# Overview of CMS Upgrade Program

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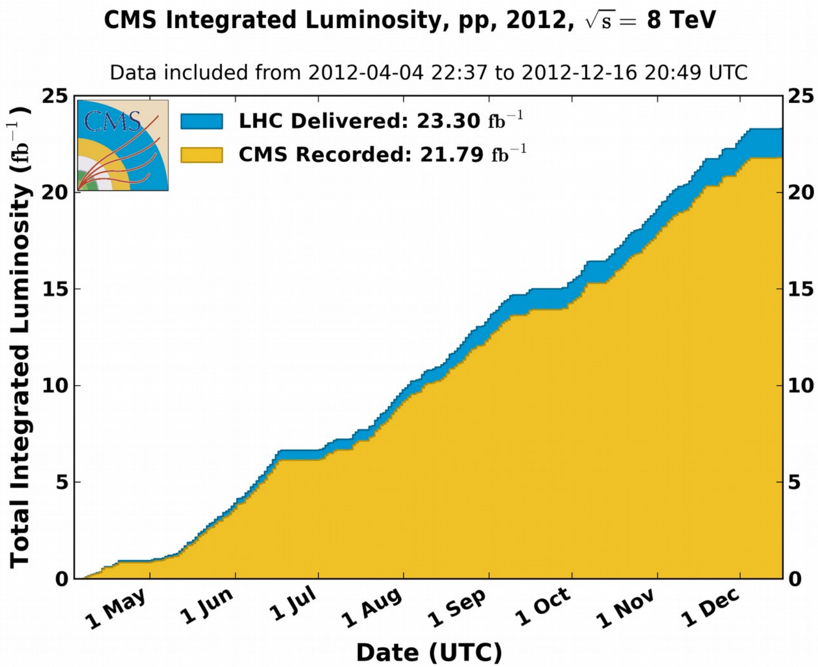
*The landscape of Flavour Physics towards the high intensity era*
Pisa – 9-10/12/2014

# Summary

- LHC schedule and CMS upgrades
  - Run-2 preparation and Phase-1 upgrades
  - High-Luminosity LHC and Phase-2 upgrades
- Impact of CMS upgrades on B physics
- Studies of CMS B-physics performance for HL-LHC
  - Trigger capabilities
  - Estimate of CMS performance for $B^0_{(s)} \to \mu\mu$

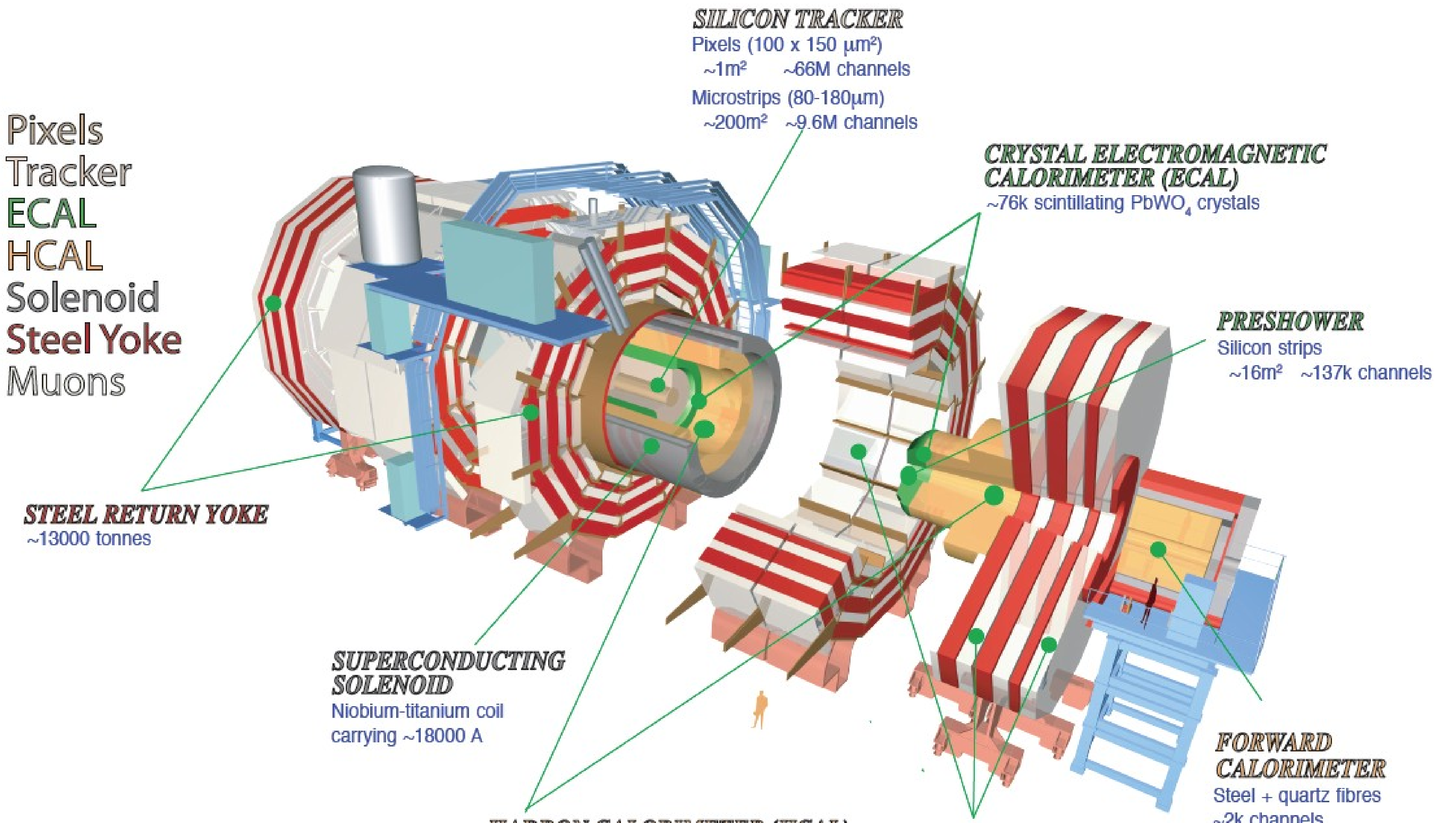
# LHC Run 1


- During Run 1 LHC has collided two proton beams with $\sqrt{s}$ = 7 TeV (2010, 2011) and 8 TeV (2012)
- The total luminosity delivered to CMS was **~29 fb$^{-1}$** (6 fb$^{-1}$ in 2011 and 23 fb$^{-1}$ in 2012)
- The good data recorded by CMS was **~25 fb$^{-1}$**



