CMS Startup and First Physics

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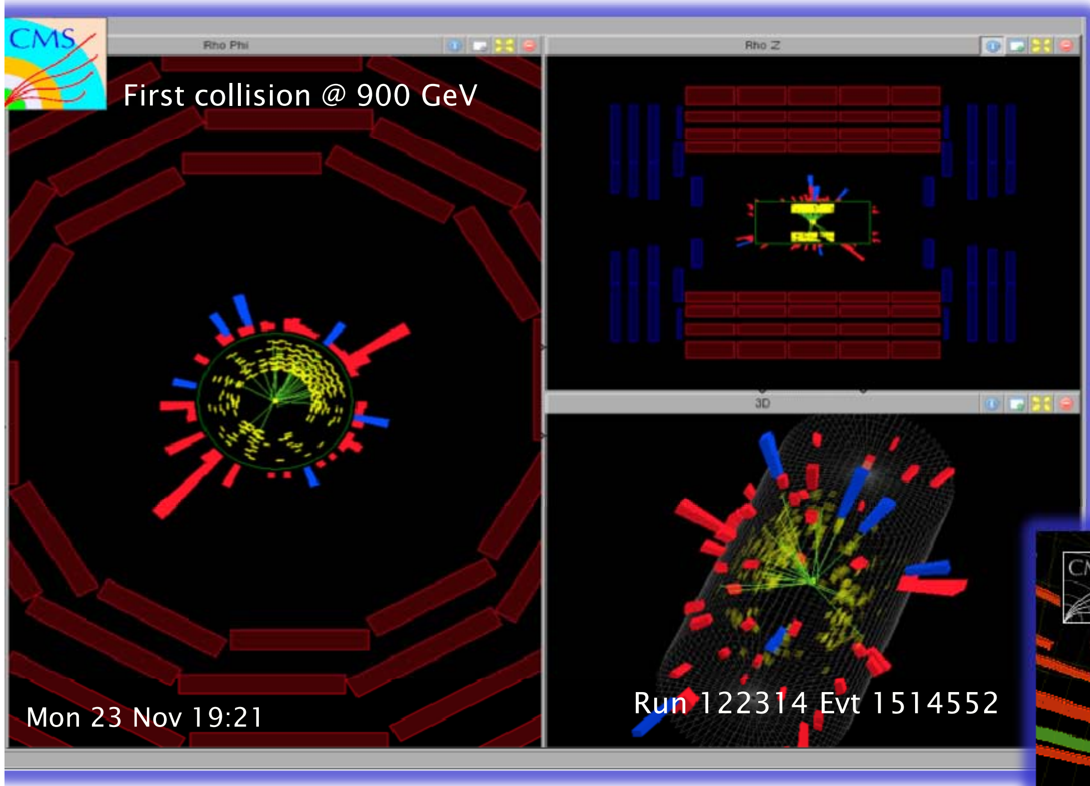
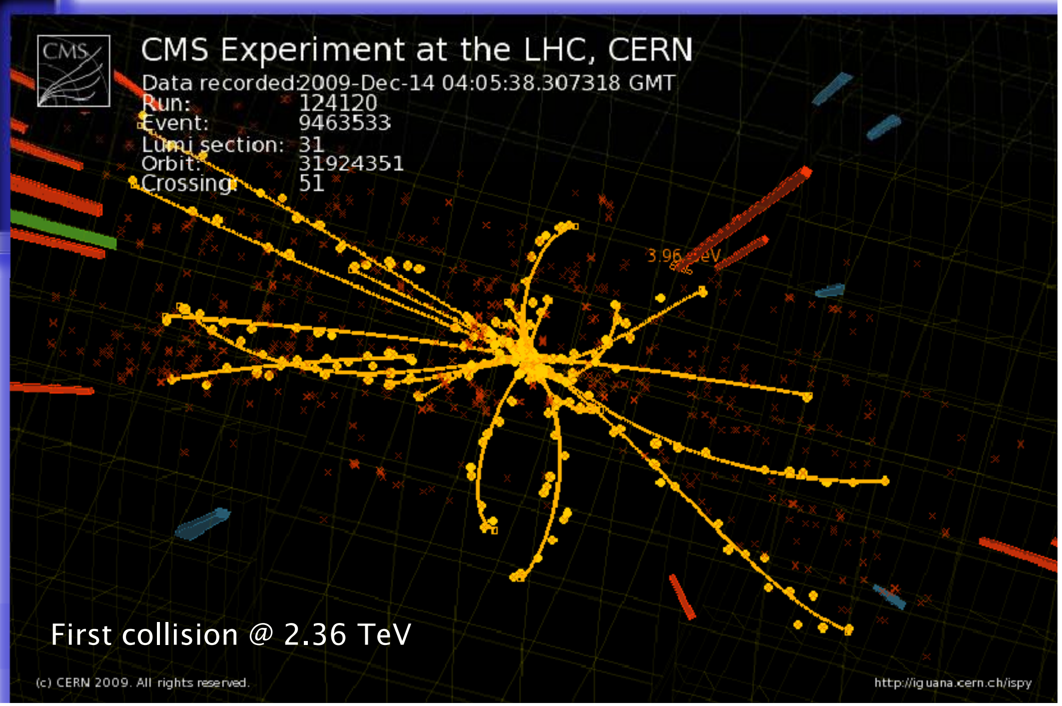
for the **CMS Collaboration**

Rencontres des Physique de la Vallee d'Aoste
La Thuile - 04/03/2010

Startup (another perspective ;-))



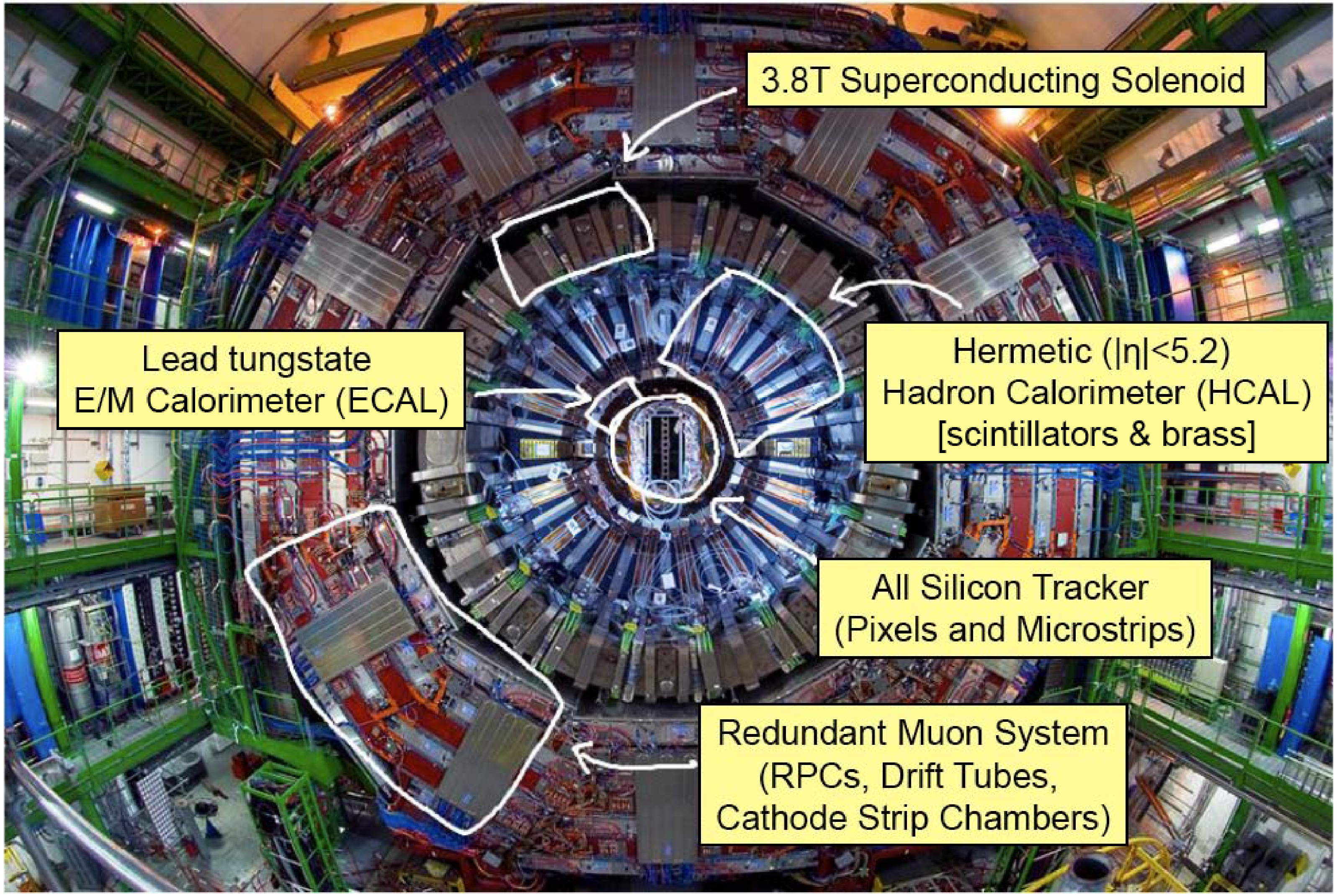


Outline

- 20 years of R&D, detector building, test beams, commissioning.
- Now, LHC & CMS are up and running

- We will discuss
  - CMS Detector status and commissioning
    - Preparation for beam: Cosmic runs
  - CMS @ LHC startup
    - Commissioning with beam
    - First physics results: first CMS published paper

CMS in a nutshell

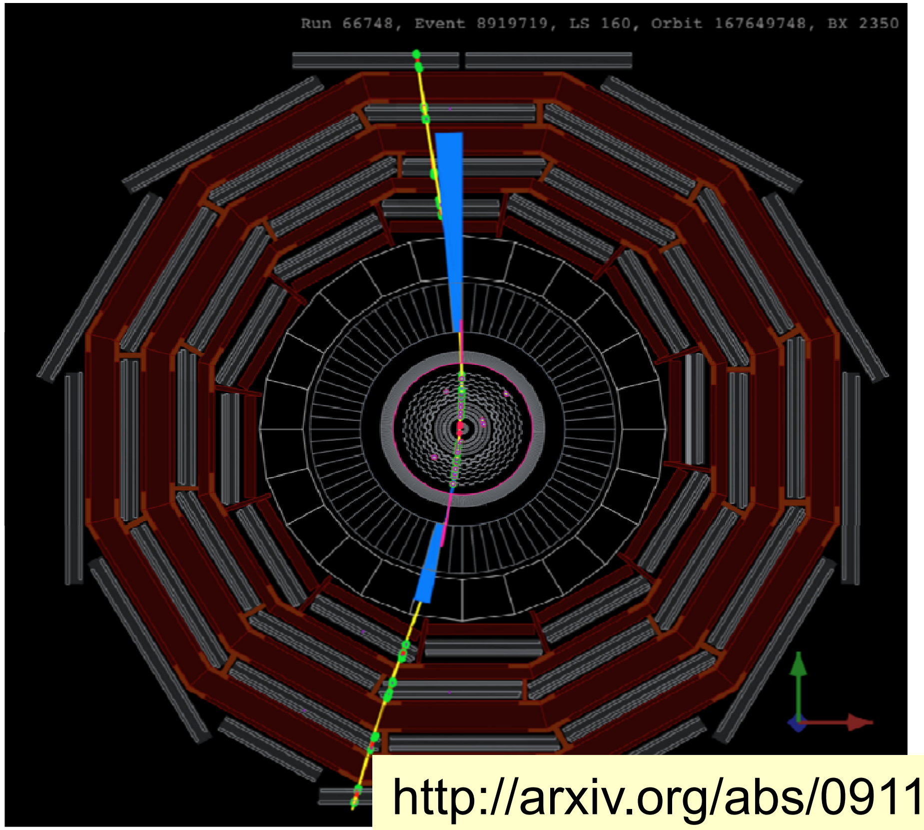


CMS comprises
66M pixel channels,
~10M Si microstrip ch,
~75k crystals,
150k Si preshower ch,
~15k HCAL ch,
250 DT chambers
(170k wires),
450 CSC chambers
(~250k wires),
~ 500 Barrel RPCs
~ 400 endcap RPCs,
100 kHz DAQ system
(~ 10k CPU cores),
Grid Computing (~ 50 k cores),
offline (> 2M lines of source code).

182 Institutions
>3000 scientists and engineers
~ 2000 Authors
(including students)

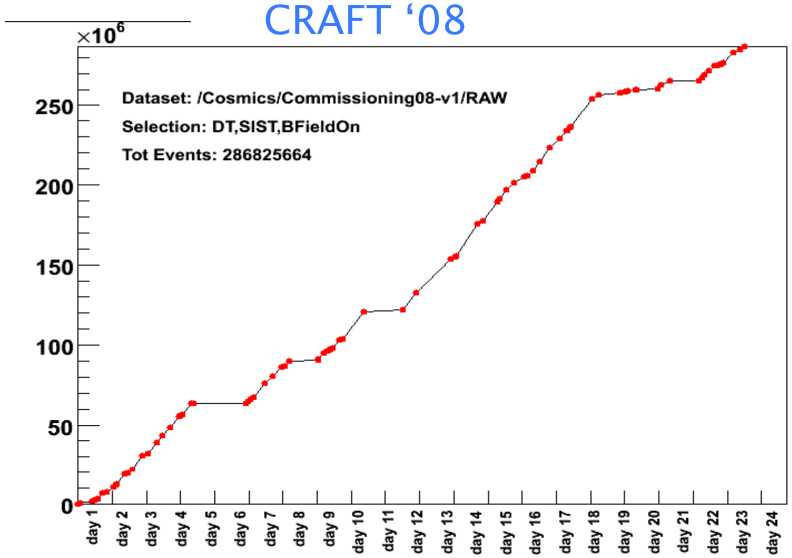
Last year of preparation (sept 08 – nov 09)

