Strategy discussion meeting at Milano

High Luminosity LHC
ATLAS e LHCb, stato e prospettive

T. Lari

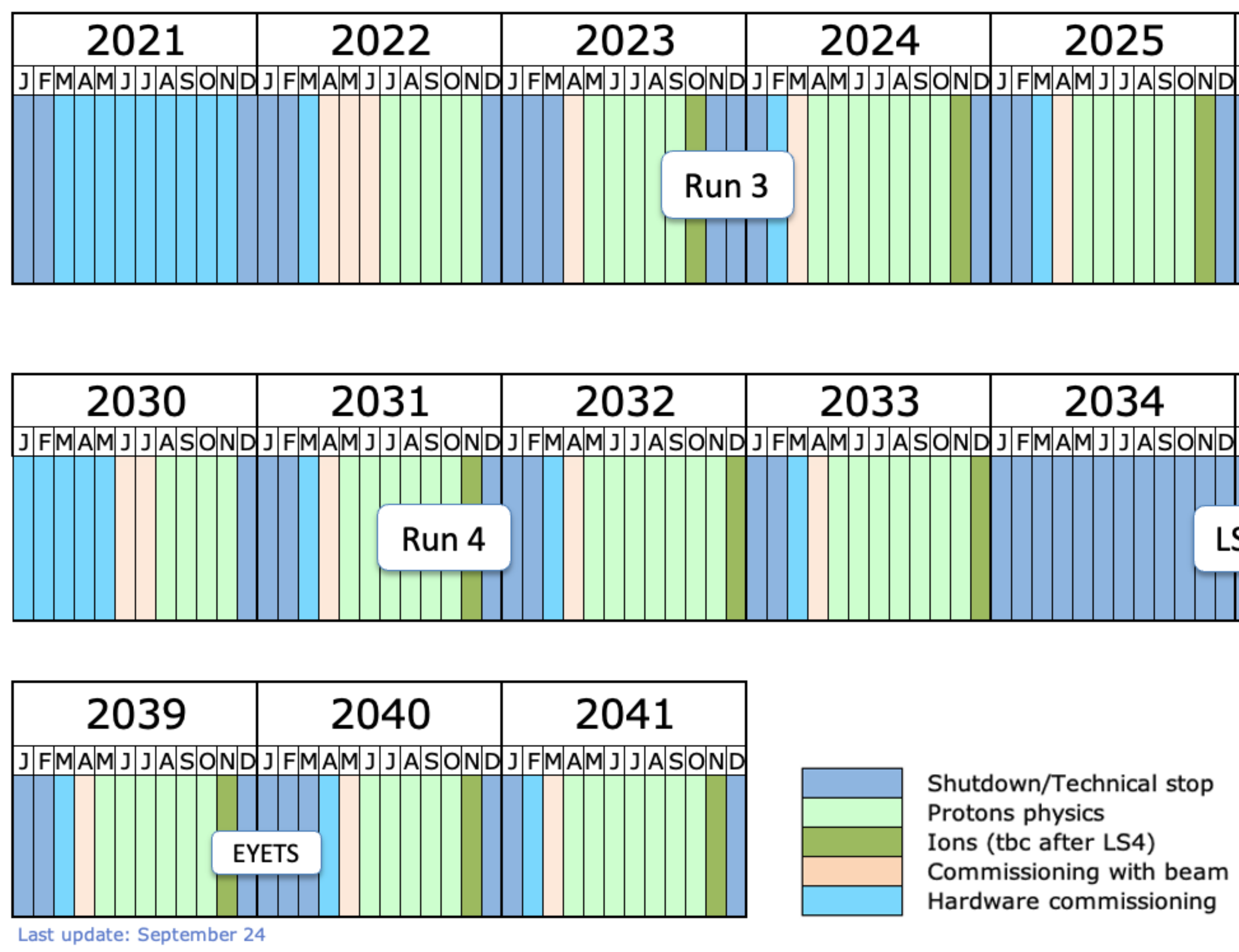
N. Neri

The European Strategy Update

- The main point of the strategy update is what to do after LHC. People often expresses concerns over the long lead times to the next collider
- In the next 20 years we still have to build and exploit HL-LHC though
  - Building the collider and the detector is still a very challenging task
  - The increase in luminosity and the detector upgrades result in a dramatic leap in physics potential from LHC to HL-LHC
- It would be good to re-affirm the exploitation of HL-LHC as a priority

European Strategy 2020 : "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, … should be exploited"

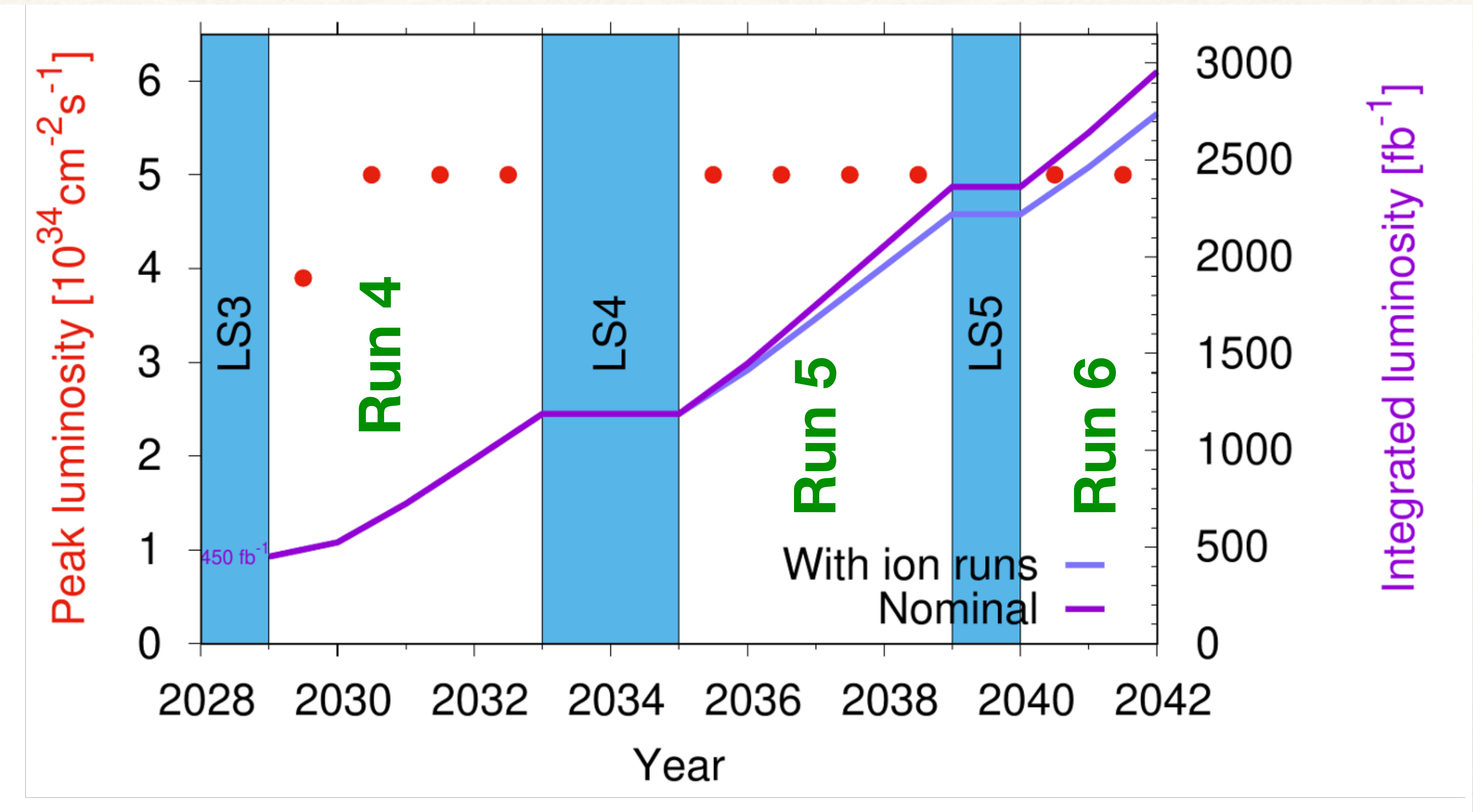
LHC new schedule



- Shift of LS4
- LS5 to EYETS

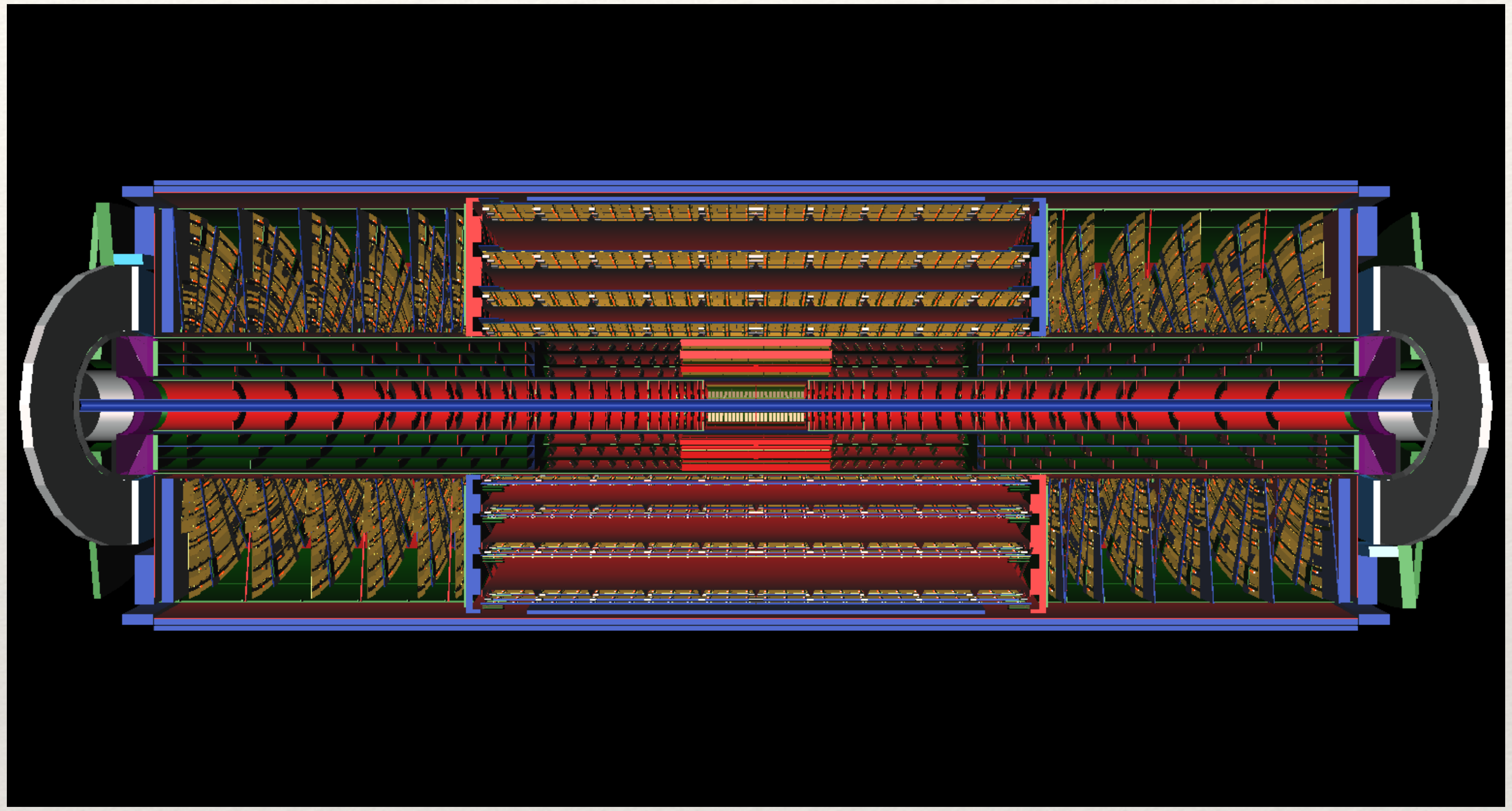
ATLAS data

	Int. lum. (fb^{-1})	comments
Run 1	25	
Run 2	140	**Most papers still based on run1 or run 2, 3-5% of ultimate dataset**
Run 3	400	125 fb^{-1} delivered in 2024 alone
Run 4	700	phase-2 upgrade
Run 5	2000	



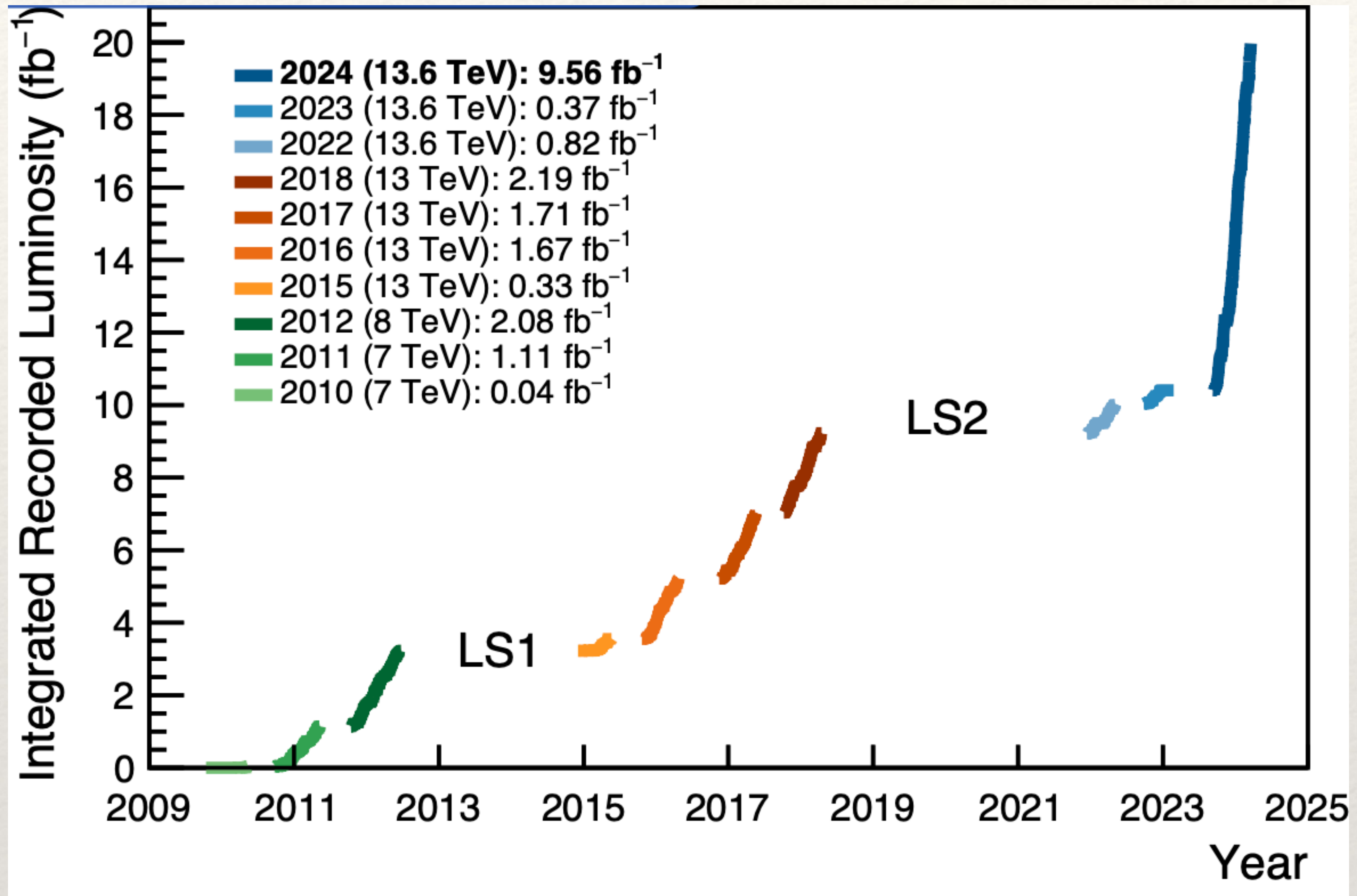
ATLAS upgrades for HL

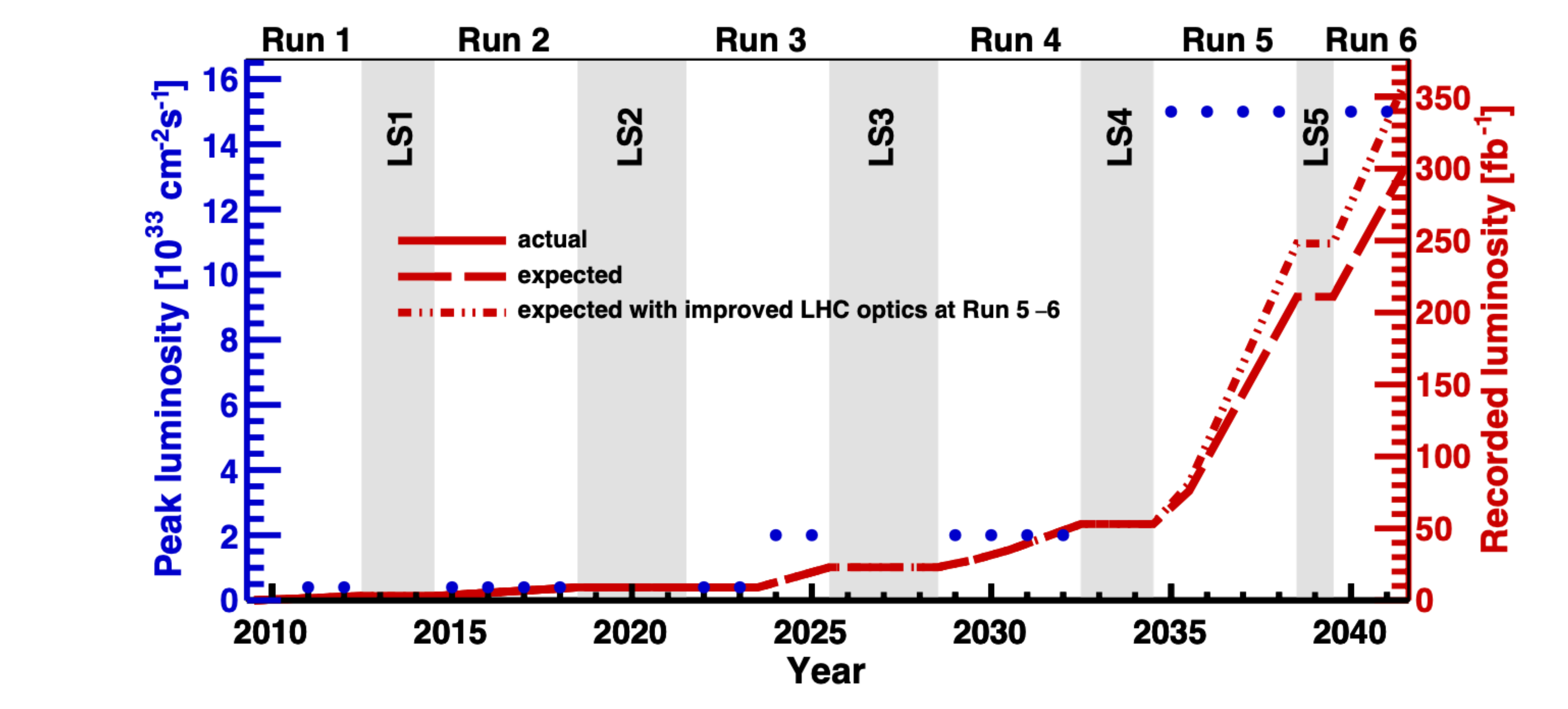
- **New all-silicon tracker.** Milano contributing to pixel module assembly and cooling.
- **Calorimeter electronics.** Milano contributing to power supplies and mezzanines
- Muon additional detectors and new electronics
- New timing detector for pileup vertices identification
- TDAQ with 10x rate both at first and 2nd level trigger
- Similar or better performances despite 3x pileup



