



ALICE

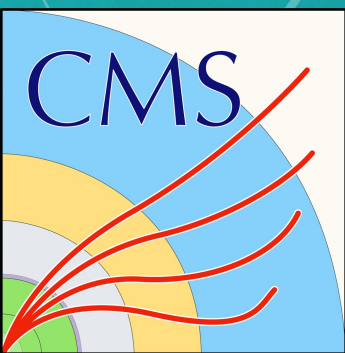


ATLAS  
EXPERIMENT

LHcb  
LHCb



Istituto Nazionale di Fisica Nucleare



# HIGHLIGHTS FROM HL-LHC PHYSICS PROSPECTS

DAVIDE ZUOLO

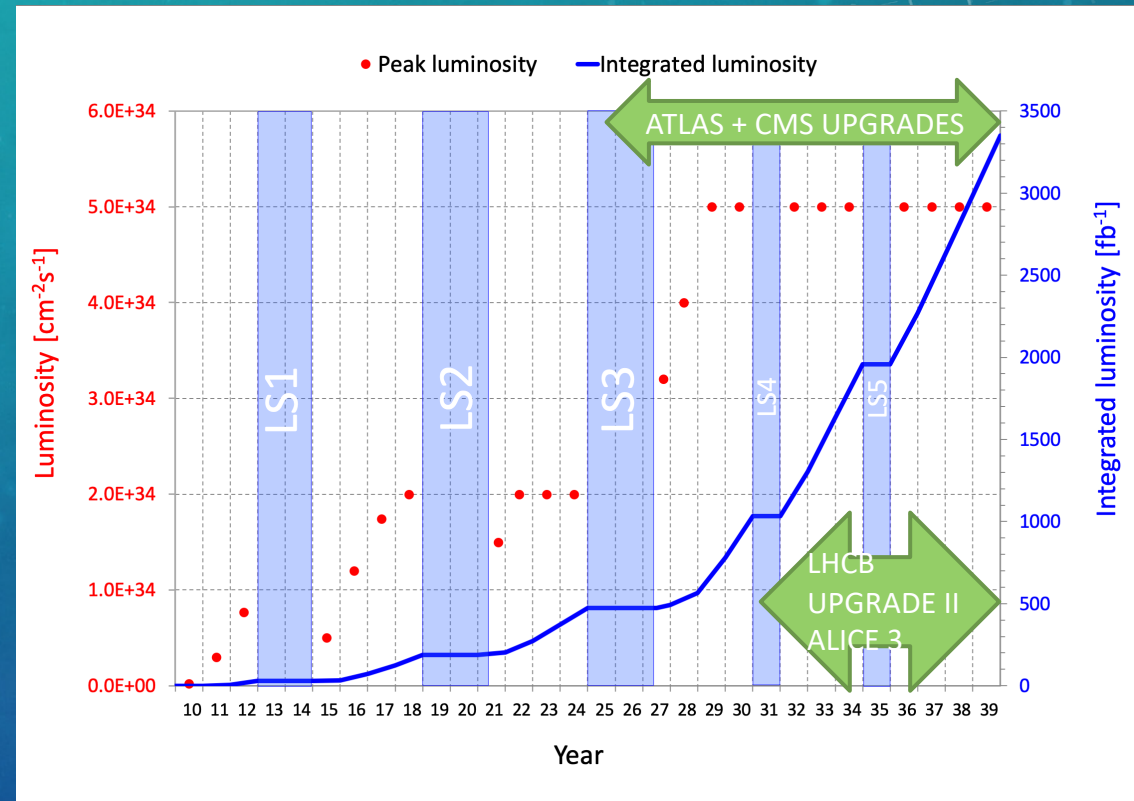
INFN MILANO - BICOCCA

*ON BEHALF OF THE ALICE, ATLAS, CMS, LHCb COLLABORATIONS*

# INTRODUCTION

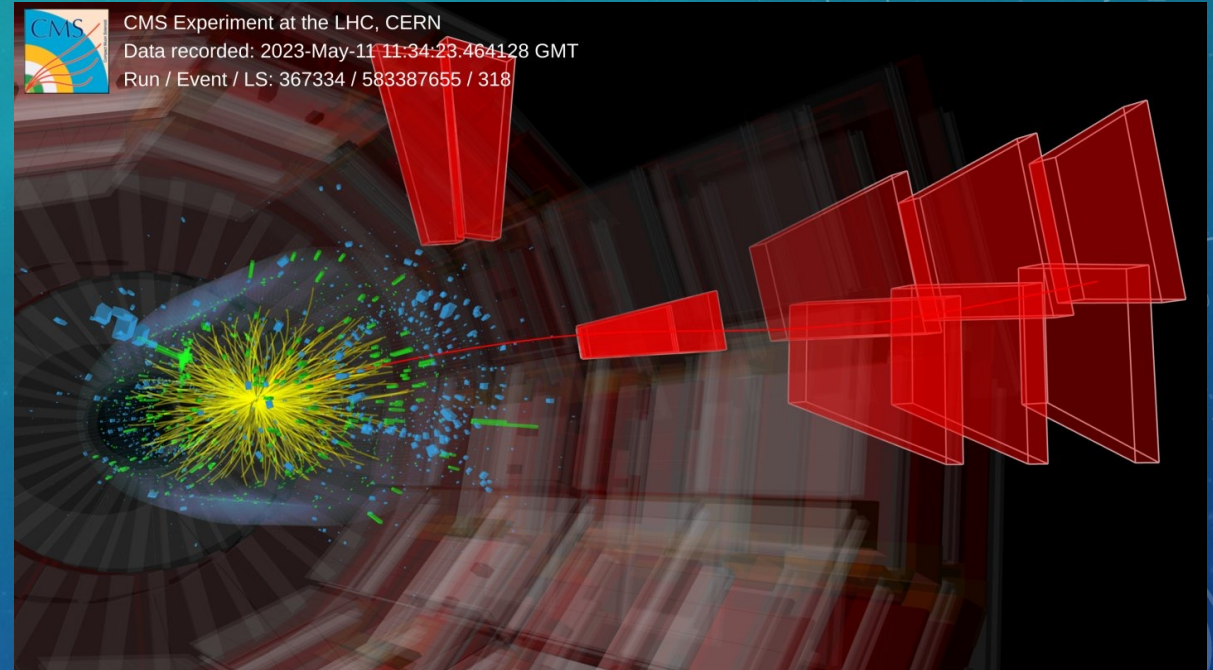
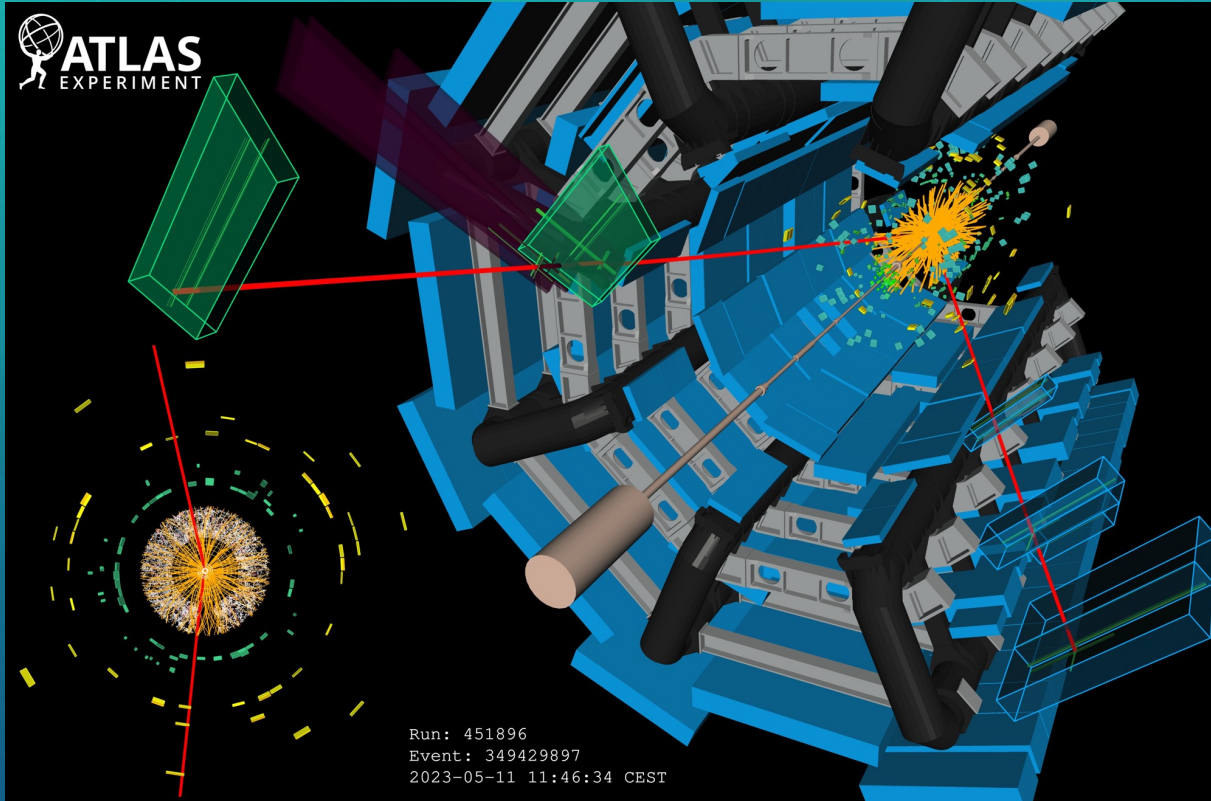
A personal selection of physics topics

- “high- $p_T$ ” physics at ATLAS and CMS
  - from the Snowmass 2021 white paper ([link](#))
- Flavour physics at LHCb
  - from the Upgrade II physics case ([link](#))
- Heavy ions physics at ALICE
  - from the ALICE 3 letter of intent ([link](#))
- **My apologies to all who worked on topics that I could not present here**



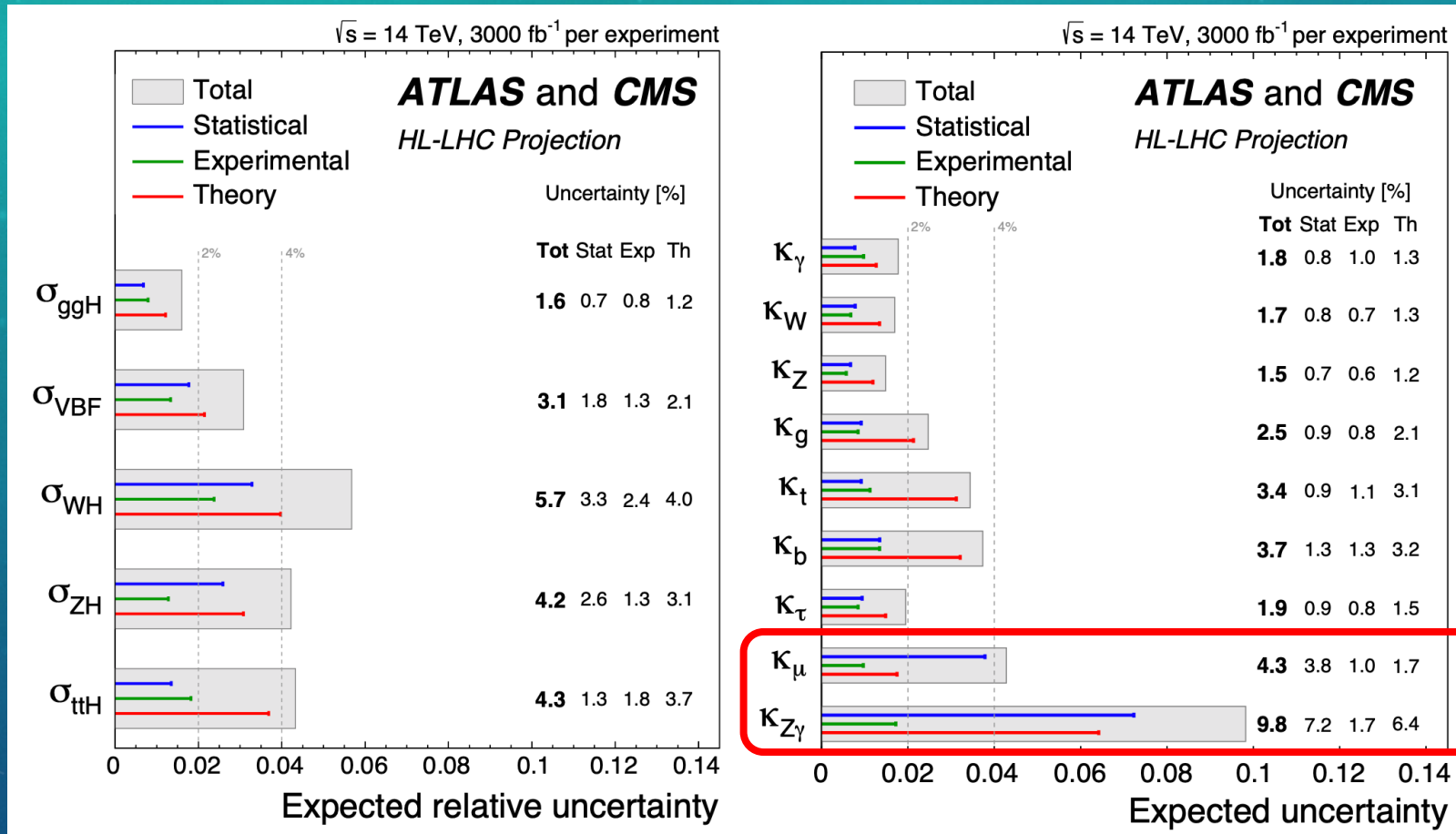


# HIGH $P_T$ PHYSICS





# DESIRABLE #1: THE HIGGS BOSON



We will probably do better given the current state of the art! (Evidence of  $H \rightarrow \mu\mu$  @CMS, CMS+ATLAS Evidence of  $H \rightarrow Z\gamma$  new for LHCp 2023)



