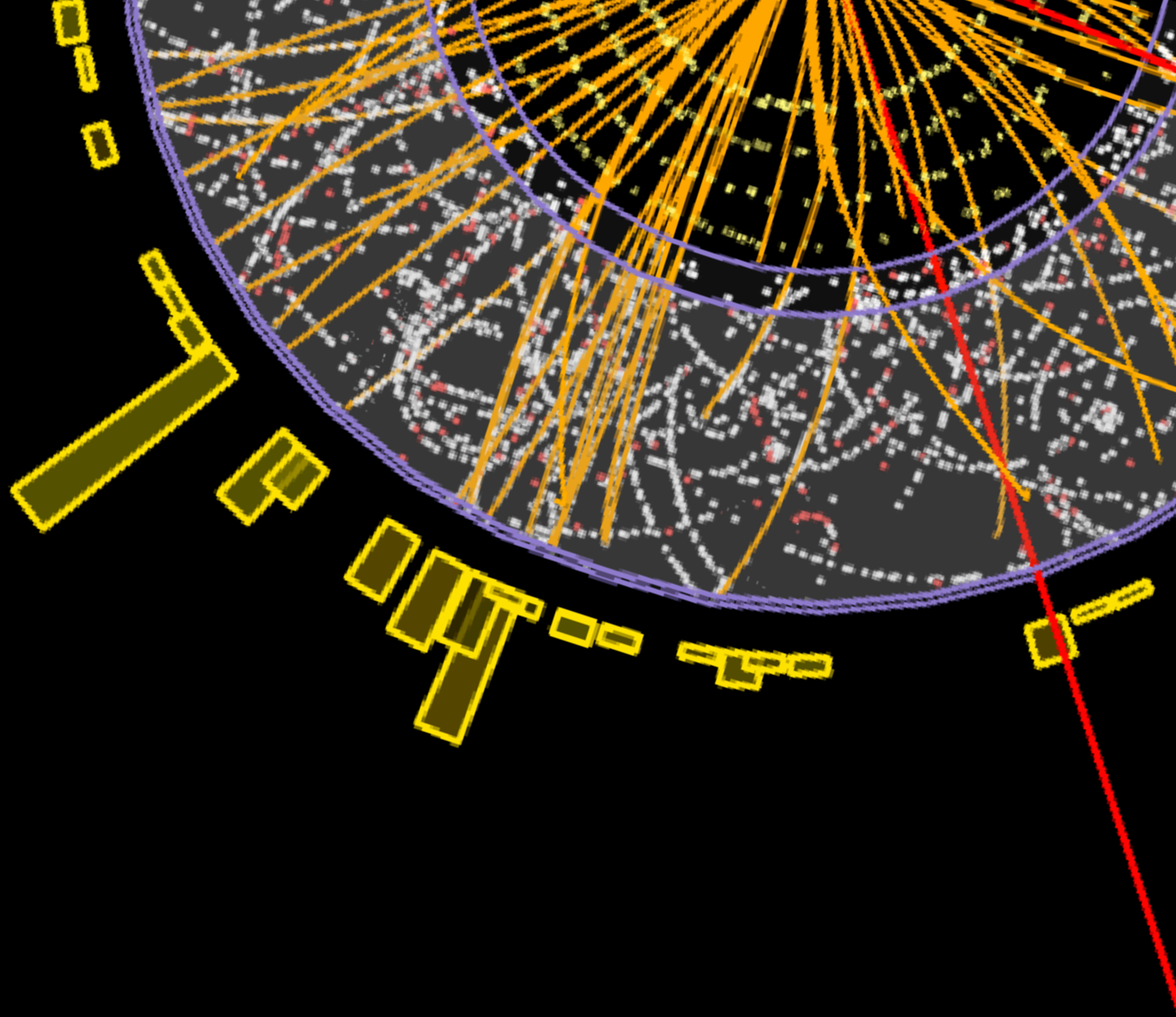
Valerio Ippolito
INFN Sezione di Roma
on behalf of the ATLAS and CMS collaborations



ATLAS AND CMS:
THE PAST AND PENDING

highlights and future perspectives of LHC experiments

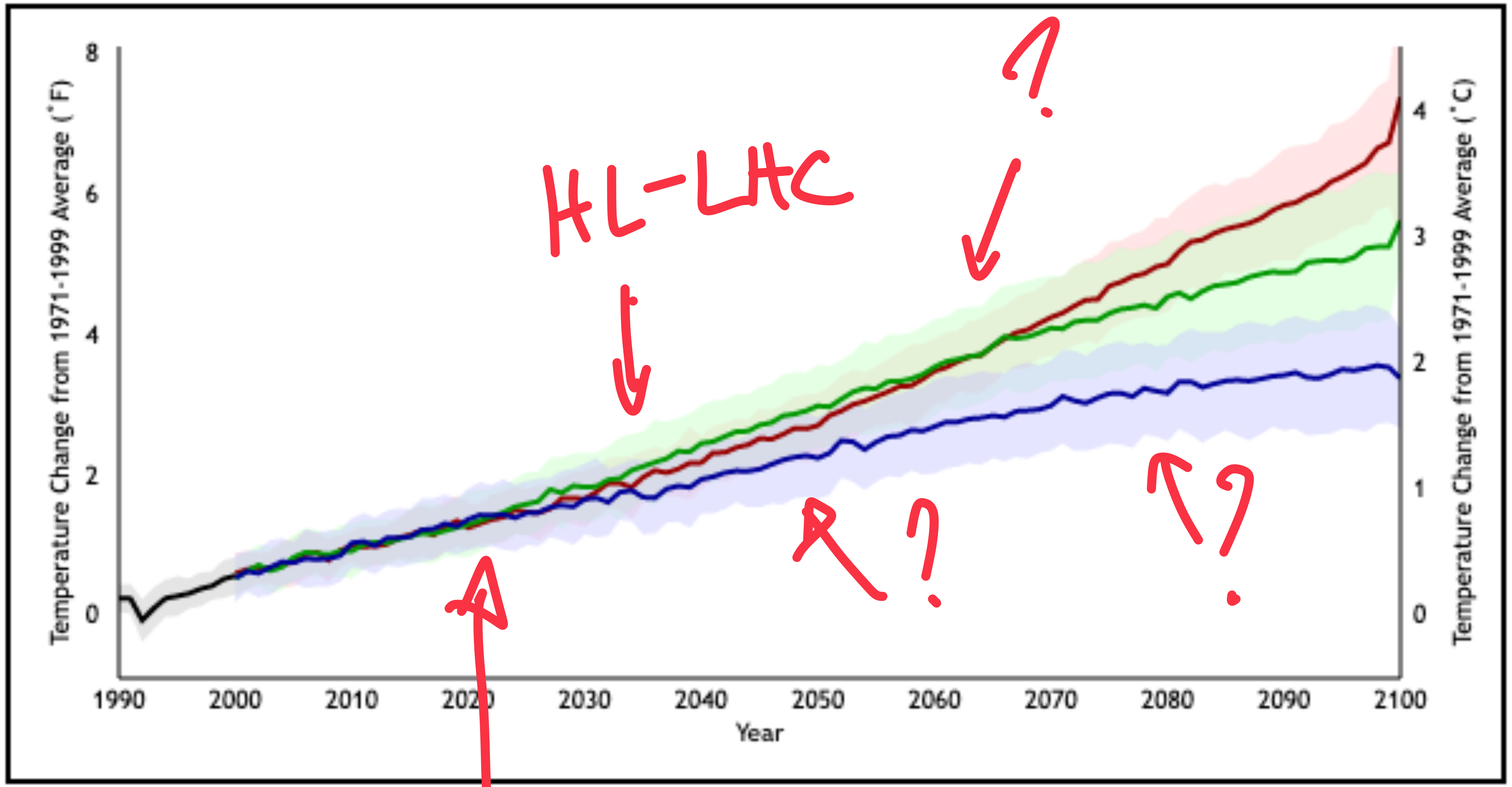
Istituto Nazionale di Fisica Nucleare

ATLAS

LEP

CMS

https://www.youtube.com/watch?v=7BA21a3vk_Y [2001]


Temperature Change from 1971-1999 Average (˚F)
8
6
4
2
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Temperature Change from 1971-1999 Average (˚C)
4
3
2
1
0

HL-LHC

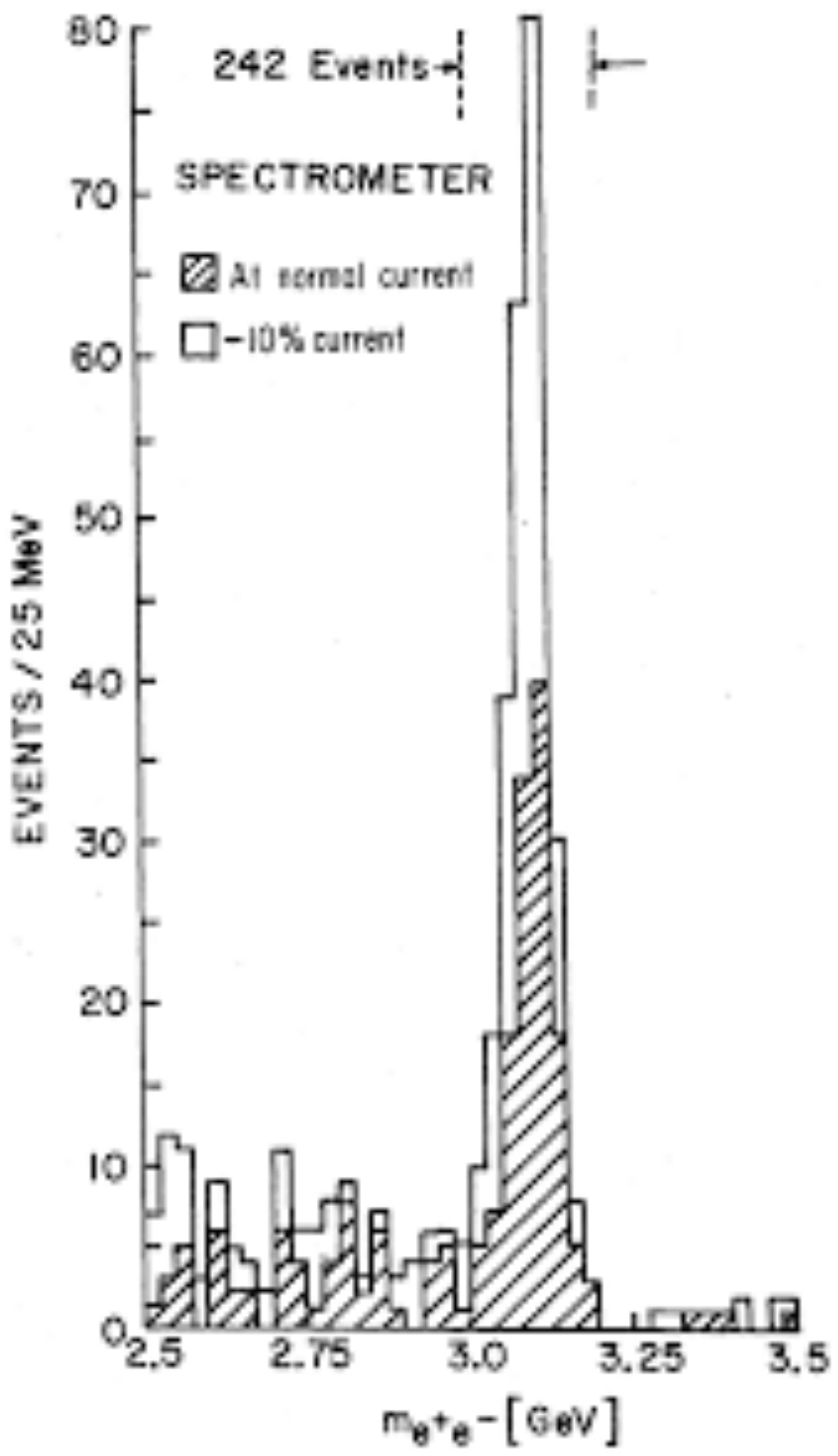
?

?

?

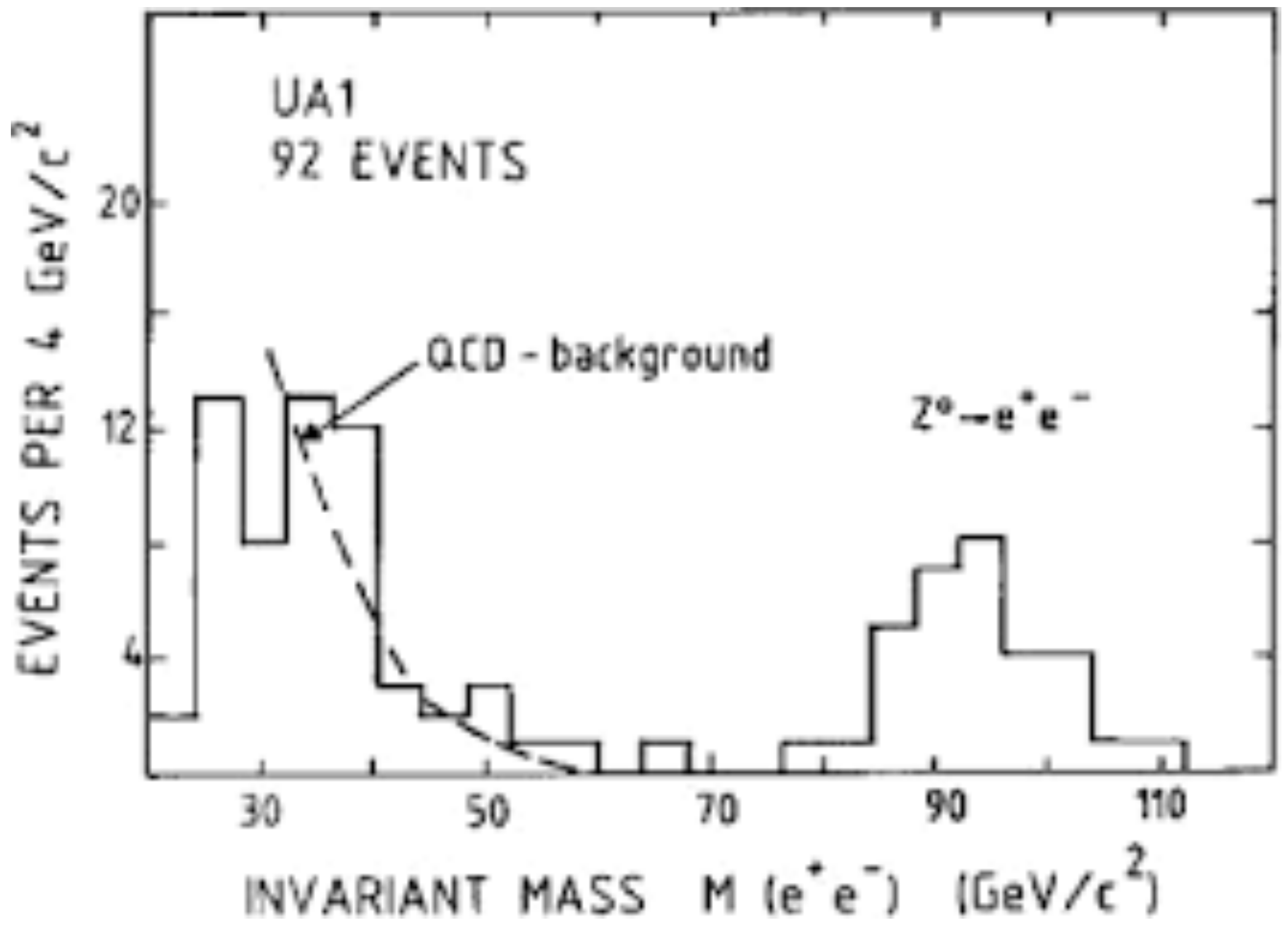
TODAY

small prior



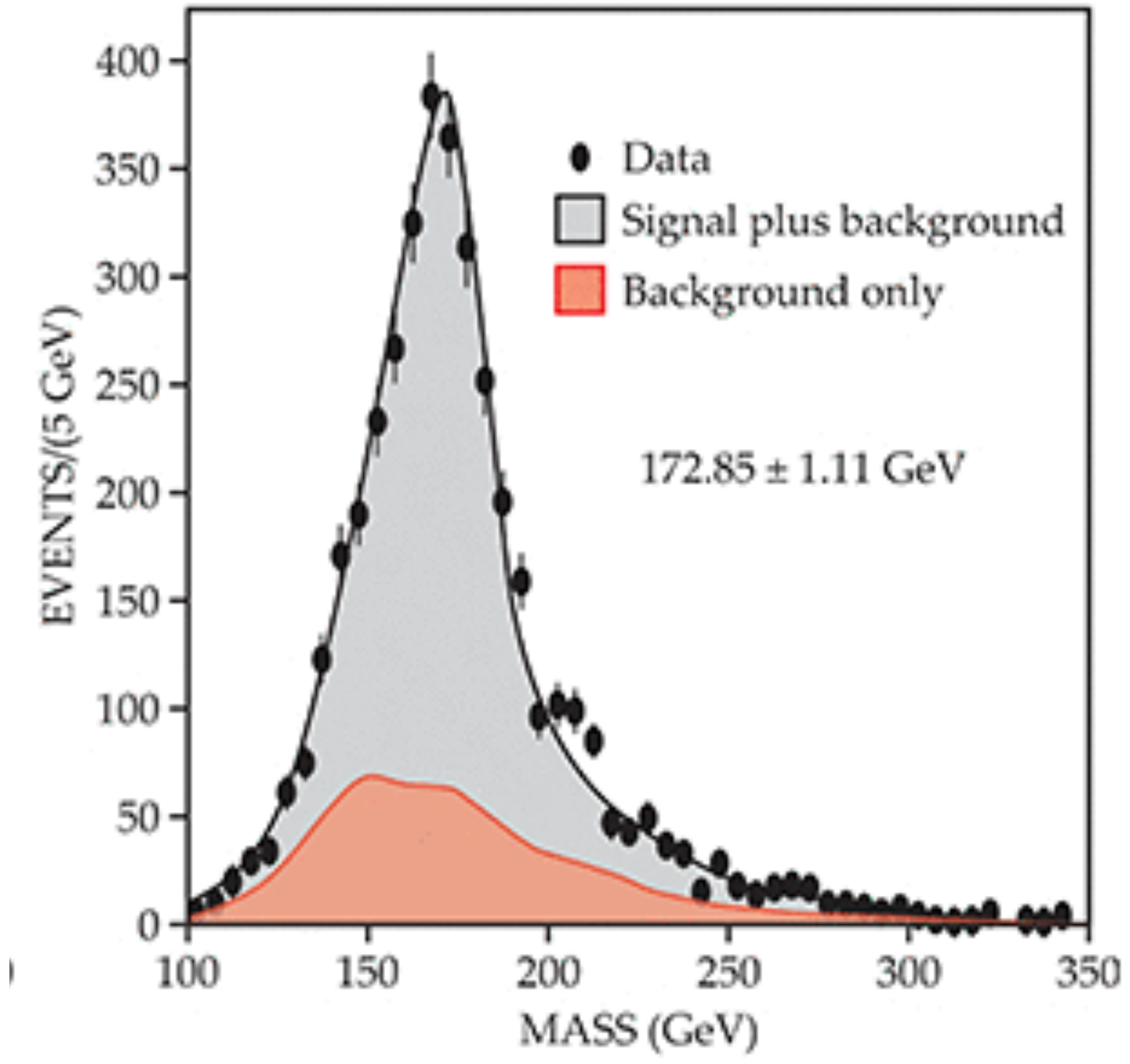
~ 50 years ago

higher prior



~ 40 years ago

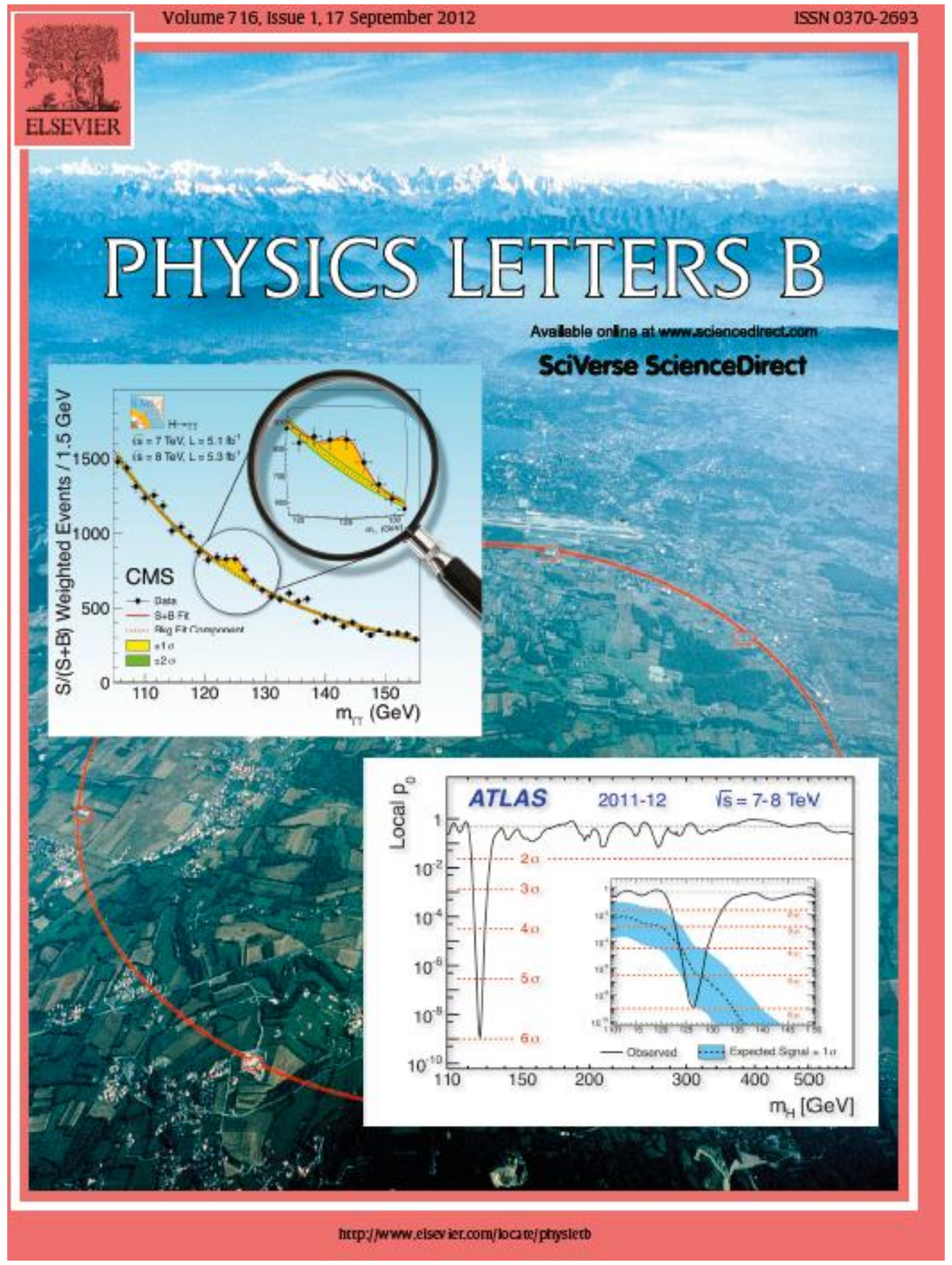
even higher prior



~ 20 years ago

Valerio Ippolito
INFN Sezione di Roma

a relief (?)


Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693

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~10 years ago

$P(\text{new}) \sim 10^{-x}$?

today

$P(\text{new}) \sim$?

in 10 years

- **make-believe: it's 2040, what's going on?**

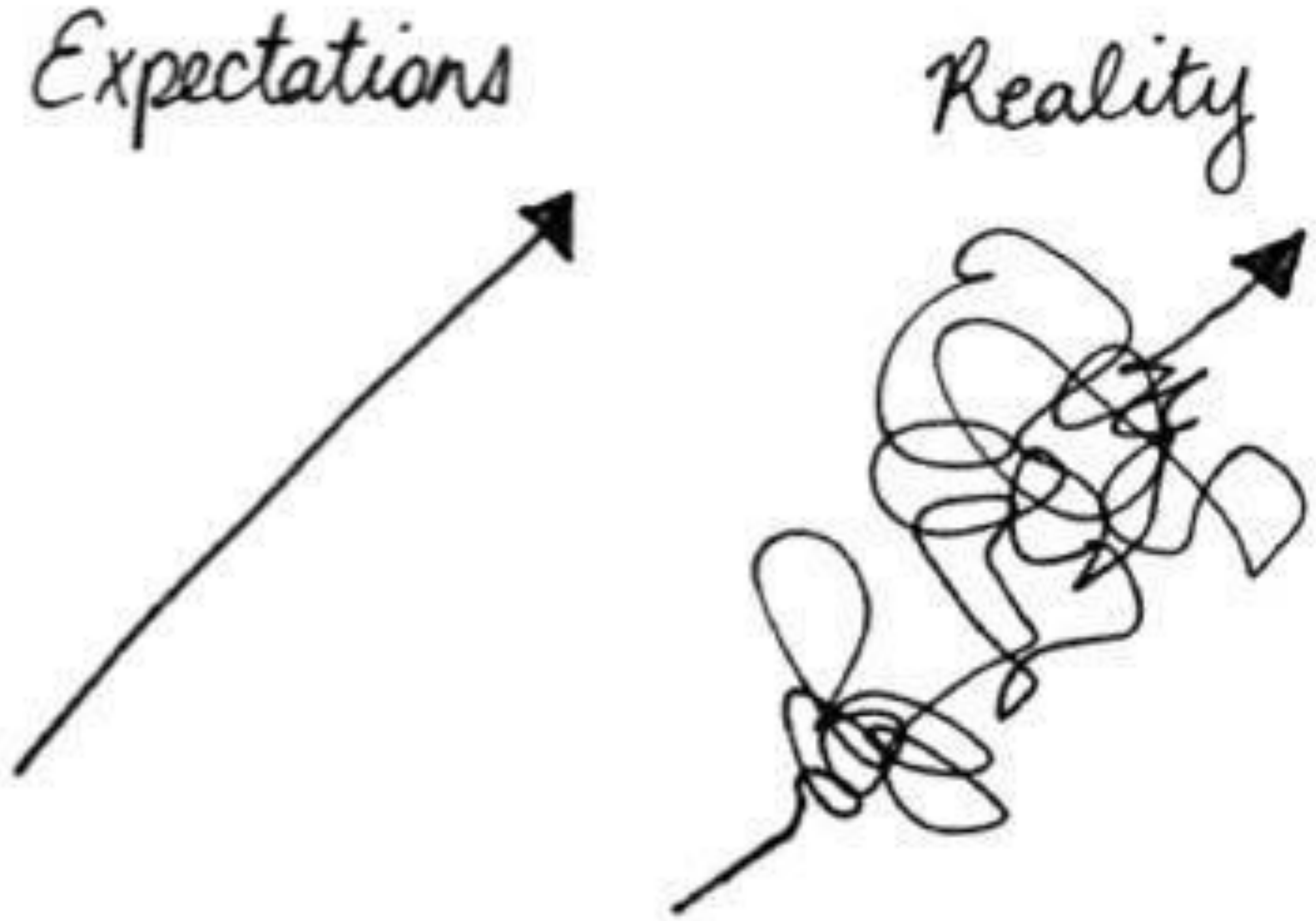
  predict the future, with all caveats

- **we'll focus on today vs tomorrow**

  whenever possible

- **for a selection of topics**

  for the many more see here and here,
  and the Snowmass 2022 white paper



bibliography will appear here

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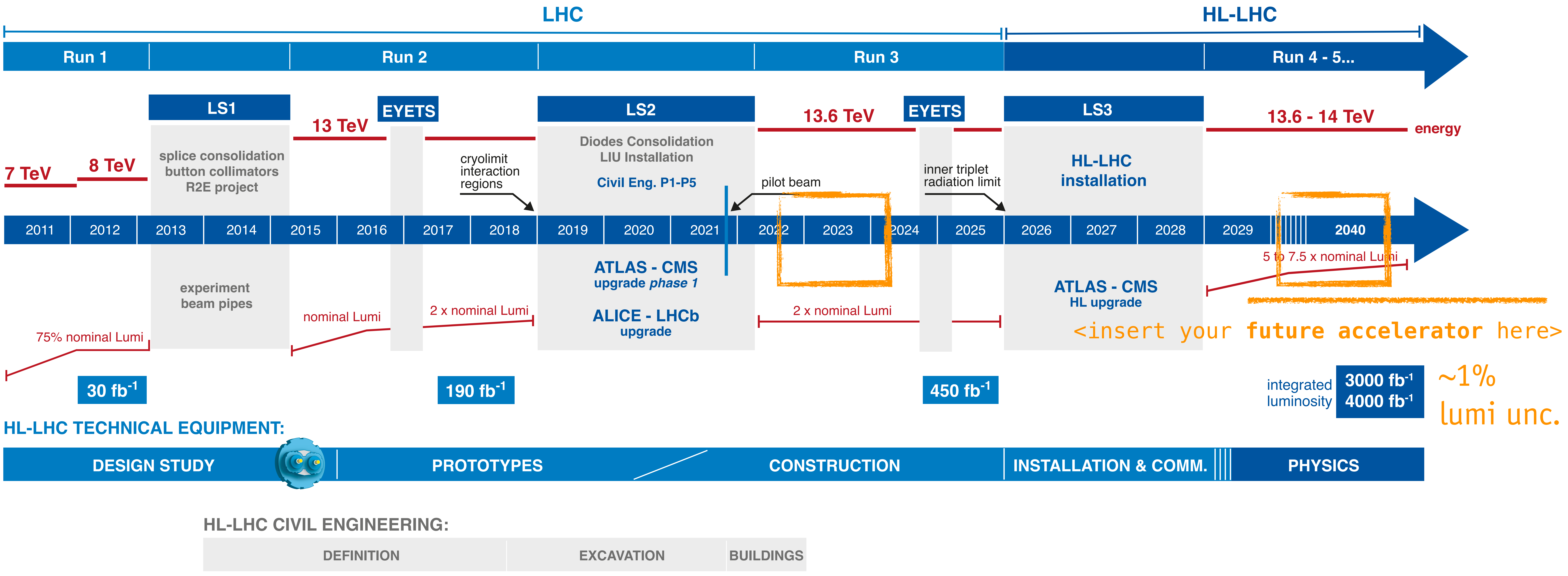
INFN Sezione di Roma

LHC / HL-LHC Plan

HiLumi
LARGE HADRON COLLIDER



LHC
HL-LHC

Run 1
Run 2
Run 3
Run 4 - 5...

7 TeV
8 TeV
LS1
splice consolidation
button collimators
R2E project
13 TeV
EYETS
cryolimit
interaction
regions
LS2
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
13.6 TeV
EYETS
inner triplet
radiation limit
LS3
HL-LHC
installation
13.6 - 14 TeV
energy

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2040

75% nominal Lumi
experiment
beam pipes
nominal Lumi
2 x nominal Lumi
ATLAS - CMS
upgrade *phase 1*
ALICE - LHCb
upgrade
2 x nominal Lumi
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi

`<insert your future accelerator here>`

30 fb^{-1}
190 fb^{-1}
450 fb^{-1}
integrated
luminosity
3000 fb^{-1}
4000 fb^{-1}

~1%
lumi unc.

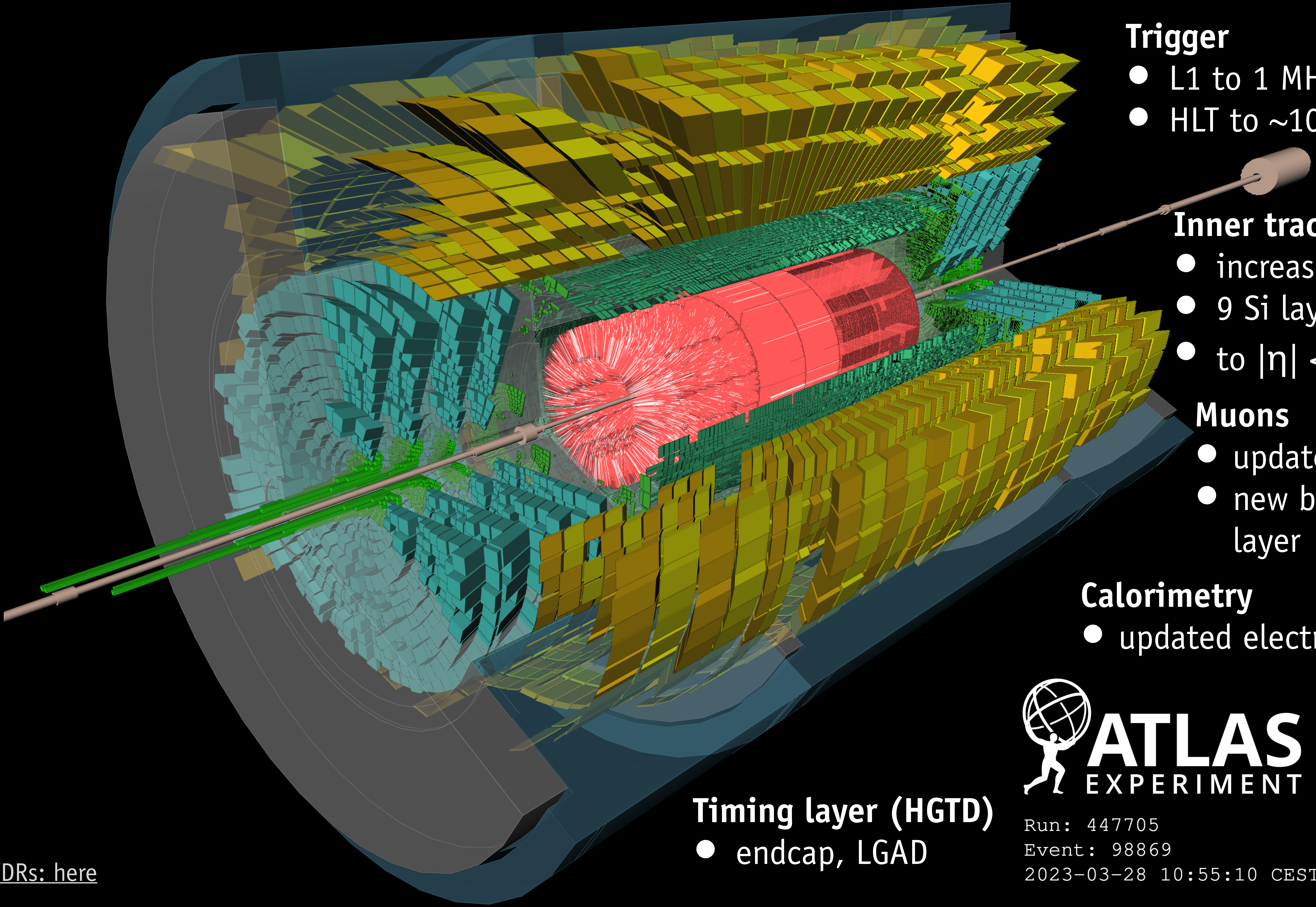
HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS

HL-LHC CIVIL ENGINEERING:

DEFINITION
EXCAVATION
BUILDINGS

Valerio Ippolito
INFN Sezione di Roma



Trigger

- L1 to 1 MHz
- HLT to ~10 kHz (now: 0.1x)

Inner tracker (ITk)

- increased granularity
- 9 Si layers, less X_0
- to $|\eta| < 4$ (now: 2.5)

Muons

- updated electronics
- new barrel trigger layer

Calorimetry

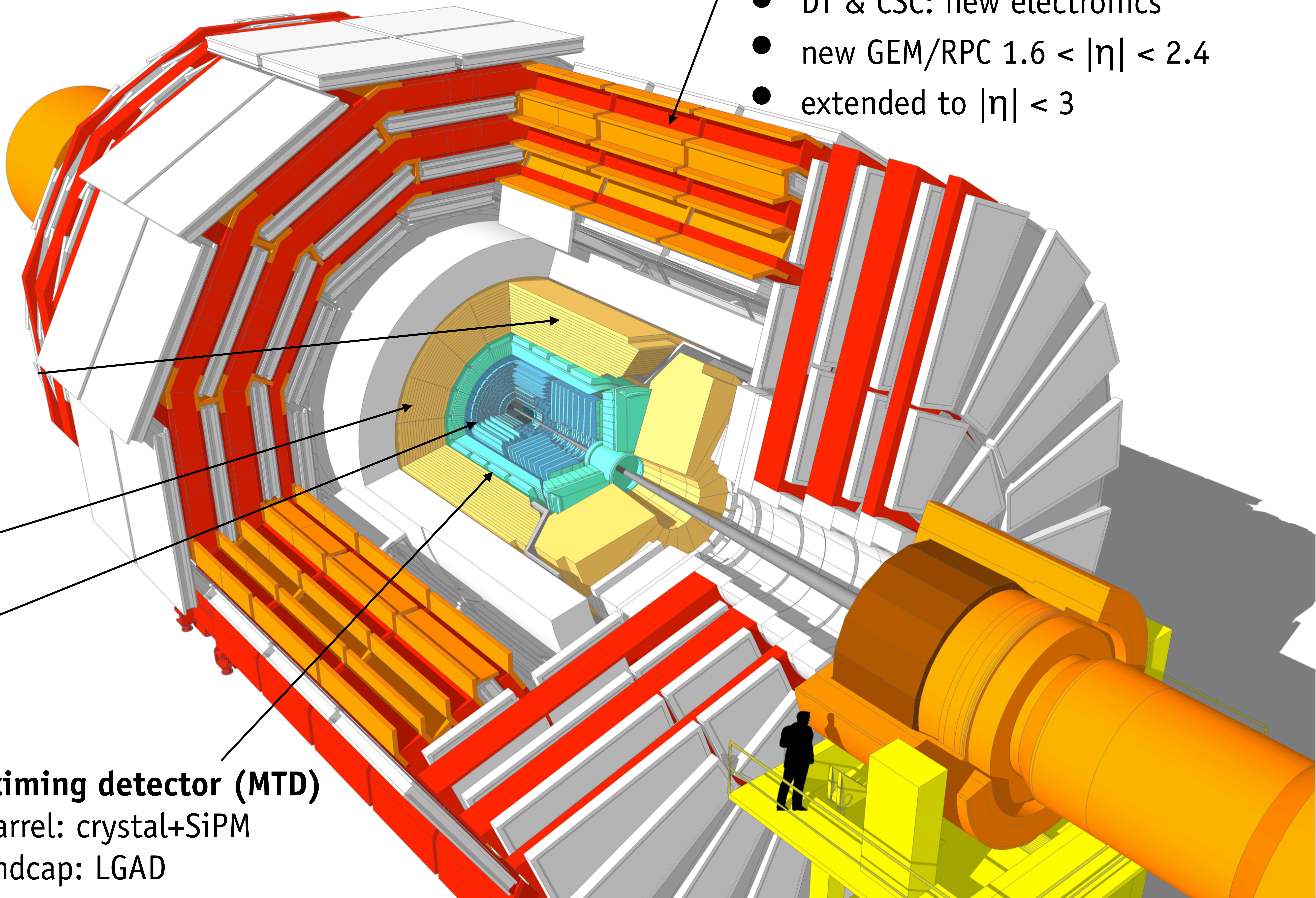
- updated electronics

Timing layer (HGTD)

- endcap, LGAD

TDRs: here

TDRs: here



L1 trigger

- tracks@40 MHz
- PFlow 750 kHz output
- 12.5 μs latency

DAQ/HLT

- 7.5 kHz output
- 40 MHz data scouting

Barrel calorimeters

- ECAL granularity readout @40MHz
- precise timing for 30 GeV e/gamma
- new ECAL/HCAL electronics

Endcap calorimeter

- 3D showers, precise timing
- Si, Scint+SiPM in Pb/W-SS

Tracker

- less X_0
- increased granularity in Si-strip & pixels
- to $|\eta| < 3.8$

MIP timing detector (MTD)

- barrel: crystal+SiPM
- endcap: LGAD

Luminosity

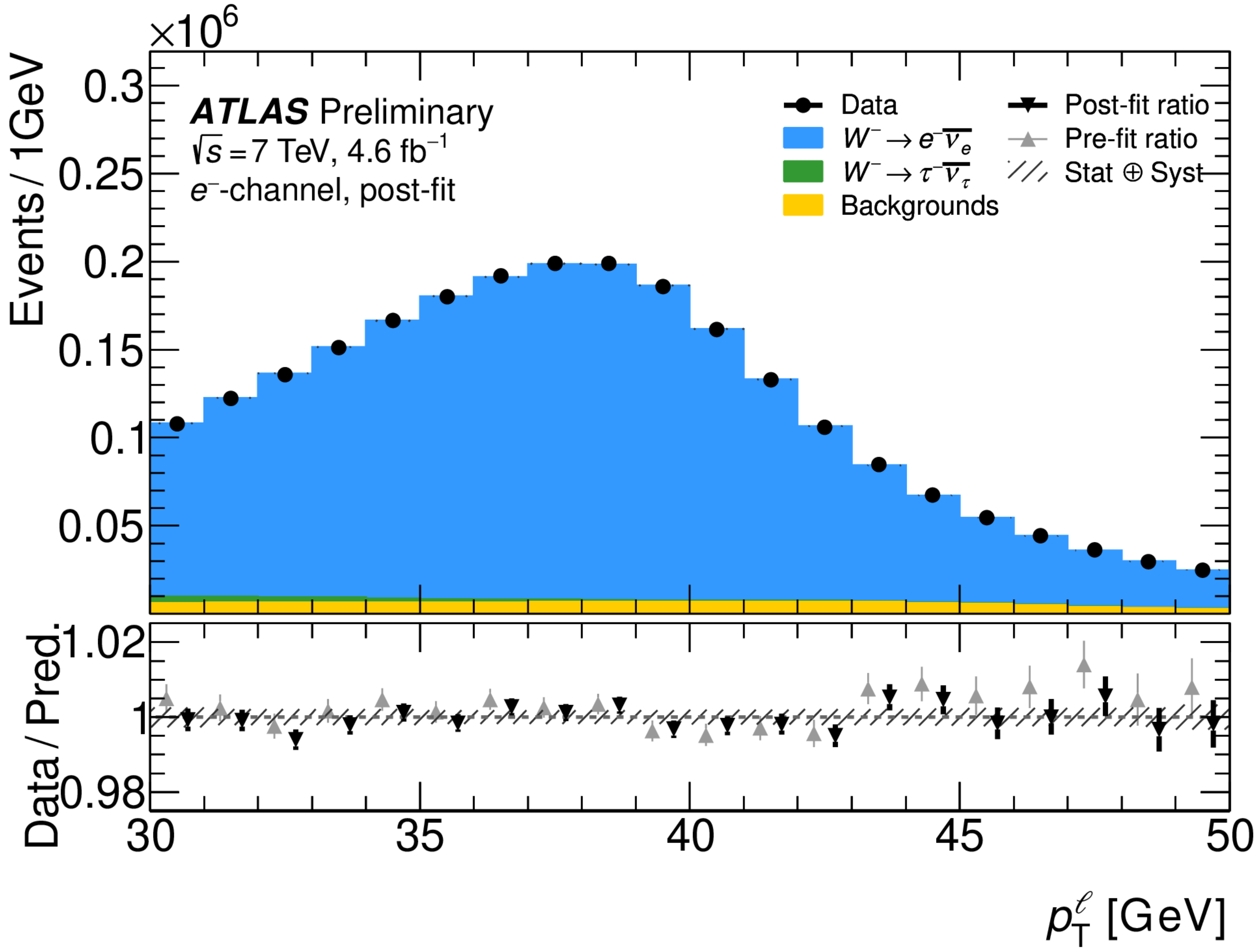
- 1% offline measurement, as ATLAS (2% online)

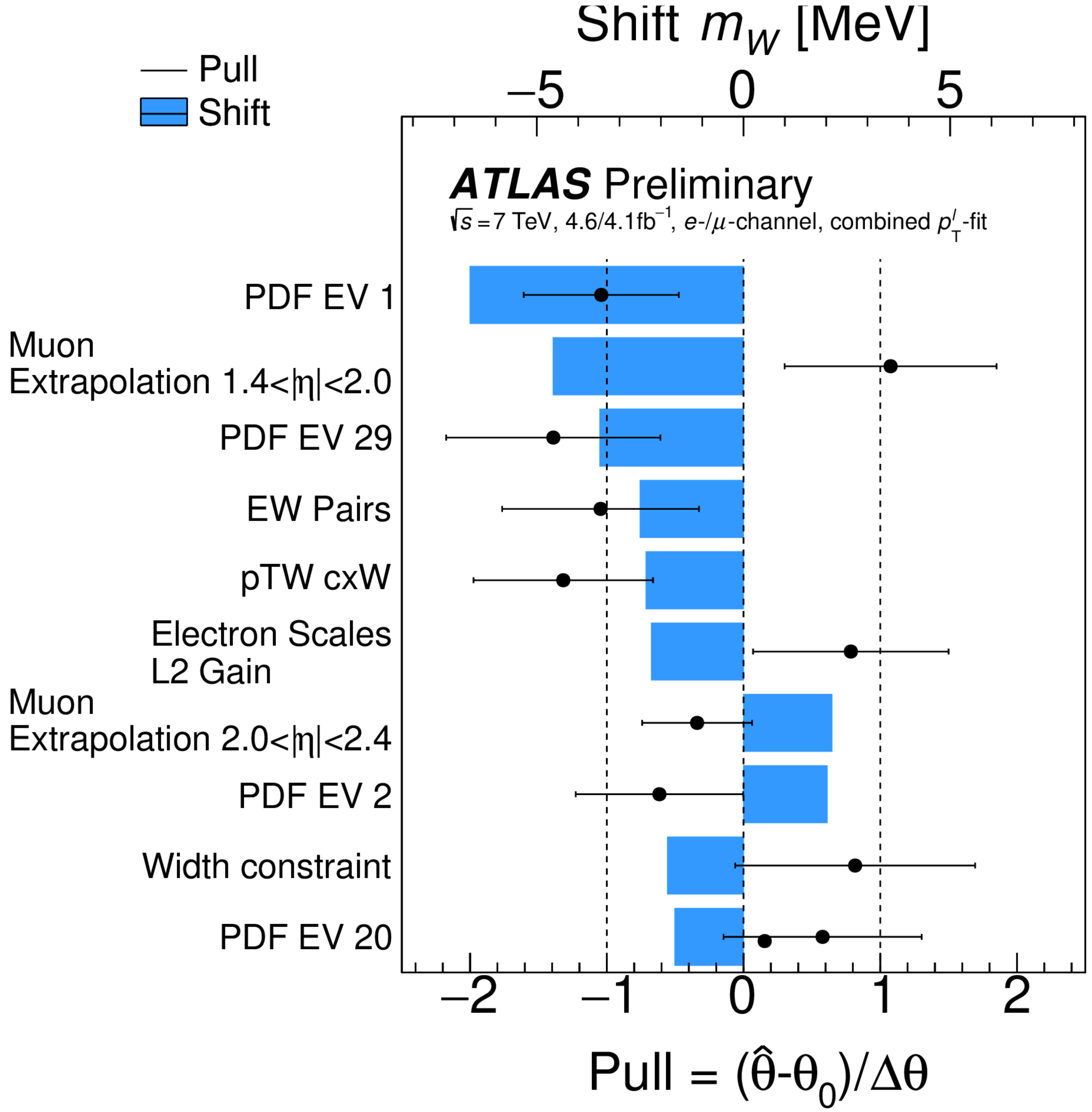
Muon system

- DT & CSC: new electronics
- new GEM/RPC $1.6 < |\eta| < 2.4$
- extended to $|\eta| < 3$


STANDARD MODEL
STANDARD MODEL EVERYWHERE
imgflip.com

THE W BOSON MASS 2023!



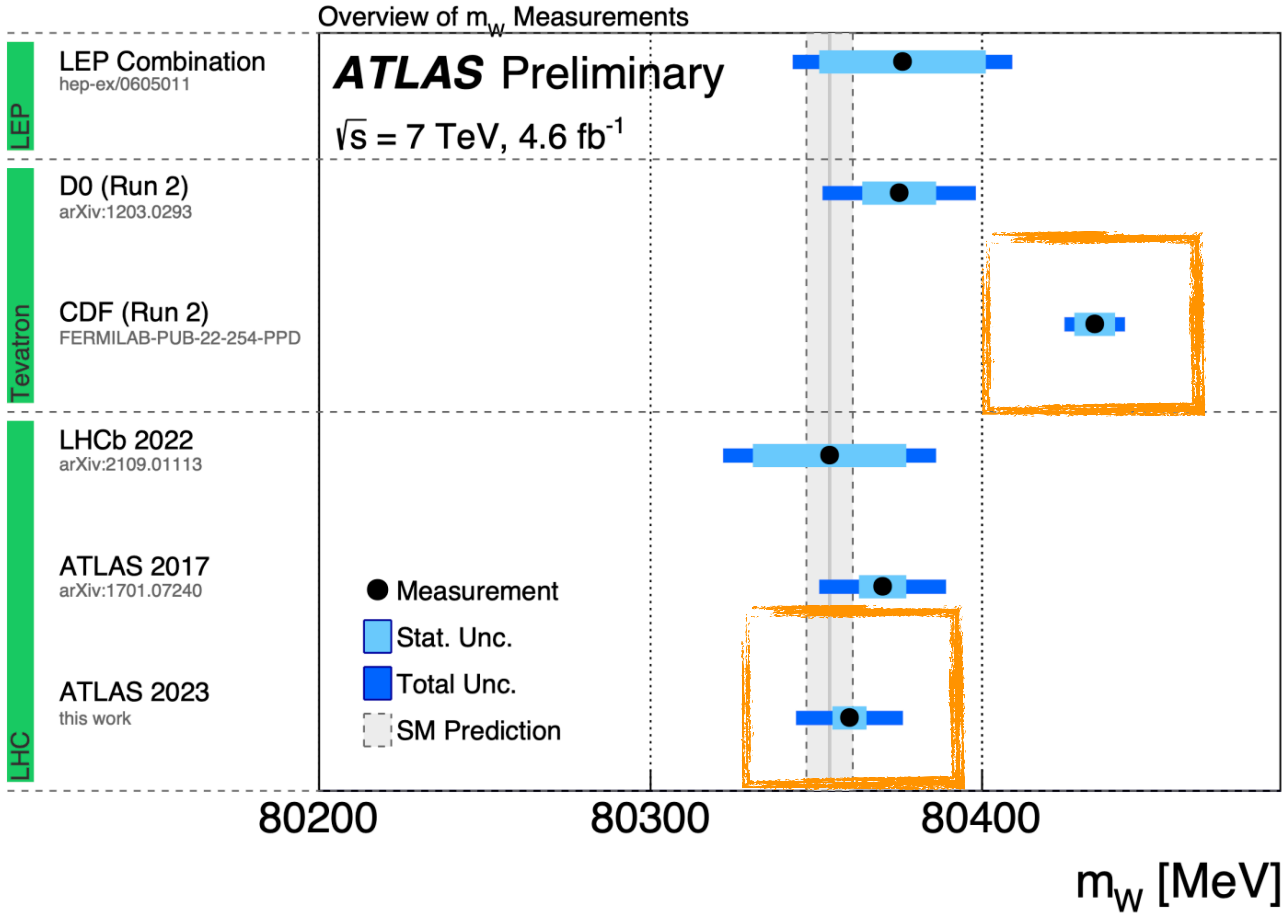


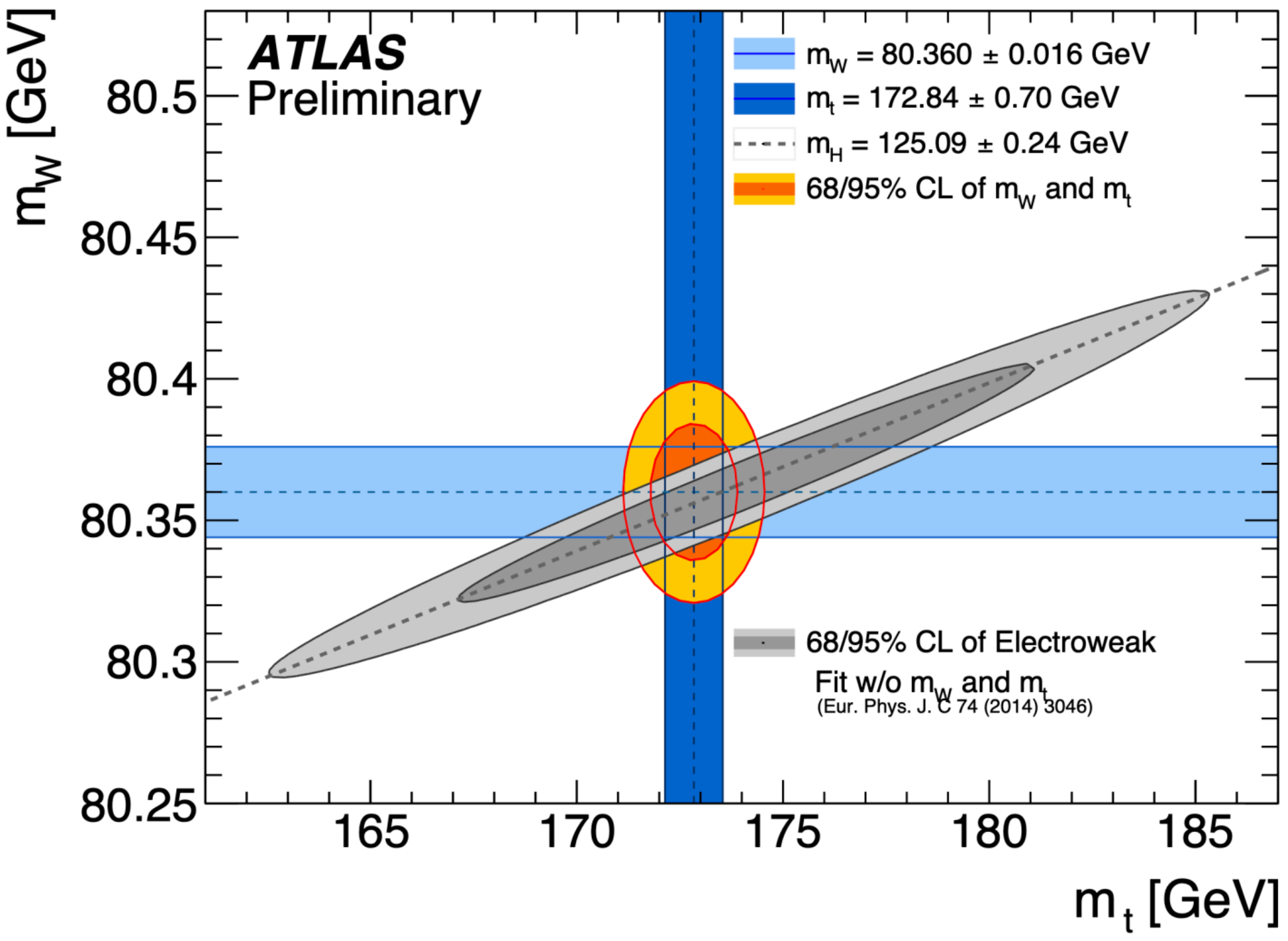
- constrain systematic uncertainties on data
- **m_W** = 80360 ± 5 (stat.) ± 15(syst.) = 80360 ± **16 MeV**

ATLAS-CONF-2023-004

what does this tell us?

- good agreement with electroweak fit
- tension with recent CDF measurement

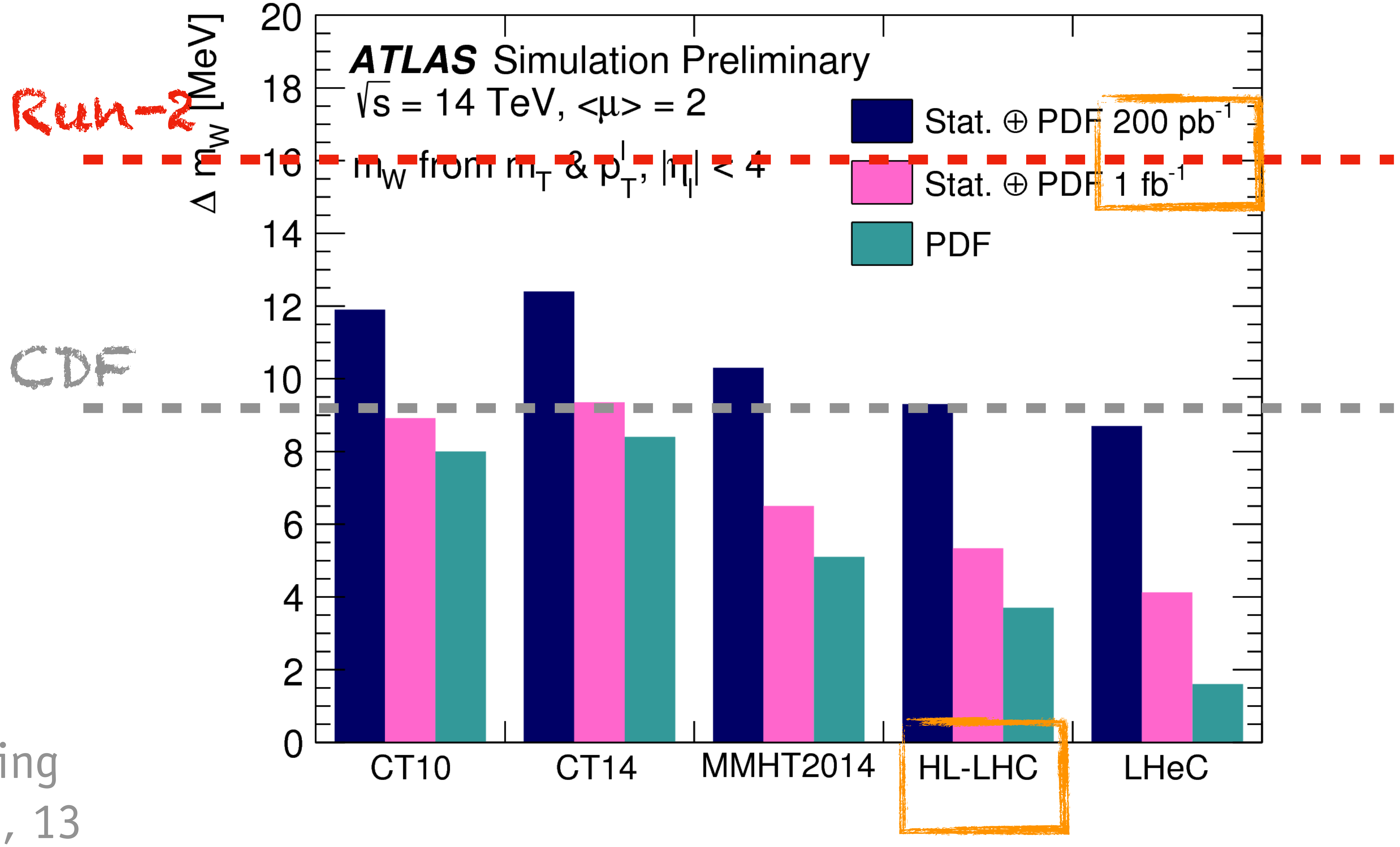




where can this go?

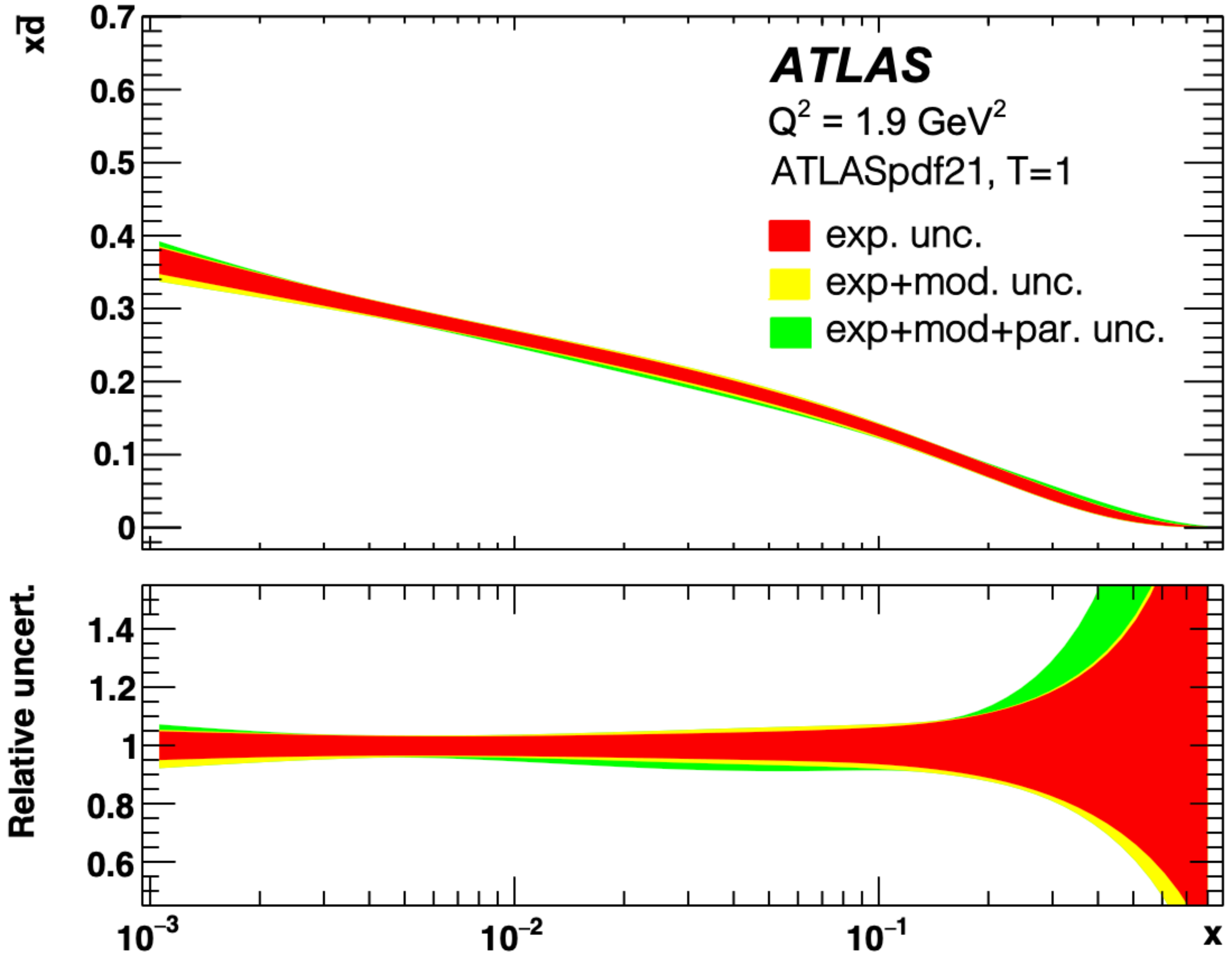
- larger Bjorken's x acceptance from enhanced |η| coverage of LHC Phase-2 detectors
- requires dedicated low-luminosity run
- constrain PDF uncertainties

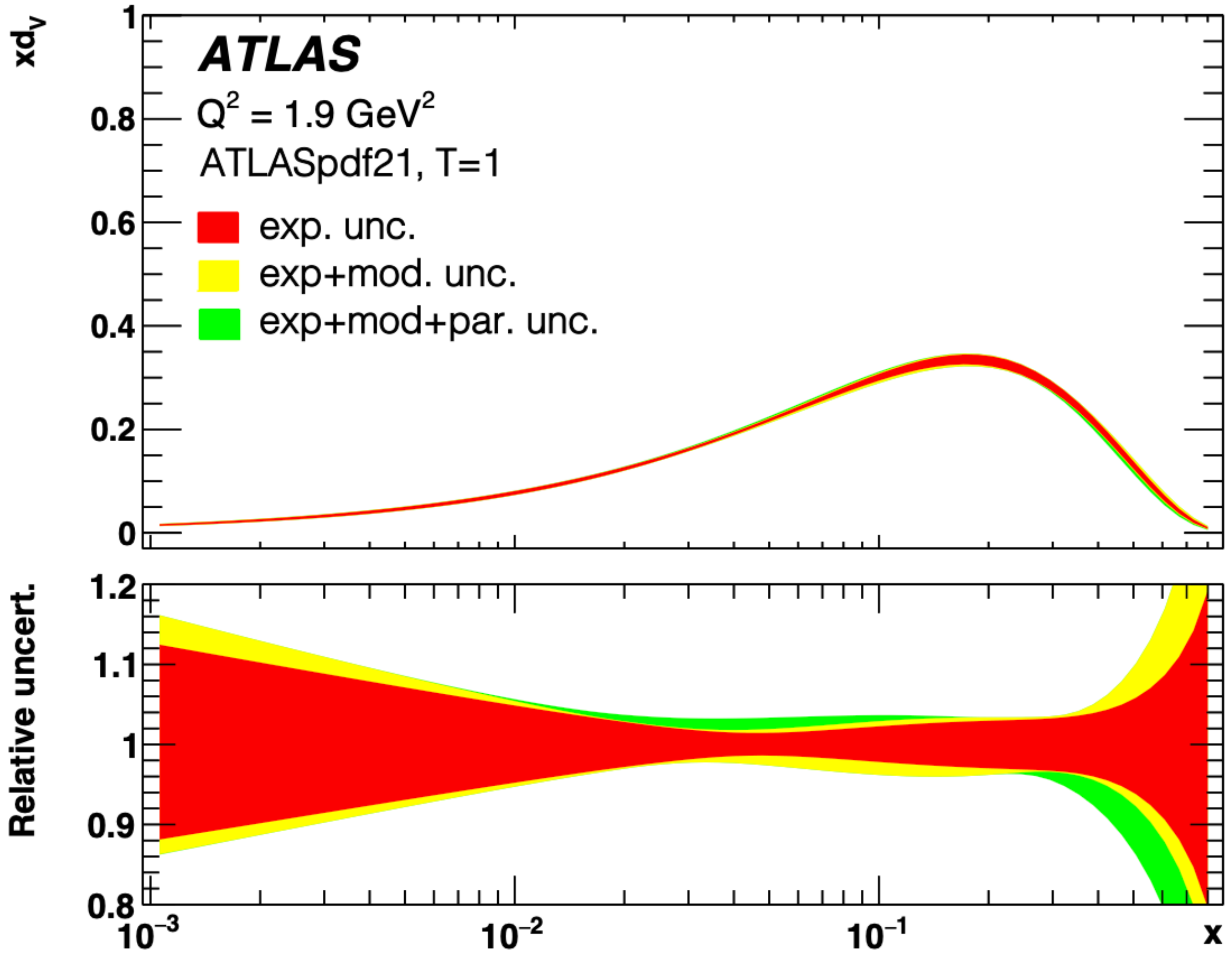
something we've been doing combining HERA and 7, 8, 13 TeV LHC data (e.g. ATLASpdf21)

