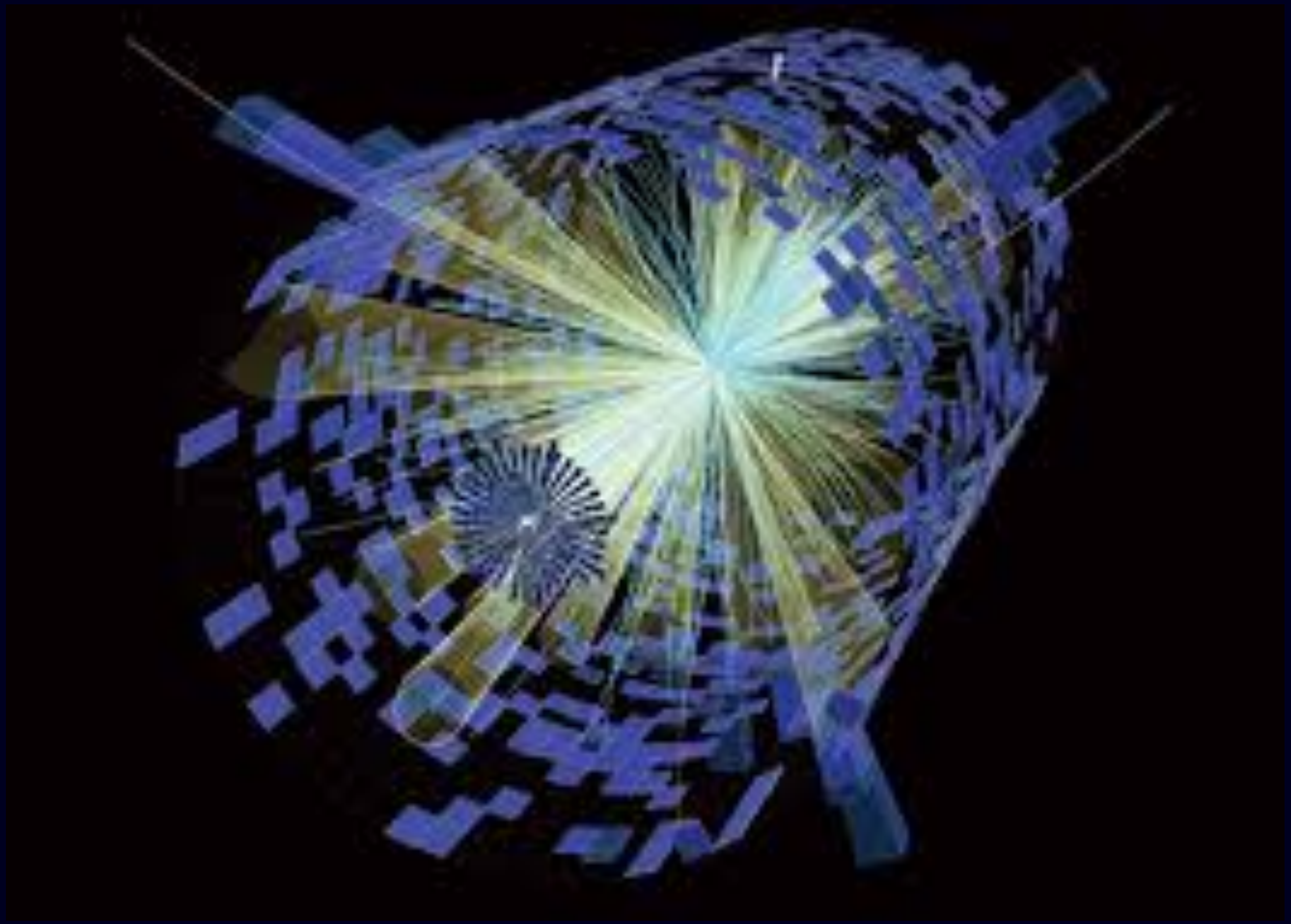
CMS Run 3 highlights and HL-LHC prospects



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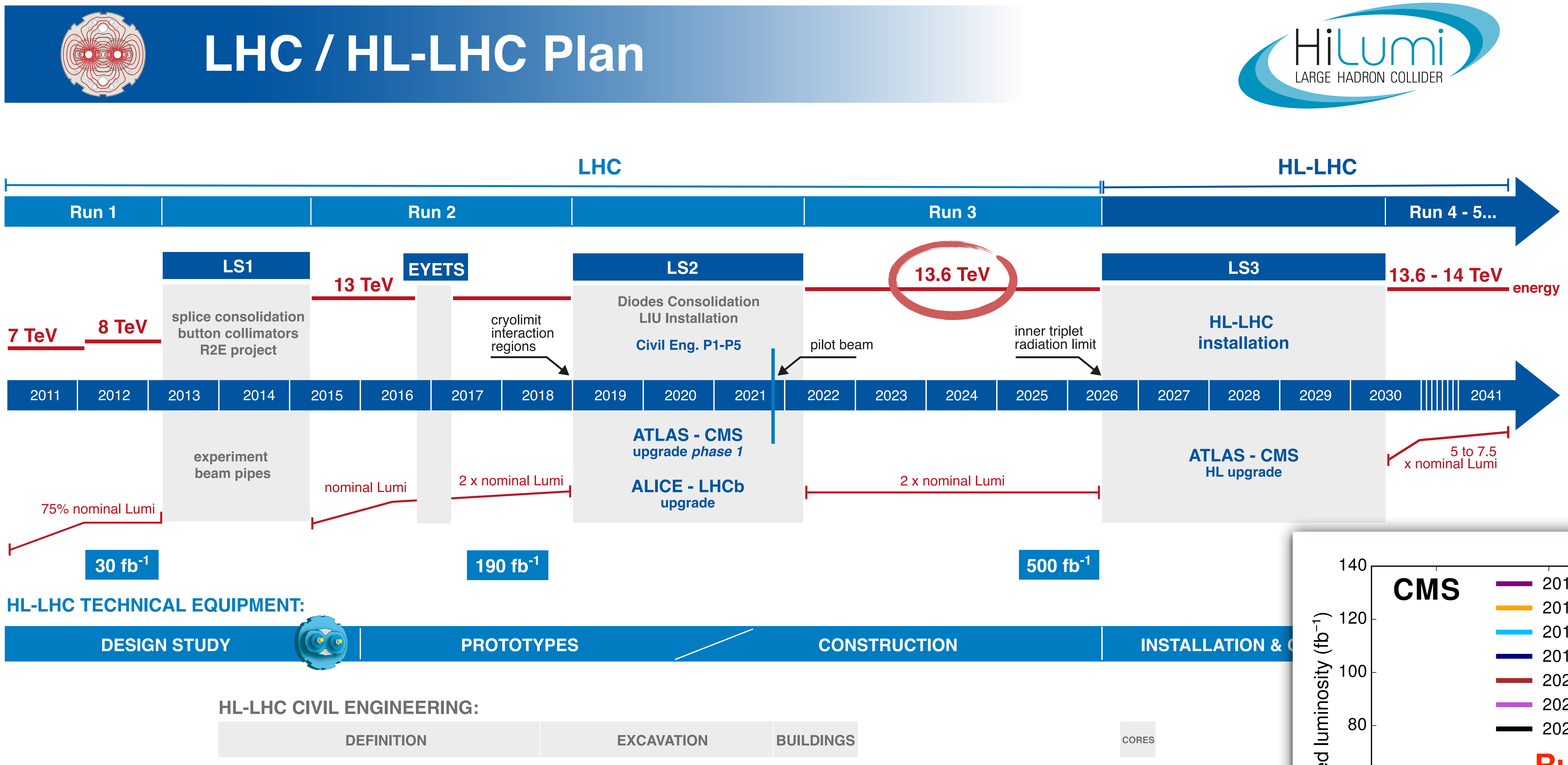
Introduction

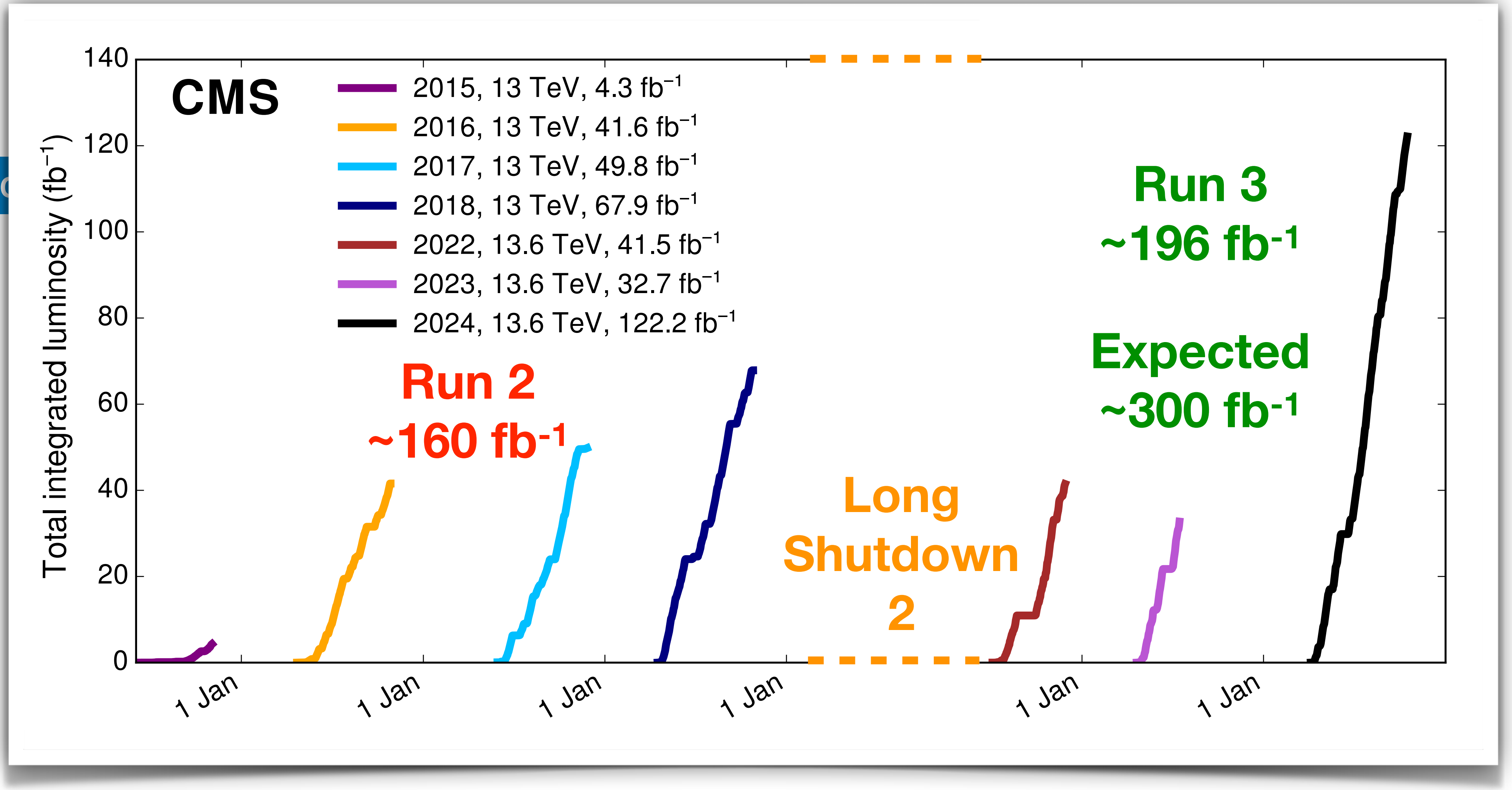
Very broad and evolving topic: here a personal selection of Run 3 results and HL-LHC projections

- More Run 3 results expected at upcoming Winter conferences.
  - Highlights on novel techniques enhancing sensitivity
- New and updated HL-LHC projections to be released soon for input to the European Strategy

LHC Run 3 data taking



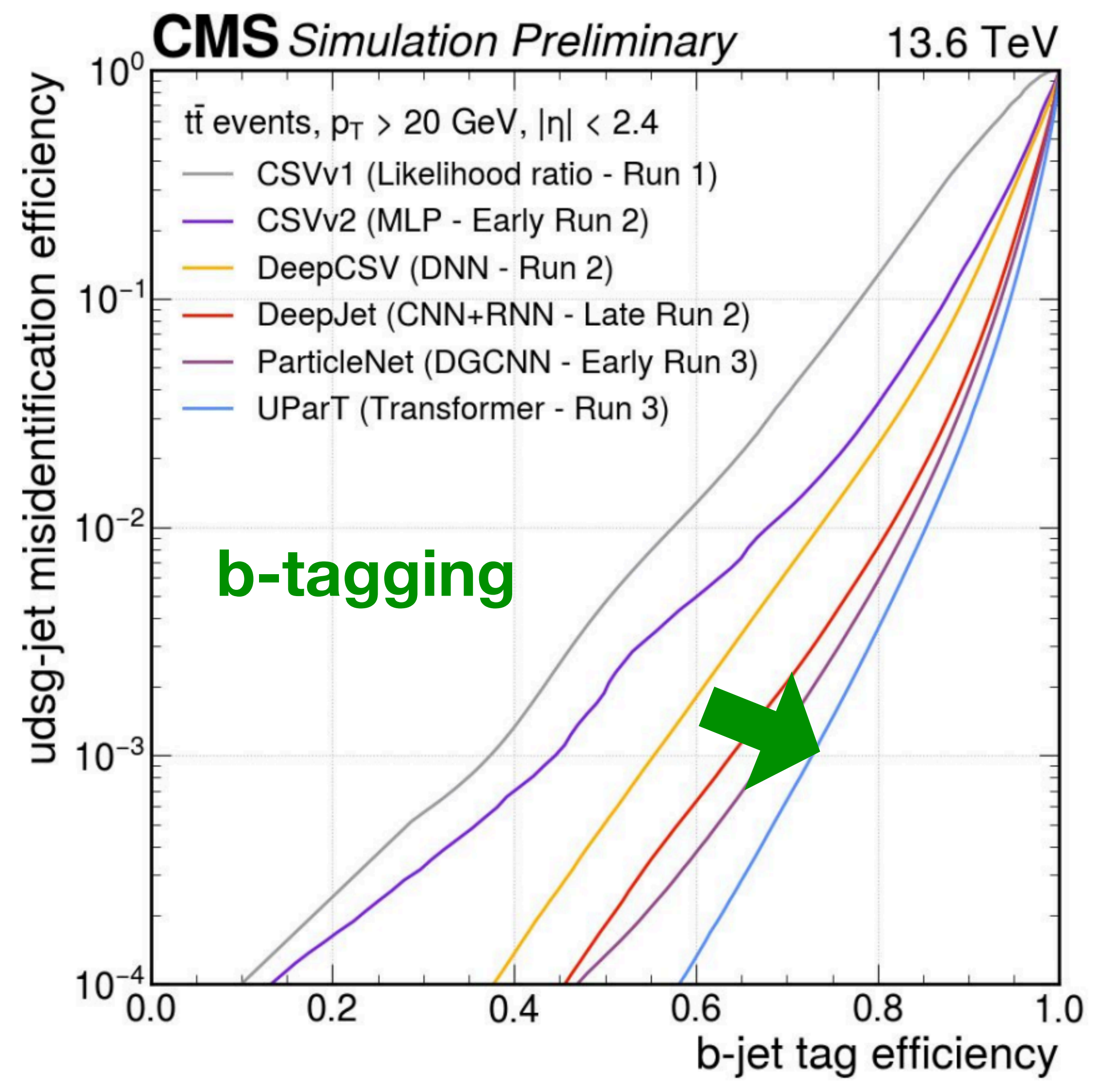
LHC Run 3 extended until mid 2026

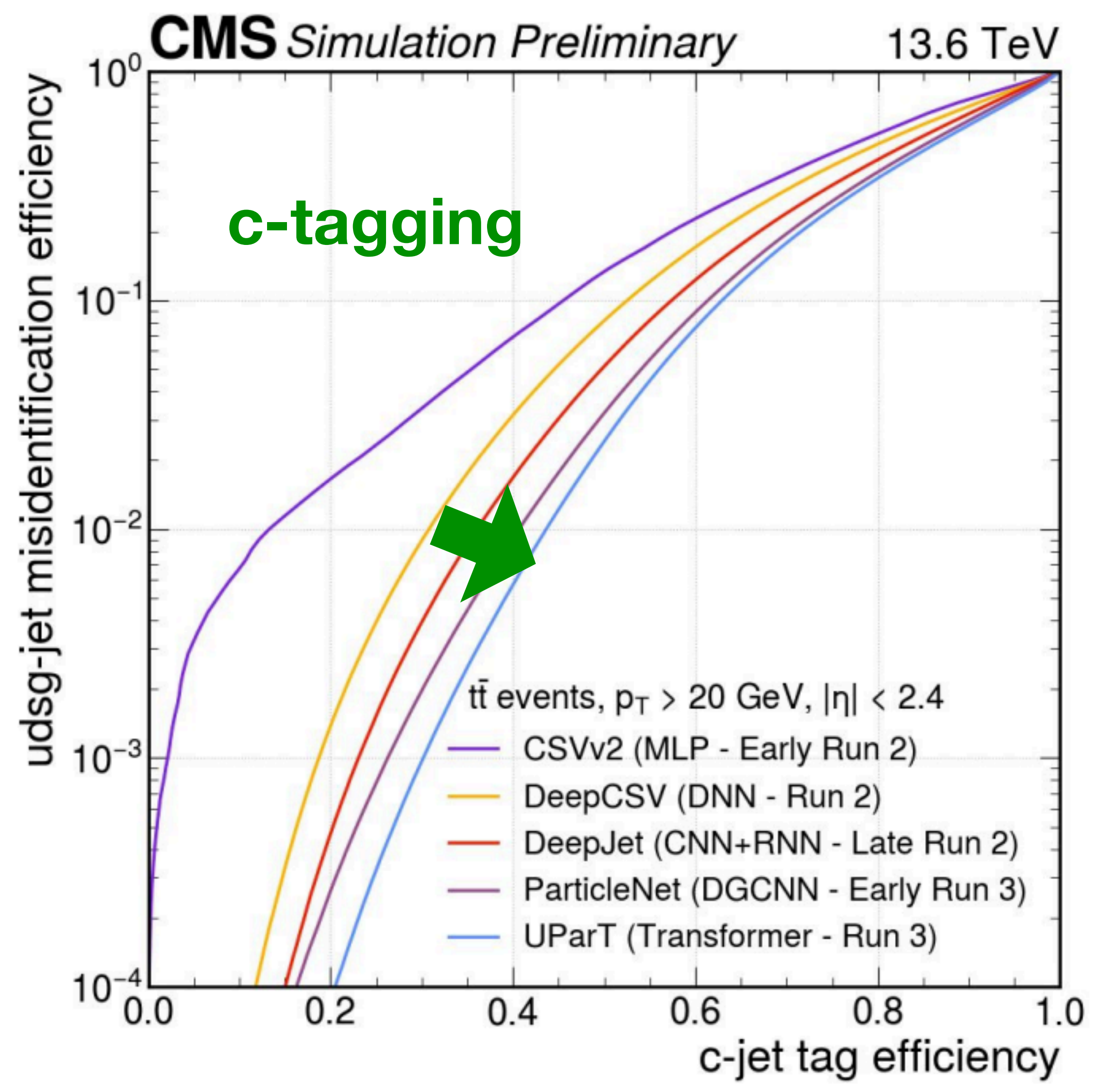


What changed with respect to Run 2

- **Increased statistics**
  - Many Run 2 analyses statistically limited, e.g. heavy $H/A \to \tau\tau$ limited at high mass
- **Increase in $\sqrt{s}$** from 13 to 13.6 TeV
- **Improved data-taking strategy** (Parking, Scouting and unconventional online data selection)
- **Improvement in identification algorithms using ML**
  - e.g **b-tagging** light jet rejection **improved by a factor 59 wrt Run 2**
  - Also improved performance for c-tagging

Large improvements expected in Run 3 and new results are underway

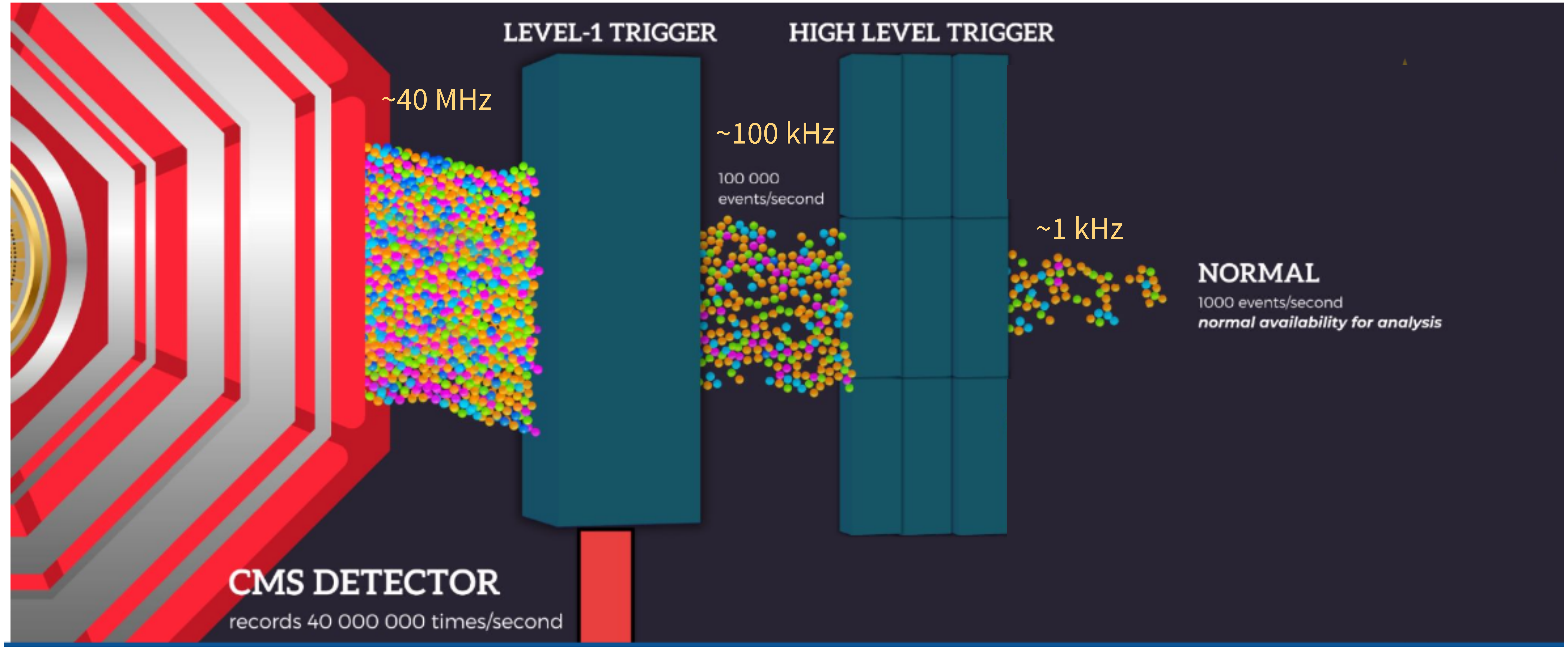




Online Data Selection: Trigger

CMS online data selection (Trigger) has two levels:

- Hardware based Level 1 Trigger (L1): 40 MHz → 100 kHz
- Software based High Level Trigger (L2): 100 kHz → **1 kHz** ➡ **Limited capability to process and store data reflects in reduced output**

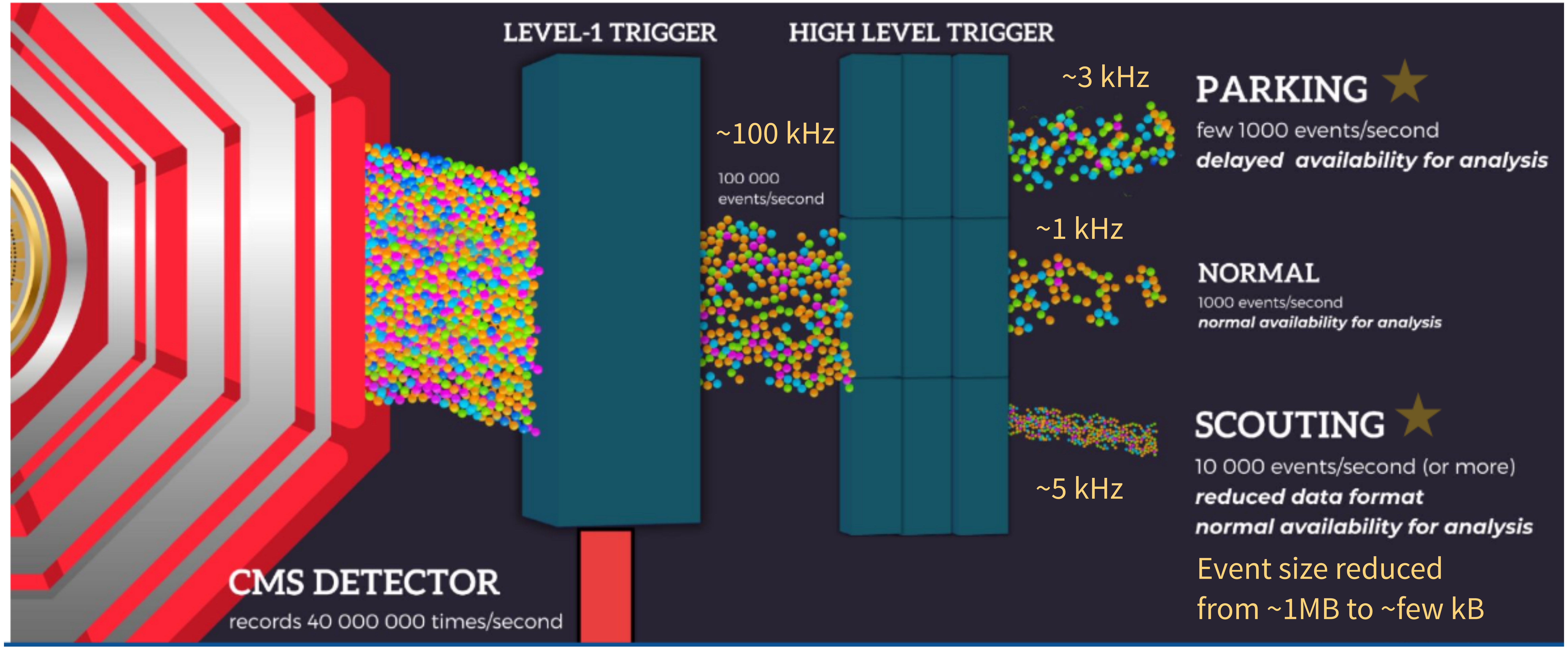


High threshold on physics observables limit data rate, but also the sensitivity reach

Alternative data acquisition strategies

Alternative strategies based on data-size reduction, processing delay and non-conventional triggers

- **Data Scouting**: Save only high-level features reconstructed online - reduced event size
- **Data Parking:** Save full event infos for later offline reconstruction - delayed processing
- **Dedicated Long Lived Particle triggers:** implemented at L1



DataFlow for a typical 2018 data-taking scenario

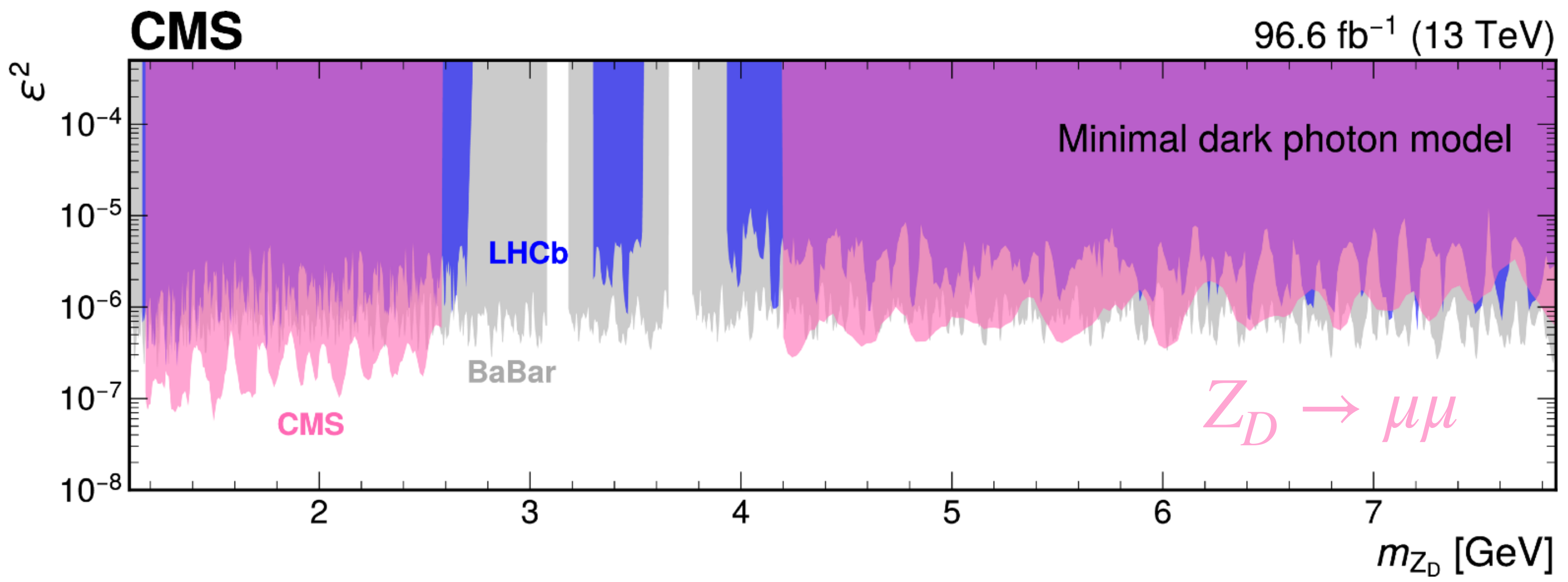
Parking data stream: ~ 3 kHz, ~ 2000 MB/s	Delayed offline reconstruction
Standard data stream: ~ 1 kHz, ~ 1000 MB/s	Prompt offline reconstruction
Scouting data stream: ~ 5 kHz, ~ 40 MB/s	No offline reconstruction