# DESIRABLE #1: THE HIGGS BOSON

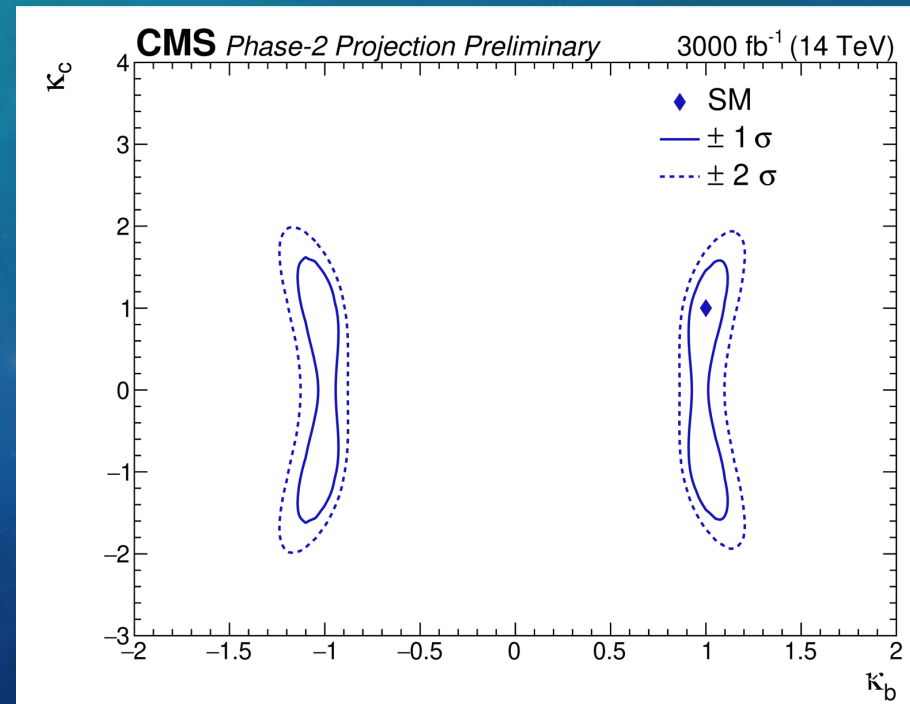
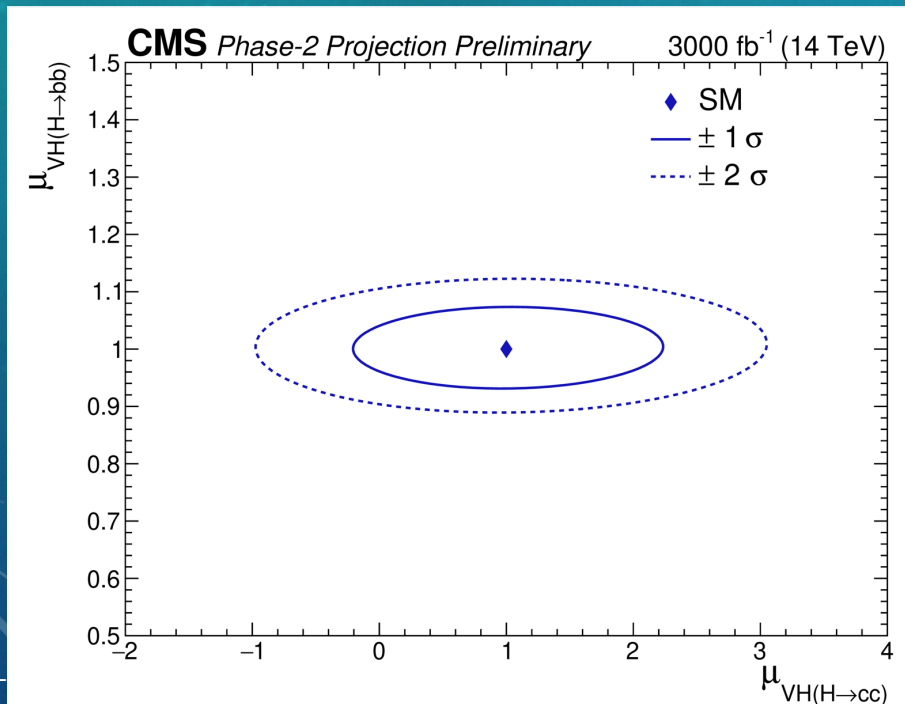
Observation of  $VH \rightarrow bb$  was tough but we made it!

$VH \rightarrow cc$  was so tough that did not enter in the Yellow Report

Thanks to the use of machine learning in jet identification algorithms we are as close as ever

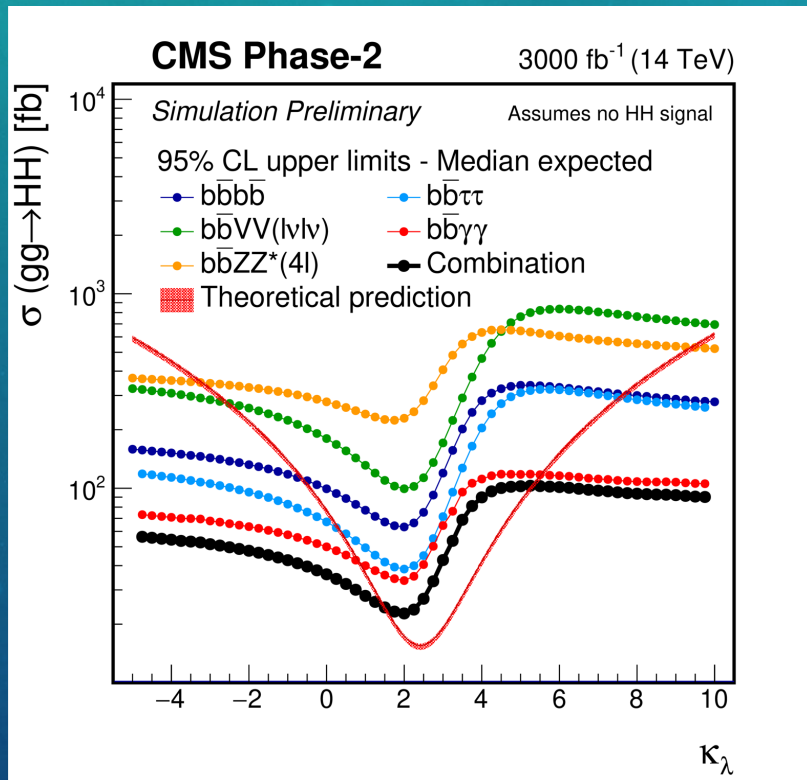
95% CL expected upper limit on  $\sigma \times BR$ : 7.6 x SM (CMS) and 31 x SM (ATLAS)

Simultaneous measurements becomes appealing at HL-LHC



# DESIRABLE #2: 2 HIGGS BOSONS

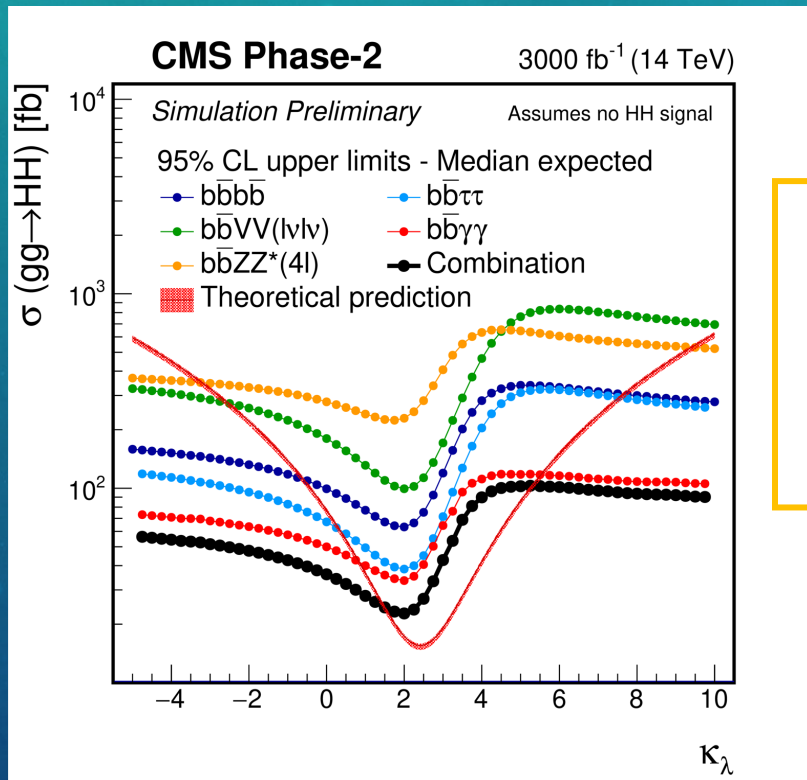
CMS Yellow Report projection (2018) - assumes no  
HH signal found





# DESIRABLE #2: 2 HIGGS BOSONS

CMS Yellow Report projection (2018) - assumes no HH signal found



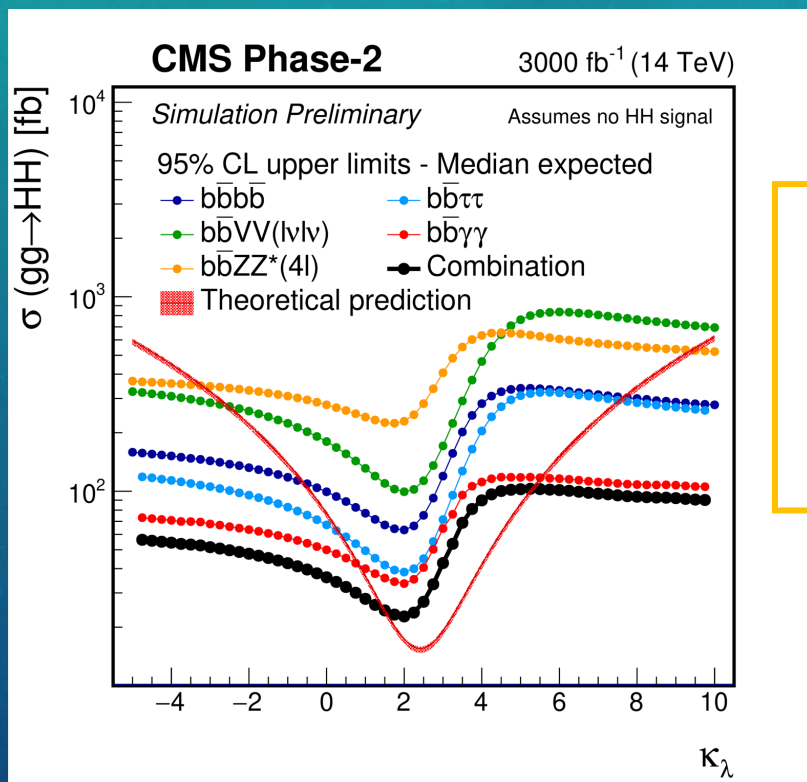
Many technical improvements:

- DNN for categorization and signal extraction
- new jet tagging techniques

# DESIRABLE #2: 2 HIGGS BOSONS

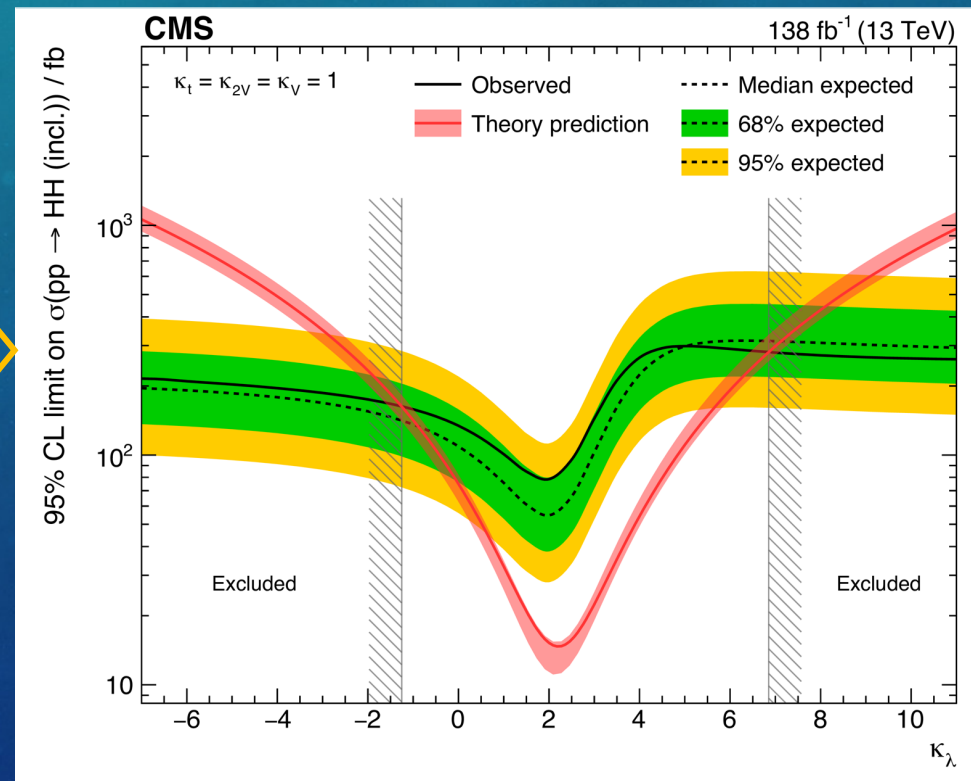
CMS Yellow Report projection (2018) - assumes no HH signal found

CMS Full Run II results (2022): the constraint is similar to the one estimated in 2018 with 20 times the integrated luminosity!!!



