CMS TRACKER ALIGNMENT AND MATERIAL BUDGET MEASUREMENTS

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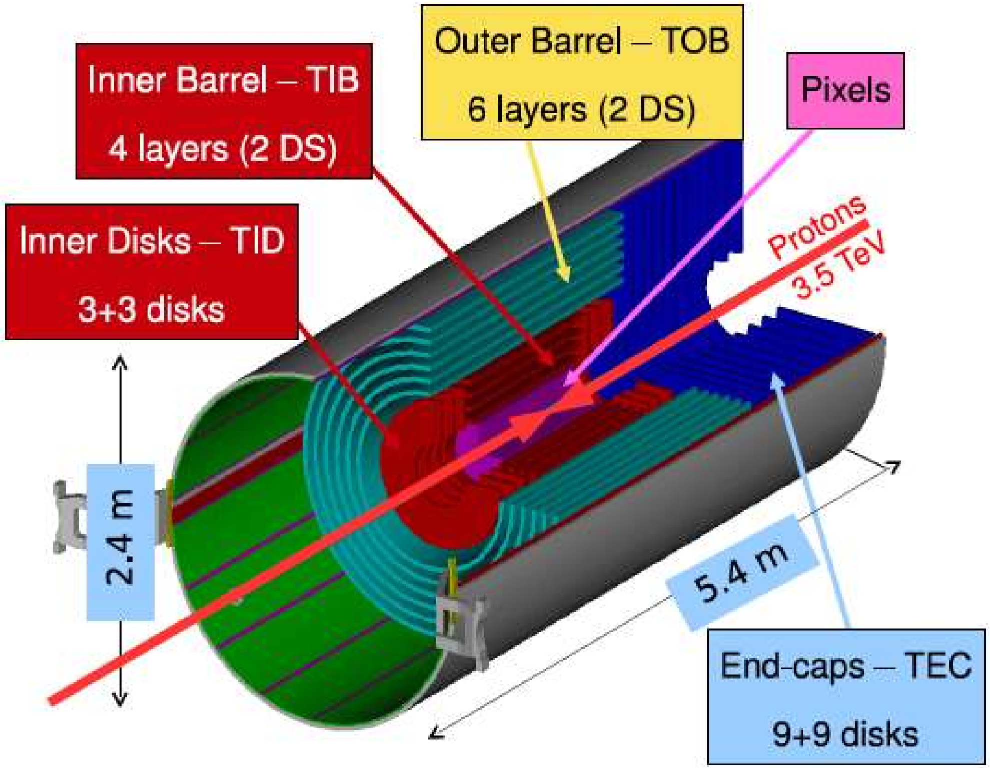
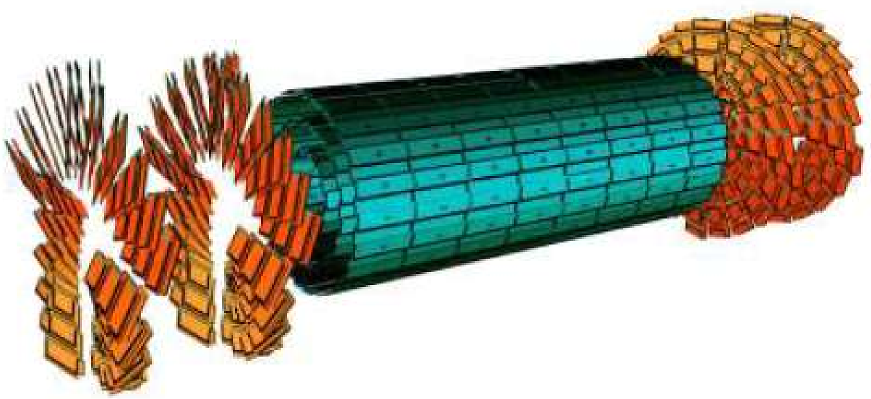
On behalf of the CMS Collaboration

The CMS Inner Silicon Tracker





- StripTracker (TIB,TID,TOB,TEC)
  - 15148 modules (1D meas.)
- Pixel Tracker (BPIX,FPIX)
  - 1440 modules (2D meas.)
- Total estimated mass: ~ 4150 kg

Goal of alignment:

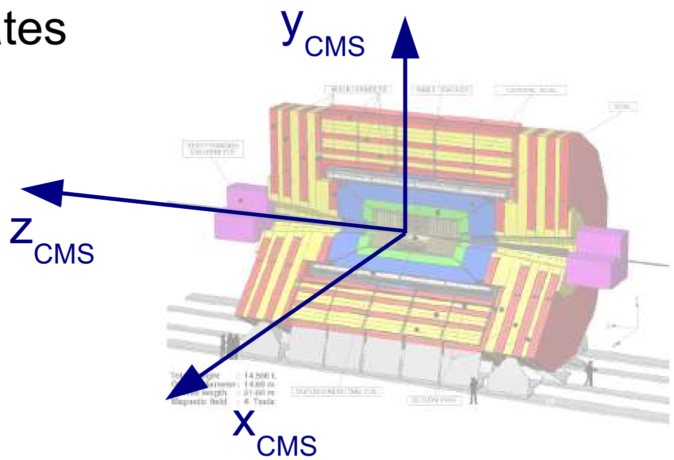
precise knowledge of the position/orientation of the “active” volumes

Goal of Material Budget studies:

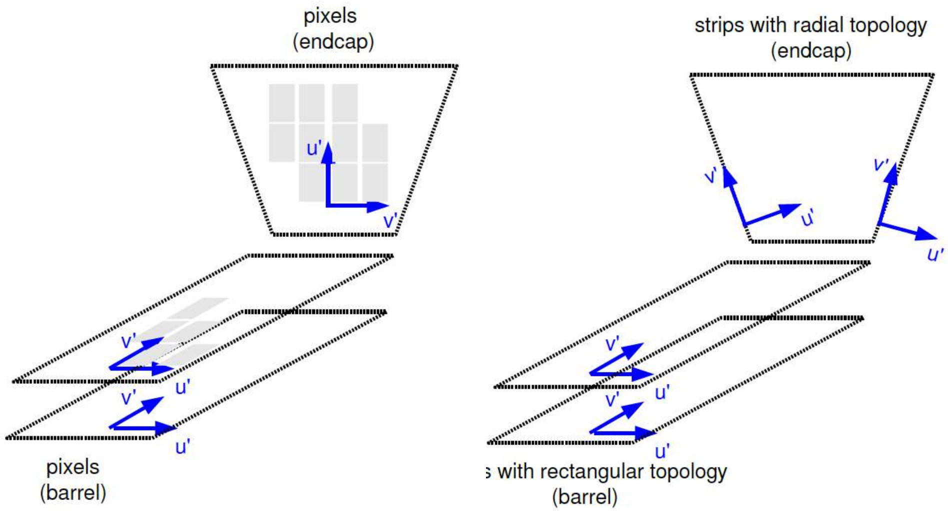
precise knowledge of the shape/chemical composition of the components (95% passive)

Basics definitions

- Global (CMS) coordinates



- Local coordinates



u' =rϕ coordinate in BPIX,TIB,TOB,TID,TEC
=r coordinate in FPIX

v'=z coordinate in BPIX,TIB,TOB
=r coordinate in TID,TEC
=rϕ coordinate in FPIX

- Geometry ≡ set of corrections to the nominal position/orientation of the active volumes as determined by the alignment procedure

ALIGNMENT

Pre-collision knowledge

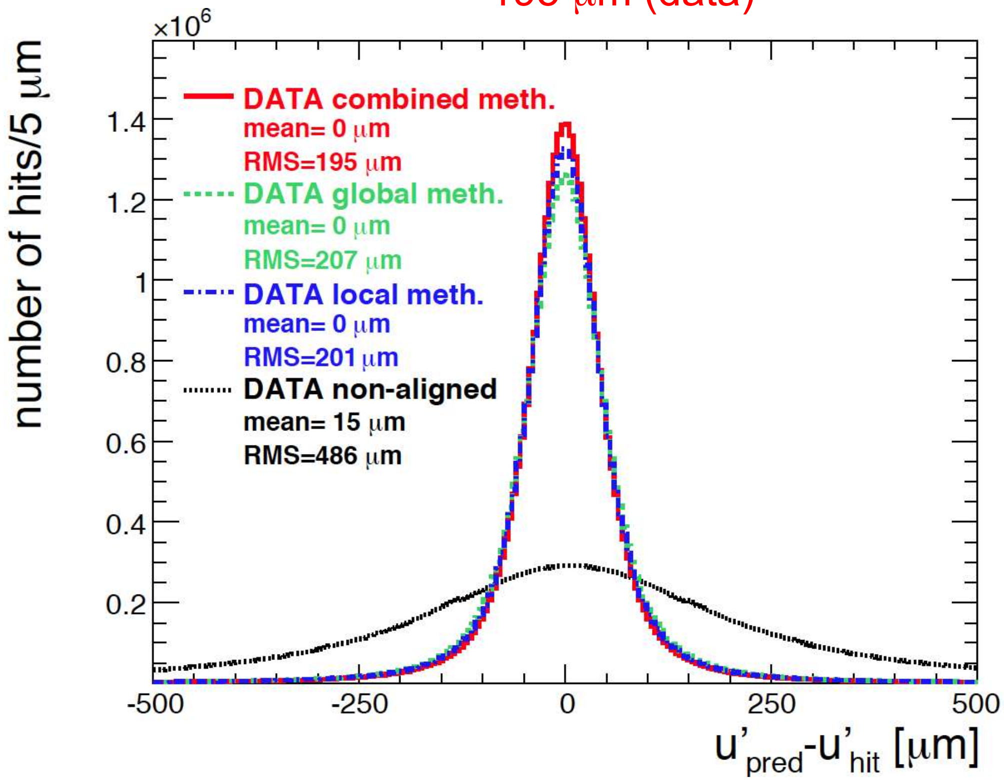
- Optical survey
  - surveys used as conformance criteria during the assembly for all the components of the Tracker but not taken for all components wrt the next highest structure → full Tracker geometry at module-level based on surveys not available after construction
- Cosmics
  - first geometry of the full Tracker from a track-based alignment available after the Cosmic Run At Four Tesla (CRAFT) in Fall 2008.
  - based on 3.2 M cosmic ray tracks collected in the Tracker at B=3.8T (~110k in the BPIX)
  - best post-alignment track-to-hit residuals obtained with the **combined method**, e.g. when aligning with the **local method** (Hits and Impact Points) on a geometry obtained with the **global method** (Millepede II)
  - statistical precision already close to the “no misalignment” case in the barrel sub-detectors (BPIX, TIB, TOB)
  - Similar exercise with cosmics repeated in 2009 (before pilot LHC collisions), 2010 (before LHC restart) and 2011 (before resuming LHC operations)