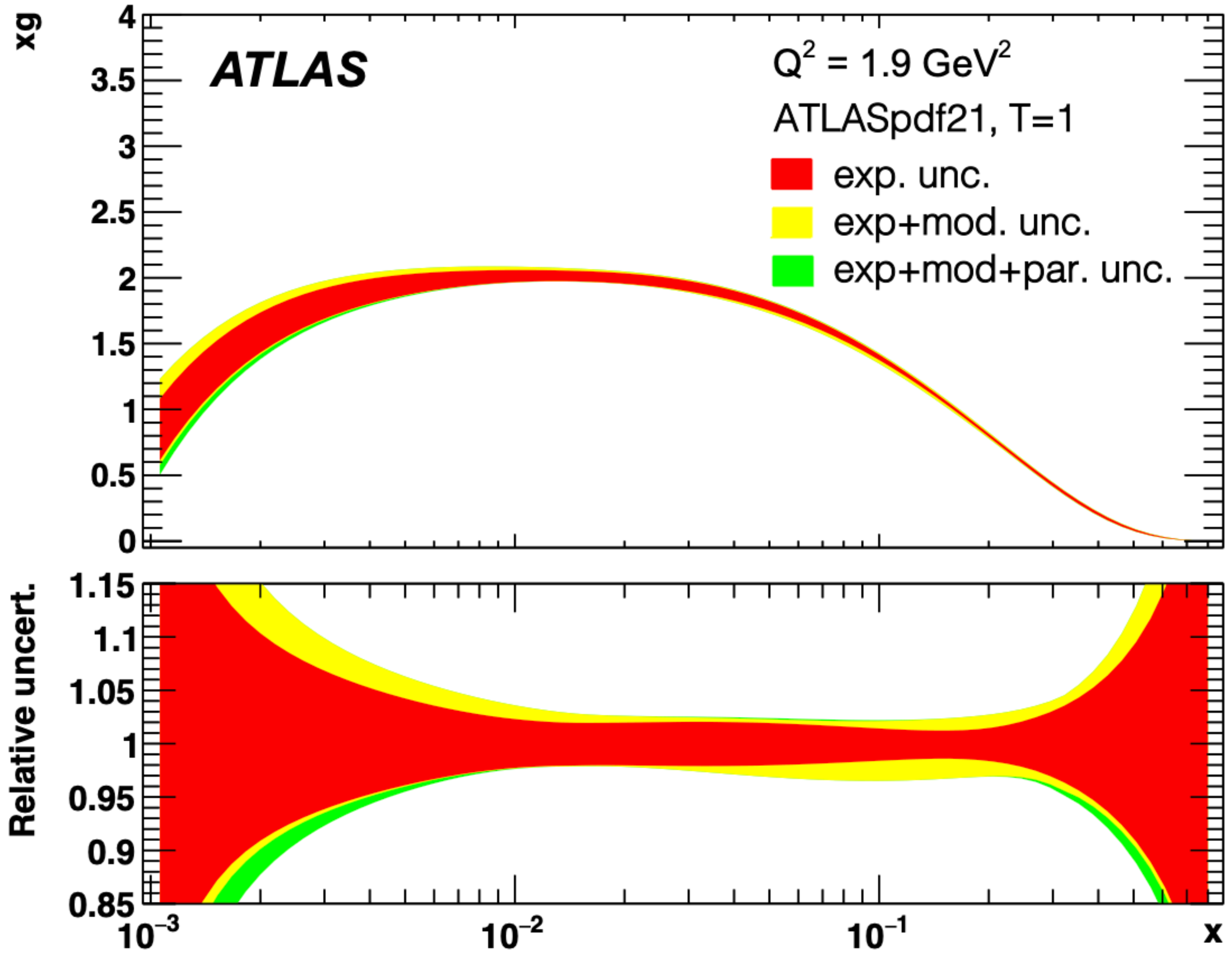


ATL-PHYS-PUB-2018-026, Eur. Phys. J. C 82 (2022) 438

PDFs





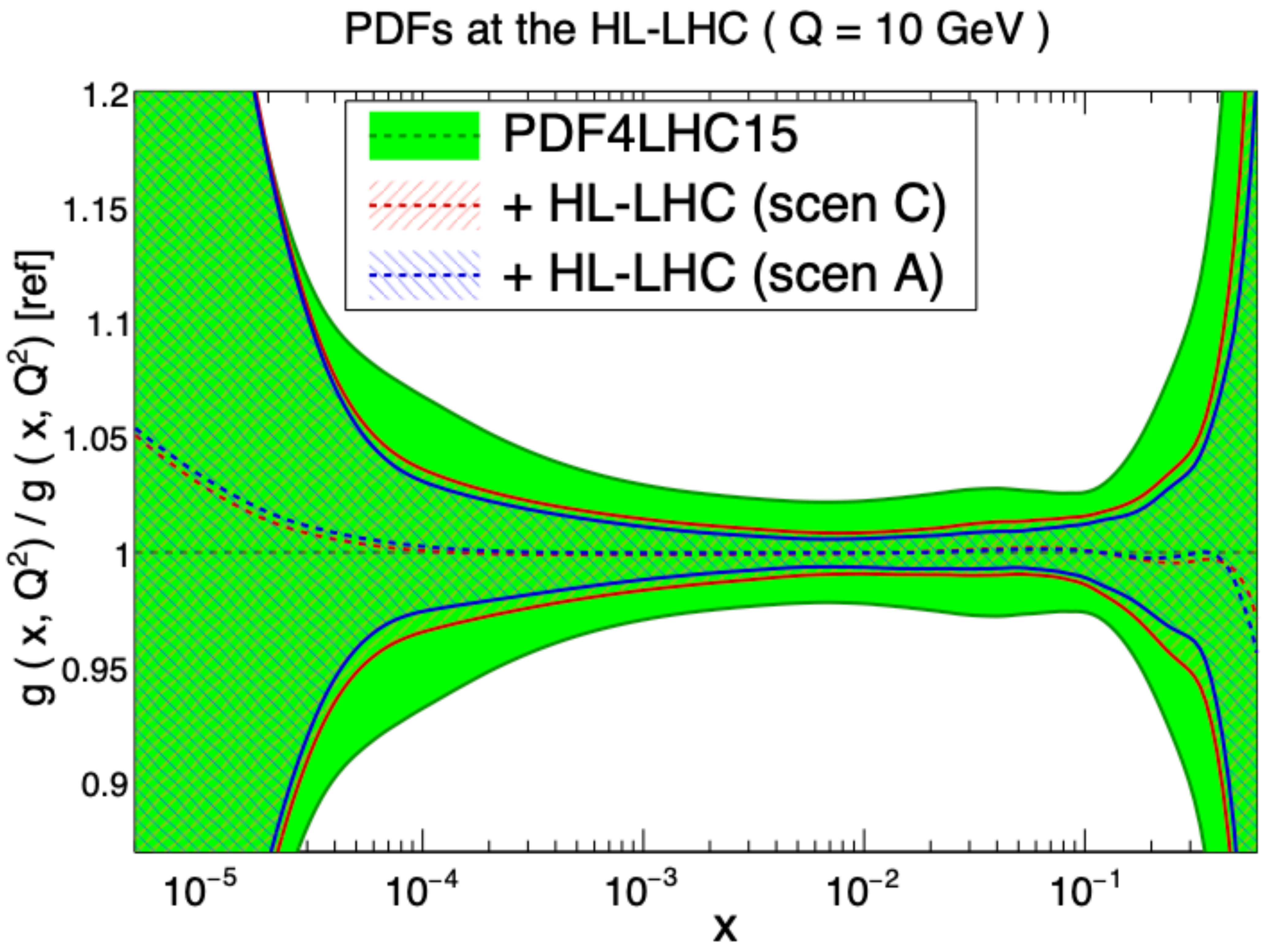


- reduce uncertainties on valence quarks and gluon PDFs
  -V+jets: constrain high-x light-quark sea
  -ttbar: reduce uncertainty in high-x gluon
  -jets: reduce uncertainty in medium-high-x gluon
- not big change when excluding >500 GeV "BSM" region

Eur. Phys. J. C 82 (2022) 438

a subset of "PDF estimation tools"

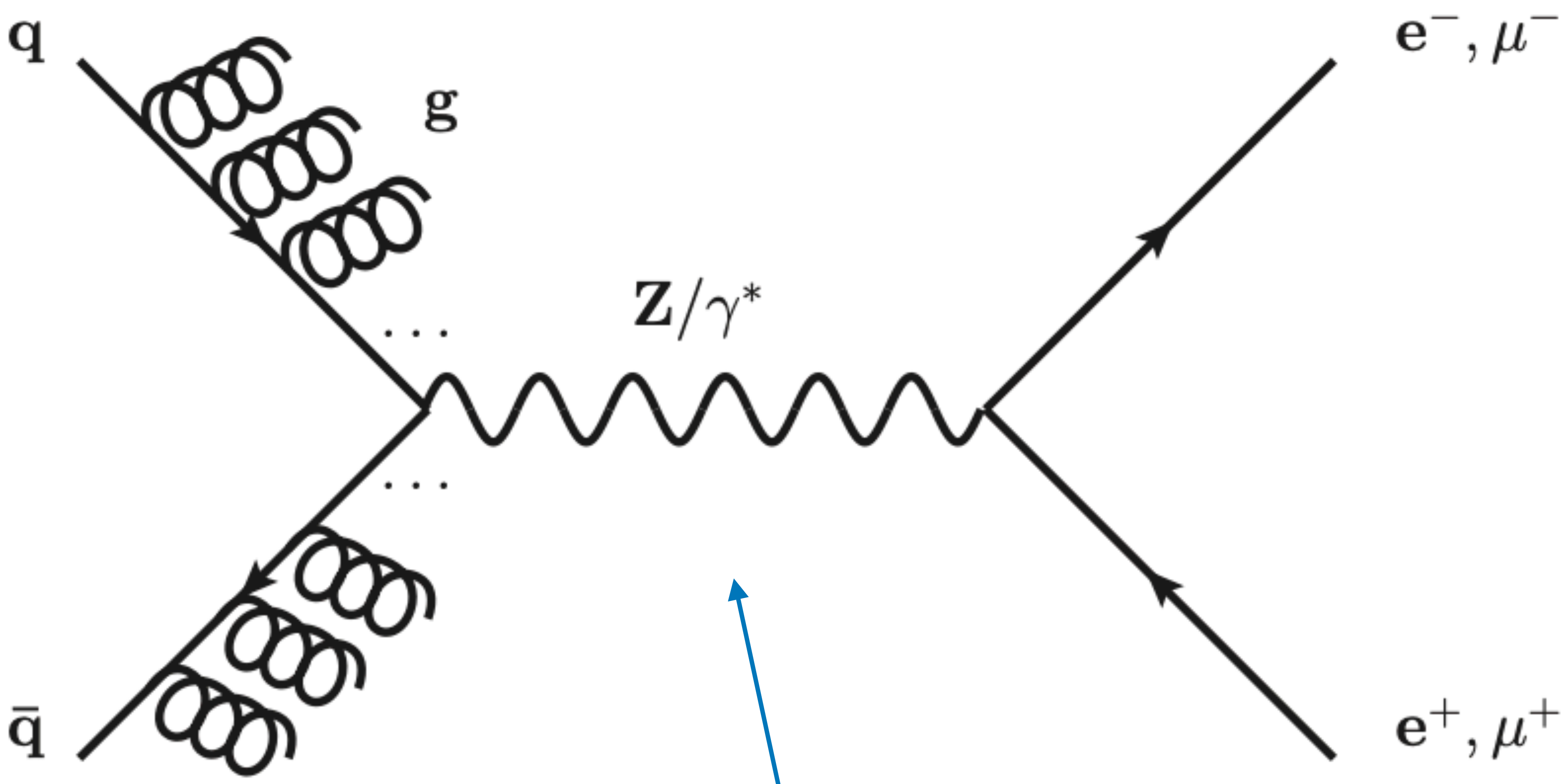
what	notably for
high-mass Drell-Yan	large-x sea quarks
ttbar differential distributions	large-x gluon
high $p_T(Z)$ vs m_{ll}	gluon and anti-quarks, mid-range x
W+c	s
isolated photons	mid-range x
forward Z and W	s, c for large and small x
inclusive jets	large-x gluon, valence quarks

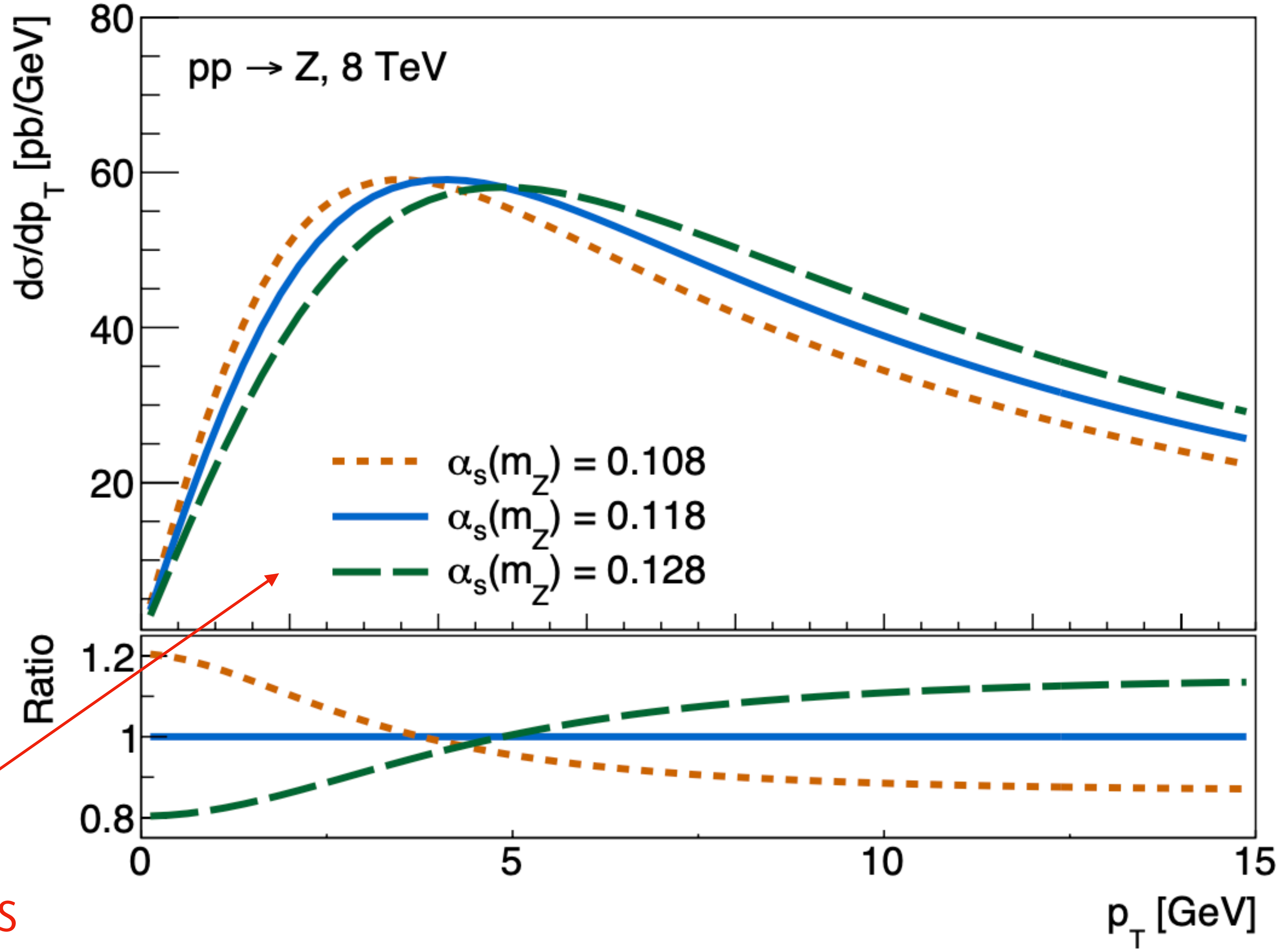


- key message: HL-LHC data should reduce by a factor 2-4 uncertainties on e.g. Higgs boson or SUSY production
- careful programme ongoing with precision measurements at ATLAS and CMS

CERN-2019-007

THE STRONG COUPLING CONSTANT 2023!





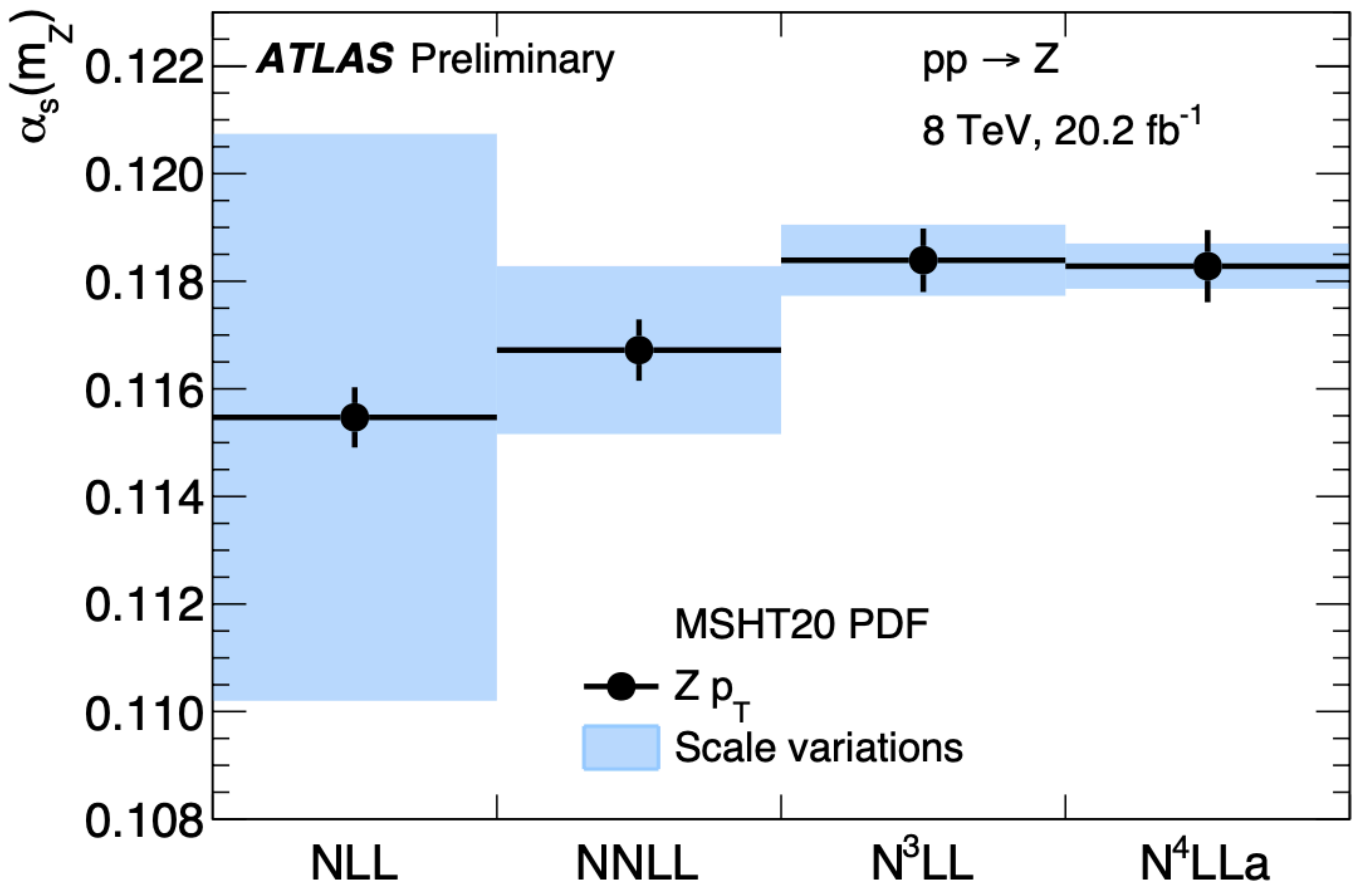
$p_T(Z)$ measures recoil

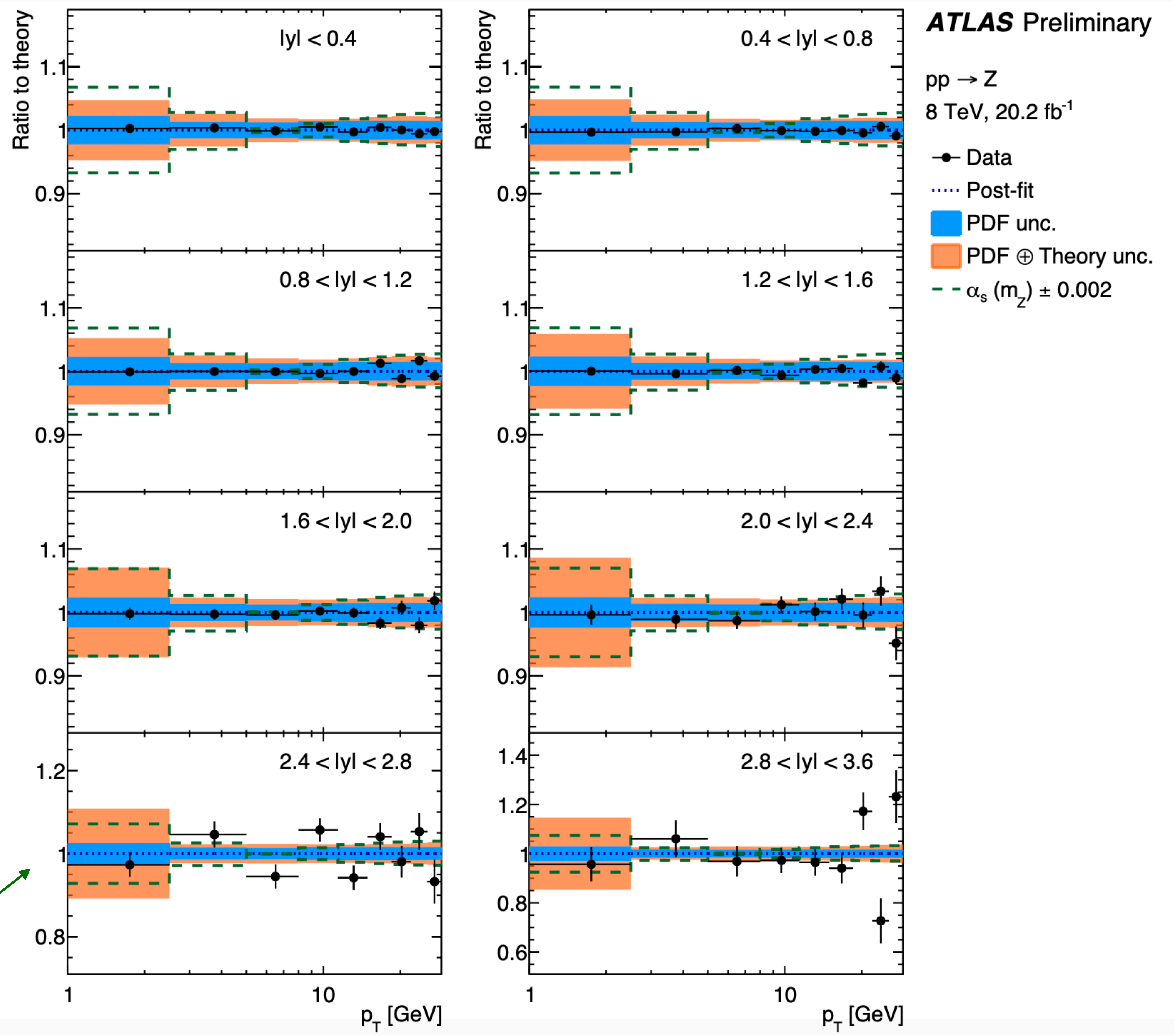
recoil depends on ISR, hence on α_S

- measure at $Q^2 = m_Z^2$
- low $p_T(Z)$ regime not included in PDF fits: less correlation with α_S measurement

ATLAS-CONF-2023-015

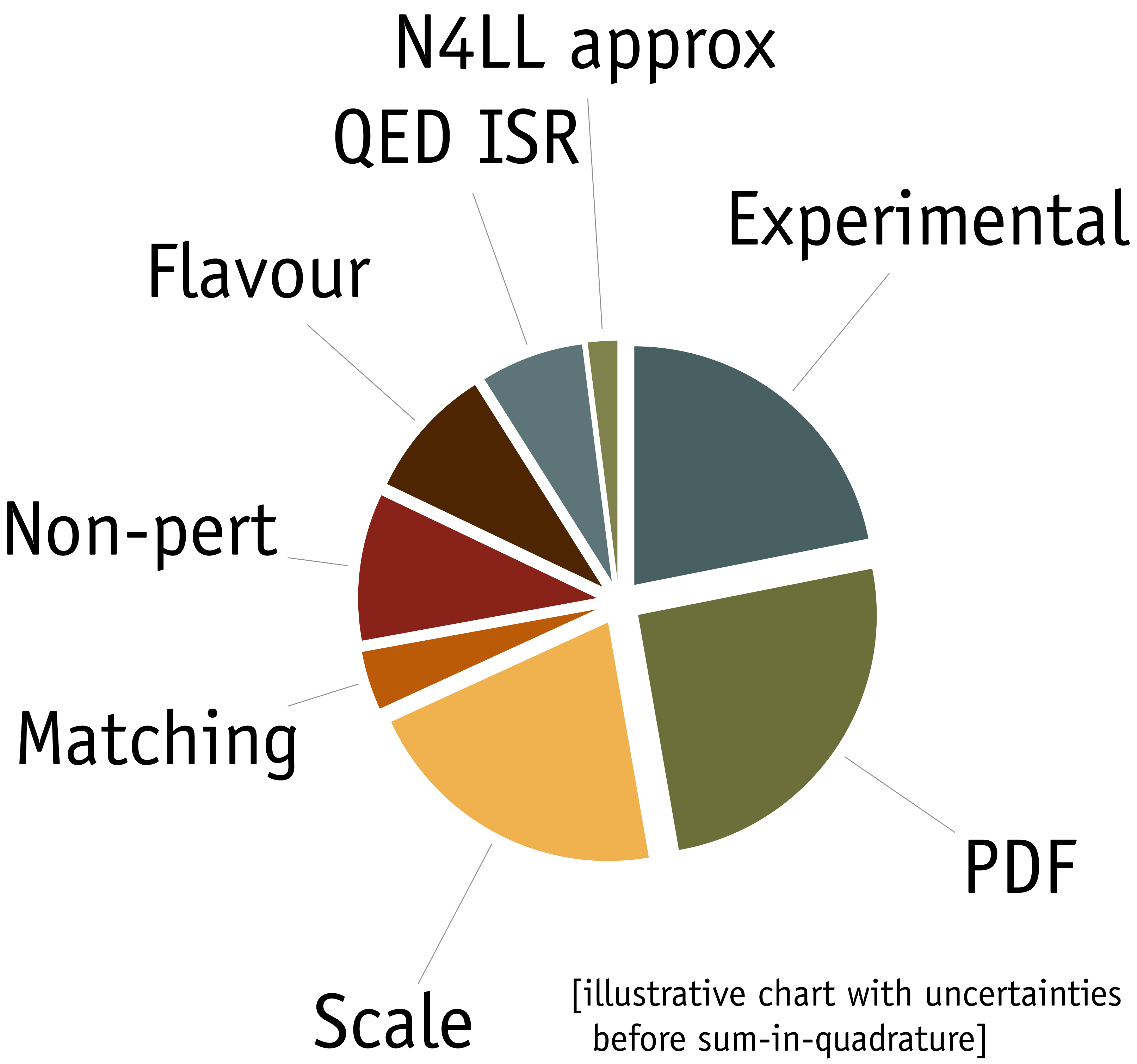
- ~15M Z(ee/μμ) decays (8% with one forward e$^-$)
- σ from Y_{lm} template fits to Collins-Soper angles (extrapolate to full phase space)



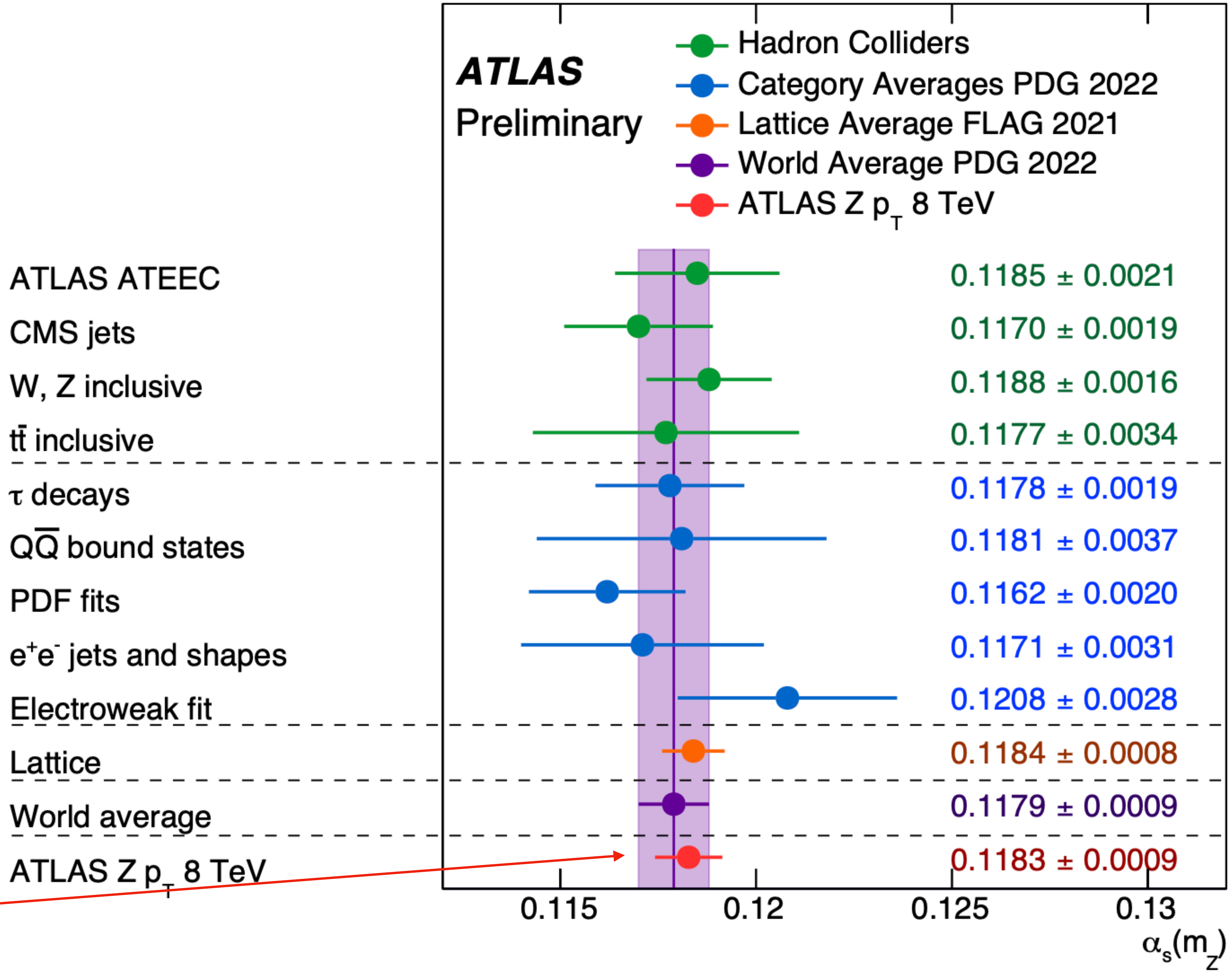


good agreement of theory with double-differential Z p_T/y xsec

(normalization effects within 1.7% luminosity uncertainty)



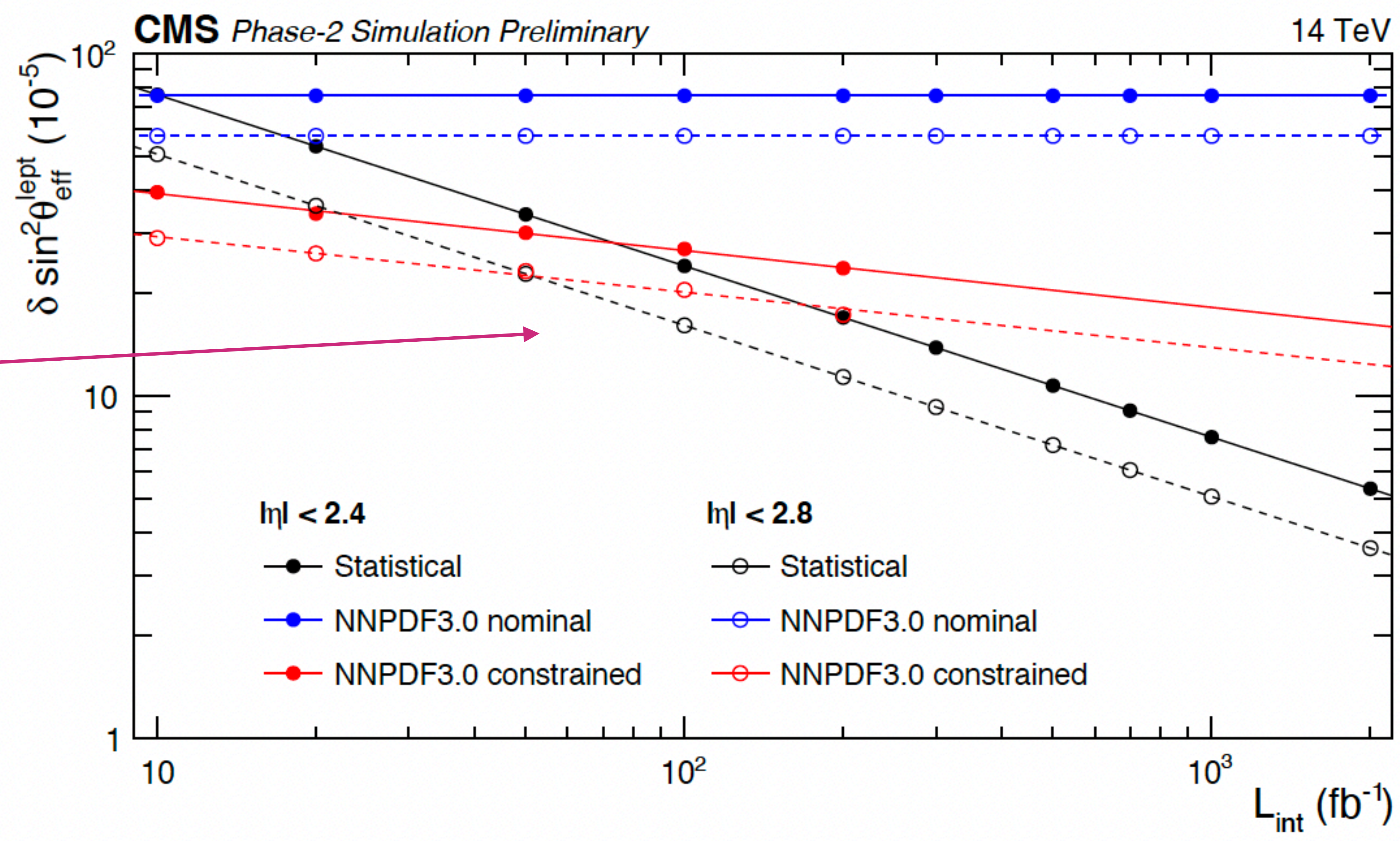
[illustrative chart with uncertainties before sum-in-quadrature]



most precise result
opens new precision era

THE WEAK MIXING ANGLE

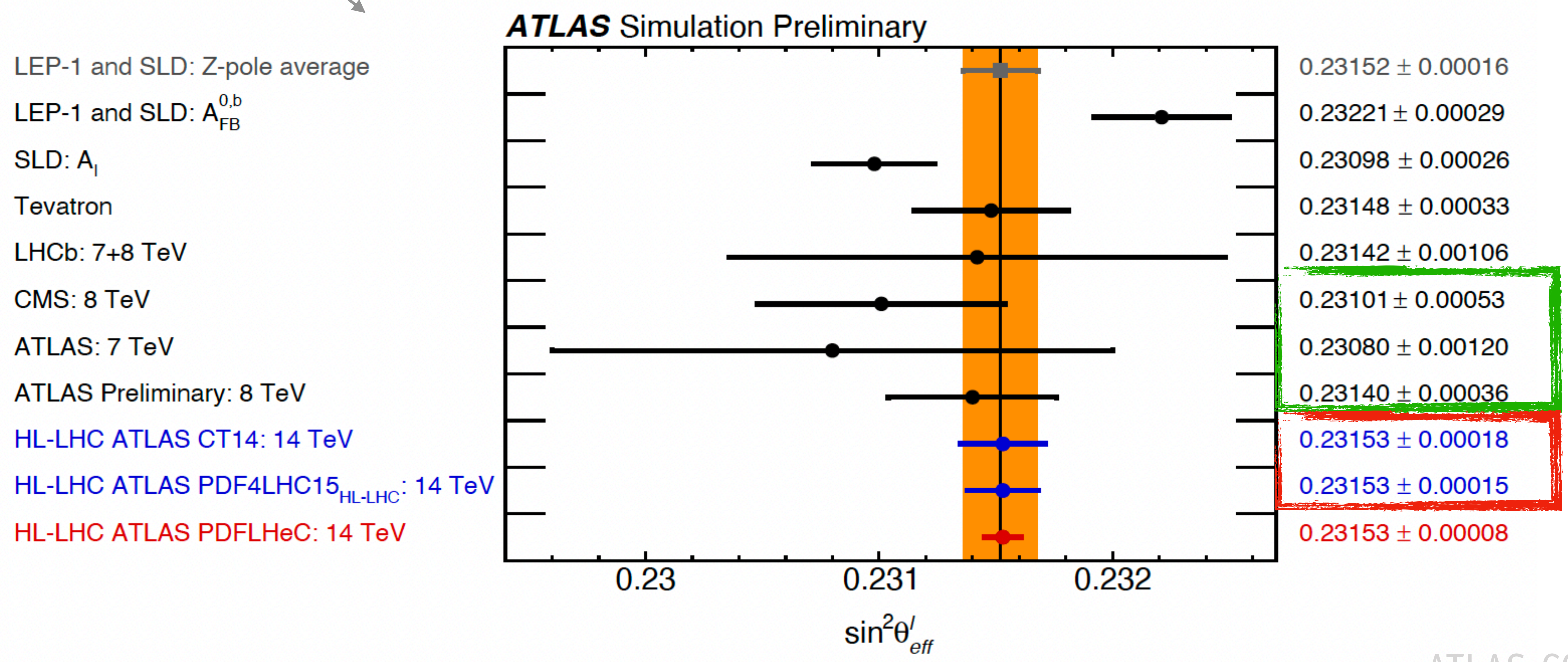
extended inner tracker and muon system coverage (30% more events, 20% more precise PDFs)



0.4%

0.07%

O(10%) improvement from HGTD



0.2%

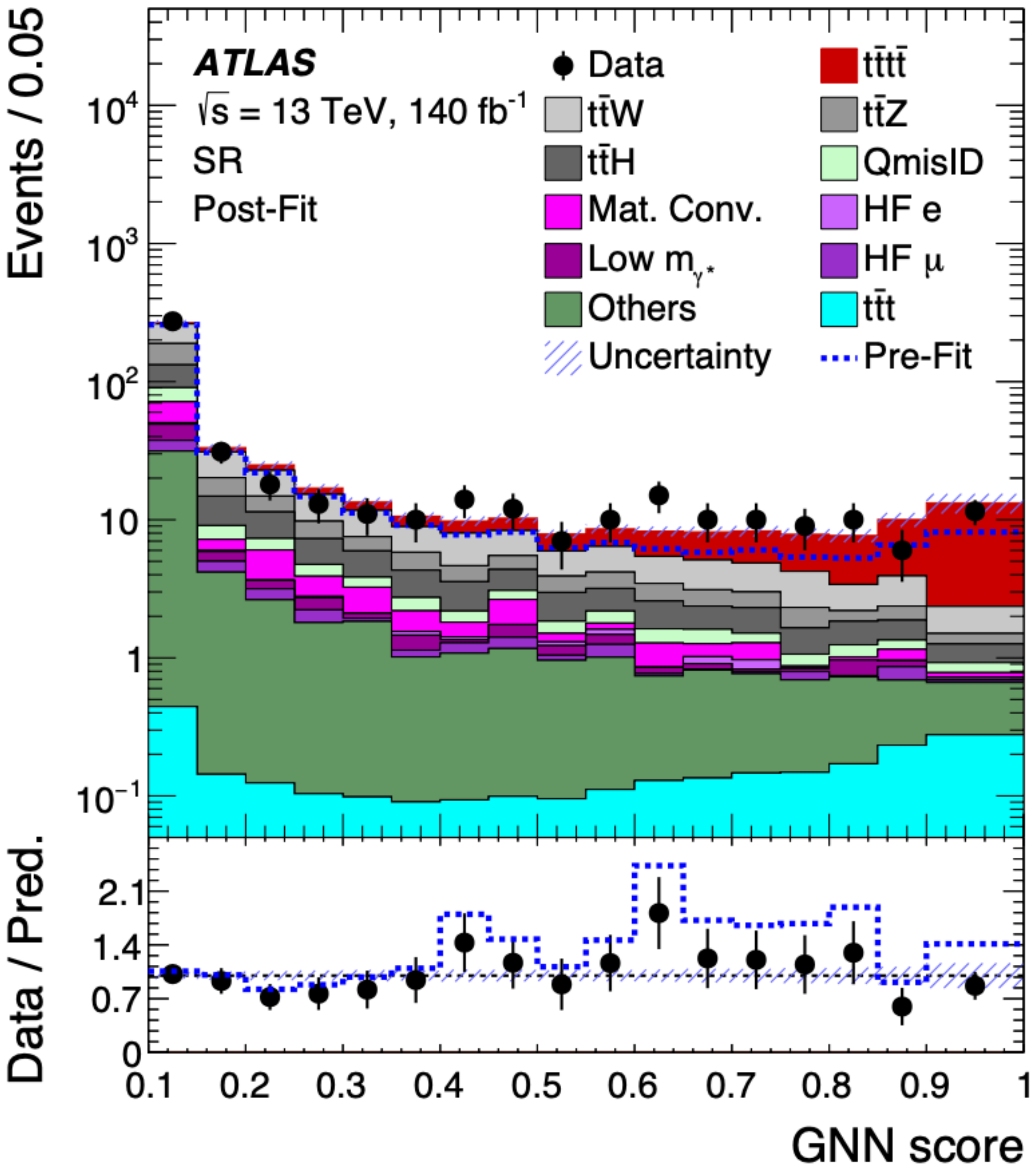
- from fit to A_{FB} vs rapidity, mass
- can reach LEP+SLD 0.07% precision with ee & μμ
- HL-LHC results dominated by PDF uncertainties

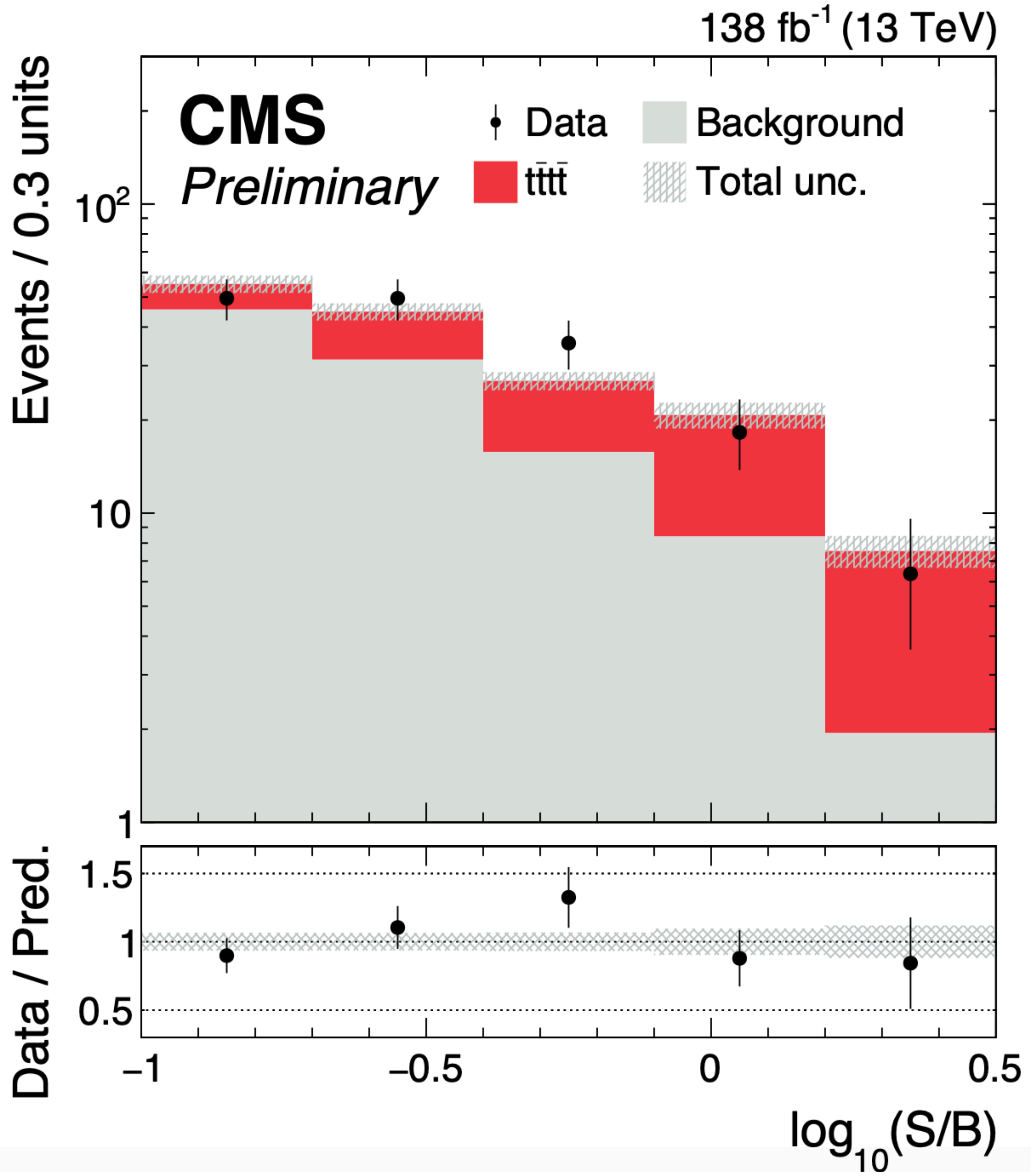
ATLAS-CONF-2018-037, ATLAS-TDR-031, CMS-PAS-FTR-17-001

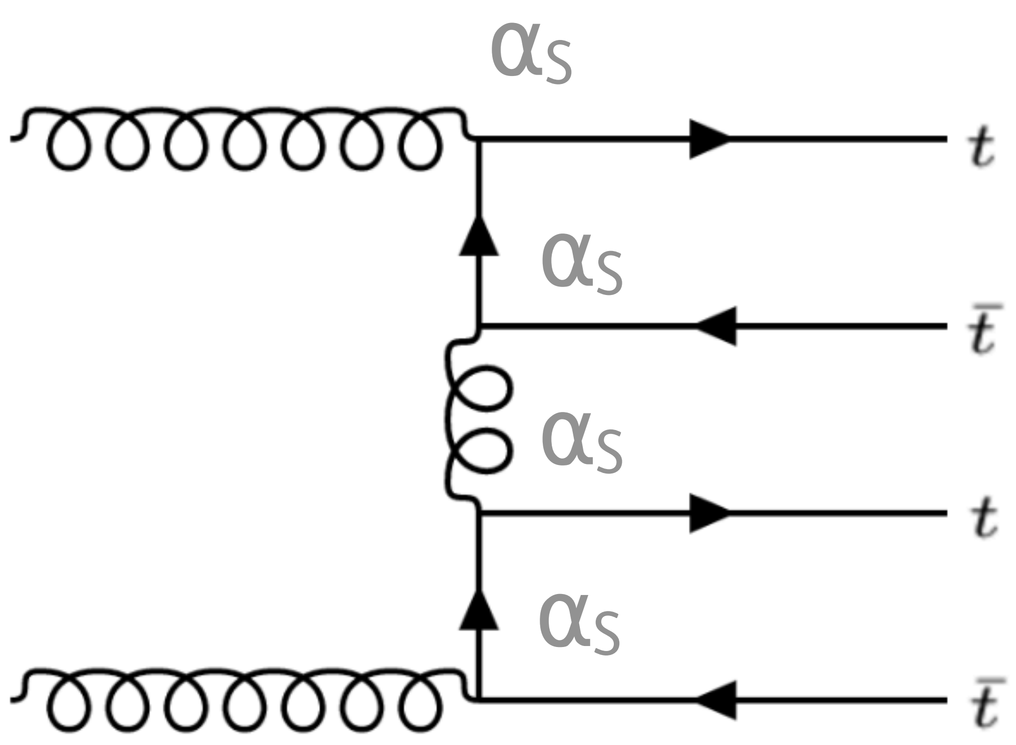
to the place where the possible
and the impossible meet

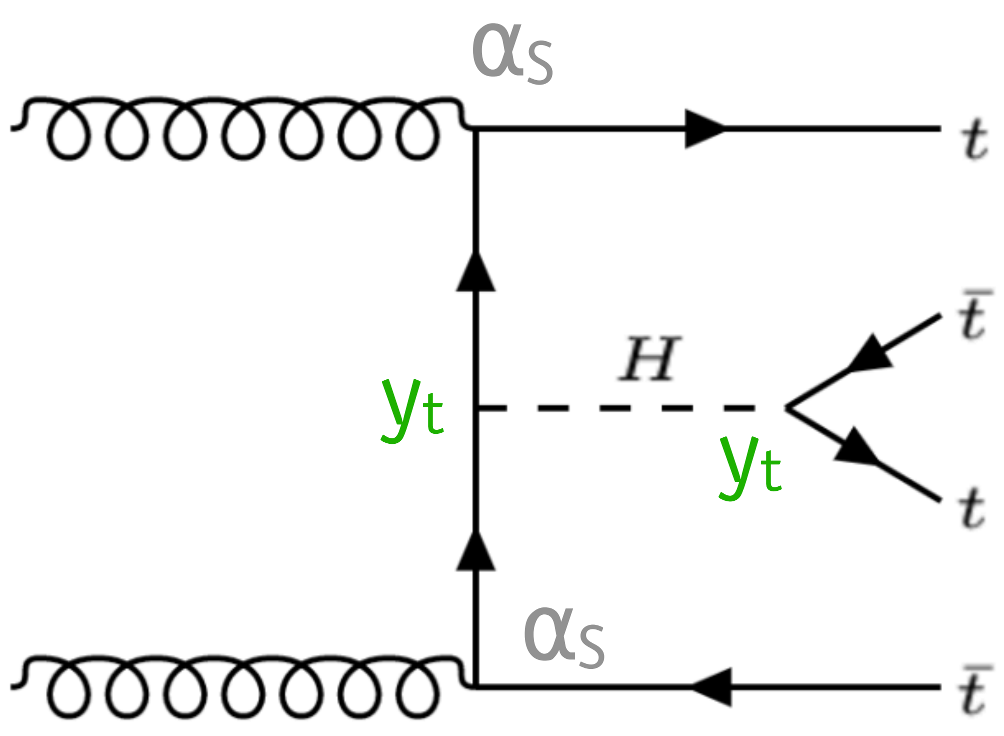
FOUR TOP-QUARK PRODUCTION 2023!

- sensitive to new physics
- best with 2+ lepton channels
- relies on measurement of irreducible ttW background (ATLAS) / simultaneous fit of σ(ttW), σ(ttZ), σ(tttt) (CMS)
- **reached >5σ** with optimised selection and b-tagging



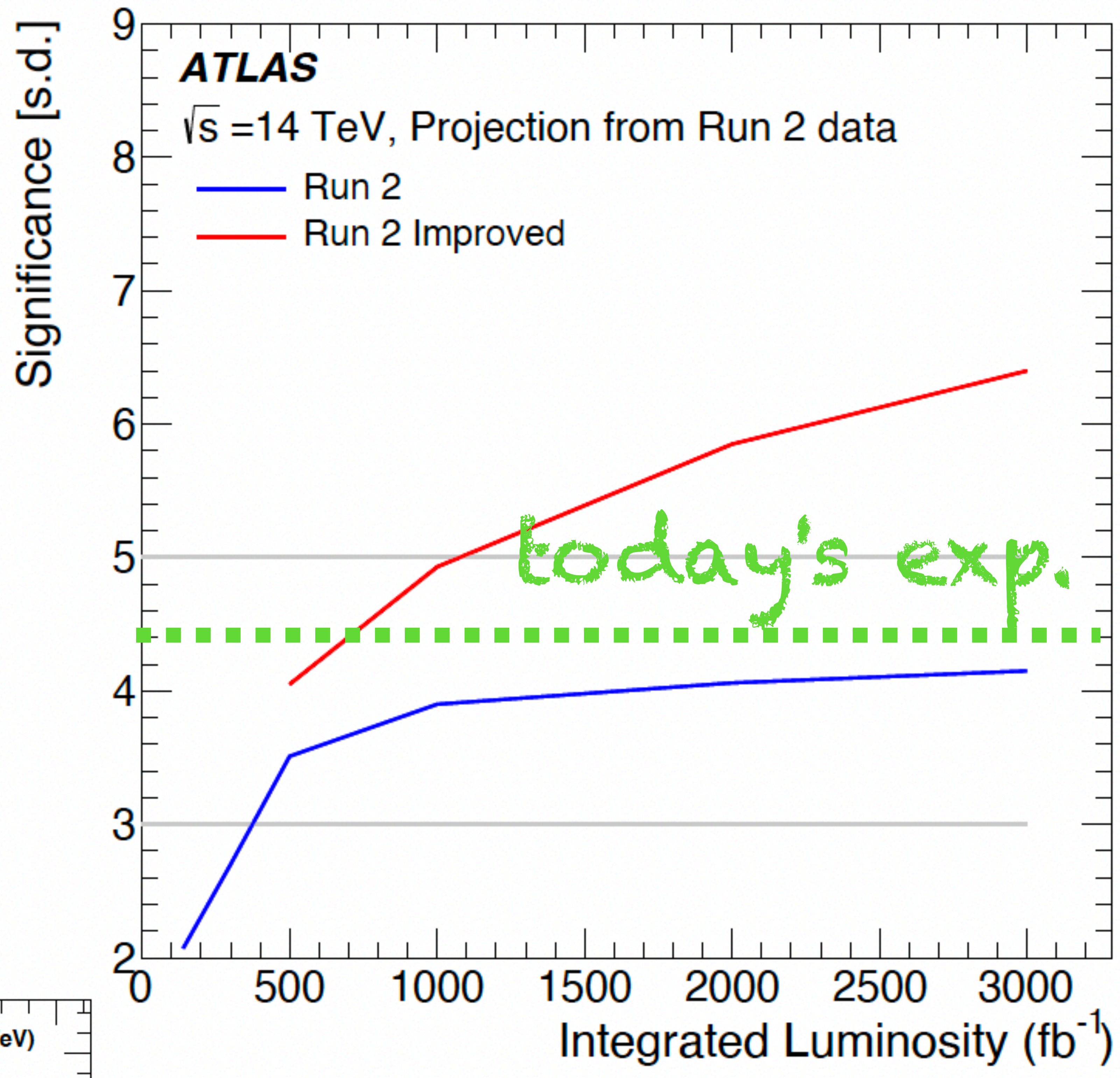


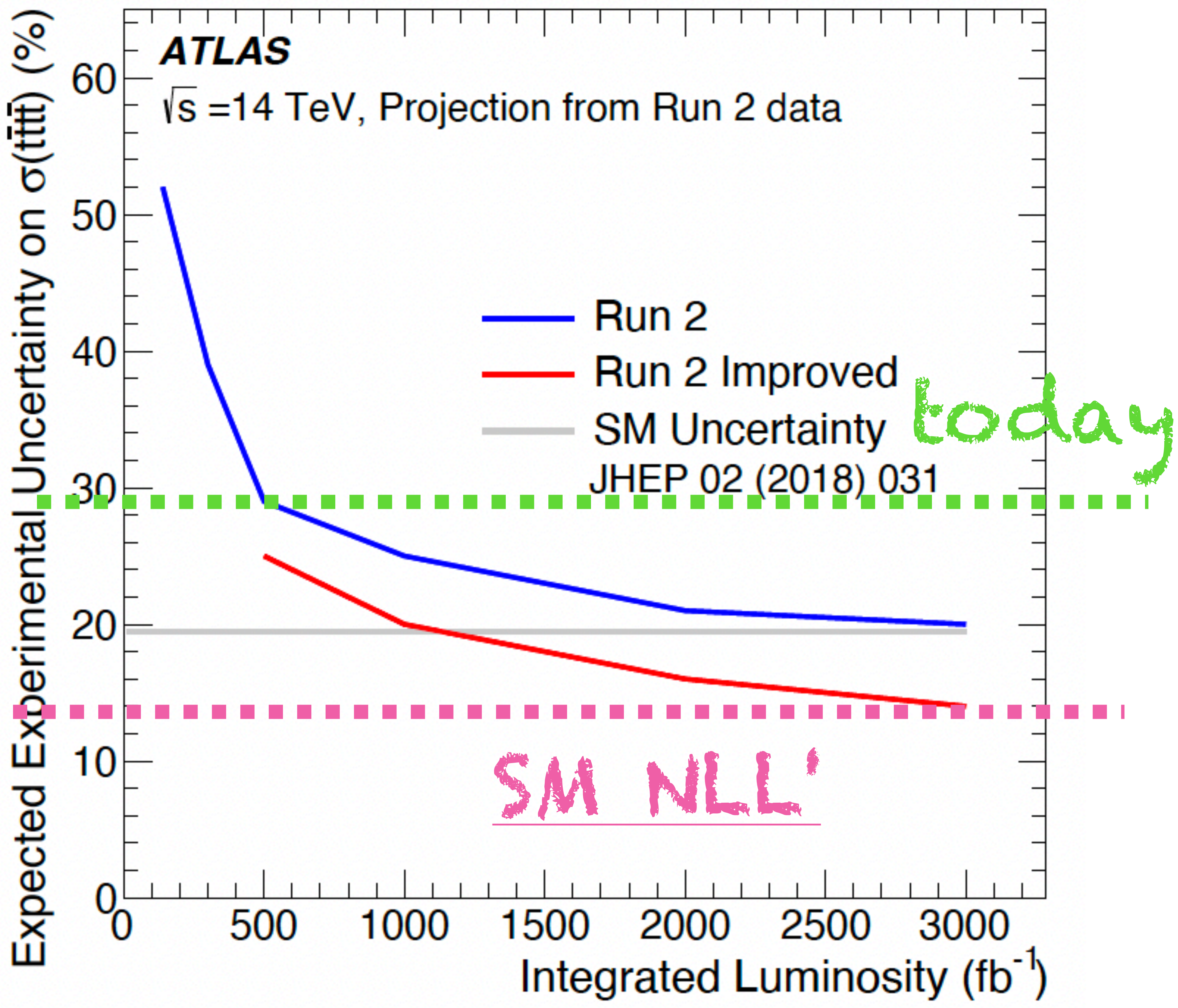




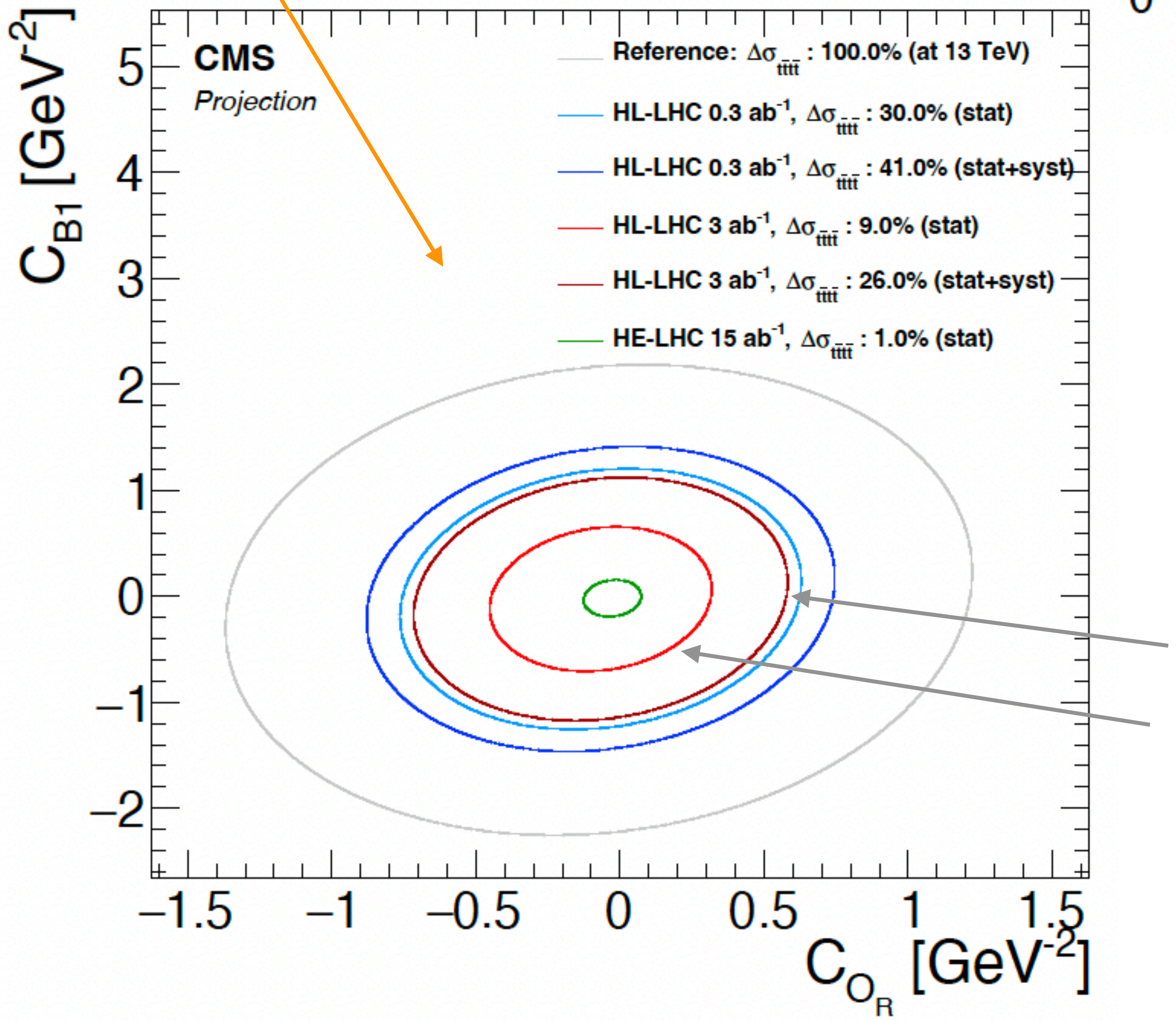
leitmotiv: improved background estimation techniques and Machine Learning (ML) are making LHC exceed expectations

arXiv:2303.15061, CMS-PAS-TOP-2022-013





tttt contact interaction



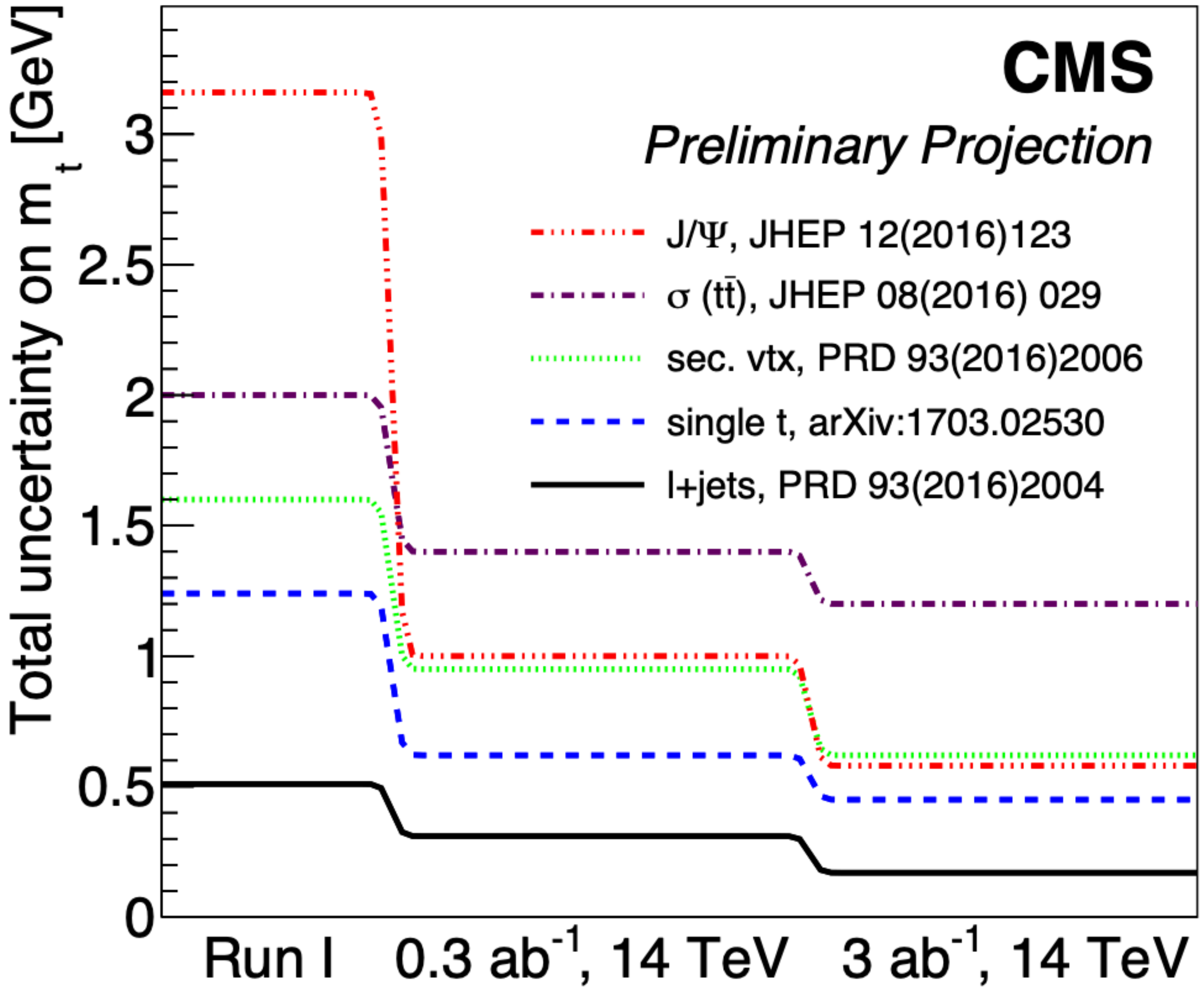
stat+syst

stat only

- HL-LHC dominated by systematics
- crucial aspects: ttV+HF modeling, and b-tagging
- theory error is competing...

ATL-PHYS-PUB-2022-004, CMS-PAS-FTR-18-031

THE TOP-QUARK MASS



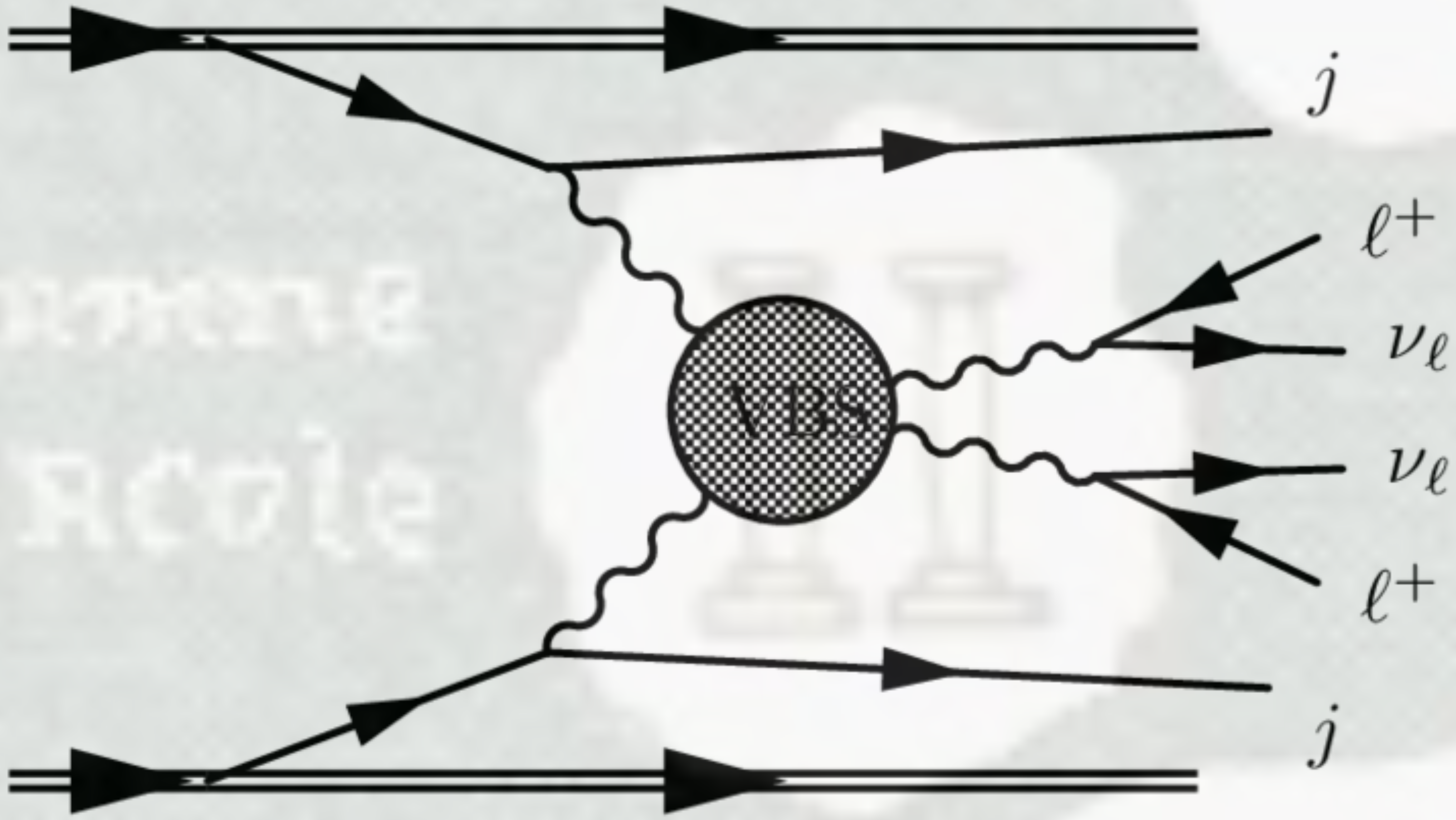
today:

- top-quark mass measured to less than 0.3%
- ttbar cross-section to 1.8%

tomorrow

- can go to ~0.1%
- requires same detector performance as pre-HL phase
- MC modelling is crucial!

