PAUL SCHERRER INSTITUT

THEORETICAL PHYSICS

Michael Spira (PSI)

I *INTRODUCTION*

- SM very successful ← precision data [LEP, Tevatron, LHC, low energy]

- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

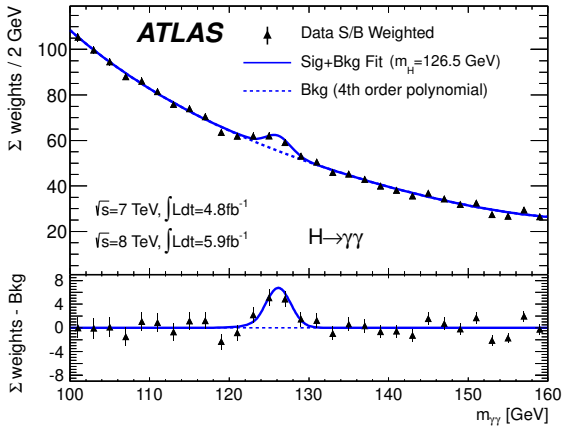
- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Composite states (H, t) ?

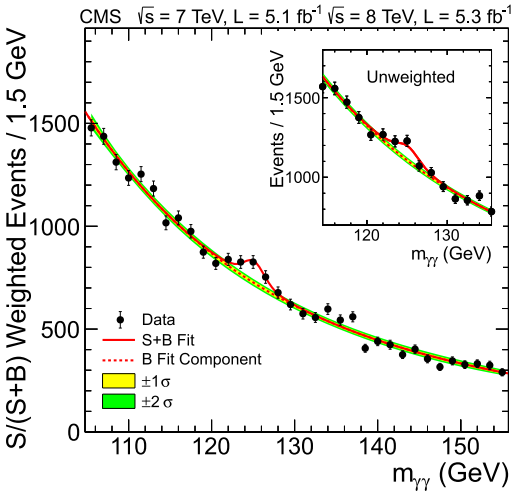
- FCC$_{ee}$: precision measurements → indirect effects
  ← precision calculations

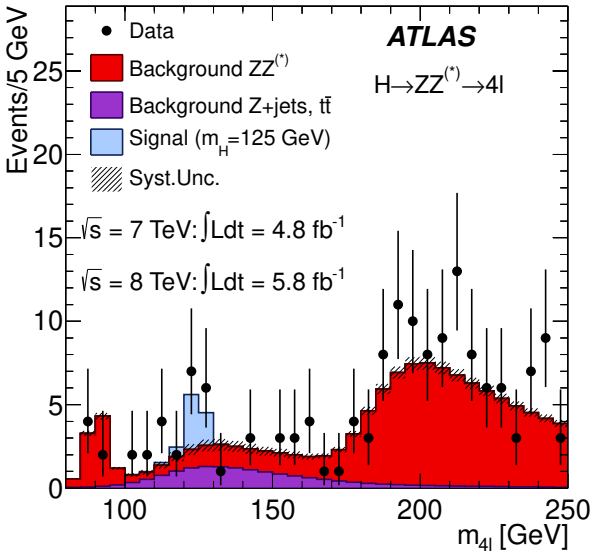
- low-energy observables ($g-2$, nEDM, $\mu^{\pm}$ etc.) → indirect effects
  ← precision calculations

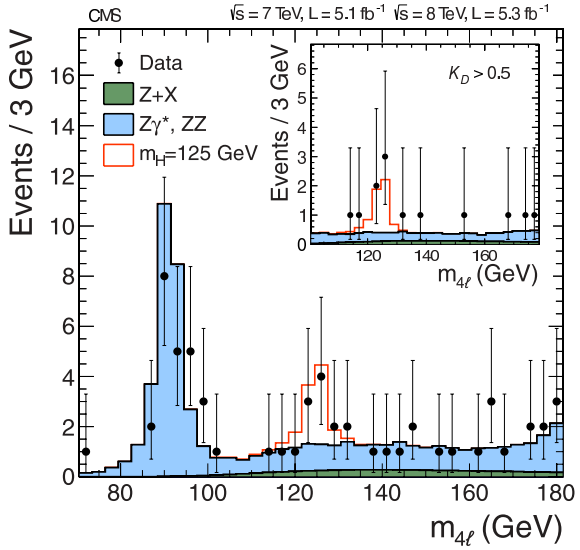
- astro-particle physics → Dark Matter/Energy, simulations

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \to H$ dominant

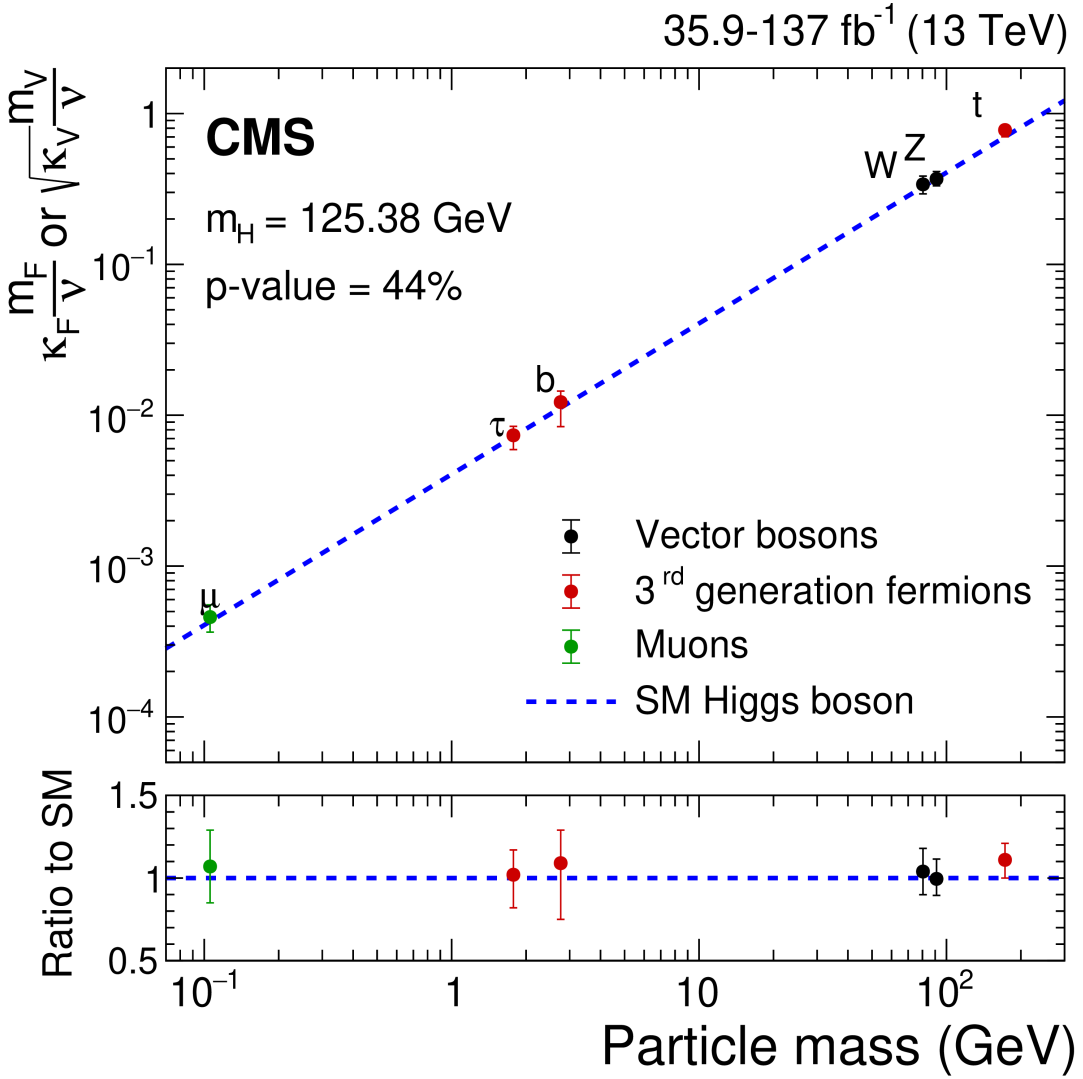




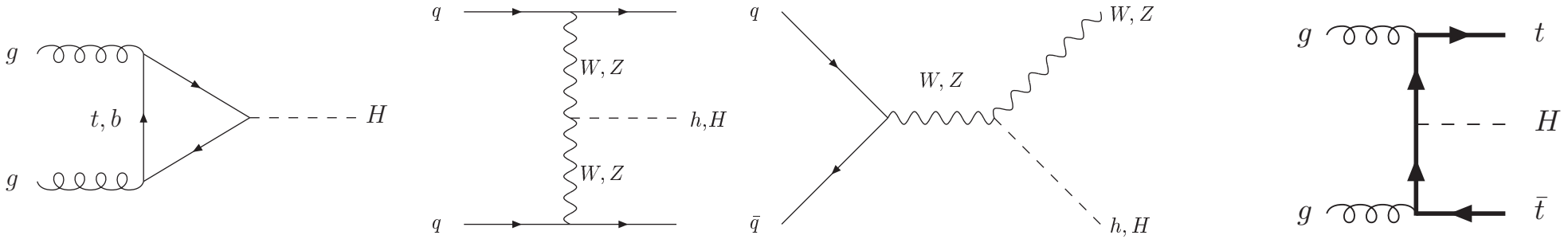


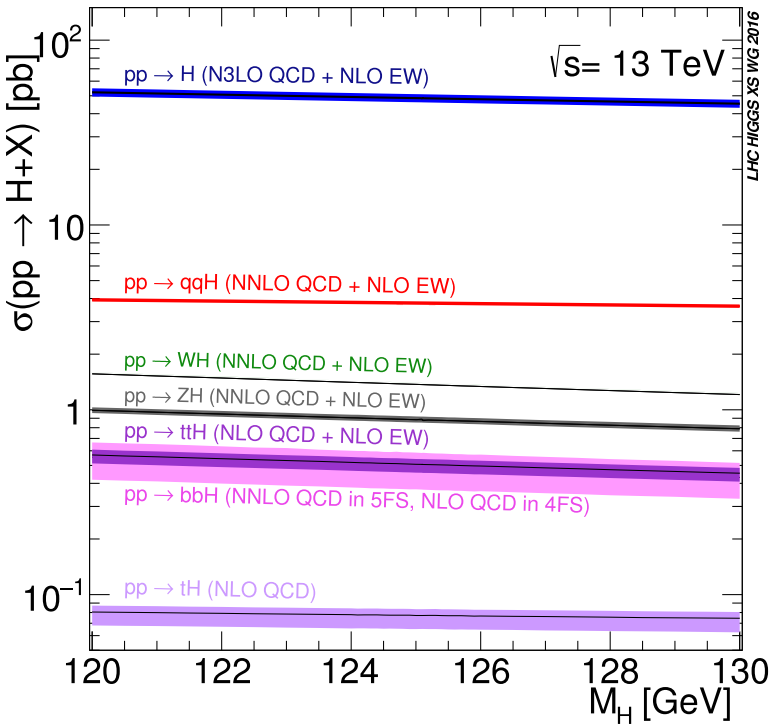


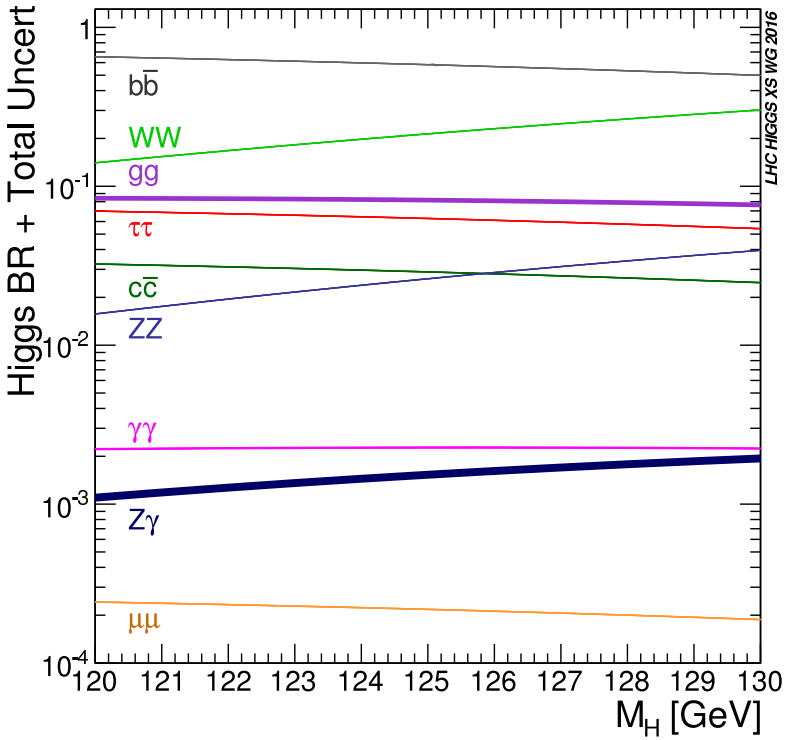
- Discovery: LHC [Tevatron]
  → Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  charm ?
  λ ?



- Higgs Boson Production & Decay







LHC Higgs WG

II *SWISS INSTITUTES*

• University of Geneva: cosmology, astro-particle physics, BSM, LHC, mathematical physics

	HE	LE	ν	astro	cosm./string	other
Maggiore					1.00	
Riva	0.50				0.50	

• EPF Lausanne: EFT, BSM, collider physics, neutrinos, cosmology, string theory

• University of Bern: QCD, χPT, K & B mesons, SUSY, Lattice, string theory, gravity

	HE	LE	ν	astro	cosm./string	other
Becher	1.00					
Blau					0.30	0.70
Colangelo		1.00				
Greub	1.00					
Hoferichter		0.90	0.05	0.05		
Laine				0.50	0.50	
Reffert					0.50	0.50
Wenger		1.00				

• University of Basel: neutrinos, flavour, SUSY, unified theories, cosmology

	HE	LE	ν	astro	cosm./string	other
Antusch	0.40	0.30		0.30		
Greljo	0.40	0.40	0.10	0.05	0.05	
Thielemann		0.20		0.30	0.50	

• PSI: Higgs, SUSY, low-energy muon and hadron physics, amplitudes, lepton-flavour physics, precision calculations, collider physics

	HE	LE	ν	astro	cosm./string	other
Ita	0.70				0.30	
Signer	0.10	0.90				
Spira	0.98	0.02				
Stoffer	0.10	0.90				
Zoller	1.00					

• University of Zurich: precision QCD, Higgs, SUSY, BSM, flavour physics, EFT, astro-physics, cosmology

	HE	LE	ν	astro	cosm./string	other
Gehrmann	1.00					
Grazzini	1.00					
Isidori	0.35	0.50	0.05	0.05	0.05	
Pozzorini	1.00					
Saha					1.00	
Sotnikov	0.97				0.03	

• ETH Zurich: precision QCD, Higgs, mathematical physics, string theories, astro-phyics, cosmology

	HE	LE	ν	astro	cosm./string	other
Fröhlich					0.05	0.95
Gaberdiel					1.00	
Gehrmann-De Ridder	1.00					

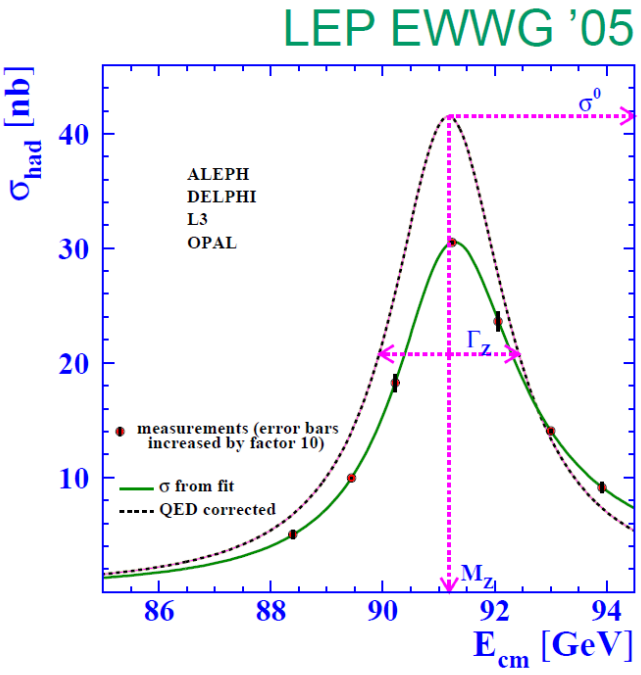
Total sum:

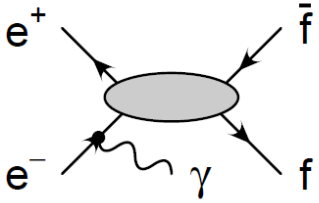
HE	LE	ν	astro	cosm./string	other
0.50	0.27	0.01	0.05	0.27	0.09

II *PHYSICS*

(→ pillar 1)

FCC$_{ee}$: Z line shape ← ISR





$$\sigma(e^+e^- \to f\bar{f}) = \mathcal{R}_{ISR} \otimes \sigma_{hard}$$

$+$ interference between ISR and FSR

$+ \sigma_{hard}$

$\Rightarrow$ sizeable uncertainties

Kuraev, Fadin
Berends, Burgers, van Neerven
Kniehl, Krawczyk, Kühn, Stewart
Beenakker, Berends, van Neerven
Bardin,. . .
Skrzypek
Montagna, Nicrosini, Piccinini
Ablinger, Blümlein, De Freitas, Schönwald

- $e^+e^- \to WW$: $\delta_{th} M_W \sim 4$ MeV $\leftrightarrow$ 1 MeV (exp)
- $e^+e^- \to t\bar{t}$: $\delta_{th} m_t \lesssim 60$ MeV $\leftrightarrow$ 100 MeV (exp)

	current exp.	FCC$_{ee}$	current th.	∼3(4)-loop
M_W [MeV]	12	1	4 ($\alpha^3, \alpha^2\alpha_s$)	1
Γ_Z [MeV]	2.3	0.1	0.4 ($\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$)	0.15
R_ℓ [10^{-3}]	25	1	5 ($\alpha^3, \alpha^2\alpha_s$)	1.5
R_b [10^{-5}]	66	6	10 ($\alpha^3, \alpha^2\alpha_s$)	5
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	∼13	0.5	4.5 ($\alpha^3, \alpha^2\alpha_s$)	1.5

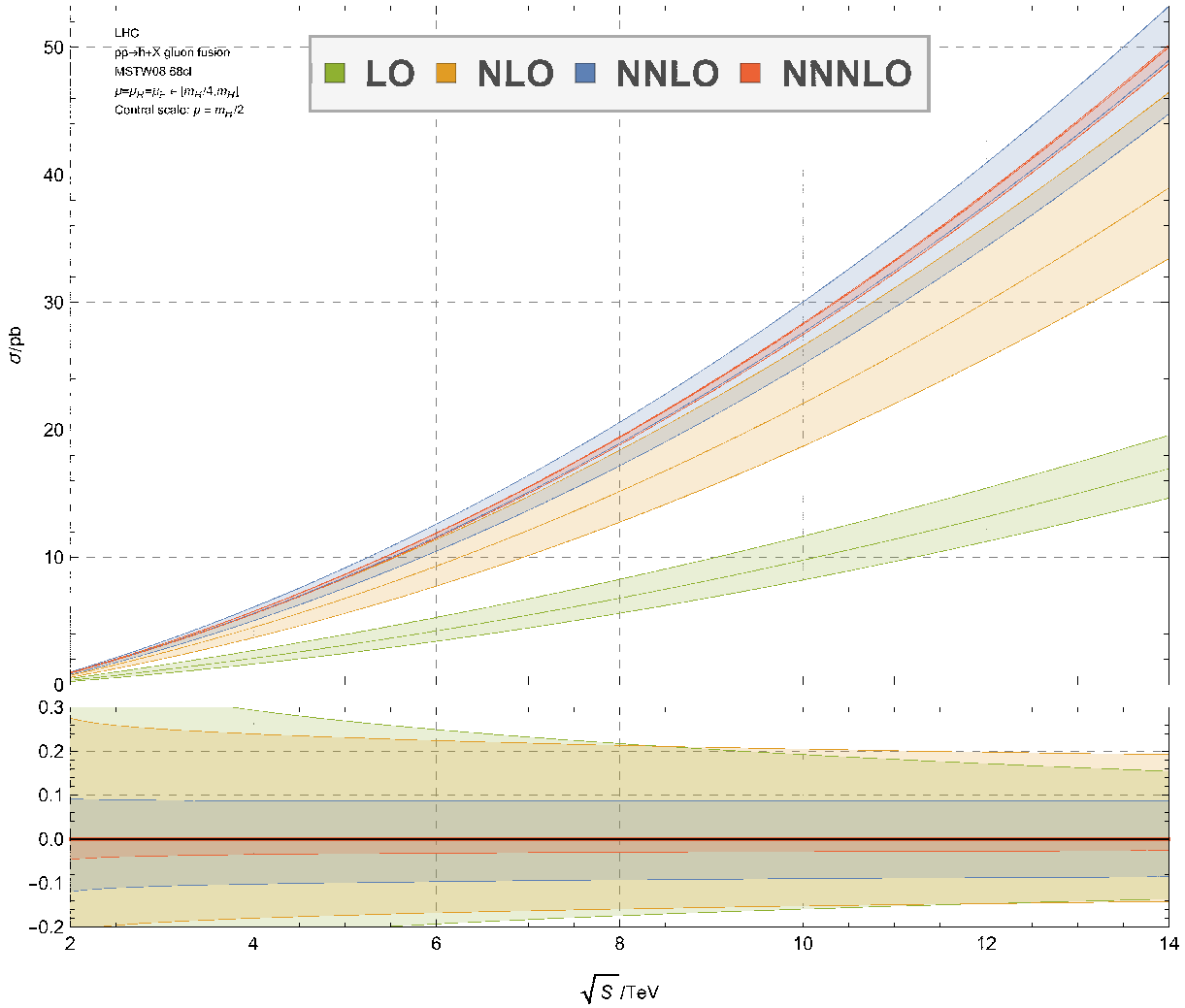
Freitas, Heinemeyer, Beneke, Blondel, Dittmaier, Gluza, Hoang, Jadach, Janot, Reuter, Riemann, Schwinn, Skrzypek, Weinzierl

- 3/4-loop: numerical integration? Asymptotic expansions?
  ← convergence? CPU time? grids?

	FCC$_{ee}$	current th.	current par.
$H \to b\bar{b}$	0.8%	0.5%	2.2%
$H \to c\bar{c}$	1.4%	0.5%	5.5%
$H \to \tau^+\tau^-$	1.1%	0.5%	$< 0.1\%$
$H \to \mu^+\mu^-$	12%	0.5%	$< 0.1\%$
$H \to gg$	1.6%	3.2%	3.0%
$H \to \gamma\gamma$	3.0%	1.0%	$< 0.1\%$
$H \to Z\gamma$	???	5.0%	$< 0.1\%$
$H \to WW$	0.4%	0.5%	$< 0.1\%$
$H \to ZZ$	0.3%	0.5%	$< 0.1\%$

LHC

$gg \to H$ @ N^{3}LO (HTL):

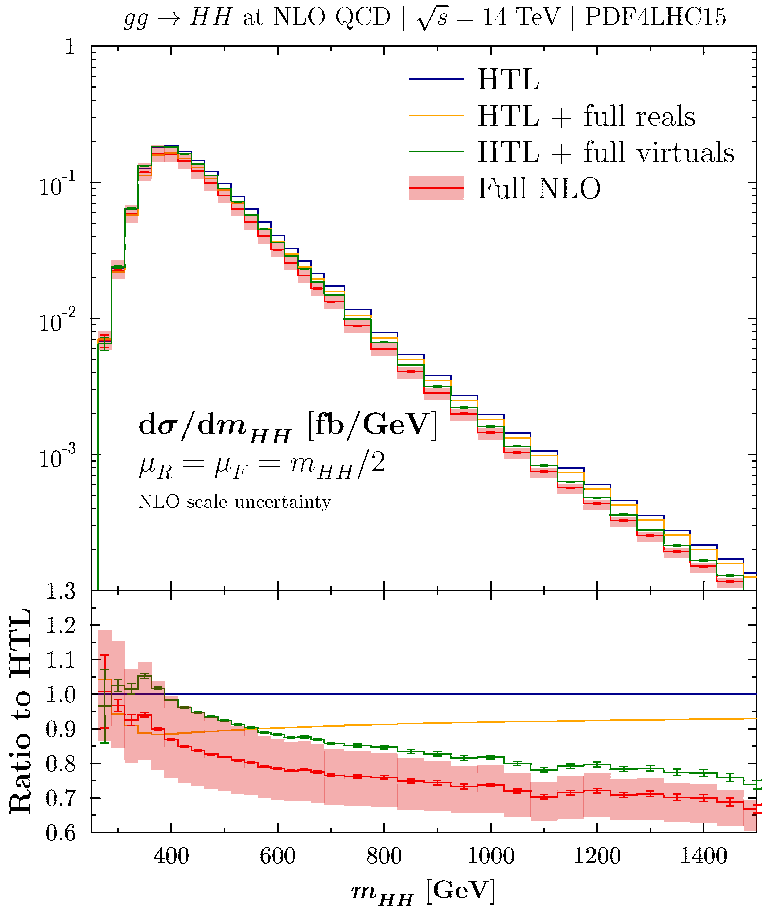


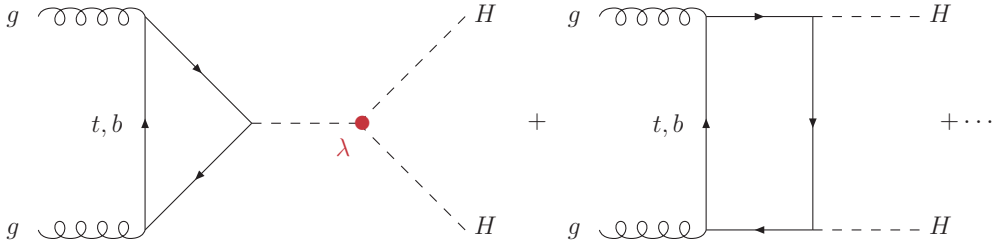
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger

$gg \to HH$: full NLO

14 TeV

$m_t = 172.5$ GeV





sensitive to trilinear Higgs coupling λ

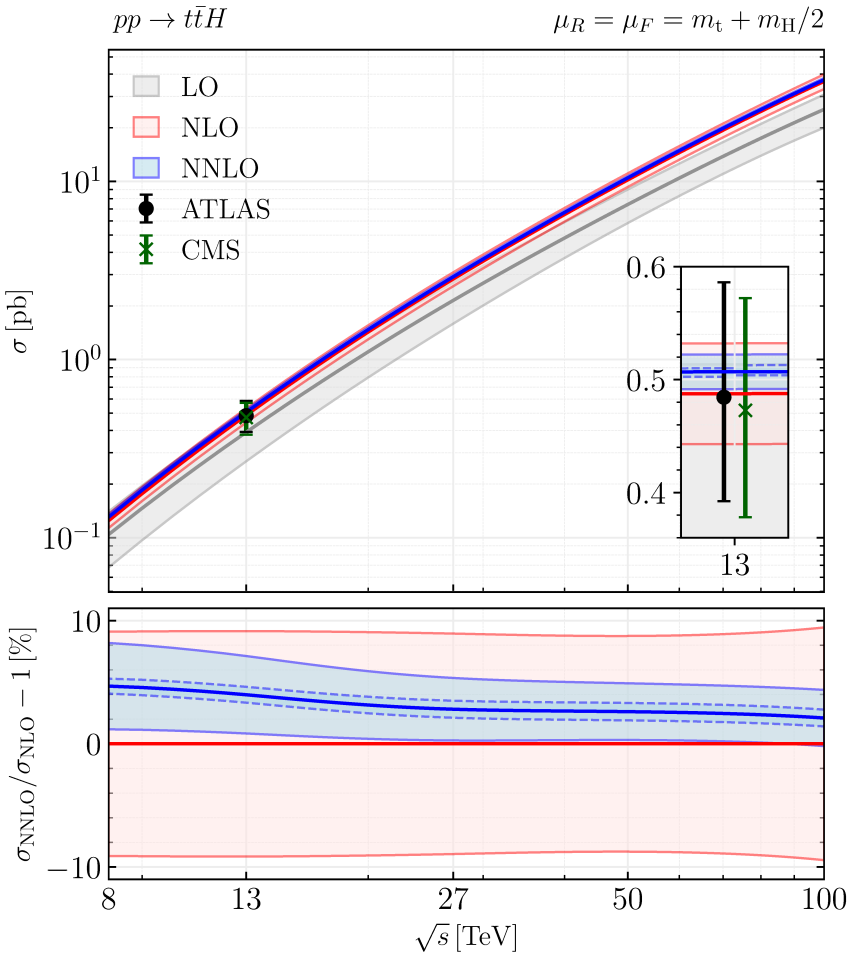
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher

$$\sigma_{NLO} = 32.81(7)^{+18\%}_{-31\%}\ fb \quad (-15\% \text{ mass effects @ NLO})$$

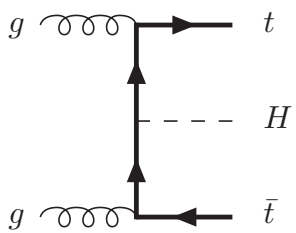
$$\to \sigma_{\text{NNLO FTapprox}} = 36.69^{+6\%}_{-23\%}\ fb \quad (\leftarrow \mu_{R/F},\ m_t \text{ scheme/scale})$$

- NNLO FTapprox: Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli

$pp \to t\bar{t}H$: approx. NNLO



$m_t = 173.3$ GeV

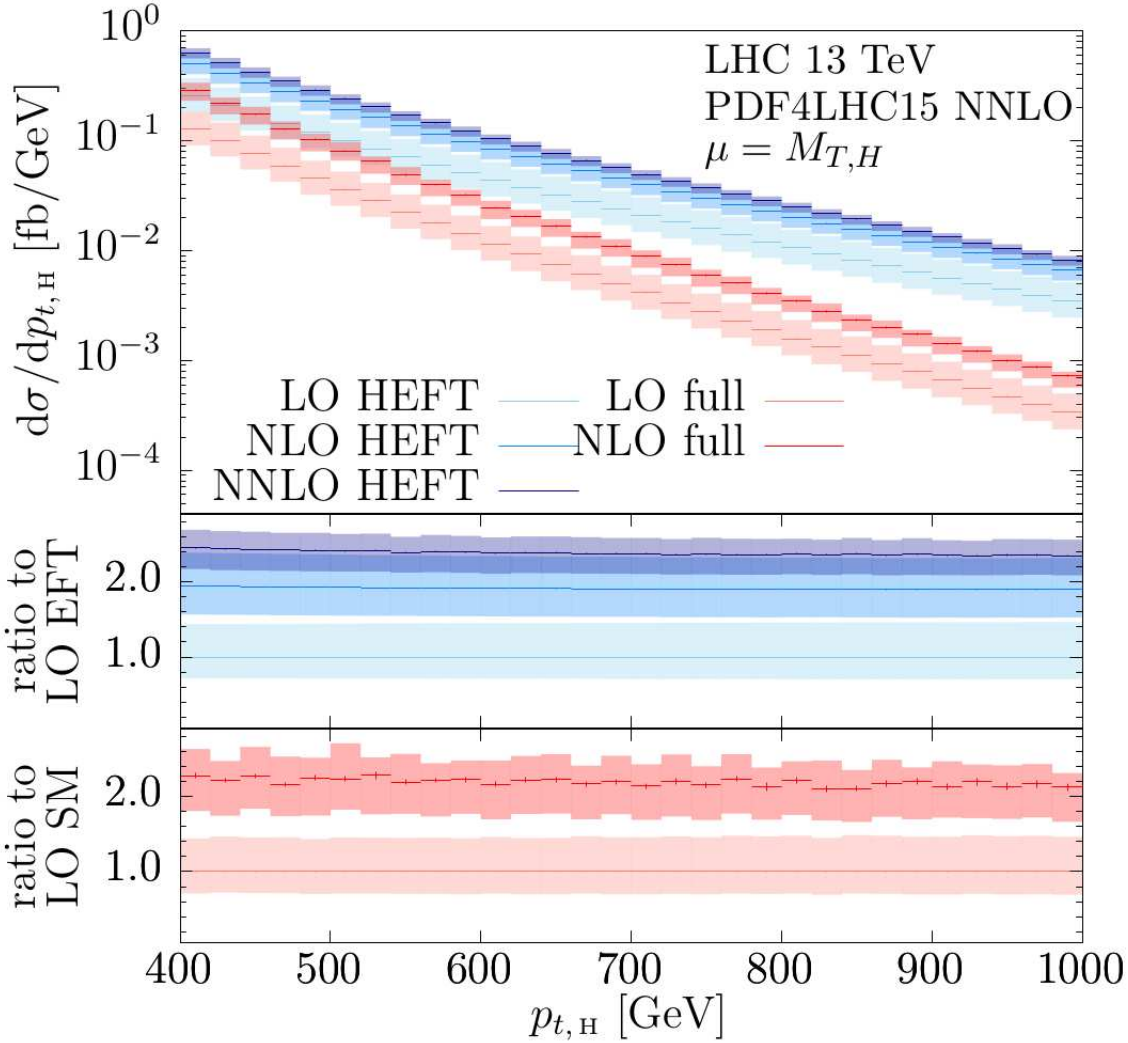


sensitive to top Yukawa coupling

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini

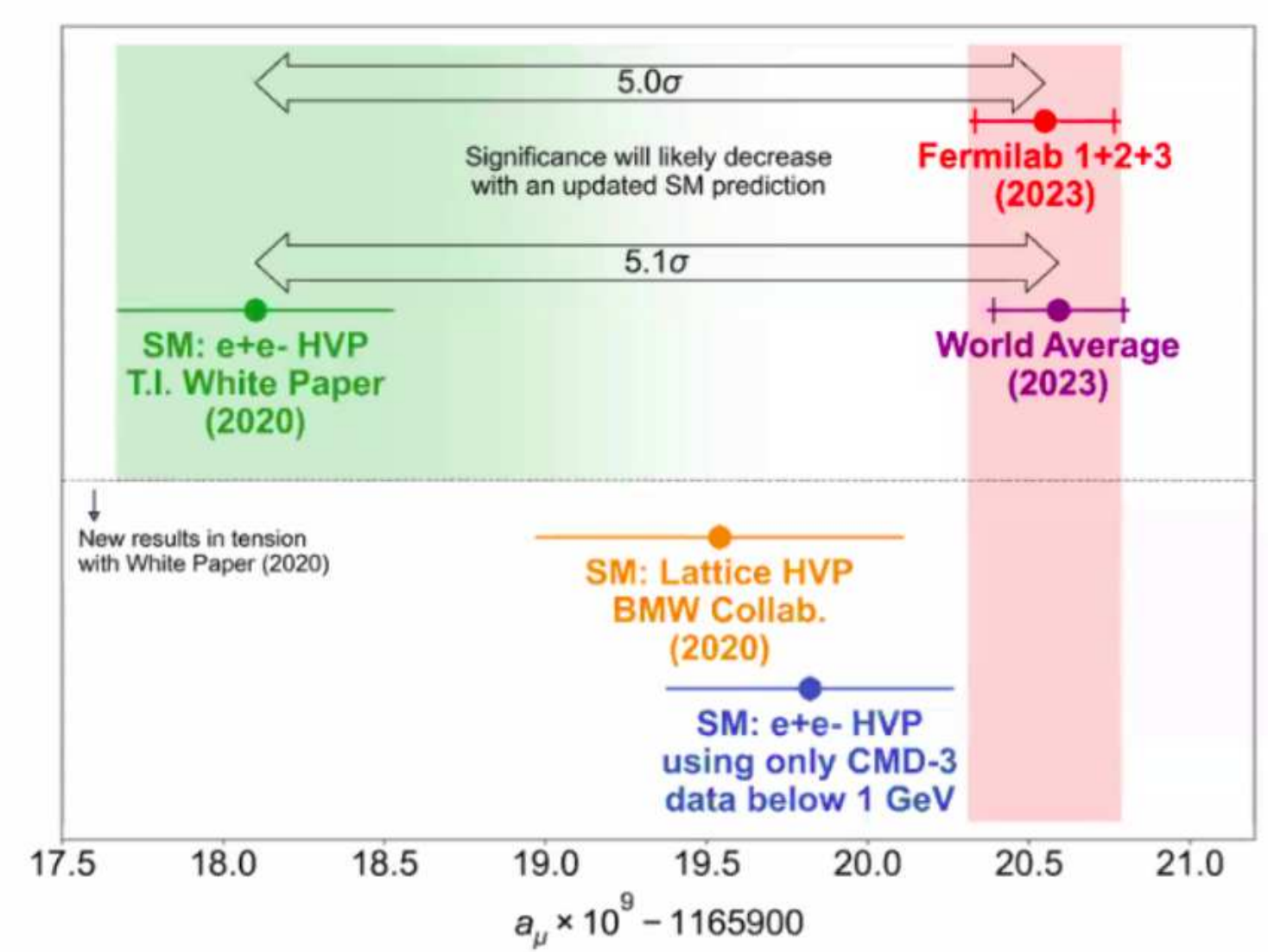
- 2-loop virtual corrections: soft Higgs approximation
  single + double real corrections: exact

large p_{TH} in $pp \to Hj$ [LHCHWG]

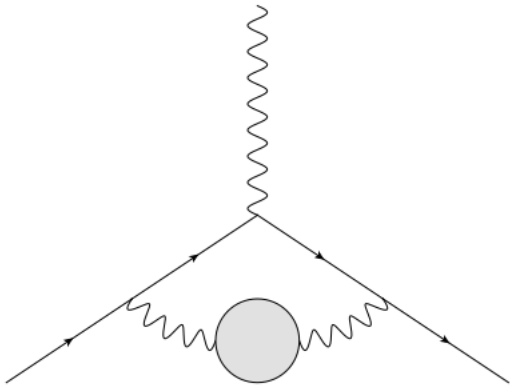


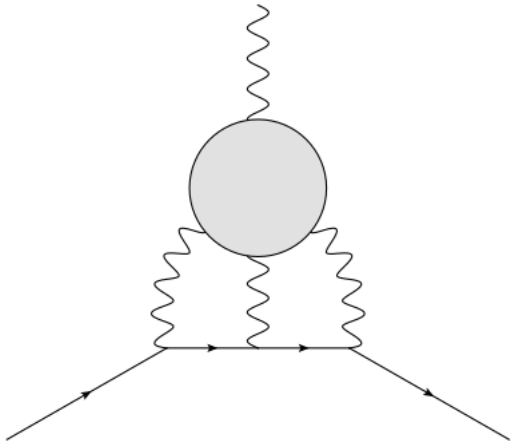
Becker, Caola, Massironi, Mistlberger, Monni, Chen, Frixione, Gehrmann, Glover, Hamilton, Huss, Jones, Karlberg, Kerner, Kudashkin, Lindert, Luisoni, Mangano, Pozzorini, Re, Salam, Vryonidou, Wever

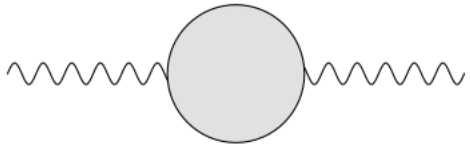
$(g-2)_\mu$: tension by 5 σ?



- dominant uncertainties from HVP and HLbL:



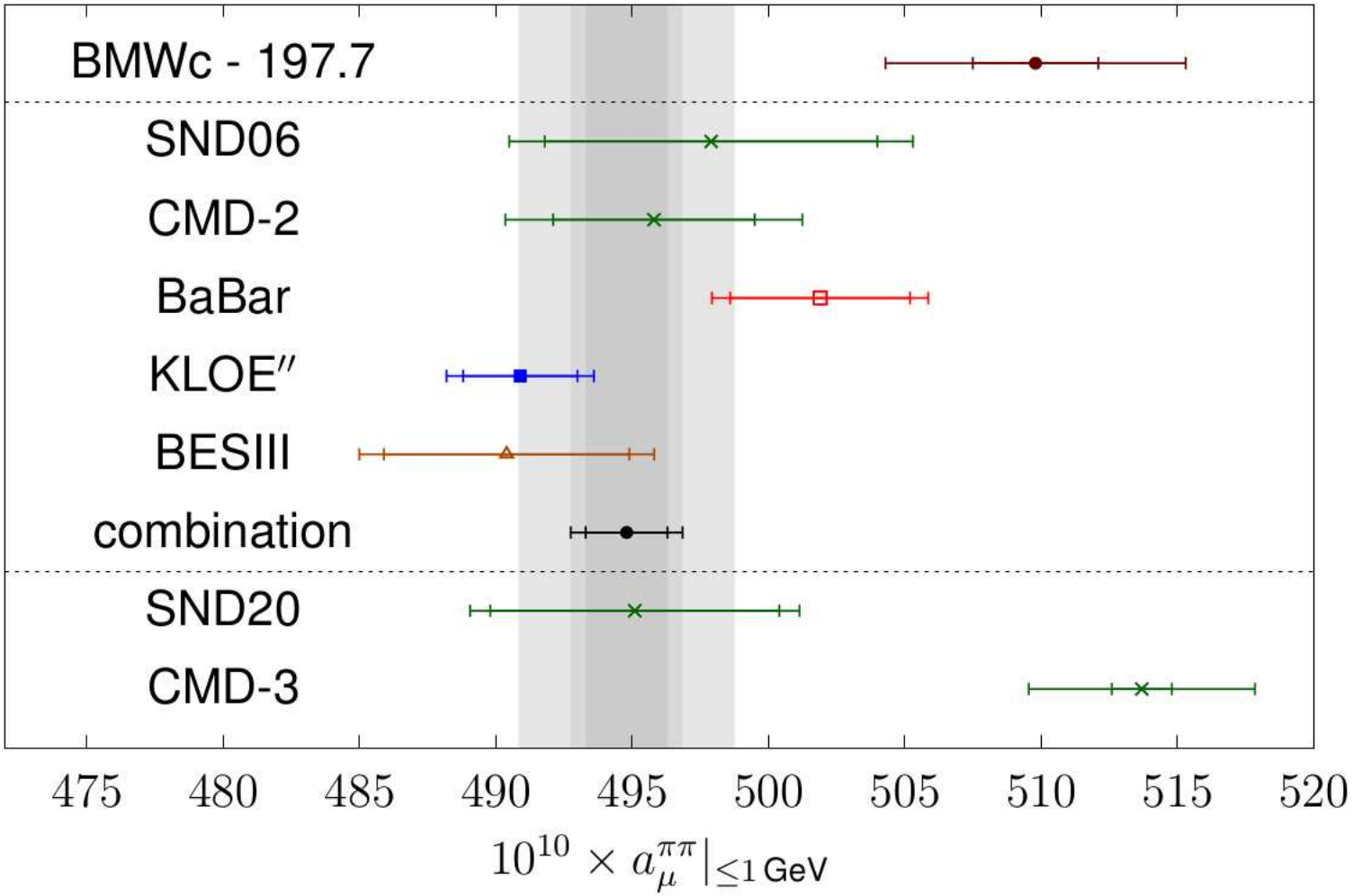


HVP:  $= i(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi(q^2)$

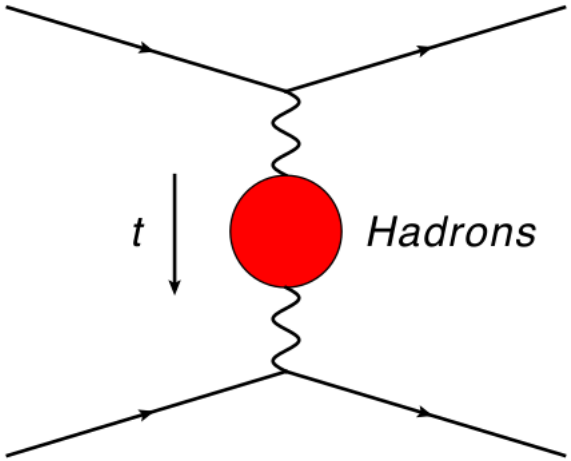
- optical theorem: $Im\Pi(s) = \dfrac{\sigma(e^+e^- \to hadrons)}{es}$

- HLbL: dispersive approach under development

Colangelo, Hoferichter, Procura, Stoffer


BMWc - 197.7
SND06
CMD-2
BaBar
KLOE″
BESIII
combination
SND20
CMD-3
475
480
485
490
495
500
505
510
515
520
$10^{10} \times a_\mu^{\pi\pi}|_{\leq 1\,\mathrm{GeV}}$

- alternative method: MuonE experiment $\mu e \to \mu e$



- anticipated precision: 10^{-5} $\to$ NN(N)LO QED + elw.

- programs: `McMule`, `Mesmer`

  ↑ Signer group @ PSI

- `McMule`: $\ell e \to \ell e$; $\ell p \to \ell p$; $\mu \to e\gamma, eee$; Bhabha/Møller scattering @ (N)NLO QED

- $\mu \to e\gamma, eee$: SMEFT (dim 6,8,. . .) $\to$ LEFT (W, Z, H, t int. out)

  UZH, PSI

- LEFT matching/running; 1-loop known, ongoing work @ 2 loops

  UZH, PSI
  Stoffer, Signer,. . .

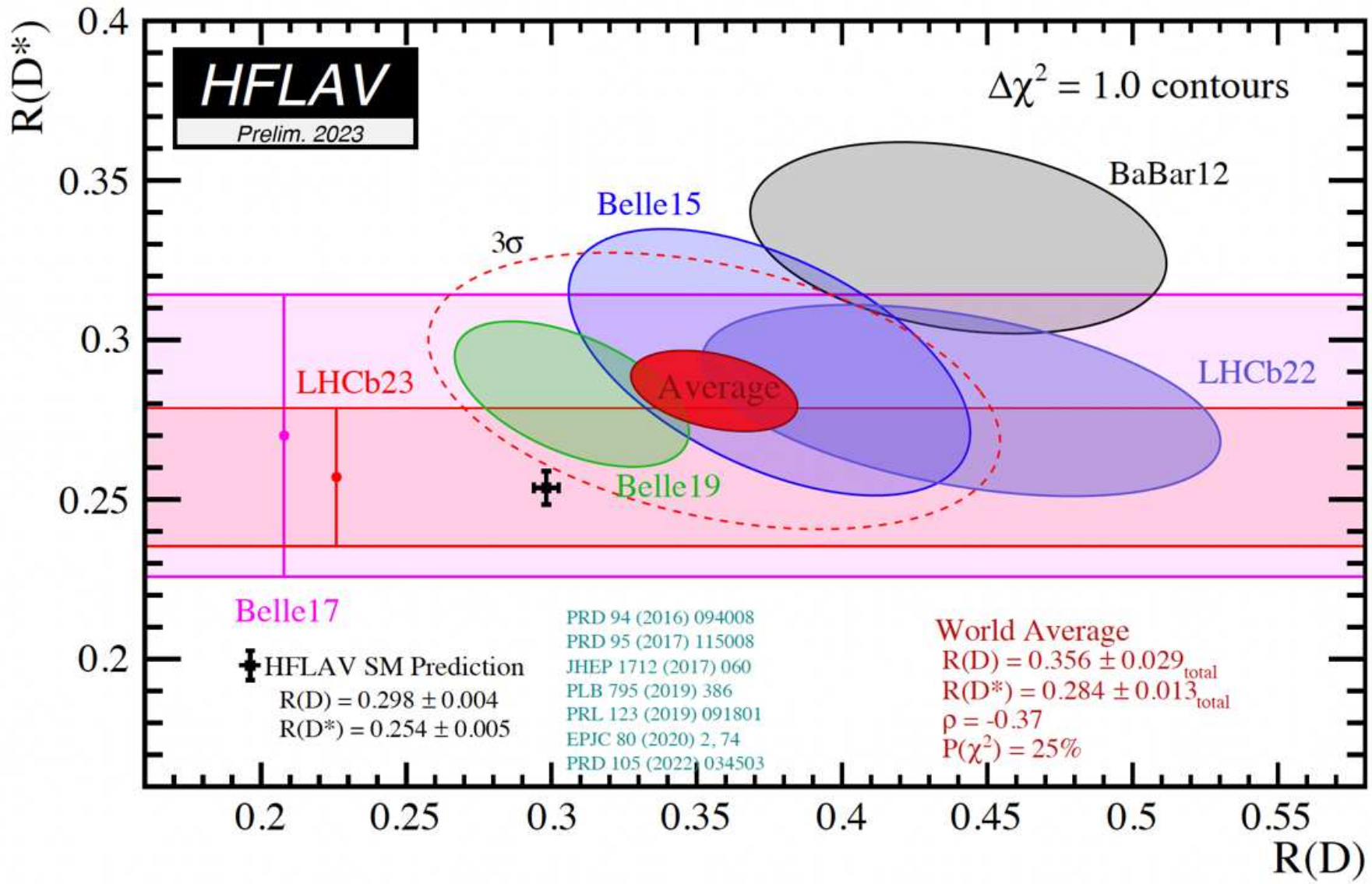
- HEFT: non-linear extension of SM (strong interactions, compositeness) $\to$ conceptual work

  Geneva, Lausanne, UZH

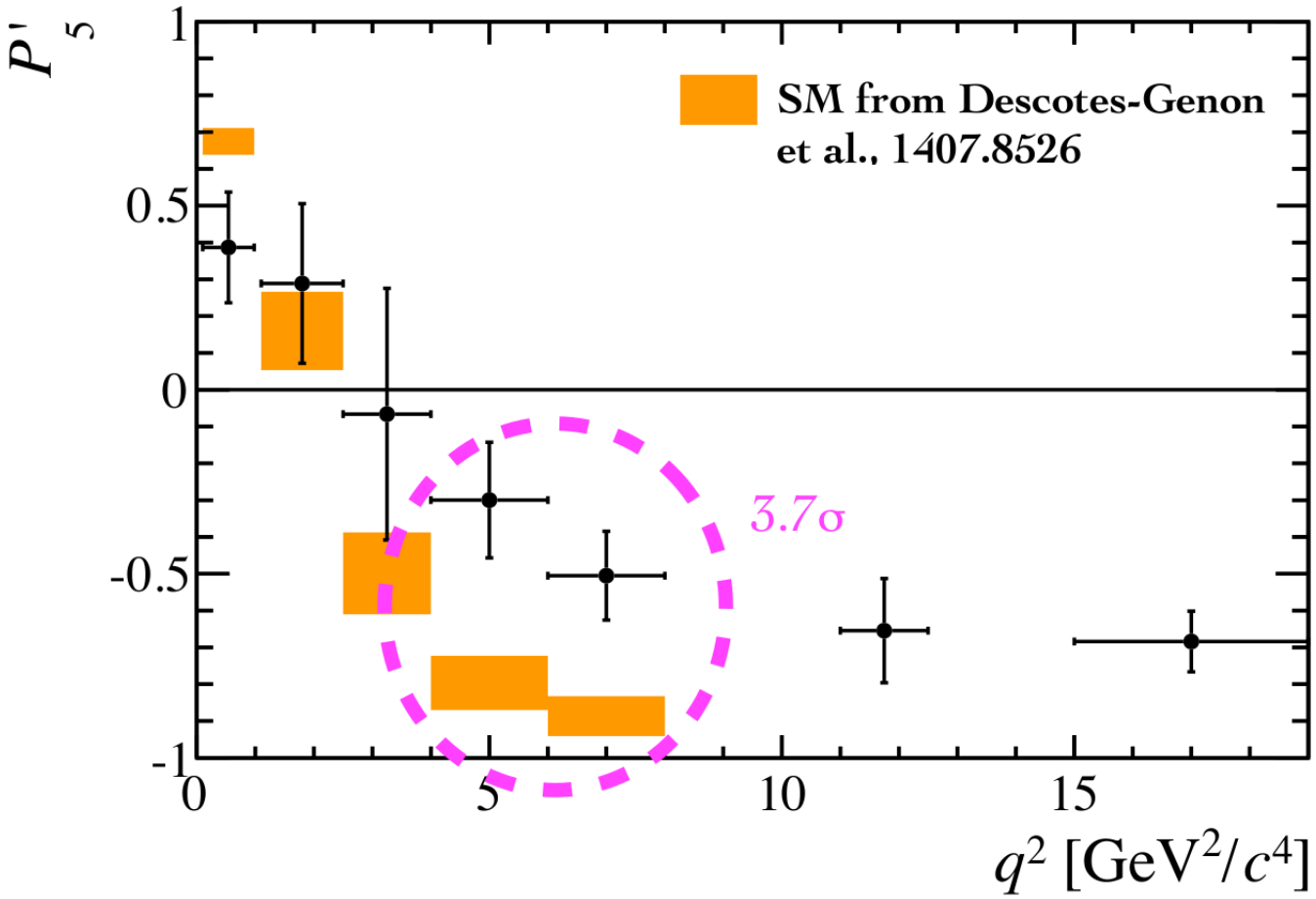
- SMEFT @ LHC: RG-evolution, single and double Higgs-boson production

  ETH, Geneva, UZH, PSI

B anomalies


HFLAV
Prelim. 2023
$\Delta\chi^2 = 1.0$ contours
BaBar12
Belle15
3σ
LHCb23
Average
LHCb22
Belle19
Belle17
HFLAV SM Prediction
R(D) = 0.298 ± 0.004
R(D*) = 0.254 ± 0.005
PRD 94 (2016) 094008
PRD 95 (2017) 115008
JHEP 1712 (2017) 060
PLB 795 (2019) 386
PRL 123 (2019) 091801
EPJC 80 (2020) 2, 74
PRD 105 (2022) 034503
World Average
R(D) = 0.356 ± 0.029 total
R(D*) = 0.284 ± 0.013 total
ρ = -0.37
P(χ²) = 25%
R(D*)
R(D)
0.4
0.35
0.3
0.25
0.2
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55

[LHCb-CONF-2015-002]



- $P'_5, R(D^{(*)})$ anomalies at the 2-3 σ level $\rightarrow$ BSM? Leptoquarks,...?

IV *SUMMARY*

- elw/QCD corrections extremely important at low and high energies

- a lot of precision calculations for the LHC inside Switzerland

- demands by FCC: beyond present state of the art
  $\Rightarrow$ new techniques (numerical, approx., analytical???)
  many improvements needed $\rightarrow$ 30 years (?)

- low energy: progress for $(g-2)_\mu$ and μ scattering expected (dispersive approach, lattice, precision QED)

- a lot of progress on the TH side all over Switzerland

- apologies for not covering pillars 2 and 3

BACKUP SLIDES