LI - International Meeting on Fundamental Physics

(Benasque Science Center, Sep 09 - Sep 14, 2024)

Near-future,
Future Colliders
and Futuristic

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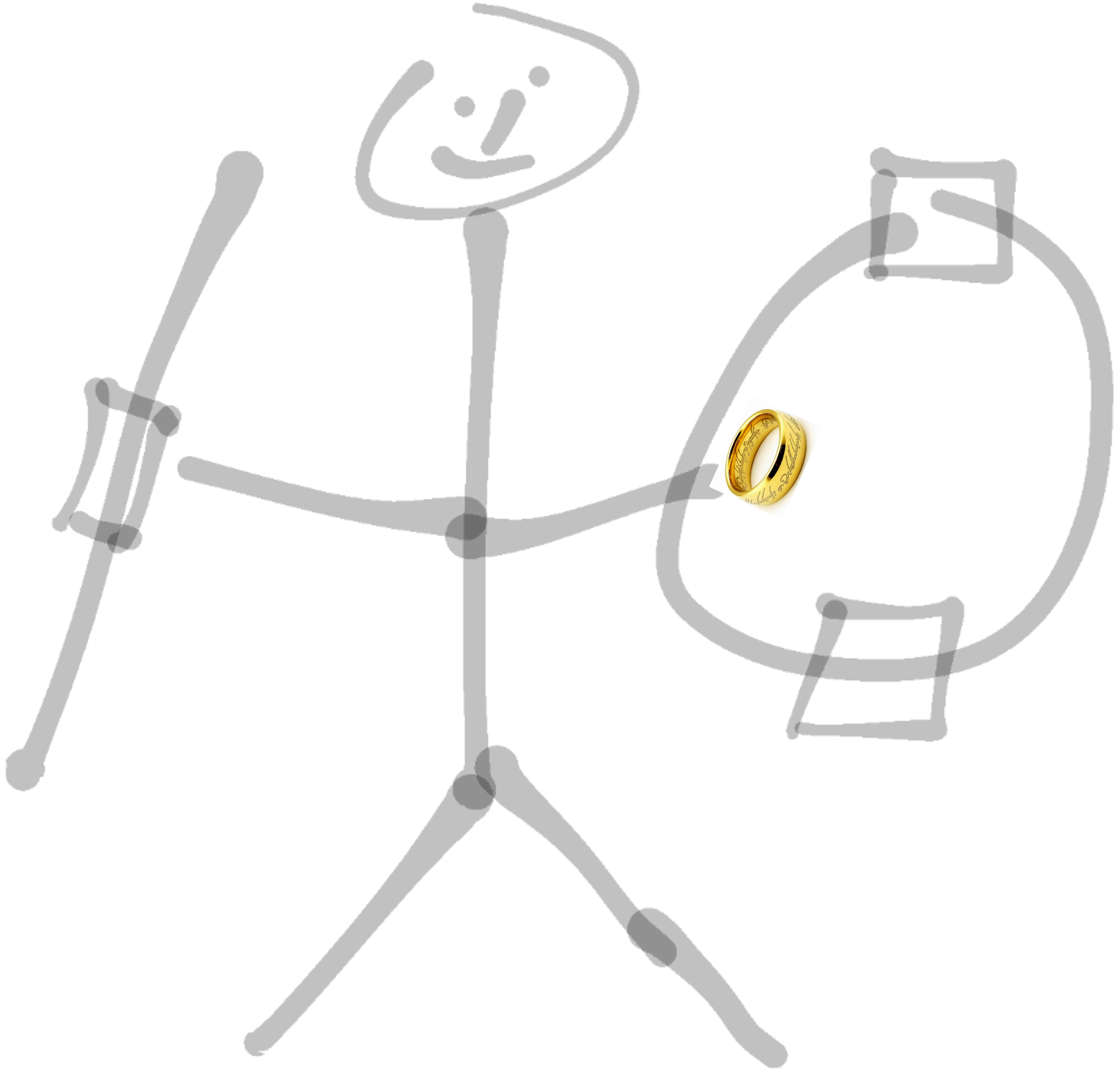
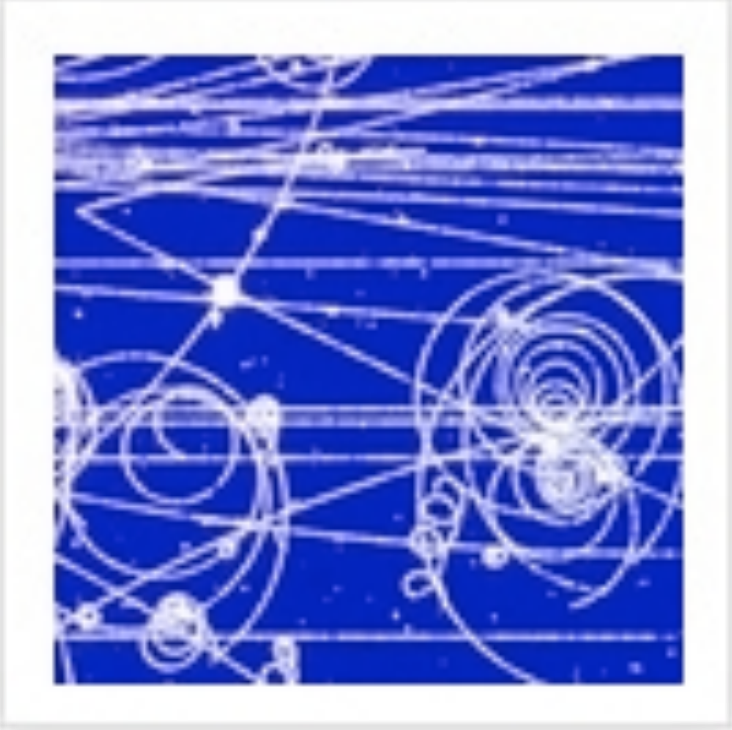


Adapted from Frank Simon’s original art work.



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2025 Near future 2050 Future 2075

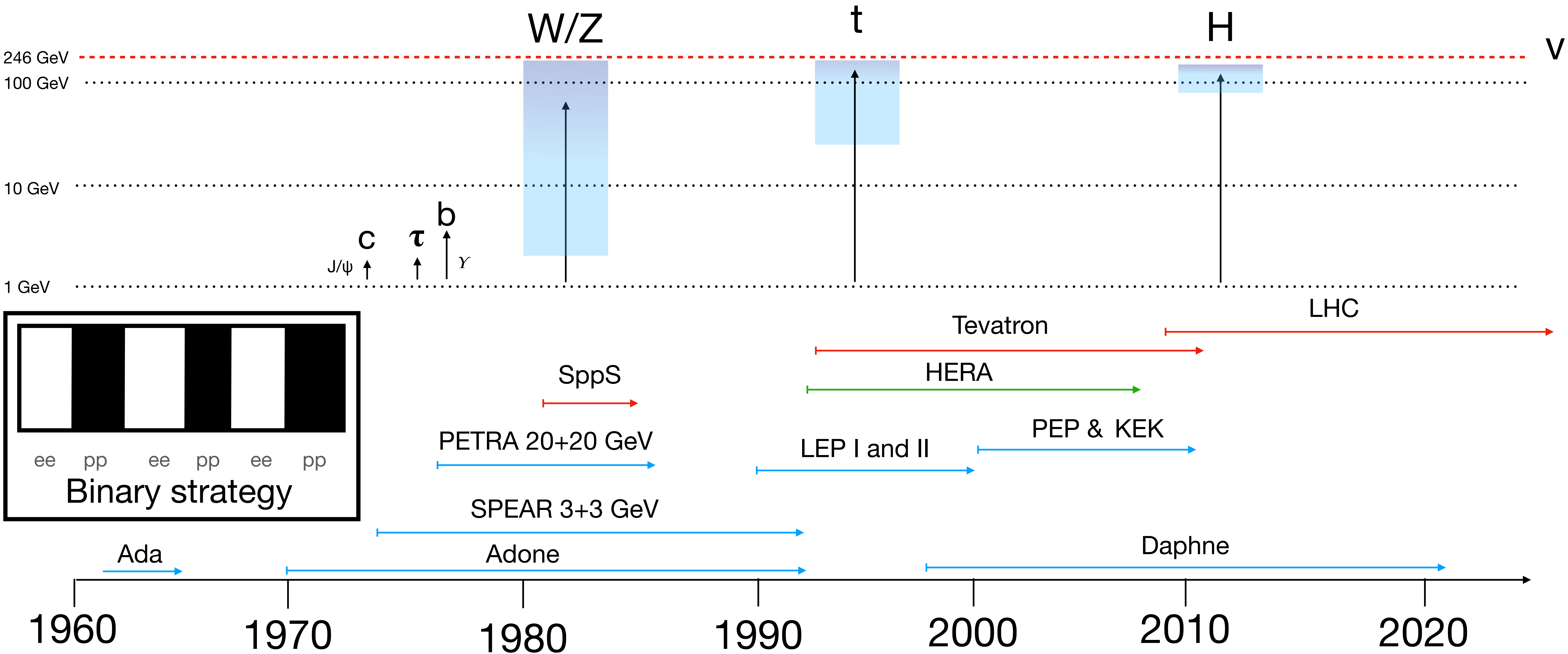
2025 → Benasque

2050 → Europe is the first climate neutral continent

2075 → 0% growth rate of human population

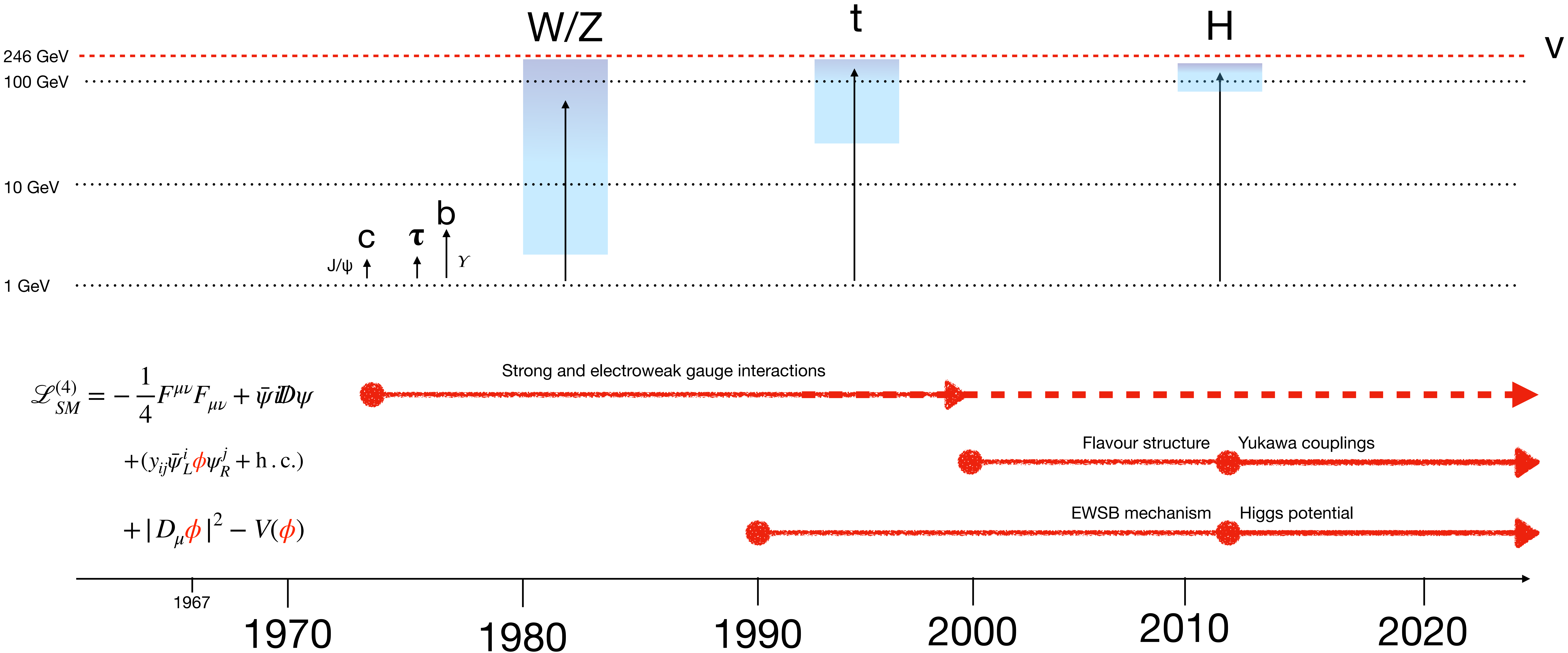
Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



(A) theorist's point of view

The story of collider physics in the last 60 years is the slow yet steady turning of the Standard Model into a Standard Theory for Strong and EW interactions.



$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi$$

Strong and electroweak gauge interactions

$$+(y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.})$$

Flavour structure

Yukawa couplings

$$+|D_\mu \phi|^2 - V(\phi)$$

EWSB mechanism

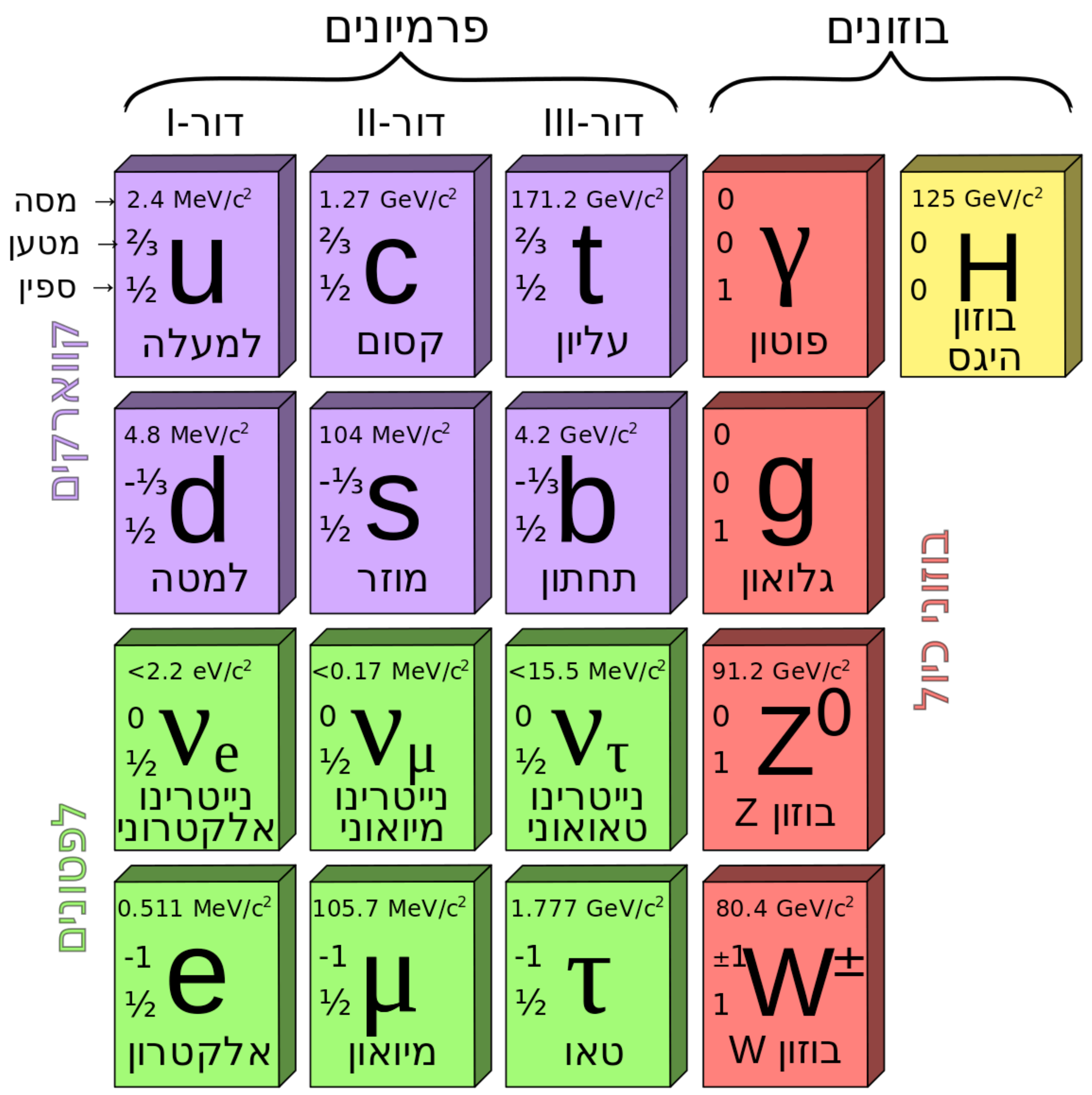
Higgs potential

Where do we stand?

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

3 gauge forces

1 scalar force



- SU(3)$_C$ x SU(2)$_L$ x U(1)$_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The SU(2) x U(1) symmetry is spontaneously broken to U(1)$_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free.
- (Curse of) Renormalizability = valid to “arbitrary” high scales.

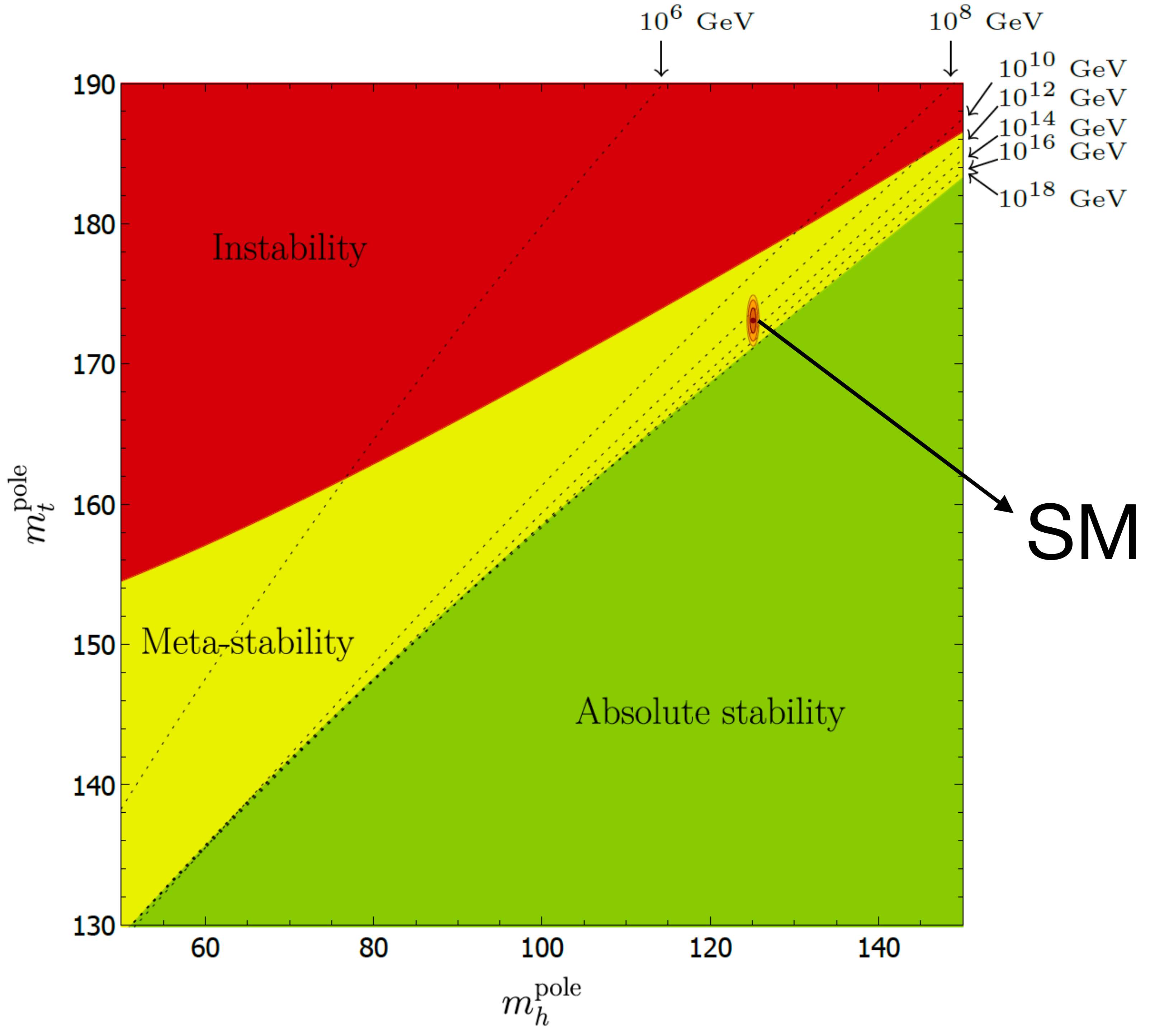
Where do we stand?

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

MF, CPV, Flavour

Custiodial, MV

EWBG



[Andreassen et al. 1707.08124]

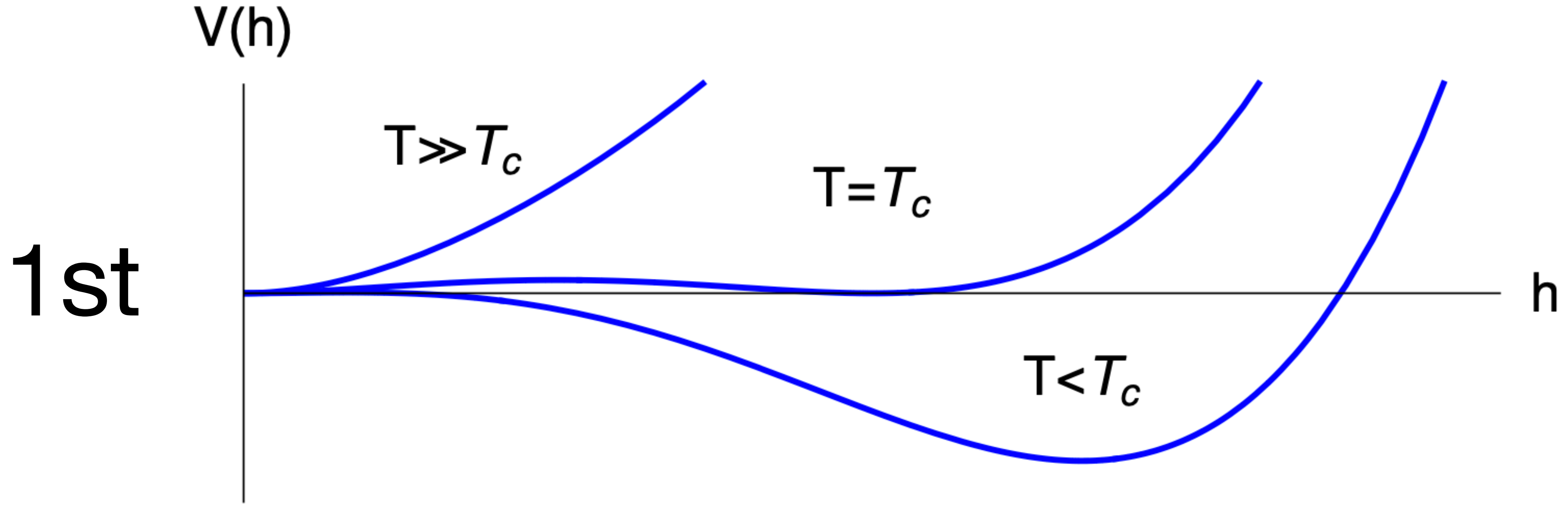
Apparently accidental, but key aspects for successful phenomenology:

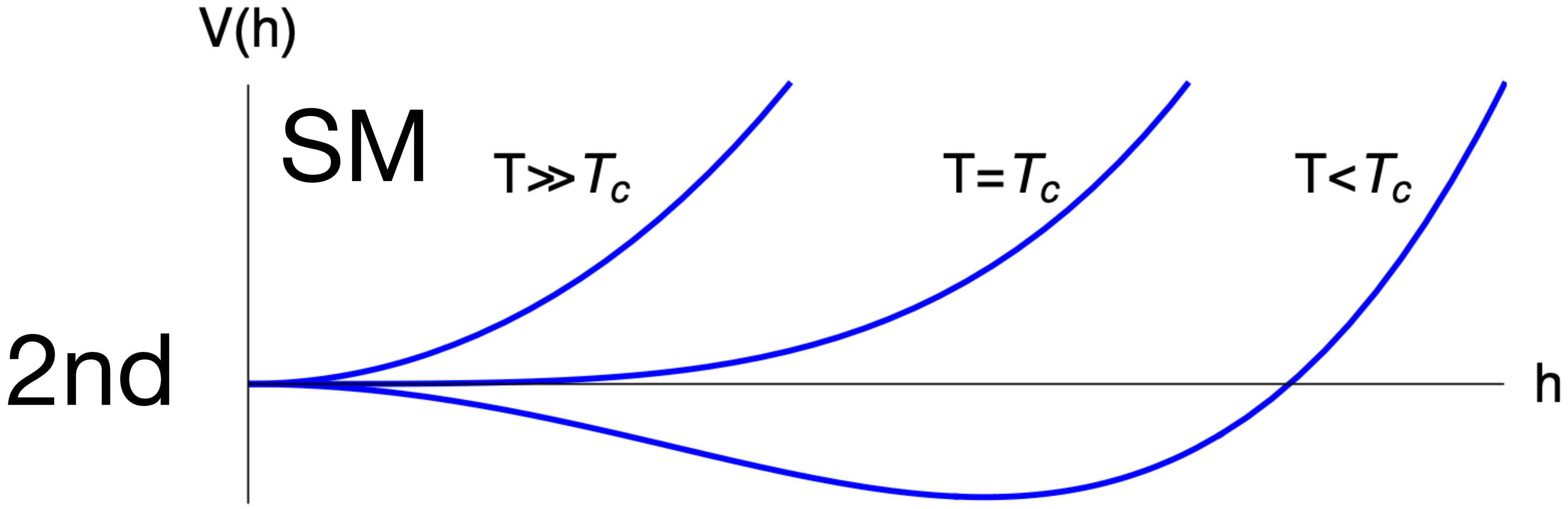
- Lepton and Baryon number conservation
- Custodial symmetry
- Absence of FCN interactions
- Small and hierarchical mixing among quarks
- Collective suppression of CP violation
- IR values of the parameters do not indicate any problem at high scales, including vacuum stability
- Neutrino masses can be accommodated in a natural way

All these aspects are not only difficult to explain in one go, but are also typically not respected by extensions of the SM.

Where do we stand?

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi + (y_{ij}\bar{\psi}^i_L\phi\psi^j_R + \mathrm{h.c.}) + |D_\mu\phi|^2 - V(\phi)$$



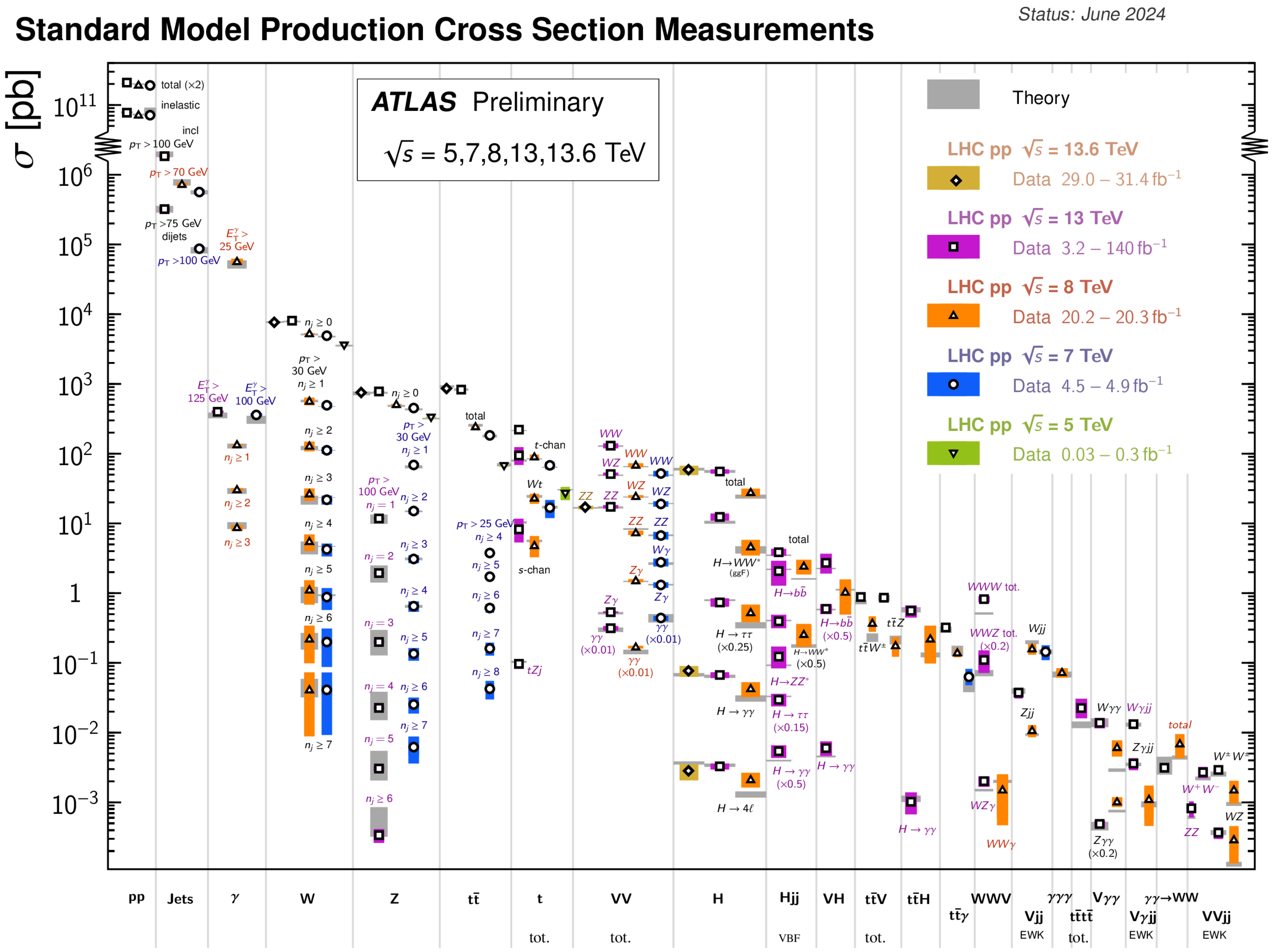


Yet many aspects of the SM are problematic vis-à-vis phenomenology:

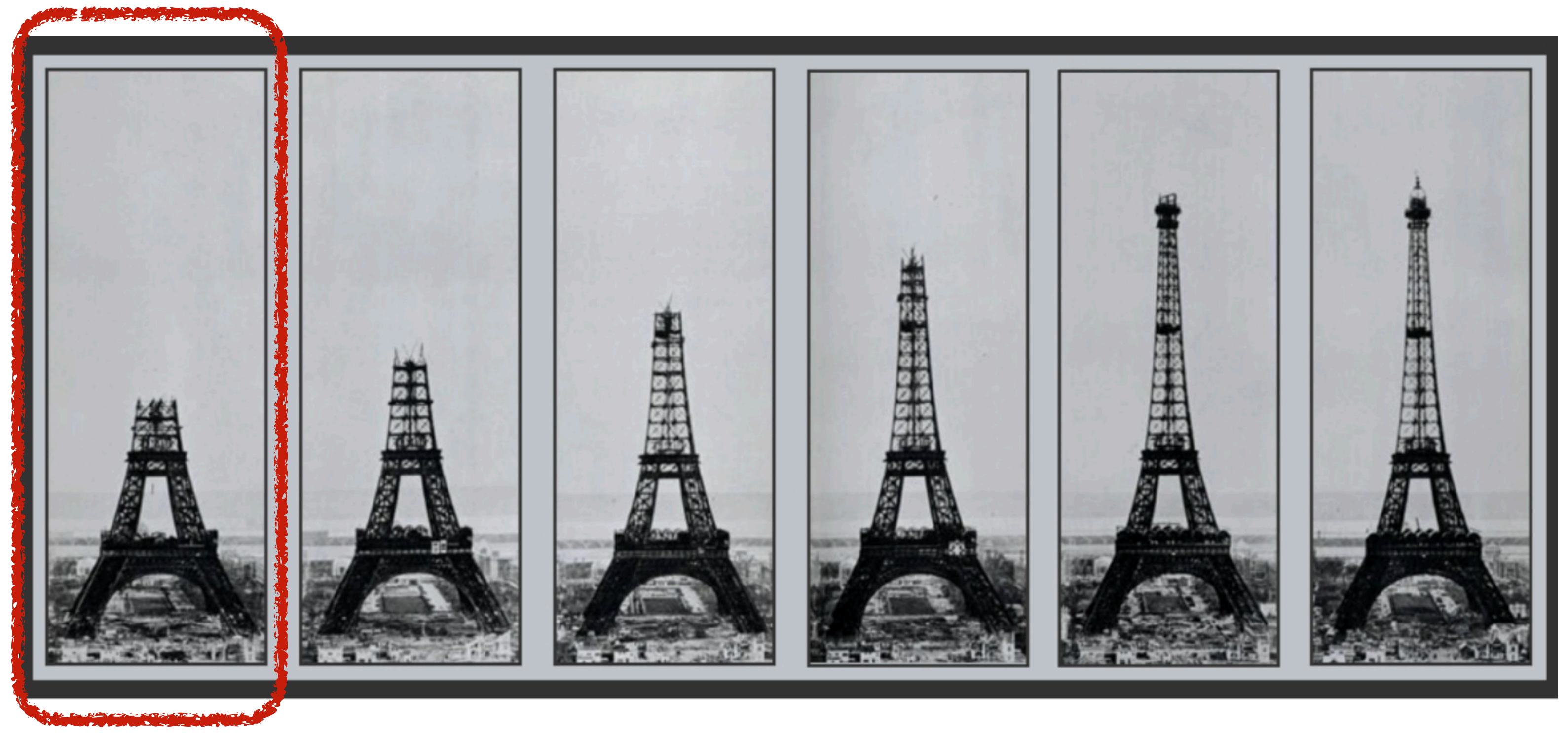
- EWBG difficult because of smallness of CPV and no 1st order transition
- Nature of Dark Matter
- Unnaturally small Higgs mass
- Unnaturally small strong CP violation
- Fermion mass hierarchy

Beyond SM theories typically address one of the above problems at the time. We don't have a precise idea of where the scale of NP might reside.

Where do we stand?



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).
- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



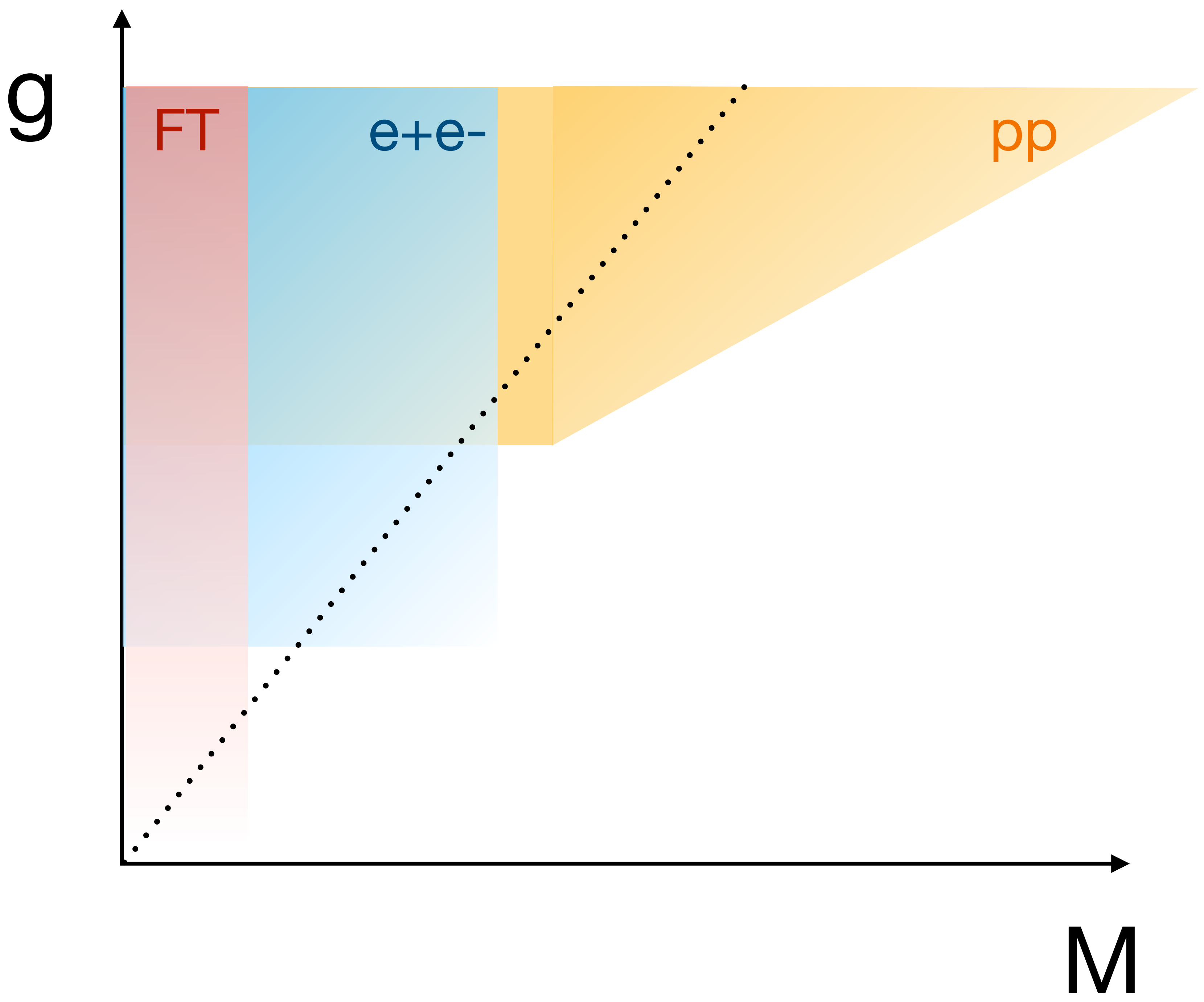
A quote

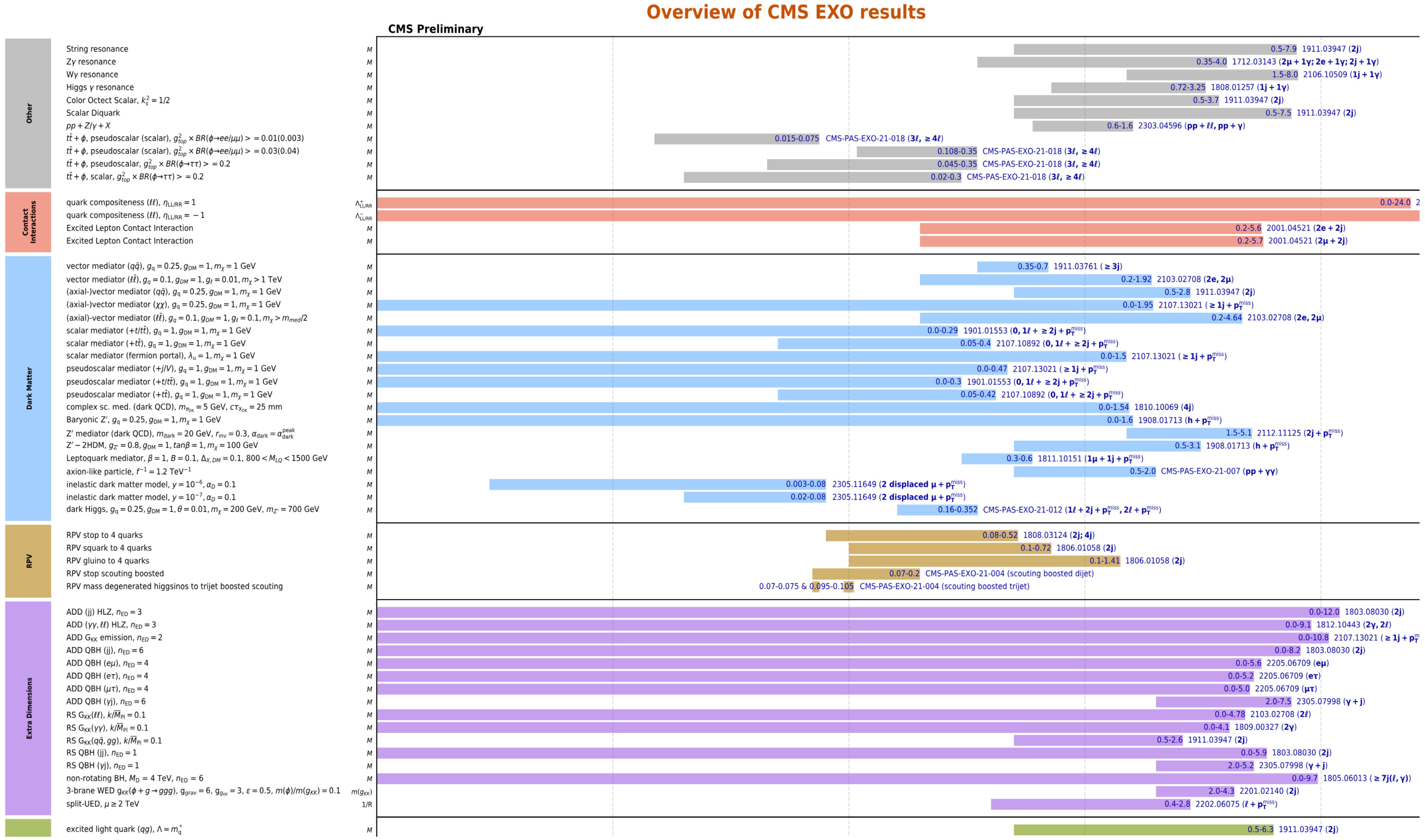
[S]He who knows the art of
the direct and the indirect approaches
will be victorious.

