Aug. 9th, 2018

Physics Prospects at the High-Luminosity LHC with CMS

ICISE2018: 25th Rencontres du Vietnam - Windows on the Universe

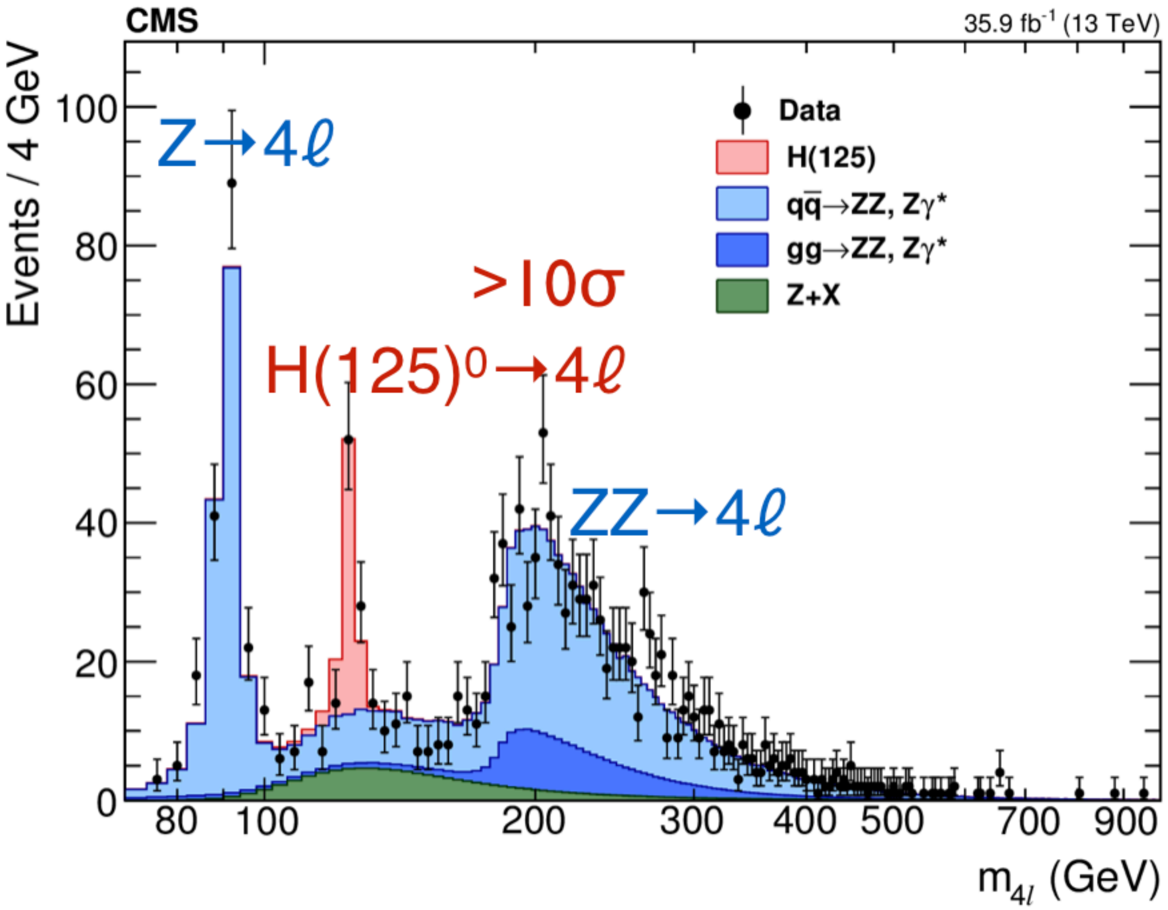
Isobel Ojalvo
Princeton University
on Behalf of the CMS Collaboration

Current State of the Universe (to a Particle Physicist)

LHC Experiments have confirmed that the Standard Model is Robust!

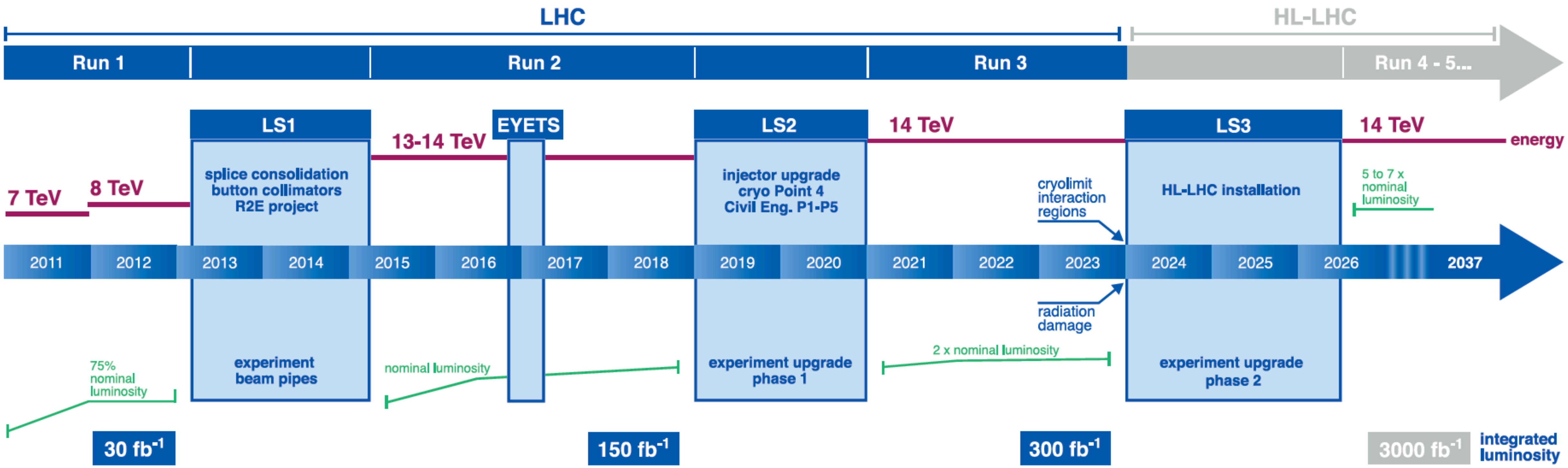
However, there are still **many open questions** and it **is not an ultimate theory** for everything

- Why is the **Higgs Boson so light**?
- What is the nature of **Dark Matter**/**Dark Energy** (96% of the universe!!)
- Why is there **more matter** than **anti-matter**?
- Why are the scales of the weak force and the gravitational force so different?



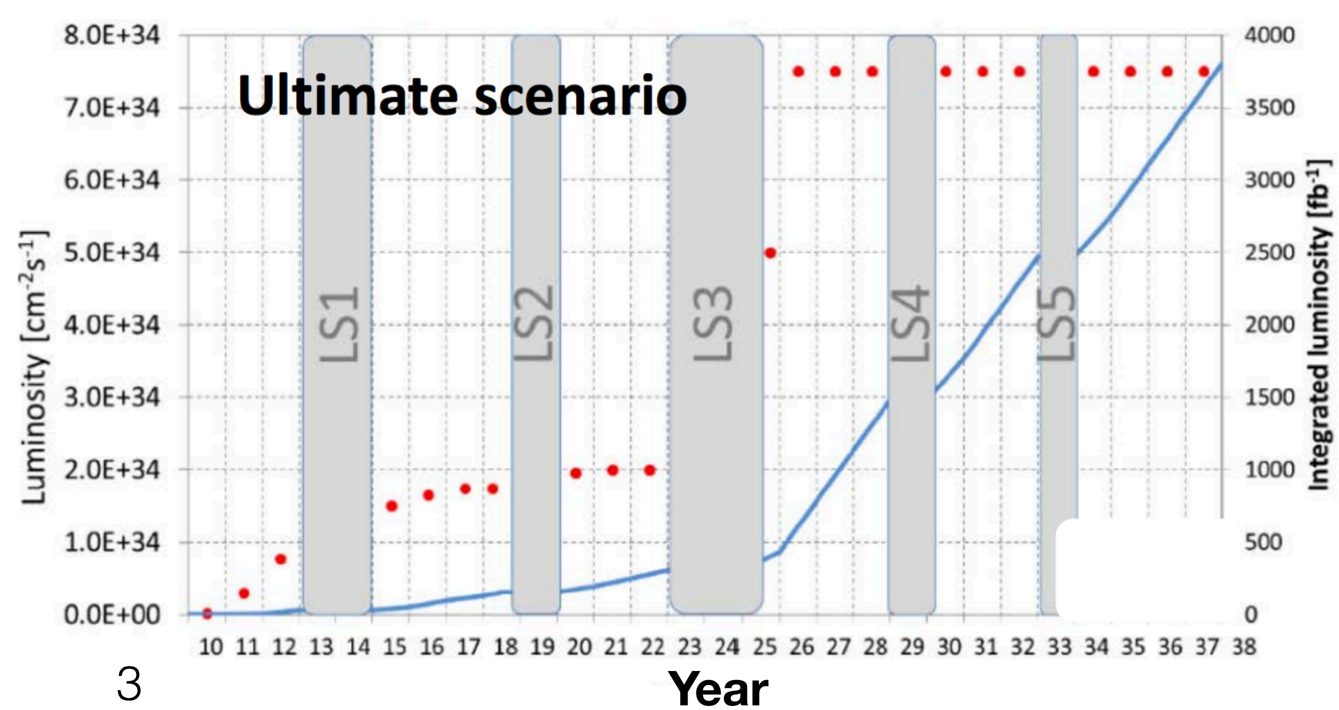
With the HL-LHC we may be able to answer these questions!
Either Indirectly: Precision measurements of SM processes
or Directly: SUSY, Long Lived Particles, New Heavy Resonances, Dark Matter

HL-LHC schedule



Nominal Scenario: L = **5.0**x10e^{34} cm^{-1}s^{-1} up to 3000 fb^{-1} (140 PU)

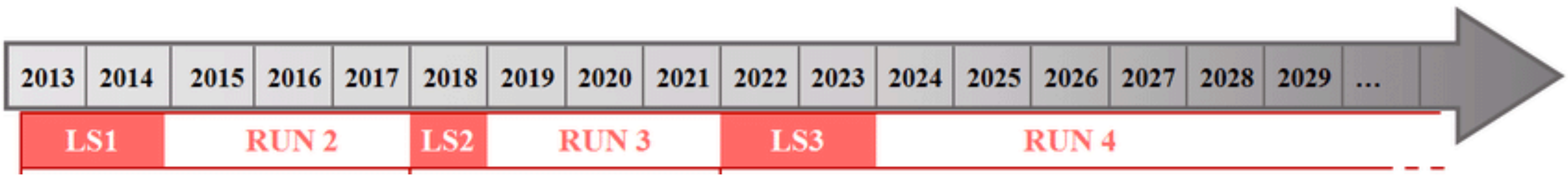
Ultimate Scenario: L = **7.5**x10e^{34} cm^{-1}s^{-1} up to 4000 fb^{-1} (200 PU)



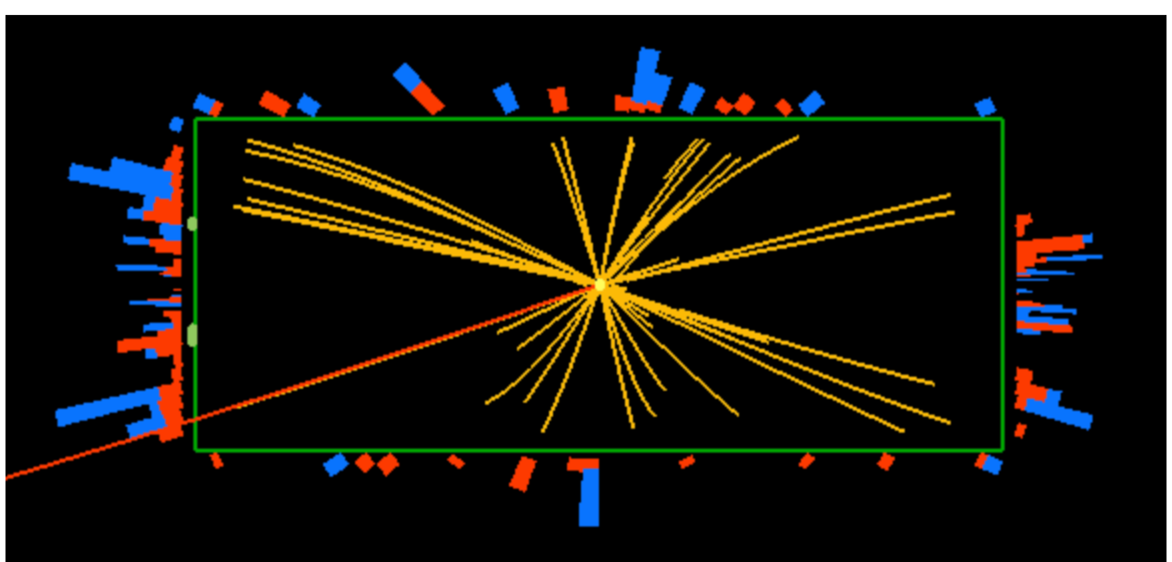
Motivations for an High Luminosity-LHC

The LHC plans a program of Increased Luminosity over the next 10 years in order to increase collected data rate

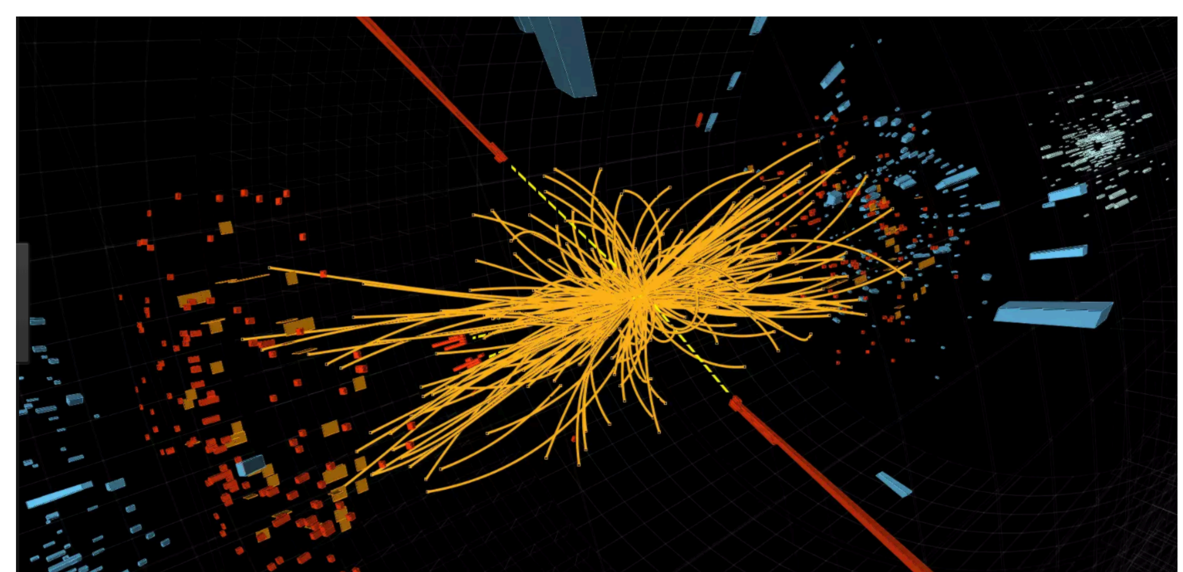
➡More data **should** lead to more precise measurements and searches with finer sensitivity



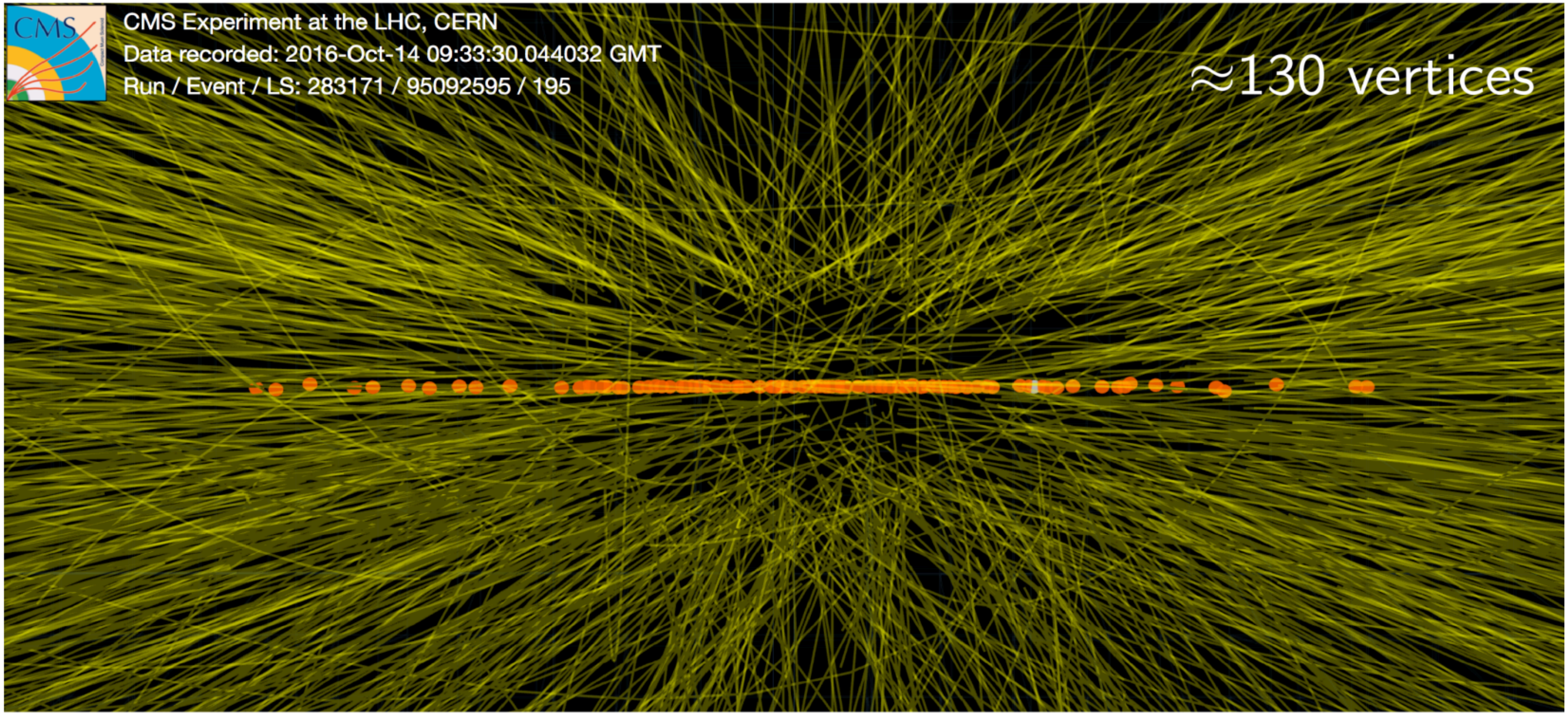
2011 ~0.5x10^{34}cm^{-2}s^{-1}



2016 2x10^{34}cm^{-2}s^{-1}



Challenges of the High Luminosity LHC (HL-LHC)

