Alignment of the CMS tracker and Track reconstruction with collision data in CMS

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on the behalf of the CMS Collaboration

Physics at LHC,
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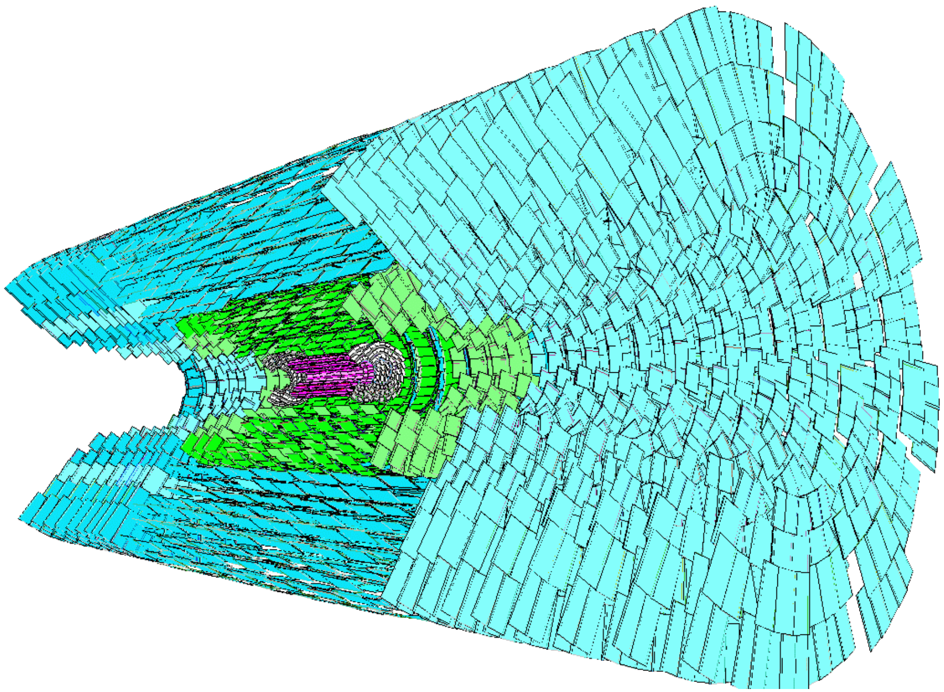
Outline

- The Si-Tracker of CMS
- The Alignment challenge
- Basic Tracking and Vertexing performances
- Reconstruction of resonances and B-tagging

The CMS Si-Tracker

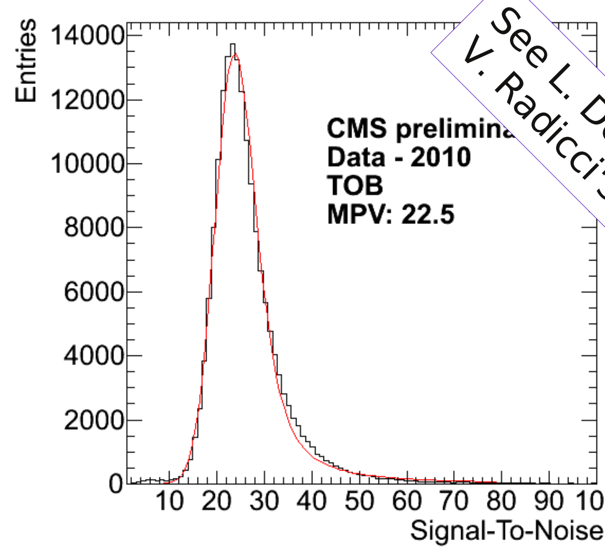


The largest Si-Tracker ever built:
Length: 5.6 m, Radius: 1.1 m

Si Pixel + Si μ-strip sensors:
BPIX (3 layers)
FPIX (2 disks x 2 endcaps)
TIB (4 layers, 2 double-sided)
TID (3 disks x 2 endcaps, 2 double-sided rings)
TOB (6 layers, 2 double-sided)
TEC (9 disks x 2 endcaps, 3 double-sided rings)

15118 strip + 1440 pixels modules:
Pixel resolution: ~10 (~25) μm in local-x (y) coord.
Strip resolution: pitch-dependent, from 10 to 30 μm

Excellent operational performances during commissioning with cosmics global runs and collisions.
98.1 % of modules operational
Fine tuned timing of the devices
S/N of strips as expected

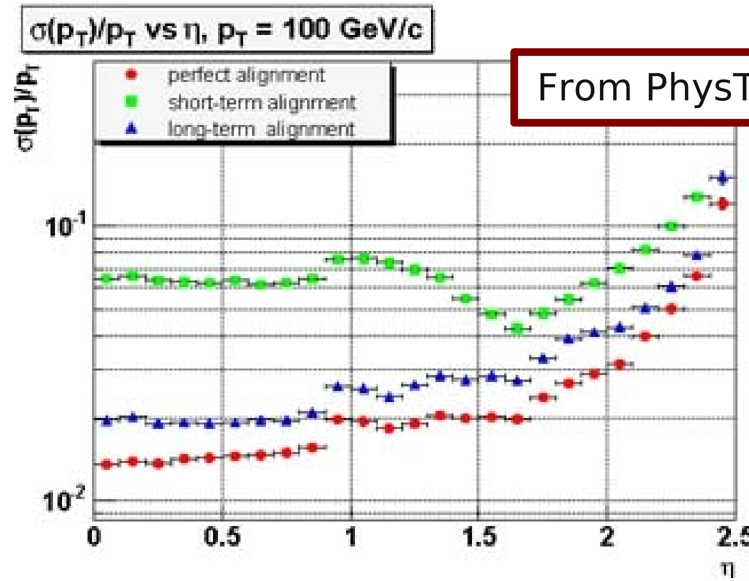


See L. Demaria's & V. Radicci's talks

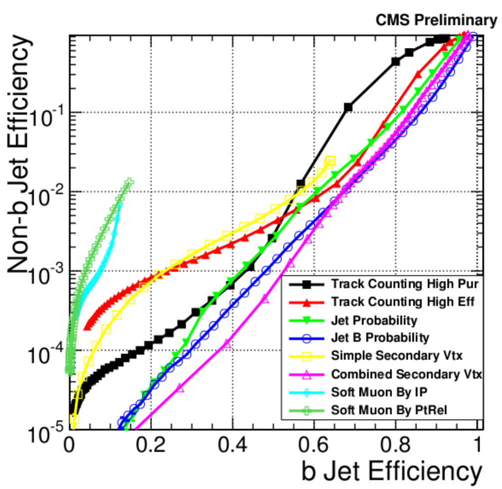
Targeted performances

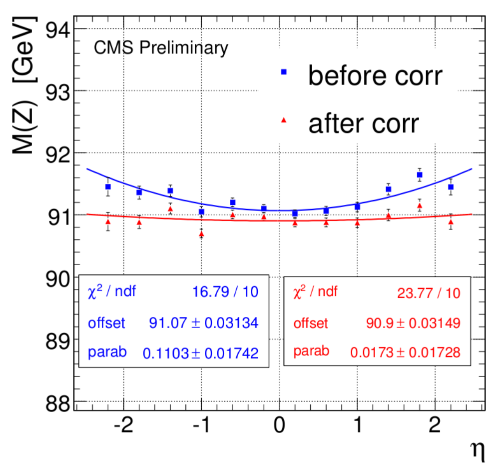
Pixel and strip modules are very sophisticated and precise measurement devices.
Tracking in a dense environment with high efficiency and resolution

Alignment uncertainties negligible w.r.t. intrinsic hit resolution



From PhysTDR (2006)





