The LHC: always exciting

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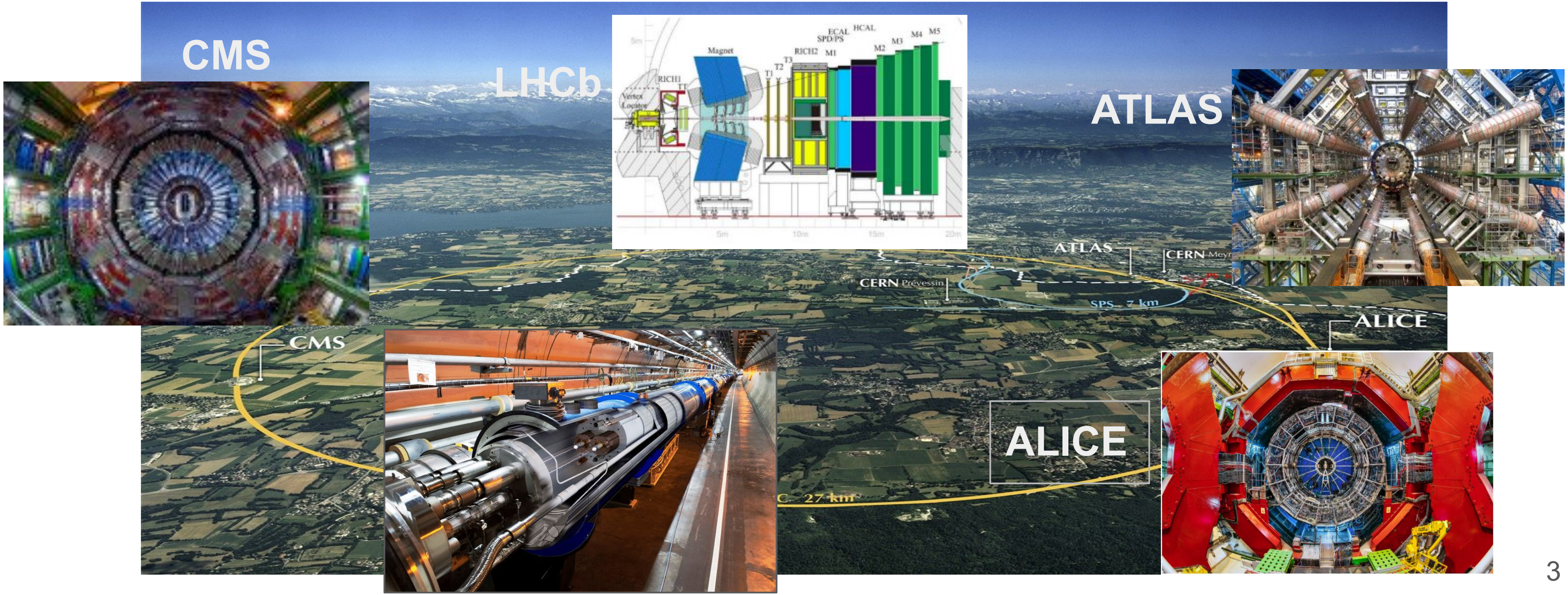
Plan of the talk

- Introduction
- Physics platter:
  - Measurement of the W-mass
  - Search for multi-Higgs productions
  - Top quark front
  - A brief from the heavy ion sector
  - Another from the heavy flavor domain
- Beyond the LHC?
- Conclusion

The large hadron collider (LHC)

- Conceived in early 1980s
- Start of the LHC construction: 1998
- First p-p collision: November, 2009
- **Higgs boson discovery: 2012 →first motivation for the project**
- To operate for ~2 more decades!

Motivation 2: *unfinished job as yet.*
No direct evidence for physics beyond the Standard Model (SM)



Proton-on-proton collisions at the LHC

Excellent performance of the LHC machine for more than a decade of operation.

$\mathcal{L}$

$$N_{\text{observed}} = \sigma_{\text{process}} \times \epsilon \times A \times \int L dt + N_{\text{background}}$$

Low luminosity datasets in 2017

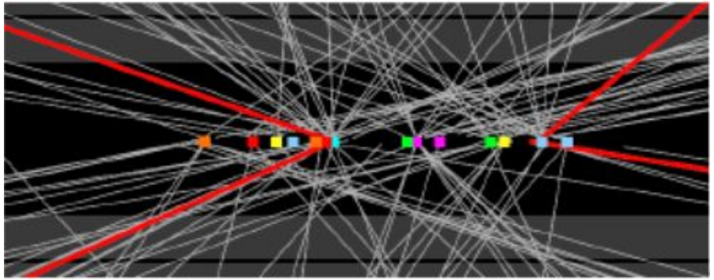
$\mathcal{L}$ = 298 pb^{-1} @ $\sqrt{s}$ =5.02 TeV

$\mathcal{L}$ = 201 pb^{-1} @ $\sqrt{s}$ =13 TeV

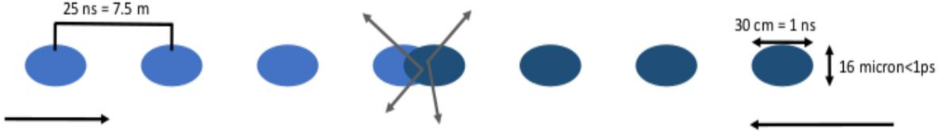
\+ Heavy ion runs

p-p collision data collected by each of the ATLAS and CMS experiments:

- Run-1 at $\sqrt{s}$ = 7, 8 TeV (2010 - 2012) : $\mathcal{L}$ ~ 20 fb^{-1}
- Run-2 at $\sqrt{s}$ = 13 TeV (2015 - 2018): $\mathcal{L}$ ~ 140 fb^{-1}
- Run-3 at $\sqrt{s}$ = 13.6 TeV (2022+2023+2024): $\mathcal{L}$ ~ 105 fb^{-1}



In 2024, peak instantaneous luminosity **L ~ 2.5X10^{34} cm^{-2}s^{-1}**
~ 65 p-p collisions/crossing on average
→ pile up for a triggered event

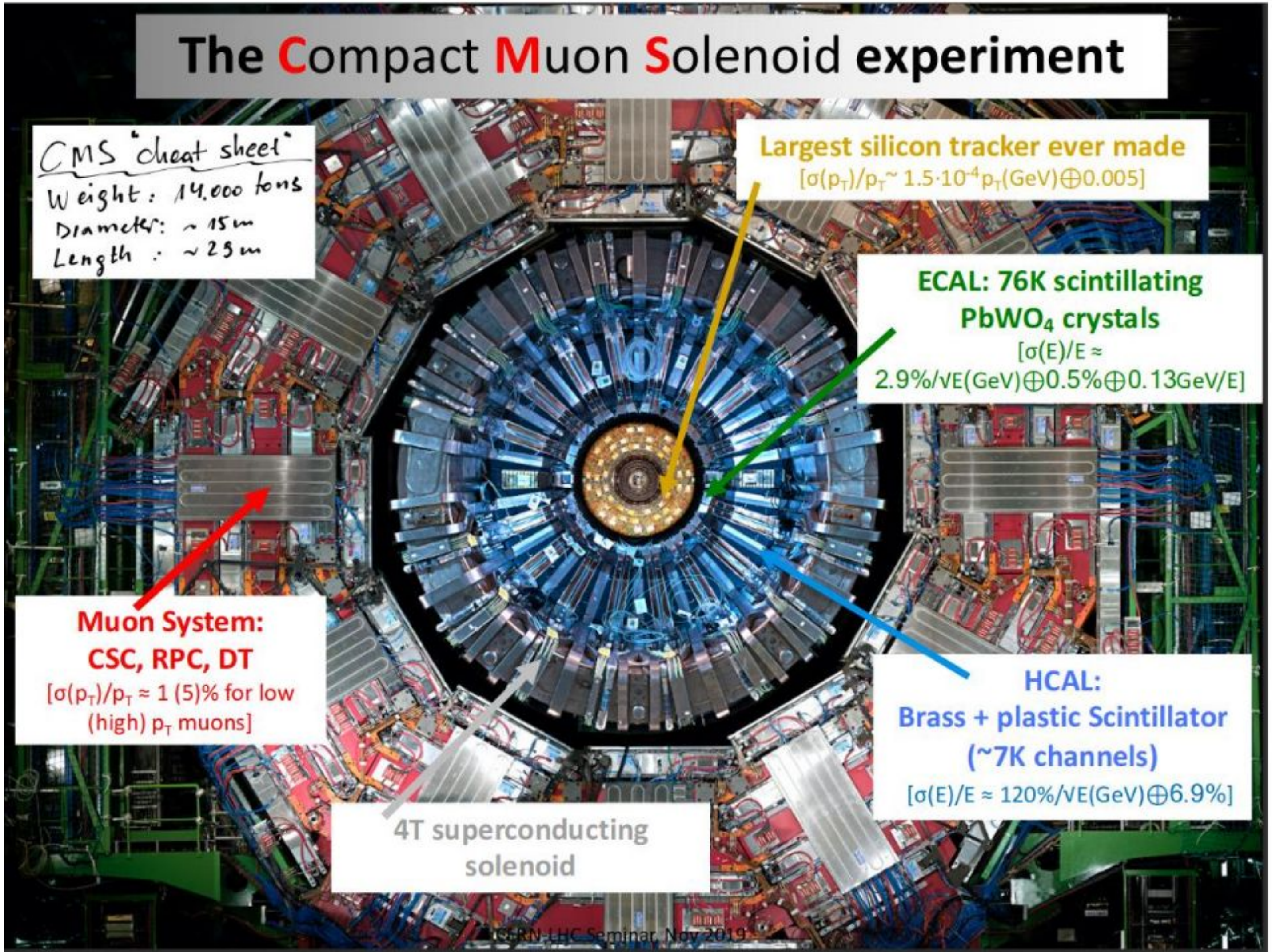


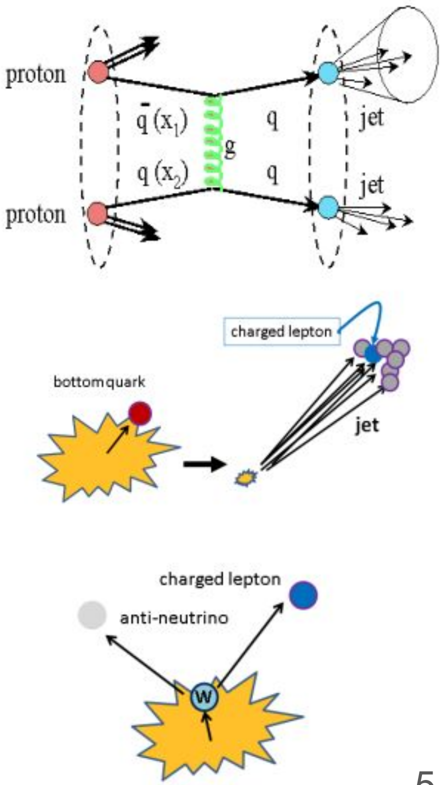
Run-3 will continue till 2026, expected total $\mathcal{L}$ ~ 250 fb^{-1}

Pileup: multiple interactions at **different** hard-scales

Data collected by each experiment ~ 150 PB

ATLAS and CMS experiments are THE multi-messenger tools!

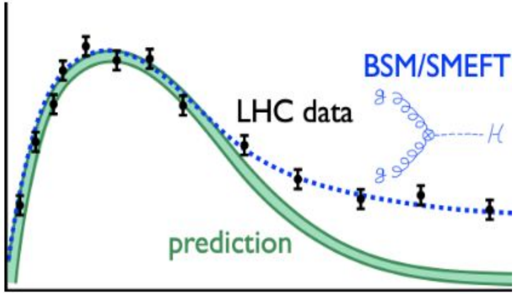


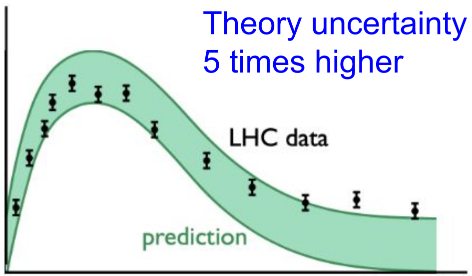


Dividend of collective efforts: achieve more than anticipated!

- Huge amount of physics harvest including Higgs boson discovery, measurements, search for rare processes and physics beyond the SM.
- Enormous progress in computing capabilities.
- Precision theoretical description of the crucial processes
- Extensive understanding of the performance of the experiments.
- Judicious application of sophisticated machine learning techniques!
  - eg. b-jet identification: Deep Jet in CMS: JINST 15 (2020) P12012 , CMS-DP-2021-014

We cannot afford to miss a discovery!





Note: LHC is the only APPROVED future project of HEP as of today

⇒ maximise the physics harvest.

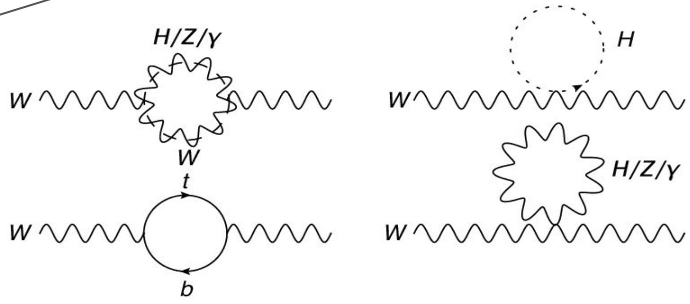
Electroweak physics

Milestones

- Neutral currents: 51 yrs
- QCD: 51 yrs
  ….
- W, Z turns 41
- Top: 29
- BEH particle: 12

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha_{EM}(M_Z)}{\sqrt{2}G_F(1-\Delta r)}$$

Higher order corrections, depend on m_t, m_H, m_{BSM} ?