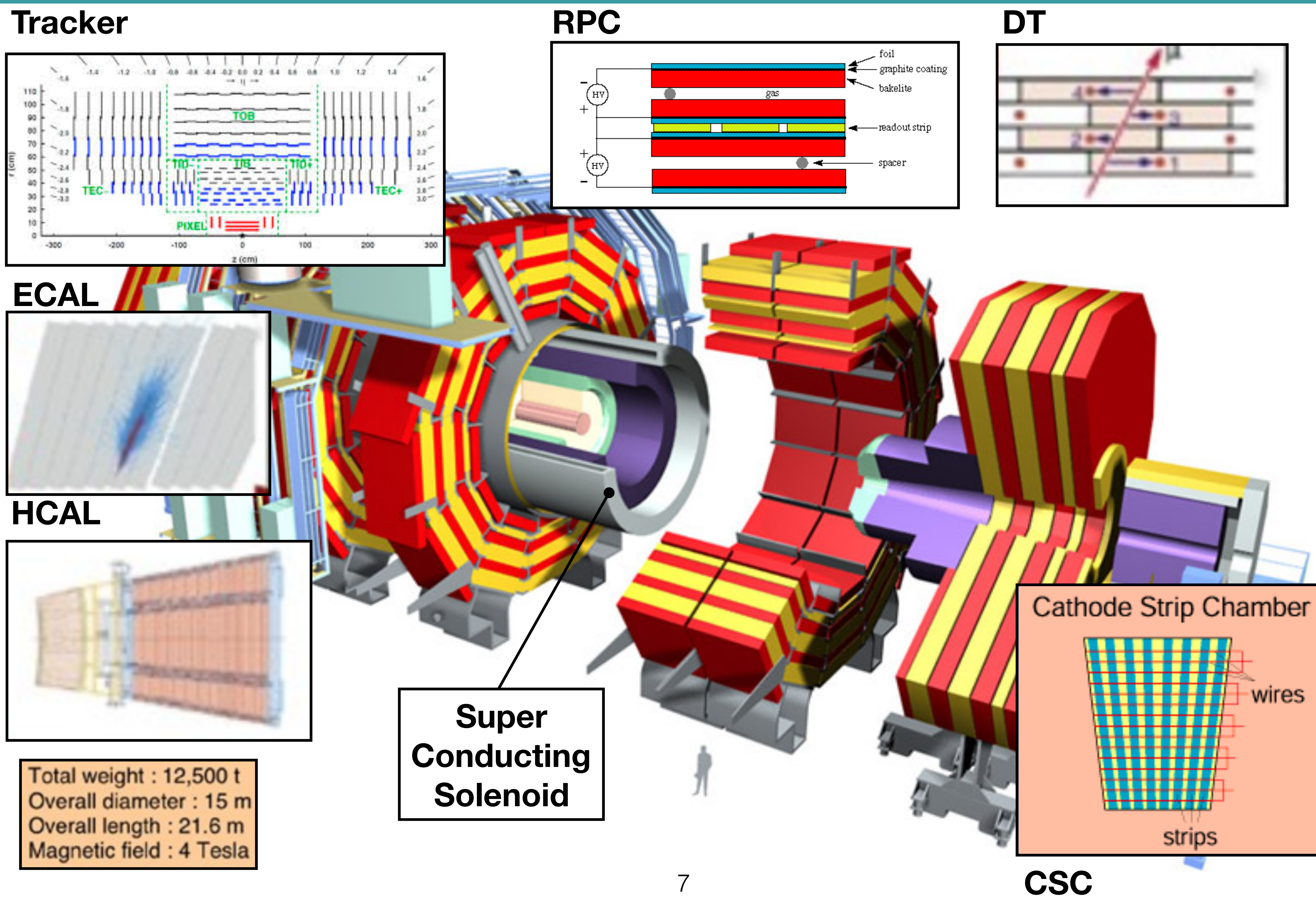


Event from Special Run in 2016, HL-LHC 150-200 vertices

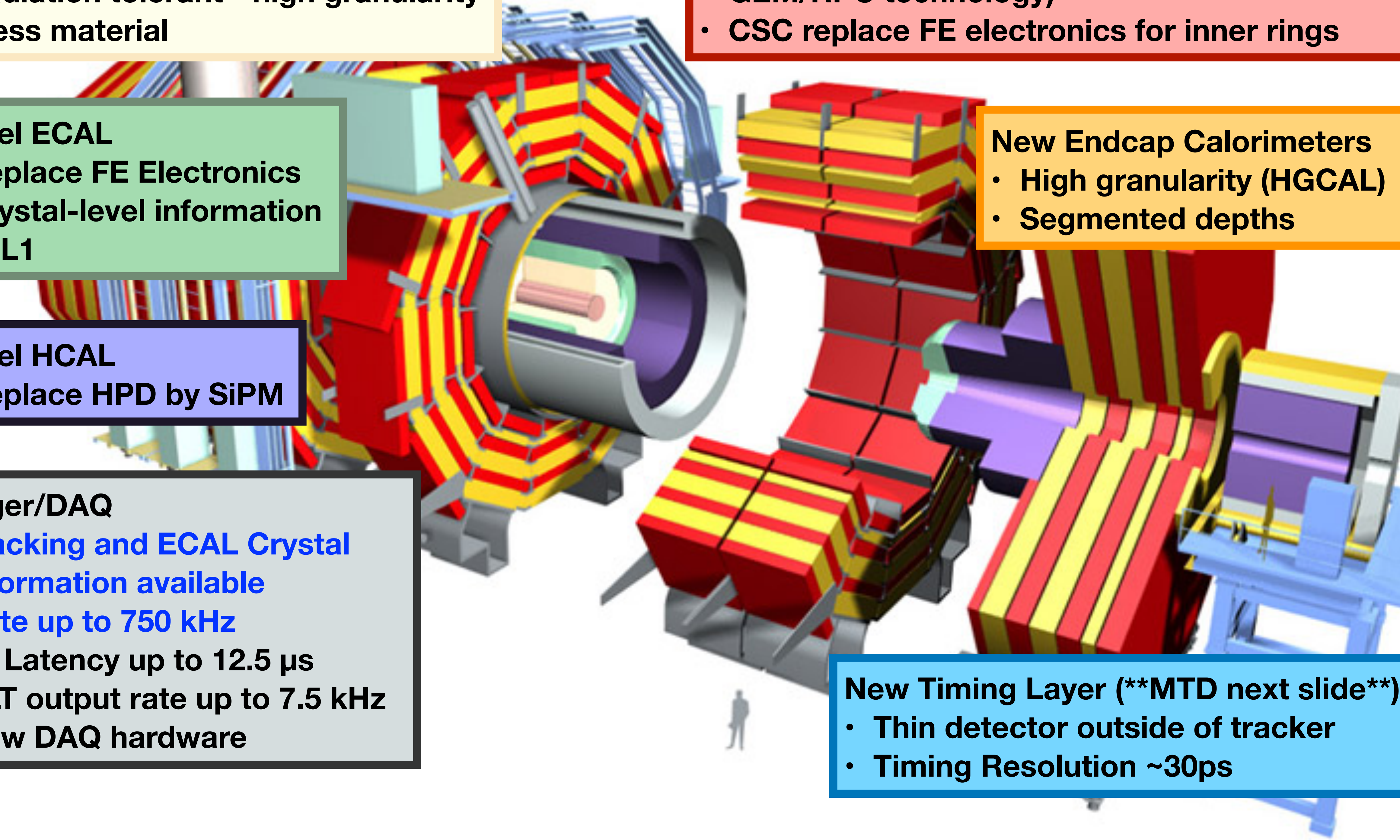
- Due to the **increased instantaneous luminosity**, the HL-LHC represents a significant challenge for **Event Reconstruction** and **Primary Vertex** identification
- Improvements to the CMS detector are planned to replace portions of the detector which will have **degraded due to radiation damage** and to **upgrade the detector** in order to **maintain a strong physics program**

The CMS Detector

CMS Phase 2 Upgrade



CMS Phase 2 Upgrade



New Tracker
- Coverage up to |η|<3.5
- Tracks available at Level 1 Trigger
- Radiation tolerant - high granularity - less material

Muons
- Replace DT FE Electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- CSC replace FE electronics for inner rings

Barrel ECAL
- Replace FE Electronics
- Crystal-level information at L1

New Endcap Calorimeters
- High granularity (HGCAL)
- Segmented depths

Barrel HCAL
- Replace HPD by SiPM

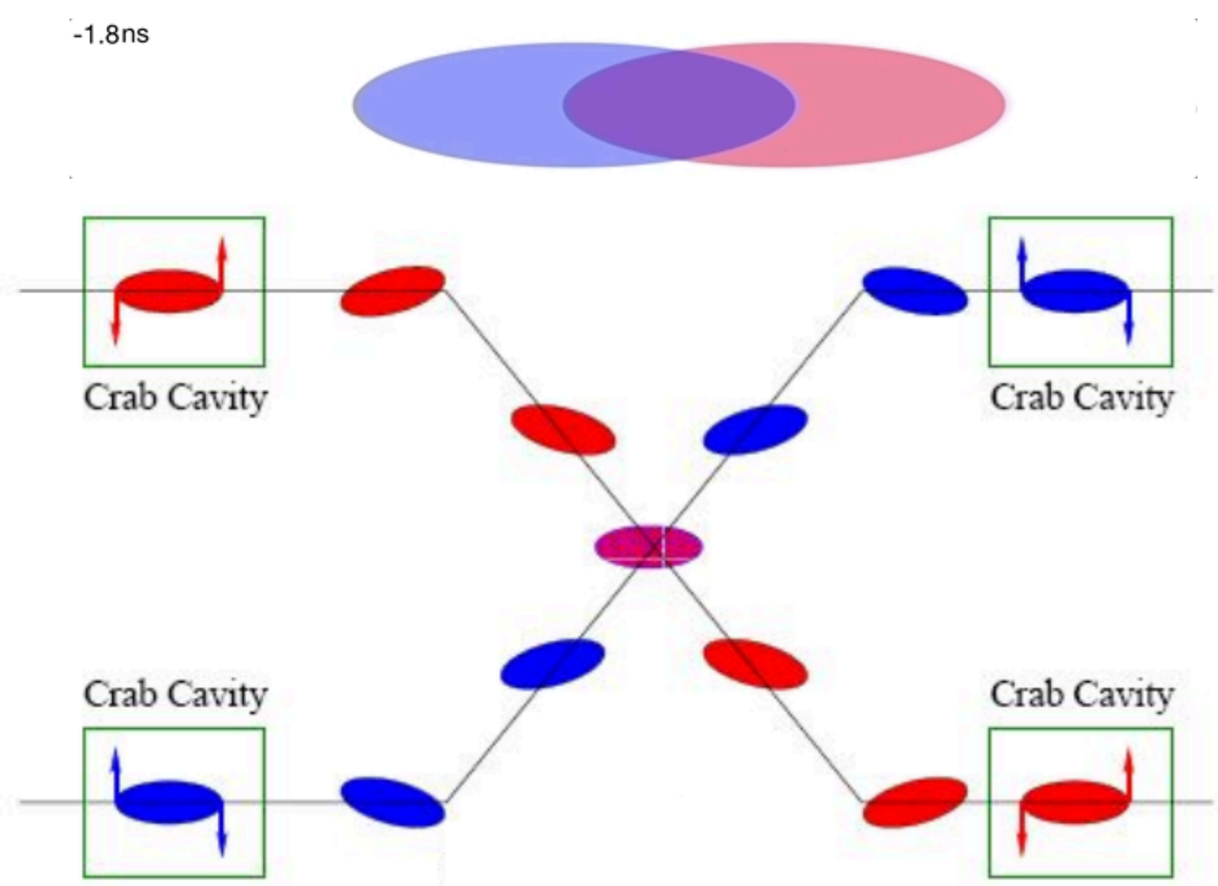
Trigger/DAQ
- Tracking and ECAL Crystal information available
- Rate up to 750 kHz
- L1 Latency up to 12.5 μs
- HLT output rate up to 7.5 kHz
- New DAQ hardware

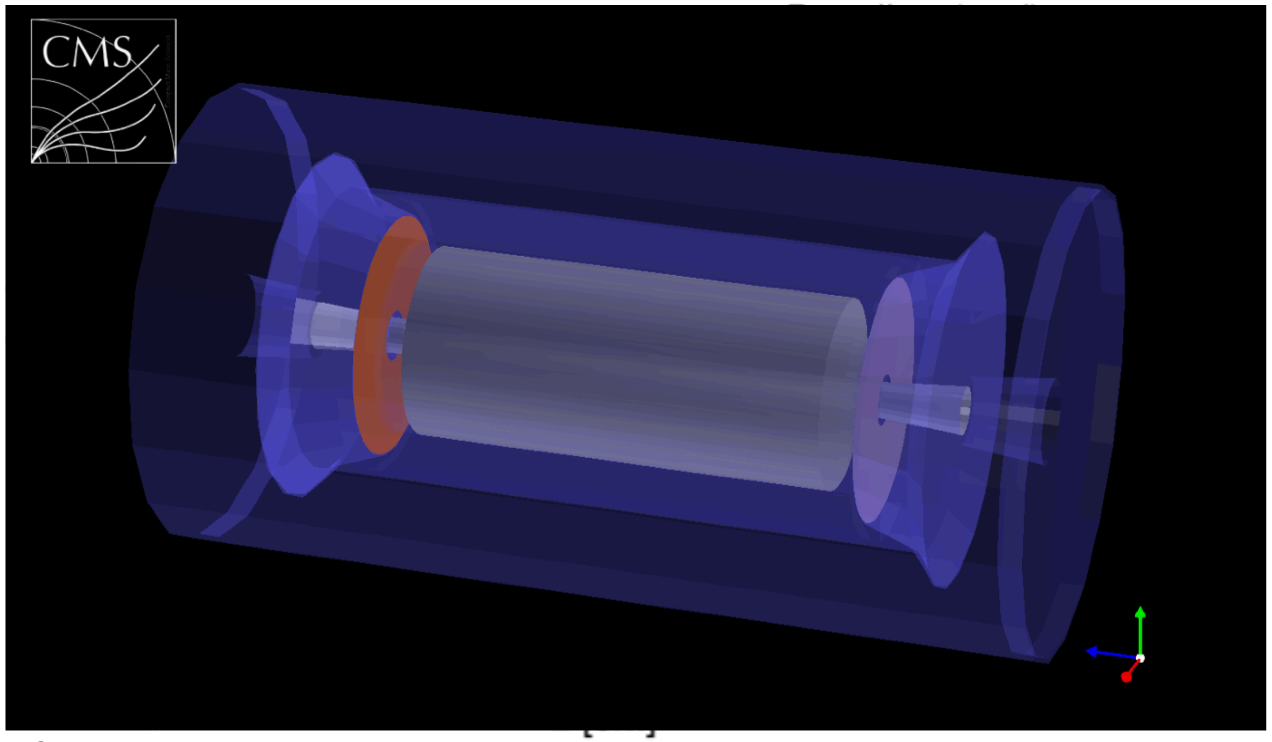
New Timing Layer (MTD next slide**)**
- Thin detector outside of tracker
- Timing Resolution ~30ps

MIP Timing Detector

Proton Bunch Interactions are Spread in Time

- During collisions, **bunch crossing operates over a discrete time interval**
- **Currently CMS sees only the integral of this process over time**
- Need to discriminate between vertices over an RMS of ~180 ps
- Additional **thin MIP Timing Detector** between tracker outer layer and ECAL Front End cooling plates





Expected Physics Performance: Higgs

Higgs at CMS

≈125.09 GeV/c²
0
0
H
Higgs

Fundamental New Discovery
→ Represents a Window to the Unknown

Using **Run I + Run II Data** we have **measured well the Higgs properties** using **H→ZZ** and **H→γγ**

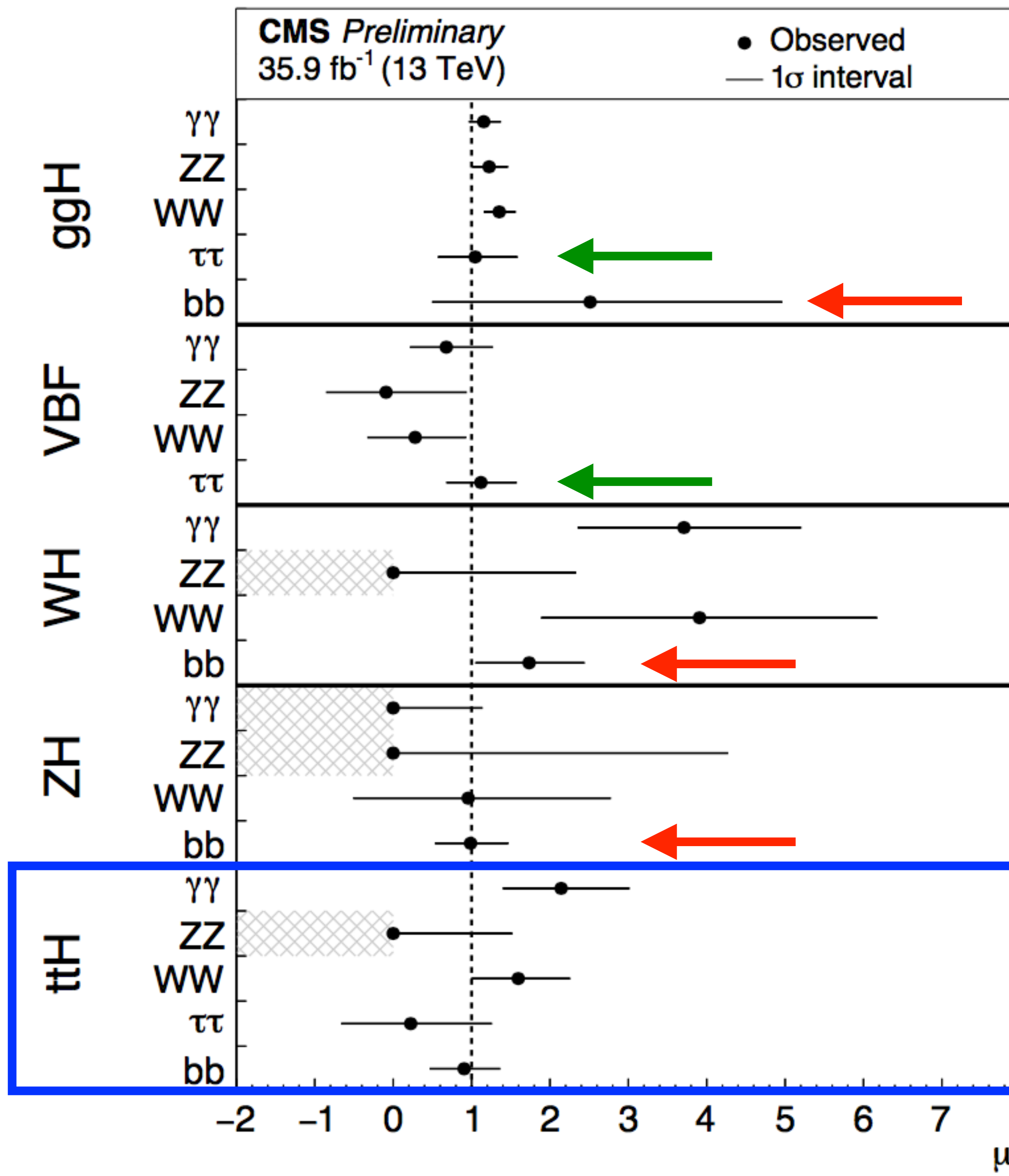
Discovered H→bb

Discovered ttH production

Discovered H→ττ

Remains important to study carefully this particle
But Also, Measure/Search for more Couplings (Production and Decay), Self Coupling, Rare Decays, Exotic Decays

Performance studies are used to motivate upgrade efforts!!



