INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma

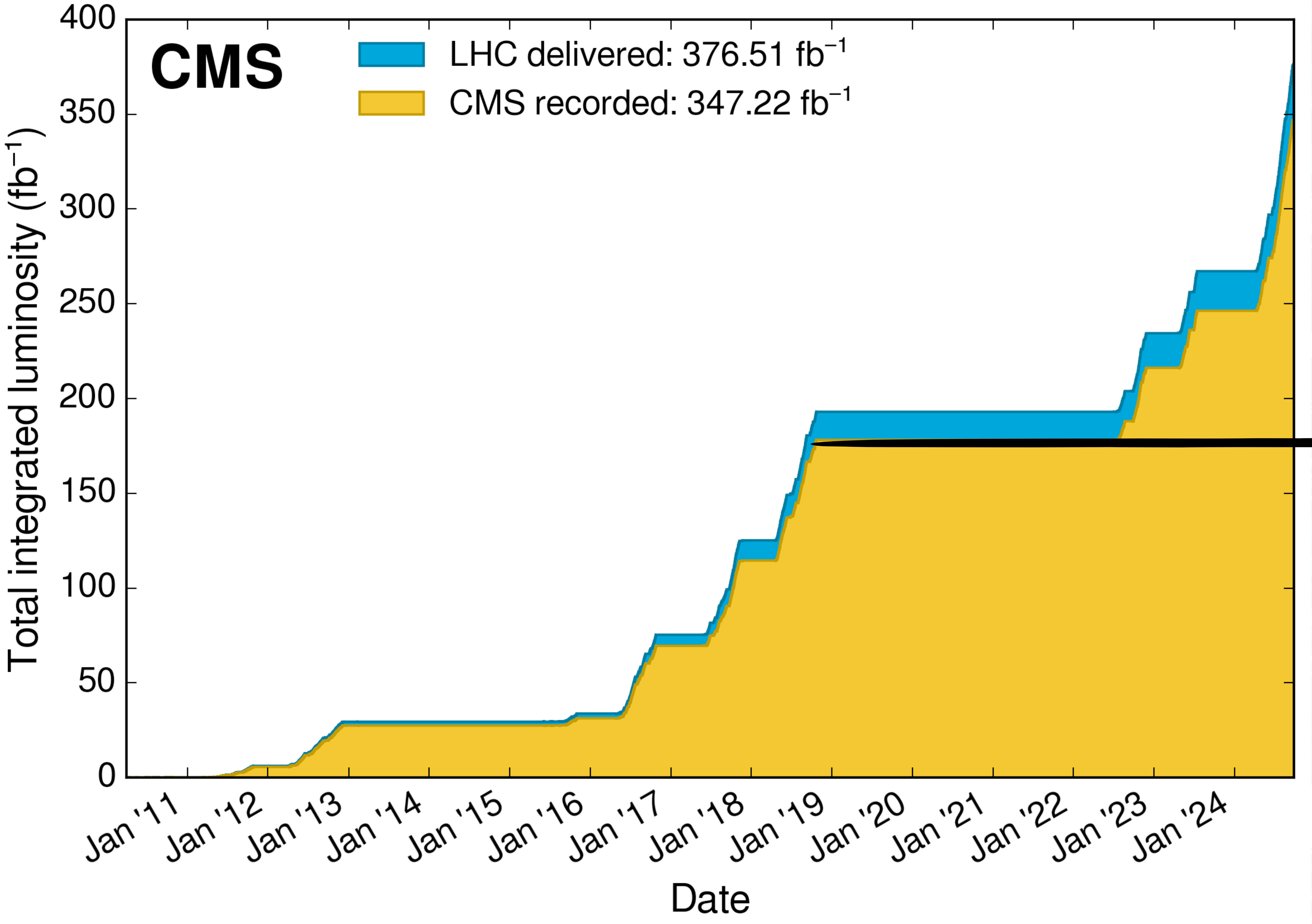
Standard Model and Beyond at HL-LHC: Experimental talk

Livia Soffi

Workshop on High Luminosity LHC and Hadron Colliders - October 4, 2024

LHC data taking overview

Excellent accelerator performance over many years



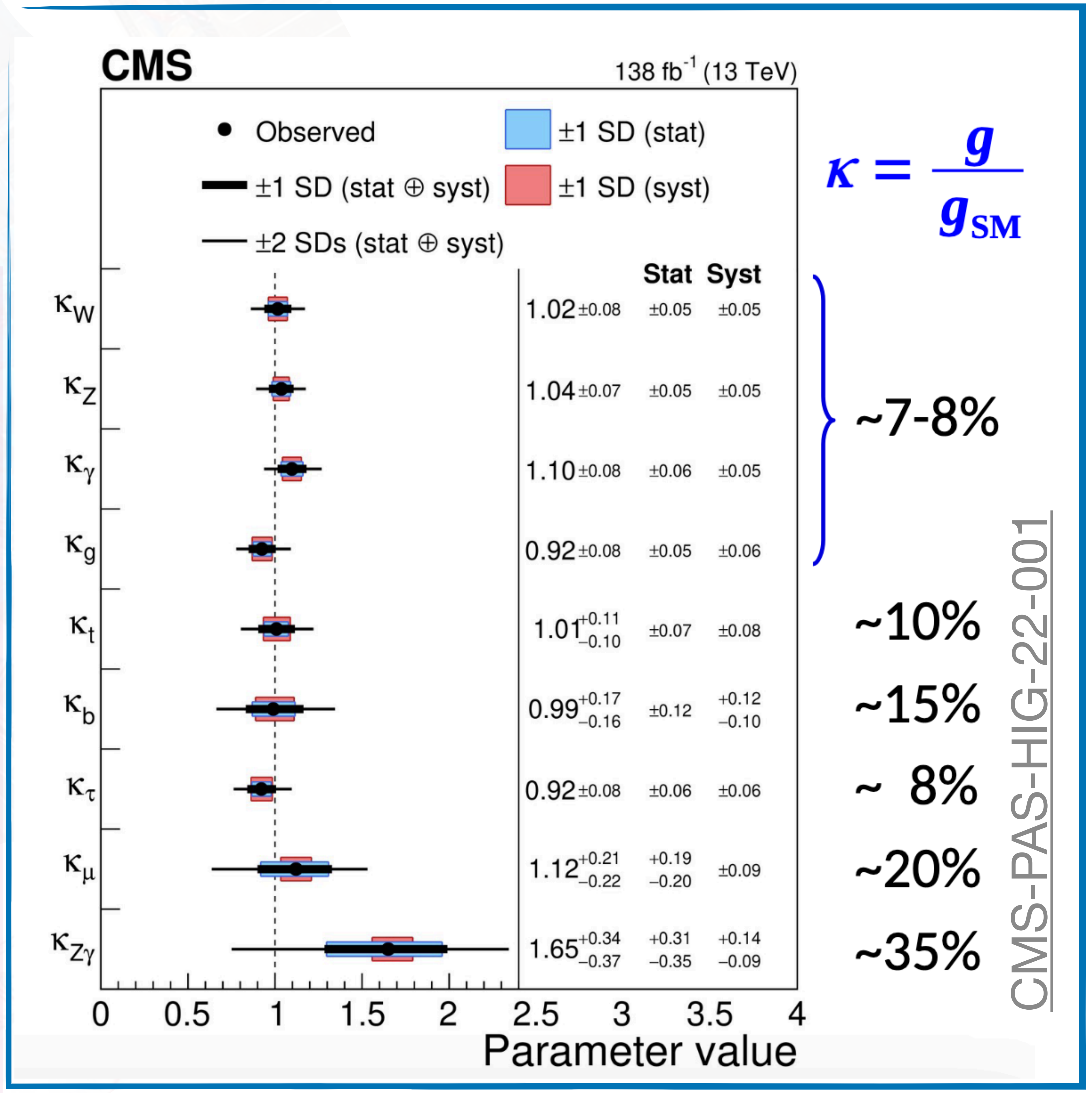
- **Run 3 dataset (13.6 TeV)**
  - Being collected now
  - ~110 fb-1 good for physics in 2022-2023-2024, expect >300 fb-1 at the end of 2025
- **Run 2 dataset (13 TeV)**
  - ~140 fb-1 good for physics
  - ~ 7M Higgs bosons produced
  - ~ 5000 reconstructed H→γγ

Run 2: Higgs boson physics legacy

- Very broad ongoing Higgs boson physics program at CMS and ATLAS
- Precision measurements: **few-% level on some couplings, 0.1% on mH.**
- Significant reduction in uncertainties on charm coupling
- Di-Higgs is reaching SM sensitivity with Run 2 data only
- Improvements driven by better analysis techniques and performance

CERN-EP-2024-160

CERN-EP-2024-175



$$\kappa = \frac{g}{g_{SM}}$$

CMS-PAS-HIG-22-001

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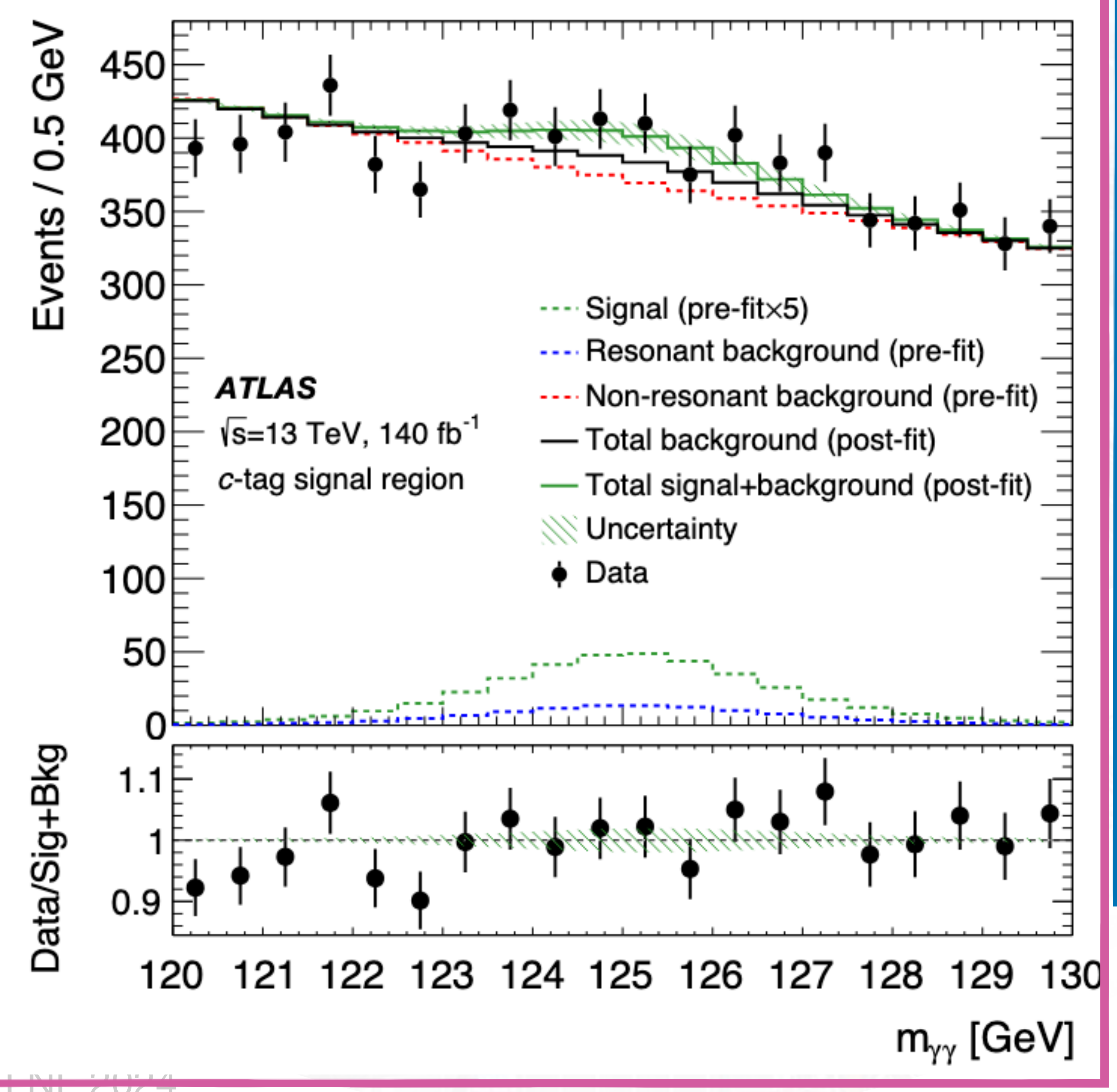
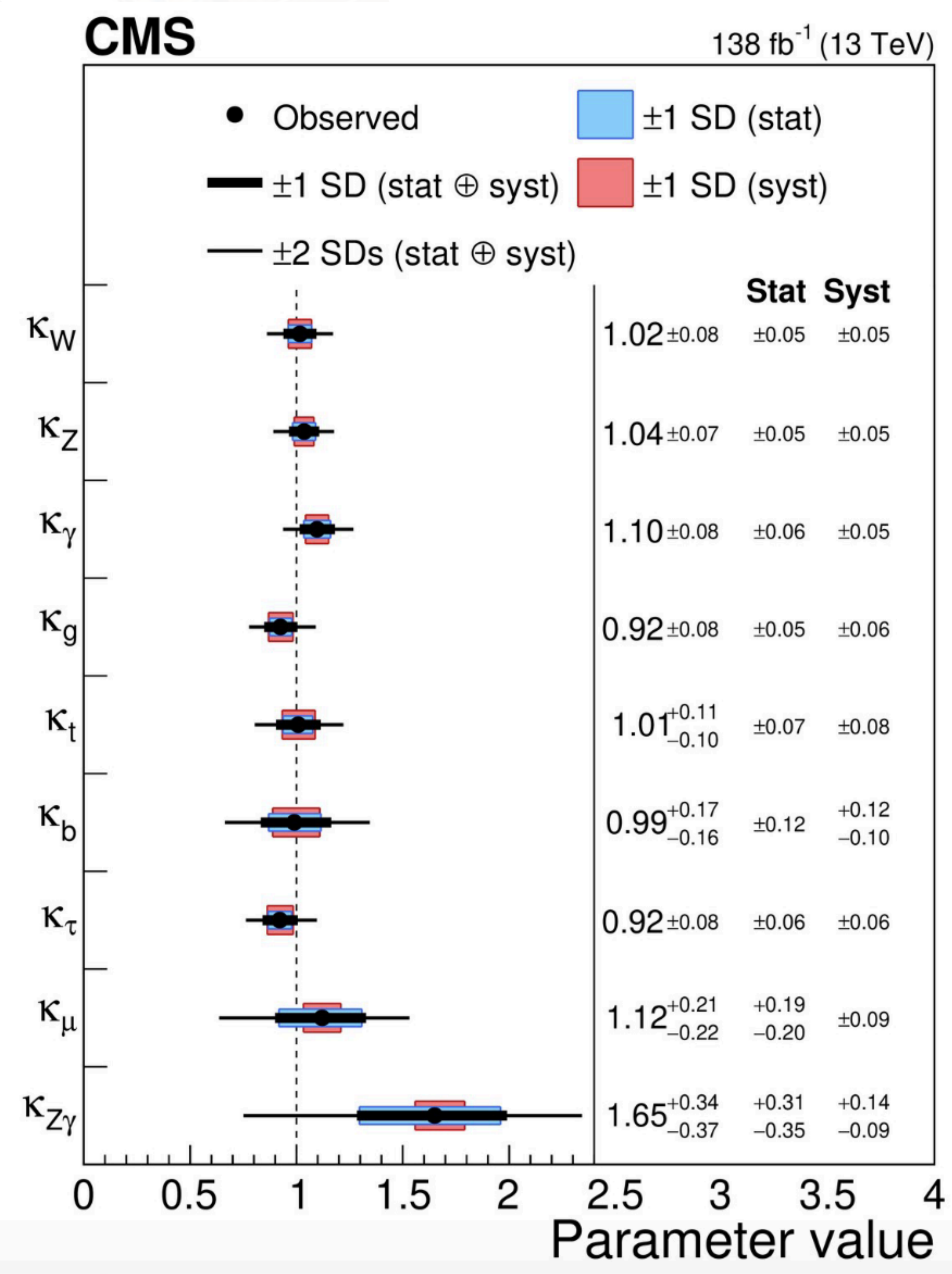
CERN-EP-2024-160

ATLAS: target inclusive H+c → σ(H+c) = 5.2 ± 3.0 pb (SM: 2.9 pb), < 10.4 pb @ 95% CL

CMS: target κ_c-dependent part : μ_{cH} < 243 (355) ⇒ $|\kappa_c|$ < 38.1 (72.5) @ 95% CL



CERN-EP-2024-175



$$\kappa = \frac{g}{g_{SM}}$$

~7-8%
~10%
~15%
~ 8%
~20%
~35%

CMS-PAS-HIG-22-001

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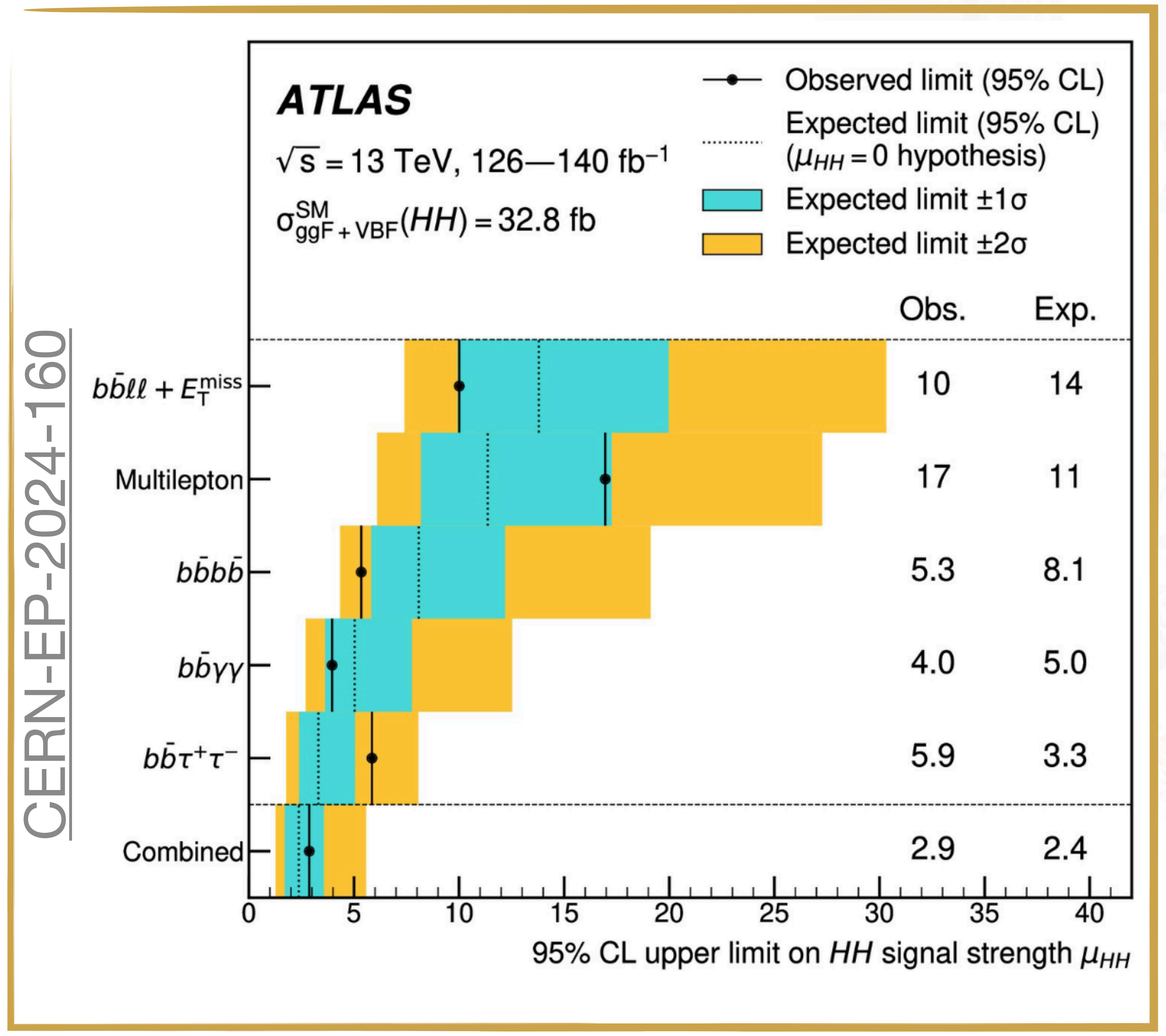

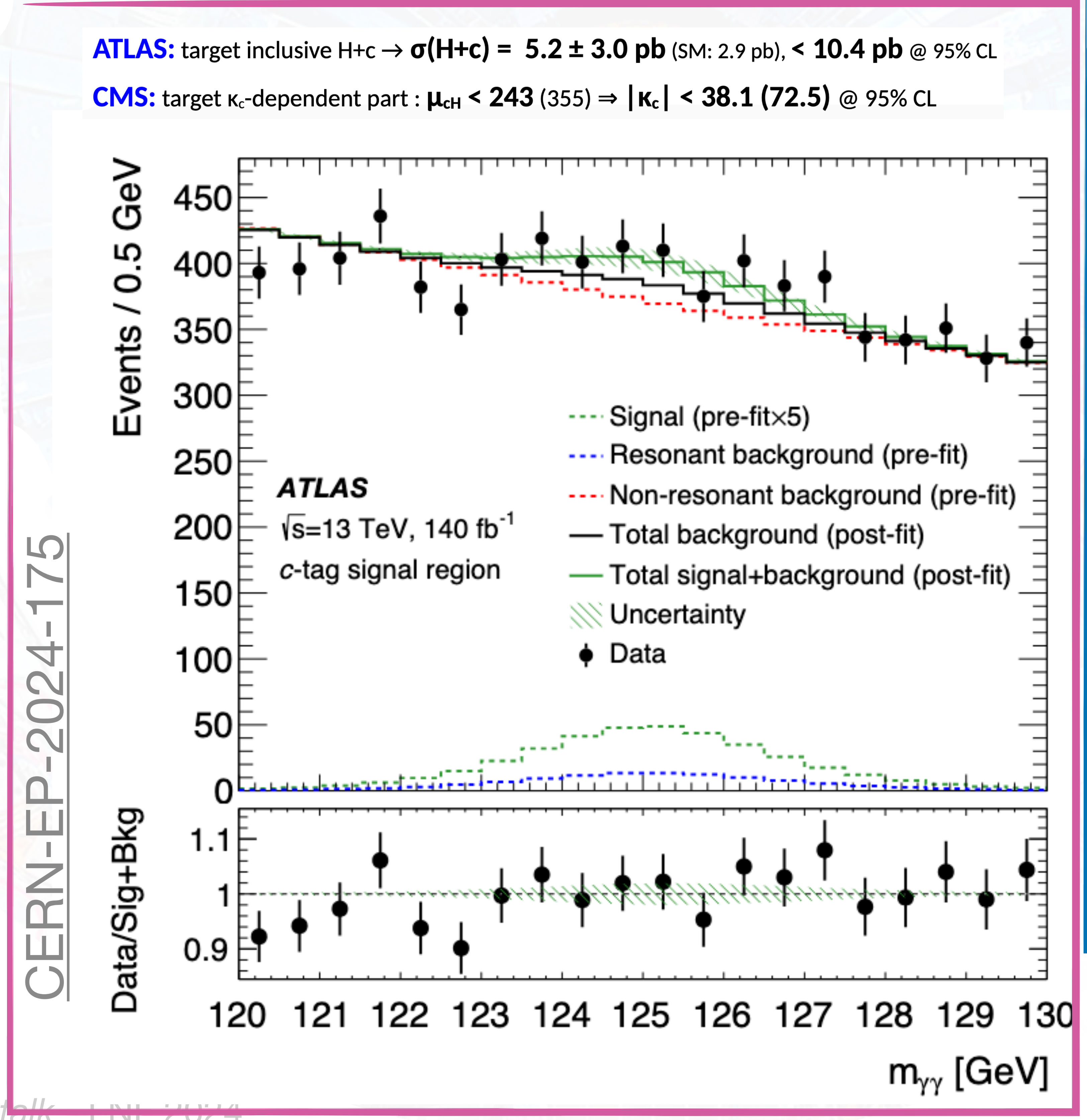

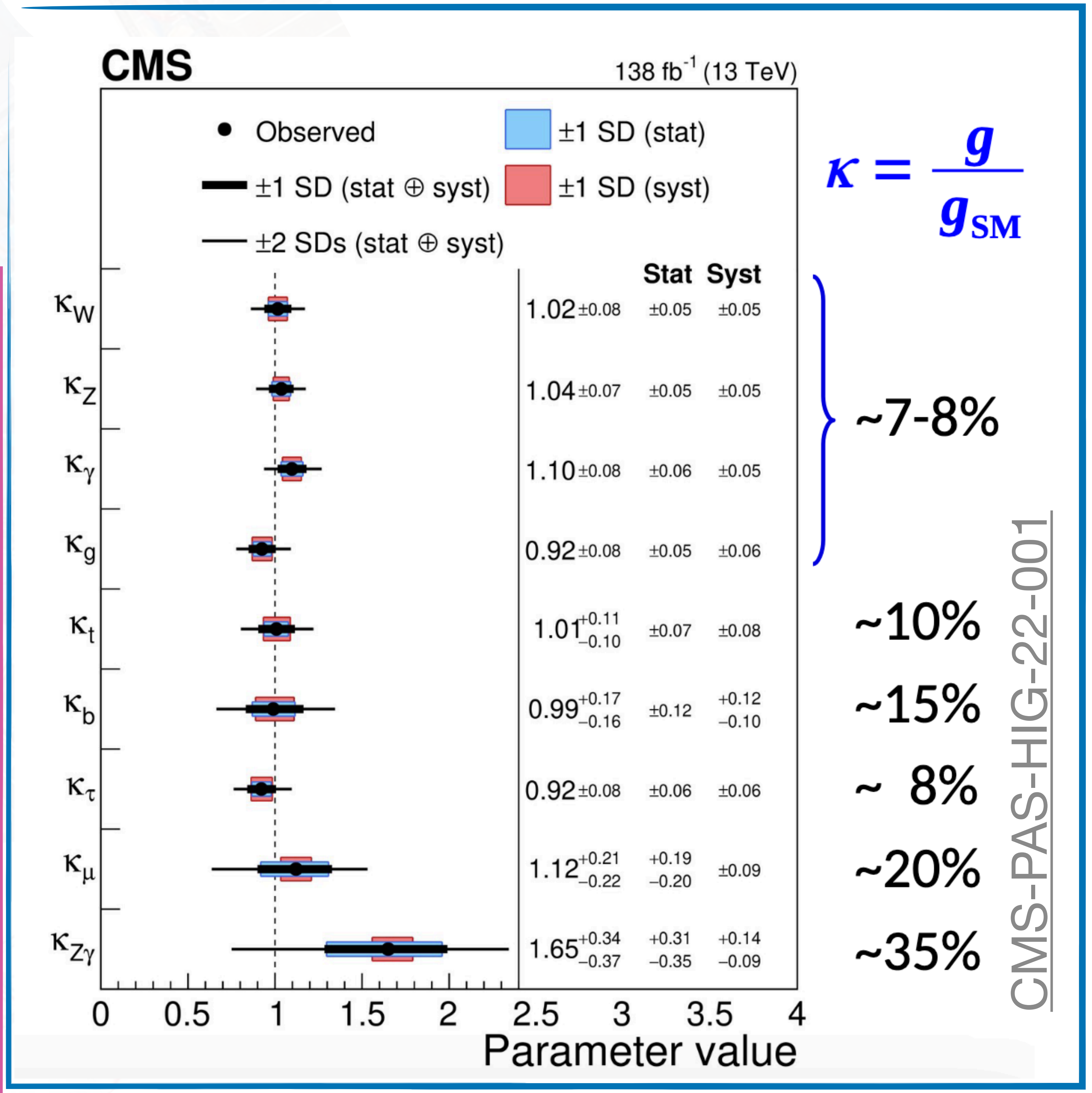

Run 2: searches overview

Reference	Topic	Experiment	Model	Explored energy range (0, 300, 600, 900, 1200, 1500, 1800, 2100, 2400, 2700, 3000 [GeV])
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector	
HDBS-2020-11	$H^{\pm} \to cs$	ATLAS		
HDBS-2023-19	Combination of charged Higgs searches	ATLAS		
EXOT-2022-13	$A \to t\bar{t}$	ATLAS		
HIG-24-002	$H \to ZZ \to 4l$	CMS		
HIG-22-004	$A \to Zh(\tau\tau)$	CMS		
SUS-24-001	$\phi \to b\bar{b}$	CMS		
EXOT-2018-55	Prompt Lepton-Jets	ATLAS	Dark Sector	
EXOT-2022-04	Long Lived Particles in the hadronic calorim.	ATLAS		- displaced
SUS-23-004	$\mathrm{mono}-t$	CMS		dark matter
SUS-23-012	$\mathrm{mono}-h(\tau\tau)$	CMS		dark matter
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS		
SUS-24-004	pMSSM	CMS	Supersymmetry	
SUS-23-003	Compressed Supersymmetry	CMS		Δm
ATLAS-CONF-2024-011	Run3 displaced leptons*	ATLAS		- displaced
SUS-23-002	Supersymmetry w/ charged leptons and	CMS		
ATLAS-CONF-2024-008	Vector Like Leptons (VLL) 4321 model (tau	ATLAS	Heavy Fermions	
EXOT-2021-02	Combination of VLQ	ATLAS		
EXO-23-015	$\mathrm{VLL} \to \tau a(\gamma\gamma)$	CMS		- displaced
B2G-22-005	$t^* \to tg$	CMS		
EXO-23-010	$ll + \mathrm{b-jets, non-resonant}$	CMS	EFT	
EXOT-2022-33	Low mass dijet + ISR gamma	ATLAS	New Mediators	
EXOT-2020-26	Dark Higgs via Z'	ATLAS		
EXO-24-007	Low mass dijet+ISR	CMS		
EXO-22-006	$Z' \to \mu\mu + \mathrm{b-jets, resonant}$	CMS		
EXO-22-013	t-channel scalar and vector leptoquark	CMS	Leptoquarks	up t 5 TeV

*(+ 1 result Run 3)

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New summary plots from Leptoquarks and Dark Matter (ATLAS) and Heavy Resonances (CMS)

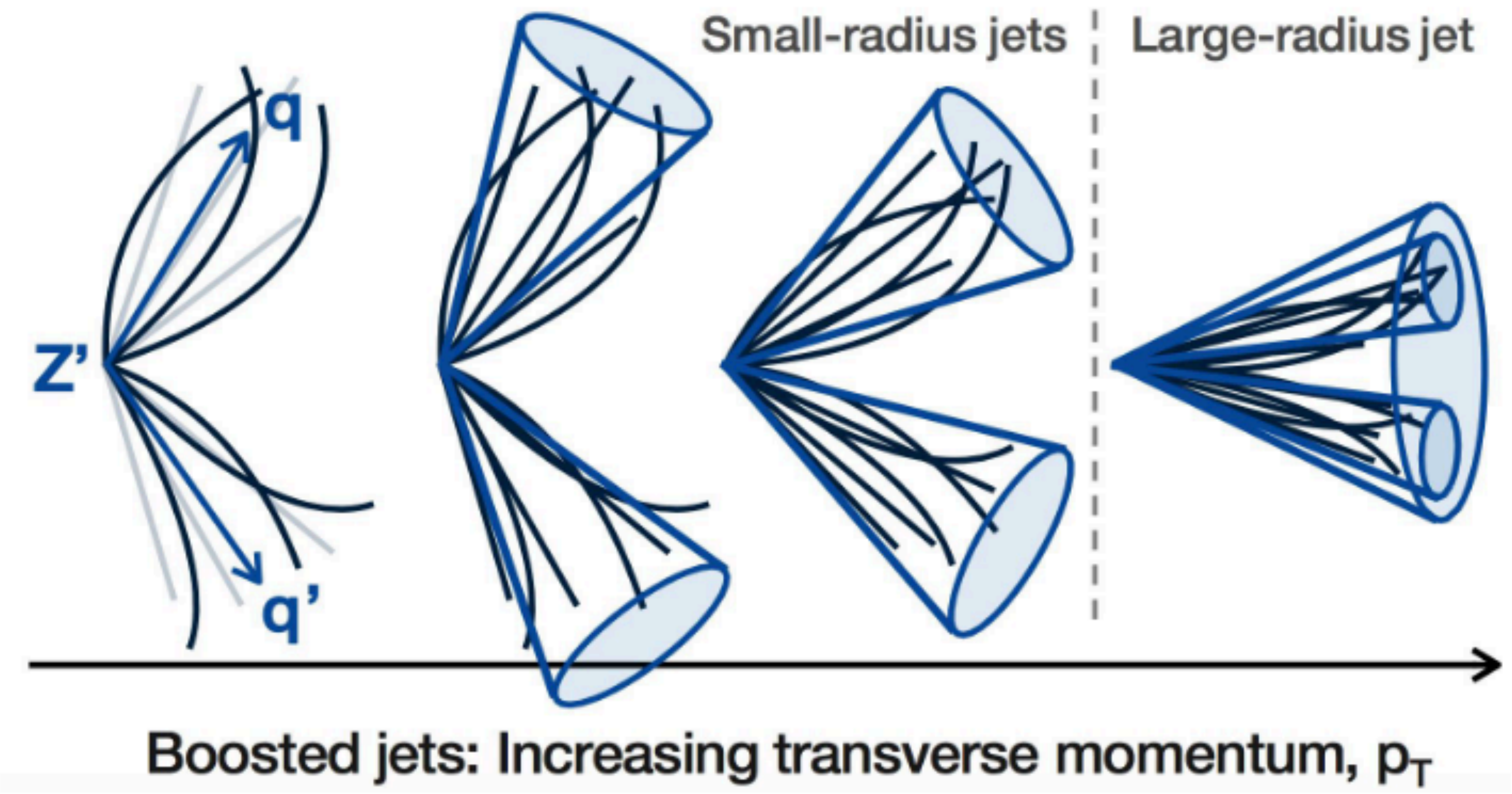
Many **standard summary plots** in the public pages of ATLAS and CMS

Many **Physics Reports about BSM Run 2 physics @LHC** submitted: state-of-the-art of a broad set of physics results and techniques in many areas of LHC BSM physics: CMS and ATLAS

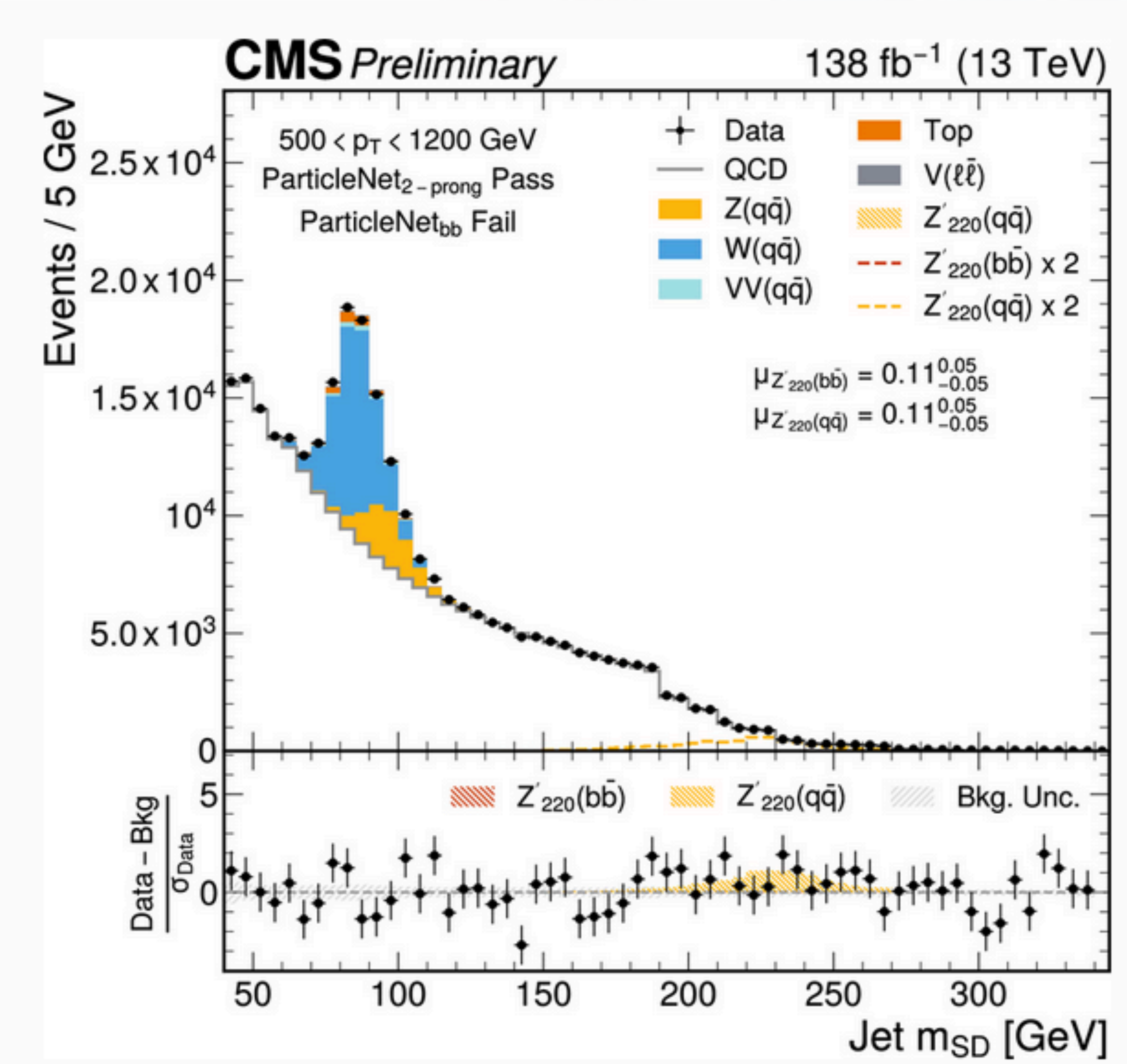
*(+ 1 result Run 3)

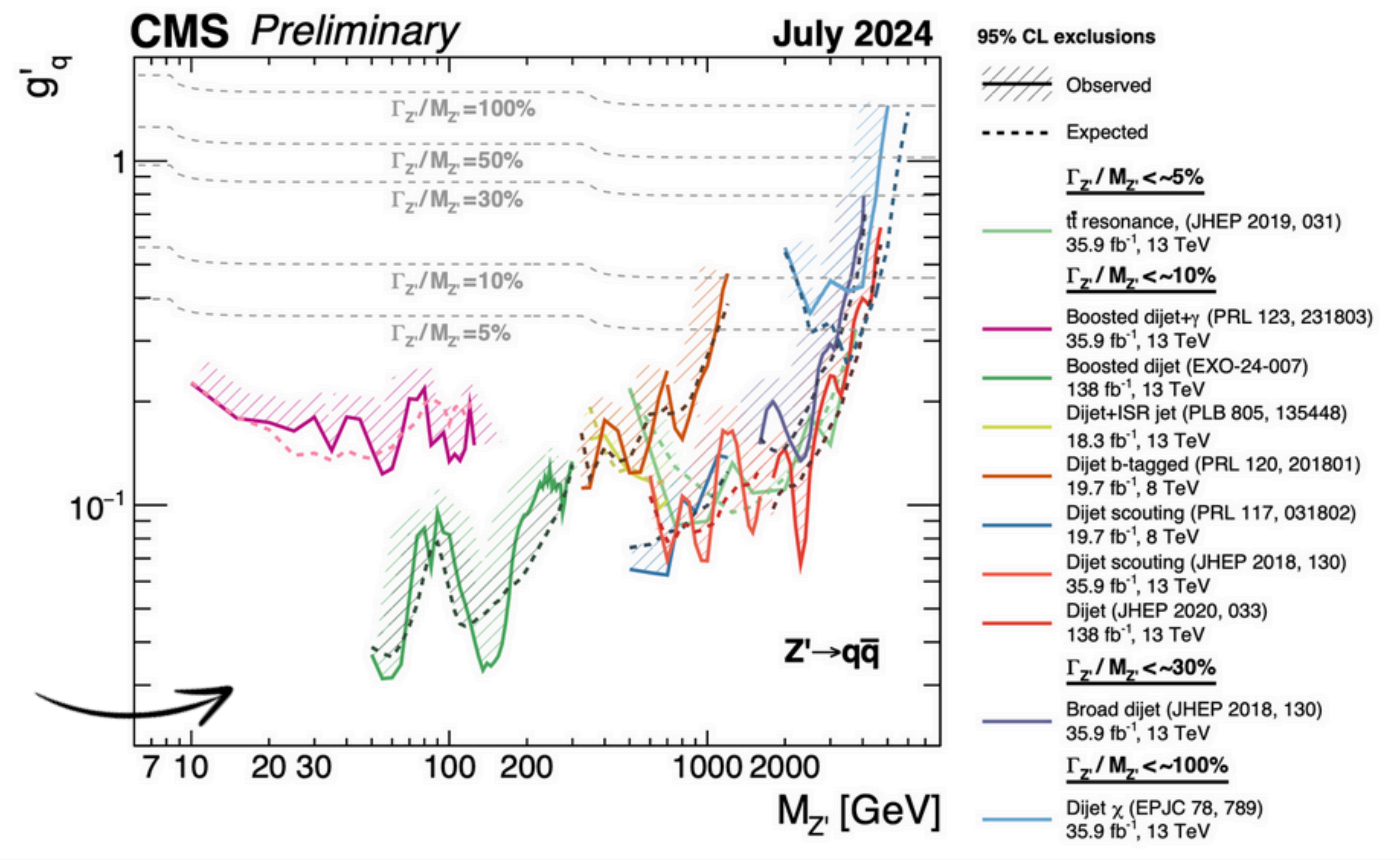
Run 2: impact of GNN tagging

- Previously search for **boosted resonances** reconstructed as large-radius jets with substructure
- Now signal distinguished from the backgrounds using **ParticleNet GNN discriminants**
- Stringent limits on universal coupling



PRL 119 (2017) 111802



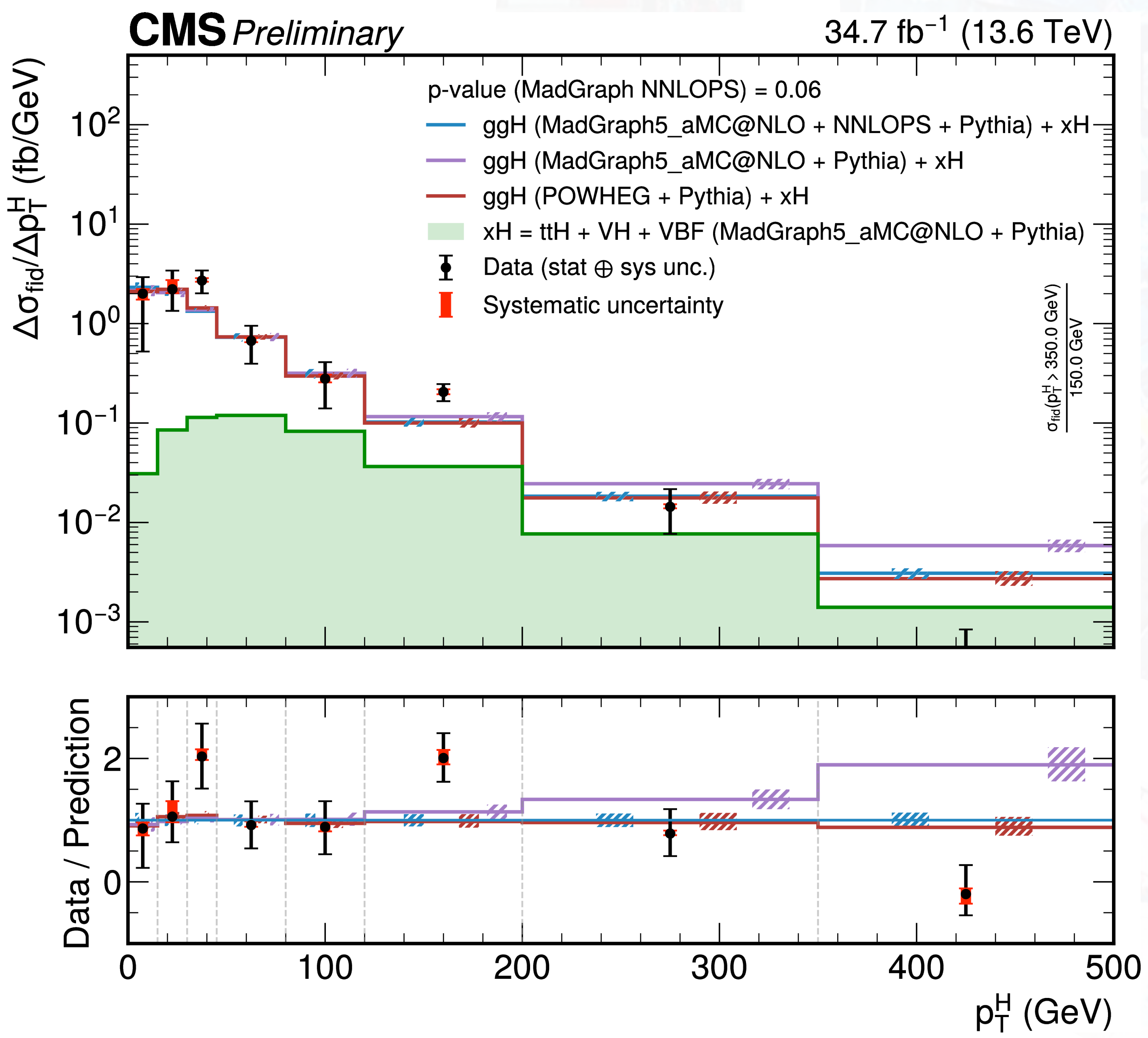


Run 3: status of the art

- Higher collision energy and aiming for **2 × larger dataset** – There is much more to come!

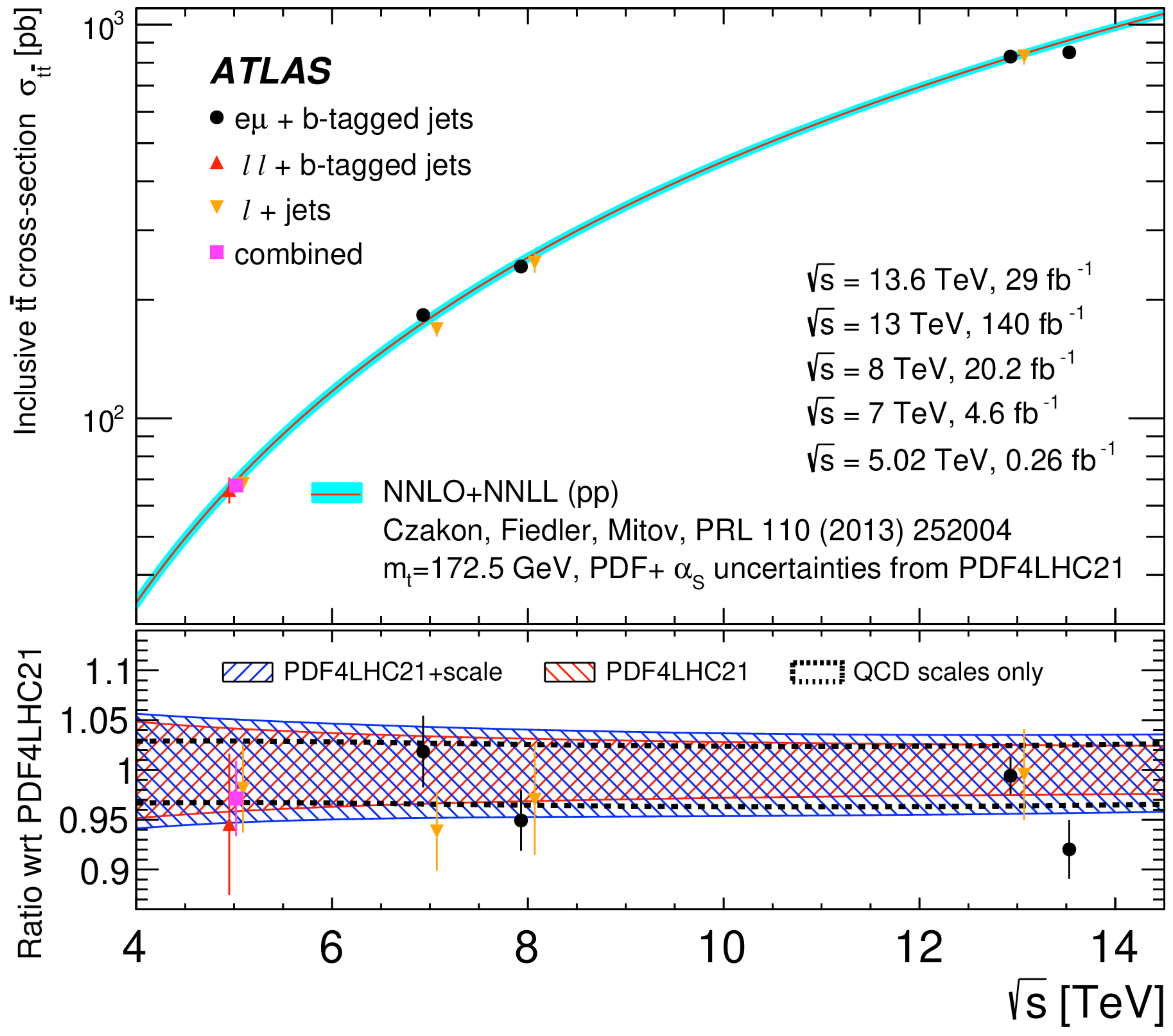
CMS:

- Higgs and EW processes (HIG-23-014, HIG-24-013, SMP-24-005, SMP-24-001, SMP-22-017, TOP-22-012, TOP-23-008)
- First w/ parking (BPH-23-008)
- Two searches (EXO-23-014, EXO-23-013)



ATLAS:

- Higgs and EW processes (STDM-2023-16, STDM-2022-17, TOPQ-2023-21, HIGG-2022-12)
- Search: ATLAS-CONF-2024-011
- Run 3 results twiki



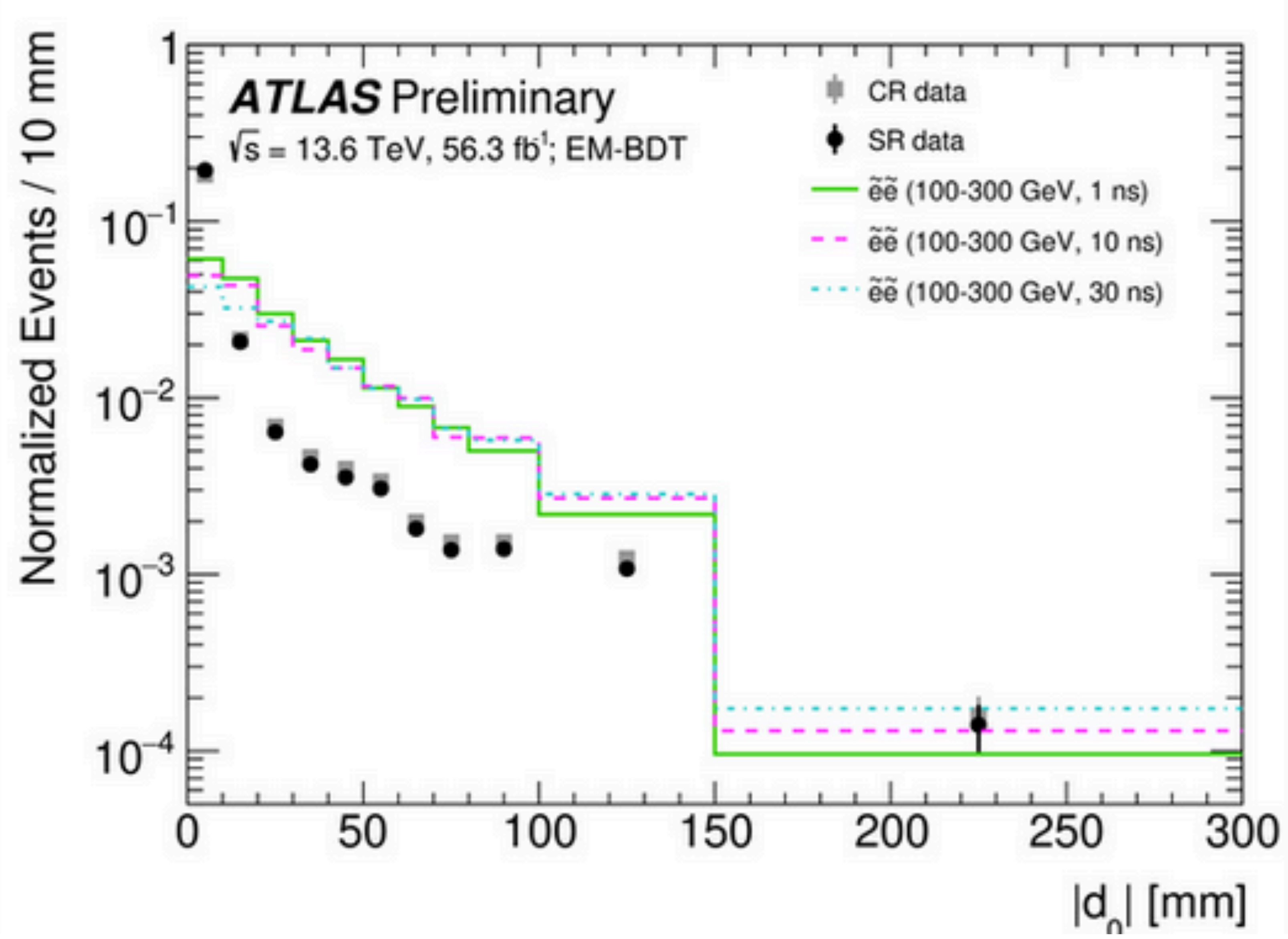
Run 3: Boosting the sensitvity with new triggers

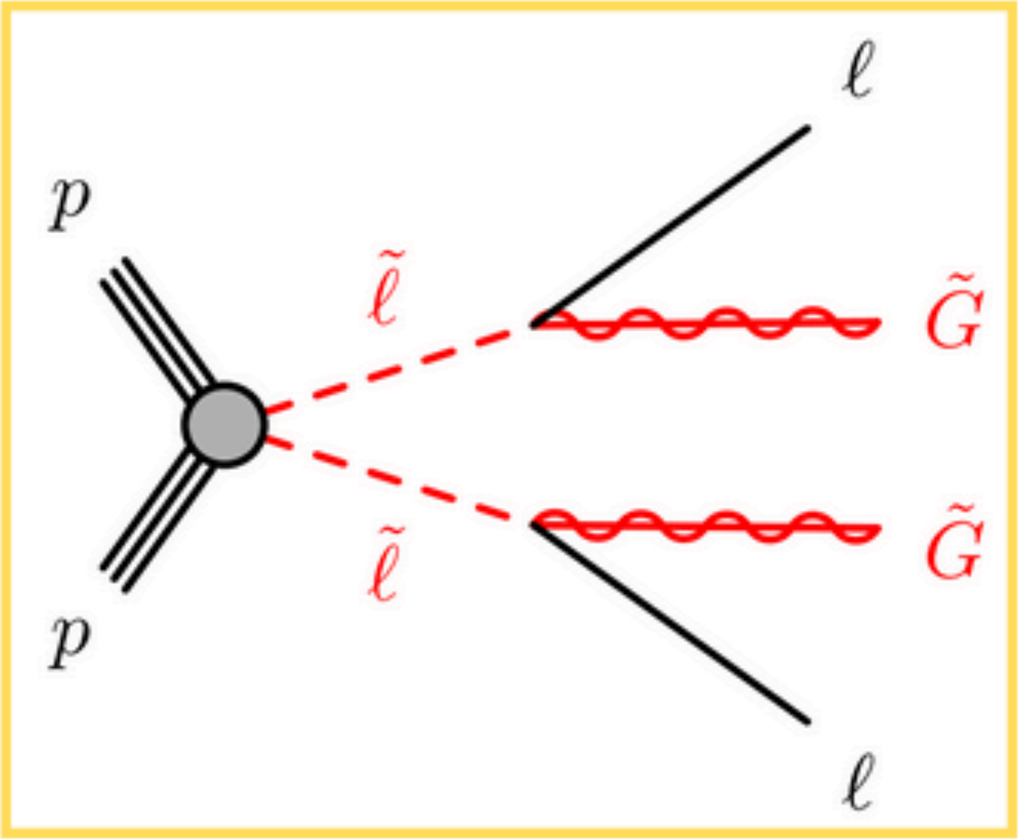
An example: Search for displaced leptons in 13 TeV and 13.6 TeV

ATLAS-CONF-2024-011

Large Radius Tracking: designed to increase efficiency for decay products of LLPs.