Efficiency and resolution on b-tagging and SM VB measurements given basically by the Si-Tracker

Si-Tracker is a key device in all analyses at CMS

Alignment of the CMS Tracker

Introduction

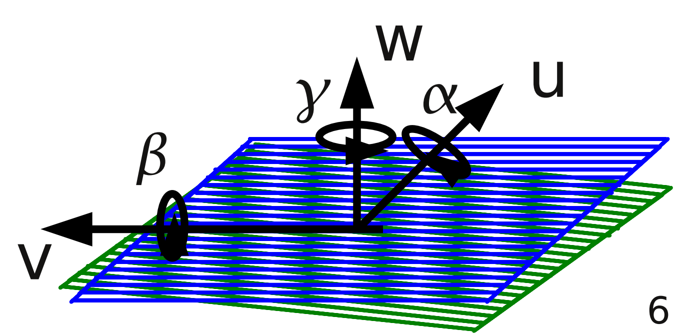
- **TASK**: Find the positions of ~17k modules with a precision negligible if compared to hit resolution.
- Hit residual, **ε**: difference between measured position of the hit and prediction from the track fit.
- Find the Tracker geometry that minimizes χ^2 of the hit residuals

$$\vec{\varepsilon} = \vec{x} - \vec{p} \quad , \quad \chi^2 = \sum_{i=1}^{Nhits} \vec{\varepsilon}_i^{\,T} V_i^{-1} \vec{\varepsilon}_i$$

V = covariance matrix (tracks and hit unc.)

Two statistical methods:
Local method (Hit and Impact Points): solves by large # of iterations
Global method (MillePede II): solves large system of linear equations

- Pixel modules in 6 dof, Strip modules in 3 dof (u,w,γ).
- Only modules collecting > 30 hits are moved (keep stat uncertainties under control)
- Tight track and hits selections for ensuring purity of input sample and outlier rejection.



Alignment with cosmics

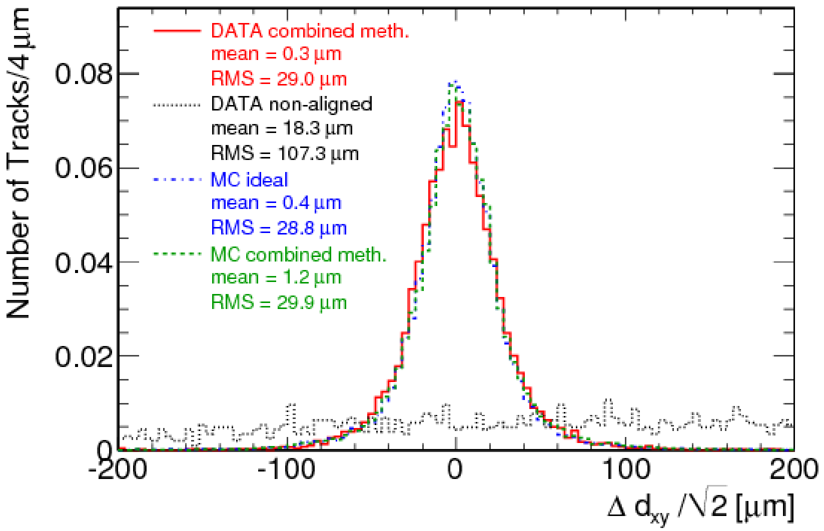
Long-standing experience with cosmics, started before insertion of the TK and further developed during **C**osmic**R**un**A**t**F**our**T**esla:
[2009 J. Inst. 4 T07001]
[2010 J. Inst. 5 T03009] (+ 22 other CMS articles on JINST)

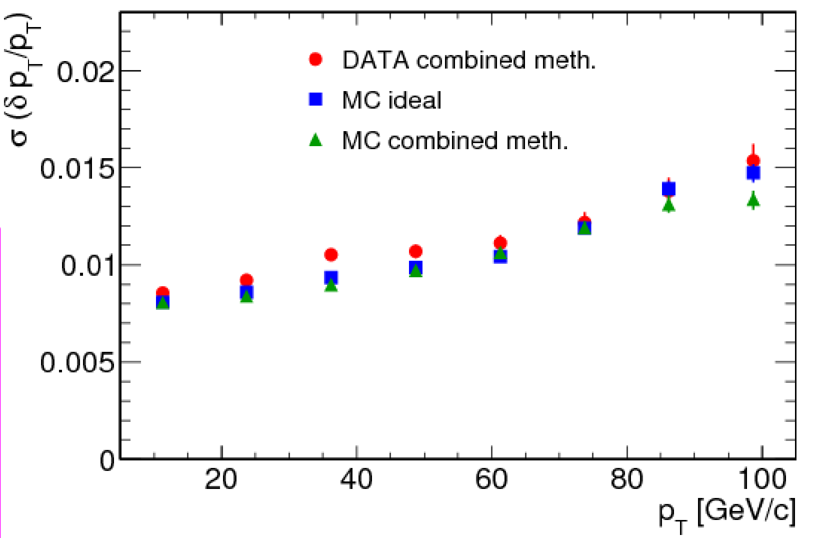
Only cosmic tracks of very high quality:
p>4 GeV, #hits>8, χ^2/ndf cut (algo dependent), filters on hit quality, rejection of outlier hits

Several validation tools: residuals, distribution of median of residuals, direct inspection of geometry, cosmic splitting

Performances in barrel already close to MC with no misalignment

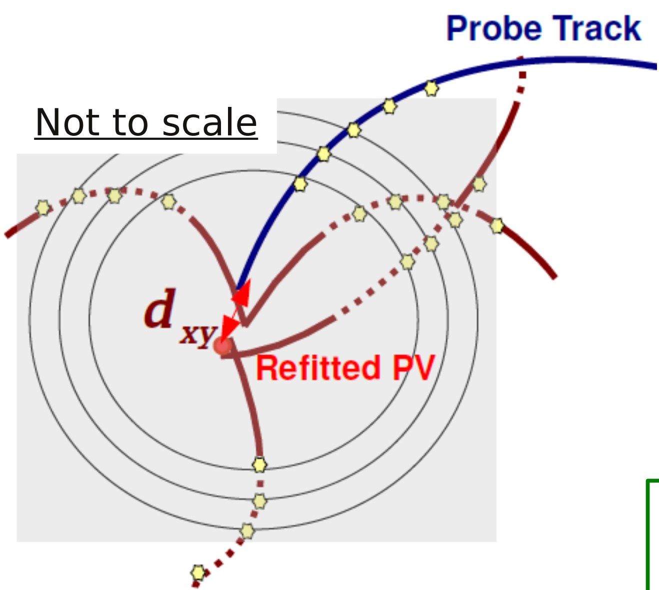
After CRAFT08, several other rounds of full TK alignment, last of them in March 2010 ("CRAFT10").





- Tracking performances stable over the different alignment rounds.
- Excellent starting point for physics with collisions, used for prompt reconstruction. Better than scenarios expected after medium int. lumi !
- STARTUP-MC scenario reflecting the status after the cosmics-only exercise.

