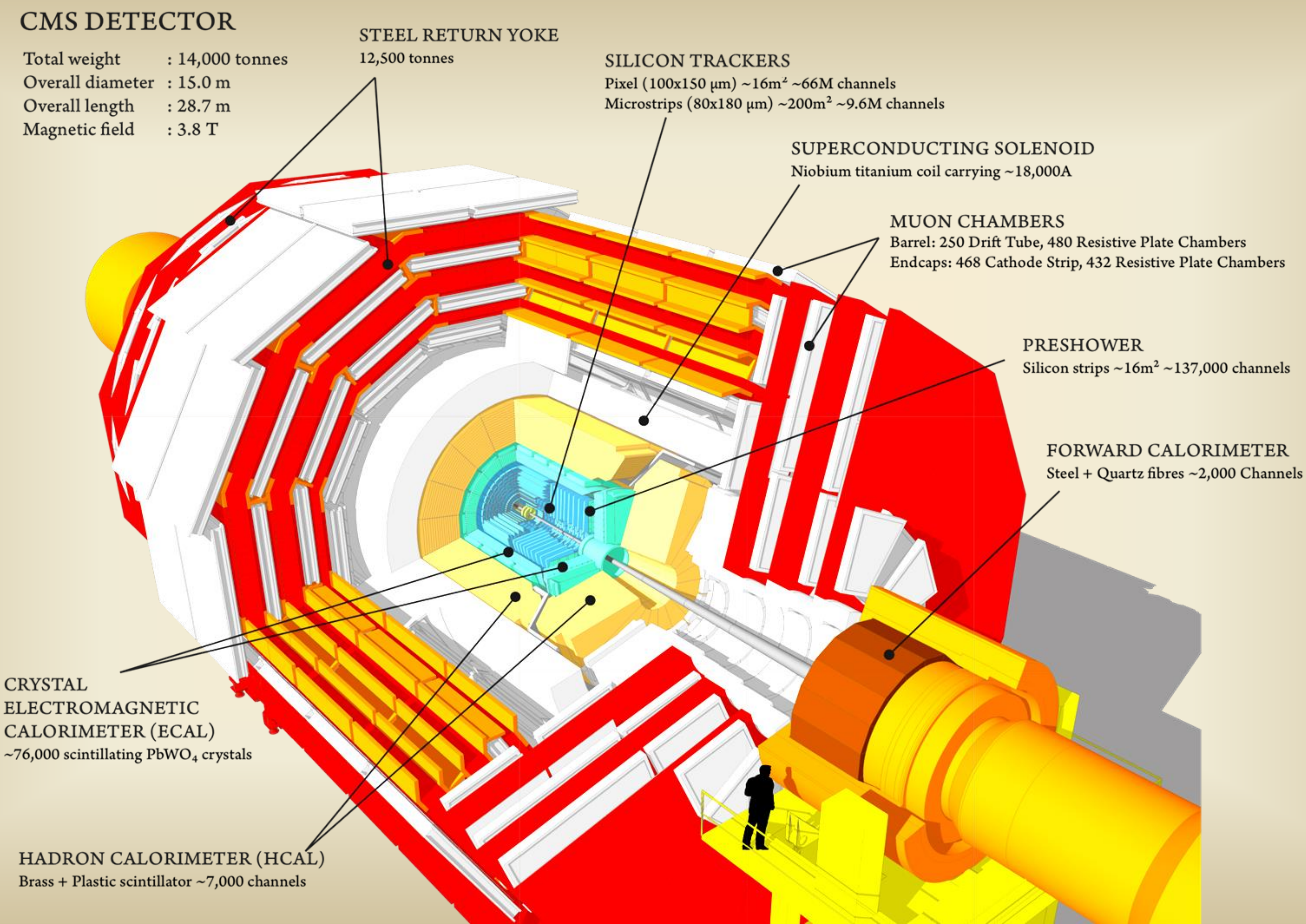


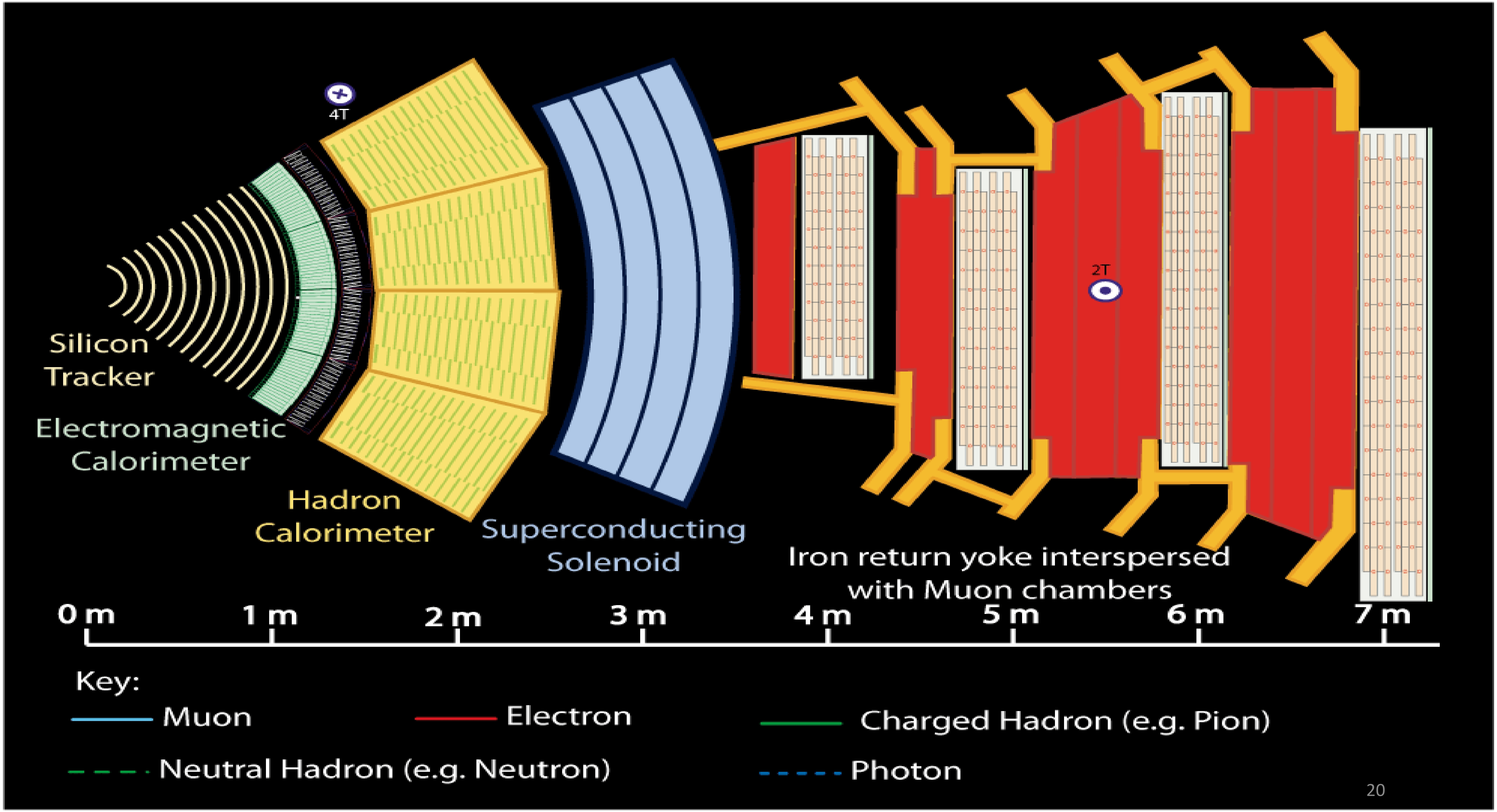


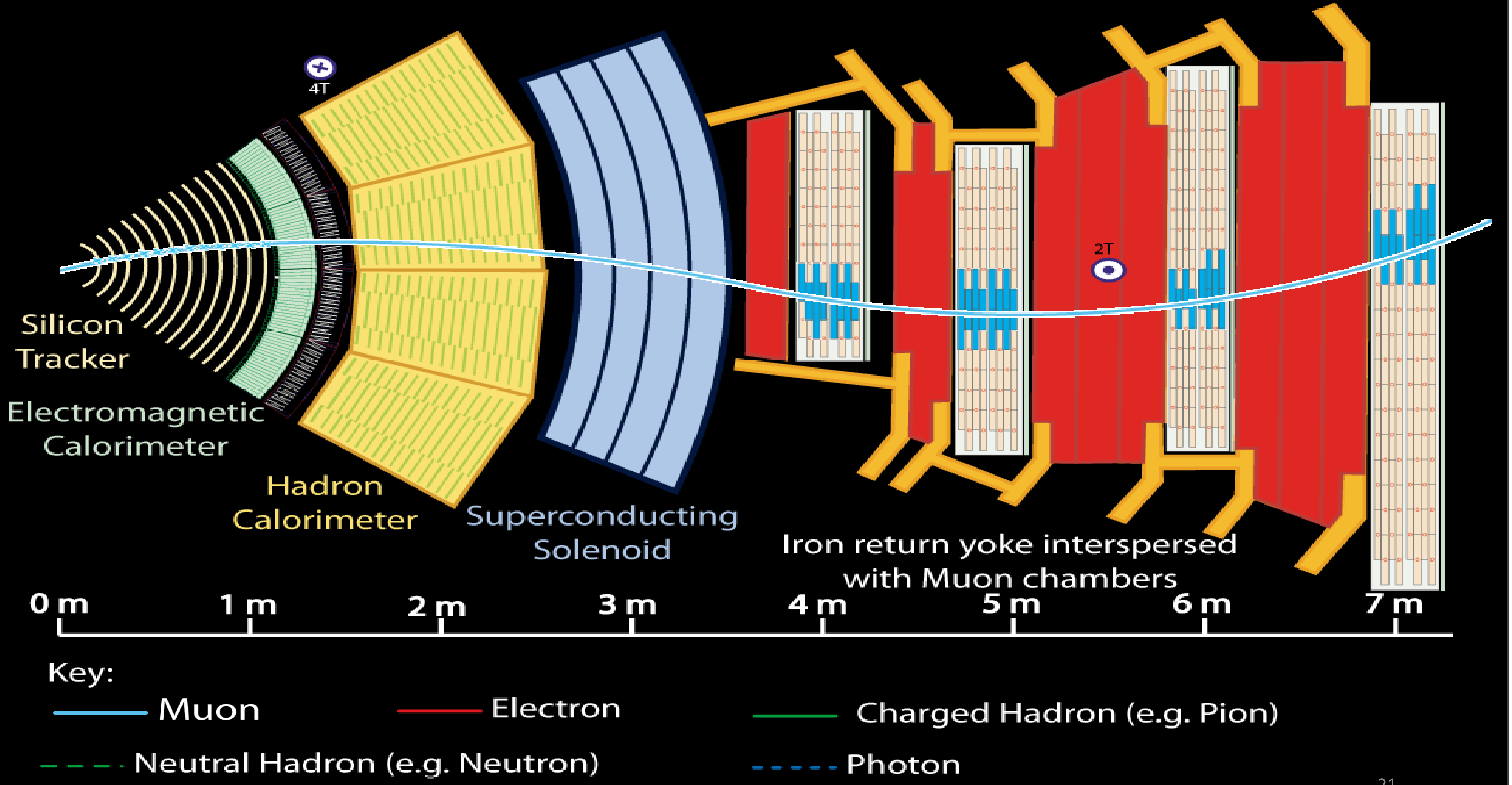




Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by any of CMS's calorimeters. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal.


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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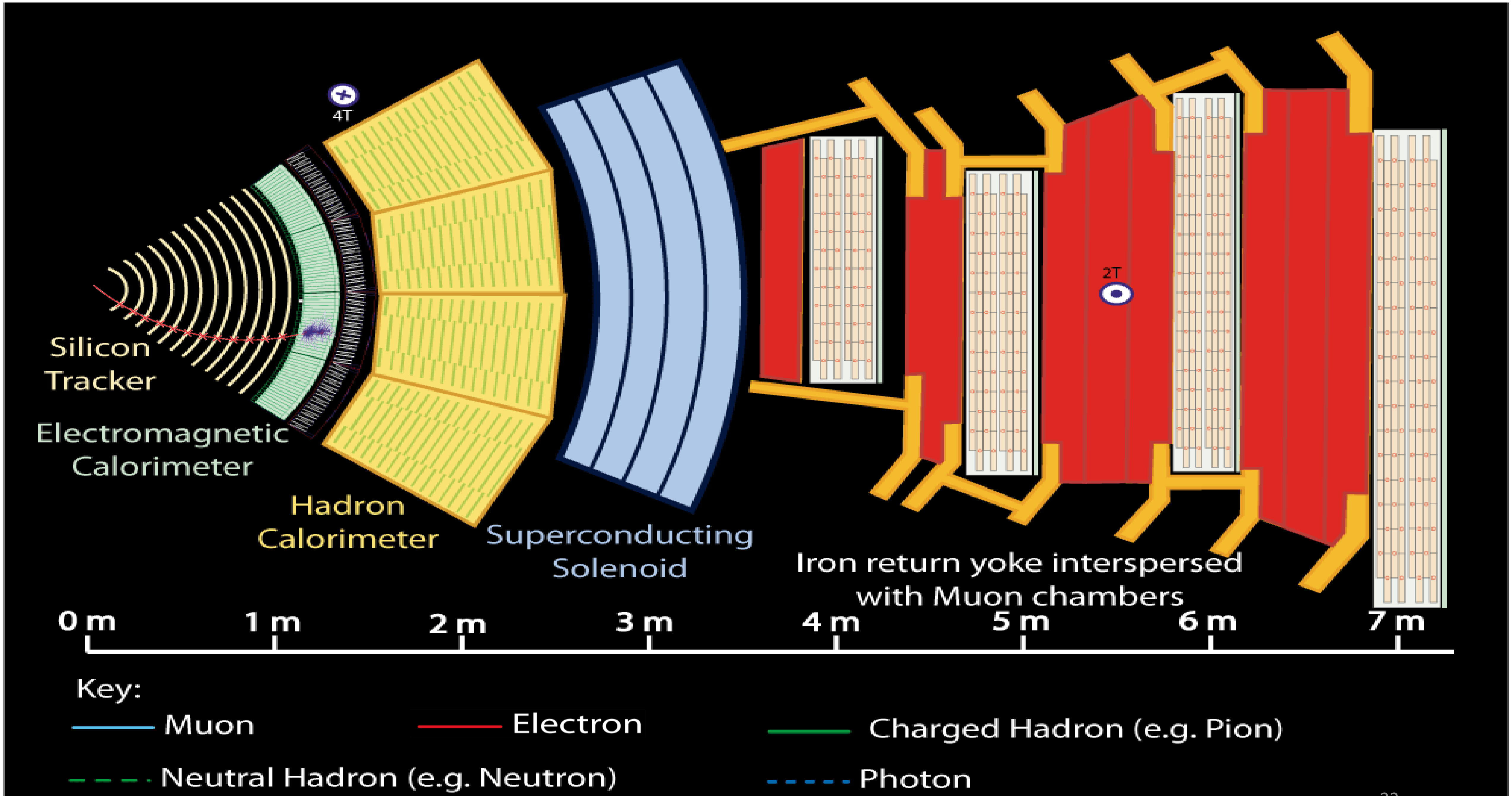
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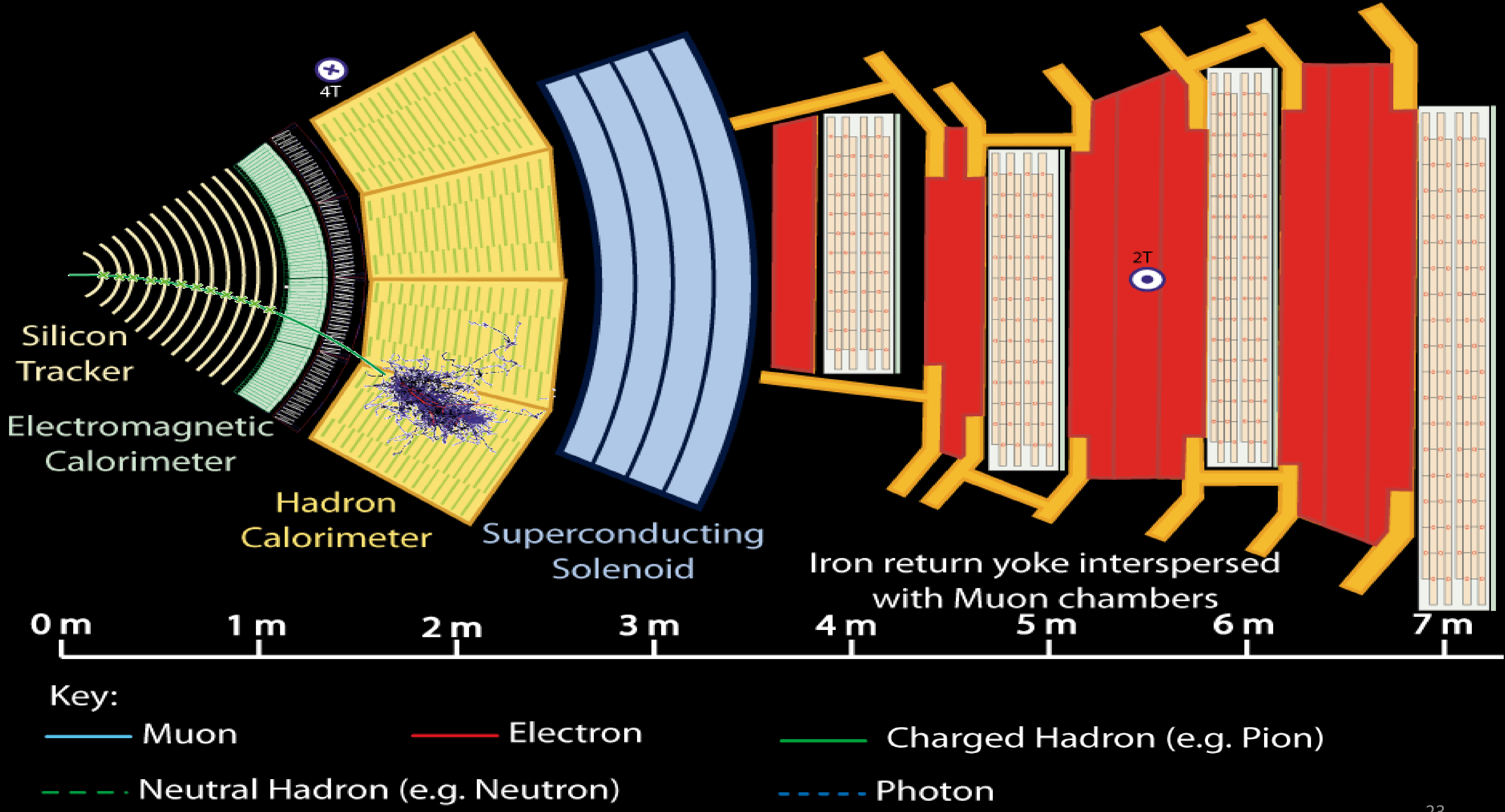
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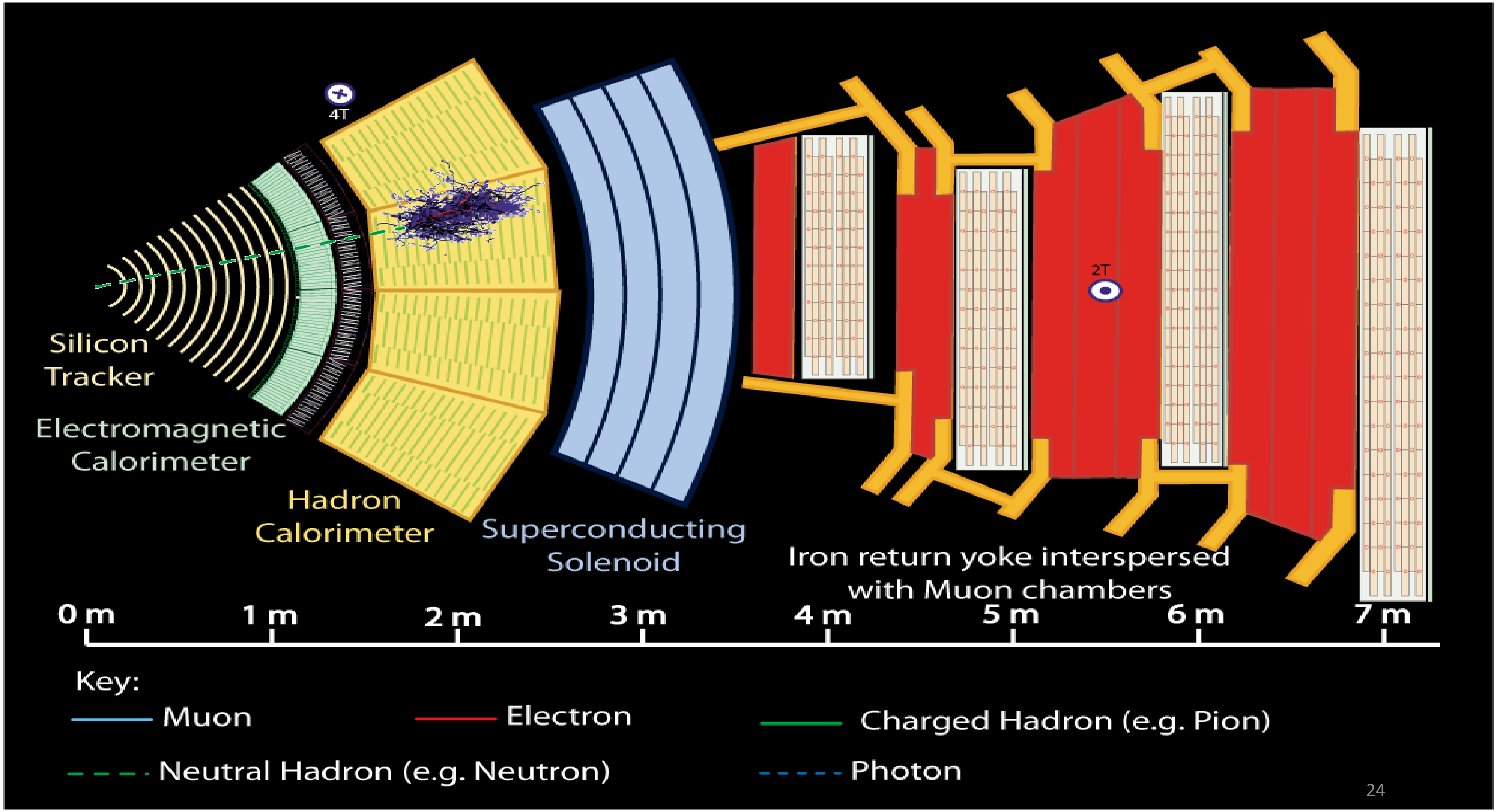
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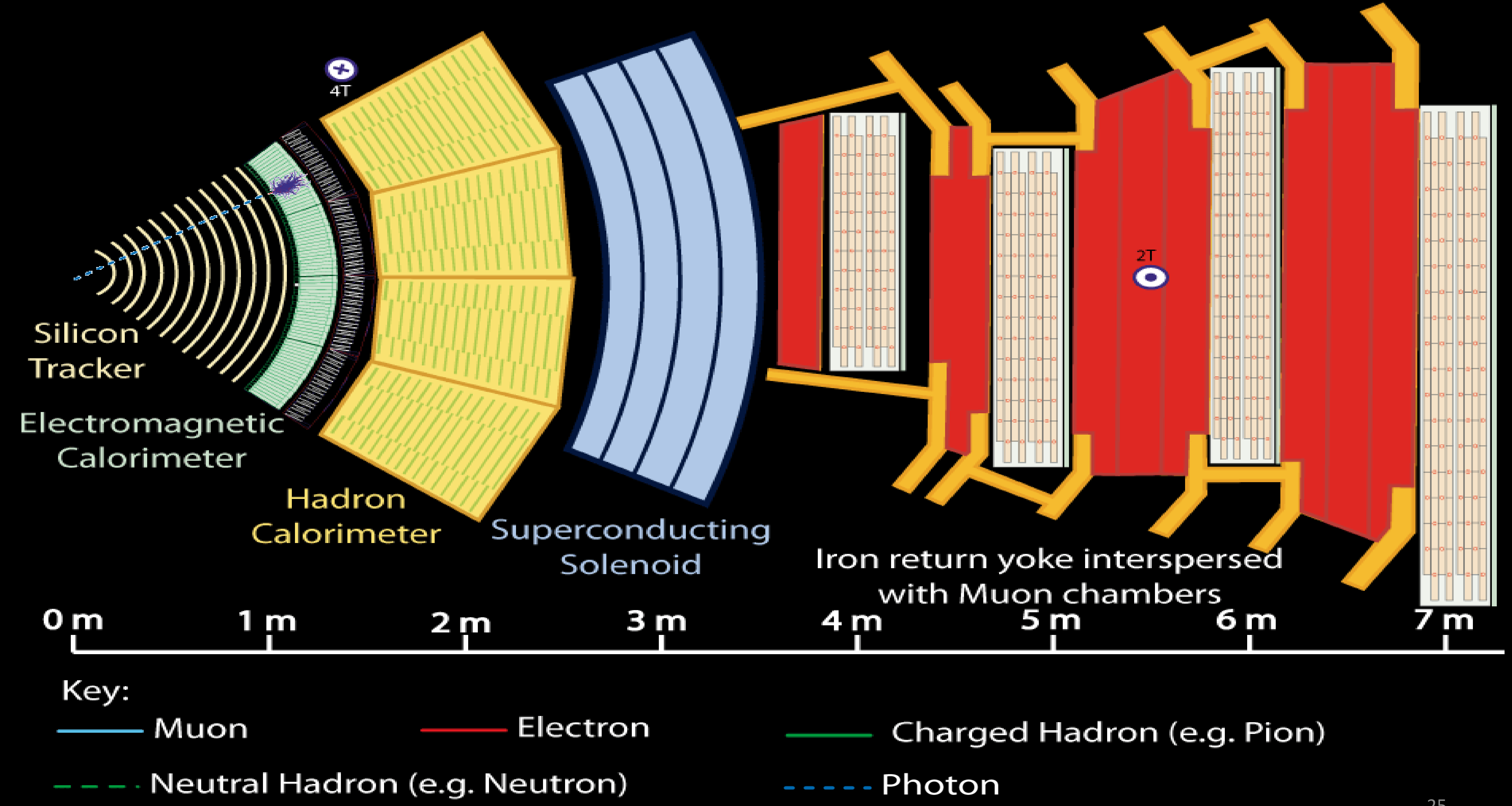
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Bose Einstein Correlations (BEC)

What is BEC ?