LRT run in the HLT for the first time at Run 3

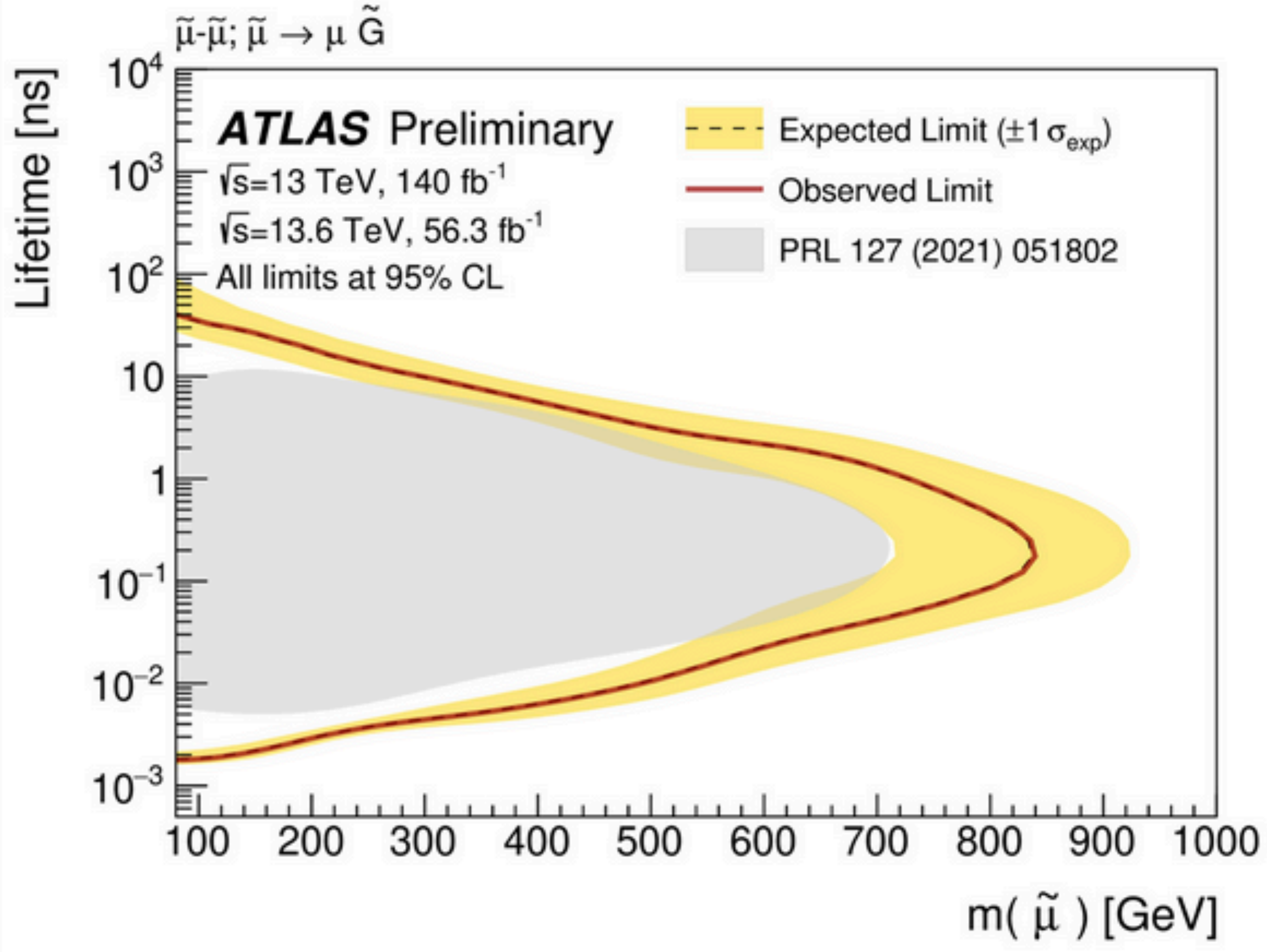




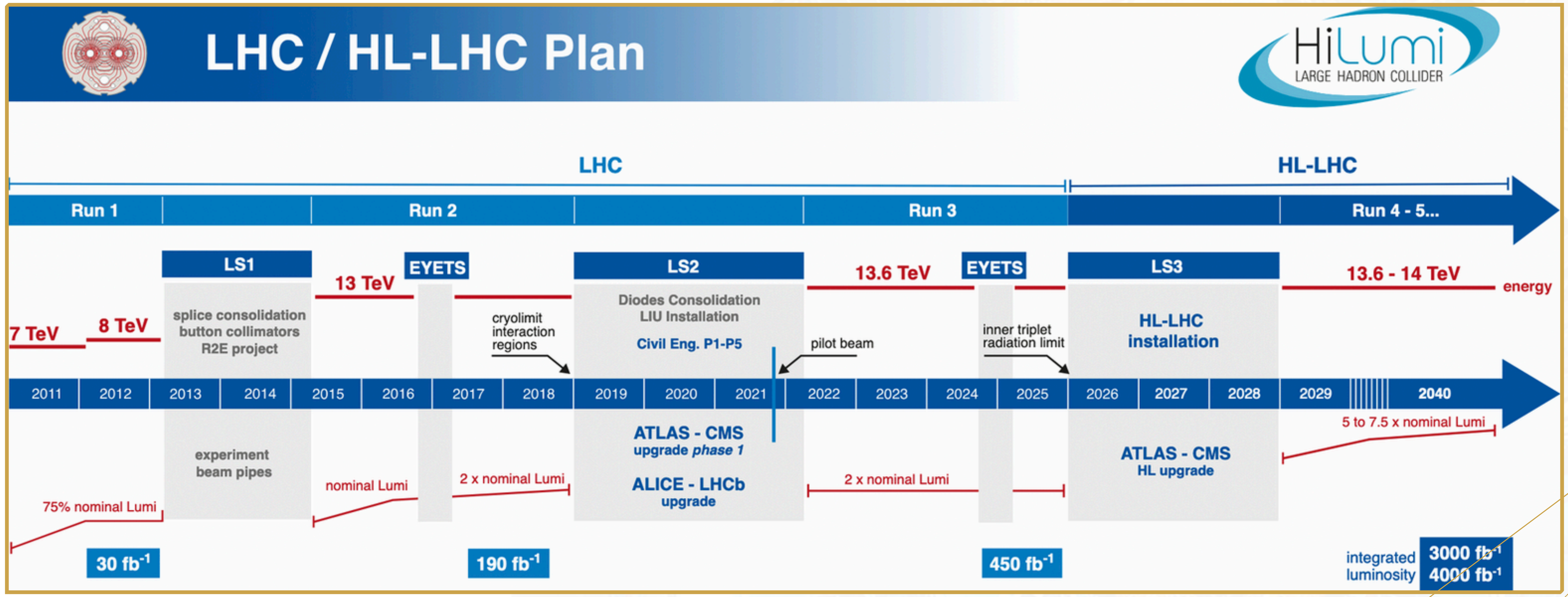
Enhanced discovery reach beyond prior searches through several

← **novel additions.**

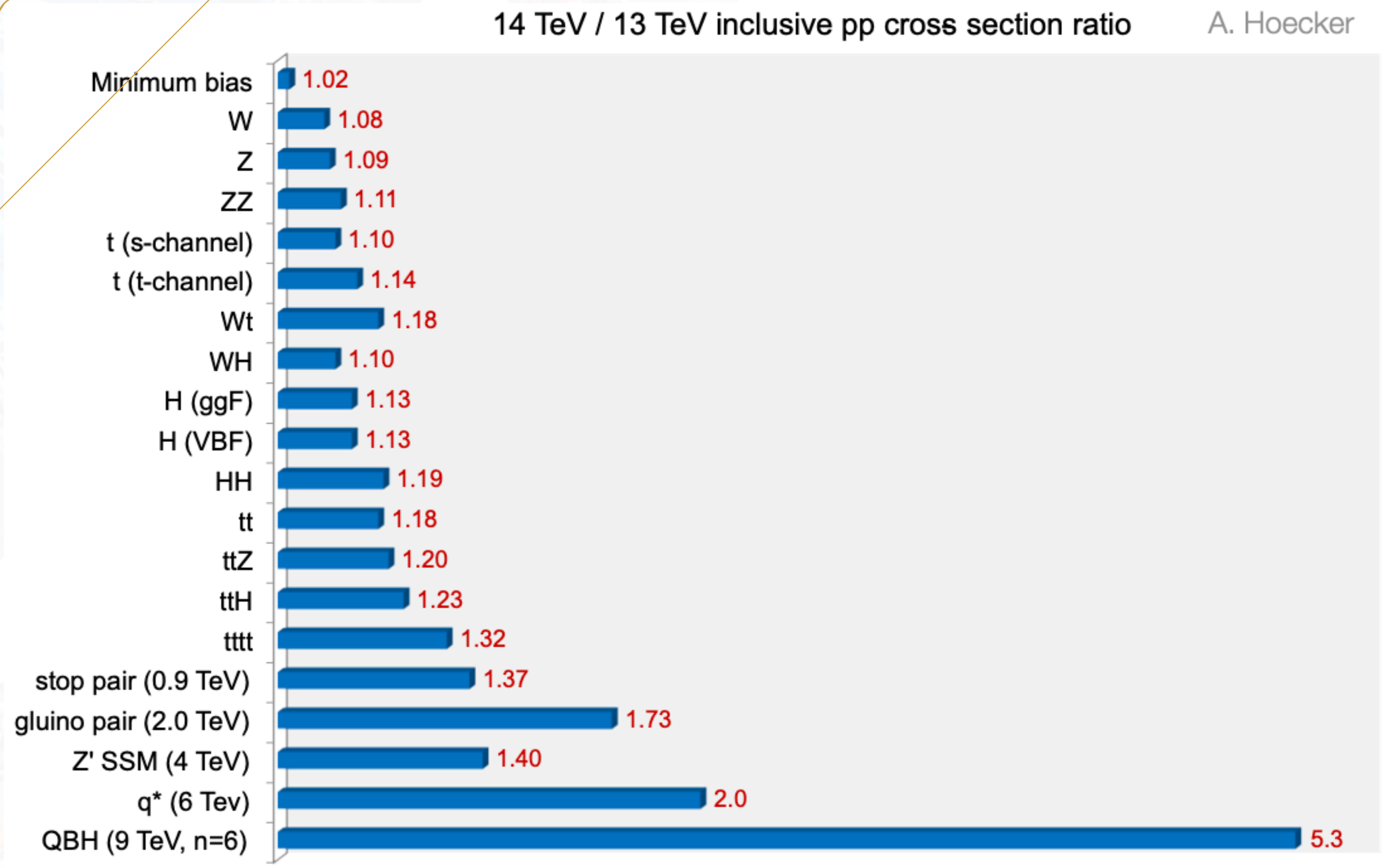
95% CL exclusion contours for **long-lived selectrons (smuons** and **staus**, see backup)



High Luminosity (HL) LHC timeline



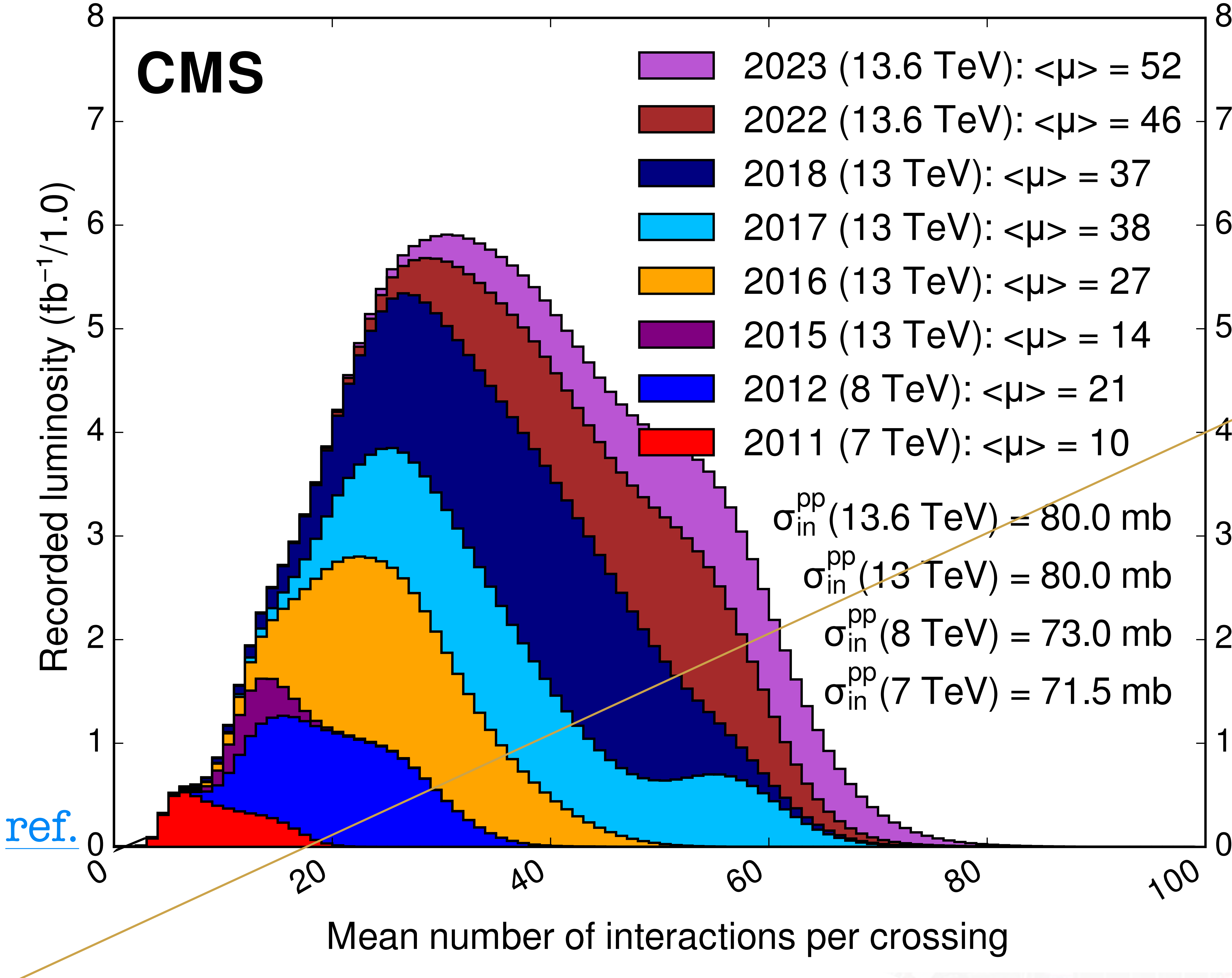
- HL-LHC represents the **ultimate evolution of LHC machine performance:** operation at up to **$L=7.5 \cdot 10^{34}$ Hz/cm²**



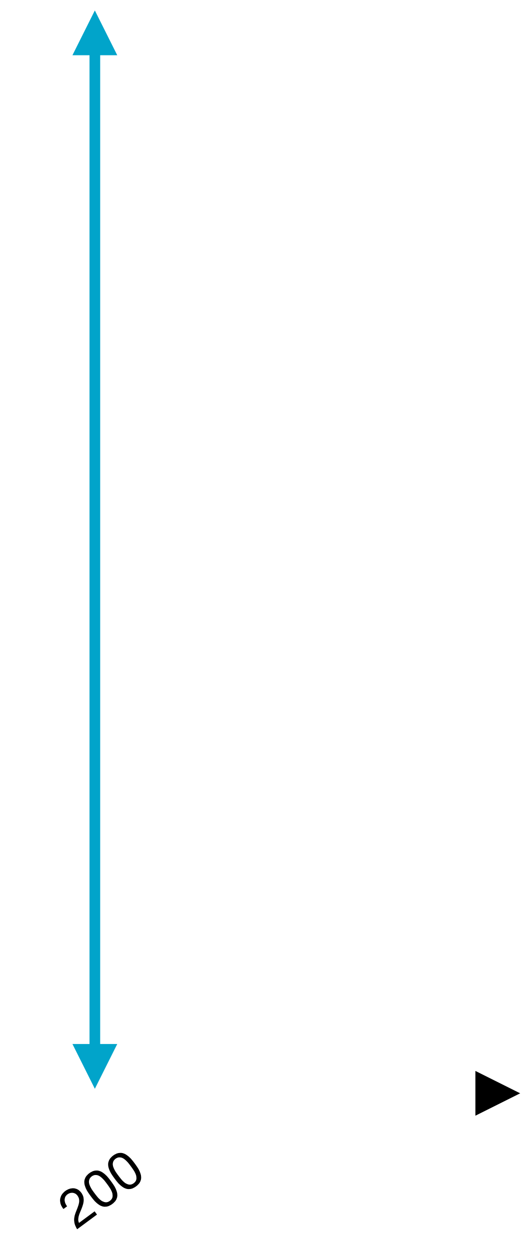
- Targeting **~3000 fb^{-1} of data or 180 million Higgs bosons**
- 50 fb^{-1} for LHCb 5 fb^{-1} for ALICE, Pb–Pb (13 nb^{-1}) and p–Pb (50 nb^{-1})

Raising the challenge

- **Pileup (PU) conditions particularly challenging** for data-taking: detector irradiation, higher occupancy, higher trigger rates
- Much higher collision rates will far **exceed the capabilities of the existing detectors**



ref.



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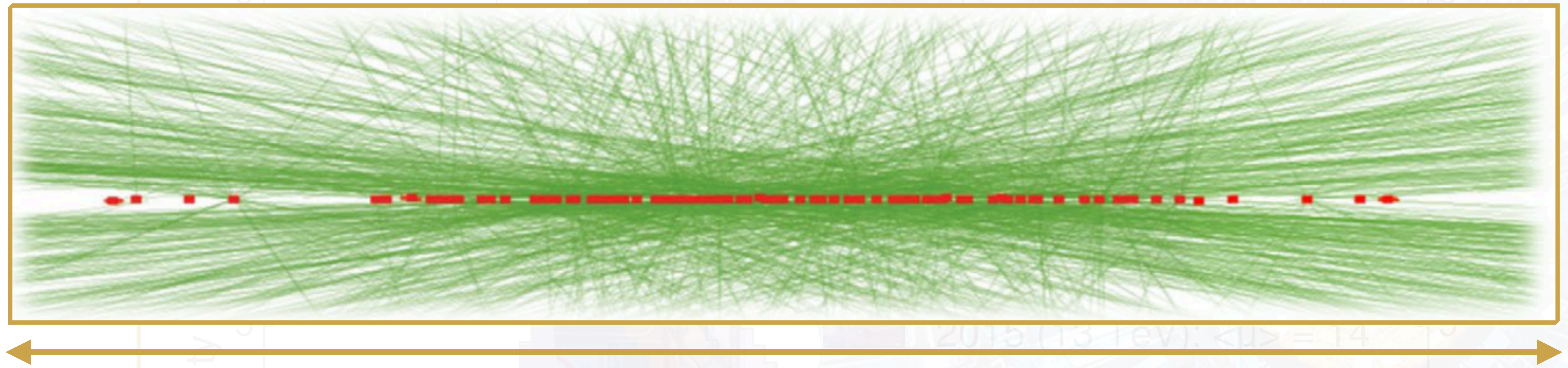
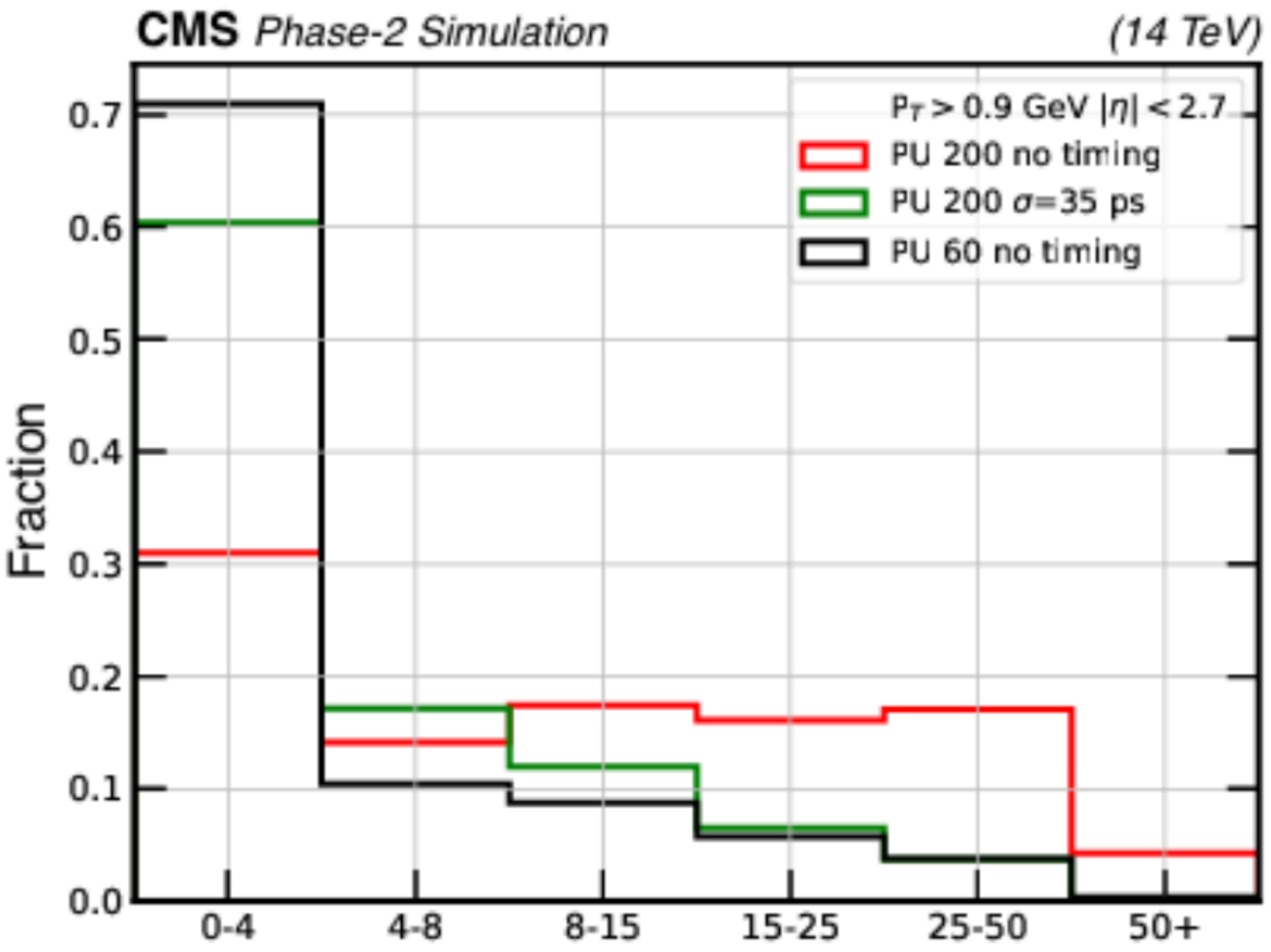


140-200 vertices in beam-spot space [5 cm]

- **Primary goal** at HL-LHC is to **maintain the current excellent detectors performance** in terms of efficiency, resolution, and background rejection for all final state particles and physics observables used in data analyses.



ref.

Main priorities at HL-LHC

Spatial overlap of tracks and energy deposits:

- **degrade the identification and the reconstruction** of the hard interaction
- **increase the rate** of false triggers

→

- good reconstruction efficiency
- **Increase detector granularity**
- **Sophisticated detector**

Higher collision rate:

- more **radiation damage**
- **harsher radiation** (~ 10^{16} neq/cm^2 ; 10 MGy)
- **higher rate** of data

→

- Increase data acquisition **bandwidth**
- Increase **processing power** for online reco

- Phase-2 improvements in detectors, triggers and reconstruction will **extend sensitivity in precision measurements and new physics searches**
- **Higher order theory calculations** and larger MC samples required to fully exploit the HL-LHC

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The Physics Landscape at HL-LHC

- LHC experiments have an **ambitious physics program** ahead:
  - Precision Measurements of the Higgs Boson (couplings and rare decays)
  - Searches for New Physics Beyond the Standard Model (SUSY, Dark Matter, Exotic signatures)
  - Precision Tests of the Standard Model (Top quark, EW tests)
  - Rare Processes and Flavour Physics (FCNSs, CP violation)
  - Heavy Ion Collisions (QGP, UPC)

- New **techniques and detectors** will extend analyses sensitivity:
  - Advanced Detector Technologies → improved tracking, calorimeters, and timing detectors
  - Machine Learning and AI → will help in handling the vast amounts of data generated and in identifying rare events more efficiently.

- **Theoretical and computational** advances:
  - Improved theoretical models and higher-order calculations (PDFs and QCD effects)
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- **Theoret**
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- LHC experiment pushed very hard the performance studies while preparing TDRs and legacy documents (see bibliography)
- Recently the community is clearly **focussing on prototyping and building these beautiful detectors**
- In this talk **I will highlight some examples of niche physics cases that I find elegant and emblematic** in the context of showing the huge potentiality of the upgraded LHC detectors in few years from now

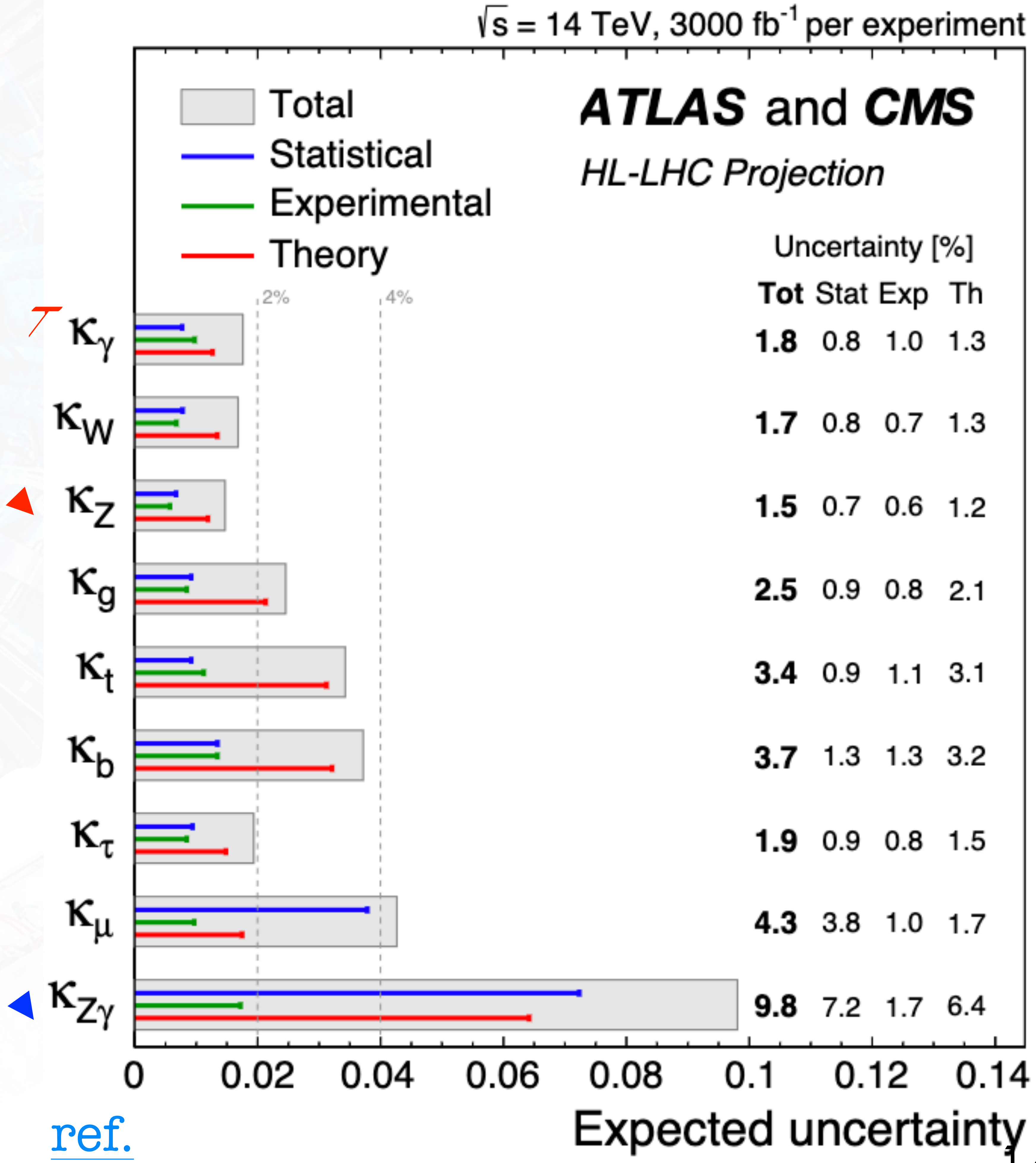
Methods for HL-LHC prospect studies

- MC event Generator + Fast detector simulation
- Start from published LHC Run 2 results, adapt to HL-LHC conditions
- Assumptions on uncertainties:
  - **Theory uncertainties reduced by a factor of ~ 2** (higher-order calculation as well as reduced PDF uncertainties)
  - Limited number of **simulated events neglected**
  - **Detector performance as good or better than now**, but with harsher pileup conditions
  - **Experimental uncertainties reduced by 1/**$\sqrt{\mathcal{L}}$
  - Luminosity uncertainty: **1%**

Standard Model Physics

Higgs boson properties and couplings

- Essential task to **test the self-consistency of the SM** at HL-LHC
- Sensitivities at 3000 fb^{-1} **extrapolated from Run 2 measurements**
- **Most couplings** measurements expected to be limited by uncertainties with HL-LHC datasets: **precision < 4%**
  - **H→μμ and H→Zɣ** still limited by **stat. uncertainty**
  - Estimates include **improved acceptance and performance** of the detectors
  - Very interesting prospects to probe Yukawa couplings to **2nd generation fermions**



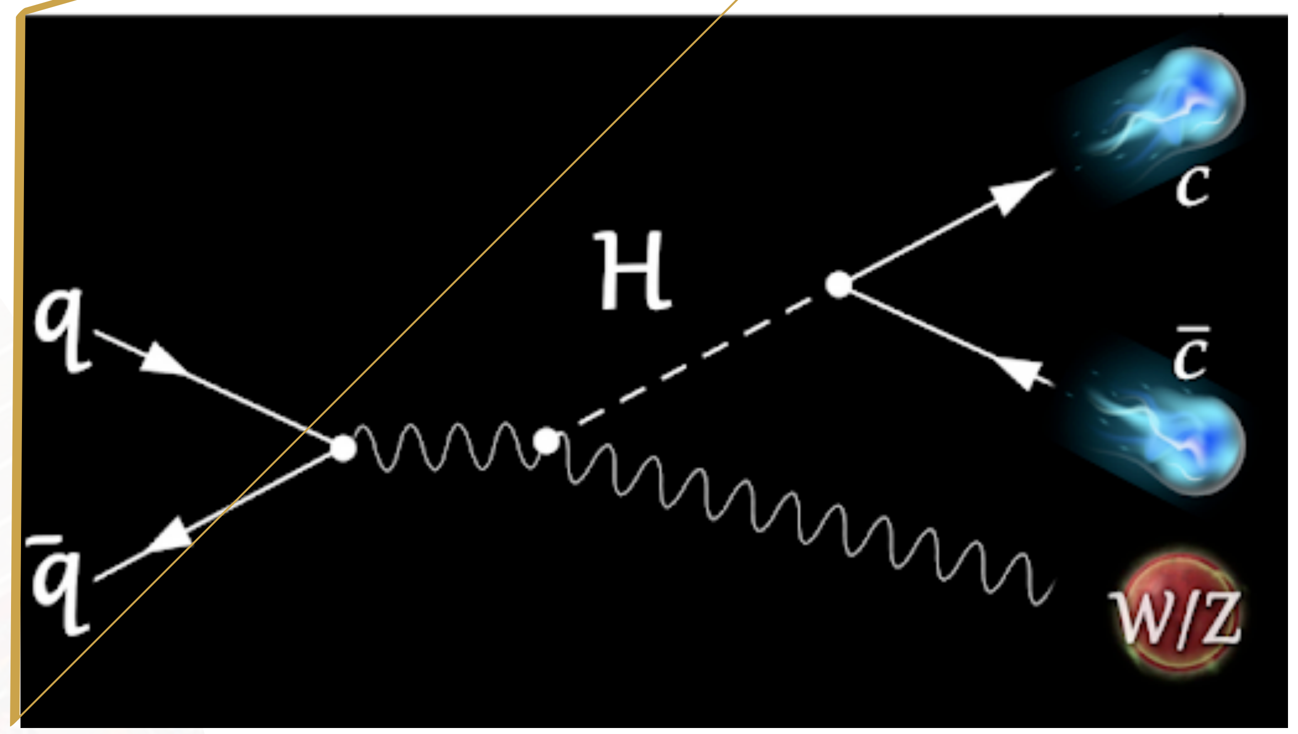
Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	1.8	0.8	1.0	1.3
κ_W	1.7	0.8	0.7	1.3
κ_Z	1.5	0.7	0.6	1.2
κ_g	2.5	0.9	0.8	2.1
κ_t	3.4	0.9	1.1	3.1
κ_b	3.7	1.3	1.3	3.2
κ_τ	1.9	0.9	0.8	1.5
κ_μ	4.3	3.8	1.0	1.7
$\kappa_{Z\gamma}$	9.8	7.2	1.7	6.4

ref.

C-Challenging Higgs Physics at HL-LHC

- $H \to cc$ **direct measurement:** small branching fraction + very large QCD



- **Jets b/c-tagged** using a multivariate discriminant

- Analysis simultaneously measure the $VH(H \to bb)$ **and the** $VH(H \to cc)$ processes

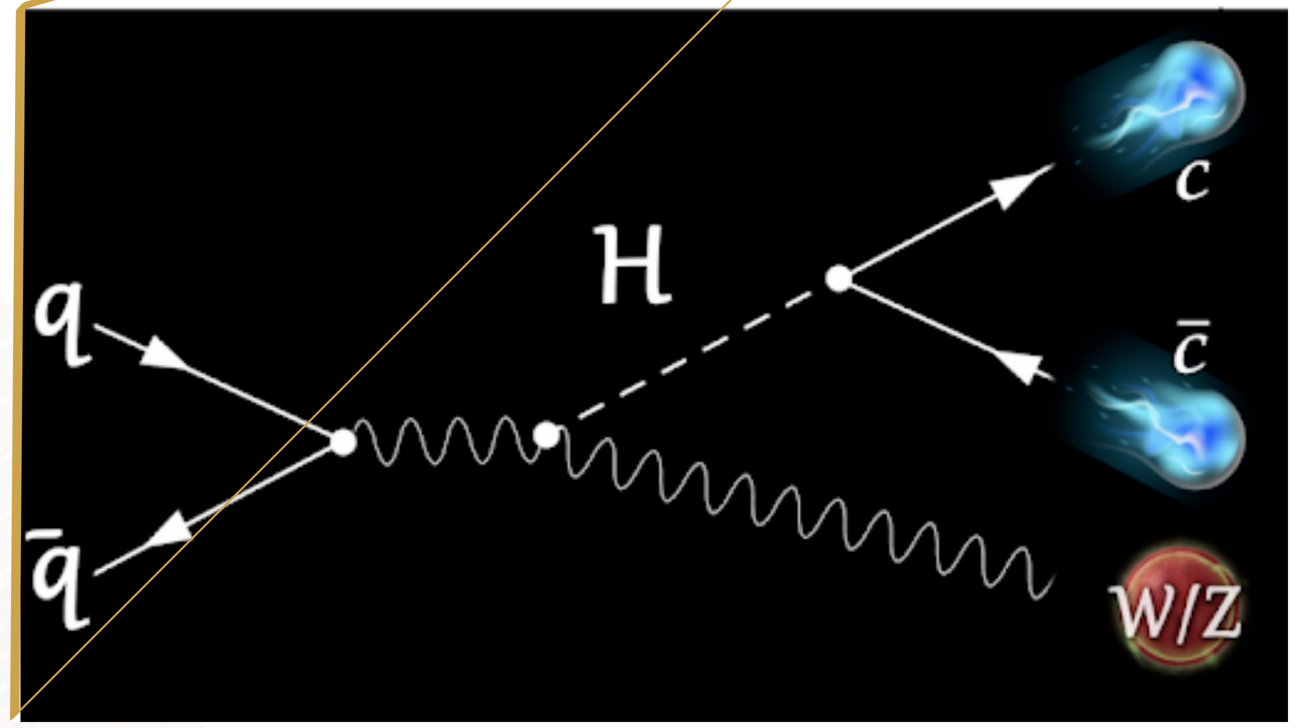
  - 95% CL expected upper limit on σ x BR:
    - @ ATLAS Run 2: 31 x SM
    - @ ATLAS HL-LHC: 6.4 x SM

ATLAS: μ(VH, H→cc) = 1.0 ± 2.0 (stat.) ± 2.5 (syst.)

CMS: μ(VH, H→cc) = 1.0 ± 0.6 (stat.) ± 0.5 (syst.)

- With further improvements **could be in reach at HL-LHC!** ref.

C-Challenging Higgs Physics at HL-LHC



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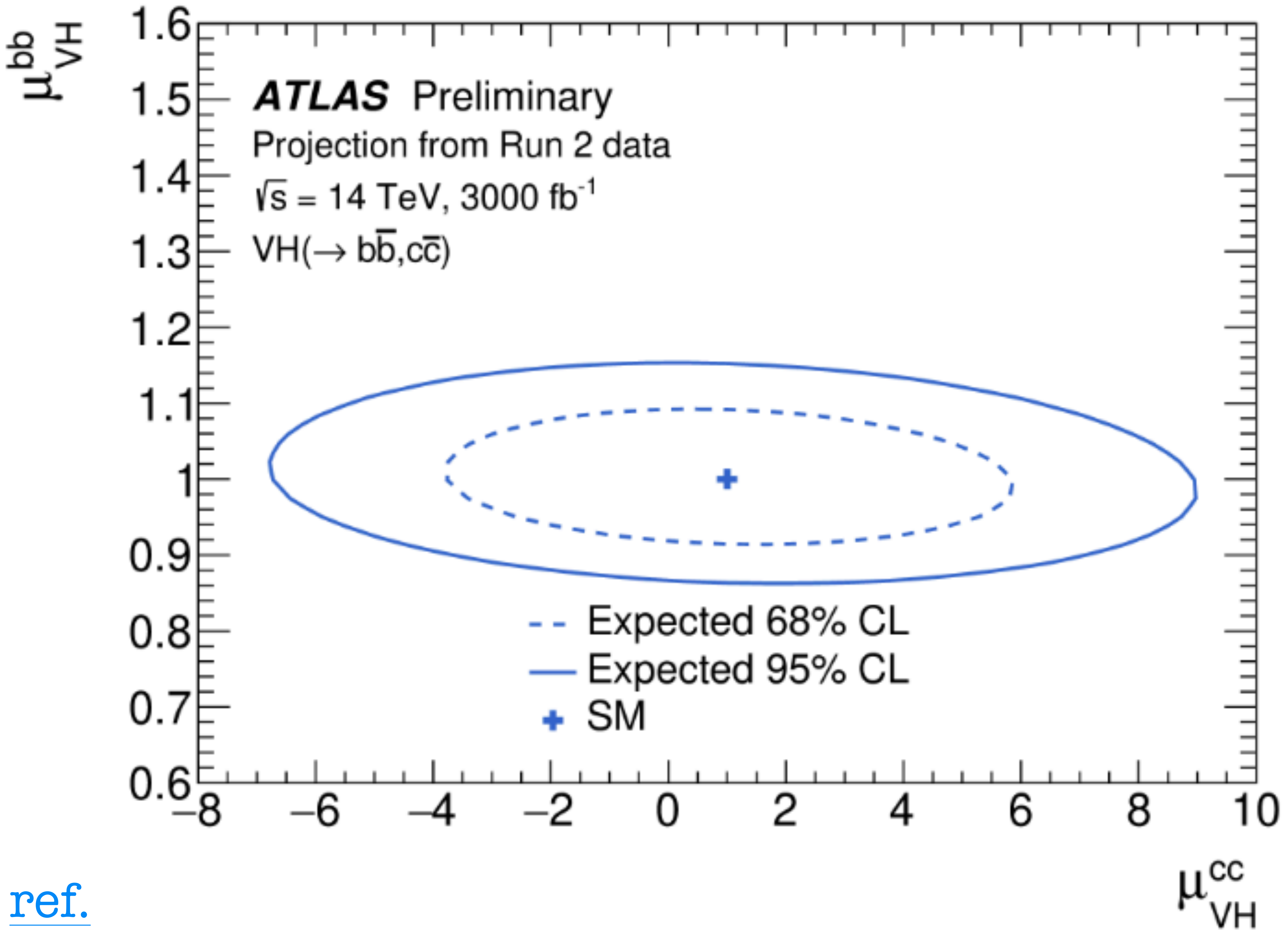

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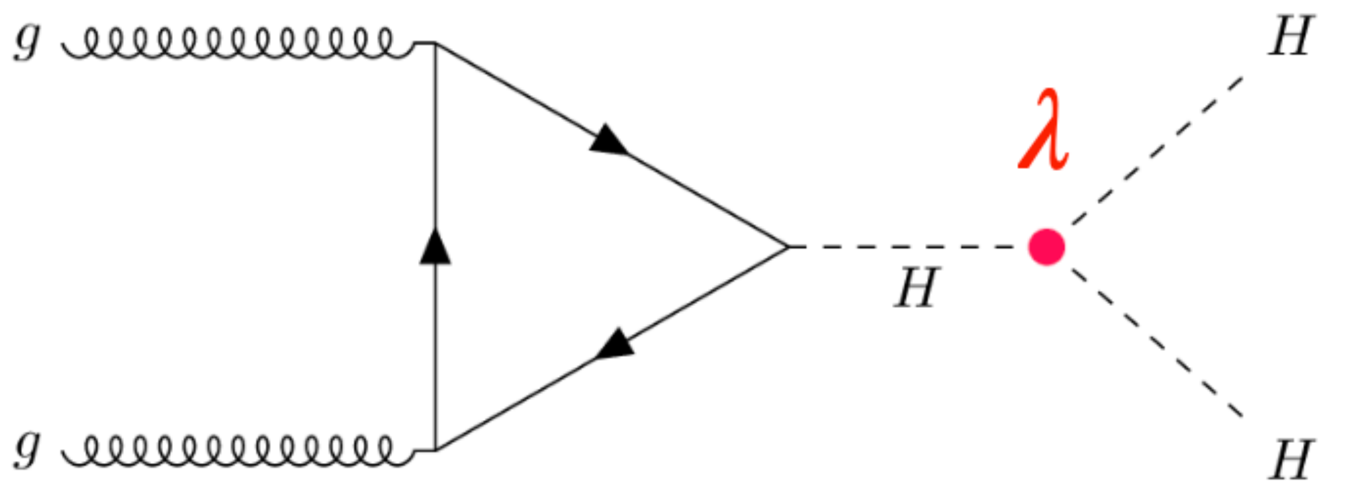
Ref.