Entering production phase (next 3 years), followed by installation and commissioning

LHCb data





Original LHCb	Run 1-2	9 fb^{-1} acquired
Upgrade I	Run 3-4	50 fb^{-1} expected
Upgrade II (in discussion)	Run 5-6	≥300 fb^{-1} expected

$\sim 10^{14} b$ ($> 10^{15} c$) with 300 fb^{-1}

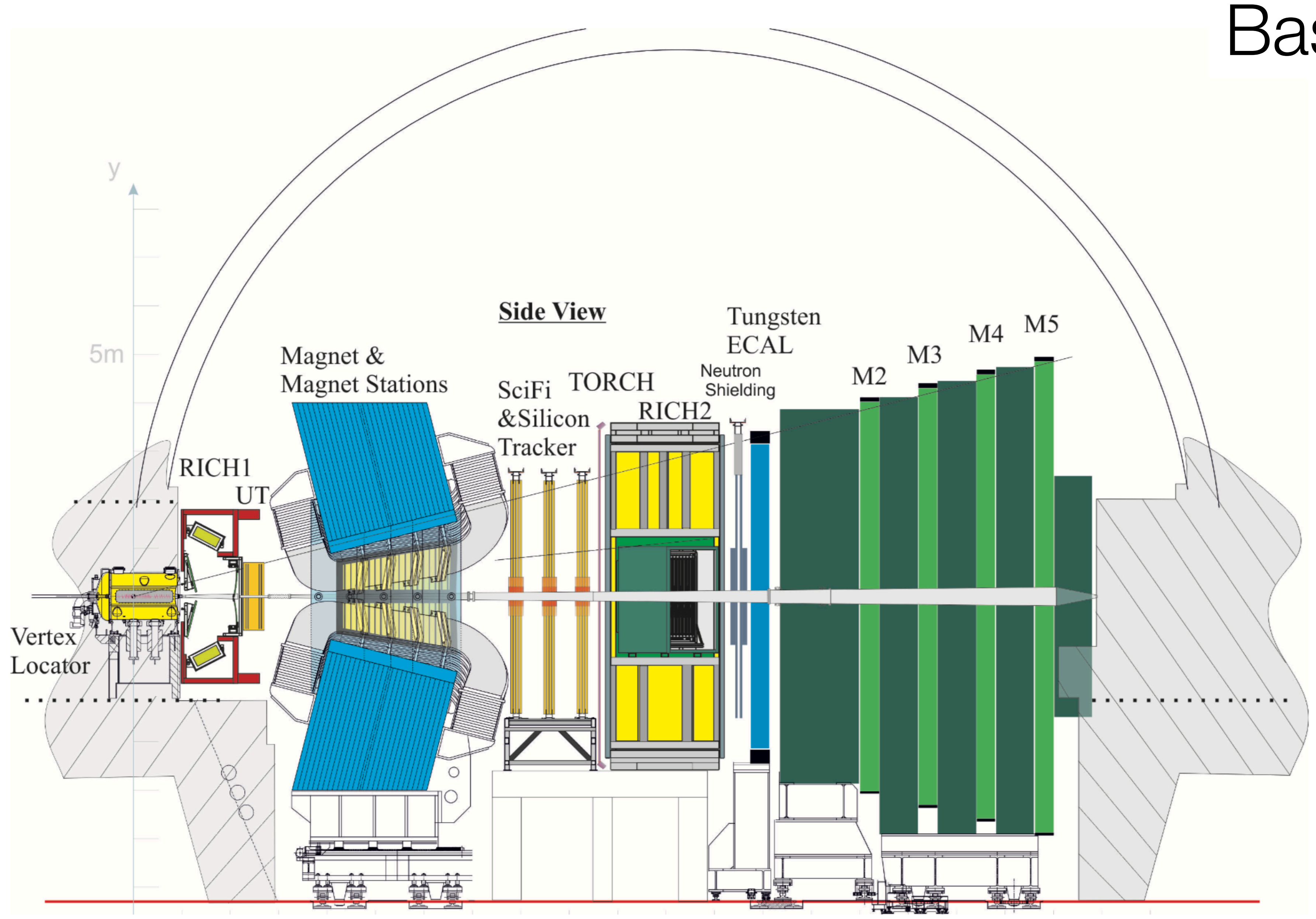
LHCC-2017-003, expression of interest

LHCC-2018-027, physics case

LHCC-2021-012, framework TDR

Upgrade II scoping document in review by LHCC, to be approved in 2025

LHCb upgrades



Baseline design: luminosity 1.5×10^{34} cm^{-2}s^{-1} about a factor 7 wrt Run3

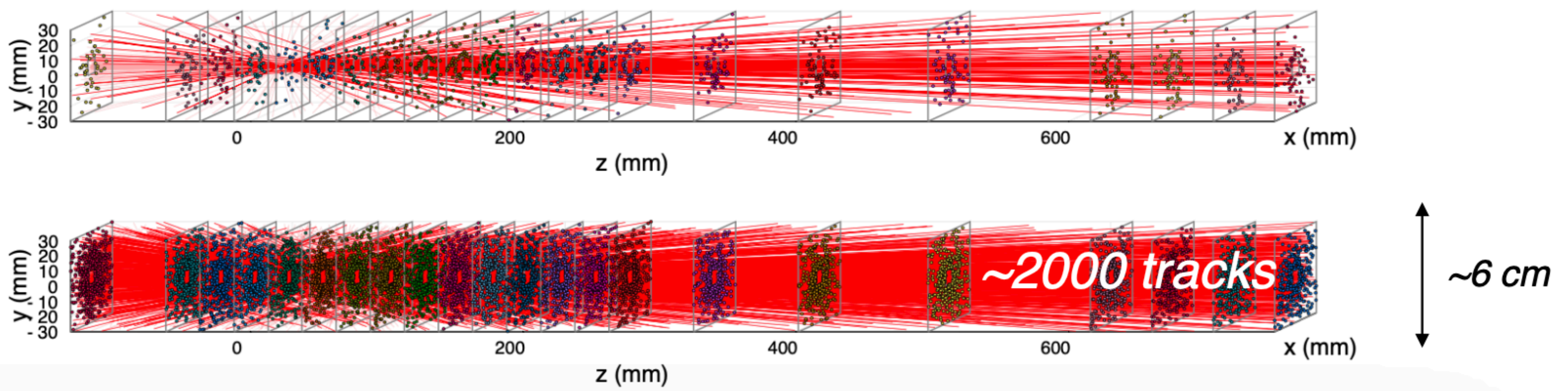
Key ingredients:

- high granularity
- fast timing (<50 ps)
- radiation hardness (> 10^{16} n_{eq}/cm^2)
- data throughput (>200 Tb/s)

VErtex LOcator (VELO)

Run 3: pile-up ~6

Upgrade II: pile-up ~40



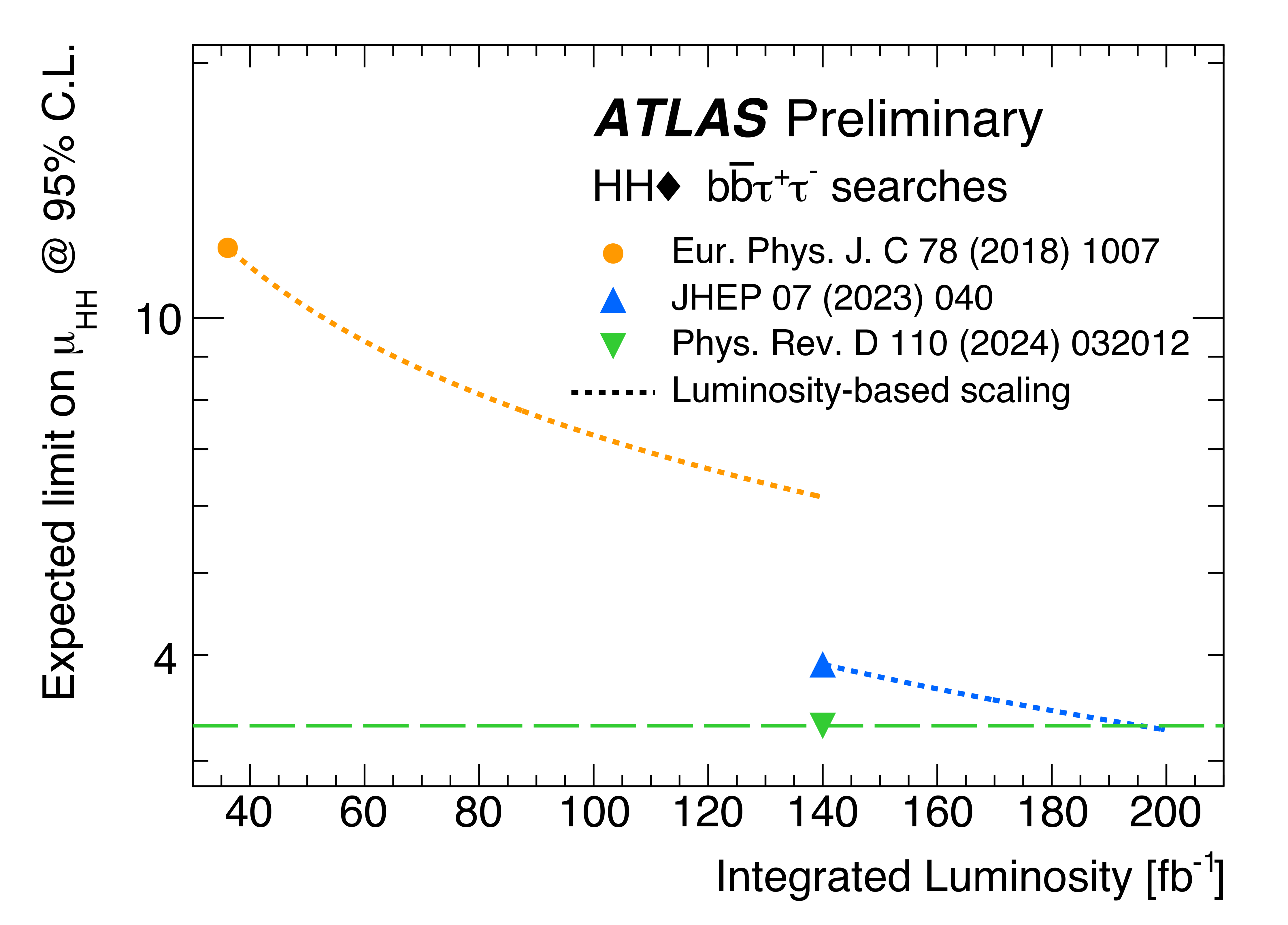
ATLAS HL physics

- Precision measurements to test the SM and hopefully find deviations.
  - Higgs particularly interesting (properties, couplings, HH) but also EWK $\sin^2$theta, top physics, W mass, B physics
- Searches for new particles, improve both mass and coupling reach

ATLAS HL physics : projections vs reality

- Projections are based on simple extrapolation of current analysis or simple analysis of HL simulated data. People are too busy to make sophisticate analyses on HL simulations
- As a results, projections are very conservative - better results can be expected

date of estimate	bbττ sensitivity for 3000 fb^{-1}	reference
2019	2.1σ	CERN-2019-007
2022	2.8σ	ATL-PHYS-PUB-2022-053
2024	3.8σ	ATL-PHYS-PUB-2024-016



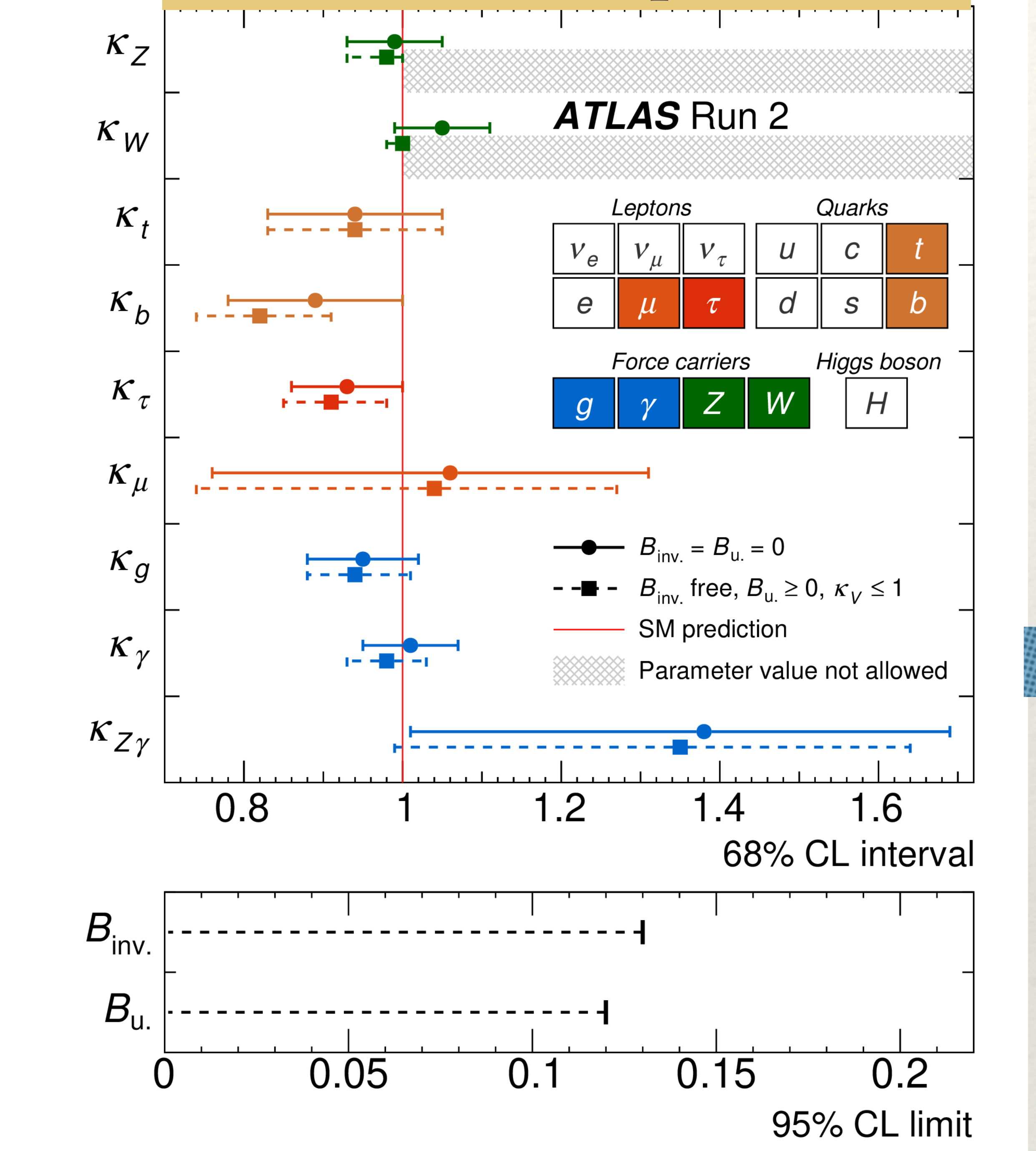
ATL-PHYS-PUB-2024-016

ATLAS HL physics : Higgs couplings

HL-LHC still competitive with FCC-ee for several couplings (tt not shown in plot, $\gamma\gamma$, gg, bb, $\tau\tau$, $\mu\mu$)

