Prospects for Higgs Physics at Future Colliders - Experimental Perspective

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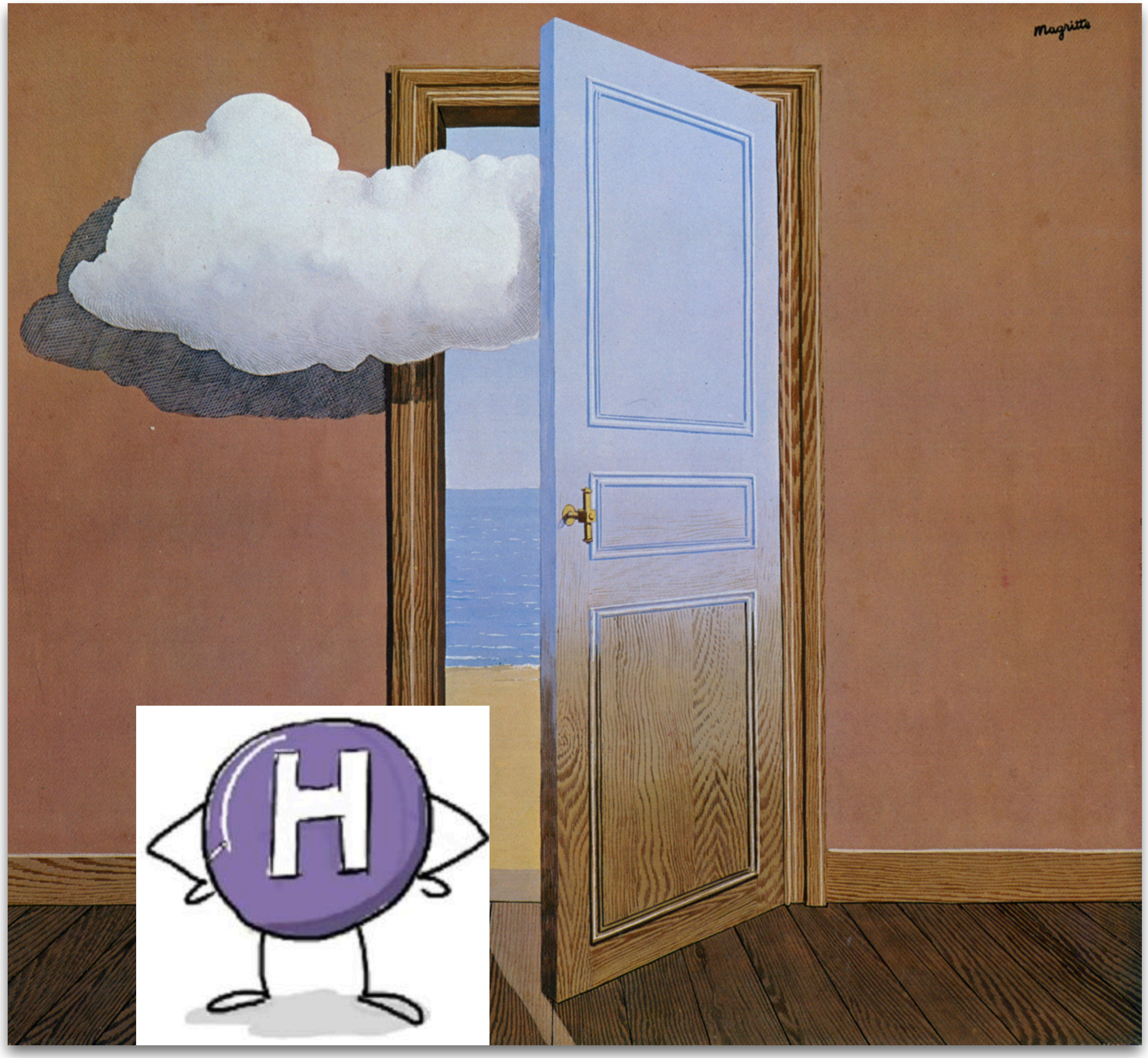
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Looking at the future

The Higgs boson is our most recent advance in the understanding of the fundamental particles and their interactions

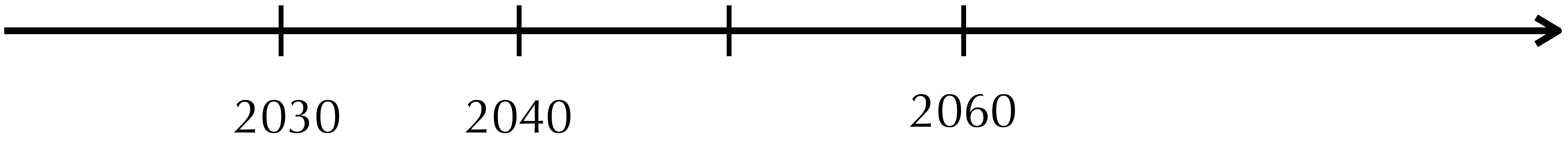
- a **new state of matter-energy**
- a **potential window to Beyond** the Standard Model physics through precision measurements
- a central element in the **future of collider physics**



Outline

- LHC and HL-LHC legacy
- Future facilities, many options:
  - 250-380 GeV lepton colliders
  - 100 TeV+ hadron colliders
  - > 1TeV lepton/gamma-gamma colliders
- Physics requirements and detector performance
- Snowmass process and a possible roadmap

Where are we?



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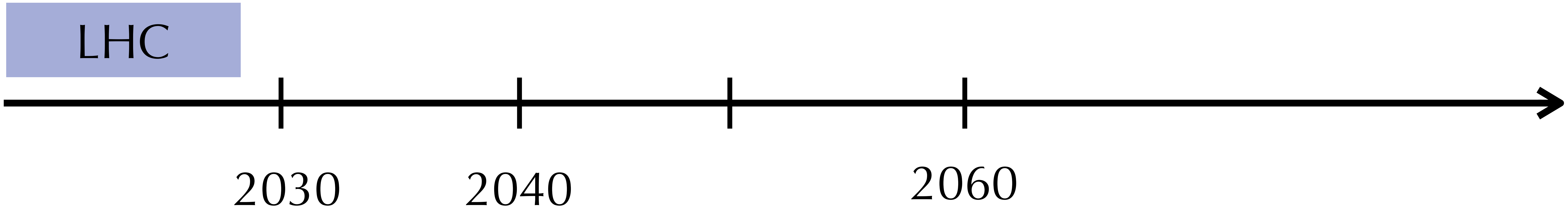

(some) Higgs boson couplings measured with O(5-10)% precision

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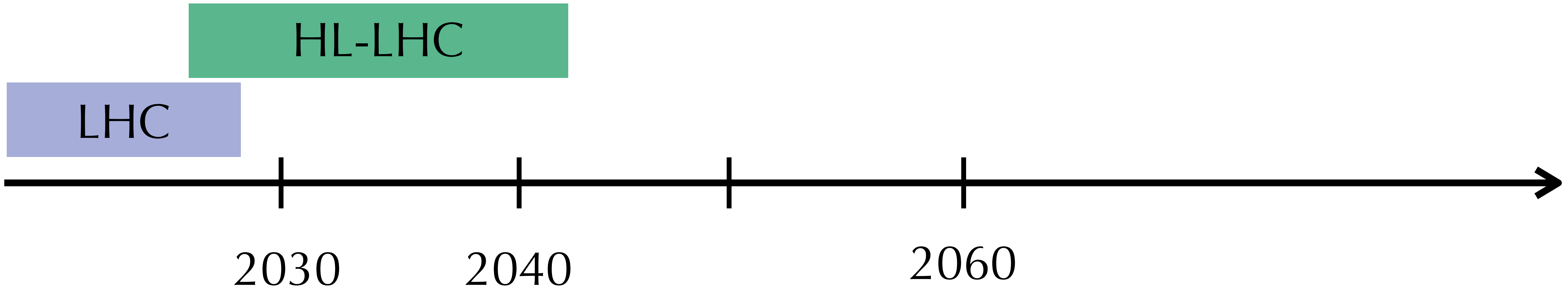

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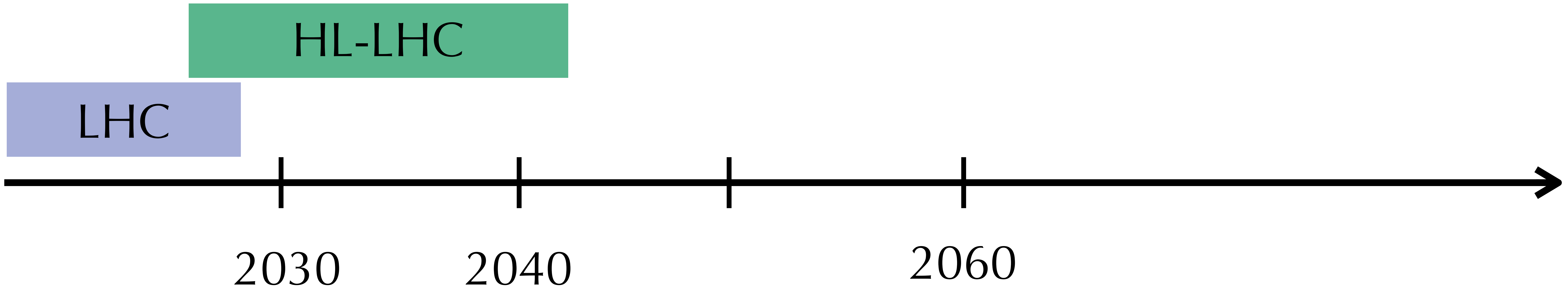

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HL-LHC as a Higgs factory: 170M Higgs bosons - 120k HH pairs for 3/ab

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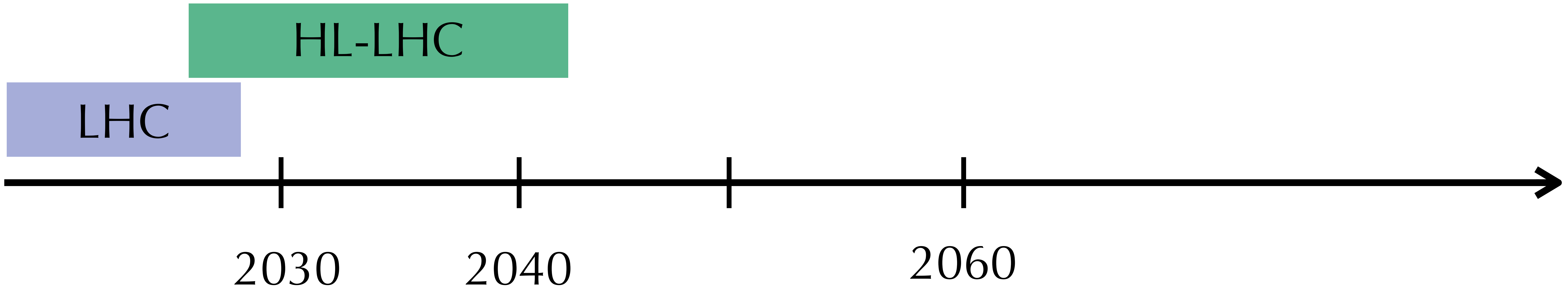

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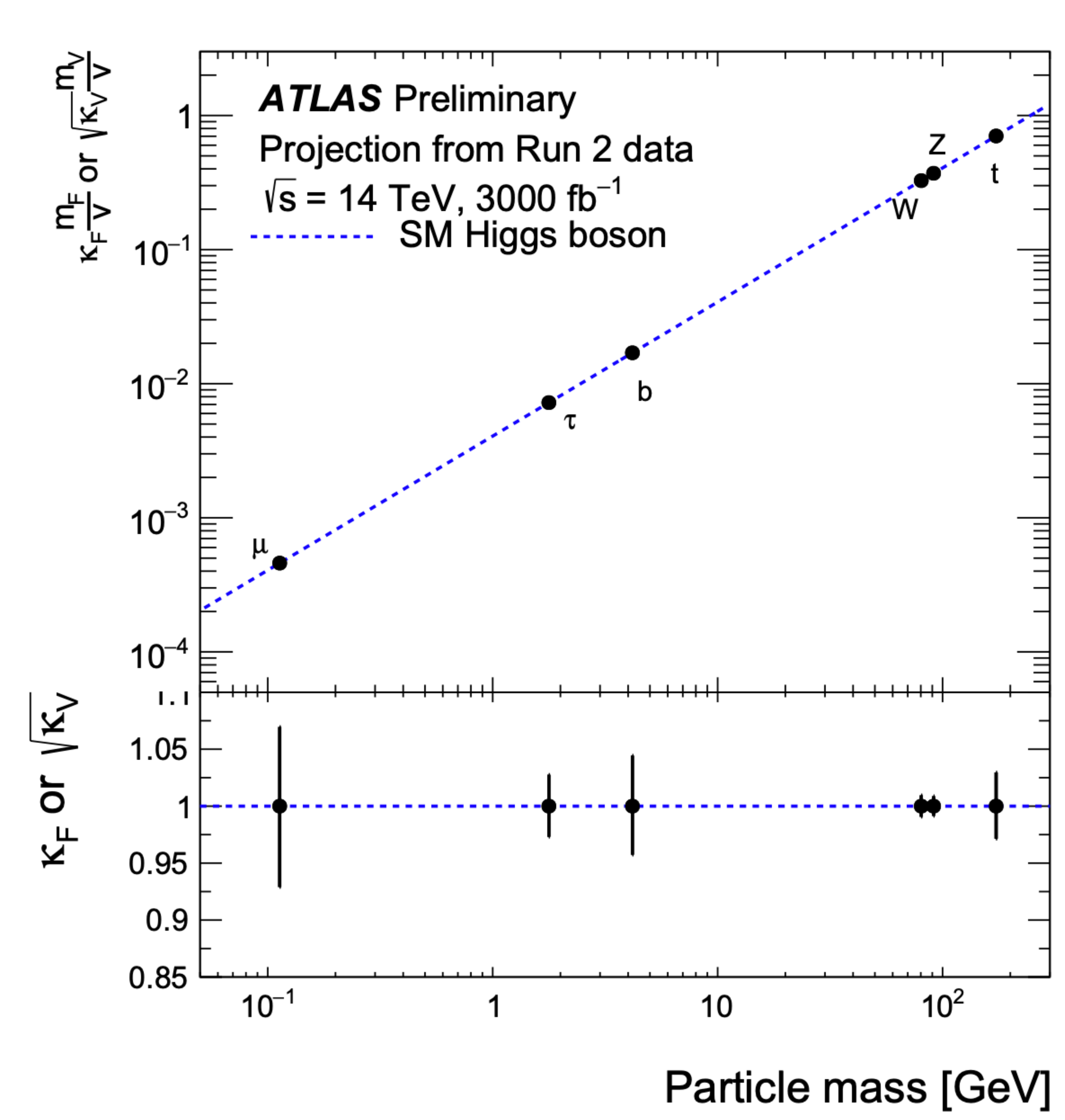
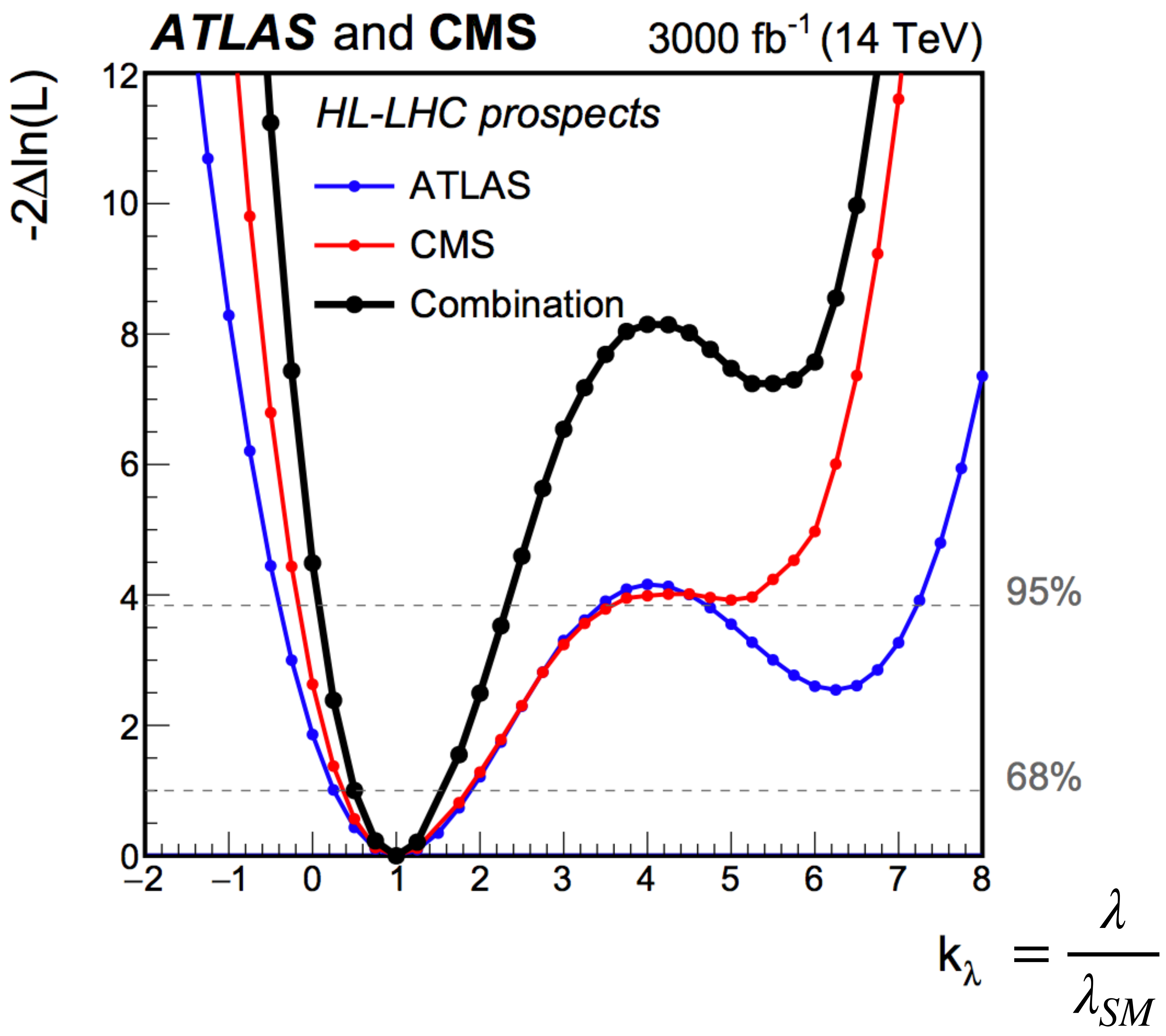
HL-LHC as a Higgs factory: 170M Higgs bosons - 120k HH pairs for 3/ab

