Universiteit Antwerpen

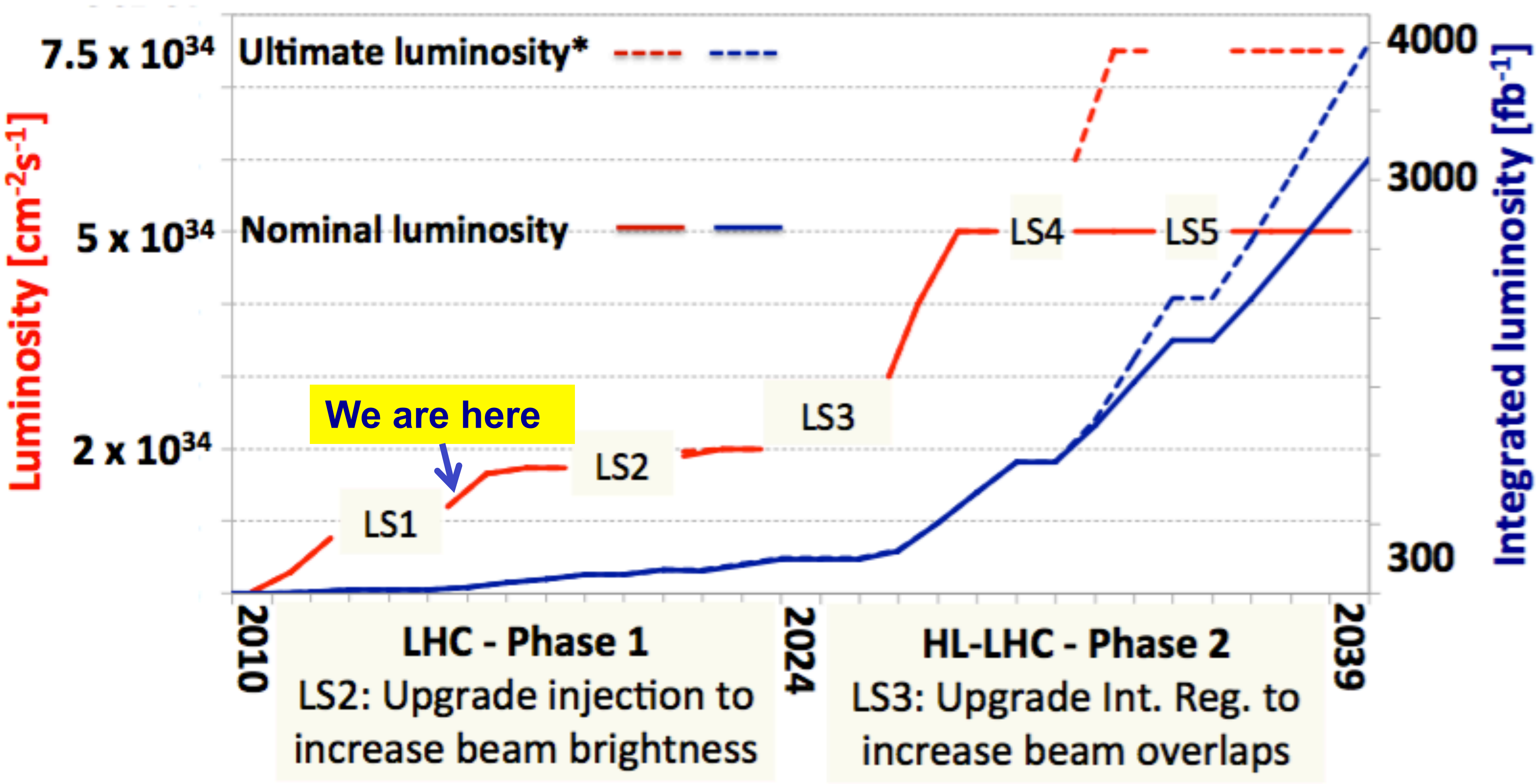
LHC/CMS High luminosity physics case

Xavier Janssen
University of Antwerp

IUAP WP8: Future Experiments
Antwerp, 19th Nov. 2015

High Luminosity LHC and CMS Upgrades

The High Luminosity LHC Upgrade

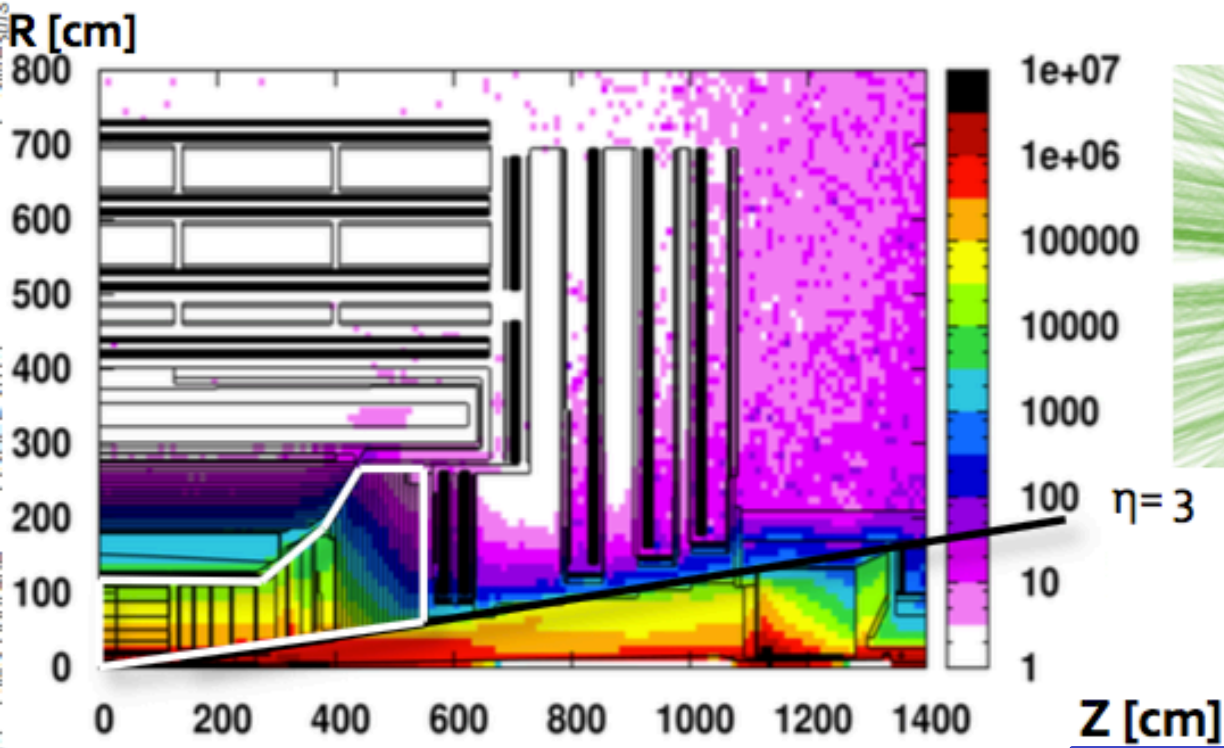


- LHC should collect up to 300 fb^{-1} before LS3
- High Luminosity LHC (HL-LHC) after LS3 should allow to collect 3000 fb-1 at $\sqrt{s}$ = 14 TeV between ~2025 and ~2039
  ➔ High Lumi ➔ High Pile-Up: 140 (200) events/beam crossing

Consequences for the experiments

High Radiation

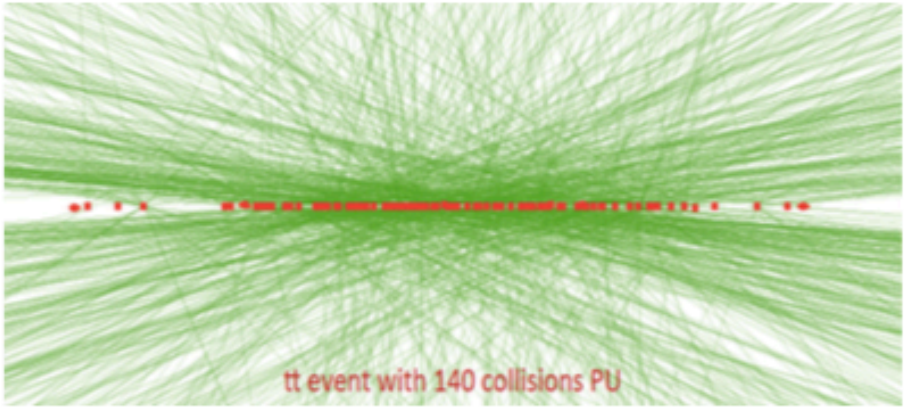
3000 fb^{-1} simulated Dose map in [Gy]



→ Aging studies show that Tracker & End cap Calorimeters need replacement to keep similar performances as in today detector

High Pile-Up

Top pair event with 140 pile-up



→ HL-LHC presents increased challenges for Triggering, Tracking and Calorimetry, in particular for low to medium p_T objects and forward region

→ Need to consolidate muon system

CMS Phase II Detector Upgrades

Tracker

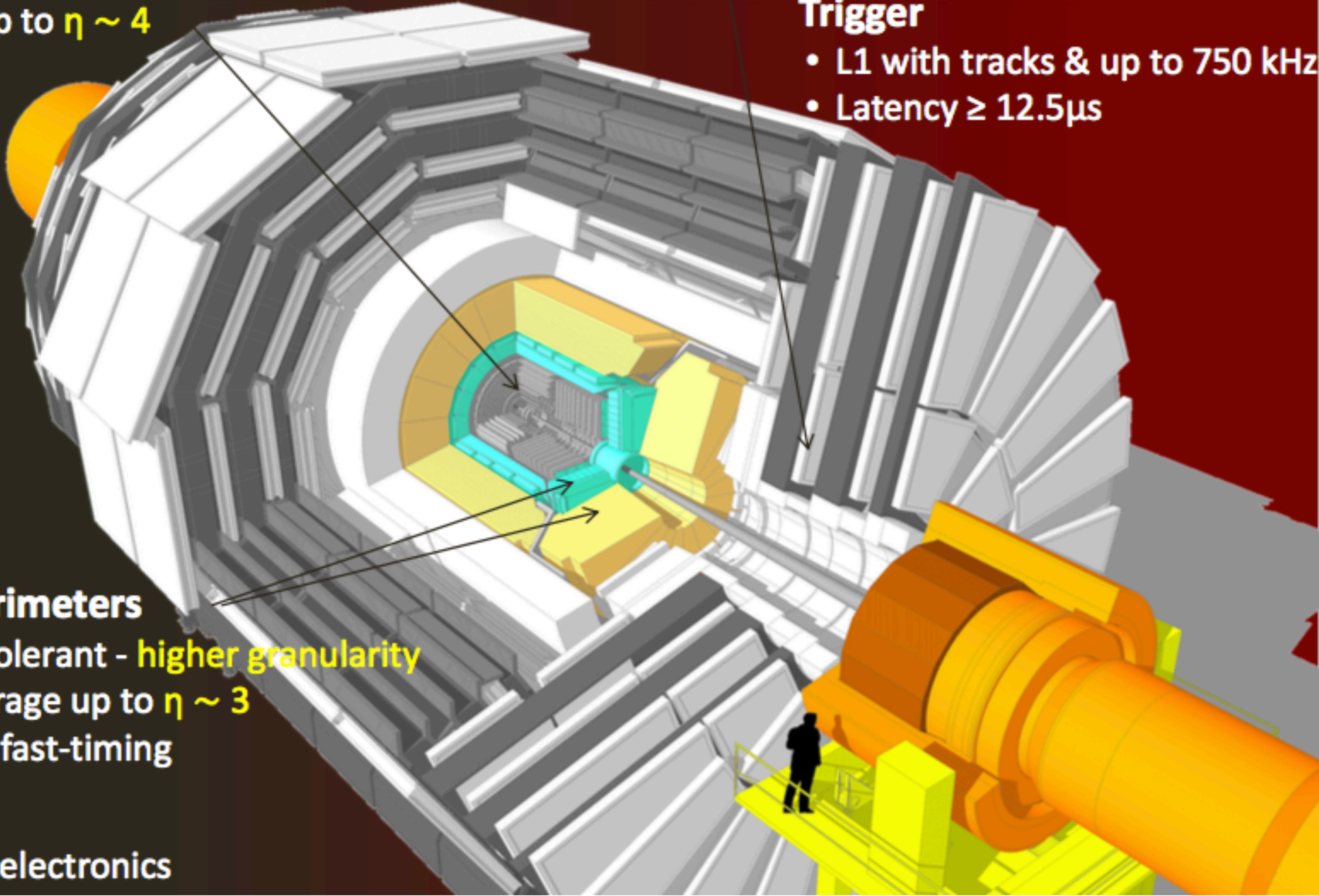
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons

- Complete coverage in forward region (new GEM/RPC technology) |η|>1.6
- Investigate muon-tagging up to η ~ 3

Trigger

- L1 with tracks & up to 750 kHz
- Latency ≥ 12.5µs



Endcap Calorimeters

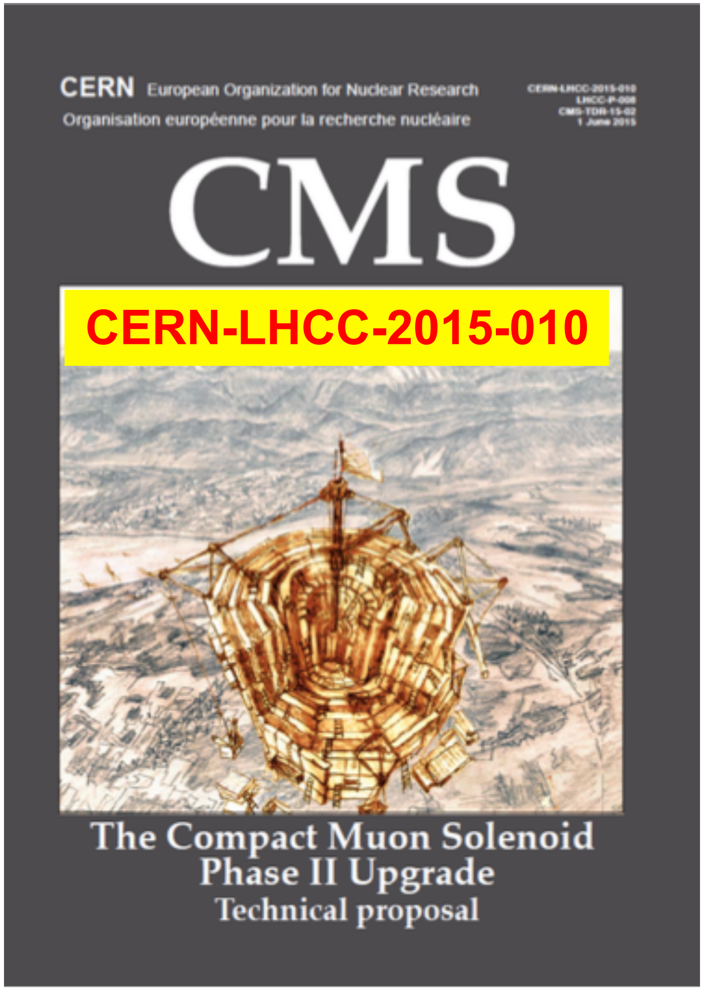
- Radiation tolerant - higher granularity
- Study coverage up to η ~ 3
- Investigate fast-timing

