New Physics at HL-LHC with CMS

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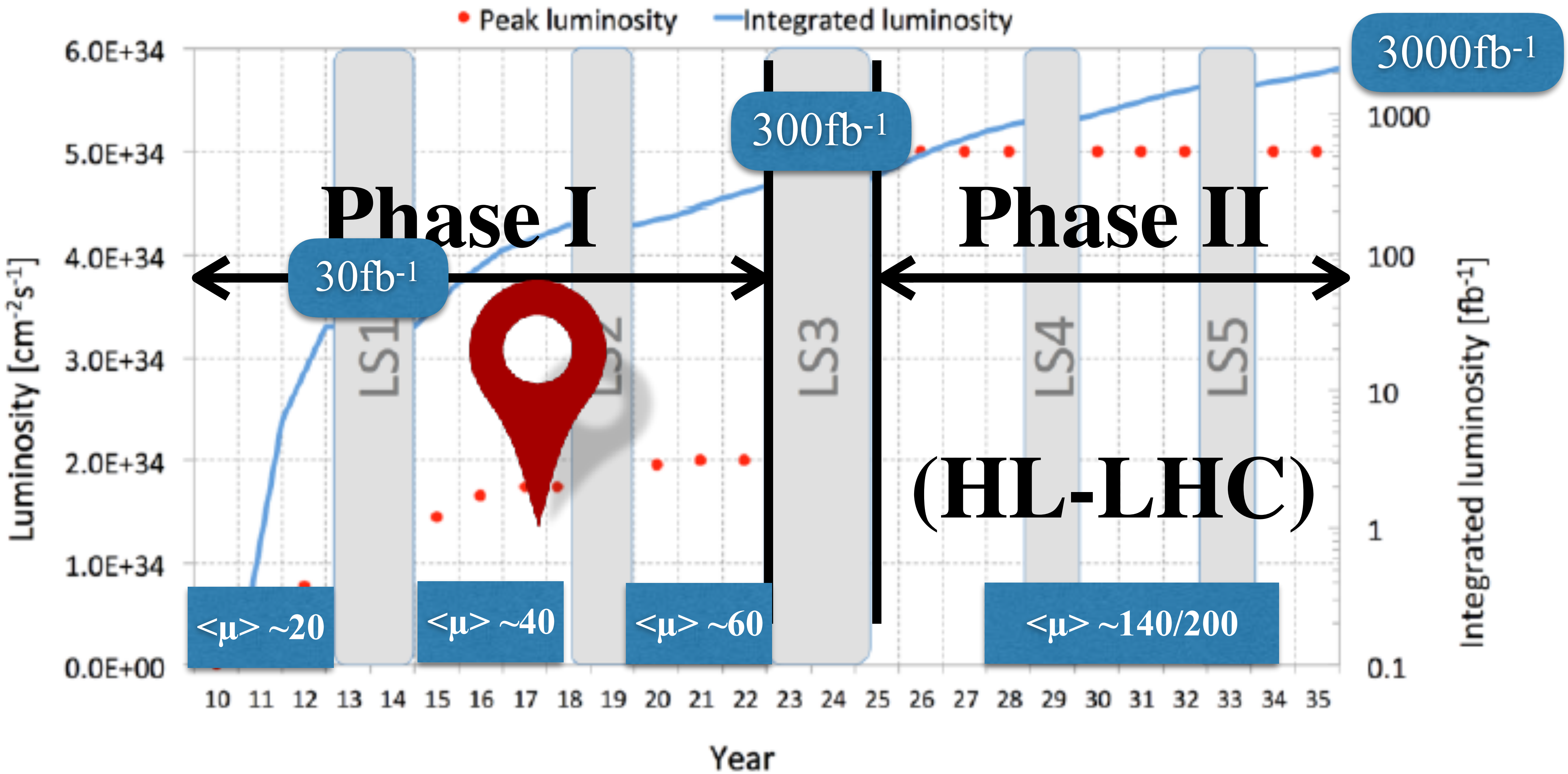
Why HL-LHC?

- **What have we learnt so far?**
  - **Standard Model works beautifully.**
  - **Currently NO direct evidence of new physics at the LHC**

- **Key questions remain unanswered**
  - **Hierarchy problem**
  - **Dark matter**
  - **Origin of matter-antimatter asymmetry**

- **HL-LHC will deliver 3/ab (~ x50 today's data sample) @ 14 TeV**
  - **Enables study of "SM-like" properties of Higgs boson in details (including study of rare Higgs decays/Higgs self coupling)**
  - **BSM physics (extra scalars, BSM Higgs resonances, exotic decays…) could manifest itself in deviations from SM predictions**
  - **Strong motivation for new physics at the TeV scale (Answers to the above questions may lie there → new particles, interactions, dimensions)**
    - **In case of discovery - Investigate properties of new particles which are observed along the way!**

LHC Schedule



- **As pile-up increases, complexity adds on from all aspects when it comes to look at such data in the detector (increased rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event)**
- **Detector elements and electronics are exposed to high radiation dose (reaching limits for several systems)** → **Need of detector upgrades**

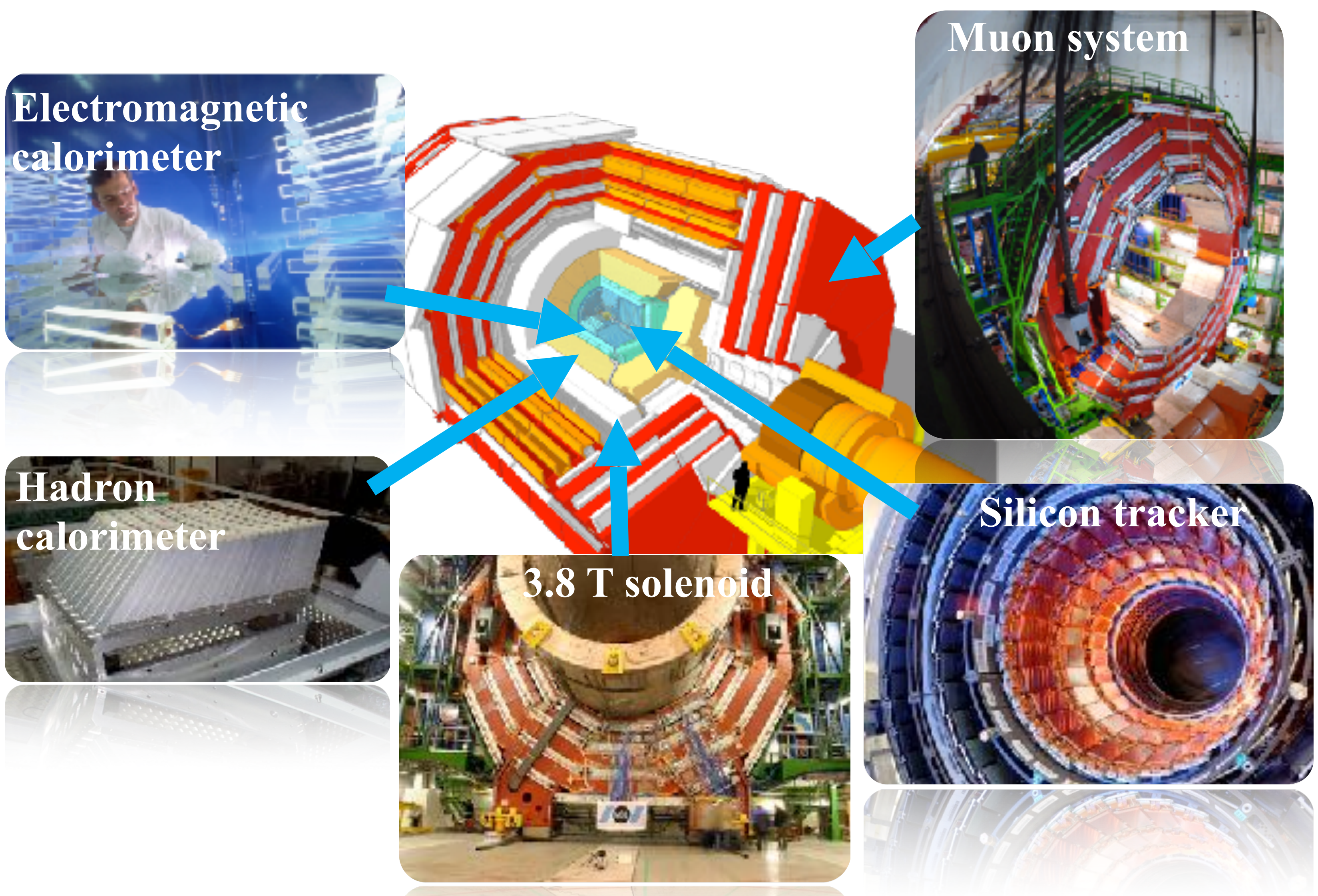
CMS upgrades

To meet the machine performance, CMS have 2 major upgrade phases as well.

Phase 1 (new PIXEL, HCAL readout, trigger)

Phase 2 (new tracker, new EC, new readout for barrel calorimeters, extended muon capabilities, new trigger, new DAQ)

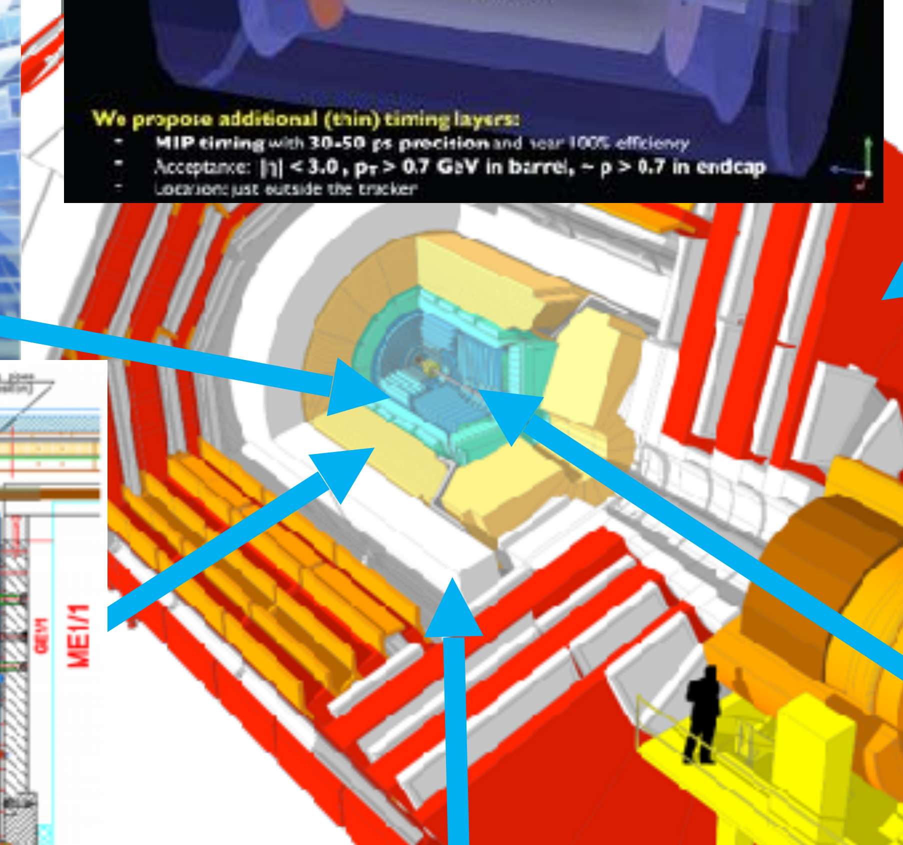
Current CMS

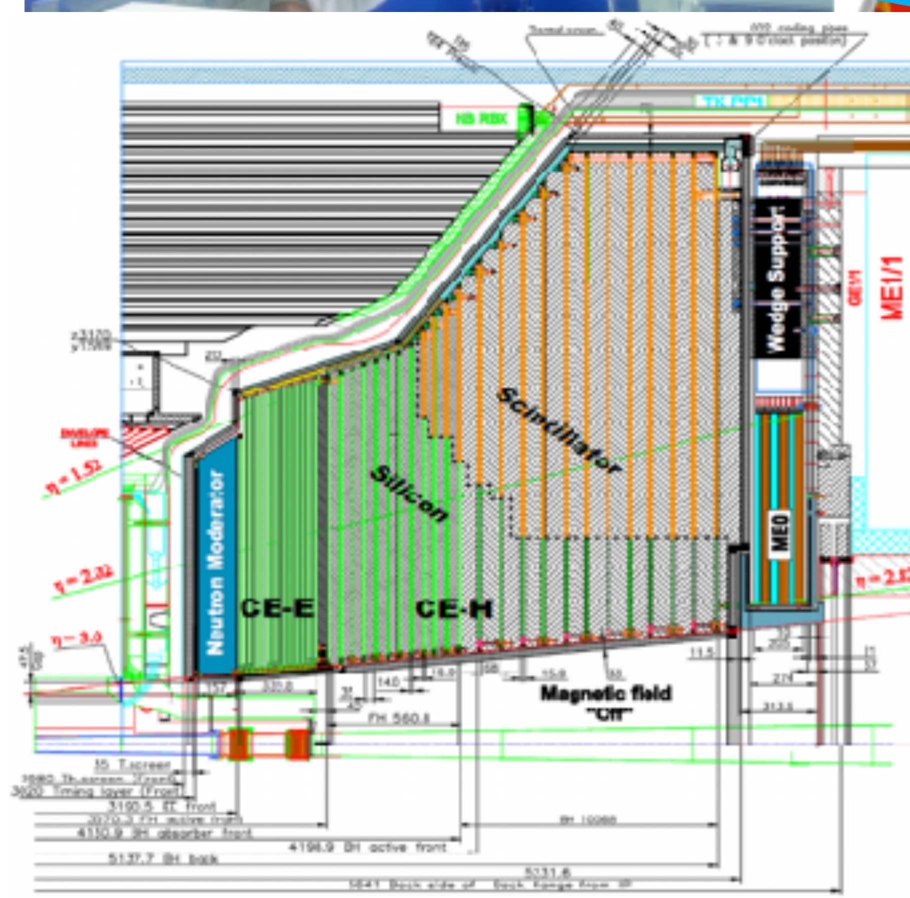


CMS upgrade

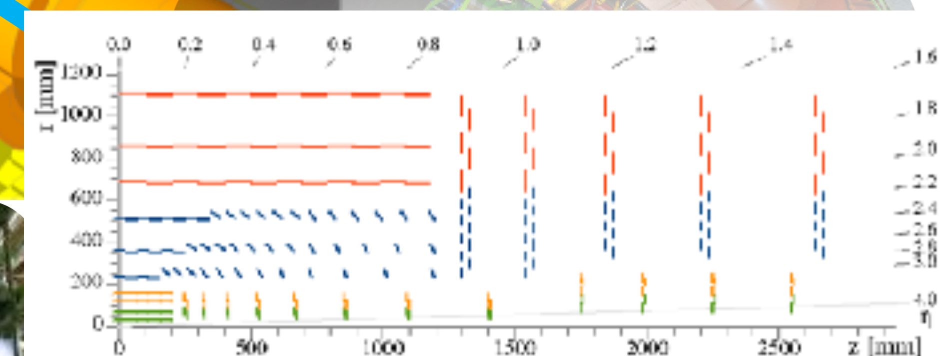
Additional chambers and η-coverage for muon system

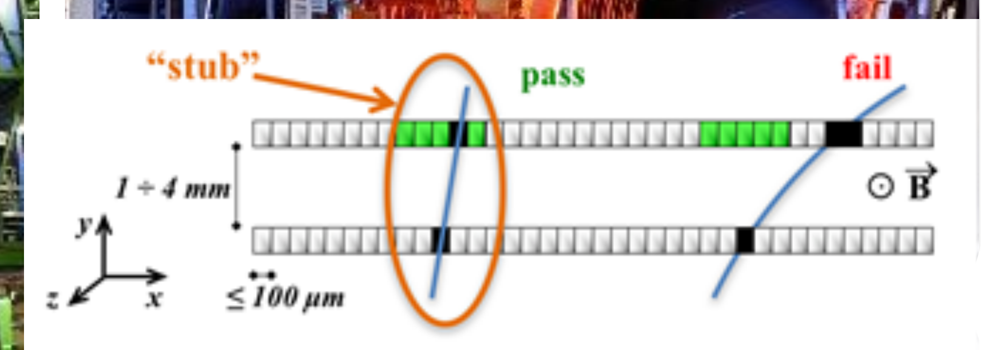

Improved barrel calorimeter readout and trigger





New high granularity silicon endcap calorimeter





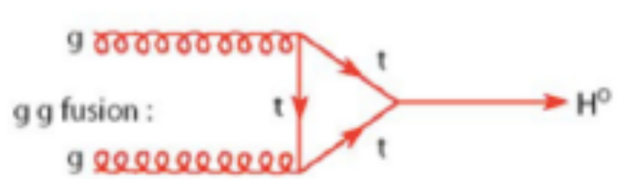
Level 1 track trigger and extended η-coverage for silicon tracker

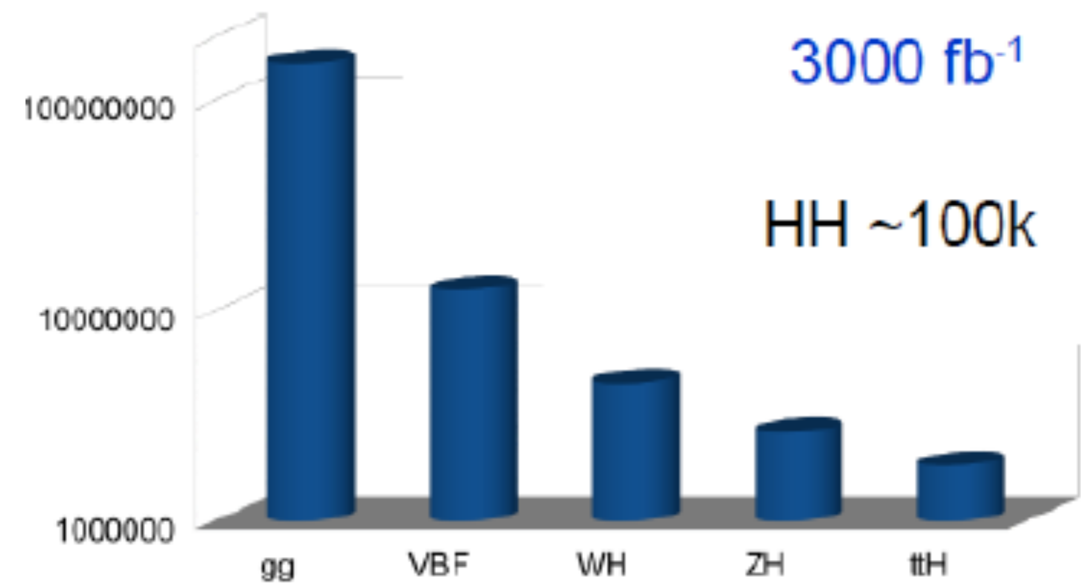
L1 trigger ~ 750 KHz
HLT ~ 7.5 kHz
Latency ~ 12.5 μs.

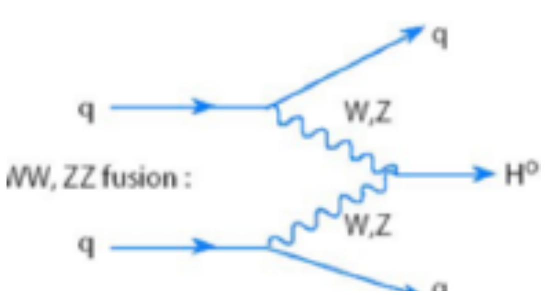
The Higgs Sector

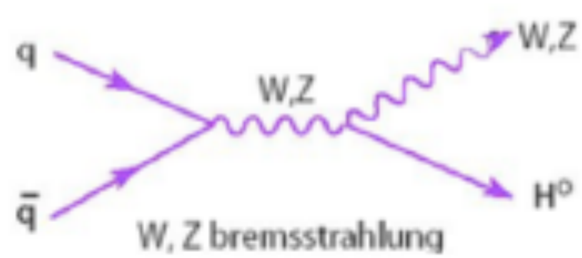
A major component of HL-LHC physics program

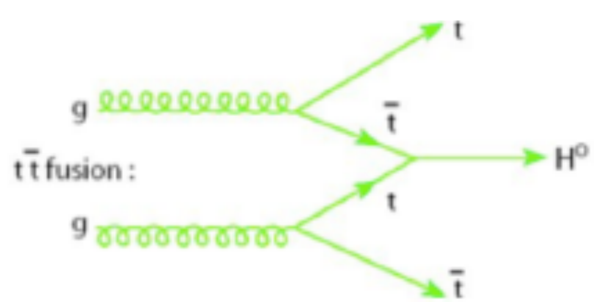
HL-LHC (Higgs factory), we expect to produce >150M Higgs Bosons (over 1Million for each of the main production mechanisms, spread over many decay modes)

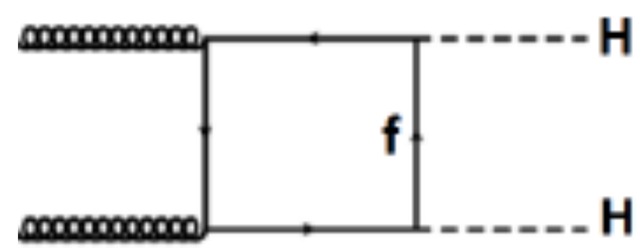


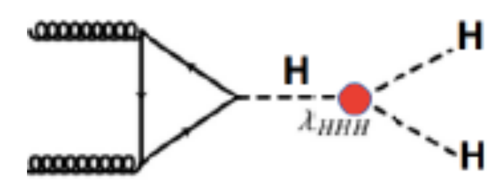












Enables a broad program:

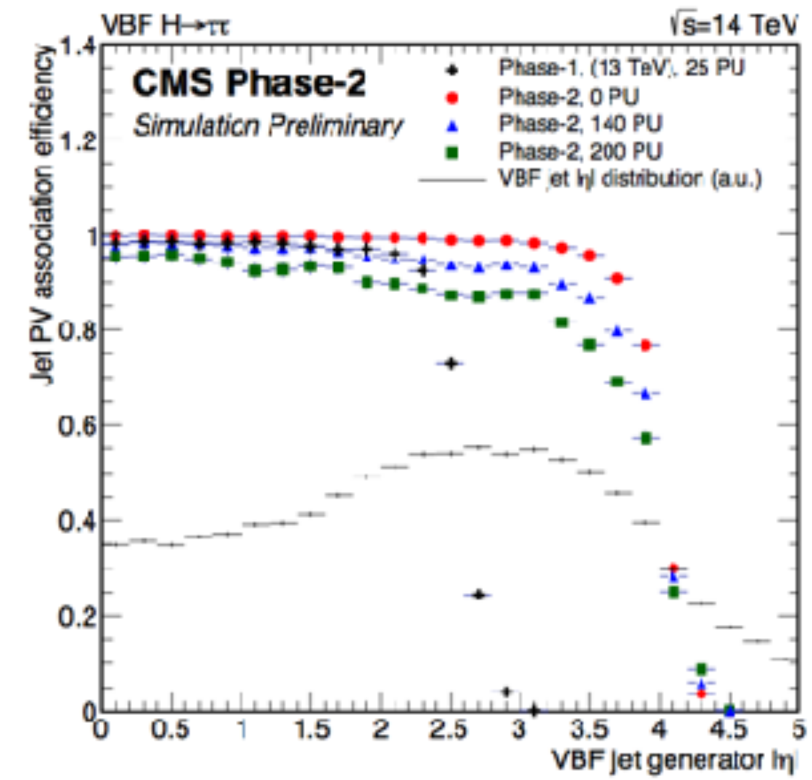
- Precision measurements of Higgs coupling across broad kinematics
- Di-Higgs production and its sensitivity to rare decays
- BSM Higgs searches

Physics potential enabled by upgraded detectors

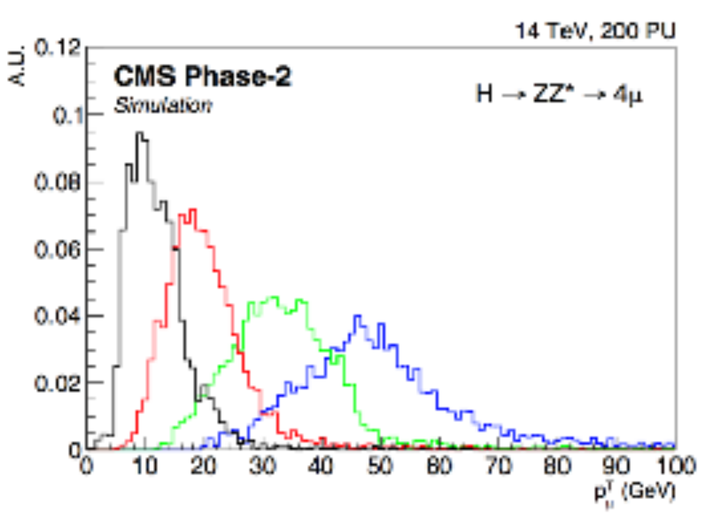
VBF topologies (H→ττ in the specific) gain in acceptance

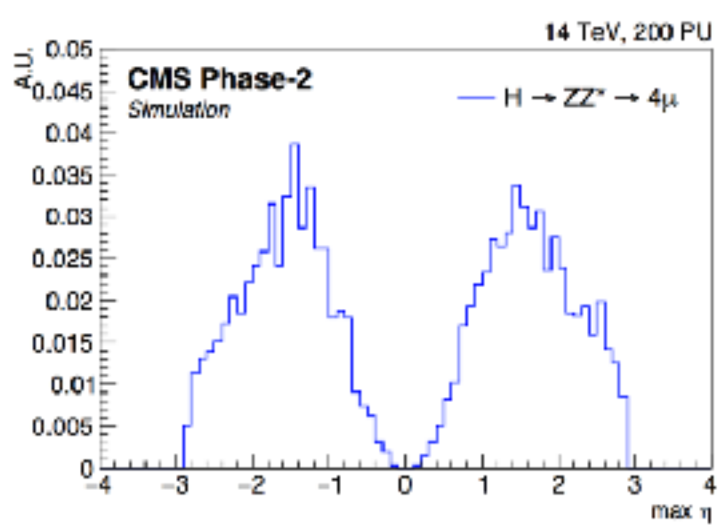
Increase in efficiency of associating forward VBF jets with the primary vertex.