Phase-2 HL-LHC detector upgrades are being built

Higgs physics at the HL-LHC





The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-4% precision for many of the Higgs couplings**
  - **BUT much larger uncertainties on $Z\gamma$ and charm and ~50% on the self-coupling**

How much precision?

- The goal is to measure Higgs boson couplings with extremely good **precision** to unveil new effects **beyond the Standard Model**
  - The target for the precision is related to the scale of new physics

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\,\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

δO = 1% —> Λ~ 2.5 TeV

- **Precision of O(few%) level or below** requires high energy collider experiments designed for high precision:
  - Complementarity between e^+e^- and p-p machines will eventually lead to the most precise understanding of the Higgs couplings

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See Laura's talk for a discussion on which precision we should target

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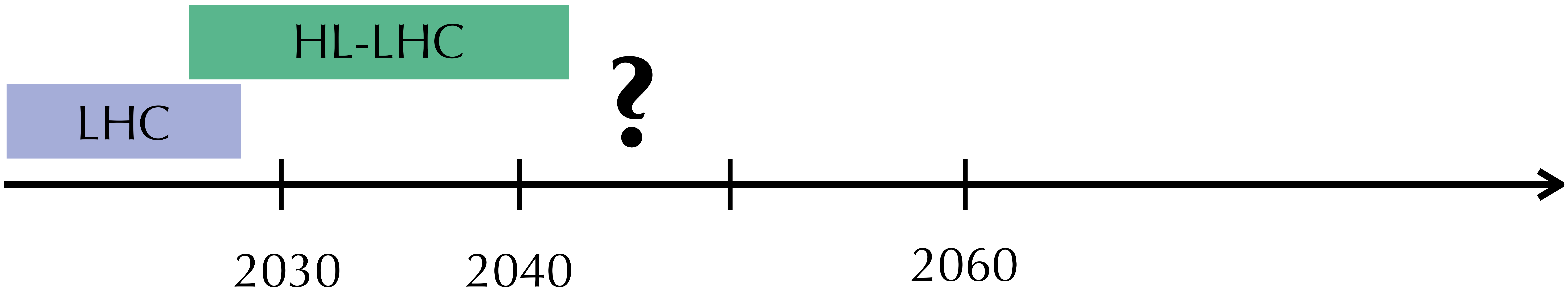
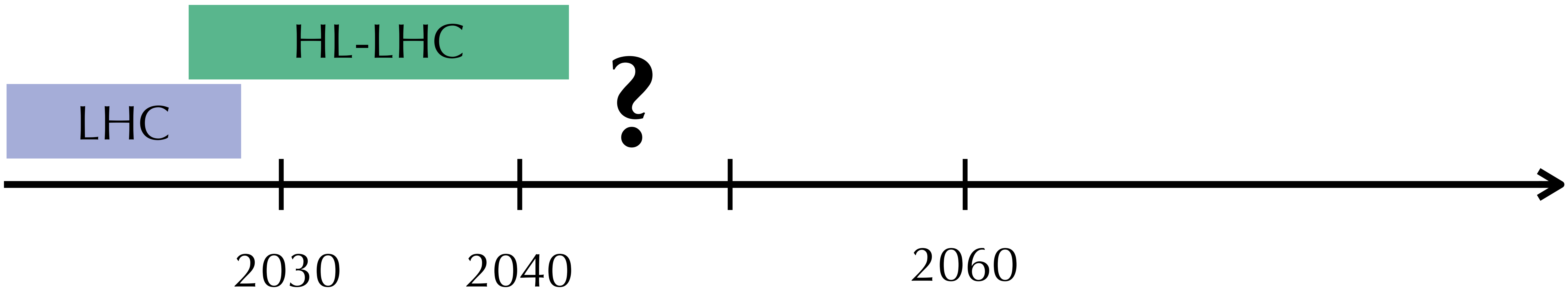


In the study of the Higgs boson properties and in the quest of new physics signs there is a complementarity between hadronic/leptonic colliders (depending on the centre-of-mass of energy) to exploit

- Direct production of new - heavy ~ O(10 TeV) - particles
- If new particles are too heavy to be produced at the HL-LHC, the resulting modifications to the Higgs couplings could be sizable enough to be detected with precision Higgs coupling measurements.



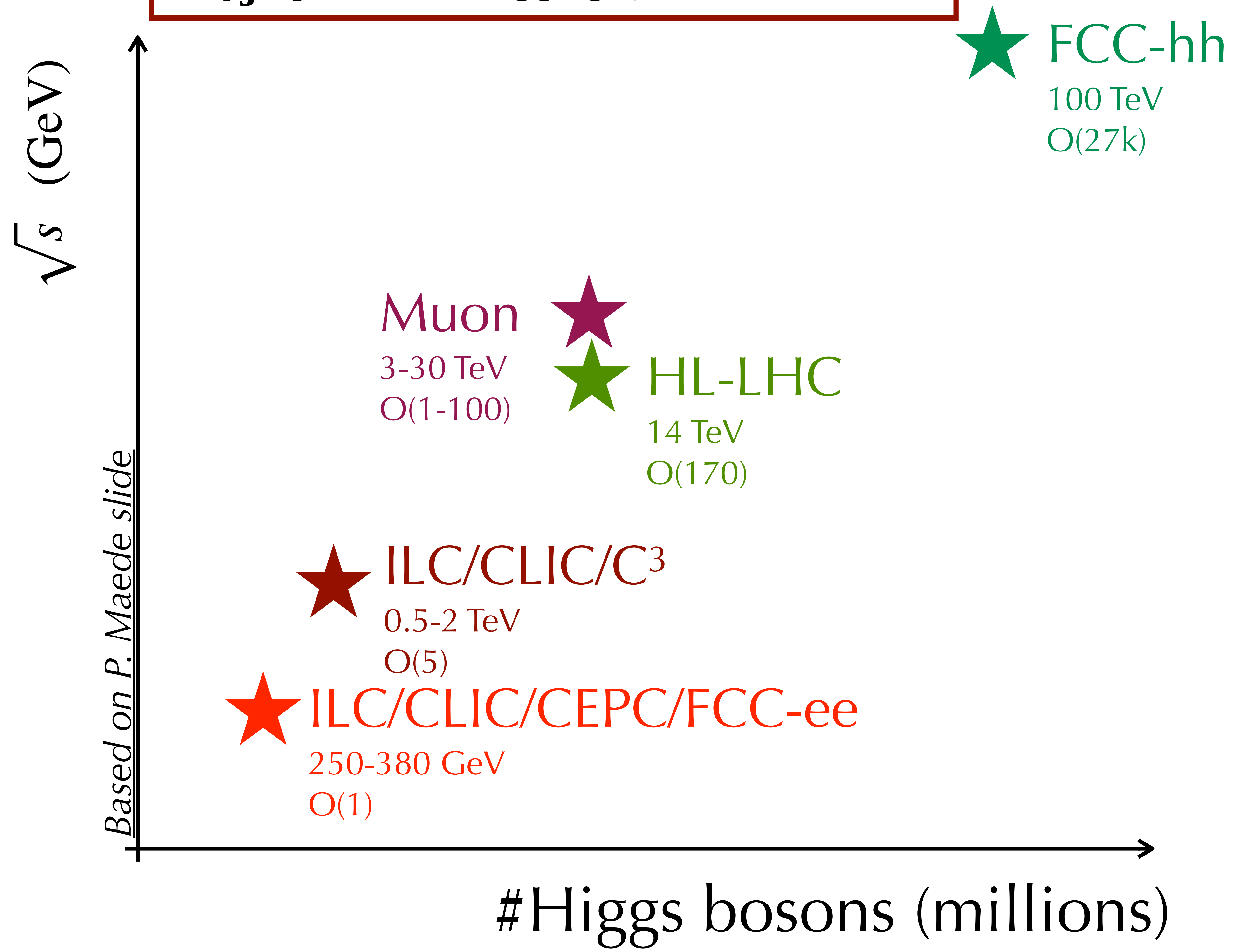
Wish list beyond HL-LHC:

- **Establish Yukawa couplings to light flavor —> needs precision**
- **Establish self-coupling —> needs high energy**

Which collider?

- Lepton colliders:
  - Circular e+e- (CEPC, FCC-ee)
    - **90-350 GeV**
  - Linear e+e- (ILC, CLIC, C^3)
    - **250 GeV — 3TeV**
  - μ+μ-
    - **3-30 TeV**
  - Gamma-gamma collider
- Hadron colliders:
  - **75-200 TeV** (FCC-hh)

PROJECT READINESS IS VERY DIFFERENT



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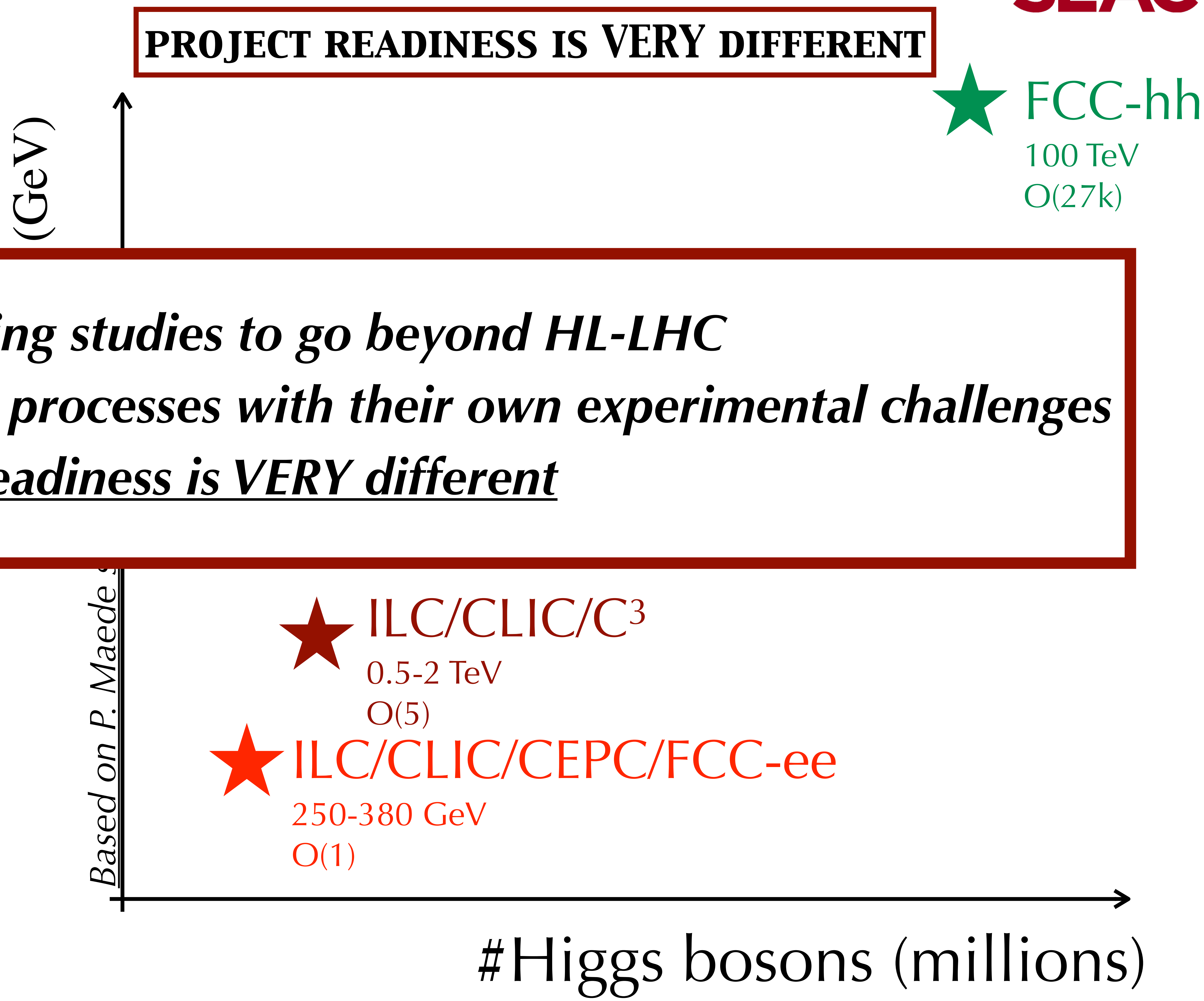
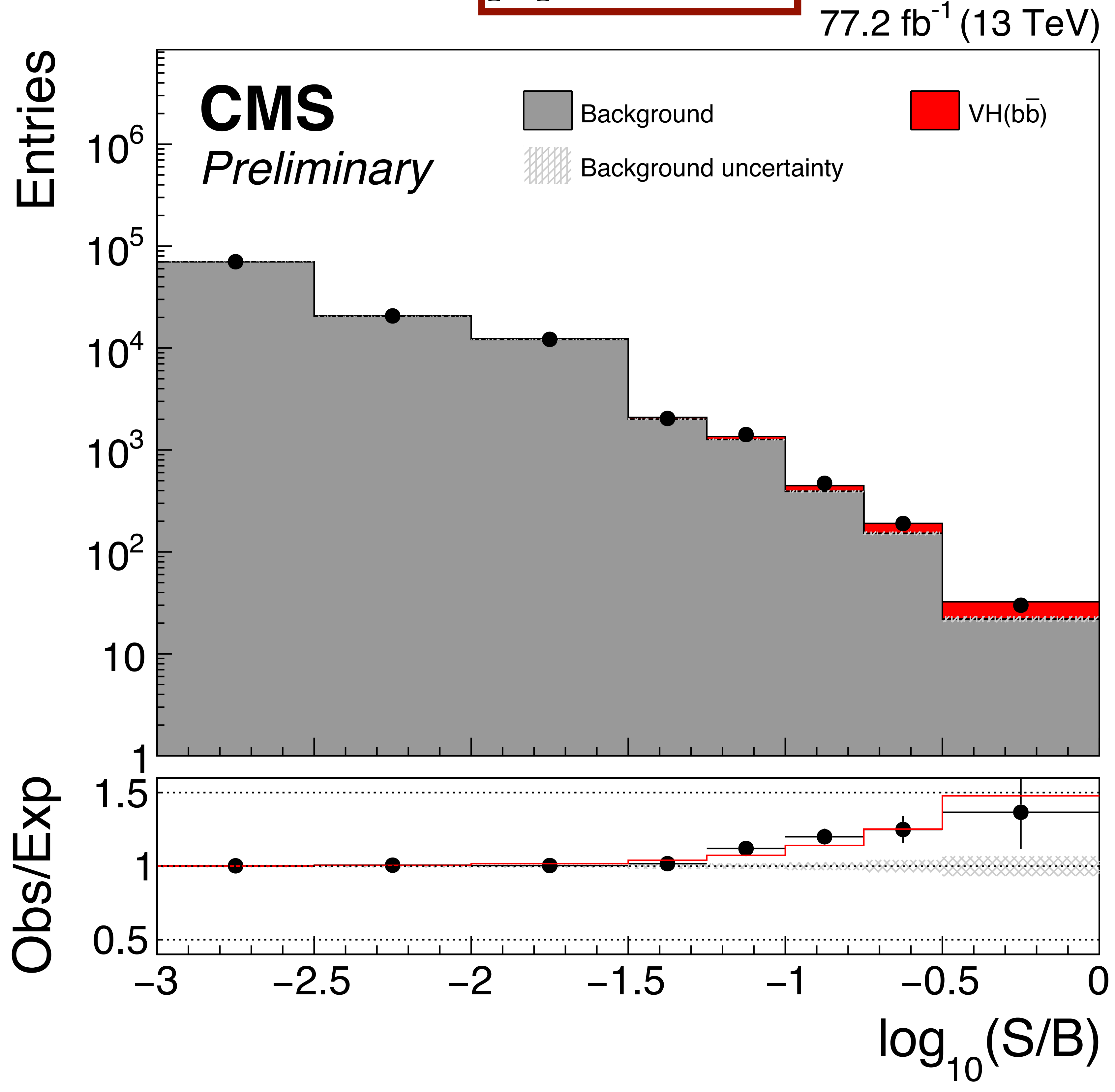


