Theory demand for future high energy colliders

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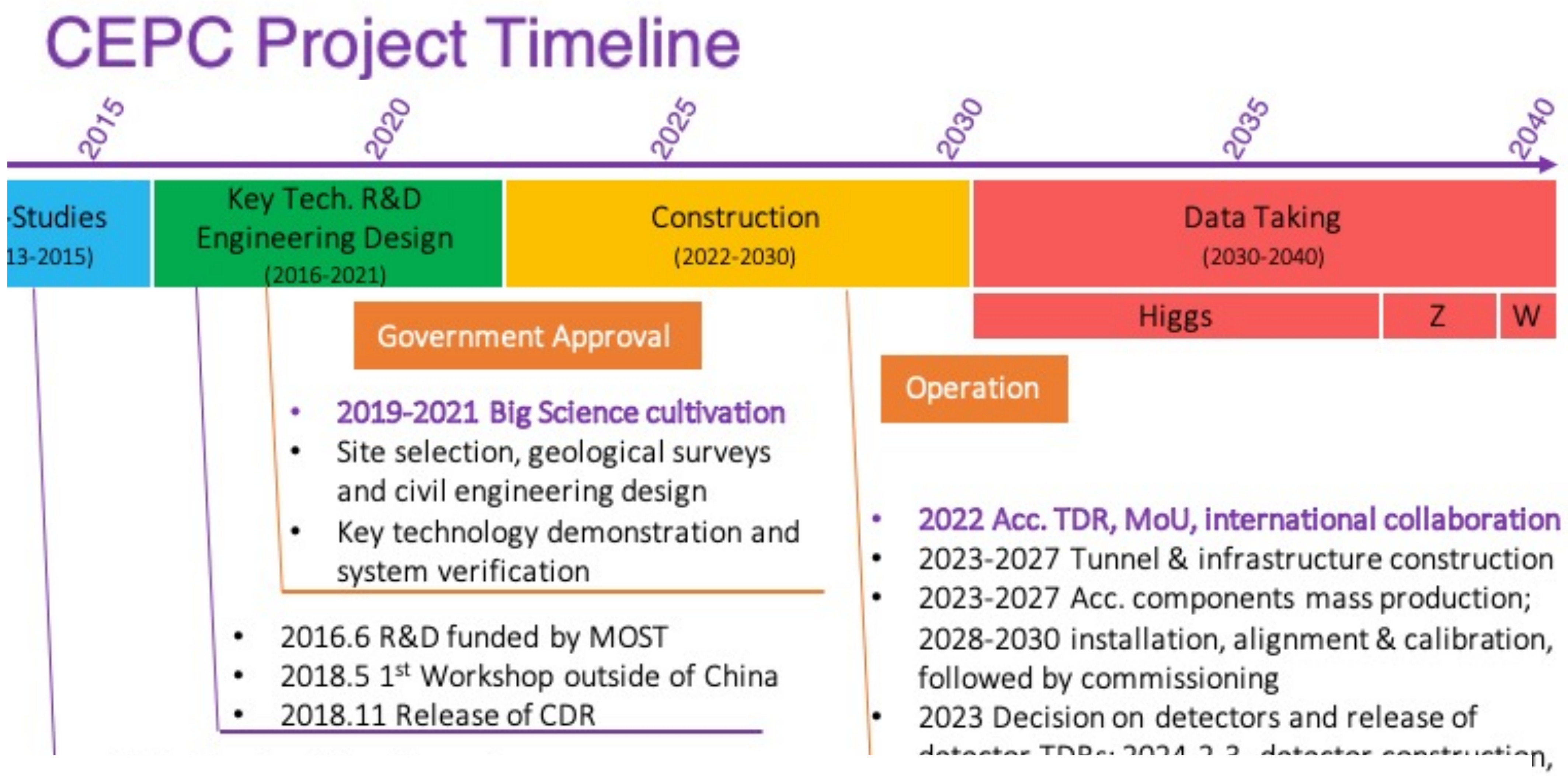
Future high-energy Lepton Colliders

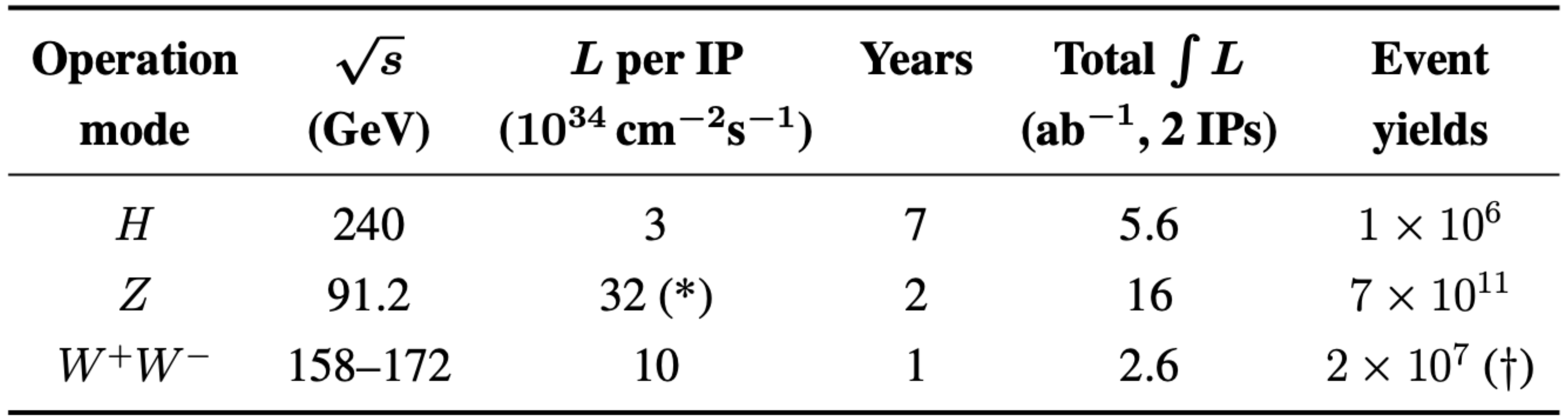
- CEPC provide us with great opportunity revealing physics beyond the standard model; future electron-positron collider has also been selected as the highest priority of CERN after high luminosity run of LHC


CEPC Project Timeline

- **2019-2021 Big Science cultivation**
- Site selection, geological surveys and civil engineering design
- Key technology demonstration and system verification

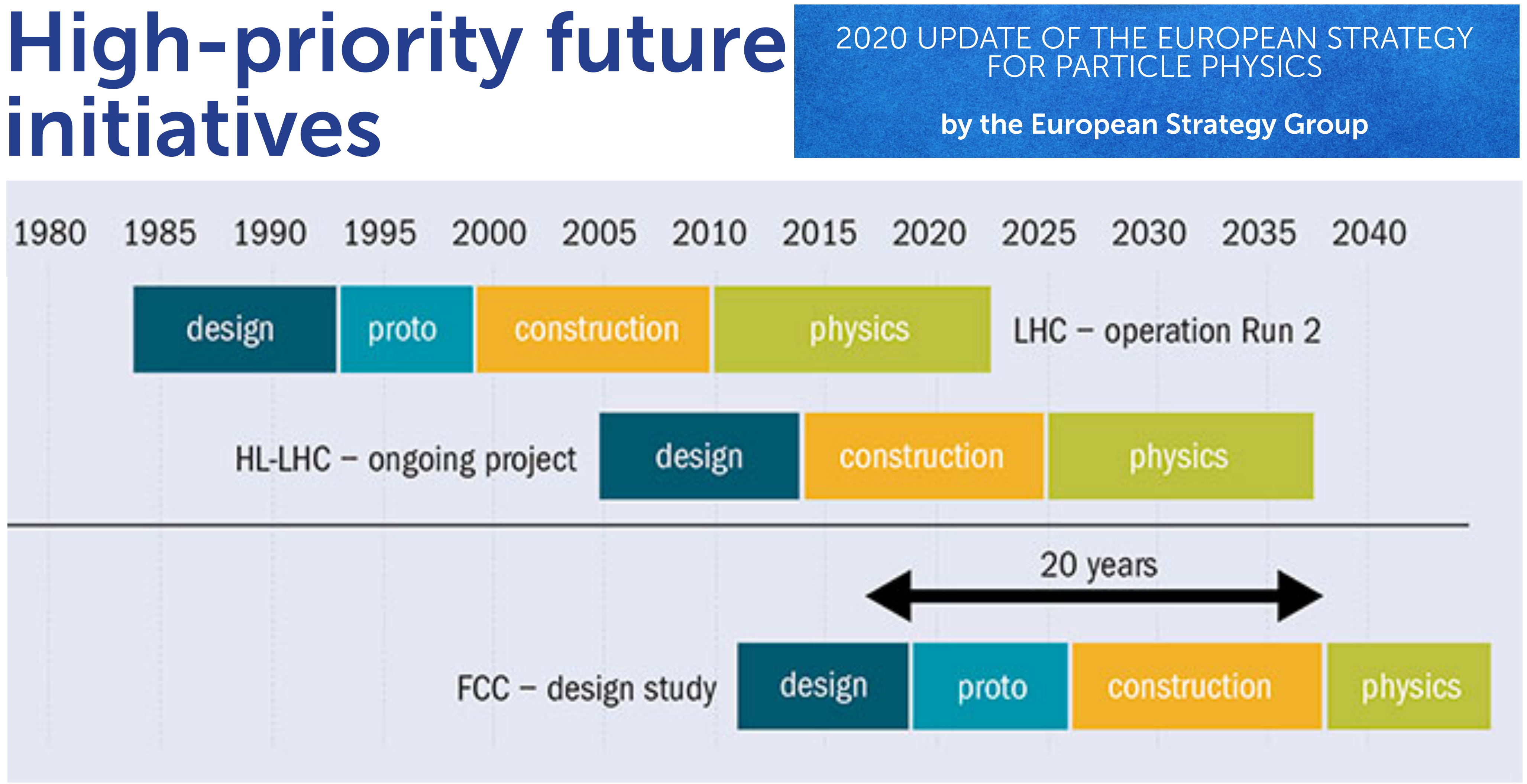
- 2016.6 R&D funded by MOST
- 2018.5 1st Workshop outside of China
- 2018.11 Release of CDR

- **2022 Acc. TDR, MoU, international collaboration**
- 2023-2027 Tunnel & infrastructure construction
- 2023-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
- 2023 Decision on detectors and release of

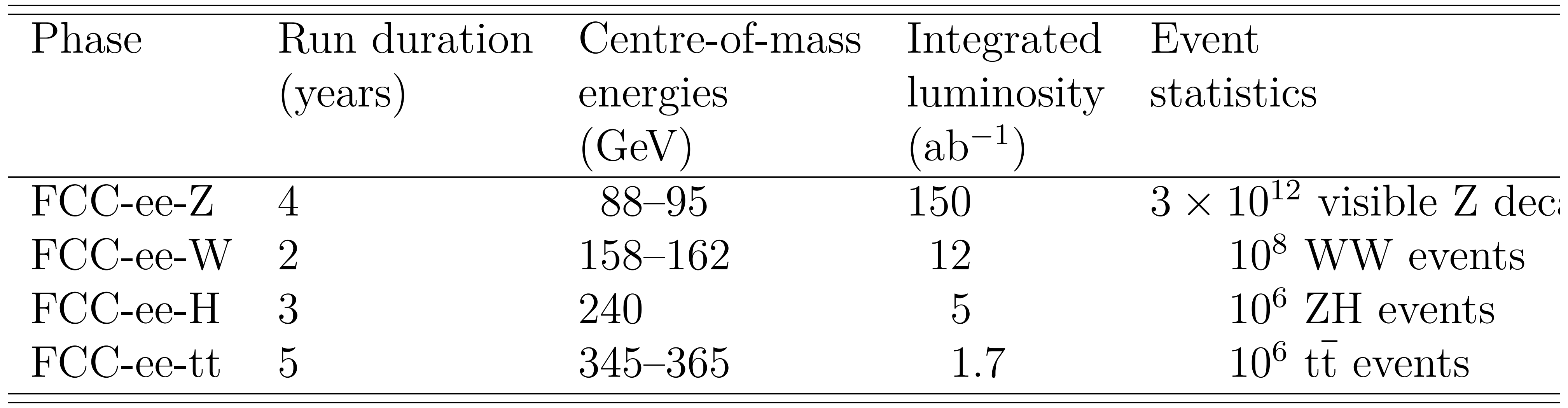


Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

[http://cepc.ihep.ac.cn]


High-priority future initiatives

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS
by the European Strategy Group

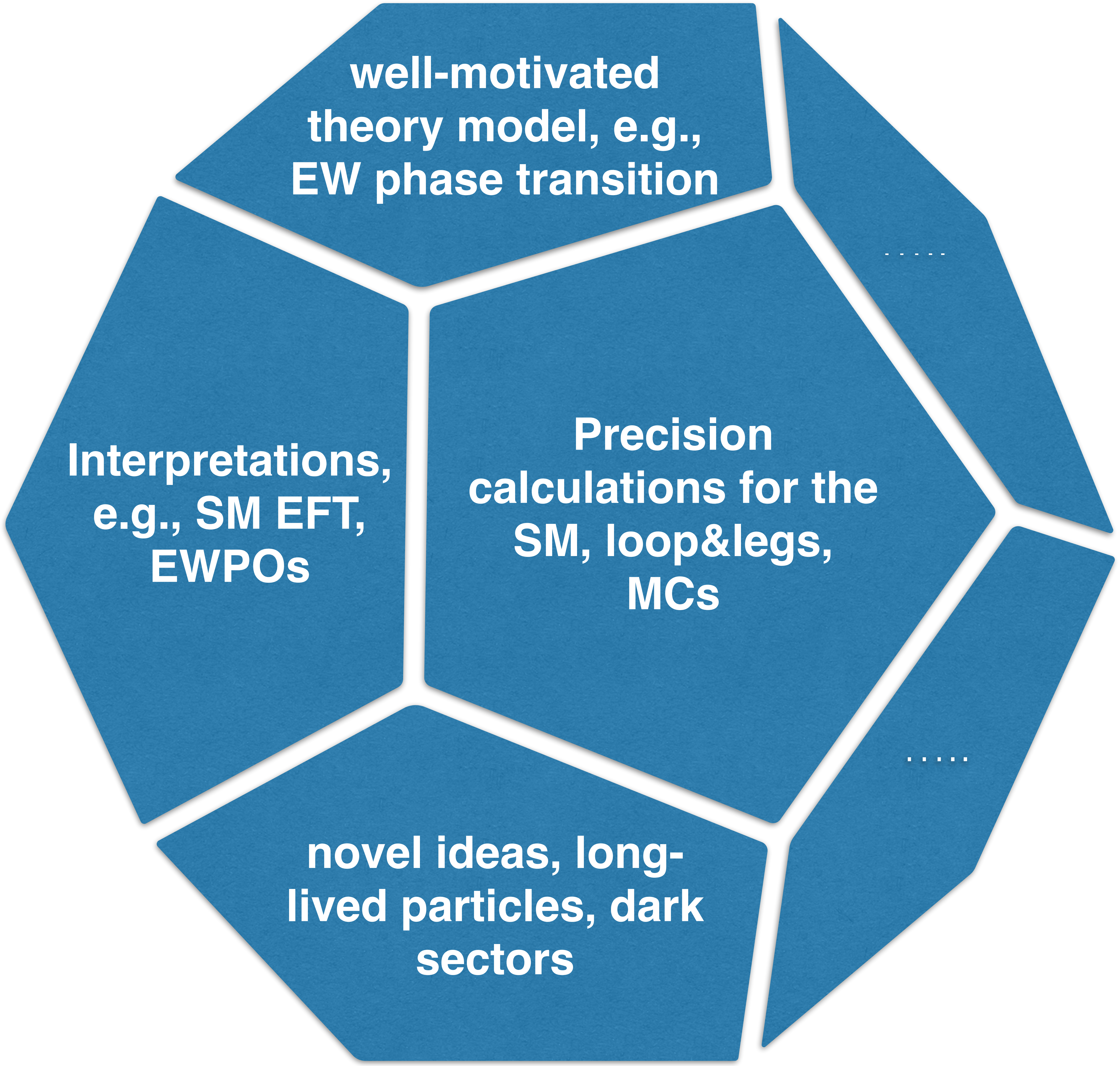


Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z dec
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345–365	1.7	10^6 $\mathrm{t\bar{t}}$ events

[http://fcc-cdr.web.cern.ch]

Theory requirements

- The huge advance in projected experimental precision naturally leads to requirement on developments of various theory components including control of theory uncertainties to similar level or well below



well-motivated theory model, e.g., EW phase transition

.....