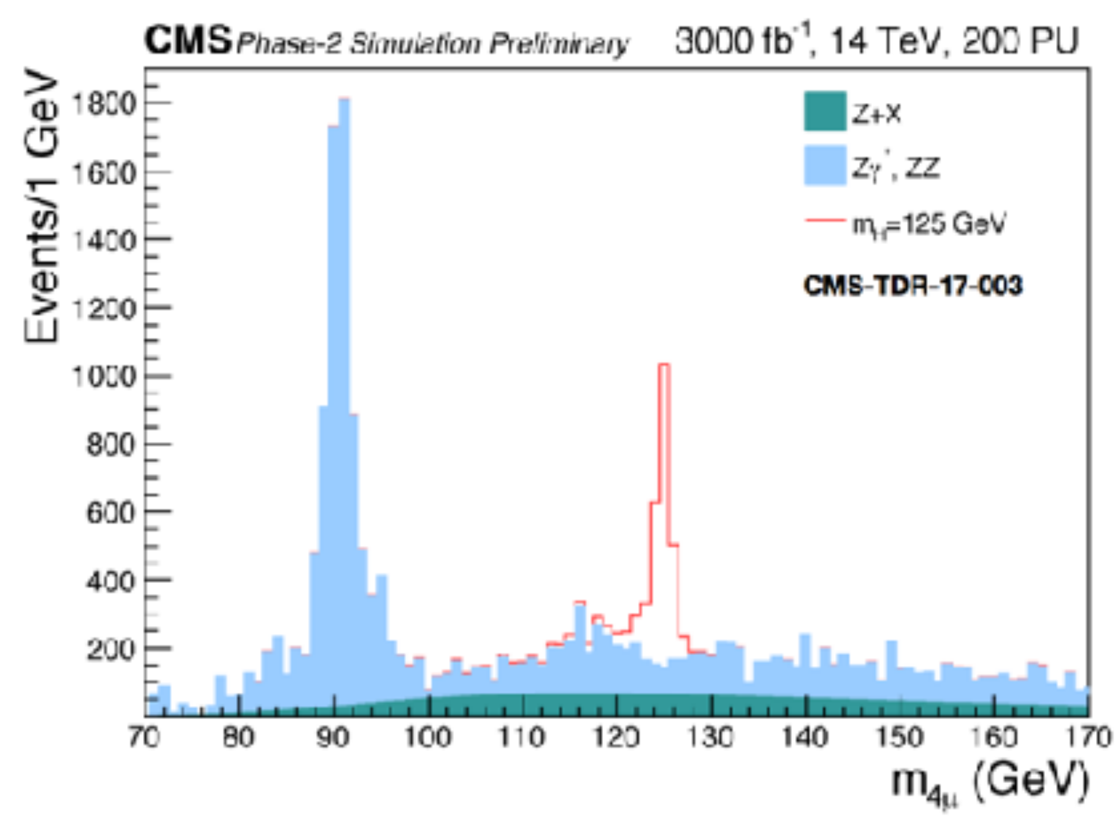
Scenario	ϵ (inclusive)	ϵ ($\lvert\eta\rvert > 2.0$)	ϵ ($\lvert\eta\rvert > 2.4$)
Phase-1	57%	27%	11%
Phase-2 (200 PU)	84%	79%	76%
Phase-2 (140 PU)	88%	83%	80%
Phase-2 (0 PU)	89%	84%	81%



Higgs into 4 muons: acceptance increase ~17%





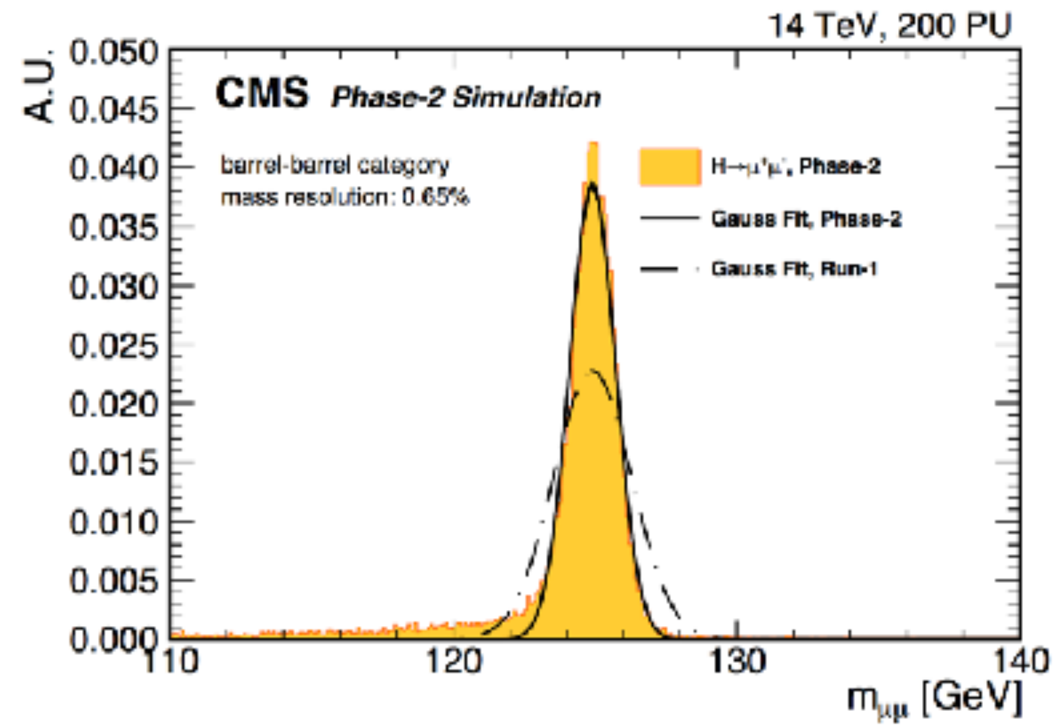


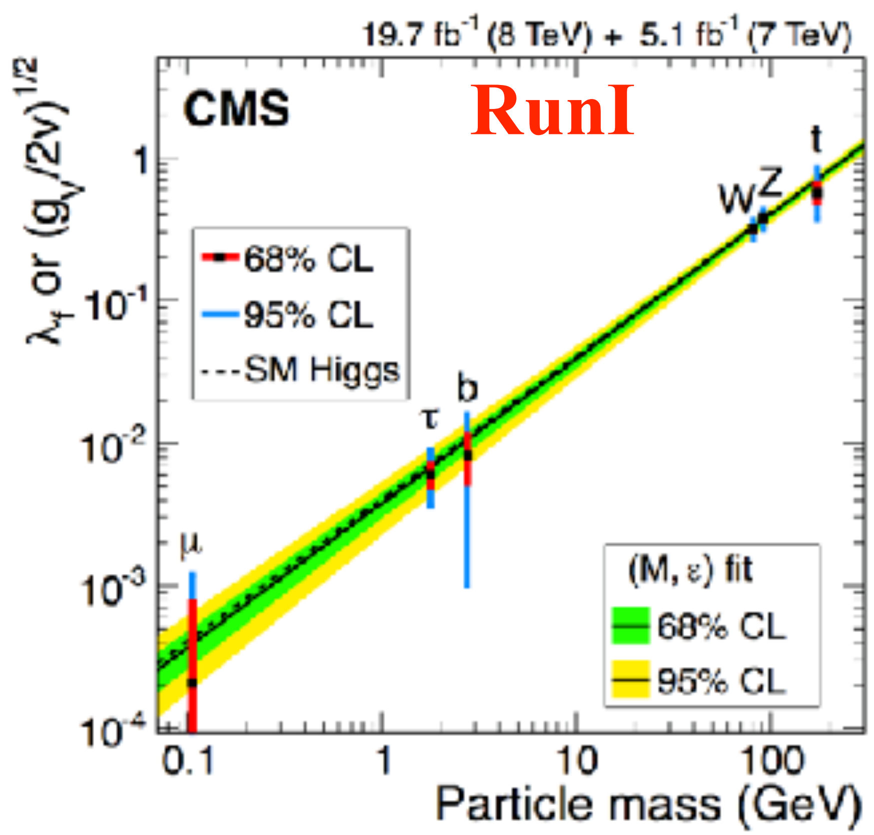
Triggering on low p_T leptons and increased coverage for leptons : maximize the acceptance.

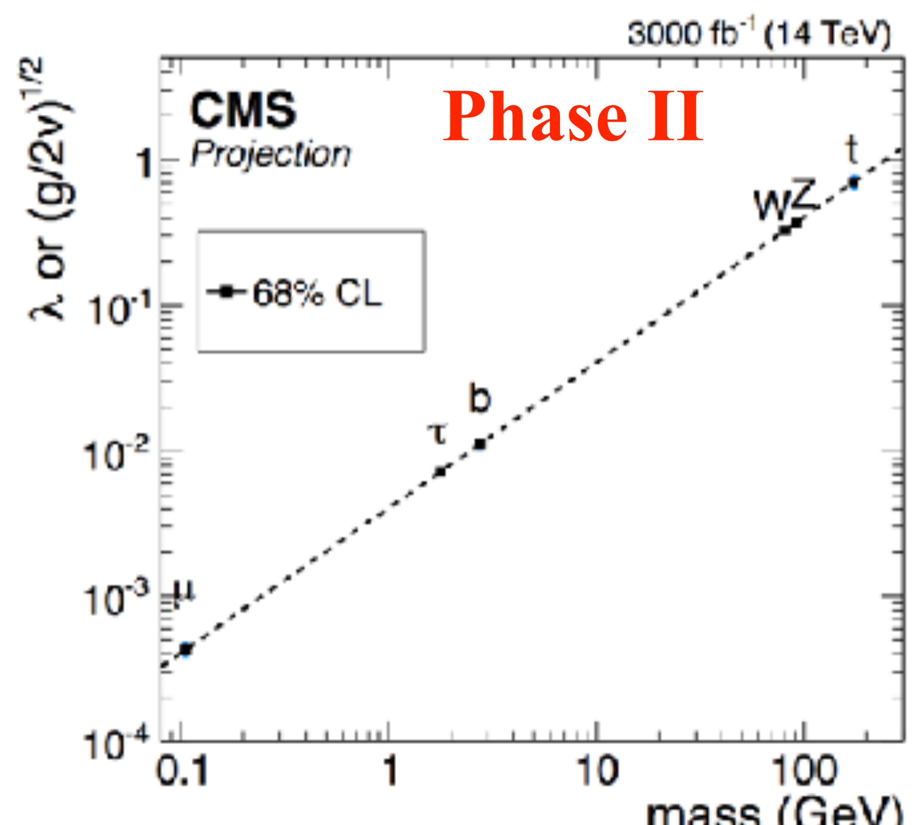
Physics potential enabled by upgraded detectors

Rare decays capabilities

- H→$\mu\mu$ analysis depends critically on di-muon mass resolution.
- New tracker achieves a much better mass resolution (low material budget, better measurement).







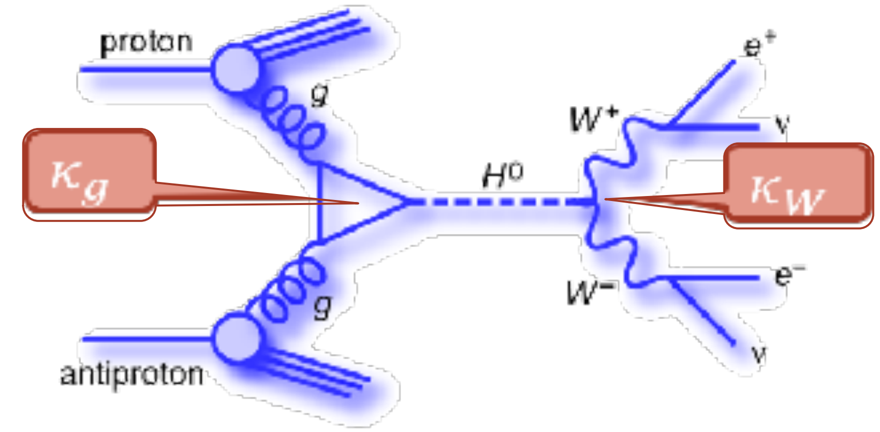
Remarkable expected improvement in measurement of the precision of the Higgs coupling

Higgs Coupling

For any process, its rate is determined by couplings involved.

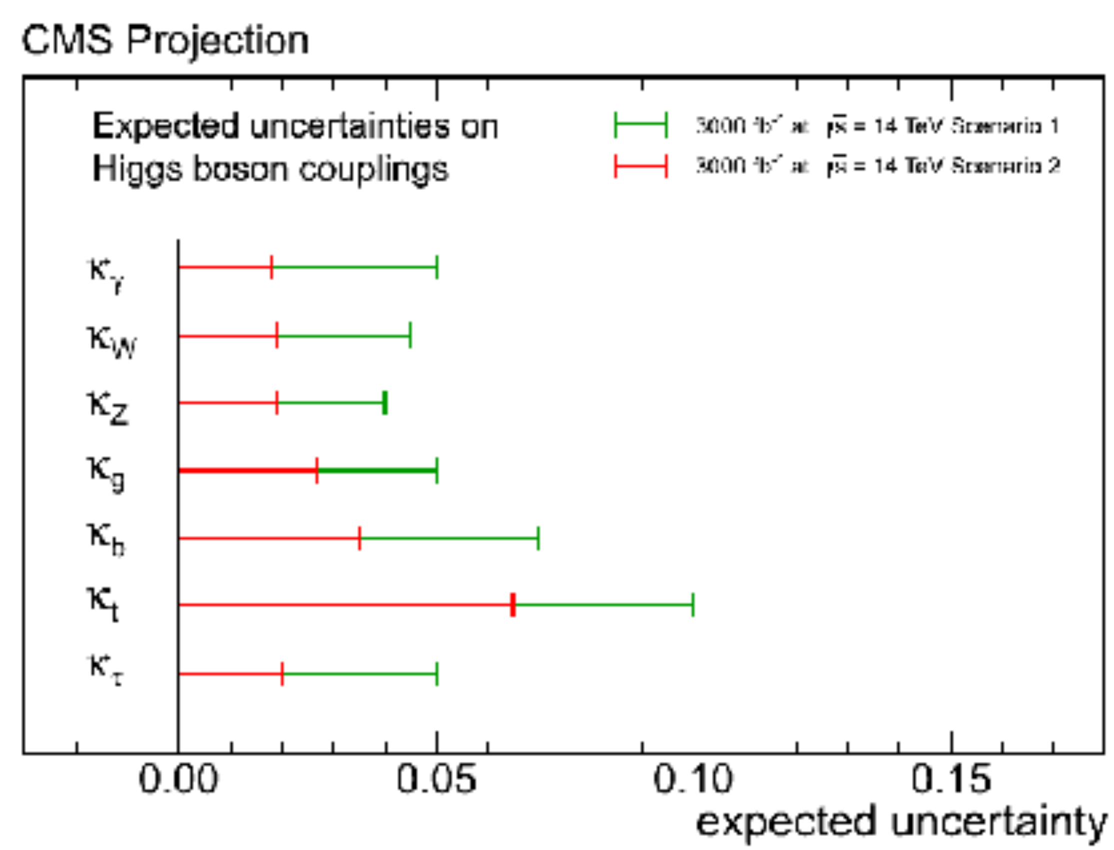
Currently measured upto 20% typically.

Projections at 3-10%-level with 3000 fb^{-1}.
HL-LHC will improve measurement precision by a factor 2-3!



Assumptions on systematic uncertainties:

Scenario 1: All systematic uncertainties kept constant with luminosity
Scenario 2: theory unc. / 2, Experimental systematics goes like 1/√L



Expected deviations from SM predictions by various models (Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top Partner..) predicted to be between 1-10%. Thus precise measurement of coupling will enable to decouple BSM physics from SM.

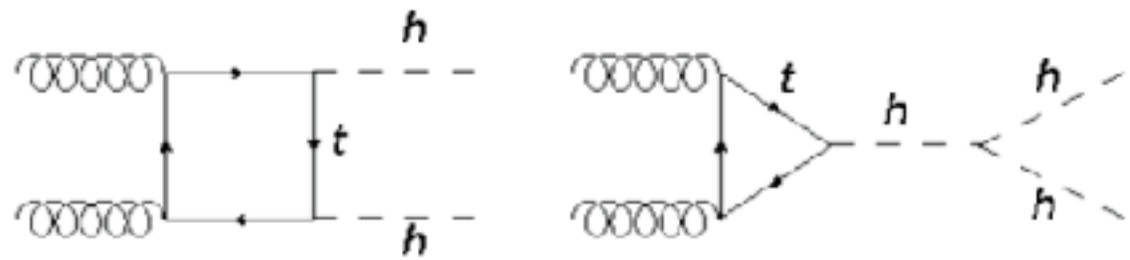
These scenarios assume : CMS upgrades will provide the same level of detector and trigger performance

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Di-Higgs production - Higgs self-coupling

Benchmark channel for HL-LHC program

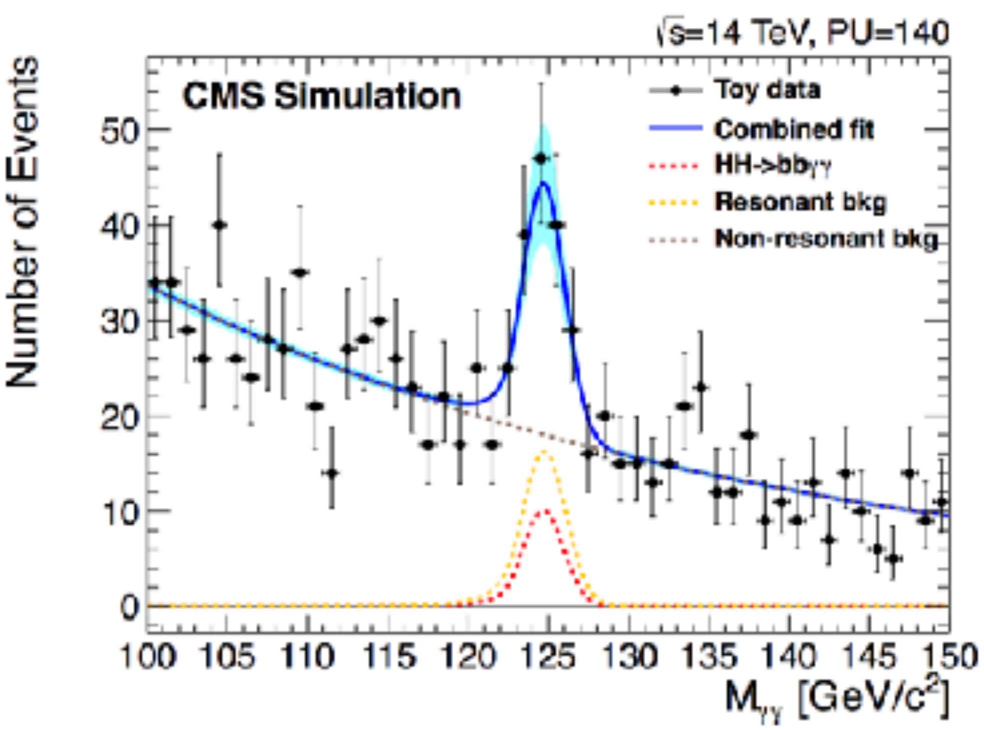
Possibility of "evidence" by combining all channels in ATLAS and CMS