Cosmic Runs At Four Tesla

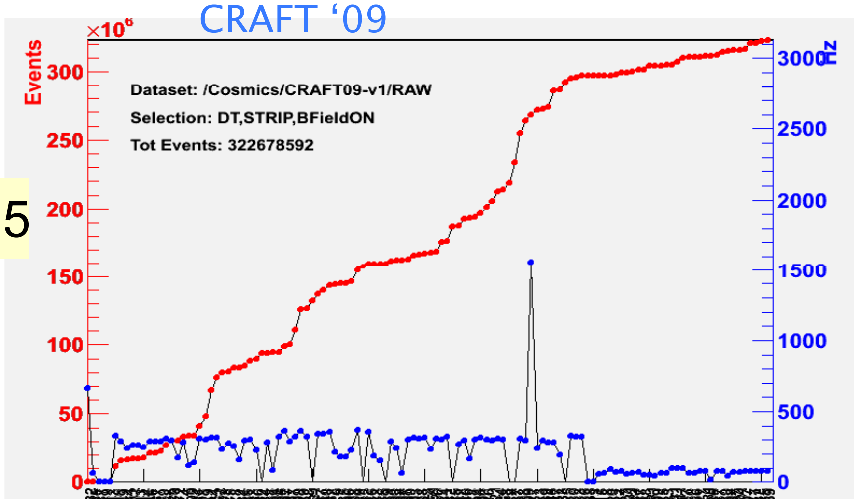


http://arxiv.org/abs/0911.4845

CRAFT '08



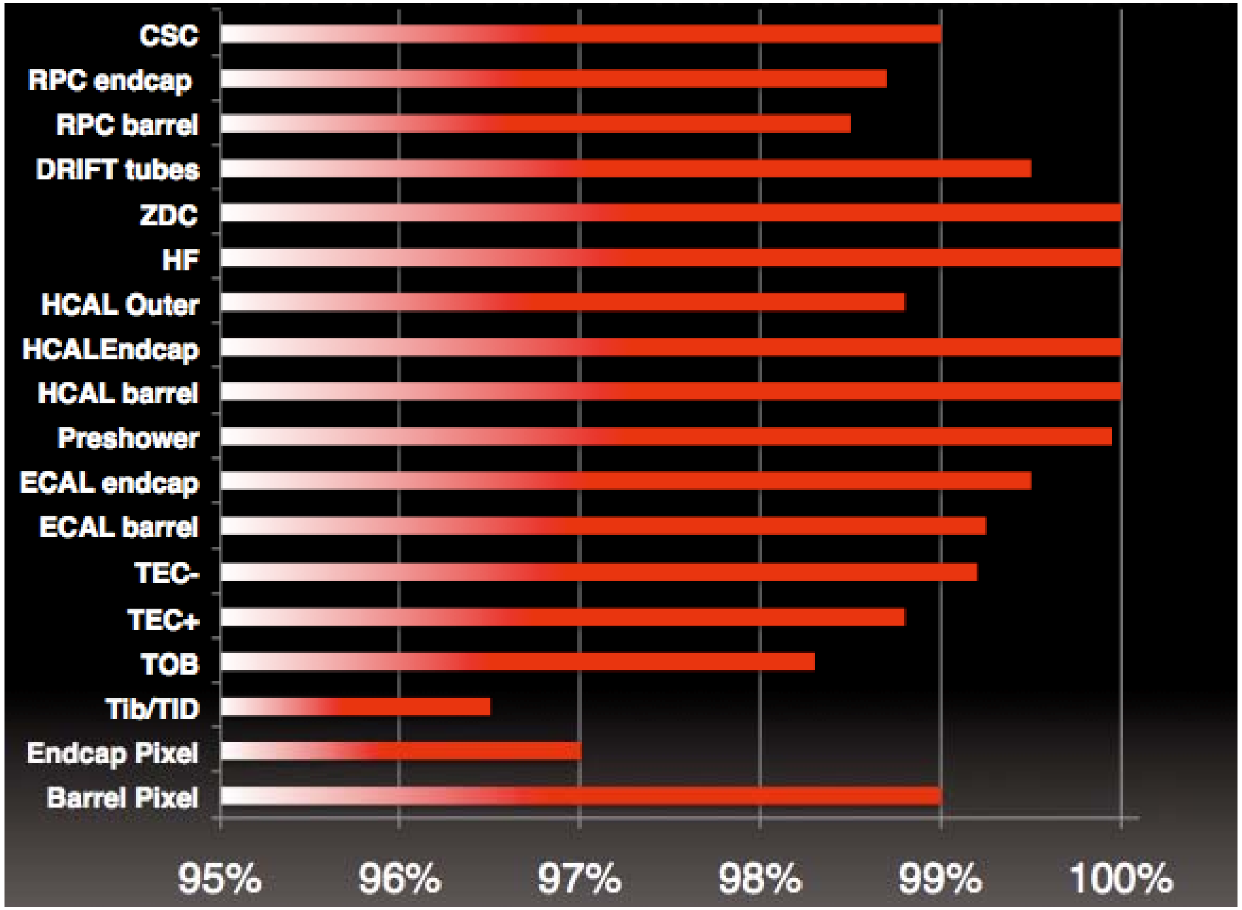
CRAFT '09



600M cosmics collected with magnetic field and all subdetectors on

- 300M in Autumn08
- 300M in Summer09

CMS operation



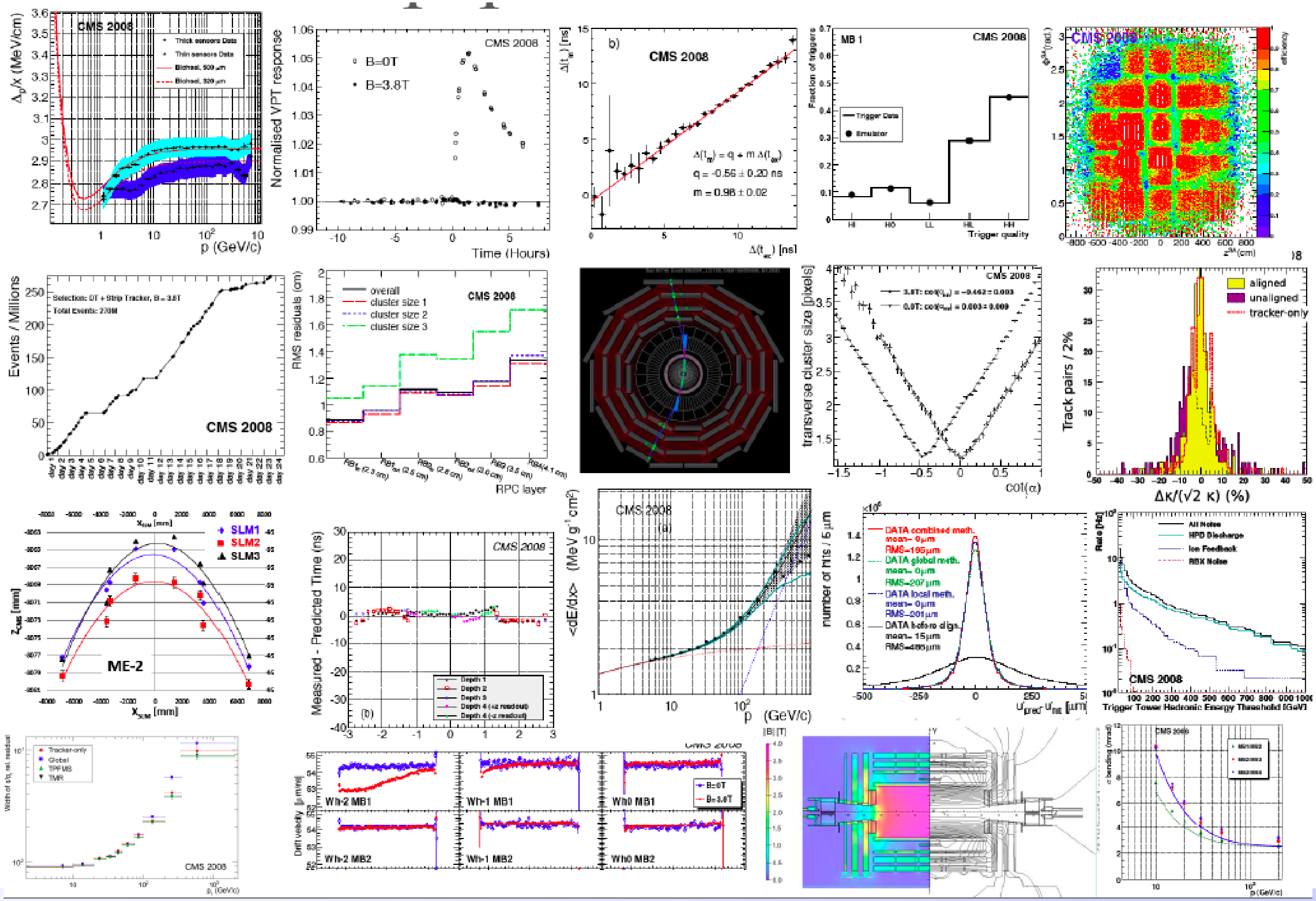
CMS is in good shape
>99% is operational

Good data taking efficiency
CRAFT09 ≈ 80% (reaching 90% during weekends)
And during LHC first beams was 85%

Rewards

- Continuous preparation while waiting for the beam
  - Improved stability and reliability of all online operational aspects (services/DAQ/Trigger)
  - Improved reconstruction software robustness
  - Test software & computing workflows
- Deeper understanding of detector performance
  - 23 articles submitted to JINST. 22 already accepted (and counting ;-))
  - Invested the maximum effort to understand the basic detector performance before LHC startup (especially for tracker and muon system)

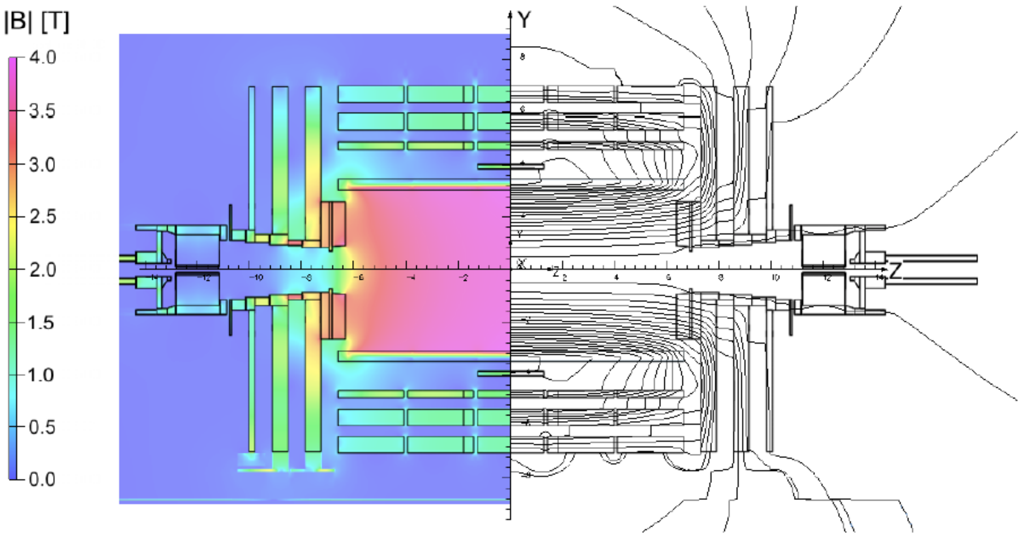
From the 23 papers submitted to JINST…



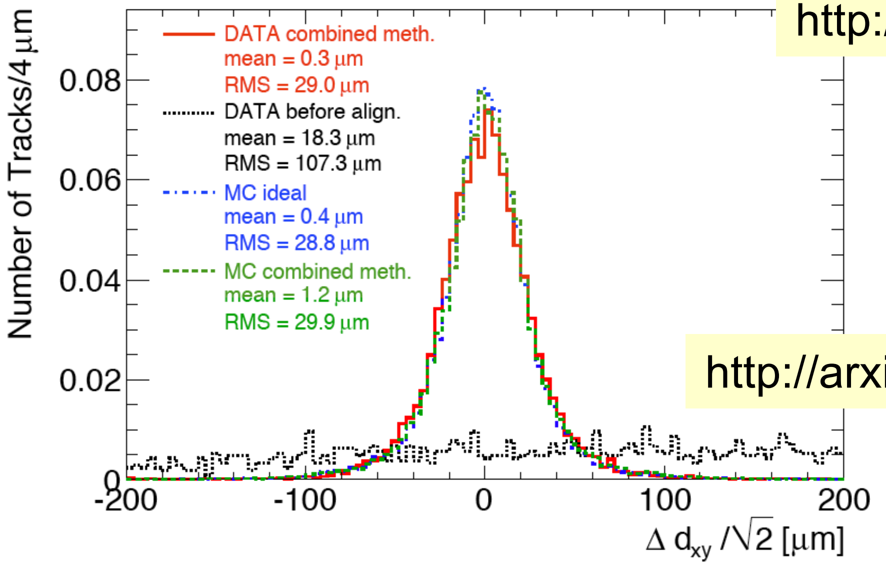
CRAFT: Measurement of B field

- Good understanding of the solenoid B field in the tracker region and in the return yoke
  - **Map in the tracker volume**
    - Measured by probes in 2006 at 0.005%
    - Verified in situ with cosmics at 0.1%
  - **Field map in the yoke** at first found over-estimated by 20% looking at muon residuals in bending plane
    - Too tight physical boundaries were imposed in the finite-element model (radius,z)
    - New model implemented, now **accuracy @ 3-8% level** (ok for physics)

http://arxiv.org/abs/0910.5530



CRAFT: Muon/Tracker



http://arxiv.org/abs/0910.2505

Approaching MC ideal alignment

3-4 μm @ module level in the barrel

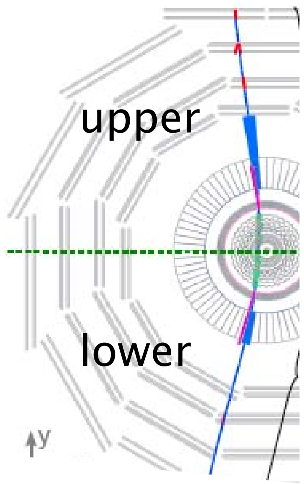
3-14 μm in the endcap

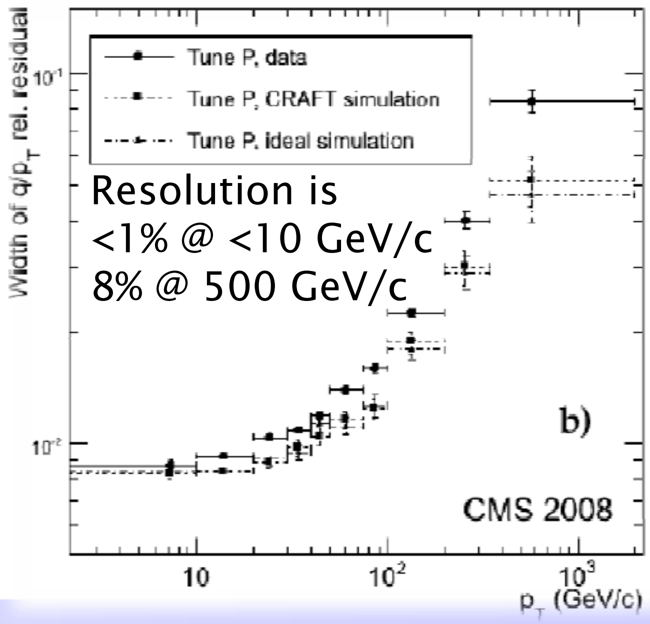
http://arxiv.org/abs/0911.4994

$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}}$$

Splitting muons tracks in “upper”/”lower”part and comparing

- transverse impact parameter
- Measured p_T





Resolution is
<1% @ <10 GeV/c
8% @ 500 GeV/c

And finally, there was beam

CMS 2009 Collision data

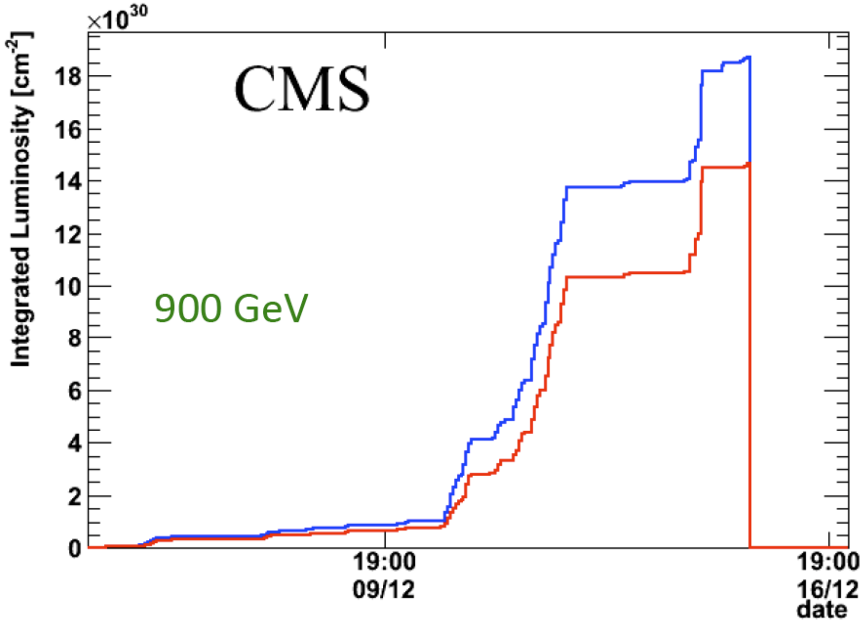
First collisions 23 November
First stable beams 6 December
First 2.36 TeV collisions 14 December

5.4×10^5 ≈ 15 μb^{-1} collisions recorded:
all beam conditions

3.9×10^5 ≈ 10 μb^{-1} (2.0×10^4 ≈ 0.4 μb^{-1}) @ 900 (2360) GeV:
Tracker on, beam background rejected

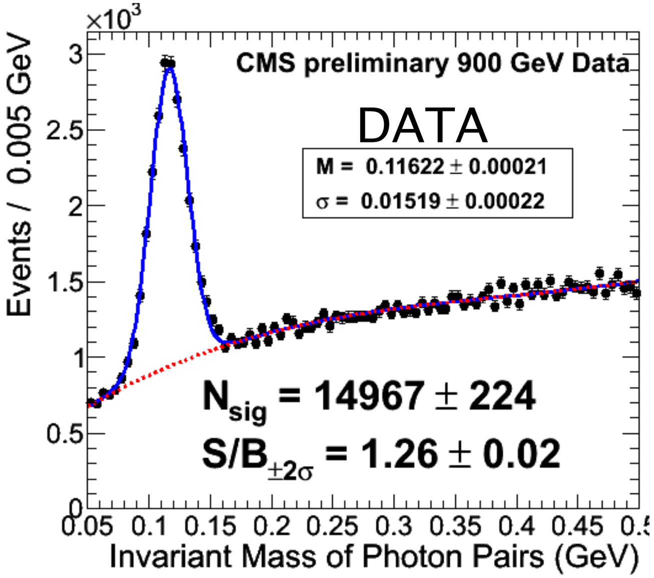
Recorded **85% of delivered luminosity**

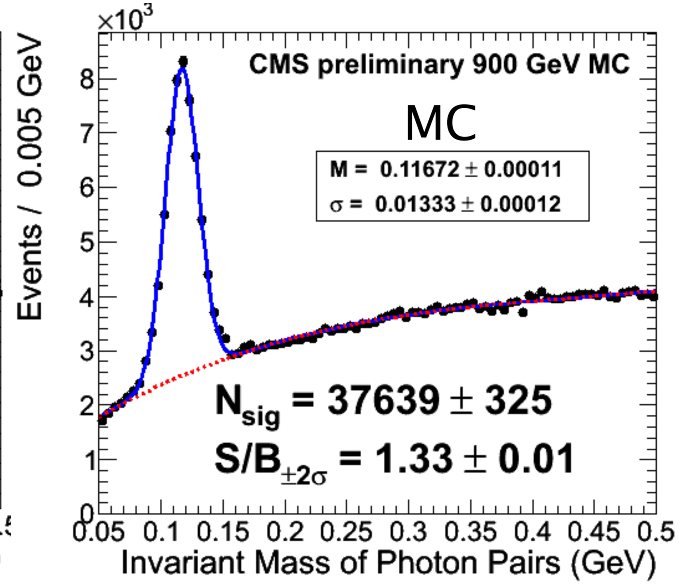
Quick analysis delivered preliminary results within hours/days



Commissioning with beam

ECAL





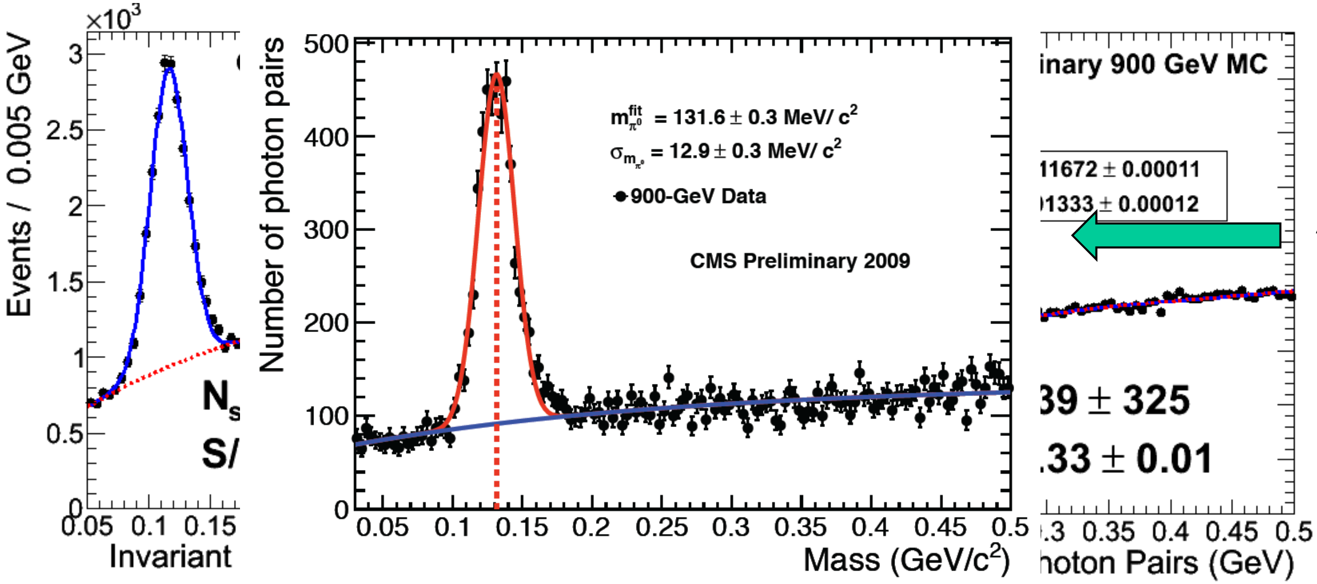
First π^0 peak shown already the 27^{th} of November

Good agreement with MC for peak position and S/B

Uncorrected energies (containment + zero suppression) are shown here

Only ECAL barrel ($|\eta|<1.479$)
$p_T(\gamma_1,\gamma_2) > 0.3$ GeV
$p_T(\pi^0) > 0.9$ GeV
S4/S9 (shower shape) > 0.85

ECAL



Applying out of the box MC based corrections. 2% within PDG mass

Only ECAL barrel ($|\eta|<1.479$)
$p_T(\Upsilon_1,\Upsilon_2) > 0.3$ GeV
$p_T(\pi^0) > 0.9$ GeV
S4/S9 (shower shape) > 0.85