Many technical improvements:

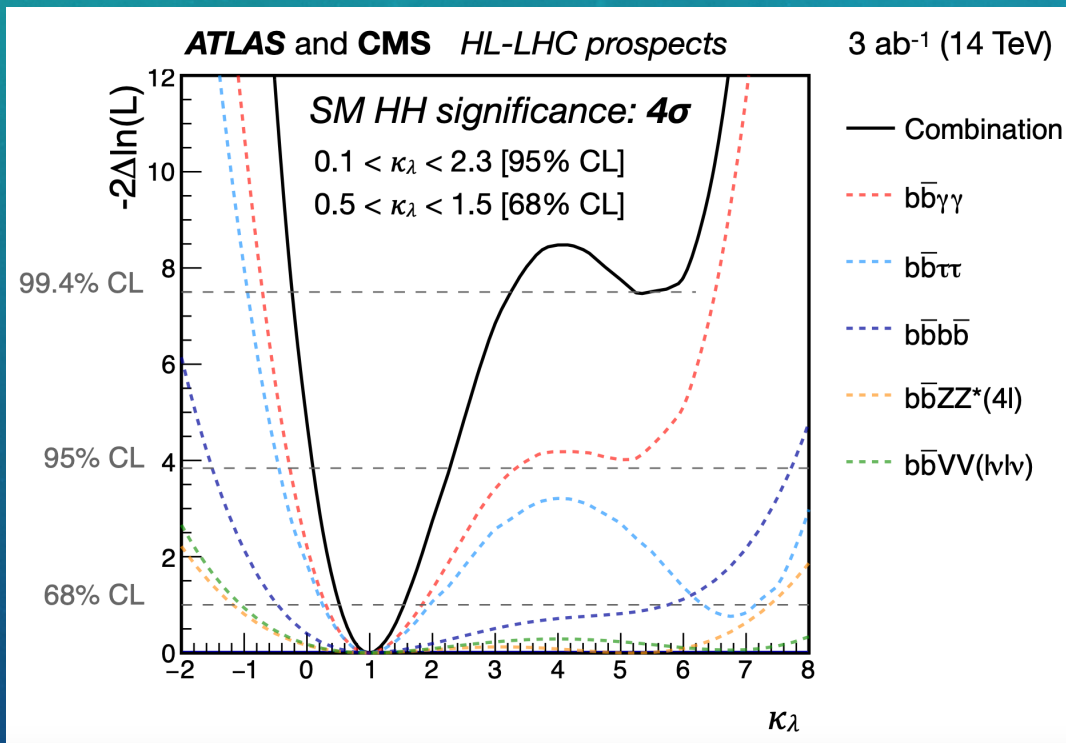
- DNN for categorization and signal extraction
- new jet tagging techniques





# DESIRABLE #2: 2 HIGGS BOSONS

## YR Projection ATLAS + CMS



# DESIRABLE #2: 2 HIGGS BOSONS

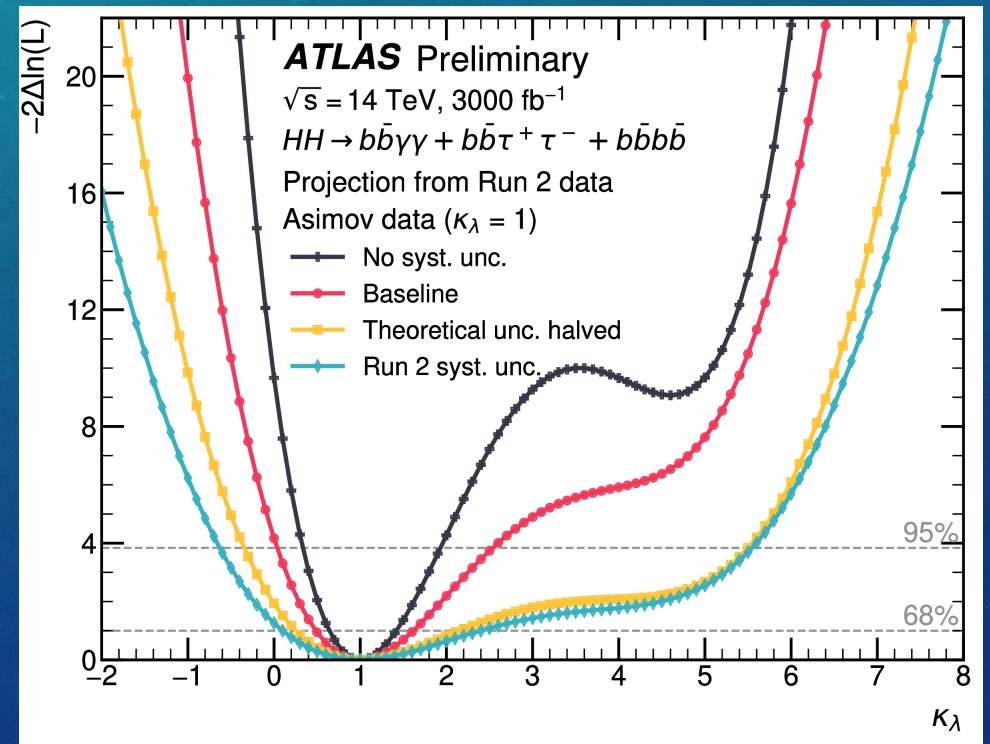
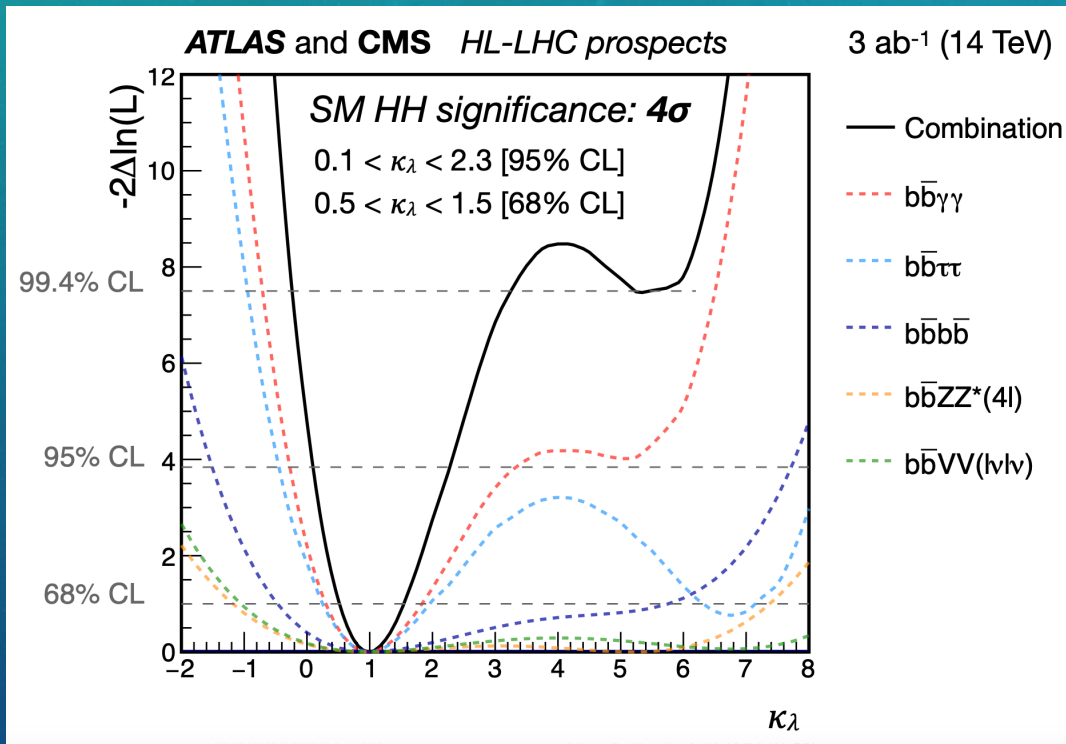
## YR Projection ATLAS + CMS

New Projection ATLAS Only

SM HH significance:  $3.4\sigma$

$0.0 < k_\lambda < 2.5$  [95% CL]

$0.5 < k_\lambda < 1.6$  [68% CL]

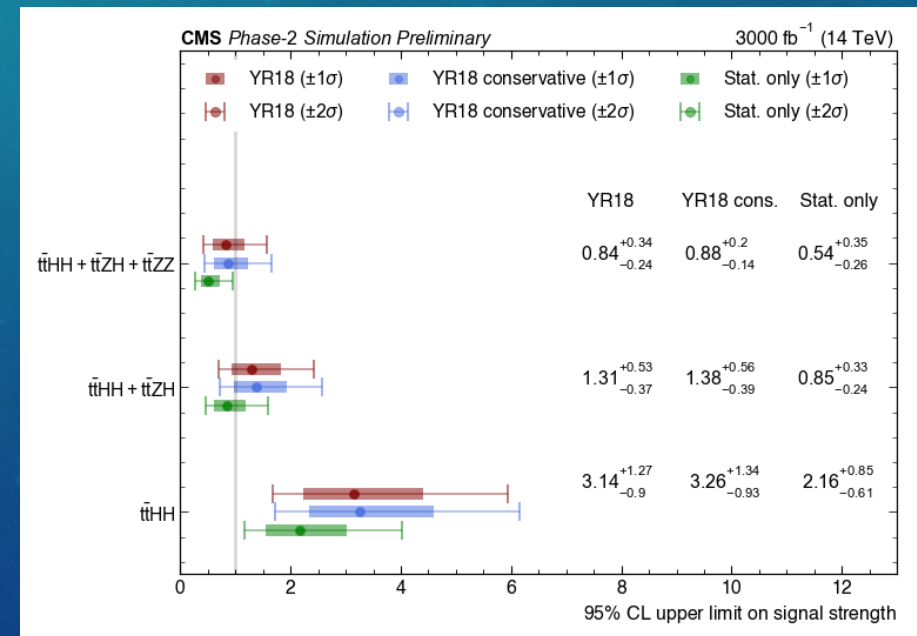
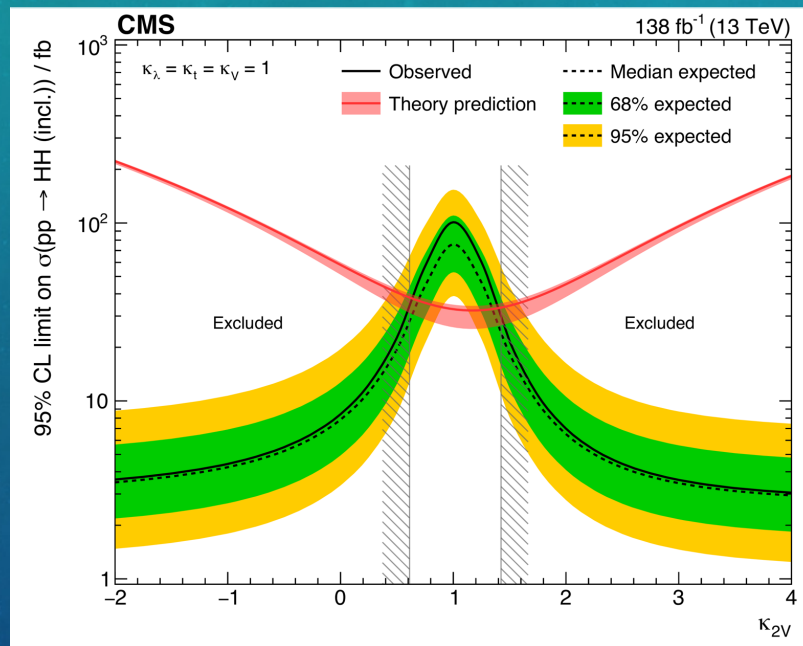




# DESIRABLE #2: 2 HIGGS BOSONS

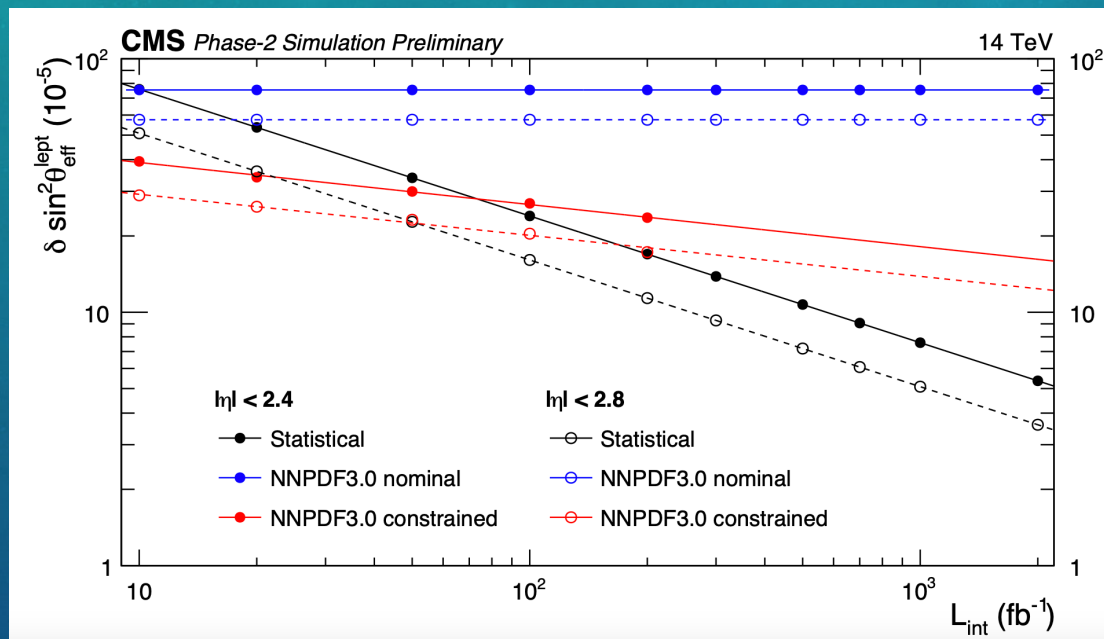
CMS excluded at  $> 5\sigma$   $k_{2V} = 0$  (with other couplings fixed to SM)  $\rightarrow$   $VVHH$  interaction exists  $\rightarrow$  what happens with 3 or 4  $ab^{-1}$  ?