Validation with Primary Vertices

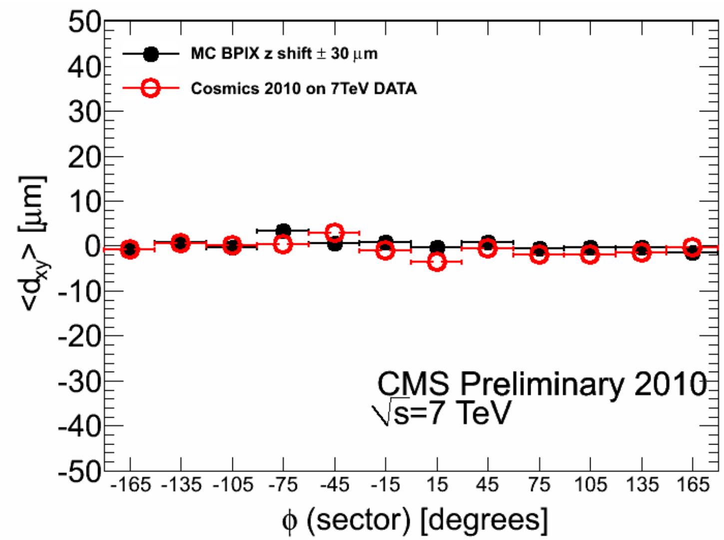


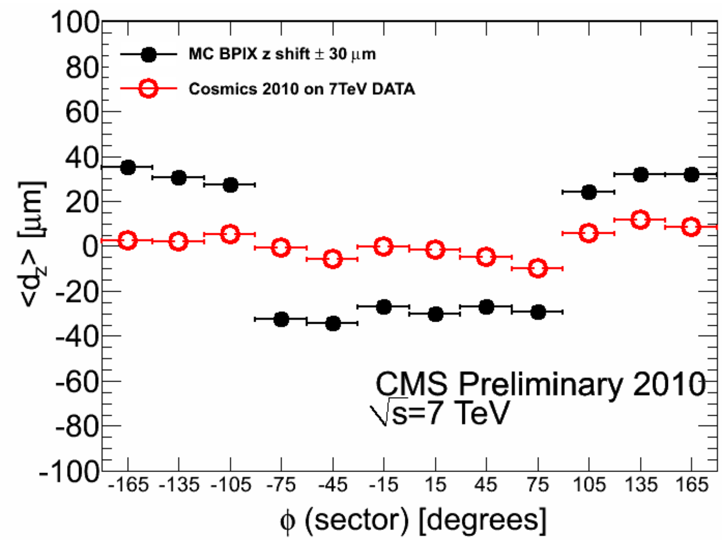
Validation tool sensitive to misalignments of pixels

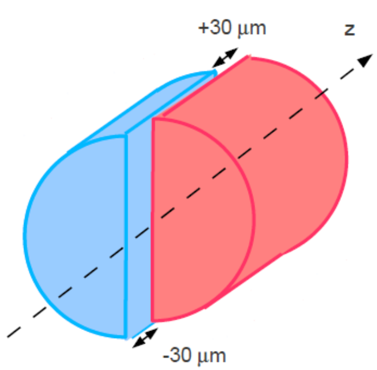
Prepare distributions impact parameter of tracks w.r.t. unbiased PV vs track direction. Check biases in these distributions (it should be centered at zero)

Cosmics-only geometry (2010) on 7 TeV MinBias data. Compare to perfectly aligned MC + example deformation

- **PV residuals in DATA do not show biases > 10 μm**
- **Geometry stable over time**



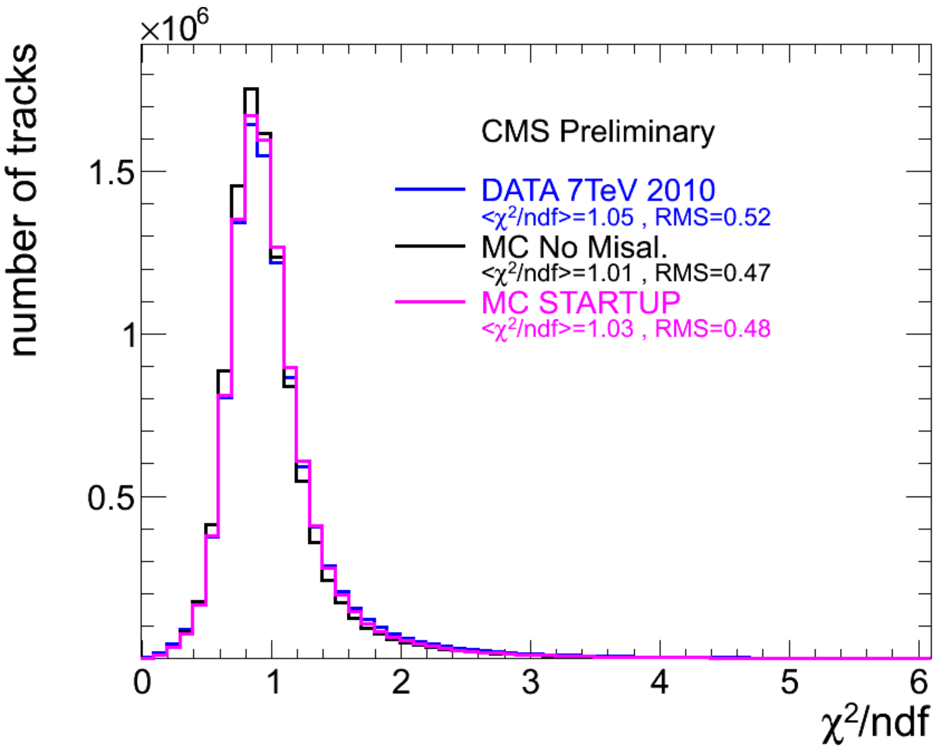




Alignment with collisions

- Results based on 1 /nb at sqrt(s)=7 TeV;
- p> 3 GeV; p_T > 2 GeV # hits >7, other cuts common to cosmic analysis
- Tracks refitted applying constraint to Primary Vertex (only constraint possible with available statistics, plan to use mass-constraint from resonances).
- Geometry of the Tracker stable in time, using CRAFT10 cosmics simultaneously with MinBias tracks (~3M cosmics through Tracker)
- Compared to cosmics-only alignment, improvements mainly in the endcaps (FPIX) thanks to more statistics at high η

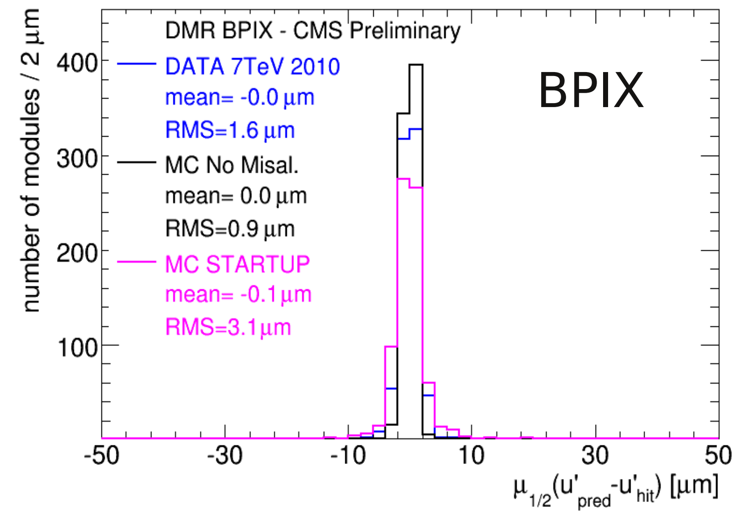
Validation on MinBias data of the **latest TK geometry** compared to the simulation using a **perfectly aligned TK** and the **STARTUP misalignment scenario** (cosmics-only)



