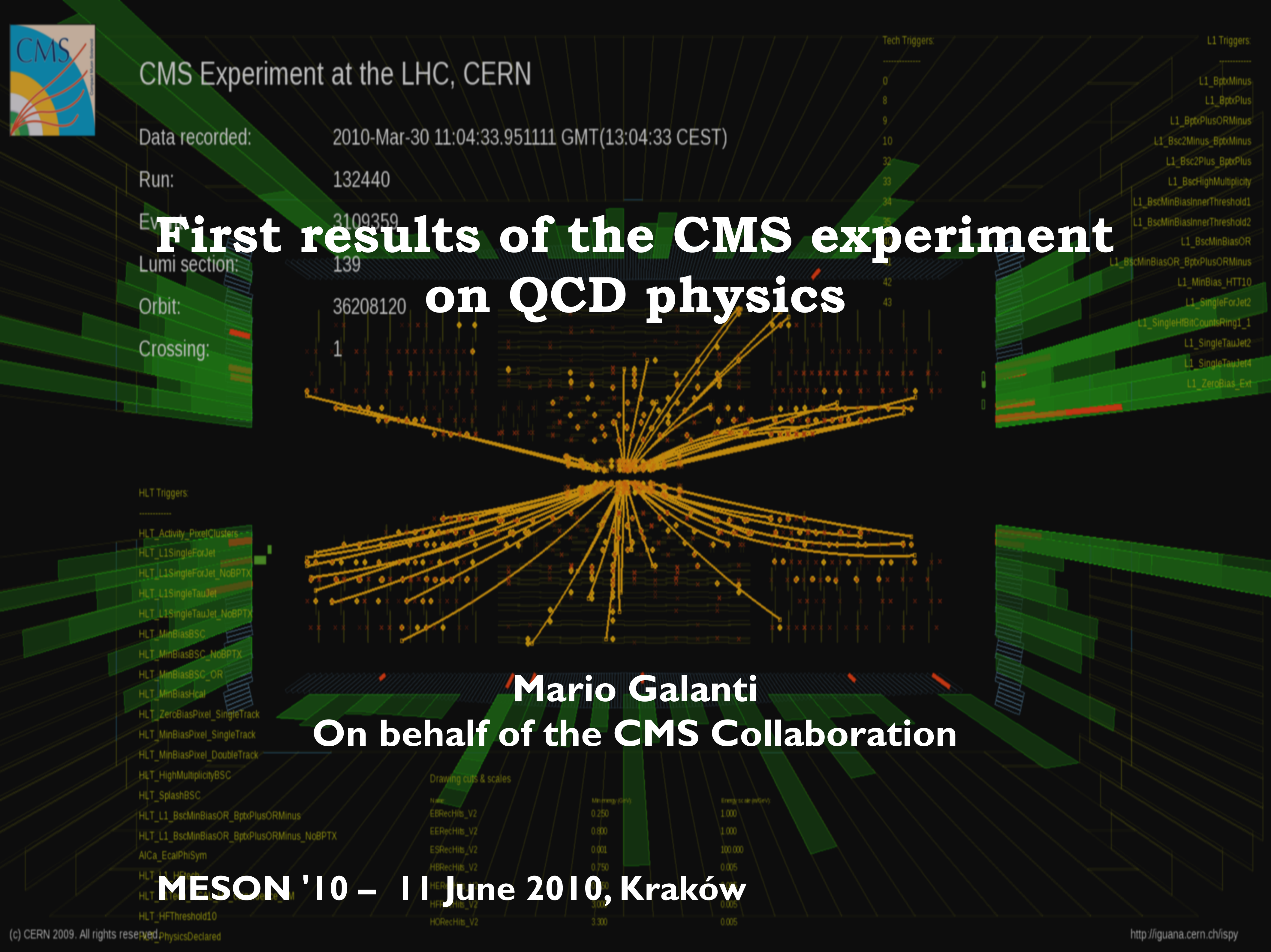
First results of the CMS experiment on QCD physics



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On behalf of the CMS Collaboration

MESON '10 – 11 June 2010, Kraków

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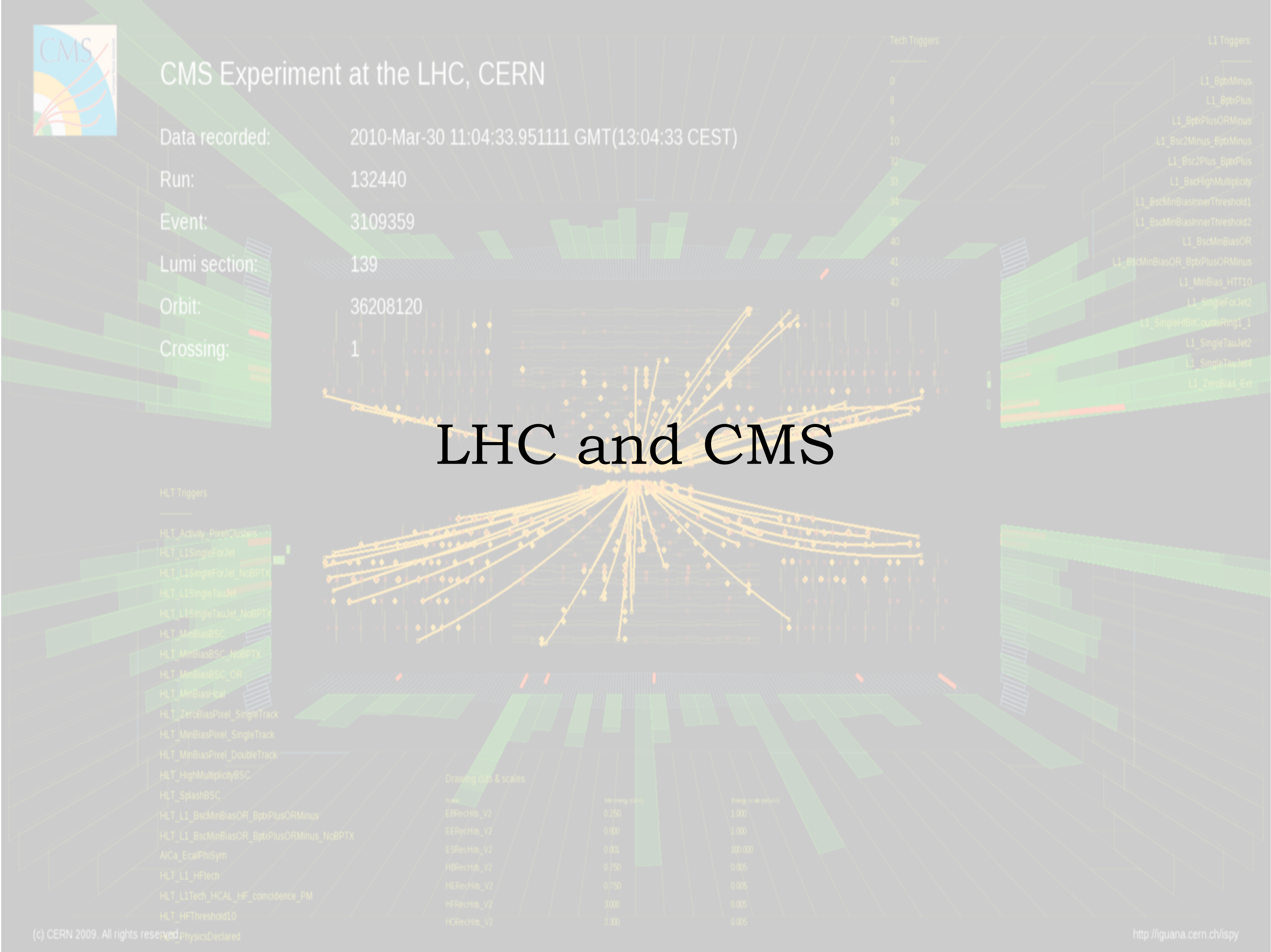
Summary

- Introduction: LHC and CMS
- Results
  - Charged multiplicity distributions
    (JHEP 02 (2010) 041 – preprint: CERN-PH-EP/2010-009)
  - Bose-Einstein correlations
    (preprint: CERN-PH-EP/2010-010)
  - Two-particle correlations
    (preliminary results: CMS-PAS-QCD-10-002)
  - Underlying event measurements
    (preprint: CERN-PH-EP/2010-014)
- Conclusions

LHC and CMS


CMS Experiment at the LHC, CERN
Data recorded: 2010-Mar-30 11:04:33.951111 GMT(13:04:33 CEST)
Run: 132440
Event: 3109359
Lumi section: 139
Orbit: 36208120
Crossing: 1
Tech Triggers
L1 Triggers
HLT Triggers
Drawing cuts & scales
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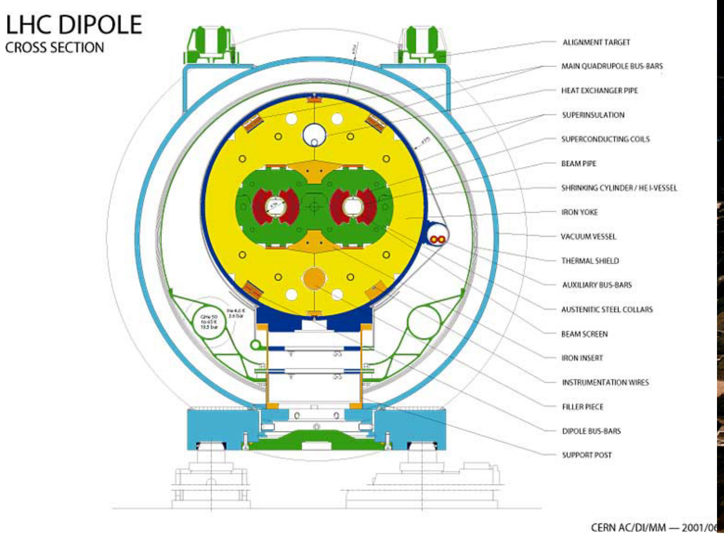
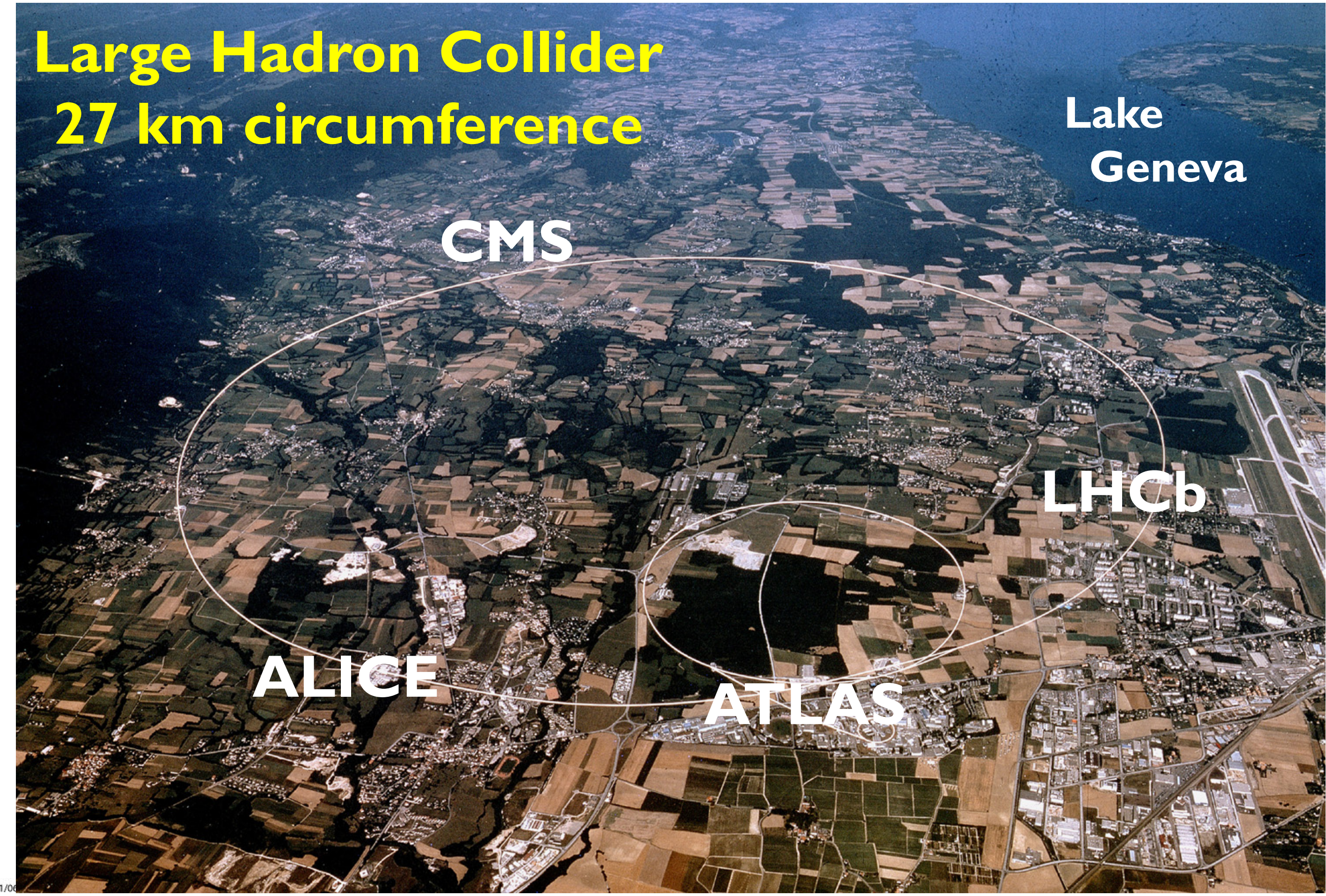
LHC