Data Scouting

CMS-HIG-21-007

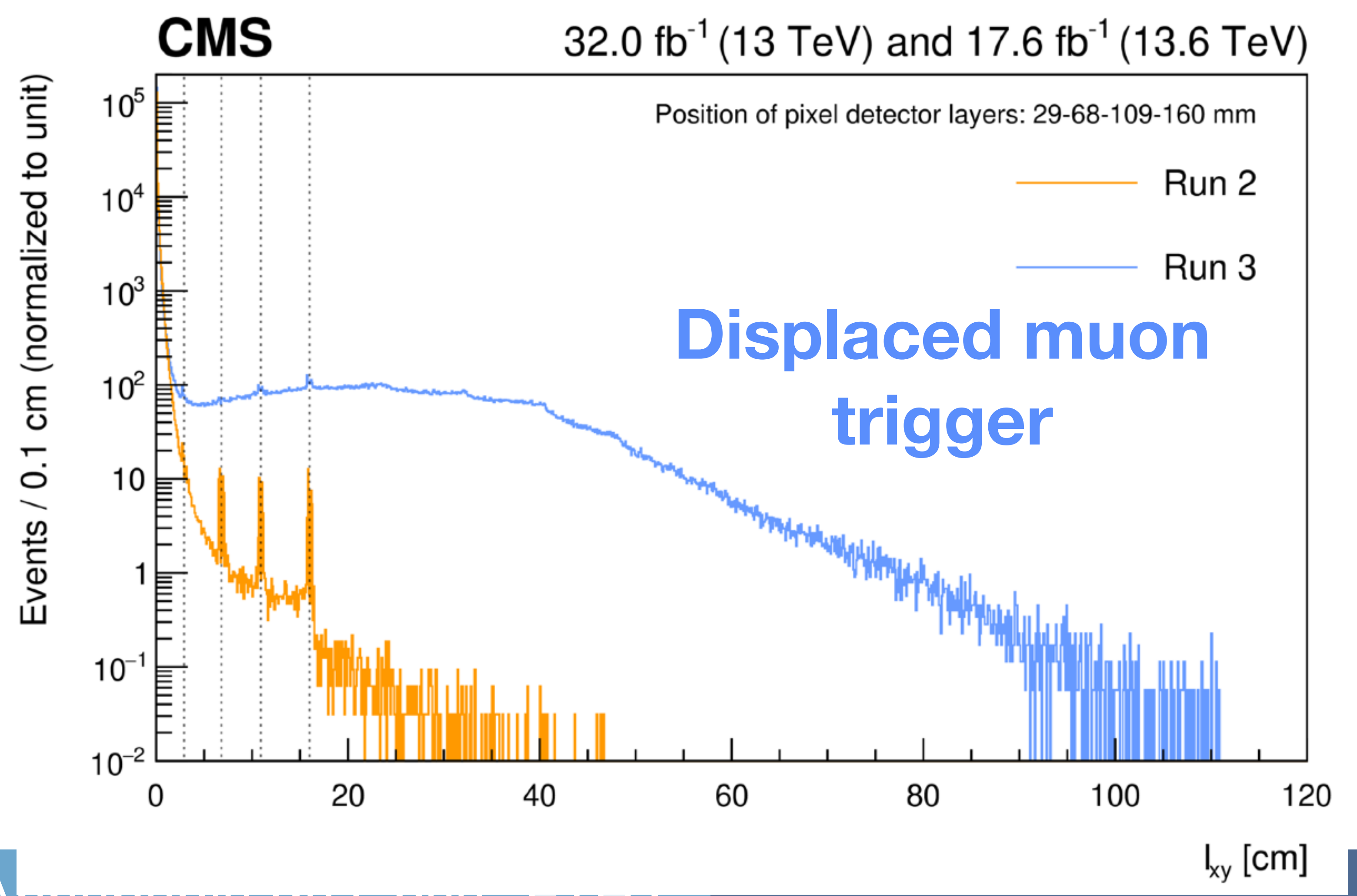
Analyses suffering from tight trigger thresholds benefit the most from scouting e.g dark-photon Run 2 analysis competitive with LHCb

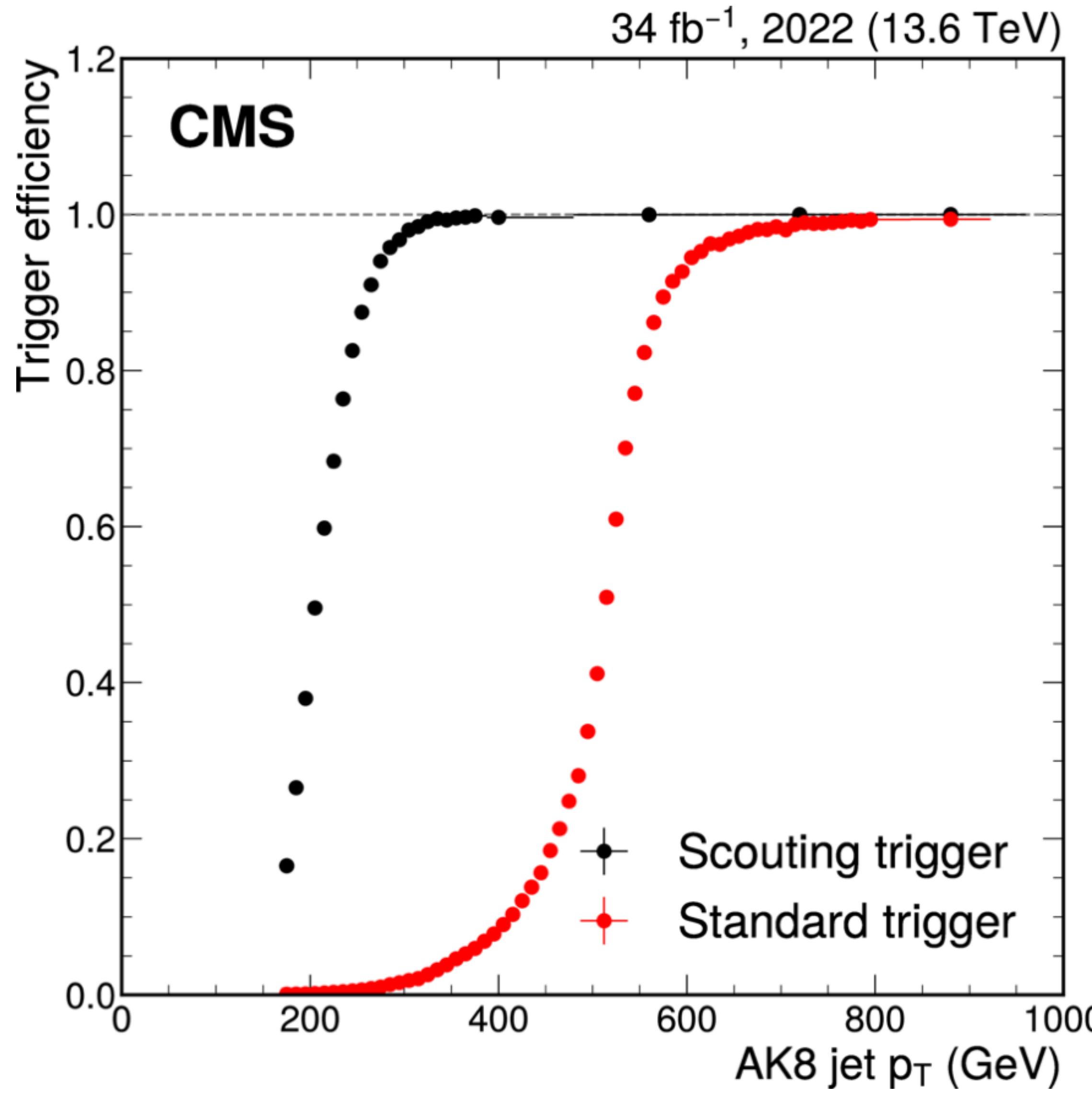
- Muon p_T threshold lowered from (20, 15) GeV to (4,4) GeV

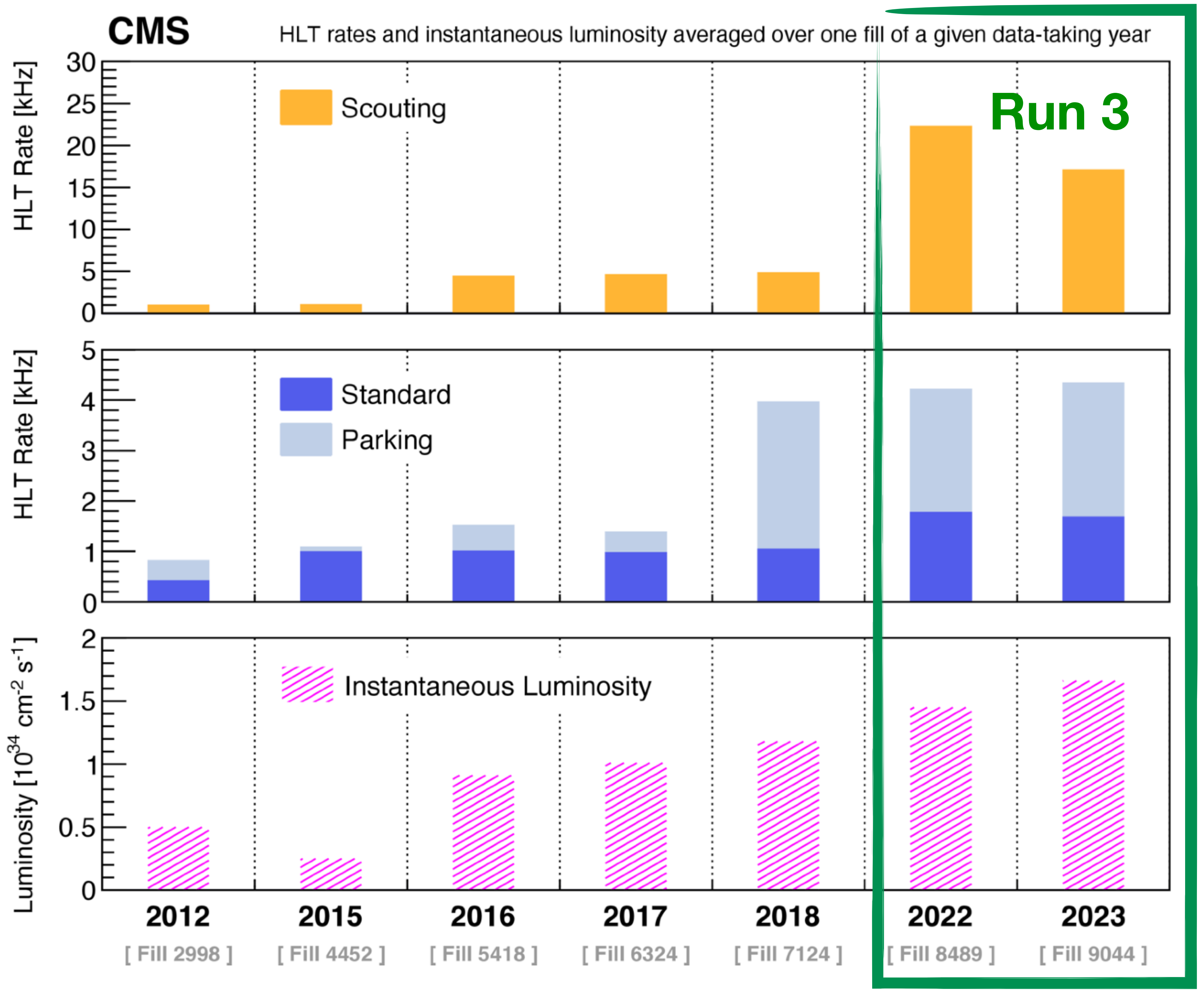


Run 3 evolution:

- Store all available HLT objects (in Run 2 only jets and muons)
- Increased rates (22kHz)
- Improved online object tracking performance
- Improved displaced muon triggers



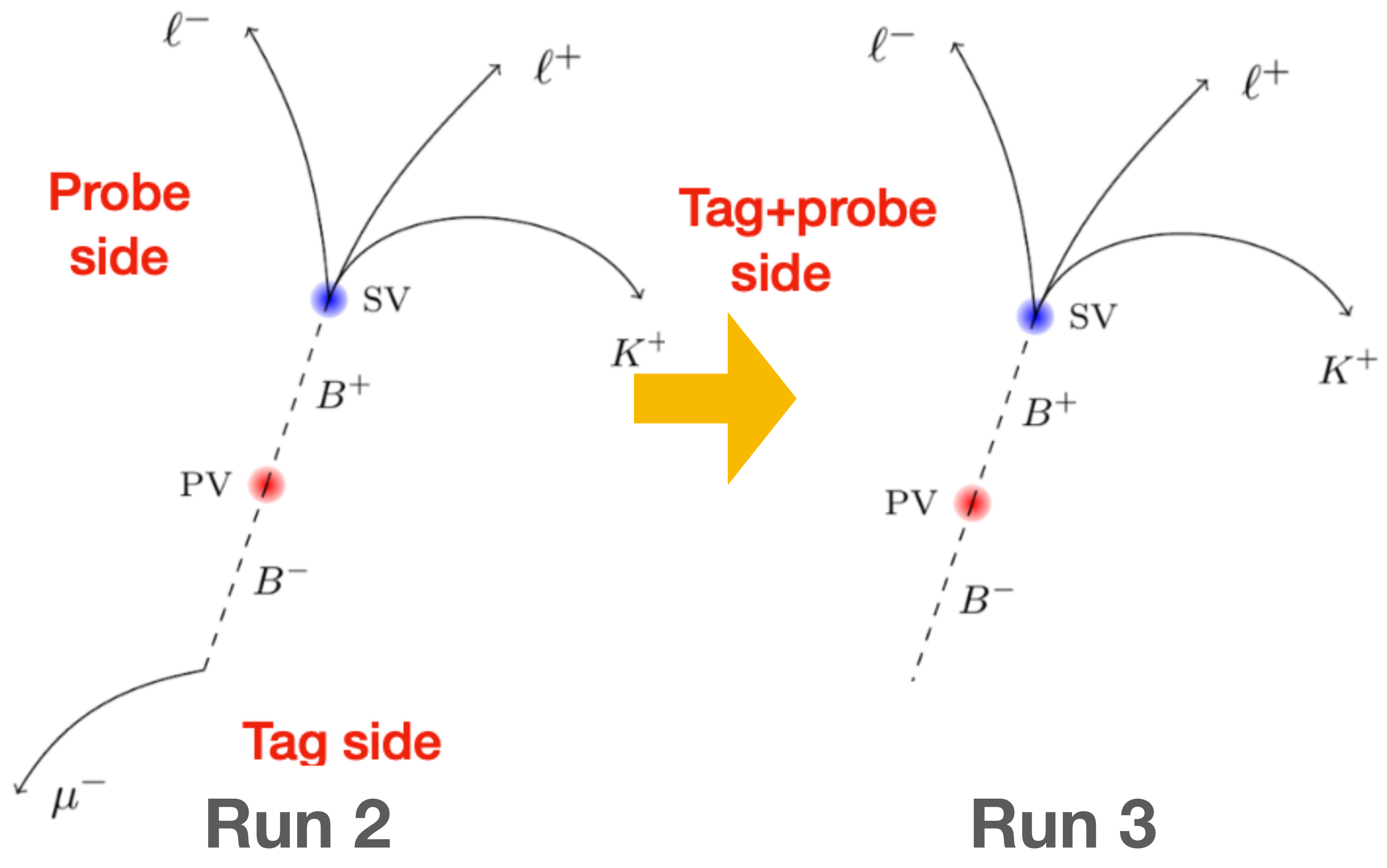


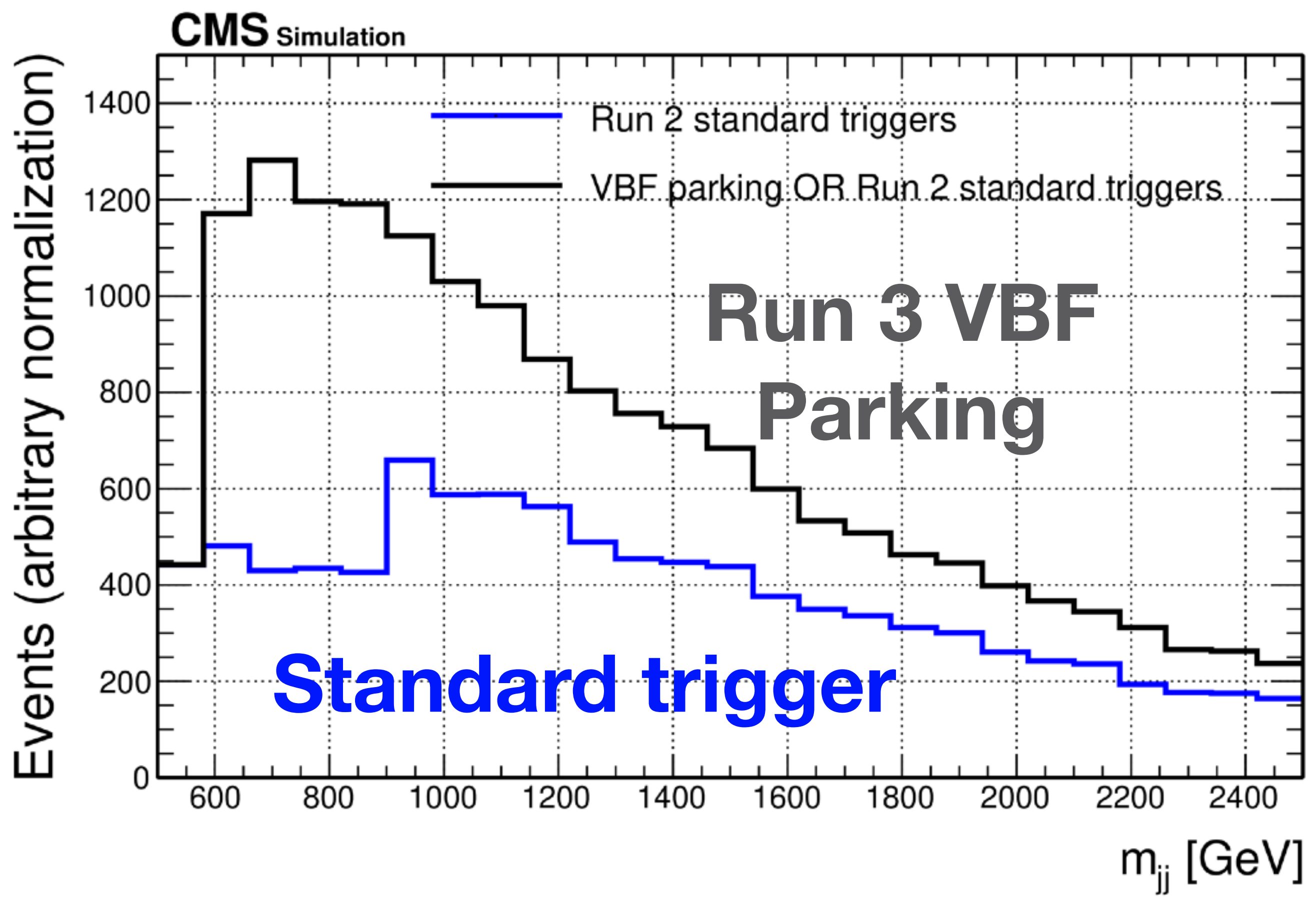


Data Parking

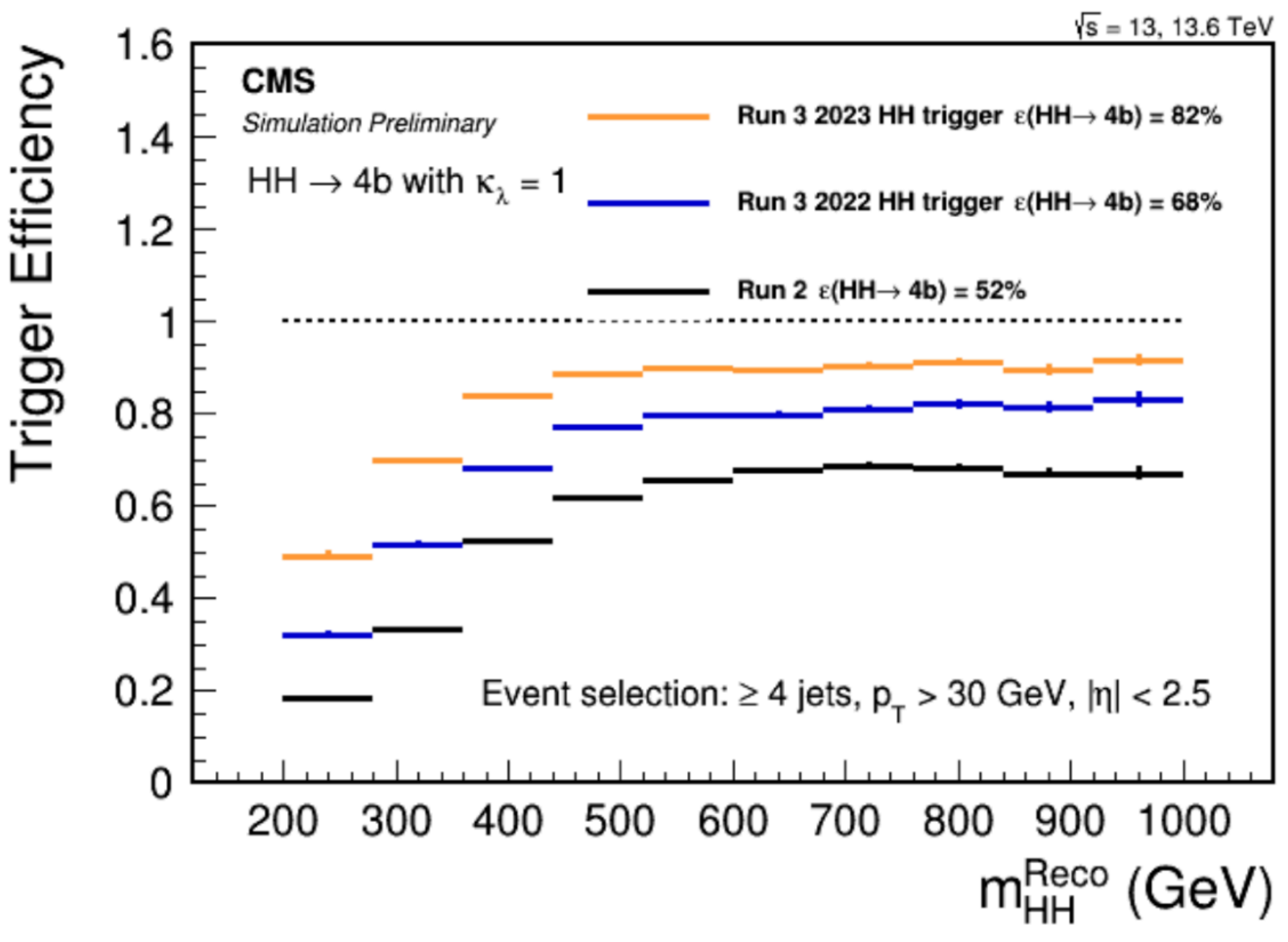
Run 2 Data Parking mainly used for BPhysics

- In 2018 CMS collected **10 billions unbiased B hadrons decays**
- **key physics results:** R_K measurement and $B \to K^*\mu^+\mu^-$ differential BR, but also HNL in b hadron decays
- Trigger strategy based on **displaced muon** from other B Hadron decays





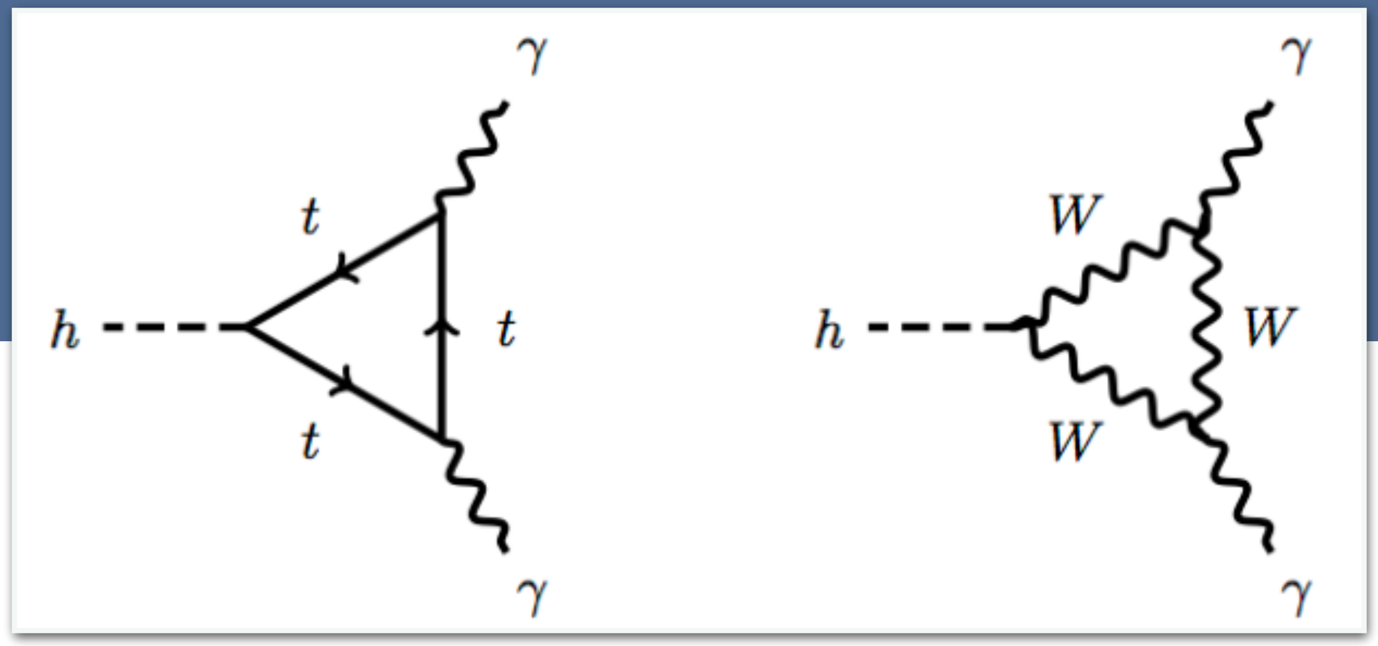
HH→4b Parking



Run 3 evolution

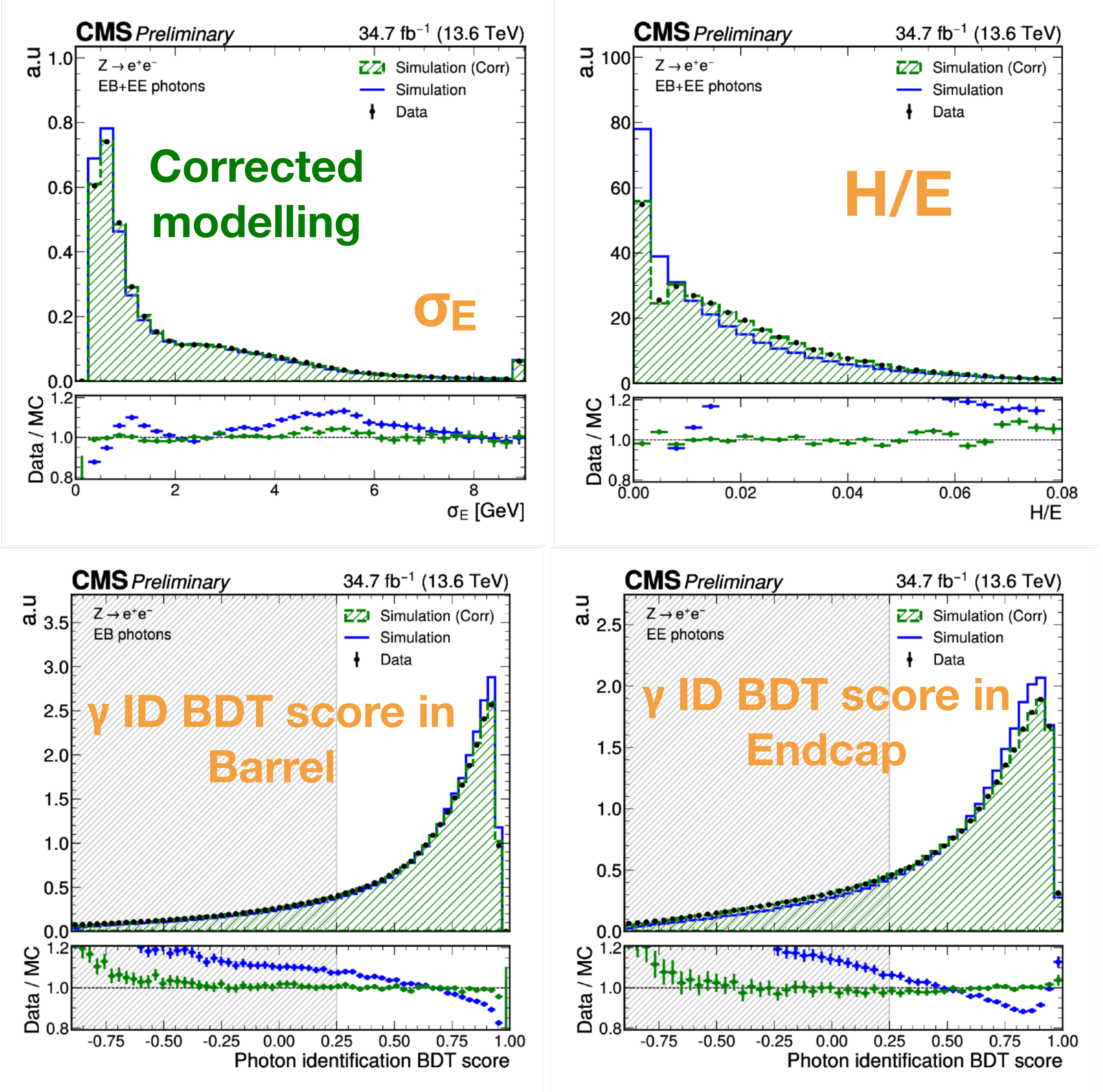
- Output data increased to **~ 4 kHz**
- Data recording targeting **VBF Higgs production, HH→4b and LLP jets** in addition to B physics
- **New strategy for Bphysics**: triggering directly one electrons (increase B-> K*e+e- acceptance)
- New parking have **looser selection criteria at HLT**

H→γγ Measurement



Measurement of fiducial inclusive and differential production cross sections

- Very clean final state topology, although low BR (~0.23%). Invariant mass can be precisely reconstructed
- Overall similar strategy than full Run 2 result
- 2022 data used: **34.7 fb^{-1}**
- **Improved energy measurement** (better than **1%**in the barrel) and **estimate of per-photon energy resolution**
- **Improved modelling of photon identification variables** using normalising flows - agreement **down to 1.7%** (2.0%) in Barrel (Endcap) - reduced uncertainties