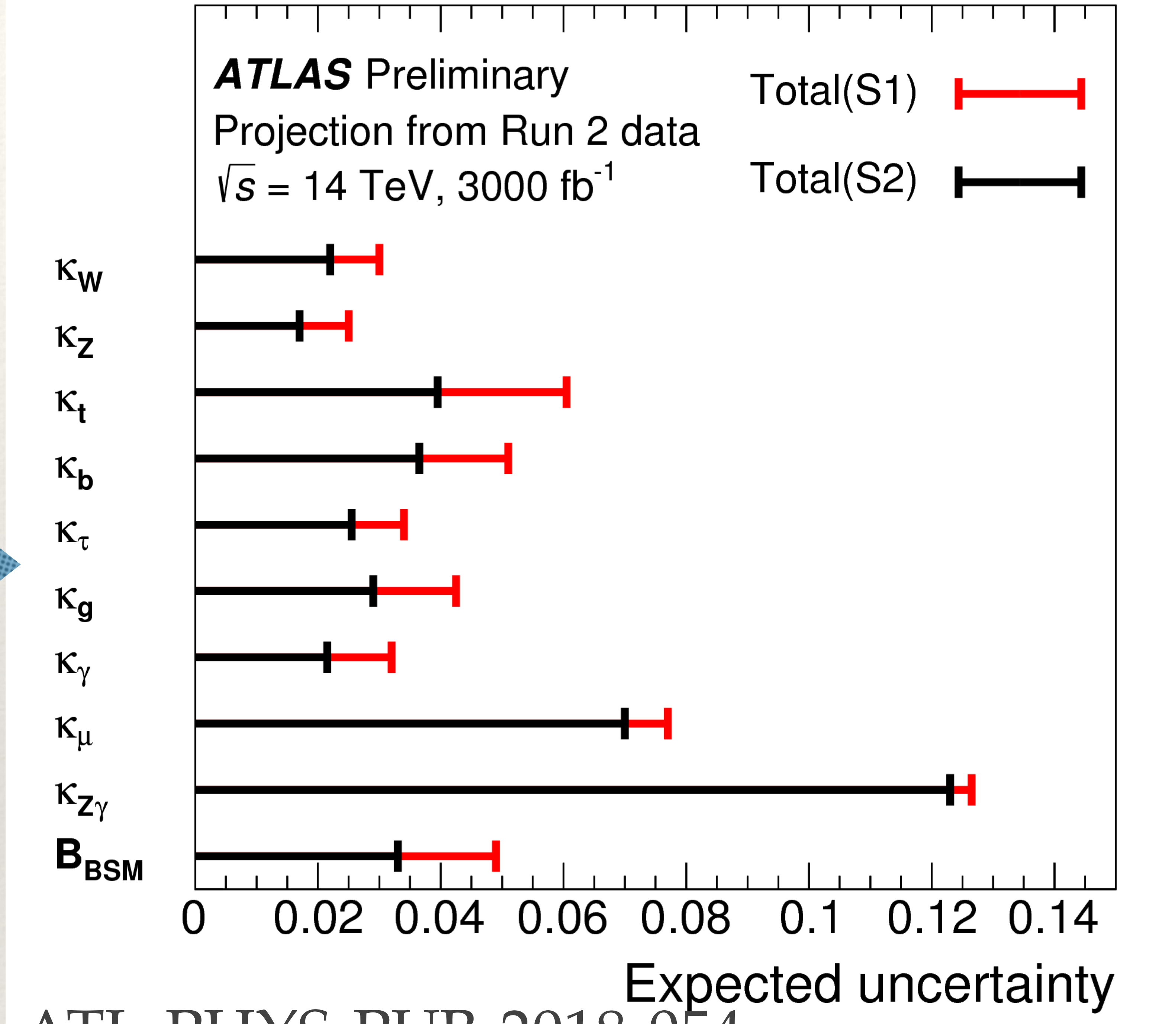
Also complementary and unique sensitivity in differential cross sections, probing heavy particles in loops at high p_T

current (6-10% precision)

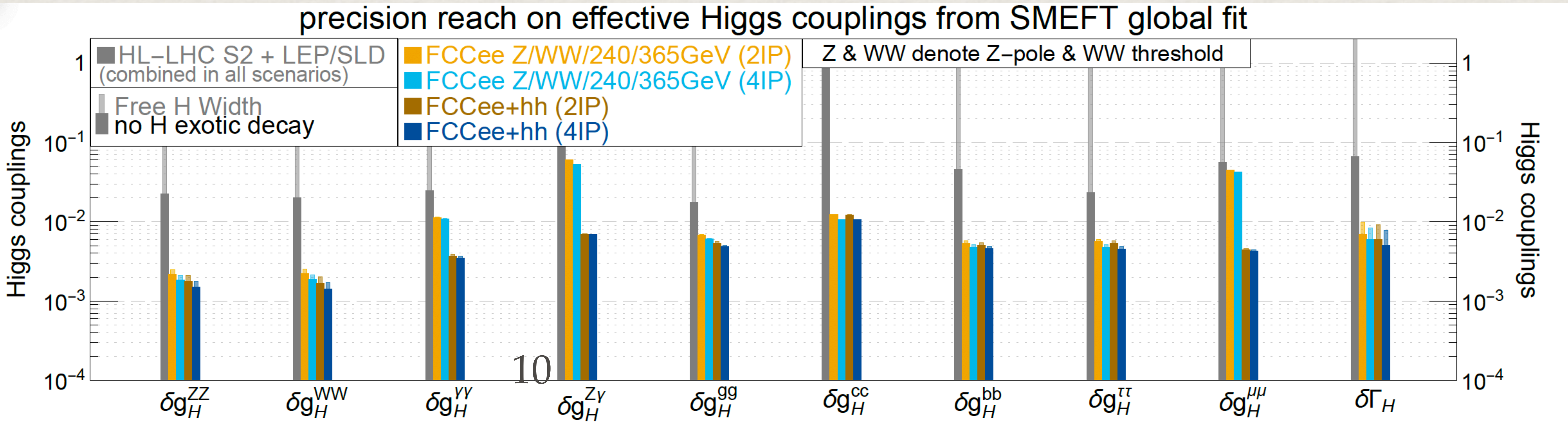


arXiv:2404.05498

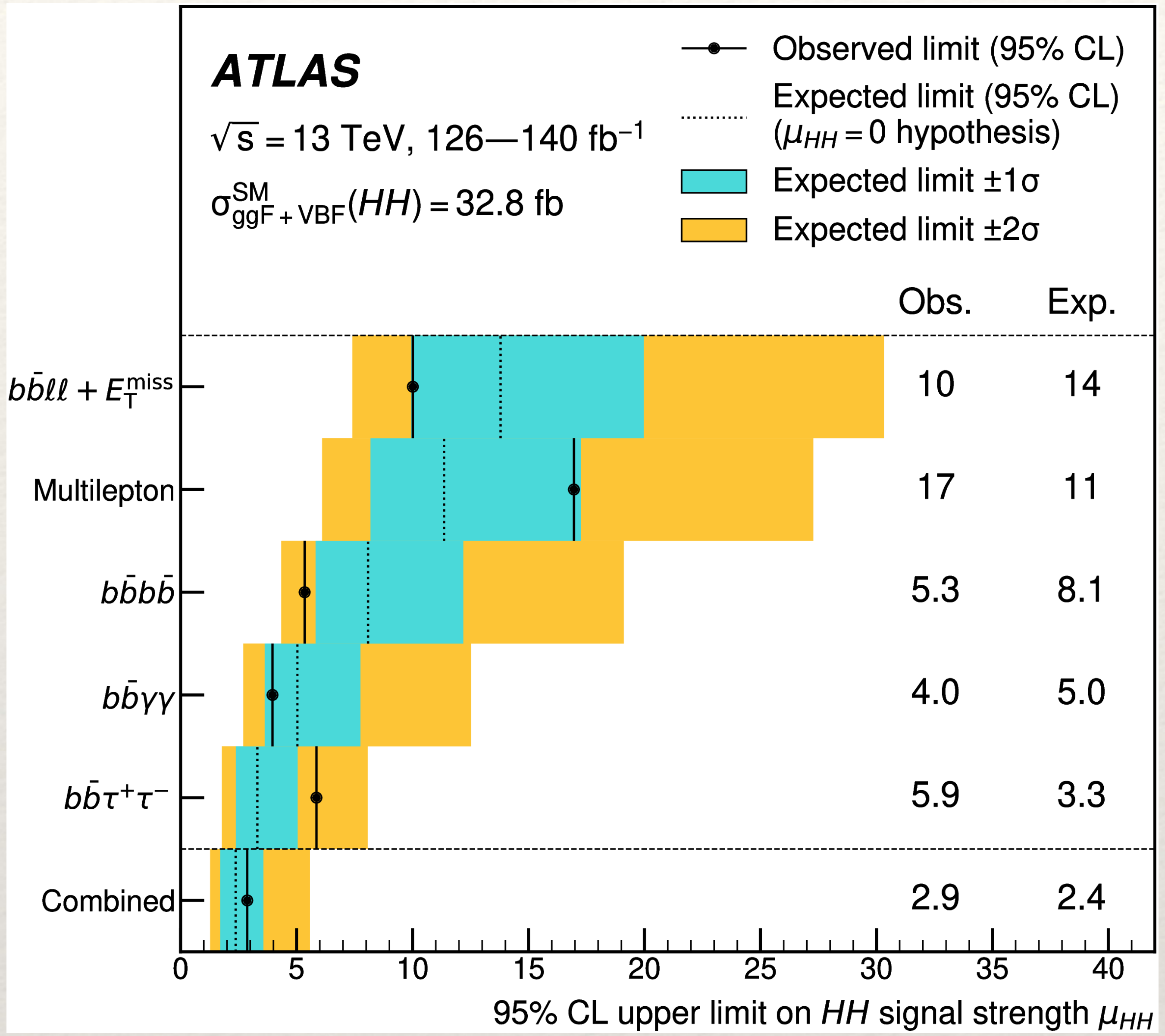
HL projections (2-4% precision)