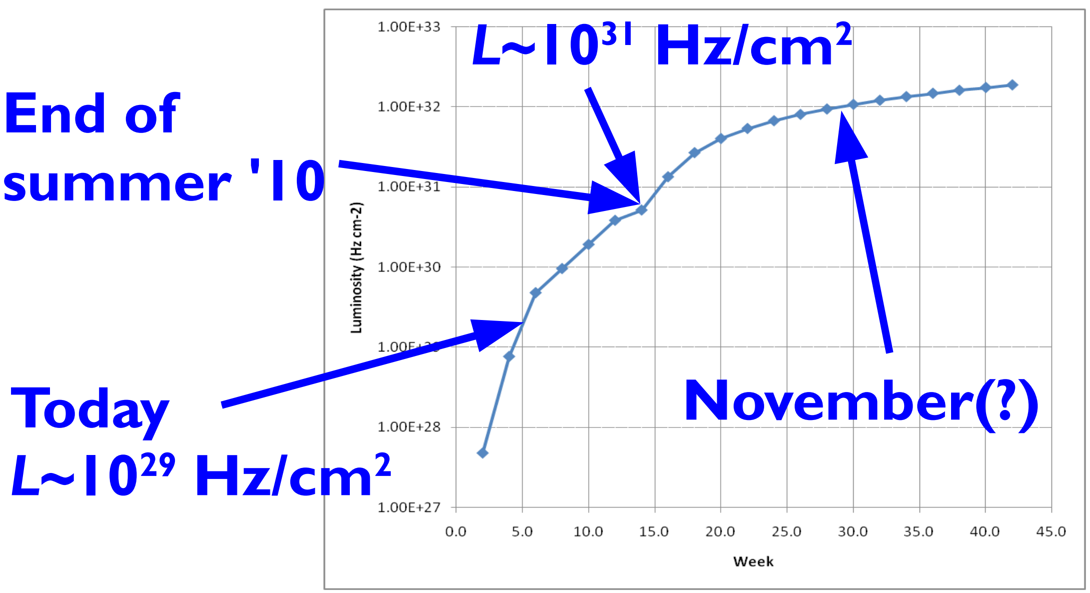
- 8 arcs (sectors)
- 8 long straight sections (700 m long)
- 2 separate vacuum chambers
- Beams cross in 4 points (ATLAS, ALICE, CMS and LHCb)

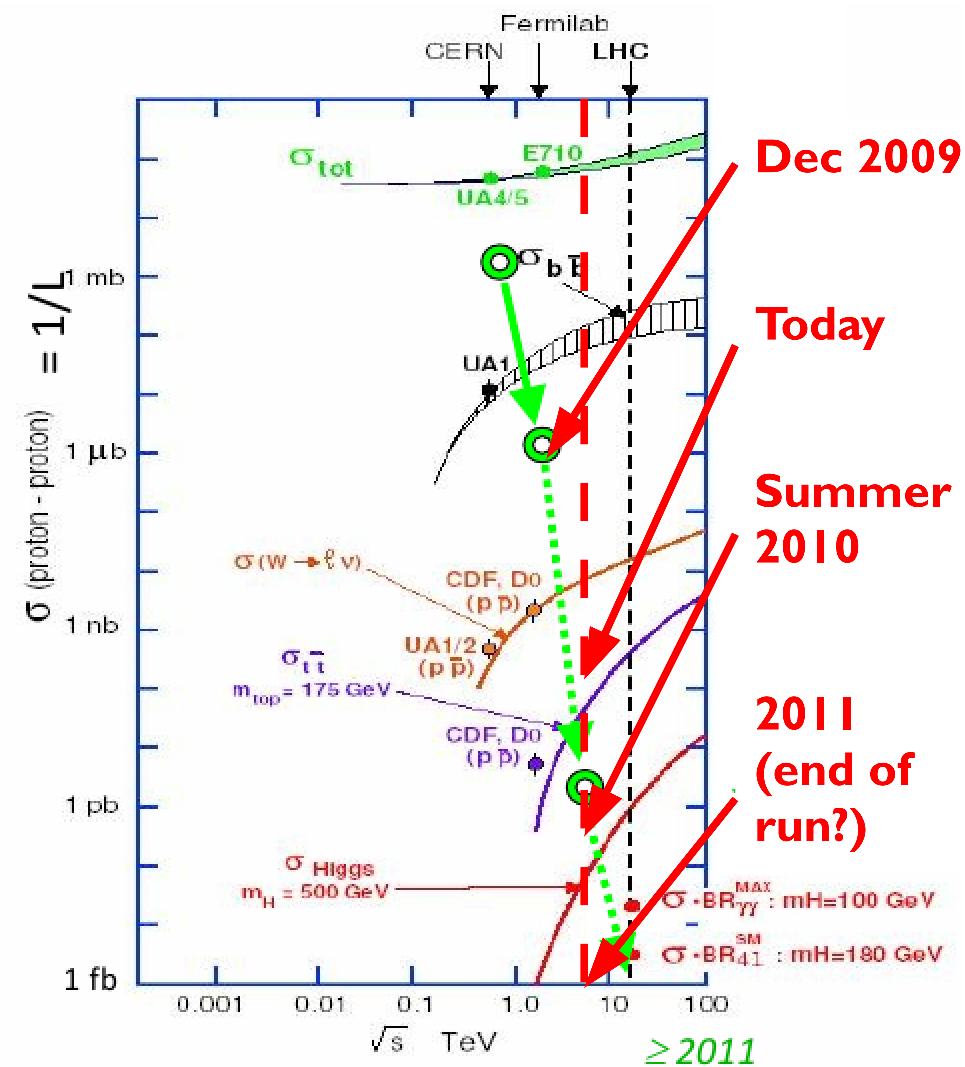




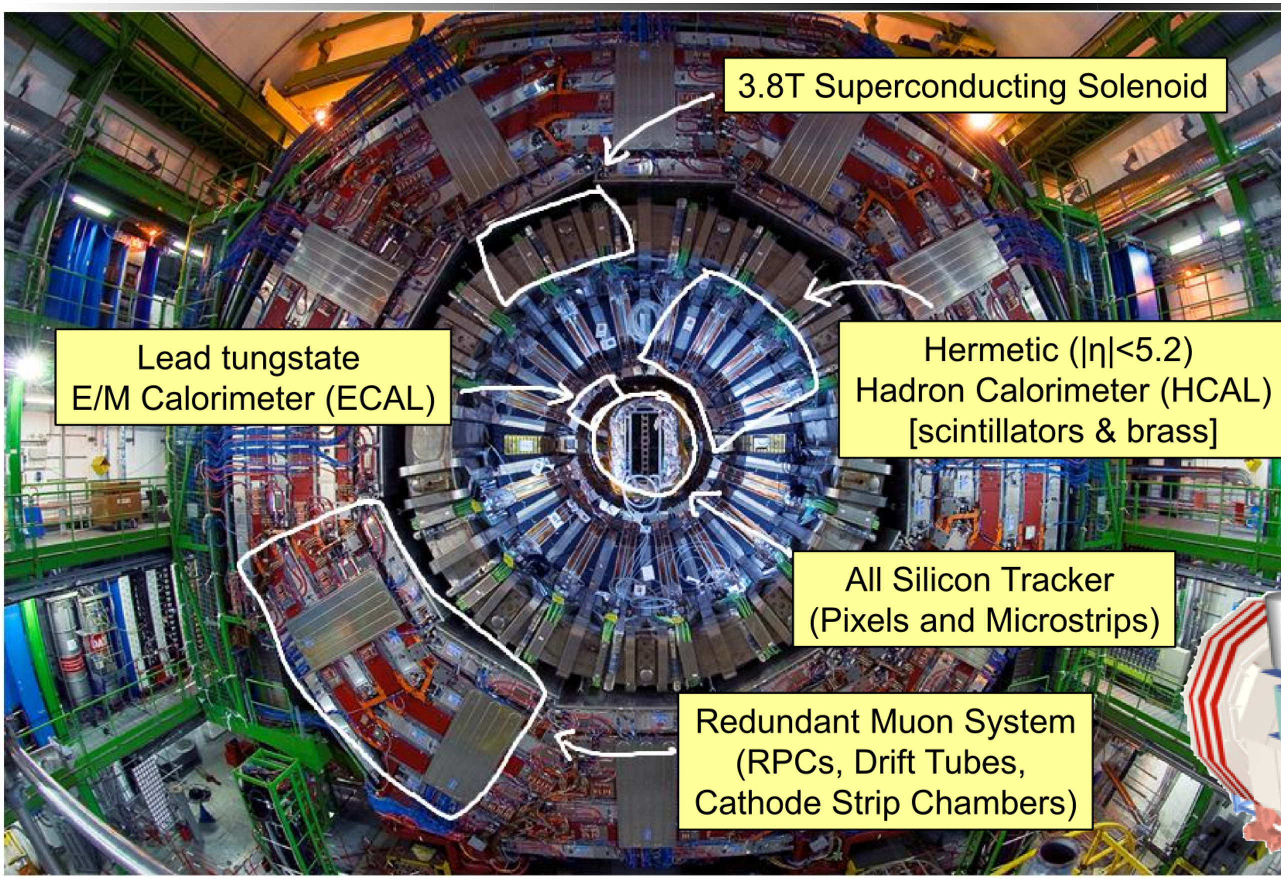
LHC status and plans for 2010-11

- LHC will continue to work at 3.5+3.5 TeV for the next ~1.5 y
  - Machine commissioning (to increase instant luminosity) + “physics” runs
- Long stop (~1 year) scheduled afterwards, to prepare for 14 TeV operation
- Short heavy ion runs in 2010 and 2011