Statistical precision

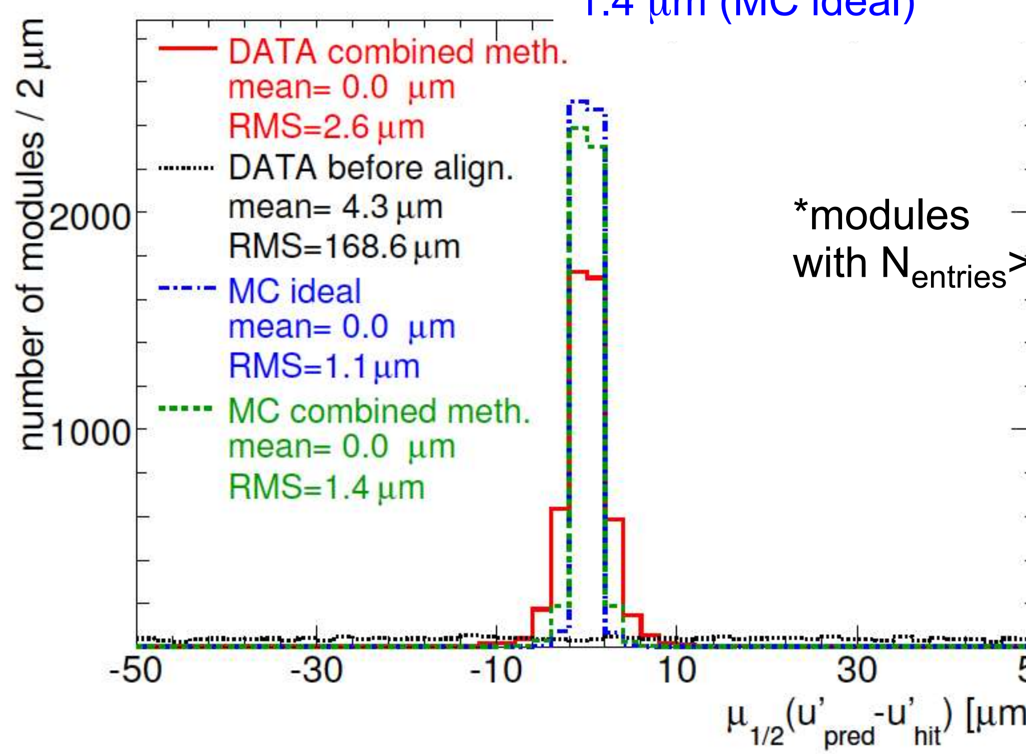
- Post-alignment track-to-hit residuals (left) already dominated by random effects (multiple scattering, hit error)
- Figure of merit for the minimization of track-to-hit residuals are the <u>D</u>istribution of <u>M</u>edian of <u>R</u>esiduals (right) → estimate average offsets of the modules wrt the tracks

CMS 2008 cosmics

$TOB_{u'}$ (strip outer barrel)
195 μm (data)



$TOB_{u'}$(strip outer barrel)
2.6 μm (data)
1.4 μm (MC ideal)



*modules with $N_{entries}$>30

Evolution of the statistical precision

	COSMICS TRACKS		COLLISIONS TRACKS (1/nb)		
DMR (rms/μm)	CRAFT μm	post-CRAFT MC μm	ICHEP2010 μm	post-CRAFT MC μm	MC not misaligned μm
BPIX (u')	2.6	2.1	1.6	3.1	0.9
BPIX (v')	4.0	2.5	5.5	8.9	1.8
FPIX (u')	13.1	12.0	5.7	10.7	2.5
FPIX (v')	13.9	11.6	7.3	14.4	6.1
TIB (u')	2.5	1.2	5.1	10.1	3.2
TOB (u')	2.6	1.4	7.5	11.1	7.5
TID (u')	3.3	2.4	4.0	10.4	2.4
TEC (u')	7.4	4.6	10.1	22.1	2.9

- First complete geometry mixing cosmics (needed to constrain χ^2 invariant distortions) and collisions tracks (to improve alignment precision in forward sub-detectors) determined in 2010 after L_{int}=1/nb
- Being already close to the statistical precision limit, most of the activity has been focused on
  - Analyzing and monitoring of the track-based geometry
  - Chasing possible sources of systematic biases

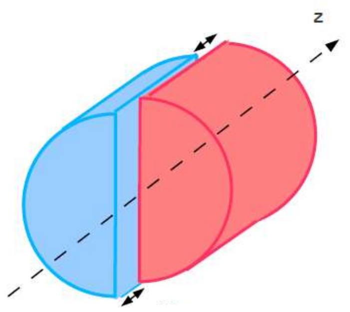
Features of the geometry of the real Tracker

- "Large scale" effects:
  - 5 mm gap along z_{CMS} direction between the two TIB halves (forward/backward) [not discussed here, see extra-slides]
  - the two BPIX halves (left/right) periodically move along the z_{CMS} independently from each other up to 100 μm
  - little tilt angle (300 μrad) between the longitudinal axis of the Tracker and the **B** field
- "Small scale" effects:
  - modules are bent

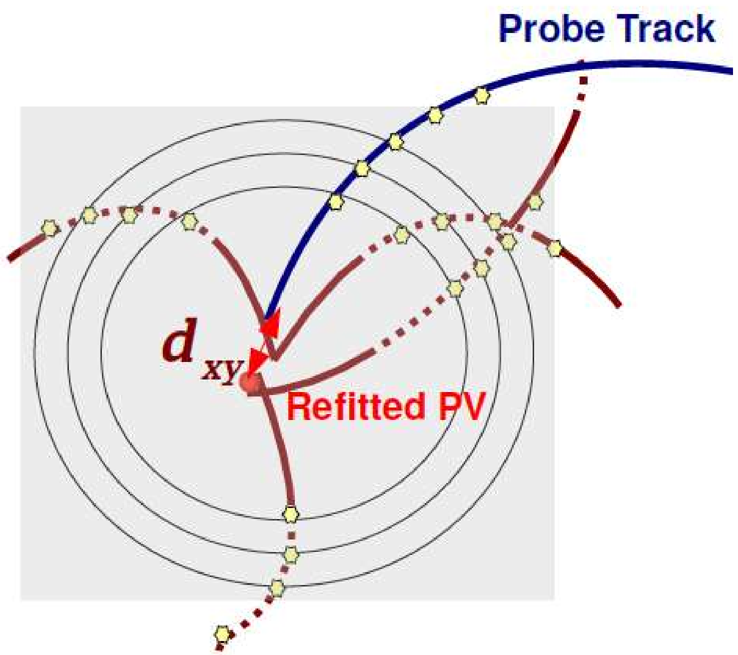
All these effects are mechanically allowed