Higgs self-coupling @HL-LHC

- Tri-linear coupling λ directly accessible via Higgs pair production
- $pp \to HH$ cross section 3 orders of mag. lower than single Higgs
- Improved trackers and ML key for HH studies (e.g. b tagging)

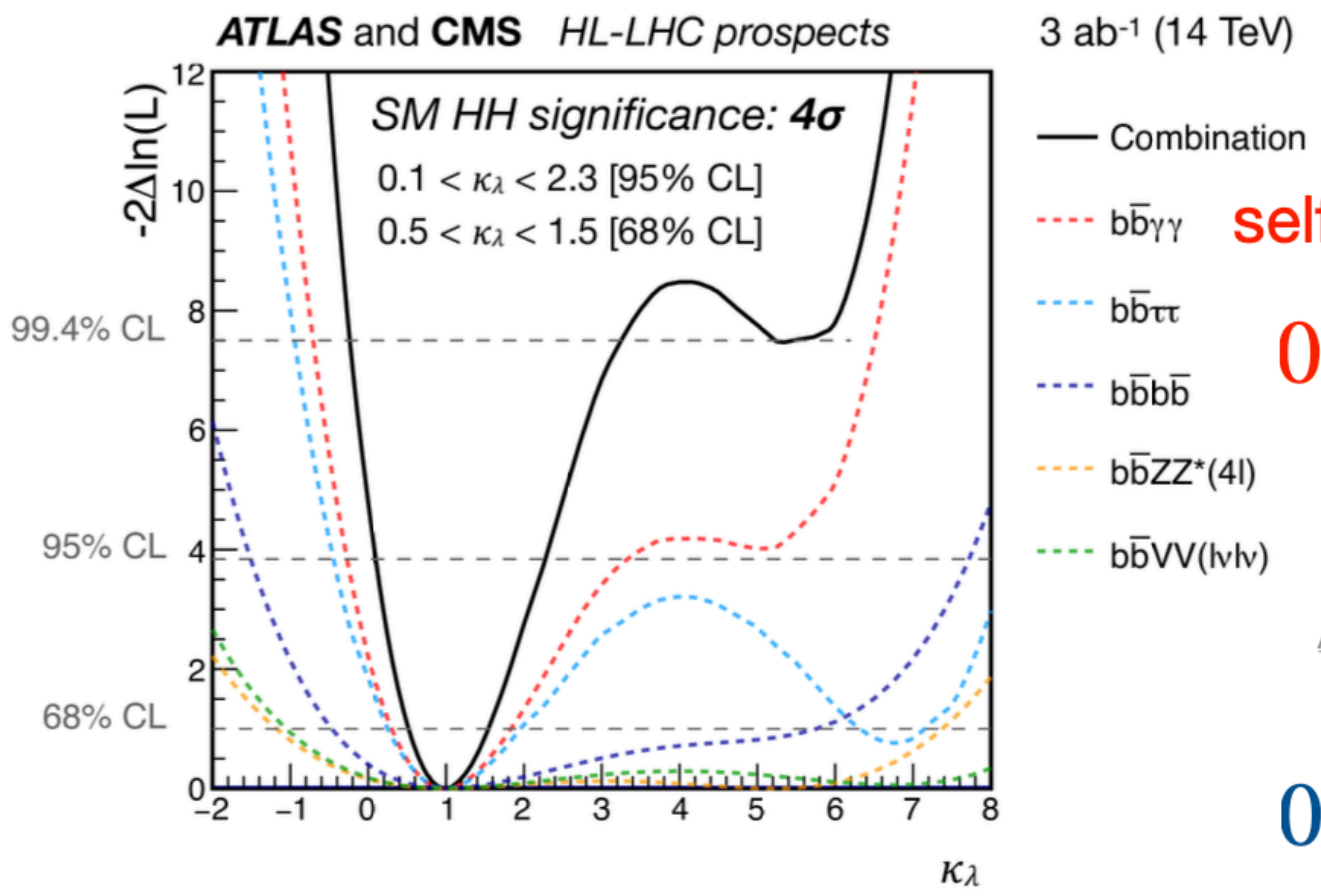


destructive interference with box diagram

- **ATLAS+CMS Yellow Report 2018**

$pp \to HH$ significance = 4.0 σ (4.5 σ stat only)

CERN-2019-007 (YR18)



self-coupling modifier

$0.52 < \kappa_\lambda < 1.5$

(68% Cl)

ATLAS-PHYS-PUB-2018-053

ATLAS only

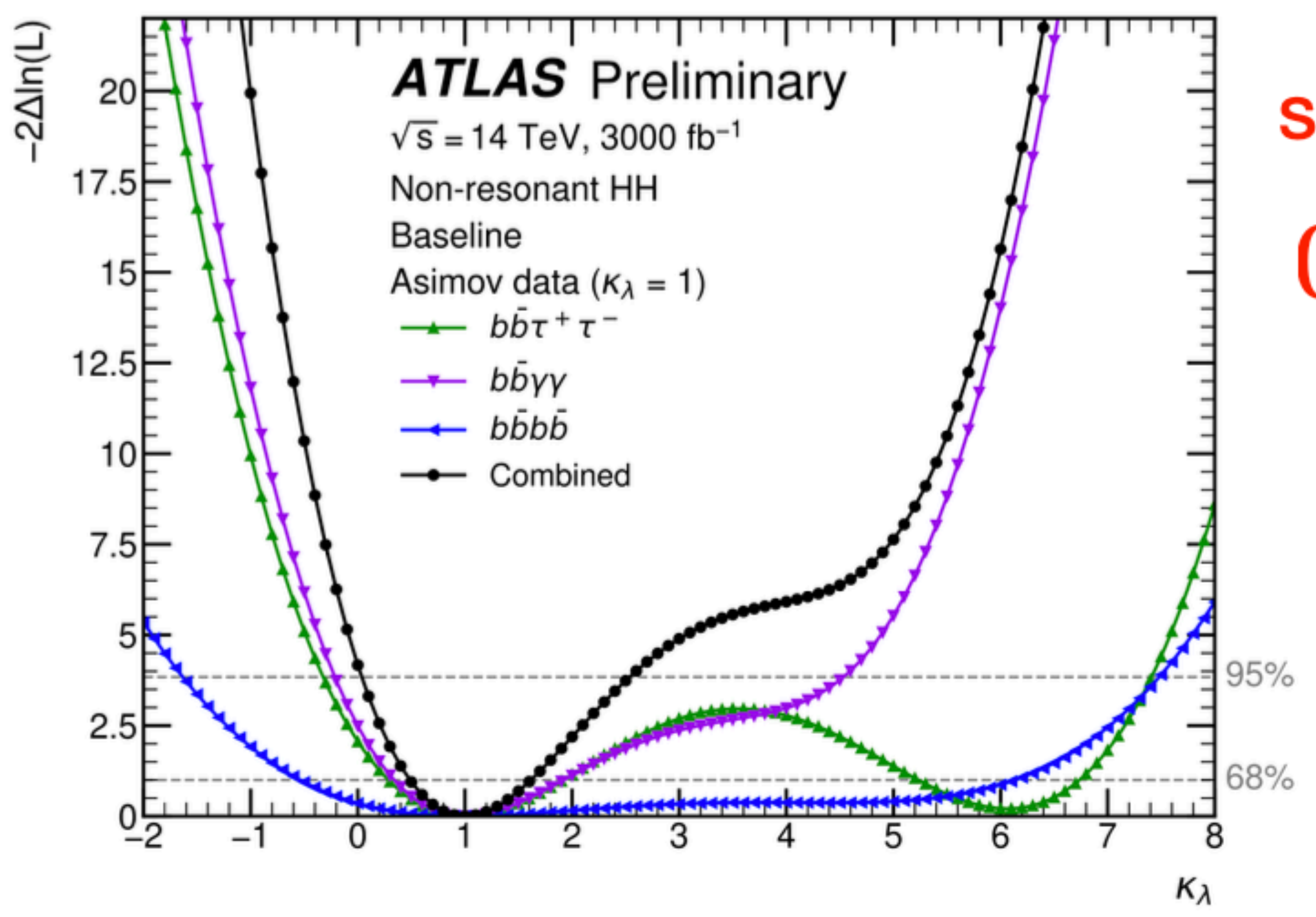
$0.25 < \kappa_\lambda < 1.9$

- **ATLAS update after Snowmass 2021**

Extrapolated from **full** Run 2 $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$

$pp \to HH$ significance = 3.4 σ (4.9 σ stat only)

ATLAS-PHYS-PUB-2022-053



self-coupling mod.

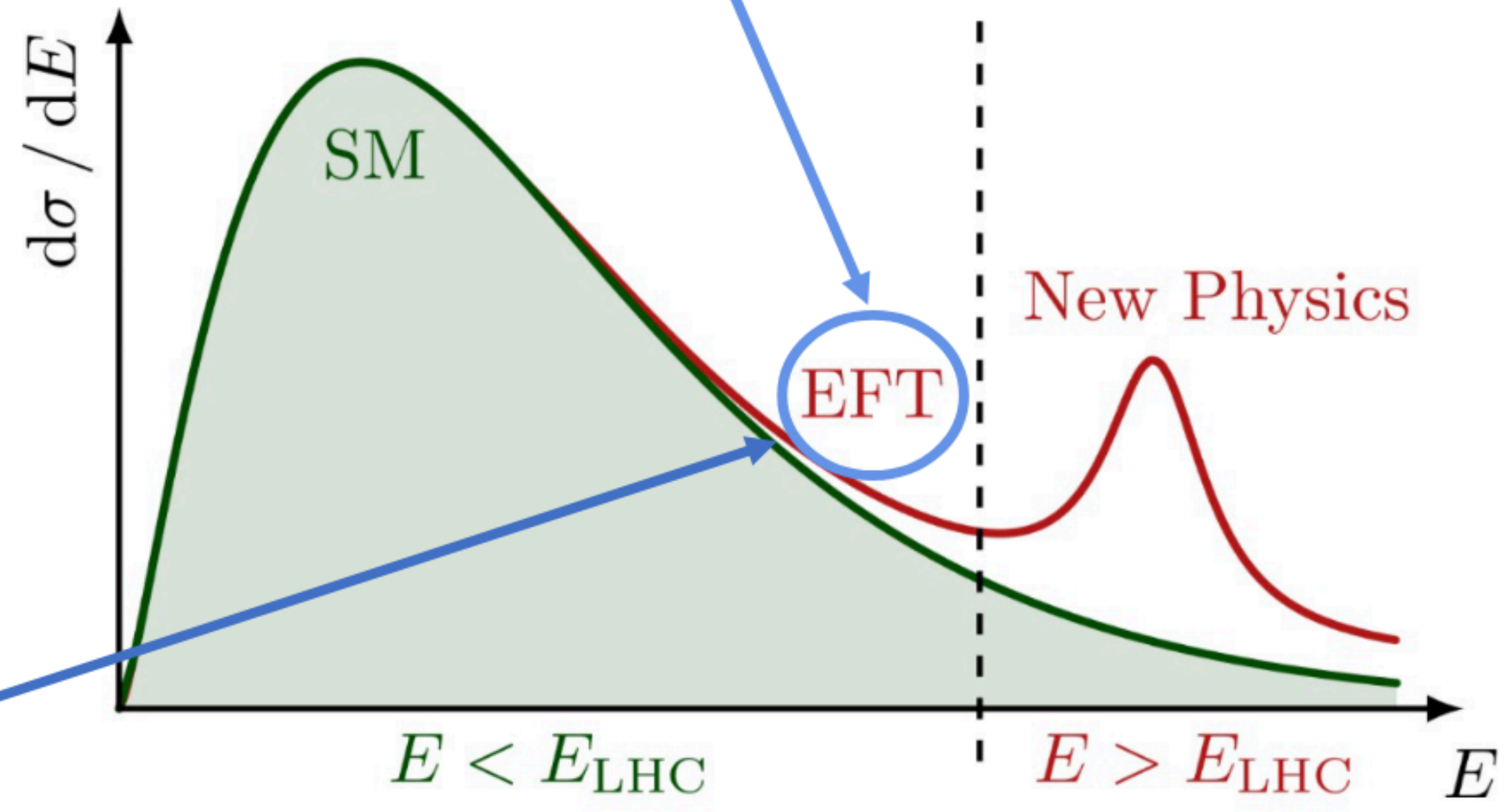
$0.5 < \kappa_\lambda < 1.6$

(68% Cl)

Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)}$$

Deformations in SM described by $\mathcal{O}_i^{(6)}$ effective interaction

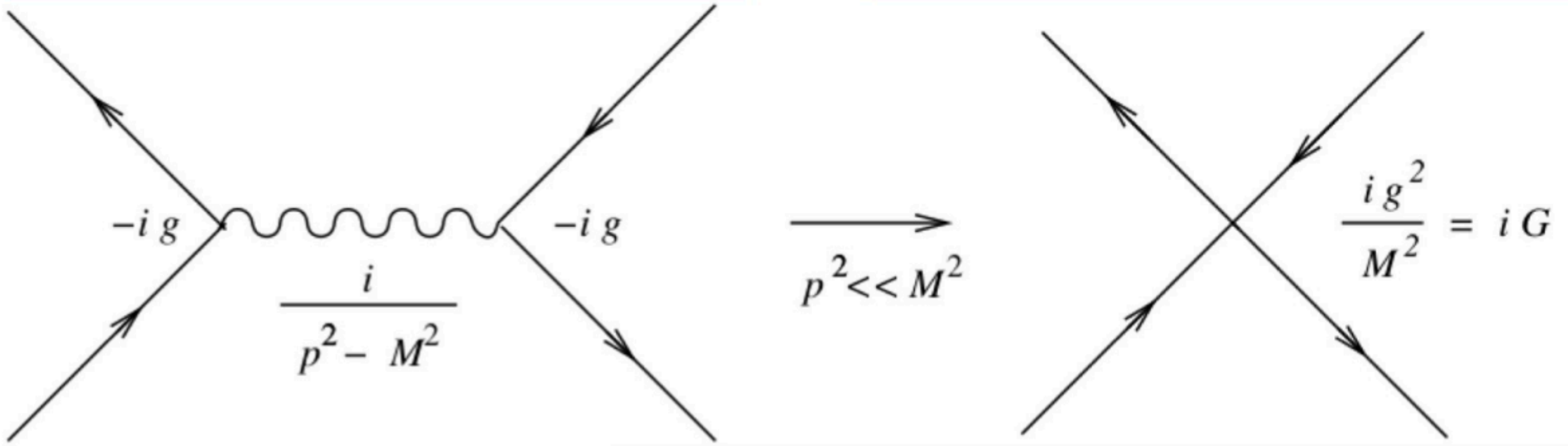


- ✓ c_i specify the strength of the new interactions
- ✓ EFT only valid at E < Λ

CMS-PAS-SMP-24-003

Full theory (*New Physics*)

Effective interaction (*EFT*)



Cross section (xs) also affected as:

SM xs + SM-BSM interference xs + BSM xs

- LHC analyses enable to accurately place limits on Wilson Coefficients (ci)
- A single operator **can influence many processes**, and **multiple operators can affect one single process.**

Standard Model Effective Field Theory (SMEFT)

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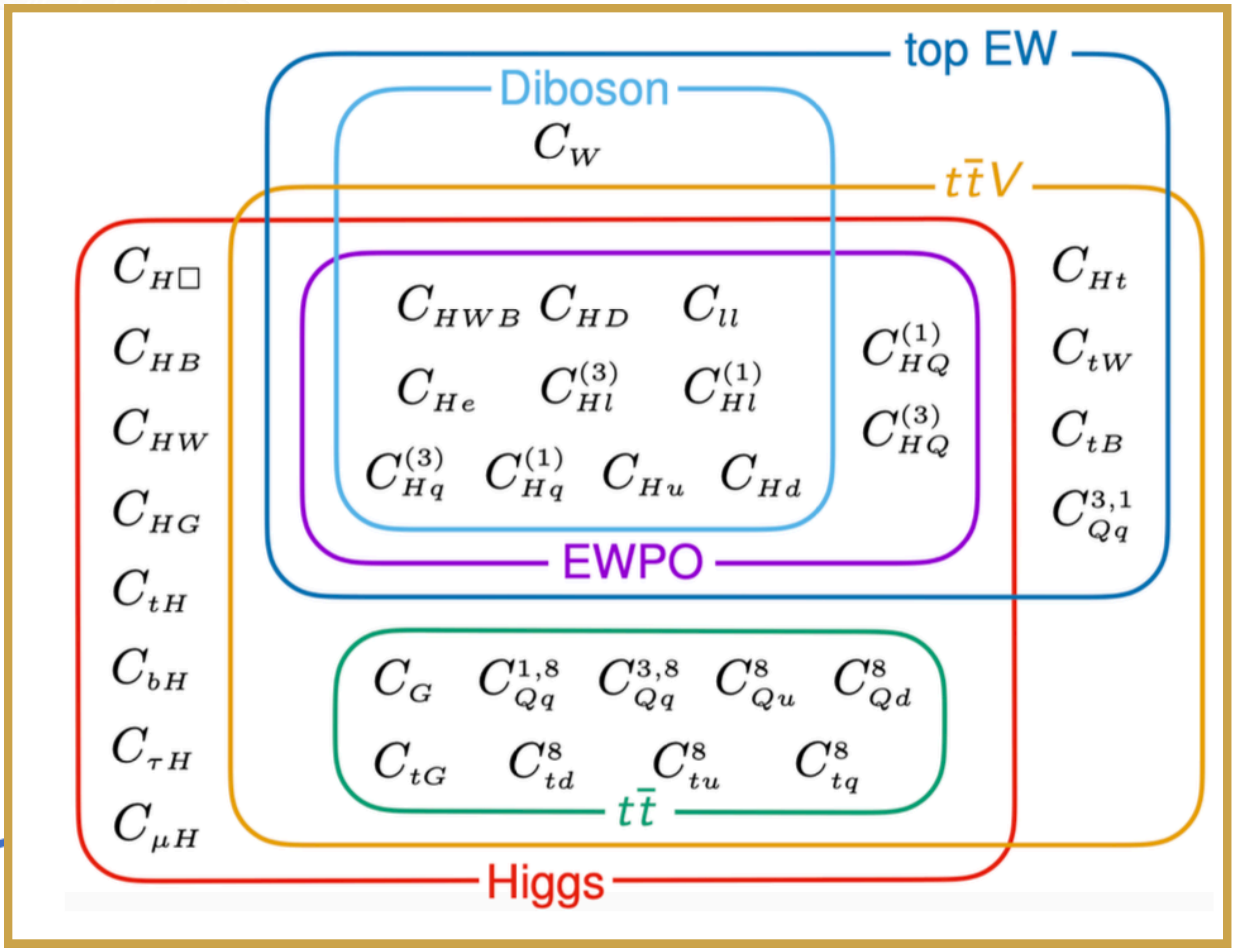

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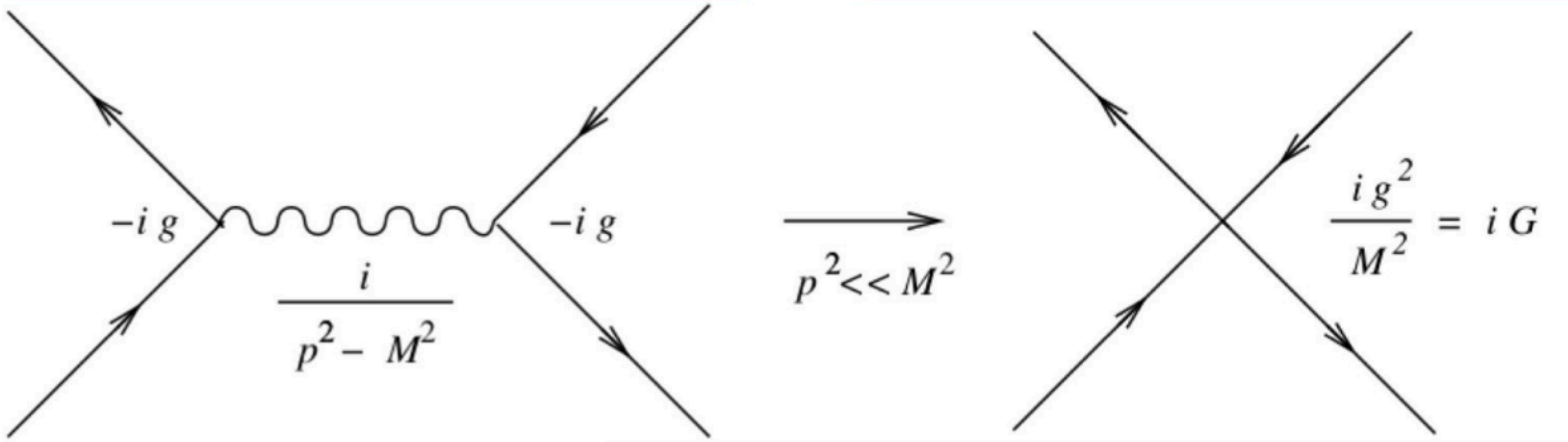

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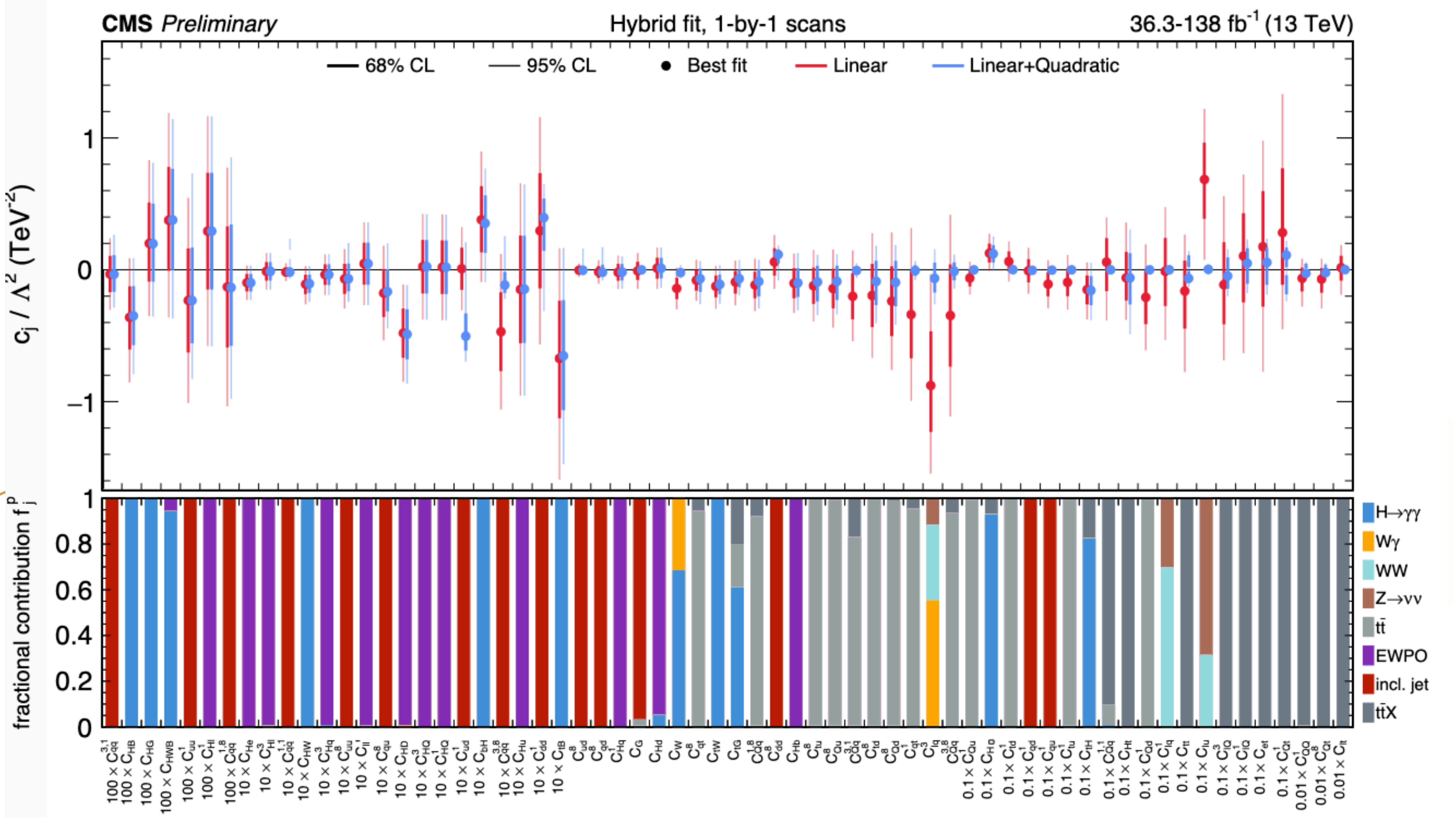
SMEFT: Impact of precision on BSM @LHC

NEW

First combination from an experiment including top, Higgs, vector boson and jet measurements in an EFT interpretation

Analysis	Type of measurement	Observables used
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]
$W\gamma$	Fid. diff. cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$
WW	Fid. diff. cross sections	$m_{\ell\ell}$
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^{Z}
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$
EWPO	Pseudo-observables	$\Gamma_Z,\ \sigma^0_{had},\ R_\ell,\ R_c,\ R_b,\ A^{0,\ell}_{FB},\ A^{0,c}_{FB},\ A^{0,b}_{FB}$
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$
$t\bar{t}X$	Direct EFT	Yields in regions of interest



CMS-PAS-SMP-24-003

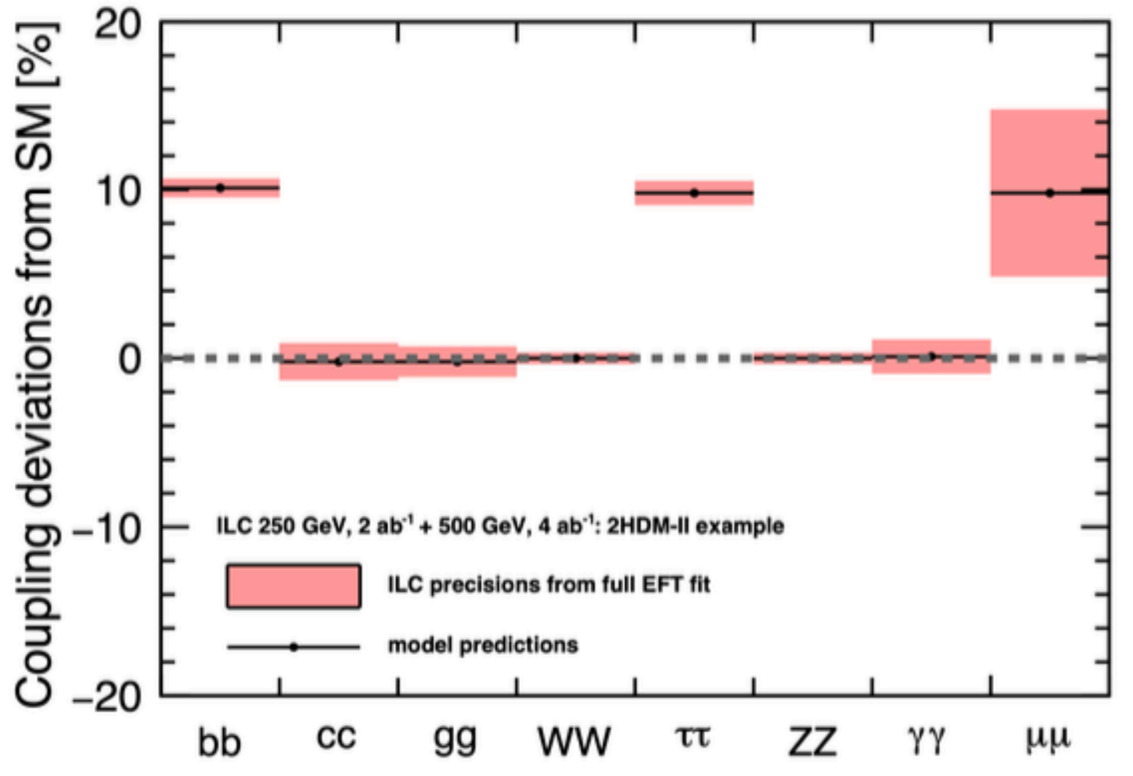
SMEFT: Impact of precision on BSM @HL-LHC

- **Higgs couplings deviations** depend on BSM scenario

Sally Dawson (LHCP 2024)

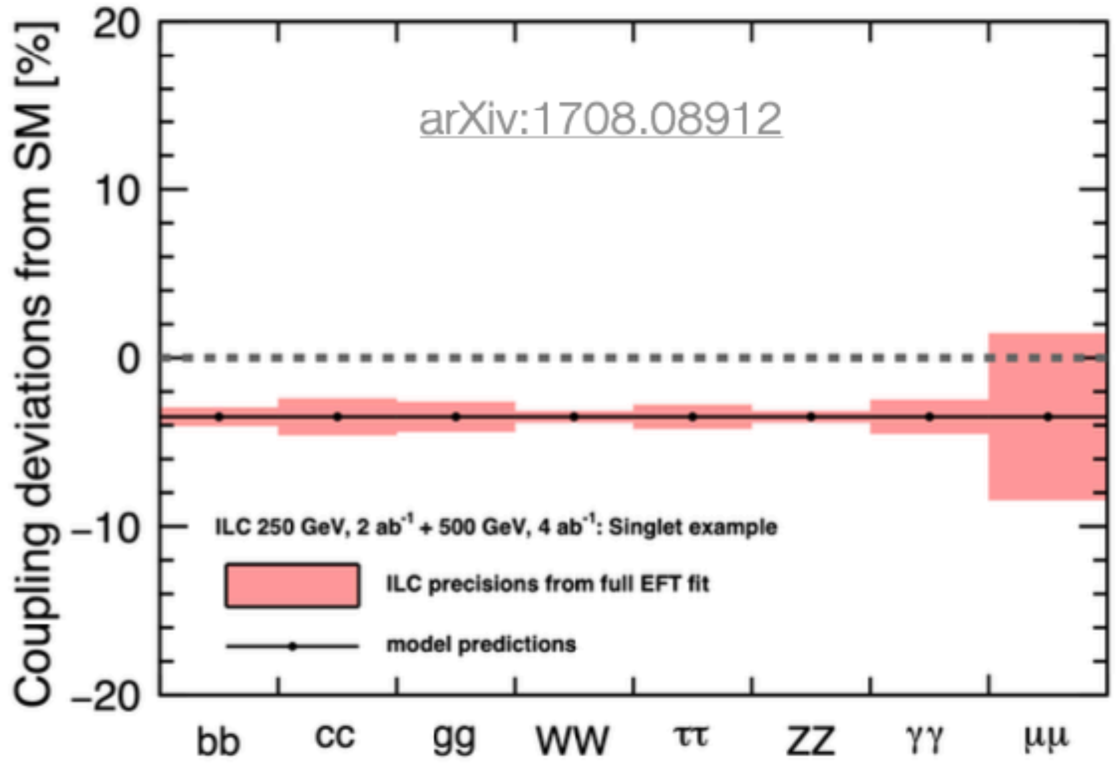
2HDM Type-II

$m_A = 600$ GeV, $\tan\beta = 7$



Extra Higgs singlet

$m_X = 2.8$ TeV, max allowed mixing

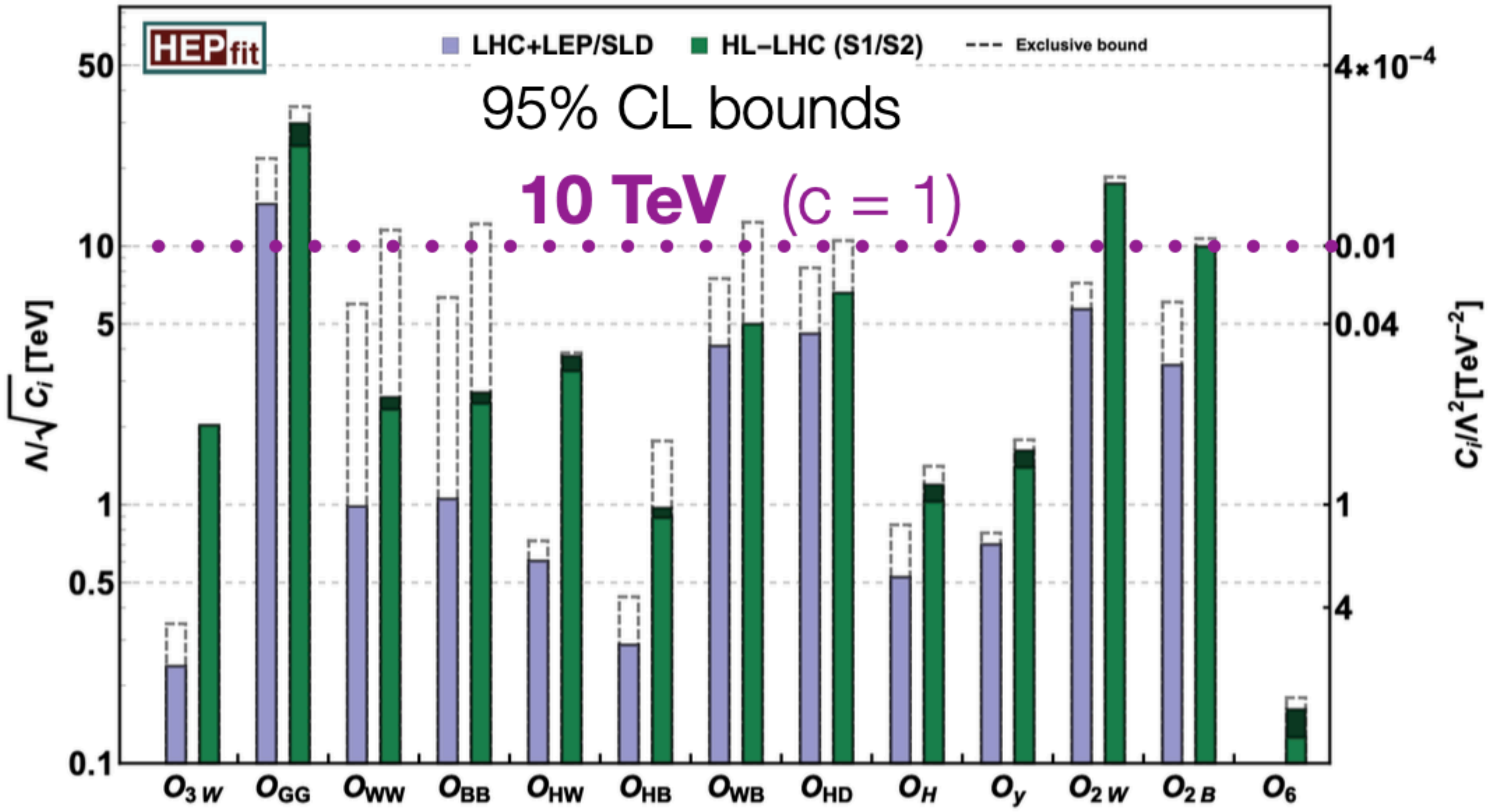


- **Generic Higgs coupling deviations**

$$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \simeq 1.6\,\% \left(\frac{2\ \text{TeV}}{\Lambda}\right)^2$$

but mapping between precision and energy scale is highly model dependent

- **Dim-6 EFT w/ Higgs + EW**
  - Large impact of tree-level $\mathcal{O}_{GG,WW,BB}$ on SM loop-induced $gg \to H$ or $H \to \gamma\gamma$ $\Lambda \gtrsim 30$ TeV $(c = 1)$
  - Also strong impact from Drell-Yan measurements on $\mathcal{O}_{2W,2B}$



CERN-2019-007 (YR18)

exclusive bounds on single operator

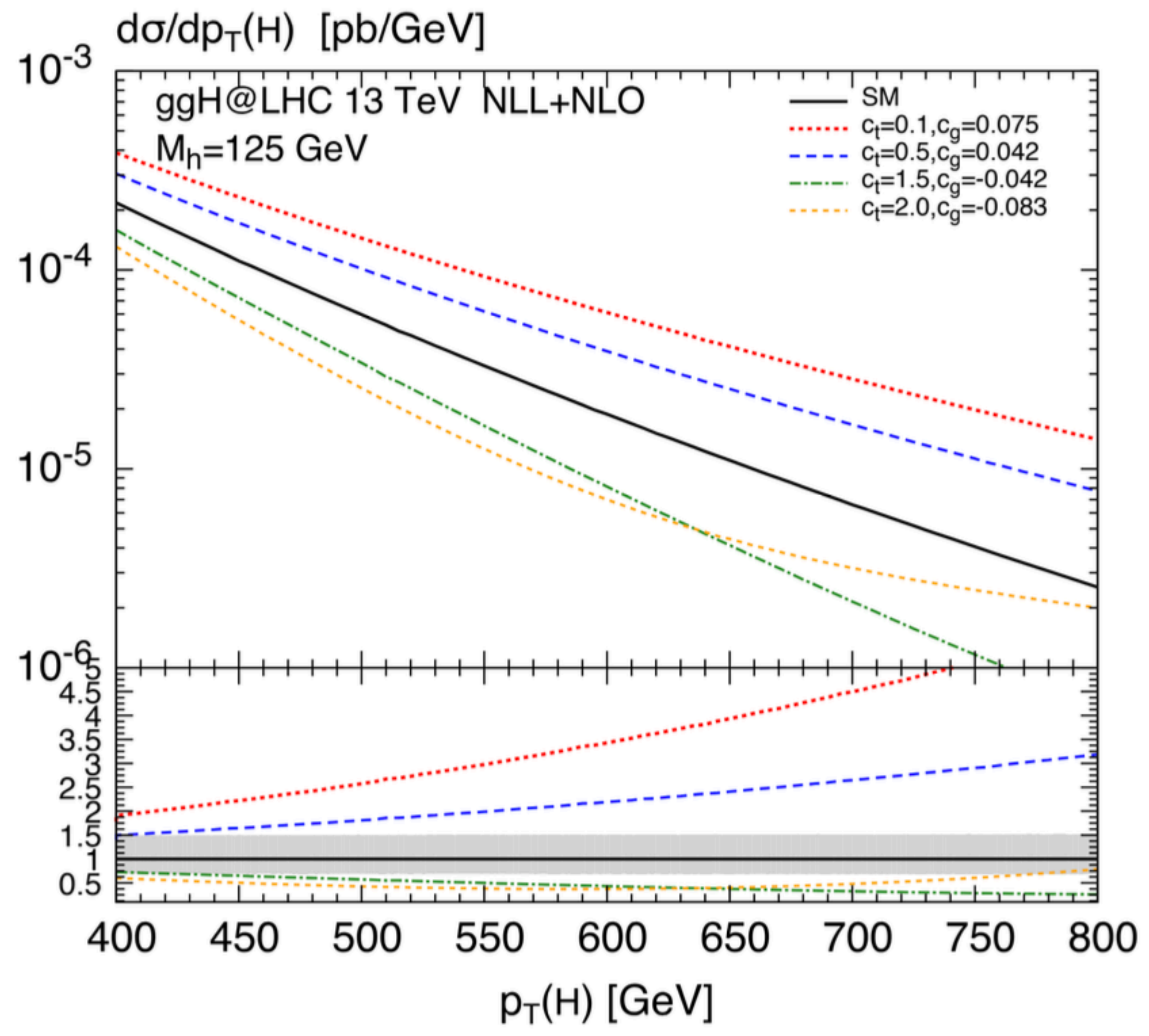
bounds from global fit

SMEFT: Impact of precision on BSM @HL-LHC

Higgs differential cross sections

- High p_T region sensitive to BSM effects
- Directly benefits from statistical power of HL-LHC

arXiv:1612.00283



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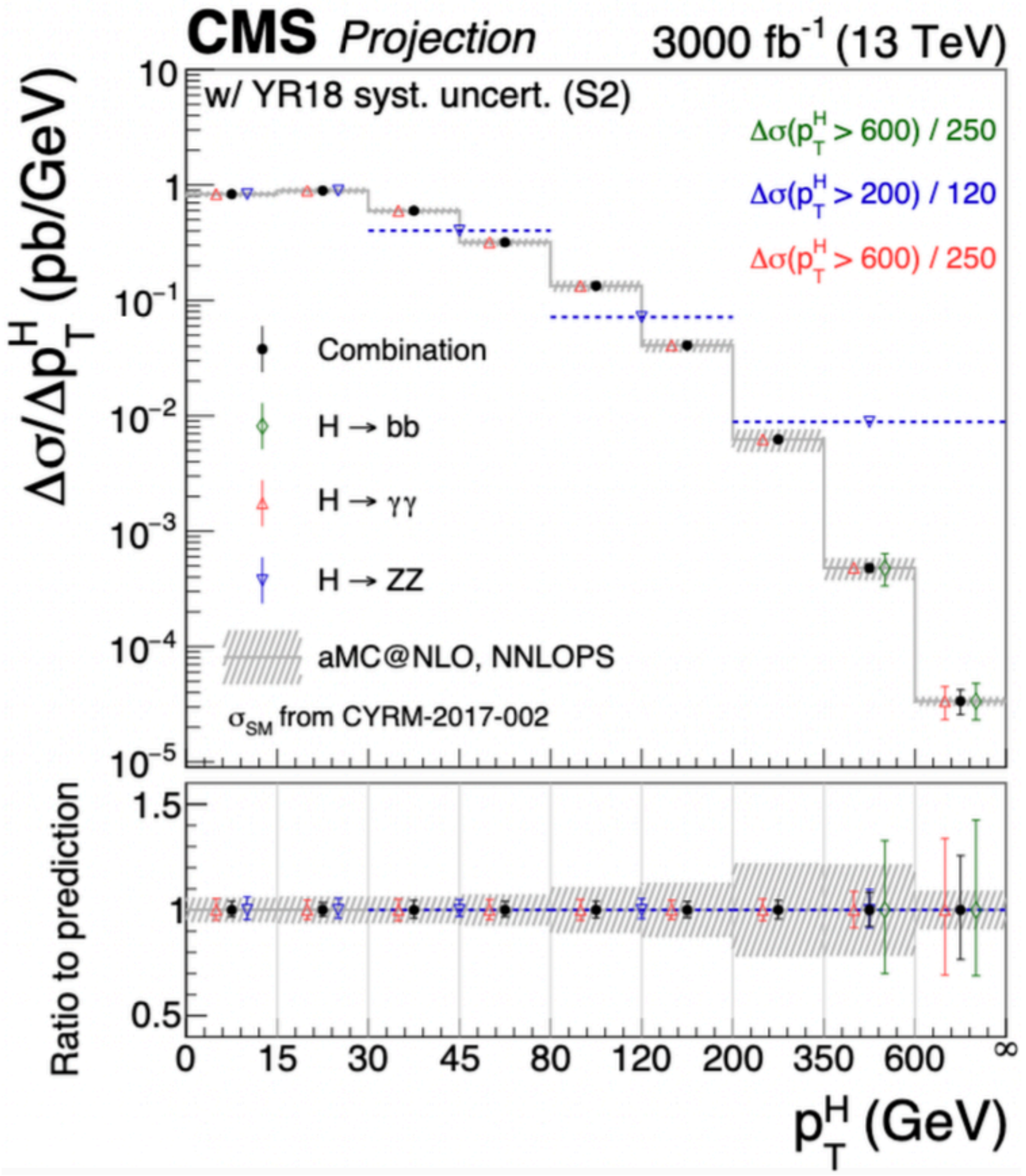
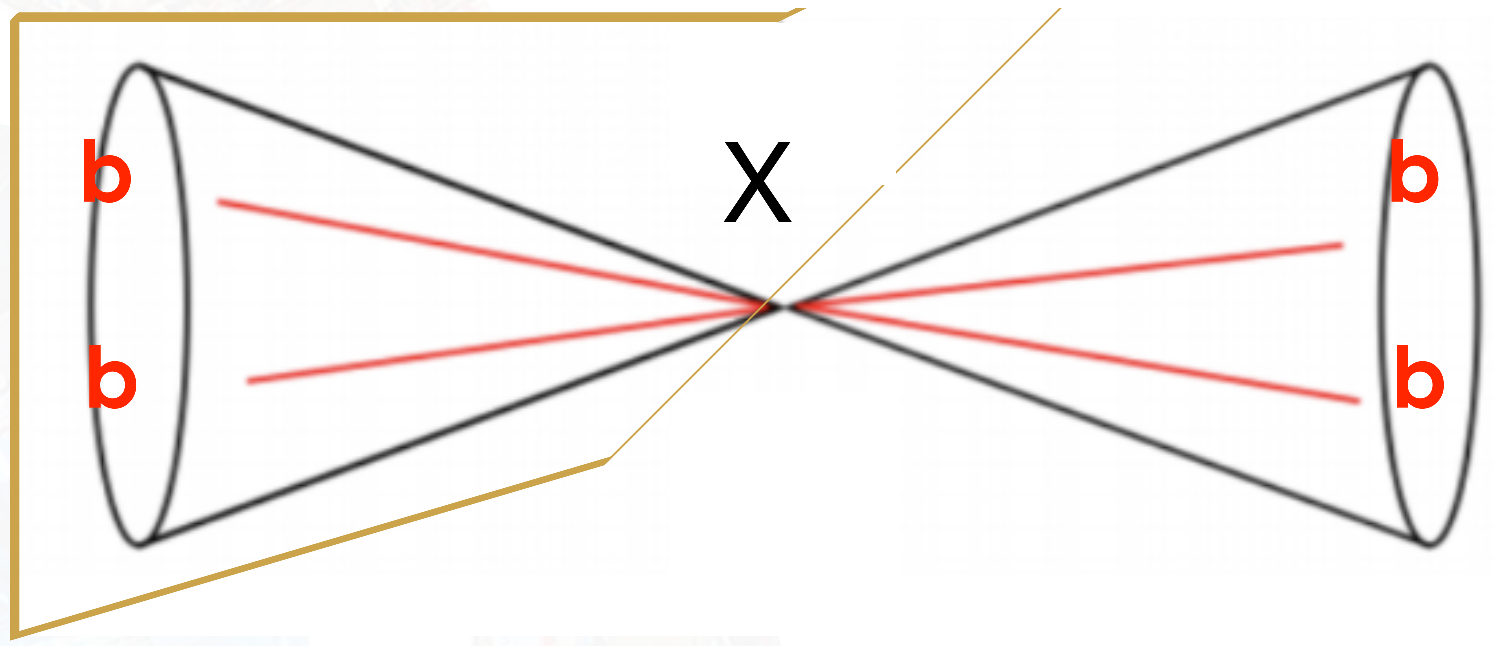


Beyond Standard Model Physics

New massive resonances decaying into Higgs boson pairs

- Spin-0 and 2 new particles **X→HH→4b**
- $H \rightarrow bb$ **are highly Lorentz-boosted**: two b reconstructed as a single large-radius jet



- GGF Spin-2 graviton masses of up to about 3 TeV
- VBF: cross section an order of magnitude smaller not yet explored

Mass reach x 2 w.r.t. Run 2

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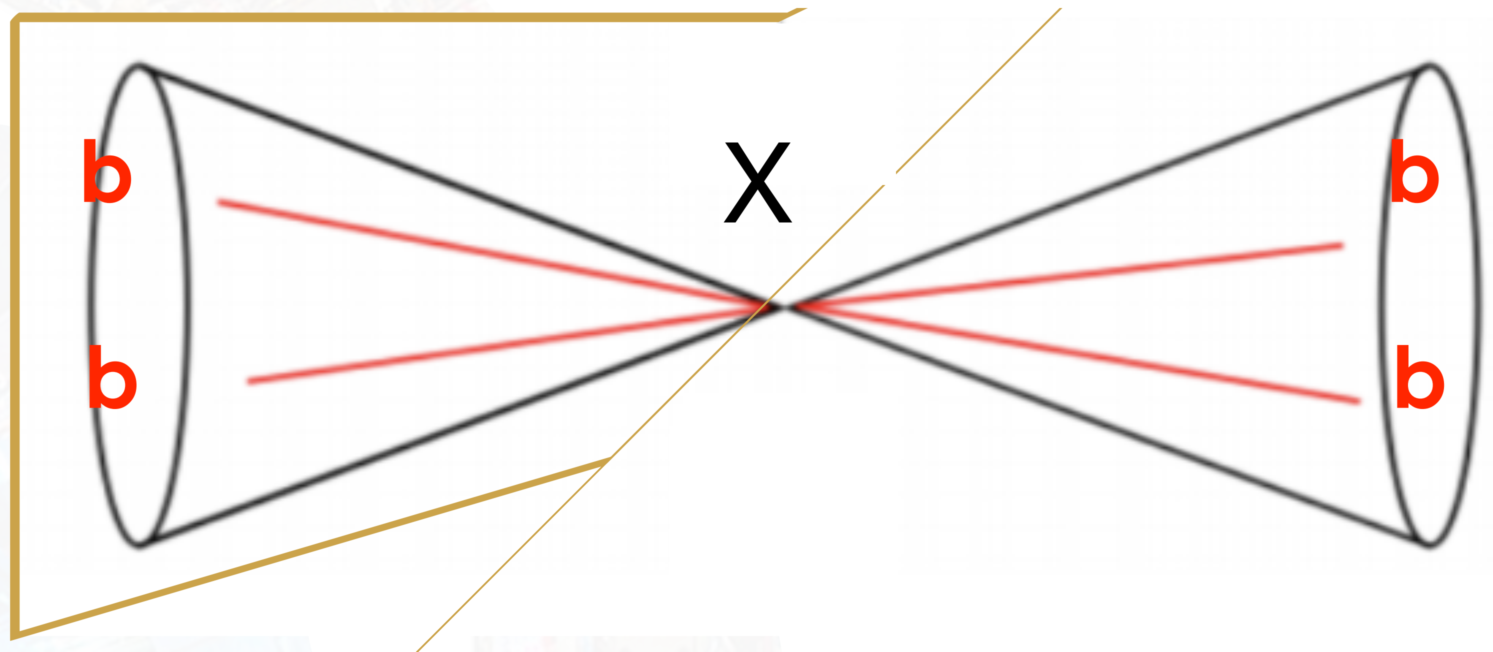

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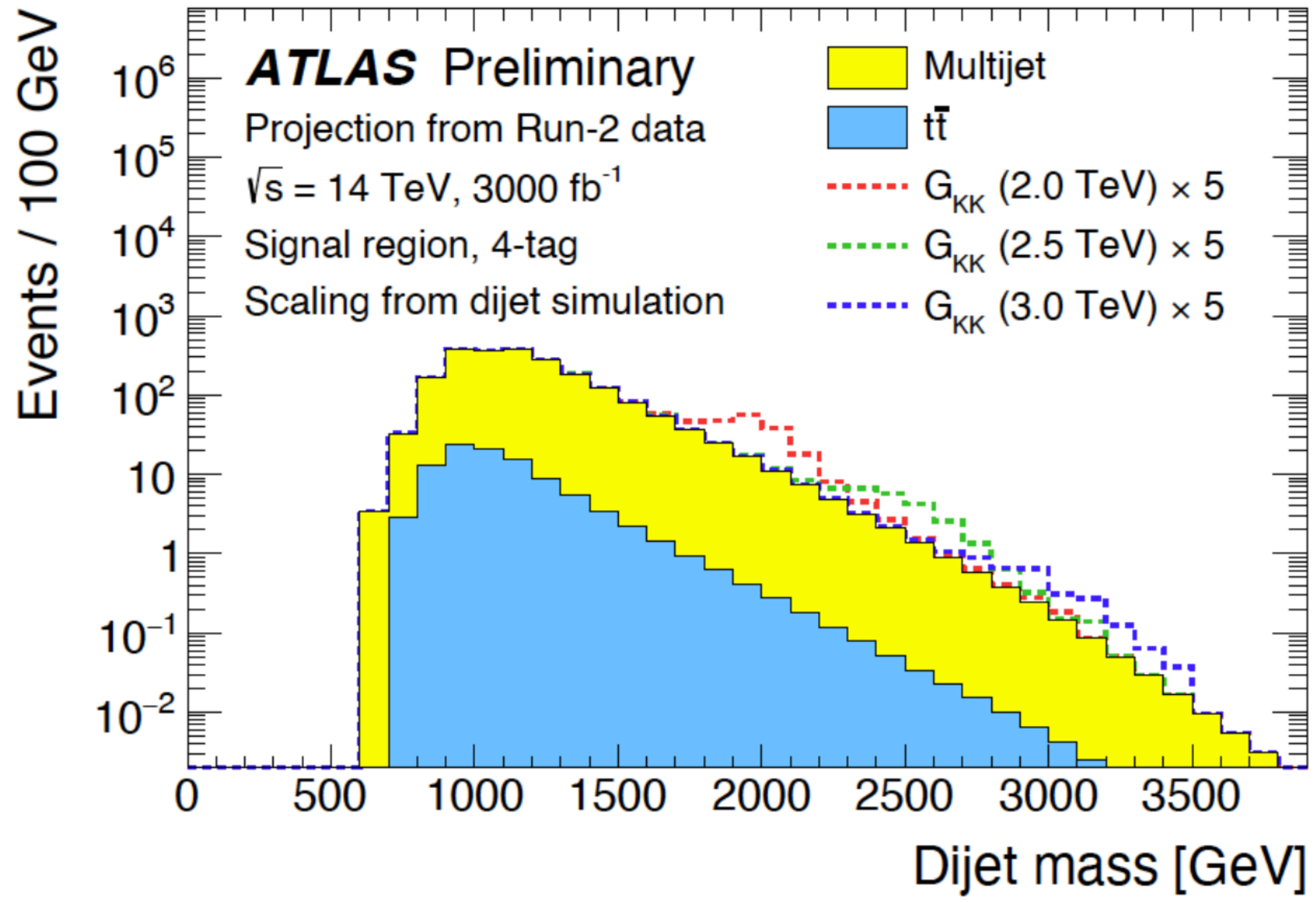