Higgs→γγ

Extrapolation from the **H→γγ 2016 analysis** (12.9 fb^{-1}) to the conditions of the **HL-LHC** with **3000 fb^{-1}** is performed

Goal: Estimate how well the signal strength and the fiducial cross-section will be measured

All systematic uncertainties are kept constant

S1: Effects of **higher pileup conditions** and **detector upgrades of** CMS **are not** taken into account

S1+: Effects of **higher pileup conditions** and **detector upgrades** of CMS **are** taken into account

Theoretical uncertainties scaled by 1/2

Experimental uncertainties are **scaled** by the **square root of integrated luminosity**

S2: Effects of **higher pileup conditions** and **detector upgrades** of CMS **are not** taken into account

S2+: Effects of **higher pileup conditions** and **detector upgrades** of CMS **are** taken into account

Extrapolation from the **H→γγ 2016 analysis** (12.9 fb^{-1}) to **300 fb^{-1}** with **current conditions** and to **3000 fb^{-1}** with **HL-LHC conditions** is performed

Goal: Estimate how well the signal strength and the fiducial cross-section will be measured

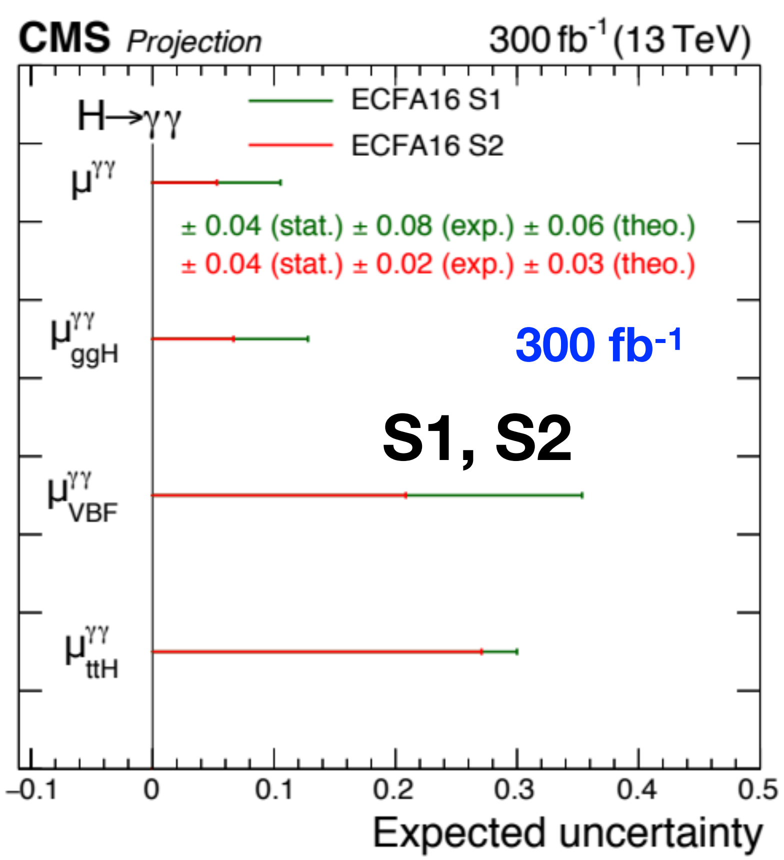
All systematic uncertainties are kept constant

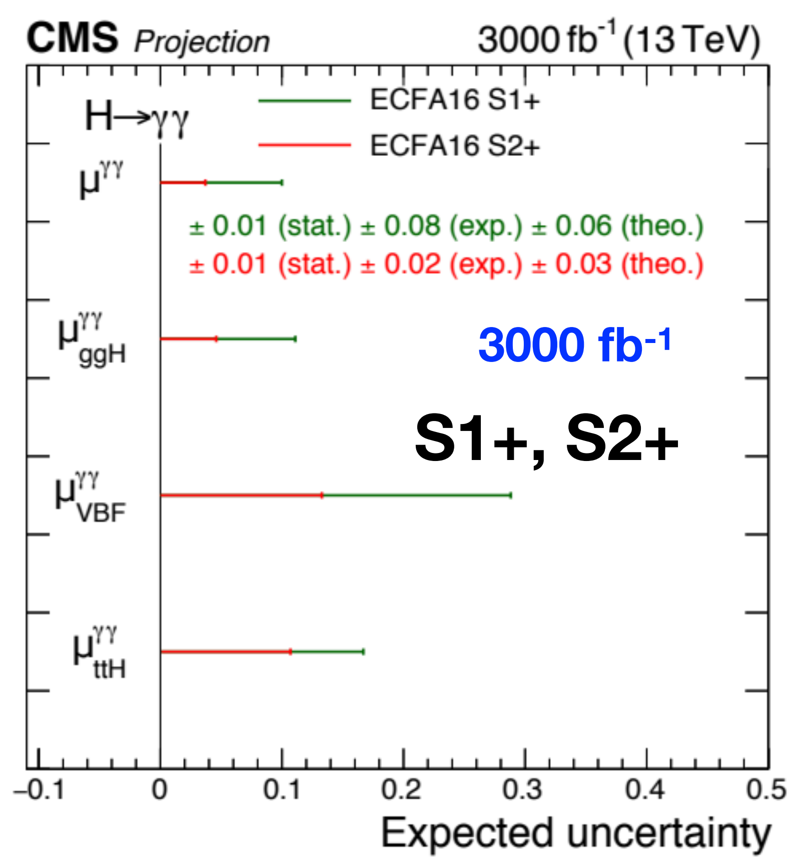
S1: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account
S1+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account

Theoretical uncertainties are **scaled down by 1/2**

Experimental uncertainties are **scaled down** by the **square root of integrated luminosity**

S2: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account
S2+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account





Higgs→γγ

FTR-16-002

Extrapolation from the **H→γγ 2016 analysis** (12.9 fb^{-1}) to **300 fb^{-1}** with **current conditions** and to **3000 fb^{-1}** with **HL-LHC conditions** is performed

Goal: Estimate how well the signal strength and the fiducial cross-section will be measured

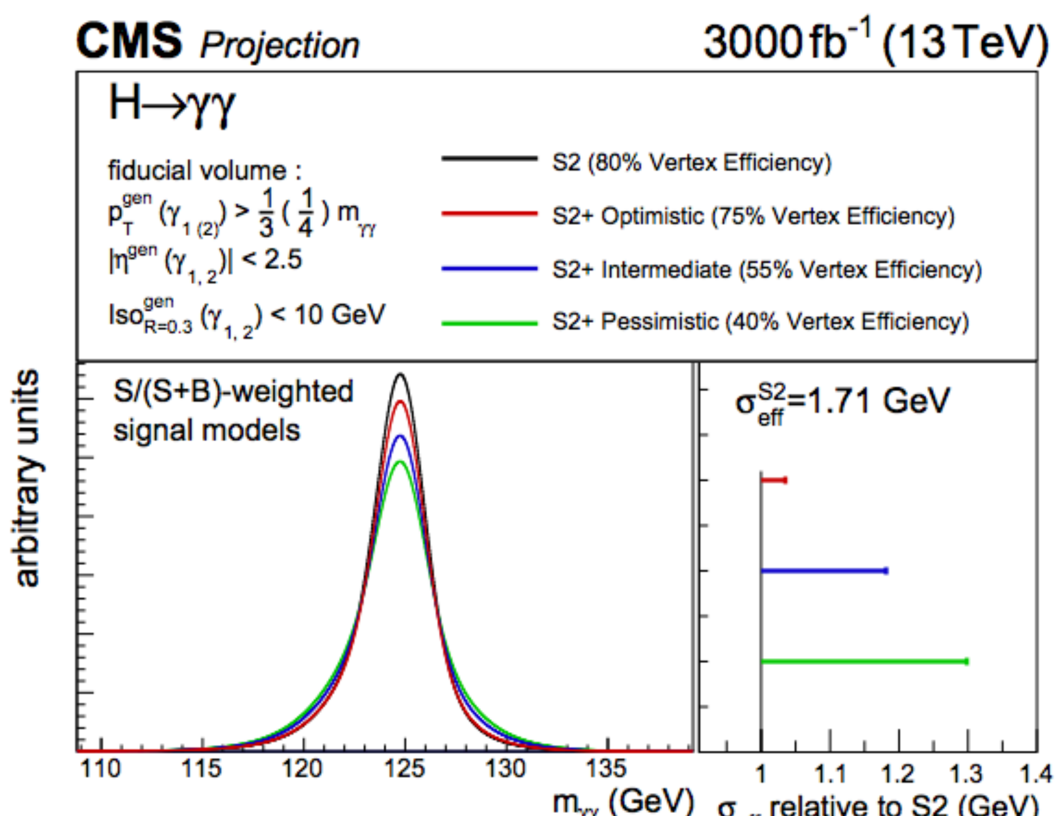
All systematic uncertainties are kept constant

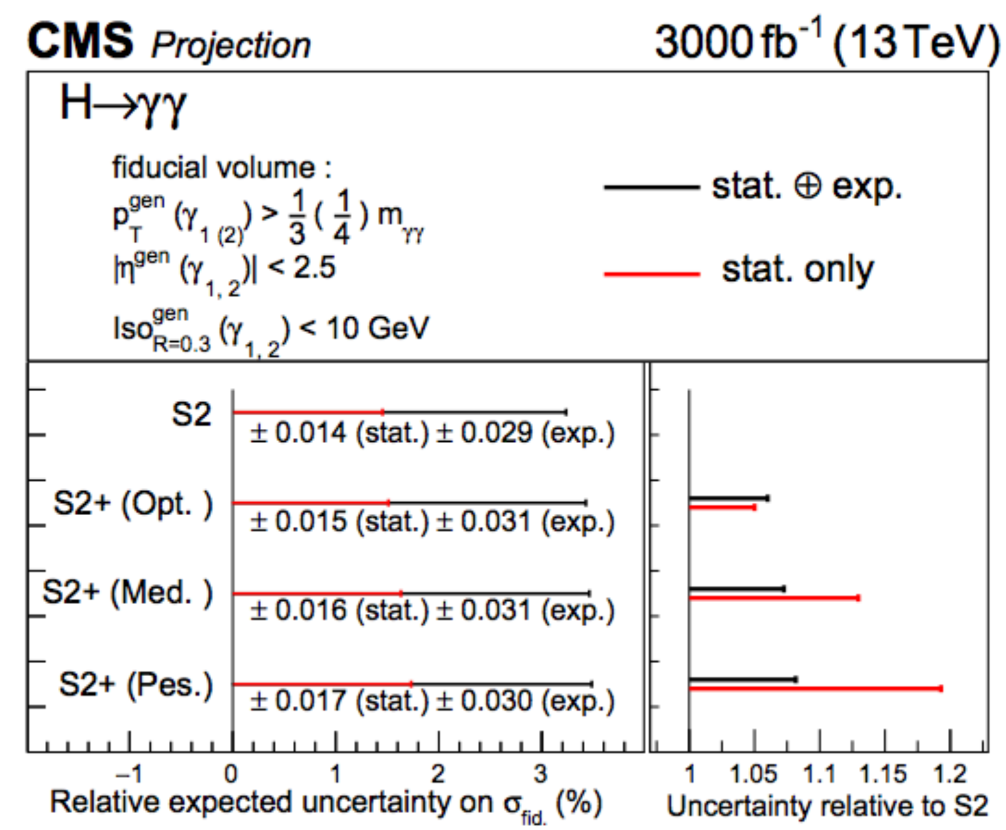
S1: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account
S1+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account

Theoretical uncertainties are **scaled down by 1/2**

Experimental uncertainties are **scaled down** by the **square root of integrated luminosity**

S2: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account
S2+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account



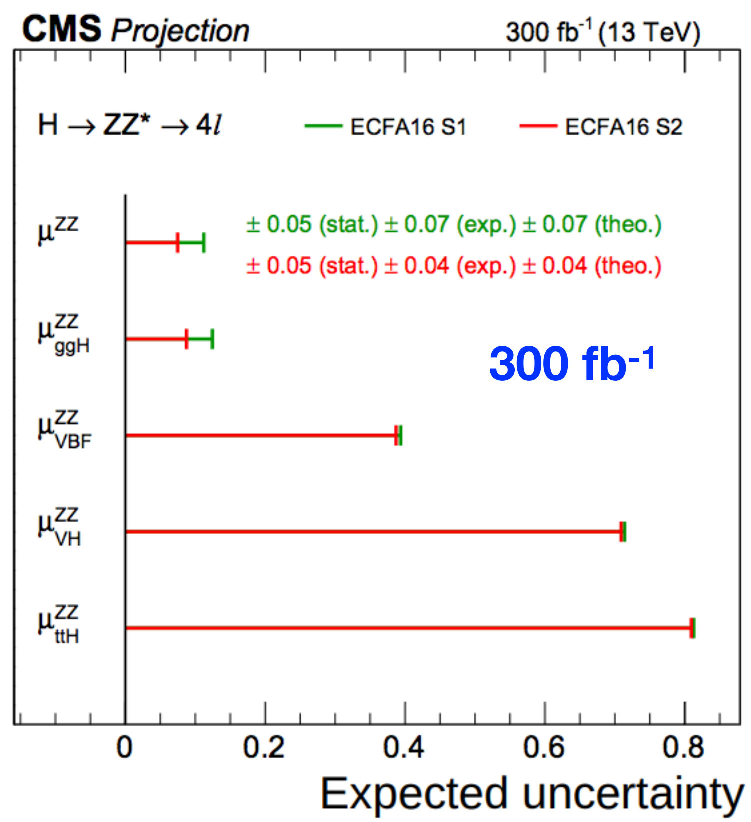


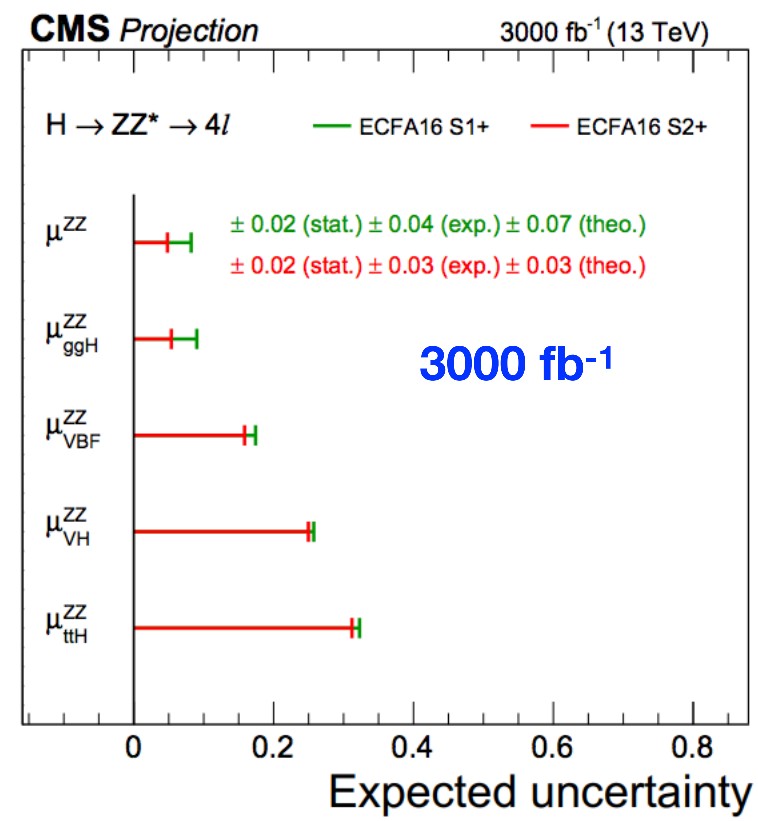
Timing For Vertex Identification

Higgs → ZZ* → 4l

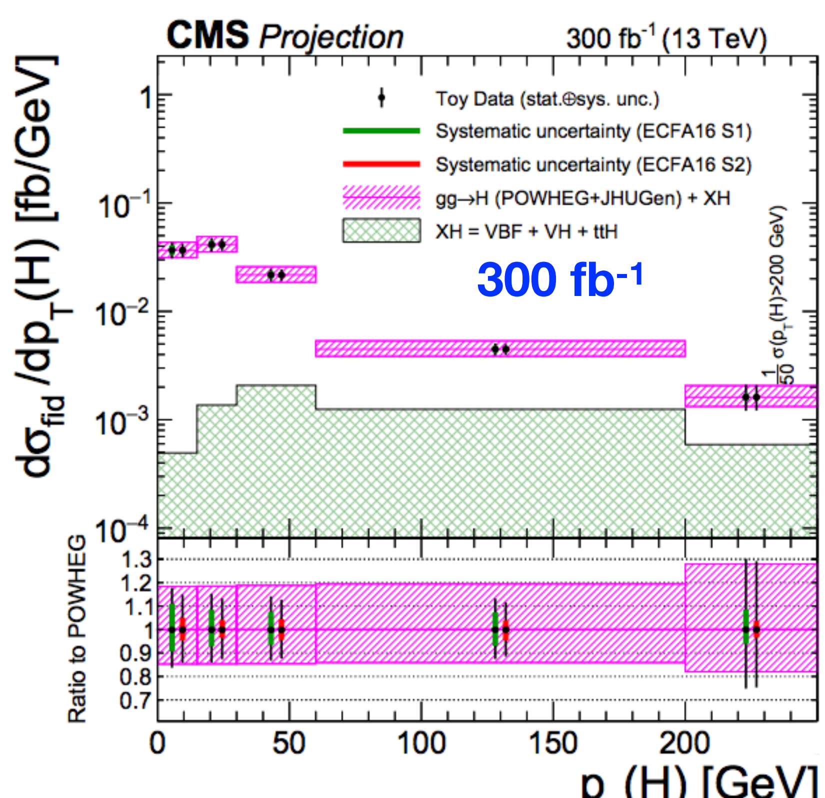
FTR-16-002

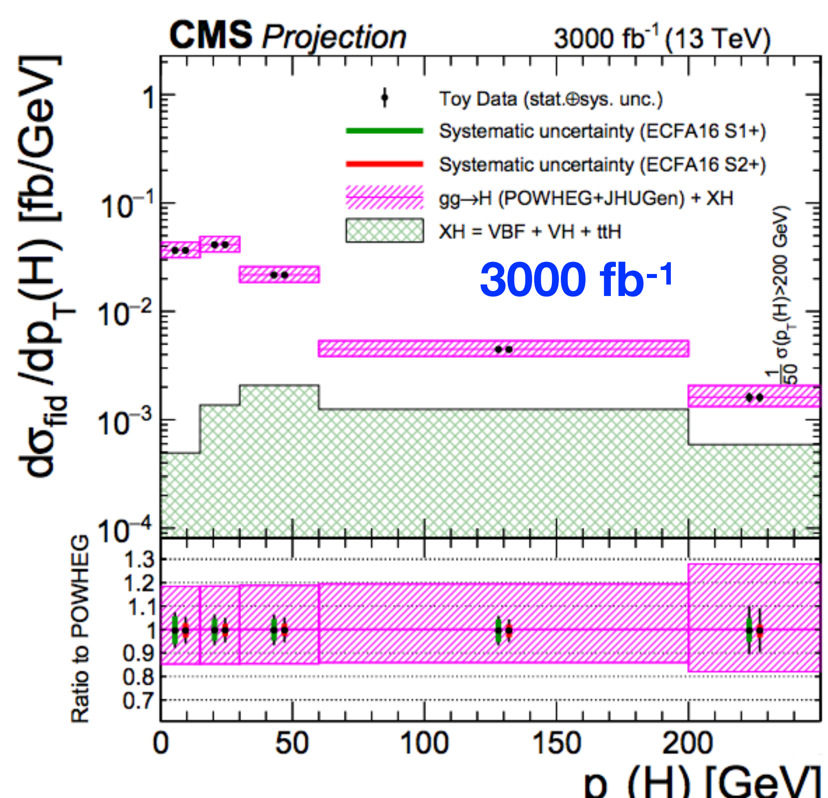
Projected uncertainties on the Higgs boson **signal strength inclusively** and for different **production modes**