Sun Tzu, The Art of War

Λ_{BSM} is low

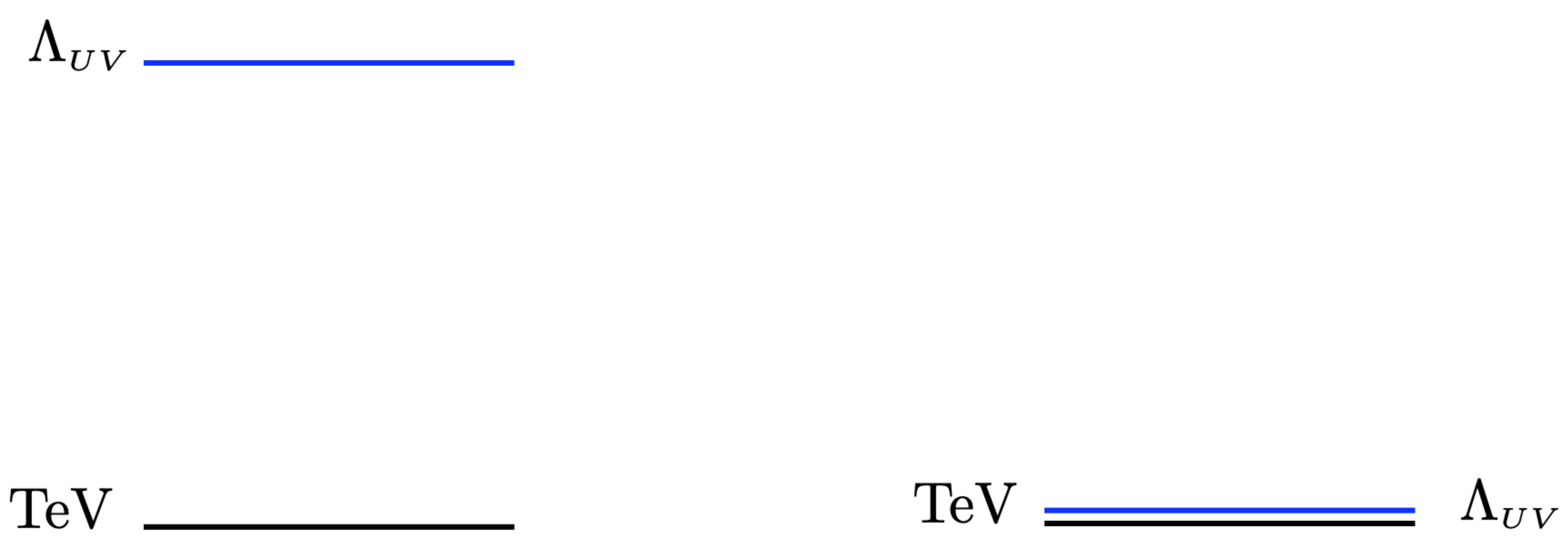
BSM direct searches





$\Lambda_{\rm BSM}$ is high

Effective field theory



Simplicity 🙂

Naturalness ☹️

Naturalness 🙂

Simplicity ☹️

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

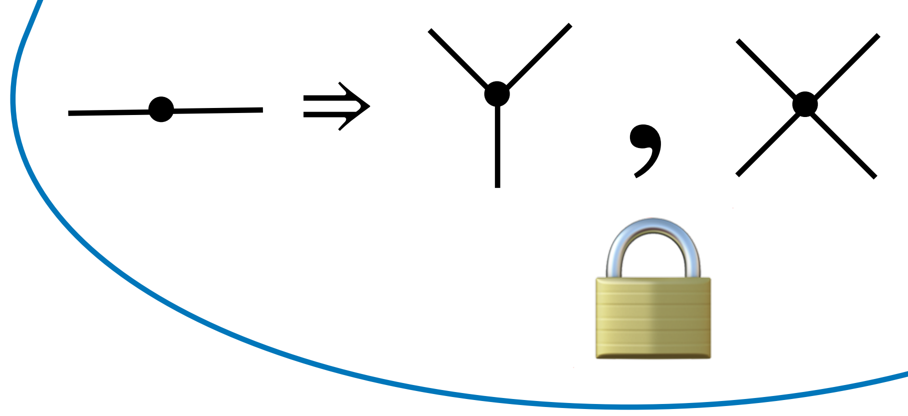
$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ ~~Flavor~~ & ~~CP~~



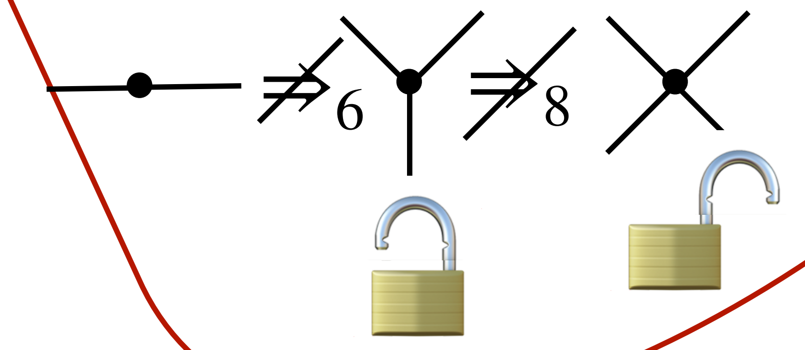
$\cancel{U(1)}_L \rightarrow m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

~~Flavor~~ $\Rightarrow \mu \rightarrow e\gamma, \Delta m_K, \dots$ $\Rightarrow \Lambda \geq 10^{6}$ GeV

~~CP~~ $\Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

$U(1)_B \Rightarrow p \rightarrow \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

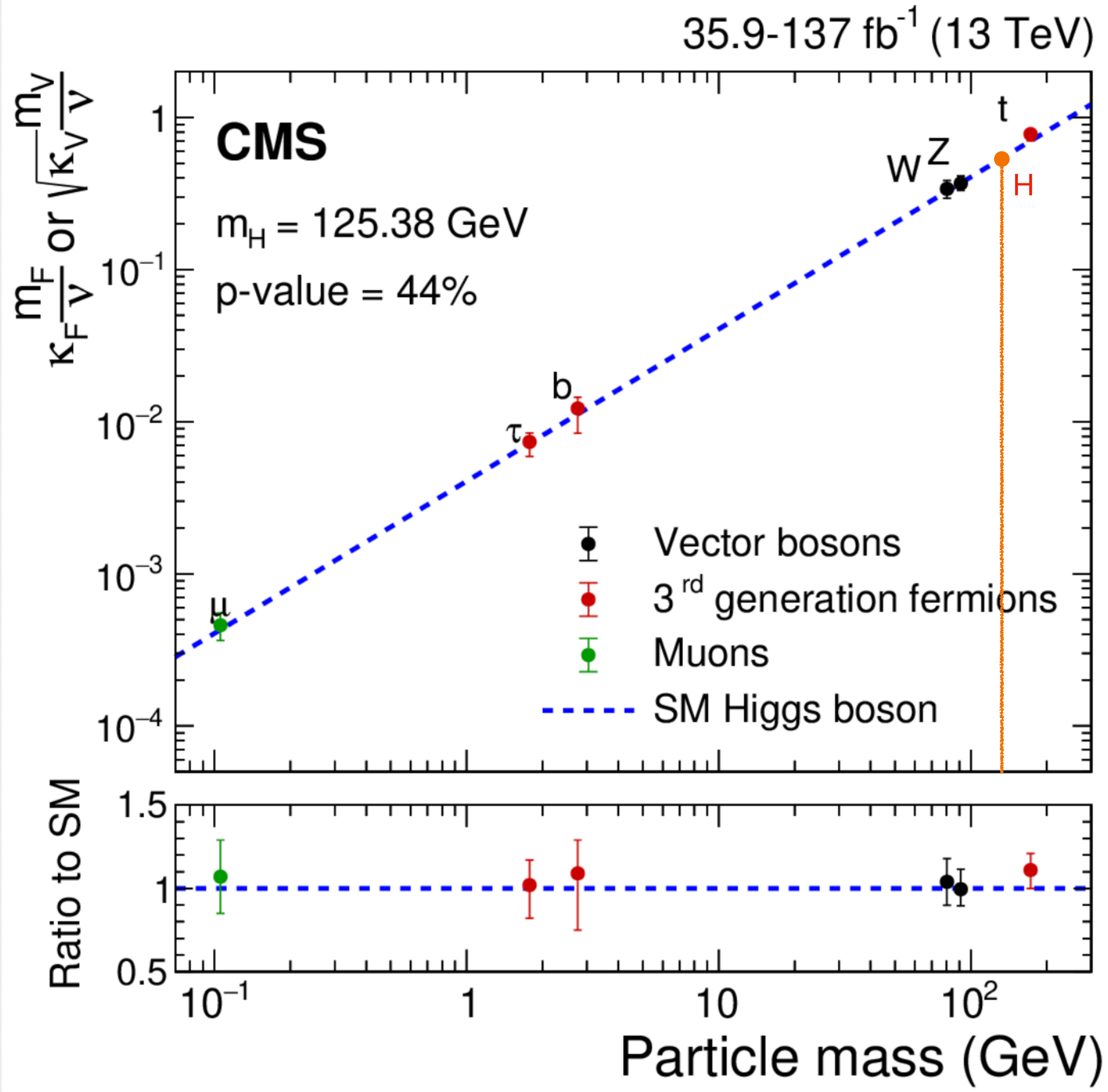


$\Rightarrow \Lambda \geq 10^{3}$ GeV

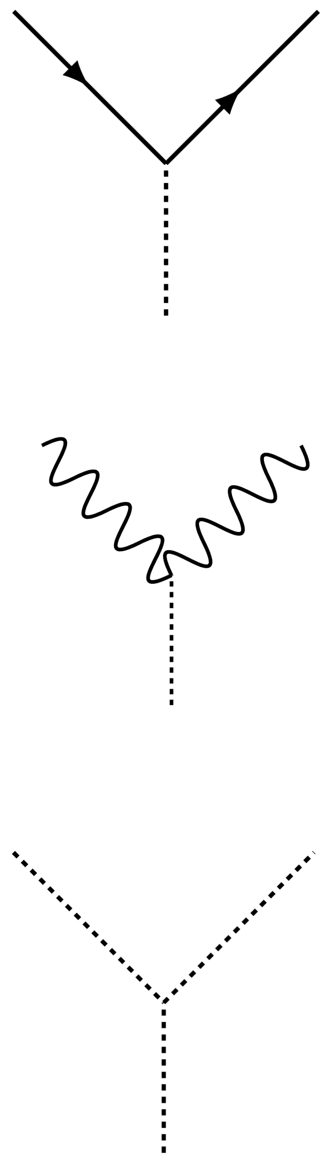
Rattazzi®GGI tea break

Present

Higgs couplings



Unique mass generation mechanism for fermions/vectors and the scalar.



$$i\,m_f/v$$

$$igm_W g_{\mu\nu} = 2i\,vg_{\mu\nu}\cdot m_W^2/v^2$$

$$ig\frac{m_Z}{\cos\theta_W}g_{\mu\nu} = 2ivg_{\mu\nu}\cdot m_Z^2/v^2$$

$$-3\,iv\cdot m_h^2/v^2$$

} + 4 point interactions.

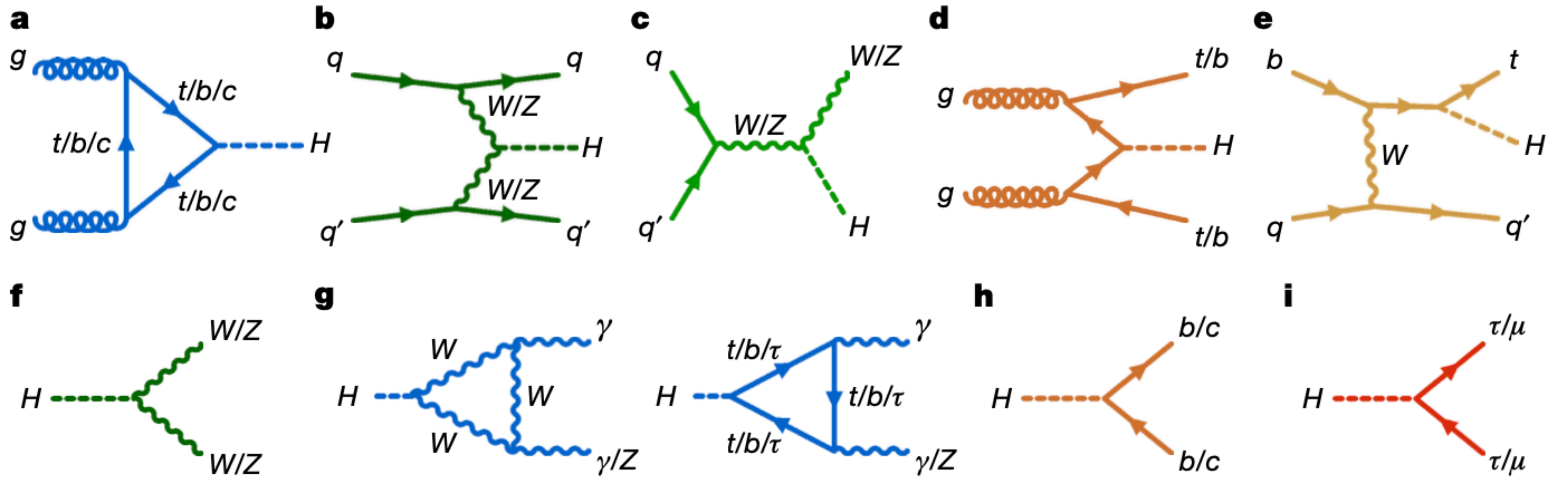
$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 vH^3 + \frac{\lambda_4}{4}H^4 + \dots$$

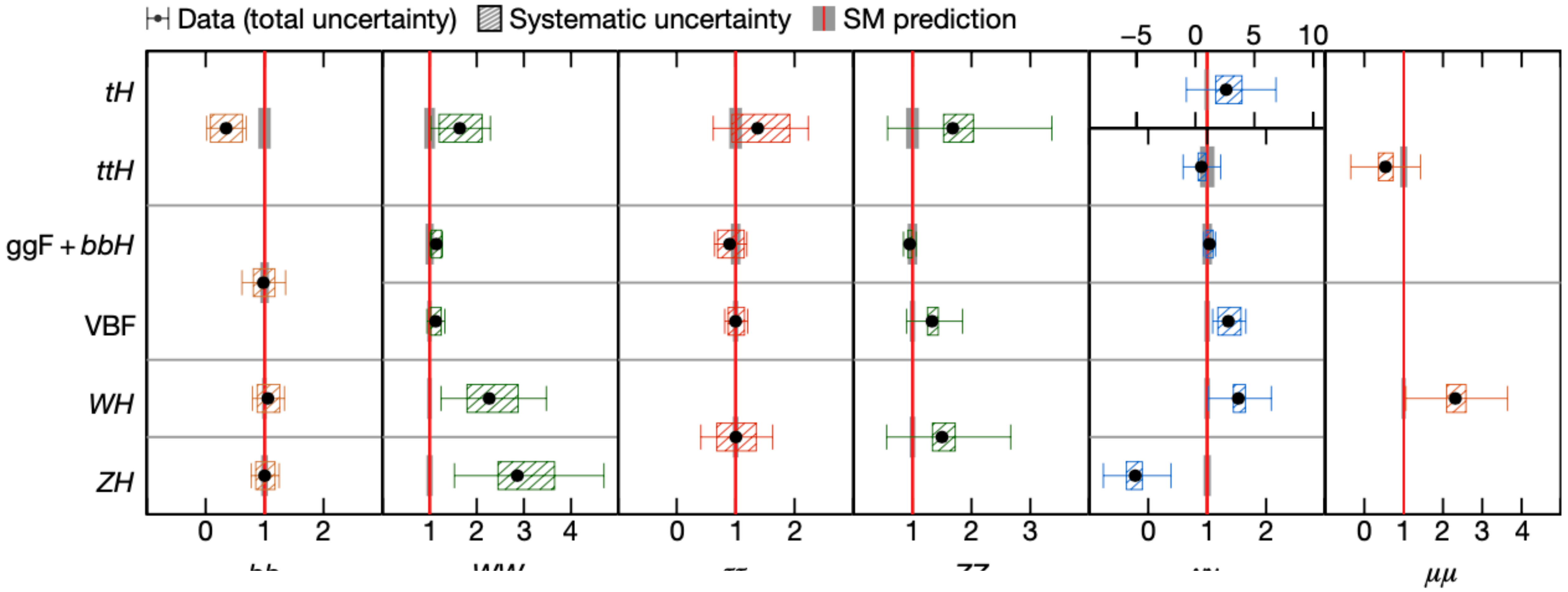
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

In the SM gauge invariance + SSB => constrained system. Two-point functions (propagators/masses) fix the 3-point and 4-point interactions!

Present

Higgs couplings





$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.})\ \pm 0.03\,(\text{exp.})\ \pm 0.04\,(\text{sig. th.})\ \pm 0.02\,(\text{bkg. th.}).$$

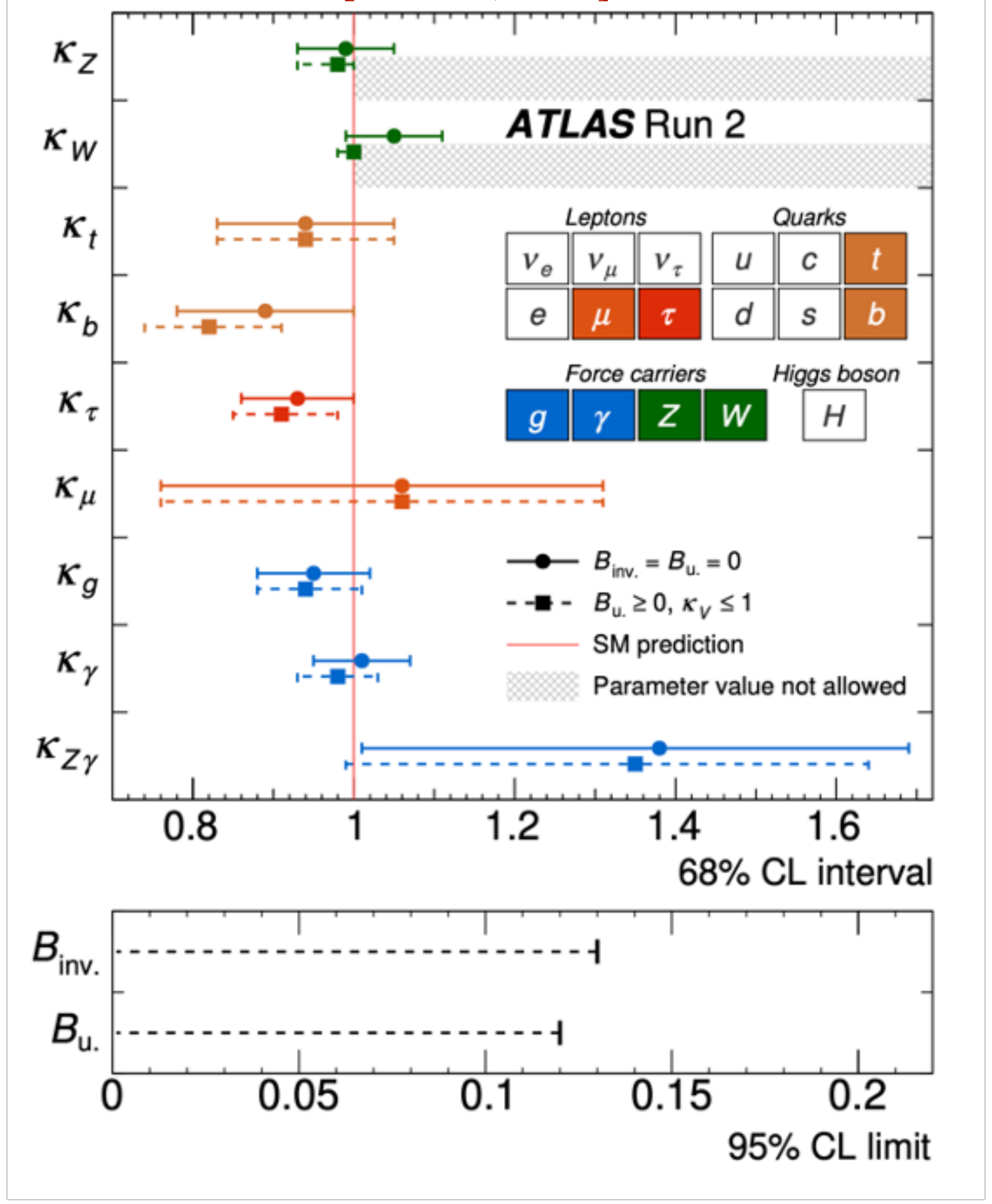
Since its discovery, impressive advances in our understanding of the Higgs boson's properties have been achieved. At this moment, the new scalar seems consistent with the expectations of the SM, with different degrees of precision yet order 10%, in all measured channels.

Need to explore 2nd and 1st fermion generation and Higgs potential.

The Higgs future

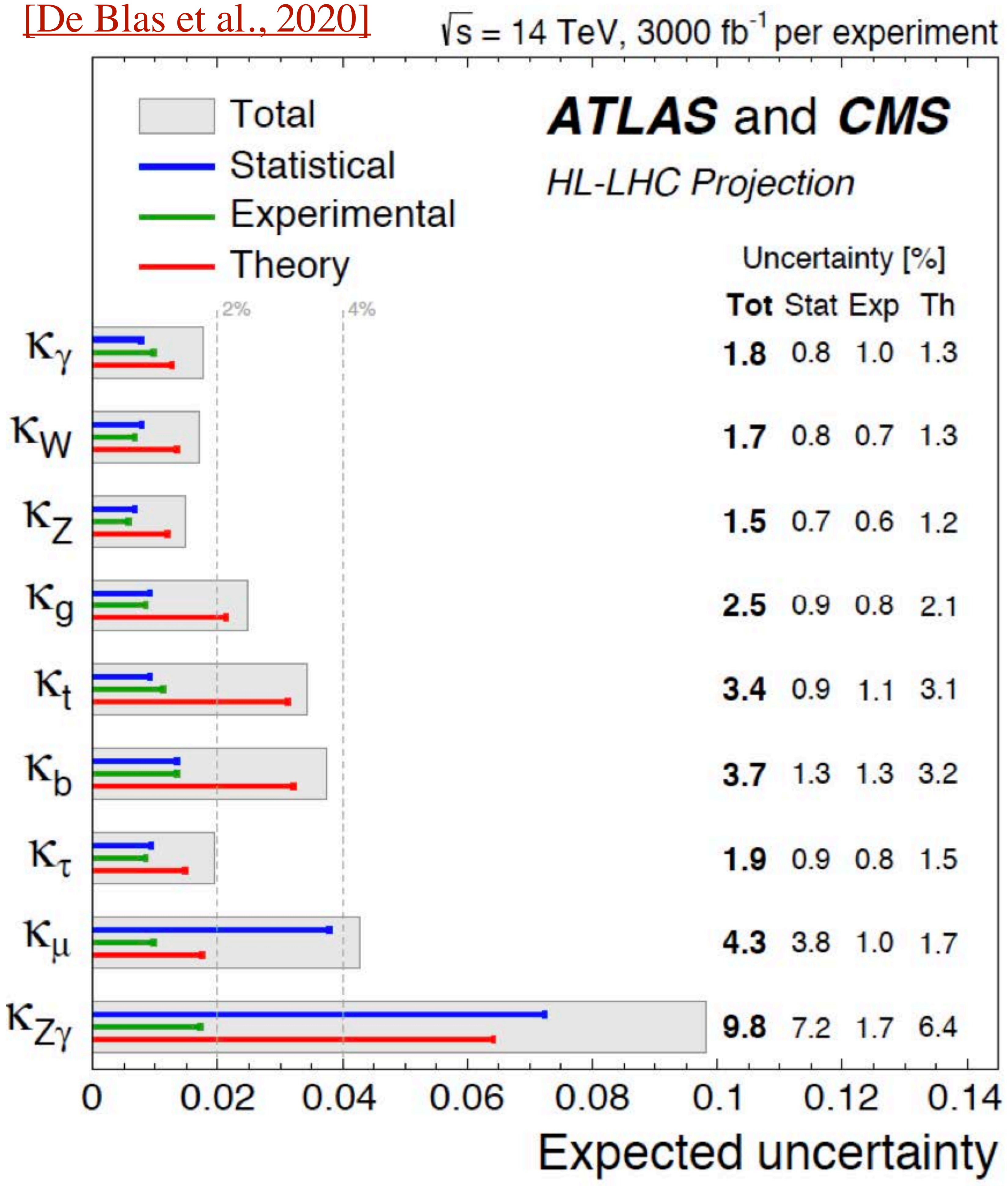
Couplings at HL-LHC

[ATLAS, 2024]



10-20% → 2-4%

[De Blas et al., 2020]



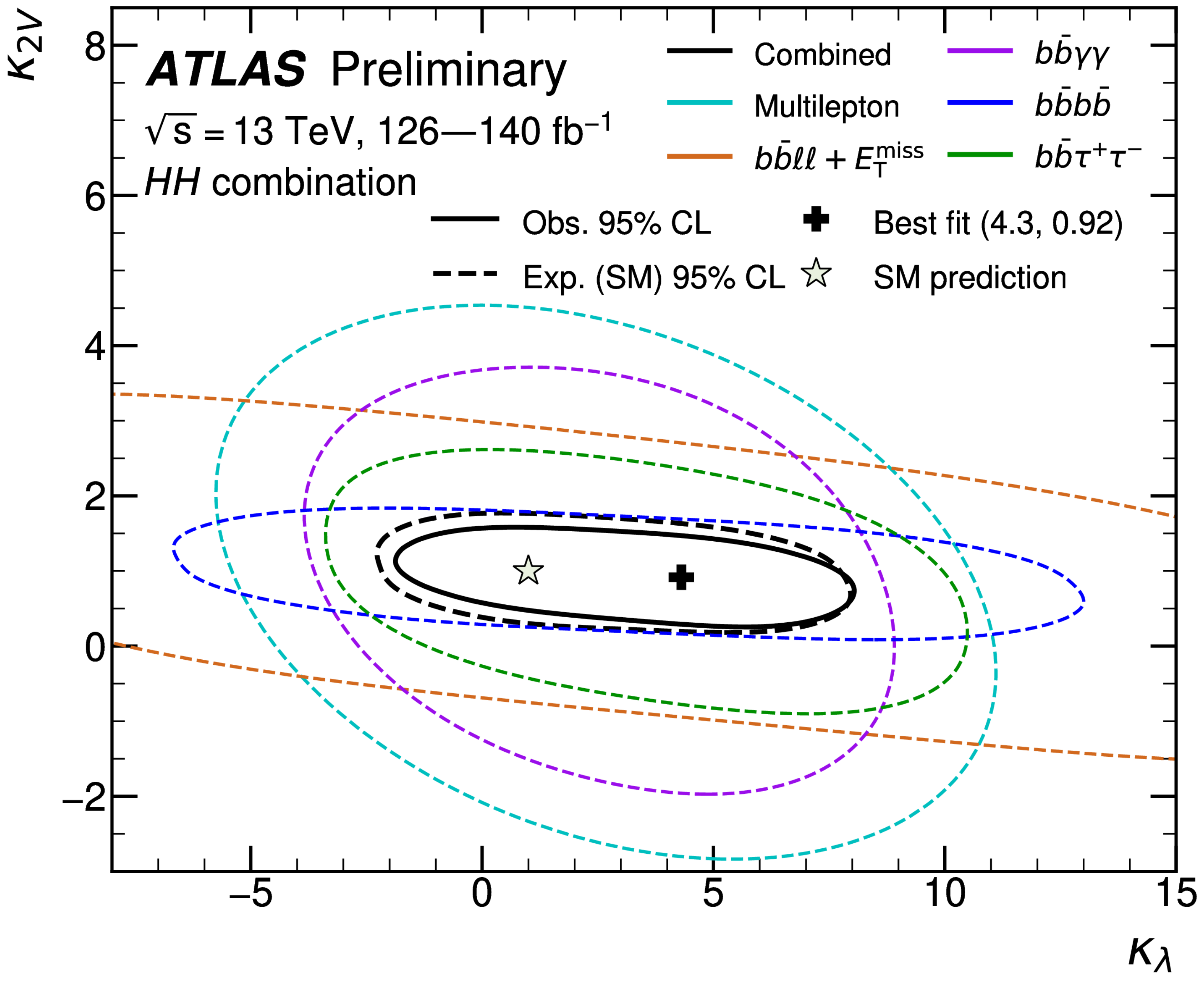
$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}\quad\rightarrow\quad\mu_i^f\equiv\frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}}=\frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

HL-LHC projections

Higgs self-coupling

Now

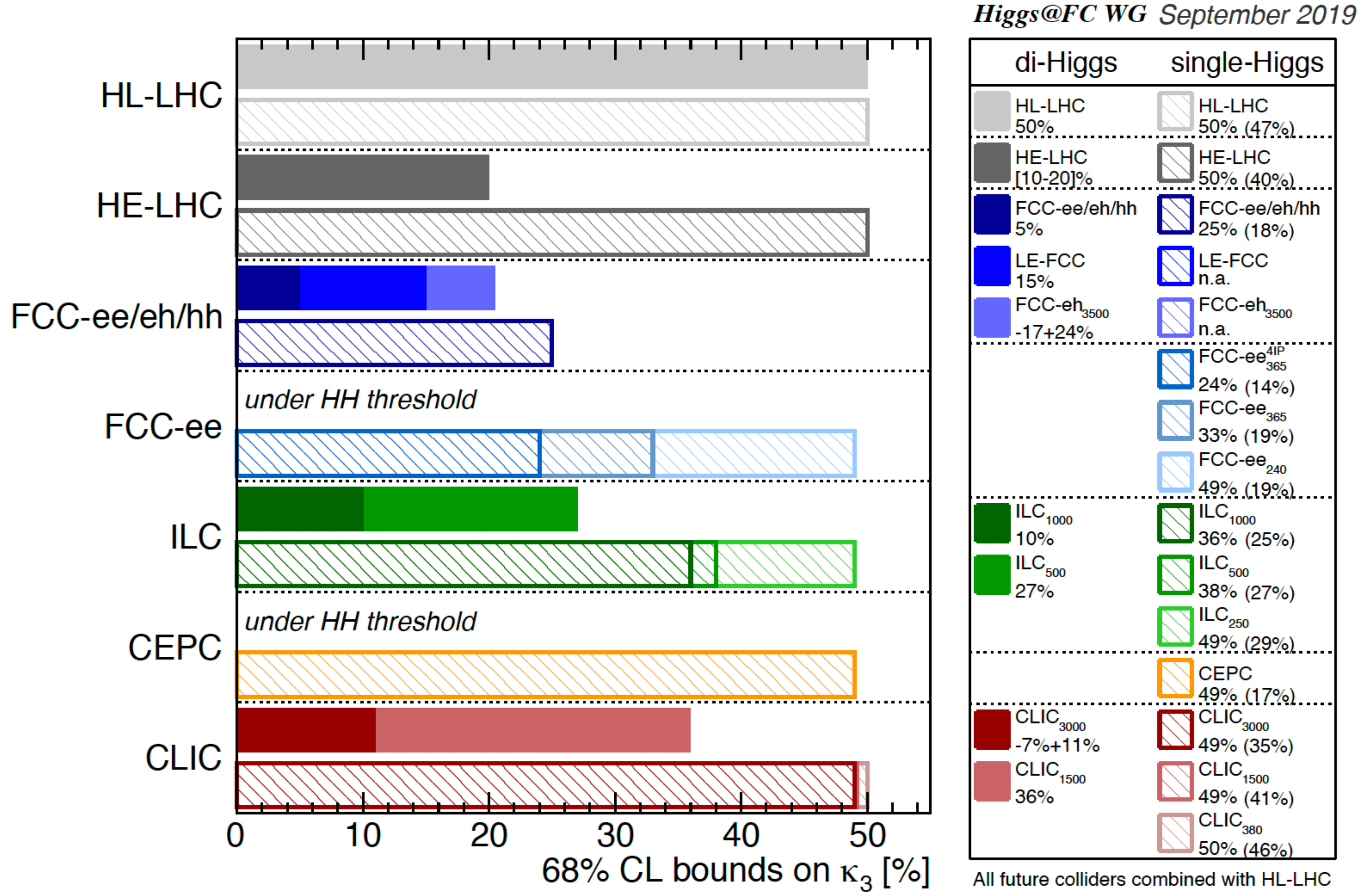
[ATLAS, 2024]



Current limits on k_λ and k_{2V}

Future

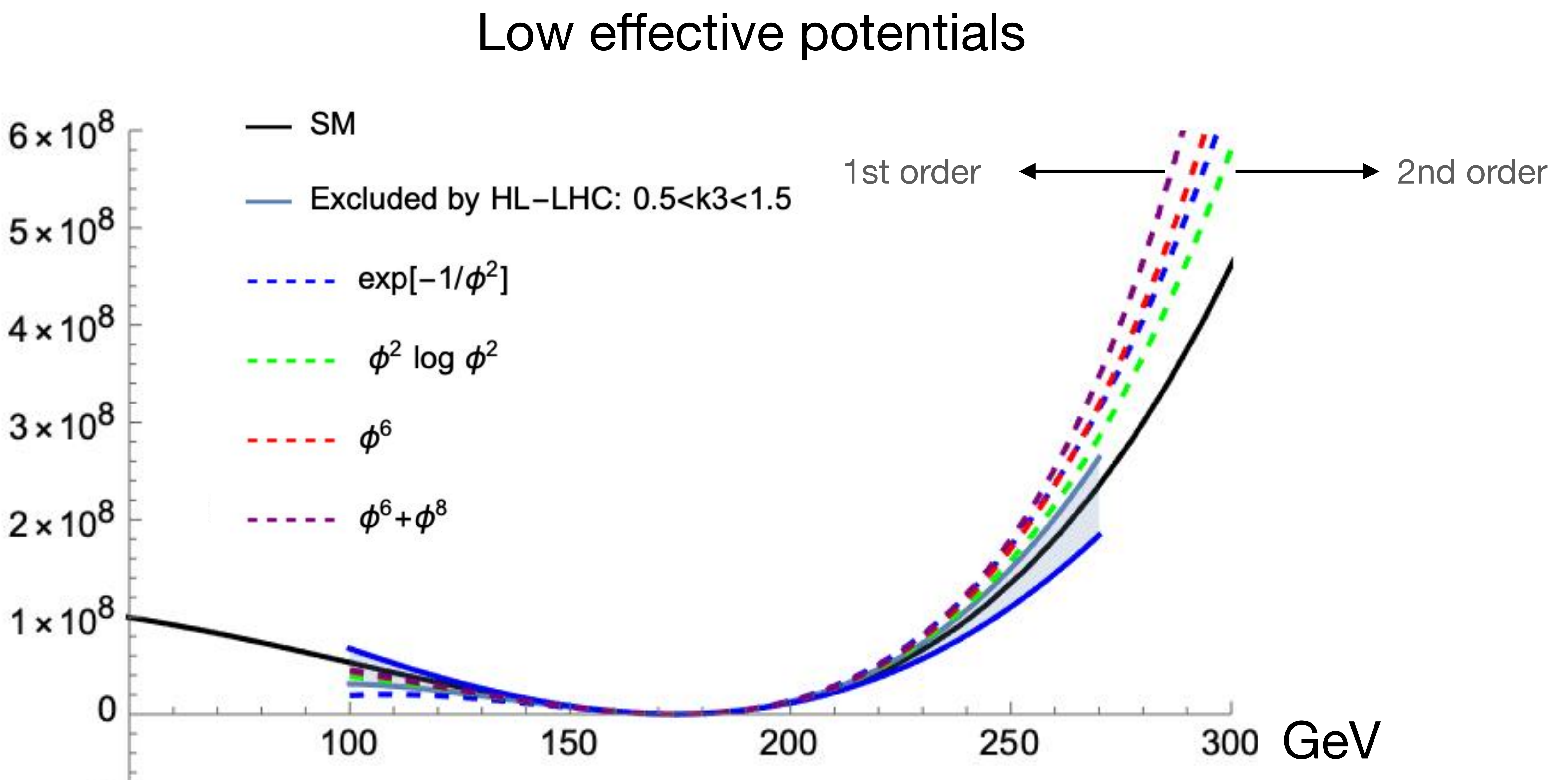
[De Blas et al., 2020]



Future limits on k_λ

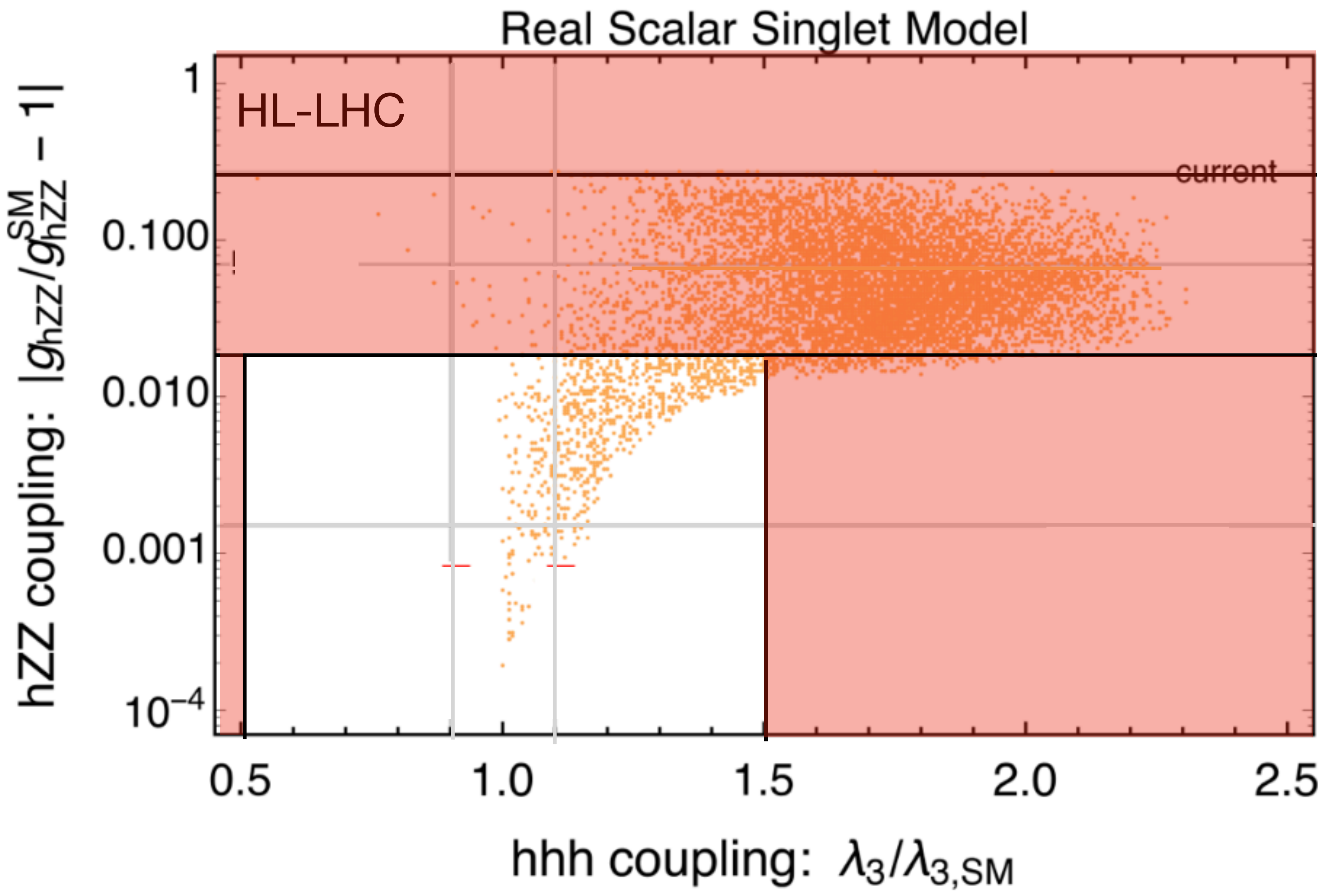
HL-LHC projections

Higgs potential



Plot based on the results of 1711.00019 [hep-ph]