Barrel ECAL

- Replace FE electronics

Physics Program at HL-LHC

TP released this summer:



- ❑ Precision studies of 125 GeV BEH Boson (couplings, rare decays, etc.), including H self coupling
- ❑ Search for extended scalar H sector
- ❑ Vector boson scattering (VBS)
- ❑ B-physics
- ❑ Searches for physics beyond SM (BSM), e.g. dark matter (DM), heavy vector bosons (Z‘, W‘), long-lived exotic particles. Searches for SUSY + If BSM found already → study its properties

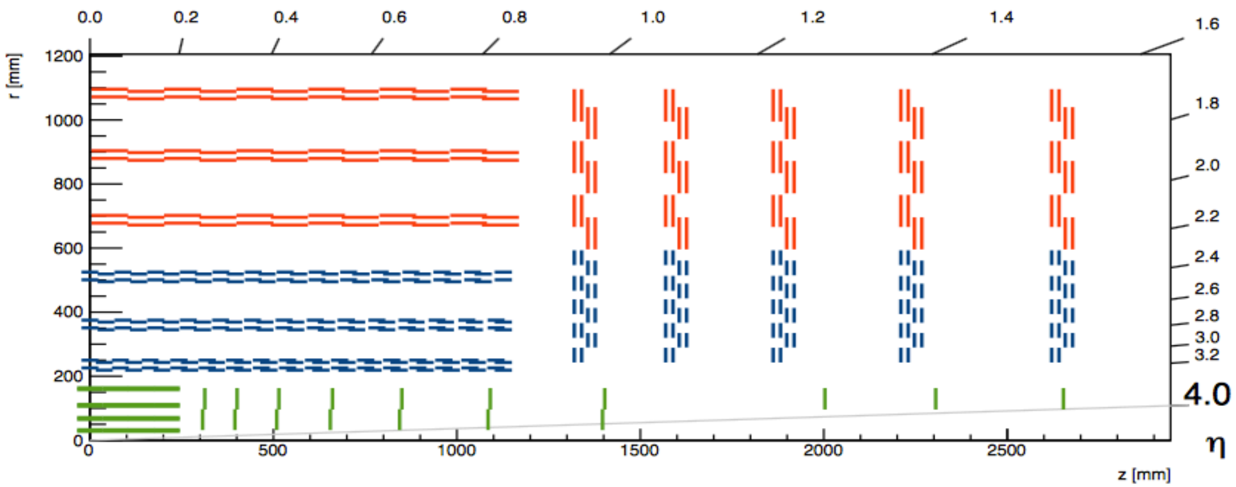
→ Study 3 detector scenarios:

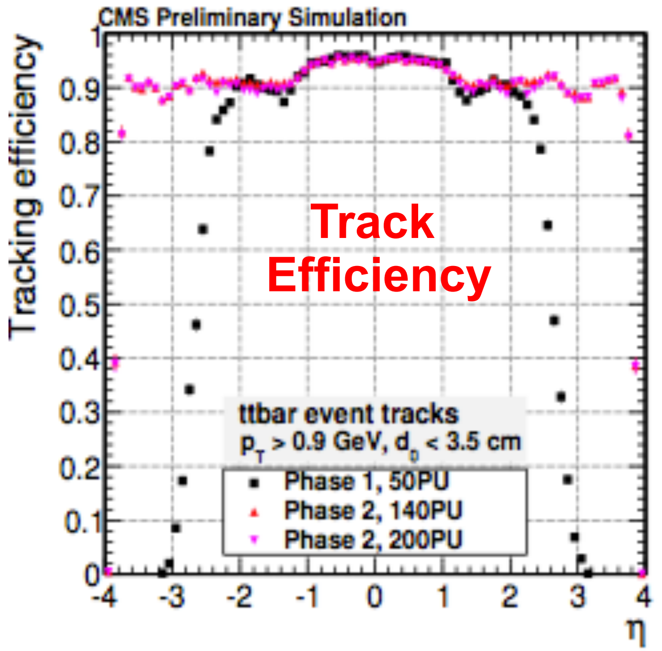
- ❑ Phase-1 detector, PU=50, 300 fb^{-1}
- ❑ Phase-1 aged (except pixels) PU=140, 3000 fb^{-1}
- ❑ Phase-2 detector PU=140, 3000 fb^{-1}

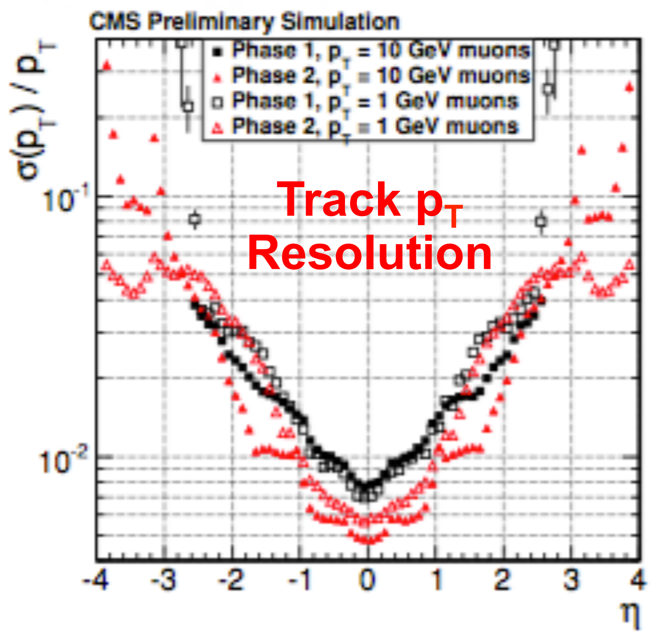
→ Aim: reach same performances with Phase-2 as with Phase-1 (non-aged) detector

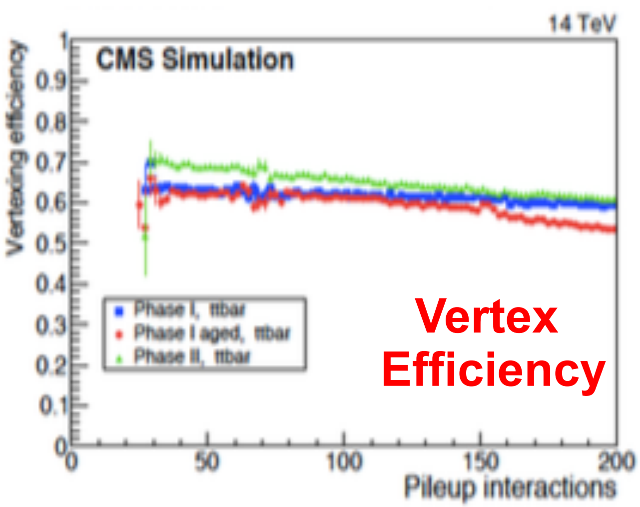
Tracker upgrade

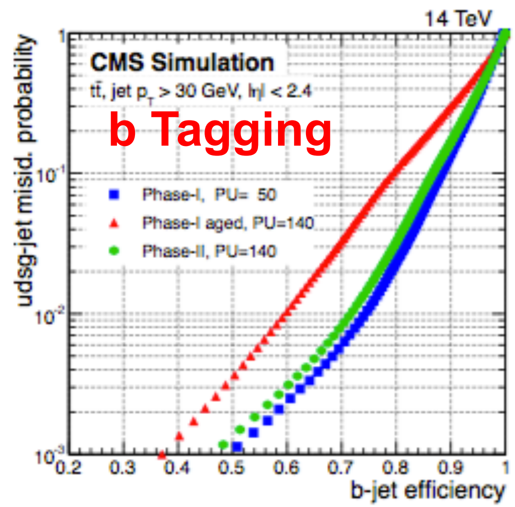
- **Extend coverage from |η|<2.5 up to |η|<4**
  → Help in reducing pile-up in forward region
- **Material lighten up!:**
  → Tracker weight 1/2 of current
  → Improved track p_T resolution & reduce rate of γ conversion (factor 2 to 3 wrt η)





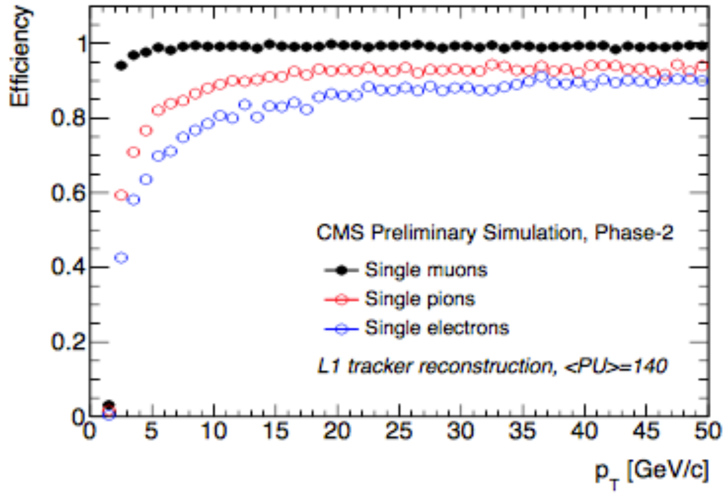




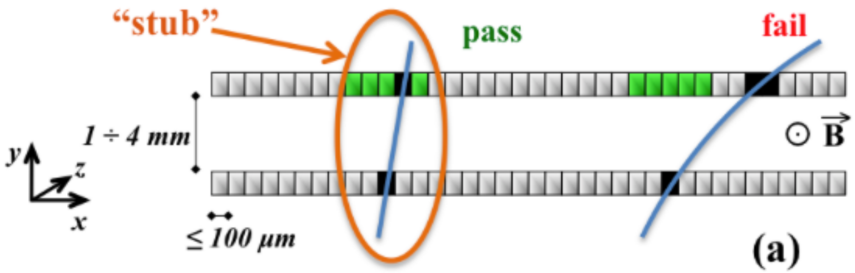


Level-1 Track Trigger

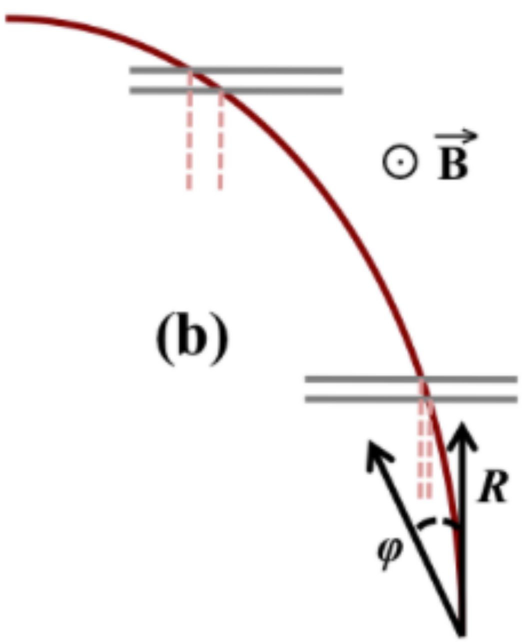
→ High efficiency for p_T > 2 GeV



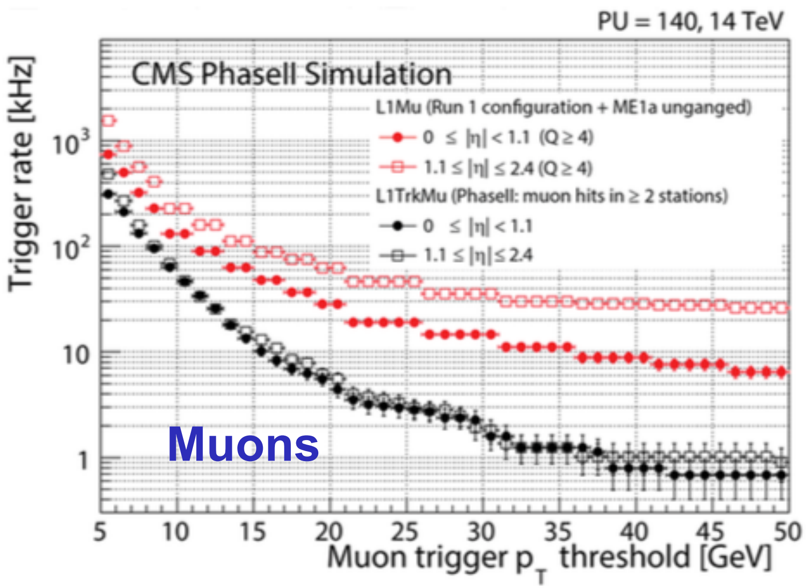
1) Several double layer with front-end logic to build track segments:

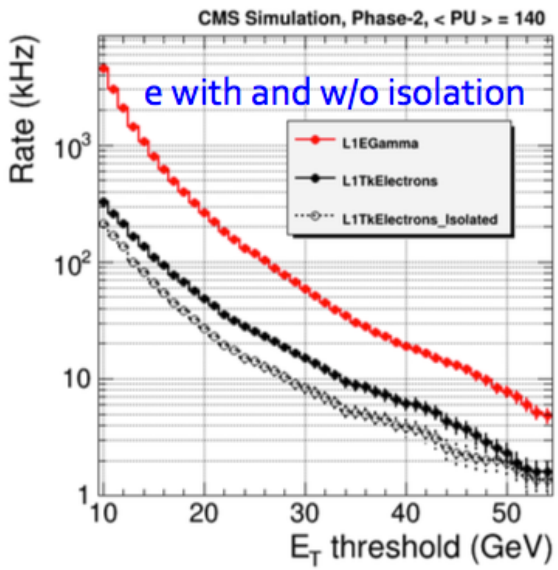


2) Build tracks at Level-1 from track segments:



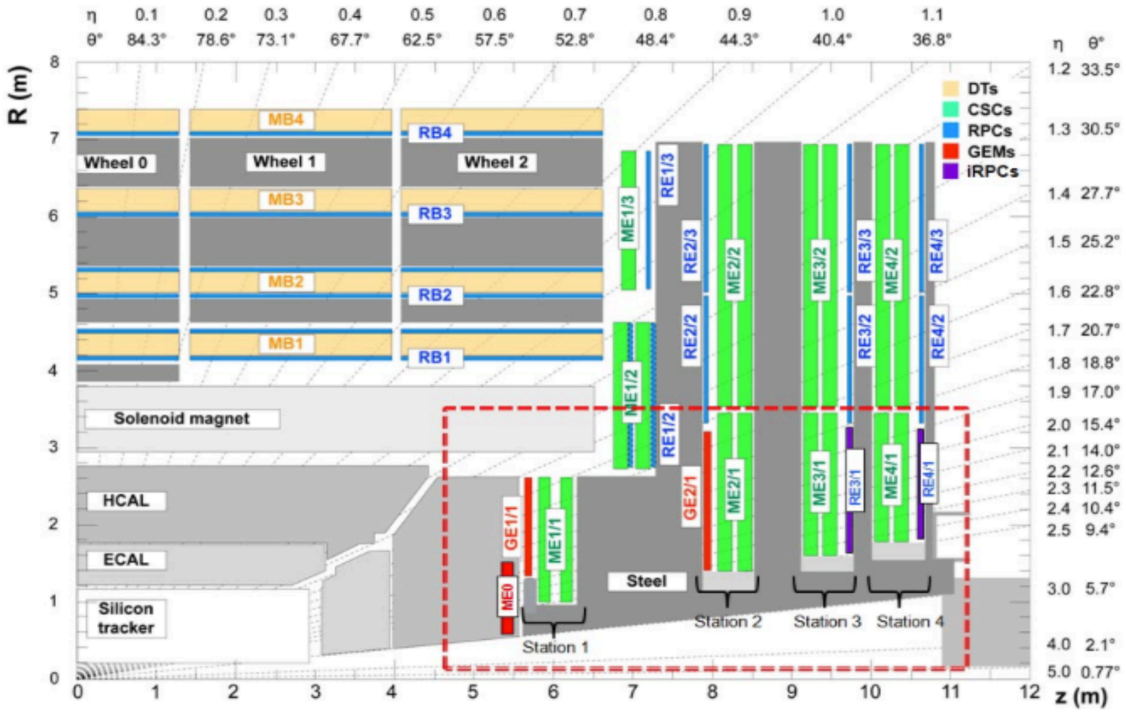
→ Allow to reduce L1 trigger rates to manageable levels for read-out and/or keep low p_T thresholds

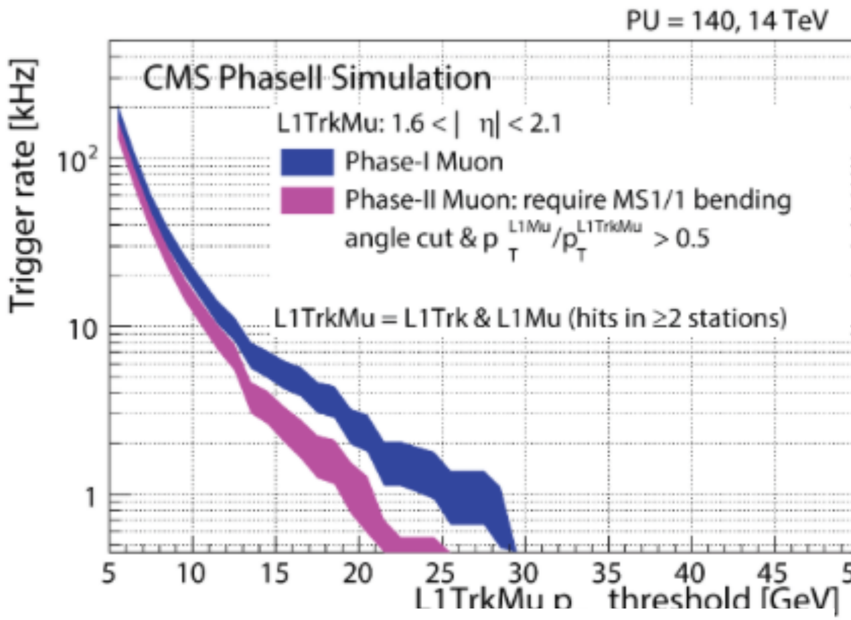


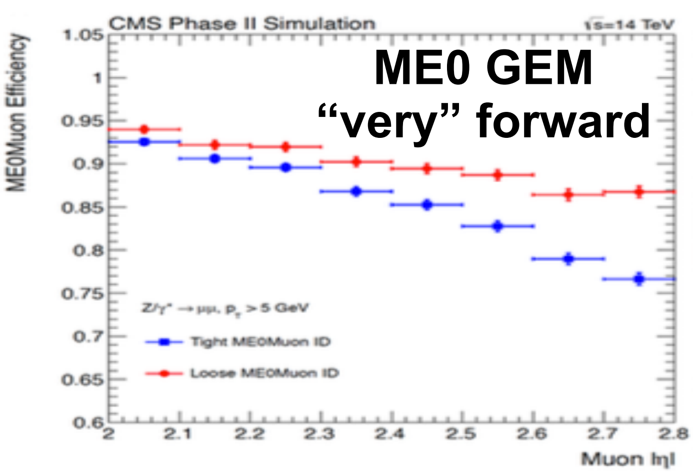


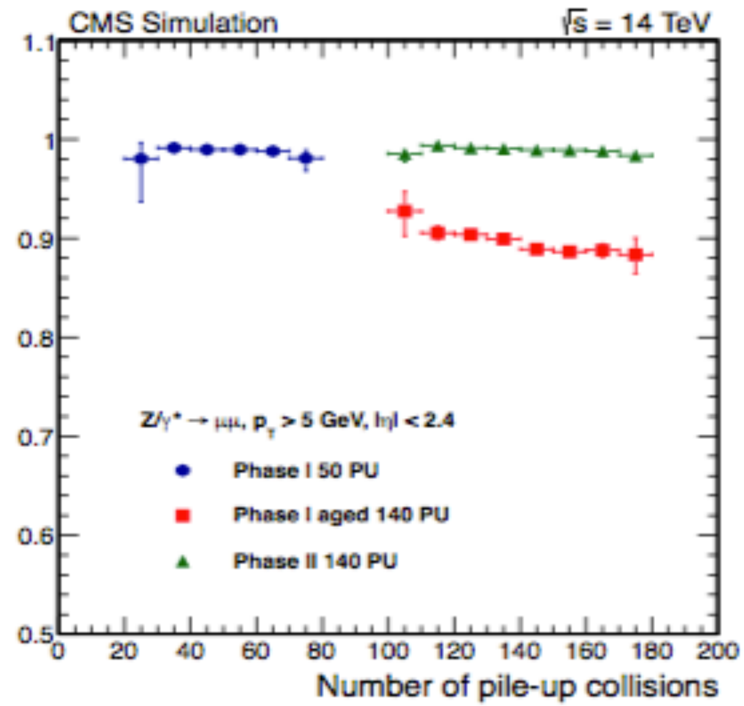
Muon Upgrade

Instrument forward region with GEM and RPC:
→ Extend coverage up to |η|<2.8
→ Improve trigger and reconstruction









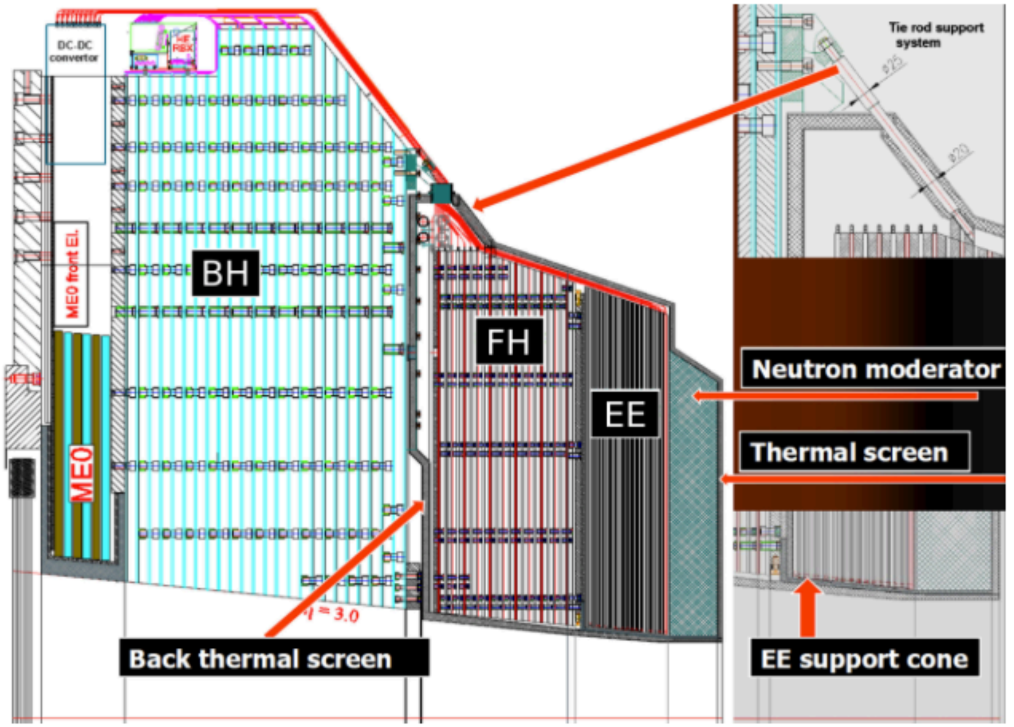
Calorimeter Upgrade

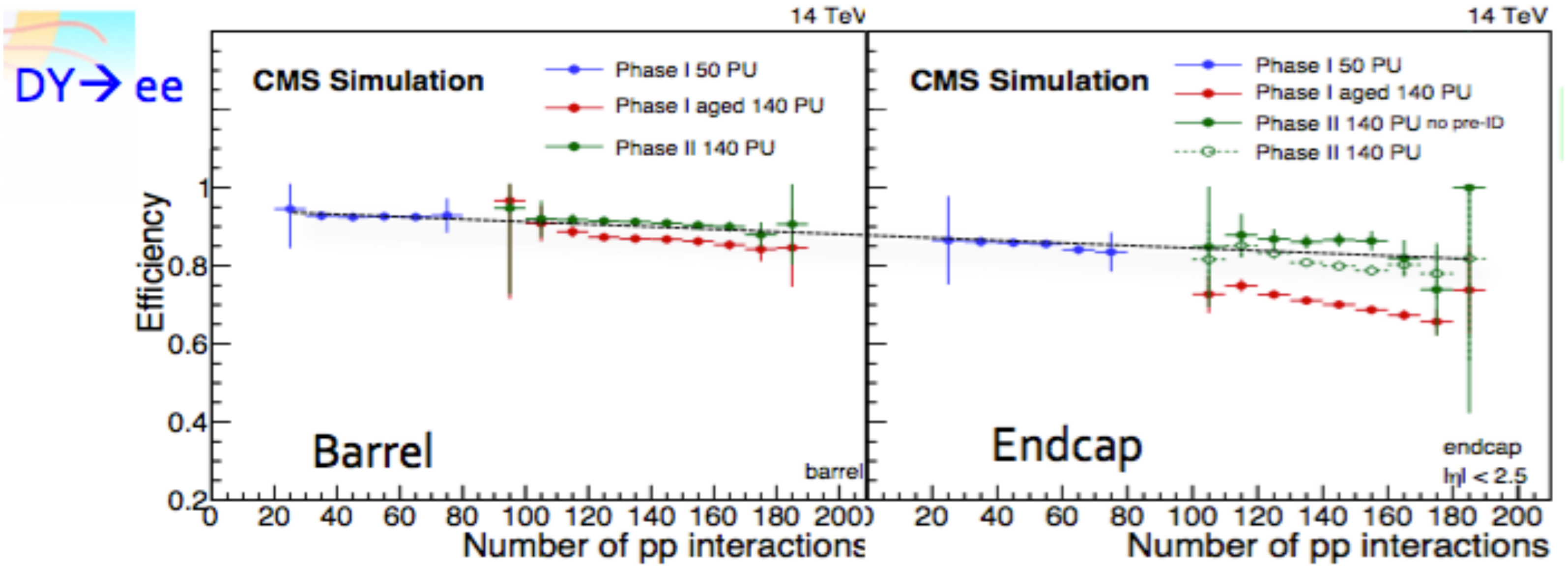
Barrel:

- ❑ Redesign/adapt ECAL electronic (trigger)
- ❑ Improve ECAL electronic cooling to reduce radiation induced noise
- ❑ Replace HCAL scintillators closest to beam

Endcap:

- ❑ Full replacement with radiation hard detector (silicon wafers)
- ❑ Increase granularity (mitigate pile-up)