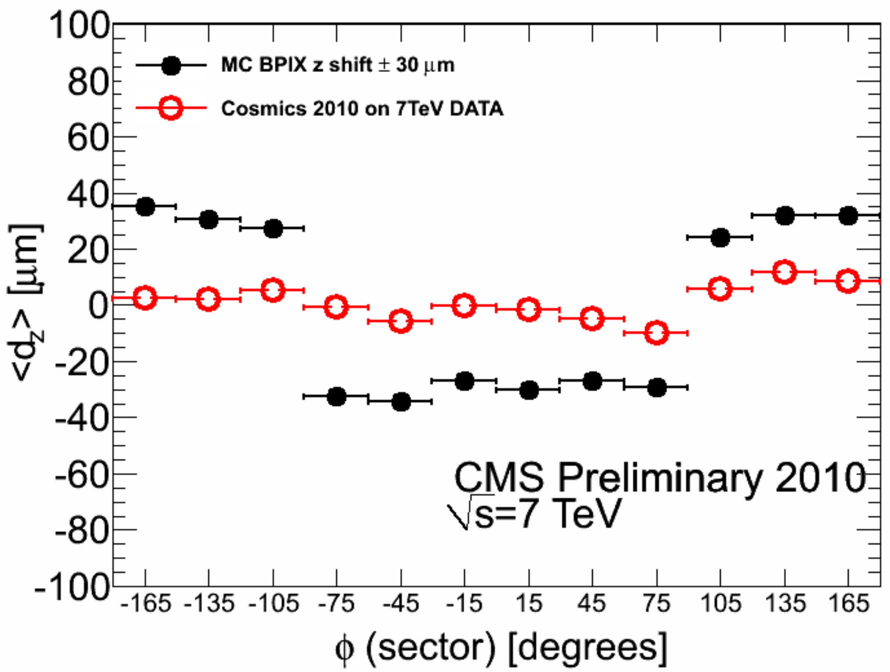
Drifts of the BPIX half-barrels along the beamline

- Movements of the BPIX half-barrels already observed in the geometries determined in the pre-collisions era

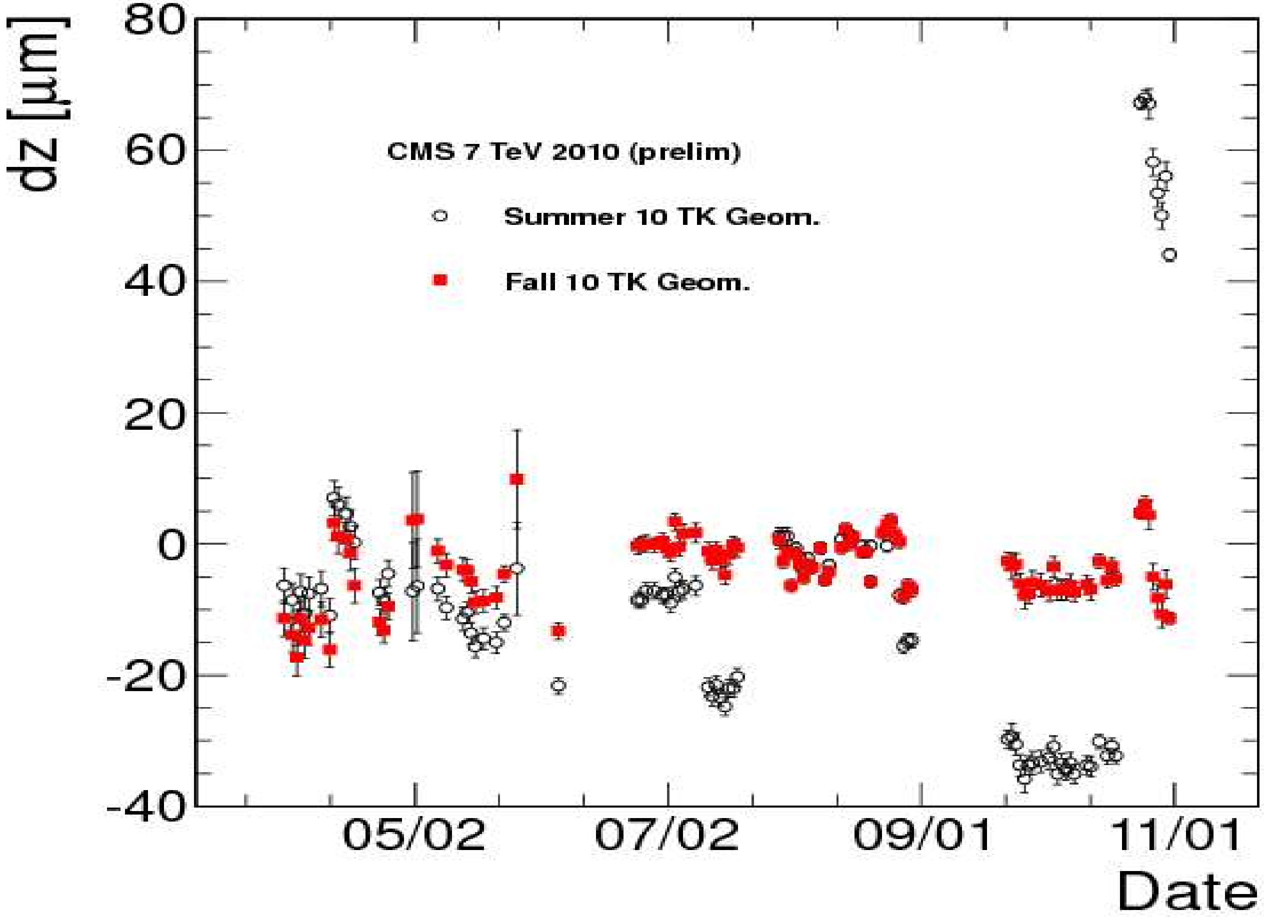


- Careful daily monitoring of the BPIX geometry using collisions tracks: Primary Vertex Validation
  d_{xy} and d_z of track *N* wrt the PV computed with the remaining *N-1* tracks
  as a function of ϕ-sector of the probe track





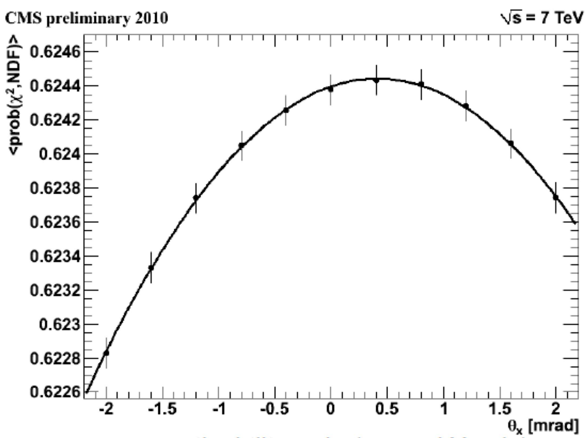
Drifts of the BPIX half-barrels in 2010



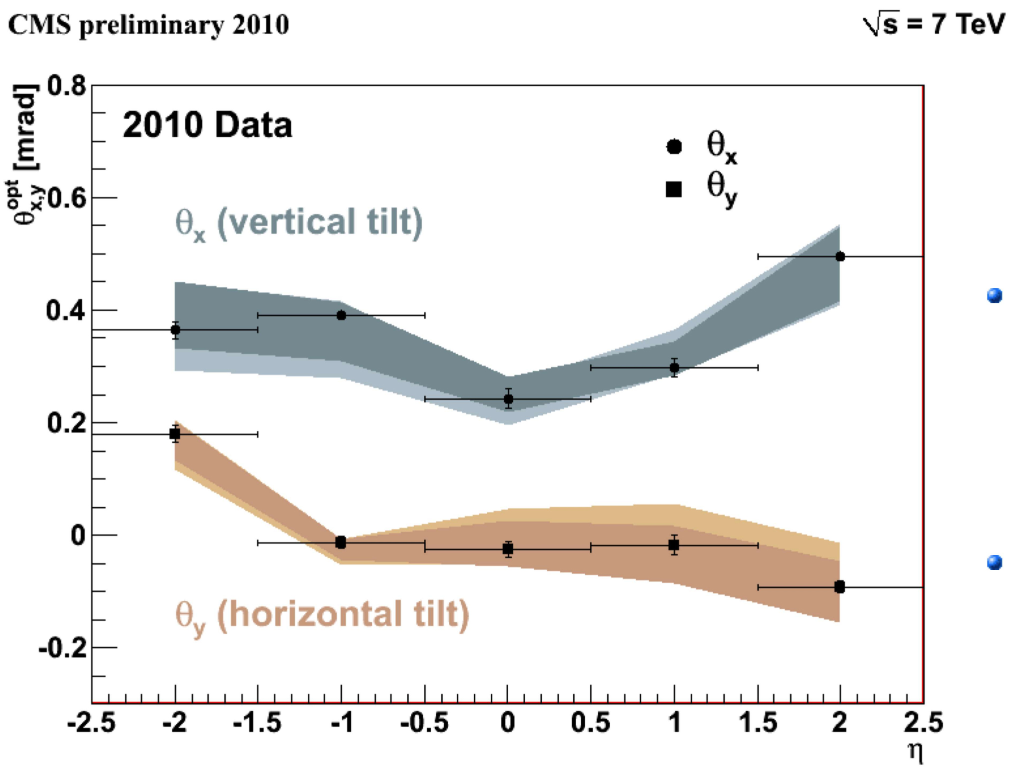
- Sudden jumps of the BPIX half-barrels up to 100 μm
  - recovered by the alignment procedure performed in seven separate periods
  - no trivial correlation with CMS or BPIX operations

Tilt of the Tracker wrt B field

- Tilt angles of the Tracker wrt the **B** field direction estimated by scanning range of horizontal and vertical tilt angles and looking for the values which optimize the track quality