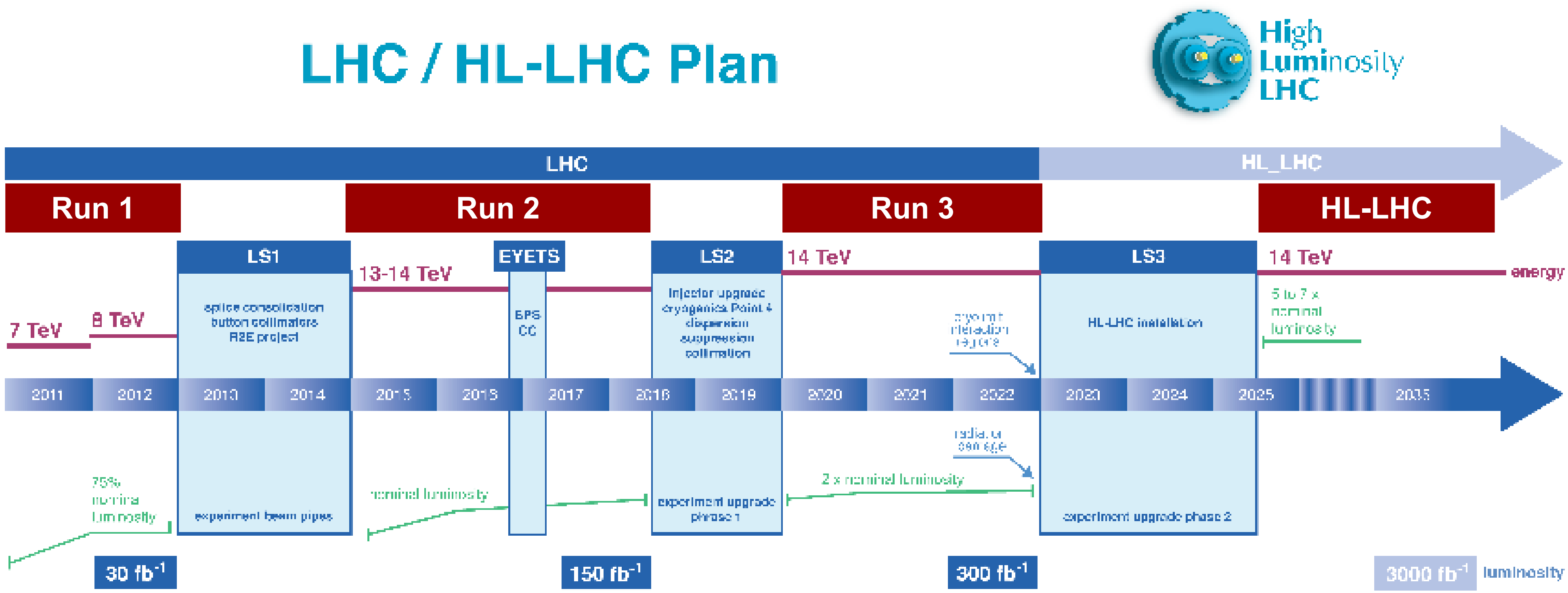
# CMS detector

JINST 3 (2008) S08004

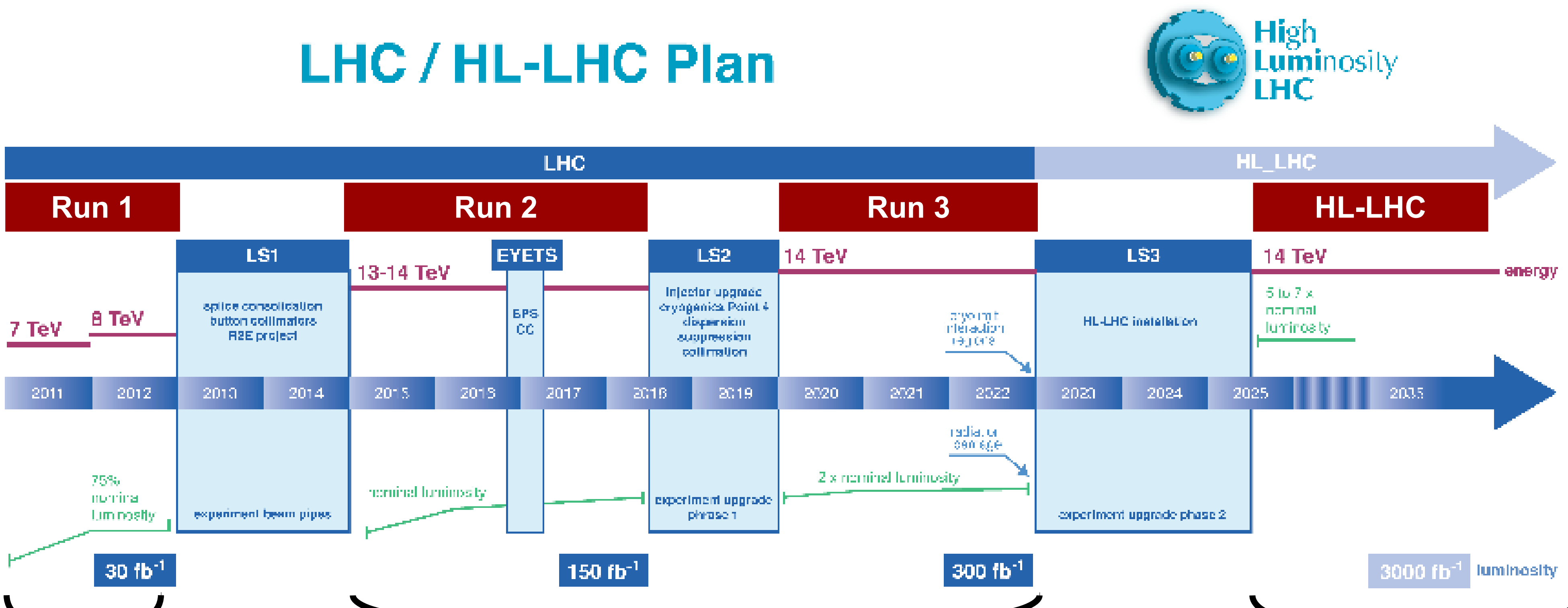



| | |
|---|---|
| **Total weight** | **: 14000 tonnes** |
| **Overall diameter** | **: 15.0 m** |
| **Overall length** | **: 28.7 m** |
| **Magnetic field** | **: 3.8 T** |

# LHC and CMS upgrade schedule



# LHC and CMS upgrade schedule




CMS

## Phase-0

- Baseline CMS detector
- $\sqrt{s_{pp}}$ = 7-8 TeV
- $L_{int}$ = 25 $fb^{-1}$

## Phase-1

- First detector upgrades
- $\sqrt{s_{pp}}$ = 13-14 TeV
- $L_{int}$ = 300 $fb^{-1}$

## Phase-2

- Major detector upgrades
- $\sqrt{s_{pp}}$ = 13-14 TeV
- $L_{int}$ = 3000 $fb^{-1}$

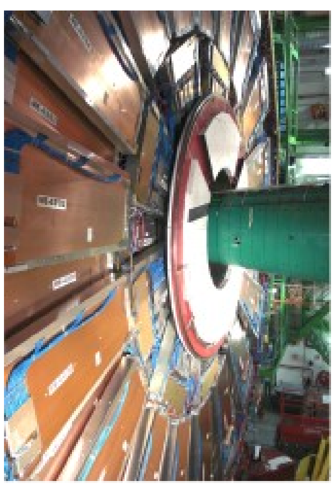
# CMS upgrades

- **Baseline (i.e. Run-1) CMS detector** was designed to operate at a luminosity $\mathbf{L \approx 10^{34} cm^{-2}\, s^{-1}}$ with 25 ns of bunch crossing (average **PU~25**)
  - These conditions will be realized during **Run-2** after the LS1 in 2015-2017
- The **Phase-1 upgrades** will allow CMS to deal with $\mathbf{L \approx 2 \times 10^{34} cm^{-2}\, s^{-1}}$ with 25 ns of bunch crossing (average **PU~50**)
  - These conditions should be realized in **Run-3** in 2019-2022
  - A total of **300 fb$^{-1}$ of pp data** should be collected at the end of Run-3
  - The most important upgrade for B physics will be **a new pixel detector**
- The **Phase-2 upgrades** involve major changes, in order to cope with a luminosity $\mathbf{L \approx 5 \times 10^{34} cm^{-2}\, s^{-1}}$ with 25 ns of bunch crossing (average **PU~140**)
  - This is going to be realized in 2024 in the **HL-LHC runs**
  - Asymptotically, up to **3000 fb$^{-1}$ of pp data** should be collected in this scenario
  - B physics will benefit the most from a completely **new inner tracker**