CMS-HIG-23-014

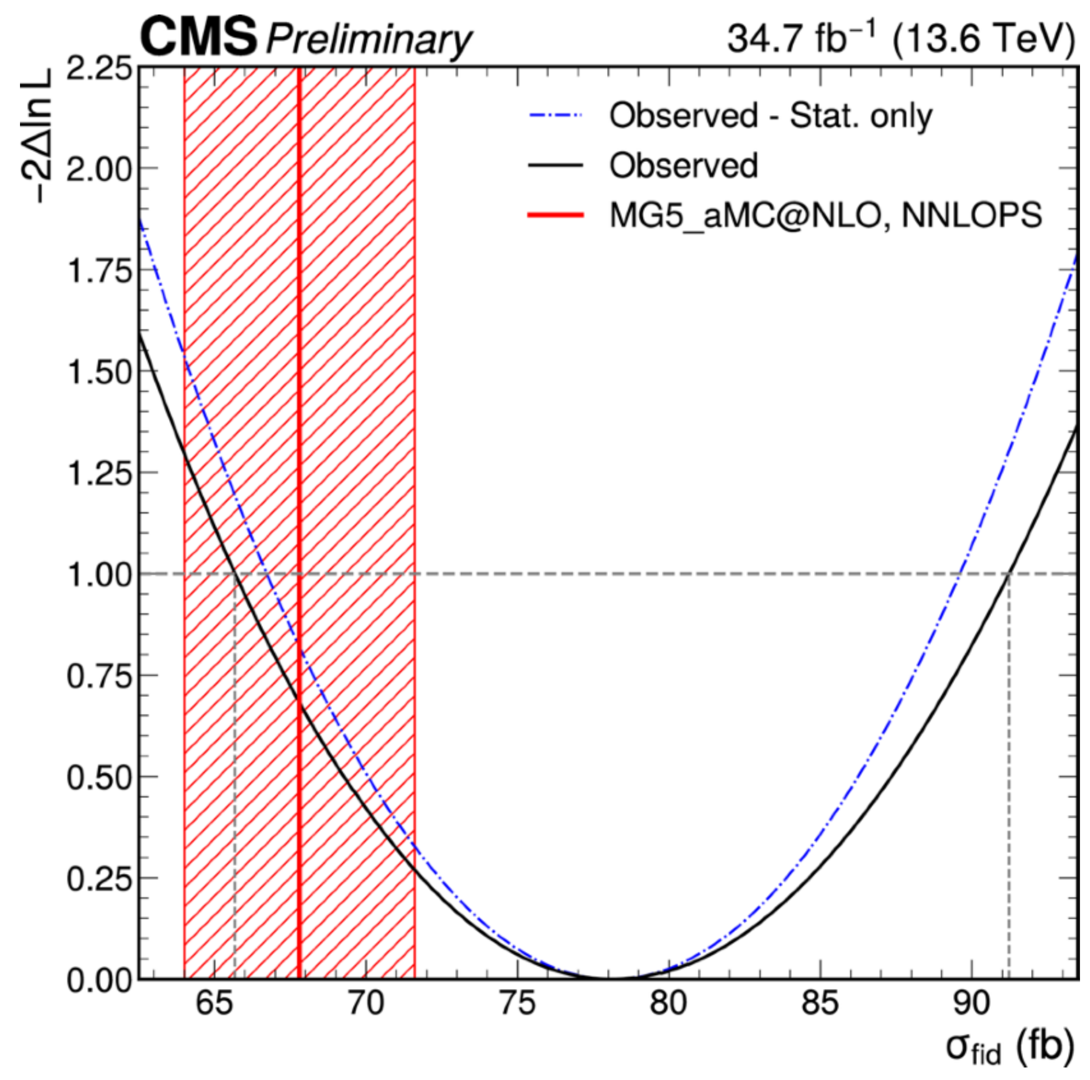
H→γγ Measurement

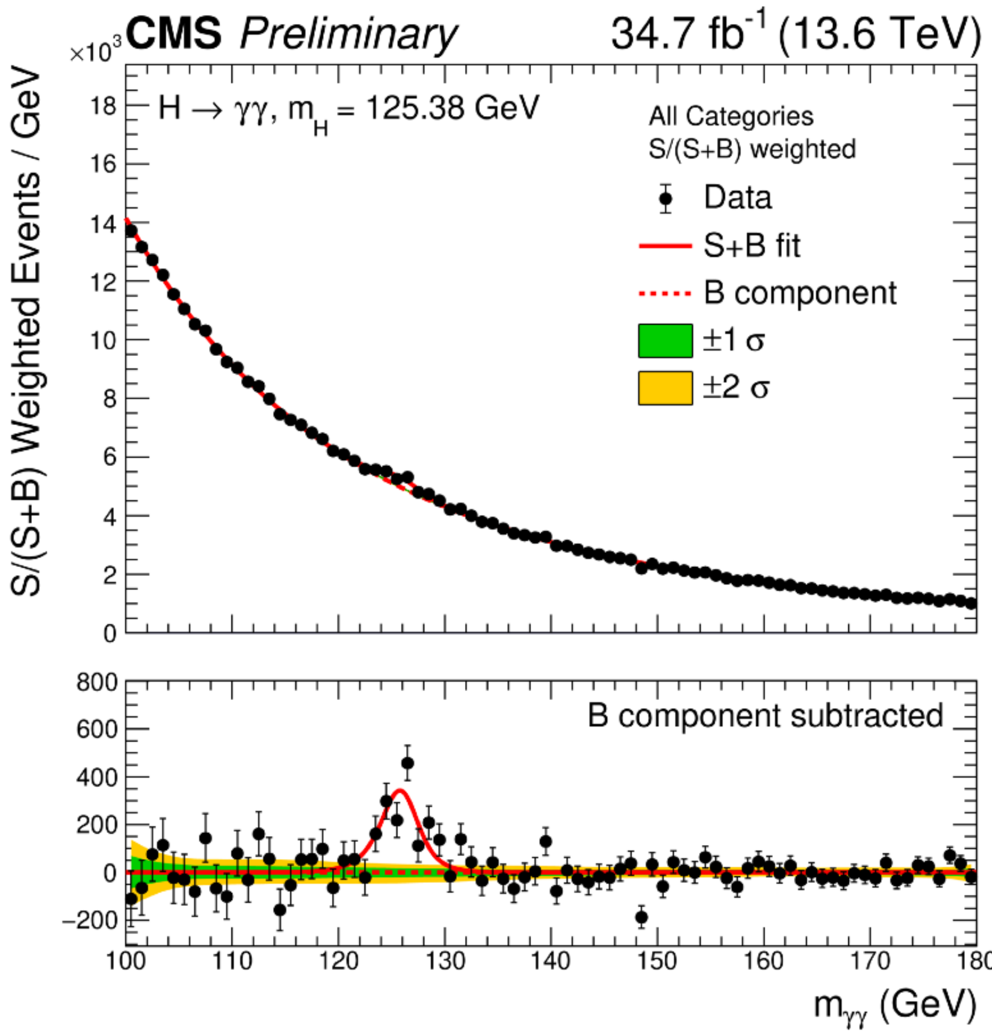
Results in agreement with SM expectation

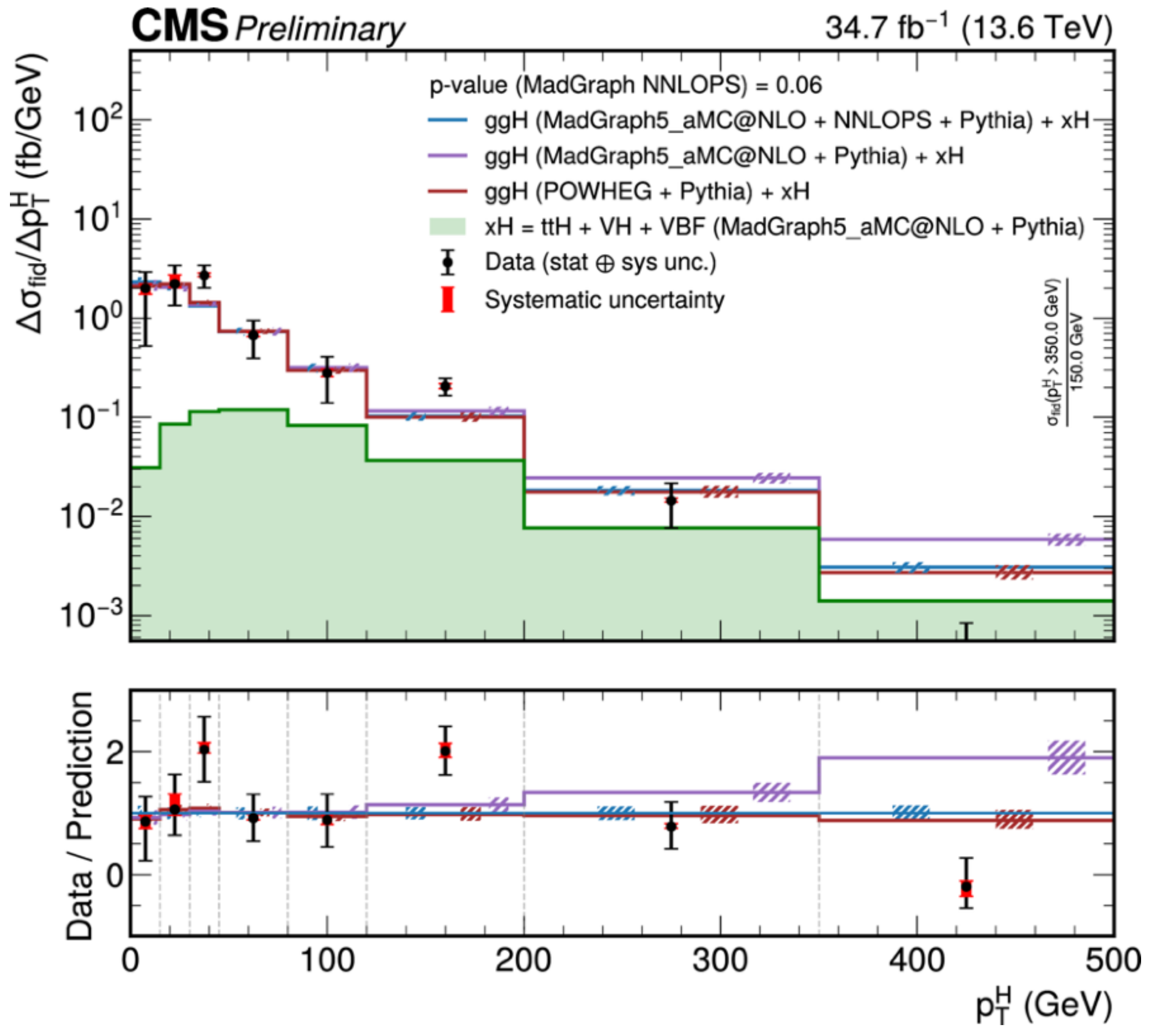
$$\sigma_{fid} = 78 \pm 11(\text{stat})^{+6}_{-5}(\text{syst}) = 78^{+13}_{-12}\text{fb}$$

- **Differential results** provided as a function of $\mathbf{p_T^H}$, $\mathbf{|y_H|}$, $\mathbf{N_{jets}}$
- **Results dominated by the statistical uncertainties**
- Within systematics, **photon energy scale and resolution dominate**
- Room for improvement with more Run 3 data

Systematic uncertainty	Magnitude
Photon energy scale and resolution group	$+5.8\%/-4.9\%$
Category migration from energy resolution	$+3.5\%/-3.9\%$
Integrated luminosity	$\pm1.4\%$
Photon preselection efficiency	$\pm1.4\%$
Energy scale non-linearity	$+0.8\%/-1.6\%$
Photon identification efficiency	$\pm1.0\%$
Pileup reweighting	$\pm0.8\%$







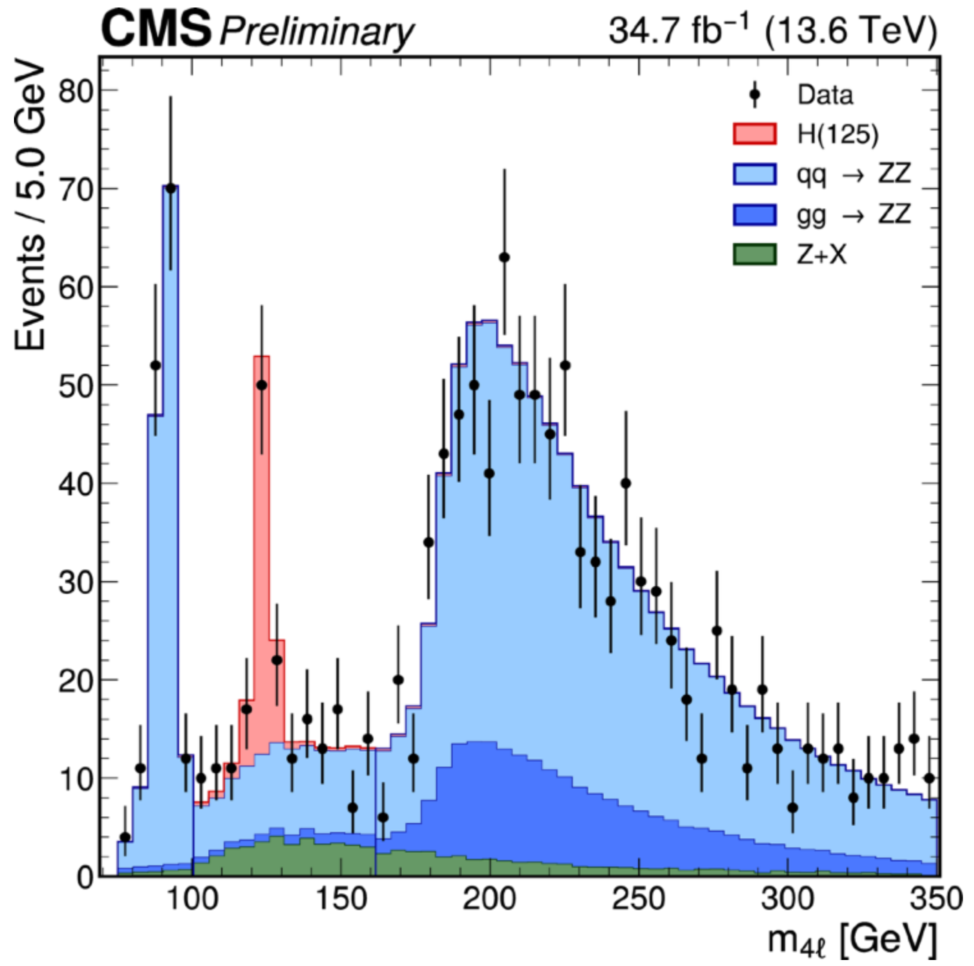
Fiducial phase space
$\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}}/m_{\gamma\gamma} > 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$
$I < 10$ GeV
$\lvert\eta\rvert < 2.5$

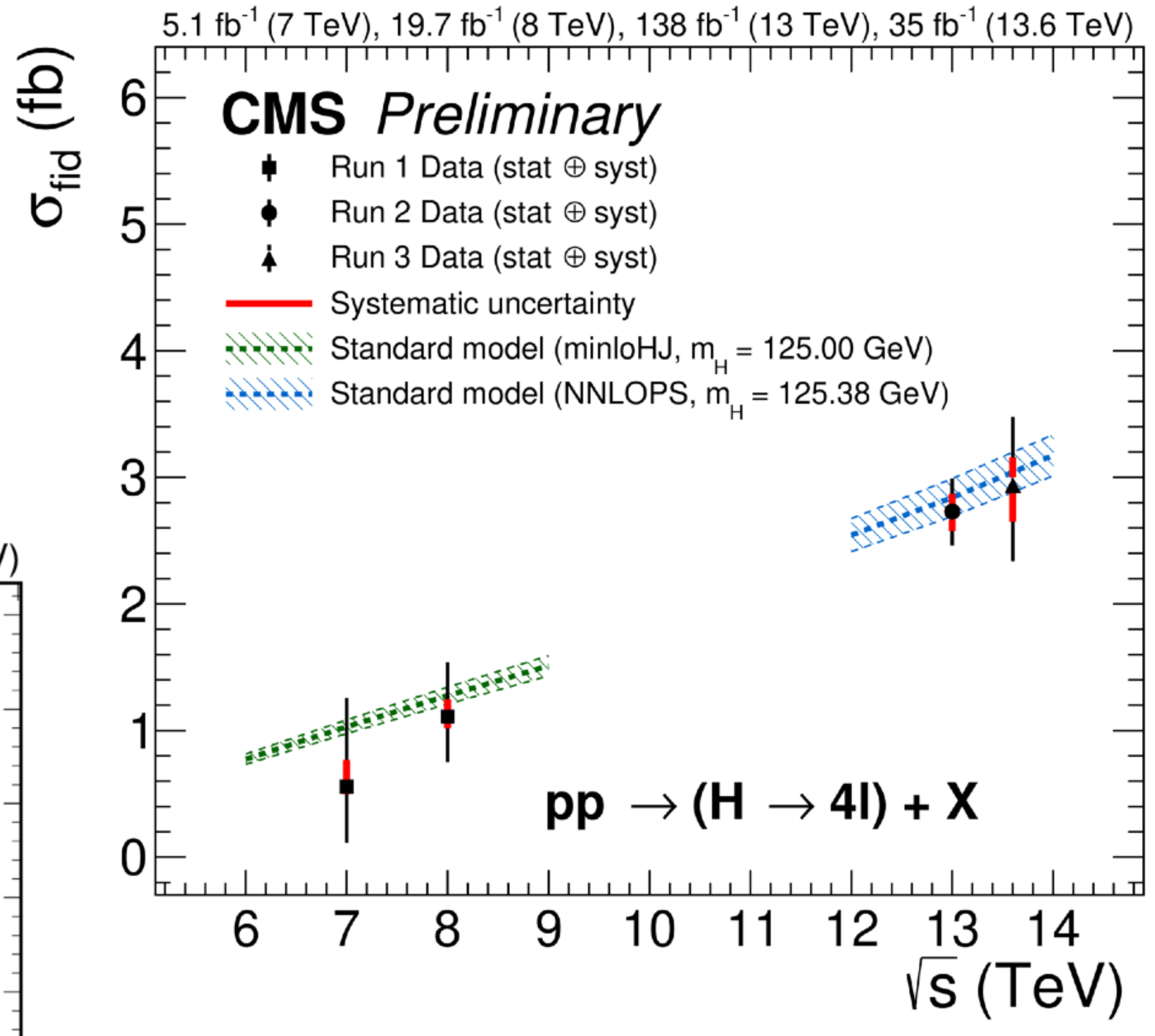
H→ZZ Measurement

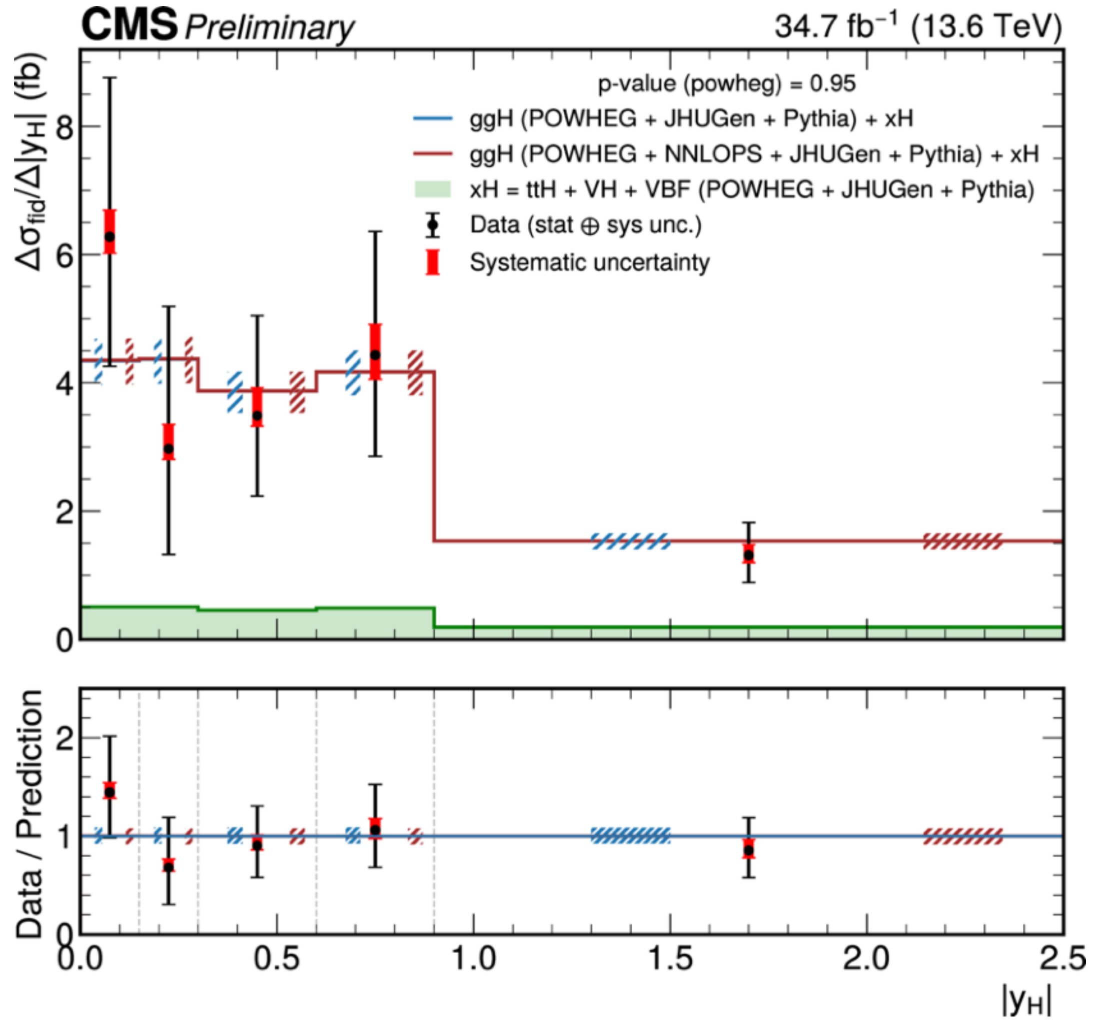
CMS-HIG-24-013

Measurement of inclusive and differential fiducial cross section

- Clean final state topology. Precise invariant mass reconstruction
- Strategy similar to Full Run 2 result
- 2022 data used: **34.7 fb^{-1}**
- **Results given as a function of lepton flavour, and** $\sqrt{s}$
  - Sensitivity dominated by muon channel
- **Some systematic uncertainties are statistically driven**:
  - e.g. trigger and lepton reco. efficiencies,
    syst. unc on reducible backgrounds derived from control samples







Results in agreement with SM expectation

$$\sigma_{fid} = 2.9 \pm^{+0.53}_{-0.49}\,(\text{stat})^{+0.29}_{-0.22}(\text{syst})$$

	σ_{fid} (fb)
$2e2\mu$ (fb)	$1.63^{+0.37}_{-0.33}(\text{stat.})^{+0.14}_{-0.12}(\text{syst.})$
4μ (fb)	$0.46^{+0.18}_{-0.15}(\text{stat.})^{+0.03}_{-0.02}(\text{syst.})$
4e (fb)	$0.83^{+0.34}_{-0.29}(\text{stat.})^{+0.16}_{-0.10}(\text{syst.})$
Inclusive (fb)	$2.94^{+0.53}_{-0.49}(\text{stat.})^{+0.29}_{-0.22}(\text{syst.})$

Top in Run 3

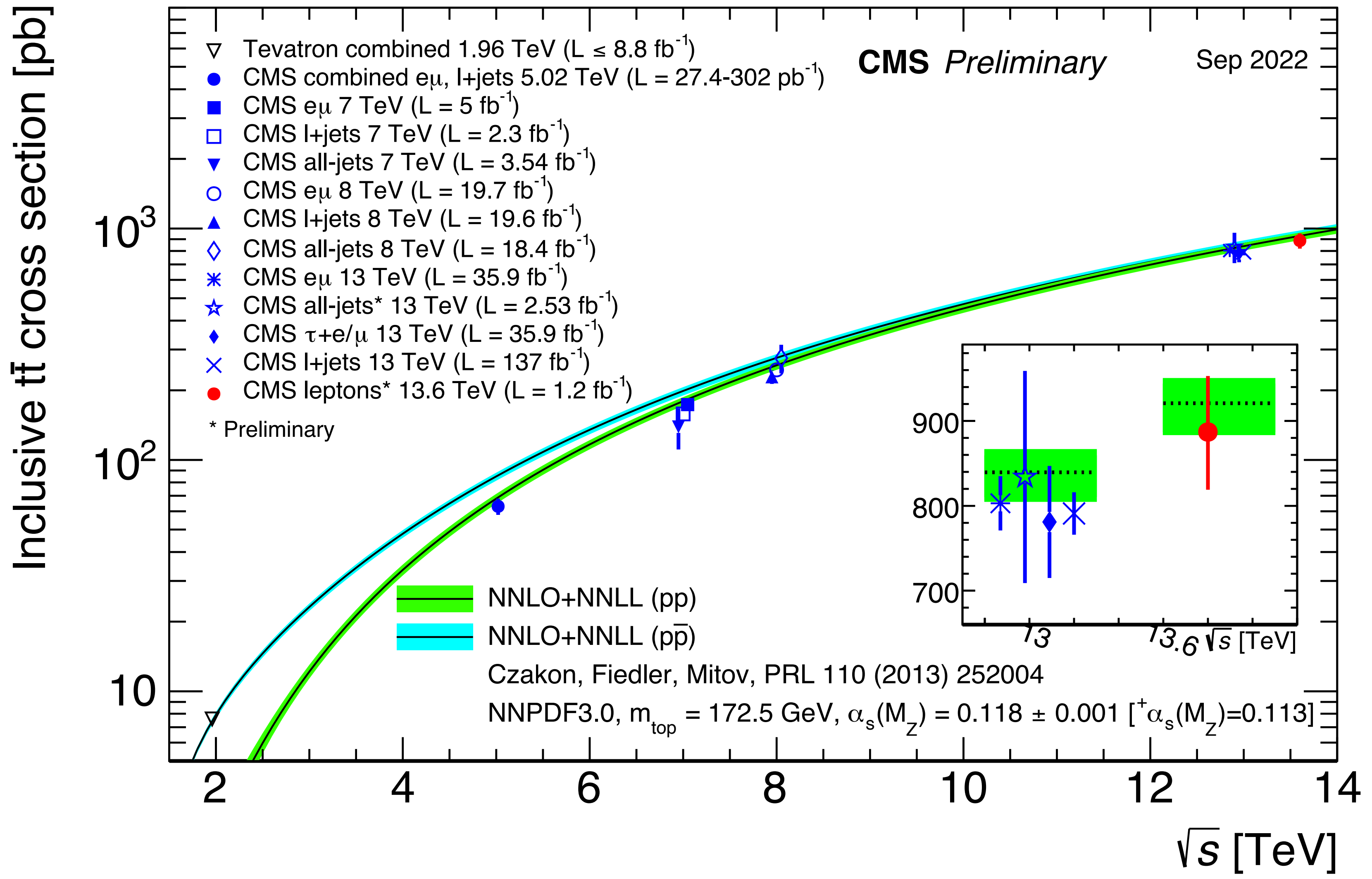
CMS-TOP-22-012

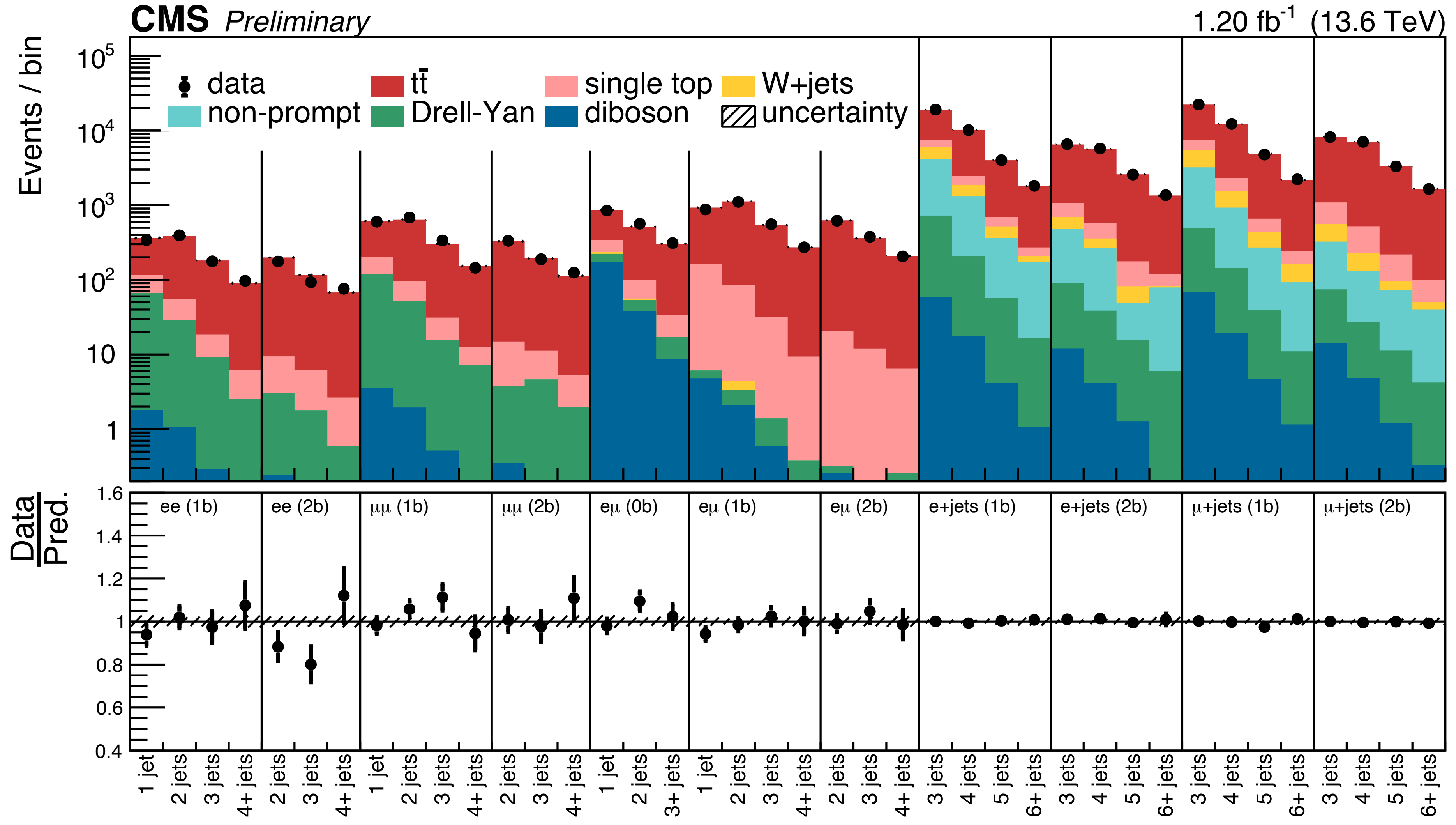
Early measurement: 1.21 fb-1 of 2022 data

- Combined analysis: dilepton ($e\mu, ee, \mu\mu$) & lepton + jets channels
- **Event categories:** lepton number & flavour, N_{jets}, N_b
- Maximum likelihood fit performed in event categories after Z+jets and QCD normalisation corrections from side-band regions
    - **In-situ Lepton ID & b-tagging efficiency estimation** enables syst. unc. reduction
- Cross-check cut-and-count analysis confirms results

Results in agreement with SM expectation

$$\sigma_{t\bar{t}} = 8.81 \pm 23(\mathrm{stat} + \mathrm{syst}) \pm 20(\mathrm{lumi})$$