CMS is studying rarer production modes like  $VHH$  and  $ttHH$   $\rightarrow$  very interesting at HL-LHC

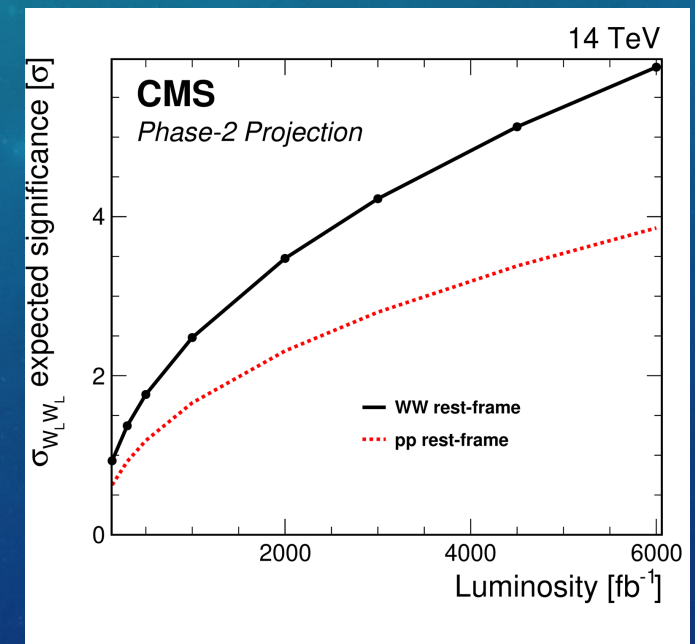


# DESIRABLE #3: EW PRECISION

Measurement of the **weak mixing angle** from the forward-backward asymmetry ( $A_{FB}$ ) in Drell-Yan events



**Vector Boson scattering (VBS)** is one of the hot topics of Run II and will be even more central at HL - LHC  $\rightarrow$  investigate longitudinal polarization (cross section unitarized by Higgs Boson contributions)





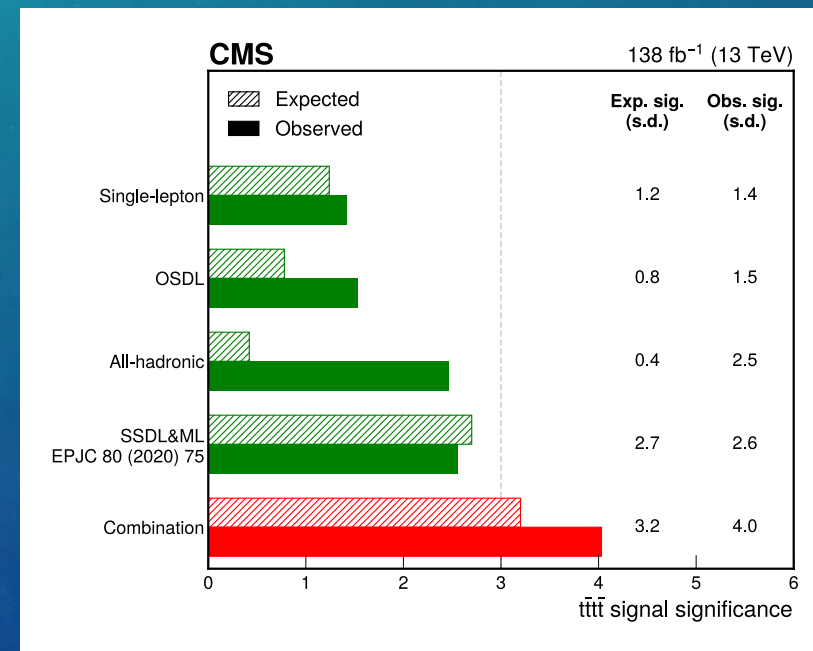
# DESIRABLE #4: 4 TOP PRODUCTION

From the YR (2018): “The production of four top quarks is one of the rare processes in top quark physics that has large sensitivity to variety of new physics effects (including effective field theory sensitivity and sensitivity to anomalous top-Higgs couplings), while at the same time it is interesting in the Standard Model context as a complex QCD process. **The production of  $t\bar{t}t\bar{t}$  is a rare SM process that is expected to be discovered by future LHC runs, including HL-LHC...**”

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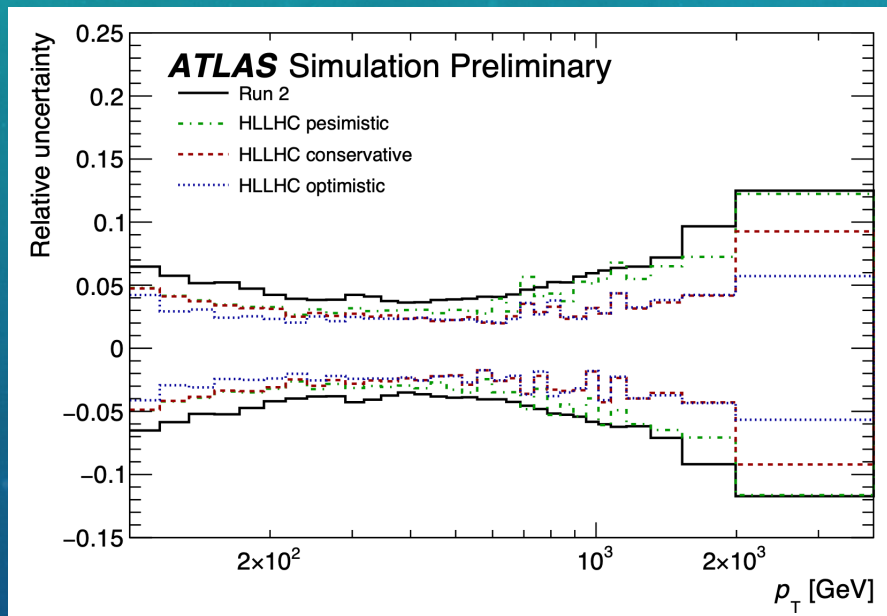
**5 years later: CMS (ATLAS) announces evidence (observation) of the process!!!**  
fully differential measurement at HL-LHC?



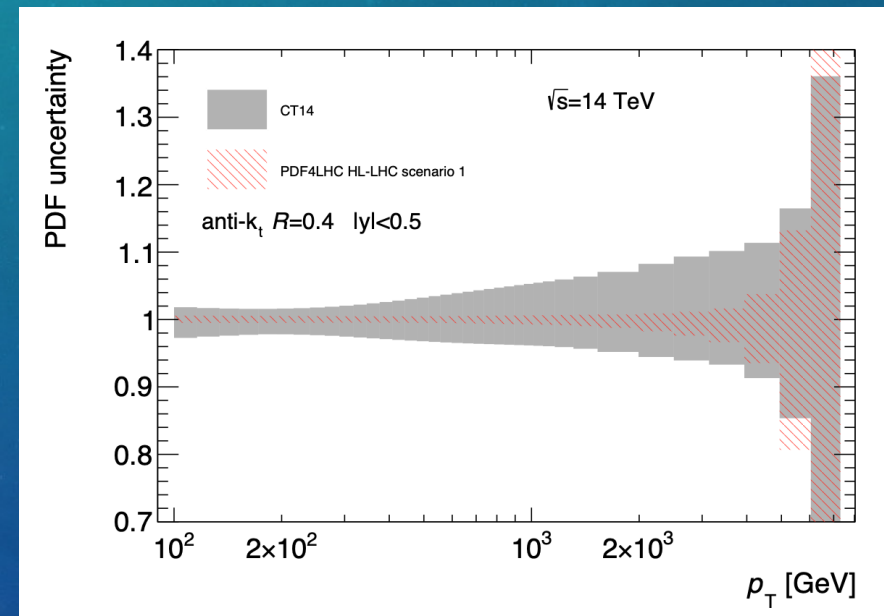


# DESIRABLE #5: QCD PRECISION

Jet Energy Scale uncertainties represent the largest systematic in many analyses



Calculation of the PDF will largely improve with the HL - LHC data



# WHAT ELSE?

ATLAS and CMS will continue exploring Beyond Standard Model (BSM) scenarios

- Supersymmetric particles
- Leptoquarks
- New gauge bosons
- Long Lived Particles
- WIMPs
- ...

Very innovative trigger strategies and data analysis techniques are being developed to get the best out of Run 2 data and will be employed also at HL-LHC

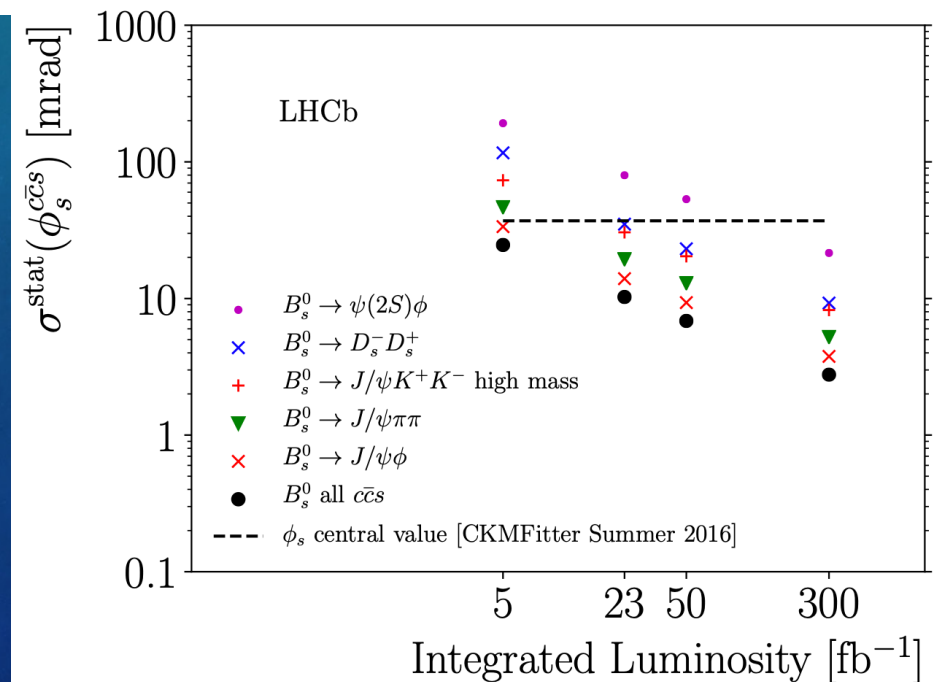
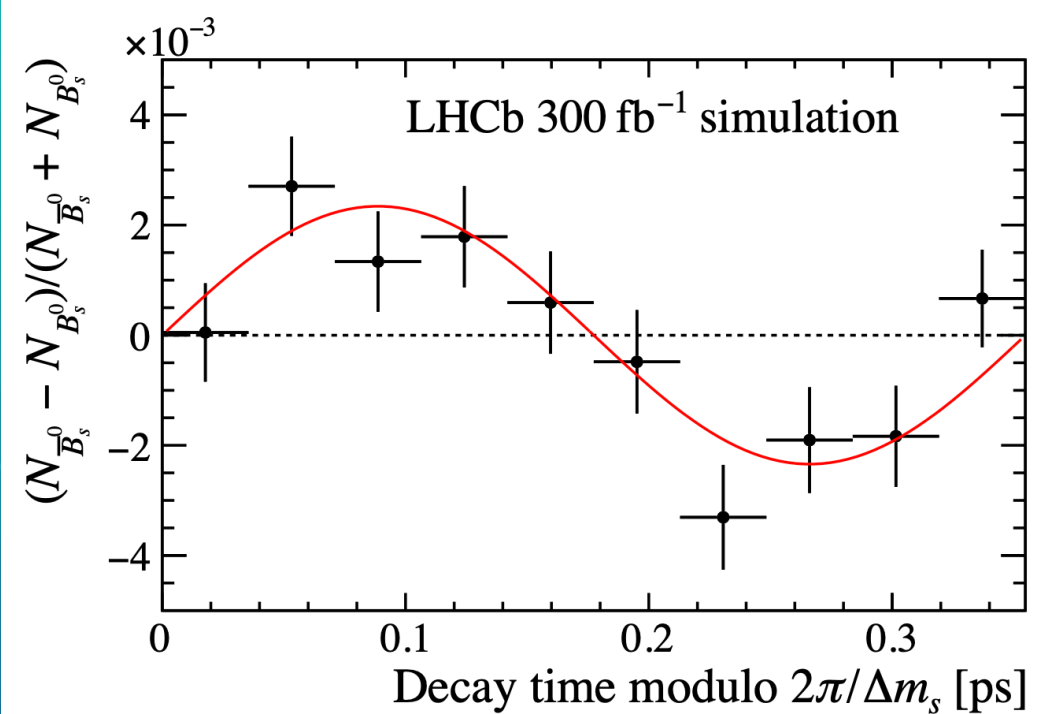