# Run-2 preparation

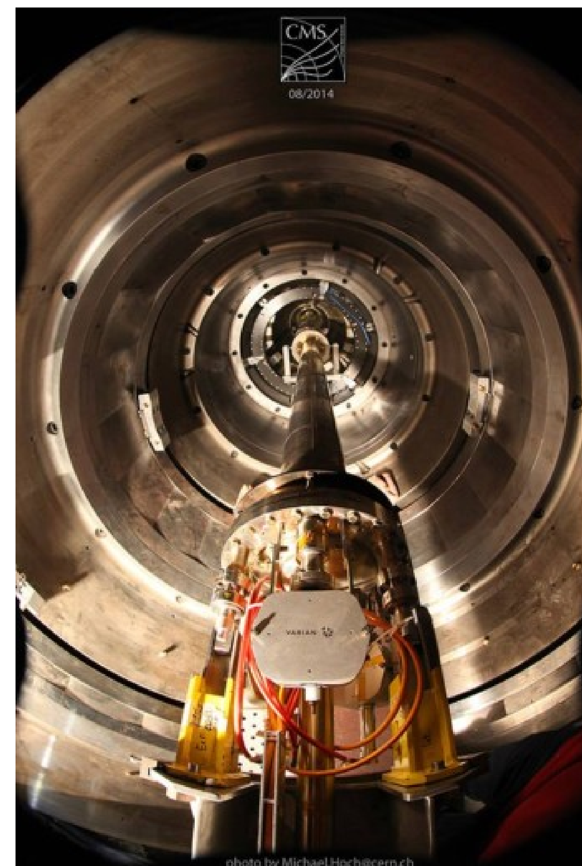
**Detector changes being deployed during current Long Shutdown of LHC**

Silicon tracker operation at $-15\ ^\circ\mathrm{C}$ to increase longevity

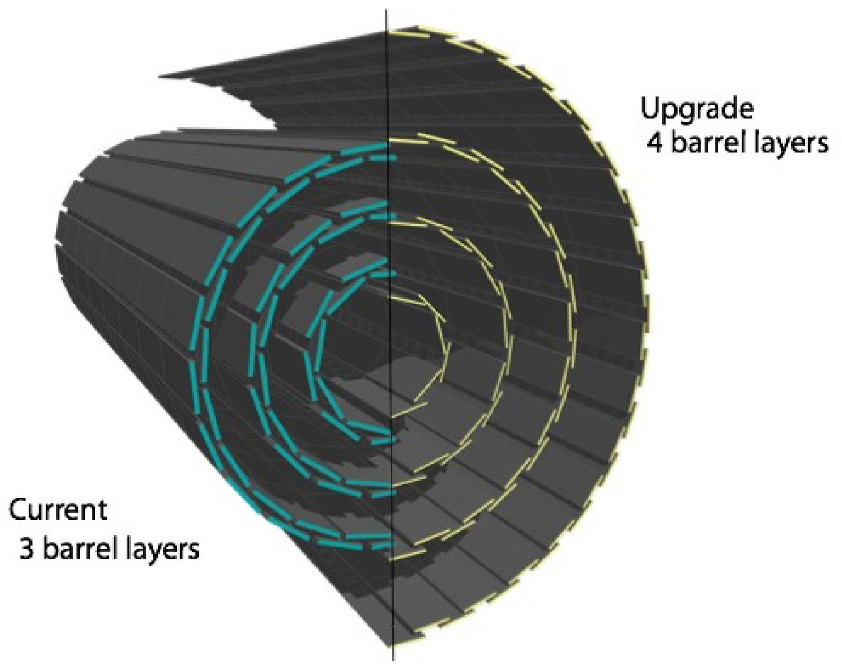


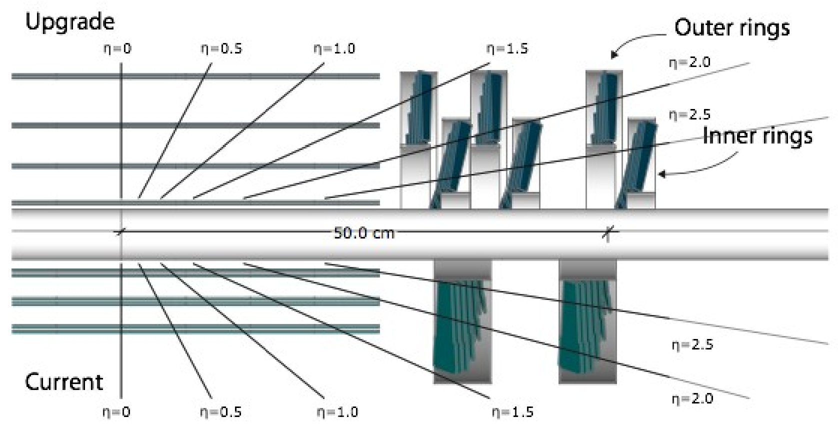
New RPC and CSC stations at high $|\eta|$

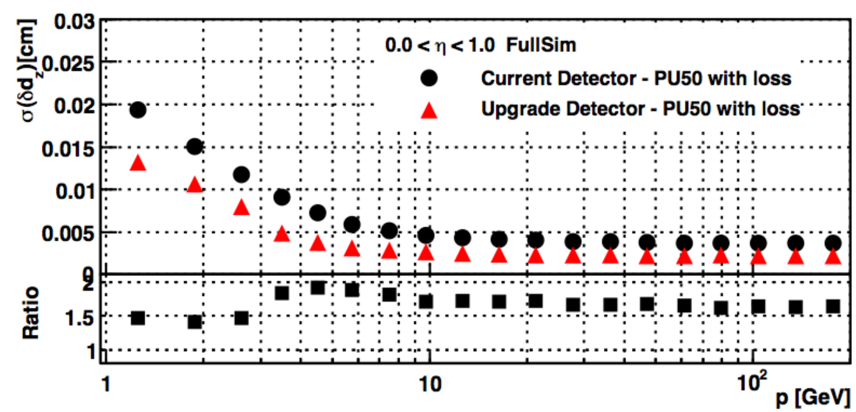
New beam pipe with reduced diameter
$\longrightarrow$ ready for installation of upgraded pixels in 2017