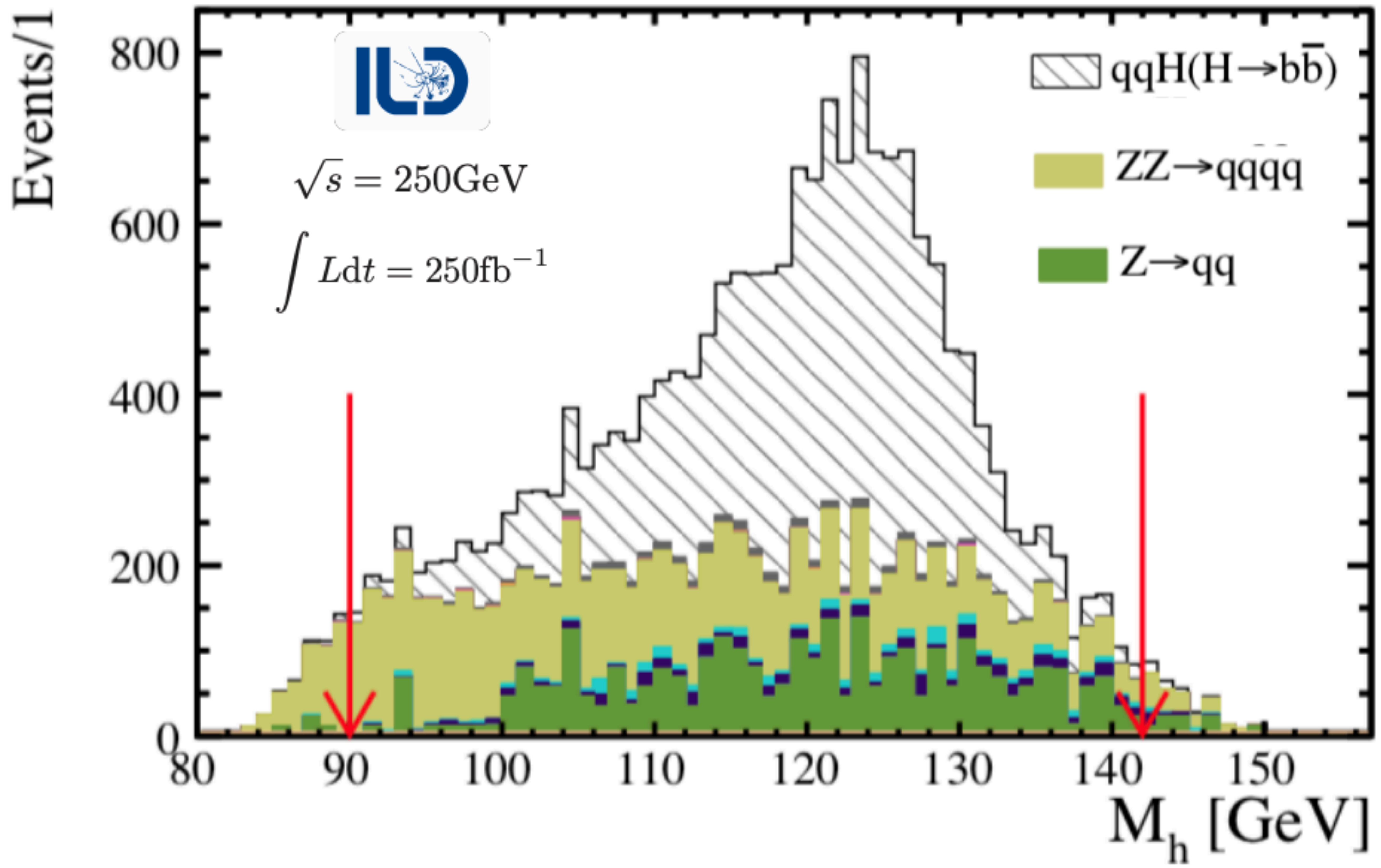
Several collider options being studies to go beyond HL-LHC
Different colliders probe different dominant processes with their own experimental challenges
And also project readiness is VERY different