- ElectroWeak sector one of the most successful and well tested parts of the Standard Model (SM).

- Precision measurements have guided discovery of the top quark, Higgs boson using accurate prediction for electroweak observables.

- Input parameters for predictions are all known now!
  - Z Mass
  - Top Mass
  - Higgs Mass
  - …

⇒ **over-constrain the SM.**

Theoretical uncertainty of
ΔM_{top} = 2.1 GeV ⇒ ΔM_W = 1.9 GeV

Today LHC: Δm_t = 330 MeV
Δm_H = 110 MeV

Nature 633, 745-746 (2024)

Precision measurements at the LHC crucial to get hint about heavier particles not directly accessible now.

Measurement of W mass

$$m_W^{SM} = 80355 \pm 6 \text{ MeV}$$

- Humongous effort by theory and experimental communities to push the measured ΔM_W to < 10 MeV

LEP measurement: ΔM_Z = 2 MeV, precision of 22 parts in a million

- Complex, indirect m_W measurement
  → requires $\mathcal{O}$(5-7) years
  →Only four W-boson mass measurements in the last 10 years.

2021 – LHCb m_W = 80.354 ± 0.032 GeV

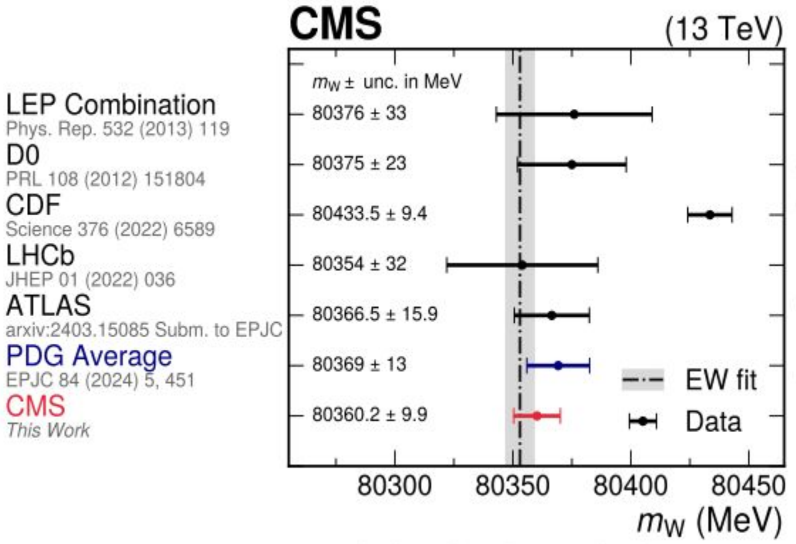
2022 – CDF m_W = 80.4335 ± 0.0094 GeV, 4.2 M events

2024 – ATLAS m_W = 80.3665 ± 0.0159 GeV [9.8 (stat) ⊕ 12.5 (syst) MeV]
(14 M events, using 7 TeV data 4.6 /fb, PDF CT18)

2024 – CMS m_W = 80.3602 ± 0.0099 GeV [2.4 (stat) ⊕ 9.6 (syst) MeV]
(1 B events, using ~ 10% of 13 TeV data, uses CT18Z PDF)

Used 5 billion Monte Carlo samples

History of m_W measurements

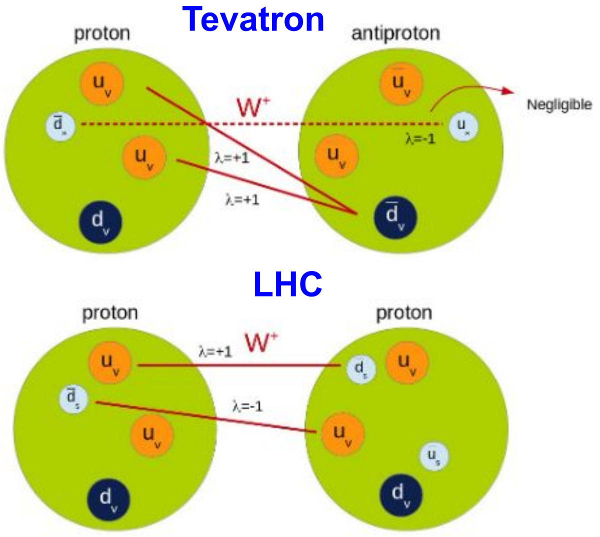


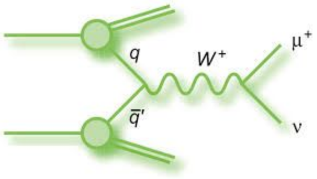
Uncertainty due to muon momentum scale
ATLAS: ΔM_W ~ 6 MeV
CMS: ΔM_W ~ 4.4 MeV
CDF: ΔM_W ~ 3 MeV

Uncertainty due to parton density function
ATLAS: ΔM_W ~ 5 MeV
CMS: ΔM_W ~ 2.8 MeV
CDF: ΔM_W ~ 3.9 MeV

W boson production and decay

- p-pbar collisions: W bosons mostly produced in the same helicity state.
- p-p collisions: both positive and negative polarization states.
- Large PDF-induced W-polarisation uncertainty affecting the p_T lepton distribution, peak at $m_W/2$
- Sea-quark PDFs play a larger role at the LHC.



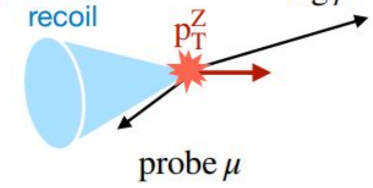


$$m_T^W = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} (1 - \cos \Delta\phi_{\ell \vec{p}_T^{\text{miss}}})}$$

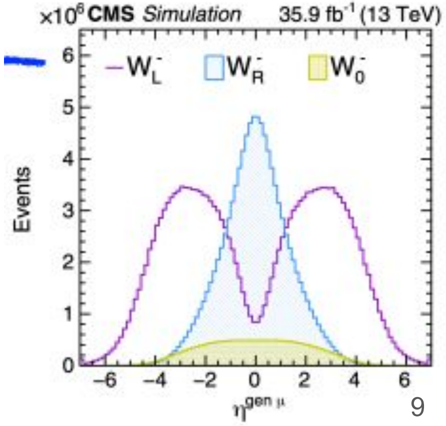
$$\vec{p}_T^{\text{miss}} = -(\vec{p}_T^{\ell} + \vec{u}_T)$$

Additional QCD complications

1. Heavy-flavour-initiated processes
2. W+, W- and Z are produced by different light flavour fractions
3. Larger gluon-induced W production



$$u_T = \frac{\vec{p}_T^Z \cdot \vec{p}_T^{\mu}}{|\vec{p}_T^{\mu}|}$$



Note: CDF and LHC experiments performed at different times, with different baseline PDFs and QCD tools, different experimental conditions,..

CMS strategy: highlights

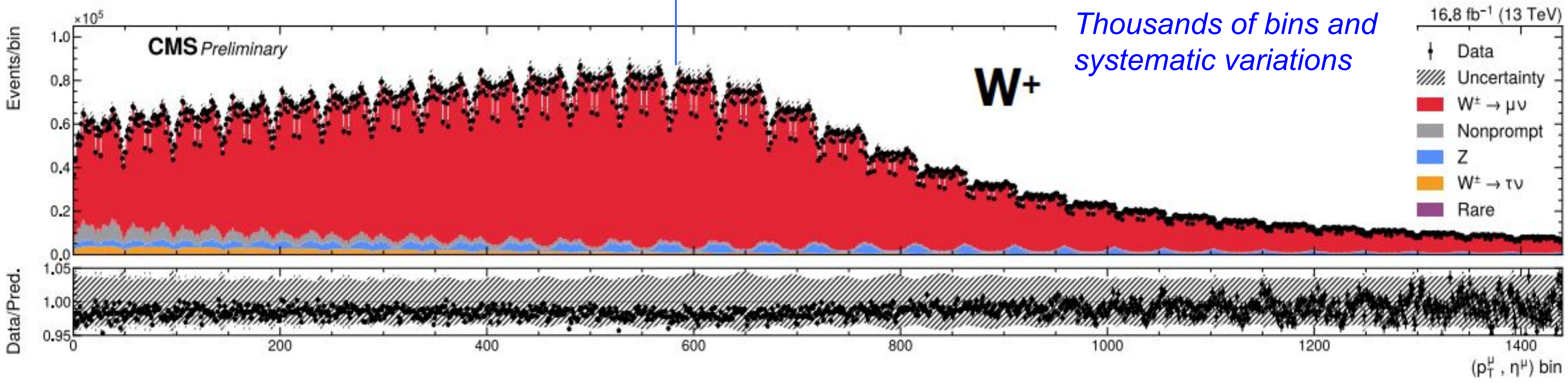
SMP-23-002

- Measure m_W by fitting the observed 3D distribution of lepton charge, η^ℓ and p_T^ℓ using template shapes for the signal and the background processes.
- Used large data volume collected during Run2.
- High pileup (avg.~ 45) data makes p_T^{miss} resolution worse extracting m_W from m_T^W particularly challenging
- Focus on lepton kinematics, restrict to muon channel (better calibration).
- Data has strong constraining power ➡ utlise sensitivity to PDF from η^ℓ distribution
- Low p_T^W region treated in the best possible way (N3LL) + analytical resummation in recoil, high p_T^W @ N2LO
- Critical to control the lepton efficiency and momentum calibration. ($\Delta p_T^\mu \sim 10^{-4} \Rightarrow \Delta m_W \sim 8$ MeV)
- p_T^μ distribution strongly dependent on the theoretical modeling of p_T^W distribution
  → calibration of the p_T^μ measurement only uses muons from the $J/\psi \rightarrow \mu\mu$ resonance.
  → sample of muons from Y(1S) and Z decays used for an independent validation of the p_T^μ calibration
- 100 M selected (out of 300 M data) $W \rightarrow \mu\nu$ events - 87% signal
  rest mainly QCD multijet events: contributions estimated in data-driven method
- 7 M selected $Z \rightarrow \mu\mu$ events - $m_{\ell\ell}$ in [60, 120] GeV - >99% signal
  Validation:measured m_Z = 91 182 ± 7 (stat) ± 12 (syst) = 91 182 ± 14 MeV ,

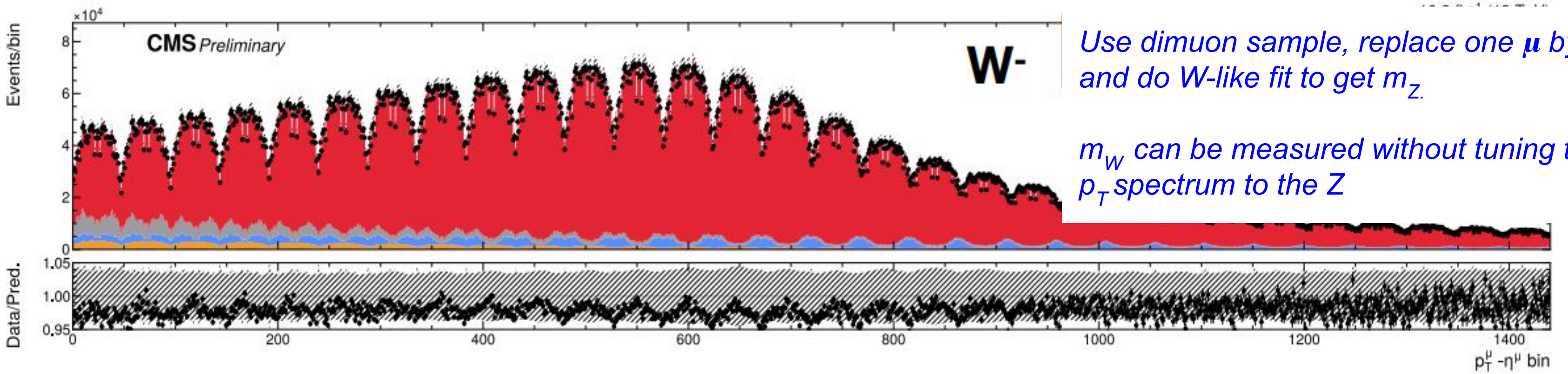
Measured distributions

SMP-23-002

40 GeV



Thousands of bins and systematic variations



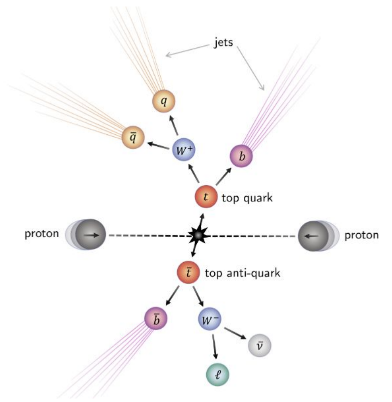
Use dimuon sample, replace one $\boldsymbol{\mu}$ by a $\boldsymbol{\nu}$ and do W-like fit to get m_Z.