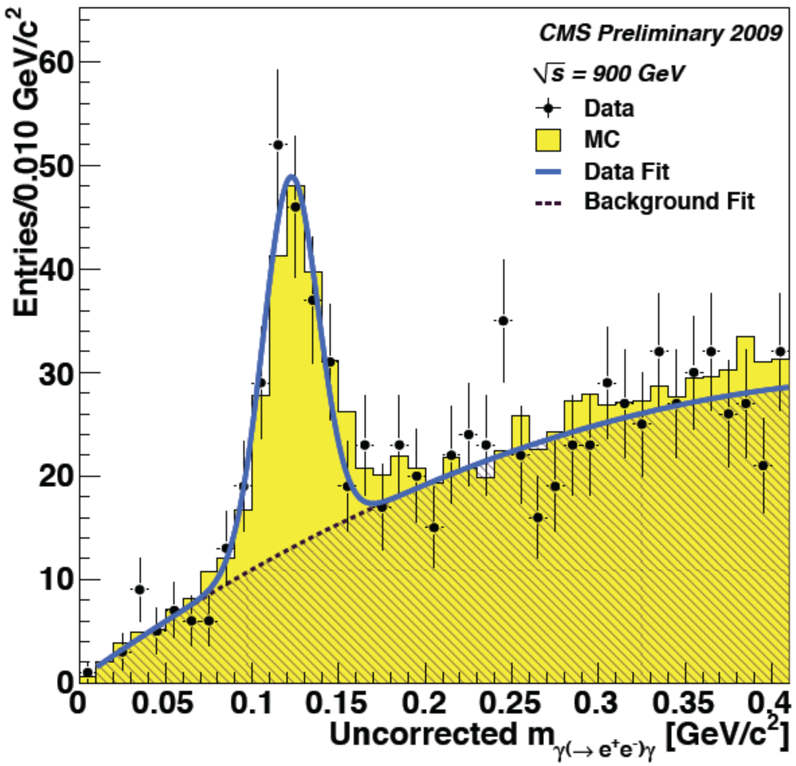
π^0 with one leg reconstructed as a conversion

Soon after, also observed a peak of π^0 with one leg reconstructed as a conversion

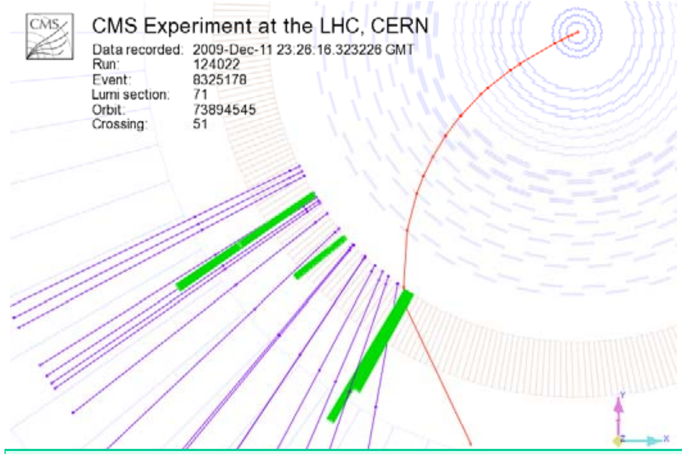
Using conversion selected only with tracks (no ECAL matching)

Clusters only in ECAL barrel ($|\eta|<1.479$)

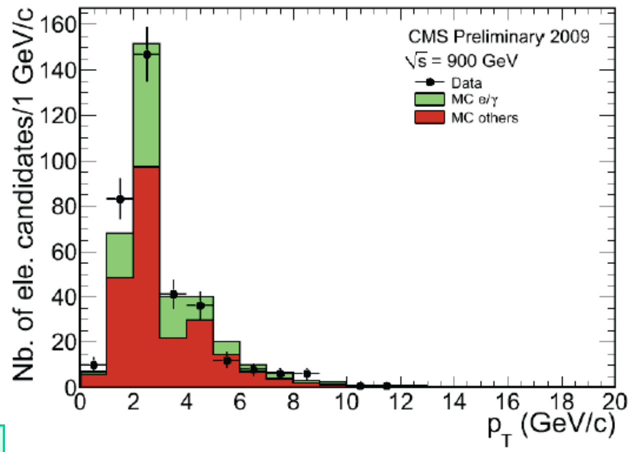
$p_T(\gamma) > 0.3$ GeV
$p_T(\pi^0) > 0.85$ GeV

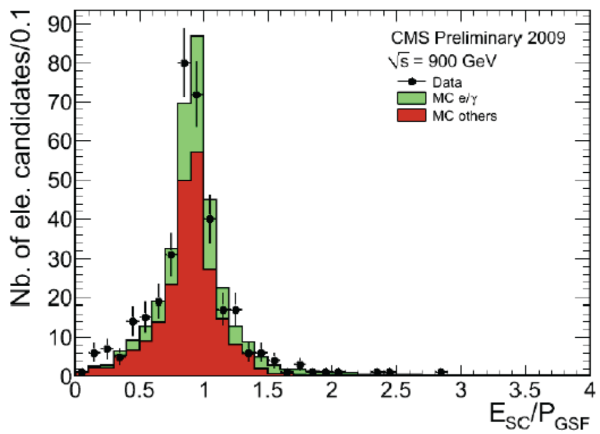


Electrons



2.5 GeV electron candidate with bremsstrahlung





Low statistics for signal in these data

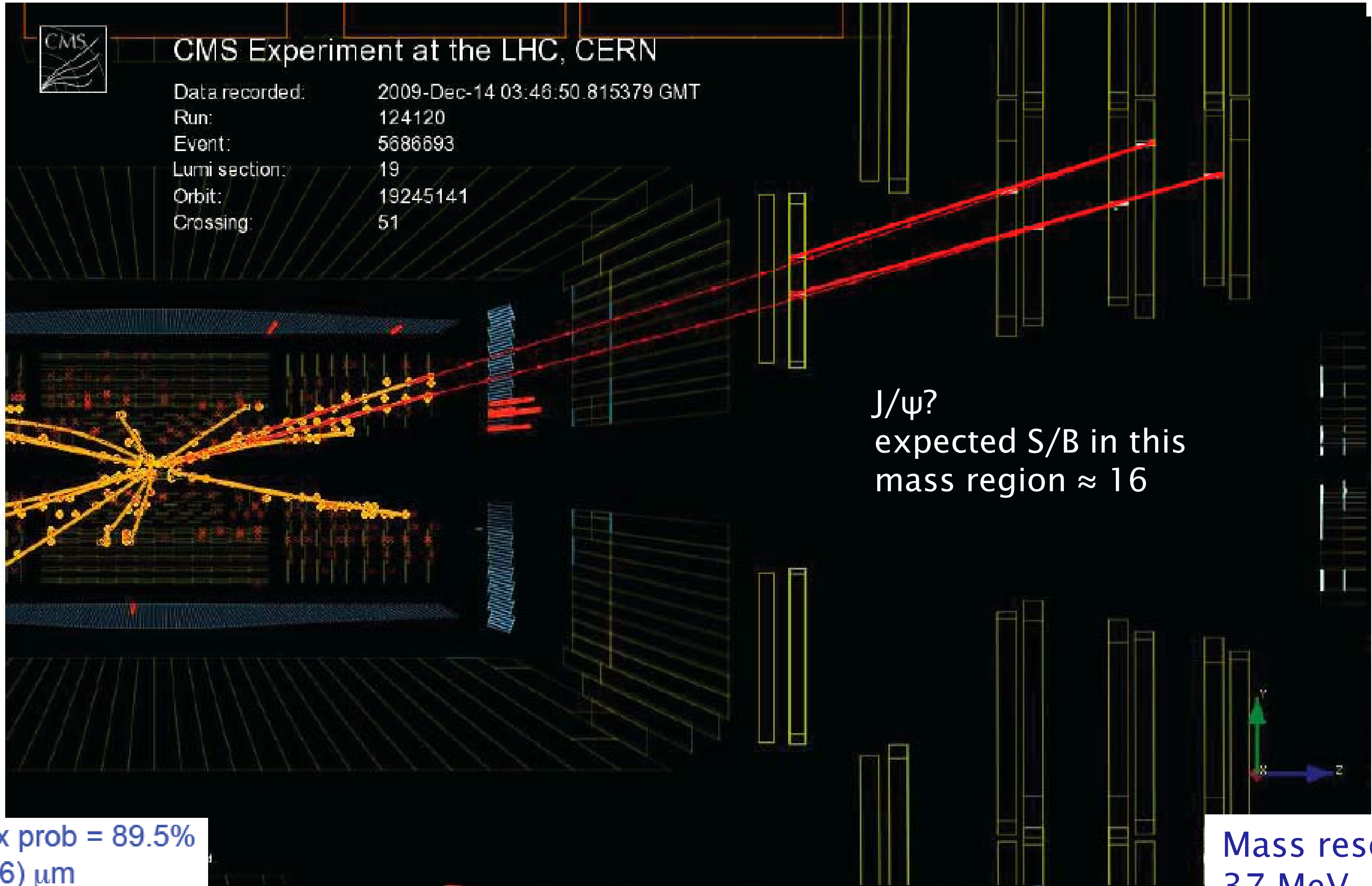
Comparison with MC performed mainly for background (only 1/3 of electron candidates are electrons, mostly from conversions)

Commissioning will continue in the next run

Agreement with MC is promising

Reconstructed electrons candidates combining two seeding algorithms
- “ecal driven” optimized for W/Z electrons, starting from clusters of $E_T > 4$ GeV
- “tracker driven” more suitable for low p_T electron and electrons in jets

Di-muon event @ 2.36 TeV

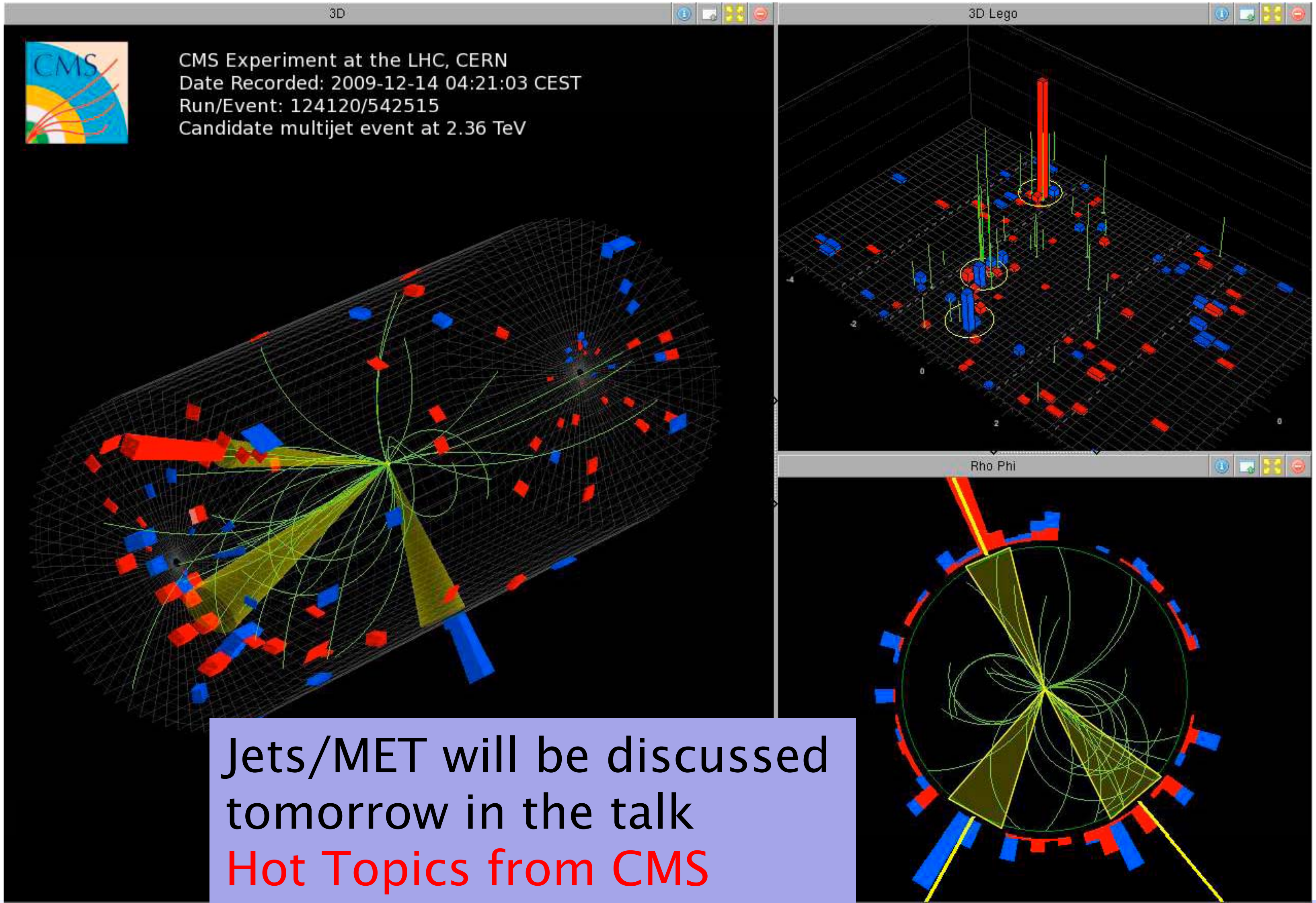


Dimuon vertex prob = 89.5%
$c\tau$ = (- 31 ± 46) μm

Mass resolution is 37 MeV

$p_T(\mu_1)$ = 3.6 GeV/c, $p_T(\mu_2)$ = 2.6 GeV/c, $m(\mu\mu)$= 3.03 GeV/c^2

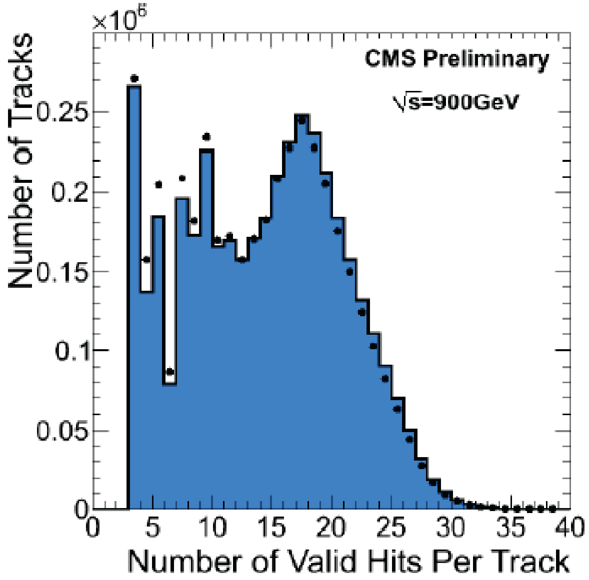
Multijet event @ 2.36 TeV

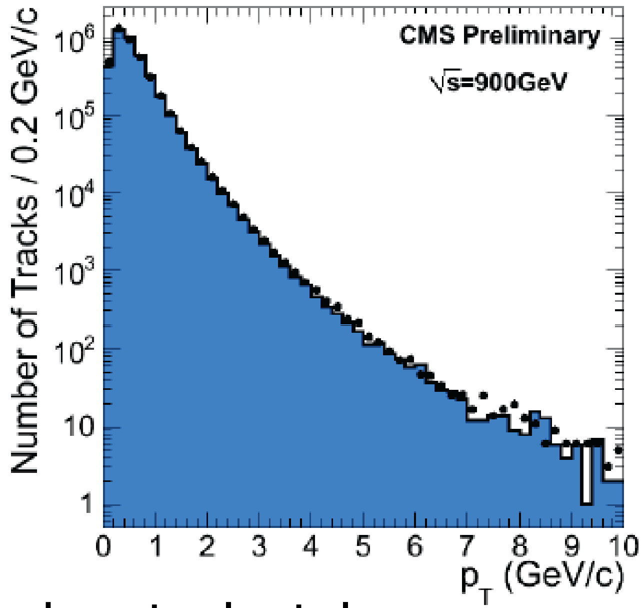


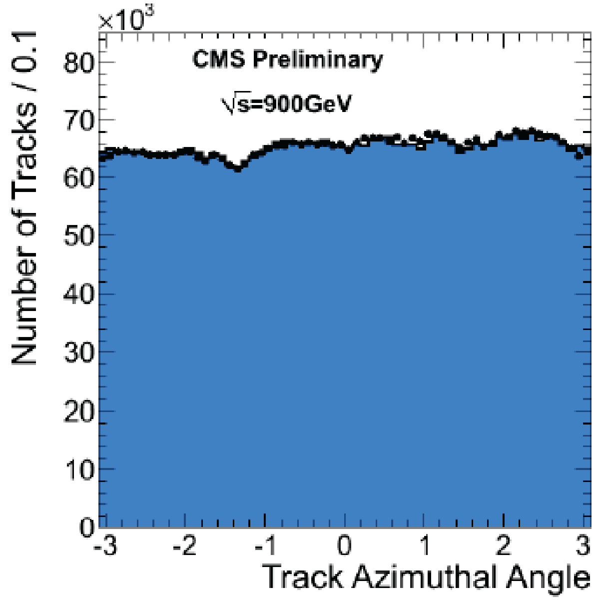
Jets/MET will be discussed tomorrow in the talk Hot Topics from CMS from S. Beauceron

Tracker

Agreement with MC of basic tracker performance







Tracks are seeded either by pixel triplets or pairs with constraint on the beam spot

Track selection applied here:

$|d_z/\sigma| < 10$

$\sigma_{pT}/p_T < 10\%$

Dips in azimuthal distribution are due to inactive modules and are well reproduced in MC

Tracker: dE/dx

CMS Silicon tracker has analog readout

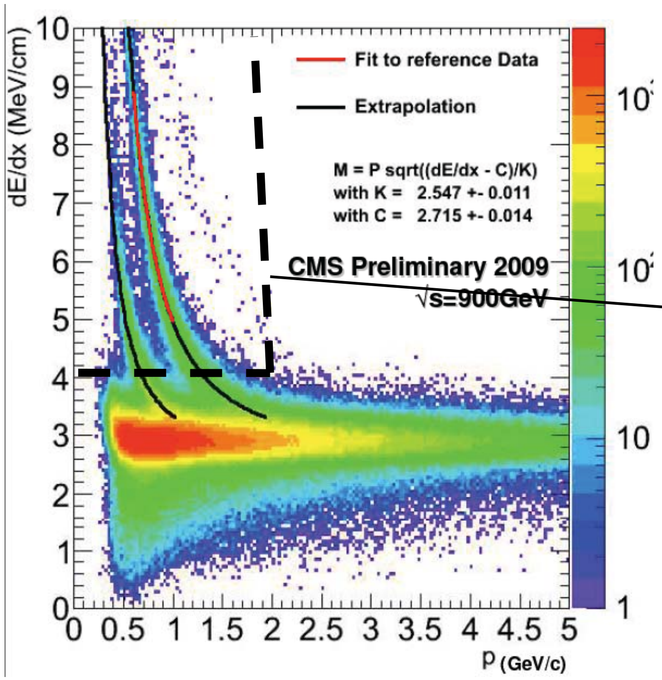
The most probable value of the ionization loss for a track in silicon is estimated from a generalized mean of hits charges/path length

$$dE/dX = \left(\frac{1}{N}\sum_i c_i^k\right)^{1/k} \qquad k = -2$$

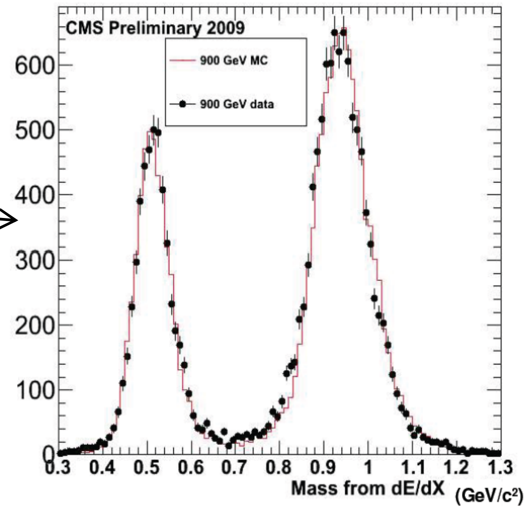
dE/dX computed for tracks:

- $\geq$ 10 Strip Hits
- compatible with primary vertex $|d_{xy}|<2$cm $|d_z|<15$cm

K p



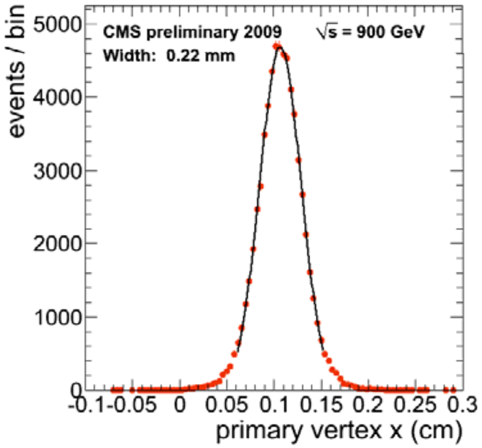
p < 2 GeV
dE/dX > 4.15 MeV/cm



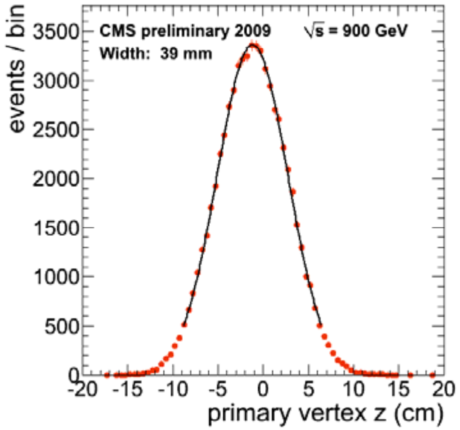
Primary vertex

Primary vertex distribution for a single run
Using full tracks and Adaptive Vertex Fitter (assign a compatibility weight between 0 and 1)

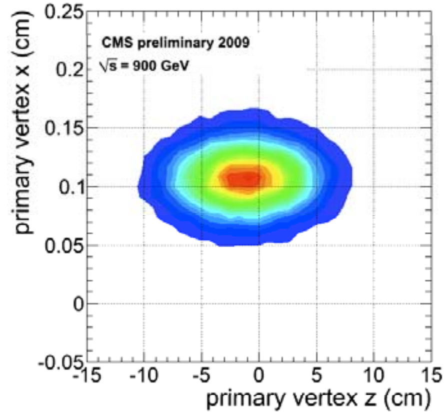
Transverse



Longitudinal

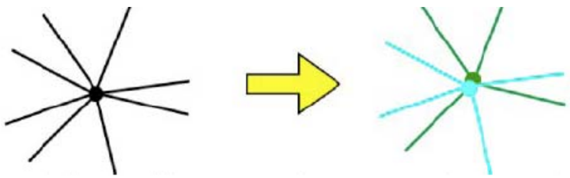


2D

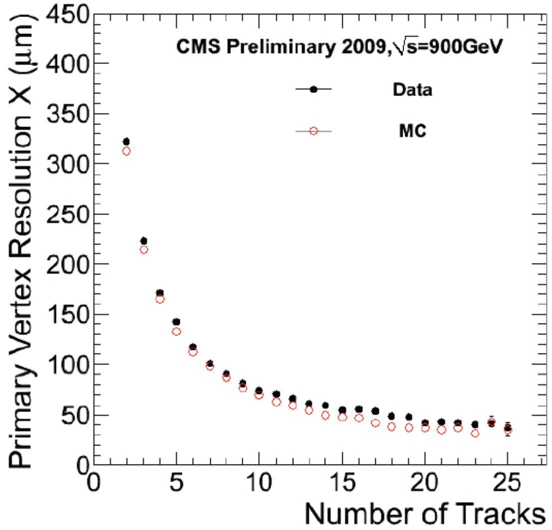


Primary vertex resolution obtained splitting tracks and comparing fits

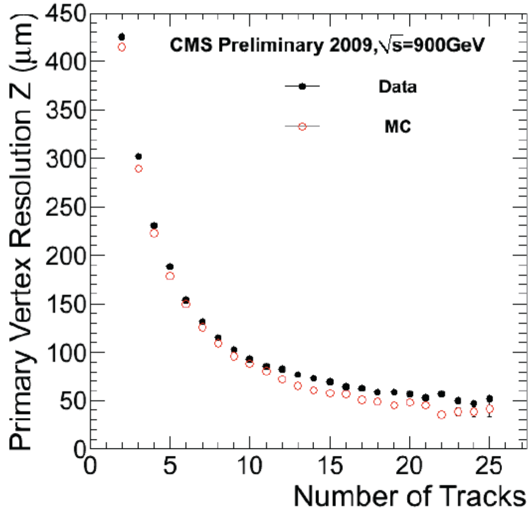
Nice agreement with MC



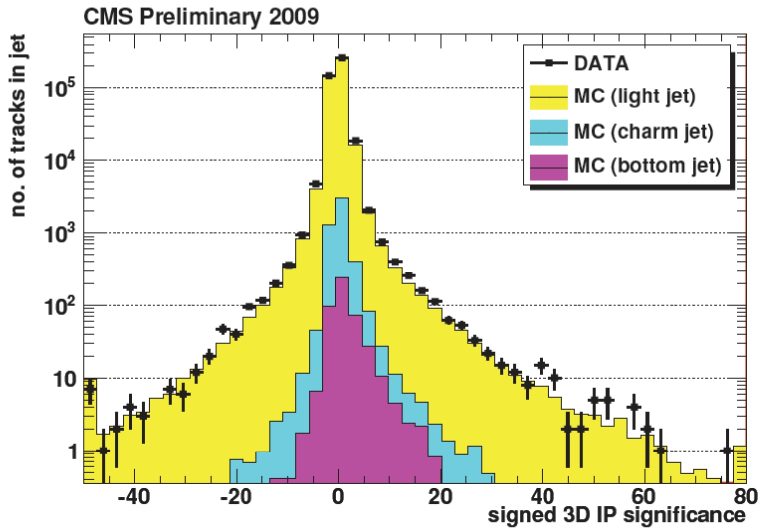
Transverse



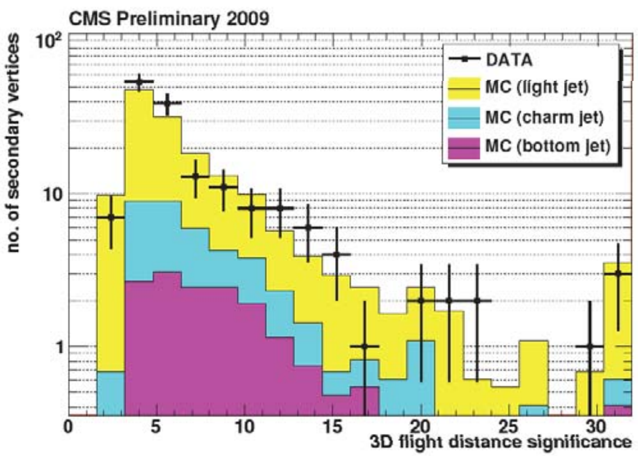
Longitudinal

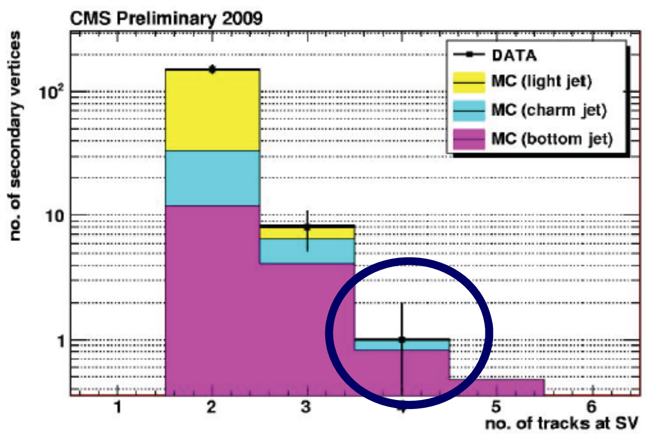


Secondary vertex: b-tagging



Using track associated with jets
Number of Hits ≥ 7
Impact parameter computed wrt primary vertex

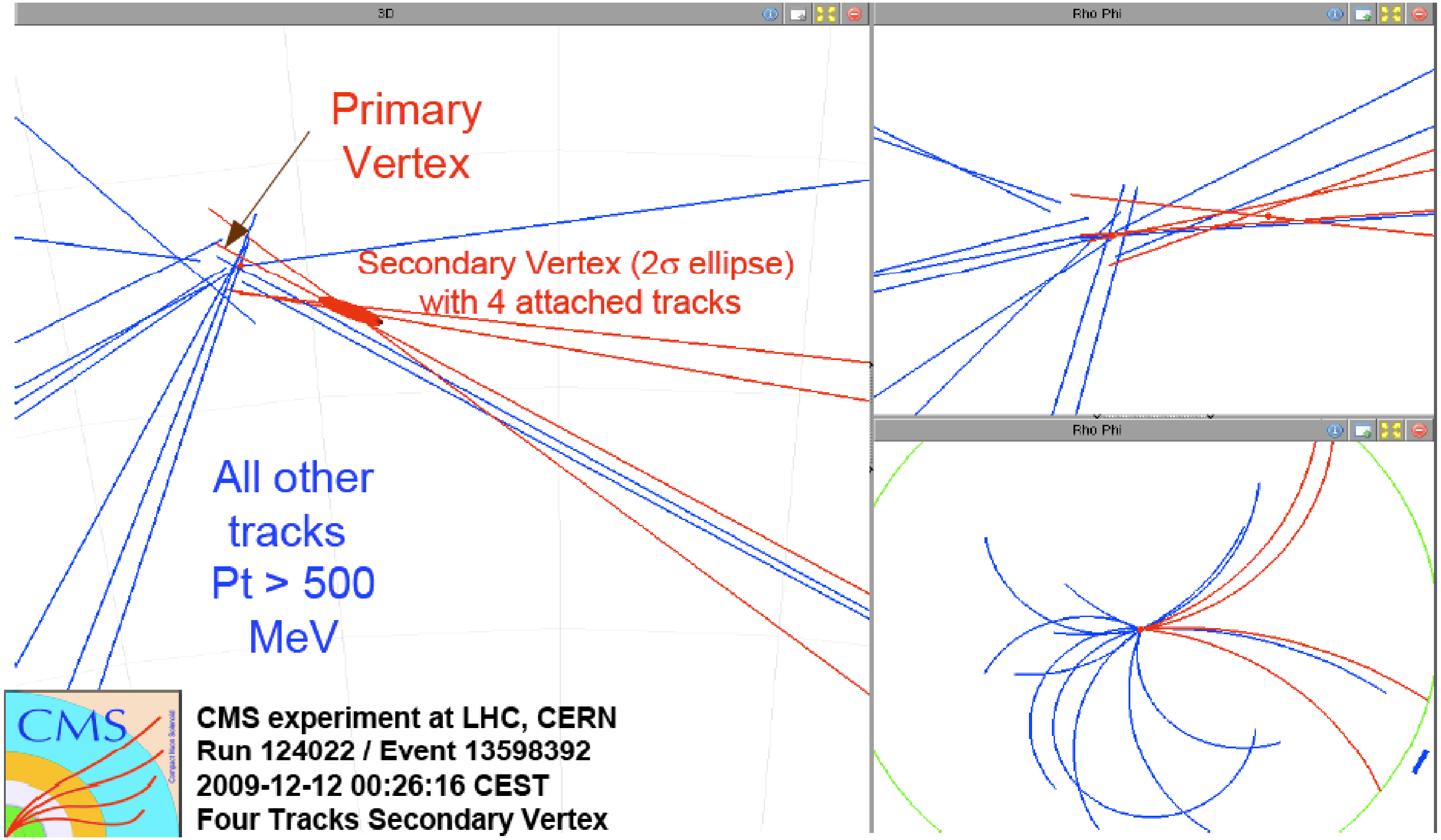




Significance of vertex 3D decay length and number of associated tracks

Secondary vertices reconstructed with tracks associated with jets
K_s rejection:
L_{xy}<2.5 cm
$|M_{vtx}-M_{Ks}|$>0.015 GeV

b candidate



B-tagging algorithm found a secondary vertex made of 4 tracks

- 3D Decay length 2.6mm (significance 7.02), mass = 1.64 GeV

First CMS paper on LHC data

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *February 4, 2010*
ACCEPTED: *February 7, 2010*
PUBLISHED: *February 10, 2010*

J. High Energy Phys. 02 (2010) 041

Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

CMS Collaboration

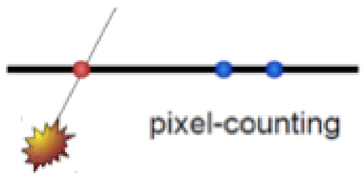
ABSTRACT: Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in p$\bar{\text{p}}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

KEYWORDS: Hadron-Hadron Scattering

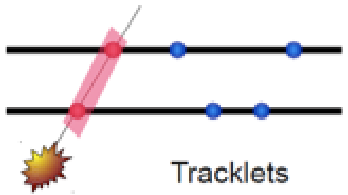
ARXIV EPRINT: 1002.0621

Measurement of dN/dη& dN/dp$_T$

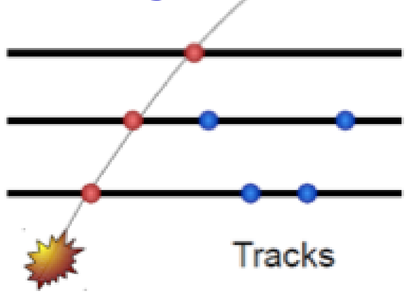
- Hadron production in soft pp collisions is modeled **phenomenologically**
- Inclusive dN/dη & dN/dp$_T$ distributions of primary charged hadrons are measured @ 0.9 & 2.36 TeV
- Relevant for future LHC physics: pile-up. 2.36 TeV measurement is a first step in a new energy regime
- 3 methods are used and compared. Good understanding of tracker performance was crucial to quickly produce final results



- **Pixel Counting**
  - Clusters/layer
    - Three dN/dη measurements
  - Largest acceptance but most sensitive to bkg



- **Tracklets**
  - 2 of 3 pixel layers
    - Three dN/dη measurements
    - Less sensitive to backgrounds



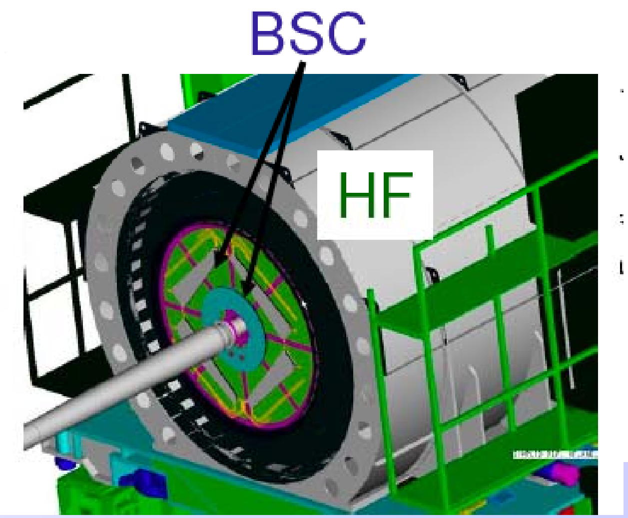
- **Tracks**
  - dN/dη and dN/dp$_T$
    - Most robust against backgrounds

Event selection

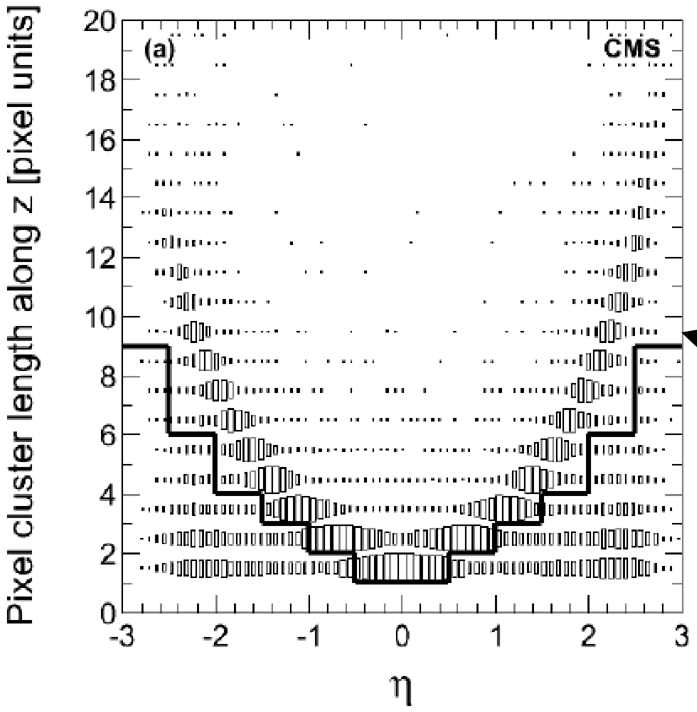
- Aimed at selecting NonSingleDiffractive events with high efficiency (rejecting a large fraction of SingleDiffractive). Efficiencies:
  - NSD: ≈ 86%
  - SD: ≈ 19%

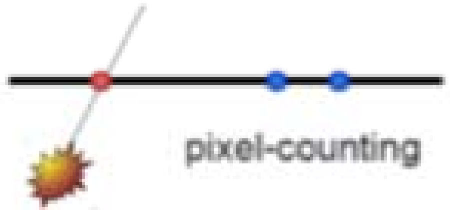
NSD are chosen to minimize effect of model dependence of the corrections and allow comparison with previous experiments

- ≈ 10 Hz collision rate (pile-up probability < 2 x 10^{-4})
- Measurement done on 40k events at 0.9 TeV and 10k events at 2.36 TeV
- Event selection common to the 3 methods requiring:
  - Trigger level: at least 1 hit in Beam scintillation counters AND coincidence with beam pickups (BPTX)
  - >3GeV total energy on both sides of the Forward calorimeter (HF)
  - Beam halo rejection
  - Beam background rejection
  - A collision vertex



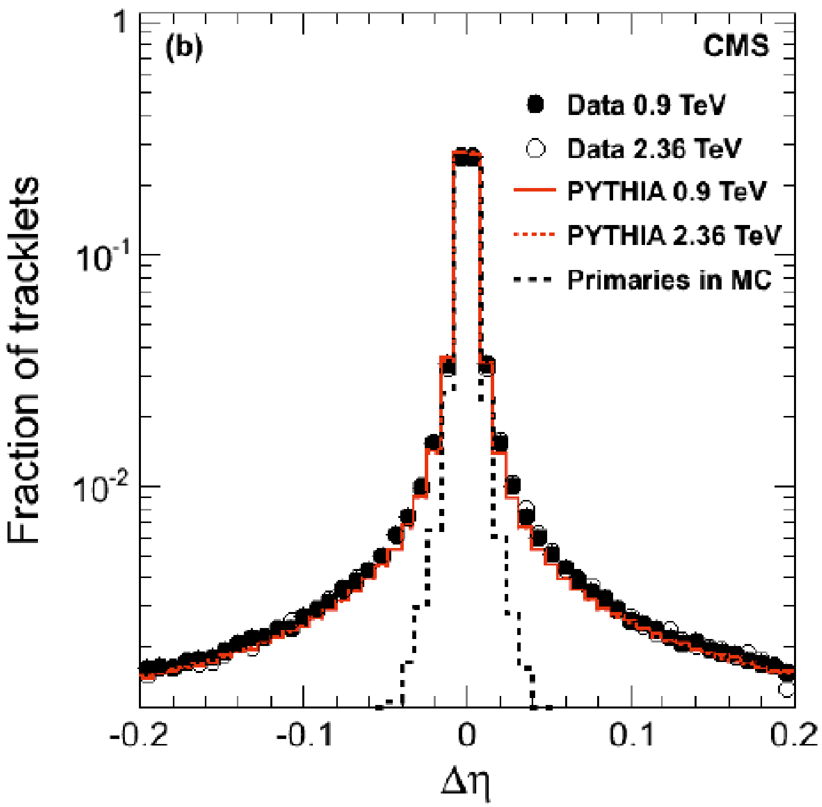
Pixel cluster counting

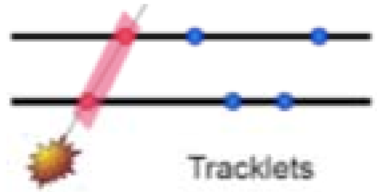




Counting clusters of pixel hits in pixel barrel layers (acceptance p_T>30 MeV/c |η|<2)
Applying a cut on cluster length ≈ |sinh(η)| to eliminate loopers and secondaries (shorter clusters)
Corrections for loopers, weak decays, secondaries
Independent results for the 3 layers agree
Insensitive to detector misalignment, sensitive to beam background

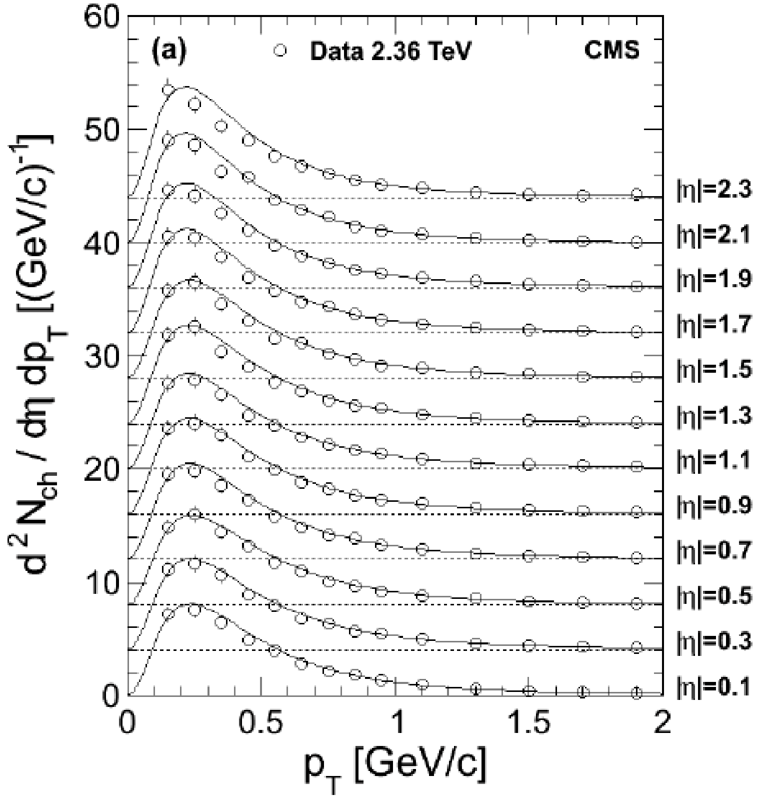
Tracklet method



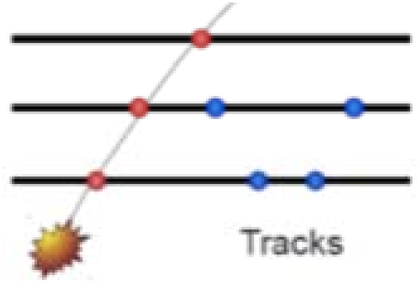


Tracklets: pairs of clusters in 2 different pixel barrel layers (acceptance p_T>75 MeV/c $|\eta|$<2)
$|\Delta\eta|$ and $|\Delta\varphi|$ between clusters are used to select signal from primaries
Combinatorial background is subtracted using $\Delta\varphi$ sidebands
Corrections are applied for efficiency, secondaries, weak decays
Less sensitive to beam background

Tracking method

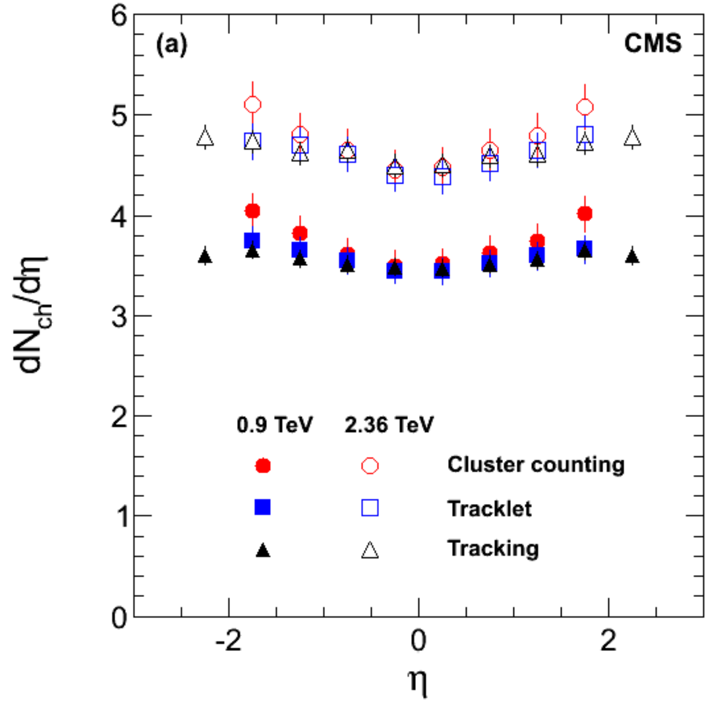


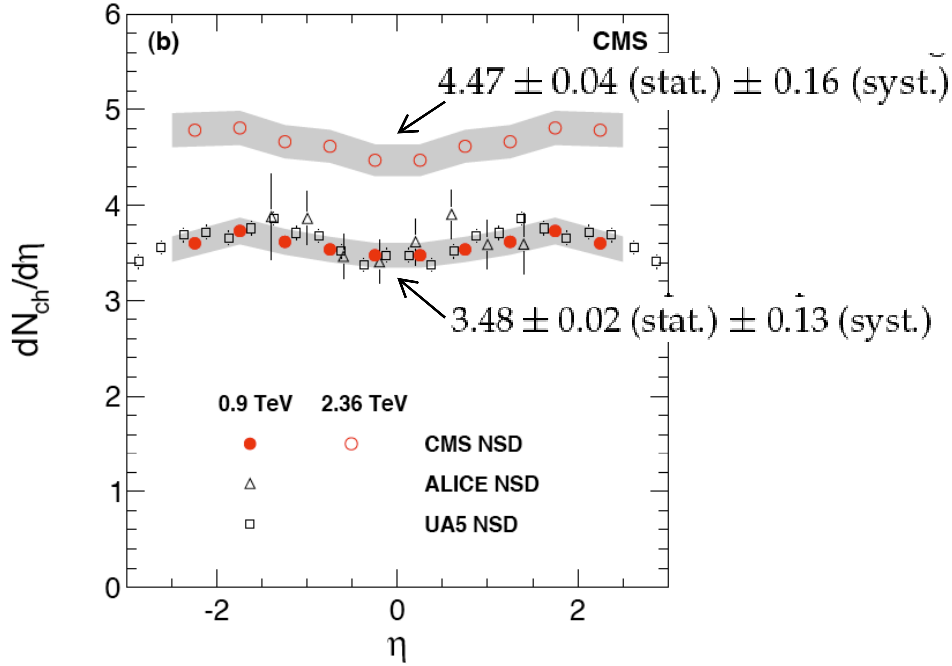
Differential yield of charged hadrons in different η bins (vertically shifted by 4 units). Points include systematics errors



Use all pixel & strip layers
Acceptance (|η|<2.4, >50% for $p_T \approx 0.1, 0.2, 0.3$ for π,K,p)
Compatibility with beam spot and primary vertex is required
Low fake rate (<1%) achieved with additional cleaning on cluster shapes
Immune to beam background
More sensitive to beam spot & alignment

Results: dN/dη

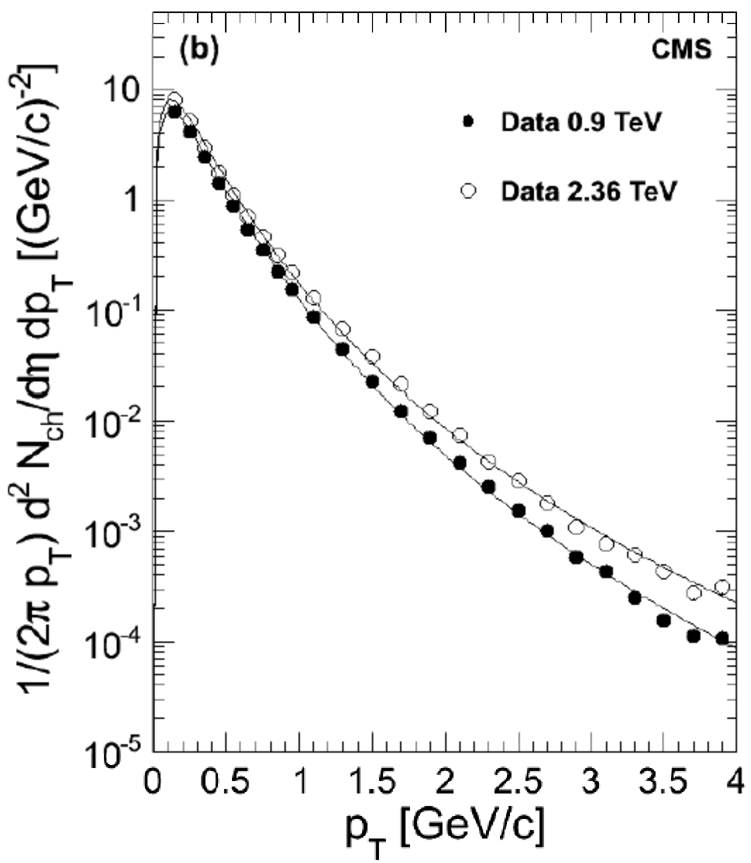




Comparing the 3 methods at 0.9 & 2.36 TeV
Error bars show systematic errors (going from 4.4% to 2.4%) excluding common contributions

Comparison with UA5 and ALICE
Averaging the 3 CMS methods
Largest systematic error contribution is coming from from the uncertaintainty in SD contamination (2%)
UA5 and ALICE errors are statistical only

Results: dN/dp_T

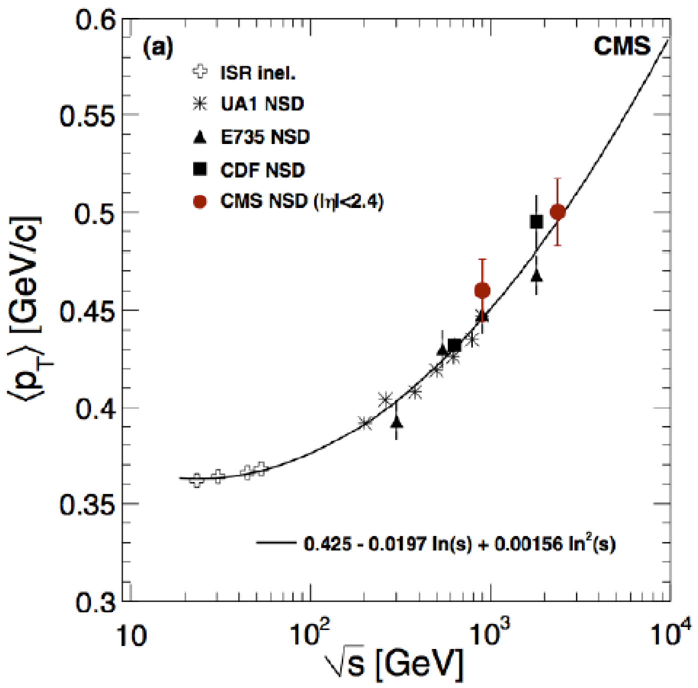


The transverse momentum of charged hadrons is measured up to 4 GeV/c (integrating up to $|\eta|<2.4$) @ 900 & 2.36 TeV

Points (including systematic errors) are fitted with the empirical Tsallis function (exponential at low p_T, power law at high p_T)

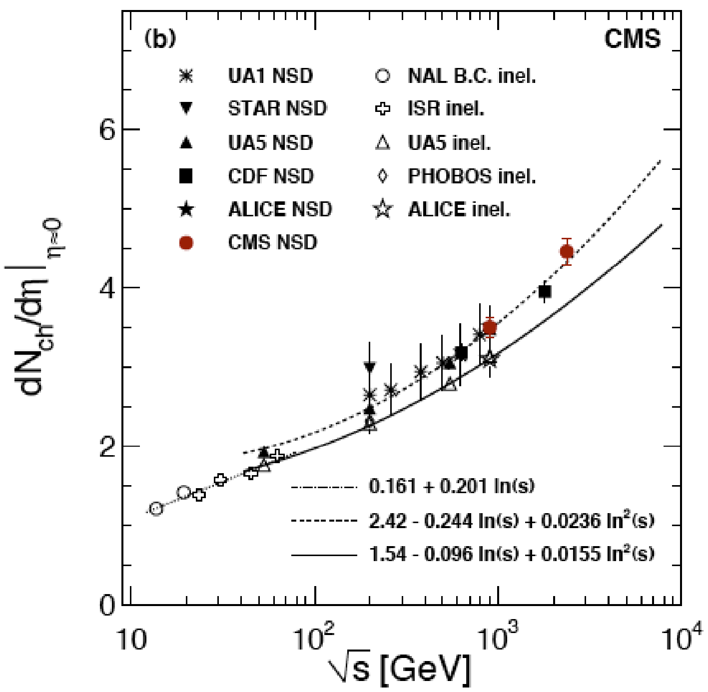
Spectrum is harder at higher center of mass energy as expected

Results: scaling with energy



Variation with energy of average transverse momentum

@0.9 TeV $0.46 \pm 0.01\,(\text{stat.}) \pm 0.01\,(\text{syst.})\ \text{GeV}/c$
@2.36 TeV $0.50 \pm 0.01\,(\text{stat.}) \pm 0.01\,(\text{syst.})\ \text{GeV}/c$



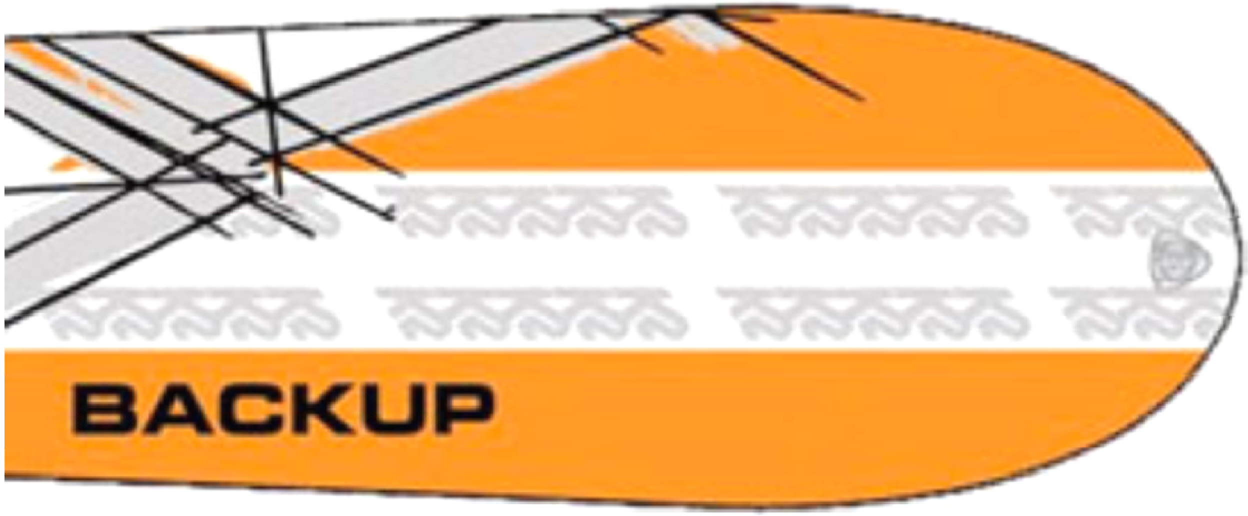
Variation of dN/dη with center of mass energy.
dN/dη(@2.36TeV)/dN/dη(@0.9TeV)

$$(28.4 \pm 1.4 \pm 2.6)\%$$

significantly larger then prediction from PYTHIA&PHOJET tunes used in the analysis 18.4% & 14.5%

Summary

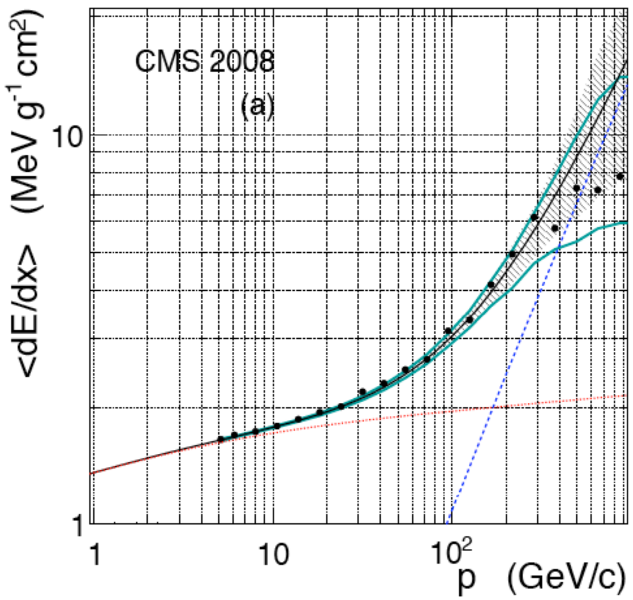
- **CMS arrived prepared** to **first collision data** and was ready to **quickly analyze the data** and to **produce physics results**
  - **At this energies we have a good understanding our detector: agreement with simulation is good out of the box**, many years of preparation with test beams, cosmic runs, simulation tuning
  - **First paper on collision data is published**, 5 other papers are in preparation
  - **Excellent detector performance** is shown with **high data quality**
- Looking forward to 7 TeV data
  - Explore/understand a new region of the Standard Model
  - Prepare for searches
- Clearly a lot of work is ahead of us!