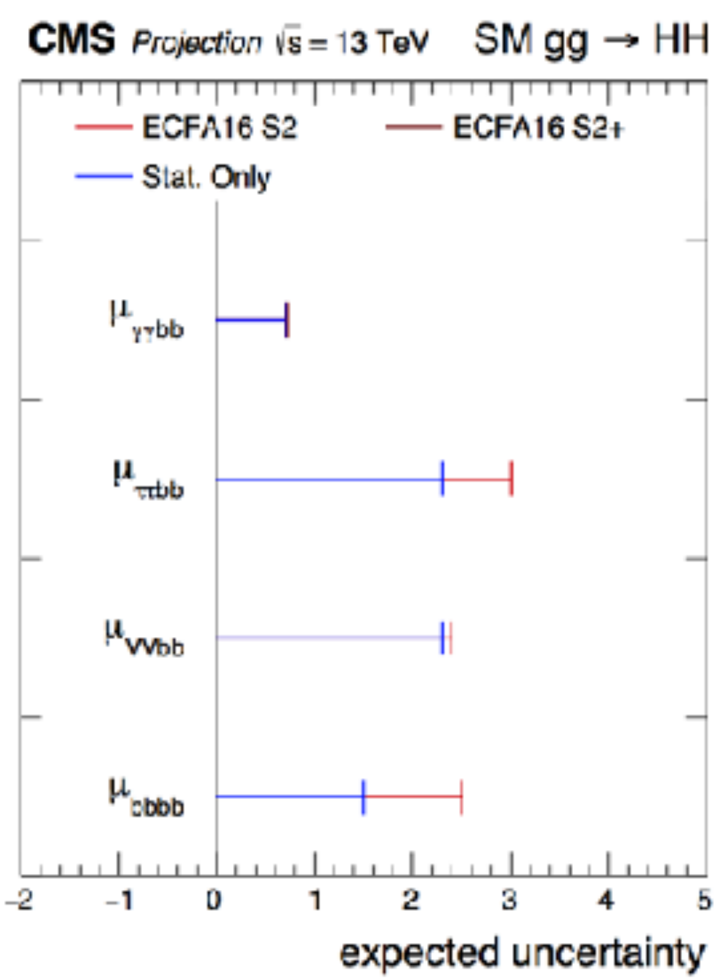


SM σ= 39.5 fb @14 TeV

Improvement foreseen driven by :

Detector optimization, Analysis algorithms



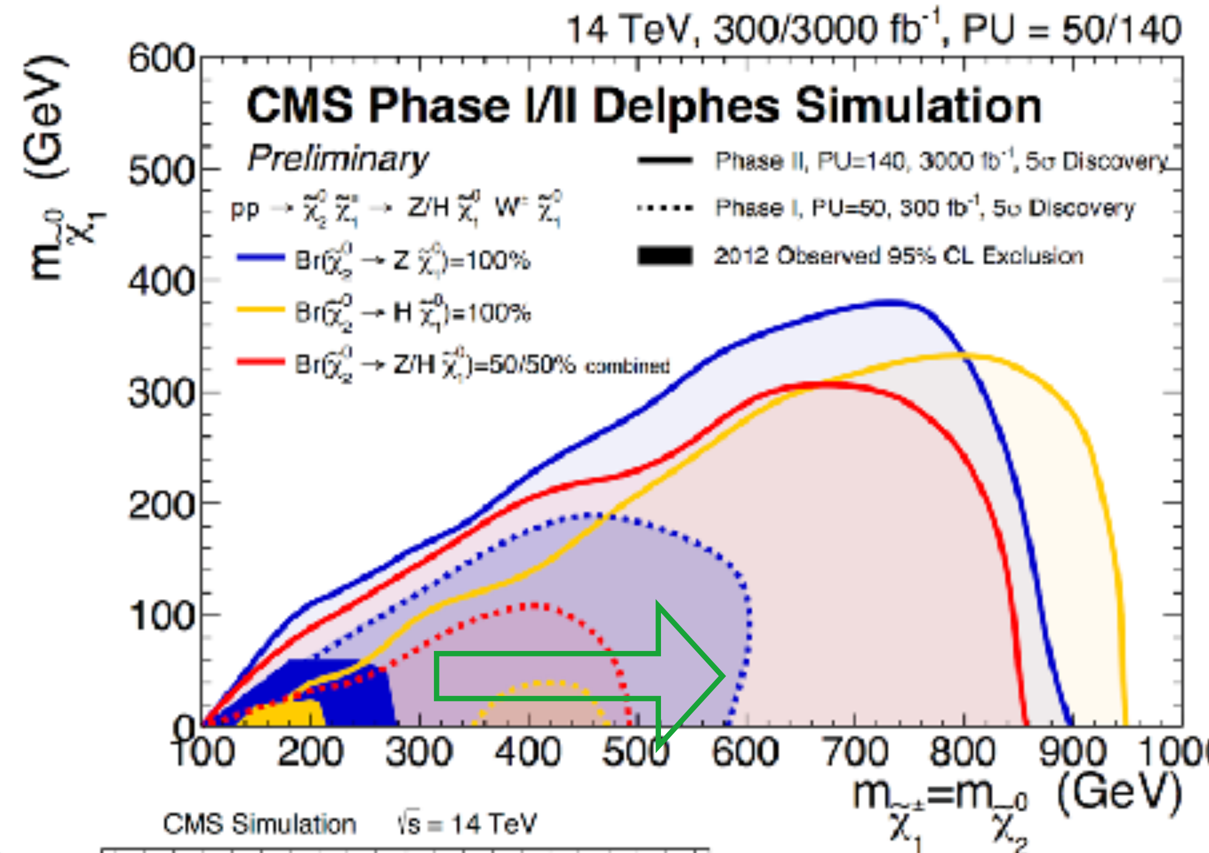


Statistically bbγγ seems the most promising channel

New tracker allows for +15% efficiency per b and EC allows for +10% efficiency per γ

S2+ : The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account

SUSY projections



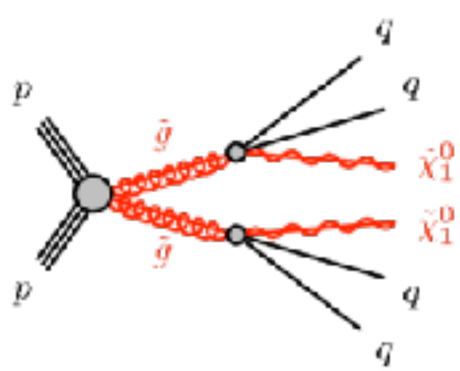
In EW produced SUSY scenario we could reach:

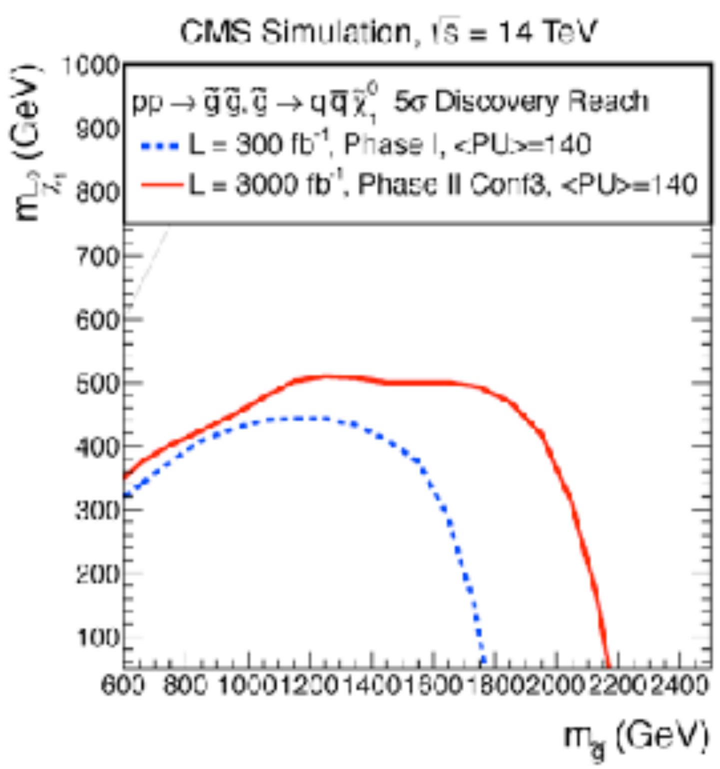
- **chargino limits up to 800 GeV**
- **neutralino up to 300 GeV**

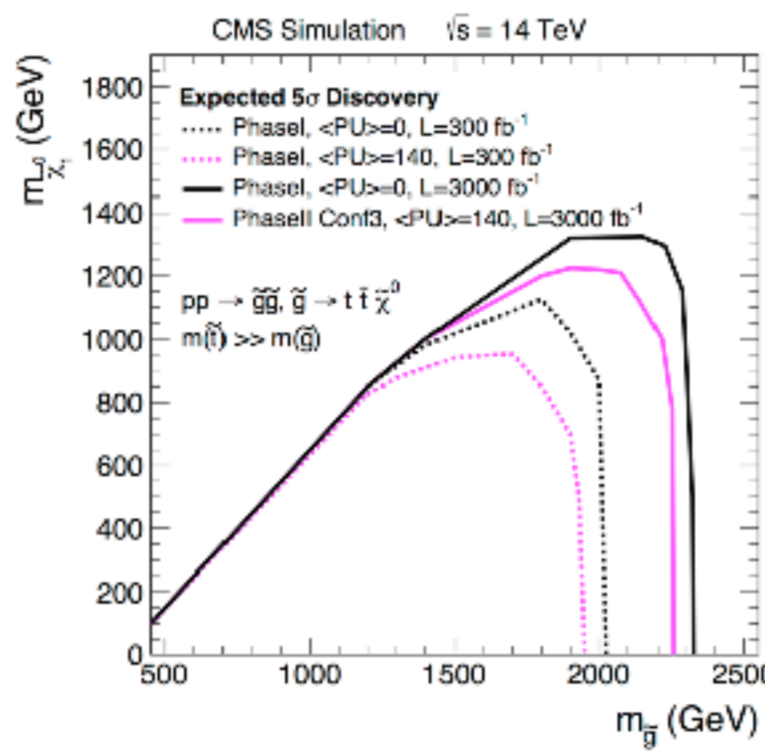
or equivalently

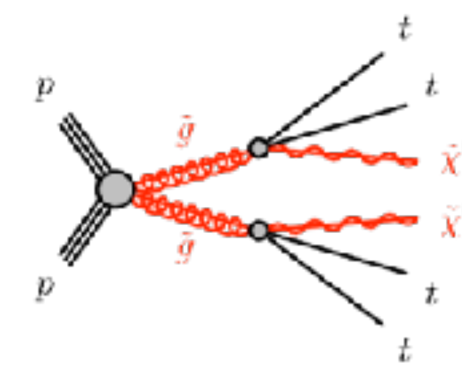
- **chargino discovery potential up to 600 GeV**
- **neutralino discovery potential up to 200 GeV**

For gluions:



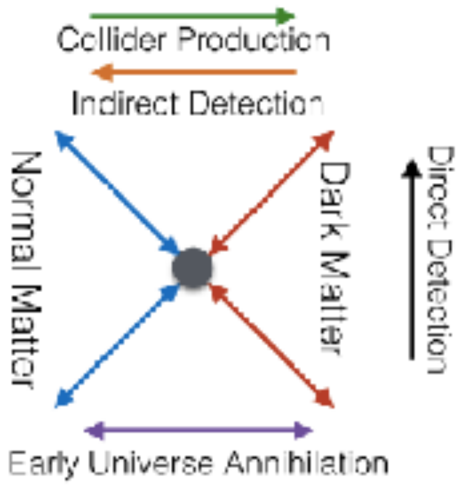




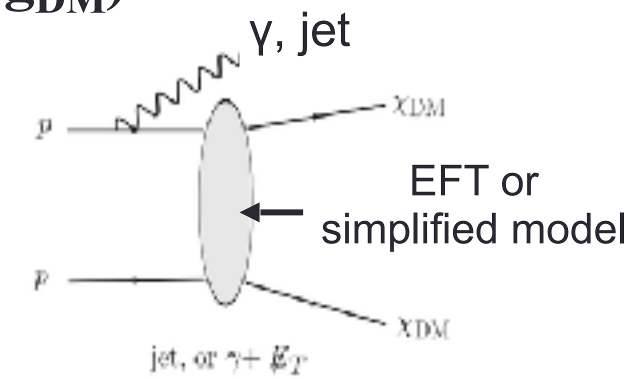


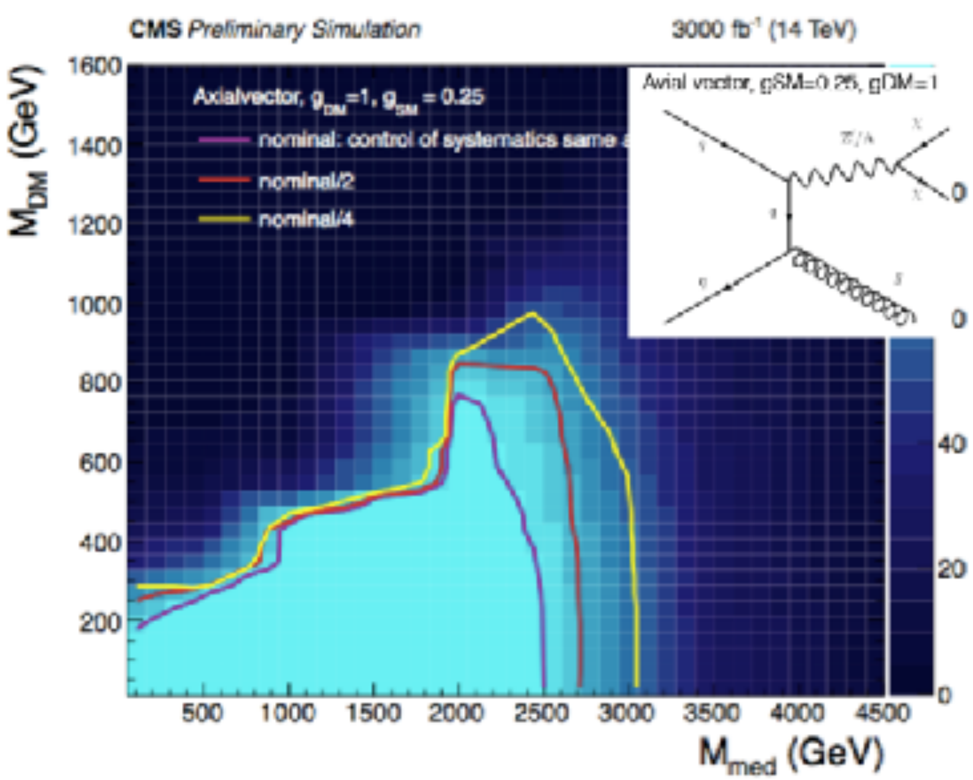
5σ discovery reach extended up to 2.2 TeV,
up to 2.3 TeV for decays through top quarks

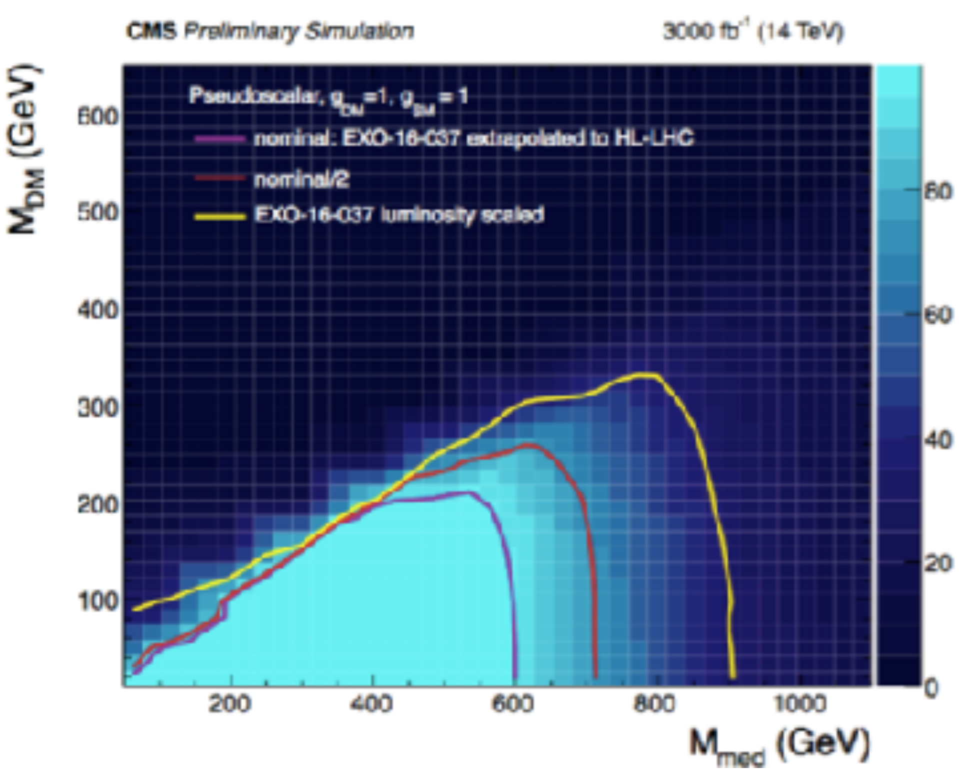
Dark Matter



- **Weak-scale interactions with the SM**
- **Complementary to direct detection experiments.**
- **Searches based on Simplified Models**
- **Search for Dark Matter in Missing E_T+jets - Benchmark among other searches.**
- **Interpretation in simplified models with 4 parameters (M_{med}, m_{DM}, g_{SM}, g_{DM})**
- **Axial vector mediator :**
  - **Exclusion possible up to 3 TeV. (current reach ~2TeV)**
- **Pseudoscalar Mediator:**
  - **Spin-0 mediator, pseudoscalar gSM = 1, gDM = 1**
  - **Exclusion possible up to 900 GeV (current ~0.4 TeV)**

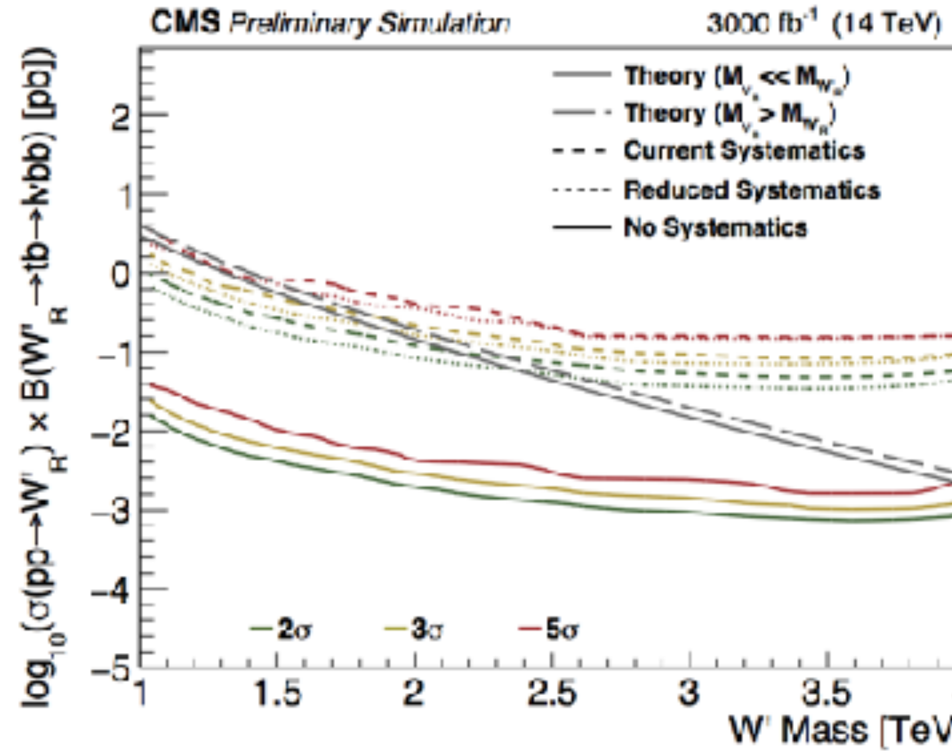




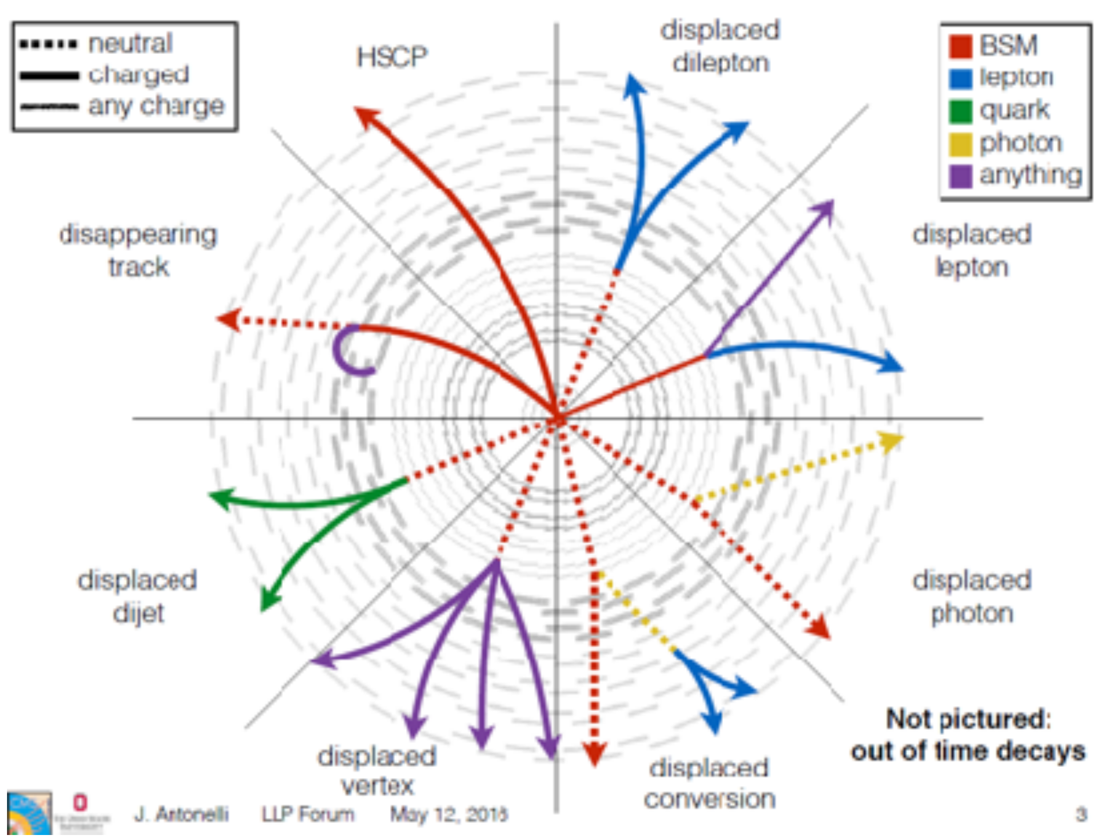


Exotica searches

- **Heavy resonances** reach can extend up to **4-5 TeV** in both tt (Z') and tb (W') channels



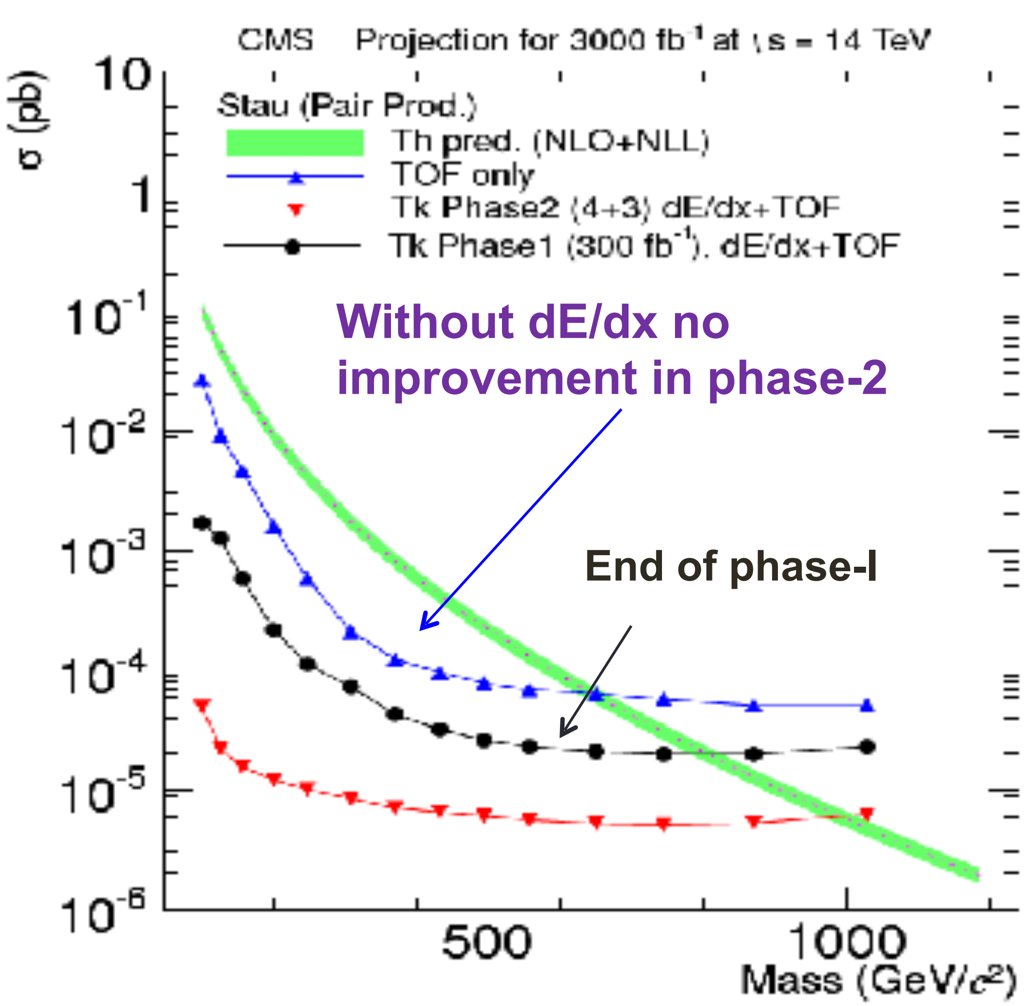
Long Lived particles (LLP)

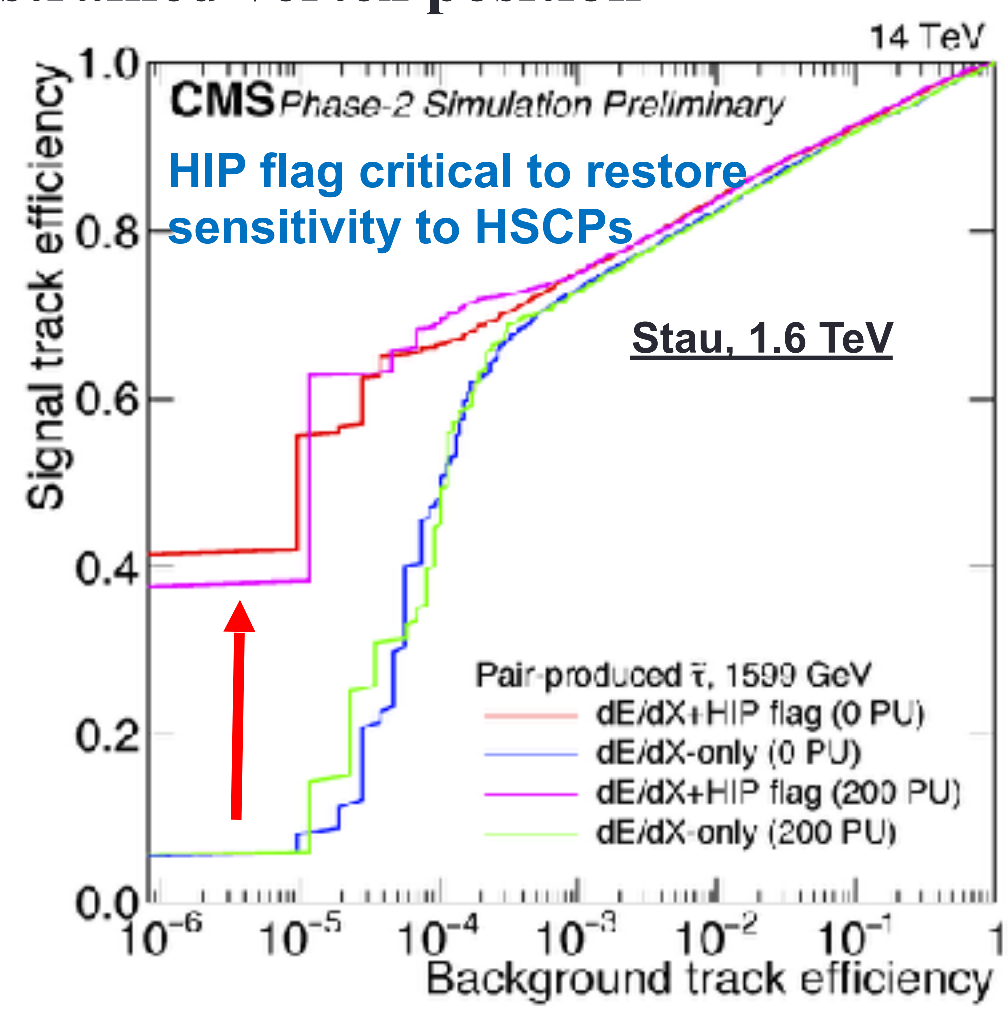


- LLPs decaying non-promptly (after some cτ) predicted by many new physics models
- great discovery potential -> new focus at the LHC
- Use different signatures to search for LLPs :
  - Need dedicated tools for non-standard objects, custom trigger/reconstruction/ simulation
  - Potential gains from high luminosity, track-trigger, fast timing, better directionality.

Heavy Stable Charged particles

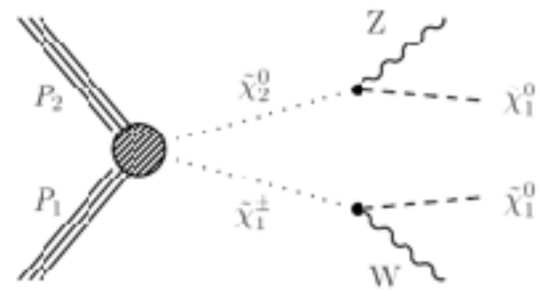
- Detection technique
  - Could look like heavy, highly-ionizing, slow-moving muons
  - Depending on their mass and charge, we can expect anomalously high energy loss through ionization (d*E*/d*x*) in the silicon sensors with respect to the typical energy loss for SM particles
  - dE/dx discriminator shows large separation between signal and backgrounds demonstrating the need to keep dE/dx capability in the tracker
  - dedicated reconstruction able to cope with unconstrained vertex position





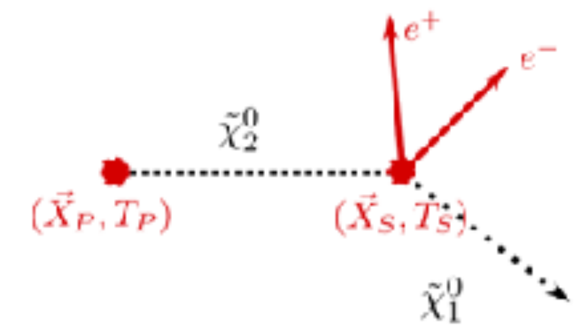
CMS TP and CMS-PAS-EXO-14-007

Long lived neutralinos



- Long-lived neutralinos **with small mass difference**

$$M(\tilde{\chi}^{\pm}) = M(\tilde{\chi}_2^0) = 400 \text{ GeV},$$
$$M(\tilde{\chi}_1^0) = 390 \text{ GeV}$$



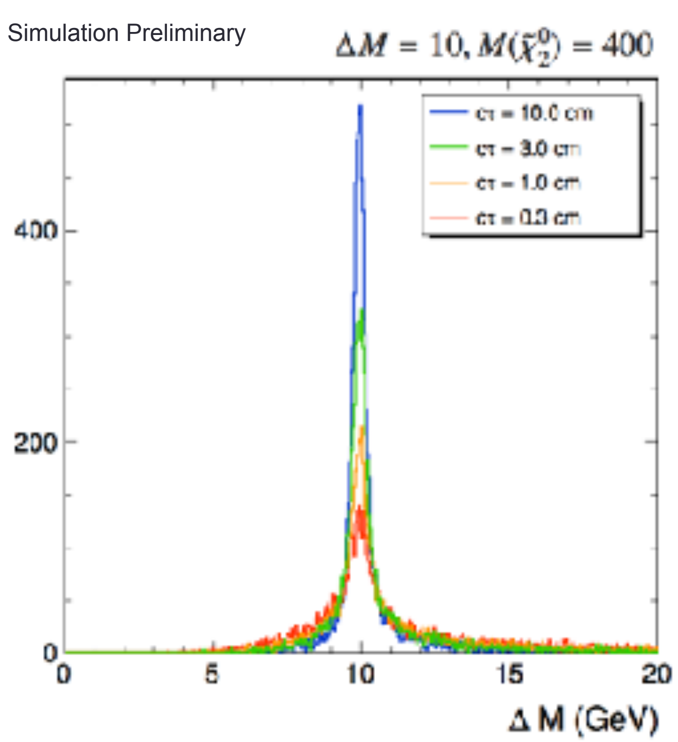
- Use MIP timing detector for precision measurement time of flight
- **assign time to vertices and charged particles**
- **With the timing information, can reconstruct LLP time-of-flight and mass**

In the limit where the light charginos and neutralinos are degenerate in mass ($\Delta M \simeq 0$), the energy of the e e (visible) system in the LLP rest frame provides a direct measurement of the mass splitting.

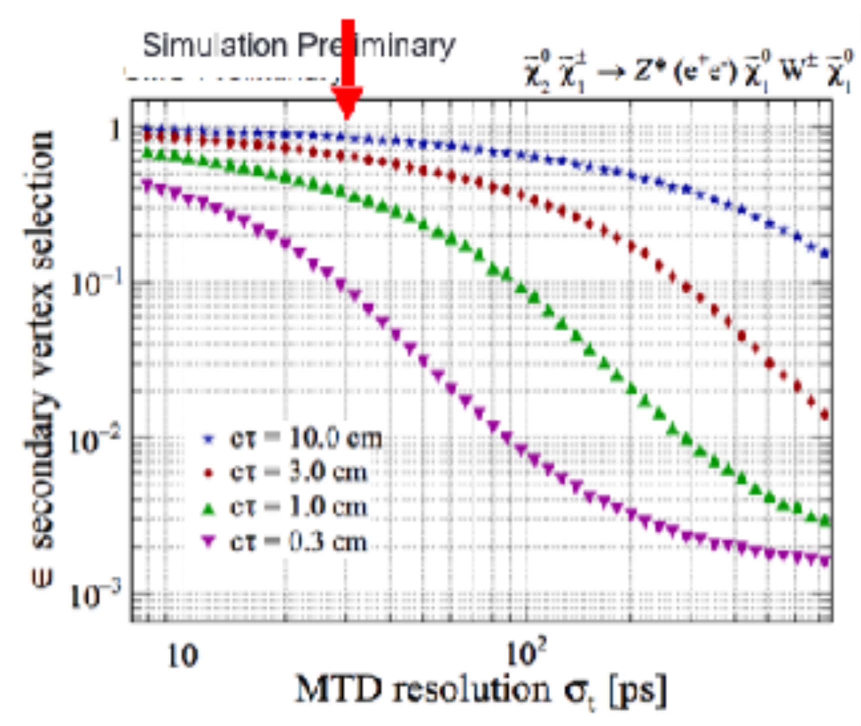
Reconstructed E_{e+e-}

$$E = \Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$$

Assume 30 ps timing resolution of MTD



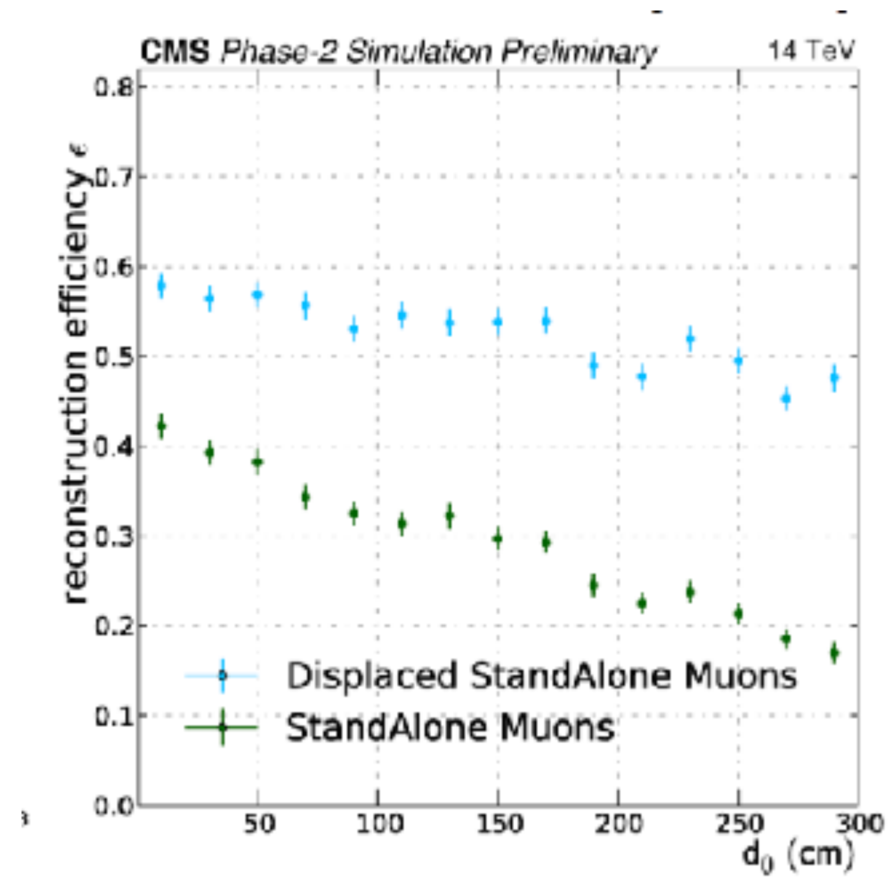
Select events with a displaced secondary vertex with 3σ significance in both space and time:



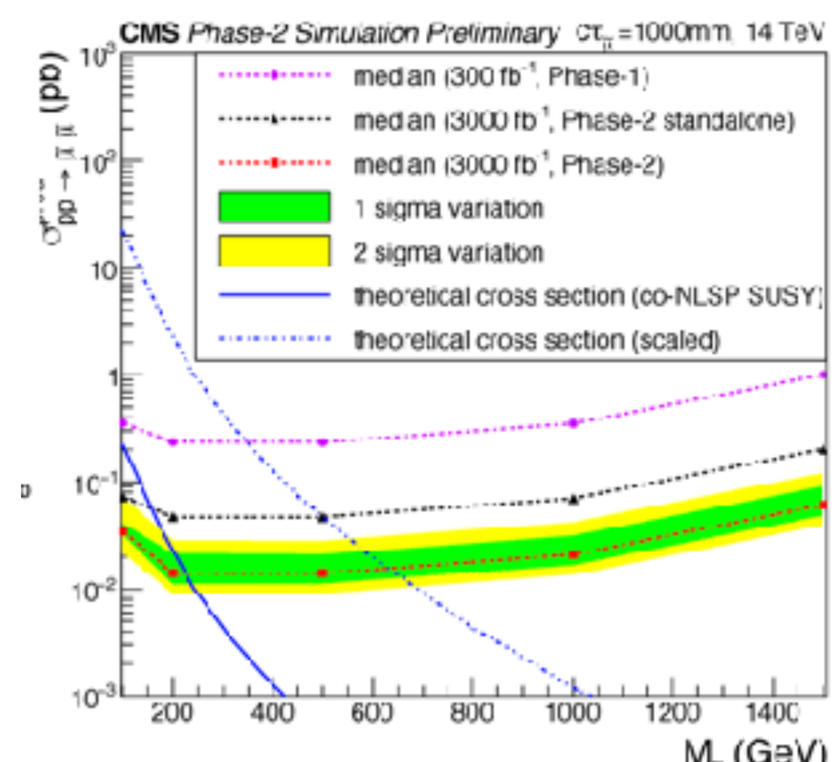
Long Lived particles (LLP)

sMuons:

- **need to keep/exploit trigger capabilities on displaced muons**
- **A dedicated muon reconstruction algorithm for non prompt muons that leave hits only in the muon system to cope with unconstrained vertex position.**
- **Gives better reconstruction efficiency compared to SA muons that use information of the primary vertex**



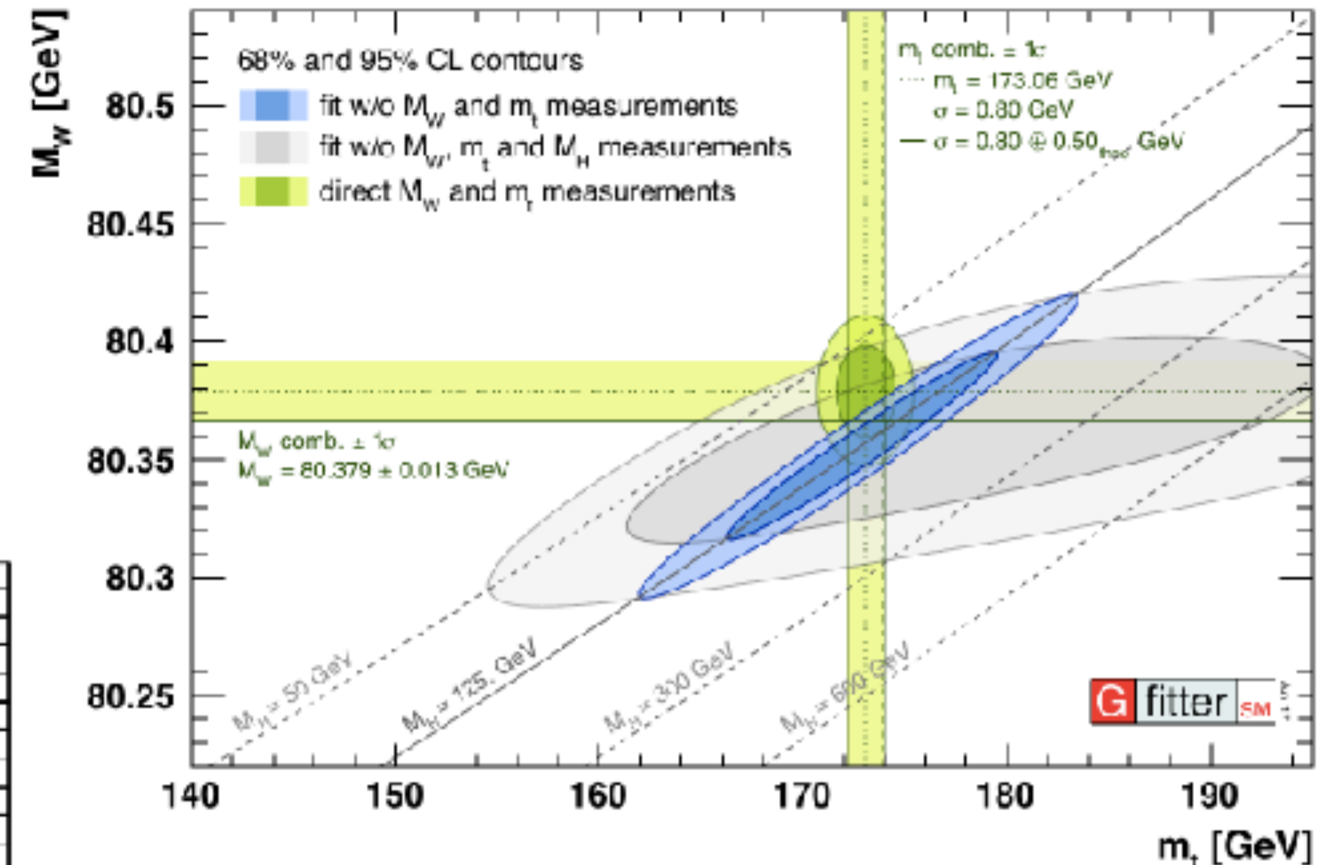
- **Expected exclusion limits for the gauge-mediated SUSY breaking model with the smuon being a (co-)NLSP for the predicted cross section as well as for a factor 100 larger cross section**

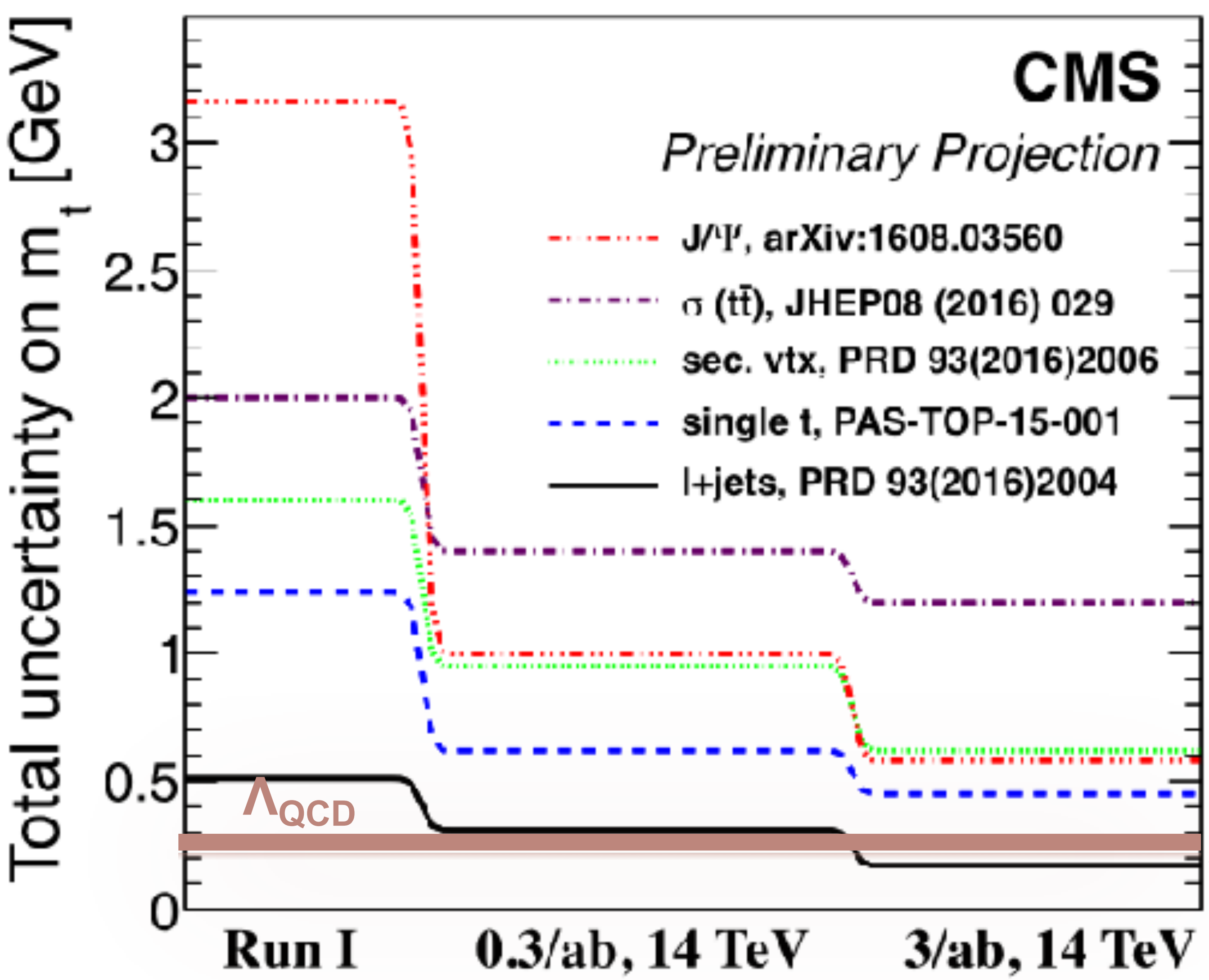


$$\tilde{\mu} \rightarrow \mu + X$$

Precision Physics: Top Quark Mass

- **Powerful way to look to new physics through loops.**
- **top mass unc: ~0.5GeV → ~ 0.17 GeV**





From $t\bar{t}$ cross-section
- Limited by theory uncertainty and luminosity measurement

J/ψ and secondary vertex
- Statistically dominated

Single top

Standard $t\bar{t} \rightarrow \ell$+jets measurement
- Expect Δm_{top} ~ 0.17 GeV

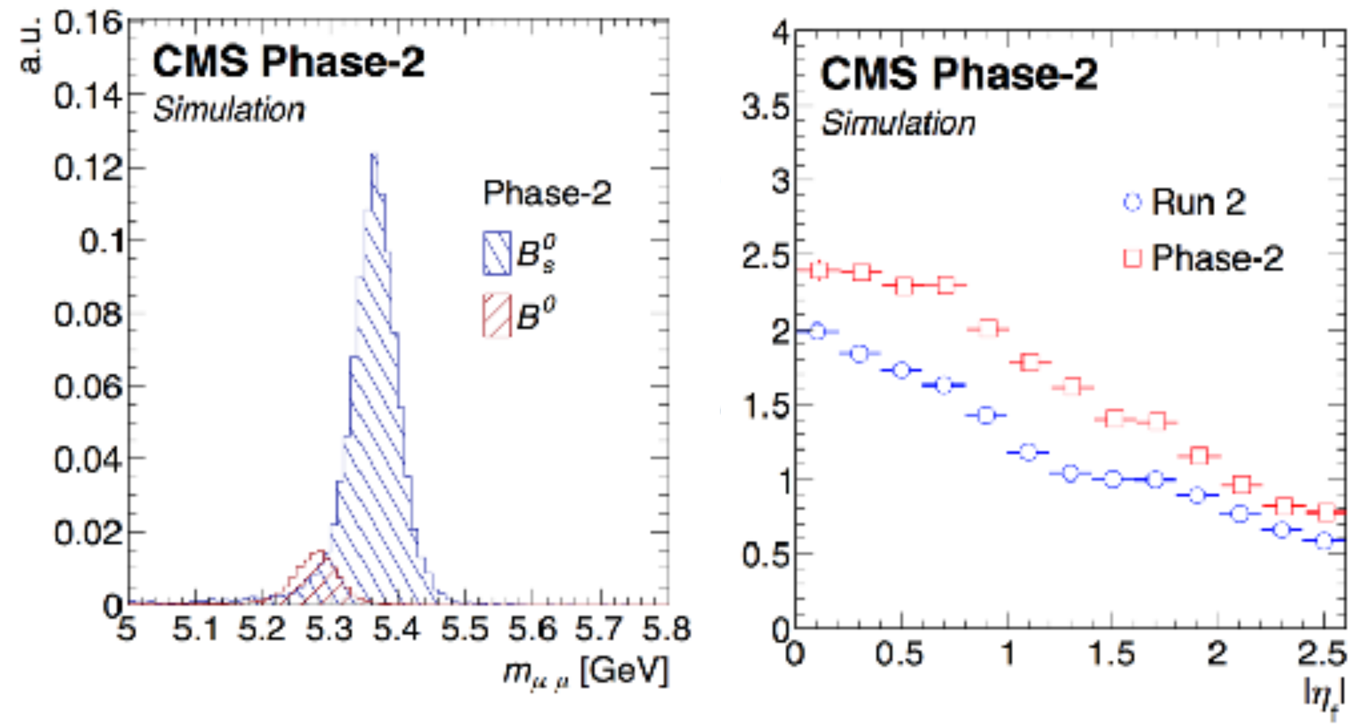
Precision Physics : Bs $\rightarrow \mu^+\mu^-$

- **This analysis of $B_s \rightarrow \mu^+\mu^-$ will become a precision measurement, and the observation of the decay of B^0 to two muons is expected to reach a significance of 6.8 σ.**

- **This result places very strict constraints on models of new physics**

- **Companion decay of B_d has a branching fraction factor of 30 lower. Improving the precision of the B_s measurement and observing B_d decay (its branching fraction) are important goals of HL- LHC.**

- **Gain in di-muon mass resolution as discussed earlier leads to 25% significance gain in separation B_d/B_s.**



Summary

- HL-LHC offers exciting physics perspectives with challenging conditions.

- Main challenge is to mitigate large pile-up interactions.
  - Trigger with increased bandwidth
  - Increased granularity of calorimeter endcap detectors and more coverage in eta.
  - Timing information from MIP timing detector

- Baseline for the upgraded detectors is defined.

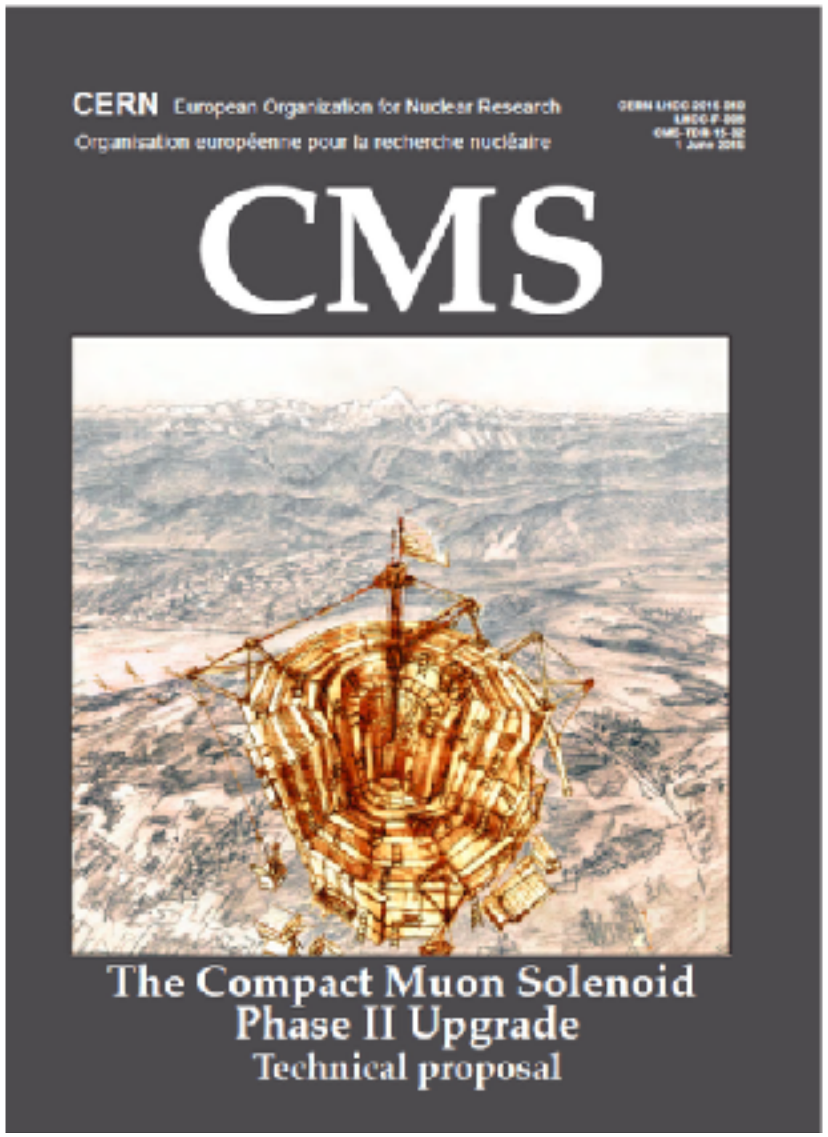
- We look forward to exciting physics program in coming years.

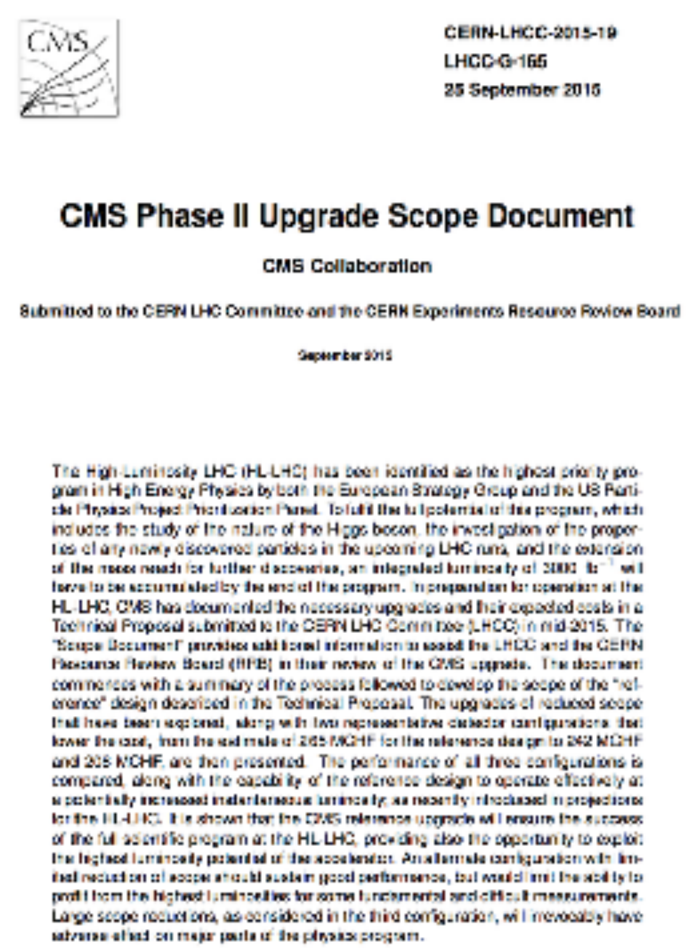
References

- CMS Collaboration, "Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid", Technical Report CERN-LHCC-2015-010, LHCC-P-008, 2015.
- CMS scope document LHCC-G-165, 2015.
- Documents on ATLAS and CMS Public Results pages
- For details see presentations at the HL/HE-LHC kick-off workshop at CERN: https://indico.cern.ch/event/647676/.
- Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex]
- Slides of previous talks by colleagues
  - Some of which I have shamelessly borrowed/co from (many thanks).

Status of documentation

- CMS technical proposal and scope document till 2016





CERN-LHCC-2015-19
LHCC-G-165
25 September 2015

CMS Phase II Upgrade Scope Document

CMS Collaboration

Submitted to the CERN LHC Committee and the CERN Experiments Resource Review Board

September 2015

The High-Luminosity LHC (HL-LHC) has been identified as the highest priority program in High Energy Physics by both the European Strategy Group and the US Particle Physics Project Prioritization Panel. To fulfil the full potential of this program, which includes the study of the nature of the Higgs boson, the investigation of the properties of any newly discovered particles in the upcoming LHC runs, and the extension of the mass reach for further discoveries, an integrated luminosity of 3000 fb^{-1} will have to be accumulated by the end of the program. In preparation for operation at the HL-LHC, CMS has documented the necessary upgrades and their expected costs in a Technical Proposal submitted to the CERN LHC Committee (LHCC) in mid-2015. The "Scope Document" provides additional information to assist the LHCC and the CERN Resource Review Board (RRB) in their review of the CMS upgrade. The document commences with a summary of the process followed to develop the scope of the "reference" design described in the Technical Proposal. The upgrades of reduced scope that have been explored, along with two representative detector configurations that lower the cost, from the estimate of 265 MCHF for the reference design to 242 MCHF and 205 MCHF, are then presented. The performance of all three configurations is compared, along with the capability of the reference design to operate effectively at a potentially increased instantaneous luminosity, as recently introduced in projections for the HL-LHC. It is shown that the CMS reference upgrade will ensure the success of the full scientific program at the HL-LHC, providing also the opportunity to exploit the highest luminosity potential of the accelerator. An alternate configuration with limited reduction of scope should sustain good performance, but would limit the ability to profit from the highest luminosities for some fundamental and difficult measurements. Large scope reductions, as considered in the third configuration, will irrevocably have adverse effect on major parts of the physics program.

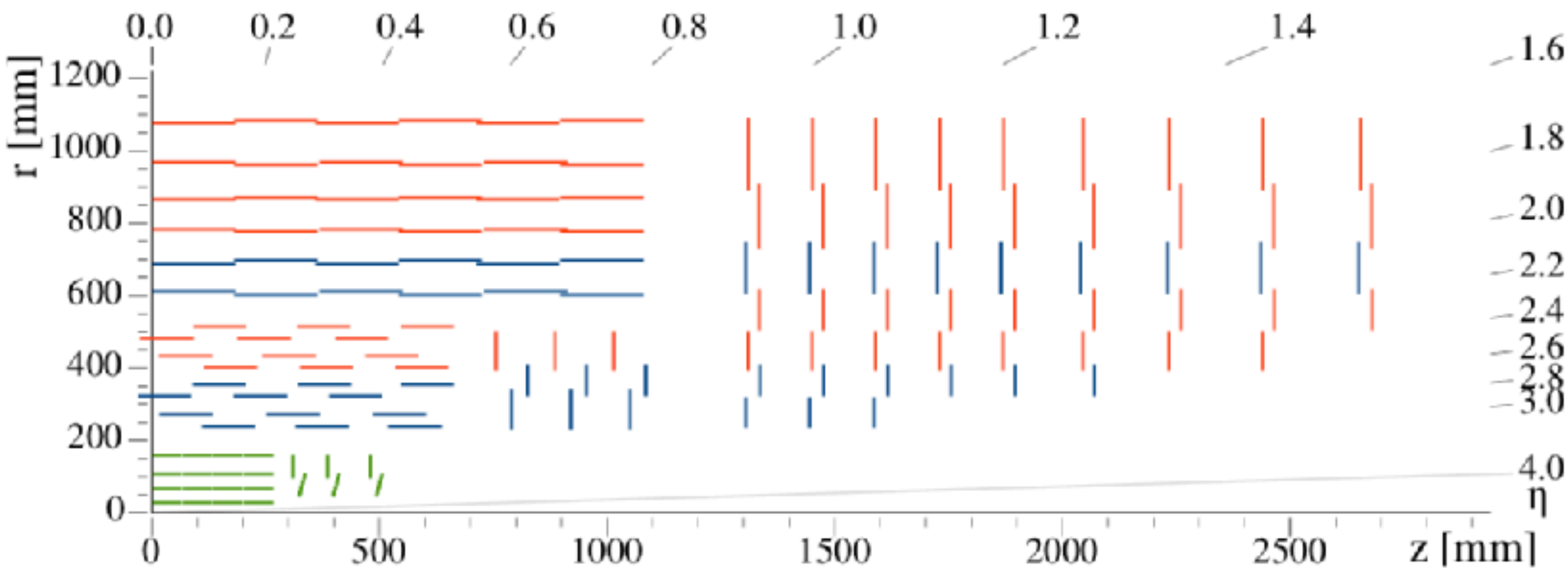
CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886
CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167

TDR's this year for sub-detector systems being prepared and under review.

Tracker, Muon and Barrel TDR's submitted to LHCC

Phase-1 Tracker

The radial region below 200 mm is equipped with pix- elated detectors. Beyond 200 mm, the present tracker features single-sided strip modules and double-sided modules composed of two back-to-back silicon strip detectors with a stereo angle of 100 mrad. Double-sided modules provide coarse measurements of the *z* and *r* coordinates in the barrel and endcaps, respectively. The tracking system was designed to provide coverage up to a pseudorapidity of $|\eta| \approx 2.4$.



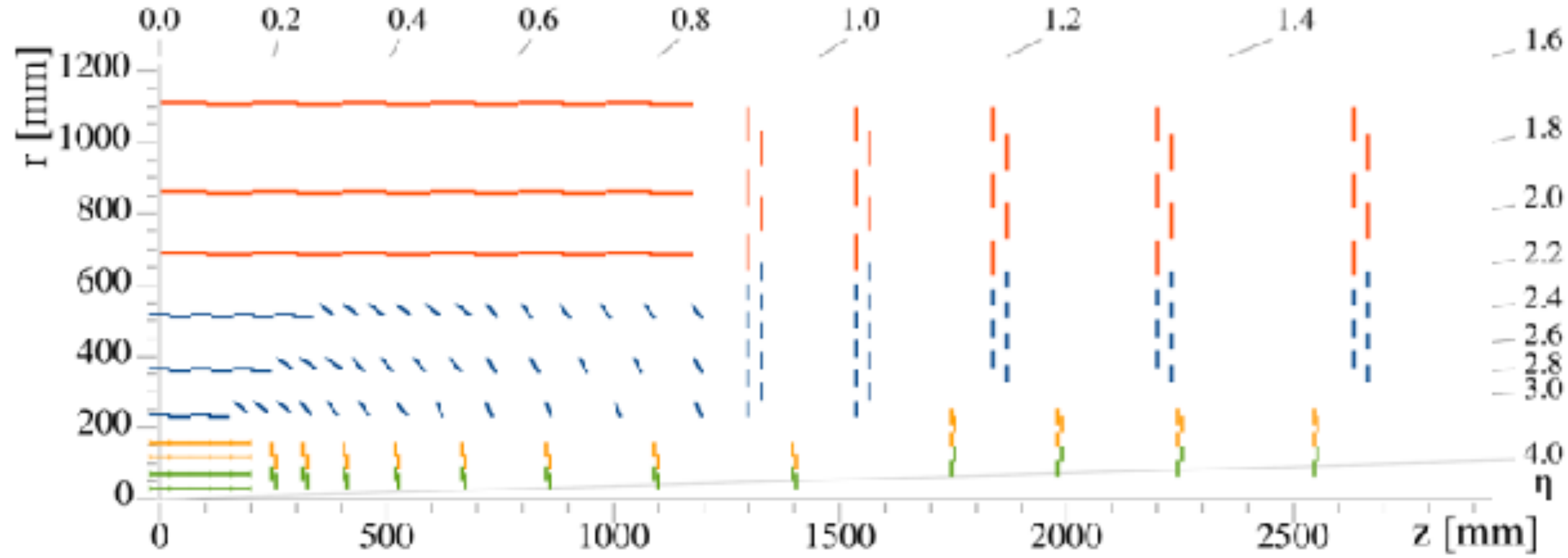
It has been demonstrated that basically all double-sided strip modules cannot be operated anymore at the nominal cooling temperature already after 1000 fb^{-1}.

CMS Tracker upgrade

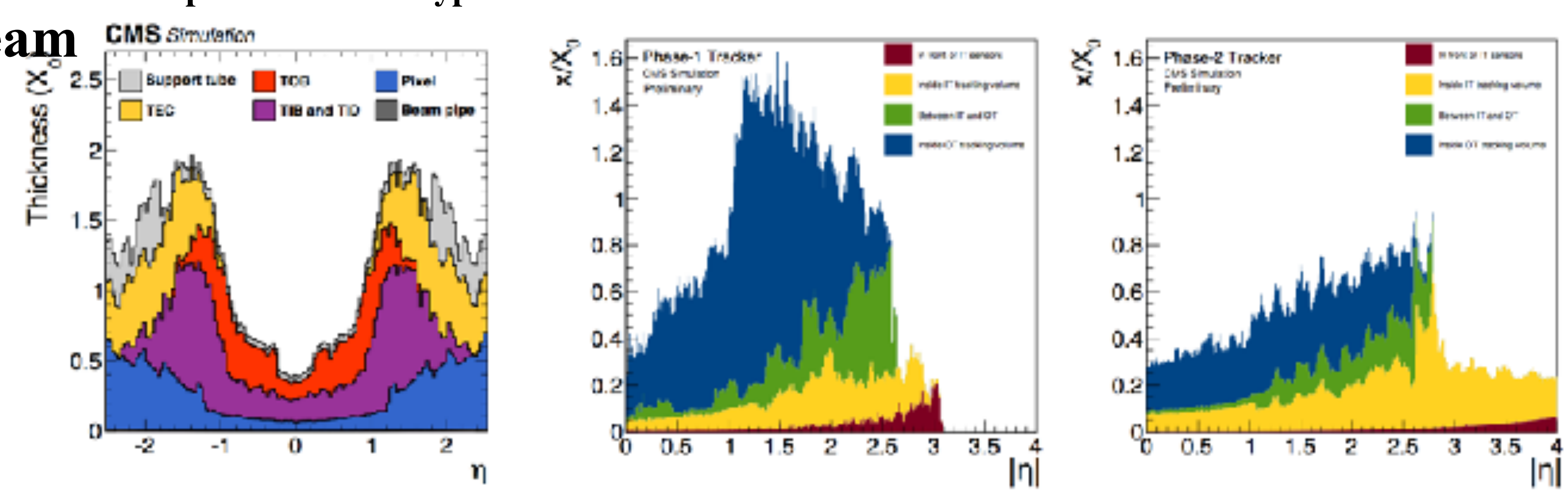
Outer tracker:
- Double-layer modules for trigger purpose
- Higher granularity
  - 4 times current

Pixel Tracker:
- 12 forward disk covering up to $\eta=4$
- inner layer at ~3cm from beam line

Mechanics and electronics:
- low material budget
- operations at -40 C
- Readout at 750kHz



Inner Tracker the green lines correspond to pixel modules made of two readout chips and the yellow lines to pixel modules with four readout chips. In the Outer Tracker the blue and red lines represent the two types of modules PS and 2S.