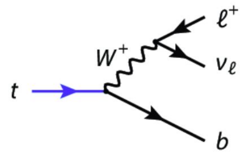
m_W can be measured without tuning the p_T spectrum to the Z

Likelihood function to check the compatibility of data with simulation

$$\mathcal{L}\left(\vec{n}\,|\,\mu,\vec{\theta}\right) = \prod_j \prod_i \text{Poisson}\left(n_{ji}\,|\,\nu_{ji}(\mu,\vec{\theta})\right)\cdot \text{Gauss}\left(\vec{\theta}\right)$$

Physics of the top quark

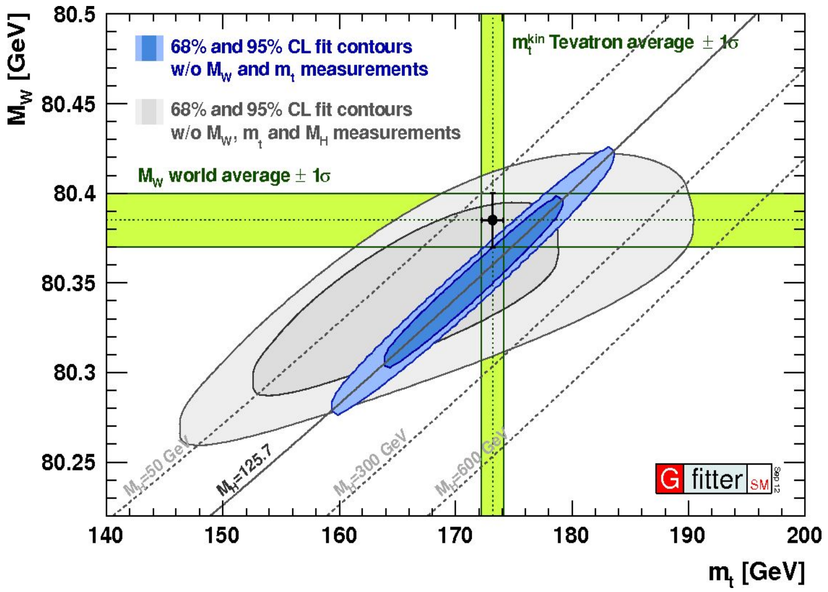




- Heaviest known elementary particle so far.
- Extremely short-lived, decays before hadronization.
  ⇒ spin information transferred to decay products.

  → possible to observe properties of the bare quark
- Abundant production at the LHC (in Run 2 ~10^8 per expt.)
- **m_t = 172.52 ± 0.33 [0.14 (stat) ⊕ 0.33 (syst)] GeV**
  → impressive *precision of 0.18%* [2403.01313]
- Mass/ Yukawa coupling: free parameter in SM,
  → to be measured in experiments: **$y_t = \sqrt{2}\, m_t/v$.**
- **m_t** key factor in the stability of SM Higgs potential and hence the evolution of the universe.

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$



Spin entanglement of top quark pairs

Nature 633 (2024) 542

- Entanglement: key feature of QM
- Spin correlation explored typically in low energy regime in various context.
- LHC: a pair of quarks available at relativistic energies: minimum 2-qubit system.
- Challenge for observation of spin-entanglement in tt system.

  ⇒ Cannot control the internal degrees of freedom in the initial state.
  ⇒ Entanglement can be detected only with dedicated analysis in a restricted phase space.

- Study two-qubit states of ttbar at production threshold ⇒ mostly singlet → rotational invariance with well-specified fiducial phase-space → maximally correlated or entangled!

Spin density matrix of 2-qubit system

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j \right]$$

I_n: normalization
B_i: individual polarization
C_{ij}: spin correlation

each diagonal element of C corresponds to the spin correlation in a particular direction,
→good entanglement witness.

Require Tr(C) + 1 < 0

Observation of spin entanglement at the highest energy

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+\cdot\hat{\mathbf{q}}_+ - \mathbf{B}^-\cdot\hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+\cdot\mathbf{C}\cdot\hat{\mathbf{q}}_-}{(4\pi)^2}$$

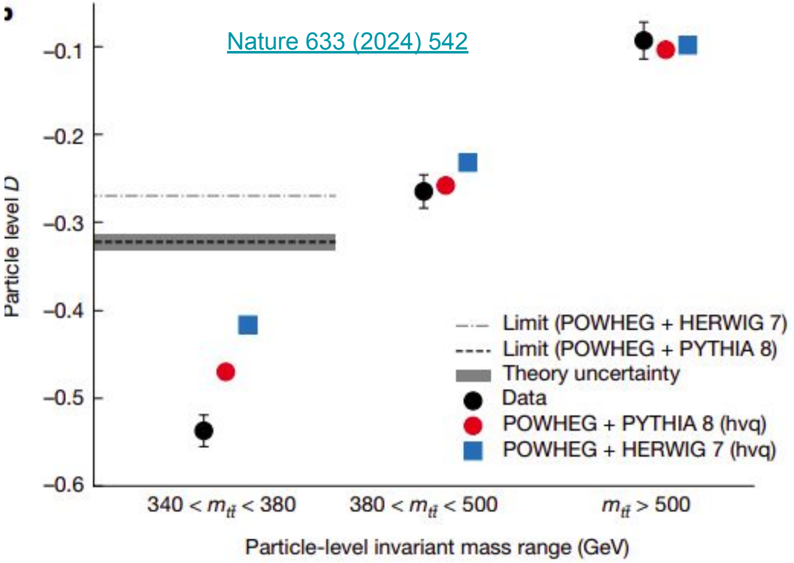
B : top polarization
q: individual momentum

Entanglement marker D = − 3cos φ

$$D = \frac{\mathrm{Tr}\,[\mathbb{C}]}{3} \Rightarrow D < -\frac{1}{3}$$

→ observable dependent on the angle φ between the charged leptons in the rest frame of their parents.

→ cos φ can be measured experimentally in an ensemble dataset.



ATLAS: D= -0.547 ± 0.002 (stat) ± 0.020 (syst) **for** $340 < m_{tt} < 380$ GeV

Significance more than 5σ compared to null hypothesis of no-entanglement

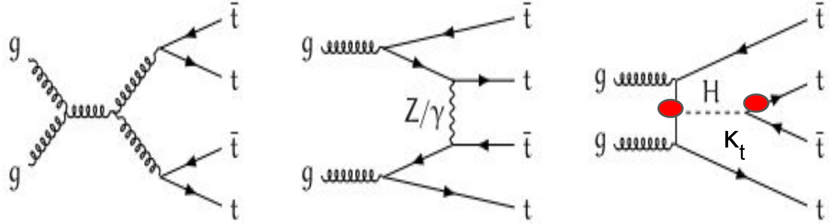
2406.03976
Submitted to RPP

CMS also confirms observation of spin-entanglement
Analysis takes into account parton level entanglement combined with non-relativistic effects, contribution from toponium production.

Observation of 4 top production

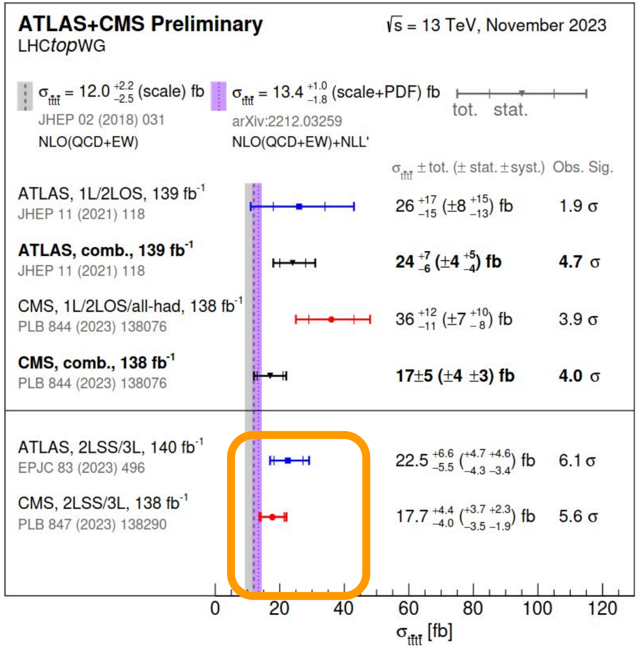
- Heaviest final state : σ(tttt) ~ 13.4 ±1.4 fb
  @NLO QCD, NLO EWK + NNLL

O(100M) tt events and O(1k) tt tt events, 100 ttt events



Observed (expected) significance **6.1 (4.7) s.d. : ATLAS**
5.6 (4.9) s.d.: CMS

EPJC 83 (2023) 496
PLB 847 (2023) 138290



- Possible enhancement in BSM: ⇒ Several constraints on new physics.
- Cross section sensitive to top Yukawa coupling, CP properties of $\boldsymbol{\kappa_t = y_t / y^{SM}}$.

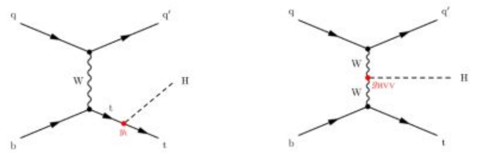
Assuming a pure CP-even coupling (α = 0), **observed upper limit on**

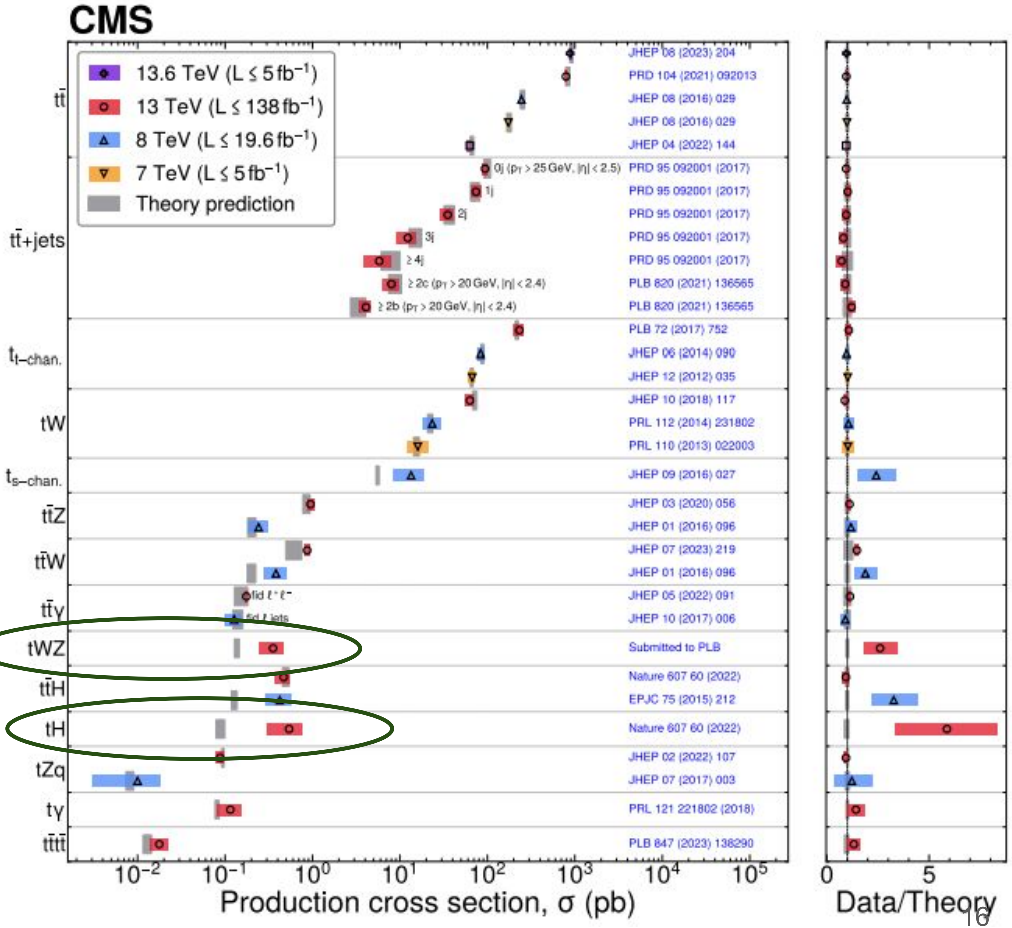
$|\kappa_t|$ = 1.9 at 95% CL

- EFT: constrain 4-fermion interactions of dim-6.

EPJC 84 (2024) 156

Watch out on tH, tWZ processes





Current upper limit on tH production rate ~ 15*SM

tHq, tHW: interference between Higgs boson emission from t or W: in SM, almost maximally destructive
⇒ very low rates.
⇒ BSM can enhance it!