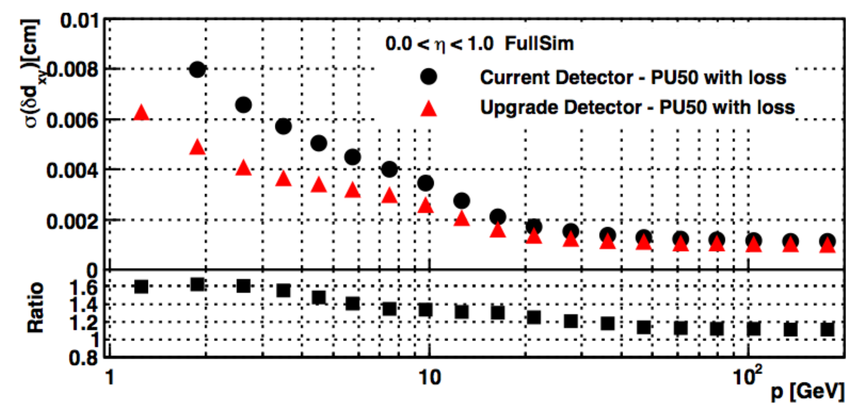


# Phase-1 pixel upgrade



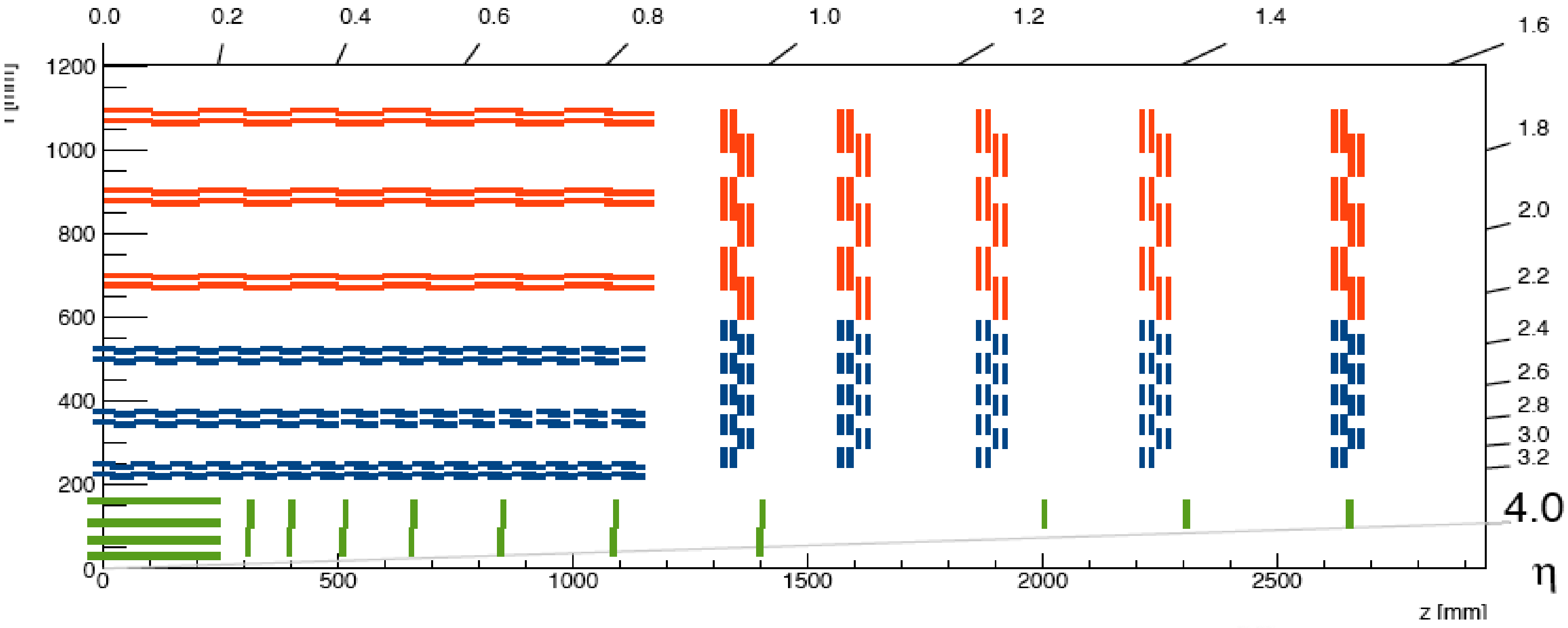



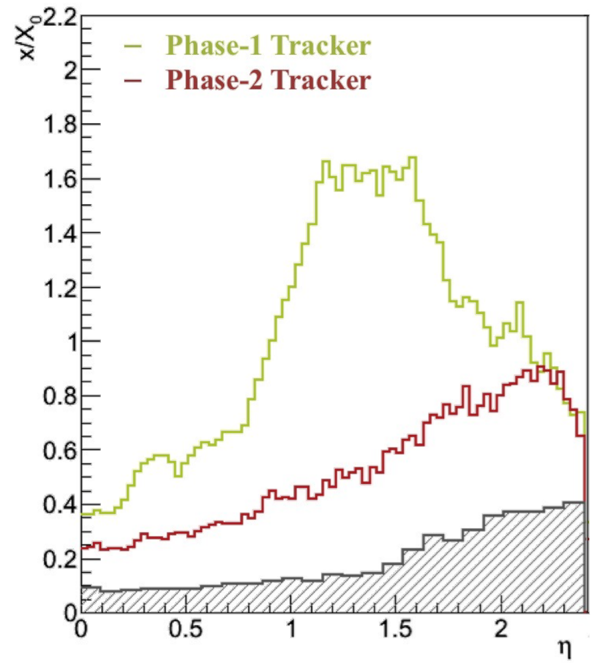




- In 2017 the **pixel detector** will be replaced
  - One more layer, closer to the beam pipe
    ⟶ more precise
  - Lower material budget
    ⟶ smaller multiple scattering
- **Better performance for low $p_T$ tracks**, used for B physics

# Phase-2 tracker upgrade

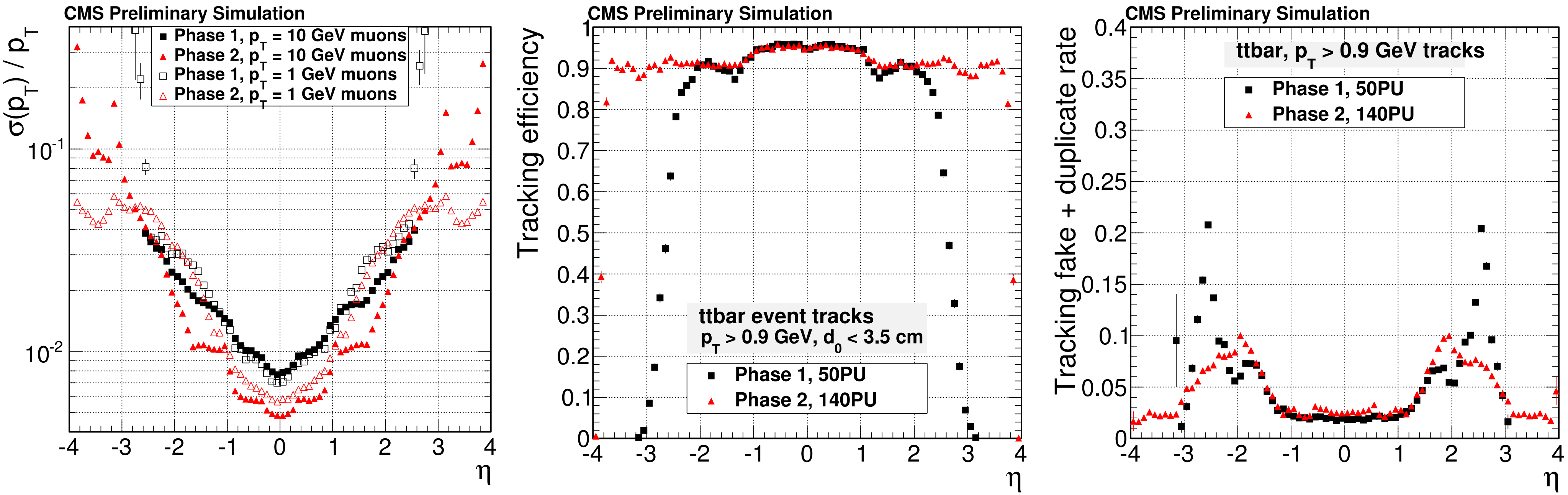



- The **CMS tracker** will be completely renewed for the High-Luminosity LHC runs starting in 2024
  - 6 barrel + 5 endcap layers + pixels
  - Lighter than the Phase-1 tracker ⟶ better $p_T$ resolution
- New design including pixels also in the outer part
  - **7004 PS(Pixel+Strip) modules (60% in the barrel)**
  - **8344 2S(Strip+Strip) modules (50% in the barrel)**



# Offline tracking performance

- Performance of Phase-2 tracker evaluated with full Geant4 simulation of the detector
- Improved resolution for low- and medium-$p_T$ muons, especially in the barrel
- Coverage up to $|\eta|<4$ (in the hypothesis of an extended pixel detector)
- Reduced track fakes at high $|\eta|$