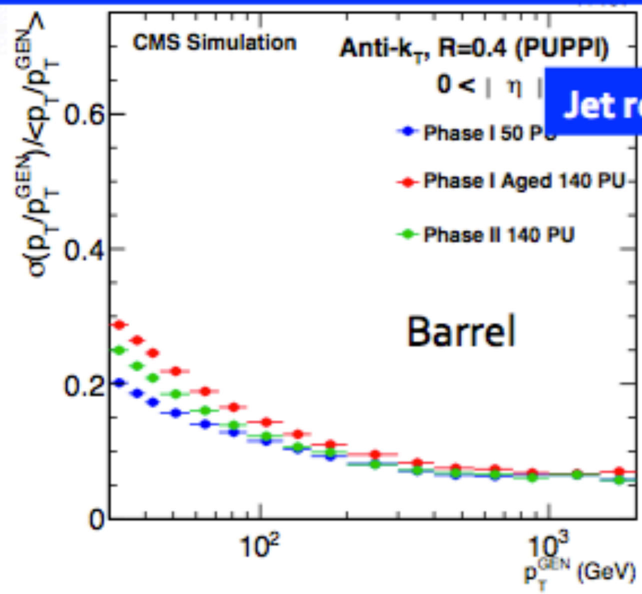


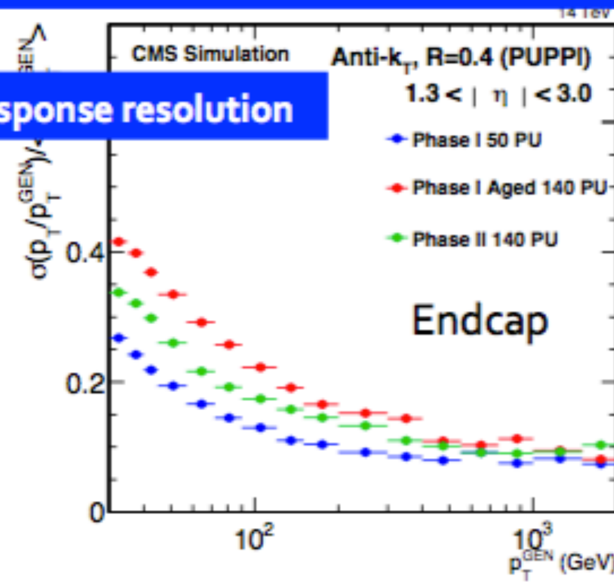


Jet and Missing E_T Performances

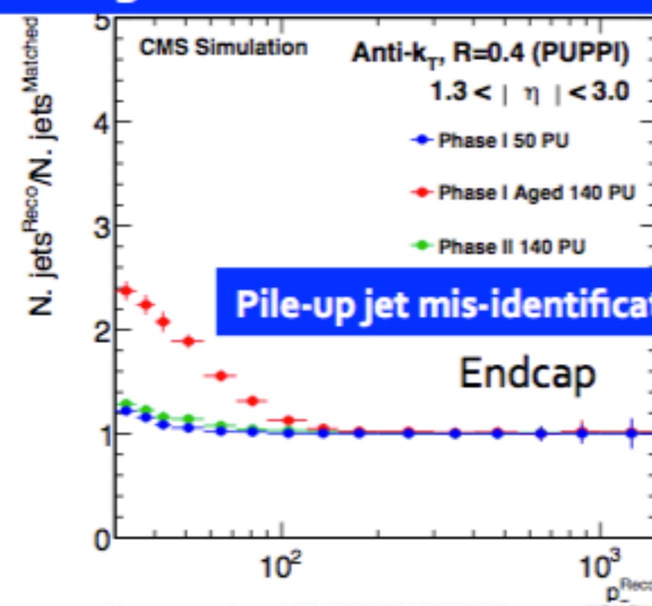
Combined effect of new EC and Tracker extension allows Phase-II to mostly recover energy resolution & fake rate of Phase-I detector at 50 PU

Jet response resolution



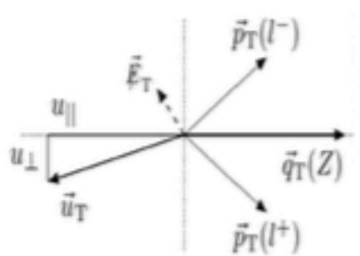


Pile-up jet mis-identification

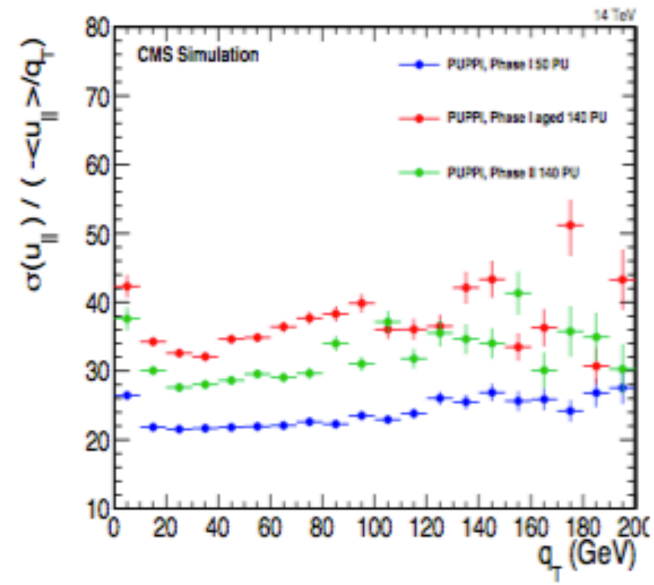


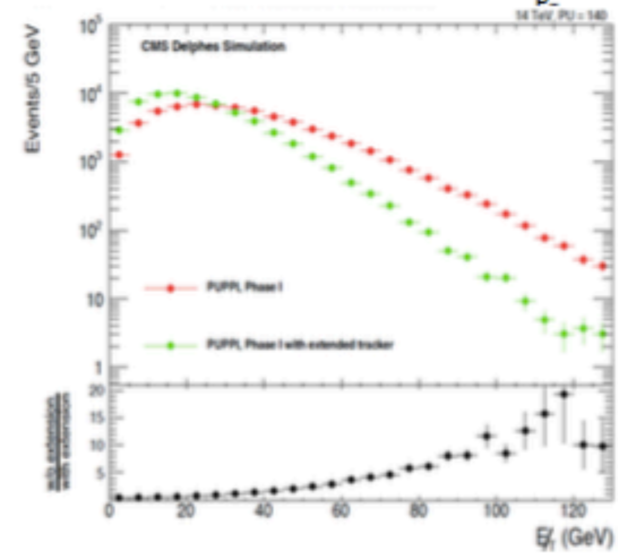
Phase-II detector recovers MET resolution partially

MET tails significantly reduced by tracking extension



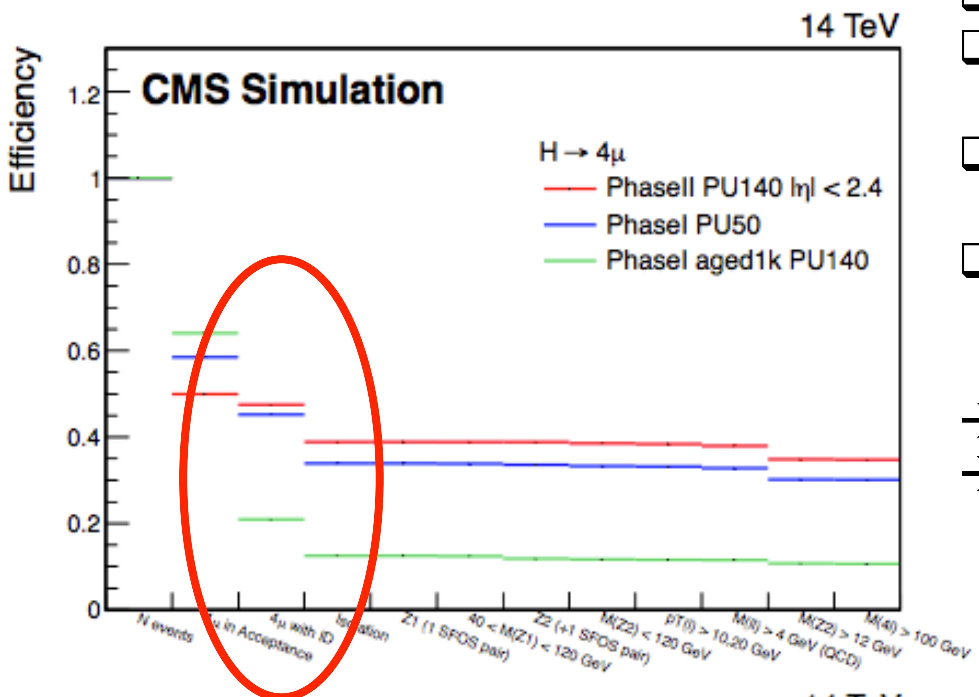
MET energy resolution from hadronic recoil in Z → μμ

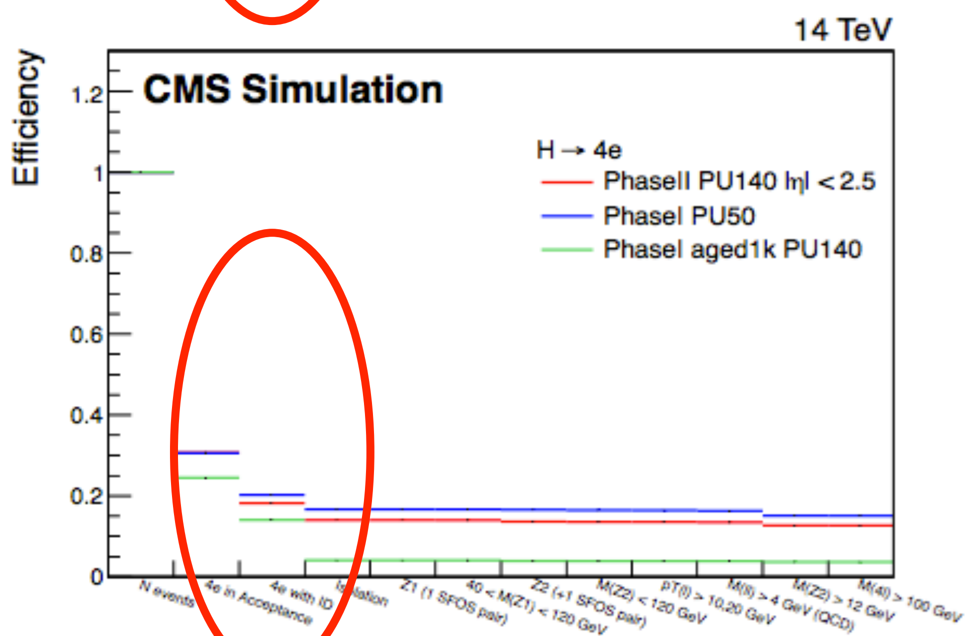




HL-LHC as a Higgs Factory

H→ZZ→4l: Precision Measurements

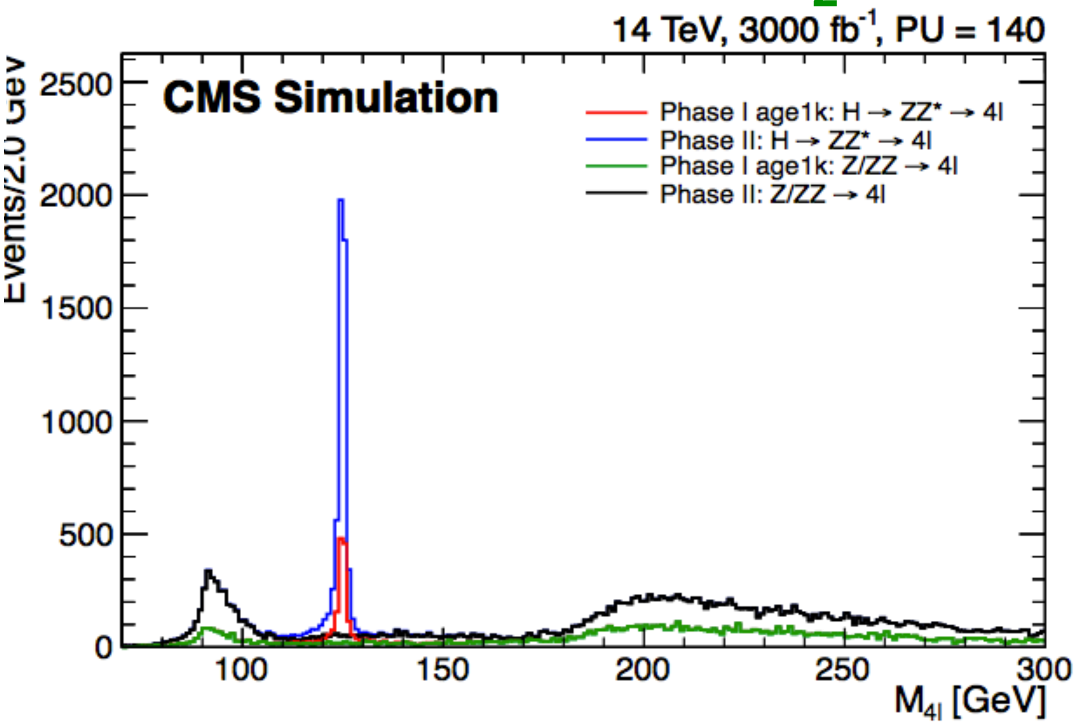




- Apply same analysis technique as for Run-1
- For Phase-I aged detector, large loss due to lepton ID and Isolation
- Phase-II detector recover Phase-I non- aged detector efficiencies
- Phase-II detector also improve mass resolution

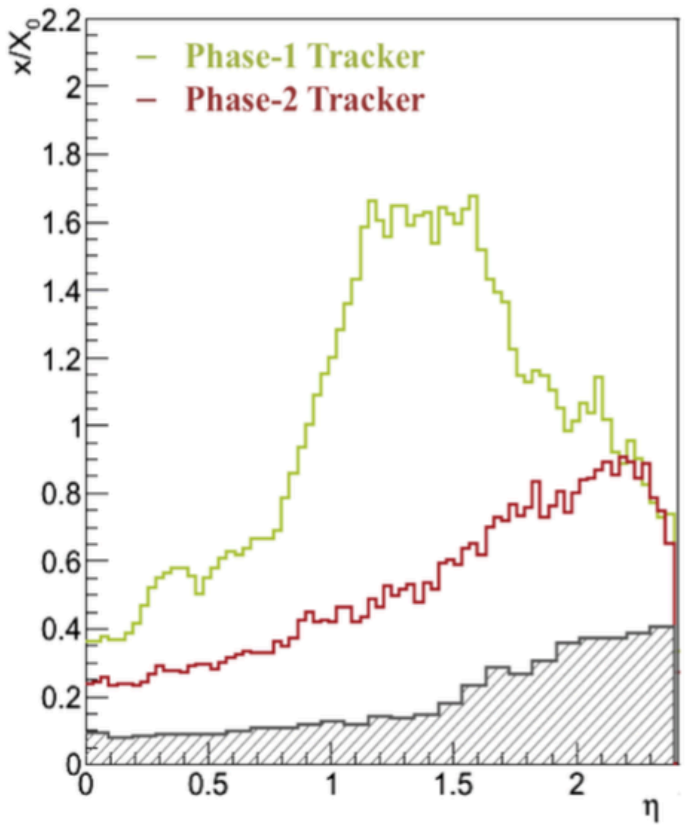
→ Expect O(4000) H bosons very clean events