- Sign flip can make σ(tH) >> σ(ttH)

- CP nature of coupling: the relative sign of ttH coupling wrt HWW coupling

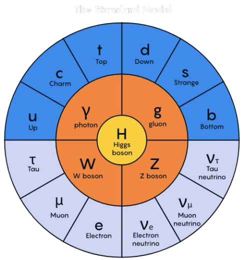
Measured σ(tWZ) = 354 ± 54 (stat) ± 95 (syst) fb
statistical significance 3.4

2σ above the SM prediction of 136 ± 9 fb at NLO(QCD)

PLB 855 (2024) 138815

Higgs boson: more than a decade after the discovery

- Total no. of Higgs bosons already produced at each interaction point ~ 15 M
- Higgs signal strength measured with ~ 6% precision, uncertainty still dominated by statistics.
- Higgs physics is now the tool for probing anomalies in data wrt Standard Model predictions or models beyond SM.



new interaction of Nature

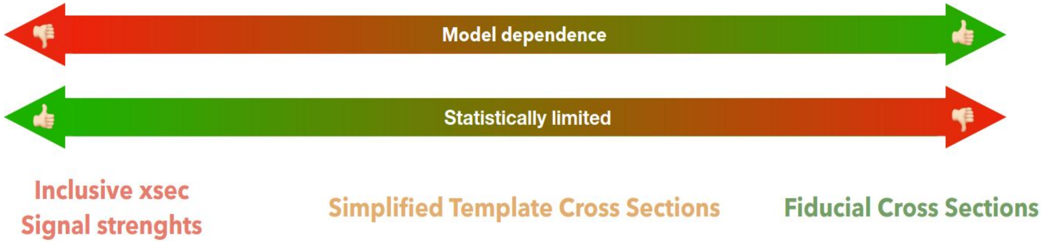
Essentially, we study the dynamics of production and decay to understand the properties

- determine the quantum numbers: charge, spin, parity, mass and width
- check if all the predicted decay channels exist or not
- look for indications for anomalous couplings
- estimate the shape of the Higgs potential: constrain the trilinear and quartic couplings
- study if the Higgs sector is minimal or an extended one

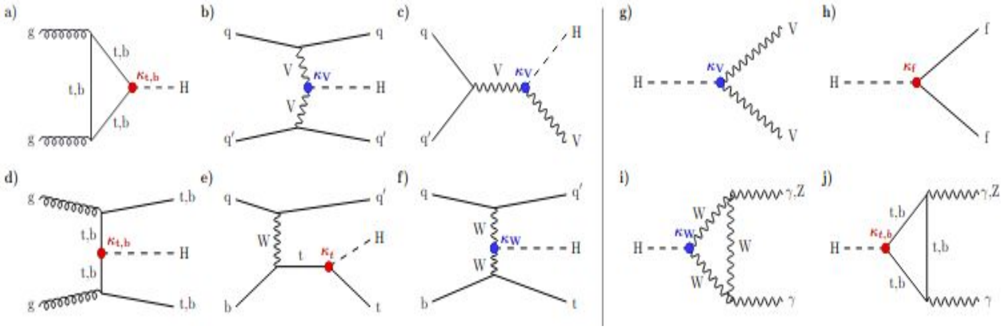
Signal strength: $$\mu_{if} = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \times \frac{B_f}{B_f^{\mathrm{SM}}}$$

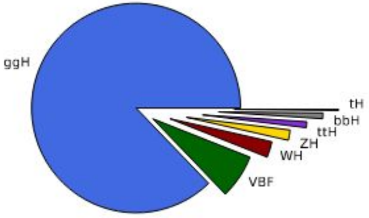
$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

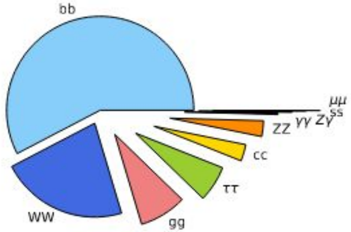
Evolution in interpretation of data for Higgs physics

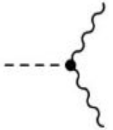


Higgs production at the LHC and decay

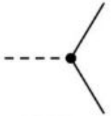




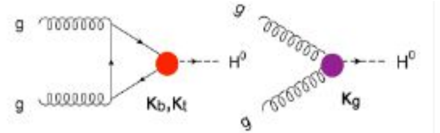




$g_V = 2\frac{m_V^2}{v}$



$g_F = \sqrt{2}\frac{m_f}{v}$

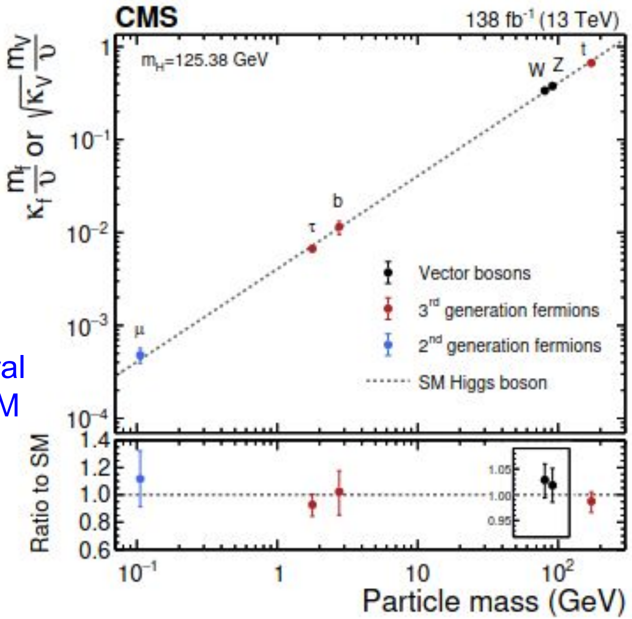


resolve loops effective couplings κ

κ: reduced coupling modifiers wrt the SM

Cannot explore general deviations from the SM

Higgs couplings to the lighter fermions yet to be established



Properties of the discovered BEH particle compatible with those envisaged for a spin-0 boson in the SM

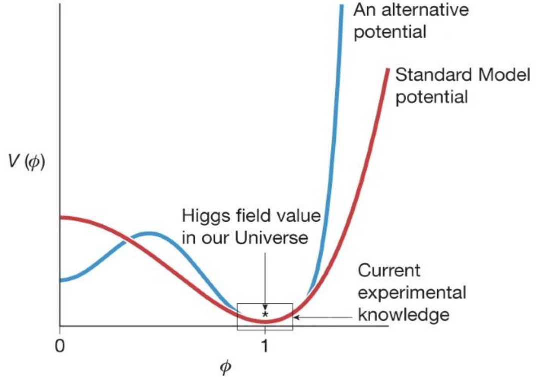
Measurement of Higgs self-interaction

After the electroweak symmetry breaking, Higgs potential:

$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$

In SM :

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{m_H^2}{2v^2} = 0.13$$

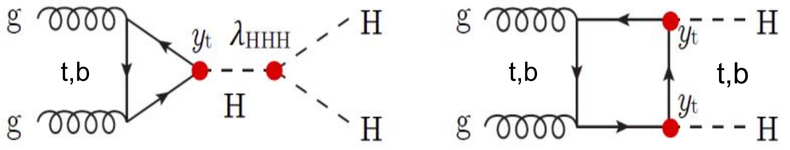


Determination of Higgs self-coupling parameter λ:

→ **Currently, THE most important mandate** of the community

⇒ shape of the Higgs potential near the minimum

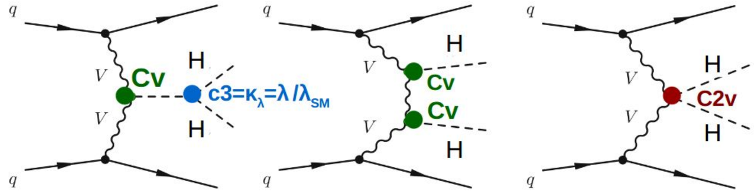
→ related to the evolution of the Universe at the EW scale.



- Inclusive Higgs pair production at the LHC
  → direct access to HHH and VVHH vertices → κ_λ, κ_{2V}

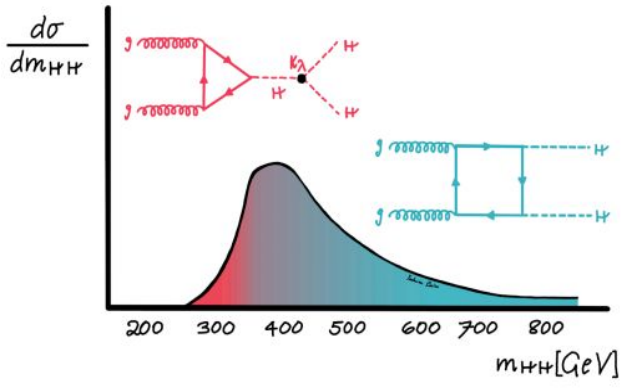
Gluon-gluon fusion σ(gg→HH+X) ~ 31 fb @ 13 TeV with N2LO QCD
almost 10^3 times smaller than σ(pp→H+X)

Vector Boson fusion: the sub-lead mode, σ_{VBFHH} = 1.73 fb at N^{3}LO,
Unique access to HHVV vertex.

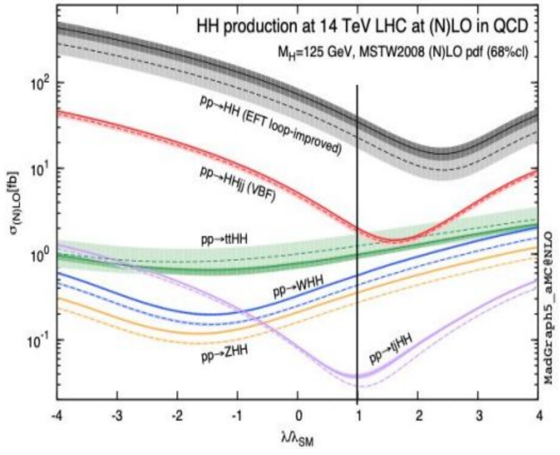


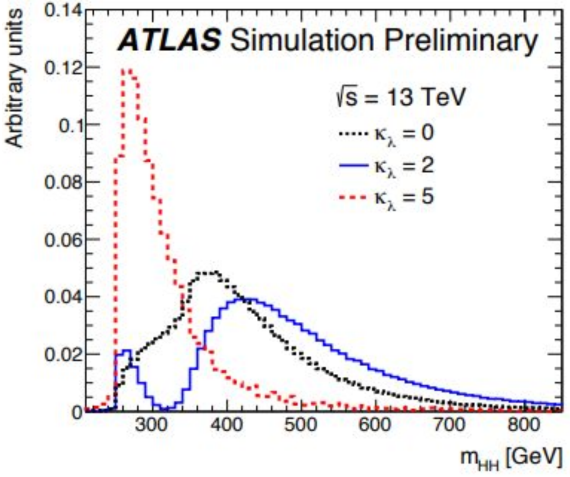
Higgs pair production process is yet to be observed experimentally.

General strategy to search for Higgs boson pair production

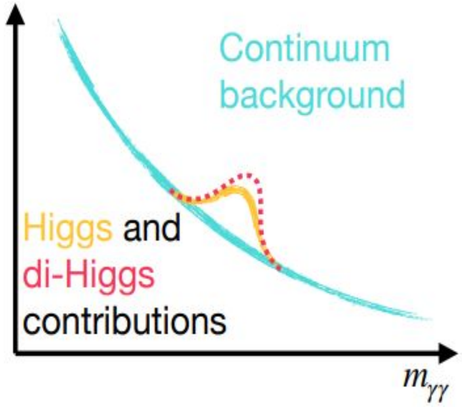


Interference among relevant diagrams→cross section dependency on the coupling modifiers



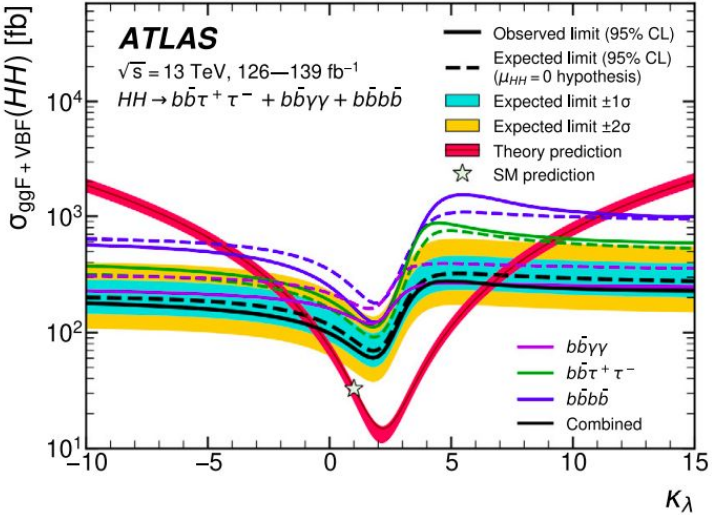


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

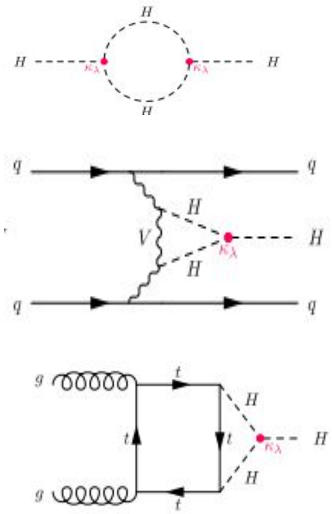


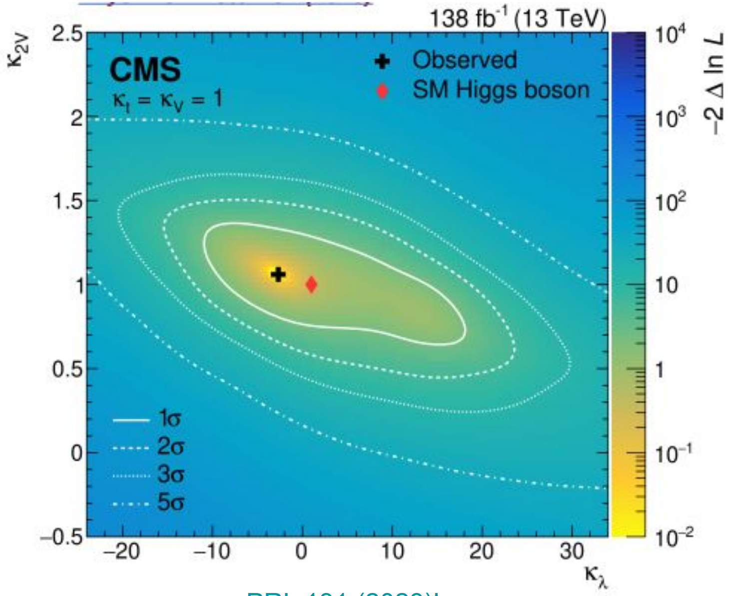
- There is no clear *golden* channel /combination several promising combination for experimental signatures:
- H→ bb : large branching fraction, large background
- H→ $\gamma\gamma$ good mass resolution
- H→ $\tau\tau$:: lower background

Results from search for non-resonant HH production



PLB 843 (2023)





PRL 131 (2023)L

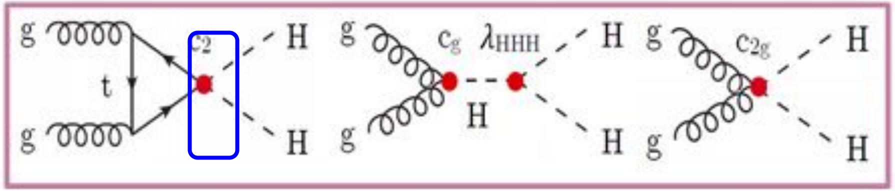
Observed (expected) value of HH production cross section lower than 3.4 (2.5) * SM value

Constraints on κ_λ with 95% CL : [−1.24, 6.49]

Hypothesis of $\boldsymbol{\kappa}_{2v}$ (C_{2V}) = 0 excluded with a significance of 6.3 standard deviations.