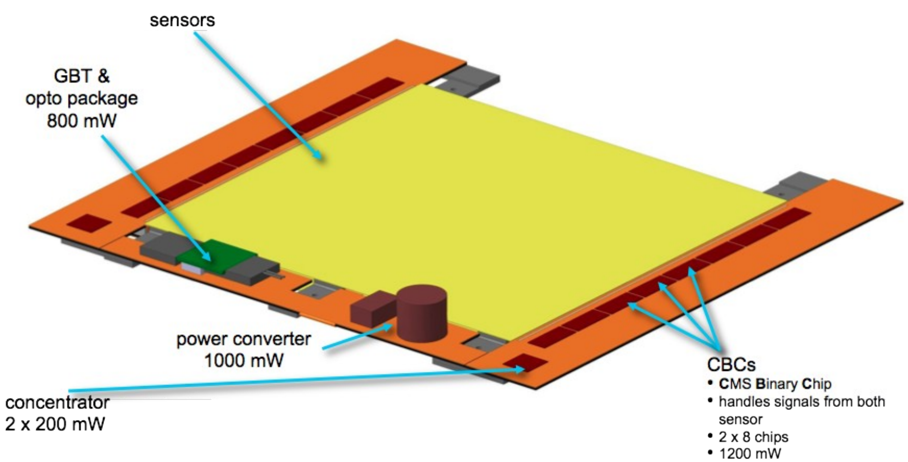


# CMS $p_T$ modules for trigger

Future CMS tracker will have **L1 trigger** capabilities for **$p_T$>2 GeV** and **|η|<2.5** tracks

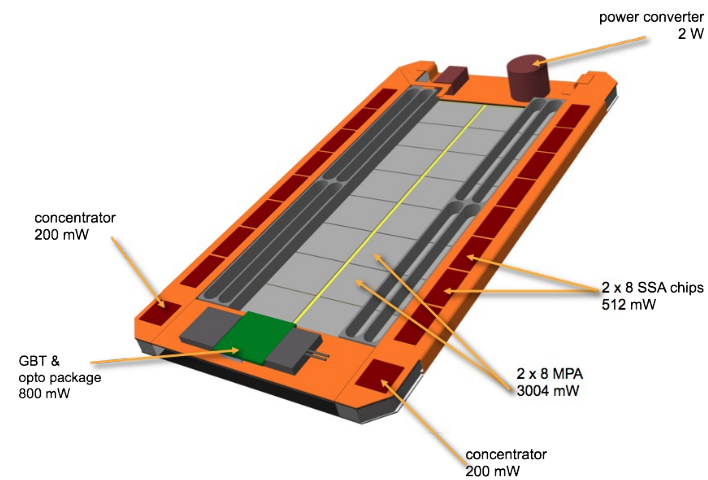
2S(trip) sensors modules

100 µm x 5 cm long strips on both sensors

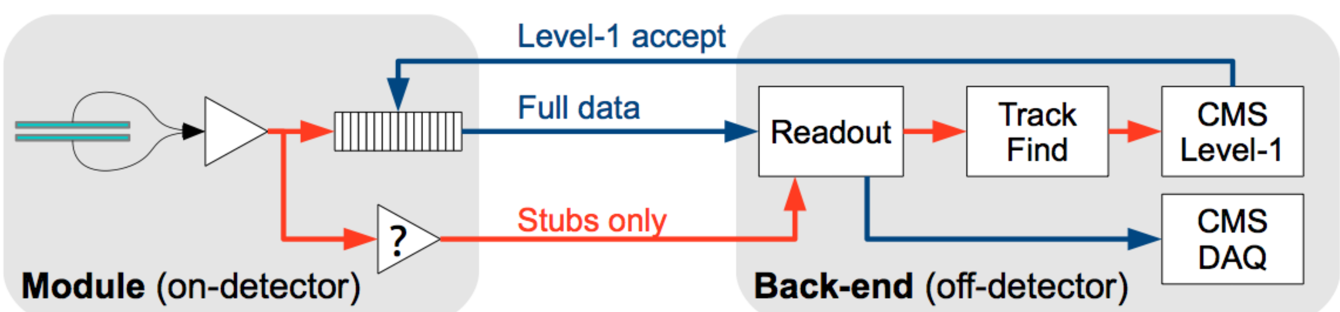



P(ixel)S(strip) module

strips = 100 µm x 2.4 cm, pixels = 100 µm x 1.5 mm

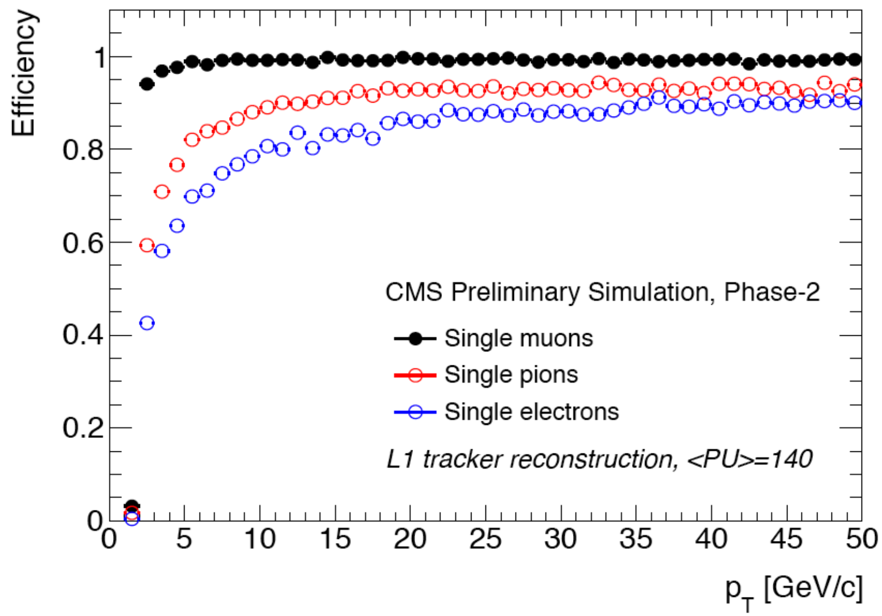


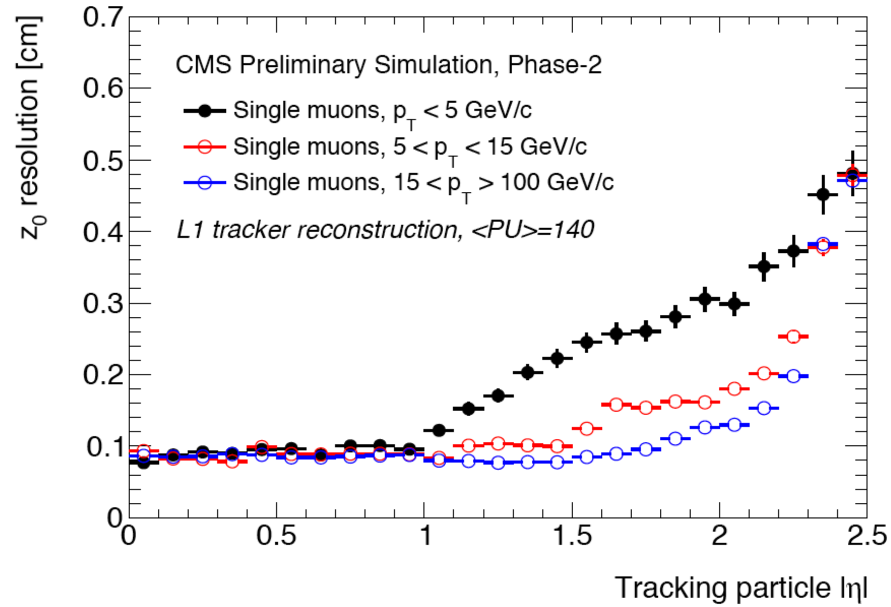

Pixels are logically OR-ed for finding coincidence in the r-ϕ plane, and the precise z-coordinate is retained in the pixel storage and provided to the trigger processors