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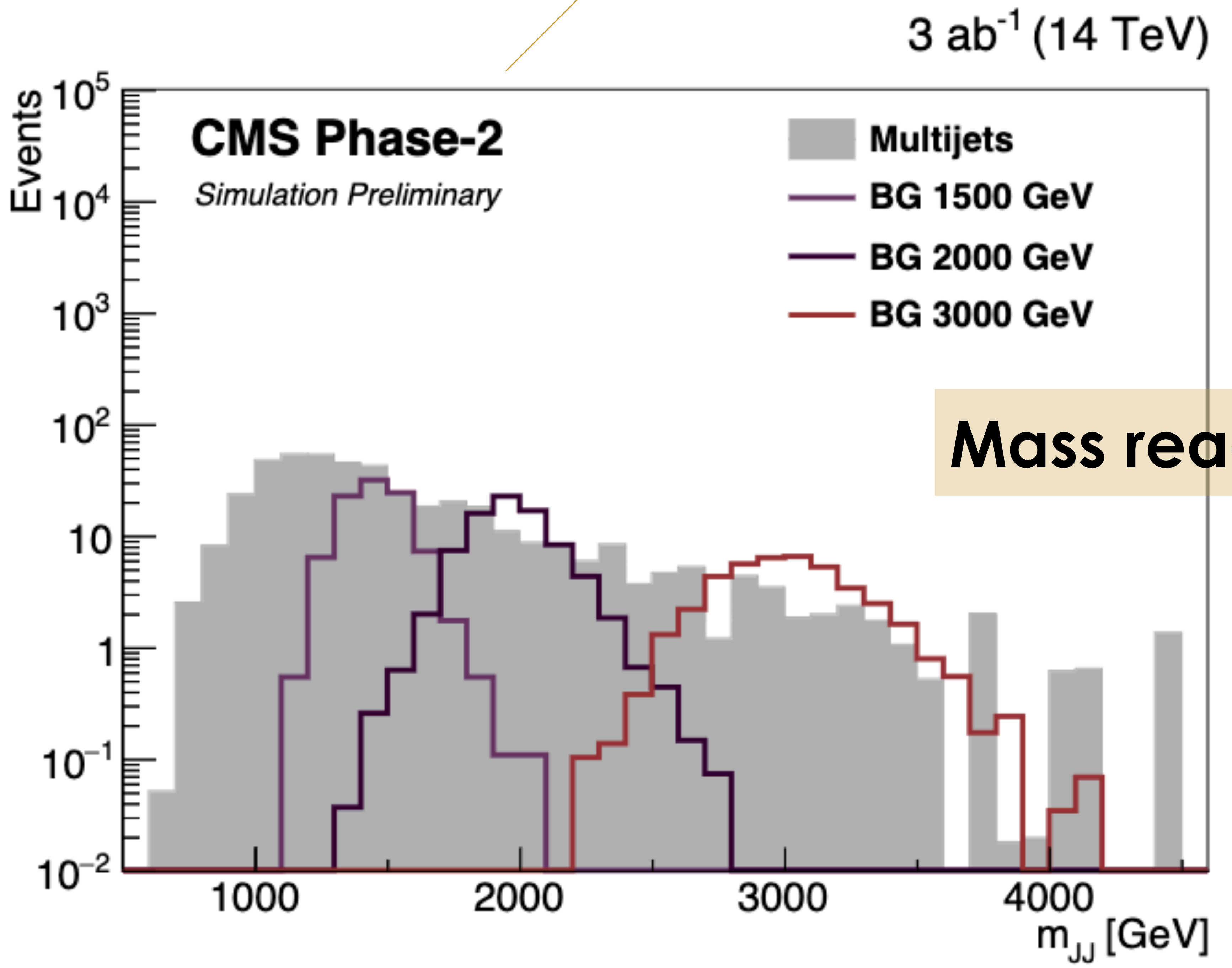


Mass reach x 2 w.r.t. Run 2

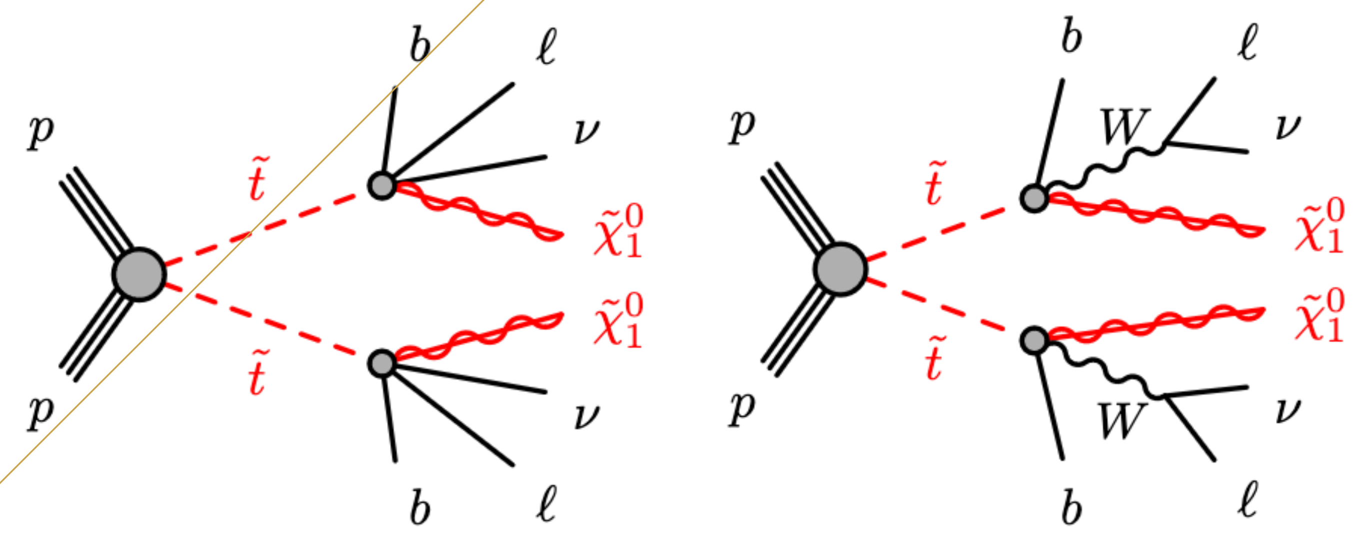
Search for direct pair production of top squarks at HL-LHC

NEW

- Analysis strategy similar to the Run 2 one in final states with two leptons, jets and missing transverse momentum

- Three and four bodies decays studies under the assumption:

$$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$$



- At HL-LHC the Fake Non Prompt background rejection will benefit from **higher granularity improved isolation performance**

- Different kinematic variables are exploited to separate the signal from the SM background and **cuts optimized w.r.t. Run 2**

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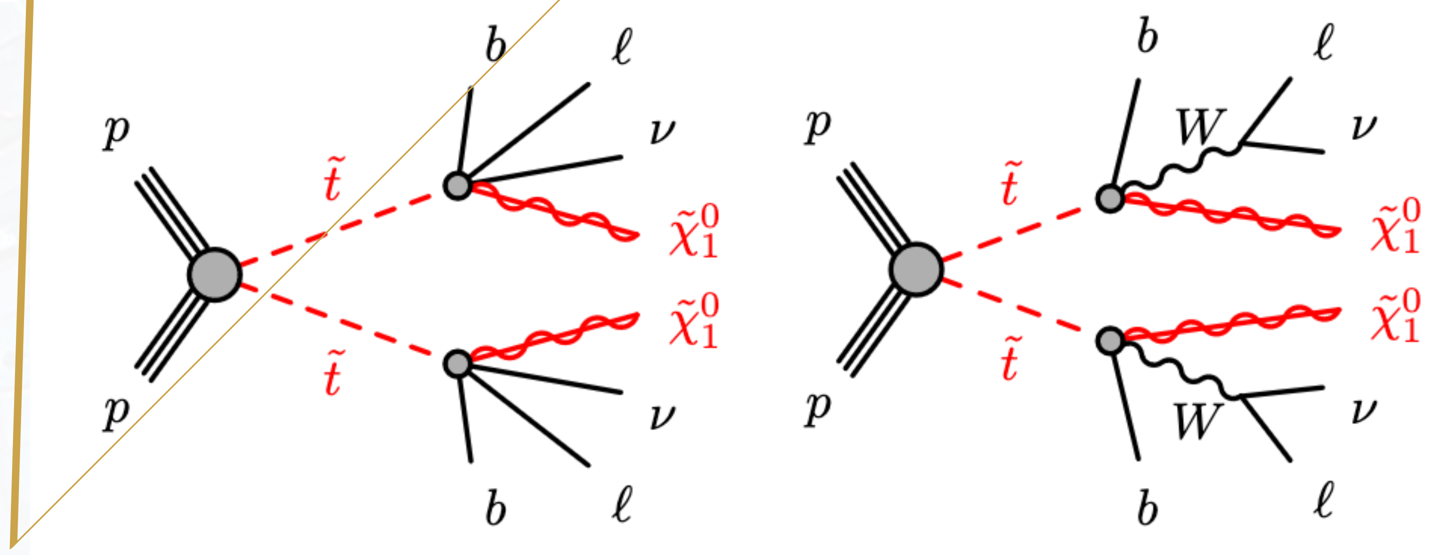

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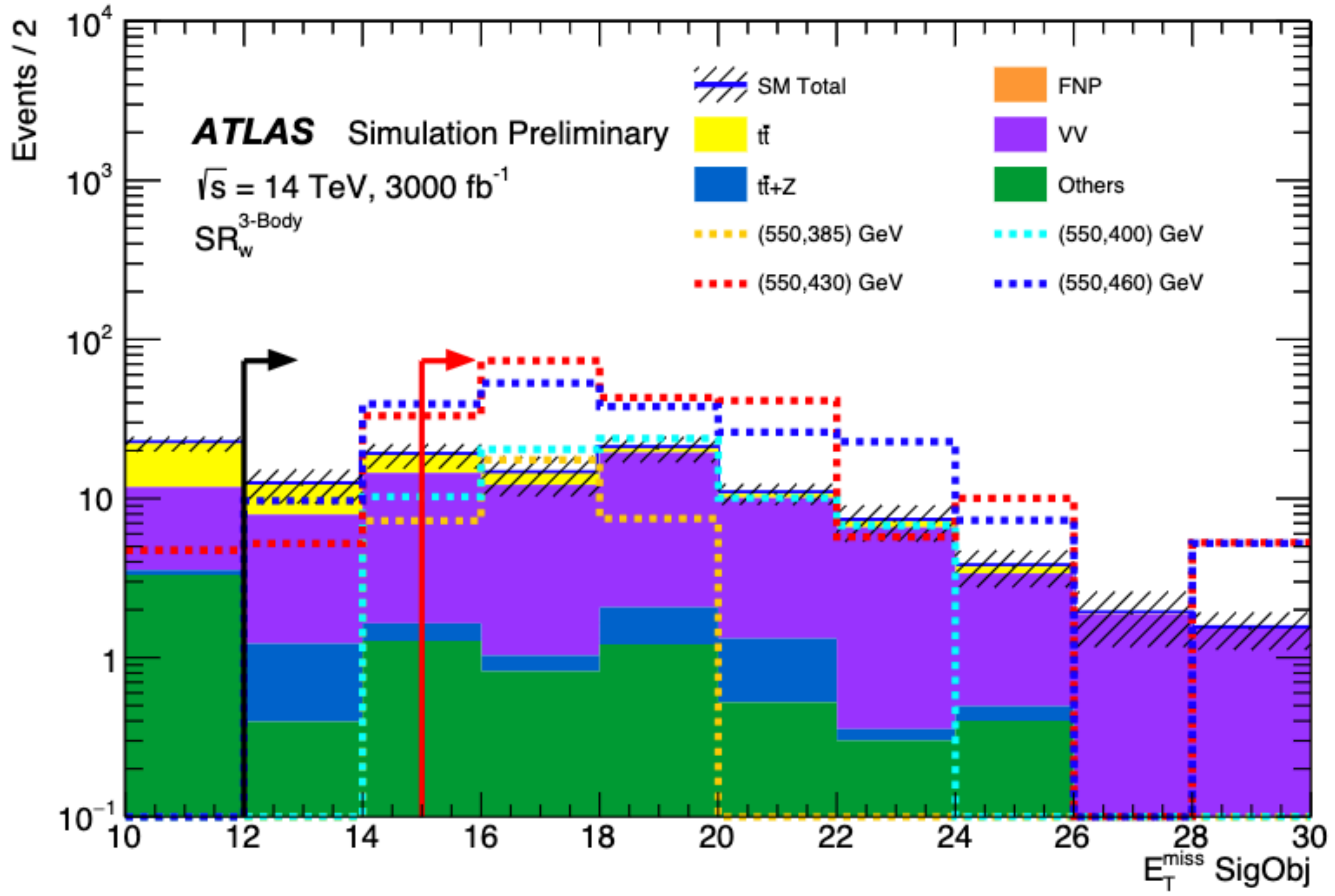

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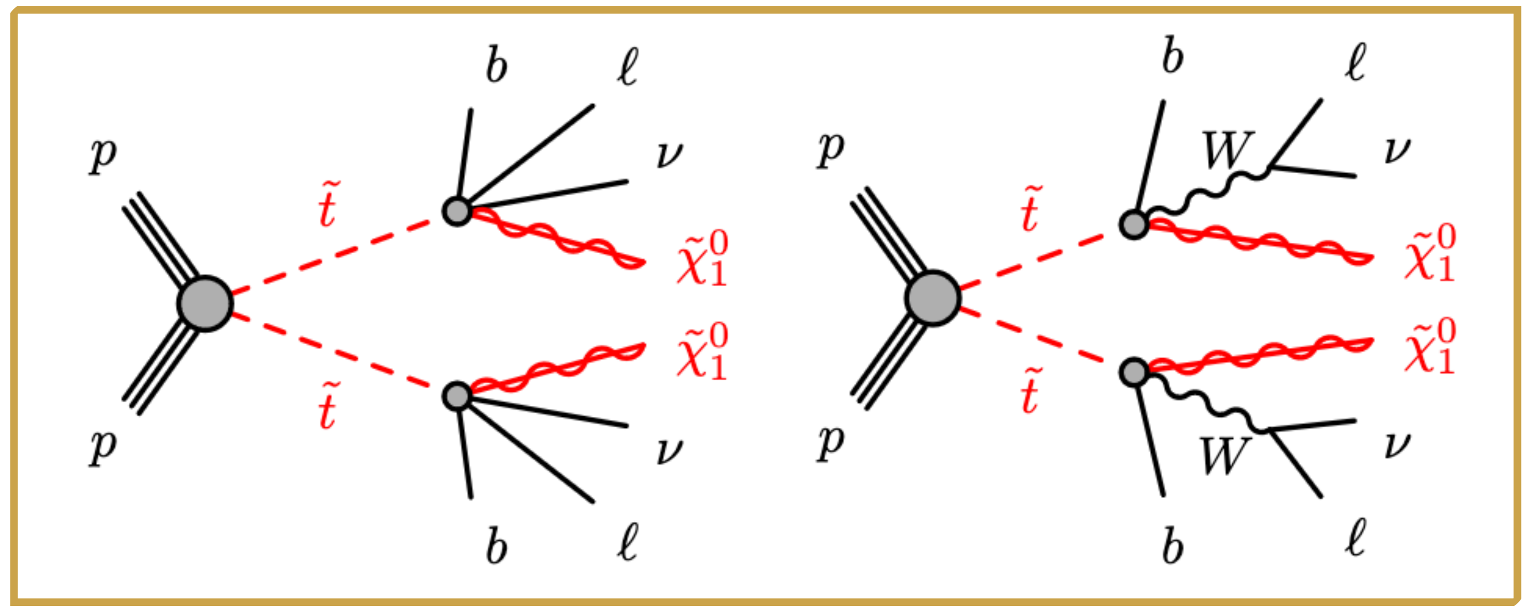
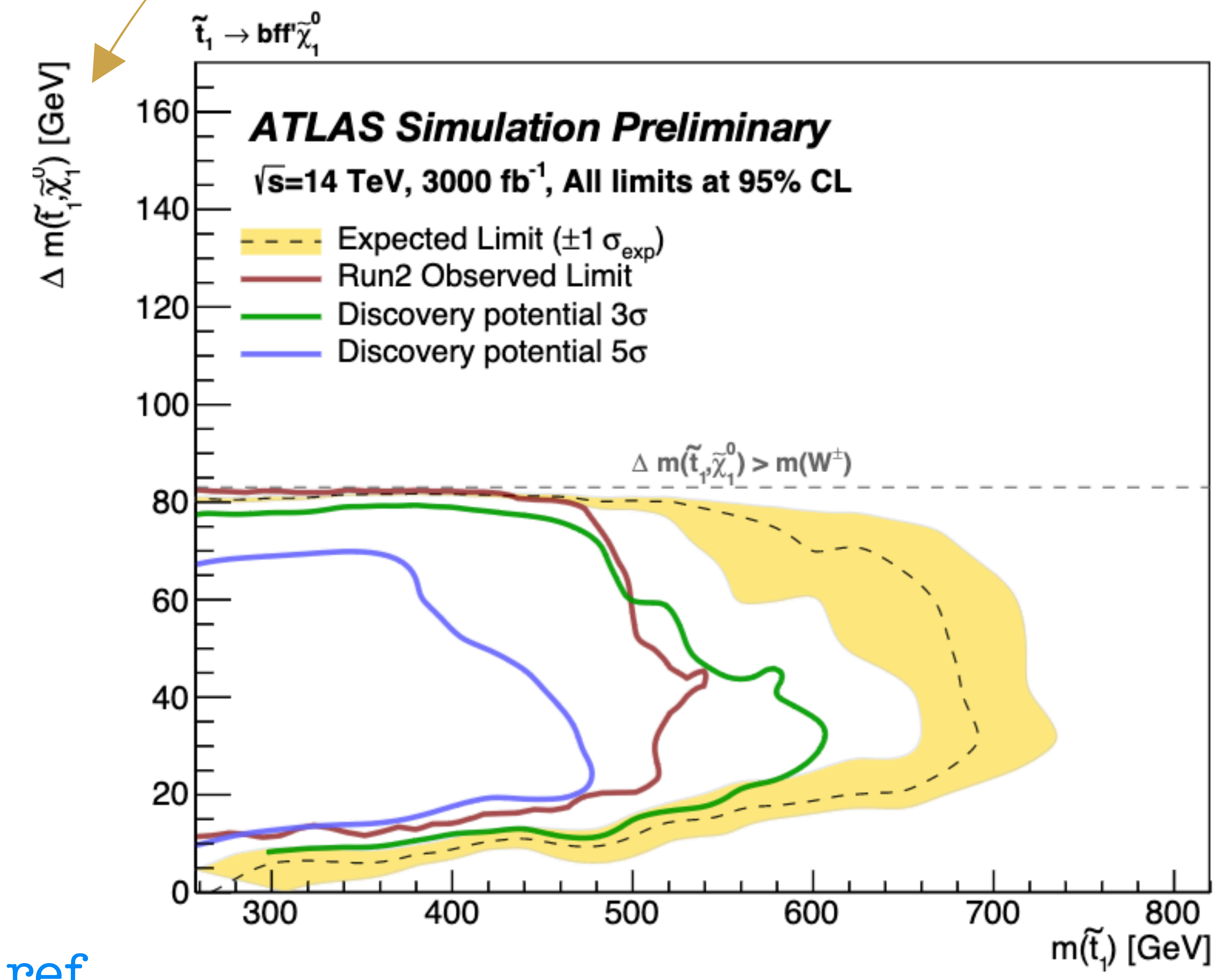
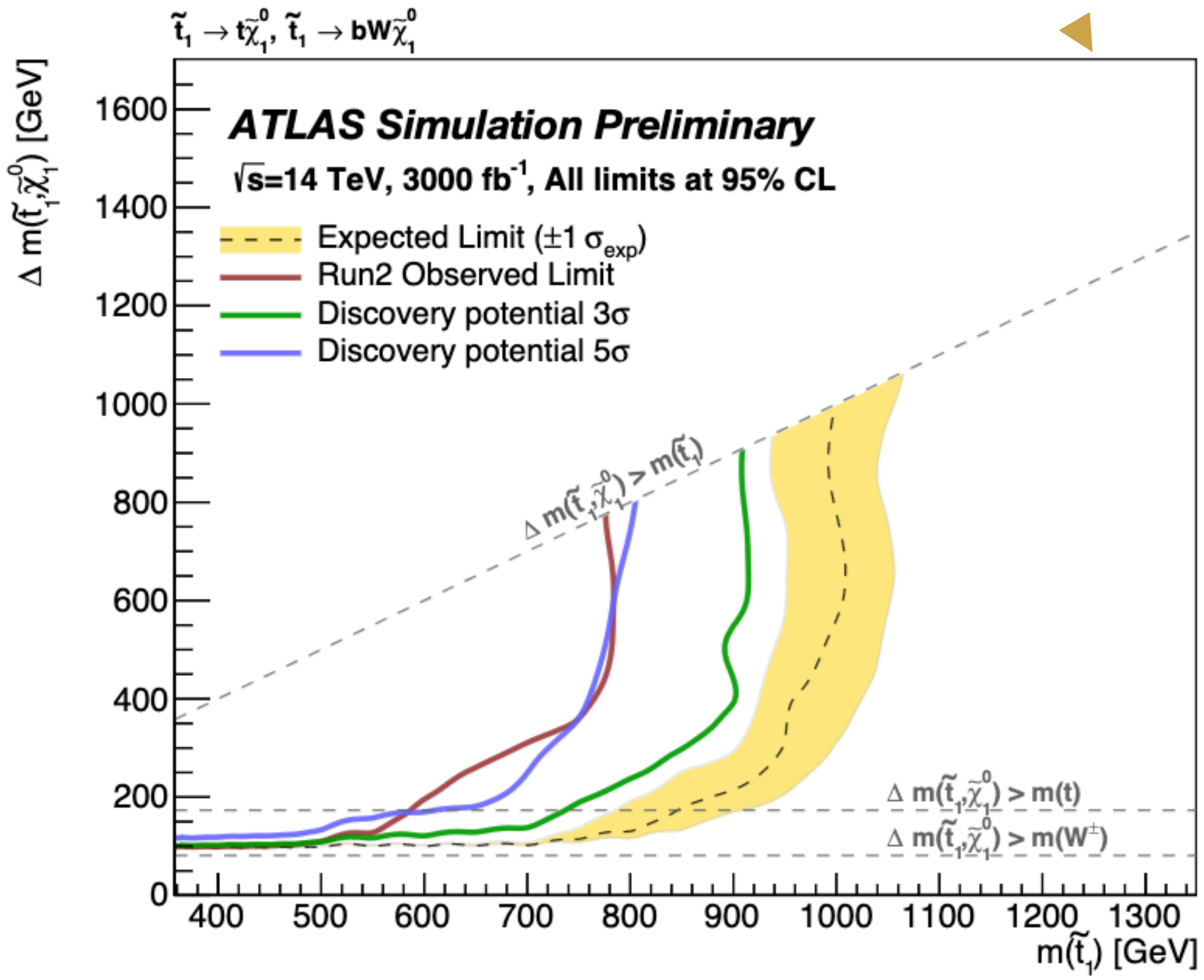


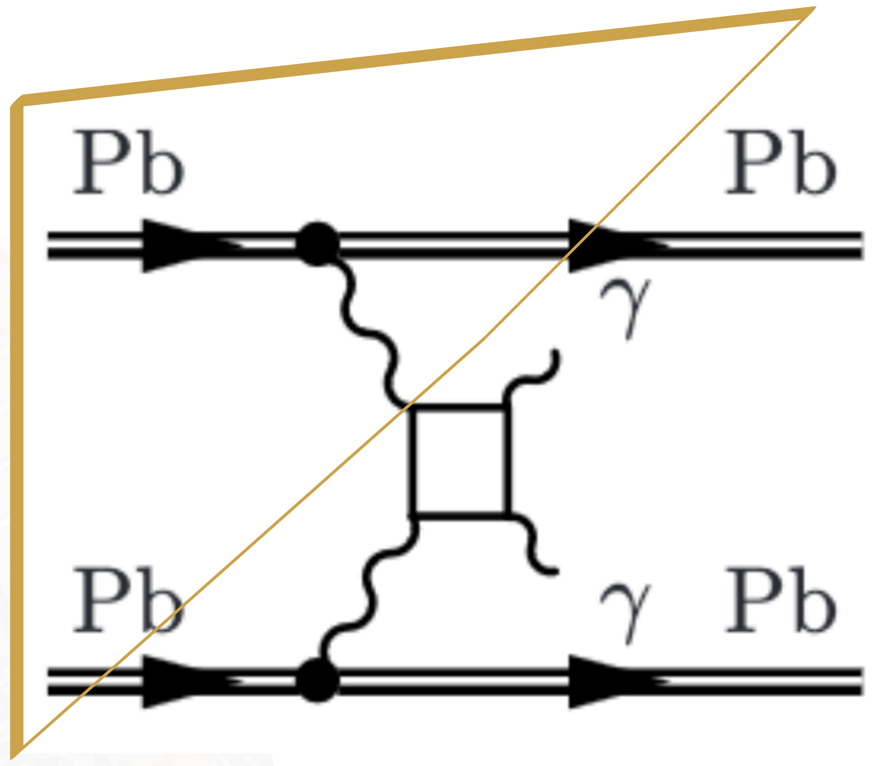
- Sensitivity **estimates conservative**: assumed Run 2 objects reconstructions same trigger thresholds





ref.

The HL-LHC photon collider @ ALICE



- **Ultra-peripheral collisions (UPCs) of heavy ions**: light-by-light scattering, axion-like particle

- ALICE 3 can access invariant **masses below 5 GeV**:
  - s, t and u–channel play an important role
  - largest theoretical uncertainties in the calculation of the muon anomalous magnetic moment

- Final state: two photons emitted back-to-back

- **$\pi^0\pi^0$ dominant background below 2 GeV** (final state with four photons of which only two are detected)

Below 0.5 GeV/c2, signal is dominant

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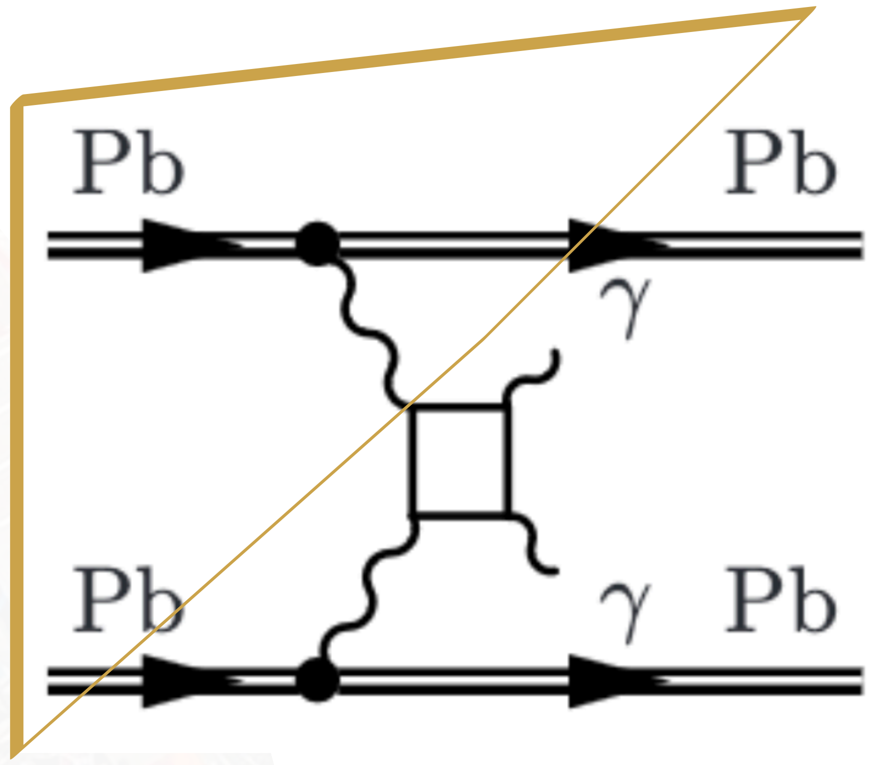

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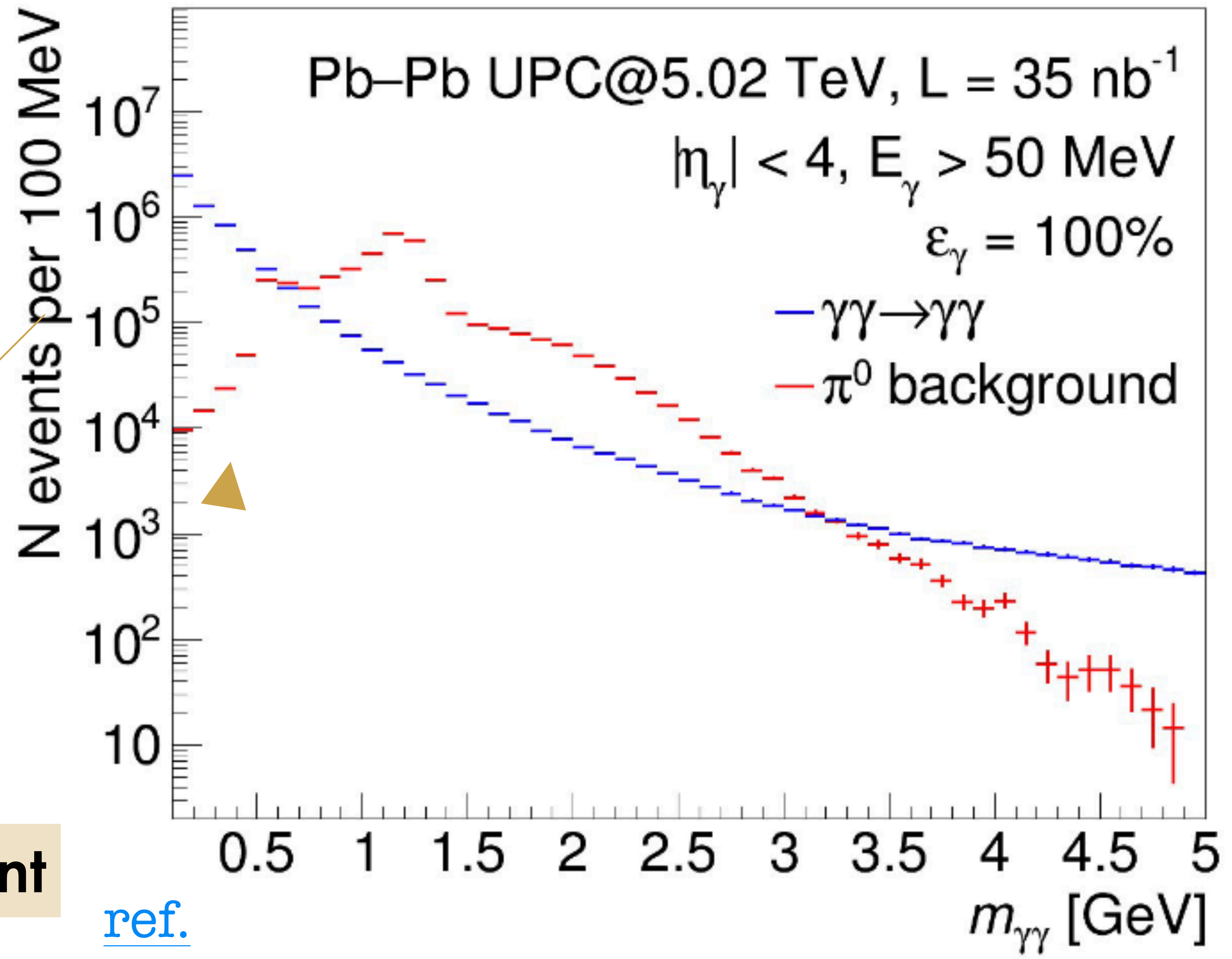

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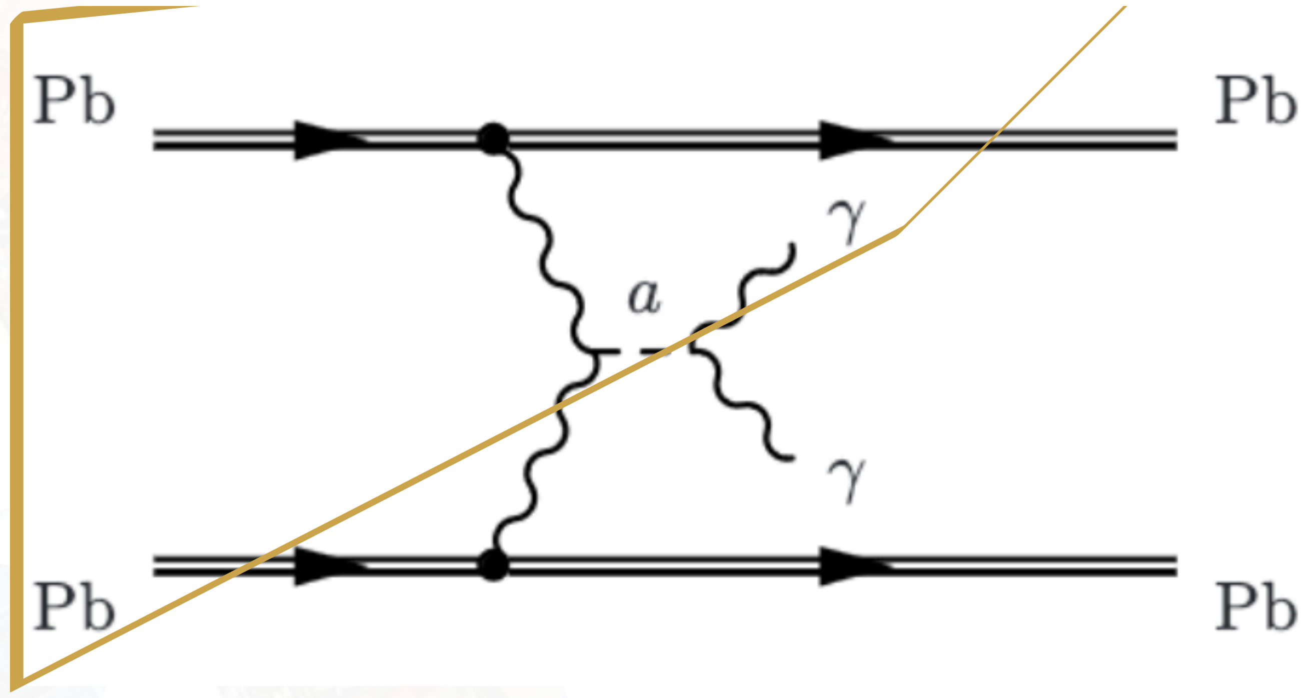
A new approach in BSM searches @ ALICE

- ALPs via the γγ → a → γγ process naturally couple to photons via an effective Lagrangian



- Two-dimensional parameter space of the **axion mass m_a and the coupling w/ photons**

- ATLAS and CMS: limited abilities to light masses due to the difficulties in the triggering and reconstruction of photons with transverse energy below 2 GeV

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ALICE 3: unique opportunity to fill the gap in the intermediate ALP mass range from 50 MeV to 5 GeV

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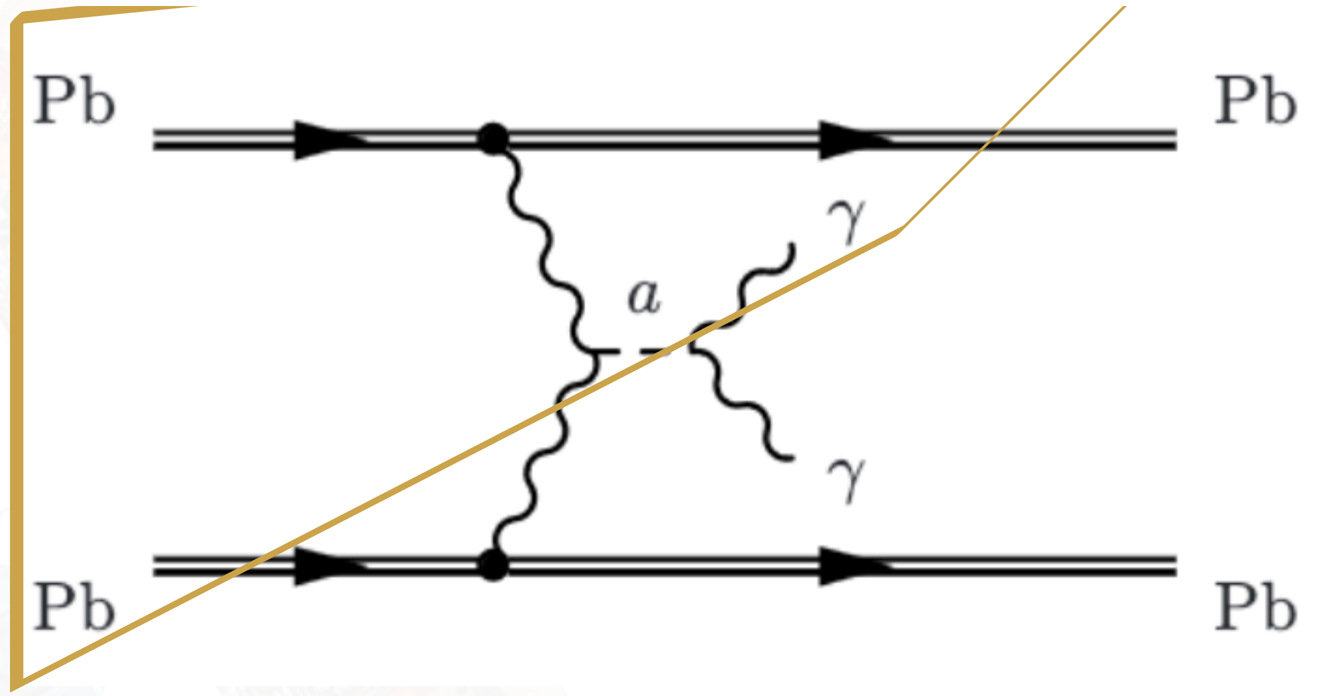

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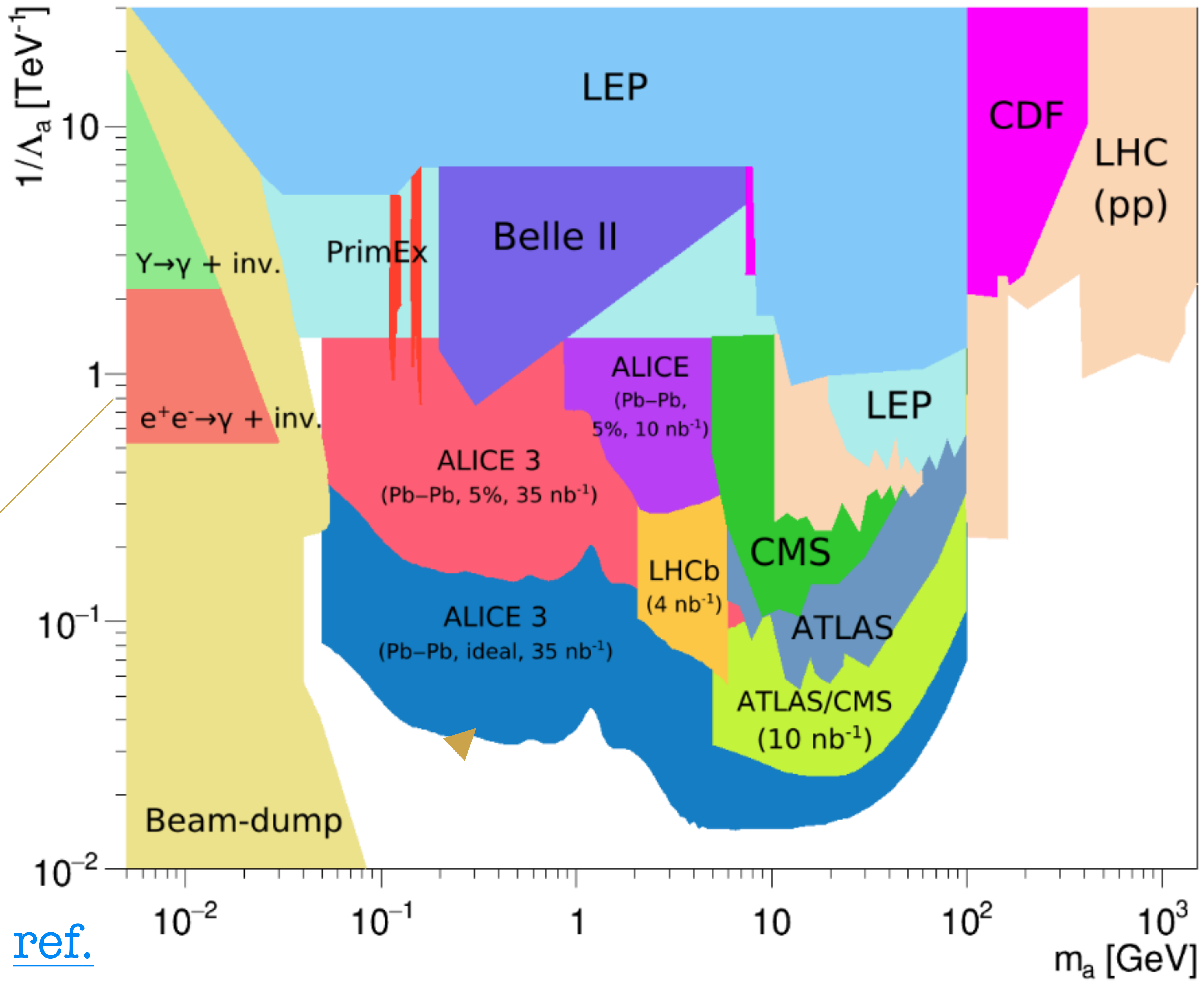

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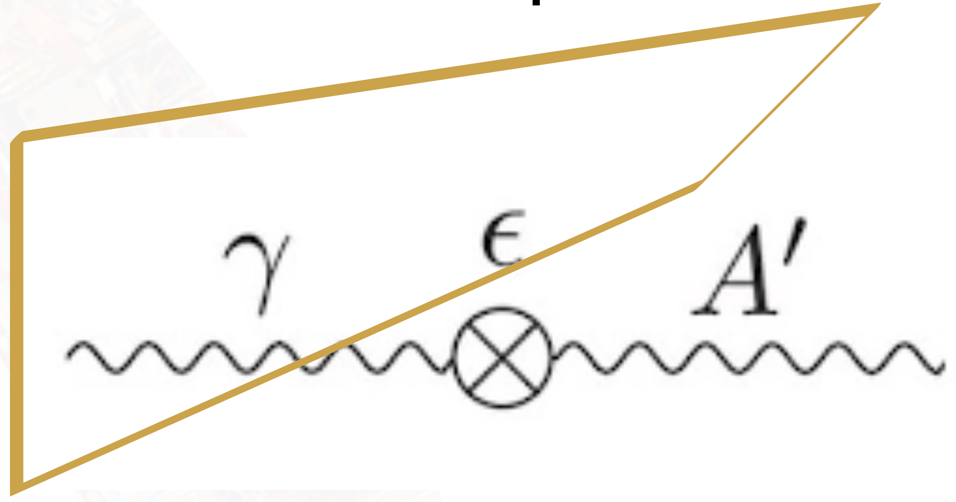
Boosting Dark Photon Sensitivity @ LHCb

- **Dark Photon A'**, mediator of a new U(1) dark force kinetically mix with the photon: observed in final states produced by the EM current



- Two free parameters: mixing term **ε^2** and mass of A', **$m_{A'}$**
  - prompt and displaced searches using D^{*0}
  - inclusive dimuon production
  - light meson decays:
    $\pi 0 \rightarrow e^+e^-\gamma$
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- Three core capabilities of LHCb: **excellent secondary vertex resolution, particle identification, and real-time data-analysis.**

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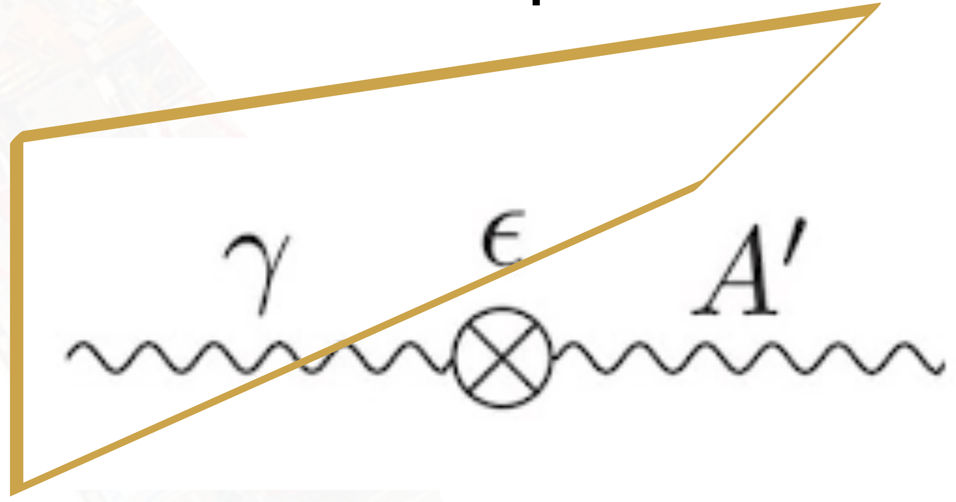

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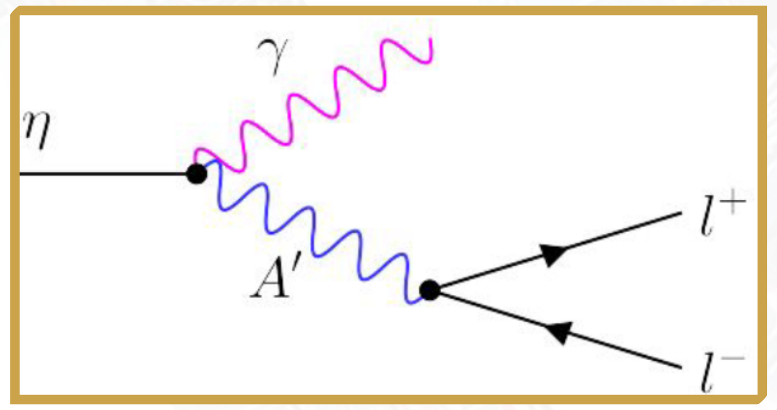

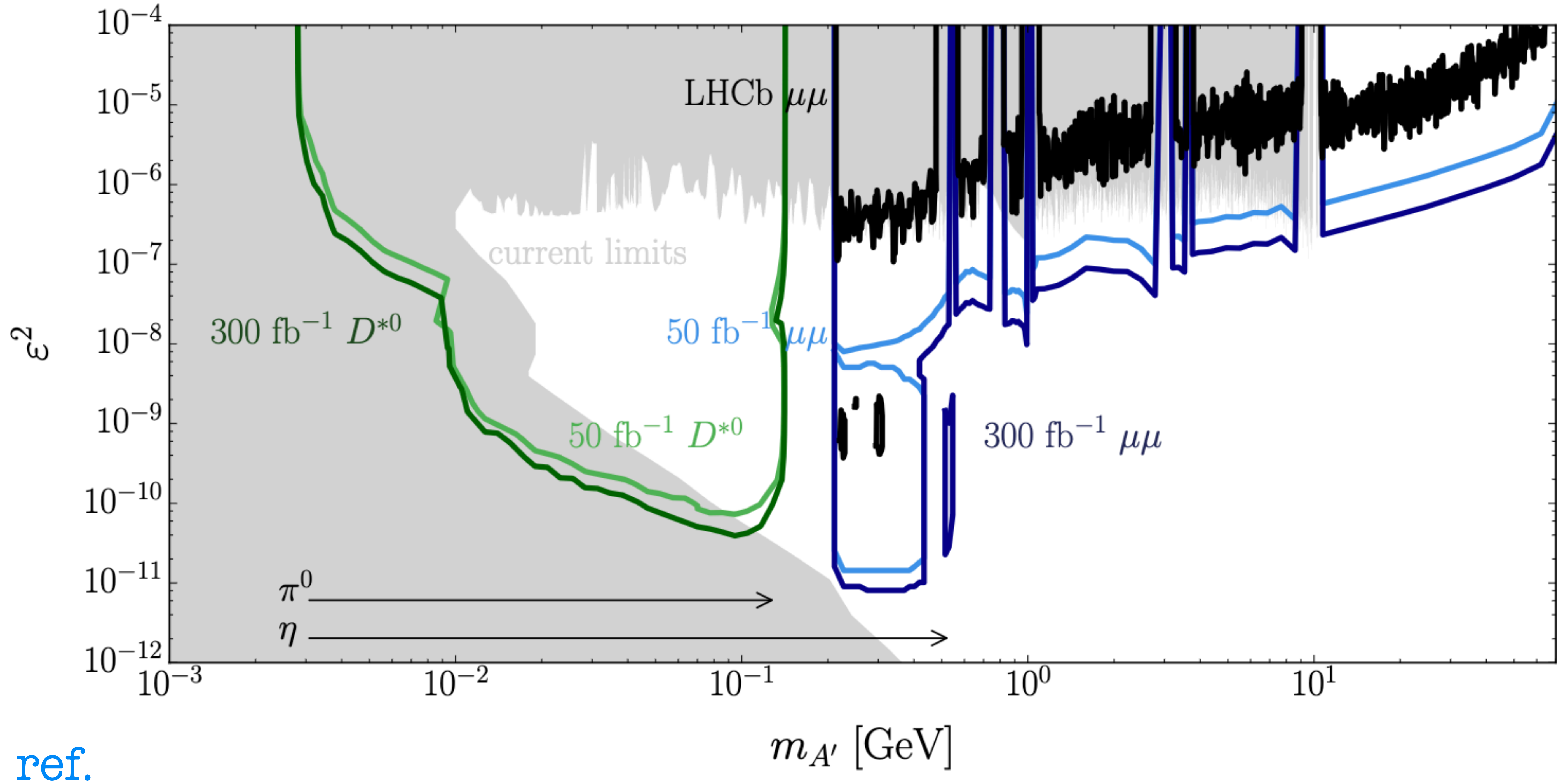

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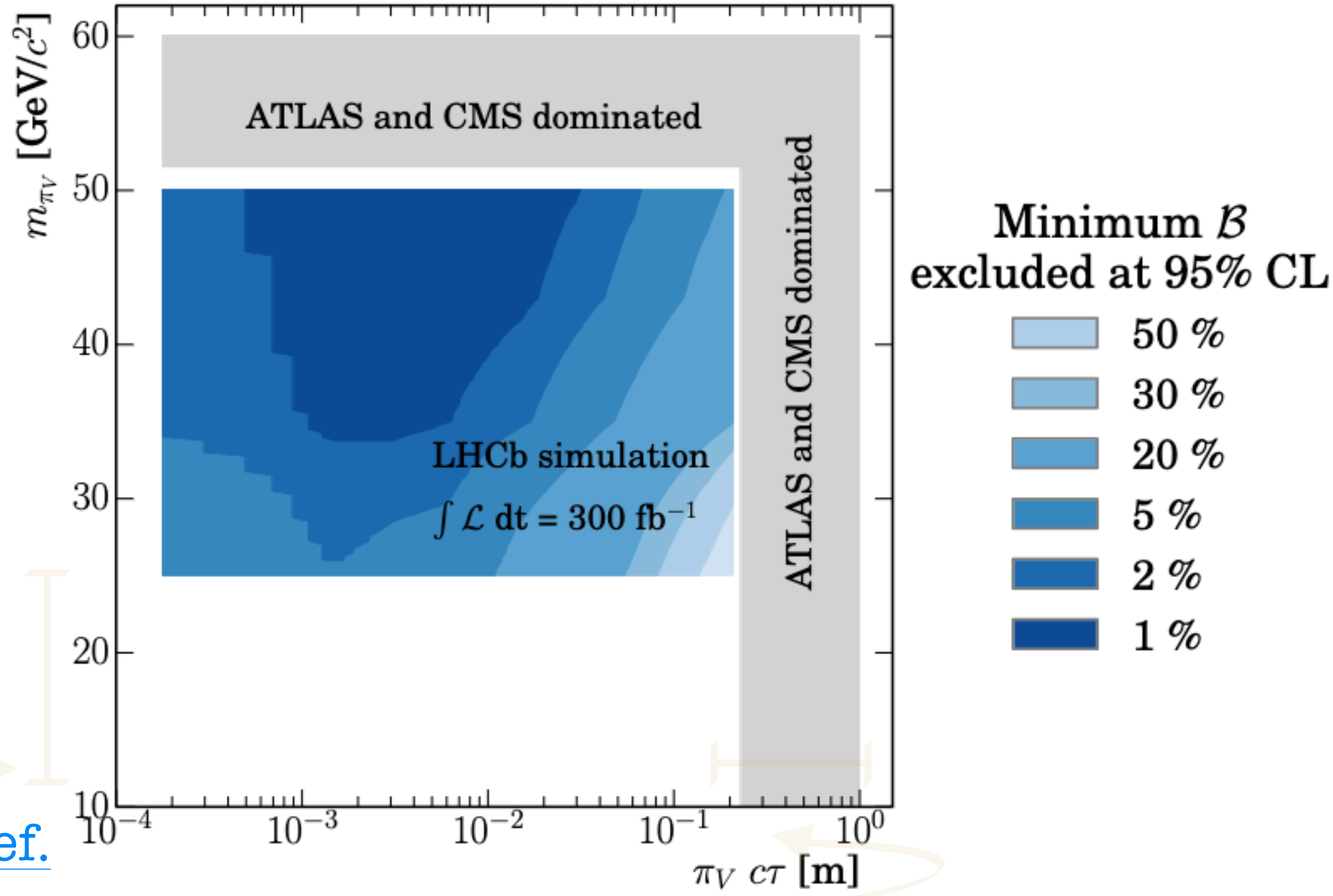
Long Lived Particles @ LHCb