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

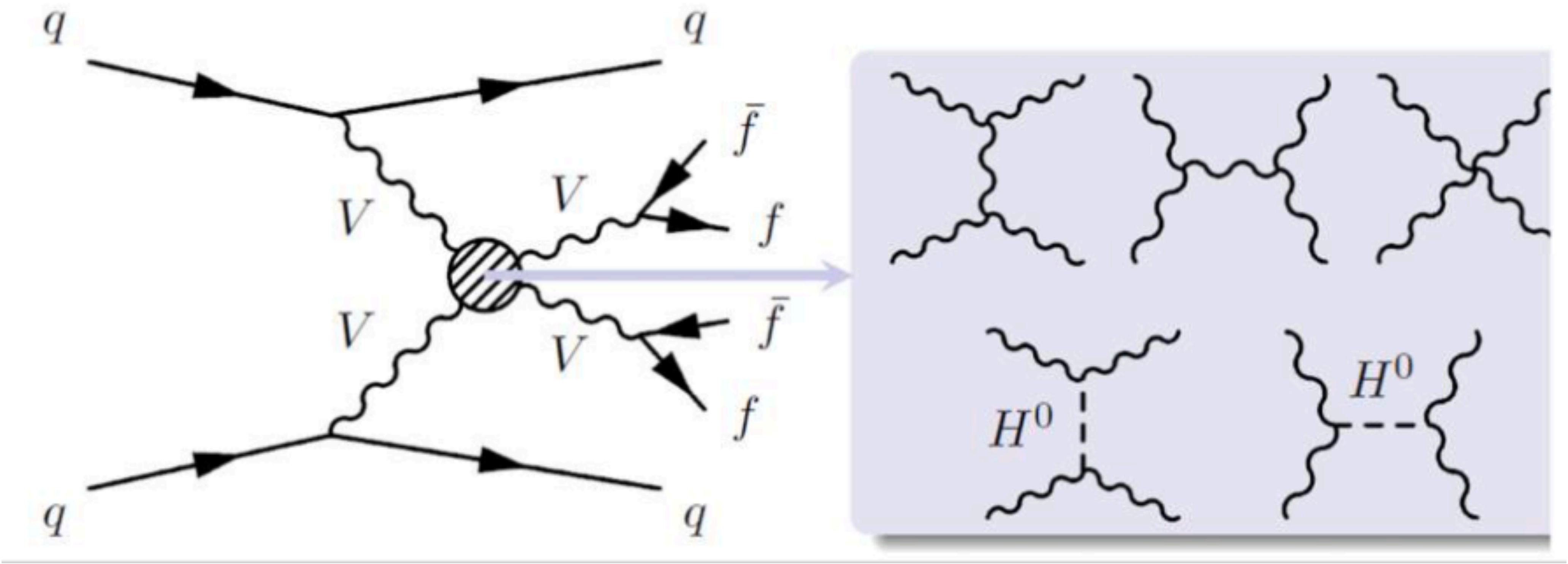


FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

HL-LHC projections

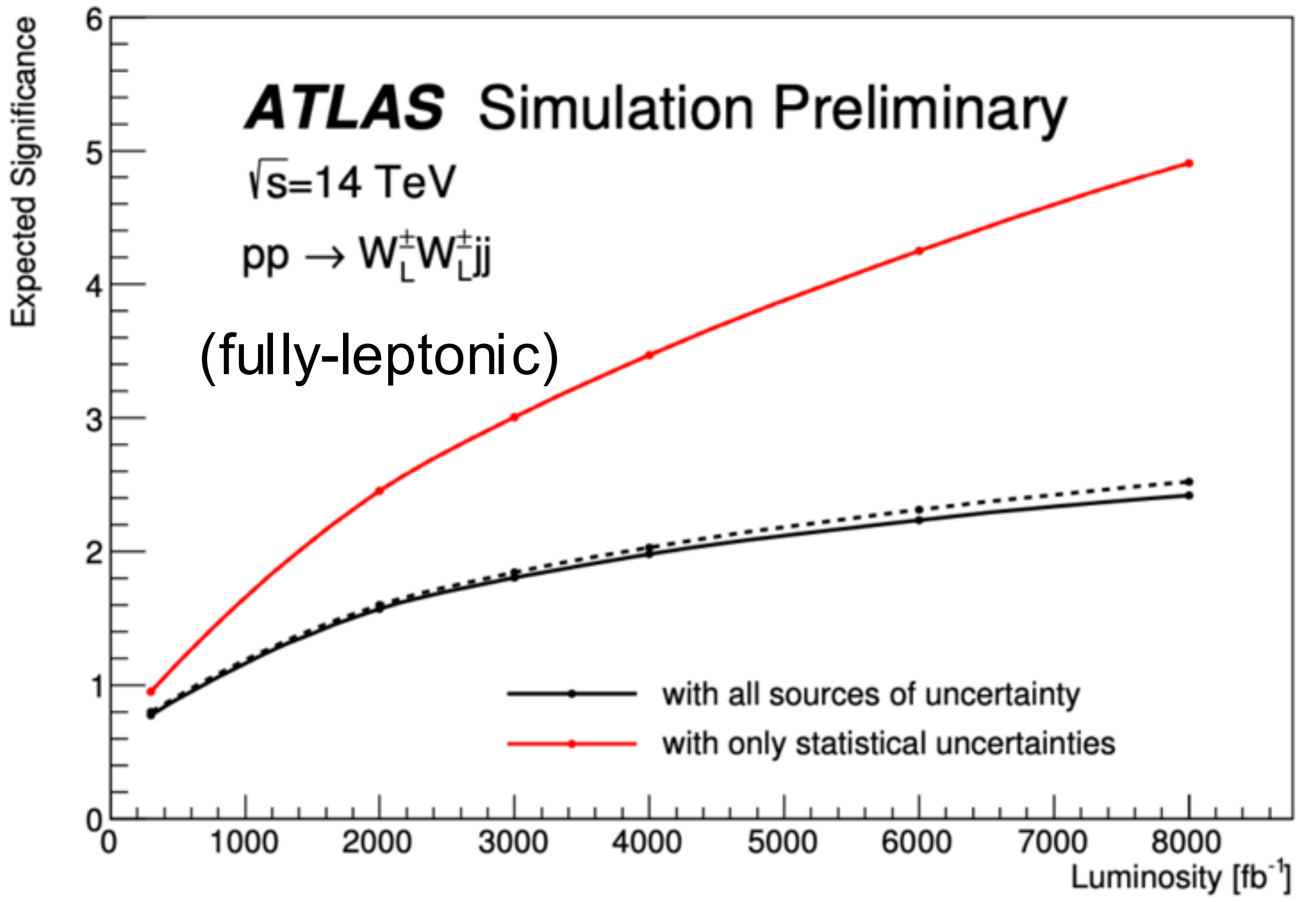
VV scattering



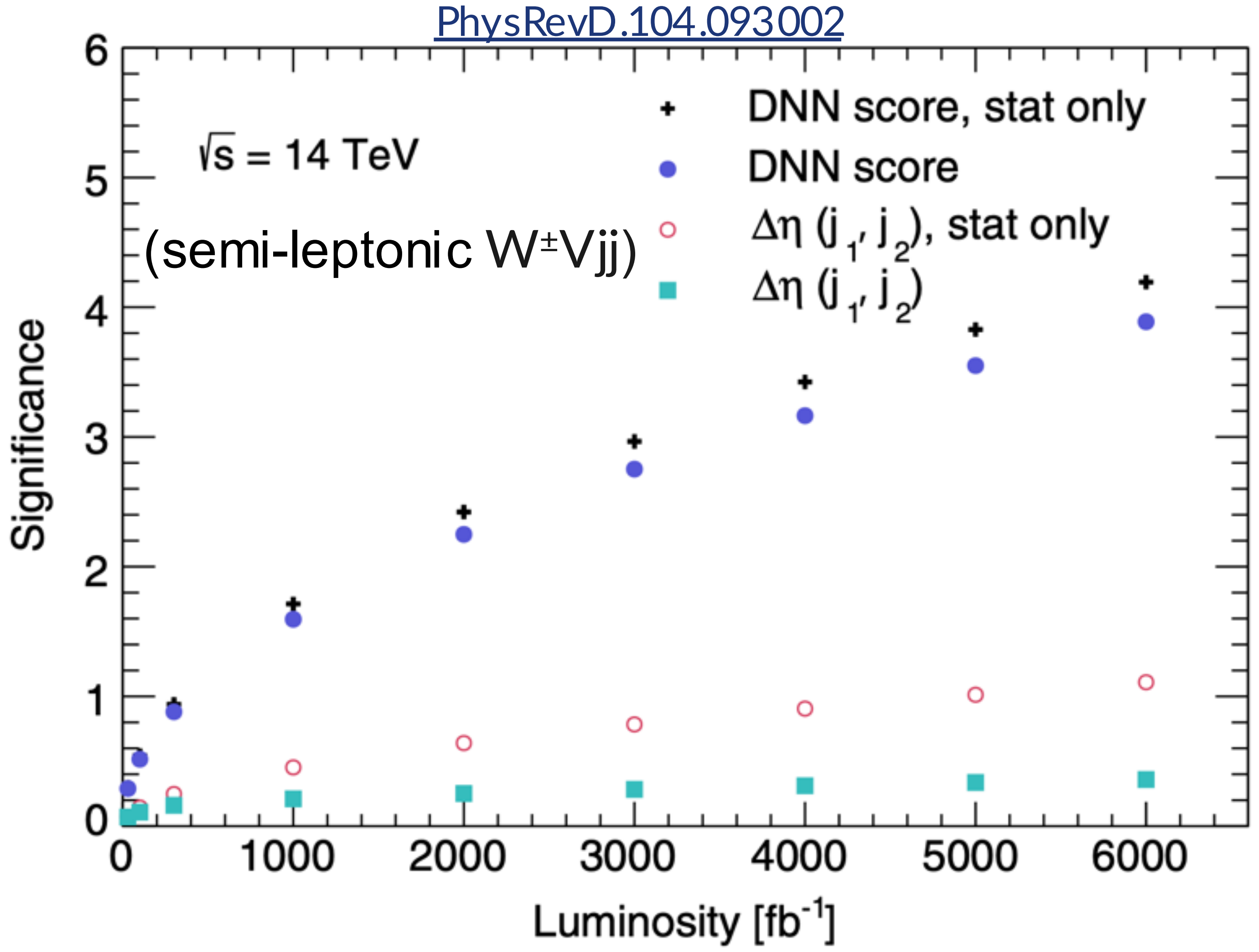
[Mwewa, FCC-hh kick-off meeting]

- Access to longitudinally polarized W±W±jj is challenging at the LHC
  - Cross-section is very small (less than 10% of the total W±W±jj scattering cross-section)

ATL-PHYS-PUB-2018-052



PhysRevD.104.093002



Expected significance at the HL-LHC with 3000 fb^{-1} of data is below 5σ

3

Considering all channels, and both experiments we could get at 5 sigma level for LL at 3 iab.

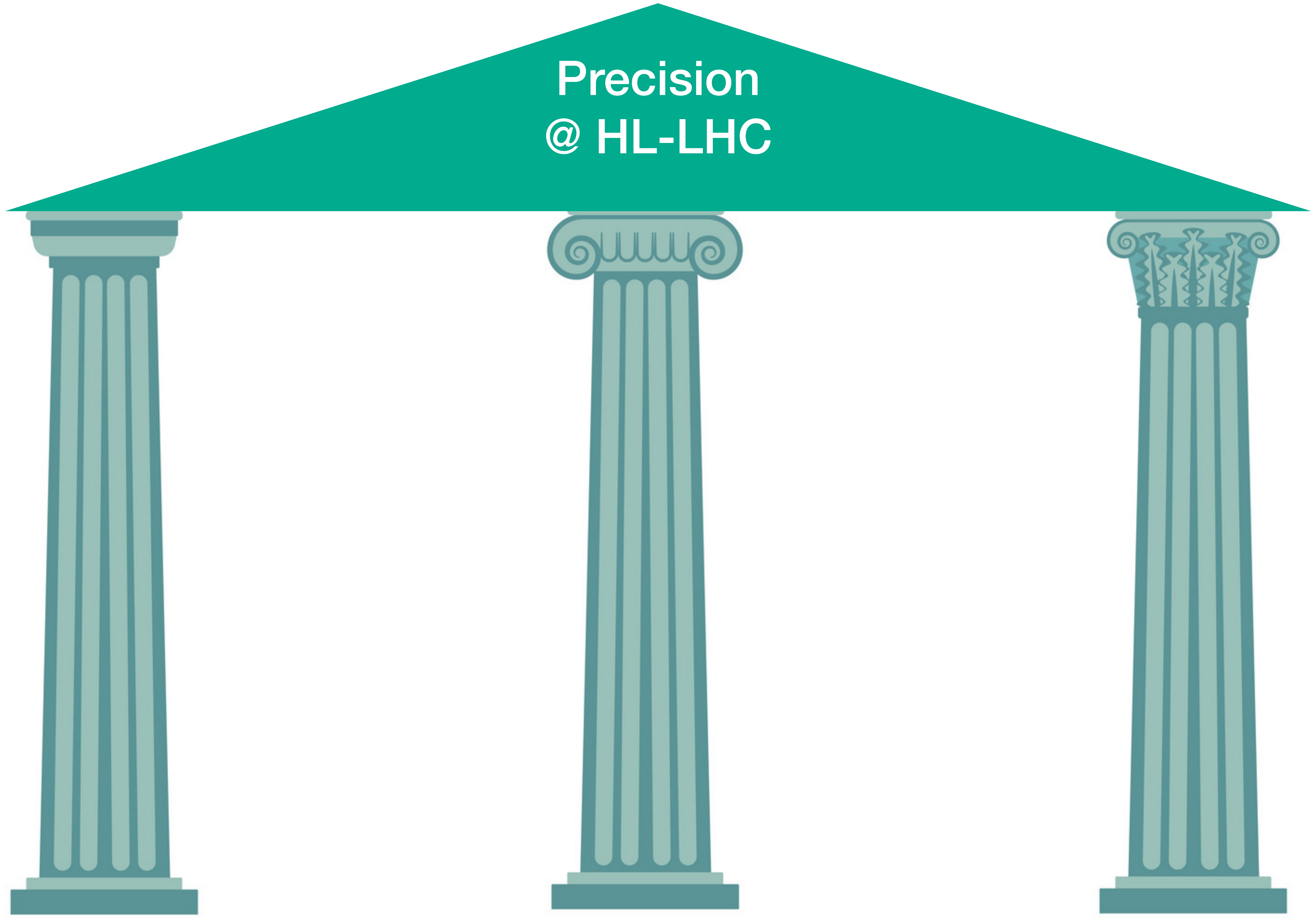
The precision goal

Hubble 1990

JWT 2022

Theoretical challenges of the HL-LHC

Status



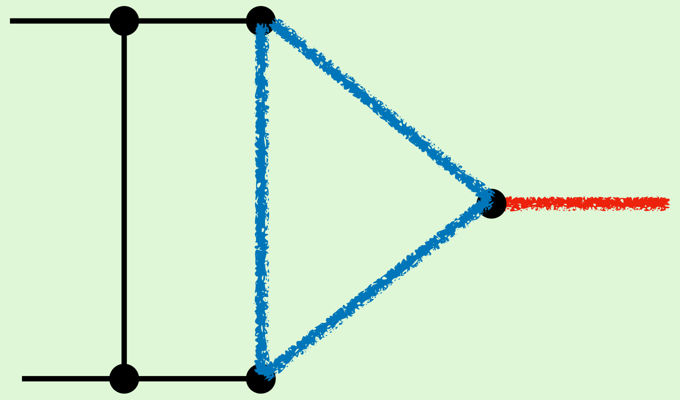
Fixed Order
LO, NLO,…
QCD EW

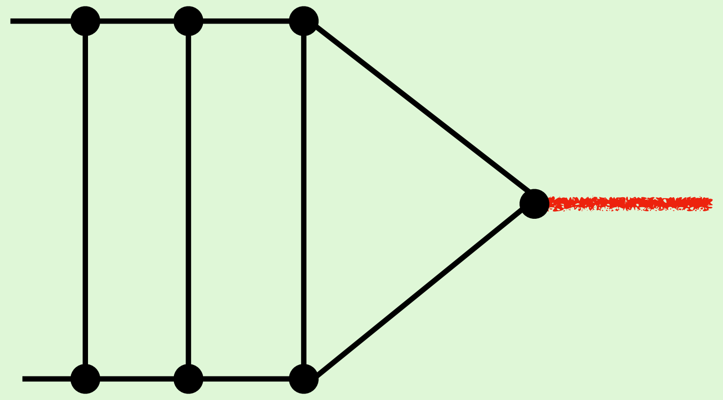
Resummation
LL, NLL,…
Parton Showers

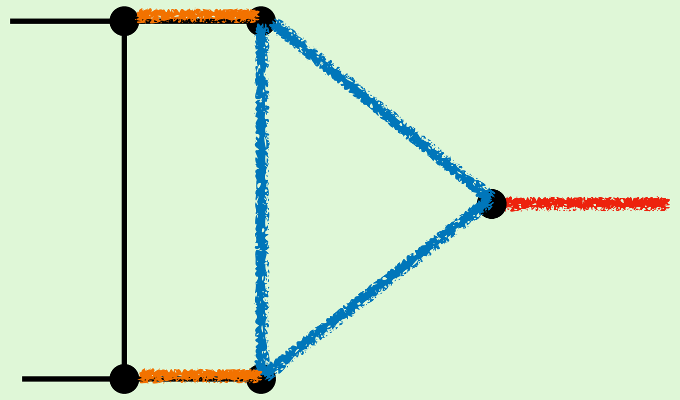
PDF’s
LO,NLO,..Evolution
Fits

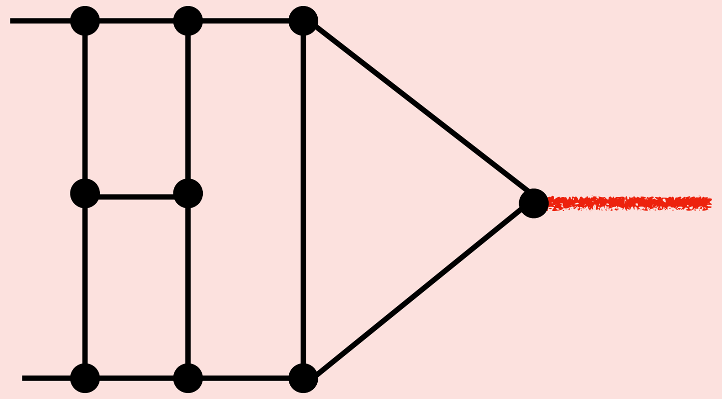
The multi-loop frontier

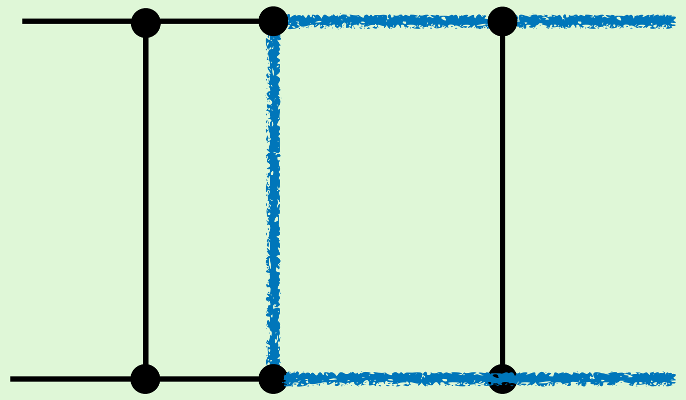
DONE

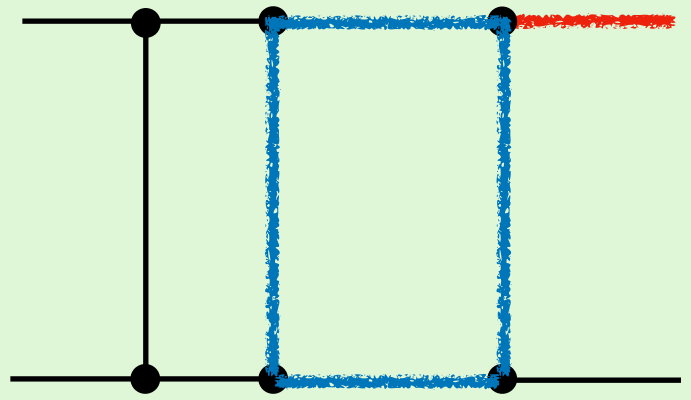

H,Z,W at N2LO$_{\text{QCD}}$

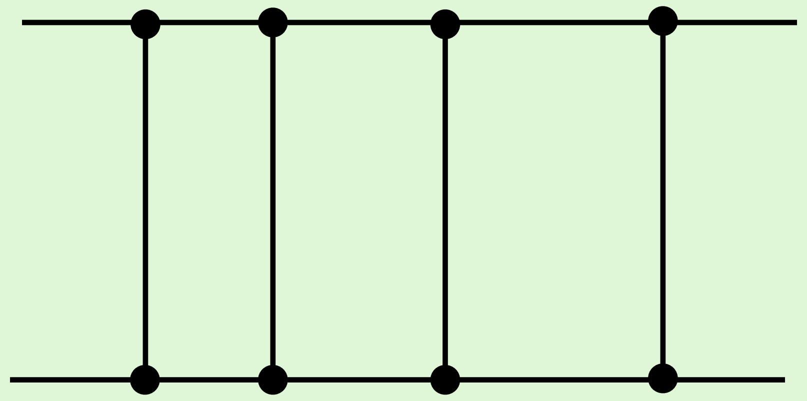

H,Z,W at N3LO

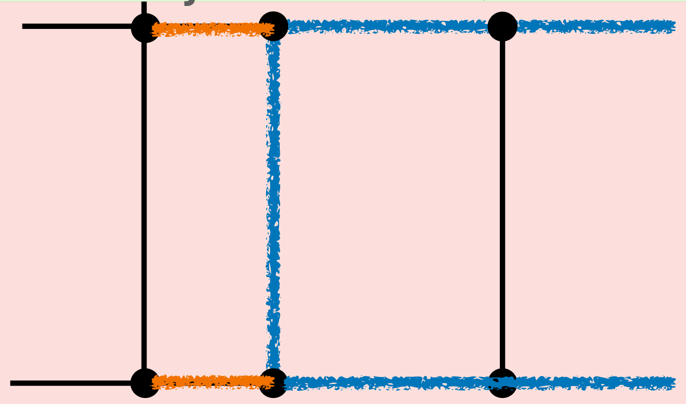

H,Z,W at NLO2$_{\text{EWxQCD}}$

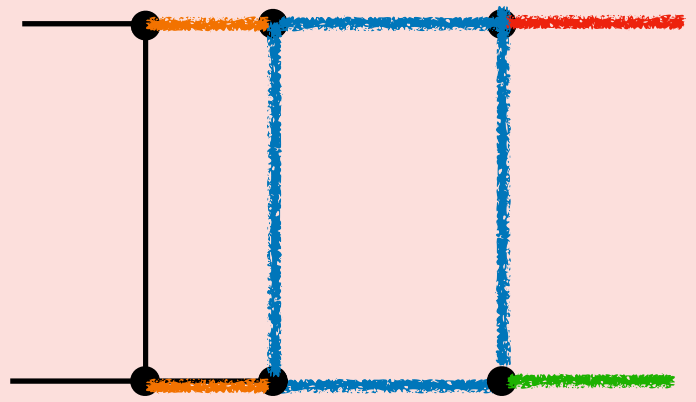

H,Z,W at N4LO$_{\text{QCD}}$

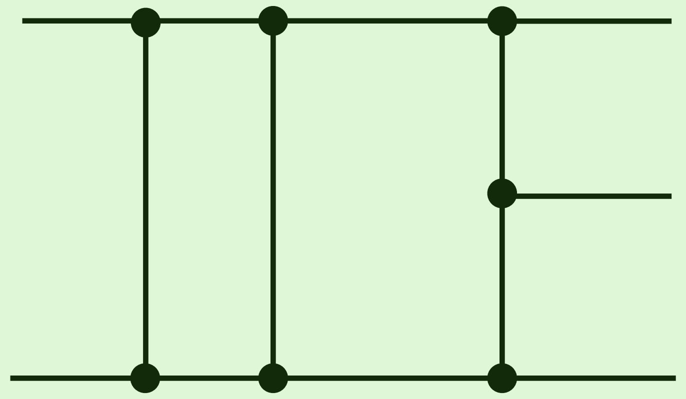

tt at N2LO$_{\text{QCD}}$


H+j at NLO$_{\text{QCD}}$

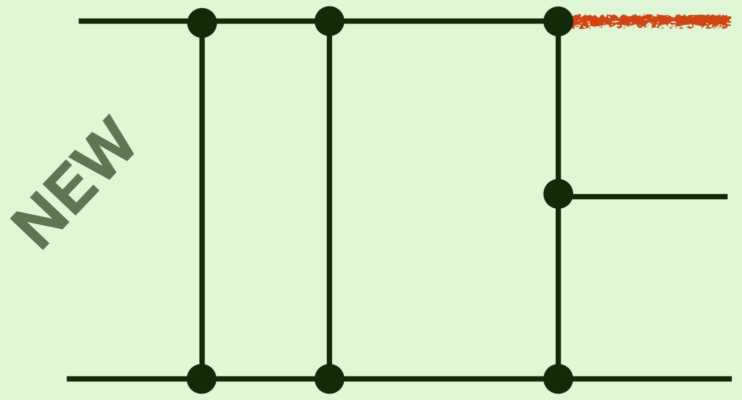

2j at N3LO$_{\text{QCD}}$

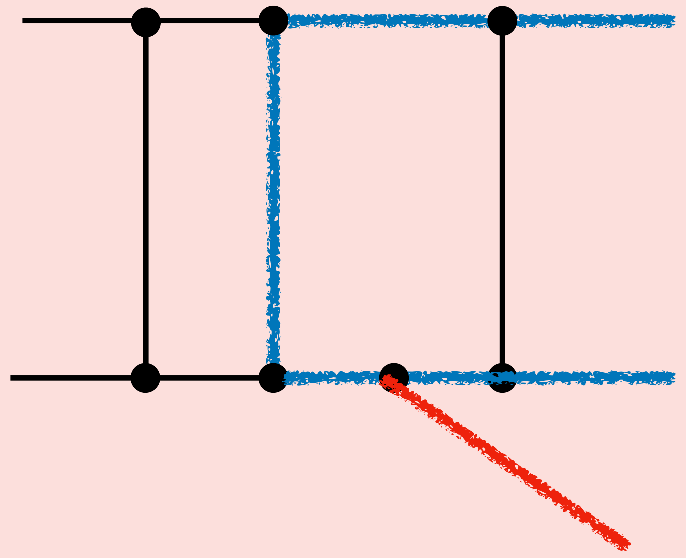

tt at NLO2$_{\text{EWxQCD}}$

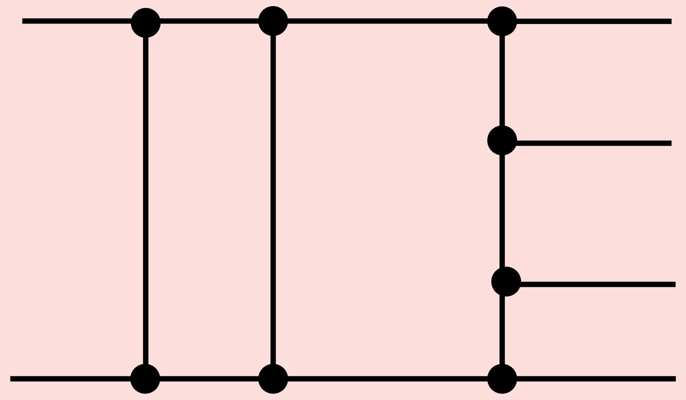

ZH at N2LO$_{\text{EW}}$

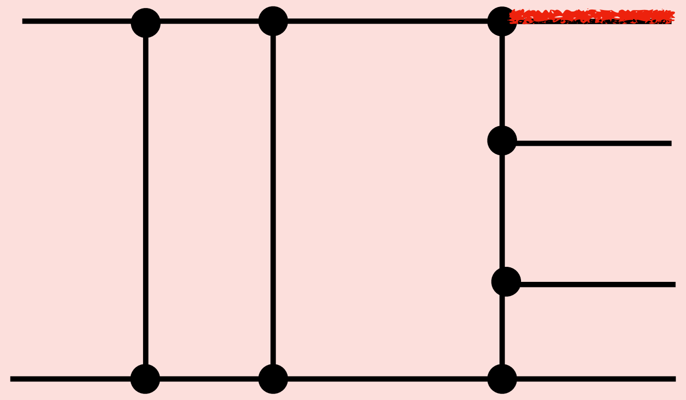

3j at N2LO$_{\text{QCD}}$

NEW


Vbb at N2LO$_{\text{QCD}}$


ttH at N2LO$_{\text{QCD}}$


4j at N2LO$_{\text{QCD}}$


V+3j at N2LO$_{\text{QCD}}$

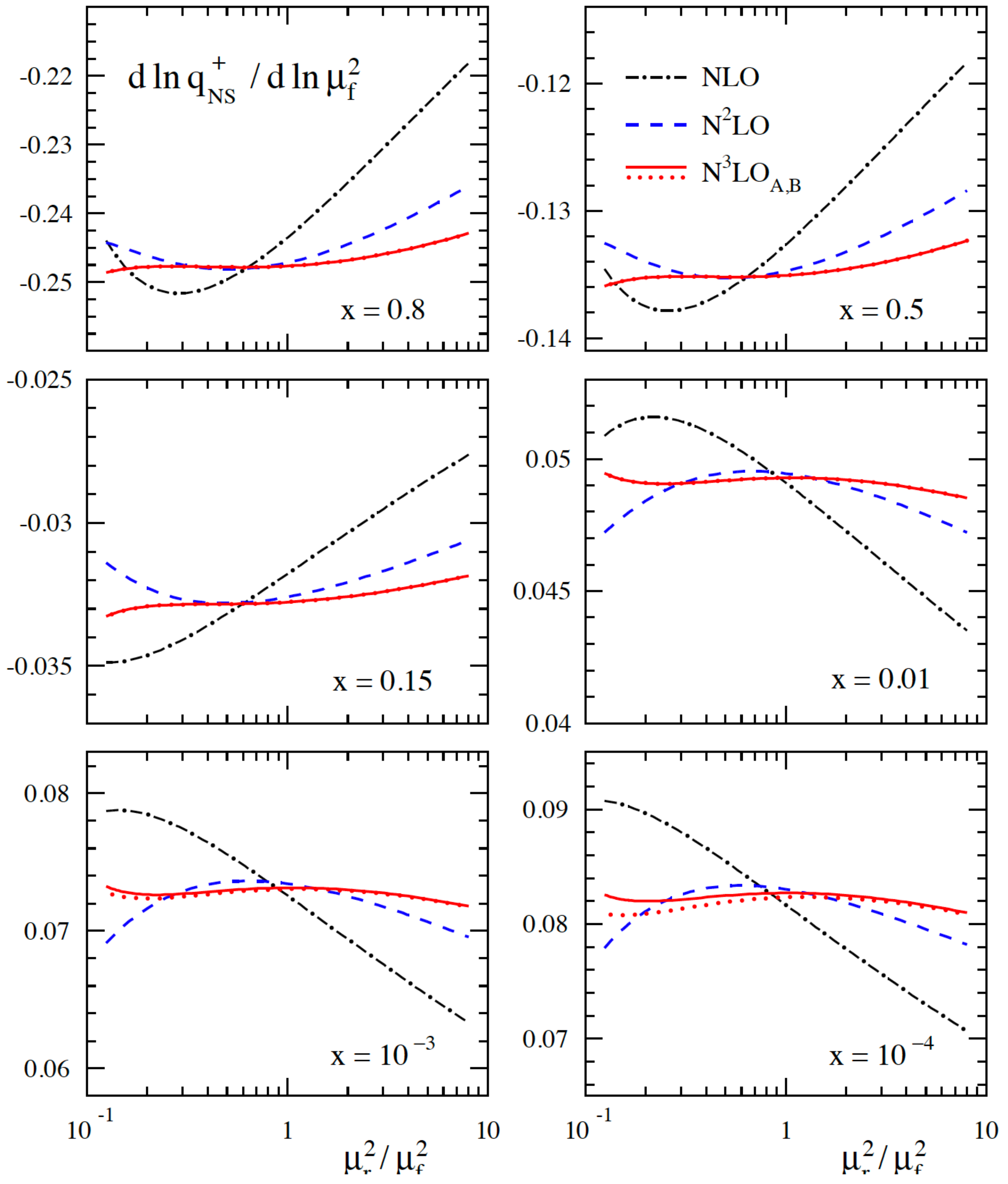
FAST MOVING FRONTIER

- * The more # of loops/legs/scales (colors) the more difficult.
- * Only Z,W,H 2 to 1 production known at N3LO
- * EWxQCD corrections very limited
- * EW N2LO still to be explored
- * Need a subtraction method to turn to IR safe observables

TO DO

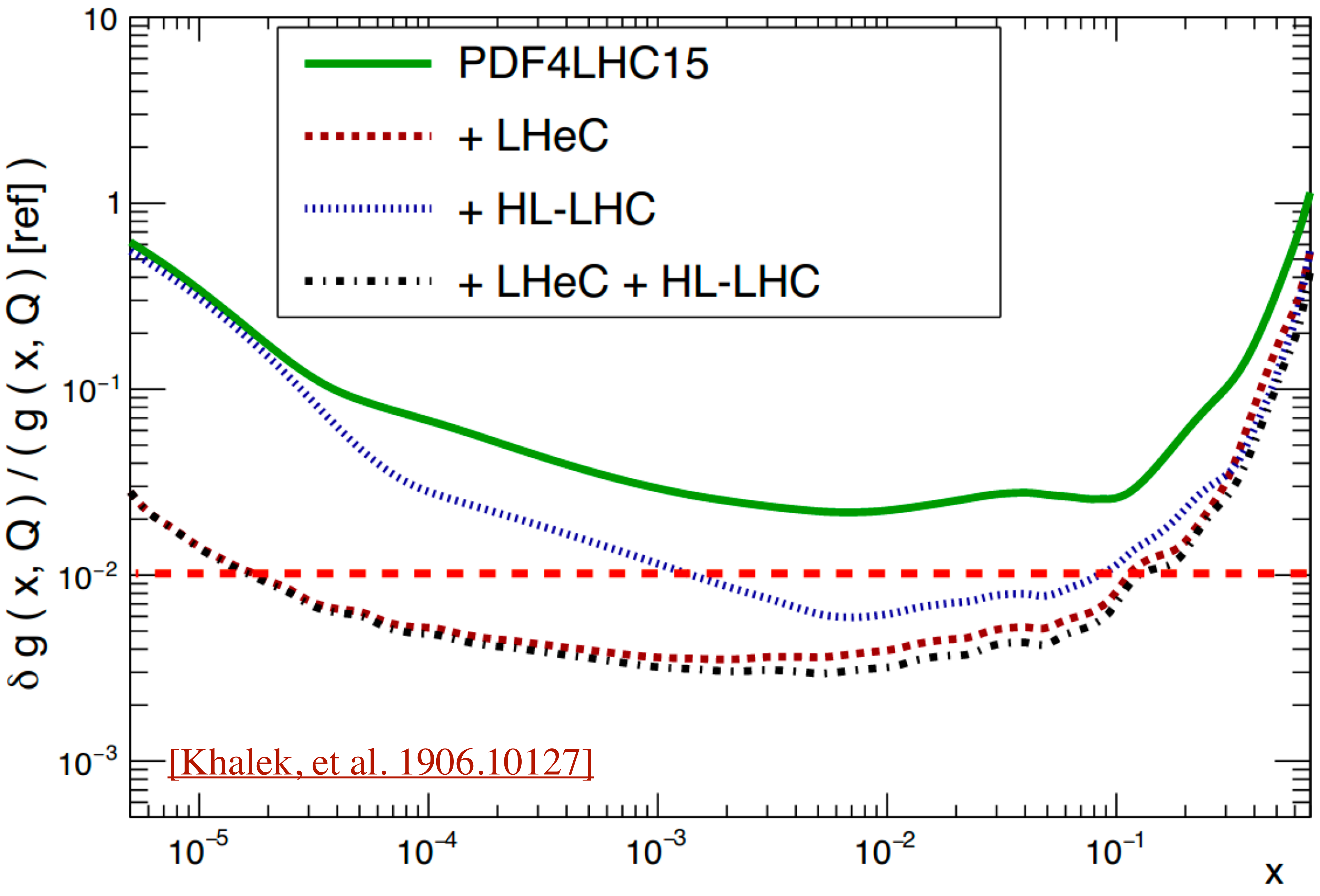
Precision calculations for the LHC

Status: PDF’s



[Moch et al. , 1707.08315]

- Complete N3LO PDF’s evolution not available yet. Non-singlet evolution available at 4 loops already.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice?

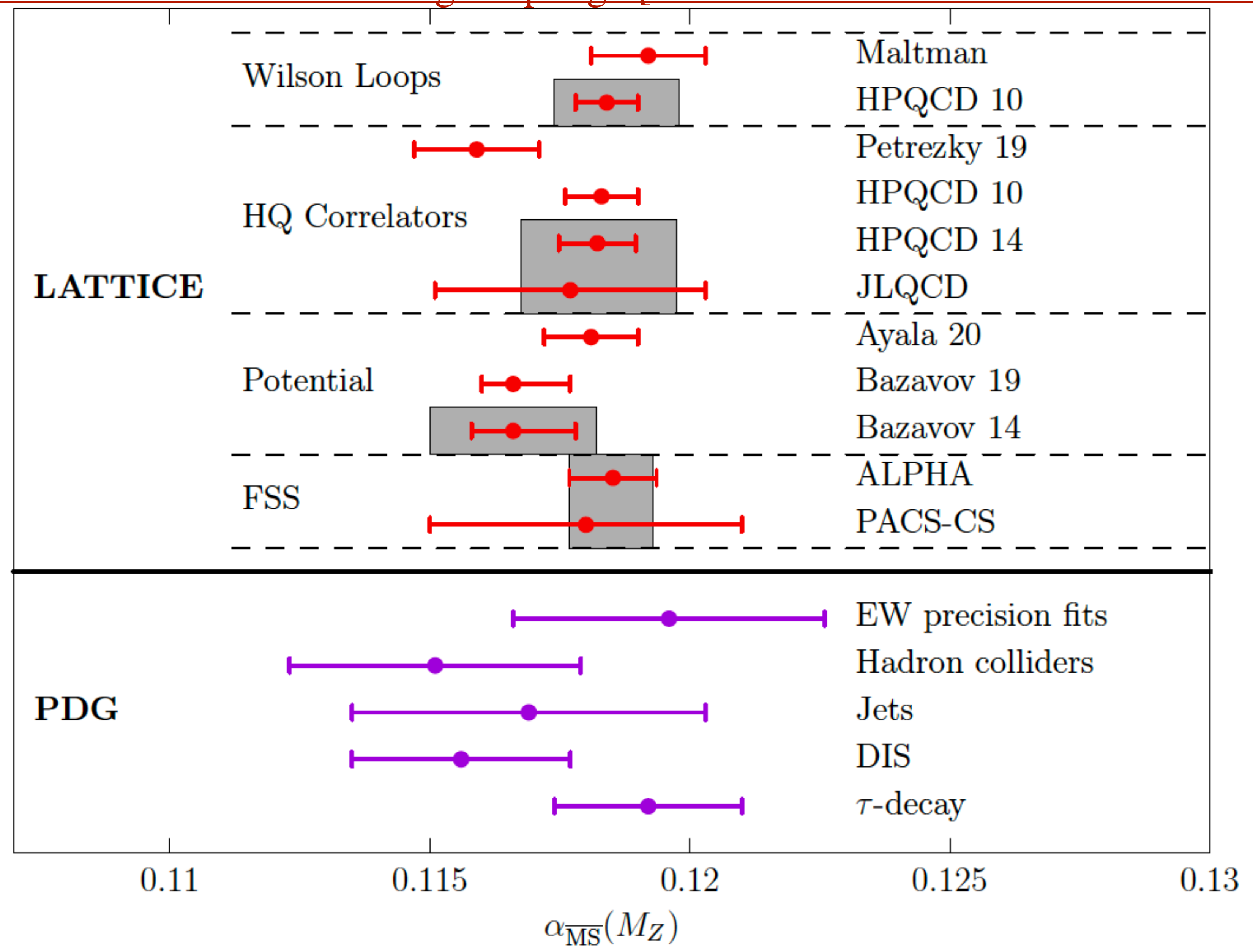


[Khalek, et al. 1906.10127]

The lattice frontier

α_S and PDF's

Lattice determinations of the strong coupling [Del Debbio and A. Ramos e-Print: 2101.04762]

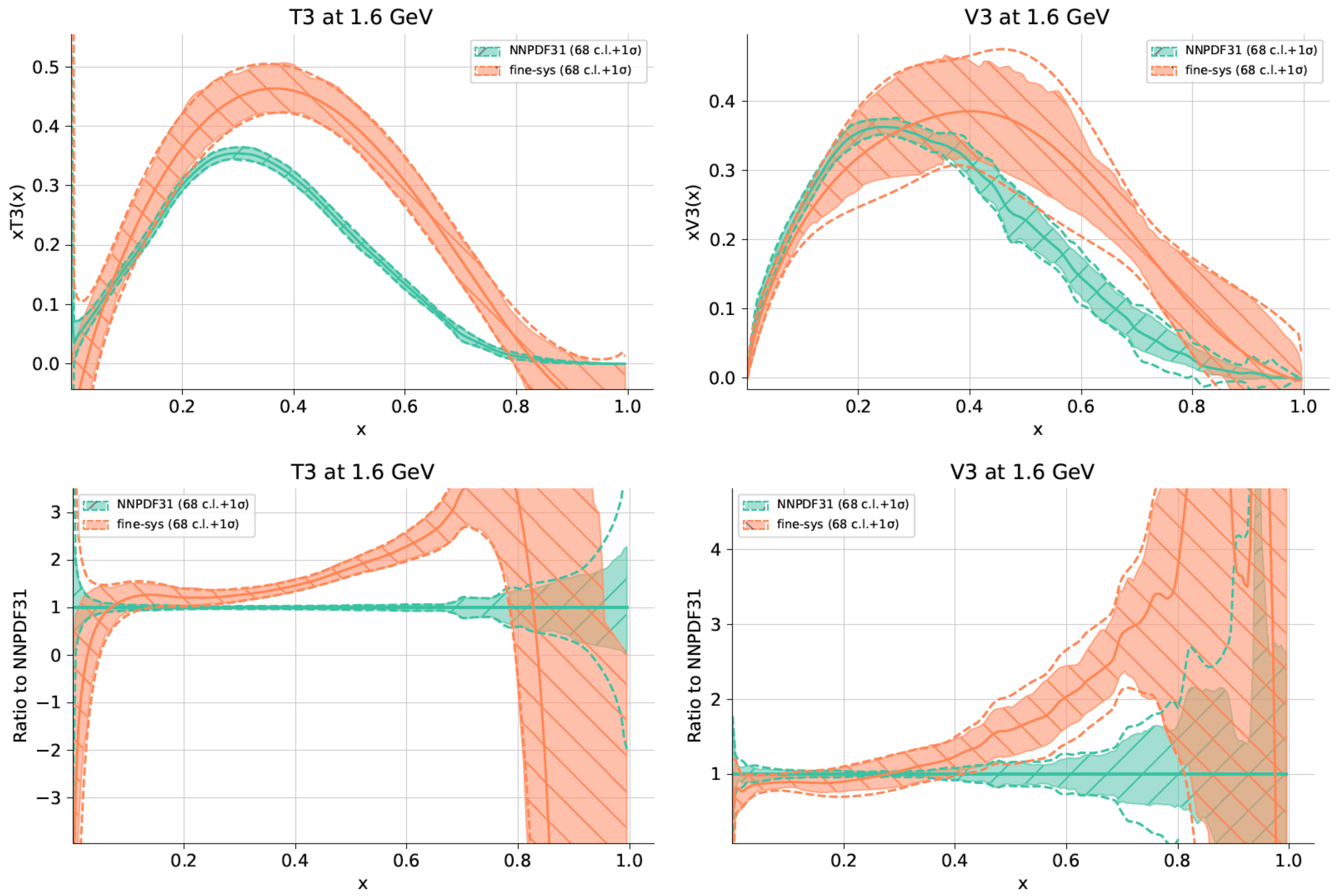


$$P(Q) = \sum_{k=0}^{n} c_k(s)\alpha^k_{\overline{\mathrm{MS}}}(\mu) + \underbrace{\mathcal{O}(\alpha^{n+1}_{\overline{\mathrm{MS}}}(\mu))}_{\text{MHO}} + \underbrace{\mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right)}_{\text{PC}}, \qquad (s = \mu/Q)\,.$$

Using Lattice QCD, one can combine input from well-measured QCD quantities -- like for example the proton mass, or a meson decay constant -- with the perturbative expansion of a short distance observable that does not need to be directly observable (like the quark anti-quark force). The advantage of this approach is that the experimental input comes from the hadron spectrum with a negligible uncertainty.