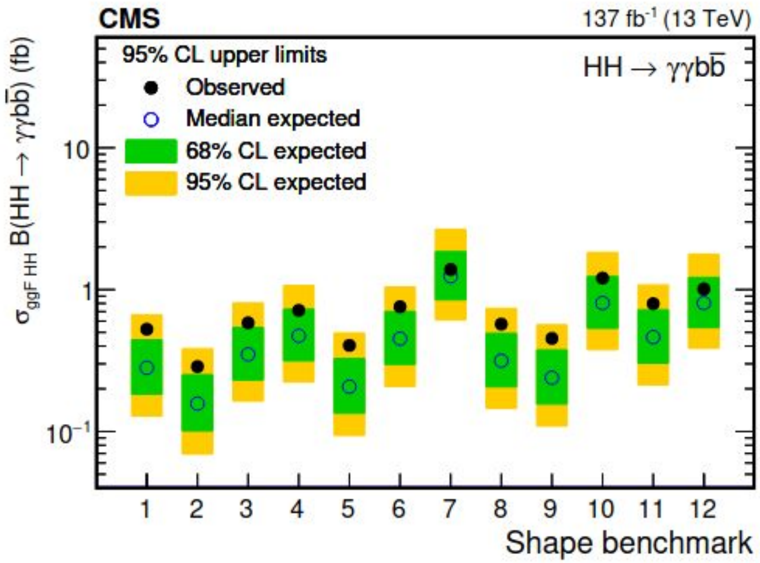
We may have good news on diHiggs measurement sooner than expected!

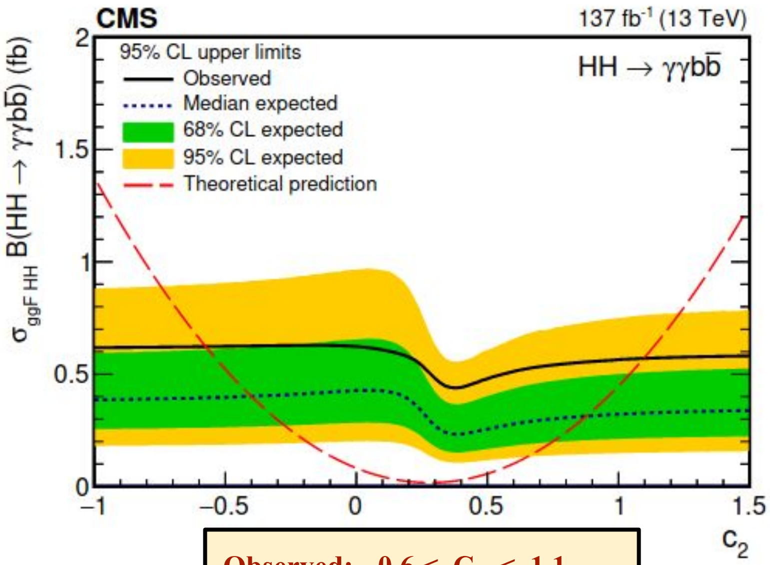
Search for anomalous self-couplings



EFT approach for gg→ HH process includes **three** types of contact interactions described by dim-6 operators.
→ **additional couplings for gg→ HH compared to SM.**

Compatibility of data with different representative BSM scenarios



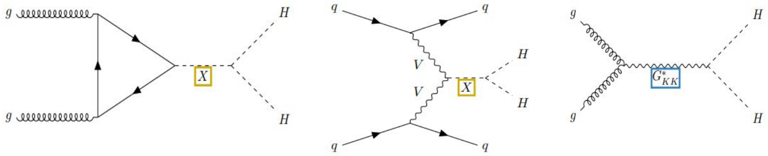


Observed: $-0.6 < C_2 < 1.1$
Expected: $-0.4 < C_2 < 0.9$

Resonant HH production

HH final state provides 2-way probe

- nature of couplings to BSM particles
- new topologies

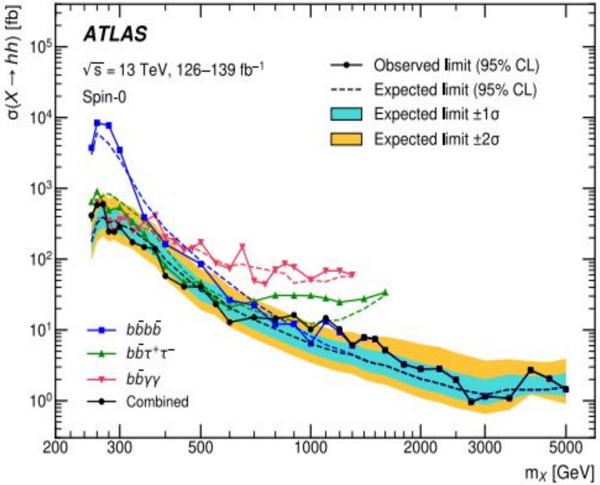


Spin-0: Two-Higgs-Doublet-Models completed by an Electroweak Singlet.

Spin-2: Kaluza–Klein graviton in the context of the bulk Randall-Sundrum model of warped extra dimensions

The different searches often complementary for different mass ranges. 2405.20040

Results presented in a model agnostic way and often reinterpreted in the 2HDM and MSSM model.



ATLAS: small excess with combined local (global) significance of 3.2 (2.1) at 1.1 TeV.

CMS: limits below 320 GeV and above 1 TeV.

Watch out!!

No significant excess in resonant VBF search.

ATLAS analysis excludes parameter space in the region $2 \lesssim \tan\beta \lesssim 5$, which is not excluded by the standard SUSY H searches

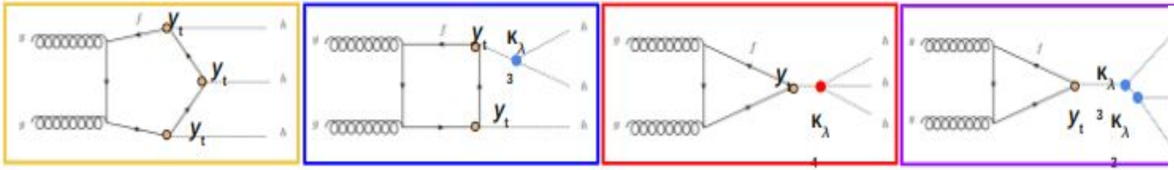
ATLAS-CONF-2024-006

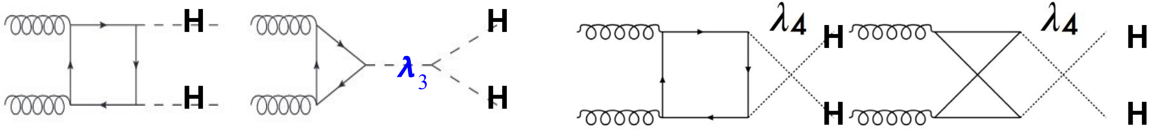
More the merrier!

Can LHC make triple Higgs final state? YES! σ_{SM} = 0.0893 fb

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

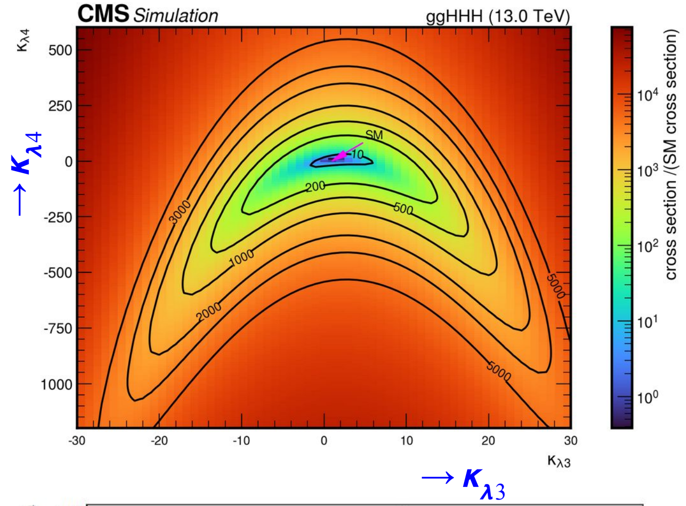
In BSM, $\boldsymbol{\lambda}_3$ can be different from $\boldsymbol{\lambda}_4$

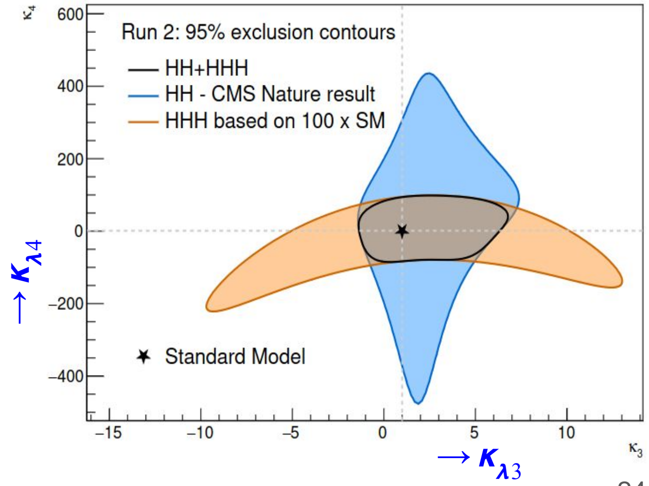




Multi-Higgs production modes directly accessible at the LHC, mainly via

- Di-Higgs production sensitive to λ_3
- Triple Higgs production sensitive to both λ_3 and λ_4, *with stronger dependence on λ_3*
- Consistent determination of the Higgs potential require combined measurement of $\boldsymbol{\lambda}_3$ and $\boldsymbol{\lambda}_4$.





Work in progress

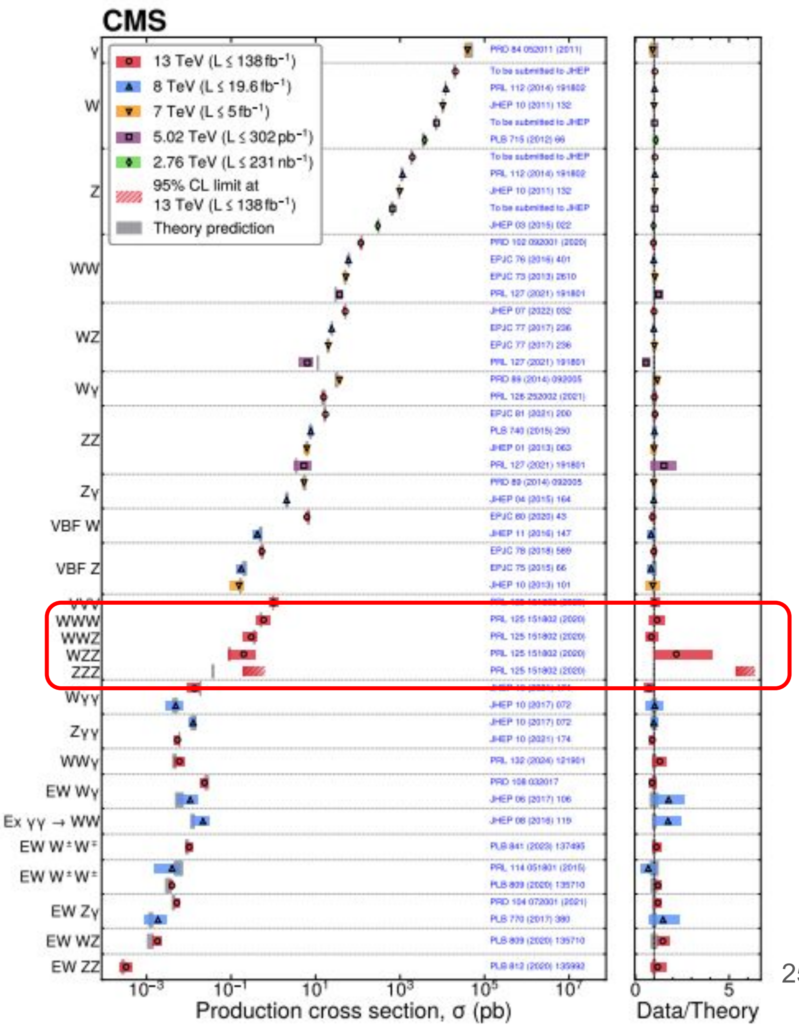
Particle production at the LHC
and stairways to heaven!

[2405.18661](2405.18661)
Submitted to Phys.Rep.

Bottom quark: 1 in a hundred pp collisions
W boson: 1 in a half a million
 Z boson: 1 in a million
H boson: 1 in a billion
HH pair: 1 in a trillion
Triple H: 1 in 100 trillion

Measured cross sections varies over 12-13 orders of magnitude

Watch out on triboson productions: WZZ, ZZZ



Measured σ (tWZ) = 354 ± 54 (stat) ± 95 (syst) fb
statistical significance 3.4 s.d. (expected: 1.4 s.d.)
2σ above the SM prediction of 136 ± 9 fb at NLO(QCD)

Where are others?