- **Long Lived pions** predicted by Hidden Valley scenarios decaying hadronically **into 2 jets**

- Huge potential for **low mass and low lifetime**

- LLP decaying within the VELO:
  - Excellent **spatial and momentum resolution** and reconstruction of **displaced vertices**



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- Exploring downstream tracks (outside VELO):
  - new **trigger** strategies
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  - removal of neutral particles from the jet reconstruction (**Machine Learning**)
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- Below 25 GeV final state reconstructed as a single jet (merged jet)w/ **substructure**

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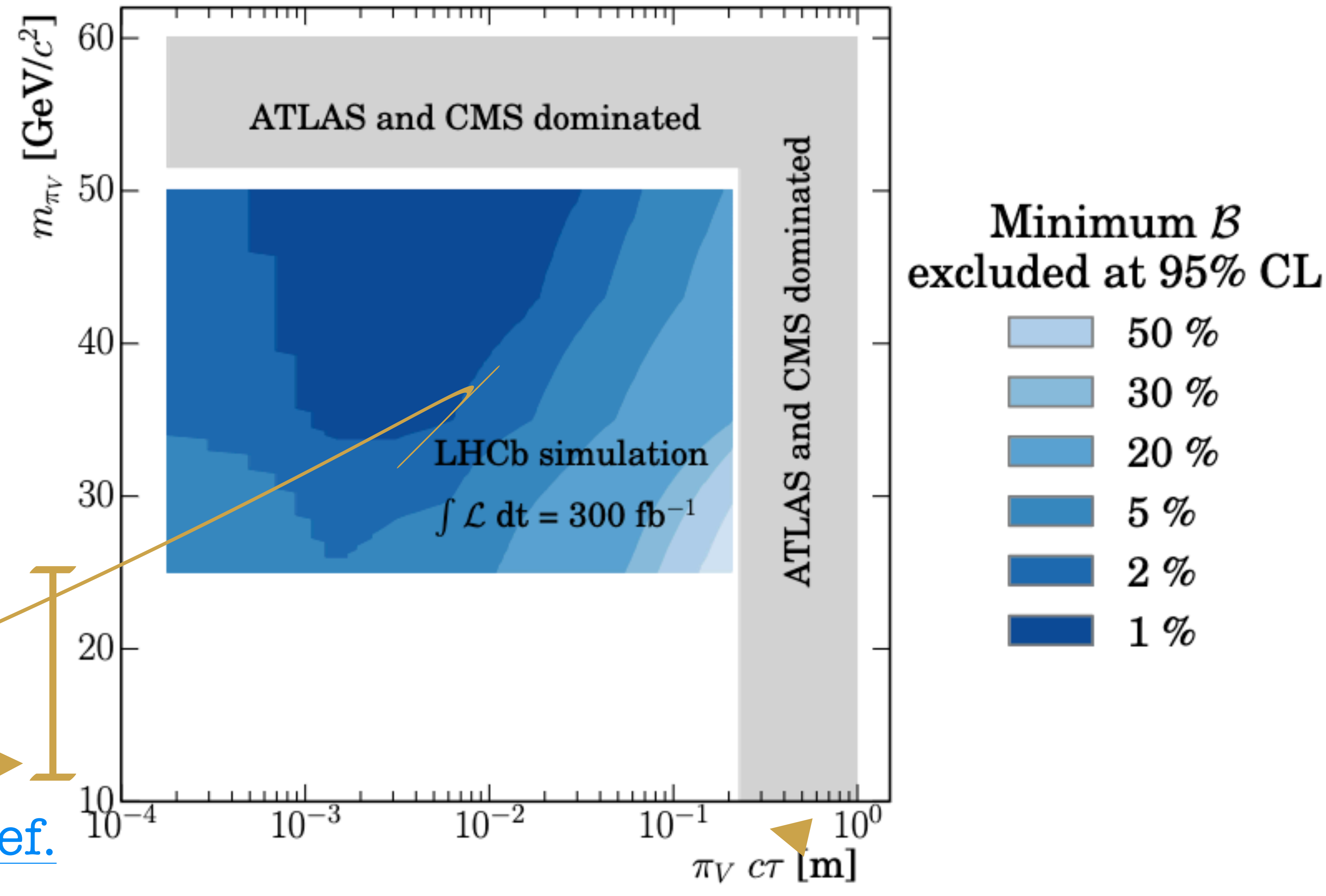

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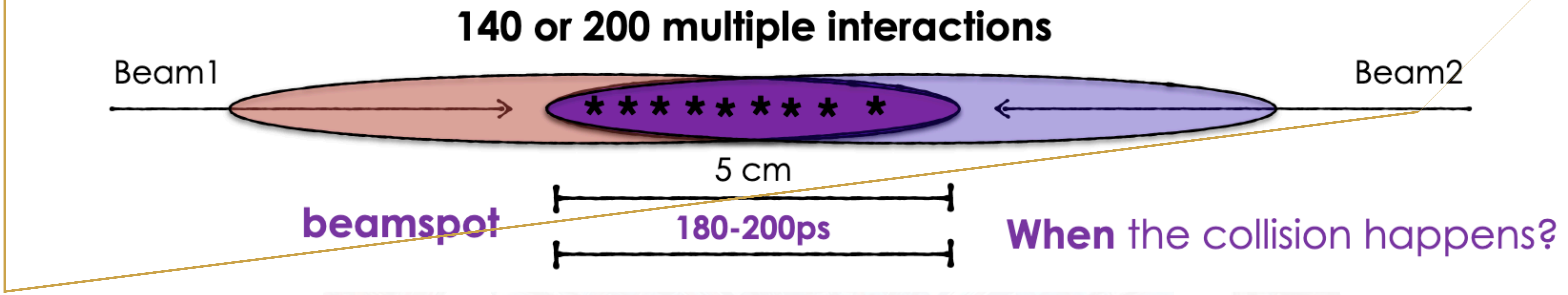
New timing detectors at LHC



Mip Timing Detector @CMS

High-Granularity Timing Detector @ ATLAS

TORCH @ LHCb

ALICE3

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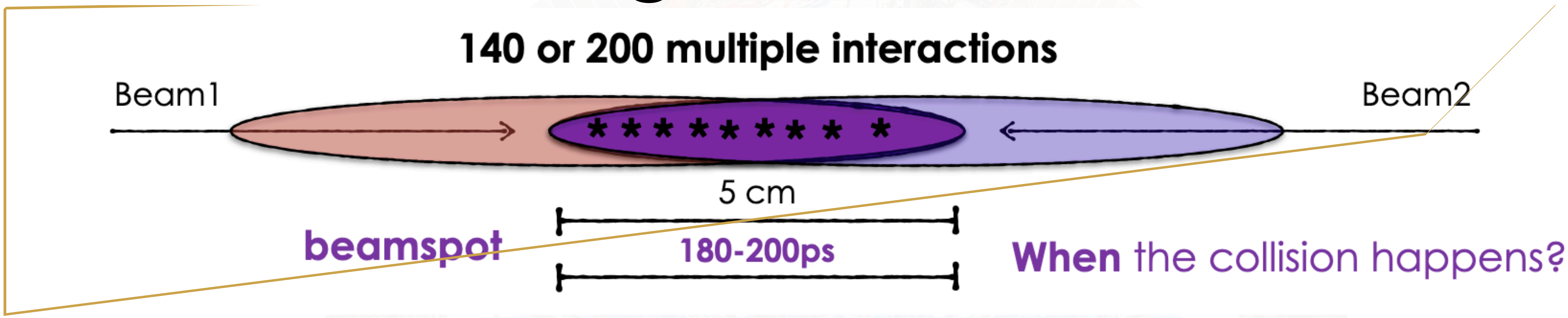

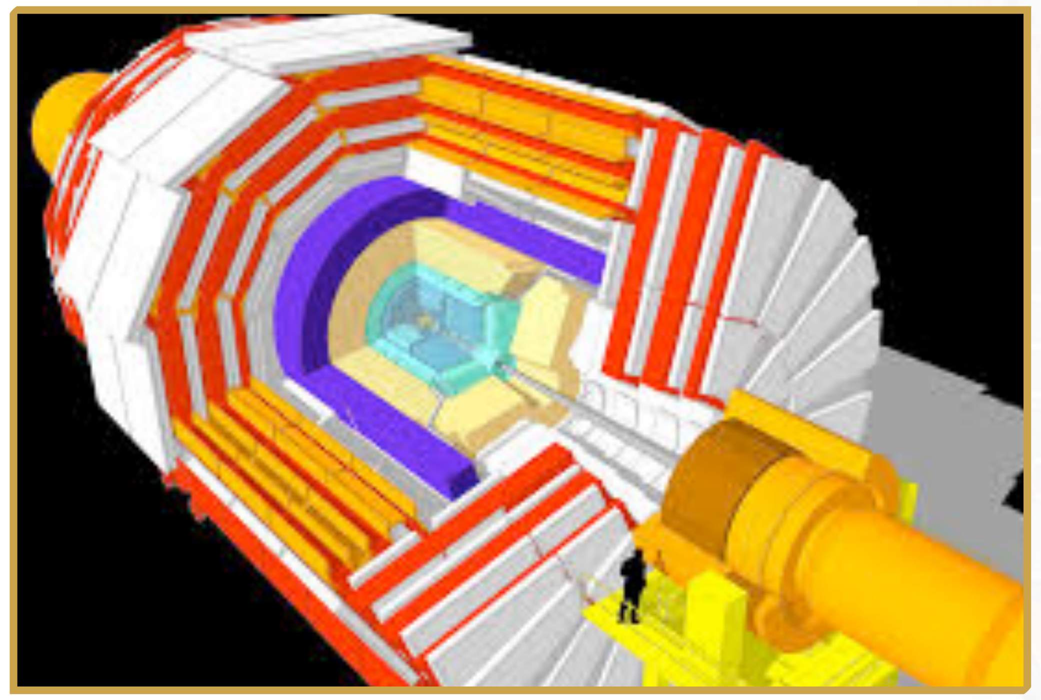

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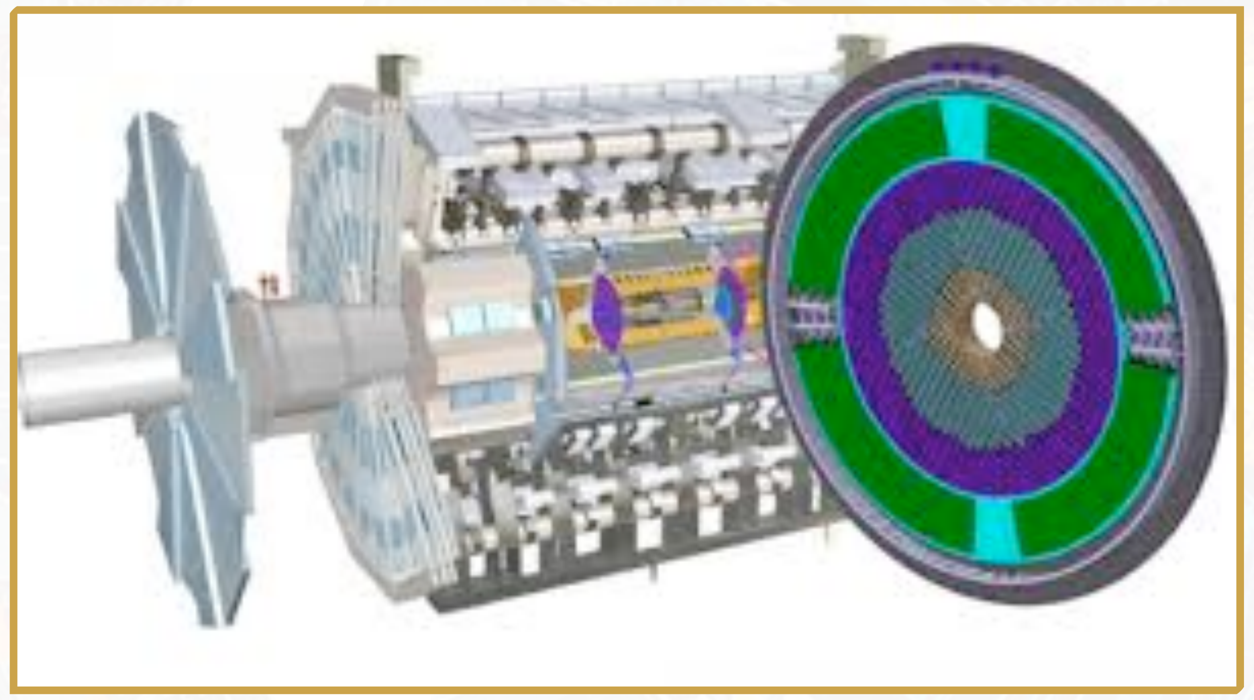

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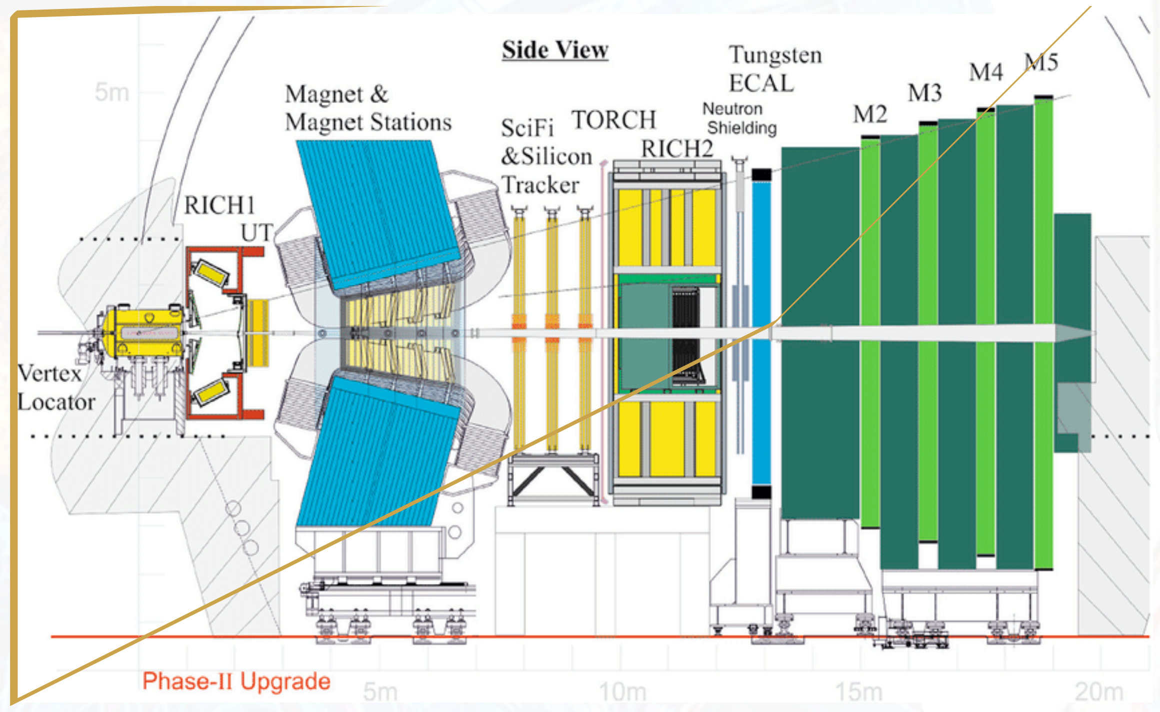

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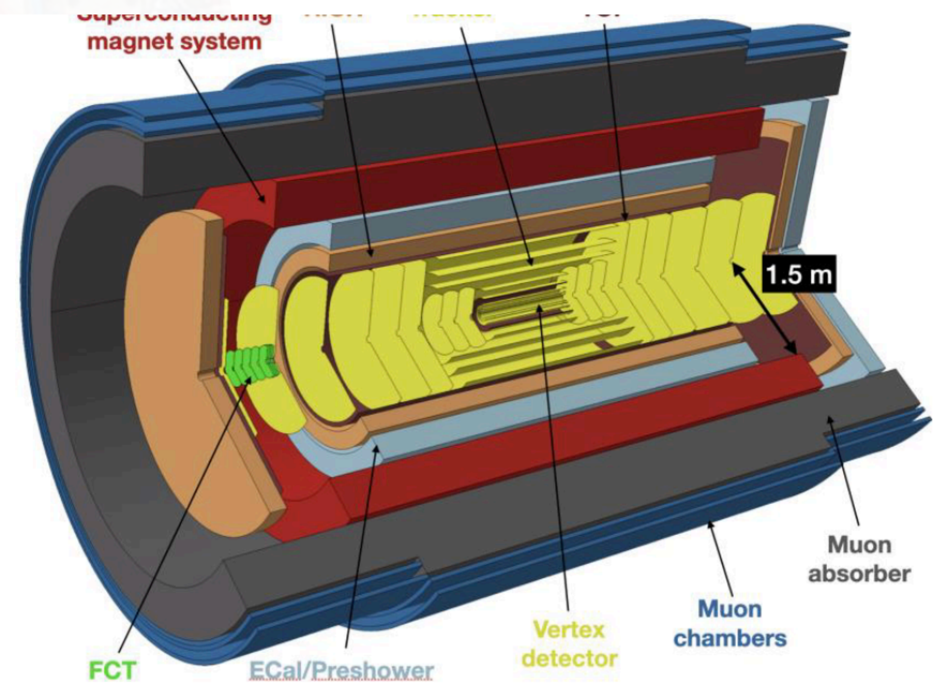

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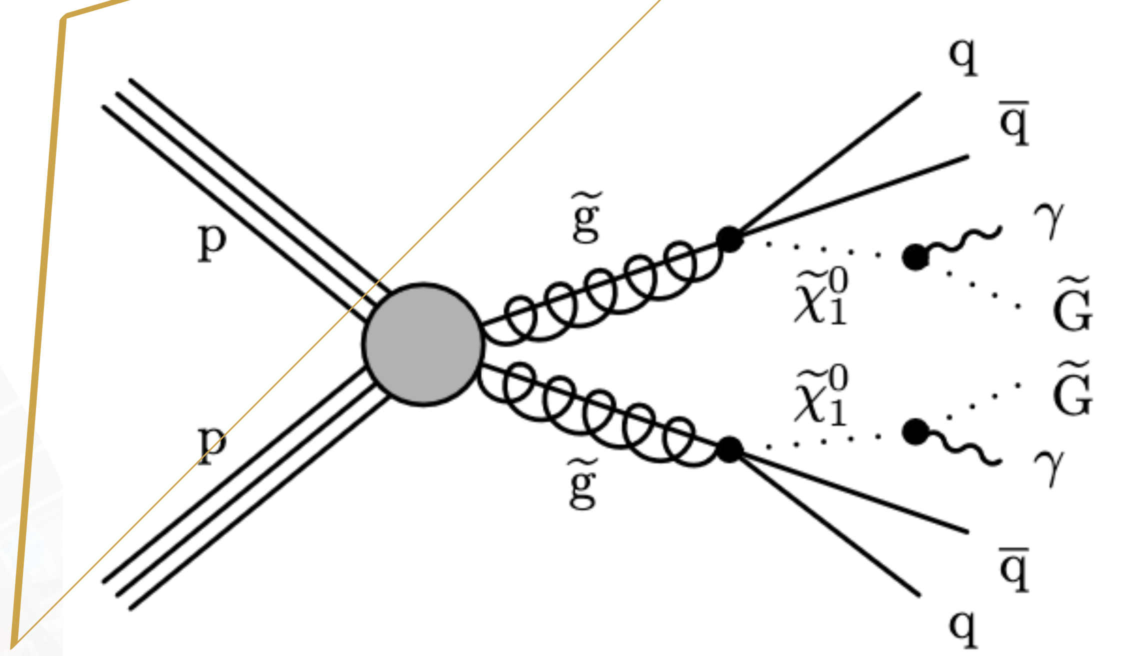
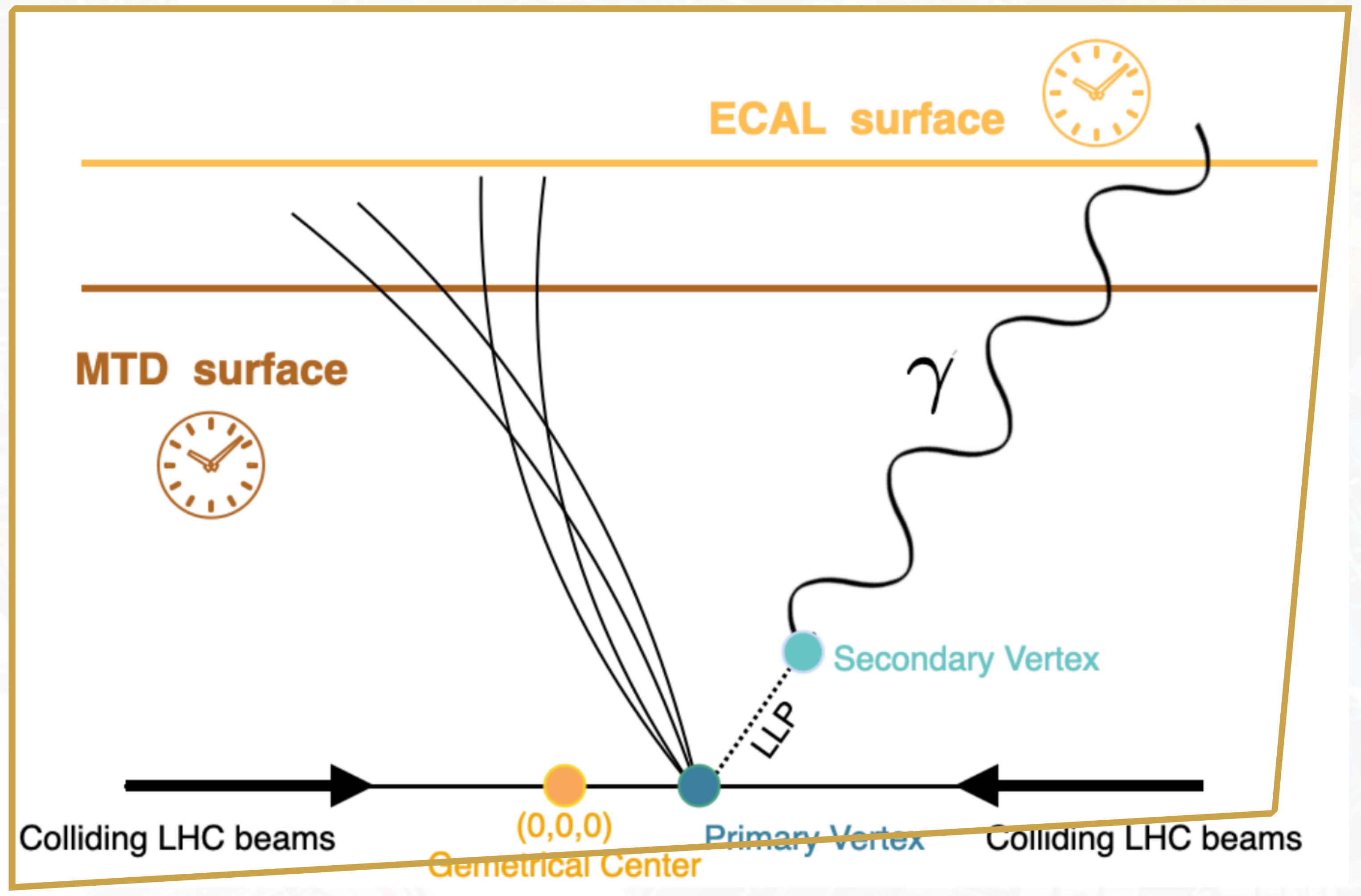
Detection of late photons with CMS MTD



- New **30 ps Mip Timing Detector (MTD)** essential to properly determine the **primary vertex time and particles' time of flight**

- **Weighted vertex time resolution**: estimating number of tracks in barrel/endcap



- Signatures with **delayed photons**: **(**ECAL time resolution: 30 ps)

large gain in sensitivity w.r.t. ECAL only scenario

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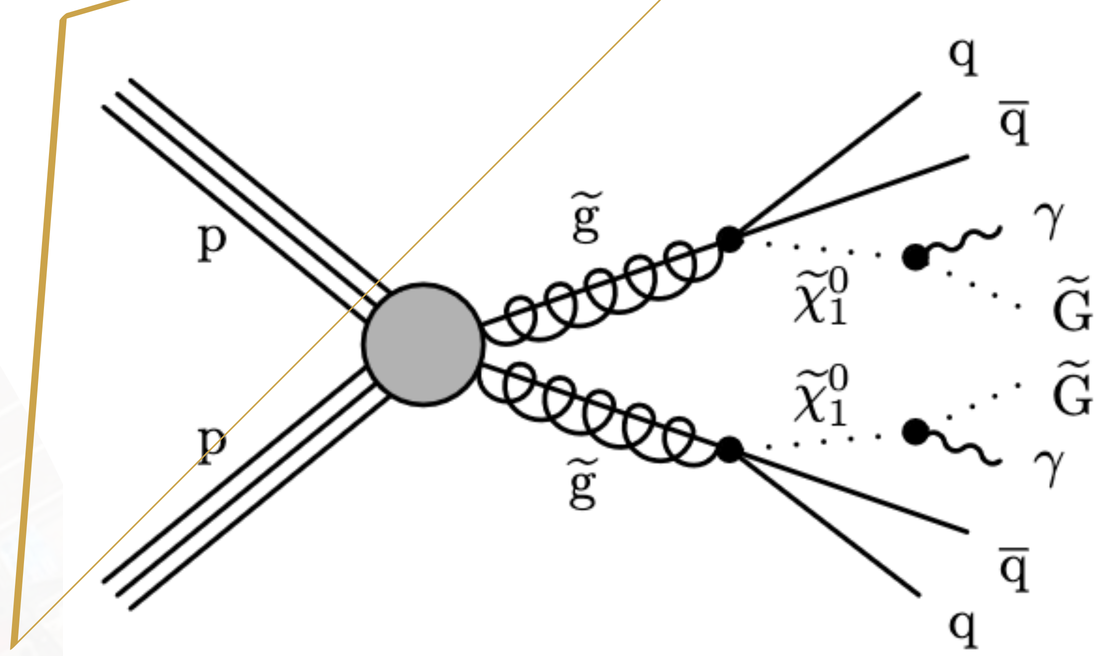

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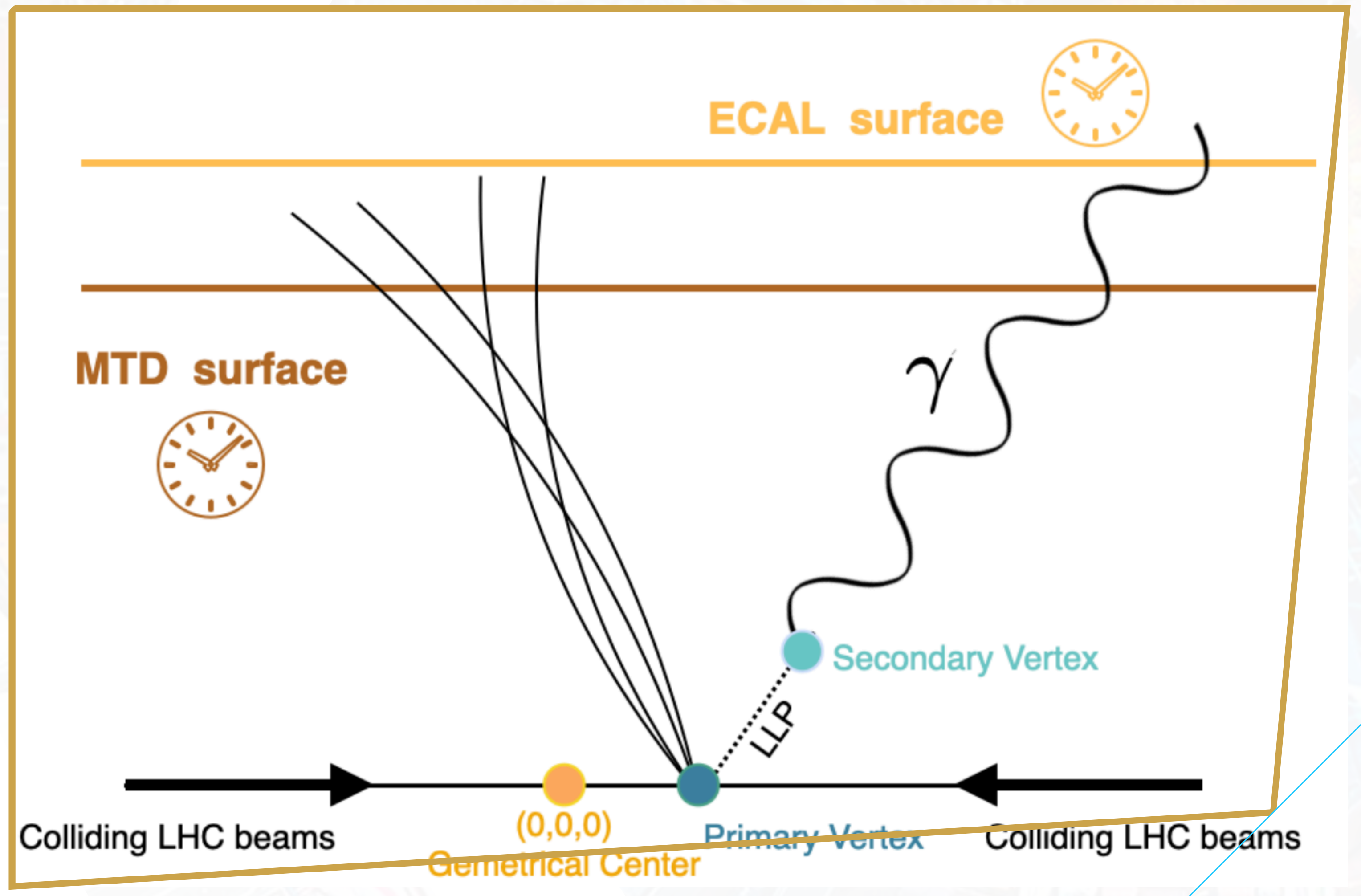

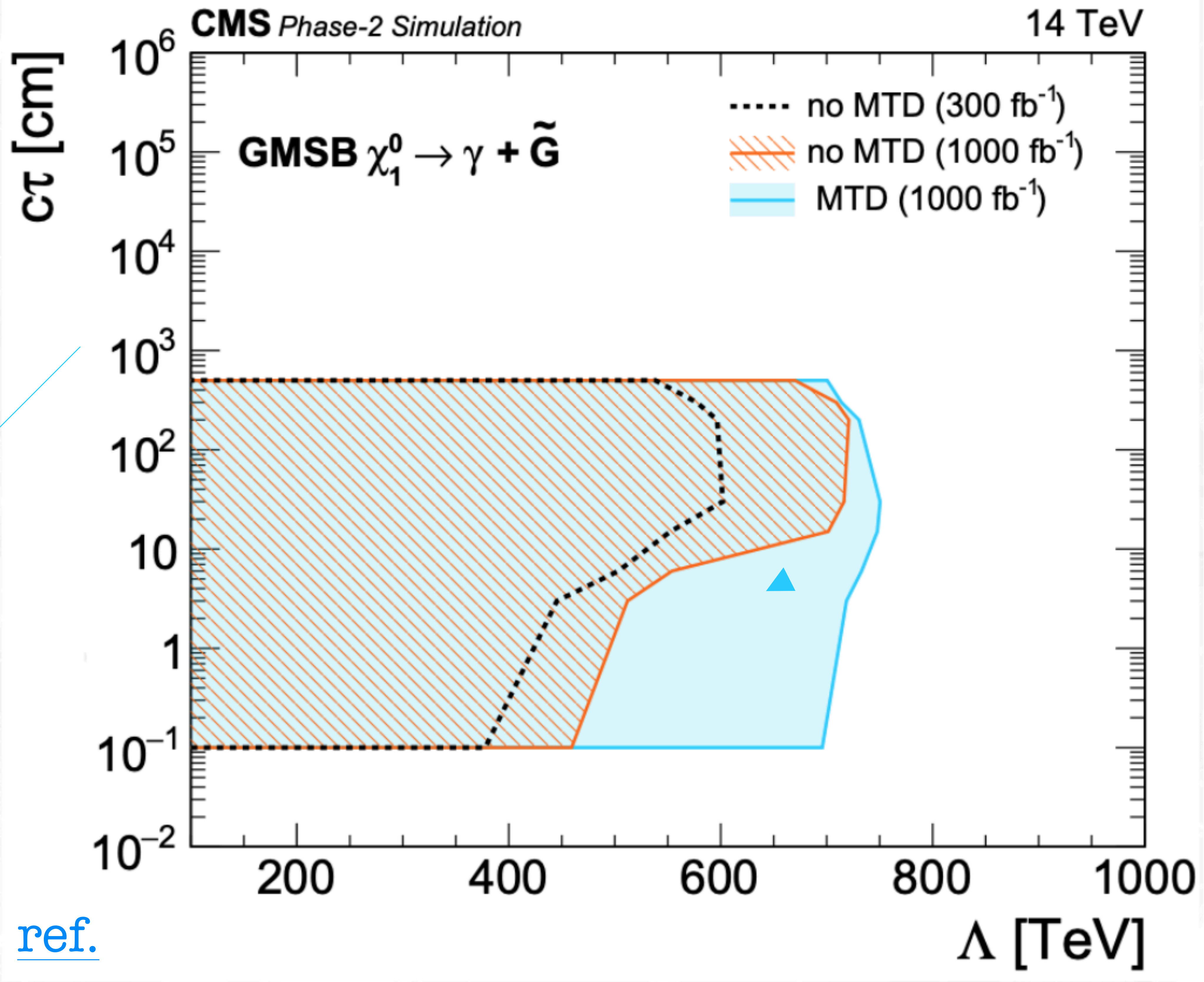

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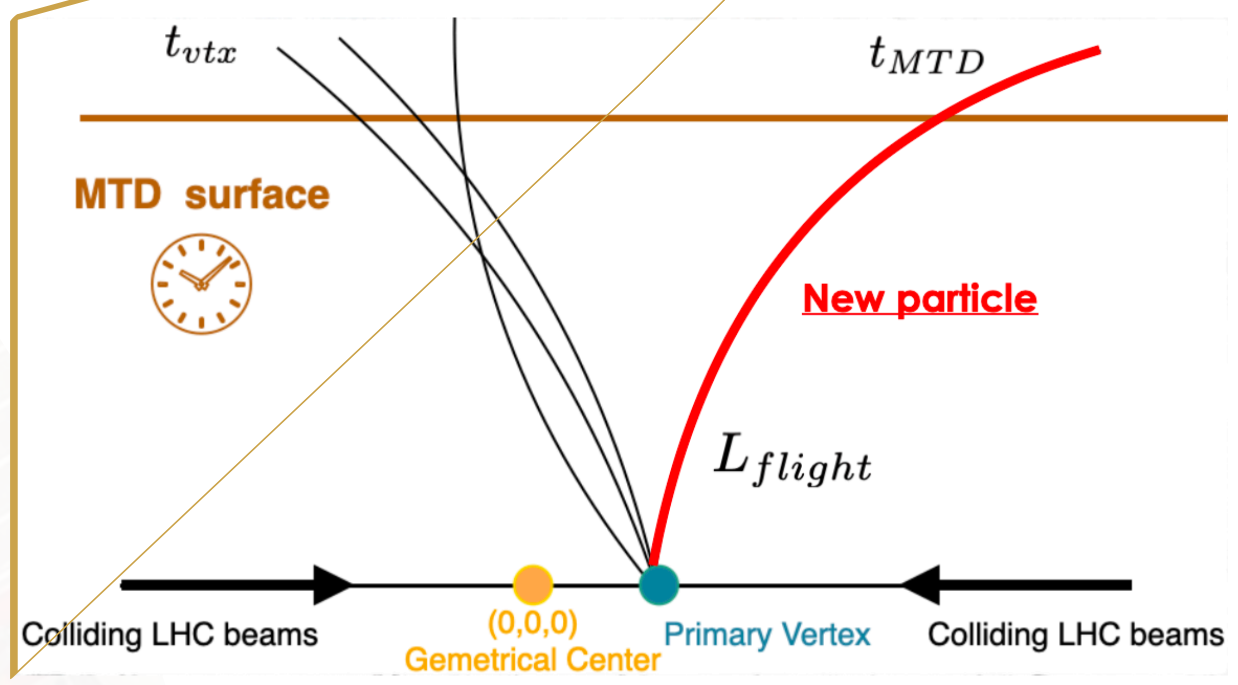
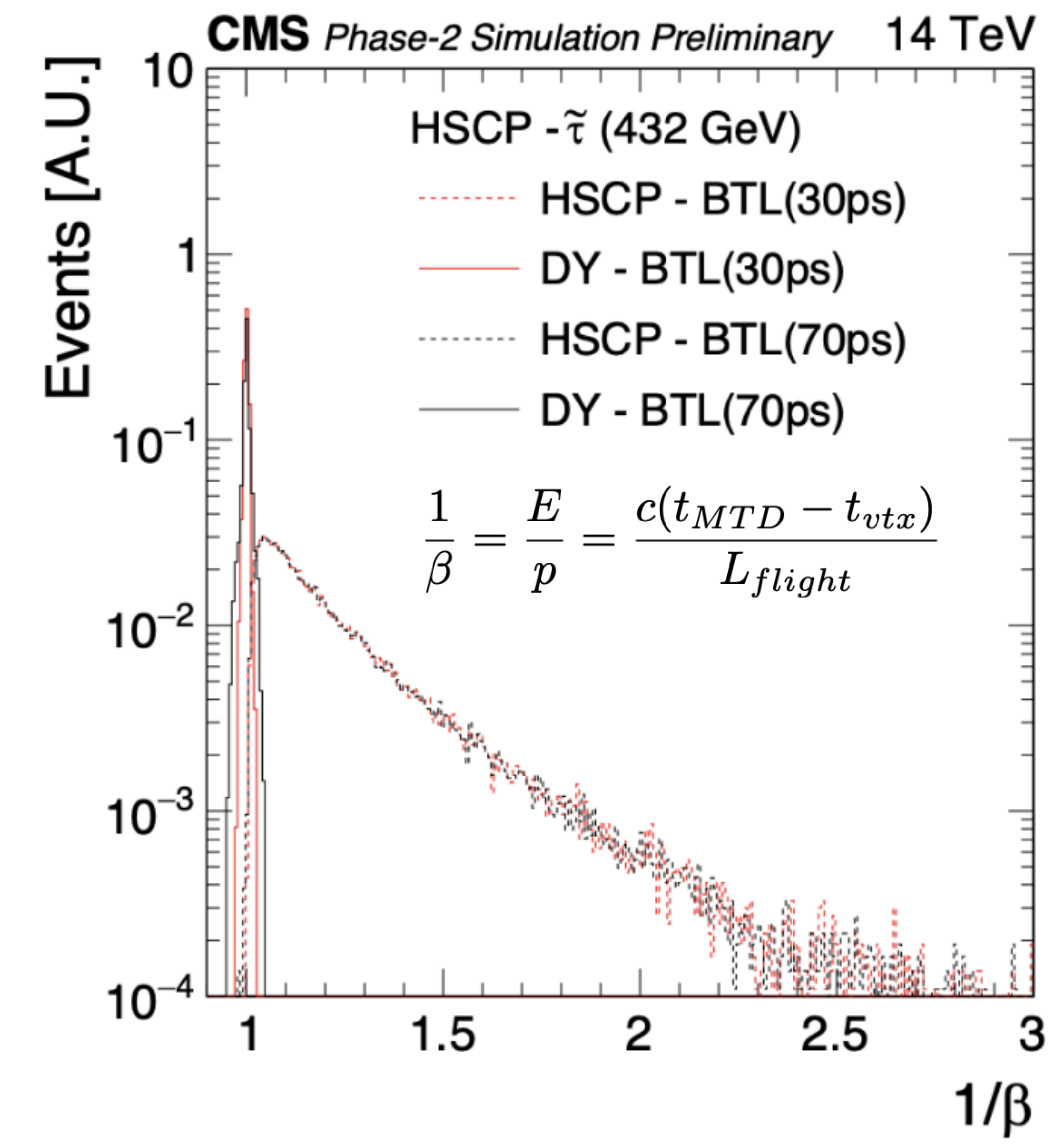
CMS MTD as a time-of-flight detector



- Turn the MTD into a time of flight detector and look for anomalous moving particles (slow velocities, q!=1, large mass)

- Complement Muon Detector based searches at short lifetimes

- **Promising performance** through the entire HL-LHC data taking period expected



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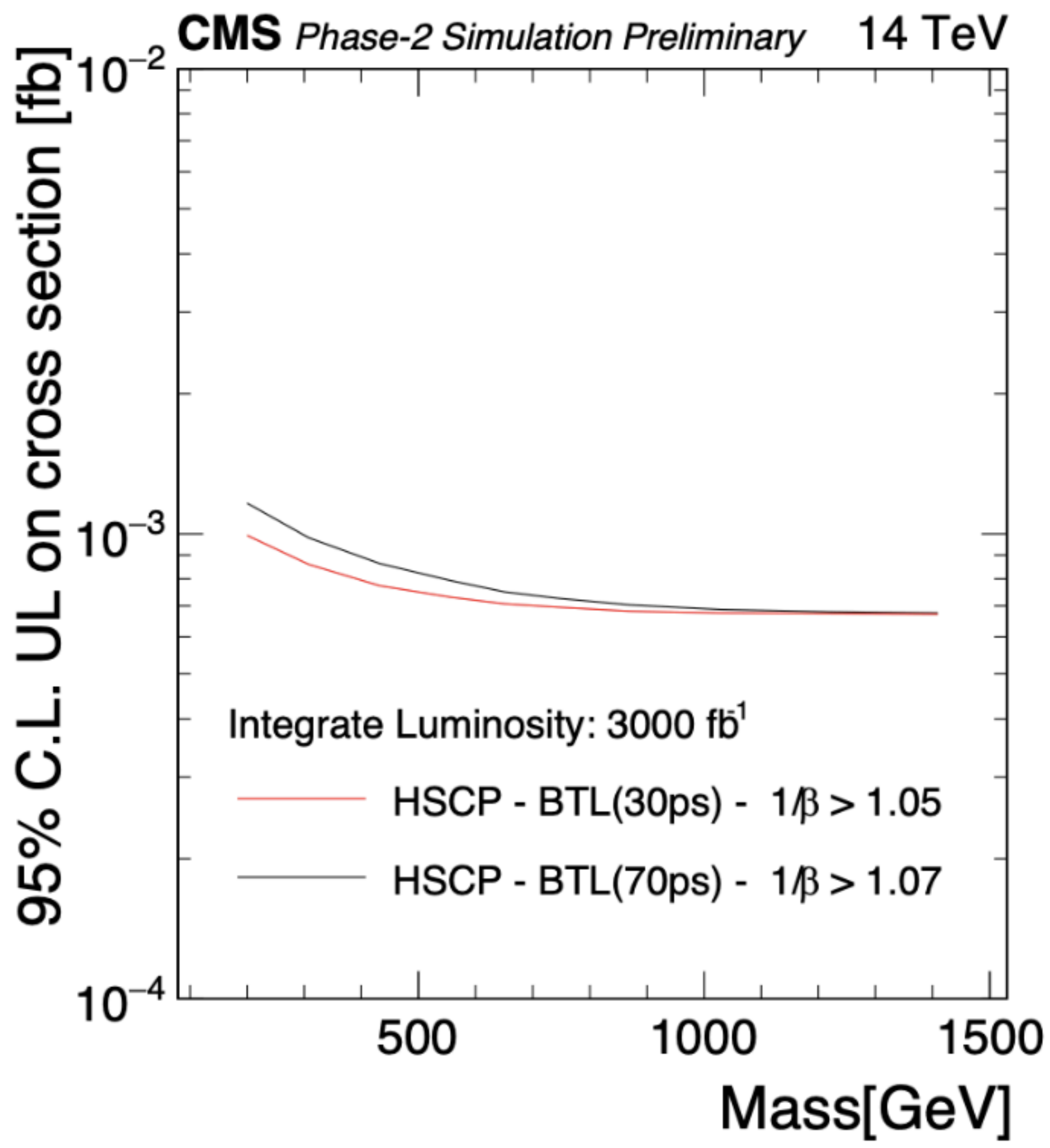
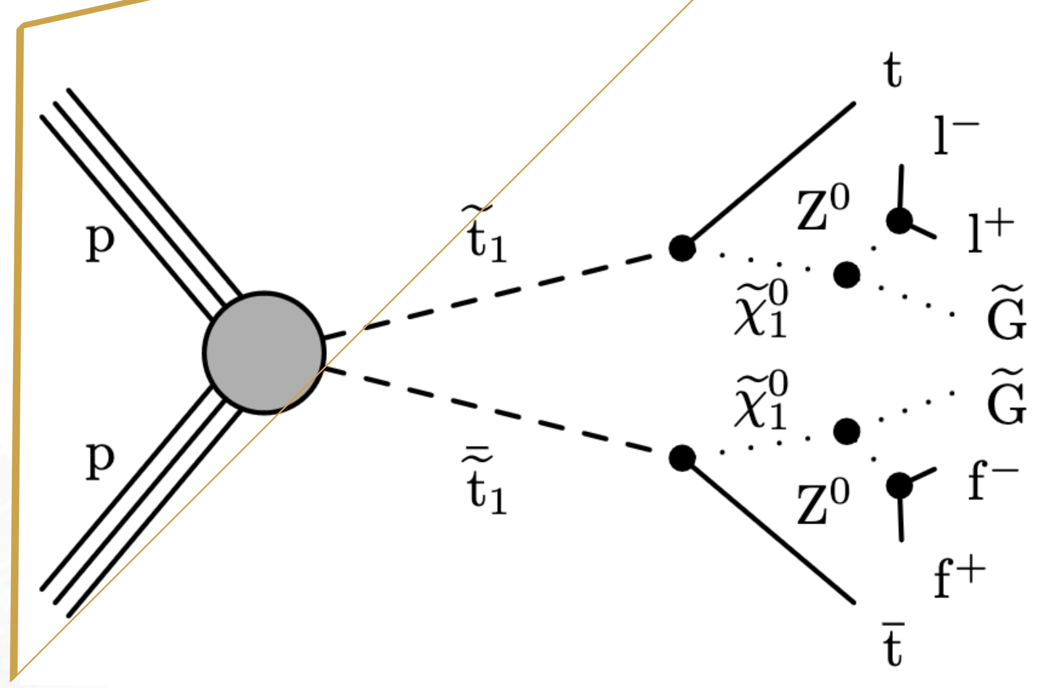


Mass reconstruction of SUSY particles

- Precision timing gives β of the Long Lived Particle (LLP)



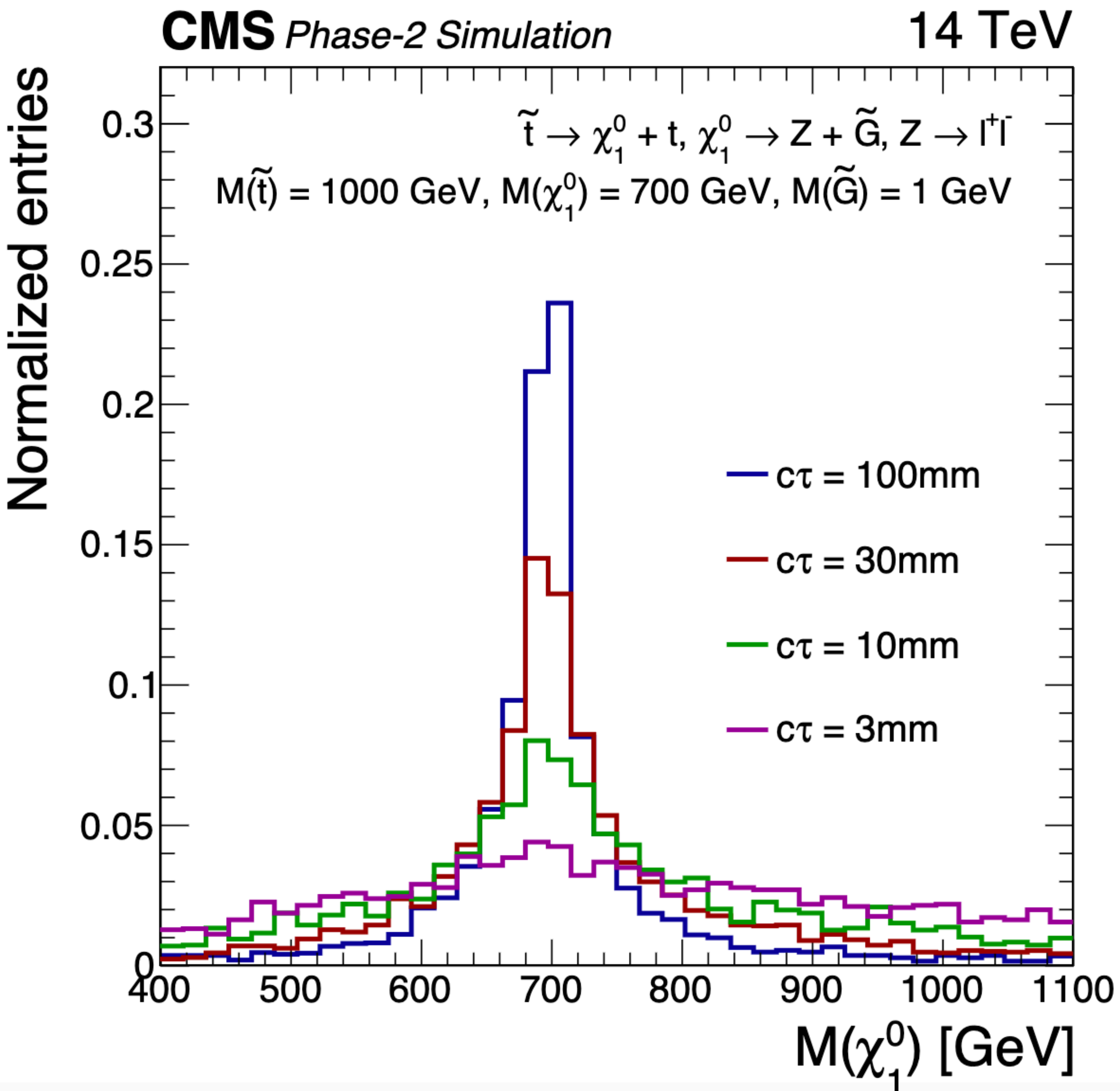
- By measuring the energy and momentum of the visible products of the LLP decay one can boost the visible system tot he LLP frame:

$$E_V^P = \gamma_P \left(E_V^{LAB} - \vec{P}_V^{LAB} \cdot \vec{\beta}_P^{LAB} \right)$$

- By assuming the mass of the invisible system once can compute the mass of the LLP particle:

$$m_P = E_V^P + \sqrt{E_V^{P2} + m_I^2 - m_V^2}$$

- New potentialities for new timing detectors!