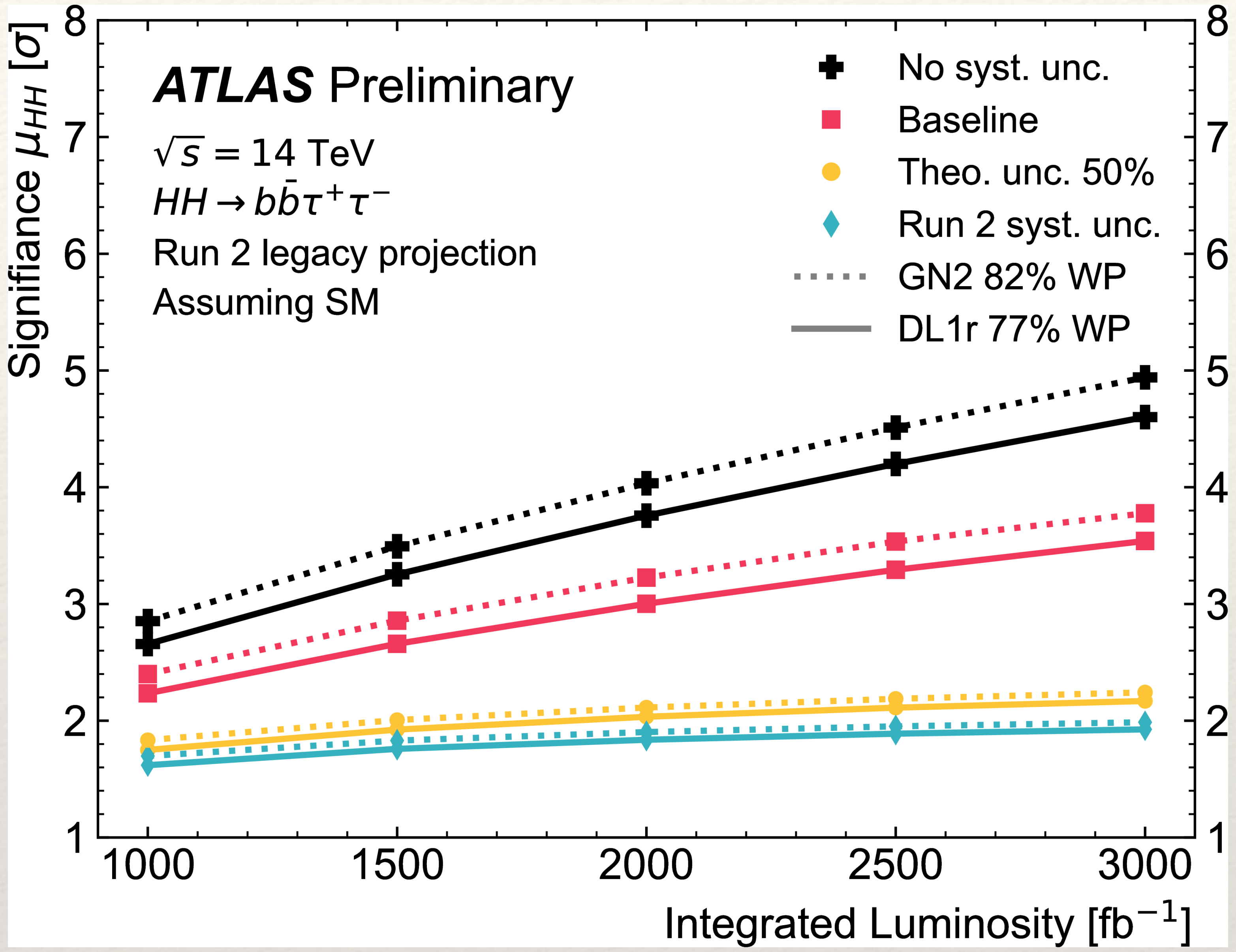
ATL-PHYS-PUB-2018-054



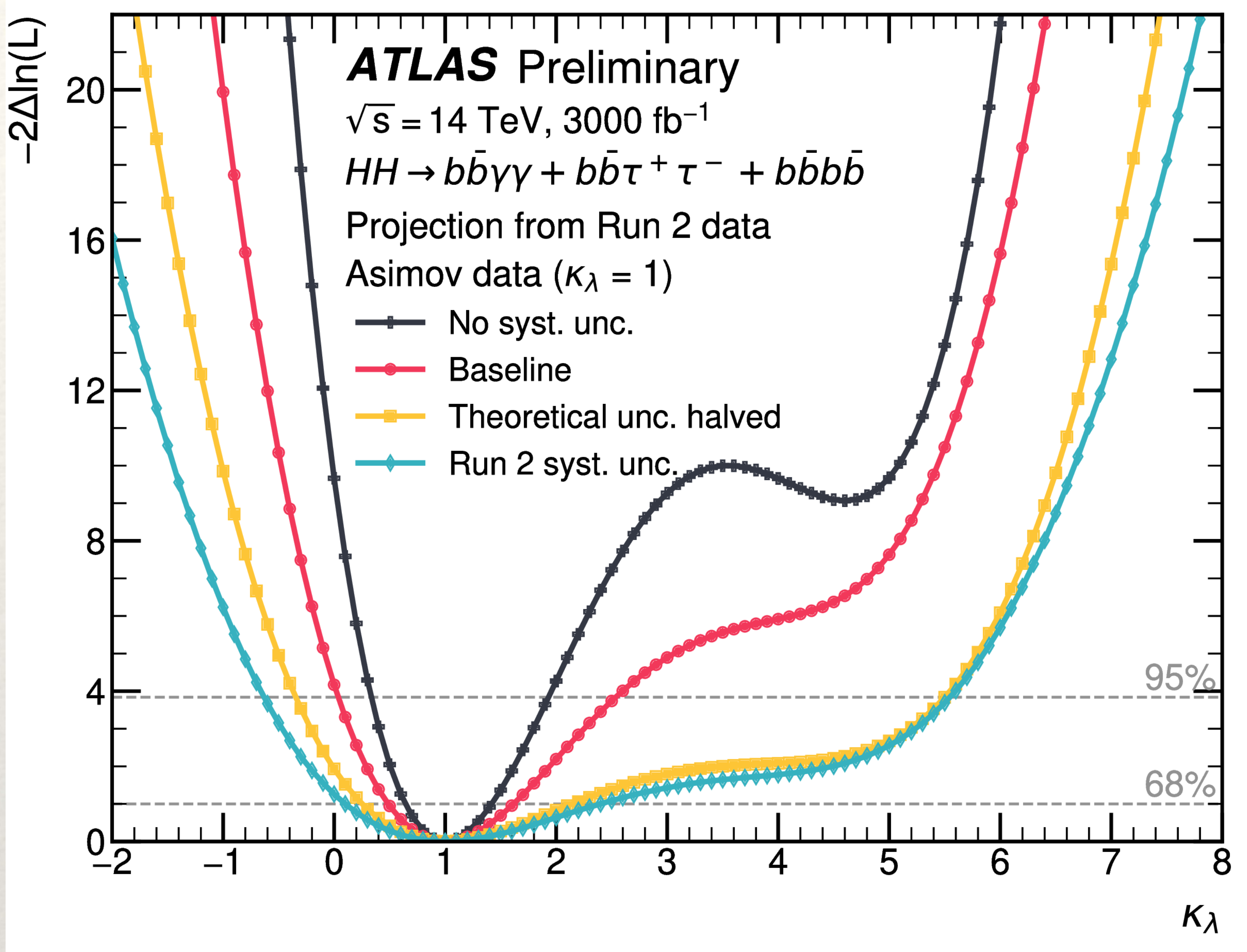
ATLAS HL physics : HH



PRL 133, 101801



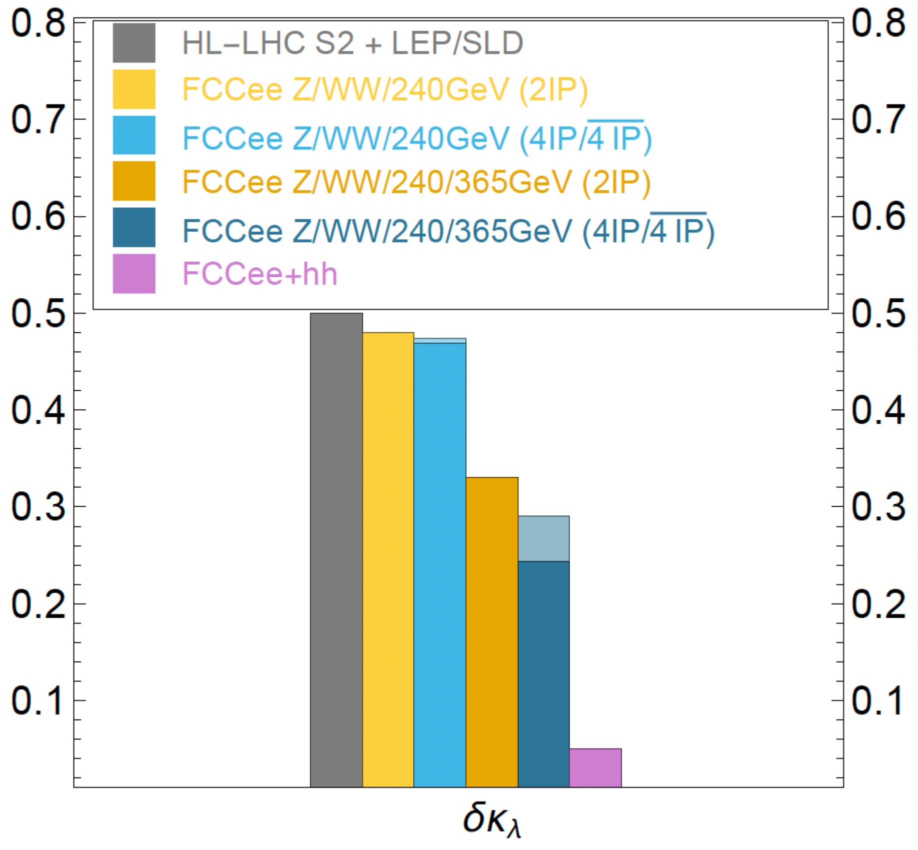
ATL-PHYS-PUB-2024-016



ATL-PHYS-PUB-2022-053

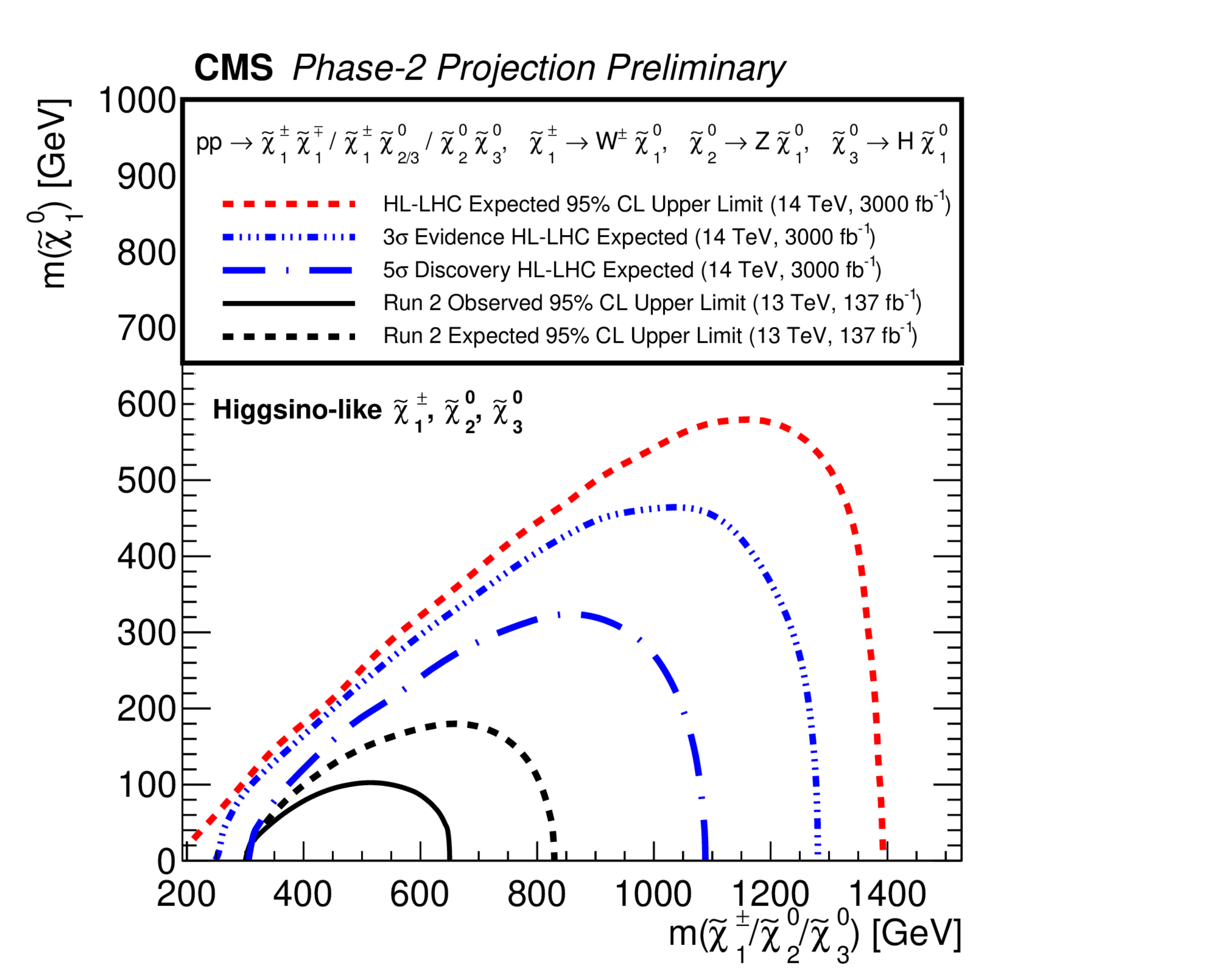
bbττ now better than the (older) channel combination, and further improvements are likely. Evidence with Run 2+3 data might be possible.

HL-LHC kλ measurement will be hard to improve at FCC-ee



ATLAS HL physics : new physics example

- HL-LHC will explore the 100 GeV - few TeV mass range, looking for new particles predicted by a variety of new physics models
- FCC-ee will improve LHC only for weakly coupled light particles.
- Good complementarity between FCC precision measurement and high mass direct searches



be learned, regardless of the outcome: theories beyond the SM will be very much constrained even with a null result from the precision measurements, and the day some new physics signal is eventually observed somewhere, these precision measurements – whether they agree or deviate from the SM – will be precious in establishing the nature of the signal.

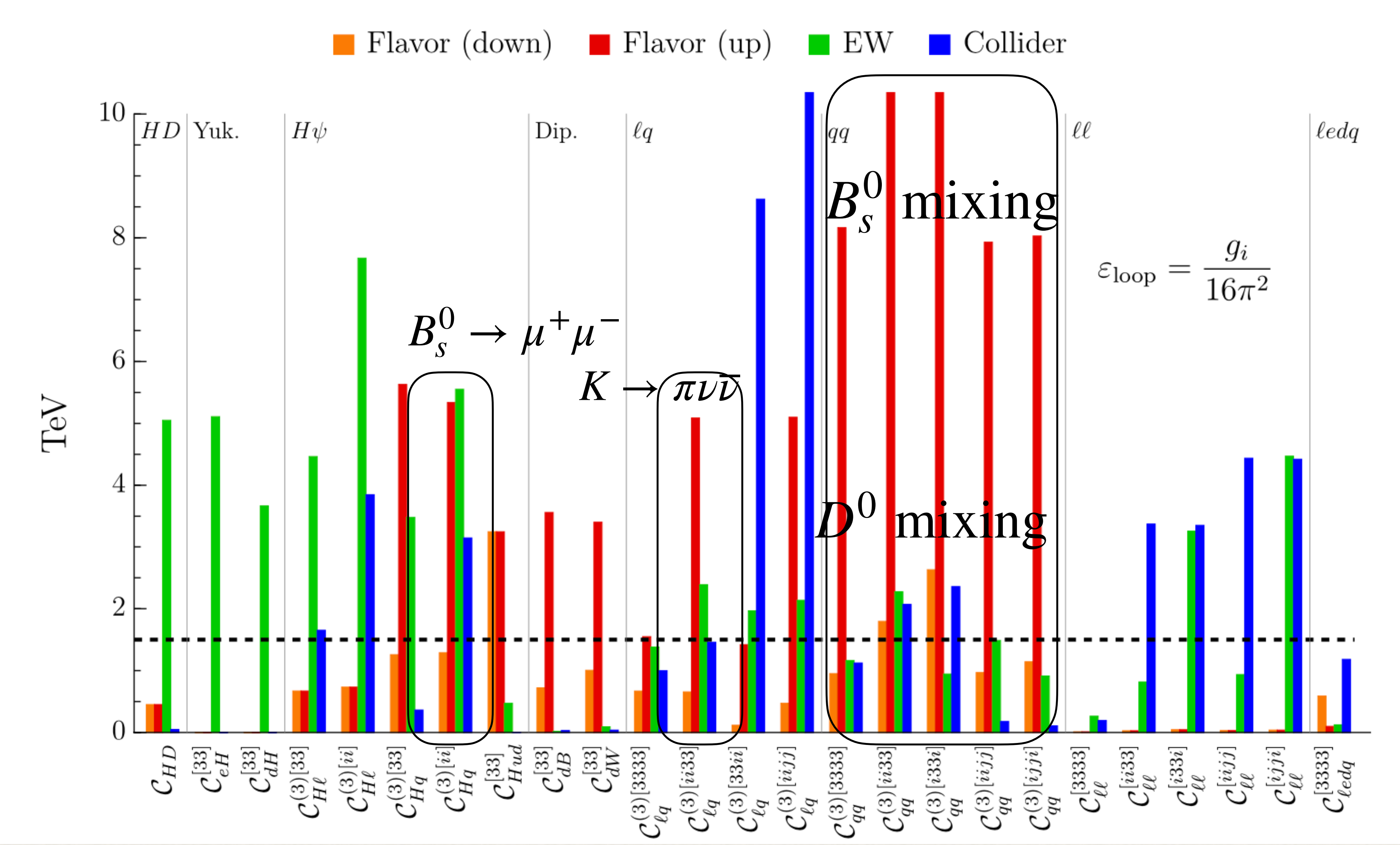
Flavor physics

identify symmetries and symmetry-breaking patterns beyond SM

indirect probe of new physics at energy scales not directly accessible at LHC

Energy range probed by flavour measurements at LHCb Upgrade II will double wrt pre-HL-LHC

Key ingredients for discoveries: high statistics, low systematic uncertainties, precise SM predictions



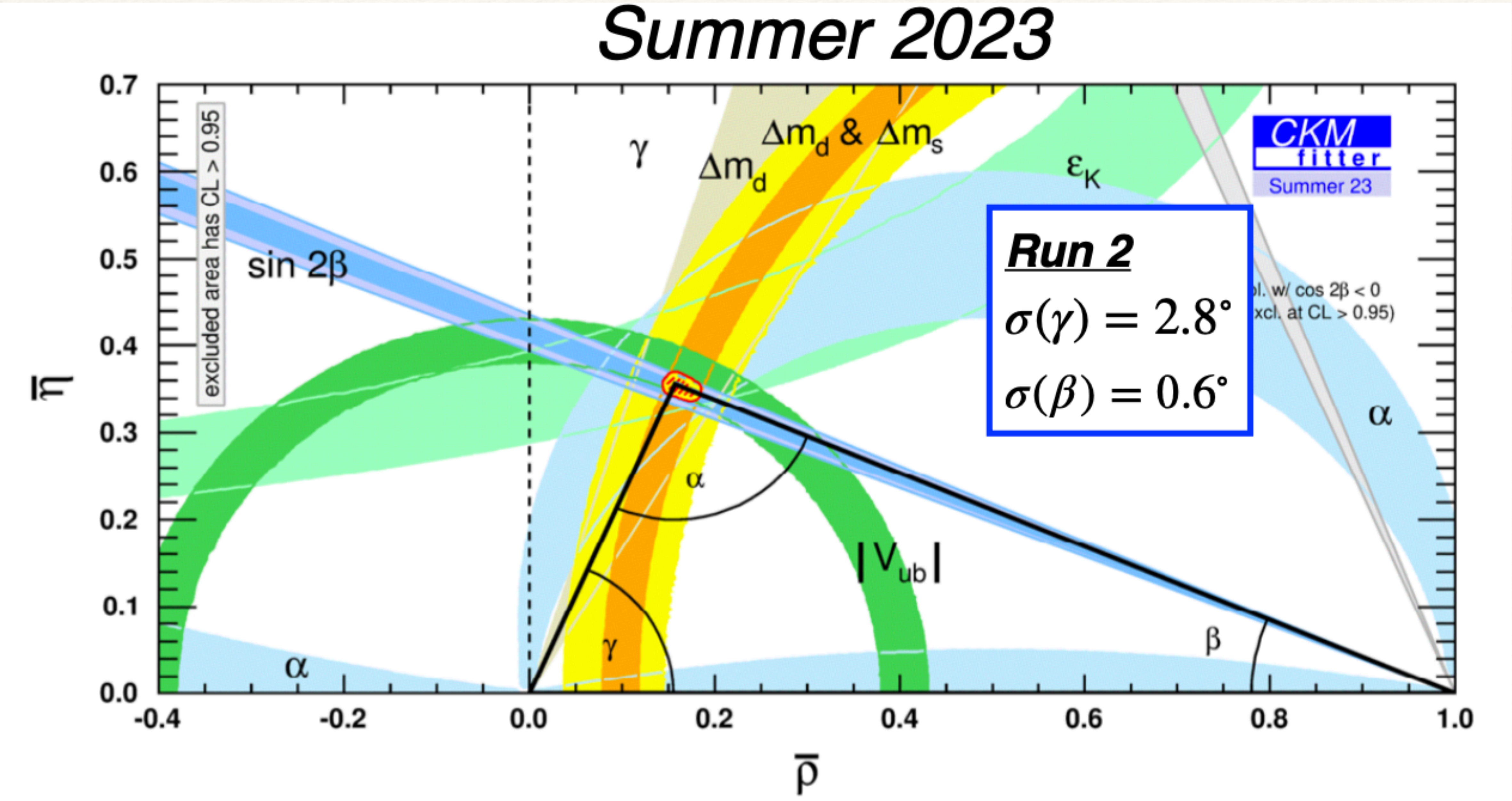
3rd gen. SMEF operators, arXiv:2311.00020

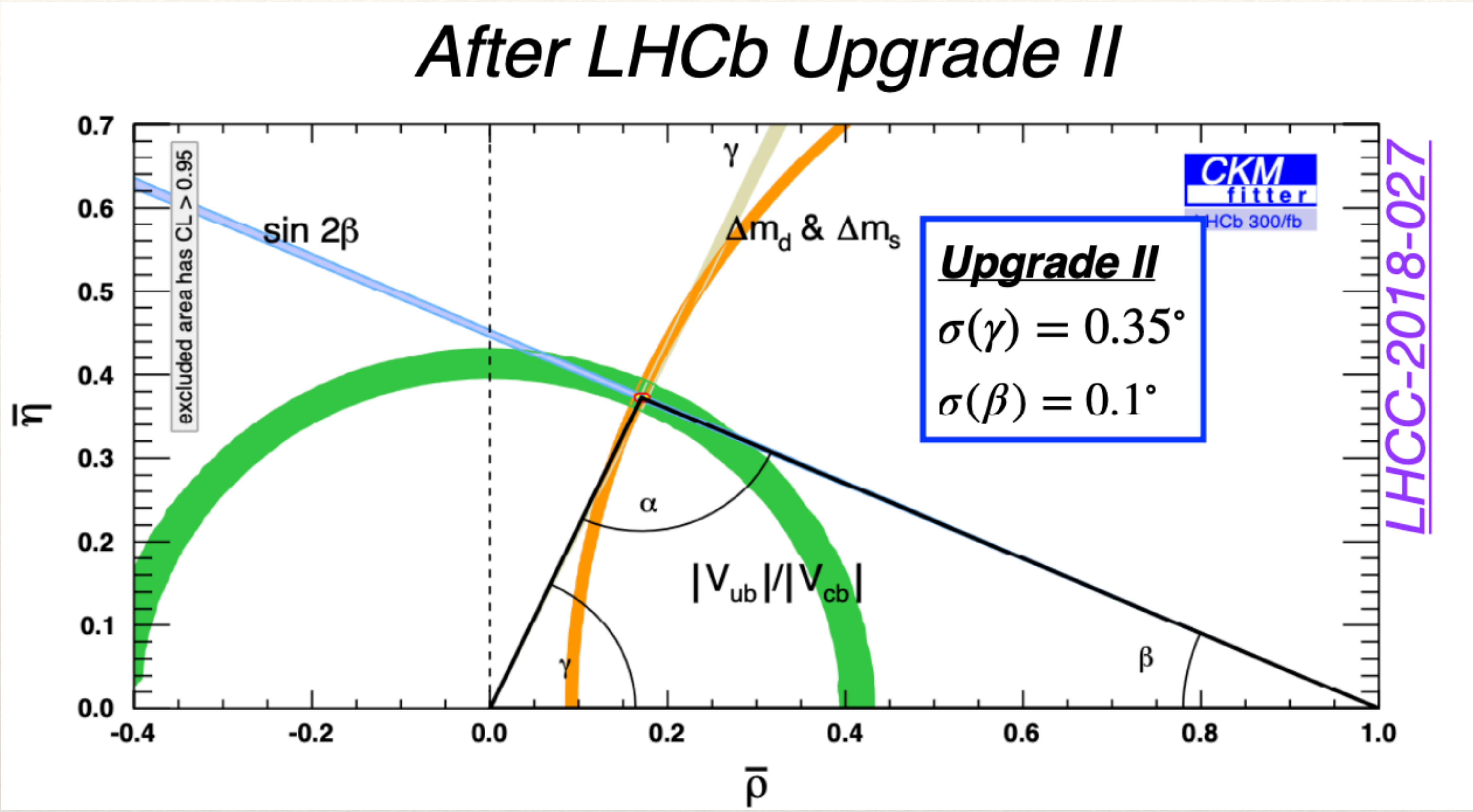
Flavor physics at upgrade II

- Perform ultimate test of CKM mechanism for **CP violation** in beauty and charm sector
- Constraints SM extension with RH currents in **rare decays**
- Unique discovery potential for understanding of **exotic hadrons**: tetra quarks, pentaquarks, …
- Forward physics: QCD, heavy ion, long-lived particle searches, fixed-target

Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)		Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	$2.8°$	[18, 19]	$1.3°$	$0.8°$	$0.3°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[25]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148	0.097	0.038