The CMS detector

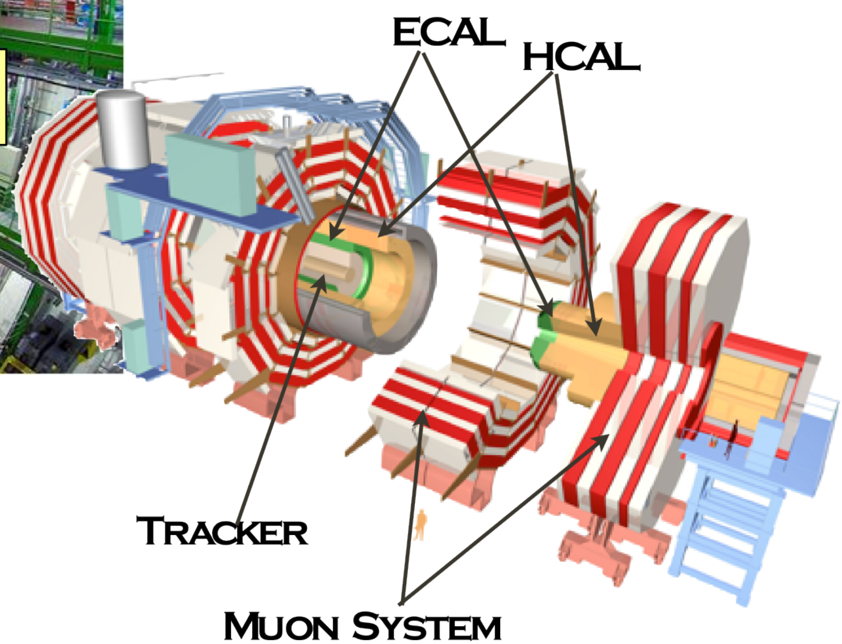


Total weight: 12'000 tons

Diameter: 15 m

Length: 22 m

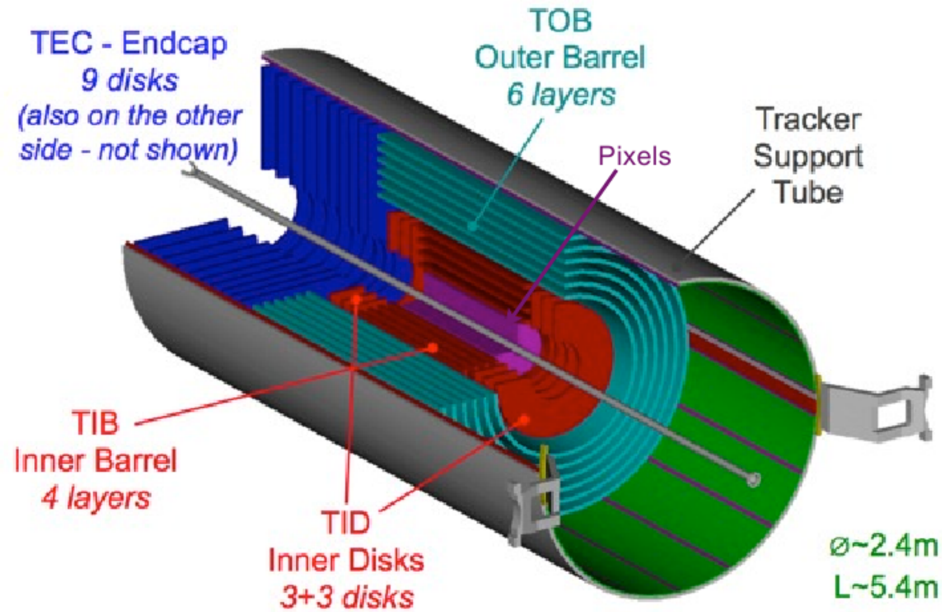
Superconducting coil temp.: 4 K



The CMS tracker

Silicon pixel detector surrounded by silicon strip detectors

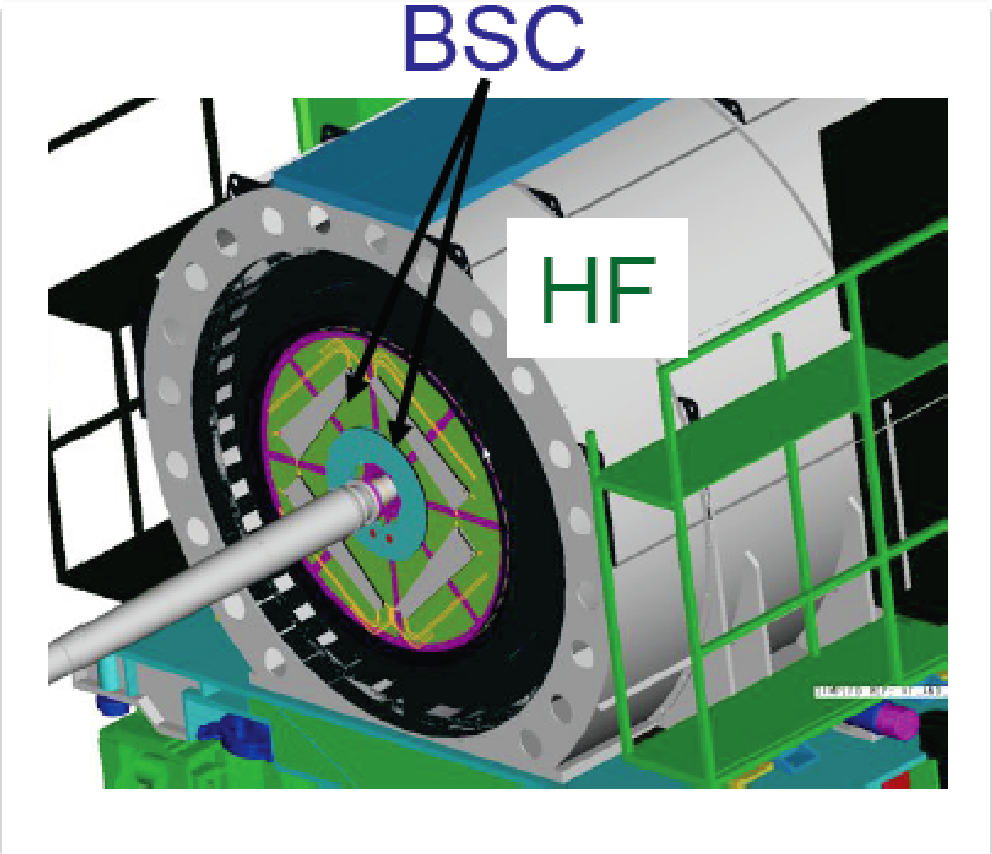
- $|\eta|<2.5$ $[\ \eta = -\ln(\tan(\theta/2))\ ]$
- Pixel
  - 3 barrel layers (R=4, 7, 11 cm), 2 endcap disks
  - ~1 m^2 of Si sensors, 66M channels, 1440 modules
- Strips
  - 10 barrel layers, 9+3 endcap wheels per side
  - ~198 m^2 of Si sensors, ~9.6M channels, 15148 modules
- From simulation studies
  - Tracking efficiency > 99% (μ), >90% (hadrons)
  - Resolution: $\Delta p/p$ ~ 1-2% (@100 GeV, $|\eta|<1.6$)



Physics environment	Design requirements
High particle fluence	Radiation hardness
High track density	High granularity
25 ns bunch crossing	Fast analog readout

The CMS HF calorimeter

- The Hadron Forward (HF) calorimeter covers the range $2.9 < |\eta| < 5.2$
- ~11m from interaction point
- Steel – Cherenkov quartz fiber
- Fast readout
- η, φ segmentation of 0.175x0.175
- Embedded Beam Scintillation Counters (BSC) used to trigger on collision events

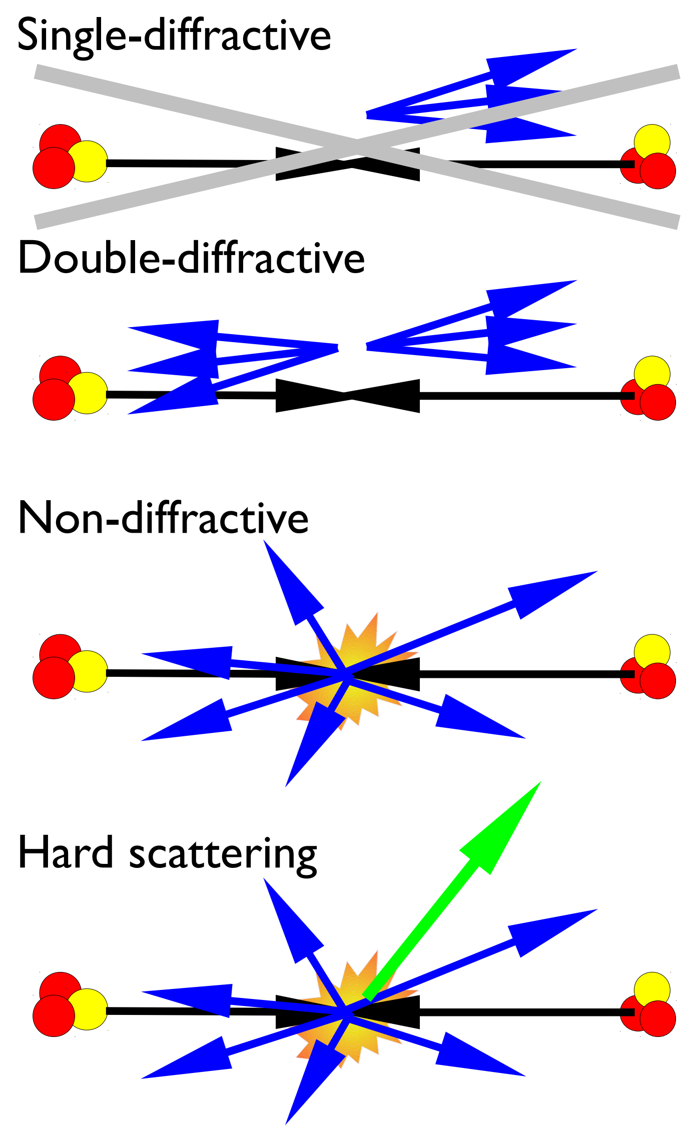


CMS data taking in a nutshell

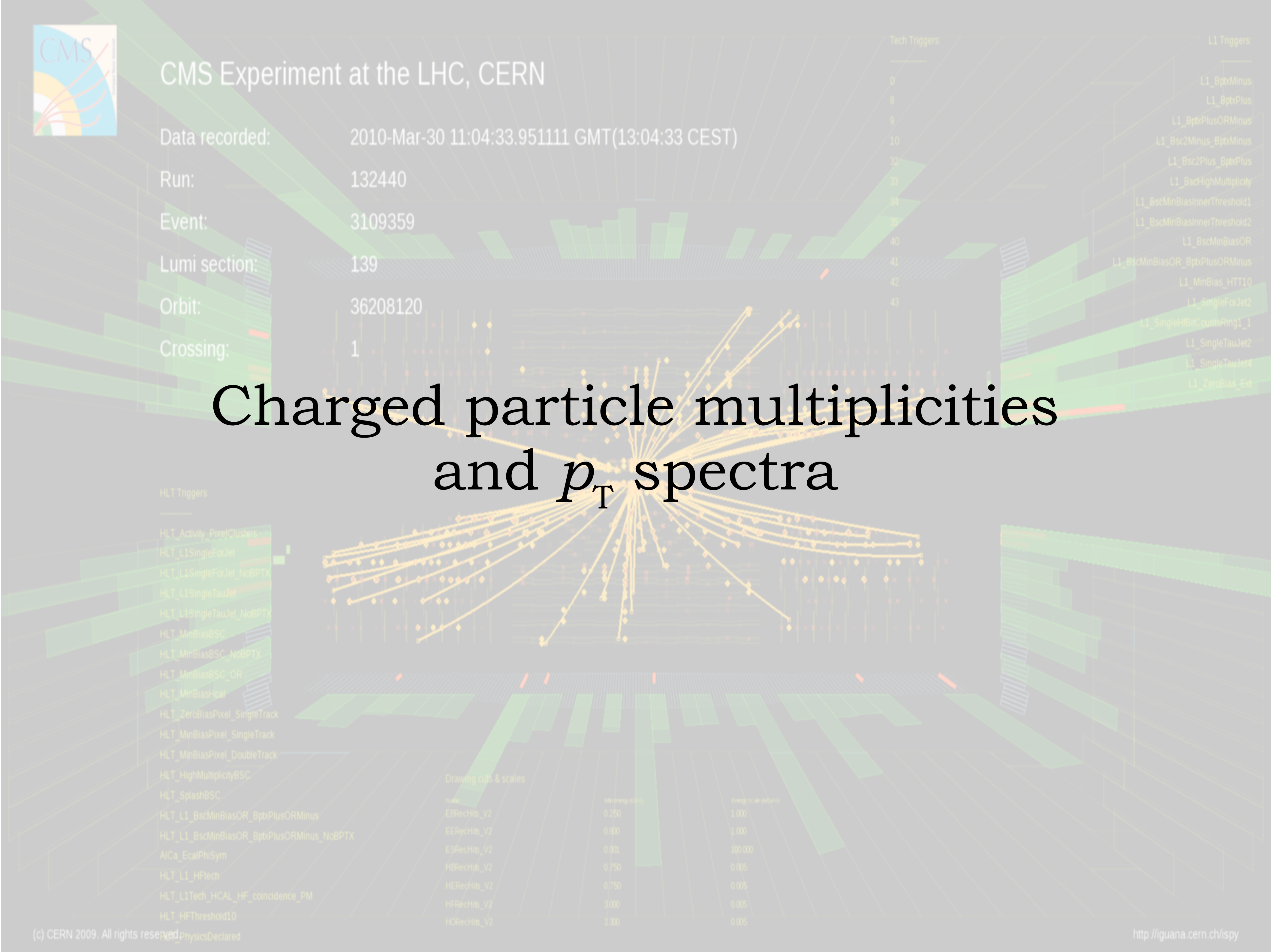
- Total integrated luminosity (beginning of June '10)
  - 0.9 TeV ($3.9 \cdot 10^5$ evts – L_{int}~10 μb^{-1})
  - 2.36 TeV ($2 \cdot 10^4$ evts – L_{int}<1 μb^{-1})
  - 7 TeV (L_{int}>18 nb^{-1}) ~Growing exponentially with time!
- Analysis work ongoing: only a small fraction of the 7 TeV data has been used for the results shown in the next slides
- CMS has had a very good performance
  - >99% of detector channels operational
  - High data taking efficiency (~90%)
  - Prompt analysis chain working
  - First results shown already after ~2 days from first collisions!

Trigger and selection

- "**Minimum bias**" collision events are selected using signals from
  - **BSC**
  - **Beam Pick-up Timing for Experiments (BPTX)**: two detectors at 175 m from interaction point that measure the presence of the beam
- **Requirements**:
  - Coincidence of BSC and BPTX on both sides
  - Request for a well reconstructed primary vertex
- Rejection of events induced by beam halo and beam background
- Some analyses use only **Non Single-Diffractive (NSD)** events
  - Selected requiring at least one tower with E > 3 GeV in **each** side of HF

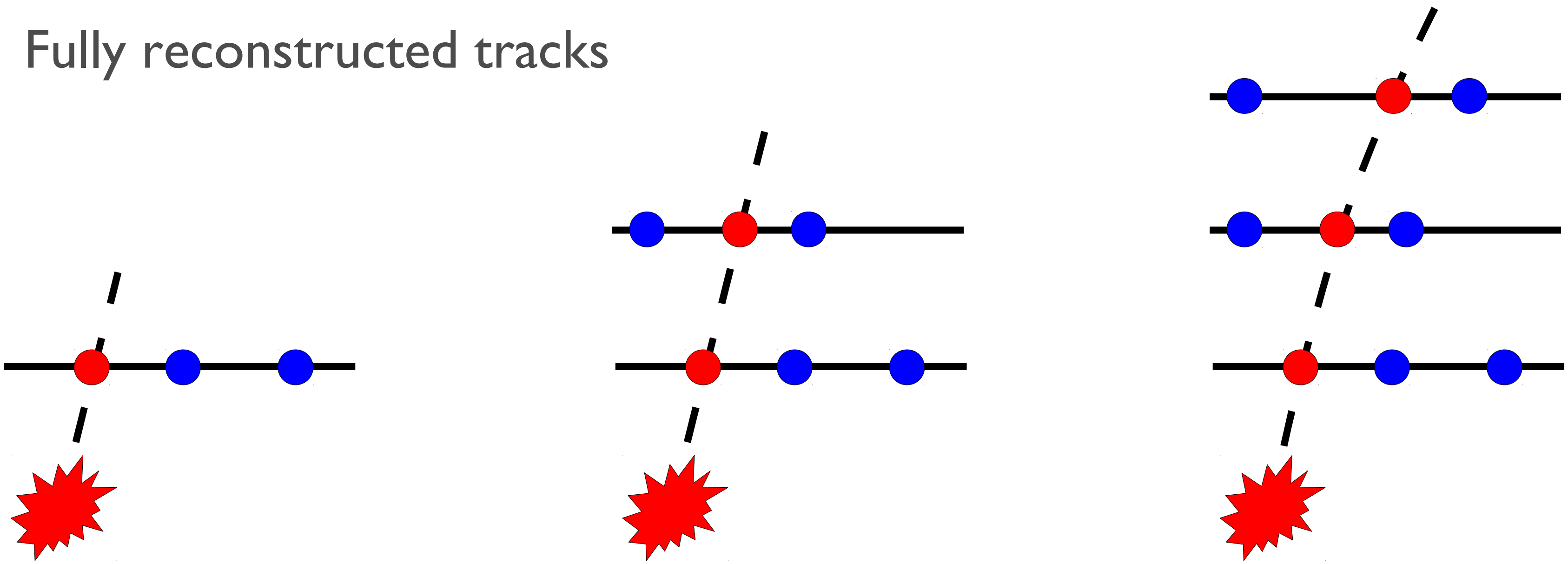


Charged particle multiplicities and p_T spectra



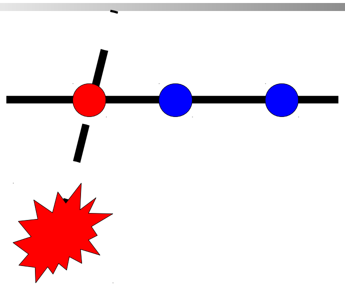
Measurement techniques

- Three different measurement techniques applied
  - Number of clusters (hits) in the pixel detector
  - Track fragments (“tracklets”) obtained correlating two hits in the pixel detector, compatible with the vertex
  - Fully reconstructed tracks

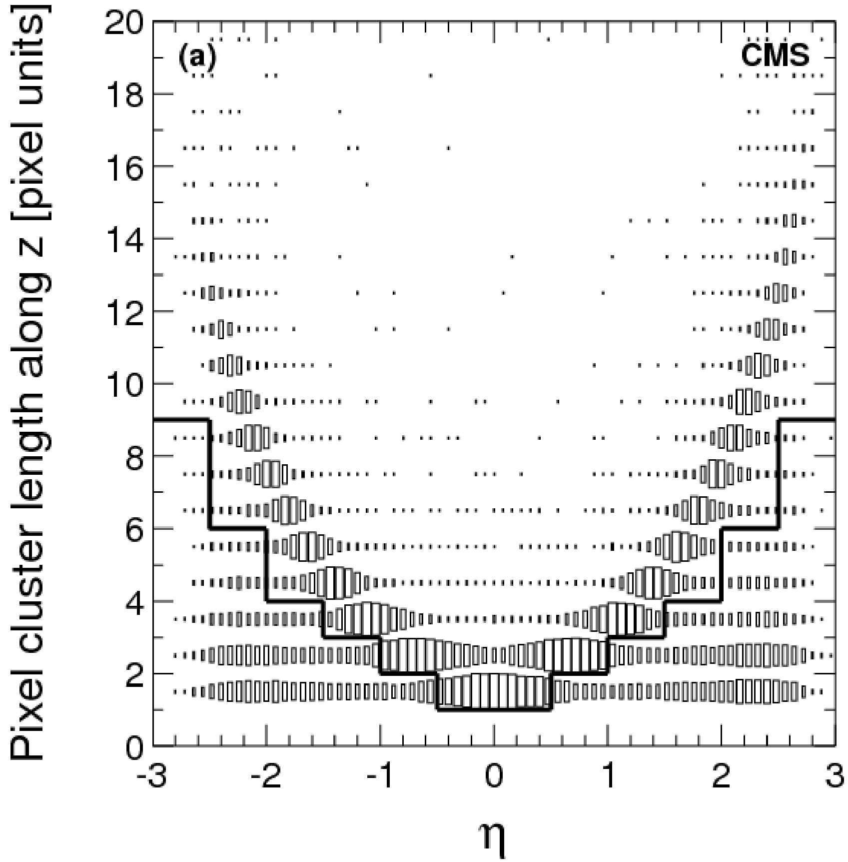


Pixel hit counting $p_T > 30$ MeV | Tracklets $p_T > 50$ MeV | Tracks $p_T > 100$ MeV

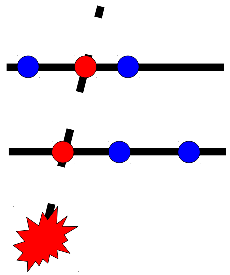
Pixel cluster counting



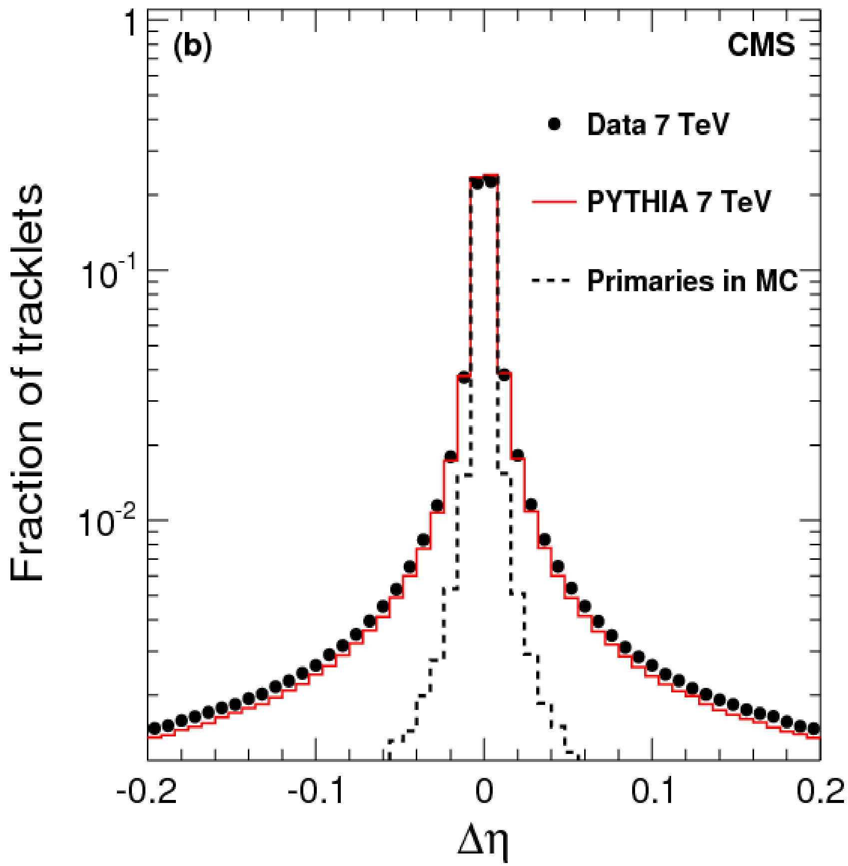
- Clusters belonging to tracks coming from the interaction point are selected cutting on their size along z
- Cluster length for tracks coming from primary vertex is ~|sinh(η)|
- Short clusters coming from loopers, displaced decays, secondaries are removed



Tracklets

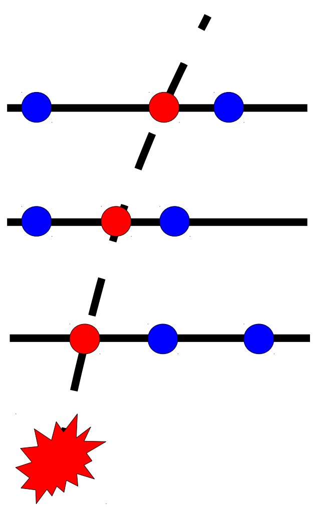


- Track fragments (tracklets) coming from interaction point are selected exploiting the strong correlation in η between their two hits
- Combinatorial background subtracted using sideband technique
  - Signal region $|\Delta\varphi|<1$, $|\Delta\eta|<0.1$
  - Sideband region $1<|\Delta\varphi|<2$
  - Background flat in $|\Delta\varphi|$
- MC-based corrections for acceptance, weak decays, secondaries, pixel efficiency, splitting



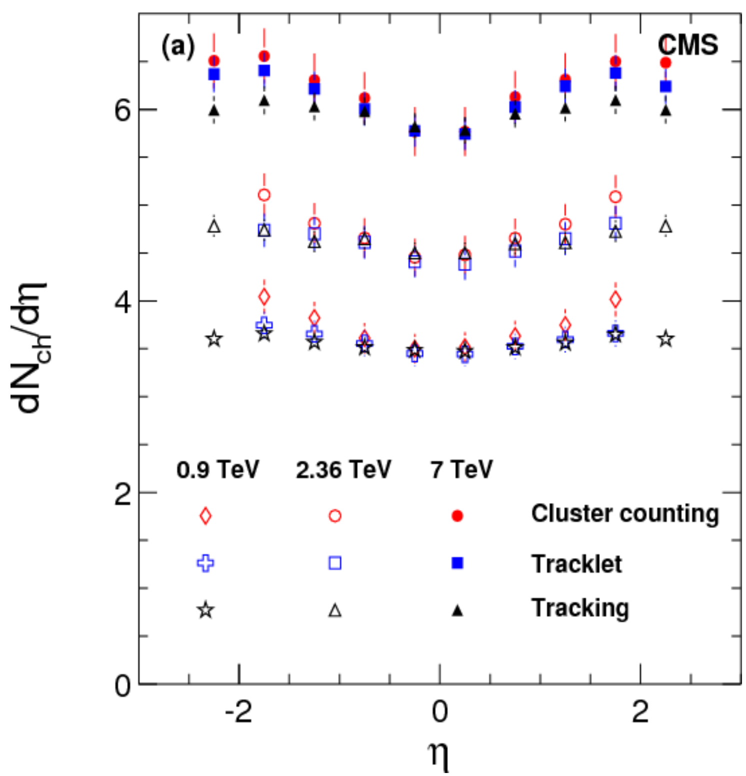
Tracks

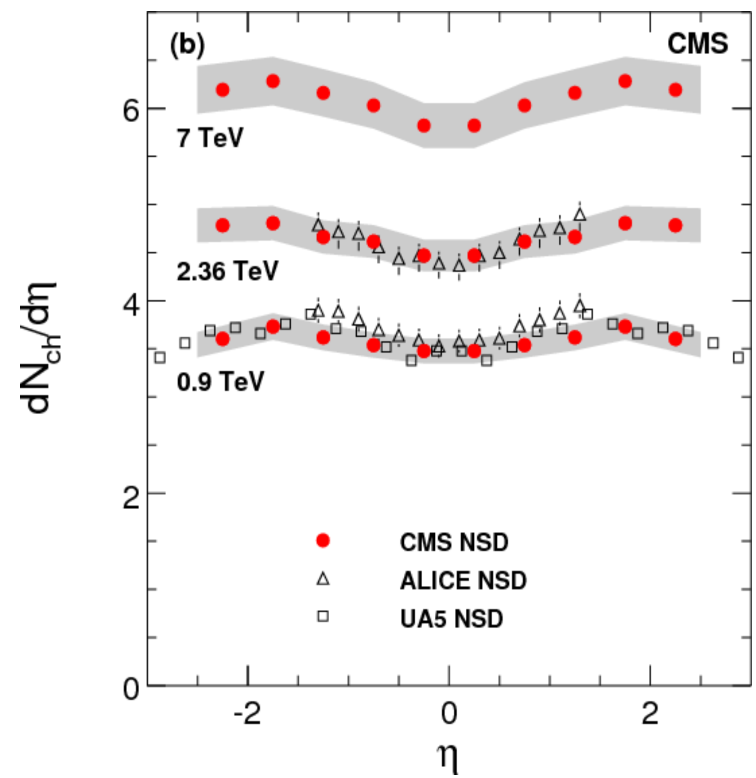
- The third method uses fully reconstructed tracks in pixel and strip detectors
- Tracking algorithm uses several iterative steps
- Background reduced by selecting tracks
  - with at least 3 hits in pixel + strips
  - compatible with primary vertex
- This method gives the cleanest results, but
  - Has the highest p_T threshold
  - Requires good knowledge of alignment and beam-spot



Results: $dN_{ch}/d\eta$

- **Left**: results obtained with the three methods for NSD events
  - Compatible within the errors
- **Right**: averaged results compared with ALICE and UA5
  - Systematic uncertainties mainly coming from trigger, event selection, reconstruction efficiencies (~5%)



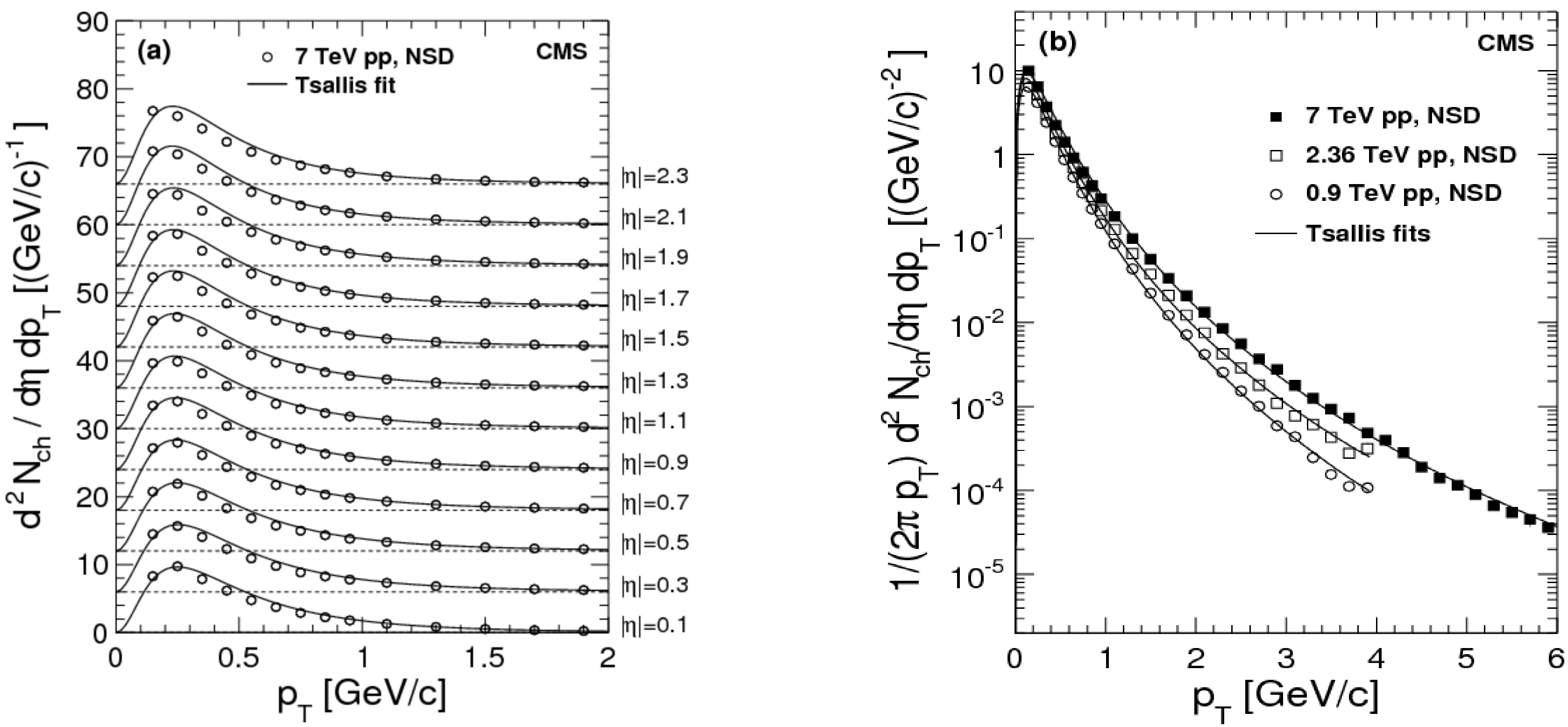


Results: p_T

- p_T distributions fitted with Tsallis function (exp + power law)

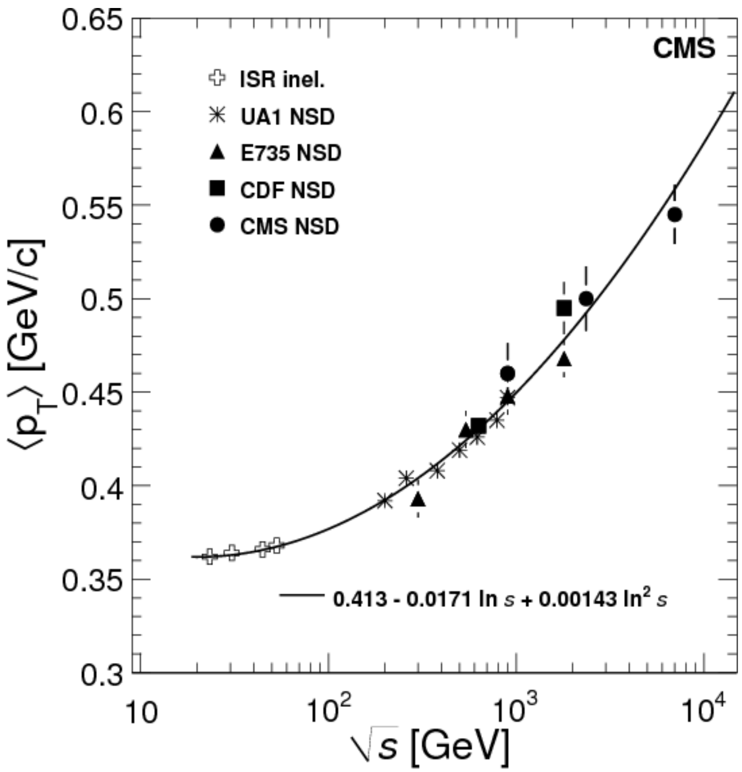
$$E\frac{d^3N_{ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$

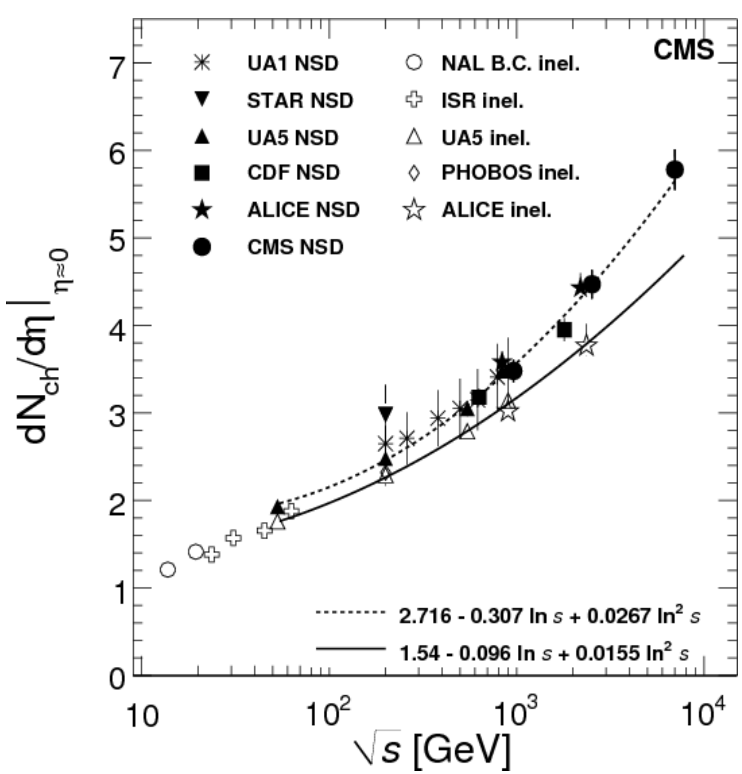
Loose depencence on η, so fit in the whole range possible



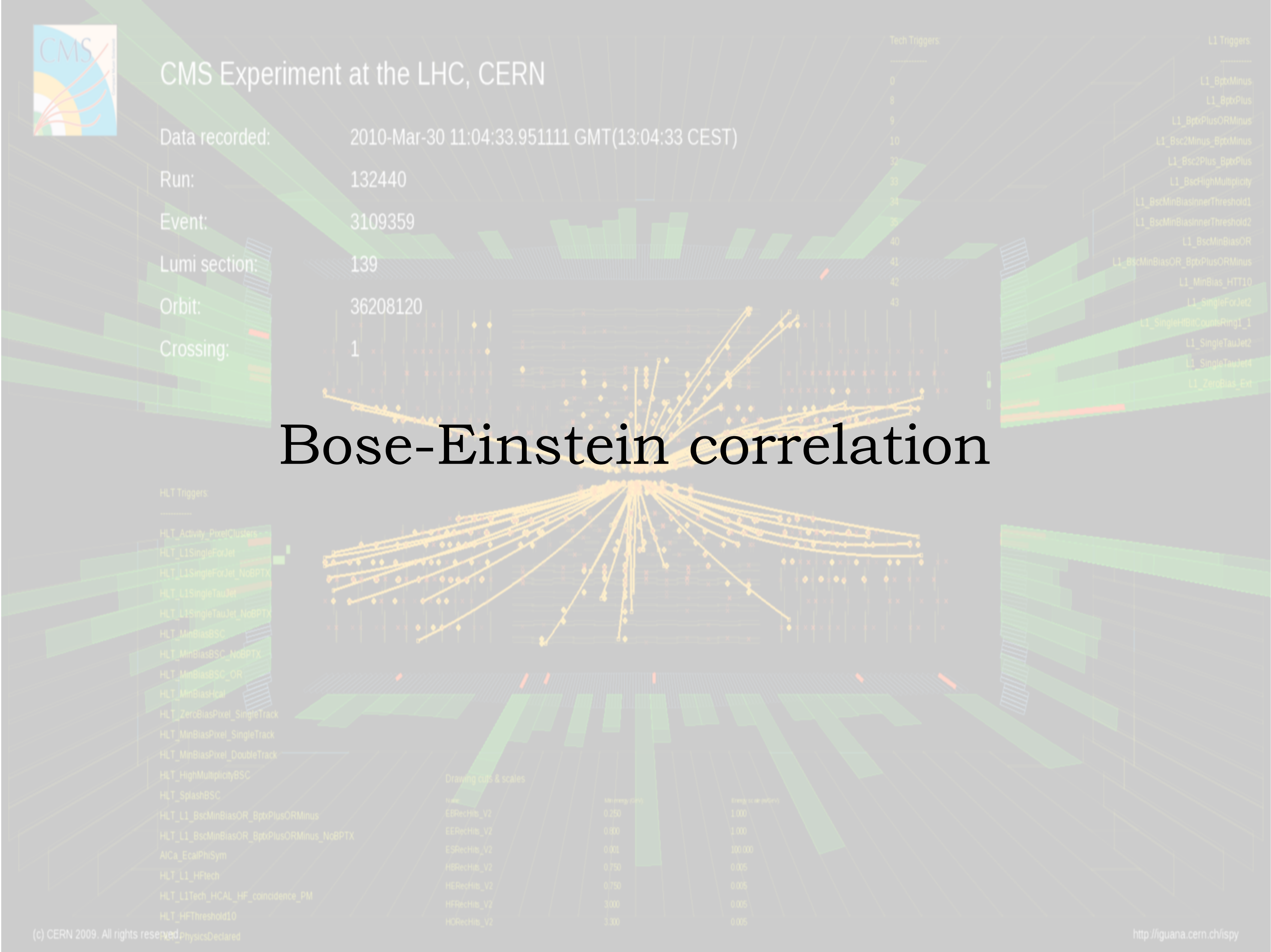
Energy dependence

- Dependence ~ $\ln^2 s$
- Steep increase in $dN_{ch}/d\eta|_{|\eta|\approx 0}$ with energy
  - Similar to what is found by ALICE at the same energies
  - Significantly higher than most event generator predictions





Bose-Einstein correlation



Bose-Einstein Correlation (BEC)

- Probability for identical bosons produced incoherently by a source to have similar momenta is enhanced with respect to uncorrelated case **(reference)**

$$R = \frac{P(b_1, b_2)}{P(b_1)\,P(b_2)}$$

- BEC gives information on the **size and shape** of the primary source

$$R = \left(\frac{dN_{sig}/dQ}{dN_{ref}/dQ} \right)$$

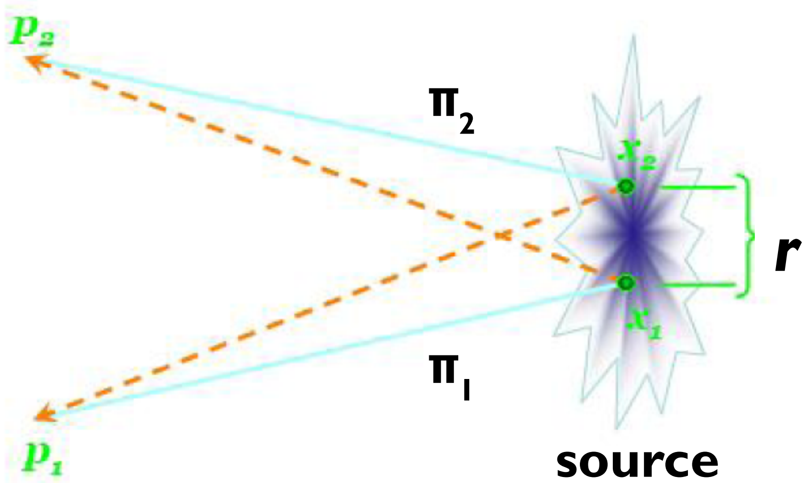
- R is expressed as a function of the pair **Q-value**:

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

- We parameterize $R(Q)$ with a Lorentz-invariant form describing the emission from **a spherical region**:

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

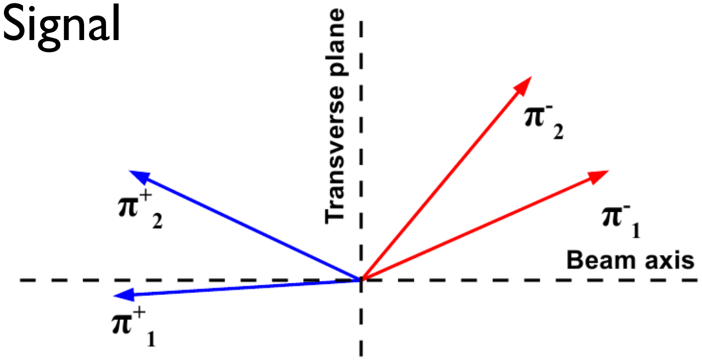
  - Ω is the **Fourier transform** of the space distribution of the emission region, whose **effective size** is given by r;
  - λ is a **strength parameter** and
  - δ allows for **long-range correlations**



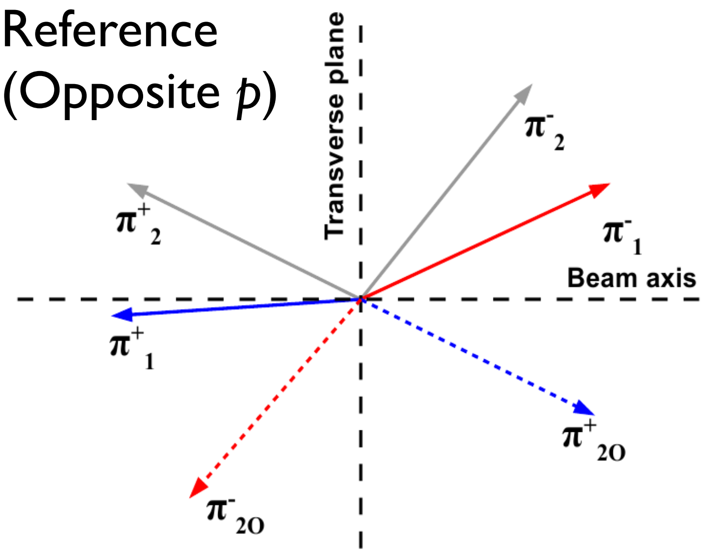
BEC – Signal and reference samples

- In this study we considered **7 reference samples**, considering pairs made with:
  - **1.** Opposite-charge tracks
  - **2.** Opposite-charge tracks in which one has p inverted
  - **3.** Same-charge tracks in which one has the p inverted
  - **4.** Same-charge tracks in which one has p_T inverted
  - Same-charge tracks from different events
    - **5.** Random mixing
    - **6.** Event mixing based on similar $dN_{ch}/d\eta$ distribution
    - **7.** Event mixing based on similar total invariant mass
- **No golden reference. All are used and results are combined**

Signal



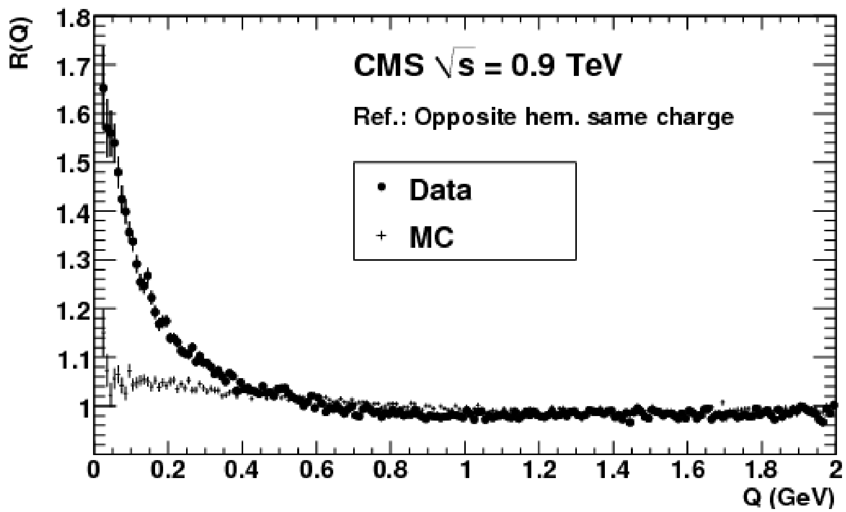
Reference (Opposite p)

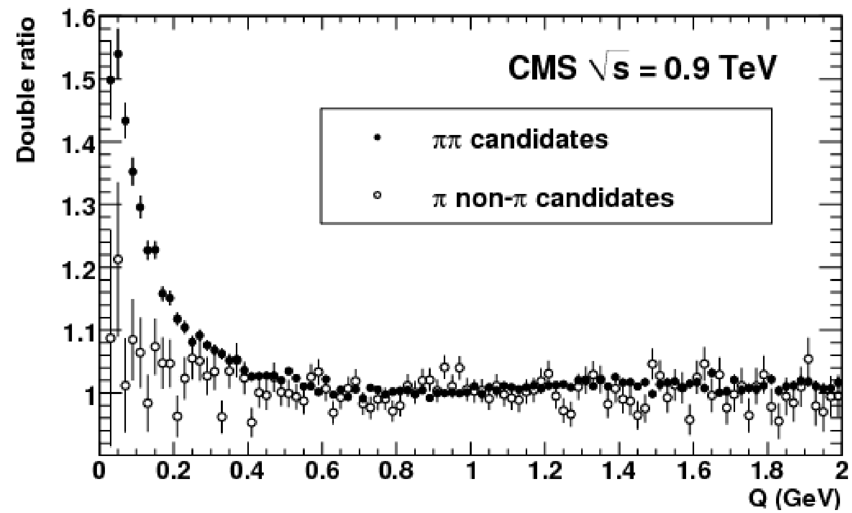


BEC – Double ratios

- The ratio R defined above shows a clear BEC signal at low Q
  - Monte Carlo simulates no BEC
- The distribution $R(Q)$ is distorted by resonances and long-range correlations at high Q
  - These are generally well reproduced by simulation
- We use **double ratios** to remove these and other unwanted features from the $R(Q)$ distribution
- **Cross-check**: if we form pairs with pion – non-pion candidates (identified with dE/dx in the tracker) the BEC effect disappears

$$\Re = \frac{R}{R_{MC}} = \frac{\left(\frac{dN_{sig}/dQ}{dN_{ref}/dQ}\right)}{\left(\frac{dN_{sig,MC}/dQ}{dN_{ref,MC}/dQ}\right)}$$





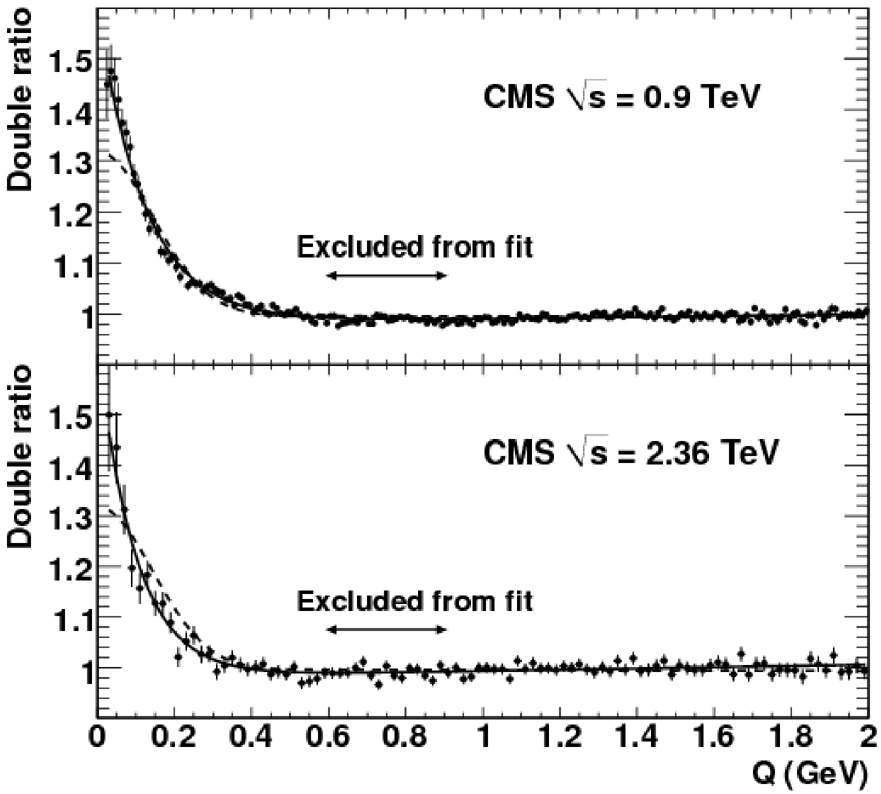
BEC – Results

- Fits are performed with an exponential and a Gaussian form for Ω:

$$\Omega = \exp(-Qr),\ \Omega = \exp(-Qr)^2$$

- Our data is well described by exponential fits, while **the Gaussian form is very disfavored** (bad fit p-value)
- A single value for the BEC parameters can be obtained by building a combined reference sample (m=7):

$$\Re_{comb} = \frac{dN_{sig}/dQ}{dN_{sig,MC}/dQ} \cdot \left(\frac{\sum_{i=1}^{m} dN_{i,MC}/dQ}{\sum_{i=1}^{m} dN_{i}/dQ} \right)$$



- Results of the fit (combined sample):

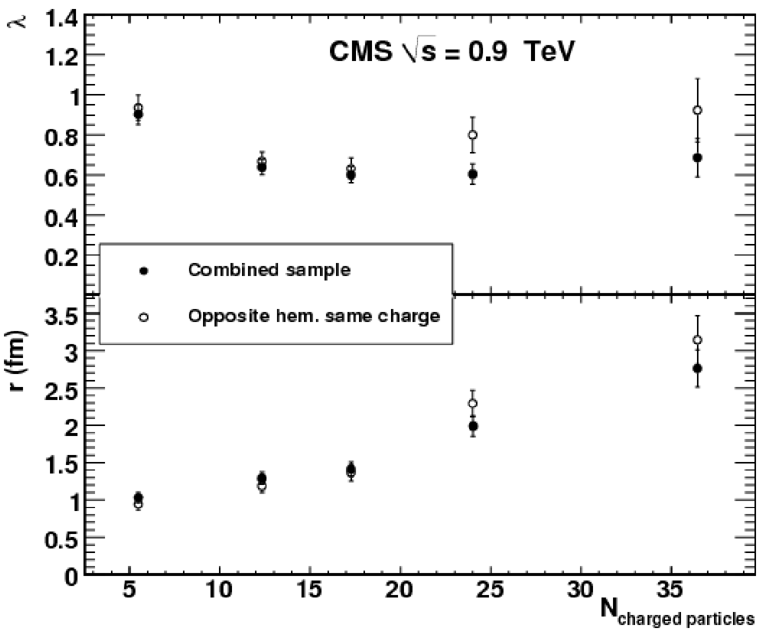
  λ = 0.625 ± 0.021 (stat.) ± 0.046 (syst.) and r = 1.59 ± 0.05 (stat.) ± 0.19 (syst.) fm at 0.9 TeV

  λ = 0.663 ± 0.073 (stat.) ± 0.048 (syst.) and r = 1.99 ± 0.18 (stat.) ± 0.24 (syst.) fm at 2.36 TeV

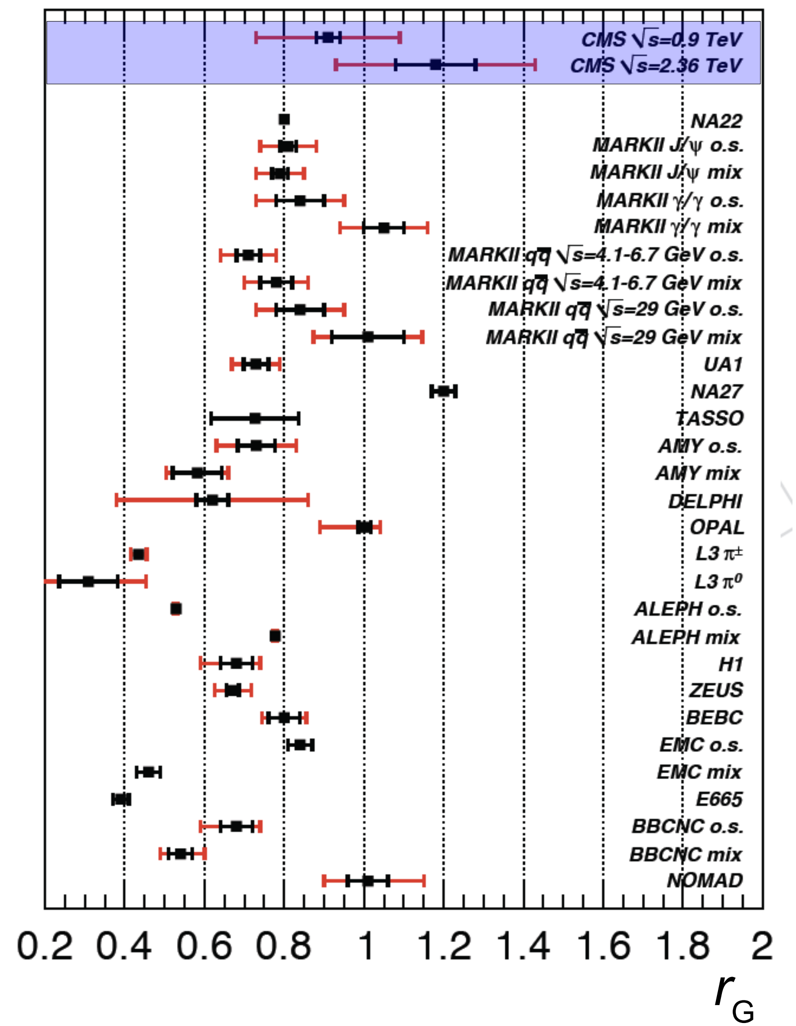
- Main systematics source is the choice of the reference sample

BEC – Results (2)

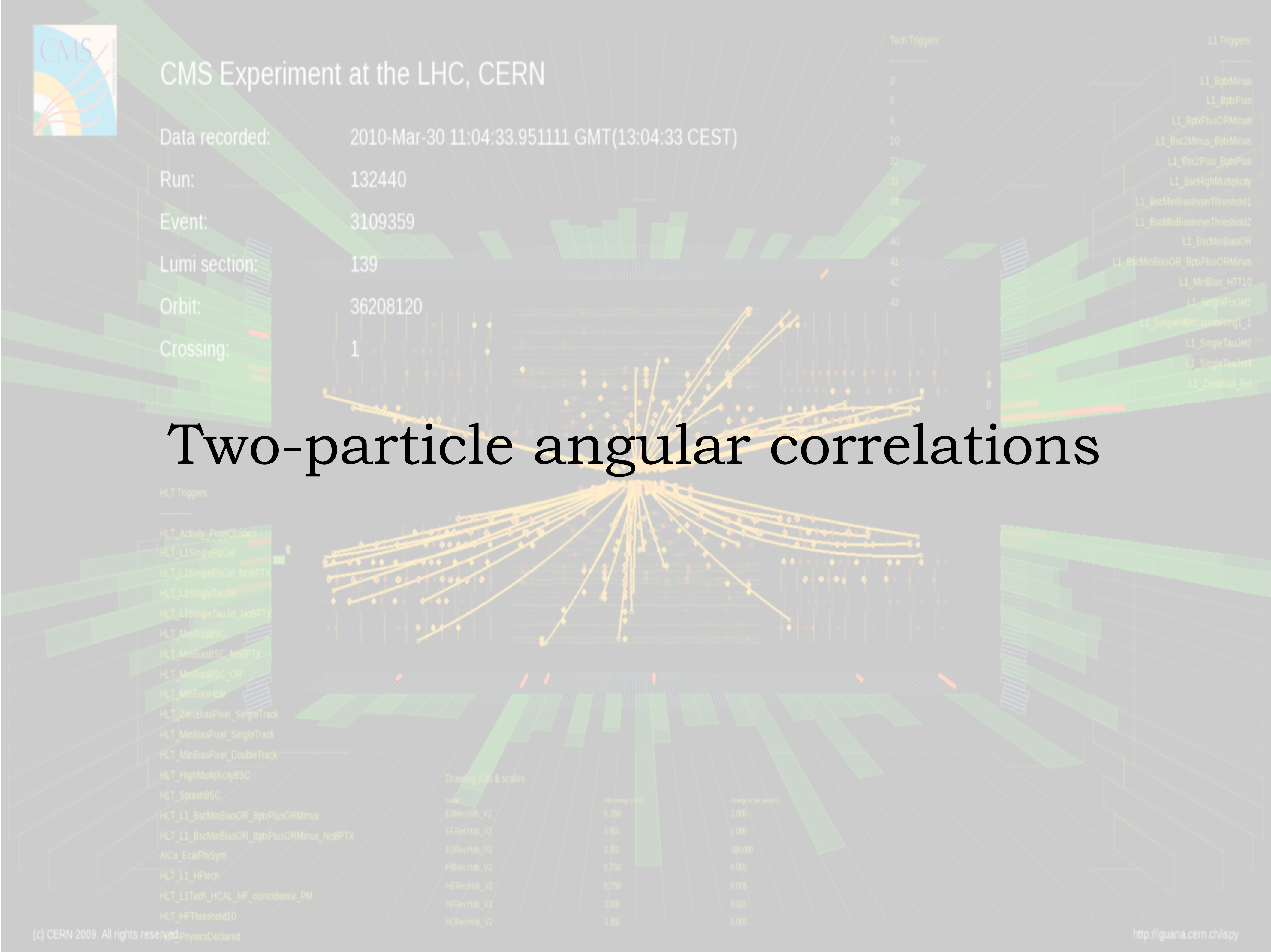
- The parameters of BEC depend on the **total charged multiplicity** in the event
  - The radius r **increases significantly** with N_{tracks}
  - The strenght λ **slightly decreases**
- This effect is present in 0.9 TeV and in 2.36 TeV data
- CMS results consistent with previous measurements



CMS results scaled ($r_G = r/\sqrt{\pi}$)



Two-particle angular correlations

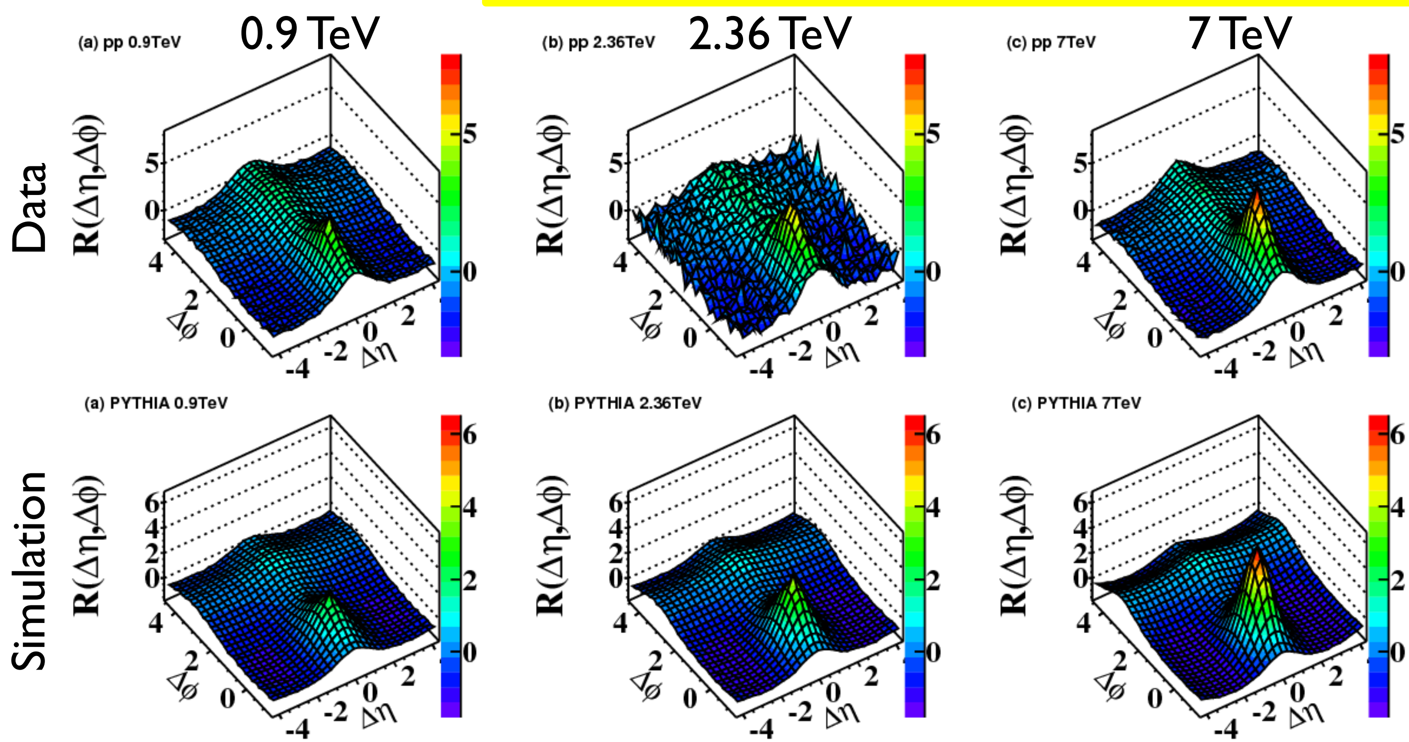


Two-particle correlations

- Initial particle production modeled with "clusters"
  - Each cluster is independent and decays isotropically
  - Typical observables: **size** (number of decay products) and **width** (separation in η of products)
- Two-particle angular correlations provide a way to measure the cluster properties

$$R(\Delta\eta, \Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

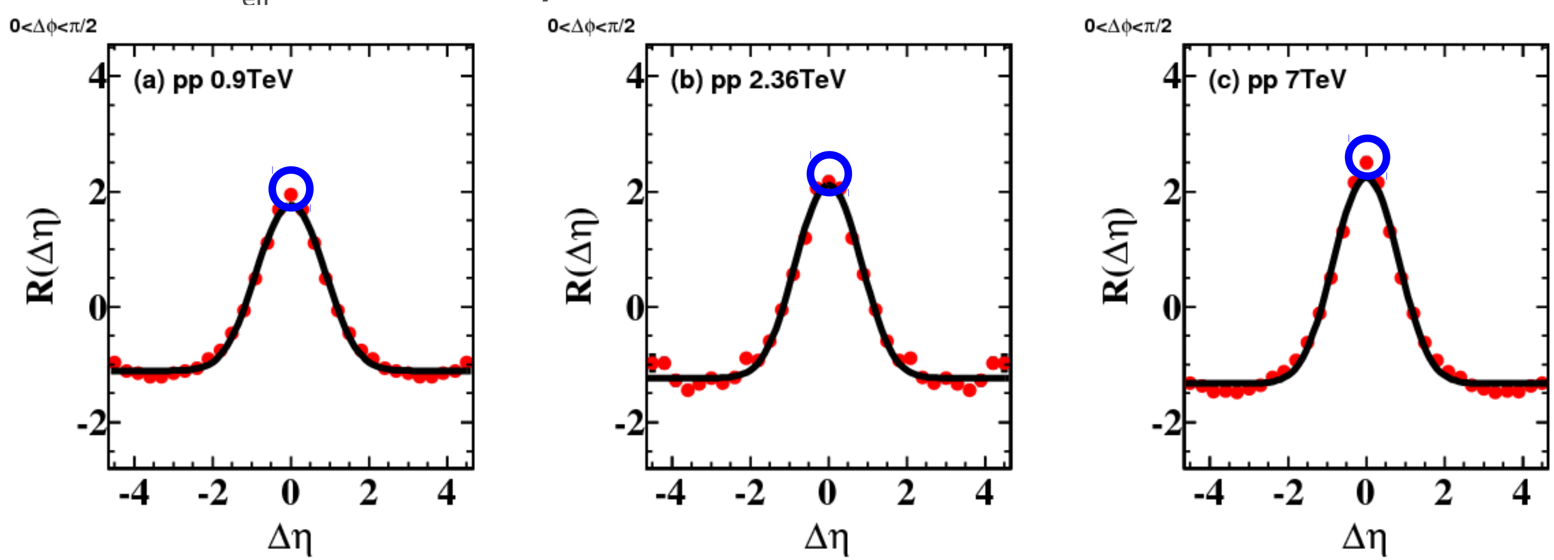
- Correlations studied as a ratio *R* between
  - S_N: **signal** (particle pairs in the same event)
  - B_N: **reference** (pairs in different events, mixed according to similar track multiplicity *N*)
- *R*(Δη, Δφ) averaged over all multiplicity bins



Fit of the correlation distribution

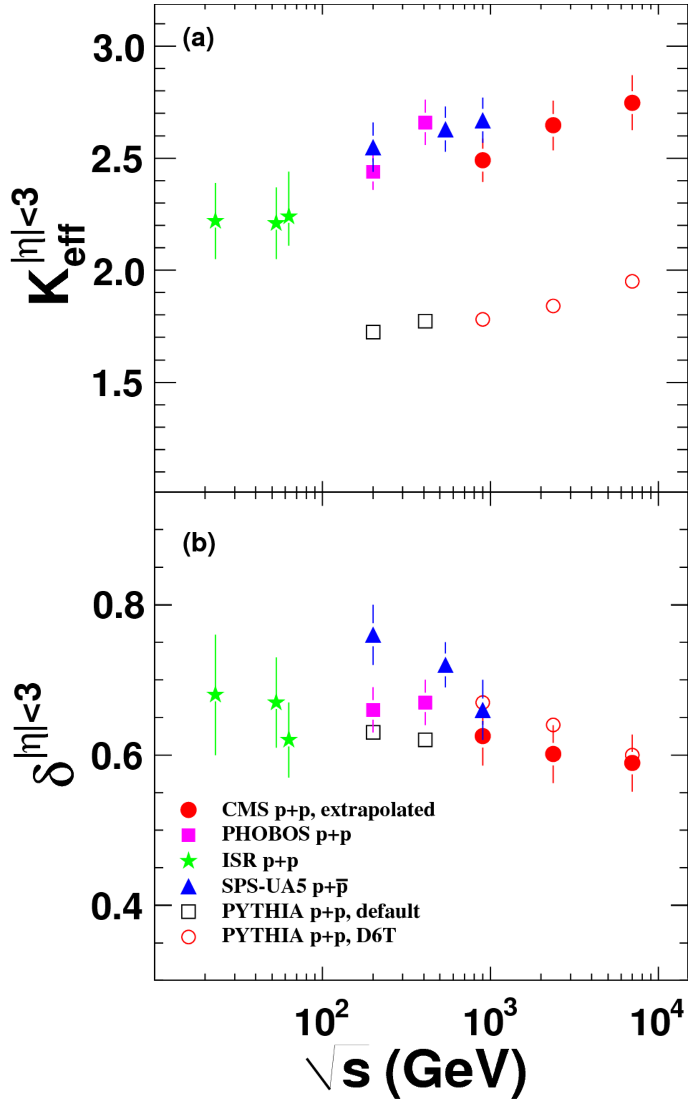
- The 2-D structure is ~Gaussian in Δη over all the Δφ range
  - Qualitatively consistent with an Independent Cluster Model (ICM)
- Distribution integrated over Δφ and fitted with the function $R(\Delta\eta) = \alpha\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$
  - $\Gamma(\Delta\eta) \propto exp[-(\Delta\eta)^2/(4\delta^2)]$ for particles emitted by a single cluster
  - $\alpha = K_{eff} - 1$
- ICM provides a good fit over a large Δη range
  - The effective cluster size K_{eff} and the decay width δ can be extracted from the fit

Circled points removed from fit (to reject residual secondary effects)



Results

- Size is seen to significantly increase with energy
  - Trend already seen at lower energies
  - Increase concentrated in near-side ($0 < \Delta\varphi < \pi/2$)
  - Only qualitatively reproduced by simulation
- Width is almost constant
  - Well reproduced by simulation
- Systematics mainly from event selection, tracking/acceptance, model-dependent extrapolations (~4%)



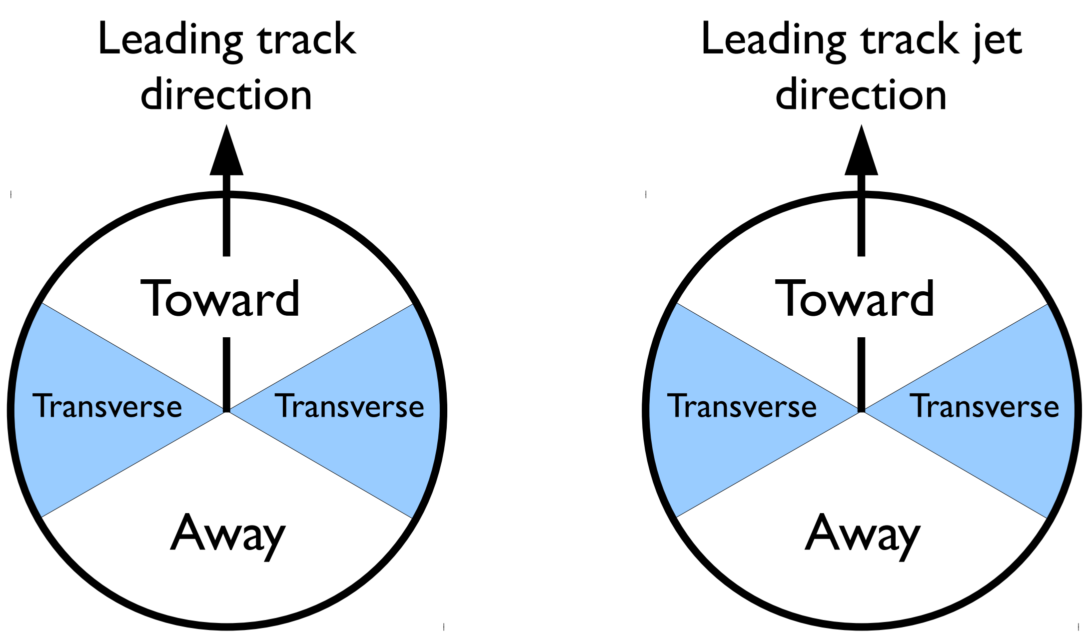
Underlying event

Underlying event

- In a typical event at a hadron collider, the "hard" parton scattering is accompanied by other processes
  - Additional "soft" interactions among beam partons (**Multiple Parton Interactions**, MPI)
  - Hadronization of non-interacting beam partons (**Beam-Beam Remnants**, BBR)
- Products of MPI and BBR form the **Underlying event (UE)**
- UE knowledge is crucial for MC tuning, precision SM measurements, searches for physics beyond the SM

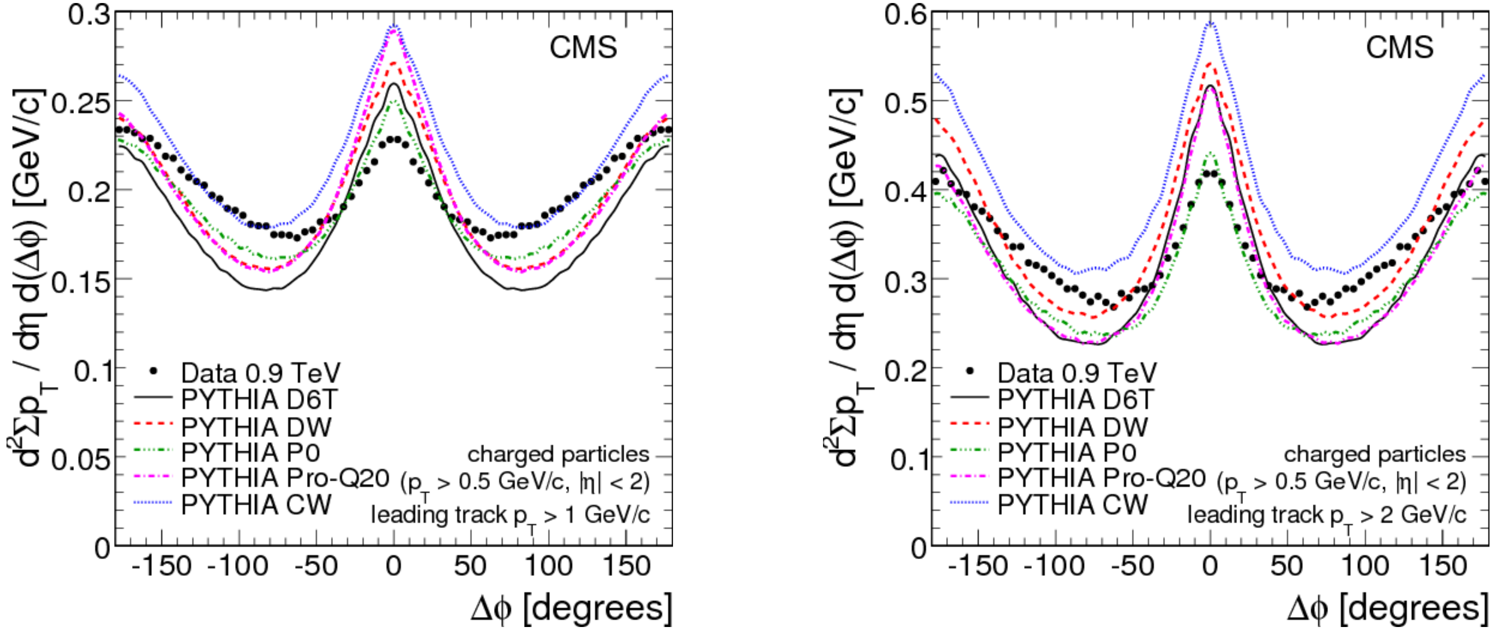
Starting from leading track/jet:

- "**Toward**" ($|\Delta\varphi|<60°$): hard interaction
- "**Away**" ($|\Delta\varphi|>120°$): recoiling jet
- "**Transverse**": Dominated by UE



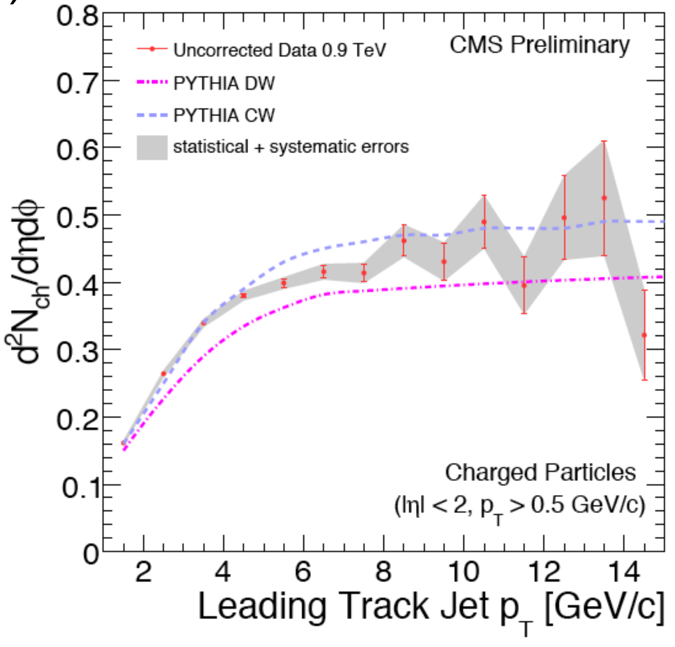
Correlation with leading track

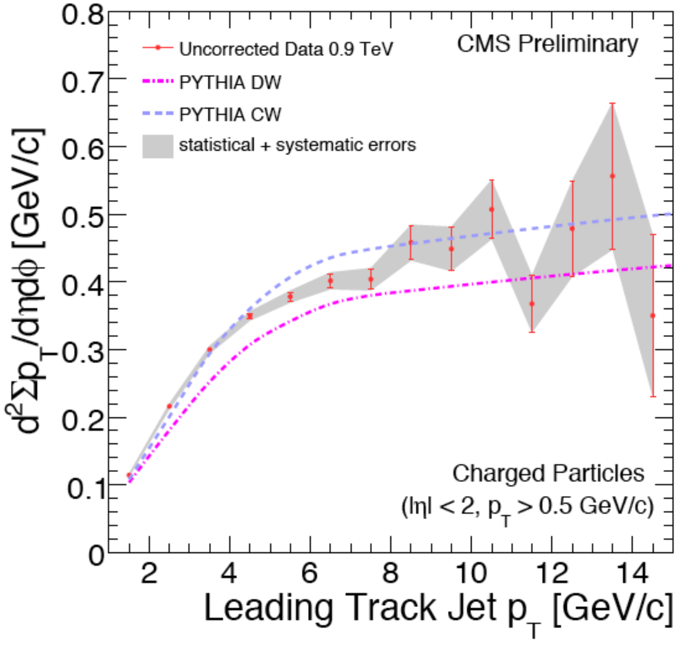
- In the toward and away regions, high activity due to radiation and to the fragmentation of the two outgoing partons
  - It increases with leading track p_T
- Non-null activity in transverse region is attributed to UE
- No PYTHIA tune models accurately data
  - CW and DW provide the closest available description



Particle production in the transverse region

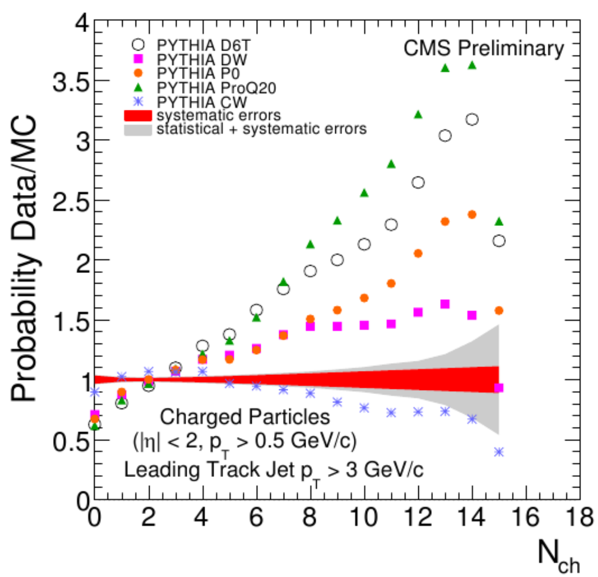
- Activity of the UE (multiplicity and average momentum) increases with leading jet / leading track p_T
  - Slower increase for jet p_T>4 GeV (track p_T>3 GeV)
  - Behavior well-reproduced by simulation (CW and DW tunes “bracket” the data)
- Bands are statistical+systematic errors (material budget, background contamination, selection)



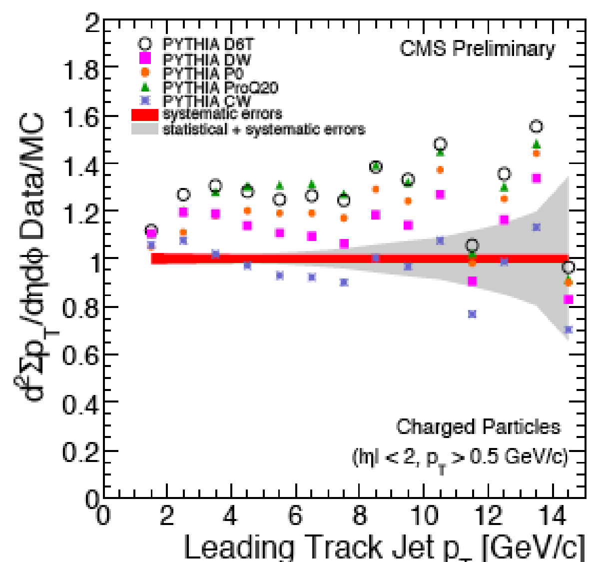


Comparison with simulation

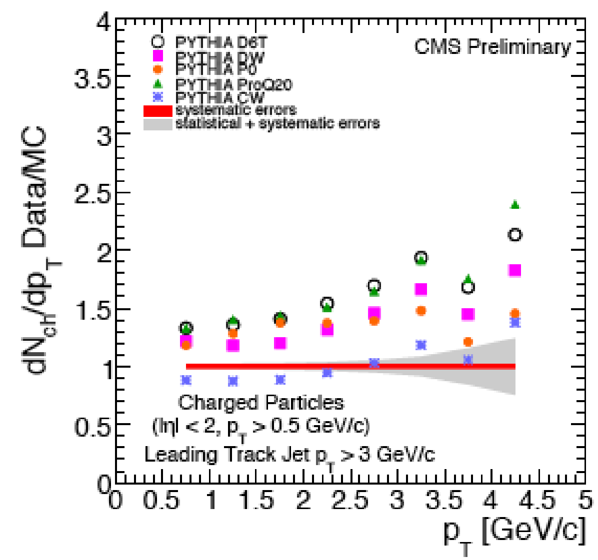
- Monte Carlo simulation does not represent well the data
- Plots show data/MC ratios
  - Data are above MC for most tunes (except CW)
  - Data trends (expecially for N_{ch}) are not well simulated
- These measurements allow for a better MC tuning (ongoing effort)



N_{ch}



Σp_T vs. leading jet p_T



N_{ch} vs. leading jet p_T

Conclusions

- LHC has started providing very high quality data to the experiments
- CMS has had an impressive performance during these months of data taking
- Early measurements on soft hadron physics give the first insight on the new energy domain
- Particle correlations and distributions are interesting results *per se*
  - They unveil shortcomings of available MC models
  - Useful references for the upcoming heavy-ion runs
- Other analyses are being prepared as the total collected data increase
- Many more results coming soon!