Towards a new era

- HL-LHC will significantly **increase physics reach of LHC experiments** across Higgs, SM, and BSM

- **Challenging experimental conditions** w/ unprecedented pileup

- Extensive **detector upgrades will preserve performance**

- Gains from high luminosity and **new clever algorithms**

    - *Standard model: ultimate precision and rare processes*
    - *Higgs: precise determination of the H(125) properties and searches*
    - *Direct searches: discover new physics or close a few chapters*
    - *Flavour: high/low pT complementarity*
    - *Heavy Ion: precise differential measurements*

- **HL-LHC will provide a massive amount of new knowledge and we are expecting to exceed expectations!**

Towards a new era

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- **HL-LHC will provide a massive amount of new knowledge and we are expecting to exceed expectations!**

Backup

Bibliography

Recent efforts for HL-LHC projections

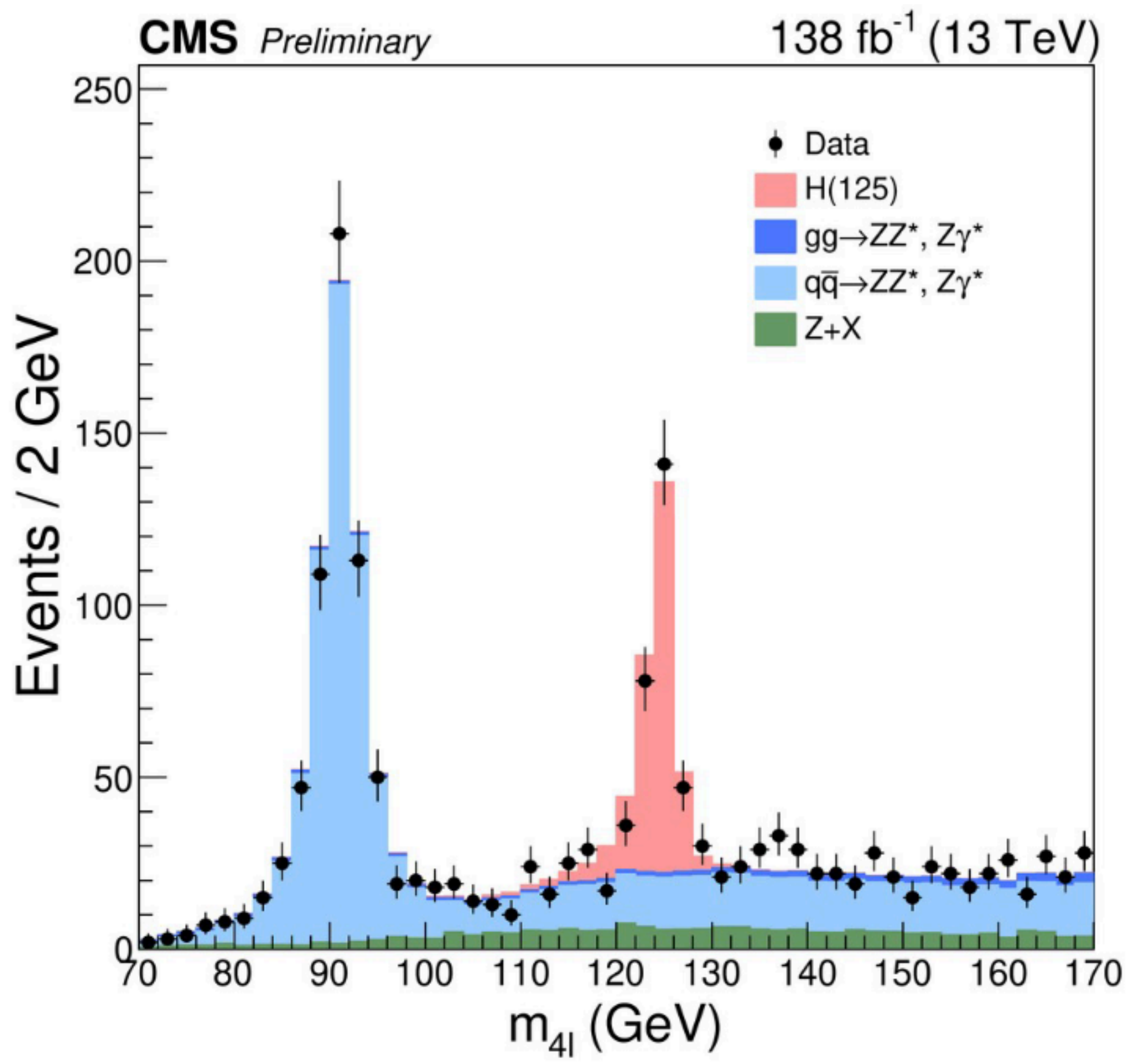
- European Strategy Update (2018-2020)
- CERN Yellow report (CERN-2019-007)
- Snowmass White Paper Contribution, 2022
- ALICE 3 LoI: arXiv:2211.02491

Current state-of-the-art: Mass

CMS: using **H→ZZ*→4l** : **CMS-PAS-HIG-21-019**

$$m_H = 125.08 \pm 0.10\ (\text{stat}) \pm 0.05\ (\text{syst})\ \text{GeV}$$

Most precise single measurement (< 1 ‰)



ATLAS: combining H→4l + H→γγ :

Phys. Lett. B 843 (2023) 137880, Phys. Lett. B 847 (2023) 138315

$$m_H = 125.11 \pm 0.11\ \text{GeV}\ (\text{syst: } 0.09\ \text{GeV})$$

Most precise measurement to date

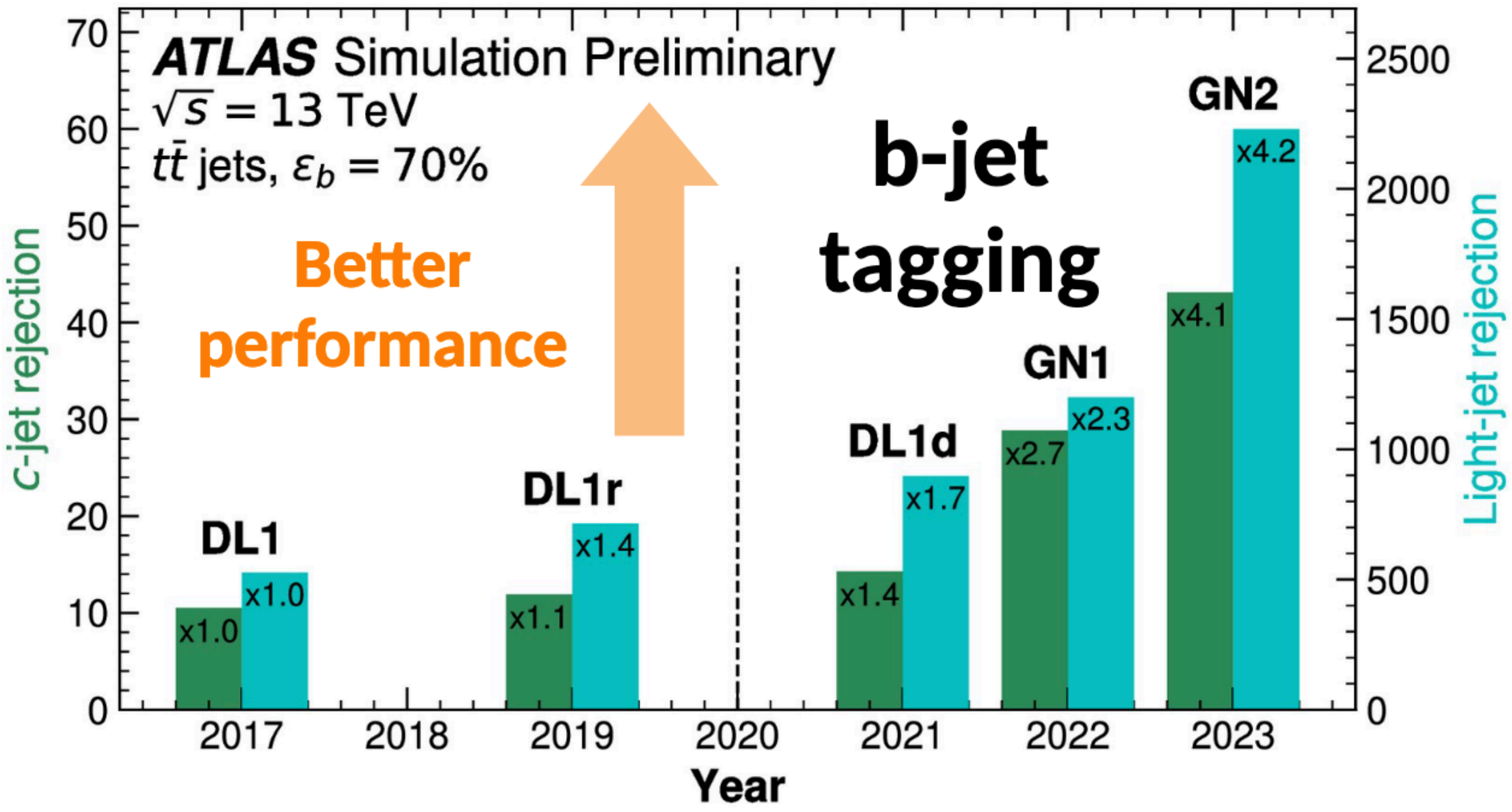
H→γγ mass resolution systematics reduced by a factor 4 !

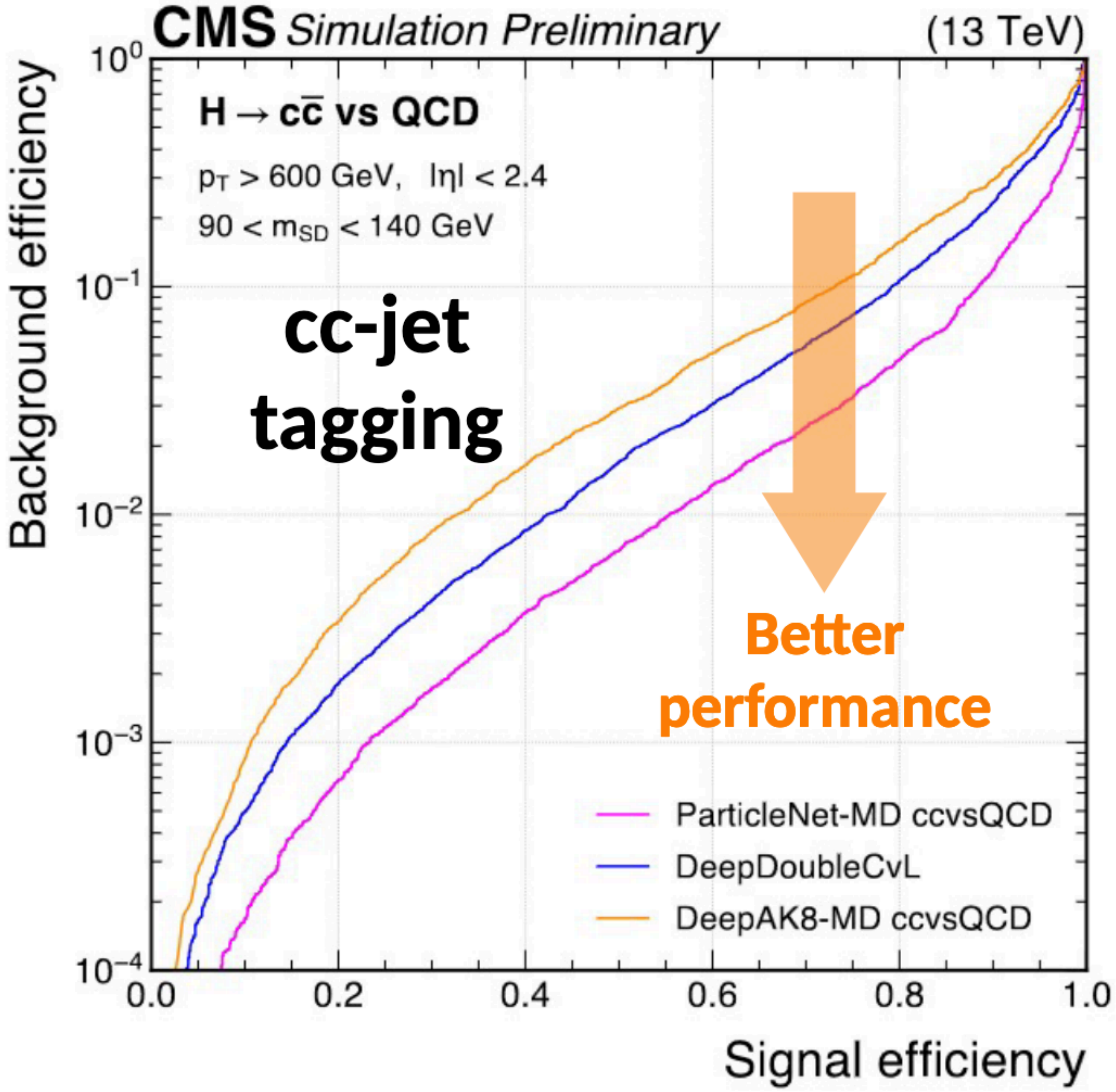
JINST 19 (2024) P02009

See taks by Camila Pazos, Léo Boudet, Badder Marzocchi and Federica Primavera for details

Aside: Improvements in flavor tagging

ATLAS: Eur. Phys. J. C 83 (2023) 681, FTAG-2023-01

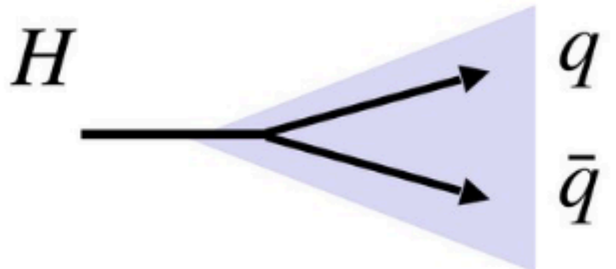




CMS: CERN-CMS-BTV-22-001-PAS

Rapid progress in techniques: **BDTs** → **feed-forward DNNs** → **Graph NNs, transformer networks**…

- Single b-jet and c-jet tagging
- Merged H→bb|cc|ττ tagging



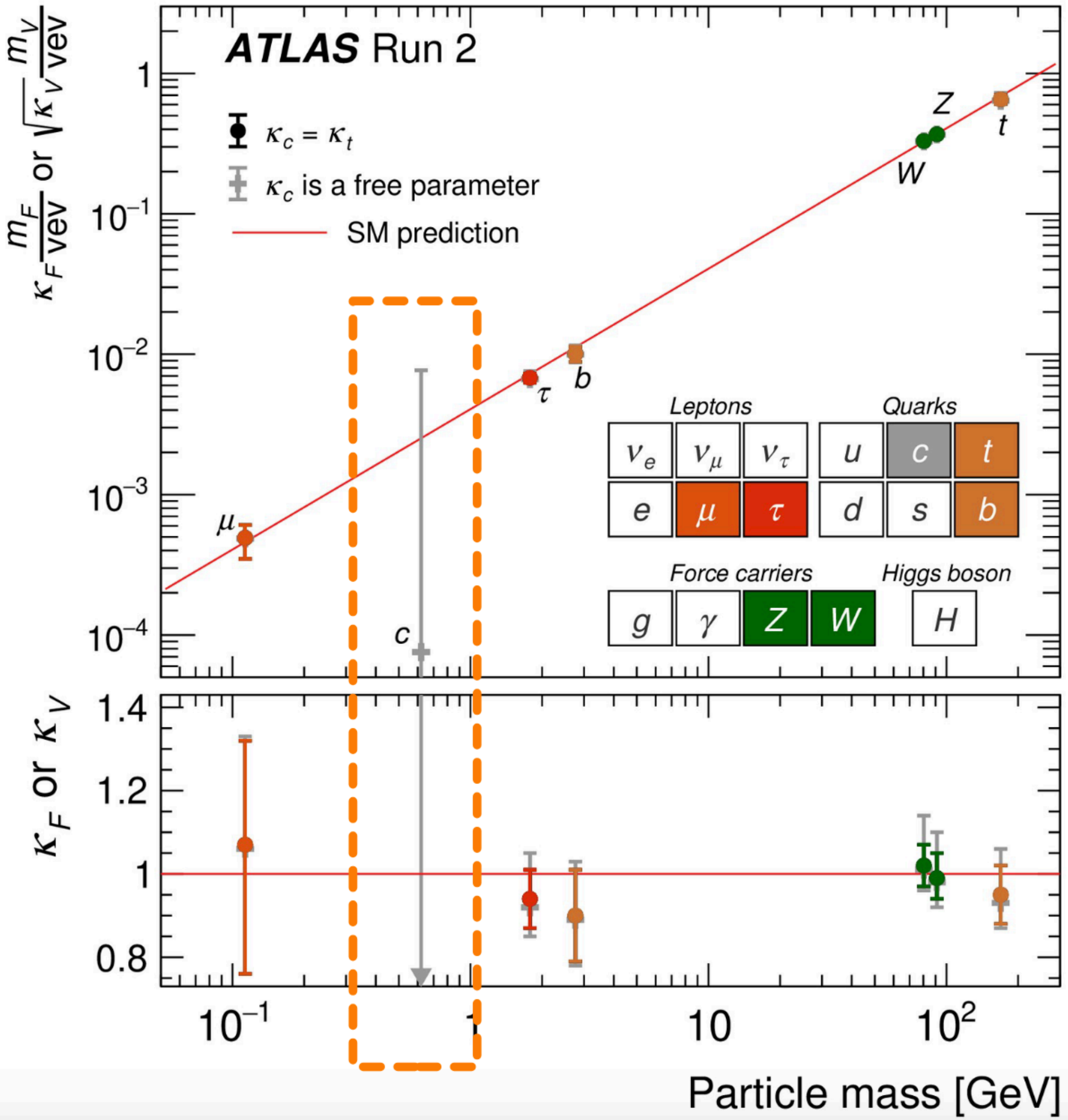
More details in Maxence Draguet's talk

Large gains in past years, still improving quickly! → Major driver of sensitivity increases

Aside: Higgs-charm coupling

Only accessible second-generation quark Yukawa coupling

⇒ Important check of the Higgs mechanism, but currently very large uncertainties



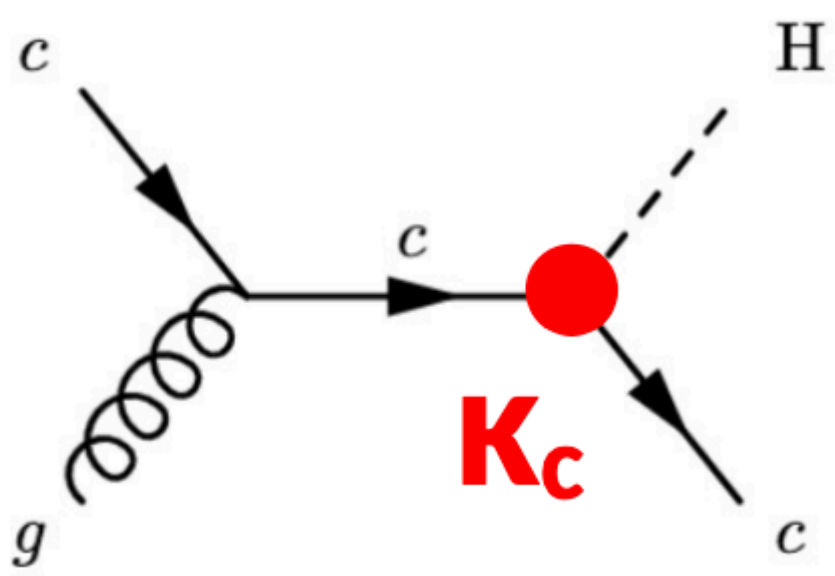
ATLAS & CMS H→γγ + c

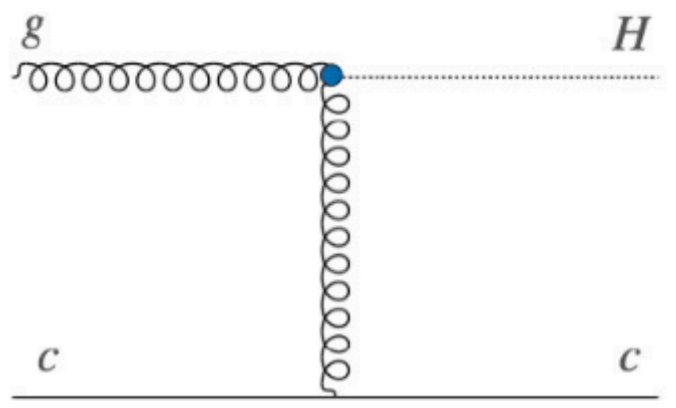
More in Andrea Cardini's talk

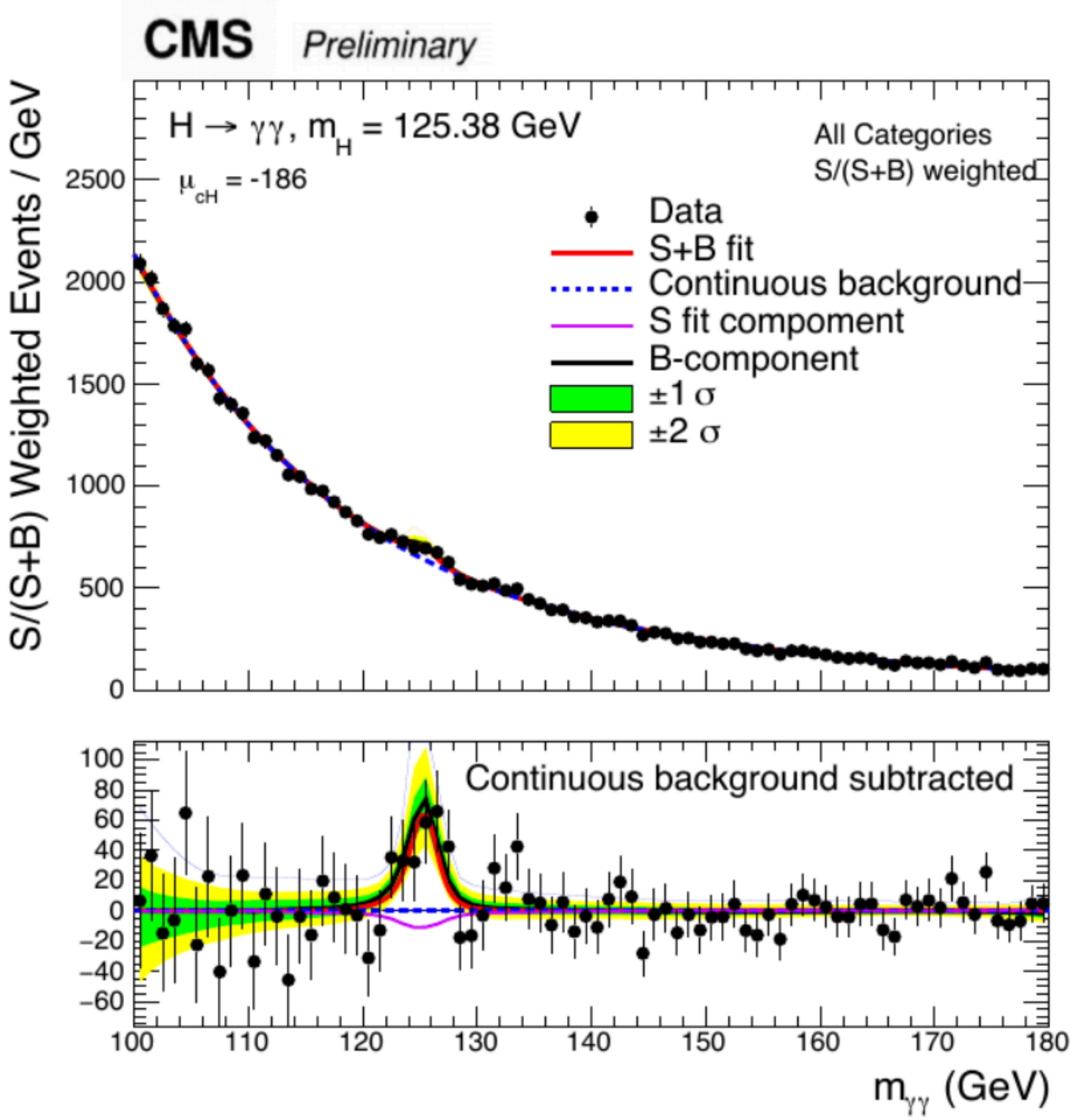
Background modeling using Gaussian process regression

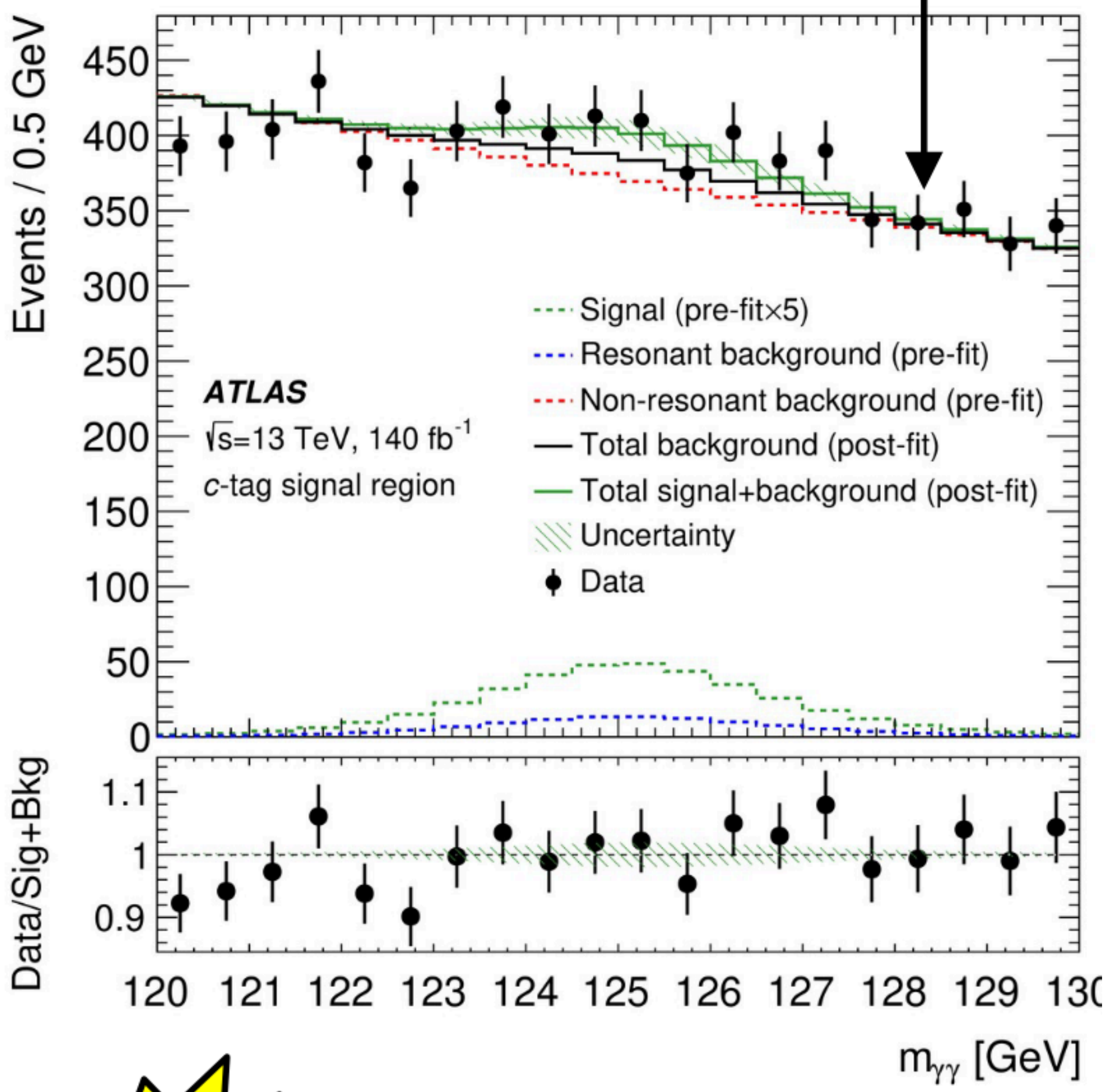
Target pp→H+c production

Potential to constrain κ_c, also large contributions from non-κ_c-dependent processes.









CMS-PAS-HIG-23-010

New

CERN-EP-2024-175

Large backgrounds ⇒ use clean **H→γγ** decay

ATLAS: target inclusive H+c → **σ(H+c) = 5.2 ± 3.0 pb** (SM: 2.9 pb), **< 10.4 pb** @ 95% CL

CMS: target κ_c-dependent part : μ_{cH} **< 243** (355) ⇒ **|κc| < 38.1 (72.5)** @ 95% CL

ATLAS and CMS VH→cc

More in Andrea Cardini's talk and Maarten de Coen's poster

New

ATLAS VH→cc

Simultaneous fit with VH→bb

$\mu_{VH\to cc}$ **< 11.3 @ 95% CL** (10.4 exp.)

Best limit to date

Factor 2.5 improvement over previous limit !

More in Francesco Di Bello's talk

⇒ $|\kappa_c|$ **< 4.2** @ 95% CL

Factor 2 improvement over previous

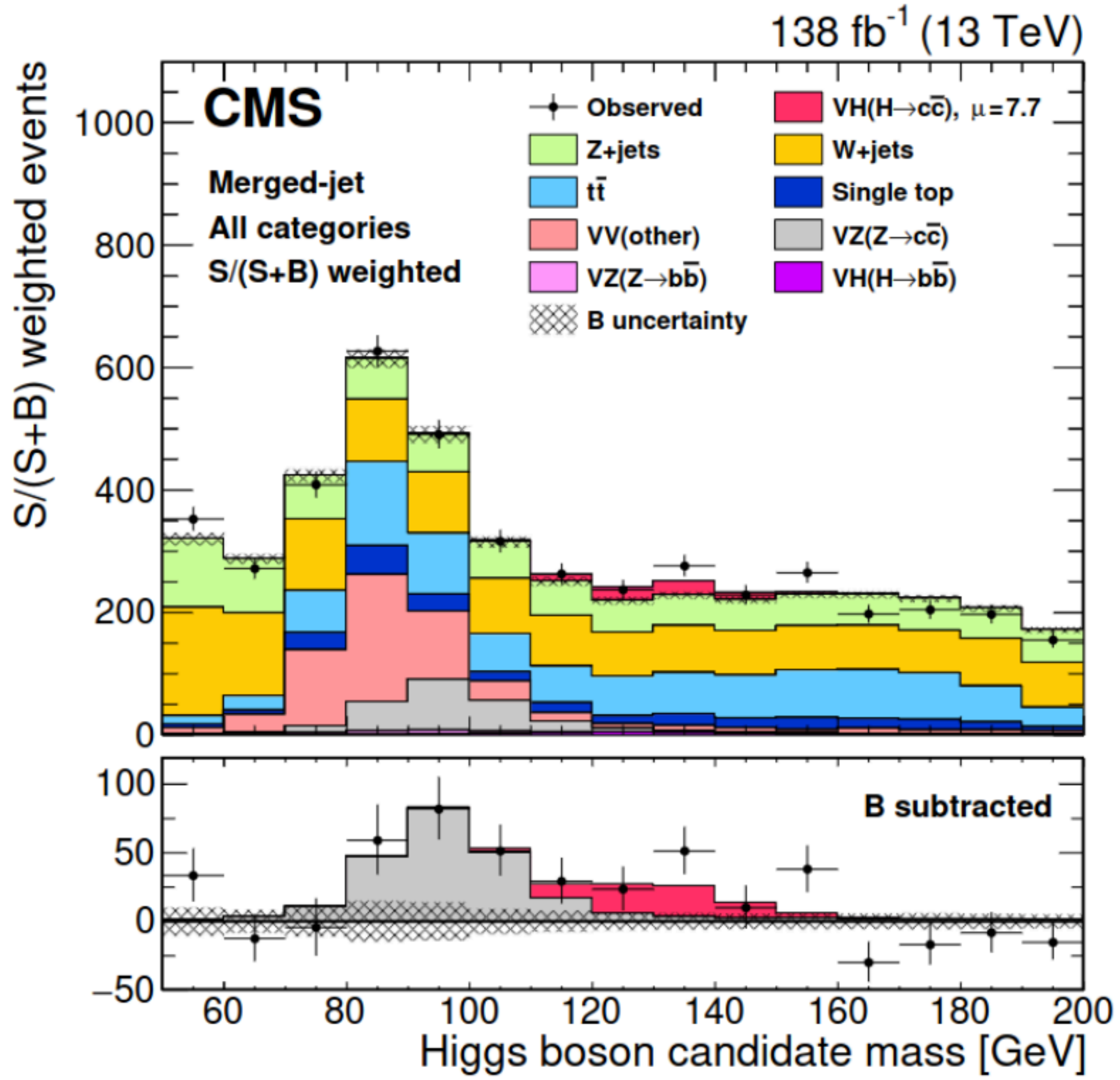
CMS VH→cc :

Includes boosted H→cc (p_T^H > 300 GeV)

$\mu_{VH\to cc}$ **< 14 (7.6)** @ 95% CL **best sensitivity**

⇒ 1.1 < $|\kappa_c|$ < 5.5

First observation of Z→cc in hadronic collisions.

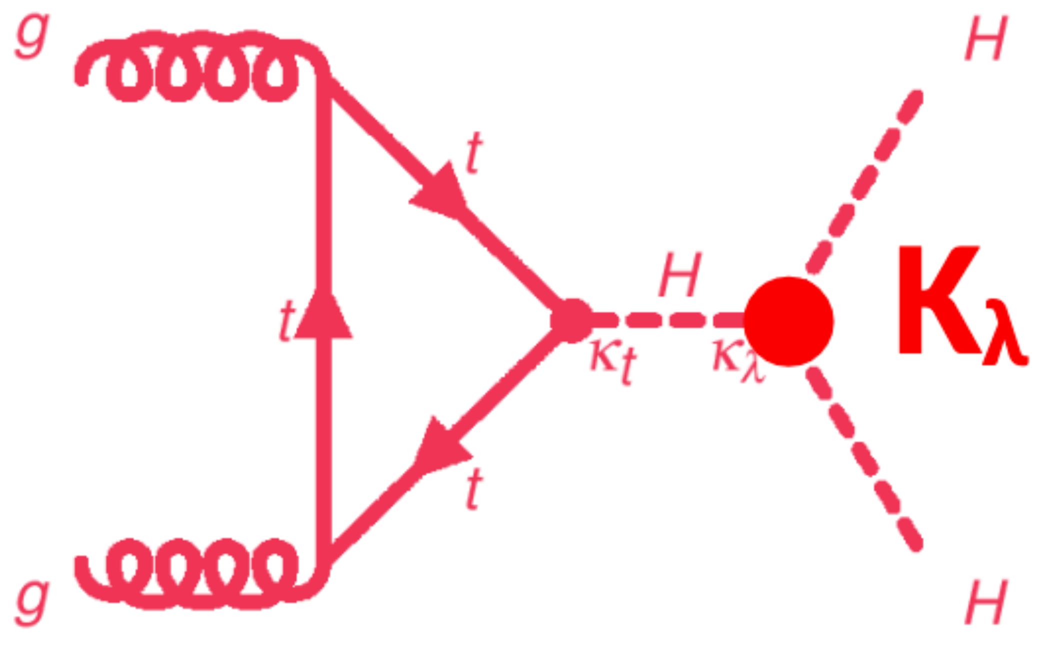


PRL 131 (2023) 041801,
PRL 131 (2023) 061801

Higgs pair production at LHC

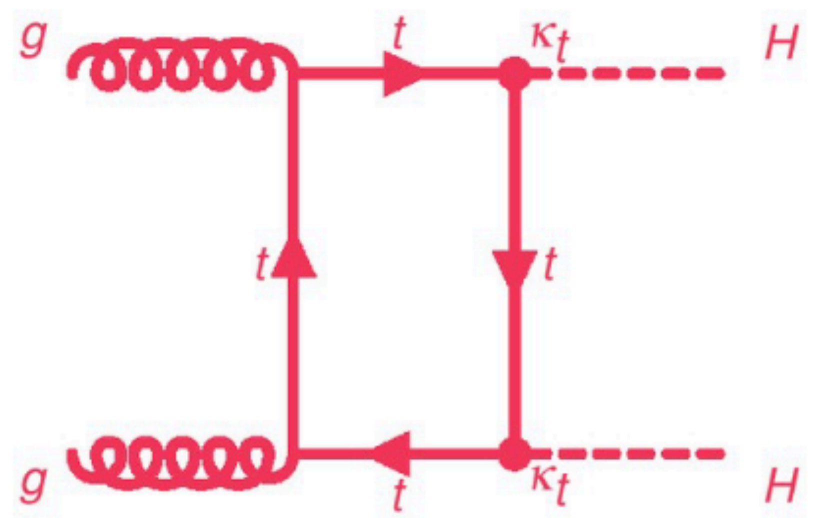
From G. Salam et al, Nature volume 607, pages 41–47 (2022)

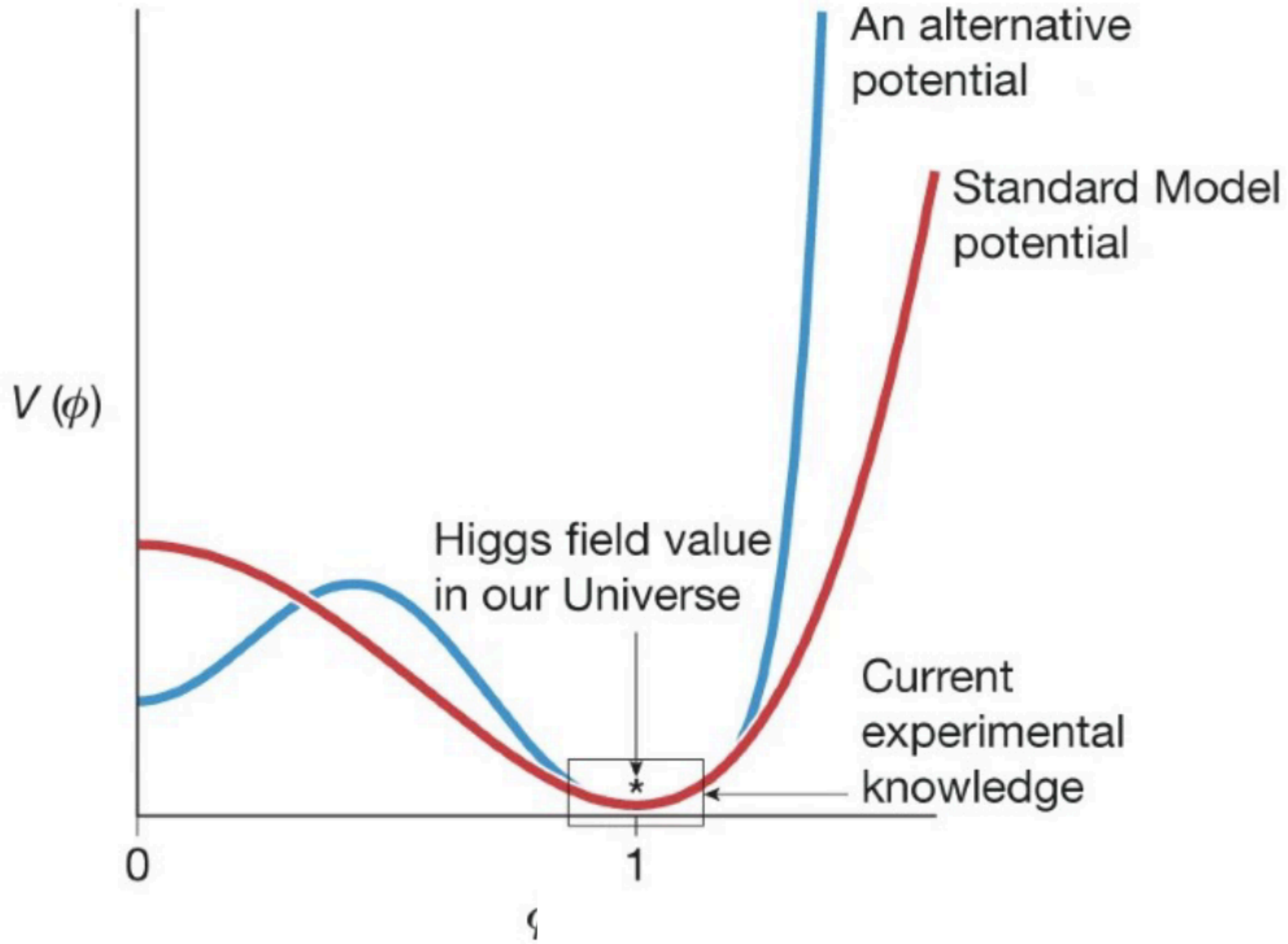
pp→HH : 1000× smaller than pp→H



+

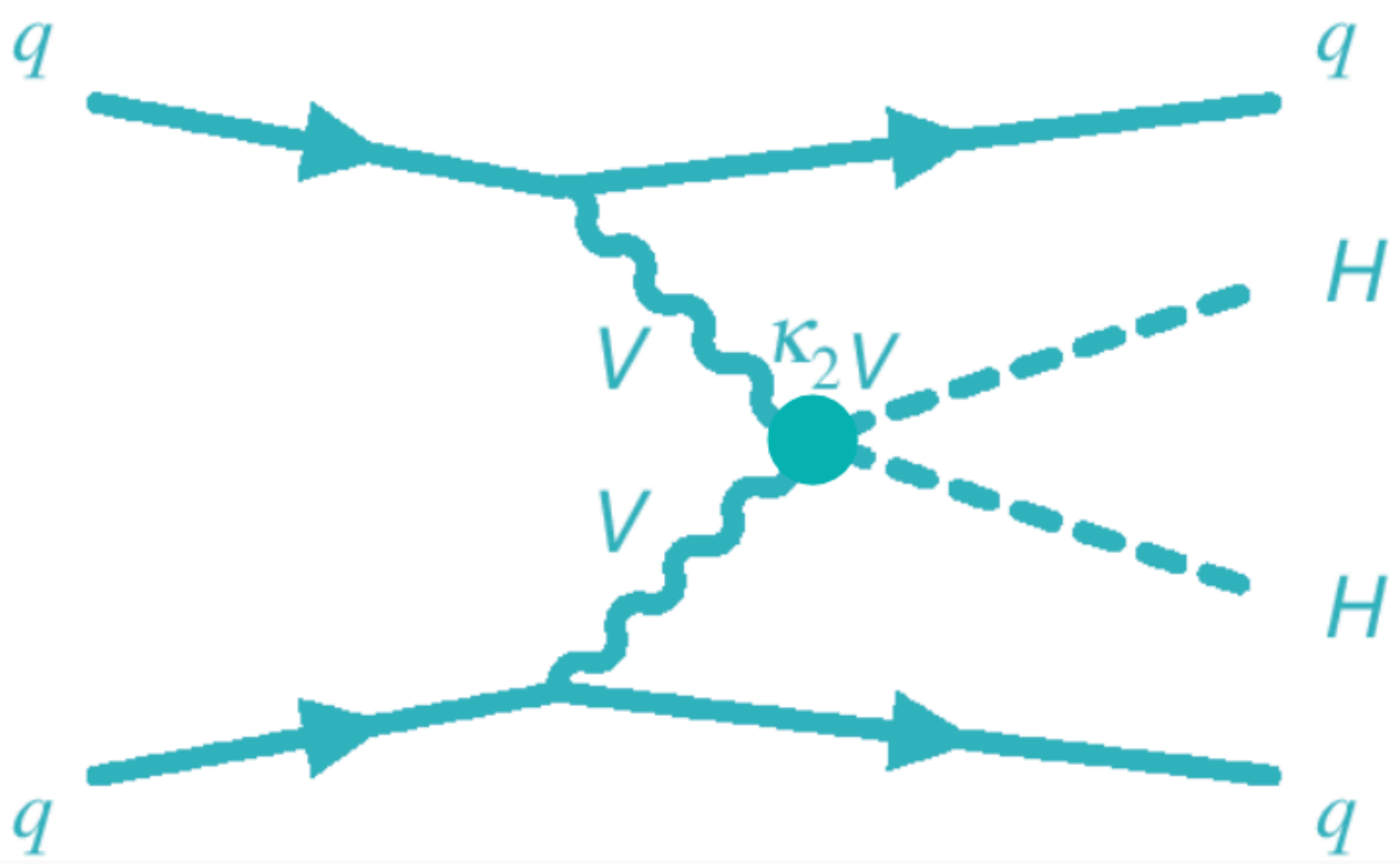
(destructive interference)





Access the triple Higgs boson coupling (→ K_λ)

⇒ Probe the shape of the Higgs potential



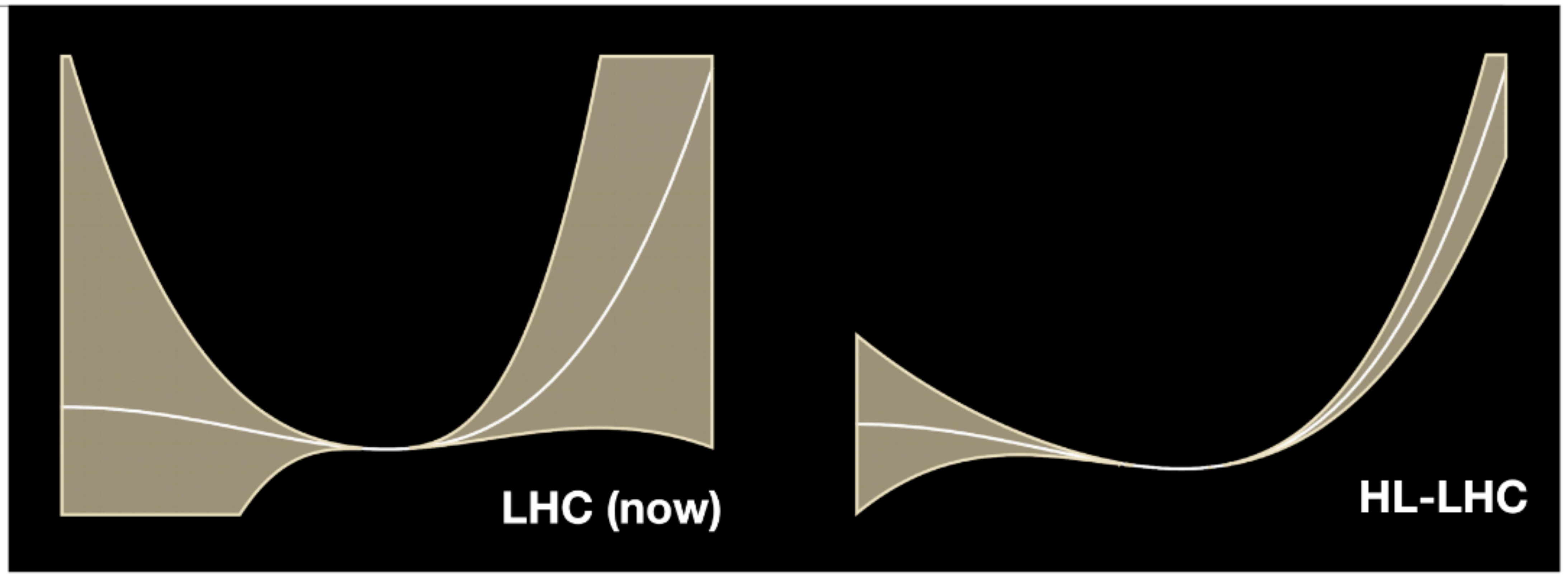
Also accesses other interactions, e.g. VVHH (→ K_{2V}).

Higgs potential

EW phase transition resp. for baryon asymmetry? Vacuum stable?

N. Craig (Dec 2022)

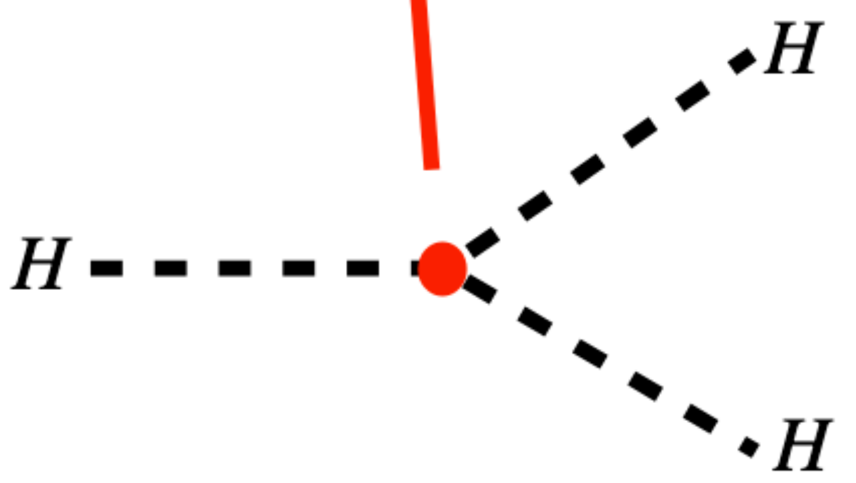
- **Measurement of Higgs potential a *science driver* for HL-LHC,** largely unconstrained so far
- Shape of potential key to understand **EW phase transition in early universe**
- Shape of potential determines **vacuum stability**

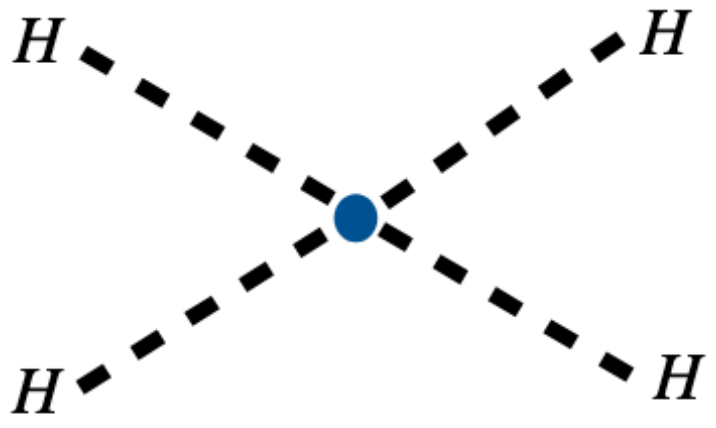


$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

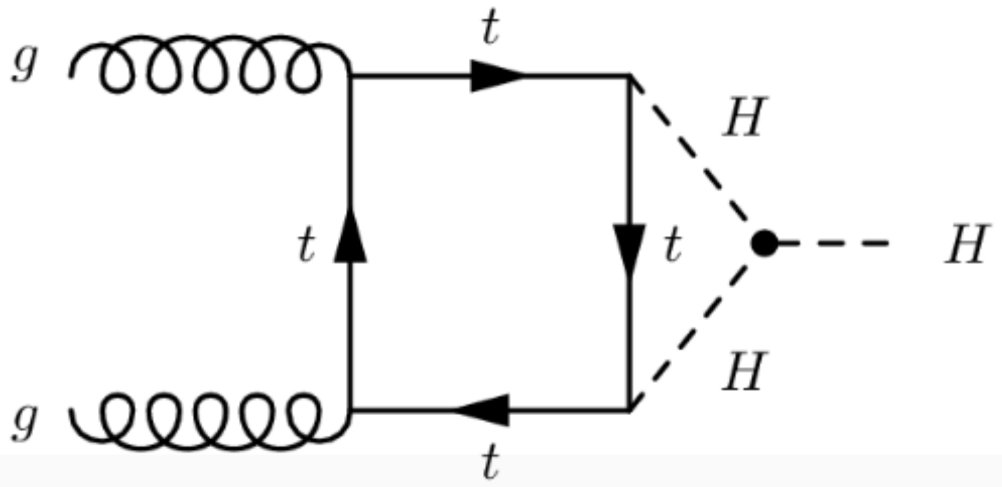
$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

Higgs mass already measured at LHC with ~per-mill precision





- Cubic (aka tri-linear) coupling λ ($\equiv \lambda_3$) via Higgs pair production
- Single Higgs measurements sensitive to λ via higher-order corrections



ATLAS Run 2 Di-Higgs Combination

CERN-EP-2024-160

More in Dilia Portillo's talk and Song-Ming Wang's talk on HL-LHC prospects

Combine HH→bbττ + bbγγ + bbbb + multileptons + bbll+MET:

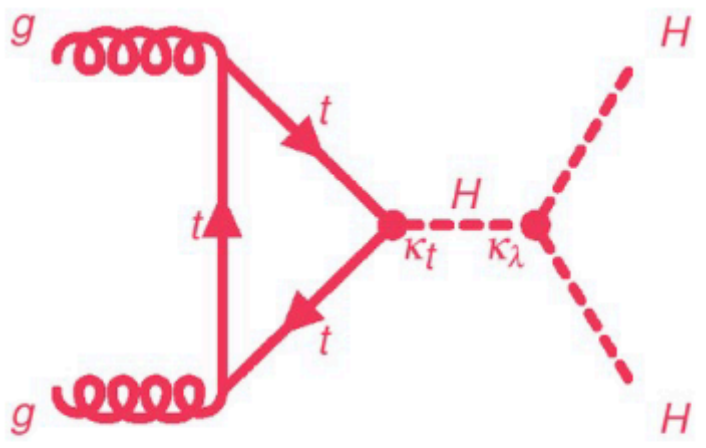
$$\mu_{HH} = 0.5\,^{+1.2}_{-1.0}\left(\,^{+0.7}_{-0.6}\ \text{syst.}\right)$$

Uncertainty comparable to SM signal!