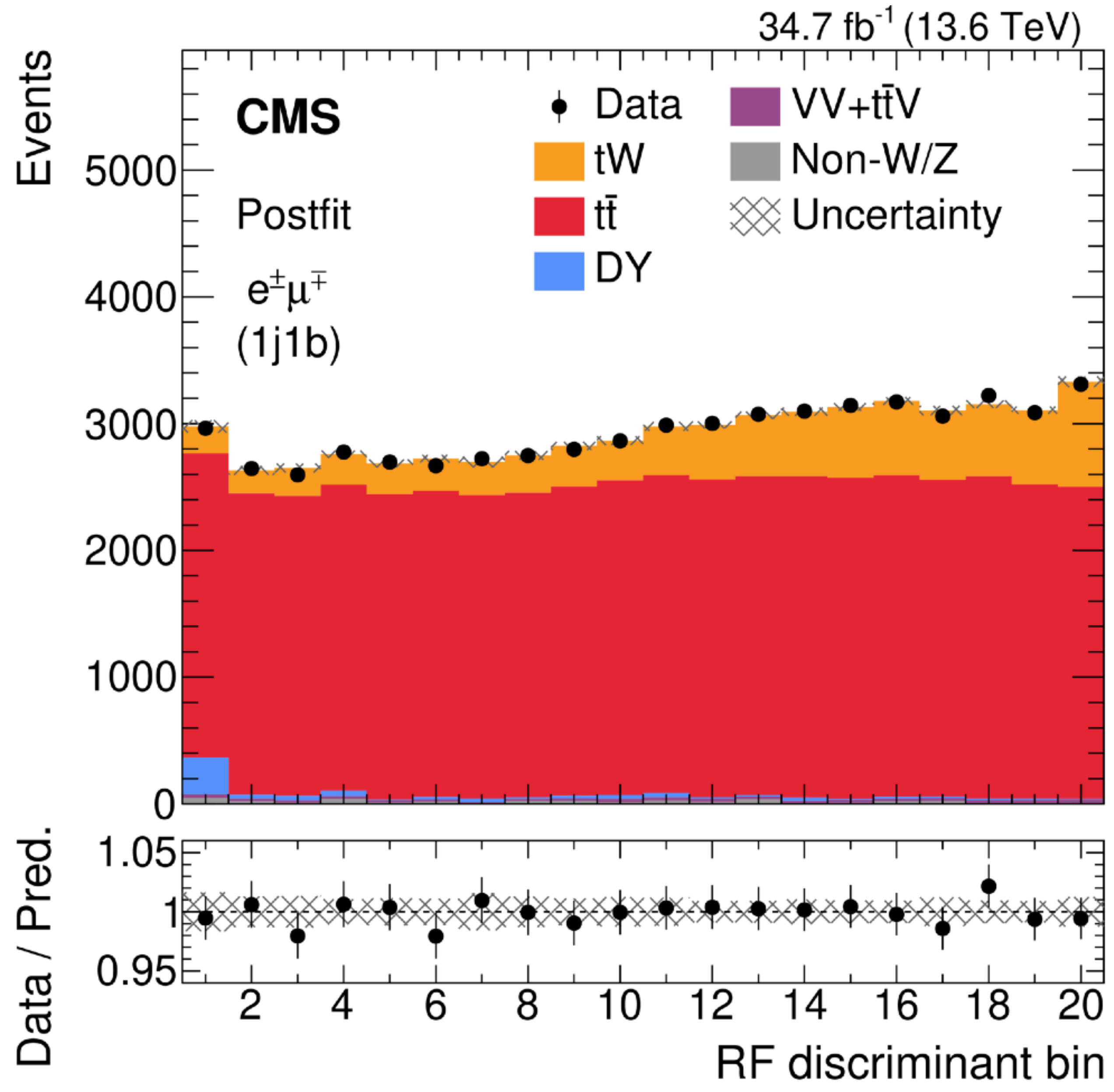


tW at 13.6 TeV

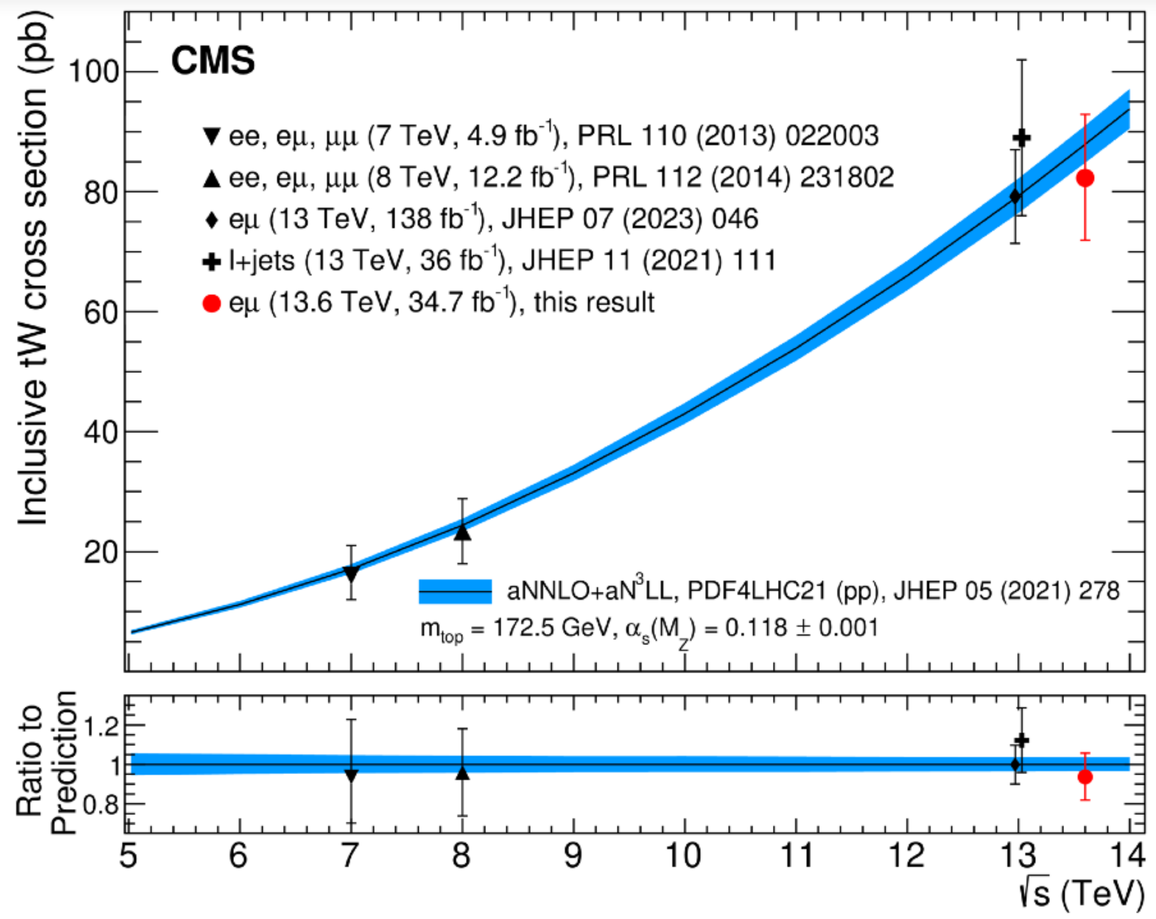
CMS-TOP-23-008

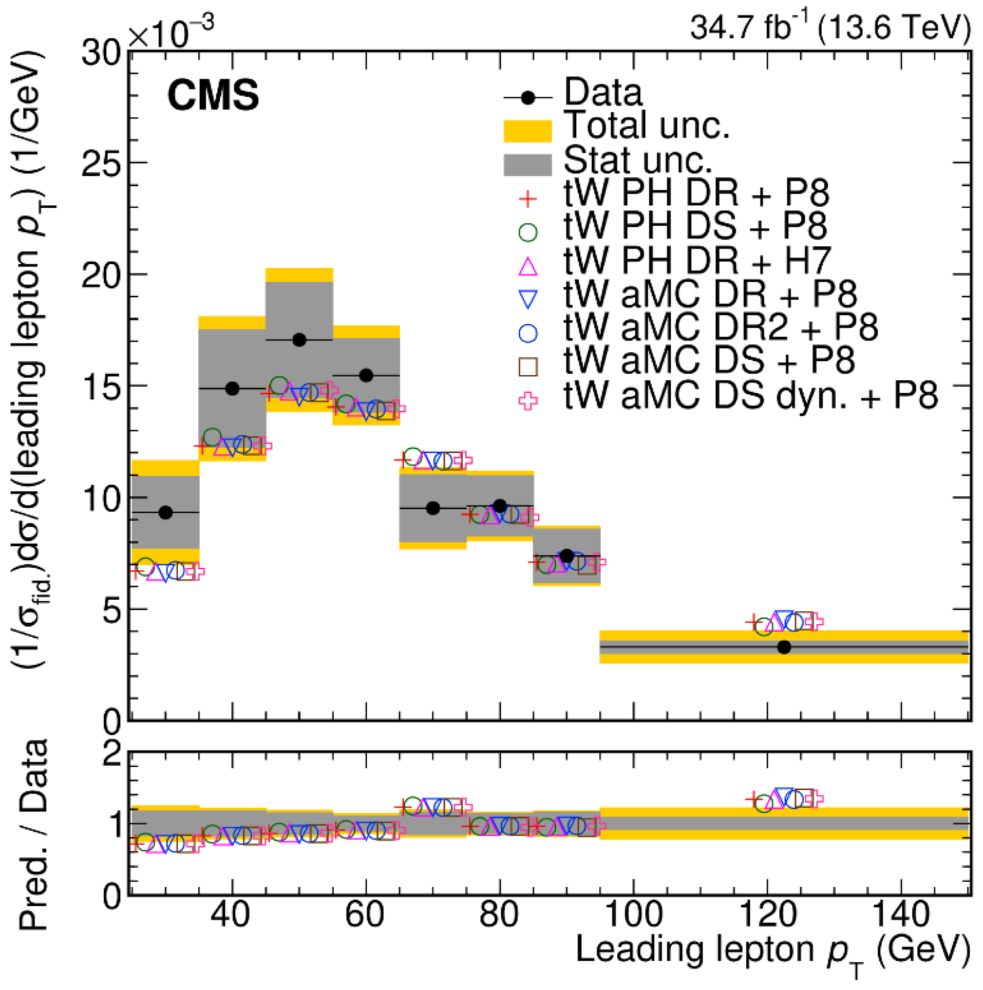
First inclusive and differential tW cross section measurement at 13.6 TeV using 34.7 fb^{-1}

- Challenges: **Irreducible tt background largely dominating** signal contribution
  - NLO interference between tW and tt
- **tW and tt discrimination achieved by using two Random Forests**, RF (*) categories. RF trained using the kinematic properties of the events
  - **Maximum Likelihood fit** performed to extract signal using the 2 RFs (1j1b and 2j1b) and subleading jet p_T in 2j2b



$$\sigma_{t\bar{t}} = 82.3 \pm 2.1(\text{stat})^{+9.9}_{-9.7}(\text{syst}) \pm 3.3(\text{lumi})\text{pb}$$





Differential measurements **statistically limited**

Main syst. unc. from jet energy scale, btagging and misidentified leptons normalization

(*) An RF classifier is a ML method that combines predictions of multiple decision trees to reach a single result

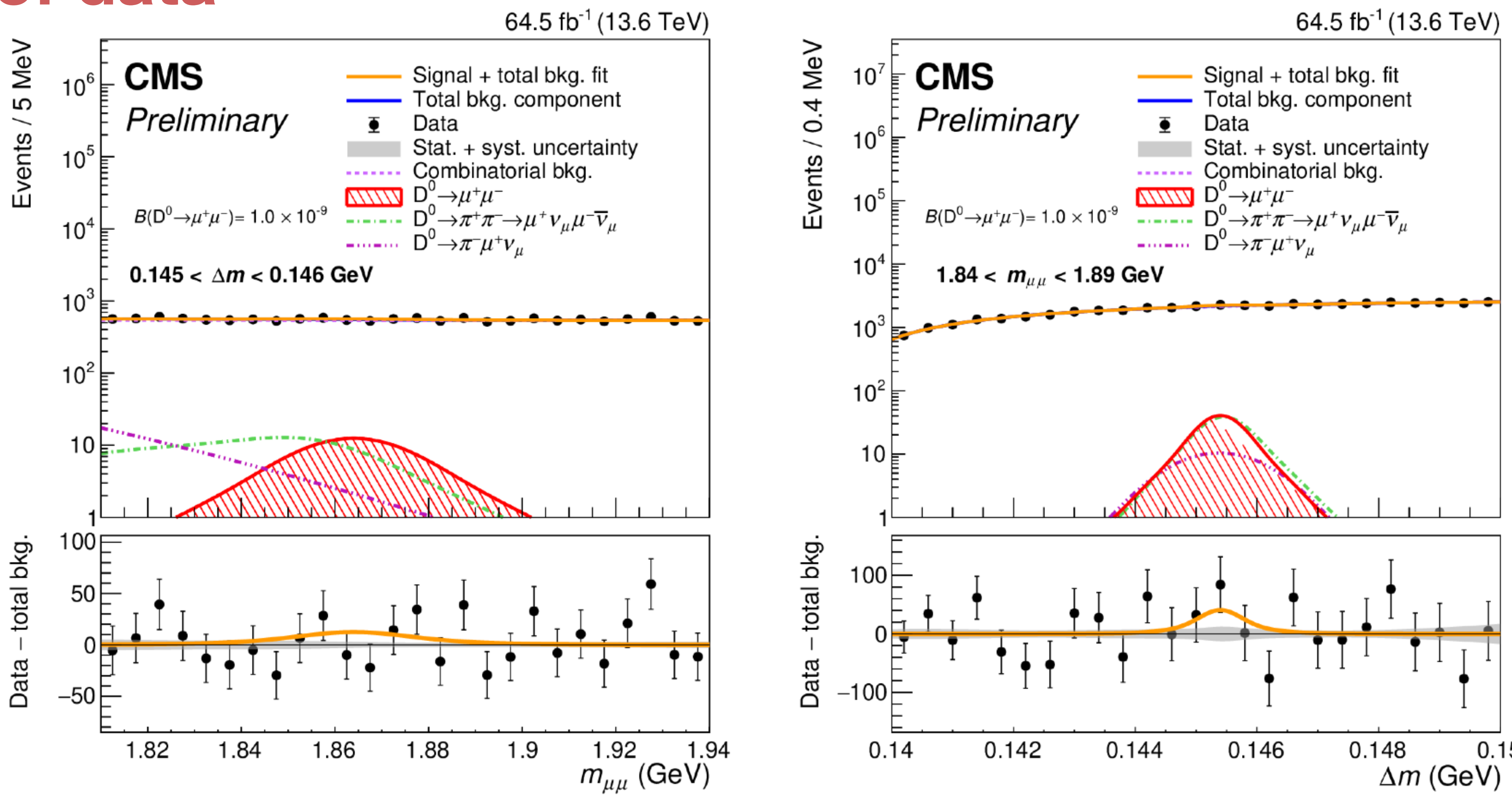
BPhysics in Run 3

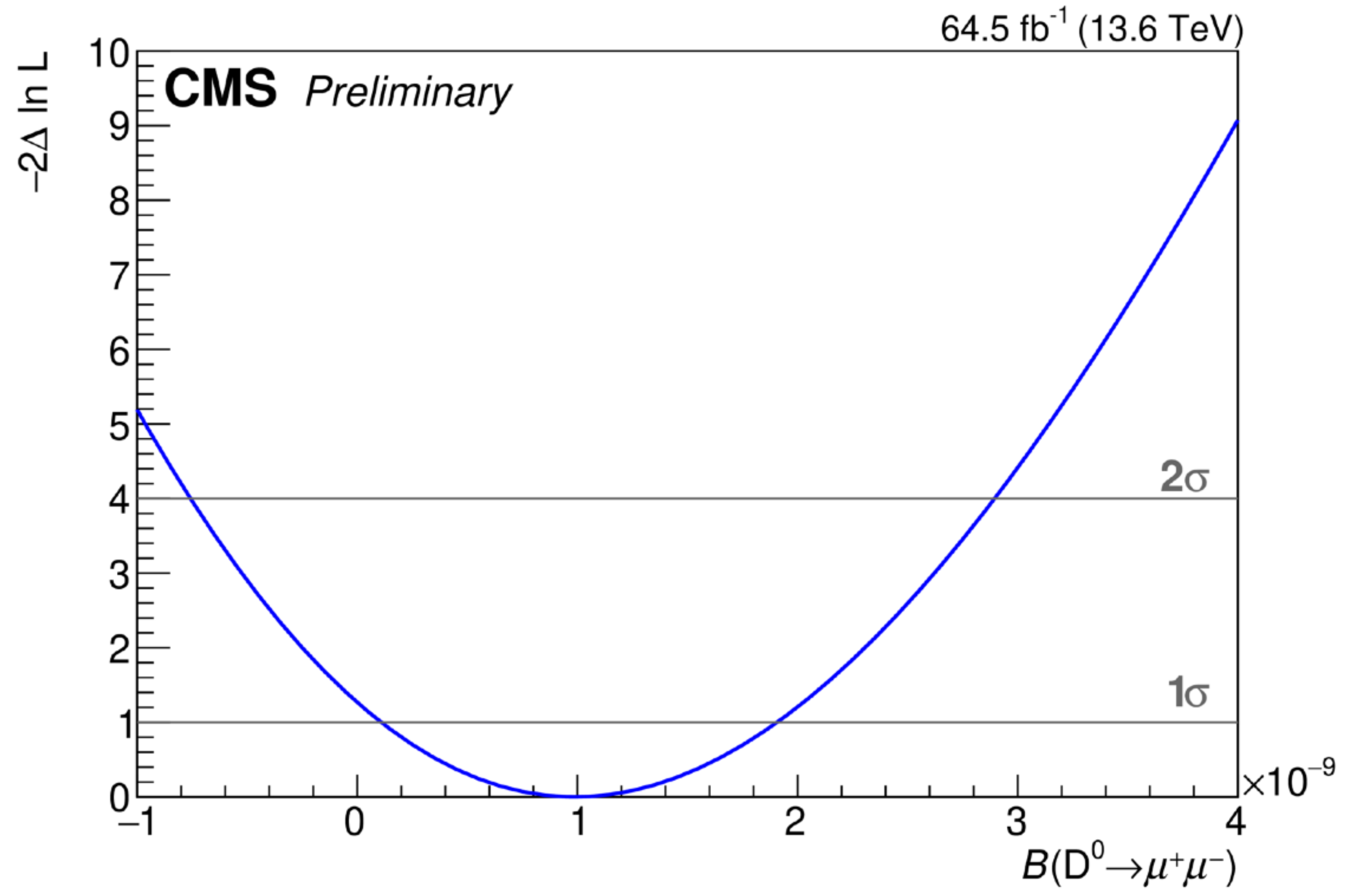
CMS-BPH-23-008

Search for rare charm decays into 2 μ at 13.6 TeV with 64.5 fb^{-1} of data

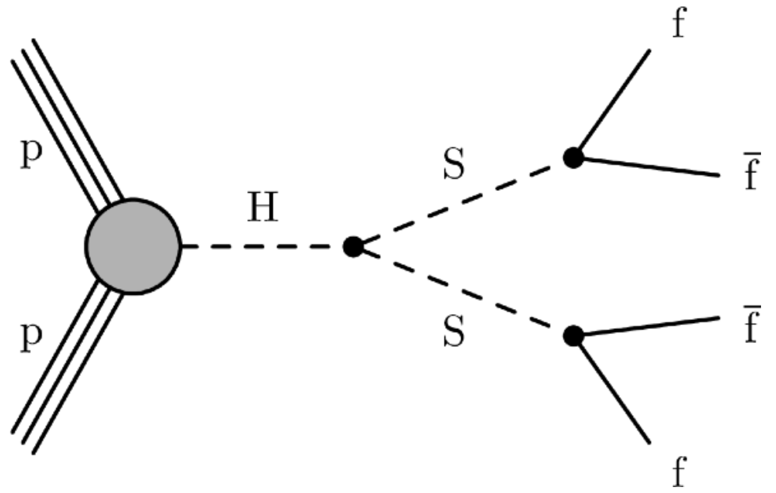
- **Newly developed low-mass double muon parking trigger** made possible first BR measurement: low threshold (4GeV and 3 GeV muon p_T) and high rate
  - **35% improvement** wrt world best measurement from LHCb
- **Signal extracted from cascade decay** $D^{*+} \to D^0\pi^+$
  - 2D Max.Like. fir to m_{D^0} and $\Delta m = m(D^{*+}) - m(D^0)$
  - BR estimated wrt $D^{*+} \to D^0\pi^+, D^0 \to \pi^+\pi^-$
- **Displaced D⁰ vertex most discriminative variable** against combinatorial bkg
- **Major uncertainties** from $D^0 \to \pi^+\pi^-$normalisation and misidentification rate

$$\text{BR}(D^0 \to \mu\mu) < 2.6 \times 10^{-9} \text{at 95 \% CL}$$





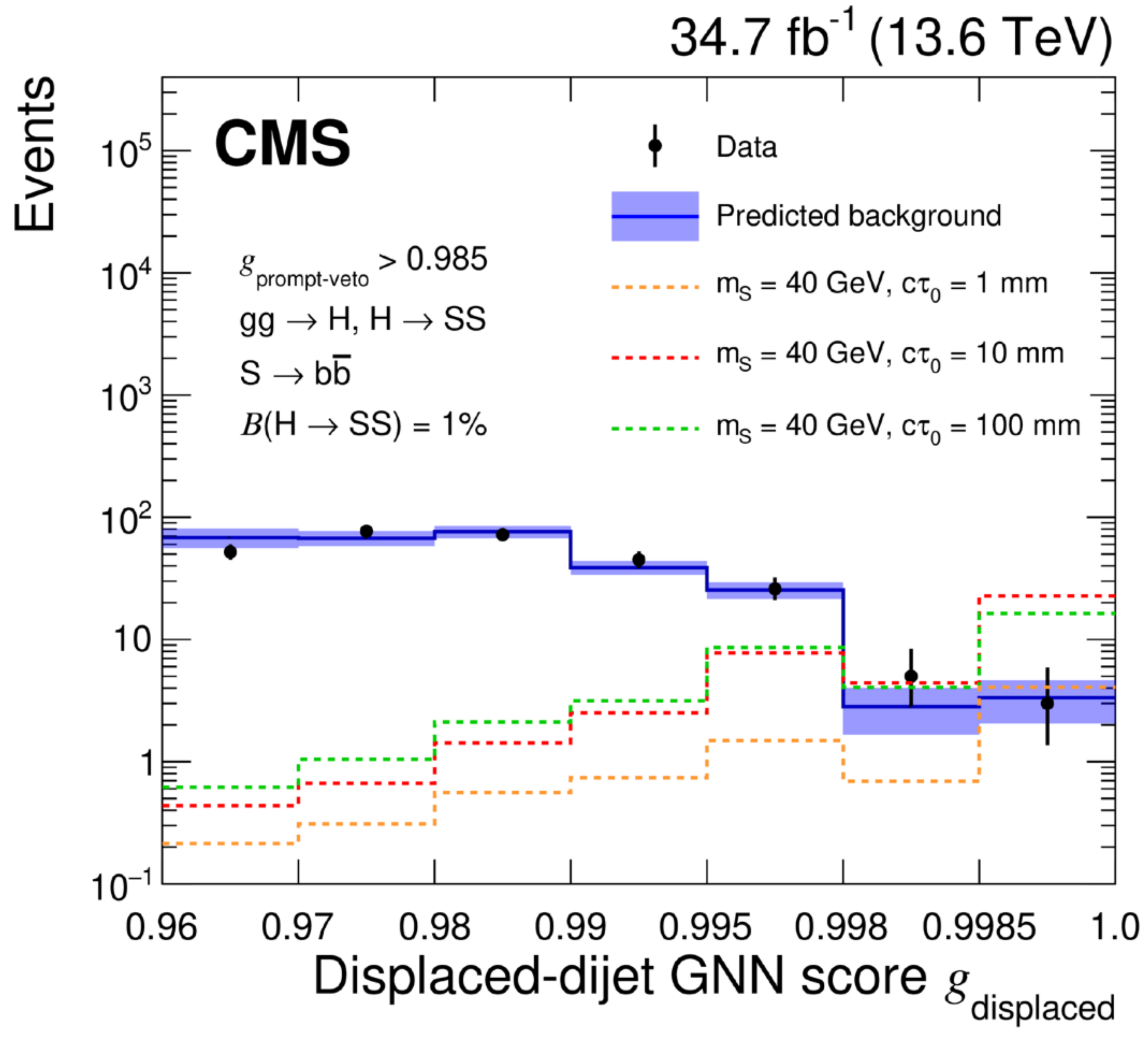
LLPs to displaced jets in Run 3

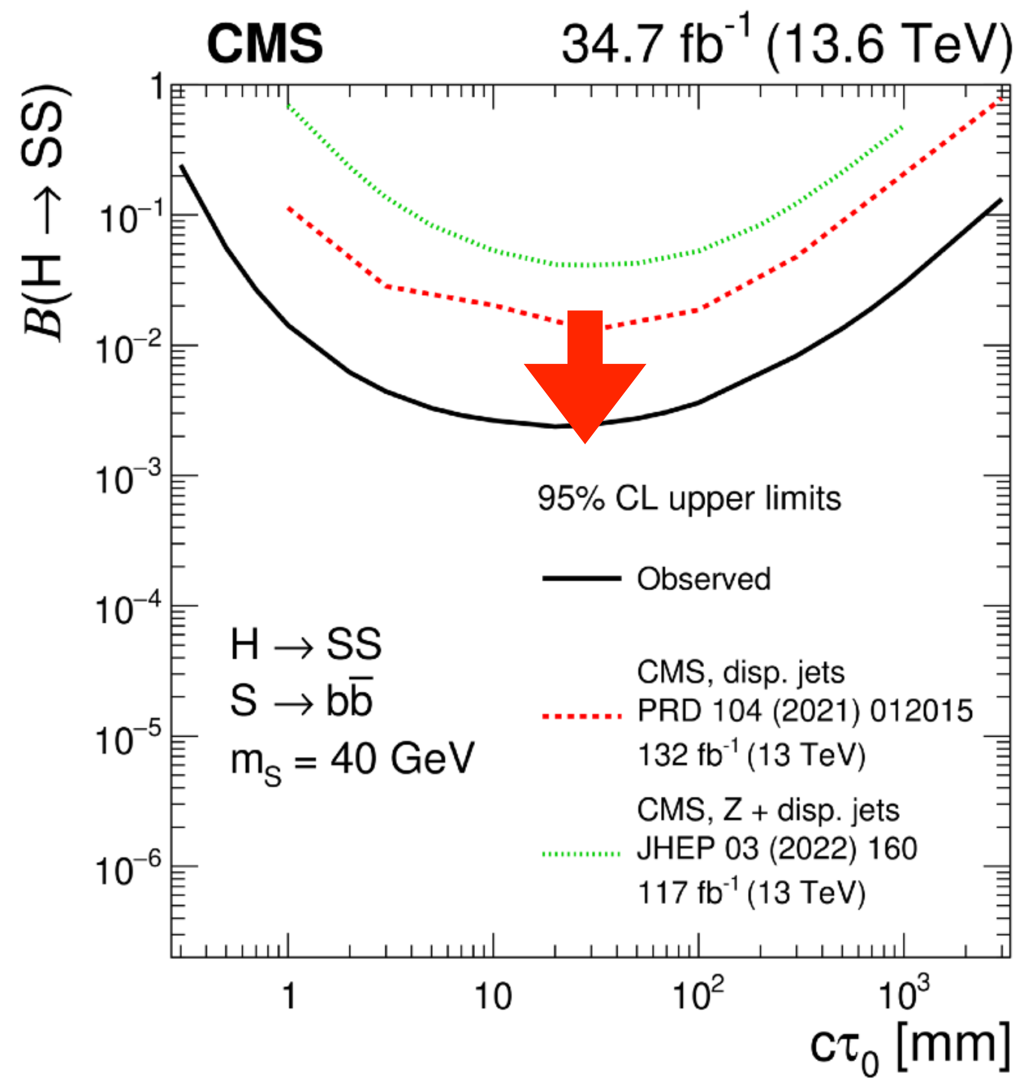


Long Lived Particles to dispaced jet pairs

- Novel displaced-jet trigger + reconstruction + Graph-NN LLP taggers (displaced/prompt GNN)
  - **Outperforming (x10) full Run 2 result** with fraction of Run 3 data
  - First limits on (tracker-based) displaced LLP τ_h channel at LHC
- Best limits set for $15 < m_S < 55$ GeV and $c\tau < 1\text{m}$

CMS-EXO-23-013

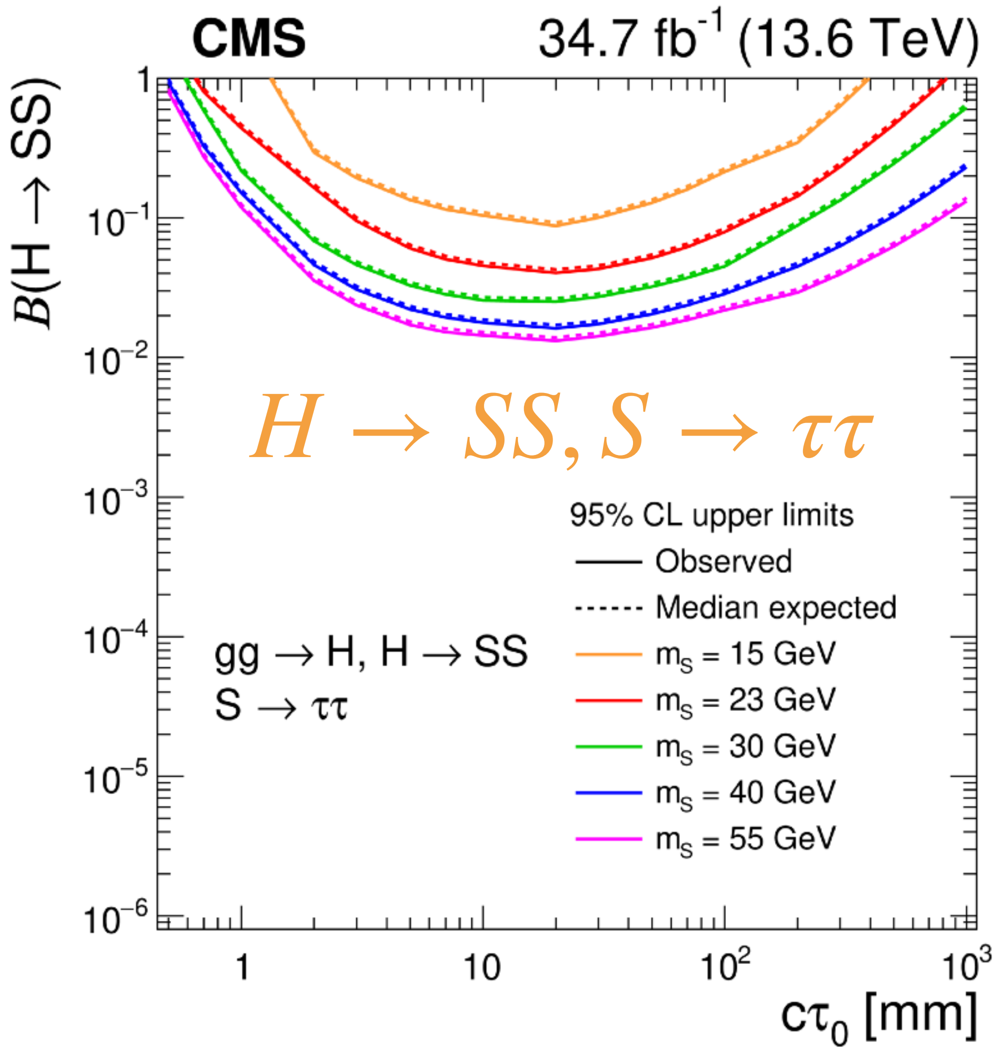




132 fb^{-1} Run 2

34.7 fb^{-1} Run 3

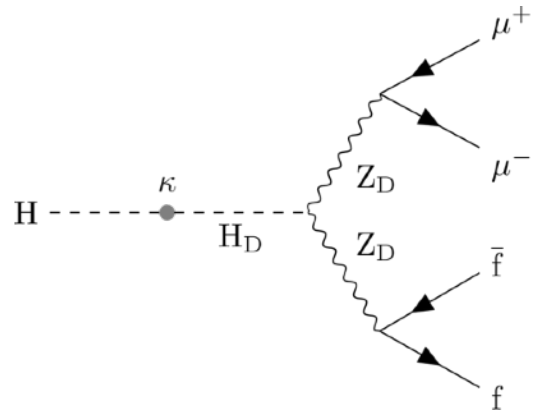
$H \rightarrow SS, S \rightarrow b\bar{b}$