One example: $H(b\bar{b})$

pp LHC

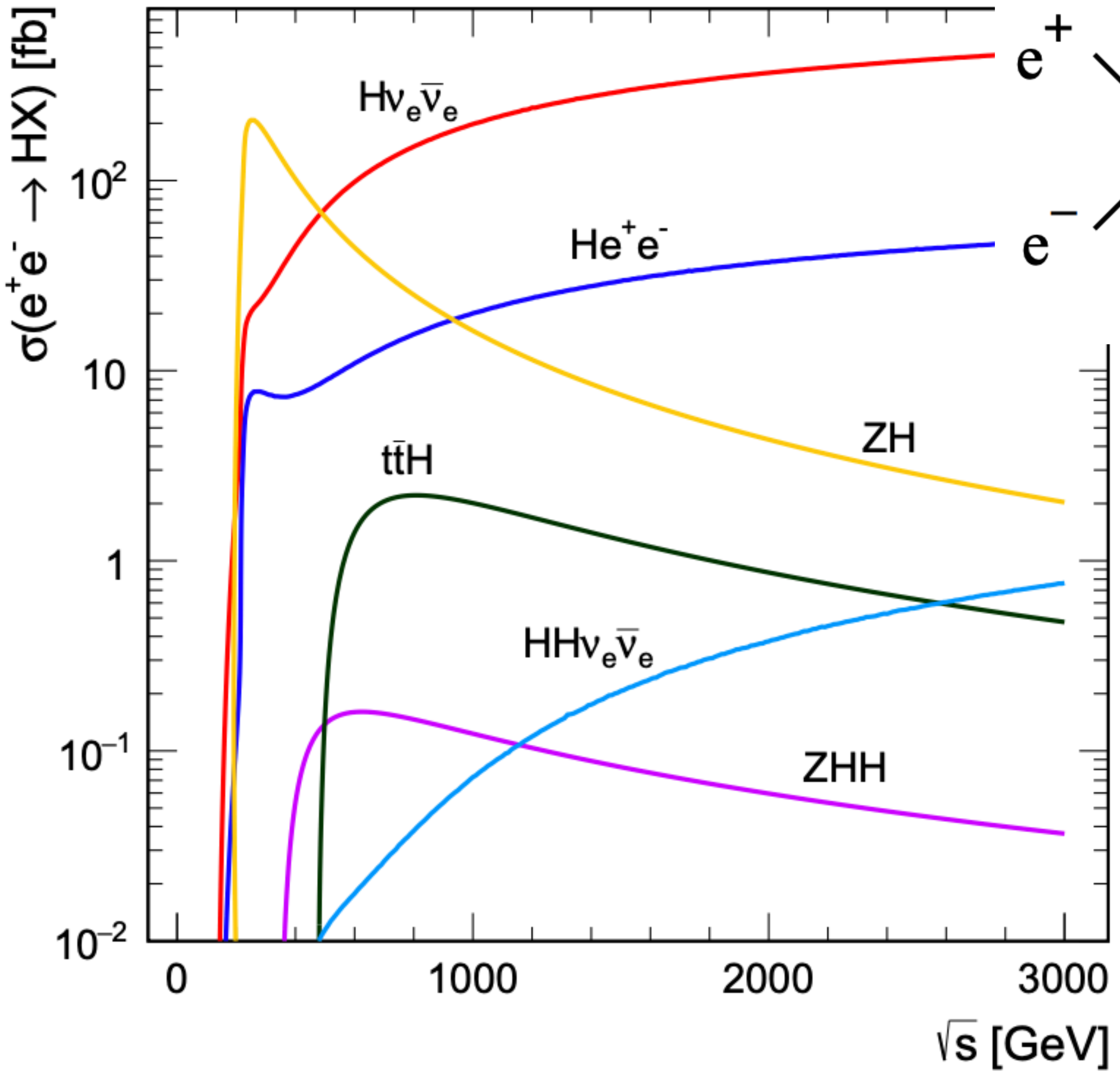


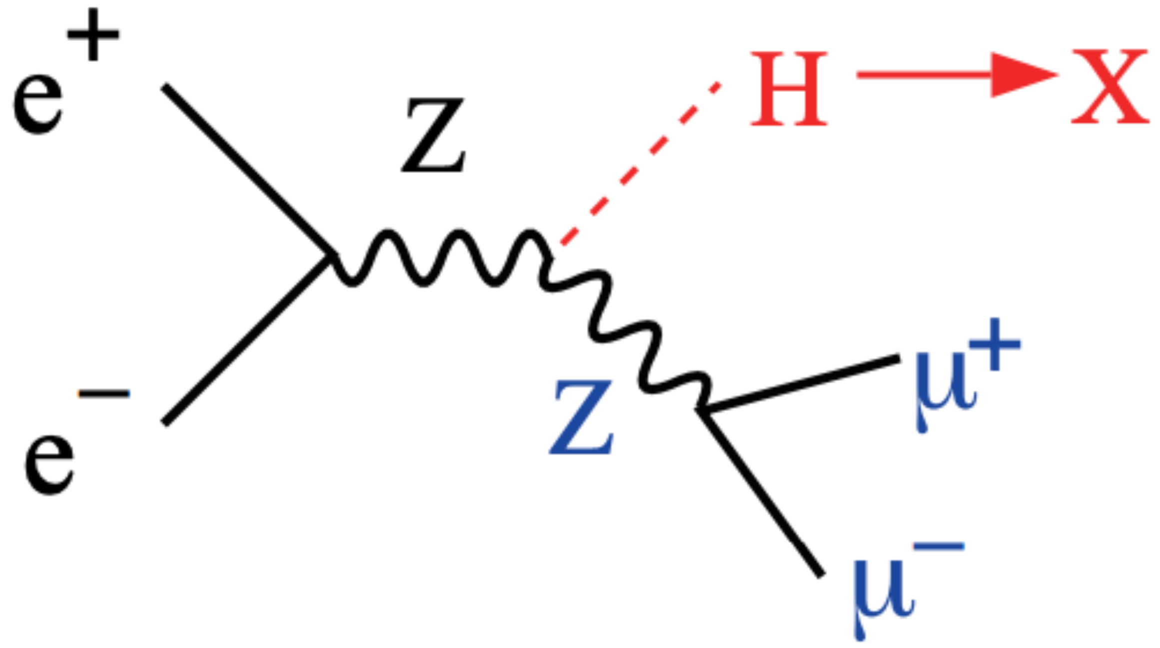
e+e- ILC



	pp LHC	e+e- ILC
# of Higgs produced:	**~4M**	**~400**
	4.8σ (VH only)	**5.2σ**

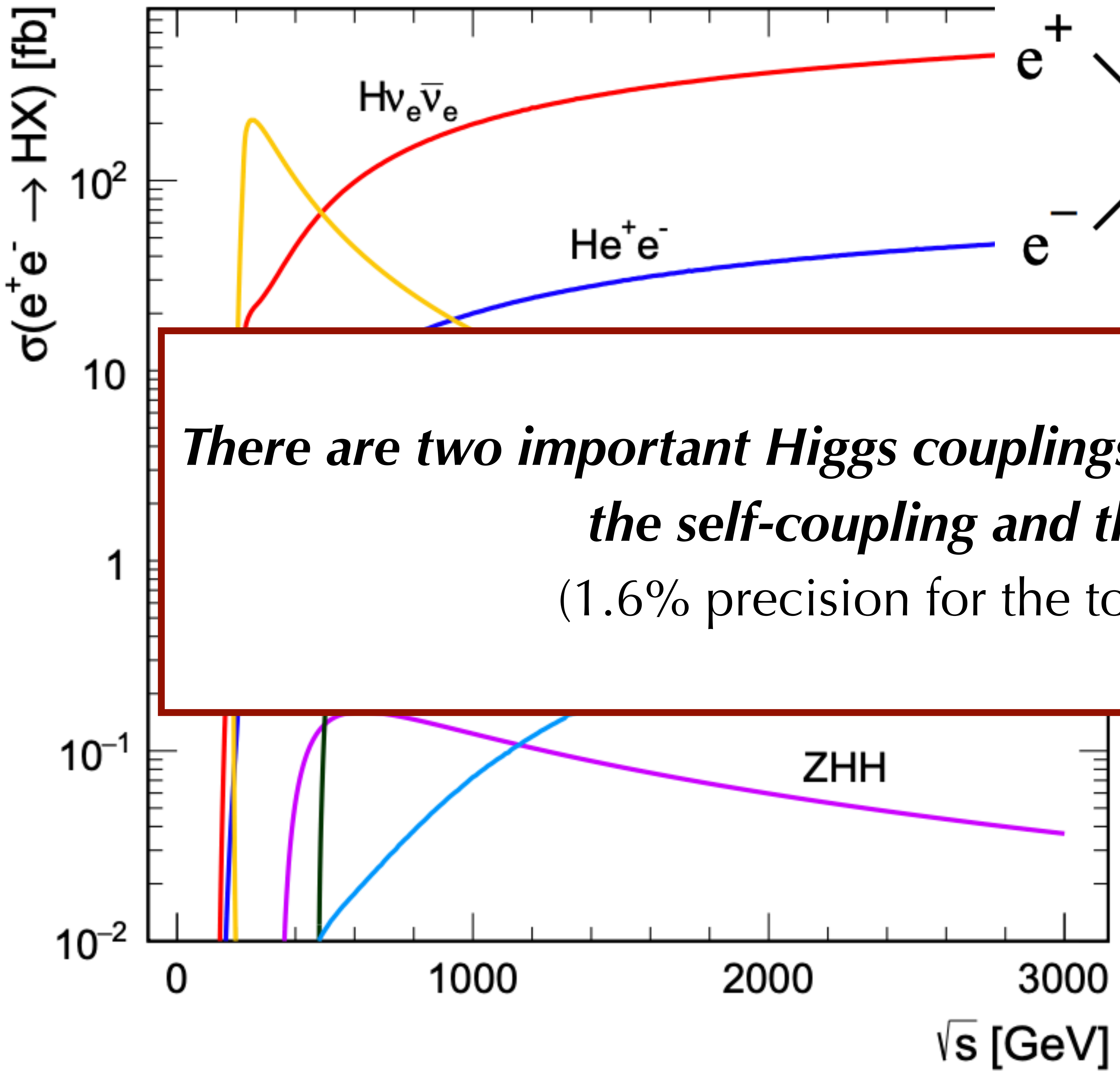
Higgs at e+e-

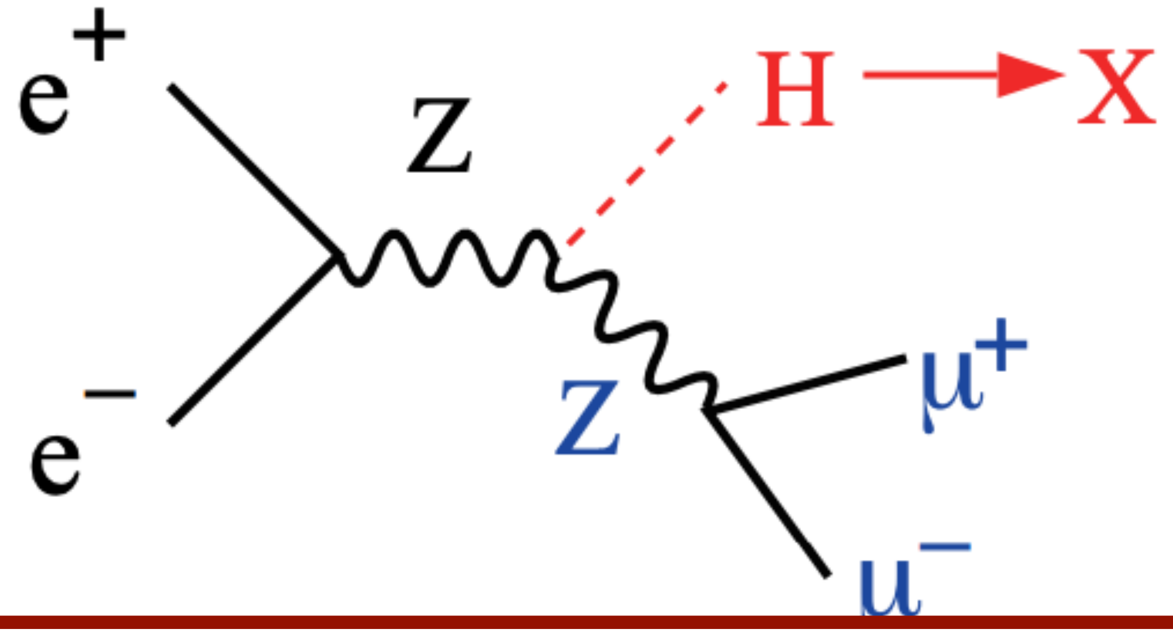




- ZH is the dominant production mode for √s ~ 250 GeV
- The well defined initial states allows to tag the Higgs boson without looking into its decay with **"recoil" technique**
  - Measurement of the inclusive ZH cross section at 0.5-1%
  - Recoil technique observes all final state, including all invisible and exotic decay modes
    - **ZH is key for the determination of the absolute Higgs couplings**
- Clean environment for **excellent b- and c-tagging performance**: Hbb/cc/gg separation

Higgs at e+e-





There are two important Higgs couplings that cannot be measured directly below 500 GeV — the self-coupling and the Higgs-top quark Yukawa coupling

(1.6% precision for the top quark Yukawa coupling at ILC 1 TeV)

oson

-1%

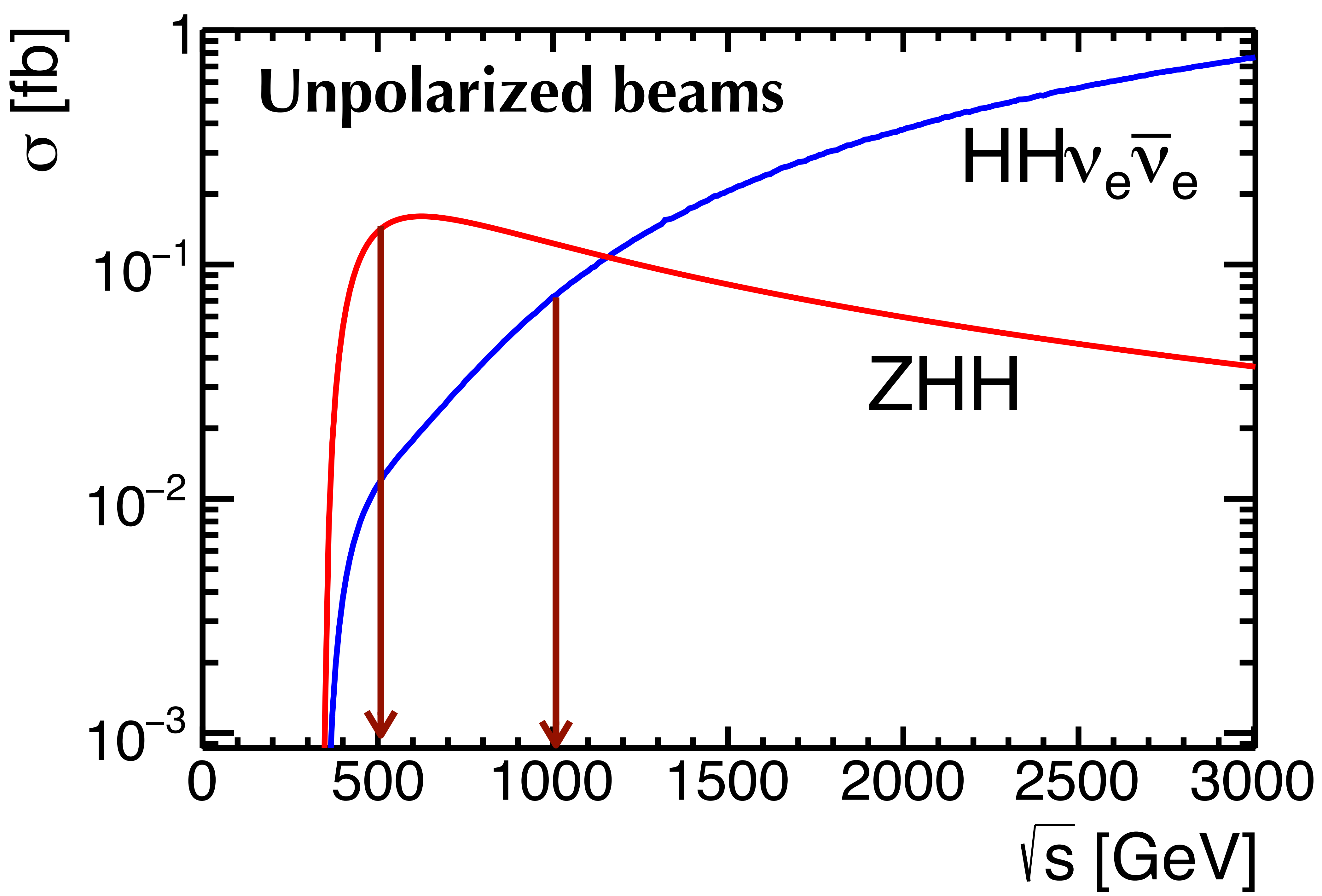
invisible and exotic decay modes

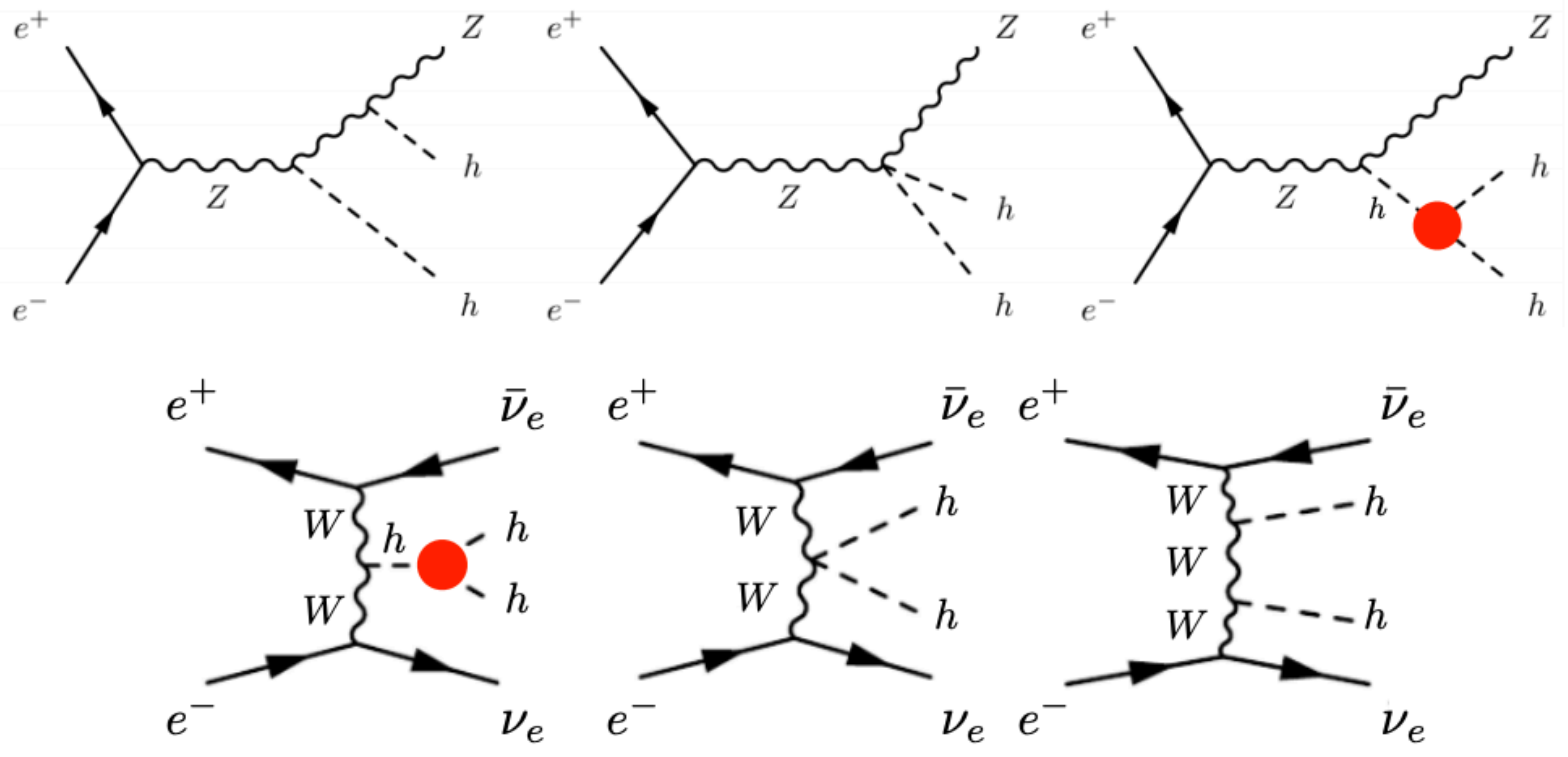
- **ZH is key for the determination of the absolute Higgs couplings**

- Clean environment for **excellent b- and c-tagging performance**: Hbb/cc/gg separation