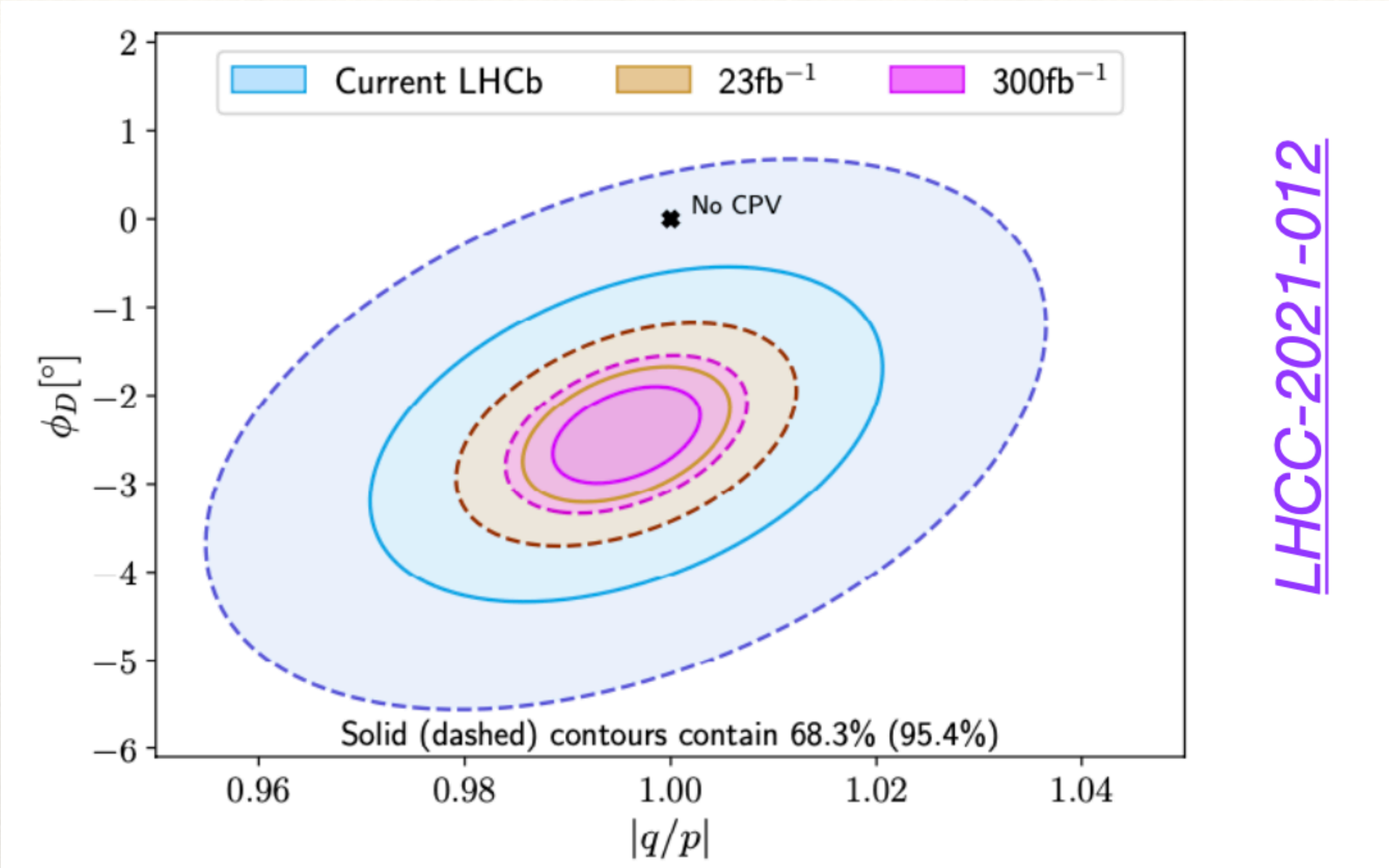
CP violation in B sector

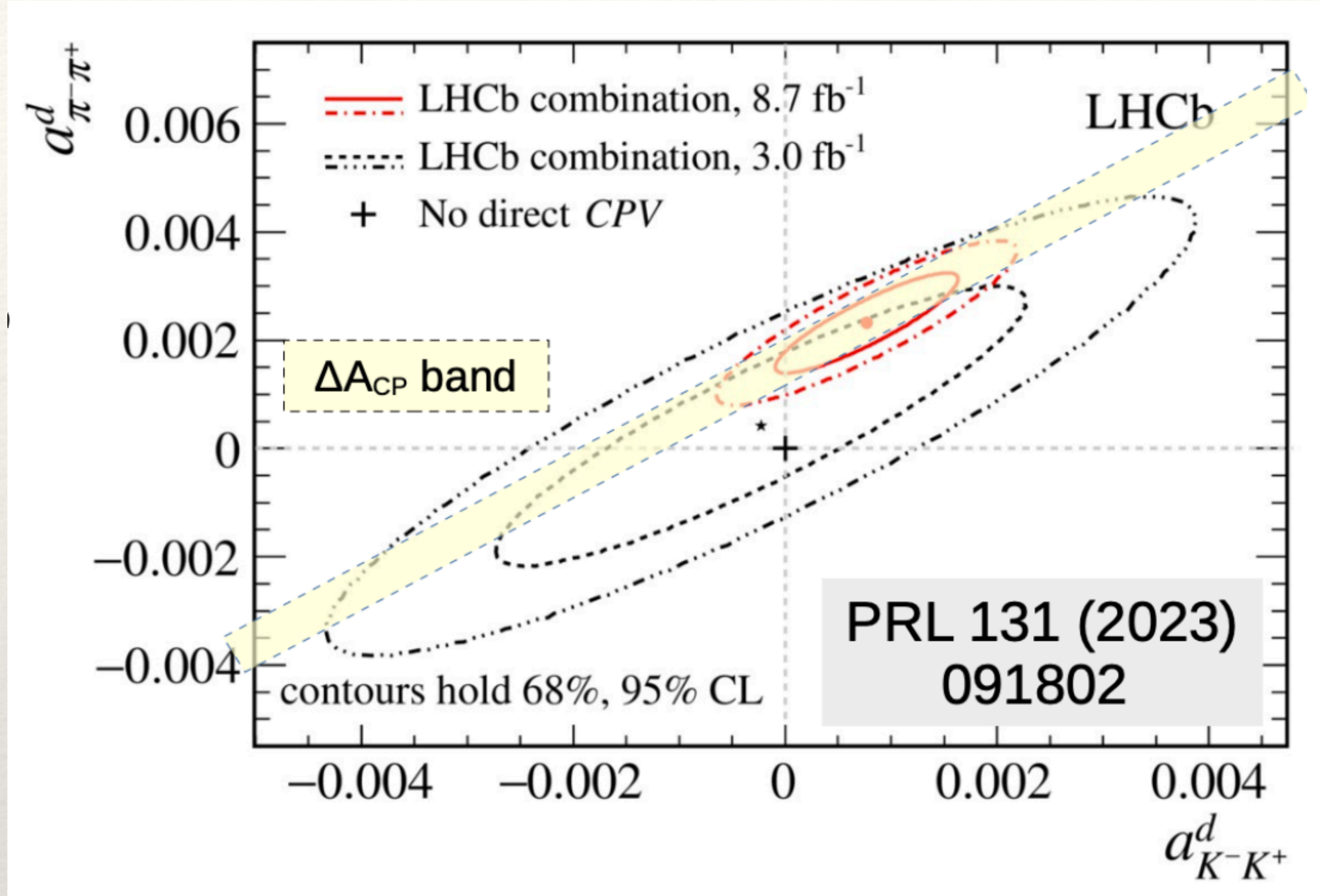




- Ultimate test of CKM mechanism for CP violation is possible with Upgrade II
- Theory clean measurements, not dominated by systematic uncertainties, will benefit of the larger data sample of Upgrade II

CP violation in D sector



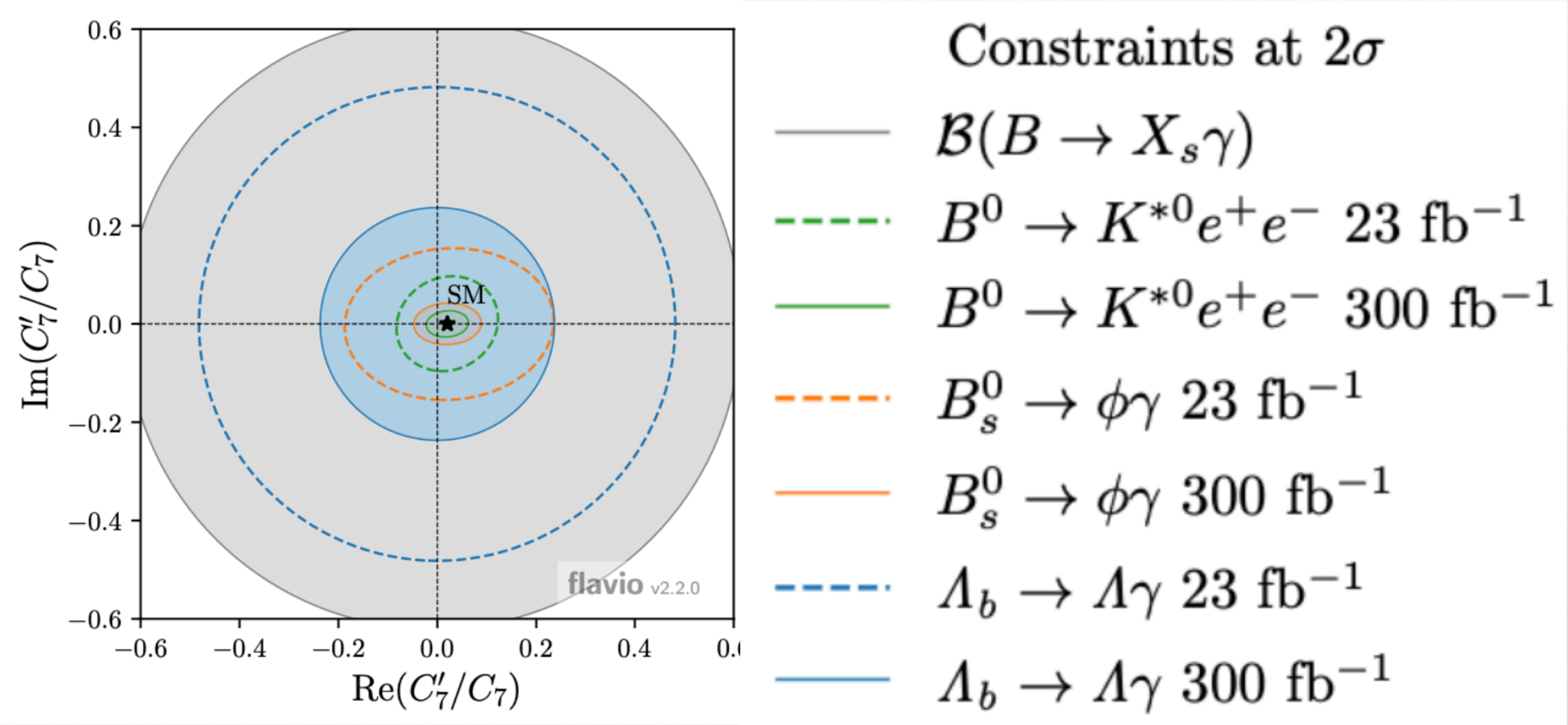


- CP violation in D^0 mixing, $q/p \neq 1, \phi \neq 0$ is a sensitive probe for new physics
- Null test for SM: mixing amplitudes are real and GIM or CKM suppressed

- Significant CP violation in D^0decays is observed. More measurements are needed to overconstraint theory parameters
- Sensitivity at 10^{-5} level at Upgrade II, which is needed to understand CP violation in charm

Search for new symmetry violations in rare decays

- Symmetry breaking of SM weak interaction with V-A structure
- Search for right-handed (RH) currents in rare decays



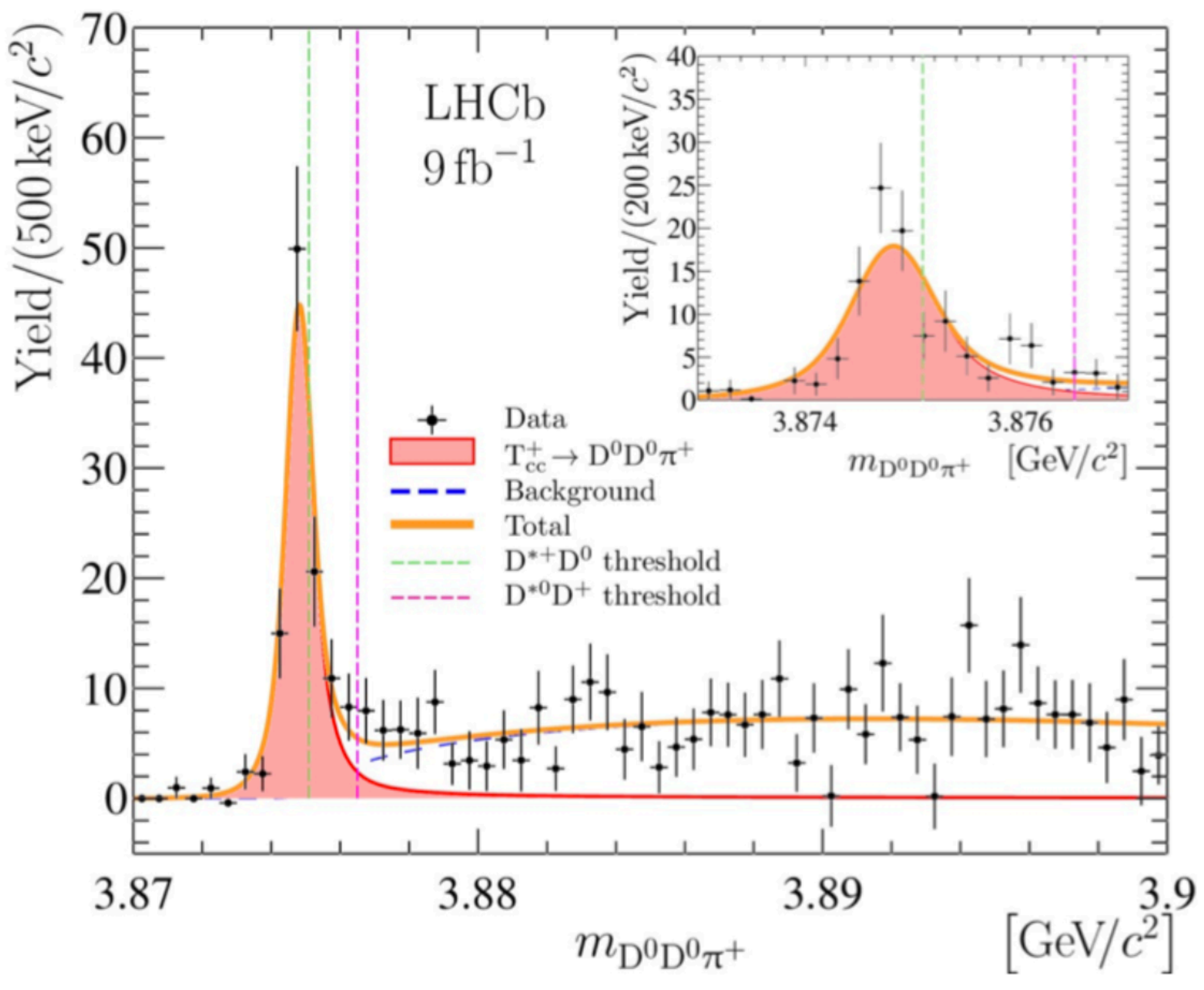
Unique, high precise probes for RH currents

- $B^0 \to K^{*0}e^+e^-$ angular distribution
- $B_s^0 \to \phi\gamma$ decay-time distribution
- $\Lambda_b^0 \to \Lambda\gamma$ polarisation

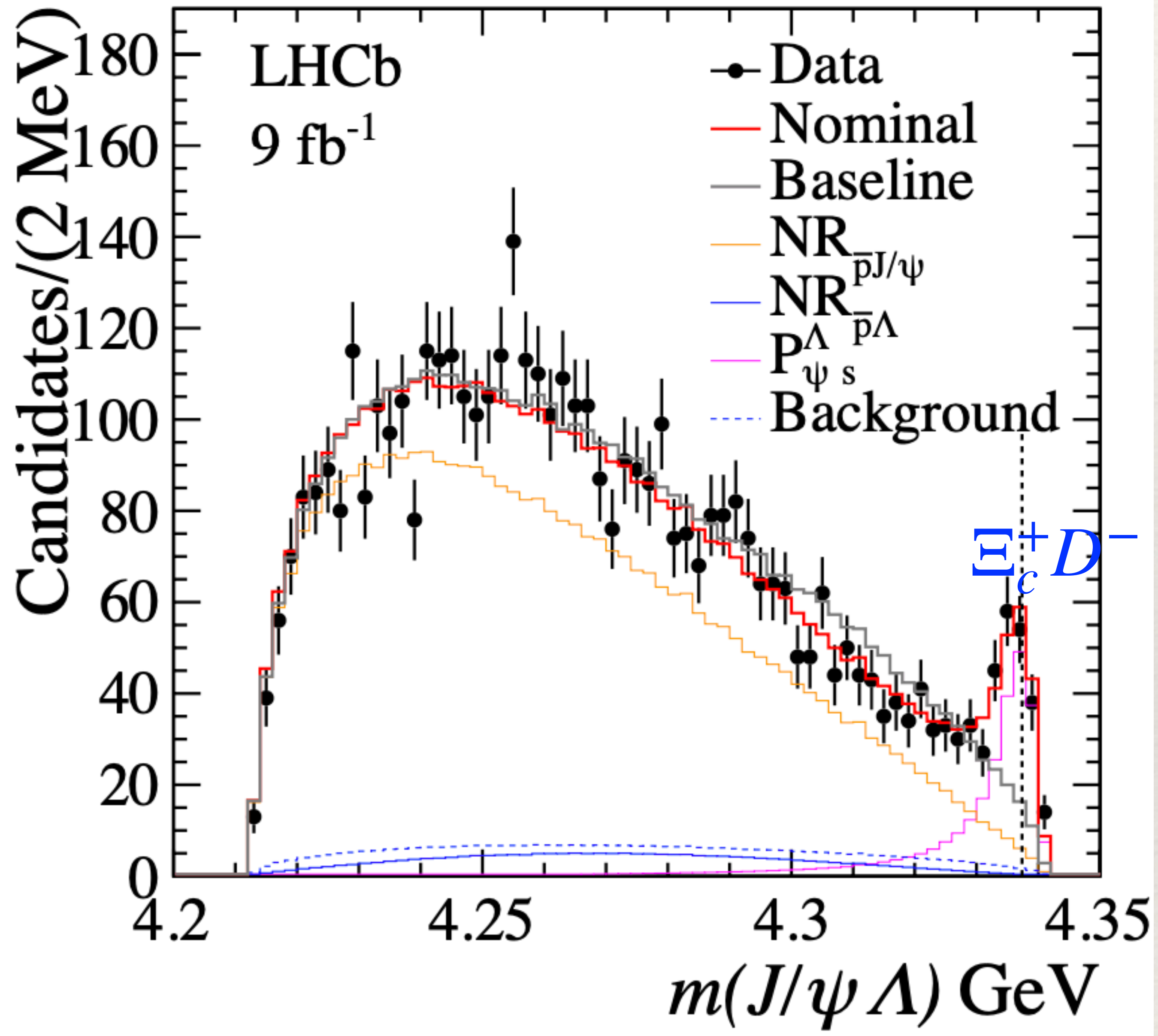
Spectroscopy of "exotics" hadrons

- Discoveries of several tetraquarks and pentaquarks at LHCb
  - T_{cc} tetraquark opens the possibility to search for T_{bc}, T_{bb} states
  - $J/\psi p = [c\bar{c}uud]$ and $J/\psi\Lambda = [c\bar{c}uds]$ resonances can be studied systematically to understand their nature
- LHCb Upgrade II is the only experiment that can perform this kind of physics