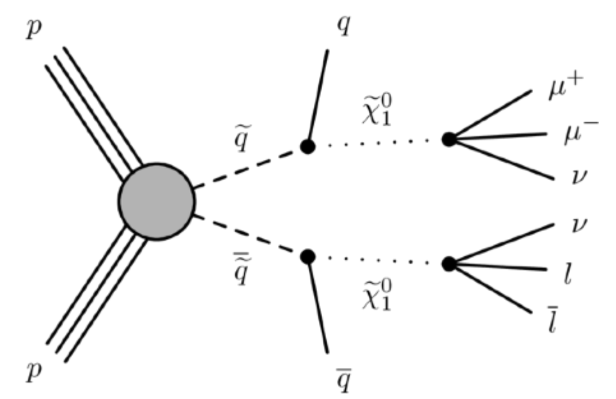


$H \rightarrow SS, S \rightarrow \tau\tau$

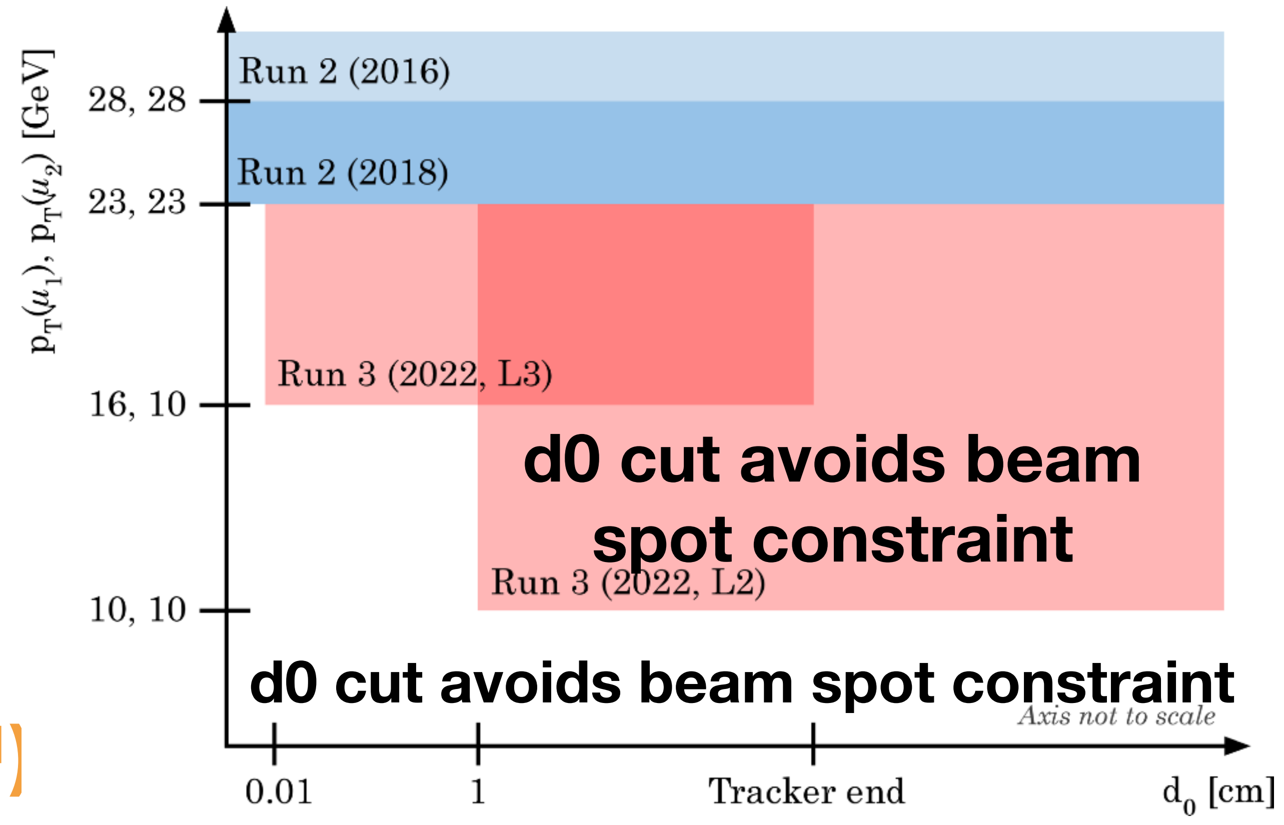
LLPs to displaced μ pairs in Run 3

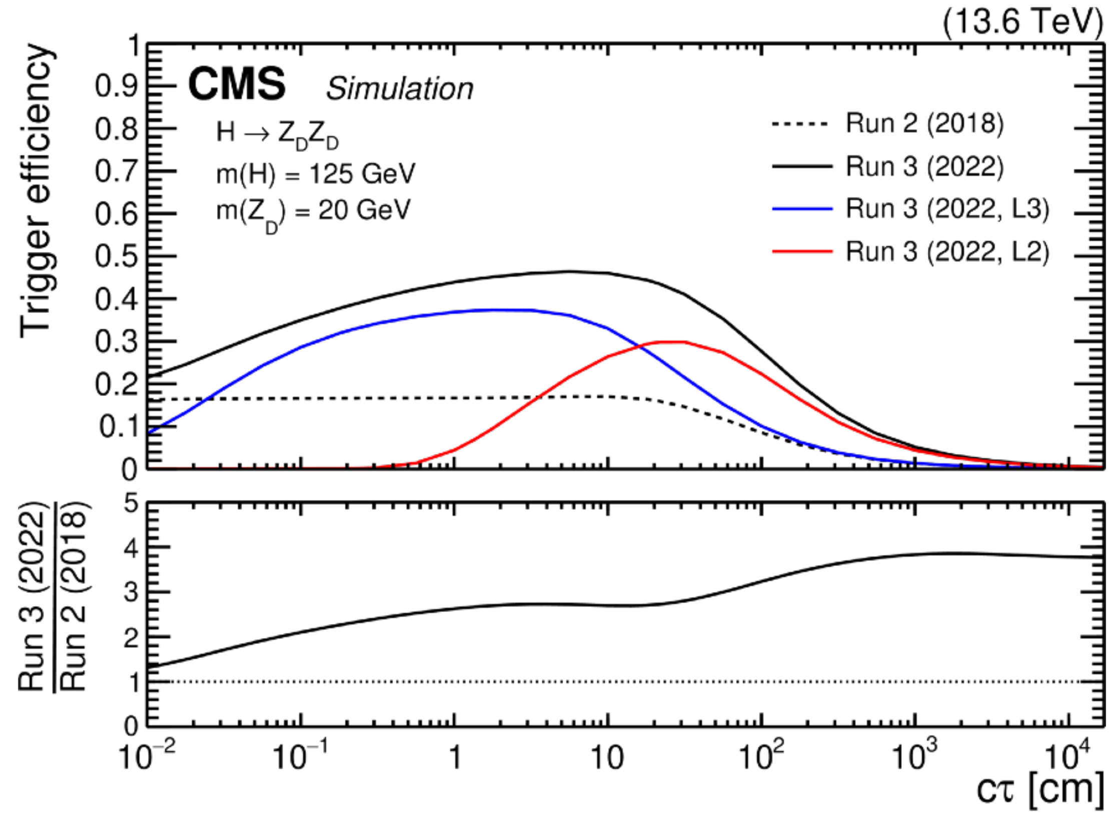
Dark Higgs (H_D) decaying to LL dark photons (Z_D)

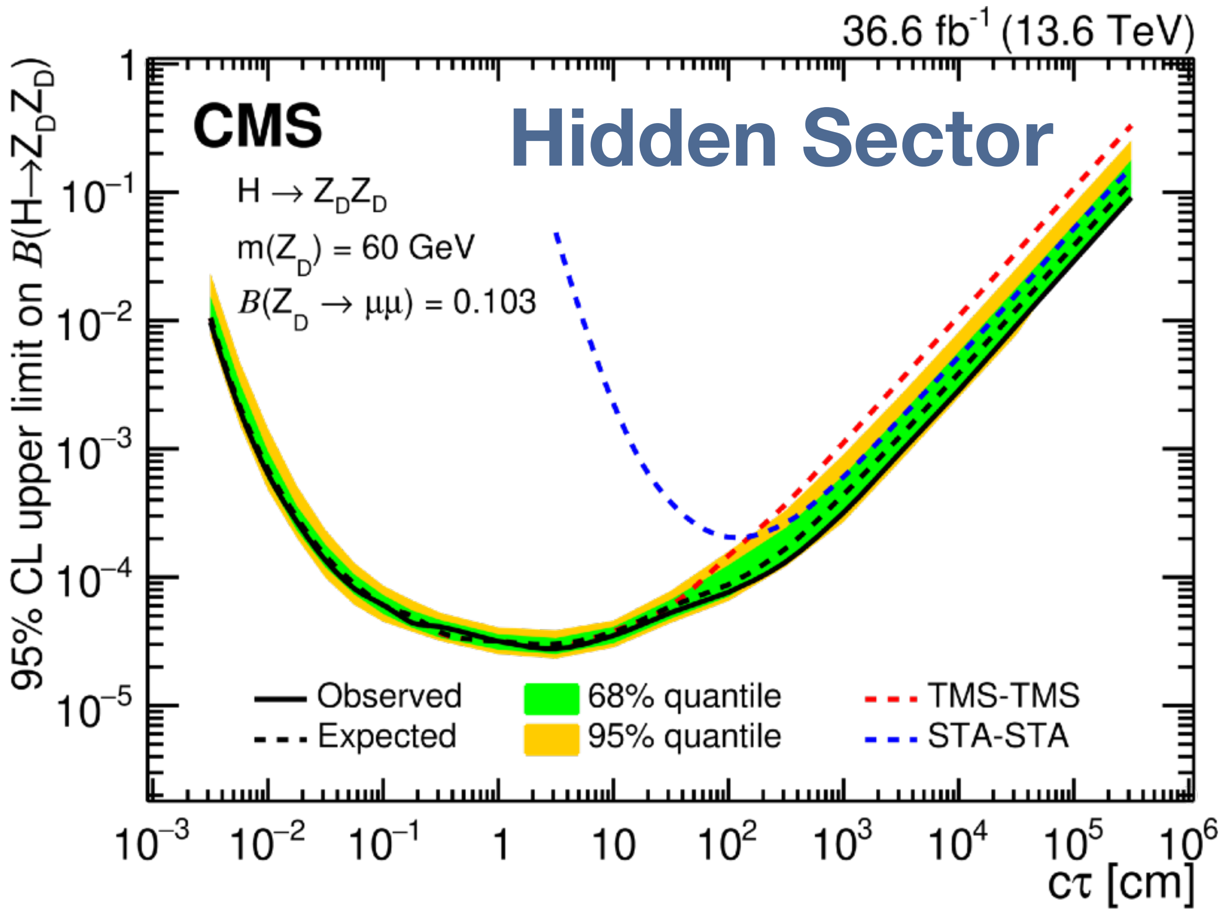


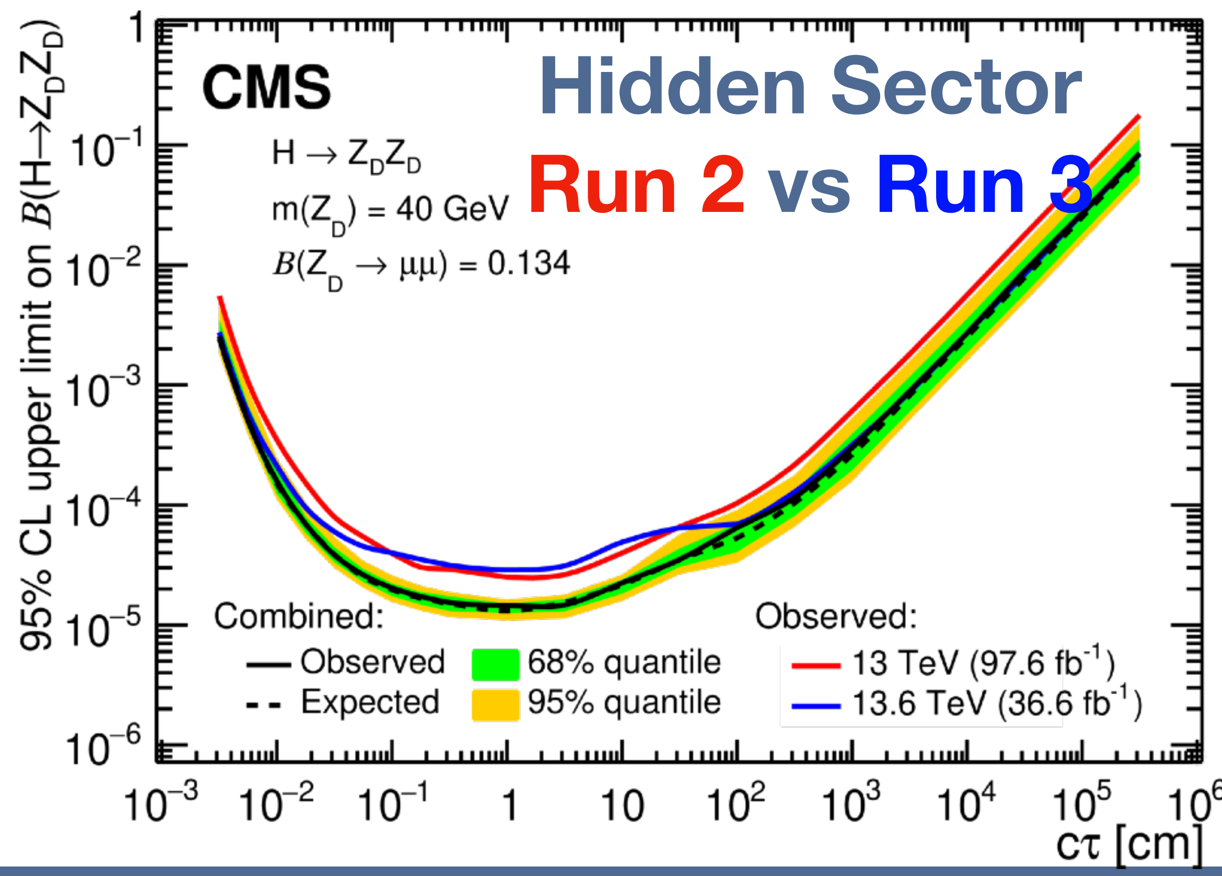


- **New dedicated displaced-dimuons trigger** using tracker+ muon stations
  - lower pT threshold and no beam spot constraint at L1
- Two categories based on μ reconstruction:
  - using both tracker and muon spectrometer (TMS)
  - standalone muon spectrometer (STA)
- **Partial Run 3 (36.6 fb-1) result competitive with Run 2 (97.6 fb-1)**
- Run 3 analysis better for length > 100 cm for various ZD masses









Dominant uncertainties from data to MC corrections from muon identification, muon reconstruction and trigger efficiencies

CMS-EXO-23-014

HL-LHC plans

Planning for 3 ab^{-1} of pp collisions

- pp collisions at $\sqrt{s} = 14$ TeV
    - Significant cross section increase for massive final states
- 20 times more int.luminosity than Run 2
- Huge statistical power for heavy particles
    - and access to rare processes ~5x10^5 4tops
    - exotic Higgs decays down to BR ~ 10^{-5} - 10^{-6}

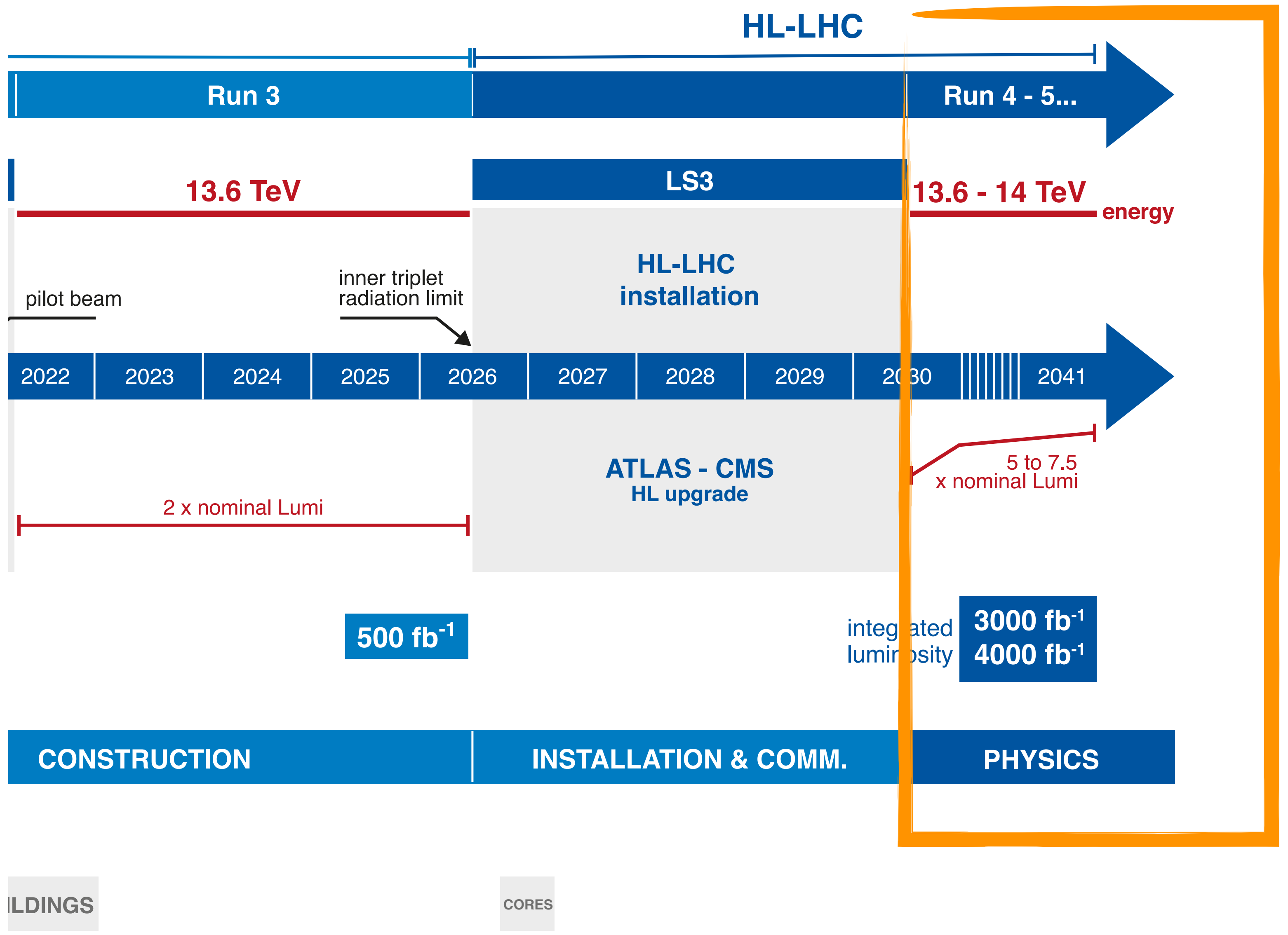
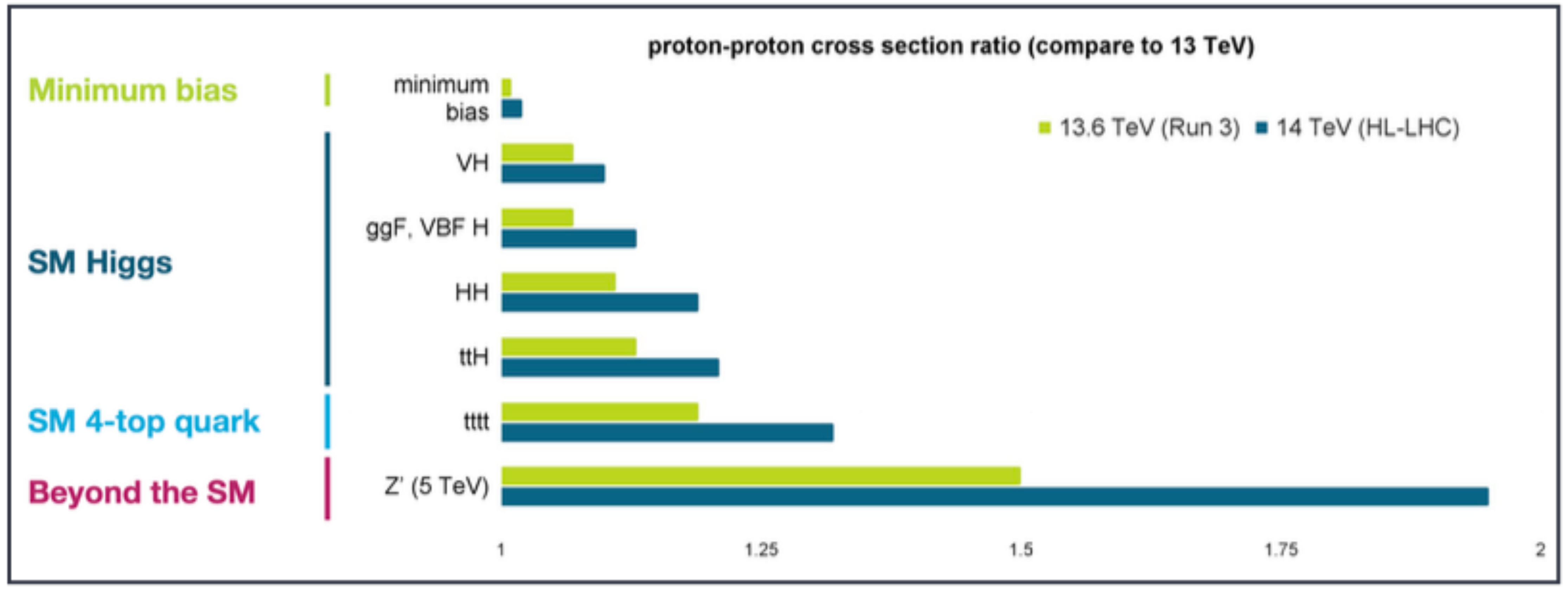
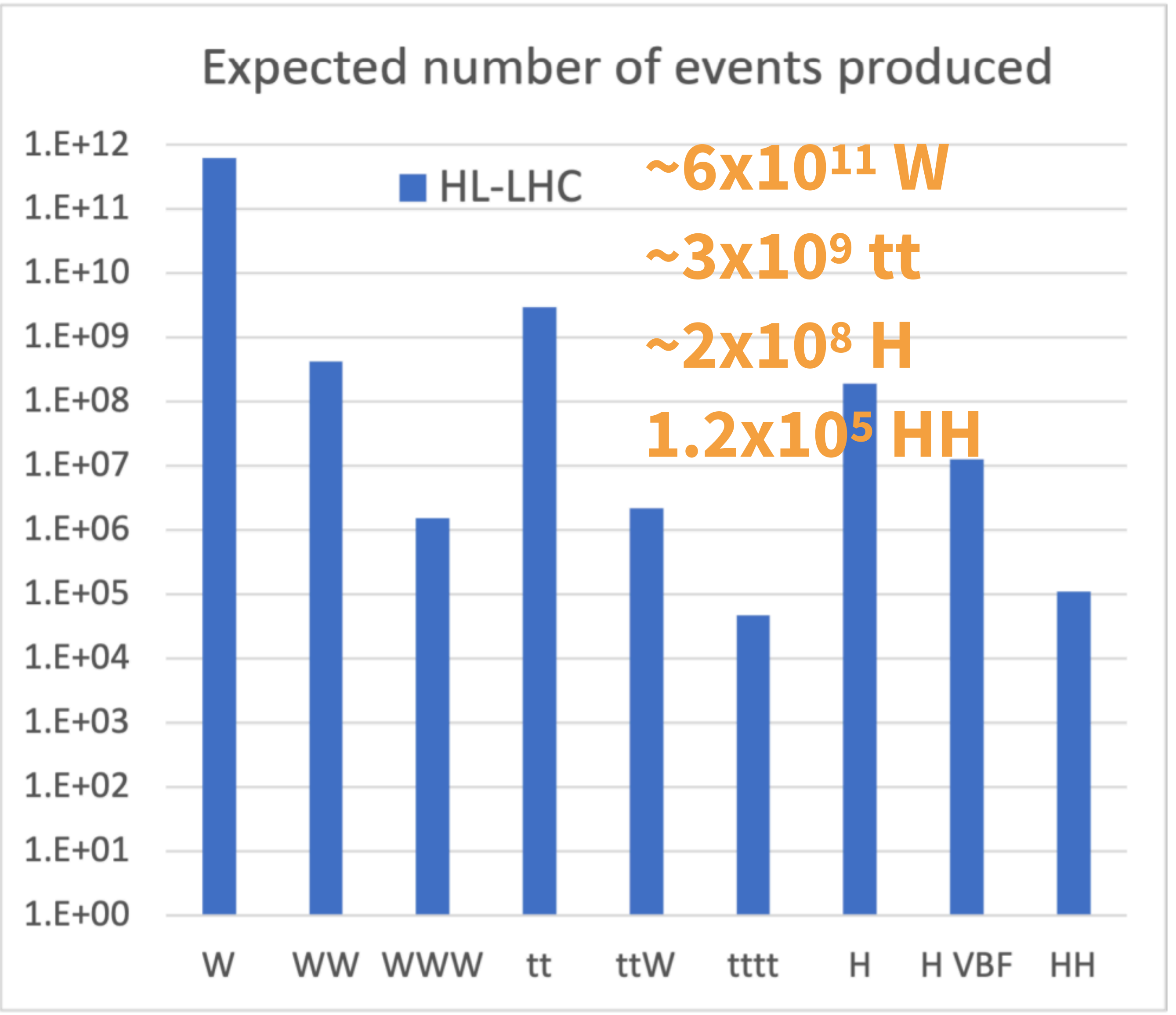


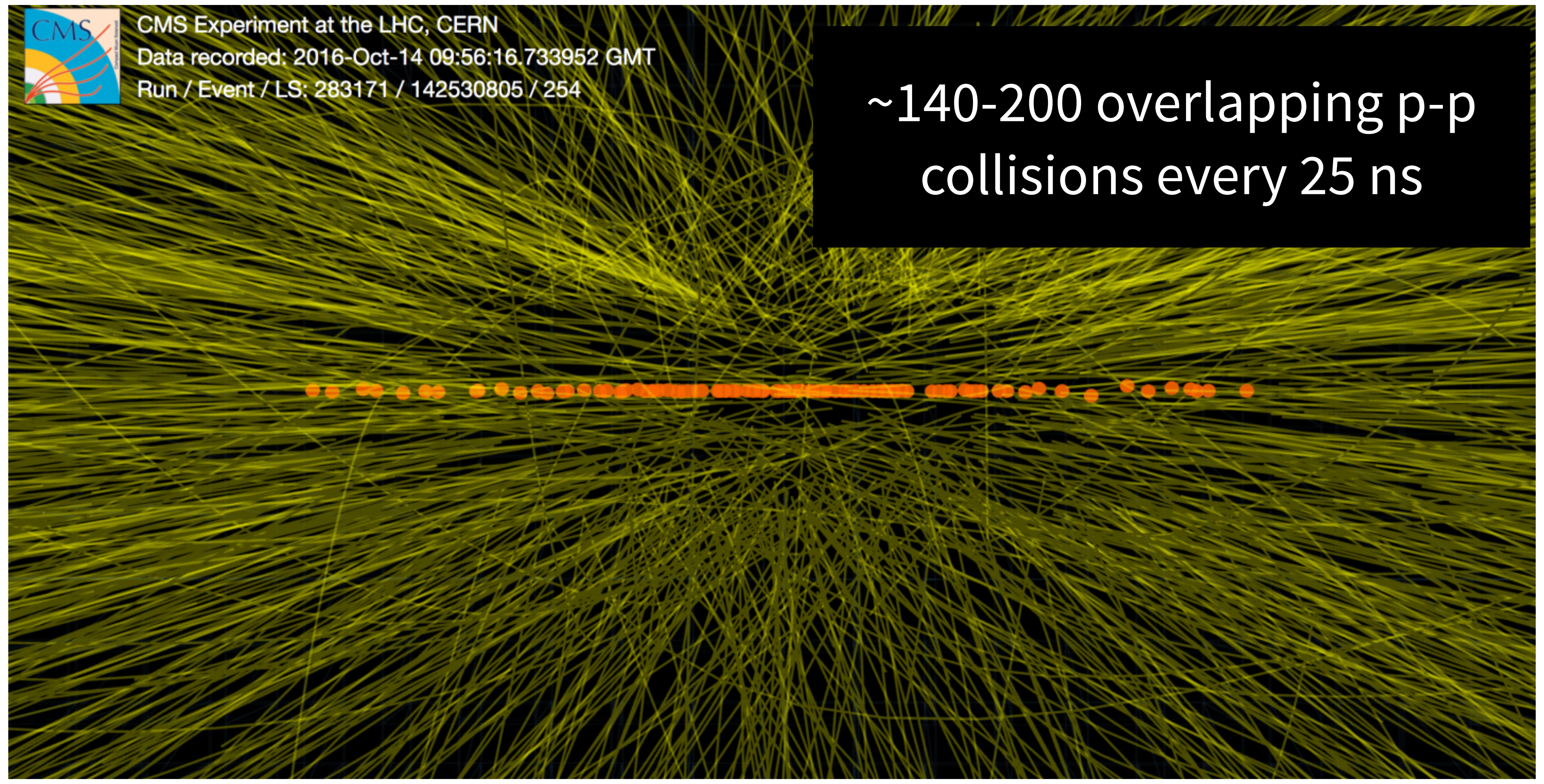
Image: E. Brost



Exploration at both energy and intensity frontier



HL-LHC plans



New challenges

- High data acquisition rates (**inst. lumi 5 to 7x** nominal values)
- **More complex event reconstruction** - PU: from 34 (Run 2) to 200 (HL)
- **High radiation doses**