# FLAVOUR PHYSICS PROGRAM

- LHCb major upgrade during LHC Long Shutdown (LS) 2 aiming at collecting 50 fb<sup>-1</sup> in Run 3+4
  - full software trigger and readout all detectors at 40MHz
  - replace tracking detectors + PID + VELO
  - increase instantaneous luminosity to  $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- LHCb upgrade II during LS3 for operation in Run 5+6
  - collect 300 fb<sup>-1</sup> with an instantaneous luminosity of  $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - employ new detector technologies and exploit timing information

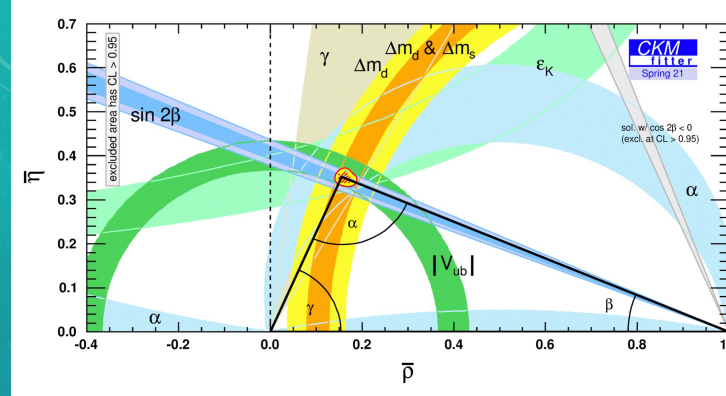
# $B_s^0$ MIXING PHASE, $\phi_s$

- CP-violating phase arising from interference between mixing and decay, precisely predicted.
- Golden channel exploited by LHCb, ATLAS, CMS:  $B_s^0 \rightarrow J/\psi(\mu\mu) \phi(KK)$
- HFLAV combination:  $\phi_s = -0.049 \pm 0.019$  rad
- measurement is, and will be, statistically limited
- Same performances as in Run 2 (tagging power, i.e. flavour identification of the  $B_s^0$  at production,  $\sim 4\%$ )  $\rightarrow$  **strong constraint on detector performance**

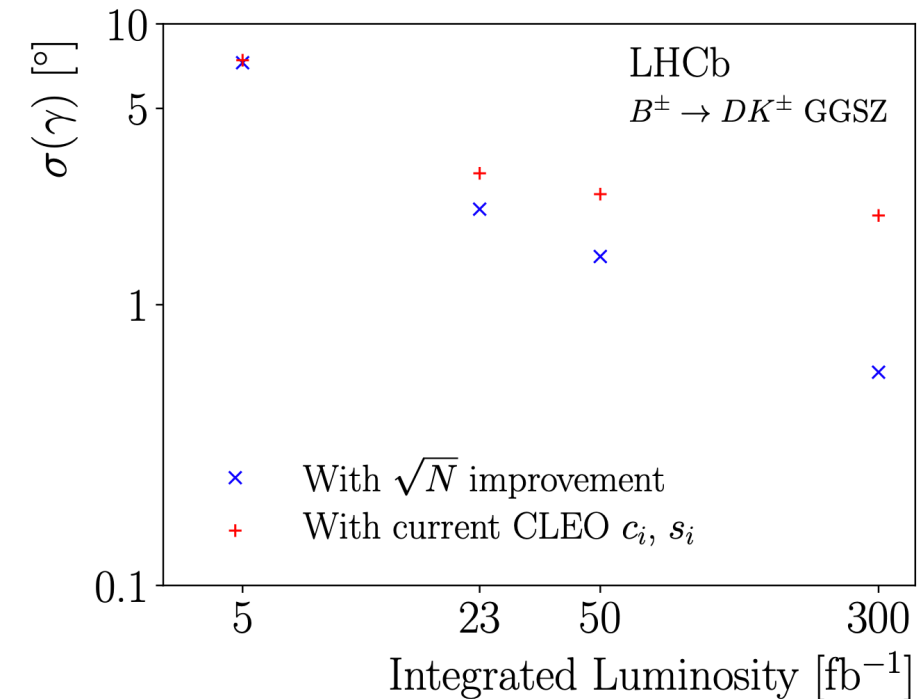
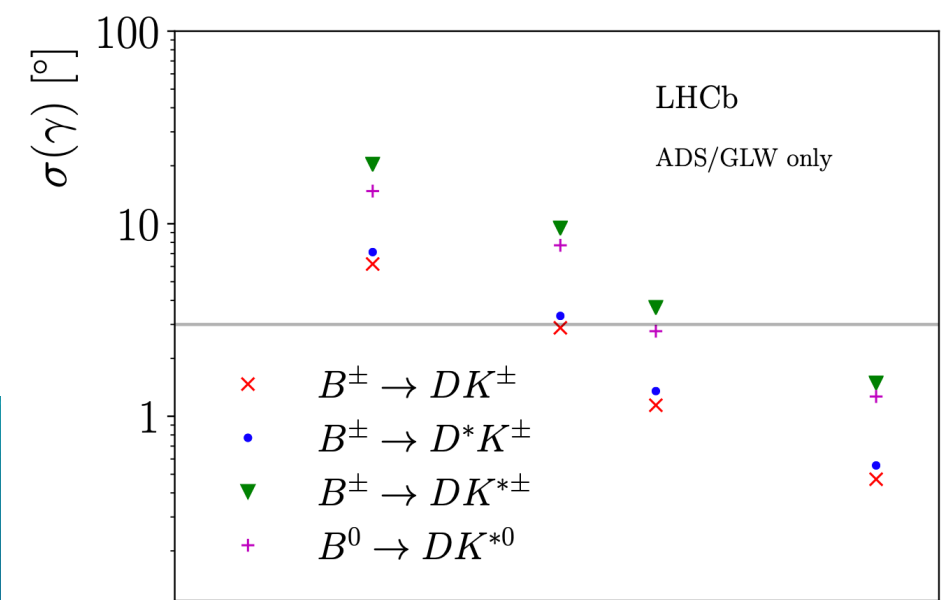




# CKM ANGLE $\gamma$

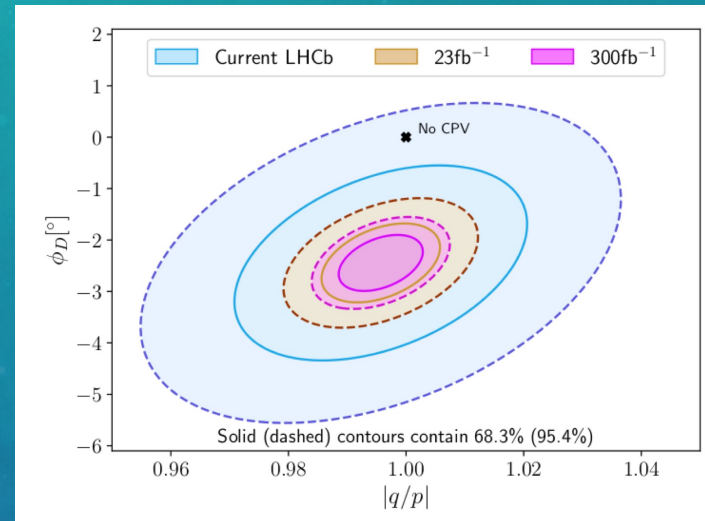


- The only angle that can be determined exclusively from tree processes
- Theoretically clean:  $|\delta\gamma/\gamma| < 10^{-7}$  ([JHEP 1401 \(2014\) 051](#))
- Measured via interference of  $b \rightarrow u$  and  $b \rightarrow c$  transitions.
- $B \rightarrow D(\pi\pi/KK/\pi K)K$  (ADS/GLW) and  $B \rightarrow D(K_s^0\pi\pi/K_s^0KK)K$  (GGSZ)
- [LHCb best result](#) (combination of CPV studies):  $\gamma = (63.8^{+3.5}_{-3.7})^\circ$
- Expected stat. unc. down to the degree level for individual modes,  **$0.35^\circ$  stat. unc. for combined measurement.**
- Comparison of measurements made in single decay modes interesting after Upgrade II  $\rightarrow$  NP in tree level different for different final states.

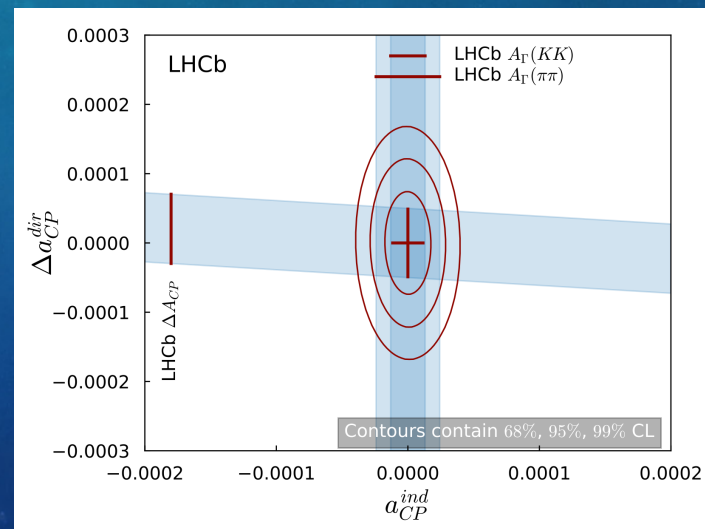


# MIXING AND CP VIOLATION IN CHARM

- SM: CPV in charm at level of  $10^{-4}$
- **Fully software LHCb trigger** → more charm hadrons than B-factories.
- **Tracking stations inside magnet** → more flavour-tagged decays
- LHCb Upgrade II is the only planned experiment with possibility to **observe CPV in charm mixing at the level of  $10^{-5}$**



Indirect CPV in mixing of  $D \rightarrow K\pi$  decays



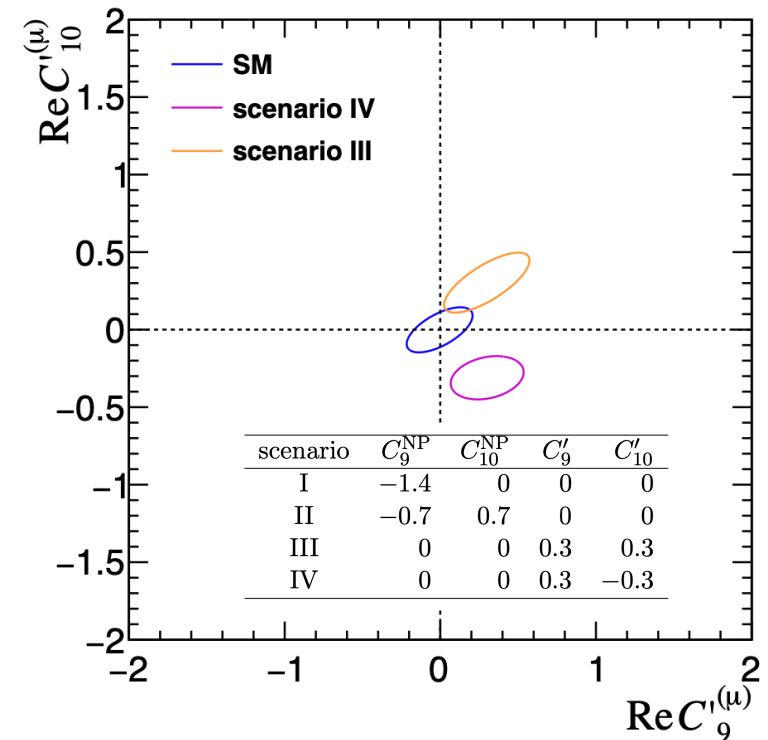
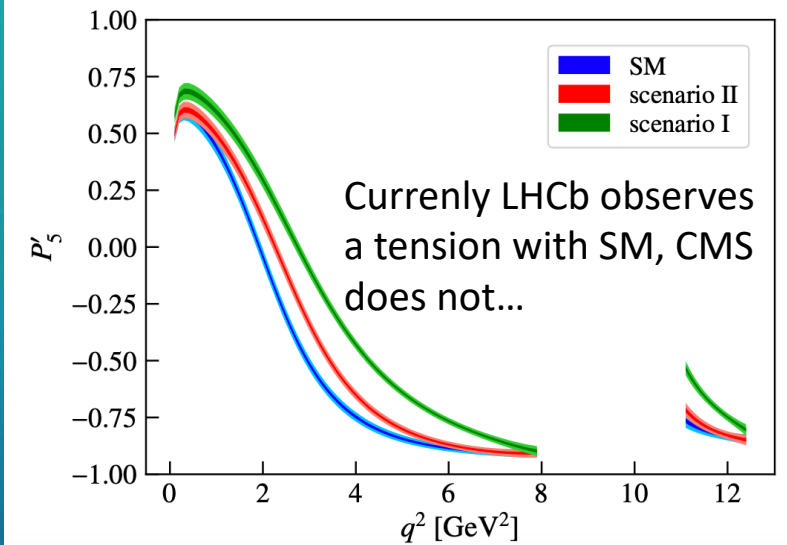
Direct CPV in  $D \rightarrow KK/\pi\pi$  decays



# RARE DECAYS

- New particles can affect decay rate and **angular distributions of loop suppressed FCNC decays** like  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Measure optimized angular observables with reduced hadronic uncertainty, like  $P_5'$
- Expect  $\sim 440\,000$   $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  candidates in Upgrade II
  - **unprecedented precision in angular observable**
  - **different NP scenarios can be cleanly separated**
- Model independent description using effective, four-fermion point interactions