It is an effect connected with the wave functions of bosons which interfere with each other and produce an enhancement, or a suppression, of their individual amplitudes or probabilities.

This means that wave-functions of bosons interfere constructively: if you place a boson in a certain point of space, with certain characteristics, then the chance that additional identical bosons will be found in the same location, with the same characteristics of the first one is enhanced.

The opposite happens to fermions: the probability to find two fermions have identical properties is zero, this is the famous Pauli exclusion principle.

Why do we study BEC ?

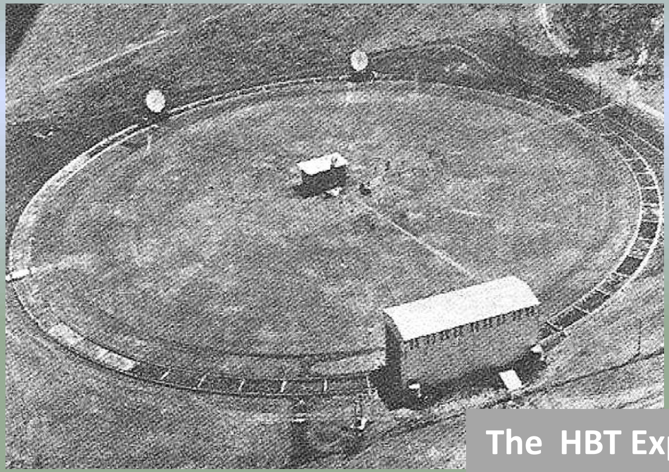
BECs give access to quantitative information about space-time characteristics of the particle emission region :

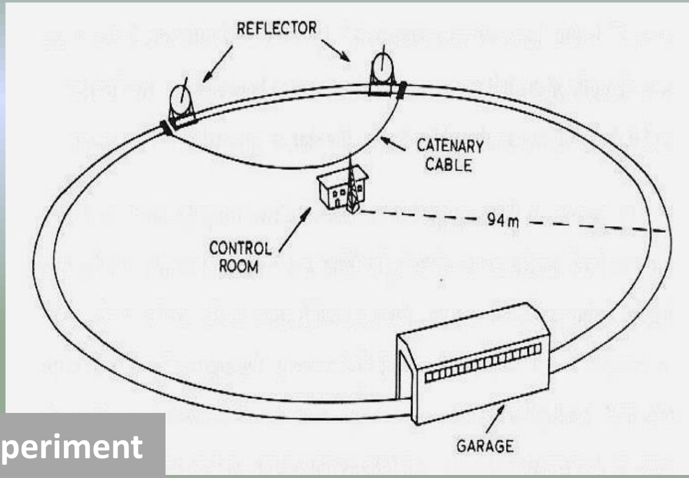
- The structure of the source of hadrons, such as the geometrical size of the source and its shape.

- The life time of the source, the fraction of this lifetime, when the hadrons are actually being produced.

History

The **two-particle intensity interferometry was discovered** in the early **1950's** by **Hanbury Brown and Twiss (HBT)**, who applied this method to measure the **stellar radii** through the **angle subtended by nearby stars**, as seen from the Earth's surface. **They observed that photons tend to arrive at the two detectors in pairs as a consequence of Bose-Einstein statistics** (**HBT Effect**).

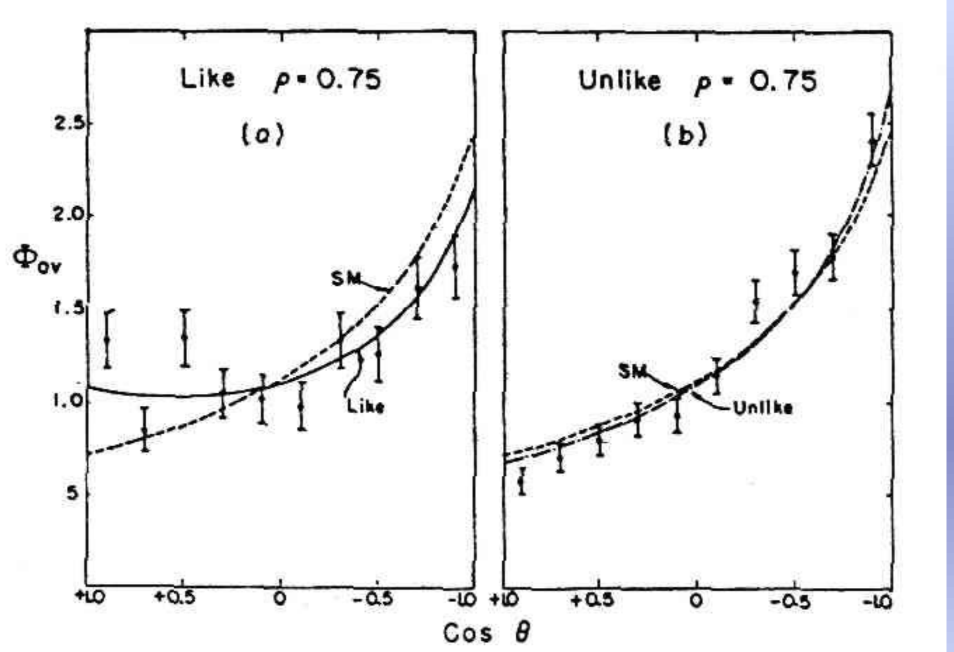




The HBT Experiment

In multiple particle production BECs were discovered accidentally by **G.Goldhaber**, **S.Goldhaber**, **W.Lee** and **A.Pais** (**GGLP**) in **1960**, as a byproduct of an unsuccessfull (because of not enough statistics) attempt to find the $\rho^0 \rightarrow \pi^+\pi^-$.

- The graph shows the opening angle distribution of pions from proton-antiproton annihilation at 1.05 GeV/c in a bubble chamber.
- **Unexpected difference between like-sign pions and unlike-sign pions was observed.**
- GGLP **interpreted** this as being due to **BECs** between **identical bosons**.
- In the **1970's** HBT/GGLP effect was **proposed** to be a **technique** to determine **source sizes** in **nuclear collisions**.

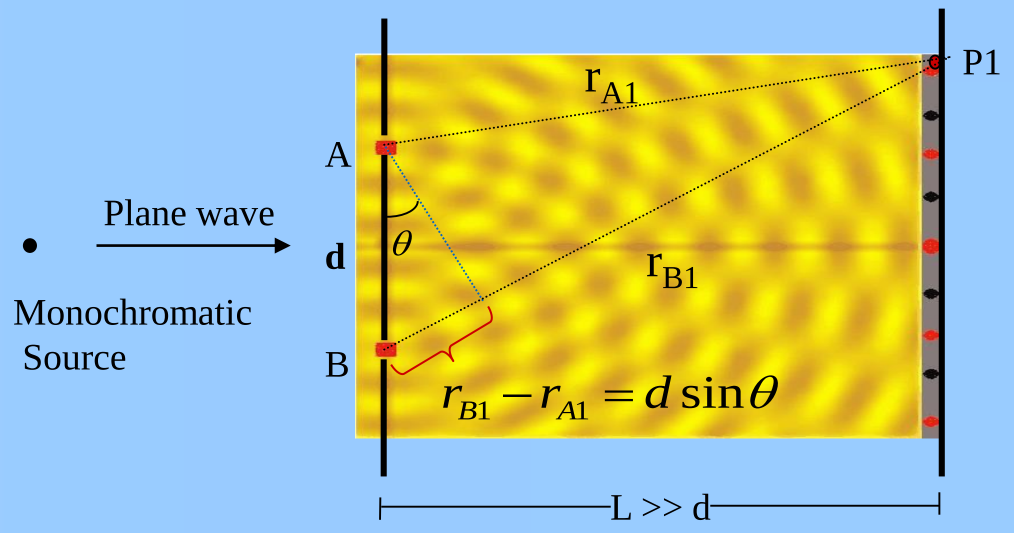


G.Goldhaber, S.Goldhaber, W.Lee, A.Pais, *Physical Review* **120** 300 (1960).

Introduction

Examples in Optics

1- Young's double slit.



$$I_{P1} = |e^{i\vec{k}\cdot\vec{r}_{A1}} + e^{i\vec{k}\cdot\vec{r}_{B1}}|^2$$
$$= 2(1 + \cos[k\,\underbrace{(r_{B1} - r_{A1})}_{\mathbf{d}}])$$

The interference pattern is related
to the "source geometry" (d)

Other Examples
2- Fraunhofer diffraction.
3- Michelson's interferometer.
4- Michelson's stellar interferometer.

In all, the interference pattern is related to the "source size".

Two Particle Correlation Function

The two-particle correlation function is defined as

$$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{\text{two particle coincidence probability density}}{\text{product of the two single particle probabilities}} \quad (1)$$

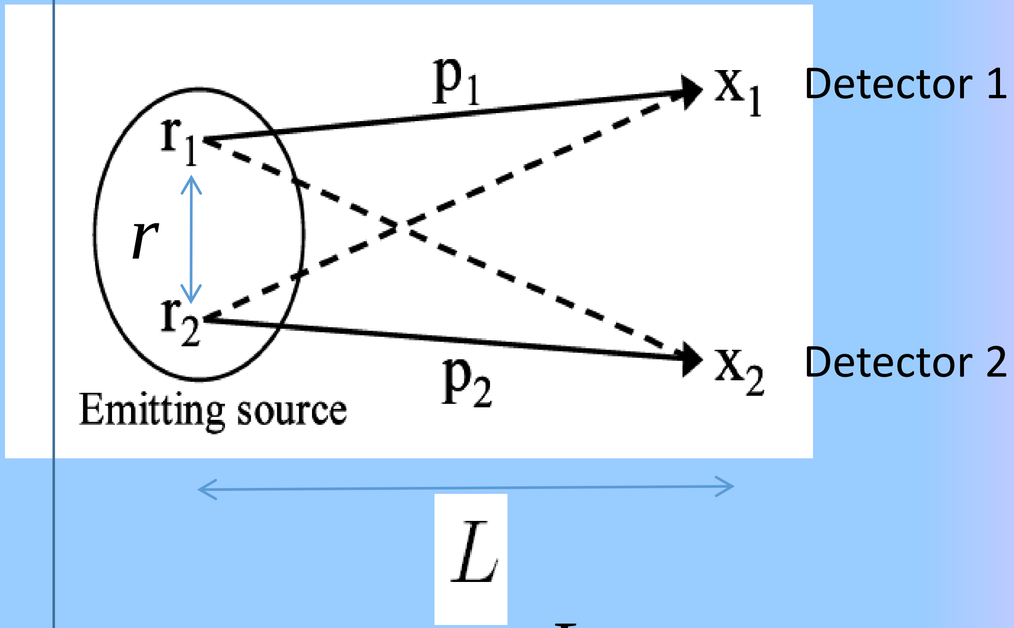
where p_1 and p_2 denote 4-vector momenta of observed identical particles.

To explain how BEC term works in Eq (1), we consider a simple model which can be described in plane wave.

If we assume the particles are emitted independently ("chaotic source"), the probability amplitude of detecting two identical particle is given as

$$\psi_{12} = \frac{1}{\sqrt{2}}\{A(p_1, x_1)A(p_2, x_2)e^{-ip_1(x_1-r_1)}e^{-ip_2(x_2-r_2)} \pm A(p_1, x_2)A(p_2, x_1)e^{-ip_1(x_2-r_1)}e^{-ip_2(x_1-r_2)}\}$$

Where +/- signs stands for bosons/fermoins.



$$r << L$$

The corresponding probability density of two-particle momentum;

$$
\begin{aligned}
P(p_1, p_2) &= \int d^4r_1 d^4r_2 \rho(r_1)\rho(r_2)|\psi_{12}|^2. \\
&= \frac{1}{2}\int d^4r_1 d^4r_2 \rho(r_1)\rho(r_2)\Big\{A^2(p_1,x_1)A^2(p_2,x_2) + A^2(p_1,x_2)A^2(p_2,x_1) \\
&+ A(p_1,x_1)A(p_2,x_2)A(p_1,x_2)A(p_2,x_1)e^{ir_1(p_1-p_2)}e^{-ir_2(p_1-p_2)} \\
&+ A(p_1,x_1)A(p_2,x_2)A(p_1,x_2)A(p_2,x_1)e^{-ir_1(p_1-p_2)}e^{ir_2(p_1-p_2)}\Big\}
\end{aligned}
$$

$$
\begin{aligned}
P(p_1, p_2) &= \int d^4r_1 d^4r_2 \rho(r_1)\rho(r_2)A^2(p_1,x_1)A^2(p_2,x_2) \\
&+ \left|\int d^4r \rho(r)A(p_1,r)A(p_2,r)e^{-ir(p_1-p_2)}\right|^2.
\end{aligned}
$$

In case of the detection single particle, the probability amplitude and the probability density are

$$
\psi_1 = A(p,x)e^{-ip(x-r)},
$$

$$
P(p) = \int d^4r \rho(r)|\psi_1|^2 = \int d^4r \rho(r)A^2(p,x).
$$

The two-particle correlation function can be described as

$$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = 1 + \frac{\left|\int d^4 r\, \rho(r) A(p_1, r) A(p_2, r) \exp(-irQ)\right|^2}{\int d^4 r_1 \rho(r_1) A^2(p_1, x_1) d^4 r_2 \rho(r_2) A^2(p_2, x_2)} \qquad (2)$$

Which can be rewritten by using the Fourier transform of *ρ(r) as*

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

Where Q is the Lorentz invariant relative difference of the 4-vector momentum of the pair,

$$Q^2 = -(p_1 - p_2)^2 = M_{inv}^2 - 4m_\pi^2$$

C is the normalization factor , λ is the chaoticity parameter where λ = 0 for the totally coherent case, and λ = 1 for the totally incoherent case. *δ is a* factor accounts for long-distance correlations.

$\Omega(Qr)$ is the Fourier transform of the emission region, characterized by an effective size r.

$\Omega(Qr) = e^{-Qr}$ for “Cauchhy” shape of *ρ(r)* *and* $\Omega(Qr) = e^{-Q^2 r^2}$ for “Gaussian” shape of *ρ(r)* *…etc.*

Results

R(Q) is measured experimentally by comparing the Q distribution signal of pairs of identical bosons to a reference sample which does not exhibit any BEC correlation effect:

$$R(Q) = \left(\frac{dN_{\text{signal}} / dQ}{dN_{\text{reference}} / dQ} \right) \quad (Single\ Ratio),$$

$$\mathcal{R} = \frac{R}{R_{MC}} = \frac{\left(\dfrac{dN_{signal} / dQ}{dN_{reference} / dQ} \right)}{\left(\dfrac{dN_{MC,signal-like} / dQ}{dN_{MC,reference} / dQ} \right)} \quad (Double\ Ratio)$$

Different choices of reference sample may be:

1. opposite charge (natural choice but contains resonances)
2. opposite hemisphere same charge (p → -p for one track)
3. opposite hemisphere opposite charge
4. rotated ($[p_x, p_y, p_z] \rightarrow [-p_x, -p_y, p_z]$ for one track)

Event and track selections:

Non-Single Diffractive (NSD) Events: To preferentially select NSD events, a coincidence of at least one HF calorimeter tower with more than 3 GeV total energy on each of the positive and negative sides of the HF was required.

Spurious Collisions: *FilterOutScraping* offline filter is also applied to clean up remnant spurious collisions.

The sequence of following paths are applied to select minimum bias events (for 2010B 7 TeV data only):

HLTsequence = *cms.Sequence(HLTR_filter*hltPhysicsDeclared*bscOrBptxOr*bptxAnd*bscOr*noBSChalo), which corresponds to the following parts:*

HLTR_filter: *corresponds to HLT_L1Tech_BSC_minBias_OR OR HLT_ZeroBias.*

hltPhysicsDeclared: *corresponds to Physics declared filter.*

bscOrBptxOr: *corresponds to L1_BscMinBiasOR_BptxPlusORMinus.*

bptxAnd: *corresponds to 0 (bit zero).*

bscOr: *corresponds to (34) AND NOT (36 OR 37 OR 38 OR 39), where 34 corresponds to L1Tech_BSC_minBias_OR.v0, and requires that there is at least one hit in the BSC.*

noBSChalo: *corresponds to NOT (36 OR 37 OR 38 OR 39).*

High Multiplicity events were selected using the following high level triggers (HLT):

HLT_PixelTracks_Multiplicity85 for 7 TeV and

HLT_PixelTracks_Multiplicity85_v2 for 13 TeV.

The following are some track cuts based on the needs of the measurement and removing fake tracks:

- Low-momentum pions, for which the effect of BEC is known to be largest and since pions are the most dominant produced hadrons.

- $p_{\mathrm{T}} > 200\ \mathrm{MeV}/c$ (enough for produced particles to cross the third layer of pixels).

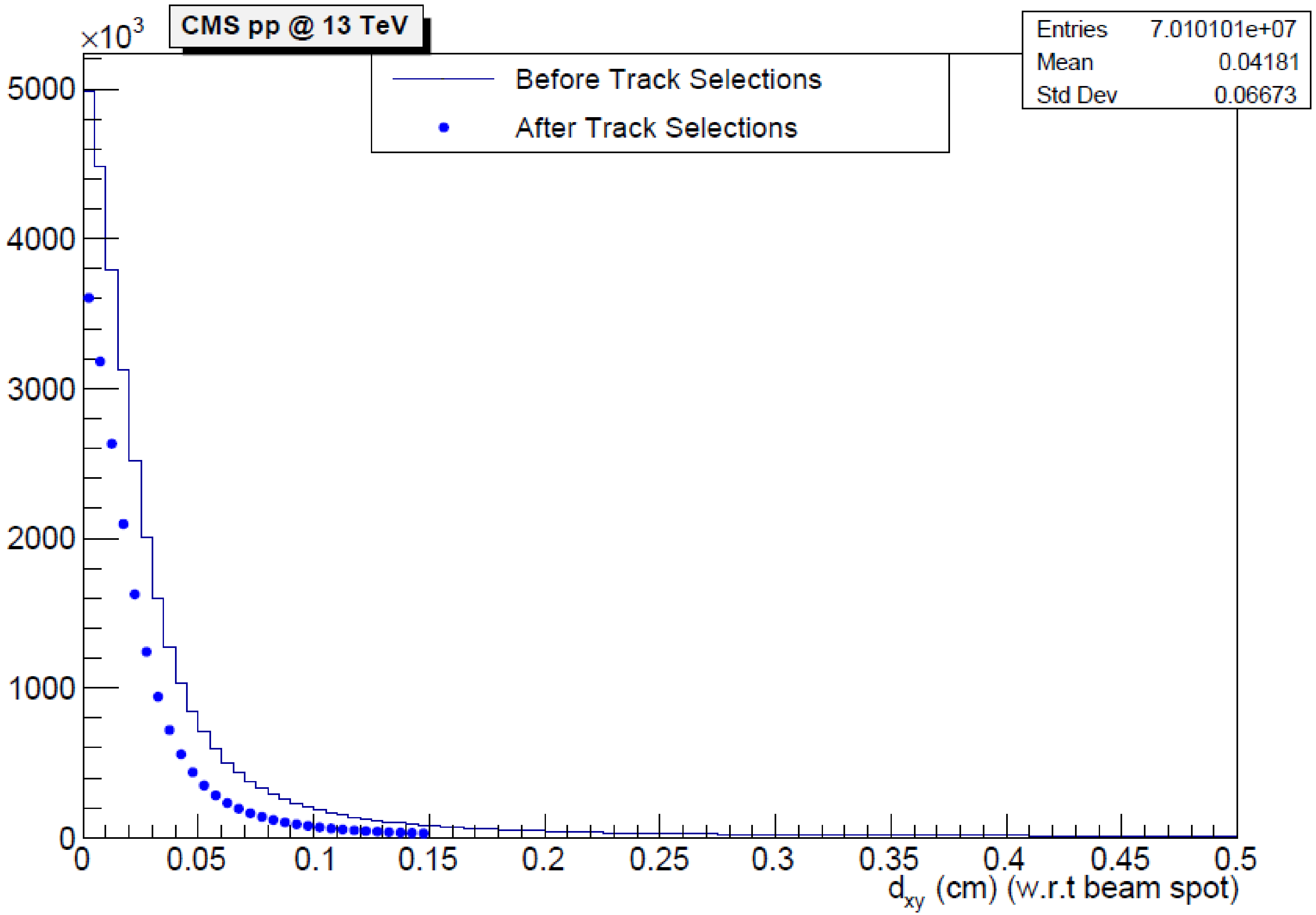
- $|\eta| < 2.4$ (tracking efficiency falls very rapidly above this value).