θ_X = vertical tilt angle (around X axis)

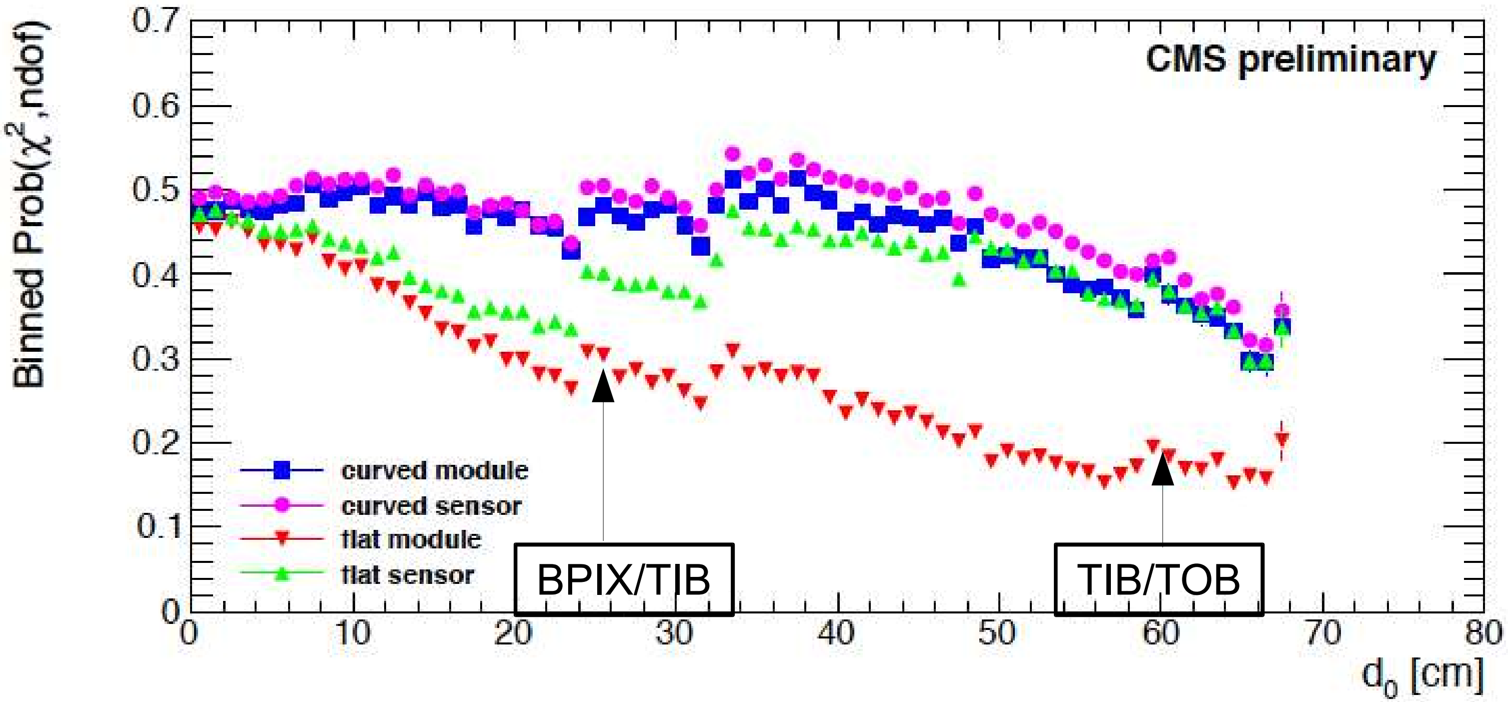


- θ_x=300 μm tilt around x_{CMS} (pointing to the LHC center)
- θ_y compatible with no tilt

- Systematics:
  - different pT cut (pT>0.5 GeV, pT>1 GeV, pT>2 GeV),
  - different choice for the estimator of the track quality (<prob(χ^2,ndf)>, <χ^2/ndf>, $\sum\chi^2$)
  - simulation with no tilt: optimal θ_x, θ_y compatible with null angles

Bowing of the modules

- Triggered by the dependence of the track χ^2 probability on the impact parameter observed for cosmic rays tracks



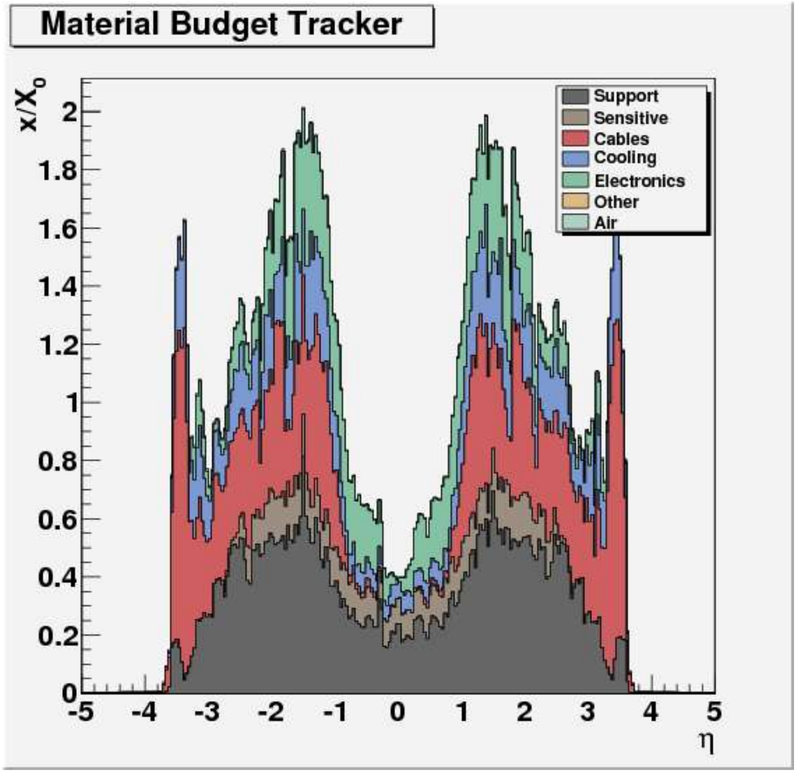
- Large d_0 → large impact angle of the track wrt the normal to the sensor/module surface
  - Sensors are bowed (sagitta up to 30 μm both in pixels and strips)
  - Two-sensors modules (TOB,TEC) have an average kink of 1.5 mrad

MATERIAL BUDGET STUDIES

Pre-collision knowledge

- Large effort in producing a detailed description of the Tracker (350k volumes) in the CMS simulation

	Mass [kg]	Fraction
CarbonFiber	1144.5	27.6%
CopperAndAlloys	644.5	15.6%
Aluminium	595.0	14.4%
OrganicMaterials	472.1	11.4%
C6F14	258.9	6.3%
SiliconSensitive	225.8	5.5%



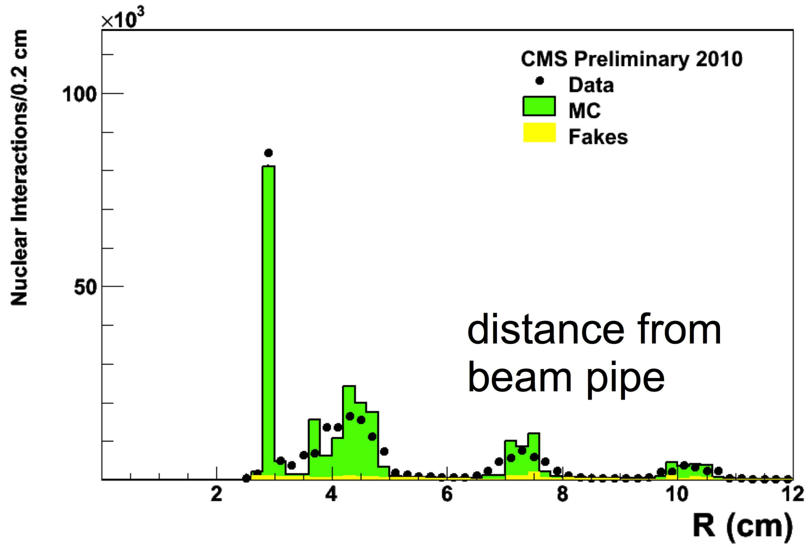
- Possible inaccuracies in:
  - overall amount of the different materials
  - approximations used in the description of the passive structures