BACKUP

CRAFT: Calorimeters

First measurement of muon critical energy in lead tungstate $160^{+5}_{-6} \pm 8\,\mathrm{GeV}$,

Using only bottom half of ECAL
Angle between muon and crystal axis < 0.5 radians
Scale measured in TB confirmed at 2% accuracy

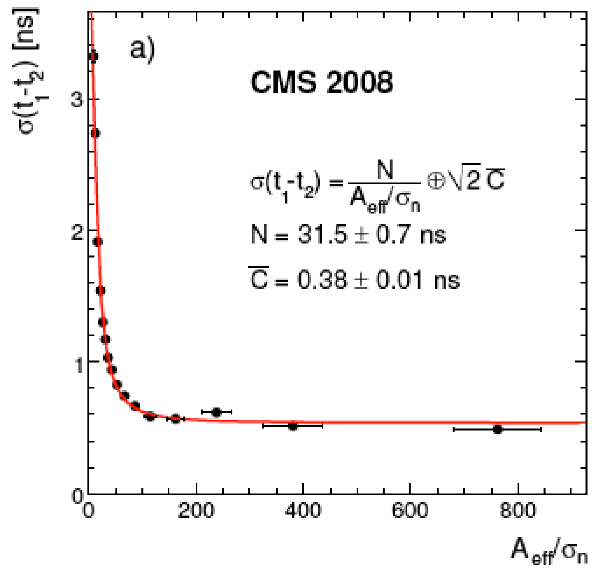


Muon stopping power as a function of muon momentum

http://arxiv.org/abs/0911.5397

Improved understanding of noise and synchronization in ECAL and HCAL

http://arxiv.org/abs/0911.4044



ECAL time resolution as a function of effective amplitude (amplitude/noise). **Sub-ns synchronization** between channels is achieved

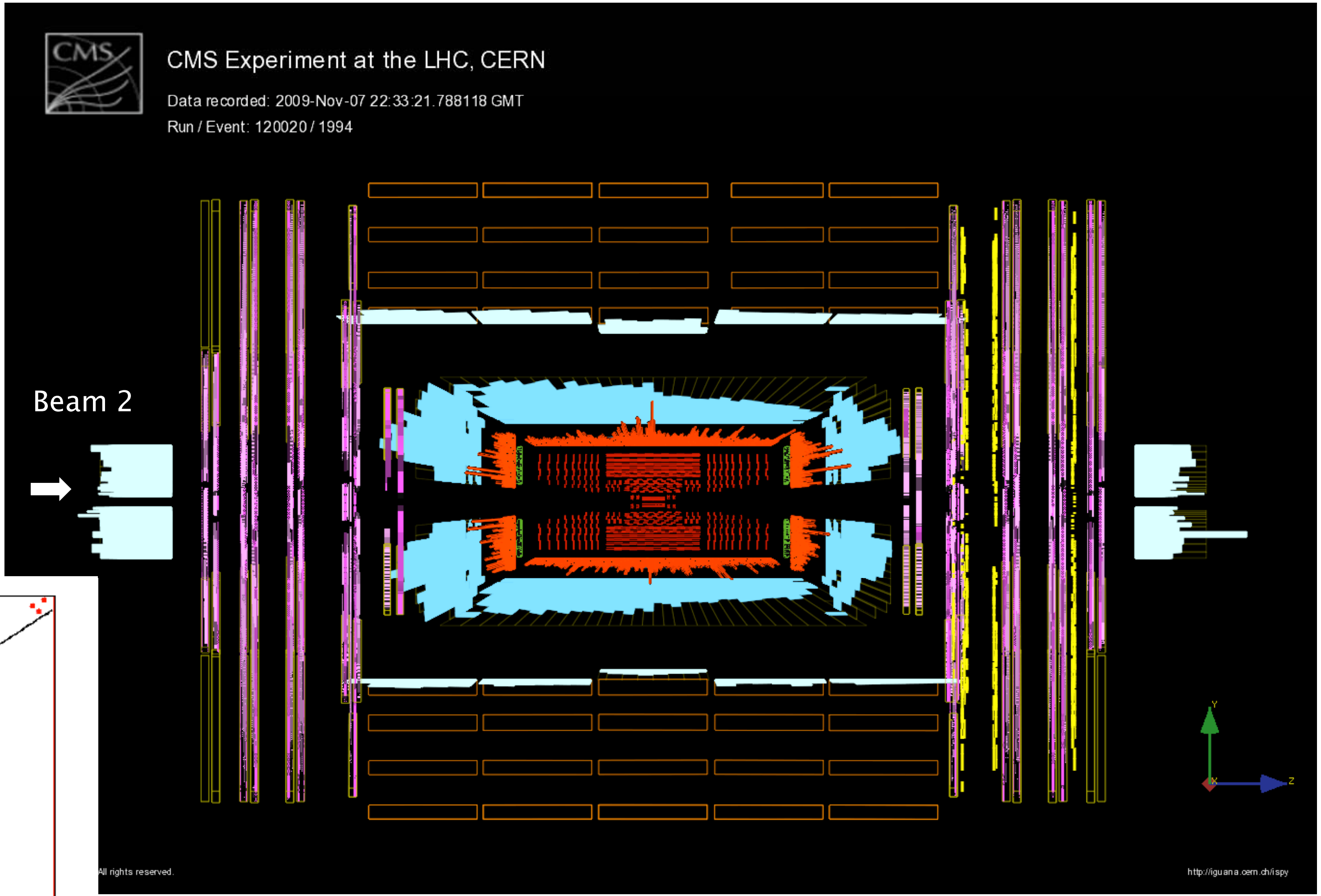
For HCAL time spread measured to be ±2ns

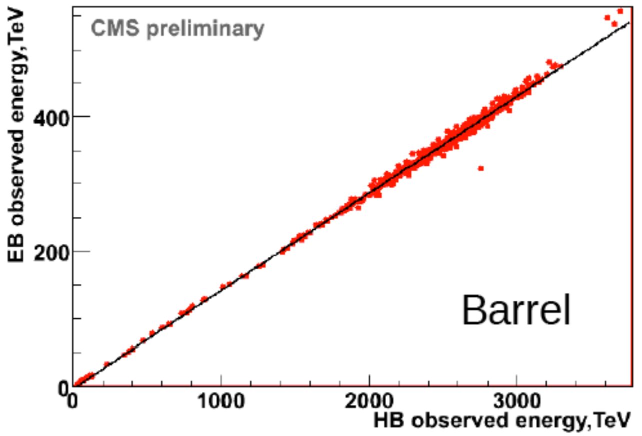
http://arxiv.org/abs/0911.4877

Dump LHC beam on collimators upstream to CMS

2 series of “splash events” in Sept08 and Nov09 (in 2009 collected 1105 shots)

Allow to improve synchronization of individual channels in calorimeters (tracking off, muons at reduced HV)



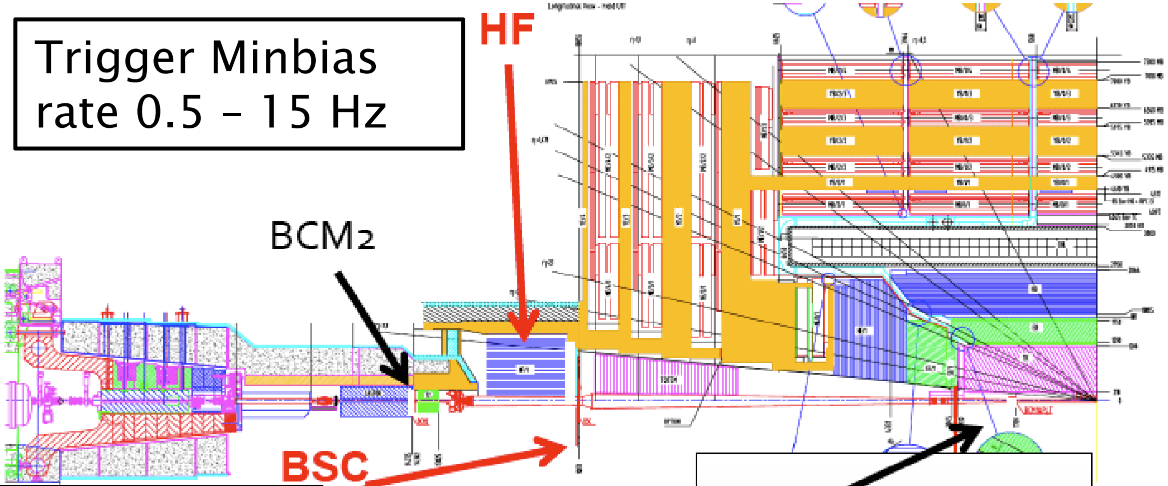


Correlation between energy measured in ECAL and HCAL barrel

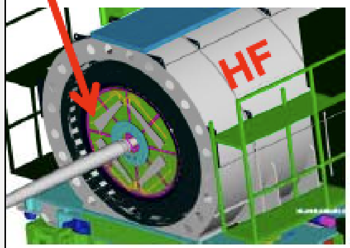
Minimum bias triggers @ startup

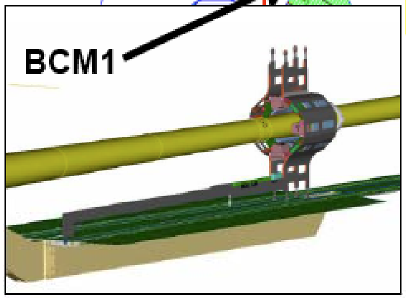
- Hadronic Forward
  - HF: $2.5 \leq |\eta| \leq 5$.
- Beam Scintillator planes
  - BSC: $\pm$10.5 m from IP
- Beam Pick-up Timing
  - BPTX: $\pm$175 m from IP

Trigger Minbias
rate 0.5 – 15 Hz



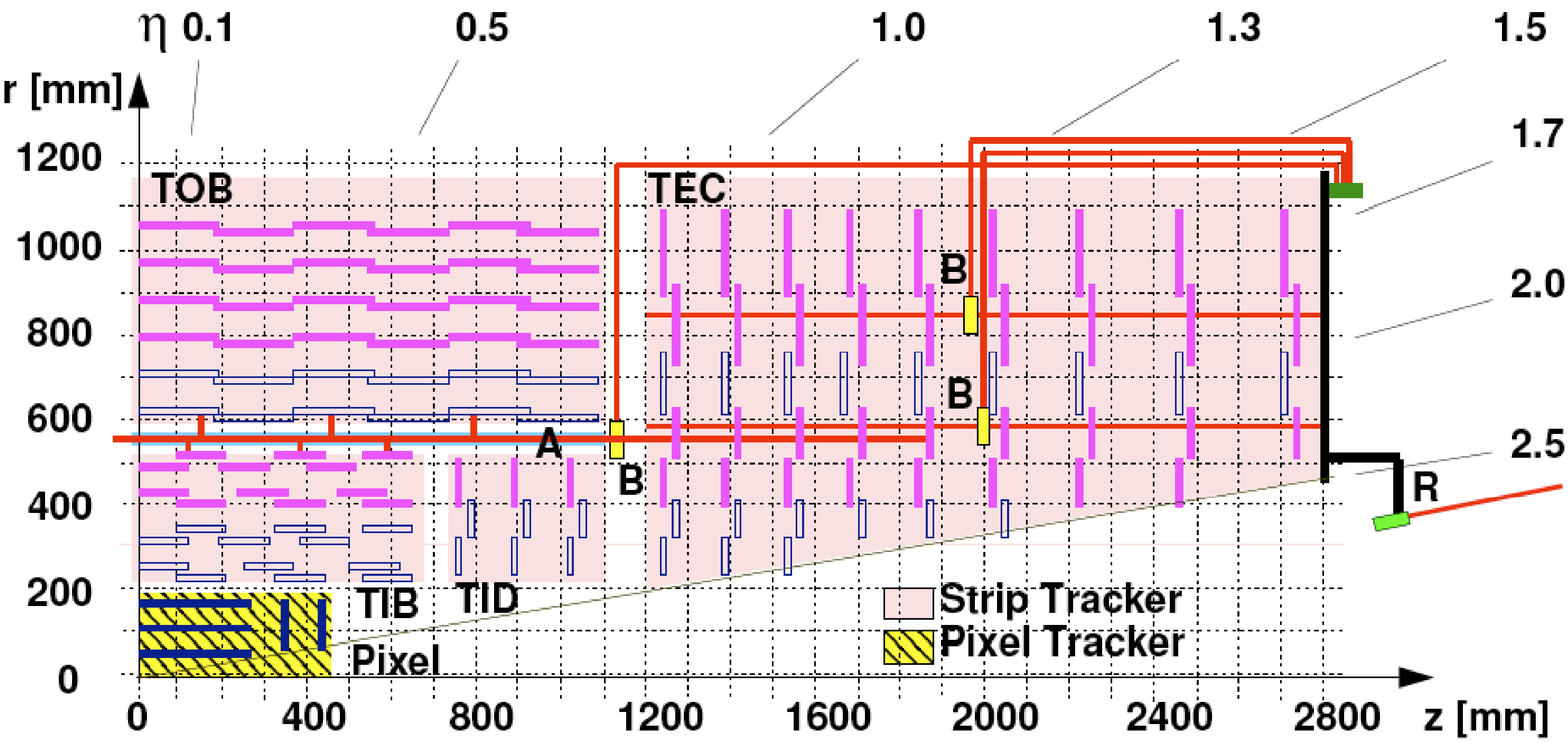
- Trigger: Min Bias & Zero Bias
  - L1 Beam Scintillator Counters
  - L1 Trigger "BPTX" prescaled
  - HLT output $\lesssim$ 600Hz
- Minimum Bias selection:
  - BSC (OR 2 planes) + vertex: $\epsilon > 80\%$
  - HF (E > 3 GeV both sides): $\epsilon > 80\%$
    - Combined high ϵfficiency



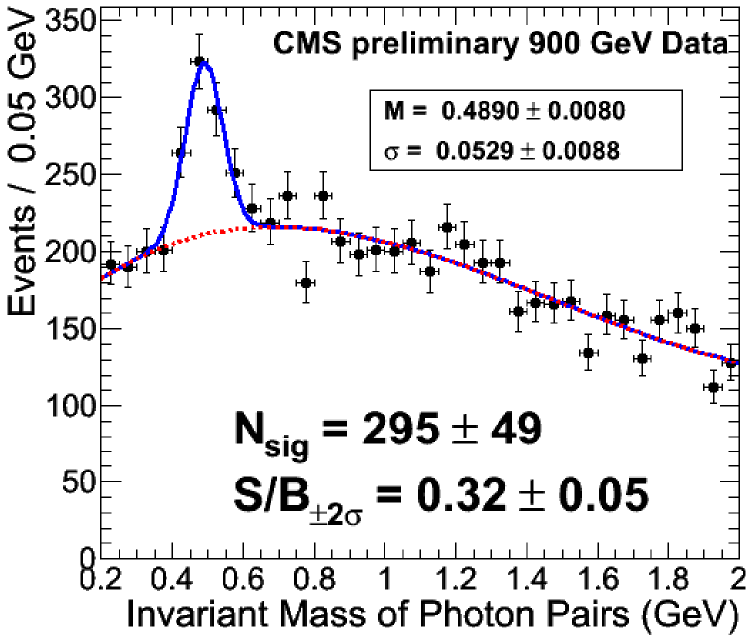


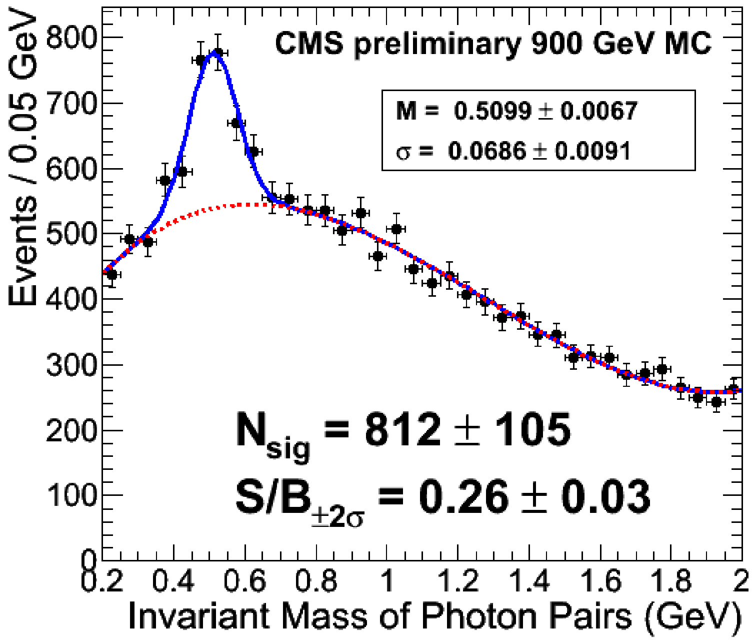
- BCM (Beam conditions Monitor)
  - polycrystalline diamonds (pcd)
  - measure background rates for safe operation of inner detectors