Parton Distribution Functions from Ioffe Time Pseudodistributions from Lattice Calculations: Approaching the Physical Point [Bálint Joó et al. : 2004.01687]

Neural-network analysis of Parton Distribution Functions from Ioffe-time pseudodistributions [L. Del Debbio et al. 2010.03996]



$$V_3(x) = u(x) - \bar{u}(x) - [d(x) - \bar{d}(x)]$$
$$T_3(x) = u(x) - \bar{u}(x) + [d(x) - \bar{d}(x)]$$

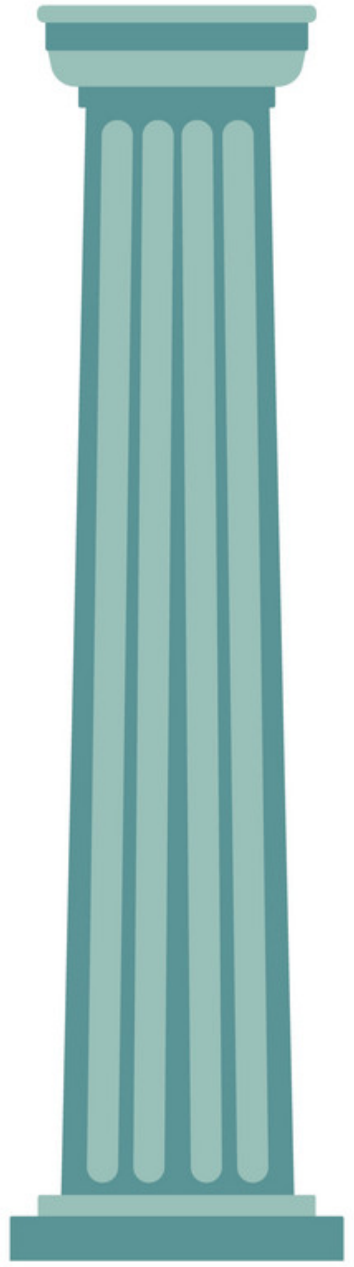
$$\mathfrak{M}\left(\nu, z_3^2\right) = \int_{-1}^{1} dx\, C\left(x\nu, \mu^2 z_3^2\right) f\left(x, \mu^2\right) + \mathcal{O}\left(z_3^2\Lambda^2\right)$$

$$C\left(\xi, \mu^2 z_3^2\right) = e^{i\xi} - \frac{\alpha_s}{2\pi} C_F \int_0^1 dw \left[\frac{1+w^2}{1-w} \log\left(z_3^2\mu^2 \frac{e^{2\gamma_E+1}}{4}\right) + 4\frac{\log(1-w)}{1-w} - 2(1-w)\right]_+ e^{i\xi w} + \mathcal{O}\left(\alpha_s^2\right)$$

This formula allows to relate collinear PDFs to quantities which are computable in lattice QCD simulations, through a factorized expression similar to those relating collinear PDFs to physical cross sections.It can be used in a fitting framework, to extract PDFs from lattice data, performing the same kind of analysis which is usually done when considering experimental data.

Theoretical challenges of the HL-LHC

Reach the 1% goal for the HL-LHC

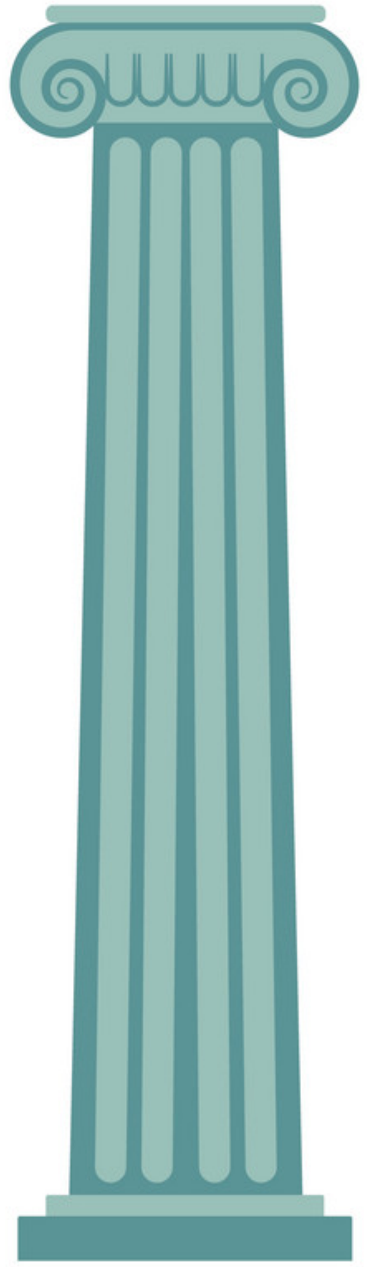


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

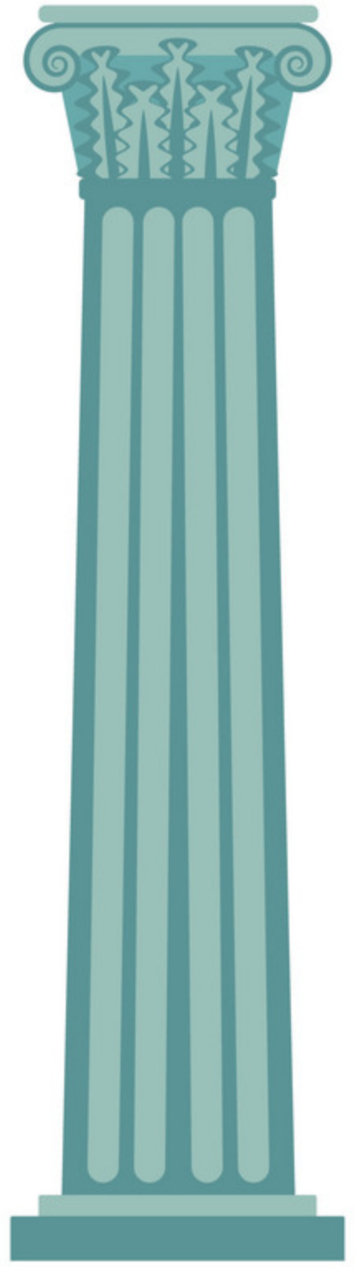


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF's

LO,NLO,..

Fits

- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e+e- ILC 250

e+e- ILC 500

e+e- ILC 1000

A

e+e- FCC-ee : 91,240,365 GeV

FCC-hh

FCC-eh with ERL

LHC

HL-LHC

FCC-hh at 80 TeV with 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

2025

Near future

2050

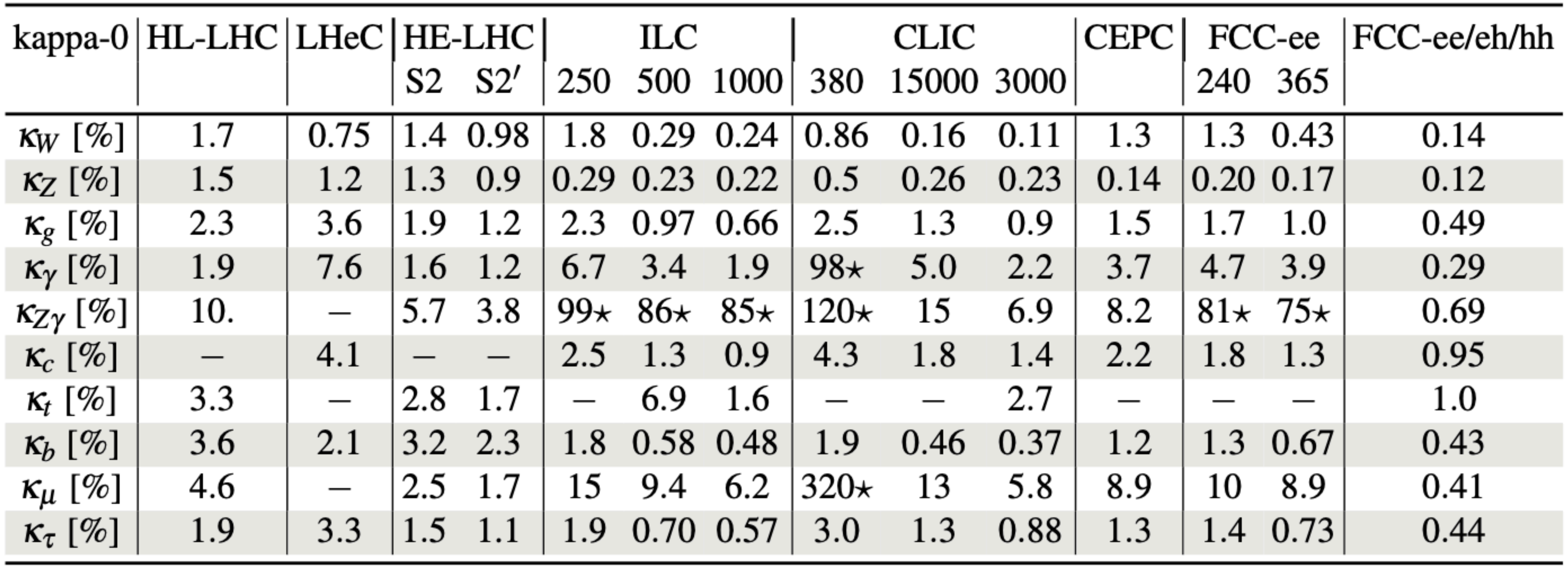
Future

2075

Future colliders

Reach in Higgs couplings

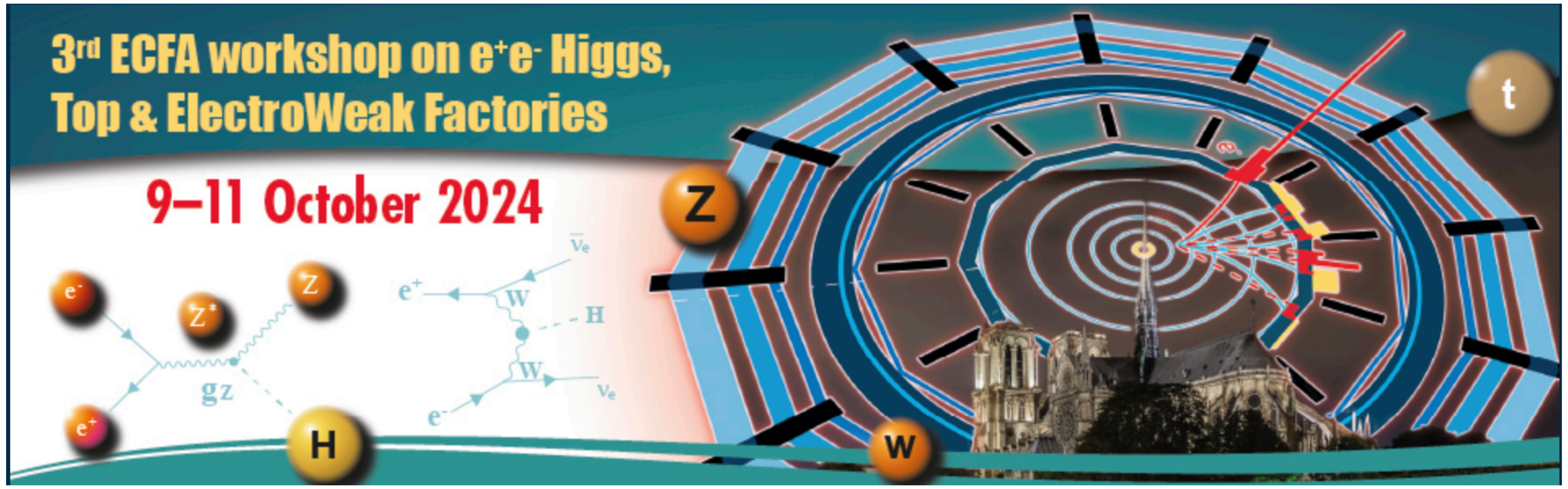
[De Blas et al., 2020]

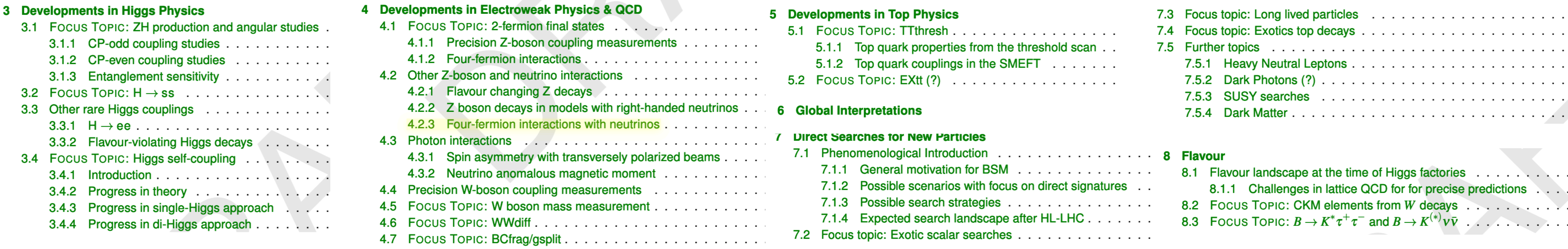


kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

ECFA Higgs/Top/Electroweak Factory Study

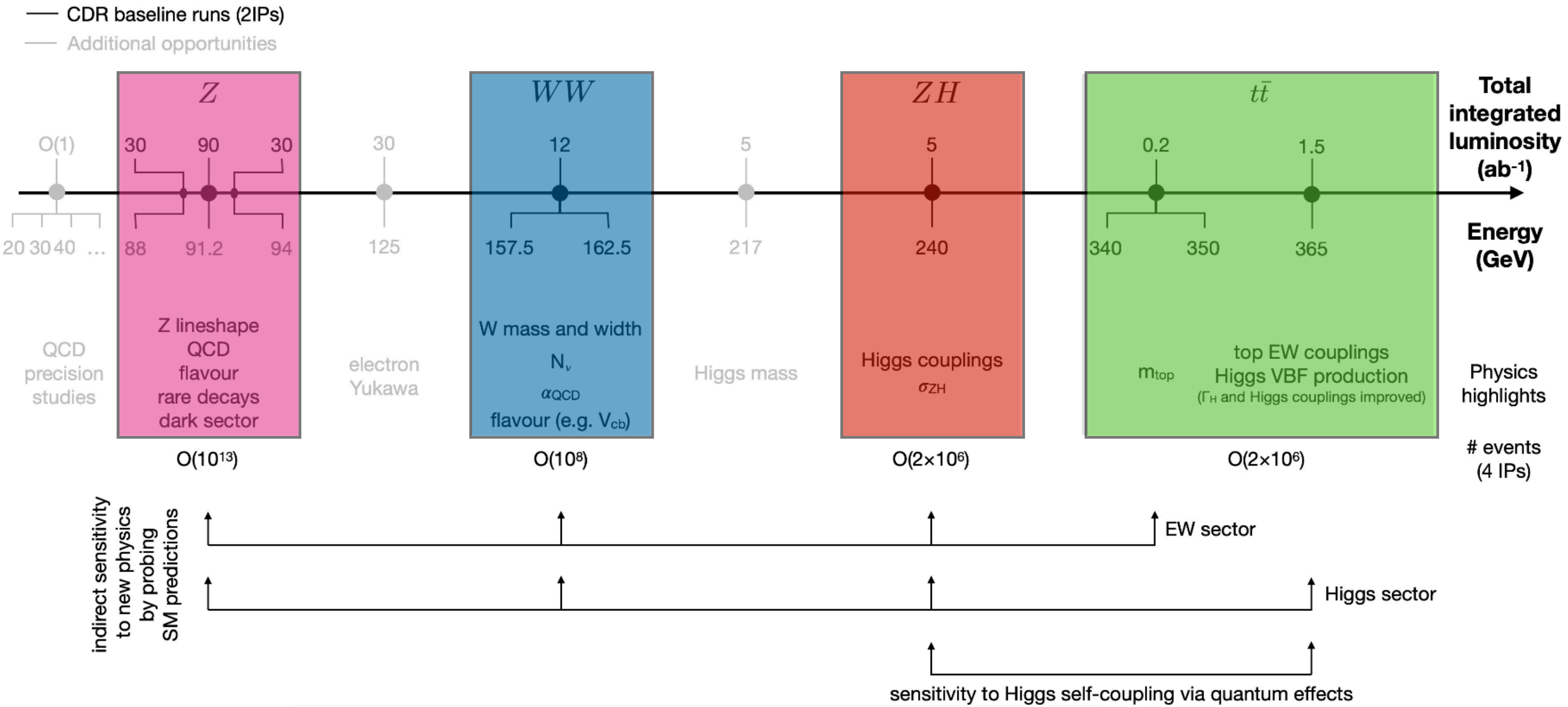
Joint effort of linear and circular collider communities





Future collider example: FCC-ee

FCC-ee runs



CDR baseline runs (2IPs)

Additional opportunities

Total integrated luminosity (ab^{-1})

Energy (GeV)

Physics highlights

events (4 IPs)

O(1)

20 30 40 …

QCD precision studies

Z

30 90 30

88 91.2 94

Z lineshape
QCD
flavour
rare decays
dark sector

$O(10^{13})$

30

125

electron Yukawa

WW

12

157.5 162.5

W mass and width

N_ν

α_{QCD}

flavour (e.g. V_{cb})

$O(10^8)$

5

217

Higgs mass

ZH

5

240

Higgs couplings

σ_{ZH}

$O(2\times10^6)$

$t\bar{t}$

0.2 1.5

340 350 365

m_{top}

top EW couplings
Higgs VBF production
(Γ_H and Higgs couplings improved)

$O(2\times10^6)$

indirect sensitivity to new physics by probing SM predictions

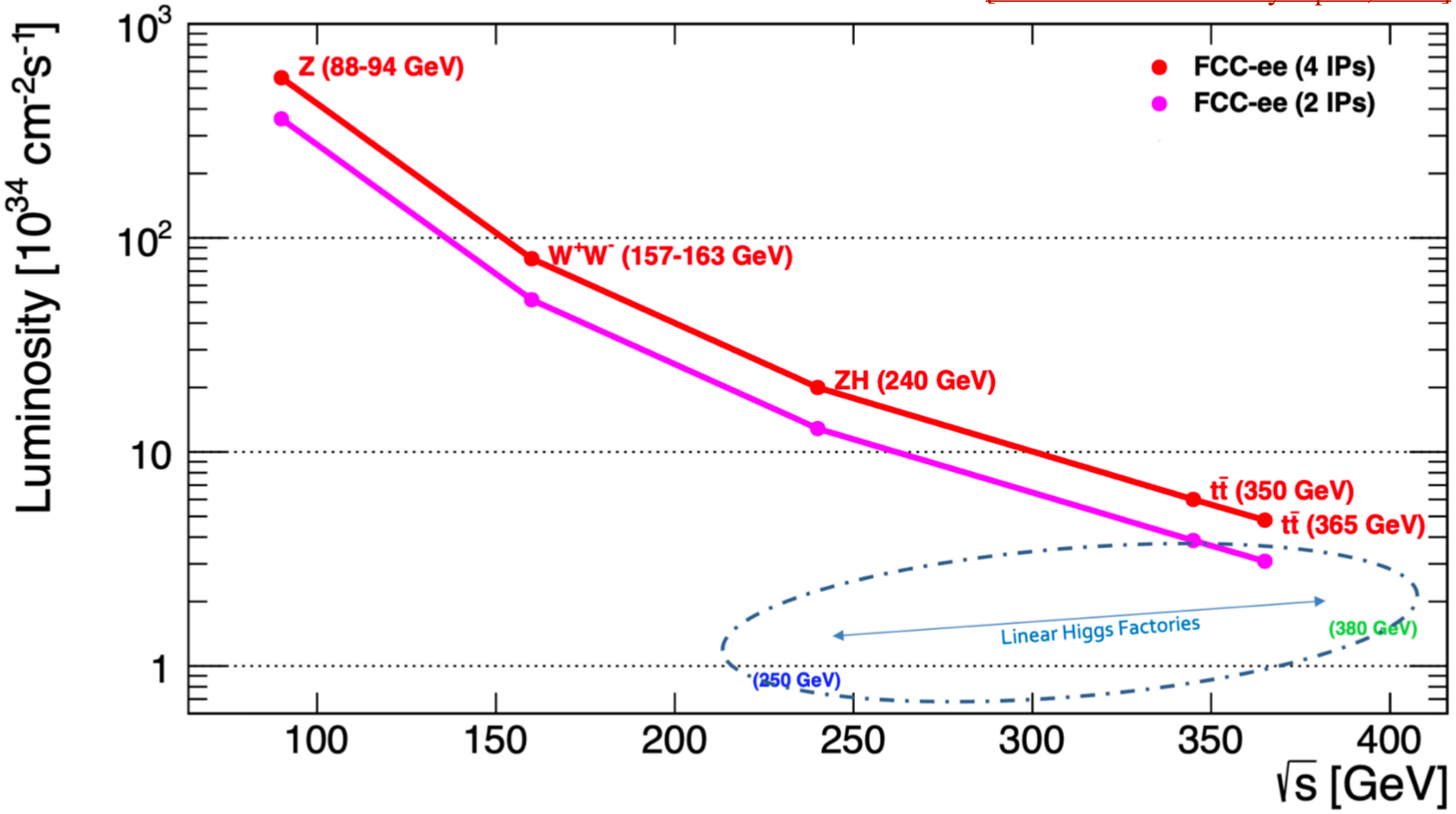
EW sector

Higgs sector

sensitivity to Higgs self-coupling via quantum effects

FCC-ee runs

[Interim FCC feasibility report, 2024]



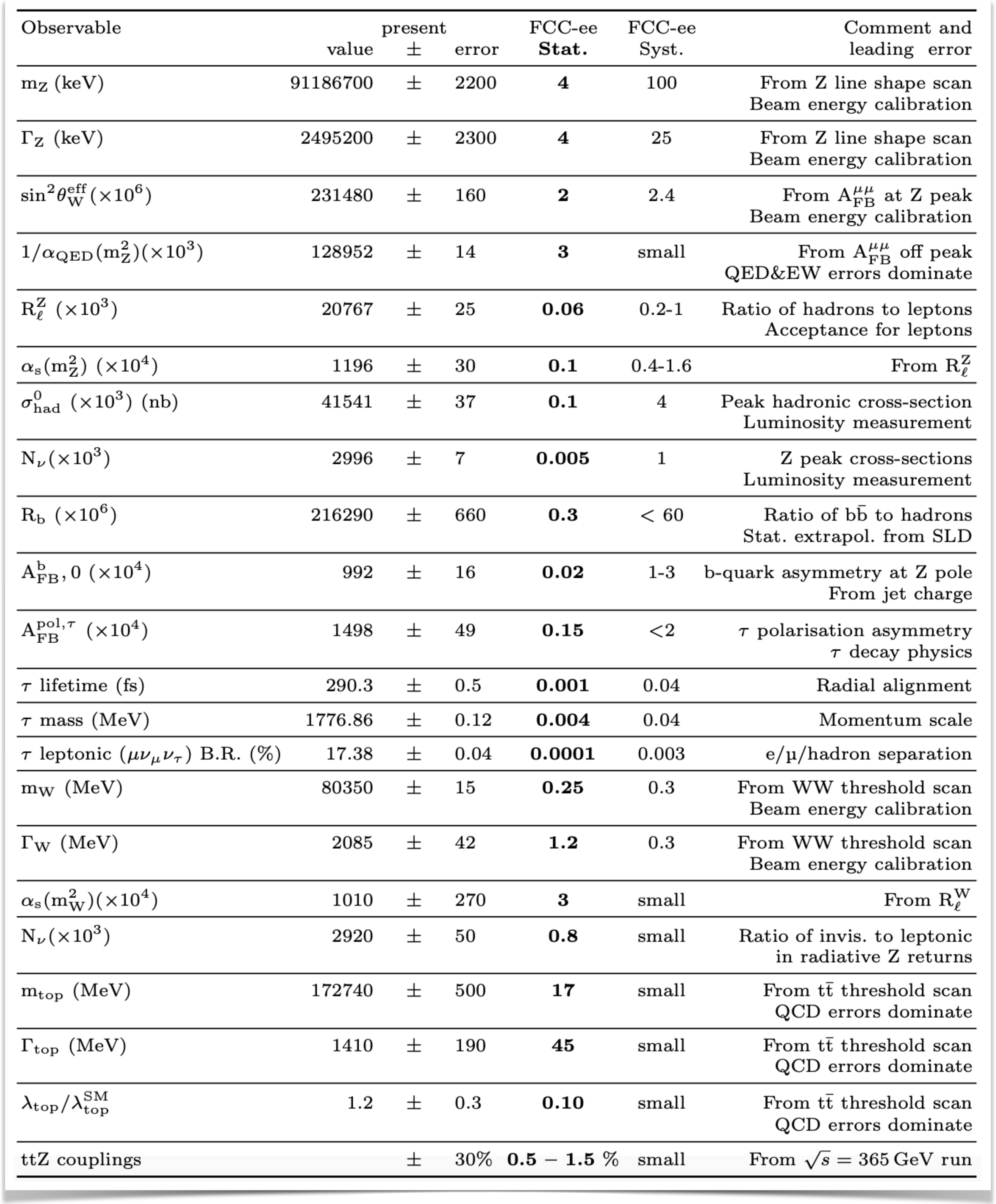
in each detector:

- 10^5 Z / sec
- 10^4 W pairs / hour
- 1500 H / day
- 1500 top pairs / day

EWPO

FCC-ee

[Interim FCC feasibility report, 2024]



Observable		present		FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/µ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365\,{\rm GeV}$ run

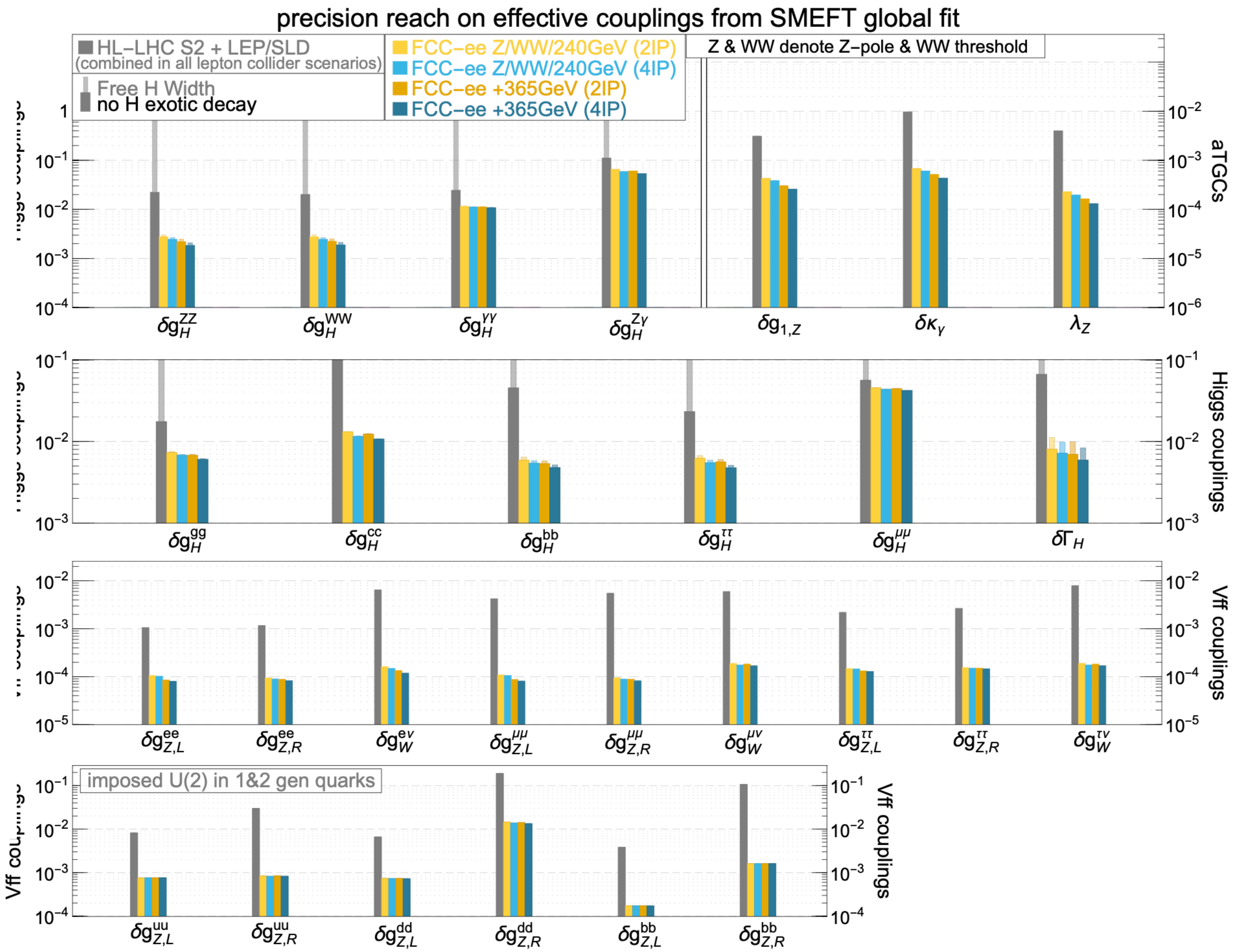
- Experimental precision of the typical EWPO attainable at FCC-ee runs.
- Improvements in precision typically at level of 2-3 orders of magnitude.
- Sensitivity to NP goes up to10-100 TeV scale
- $5 \cdot 10^{12}$ Z bosons would allow the electroweak precision tests, the KM consistency checks and flavour physics in general, including the study of rare decays, and the search for feebly-interacting particles.
- $5 \cdot 10^{9}$ Z bosons would enough to meet the needs for the HZ run.

[Interim FCC feasibility report, 2024]

Global fits

FCC-ee

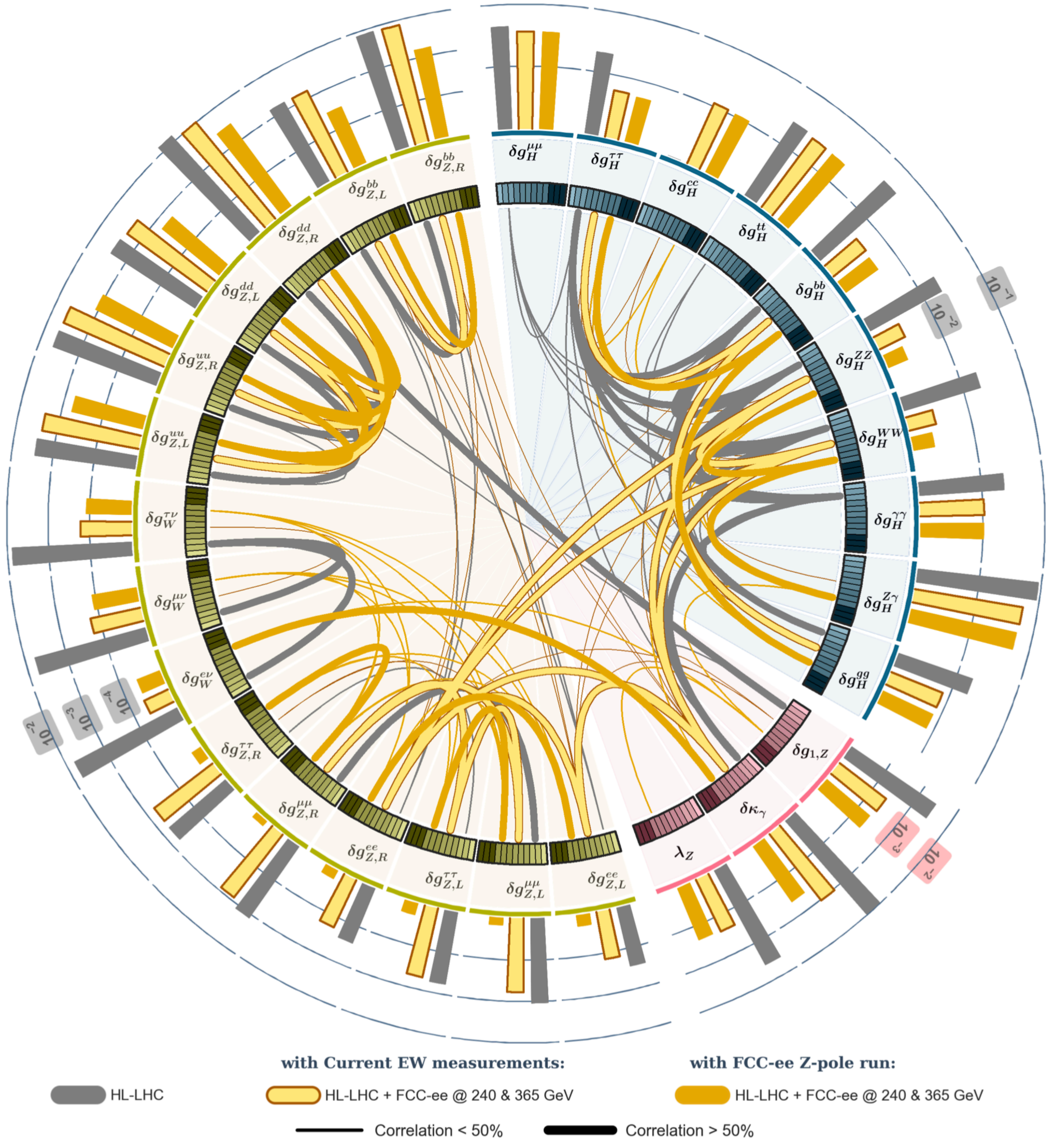
Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

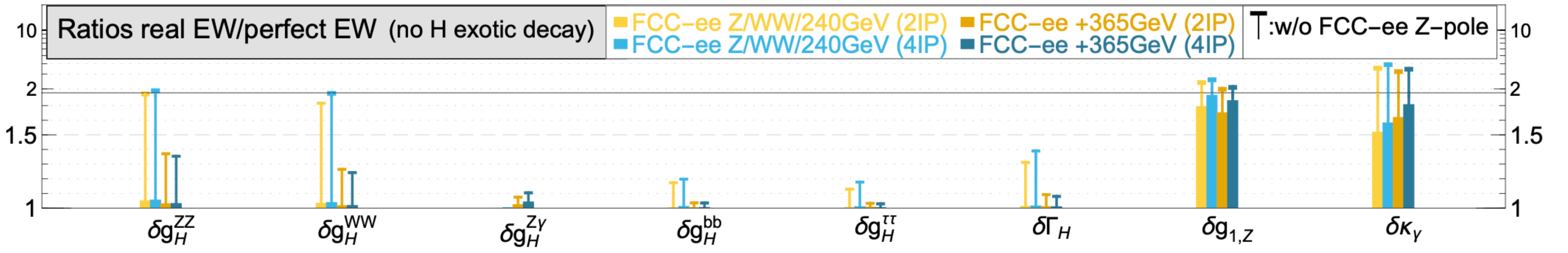


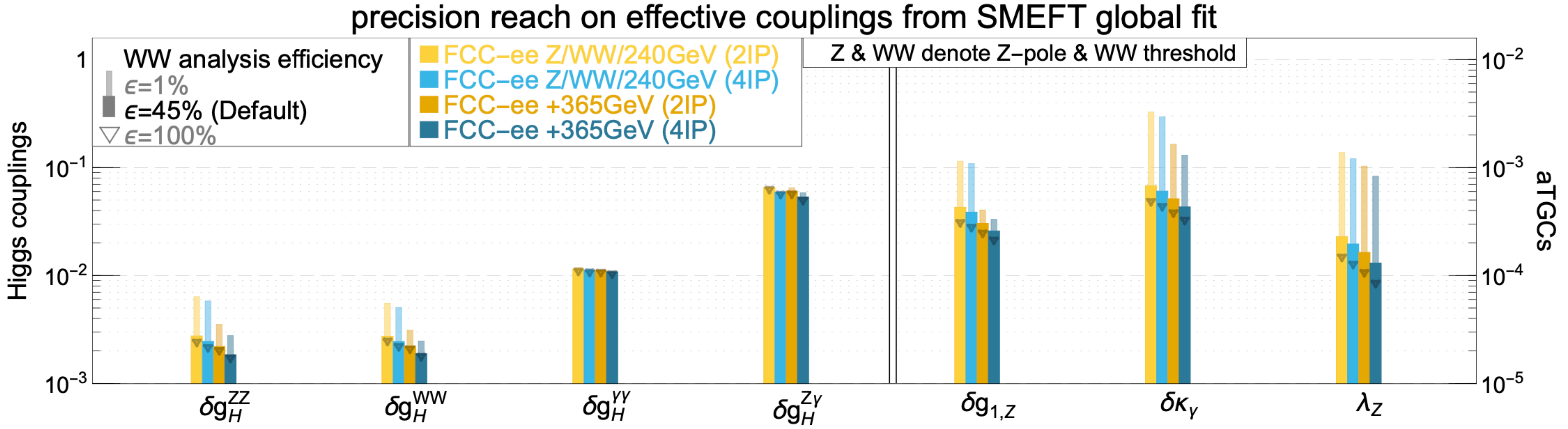
[Interim FCC feasibility report, 2024]

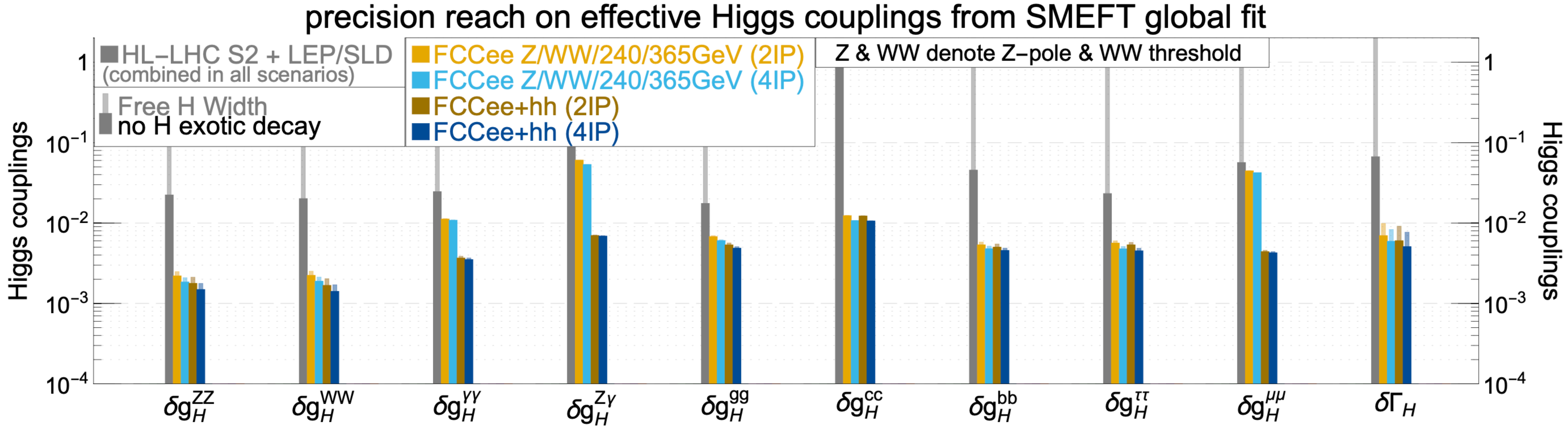
Global fit

FCC-ee





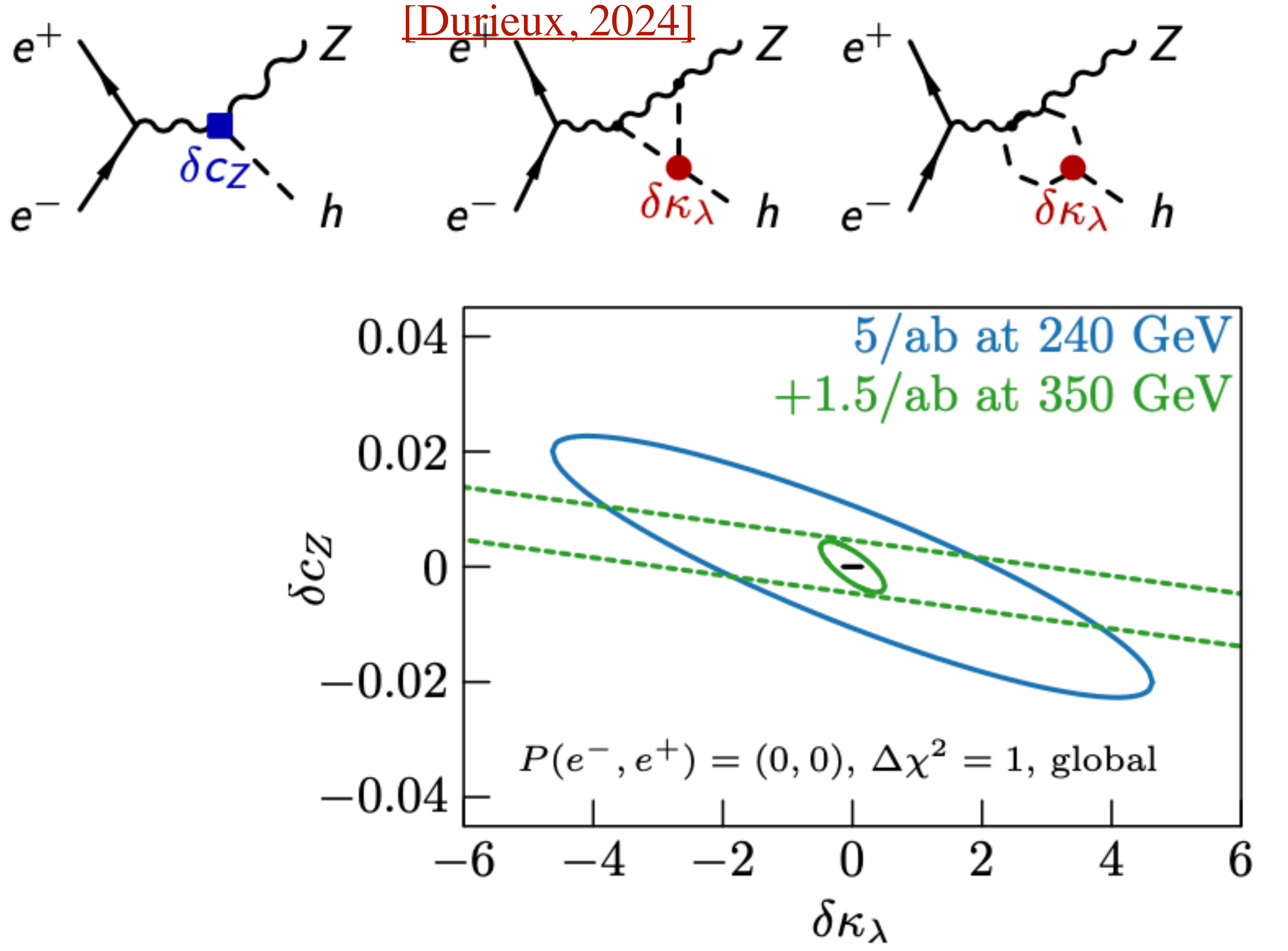




Higgs self-coupling

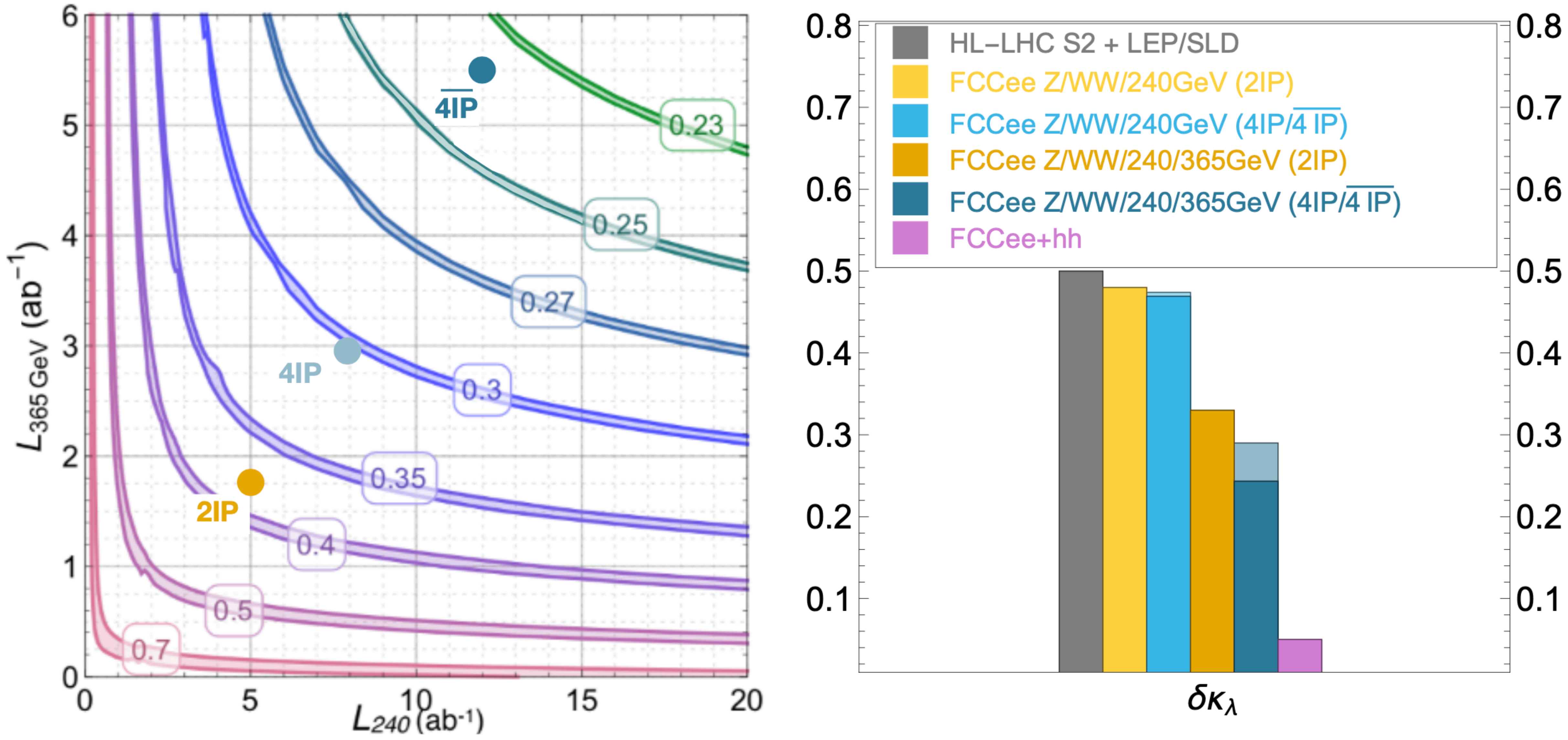
FCC-ee (and FCC-hh)