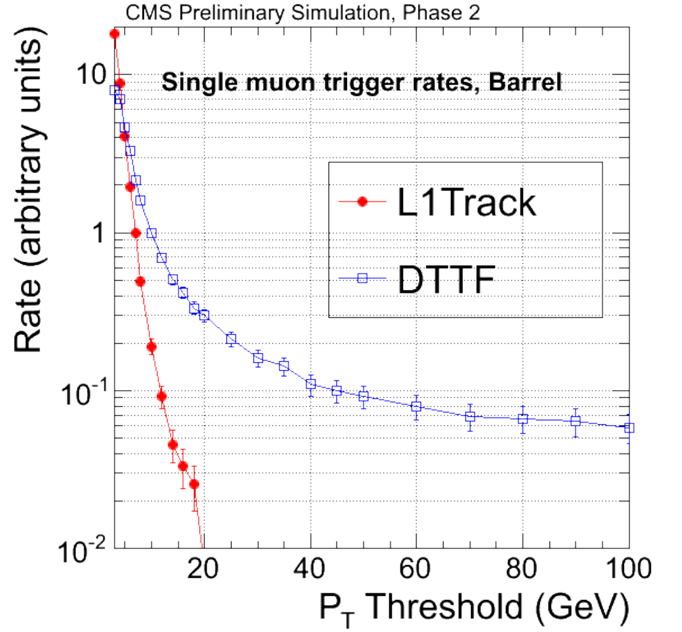

**L1 Latency 10 µs**
**(20 µs in option)**
**L1A rate ≤1 MHz**
**HLT rate ≤10 kHz**

# L1 track trigger expected performance




- **High efficiency** for the reconstruction of muon and hadron tracks at L1
- **Good resolution** of track parameters
    - E.g. momentum, $z_0$
- **Large reduction of L1 muon trigger rate** matching L1 tracks to trigger primitives in muon chambers (plot normalized to present CMS muon trigger with threshold $p_T$>10 GeV)



# B physics studies

- The B-physics performance of the CMS Phase-1 and Phase-2 upgraded detectors has been estimated by looking at one benchmark channel: **search for $B^0 \rightarrow \mu\mu$ decays and measurement of the $B^0_{(s)} \rightarrow \mu\mu$ branching fraction**

- **Intrinsically important**: observing the $B^0 \rightarrow \mu\mu$ decay and determining precisely its branching fraction can pose stringent limits to new physics models
- Comprising several other **possible measurements at HL-LHC**: cross section ratios, polarization, etc.
- The results can give hints on the CMS performance in **similar heavy-flavor physics channels**: B hadron and quarkonia decays to muons(+hadrons), searches for LFV decays including muons, etc.

# Analysis setup

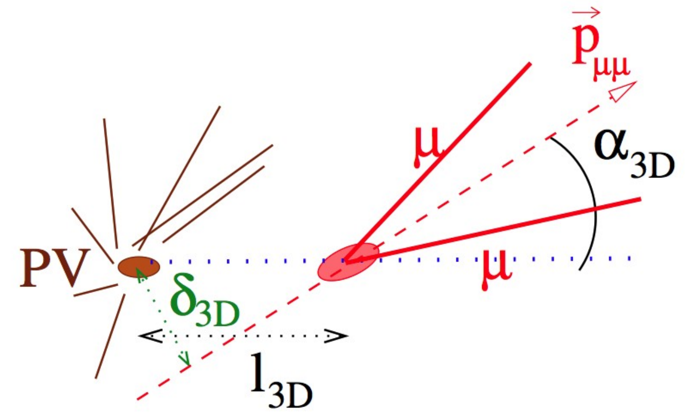
- Analysis performance evaluated in two scenarios:
  - **Phase-1**: corresponding to the expected performance of the CMS detector after the Phase-1 upgrades and to 300 $fb^{-1}$ of integrated luminosity
  - **Phase-2**: corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to 3000 $fb^{-1}$ of integrated luminosity

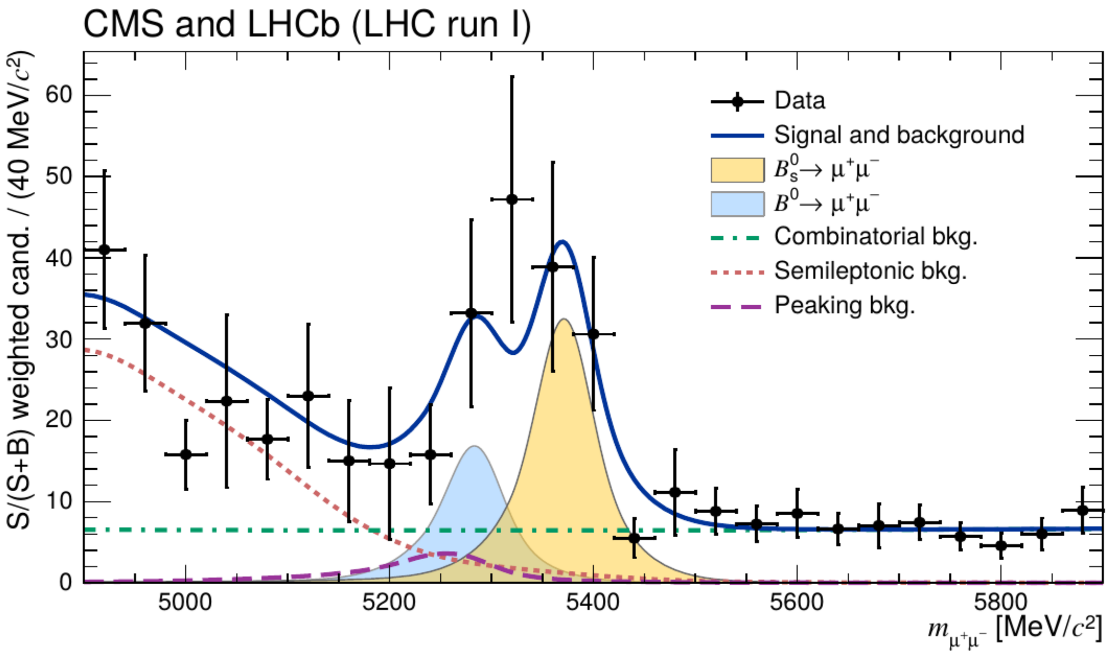
- In both cases the **public results of the CMS Run-1 $B_s \to \mu\mu$ analysis** were used as a starting point, incorporating also the improvements present in the CMS-LHCb combination just published. These improvements are:
  - Changes in the way the signal efficiency depends on proper life time (increases $B_s$ signal yield)
  - Change in the shape of the semi-leptonic background due to the use of an improved theoretical model