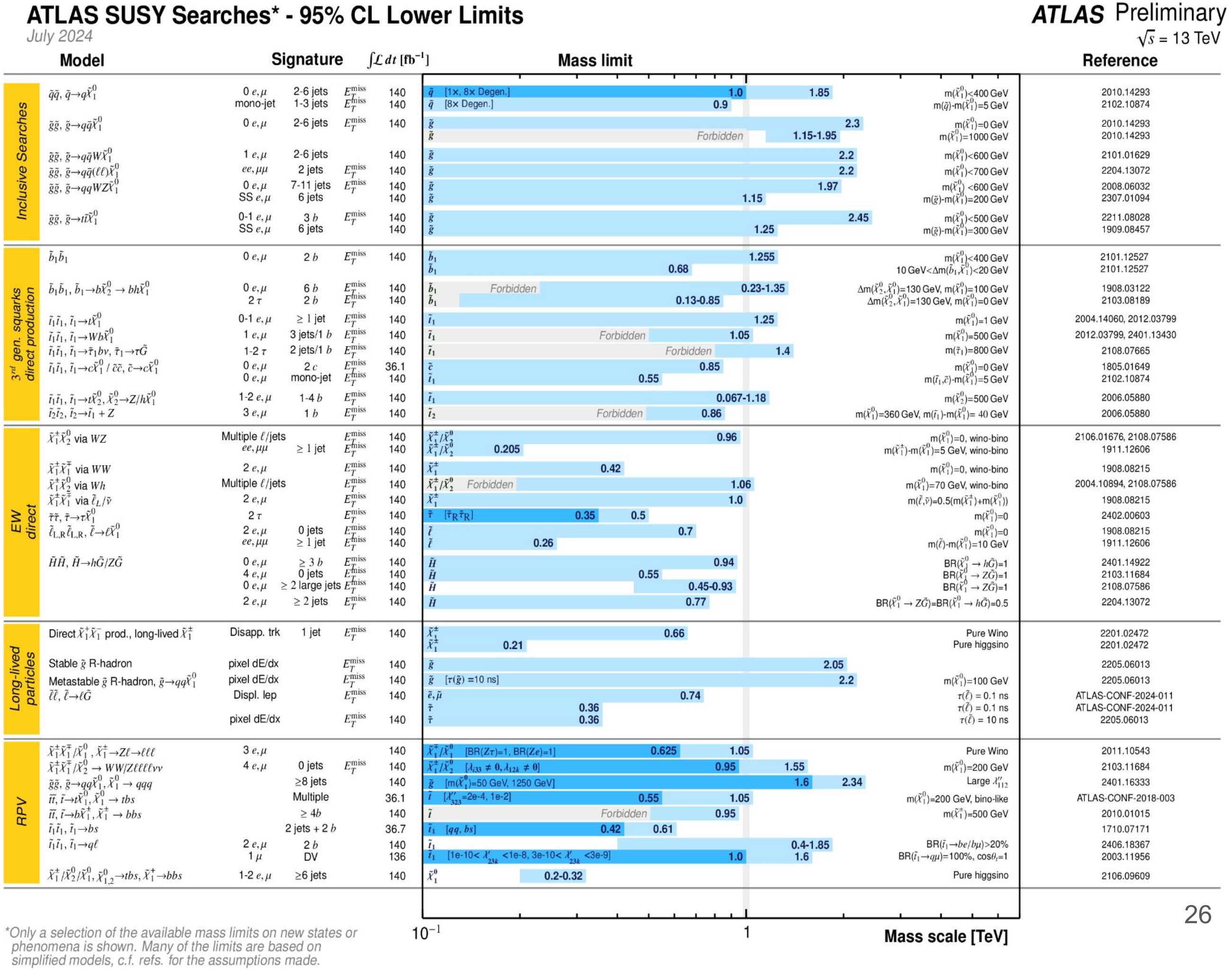
SUSY particle search

- Mass reach: near-maximal
- Displays the range in model space of search sensitivity.

Note: some analyses have additional assumptions about intermediate states → indicated by darker bands.

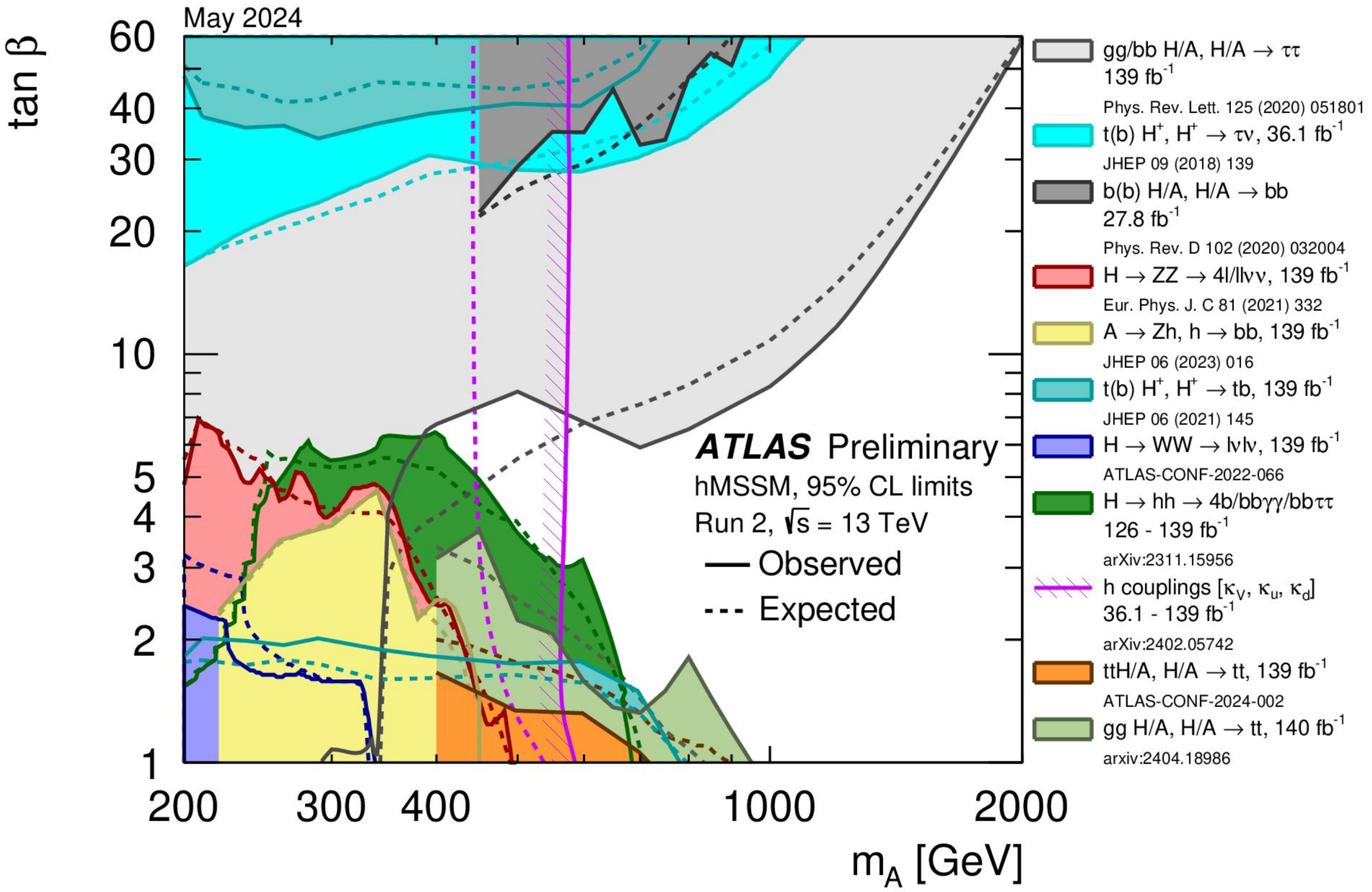
Long-lived sleptons: selectrons, smuons and staus with 0.3 ns lifetime are excluded, up to masses 740, 840 and 380 GeV, respectively

ATL-PHYS-PUB-2024-014

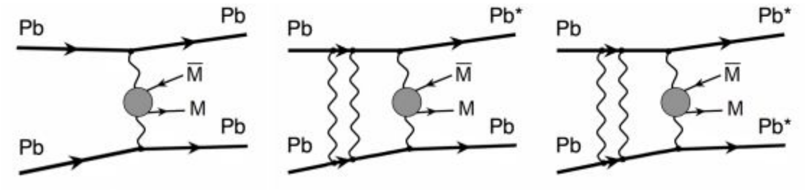


Searches for SUSY Higgses

ATLAS-CONF-2024–010



Search for monopoles



MoEDAL expt within CMS beam pipe: excluded magnetic monopoles with **mass < 80 GeV**

2402.15628

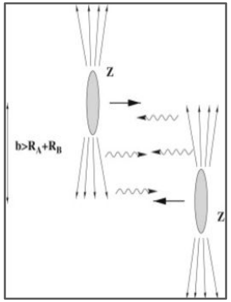
ATLAS ZDC: excluded mass < 120 GeV

2408.11035

- Heavy ion collisions at the LHC generate magnetic fields stronger than in neutron stars.

- Such intense fields could lead to the spontaneous creation of composite magnetic monopoles.

- Ultra peripheral collisions (UPC) in lead-lead provide quasi-real photons→ suitable to search magnetic monopole pair production.



- Soft photons emitted by one lead nucleus can excite the other, typically through the giant dipole resonance, → induce the emission of one or more neutrons, each of which carries, on average, the full per-nucleon beam energy.

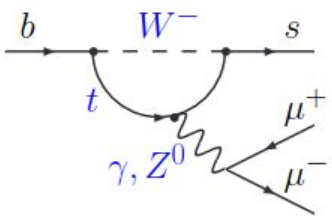
  ⇒ three distinct EM breakup topologies:

  $0n0n$ (no neutron emission)
  $0nXn$ (at least one neutron emitted by one nucleus)
  $XnXn$ (at least one neutron is emitted by each nucleus) → analysis uses only this data

- Use data at $\sqrt{s_{NN}}$ =5.36 TeV collected in 2023, with ZDC detector based software trigger

- Look at high pixel activity without associated reconstructed tracks, and low mass, low ET event

Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays at LHCb



- Last few years: several anomalies in various measurements in heavy flavour sector (quark transitions observed in B hadron decays).
- Main issue: lower rate for $b \to s\,\mu^+\mu^-$ in decays of B_s, B^0, B^+
- Interpretation not straightforward due to hadronic uncertainties in SM predictions (form-factors, decay constant etc.).
- Also non-perturbative effects. Including long-distance charm loops.

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i^{SM} + \Delta C_i^{NP})\mathcal{O}_i$$

Wilson coefficients (effective couplings) — Local operators

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha \,, \quad \textit{photon}$$

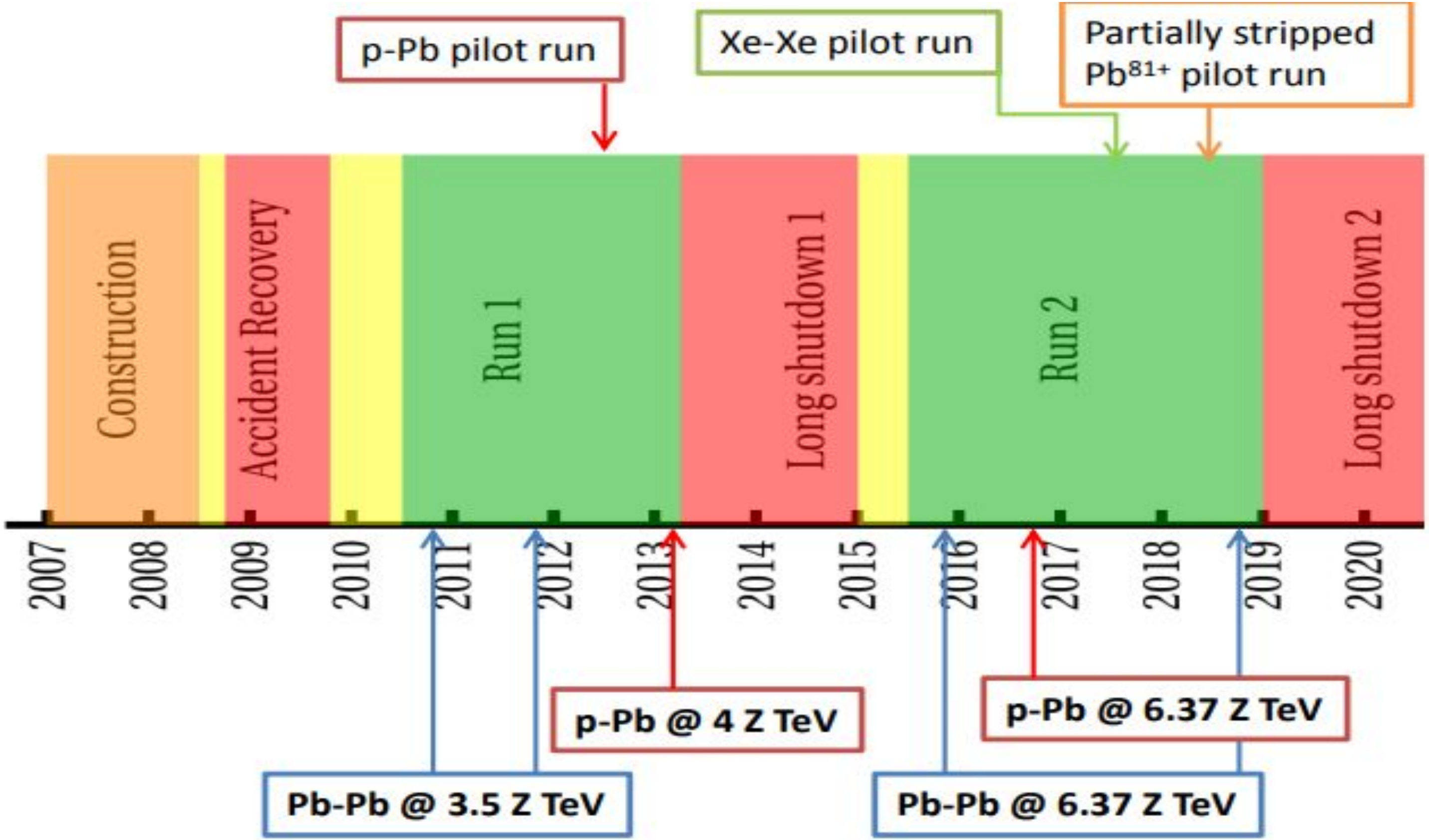
$$\mathcal{O}_{9V} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell}\gamma_\mu \ell \,, \quad \textit{vector}$$

$$\mathcal{O}_{10A} = \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell}\gamma_\mu \gamma_5 \ell \,, \quad \textit{axial-vector}$$

- First q^2-unbinned (model-dependent fit) amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- Estimation of non-local hadronic contributions (incl.charm loop) from data (with certain assumptions).
- **Result consistent with anomalies observed in $b \to s\,\mu^+\mu^-$ studies:** PRL 132 (2024) 13, 131801

  1.8σ in C_9 and 1.4σ global deviation in data from SM.