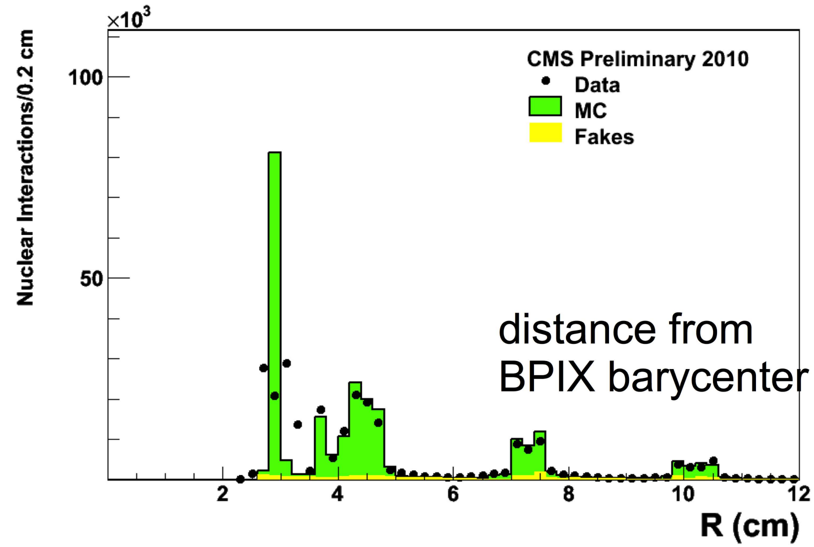
investigated in collisions events using

- photon conversions (about 70% of all γ) → probing X_0 (σ_r=0.2-0.5 cm)
- nuclear interactions (about 5% of pT=5 GeV $\pi^{\pm}$) → probing λ_I (σ_r=100 μm)

From maps of vertices to maps of material

- Well known offsets between BPIX and beamline from tracking and alignment studies:
  x_{BL}-x_{BPIX}=2.3 mm, y_{BL}-y_{BPIX}=3.8 mm
  O(100 μm) between beamline and beam pipe



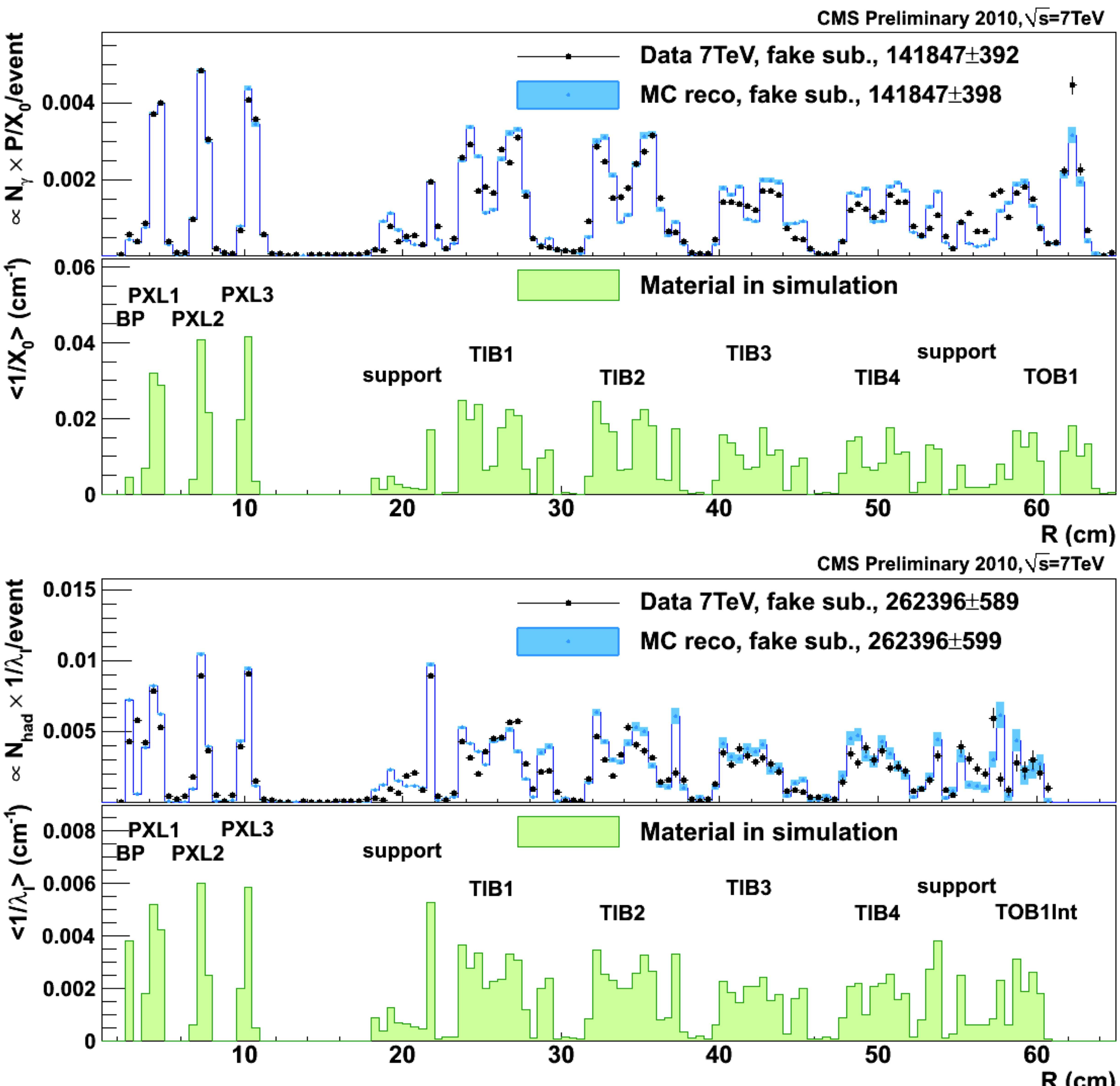


- convert the number of vertices in a volume V into an average interaction probability in that volume

$$\left\langle \frac{7/9}{X_0} \right\rangle \propto \frac{1}{N_{evts}} \cdot \frac{N_{conv}^{raw} - N_{conv}^{fakes}}{\epsilon_{conv} f_{geom(\gamma)}}$$

$$\left\langle \frac{1}{\lambda_I} \right\rangle \propto \frac{1}{N_{evts}} \cdot \frac{N_{n.i.}^{raw} - N_{n.i.}^{fakes}}{\epsilon_{n.i.} f_{geom(had)}}$$