Differential fiducial cross section measurement of the Higgs boson as a **function of the Higgs Transverse Momentum**



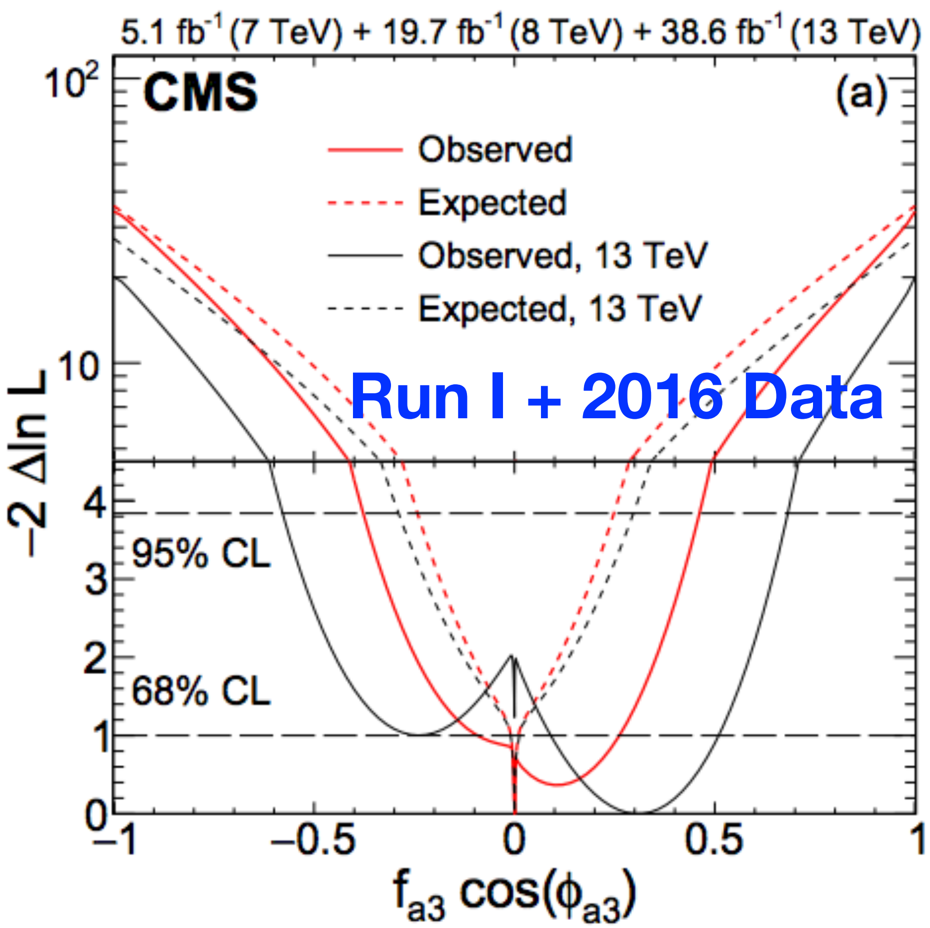


Anomalous Couplings Higgs→ZZ*→4l

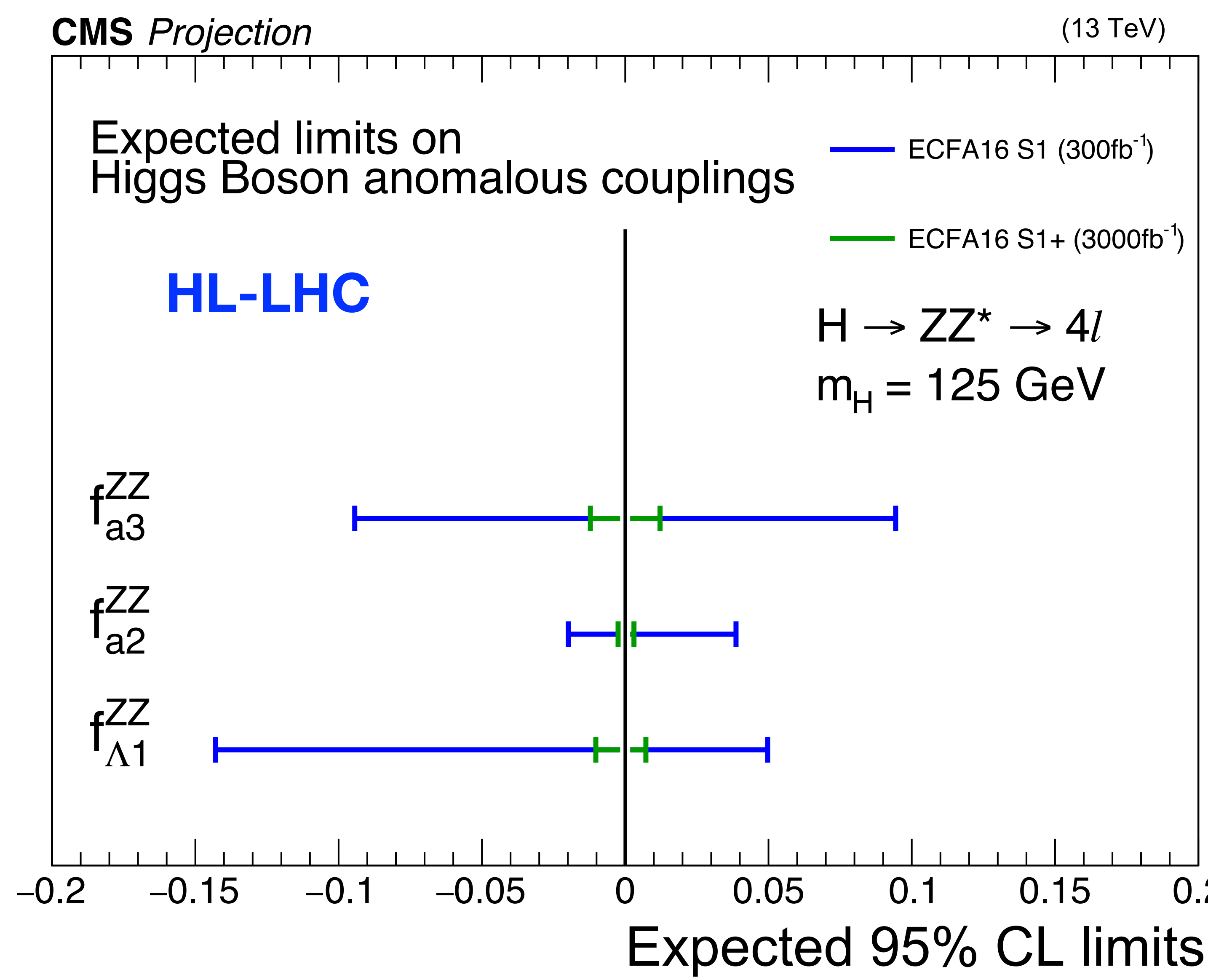
FTR-16-002

CP properties of the Higgs have been studied using boson decays and provide **constraints on anomalous HVV couplings**

Although **hypothesis of pure pseudoscalar state is ruled out**, the H(125) state **could be a mixture of CP-even and CP-odd** states (with a small pseudoscalar component)



[arXiv: 1707.00541](https://arxiv.org/abs/1707.00541)



*All systematic uncertainties are kept constant with integrated luminosity, assumes unchanged CMS detector

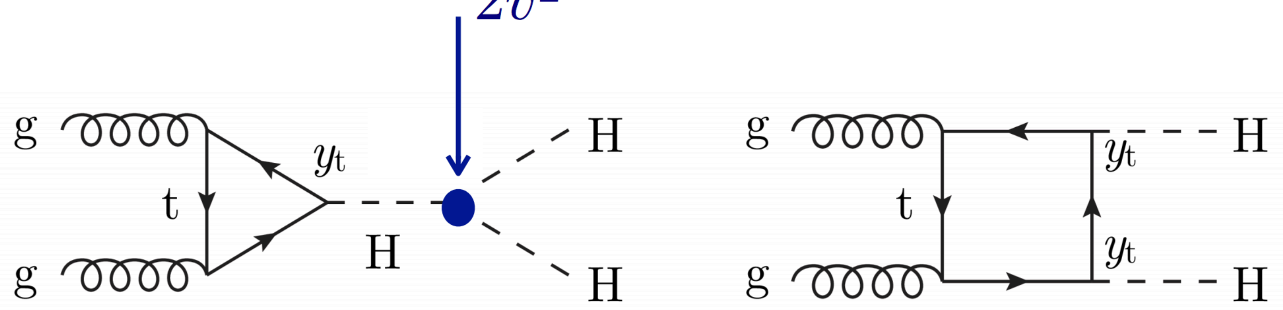
Di-Higgs

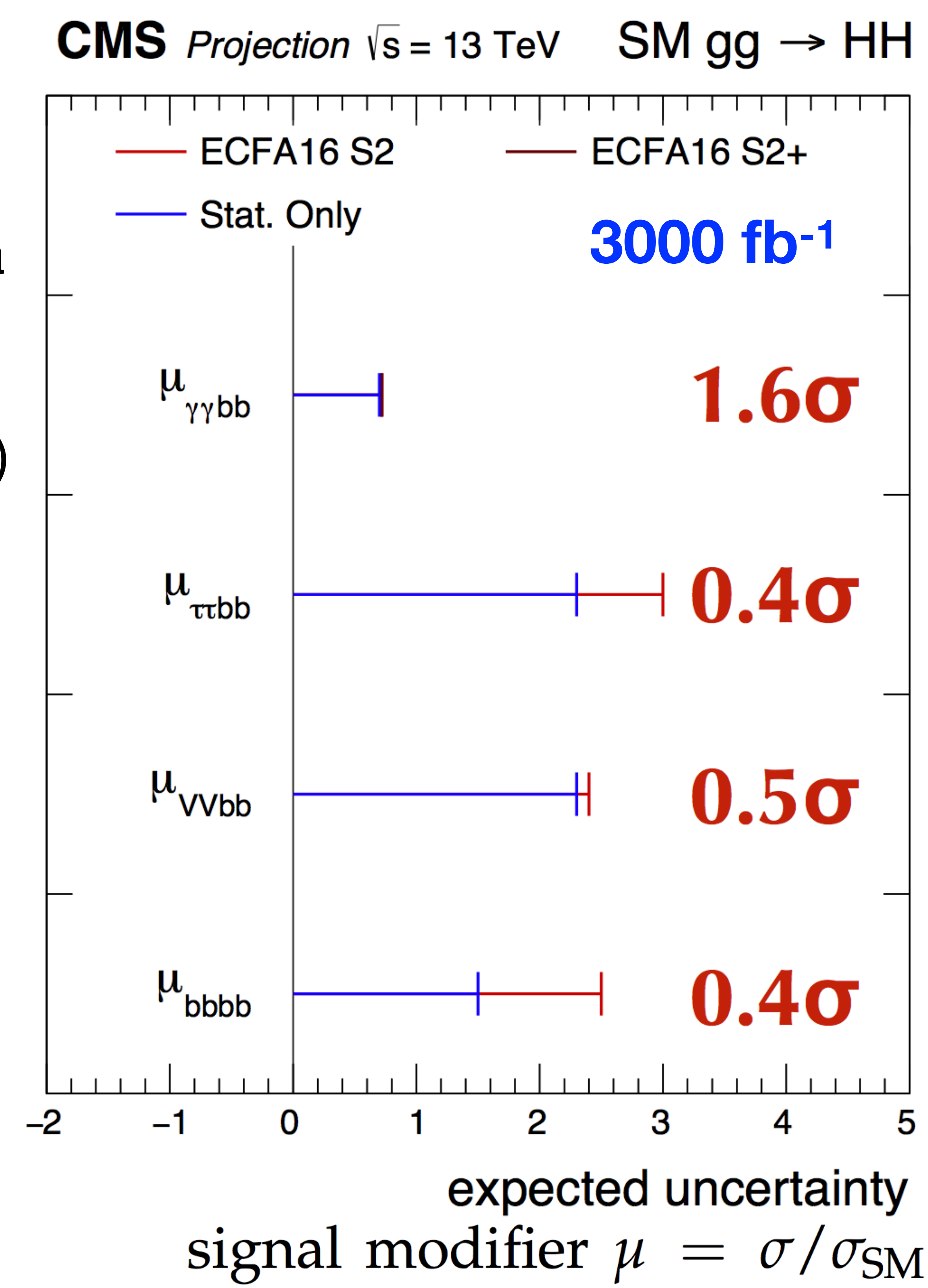
FTR-16-002

Higgs boson self coupling measurement is a fundamental test of the SM
- SM predicts an extremely small cross section for HH production (33.5 fb at 14 TeV)

Extrapolation to Run II is based on 2015 dataset

$$\lambda_{\mathrm{HHH}} = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$





Higgs VH, VBF, Rare

Also use the HL-LHC as an opportunity to study production and rare decay modes

VBF with Higgs decay to ττ

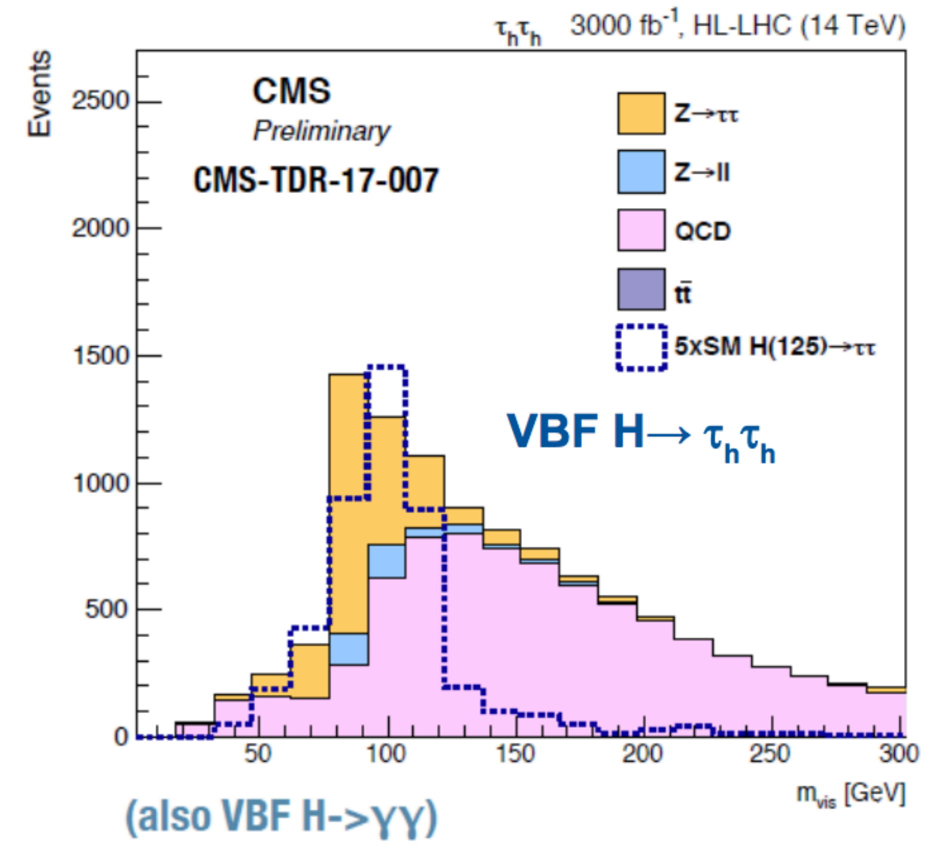
- Sensitive probe for studying VBF Production

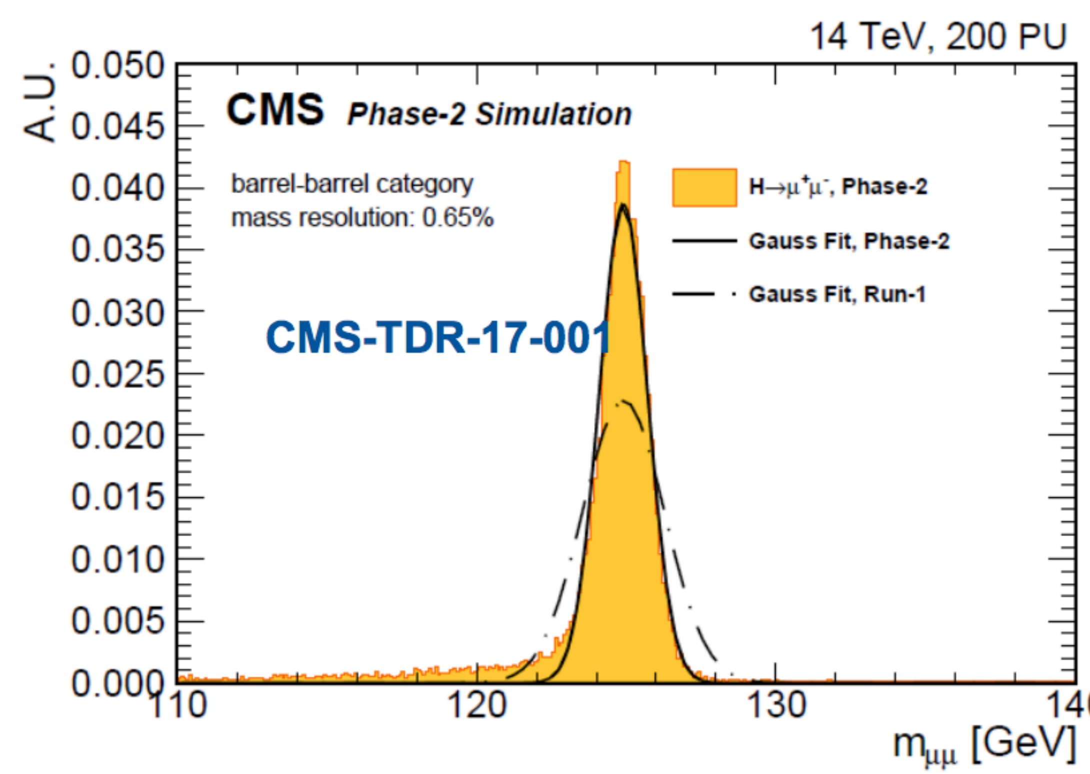
Higgs decaying to μμ

- Rare decay which will only be accessible with HL-LHC dataset

Higgs decaying to cc

- Very difficult to detect, possible case for a dedicated Level 1 Trigger?