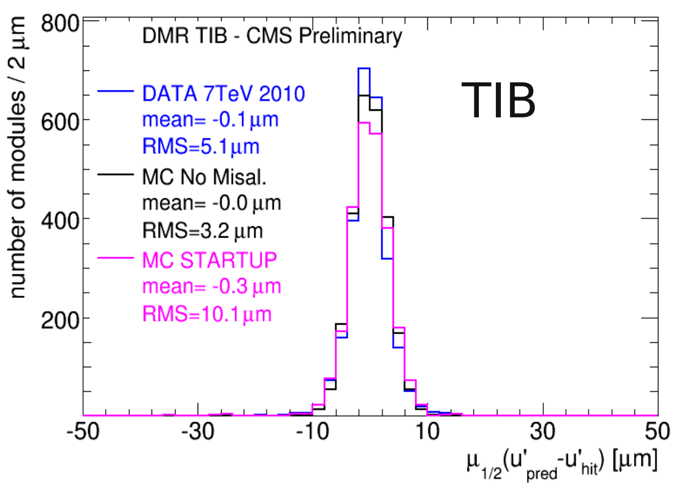
Distribution of the Median of the Residuals

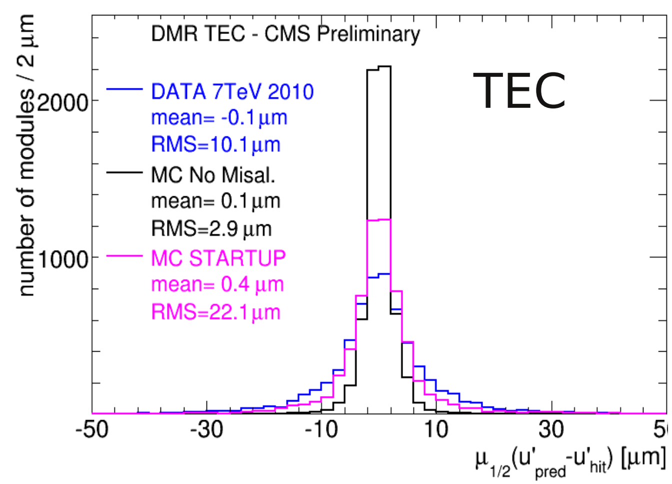
Distribution of hit residuals folds effects from alignment, multiple scattering and resolution on local reconstruction.

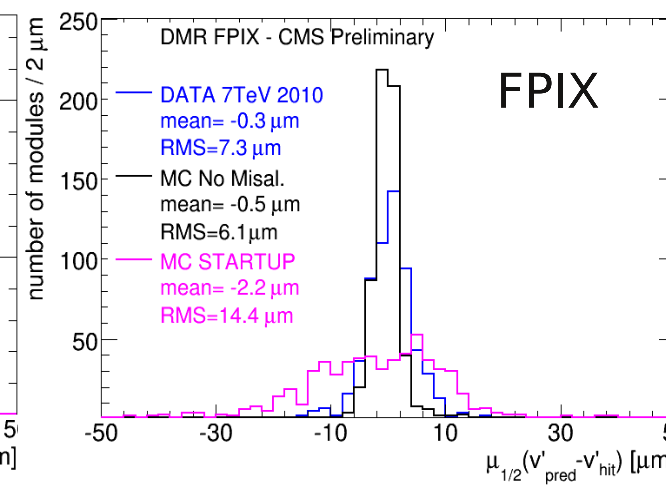
Distribution of the Median of Residuals (DMR): sensitive only to misalignments that bias the hit residuals (i.e., change the track χ^2).



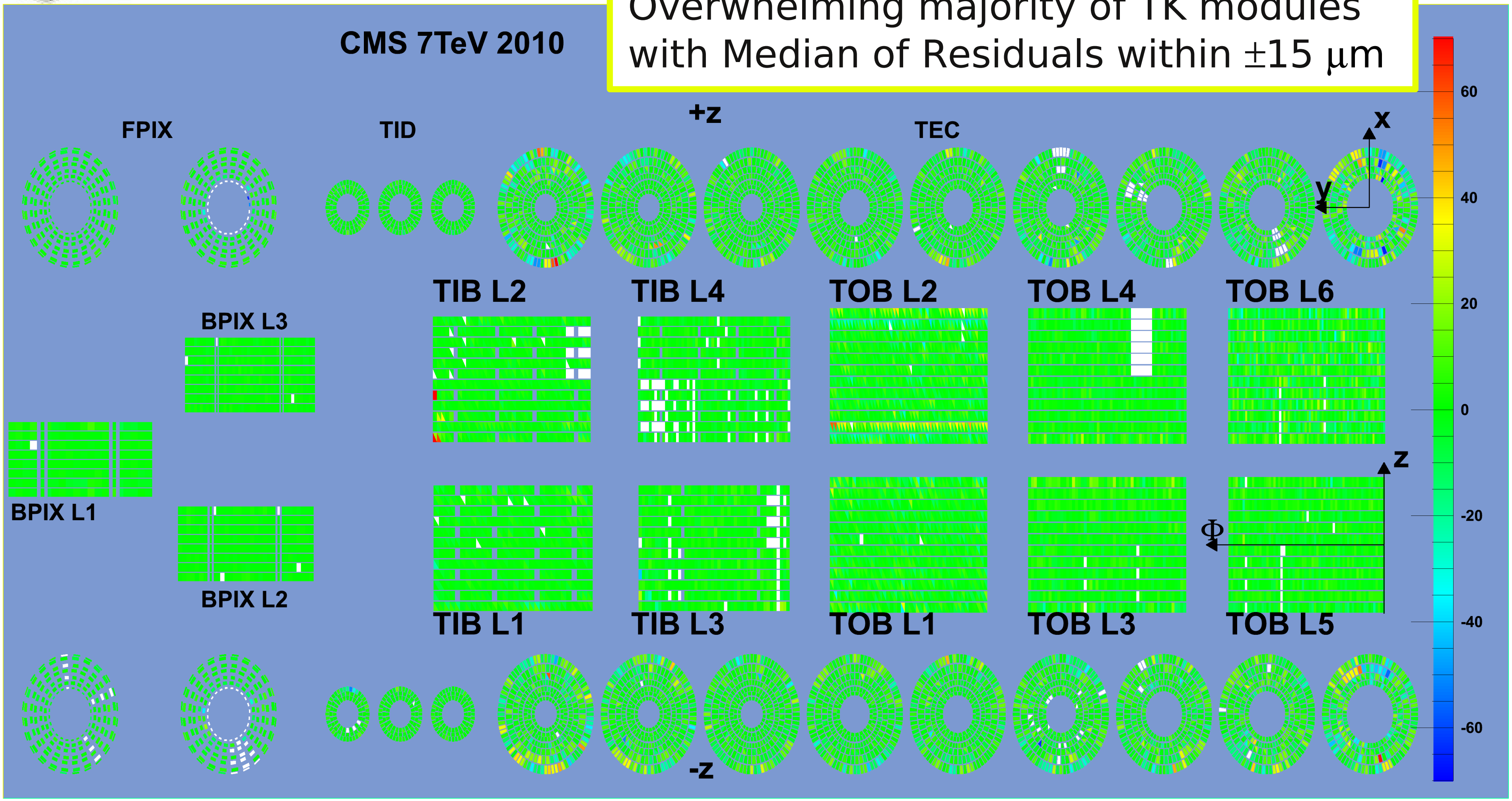
DMR of data already not far from perfectly aligned MC simulation. Better than STARTUP scenario in regions worse illuminated by cosmics.