Nature Physics 18 (2022) 751 &
Nature Comm. 13 (2022) 3351



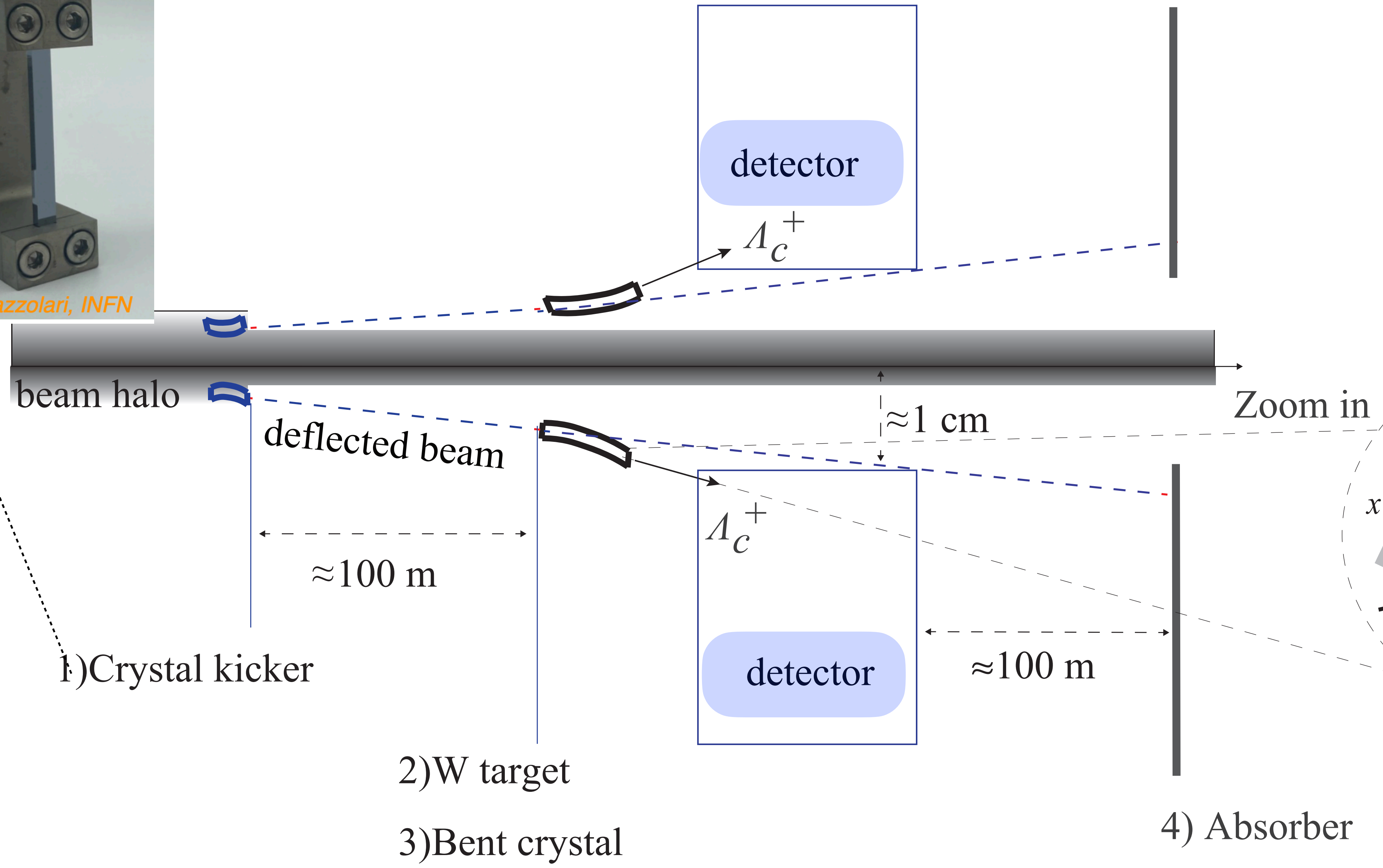
Phys.Rev.Lett. 131 (2023) 3, 031901

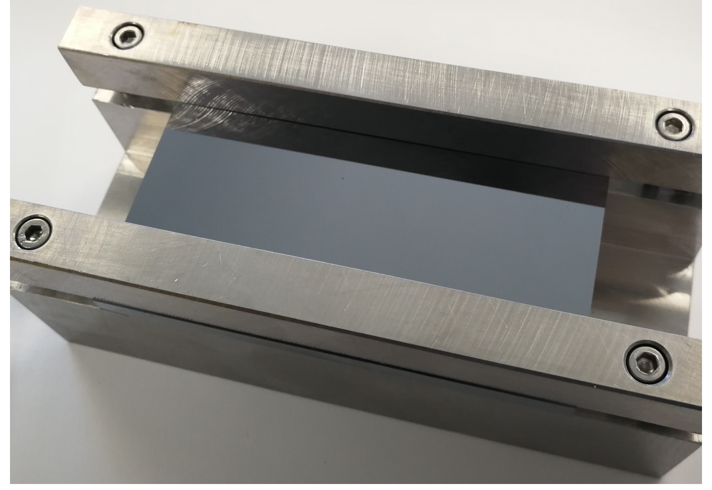


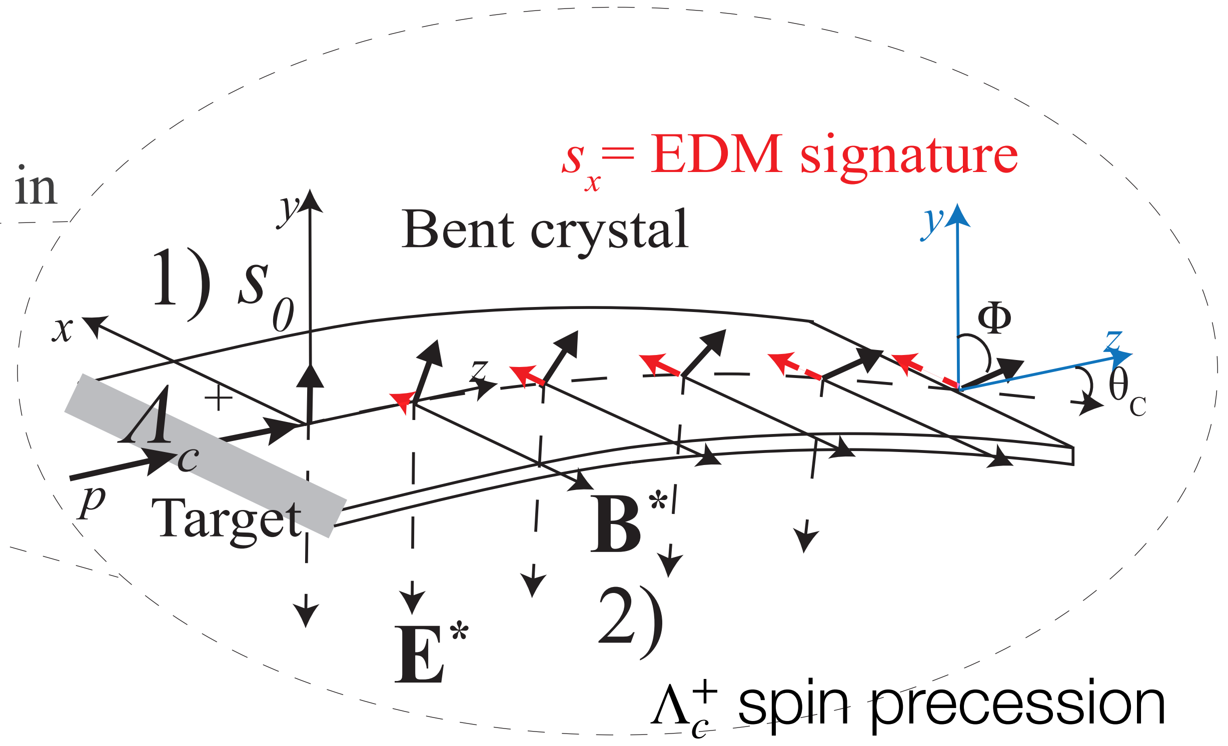
- **ALADDIN** experiment for direct measurement of dipole moments of charm baryons at LHC. LoI document on CDS link CERN-LHCC-2024-011; LHCC-I-041. [Idea to explore τ lepton]

- Expected precision $4\,\%$ on Λ_c^+, Ξ_c^+ MDM (EDM at $3 \cdot 10^{-16} e$ cm) with $1.4 \cdot 10^{13}$ PoT (2 years). Exploit particle channeling and spin precession in bent crystals

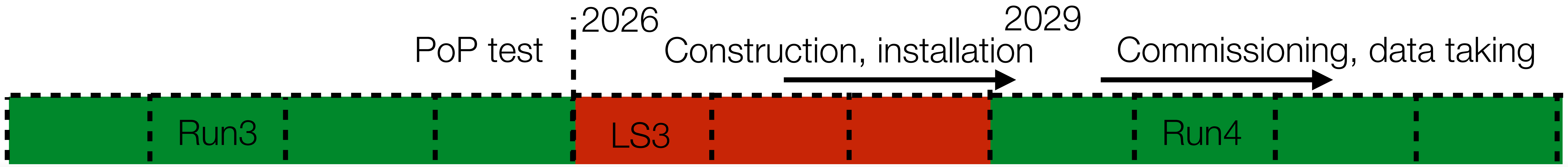
- Proof-of-Principle (PoP) test in 2025 (TWOCRYST project, installation in next YETS) approved by the LMC 467 link. Demonstration of achievable PoT







- Reuse of existing hardware: Roman Pot (RP) stations, warm magnet corrector for spectrometer, collimators. Machine layout designed and simulated. No civil engineering needed



Conclusions

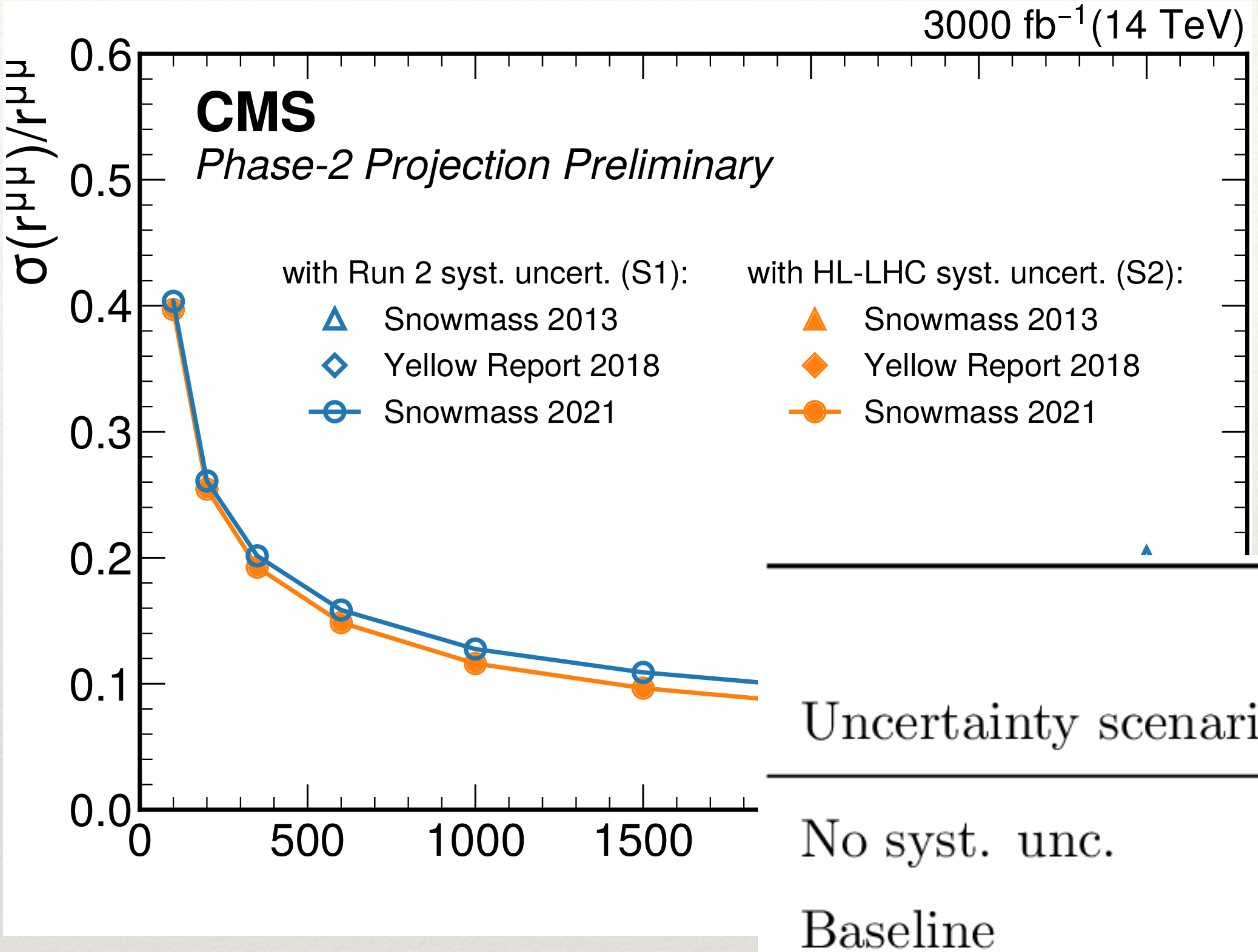
- HL-LHC data have a huge physics potential
- This is "known" and appears in the previous European Strategy and P5 outcomes, but it would be good to raise the point again, in case the Council might consider shortening the HL data taking to free funds for FCC

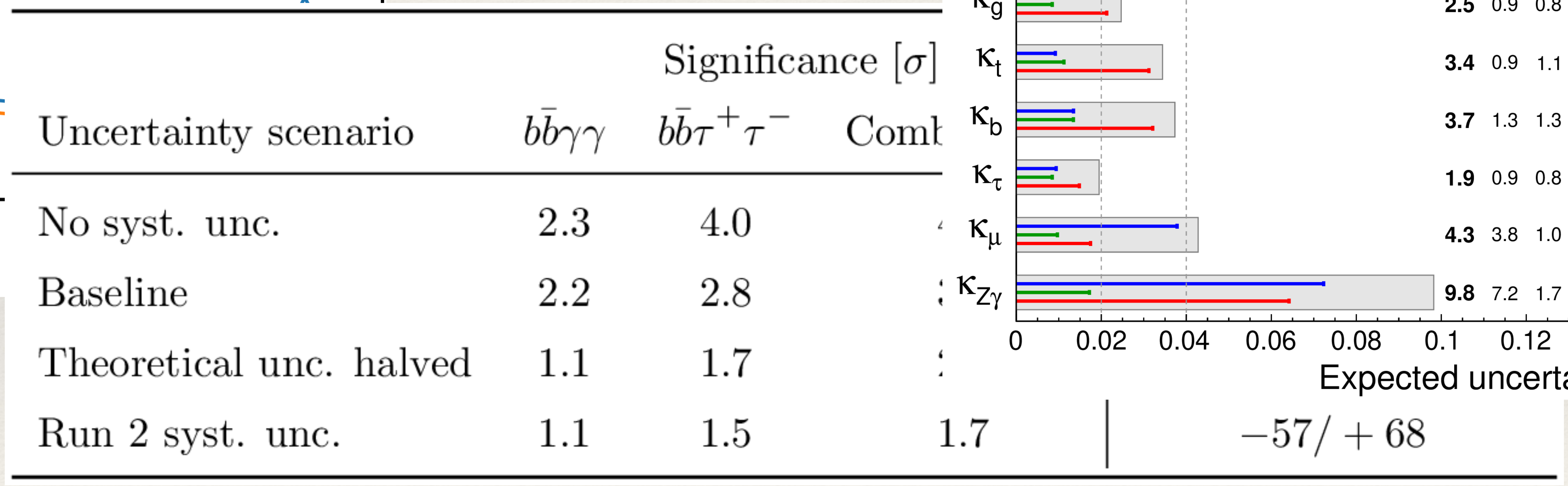
Bonus : accelerator costs

cost item	MCHF	reference / comments
LHC construction	4330	https://home.cern/resources/faqs/facts-and-figures-about-lhc
detector construction	1500	https://home.cern/resources/faqs/facts-and-figures-about-lhc
LHC operation (2009-2026)	4200	Assuming 300 MCHF/year as quoted in "fact and figures"
detector operation (2009-2026)	1200	20 MCHF/year for ATLAS and CMS M&O; assuming LHCb is the same
Total LHC	**11200**	Not including personnel and computing
detector upgrades	700	going by memory, but should be ok
HL-LHC operation (2030-2041)	3000	Assuming still 300 MCHF/year (probably a bit low)
detector operation (2027-2041)	900	Assuming 60 MCHF/year
Total HL-LHC	**4600**	Not including personnel and computing
FCC cost (construction+operation)	**21700**	Revised CDS cost from socio-economic cost-benefit analysis (wo detectors?)