Tracker layout



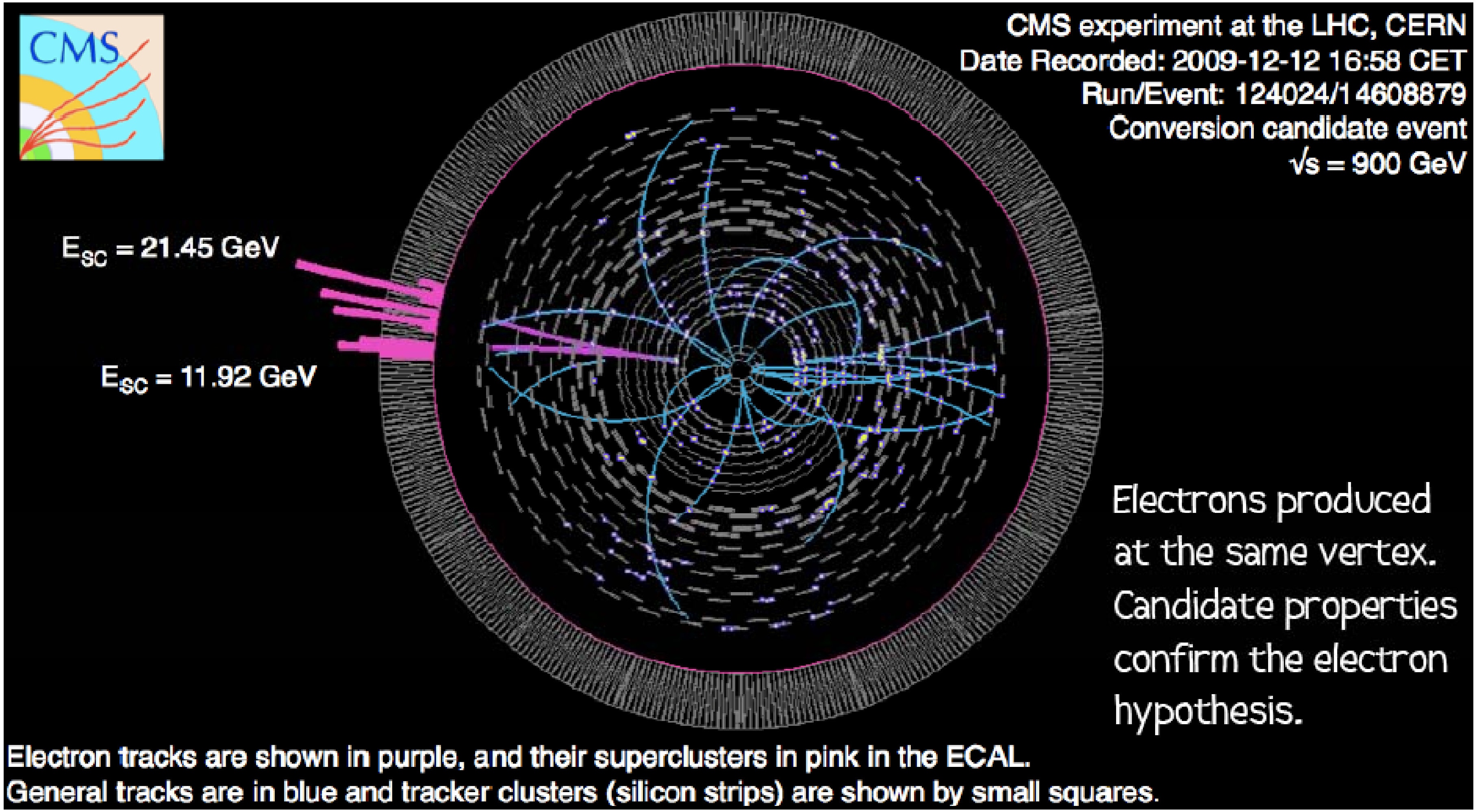
ECAL:η





- Mass and width compatible with MC
  - η yield scale as expected wrt π^0
    - $N(\eta) / N(\pi^0) = 0.020 \pm 0.003$ DATA
    - $N(\eta) / N(\pi^0) = 0.021 \pm 0.003$ MC

Conversion candidate

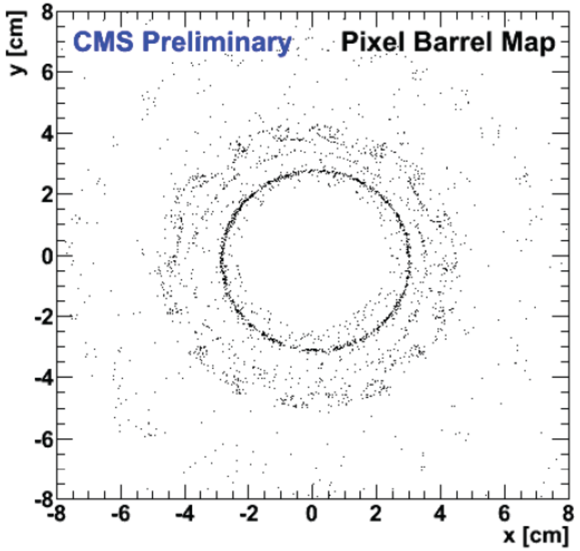


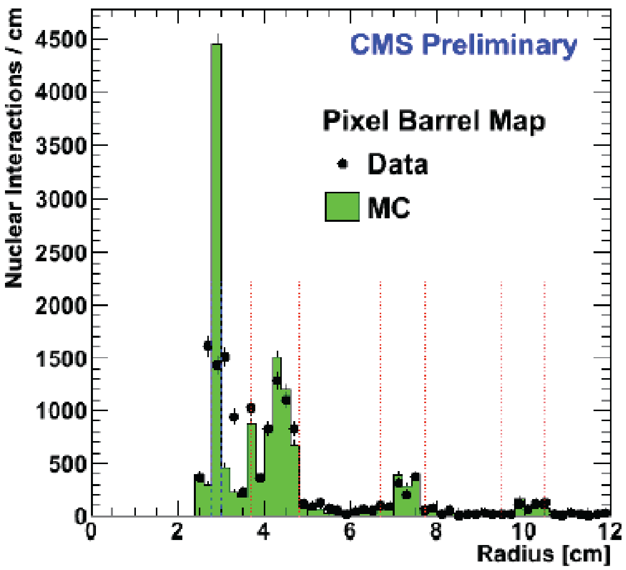
J/psi expected

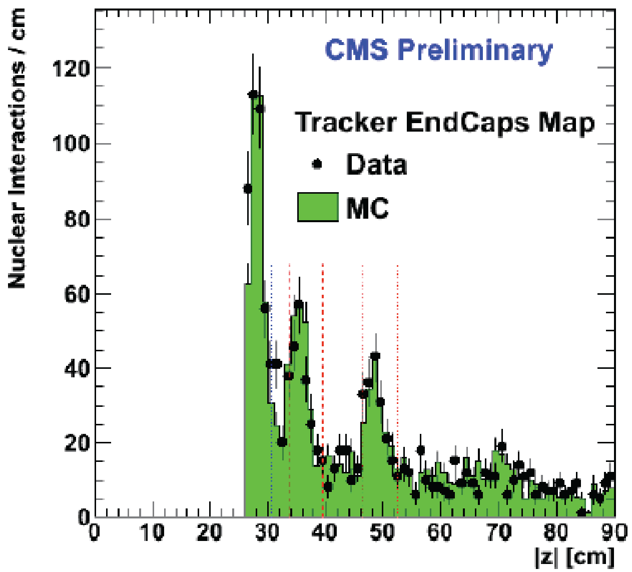
➢ Expected number of opposite-sign dimuons reconstructed in the mass window 3.0-3.2 GeV, per nb^{-1}, after cuts:

	900 GeV		2.36 TeV	
	prompt J/ψ	background	prompt J/ψ	background
global - global	5	~ 0	**16**	**0.9 ± 0.4**
global - tracker	16	5 ± 5	**38**	**10 ± 1**
tracker - tracker	7	~ 0	**13**	**13 ± 2**

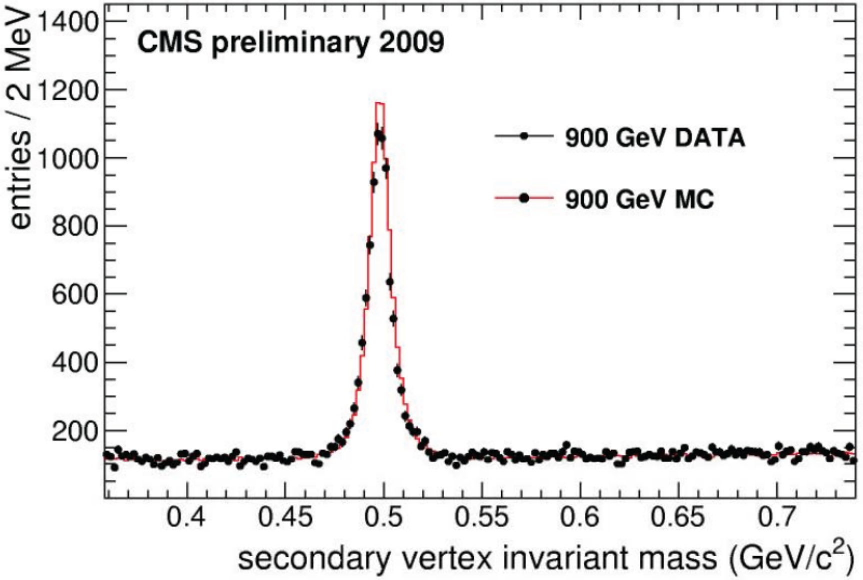
Nuclear interactions



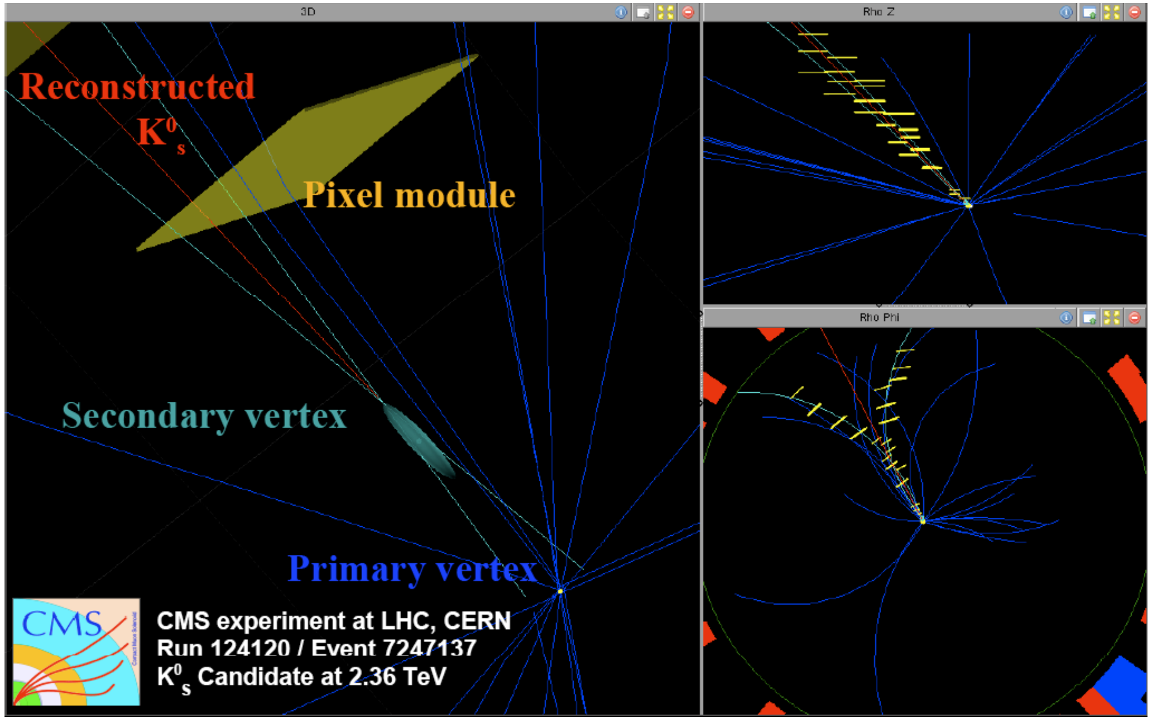




K^0_s from inclusive vertexing



A K^0_s candidate @ 2.36 TeV



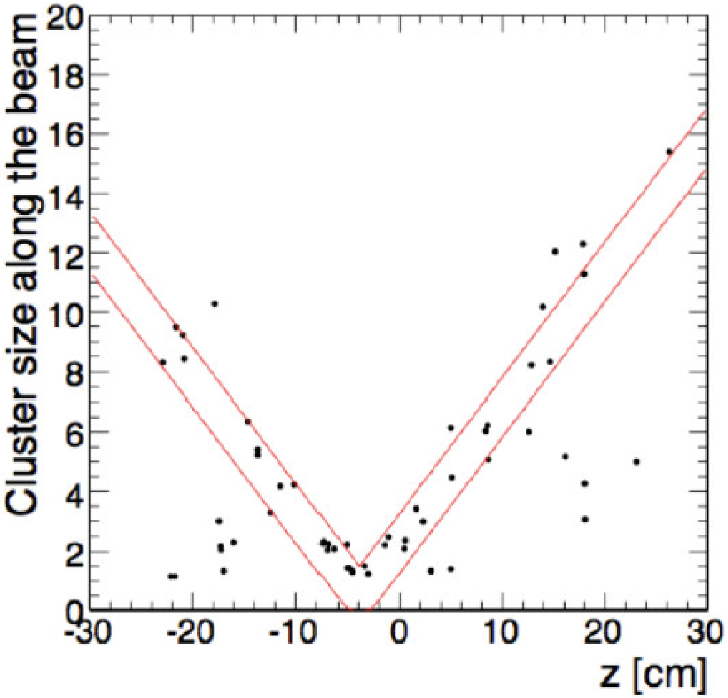
- Running inclusively the secondary vertex finder on all tracks (no preselection)
- Studying sensitivity for two tracks vertices using the K_s peak

Event selection: numbers

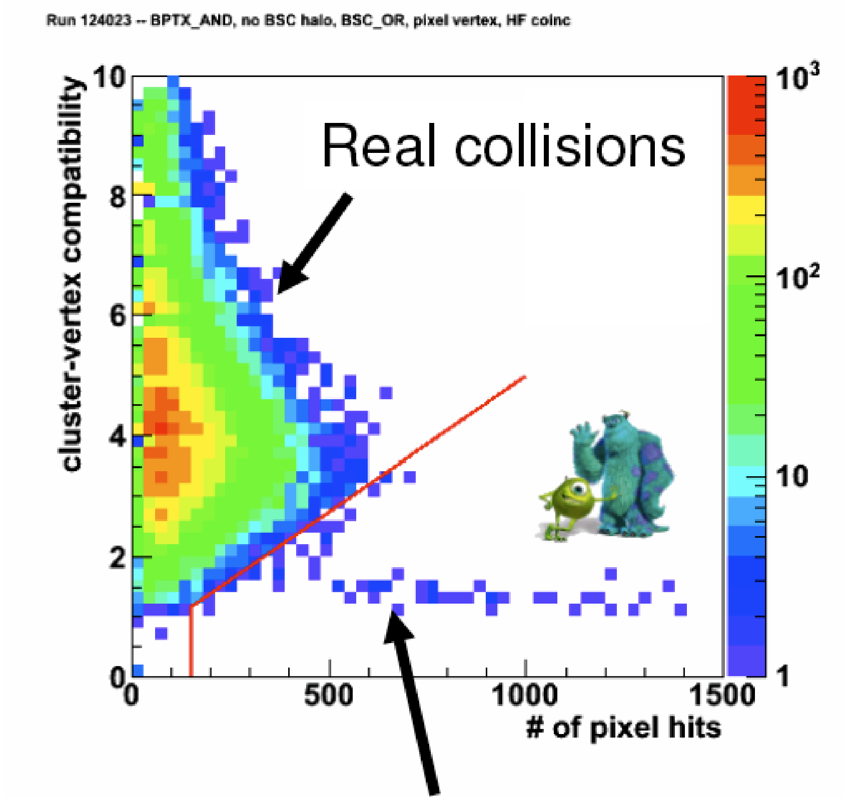
Table 1: Numbers of events per data sample used in this analysis. The offline event selection criteria are applied in sequence, i.e., each line includes the selection of the lines above.

Centre-of-mass Energy	0.9 TeV	2.36 TeV
Selection	Number of Events	
BPTX Coincidence + one BSC Signal	72 637	18 074
One Pixel Track	51 308	13 029
HF Coincidence	40 781	10 948
Beam Halo Rejection	40 741	10 939
Beam Background Rejection	40 647	10 905
Valid Event Vertex	40 320	10 837

Beam-gas scraping events rejection

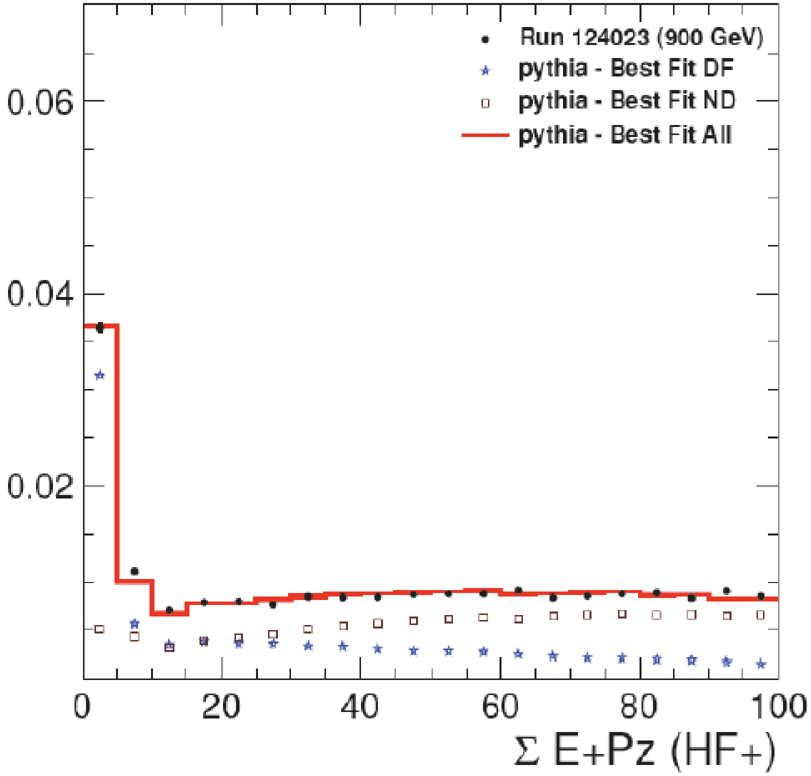


Vertex-cluster compatibility:
Ratio of #clusters in the V shape and #clusters in the offset V-shape by ±10 cm



Beam-scraping events have a lot of pixel hits but ill-defined vertex

Measuring diffractive component



The HF calorimeter data is used to fit the SD+DD fraction in data using PYTHIA event shapes. PHOJET was also studied similarly.

dN/dη: detailed sistematics

Table 3: Summary of systematic uncertainties. While the various sources of uncertainties are largely independent, most of the uncertainties are correlated between data points and between the analysis methods. The event selection and acceptance uncertainty is common to the three methods and affects them in the same way. The values in parentheses apply to the $\langle p_T \rangle$ measurement.