- “highPurity” tracks (to remove spurious tracks).

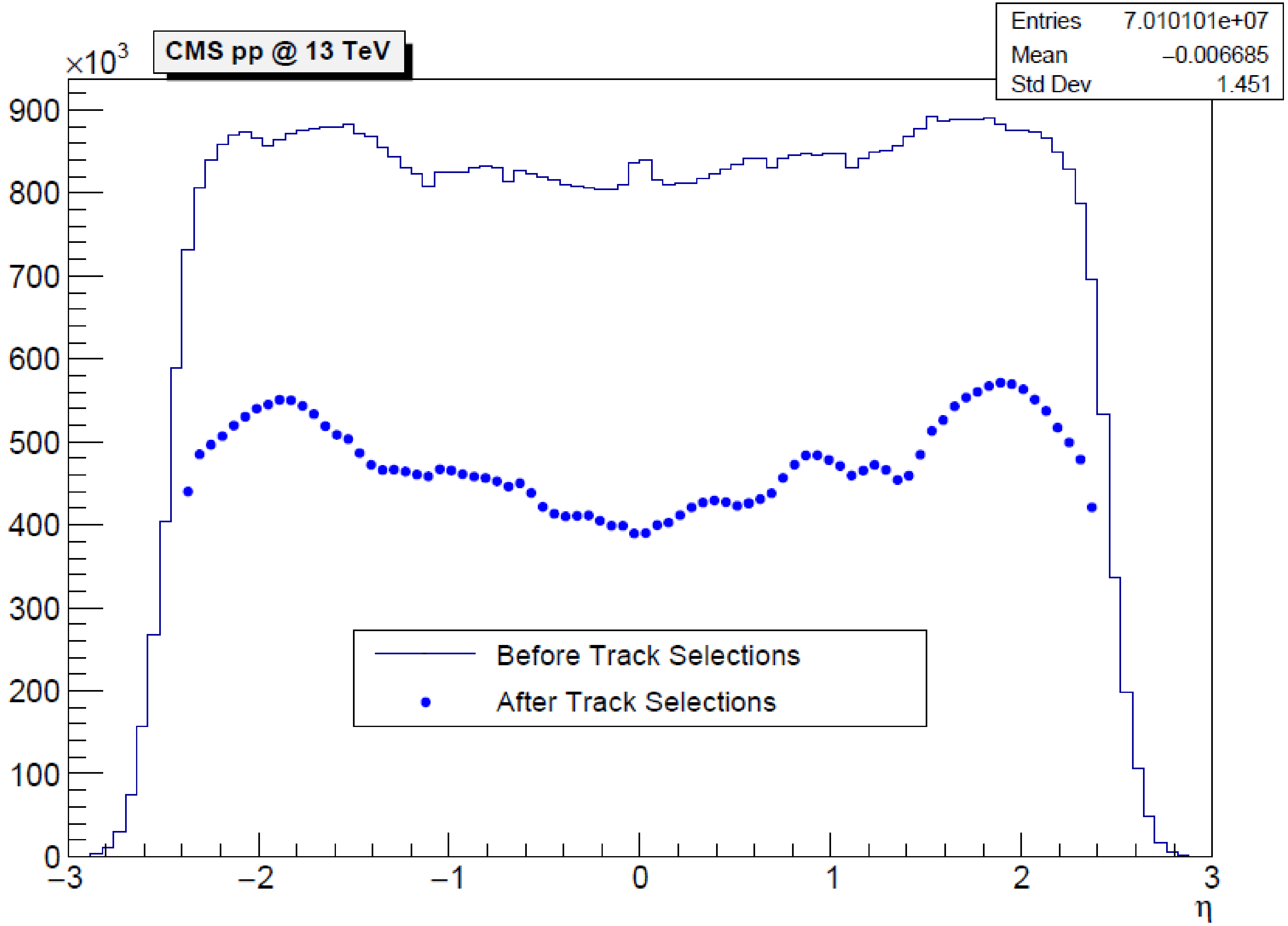
- $|d_{xy}| < 0.15\ \mathrm{cm}$ (removing e^-,e^+ produced from photon conversions in the detector material).

- Events with less than 150 tracks are selected for minimum bias (MB) trigger events (to insure good track reconstruction) and from 150 up to 300 tracks for (HM) trigger events.