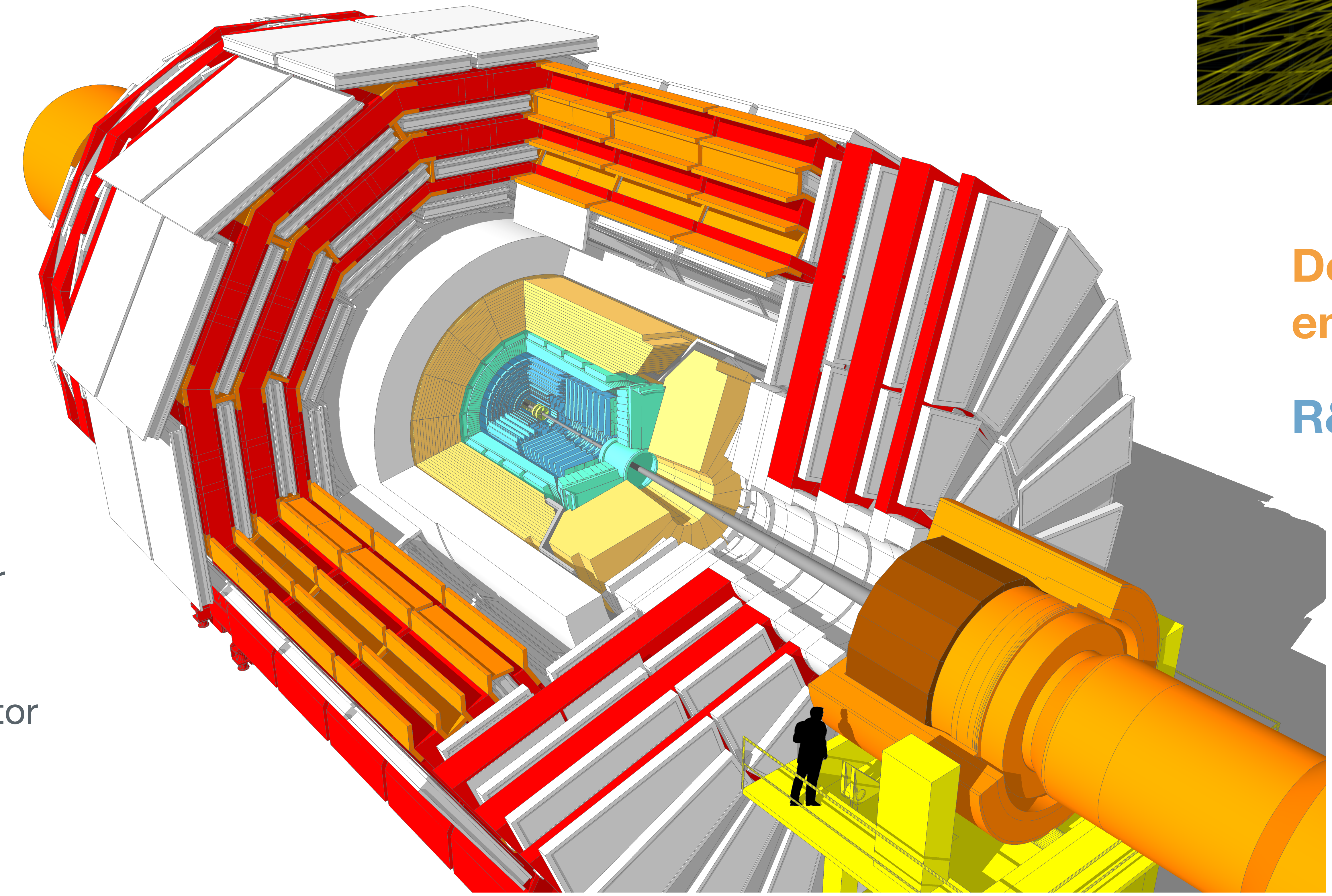
Trigger/DAQ
L1 rate: 750 kHz
HLT rate: 7.5 kHz
Tracking at L1

Inner Tracker
New higher resolution tracker
Extended η coverage
Reduce material budget

Endcap calorimeters
New high-granularity calorimeter

Timing detector
New MIP precision timing detector for pileup mitigation

Muon detector
Extended η coverage



Detector upgrades to cope with harsher environment

R&D in trigger, software and computing

- Exploitation of AI/ML techniques online and offline
- Heterogeneous computing technologies

HL-LHC Projections

Method

- Run 2 results extrapolated to **3 ab^{-1}** and to **14 TeV**
- Based on simulations (often uses simplified detectors simulation)
- No specific upgraded detector model or special assumptions on PU

Systematic uncertainties scenarios

- **Scenario 1:** same uncert. as measured in Run 2
- **Scenario 2:** syst. scale down with luminosity (for data-driven syst.) down to a floor. Theoretical unc. are halved assuming progress in calculations

Studies presented here from:

- Yellow Report 2019
- Snowmass 2021
- New/Updated studies underway to be released in the upcoming months

Diving into the Higgs potential

HL-LHC will enable preciser measurement of Higgs potential (largely unconstrained so far)

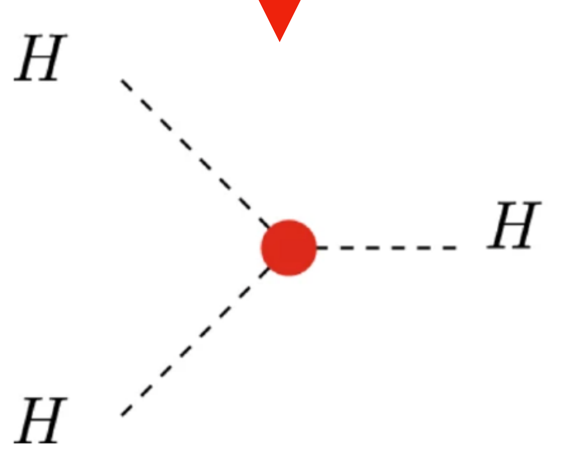
Key to:

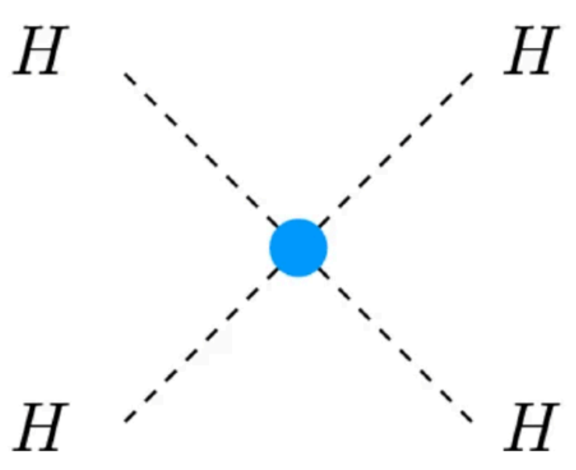
- Understand EW phase transition in early universe
- Determines vacuum stability

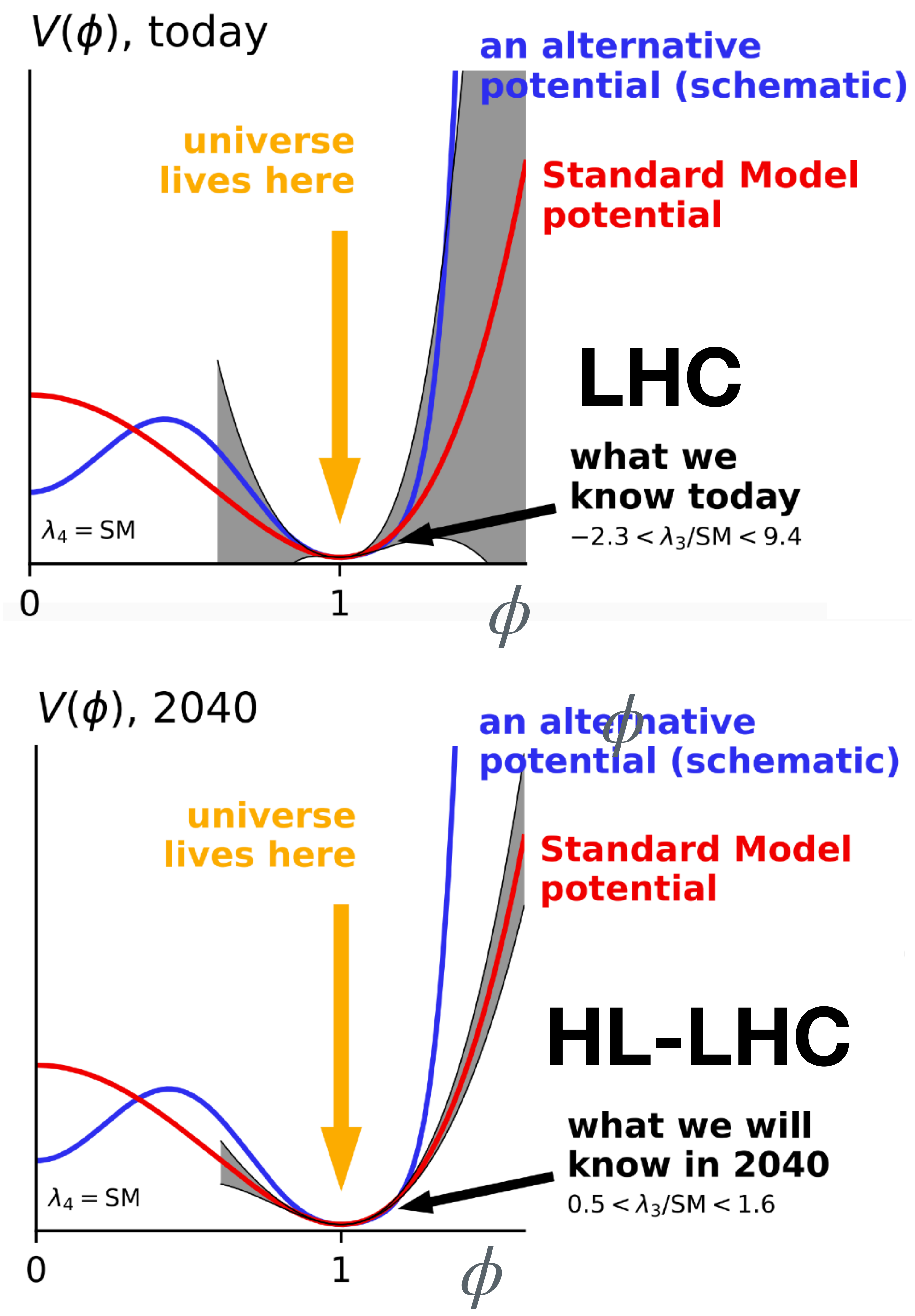
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

Higgs mass, measured at ~per mill precision at LHC





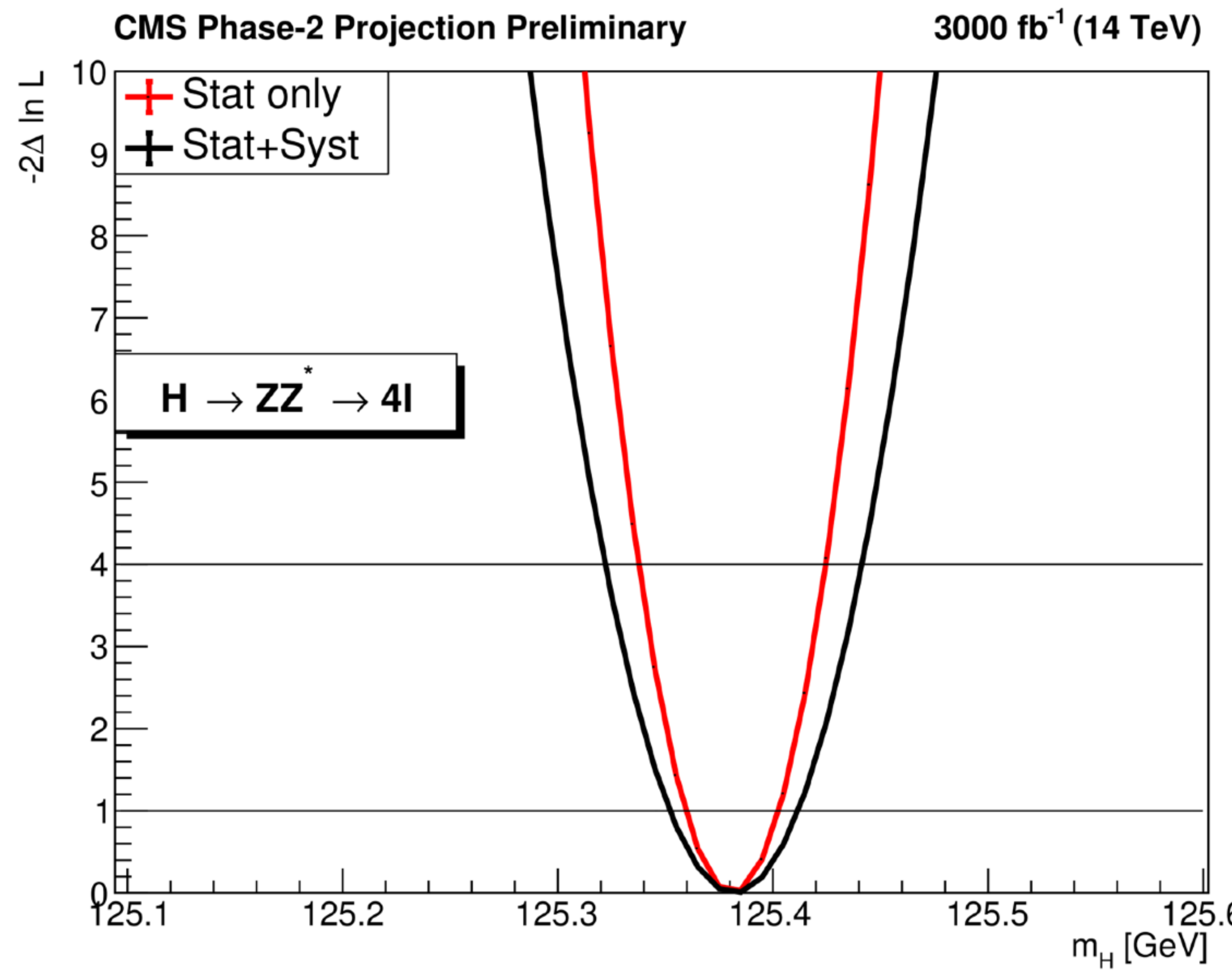


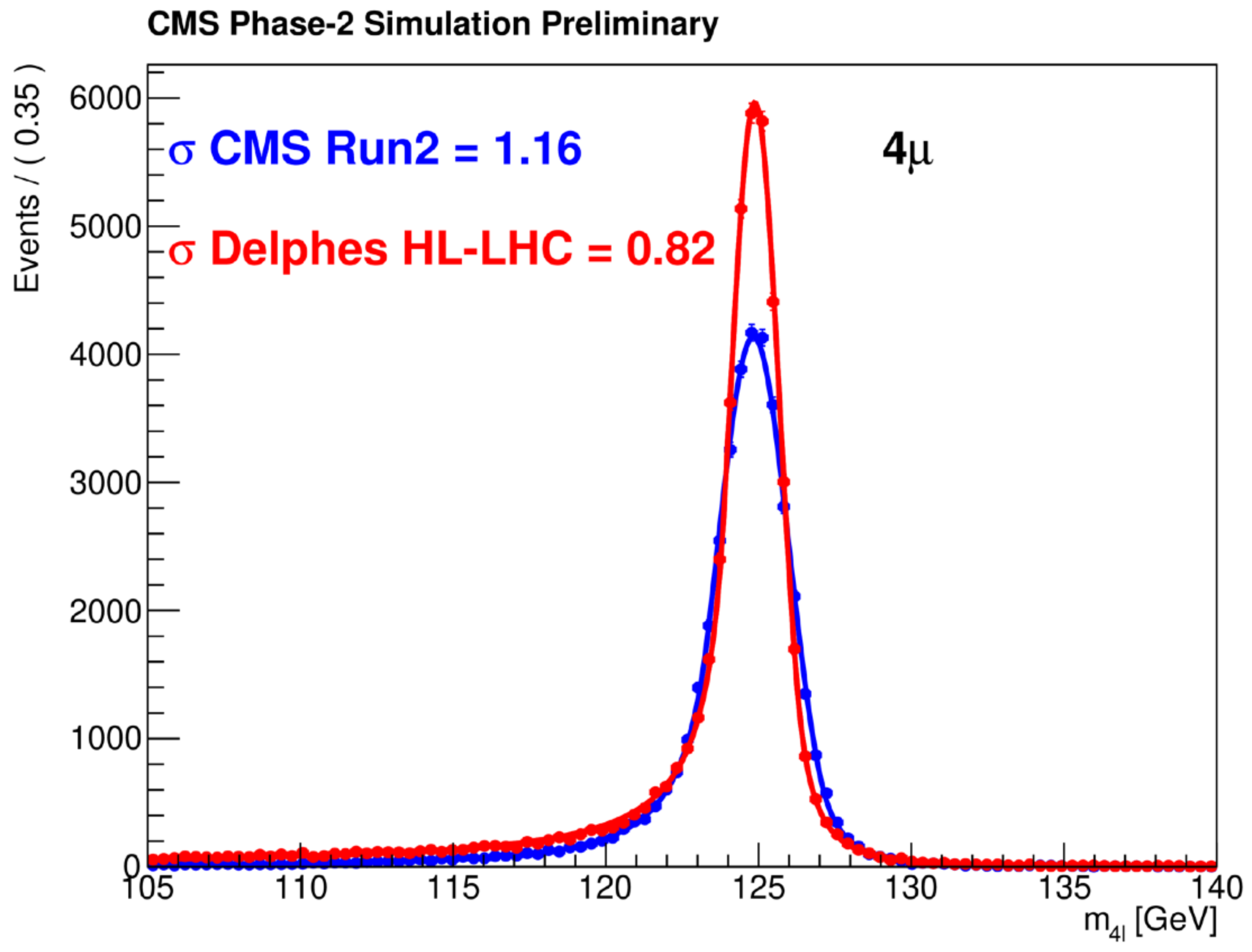
Sketch from G. Salam (2022)

Higgs mass

CMS-PAS-FTR-21-007

- **Current state** (Run 2 H→4l) limited by statistics:
  - $m_{\mathrm{H}} = 125.26 \pm 0.20\ (stat)\ \ \pm 0.08\ (syst)\ \mathrm{GeV}$
  - $\Gamma_{\mathrm{H}} < 0.41(1.10)\ \mathrm{GeV}$ at 68(95)%CL
- **HL-LHC** Projections based on Run 2 results (*pessimistic* uncertainties scenario)
  - $m_{\mathrm{H}} = 125.38 \pm 0.022\ (stat)\ \ \pm 0.020\ (syst)\ \mathrm{GeV}$
  - $\Gamma_{\mathrm{H}} < 0.09(0.18)\ \mathrm{GeV}$





Mass error can go down to 20 MeV including detector upgrades - larger acceptance and improved mass resolution (25%)

Higgs self-coupling

CMS-HIG-20-011

HL flagship measurement: di-Higgs production

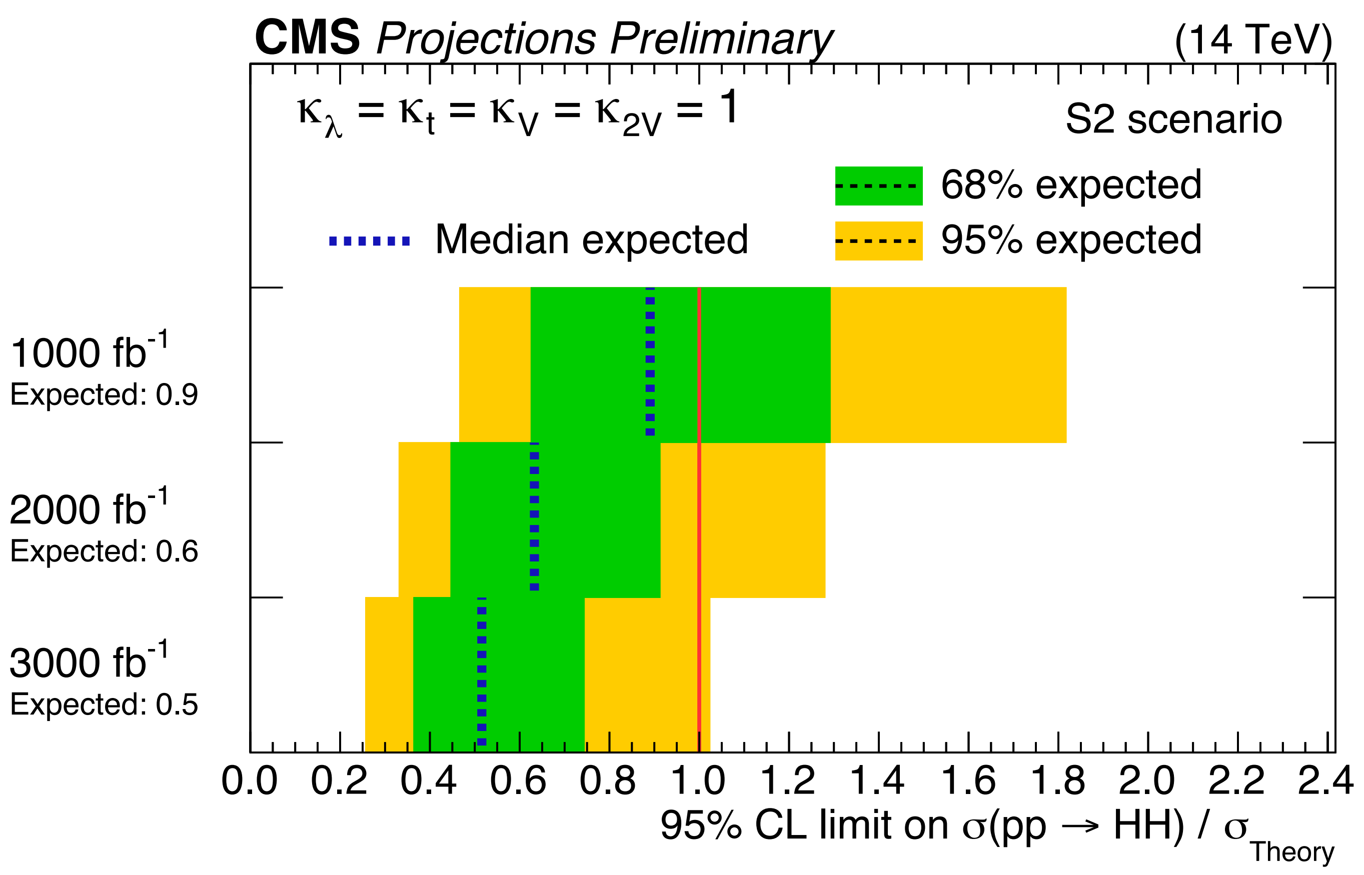
- HH xsec ~1000 lower than single H
- Recent HL-LHC projections based on Run 2 search much improved with respect to 2018 YR
  - Expect observation from combined ATLAS and CMS results

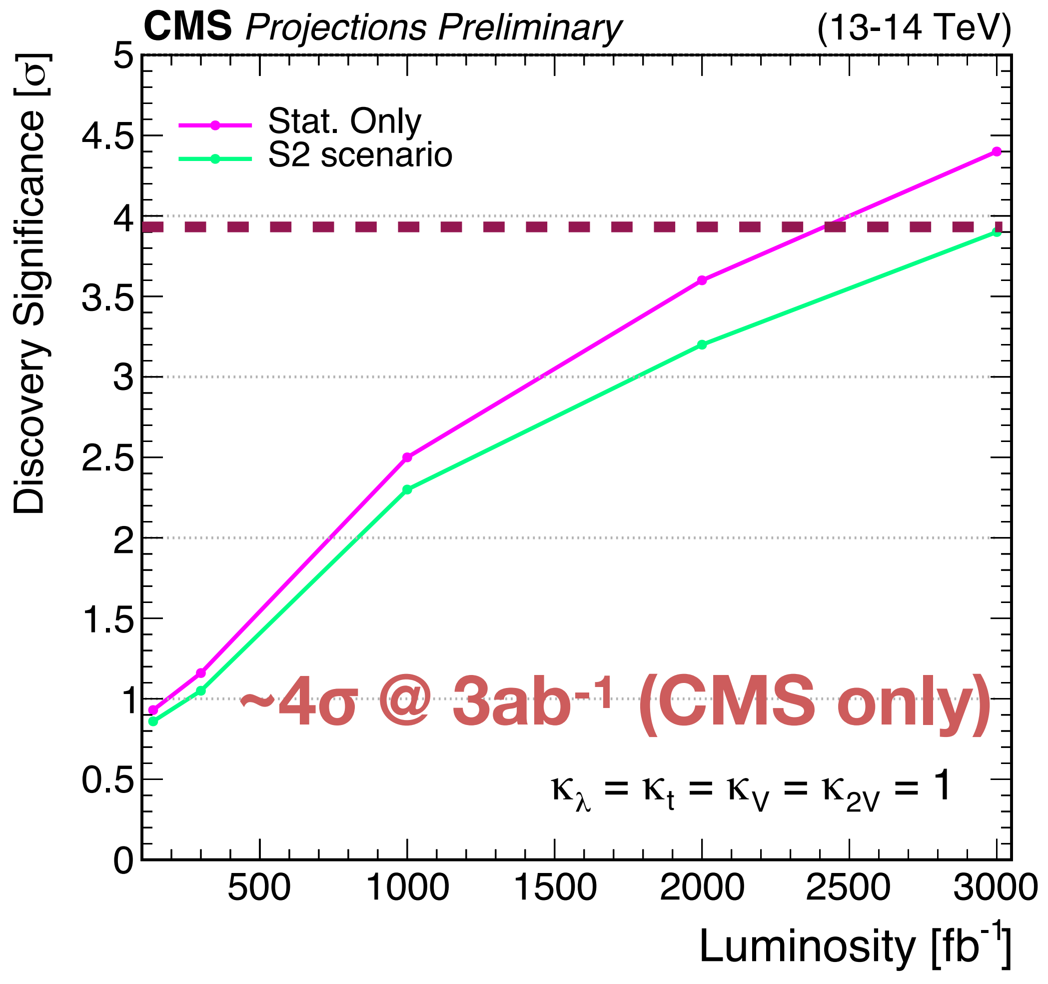
Yellow Report 2019

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

CMS-HIG-20-011

	Significance (σ) at 2000 fb^{-1}		Significance (σ) at 3000 fb^{-1}	
	S2	Stat. only	S2	Stat. only
$b\bar{b}b\bar{b}$ resolved jets	1.0	1.3	1.4	1.6
$b\bar{b}b\bar{b}$ merged jets	1.7	1.7	2.0	2.1
$b\bar{b}\tau\tau$	1.7	1.9	2.1	2.3
$b\bar{b}WW$	0.6	0.8	0.7	0.9
$b\bar{b}\gamma\gamma$	1.8	1.9	2.2	2.3
Combination	3.2	3.6	3.8	4.3





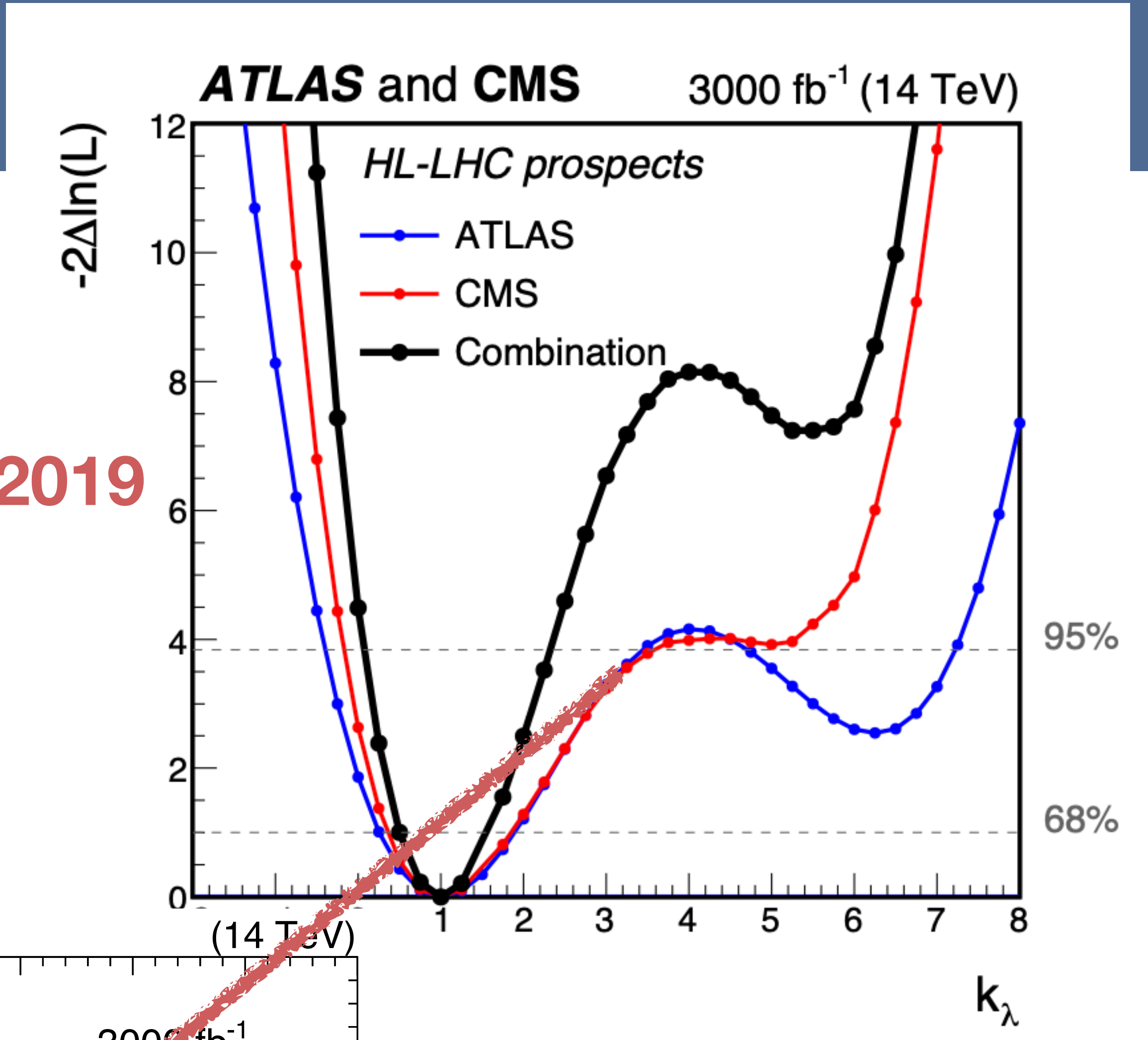
Higgs self-coupling

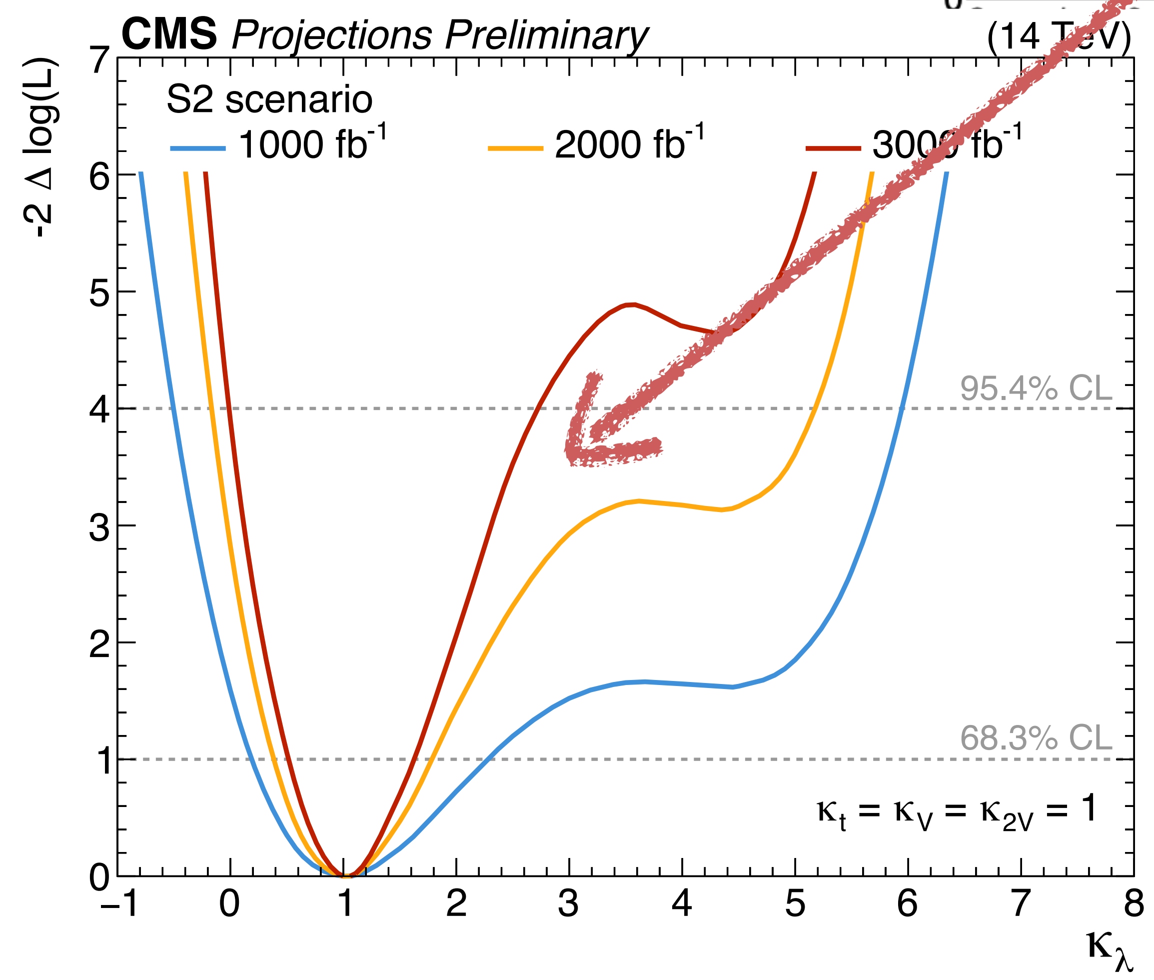
[CMS-HIG-20-011](CMS-HIG-20-011)