HH at future e+e- colliders

arXiv:1910.00012



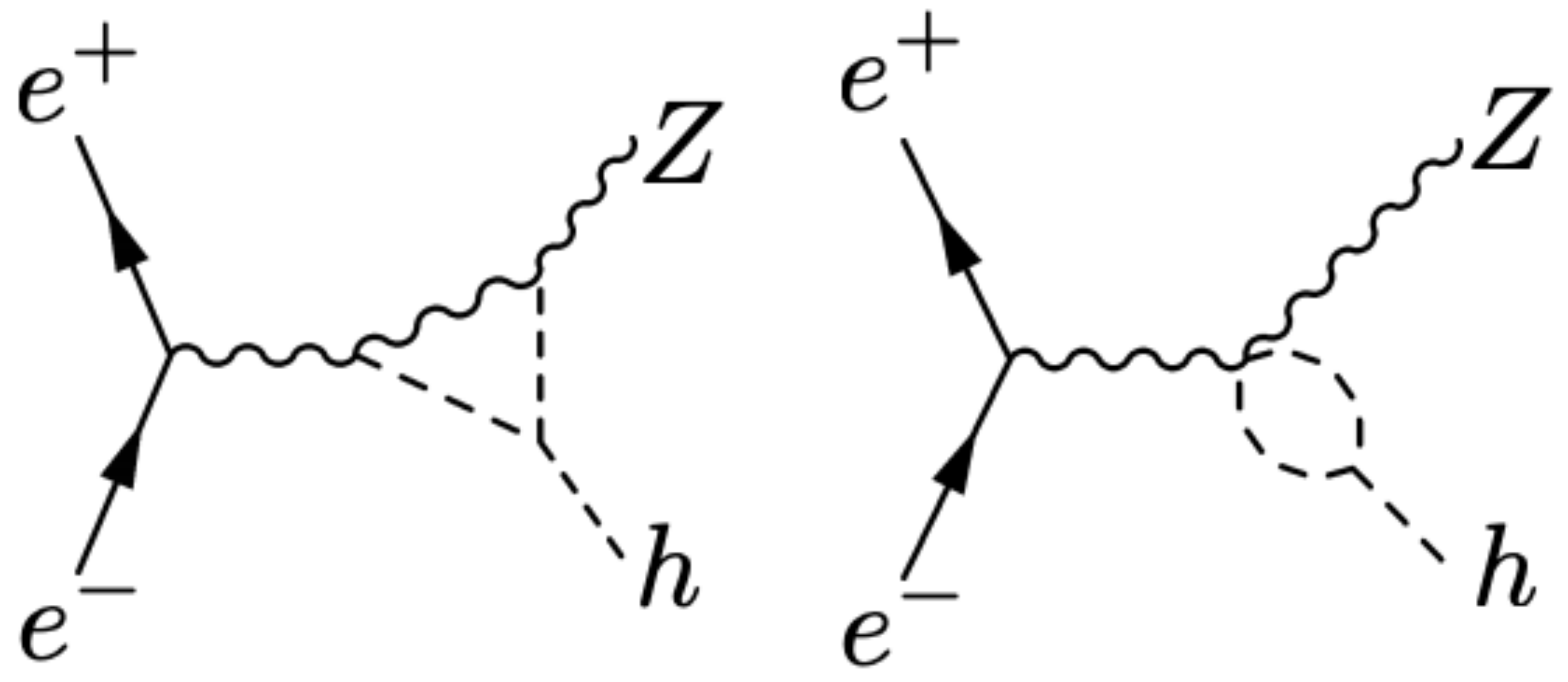


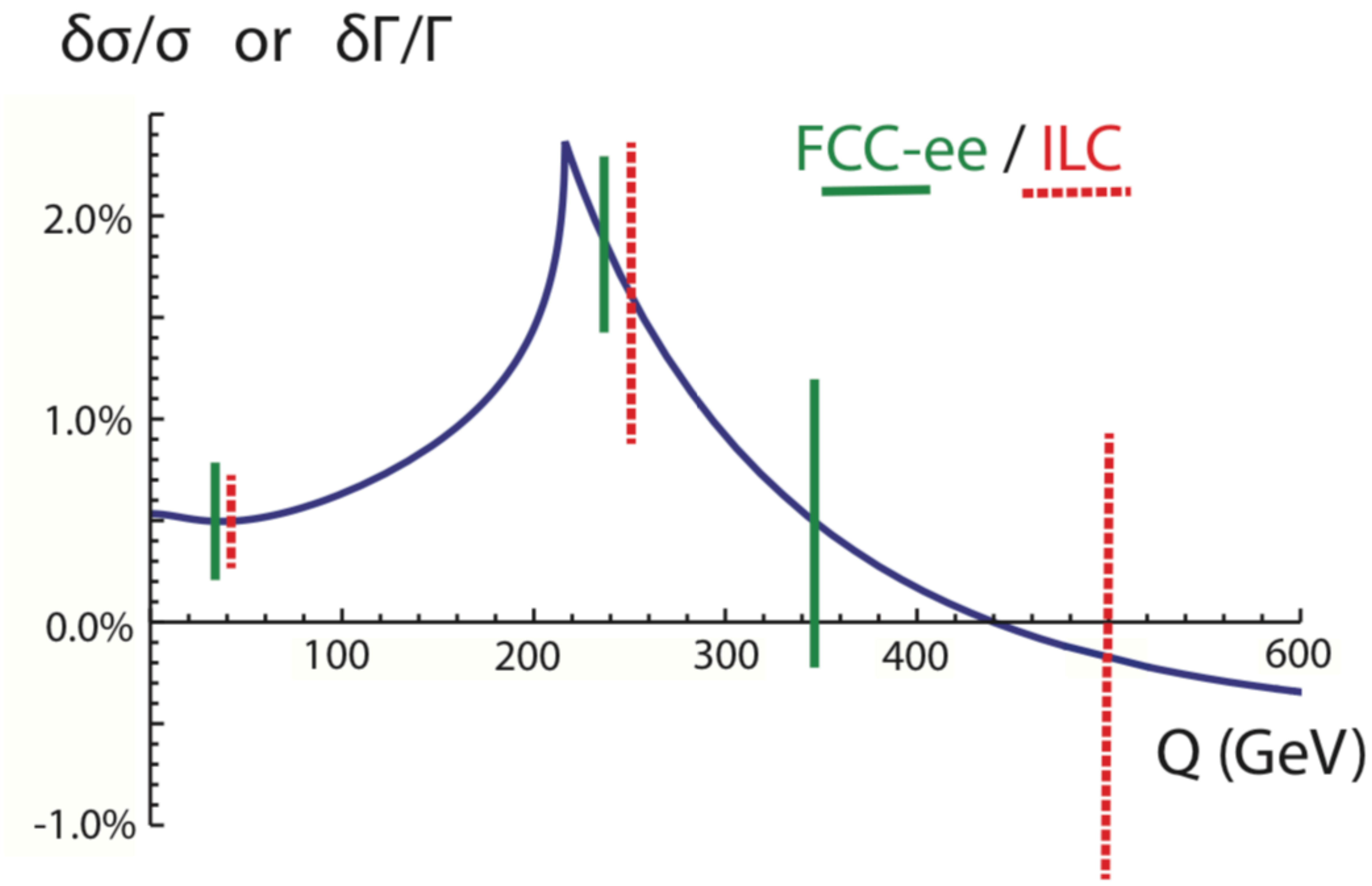
- The self-coupling can be probed at e+e- through double Higgs with ZHH ~500GeV and νvHH ≥1TeV
  - **HHνν** requires $e^-_L e^+_R$, the use of polarized beams could increase the cross-section by a factor ~2
- For **ZHH** / **HHνν** processes there is a constructive/deconstructive interference between diagrams with and without the self- coupling
  - No matter what is the sign of the deviation of the Higgs self-coupling from its SM value, one process is always enhanced

Self-coupling at e+e-

The self-coupling could be determined also through single Higgs processes

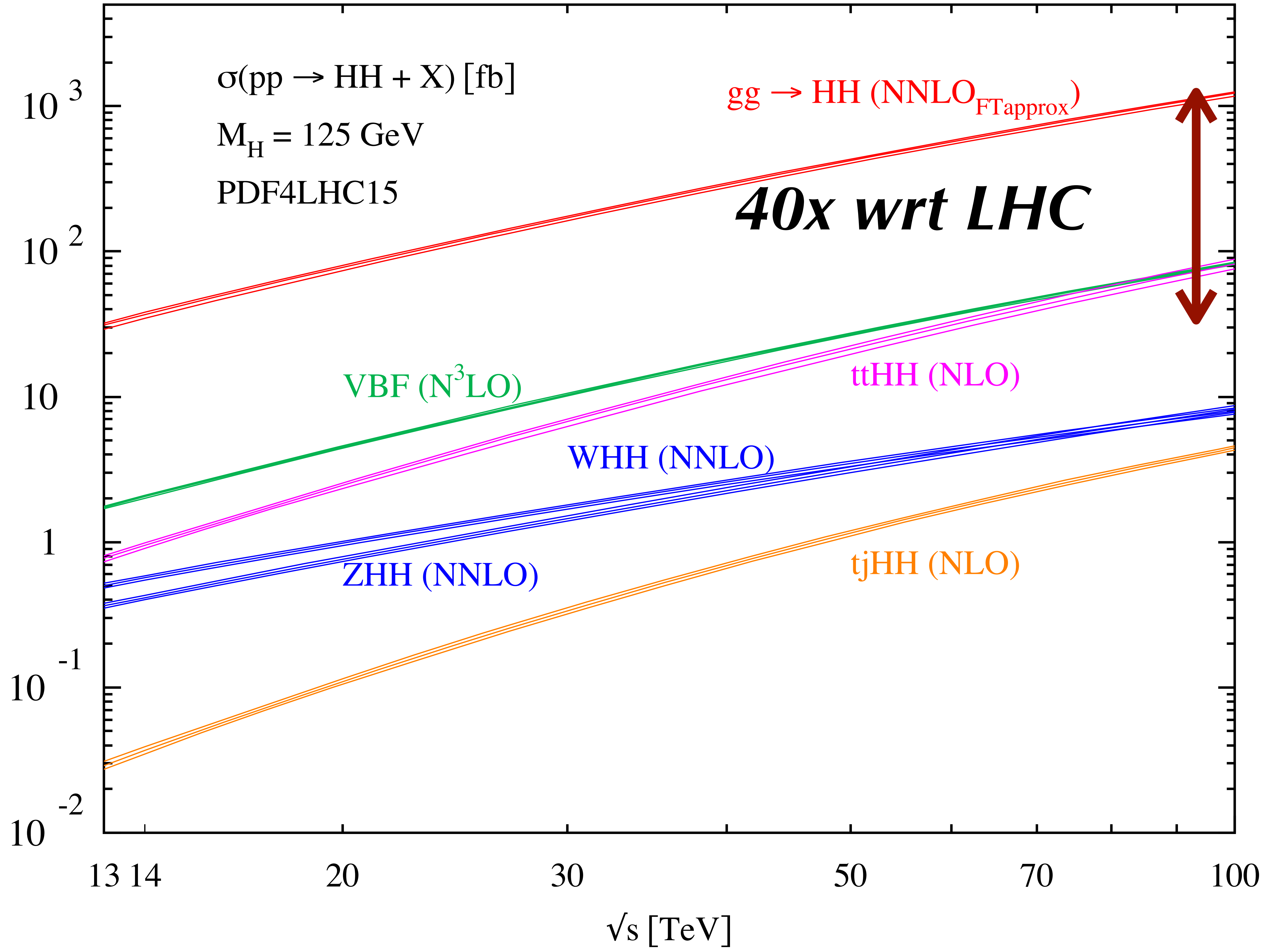
- Relative enhancement of the e+e– → ZH cross-section and the H→W+W– partial width
- Need multiple Q^2 to identify the effects due to the self-coupling

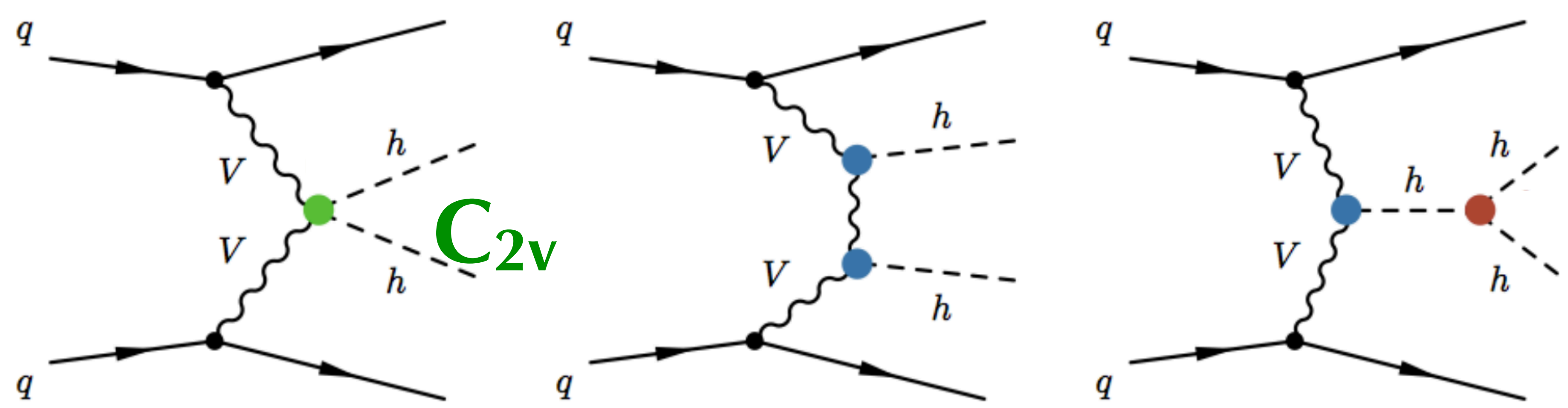




Higgs at pp colliders

arXiv:1910.00012



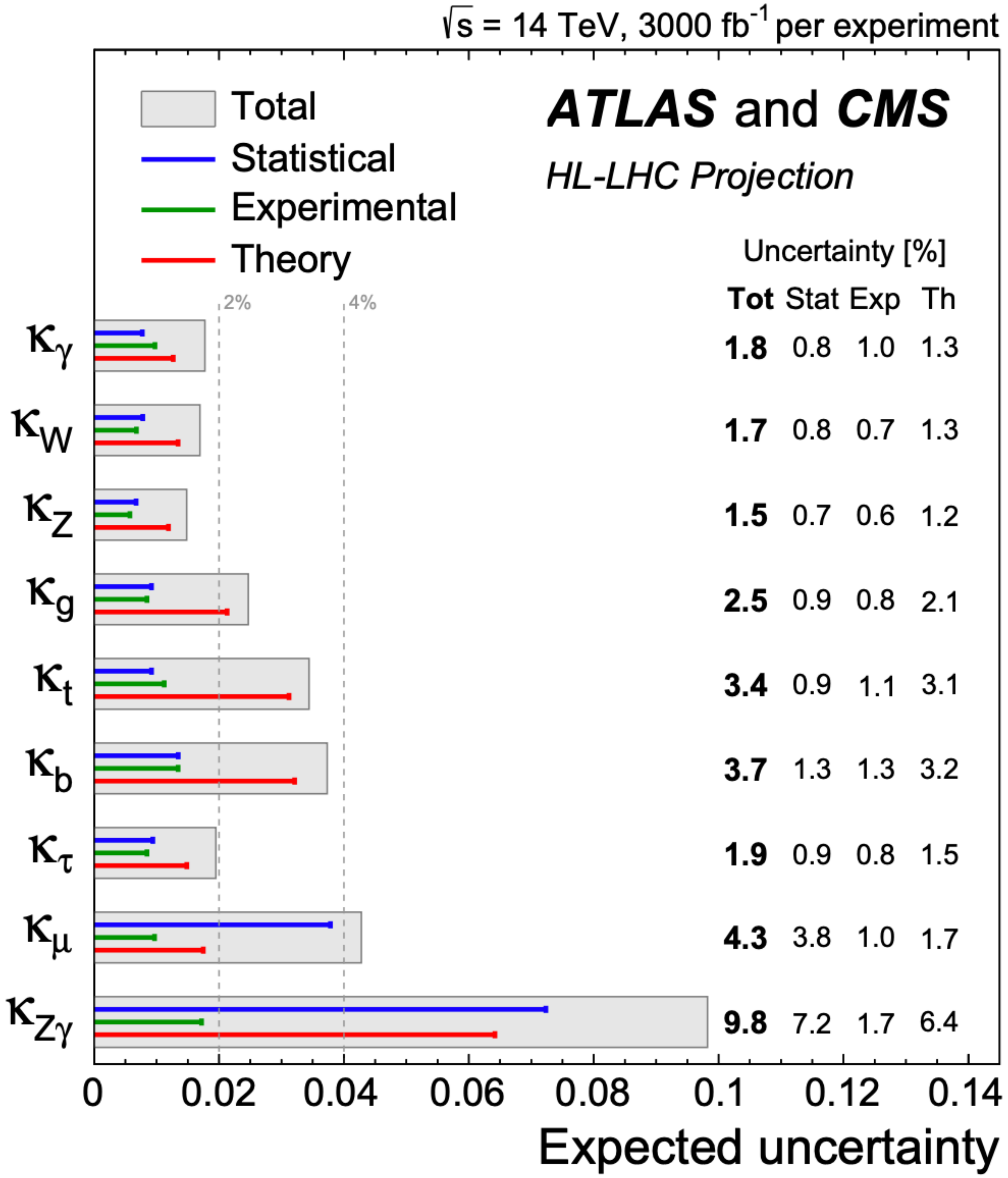


- The physics potential of a future 100 TeV collider is evaluated assuming the **input of a previous e+e- run**
- Taking as a given the value of the HZZ coupling, it could be possible to study **rare decays**
  - absolute couplings of the Higgs to **γγ** (0.4%), μμ (0.7%), and Z**γ** (0.9%)
- FCC-hh will provide huge statistics of HH events for Higgs self-coupling and ttH
  - **top quark Yukawa** coupling determined to 1% and **self-coupling** to 2.9-5.5% depending on the systematic assumptions
- Given the measurement of c_V at e+e- colliders, FCC-hh can measure **c_{2V} to 1%**
  - This is a fundamental test of the SMEFT framework

arXiv:1910.11775,arXiv:1905.03764
CERN-LPCC-2018-04

Higgs couplings at future colliders

- Future colliders under consideration will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
  - **Coupling to charm** quark could be measured with an accuracy of ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC and not really improved at future colliders
  - At low energy top-Higgs coupling is not accessible at future lepton colliders
- **Complementarity between HL-LHC and future colliders** (depending on their timeline) **will be the key to explore the Higgs sector**



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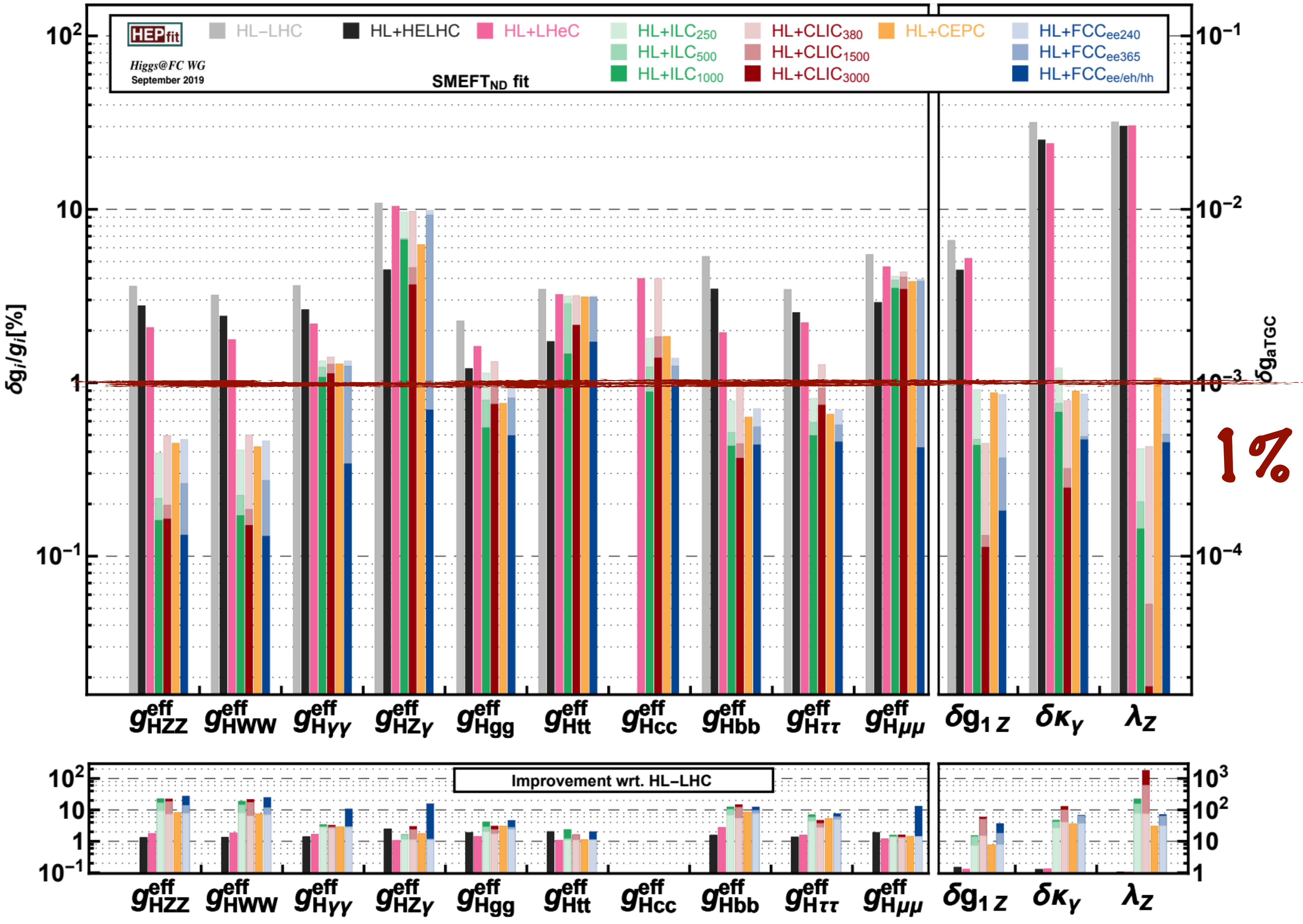