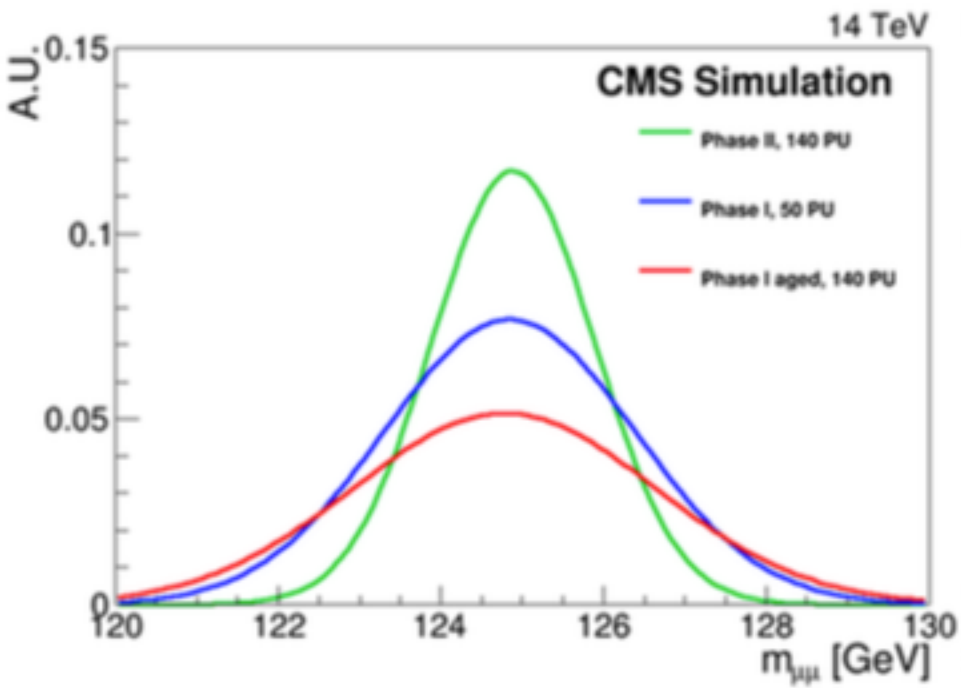
→ Detailed H properties study: Anomalous Spin structure, differential x-sections, K_Z ~2-4%, …



H→μμ: Probe second generation couplings

H→μμ (rare decay): Search of narrow resonance with huge DY background





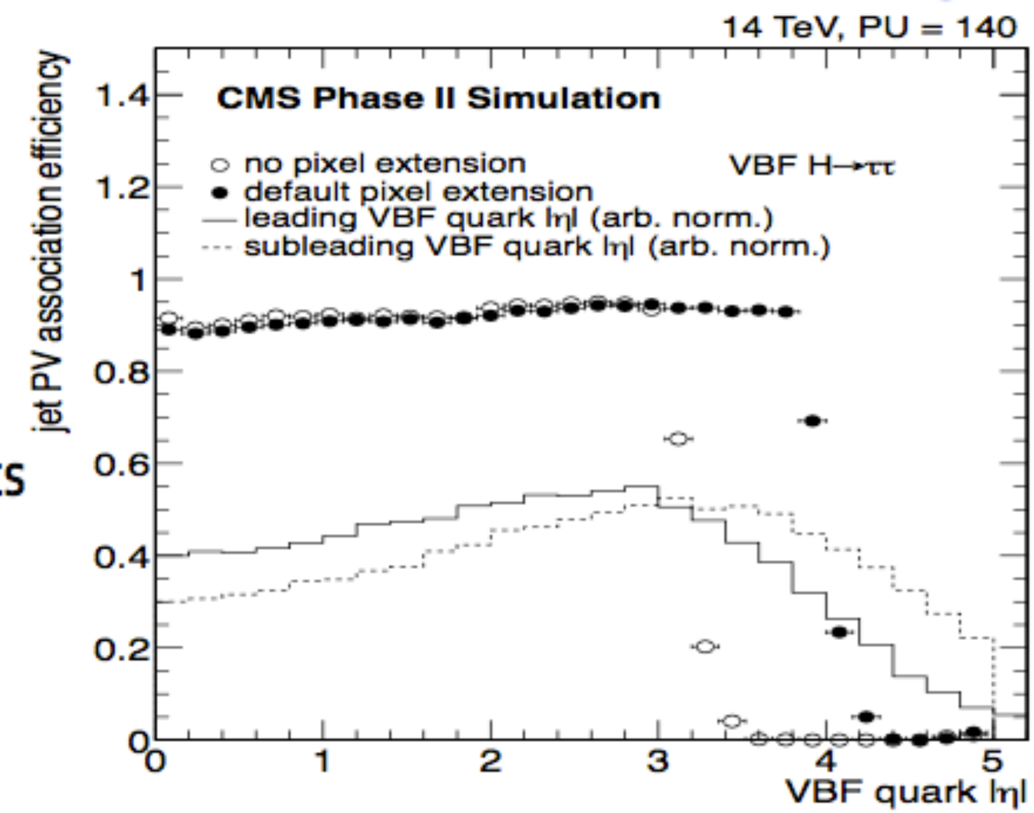
Lower tracker material at Phase-II
→ Improve mass resolution w.r.t. Phase I

Improvements:
20% efficiency & 45% mass resolution → expect ~5-10% uncertainty on κ_μ

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

VBF H→ττ : Forward Jets

Test bench analysis to quantify improvements on identifying forward jets in high pile-up environment



Phase II detector

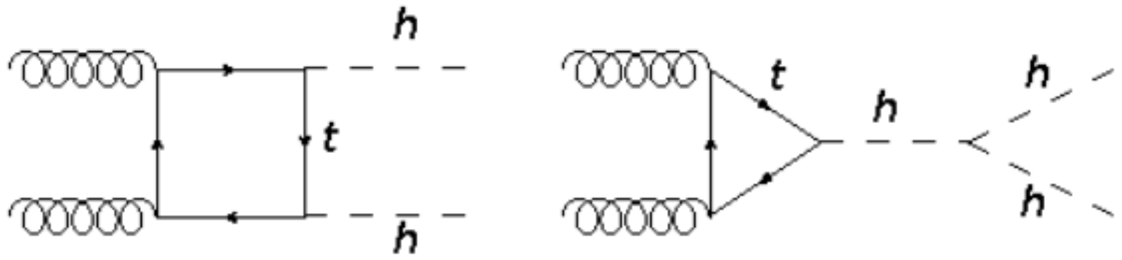
- ✓ x 5.5 acceptance with Track-Trigger
- ✓ Tracker extension help in rejecting fake jets
- ✓ 90% efficiency for Jet-ID with tracks
- ✓ 15 % gain expected from improved mass resolution (MET)

→ ~2-5% precision on couplings to τ

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15	[6, 8]	1, 41]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	0, 12]

→ Precision of ~2-5% on K_γ, K_W, K_g, ~4-7% on K_b, 7-10% on K_t

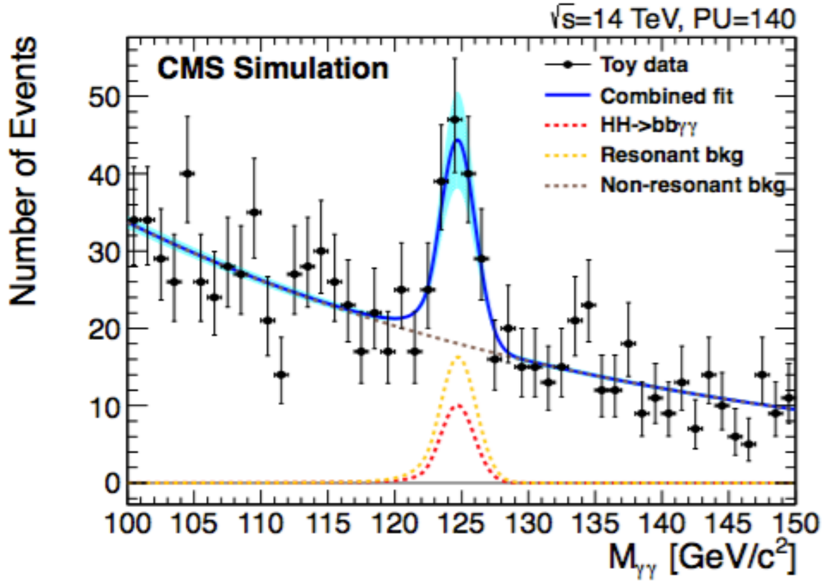
di-Higgs production

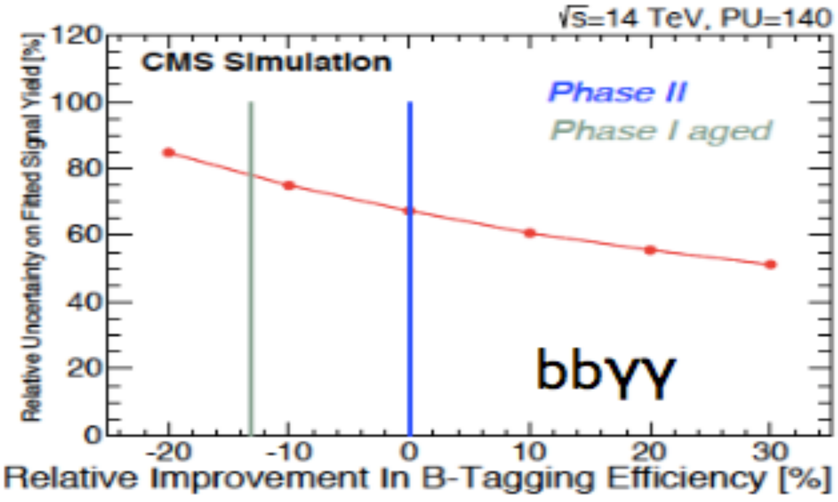


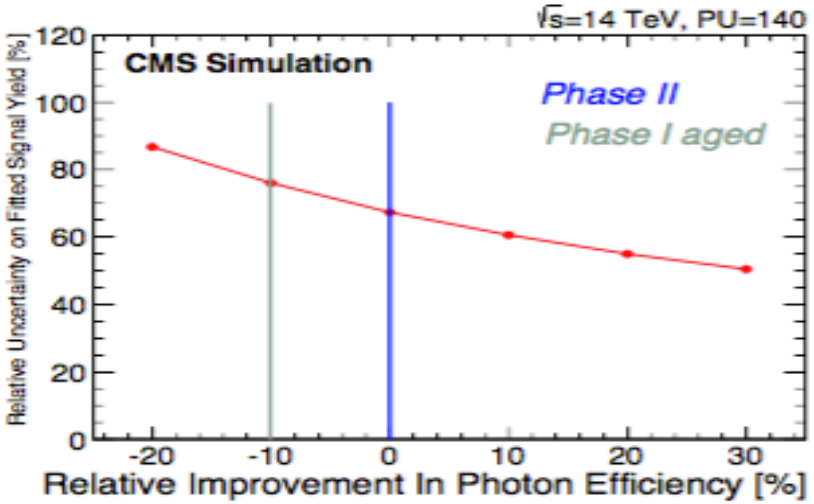
→ **Higgs self-coupling**
→ **Search for new physics**

bbγγ:
Need good:
- ❑ Tracker b-tagging
- ❑ ECAL γ-ID performance

→ **2D Fit of M_{bb} and $M_{\gamma\gamma}$**







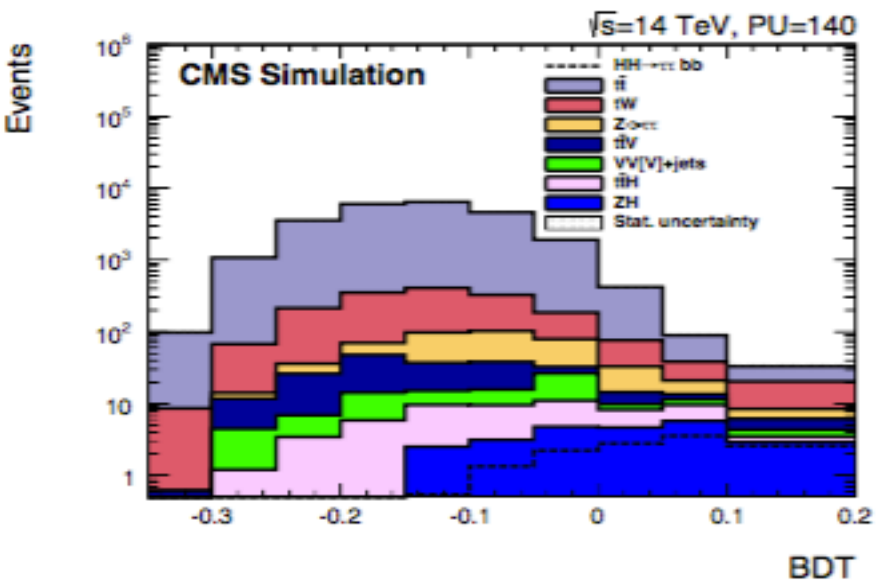
→ **~67% precision on di-Higgs production with Phase-II nominal detector**

di-Higgs production

bbττ:

- ❑ Large amount event (~9000)
- ❑ Need Track trigger
- ❑ But large background: tt, single t

→ **Multivariate discriminant:**

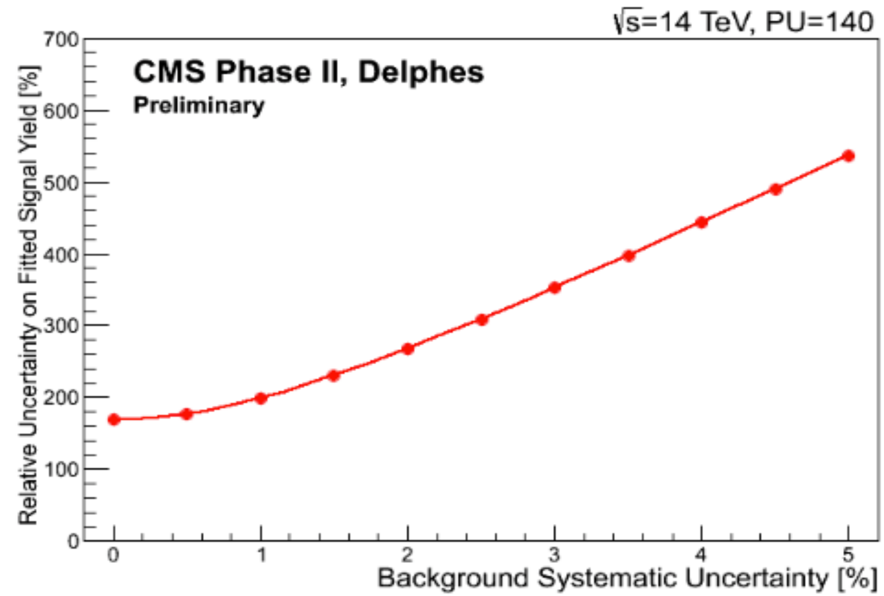


→ **~100% precision on SM di-Higgs production with Phase-II nominal detector**

bbWW:

- ❑ ~1500 fully-leptonic event
- ❑ But also large top background

→ **Multivariate discriminant:**



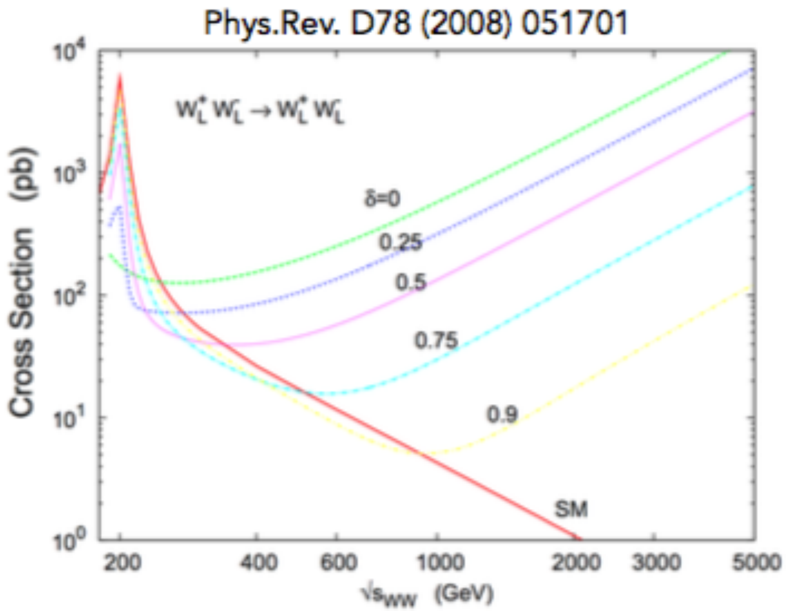
→ **~200% precision on SM di-Higgs production with Phase-II nominal detector**

bbγγ/bbττ combination → 1.9 σ expected significance for SM di-Higgs (~54% precision on x-section)

Vector Boson Scattering

Vector Bosons Scattering (VBS) allows probing the EWSB:

- **After H discovery: Test its nature by checking the expected cancellation between H and VBS**
- **VBS allows to search for new physics by studying anomalous couplings**



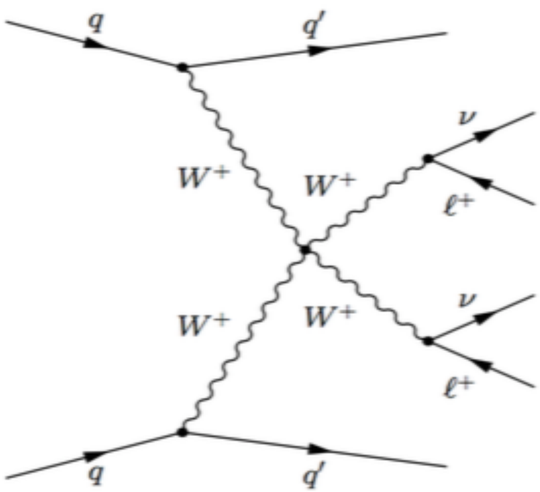
BENCHMARKS

non-unitarization	$V_L V_L$ cross section	anomalous couplings
compare VBS to the 125 GeV Higgs boson to a Higgs-less model, generated with Phantom *0801.3359*	Madgraph generation of VV scattering, separating at the V level the polarisation components: LL as signal, LT and TT as background *1405.0301*	anomalous quartic couplings with the EFT formalism in the Lagrangian used in Madgraph generation *1205.4231*

FINAL STATES:

- **same-sign WW scattering → fully leptonic: 2 forward jets + 2 leptons**
- **WZ scattering → 2 forward jets + 3 leptons**

Same-sign WW



IRREDUCIBLE BKG

- **WW + 2 jets** $O(\alpha_{EW}^4\alpha_S^2)$
  - small interference with the signal
- **WZ + 2 jets** $O(\alpha_{EW}^6 + \alpha_{EW}^4\alpha_S^2)$
  - with an undetected lepton

REDUCIBLE BKG

- **one jet ID as a lepton**
  - in semi-leptonic ttbar and QCD W+jets
- one **lepton with wrong charge**
  - in fully-leptonic ttbar and DY

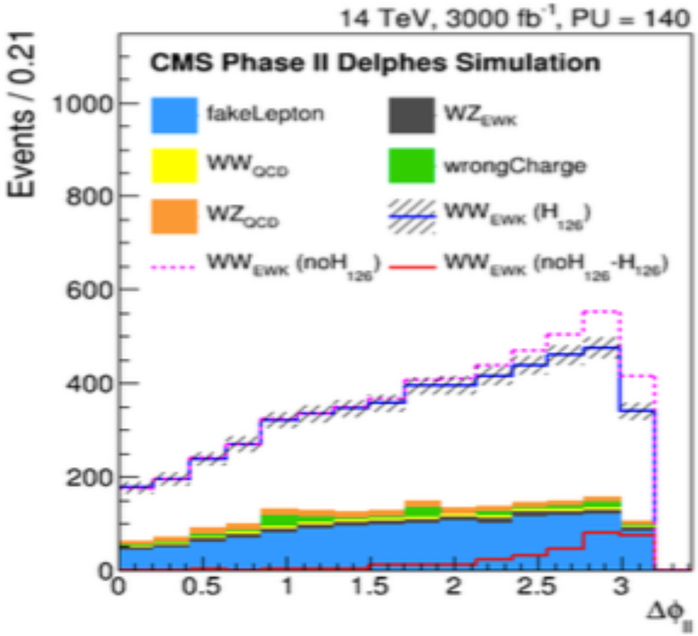
selection	limit
tight leptons	
minimum lepton p_T	20 GeV
maximum electron relative isolation	0.25 (0.6)
maximum muon relative isolation	0.6
loose leptons	
minimum lepton p_T	20 GeV
maximum lepton relative isolation	0.75
jets	
minimum jet p_T	30 GeV
cleaning from tight leptons within $\Delta R = 0.3$	
selections	
number of tight leptons	2
charge of the tight leptons	same sign
number of loose leptons	0
number of jets	≥ 2
minimum MET value	40 GeV
minimum tag jet m_{jj}	300 GeV
minimum tag jet $\Delta\eta_{jj}$	2
minimum di-lepton invariant mass m_{ll}	40 GeV
maximum leptons separation $\Delta\eta_{\ell\ell}$	2

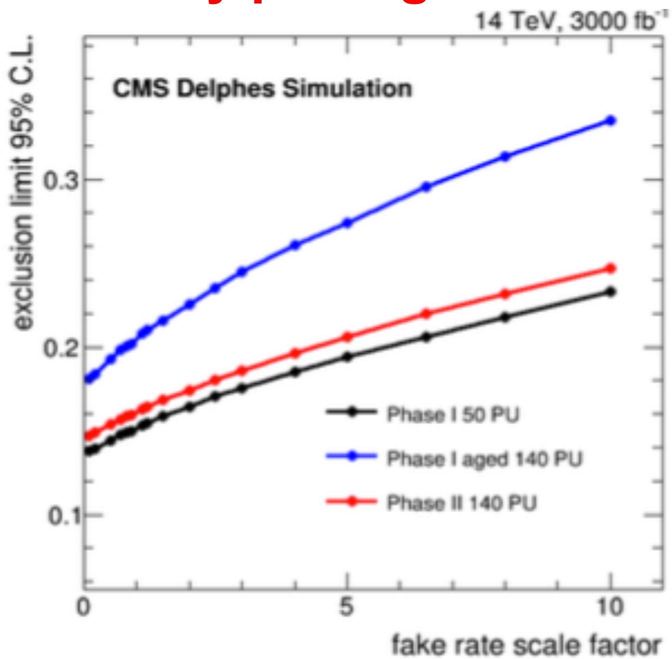
- exactly **two leptons** (*e* or μ) with opposite charge
  - quality requirements on the leptons ID reduce the wrong identification of jets
  - required to be central ($|\eta| < 2.5$)
- at least **two non-btagged jets**
  - suppress the ttbar
  - veto additional soft muons in the jets
  - no b-jets in the event
- **VBS topology**
  - impact on all bkg, suppress the irreducible one

tight: $\Delta\eta_{jj} > 2.5$ and $m_{jj} > 850$ GeV
loose: $\Delta\eta_{jj} > 2.5$ and $m_{jj} > 625$ GeV

Partial unitarization and $W_L W_L$

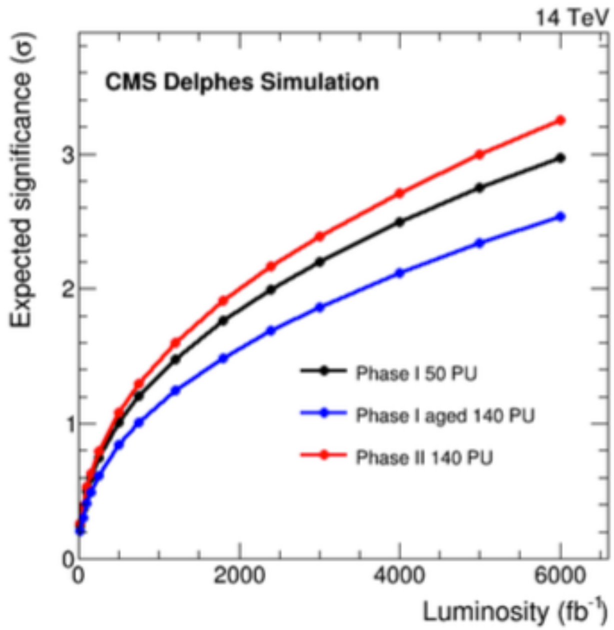
Test sensitivity to partial unitariztion by putting limit on no-Higgs scenario:





- ❑ Use shape difference in several variables between simulation with and without Higgs diagrams
- ❑ Fully exclude no-Higgs
- ❑ Can study partial unitarization with good sensitivity

Extract $W_L W_L$ component from kinematic properties:



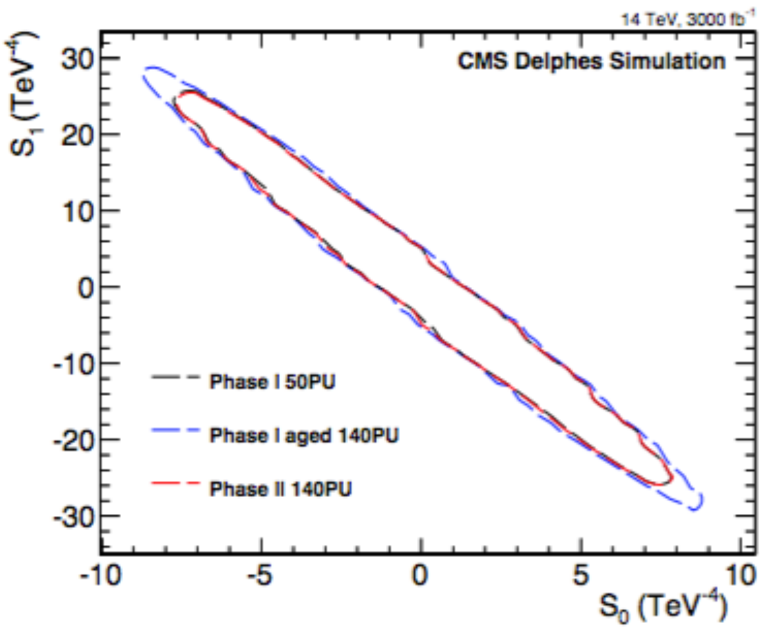
~2 σ expected significance for longitudinal WW component at 3 ab^{-1}

WW: Anomalous Couplings

Add dimension 8 operators in an Effective Field Theory approach

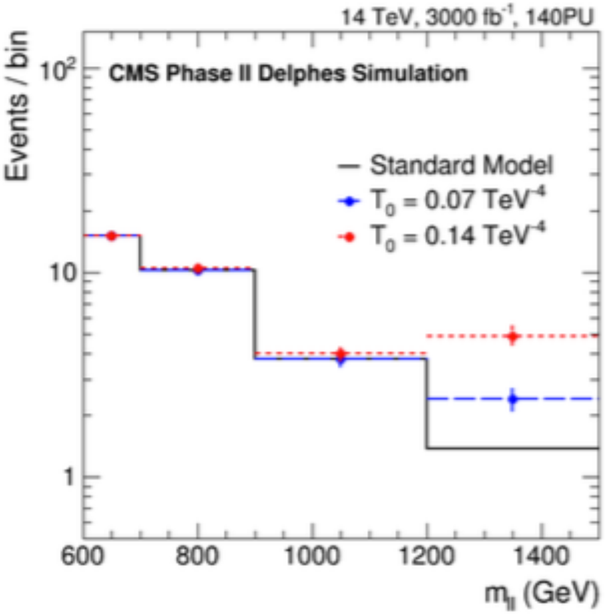
$$L_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]$$
$$L_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D_\nu\Phi\right]$$
$$L_{M,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$L_{M,1} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$L_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$L_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$
$$L_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$L_{T,1} = Tr\left[W_{\alpha\nu}W^{\mu\beta}\right] \times Tr\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$L_{T,2} = Tr\left[W_{\alpha\mu}W^{\mu\beta}\right] \times Tr\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

→ **Deviations expected for large momentum**
→ **Use di-lepton invariant mass as discriminant**



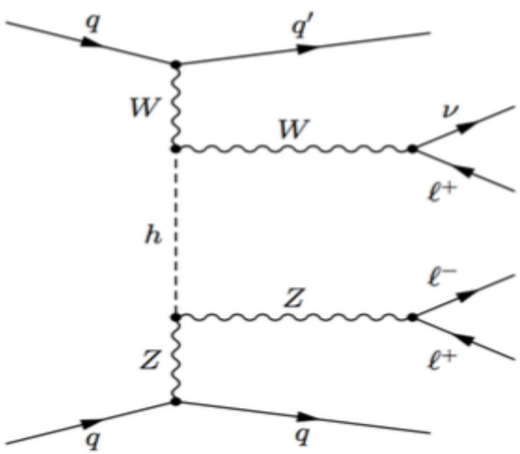
For 3000 fb^{-1}:

	phase I	phase II	phase I aged
S_0	1.06	1.07	1.17
S_1	3.51	3.55	3.87
M_0	0.78	0.75	0.82
M_1	1.10	1.06	1.14
M_6	1.56	1.49	1.63
M_7	1.37	1.32	1.45
T_0	0.067	0.077	0.083
T_1	0.036	0.033	0.036
T_2	0.119	0.111	0.119