[Durieux, 2024]



[Interim FCC feasibility report, 2024]

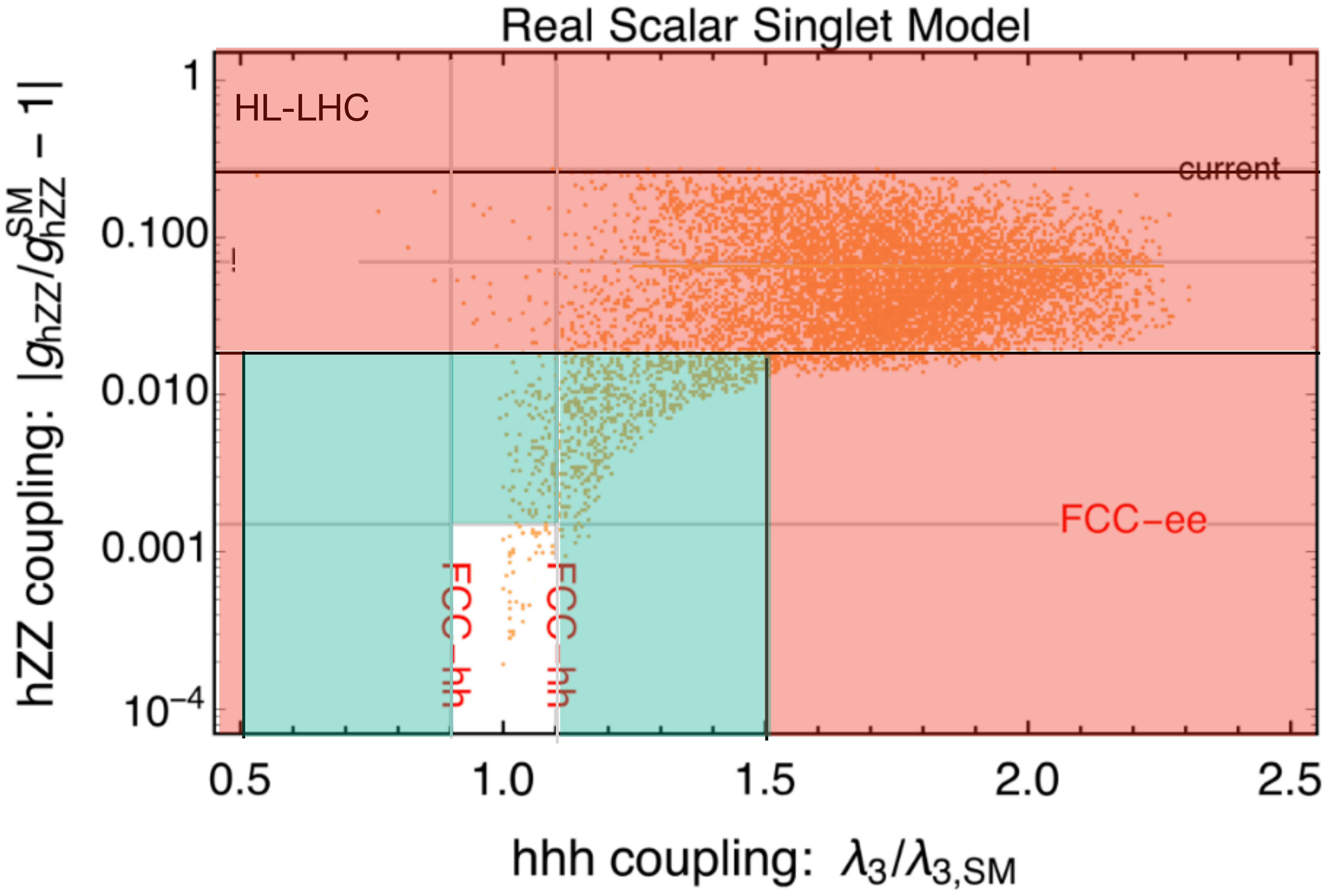
Precision of $\delta\kappa_\lambda$ from EFT global fit (FCC-ee + HL-LHC)



k_λ can be constrained by two measurements and provide competitive info.

Scalar singlet

FCC-ee (and FCC-hh)

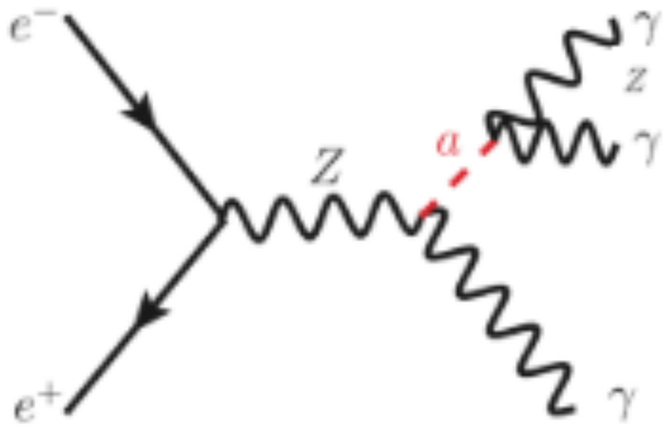


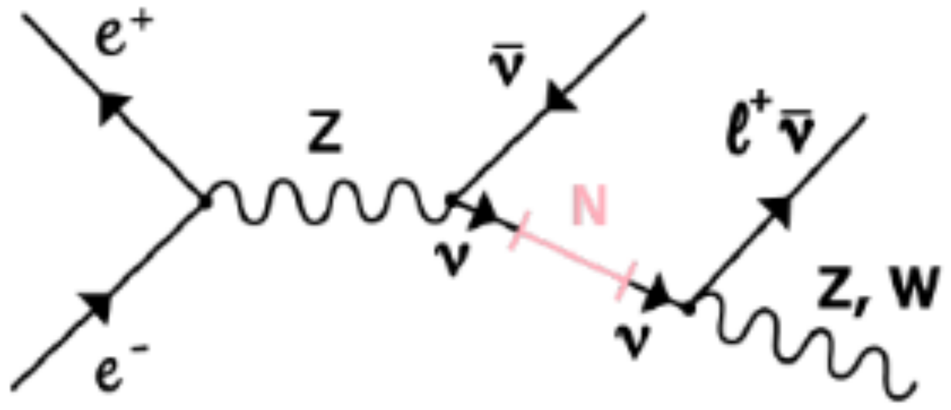
FCC Physics Opportunities : Future Circular Collider Conceptual Design Report Volume 1 Eur.Phys.J.C 79 (2019) 6, 474

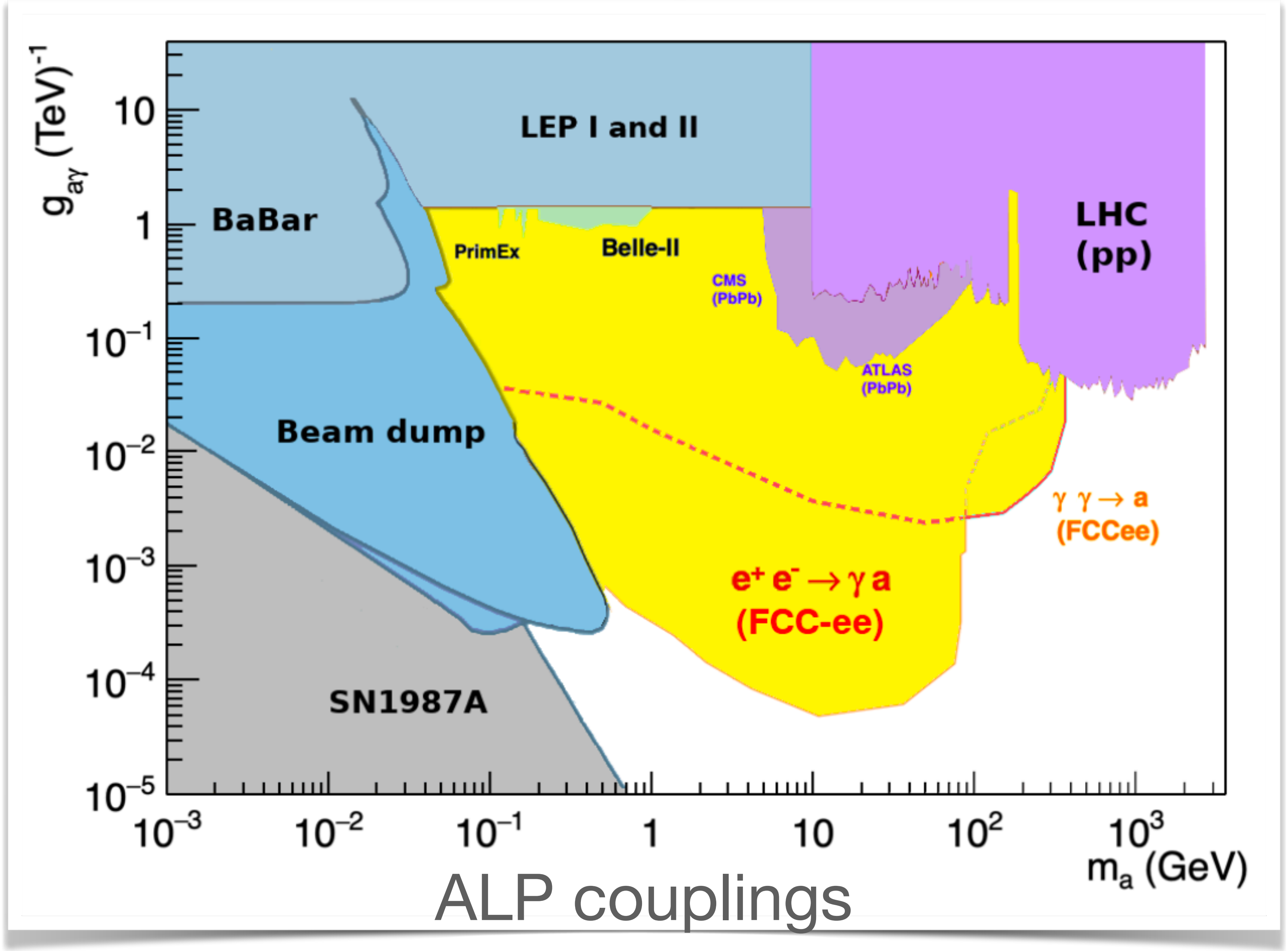
[Interim FCC feasibility report, 2024]

Alps and $\nu'_R s$

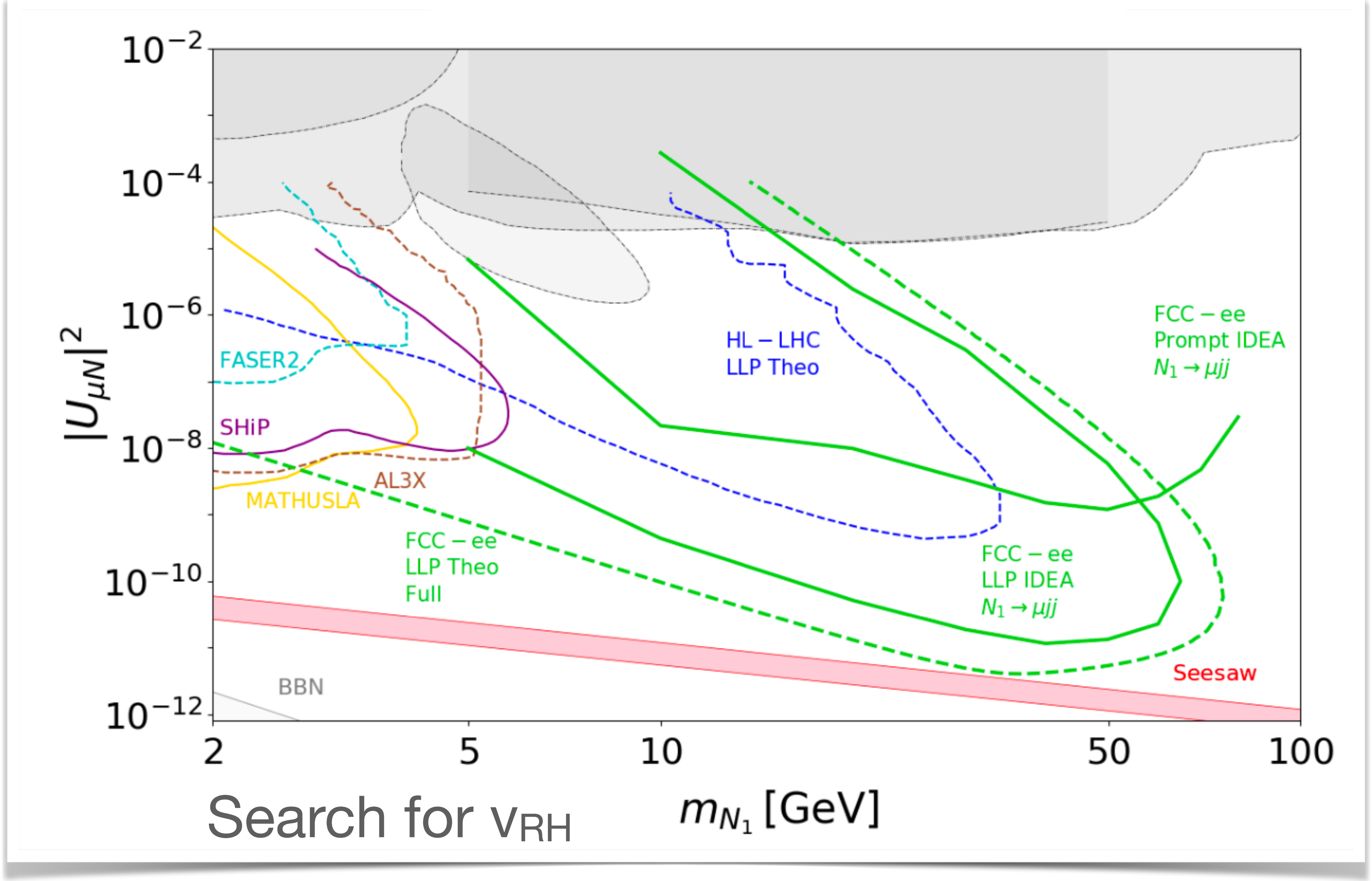
FCC-ee







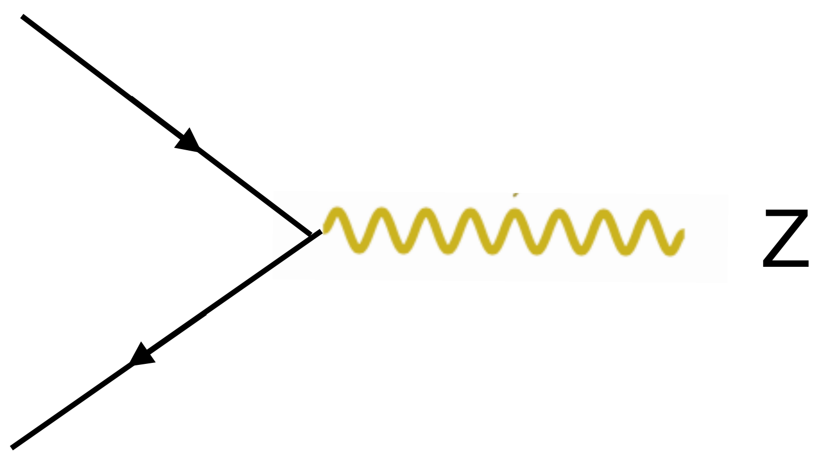
ALP couplings



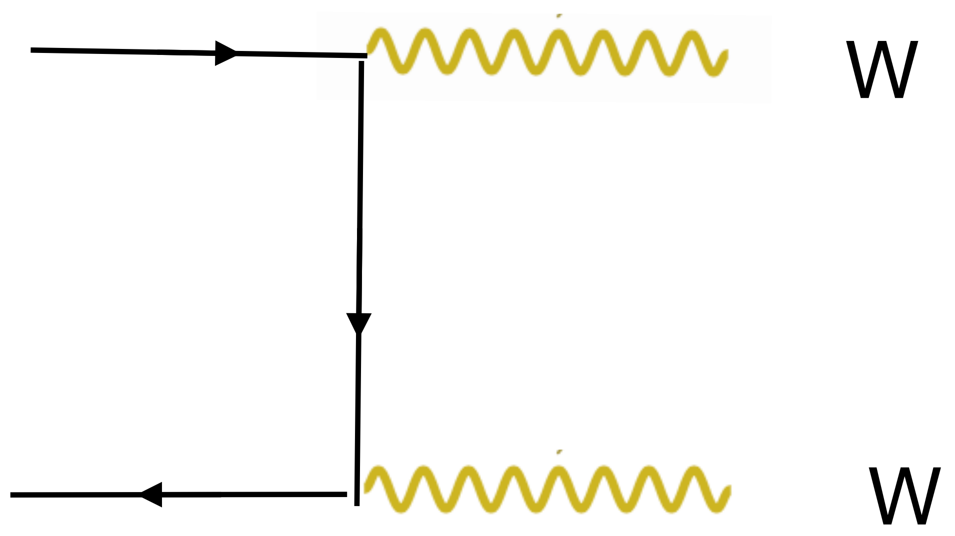
Search for ν_{RH}

Precision calculations for weak scale factories

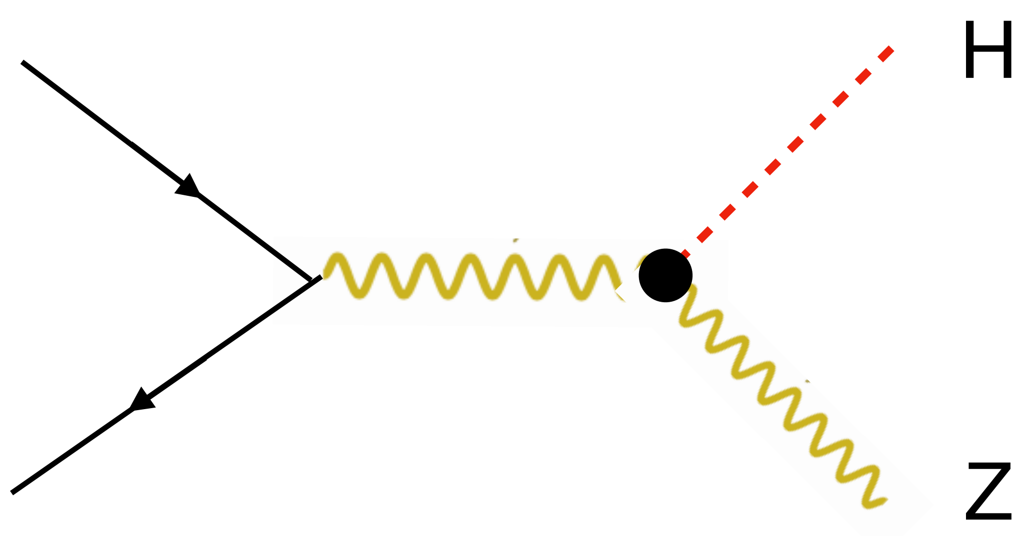
The workhorses



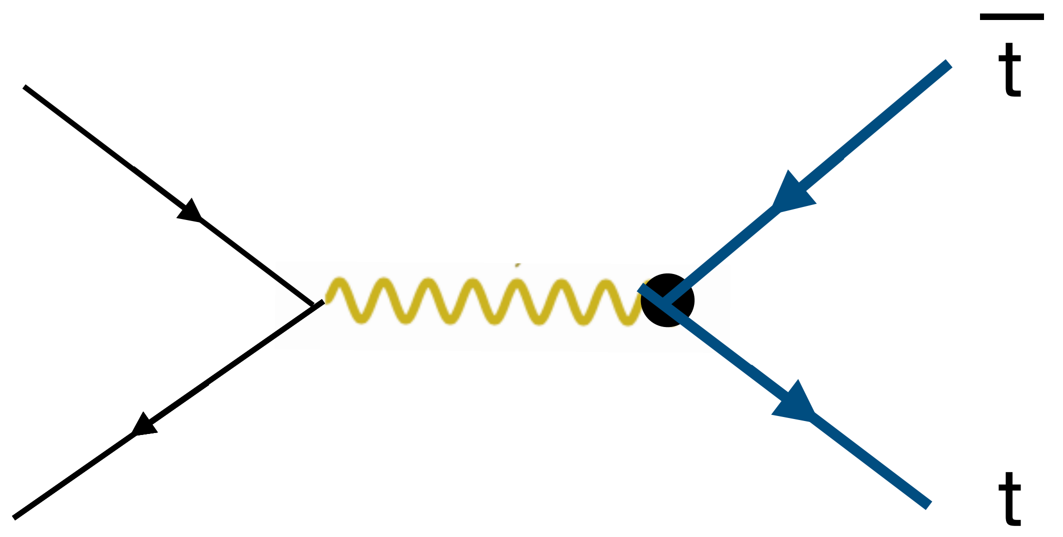
Z-pole observables. Need for NNLO EW in $2 \to 2$ scatterings and N3LO for $2 \to 1$. The current use and definition of PO's will need to be reconsidered.



Known at NLO in EW with W decays. In order to determine mW at 1 MeV needs to be known at the subpermill level. NNLO EW computation involves many scales. In addition an EFT treatment of the W threshold is necessary.



Workhorse for H studies. Known at NLO in EW with Z decays. NNLO correct. Gives access to trilinear and top-Yukawa at one loop and quadrilinear Higgs self-couplings and others at two loops.

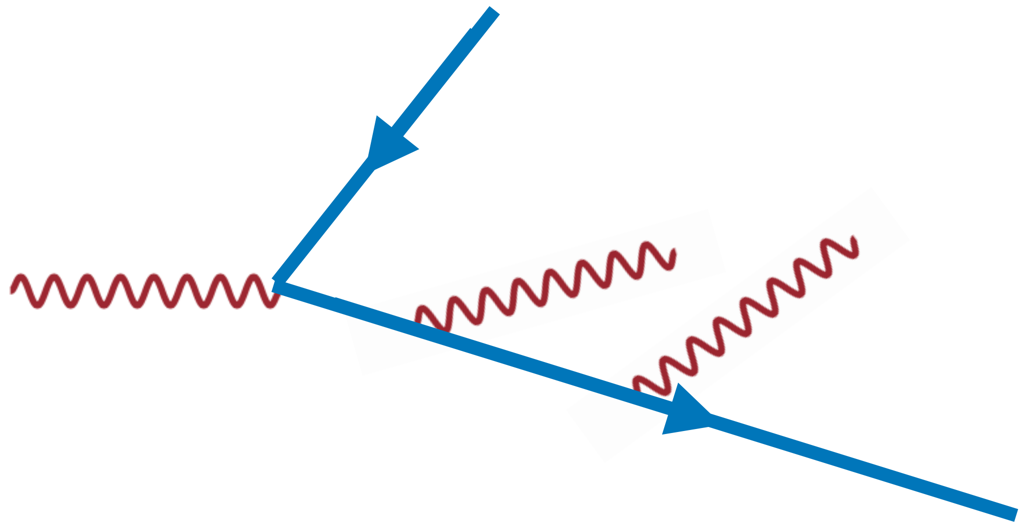


Known at N3LO in the NRQCD EFT approach at threshold for top mass and width determination. NLO QCD corrections for the 2->6 known. NNLO EW corrections are not known.

In addition ISR effects, collinear and soft need to be included.

Precision calculations for weak scale factories

QED showers



In QED the charges are scalars. No flows! -Qi * Qj can be negative emission of a photon is independent from the others and the dipole does not change. Interleaving with the much more probable QCD radiation in the case of quarks is a challenge.

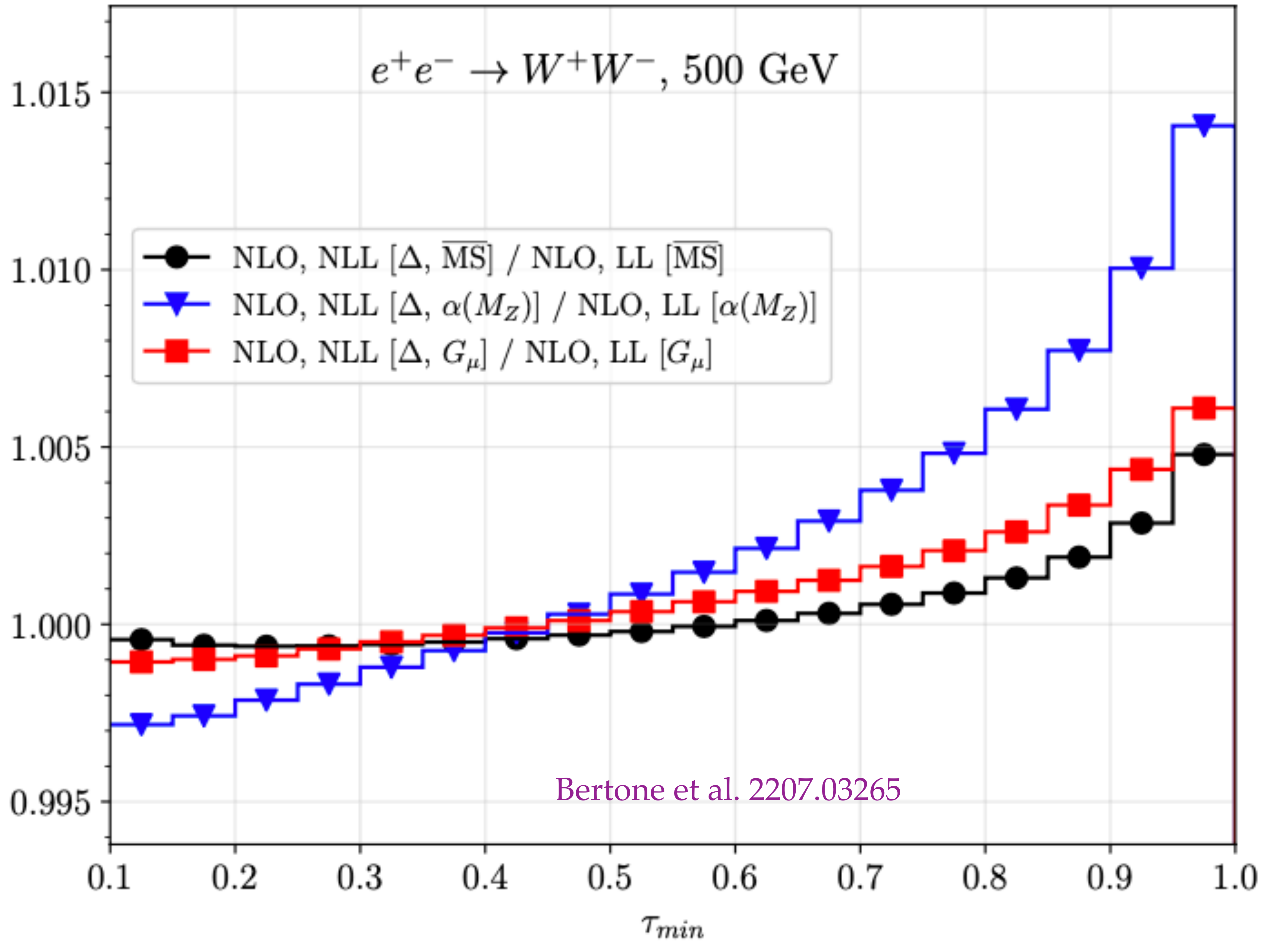
However, YFS Soft resummation provides a way to resum soft contributions

$$\mathrm{d}\sigma = \sum_{n_\gamma=0}^{\infty} \frac{1}{n_\gamma!} \mathrm{d}\Phi_Q \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_i^\gamma \right] (2\pi)^4 \, \delta^4 \left(\sum_{\text{in}} q_{\text{in}} - \sum_{\text{out}} q_{\text{out}} - \sum_{i=1}^{n_\gamma} k_i \right) \left| \sum_{n_\gamma^V=0}^{\infty} \mathcal{M}_{n_\gamma}^{n_\gamma^V + \frac{1}{2} n_\gamma} \right|^2 .$$

$$\mathrm{d}\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!} \mathrm{d}\Phi_Q \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_i^\gamma \, \tilde{S}(k_i) \right] \left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{\tilde{S}(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j,k_k)}{\tilde{S}(k_j)\,\tilde{S}(k_k)} + \cdots \right)$$

Collinear effects captured through the residuals. Improvements necessary to also have Ɣ to fermions splitting included at order α^2 .

NLO+NLL vs NLO+LL

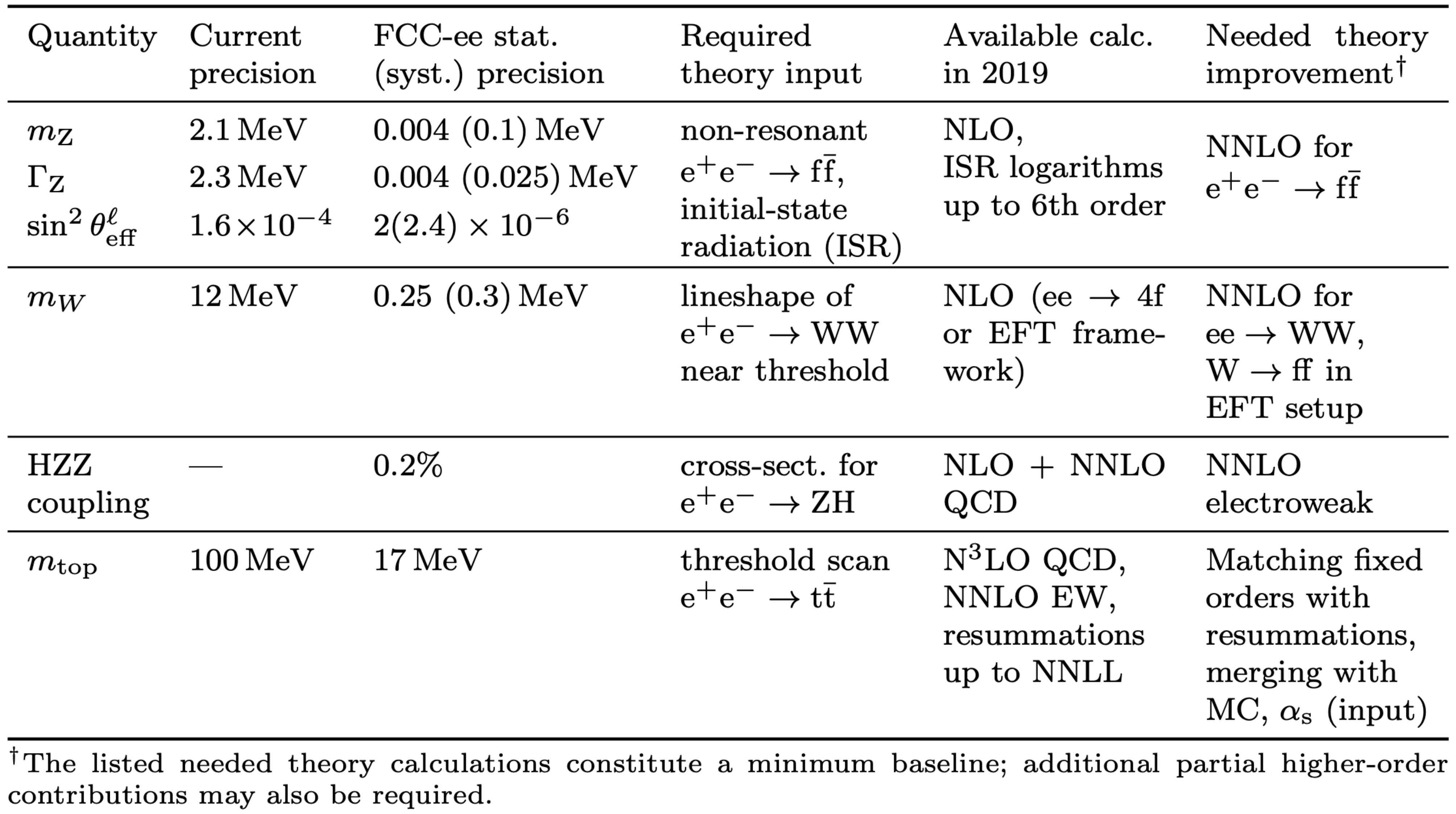


Bertone et al. 2207.03265

[Interim FCC feasibility report, 2024]

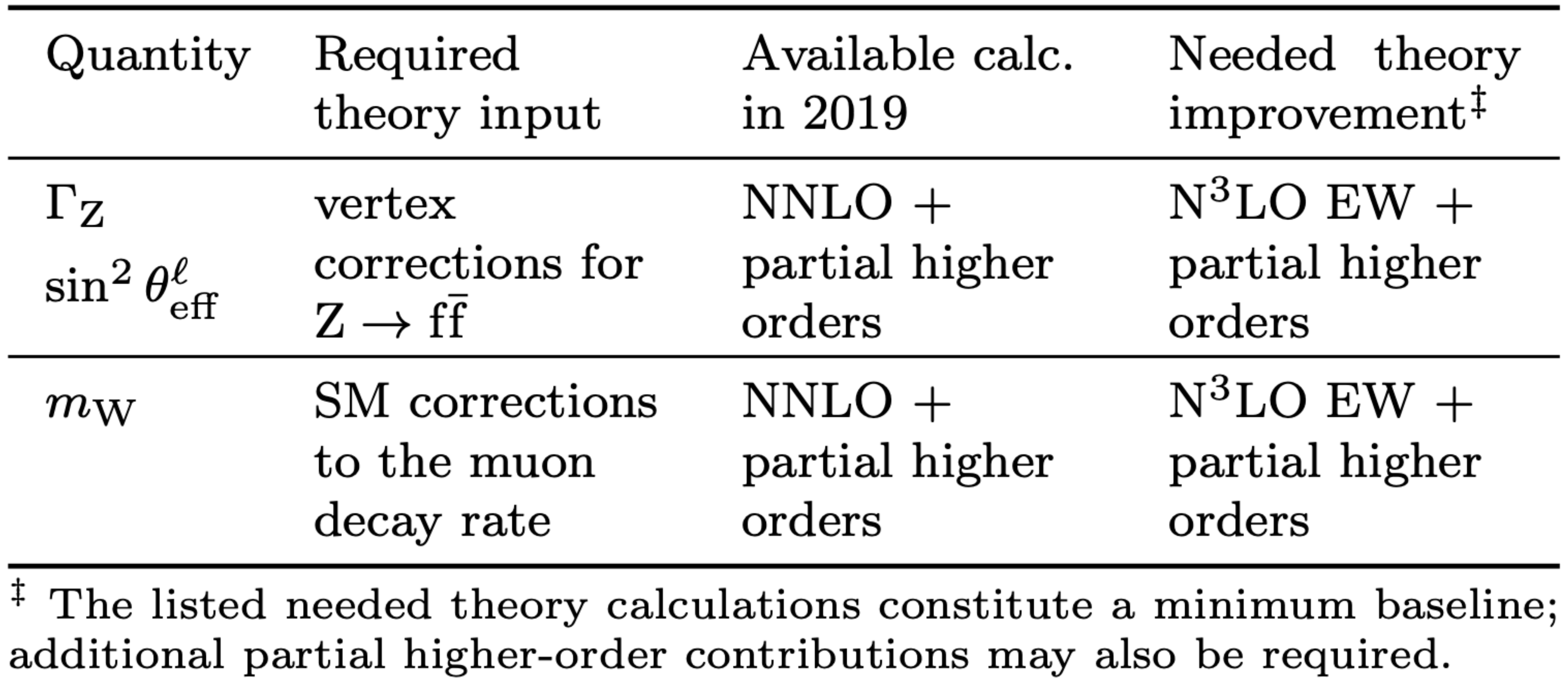
Precision calculations for weak scale factories

Summary of the needs



Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement[†]
m_Z Γ_Z $\sin^2\theta^{\ell}_{\mathrm{eff}}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
m_{top}	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

[†] The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.