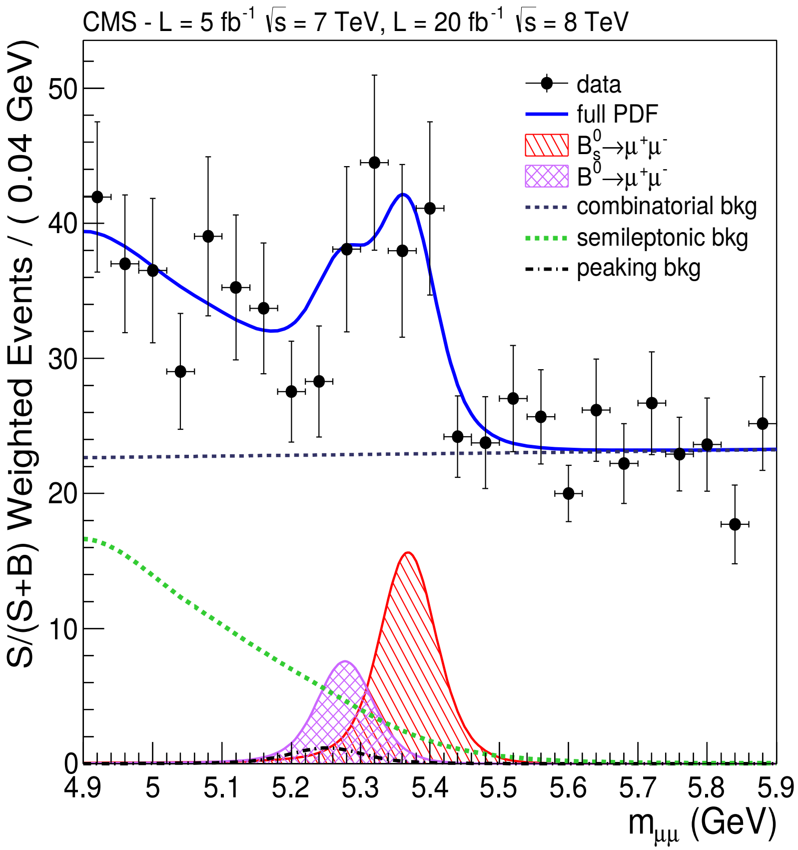
# B→μμ Run-1 analysis

PRL 111 (2013) 101804
arXiv:1411.4413

- Main ingredients of Run-1 analysis
  - Low μ trigger $p_T$ thresholds (3 GeV at L1)
  - Muon and di-muon vertex isolation
  - Displaced vertex
  - Di-muon vertex aligned with flight path
  - Low muon fake rate $\varepsilon(\mu|\pi) < 0.15\%$



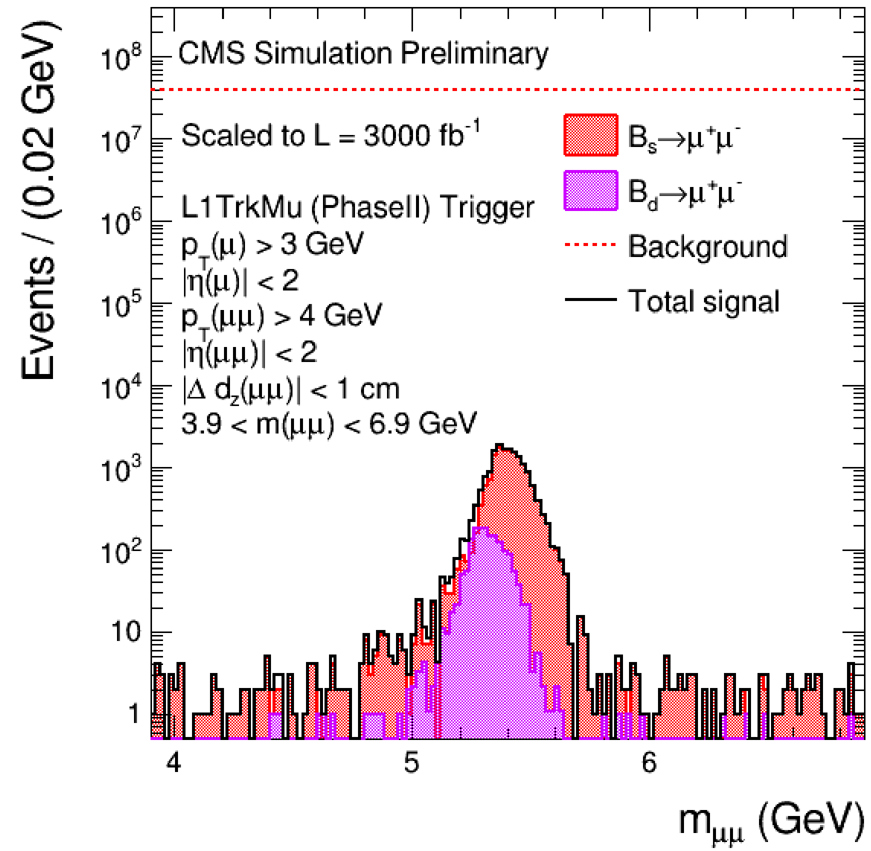
# L1 trigger for $B^0_{(s)} \to \mu\mu$ in Phase-2 (1)

- One of the main issues for the Phase-2 scenario will be the triggering of low-$p_T$ muons
- The performance of a low-$p_T$ di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker was simulated with Geant4
- A prototype trigger algorithm having the same $p_T$ threshold of the one used in Run-1 was built and tested
  - 2 opposite-charge L1 "Tk muons", reconstructed from matching the L1 tracks and L1 standalone muons
  - $p_T(\mu) > 3$ GeV
  - $|\eta(\mu)| < 2$
  - $p_T(\mu\mu) > 4$ GeV
  - $|\eta(\mu\mu)| < 2$
  - $\mathbf{\Delta d_z(\mu\mu) < 1}$ **cm**
  - $\mathbf{3.9 < m(\mu\mu) < 6.9}$ **GeV**

**Important selections to reduce L1 rate by eliminating background from PU and non interesting muon pairs**

# L1 trigger for $B^0_{(s)} \to \mu\mu$ in Phase-2 (2)

- Mass resolution at L1 estimated to be ≈ 70 MeV using Gaussian fits to the signal peaks
- Trigger rate in the HL-LHC conditions (average of 140 PU events) is estimated to be **a few hundred Hz**
  - It constitutes only a tiny fraction of the total L1 bandwidth (~1MHz)
- Performances of the upgraded CMS L1 trigger found to be more than sufficient to implement an **efficient trigger algorithm for B→μμ** having the same $p_T$ threshold of the L1 trigger used in LHC Run 1

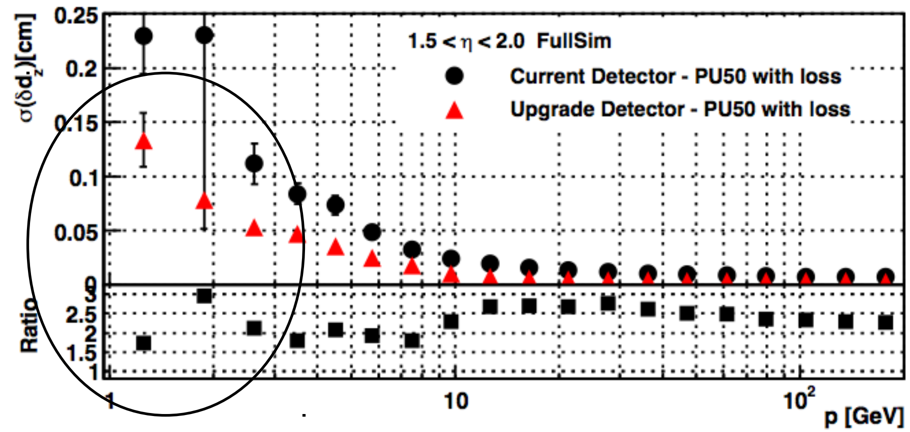


# Toy experiments setup

- The offline analysis performance was evaluated with toy MC experiments
- The toy experiments use the **invariant mass resolution coming from the full Geant4 simulation** of the CMS detector as input:
  - In the case of the Phase-1 scenario, this is roughly equal to the resolution measured with the Run-1 CMS detector, i.e. **≈ 42 MeV** when both muons are in the barrel ($|\eta| < 1.4$)
  - In the case of the Phase-2 scenario, this is **≈ 28 MeV** when both muons are in the barrel ($|\eta| < 1.4$), with **an improvement of a factor 1.5 with respect to the Phase-1 scenario**
- Other inputs to the toy experiments come from extrapolations from the Run-1 analysis (detailed in the next slides)
- Input signal branching fractions from **Standard Model predictions** are assumed everywhere
  - $\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
  - $\mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$