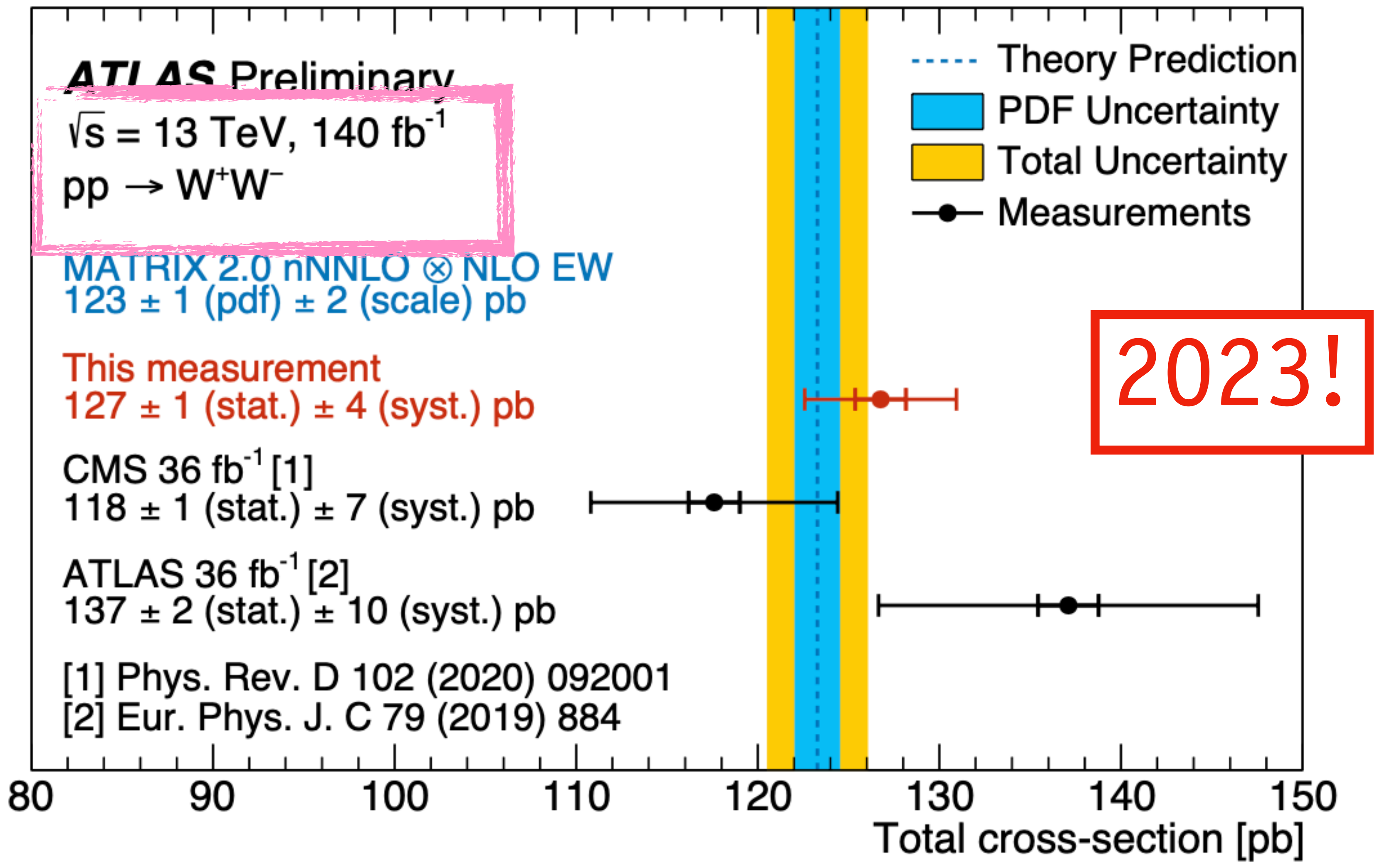
CMS-PAS-FTR-18-031



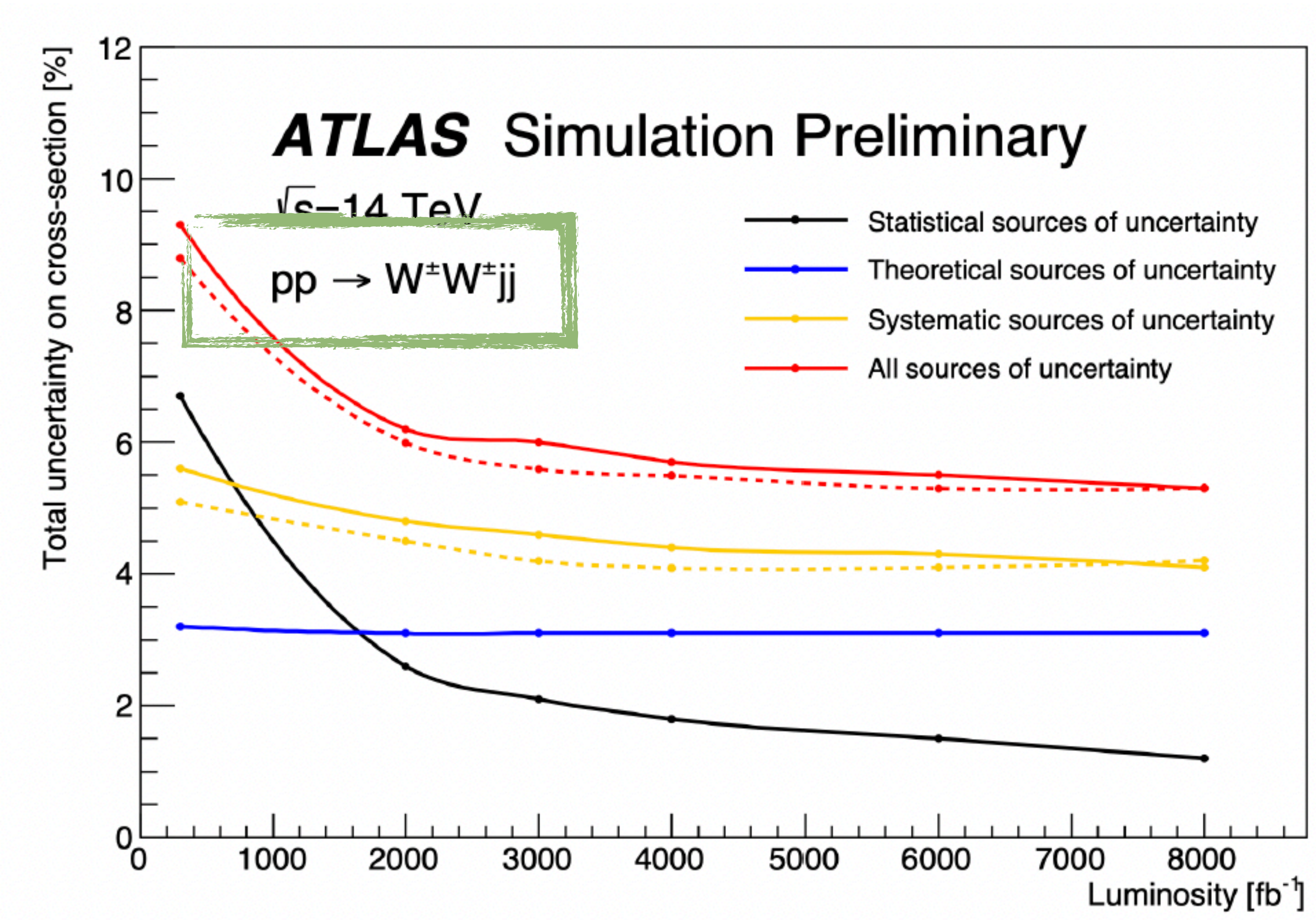
Higgs-solved?

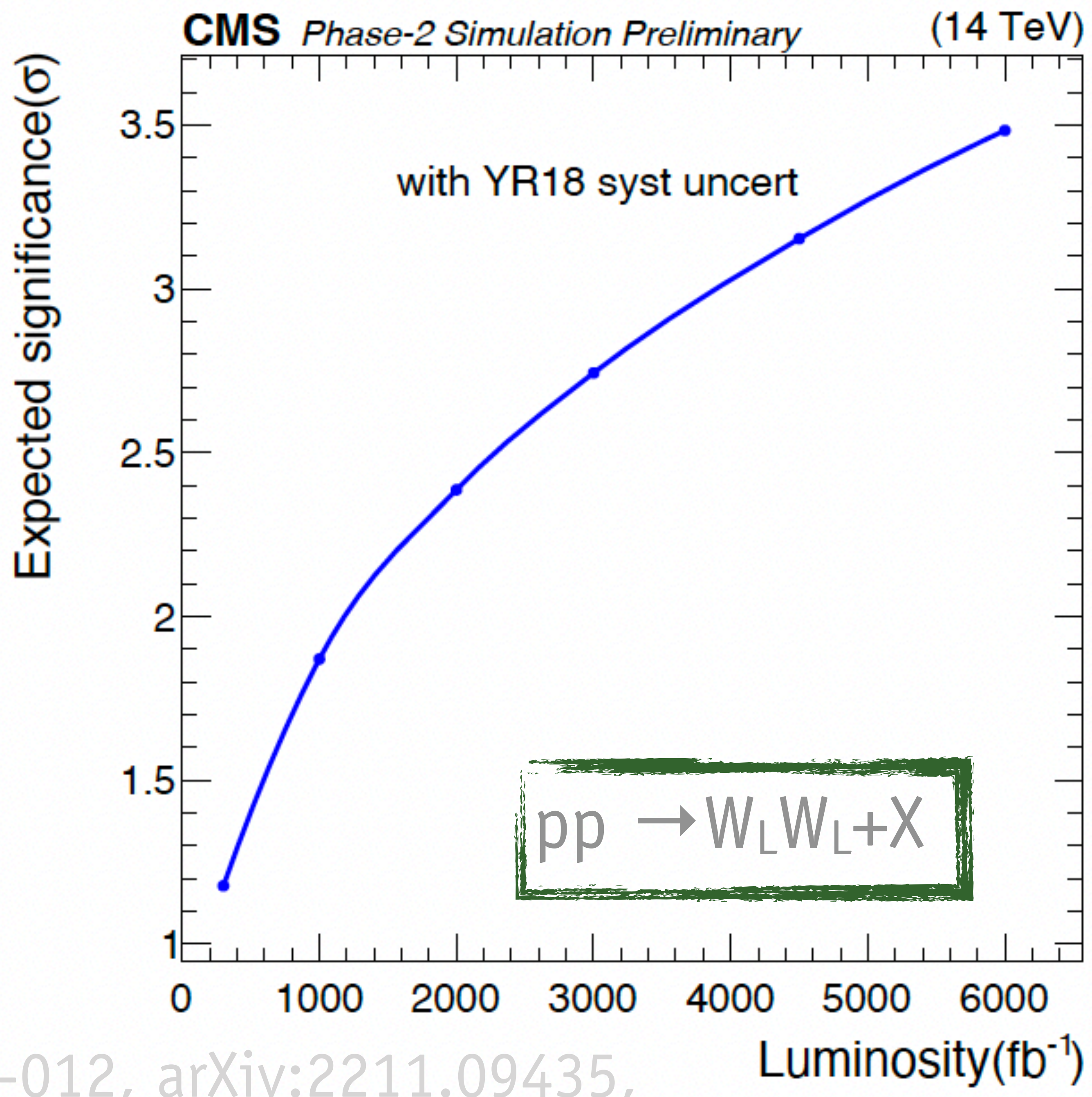
VECTOR-BOSON SCATTERING

- diboson physics reached few % precision already (left: WW)
- VBS: confirmed all major channels with Run-2 data
- e/μ final states: from **>20%** (Run-2) to **3%** (WW)-**10%** (ZZ) precision at HL-LHC thanks to **increased statistics** and **|η| coverage**
- also **semi-leptonic** with ML substructure
- longitudinally-polarised-V scattering puts **BEH mechanism** at a test (e.g. Run-2 W_LZ_L at 7σ)



2023!

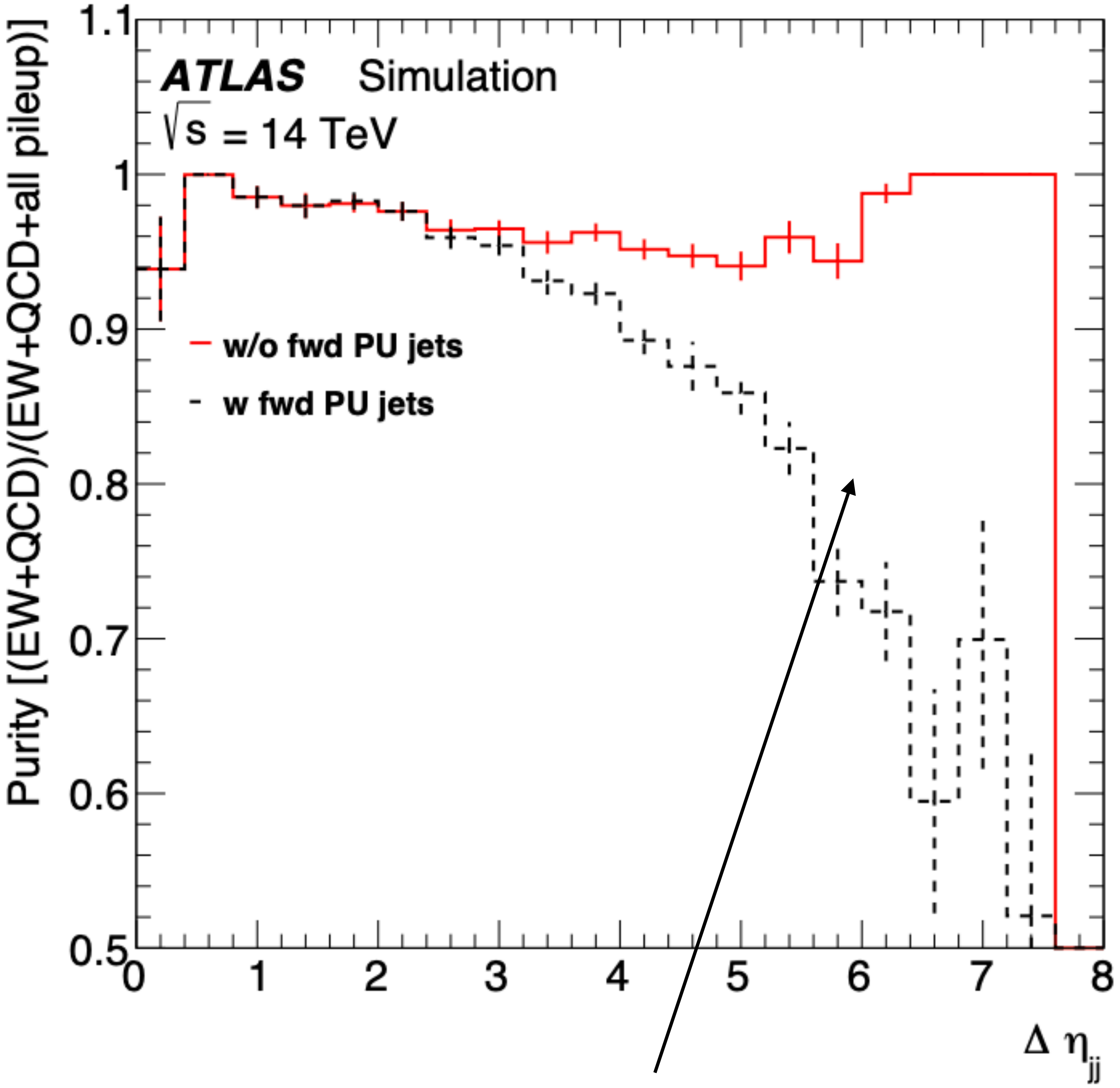




HL-LHC reach might be a playground for more advanced analysis techniques

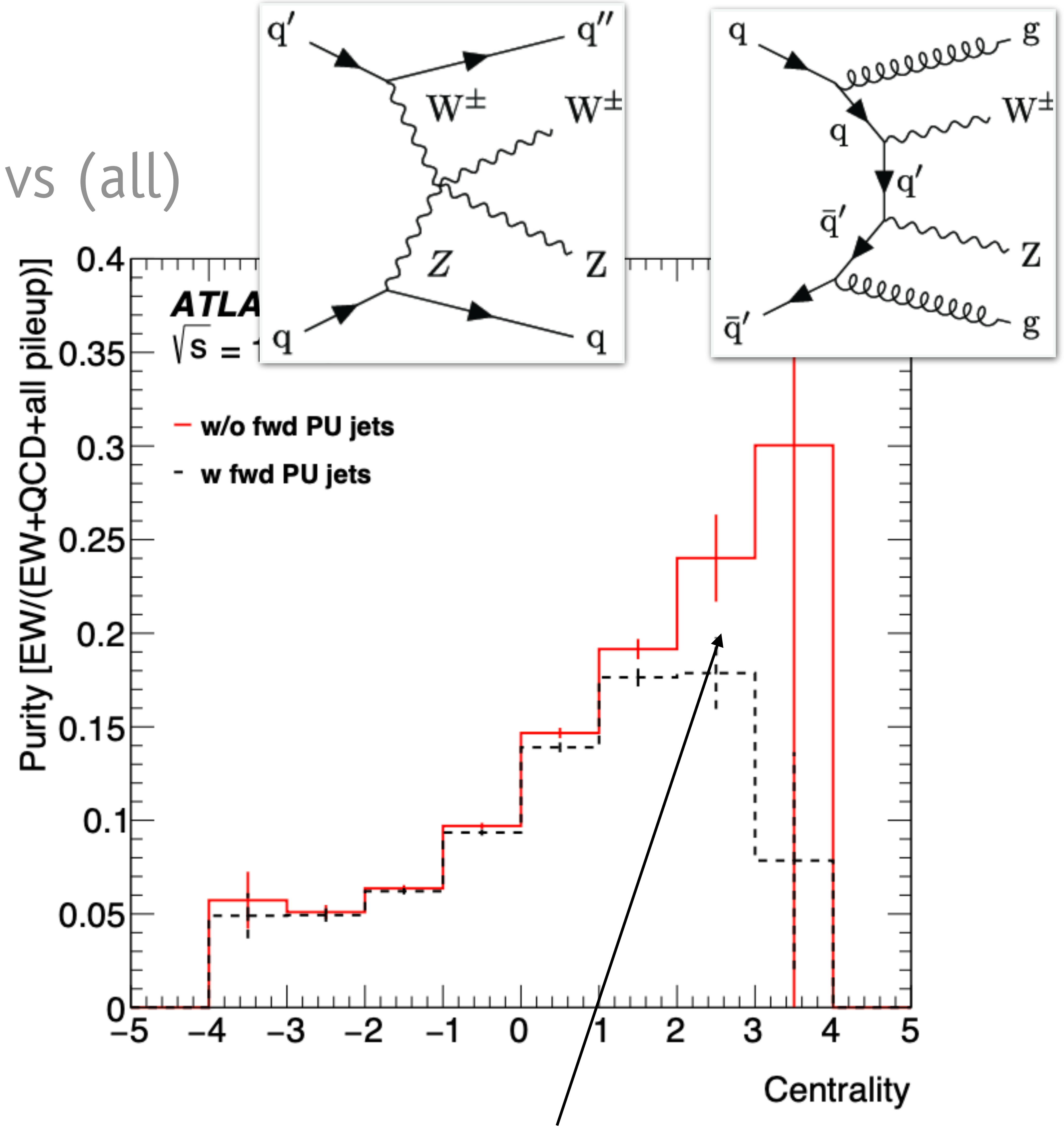
ATLAS-CONF-2023-012, arXiv:2211.09435, ATL-PHYS-PUB-2018-052, CMS-PAS-FTR-18-005

WZjj purity vs (WZjj+pileup)



pile-up suppression with HGTD will improve sensitivity to high-q² new physics

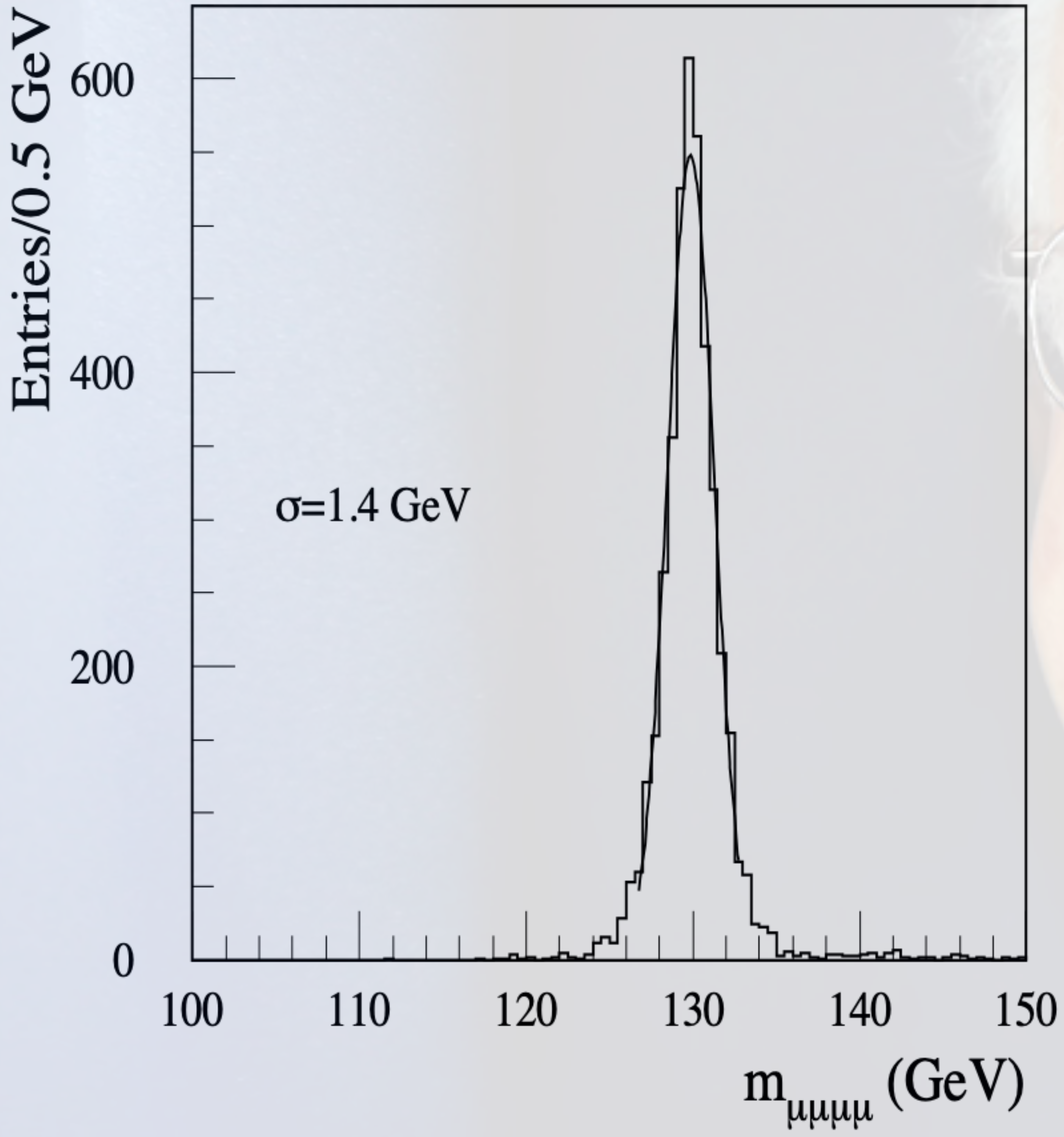
EW vs (all)



high centrality to discriminate QCD and EW WZ production

ATLAS-TDR-031

$H \rightarrow ZZ^* \rightarrow 4l$ projections for 30 fb^{-1}

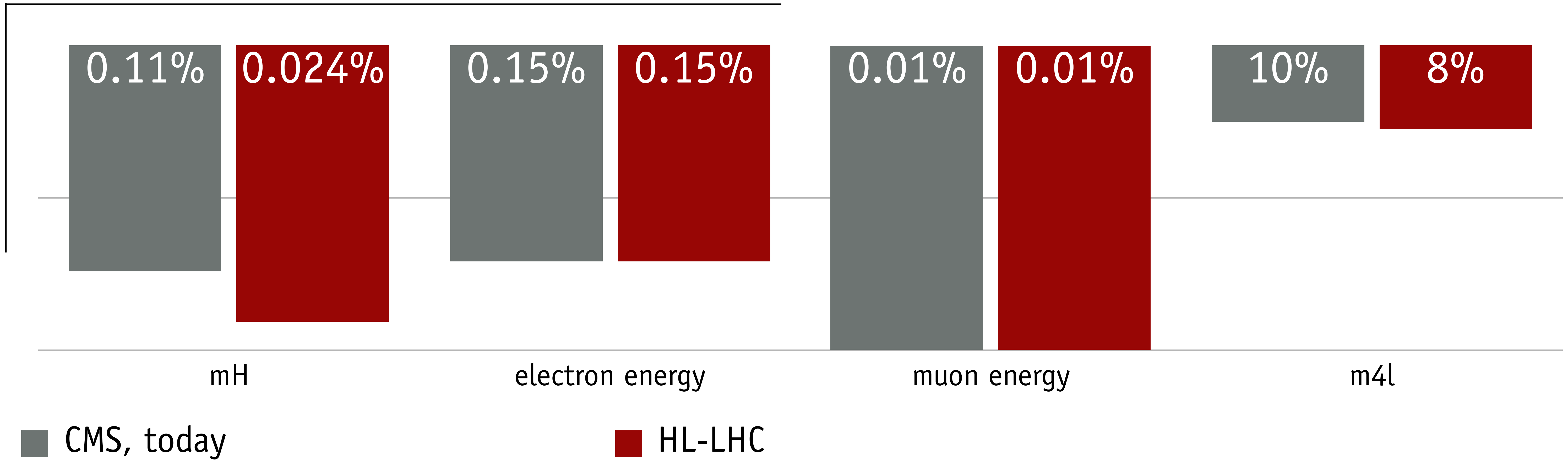


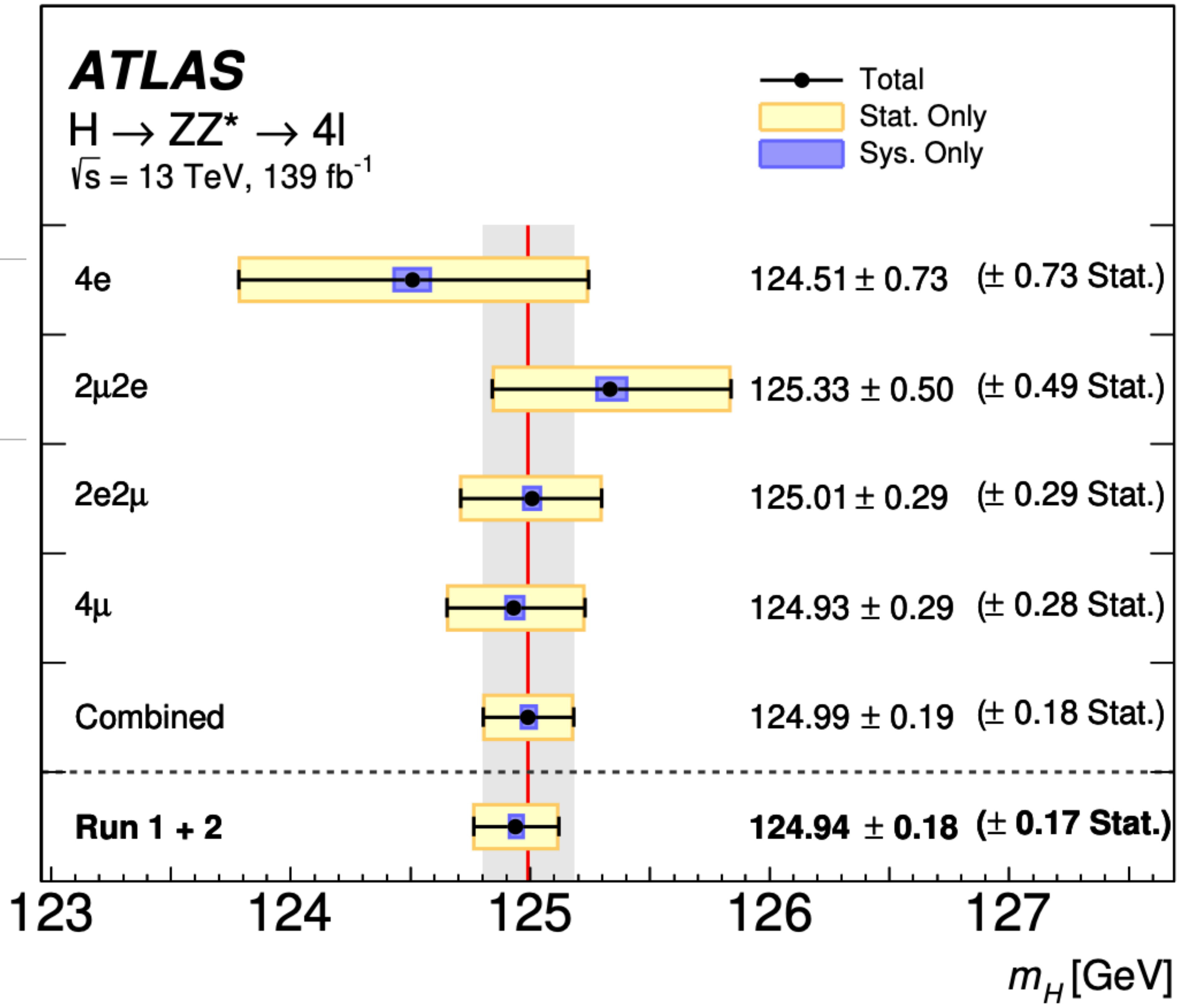
Higgs mass (GeV)	**120**	**130**
Signal	4.1	11.4
$t\bar{t}$	0.01	0.02
$Zb\bar{b}$	0.08	0.12
ZZ^*	1.23	2.27
$ZZ \rightarrow \tau\tau ll$	0.13	0.20
Significance ($S/\sqrt{B}$)	3.4	7.0
Significance (Poisson)	2.4	4.8

[1999]

ATLAS TDR 15

HIGGS BOSON: THE MASS

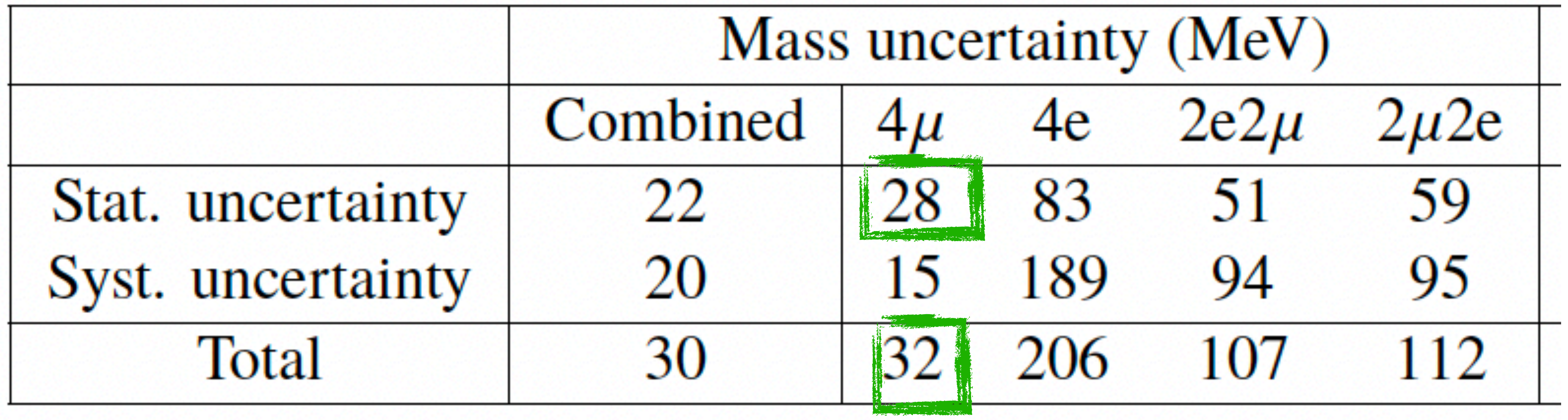




- HL-LHC: ~30 MeV uncertainty (4.5x better)
  - improved by beam-spot information (+5%)
  - Z mass constraint and per-event errors (+10%)
  - ZZ/H(ZZ) matrix-element discriminant (+4%)
  - assuming same e/μ energy scale/resolution as in Run-2

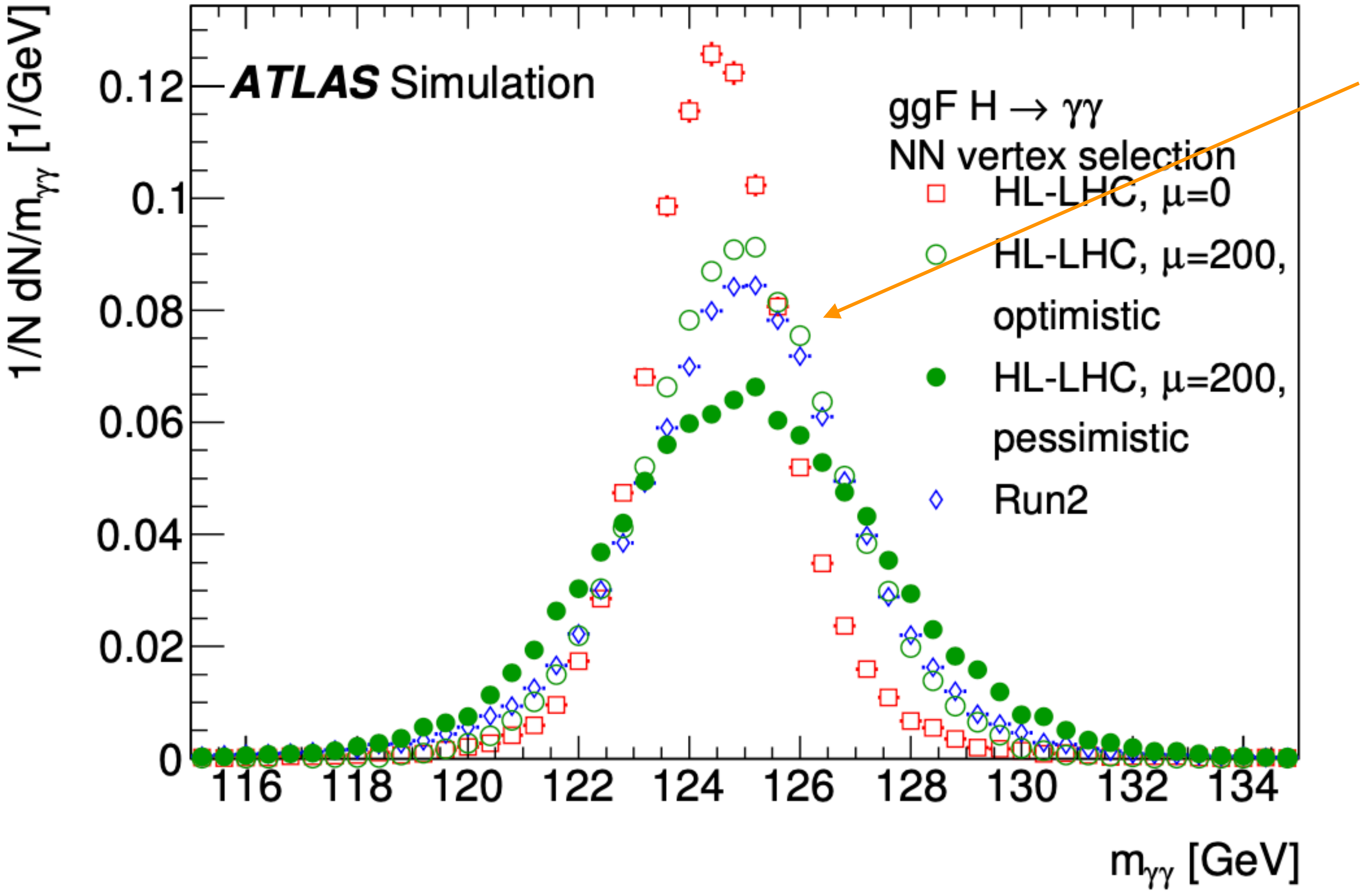
- improves further with Phase-2 detectors
  - new tracker: $m_{4\mu}$ resolution +25%
  - larger muon acceptance: 4μ rate accuracy +7%
  - both would reduce stat uncertainty from 28 to 20 MeV

HL-LHC from Run-2 Monte Carlo

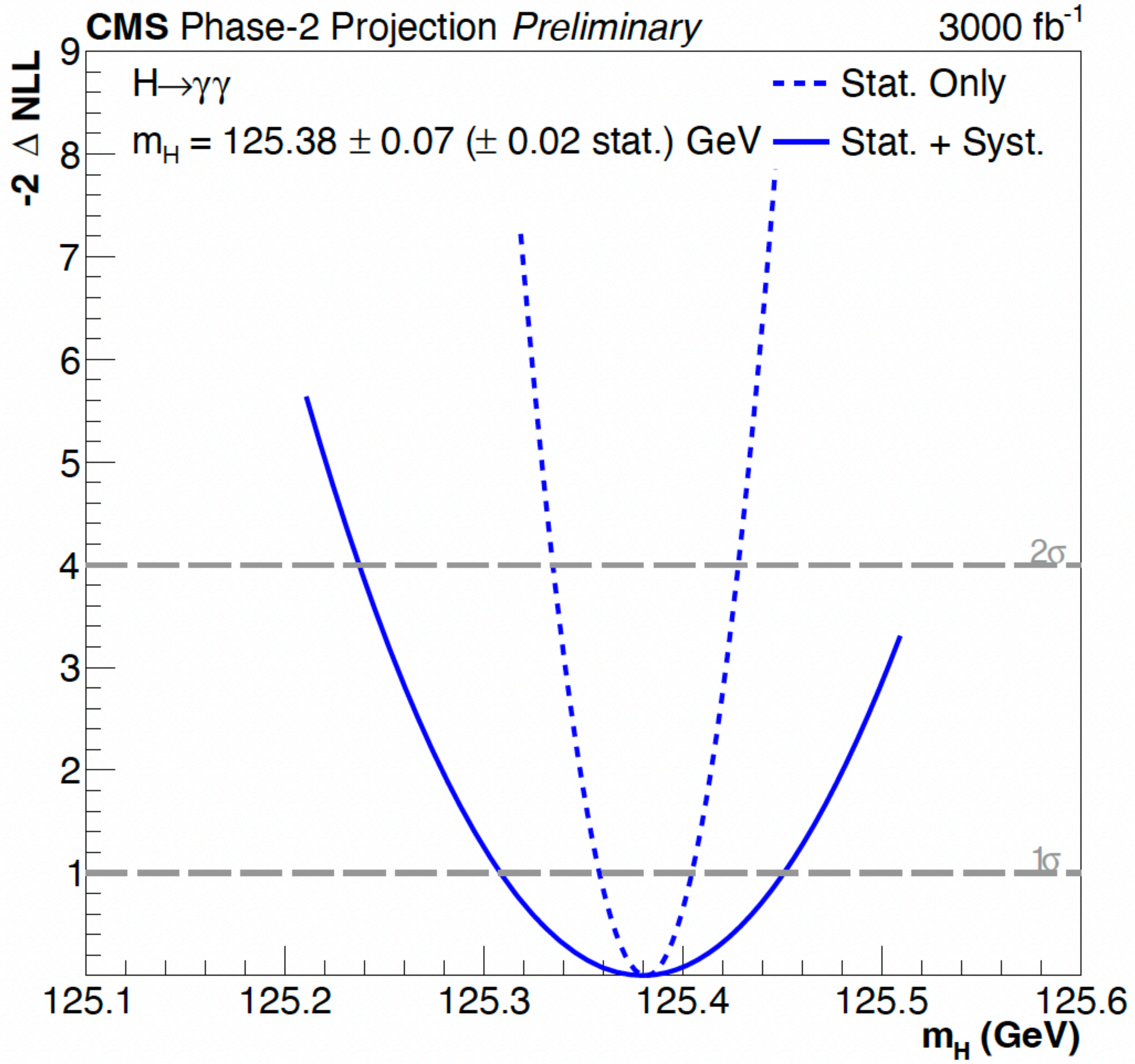


	Mass uncertainty (MeV)				
	Combined	4μ	4e	$2e2\mu$	$2\mu 2e$
Stat. uncertainty	22	28	83	51	59
Syst. uncertainty	20	15	189	94	95
Total	30	32	206	107	112

arXiv:2207.00320, CMS-PAS-FTR-21-007



ATLAS LAr upgrade neutralises pile-up worsening wrt Run-2

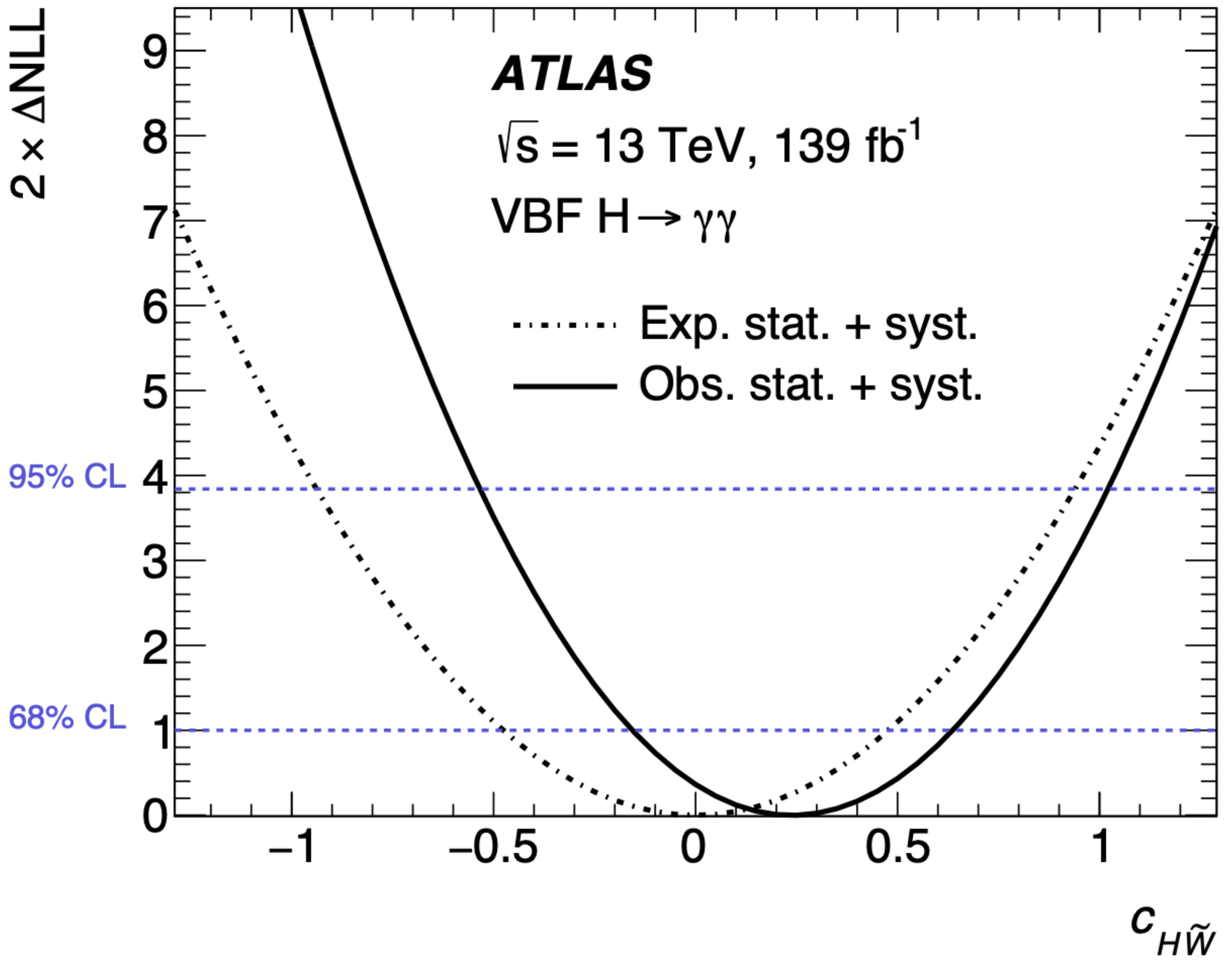


- HL-LHC improves Run-2 γγ results by 3x
  - new tracker (less material)
  - HGCAL precision and stability
  - barrel calorimeters
  - pile-up suppression from MTD
- limited by photon energy scale (0.05%)

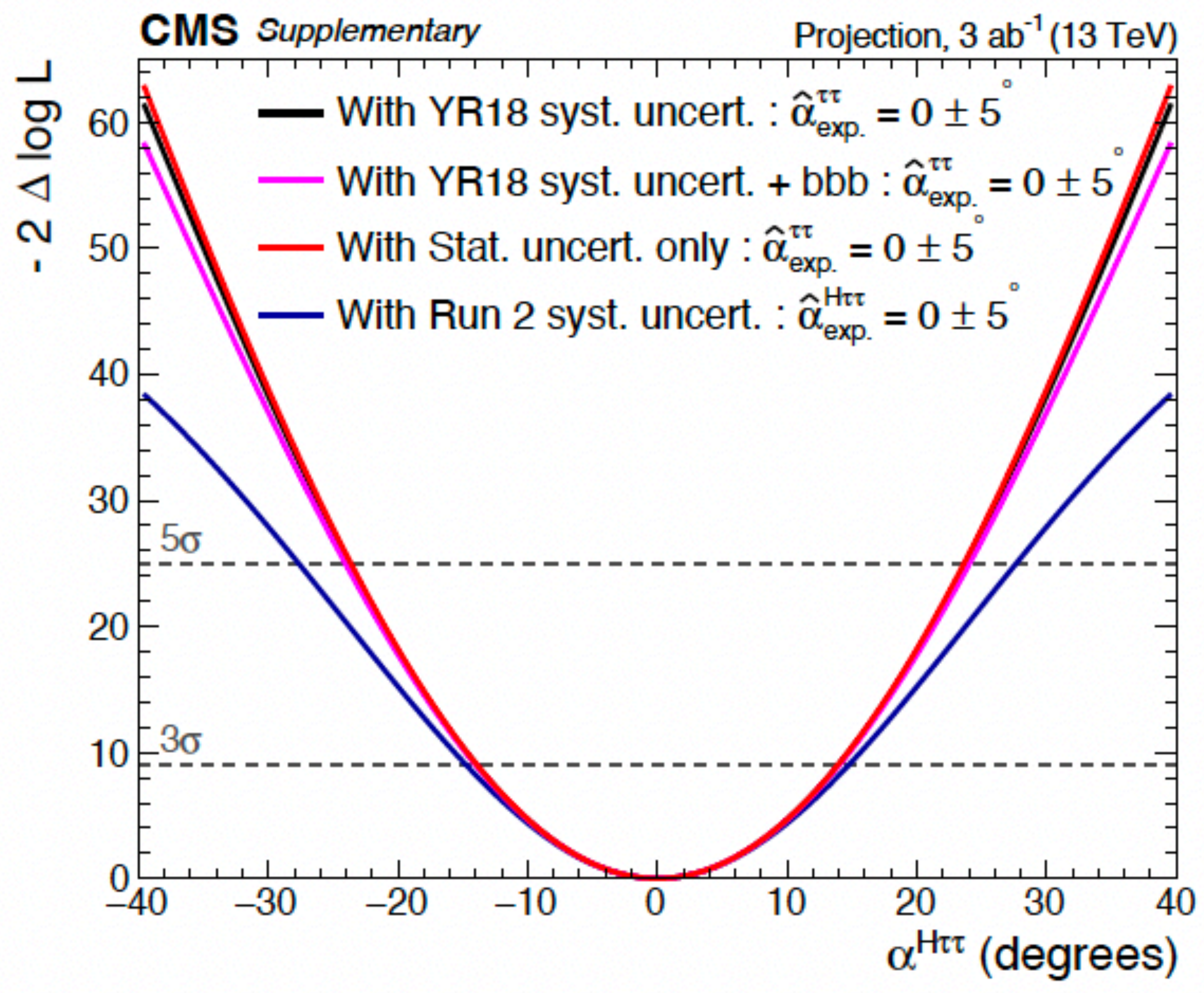
ATLAS-TDR-027, CMS-PAS-FTR-21-008, CMS-PAS-FTR-21-007

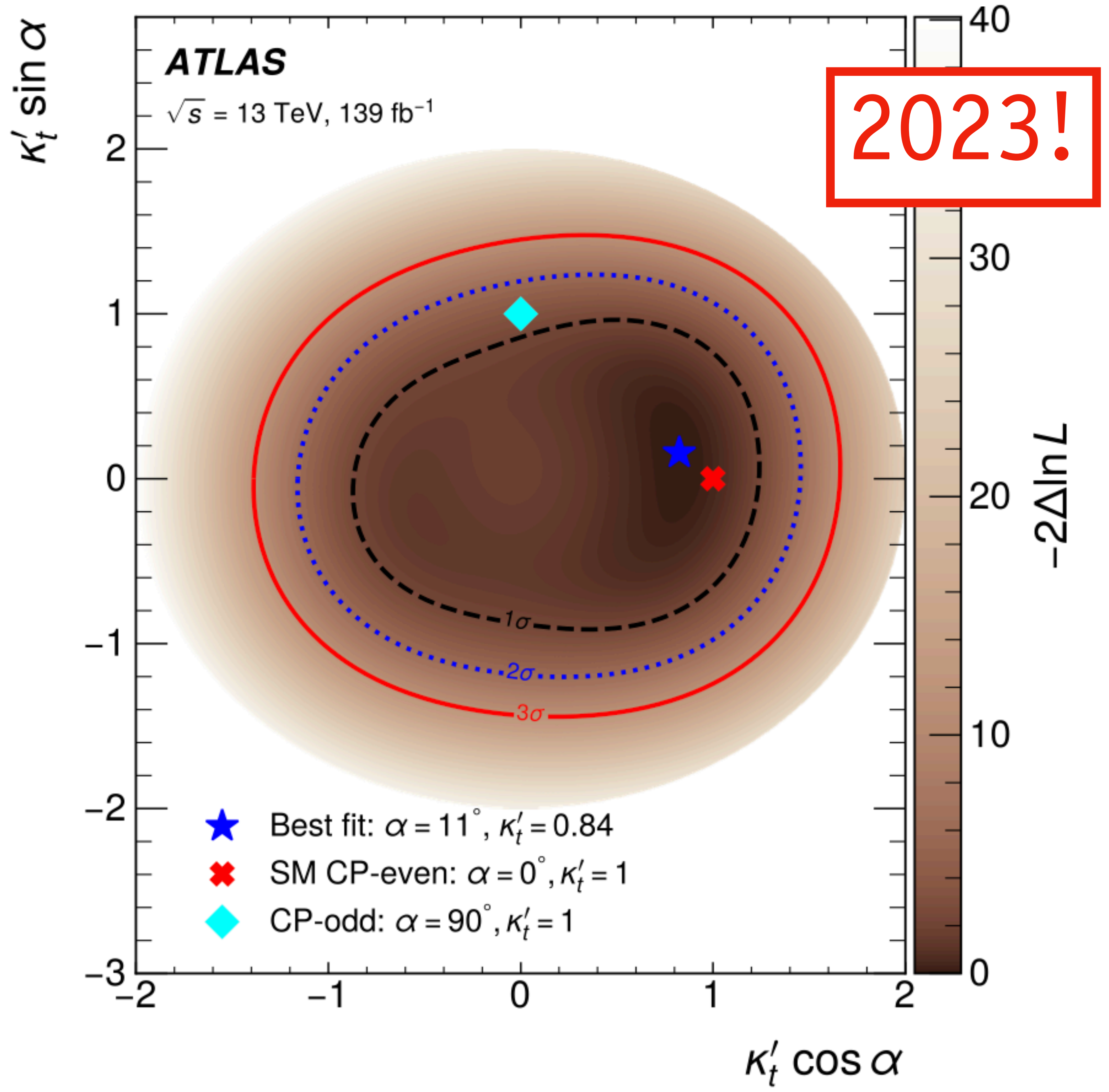
HIGGS BOSON: THE SPIN-PARITY STATE

- might be more complex than $J^P=0^+$ ($0^+/0^-$ admixture with CP violation?)
- ten years of measurements, from H→ZZ to VBF H→γγ and ttH/H→ττ production
- HL-LHC stat limited…

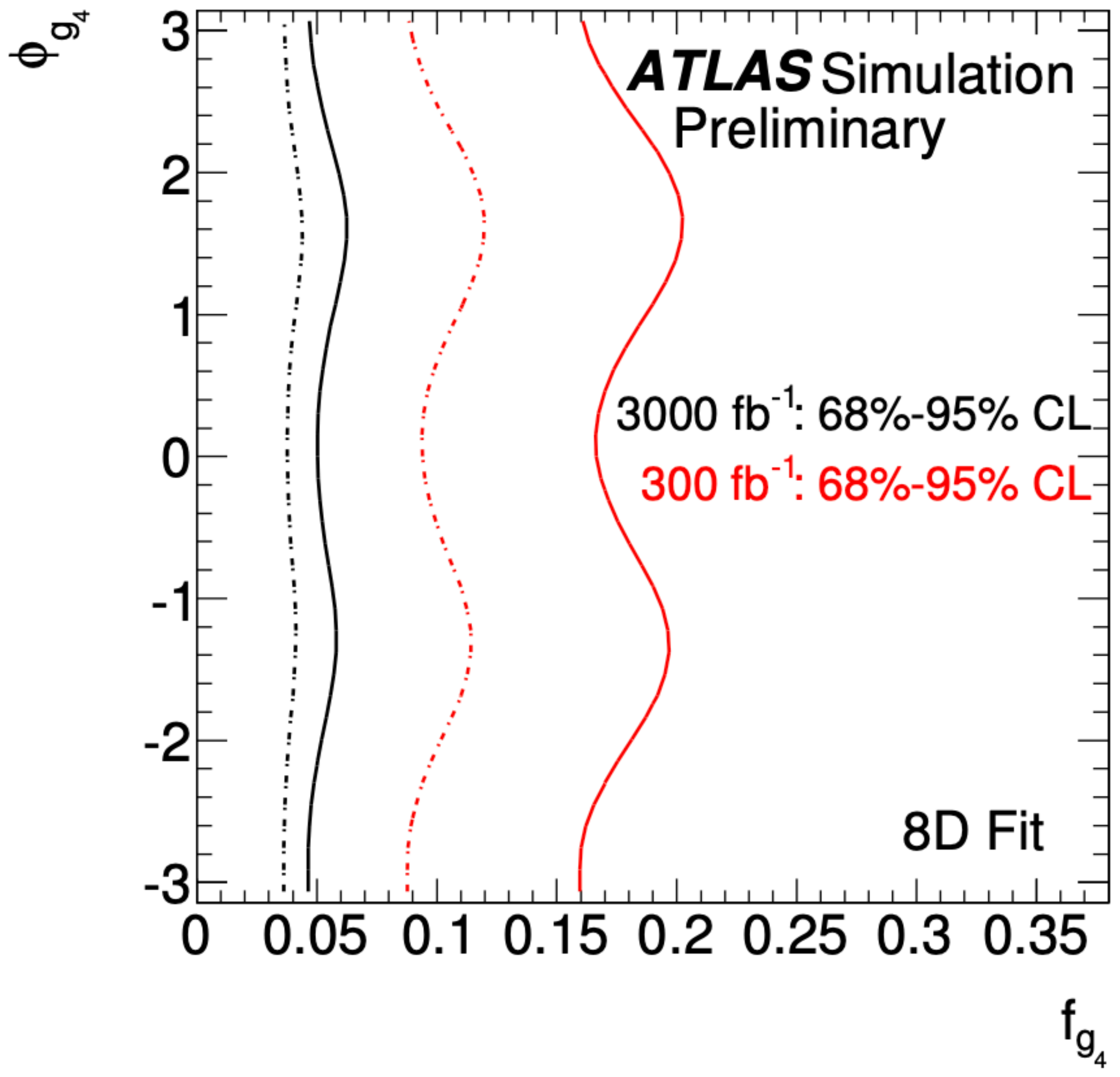


$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$





2023!

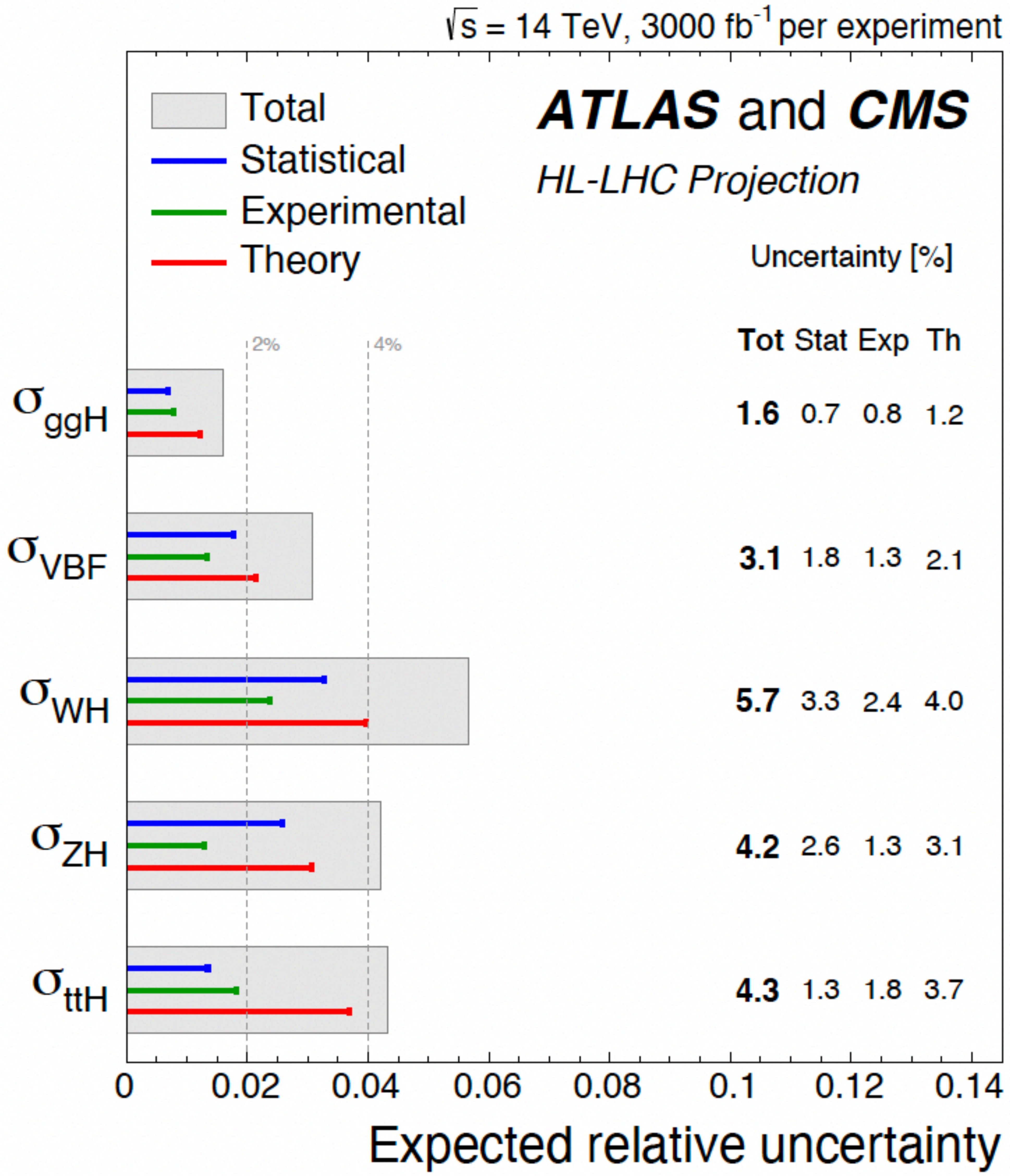


ATL-PHYS-PUB-2013-013, arXiv:2303.05974, CMS-PAS-FTR-18-011, arXiv:2110.04836, arXiv:2208.02338

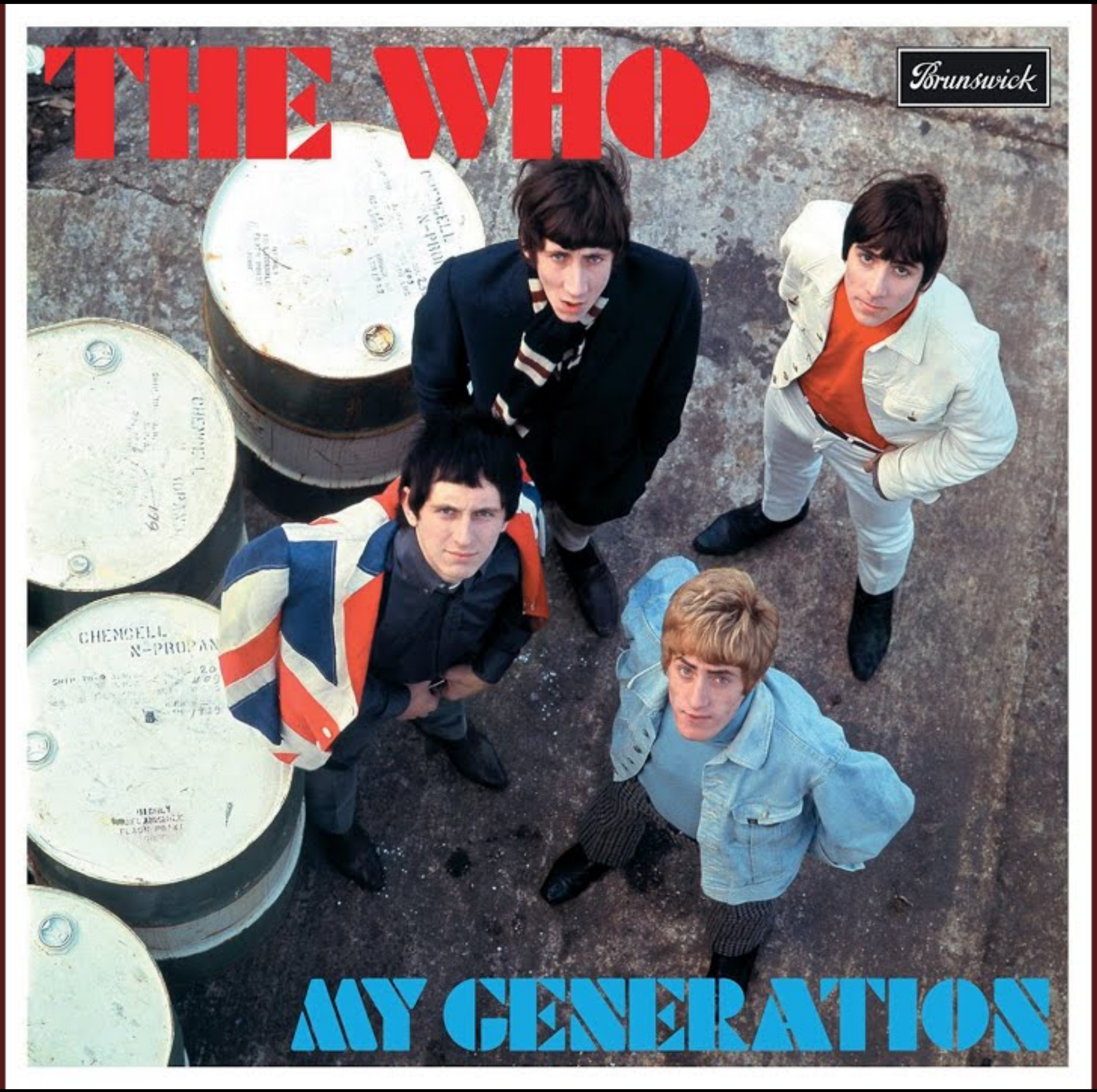
Valerio Ippolito
INFN Sezione di Roma

HIGGS BOSON: PRODUCTION

- HL-LHC precision from 1.6% (ggF) to 5.7% (WH)



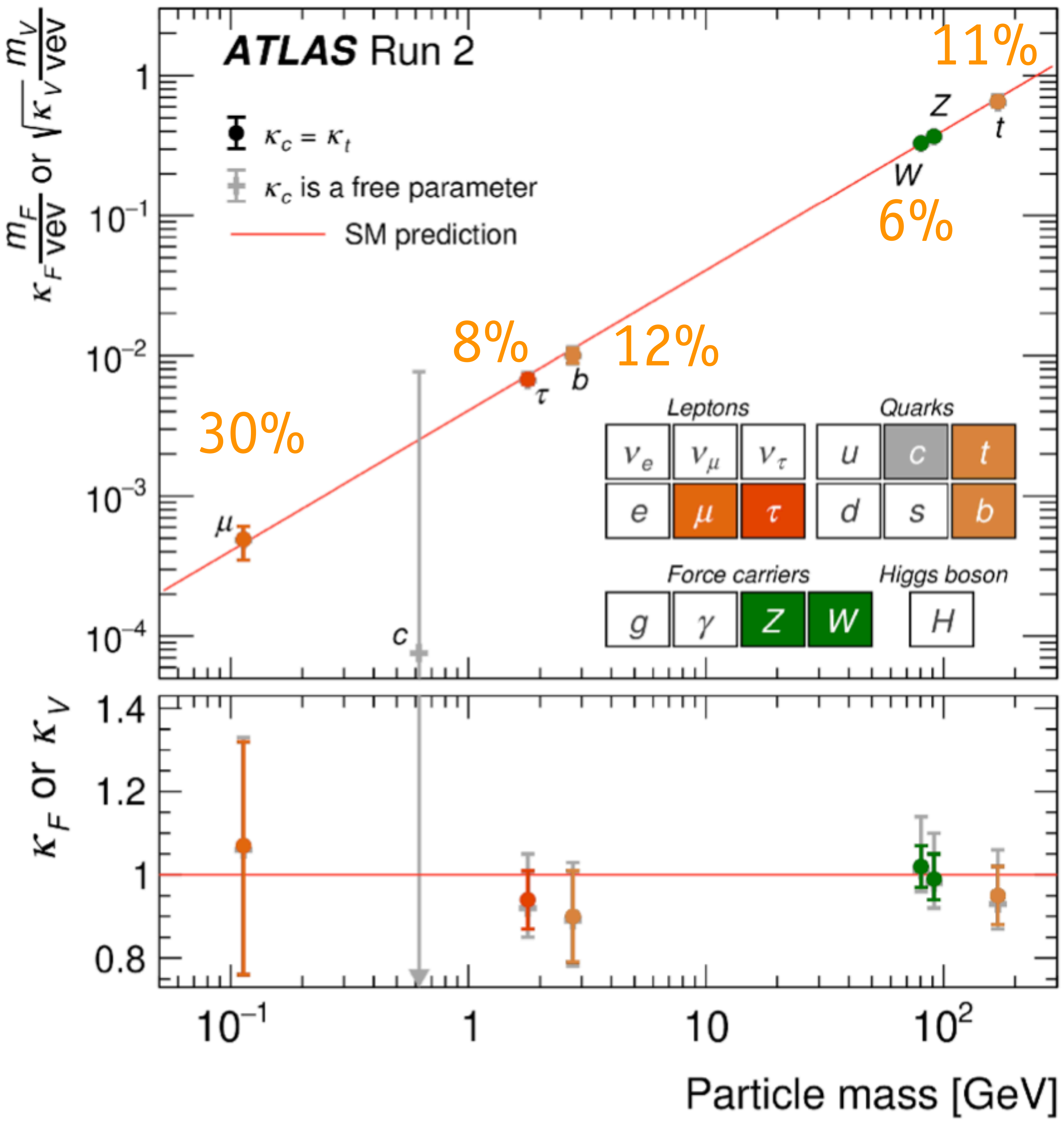
CERN-2019-007



https://www.youtube.com/watch?v=qN5zw04WxCc

[1965, just after BEH]