Quantity	Required theory input	Available calc. in 2019	Needed theory improvement[‡]
Γ_Z $\sin^2\theta^{\ell}_{\mathrm{eff}}$	vertex corrections for $Z\to f\bar{f}$	NNLO + partial higher orders	N^{3}LO EW + partial higher orders
m_W	SM corrections to the muon decay rate	NNLO + partial higher orders	N^{3}LO EW + partial higher orders

[‡] The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e

C 1000

A

GeV

FCC-hh

LHC

HL-LHC

-eh with ERL

h 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

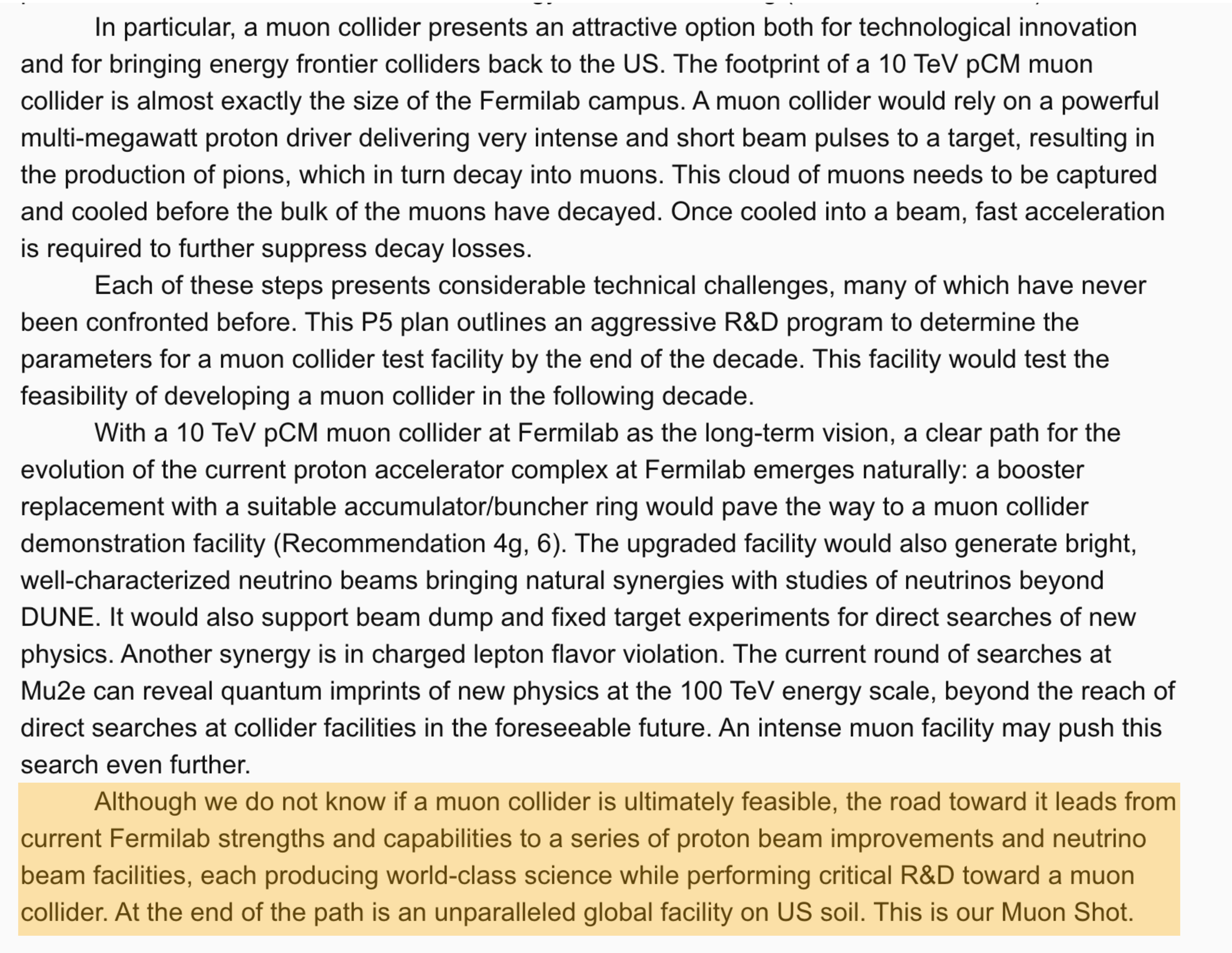
ee pp ee pp ee pp μC ee pp

The non-binary strategy

2025 Near future 2050 Future 2075

A **new** interest in a muon collider

P5:

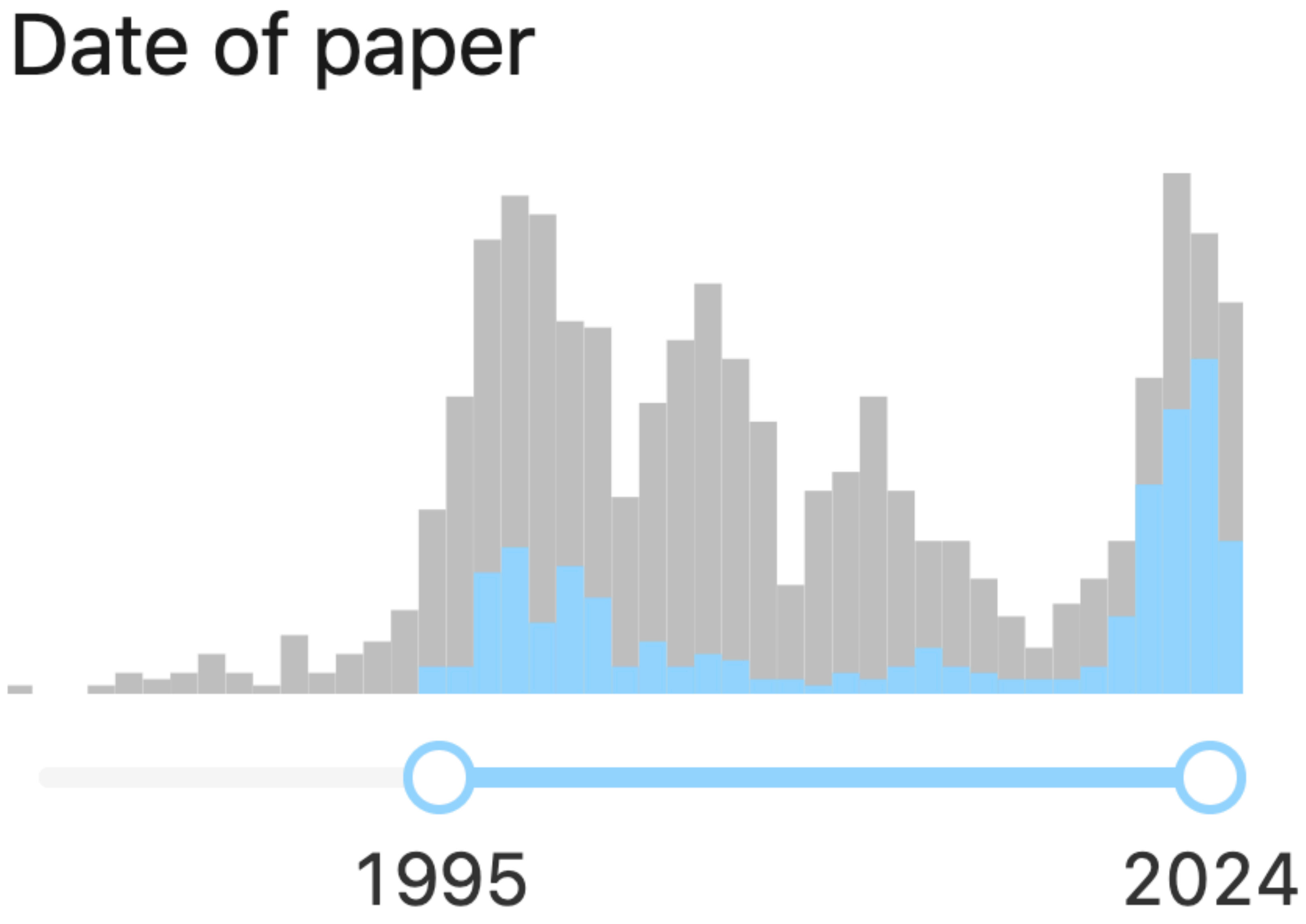


In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

Each of these steps presents considerable technical challenges, many of which have never been confronted before. This P5 plan outlines an aggressive R&D program to determine the parameters for a muon collider test facility by the end of the decade. This facility would test the feasibility of developing a muon collider in the following decade.

With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal quantum imprints of new physics at the 100 TeV energy scale, beyond the reach of direct searches at collider facilities in the foreseeable future. An intense muon facility may push this search even further.

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

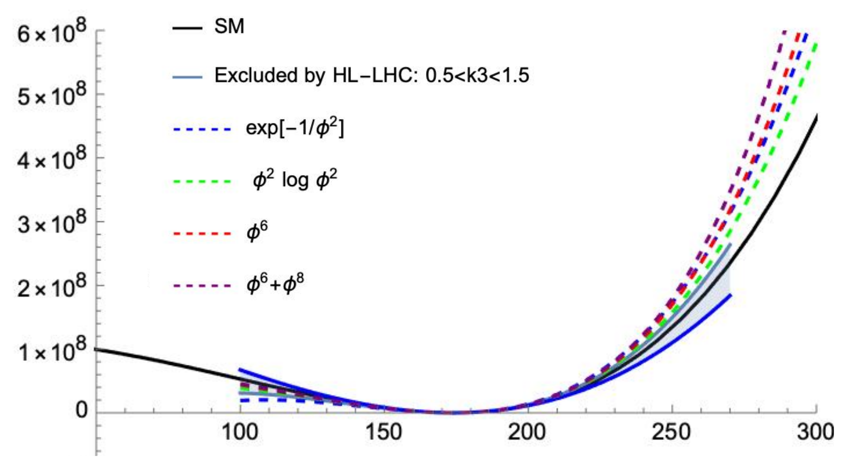


122 pheno papers in the last 5 years

A **new** interest in a multi-TeV muon collider

Why?

Physics: We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.

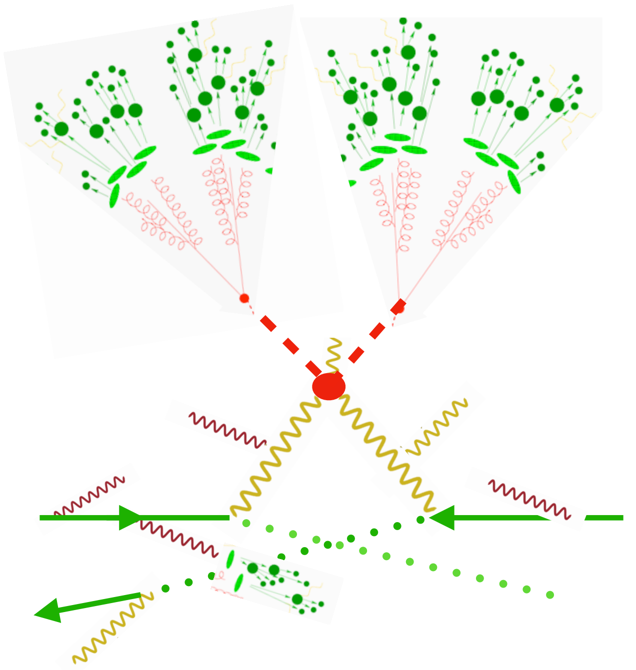


1st or 2nd order

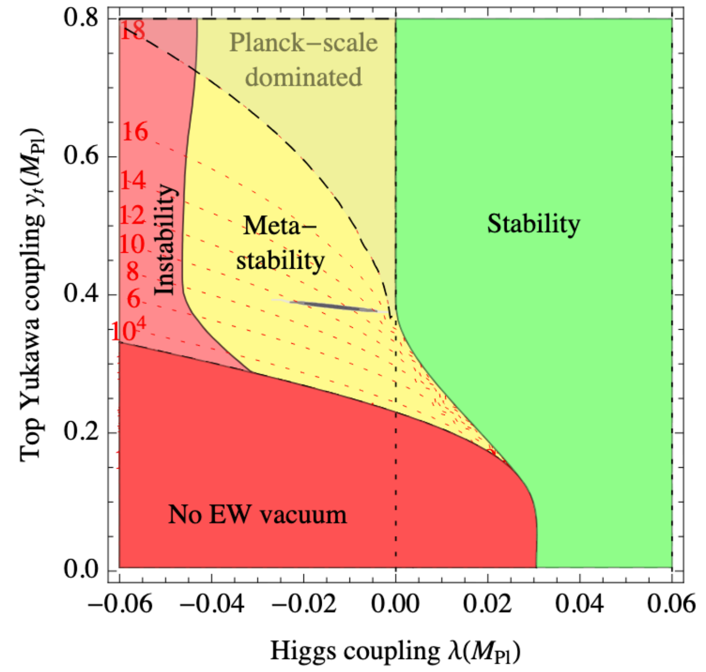
$$\phi^\pm = W_L^\pm$$

$$\phi^0 = Z_L^0$$

EW restoration



EW showers



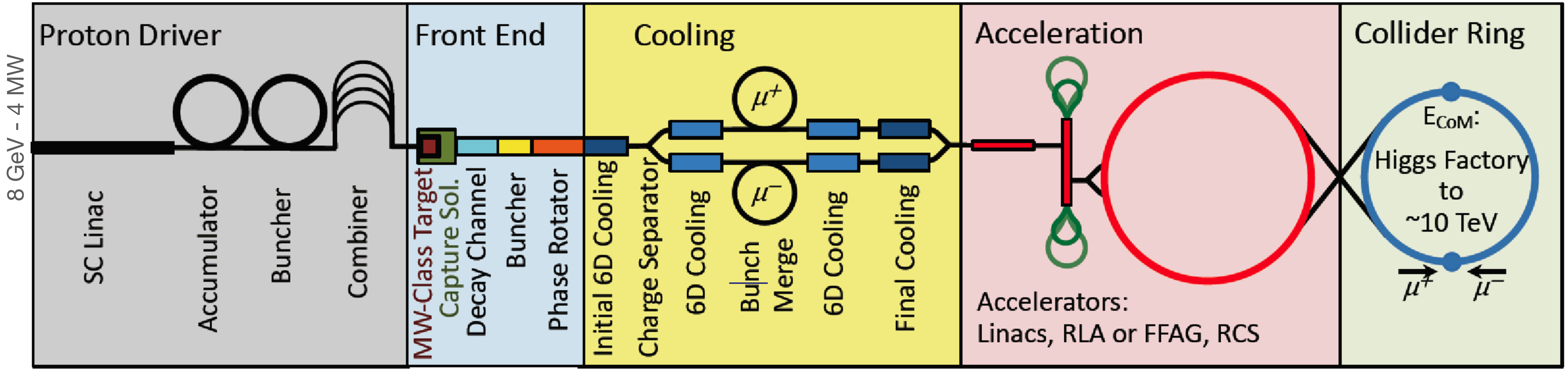
Vacuum Stability

2407.12450 Muon Collider Interim Report

A new interest in a multi-TeV muon collider

Why?

Technology: new generation of accelerator technologies.
No known showstoppers.



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

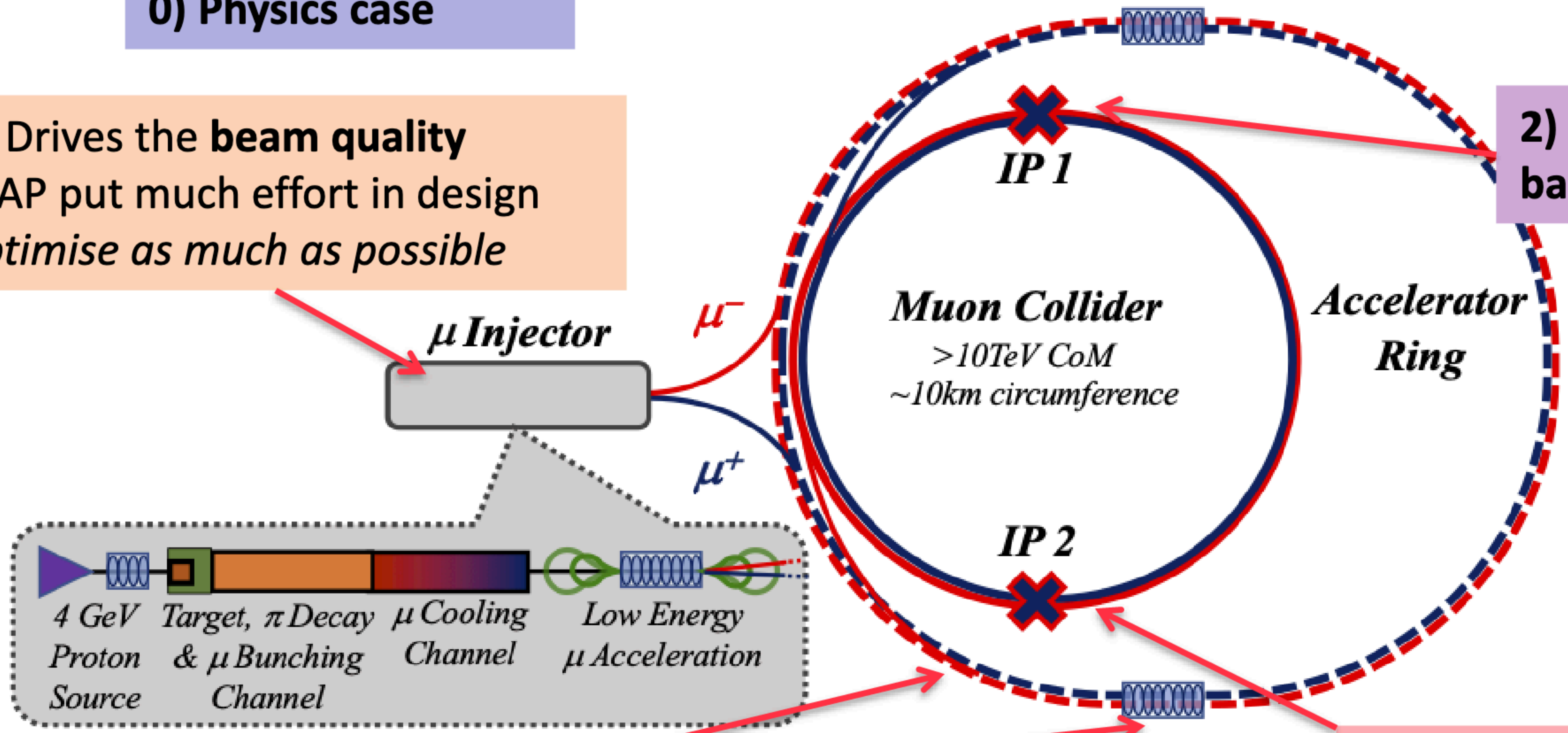
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

2407.12450 Muon Collider Interim Report

Key Challenges



0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

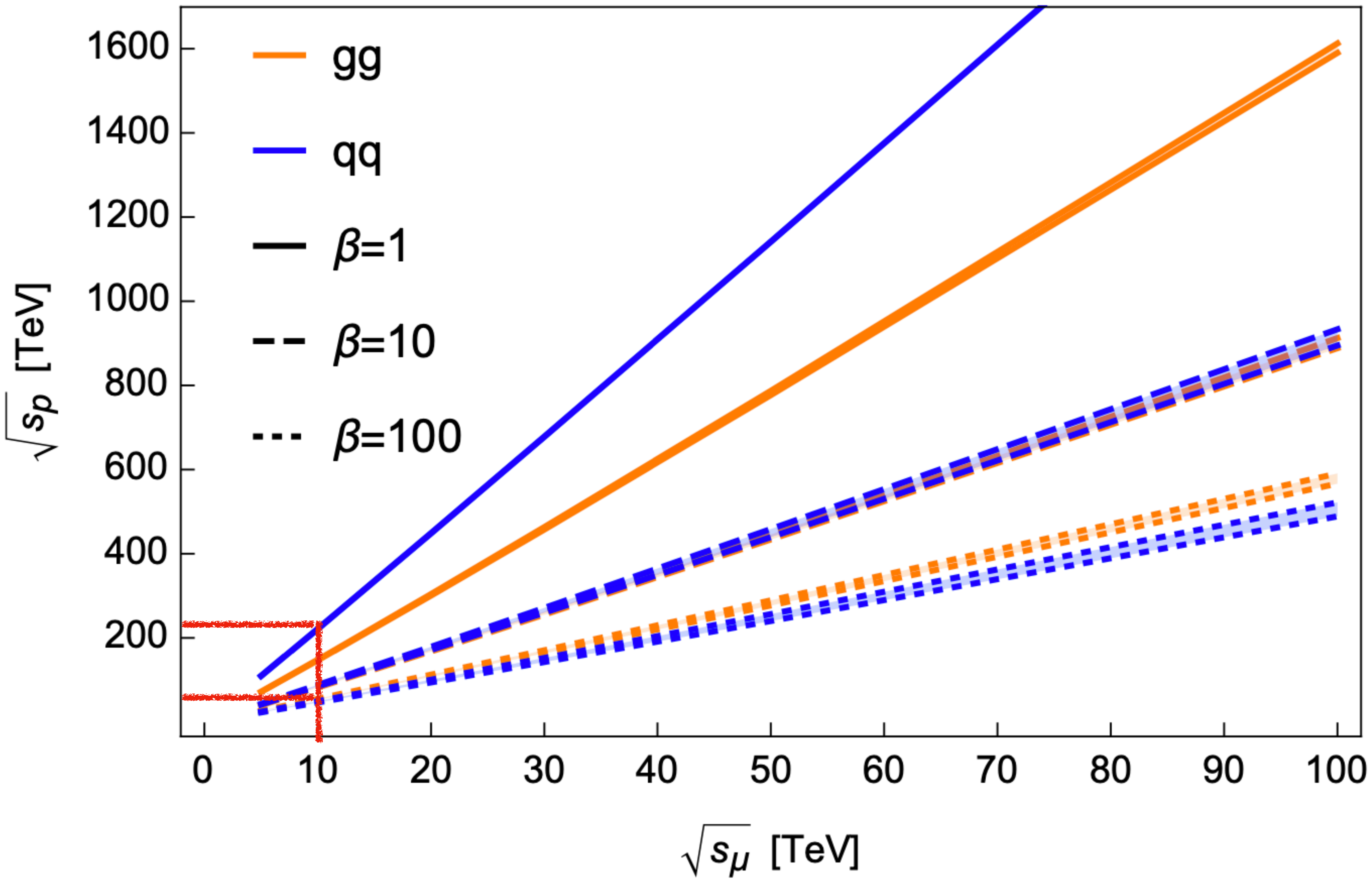
2) Beam-induced background

1) Dense neutrino flux
mitigated by mover system and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Muon collider physics

The essentials #0 : physics potential



muC@10 TeV ~ pp@70 TeV

Simple/Naive/Rough estimate based on parton-parton luminosity for a generic $2 \to 2$ scattering.

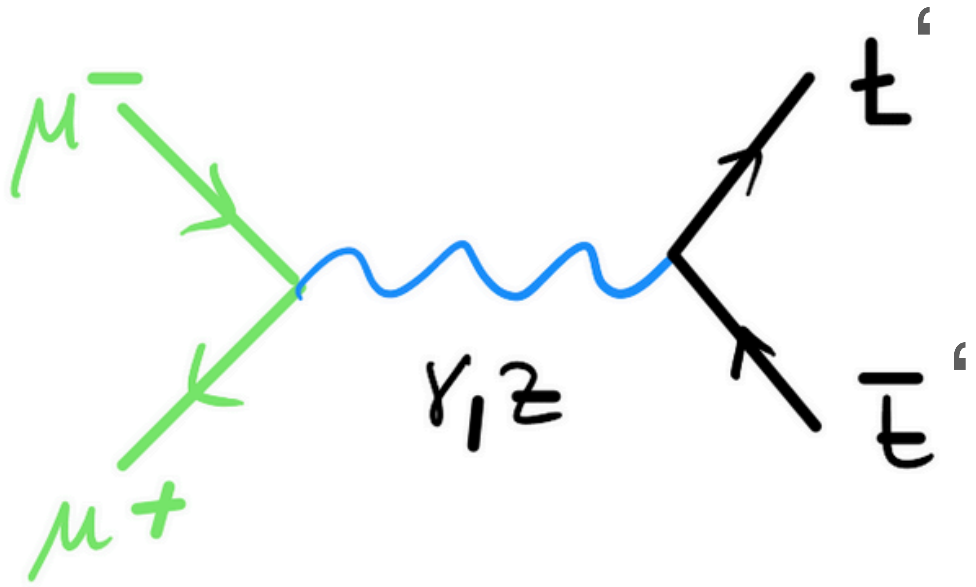
$$EW : \beta \sim 1$$

$$QCD : \beta \sim (\alpha_S/\alpha)^2 \sim 100$$

Muon collider physics

The essentials #1 : two colliders in one

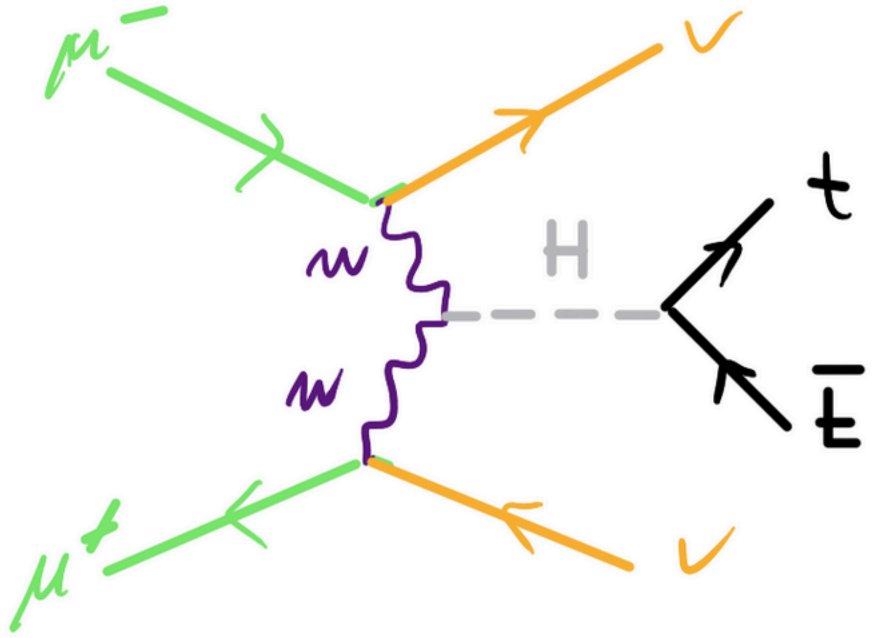
O(10) TeV muon collider energy allows to have two colliders in one:



$$\sigma_s \sim \frac{1}{s}$$

$$\Longleftrightarrow$$

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



Energetic final states
(either heavy or very boosted)

Large production rates,
SM coupling measurements
Discovery light and weakly interacting

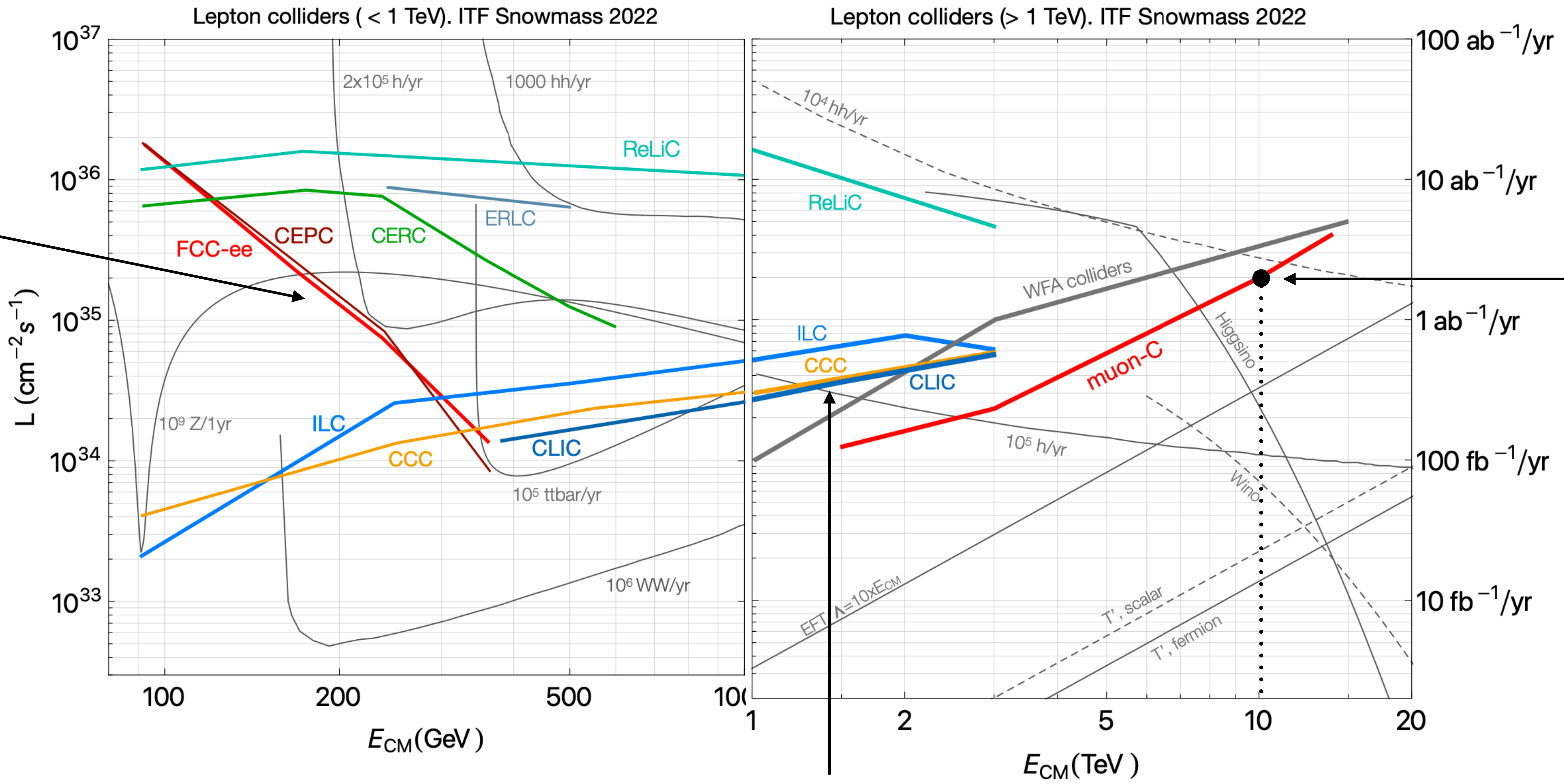
A completely new regime opening for a multi-TeV muon collider

Different physics being probed in the two channels

arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #2 : luminosity with energy



$L = P_{\rm synrad} E_{\rm cm}^{-3.5}$

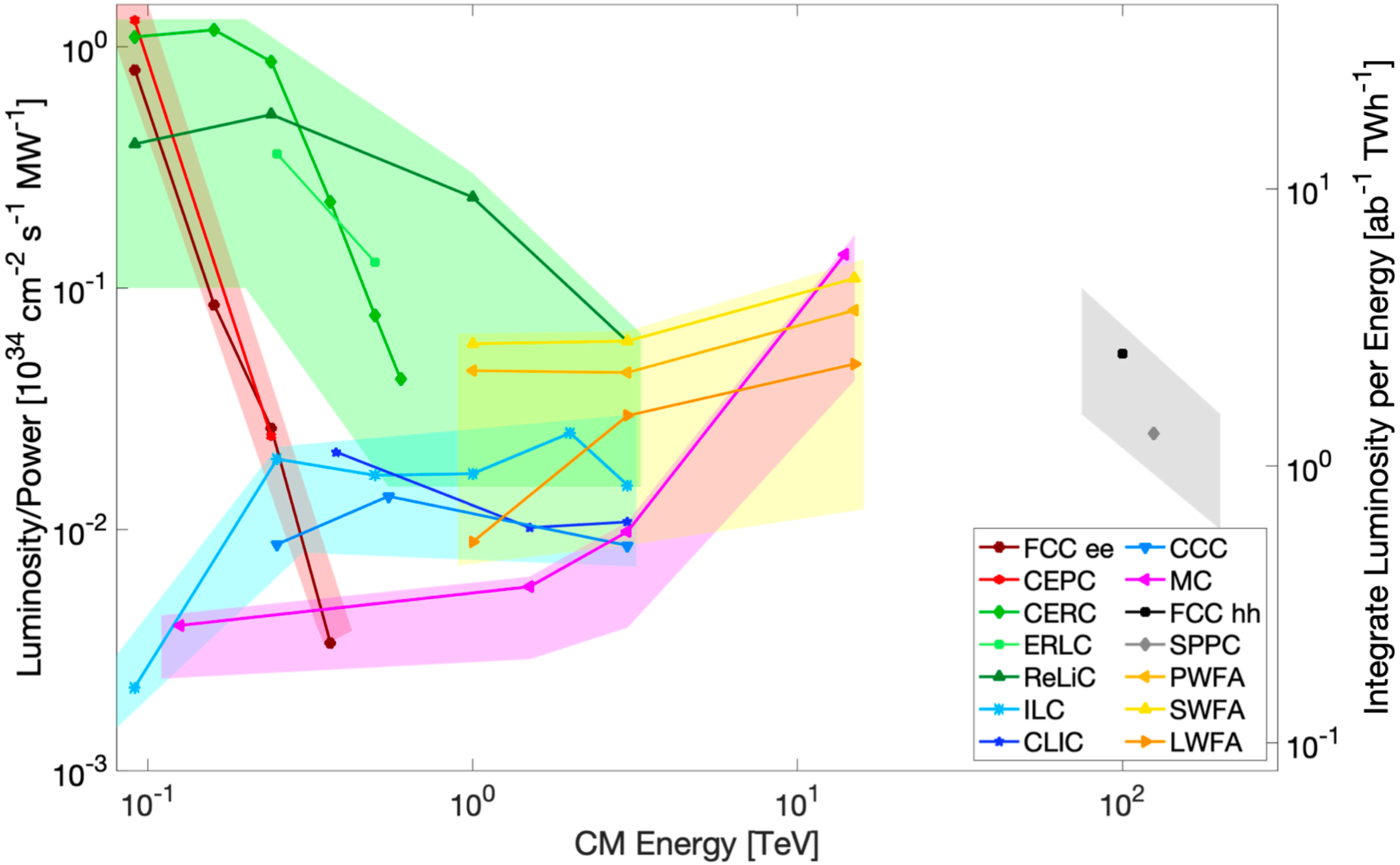
10 ab^{-1} in 5 years

$L = P_{\rm RF}$

arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #3 : the green side

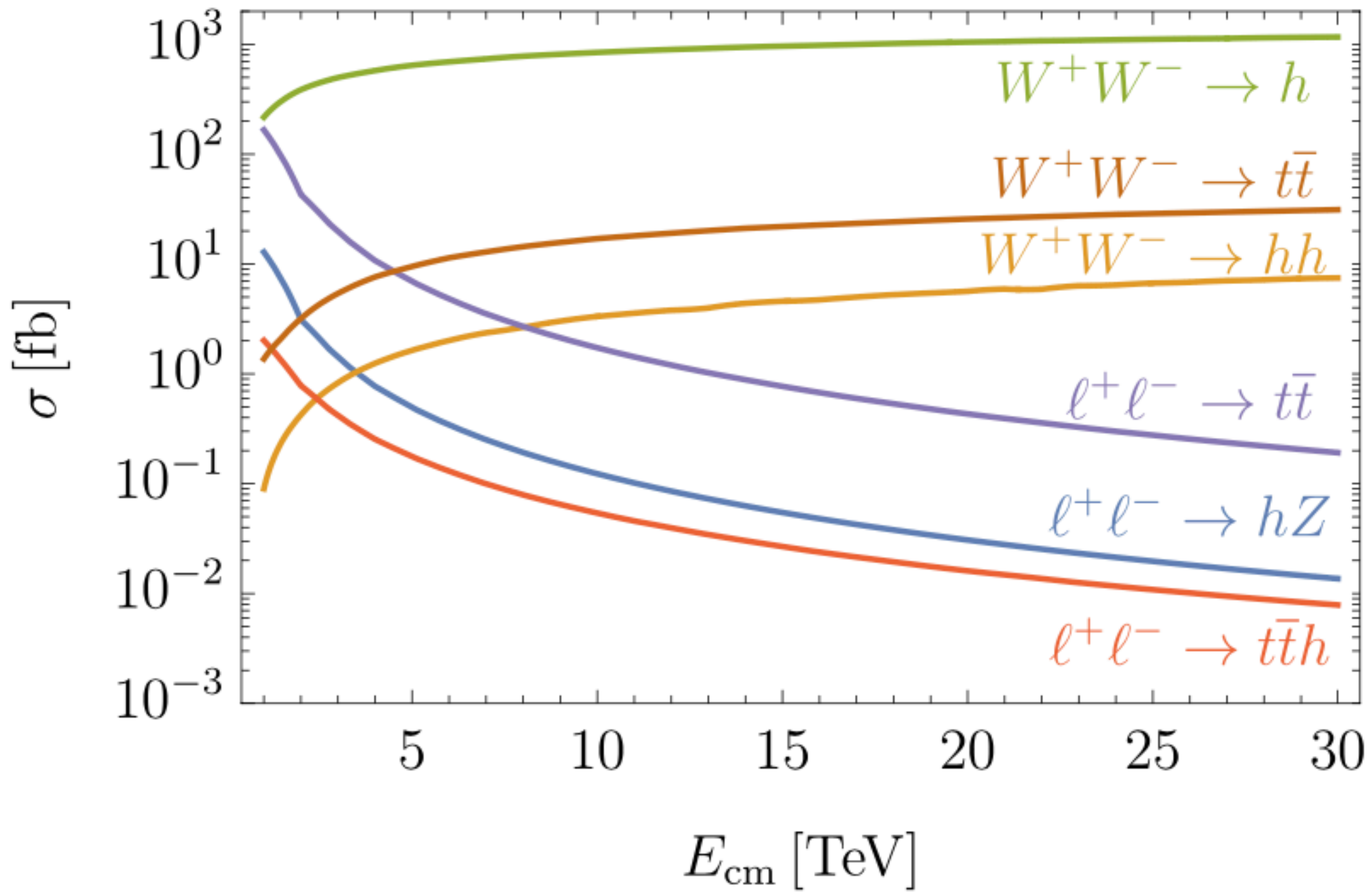


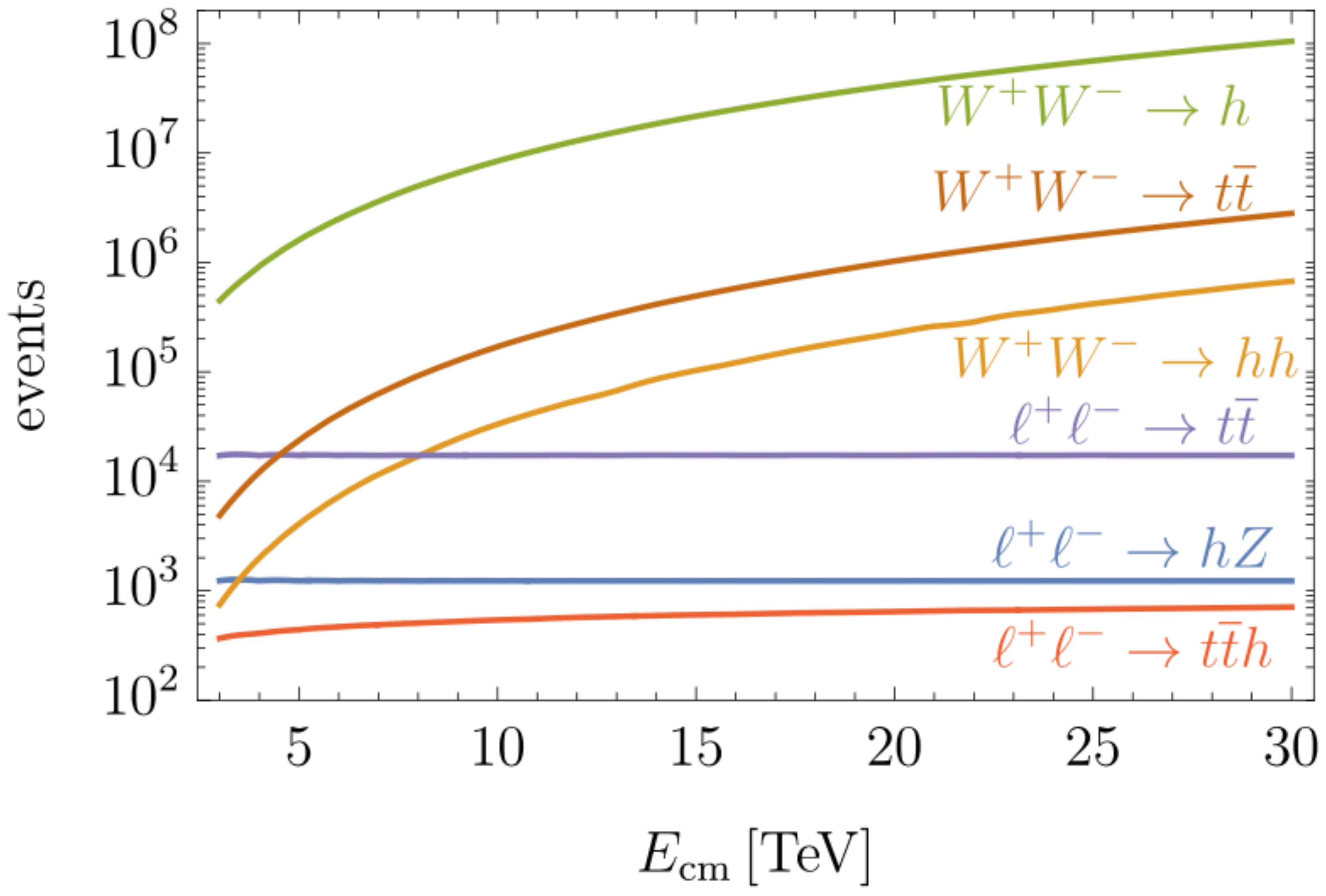
[Buttazzo, Franceschini, Wulzer 2012.11555]

Muon collider physics

The essentials #4 : luminosity with energy

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$



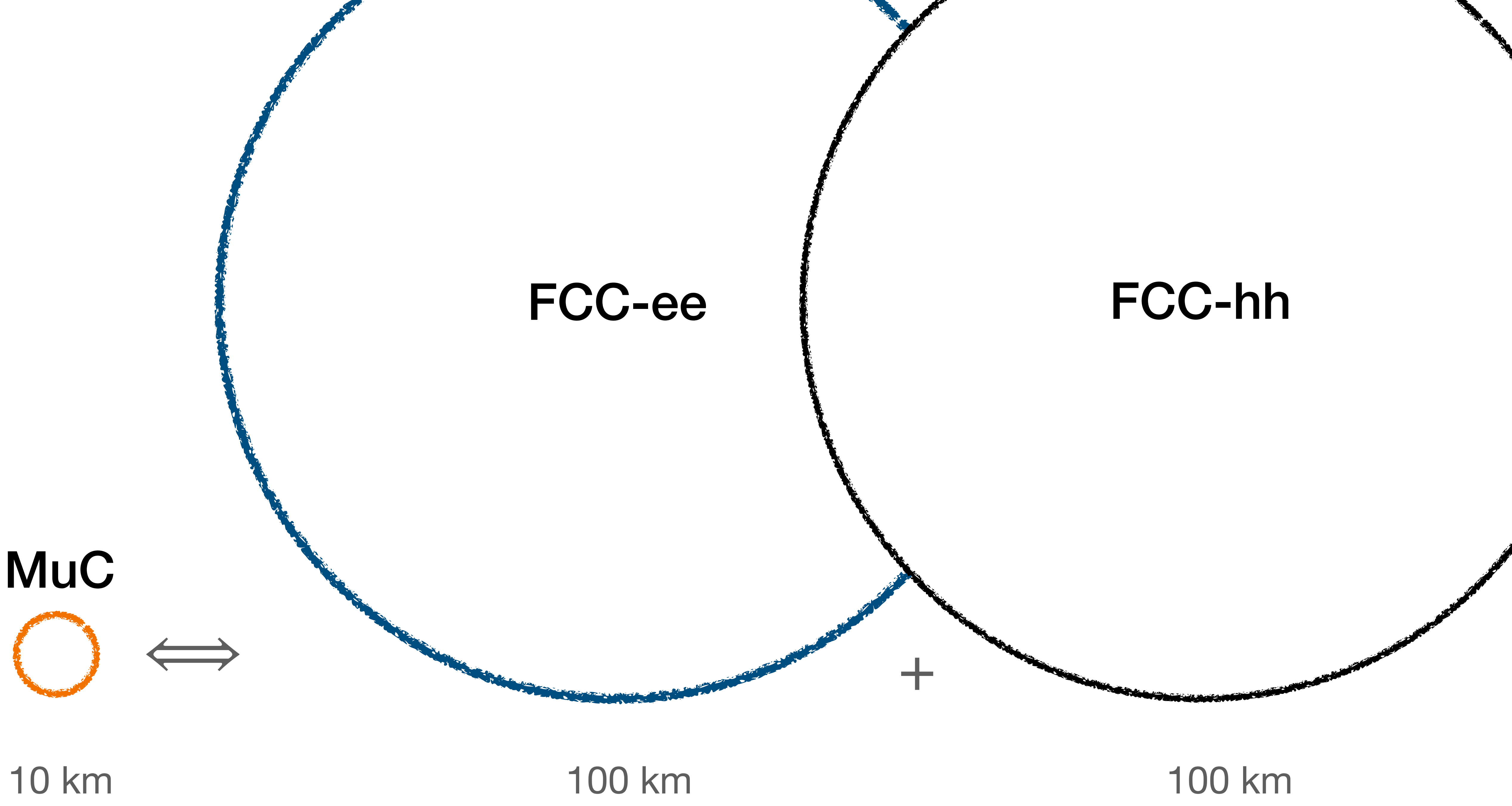


$$\widehat{\mathcal{L}} = 10\,\text{ab}^{-1} \left(\frac{E_{\text{cm}}}{10\,\text{TeV}} \right)^2$$