Map of the DMR

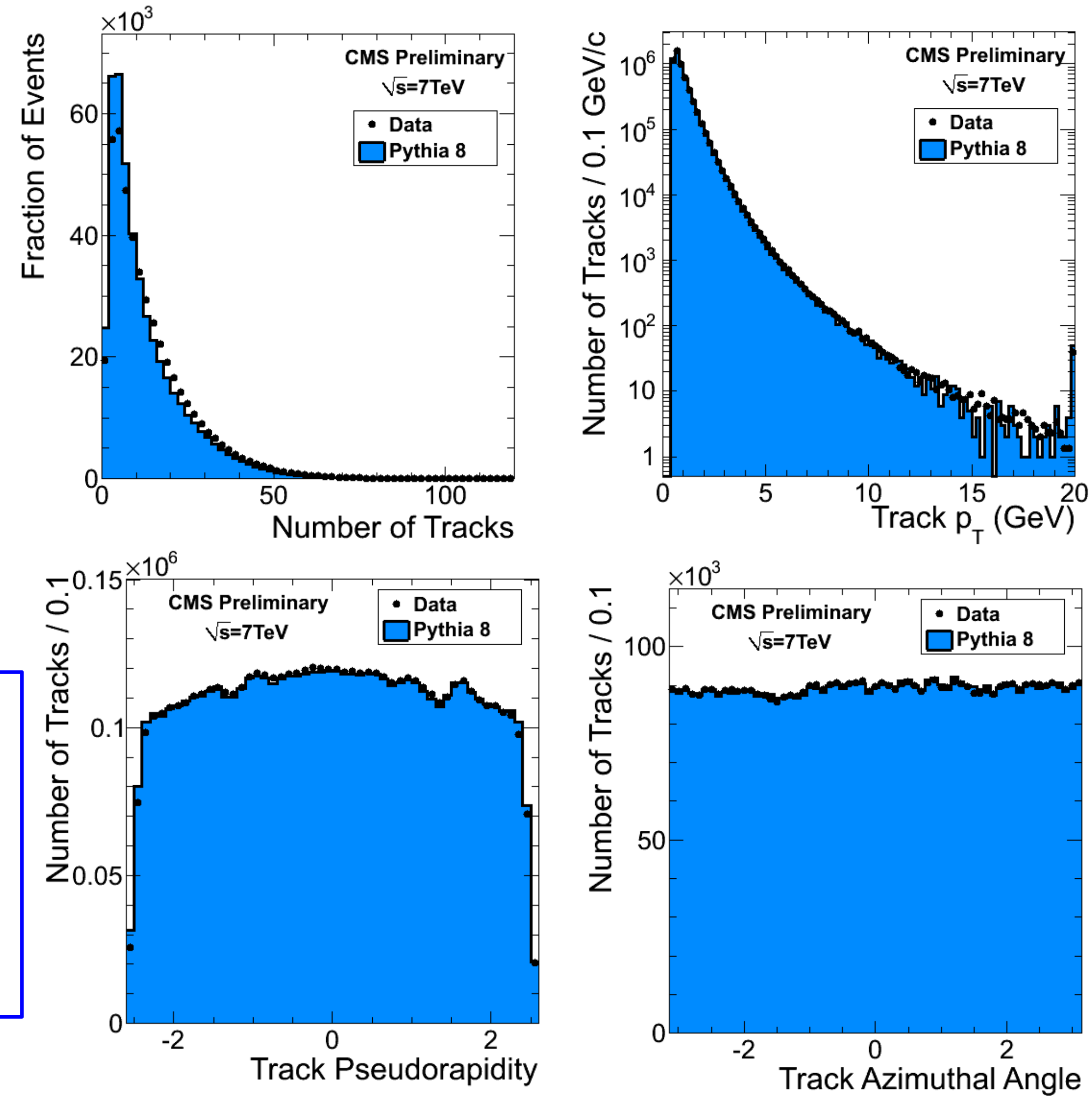


- Few “hot” regions (seen also in MC):
  - TEC D±1/R7, TOB L2 |z|=80 cm → both at |h|~1 (a lot of material crossed)
  - TOB L6 , TEC D±9 → likely because of limited statistics

Tracking and Vertexing

Tracking with collisions

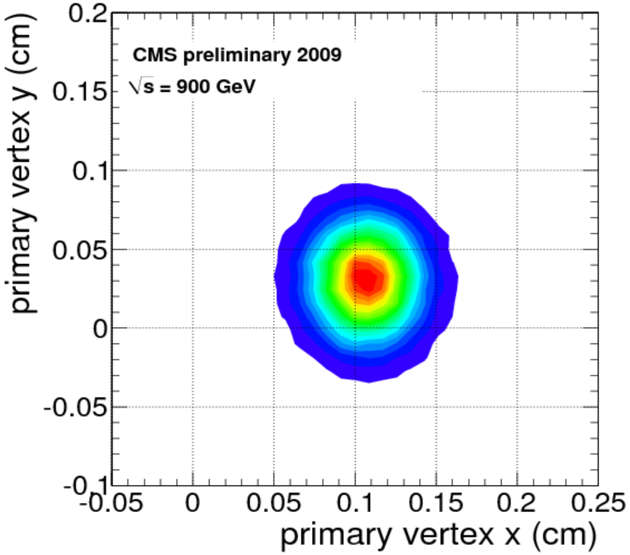
- Combinatorial Track Finder, iterative hit-to-track association
- Event/track selection:
  - one PV (>3 tracks)
  - |dxy|< 2cm, |dz| < 15 cm
  - rejection of beam-induced backgrounds
  - p_T > 0.5 GeV/c
- Comparison to Pythia 8 Tune 1 default tune in Pythia 8)



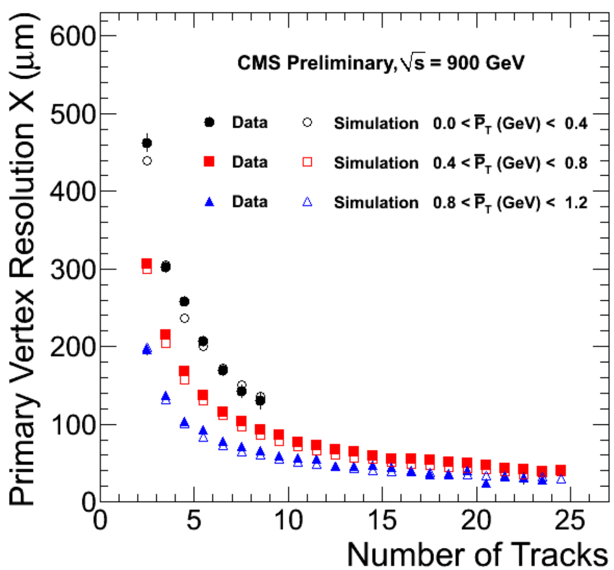
Distributions of # tracks normalized to # events in data.
Other distributions normalized to # tracks in data.

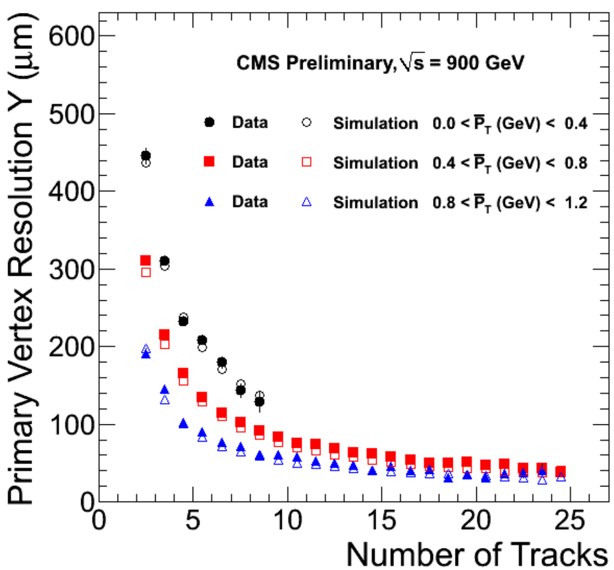
Asymmetry in ϕ due to inactive modules.