Nature 607 (2022) 52-59 & 60-68



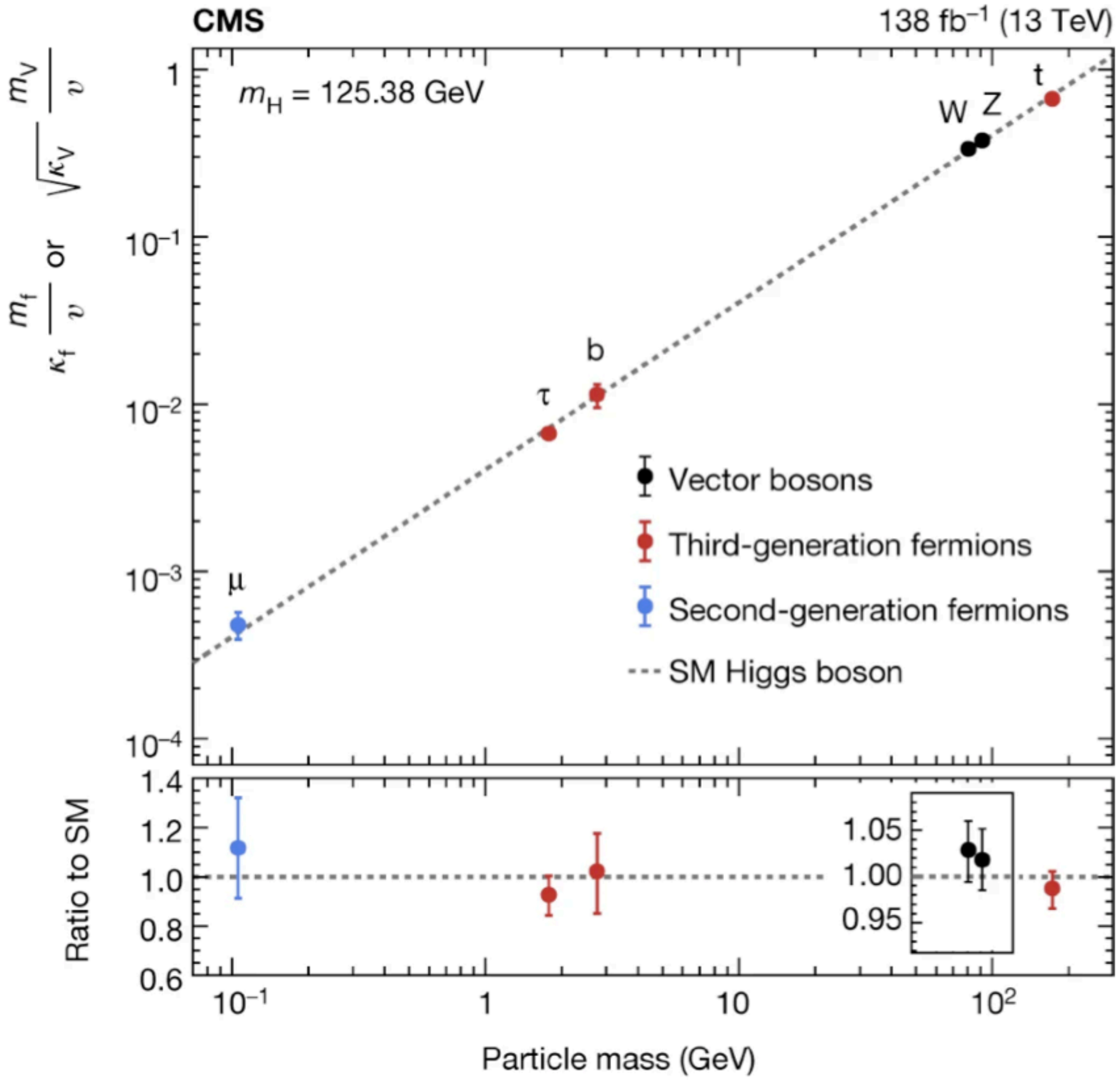
30%

8%

12%

6%

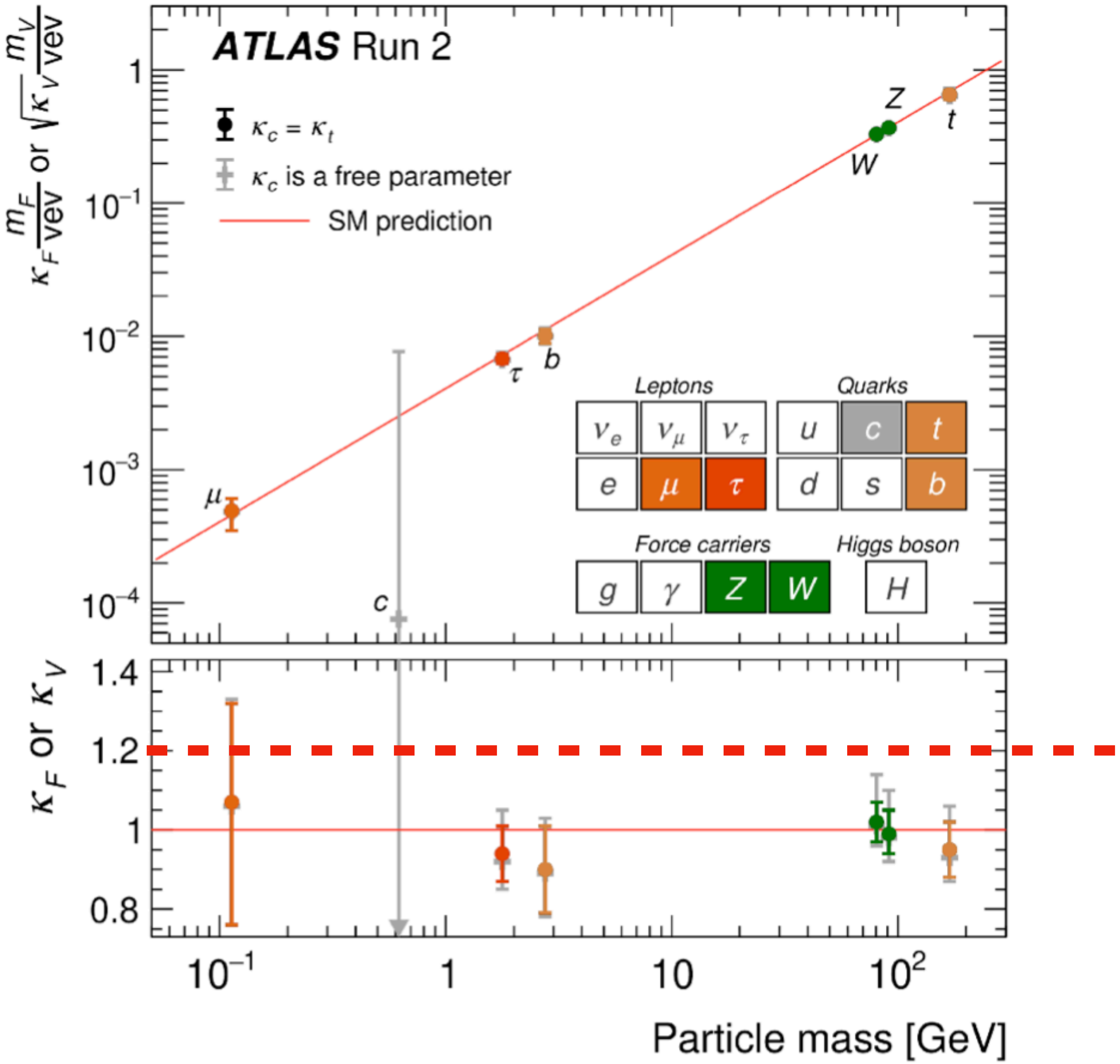
11%

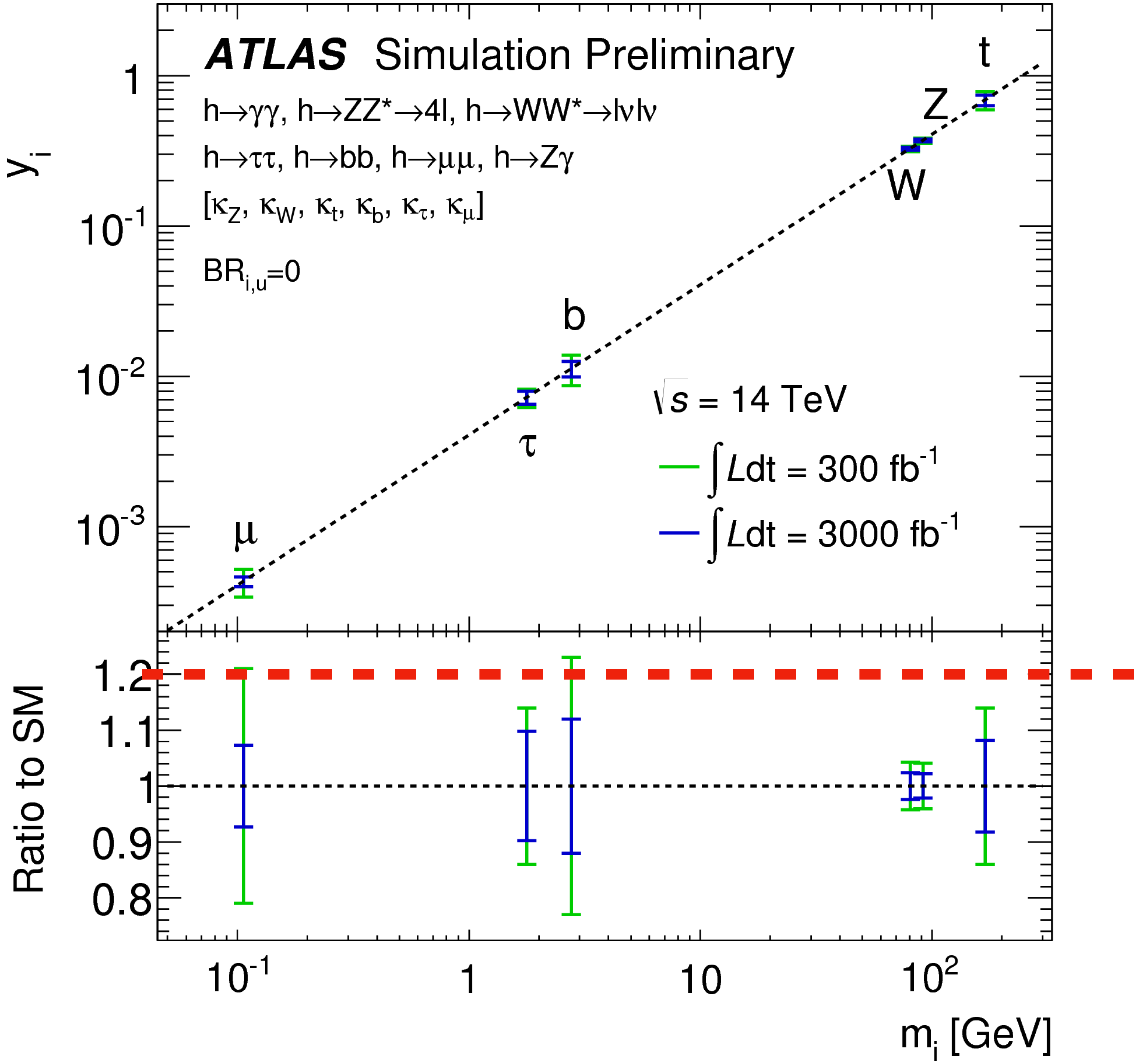


Nature 607 (2022) 52-59 vs ATL-PHYS-PUB-2014-016

today

our 2014 view of HL-LHC

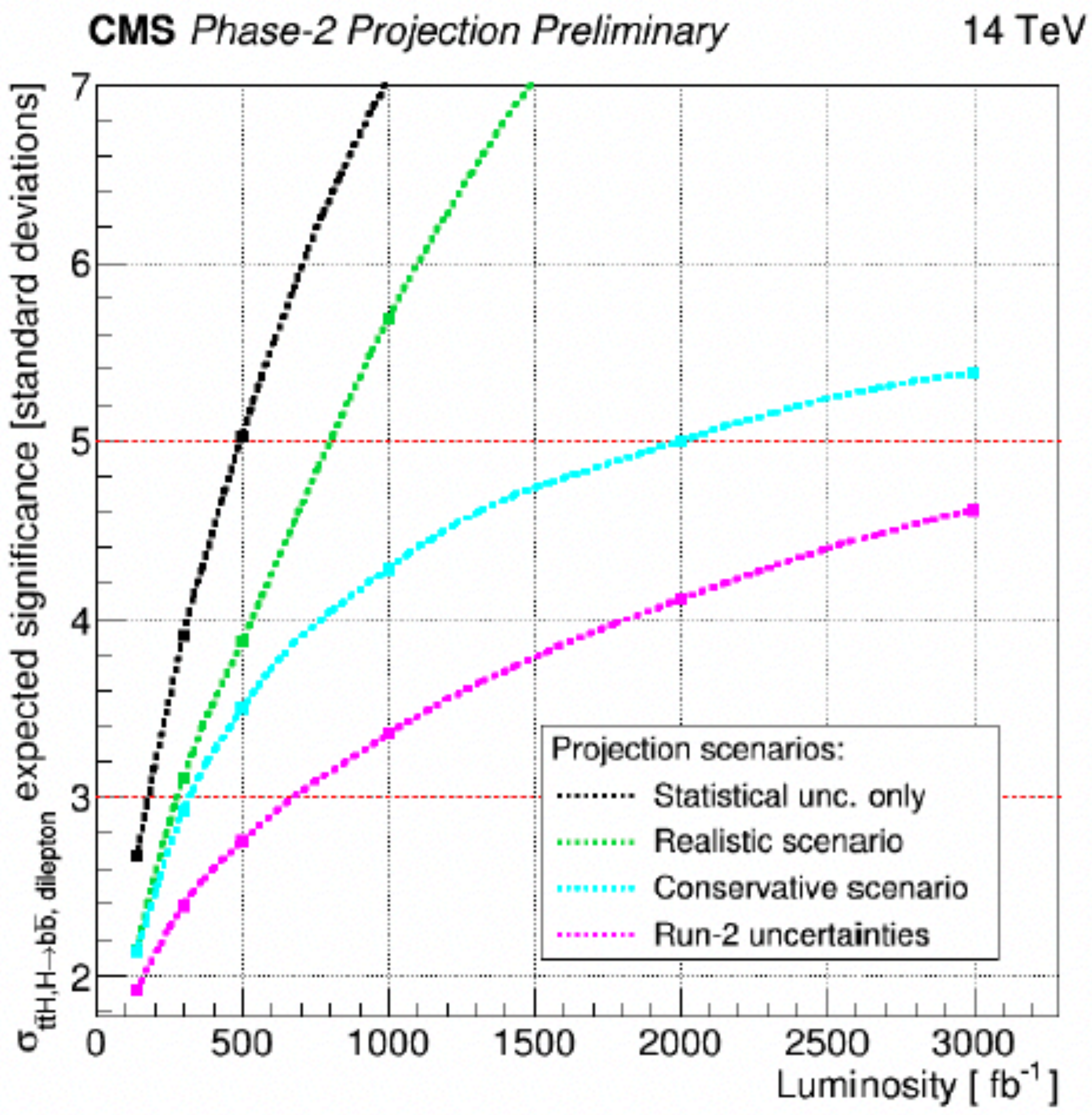


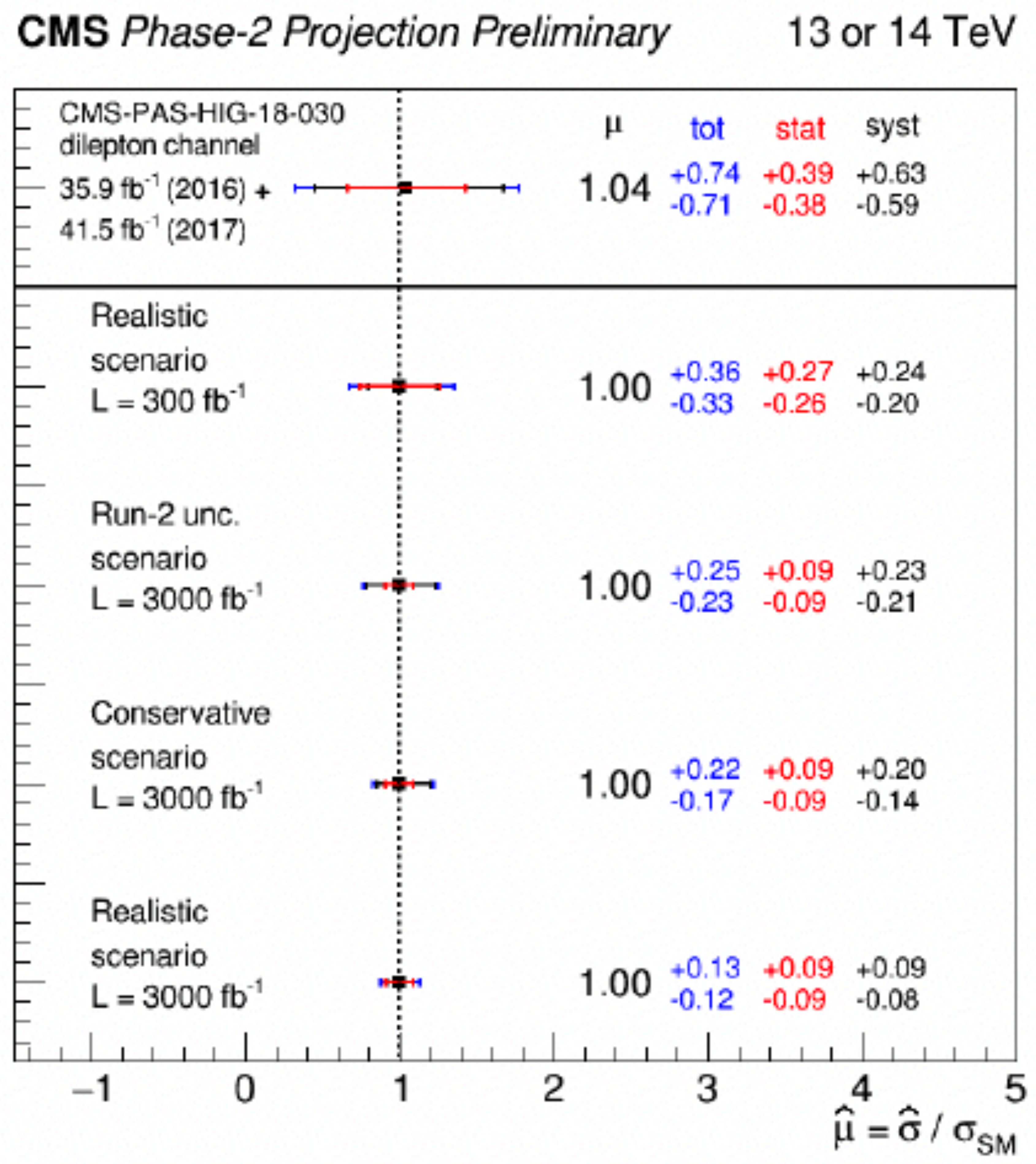


present > forecast → future > forecast'?

HIGGS BOSON: THIRD GENERATION

- 12% precision on y_t from ttH(bb)
- opposite-sign 2-lepton final state could reach observation with 1000 fb^{-1}

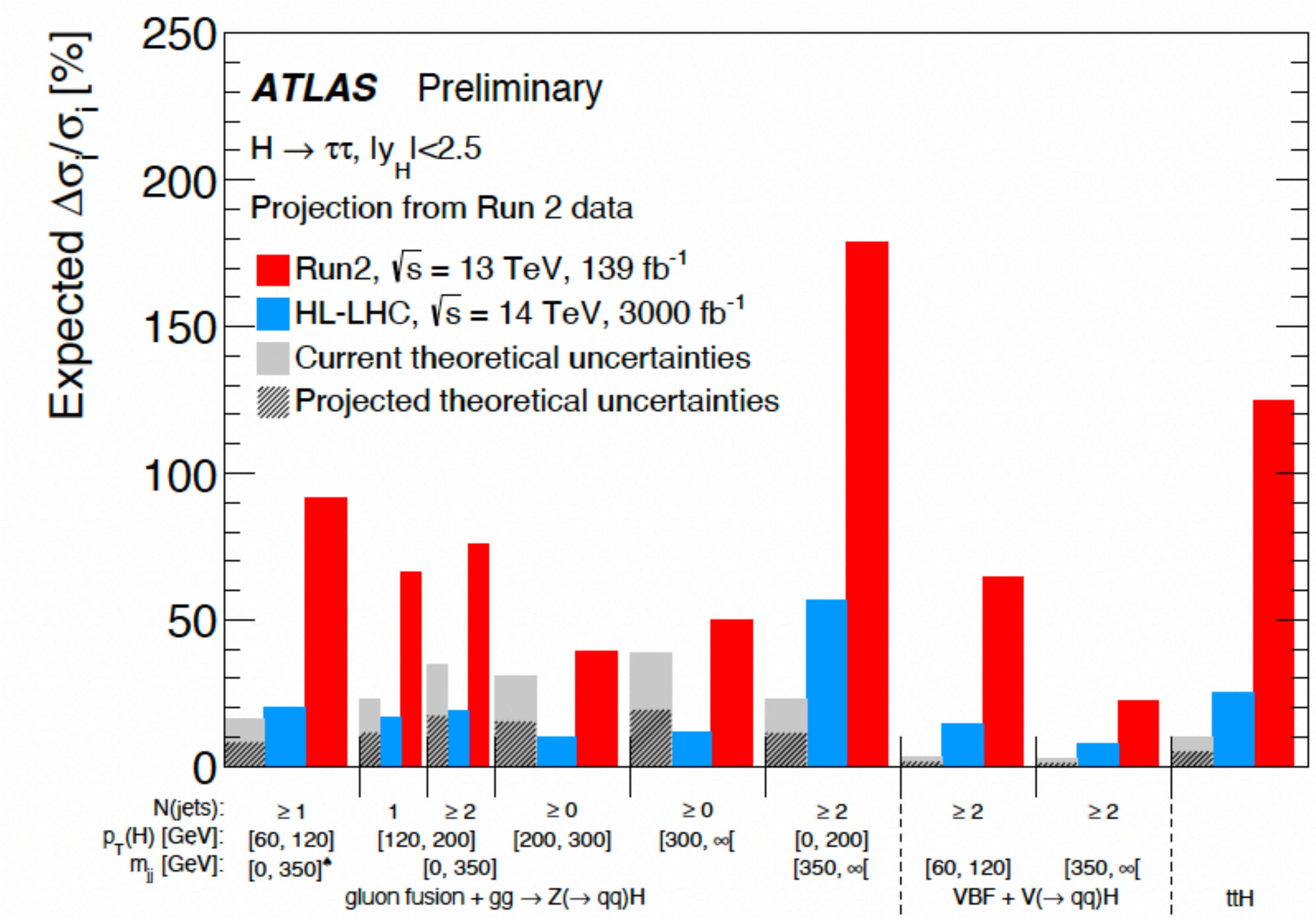




CMS-PAS-FTR-21-002

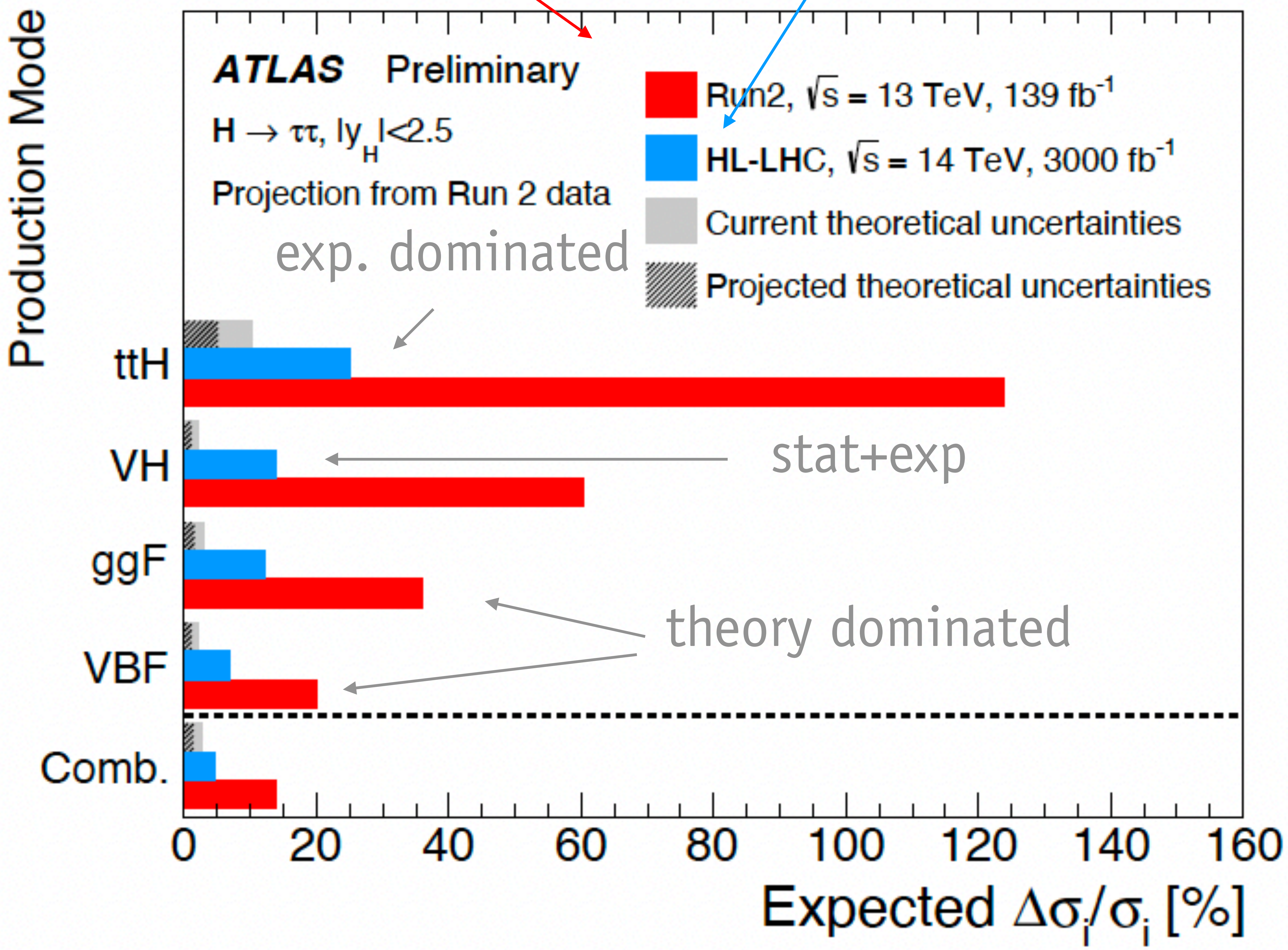
τ

- reach 2.5% precision on y_τ
- O(10%) uncertainty on current simplified-template-cross-section (STXS) bins



today

HL-LHC



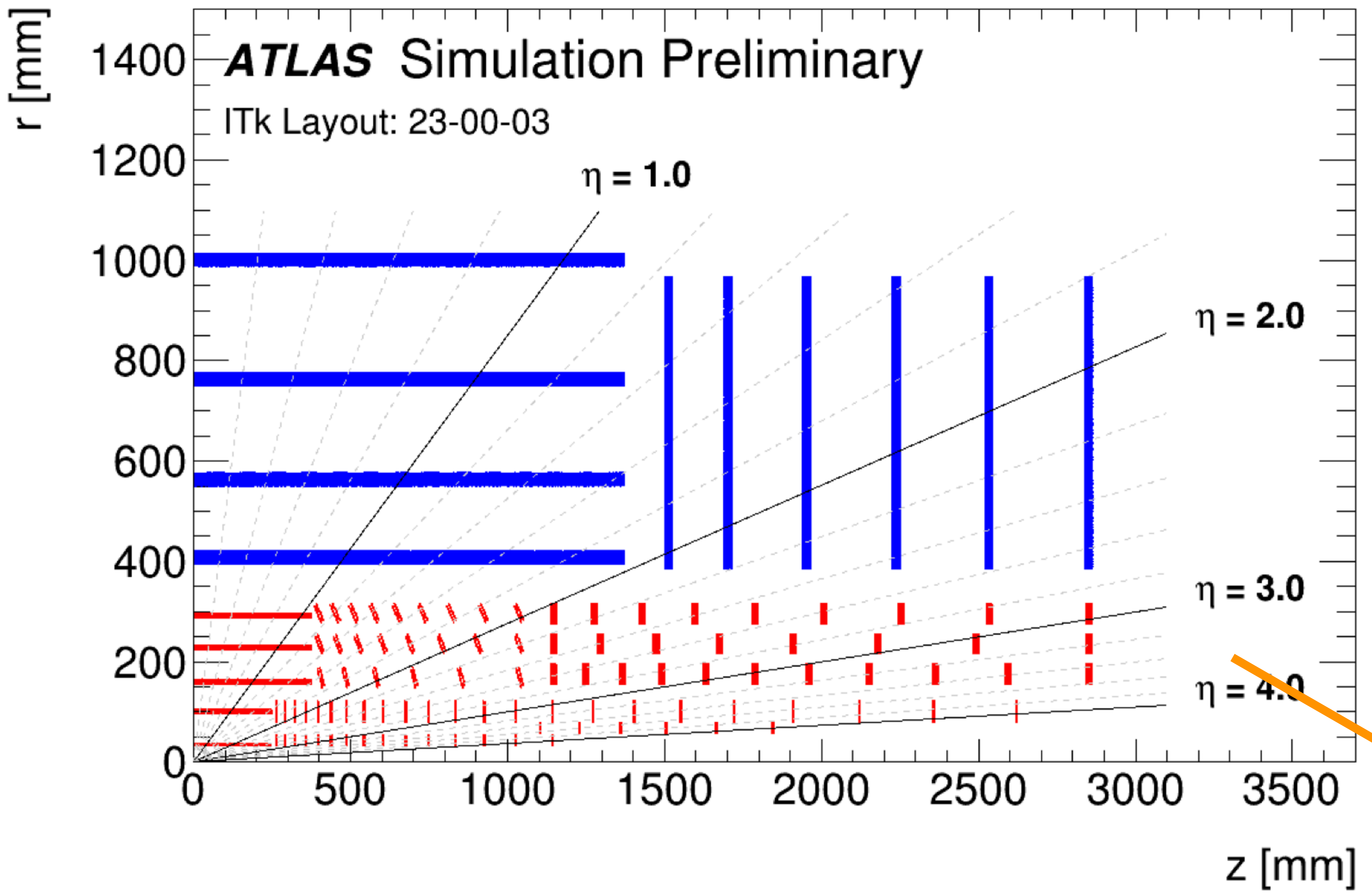
exp. dominated

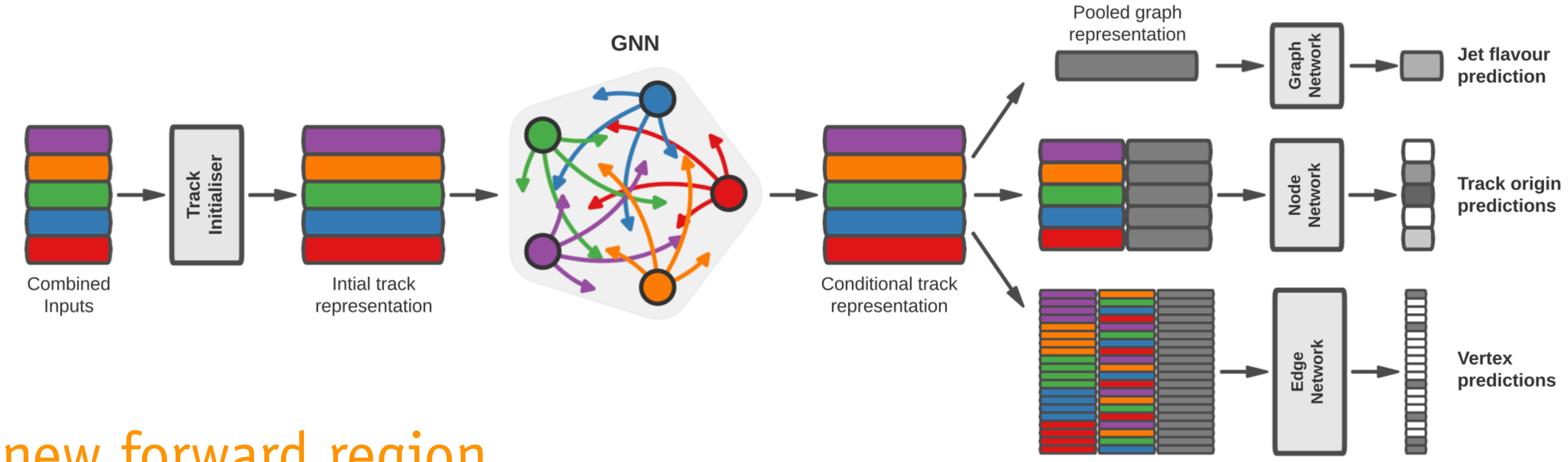
stat+exp

theory dominated

ATL-PHYS-PUB-2022-003

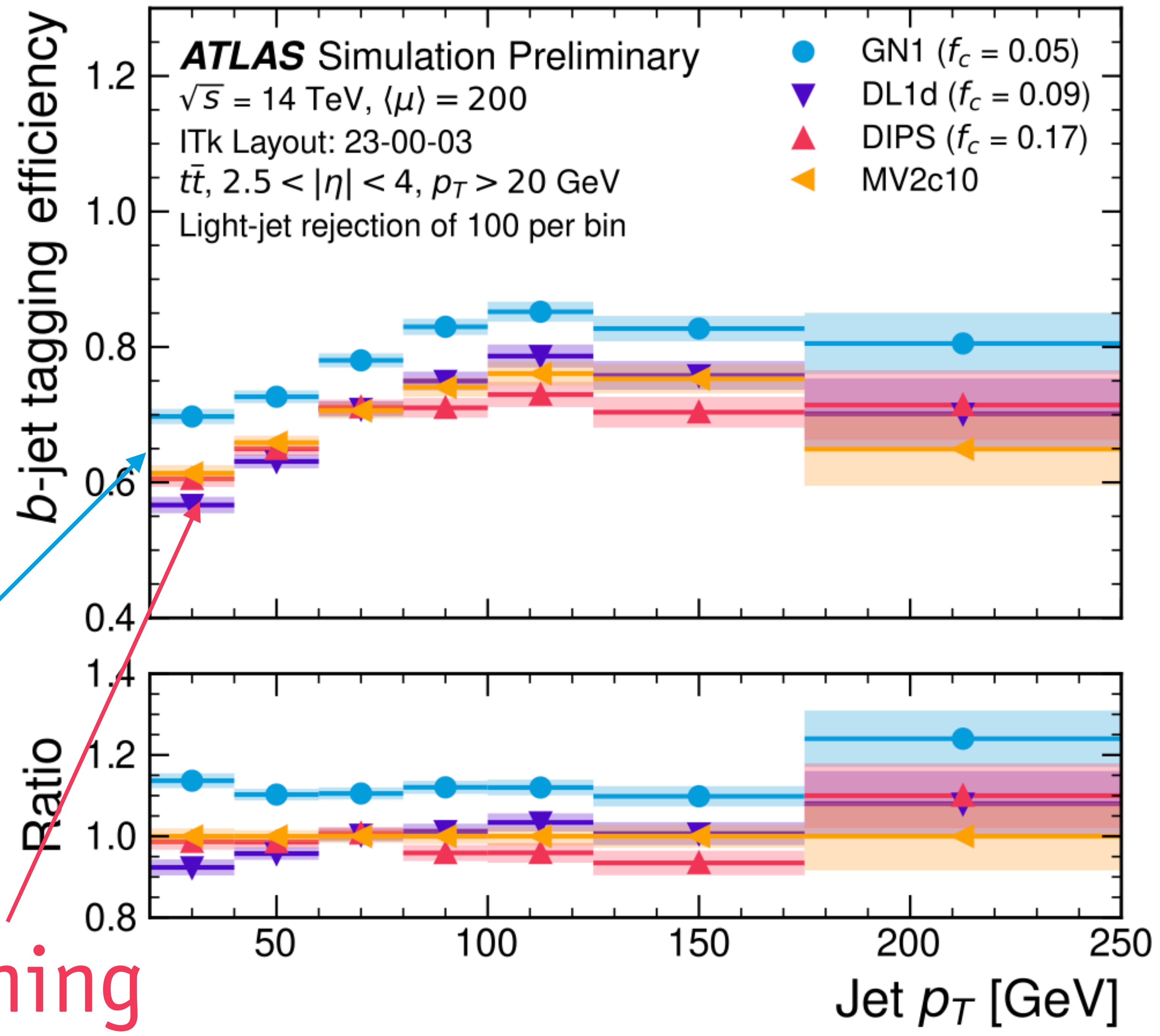
- target **VH**(bb)
- **ML essential** for b-tagging and S/B discrimination
- bin in $p_T(V)$, Njets, SR/CR
- HL:LHC: **syst limited**, mainly from **signal modeling**
  - STXS cross-section with **8-17%** uncertainty vs $p_T(V)$

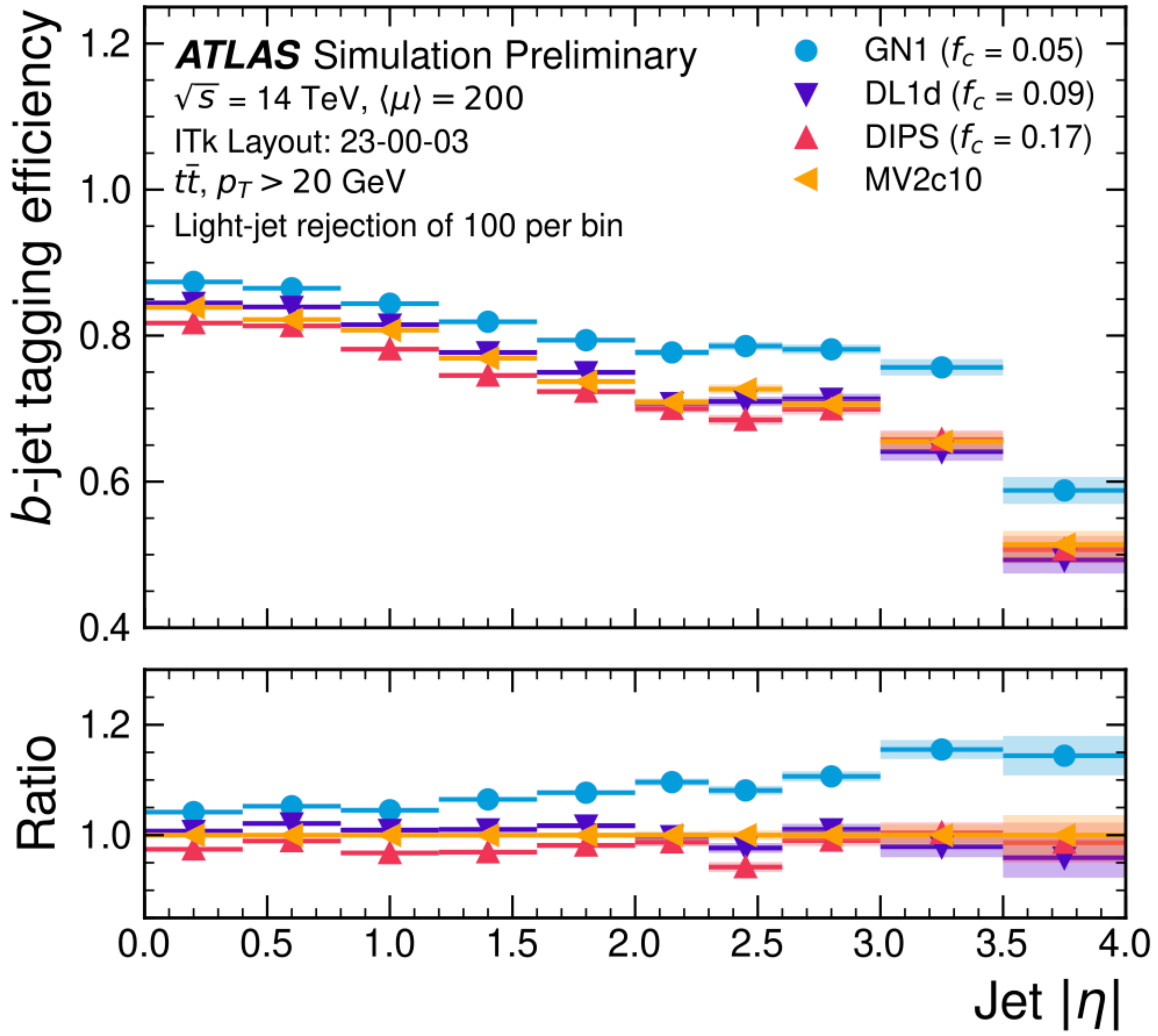




new forward region

- b(c)-tagging algorithmic performance evolving fast
- boost from inner tracker upgrade





graph neural networks

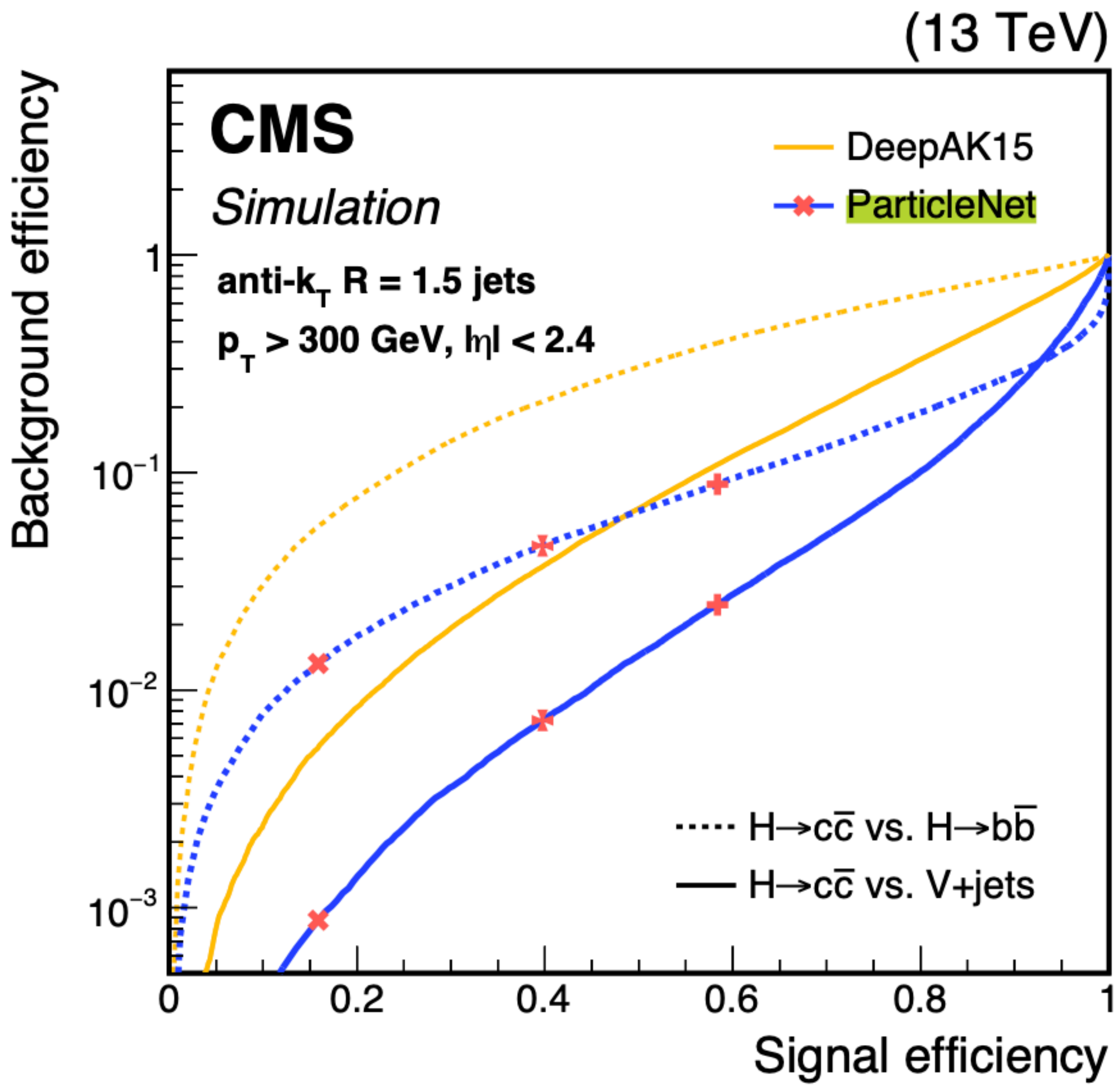
"standard" deep learning

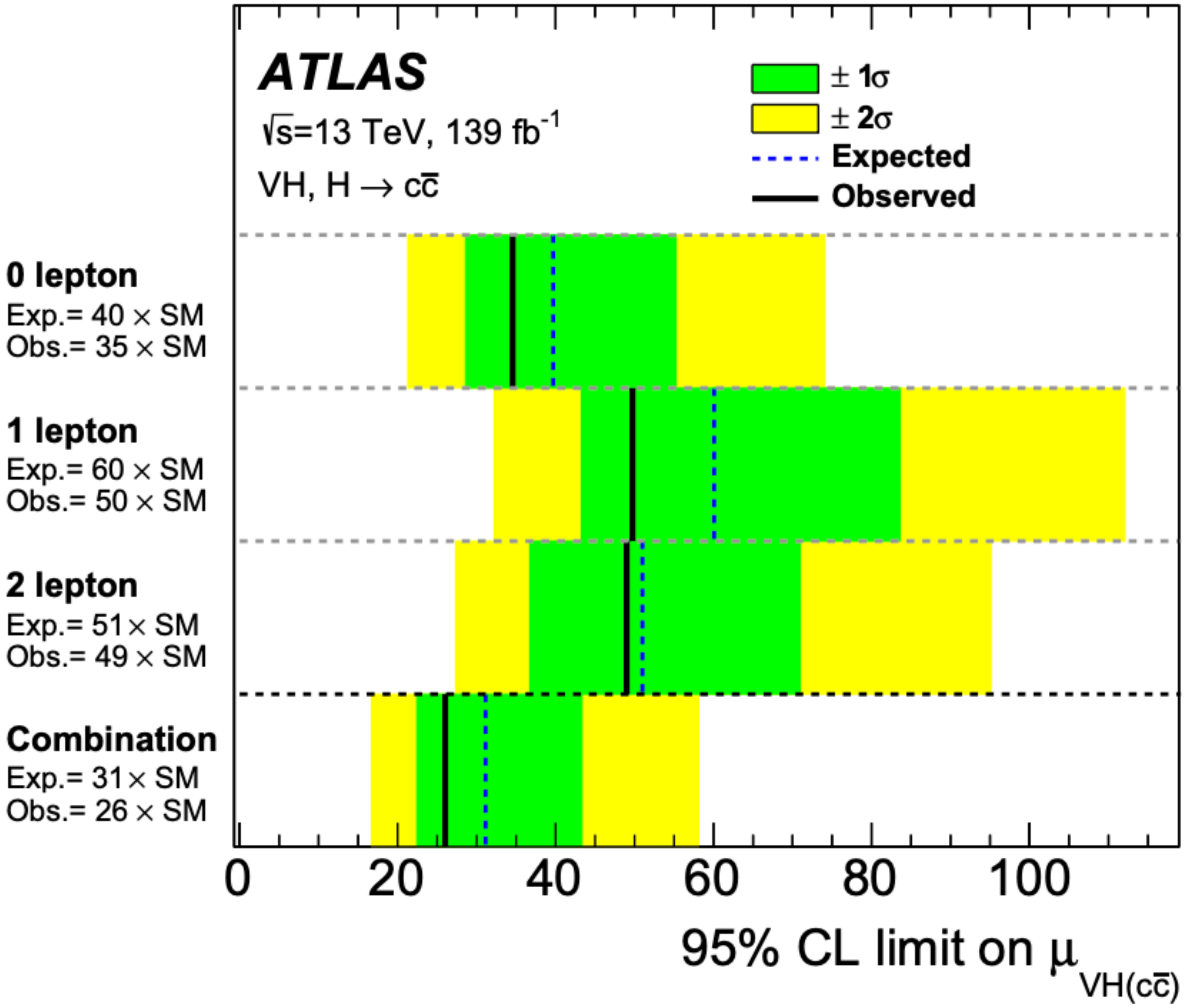
ATL-PHYS-PUB-2022-047

HIGGS BOSON: SECOND GENERATION

- H→cc (SM: BR=3%)
  - -VH search, multiple regions
  - -simultaneous H→bb and H→cc fit
  - -dedicated ML for c-tagging

C

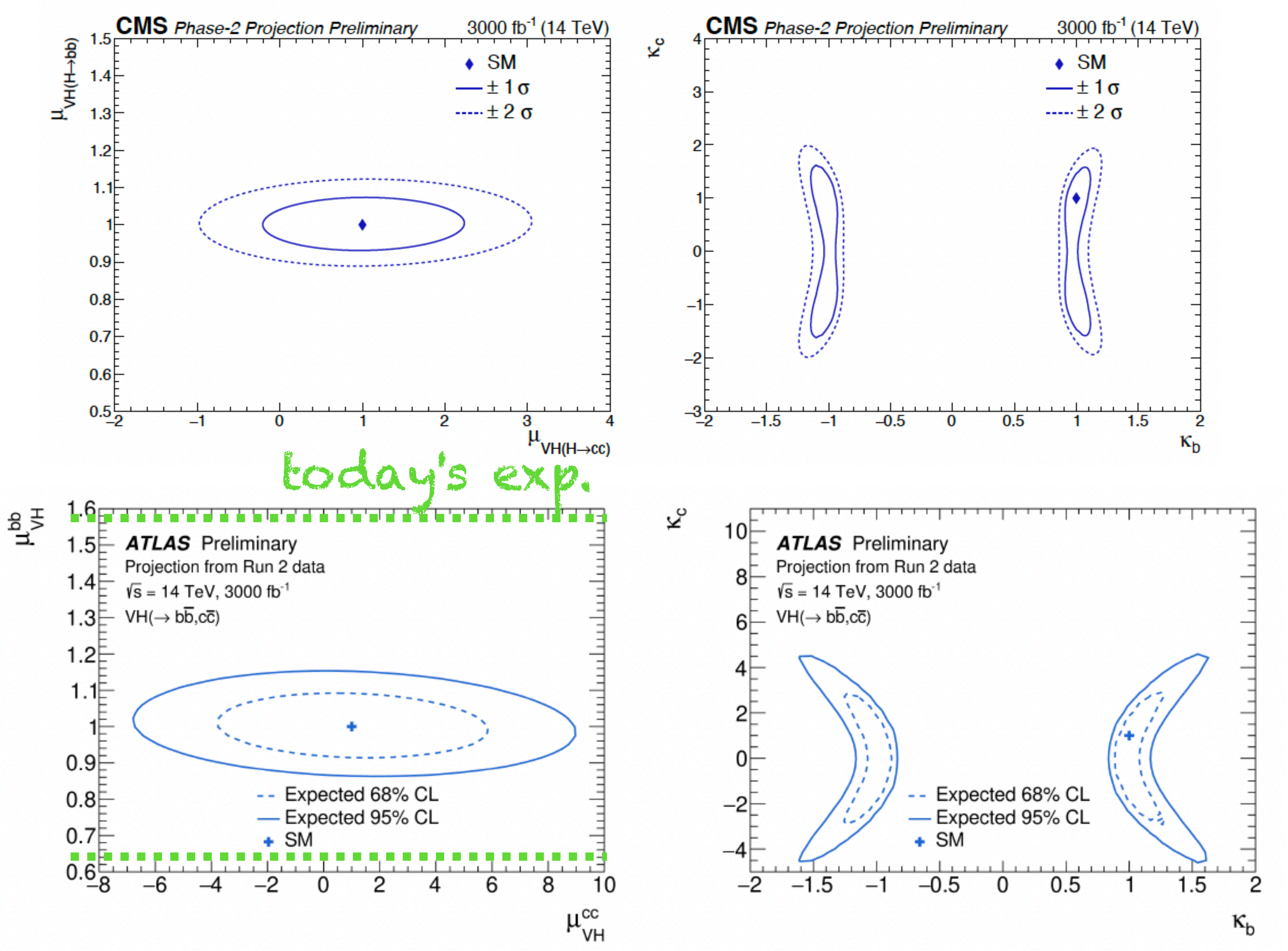




- current reach ~14x σ_{SM}, 1.1 < $|k_c|$ < 5.5
  - -VW and VZ used to validate method (evidence/observation)
  - -also: DNN techniques to target boosted decays

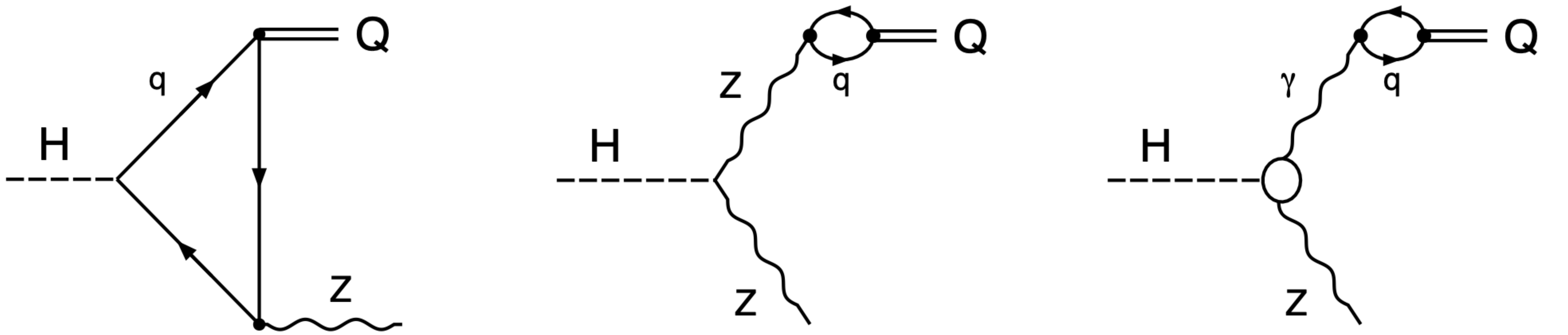
Eur. Phys. J. C (2022) 82:717, arXiv:2205.05550, arXiv:2211.14181

- assume 3% and 5% uncertainty on bb and cc tagging (CMS), constrained on data
- **bb misidentified as cc** is the worry, 20% uncertainty assumed on the rate
- limited Monte Carlo statistics can be an issue, neglected in projections
- HL-LHC reach 6.4x SM, H-charm coupling modifier $|k_c|<3$



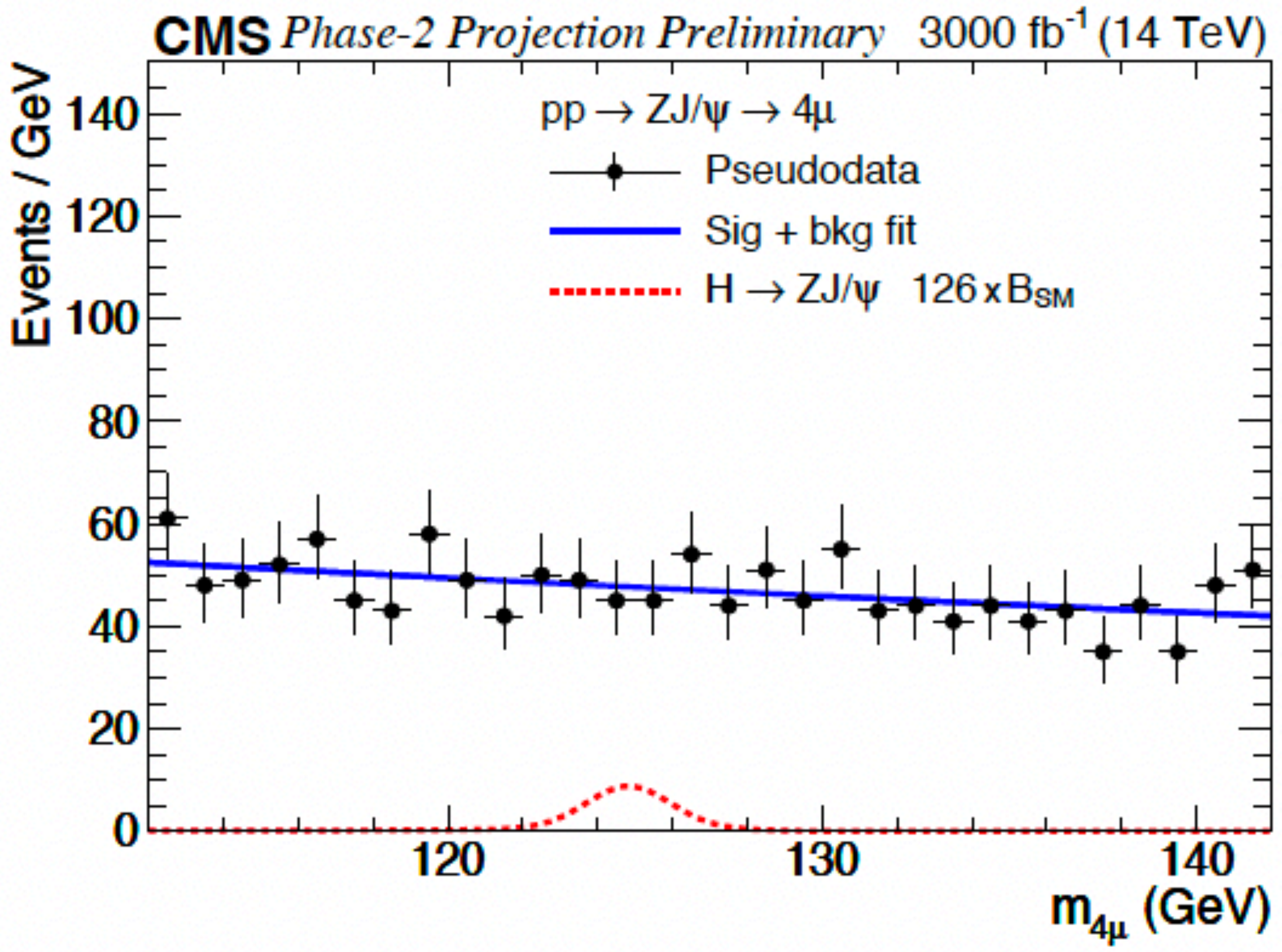
ATL-PHYS-PUB-2021-039, CMS-PAS-HIG-21-008

- $H \to J/\Psi\ Z/\gamma$, $H \to \Upsilon\,\Upsilon$ (c) with μμ quarkonium decays
  - current limits 10^2-10^3 times the SM BR
  - might observe them at HL-LHC (a handful of events)
  - overall, may reach $k_c \sim 1$ with ATLAS+CMS+LHCb

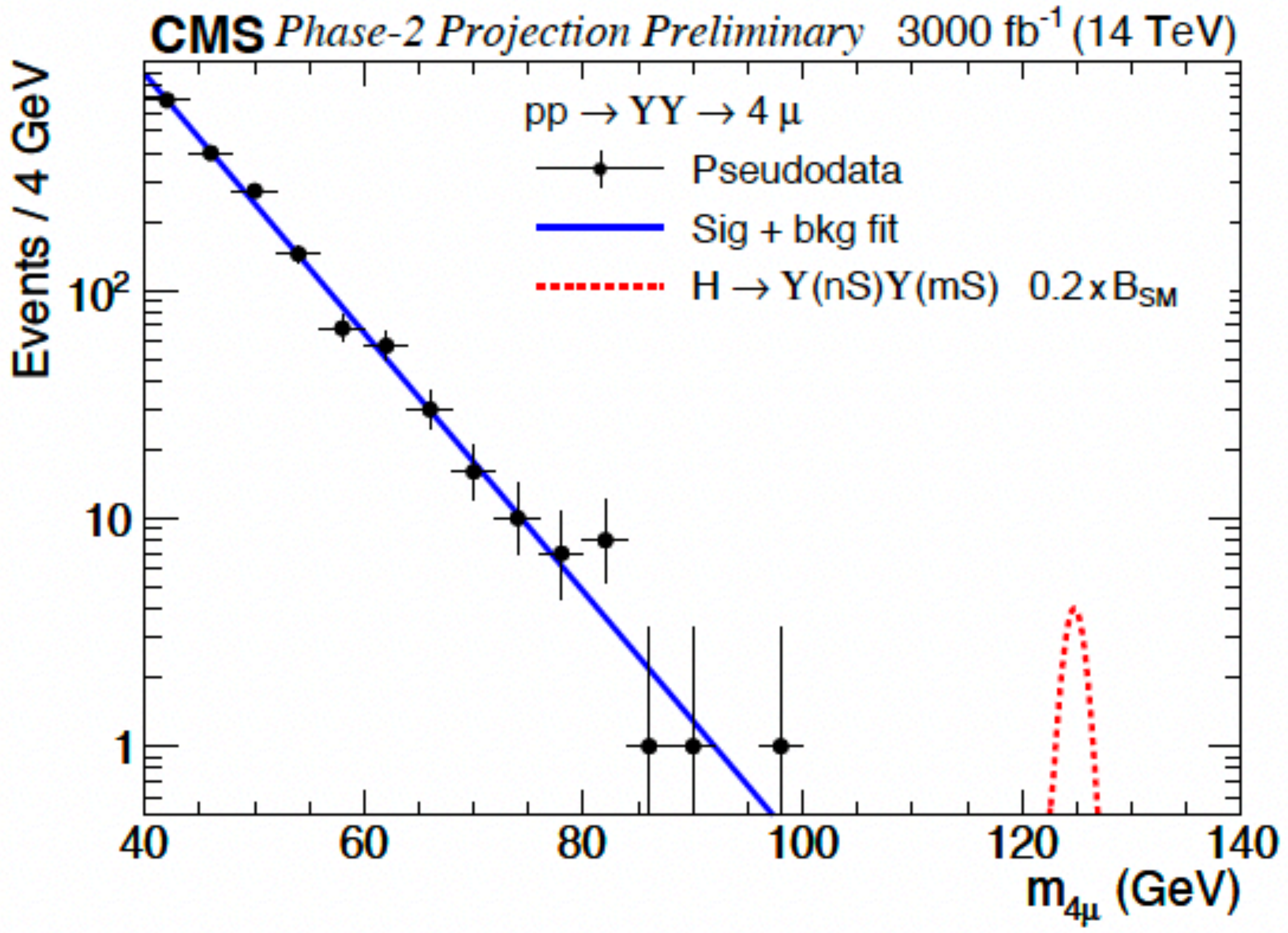


Channel	3000 fb^{-1}	(×SM)	4500 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)

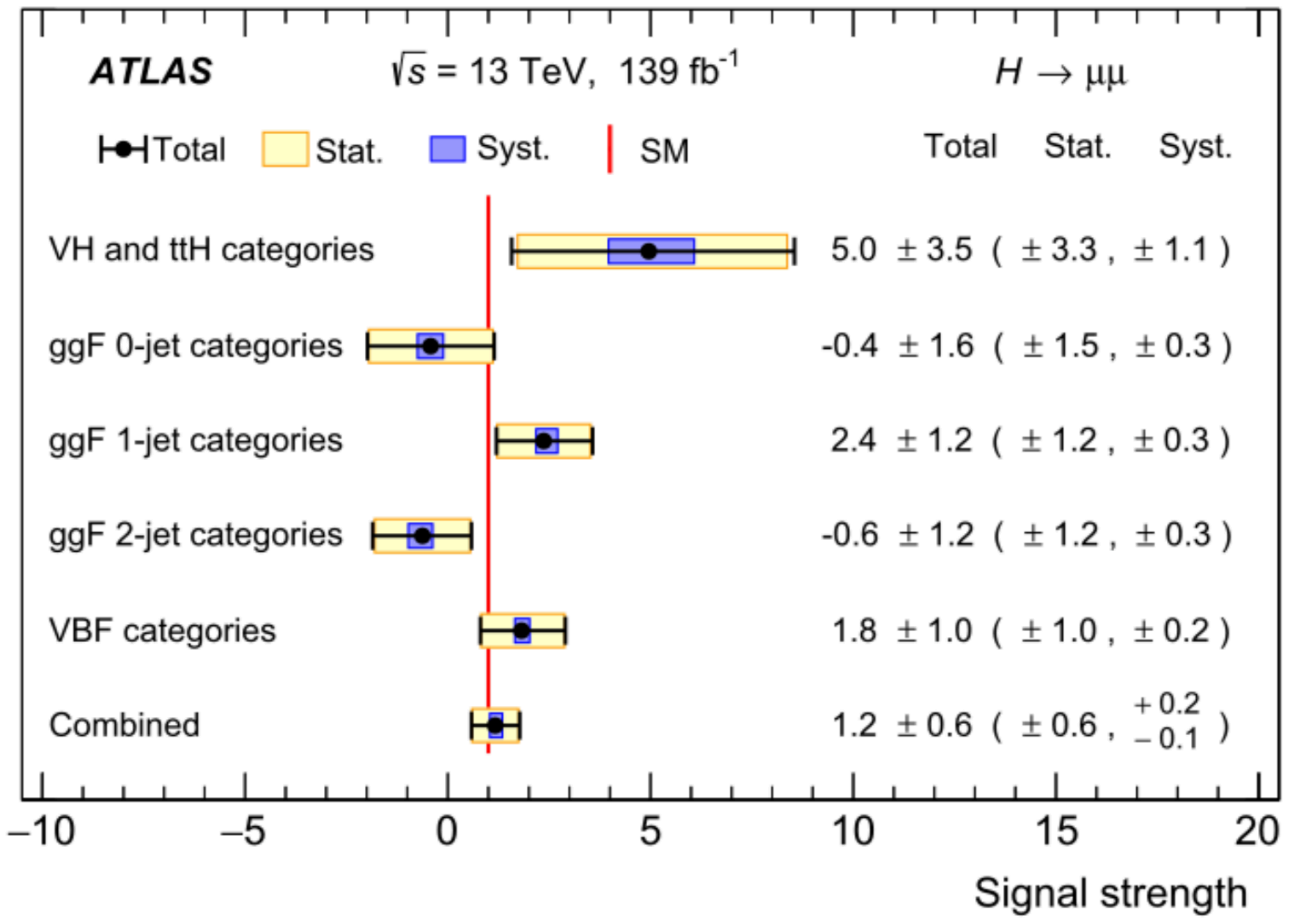
$H \to \phi\ Z/\gamma^*$

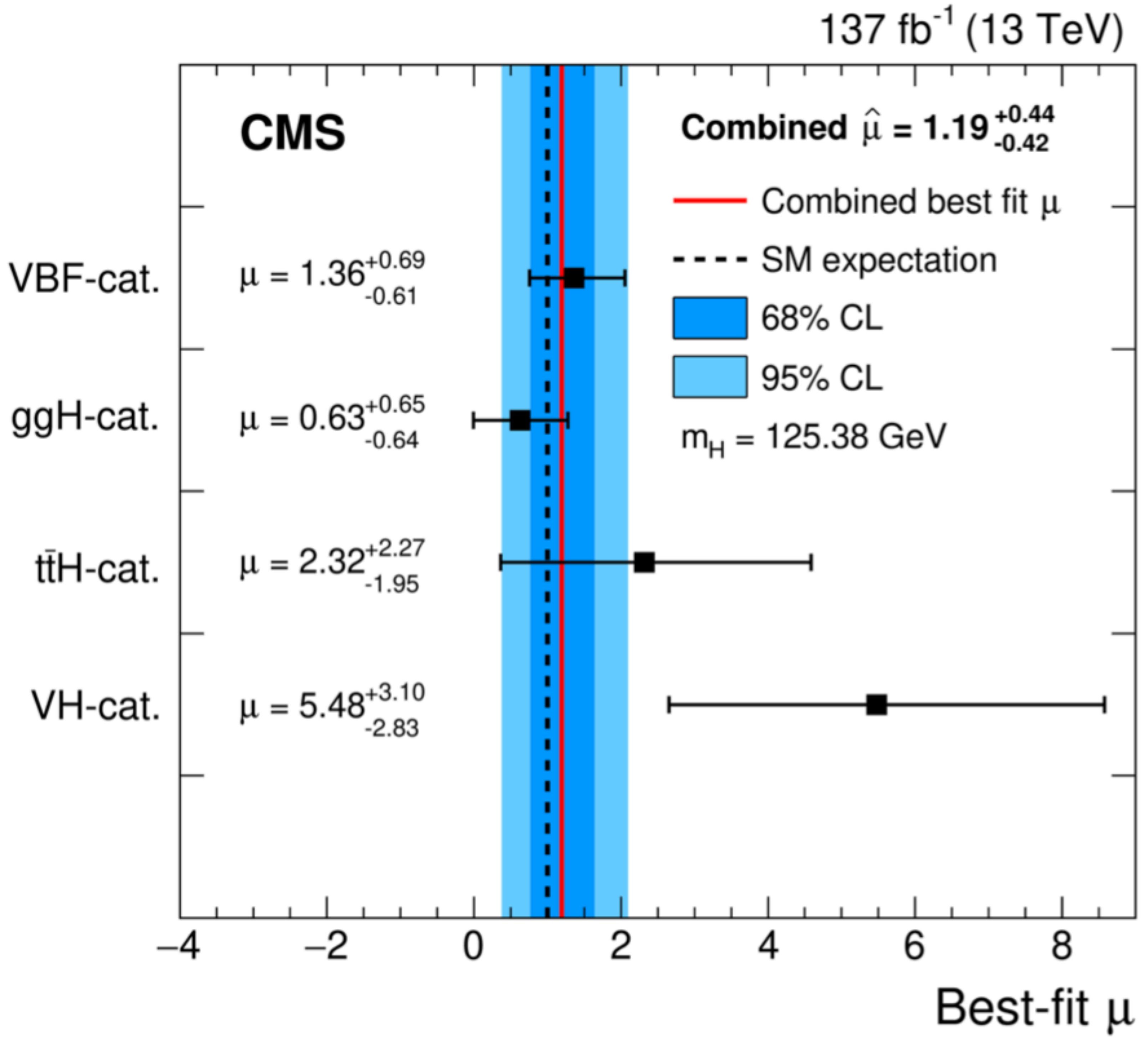


$H \to \Upsilon\,\Upsilon$

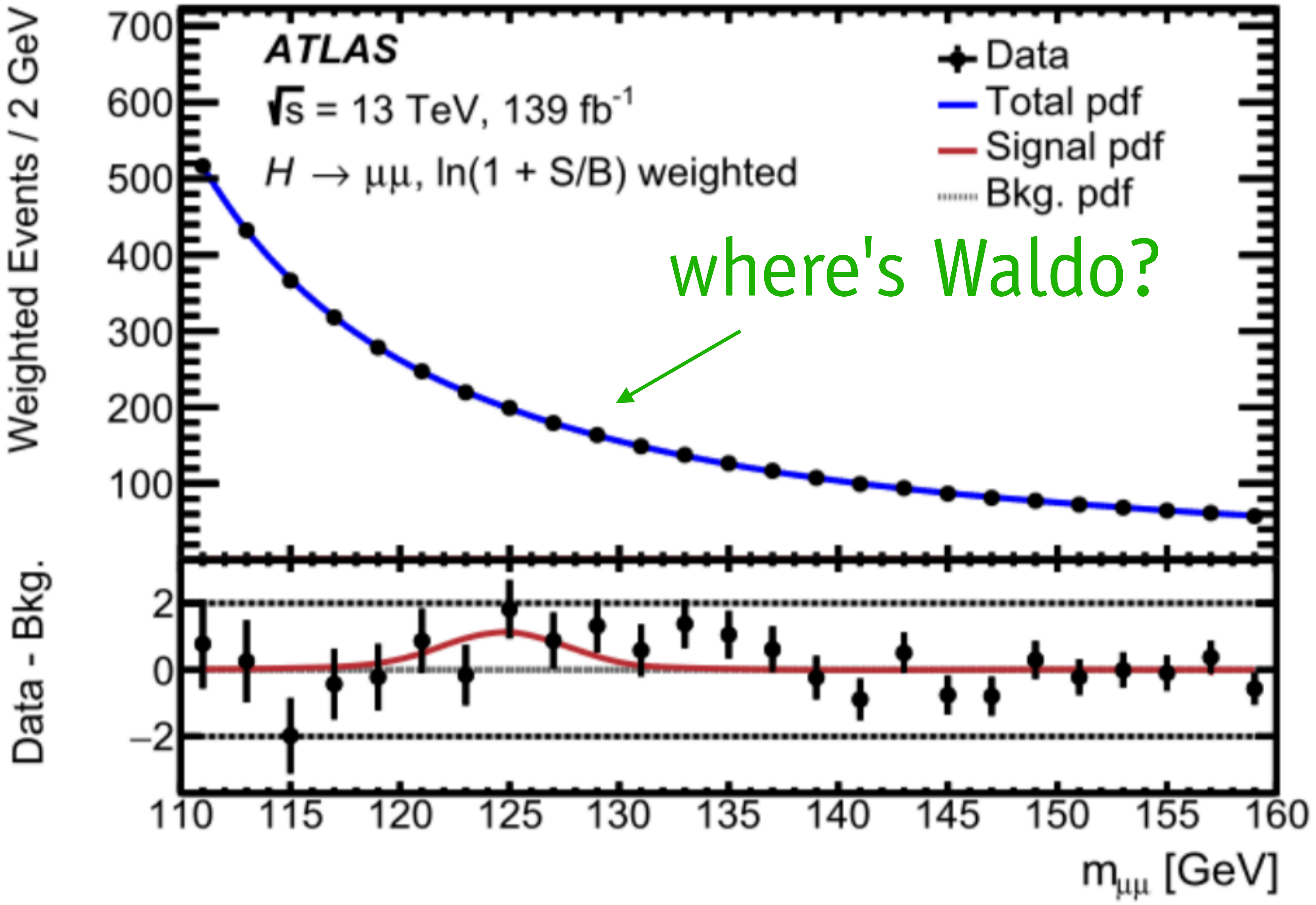


CMS-PAS-FTR-21-009





μ

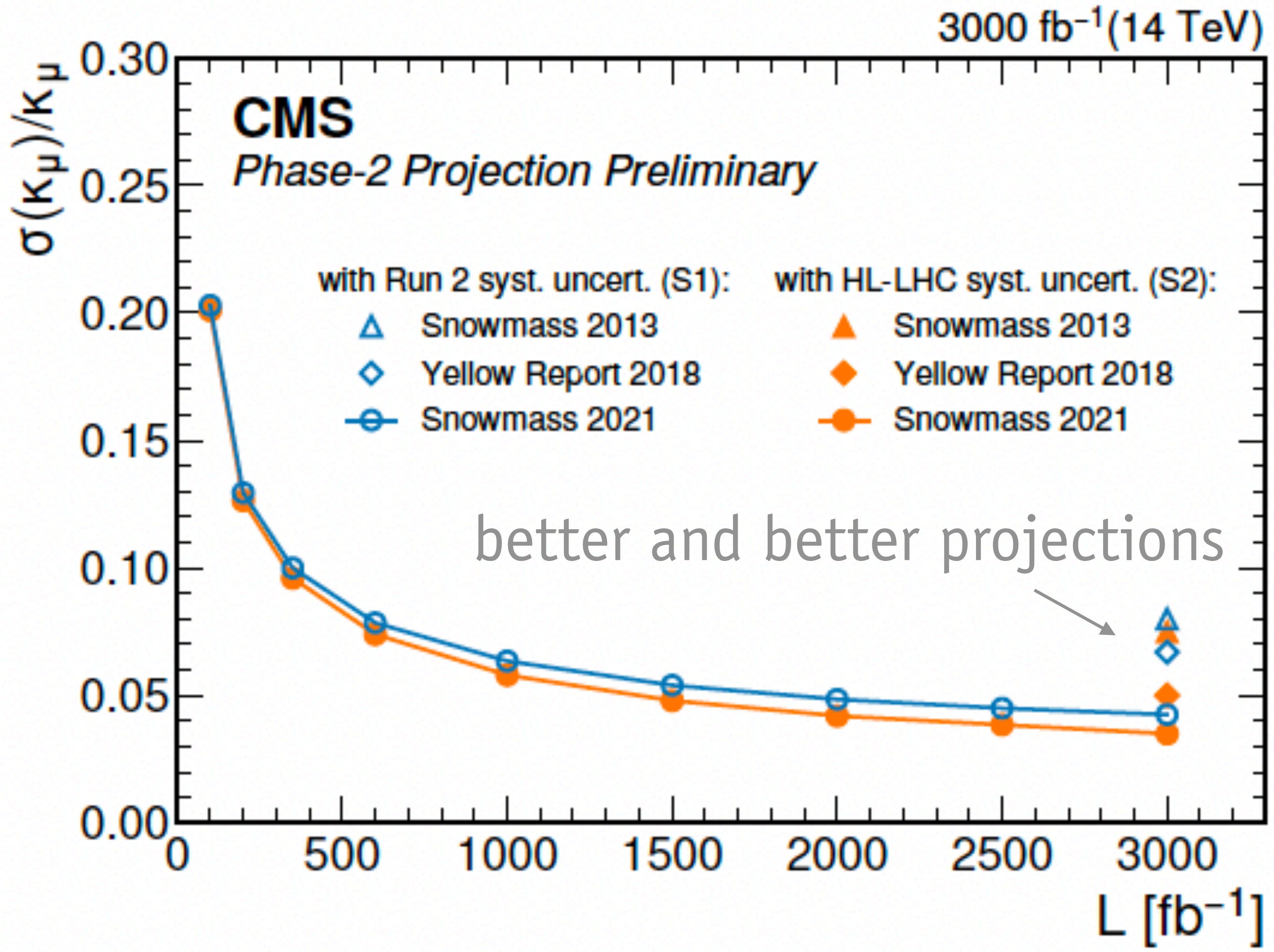


where's Waldo?