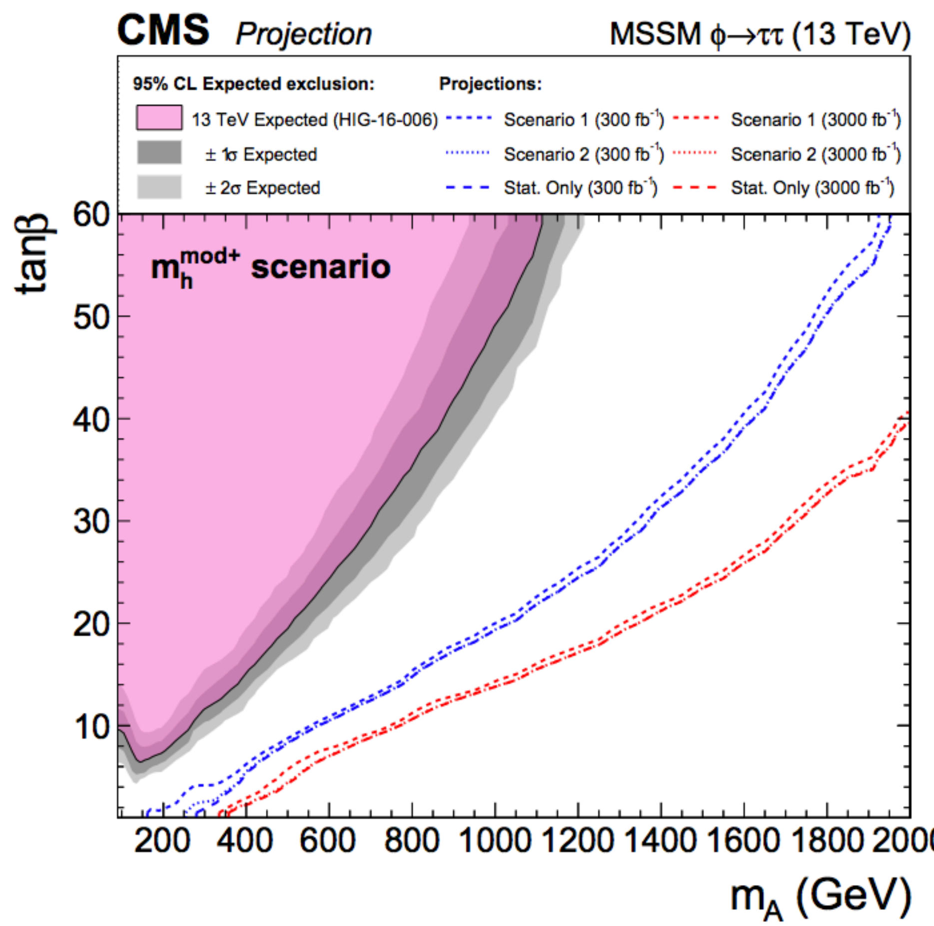




MSSM φ → ττ

FTR-16-002

In the 2HDM MSSM there are **five physical Higgs** particles, $H^{\pm}$, A, h, H
- **h** is usually considered to be the **125 GeV Higgs**
-**“Benchmark scenarios”** fix parameters
- **Model independent case** searches for a single resonance between 90 GeV and 3.2 TeV

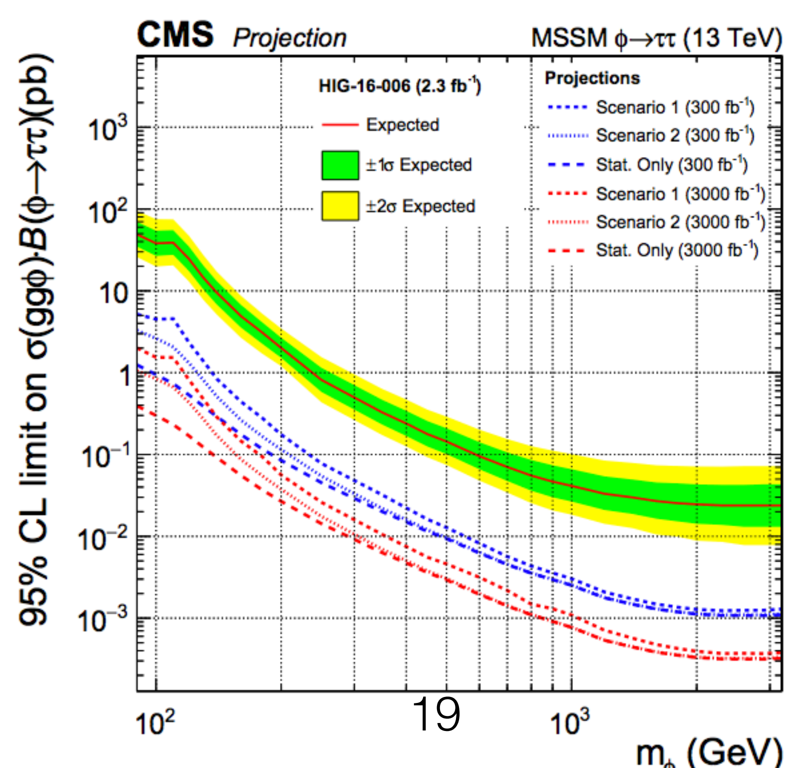


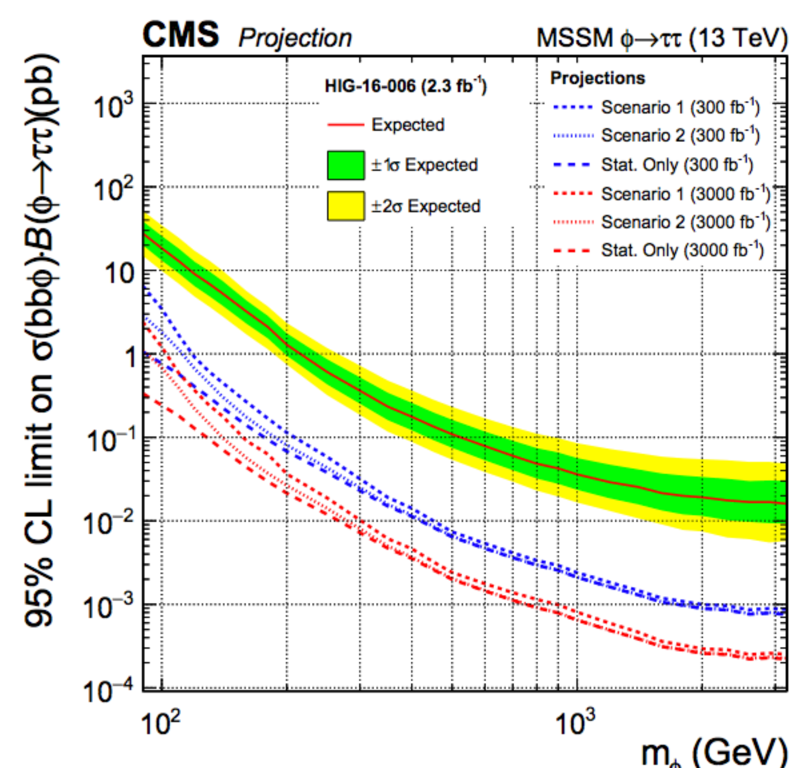
Analysis used for projections based on 2.3 fb-1 from 2016 data set

Final states analyzed:

μτh, eτh, τhτh and **eμ**

- (**τ** decays quickly)





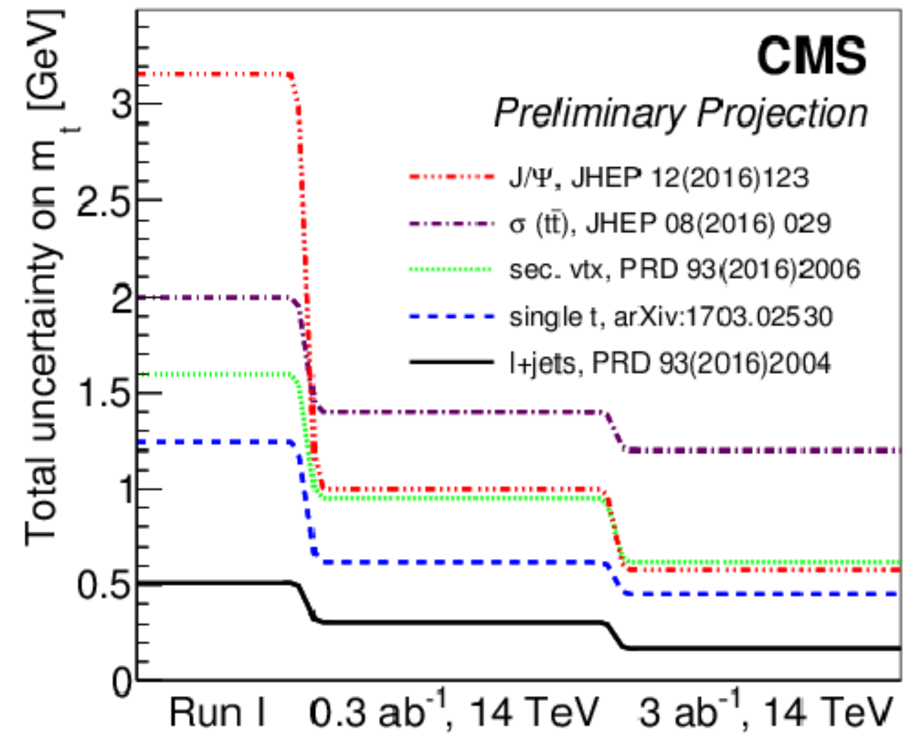
Expected Physics Performance: Standard Model

Standard Model: Top Quark Mass

FTR-16-006

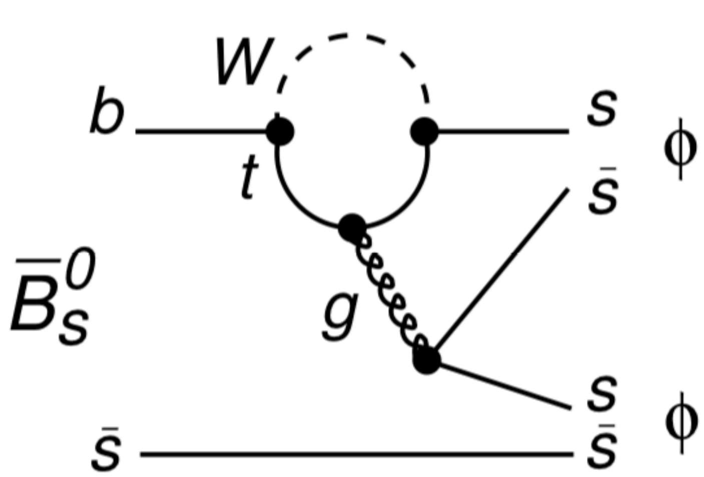
Top Quark Mass Mass Measurements Projections with 3 ab^{-1}

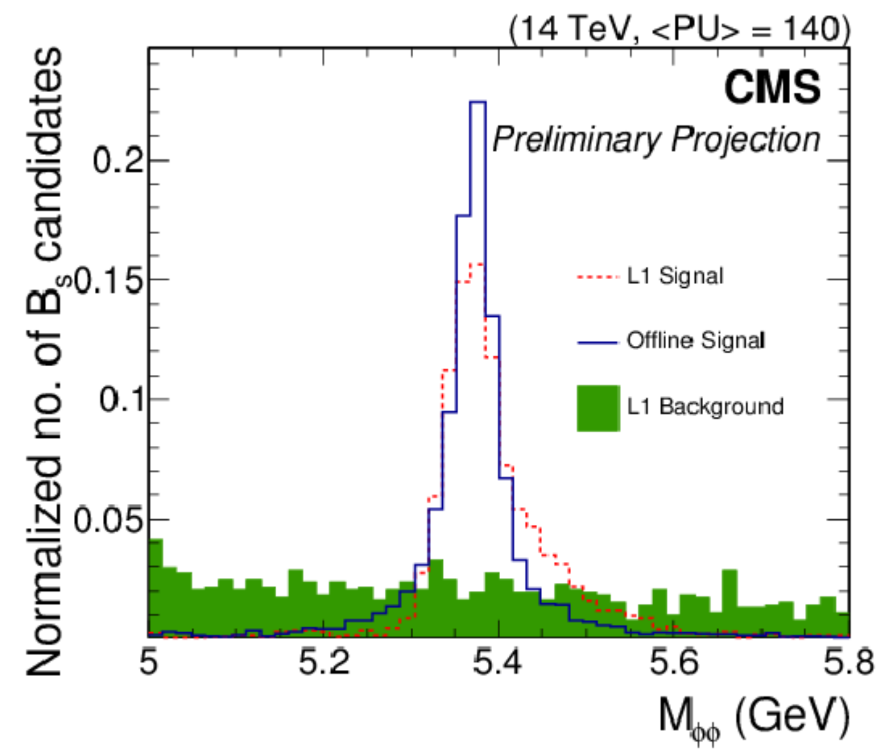
- Measurements limited by theoretical modeling uncertainties
  - Though, theo. expected to reach 0.1%
- Experimental systematic uncertainties can be further reduced when fit in combination (as in the reference analysis)



$\bar{B}^0_S \rightarrow \phi\phi \rightarrow 4K$ decay is a FCNC process that is forbidden at tree level in the SM

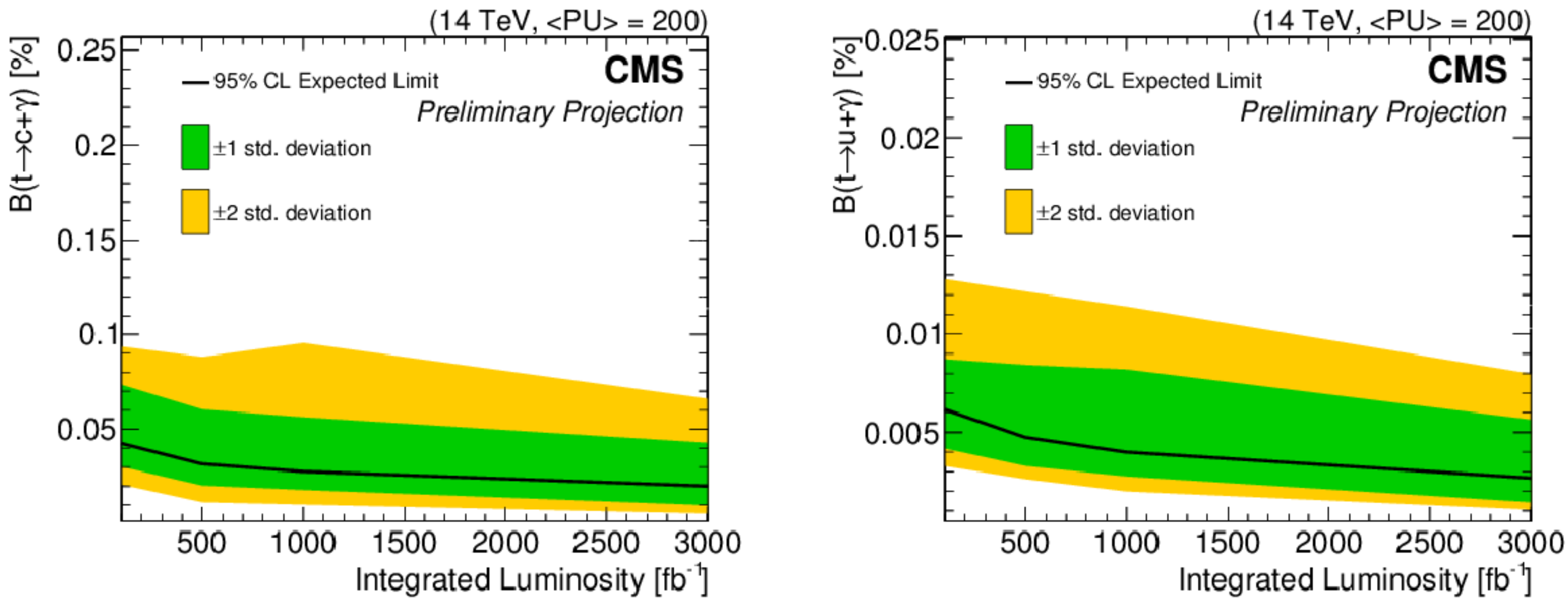
- This process can receive **contributions** in the loop **from BSM particles** with high masses
- **Probe for New Physics** at **Energy Scales** that are **not reachable by direct measurements**
- Study developed a special L1 Trigger to catch the low p_T signature





Standard Model: FCNC Search using Top Quarks

FTR-16-006



Search for Flavor Changing Neutral Current processes in **Top Quark** associated with a photon at a luminosity of 3 ab^{-1} upper limits at 95% CL

B(t→u+γ) < 0.0027% and **B(t→c+γ) < 0.020%** are **expected**

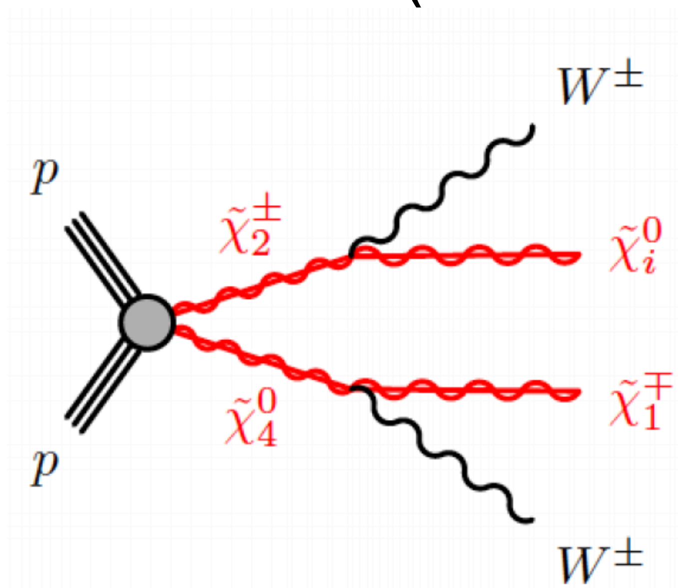
Expected Physics Performance: SUSY/Exotica