The Higgs self-coupling at future colliders

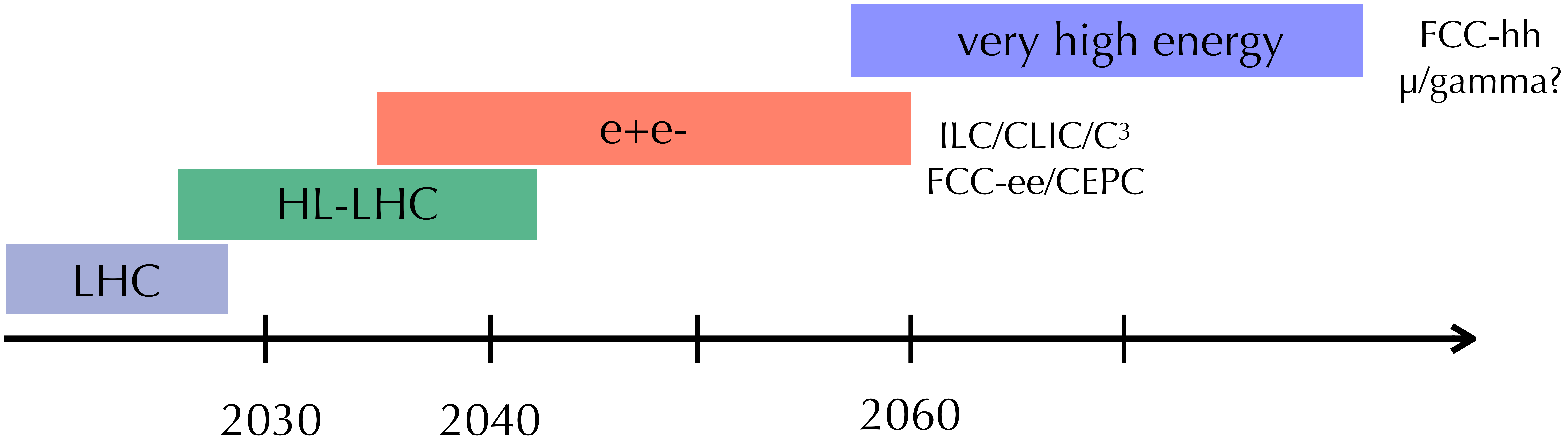
The goal for **future machines** beyond the HL-LHC should be to be able to reach at least **5-10%** precision for the Higgs boson self-coupling :

- **Future circular** (CEPC/FCC-ee@240GeV) and **Linear e+e-** machines (ILC250/CLIC380) can probe the Higgs self-coupling through single Higgs processes, and reach levels of 33-50% precision
- **Linear e+e- at high energy** can probe the self-coupling through HH production
- **Future circular hadronic machines**, FCC-hh (100 TeV) can access HH with high statistic

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Looking to the future



H couplings to few %

H couplings to %

H couplings to ‰
H self-coupling to %

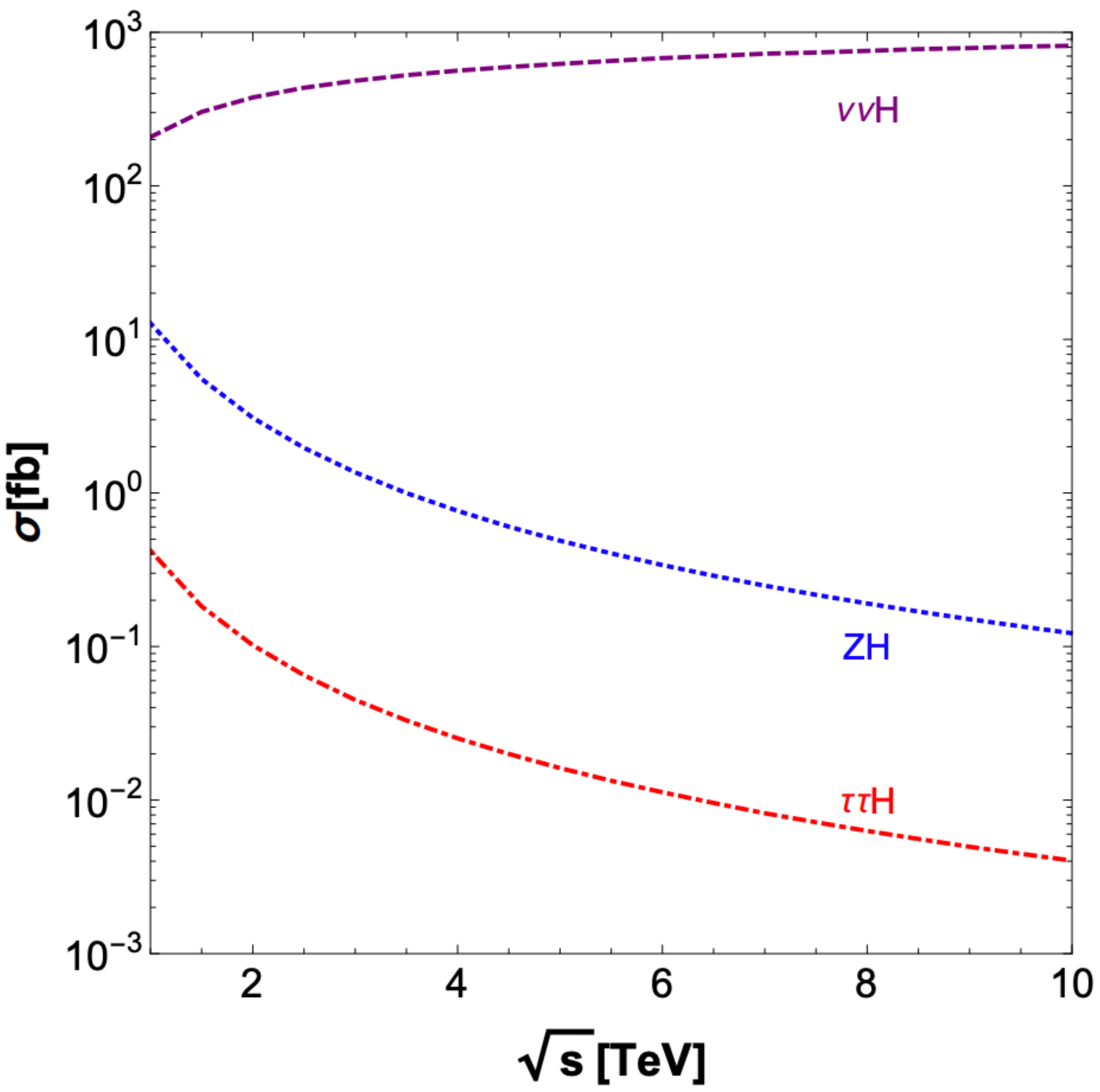
Planning ahead

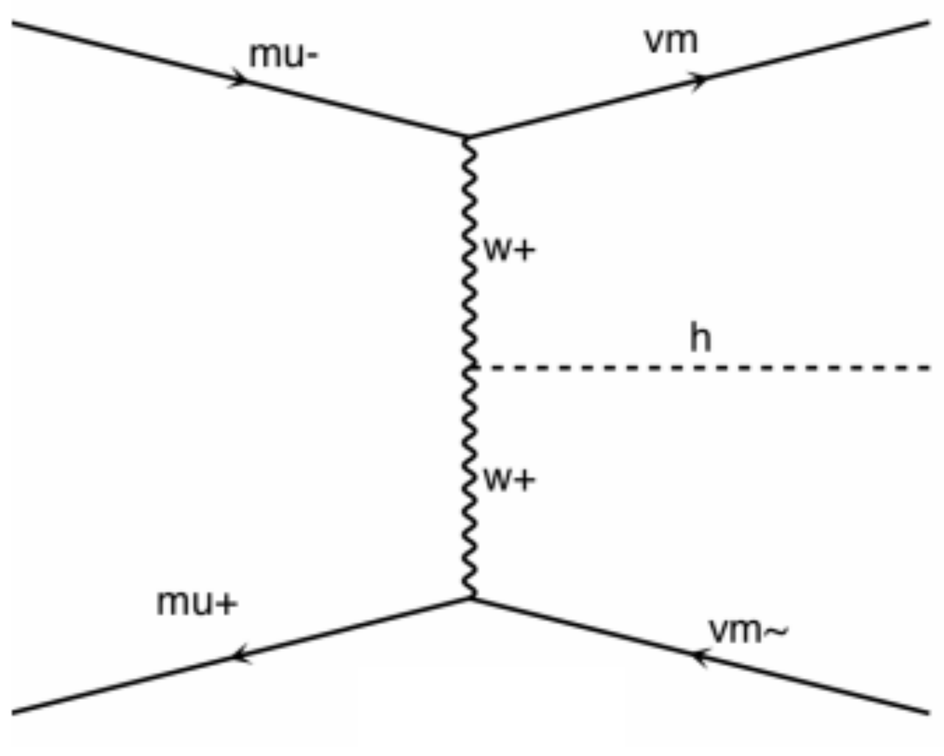
- ***It would be ideal to start the have data from the next Higgs factory at ~ the same time as HL-LHC***
  - The goal of a next-generation e+e– collider to carry out precision measurements on the Higgs boson not accessible at the LHC/Hl-LHC
    - precision experiments require a conservative and highly controllable machine design.
- ***Which energy is enough for the next collider beyond HL-LHC and Higgs factories?***
  - Once we have acquired **sufficient** proof that physics beyond the SM exists (and on its energy scale) we will have *enough information* to build the next VERY high energy machine:
    - We would likely need to produce parton-parton collisions with CM energies of tens of TeV - to access new forces at energy Λ
    - **What is the right technology to create parton-parton collisions at the scale Λ?**

Exploring the very high energy regime

Beyond pp:
Muon collider
Gamma-gamma collider

Muon collider





At **low energy** (125 GeV)

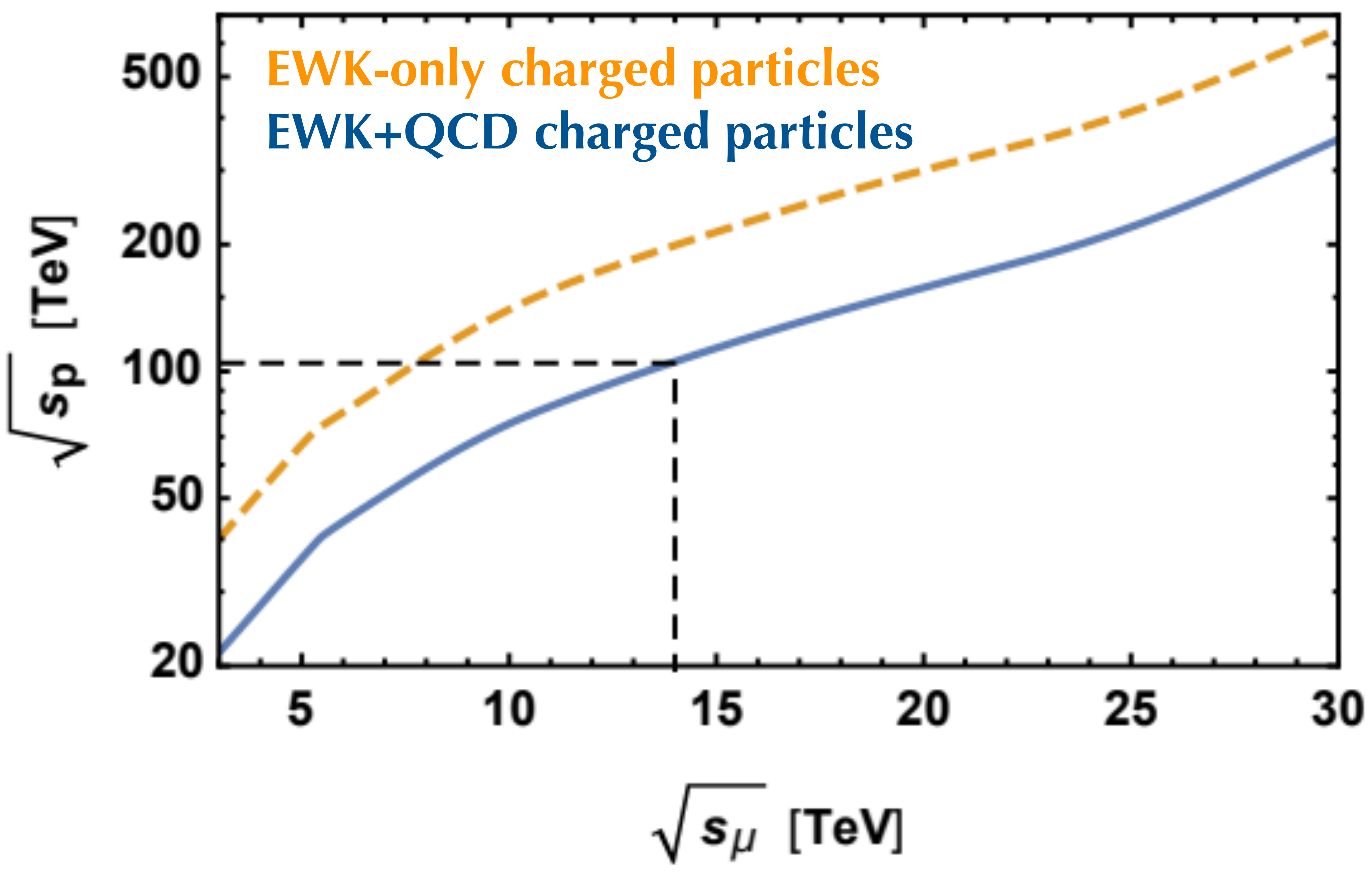
- uniquely great sensitivity to muonic Yukawa
- it provides similar precision as other lepton colliders on the Higgs boson width
- But 10 times less Higgs than other lepton colliders
  - Higgs coupling precision slightly less impressive
- The machine-induced backgrounds challenge the goal of high precision

μ collider - the next discovery machine?