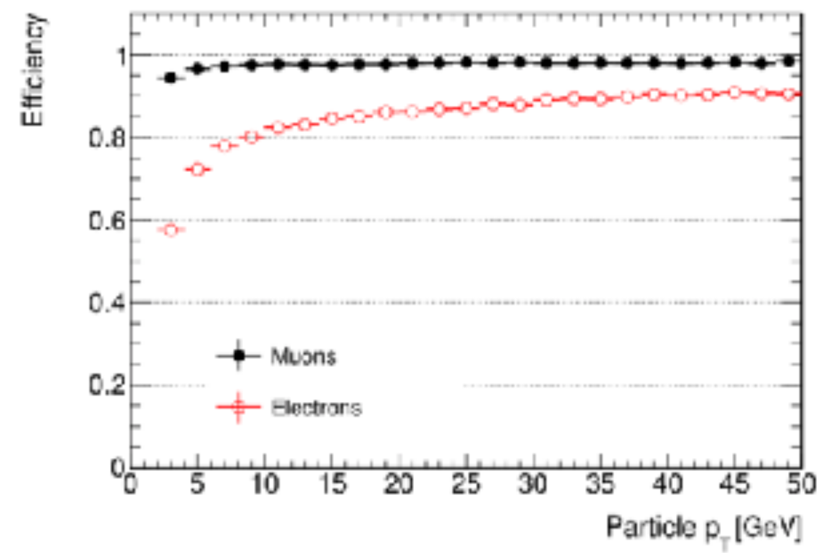
(a) Phase-0 (b) Phase-1 (Now) (c) Phase-2

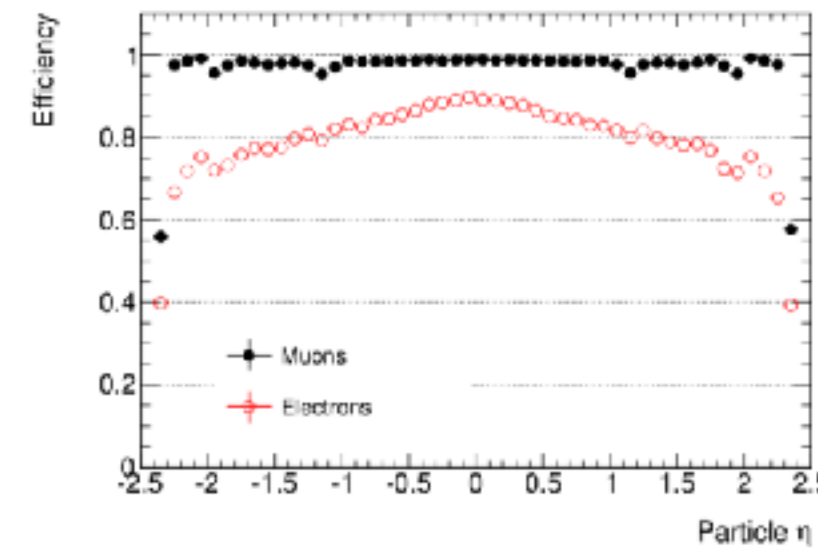
L1 trigger enables the tracker has to send out self-selected information at every bunch crossing. Such functionality relies upon local data reduction in the front-end electronics, in order to limit the volume of data that has to be sent out at 40 MHz.

CMS tracker performance

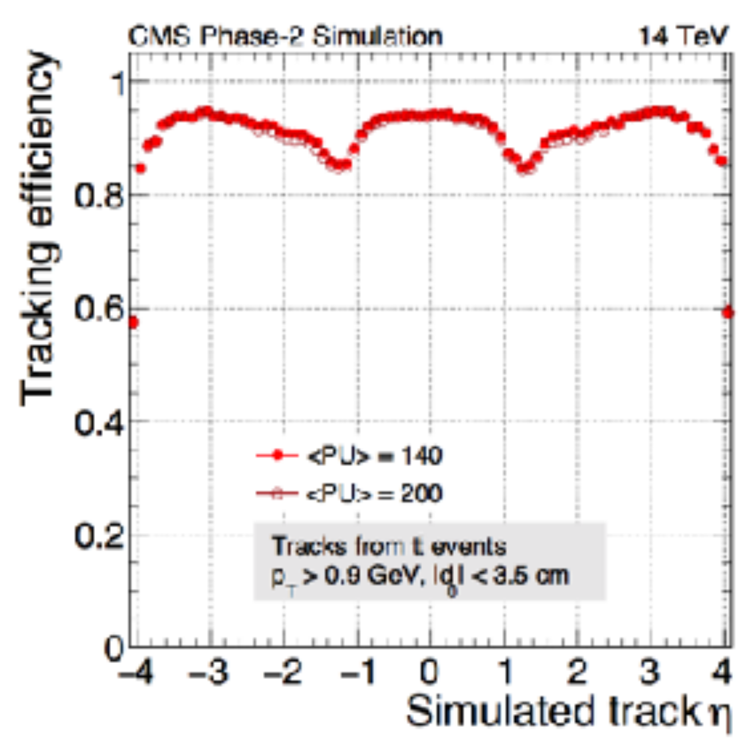
- The L1 track trigger will be a fundamental (and unique!) asset in HL-LHC:
- allows to keep low thresholds in single objects
- enables PF-like PU mitigation and PF-like algorithms at L1

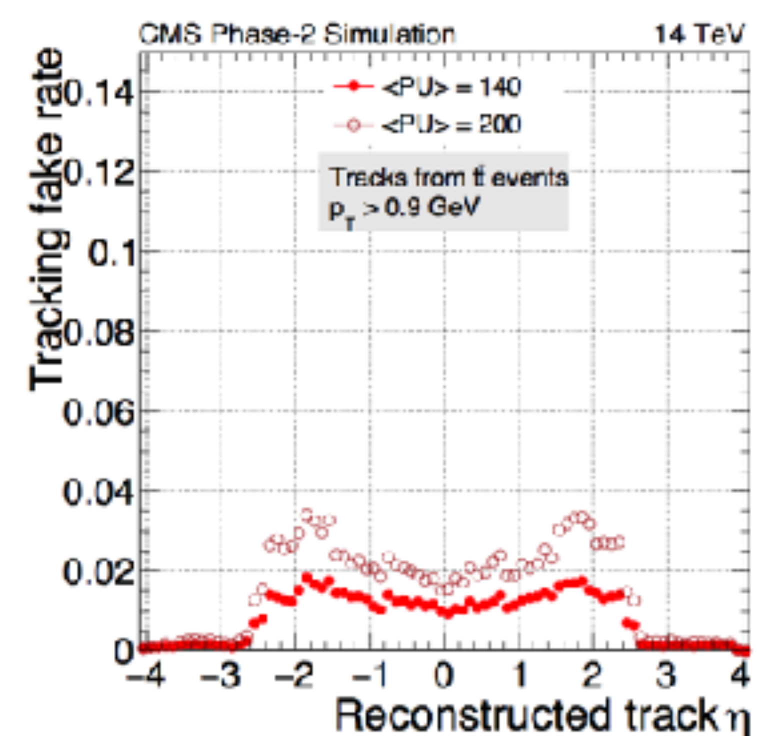
L1 - tracking efficiency





The improved coverage and reduced material budget allow to preserve and enhance basic tracking performance. Resolution on pT and IP will be almost a factor two better than current.





Offline tracking performance

CMS tracker performance

Offline tracking performance

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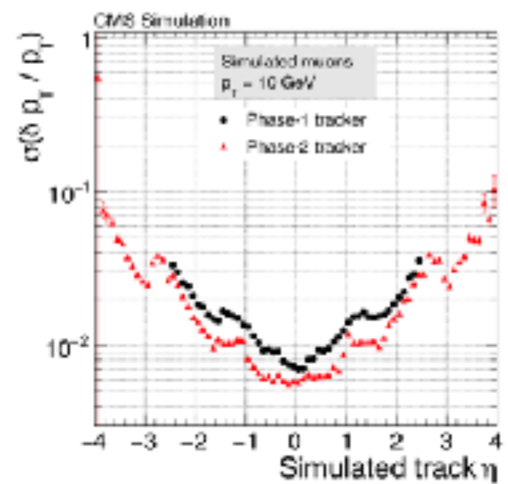
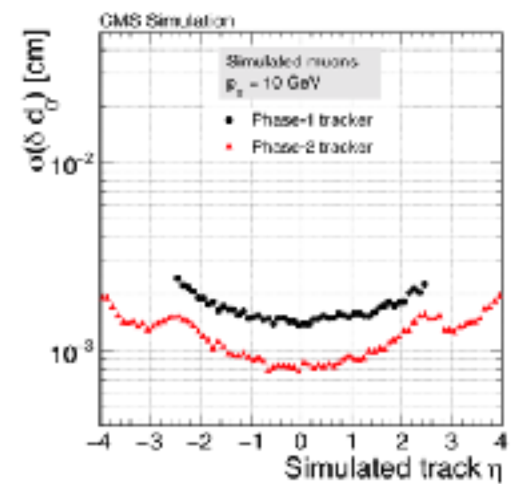
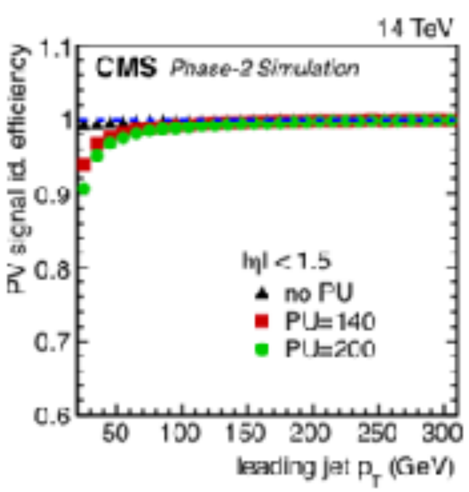
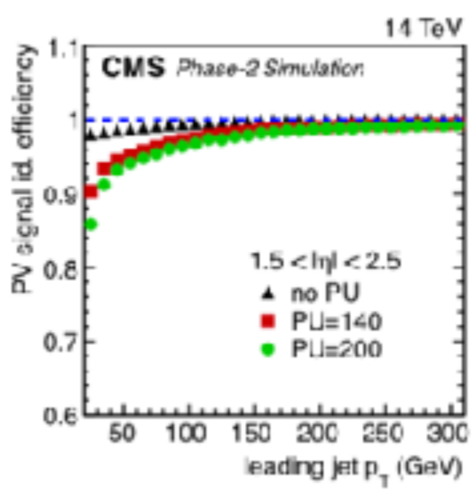
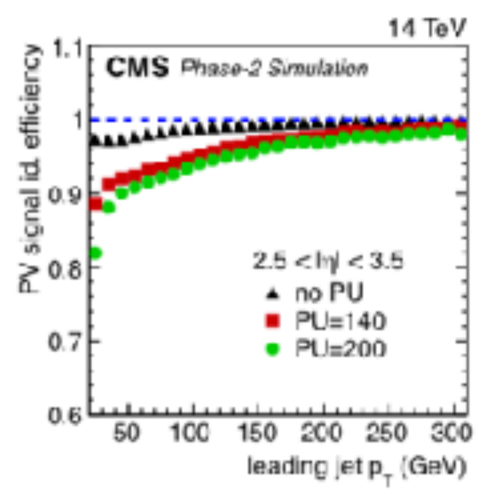


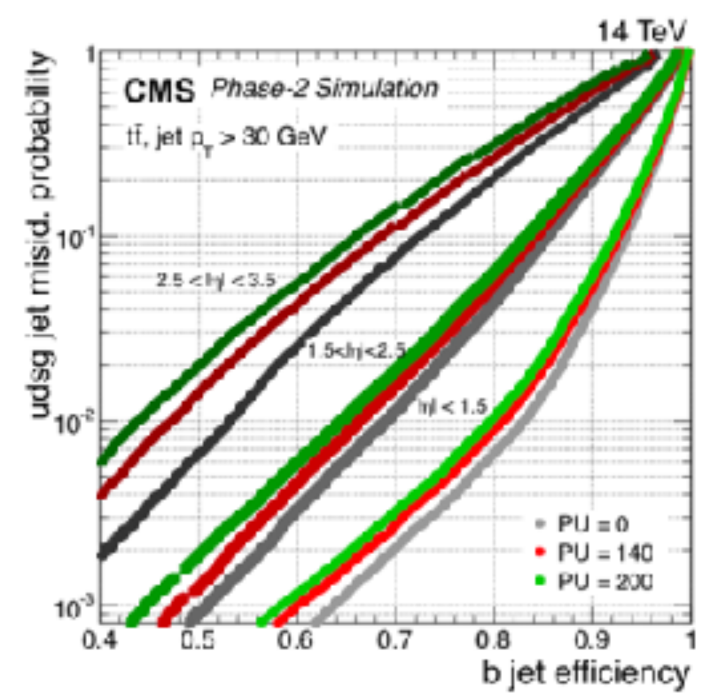








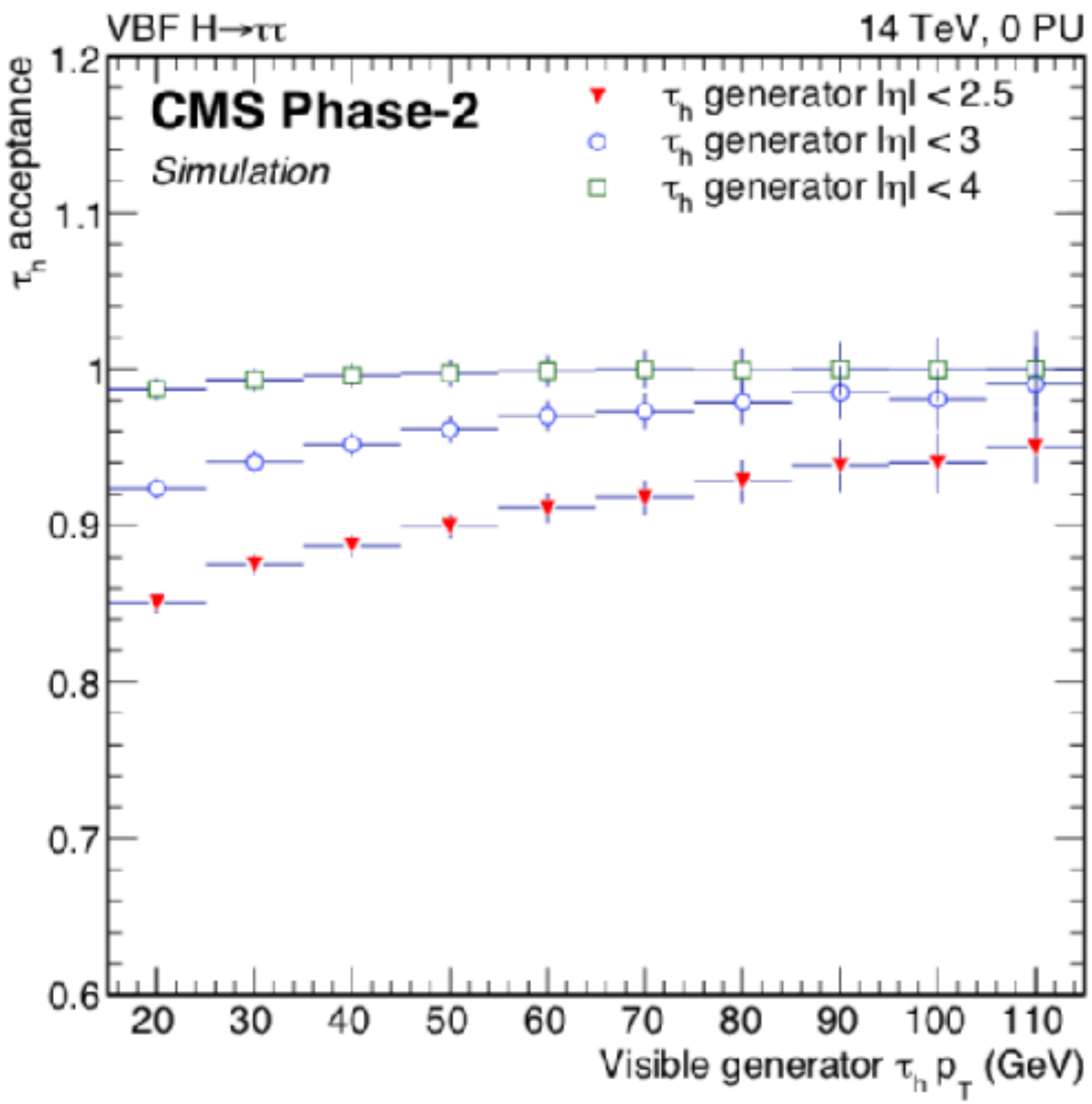
Efficiency of finding the generated primary vertex (PV) of the hard interaction, as a function of the leading jet pT in simulated multi-jet events



Performance of the b tagging in simulated tt events, expressed as misidentification probability for light jets(udsg) as a function of the bjet tagging efficiency

Physics potential enabled by upgraded detectors

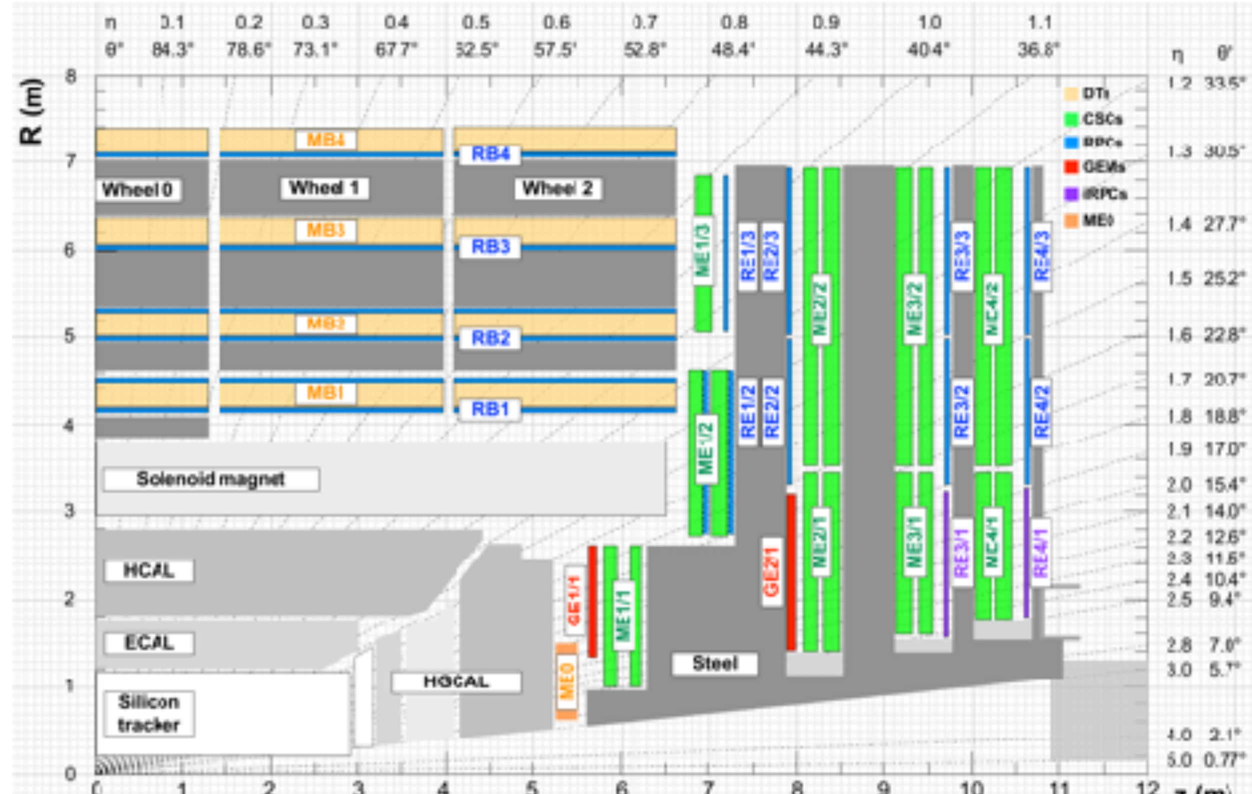
VBF topologies ($H \rightarrow \tau\tau$ in the specific) gain in acceptance



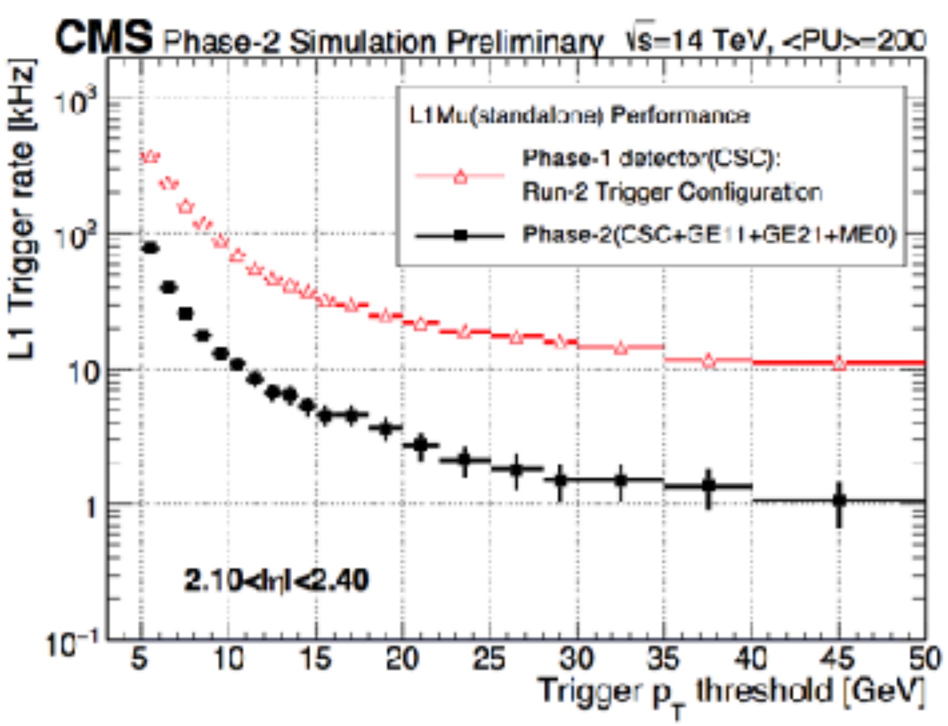
CMS Muon upgrades

Extension in 1.6 < |η| < 2.4:

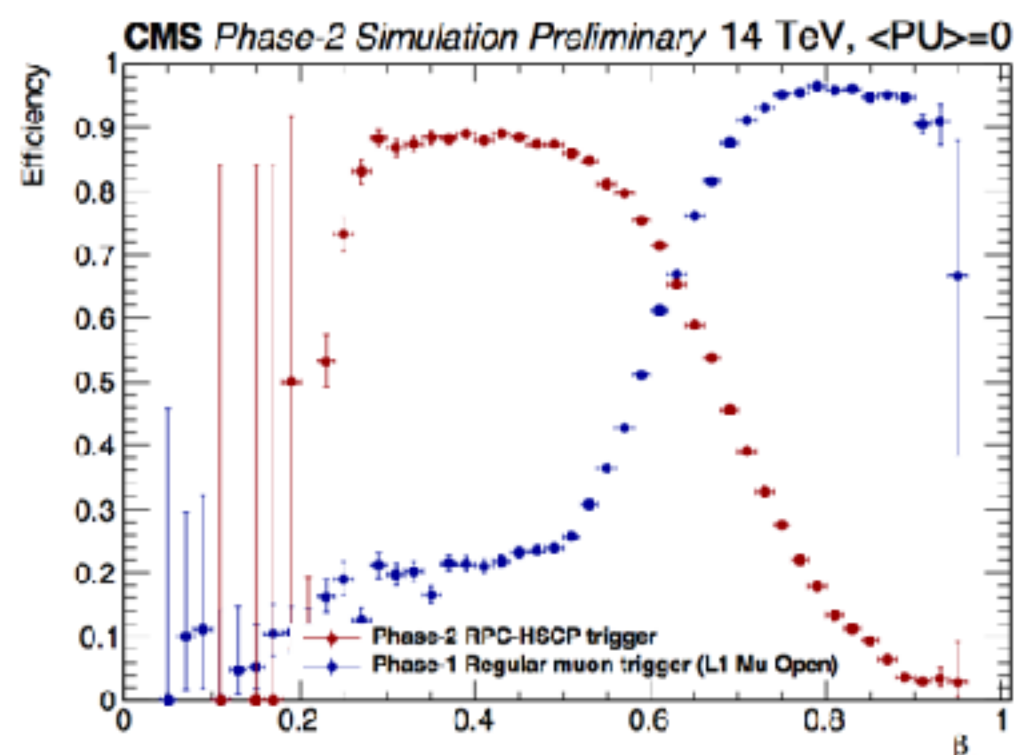
- **GEM chambers in front of existing forward muon (CSC) system.**
- **RPC's to improve trigger. Timing capabilities enable long lived/displaced muons triggering at an acceptable rate.**