HL flagship measurement: di-Higgs production

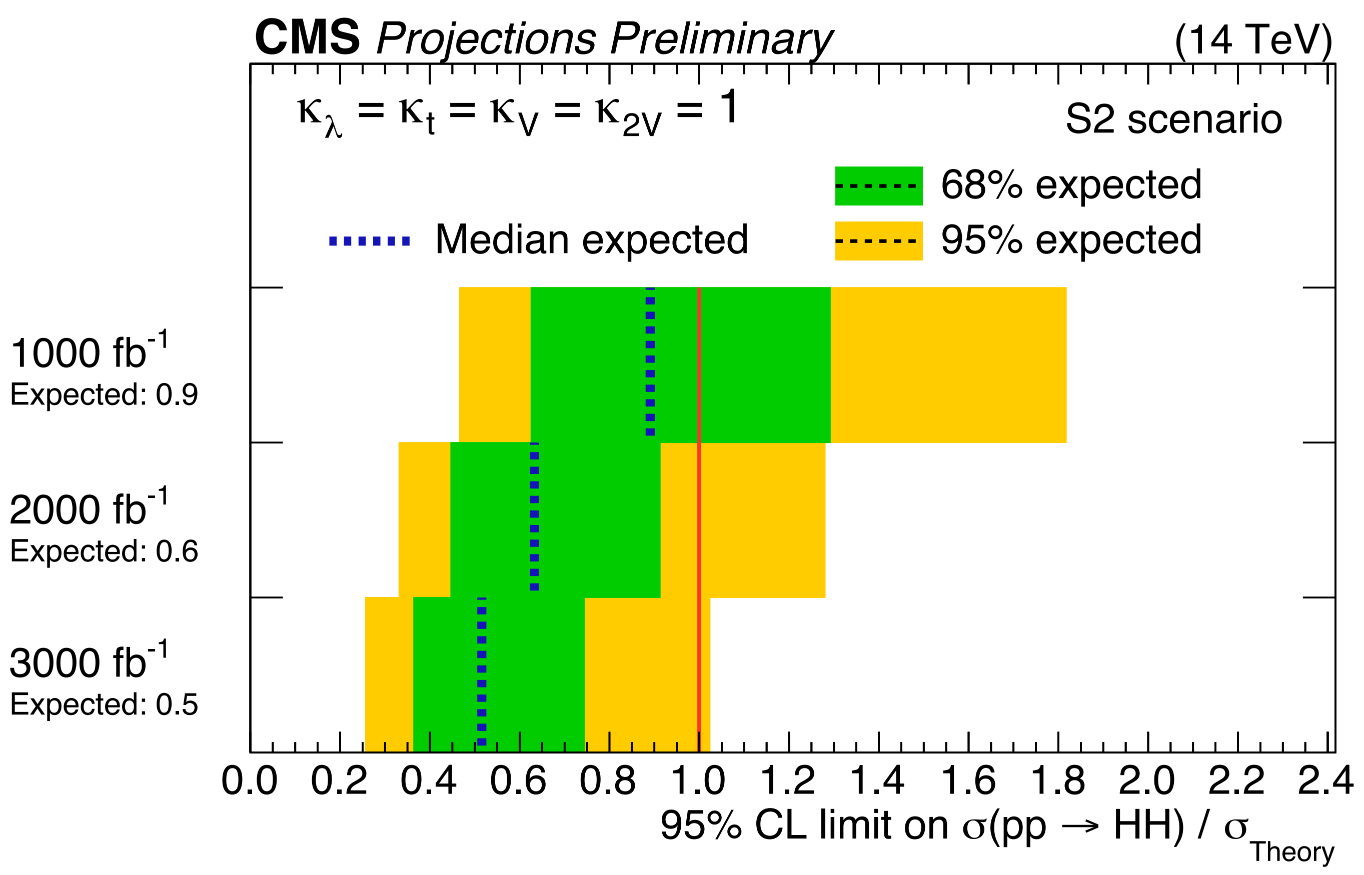
- HH ~1000x more rare than single H
- Recent HL-LHC projections based on Run 2 search much improved with respect to 2018 YR
  - Cross section and m_{HH} depend on H self-coupling
  - k_λ well below 1.5 for combined results

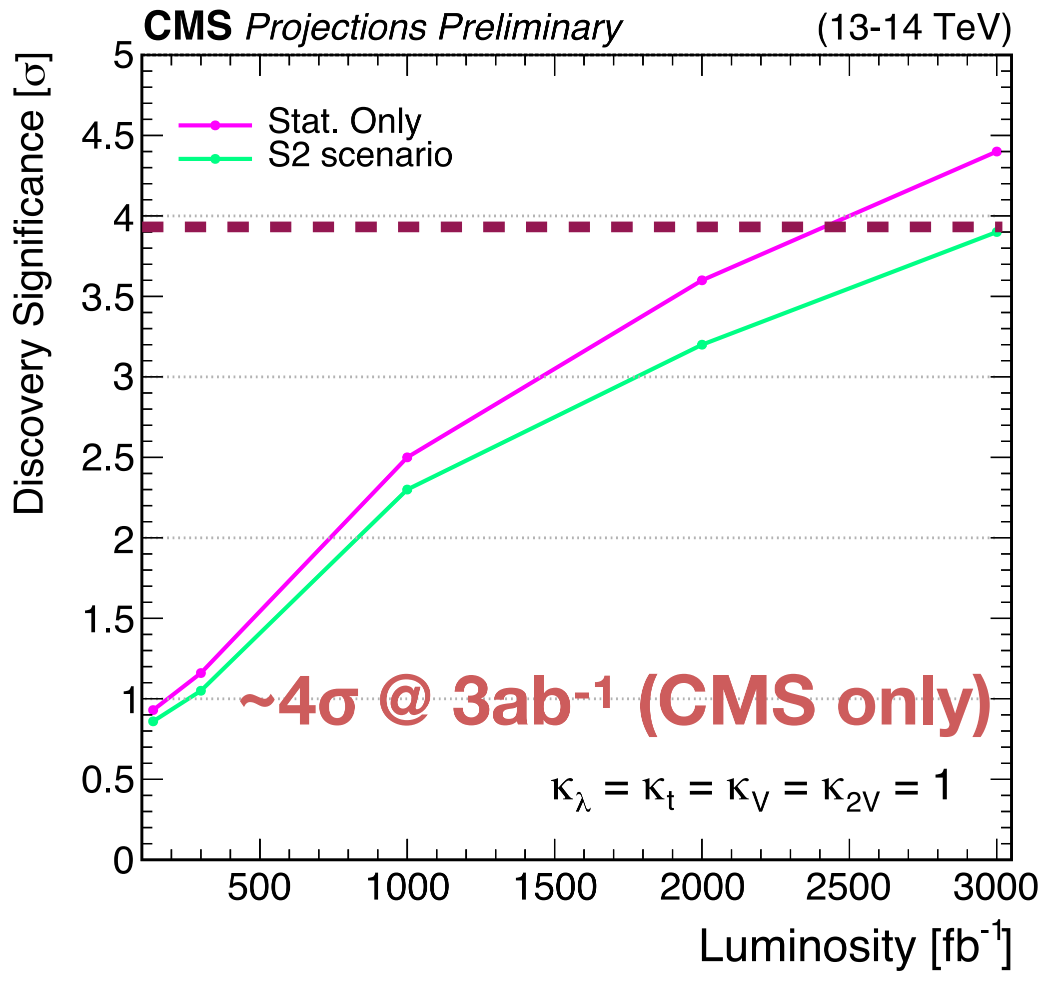
Yellow Report 2019





CMS-HIG-20-011





Latest developments on id and reco algorithms not included, not detector upgrade

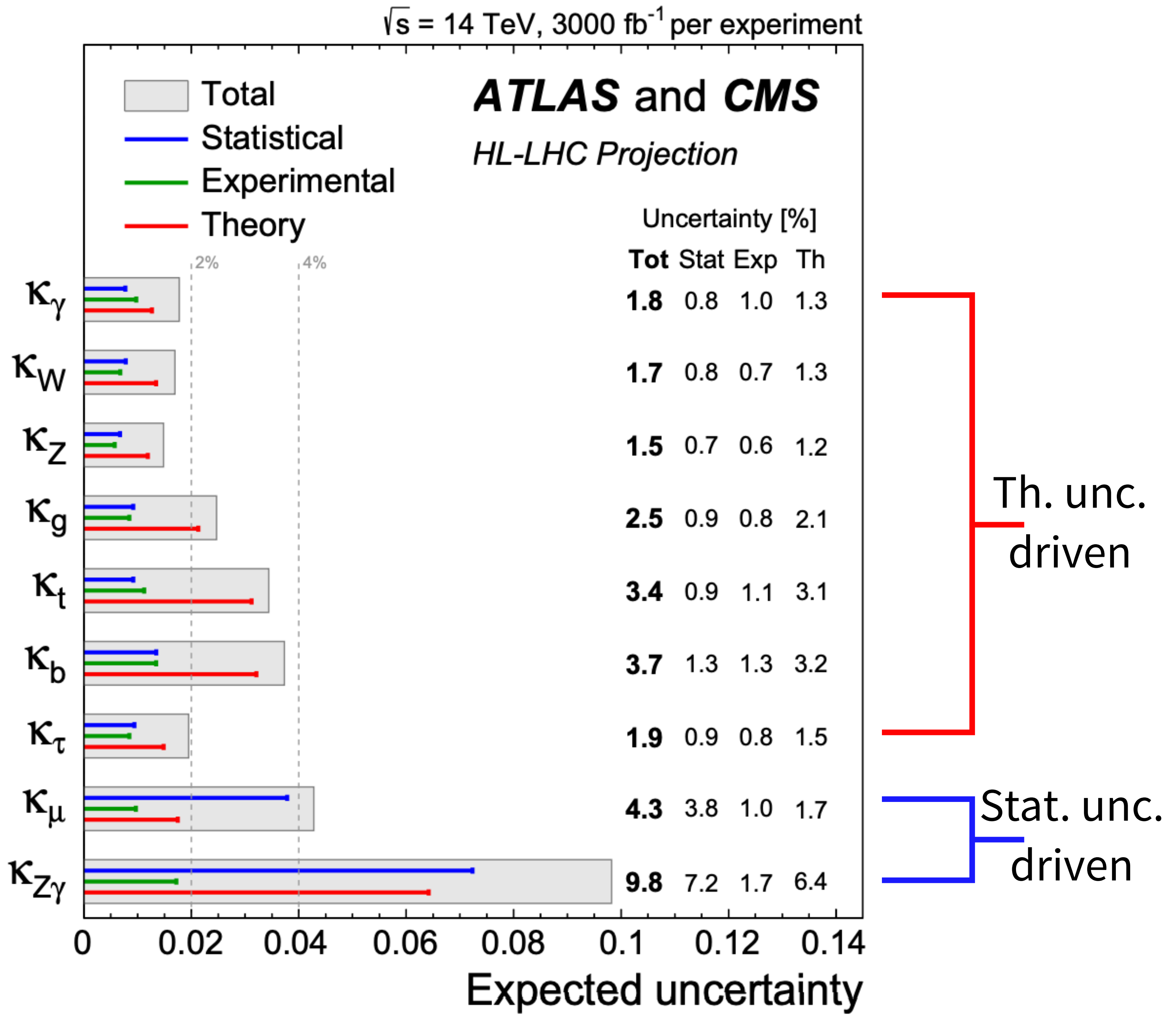
- ~10% improvement in b-tagging efficiency from new tracker

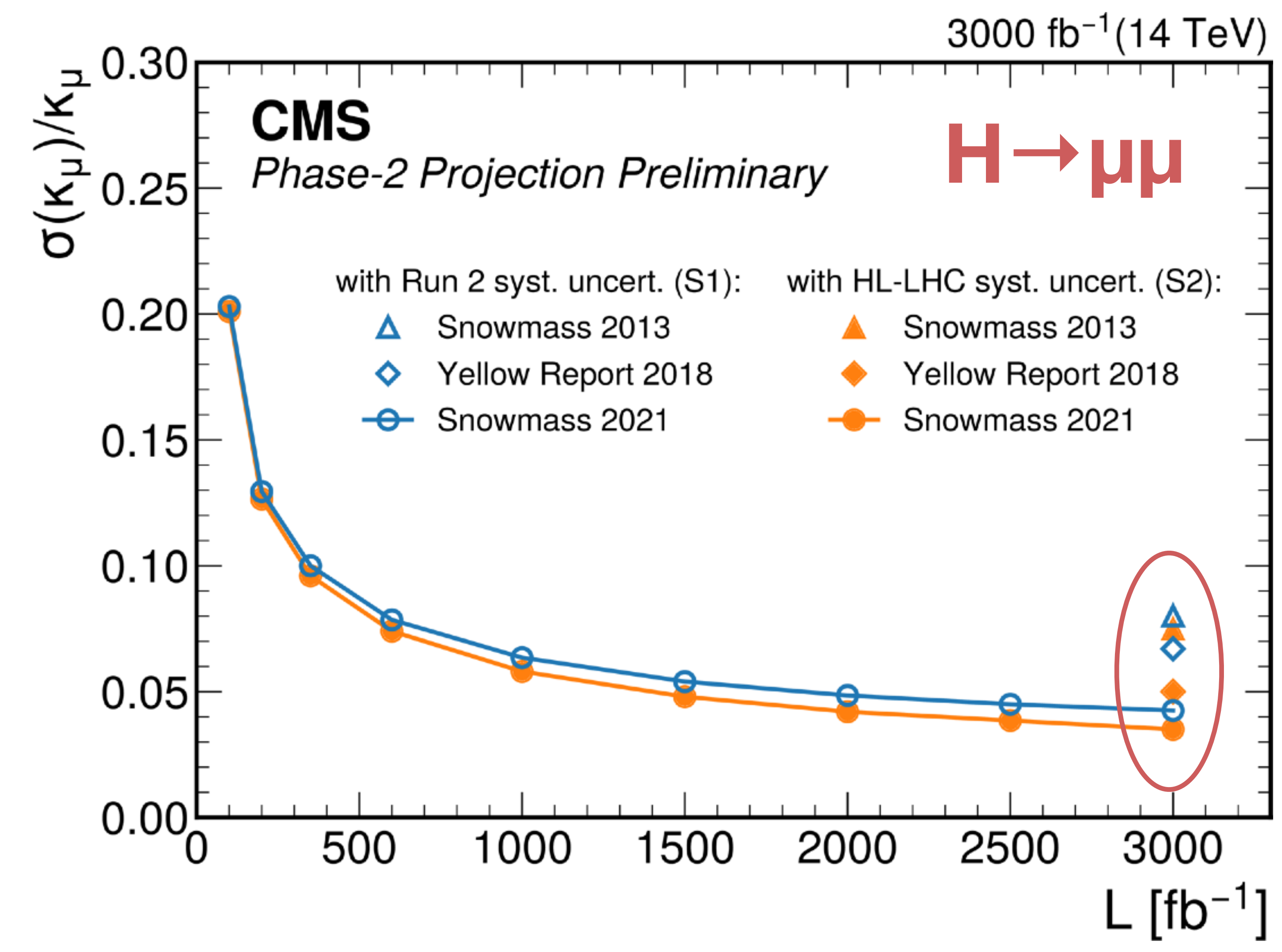
$H \to \mu\mu$

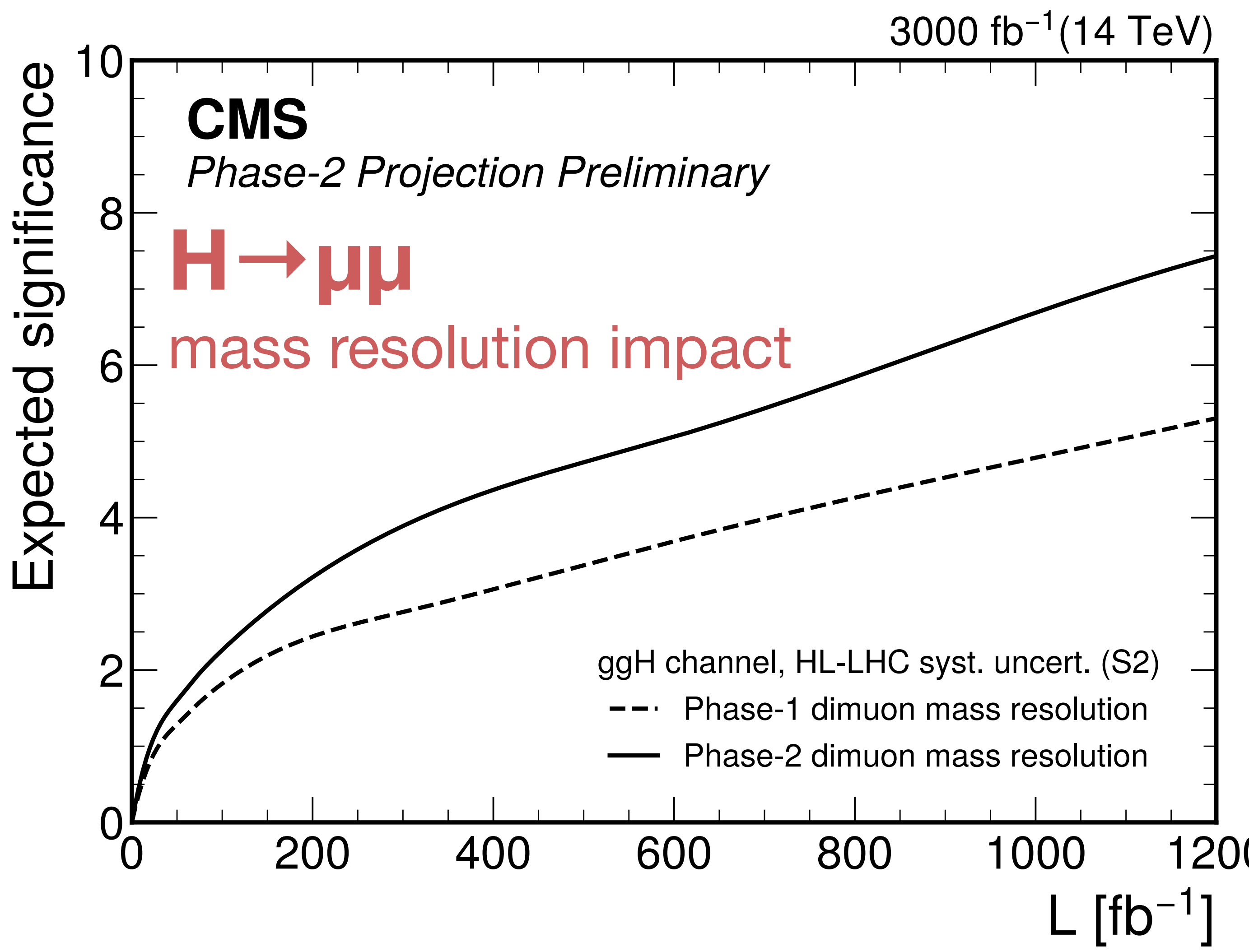
[CMS-PAS-FTR-21-006]

Most Higgs couplings expected to be known to a few percent, including H→μμ (testing origin of 2nd generation masses)

- H→μμ discovery expected by end-of-Run3/Run4.
- High precision measurement in Run 5 (**3.5 - 4.3 % unc. on** k_μ)







- **30 -35% improvement due to upgraded detector** (improved mass resolution and increased forward acceptances, $|\eta| < 2.4 \to |\eta| < 2.8$
  - and 50-60% improvement wrt extrapolations from Run1

4 tops

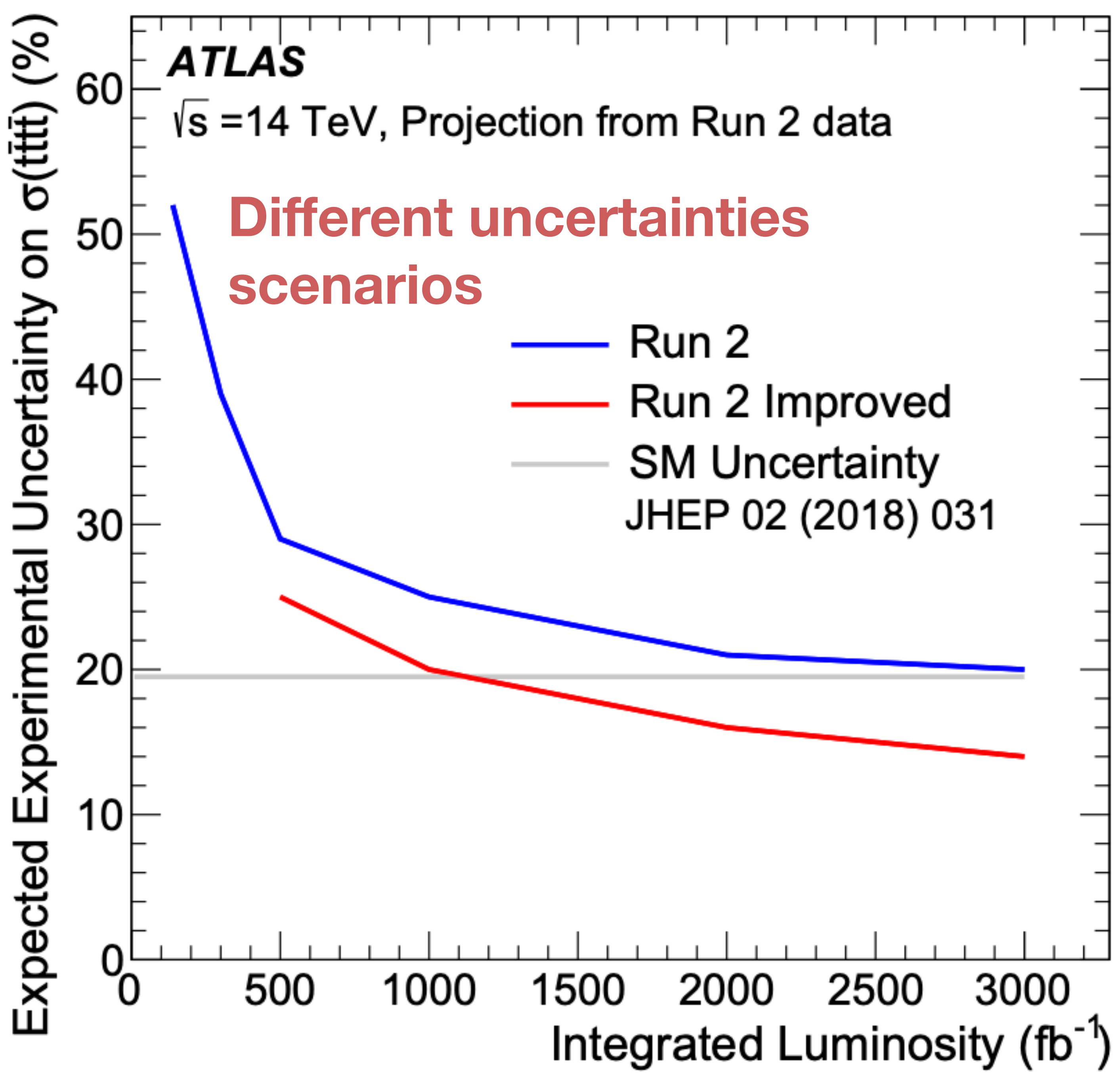
ATLAS-PHYS-PUB-2022-004

4 tops production: rare process sensitive to BSM Physics

- Projections from ATLAS (based on first Run 2 results): **~15% precision on cross section**
  - syst. unc starting to dominate ~500 fb^{-1}
  - **4.2 (6.4) σ expected with $3ab^{-1}$** for more pessimistic (optimistic) scenario

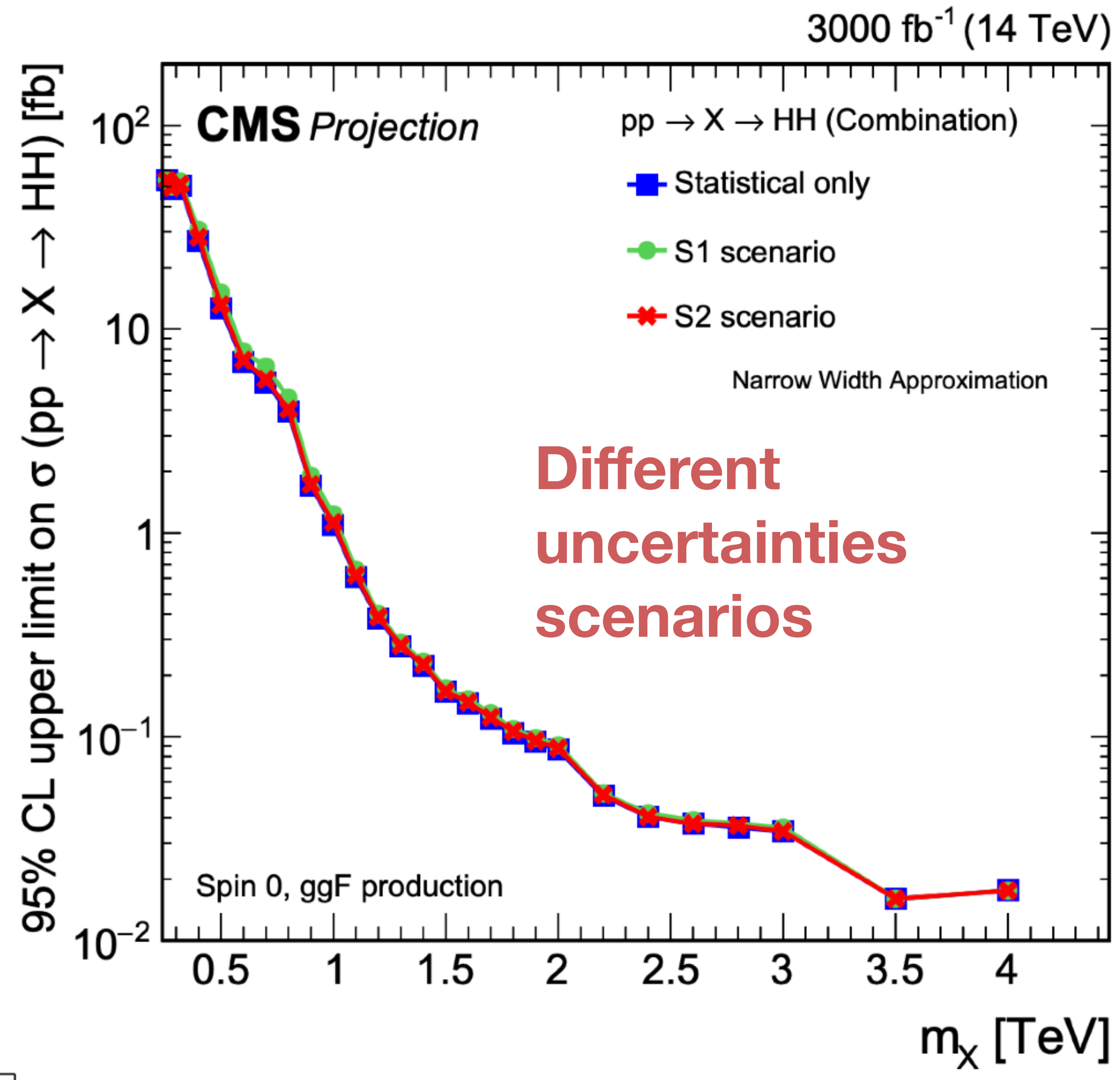
Expectations already superseded by latest Run 2 Results:

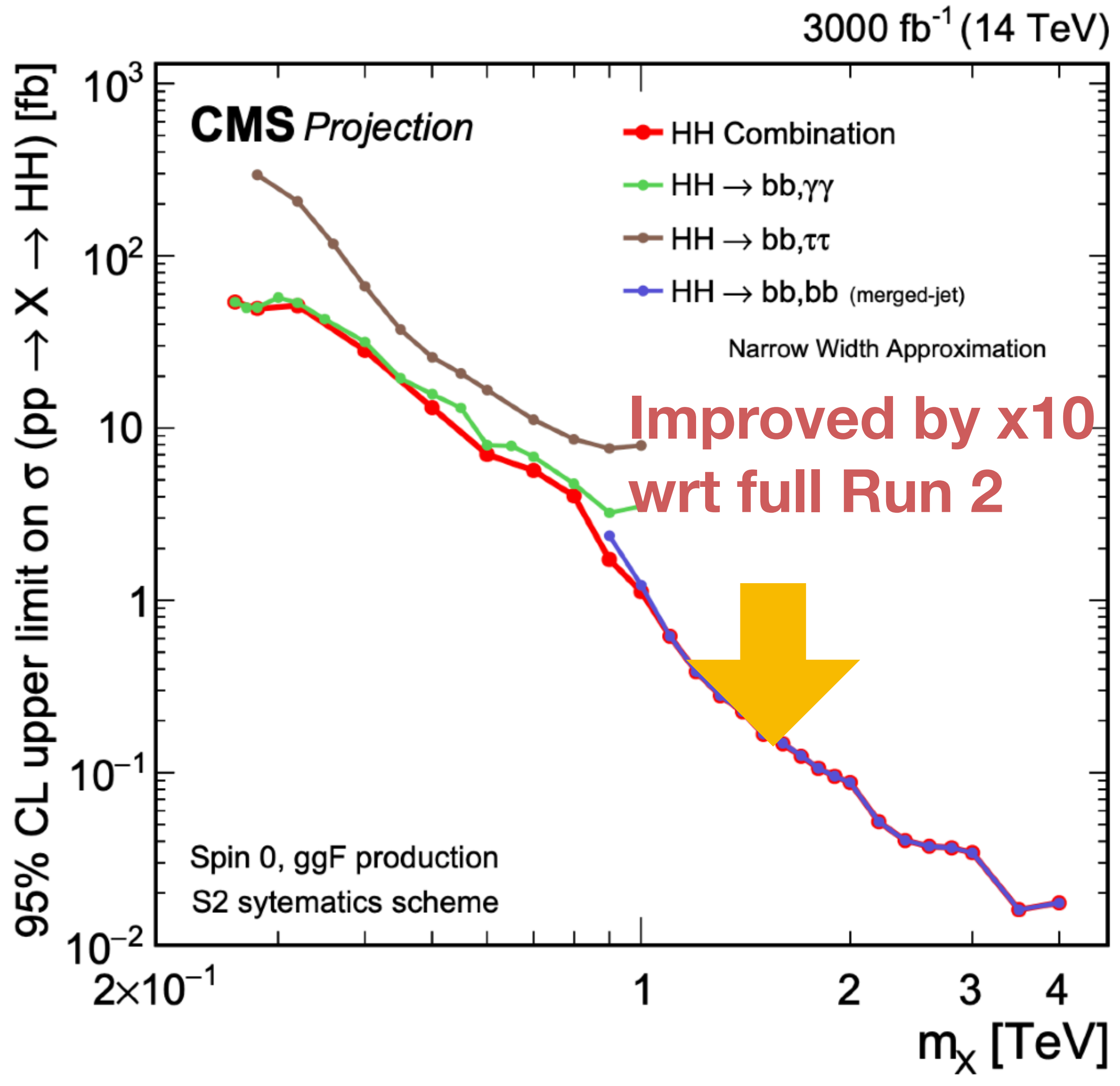
- Observation of 4 tops production announced by CMS (5.5σ) and ATLAS (6.1σ) already in 2023
  - Thanks to **improvements in identification techniques and data analysis strategy** (large use of ML) (bringing observed significance from 2.6 to 5.5 σ)