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \left[ \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu) \right]$$



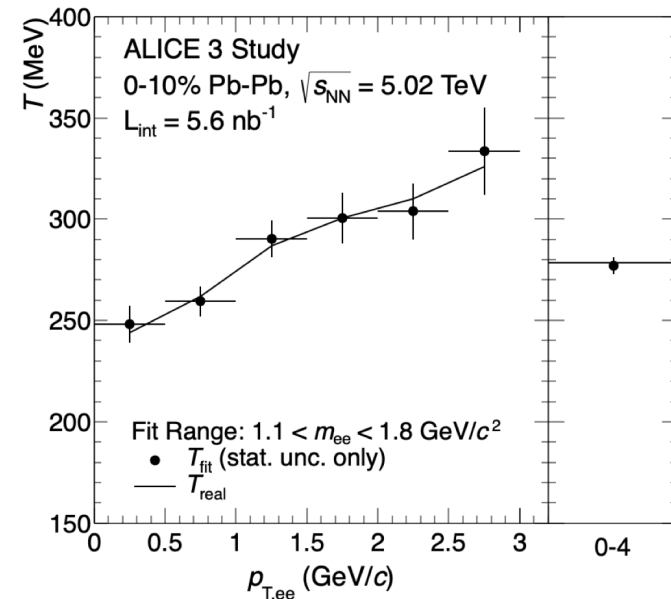
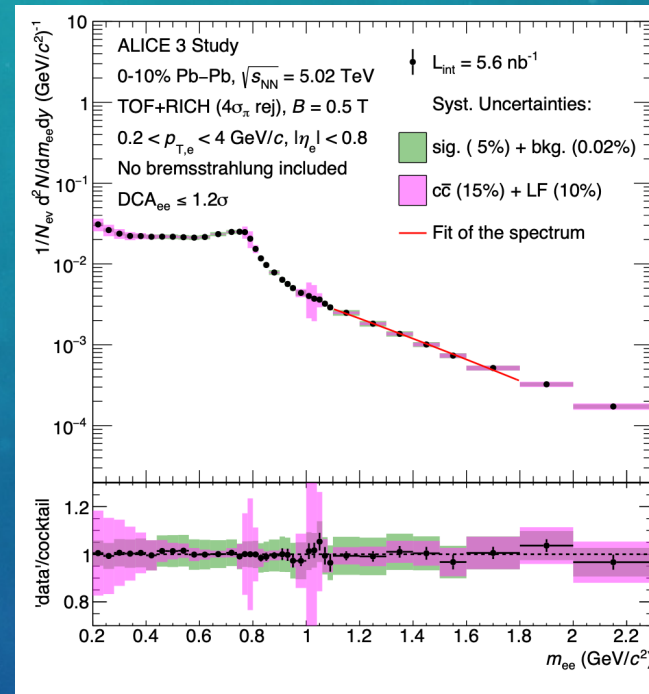
# HEAVY IONS PROGRAM

- ALICE 2 upgrade during LHC Long Shutdown 2 to operate during Run 3 and Run 4
  - New Inner Tracking System (ITS2): lighter, thinner, first layer closer to the interaction point
  - Continuous readout → increased readout rate from 1kHz to 50 kHz
  - Pb-Pb collisions luminosity goal is  $13 \text{ nb}^{-1}$
- ALICE 3: new detector to be operated during LHC Run 5+6 (letter of intent submitted at the end of 2022)
  - review detector design to cope with the harsh environment expected during HL-LHC
  - various luminosity scenarios and ions options under discussion
  - projections based on Pb-Pb collisions luminosity of  $35 \text{ nb}^{-1}$



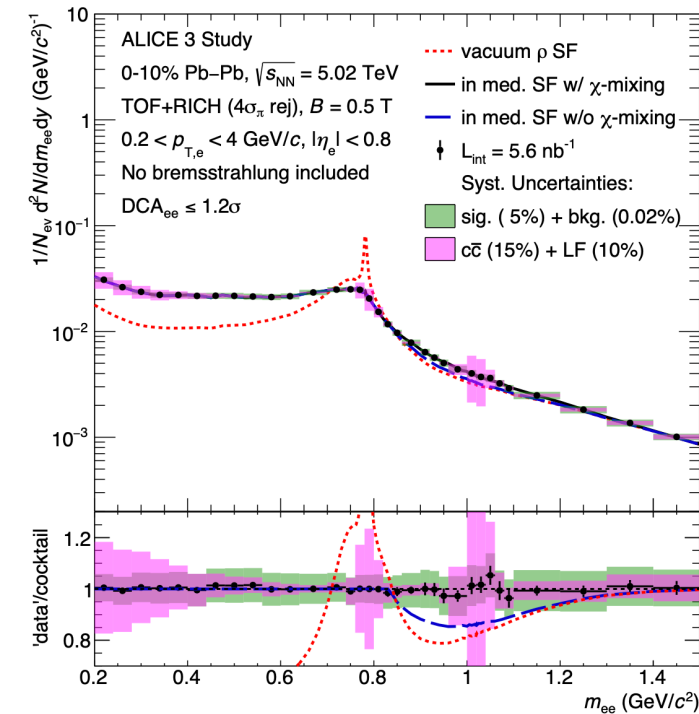
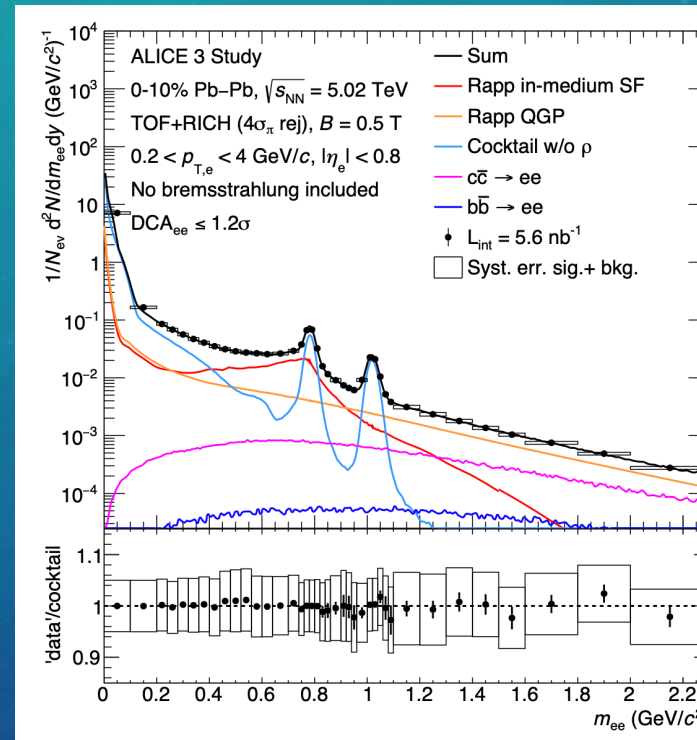
# HIGH PRECISION MEASUREMENT OF THERMAL DILEPTONS

- Double-differential analysis of the production in both transverse momentum and mass  $\rightarrow$  access to the time-evolution of the quark-gluon plasma temperature
- tracker with extremely low mass  $\rightarrow$  minimise photon conversions
- very high pointing resolution  $\rightarrow$  reject electrons from heavy flavour decays



# HIGH PRECISION MEASUREMENT OF THERMAL DILEPTONS

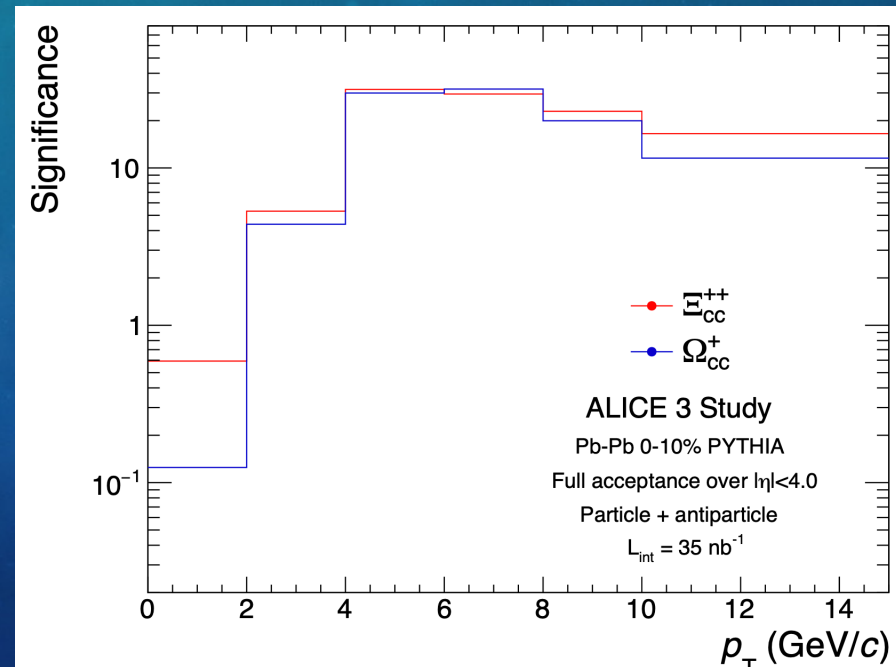
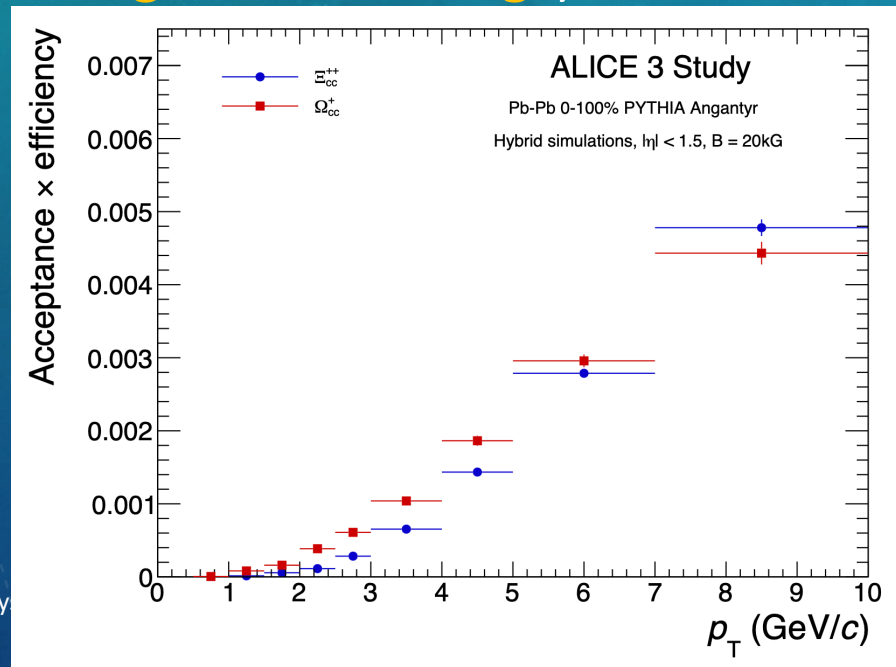
- deconfinement phase transition  
 $\rightarrow$  partial restoration of chiral symmetry  $\rightarrow$  mixing between  $\rho$  and  $a_1$  visible in dielectron mass spectrum
- large background of correlated electron pairs from heavy-flavour hadron decays
- high-precision tracking to remove conversion electrons by a prefilter technique





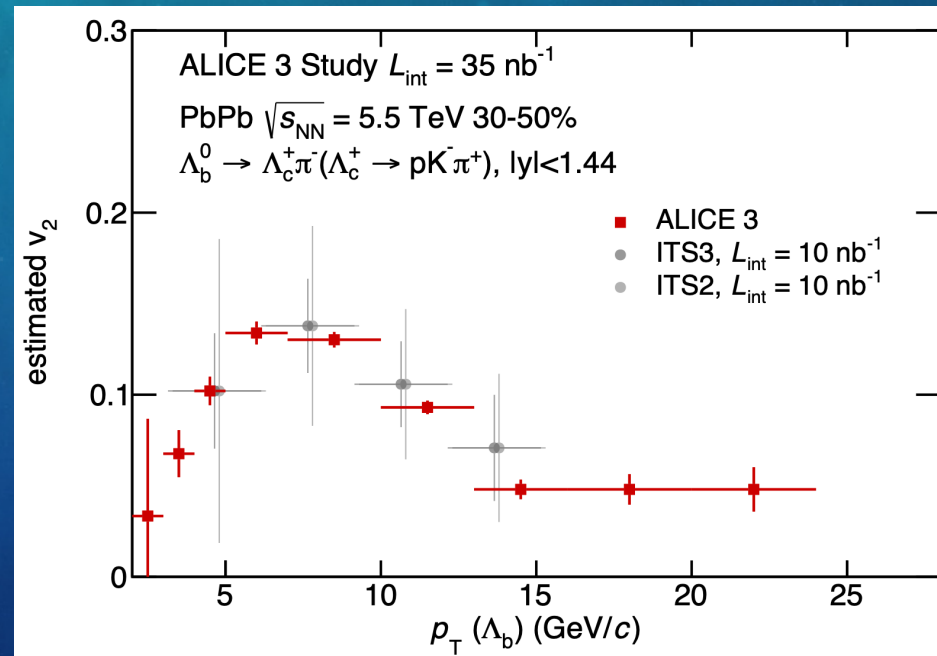
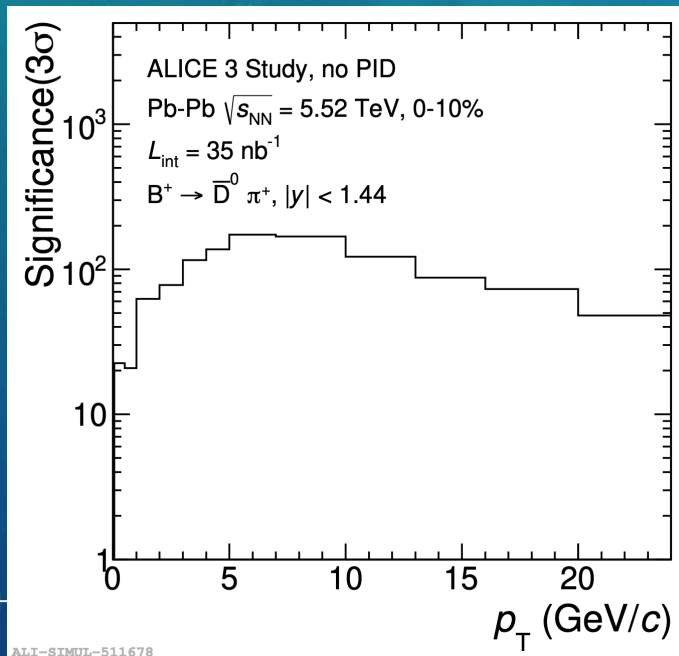
# MULTI HEAVY-QUARK PHYSICS: HADRON FORMATION