Muon subsystem Detector technology	RE3/1 + RE4/1 iRPC	GE1/1 GEM	GE2/1 GEM	ME0 GEM
$\|\eta\|$ range	1.8–2.4	1.6–2.15	1.6–2.4	2.0–2.8



L1 prompt muon rate as a function of muon pT threshold

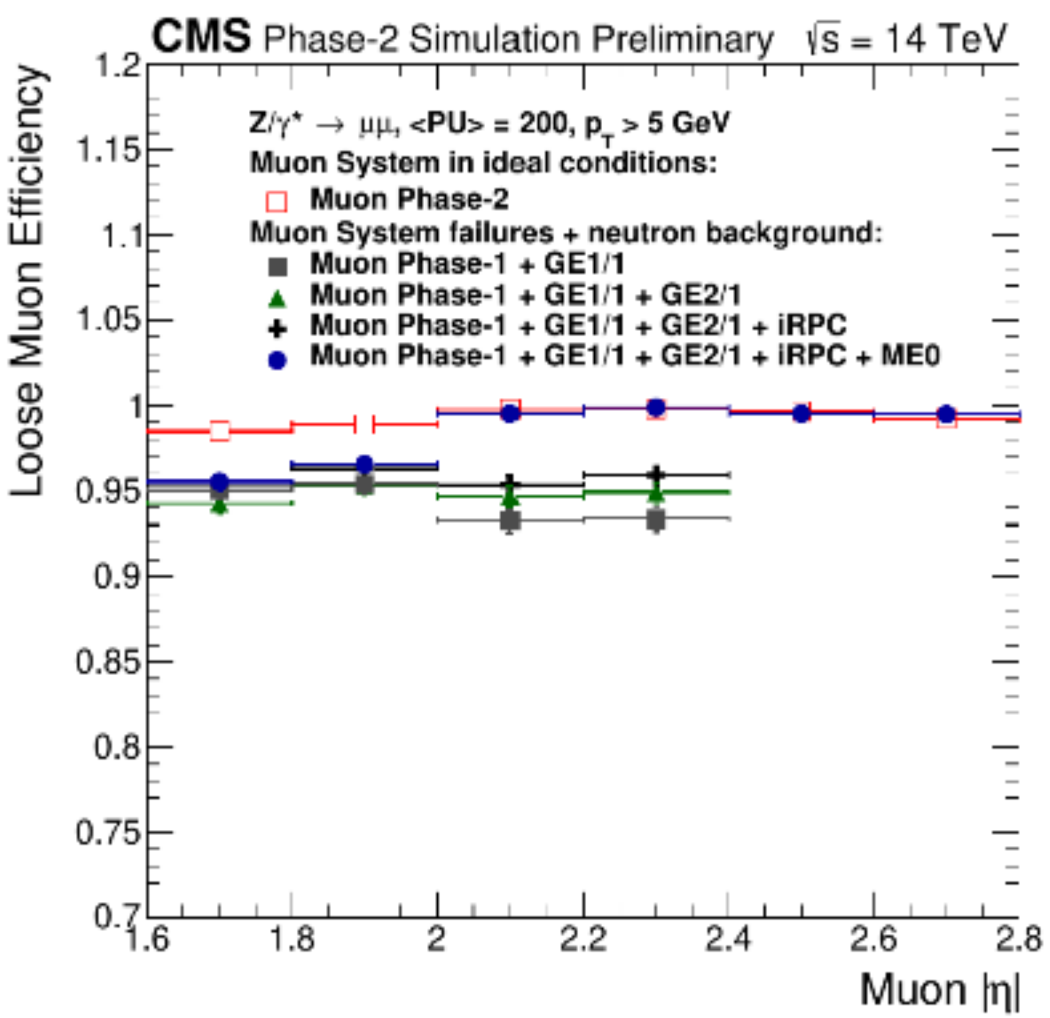


L1 Trigger efficiency as a function of an HSCP velocity β

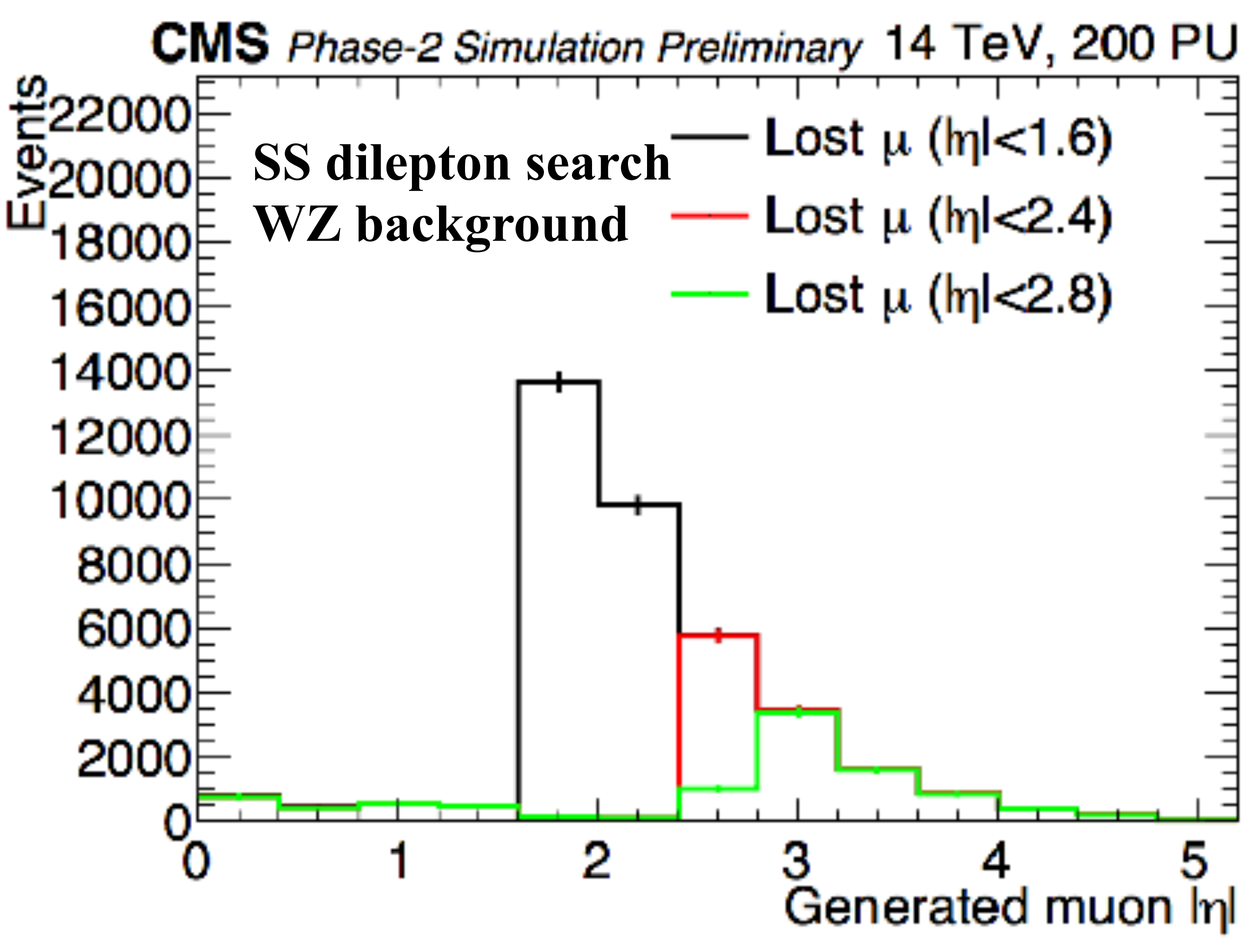
CMS Muon upgrades

Extensions in 2.4 < |η| < 2.8

- **ME0: New GEM chambers opens up new phase space**
- **Adds 0.4 pseudorapidity units to muon coverage with high performance**
- **Reduction in "lost lepton" background for searches with multileptons**



Muon reconstruction and identification efficiency

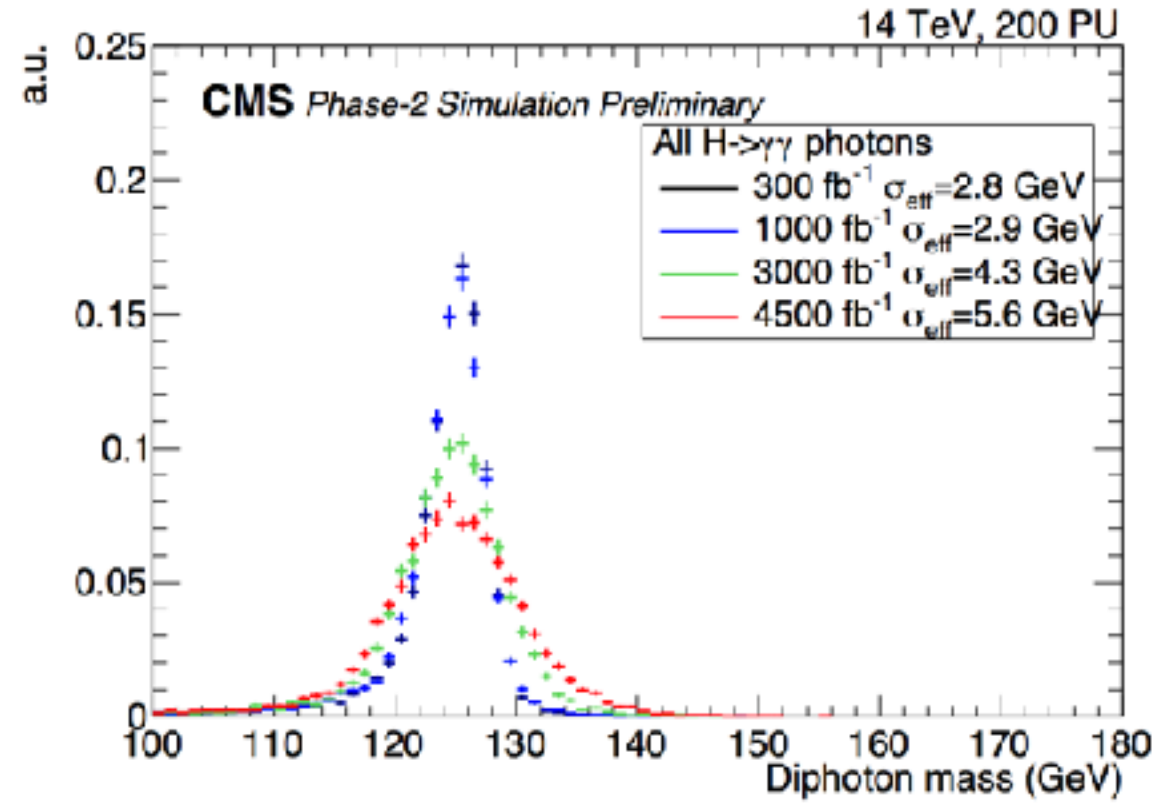


Number of WZ background events passing all selection criteria as a function of a "lost" muon's |*η*|

CMS Barrel calorimeter upgrades

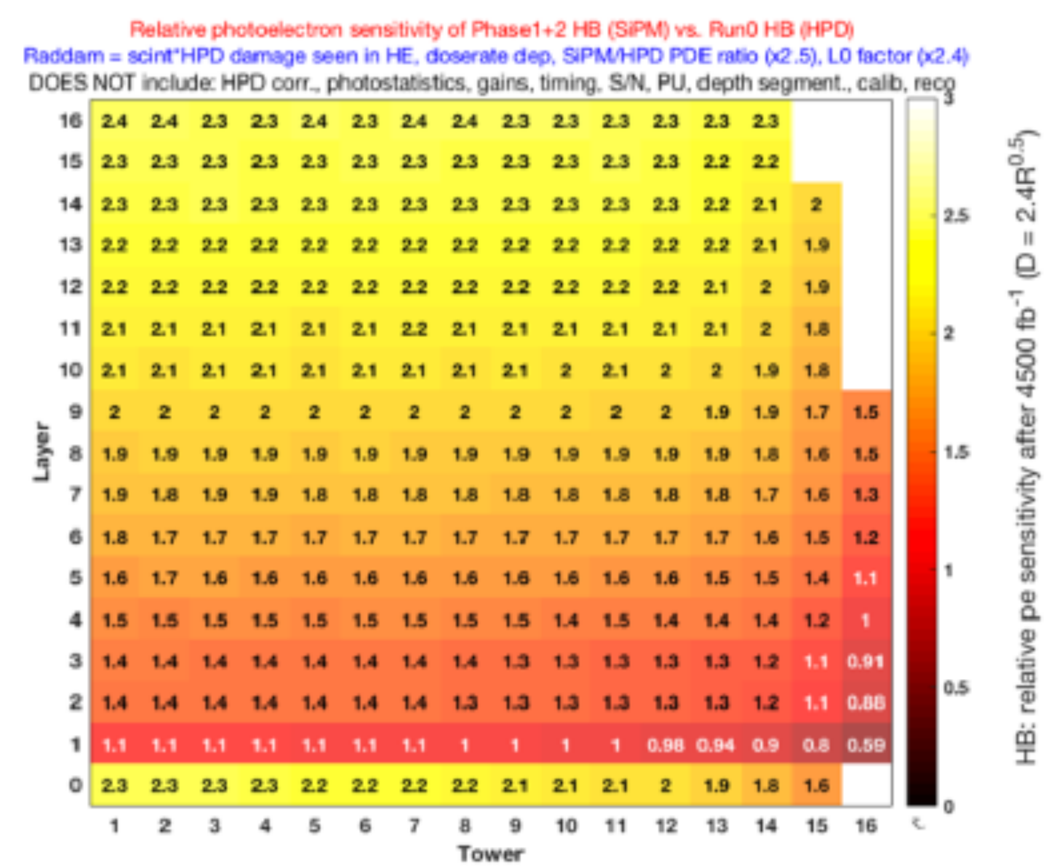
Electromagnetic calorimeter:

- Full detector granularity to hardware trigger (currently xtal towers)
- Upgrade electronics to accommodate trigger rate and latency requirements
- Significantly reduced shaping time and increase of sampling rate to 160 MHz for precision timing (30ps target), improved suppression of anomalous signals and out-of-time pileup



Hadronic barrel calorimeter

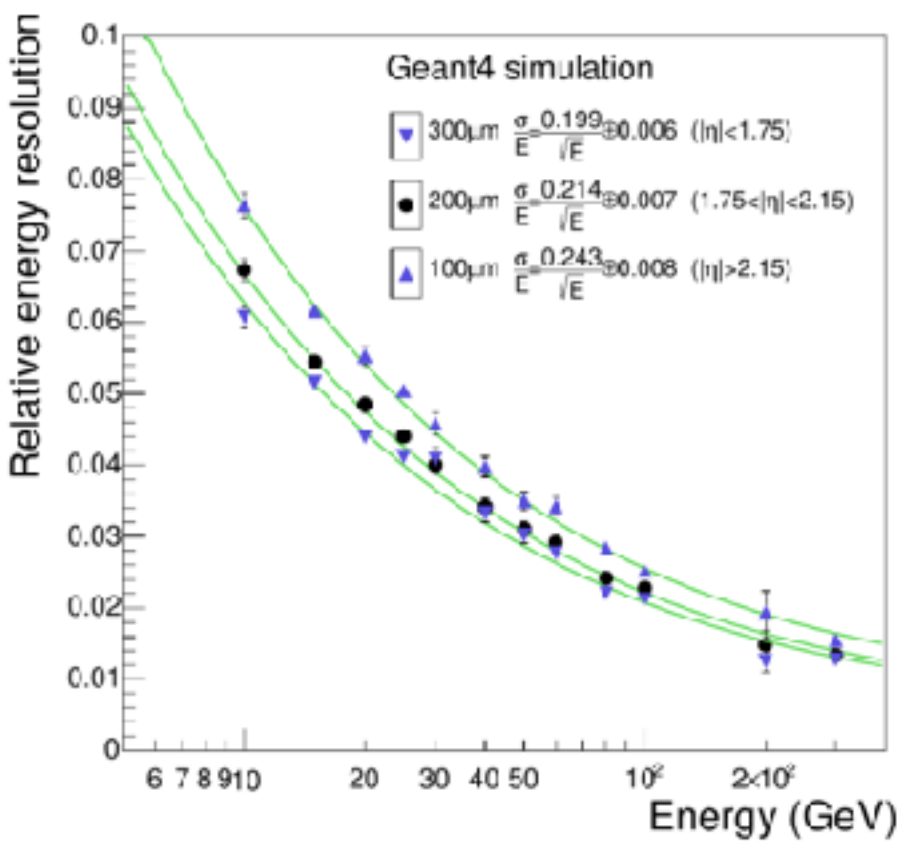
- Replacement of inner layers with radiation tolerant scintillator (still under discussion)
- New back-end electronics
- Usage of longitudinal granularity

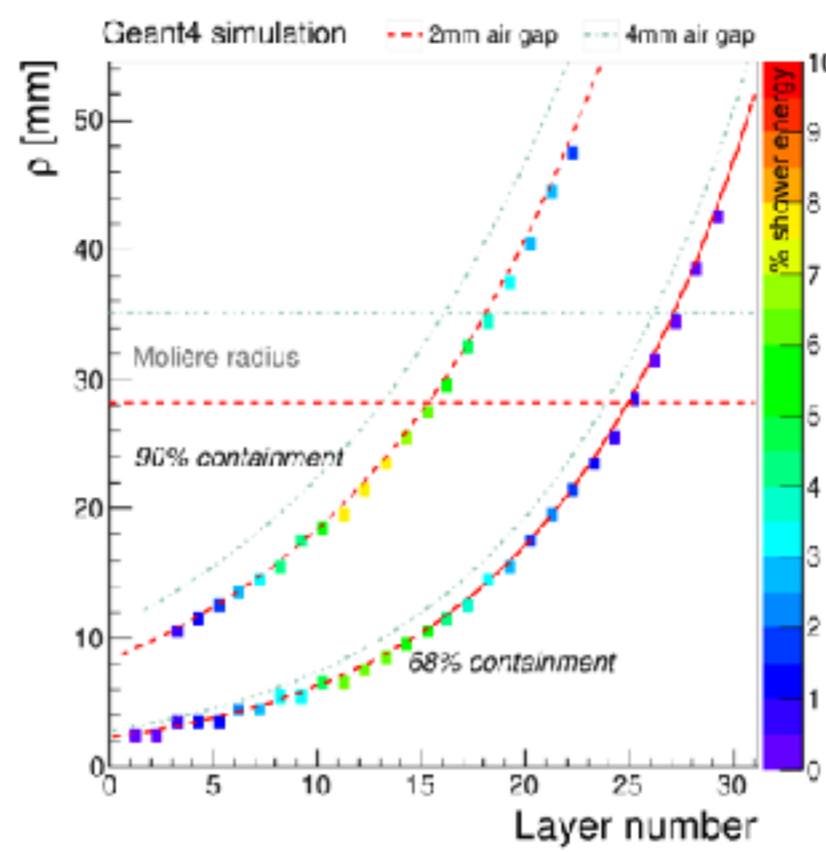


CMS End-Cap calorimeter upgrades

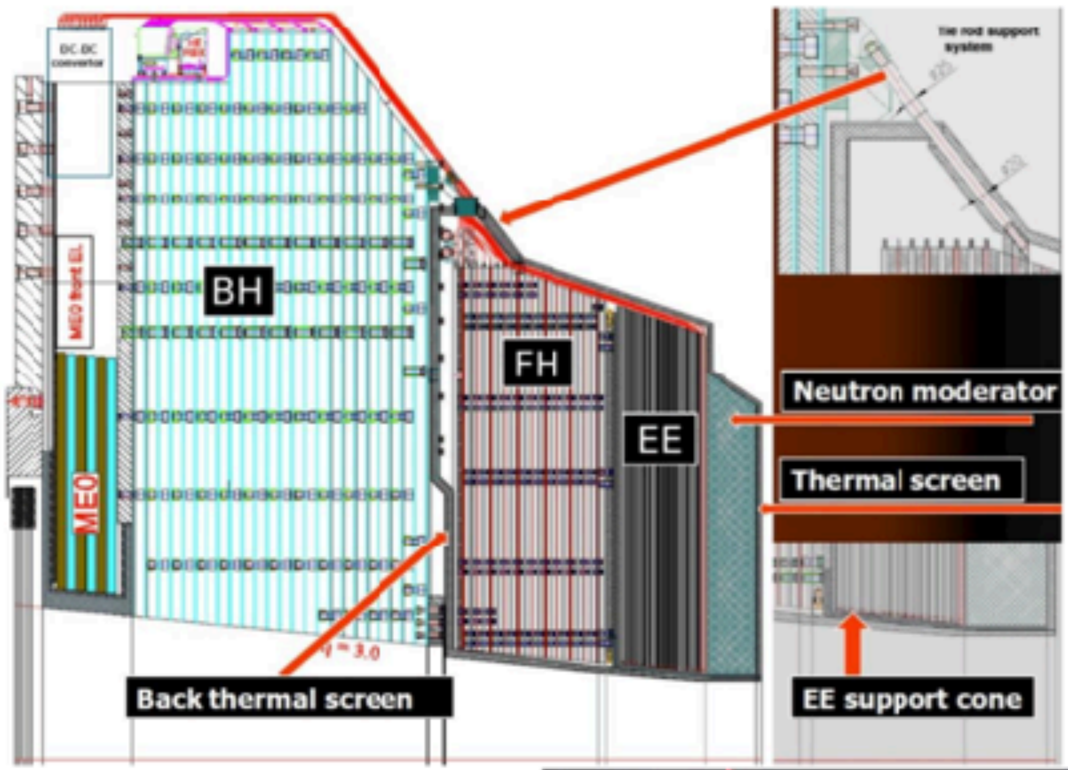
- The high granularity, both in transverse and longitudinal directions, gives powerful handles for pileup mitigation and detailed shower reconstructions.

- A full reconstruction is still in the making given that no past experience helps. Results will be shown soon in the Technical Design Report due by the end of the year.

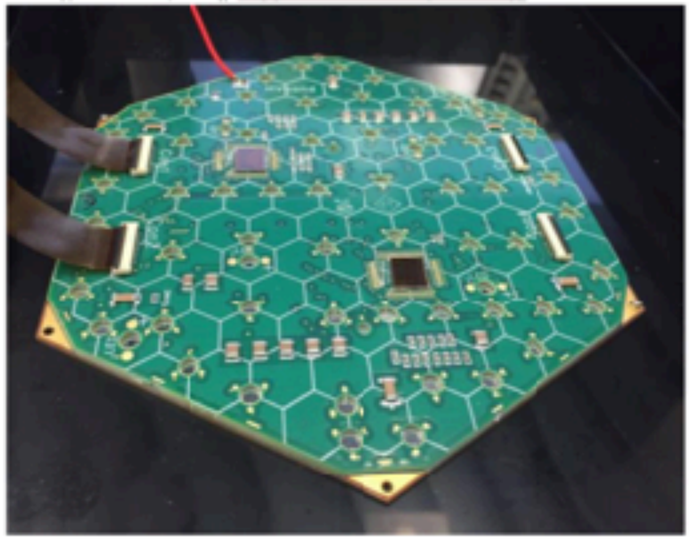




CMS End-Cap calorimeter upgrades



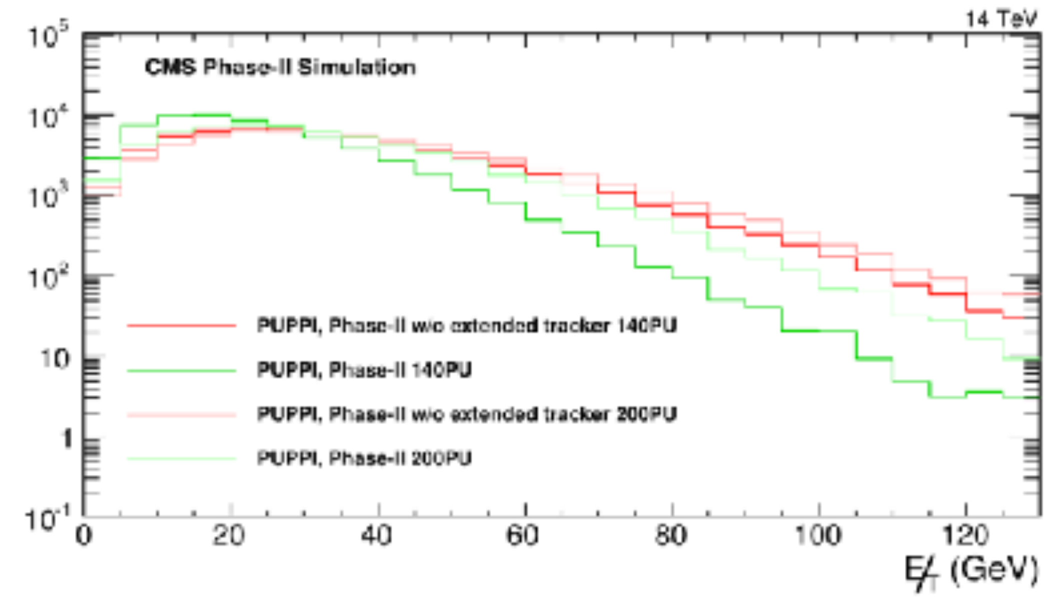
Complete module
Sensor+RO chip
ready for test



Challenging conditions push toward new paradigm:

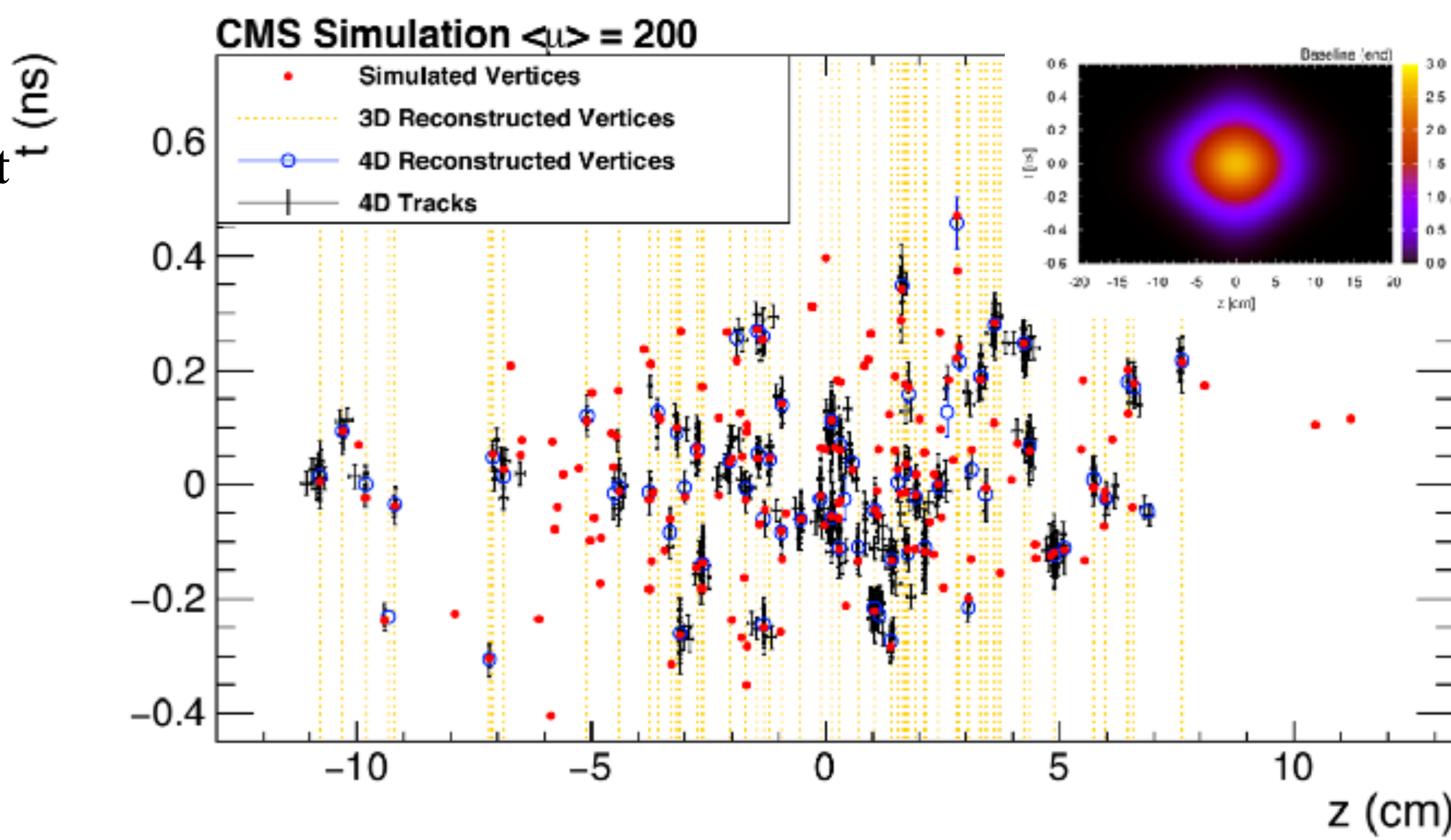
- High-granularity silicon-based readout (mixed silicon/ scintillator in back hadronic)
- Si/W EE, 26 X_0,1.5λ
- Si/Brass FH, 3.5λ
- mixed Si/Scint, Brass BH 5.0λ
- 6.1 Million channels

CMS MIP timing detector



Why do we need timing capability?

- **the number of PU events at HL-LHC will not allow to discriminate efficiently between hard scattering and PU vertices causing ambiguities and large tails.**



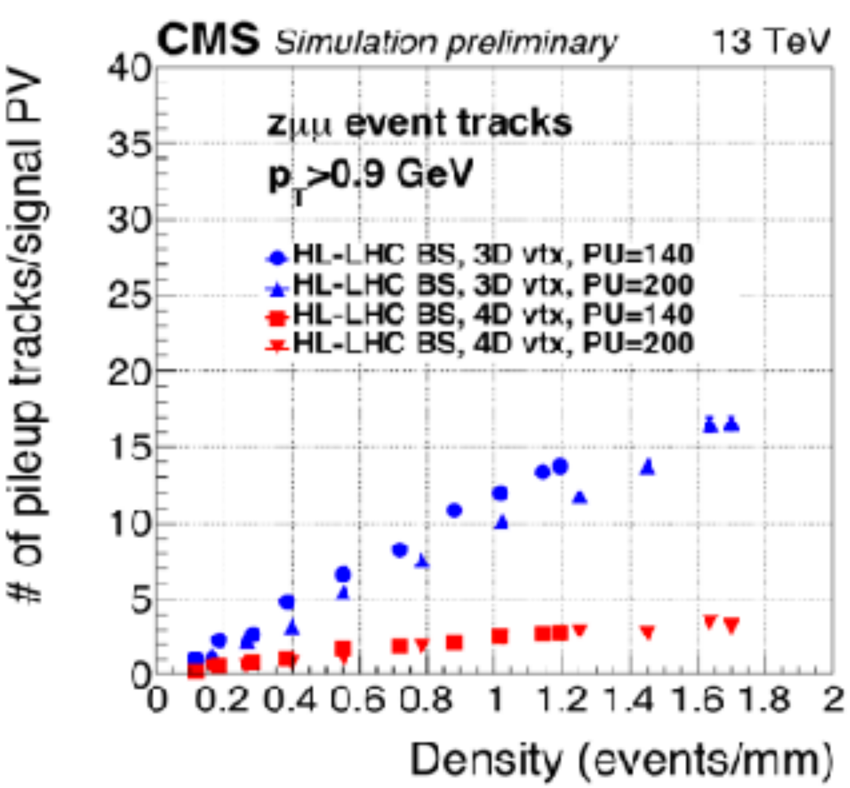
- **Vertices will be distributed in space but also in TIME.**

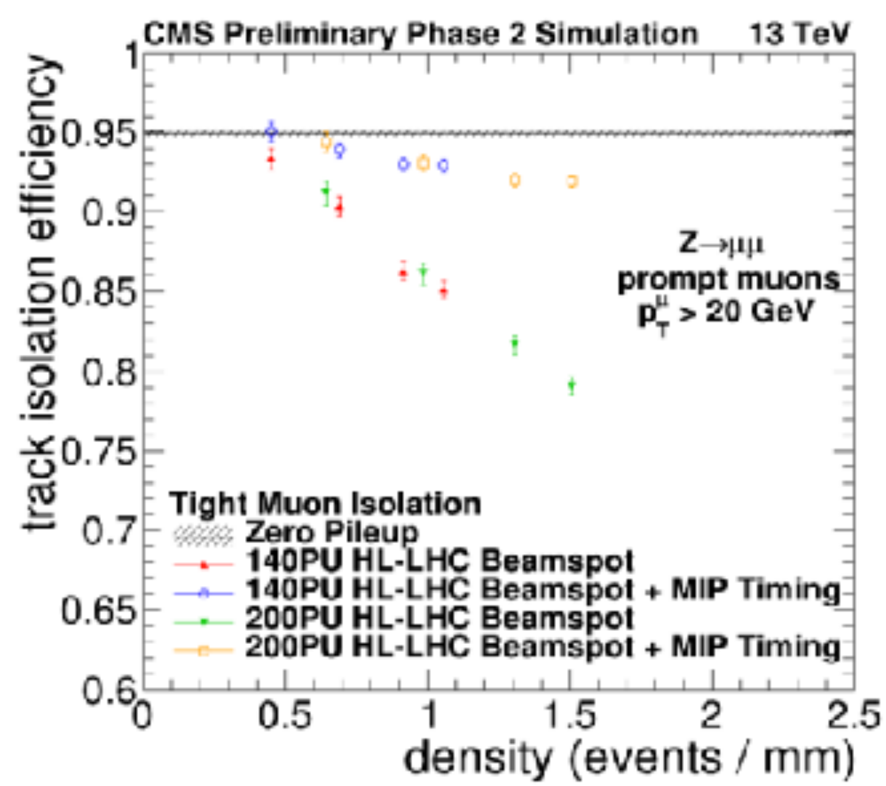
- **Timing associated to tracks (MIP) will be complementary to timing associated to calorimeter cluster and enable 4D vertexing, reducing the effective PU.**

CMS MIP timing detector

Concept for central region:
Thin LYSO + SiPM layer built into tracker barrel support tube (in between tracker and ECal Barrel)
→ precision timing for charged particles and converted photons

Concept for forward region (more stringent radiation hardness requirements):
LGAD (Silicon with Gain), with baseline location as additional final layer of strip tracker

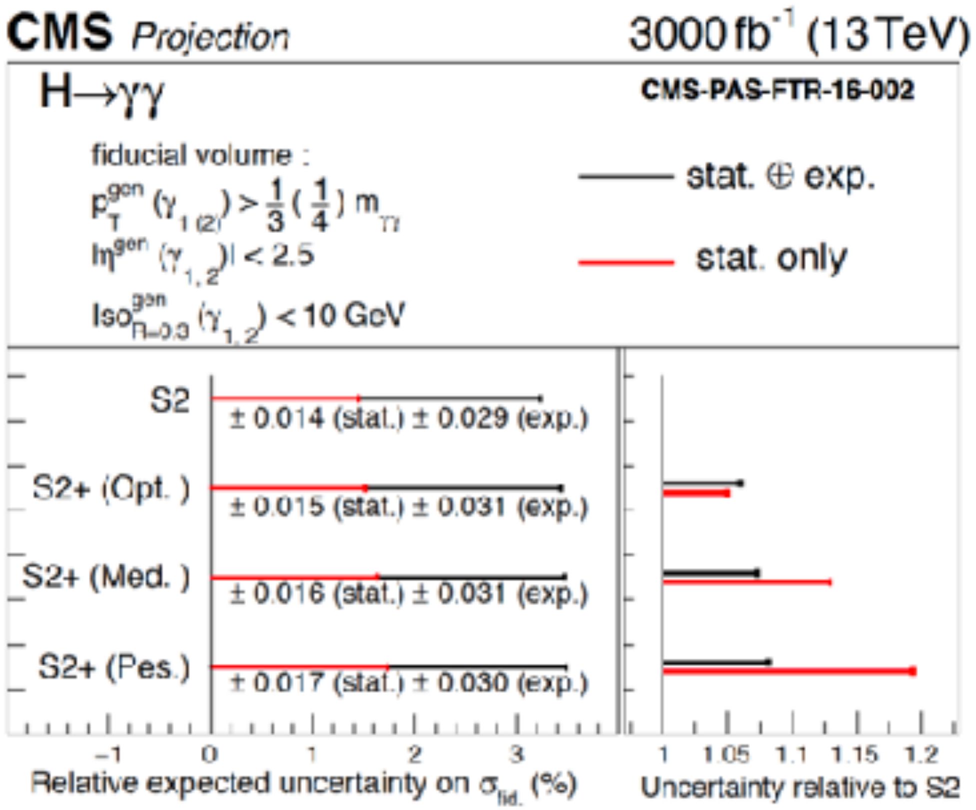




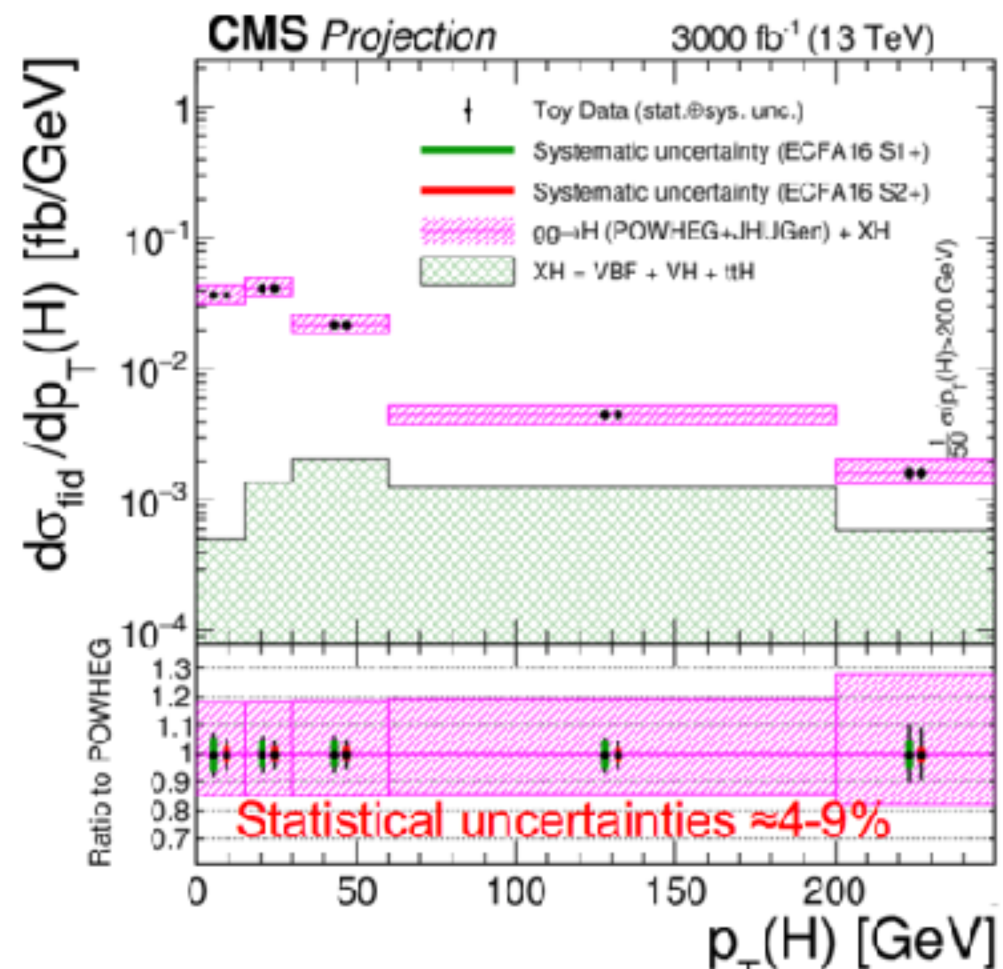
- **A reduction of 5 times effective pile-up in terms of charged tracks is expected**
- **a significant improvement in lepton isolation is expected as well as large effects on derived quantities (missing ET)**

Cross section Projections

The “5%” level is reachable!



Fiducial Cross Section (h→γγ)



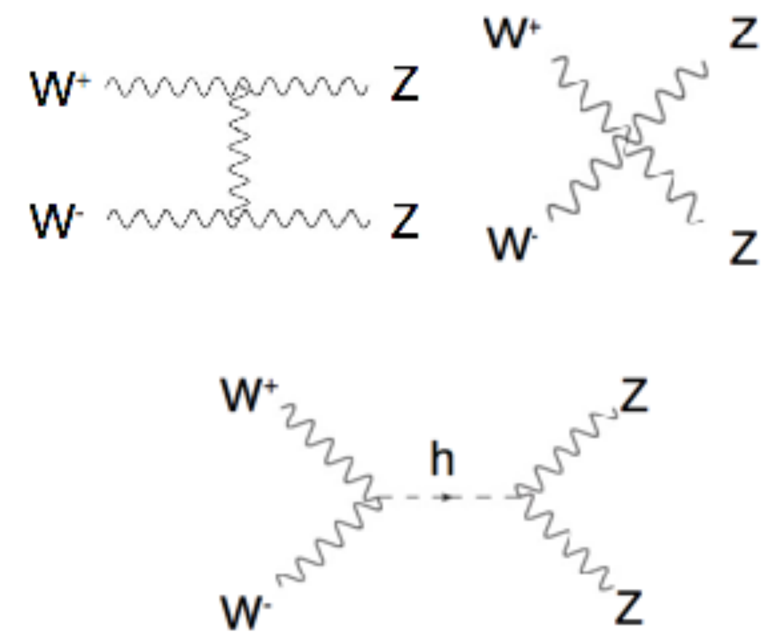
Differential pT(h) Cross Section (h→ZZ)

- Independent of theoretical uncertainty
- Improvement expected in mass resolution and uncertainty thanks to timing O(30 ps) for photons and charged particles

- Information on *new particles could be visible through its contribution to gluon fusion loop.
- Sensitive to kb/kc at low pT. kt/BSM (high)
- At high pT dominated by stat. uncertainty.
- At 300 fb-1 stat. uncertainty: 10-29%.

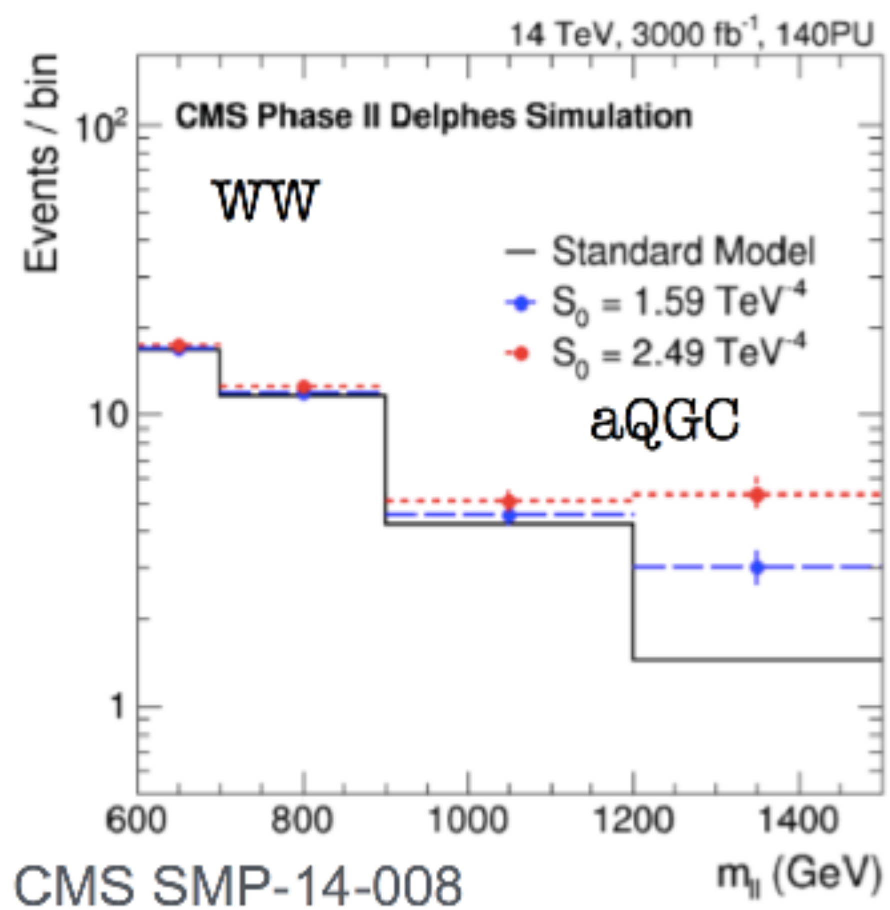
Precision Physics : Vector Boson Scattering

- **The longitudinal W scattering is one of the essential probes for studying effects of new physics.**



$V_L V_L \rightarrow V_L V_L$ (sensitivity to the longitudinal component of the vector boson scattering allows discovery significance up to 2.75σ (combining WWjj+WZjj)

Performance wrt the current limits on quartic anomalous gauge couplings



CMS SMP-14-008

HIP flag

The Phase-2 Inner Tracker will continue providing d*E*/d*x* measurements, enabled by its Time over Threshold readout, while the Outer Tracker cannot provide such information, given that the readout is binary. To increase the sensitivity for signatures with anomalously high ionization loss, a second, programmable, threshold has been implemented in the Short Strip ASICs of the PS modules of the Outer Tracker, and a dedicated readout bit signals if a hit is above this second threshold. Searches for heavy stable (or quasistable) charged particles (HSCPs) can thus be performed by measuring the energy loss in the Inner Tracker and by discriminating HSCPs from minimum ionizing particles based on the "HIP flag" in the Outer Tracker. The threshold of the minimum ionization needed to set the HIP flag is an adjustable parameter in the PS modules. A threshold corresponding to the charge per unit length of 1.4 MIPs, resulting from preliminary optimization studies, is used in the simulation, and the gain in sensitivity obtained by using the HIP flag is studied.