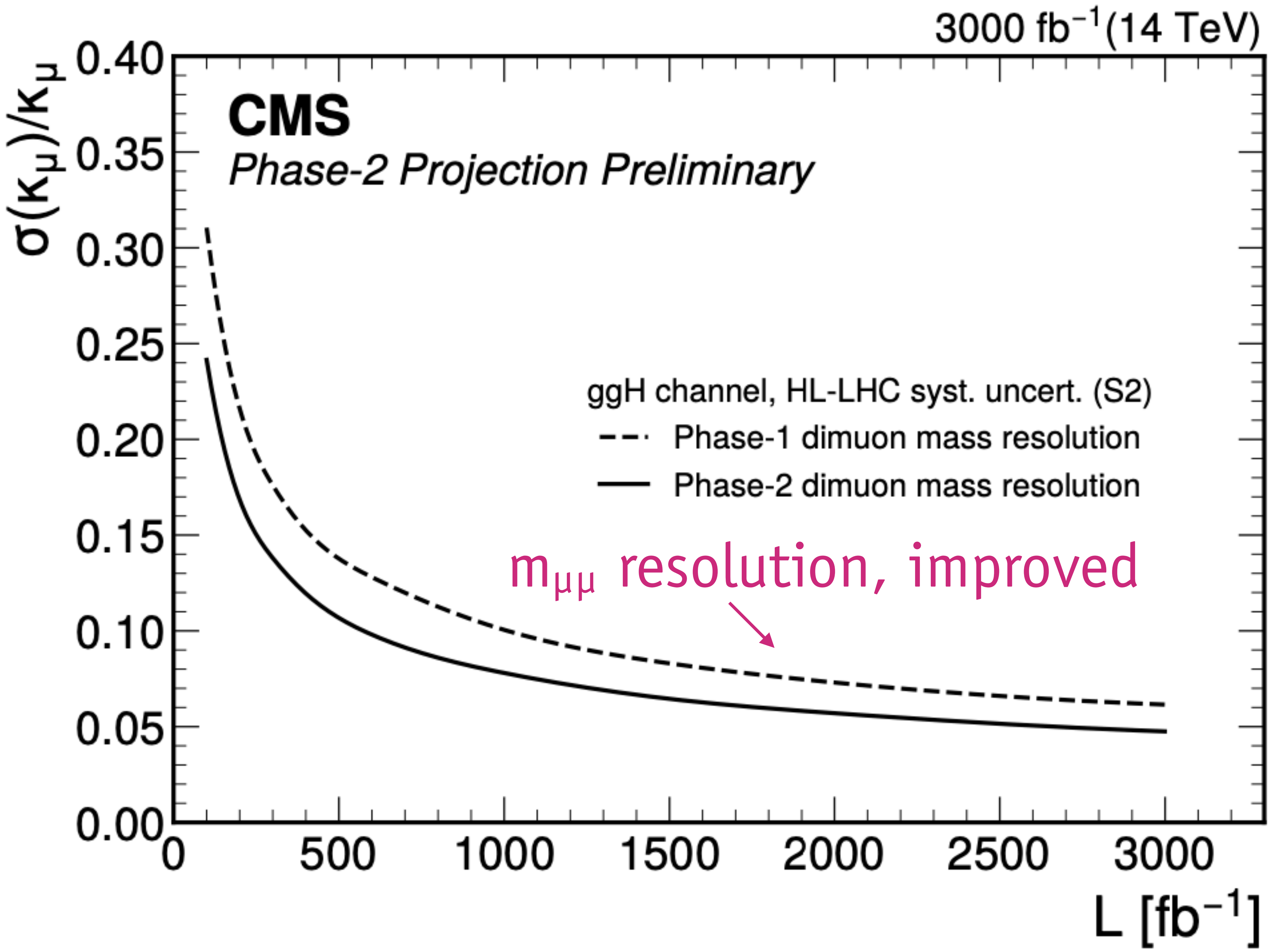
- $H \rightarrow \mu\mu$: SM BR is 2x10^{-4}, and S/B~10^{-3}
- Run-2 $H \rightarrow \mu\mu$: first evidence at CMS, 36% xsec uncertainty (stat limited)
- categorisation based on production process

PLB 812 (2021) 135980, JHEP01(2021)148

- ggF(mass)+VBF(DNN) extrapolate to HL-LHC
- **new tracker** provides **30% better $m_{\mu\mu}$** resolution
- extended muon system provides 10% more signal (15-18% more background)
- should reach **4% uncertainty** on k_μ



better and better projections

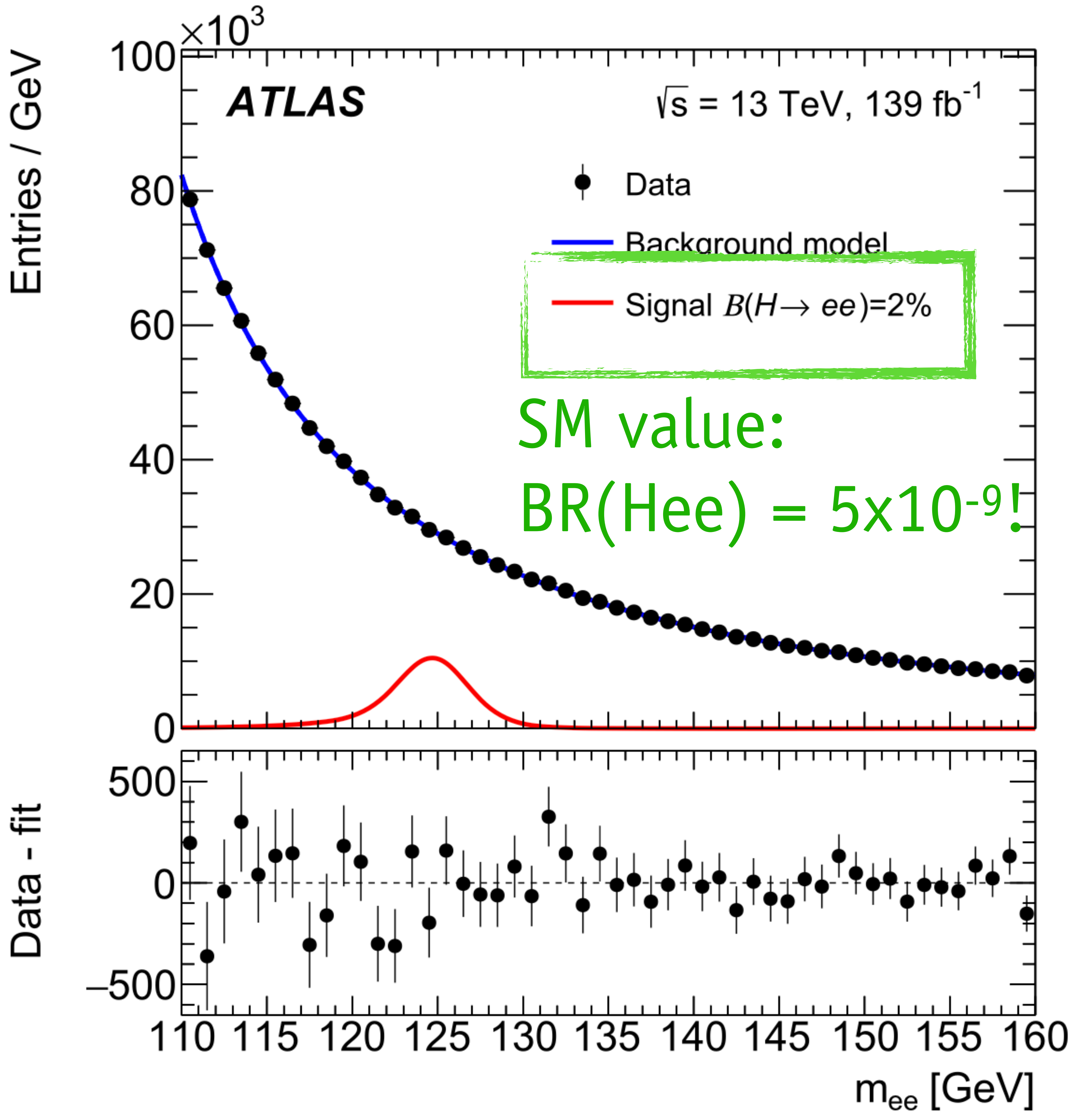


$m_{\mu\mu}$ resolution, improved

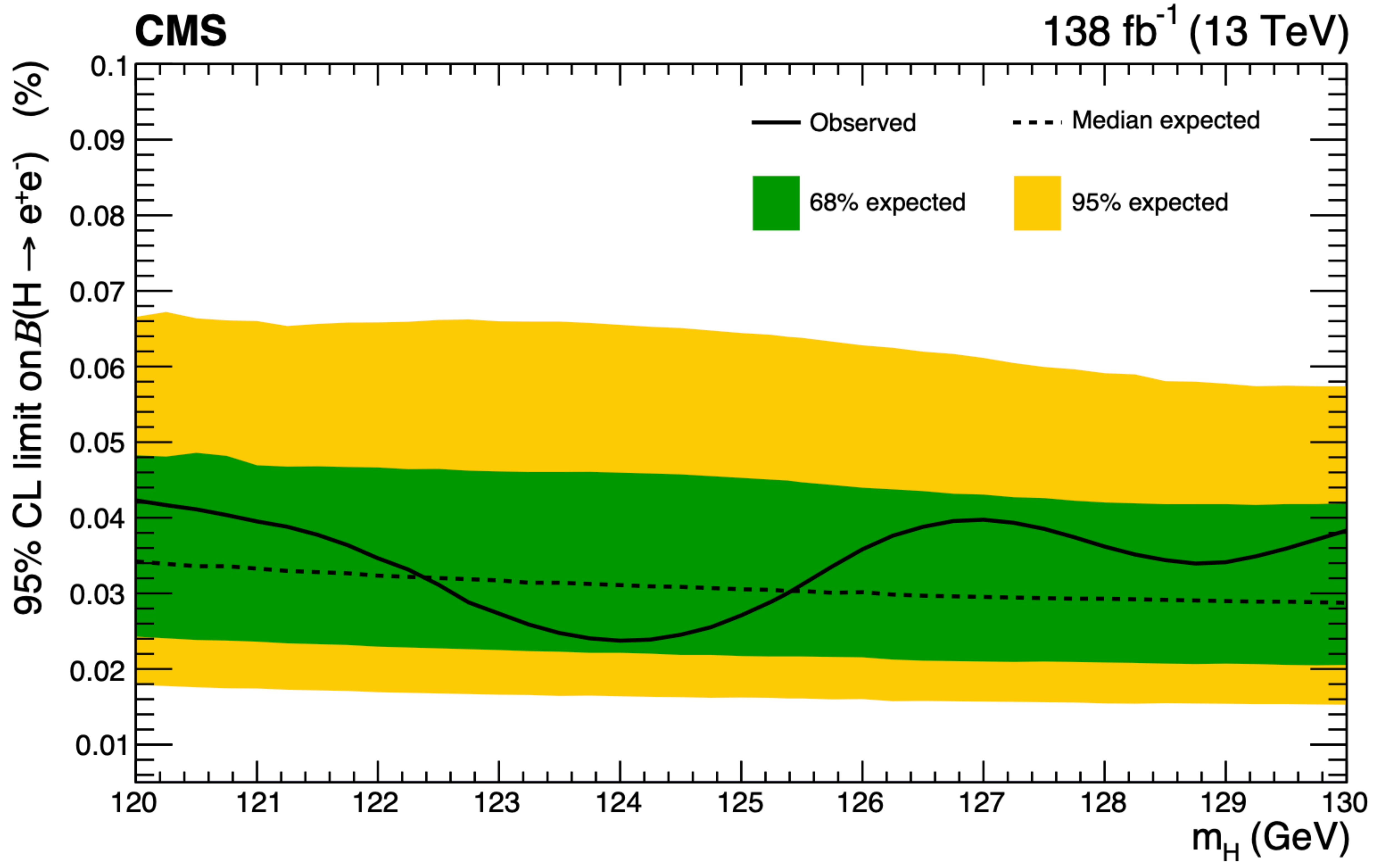
CMS-PAS-FTR-21-006,

HIGGS BOSON: TOWARDS FIRST GENERATION

- H→ρ Z/ɣ (u/d), H→ϕ Z/ɣ (s)…
  - very challenging (BR~$10^{-5}/10^{-6}$)
- not to mention H→ee…

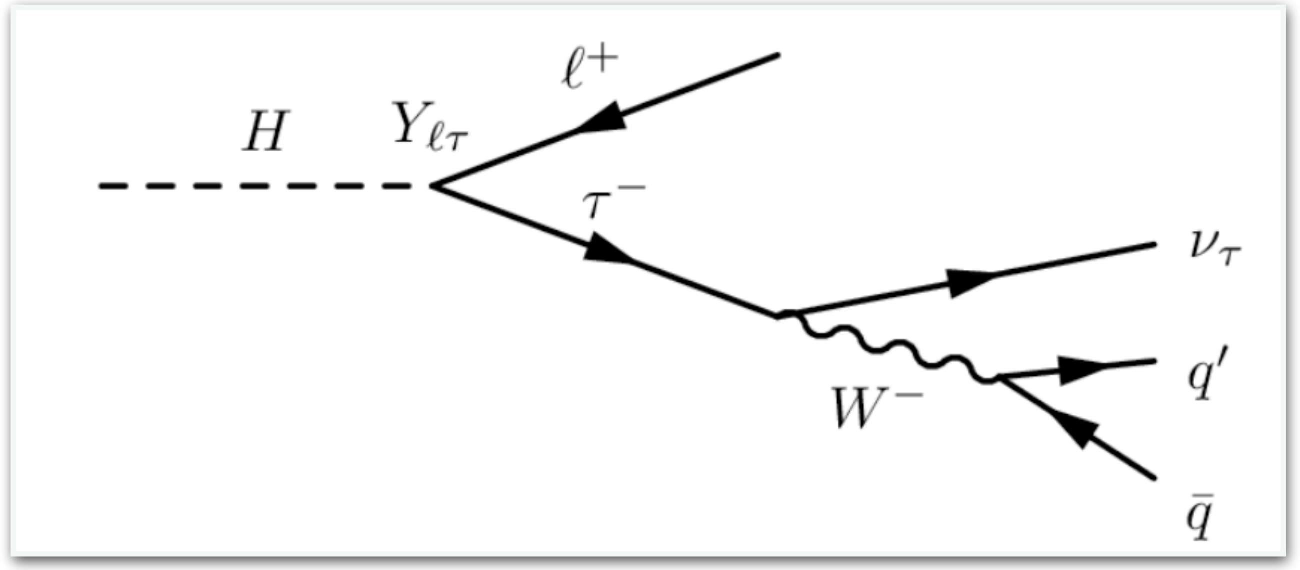


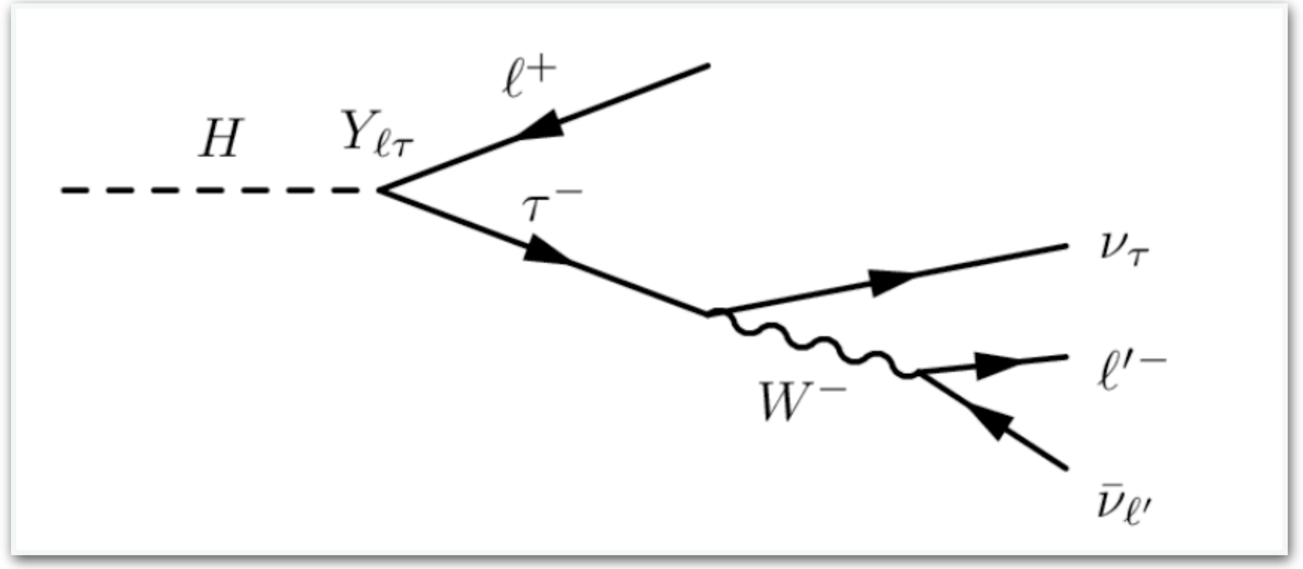
SM value:
BR(Hee) = $5x10^{-9}$!

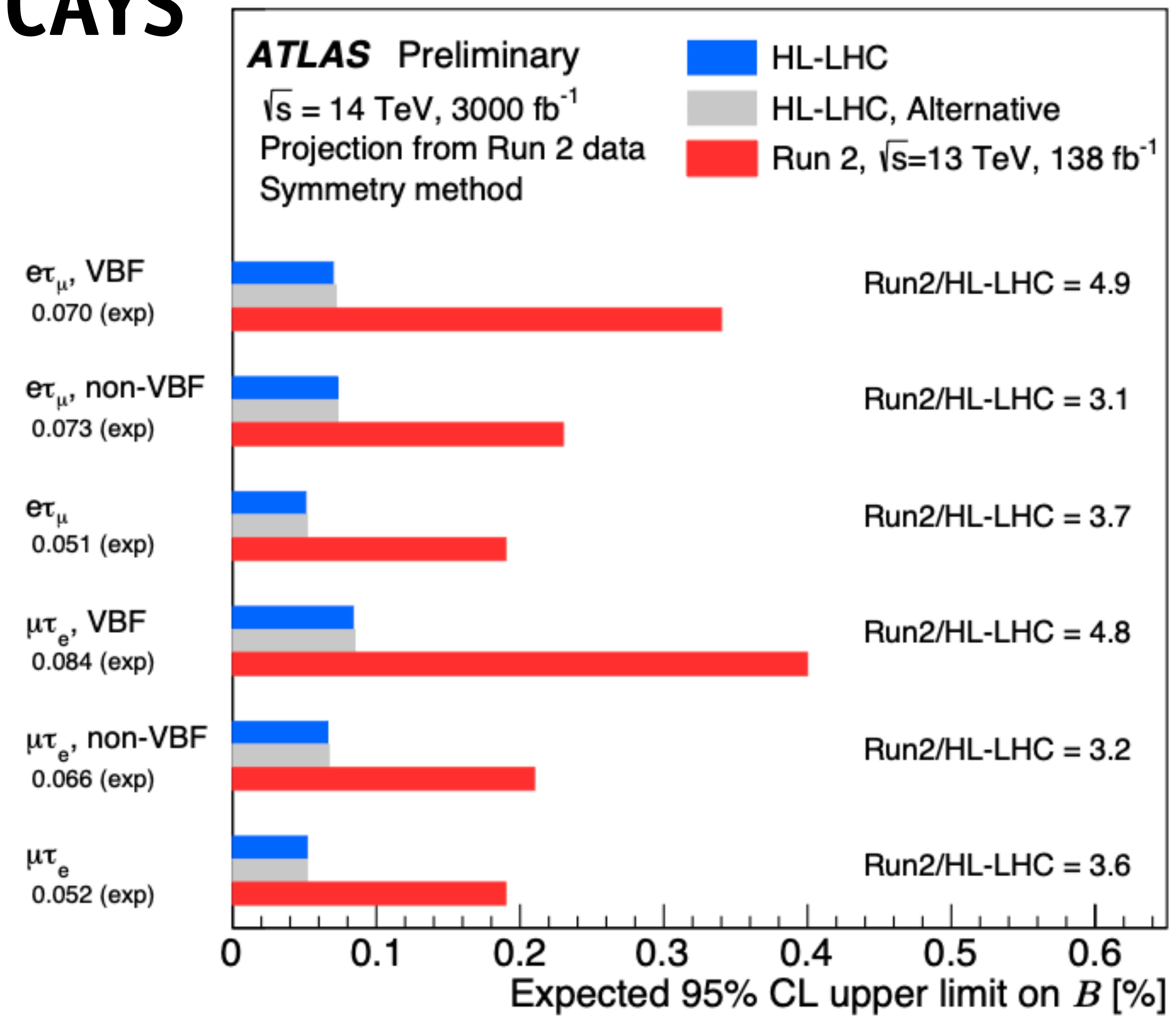


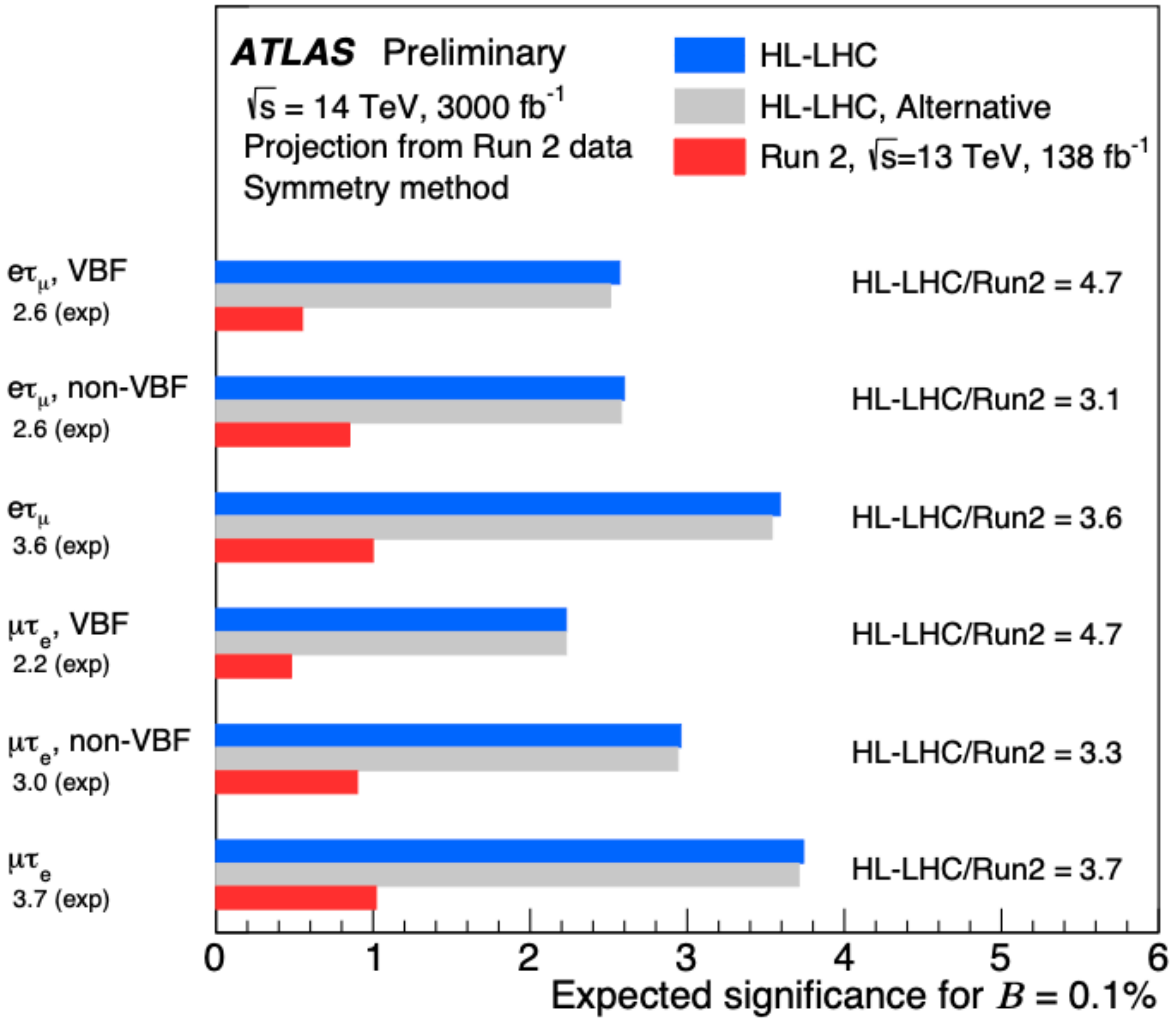
arXiv:2208.00265, PLB 801(2020)135148

LEPTON-FLAVOUR-VIOLATING DECAYS









Uncertainties	Extrapolation SF	MC template method	Symmetry method
$\tau_{\text{had-vis}}$ ID, stat.-related	0.00	√	-
$\tau_{\text{had-vis}}$, others	1.00	√	-
Electron and muon	1.00	√	√
Flavour tagging *c*- and *b*-jets	0.50	√	√
Jet, others	1.00	√	√
E_T^{miss}	0.50	√	√
Fake bkg., stat.-related	0.21	√	√
Fake bkg., others	1.00	√	√
Lepton eff. corr., stat.-related	0.21	-	√
Lepton eff. corr., others	1.00	-	√
Z bkg. modelling, PDF	0.40	√	-
Z bkg. modelling, others	0.50	√	-
Top-quark bkg. modelling, PDF	0.40	√	-
Top-quark bkg. modelling, others	0.50	√	-
Higgs modelling, PDF, ggF	0.41	√	√
Higgs modelling, PDF, VBF H	0.46	√	√
Higgs modelling, PDF, VH	0.46	√	√
Higgs modelling, others	0.50	√	√
Luminosity	0.59	√	√

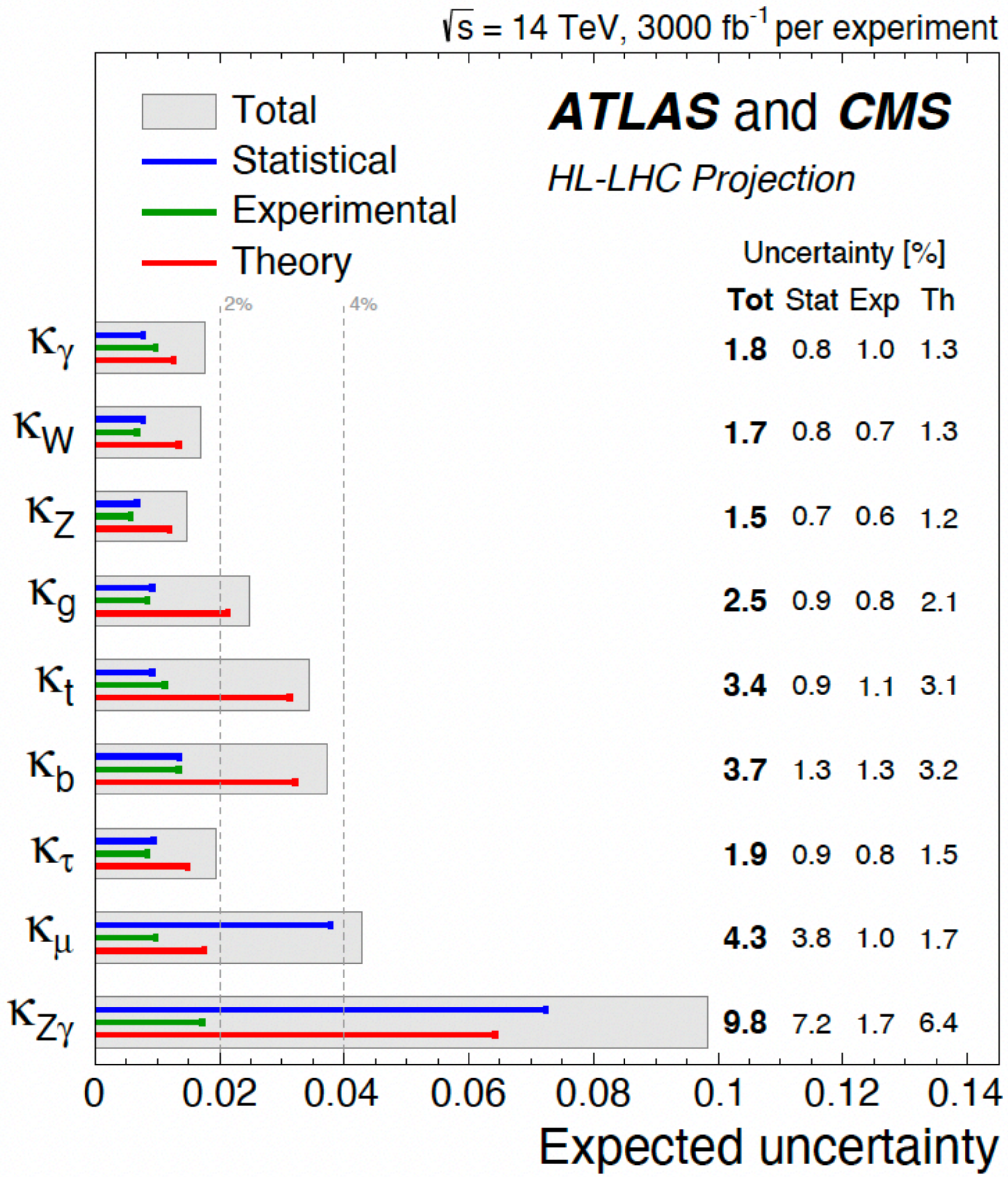
- H→τe/τμ
- two complementary methods
  - data-driven (τ_{lep}, best for VBF)
  - MC-based (τ_{lep}+τ_{had}, best for ggF)
- 3-4x improvement w.r.t Run-2 from luminosity and improved systematics

ATL-PHYS-PUB-2022-054

HIGGS BOSON: DECAY

- HL-LHC **theory** dominated BRs: γγ (2.6%), ZZ (2.9%), WW (2.8%), **ττ** (2.9%), bb (4.4%)
- HL-LHC **stat** dominated BRs: μμ (8.2%), Zγ (19.1%)
- κ framework uncertainties at the % level
  - except Zγ
- k_t, k_b, k_g dominated by theory uncertainties
- 2.5% uncertainty on BR_{bsm}
  - assuming $|k_V|<1$ to avoid degeneracies

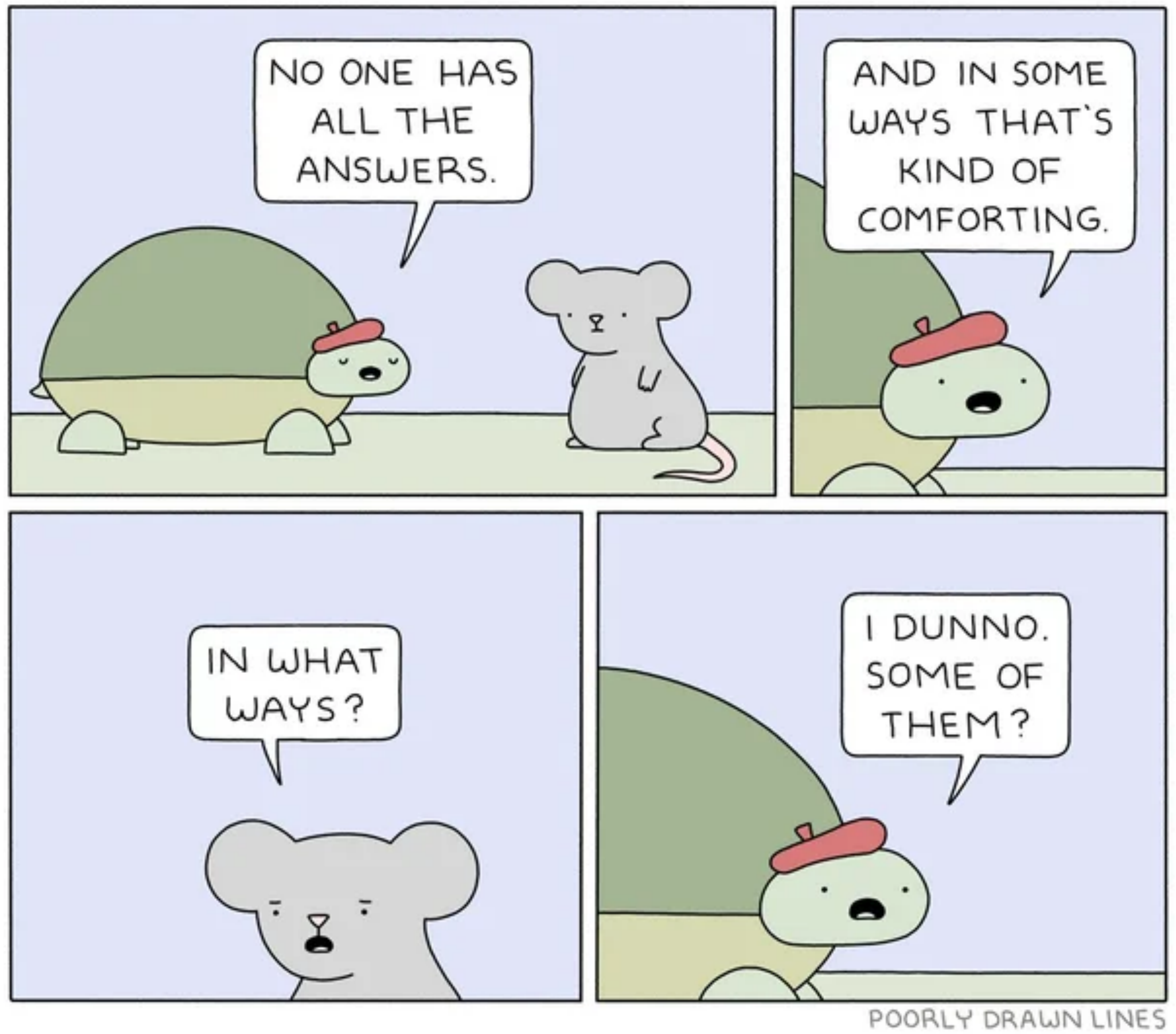
$$\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \right)$$

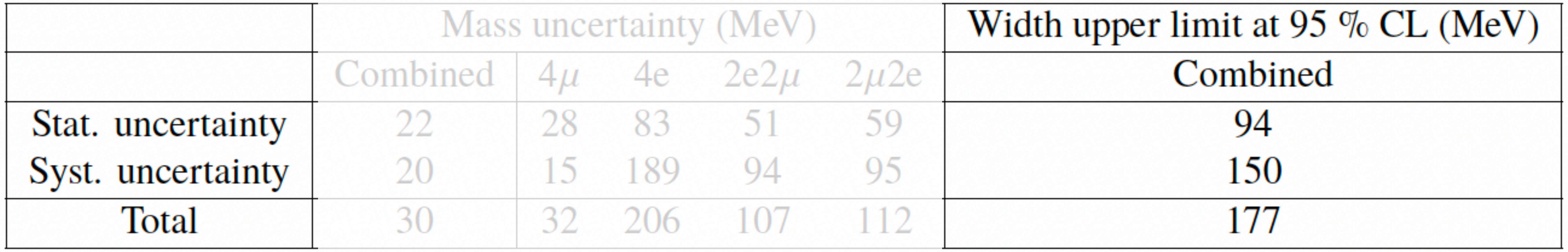


CERN-2019-007

HIGGS BOSON: WIDTH

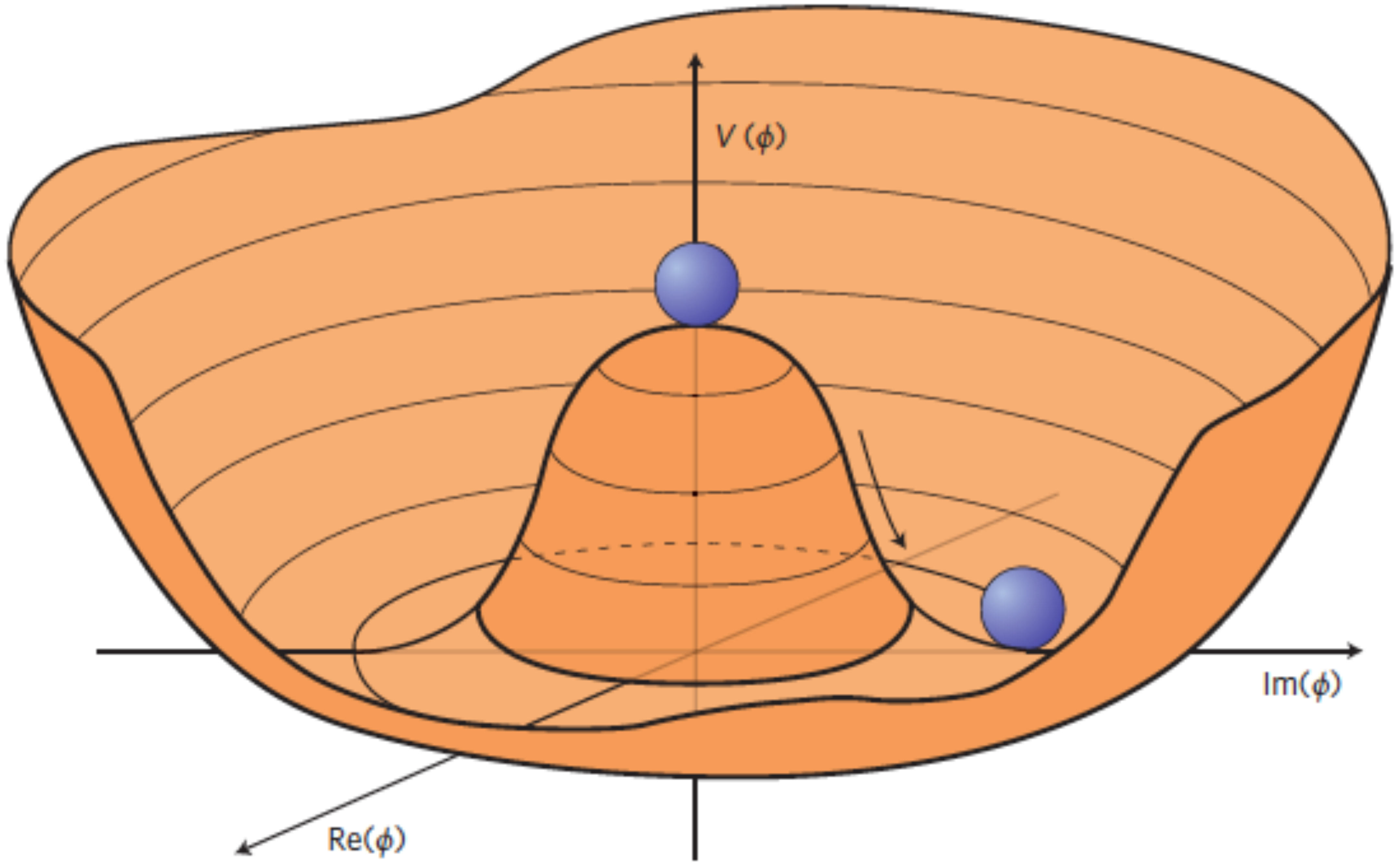
- model-independent: limited by detector resolution (SM value is 4 MeV!)
- can be derived in the $\varkappa$ framework assuming $|k_V|<1$
  - HL-LHC: CMS can reach **4% uncertainty**
- but also comparing the on-shell vs off-shell H→ZZ production
  - Run-2: 3.2 (4.6) MeV at CMS (ATLAS) with ~50% uncertainty
  - ATLAS+CMS combination may reach **20% uncertainty**, dominated by theory

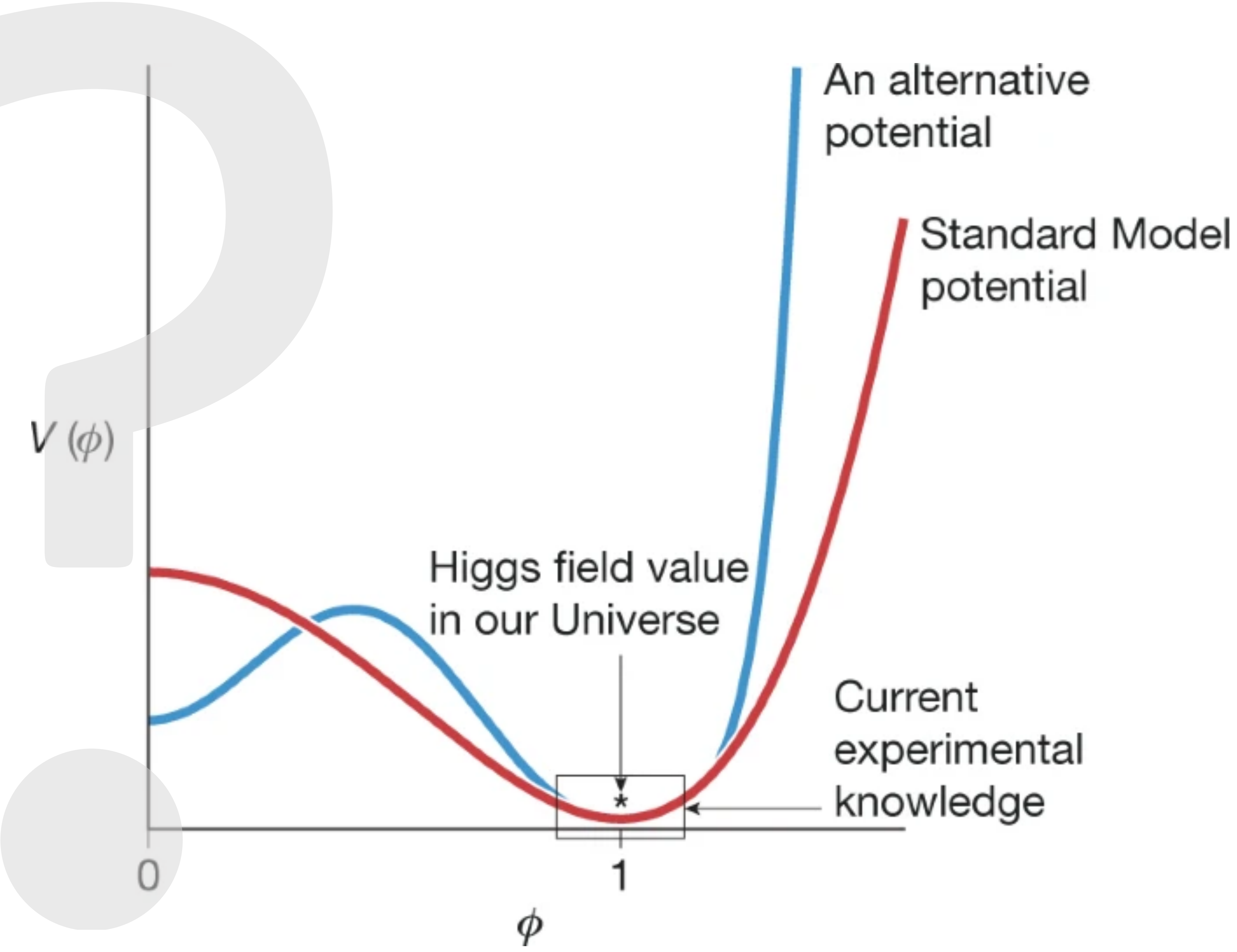




	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177

ATL-PHYS-PUB-2015-024, CMS-PAS-FTR-18-011

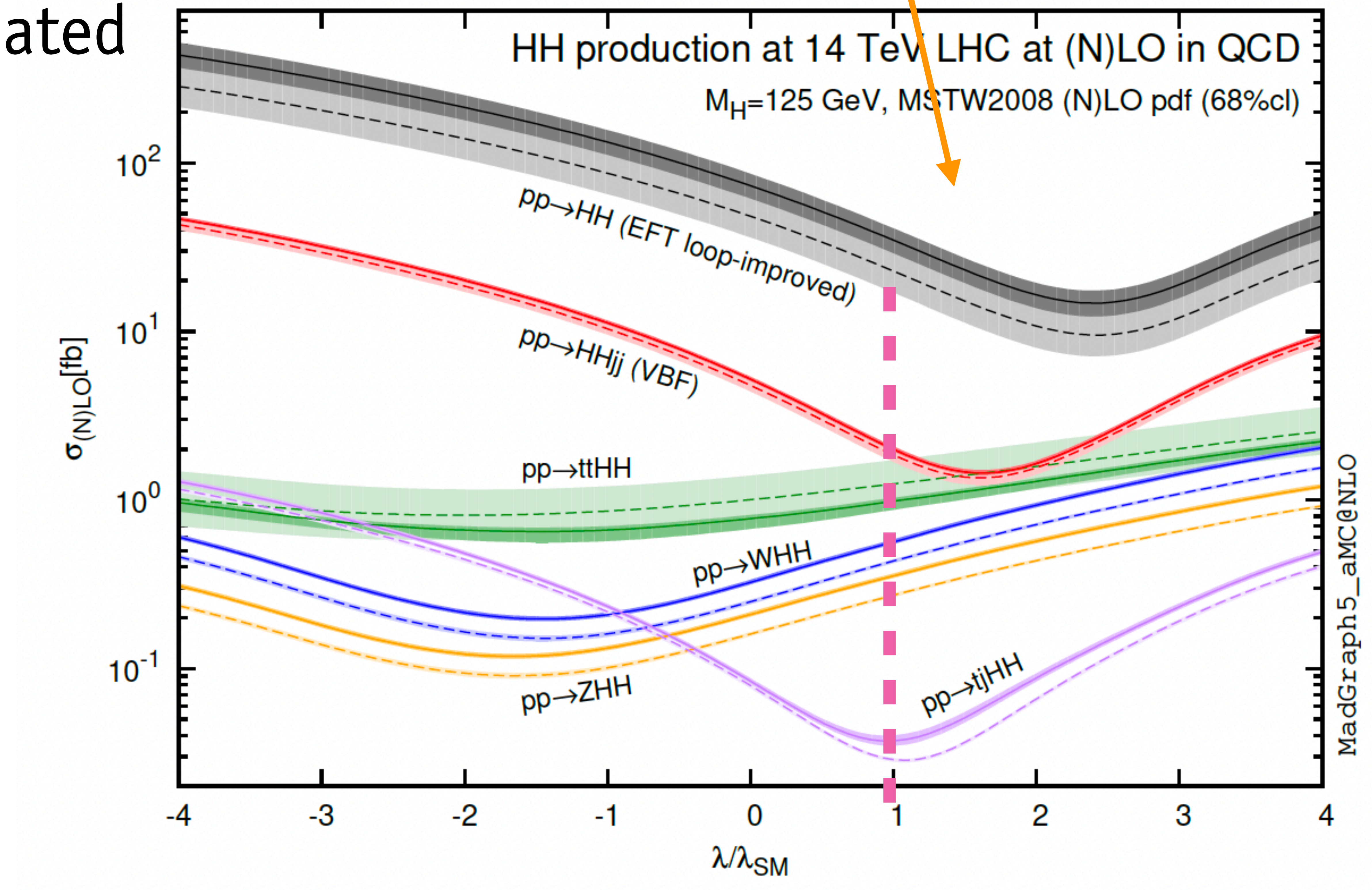

V (ϕ)
Im(ϕ)
Re(ϕ)

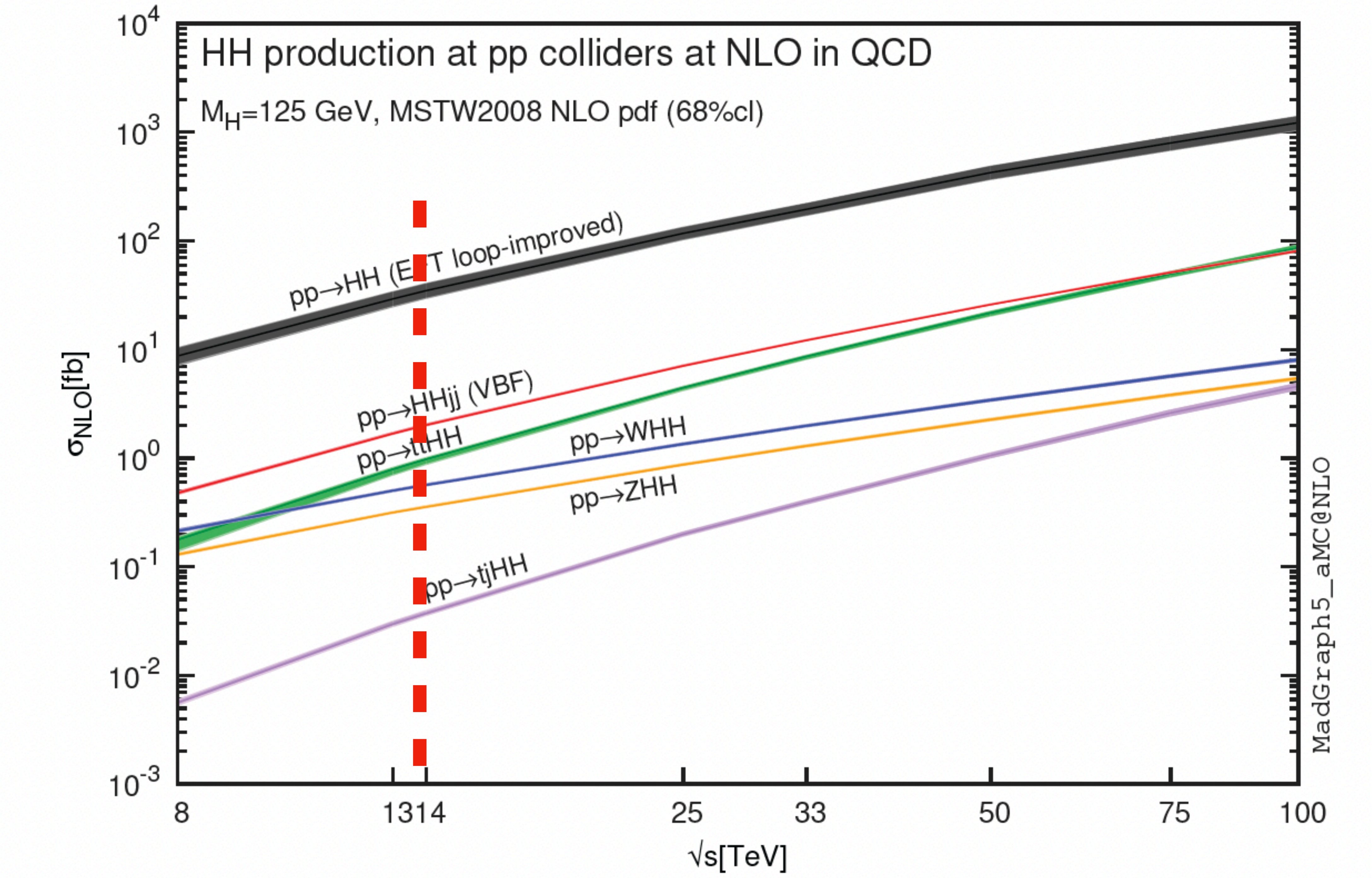

An alternative potential
Standard Model potential
V (ϕ)
Higgs field value in our Universe
Current experimental knowledge
0
1
ϕ

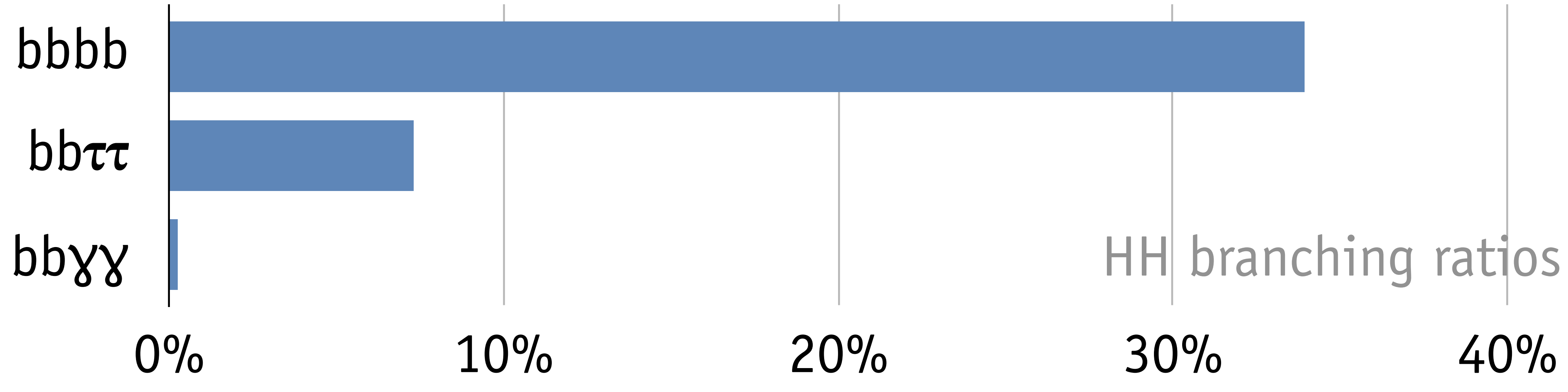
THE BEH POTENTIAL: NON-RESONANT HH

- most sensitive to λ_{HHH} (can also be done with e.g. ttH+tH, H→γγ…)
- 1/1000 wrt single Higgs production, ggF-dominated
- use one H decaying to large-BR channel
- currently stat dominated

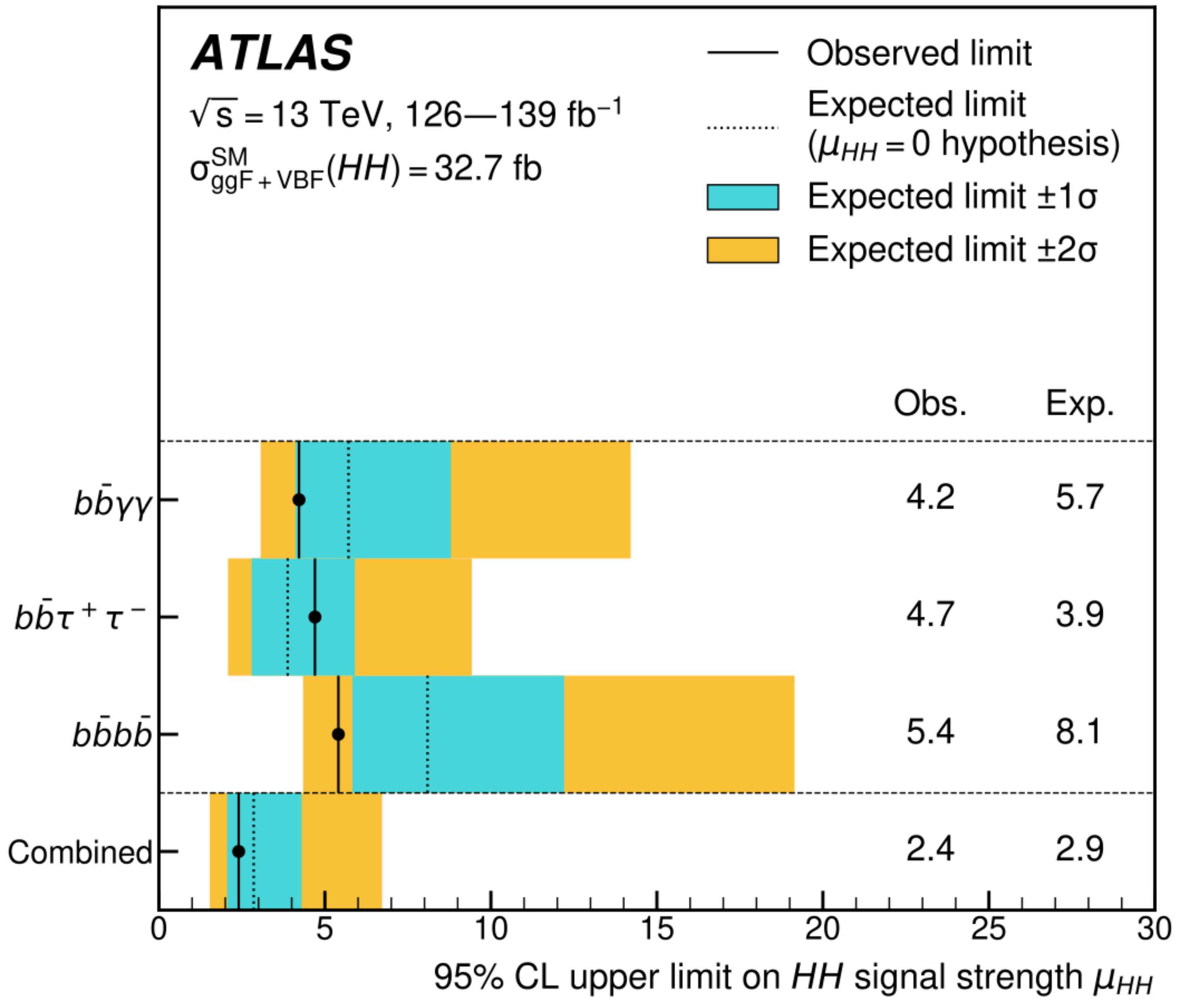
σ smallest in SM-ish region

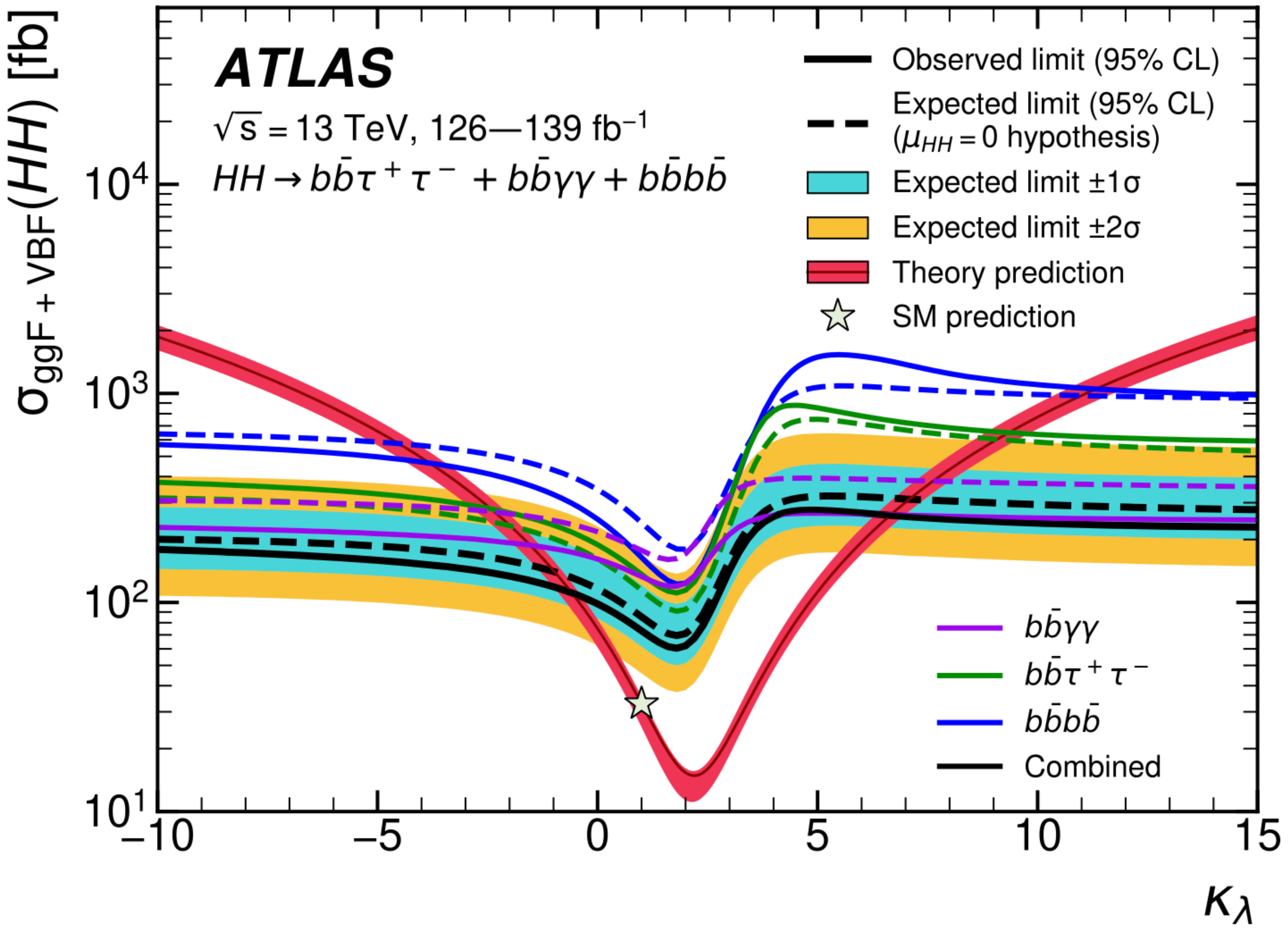


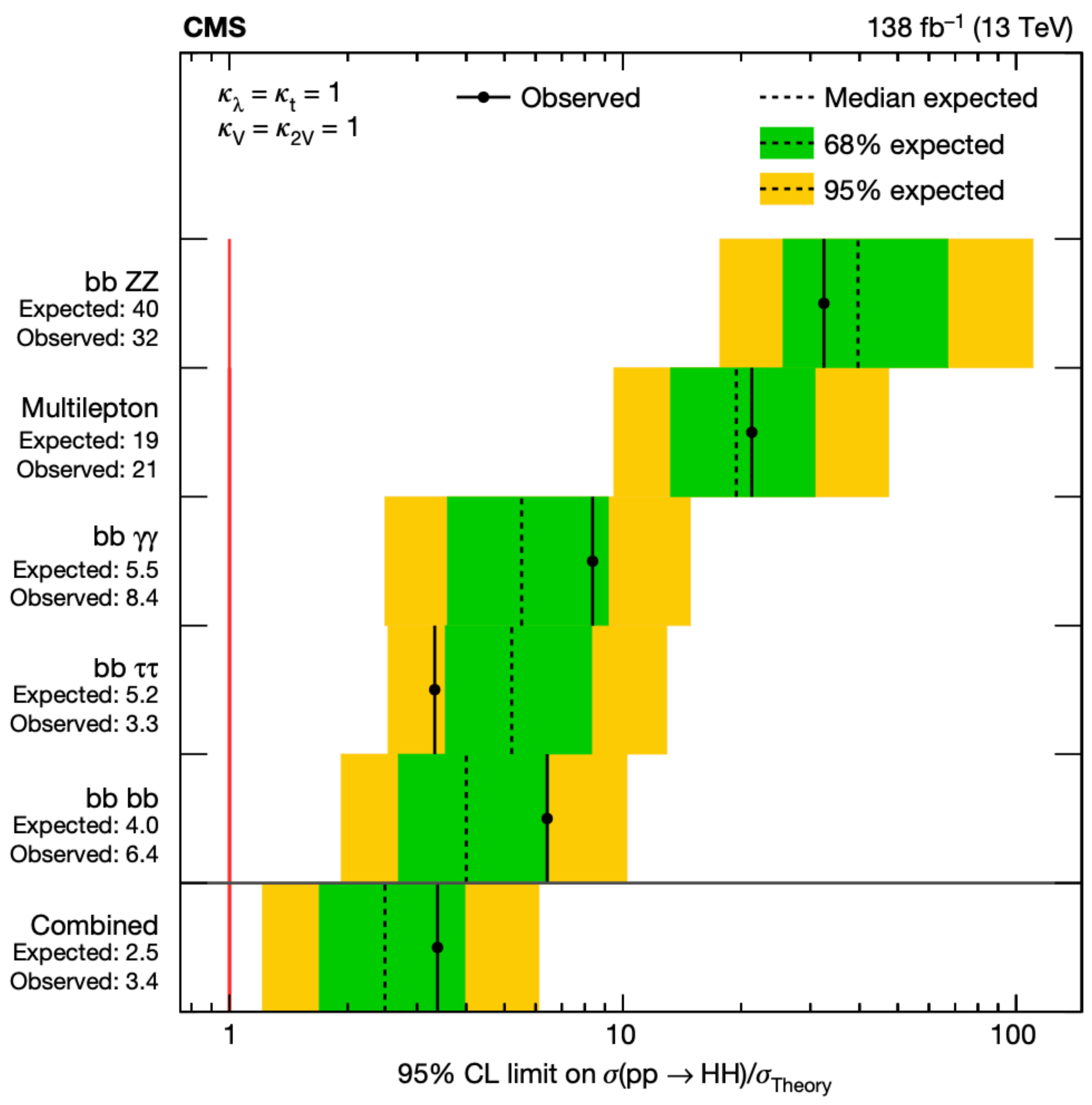


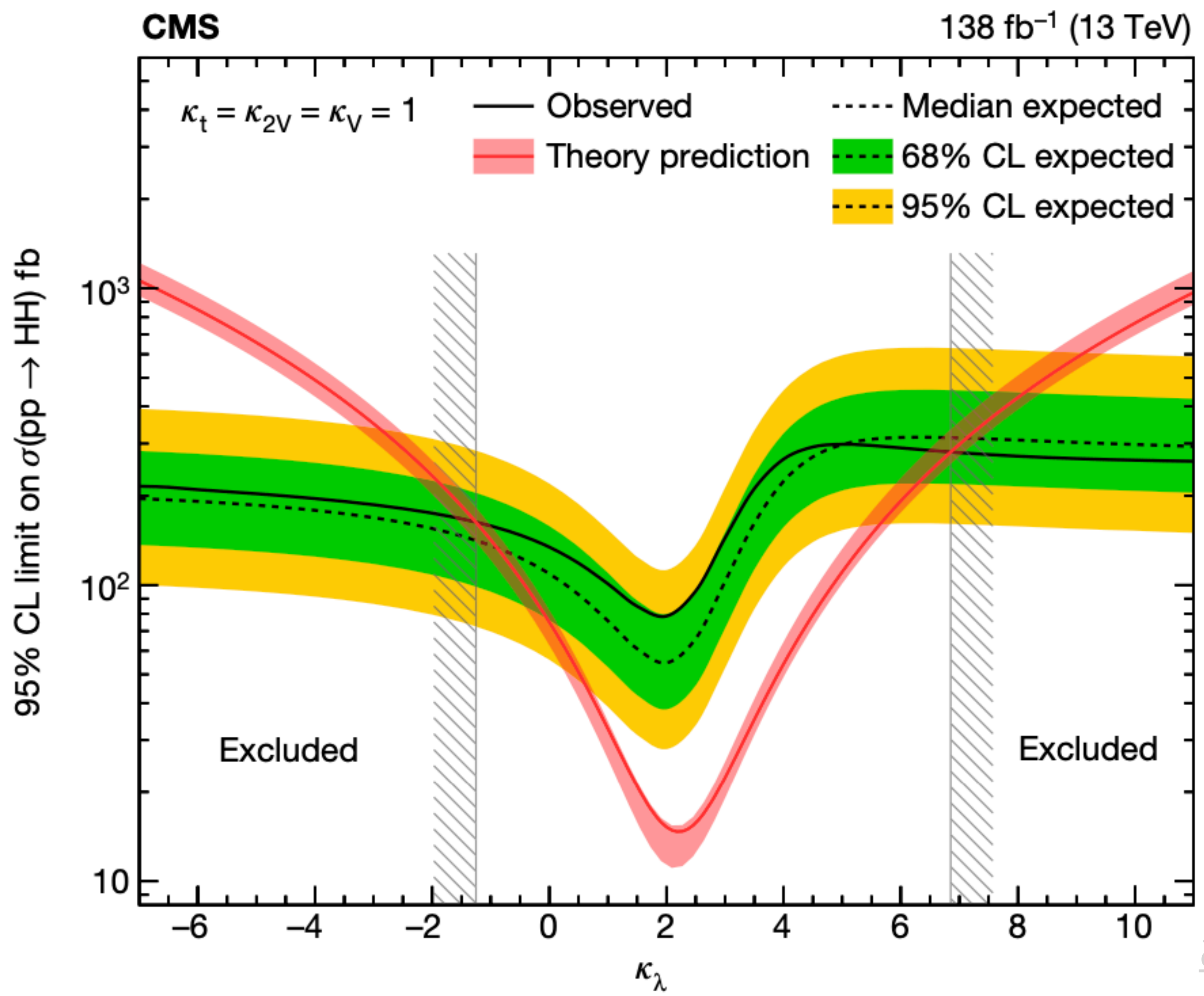


$$V(\Phi) \propto \frac{1}{2}m_H^2\Phi^2 + \lambda v\Phi^3 + \frac{1}{4}\lambda\Phi^4$$