- study the formation of hadrons from the deconfined QGP → **multi-charm hadrons** are unique probe of hadron formation requires **recombination of multiple charm quarks**
- track all their decay products, typically including hyperons, before they decay ("**strangeness tracking**")



# STUDY OF B FLAVOURED PARTICLES

- Ultimate understanding of collective flow mechanisms requires investigation of the beauty baryons and mesons behaviour
- $m_b > m_c \rightarrow$  better theoretical control on the modelling of the quark transport in the expanding QGP
- ALICE 3 vertex detector will provide first precise measurement of  $\Lambda_b$  yield and flow





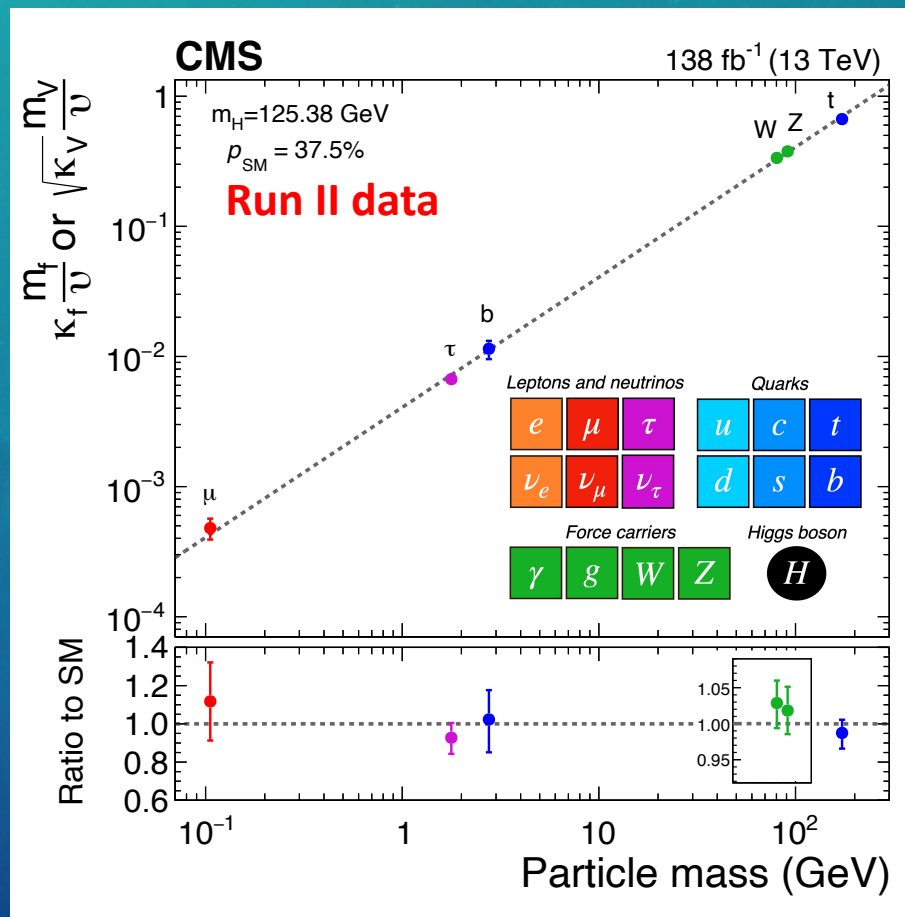
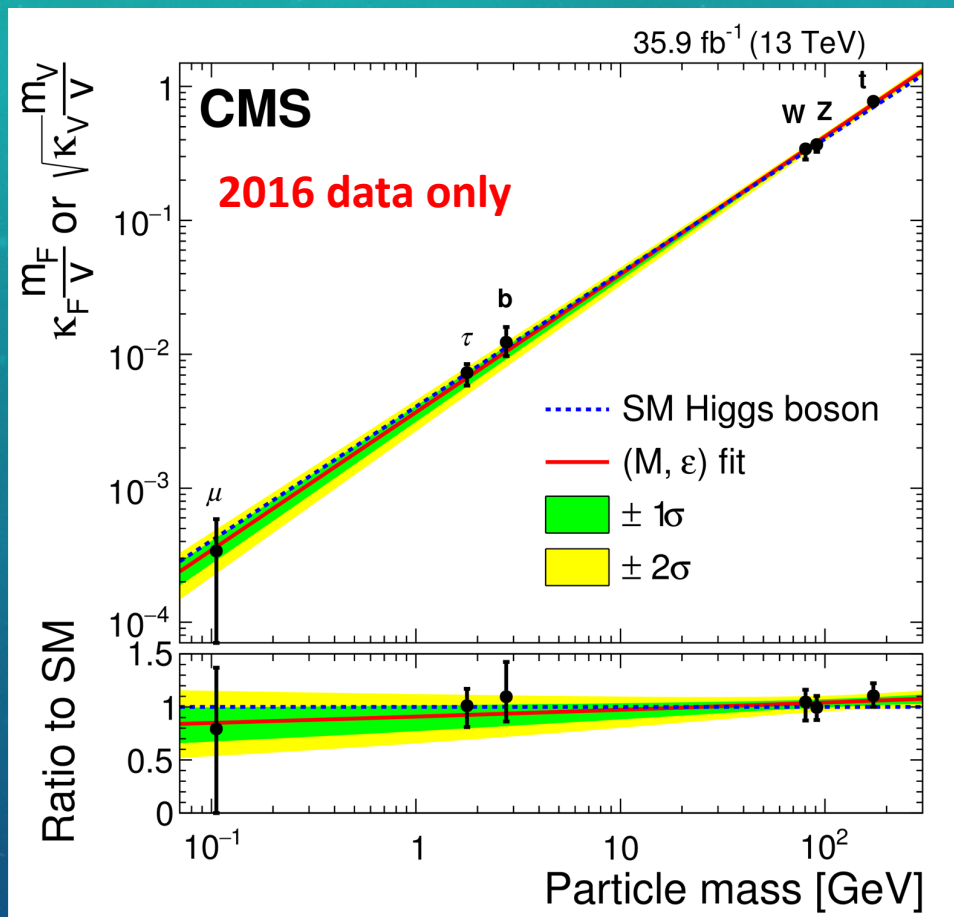
# CONCLUSIONS

- High Luminosity LHC will deliver to the four experiments the largest dataset from pp and Pb-Pb collisions ever recorded
- The creativity of scientists analysing these data allowed our community to supersede some of the projections made in 2018 (we have evidence of 4 top production,  $H \rightarrow \mu\mu$ ,  $H \rightarrow Z\gamma$  ...)
- Many more ideas will come during the analysis of the data collected during the LHC Run 3
  - **HL - LHC physics case is an evolving landscape  $\rightarrow$  stay tuned!**

# BACKUP



# DESIRABLE #1: THE HIGGS BOSON

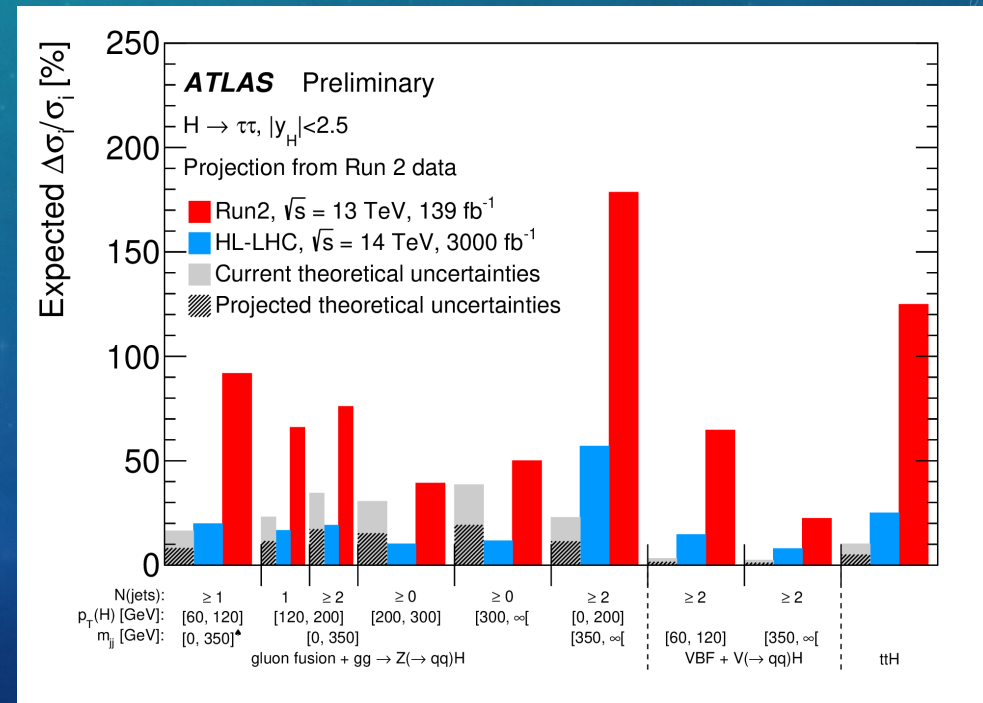
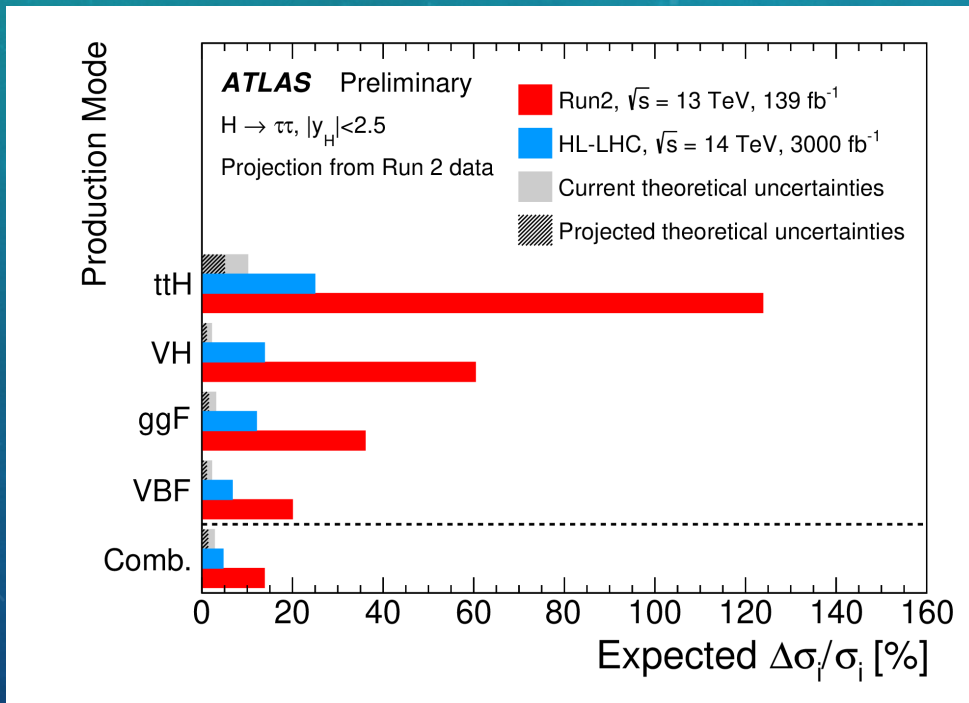


Evidence of  $H \rightarrow \mu\mu$  decay at CMS!!!