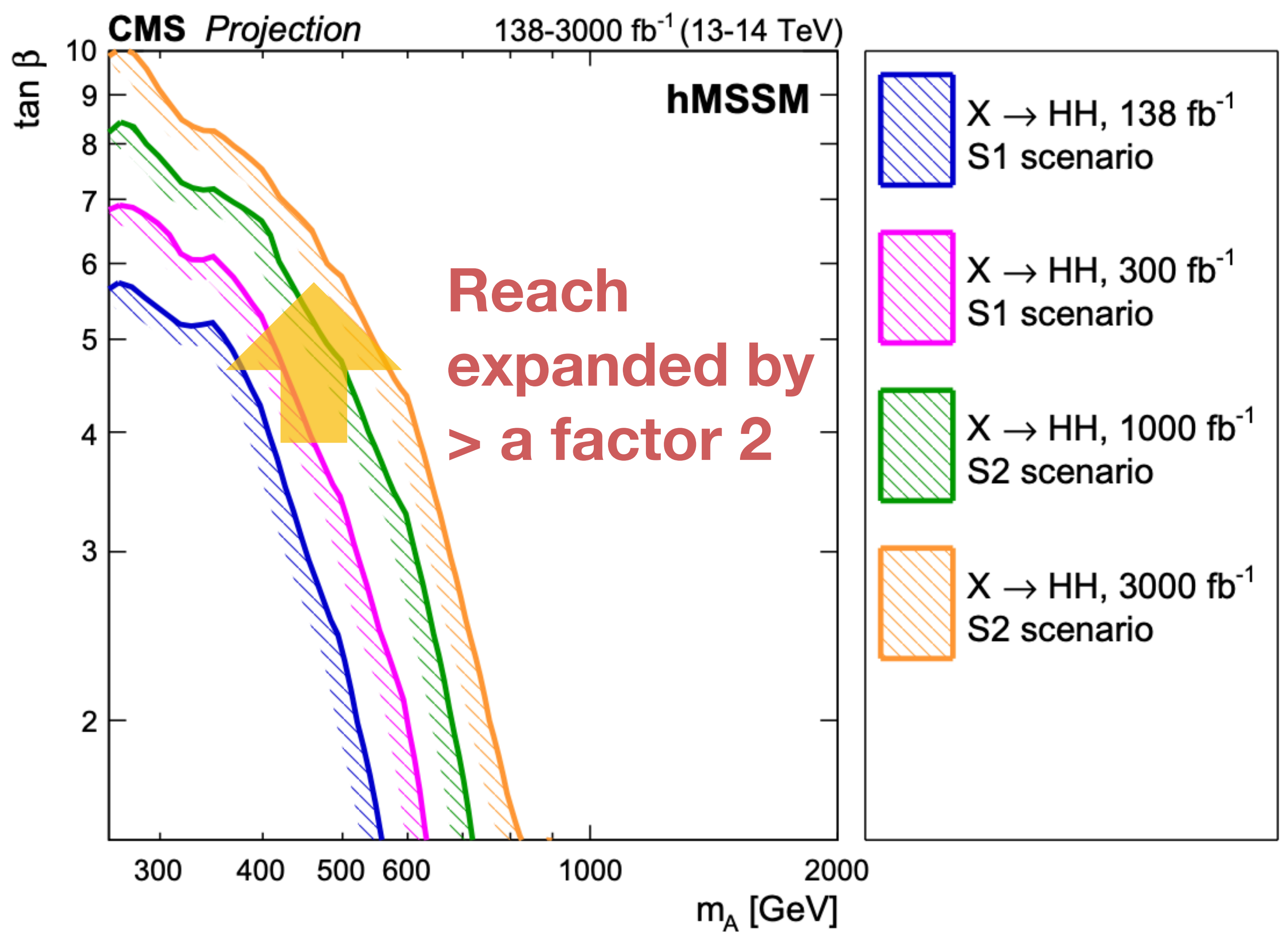


New massive resonances to H boson pairs

- Spin-0 and spin-2 new particles decaying to Higgs bosons, X->HH
  - H-> bb highly boosted: merged large-radius jets
  - **4b channel prevails at high mass**, while bbγγ at low mass
  - Minor impact of syst. uncertainties
  - **hMSSM exclusion reach extended by at least a factor 2 in** $tan\beta$







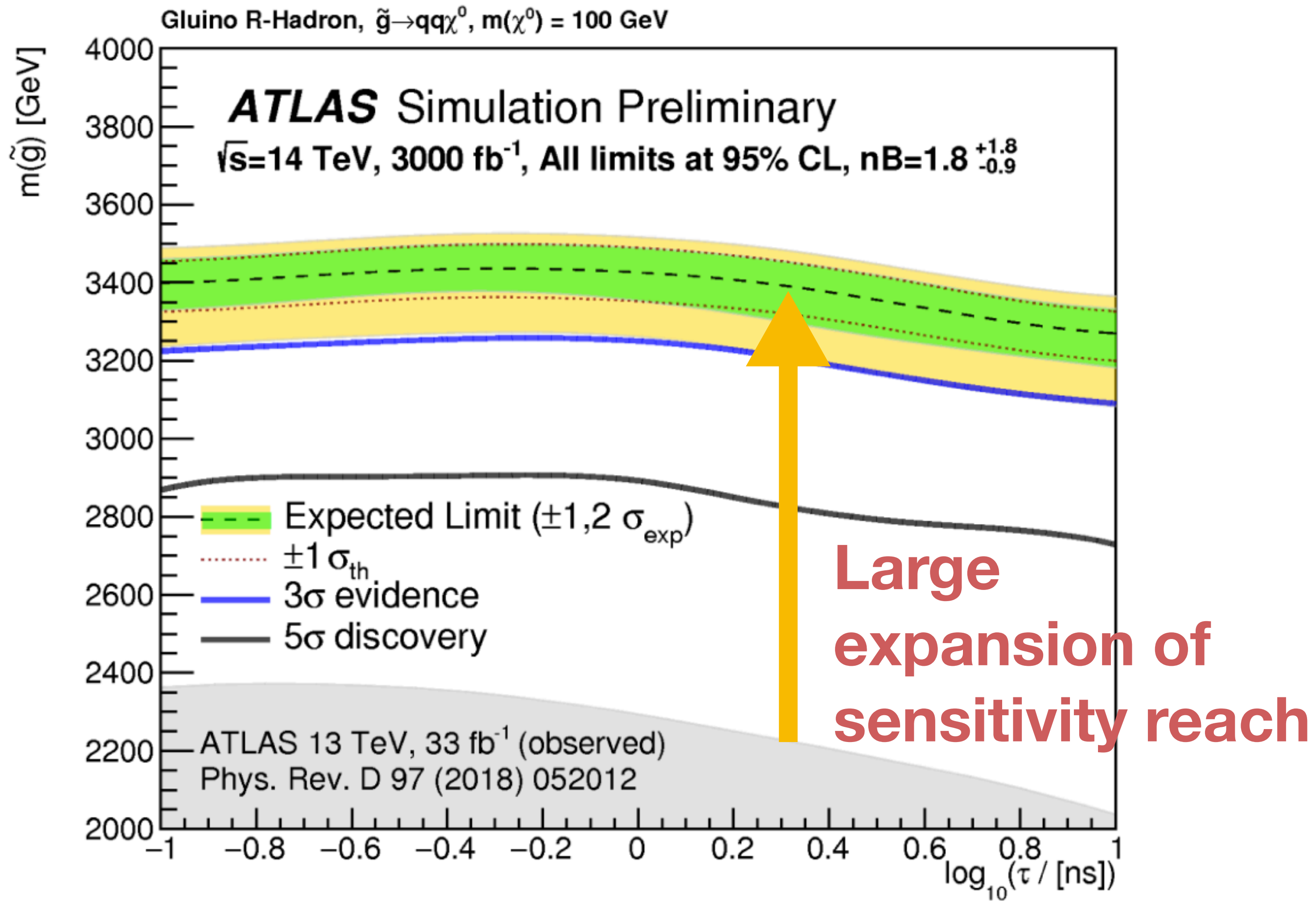
CMS-B2G-23-002

Yellow Report 2019

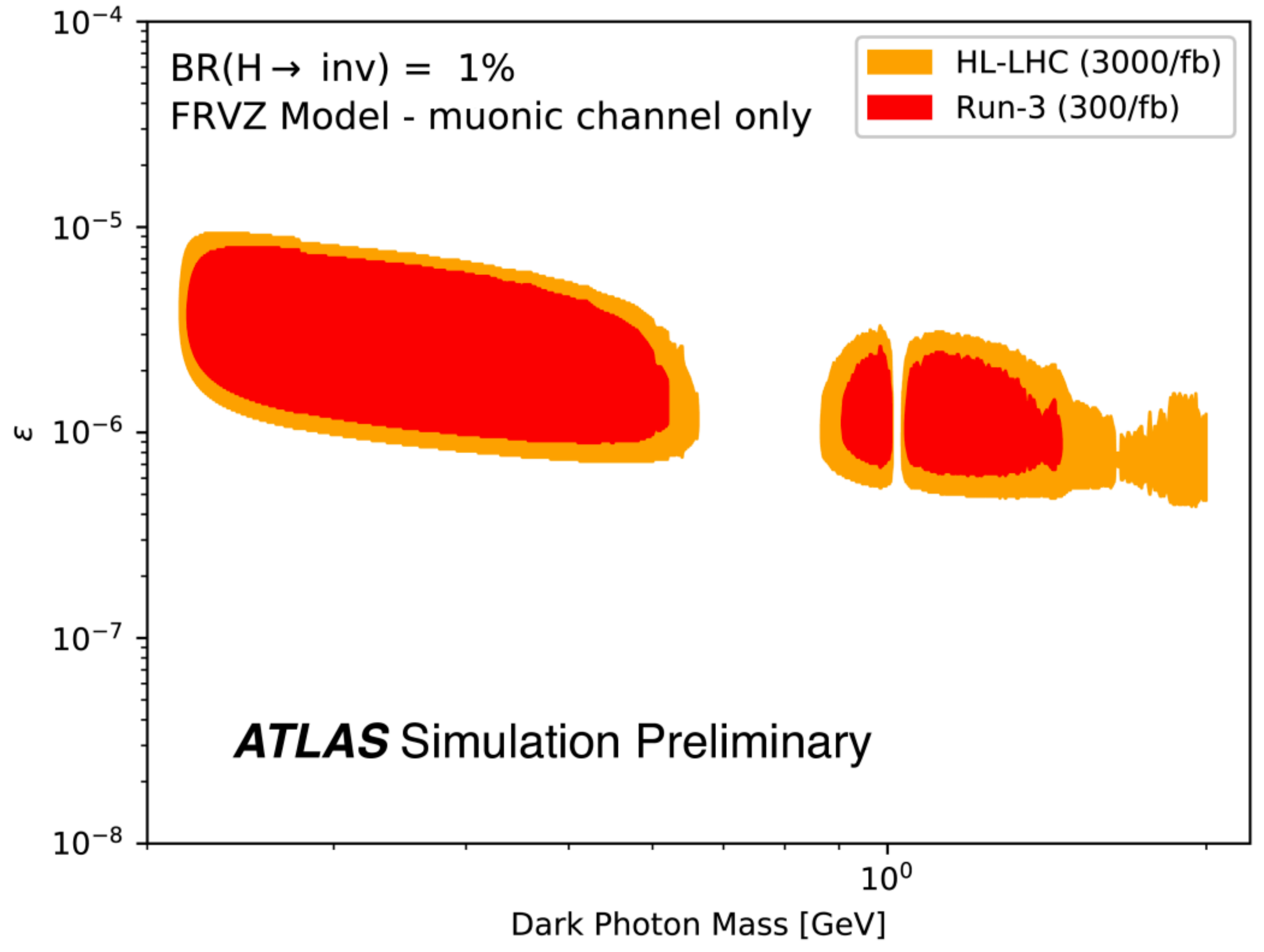
Searches for Long Lived Particles (LLPs) decaying far from the interaction point gain significantly from upgraded detector systems

- A variety of displaced signatures arise from several BSM scenarios:
  - Displaced hadron jets and missing momentum from gluino R-hadron pair production
  - Displaced collimated muon jets from dark photon decays

Gluino R-hadron decay search will gain from upgraded tracker



Dark photon decay



Summary

- **Run 3: huge advancements in trigger, reconstruction and analysis techniques**
  - New trigger strategies and AI/ML techniques as a boost to detector capabilities
  - Unconventional signatures search programme much expanded (e.g. LLP)

- **HL-LHC will further expand physics reach (despite challenging environment)**
  - Enabling precise measurements and rare processes searches

- **Run 2 analysis improvements reflected in improved HL-LHC predictions**
  - Run 3 developments not yet included
  - Huge potential from technical developments in next ~15 years

Our creativity can further push HL-LHC potential

Additional material

Higgs Mass

CMS-PAS-FTR-21-007

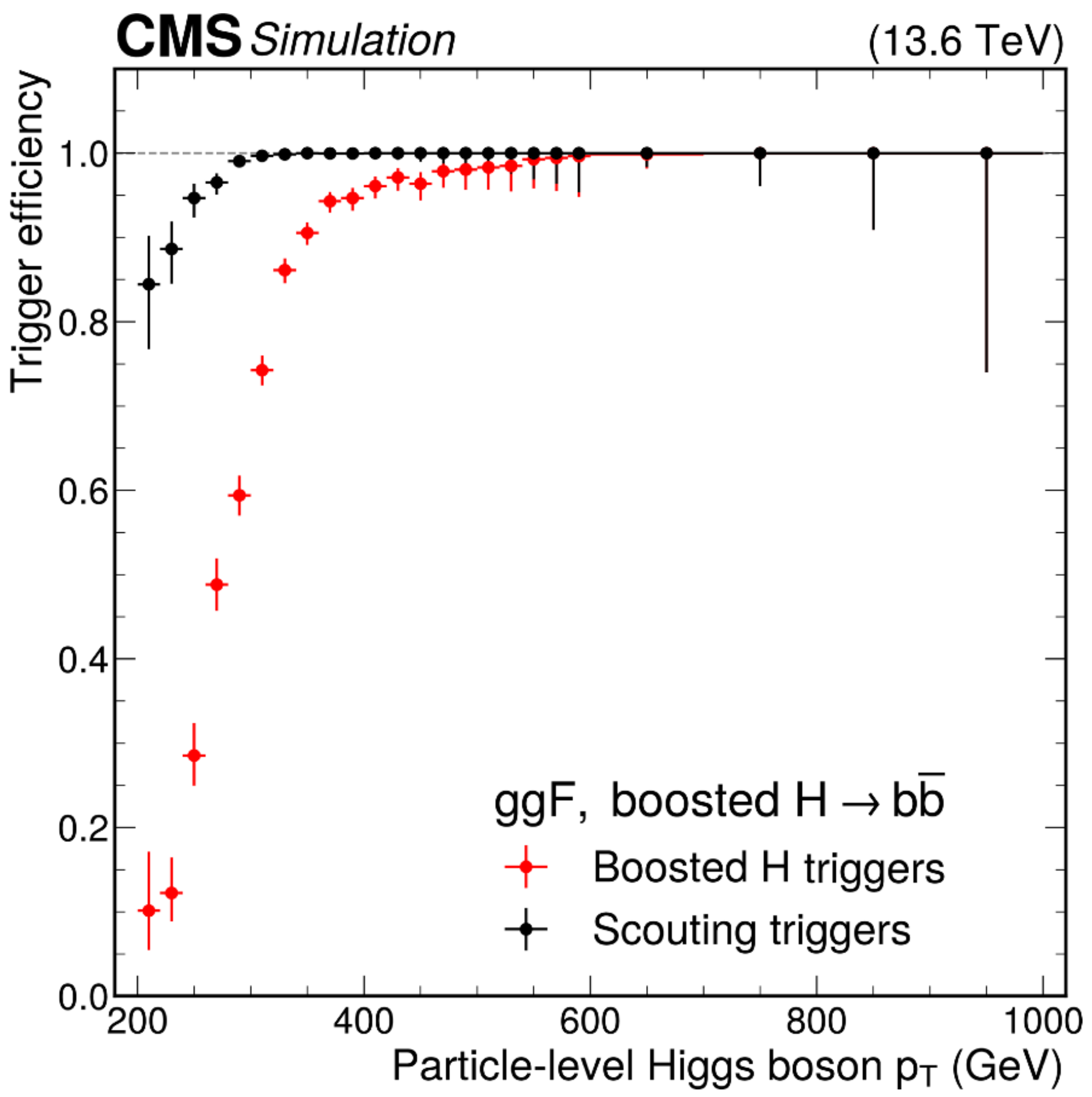
- *Optimistic scenario:* Halved dominant syst uncertainties (lepton scale and resolution)
- *Pessimistic scenario*: doubling bkg syst unc taking into account possible pileup impact on lepton identification

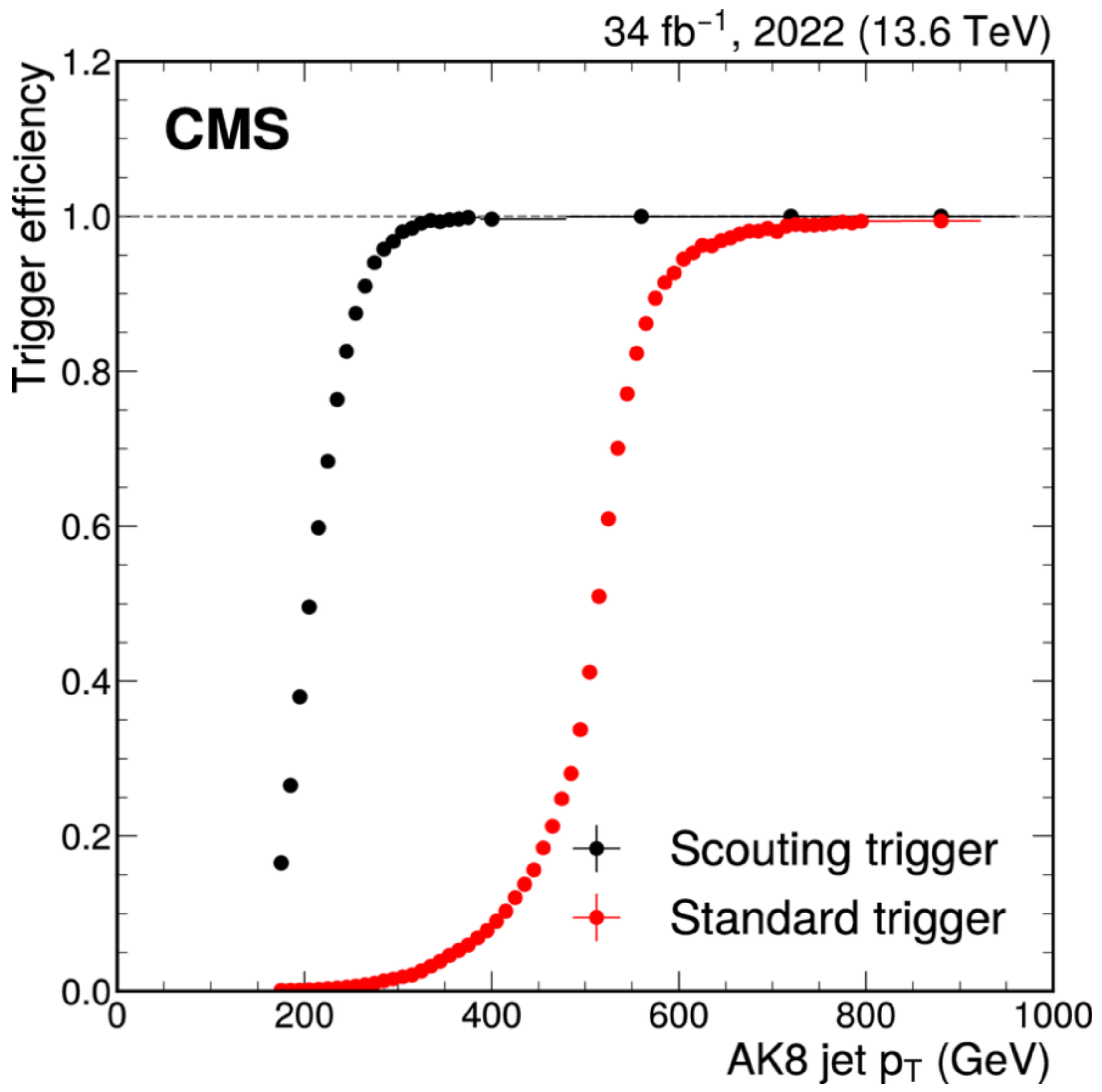
Systematic uncertainty	Baseline	Optimistic	Pessimistic	YR
Muon momentum scale	0.01%	0.005%	0.01%	0.05%
Electron momentum scale	0.15%	0.05%	0.15%	0.10-0.30%
Lepton momentum resolution	10%	5%	10%	5%

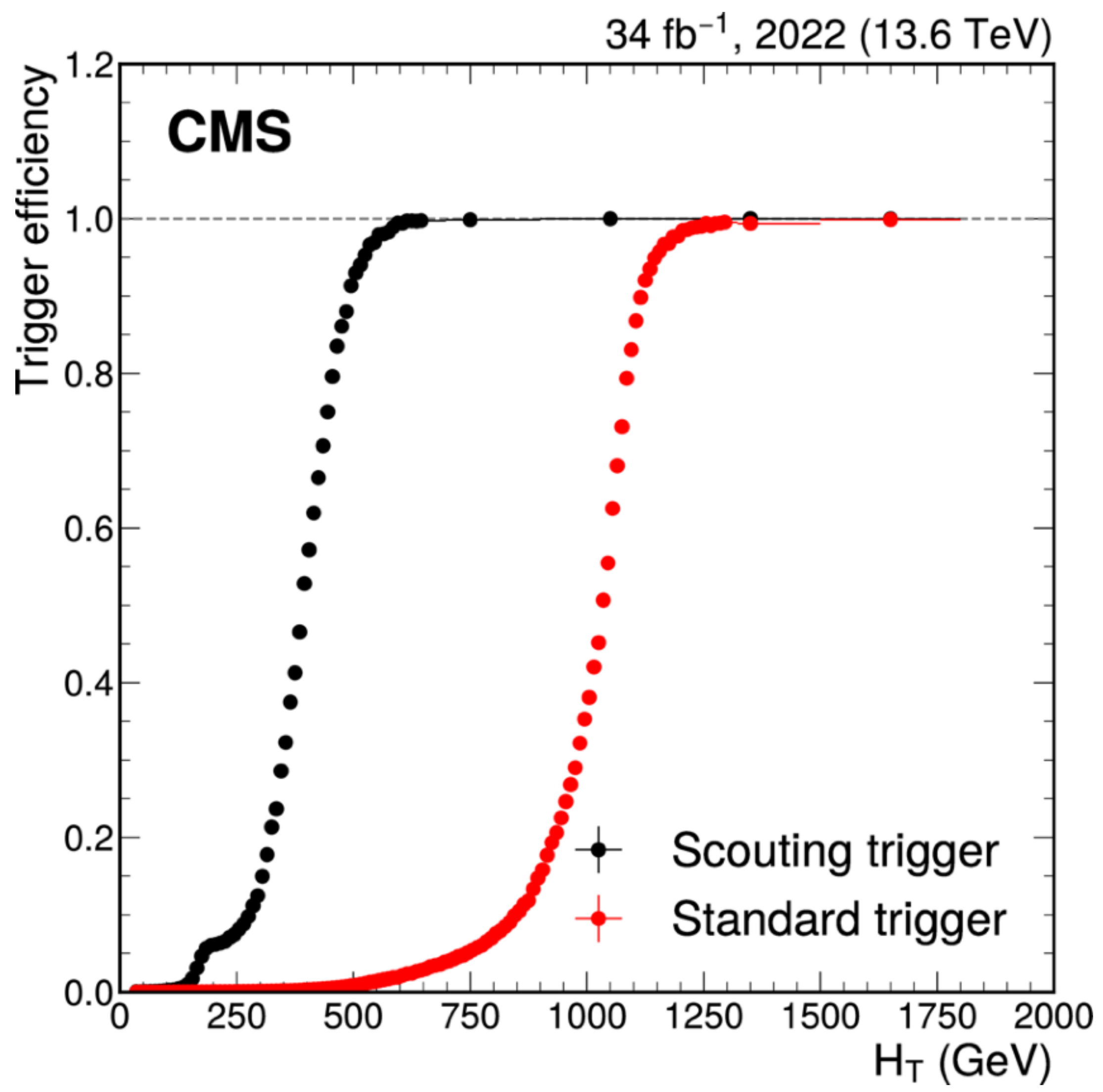
$m_{4\ell}$ expected uncertainty (MeV)	inclusive	4μ	4e	$2e2\mu$	$2\mu2e$
Optimistic					
Total	26	30	105	60	67
Syst impact	16	11	64	31	32
Stat only	22	28	83	51	59
Pessimistic					
Total	30	32	206	107	112
Syst impact	20	15	189	94	95
Stat only	22	28	83	51	59

Γ_H expected upper limit (MeV)	Projection	Optimistic	Pessimistic
Total	177	155	177
Syst impact	150	123	150
Stat only	94		

Offline vs Scouting



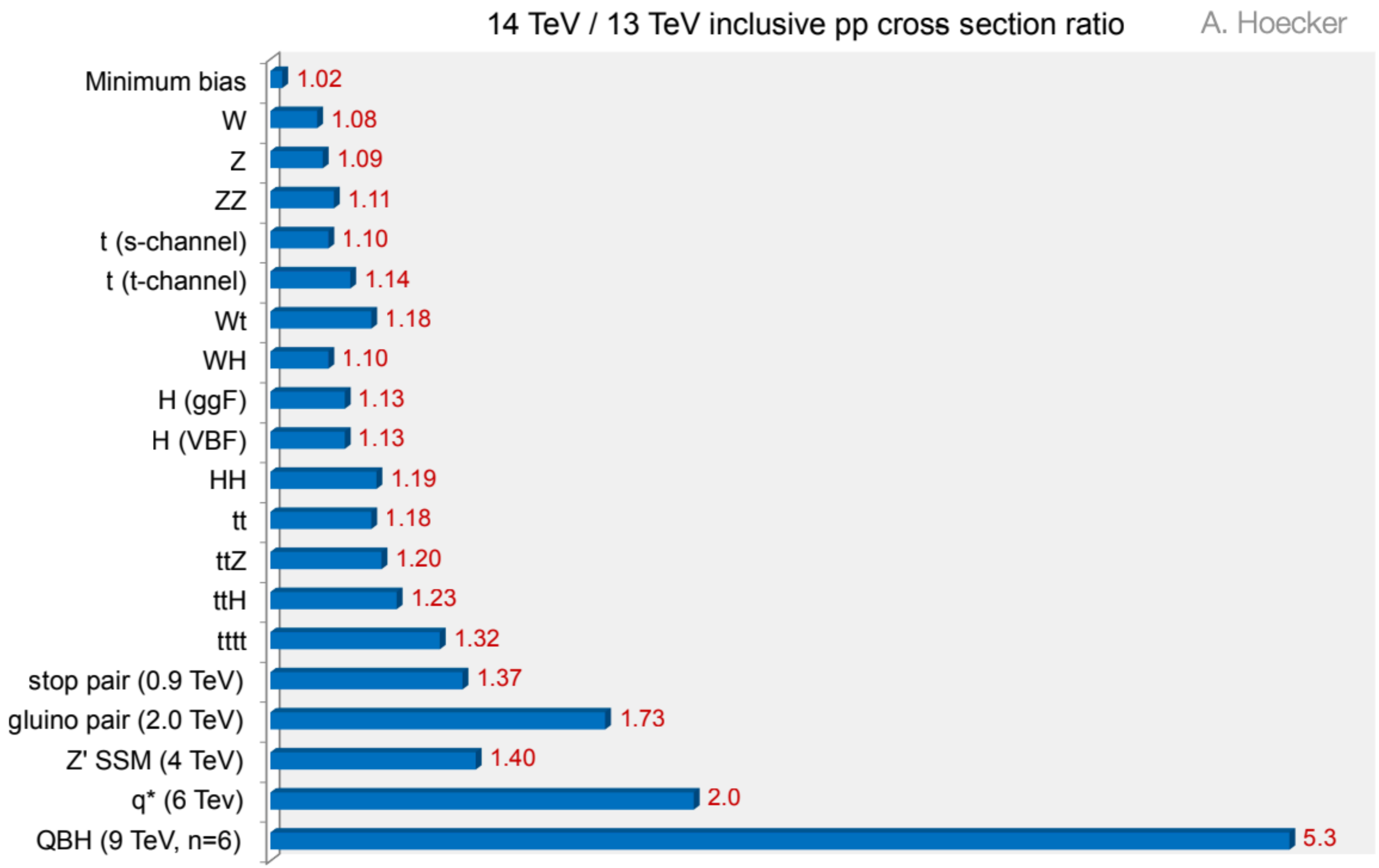




Trigger at HL-LHC

	LHC	HL-LHC	
CMS detector	Phase-1	Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB [a]	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [b]	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output [c]	1.4 MB	4.3 MB	5.9 MB
Storage throughput [d]	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day [e])	0.2 PB	1.6 PB	3.3 PB

14 TeV cross sections



MonoZ search for DM

[CMS-FTR-18-007](#)

- Expected sensitivity pushed to large DM mass and lower couplings
- Sensitivity to mediator masses expected to improve by ~ factor of 2 relative to current LHC results