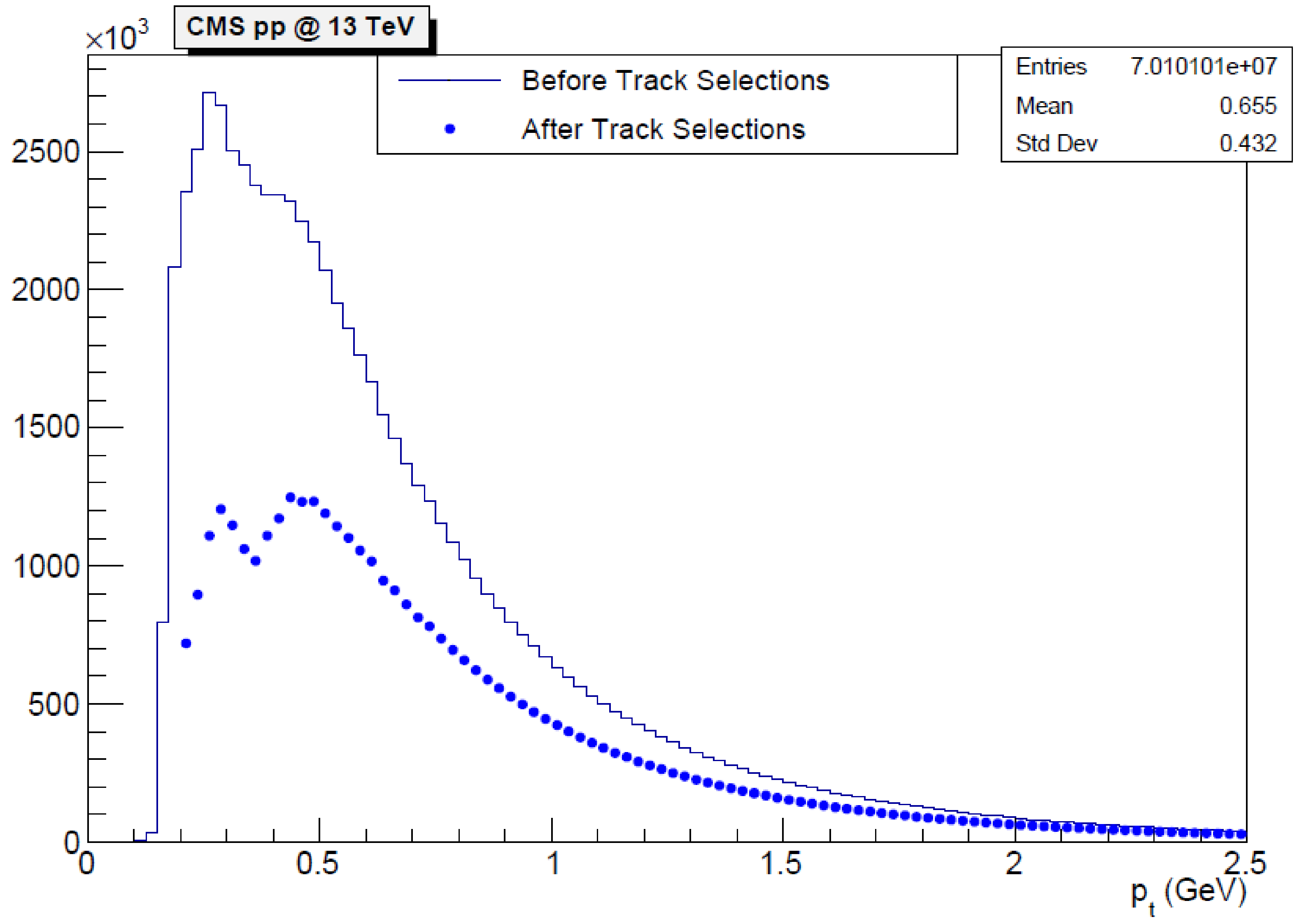
Track selection



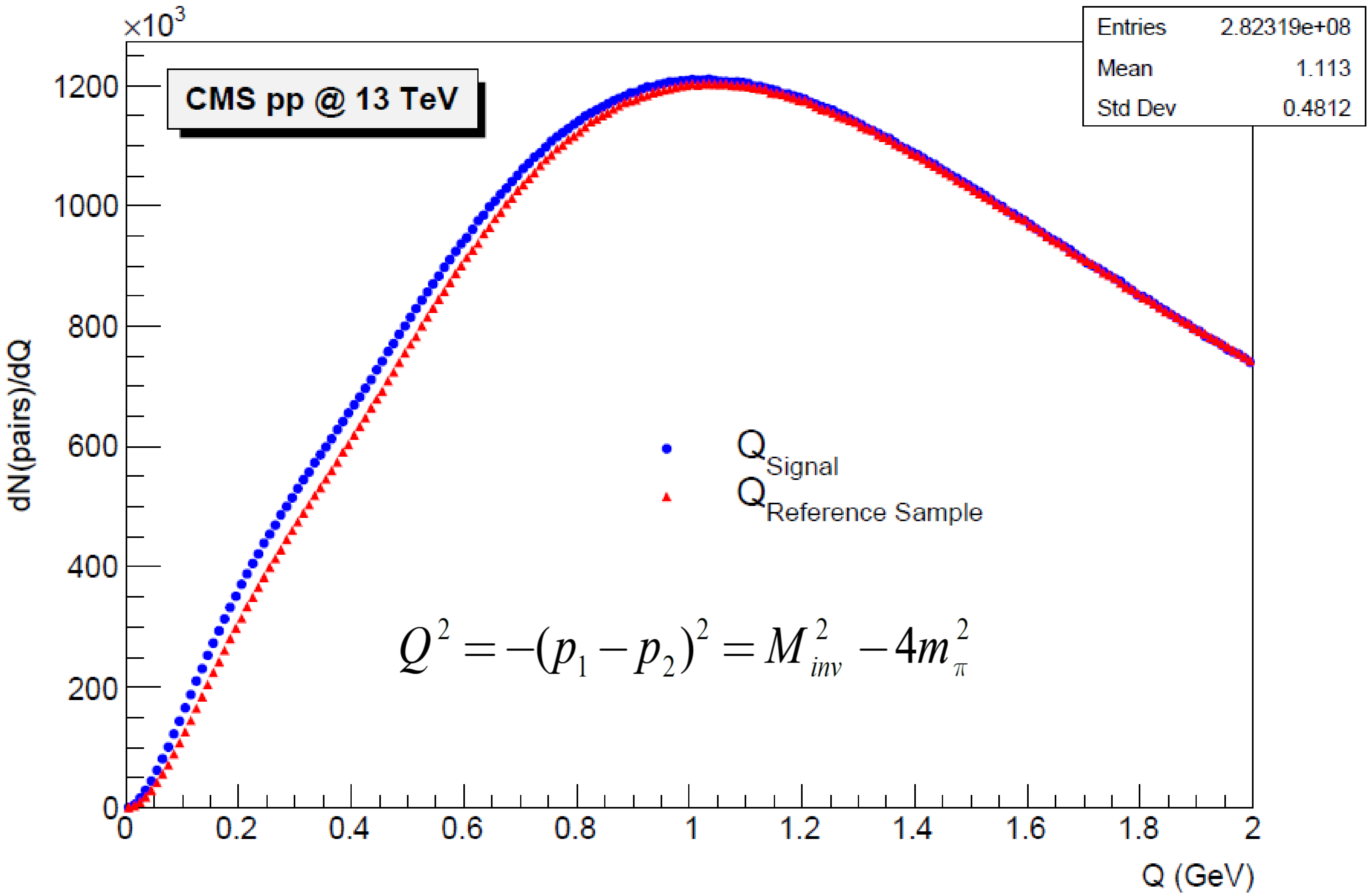
Track selection

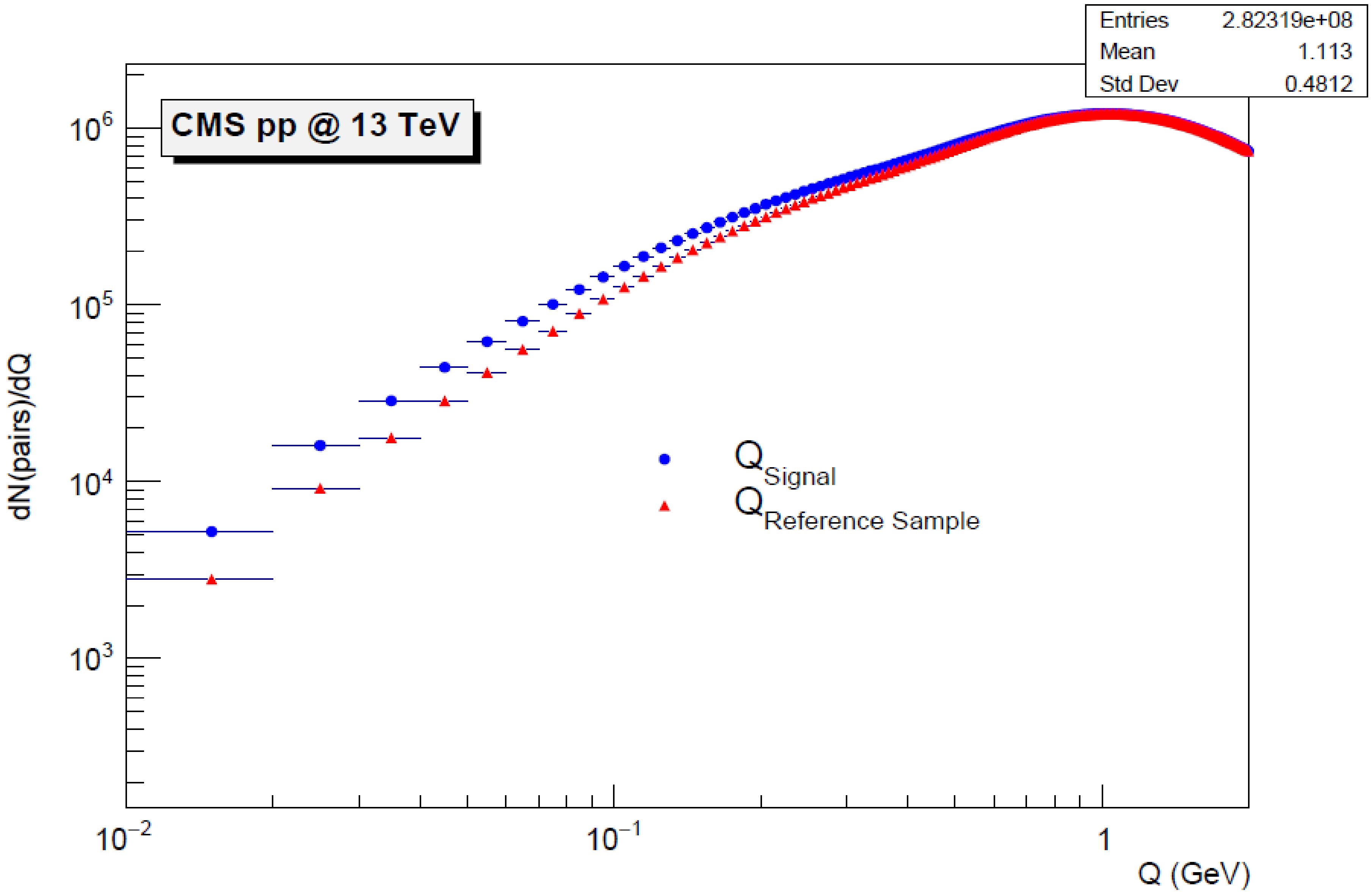


Track selection

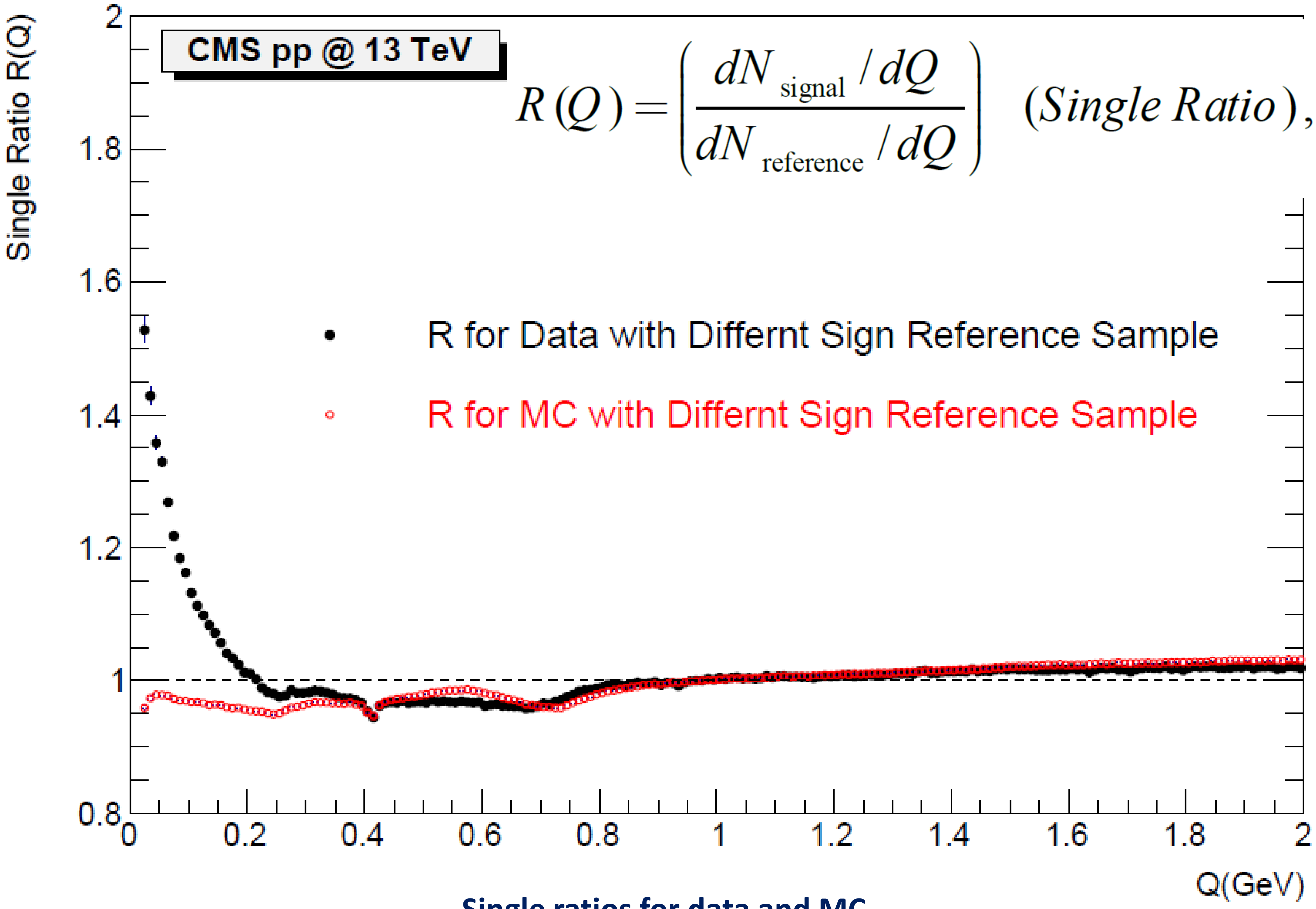


Definition of Signal and Background

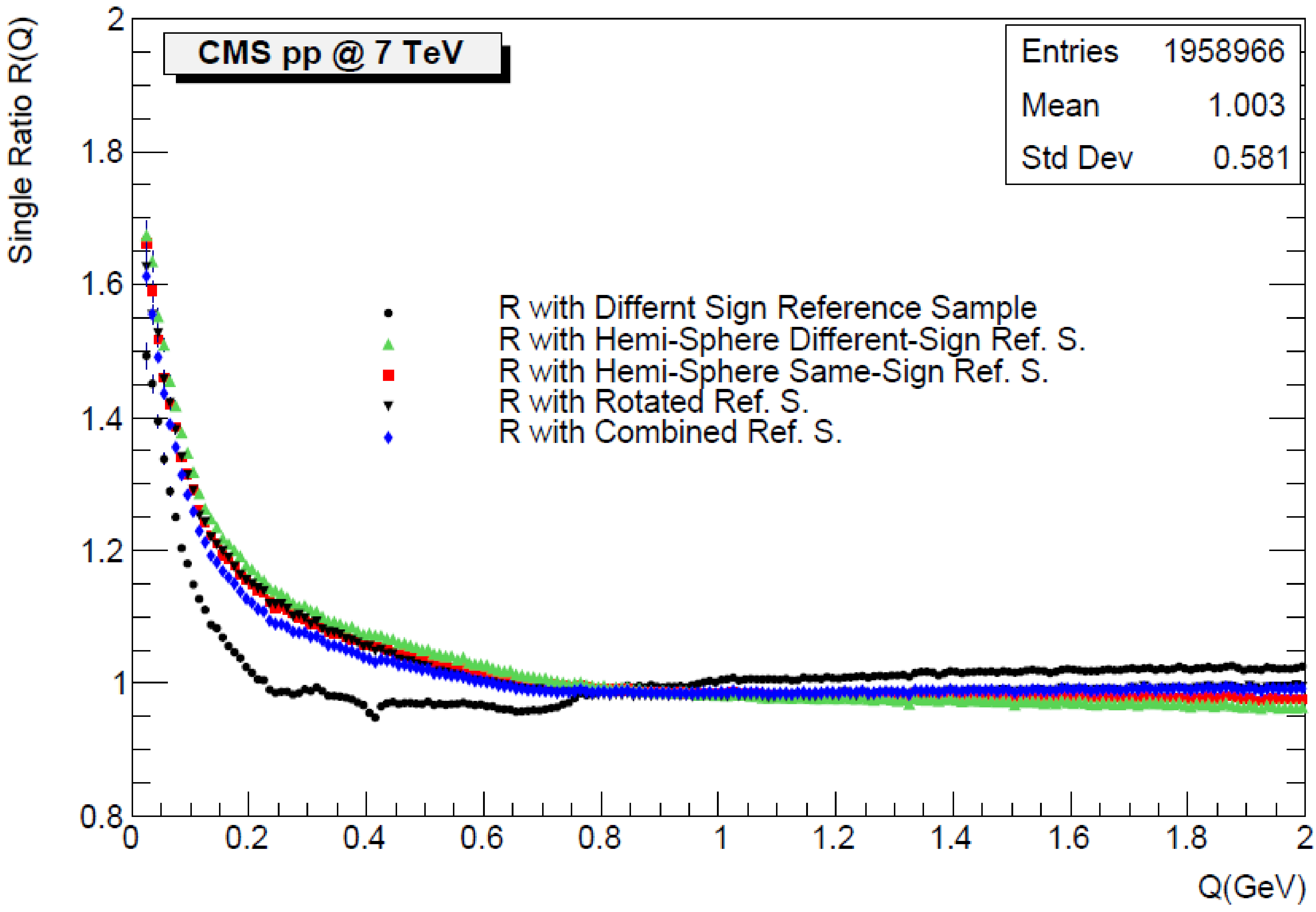




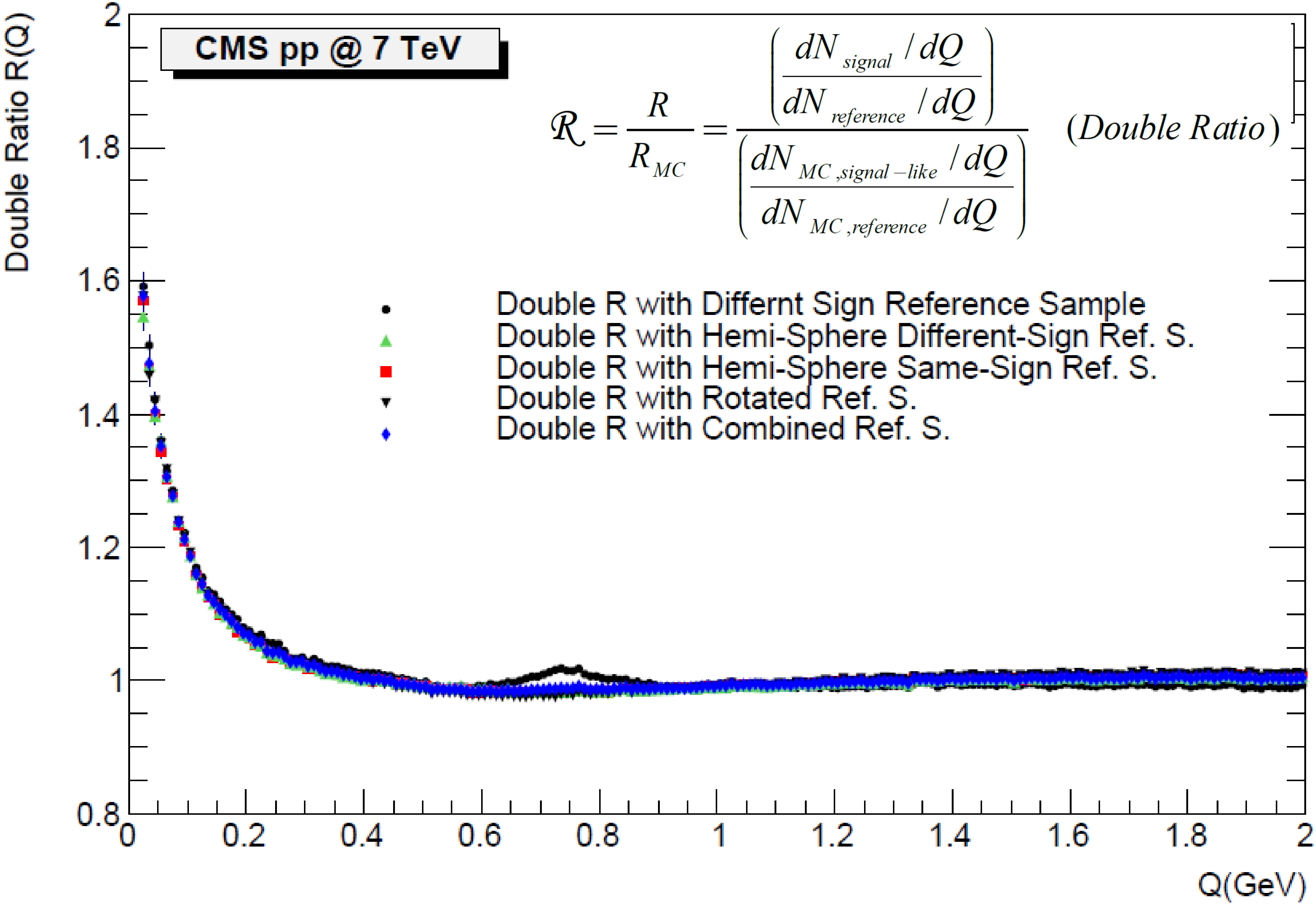
BEC is dominant at low Q as seen from comparison between signal and reference sample at log scale. pp at 13 TeV,



Single ratios for data and MC

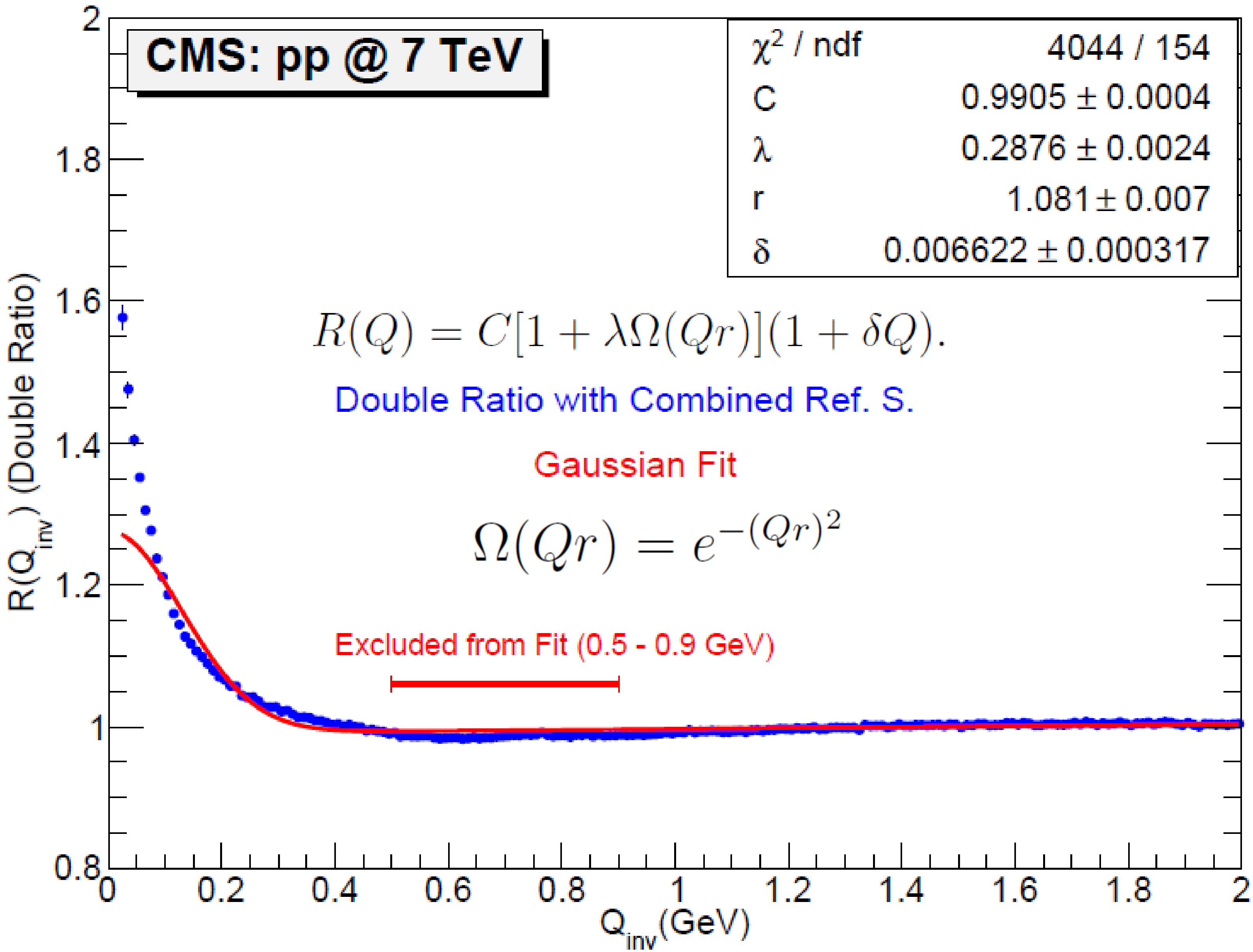


Comparison bet. Single ratios for different reference samples

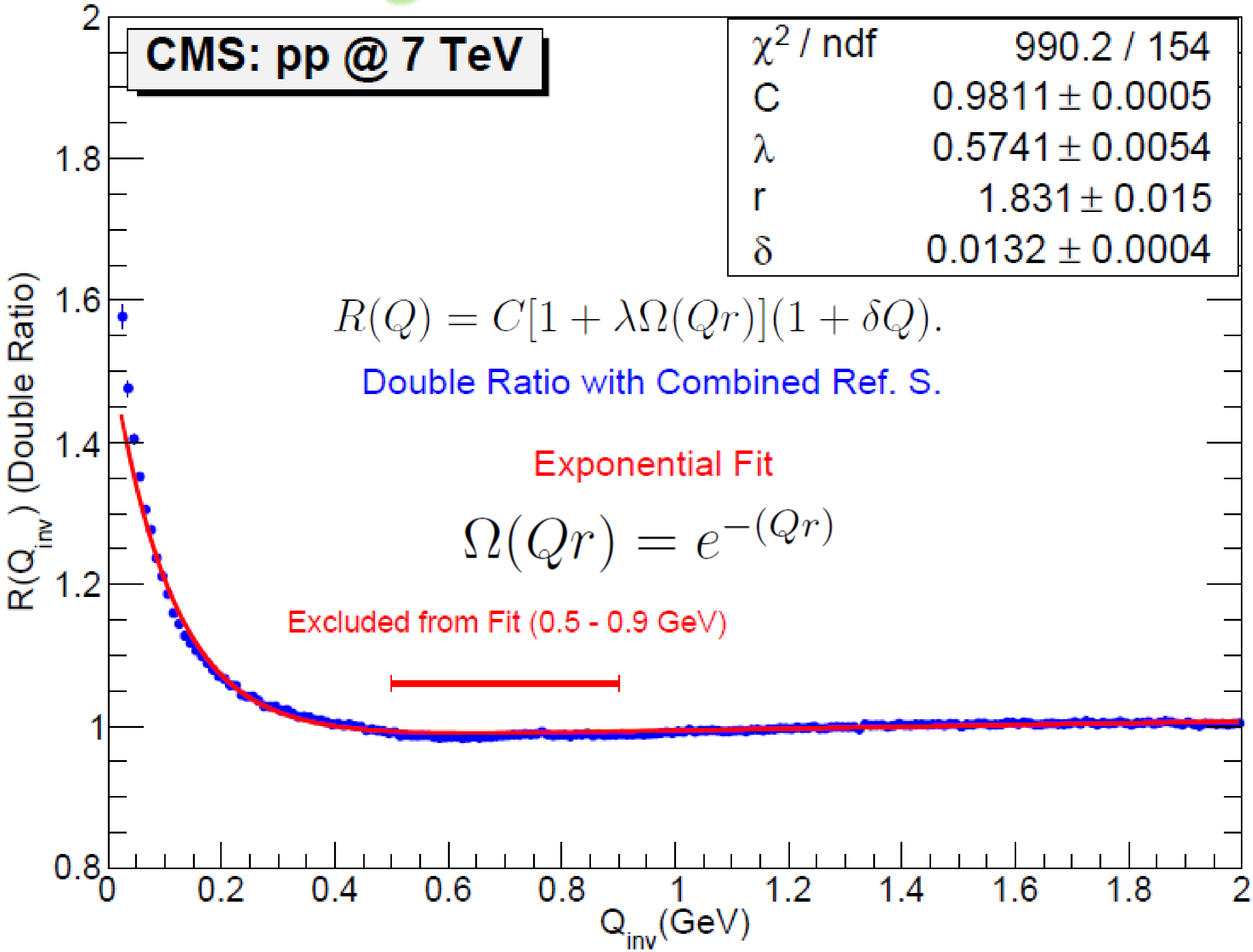


Double ratio correlation function for different reference samples (bias reduced)

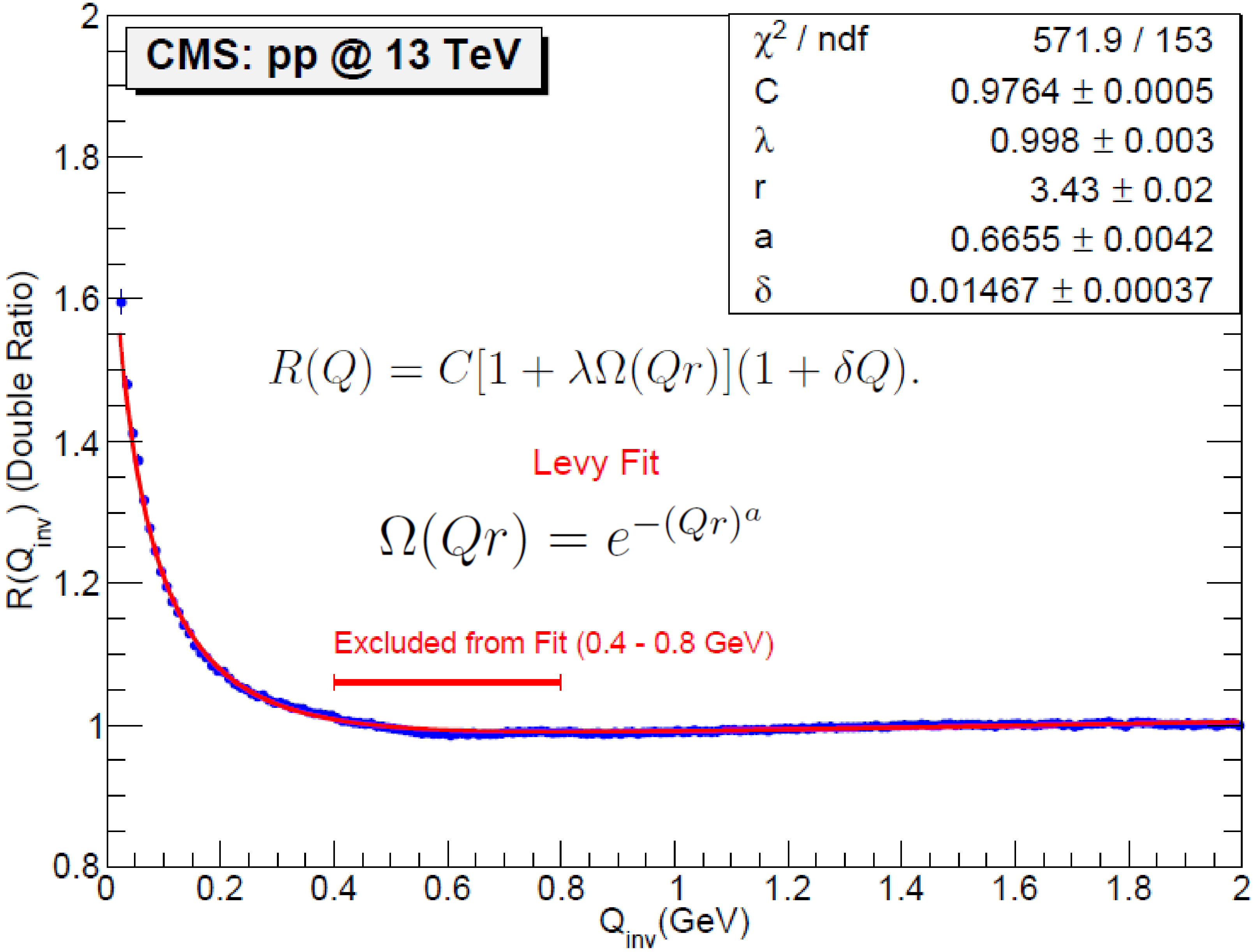
Fitting of the Correlation Function



Fitting of the Correlation Function



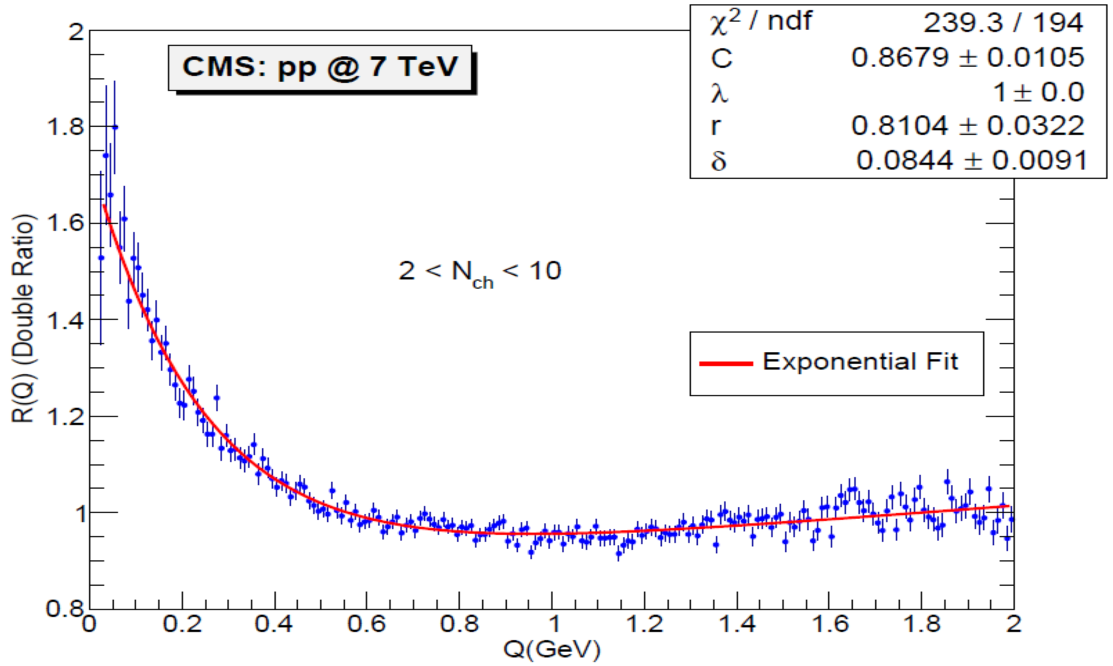
Fitting of the Correlation Function

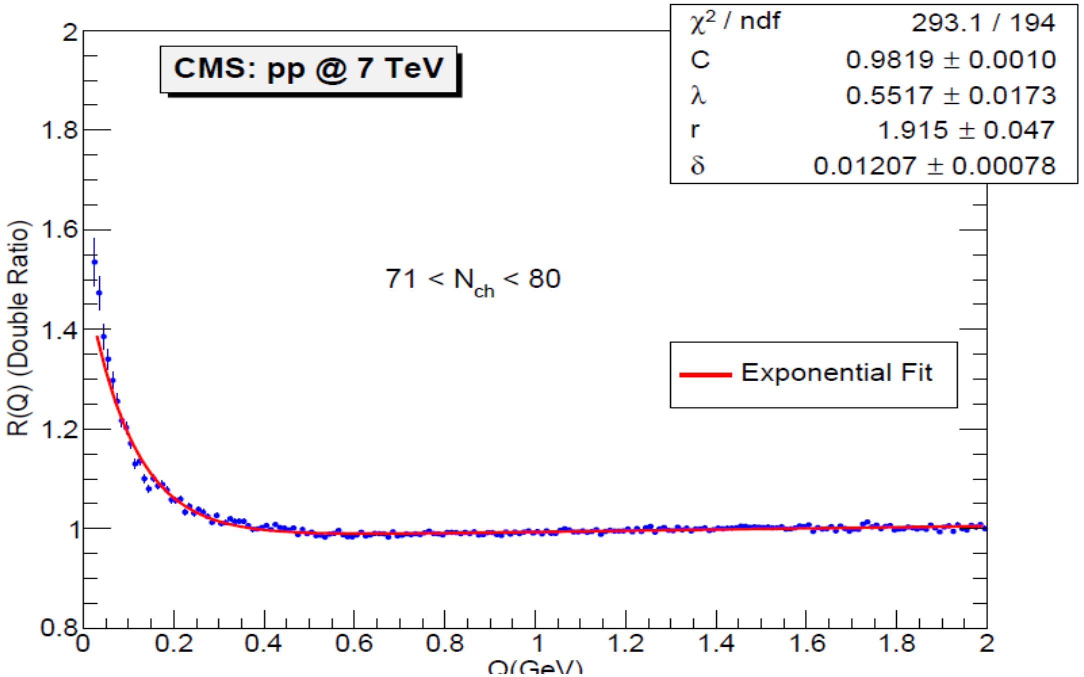


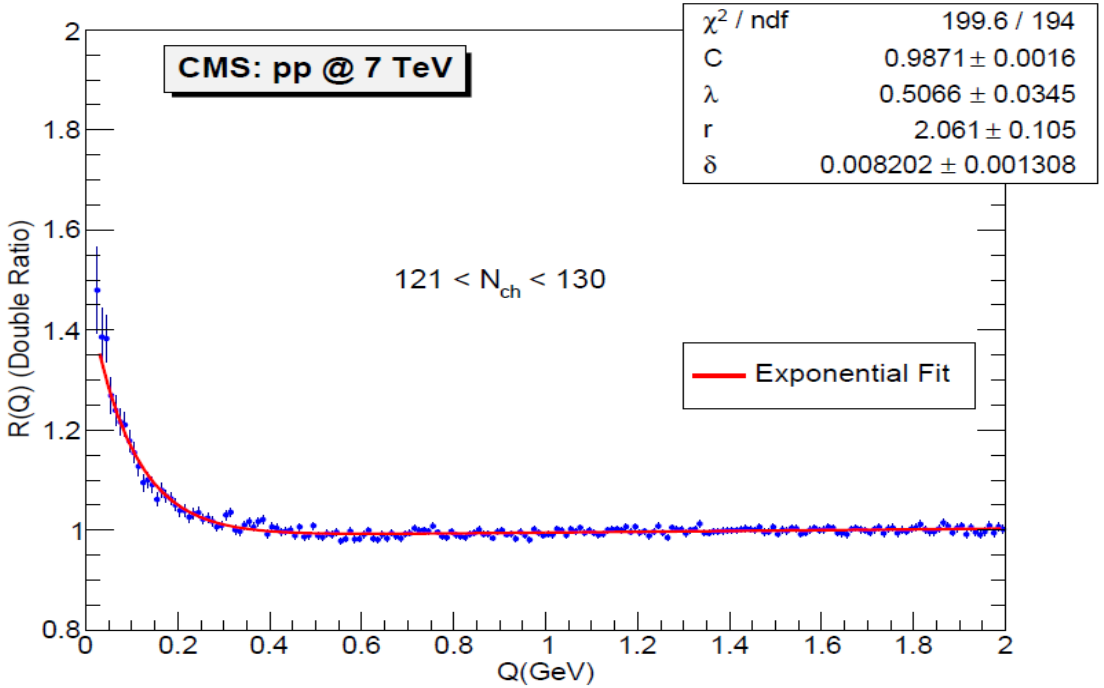
Dependence of correlation function parameters on pair kinematics