# DESIRABLE #1: THE HIGGS BOSON

Simplified Template Cross Sections (STXS): a framework common to ATLAS and CMS to study the Higgs Boson differential cross section ([twiki](#))

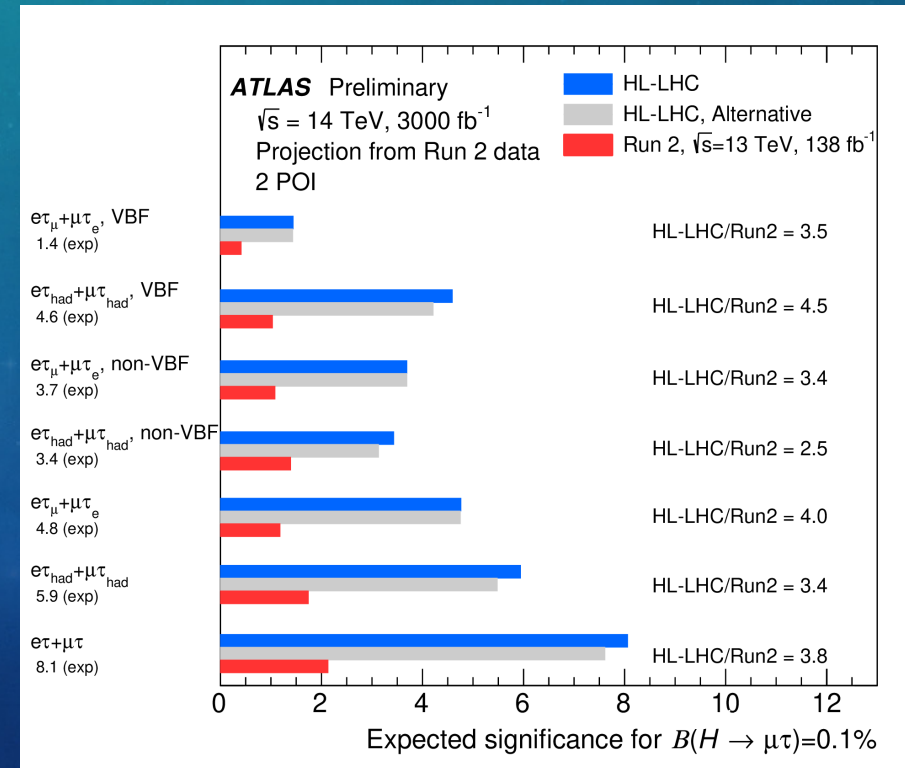
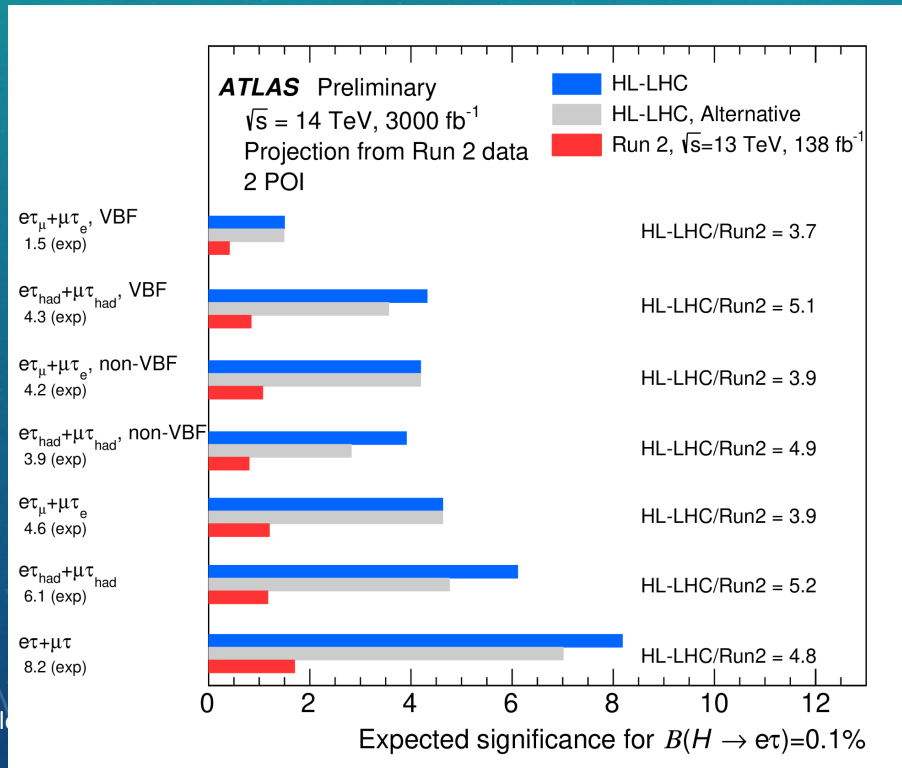
ATLAS projection of STXS measurements for the  $H \rightarrow \tau\tau$  decay mode



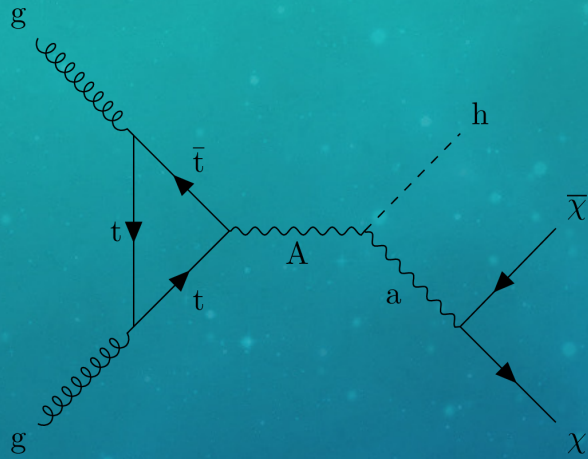


# DESIRABLE #1: THE HIGGS BOSON

Ongoing search for Lepton Flavour Violation (LFV) in Higgs decays both at ATLAS ( $H \rightarrow e/\mu + \tau$ ) and CMS ( $H \rightarrow e\mu$ ): recently presented full Run 2 analysis observing mild excess of events...

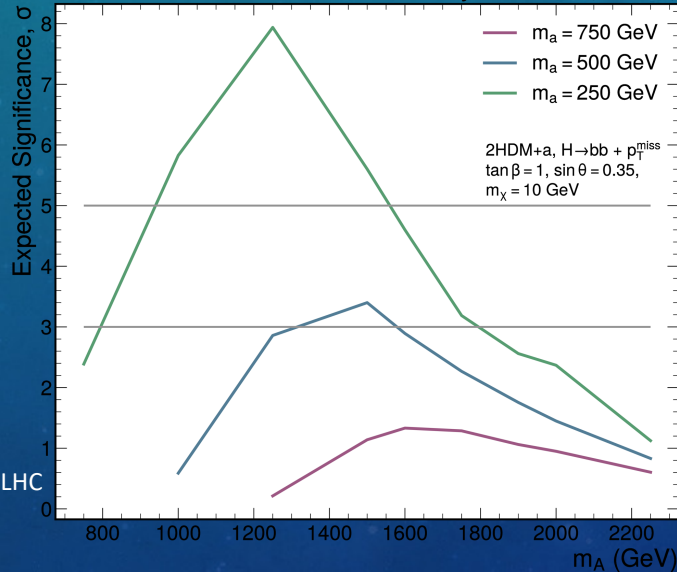


# BSM SEARCHES @ CMS

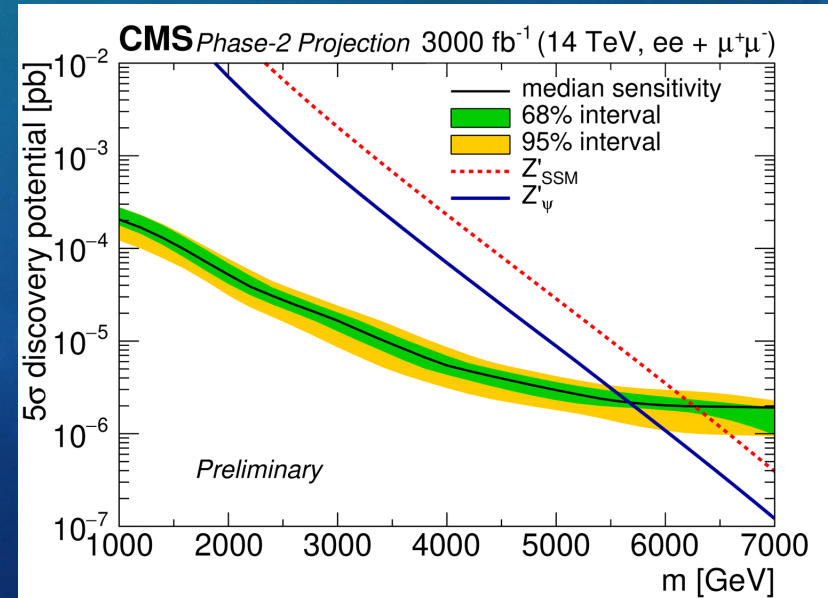
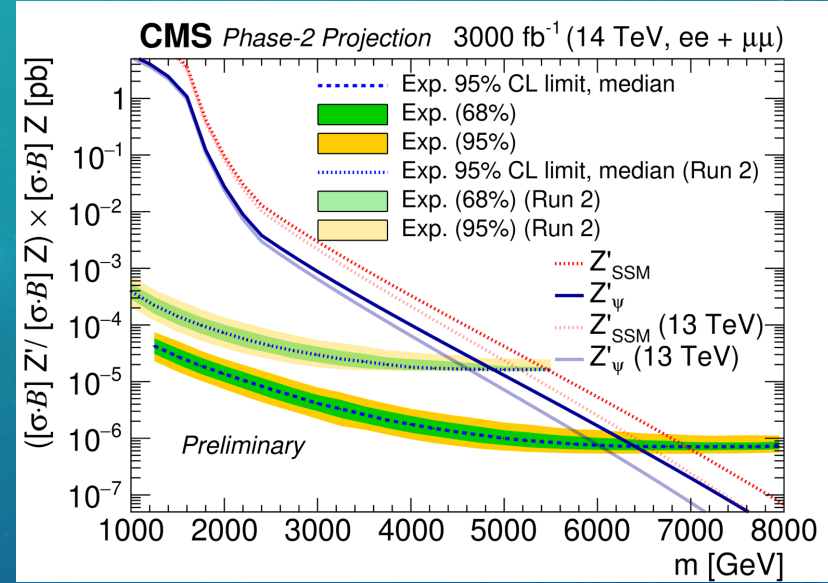


mono-Higgs sector,  
 $h \rightarrow bb$  plus  
 missing transverse  
 momentum,  
 boosted Higgs  
 bosons, 2HDM+a  
 interpretation

CMS Phase-2 Simulation Preliminary 3000 fb<sup>-1</sup> (14 TeV)



search for new heavy gauge bosons  $Z'$



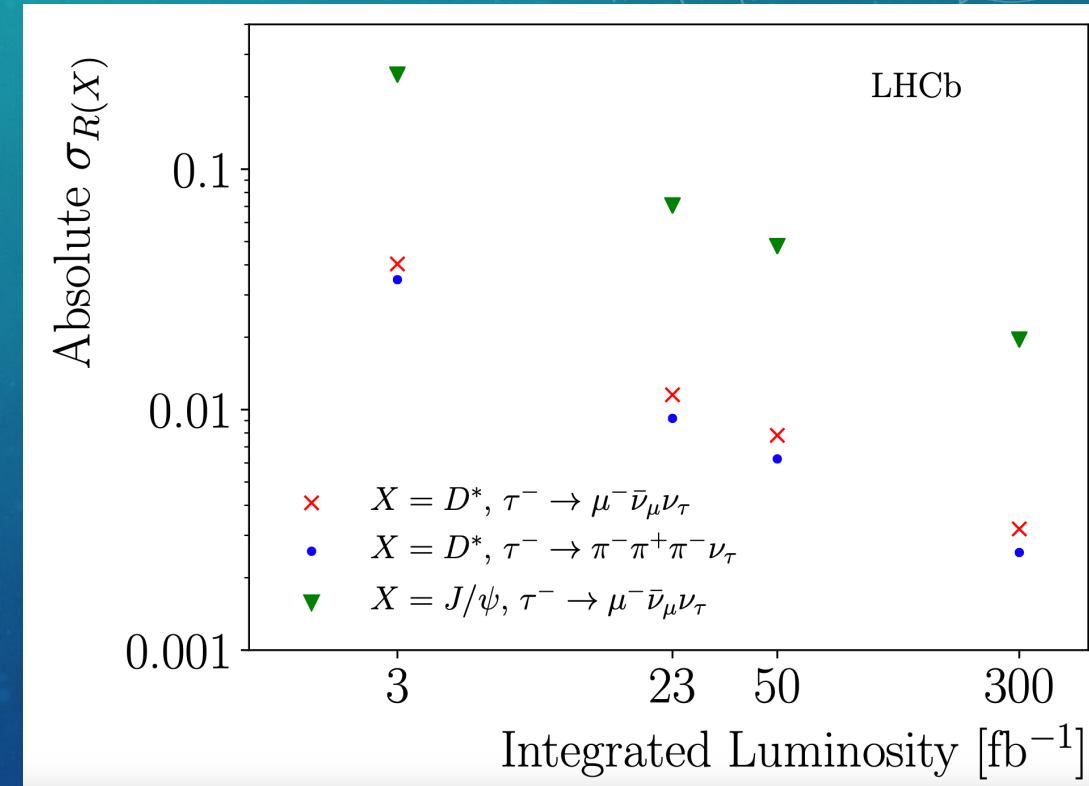


# LEPTON FLAVOUR UNIVERSALITY

- Tests of LFU in semitauonic decays are obtained measuring the following ratios

$$R_X = \frac{\Gamma(B \rightarrow X_c \tau^+ \nu_\tau)}{\Gamma(B \rightarrow X_c \mu^+ \nu_\mu)} \quad \text{with } X_c = D^* \text{ or } J/\psi$$

- Expect O(10 M)  $B \rightarrow D^* \tau \nu$  candidates
- Sensitivity Upgrade II:  $\sigma(R_{D^*}) / R_{D^*} \sim 1\%$
- LHCb currently shows some tension with SM...



# $D^0\bar{D}^0$ CORRELATIONS

Azimuthal correlations of  $D^0\bar{D}^0$  pairs in Pb–Pb collisions → direct measure of momentum broadening by the QGP → sensitivity to energy loss mechanisms and to degree of charm thermalisation in the medium