Heavy Ion collisions at the LHC



Typical instantaneous luminosity **L= 10^{27} cm^{-2}s^{-1}**

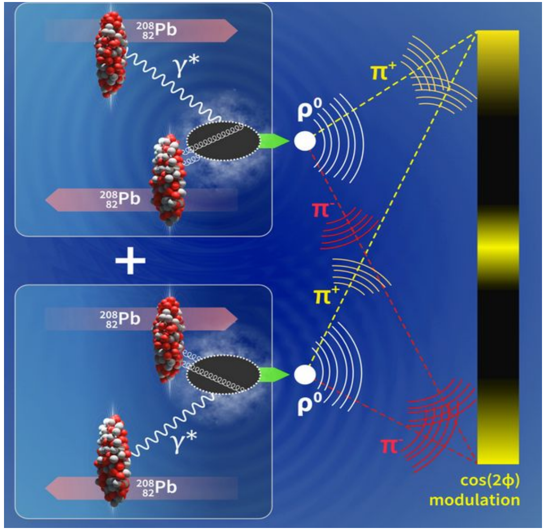
Run 3 operation: 2023
Pb-Pb @ 5.36 Z TeV
$\mathcal{L}$~ 2/nb

Expect ~1,5 /nb in 2024.

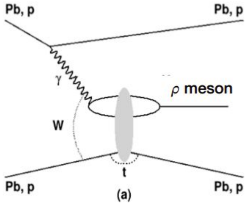
Additionally.
2x2.68 TeV p-p reference run equivalent of 6.8 Z TeV Pb-Pb

Double-slit experiment by ALICE

2405.14525



Demonstration of the wave nature of propagating particles at the femtometre scale



Study vector meson production in ultra-peripheral collisions

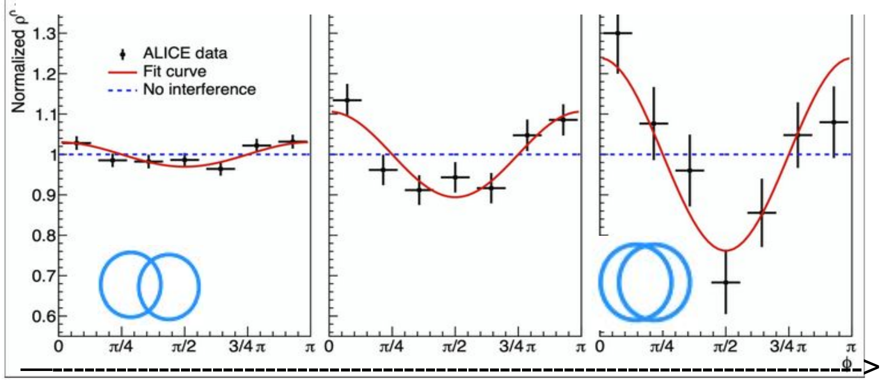
ρ^0 produced within or close to one of the two well-separated nuclei.

Decay rapidly: $\rho^0 \rightarrow \pi^+ \pi^-$, lifetime ~4.4* 10^{-24} s

Symmetric system: cannot determine which of the nuclei emits the photon and which emits the two gluons => interference pattern akin to that of a double-slit interferometer.

Azimuthal distribution of ρ^0 : cos(2φ) modulation

different values of the impact parameter→



→ smaller impact parameter

ϕ : angle between the two vectors formed by the sum and the difference of the transverse momenta of the pions.

The measured anisotropy corresponds to the amplitude of the cos(2ϕ) modulation

High Luminosity avatar of LHC: HL-LHC

Most likely,Run 3 will continue during 2026

- $\sqrt{s}$ = 14 TeV, ultimate L = **7.5X10^{34} cm^{-2}s^{-1}** (PU ~200)
- Expected total data vol. $\mathcal{L}$~ 4000 fb^{-1}
- **20 times more data** compared to current volume, in about **20 years time.**
- to be collected with **new avatars of the ATLAS and CMS detectors.**
- ***India playing significant role in the upgrade of several subsystems of CMS detector.***

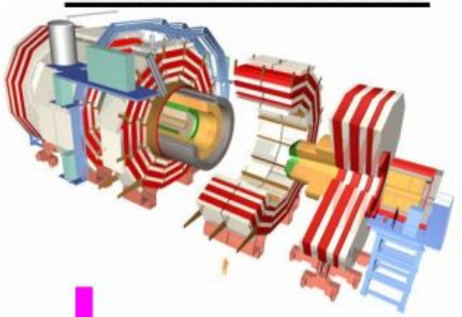
HL-LHC operation: 2029 —2040s

With more time achieve:
- More powerful analysis techniques
- More accurate theoretical tools
- Other "technological" breakthroughs (computing, AI, …)
- **New ideas!**

With more data study :
- Rare processes
- (Multi-) differential measurements
- Explore corners of phase space inaccessible with limited data volume

CMS experiment: Trigger Overview

CMS detectors



1) L1 readout
(~20 MHz)

2) L1 accept
(~110 kHz)

L1 trigger

Level-1 Trigger (L1T)

implemented in custom-designed electronics: high-end FPGAs, system-on-chip, high throughput data links.

Uses next generation control infrastructure based on Advanced Telecommunication Architecture (ATCA)

3) DAQ - Full event readout
~110 kHz x ~1 MB/event

HLT farm

4) HLT accept
~5 kHz(*)
(~1 MB/ev)
(*) including parking

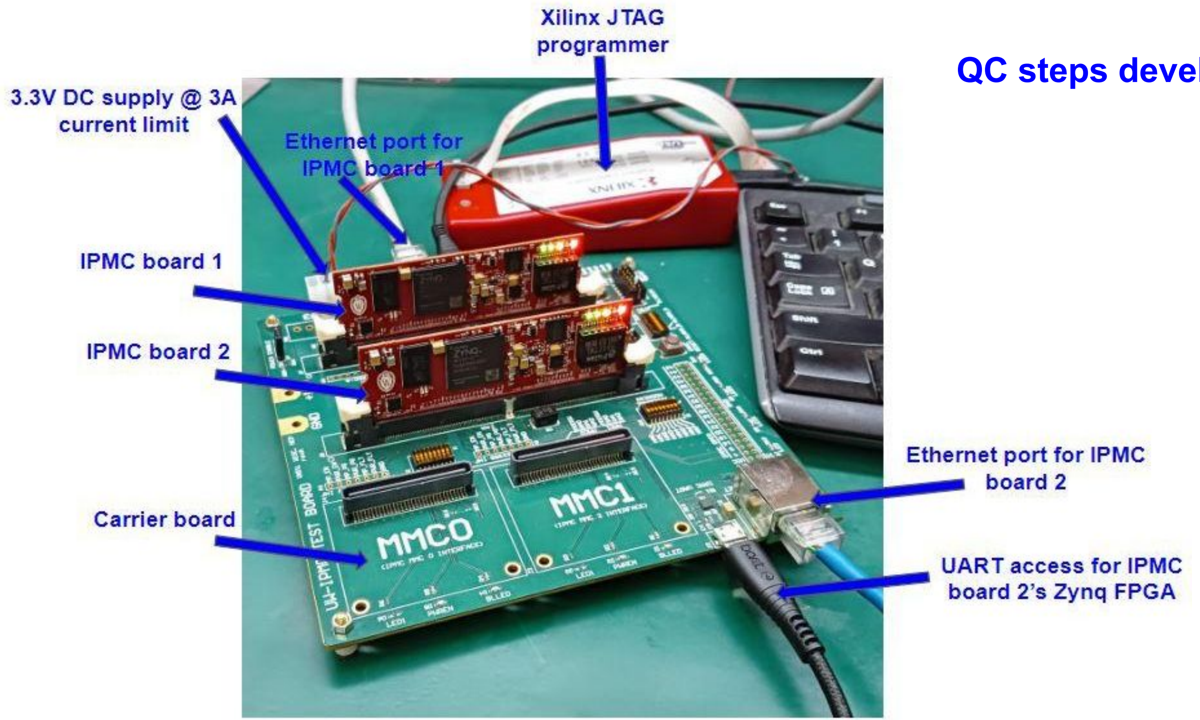
CERN Tier-0

GRID

5) offline reconstruction

Indian contribution to hardware for L1 trigger upgrade

- Indian responsibility includes: **hardware delivery + FPGA firmware development**
- Mezzanine trigger boards: IPMC + ESM
- Fabrication in the Indian industry, quality control at TIFR.



QC steps developed, tools designed in TIFR

Hardware checks:

- Visual inspection of the edge / dimm connector under high resolution lens.
- LEDs powered on the board.

Key performance checks:

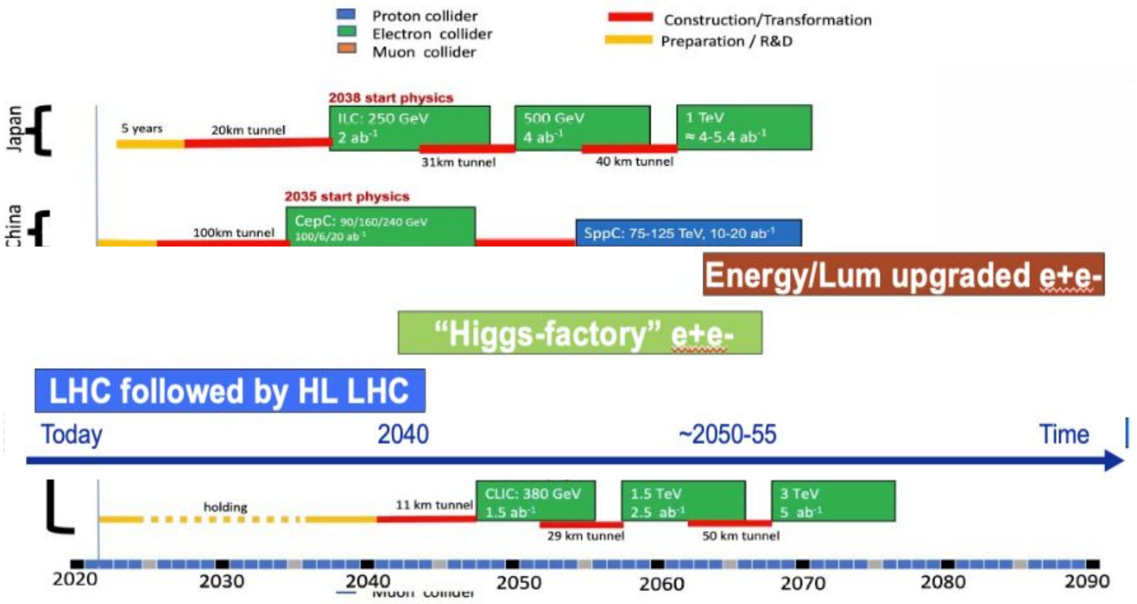
- Flash the bitstream through the Xilinx SDK tool.
- Boot image load into the flash using FTP.
- Run python software suite to check pin connectivity.

Next generation colliders on the plate

JHEP 01 (2020) 139

Data ⇒ significant gap between electroweak (EW) scale and the scale of New Physics (NP)
→ use precision Higgs measurements as a tool to probe NP indirectly.

1% uncertainty in Higgs properties ⇒ 1 TeV scale of NP causing such a deviation ⇒ probe 10 TeV region
→ go for exploratory hadron collider: 100 TeV FCC-hh!



In foreseeable future, mass-produce Higgs bosons in clean environment.

e+e- collider in about 15 -20 years time?

But Higgs factory is limited by lumi: can't probe rare H decays.
Branching fractions vary over many orders of magnitude unlike for Z.

Summary

Presented *glimpses on a very limited selection from a plethora* of very interesting analyses carried out in recent times.

Run 3 data crucial to resolve some of the current disagreements between measurements and predictions; eg., cross sections for ttW, tWZ, tttt etc..

No direct evidence for physics beyond SM as yet.

However direct and indirect searches will continue.

More data allow us to look carefully in difficult corners of phasespace.