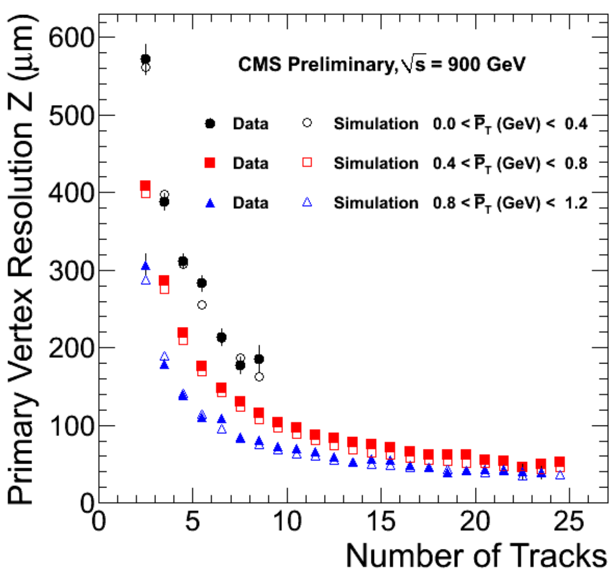
Vertex resolution



- Divide track collection used for vertexing in two groups, refit two vertices independently, compare positions.
- Asymptotic resolution in data: ~30 μm in transverse plane, ~40 μm in longitudinal direction
- MC with STARTUP alignment and calibration describes quite well the data

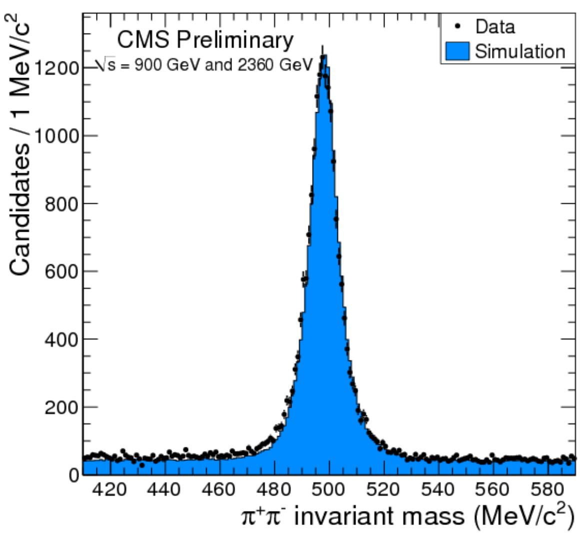


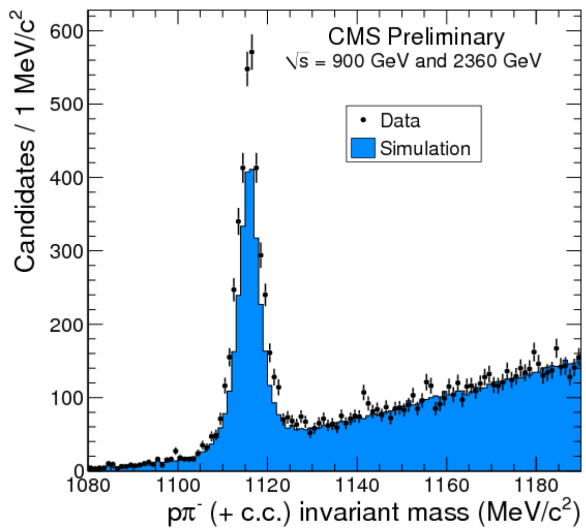




Reconstruction of Resonances

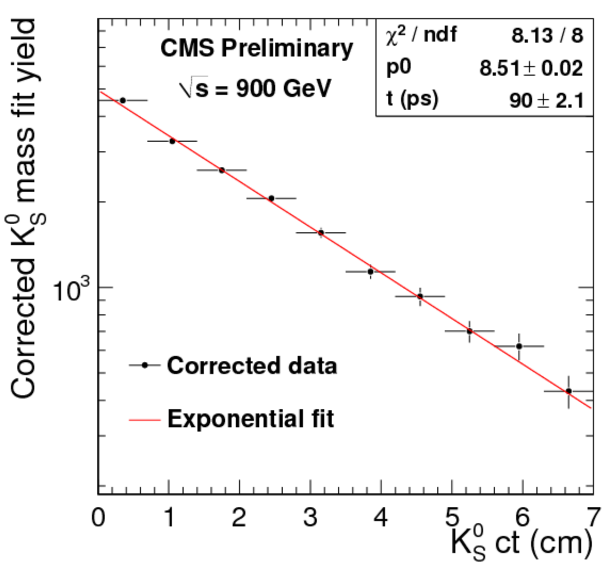
K^0_s and Λ





V^0 decaying to oppositely charged tracks, displaced vtx.
Masses agree well with PDG values
MC scaled by ratio of K^0 yield.
Sidebands well described, Pythia-MC has too little Λ (seen also at CDF).

Mass [GeV]	K^0_s	Λ
Data	497.68 ± 0.06	1115.97 ± 0.06
Simulation	498.11 ± 0.01	1115.93 ± 0.02
PDG	497.61 ± 0.02	1115.683 ± 0.006



V^0 lifetime:

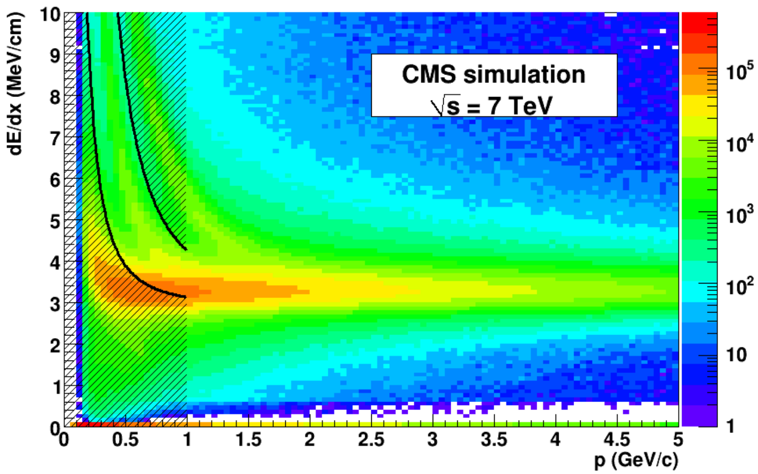
- measure from data the yield of V^0 as a function of decay length
- correct for the acceptance bin-by-bin with MC
- exponential fit

After MC corrections, nice exponential dependence !