Interpretations, e.g., SM EFT, EWPOs

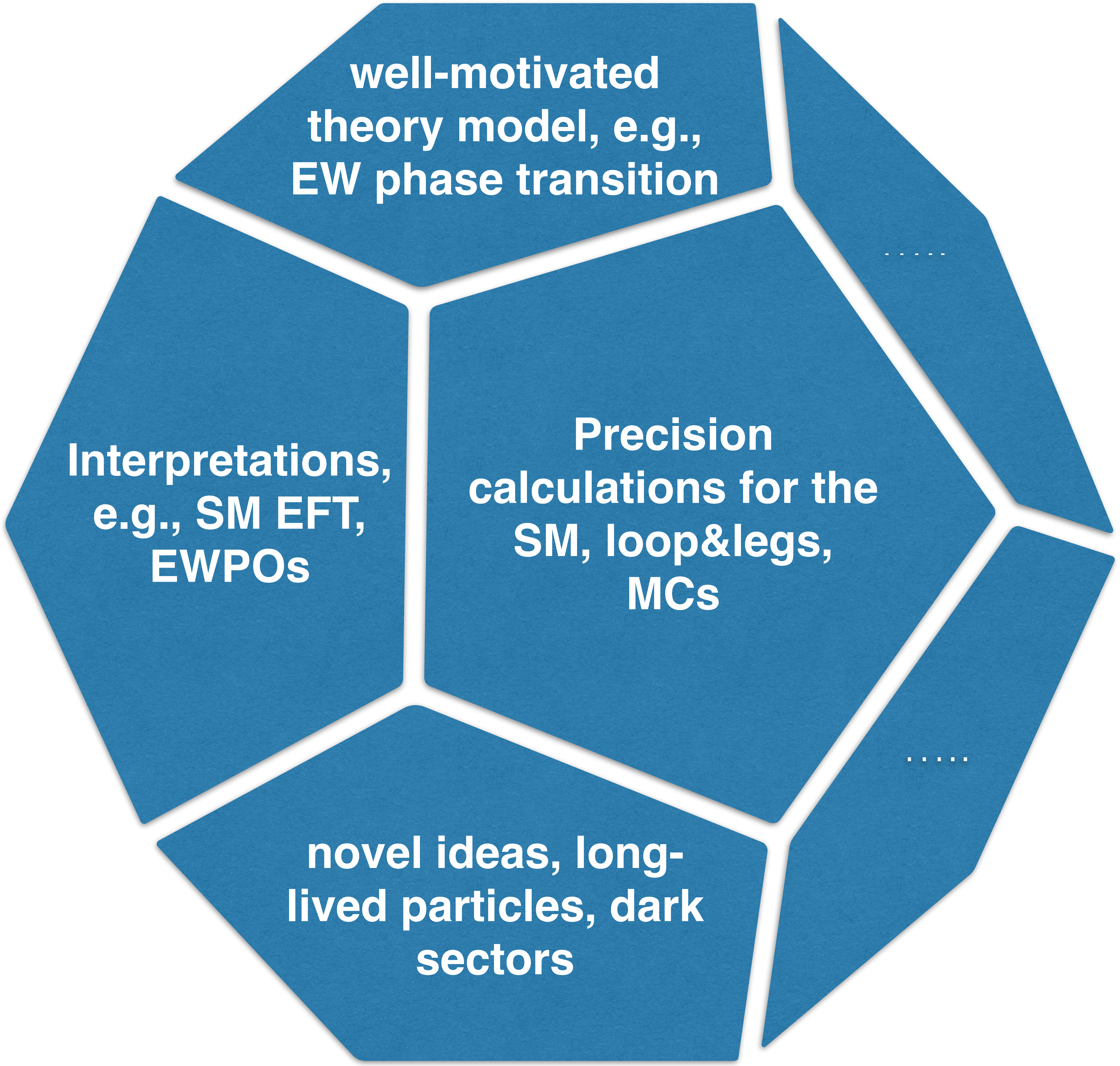
Precision calculations for the SM, loop&legs, MCs

.....

novel ideas, long-lived particles, dark sectors

Theory requirements

- The huge advance in projected experimental precision naturally leads to requirement on developments of various theory components including control of theory uncertainties to similar level or well below



- **Claims:**

1. only focus on precision calculations
2. unelaborated review on problems and challenges
3. apologize if missing your works

- **References:**

1. Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders [1901.02648]

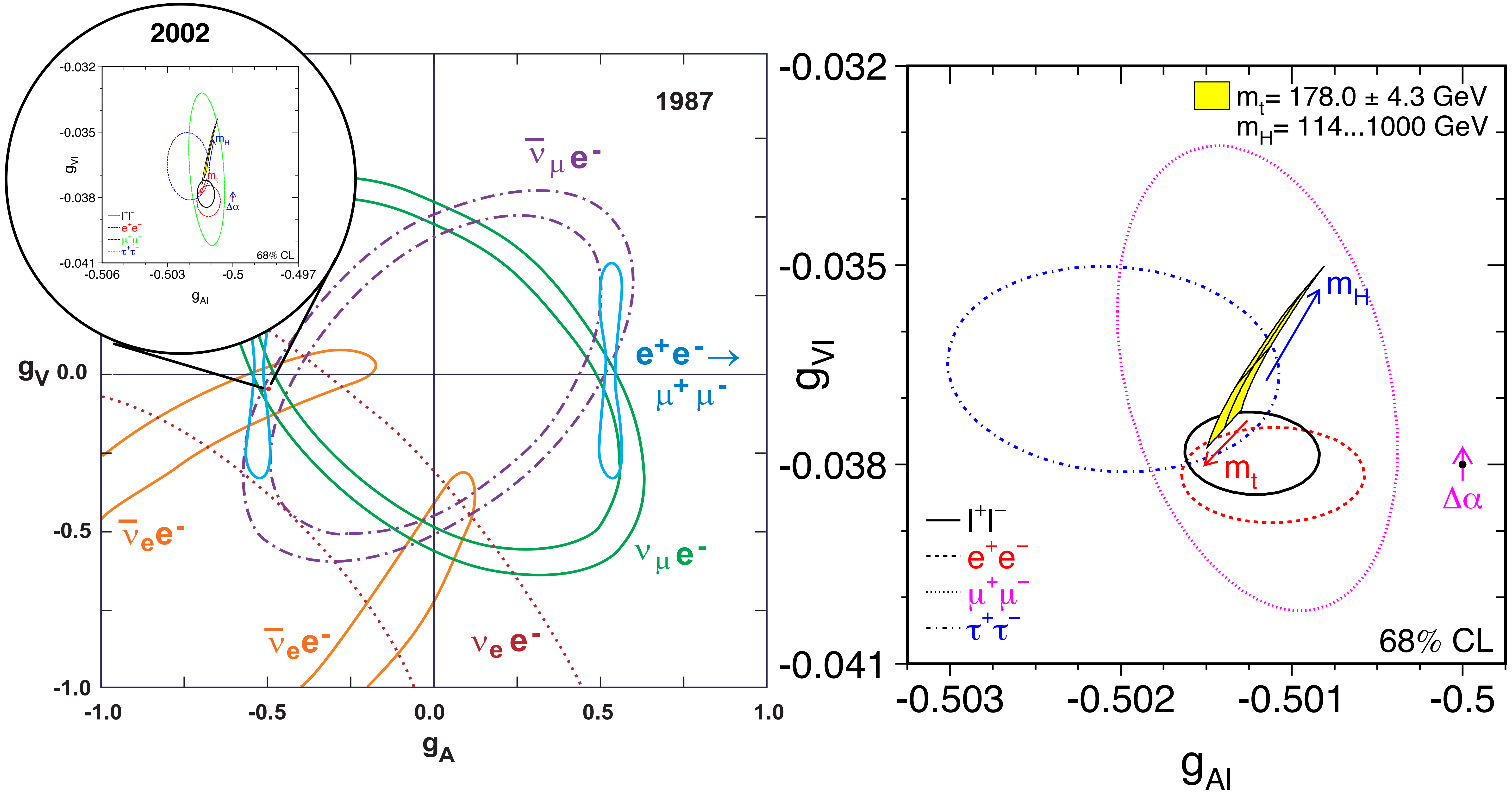
2. QED challenges at FCC-ee precision measurements [1903.09895]

3. Theoretical uncertainties for electroweak and Higgs-boson precision measurements at FCC-ee [1906.05379]

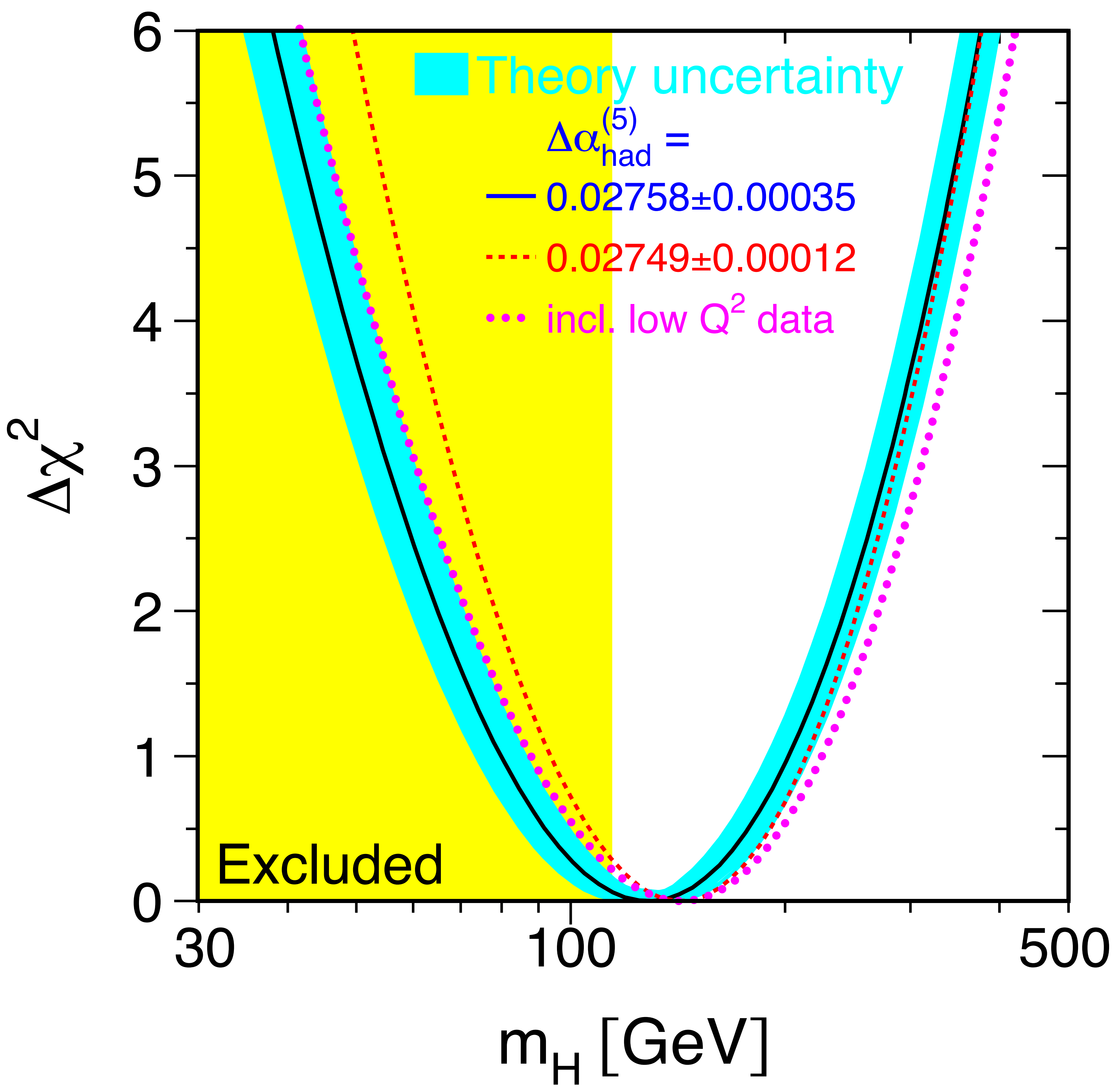
Lessons from LEP and SLC

- Measuring Z boson parameters with highest precision: mass, partial and total widths, and couplings to fermions, leading to crucial test of SM including quantum loop corrections and prediction on mass of the Higgs boson

[LEP&SLC, hep-ex/0509008]



effective couplings of charged leptons, gV vs. gA

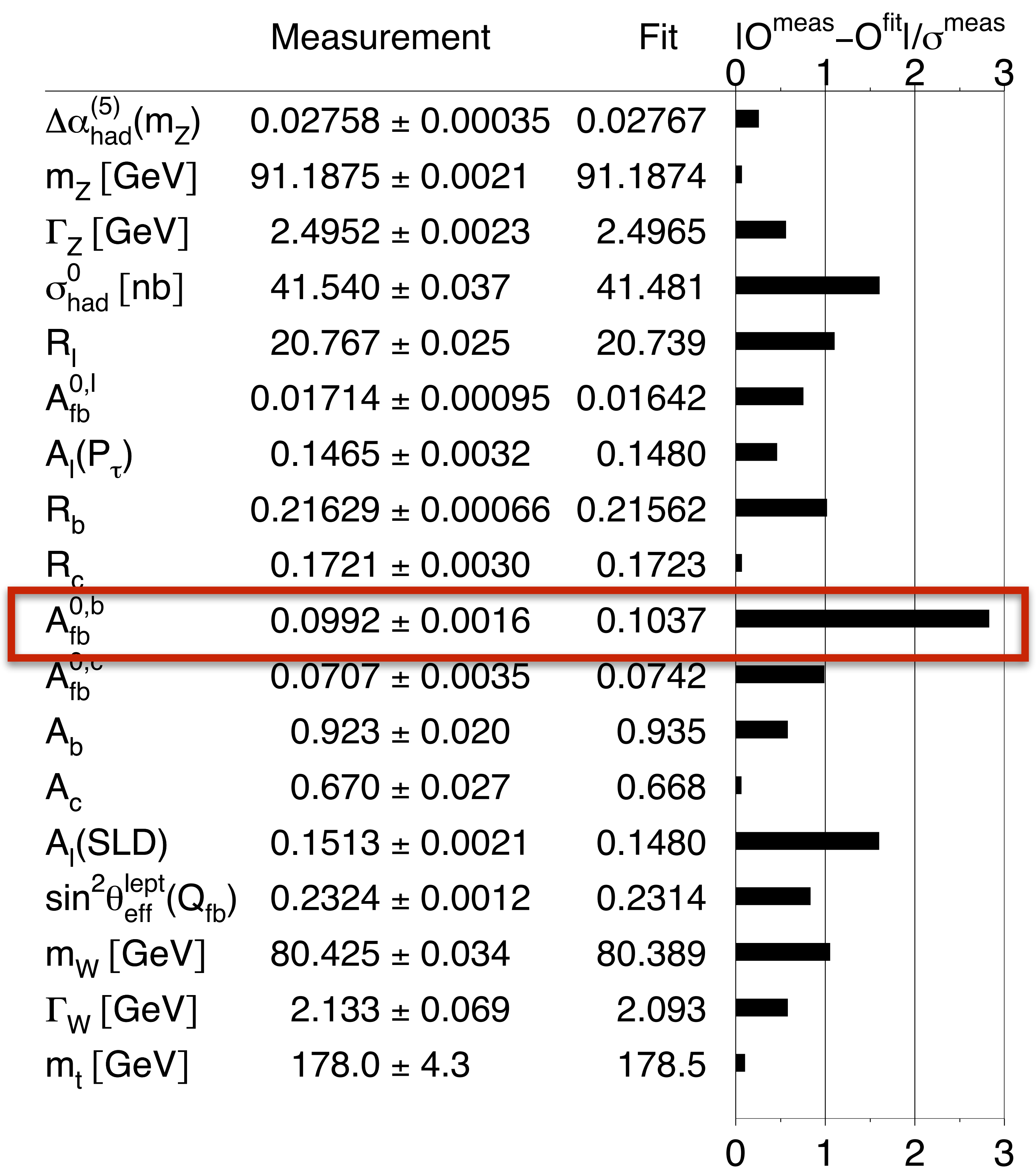


Higgs boson mass from a EW global fit

Lessons from LEP and SLC

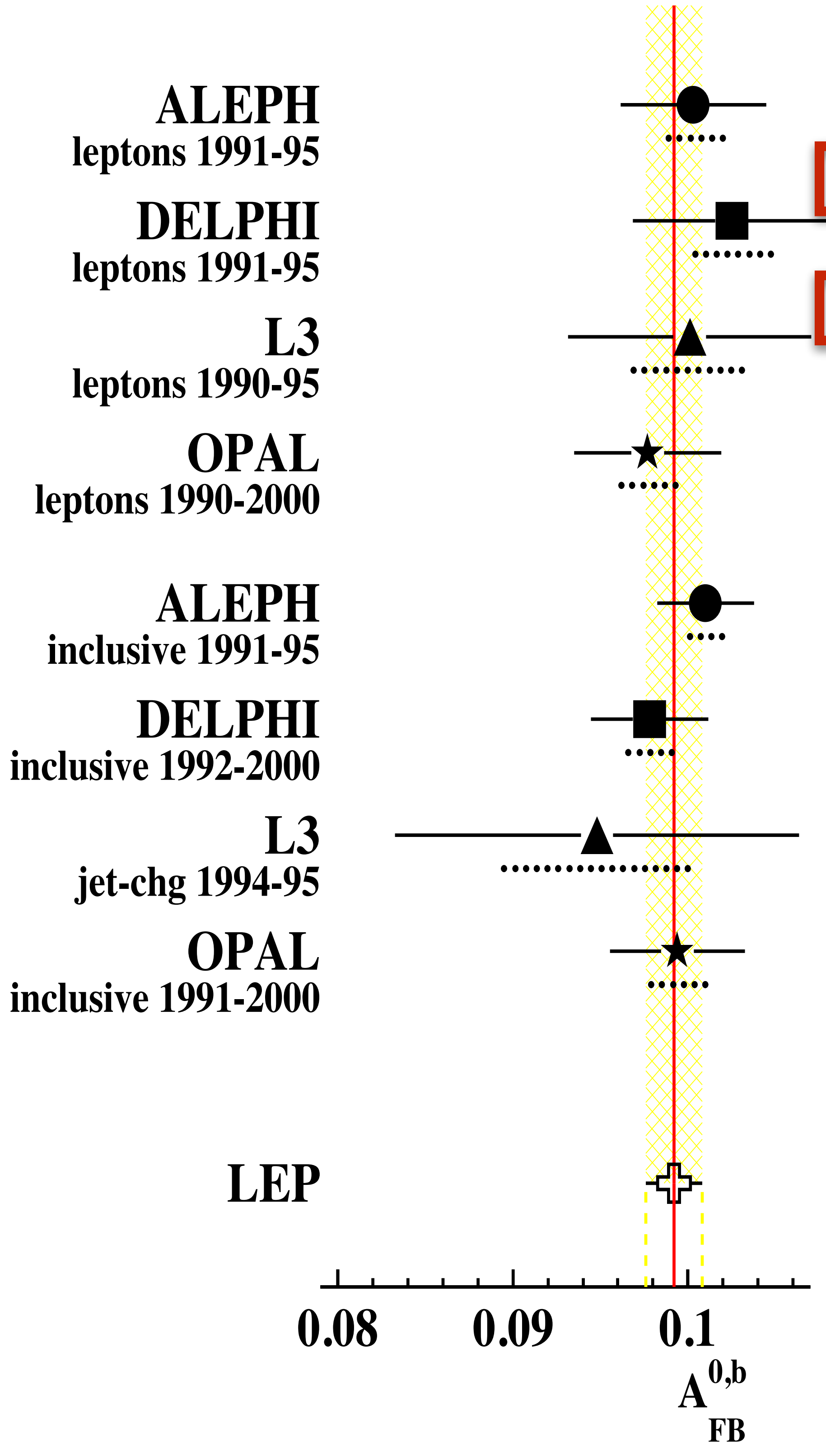
- Discrepancy on forward-backward asymmetry in bottom quark pair production at Z-pole, ~2.8σ, remains an open question; theory uncertainty from QCD modeling dominates in systematics

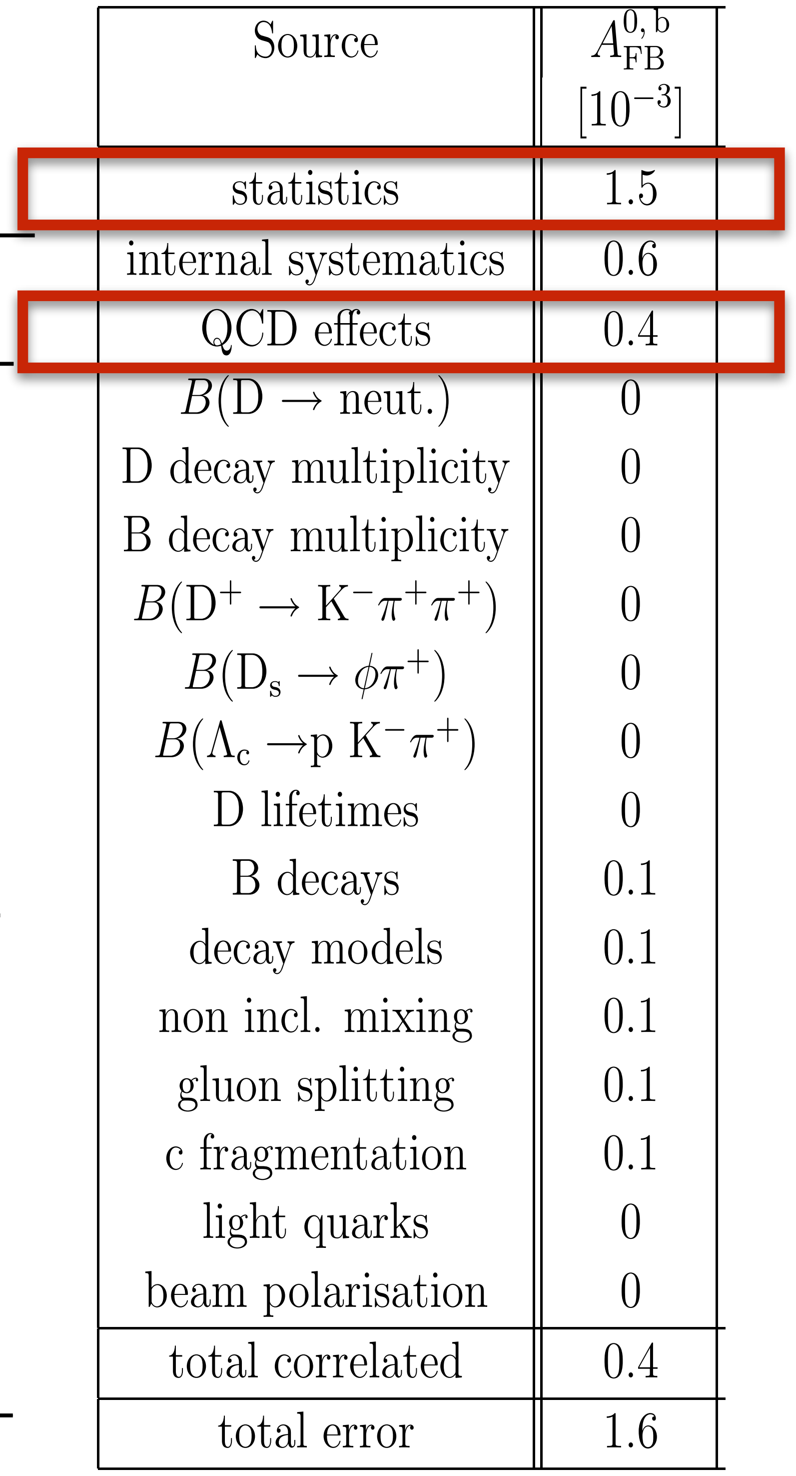
pulls in the EW global fit



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

error decomposition





Source	$A_{FB}^{0,b}$ [10^{-3}]
statistics	1.5
internal systematics	0.6
QCD effects	0.4
$B(D \to \text{neut.})$	0
D decay multiplicity	0
B decay multiplicity	0
$B(D^+ \to K^-\pi^+\pi^+)$	0
$B(D_s \to \phi\pi^+)$	0
$B(\Lambda_c \to p\, K^-\pi^+)$	0
D lifetimes	0
B decays	0.1
decay models	0.1
non incl. mixing	0.1
gluon splitting	0.1
c fragmentation	0.1
light quarks	0
beam polarisation	0
total correlated	0.4
total error	1.6

[Bernreuther, Chen+, 1611.07942]

bottom mass effects at NNLO
2.8σ ->2.6σ

[Wang+, 2003.13941]

PMC scale choice + NNLO
2.8σ ->2.1σ

[d'Enterria+, 1806.00141]

QCD MC unc. revisited
no significant changes

Lessons from LEP and SLC

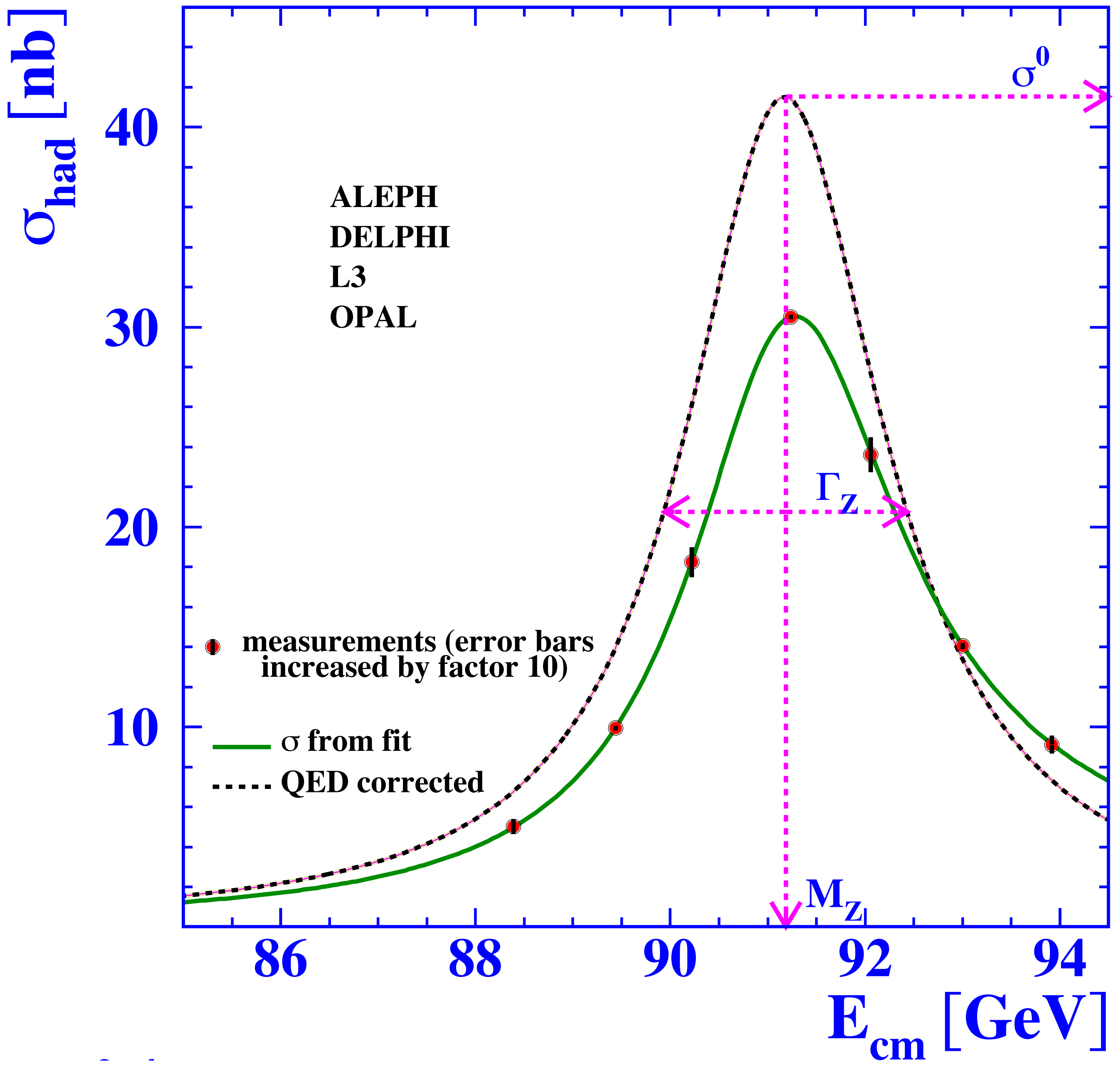
- The full two-loop QED corrections (from ISR of a s-channel process) has been revisited in a recent study; due to a discrepancy found wrt earlier results, a direct consequence on Z boson lineshape

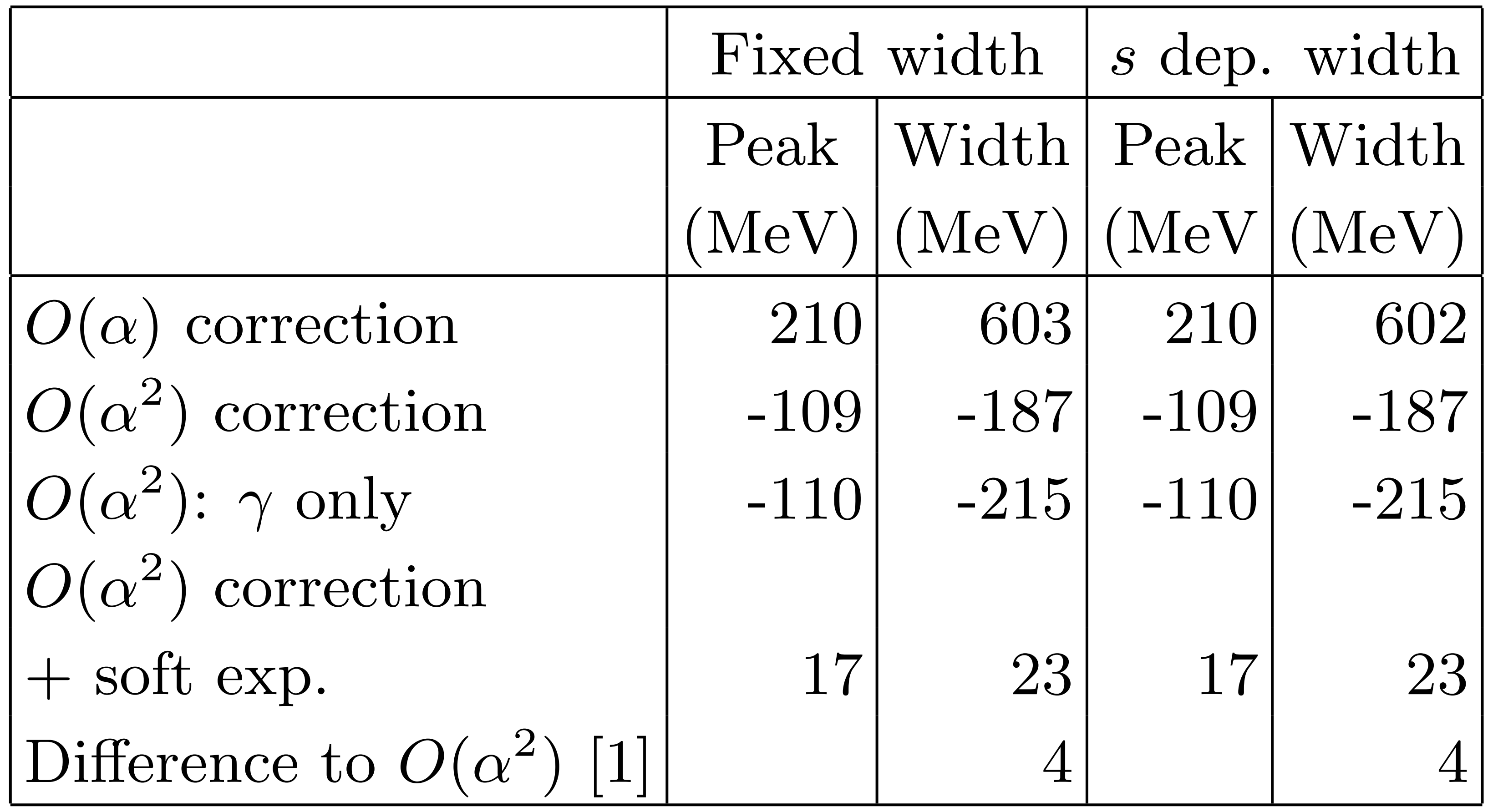
$$\frac{d\sigma_{e^+e^-}}{ds'} = \frac{1}{s}\sigma_{e^+e^-}(s')H\left(z,\alpha,\frac{s}{m^2}\right)$$

$$H\left(z,\alpha,\frac{s}{m^2}\right) = \delta(1-z) + \sum_{k=1}^{\infty}\left(\frac{\alpha}{4\pi}\right)^k C_k\left(z,\frac{s}{m^2}\right)$$

$$C_k\left(z,\frac{s}{m^2}\right) = \sum_{l=0}^{k}\ln^{k-l}\left(\frac{s}{m^2}\right)c_{k,l}(z),$$

claimed shift of 4 MeV for measured Z width at LEP (exp. precision ~ 2.3 MeV)





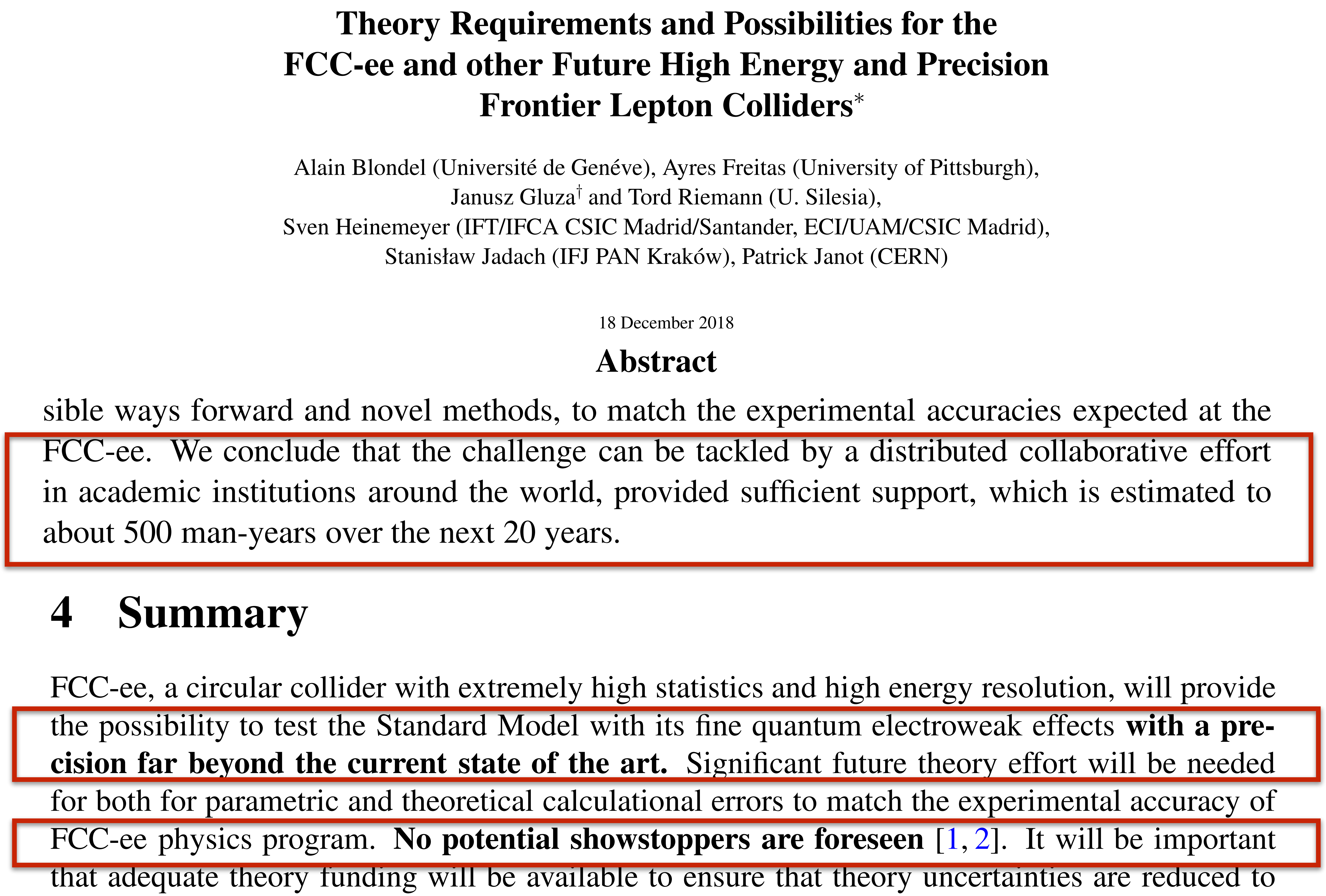
	Fixed width		s dep. width	
	Peak (MeV)	Width (MeV)	Peak (MeV	Width (MeV)
$O(\alpha)$ correction	210	603	210	602
$O(\alpha^2)$ correction	-109	-187	-109	-187
$O(\alpha^2)$: γ only	-110	-215	-110	-215
$O(\alpha^2)$ correction + soft exp.	17	23	17	23
Difference to $O(\alpha^2)$ [1]		4		4

TABLE I. Shifts in the Z-mass and the width due to the different contributions to the ISR QED radiative corrections for a fixed width of $\Gamma_Z = 2.4952$ GeV and s-dependent width using $M_Z = 91.1876$ GeV [15] and $s_0 = 4m_\tau^2$, cf. [2].

[Blumlein+, 1910.05759]

Challenge on theory precision

- The huge advance in projected experimental precision naturally leads to concerns on whether the theory uncertainties can match up or even controlled well below the precision goal



Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders[*]

Alain Blondel (Université de Genéve), Ayres Freitas (University of Pittsburgh),
Janusz Gluza[†] and Tord Riemann (U. Silesia),
Sven Heinemeyer (IFT/IFCA CSIC Madrid/Santander, ECI/UAM/CSIC Madrid),
Stanisław Jadach (IFJ PAN Kraków), Patrick Janot (CERN)

18 December 2018

Abstract

sible ways forward and novel methods, to match the experimental accuracies expected at the FCC-ee. We conclude that the challenge can be tackled by a distributed collaborative effort in academic institutions around the world, provided sufficient support, which is estimated to about 500 man-years over the next 20 years.

4 Summary

FCC-ee, a circular collider with extremely high statistics and high energy resolution, will provide the possibility to test the Standard Model with its fine quantum electroweak effects **with a precision far beyond the current state of the art.** Significant future theory effort will be needed for both for parametric and theoretical calculational errors to match the experimental accuracy of FCC-ee physics program. **No potential showstoppers are foreseen** [1, 2]. It will be important that adequate theory funding will be available to ensure that theory uncertainties are reduced to

EWPOs and QED deconvolution

- Current state-of-art generators on QED effects are not much different wrt. those used in LEP analysis 20 years ago; improvements needed ranging between a factor of 2 to 100 for different observables

Observable	Source LEP	Err.{QED} LEP	Stat[Syst] FCC-ee	$\frac{\text{LEP}}{\text{FCC-ee}}$	main development to be done
M_Z [MeV]	Z linesh.	2.1{0.3}	0.005[0.1]	$3\times3^{\star}$	light fermion pairs
Γ_Z [MeV]	Z linesh.	2.1{0.2}	0.008[0.1]	$2\times3^{\star}$	fermion pairs
$R_l^Z\times10^3$	$\sigma(M_Z)$	25{12}	0.06[1.0]	$12\times3^{\star\star}$	better FSR
σ^0_{had} [pb]	σ^0_{had}	37{25}	0.1[4.0]	$6\times3^{\star}$	better lumi MC
$N_\nu\times10^3$	$\sigma(M_Z)$	8{6}	0.005[1.0]	$6\times3^{\star\star}$	CEEX in lumi MC
$N_\nu\times10^3$	$Z\gamma$	150{60}	$0.8[<1]$	$60\times3^{\star\star}$	$\mathcal{O}(\alpha^2)$ for $Z\gamma$
$\sin^2\theta_W^{eff}\times10^5$	$A_{FB}^{lept.}$	53{28}	0.3[0.5]	$55\times3^{\star\star}$	h.o. and EWPOs
$\sin^2\theta_W^{eff}\times10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\text{FB}}^{pol,\tau}$	41{12}	$0.6[<0.6]$	$20\times3^{\star\star}$	better τ decay MC
M_W [MeV]	mass rec.	33{6}	0.5[0.3]	$12\times3^{\star\star\star}$	QED at threshold
$A_{FB,\mu}^{M_Z\pm3.5\text{GeV}}\times10^5$	$\frac{d\sigma}{d\cos\theta}$	2000{100}	1.0[0.3]	$100\times3^{\star\star\star}$	improved IFI

Table 2: Comparing experimental and theoretical errors at LEP and FCC-ee as in Table 1. 3rd column shows LEP experimental error together with uncertainty induced by QED and 4th column shows anticipated FCC-ee experimental statistical [systematic] errors. Additional factor $\times3$ in the 5-th column (4th in Table 1) reflects what is needed for QED effects to be *subdominant*. Rating from * to *** marks whether the needed improvement is relatively straightforward, difficult or very difficult to achieve.

no theoretical uncertainties included for Fcc-ee sys. projection

EWPOs and EW corrections

- Theoretical uncertainties on EWPOS can be divided as intrinsic errors due to missing EW radiative corrections and parametric uncertainties due to SM input parameters

intrinsic error vs. exp precision

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	0.5–1 ‡	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.4	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_b $[10^{-5}]$	6	11	$(\alpha^3, \alpha^2\alpha_s)$	5
R_l $[10^{-3}]$	1	6	$(\alpha^3, \alpha^2\alpha_s)$	1.5

based on current known 2-loop results

assuming 3-loop results available

parametric error vs. exp precision

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	$0.5-1$	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	0.6	2 (1)	$\delta(\Delta\alpha)$
Γ_Z [MeV]	0.1	0.1 (0.06)	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3 (0.7)	$\delta\alpha_s$

$$\Delta\alpha \equiv 1 - \alpha(0)/\alpha(M_Z)$$

$$\delta M_Z = 0.1\text{ MeV}, \quad \delta\alpha_s = 0.0002\ (0.0001),$$

$$\delta m_t = 50\text{ MeV}, \quad \delta m_b = 13\text{ MeV},$$
$$\delta(\Delta\alpha) = 5\times10^{-5}\ (3\times10^{-5}).$$

improved by a factor of 3~10

Challenges of EW corrections at 3-loops and beyond

- Ingredients for 3-loop calculations of Z decay; challenges due to both large number of diagram/integrals, multi-mass scales, as well as high numerical precision required

Table B.6: Number of topologies and diagrams for $\mathrm{Z} \to \mathrm{f}\bar{\mathrm{f}}$ decays in the Feynman gauge. Statistics for planarity, QCD, and EW-type diagrams are also given. Label ‘A’ denotes statistics after elimination of tadpoles and wavefunction corrections, and label ‘B’ denotes statistics after elimination of topological symmetries of diagrams.

$\mathrm{Z} \to \mathrm{b}\bar{\mathrm{b}}$	1 loop	2 loops	3 loops
Number of topologies	1	$14 \overset{(\mathrm{A})}{\to} 7 \overset{(\mathrm{B})}{\to} 5$	$211 \overset{(\mathrm{A})}{\to} 84 \overset{(\mathrm{B})}{\to} 51$
Number of diagrams	15	$2383 \overset{(\mathrm{A,B})}{\to} 1074$	$490\,387 \overset{(\mathrm{A,B})}{\to} 120\,472$
Fermionic loops	0	150	17 580
Bosonic loops	15	924	102 892
Planar / non-planar	15 / 0	981/133	84 059/36 413
QCD / EW	1 / 14	98 / 1016	10 386/110 086
$\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-, \ldots$			
Number of topologies	1	$14 \overset{(\mathrm{A})}{\to} 7 \overset{(\mathrm{B})}{\to} 5$	$211 \overset{(\mathrm{A})}{\to} 84 \overset{(\mathrm{B})}{\to} 51$
Number of diagrams	14	$2012 \overset{(\mathrm{A,B})}{\to} 880$	$397\,690 \overset{(\mathrm{A,B})}{\to} 91\,472$
Fermionic loops	0	114	13104
Bosonic loops	14	766	78 368
Planar / non-planar	14 / 0	782/98	65 487/25 985
QCD / EW	0 / 14	0 / 880	144/91 328

Higgs boson production and decays

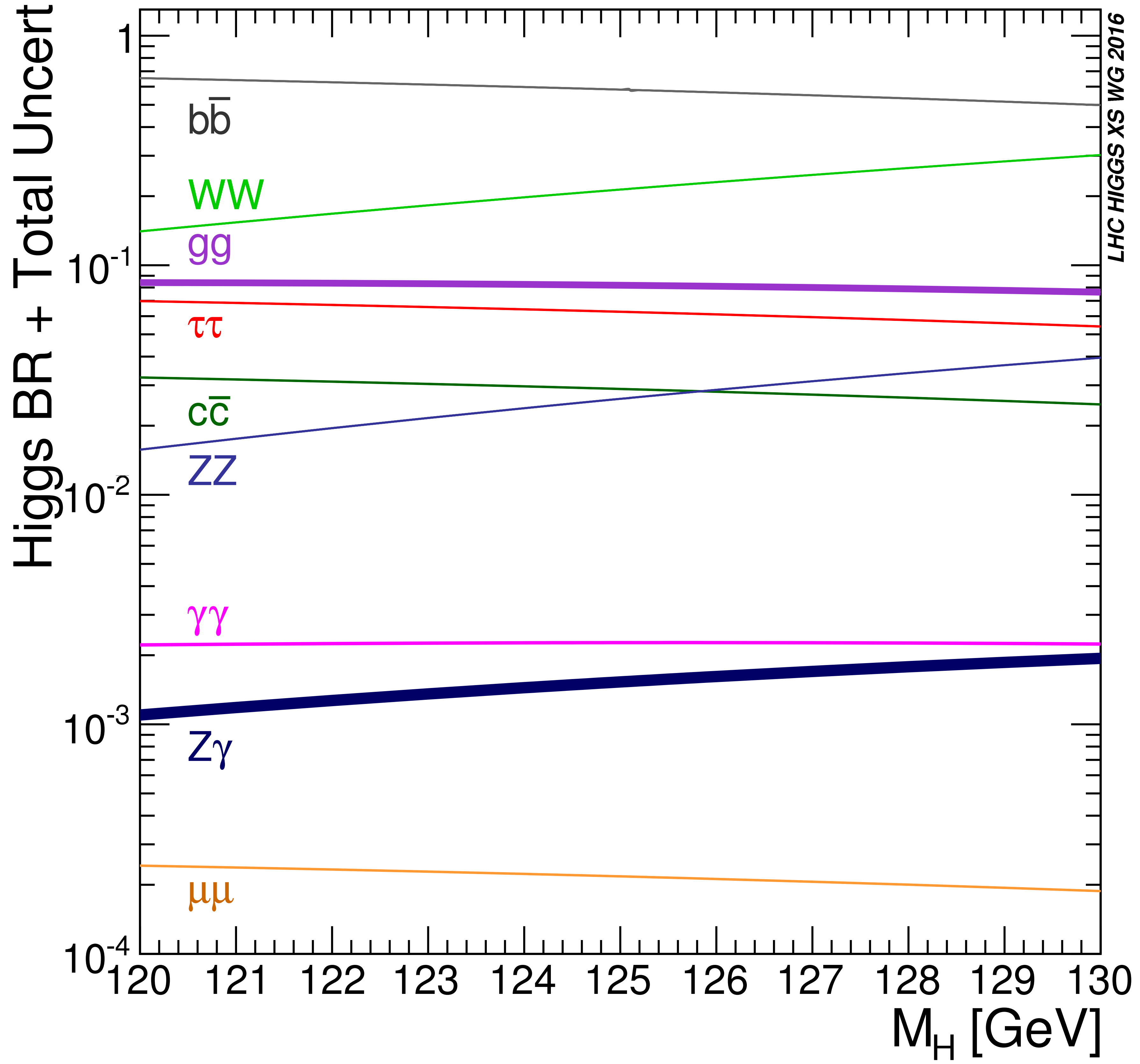
- The tiny width ($\Gamma/M \sim 3\times10^{-5}$) and 0 spin of the Higgs boson ensure a simple factorization of production and decay of the Higgs boson in most theory calculations

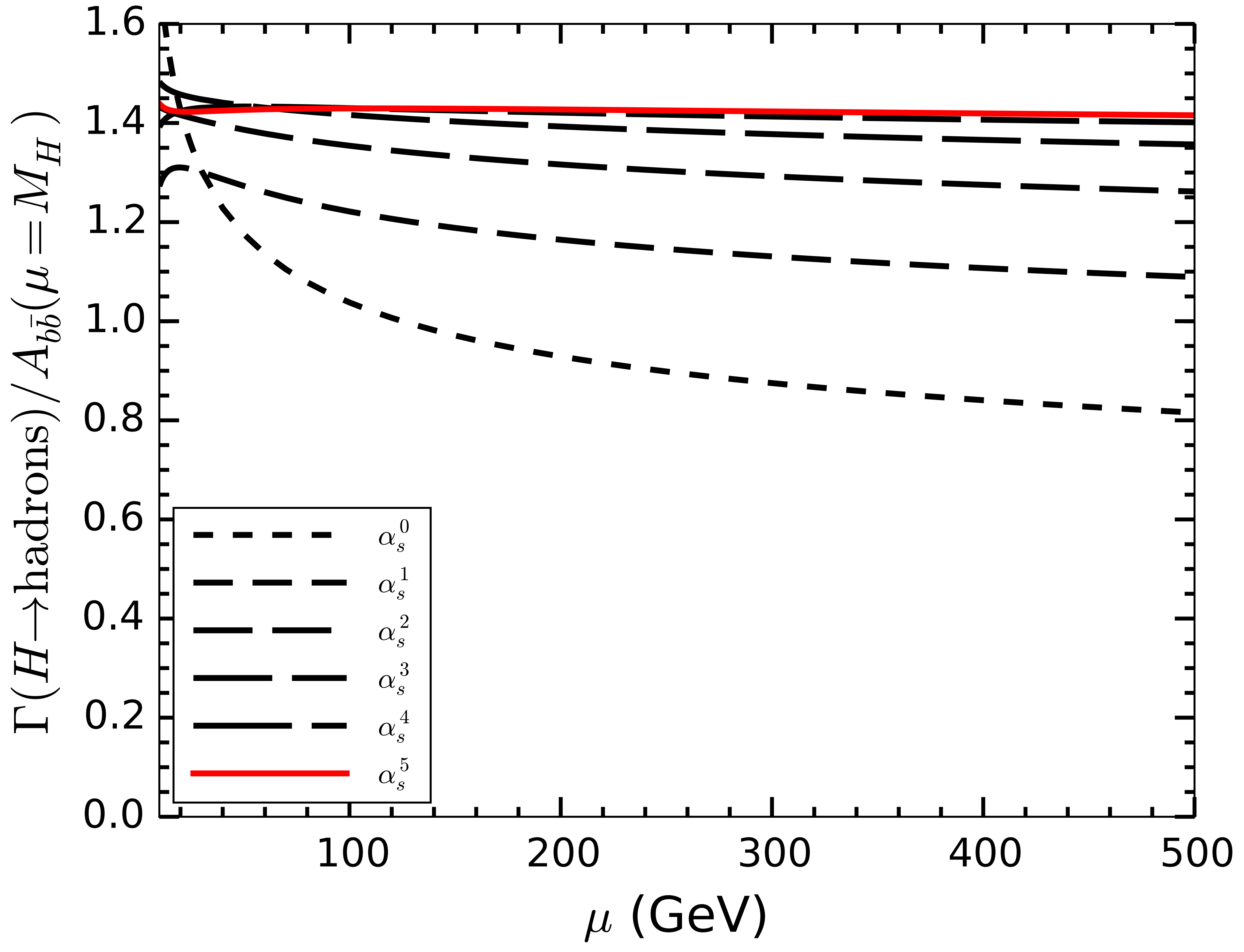
[Davies, Steinhauser, Wellmann, 2017]

[Herzog, Ruijl, Ueda, Vermaseren, Vogt, 2017]

decay branching ratios vs. mass

hadronic width of the Higgs boson vs QCD scale





known to $O(\alpha_s^4)$ neglecting certain mass corrections from Higgs effective theory in heavy top limit

Theory uncertainty on Higgs partial width

- Theory uncertainty can be under FCC-ee precision goal, giving the projected improvement on SM input parameters and some straight forward works on the perturbative calculations

intrinsic/perturbative uncertainty on partial width vs. exp. precision

Partial width	QCD	electroweak	total	available order
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	N^{4}LO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	— / NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	N^{3}LO / NLO
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	NLO / NLO
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	LO / LO
$H \to WW/ZZ \to 4\text{f}$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	NLO/NLO

decay	intrinsic	FCC-ee prec.
$H \to b\bar{b}$	$\sim 0.2\%$	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1.4\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	$\sim 1.1\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	$\sim 12\%$
$H \to gg$	$\sim 1\%$	$\sim 1.6\%$
$H \to \gamma\gamma$	$< 1\%$	$\sim 3.0\%$
$H \to Z\gamma$	$\sim 1\%$	~13% for CEPC
$H \to WW$	$\lesssim 0.3\%$	$\sim 0.4\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	$\sim 0.3\%$

due to current available QCD and EW corrections

only a few channels need some additional works

Theory uncertainty on Higgs partial width

- Theory uncertainty can be under FCC-ee precision goal, giving the projected improvement on SM input parameters and some straight forward works on the perturbative calculations

parametric uncertainty on partial width vs. exp. precision

decay	para. m_q	para. α_s	para. M_H
$H \to b\bar{b}$	1.4%	0.4%	–
$H \to c\bar{c}$	4.0%	0.4%	–
$H \to \tau^+\tau^-$	–	–	–
$H \to \mu^+\mu^-$	–	–	–
$H \to gg$	$< 0.2\%$	3.7%	–
$H \to \gamma\gamma$	$< 0.2\%$	–	–
$H \to Z\gamma$	–	–	2.1%
$H \to WW$	–	–	2.6%
$H \to ZZ$	–	–	3.0%

para. m_q	para. α_s	para. M_H	FCC-ee prec.
0.6%	$< 0.1\%$	–	$\sim 0.8\%$
$\sim 1\%$	$< 0.1\%$	–	$\sim 1.4\%$
–	–	–	$\sim 1.1\%$
–	–	–	$\sim 12\%$
	0.5% (0.3%)	–	$\sim 1.6\%$
–	–	–	$\sim 3.0\%$
–	–	$\sim 0.1\%$	~13% for CEPC
–	–	$\sim 0.1\%$	$\sim 0.4\%$
–	–	$\sim 0.1\%$	$\sim 0.3\%$

current input parameters

$$\delta\alpha_s = 0.0015 \text{ and } \delta m_b = 0.03 \text{ GeV}$$

$$\delta m_c = 0.025 \text{ GeV}$$

$$\delta m_t = 0.85 \text{ GeV and } \delta M_H = 0.24 \text{ GeV}$$

projected input parameters

$$\delta\alpha_s = 0.0002 \text{ and } \delta m_b = 13 \text{ MeV}$$

$$\delta m_c = 7 \text{ MeV}$$

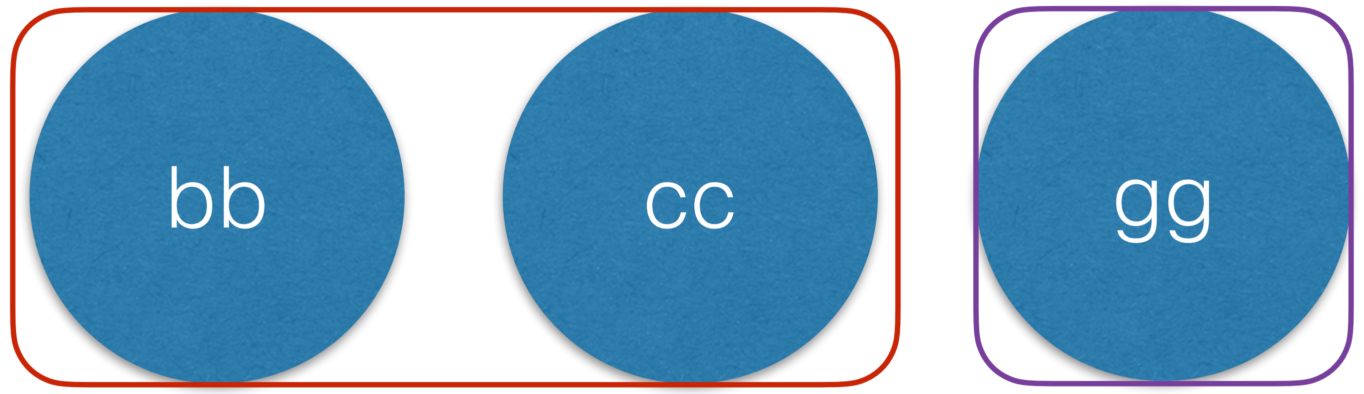
$$\delta m_t = 50 \text{ MeV} \quad \text{and } \delta M_H = 10 \text{ MeV}$$

MC modeling on Higgs hadronic decays

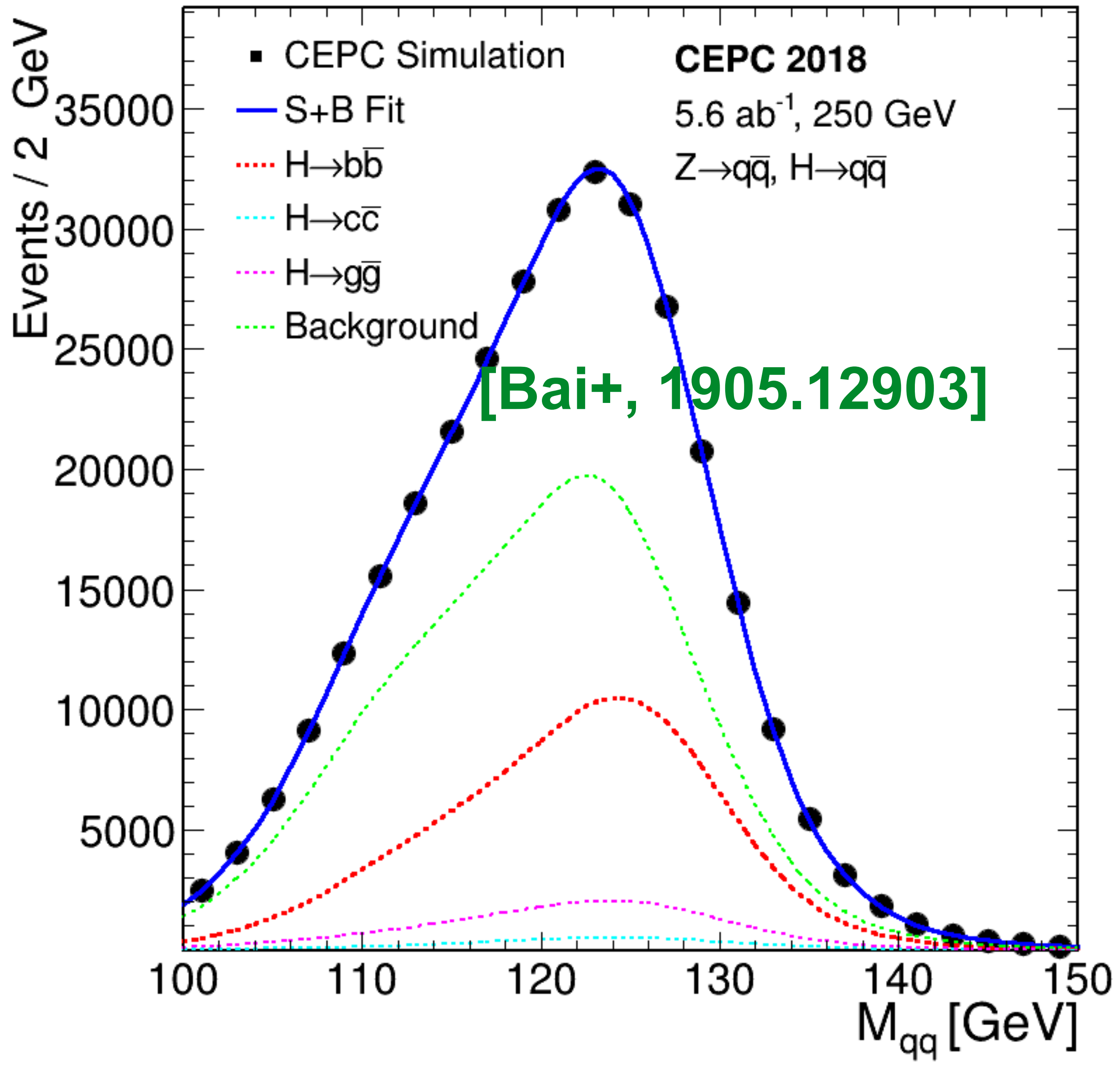
- Input of Higgs boson decay are more than just numbers of partial width/BRs, modeling on kinematics including NP QCD effects will be crucial in precision measurement of hadronic channels

[JG, to appear soon]

heavy-flavor tagging

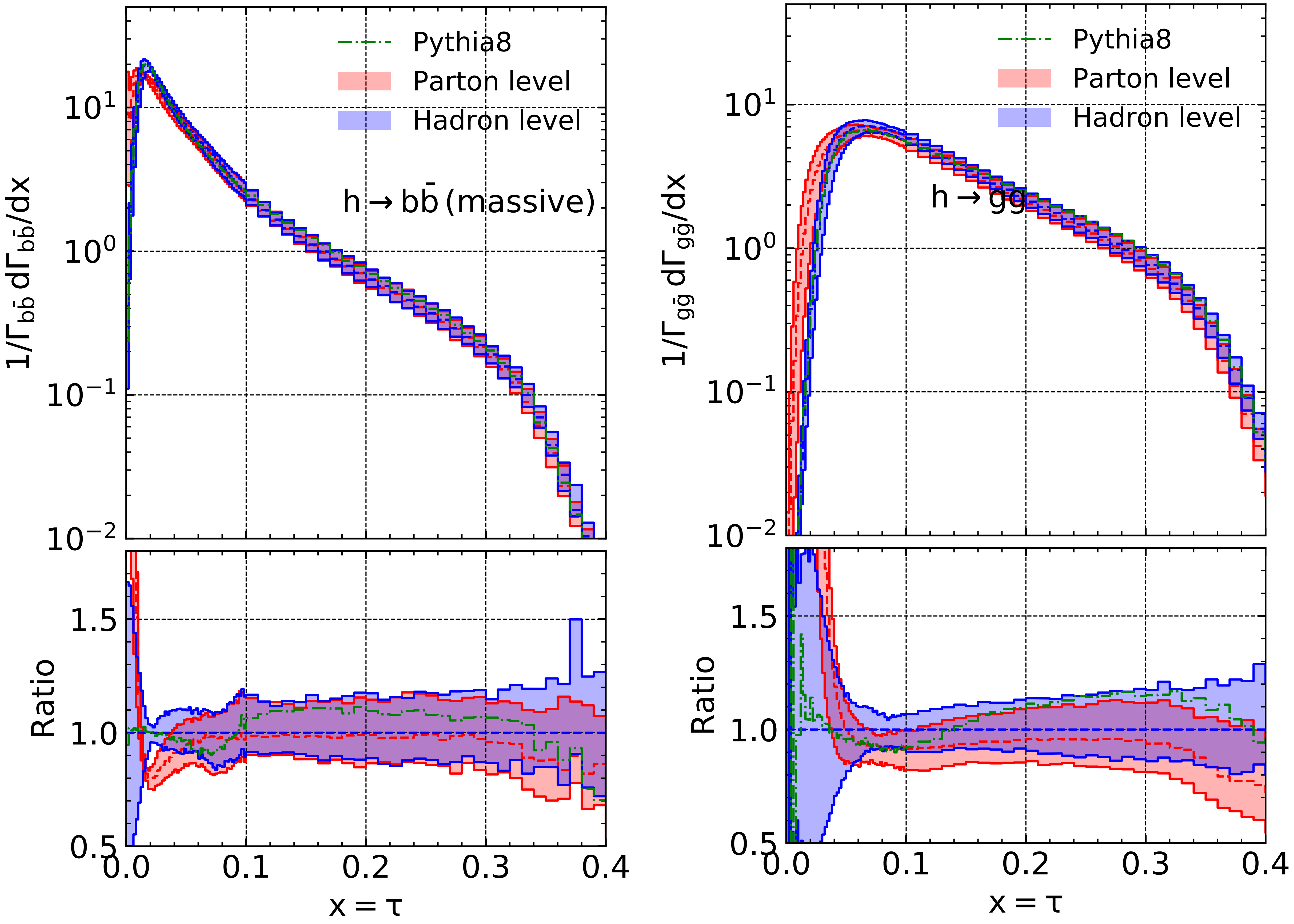


multi-jets final state



[Bai+, 1905.12903]

hadronic decays at NNLO matched with parton shower and hadronizations

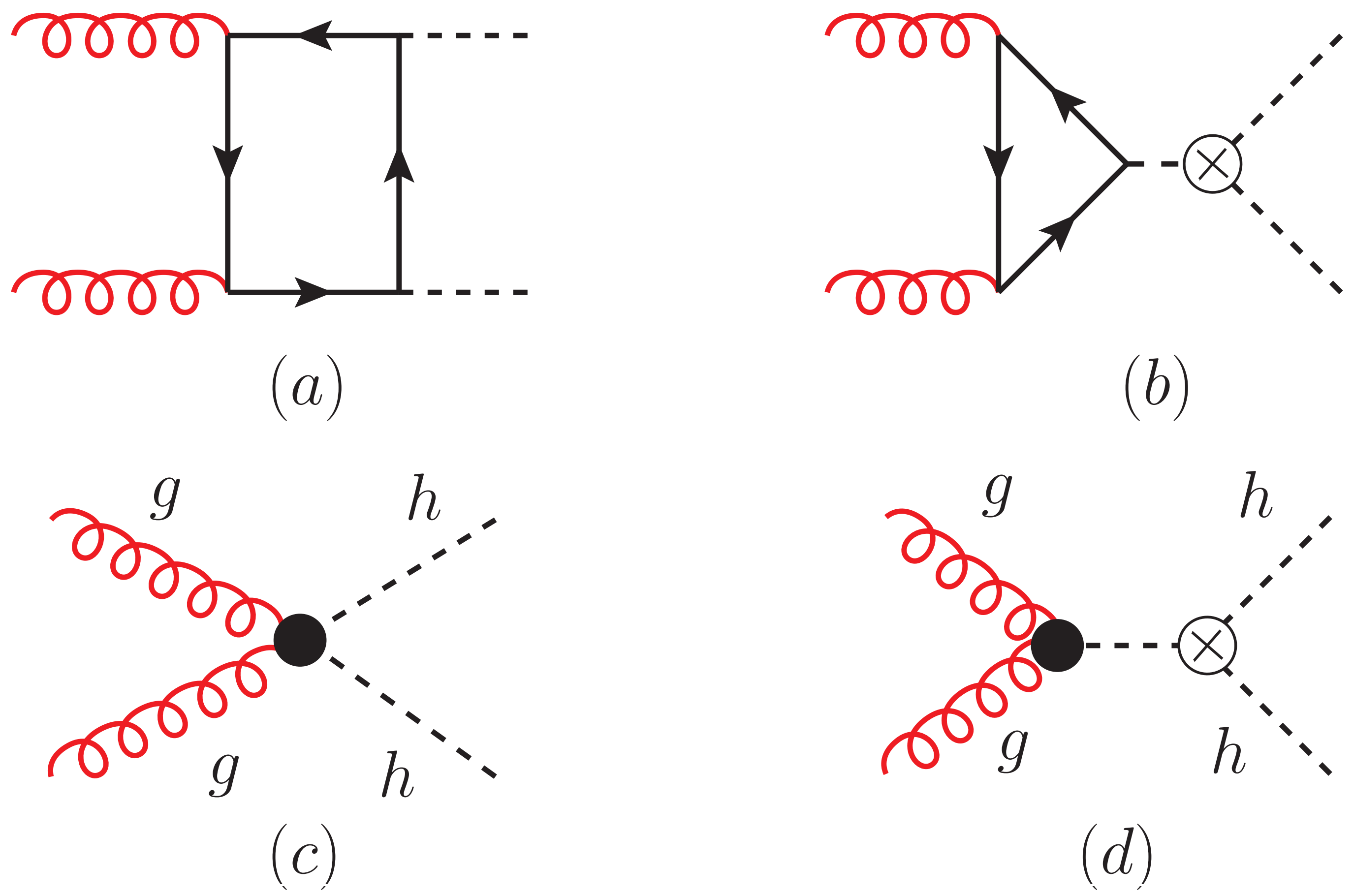


differential width vs. 1-Thrust

Higgs boson pair production at the LHC

- Higgs boson pair production has been calculated to (approximated) N3LO in QCD by Long-Bin Chen (Guang Zhou Univ.), Hai Tao Li, Hua-Sheng Shao and Jian Wang (Shangdong Univ.) **[1912.13001]**

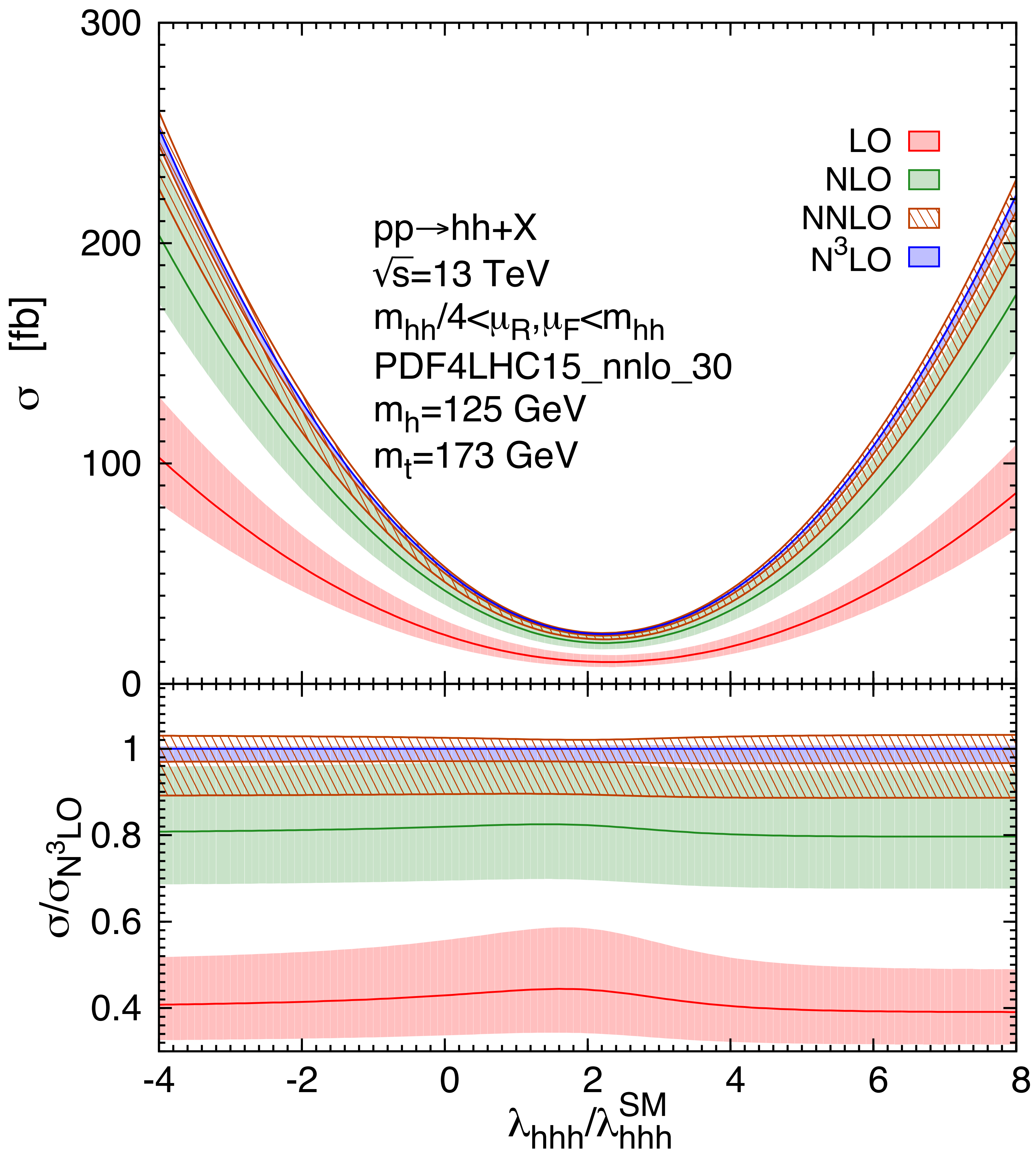
probe of Higgs trilinear coupling and dynamics of EW phase transition



inclusive cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^3LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4439^{+0.51\%}_{-1.8\%}$

cross sections as a function of coupling modification

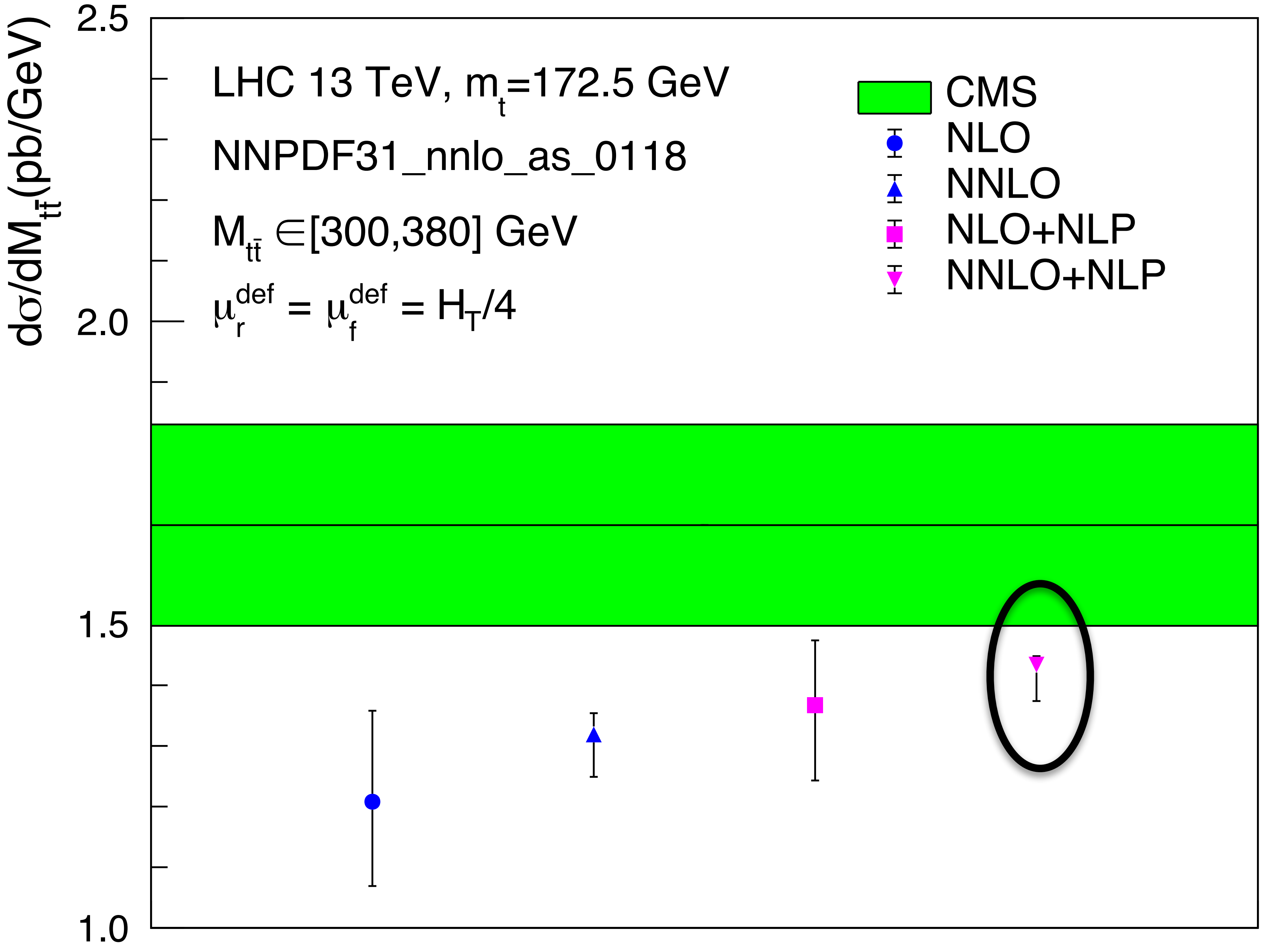


Top-quark pair production at the LHC

- QCD Resummed calculation for top quark production at threshold to next-to-leading power accuracy by Li Lin Yang (Zhejiang Univ.) et al.

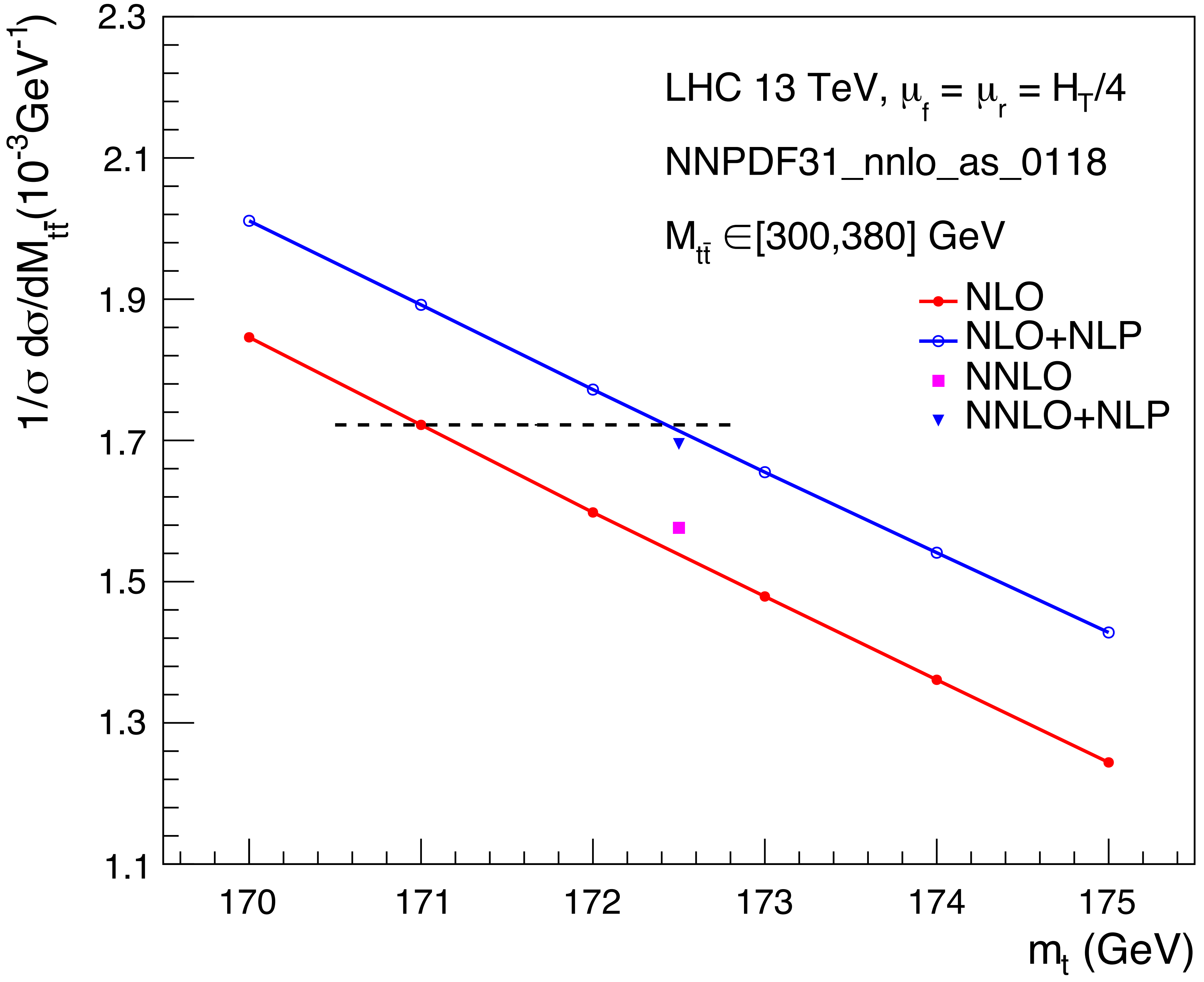
[2004.03088]

theory vs. exp for cross section close to top-quark pair threshold



We need all possibilities to scrutinize the mass of top quark

top quark mass dependence



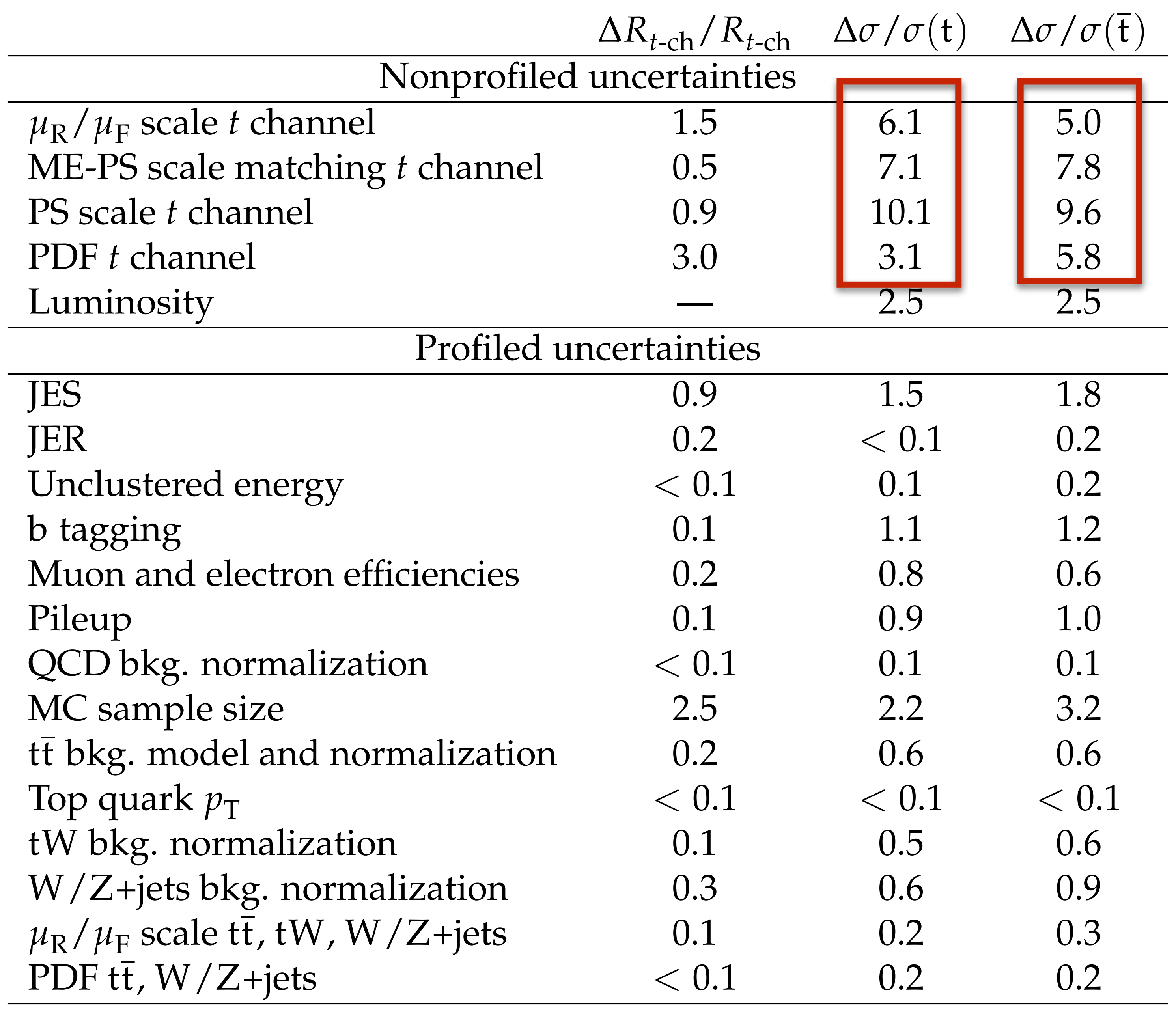
The new calculation resolve the tensions between different mass measurement

Single top-quark production at the LHC

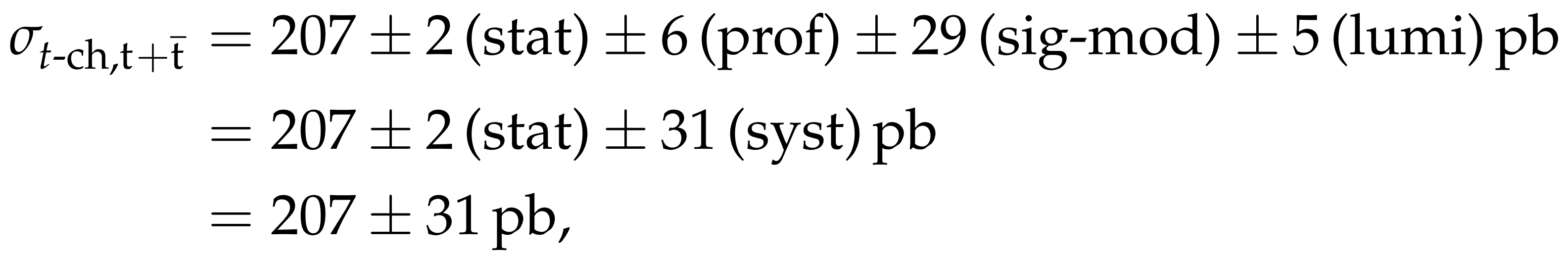
- Single top-quark production at LHC including decay of the top quark has been calculated to NNLO in QCD by JG (SJTU), Hua-Xing Zhu (Zhejiang Univ.) et al.

[2005.12936, 1708.09405]

CMS measurement at 13 TeV, 36 fb^{-1}

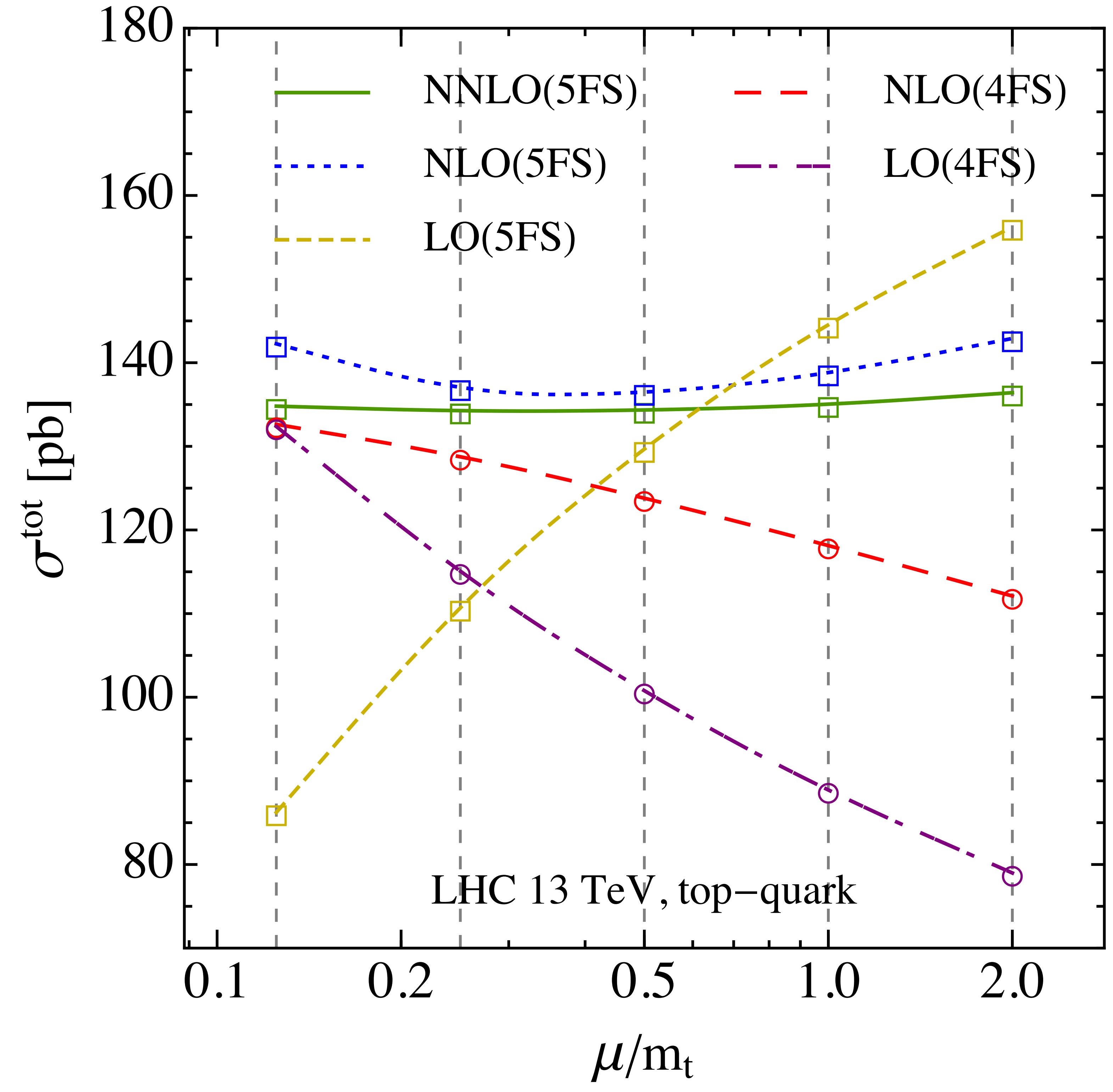


	$\Delta R_{t\text{-ch}}/R_{t\text{-ch}}$	$\Delta\sigma/\sigma(\mathrm{t})$	$\Delta\sigma/\sigma(\bar{\mathrm{t}})$
Nonprofiled uncertainties			
μ_R/μ_F scale t channel	1.5	6.1	5.0
ME-PS scale matching t channel	0.5	7.1	7.8
PS scale t channel	0.9	10.1	9.6
PDF t channel	3.0	3.1	5.8
Luminosity	—	2.5	2.5
Profiled uncertainties			
JES	0.9	1.5	1.8
JER	0.2	< 0.1	0.2
Unclustered energy	< 0.1	0.1	0.2
b tagging	0.1	1.1	1.2
Muon and electron efficiencies	0.2	0.8	0.6
Pileup	0.1	0.9	1.0
QCD bkg. normalization	< 0.1	0.1	0.1
MC sample size	2.5	2.2	3.2
$\mathrm{t\bar{t}}$ bkg. model and normalization	0.2	0.6	0.6
Top quark p_T	< 0.1	< 0.1	< 0.1
tW bkg. normalization	0.1	0.5	0.6
W/Z+jets bkg. normalization	0.3	0.6	0.9
μ_R/μ_F scale $\mathrm{t\bar{t}}$, tW, W/Z+jets	0.1	0.2	0.3
PDF $\mathrm{t\bar{t}}$, W/Z+jets	< 0.1	0.2	0.2

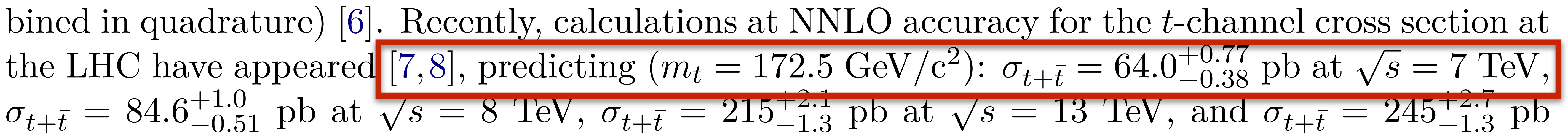


$$\begin{aligned}\sigma_{t\text{-ch},\mathrm{t}+\bar{\mathrm{t}}} &= 207 \pm 2\,(\text{stat}) \pm 6\,(\text{prof}) \pm 29\,(\text{sig-mod}) \pm 5\,(\text{lumi})\,\text{pb} \\ &= 207 \pm 2\,(\text{stat}) \pm 31\,(\text{syst})\,\text{pb} \\ &= 207 \pm 31\,\text{pb},\end{aligned}$$

inclusive cross sections at various orders



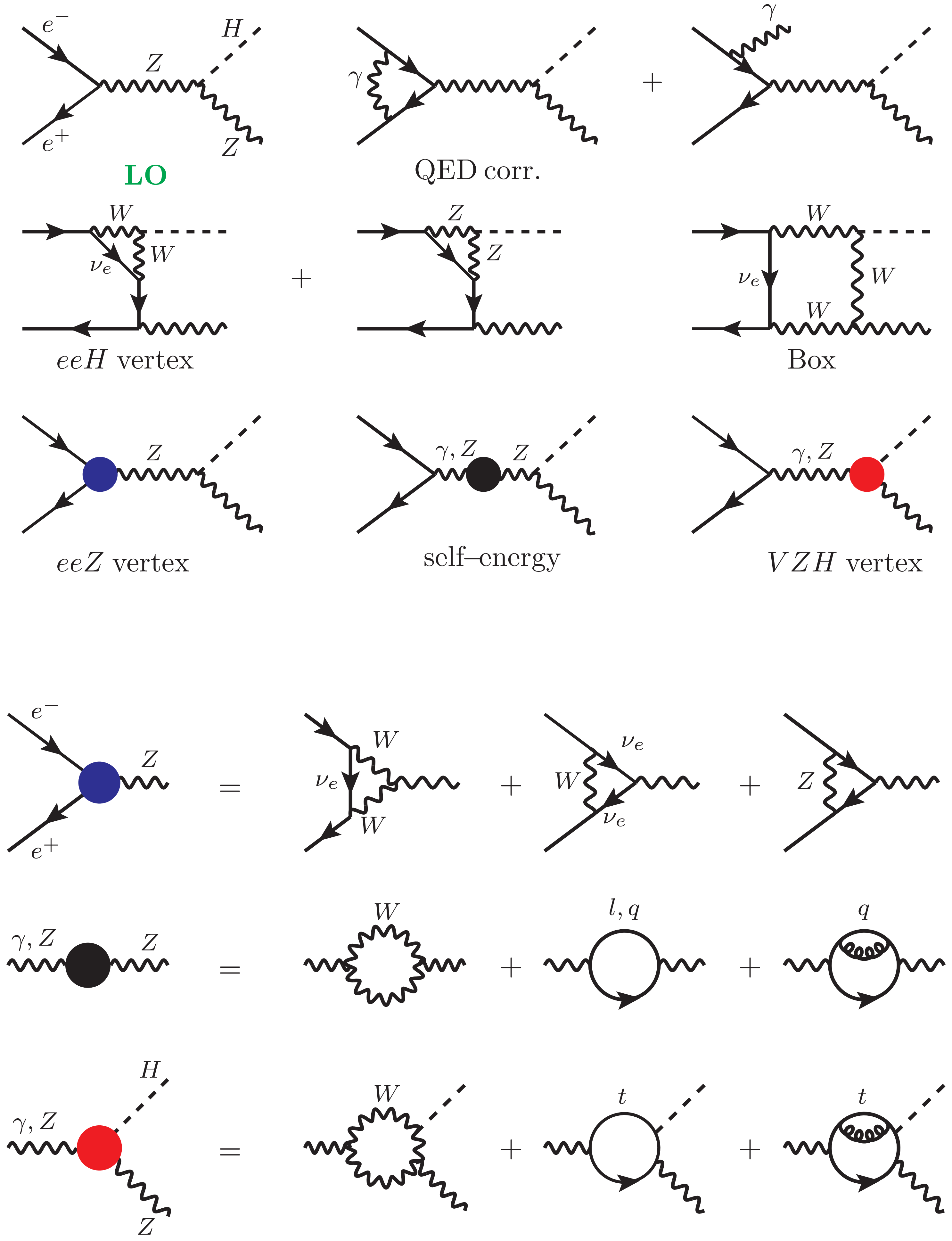
[PDG 2020]



bined in quadrature) [6]. Recently, calculations at NNLO accuracy for the t-channel cross section at the LHC have appeared [7,8], predicting ($m_t = 172.5$ GeV/c^2): $\sigma_{t+\bar{t}} = 64.0^{+0.77}_{-0.38}$ pb at $\sqrt{s} = 7$ TeV, $\sigma_{t+\bar{t}} = 84.6^{+1.0}_{-0.51}$ pb at $\sqrt{s} = 8$ TeV, $\sigma_{t+\bar{t}} = 215^{+2.1}_{-1.3}$ pb at $\sqrt{s} = 13$ TeV, and $\sigma_{t+\bar{t}} = 245^{+2.7}_{-1.3}$ pb

Higgs boson production at e+e- machine

- Mixed electroweak-QCD corrections (two-loops) are calculated independently by two groups, Yu Jia et al. (IHEP) and Li Lin Yang (Zhejiang Univ.), Zhao Li (IHEP) et al., amount to a correction of 1.3%



[Sun+, 1609.03995; Gong+, 1609.03955]

$\sqrt{s}$	schemes	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$
250	$\alpha(0)$	223.12 ± 0.47	229.20 ± 0.77	$231.63^{+0.75+0.12}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.01 ± 0.60	$227.67^{+0.82}_{-0.81}$	$230.58^{+0.80+0.14}_{-0.79-0.25}$
	G_μ	239.62 ± 0.06	231.82 ± 0.07	$232.65^{+0.07+0.04}_{-0.07-0.07}$

inclusive cross sections at various orders and its scheme dependence

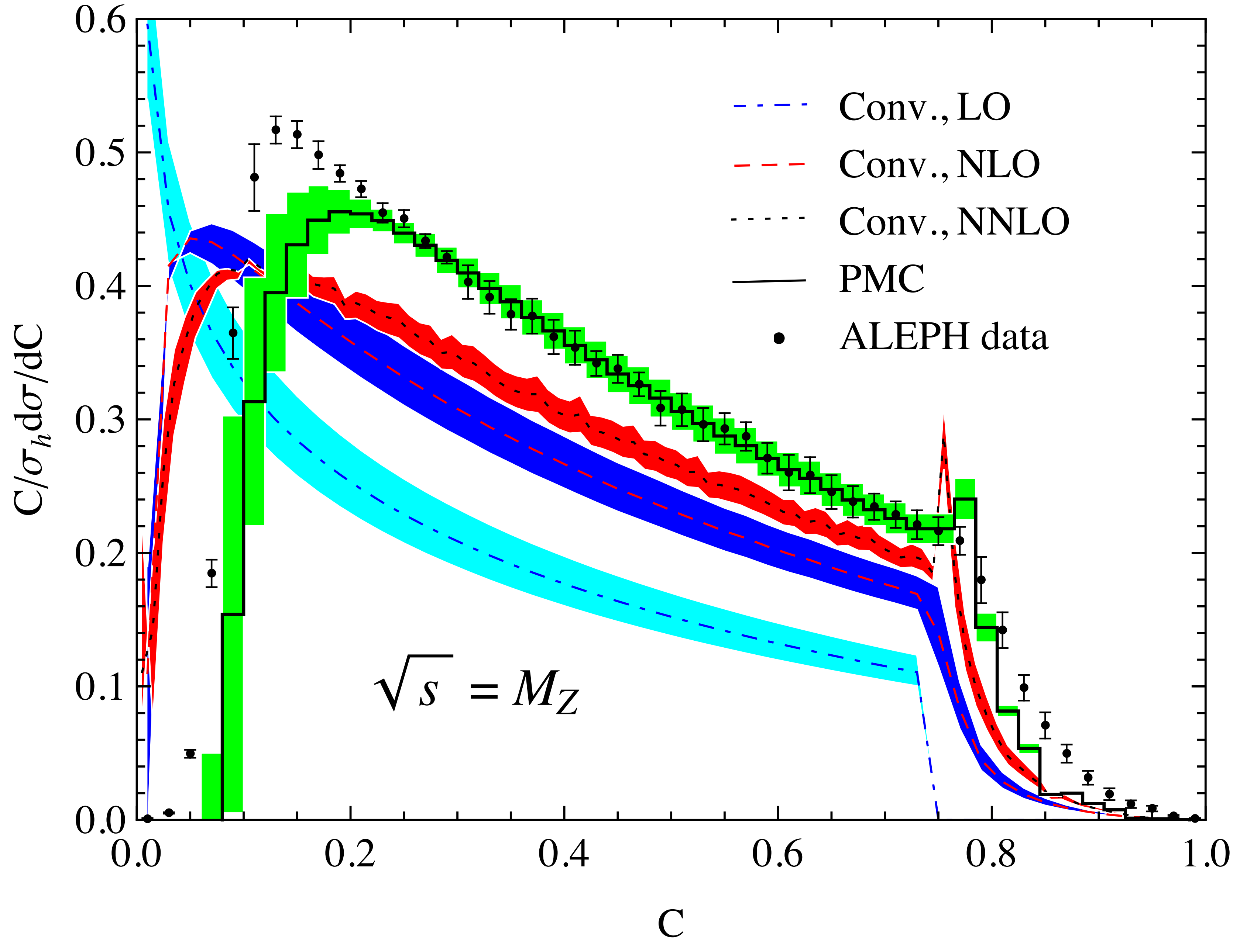
current intrinsic error of ~1% comparing to experimental goal of 0.4%; will need two-loop EW corrections!!!

PMC and event shapes at e+e- machine

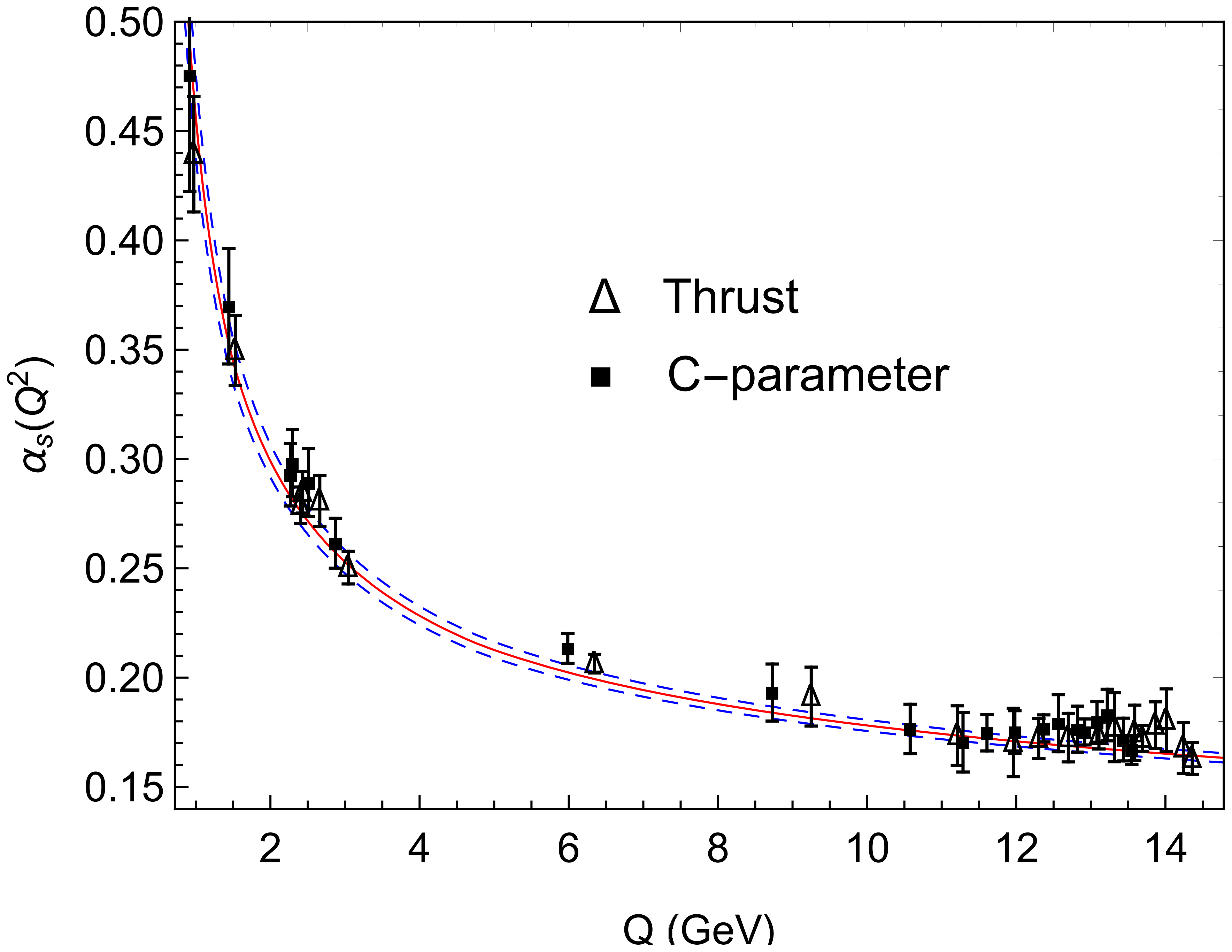
- Applications of principle of maximum conformality (PMC) on various QCD predictions at e+e- collisions by Xing-Gang Wu (Chongqing Univ.) et al., hadronic event shapes as an example **[1908.00060]**

C parameter, theory vs. ALEPH data

$$C = \frac{3}{2}\frac{\sum_{i,j}|\vec{p_i}||\vec{p_j}|\sin^2\theta_{ij}}{\left(\sum_i|\vec{p_i}|\right)^2}$$



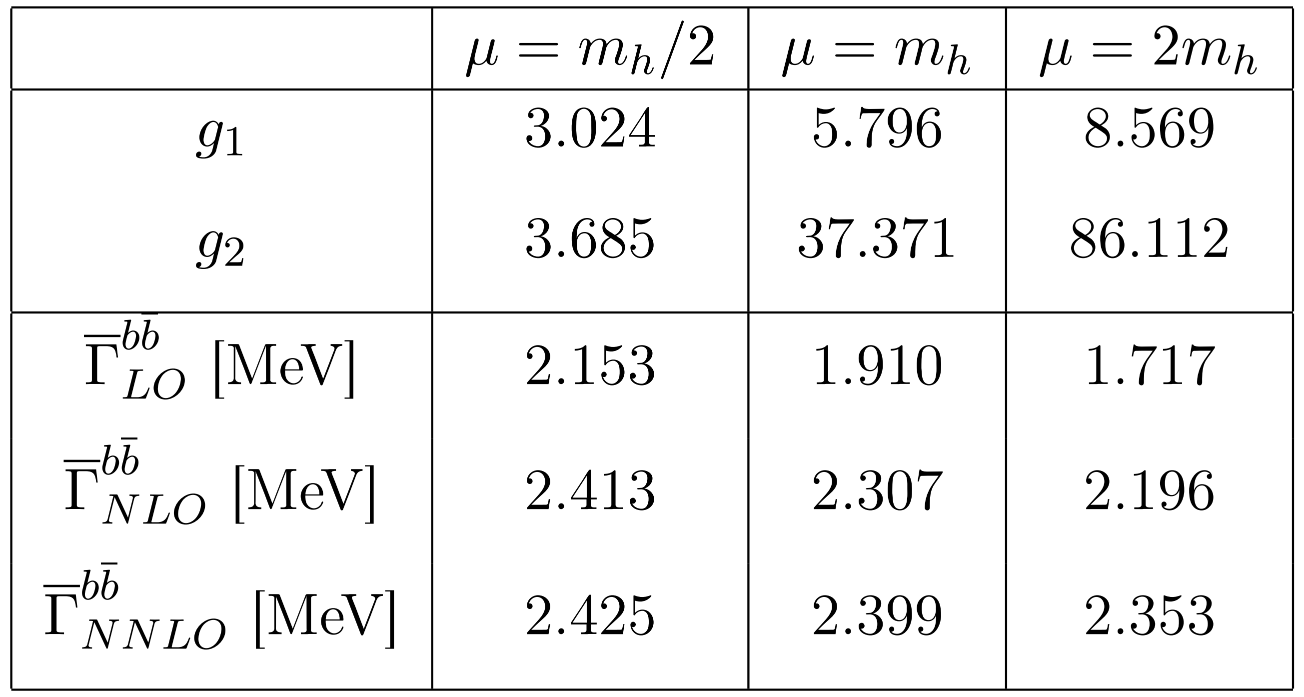
extraction of QCD coupling constant and its running behavior



$$\begin{aligned}\alpha_s(M_Z^2) &= 0.1185 \pm 0.0011(\mathrm{Exp.}) \pm 0.0005(\mathrm{Theo.})\\ &= 0.1185 \pm 0.0012,\end{aligned}$$

Heavy quark production at e+e- machine

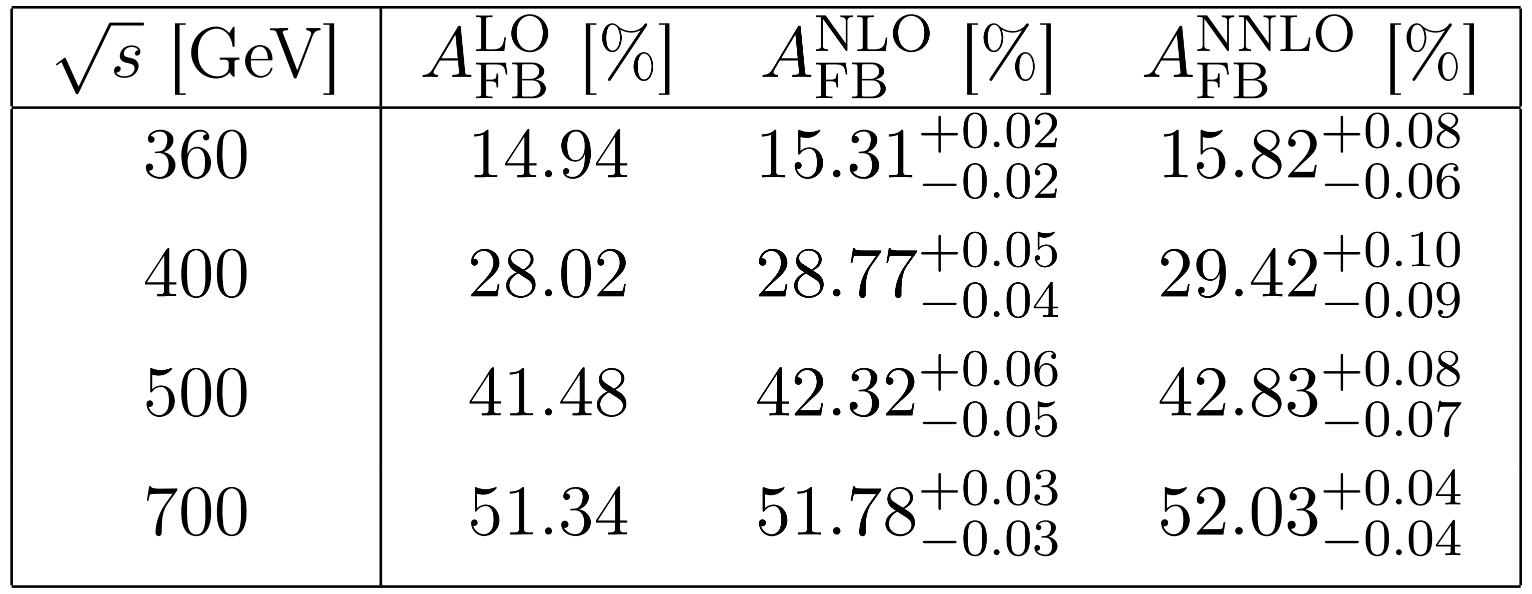
- Pioneering works on heavy quark production at e+e- machine as well as at LHC lead by Zong Guo Si (Shangdong Univ.) and Wen-Gan Ma, Ren-You Zhang (USTC)



	$\mu = m_h/2$	$\mu = m_h$	$\mu = 2m_h$
g_1	3.024	5.796	8.569
g_2	3.685	37.371	86.112
$\Gamma^{b\bar{b}}_{LO}$ [MeV]	2.153	1.910	1.717
$\Gamma^{b\bar{b}}_{NLO}$ [MeV]	2.413	2.307	2.196
$\Gamma^{b\bar{b}}_{NNLO}$ [MeV]	2.425	2.399	2.353

NNLO QCD calculations for bottom quark pair from Higgs decay with full mass dependence

[Zong Guo Si et al., 1805.06658]

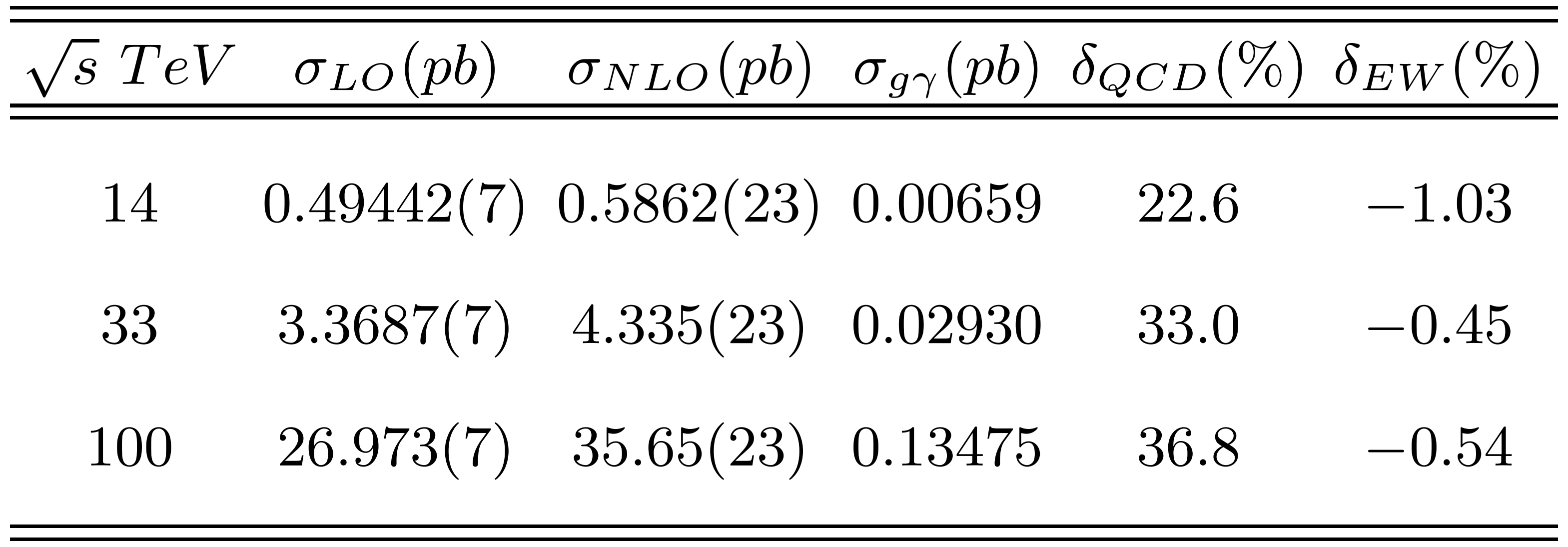


$\sqrt{s}$ [GeV]	$A^{\mathrm{LO}}_{\mathrm{FB}}$ [%]	$A^{\mathrm{NLO}}_{\mathrm{FB}}$ [%]	$A^{\mathrm{NNLO}}_{\mathrm{FB}}$ [%]
360	14.94	$15.31^{+0.02}_{-0.02}$	$15.82^{+0.08}_{-0.06}$
400	28.02	$28.77^{+0.05}_{-0.04}$	$29.42^{+0.10}_{-0.09}$
500	41.48	$42.32^{+0.06}_{-0.05}$	$42.83^{+0.08}_{-0.07}$
700	51.34	$51.78^{+0.03}_{-0.03}$	$52.03^{+0.04}_{-0.04}$

NNLO QCD calculations for top quark pair production at e+e- machine

[Zong Guo Si et al., 1610.07897]

[JG, Zhu, 1410.3165]



$\sqrt{s}\ TeV$	$\sigma_{LO}(pb)$	$\sigma_{NLO}(pb)$	$\sigma_{g\gamma}(pb)$	$\delta_{QCD}(\%)$	$\delta_{EW}(\%)$
14	0.49442(7)	0.5862(23)	0.00659	22.6	-1.03
33	3.3687(7)	4.335(23)	0.02930	33.0	-0.45
100	26.973(7)	35.65(23)	0.13475	36.8	-0.54

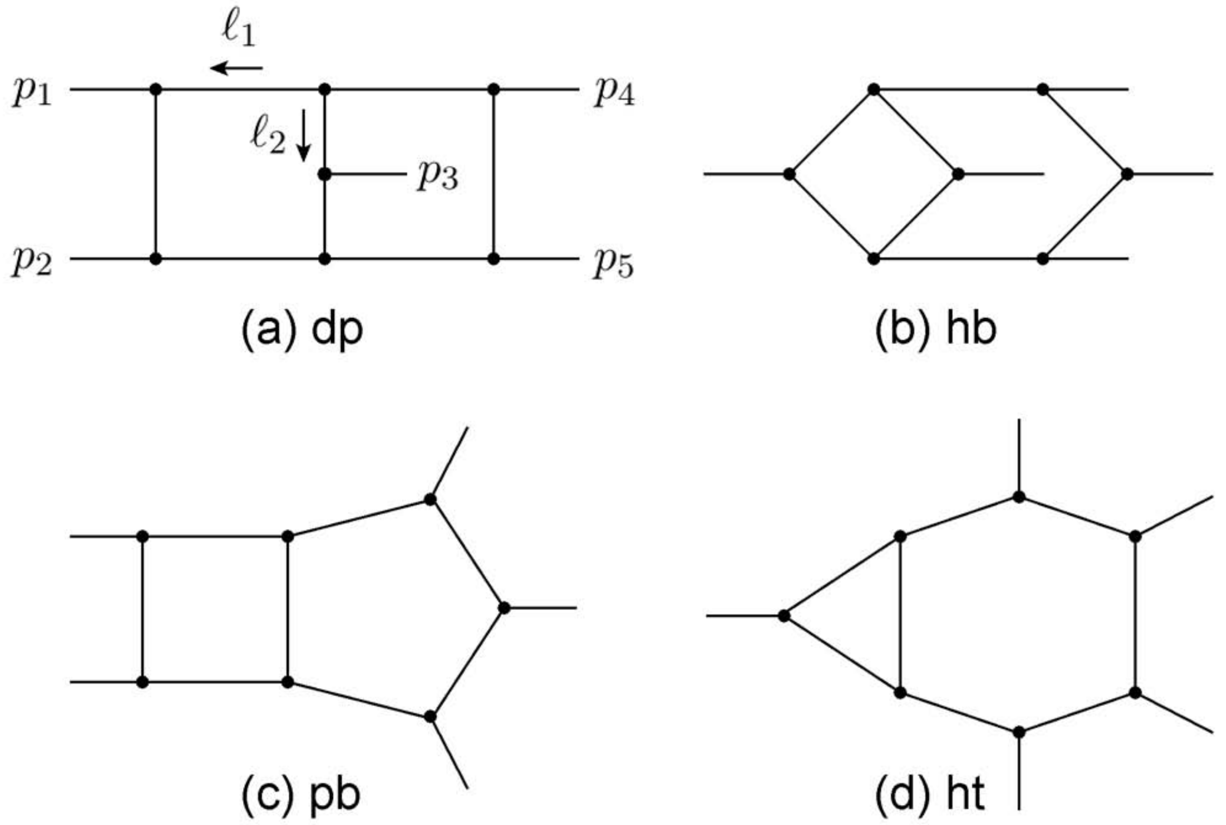
NLO calculations for top quark pair associated production with Higgs at LHC

[Wen-Gan Ma, Ren-You Zhang, 1407.1110]

Multi-loop analytical/numerical calculations

- A new approach on evaluating multi-loop Feynman integral has been developed by Yan Qing Ma (Peking Univ.) et al. **[1912.09294]**

demonstration of the efficiency for 5-point massless scattering at two-loops



(a) dp (b) hb

(c) pb (d) ht

FIG. 1. All 8-propagator families: (a) double-pentagon; (b) hexa-box; (c) penta-box; (d) hexa-triangle.

top.	#int.	#MIs	t_{search} (h)	t_{solve} (s)	size(MB)
(a)	3914	108	112	0.17	66
(b)	3584	73	31	0.090	40
(c)	3458	61	56	0.075	31
(d)	2634	28	8	0.035	11

TABLE I. Main information of the obtained reduction relations. t_{search} represents the CPU time required to search for these relations in the unit of CPU-core hours. t_{solve} represents the time spent to solve these relations numerically using one CPU.

- Yang Zhang (USTC) et al. work towards solving the two-loop 5-point amplitude for scattering of massless particles

[1812.11057]

Analytic result for a two-loop five-particle amplitude

D. Chicherin[a], T. Gehrmann[b], J. M. Henn[a], P. Wasser[c], Y. Zhang[a], S. Zoia[a]

[1812.11160]

All master integrals for three-jet production at NNLO

D. Chicherin[a], T. Gehrmann[b], J. M. Henn[a], P. Wasser[c], Y. Zhang[a], S. Zoia[a]

[1905.03733]

Analytic form of the full two-loop five-gluon all-plus helicity amplitude

S. Badger[a], D. Chicherin[b], T. Gehrmann[c], G. Heinrich[b], J. M. Henn[b], T. Peraro[c], P. Wasser[d], Y. Zhang[b,e], S. Zoia[b]

directly applicable to 3-jets or 3-photon production at the LHC

Summary

- Future lepton colliders and its high precision set a unprecedented precision target of SM predictions involving electroweak, QCD corrections, MC modelings and input parameters
- Extensive theory works required towards reducing intrinsic and parametric uncertainties in Higgs production and decay, and especially for various EW precision observables at Z pole and beyond
- We have many local groups having the expertise on precision theory calculations though the scale is much smaller than European side
- It will be important to grow a few compatible teams working on precision calculations for future lepton colliders especially if we host CEPC program

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Thank you for your attention!