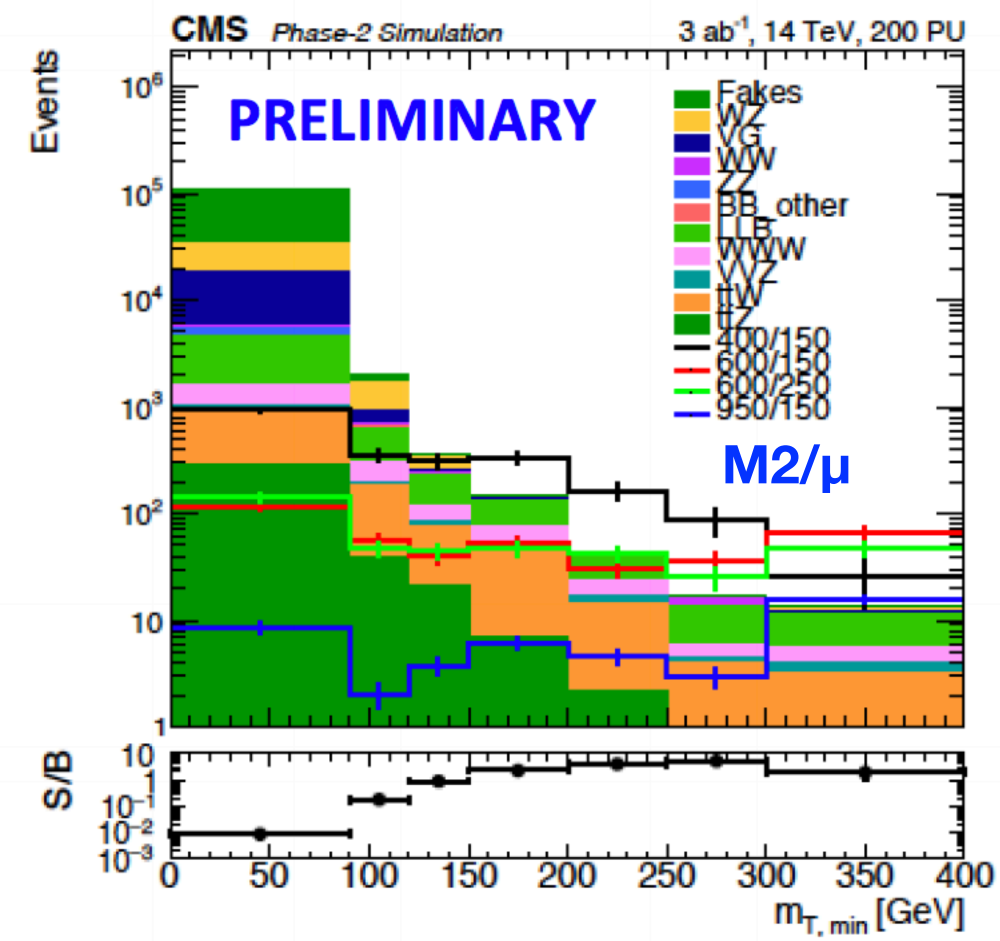
SUSY: Search for Electroweakinos

TDR-17-007

The exploration of electroweak production of SUSY particles has just started at the LHC due to its low production cross-section
In most SUSY breaking scenarios, the **supersymmetric partners** of the gauge and Higgs bosons are expected to be **lighter than a few hundreds** of GeV based on **naturalness and unification argument**

Example: wino-like $\tilde{\chi}_2^{\pm}\,\tilde{\chi}_4^{0}$ production yields two same-sign leptons and large MET in the final state (BR in Ws = 25%)





$$m_{T,min} = \min[m_{T(lep_1,p_T^{miss})}, m_{T(lep_2,p_T^{miss})}]$$

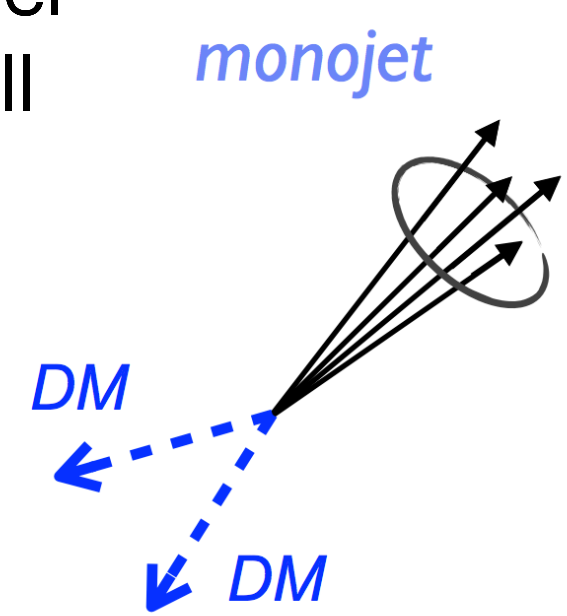
M2 = mass of wino
μ = mass of higgsino

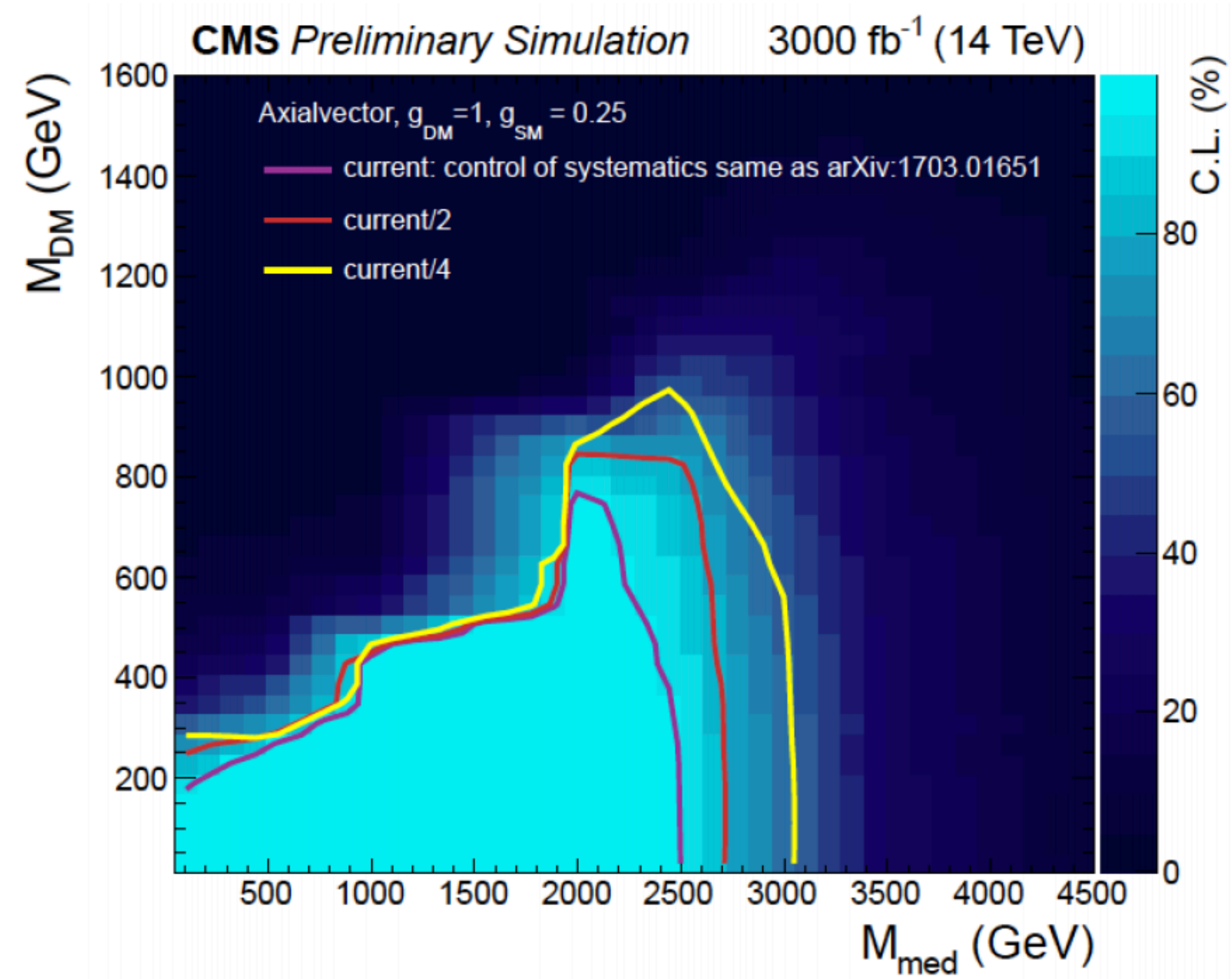
- **Forward calorimeter** is a **critical subdetector** for this analysis as **optimal MET and jet reconstruction performance is essential** in discriminating signal from background

Dark Matter

Dark Matter appears as an event excess in MET tail

- Assume weak interaction with SM
- Essential to model backgrounds well
- Compare SM prediction with data





Sensitive Distribution: bulk/low MET distribution

Three systematic uncertainty scenarios used for projections:

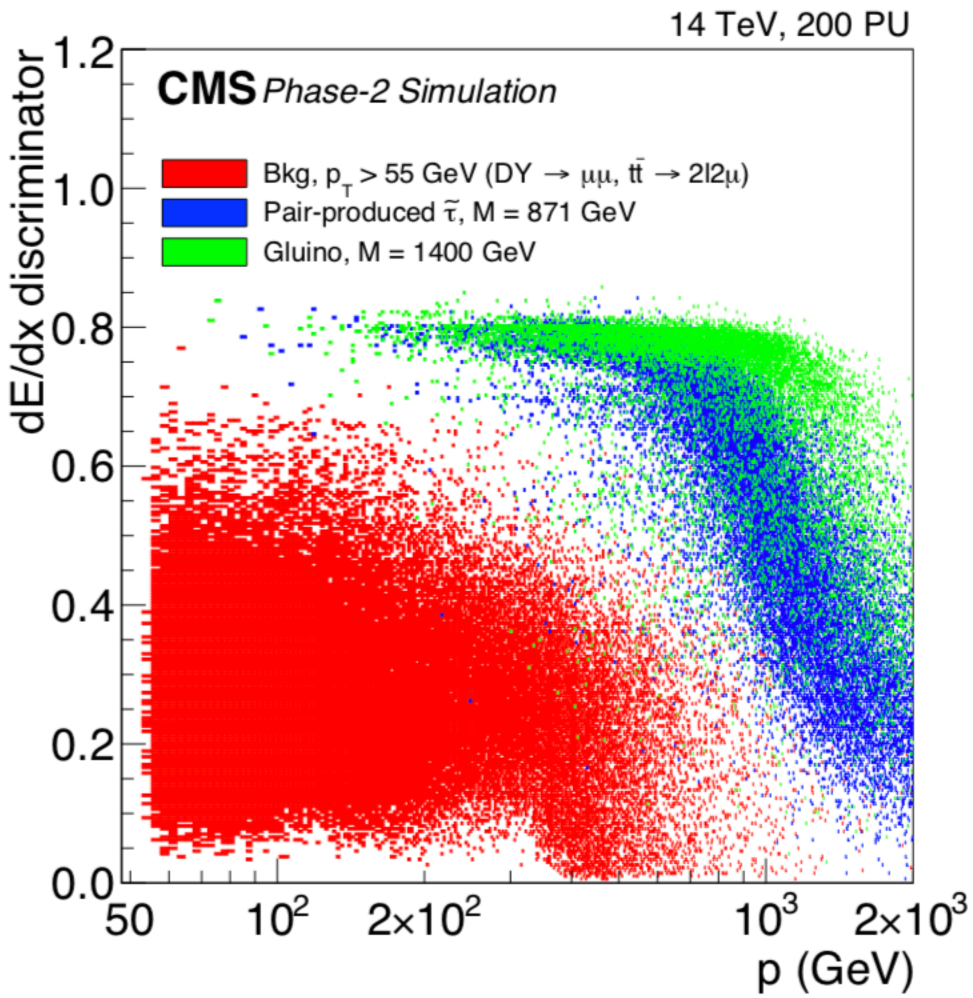
Current - ETmiss < 500 GeV, lepton identification/iso efficiency in lepton CRs (1% per leg), ETmiss > 500 GeV as CR (**from arXiv:1703.01651**)

Current/2 - current systematic scenario improved by a factor 2

Current/4 - current systematic scenario improved by a factor 4

Long Lived Particles: HSCPS

TDR-17-001



Heavy Stable Charged Particles (HSCPs) would exhibit anomalously high energy loss per distance traveled as compared to SM particles

Current Outer Tracker readout is binary

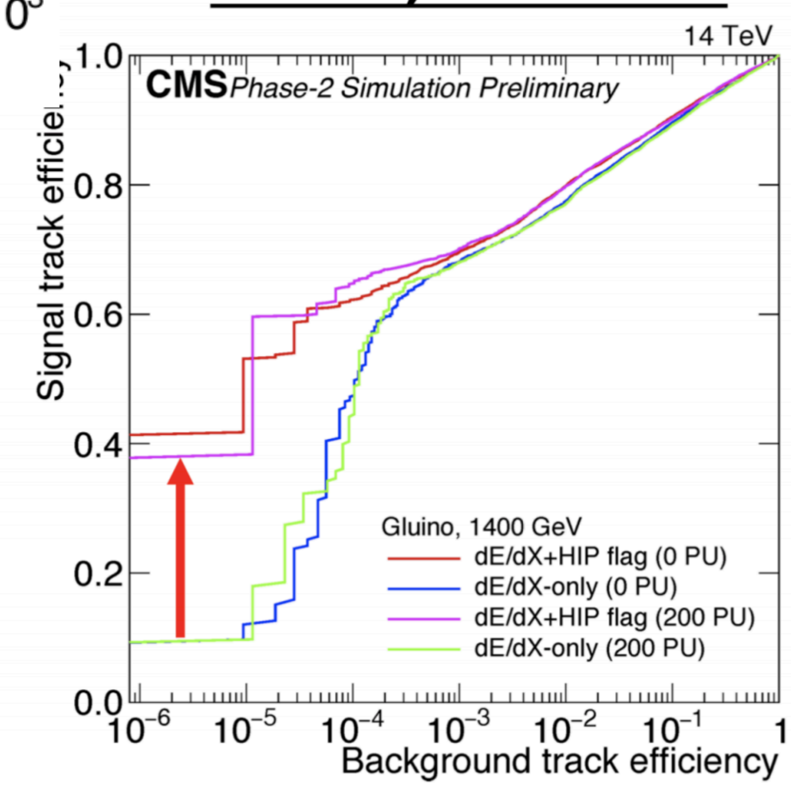
- Only one energy threshold for hit detection

Phase 2 Outer Tracker will include a dedicated programmable threshold to detect particles with high dE/dx

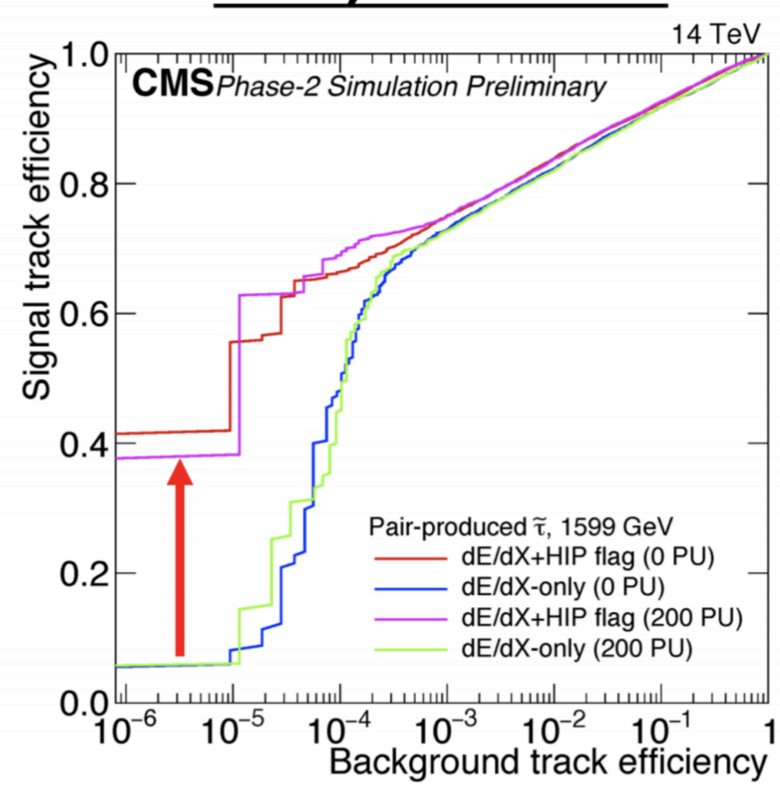
- **"HIP" flag** will separate Highly Ionizing Particles from Minimally Ionizing Particles

Signal vs. Background Eff. for:
A **gluino** (Mass 1400 GeV),
Pair Produced $\tilde{\tau}$s M(871 GeV)
Compared to tracks from SM processes

Gluino, 1400 GeV



Stau, 1599 GeV

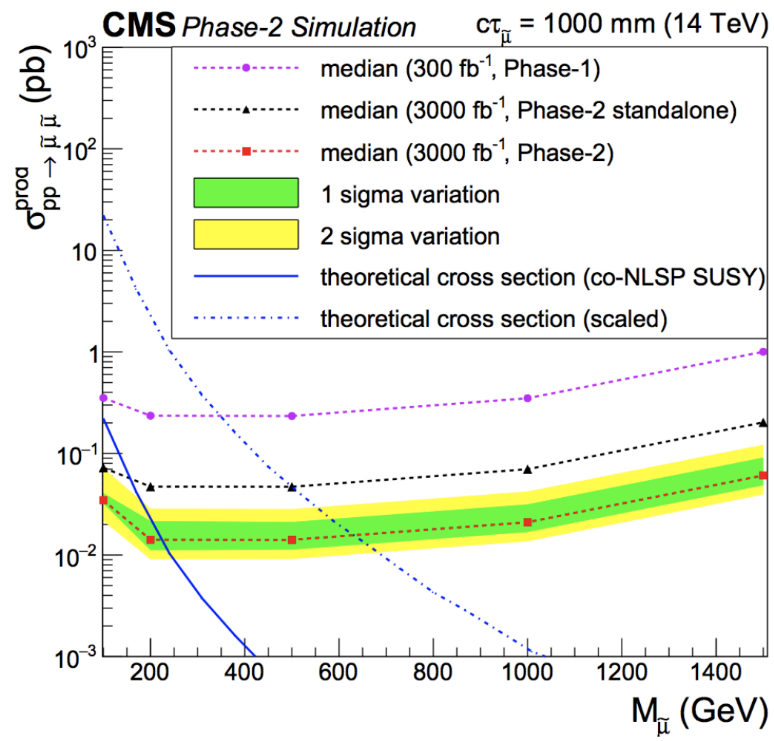


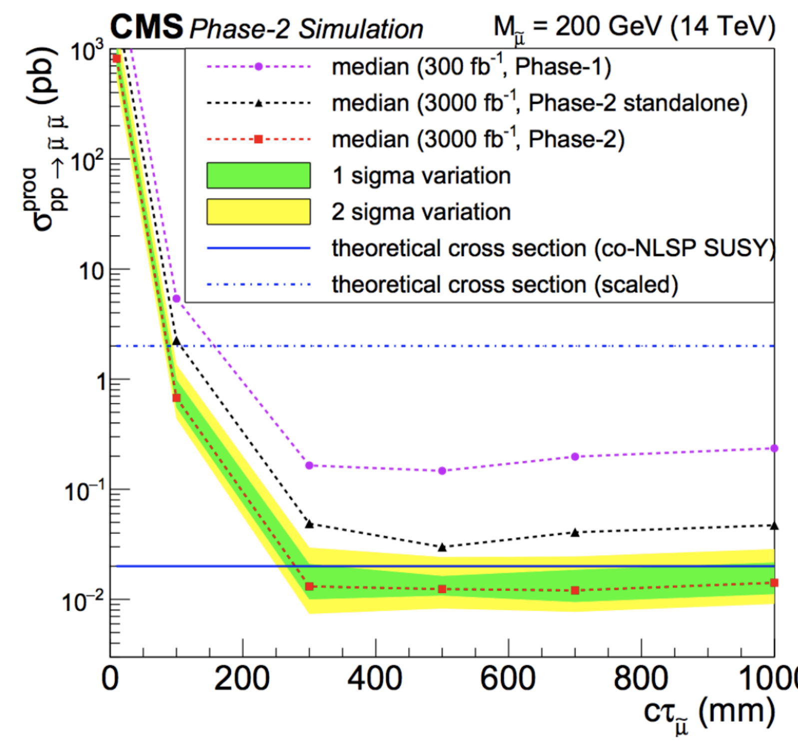
Long Lived Particles: Muon Displaced Algorithms

TDR-17-003

Gauge-mediated SUSY breaking model with the smuon as NLSP resulting in a two displaced oppositely charge muons

- Large MET (> 50 GeV) selected
- **Impact parameter significance** as **background discriminator**



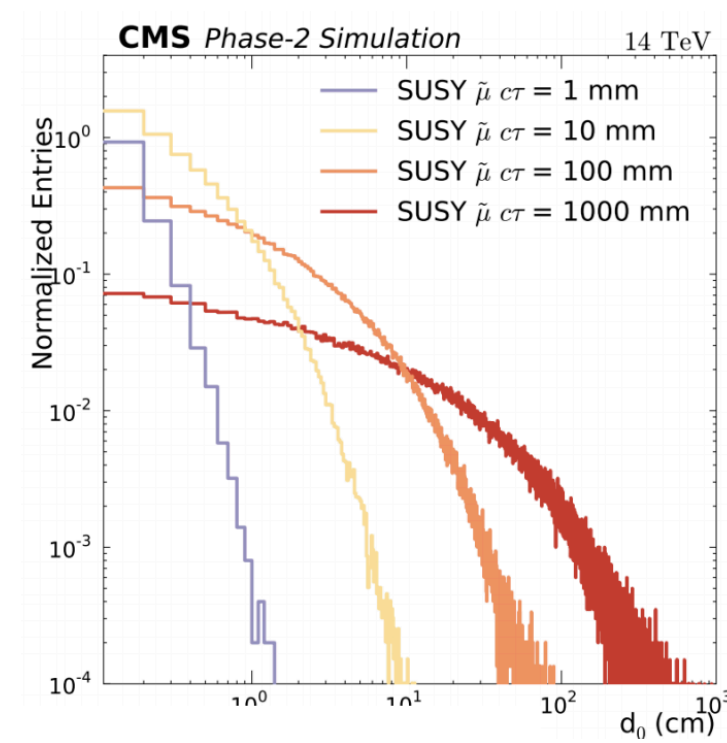


Signal efficiency 4-5% for cτ = 1000 mm vs 10^{-5} to 10^{-4} for SM processes where large impact parameters are mis-reconstructed

Black line shows sensitivity with Phase 1 algorithm
- reconstruction efficiency increases x3 with **DSA**

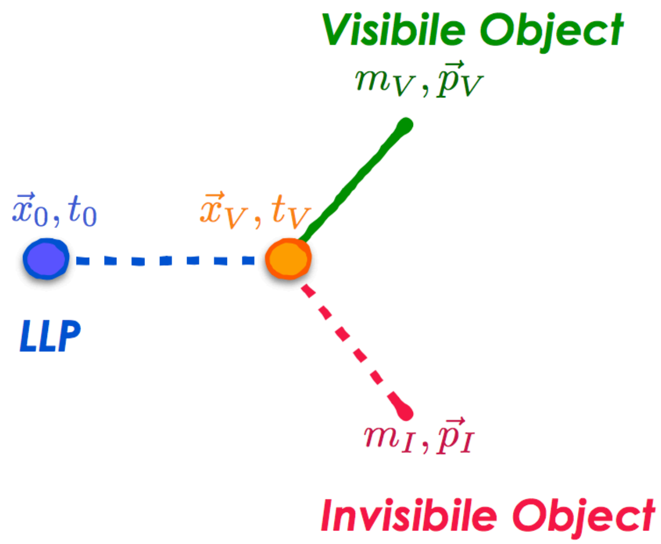
Displaced Stand Alone Algorithm (DSA)

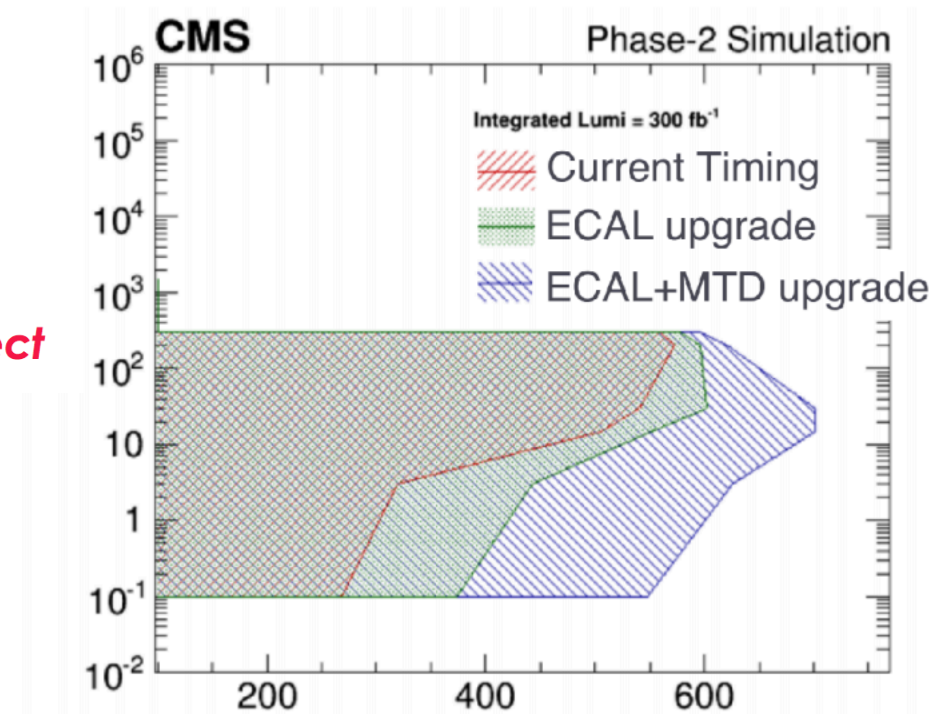
Tracks reconstructed from only hits in muon chambers
- **No constraint from Interaction Point required**
- Benefits from additional hits from the Phase 2 Forward Muon System
- **Displaced Standalone Algorithms** also designed for the **Level 1 Trigger**

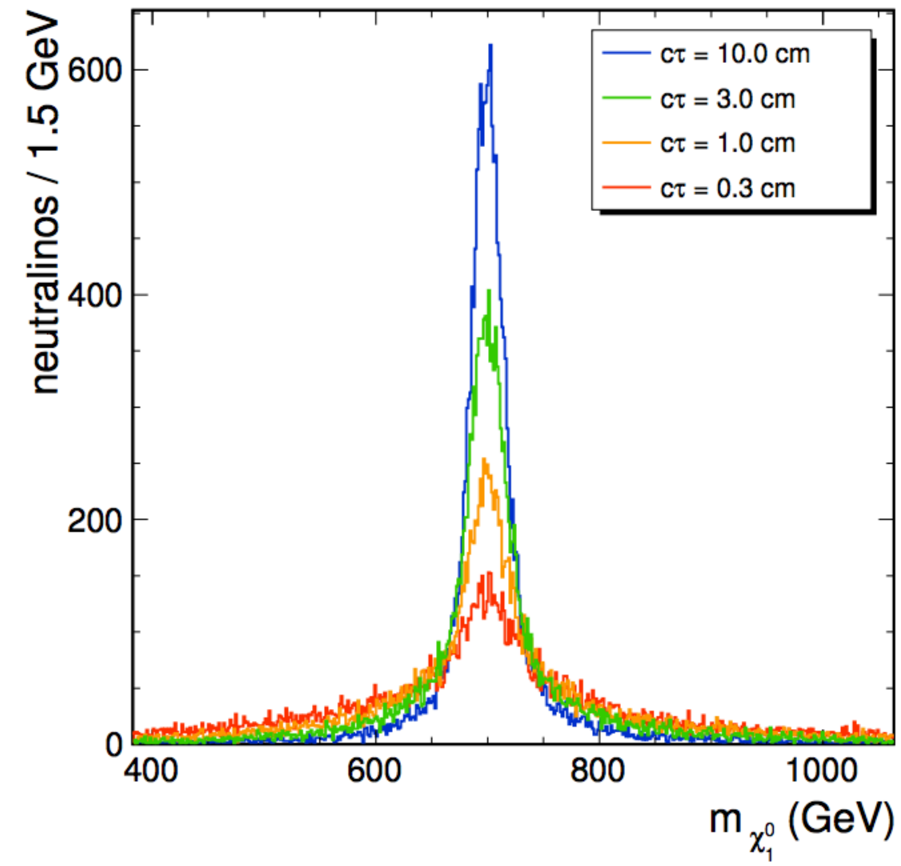


Long Lived Particles: Detection with the Timing Detector

TDR-17-006







(a) $\chi_1^0 \rightarrow G + \gamma$ Limits (b) $\chi_1^0 \rightarrow G + Z$ Peaking Variable

- Particles with a **Long Life Time will arrive at the Timing Layer with some delay** as compared to SM particles
- **Large increase in search reach** for massive long-lived particles decaying to photons, combining calorimeter and MTD timing
- For a range of topologies, **MTD allows reconstruction of a peaking mass variable**, which introduces a qualitatively new capability for long-lived-particle searches

Conclusions

- No sign of new physics… yet!
- **Data collected in the next 10 years** will be used to **measure the properties of the SM Higgs, continue the search for SUSY particles**, investigate **Hidden Sectors** and look for **Dark Matter**
- Conditions at the LHC will become more challenging and it is important to be able to maintain manageable rates and have **efficient data collection**
- **More Projections Planned as we go towards the HL-LHC Yellow Report**
- Many opportunities for innovation!

Object Performance

Higgs → γγ

Projected uncertainty in the $H \to \gamma\gamma$ signal strength (%)				
	300 fb^{-1}		3000 fb^{-1}	
	ECFA16 S1	ECFA16 S2	ECFA16 S1+	ECFA16 S2+
$\mu^{\gamma\gamma}_{\text{ggH}}$	13	7	11	5
$\mu^{\gamma\gamma}_{\text{VBF}}$	35	21	29	13
$\mu^{\gamma\gamma}_{\text{ttH}}$	30	27	17	11
3 $\mu^{\gamma\gamma}$	11	5	10	4
	(stat.) ± (exp.) ± (theo.)			
$\mu^{\gamma\gamma}$	$4 \pm 8 \pm 6$	$4 \pm 2 \pm 3$	$1 \pm 8 \pm 6$	$1 \pm 2 \pm 3$

All systematic uncertainties are kept constant

S1: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account

S1+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account

Theoretical uncertainties are **scaled down by 1/2**

Experimental uncertainties are **scaled down** by the **square root of integrated luminosity**

S2: Effects of higher pileup conditions and detector upgrades of CMS **are not** taken into account

S2+: Effects of higher pileup conditions and detector upgrades of CMS **are** taken into account

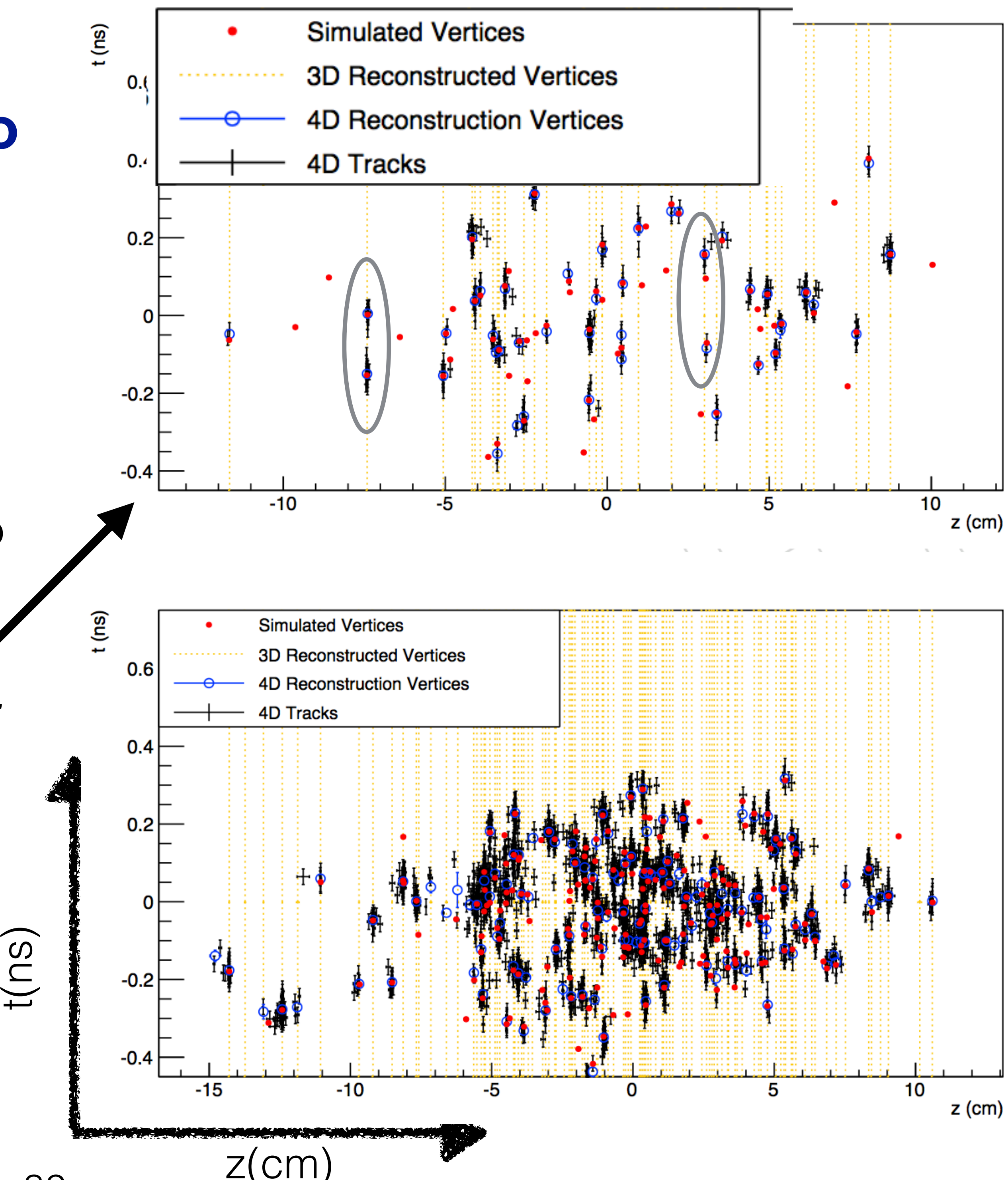
Effects of Timing Information on Track Reconstruction

Including a single layer of MIP Timing information to nominal Track Identification techniques

- **Track Minimally Ionizing Particles (MIPs) not just by position but also by Time**

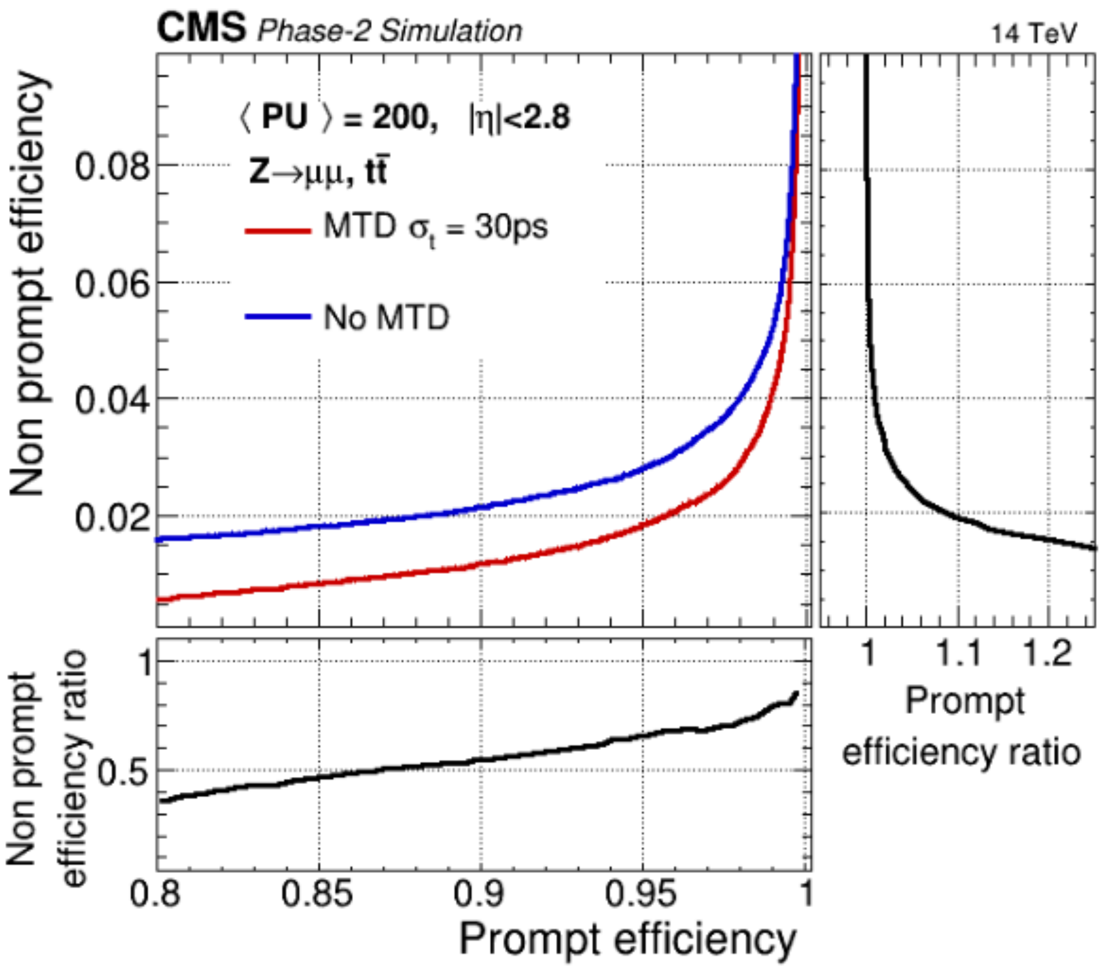
Simulated time of flight resolution $\sigma_T = 30$ ps