N.B.: Limits from the 8 TeV analysis are 30 - 60 times higher than these ones

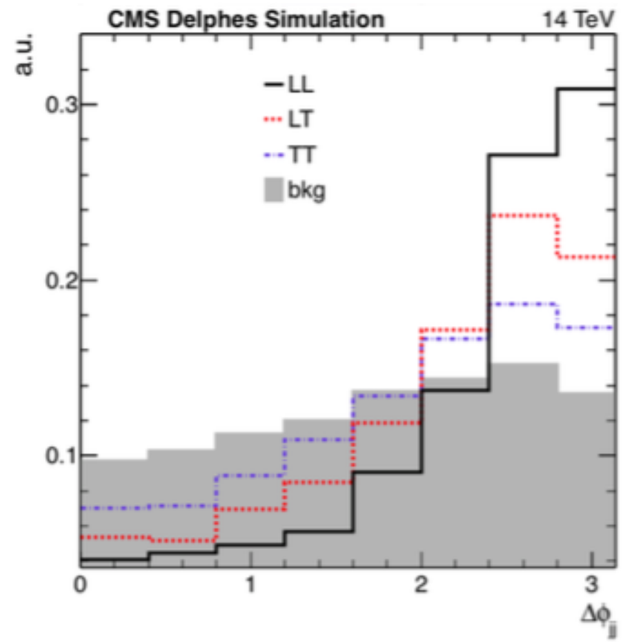
WZ and Combination with WW



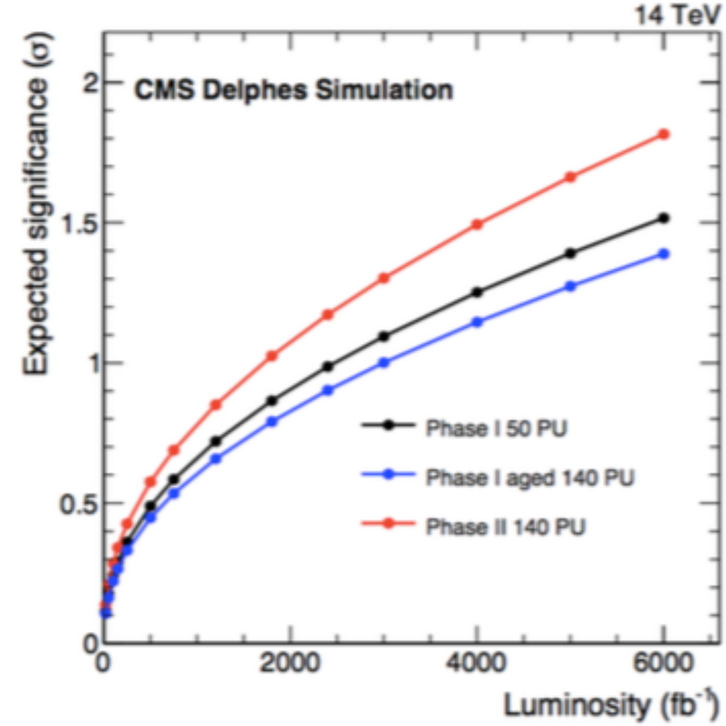
BACKGROUNDS

- **WZ + 2 jets** $O(\alpha_{EW}^4 \alpha_S^2)$
  - largest background to the analysis
  - ZZ + jets with an undetected lepton
  - Z + jets with a jet ID as a lepton

Azimuthal angle difference between jets:



→ **Expected significance for $W_L Z_L$**



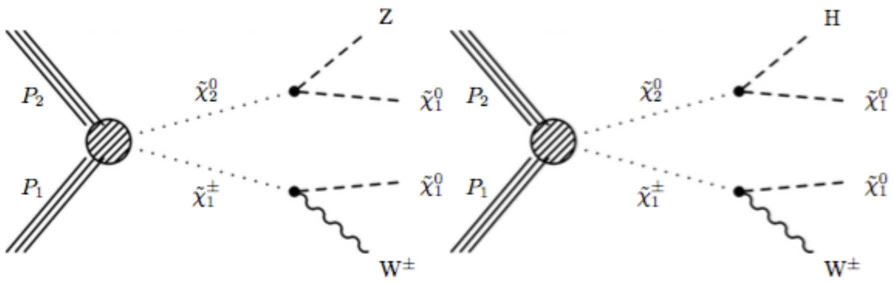
Combining WW and WZ:

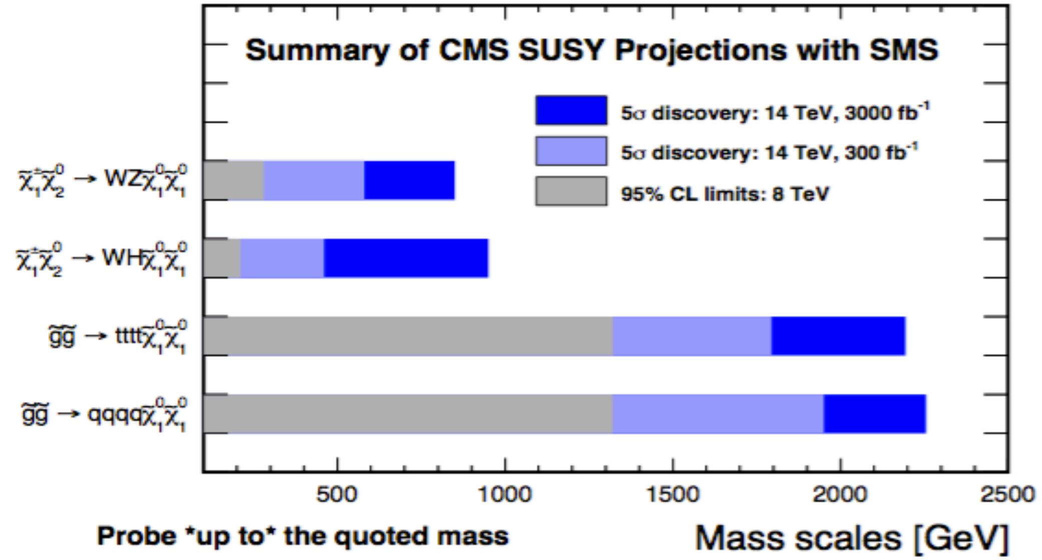
$3000\ fb^{-1}$, 14 TeV	Phase-I	Phase-II	Phase-I aged
Higgsless 95% CL μ exclusion	0.14	0.14	0.20
$V_L V_L$ scattering significance	2.50	2.75	2.14

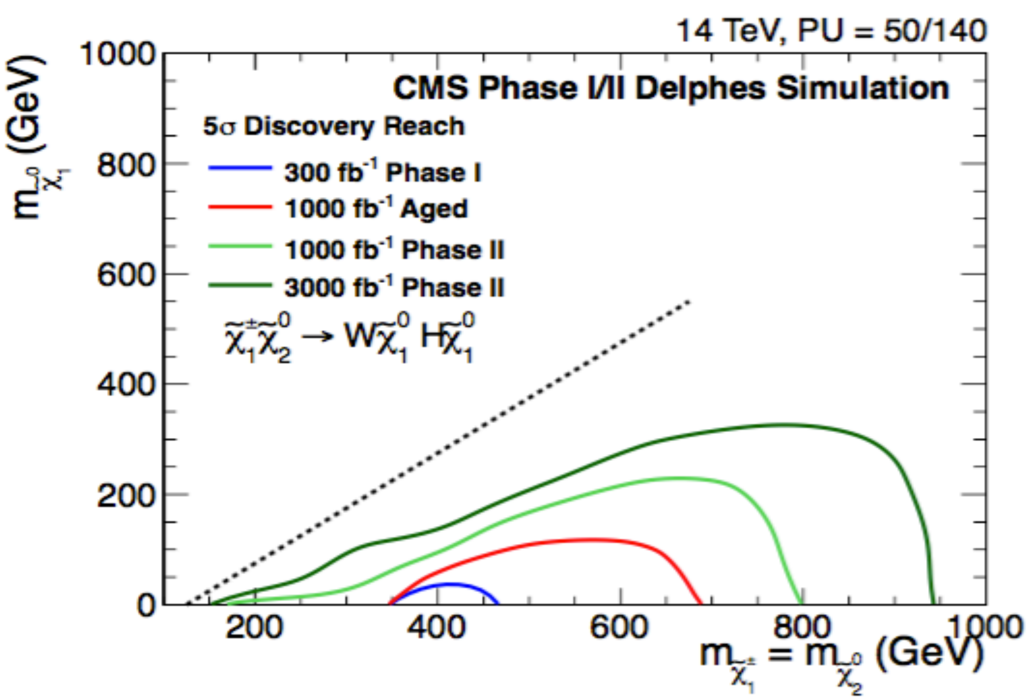
→ 2.7 σ for longitudinal VBS ; sensitivity to partial unitarization

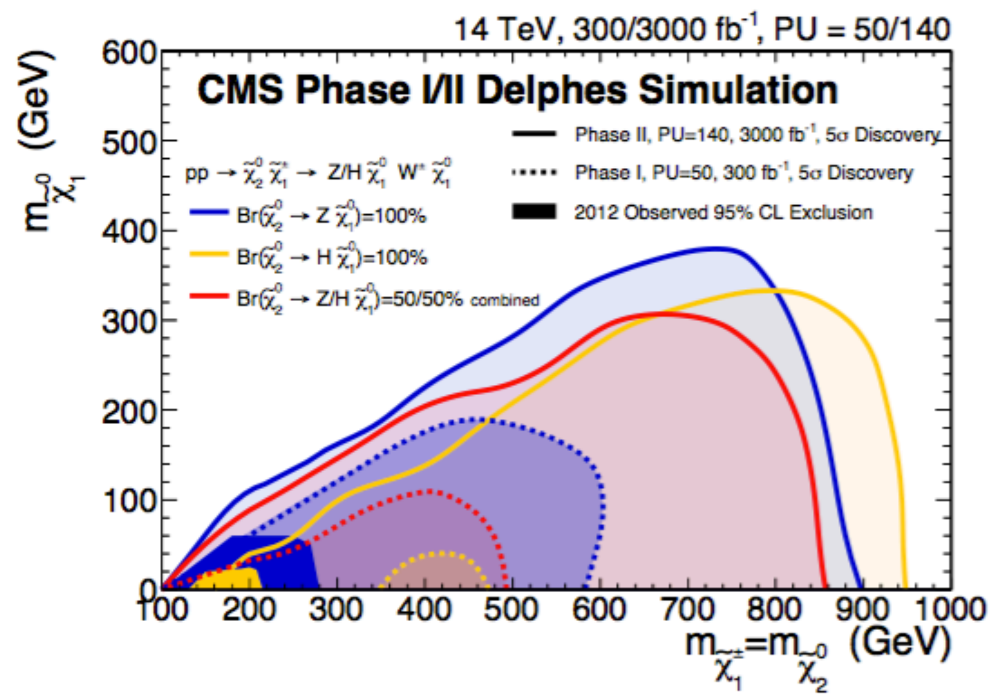
SUSY and Exotics

SUSY: Simplified chargino-neutralino production

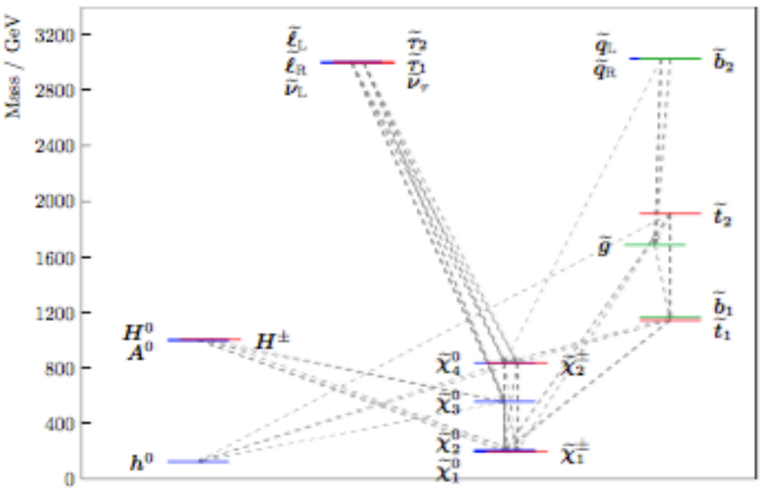








SUSY: Full Spectrum Searches



(a) NM3

Study several scenario of "Full spectrum" SUSY:

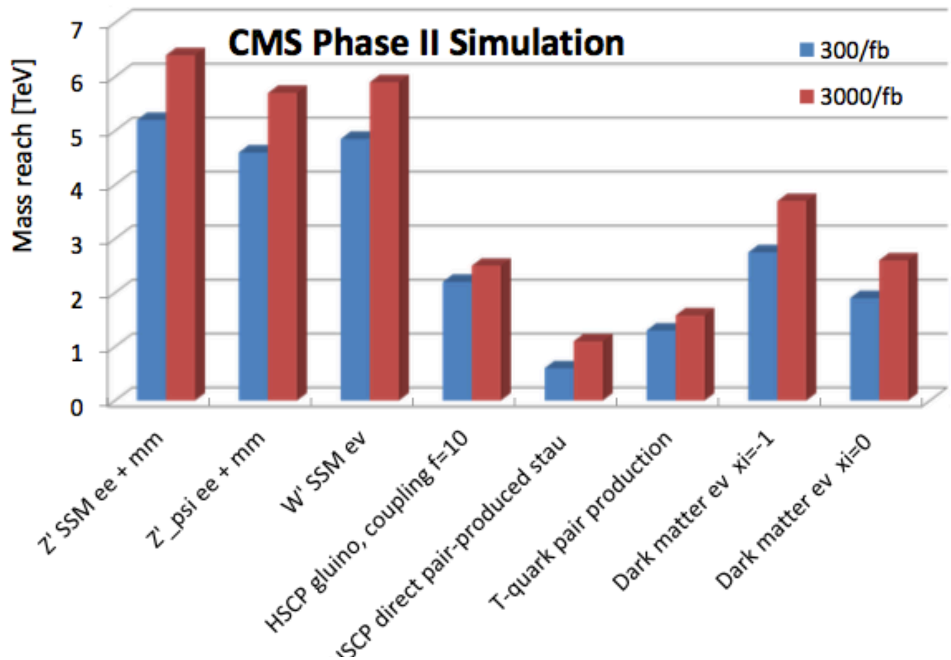
- ❑ Natural Modes: NM1 → NM2
- ❑ **Stau co-annihilation model (STC)**
- ❑ **Stop coannhilation model (STOC)**