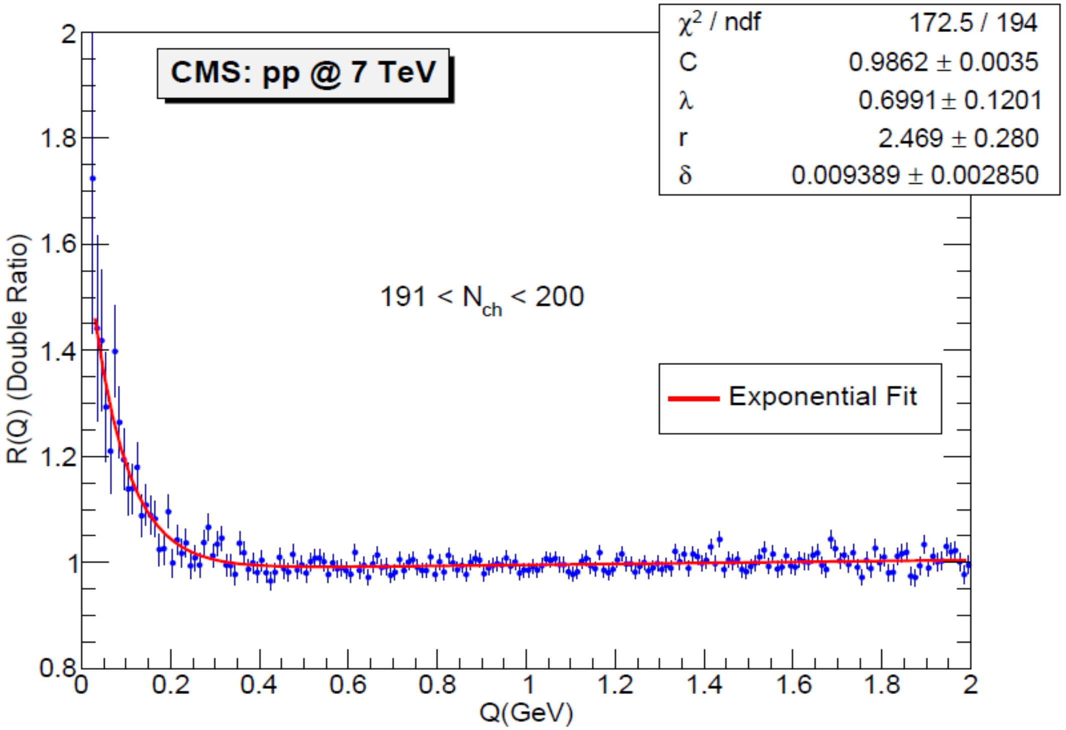
1. Charged-Particle Multiplicity N_{ch}
2. Mean-Transverse Momentum of Correlated Pairs k_T

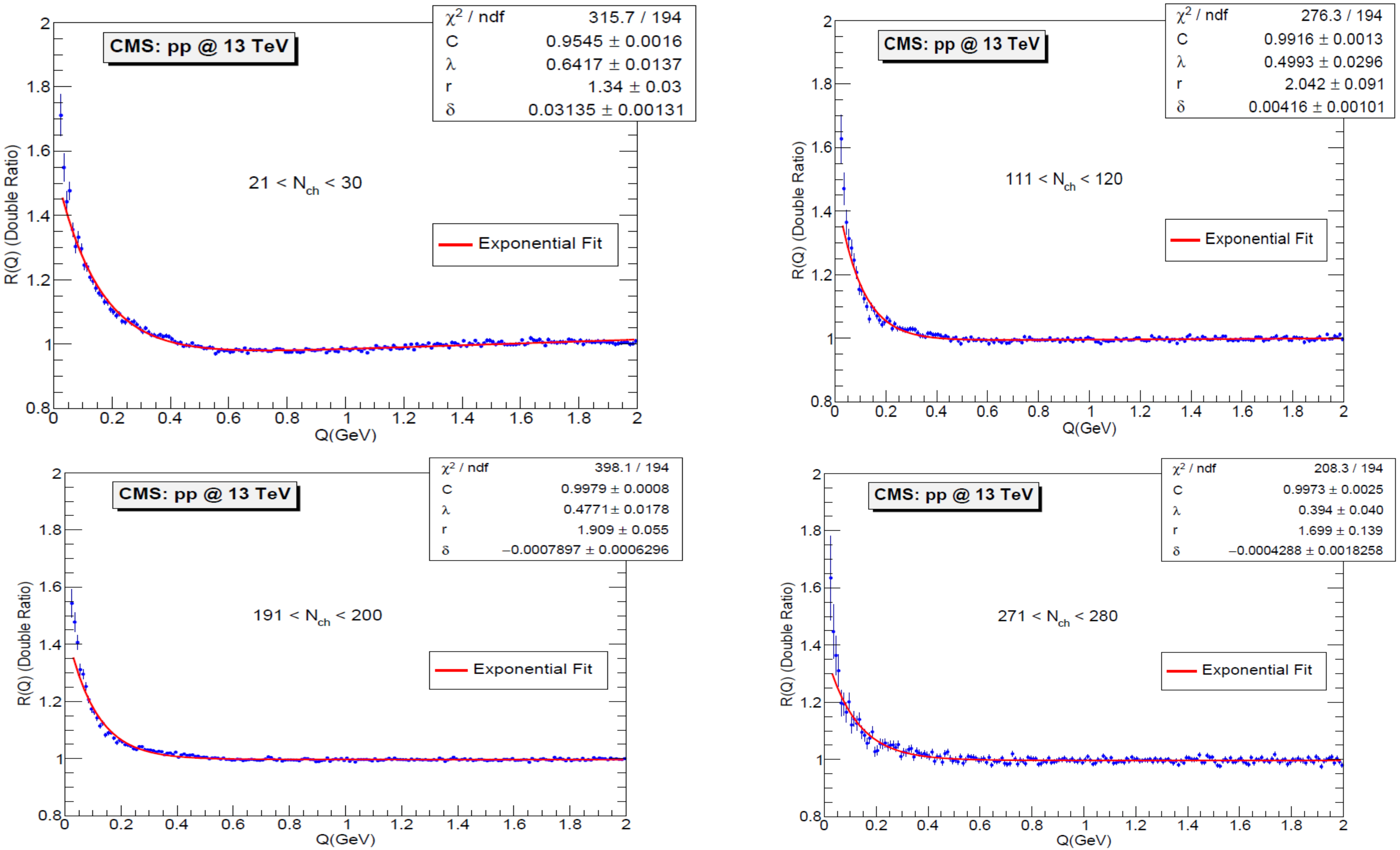
1. N_{ch}


CMS: pp @ 7 TeV
χ² / ndf 239.3 / 194
C 0.8679 ± 0.0105
λ 1 ± 0.0
r 0.8104 ± 0.0322
δ 0.0844 ± 0.0091
2 < N_ch < 10
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)


CMS: pp @ 7 TeV
χ² / ndf 293.1 / 194
C 0.9819 ± 0.0010
λ 0.5517 ± 0.0173
r 1.915 ± 0.047
δ 0.01207 ± 0.00078
71 < N_ch < 80
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)

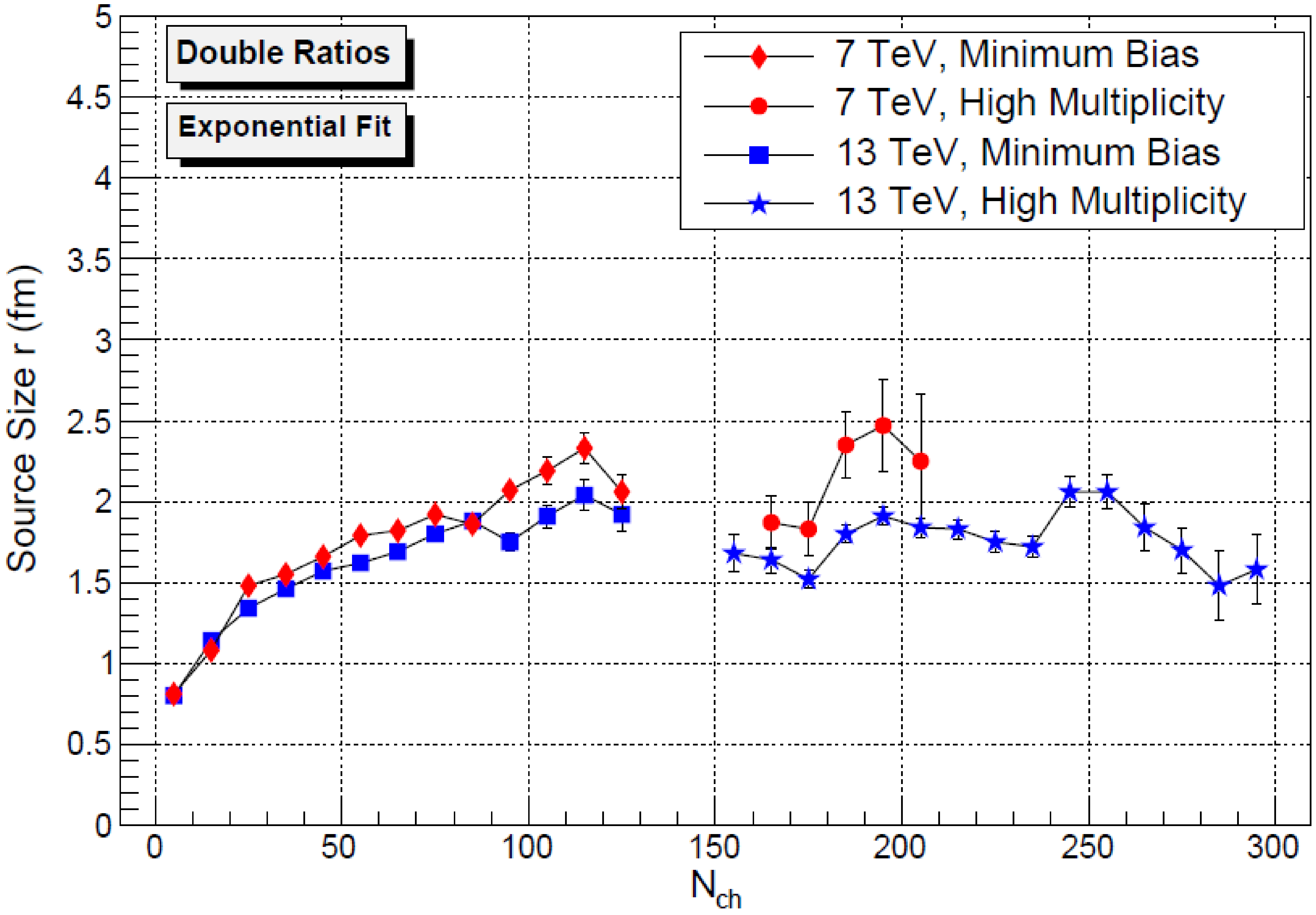

CMS: pp @ 7 TeV
χ² / ndf 199.6 / 194
C 0.9871 ± 0.0016
λ 0.5066 ± 0.0345
r 2.061 ± 0.105
δ 0.008202 ± 0.001308
121 < N_ch < 130
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)

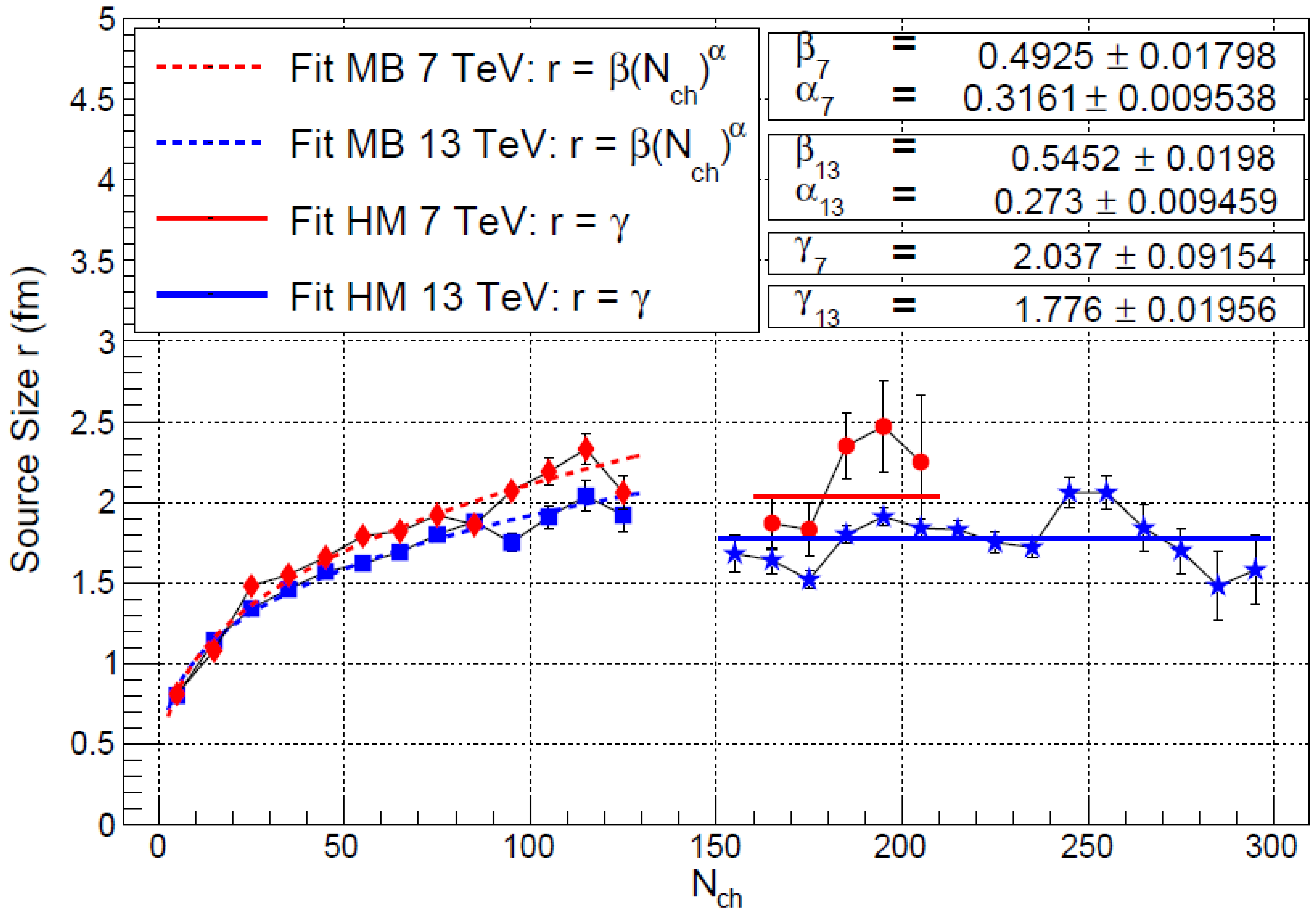

CMS: pp @ 7 TeV
χ² / ndf 172.5 / 194
C 0.9862 ± 0.0035
λ 0.6991 ± 0.1201
r 2.469 ± 0.280
δ 0.009389 ± 0.002850
191 < N_ch < 200
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)



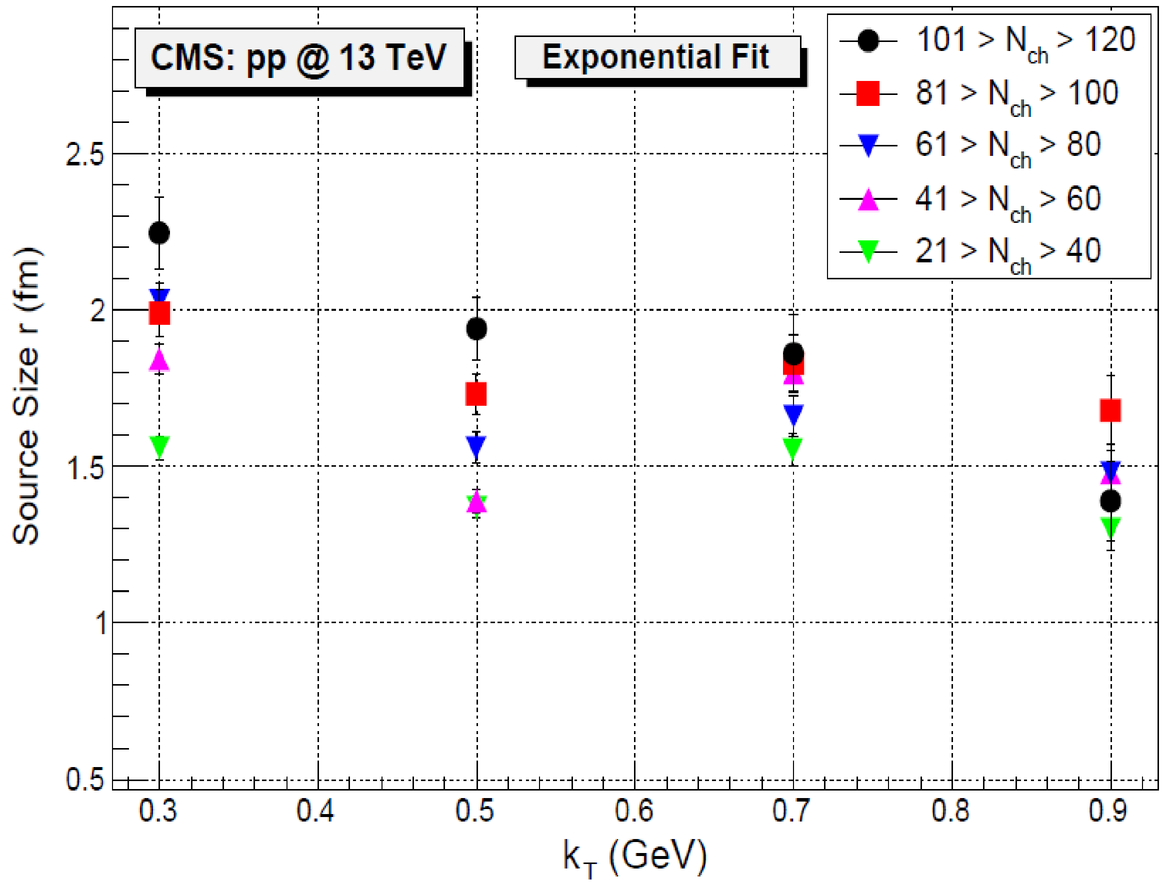
CMS: pp @ 13 TeV
χ^2 / ndf 315.7 / 194
C 0.9545 ± 0.0016
λ 0.6417 ± 0.0137
r 1.34 ± 0.03
δ 0.03135 ± 0.00131
21 < N_{ch} < 30
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)
CMS: pp @ 13 TeV
χ^2 / ndf 276.3 / 194
C 0.9916 ± 0.0013
λ 0.4993 ± 0.0296
r 2.042 ± 0.091
δ 0.00416 ± 0.00101
111 < N_{ch} < 120
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)
CMS: pp @ 13 TeV
χ^2 / ndf 398.1 / 194
C 0.9979 ± 0.0008
λ 0.4771 ± 0.0178
r 1.909 ± 0.055
δ −0.0007897 ± 0.0006296
191 < N_{ch} < 200
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)
CMS: pp @ 13 TeV
χ^2 / ndf 208.3 / 194
C 0.9973 ± 0.0025
λ 0.394 ± 0.040
r 1.699 ± 0.139
δ −0.0004288 ± 0.0018258
271 < N_{ch} < 280
Exponential Fit
R(Q) (Double Ratio)
Q(GeV)

“r” SATURATION !!!!

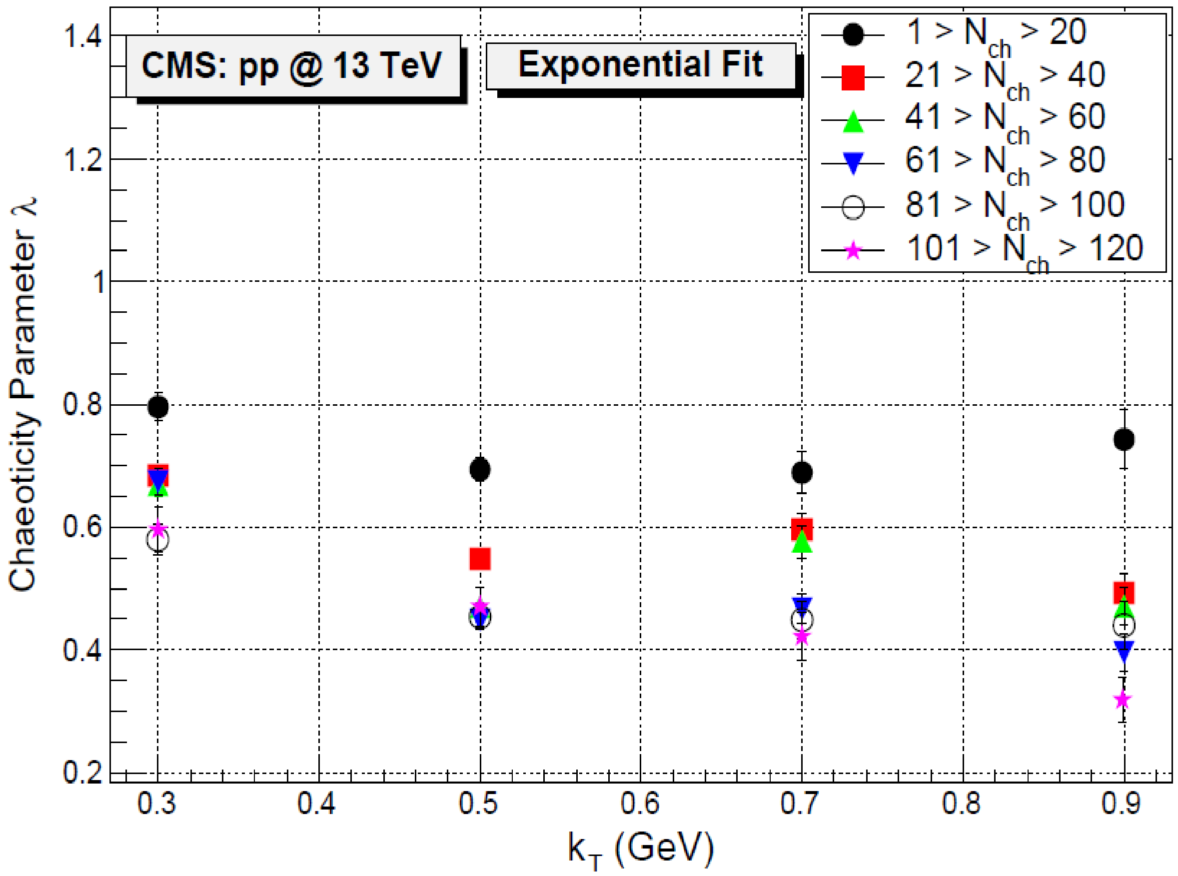



Fit MB 7 TeV: r = β(N_ch)^α
Fit MB 13 TeV: r = β(N_ch)^α
Fit HM 7 TeV: r = γ
Fit HM 13 TeV: r = γ
β_7 = 0.4925 ± 0.01798
α_7 = 0.3161 ± 0.009538
β_13 = 0.5452 ± 0.0198
α_13 = 0.273 ± 0.009459
γ_7 = 2.037 ± 0.09154
γ_13 = 1.776 ± 0.01956
Source Size r (fm)
N_ch

2. k_T



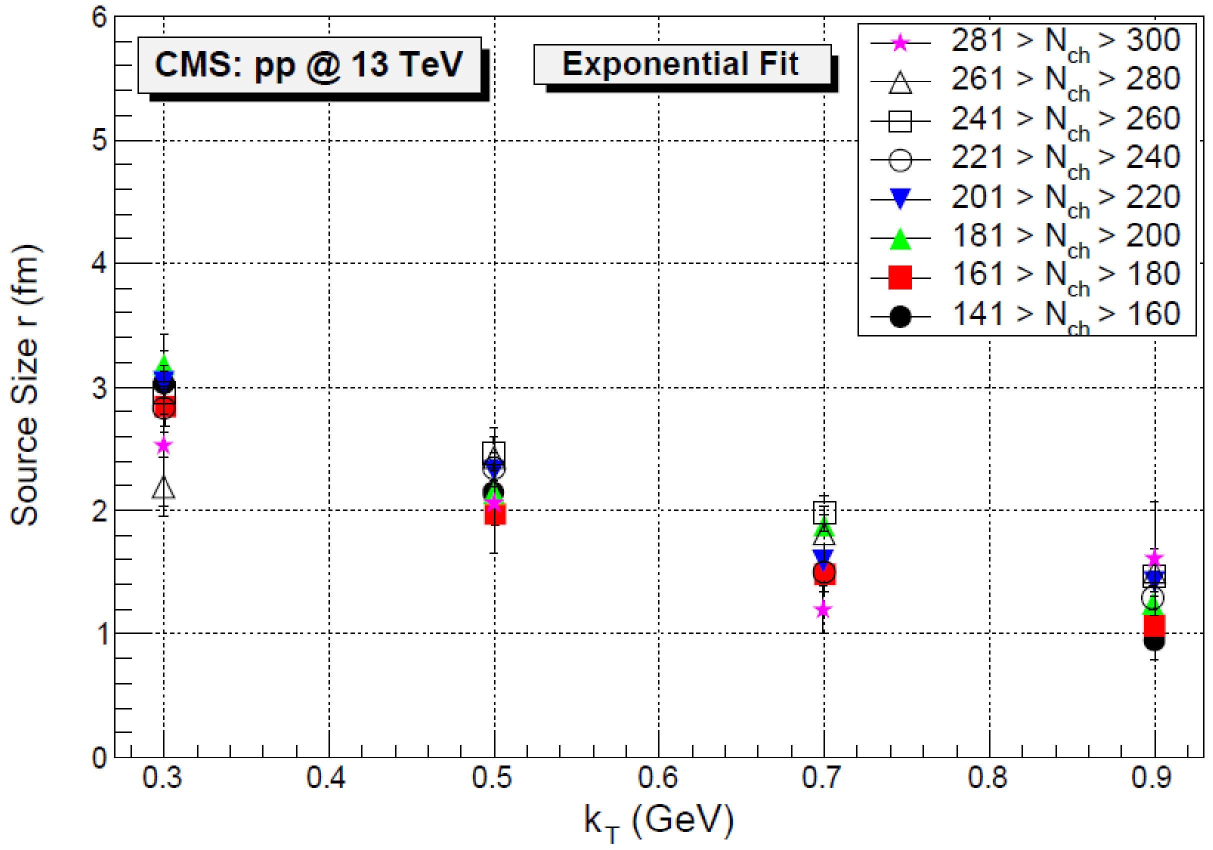
CMS: pp @ 13 TeV
Exponential Fit
101 > N_ch > 120
81 > N_ch > 100
61 > N_ch > 80
41 > N_ch > 60
21 > N_ch > 40
Source Size r (fm)
k_T (GeV)
0.5
1
1.5
2
2.5
0.3
0.4
0.5
0.6
0.7
0.8
0.9



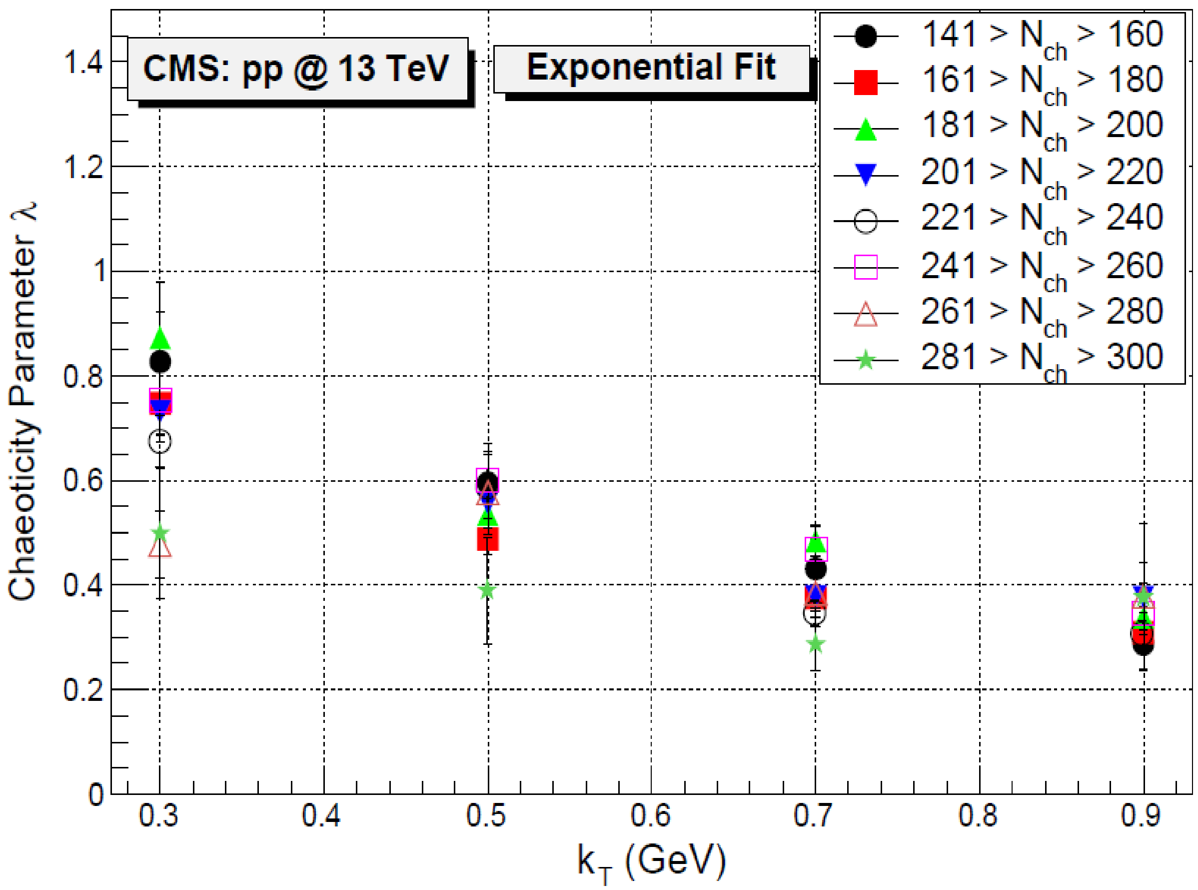
CMS: pp @ 13 TeV
Exponential Fit
1 > N_ch > 20
21 > N_ch > 40
41 > N_ch > 60
61 > N_ch > 80
81 > N_ch > 100
101 > N_ch > 120
Chaeoticity Parameter λ
k_T (GeV)
0.2
0.4
0.6
0.8
1
1.2
1.4
0.3
0.4
0.5
0.6
0.7
0.8
0.9

MB

2. k_T

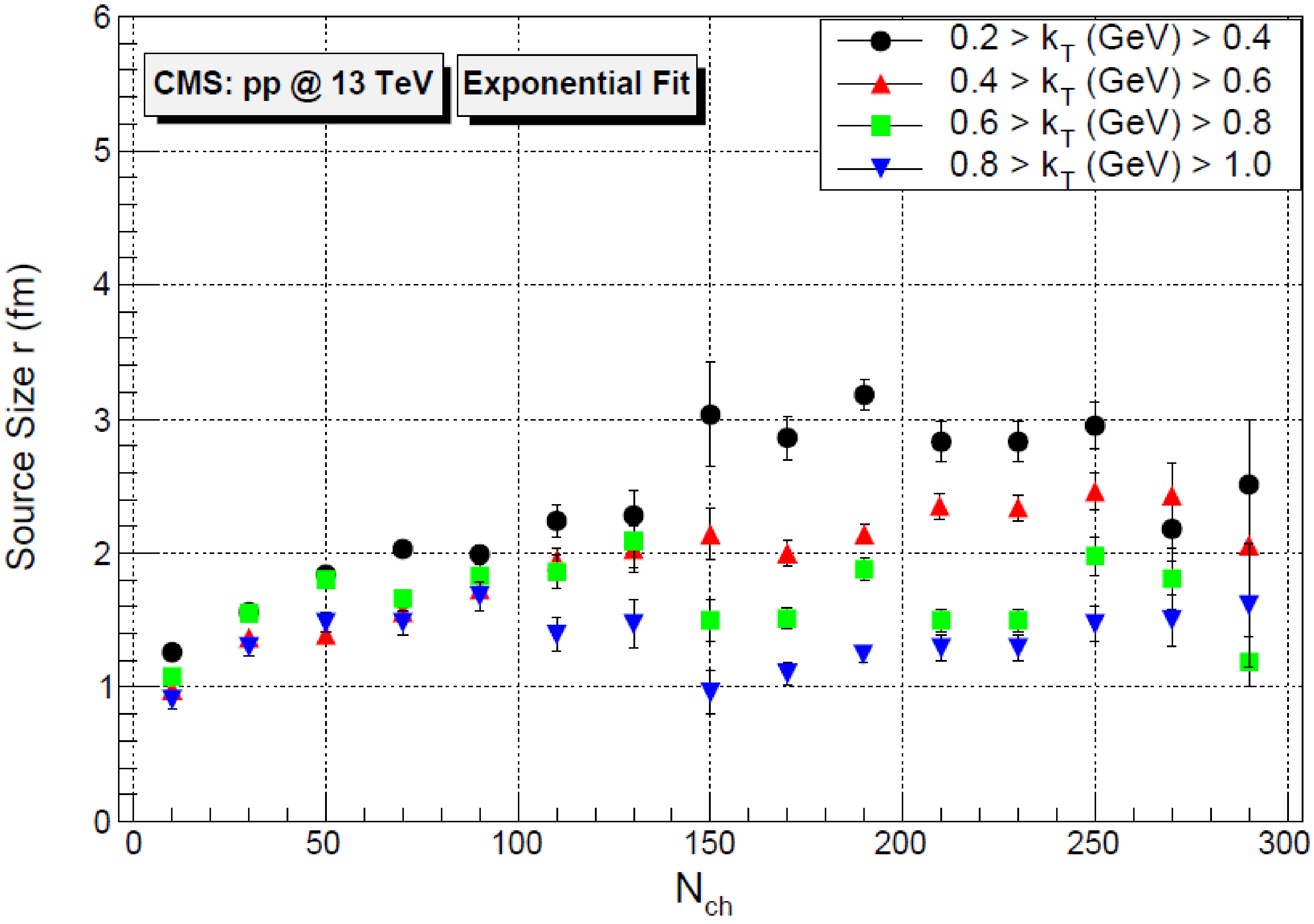


CMS: pp @ 13 TeV
Exponential Fit
281 > N_ch > 300
261 > N_ch > 280
241 > N_ch > 260
221 > N_ch > 240
201 > N_ch > 220
181 > N_ch > 200
161 > N_ch > 180
141 > N_ch > 160
Source Size r (fm)
k_T (GeV)



CMS: pp @ 13 TeV
Exponential Fit
141 > N_ch > 160
161 > N_ch > 180
181 > N_ch > 200
201 > N_ch > 220
221 > N_ch > 240
241 > N_ch > 260
261 > N_ch > 280
281 > N_ch > 300
Chaeoticity Parameter λ
k_T (GeV)

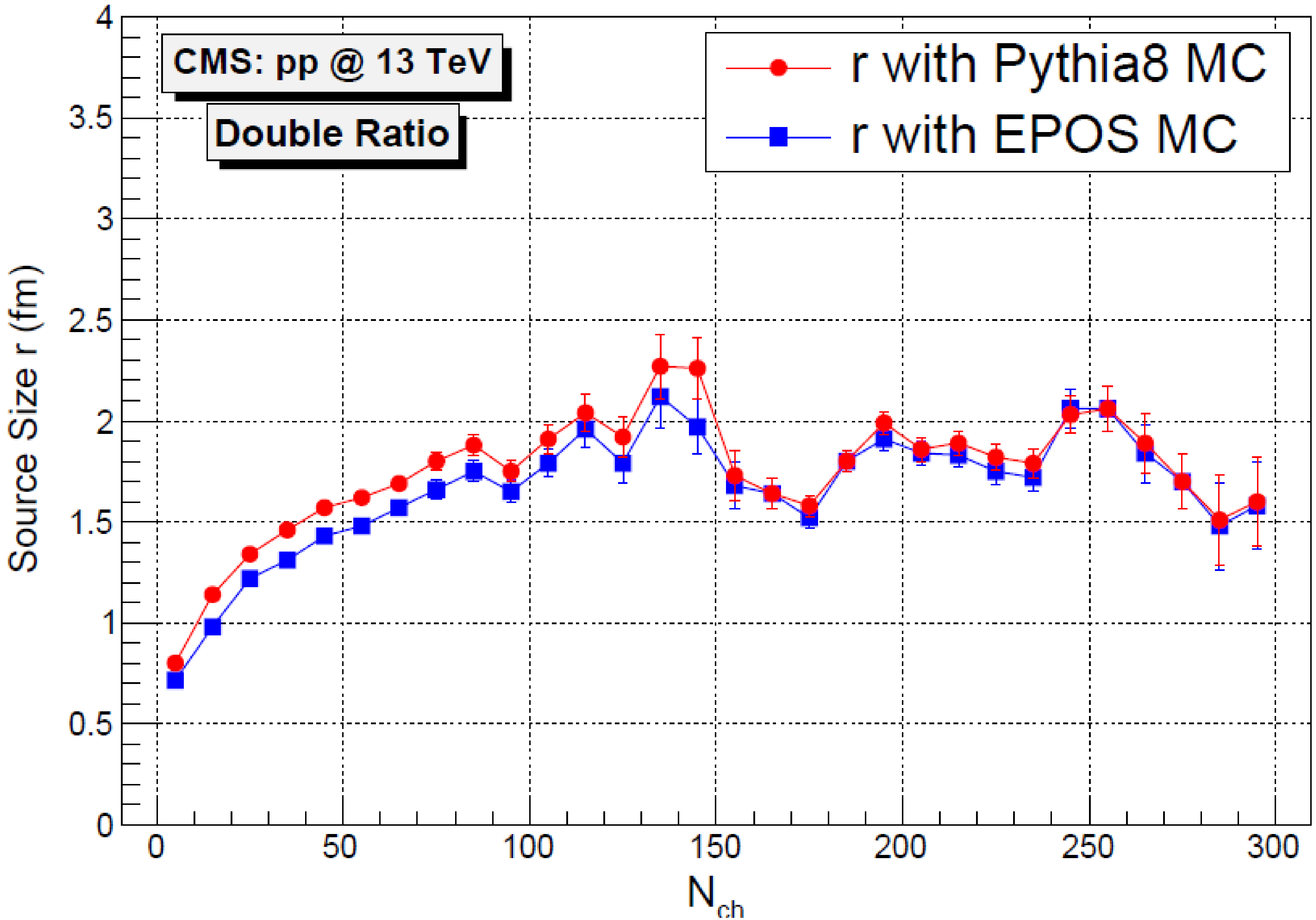
HM


CMS: pp @ 13 TeV
Exponential Fit
0.2 > k_T (GeV) > 0.4
0.4 > k_T (GeV) > 0.6
0.6 > k_T (GeV) > 0.8
0.8 > k_T (GeV) > 1.0
Source Size r (fm)
N_{ch}
0
1
2
3
4
5
6
0
50
100
150
200
250
300

k_T

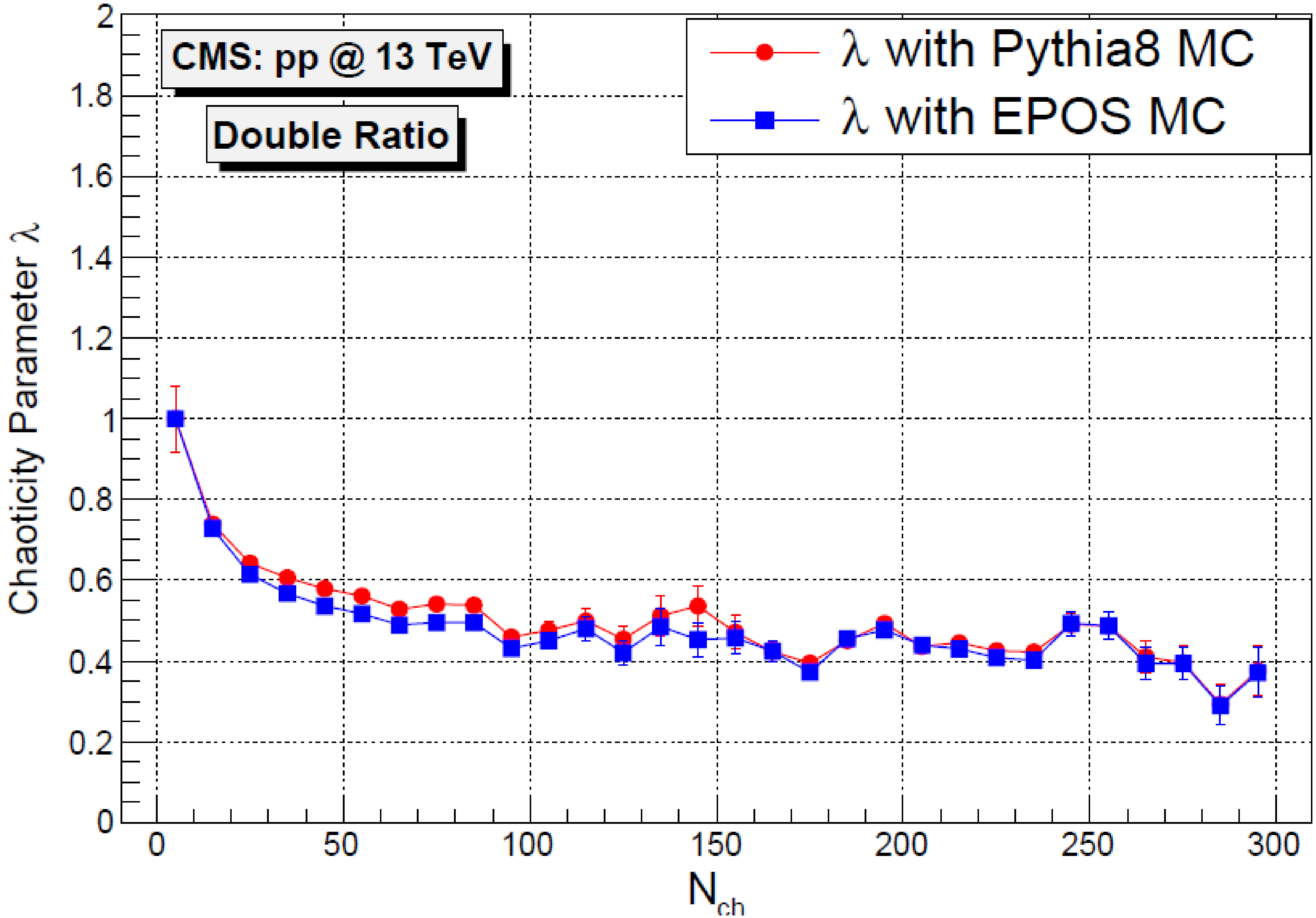
N_{ch}

Systematic Uncertainties



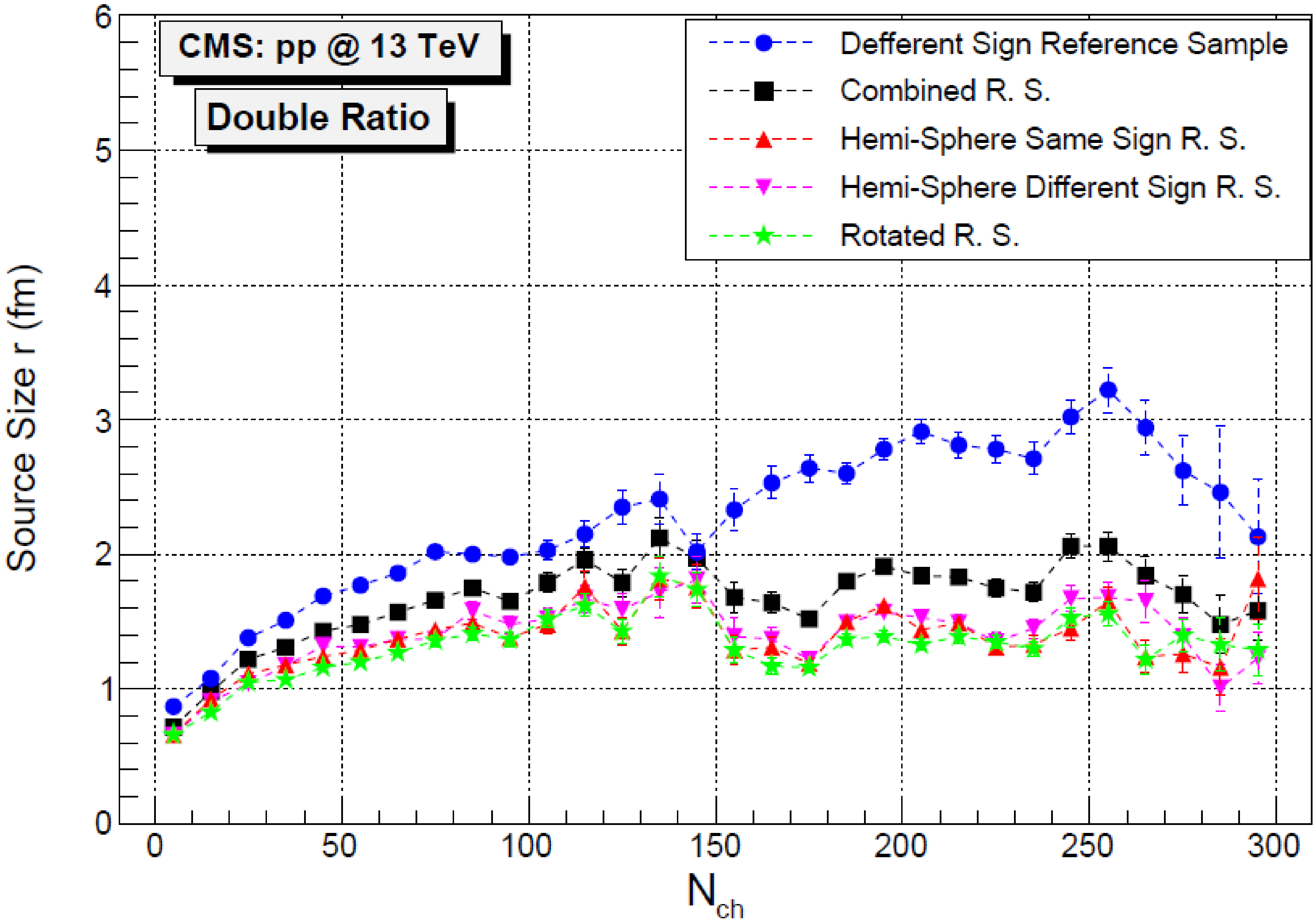
MC

Systematic Uncertainties



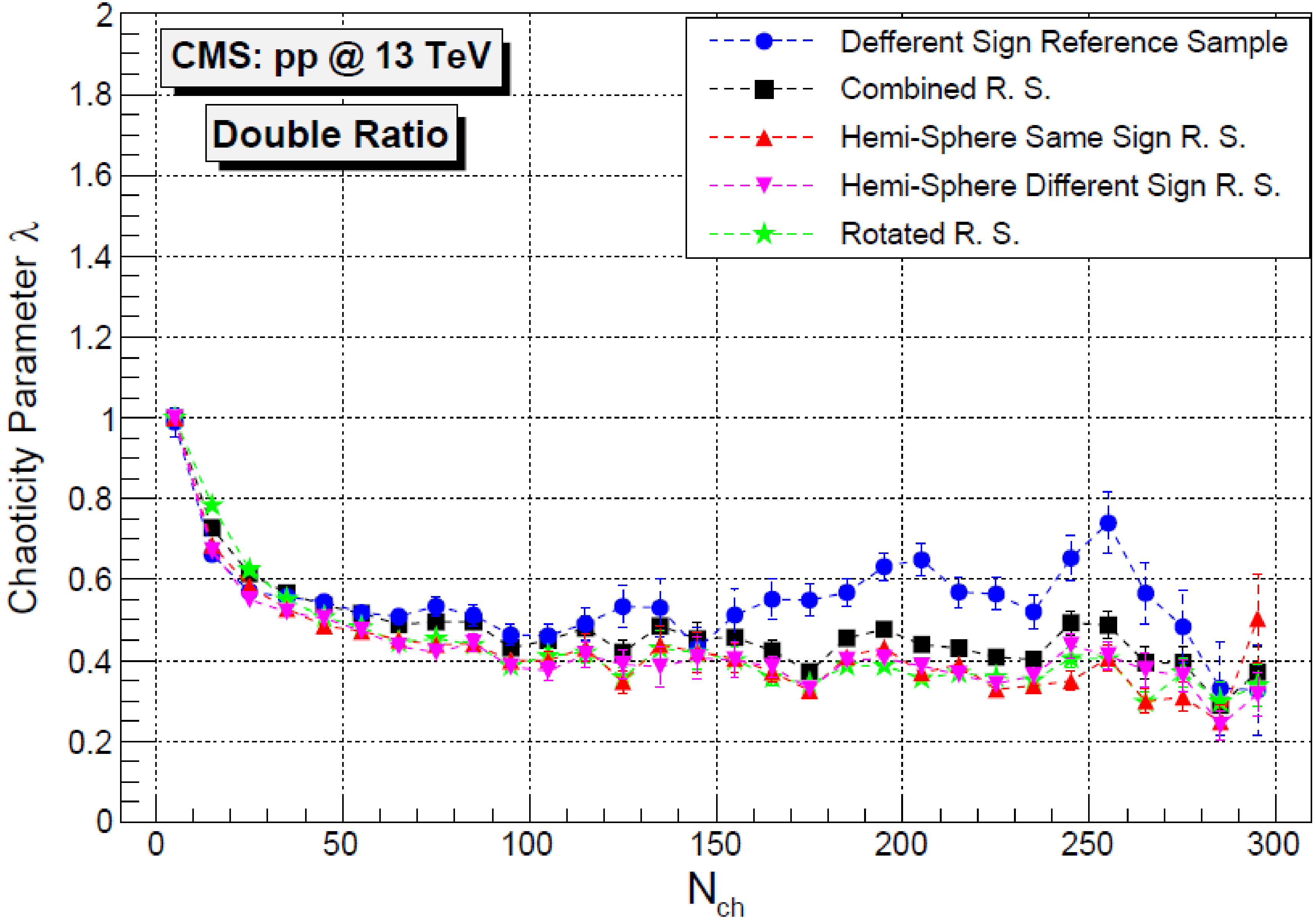
MC

Systematic Uncertainties



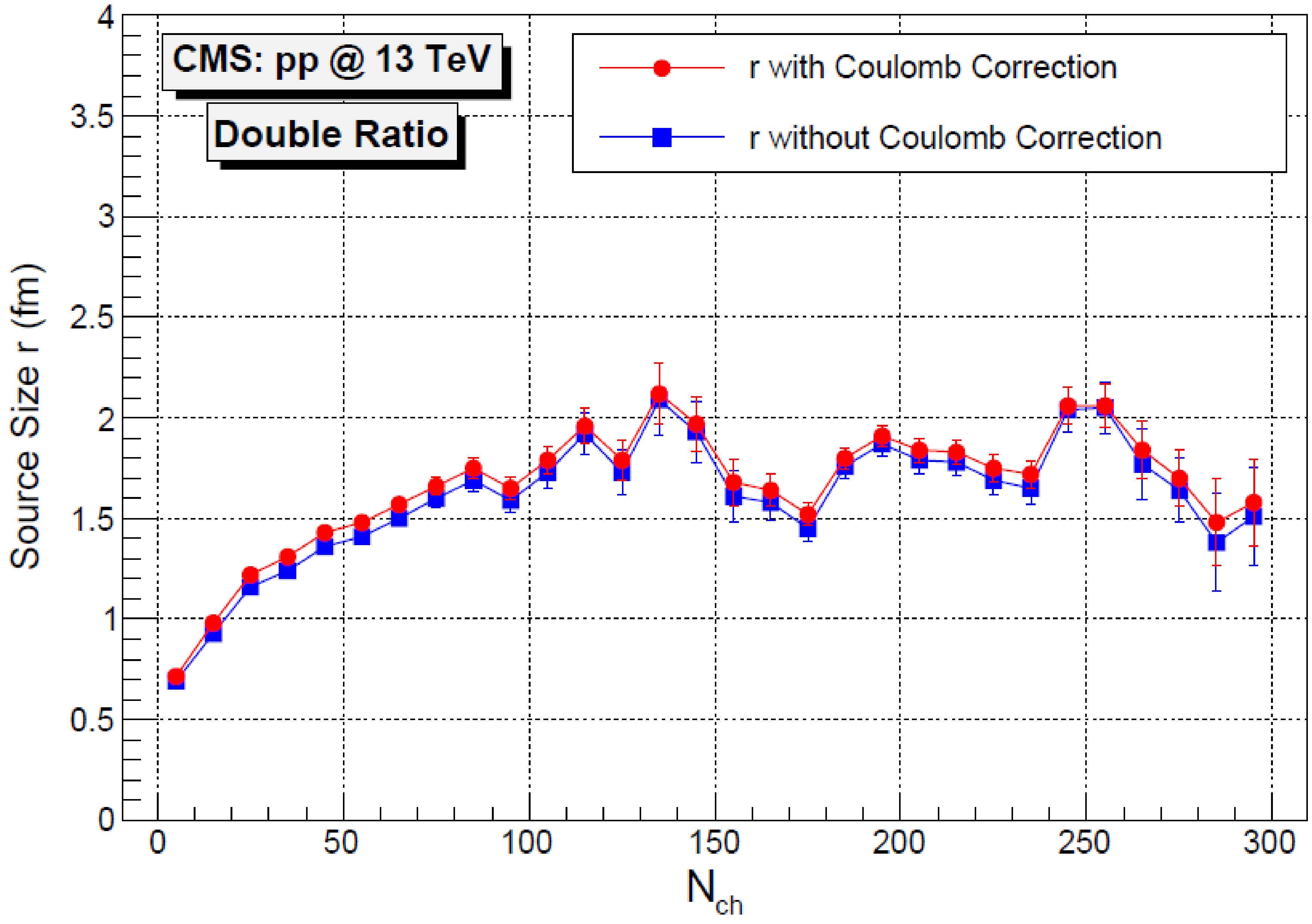
R. S.

Systematic Uncertainties



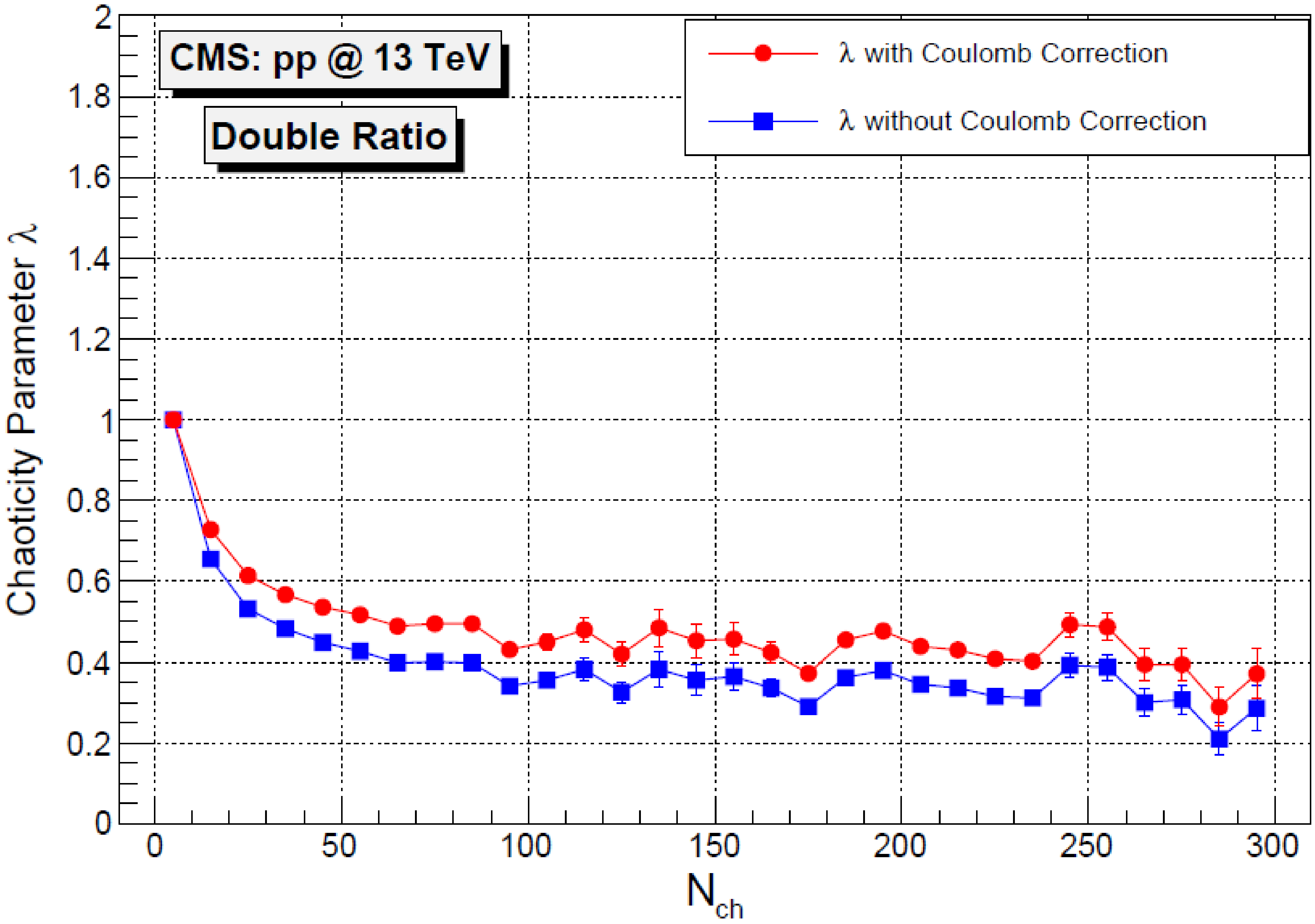
R. S.

Systematic Uncertainties



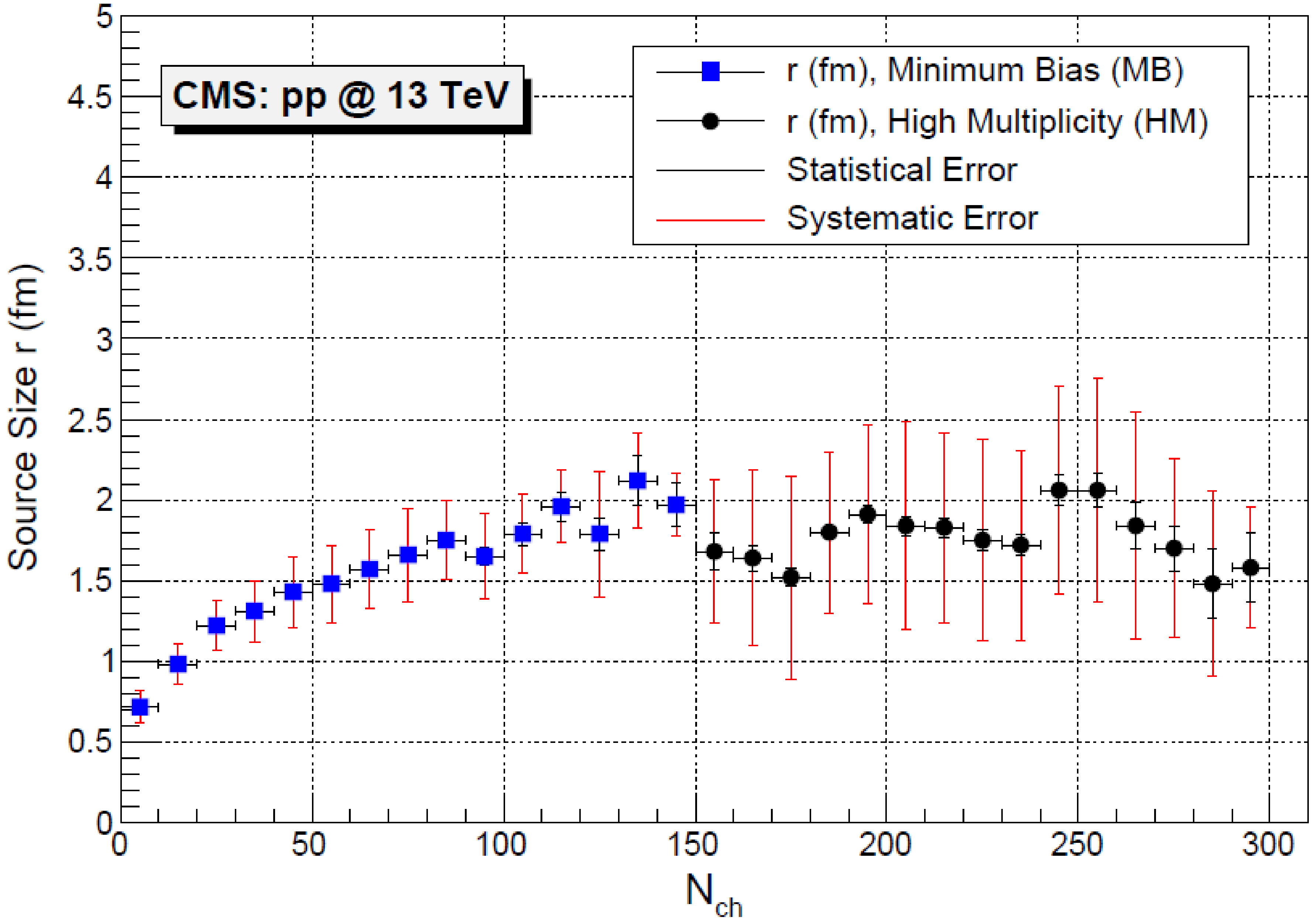
Coul.

Systematic Uncertainties

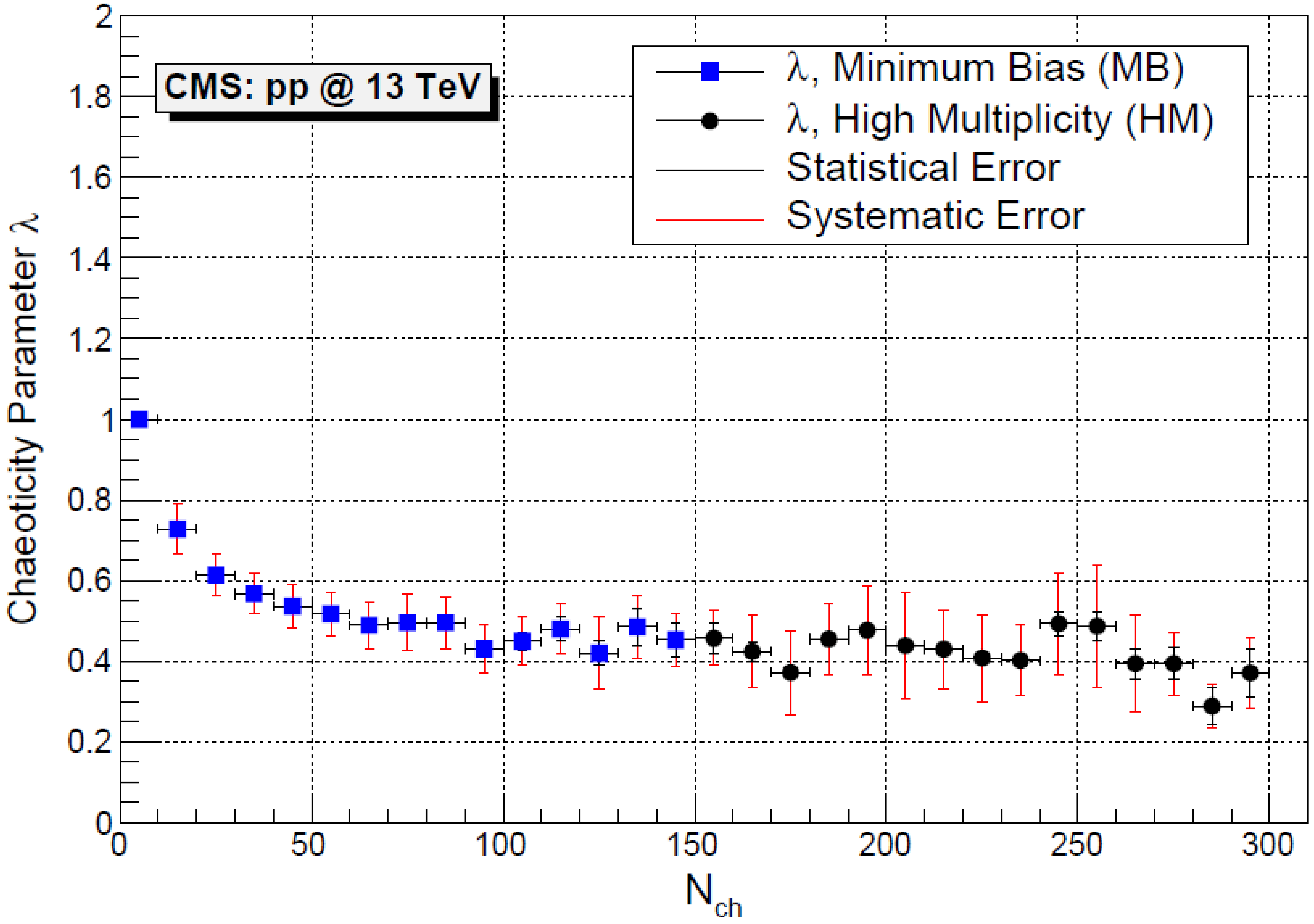


Coul.