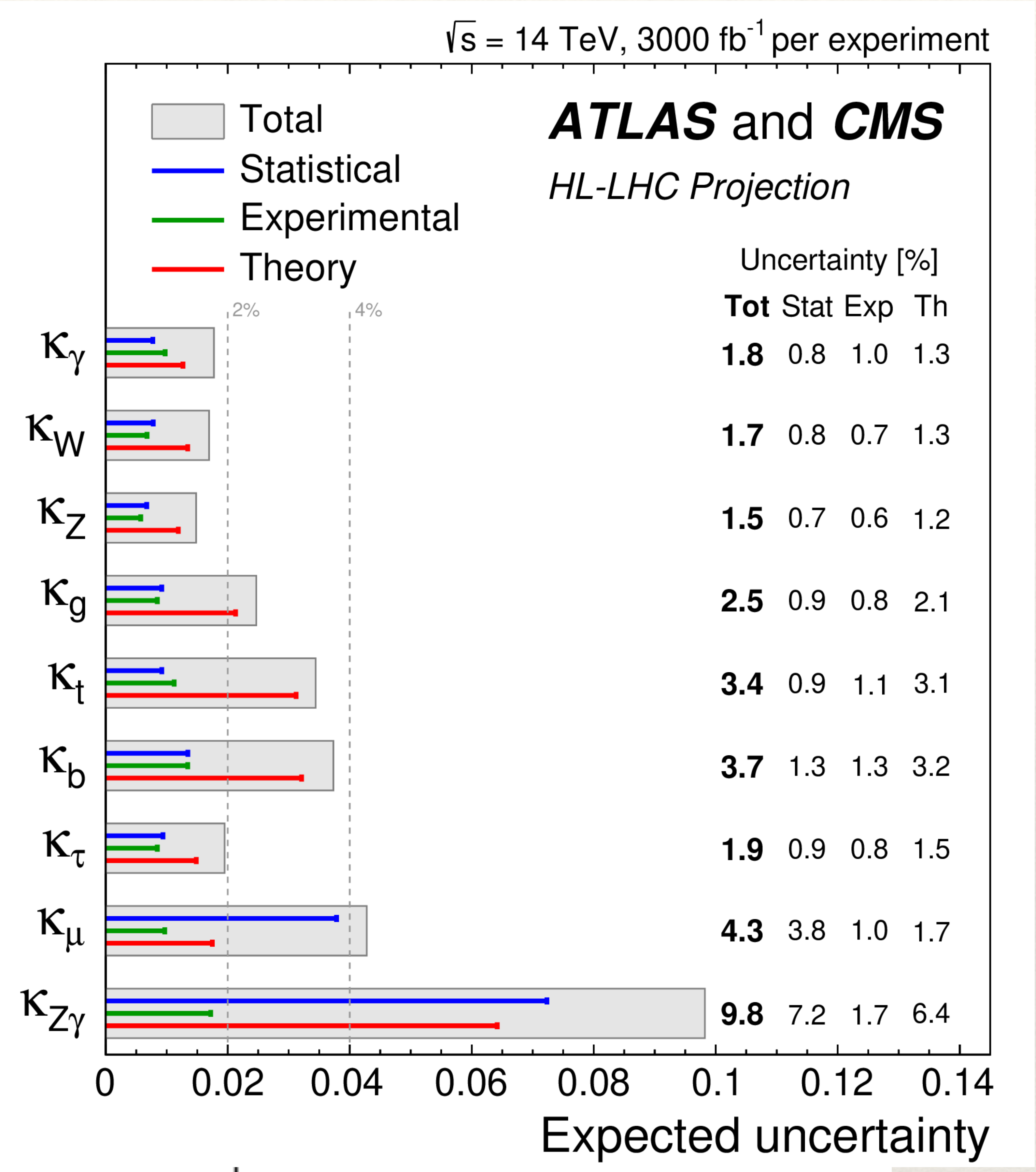
For every **one Swiss franc invested in the FCC, almost two Swiss francs of true incremental socio-economic benefit are generated**, which means that the project eventually pays for itself and generates additional wealth.

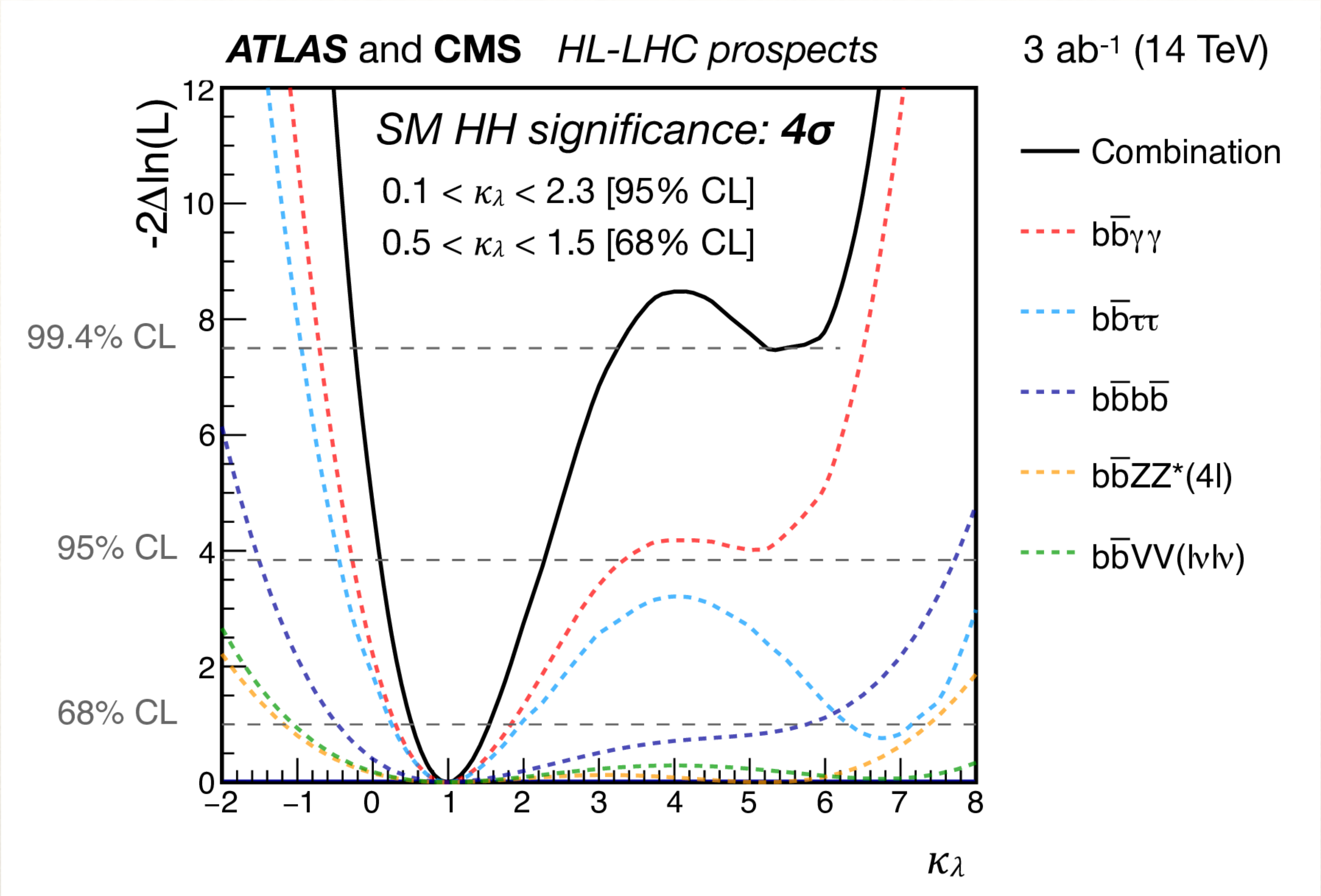
Backup

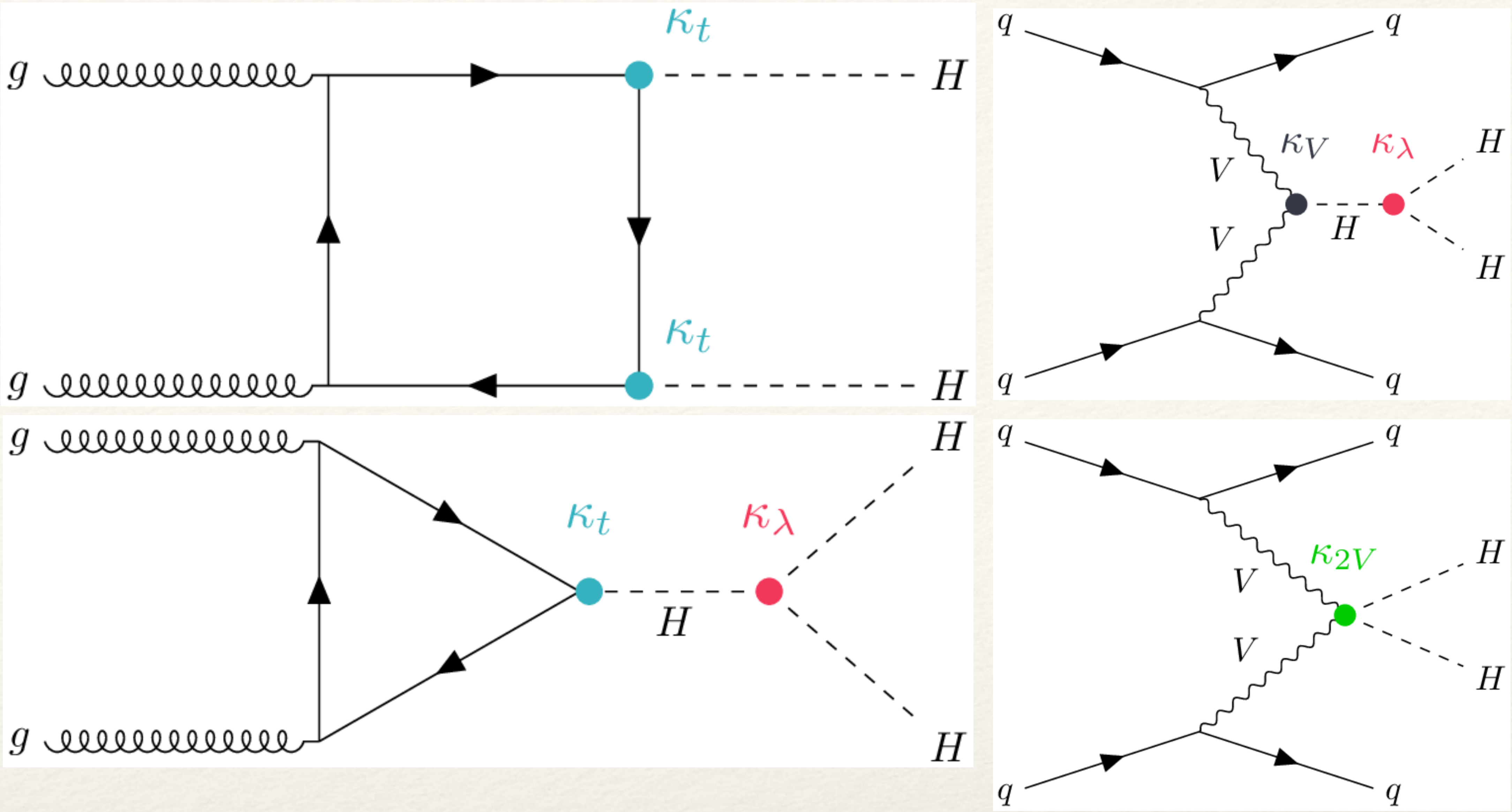


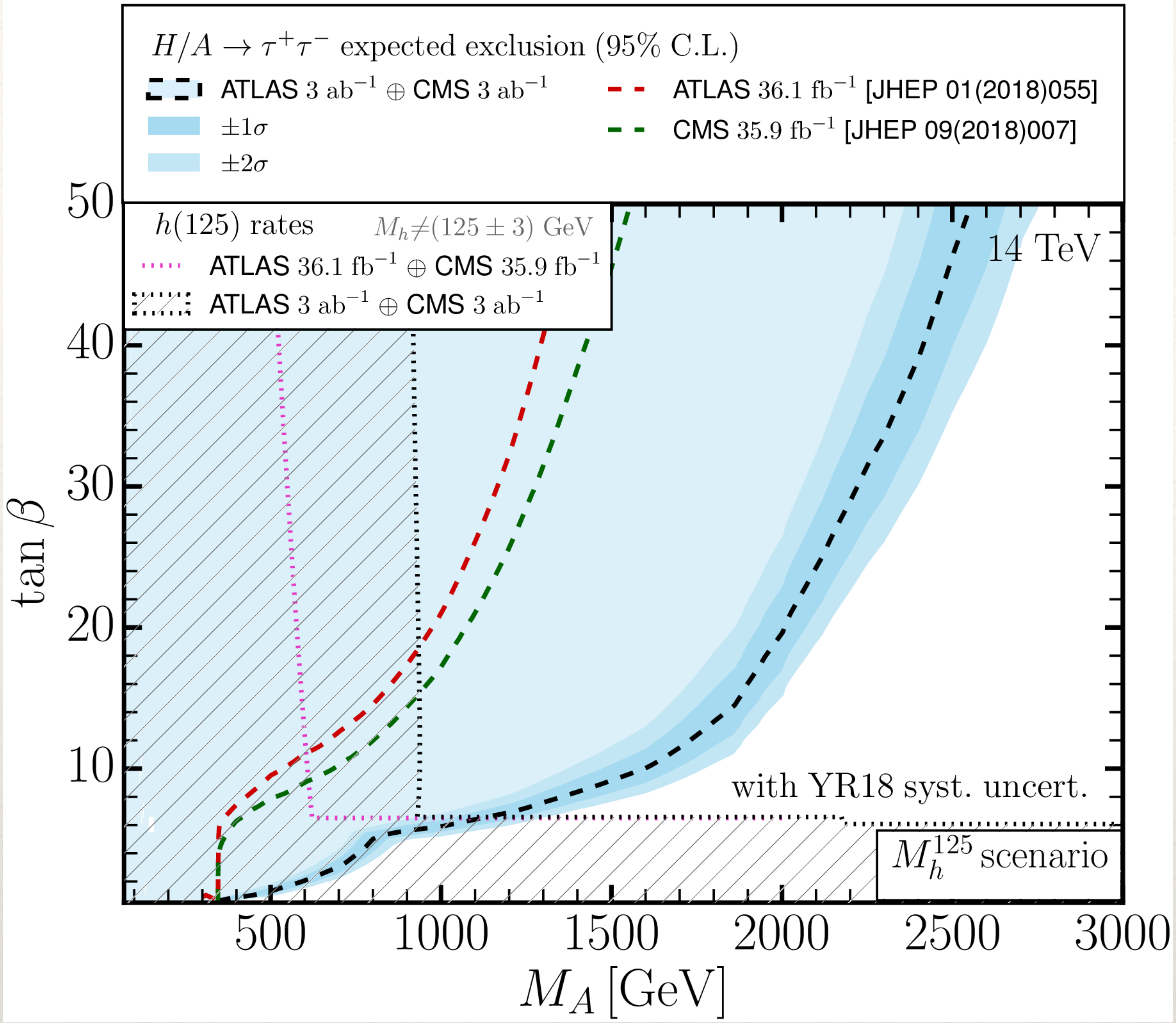


Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Comb	
No syst. unc.	2.3	4.0		
Baseline	2.2	2.8		
Theoretical unc. halved	1.1	1.7		
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

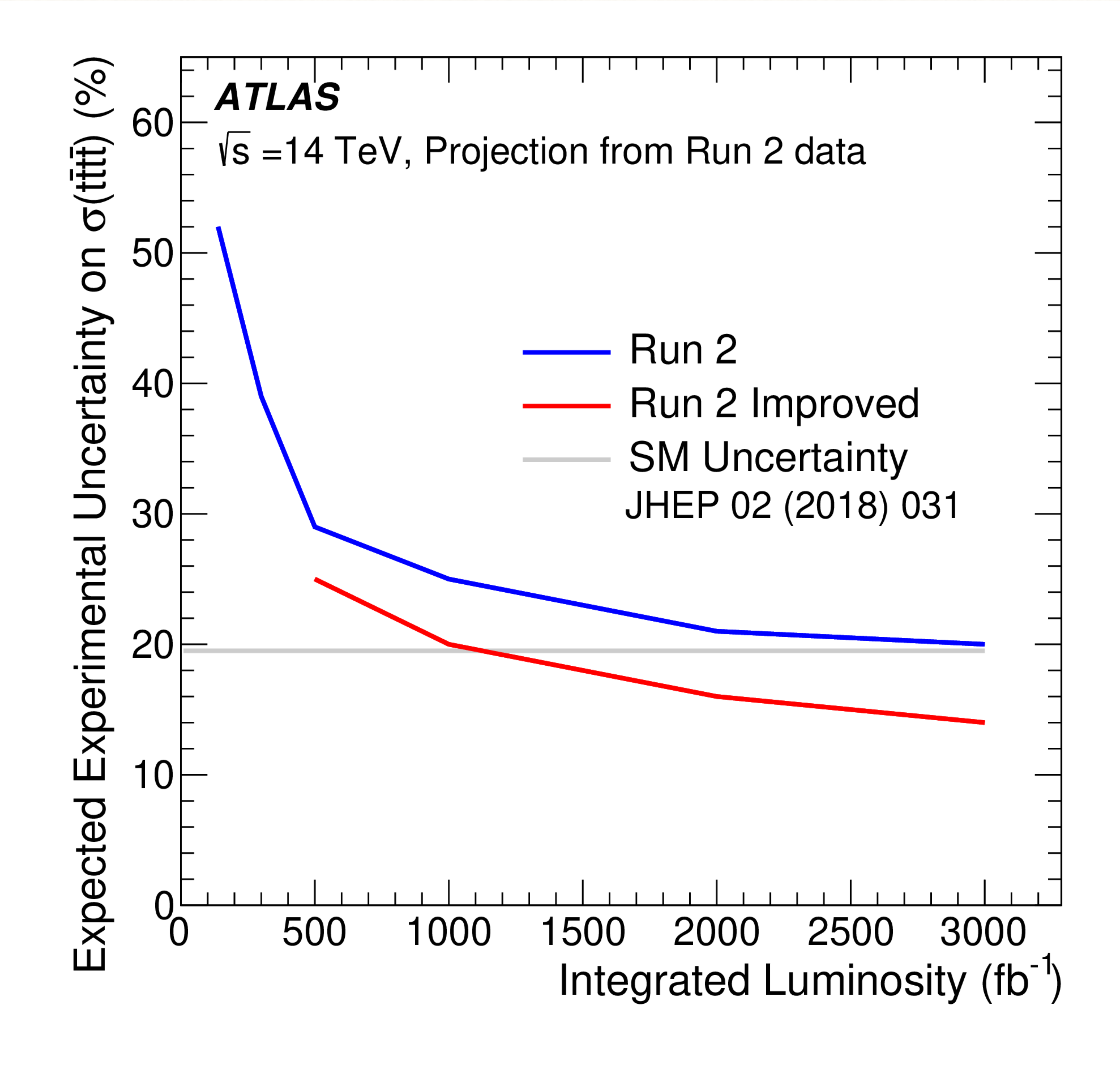



ATLAS and CMS HL-LHC prospects
3 ab-1 (14 TeV)
SM HH significance: 4σ
0.1 < κλ < 2.3 [95% CL]
0.5 < κλ < 1.5 [68% CL]
-2Δln(L)
κλ
99.4% CL
95% CL
68% CL
Combination
bb̄γγ
bb̄ττ
bb̄bb̄
bb̄ZZ*(4l)
bb̄VV(lνlν)