# Assumptions (1)

- For Phase-1, the same trigger and PU performance of the Run-1 analysis is assumed
- For Phase-2, reduced efficiencies due to 140 pileup events are expected
  - Assume 30% loss in the isolation efficiency
  - 2.5% loss per μ reconstruction efficiency
  - The resolution in the endcap (0.5 to 1 mm) is comparable to the average vertex separation
    - **Reduced impact of this region in the analysis in discerning $B_d$ from $B_s$ peak**




- The toy MC estimates are **only computed for the barrel (i.e. |η(μ)| <1.4)**
  - To ease the comparison, the same cut is applied to both Phase-1 and Phase-2 estimates

# Assumptions (2)

- Conservative **analysis assumptions** (Phase-1 and Phase-2 extrapolations):
  - No improvements in the analysis technique
  - The same hadron fake rate performance of Run-1

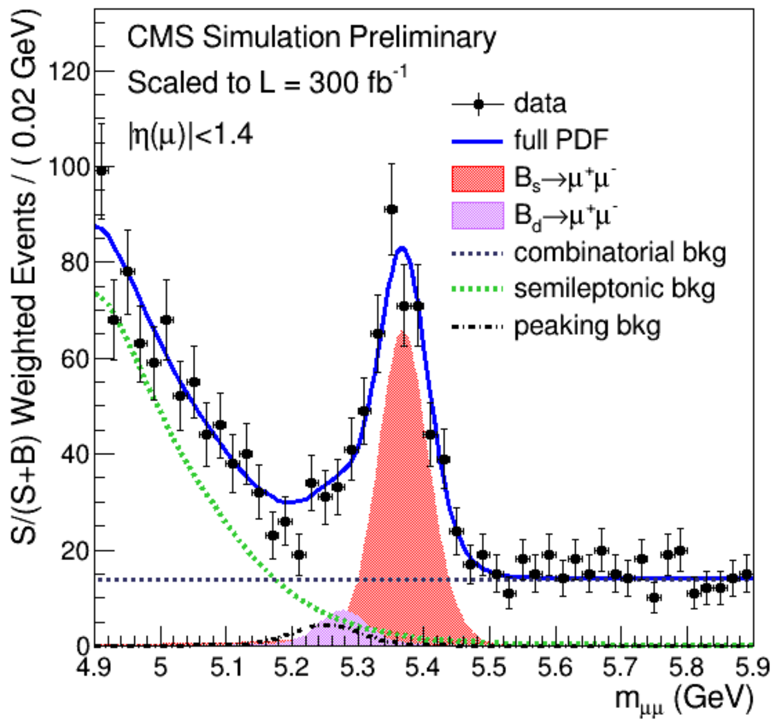
- **Systematics** as a function of integrated luminosity:
  - fs/fu = 5% [now is 9%]
  - Normalization ($B^{\pm} \longrightarrow J/\psi K^{\pm}$) = 3% ⊕ 5%/√ (L/20 $fb^{-1}$) [now 5% from yields and 3% from BR]
  - Peaking background uncertainty = 10% ⊕ 50%/√(L/20 $fb^{-1}$)
  - Semileptonic background uncertainty = 20% ⊕ 50%/√(L/20 $fb^{-1}$)

# Results for Phase-1

- Result of the toy experiments for the Phase-1 scenario is shown in the plot
  - The resolution is not good enough to allow discriminating well the $B_s$ and $B^0$ peaks
- The toy experiments also give the following estimates for 300 fb$^{-1}$ of integrated luminosity
  - **d$\mathcal{B}(B_s \to \mu\mu)$: 13%**
  - **d$\mathcal{B}(B^0 \to \mu\mu)$: 48%**

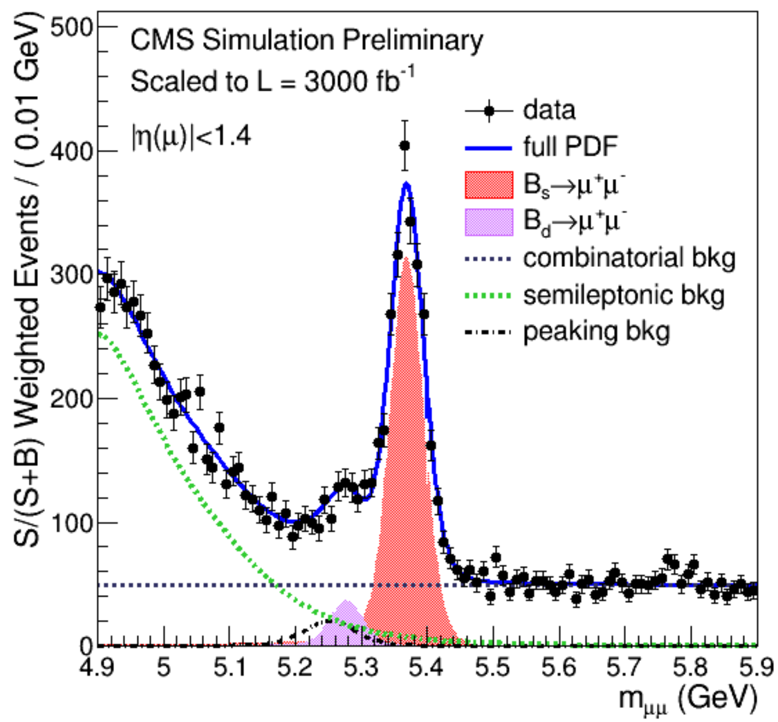
  Branching fraction uncertainties

  - **d[$\mathcal{B}(B_d \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu)$]: 50%**
  - **$B^0 \to \mu\mu$ significance: ≈2.2 σ**
- The significance expected for the SM branching fractions is still too low for claiming the $B^0$ evidence



# Results for Phase-2

- Result for the Phase-2 scenario is shown in the plot
- The resolution is much improved with respect to Phase-1 and the $B_s$ and $B^0$ peaks are now well separated
- This is reflected in the significance of $B^0$ observation and in the precision achievable in the measurement of its branching fraction (decreased from ~50% to ~20%)
  - **d$\mathcal{B}$($B_s \to \mu\mu$): 11%**
  - **d$\mathcal{B}$($B^0 \to \mu\mu$): 18%**
  - **d[$\mathcal{B}$($B_d \to \mu\mu$)/$\mathcal{B}$($B_s \to \mu\mu$)]: 21%**
  - **$B^0 \to \mu\mu$ significance: ≈6.8 σ**



# Conclusions

- CMS is performing an **extensive upgrade program** that will last ~10 years
- This program will allow CMS to **cope with the next LHC runs conditions**
  - Increased center-of-mass energy
  - Increased pile-up (up to 140 per bunch crossing)
- **CMS B-physics performance** will benefit mostly from
  - The **pixel and strip tracker upgrades**, improving the IP and momentum resolution
  - The **L1 trigger upgrades**, allowing efficient trigger of low-$p_T$ processes in a high-density environment
- **$B^0_{(s)} \to \mu\mu$ used as benchmark channel** to estimate CMS B performance
  - **Phase-1 upgrades** will allow a precise measurement of the $B_s$ observables
  - **Phase-2 upgrades** will be needed to trigger B decays at HL-LHC and precisely measure the $B^0$ observables
- **Studies show that CMS is expected to be very competitive in B physics also in the future**