τ [ps]	K^0_s	Λ
Data	90.0 ± 2.1	271 ± 20
PDG	89.53 ± 0.05	263.1 ± 2.0

<u>Only stat uncertainties</u>

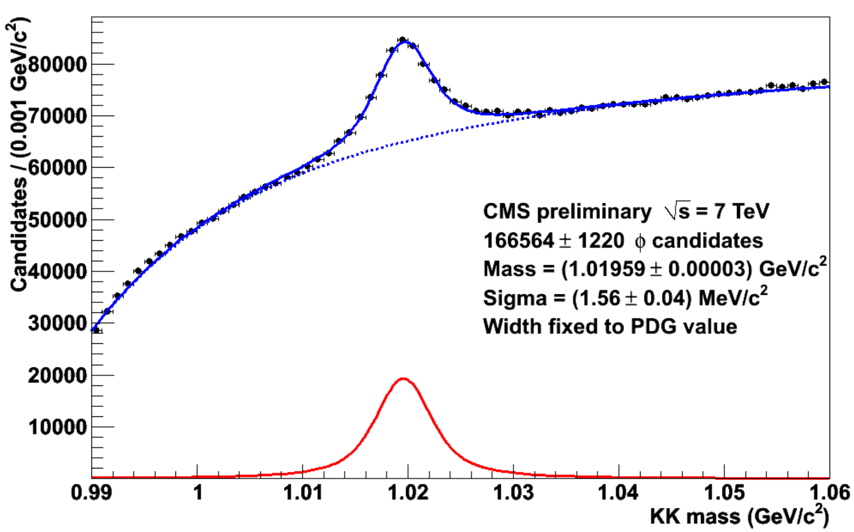
$\phi(1020) \rightarrow K^+K^-$ from dE/dX

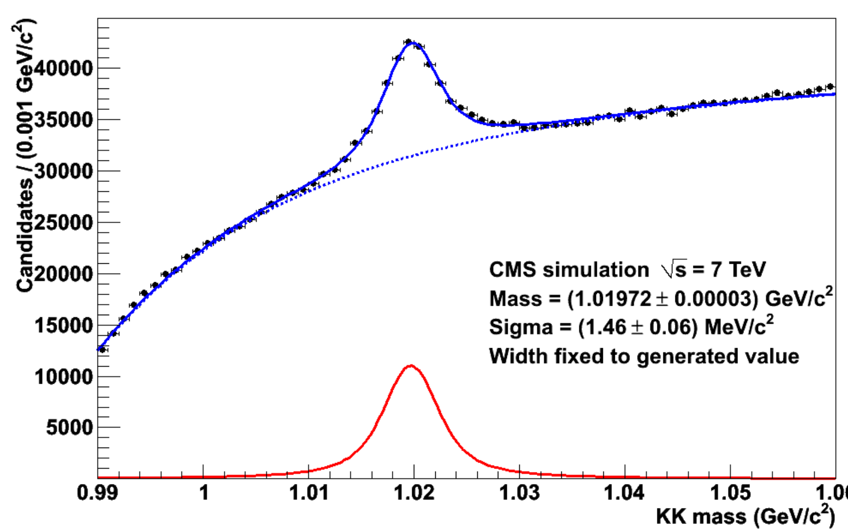


Decay products identification:

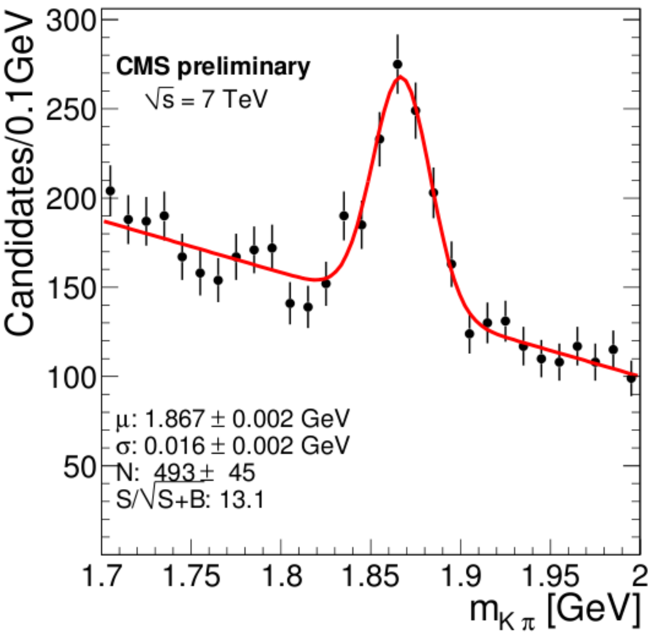
- pT > 0.5 GeV/c
- > 5 hits, χ^2/ndf of the track < 2.0
- p>1 GeV/c or dE/dX compatible with kaon (see left plot)

Combinations of track pairs fitted as Voigtian + arctan.
No signal if vetoing dE/dx requirement !
Simulation in good agreement with data.





D^0 and D^*

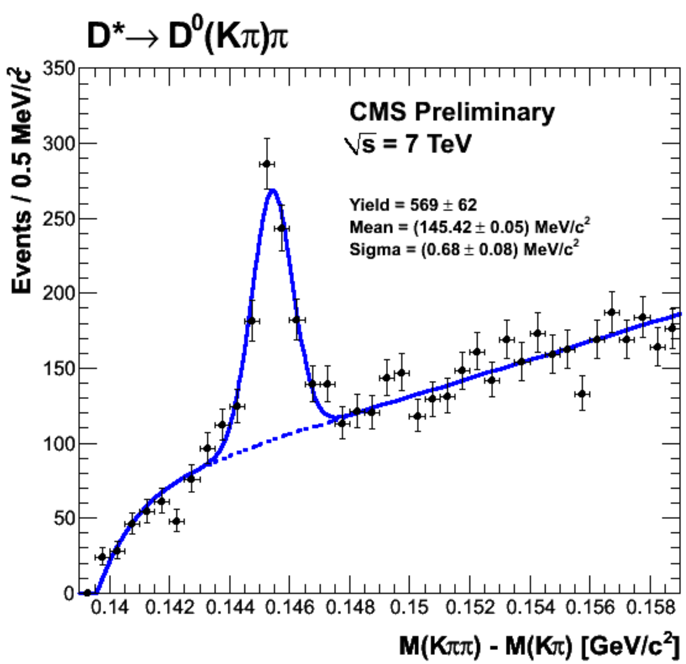


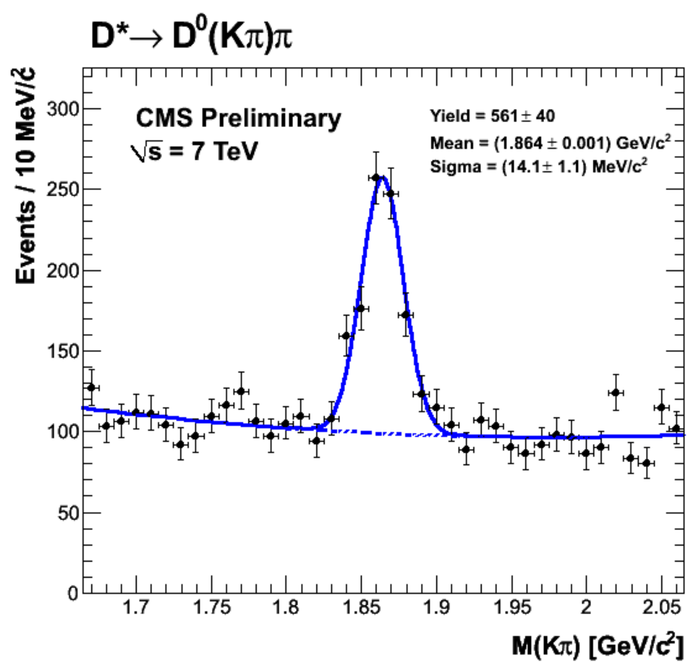
$D^0 \rightarrow K\pi$

- $p_T(D0) > 3.0$ GeV, $p_T(K) > 1.25$ GeV, $p_T(\pi) > 1.0$ GeV
- Vertex cuts: $\chi^2/ndf < 4.5$, $3 < l_{xy} / \sigma_{xy} < 20$, $\sigma_{xy} < 0.03$ cm
- $\angle(p_{D0}, \overline{PV : SV}) < 0.1$ rad