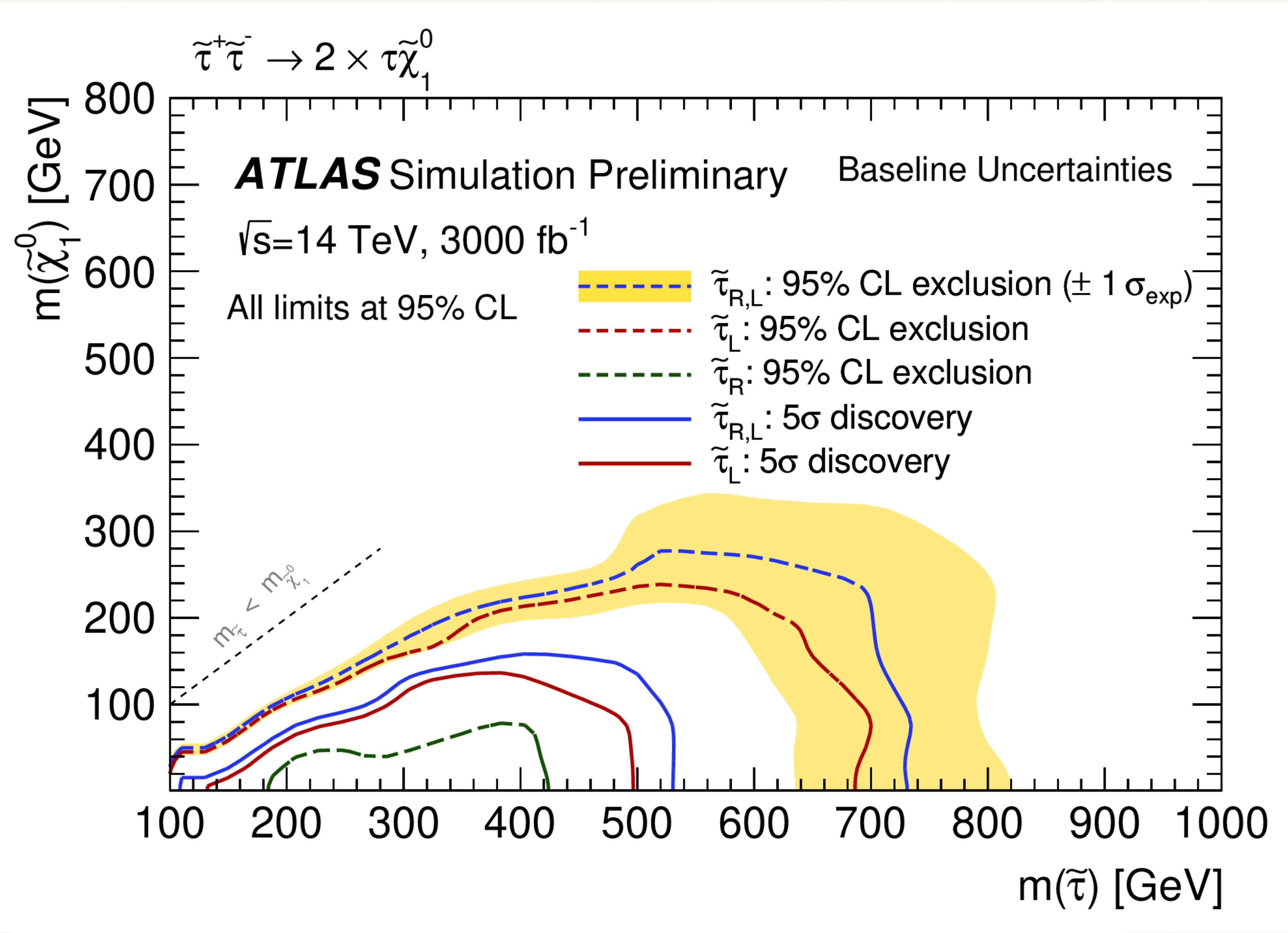

g
H
κt
κλ
V
κV
κ2V
q



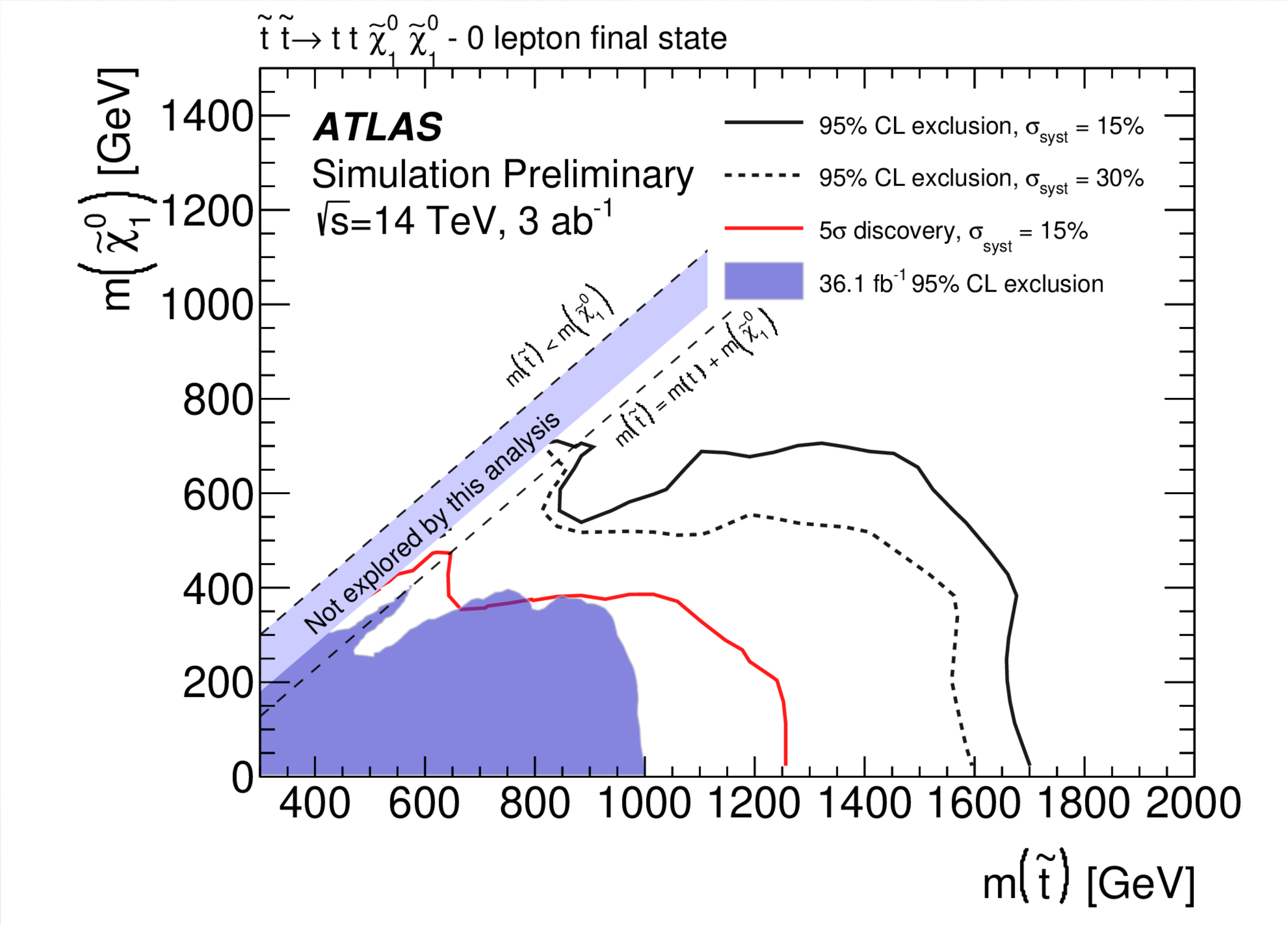
$H/A \to \tau^+\tau^-$ expected exclusion (95% C.L.)
ATLAS 3 ab^{-1} ⊕ CMS 3 ab^{-1}
±1σ
±2σ
ATLAS 36.1 fb^{-1} [JHEP 01(2018)055]
CMS 35.9 fb^{-1} [JHEP 09(2018)007]
h(125) rates
$M_h \neq (125 \pm 3)$ GeV
ATLAS 36.1 fb^{-1} ⊕ CMS 35.9 fb^{-1}
ATLAS 3 ab^{-1} ⊕ CMS 3 ab^{-1}
14 TeV
with YR18 syst. uncert.
M_h^{125} scenario
tan β
M_A [GeV]



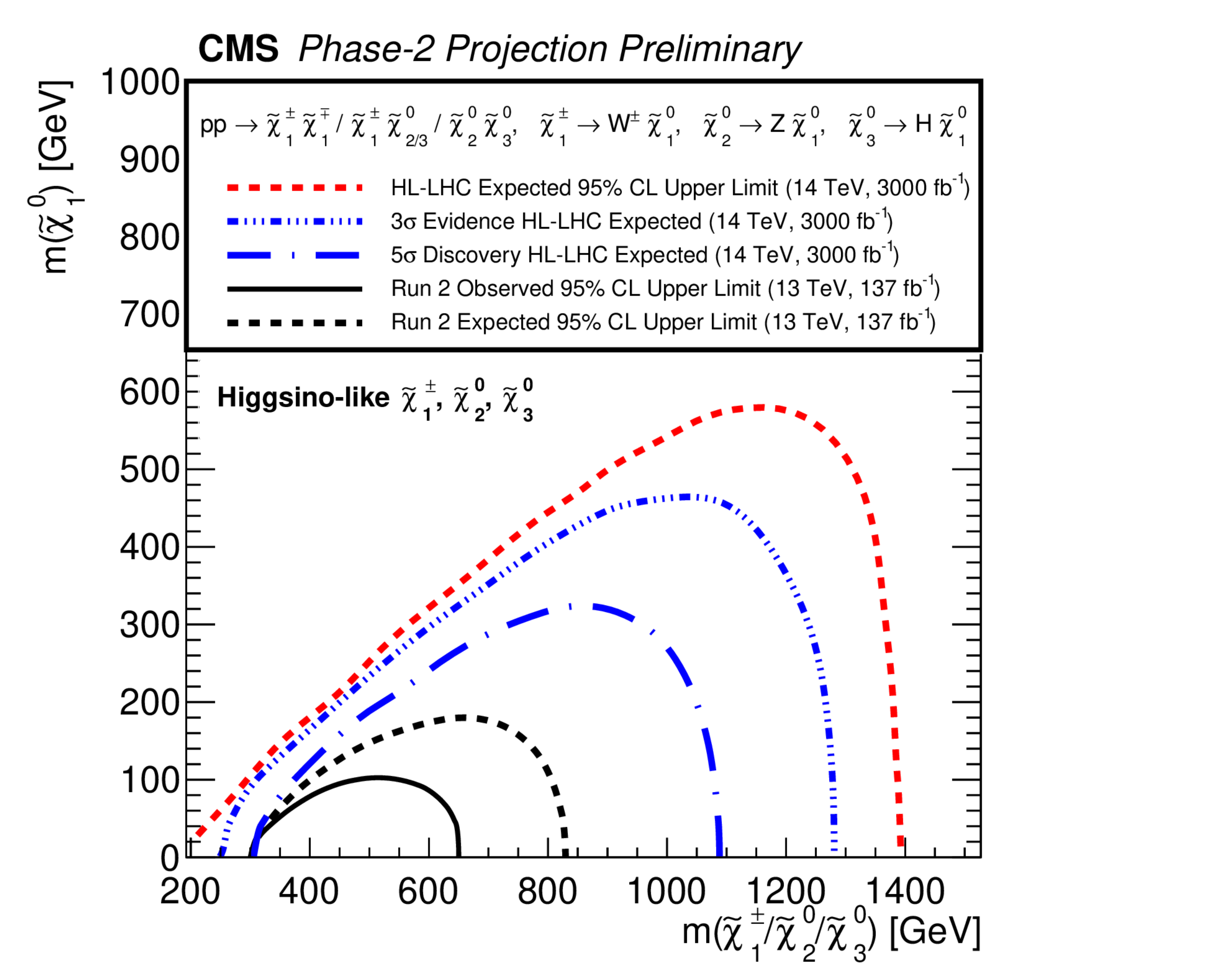
ATLAS
√s =14 TeV, Projection from Run 2 data
Run 2
Run 2 Improved
SM Uncertainty
JHEP 02 (2018) 031
Expected Experimental Uncertainty on σ(tt̄tt̄) (%)
Integrated Luminosity (fb^{-1})



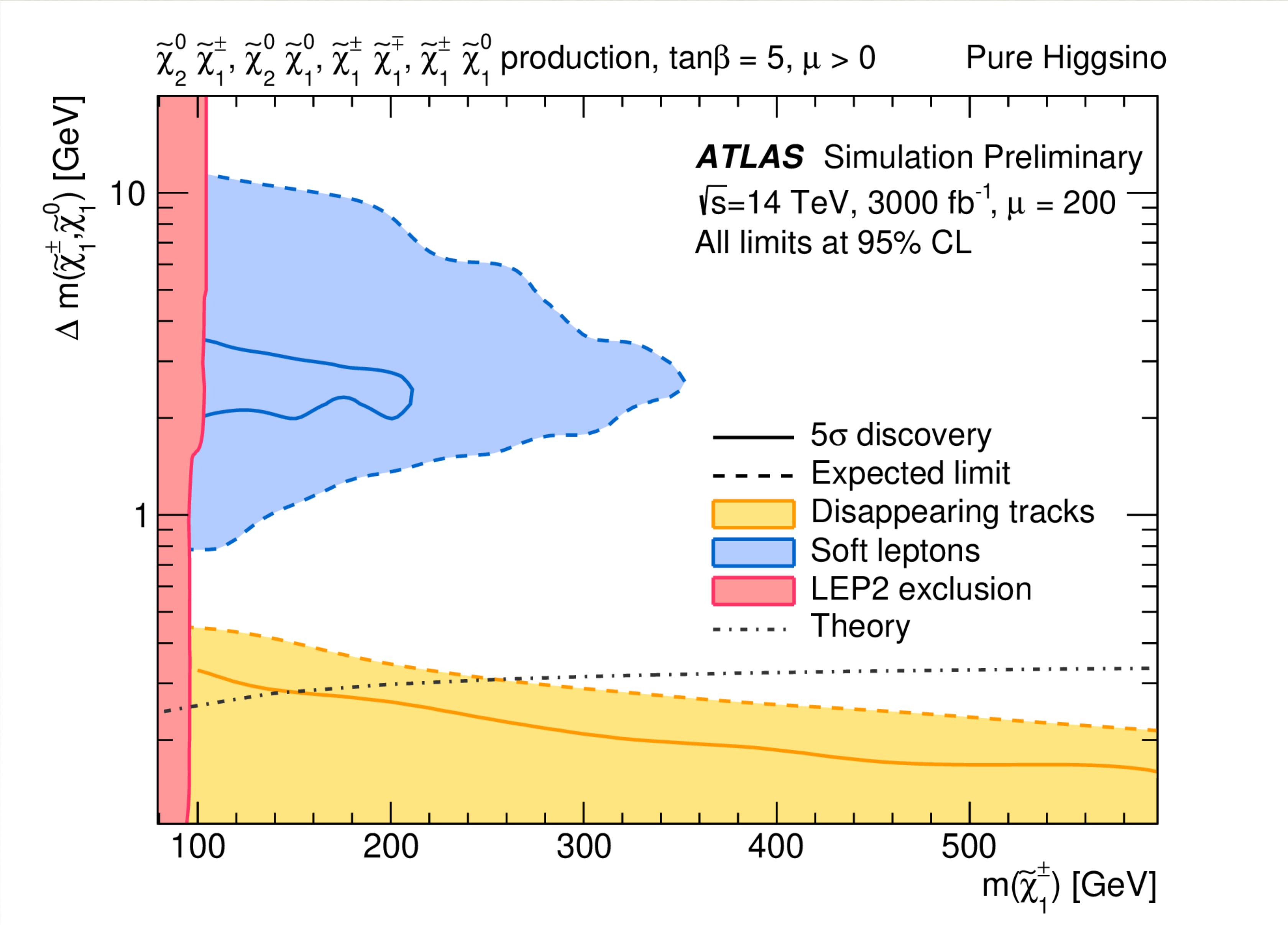
$\tilde{\tau}^+\tilde{\tau}^- \rightarrow 2 \times \tau\tilde{\chi}_1^0$
ATLAS Simulation Preliminary
Baseline Uncertainties
$\sqrt{s}$=14 TeV, 3000 fb^{-1}
All limits at 95% CL
$\tilde{\tau}_{R,L}$: 95% CL exclusion ($\pm$ 1 σ_{exp})
$\tilde{\tau}_L$: 95% CL exclusion
$\tilde{\tau}_R$: 95% CL exclusion
$\tilde{\tau}_{R,L}$: 5σ discovery
$\tilde{\tau}_L$: 5σ discovery
$m_{\tilde{\tau}} < m_{\tilde{\chi}_1^0}$
m($\tilde{\chi}_1^0$) [GeV]
m($\tilde{\tau}$) [GeV]



$\tilde{t}\,\tilde{t} \rightarrow t\,t\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$ - 0 lepton final state
ATLAS
Simulation Preliminary
$\sqrt{s}$=14 TeV, 3 ab^{-1}
95% CL exclusion, σ_{syst} = 15%
95% CL exclusion, σ_{syst} = 30%
5σ discovery, σ_{syst} = 15%
36.1 fb^{-1} 95% CL exclusion
$m(\tilde{t}) < m(\tilde{\chi}_1^0)$
$m(\tilde{t}) = m(t) + m(\tilde{\chi}_1^0)$
Not explored by this analysis
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{t})$ [GeV]



CMS Phase-2 Projection Preliminary
$pp \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} / \tilde{\chi}_1^{\pm}\tilde{\chi}_{2/3}^0 / \tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \rightarrow H\tilde{\chi}_1^0$
HL-LHC Expected 95% CL Upper Limit (14 TeV, 3000 fb^{-1})
3σ Evidence HL-LHC Expected (14 TeV, 3000 fb^{-1})
5σ Discovery HL-LHC Expected (14 TeV, 3000 fb^{-1})
Run 2 Observed 95% CL Upper Limit (13 TeV, 137 fb^{-1})
Run 2 Expected 95% CL Upper Limit (13 TeV, 137 fb^{-1})
Higgsino-like $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$
m($\tilde{\chi}_1^0$) [GeV]
m($\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_3^0$) [GeV]



$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ production, tanβ = 5, μ > 0
Pure Higgsino
ATLAS Simulation Preliminary
$\sqrt{s}$=14 TeV, 3000 fb^{-1}, μ = 200
All limits at 95% CL
5σ discovery
Expected limit
Disappearing tracks
Soft leptons
LEP2 exclusion
Theory
Δ m($\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_1^0$) [GeV]
m($\tilde{\chi}_1^{\pm}$) [GeV]