Radial distribution of the material

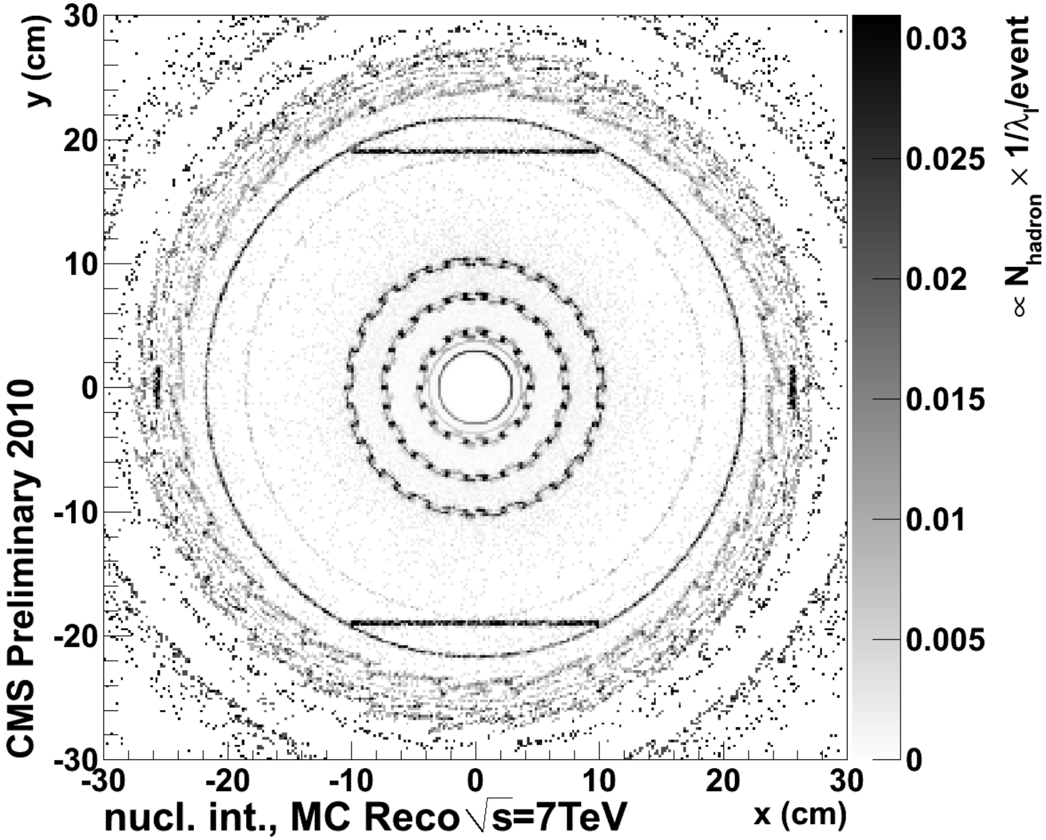


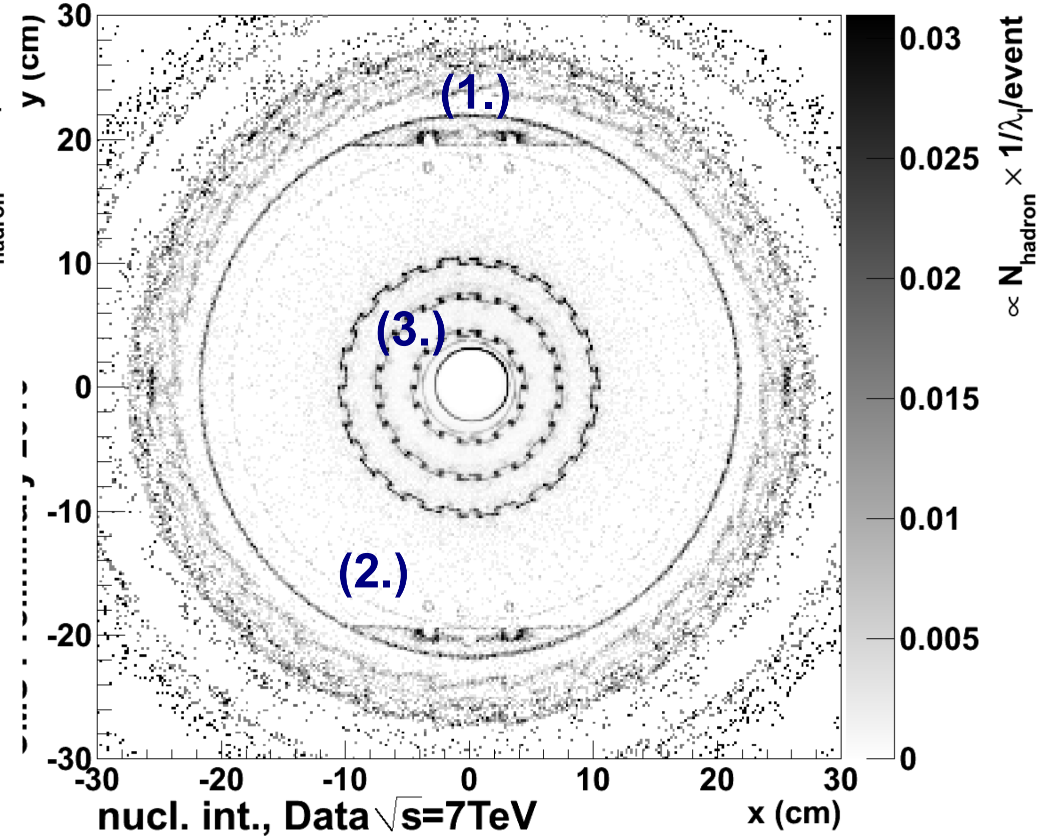
- Qualitative agreement
  - Data/MC estimate of $<1/X_0>$ and $<1/\lambda_I>$
  - $<1/X_0>$ from conversions and GEANT4 model (ditto for $<1/\lambda_I>$ and n.i.)
- Quantitative agreement
  - N_{conv}^{Data} vs. N_{conv}^{MC}
  - $N_{n.i.}^{Data}$ vs. $N_{n.i.}^{MC}$

within 10% apart from a 20% excess of the data in the “support” region between TIB and TOB

XY maps: difference between data and description

Zoom in the BPIX region |z|<26 cm

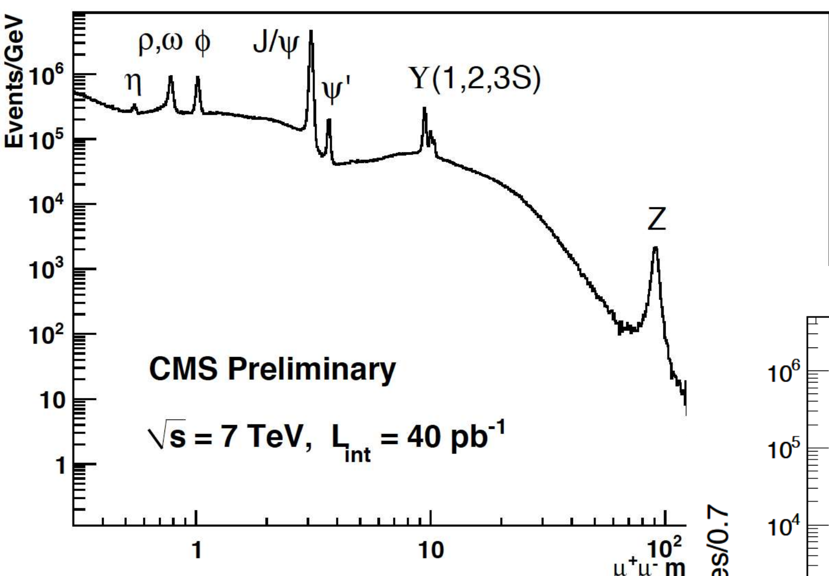


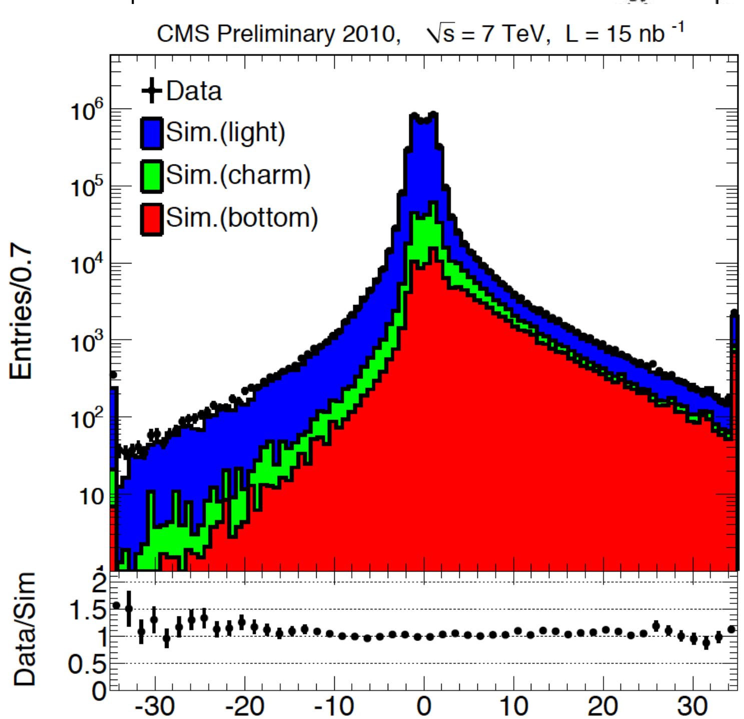


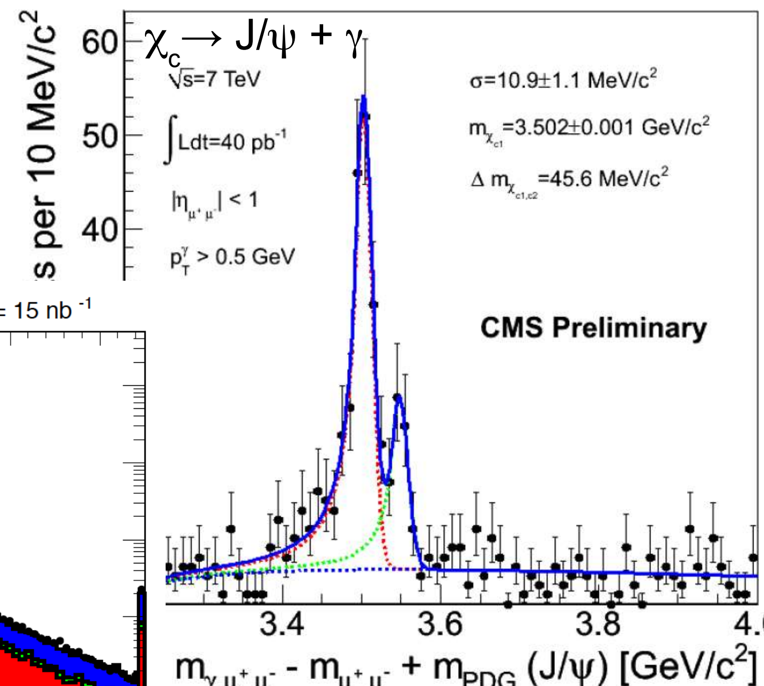
1. Missing details in the supporting rails
2. Missing pairs of CF stiffeners
3. Beam pipe off-centered wrt BPIX

Summary

- Few differences between the “design” and the “real” CMS Tracker
- Excellent performance of the “real” Tracker as a scientific instrument (resolution on invariant masses, b-tagging capabilities, reconstructions of interactions..) reached also thanks to the dedicated effort in understanding alignment and material budget