$D^* \rightarrow D^0\pi_S$, $D^0 \rightarrow K\pi$

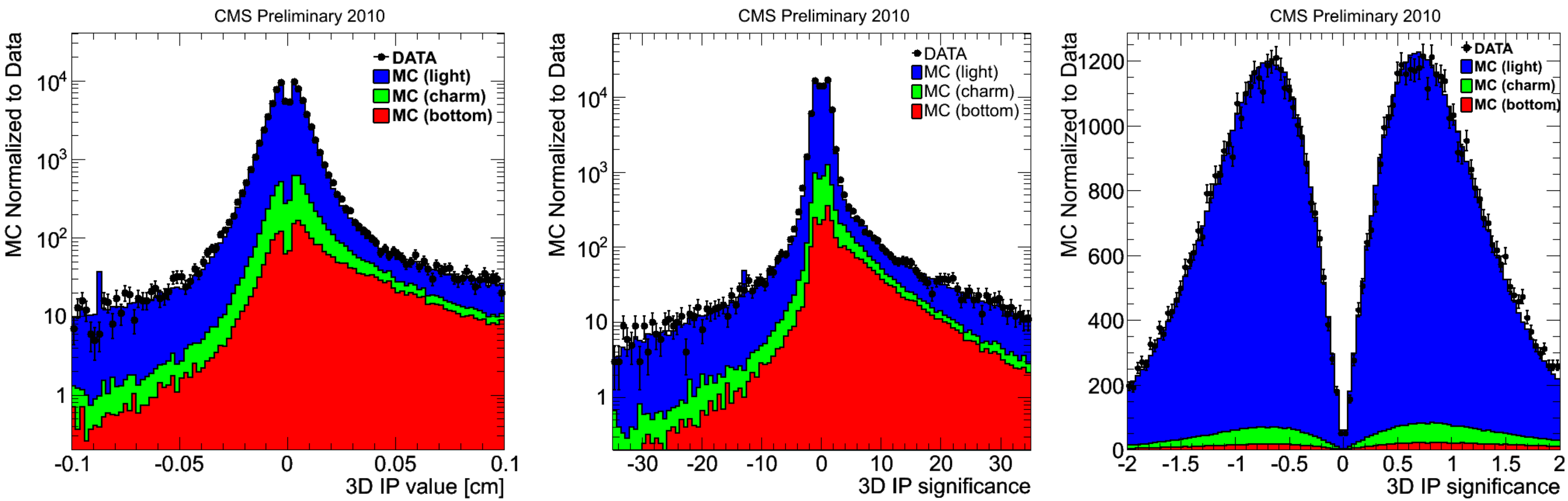
- $p_T(D^*) > 5.0$ GeV/c, $p_T(K/\pi) > 0.6$ GeV/c, $p_T(\pi_S) > 0.25$ GeV/c
- $N_{hit} > 5$ (except for π_S), $\chi^2/ndf < 2.5$, $|d_{xy}| < 1$mm, $|\Delta z| < 1$ cm
- Unbinned extended ML fit (Gaussian signal, threshold function (ΔM) or quadratic for $M(K\pi)$ for background)





Signal loud & clear !

B-tagging validation



- High precision of pixel detector allows measurement of 3D IP with excellent resolution
- B-tagging on data @ 7 TeV (0.9 /nb); jets with p_T > 40 GeV/c , $|\eta|<1.5$
- Simulation nicely describes the data, both for the value of the 3D IP and the significance (zoom in the central region of the significance in the rightmost plot)
- Tails under control, tracking and alignment errors correctly estimated

Summary

- Alignment performances approaching the ones from an ideal simulation
- Including MinBias tracks improved alignment of endcaps respect to cosmics-only alignment and cosmics-only misalignment scenario
- Coming close to statistical limit of alignment precision
- Next step is to keep under control biases and χ^2-invariant coherent deformations of the geometry. With more and more statistics to come, high-mass resonances will be one of the main tools.

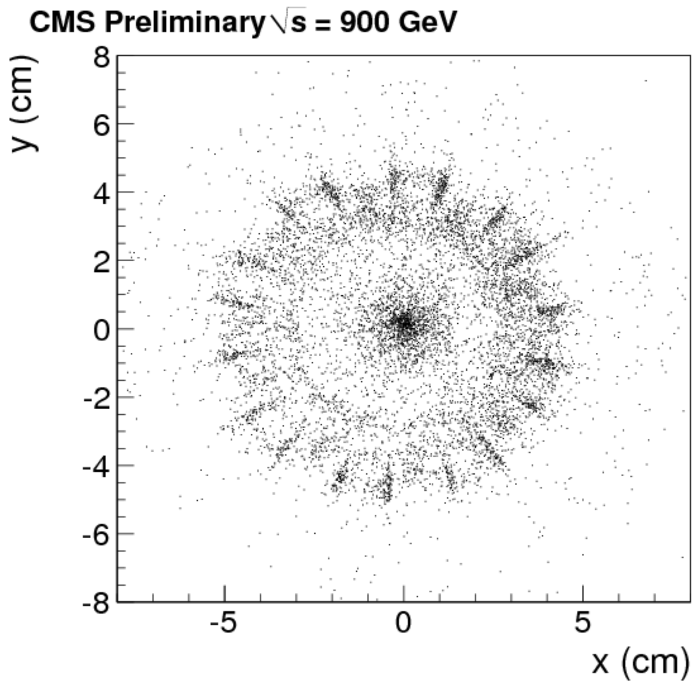
- Tracking and vertexing under control and working as expected.
- Study of resonances valuable tool for validating the tracking and the alignment. All masses compatible with PDG values within fractions of permille.
- With limited statistics, B-tagging already set up in place and working (few thousands of B already collected). Control distributions show a good understanding of the detector.

Early performances look nice and
the CMS TK is looking forward for the next challenges.

BACKUP SLIDES

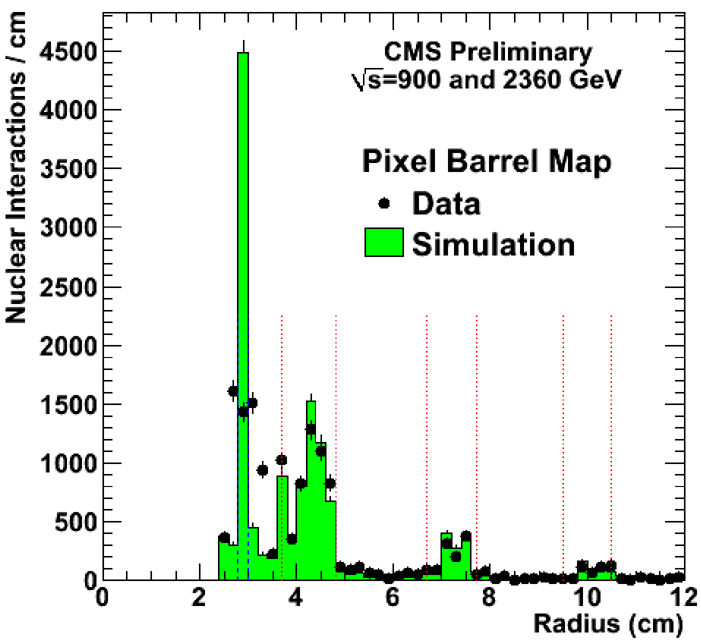
Interactions of particles in the Tracker

Photon conversions



- First CMS Tracker radiography !
- Two tracks with track-fit χ^2 prob>10^{-6}, parallel in both ⊥ and // planes, positive decay length
- Visible offset between beam pipe and pixel detector
- Estimation of material budget

Nuclear interactions



- Clustering and refitting tracks from a common displaced vertex
- ϕ-simmetry of tracker design. Dependence of # nucl inter vs radius
- Up to 3rd BPIX layer (|z|<26 cm)
- Reasonable description of material in BPIX. Smearing of the beam pipe in data (shift of pos relative to BPIX not simulated)