Muon collider physics

The essentials #5: compactness

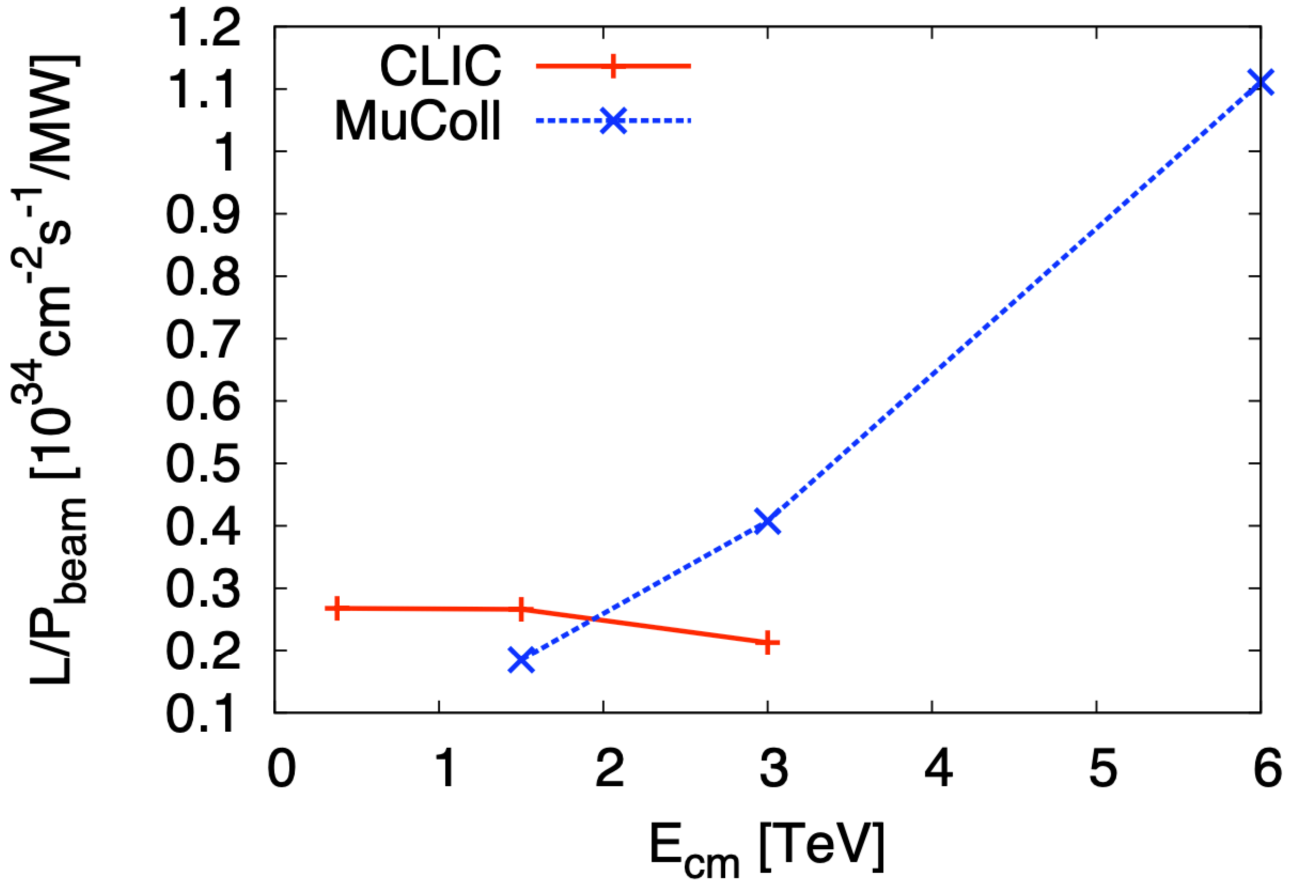
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:



⇒**MuC is an STCC = Space-Time-Compact Collider**

⇒ **Goal of the tens:**

10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

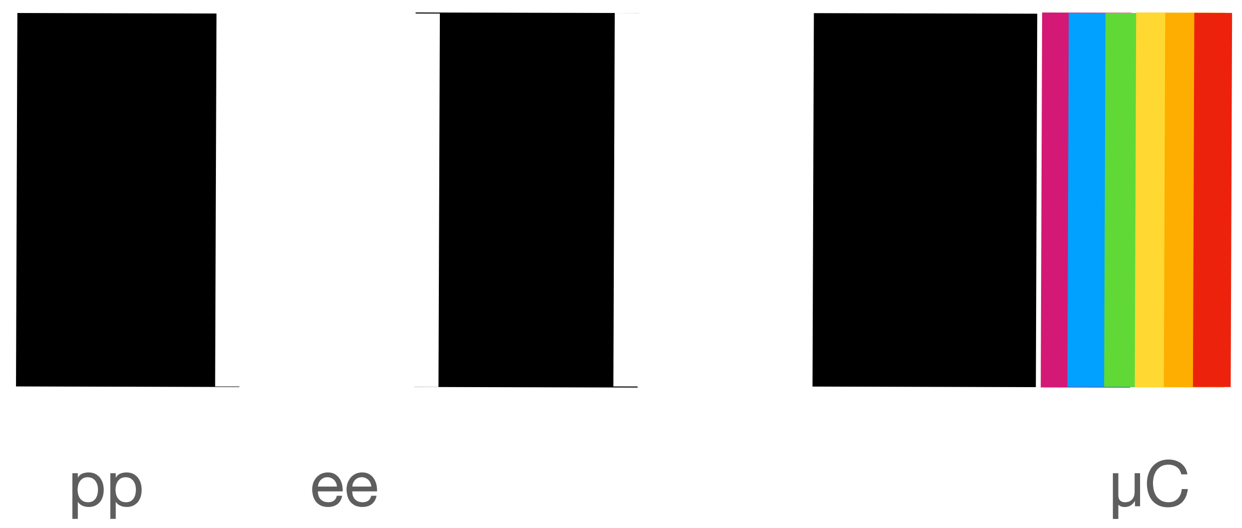
Muon collider physics

The essentials

- A O(10 TeV) muC is in the range of what could be technically achievable. No showstopper known. Strong R&D programme is needed. Demonstrator is the next step.

- It would radically change the way we do collider physics, opening the exploration of EW phenomena at higher scales through an hybrid direct/indirect approach in a clean environment.

- Given what we know now from the LHC + what will learn from HL-LHC what are the muC physics drivers?

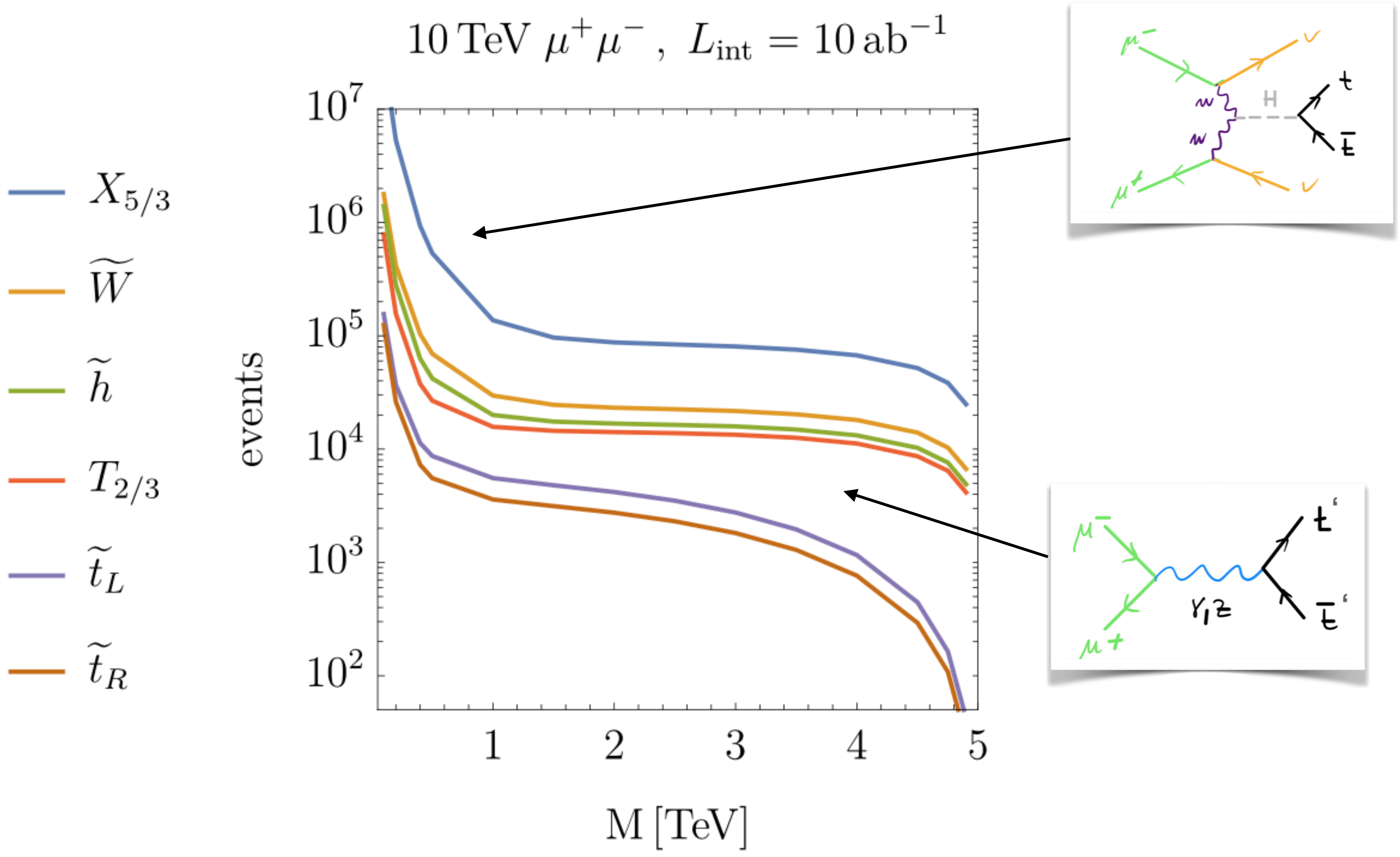


arXiv:2203.07256 Muon Collider Physics Summary

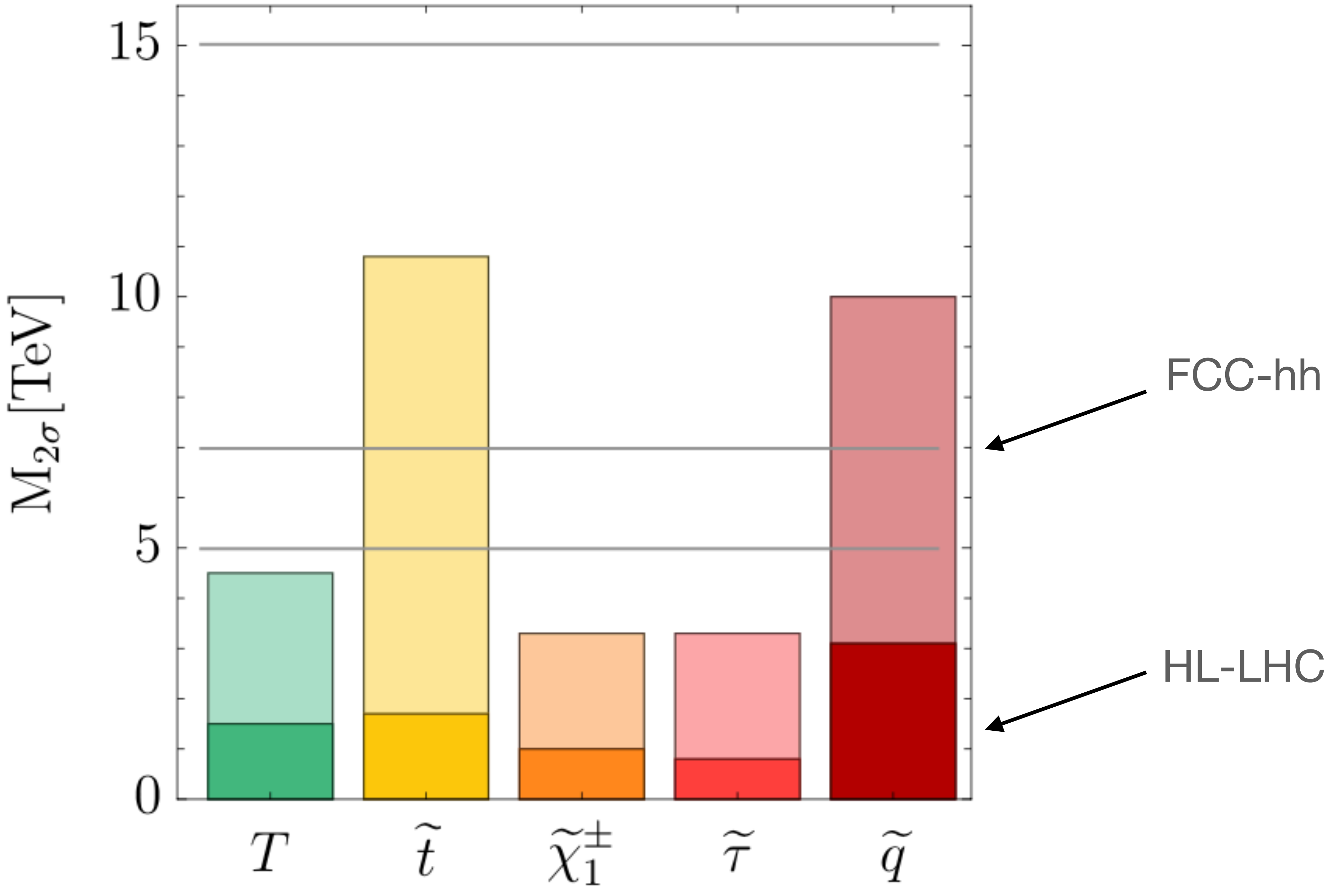
arXiv:2209.01318 Muon Collider Forum Report

Direct reach

s-channel pair production



A few months of run could be sufficient for a discovery.



Matching Higgs precision:

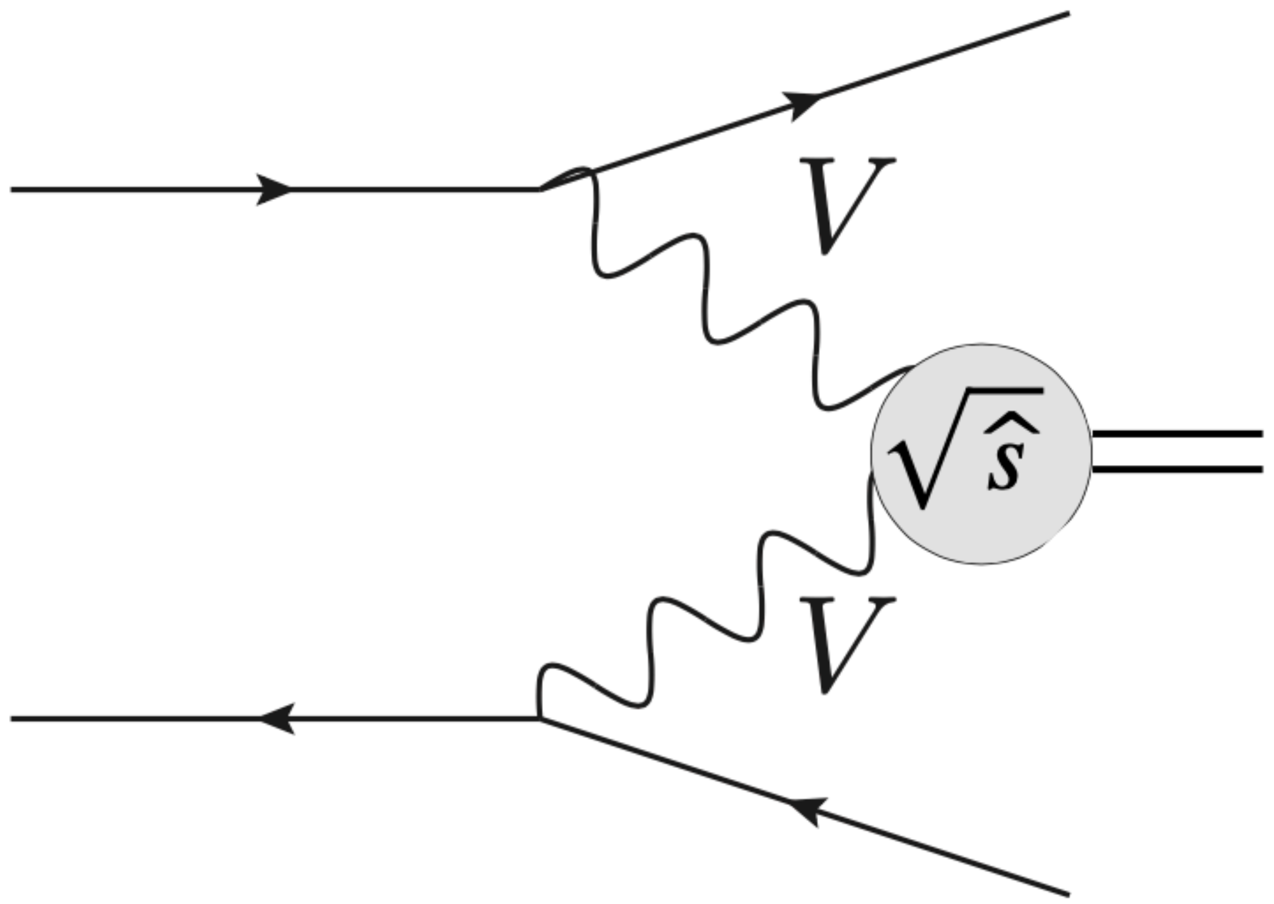
$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

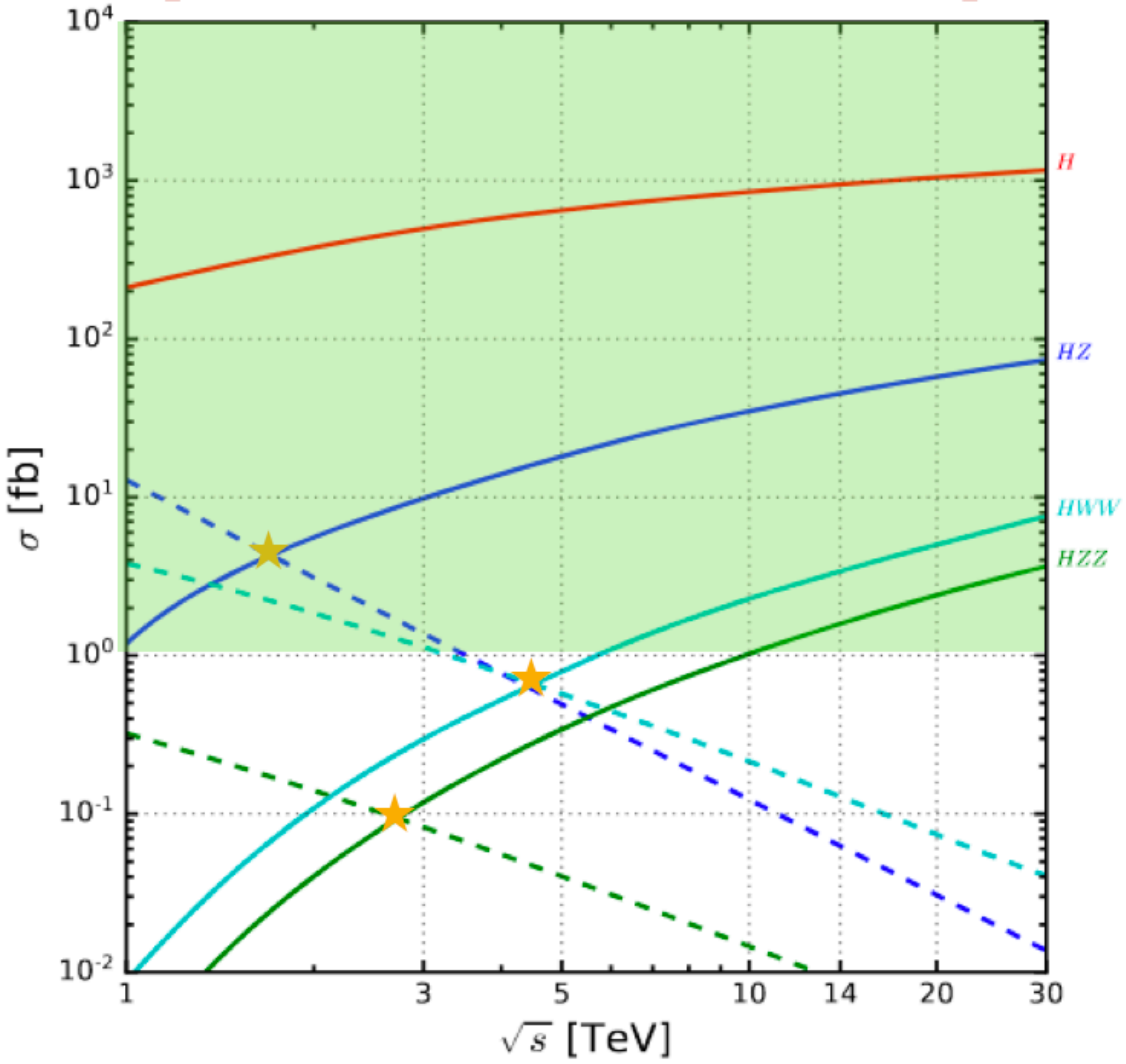
$$m_{\tilde{t}} \gtrsim 1.5\,\text{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\max}}}.$$

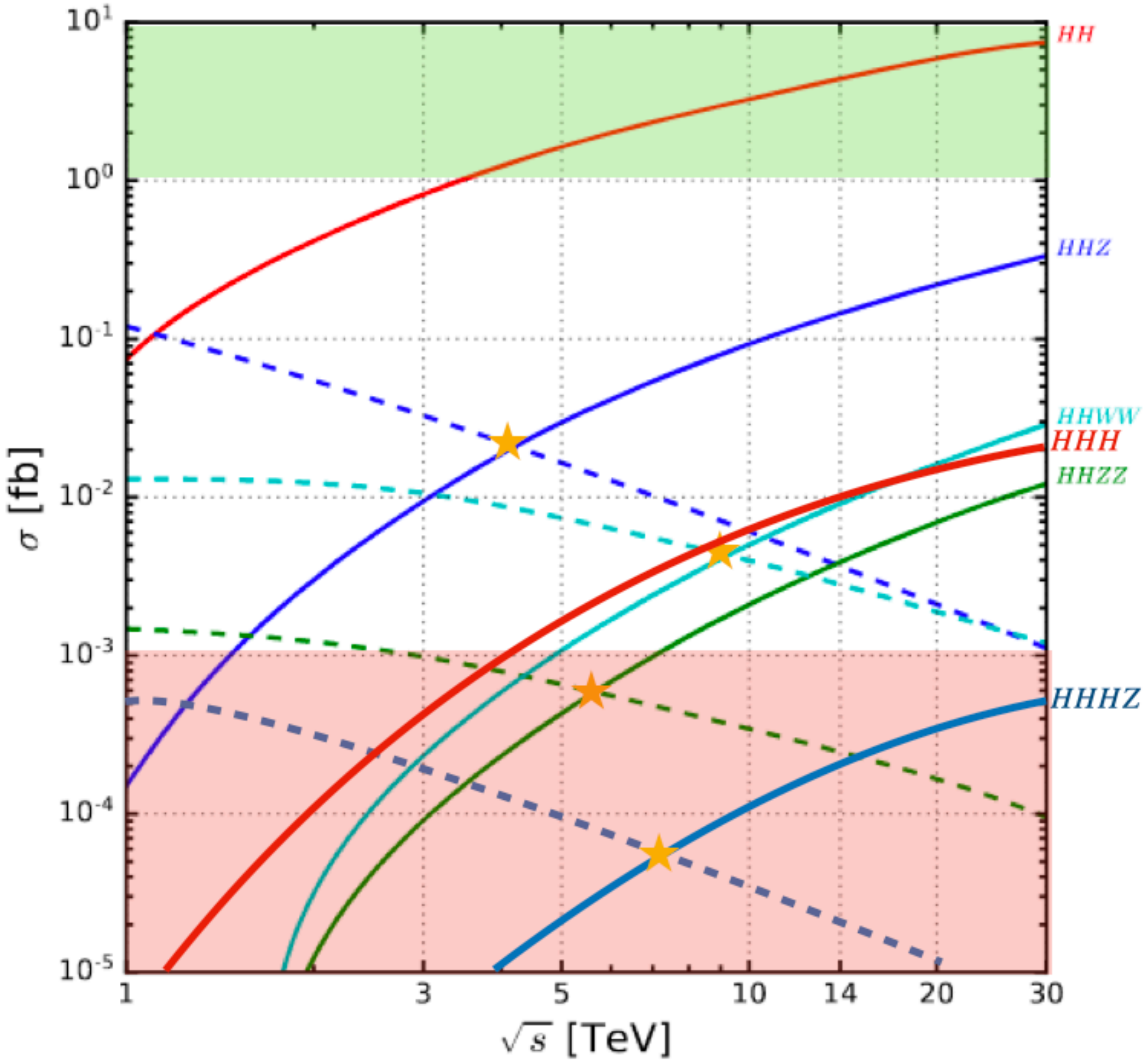
arXiv:2203.07256v1 Muon Collider Physics Summary

Precision physics

Weak boson collider



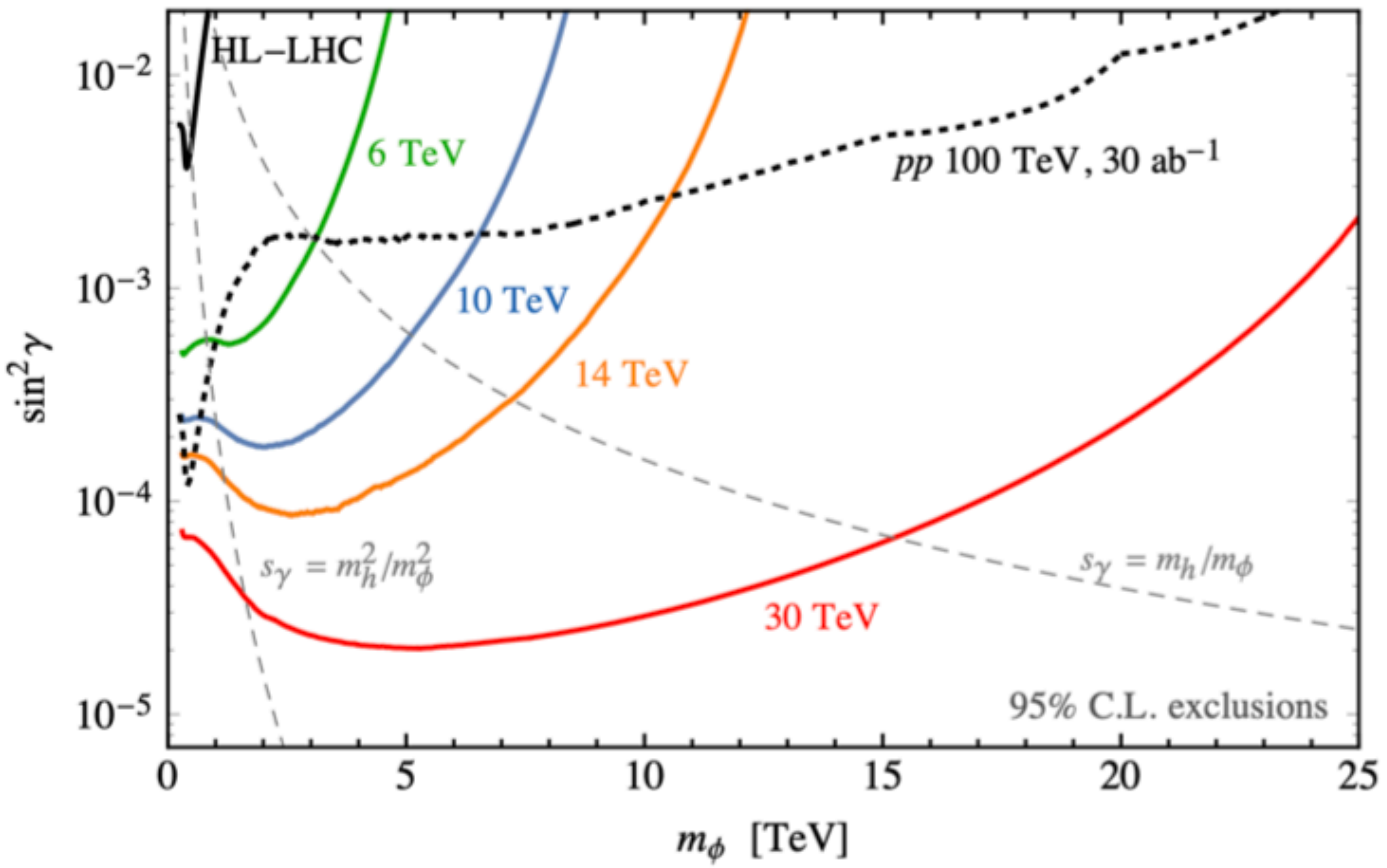


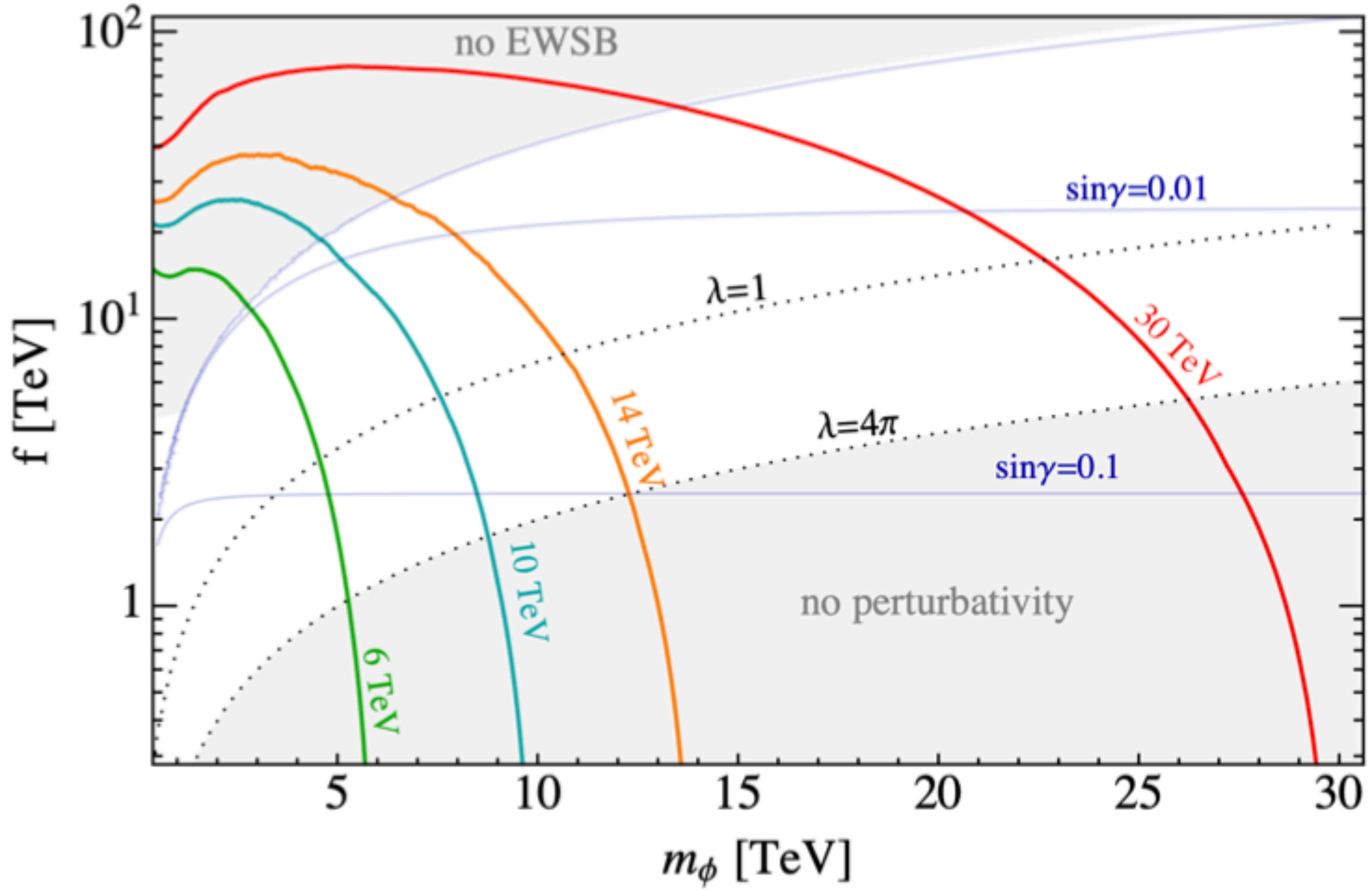


arXiv:2203.07256v1 Muon Collider Physics Summary
arXiv:2209.01318 Muon Collider Forum Report

Direct reach

VBF scalar singlet production





[Buttazzo et al. 1807.04743]

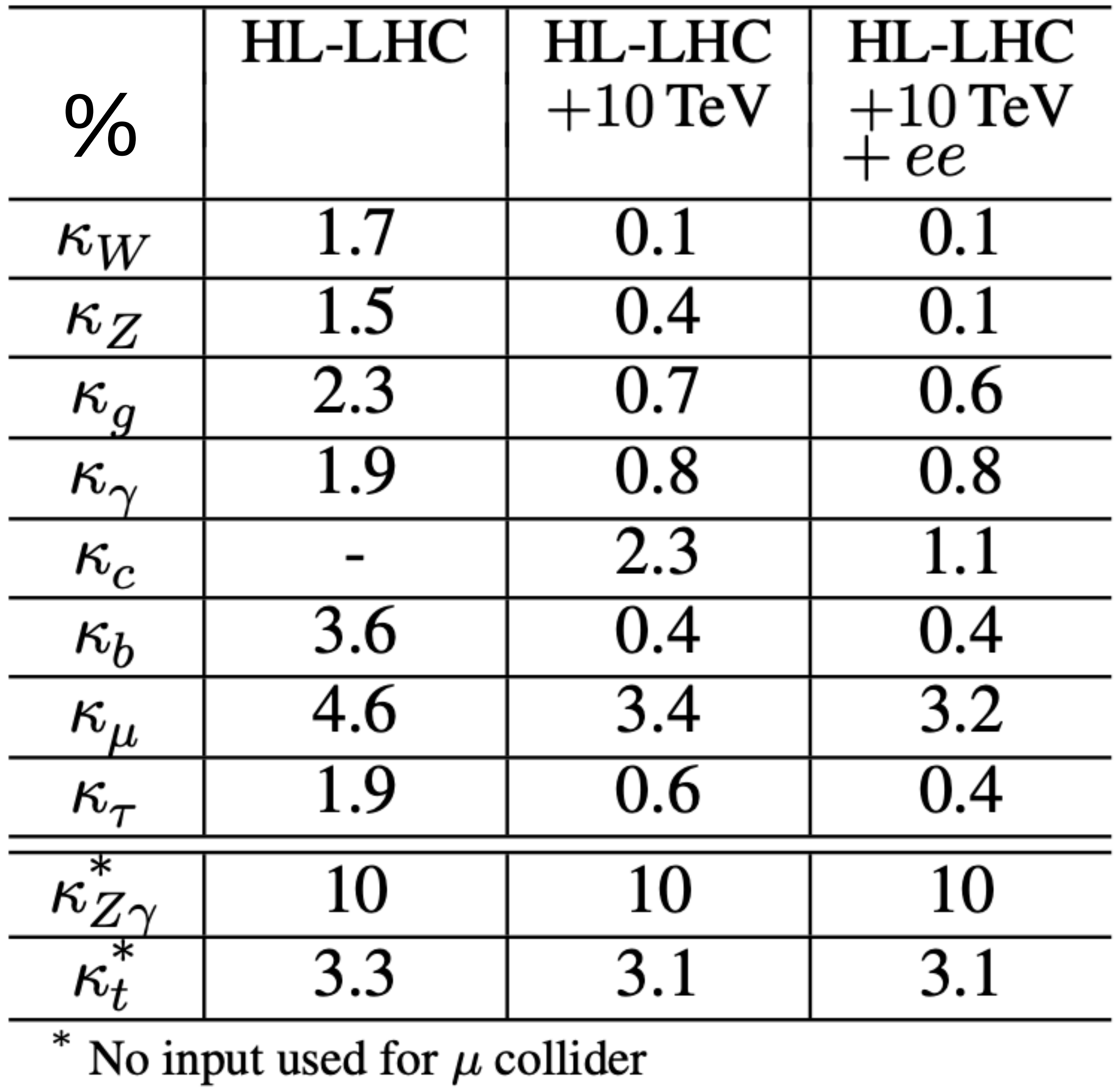
mixed with the Higgs boson with strength sin γ.