Summary of discovery reach for several "Full Spectrum" SUSY searches:

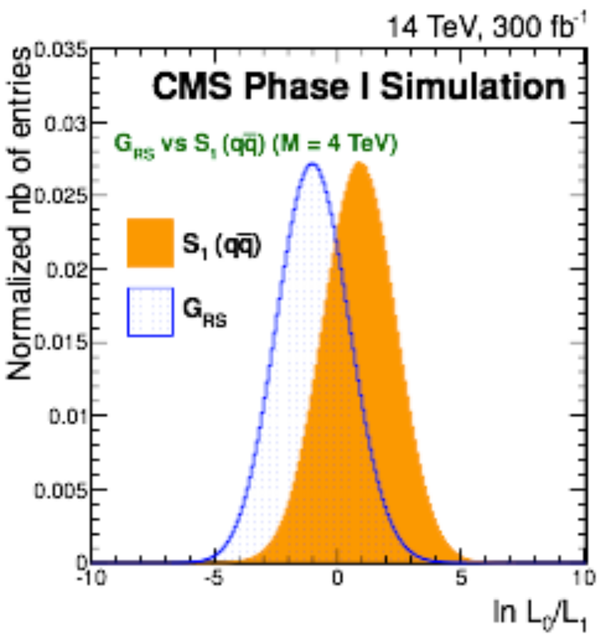
Analysis	Luminosity (fb^{-1})	Model: NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				< 3σ	3 − 5σ
	3000				3 − 5σ	> 5σ
all-hadronic (M_{T2}) search	300	3 − 5σ	> 5σ	> 5σ		
	3000	> 5σ	> 5σ	> 5σ		
all-hadronic $\tilde{b}_1$ search	300	< 3σ	< 3σ	< 3σ	3 − 5σ	< 3σ
	3000	< 3σ	< 3σ	< 3σ	> 5σ	< 3σ
1-lepton $\tilde{t}_1$ search	300	> 5σ	> 5σ	> 5σ	3 − 5σ	< 3σ
	3000	> 5σ	> 5σ	> 5σ	> 5σ	> 5σ
monojet $\tilde{t}_1$ search	300					3 − 5σ
	3000					3 − 5σ
$m_{\ell^+\ell^-}$ kinematic edge	300	< 3σ	< 3σ	< 3σ		
	3000	> 5σ	< 3σ	< 3σ		
multilepton + b-tag search	300	> 5σ	> 5σ	> 5σ	3 − 5σ	
	3000	> 5σ	> 5σ	> 5σ	> 5σ	
multilepton search	300	< 3σ	< 3σ	< 3σ	< 3σ	
	3000	3 − 5σ	3 − 5σ	< 3σ	3 − 5σ	
ewkino WH search	300		< 3σ			
	3000		3 − 5σ			

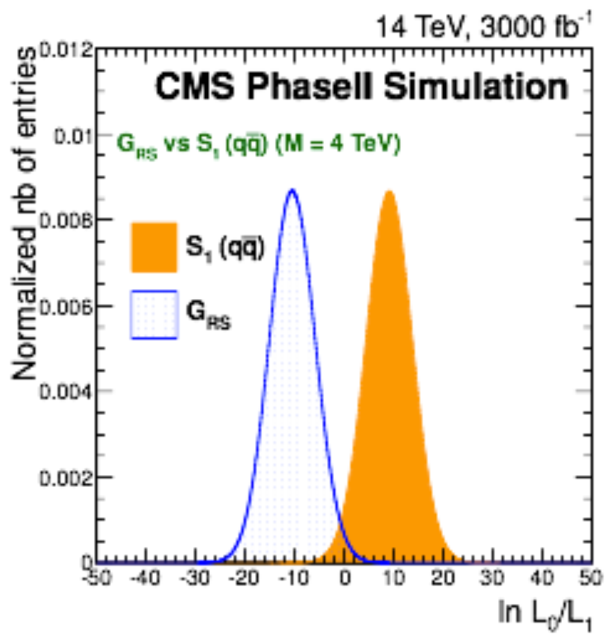
$< 3\sigma$	$3-5\sigma$	$> 5\sigma$

“Exotics” Models



→ **Phase-II / HL-LHC will extend mass range for Z’, W’ and many other exotic models**





→ **In case of discovery of di-lepton resonance, the Phase-II detector allow to distinguish among models.**

Example:
RS graviton vs Spin 1 di-lepton resonance

Dark Matter searches

Example: Study of W boson recoiling against pair of very low mass DM particles

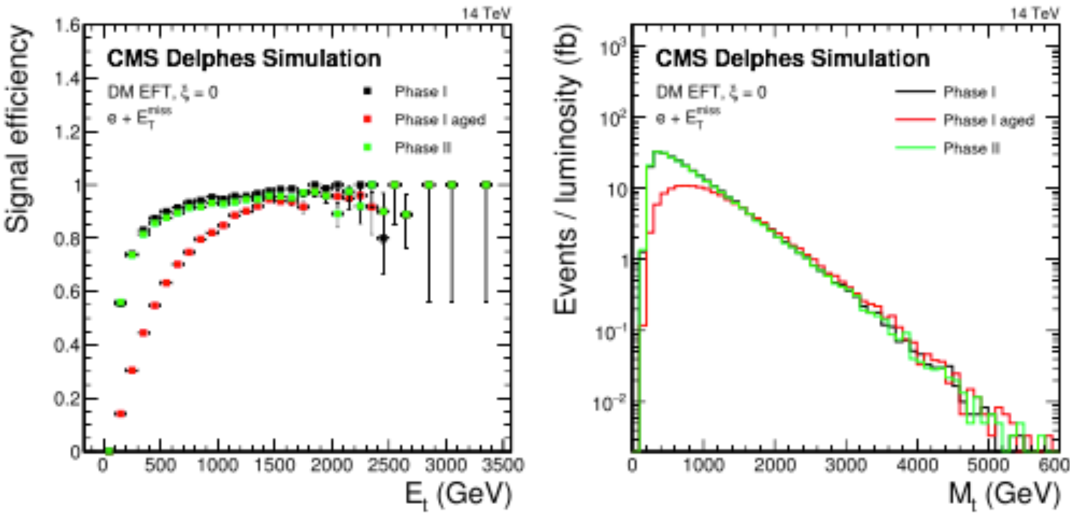
→ **Single electron: p_T >100 GeV**

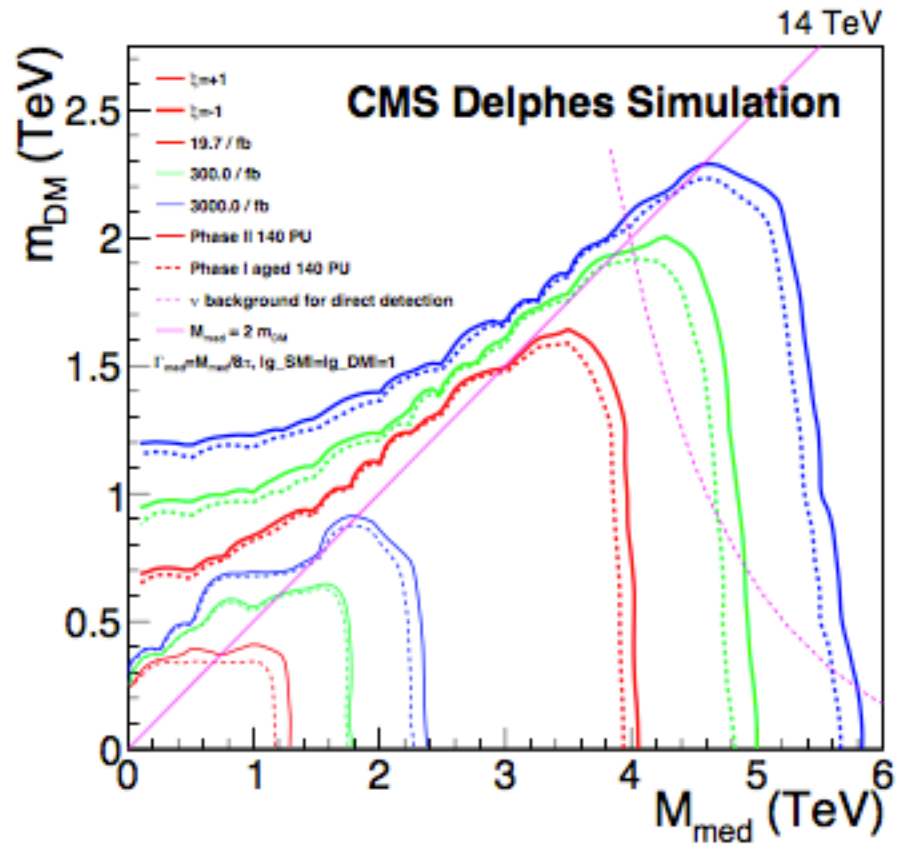
→ **Missing E_T**

→ **Use transverse mass as discriminant**

→ **Extract limits for a Z'-like mediator with vector-axial or vector couplings**

Efficiencies for Phase-I And Phase-II detectors:





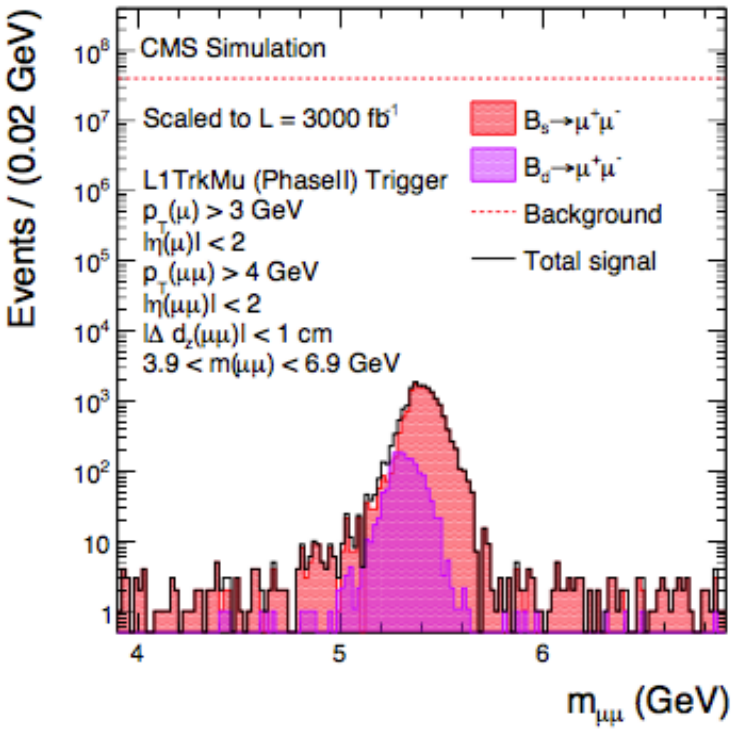
→ **Increased coverage by ~1 TeV for M_{med} and ~0.3 TeV for DM particle mass with 3000 fb-1 wrt 300 fb-1**

B Physics

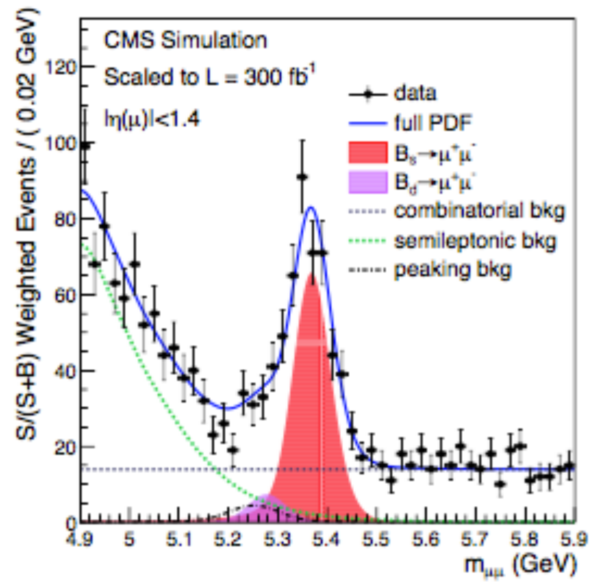
$B^0_{(s)} \rightarrow \mu^+\mu^-$

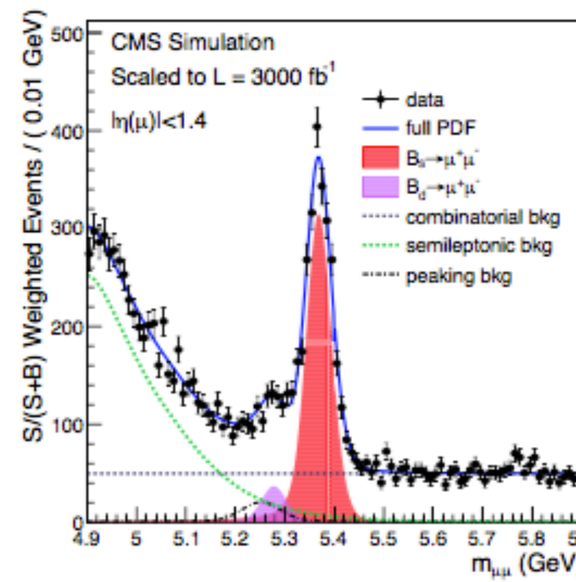
- ❑ These analysis are only possible at HL-LHC with the L1 track trigger to get reasonable di-muon trigger rates !
- ❑ Require 2 muons with p_T>4 GeV + $p_T(\mu\mu)$>5 GeV and 4.9 < $M(\mu\mu)$ < 5.9 GeV

Level-1 di-muon mass:



Fully reconstructed mass for Phase-I and Phase-II:





→ Reduced tracker material at Phase-II
→ Improved mass resolution wrt Phase-I detector

→ With Phase-II detector mass resolution, B^0 and B^0_s are well separated
→ 6.8 (2.2) s for B^0_s with Phase-II (Phase-I) detector
→ Possible to measure B^0_s branching fraction with ~13% precision at LH-LHC

CONCLUSIONS

Preparing for LHC high-luminosity operation in ≥2025.
→ Expect 10x more luminosity.

New detectors designed to cope with high rates, high pile-up and ageing and radiation damage
→Requires to rebuild tracker and forward calorimeters.
→Enhance muon detector coverage
→New trigger concepts implemented.

Physics potential:
→Large gain in Higgs precision physics
→ Possibility to study VV scattering as an important closure test
→ Low cross-section measurements such as $B^0_{(s)} \rightarrow \mu\mu$.
→ Enhanced discovery potential for BSM and SUSY physics.