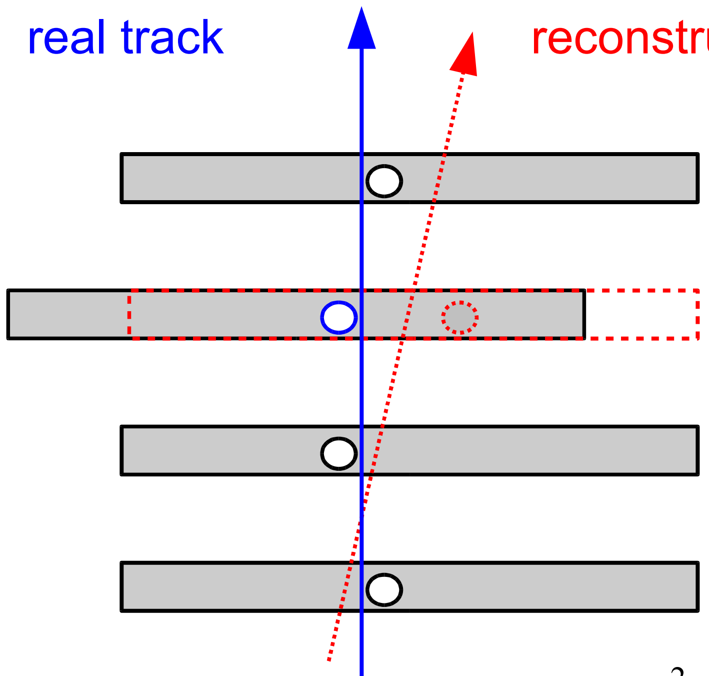


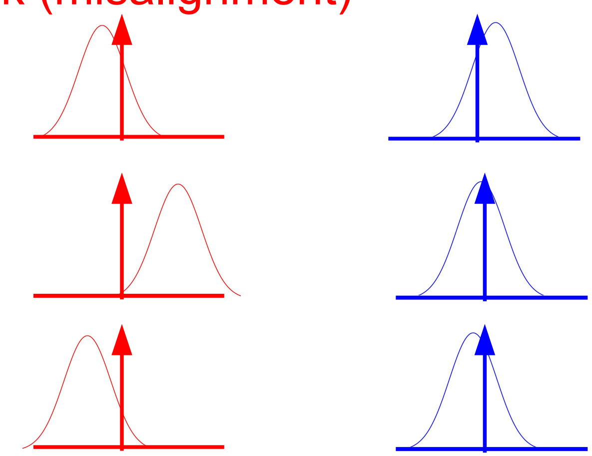




EXTRA-SLIDES

Basics of track-based alignment





$$\chi^2(\boldsymbol{p}_m, \boldsymbol{q}_{trks}) = \sum_i^{residuals} \boldsymbol{r}_i^T \boldsymbol{V}_i^{-1} \boldsymbol{r}_i$$

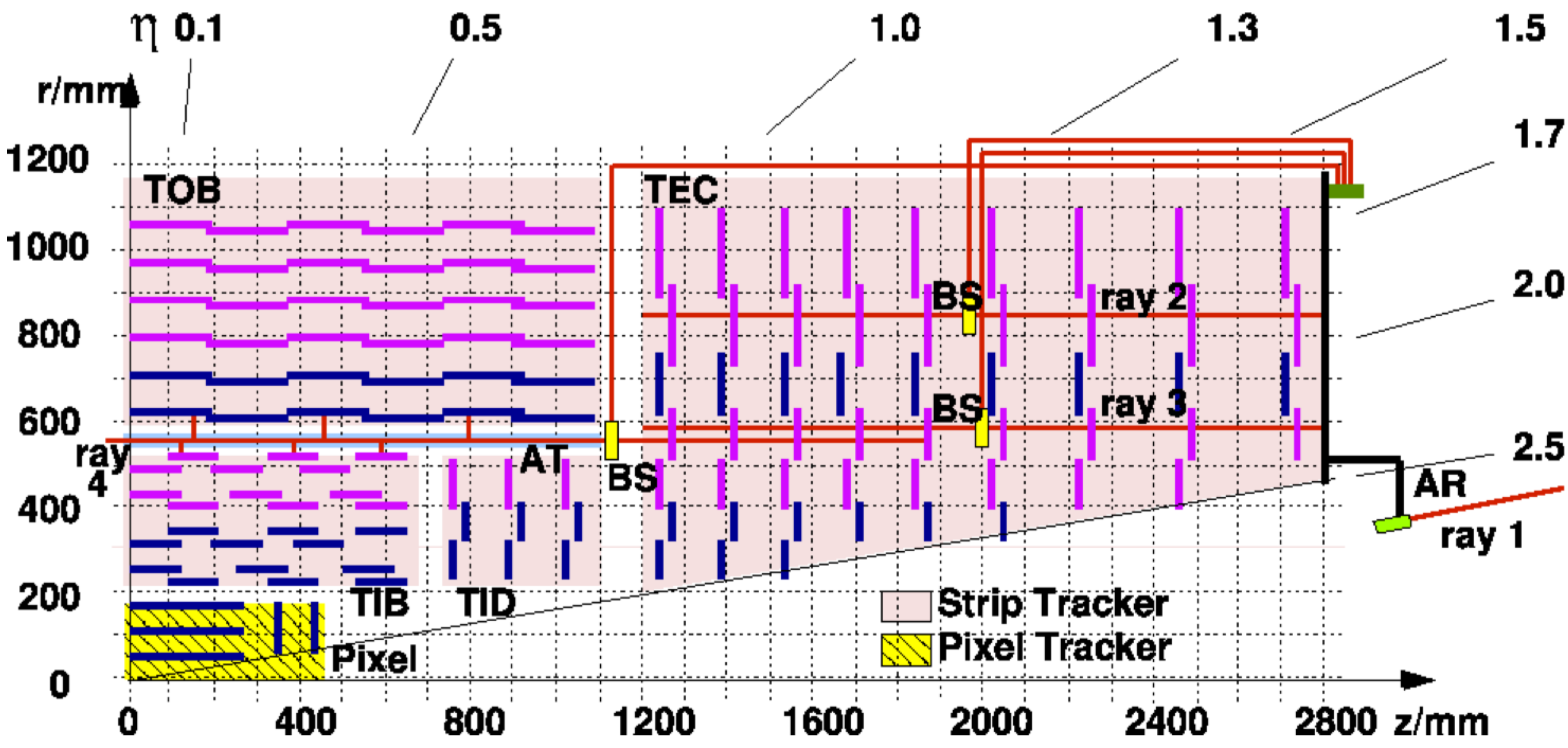
- Optimization problem: $\dfrac{d\chi^2}{d\boldsymbol{p}_m} = 0$

$$\chi^2(\boldsymbol{p}_m) = \chi^2(\boldsymbol{p}_{m0}) + \left.\frac{d\chi^2}{d\boldsymbol{p}_m}\right|_{p_{m0}} \boldsymbol{\delta p}_m \qquad \boldsymbol{\delta p}_m = -\left(\left.\frac{d^2\chi^2}{d\boldsymbol{p}_m^2}\right|_{p_{m0}}\right)^{-1} \frac{d\chi^2(\boldsymbol{p}_{m0})}{d\boldsymbol{p}_m}$$

large matrix!

- global method
  one matrix 6Nx6N
  - pros: correlations among modules included by construction
- local method
  N matrices 6x6
  - pros: same tracking routines used in reconstruction software

r-z view of ¼ of the CMS Tracker

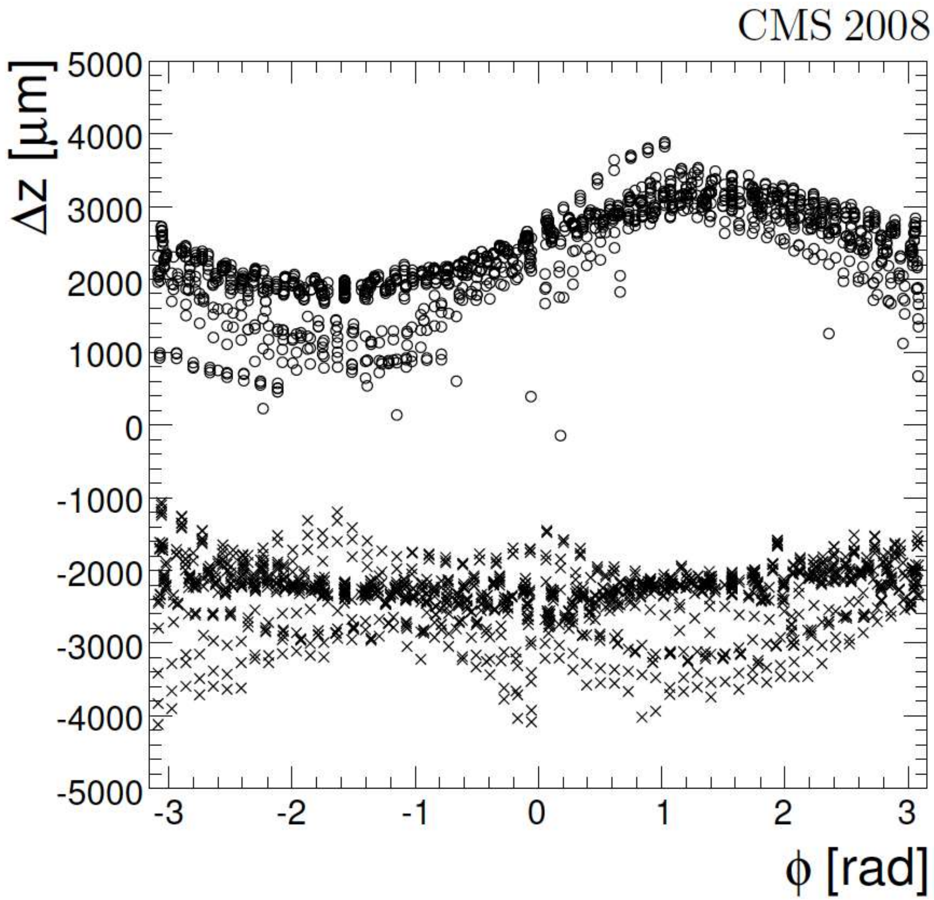


Gap between the two TIB halves

- Observed since CRAFT (confirmed by the analysis of survey data), stable since then