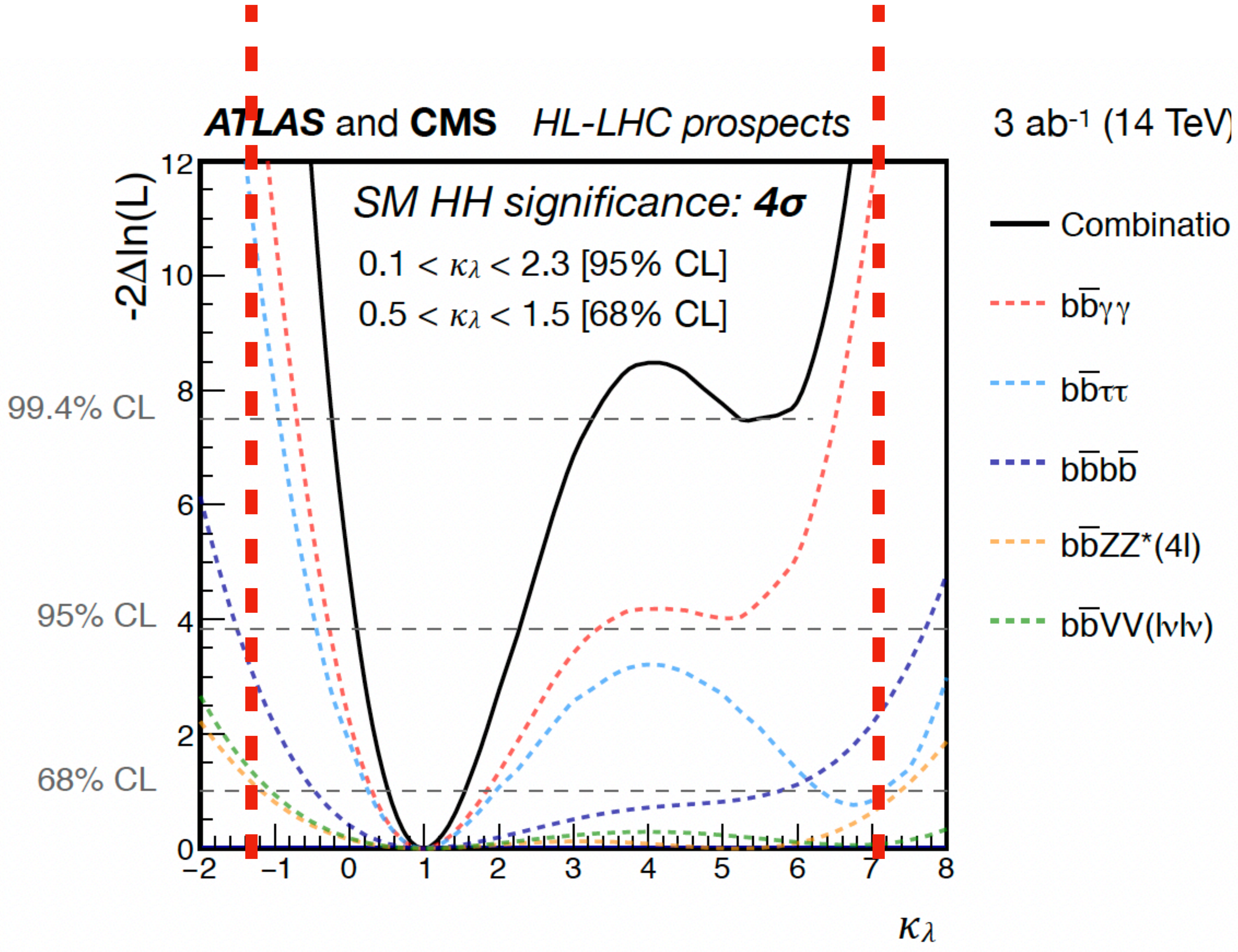




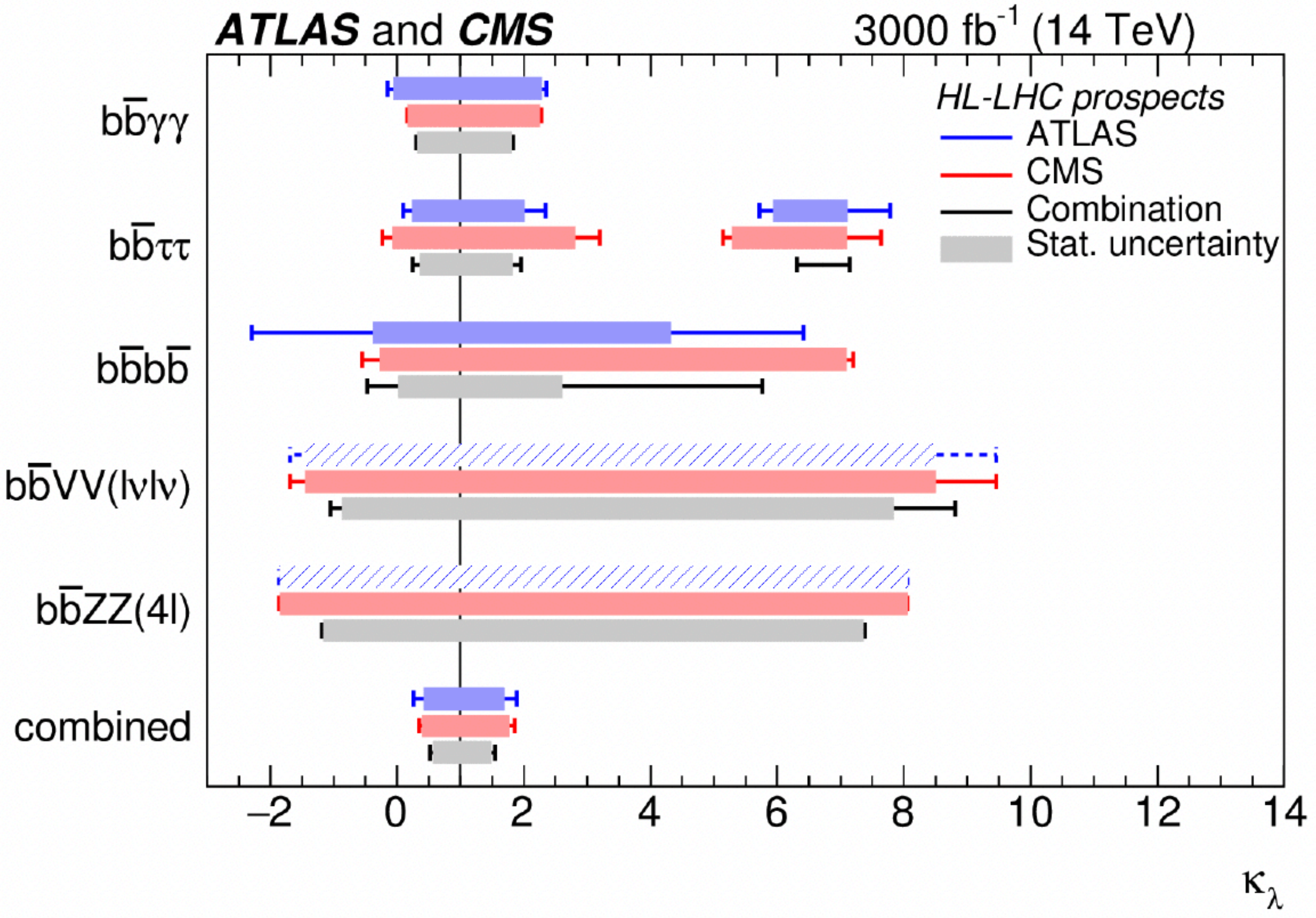


getting closer...

arXiv:2211.01216, Nature 607 (2022) 60-68

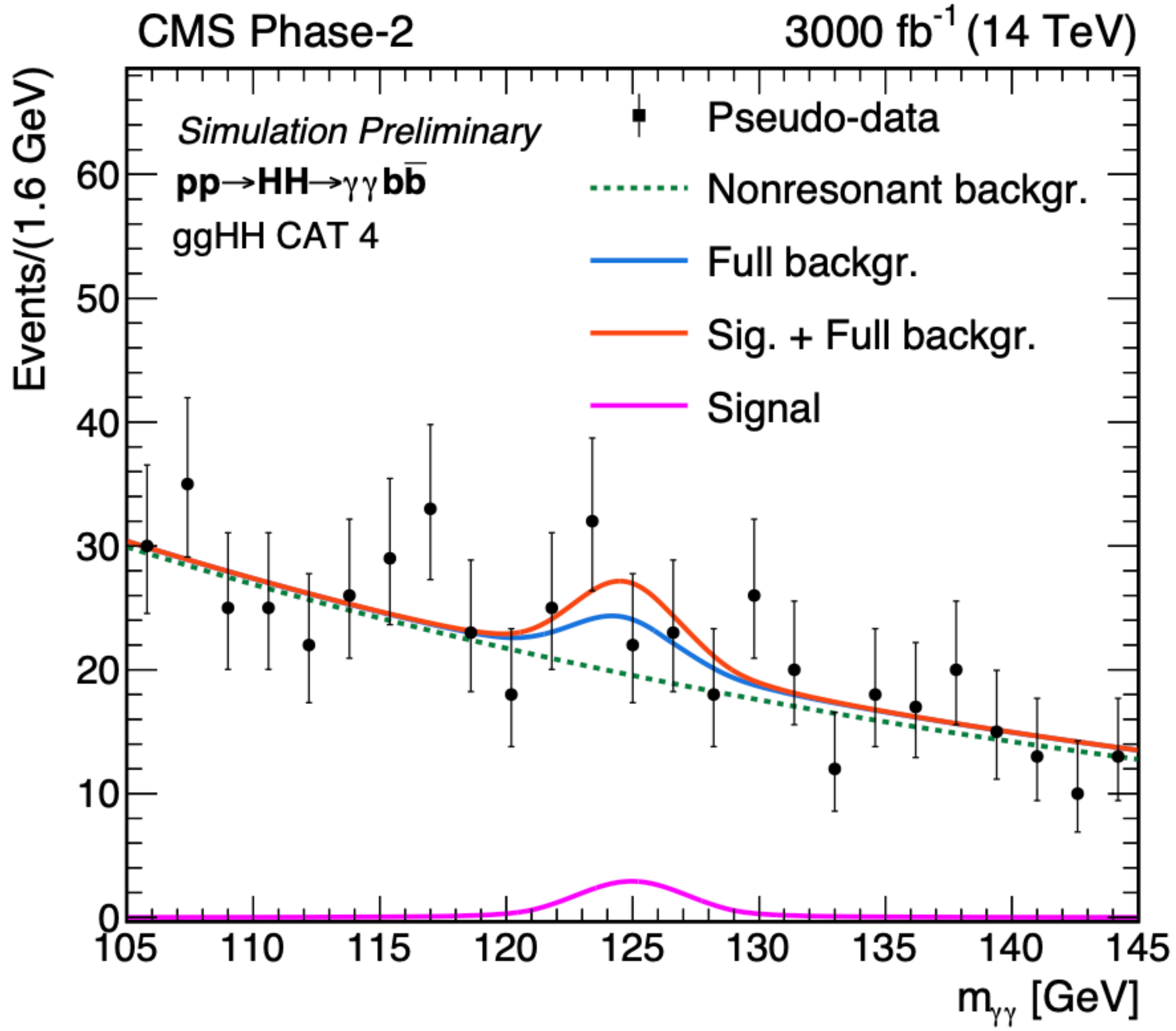


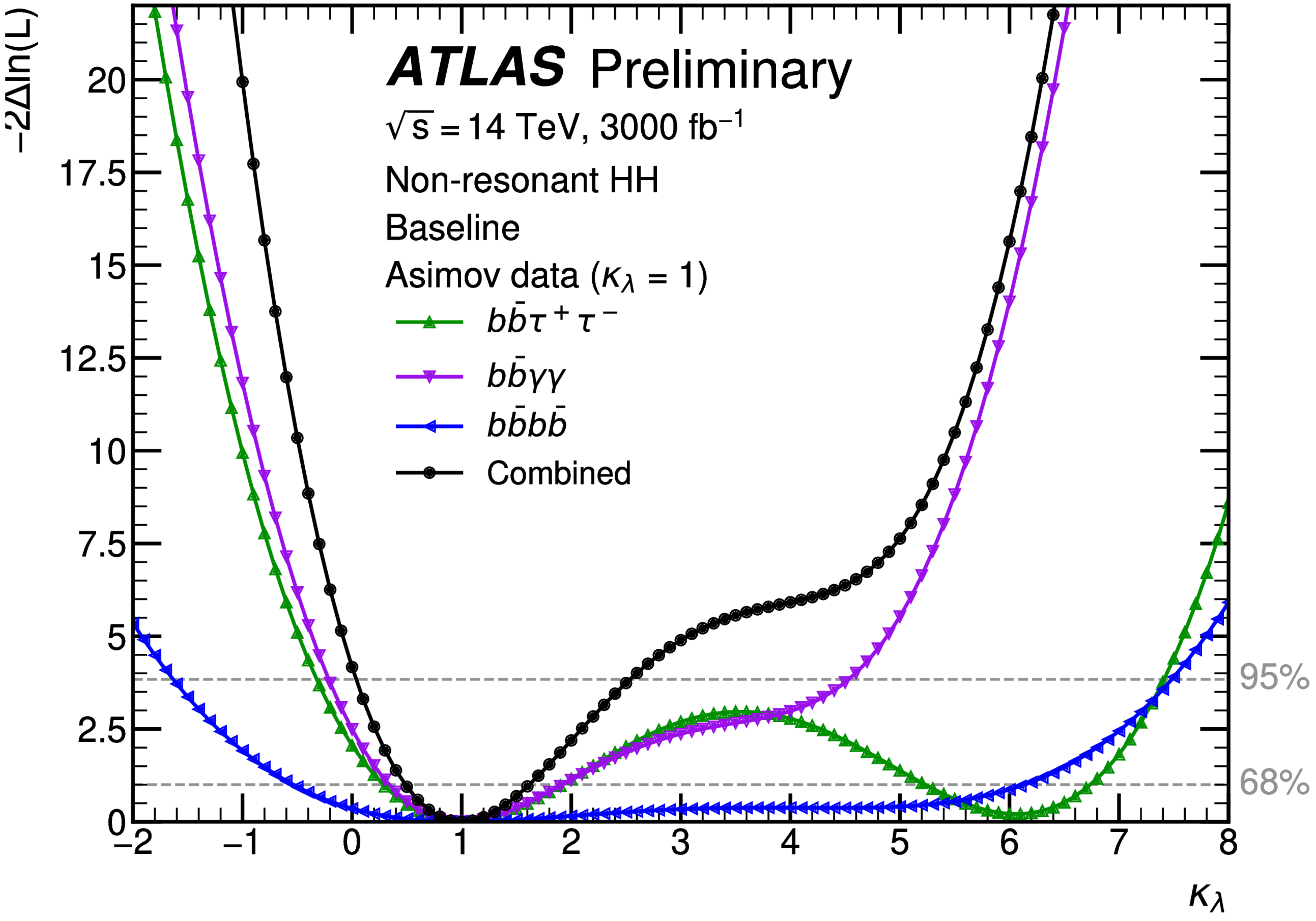
current limits



- 4σ from combination, 4.5σ without systematics
- and these were preliminary (combined) projections...

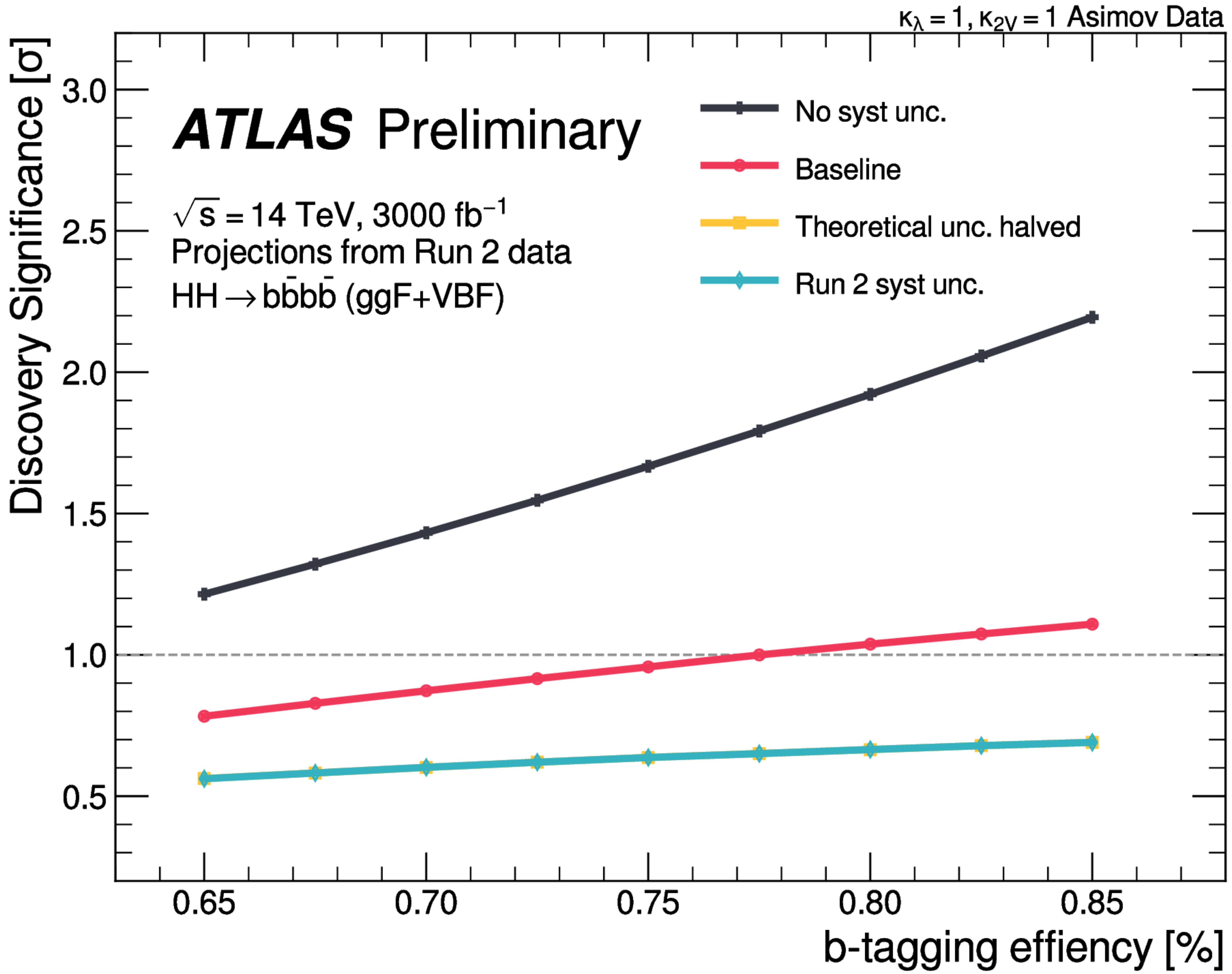
CERN-2019-007





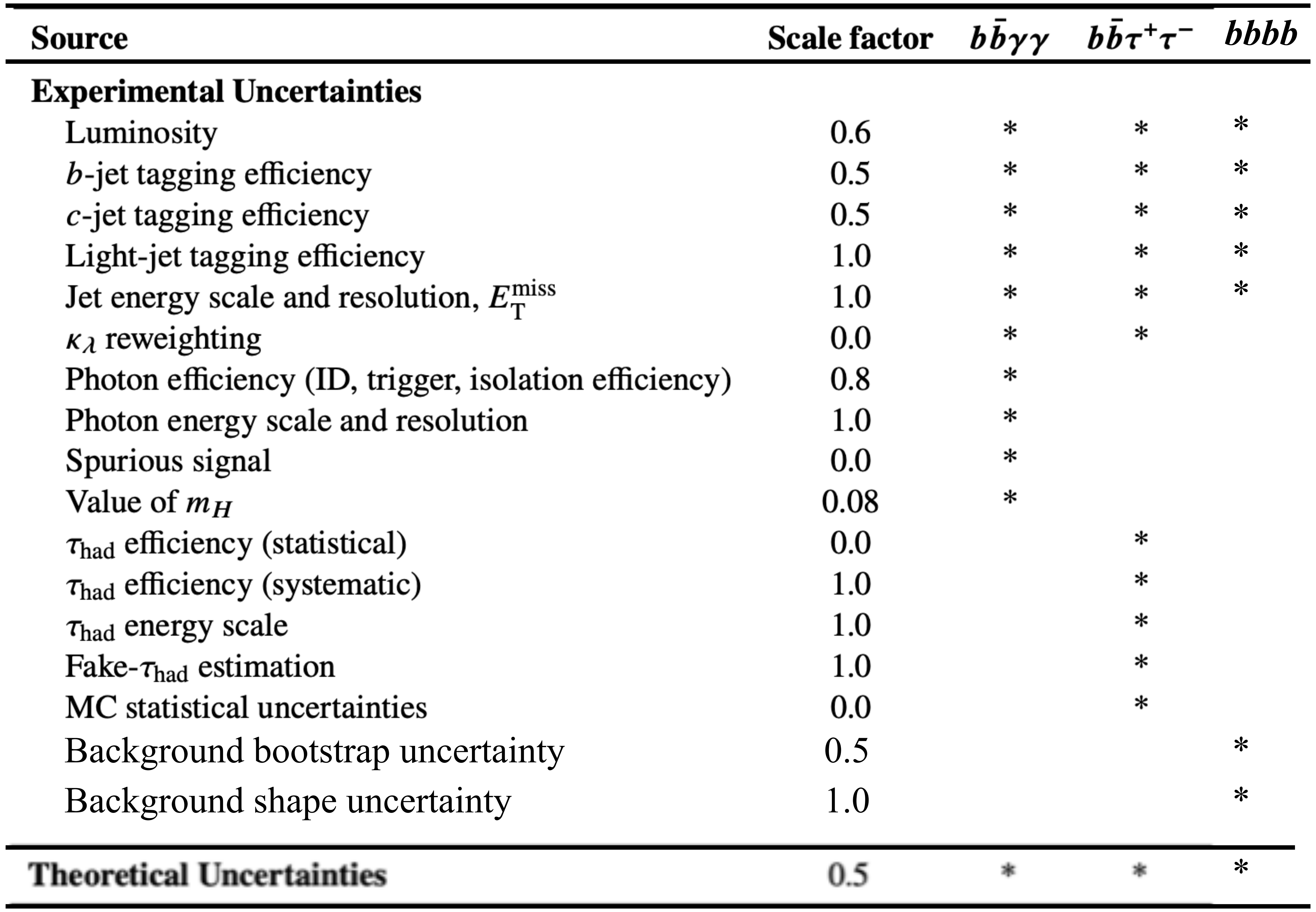
- bbγγ: ML discriminants, to reduce ttH(γγ) bkg and γ(γ)+jets, ~2σ

CMS-PAS-FTR-21-004, ATL-PHYS-PUB-2022-053

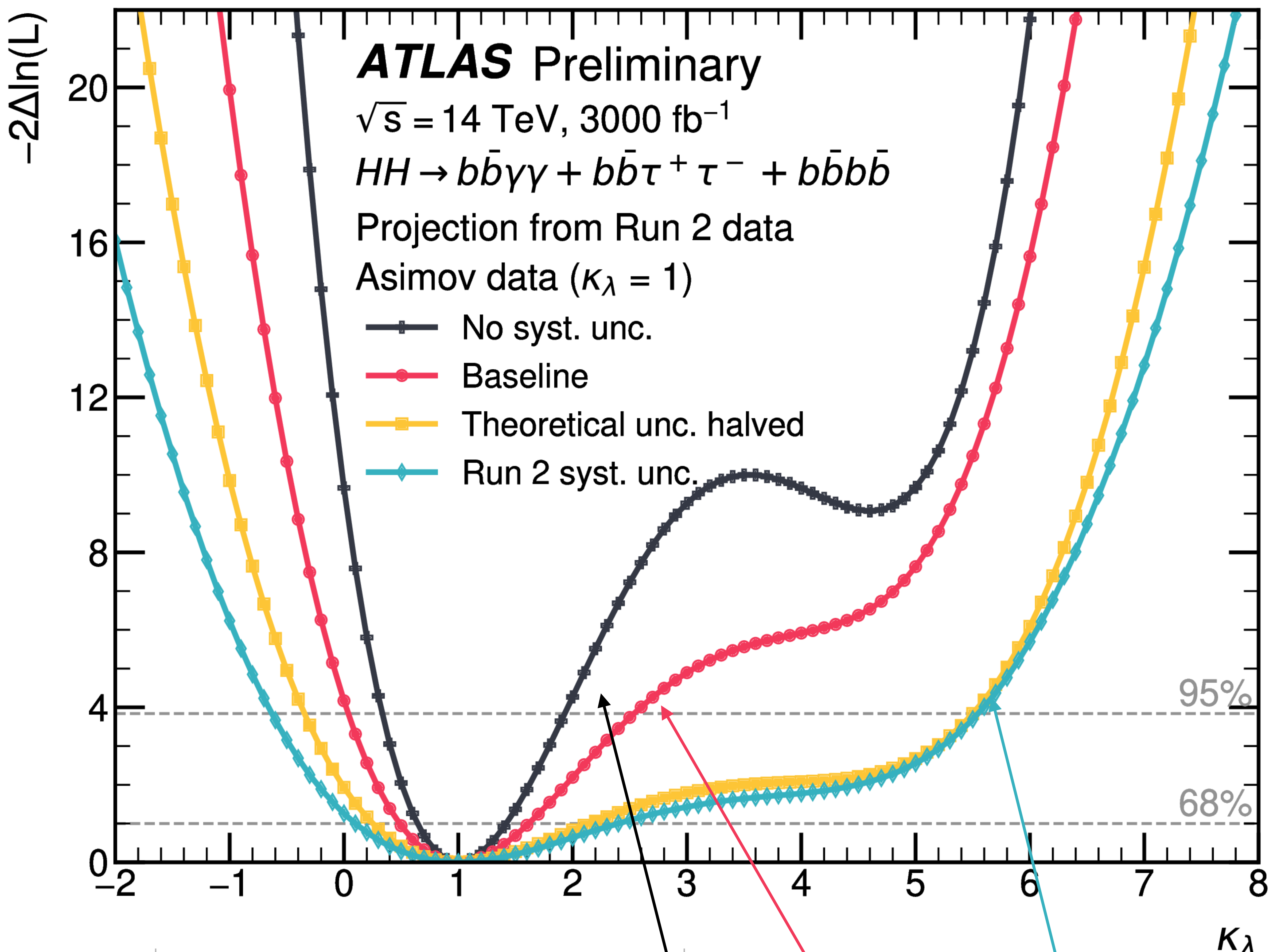


- impact of b-tagging on discovery significance for HH in bbbb final state

ATL-PHYS-PUB-2022-053



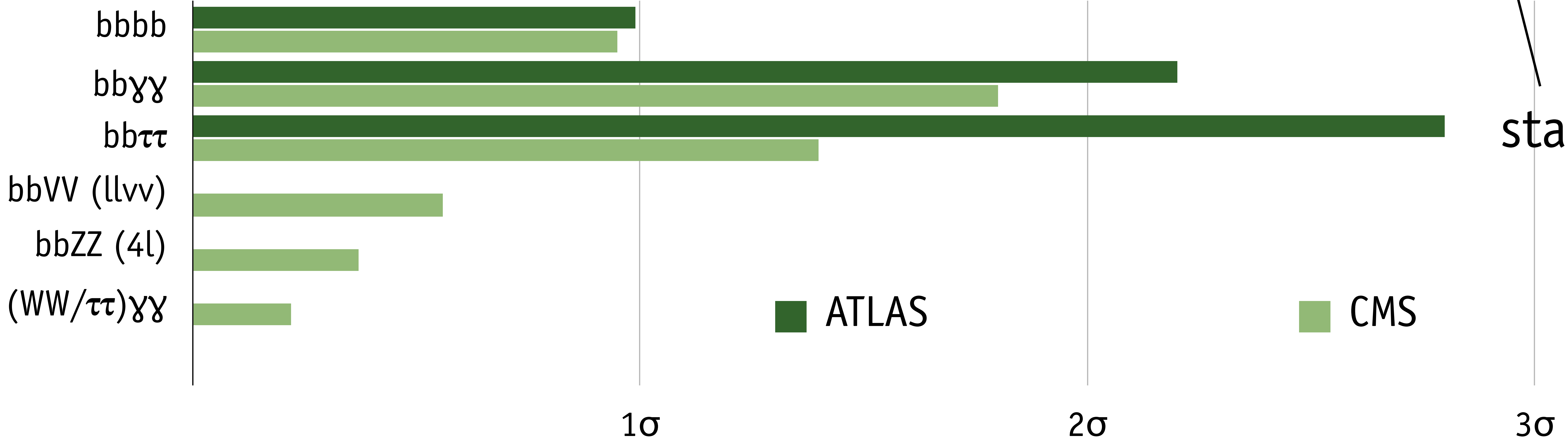
Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$bbbb$
Experimental Uncertainties				
Luminosity	0.6	*	*	*
b-jet tagging efficiency	0.5	*	*	*
c-jet tagging efficiency	0.5	*	*	*
Light-jet tagging efficiency	1.0	*	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*	*
κ_λ reweighting	0.0	*	*	
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*		
Photon energy scale and resolution	1.0	*		
Spurious signal	0.0	*		
Value of m_H	0.08	*		
τ_{had} efficiency (statistical)	0.0		*	
τ_{had} efficiency (systematic)	1.0		*	
τ_{had} energy scale	1.0		*	
Fake-τ_{had} estimation	1.0		*	
MC statistical uncertainties	0.0		*	
Background bootstrap uncertainty	0.5			*
Background shape uncertainty	1.0			*
Theoretical Uncertainties	0.5	*	*	*

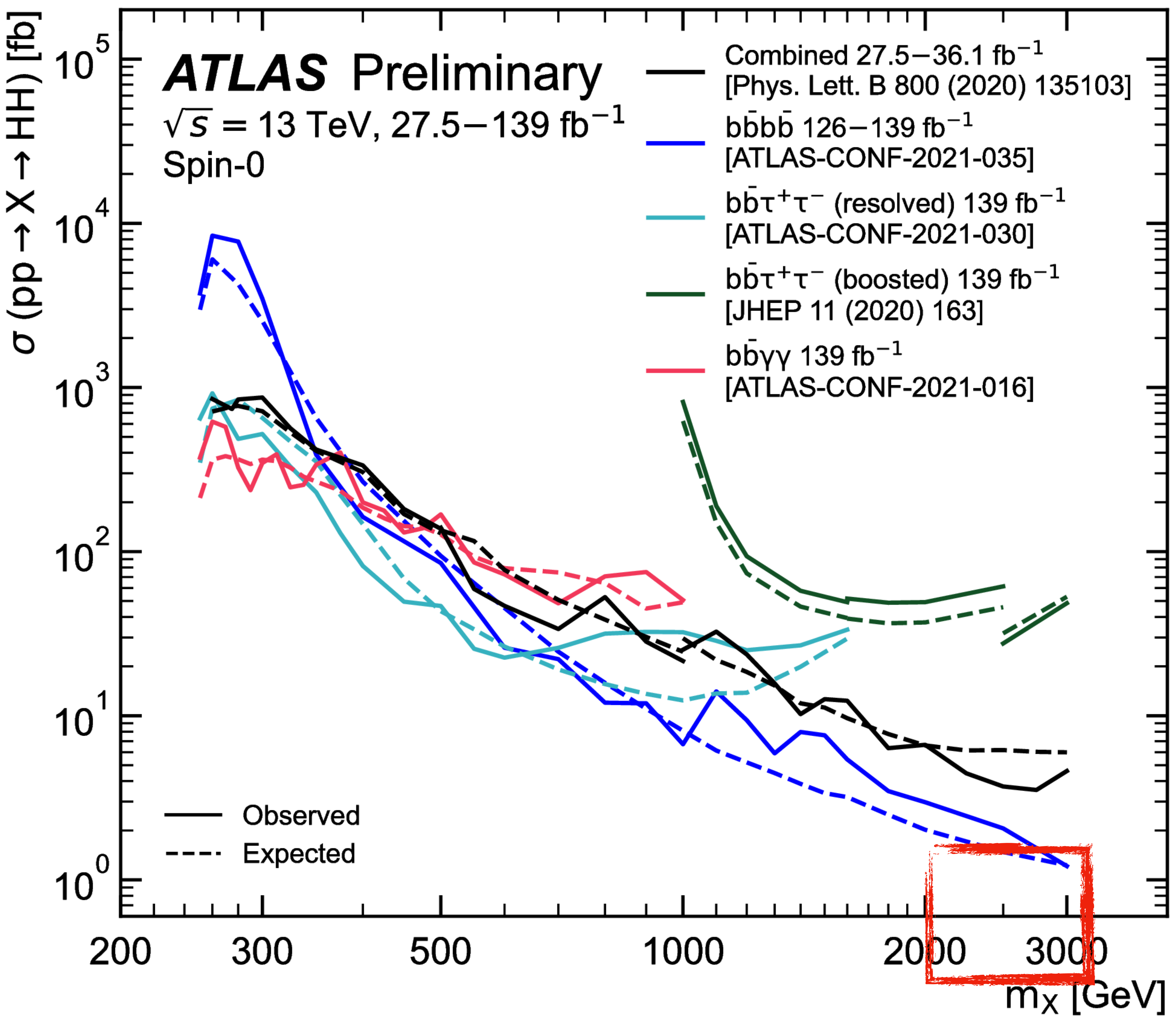


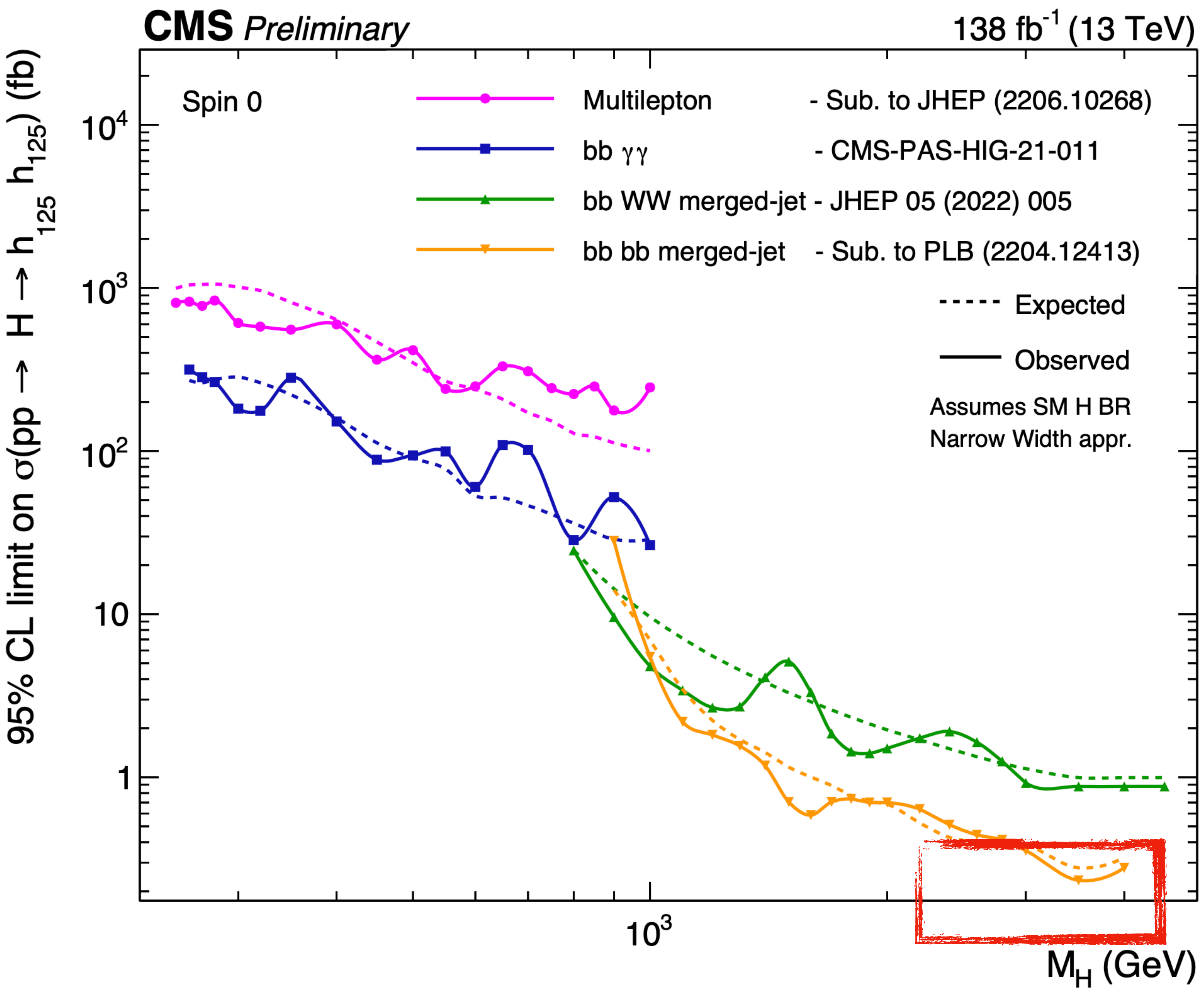
stat only

syst as in Run-2

effect of improved syst





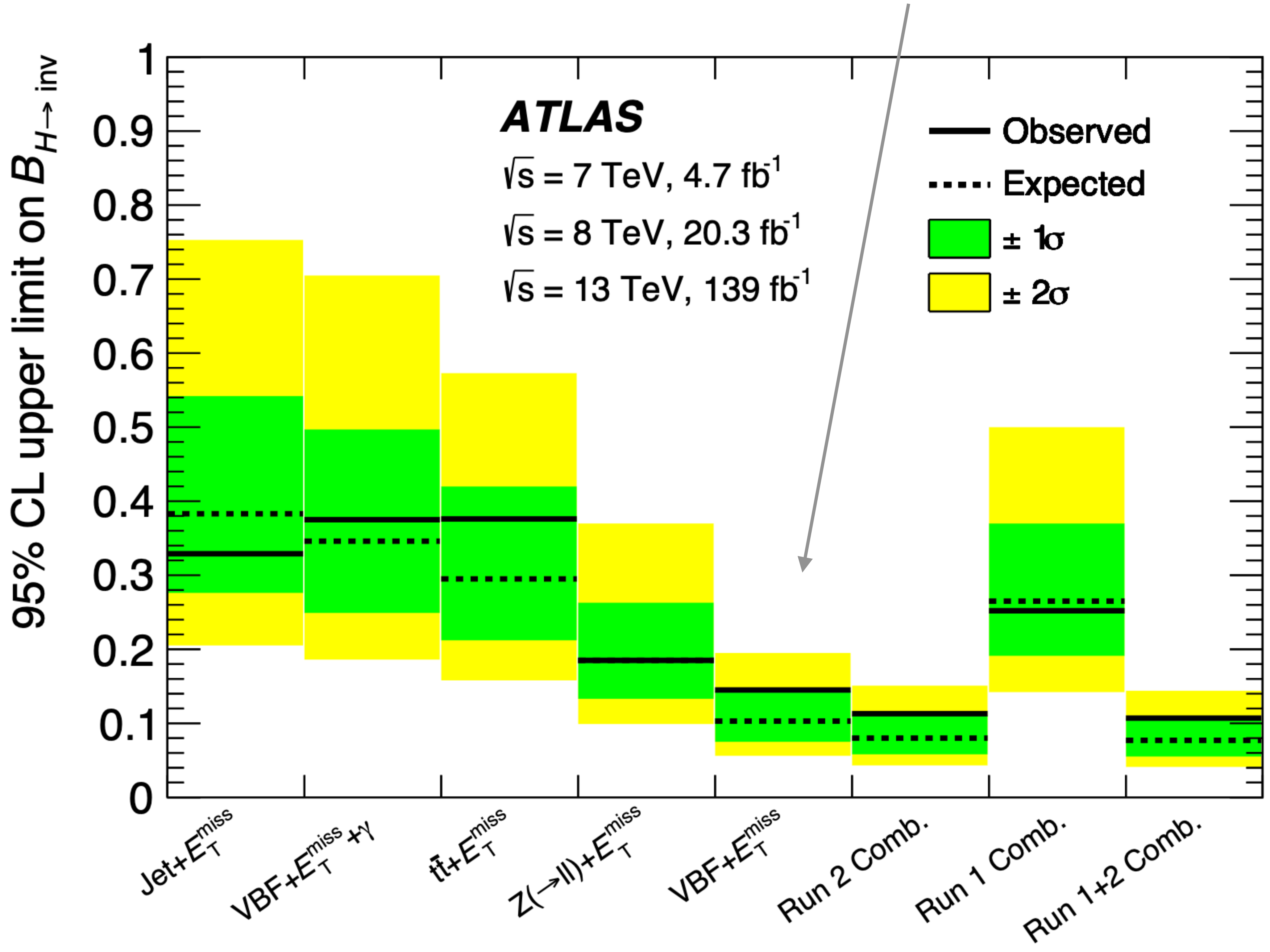


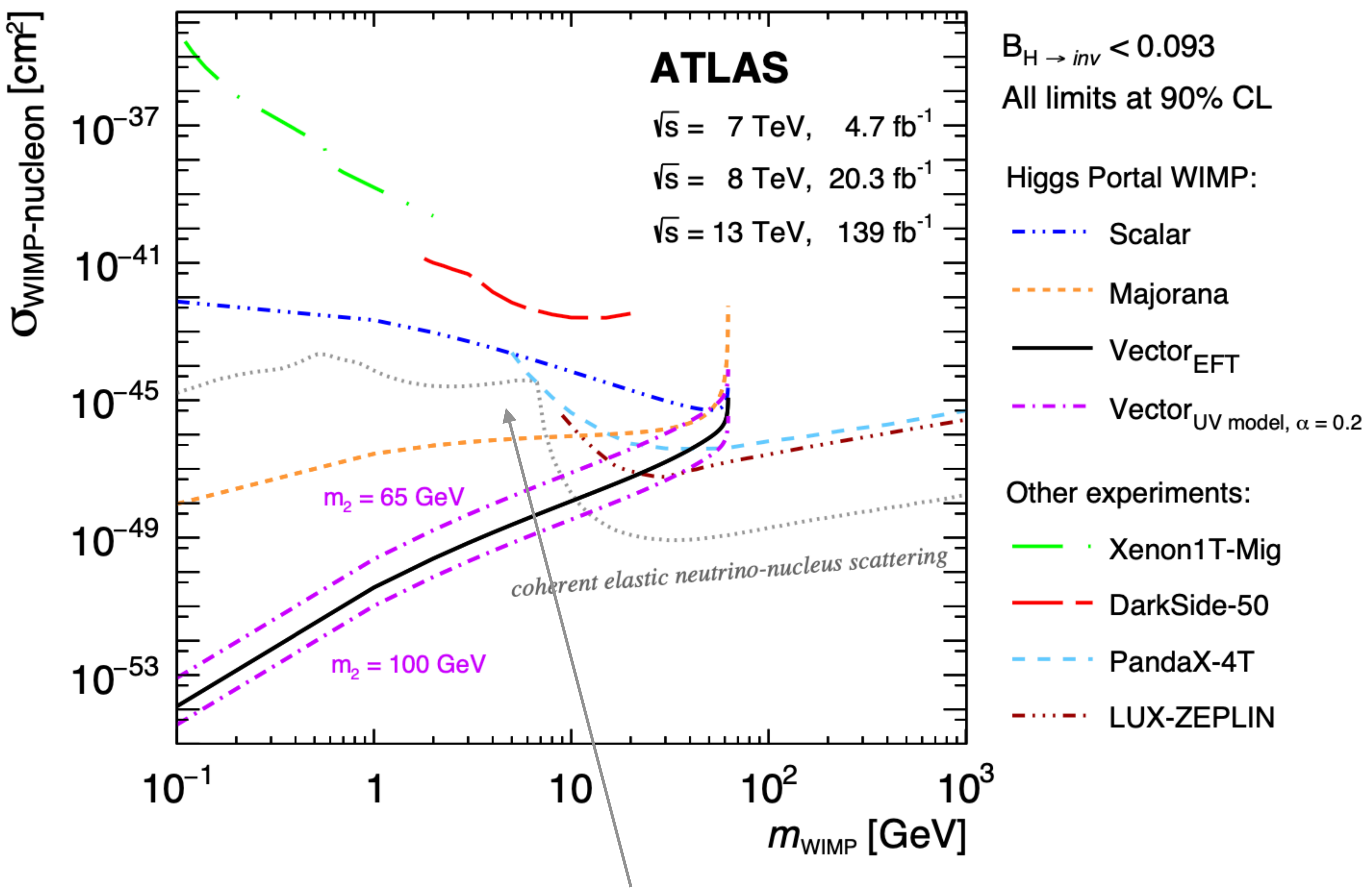
- complemented by search for heavy resonances decaying into HH
  - a client for improved b-tagging (e.g. X→HH→bbbb)
- HL-LHC improves reach in > ~3 TeV region

ATL-PHYS-PUB-2021-031, CMS summary, CMS-PAS-FTR-18-003, ATL-PHYS-PUB-2020-019, CMS-DP-2021-017, CMS-PAS-HIG-20-016

HIGGS PORTAL

VBF is the driver





not crossed by direct detection before ~10 years

- today: BR(H→inv) < 9.3% @ 90% CL
- HL-LHC: improve by a factor ~3

arXiv:2301.10731, ATL-PHYS-PUB-2013-014, CMS-PAS-FTR-18-016

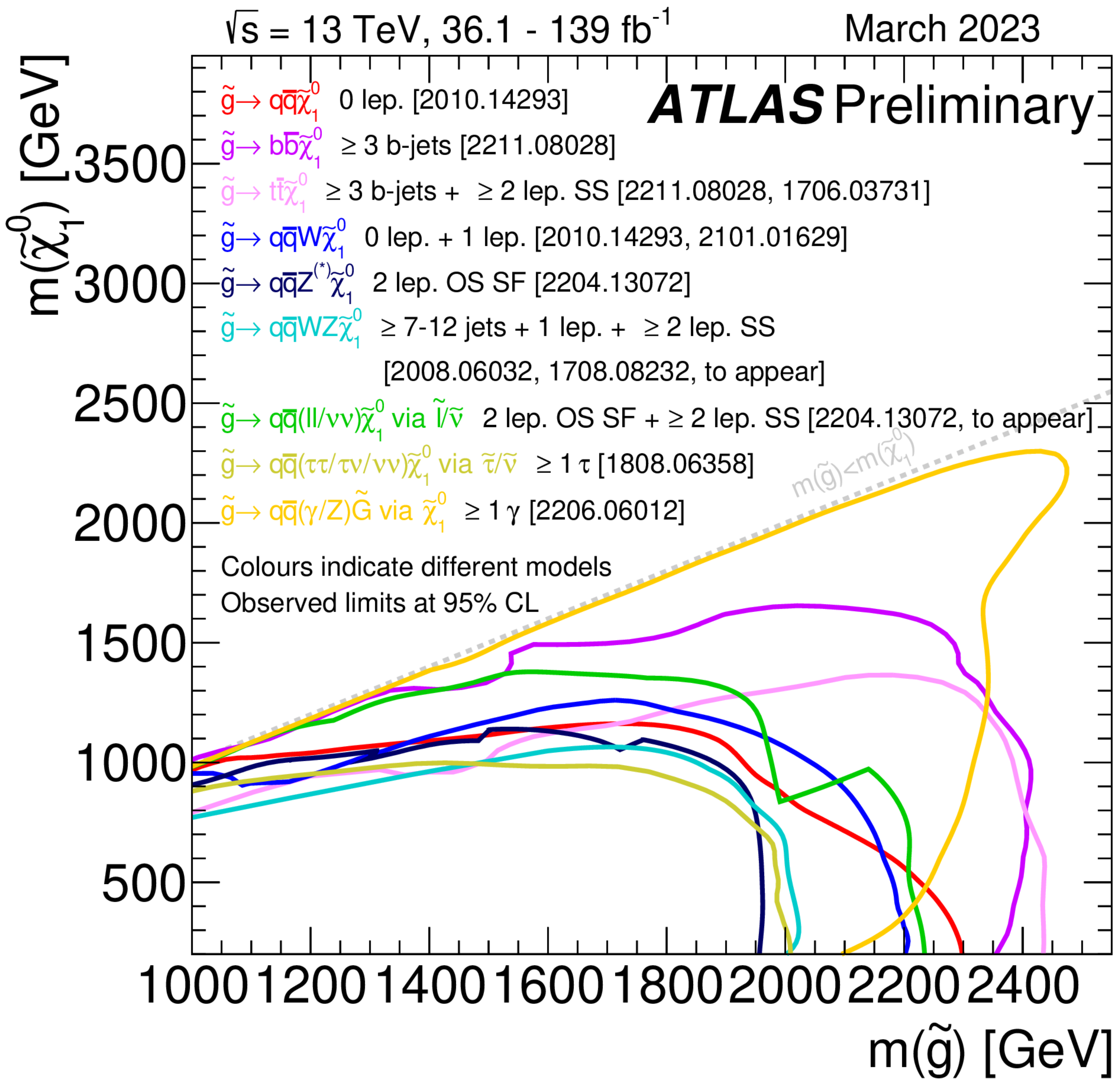
SM particles

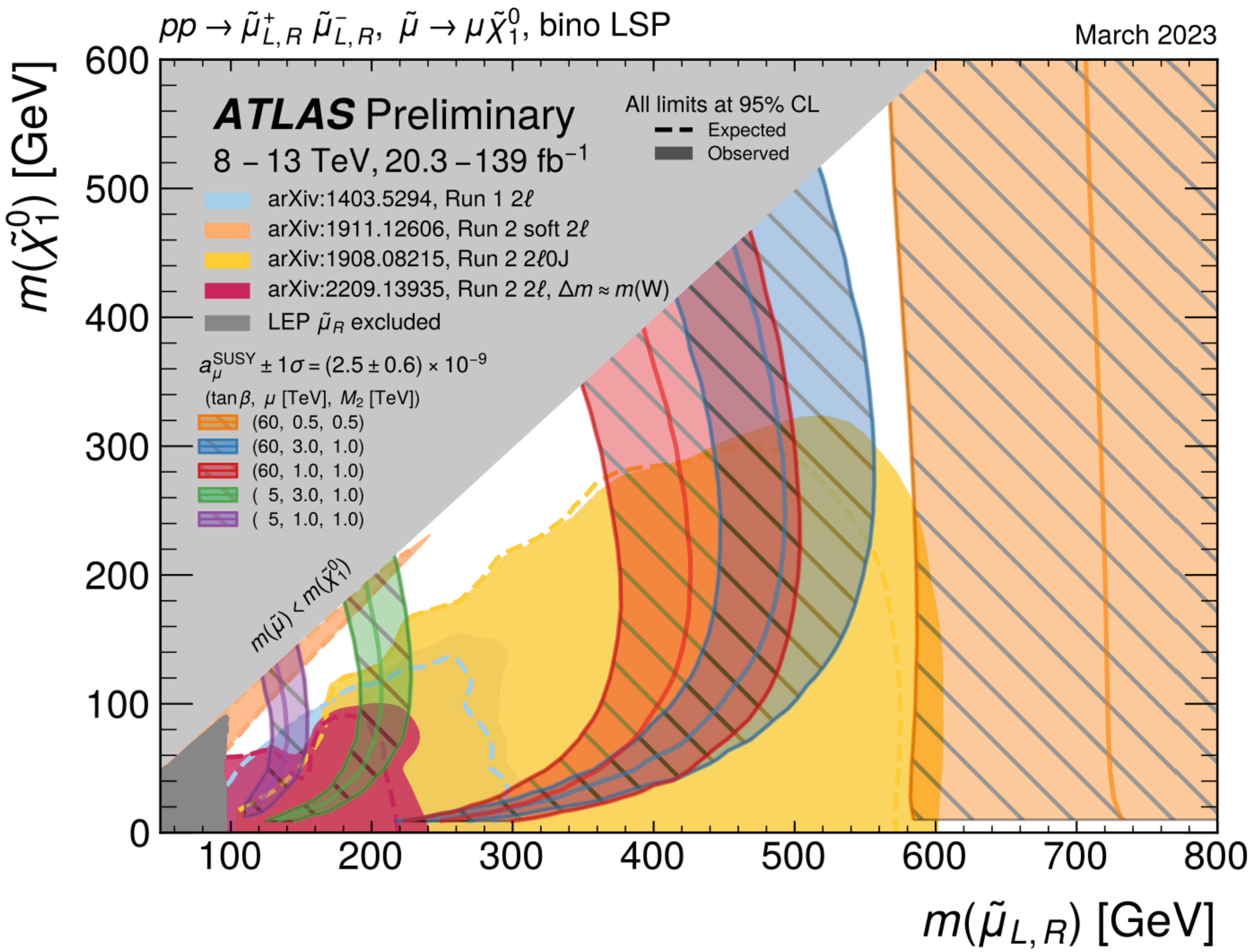
Higgs boson

Dark Matter

[2007 < LHC start]

SUPERSYMMETRY





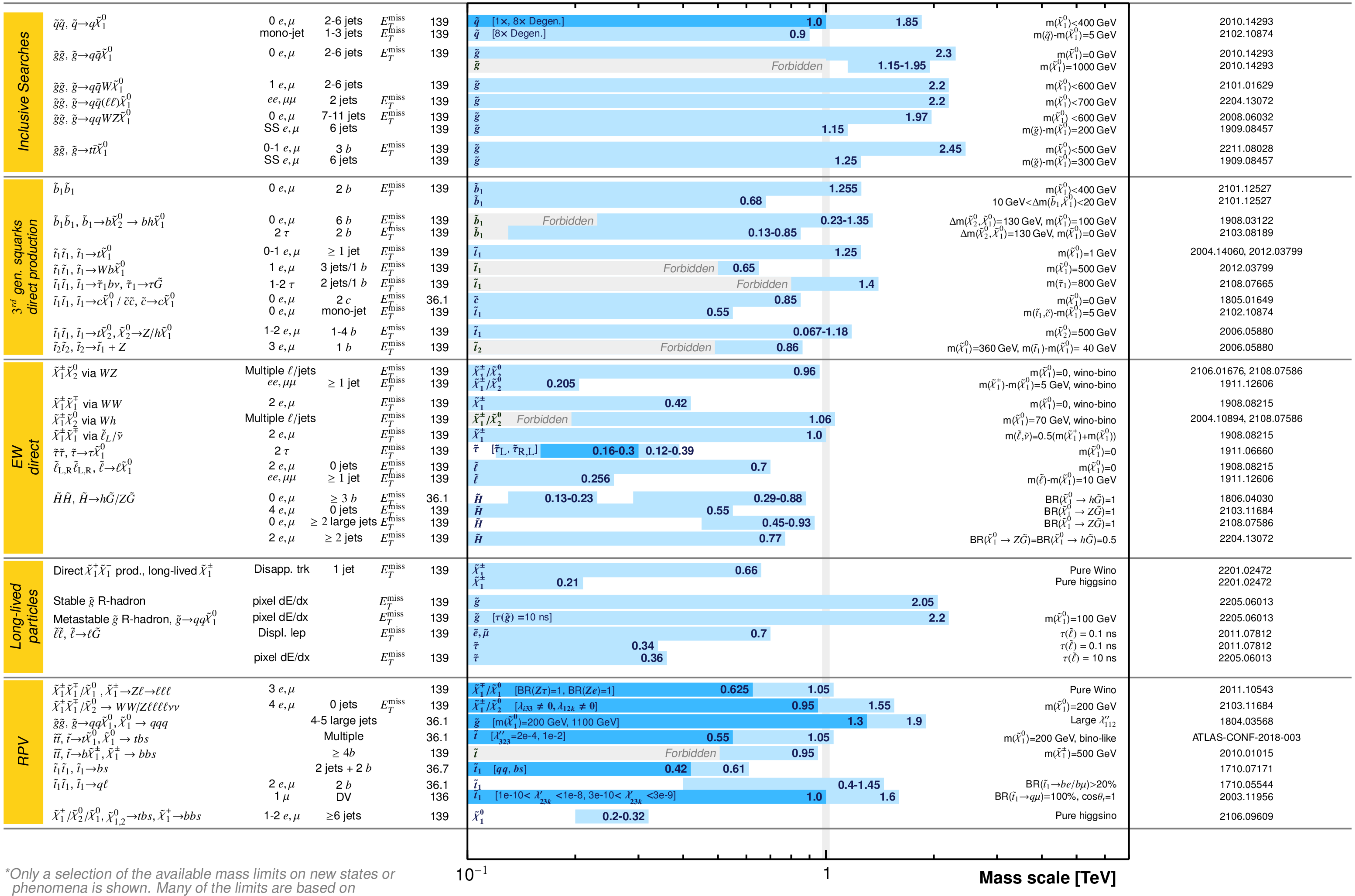
today:
- ~1 TeV neutralino bounds
- ~2 TeV gluino bounds

ATL-PHYS-PUB-2023-005

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2023

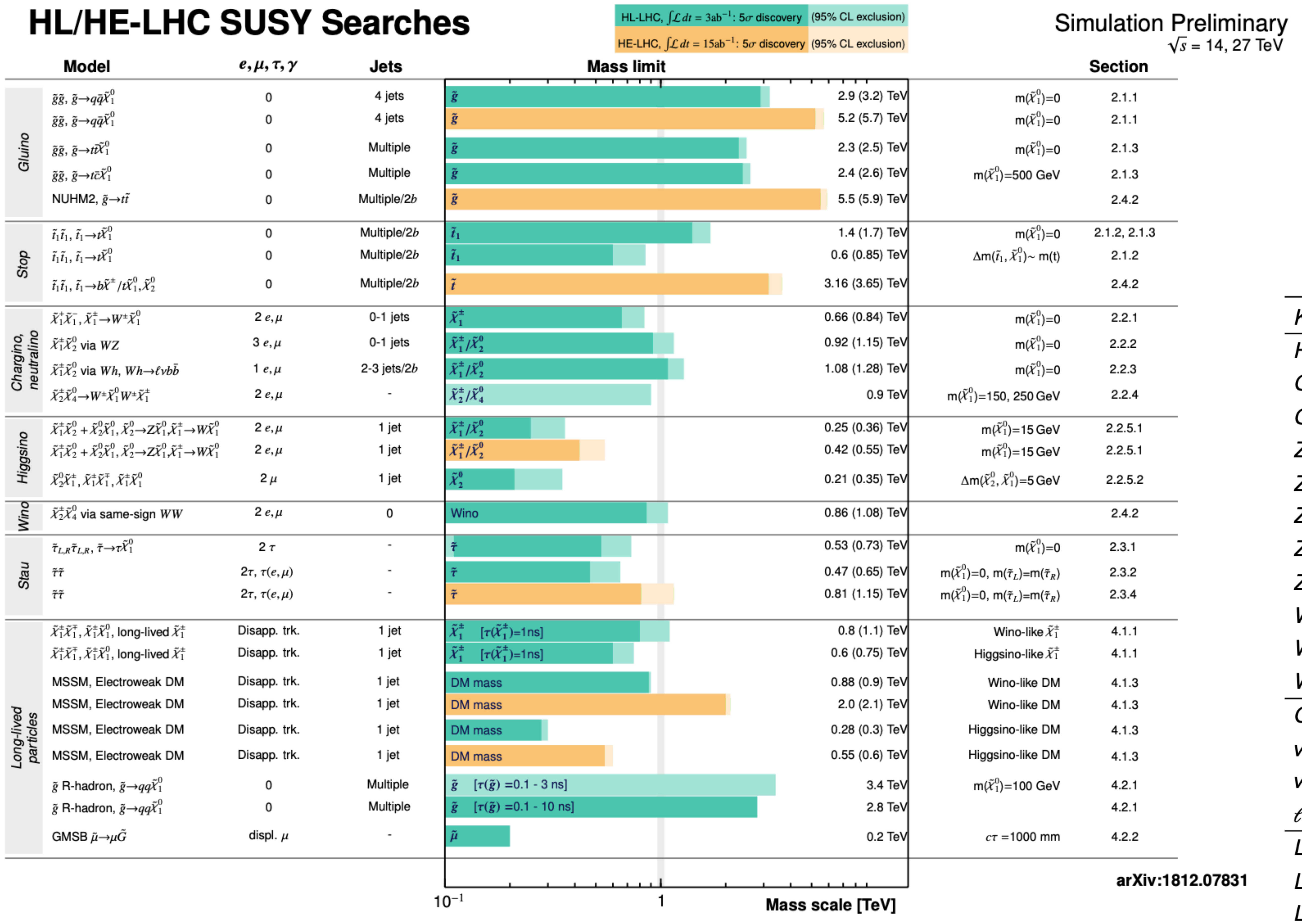
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV



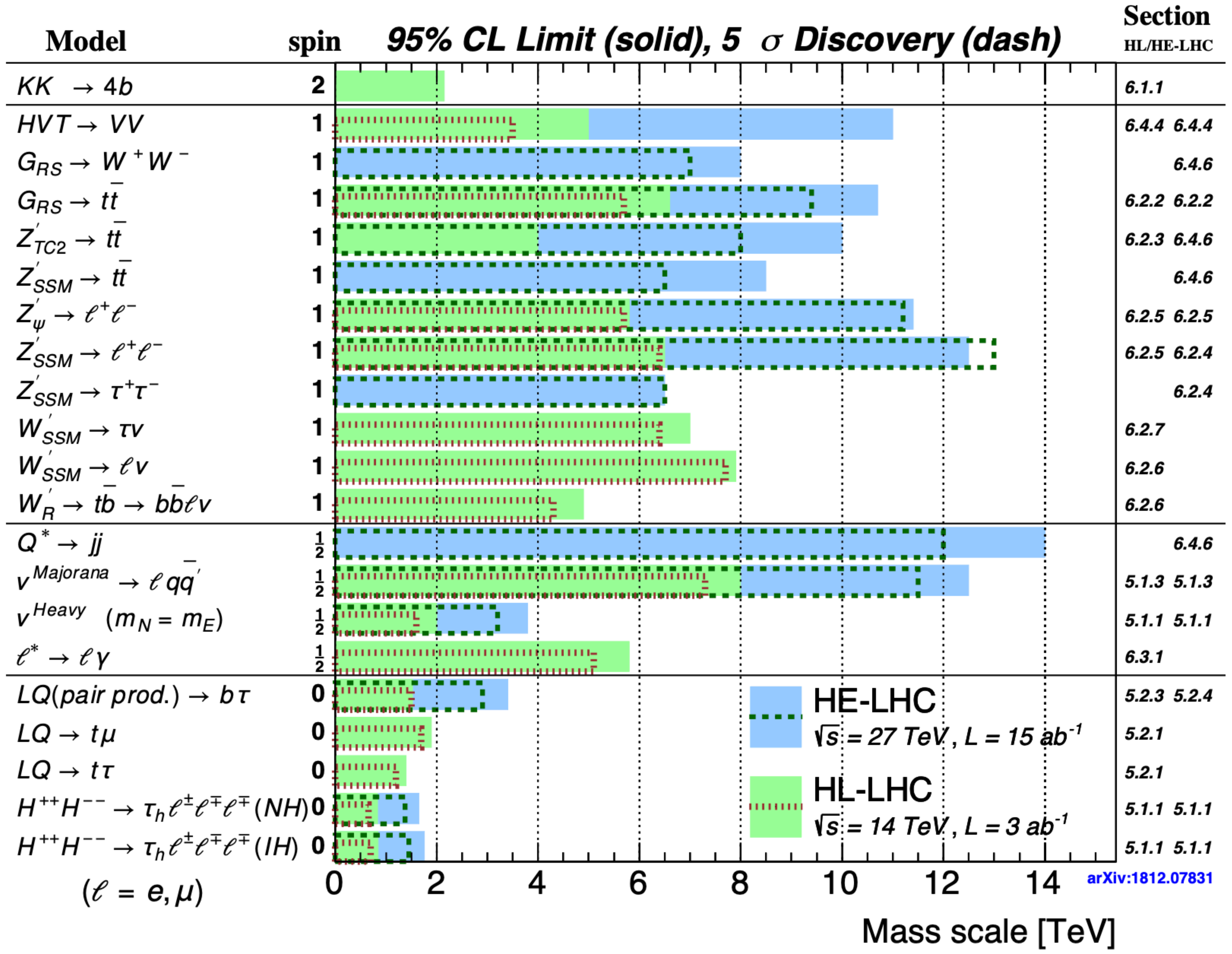
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	139	$\tilde{q}$	[8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$		2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$		1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$		1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	139	$\tilde{g}$		2.45	m($\tilde{\chi}^0_1$)<500 GeV	2211.08028
		SS e,μ	6 jets		139	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	139	$\tilde{b}_1$		1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$		0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$		1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden	0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	139	$\tilde{t}_1$		0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$		0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden	0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$		0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$		0.205	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1$		0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$	Forbidden	1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^{\pm}_1$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	[$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$		0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$		0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$		0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$		0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	139	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	139	$\tilde{H}$		0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}^{\pm}_1$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}^{\pm}_1$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{e},\tilde{\mu}$		0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$		0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	139	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_1$, $\tilde{\chi}^{\pm}_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_1$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^{\pm}_1\to bbs$		$\geq$ 4b		139	$\tilde{t}$	Forbidden	0.95	m($\tilde{\chi}^{\pm}_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$		0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Valerio Ippolito
INFN Sezione di Roma



arXiv:1812.07831

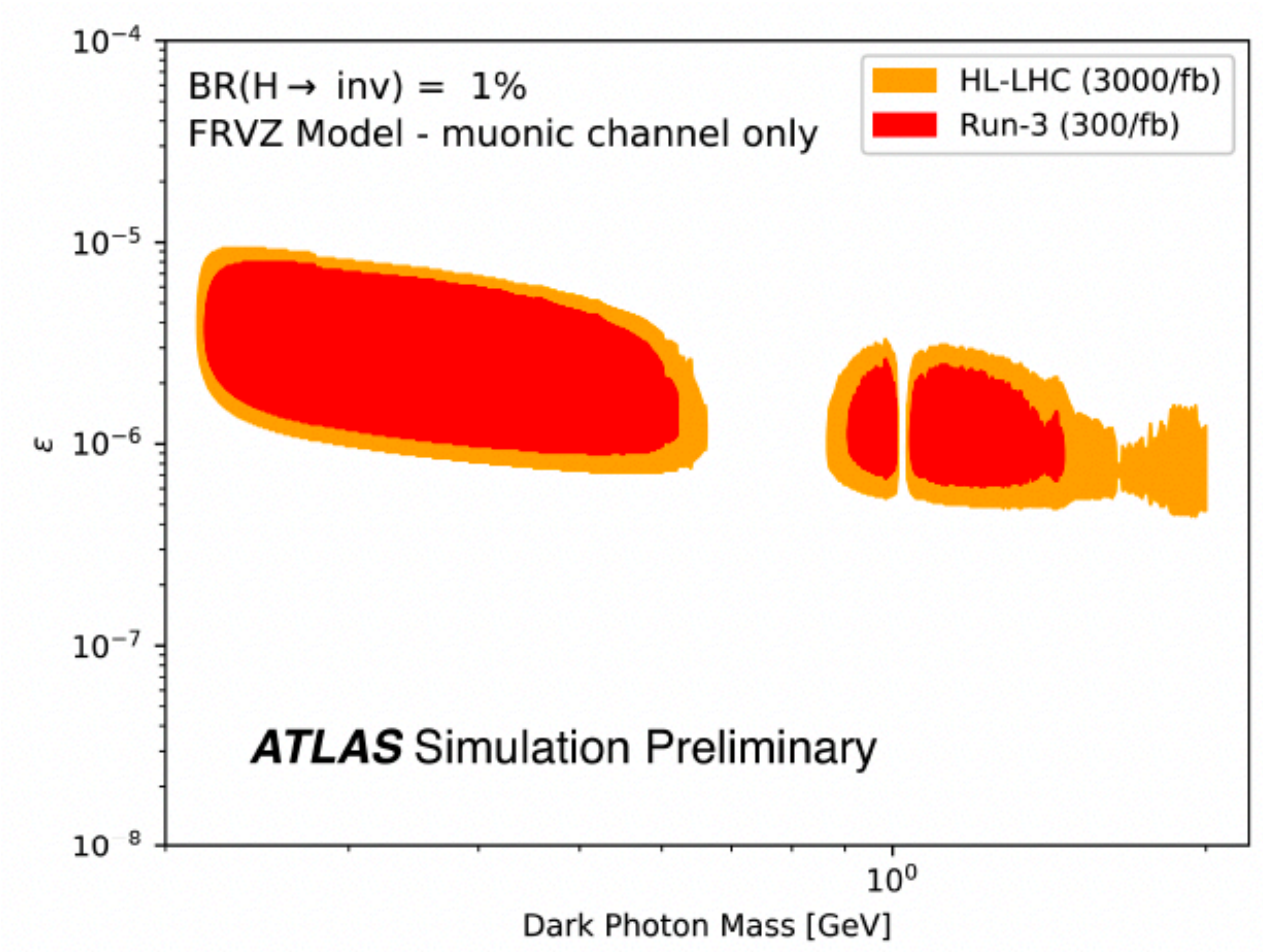


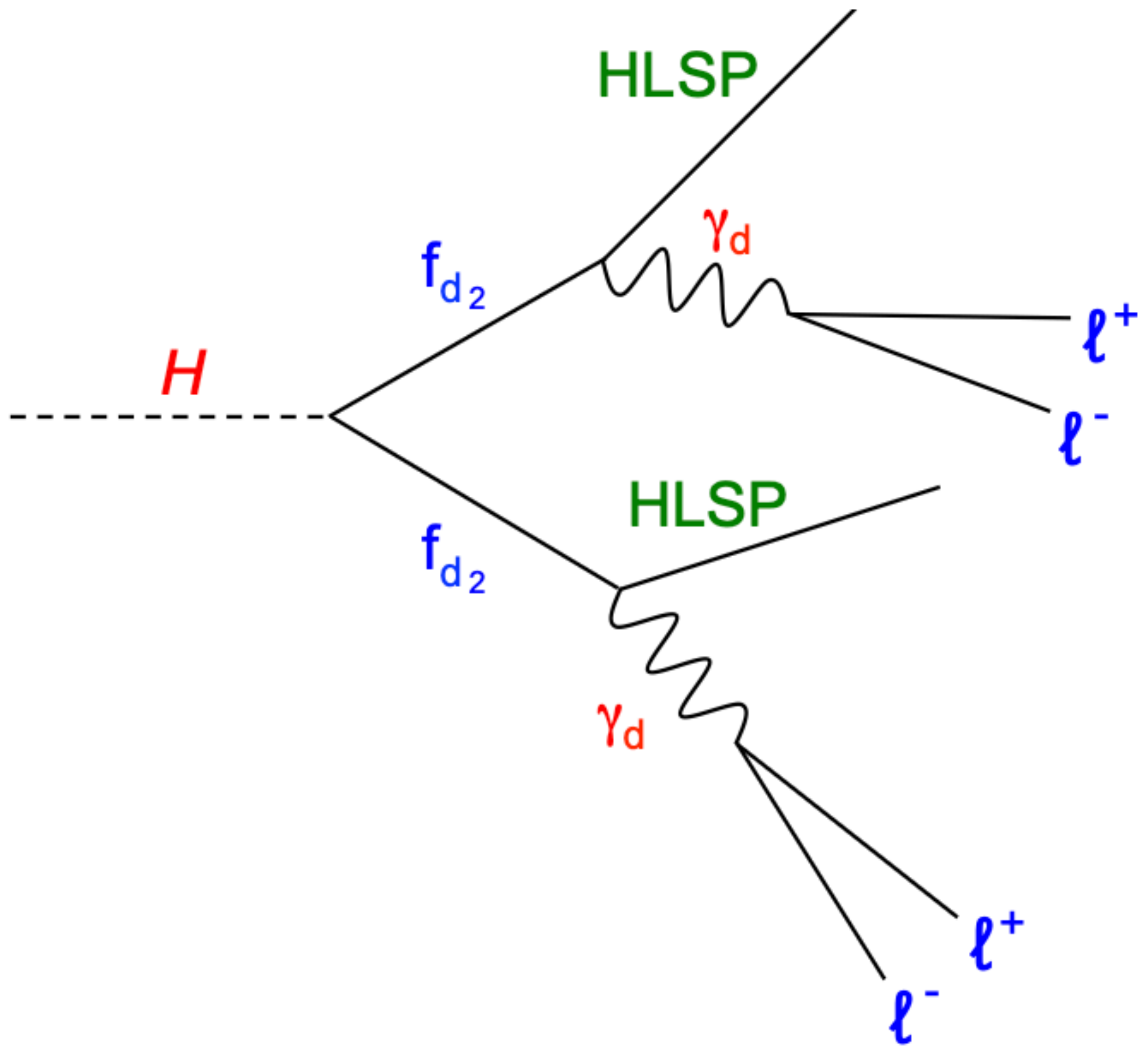
what	today	HL-LHC
gluinos	< 2 TeV	O(2-3 TeV)
stop	< 1 TeV	O(1.5 TeV)
EW SUSY	< 1 TeV	O(1 TeV)
Z' / W'	< 5/6 TeV	O(6/8 TeV)
leptoquarks	< 2 TeV	O(1.5-2 TeV)

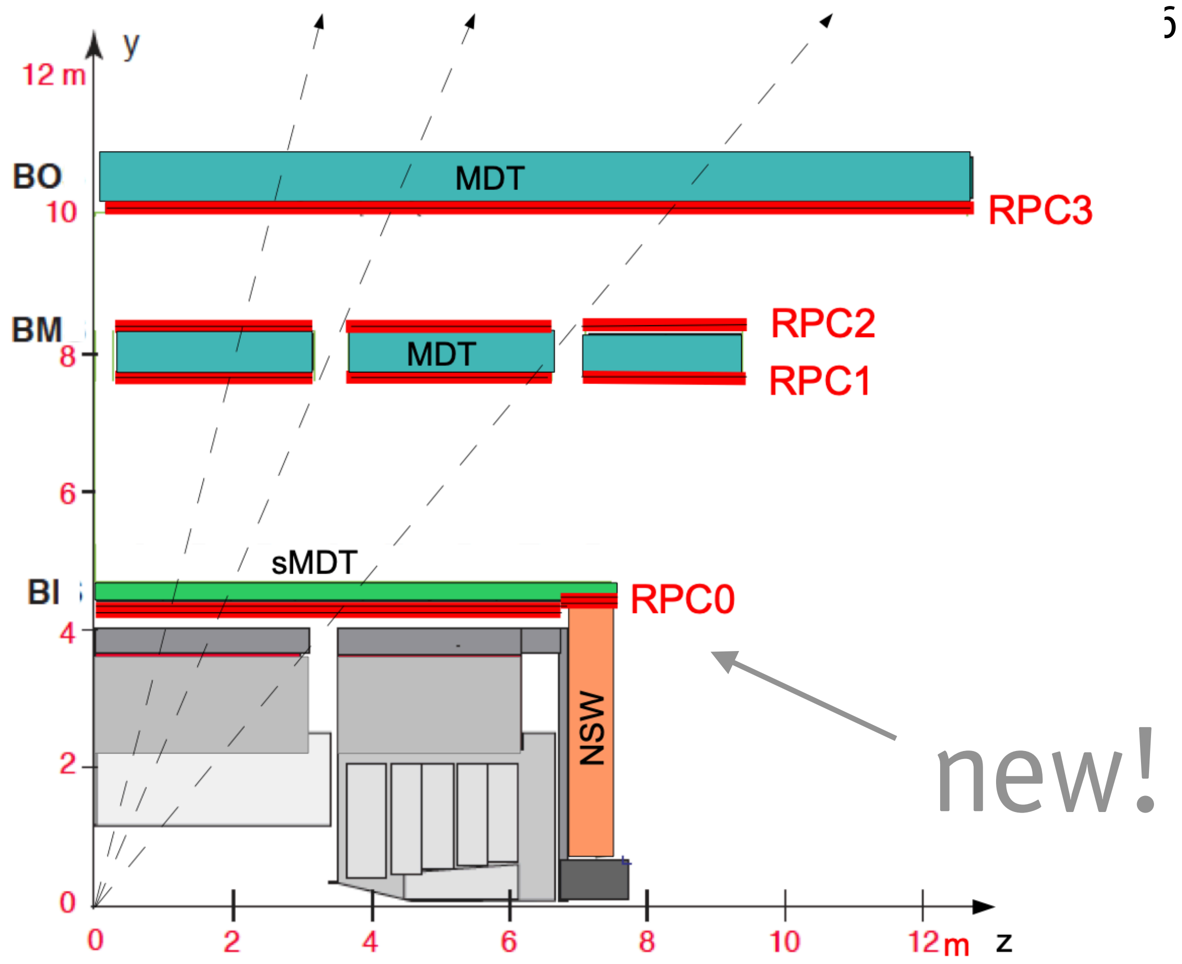
key message: lots of **searches**,
HL-LHC opportunity for **clever** ideas...