-1.2 < κ_λ < 7.2 @ 95% CL

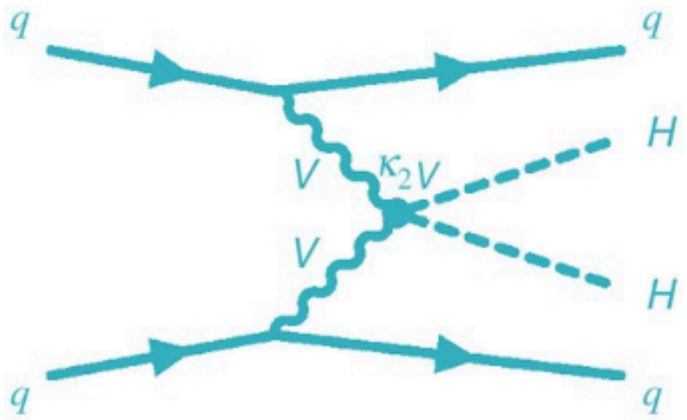
dominated by γγbb + ττbb

Best constraint to date on λ_3 coupling!

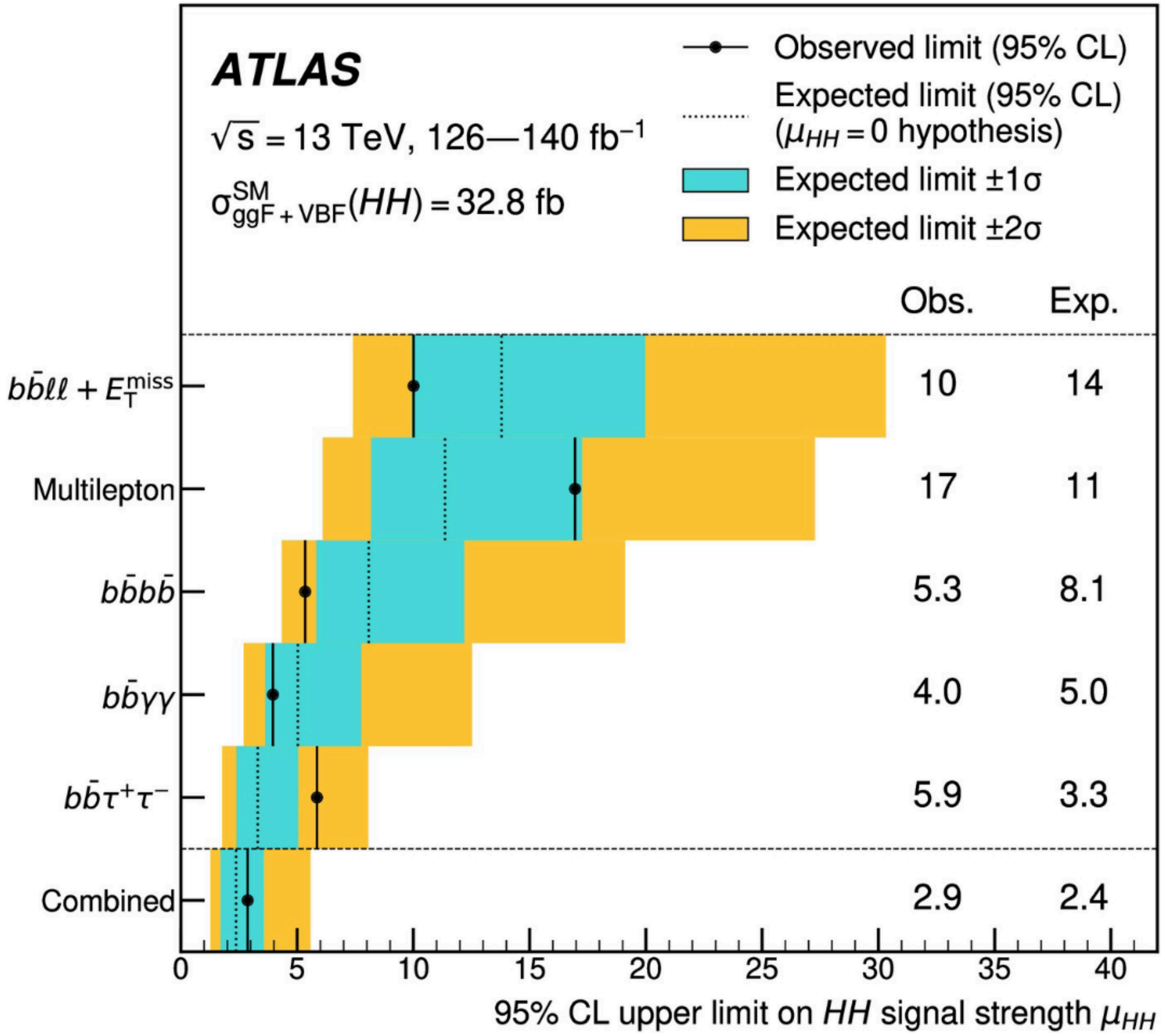


0.6 < κ_{2V} < 1.5 @ 95% CL

dominated by VBF HH→bbbb



Best constraint from CMS: **0.67 < κ_{2V} < 1.38** @ 95% CL



CMS HH Combination results: Nature 607 (2022) 60

CMS Run 2 differential combination

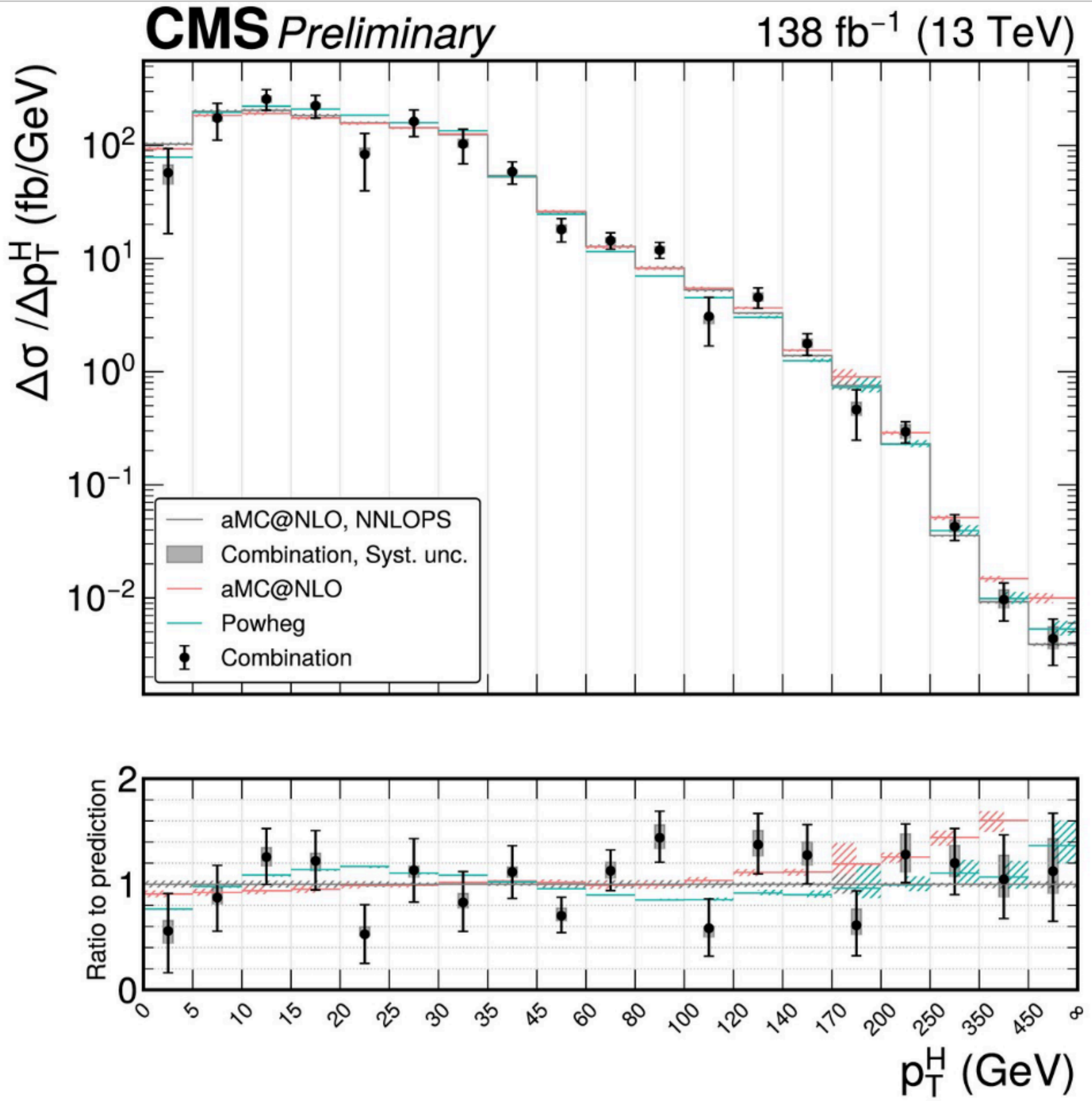
Combined measurements using:

- **H→γγ**
- **H→ZZ*→4l**
- **H→WW***
- **H→ττ**
- **H→ττ boosted**

} High-precision channels (H→γγ, H→ZZ*→4l)

} Sensitive to high-p_T^H region (H→ττ, H→ττ boosted)

New



CMS-PAS-HIG-23-013

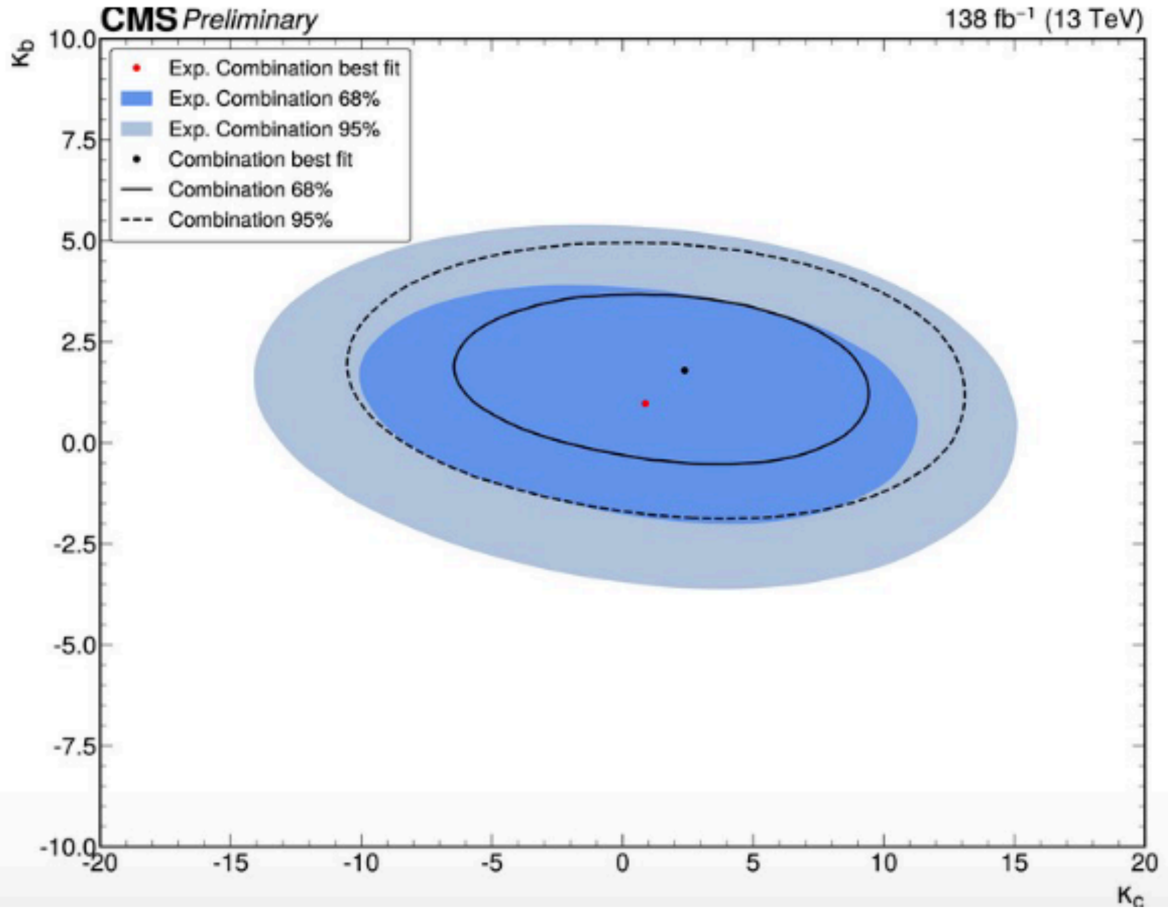
Test of the SM over a wide p_T^H range

Also N_{jets}, p_T^{j1}, $\Delta\varphi_{jj}$, …

Interpretations in terms of κ_c, EFT parameters

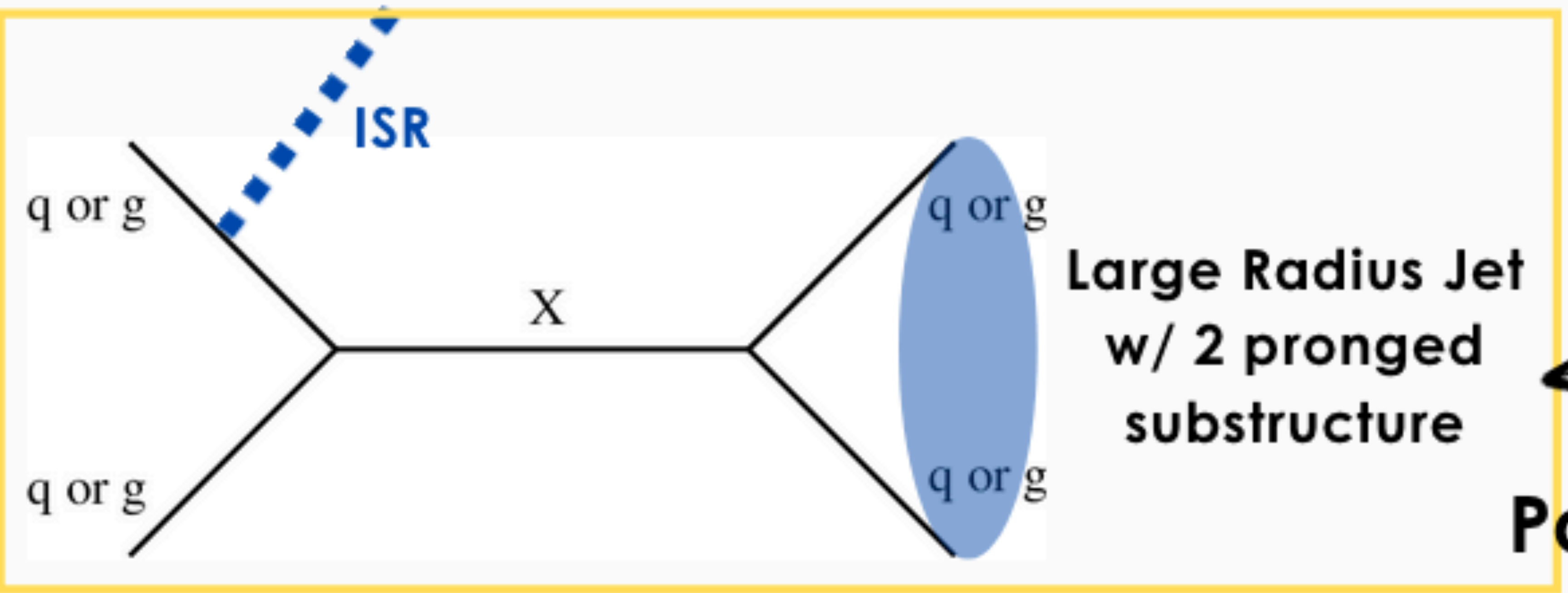
⇒ Good agreement with SM predictions in all distributions

See Irene Dutta's talk for more on EFT



Search for low mass resonances in quark-antiquark pairs

NEW

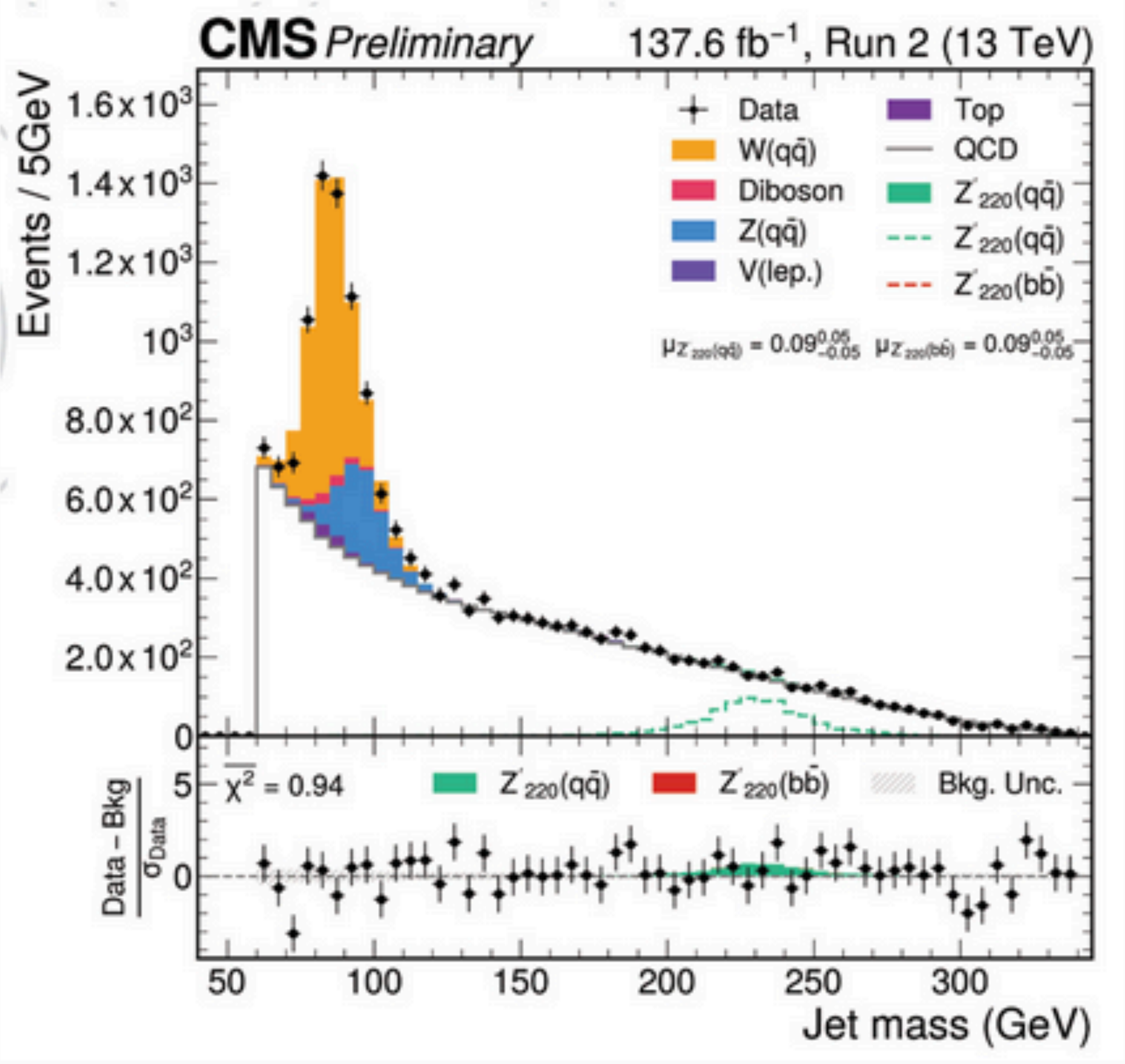


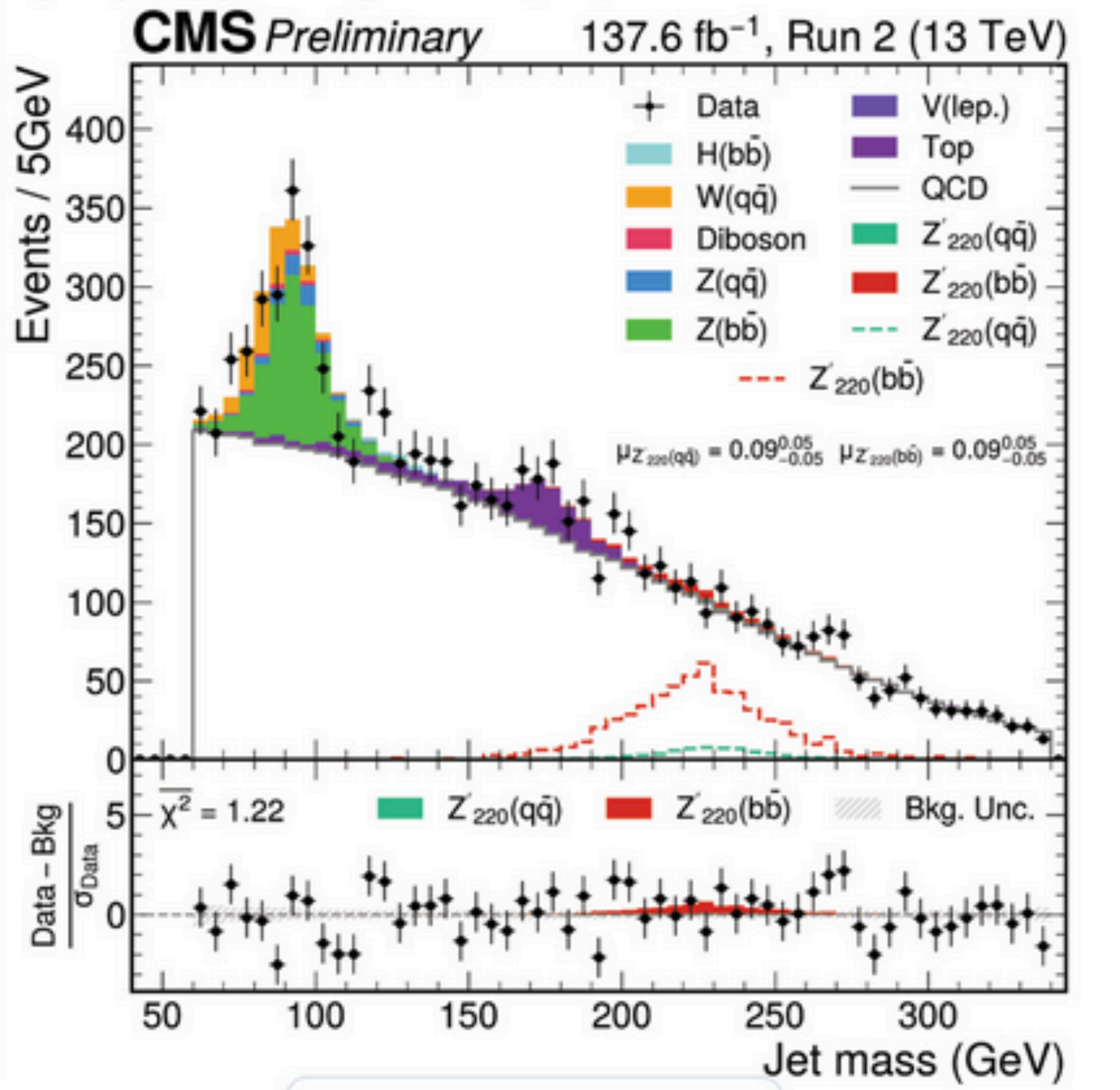
ParticleNET algorithm

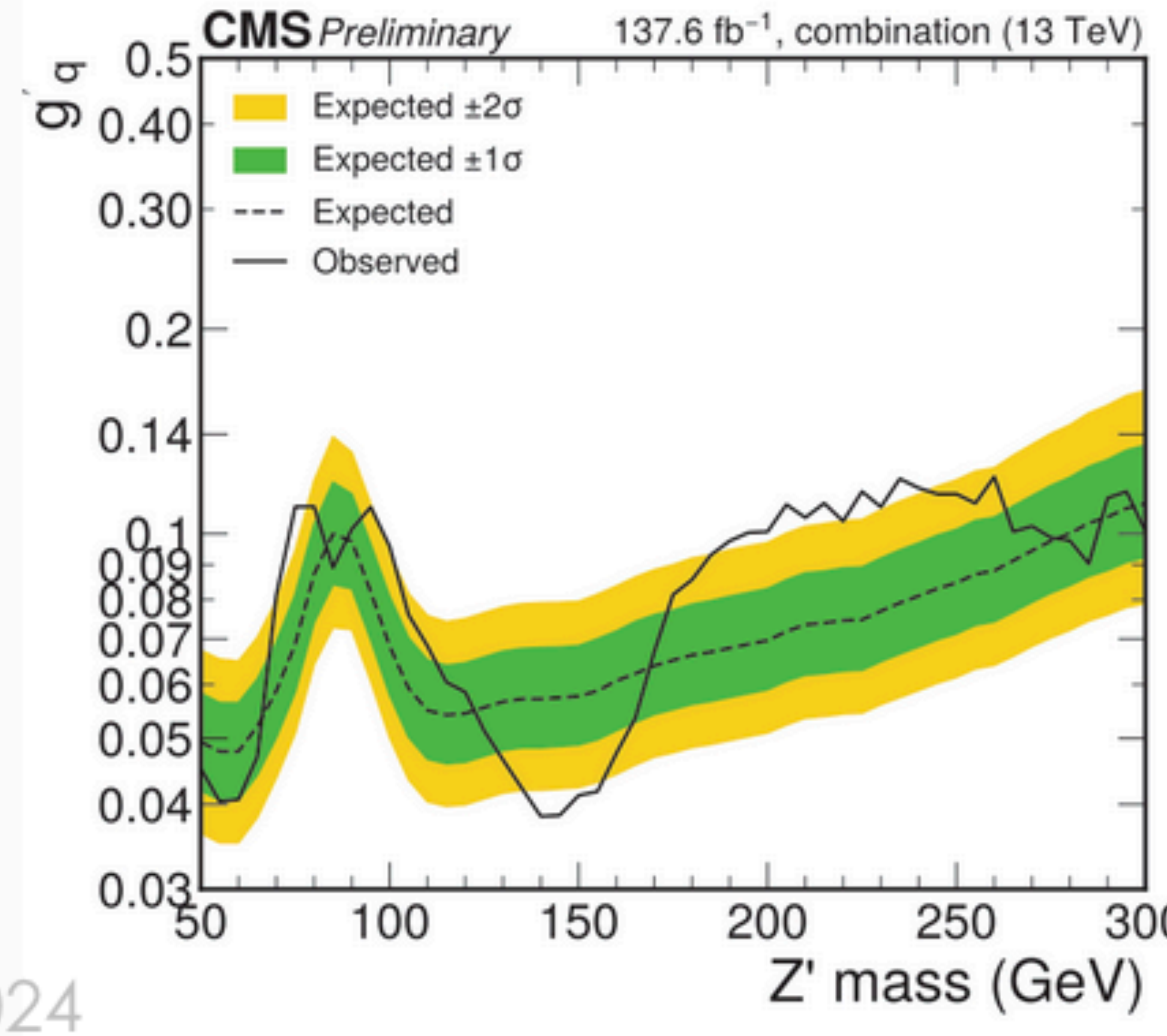
$$50\text{GeV} < M_X < 300\text{GeV}$$

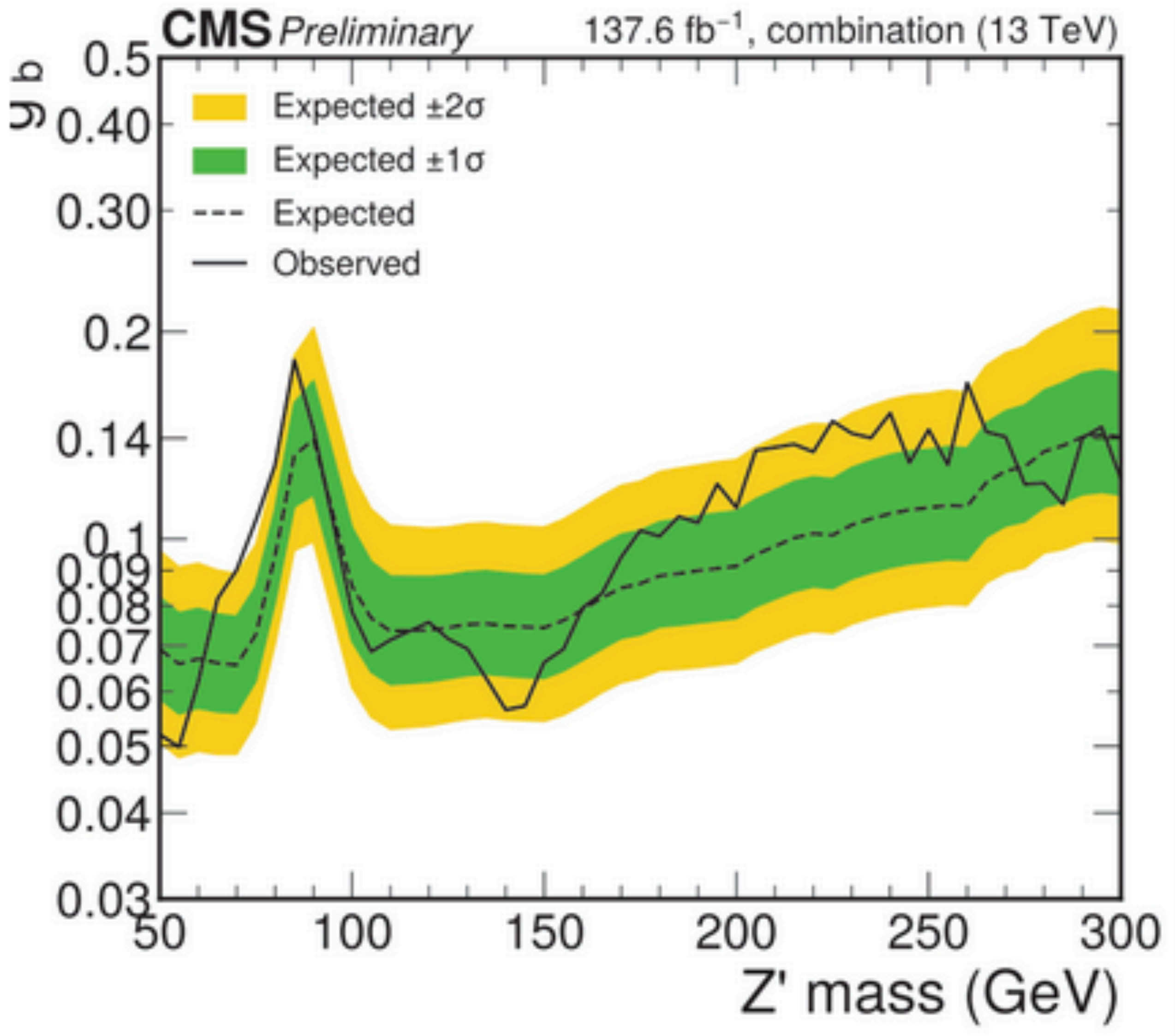
- X produced with large pT, due to significant initial state radiation (ISR)
- **Circumvent huge rate of dijet events from the QCD**

- Simultaneous fit of Jet mass in 5 pT SRs and CRs
- Maximum fluctuations in the observed limit: 2.2 σ (3.0 σ local) at m(Z') = 75GeV and 1.9 σ (2.8 σ local) at m(Z') = 225GeV









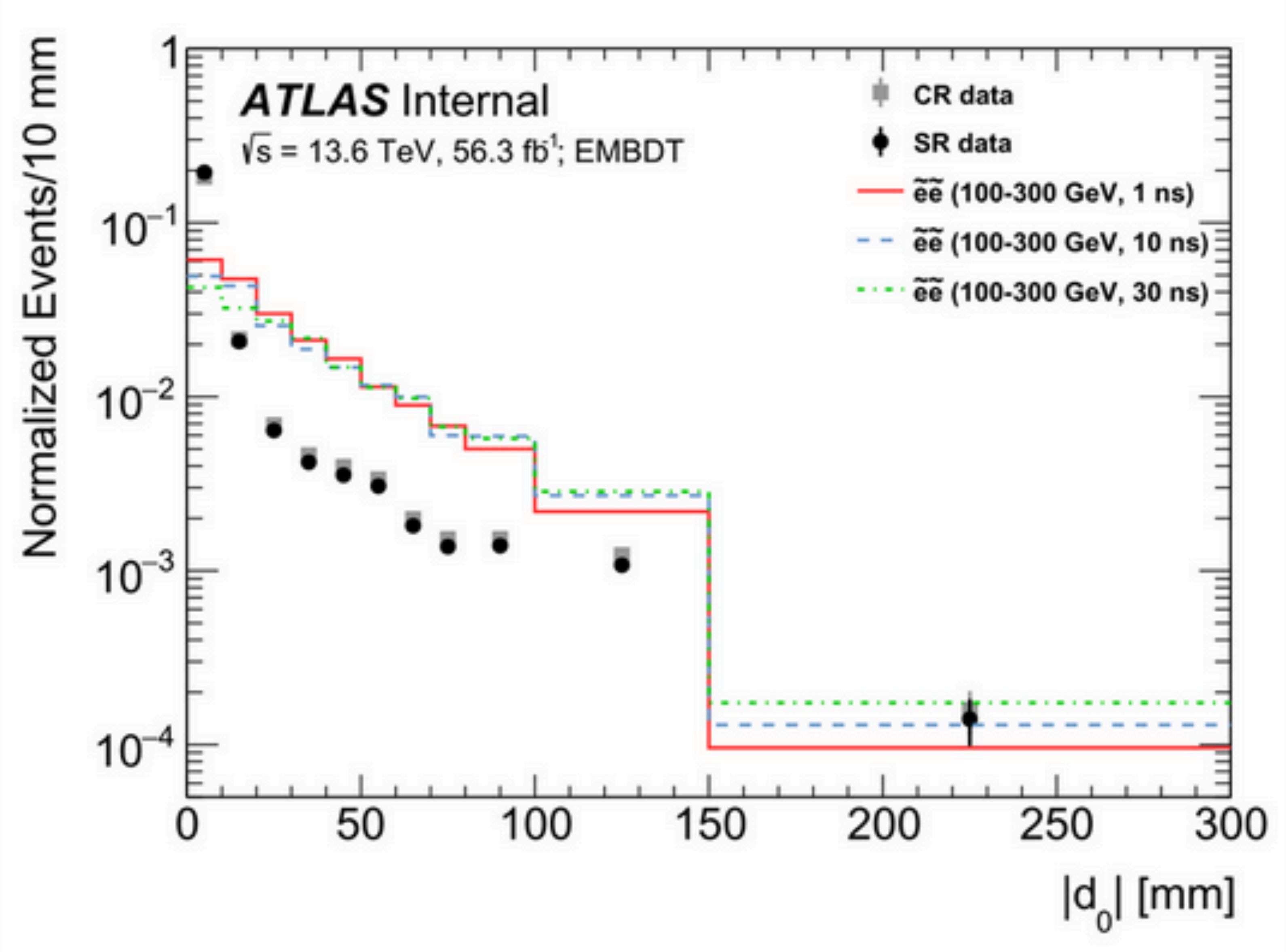
PLACEHOLDER

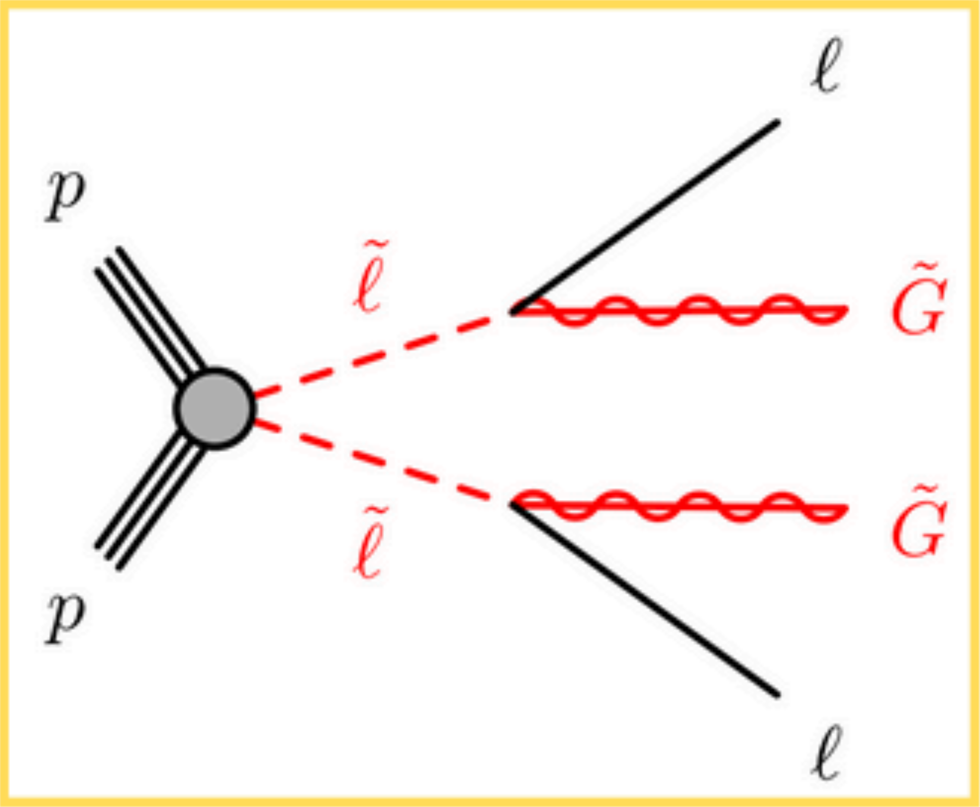
Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors

Search for displaced leptons in 13 TeV and 13.6 TeV

Large Radius Tracking: designed to increase efficiency for decay products of LLPs.

LRT run in the HLT for the first timeat Run 3

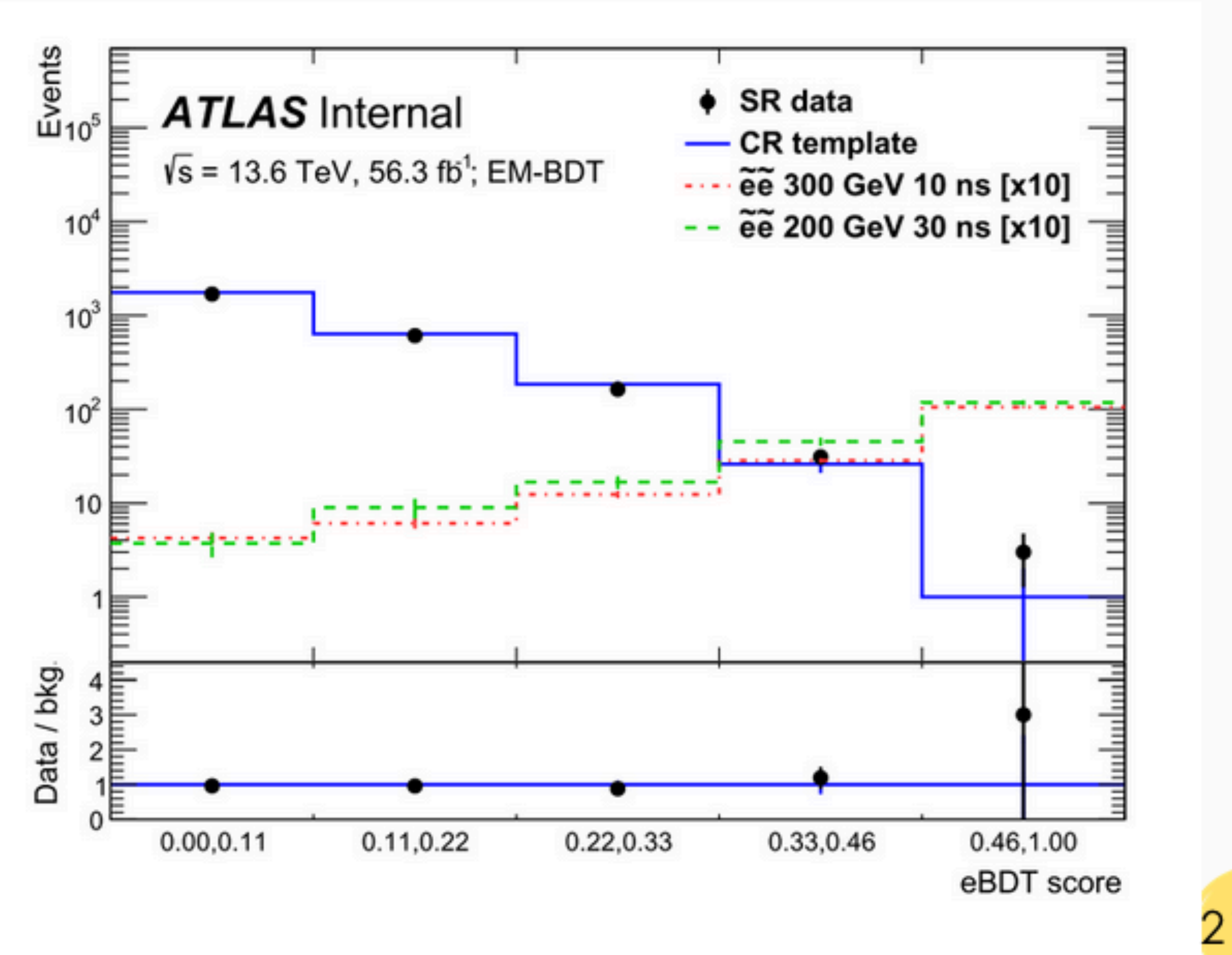




Enhanced discovery reach beyond prior searches through several

← **novel additions.** →

Dedicated **displaced electron tagger** allows to select only one displaced electron, **greatly extending the analysis sensitivity**

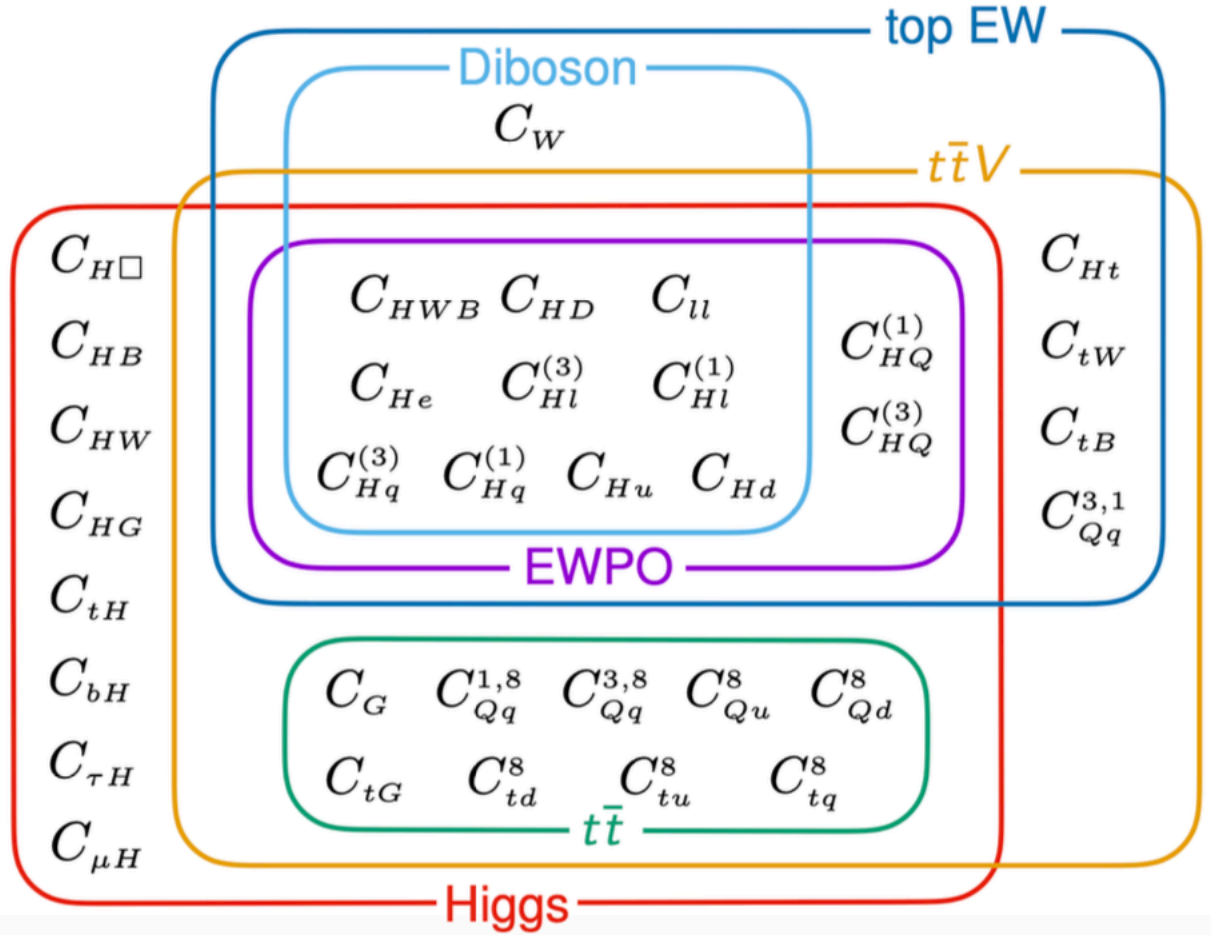


PLACEHOLDER

SMEFT: global fits

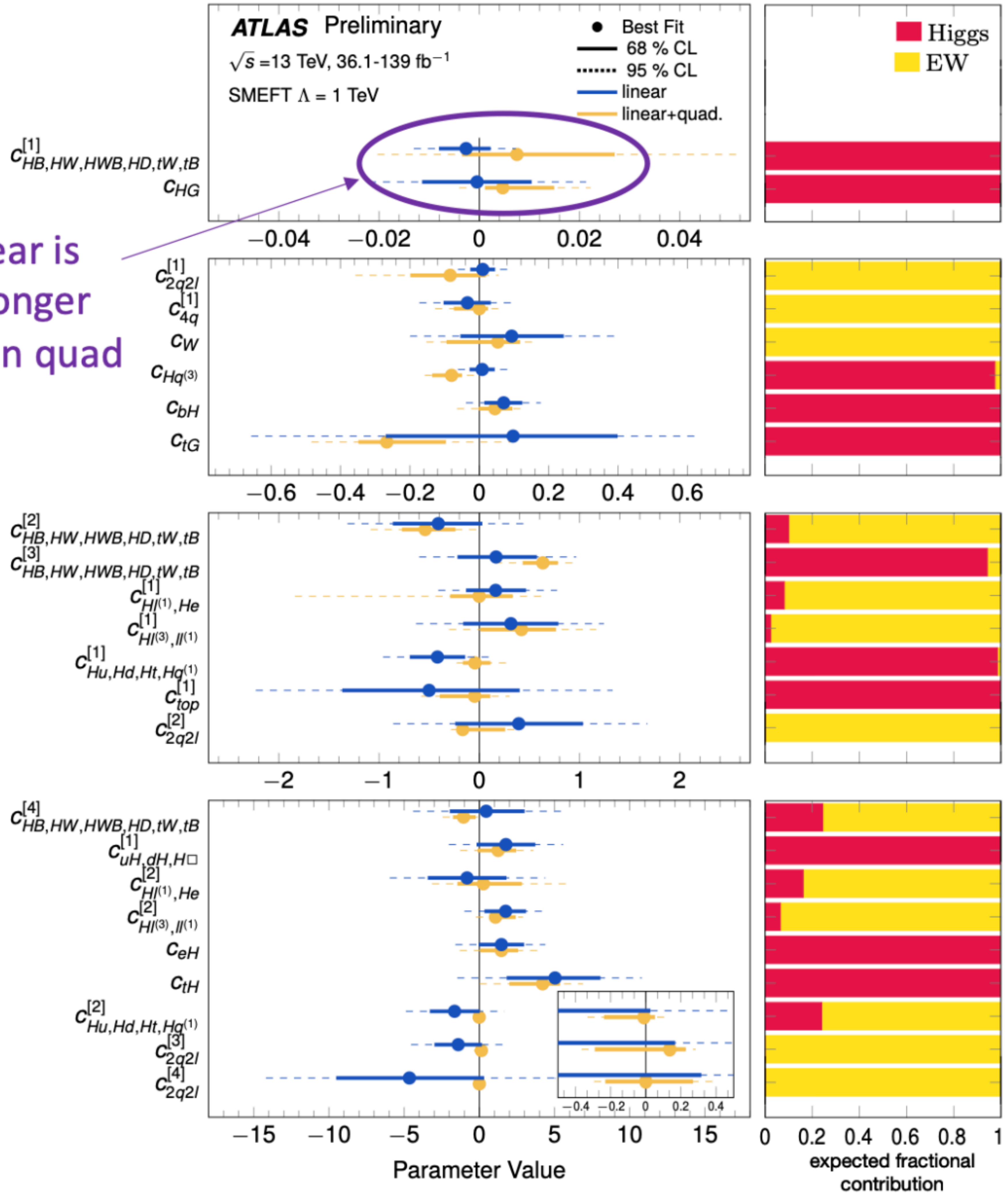
Target is to perform a global fit of many operators with **many input physics measurements**