Reach in terms of the scale f in the Twin Higgs model

arXiv:2203.07256v1 Muon Collider Physics Summary

Higgs precision physics

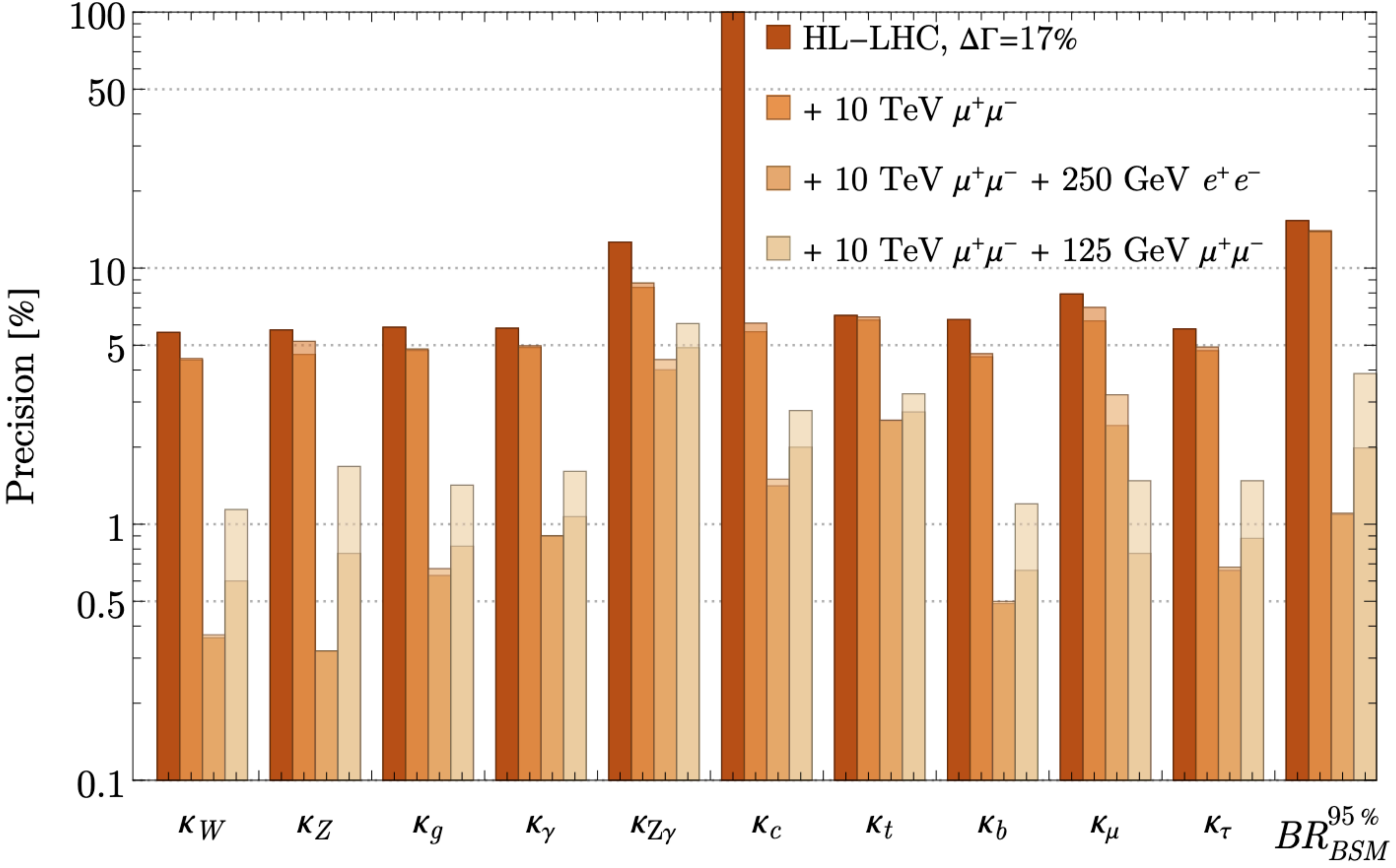
Higgs coupling sensitivities



%	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

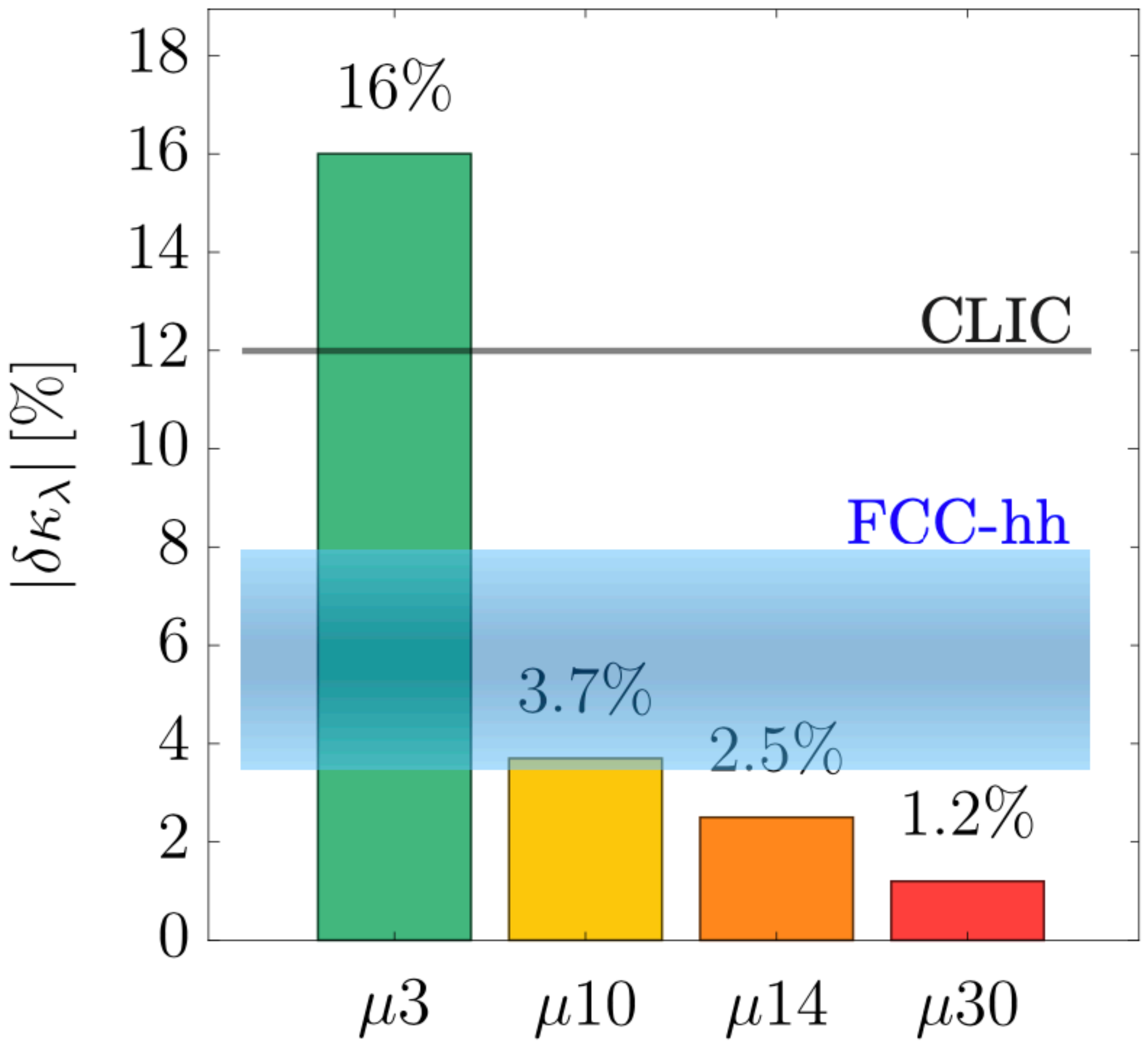
* No input used for μ collider

arXiv:2308.02633

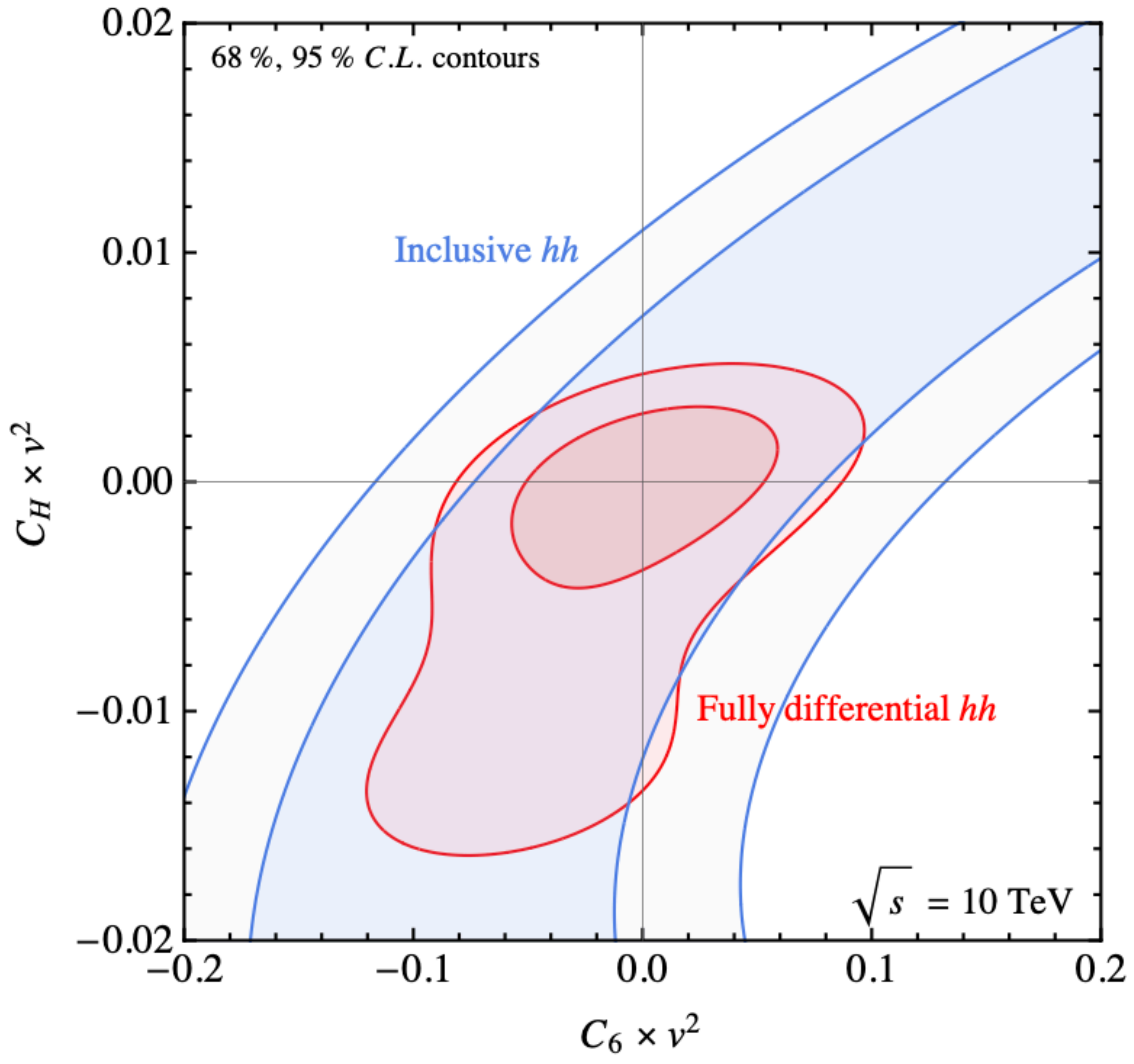


Higgs precision physics

The shape of the H potential: HH production



arXiv:2203.07256v1



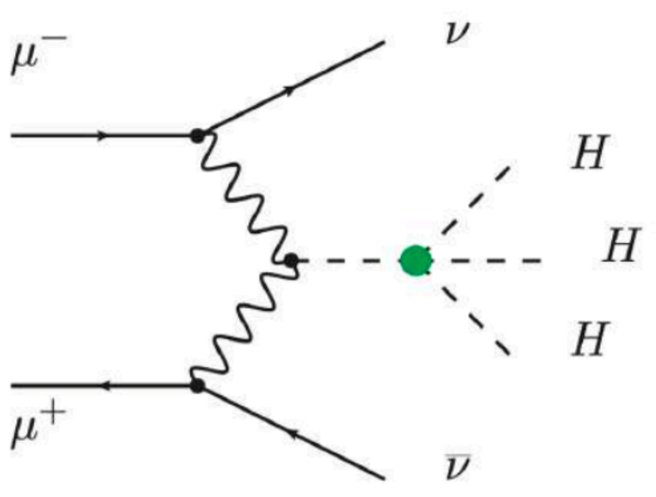
[Buttazzo et al. 2012.11555]

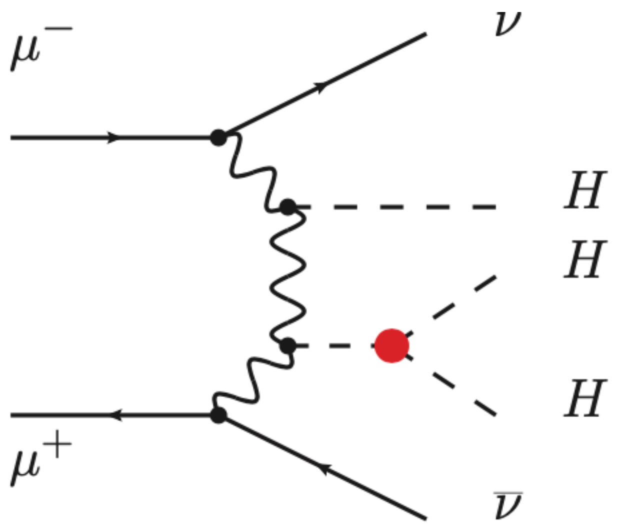
Reach on the trilinear coupling (and more) extremely competitive.

Higgs precision physics

The shape of the H potential : HHH production

3 Higgs final state

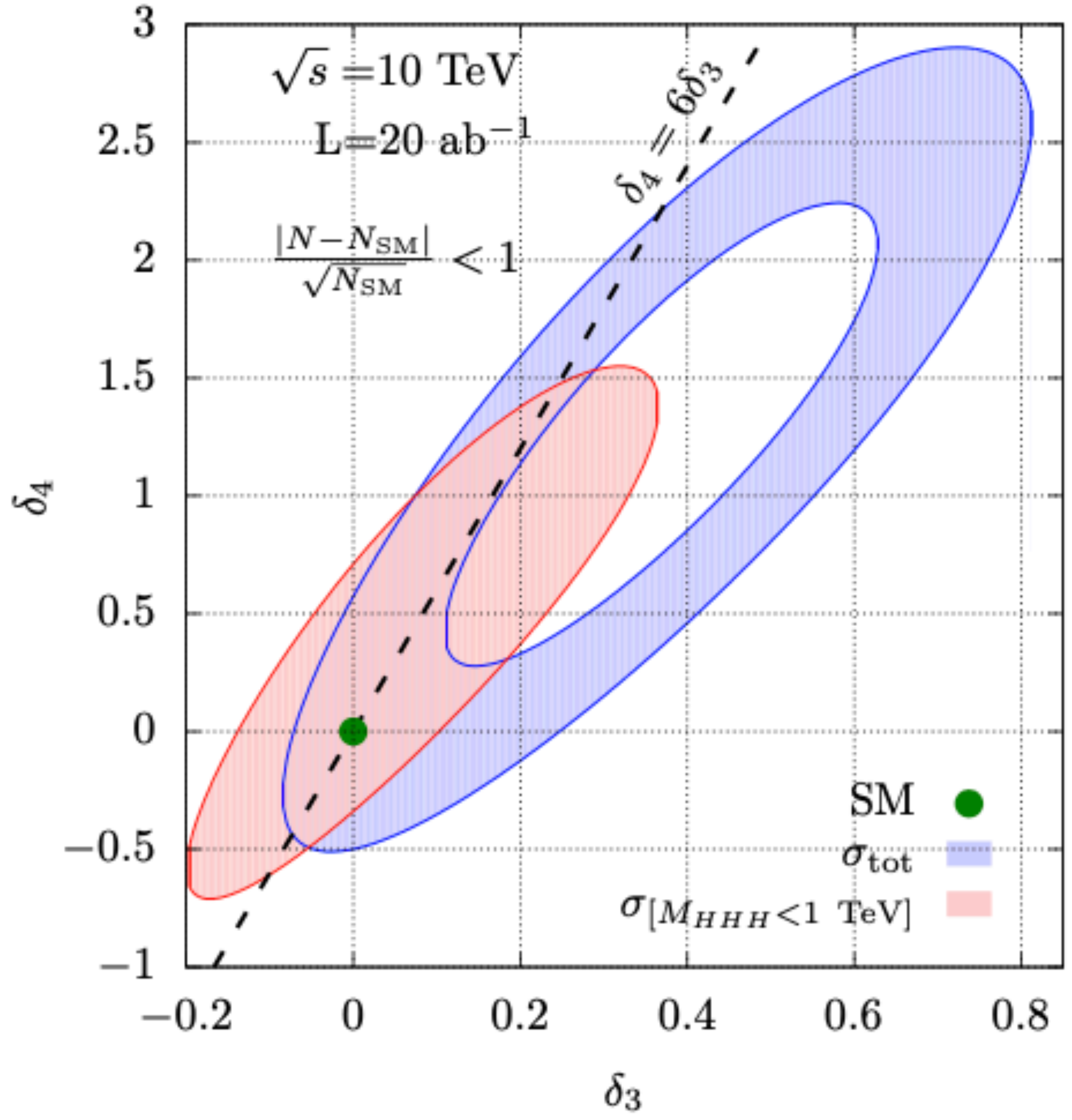




Quadrilinear determination extremely challenging at any collider, due to limited sensitivity.

$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

Very preliminary study points to the possibility of setting competitive bounds at a muon collider.



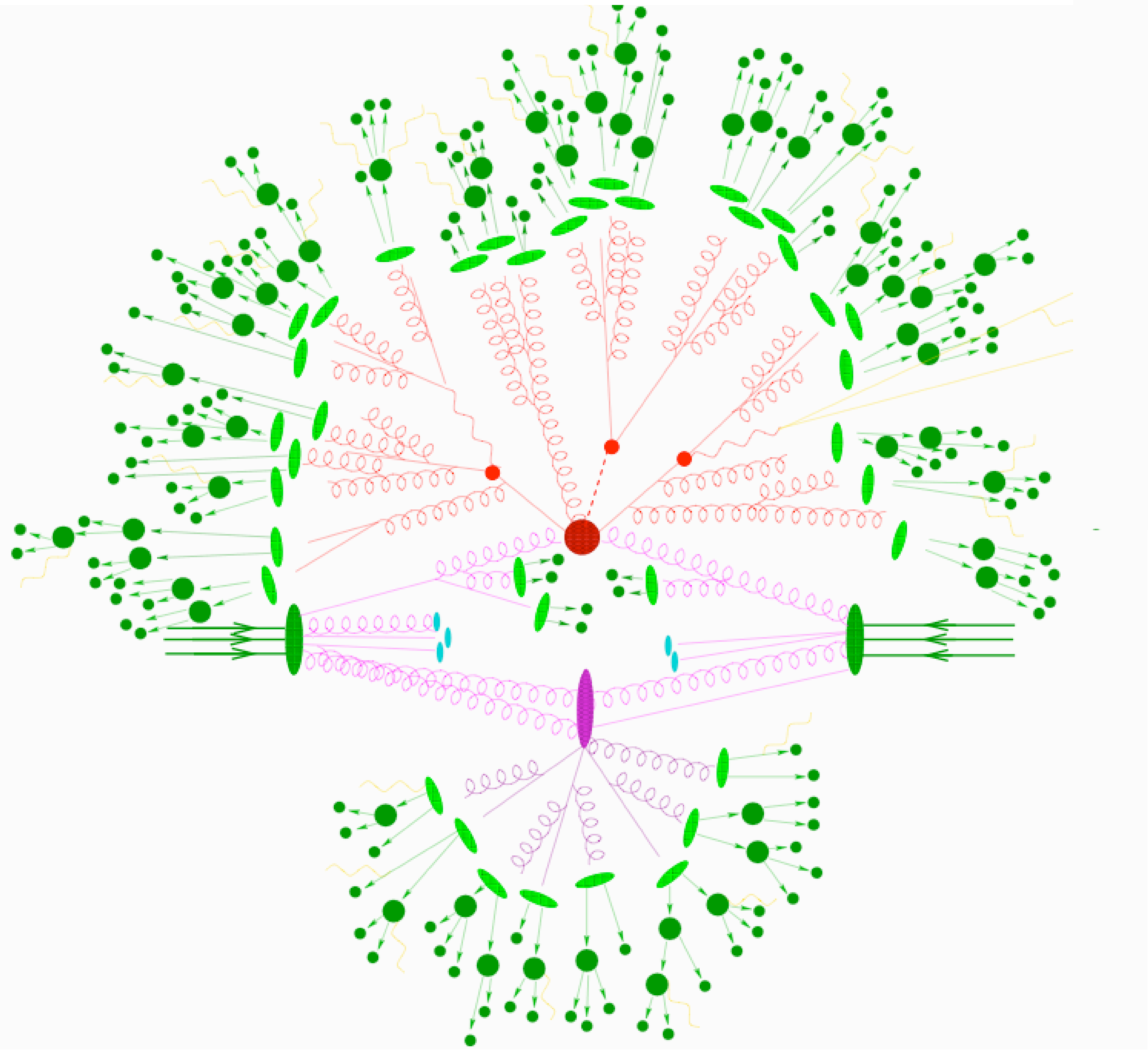
$$10\ \text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

[Chiesa et al. 2003.13268]

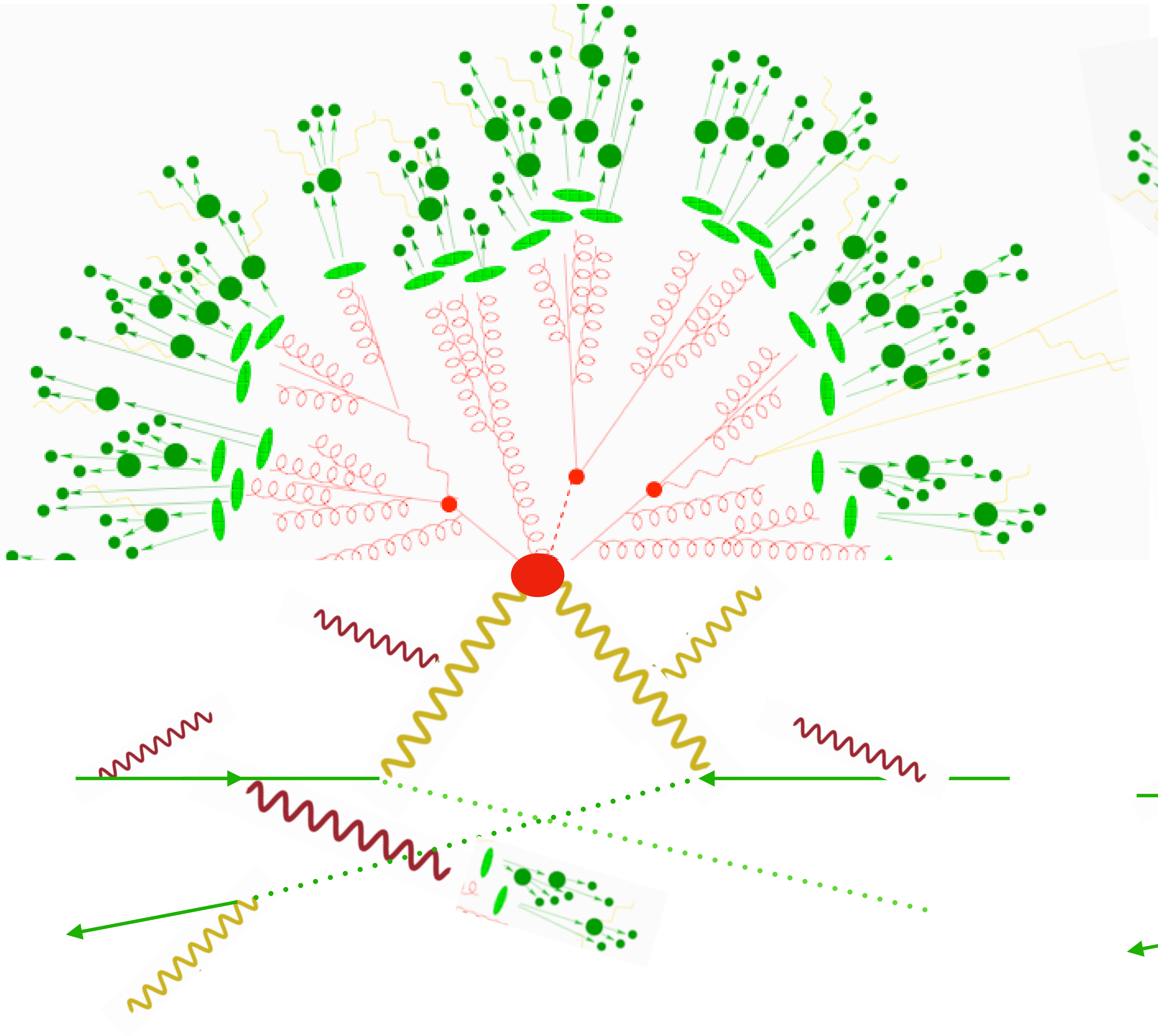
Contribution to: 2022 Snowmass Summer Study e-Print: 2203.07256 [hep-ph]

How events will look at a multi-TeV muon collider?

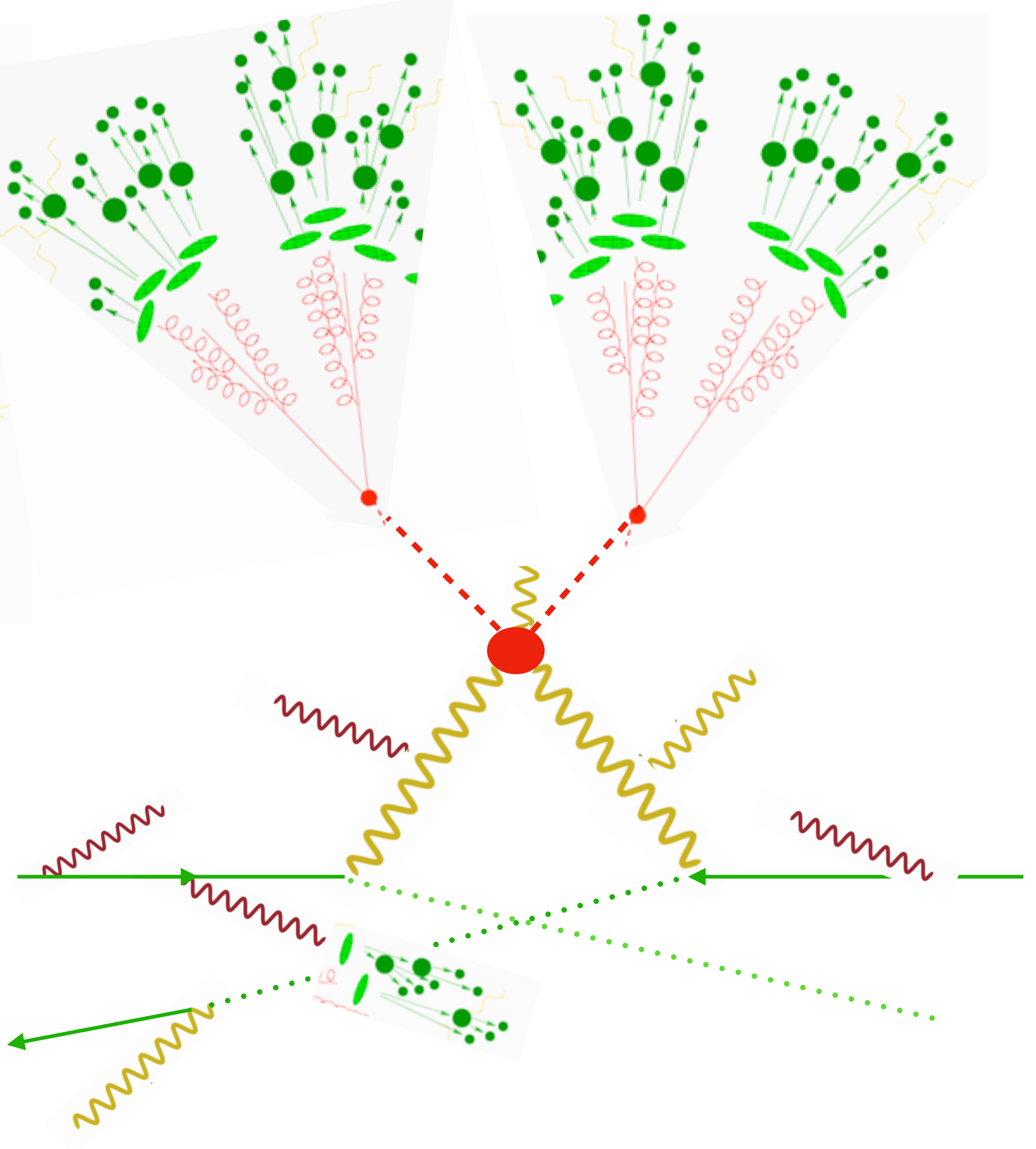
tth production at the LHC (Fully hadronic)



tth production at the muC 100 TeV



HH→4b production at a multi-TeV muC



In a muon collider gluons and quarks first appear at scales of order 100 GeV in the decays of W,Z,H (from either initial state or final state radiation) or from photon splitting.

Multijet final states are of EW origin.

Contribution to: 2022 Snowmass Summer Study e-Print: 2203.11129 [hep-ph]

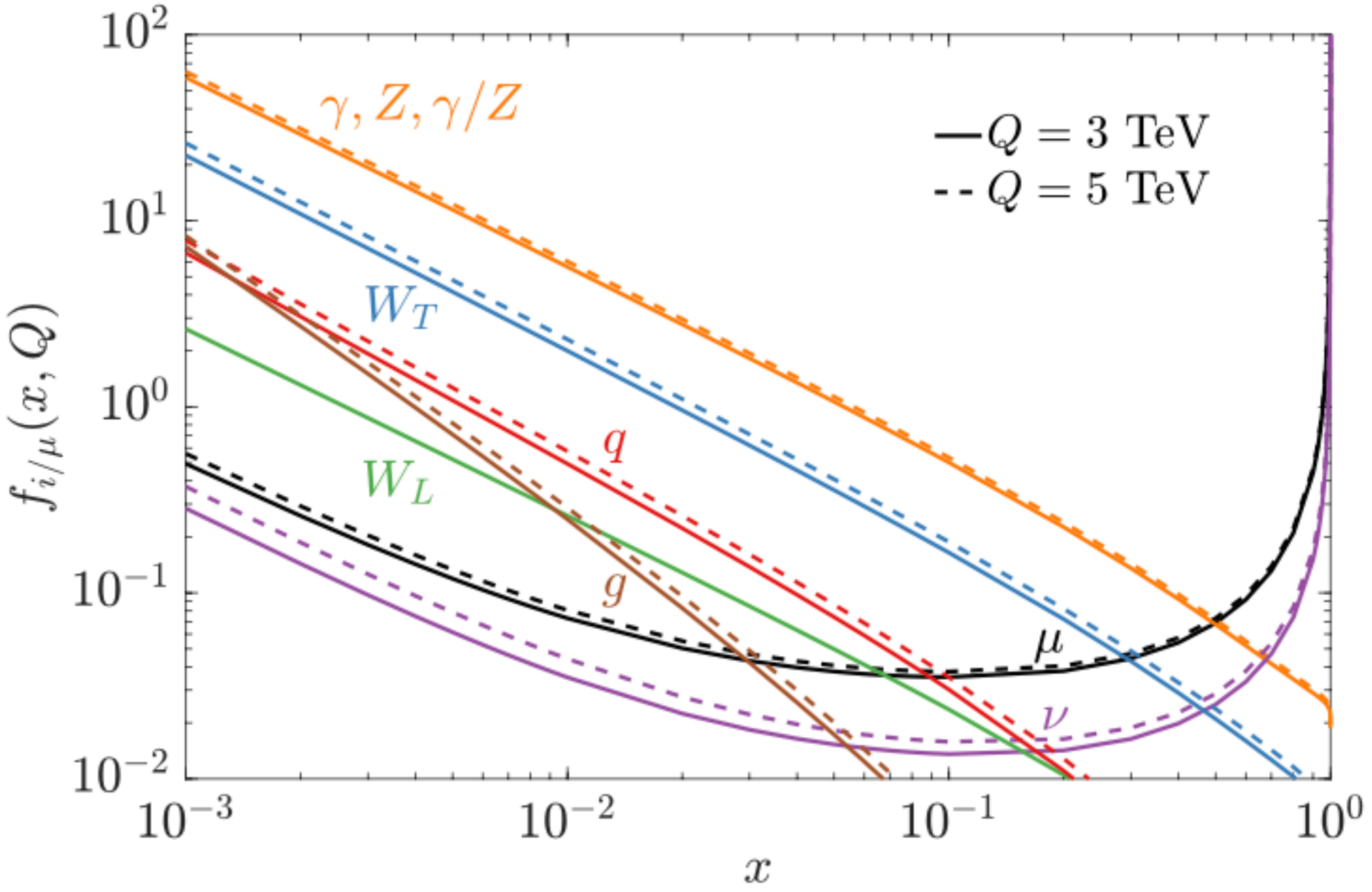
Precision calculations for multi-TeV lepton colliders

EW resummation in the initial state

$$f_B(z,\mu^2) = \sum_A \int_z^1 \frac{d\xi}{\xi} f_A(\xi) \int_{m^2}^{\mu^2} d\mathscr{P}_{A\to B+C}(z/\xi, k_T^2)$$

$$\frac{\partial f_B(z,\mu^2)}{\partial \mu^2} = \sum_A \int_z^1 \frac{d\xi}{\xi} \frac{d\mathscr{P}_{A\to B+C}(z/\xi,\mu^2)}{dz\,dk_T^2} f_A(\xi,\mu^2)$$

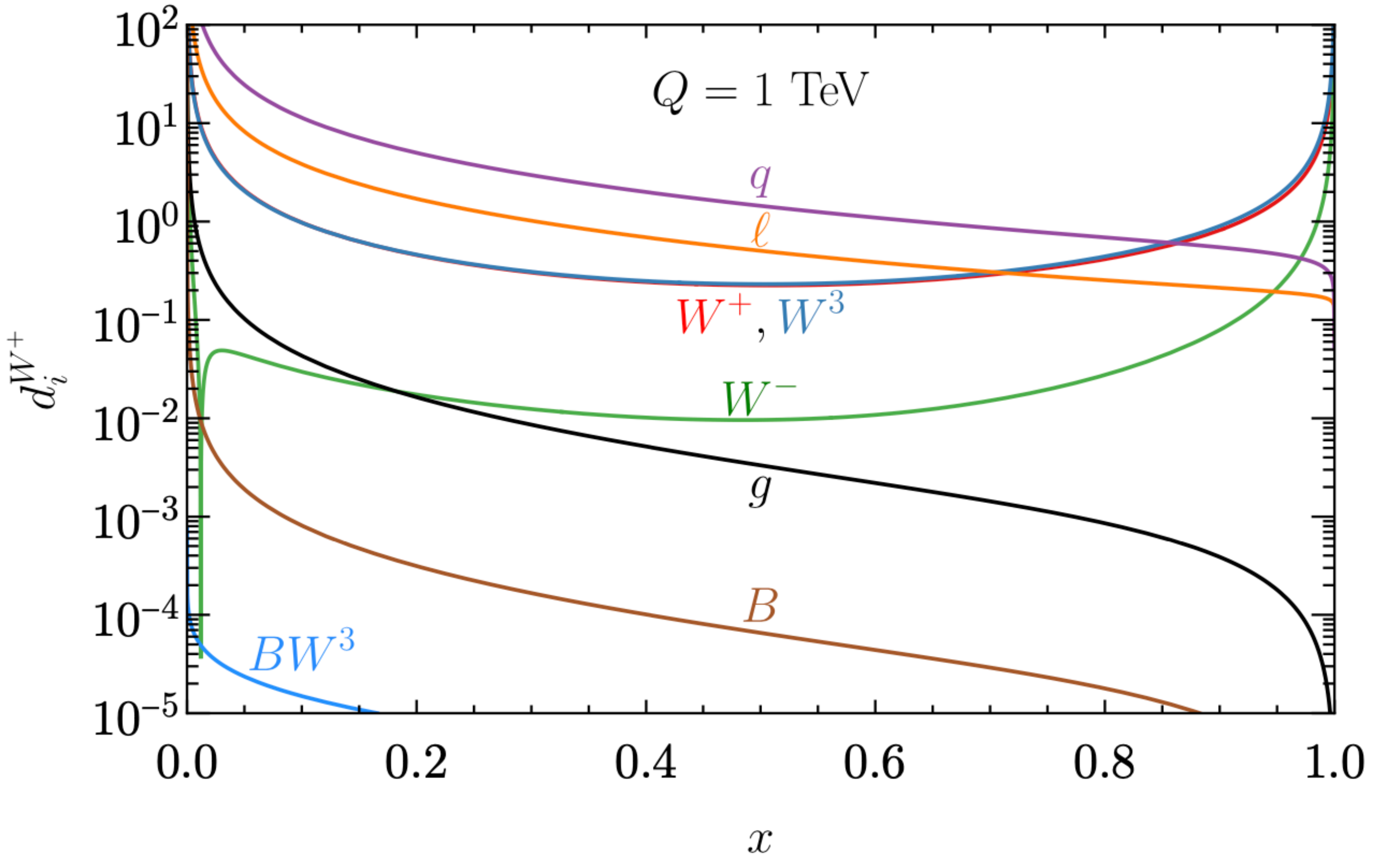
Han, Ma, Xie arXiv:2007.14300v4. 2103.09844



$$\Delta_A(t) = \exp\left[-\sum_B \int_{t_0}^{t} \int dz\, \mathscr{P}_{A\to B+C}(z)\right],$$

$$f_A(x,t) = \Delta_A(t) f_A(x,t_0) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \mathscr{P}_{A\to B+C}(z) f_A(x/z,t')$$

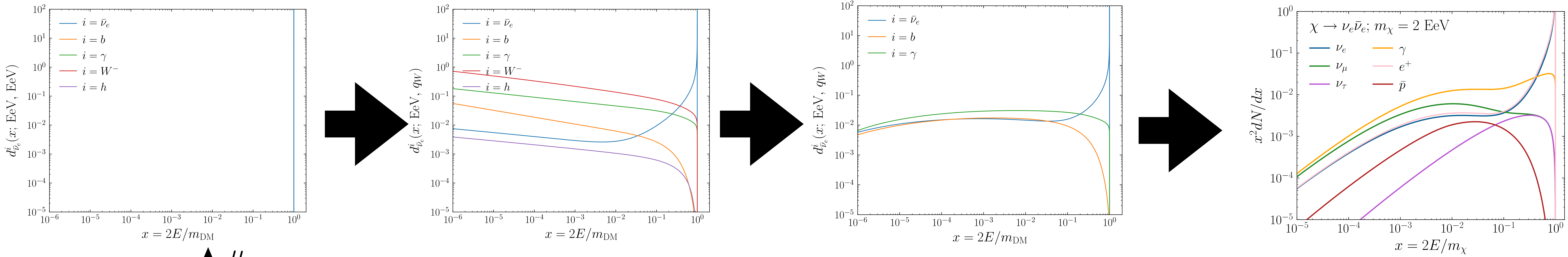
Han, Ma, Xie rXiv:2203.11129v1

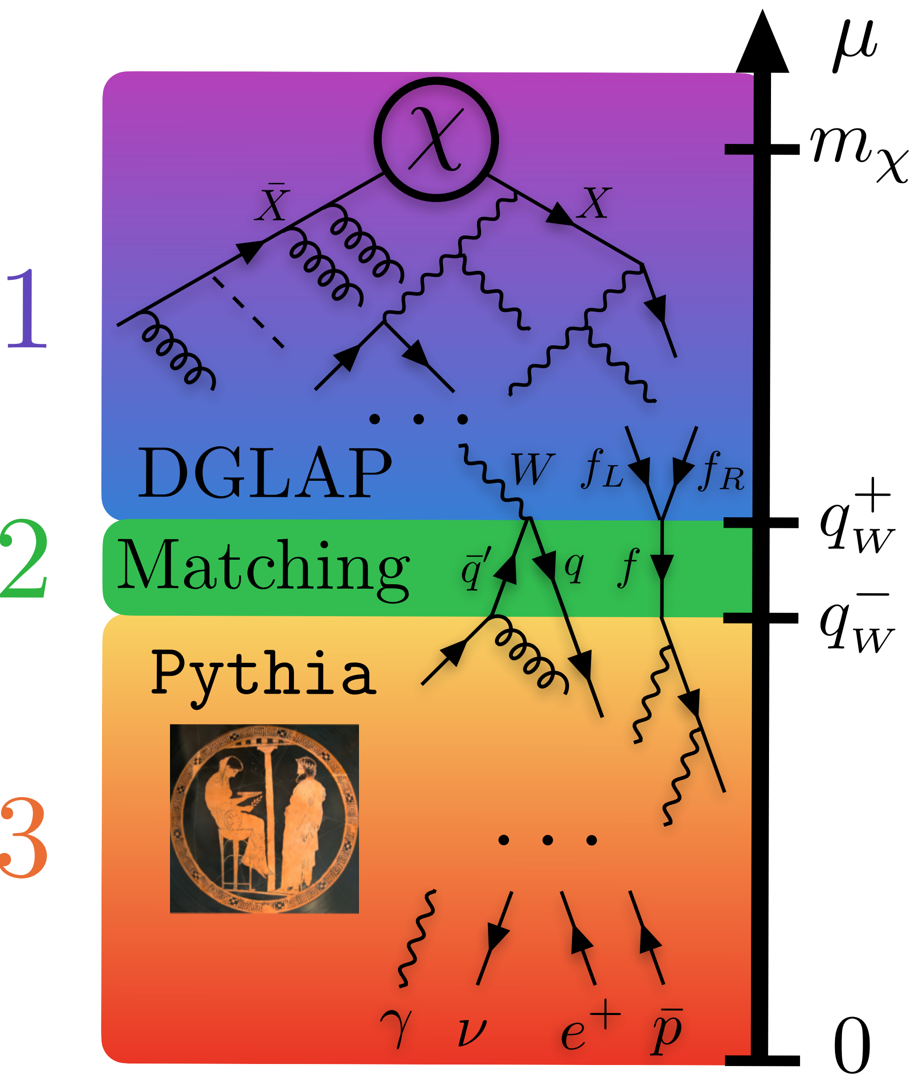


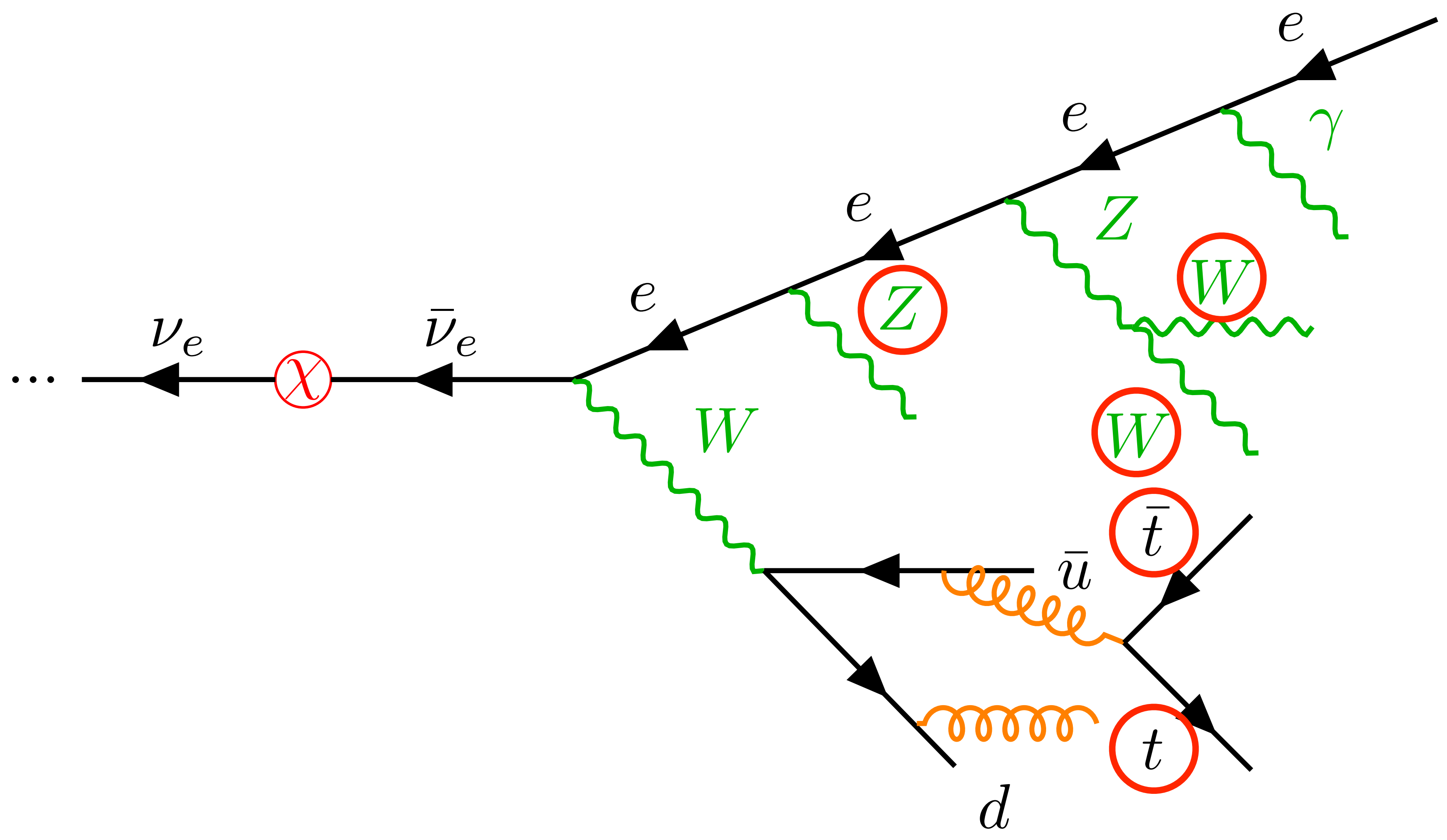
New SM Physics

EW showers

At very high energies, E>>v, SU(2) x U(1) is restored and evolution through EW radiation will take place. The non-abelian nature of SU(2) will make a shower look more like QCD. One the scales are down to ~v EWSB effects will start to become important again.







Evolution (EW double logs and polarisation):

- [Christiansen, Sjostrand 1401.5238]
- [Christiansen, Prestel 1510.01517]
- [Chen, Han, Tweedie 1611.00788]
- [Manohar, Waalewijn 1802.08687]
- [Bauer, Provasoli, Webber 1806.10157]
- [Bauer, Webber 1808.08831]
- [Kleiss, Verheyen, 2002.09248]
- [Bauer, Rodd, Webber 2007.15001]
- [Masouminia, Richardson, 2108.10817]
- [Brooks, Skands, Verheyen 2108.10786v2]

Summary

- In the **near future**, i.e. for the next 25 years the LHC will be THE machine to explore Higgs physics and the TeV scale through a compelling program of challenging measurements.
- For the **future**, i.e. after 2050, we are evaluating the options. The most mature and feasible project for CERN is an e+e- “weak-scale factory” in a new 91 Km circular tunnel and then the pp option in the 70’s.
- A **futuristic** collider based on accelerating muons could open a new era in HEP experiments, with an exciting physics case. The technology needs to be demonstrated.