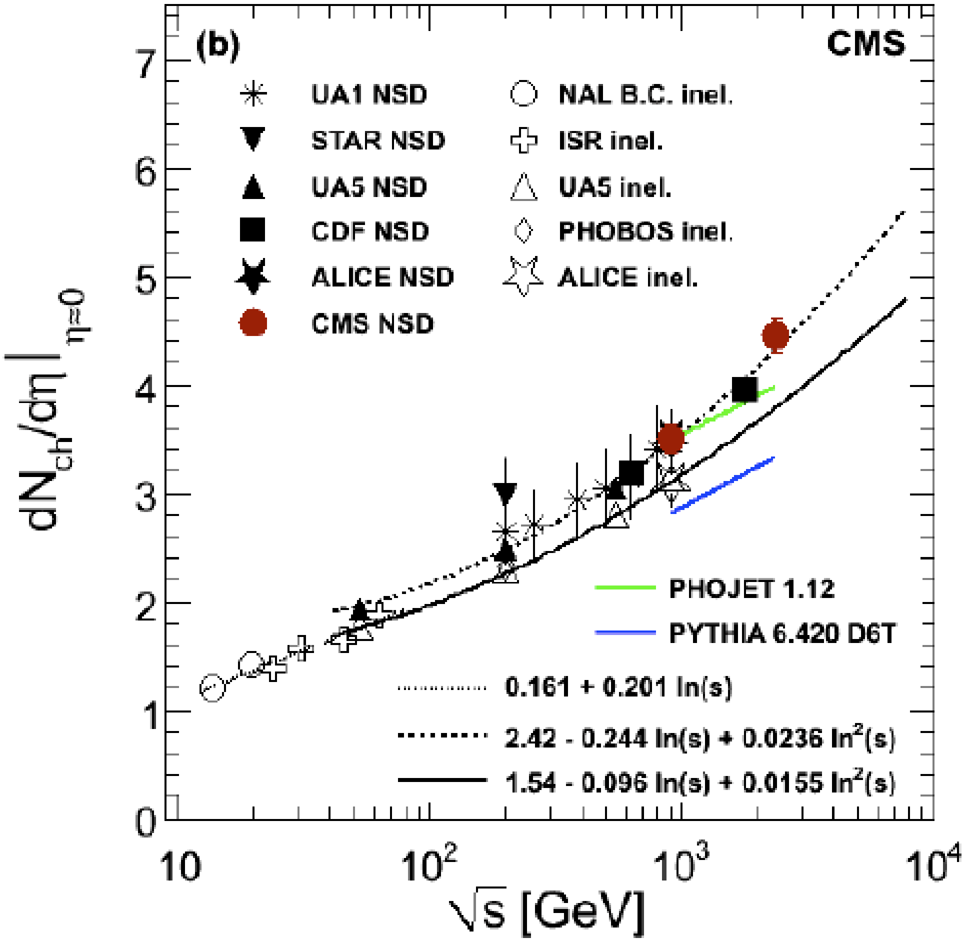
Source	Pixel Counting [%]	Tracklet [%]	Tracking [%]
Correction on event selection	3.0	3.0	3.0 (1.0)
Acceptance uncertainty	1.0	1.0	1.0
Pixel hit efficiency	0.5	1.0	0.3
Pixel cluster splitting	1.0	0.4	0.2
Tracklet and cluster selection	3.0	0.5	-
Efficiency of the reconstruction	-	3.0	2.0
Correction of looper hits	2.0	1.0	-
Correction of secondary particles	2.0	1.0	1.0
Misalignment, different scenarios	-	1.0	0.1
Random hits from beam halo	1.0	0.2	0.1
Multiple track counting	-	-	0.1
Fake track rate	-	-	0.5
p_T extrapolation	0.2	0.3	0.5
Total, excl. common uncertainties	4.4	3.7	2.4
Total, incl. common uncert. of 3.2%	5.4	4.9	4.0 (2.8)

NSD/DD/SD fractions

Table 2: Expected fractions of SD, DD, ND and NSD processes ("Frac.") obtained from the PYTHIA and PHOJET event generators before any selection and the corresponding selection efficiencies ("Sel. Eff.") determined from the MC simulation.

	PYTHIA				PHOJET			
Energy	0.9 TeV		2.36 TeV		0.9 TeV		2.36 TeV	
	Frac.	Sel. Eff.	Frac.	Sel. Eff.	Frac.	Sel. Eff.	Frac.	Sel. Eff.
SD	22.5%	16.1%	21.0%	21.8%	18.9%	20.1%	16.2%	25.1%
DD	12.3%	35.0%	12.8%	33.8%	8.4%	53.8%	7.3%	50.0%
ND	65.2%	95.2%	66.2%	96.4%	72.7%	94.7%	76.5%	96.5%
NSD	77.5%	85.6%	79.0%	86.2%	81.1%	90.5%	83.8%	92.4%

dN/dη: comparison with MC



- The energy-dependence of the multiplicity density is steeper than predicted by the PYTHIA and PHOJET model tunes used

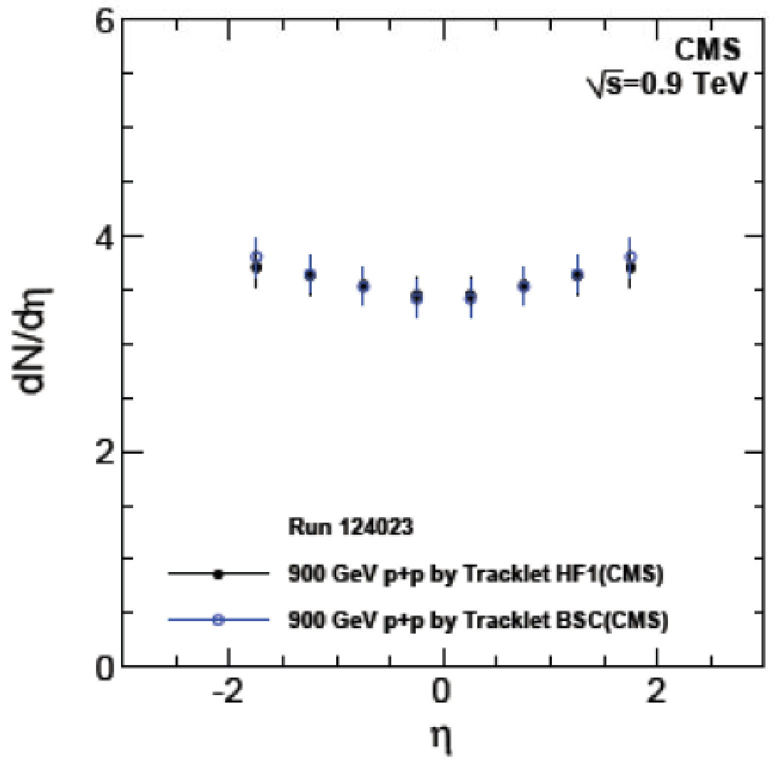
Tsallis function

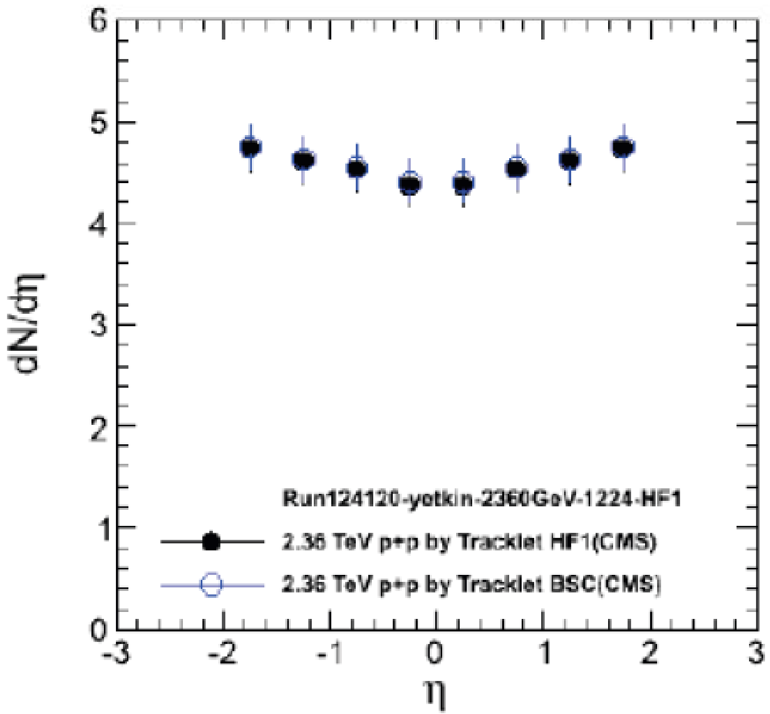
$$E\frac{d^3N_{ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$

Limits:

- exponential at low p_T
- power-law at high p_T

HF vs BSC



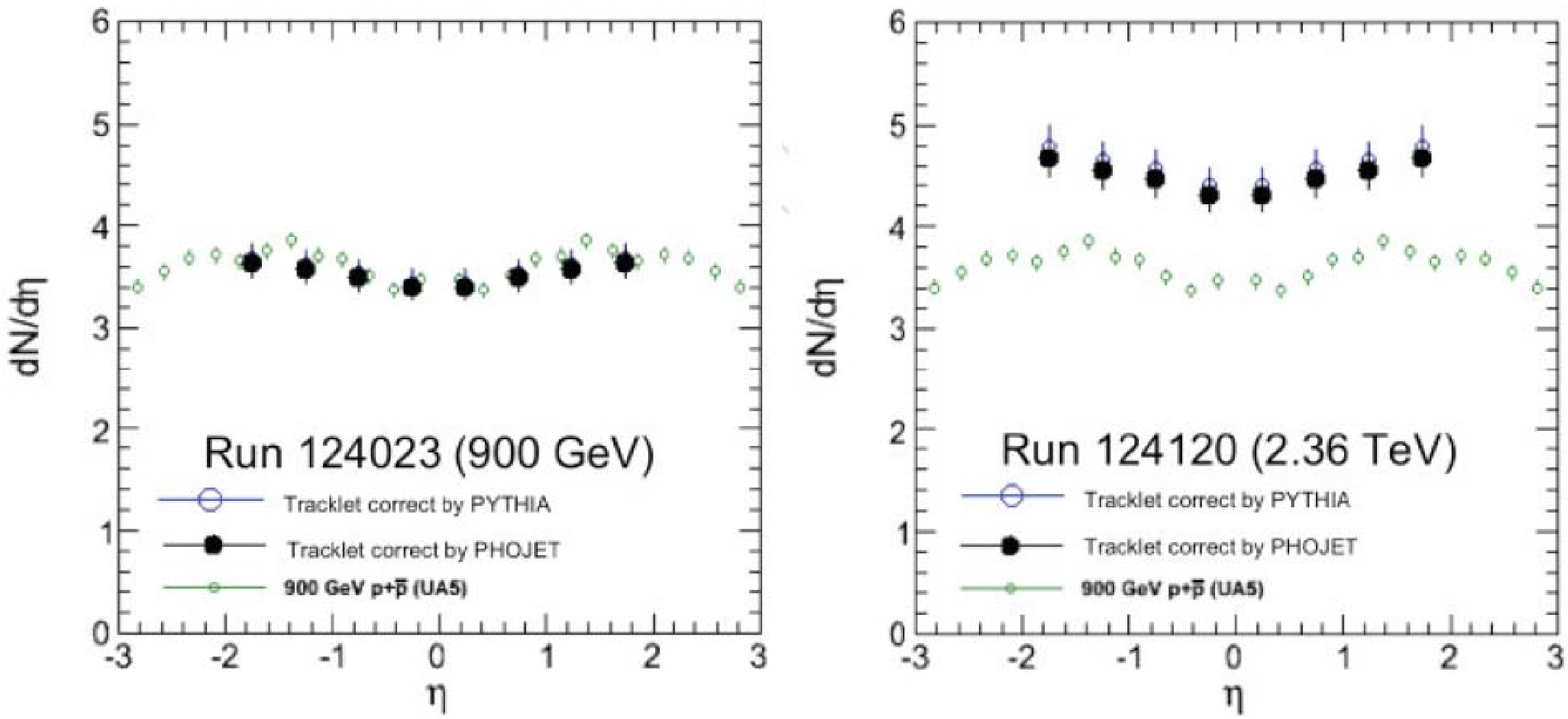


The final result is not sensitive to the trigger detector used:

BSC trigger (coincidence of at least 1 segment hit)

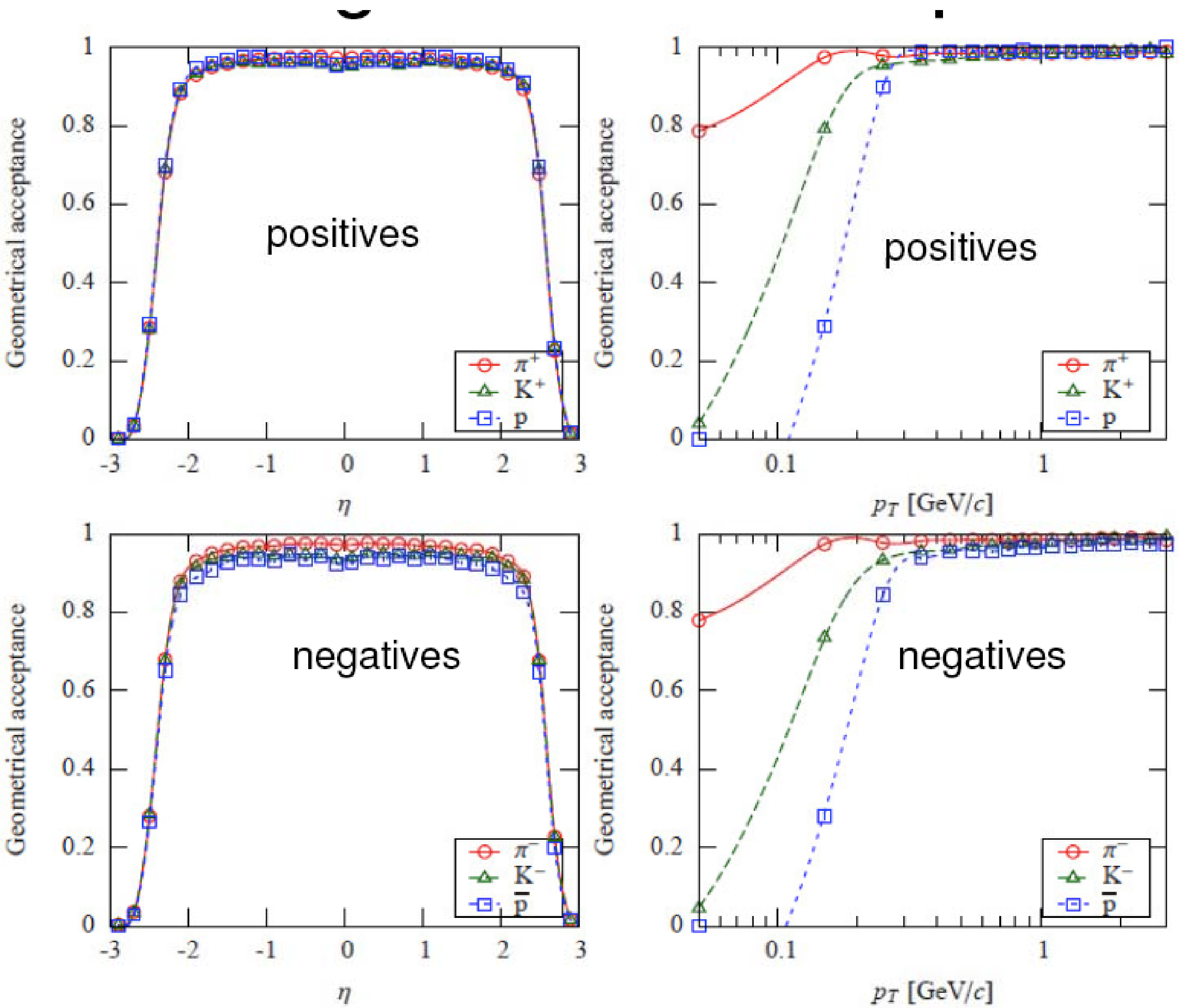
HF selection (coincidence of at least 3 GeV total energy)

Model dependence

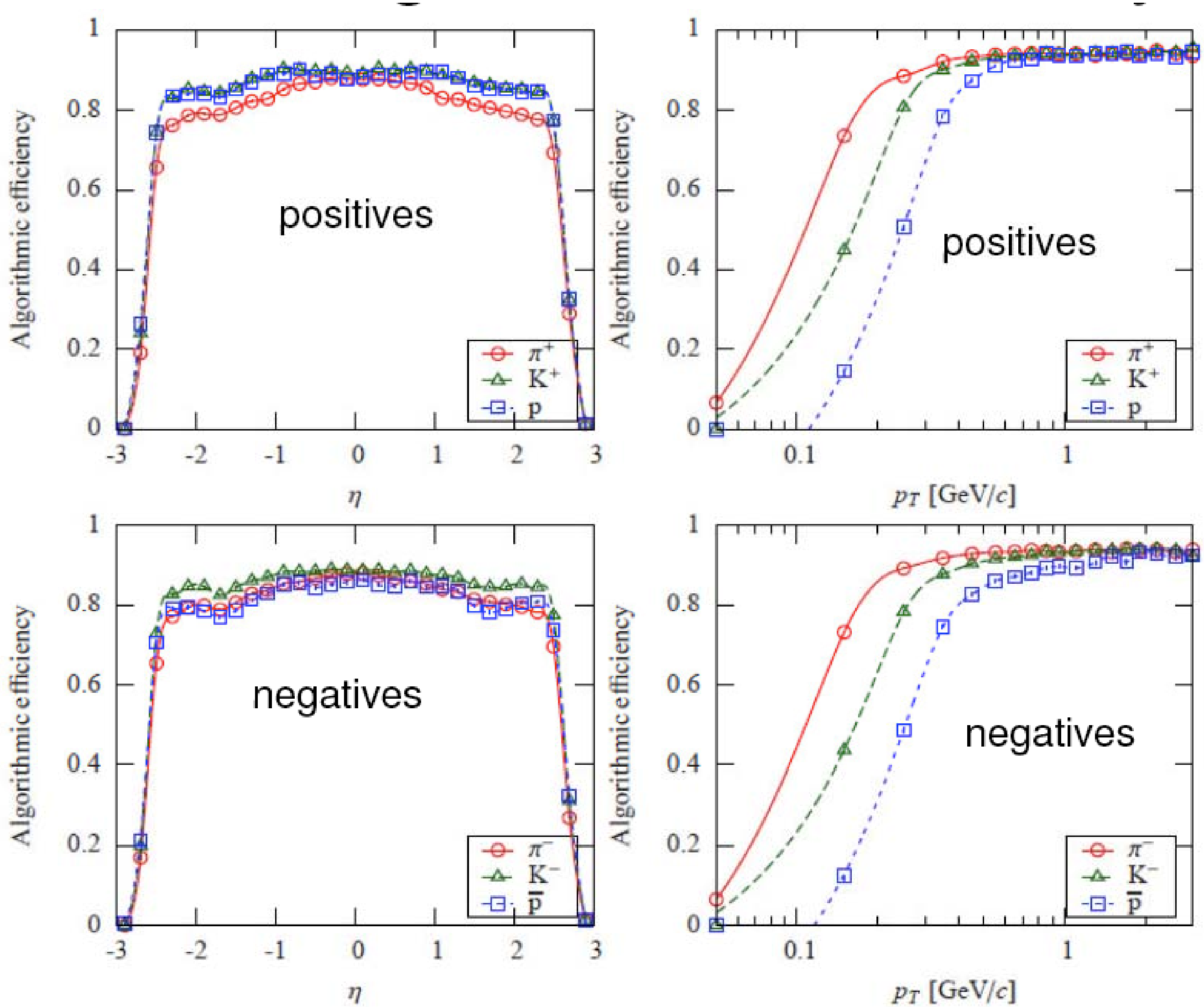


Corrections based either on PYTHIA or on PHOJET event generators yield the same final result

Tracking method: acceptance



Tracking method: efficiency



Other papers in preparation

- Underlying event
- Two particle correlations
- Bose-Einstein correlation
- Transverse energy flow at large eta and forward jets
- Observation of diffraction in minimum bias