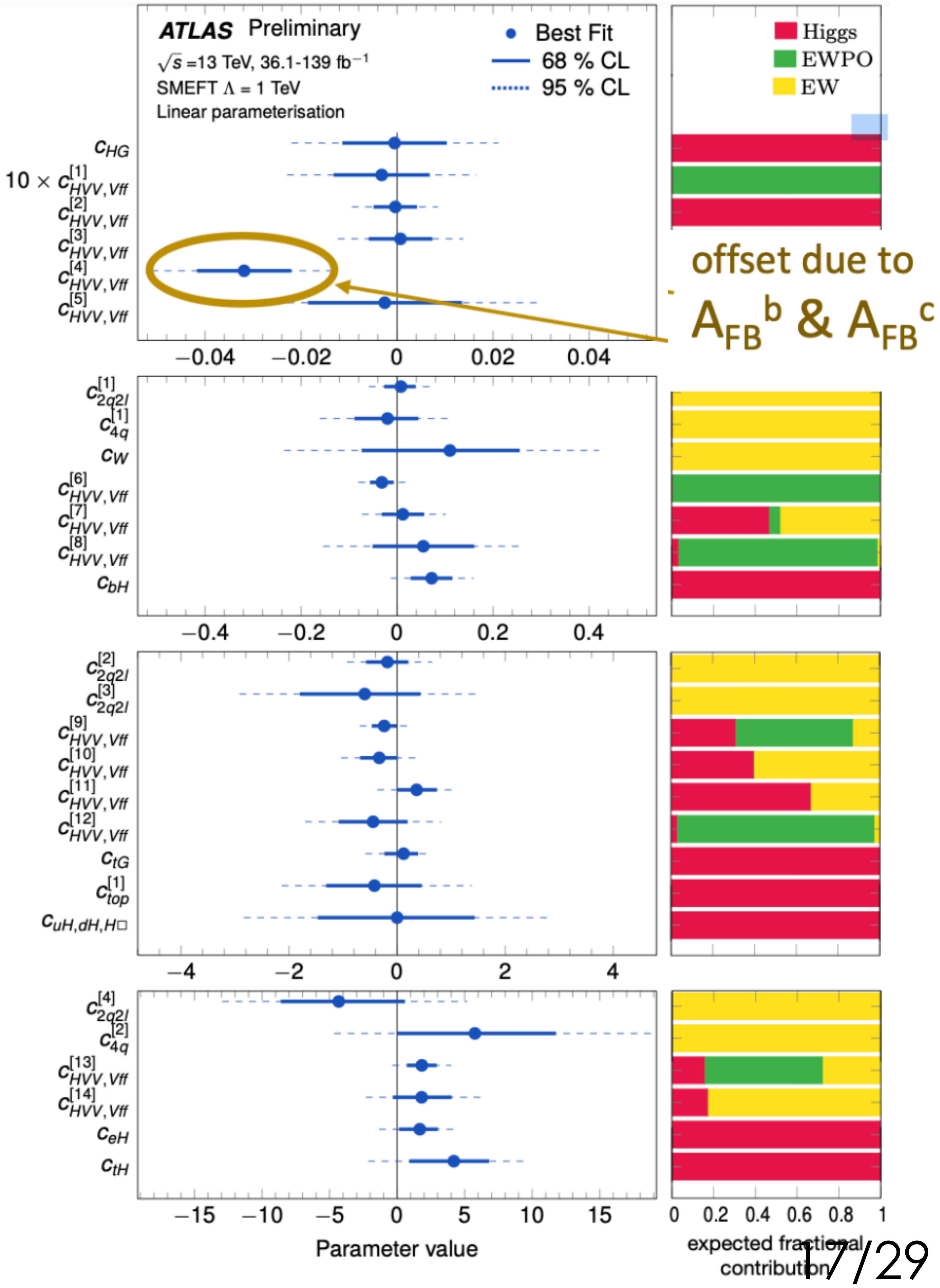
- Ultimately in the future **try to simultaneously fit dim-6 and dim-8 operators** with many measurements
- Significant step towards this direction performed by **ATLAS in 2022**
- **Dim-6 fit using Higgs+Diboson+EWPO data**



Great care taken to get details right:
- Indirect impact of operators on BRs
- Take propagator effects into account
- Handle acceptance effects in certain Higgs decay kinematics
- Consider impact of certain operators on Fermi constant

linear is stronger than quad





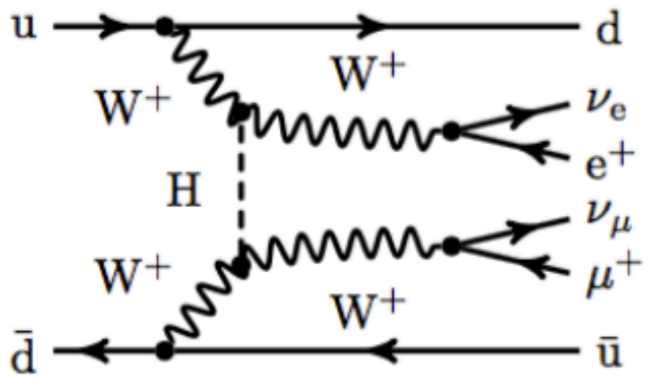
Other highlights @HL-LHC

- **EWPO & Top quark**
  - $\sigma(m_W) \simeq 5$ MeV (CDF: 9.4 MeV)
  - $\sigma(m_t) \simeq 0.2$ GeV (LHC: 0.6 GeV)
  - $\sigma(\sin^2\theta^{\ell}_{\text{eff}}) \simeq 10 \times 10^{-5}$ (LEP+SLD: 16×10^{-5})
  - $\Lambda \gtrsim 3.5$ TeV ($c = 1$) for LH tW

Snowmass EF report

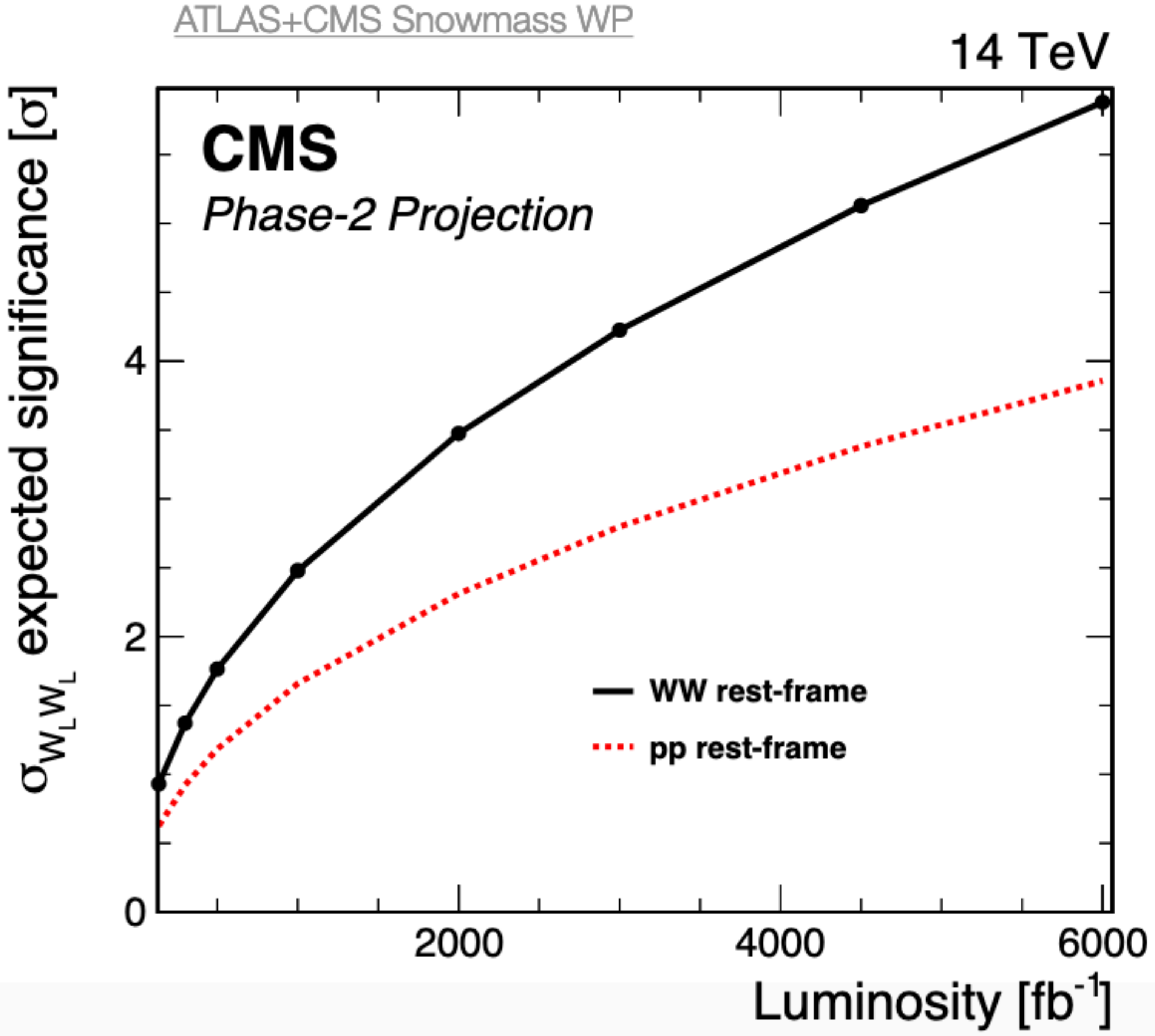
Parameter	HL-LHC
$\sqrt{s}$ [TeV]	14
Yukawa coupling y_t (%)	3.4
Top mass m_t (%)	0.10
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3
Four-top coupling c_{tt} (TeV^{-2})	0.6

- **Vector-boson scattering**
  - Higgs vs. unitarity violation
- $W^{\pm}_L W^{\pm}_L$ only 6-7% of total VBS xs



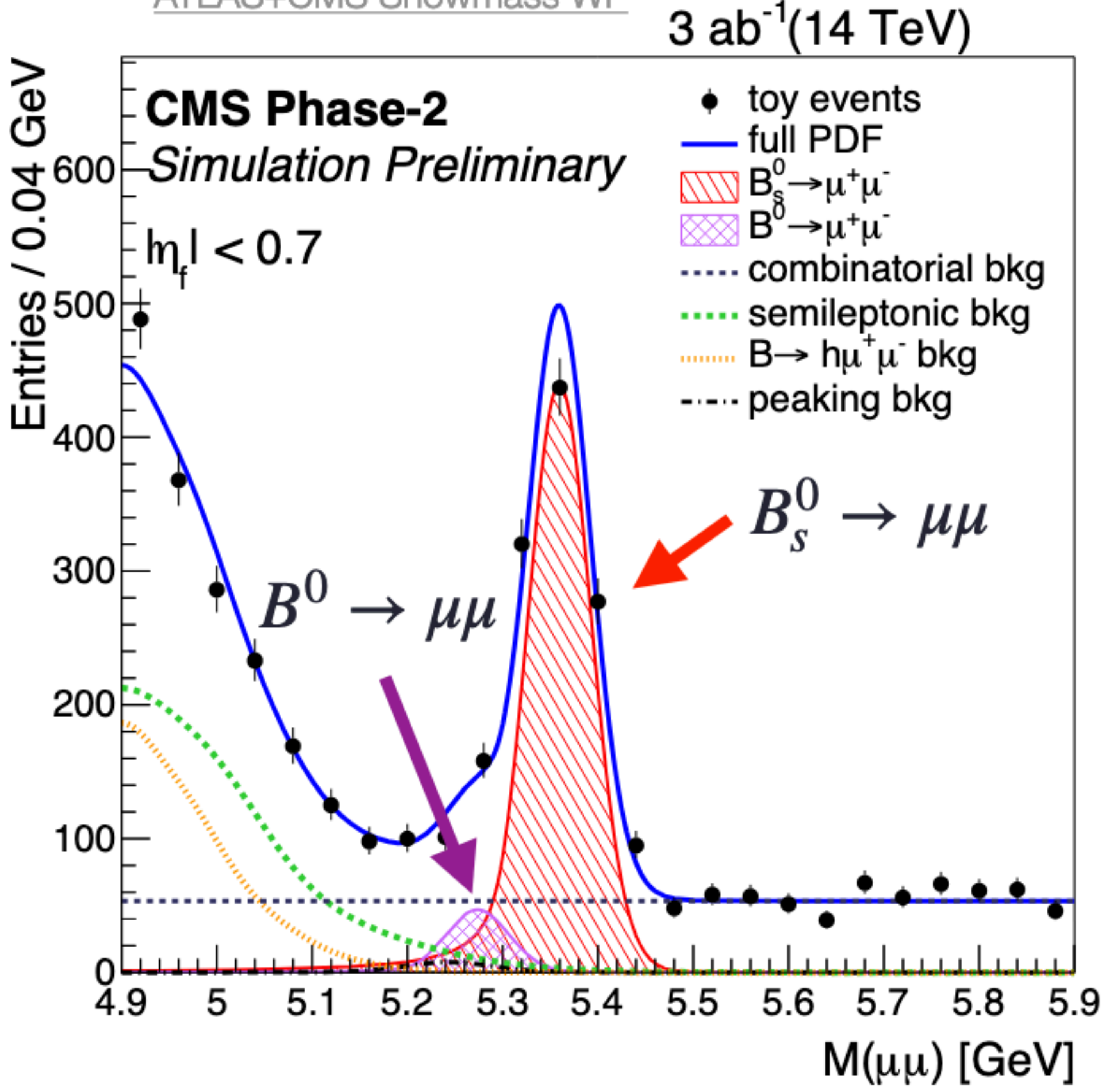
- Significance ~5 σ expected ATLAS + CMS

ATLAS+CMS Snowmass WP



- **Rare decays**
  - Observation ($> 5\,\sigma$) of FCNC $B^0 \to \mu\mu$ with SM BF $\sim 10^{-10}$
  - Requires upgraded trigger + new tracker improves $m(\mu\mu)$ resolution by 40-50%

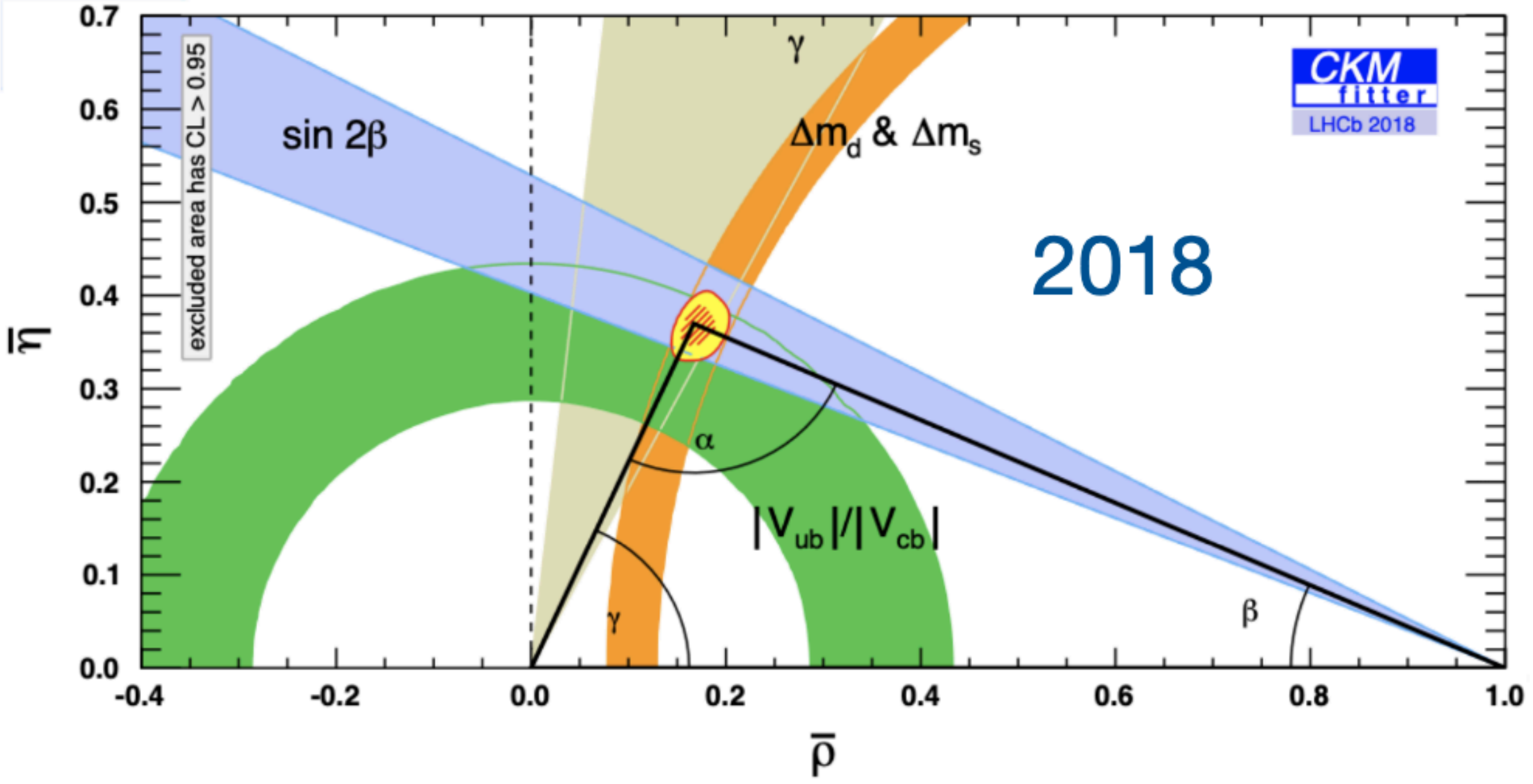
ATLAS+CMS Snowmass WP

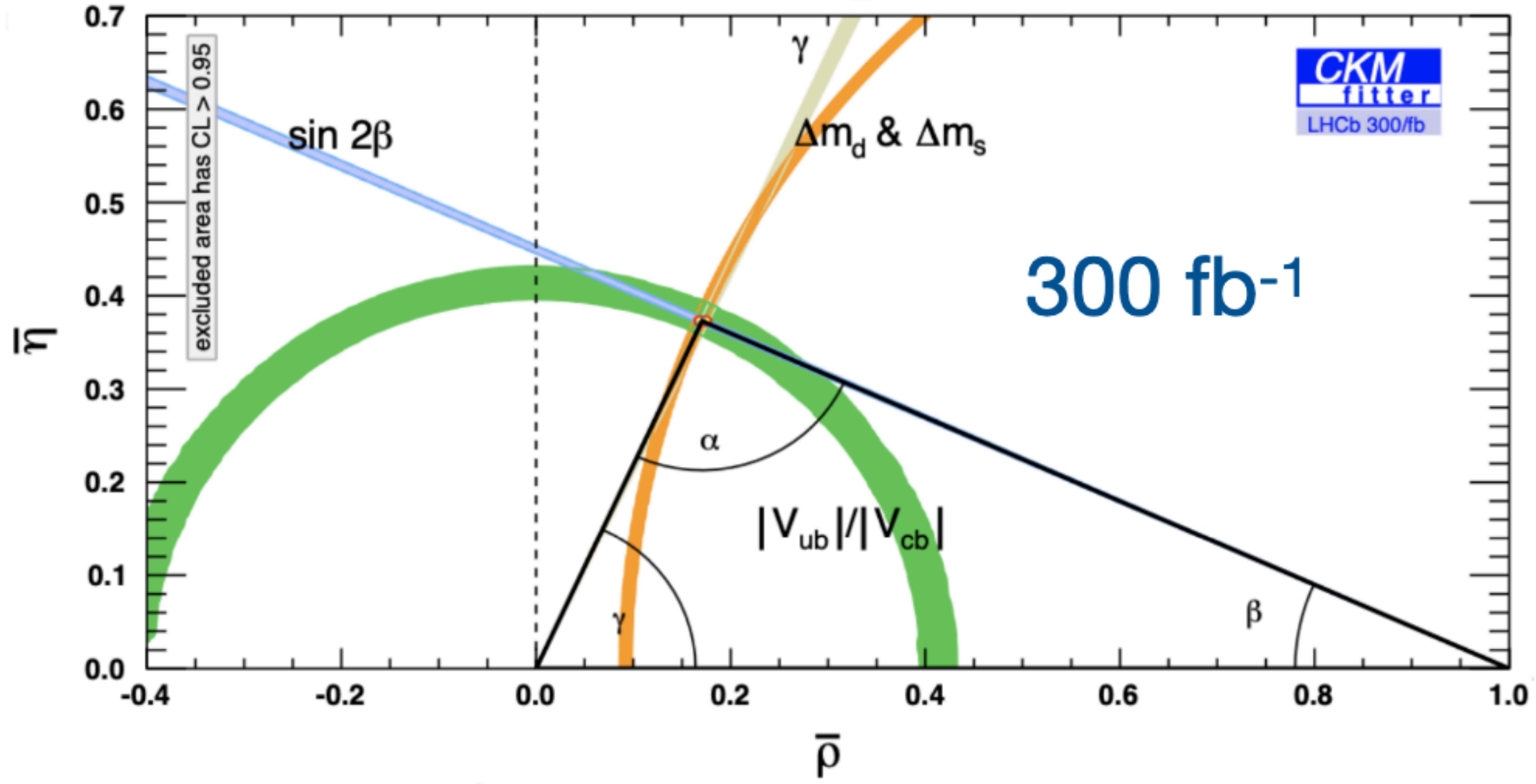


Flavor physics @HL-LHC

Are there additional sources of CP violation? Lepton flavor universality?

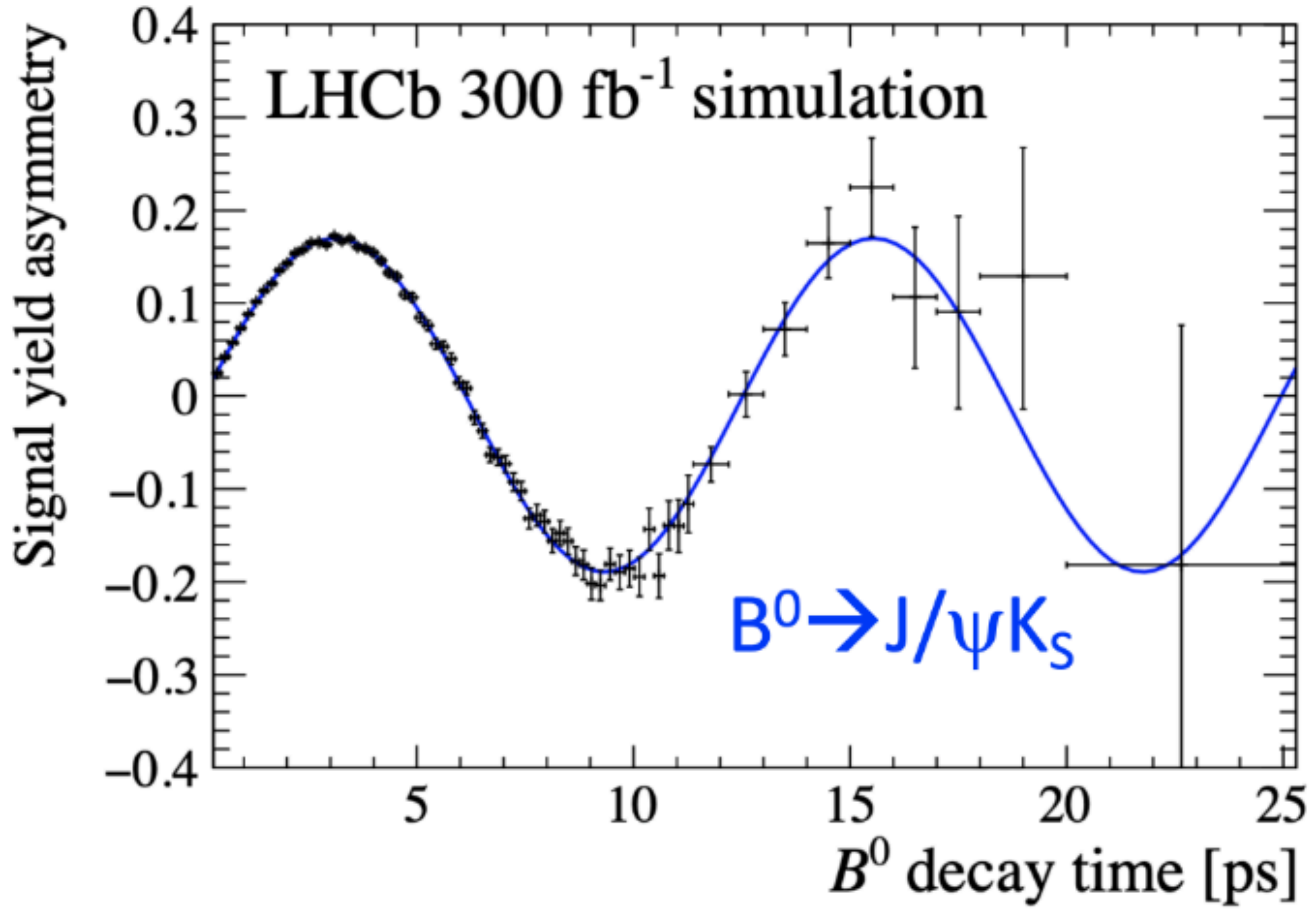
- **CP violation:** LHCb to put stringent test on CKM paradigm with 300 fb^{-1}



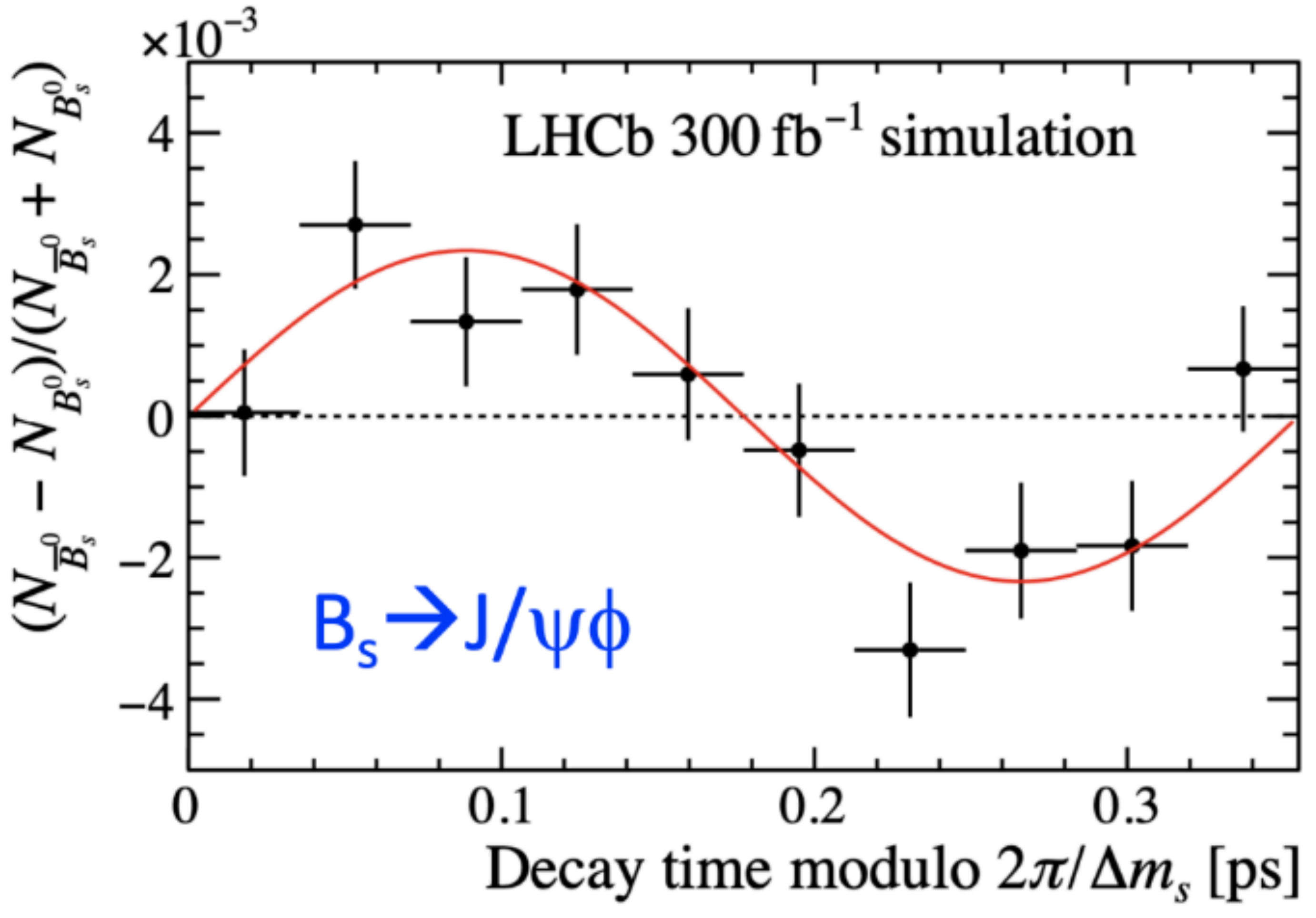


- High-precision CPV angles

arXiv:1808.08865



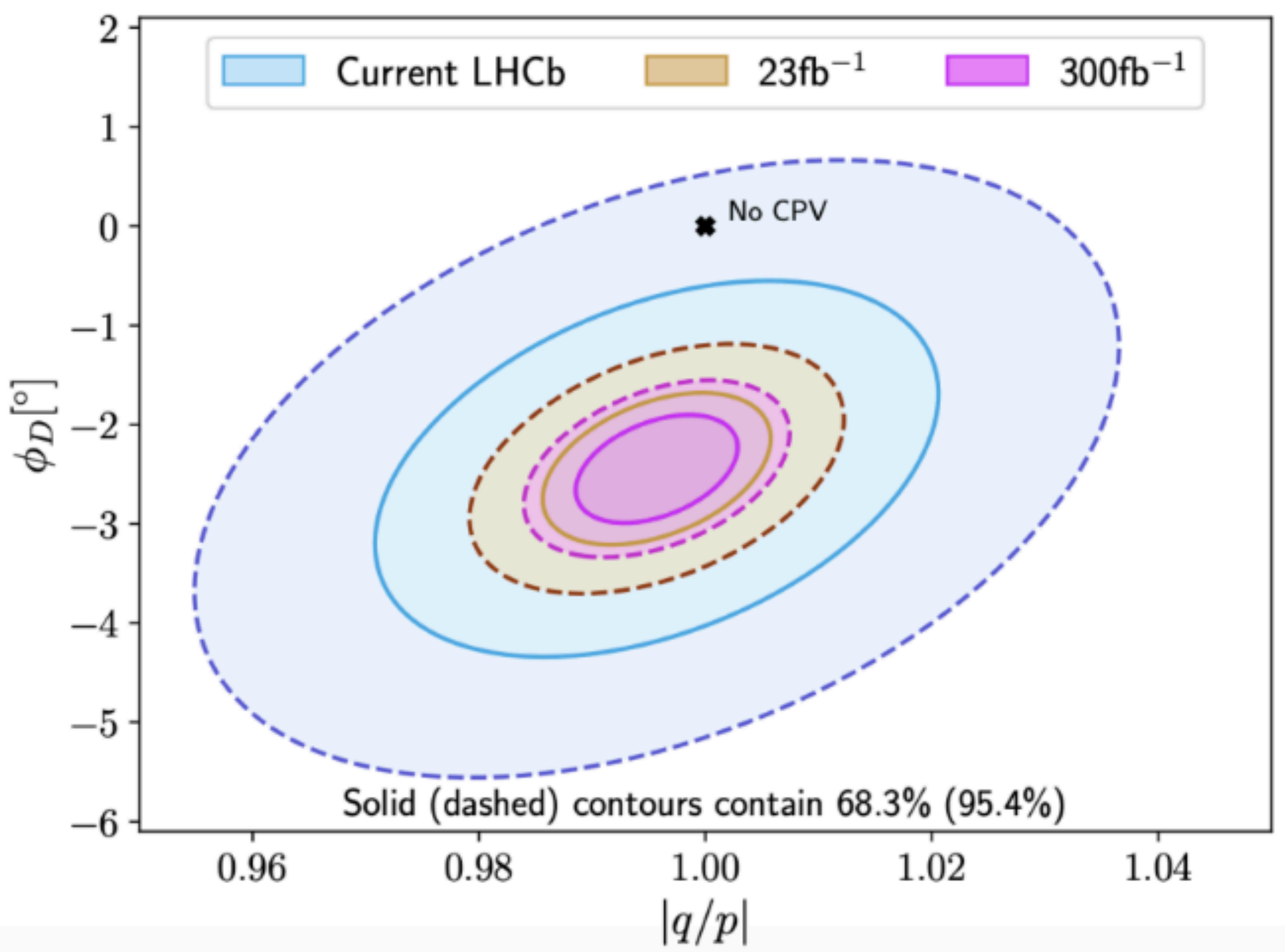
$\sigma(\sin 2\beta) = 0.003$



$\sigma(\phi_s) = 0.004$

- Highest sensitivity to find CP violation in charm mixing

LHCb-PUB-2022-012



Independent determinations of UT apex $(\Delta m_d/\Delta m_s, \sin 2\beta)$ and (V_{ub}, γ)

High-Granularity Timing Detector

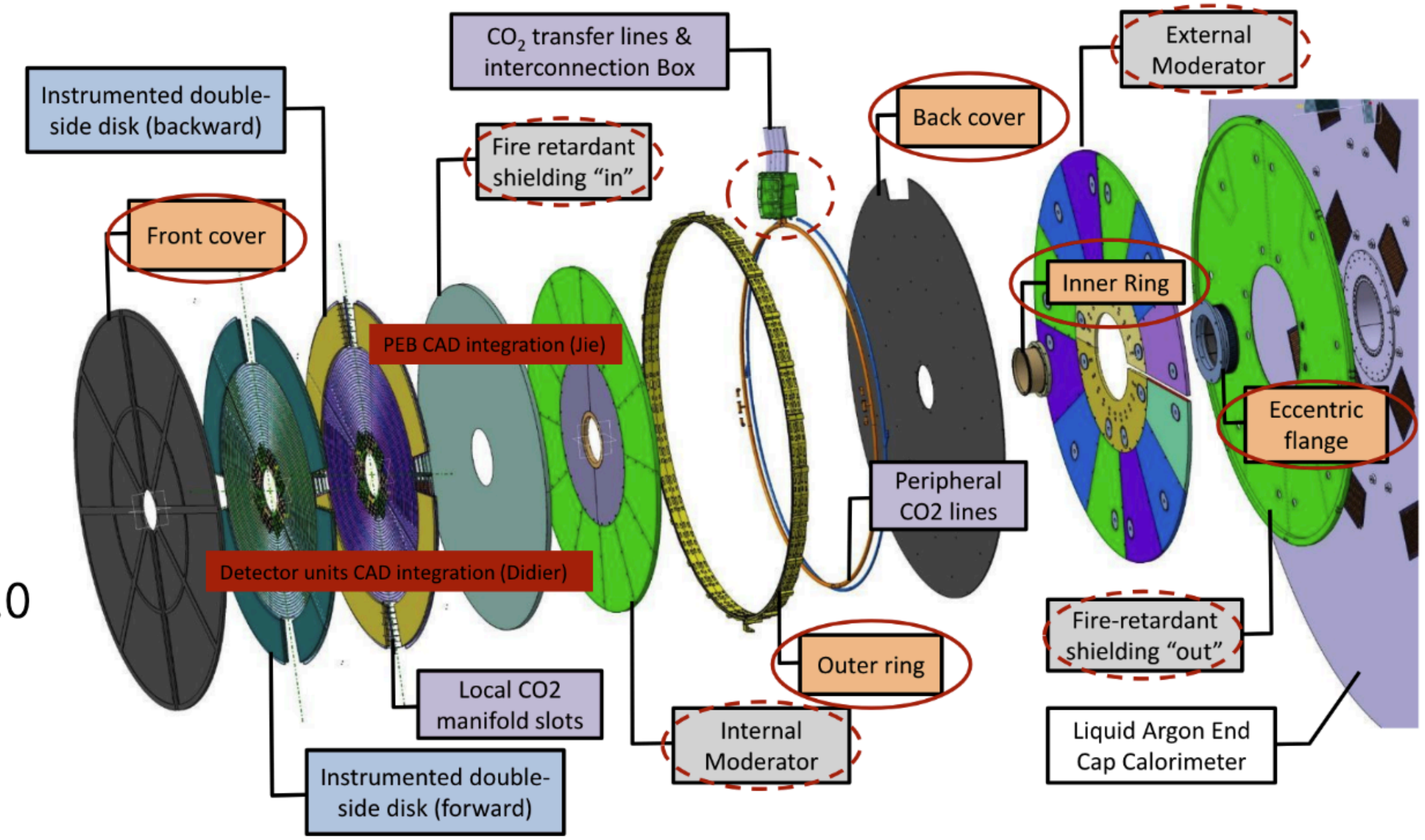
HGTD will provide:

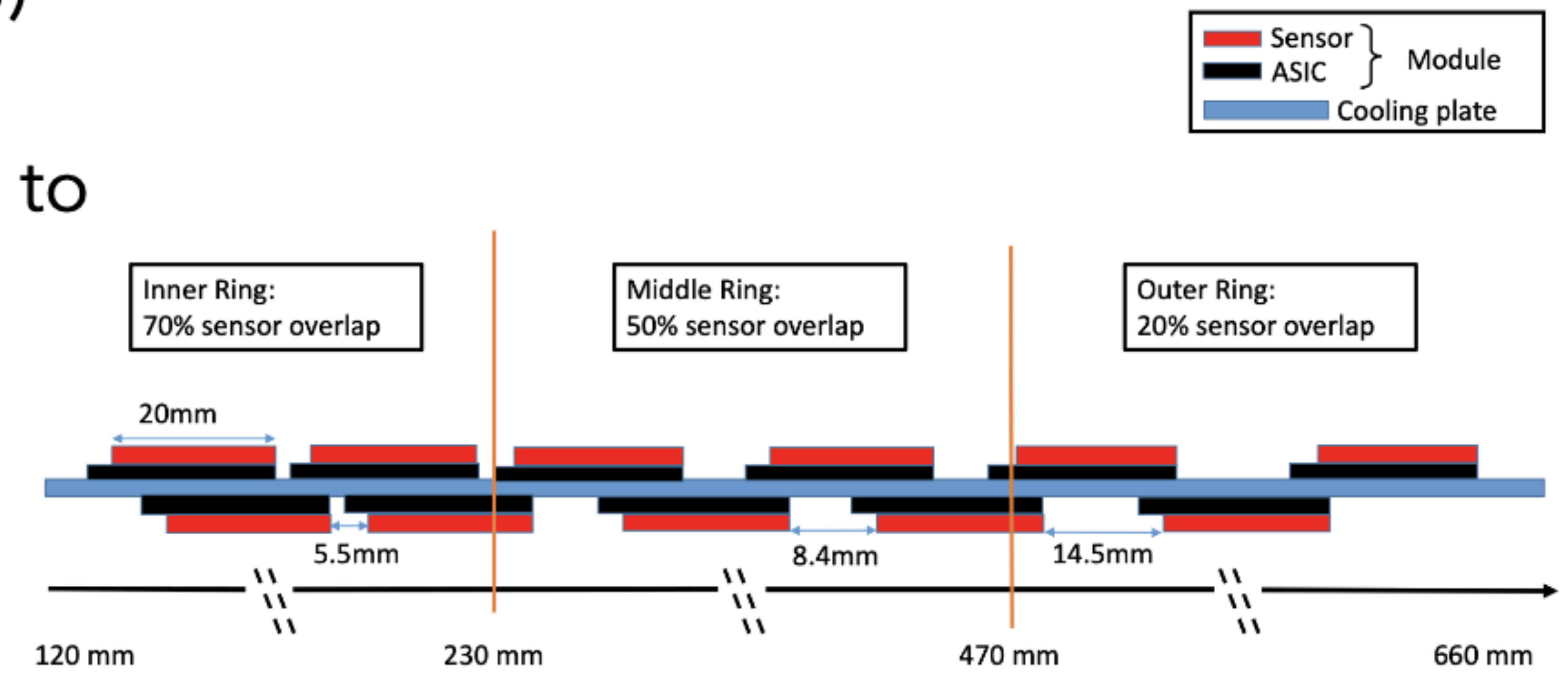
- **Timing** information for charged particles with an expected per-hit resolution of **<50-70 ps** over full lifetime
  ↠ *per-track resolution of **<35-50 ps** due to overlap*
- **Luminosity** measurement by reading hit counts at 40 MHz in outer region

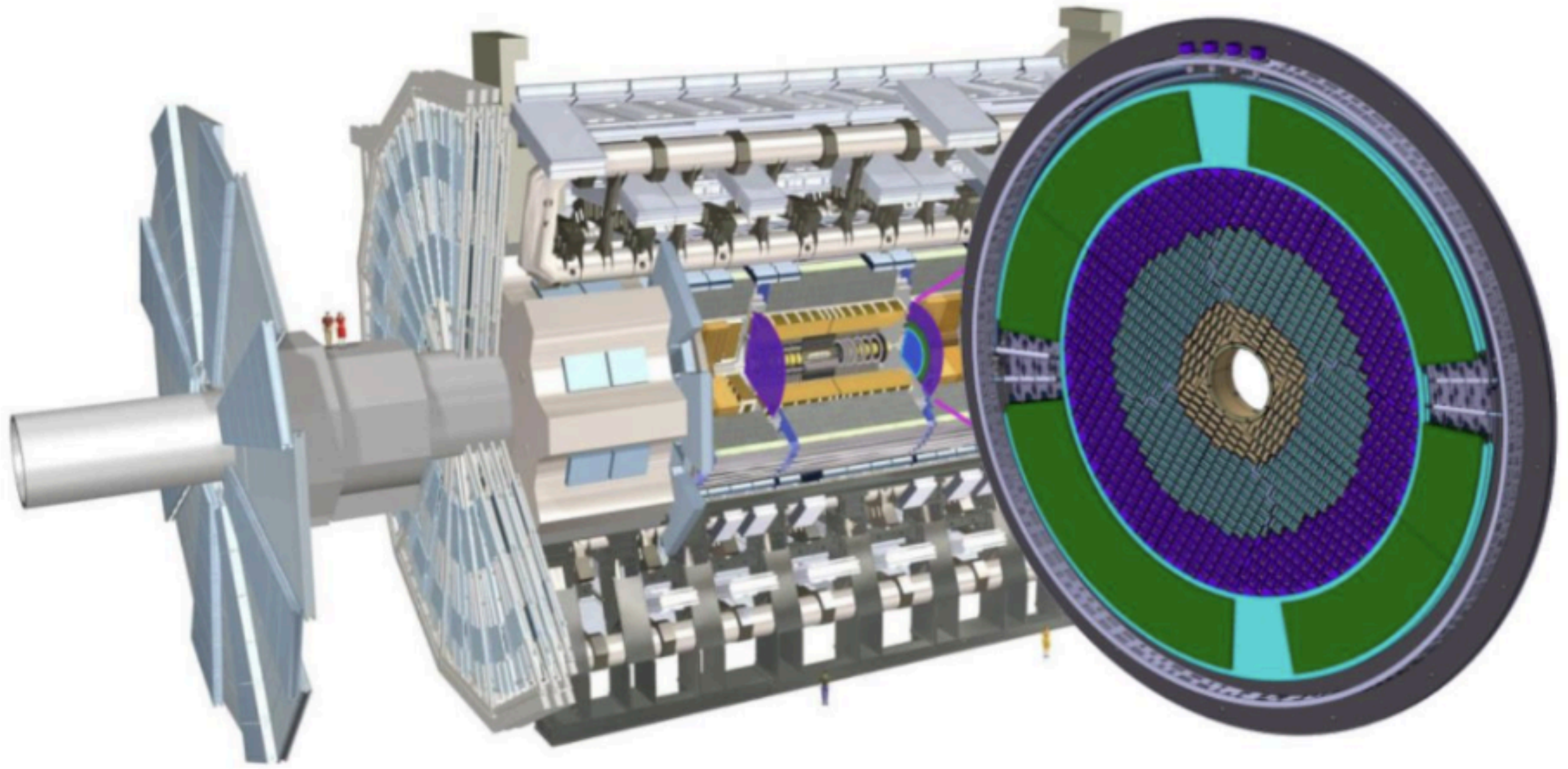
Located at z = ± 3.5 m from IP, covers forward region $2.4 < |\eta| < 4.0$ ($2.4 < |\eta| < 2.8$ for luminosity readout)

Each end-cap consists of two double-sided disks, in total 8032 modules (3.6M readout channels)

Required to be radiation hard up to $2.5 \times 10^{15}\ n_{eq}/cm^2$ (replacements of "inner -" and "middle ring" needed!)

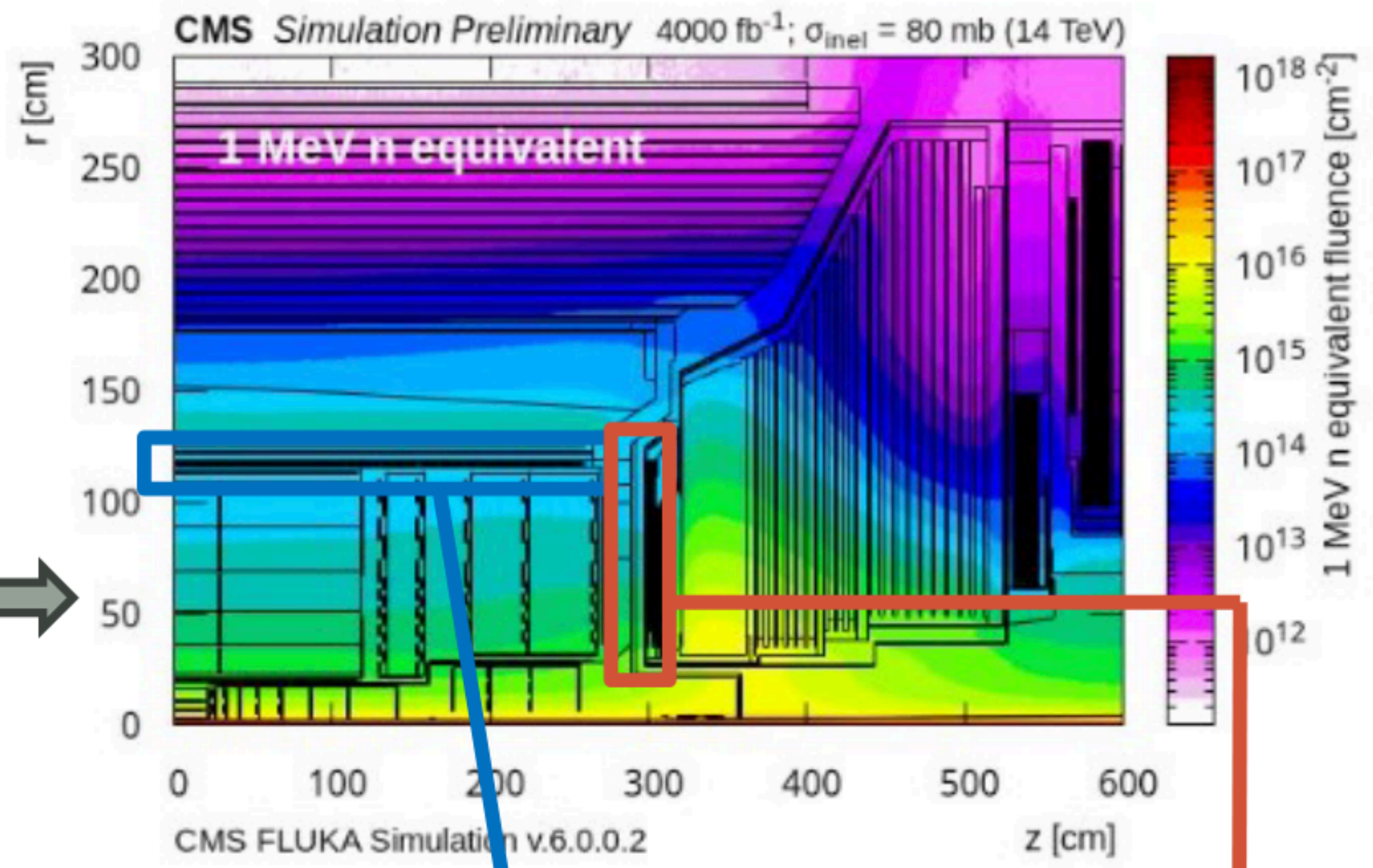




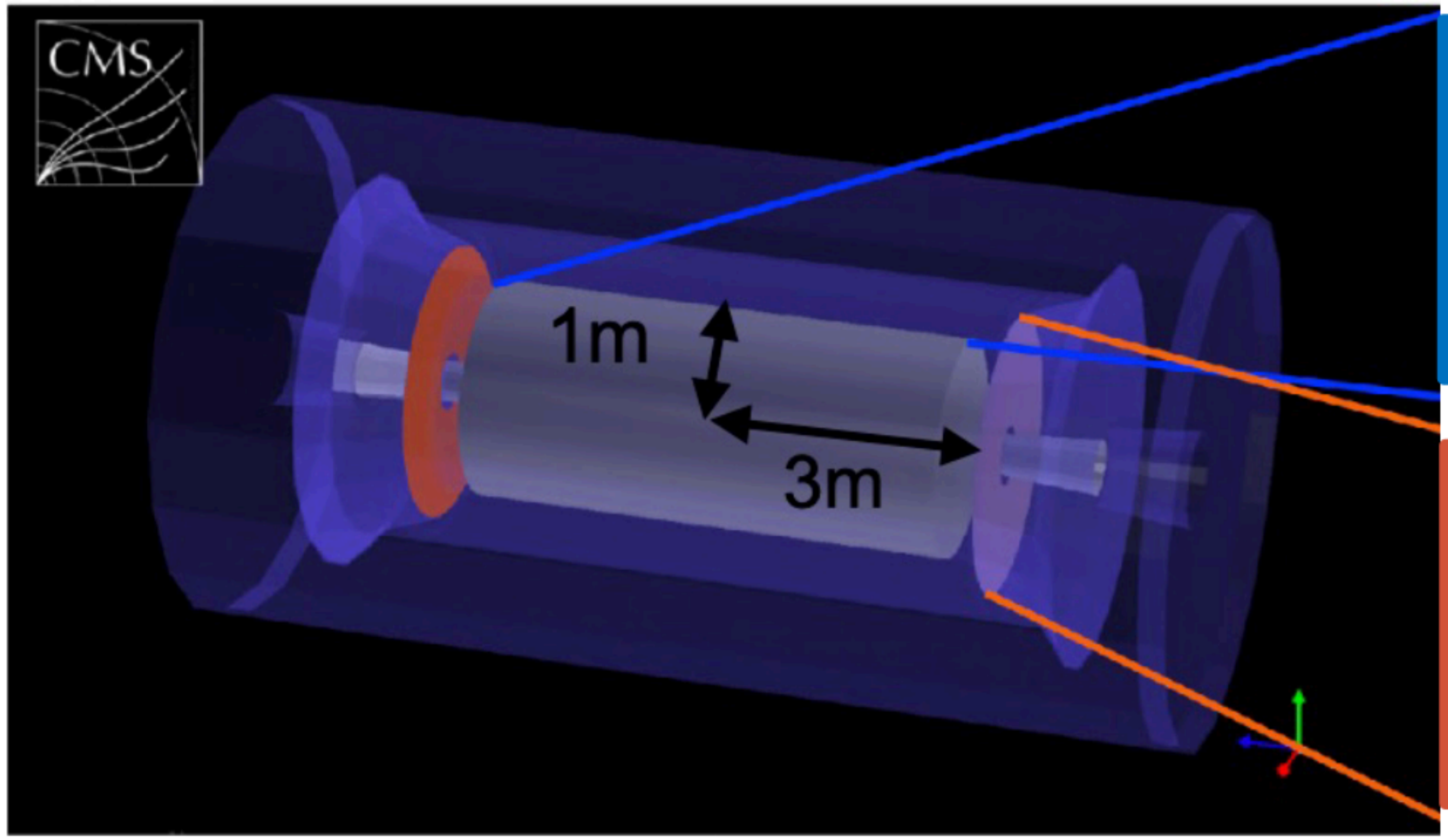


CMS approach: Mip Timing Detector

- Measure time of charged particles in between tracker and calorimeter
  - with hermetic coverage in $|\eta| < 3$
  - Barrel layer (BTL): inside the Barrel Tracker Support Tube
  - Endcap layer (ETL): on the HGCal nose, outside forward tracker
- Radiation hardness drives the sensor technology choice
  - together with cost and readout considerations



CMS-DP/2023-087



Barrel Timing Layer
- LYSO bar + 2 SiPM/bar
  - 332k channels
- $p_T > 0.7$ GeV, $|\eta| < 1.45$
- ~ 38 m^2

Endcap Timing Layer
- LGAD 16×16 pads
  - ~8.5M channels
- 2 discs/side $1.6 < |\eta| < 3$
- ~ 14 m^2