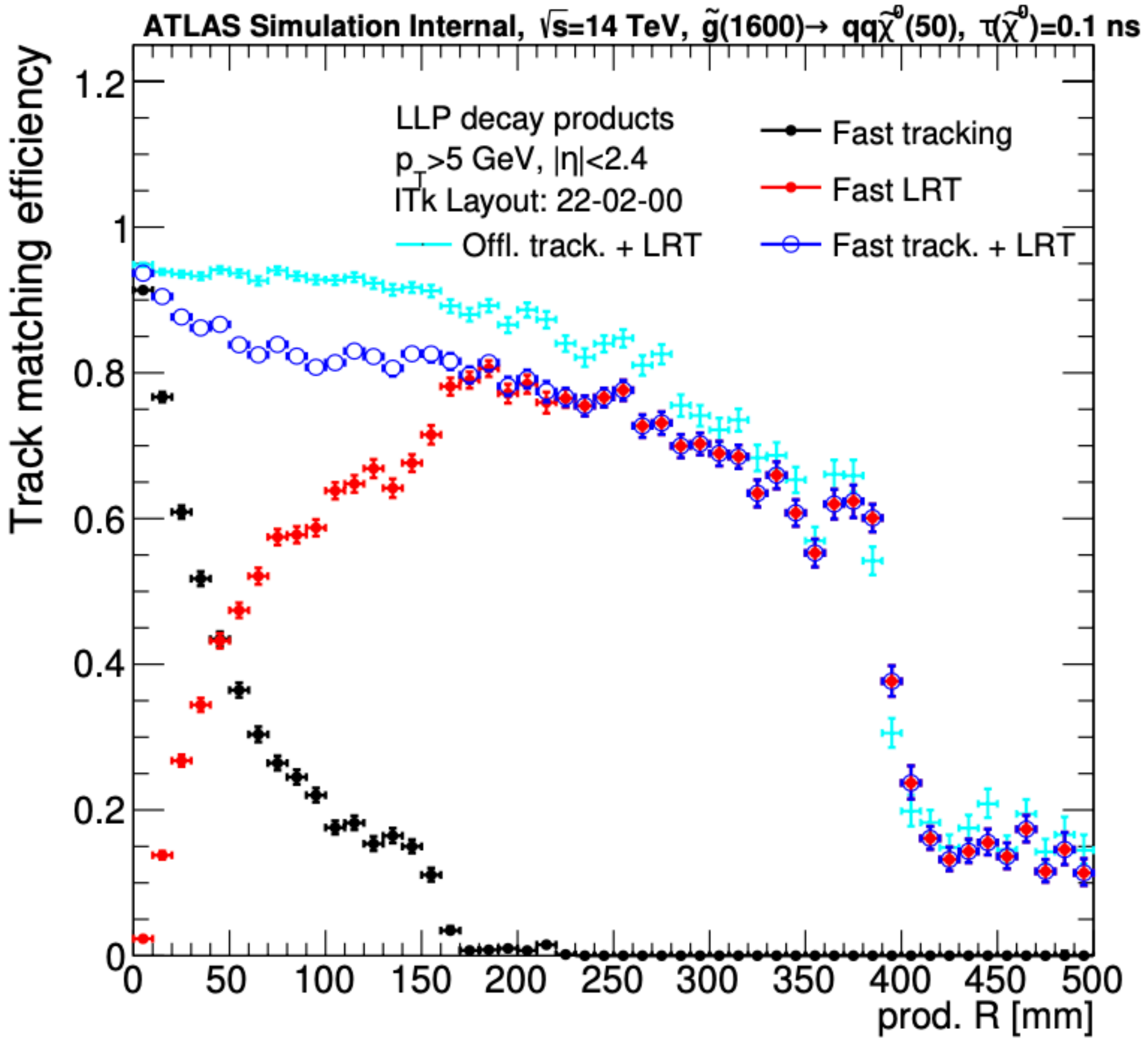
arXiv:1812.07831

LONG-LIVED PARTICLES



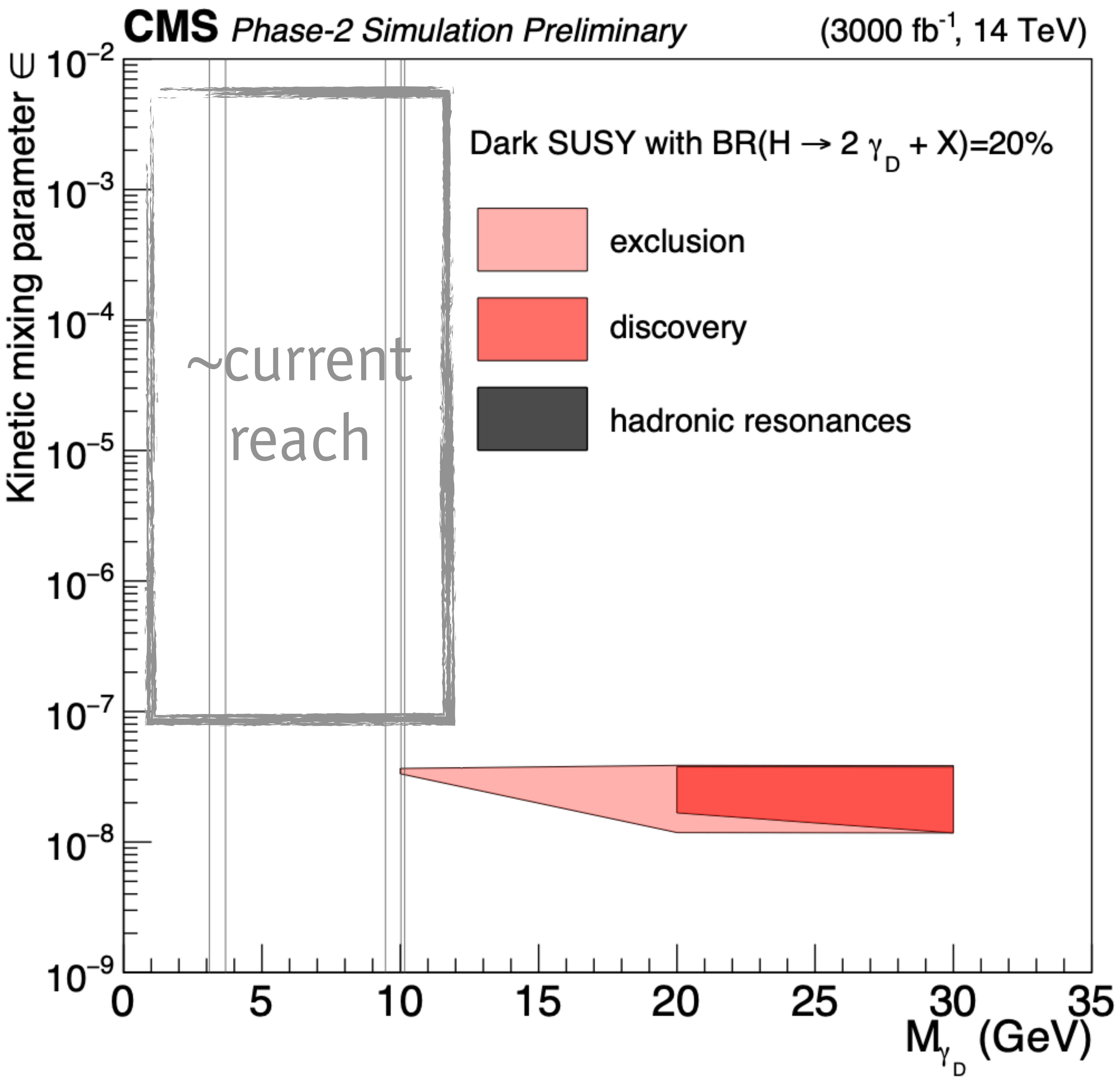


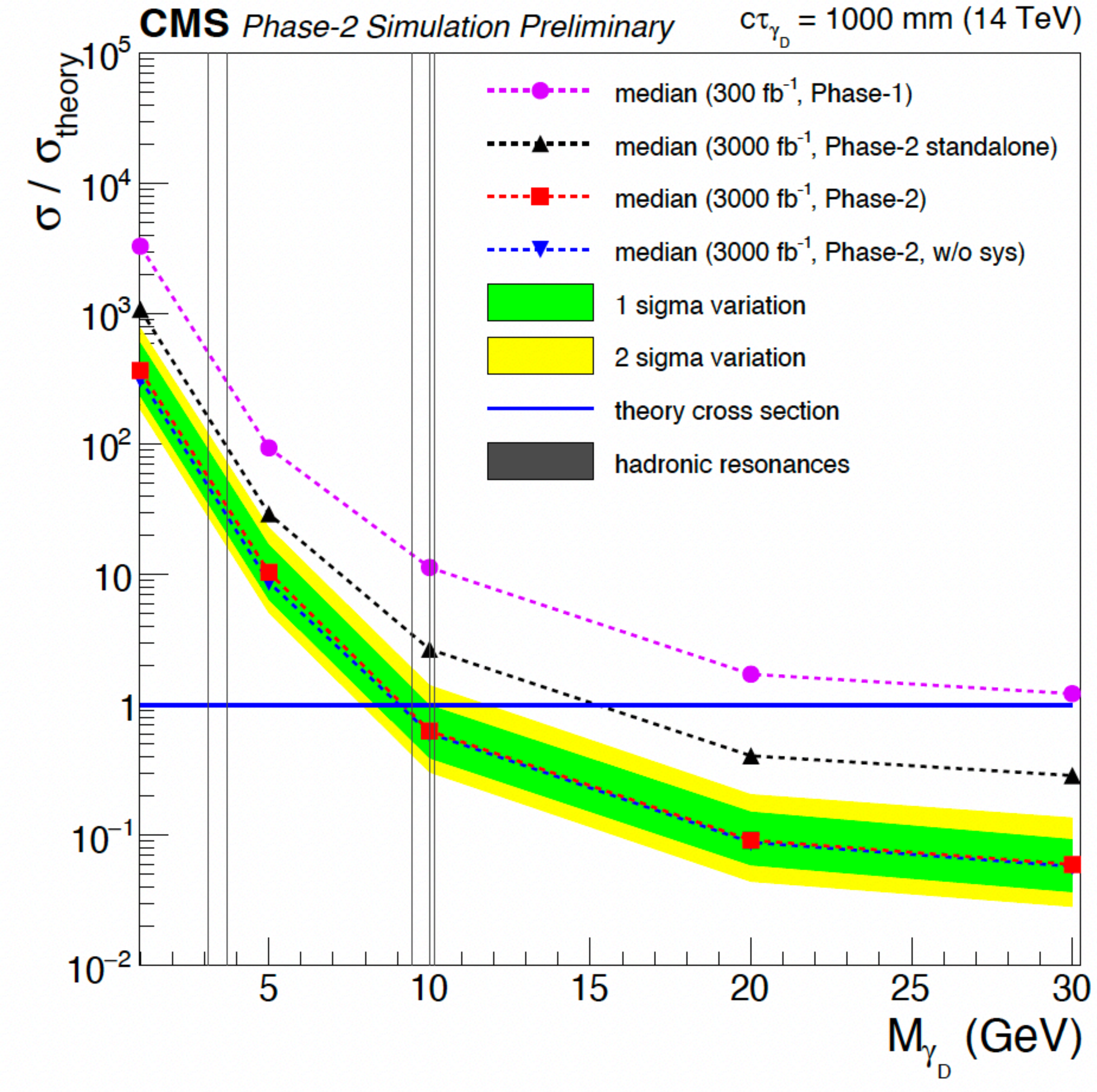




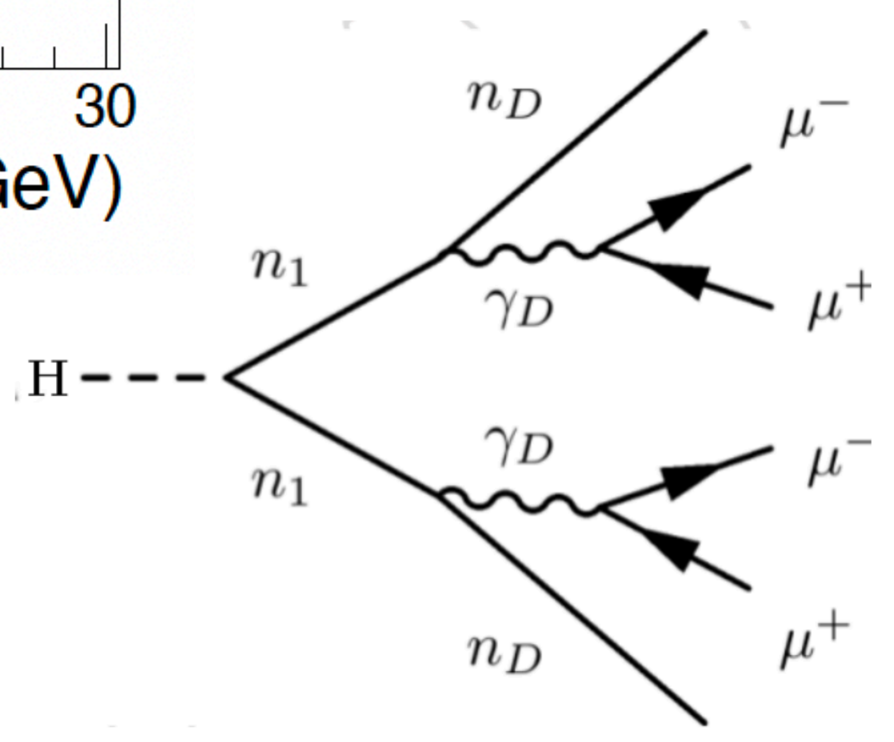
- long-lived signatures need dedicated **trigger** to exploit higher luminosity
- e.g. displaced muons jets from dark photon decays using L0 ATLAS trigger algorithms
- e.g. large-radius tracking at HLT for hadronic decays

ATL-PHYS-PUB-2019-002, ATL-TDR-029-ADD-1



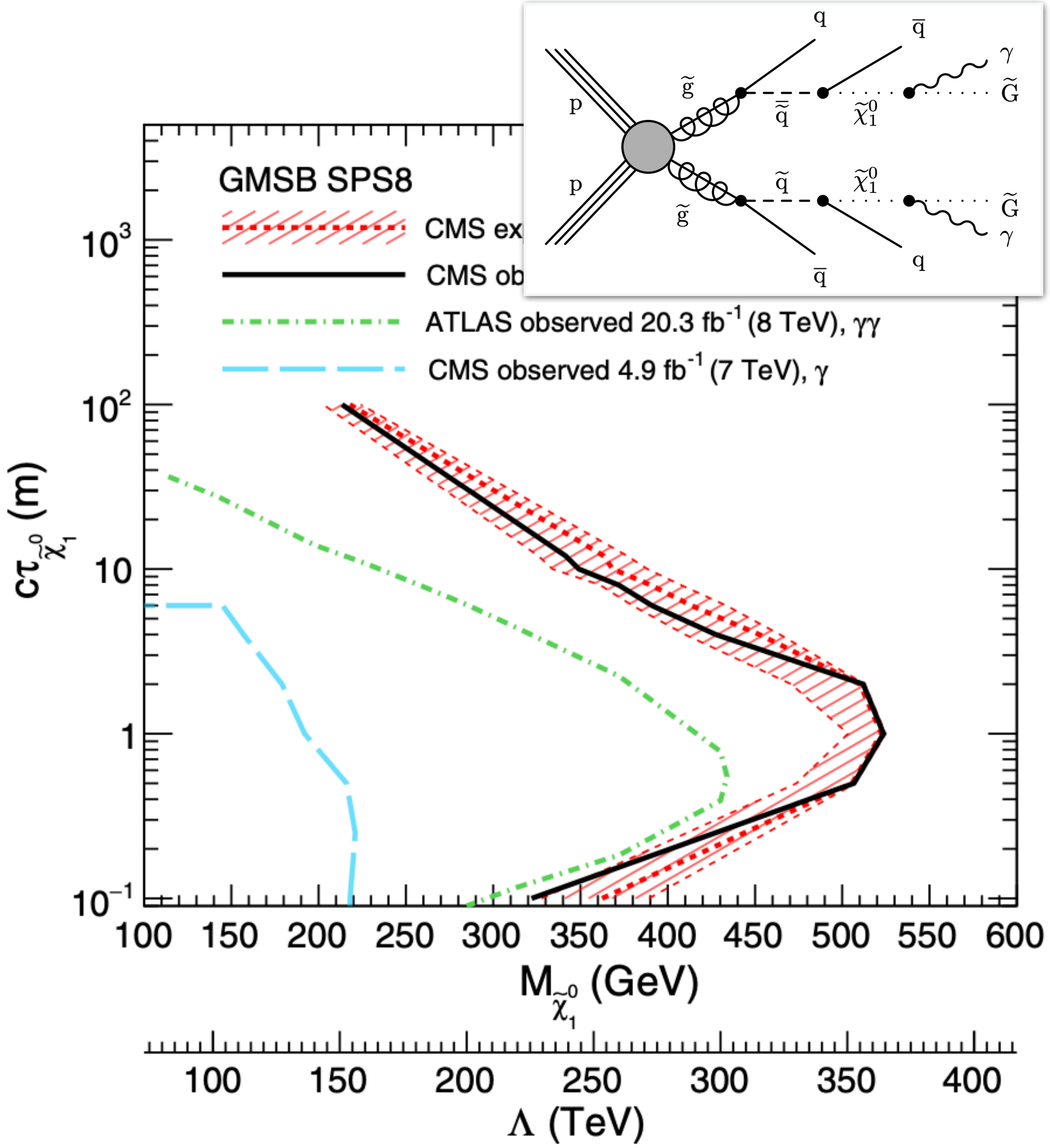


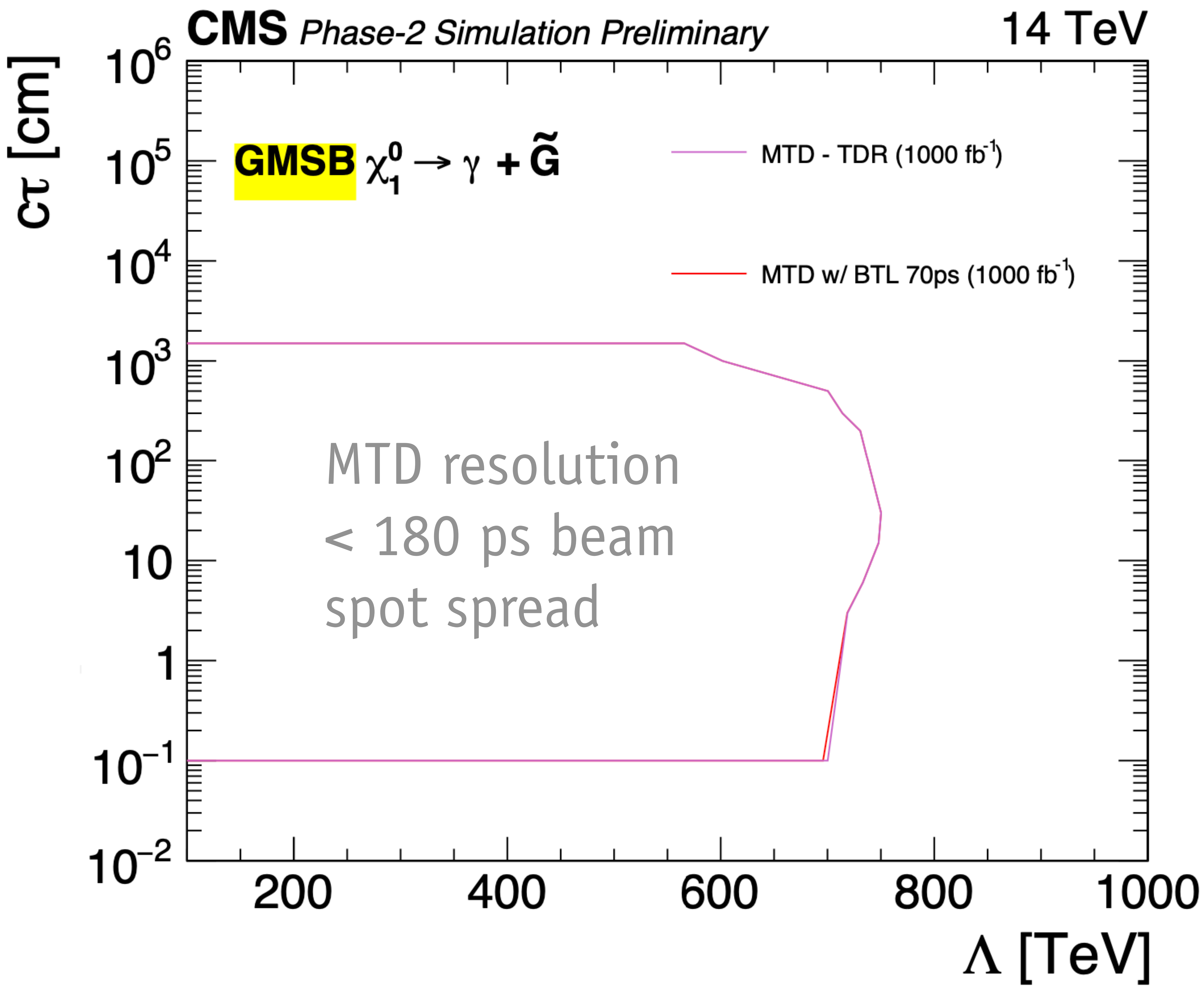
impact of dedicated reco



- long-lived signatures need dedicated **reconstruction** to exploit higher luminosity
- e.g. displaced muons from dark photon decays with/without primary vertex constraints

CMS-PAS-FTR-18-002

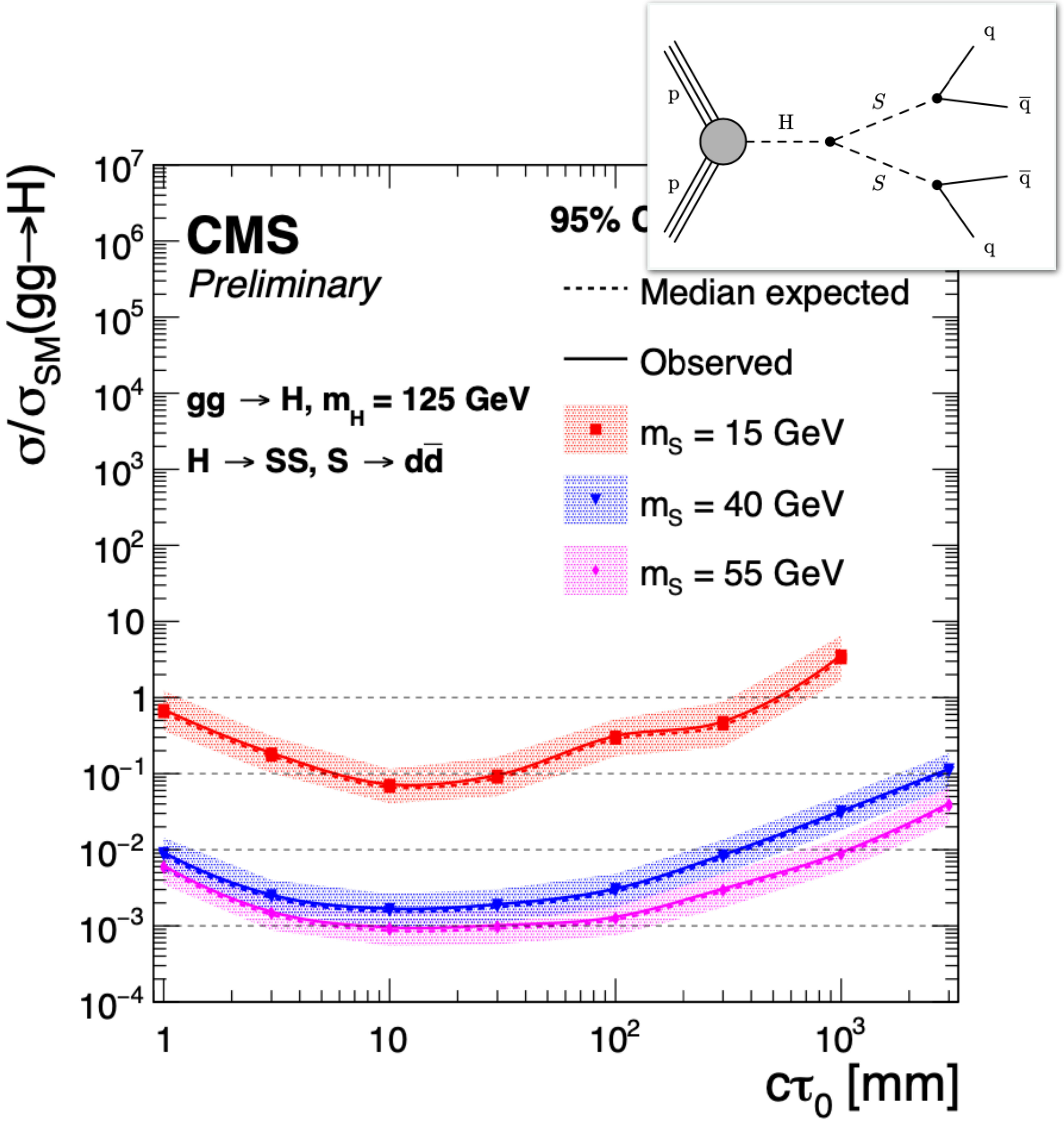


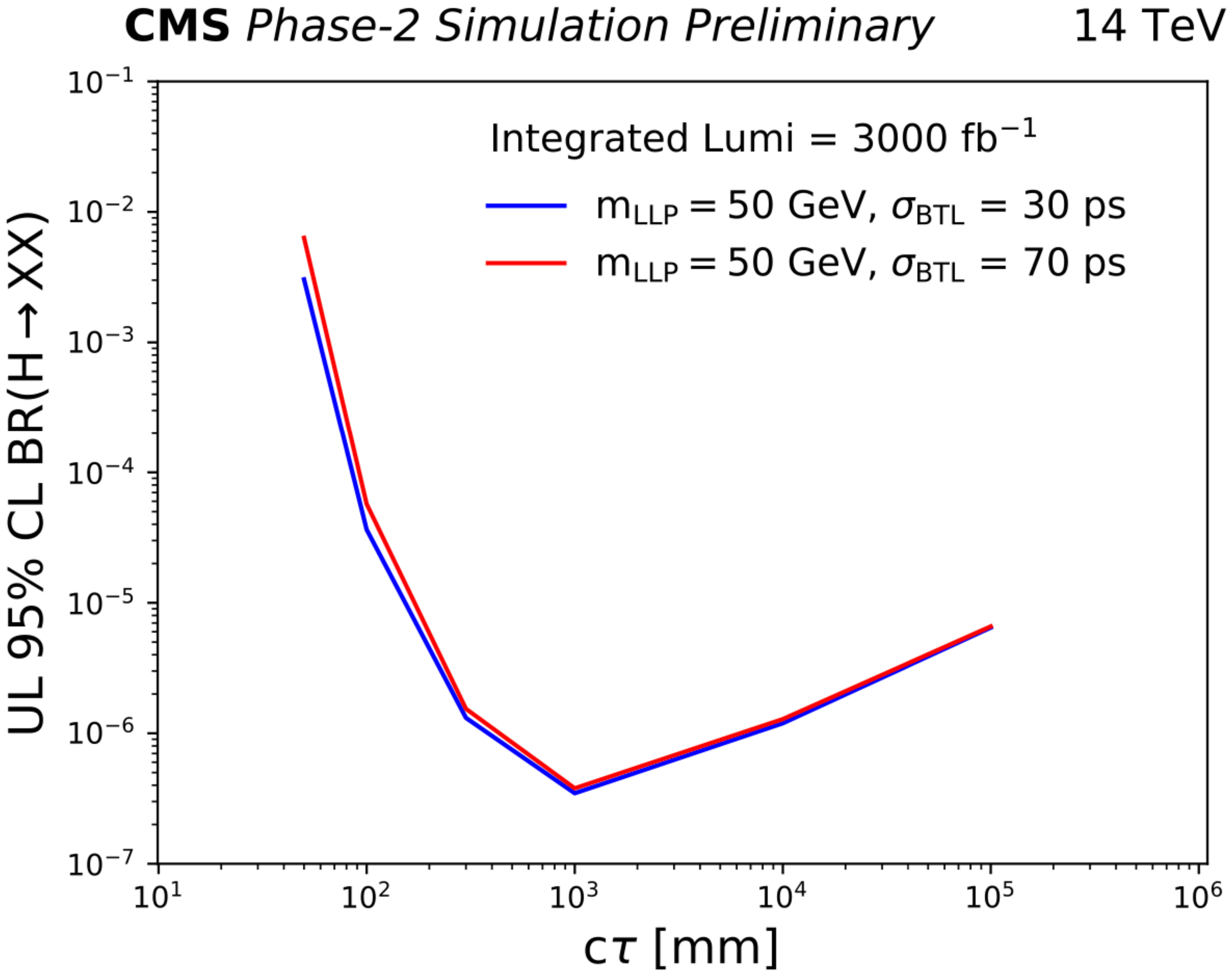


MTD resolution
< 180 ps beam
spot spread

- γ t.o.f. from ECAL, MTD gives primary vertex time
- significant improve in reach for small cτ
  (assuming no bkg)

PRD 100 (2019) 112003, CMS DP -2022/025

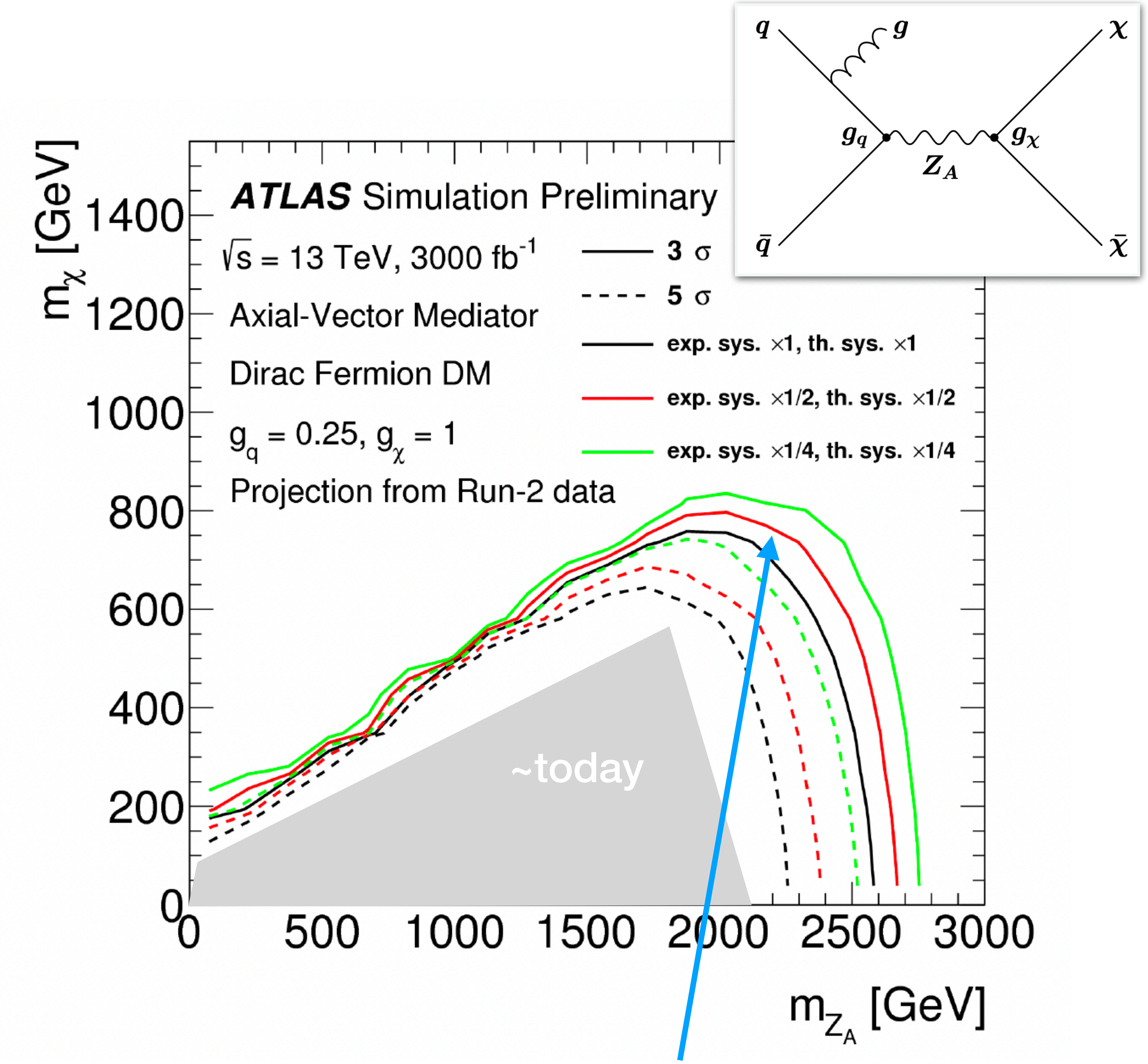




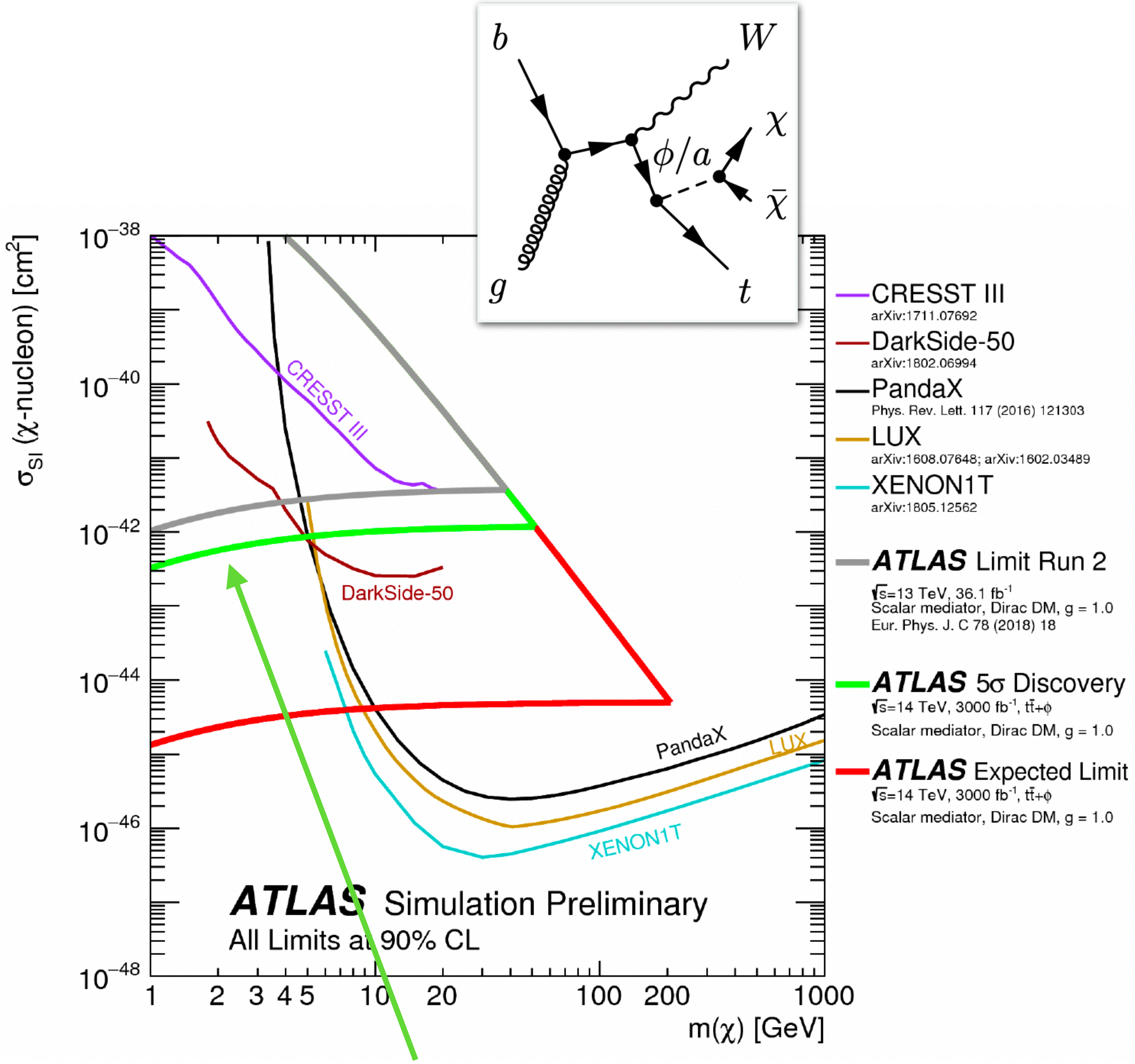
- MTD timing used to separate LLP from v=c particle from primary vertex

CMS PAS EXO-19-021, CMS DP -2022/025

WEAKLY-INTERACTING MASSIVE PARTICLES



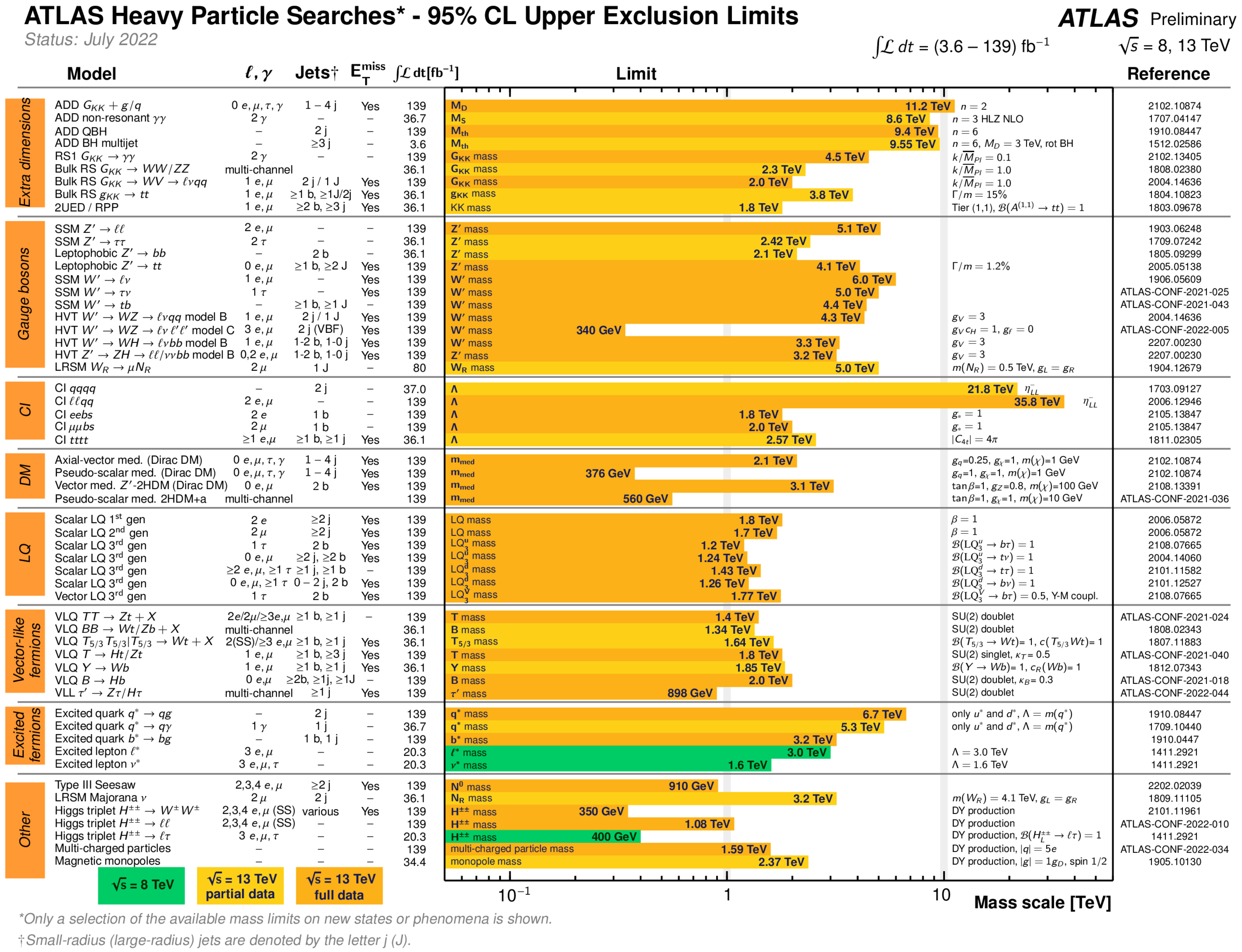
mono-jet WIMP reach improves by ~30% in WIMP mass

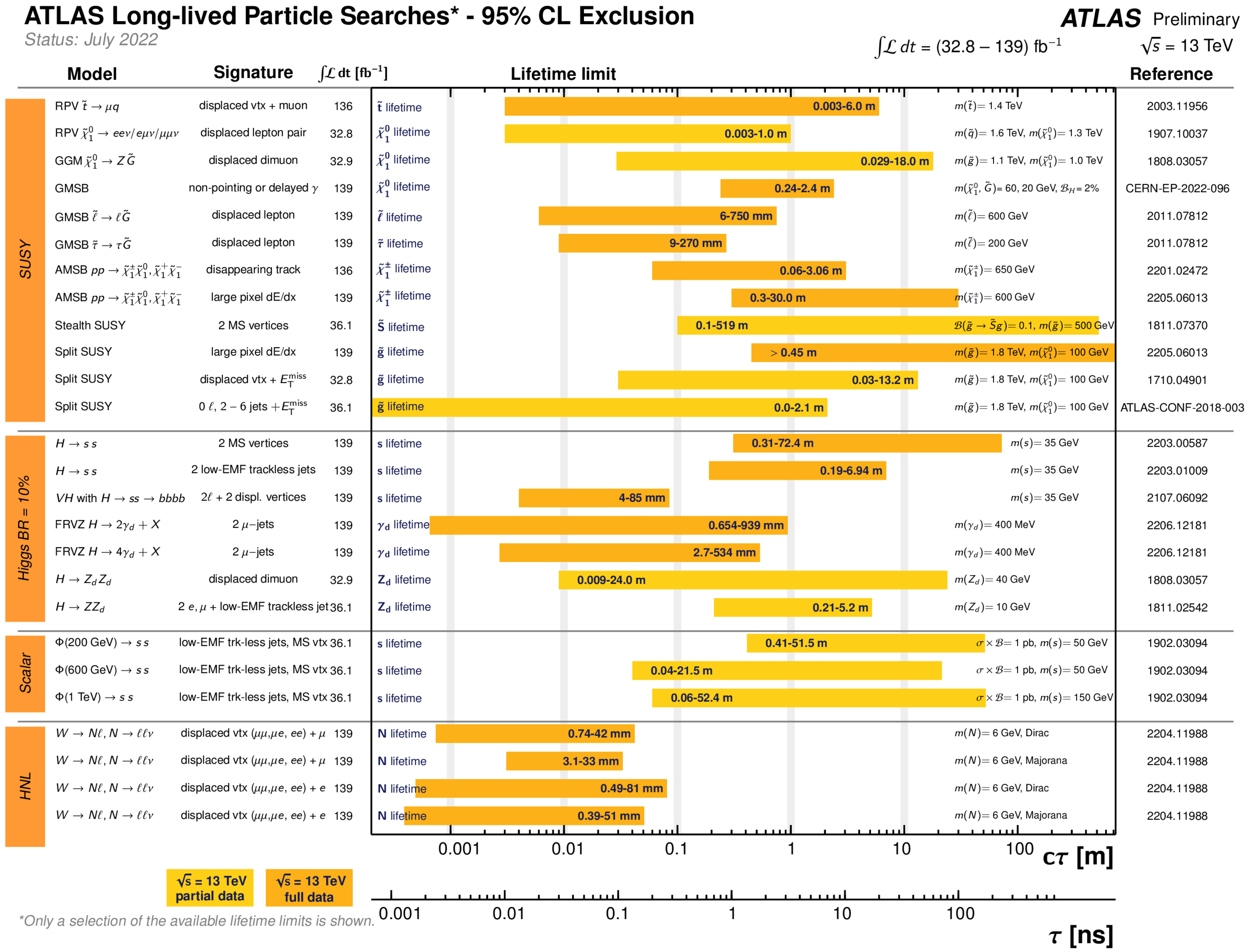


5σ discovery reach gets in direct-detection-hard mass region

ATL-PHYS-PUB-2018-043, ATL-PHYS-PUB-2018-036

HEAVY AND LONG-LIVED PARTICLES





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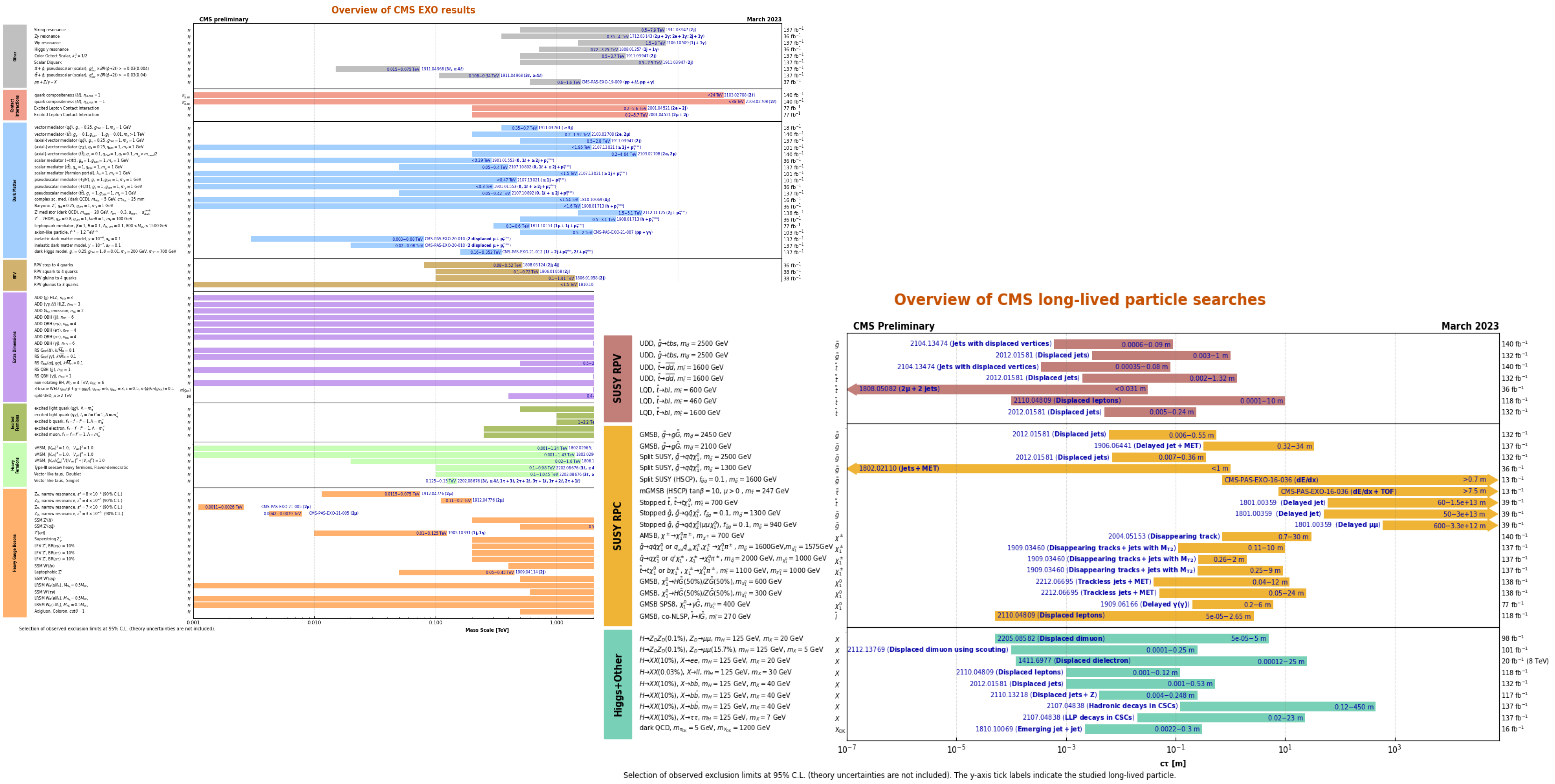
ATL-PHYS-PUB-2022-034



clickable versions here

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- **Phase-2 upgrade work ongoing**

  fight pile-up and improve reconstruction and identification

- **few % precision on many key processes**

  "30%" extended new physics reach [depends on how you compute it]

- **detector work goes along with new techniques**

  machine learning is not only an high-level-analysis tool

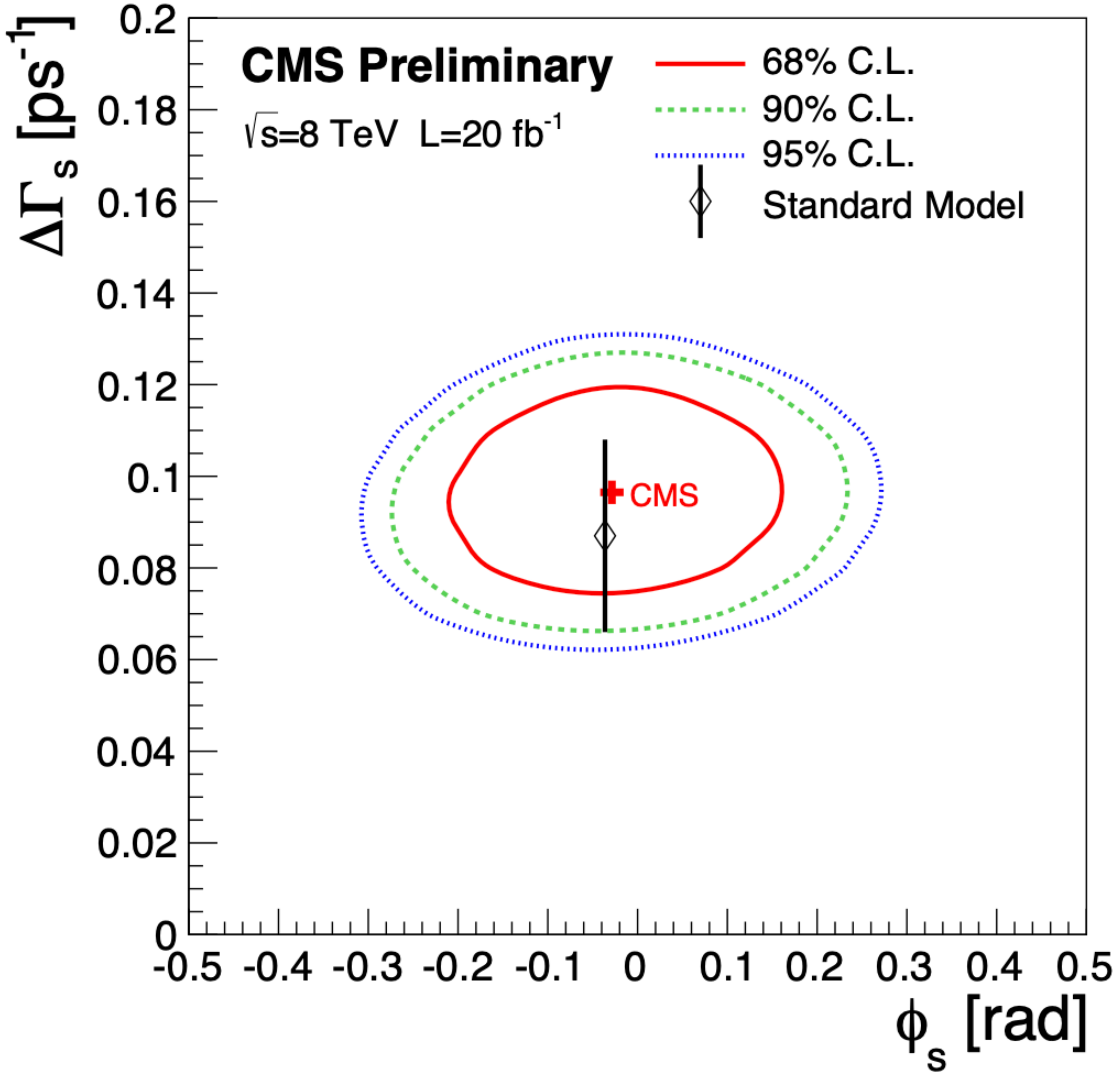
- **get ready to take the baton on stat-limited measurements**

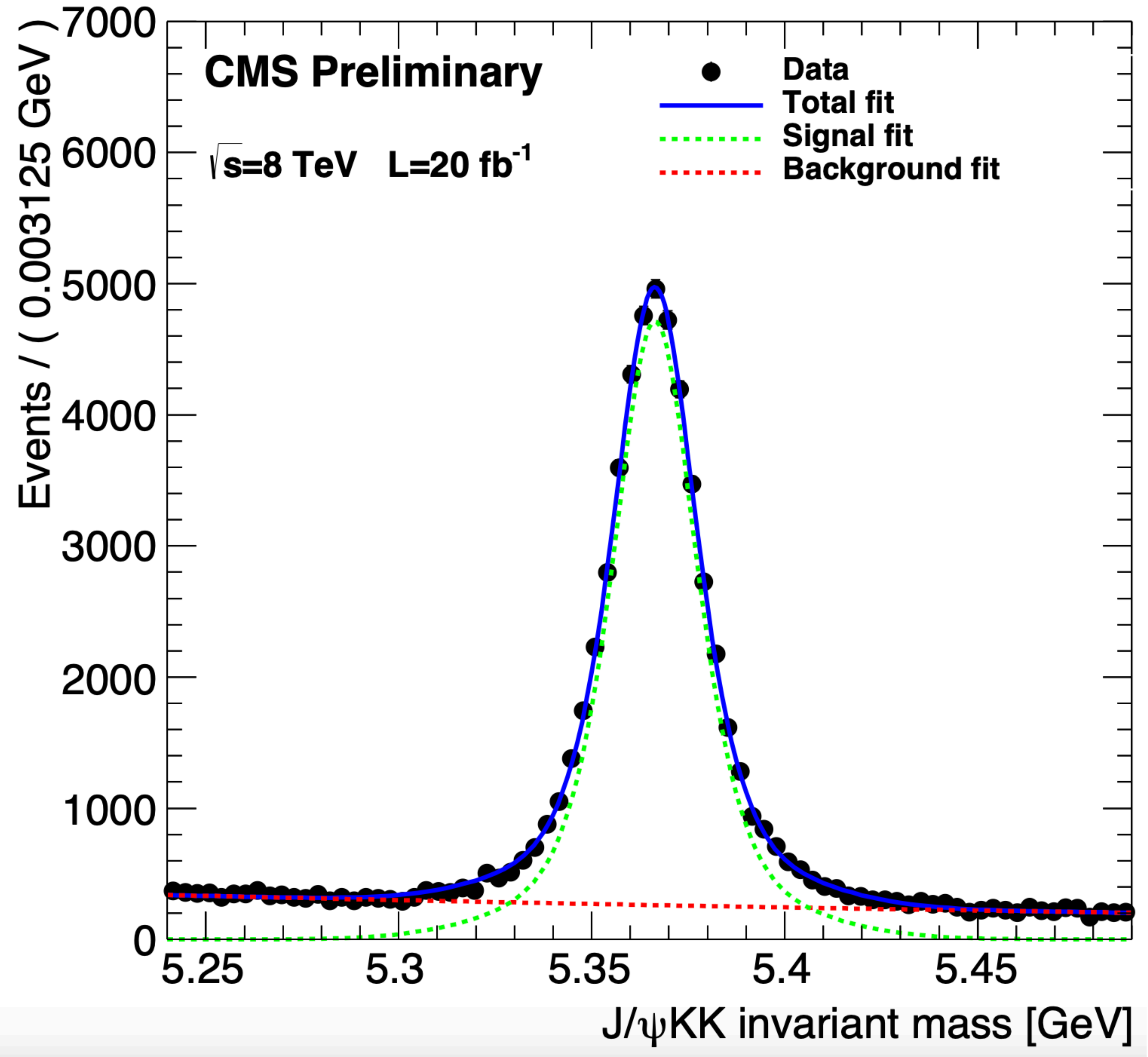
  and remember it's not been unusual for ATLAS & CMS to outperform predictions...