Δ=design-”real”
“real”=design-Δ

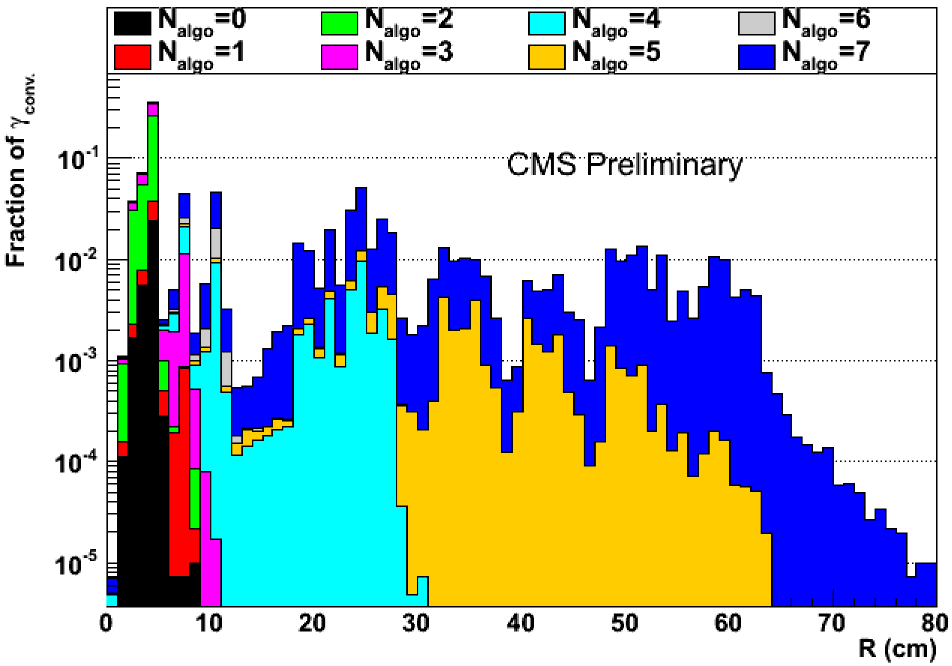
× TIB+ module
○ TIB- module



- Extra modulation in φ compatible with a skew ($\Delta z=\kappa\cos\phi$)
- The gap is not in the sensitive coordinate → not easily seen in the analysis of the overlaps

Probes for MB studies

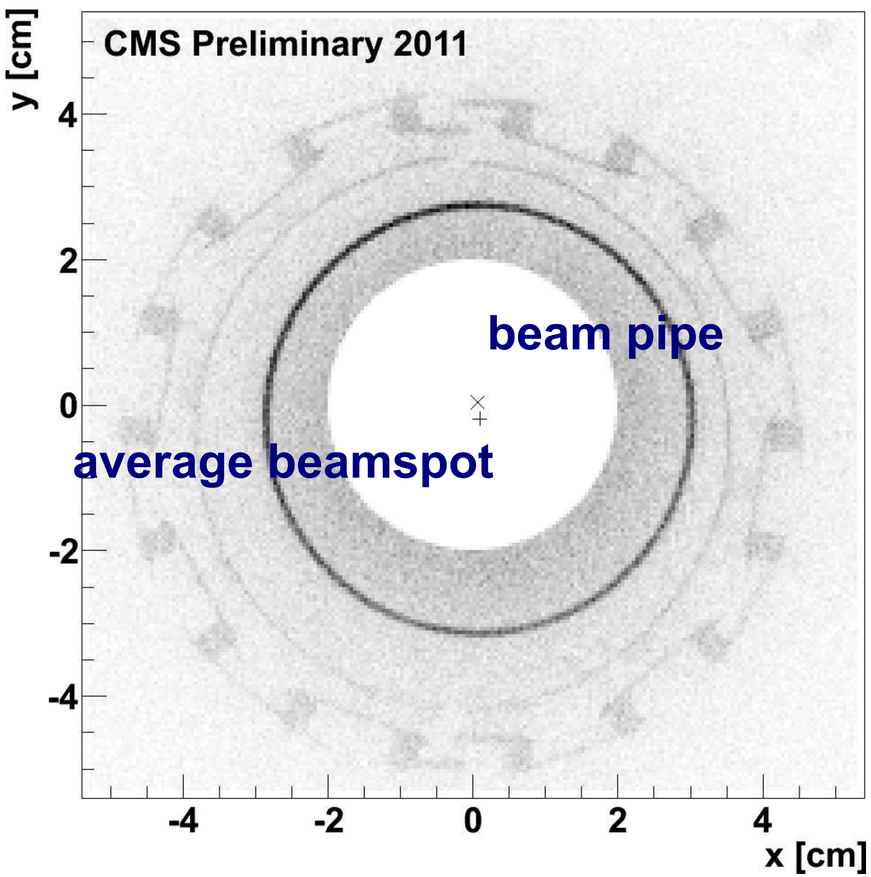
- Two different probes
  - photon conversions (about 70% of all γ) → probing X_0
  - nuclear interactions (about 5% of pT=5 GeV $\pi^{\pm}$) → probing λ_I
- Both of them are characterized by a secondary (interaction) vertex displaced from the primary vertex and featuring outgoing soft not-pointing tracks
- Two additional tracking steps deployed for material budget studies recovered x2 of conversions outside pixel volume

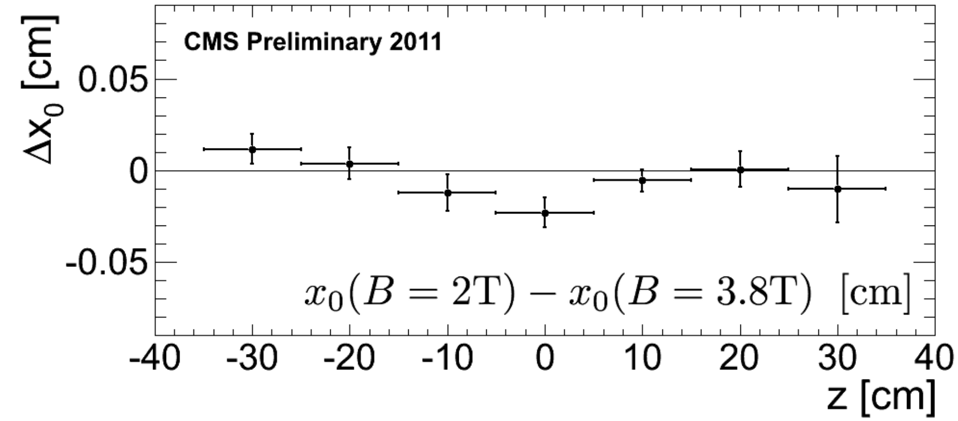


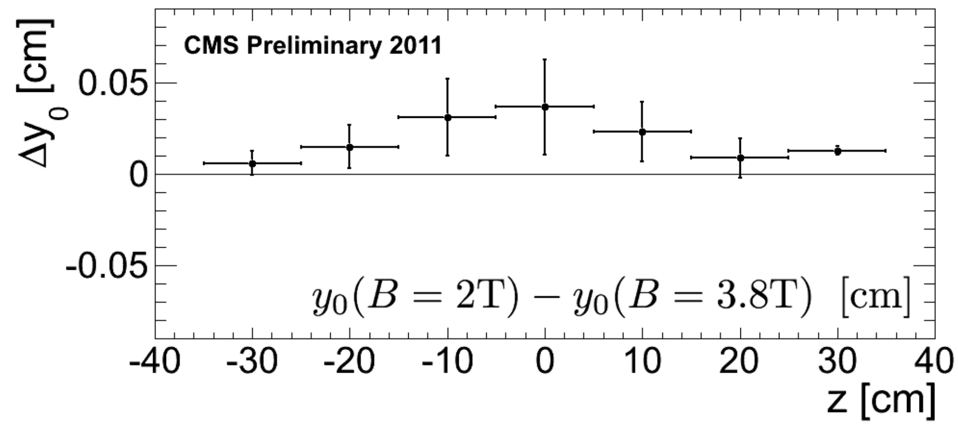
- With L_{int}=1/nb:
  - 260k reco'ed photon conversions (σ_r=0.2-0.5 cm)
  - 470k reco'ed nuclear interactions (σ_r=100 μm)

XY maps: check beam pipe stability

Reconstructed n.i. in |z|<20 cm







- Fit beam pipe center (x_0, y_0) and radius in intervals of Δz=10 cm

- Position of the beam pipe found to be stable (sensitivity ~300 μm)
  - in 2010 vs 2011
  - in datasets taken with different values of the **B** field (2 T vs 3.8 T)

Data/MC ratio for γ-conversions and n.i.