Need to study processes which are suppressed / forbidden in SM since *New Physics* interactions potentially enhance the rate providing access to higher mass scales in terms of virtual contribution.

New Physics can also effectively modify the couplings in various types of interactions

⇒ effective field theory (EFT) interpretation describes possible pattern of deviations introduced by new physics & also constrain the deviations.--> *did not discuss at all due to time constraint.*

The diversity of analyses indicates that the mining of interesting physics at the LHC will continue for next several decades.

LHC will always remain exciting and interesting!

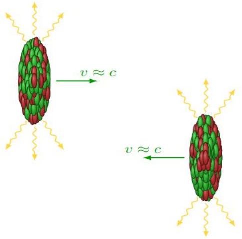
Stay tuned!

Thank you!

Backup

EW results in two-photon collisions

RPP 87 (2024) 107801



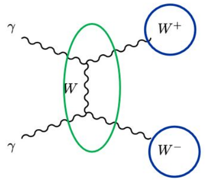
Photons can be simultaneously emitted by charged particles during p-p/ p-Pb/ Pb-Pb collisions

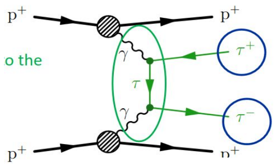
Cross section ~ Z^4 ⇒ large rate of diphoton production in heavy ion runs.

At very high masses of $m_{\gamma\gamma}$, diffracted protons can be tagged by the forward detectors ⇒ study diffractive production of WW / $\tau\tau$

Utilize excellent tracking capability of experiments

CMS: ~ 30% of the 1 mm window around the beamspot not contain any pileup track.





- 2 back-to-back objects
- No hadronic activity close to the di-W/τ vertex
- Ntracks = 0, pT > 0.5 GeV, $|\eta| < 2$

First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions by CMS

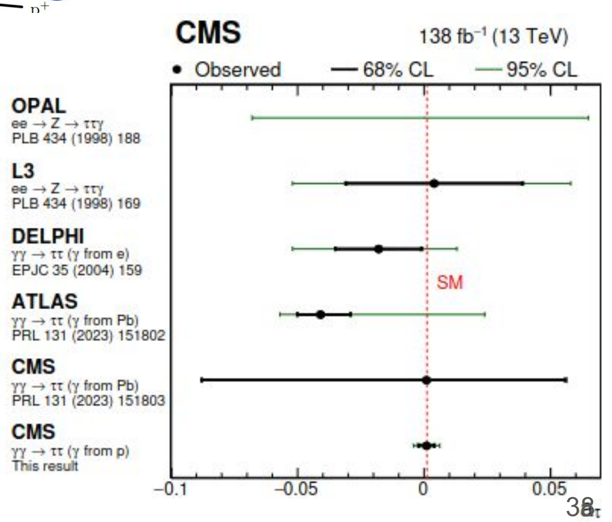
σ_{fid}(obs) = $11.2^{+3.1}_{-2.4}$ (syst)$^{+2.2}_{-2.1}$ (stat) fb, Significance 5.3 s.d. (6.5 exp.)

Constraints on the anomalous electromagnetic moments of τ:

$a_\tau = 0.0009^{+0.0032}_{-0.0031}$

Dirac a_τ: 0.0
Schwinger (SM) a_τ = 0.00116(9)

Dipole moment: $-1.7 < d_\tau < 1.7 \times 10^{-17}$ e cm.



Exclusive production of high mass diphoton at 13 TeV

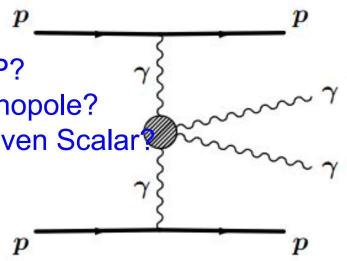
Also called light-by-light (LbyL) scattering .

Protons tagged in TOTEM precision proton spectrometer

Anomalous 4γ interaction in dim-8 EFT:

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu},$$

ζ_i =0 in SM

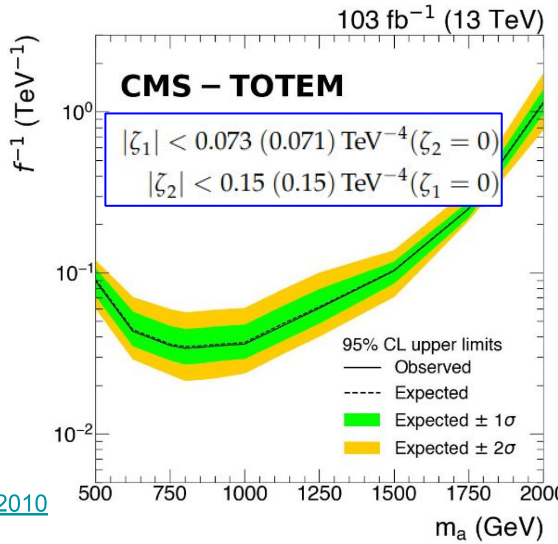


Study differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}\left(s^2 + t^2 + st\right)^2 \left[48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2\right]$$

Only 1 event found in relevant phase-space, expected background: 1.1 event

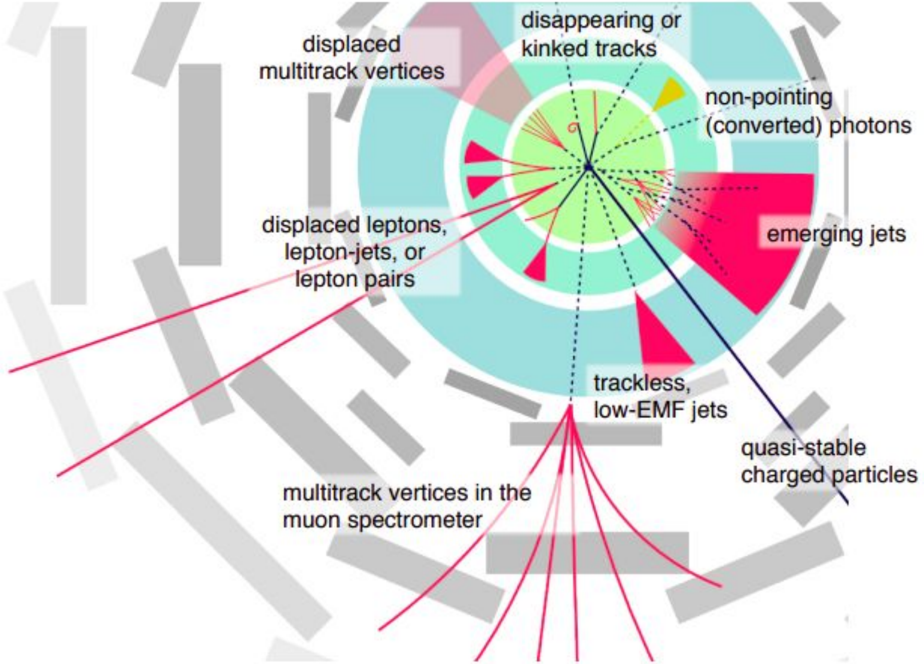
CMS σ(pp → pγγp) < 0.61 fb
for p_T^{γ} > 100 GeV, $|\eta^{\gamma}|$ < 2.5, $m_{\gamma\gamma}$ > 350 GeV
fractional proton energy loss of 0.035 < ξp < 0.150(0.180) for the +z (-z) arm of PPS.



Limits on axion-like particle (ALP) production in s-channel $\gamma\gamma \to a \to \gamma\gamma$
Coupling: $f^{-1} \geq 0.03$ to 1 TeV^{-1} for m_a = 500–2000 GeV

PRD 110 (2024) 012010

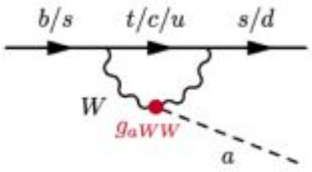
Search for long-lived particles



Possible candidates to explain neutrino mass,dark matter candidate

Unconventional signatures: require special reconstruction method, analysis strategy to identify displaced vertices.

Low mass neutral long-lived particles, including axion-like particles.
Heavy neutral leptons
Massive charged lon-lived particles
Emerging jets



Signature: a $\rightarrow \gamma\gamma$
high energy deposit in electromagnetic calorimeter without any tracking
Background: neutrino interaction with detector material

FASER experiment situated 500m from ATLAS collision point, aligned with beam collision axis.--> sensitive to long-lived axion-like-particles (ALPs) produced with (TeV) boost along the beam line and decaying inside the detector into photon pairs

Phenomenological MSSM interpretation

CMS-PAS-SUS-24-004

13 TeV data L = 138 /fb -> comprehensive analysis.

Generic realization of the MSSM with Lagrangian parameters defined at the supersymmetry (SUSY) scale O(1 TeV).
→ captures most of the observable features of the general R-parity conserving weak scale MSSM
→ allows more general conclusions to be drawn about SUSY compared with simplified models.

A global Bayesian analysis incorporates data from CMS as well as pre-CMS measuremnetsand indirect probes, estimating the marginalized posterior probability densities of model parameters, masses
→observables based on the CMS results.

The CMS data highly suppress the phase space with colored superpartner masses below 1 TeV, considerably constrain natural SUSY and the electroweak sector, and weakly constrain SUSY dark matter.

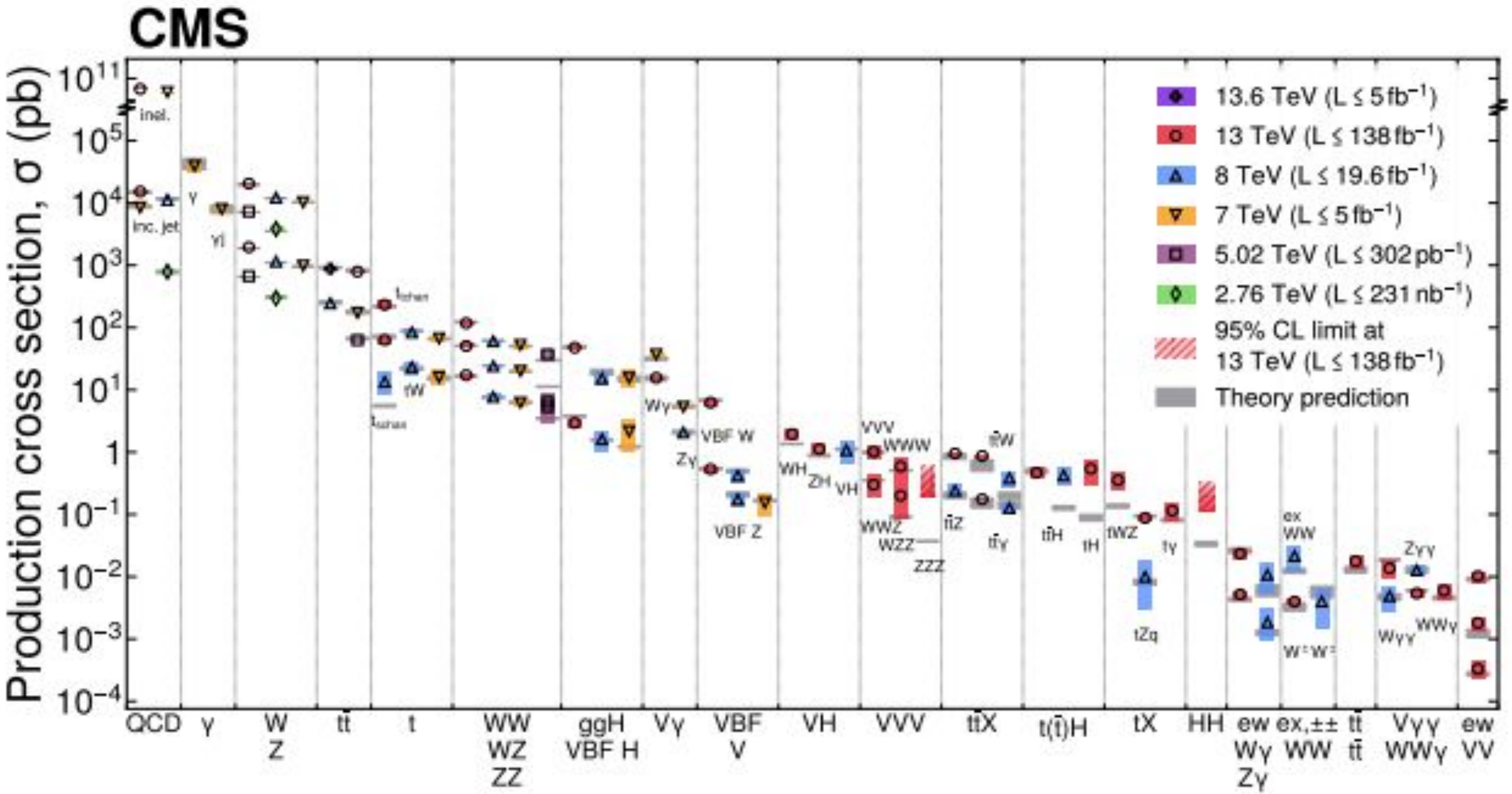
- Significant phase space remains consistent with experimental data even at low LSP mass
- The lightest chargino, second-lightest neutralino, gluino, and top squark are heavily disfavored for masses less than around 200, 200, 700, and 1100 GeV, respectively.

- Considerable MSSM phase space capable of solving the small hierarchy problem or explaining the known DM relic density remain non-excluded by the CMS searches.

- only a very small number of models that are consistent with low-fine tuning and the relic density remain viable. Most such models correspond to a roughly pure Higgsino-like dark matter candidate.

Cross sections: from millibarn to femtobarn

2405.18661
Submitted to Phys.Rep.



Physics model for W production and decay

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower