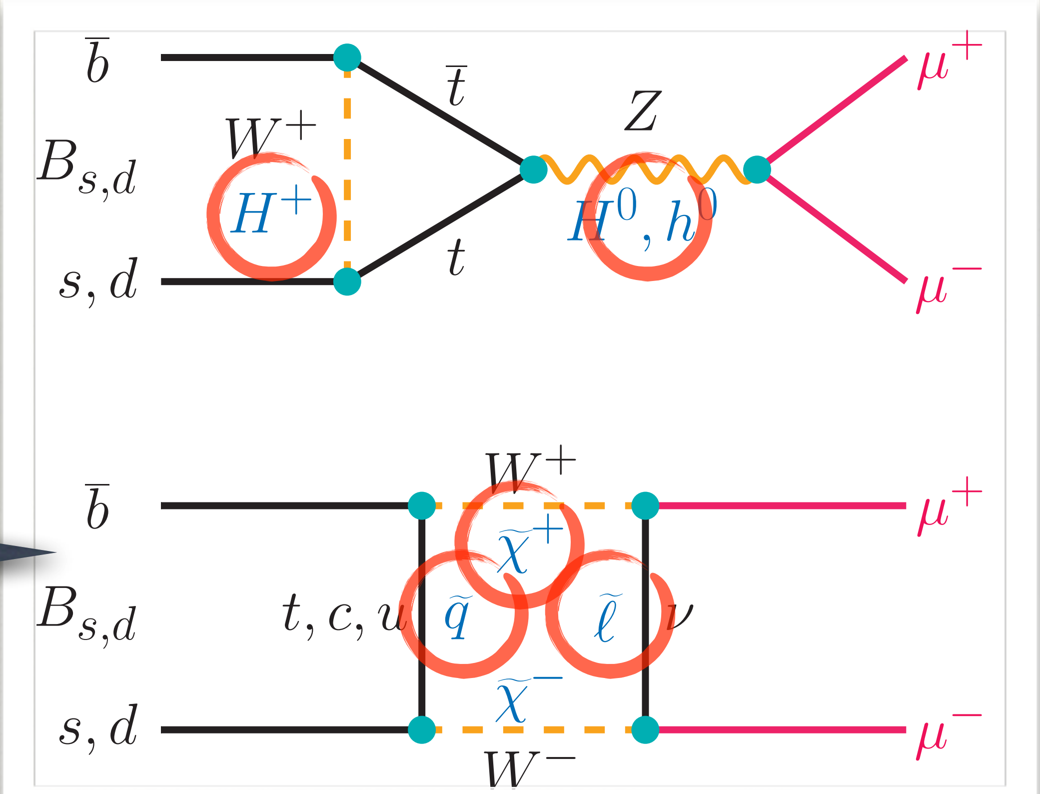
Heavy Flavour Physics at HL-LHC, Aug 31st, 2016

CMS: OVERVIEW OF HF ACTIVITIES AND UPGRADE PLANS

Kai-Feng Chen
National Taiwan University

CMS Objective in Flavour Physics

- **Understand the underlying QCD processes**
  - Measure the spectrum of standard quarkonia production, polarization, and heavy flavor productions.
  - Look for new exotic quarkonia states and new heavy baryons.
- **Test the Standard Model with high precision measurements**
  - Measurement of decay rates, lifetime, and CP phases of B hadrons.
- **Look for new physics in the loop**
  - Rare decays: $B_{s,d} \to \mu\mu$, $B \to K^{*}\mu\mu$, etc.



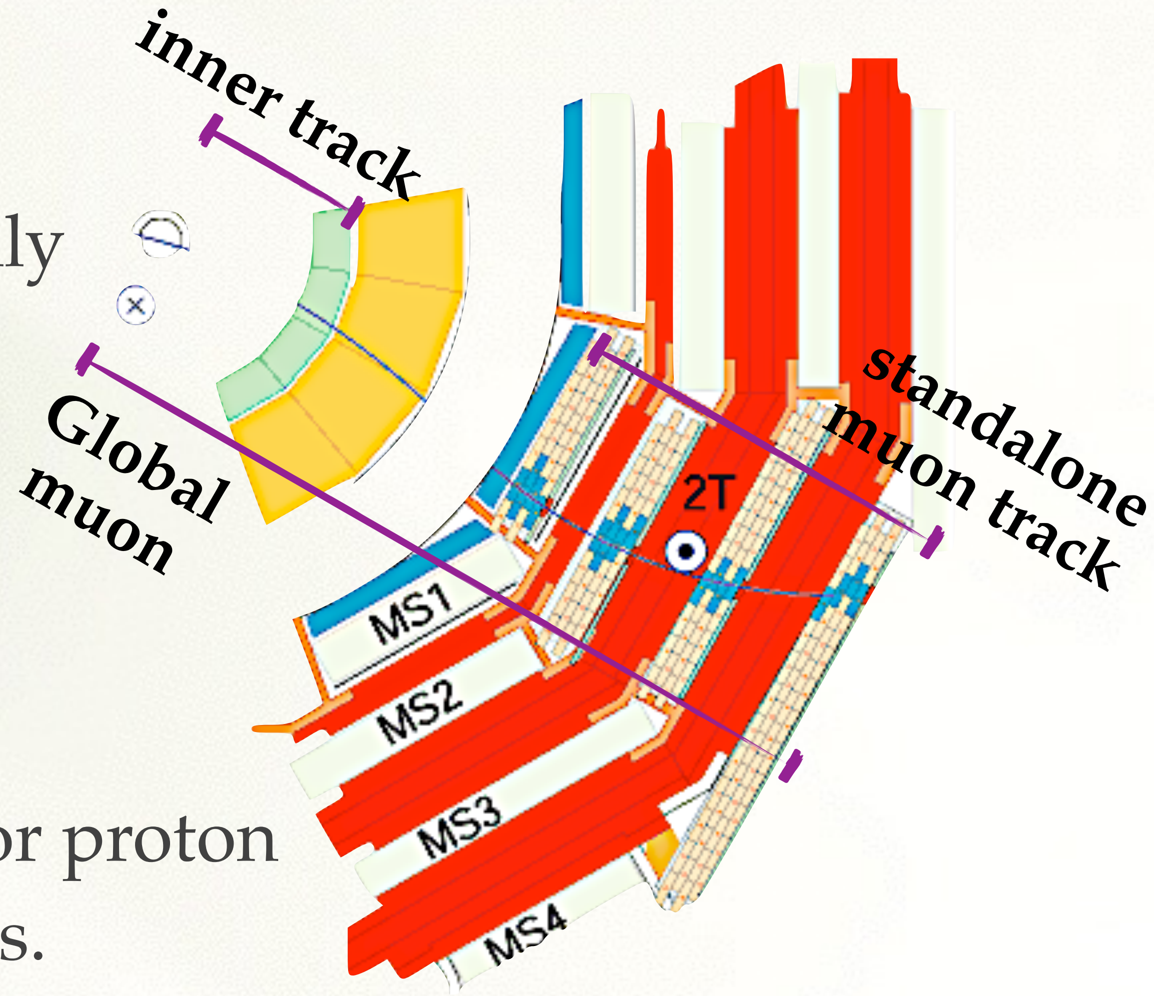
If these particles cannot be observed in the direct searches, this is the place one shall still look for!

CMS TRACKER SYSTEM

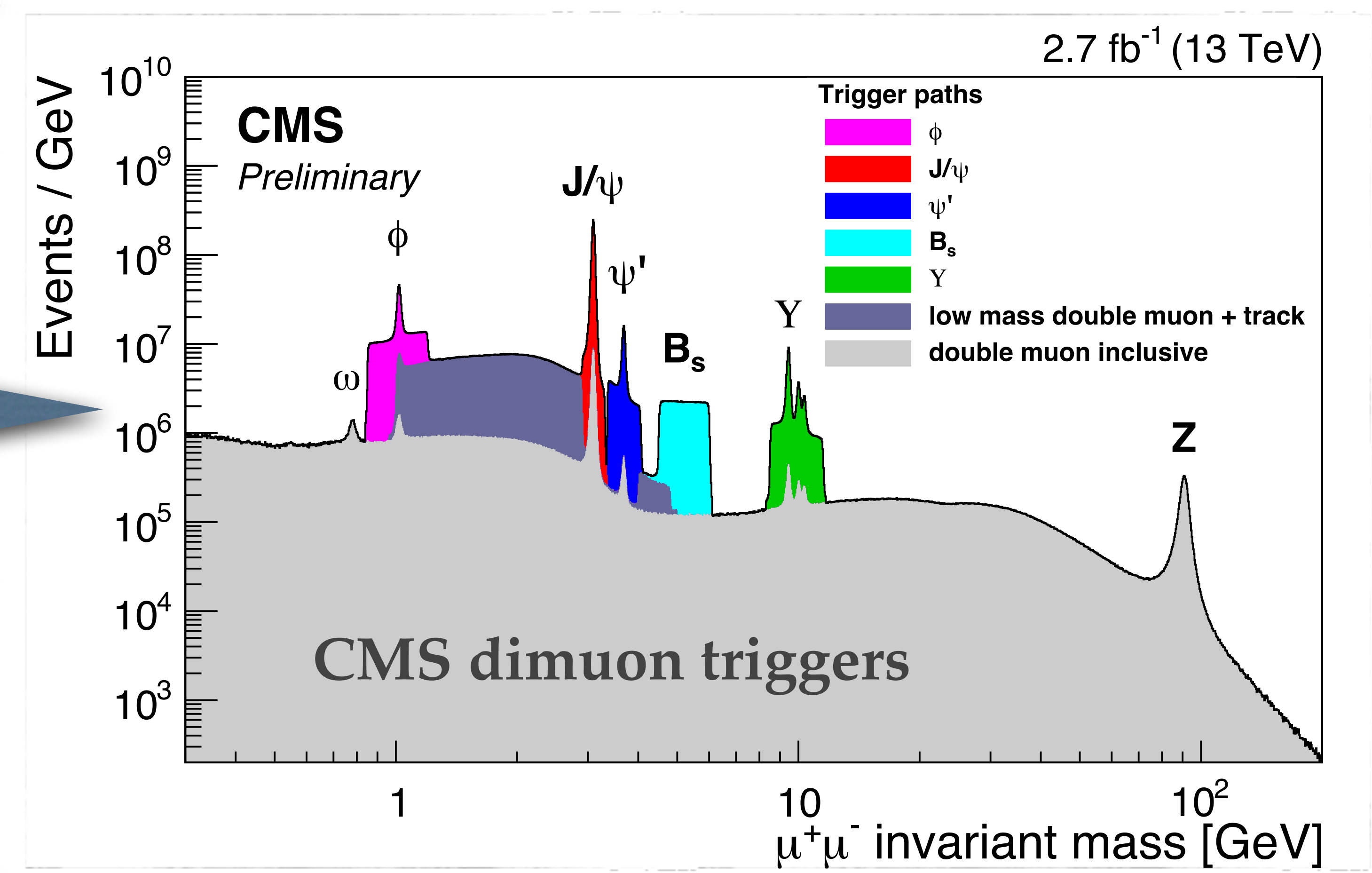
- **A full-silicon tracker is equipped:**
  - 3 barrel layers of 100x150 μm pixels (66M in total).
  - 10 barrel layers of 180 μm strips (9.6M in total).
  - Excellent track momentum resolution at low p_{T}.
  - Excellent vertex reconstruction and impact parameter resolution.

Muon Reconstruction

- **CMS muon system:**
  - 3 different devices installed, with a large coverage up to $|\eta|<2.4$.
  - Good dimuon mass resolution *~0.6-1.5% (depending on $|y|$).*
- **Reconstruction algorithms:**
  - **standalone muon:** reconstructed in muon system only
  - **global muon:** standalone muon ⇒ inner track
  - **tracker muon:** inner track ⇒ muon system
- **Excellent muon identification**
  - Fake rate ≤0.1% for π,K; ≤0.05%for proton
  - MVA-based ID for B→μμ analysis.



Triggers



The flavor physics analyses rely on displaced/non-displaced quarkonium (J/ψ, ψ′ & Υ), $B_{(s)}$, and non-resonant dimuon triggers.

- **CMS trigger system:**
  - Fast hardware trigger (L1)
  - Software trigger with full tracking & vertex reconstruction (HLT).
  - Specific triggers were developed for various analyses.
  - Trigger requirements tightened with the increased luminosity.
  - ~10% of CMS bandwidth is given to flavor physics.

FLAVOUR PHYSICS @ FUTURE CMS

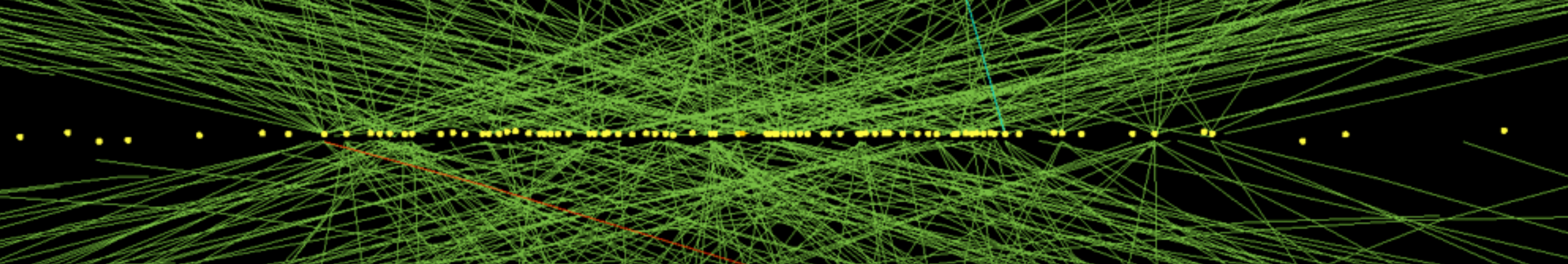
High luminosity × Large production cross section =
ONE OF THE BIGGEST B HADRON DATA SETS ON EARTH

- A unique test bench for flavour physics predictions.
- Measurements which require huge statistics will have a significant boost, such as CP phase in $B_s \to J/\psi\phi$, $B_s \to \phi\phi$, angular in $B \to K^*\mu\mu$.
- Will allow to study (ultra) rare processes at a sensitivity level never attained, such as $B \to \mu\mu$, or lepton-flavor violating decays such as $B \to \mu\tau$, $\tau \to \mu\mu\mu$.
- Utilizing additional tagging from top-pair or W events, new possibilities for precision measurements with b,c quarks or τ lepton are open. *(e.g. PRL 110, 232002)*

$B_{s,d} \to \mu^+\mu^-$ / $\tau \to \mu\mu\mu$ / $B_s \to \phi\phi$
as the benchmark analyses today!

THE CHALLENGE TOWARD HL-LHC

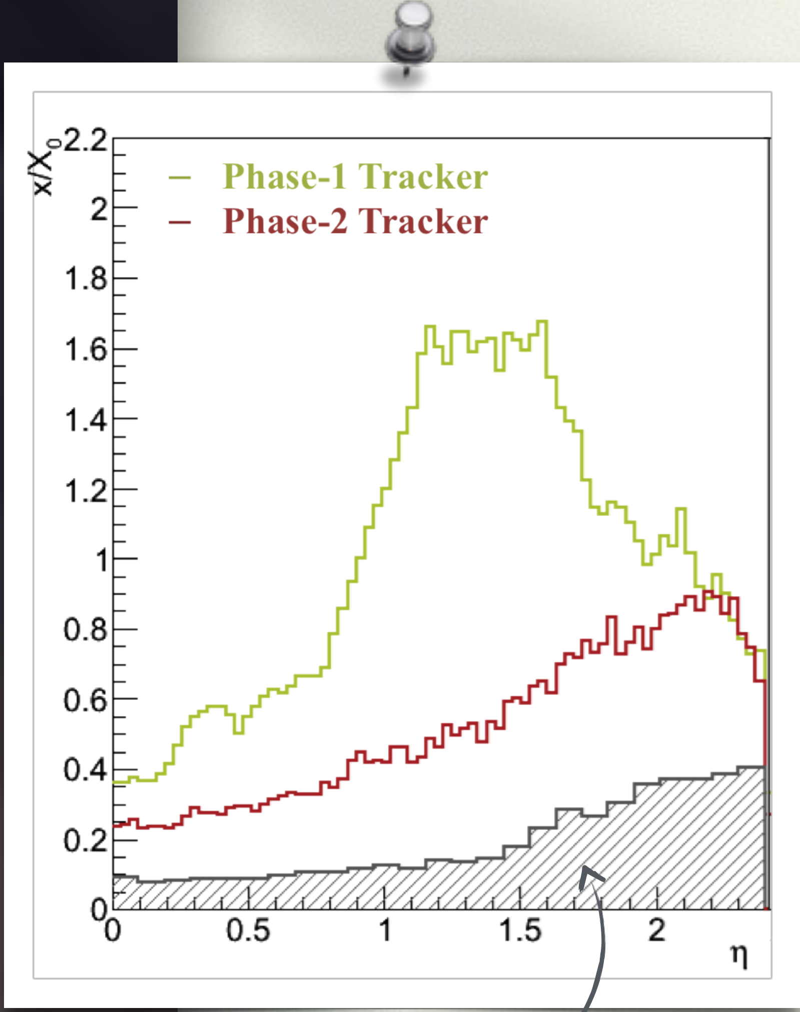
An event with **78** reconstructed vertices — expected to exceed doubled pile-up events at the running condition of HL-LHC.



- Capability of operating at a very high pile-up of 140 interactions.
- The detector has to survive up to 3000 fb^{-1}, and to year 2035.
- Need to preserve a similar performance even at 140 PU, 3000 fb^{-1} as the current detector as in Run-I/Run-II.
- Maintain current trigger acceptance for HL- LHC conditions, and preserve lowest possible trigger and analysis thresholds.

Scope of CMS Upgrade

Material budget for
Phase-I/Phase-II tracker

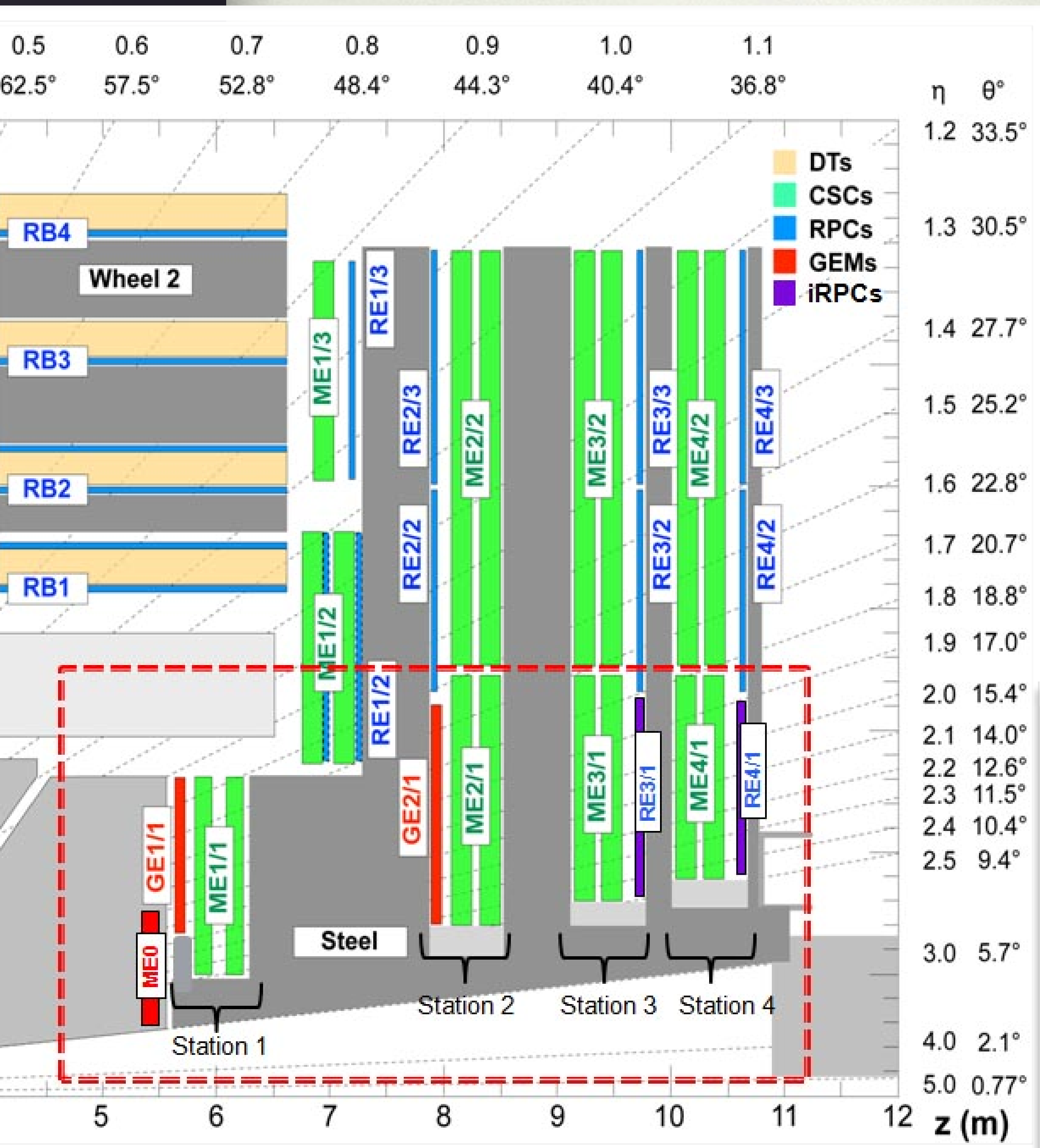


Phase-I pixel

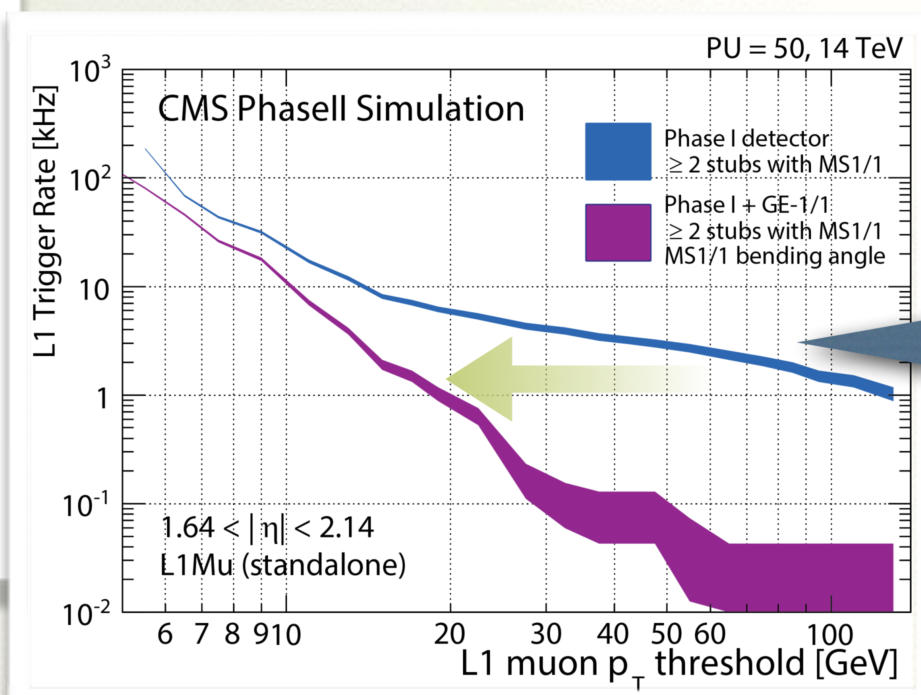
- **New tracker system:**
  - Feature 4 pixel barrel layers and 5 disks on the endcaps with half of the material budget in the central region.
  - Combined with a smaller silicon sensors pitch, the momentum resolution will be improved, and help to **separate B^0 and B_s signals**.
- **Enhanced L1 trigger:**
  - Hardware track trigger at level-1 and maintaining low thresholds at HL-LHC luminosities.
  - Higher L1 trigger and software high-level trigger (HLT) accept rates [5-10 times to the phase-I].
  - Extended trigger capabilities for the muon system with improved coverage in the forward direction.

Scope of CMS Upgrade (cont.)

- **Forward muon system**
  - Improved Resistive Plate Chambers with 2 stations (RE3/1 and RE4/1) in each.
  - Gas Electron Multipliers with 2 stations (GE1/1 and GE2/1) in each endcap; very forward ME-0 detector to provide coverage up to η = 3 or more.



Phase-II muon



Can go to lower p_T with the same rate with GE1/1.

Physics Target: B→μμ

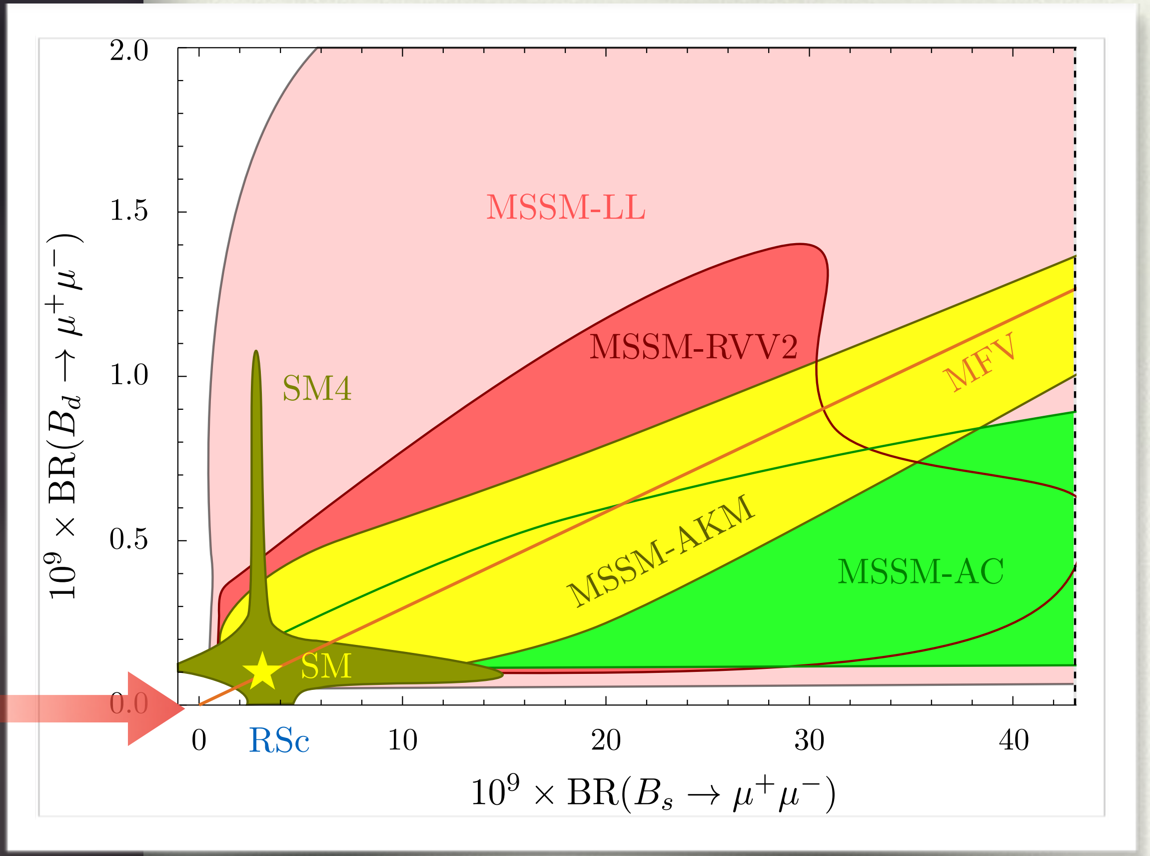
An obvious target for HL-LHC!

Ref: Bobeth et al, PRL 112, 101801 (2014)

$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Ref: D. M. Straub, arXiv: 1012.3893



- $B_{s,d} \to \mu^+\mu^-$ decays are only proceed through FCNC processes and are highly suppressed in SM:
- Loop diagram + Suppressed SM + Theoretically clean = *An excellent place to look for new physics*.
- Some of the new physics scenarios may boost the B→μμ decay rates by 10~20 times easily, for example:
  - **2HDM**: $\mathcal{B} \propto \tan^4\beta$ & $m(H^+)$
  - **MSSM**: $\mathcal{B} \propto \tan^6\beta$
- B_s/B_d ratio – a stringent test of minimal flavor violation hypothesis.

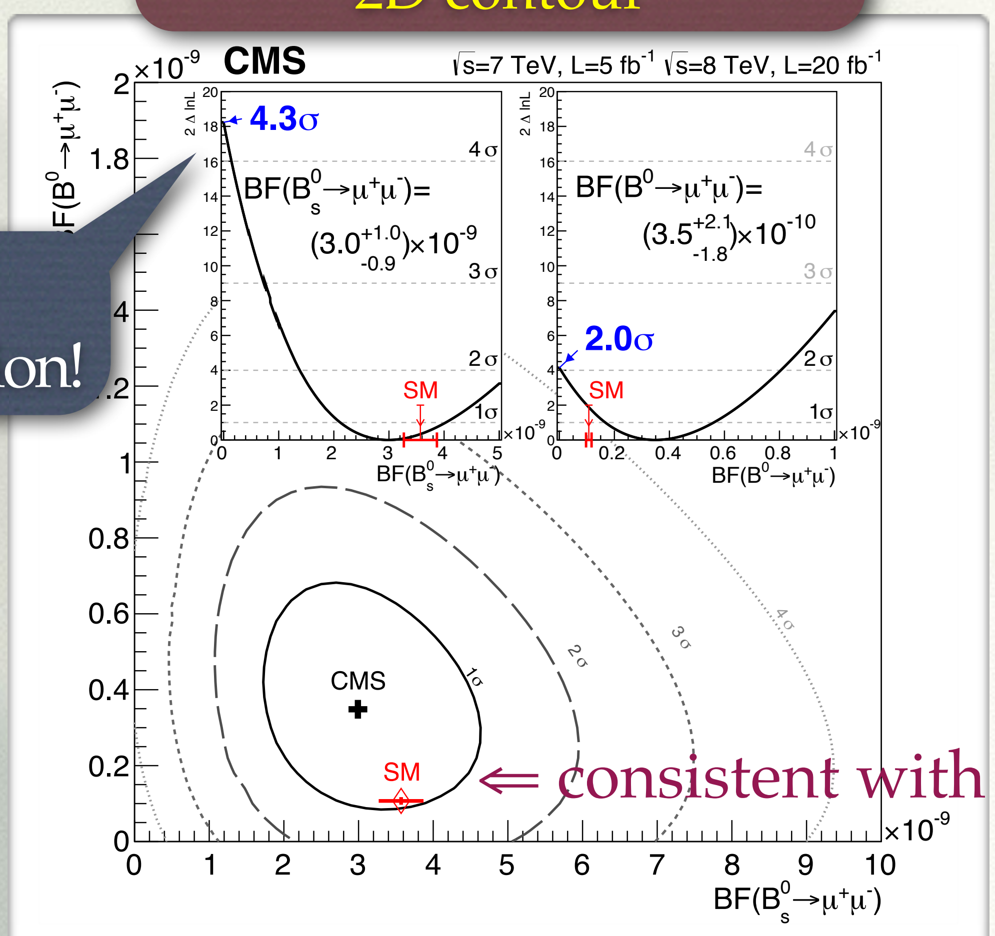
Reference Analysis

- Event classification is carried out by Boosted Decision Tree (BDT).
- Branching fractions were extracted by unbined maximum likelihood fits in 12 categorized BDT bins.

Ref. CMS PRL 111 (2013) 101804

Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(3.0^{+1.0}_{-0.9})\text{x } 10^{-9}$
$B_d \to \mu^+\mu^-$	$<1.1\text{x}10^{-9}$ @ 95% CL

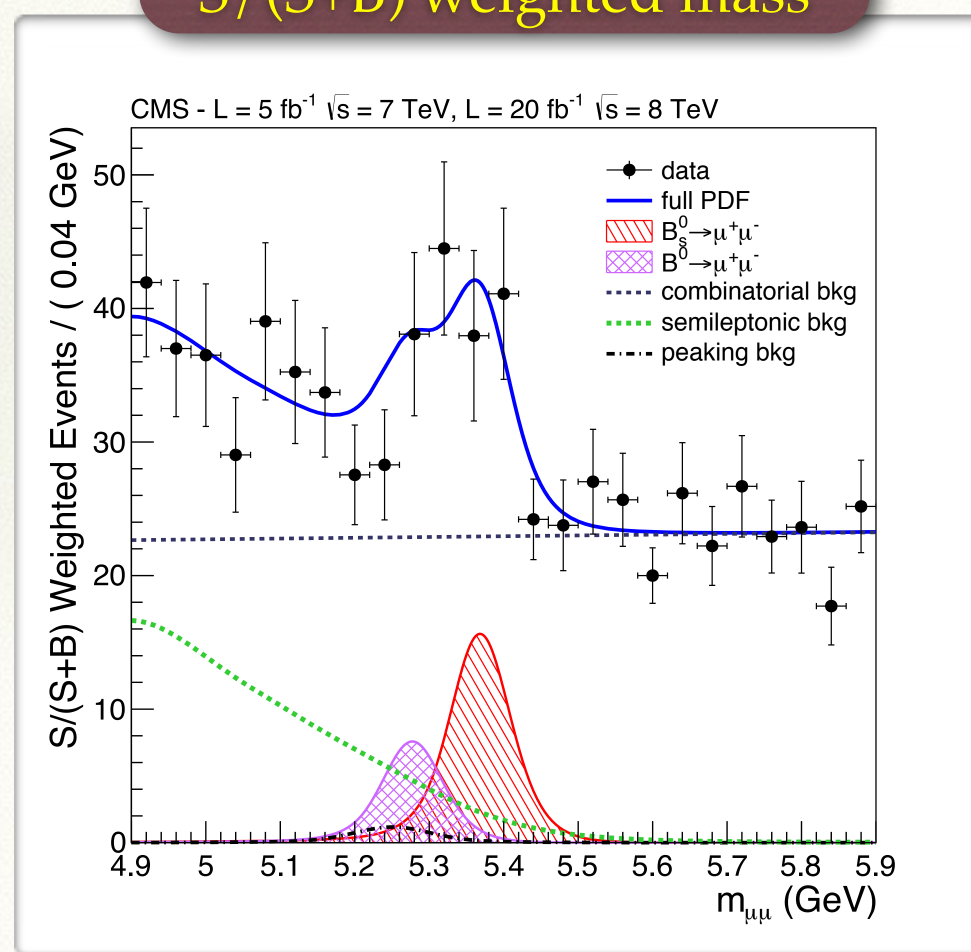
2D contour



4.3σ observation!

⇐ consistent with SM

S/(S+B) weighted mass



Reference Analysis

- Events are triggered by dimuon events at L1, and with mass/displaced vertex requirement at the HLT.
- MVA-based muon identification is introduced.
- Normalized to the reference channel $\mathbf{B^+ \rightarrow J/\psi(\rightarrow\mu^+\mu^-)\,K^+}$.
- Updates on background decay model and physics parameters presented in the **CMS+LHCb combination Nature** are incorporated.

Ref. Nature 522 (2015) 68

$$\mathcal{B}(B_{s,d}\rightarrow\mu^+\mu^-) = \frac{N_S}{N(B^\pm\rightarrow J/\psi K^\pm)} \times \mathcal{B}(B^\pm\rightarrow J/\psi K^\pm) \times \frac{A(B^\pm)}{A(B_s)}\,\frac{\varepsilon^{ana}(B^\pm)}{\varepsilon^{ana}(B_s)}\,\frac{\varepsilon^{\mu}(B^\pm)}{\varepsilon^{\mu}(B_s)}\,\frac{\varepsilon^{trig}(B^\pm)}{\varepsilon^{trig}(B_s)}\,\frac{f_u}{f_s}$$

- Acceptance
- Selection efficiency
- muon identification
- Trigger efficiency
- B-hadronization composition (B_s only)
(LHCb JHEP 04 (2013) 001: 0.256±0.020)

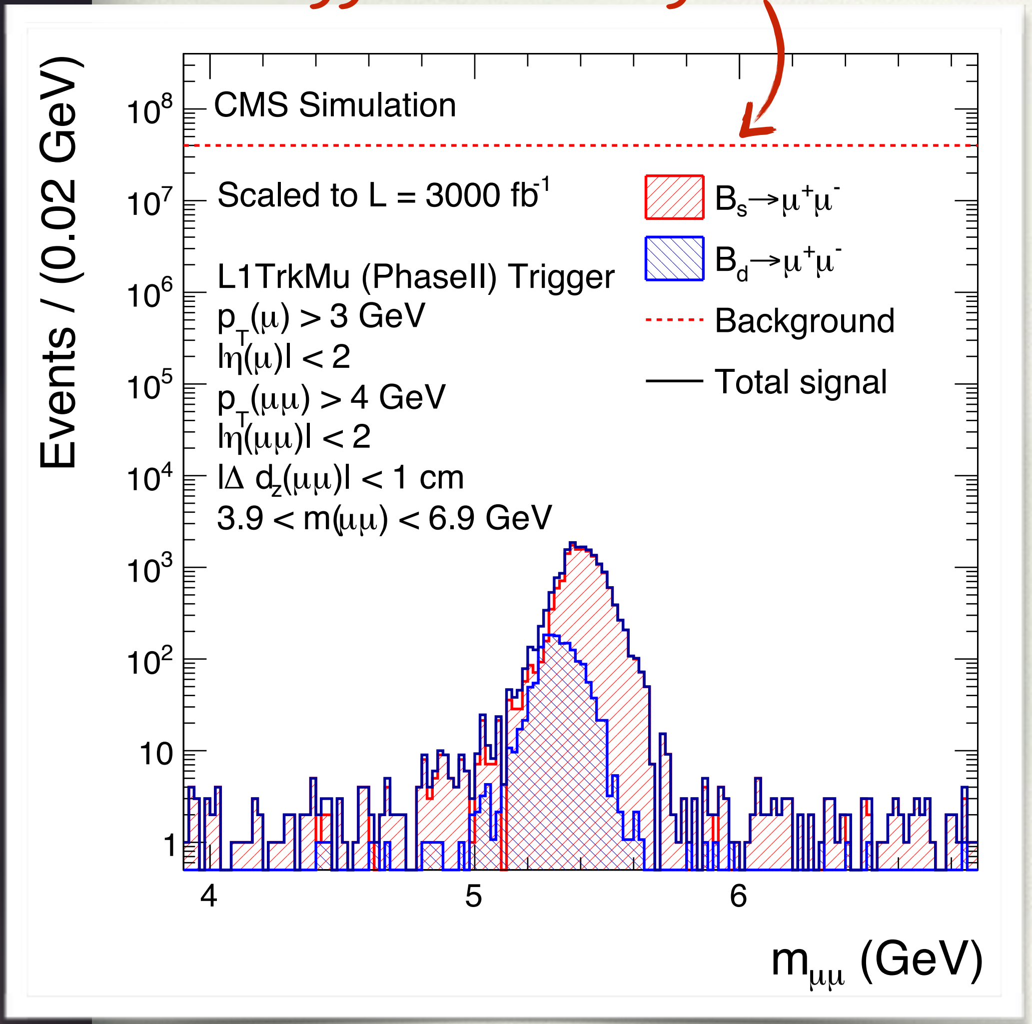
We do not introduce possible improvements on the analysis strategy itself.
An optimized analysis for $B^0\rightarrow\mu\mu$ will provide better results.

Then scale the analysis to LHC Run-2 and beyond!

Toward the Future: Analysis Assumptions

- **Pseudo experiments** are used to estimate the expected CMS performance in two different scenarios:
  - **The Phase-1 scenario**: corresponding to the expected performance of the CMS detector including LHC Run-II and Run-III, to an integrated luminosity of **300 fb^{-1}** at 14 TeV.
  - **The Phase-2 upgrade scenario**: corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to a luminosity of **3000 fb^{-1}** at 14 TeV.
- GEANT4-based simulated samples are used to estimated the performance of trigger, resolution, and pile-up effect at the phase-2 running condition.
- Muon efficiency and identification are assumed to be the same as Run-I.
- Standard Model branching fractions are assumed in the study.

Toward the Future: L1 Trigger at Phase-2

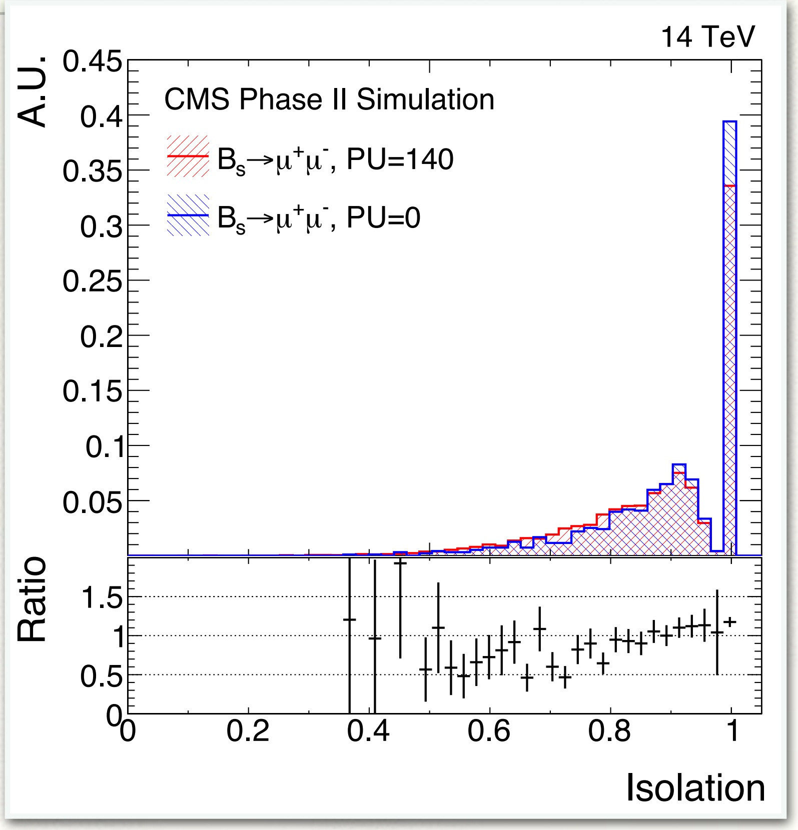


- Low-p_T di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker is studied with full simulation with the Phase-2 scenario.
- Invariant mass resolution for B→μμ at L1 is estimated to be **~70 MeV**.
- The rate of the L1 trigger is estimated from the minimum-bias simulation sample, and is equal to **a few hundred Hz**. This corresponds to a small fraction of the total available L1 bandwidth (~1 MHz).

Low-pT track-trigger-based algorithm as in Run-I is expected to be entirely feasible for Phase-2.

Toward the Future: Performance Inputs

- The offline invariant mass resolution is estimated from B→μμ simulated samples implementing the full detector simulation of the Phase-I and Phase-II scenarios.
- The effects of the high pile-up have studied based on simulated samples as well.

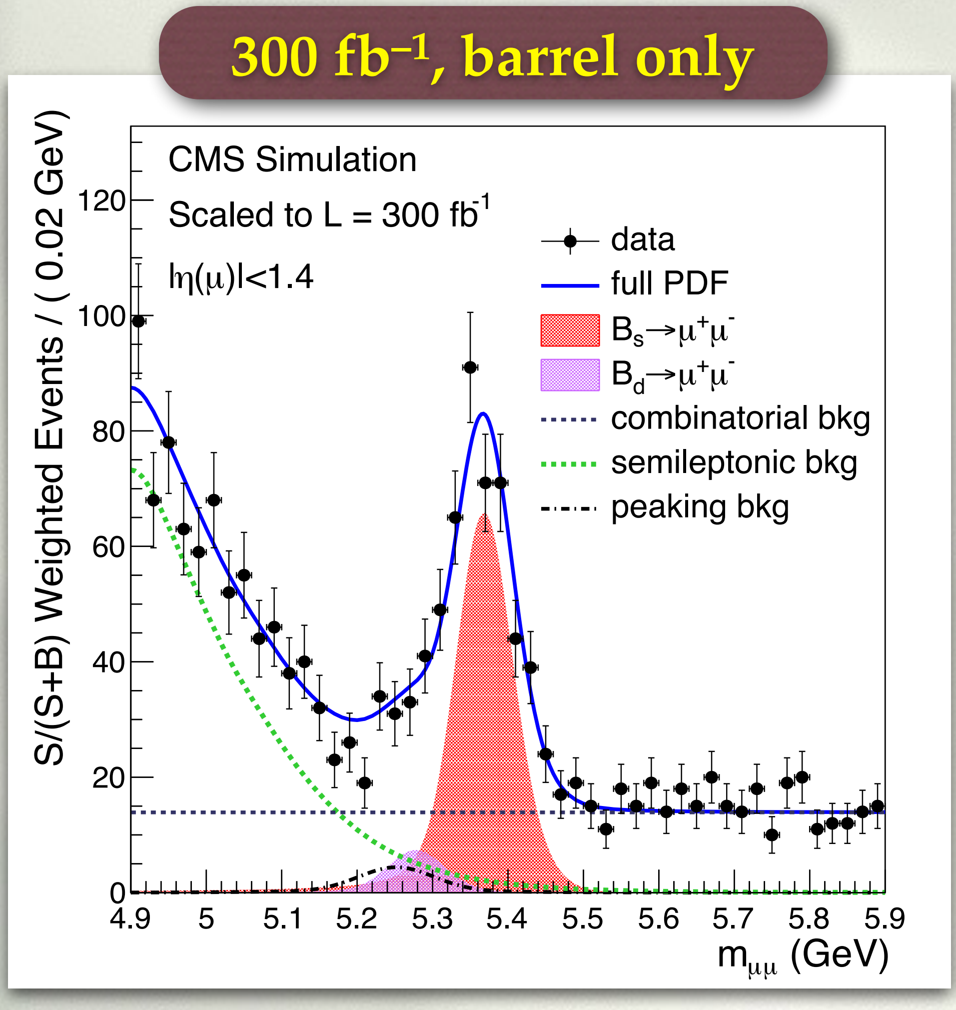


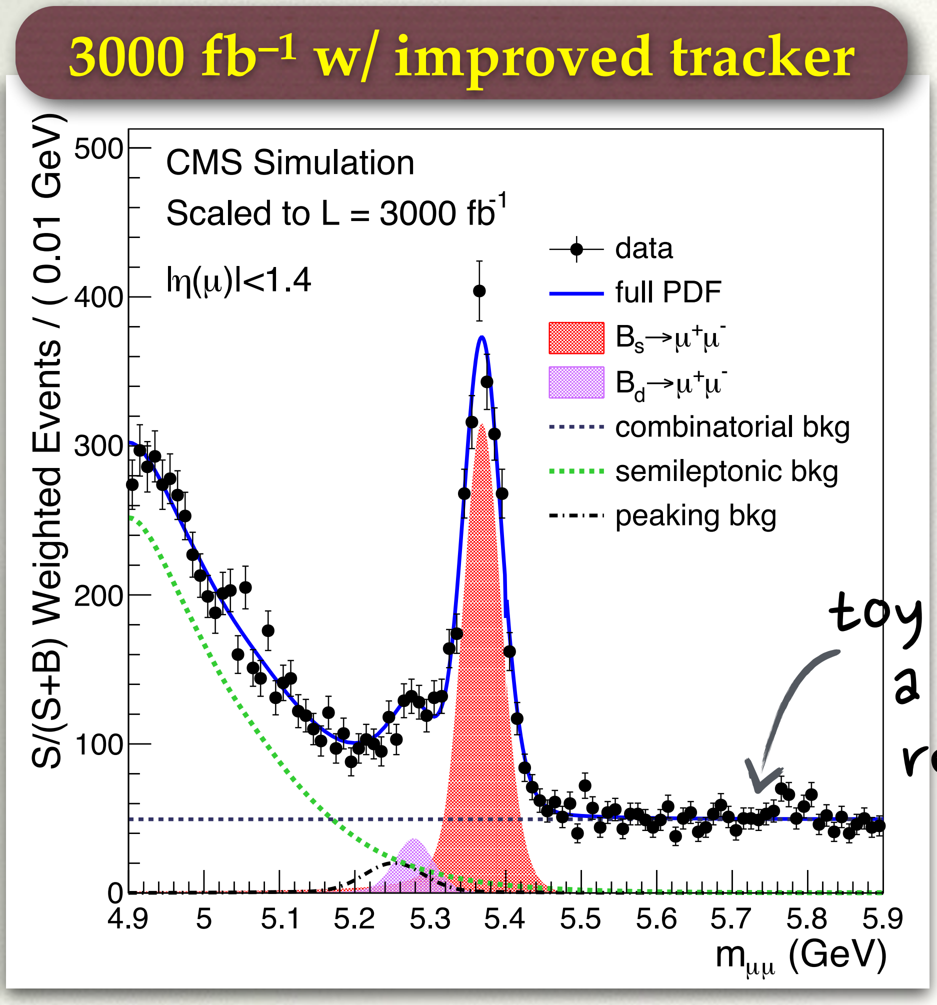
*A comparison of isolation variable in **PU=0** and **PU=140** environment.*

Inputs	Phase-1	Phase-2
Offline barrel mass resolution	42 MeV	28 MeV
Trigger & muon ID	as Run-I	as Run-I
Efficiency drop due to PU (sig./bkg.)	as Run-I	–35% / –30%
Uncertainty: B+ normalization	5%	3%
Uncertainty: peaking background	20%	10%
Uncertainty: semi-leptonic B decays	25%	20%
Uncertainty: fs / fu	5%	5%

Inject into pseudo experiments for the sensitivity estimations.

Toward the Future: Results



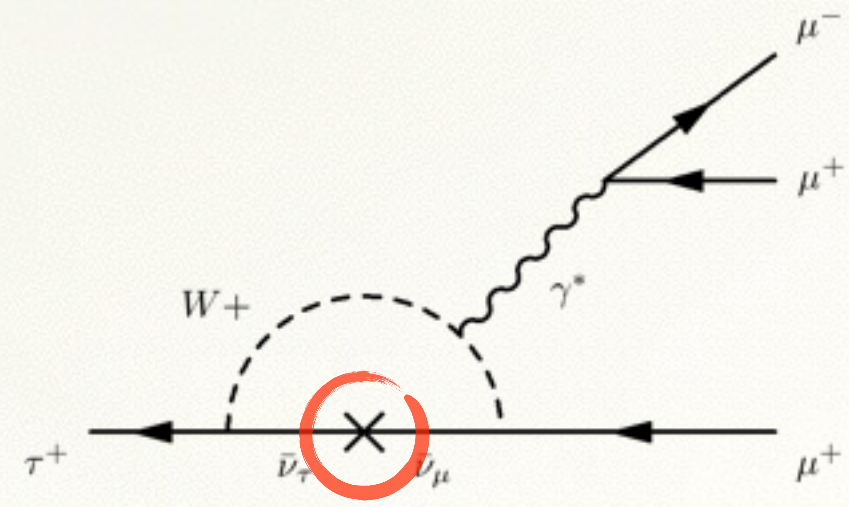


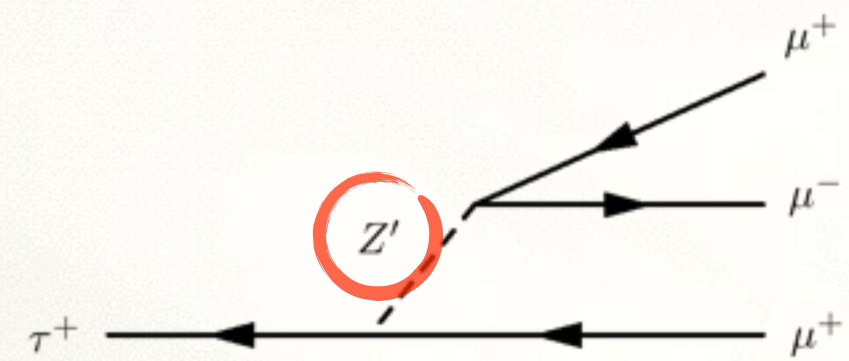
L (fb^{-1})	$\delta\mathcal{B}(B_s \to \mu^+\mu^-)$	$\delta\mathcal{B}(B_d \to \mu^+\mu^-)$	B_d sign.	$\delta[\mathcal{B}(B_d)/\mathcal{B}(B_s)]$
100	14%	63%	0.6–2.5σ	66%
300	12%	41%	1.5–3.5σ	43%
300 (barrel)	13%	48%	1.2–3.3σ	50%
3000 (barrel)	11%	18%	5.6–8.0σ	21%

Ref. CMS PAS FTR-14-015

Search for LFV τ→3μ

- τ→3μ: a **lepton flavour violation** process. Not found in the charged leptons yet, only in the neutrino sector.
- In SM it only proceeds with penguin loop and neutrino oscillation. The branching fraction is beyond the experimental reach $\mathcal{B} < 10^{-40}$ (**ref. EUJC 57, 13, 2008**).
- However with SM extensions, the decay can be enhanced by many orders of magnitudes and can be probed by the collider experiments. e.g. $\mathcal{B} \sim 10^{-8}$ (**ref. JHEP 05, 013, 2007**).
- Best limits so far: Belle ($\mathcal{B}<2.1 \times 10^{-8}$), LHCb($\mathcal{B}<4.6 \times 10^{-8}$)

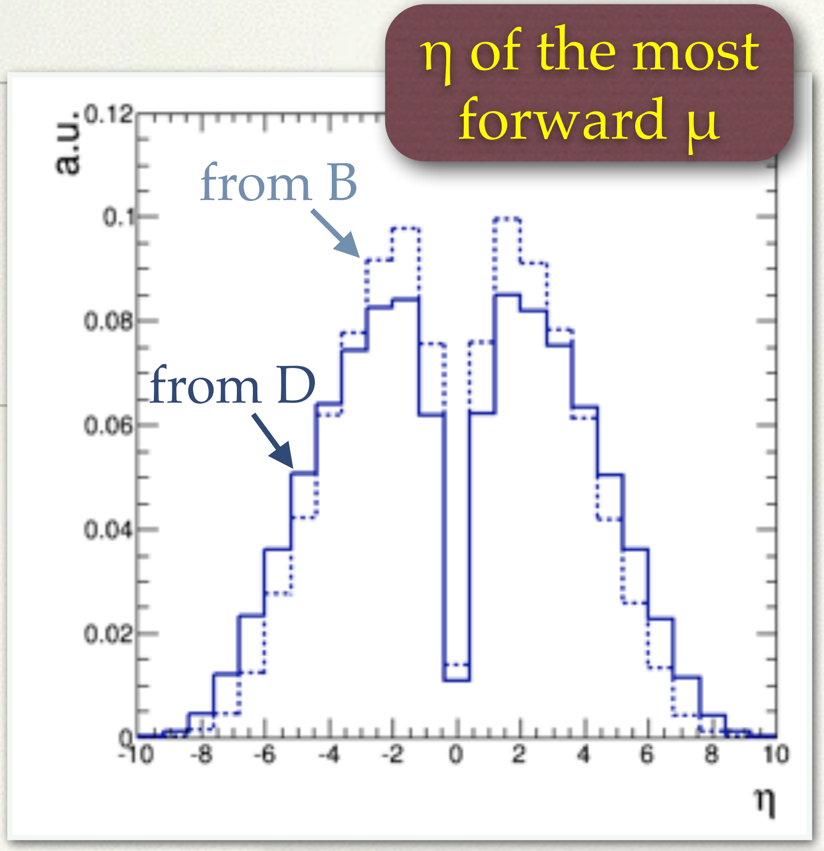


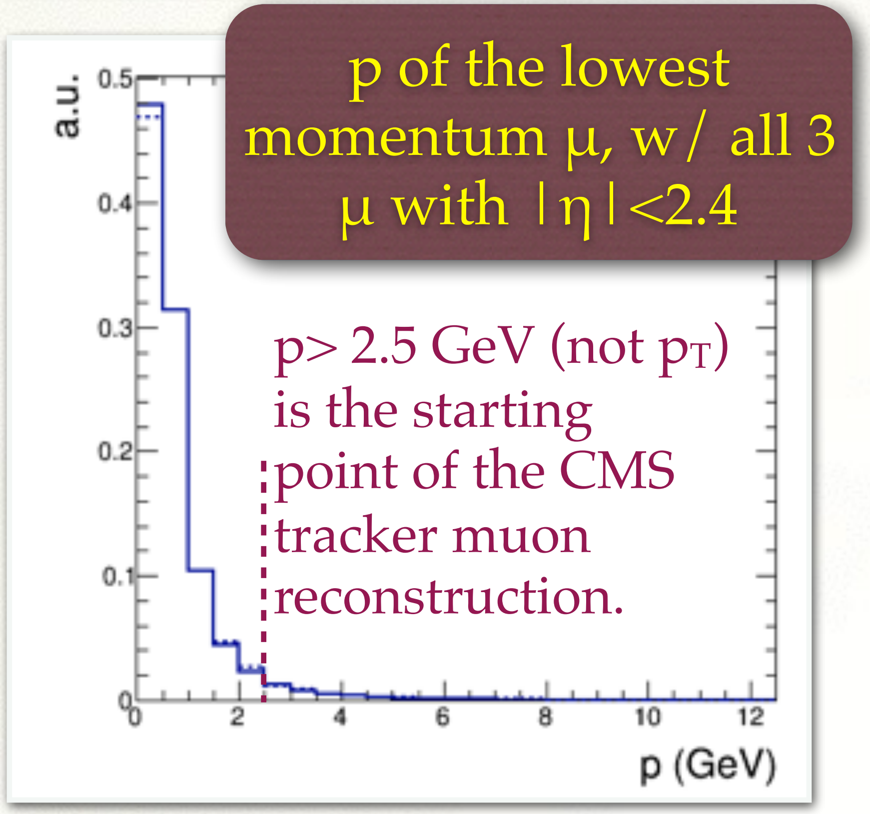


A good place to look for new physics!

Signal Acceptance

- Based on Pythia, the τ production can be as large as **1.8 × 10^{13} with 100 fb^{-1} in Run-II**. However…
  - **75% comes from D hadrons** (mostly Ds), **25% from B hadrons** (including B→D+X→τ..)
    - Very low momentum muons and hence very small acceptance
    - Large QCD background: one or two genuine muons from b/c decay, randomly combined with fakes.
  - **0.02% comes from W and Z decay**
    - Less challenging but insufficient number; but might be helpful in the future.





All tau→3μ = 100%

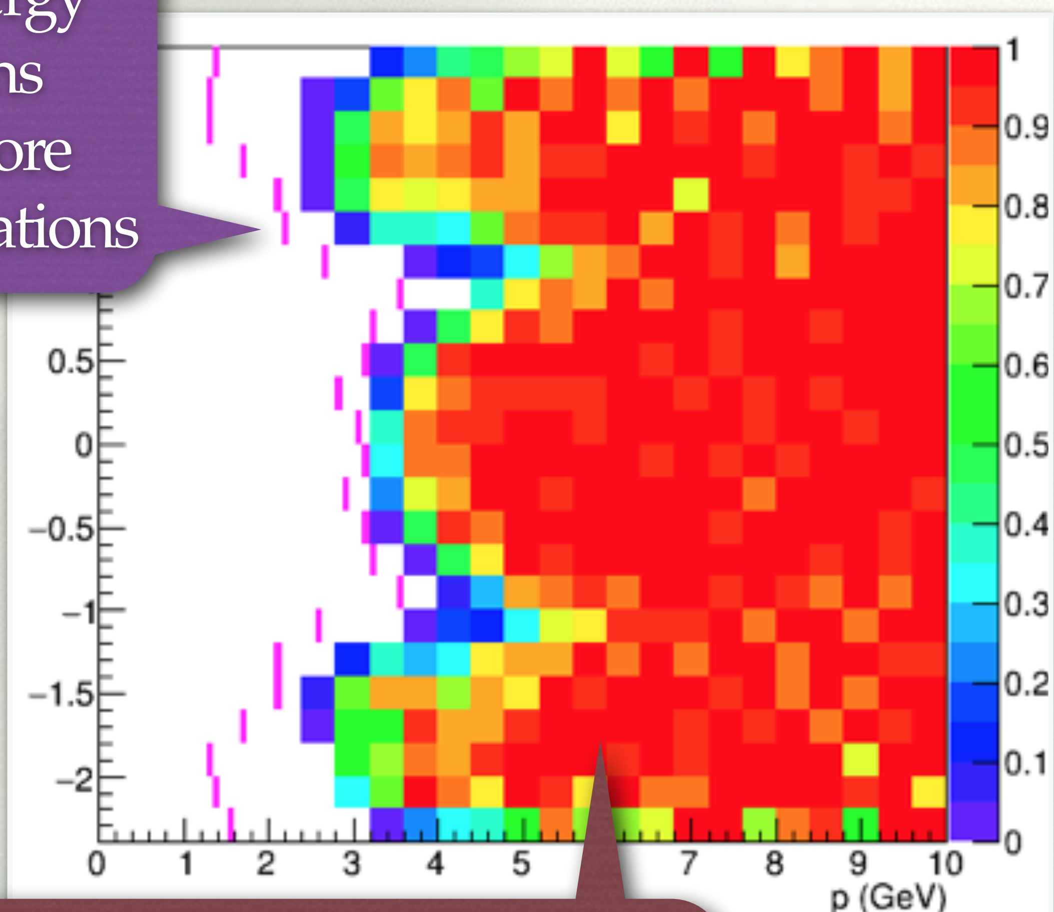
All 3μ with |η|<2.4 ~ 40%

All 3μ with p>2.5 ~ 2%

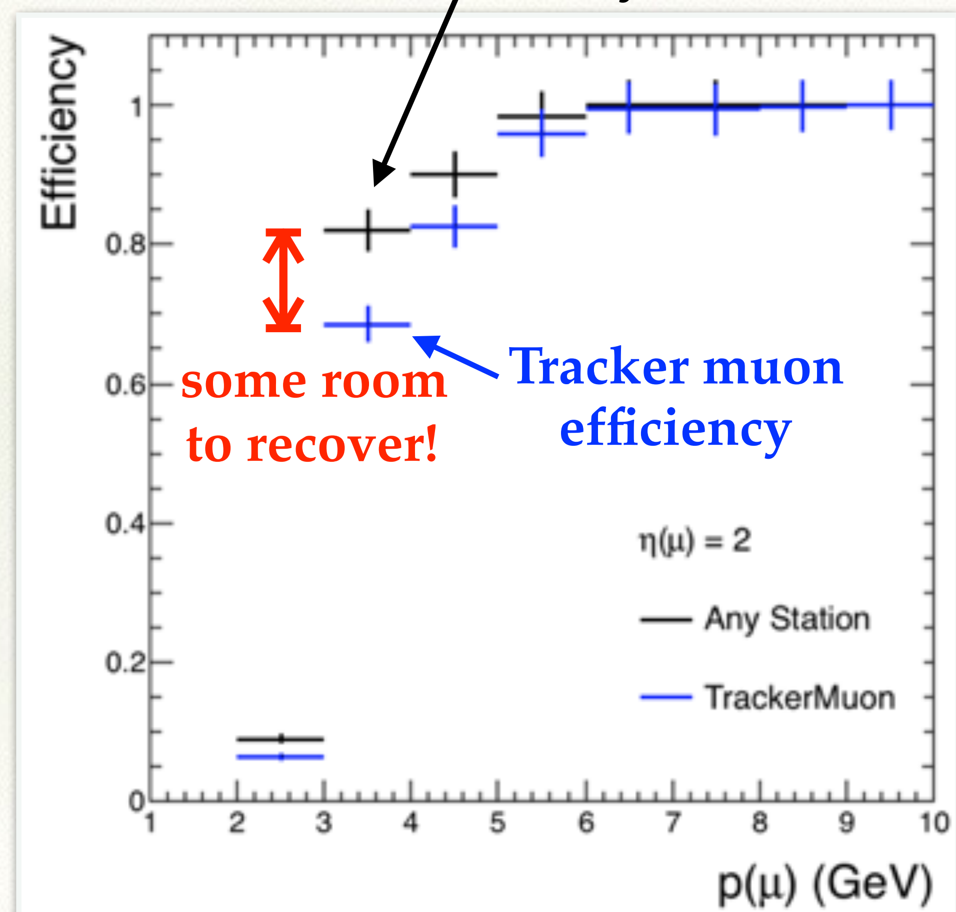
Low Momentum Muon Reconstruction

- Efficiency for all 3μ can be reconstructed offline: **~0.6%**
  - effect of energy loss before reaching muon stations
  - multiple scattering of muons out of the detector acceptance

The average energy losses of muons (p = 5 GeV) before reaching muon stations



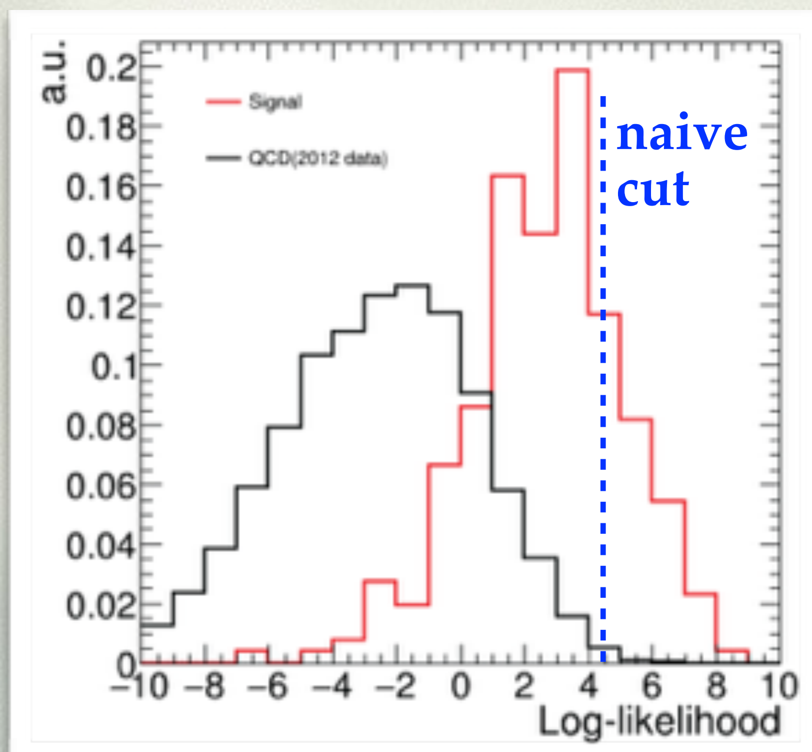
Tracker muon reconstruction efficiency map



Background Level Study

- Estimated with 2012 data, with some simple selections:
  - 3 tracker muons reconstructed with basic standard quality cuts
  - Sum of charges to be ±1
  - MVA analysis with several kinematic variables and muon qualities.
- Extrapolate to **100 fb^{-1} at 13 TeV**
  - **12 signal events if $\mathcal{B} = 1 \times 10^{-8}$.**
  - **210 background events** (estimated from sideband).
  - Expected upper limit ~ **3×10^{-8}**.

Not for distribution
CMS INTERNAL
work in progress



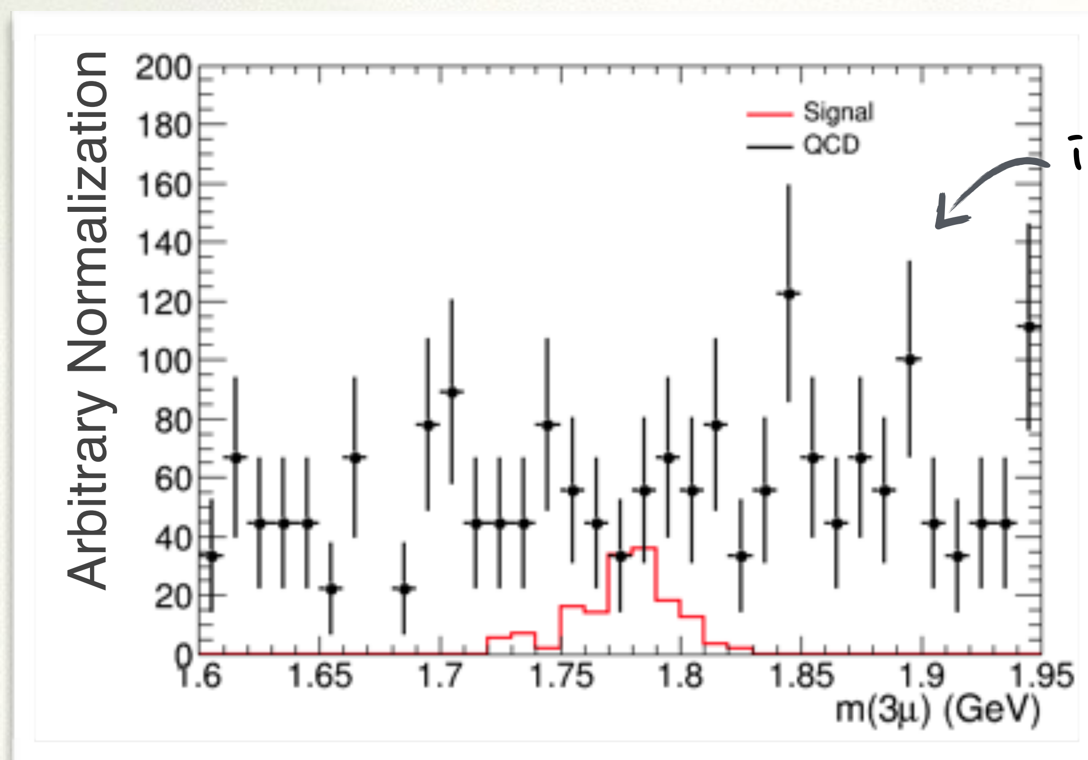
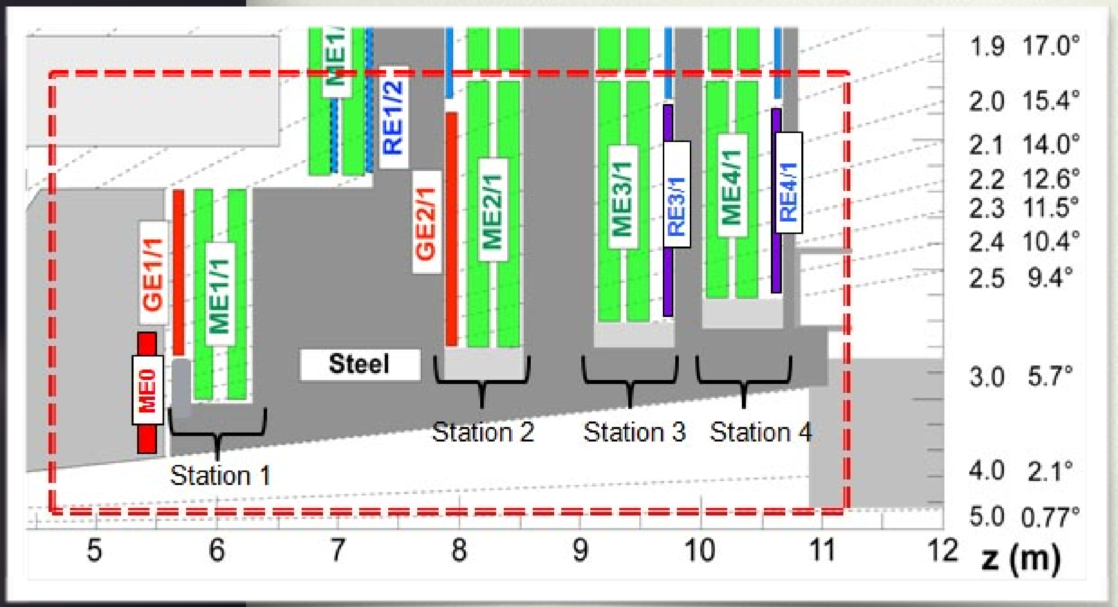
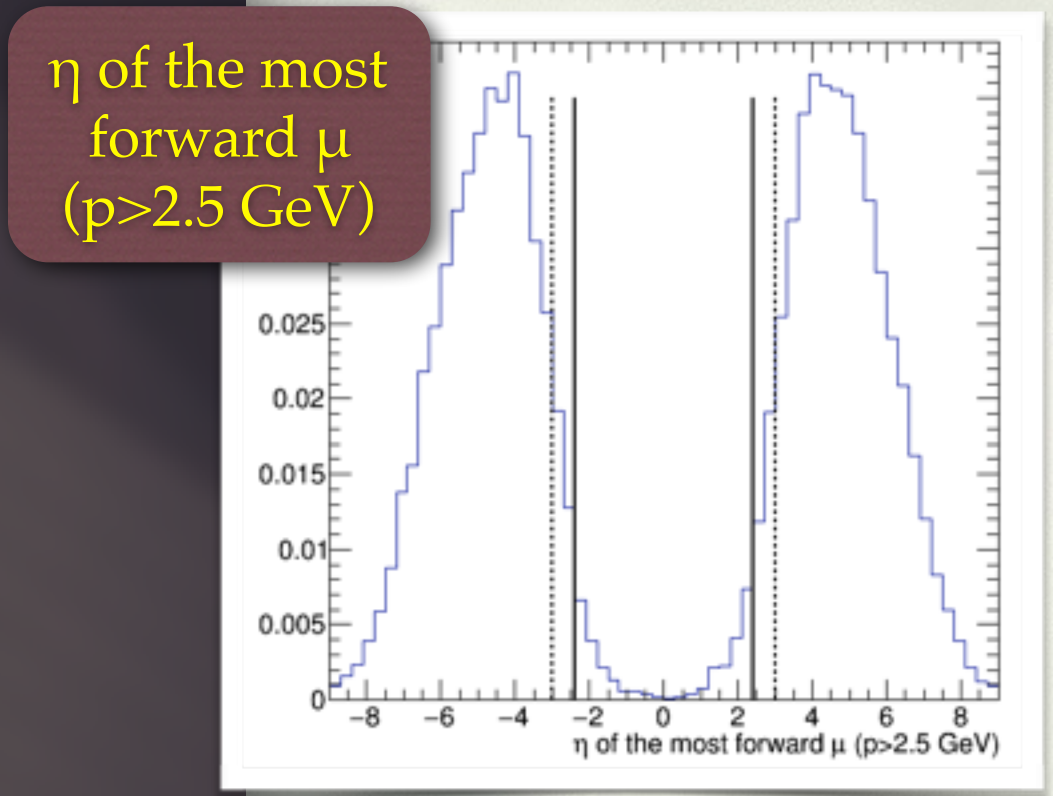


illustration only

Potential Improvements from Phase-II Detector

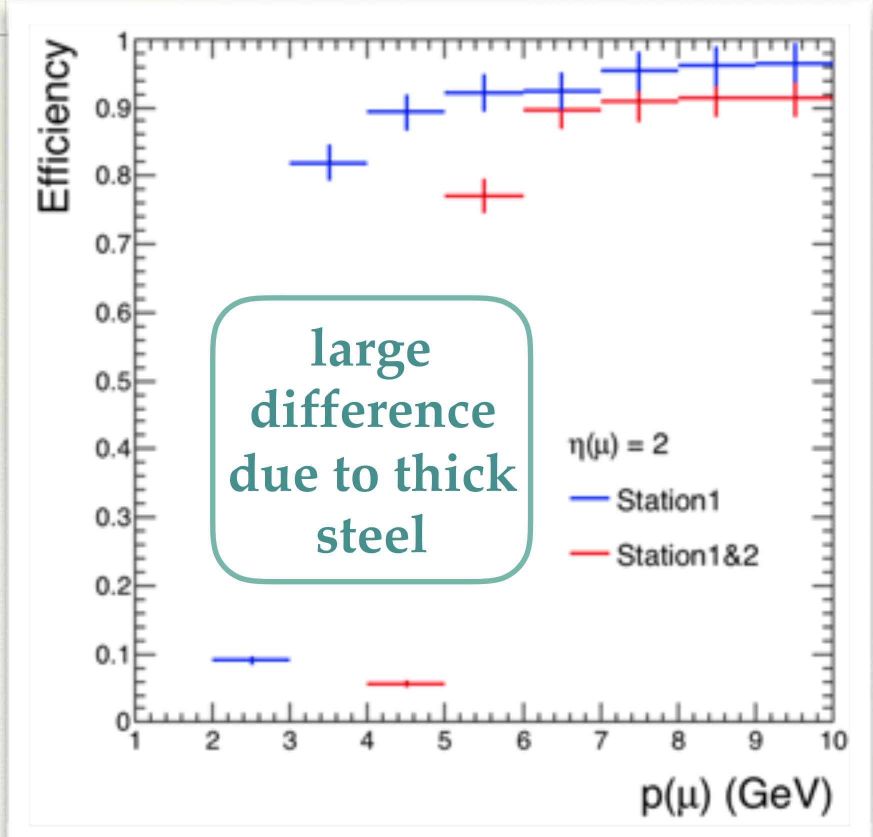


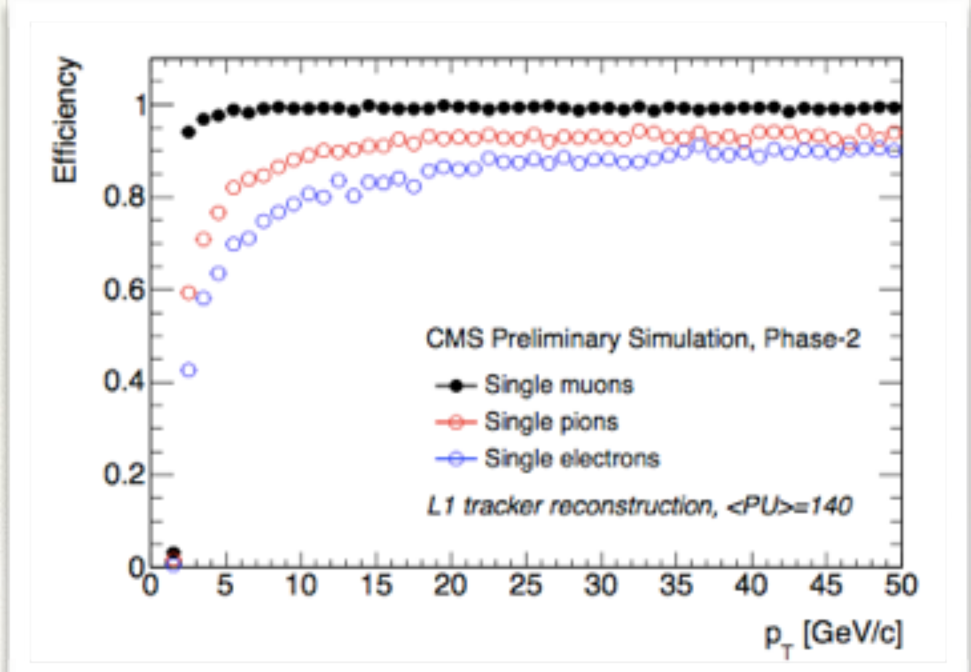


- **Signal acceptance extension by ME0**
  - If the muon detection is extended to η~3.0, the signal acceptance will gain by **a factor of 2.9**.
- **Low momentum muon reconstruction**
  - The offline tracker muon reconstruction is already efficient when muon p ≳ 3 GeV.
  - GEM detectors might help to get back lower momentum muons.

Potential Improvements from Phase-II Detector

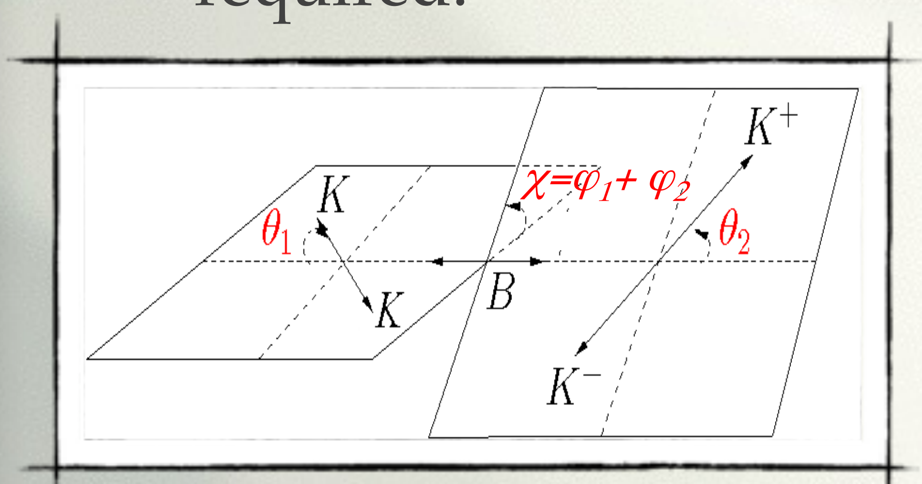
- **GEM help in endcap muon trigger**
  - GE1/1 at the high η region, where τ→3μ signal mostly sits, may recover dramatically the L1 trigger efficiency for low momentum muons.
- **Track trigger**
  - Tracking at L1 pushes down momentum of μ@L1, and improves momentum resolution significantly.
  - Studies are required to find out how much it could help τ→3μ search.

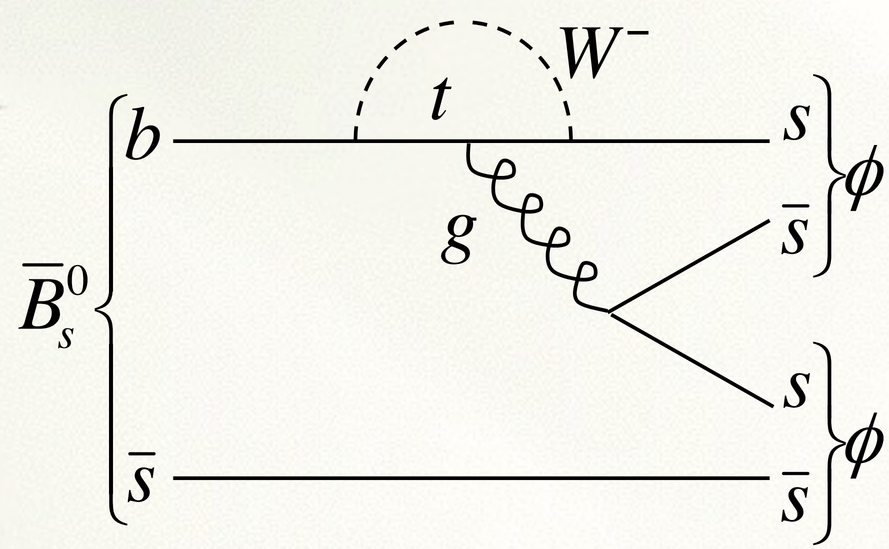




$B_s \to \phi\phi$ at Phase-II

- **The $Bs \to \phi\phi \to 4K$ decay:**
  - Processed by $b \to sss$ penguin transitions with a small decay branching fraction of ~$1.91 \pm 0.31 \times 10^{-5}$, **sensitive to the physics beyond the SM**.
  - Can be used to measure CP-violating phase though B_s mixing.
  - Decaying to two vector mesons: admixture of CP-even and CP-odd states, a time-dependent angular analysis is required.
  - Large statistics is required to perform the full analysis; **a typical target at HL-LHC!**
- **The final state kaons are rather soft:**
  - Limited acceptance and efficiency. Improved phase-II tracking is required!

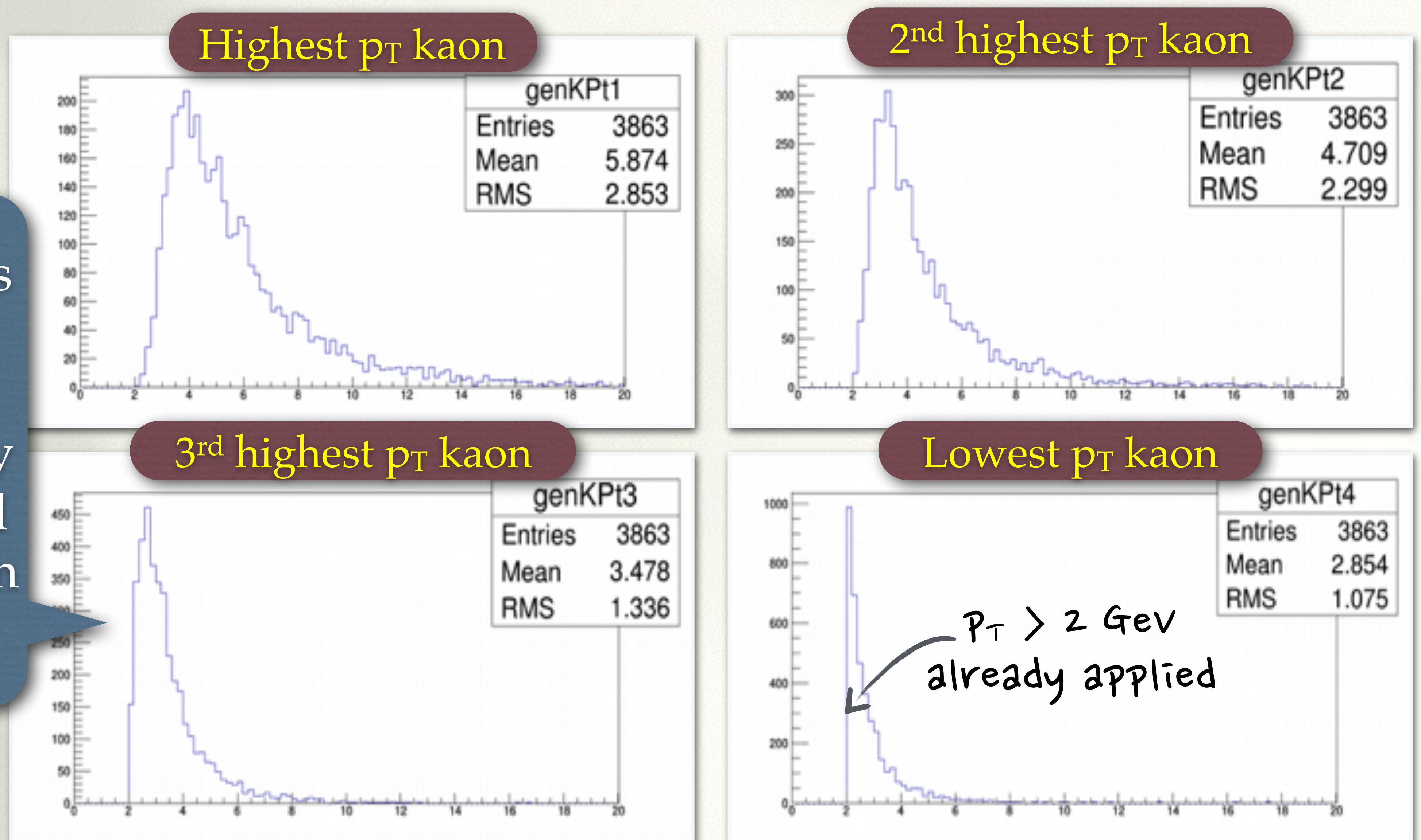




A tracking-only analysis: benchmark for L1 tracks

Performance Check w/ MC

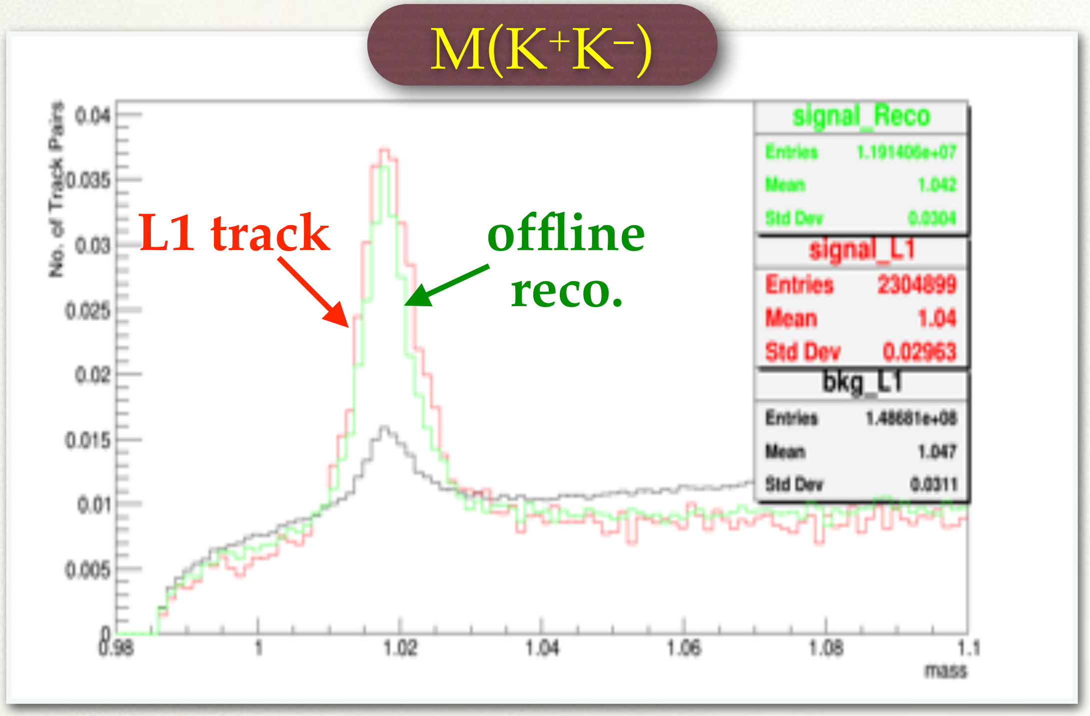
- MC samples produced with CMS phase-II TP setup. Start with daughter kaons of p_T>2 GeV.
- **Kaon distributions at the generator**:

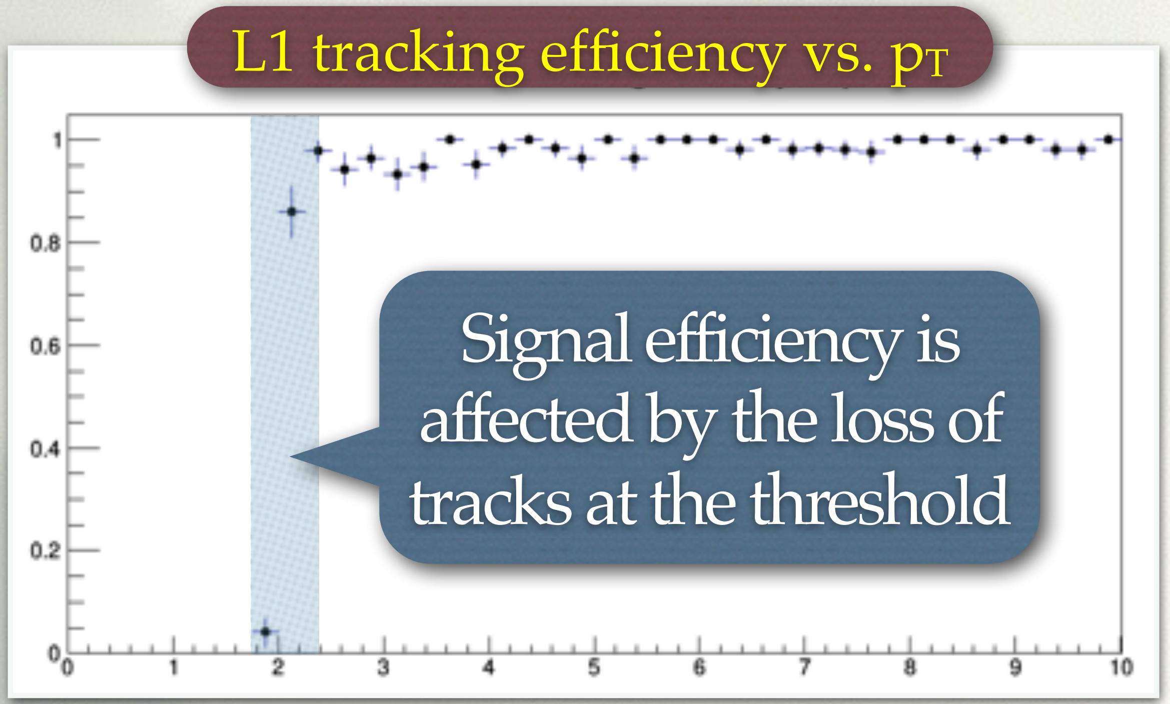


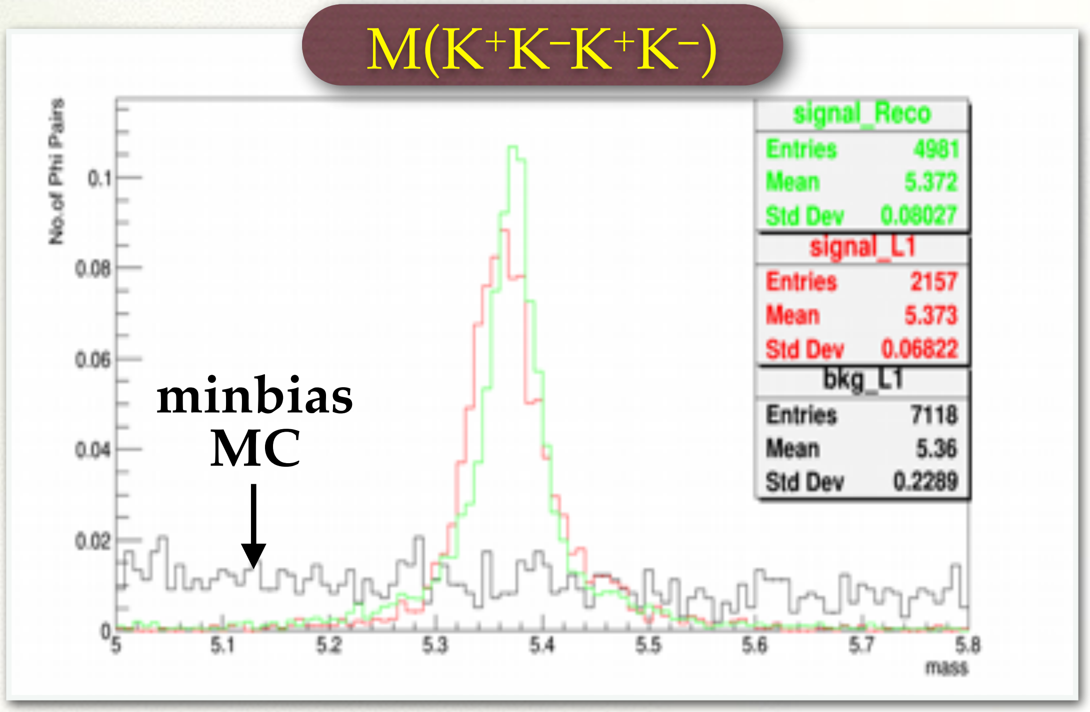
The low-p_T kaon lies very close to the threshold and the associated track may not be reconstructed at Level 1 resulting in loss of the event .

Performance Check w/ MC

- Reconstruction with all L1 tracks and look for Bs→4K candidates:
  - Loop over all the possible combinations.
  - Cut on track-pair dxy and dz, and the invariant mass of K^+K^- pair.







$B_s \rightarrow \phi\phi$ Estimate

- Studies with full simulated MC samples with TP setup are carried out.
- Different PU conditions (up to 200 PU) have been checked.
- L1 track trigger study finds the following performance numbers for several different working points:

Working point	Efficiency	Rate
Baseline	43%	29 kHz
Tight	38%	14 kHz
+Pixel tracking	32%	11 kHz

1) Still need to see what will be the "acceptable rate".
2) Eff. falls below 30% if limit the rate below 10kHz.

- First offline analysis has been performed with good efficiency on the triggered sample.

Missing a baseline analysis with real data,
more work required to produce a sensible extrapolation.

Summary

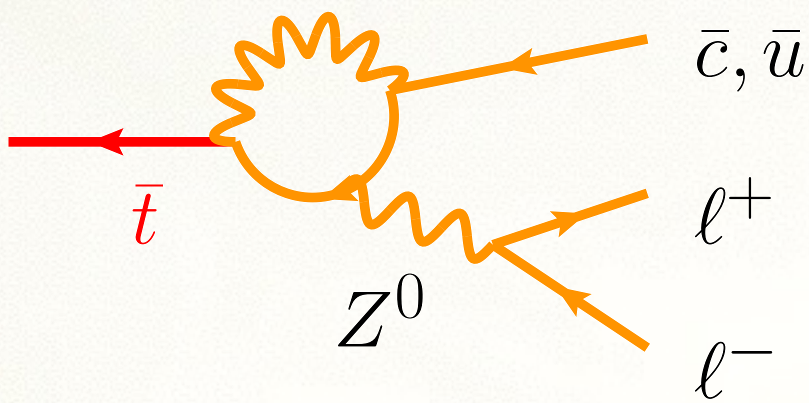
- The large data from LHC run-II and future operations will provide an excellent probe for the flavor physics.
- As a benchmark study, we estimate the CMS potential to trigger and reconstruct the $B_{s,d} \rightarrow \mu^+\mu^-$ processes at future LHC and HL-LHC runs. The physics performance for the LFV $\tau \rightarrow 3\mu$ and $Bs \rightarrow \phi\phi$ decays has been examined as well.
- With the upgraded CMS detector, it will be possible to trigger and reconstruct the signal events even with the high pile-up running conditions at HL-LHC.
- The upcoming large data set will leads to high precision measurements and provide stringent tests of the Standard Model.

Next topic: what the 40 MHz track trigger bring us (Fabrizio)

Backup Slides

The Physics: TOP FCNC

- **Flavour-changing neutral current (FCNC)** transitions are forbidden at tree level by the GIM mechanism in the Standard Model (SM).
- However FCNC transitions are still possible in the SM in the higher orders via loop induced processes, but they are highly suppressed in the top decays.



- Some extensions of the SM could **enlarge** the FCNC decay rates by including new particles (e.g. SUSY, Technic color, etc.).

Seeing TOP FCNC =
Discovery of New Physics!

Model	**BF(t→Zq, γq)**
SM	**~10^{-12}**
SUSY	**~10^{-6}**
2HDM	**~10^{-7}**

Toward the Future: TOP FCNC t→qZ

- Large sets of MC samples (generated with Madgraph, simulated with DELPHES) are used in the extrapolation.
- The analysis selection is based on the existing CMS 8 TeV search.
- The systematic uncertainty is expected to be improved from 23% (8 TeV 20 fb^{-1}) down to 7% (300 fb^{-1} and beyond), based on a better study of b-tagging performance and jet energy scale.

Ref. CMS PAS FTR-13-016

L (fb^{-1})	20 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Expected Bkg.	3.2	26.8	268
Bkg.	23%	7%	7%
Signal (B=0.1%)	6.4	57.8	578
Expected Limit	**<0.10%**	**<0.027%**	**<0.010%**

The sensitivity can be further improved with optimized analysis.

HL-HLC projection