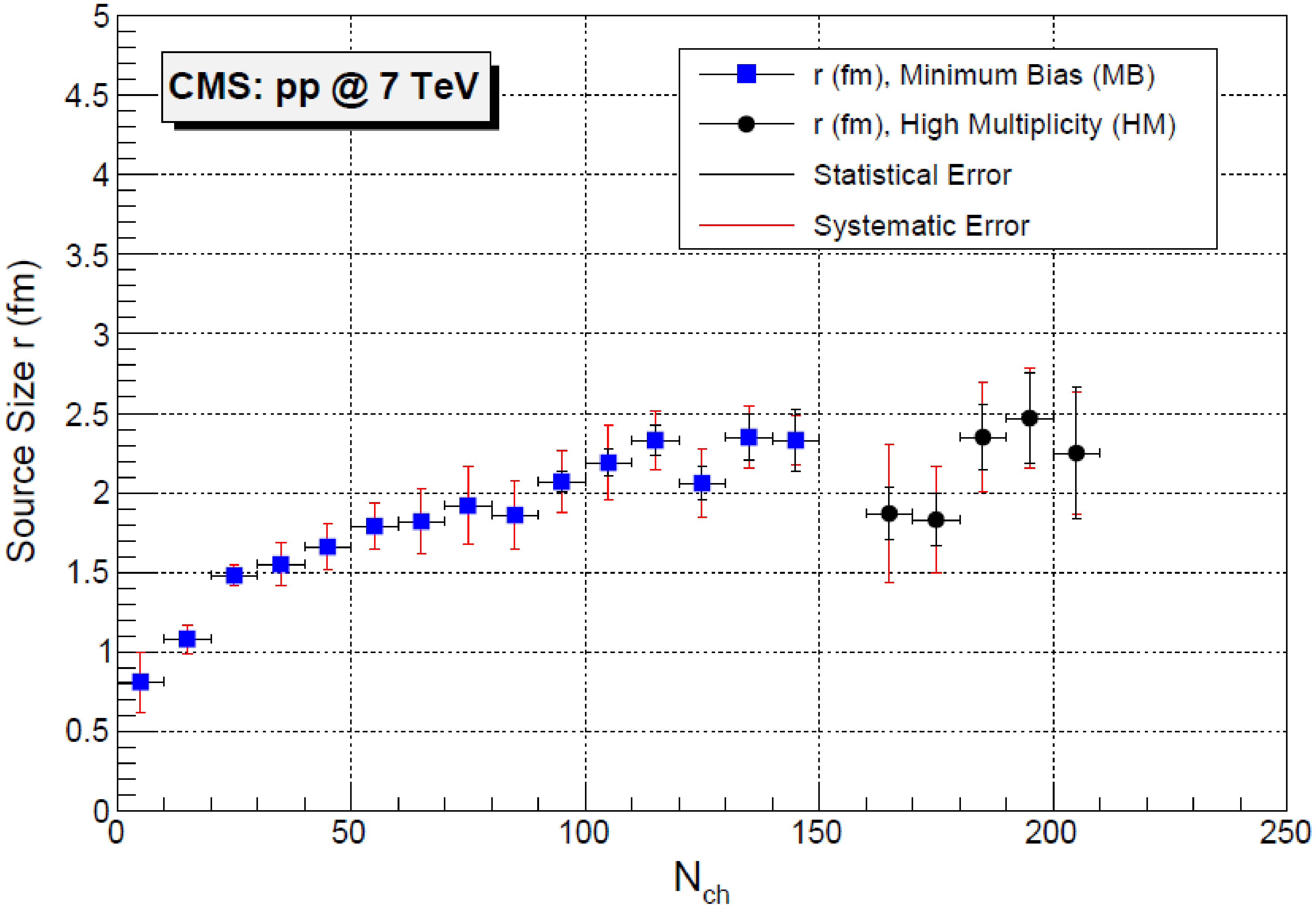
Systematic Uncertainties



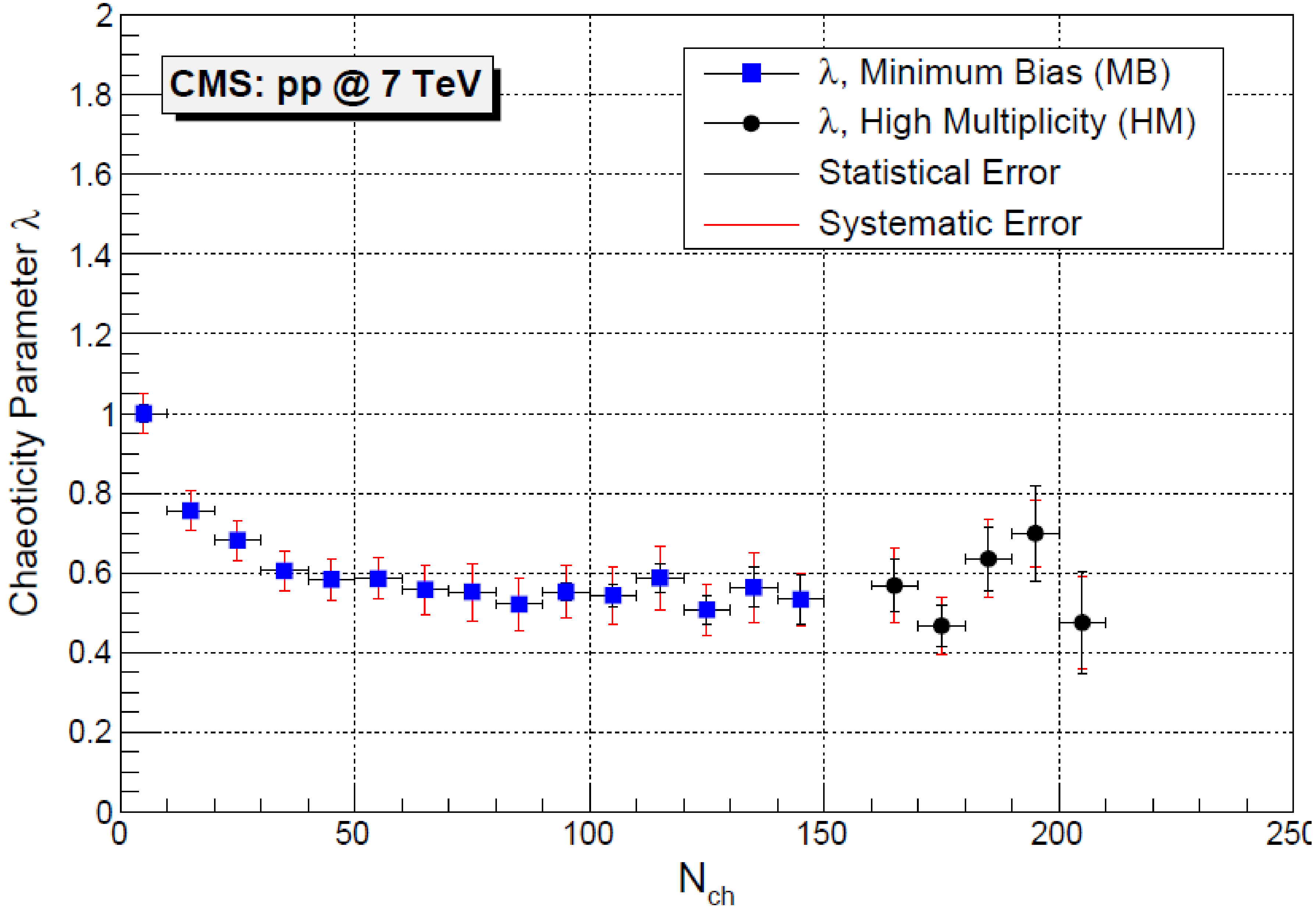
Systematic Uncertainties



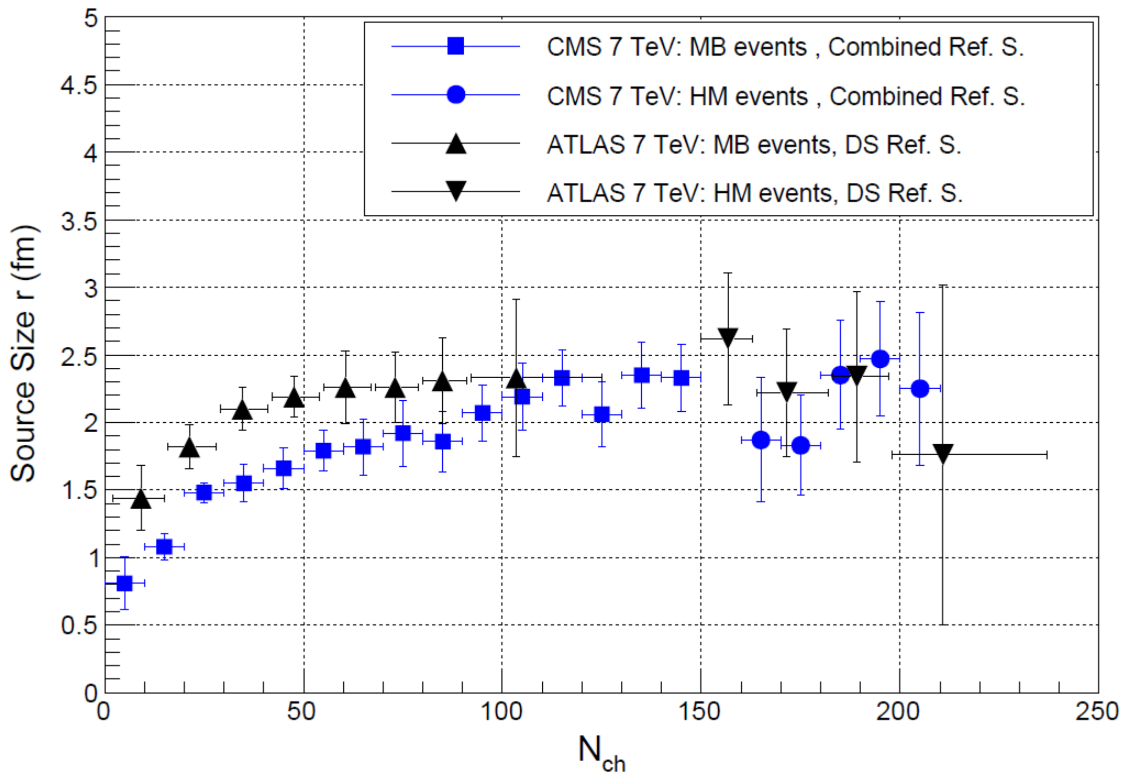
Systematic Uncertainties



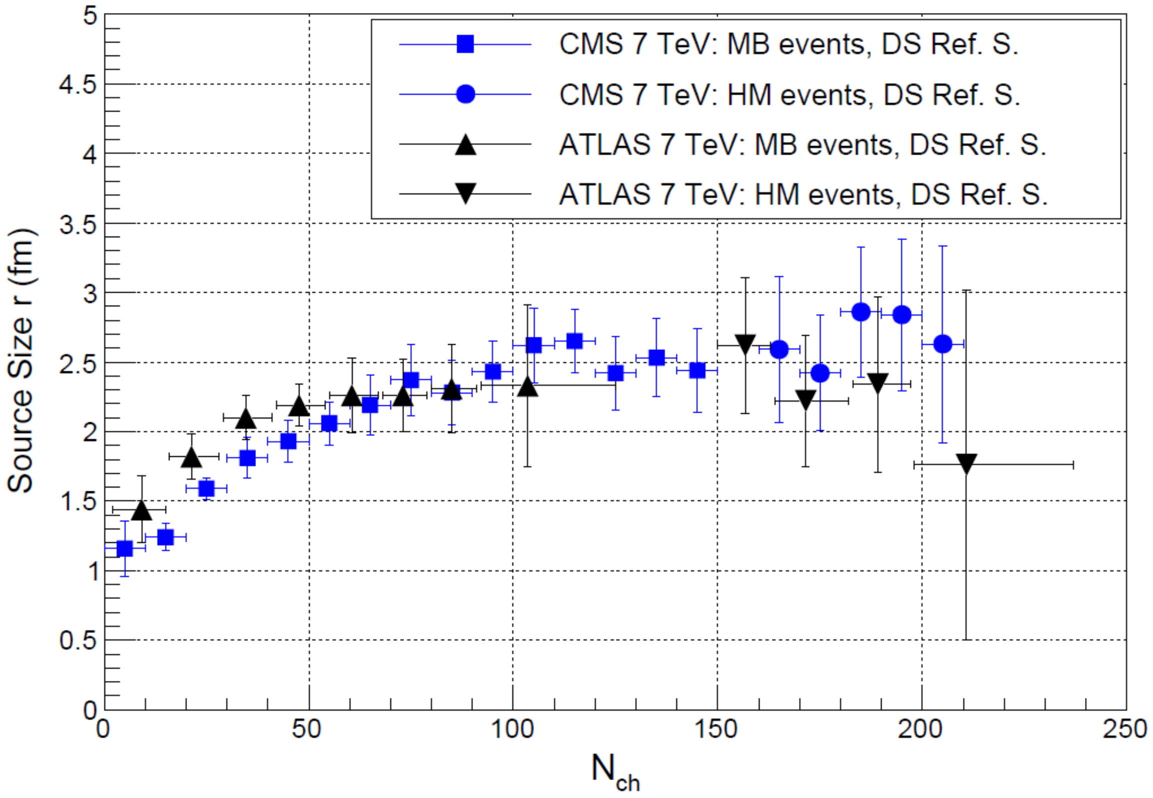
Systematic Uncertainties



Comparison with ATLAS results

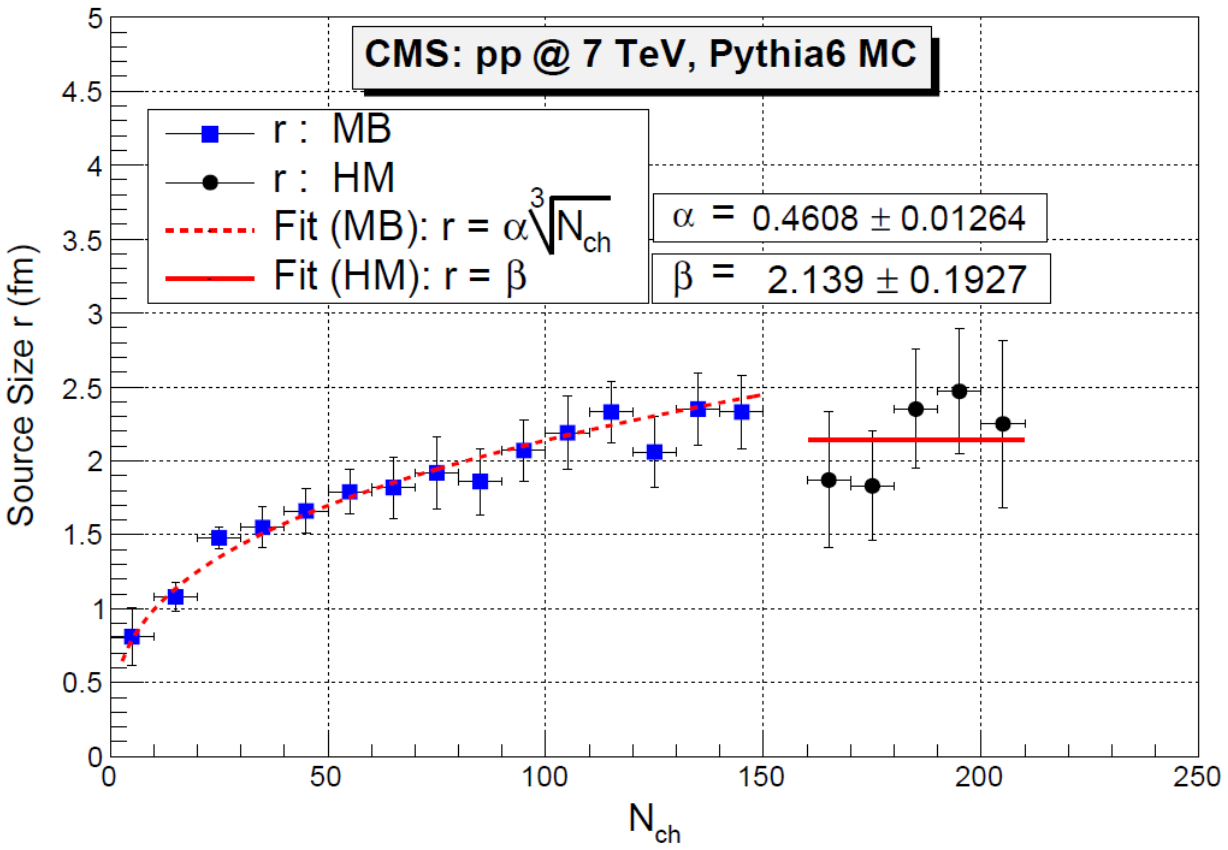


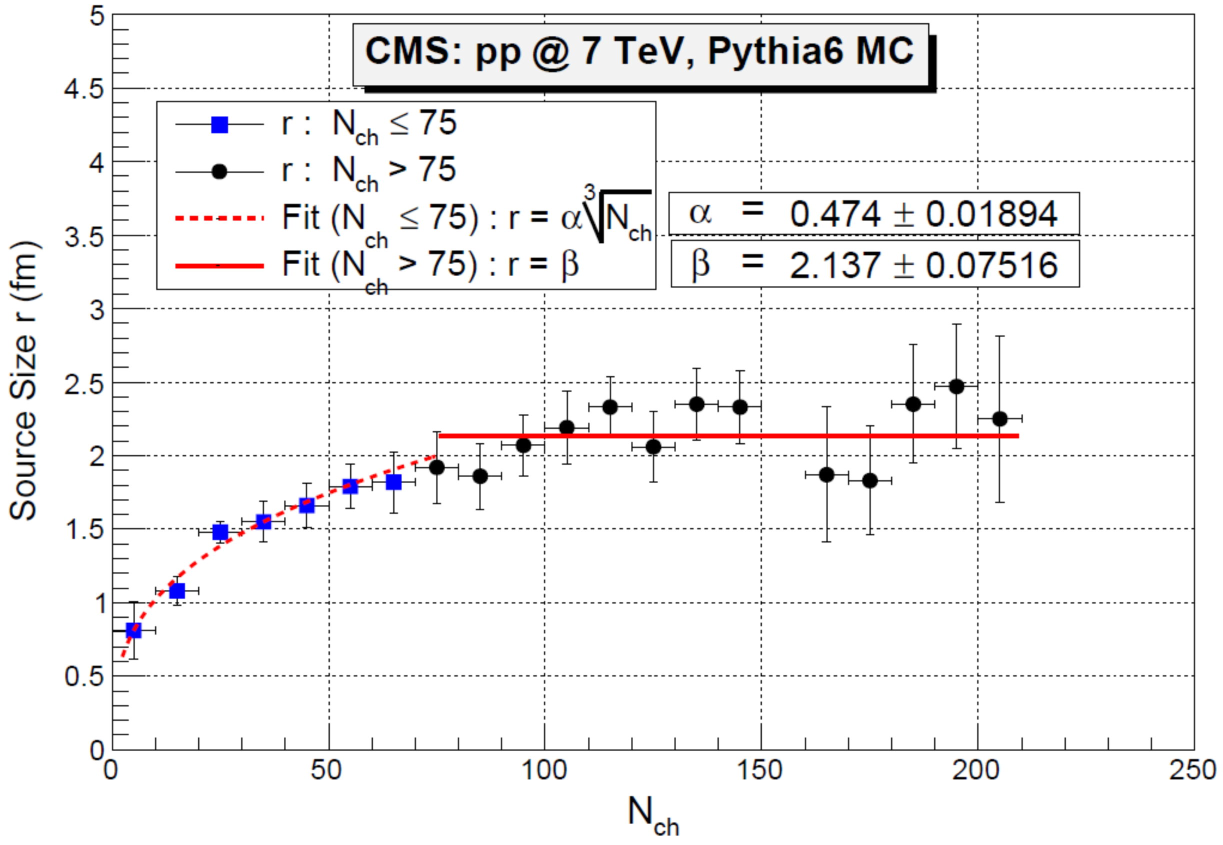
Our results (Combined R. S.) with ATLAS (D.S R.S.)



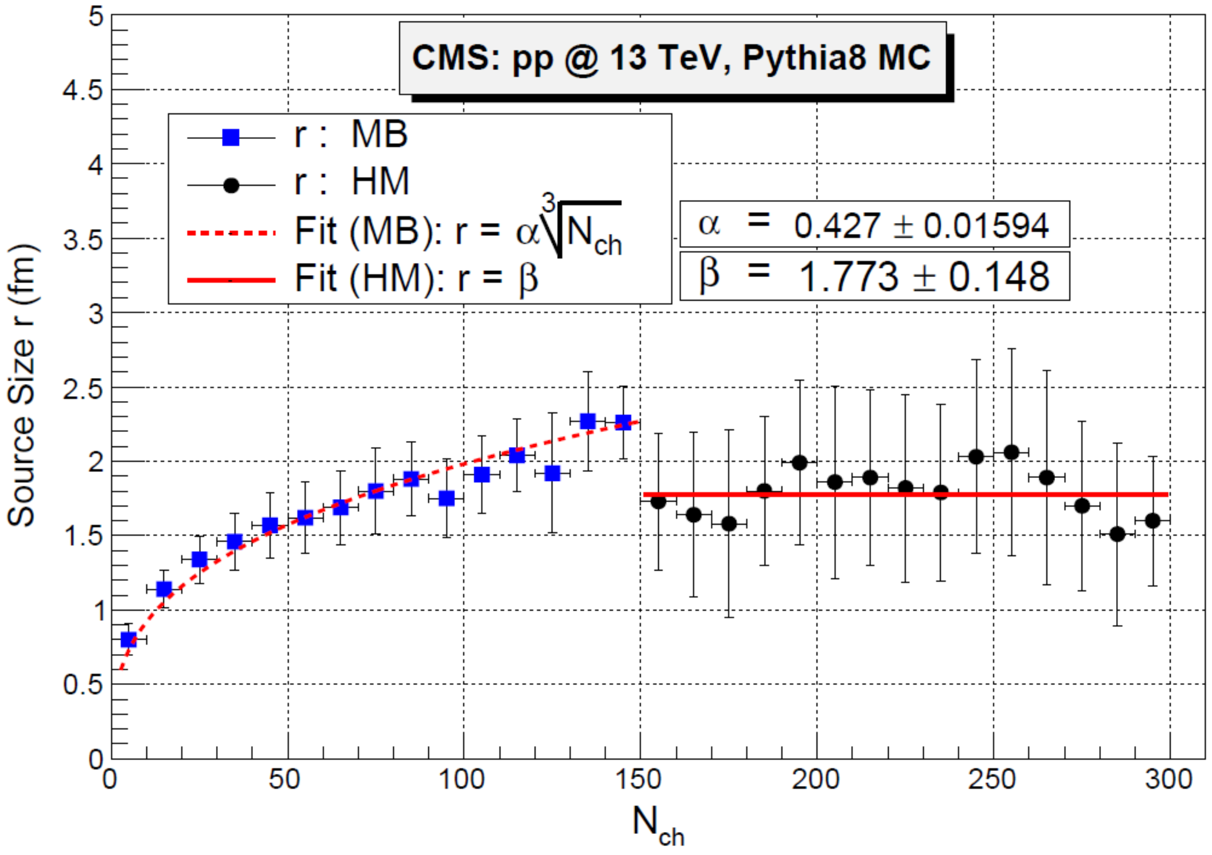
Our results (DS R. S.) V.S. ATLAS results (DS R.S.)

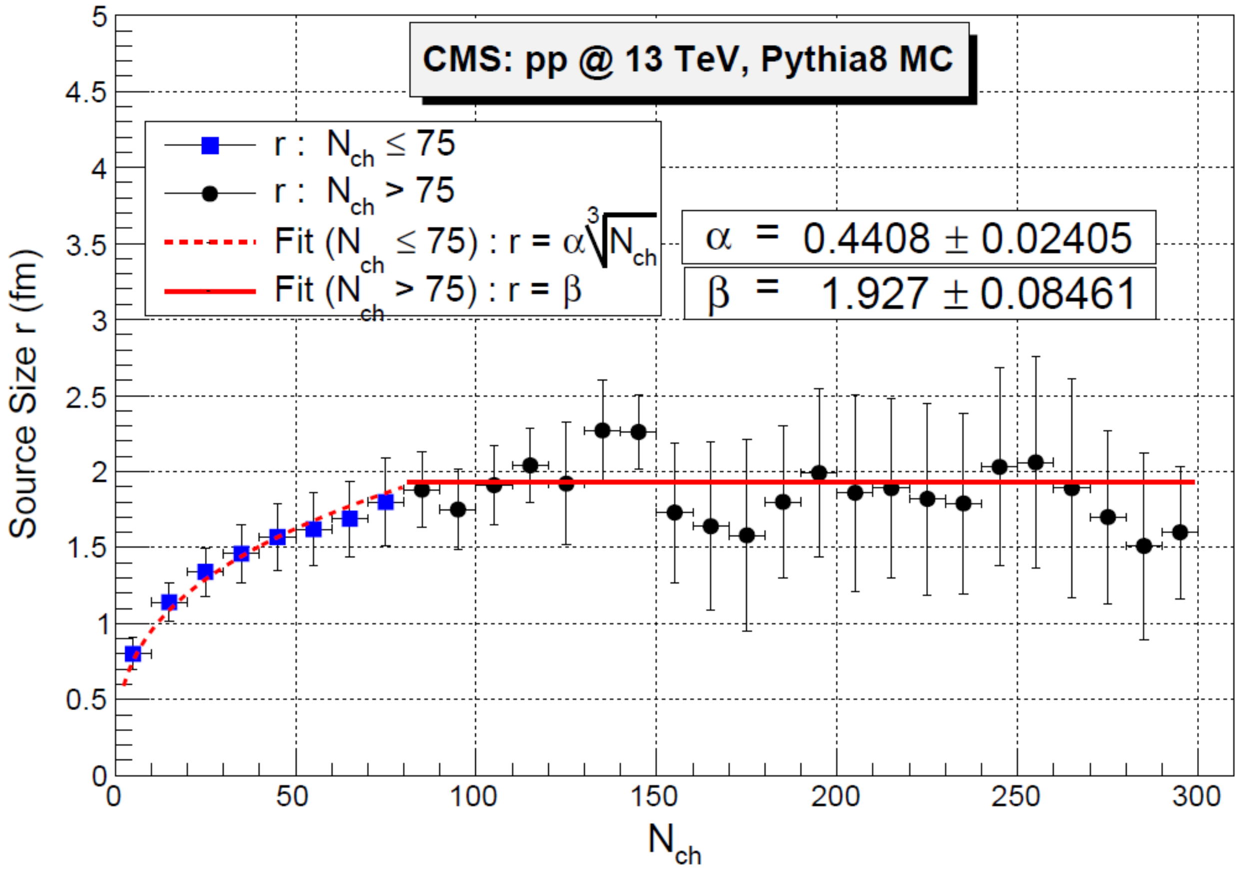
Fitting the source size (7 TeV)





Fitting the source size (13 TeV)





Conclusions

- An increase of the source size r with charged-particle multiplicity N_{ch} in the event is observed at low multiplicities.

- For the first time at CMS, a saturation in the value of the source size occurs at high multiplicities for both 7 TeV and 13 TeV pp collision energies.

- For all energies and multiplicities, the radii decrease with increasing the mean-transverse momentum of the correlated pairs k_T.

- The radii are relatively insensitive to the center-of-mass energy.

- The chaoticity parameter λ decreases with increasing N_{ch} and k_T .


Thank You