[1968; SLAC just started
with 20 MeV electrons]

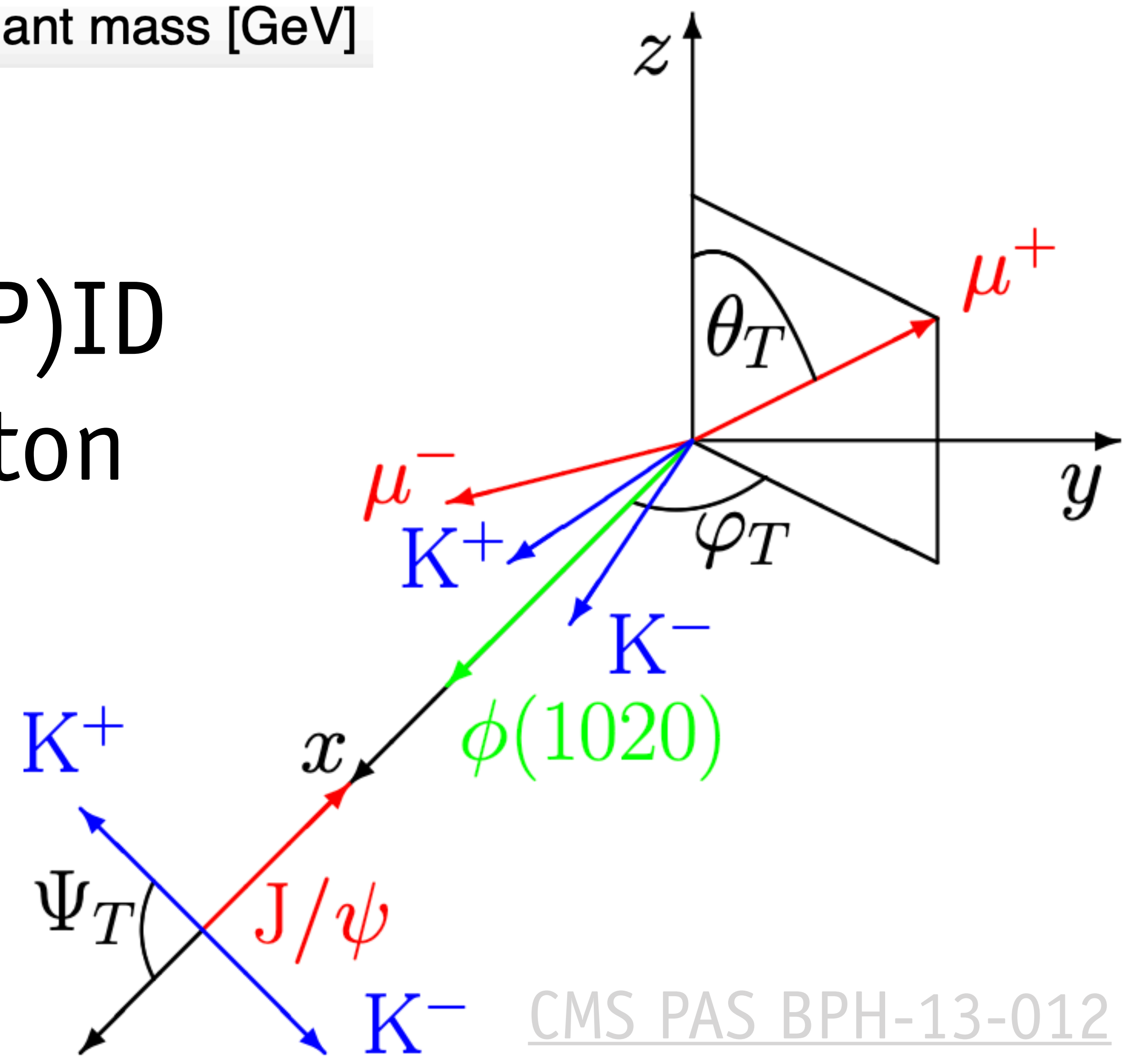
Backup

HEAVY FLAVOUR DECAYS

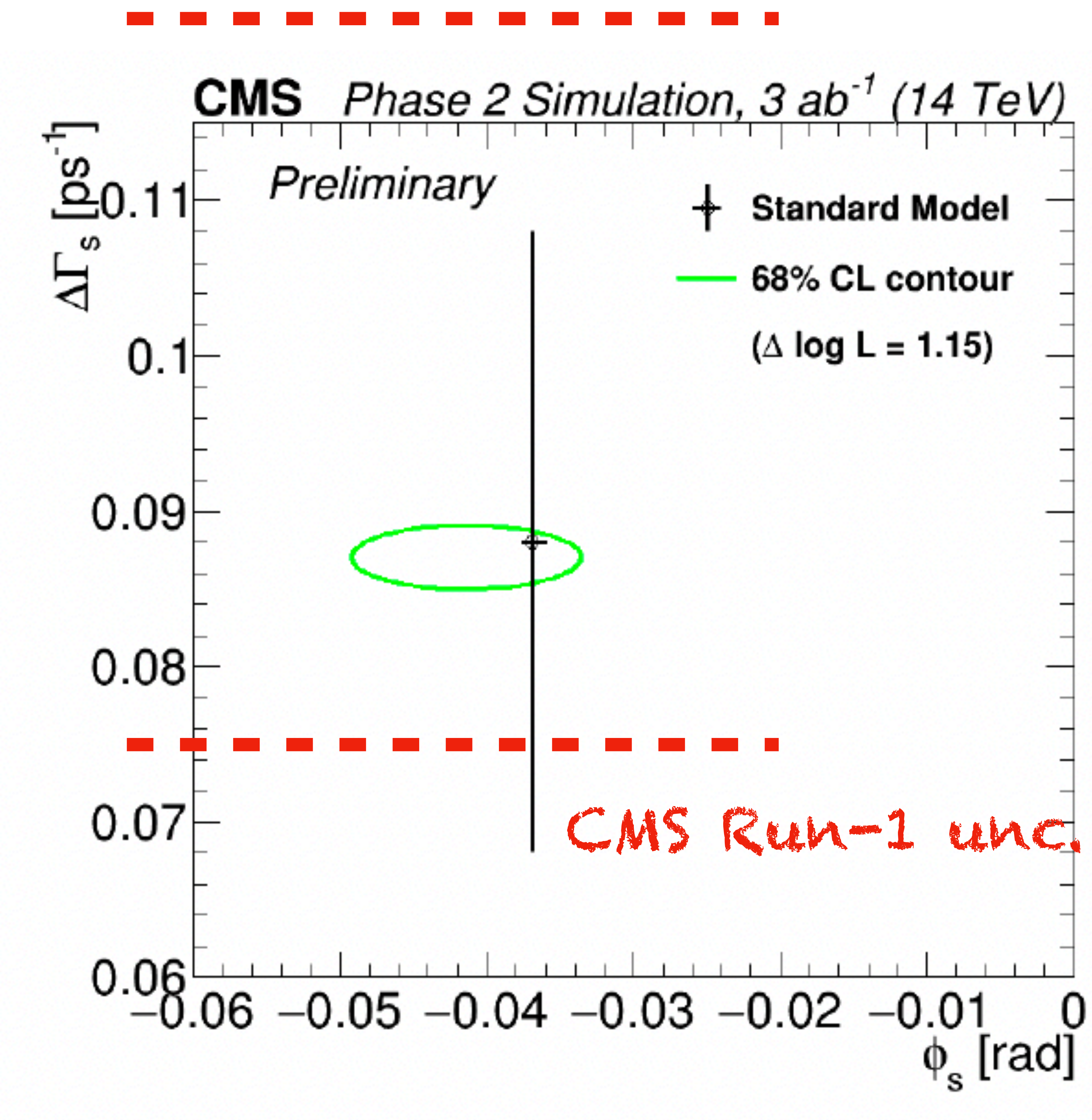




- a balance between (P)ID performance and lepton trigger thresholds
- here: $B_s \to J/\Phi\psi$

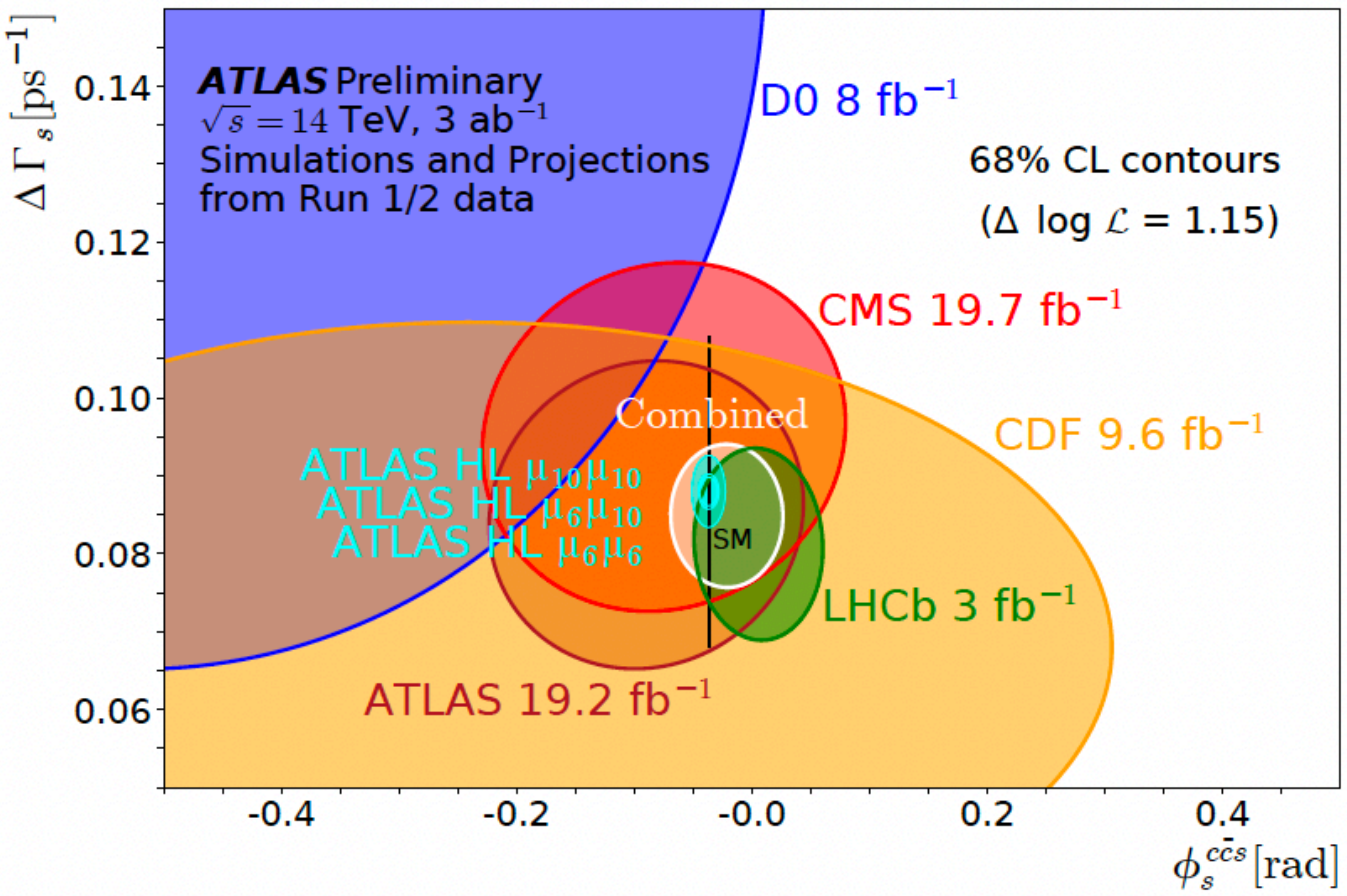


CMS PAS BPH-13-012



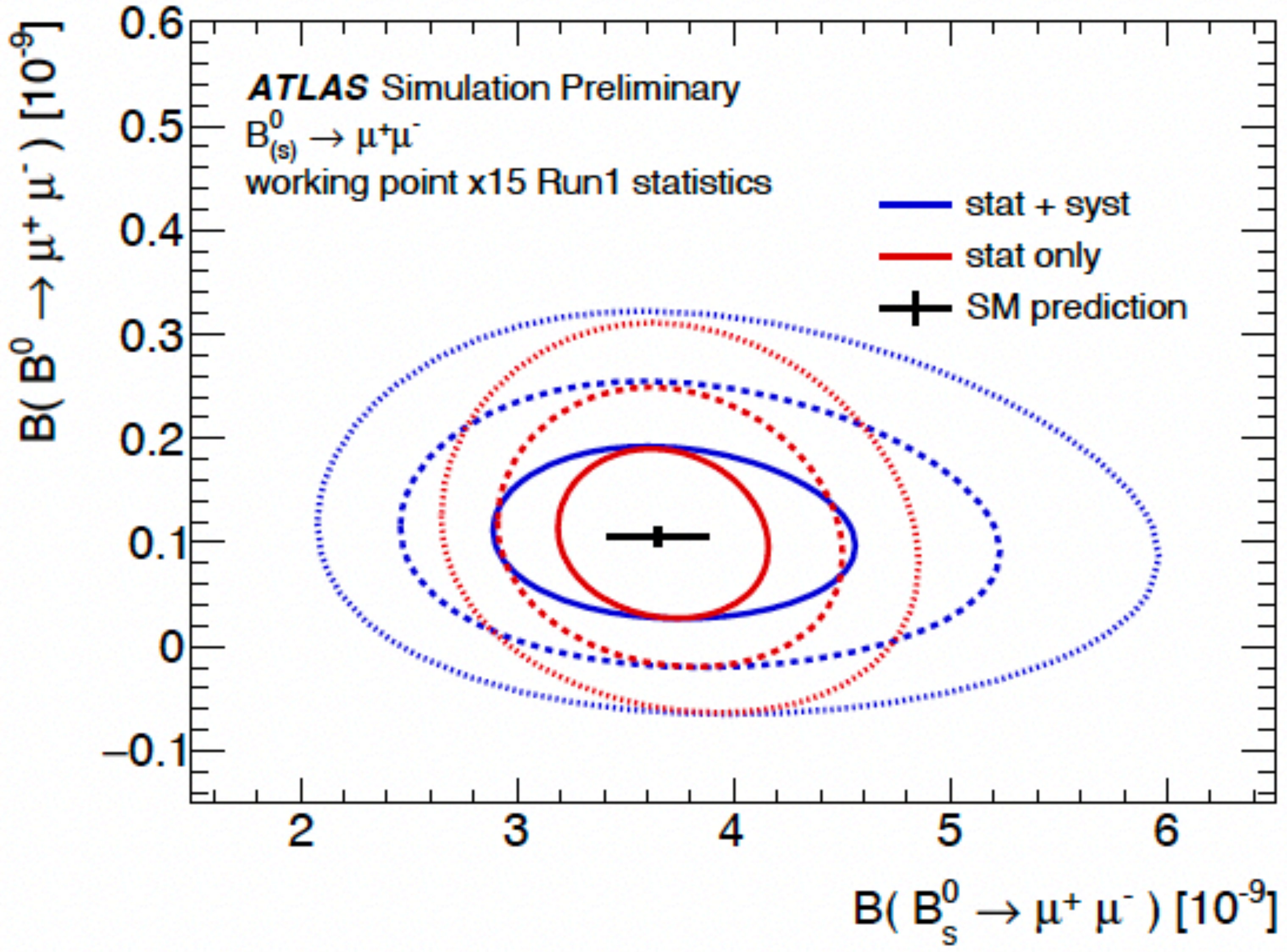
CMS Run-1 unc.

PID scenario	Gains in P_{tag}
MC truth	+66%
PID with σ_{BTL} = 40 ps	+24%
PID with σ_{BTL} = 70 ps	+14%

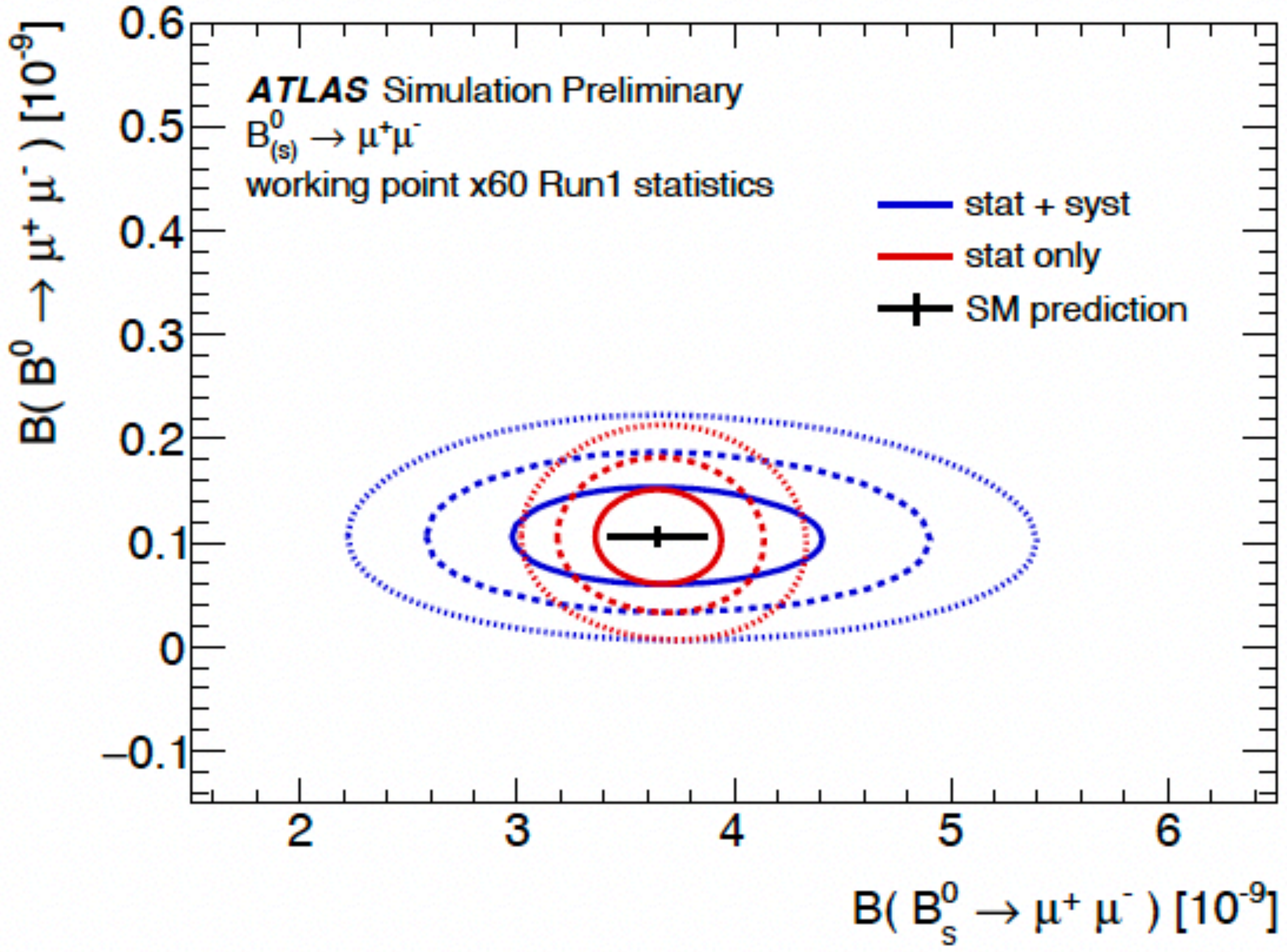


- tracker will improve proper time resolution (ATLAS: ~30% assuming same pT thresholds; CMS: 3x)
- MTD will help B-Physics and heavy ions on PID!
- μ trigger thresholds influence ATLAS Results

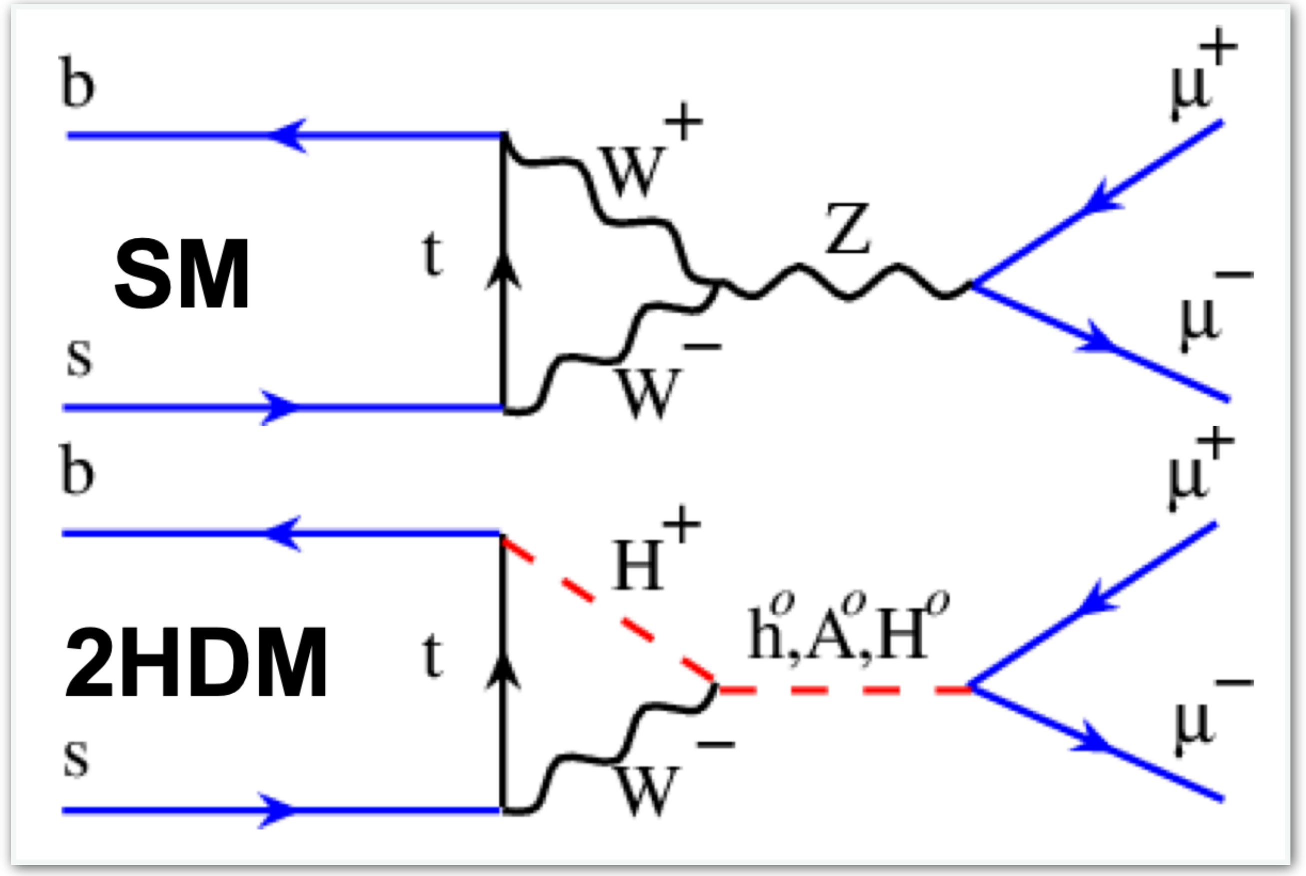
CMS PAS FTR-18-041, ATL-PHYS-PUB-2018-041, CMS DP -2022/025

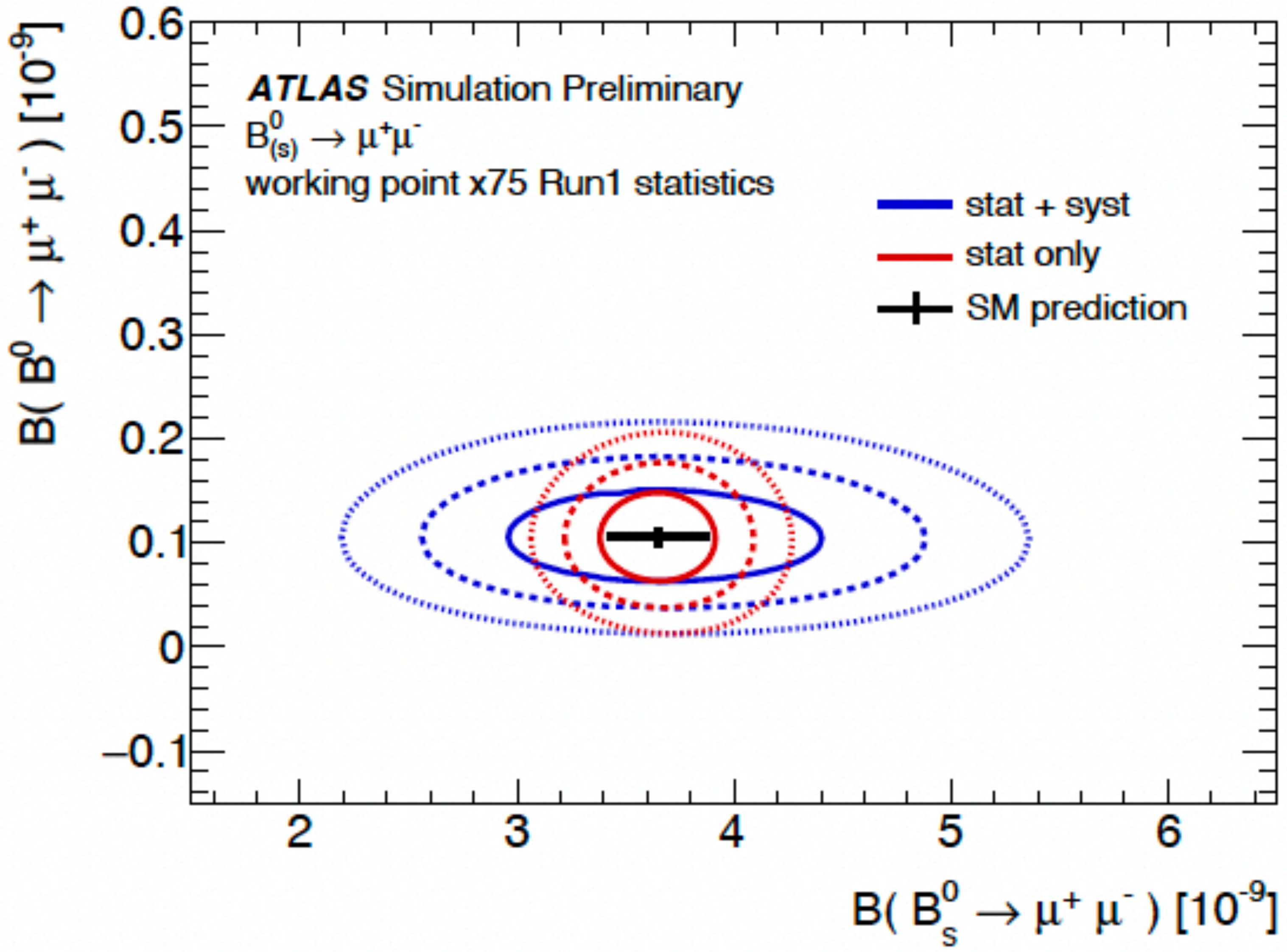


(a)



(b)



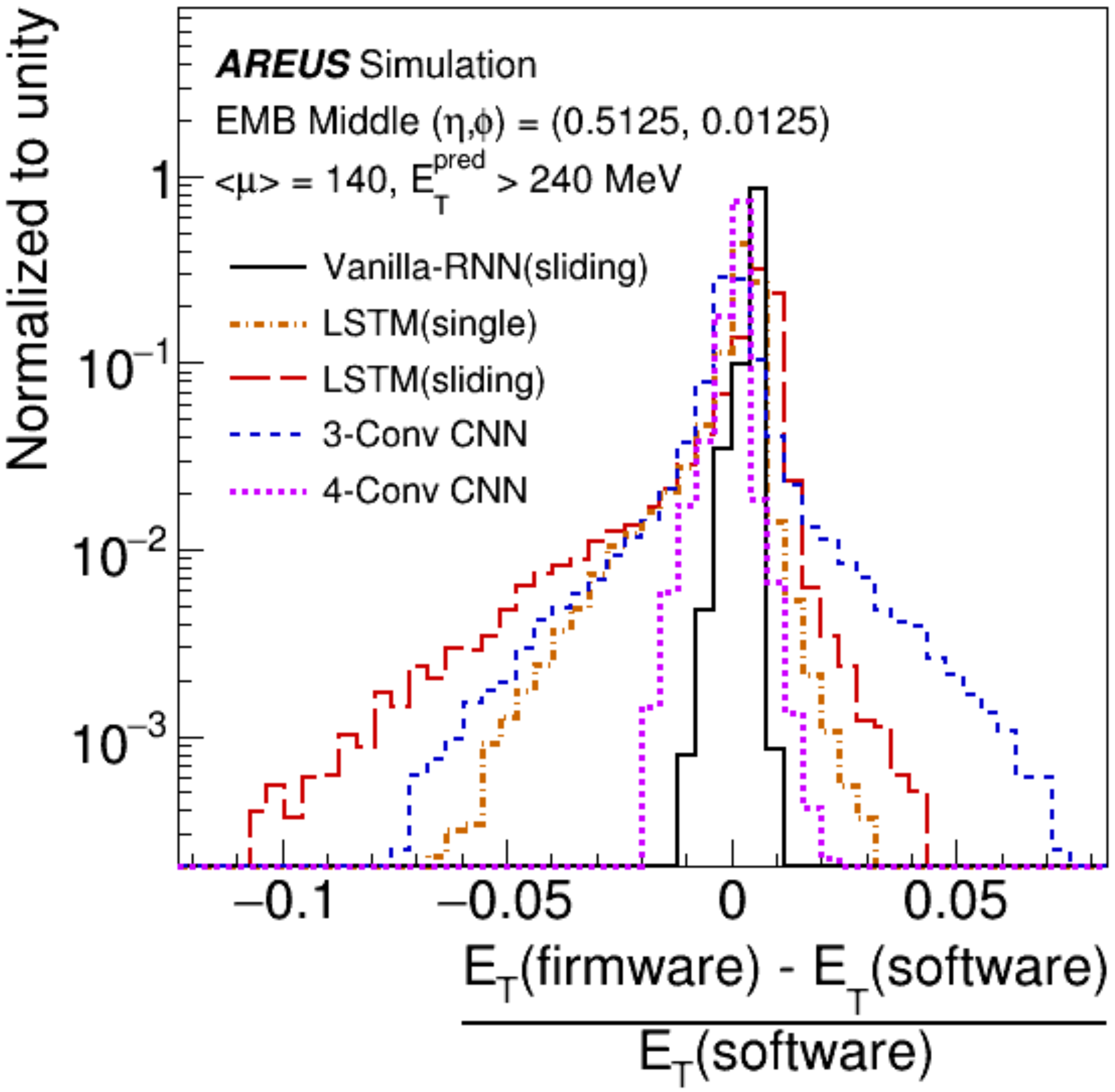


$B_s \to \mu\mu$ from 20-50% higher mass resolution and trigger flexibility, assuming same performance as in Run-1, in three acceptance scenarios

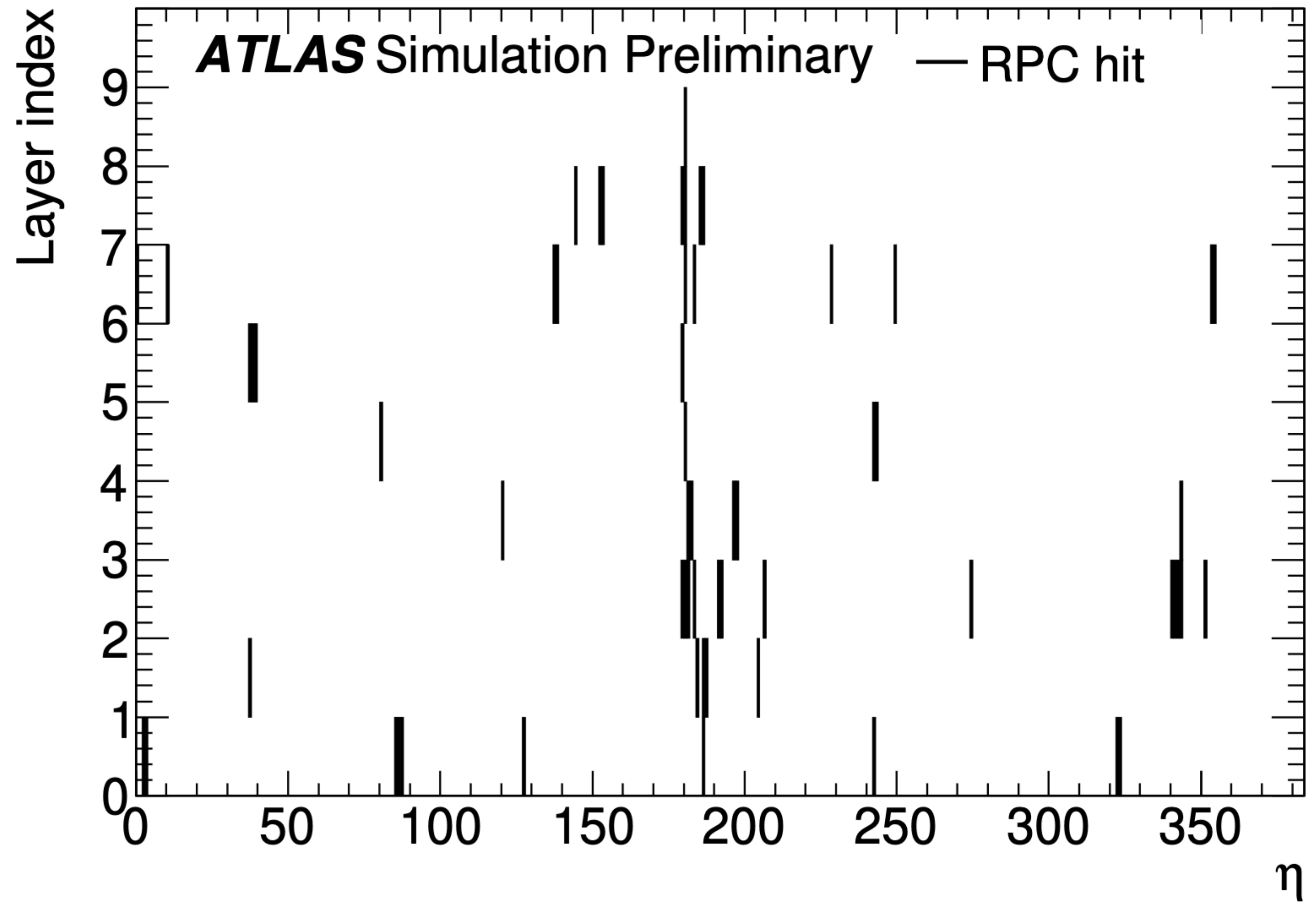
ATL-PHYS-PUB-2018-005, CMS-PAS-FTR-18-013

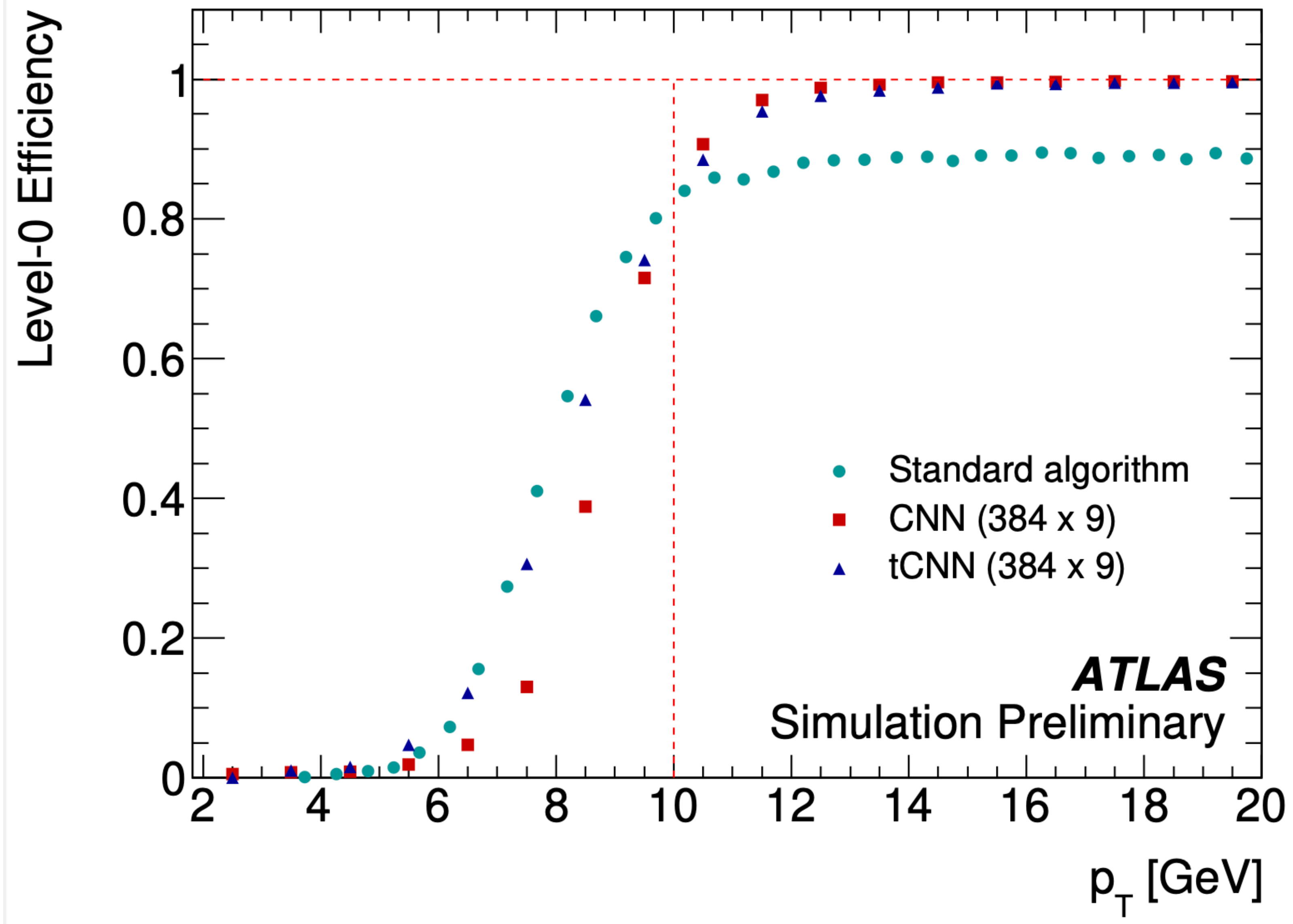
ML IN THE TRIGGER

L0Muon: 1 MHz and a latency of 10 μs

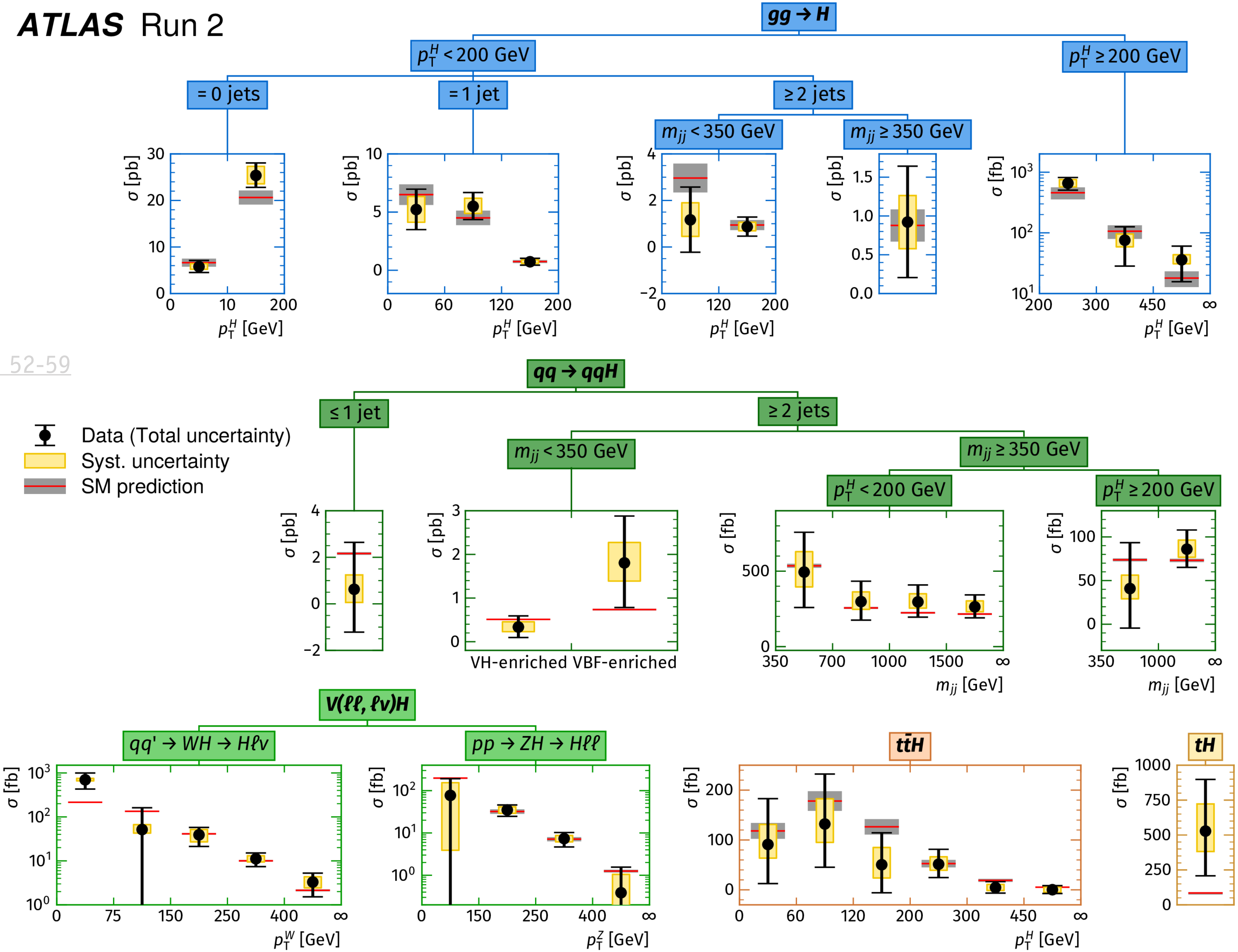


- fast reconstruction on FPGA
- fast reconstruction on GPU
- anomaly detection for new discoveries





ATLAS LAr & L0Muon upgrade



Nature 607 (2022) 52-59

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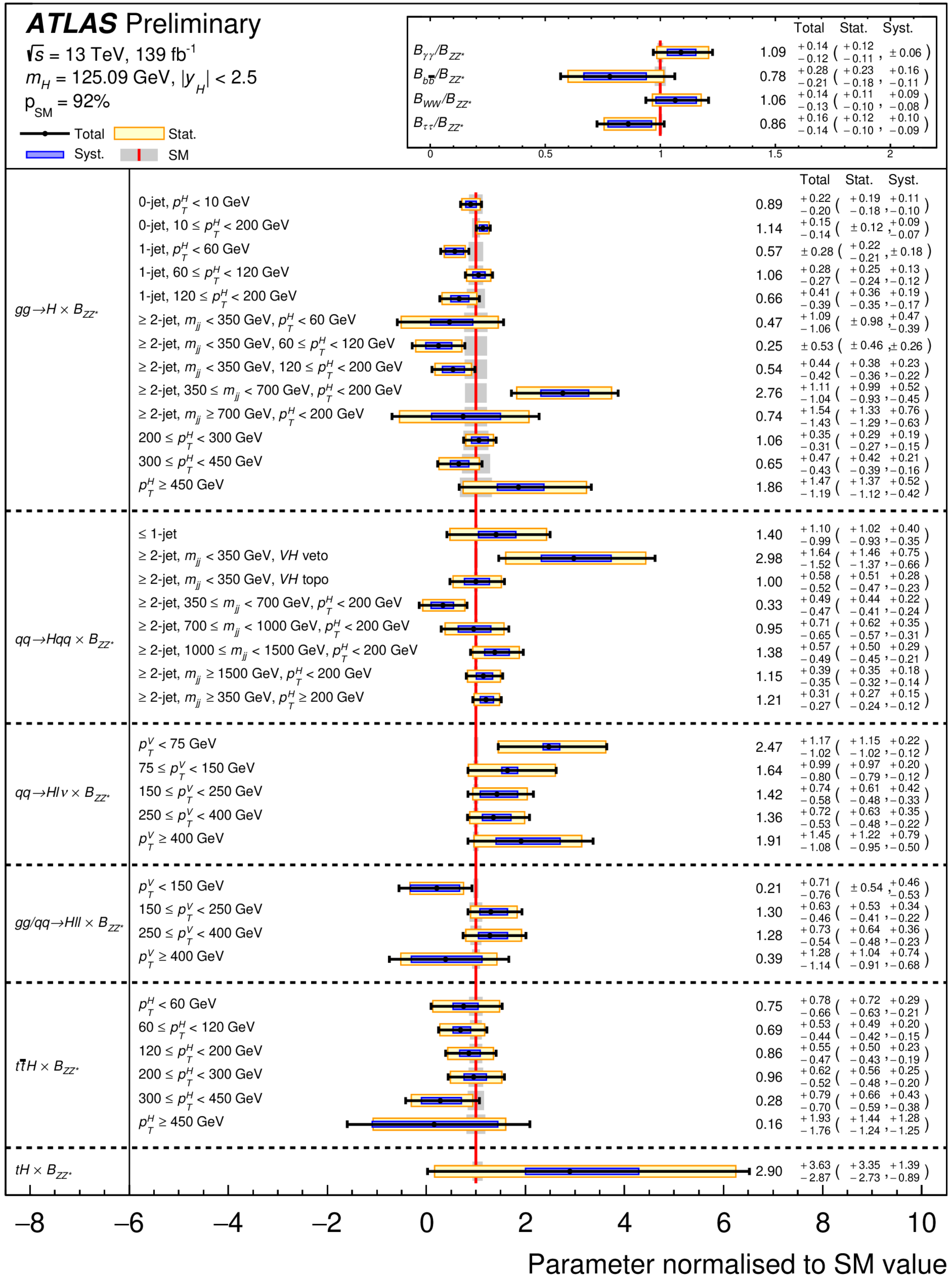

ATLAS-CONF-2021-053

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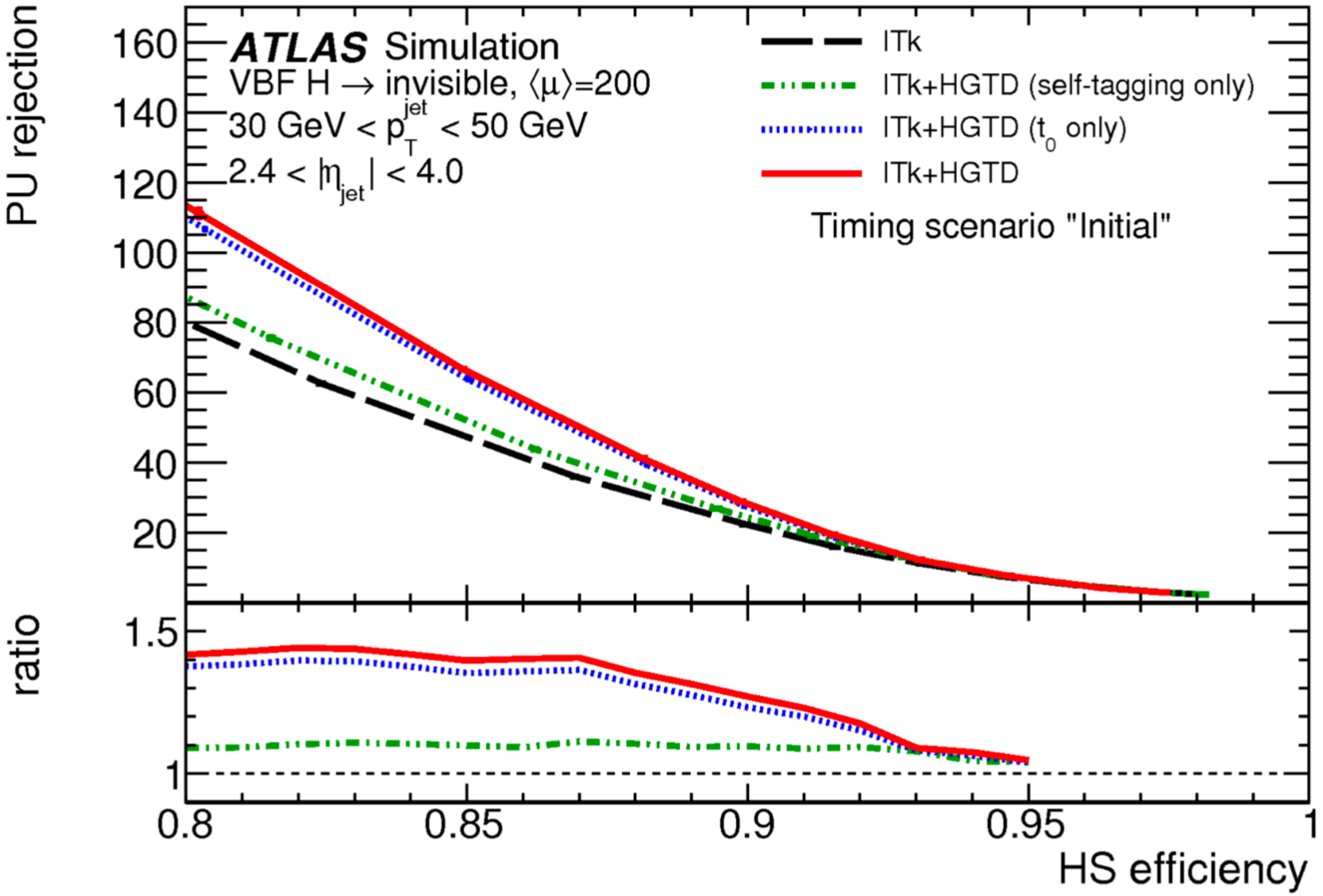
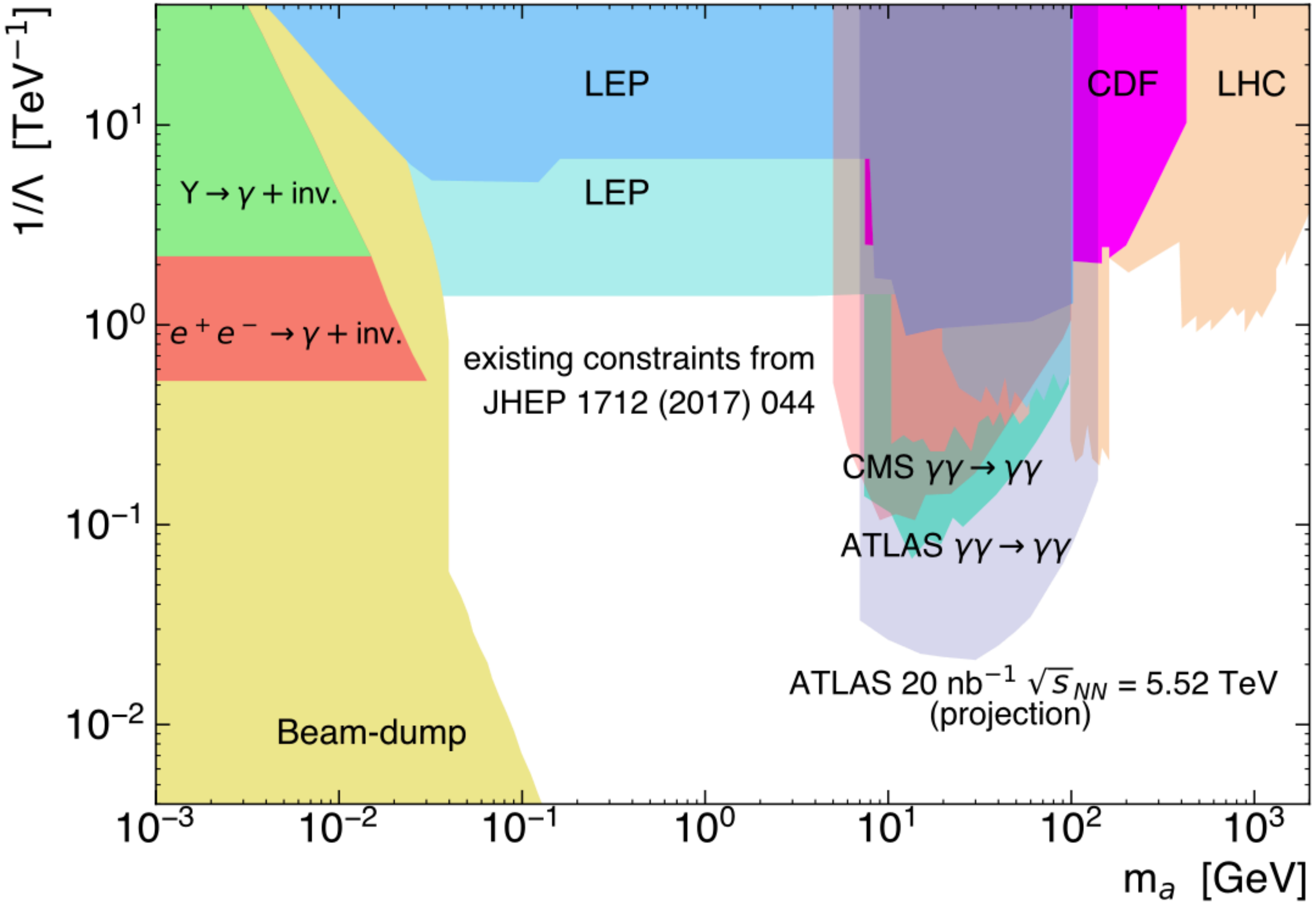
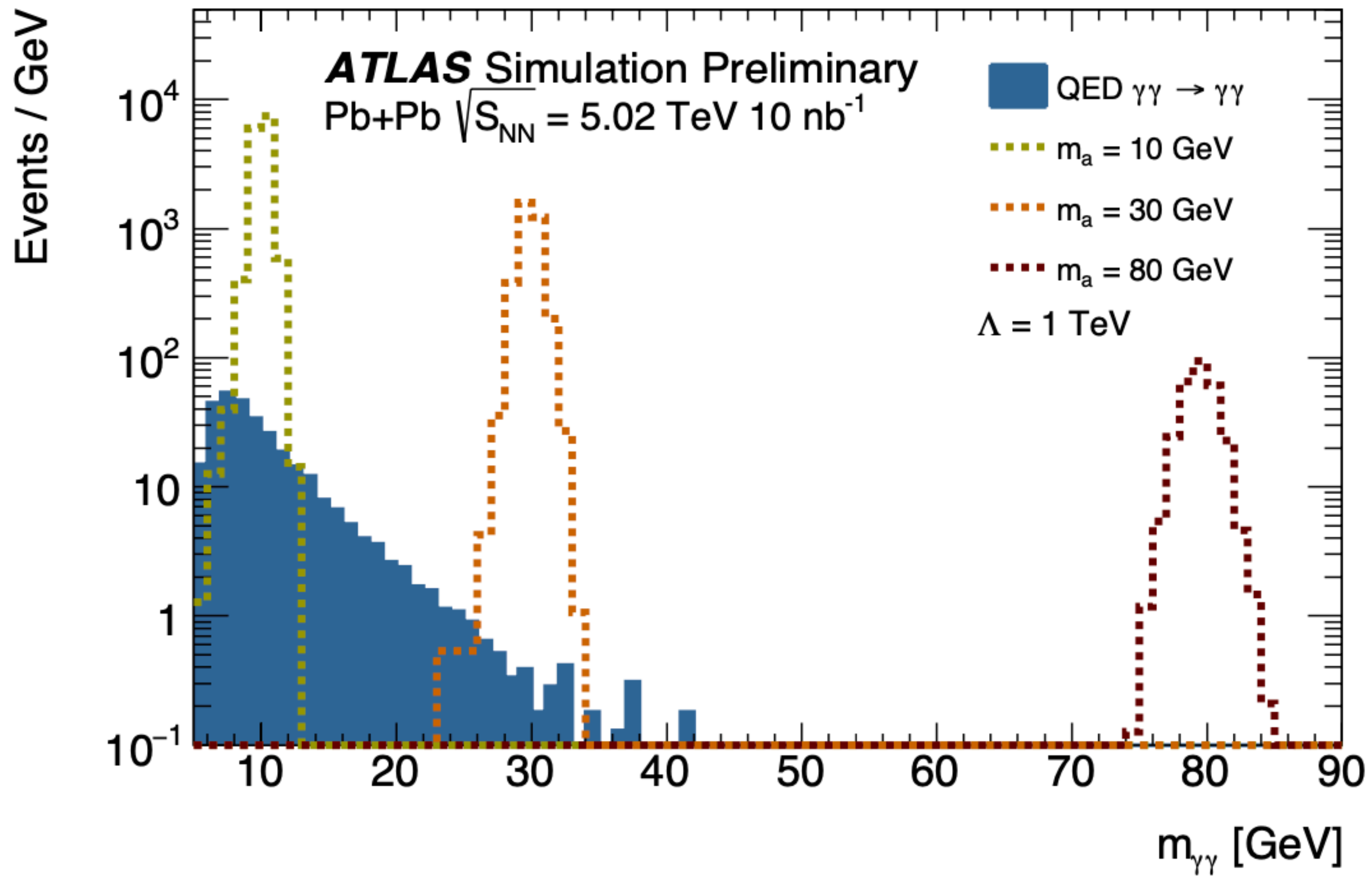
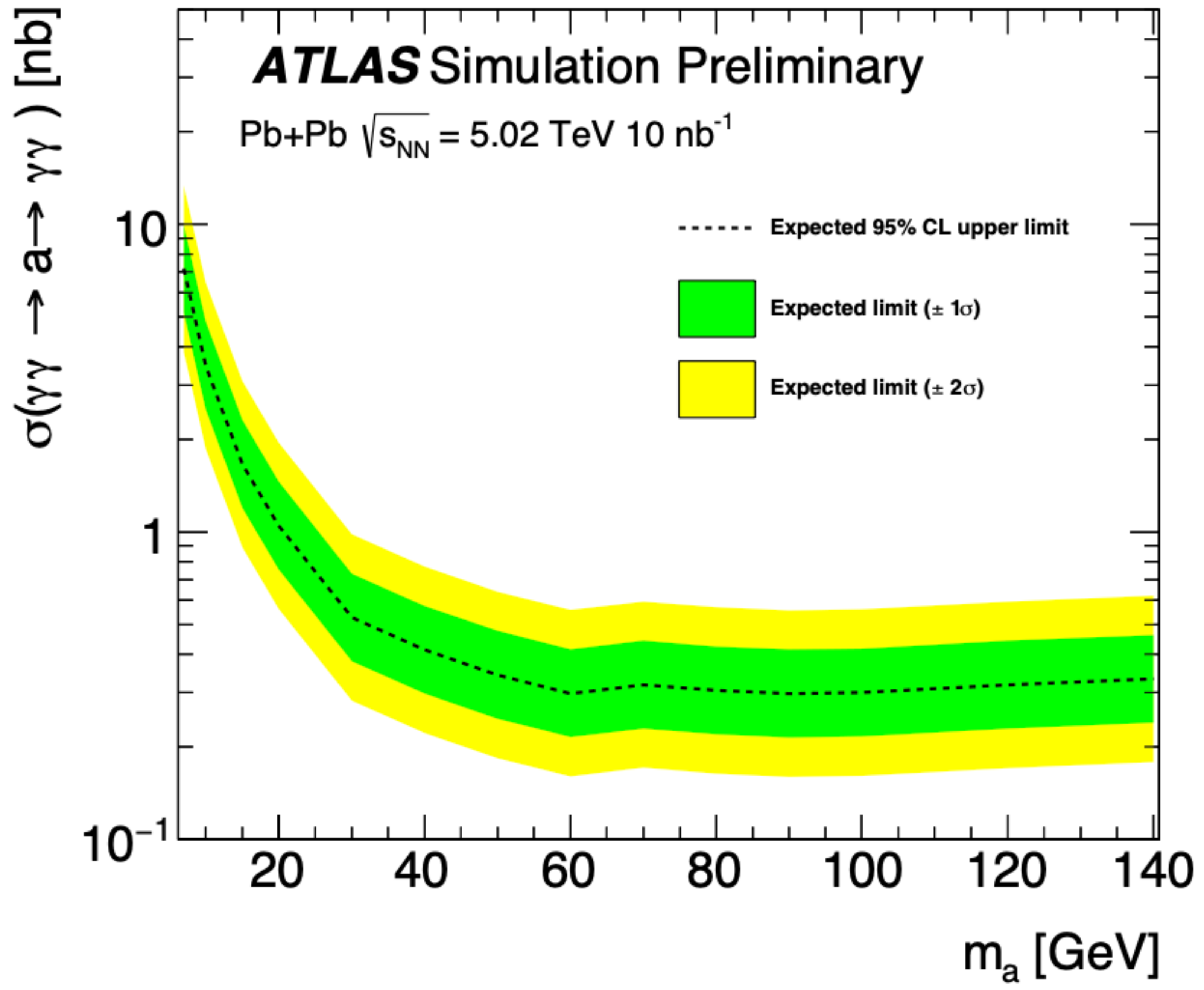
ATLAS-TDR-031



LIGHT-BY-LIGHT SCATTERING

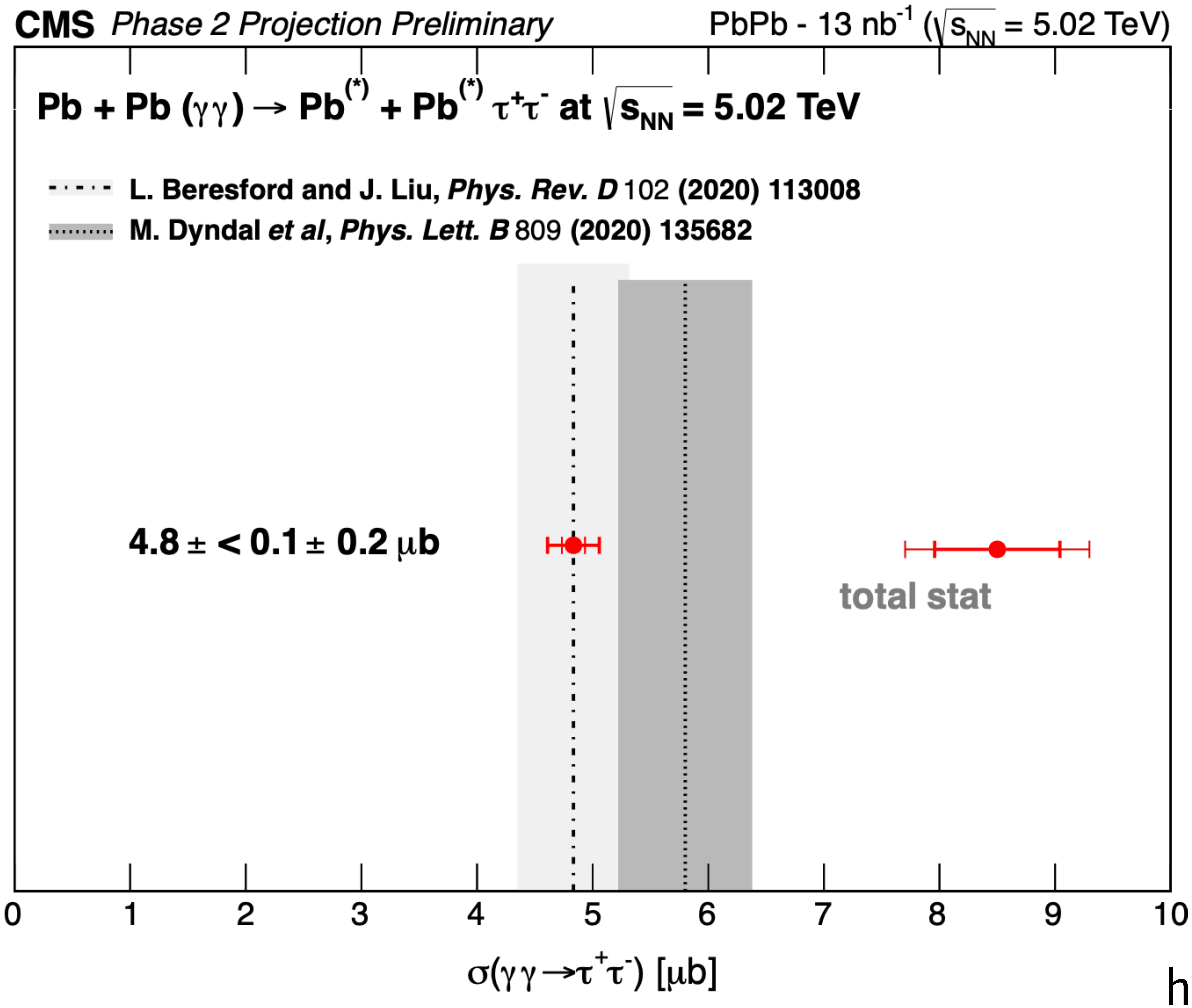






https://cds.cern.ch/record/2805993/

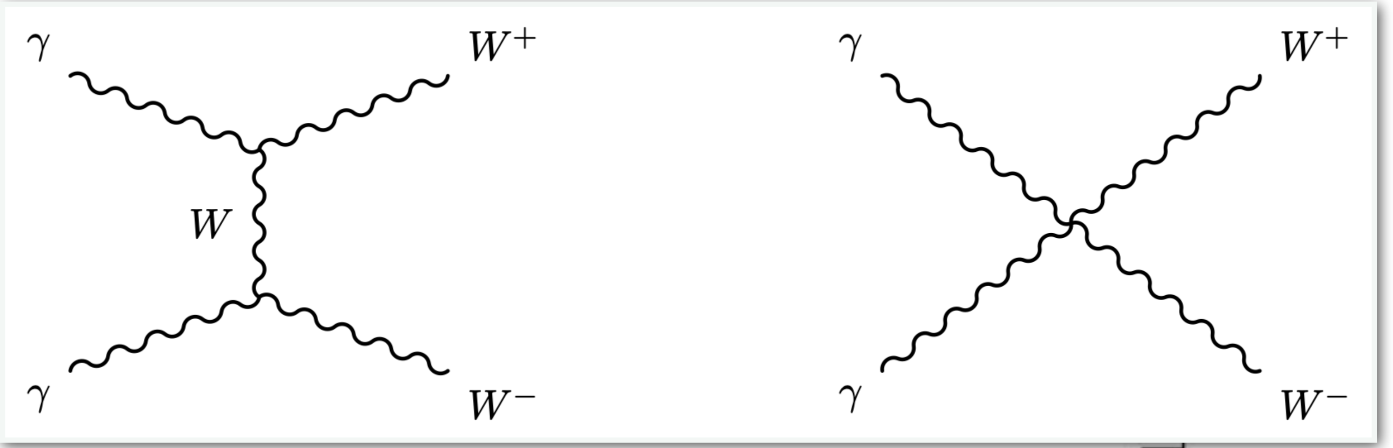
γγ→ττ

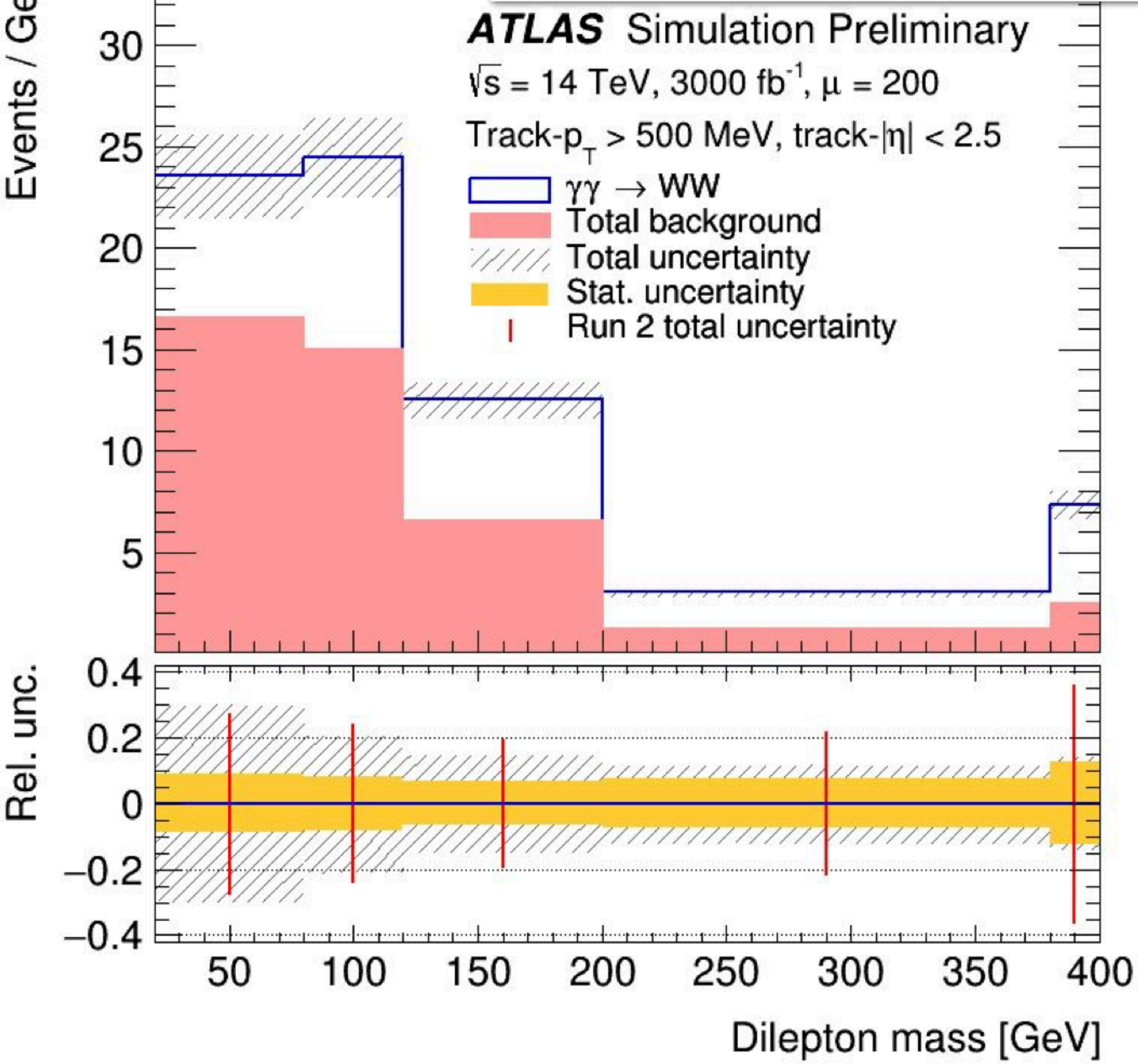


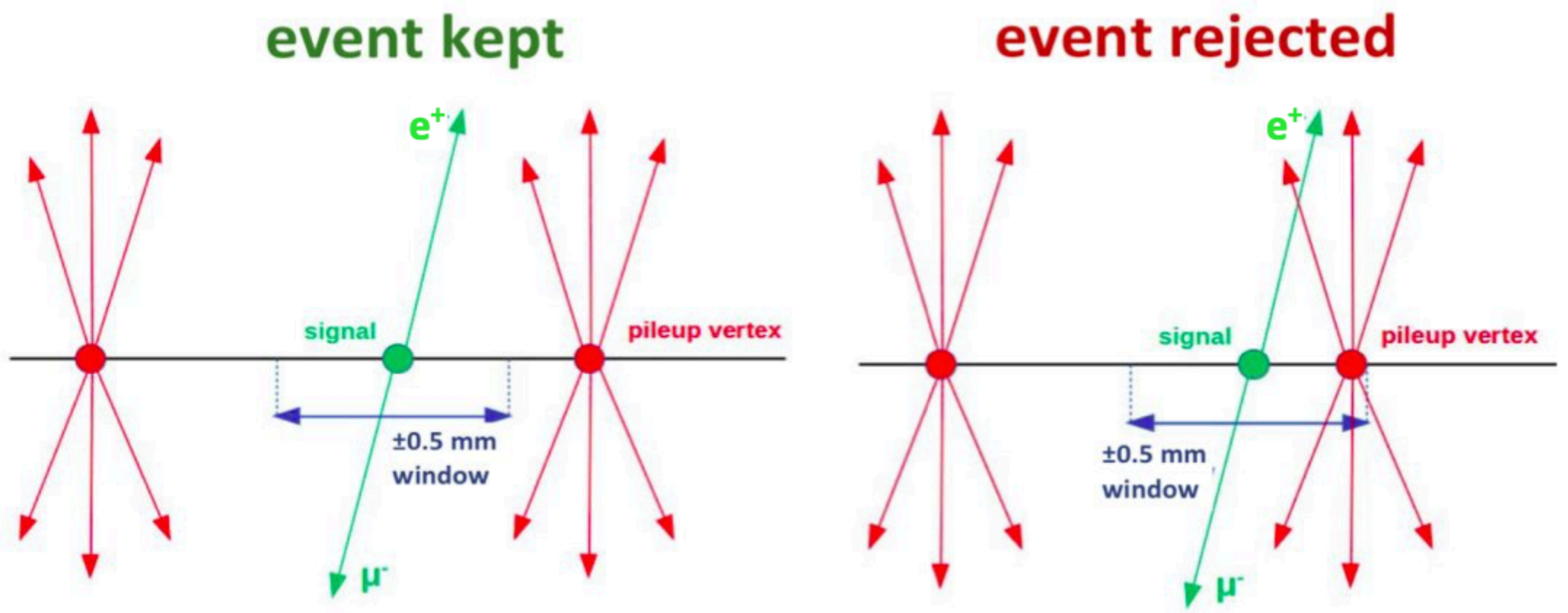
- 4x precision on tau anomalous magnetic moment w.r.t today
- 4% syst, 2% stat

https://cds.cern.ch/record/2805993/

γγ→ WW







- observed with Run-2 data
- challenging at high-lumi (track veto vs pileup), but can go differential

	Run 2 ID	ITk (HL-LHC baseline)		
	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.0$	$2.0 < \lvert\eta\rvert < 2.6$	$2.6 < \lvert\eta\rvert < 4.0$
Min. p_T [MeV]	500	900	400	400
Min. number of Si hits	7	9	8	7

PLB 816 (2021) 136190, ATL-PHYS-PUB-2021-026