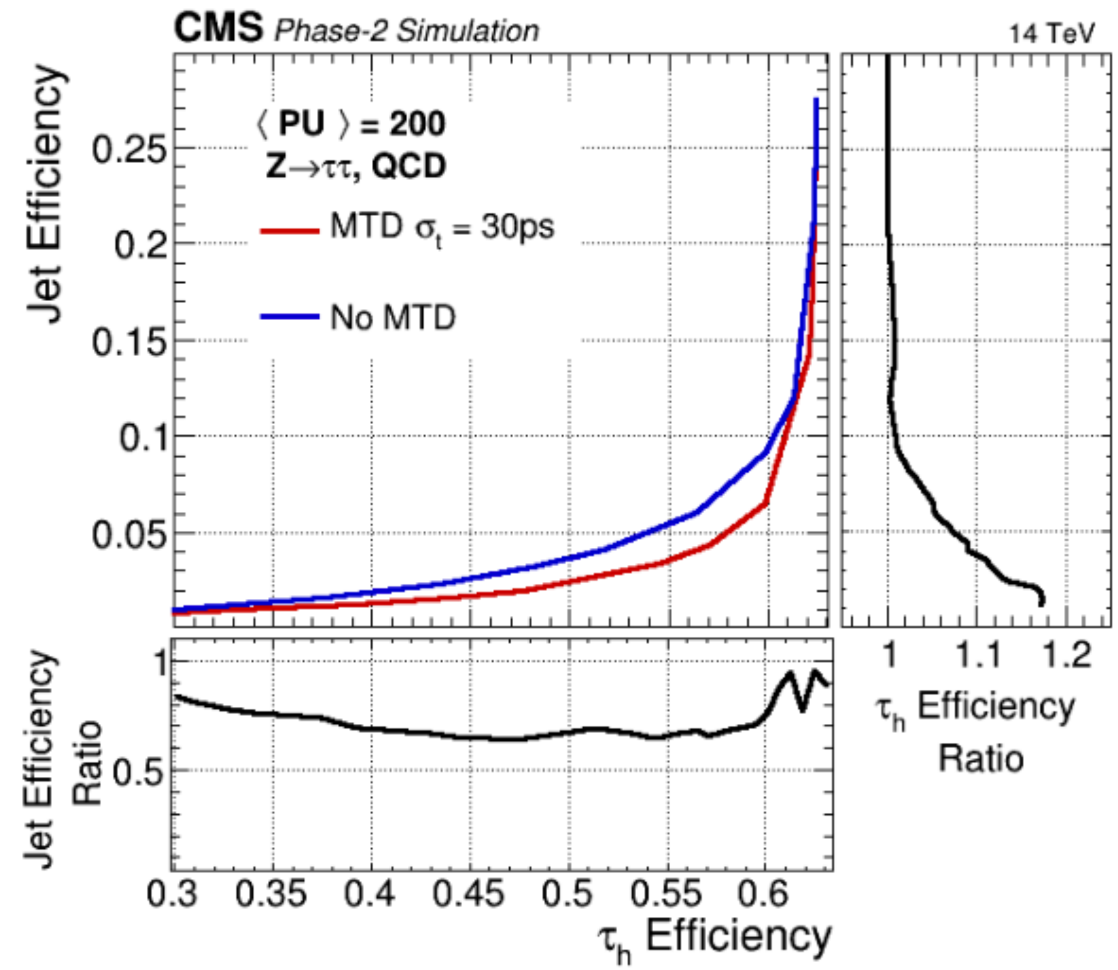
- 15% merged vertices reduce to 1.5% **- Purity of vertices recovered!**
- In **50 PU figure**, ample separation of previously merged vertices apparent at **-7.3cm** and **3cm**
  - Separation of previously merged vertices **notably present throughout 200 PU**!



I.Ojalvo Physics Prospects at the HL-LHC with CMS Aug 9, 2018

Isolation Performance τ's μ's

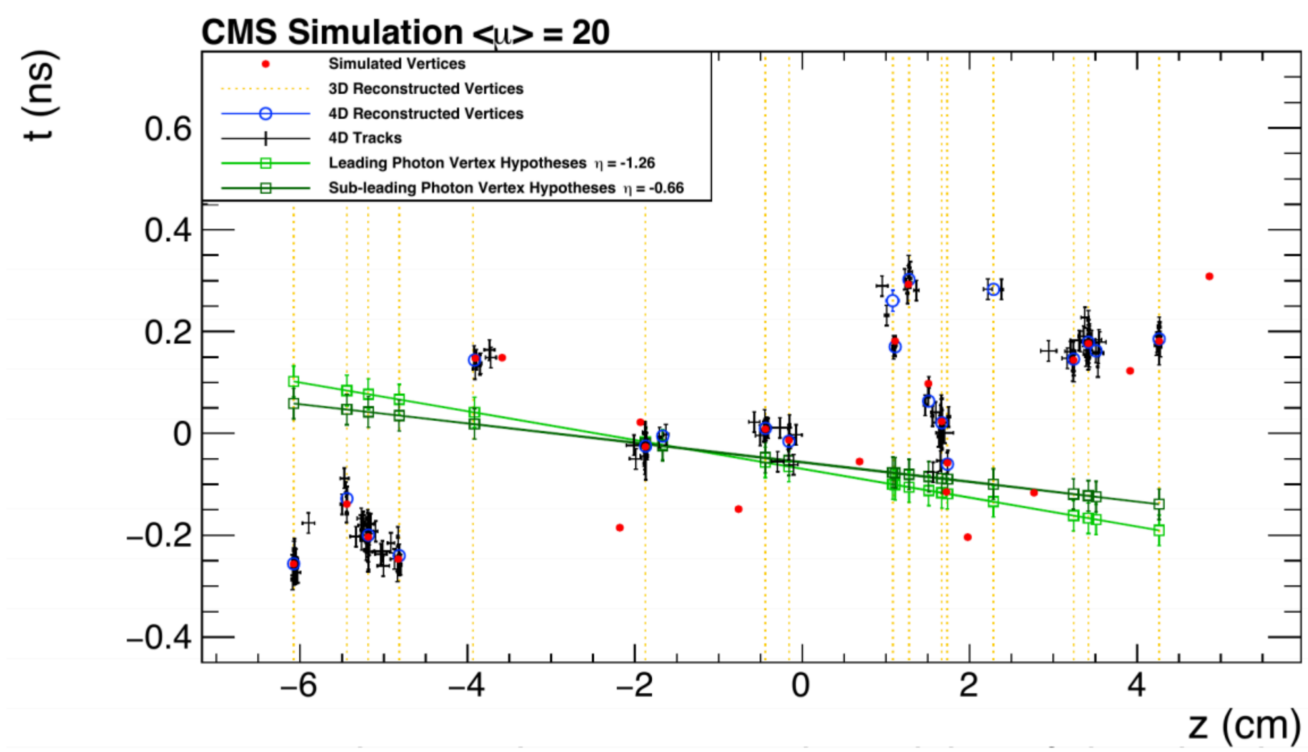


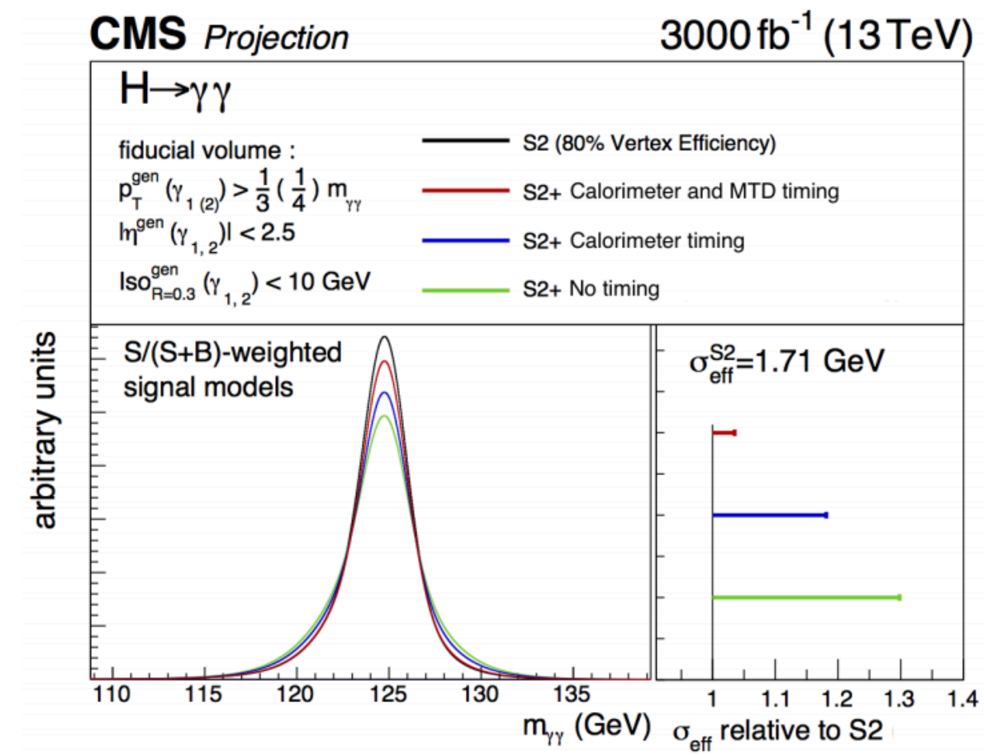


- Improved Performance of charged Isolation only studied
- Most sensitive variable for τ identification

Signal	**Projected Physics Impact**
$H \to \gamma\gamma$	25% improvement in statistical precision on xsecs $\to$ couplings
VBF $H \to \tau\tau$	20% improvement in statistical precision on xsecs $\to$ couplings
HH	20% increase in signal yield/decrease in running time $\to$ consolidate searches
EWK SUSY	40% reducible background reduction $\to$ +150 GeV mass reach
Long-Lived Particles	Peaking Mass Reconstruction $\to$ Unique sensitivity and discovery potential

Vertex Identification





- Calorimeter timing-based triangulation matched to 4d reconstructed vertices
- Efficiently identify the primary vertex for H → γγ requires timing for both the photons and the primary vertex
- Restores Run 2 vertex selection efficiency (~ 80%)

Signal	Projected Physics Impact
$H \to \gamma\gamma$	25% improvement in statistical precision on xsecs $\to$ couplings
VBF $H \to \tau\tau$	20% improvement in statistical precision on xsecs $\to$ couplings
HH	20% increase in signal yield/decrease in running time $\to$ consolidate searches
EWK SUSY	40% reducible background reduction $\to$ +150 GeV mass reach
Long-Lived Particles	Peaking Mass Reconstruction $\to$ Unique sensitivity and discovery potential

Anomalous Couplings

Scattering amplitude describing the interaction between a spin-zero H boson and two spin-one gauge bosons VV (ZZ, Zγ, γγ, WW, gg):

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_1 + q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Only tree-level contribution,
$a_1^{ZZ} = a_1^{WW}$ (custodial symmetry)

Anomalous Couplings (example on formalism)

It is convenient to measure the **effective cross-section ratios rather** than the **anomalous couplings**:

- Cancellation of systematic uncertainties in the ratio [Bounded between 0 and 1]
- Does not depend on coupling convention

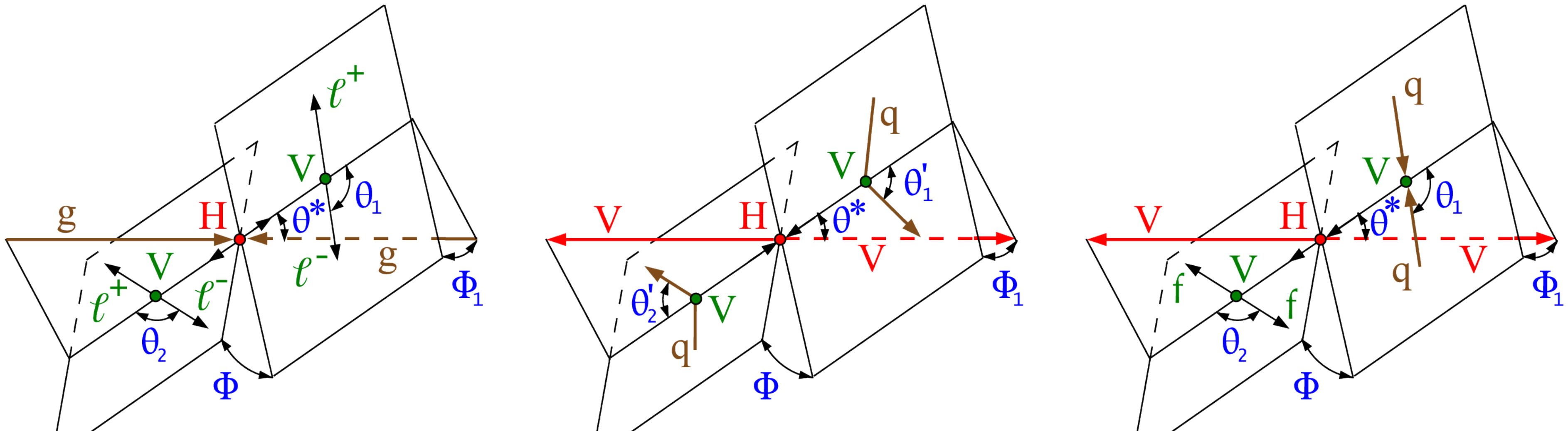
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

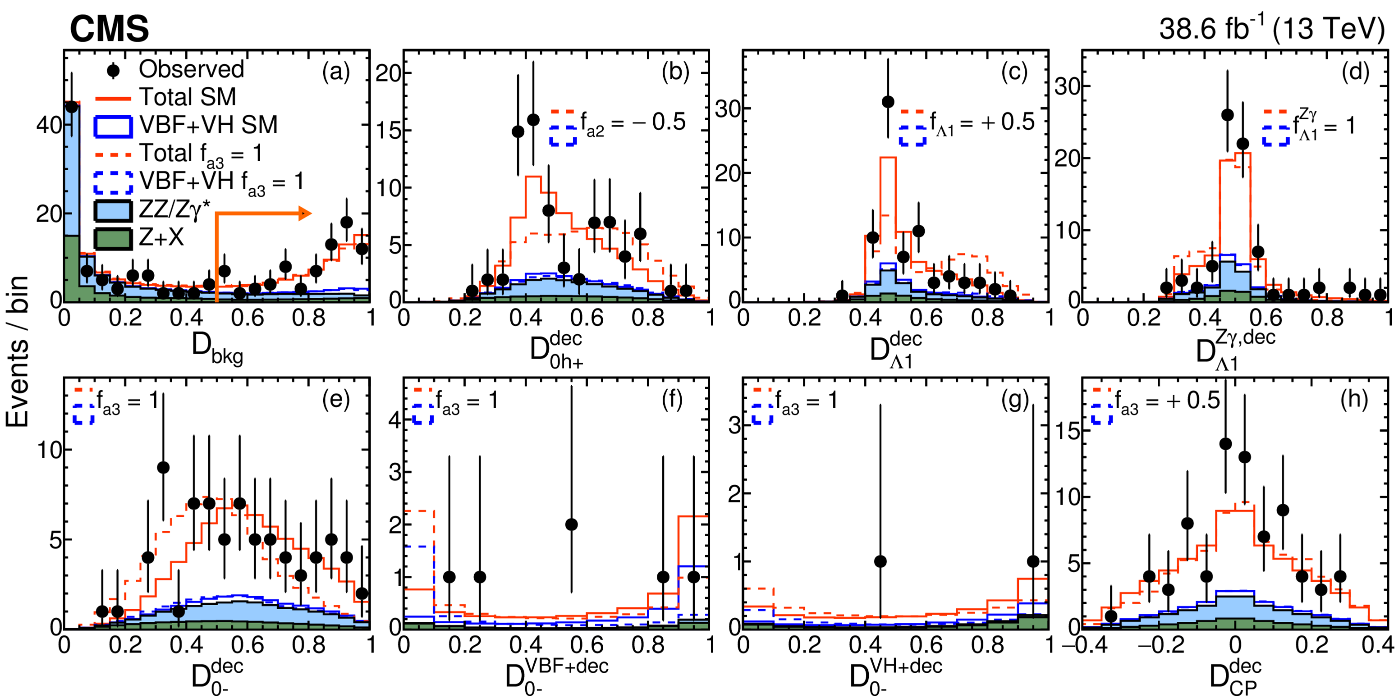
$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4}{|a_1|^2\sigma_1' + \tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4 + \ldots}, \qquad \phi_{ai}^{Z\gamma},$$

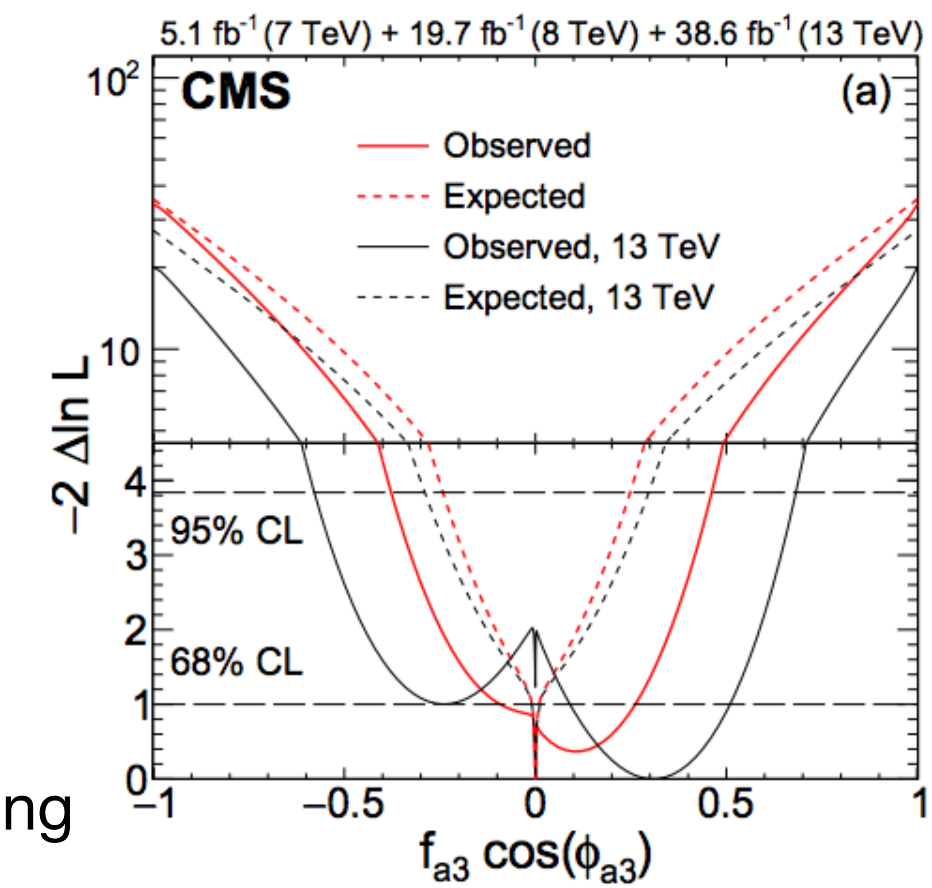
Run 2 HVV CMS



gg→H→VV→4l VBF→VV qq→V→VH→VV

Sensitive to anomalous couplings in production, decay





Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

4 Parameters probed including CP violation parameter f_{a3}

arXiv: 1707.00541