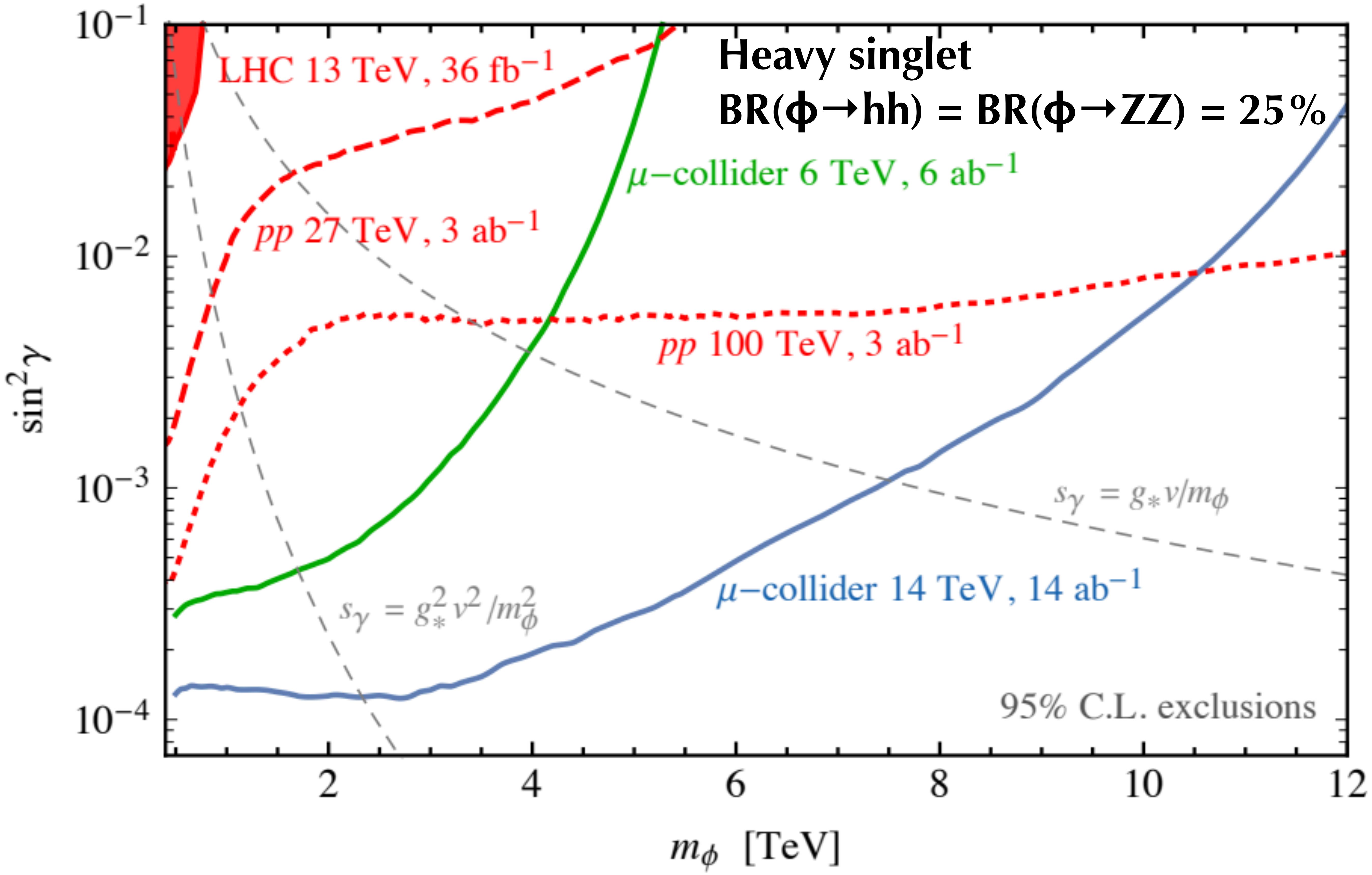
JHEP 11,144 (2018)
arXiv:1901.06150

If technological challenges are overcome, muon collider could provide a viable opportunity to reach high energy with leptons (> 3 TeV)

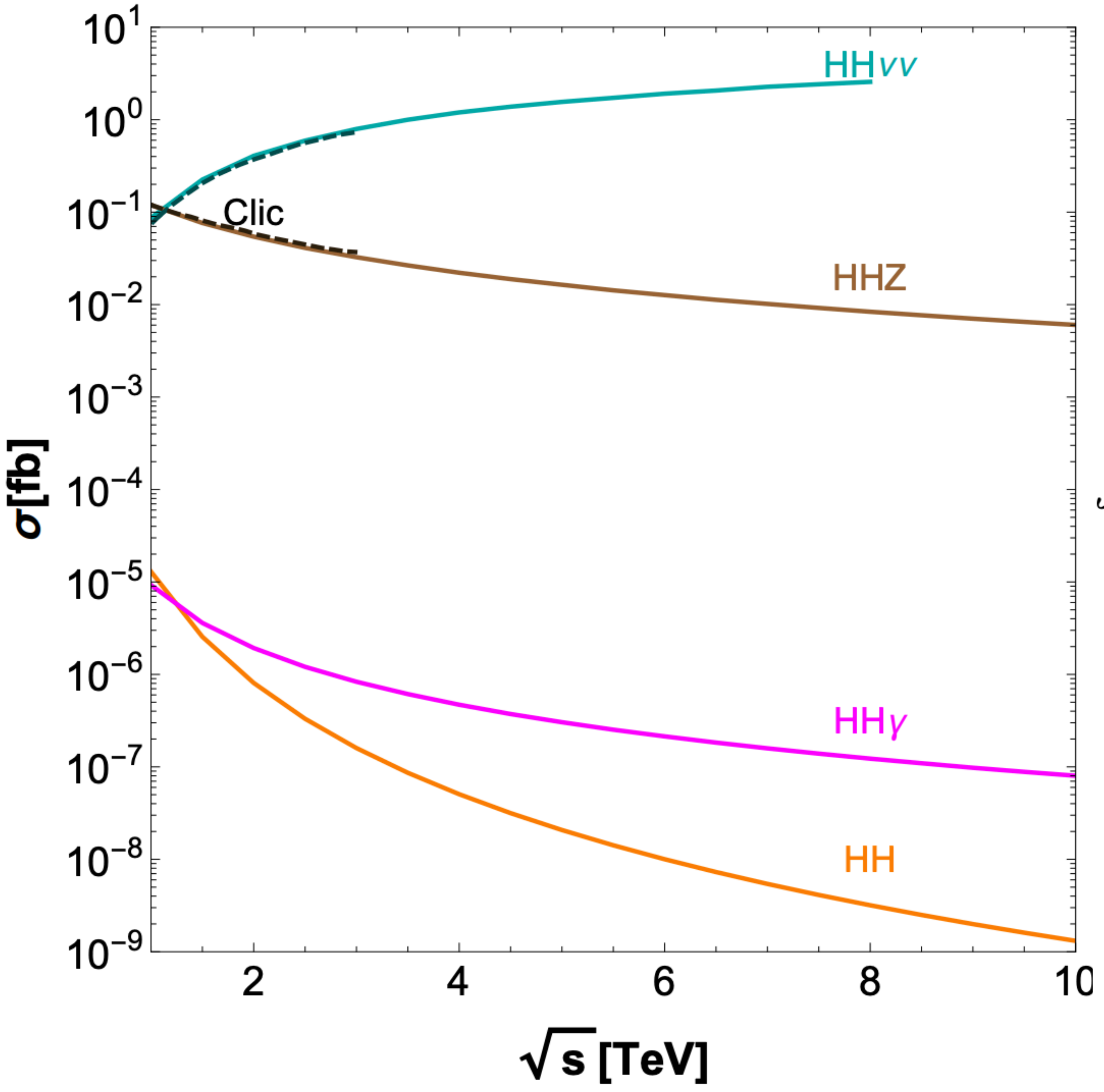
Extend the discovery reach with much smaller collider energy compared to pp initial state

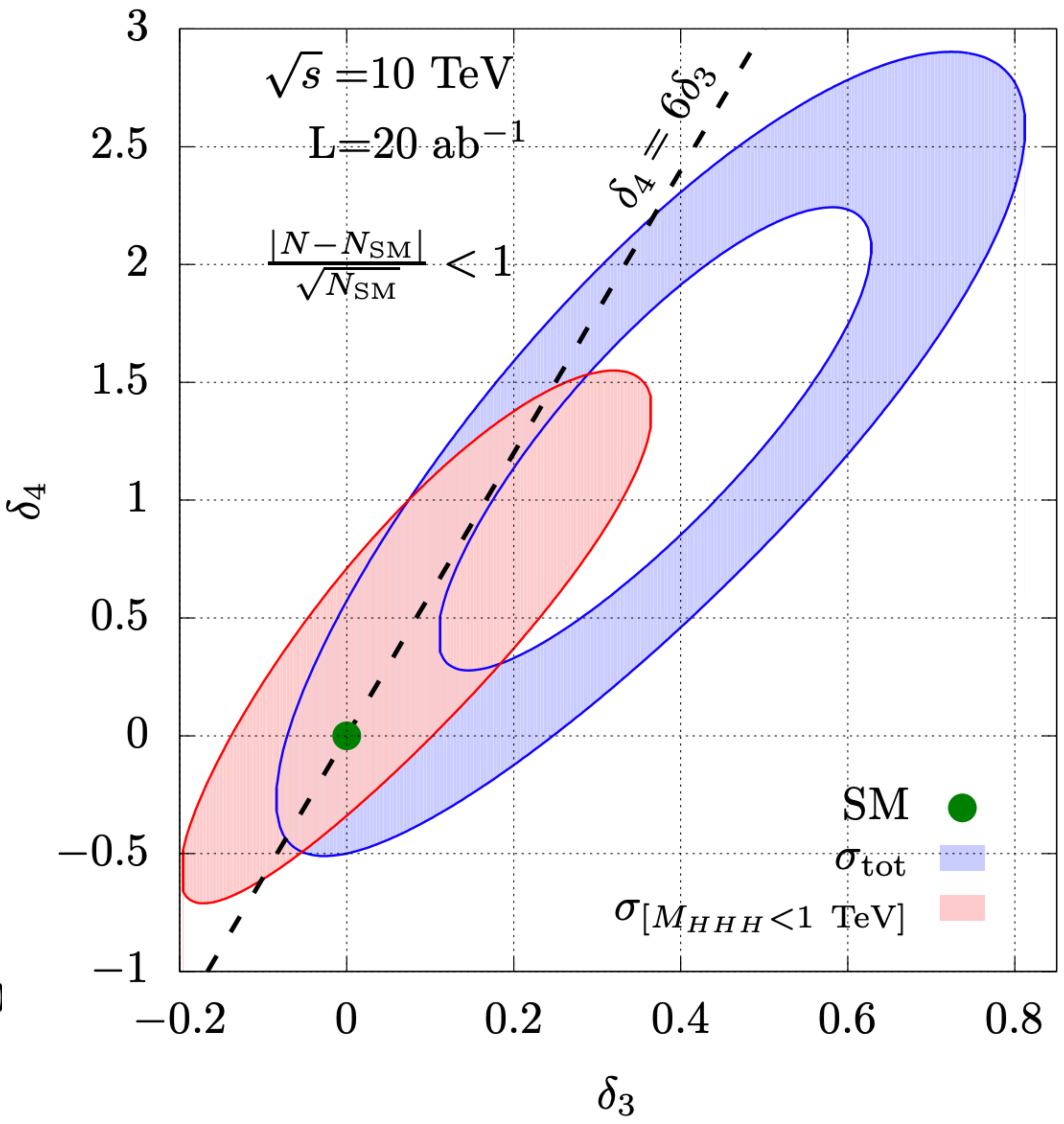


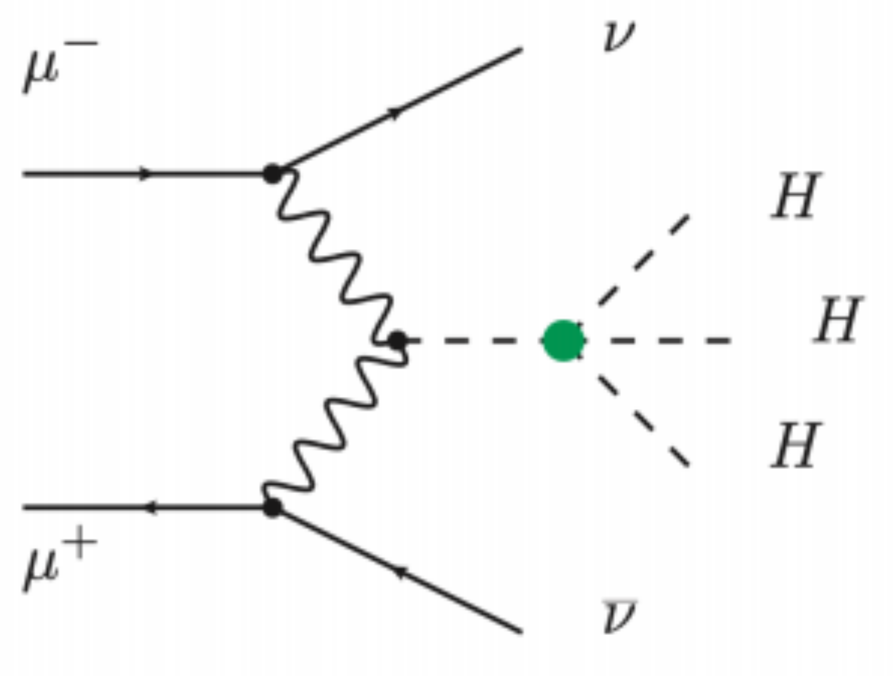
14 TeV μ-collider ~ FCC@100 TeV



μ-collider: Higgs production mechanisms







10 TeV $\delta_4 \sim [-0.4, 0.7]$

ILC $\sim [-10, 10]$

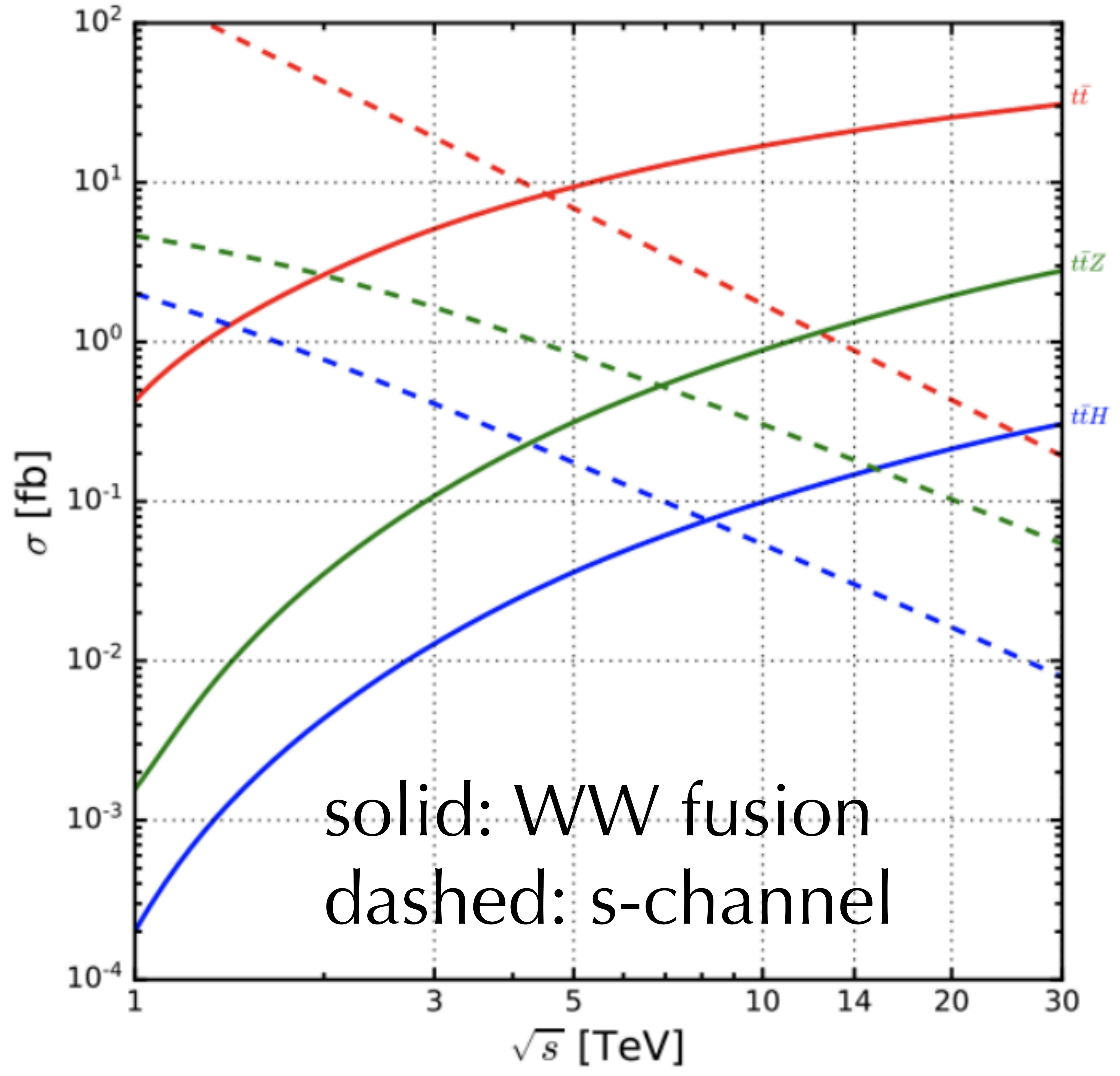
CLIC $\sim [-5, 5]$

FCC $\sim [-2, 4]$

Potentially it could measure the self-coupling at 7% at 6 TeV and 1% at 30 TeV

Gamma-gamma collider

- **Above 5 TeV**, new particles can be produced through the WW mode.
- e+e-,μ+μ- and gamma-gamma colliders probe similar physics scenarios
- **gamma-gamma colliders**, driven by linear colliders with advanced acceleration technologies have the potential to reach extremely high energies



Not just accelerator challenges…

Higgs physics as a driver for future detectors R&D

- The exploration of the **Higgs sector is one of the main drivers to derive technical requirements for future detectors** R&D
  - Advancing HEP detectors to new regimes of sensitivity
  - Building next-generation HEP detectors with novel materials & advanced techniques
- The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for tracker, calorimeters and timing detectors at e+e-
  - Detector systems at Lepton Colliders designed for **Particle Flow reconstruction**

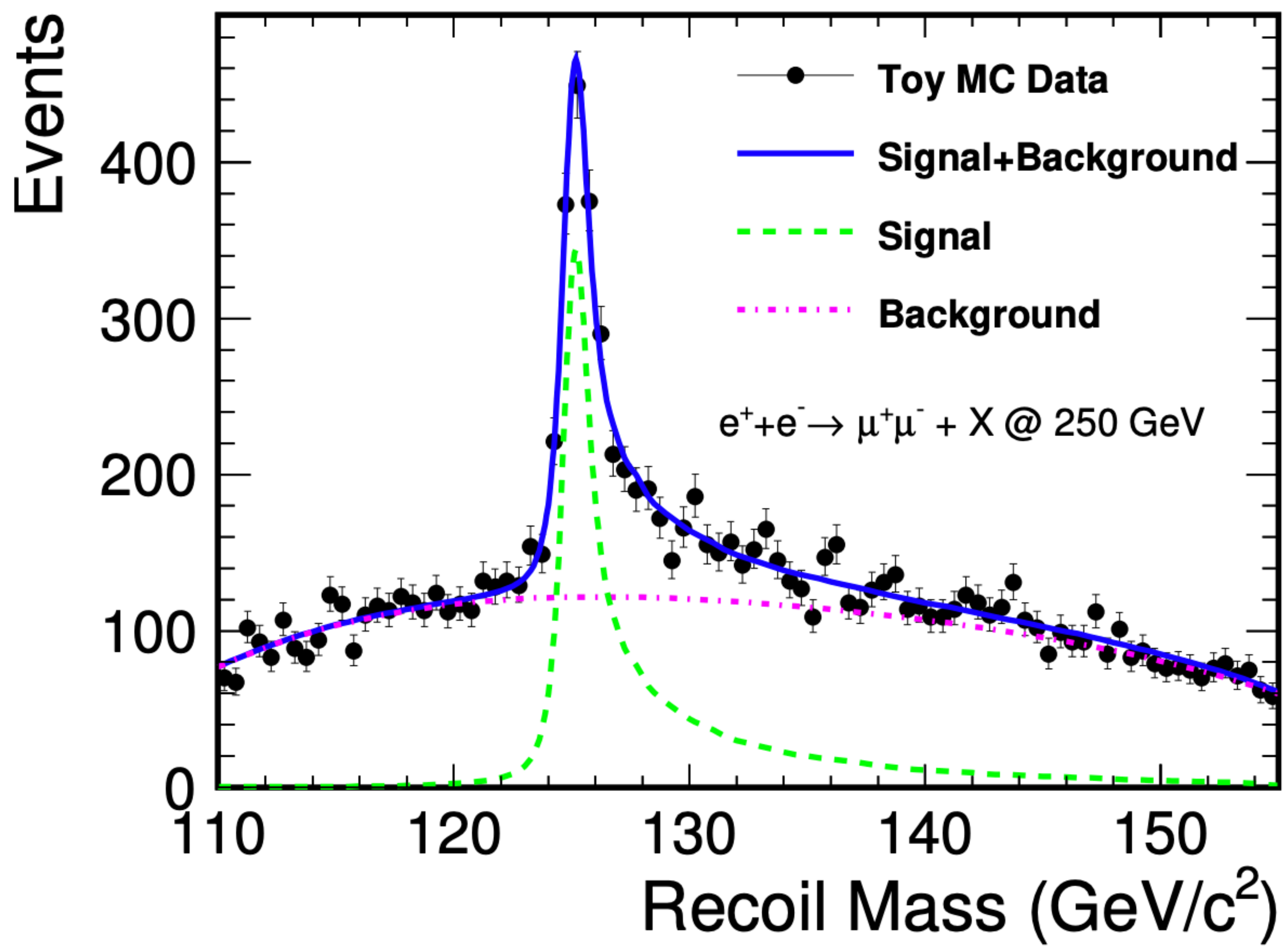
	Measurement	Technical Requirement (TR)
Tracking	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu$m TR 1.1.3: Granularity : $25 \times 50\ \mu m^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps
Calorimetry	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps

DOE Basic Research Needs Study on Instrumentation

Physics requirements for tracking detectors at e+e-

ILC TDR Vol. 4
arXiv:2003.01116

- **ZH process**: Higgs recoil reconstructed from Z →μμ
  - Drives requirement on charged track momentum and jet resolutions
  - Sets need for high field magnets and high precision / low mass trackers
  - Bunch time structure allows high precision trackers with very low X_0 at **linear lepton colliders**
- **Higgs → bb/cc decays**: Flavor tagging & quark charge tagging at unprecedented level
  - Drives requirement on charged track impact parameter resolution → low mass trackers near IP
    - <0.3% X0 per layer (ideally 0.1% X_0) for vertex detector
    - Sensors will have to be less than 75 μm thick with ~ 5 μm hit resolution (17-25μm pitch)



Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Snowmass21: planning the next steps

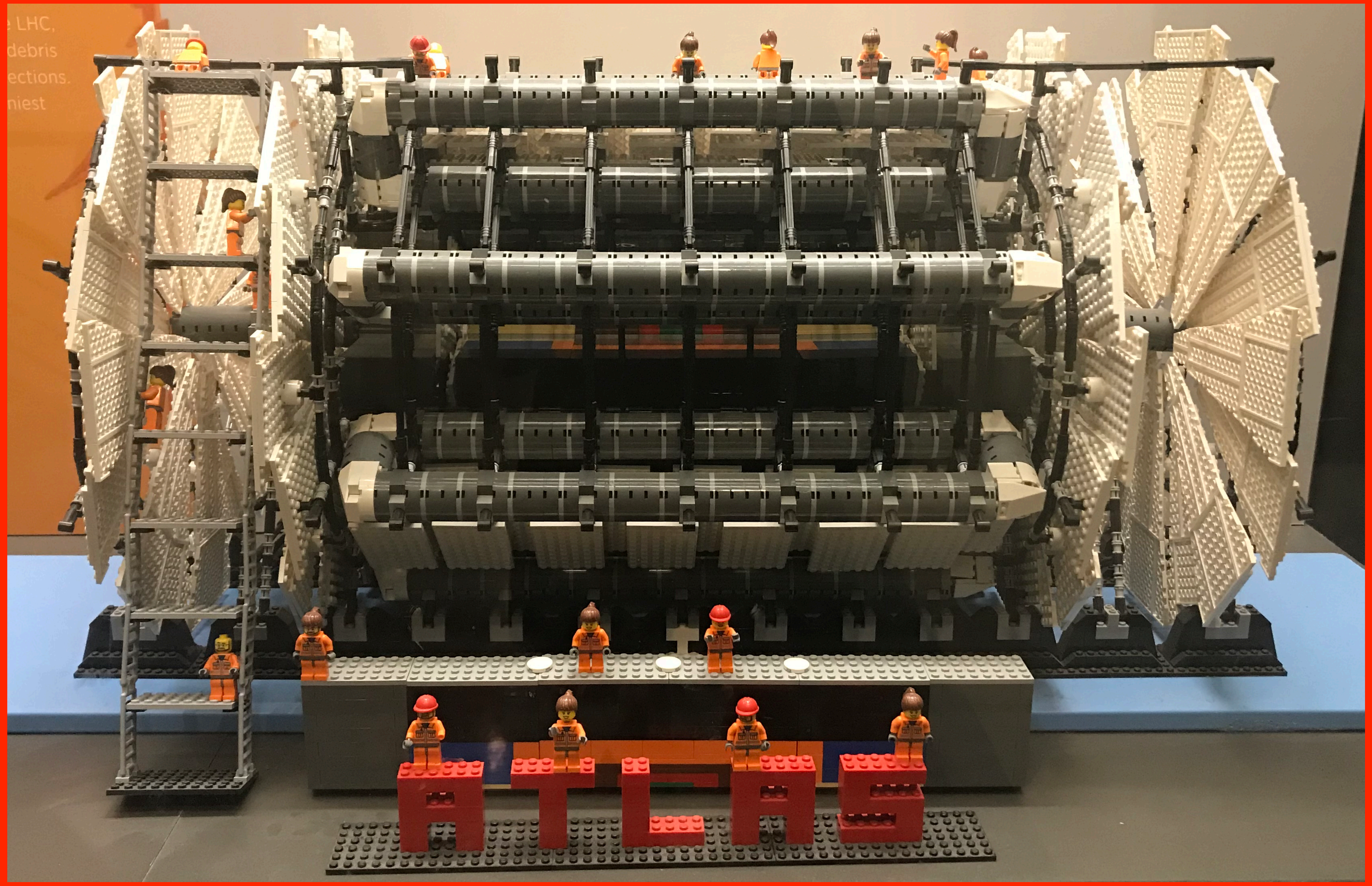
The **Snowmass21** process is underway

- Snowmass is a time for the (US) HEP community to innovate and set new directions - time to dream big
- The plan to build on the work done in the context of the European Strategy and **identify missing or outdated experimental or theory studies** (ex. muon collider)
    - **How well can Higgs interactions be measured** at future colliders?
    - **Can the Higgs give us insight into flavor?**
        - importance of measuring the flavor-dependence of Higgs couplings (μ, c, s)
    - What do measurements of the Higgs mass, width, self-coupling, invisible decays tell us?
    - **Complementary information from Higgs couplings at high Q^2**
        - **H at high p_T**
        - **H contribution to W fusion → tt**
    - Can constraints come from other effects of the EW phase transition (e.g. gravitational waves)?

Exciting time ahead for the community to think big and study the potential/complementarity of the facilities that are being proposed

Conclusions

- **LHC** Run 2 is providing a wealth of new measurements: we are entering the **era of precision Higgs physics**
  - The HL-LHC is a reality and we are evaluating updated scenario of proposed future colliders.
- Not (yet) any evidence for the new particles beyond the SM - **no roadmap to BSM**
  - **future e+e- Higgs factories** will add great opportunities on precision determination of Higgs properties
  - all proposed e+e- are capable of reaching O (1%) precision for many of the Higgs couplings
  - These unprecedented physics goals translate into very **ambitious requirements on detector performance**
- Once we have acquired **sufficient** proof that physics beyond the SM exists (and on its scale) we will have *enough information* to build the next high energy facility
  - To access new forces at energy **Λ** the new collider would likely need to produce parton-parton collisions with CM energies of tens of TeV
  - **The feasibility of alternatives to pp like muon and gamma colliders yet to be proven but could enable a new era for the exploration fo the Energy Frontier**



thank you!

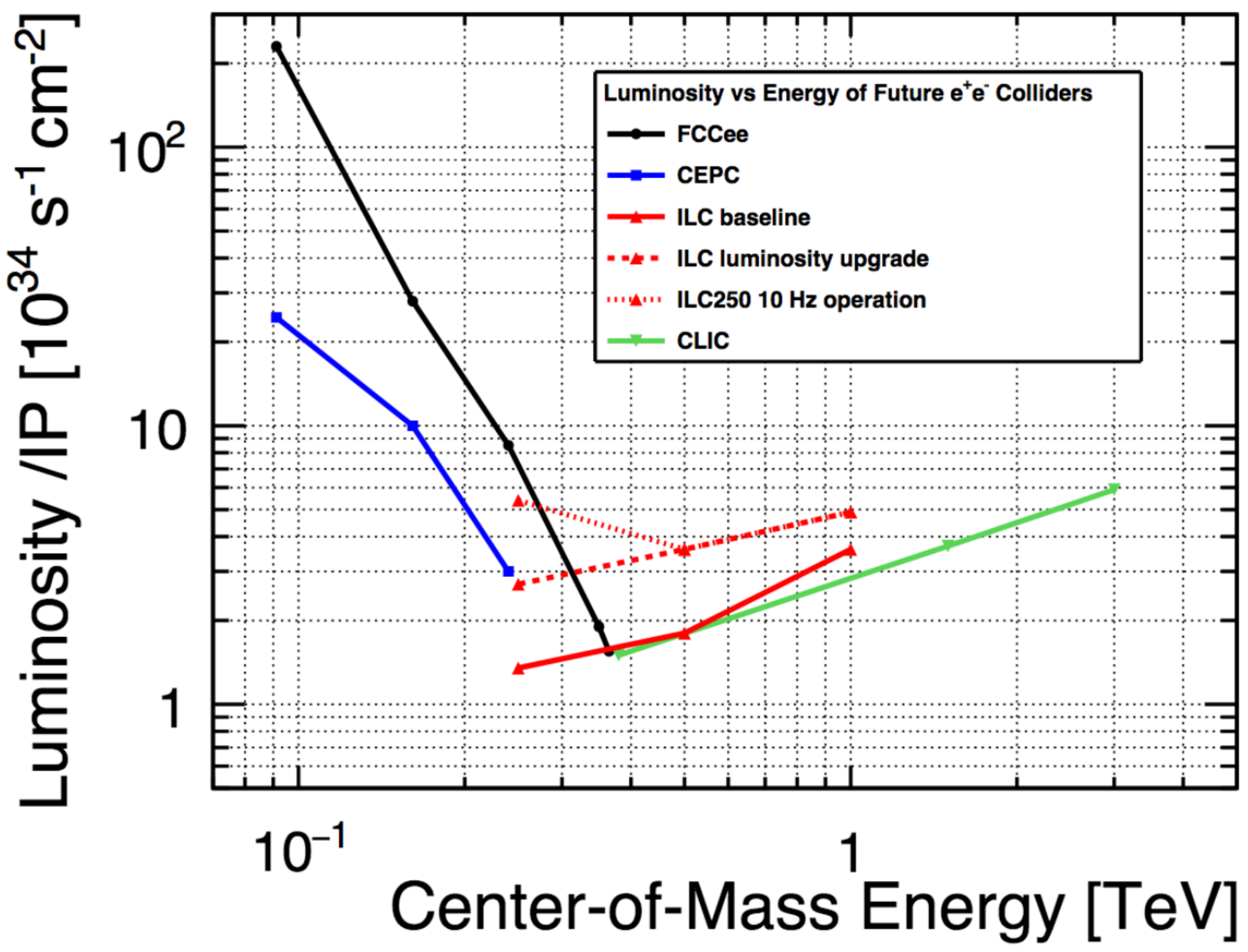
spares

Linear & Circular Collider - Detector Impact

- **Linear** colliders : ILC, CLIC
  - Only possible way towards high-energy with leptons
  - Polarized collisions possible
  - The time structure and low radiation background provides an environment which allows us to consider **very light, low power detector structures**

- **Circular** colliders : FCC, CEPC
  - Highest luminosity at Z pole/WW/ZH, but strongly limited by synchrotron radiation above 350– 400 GeV
  - The interaction rates (up to 100 kHz at the Z pole) put strict constraints on the event size and readout speed
  - Due to beam crossing angle, solenoid magnetic field is limited to 2 T to avoid a significant impact on the luminosity
  - Trackers must achieve good resolution without power pulsing

- Linear colliders allow lower mass Si pixel and strip trackers



Which precision on the self-coupling is needed?

arXiv:1910.00012

Bronze 100%

Silver 25–50%

Gold 5–10%

Platinum 1%

Sensitivity to models with the largest new physics effects, in which new particles of few hundred GeV mass appear in tree diagrams or as s-channel resonances

Sensitivity to mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV (i.e. electroweak baryogengesis)

Sensitivity to a broad class of loop diagram effects that might be created by any new particle with strong coupling to the H

Sensitivity to typical quantum corrections to the Higgs self-coupling generated by loop diagrams

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Interplay between precisions inference and direct searches for new particles

Beyond HH, quartic coupling

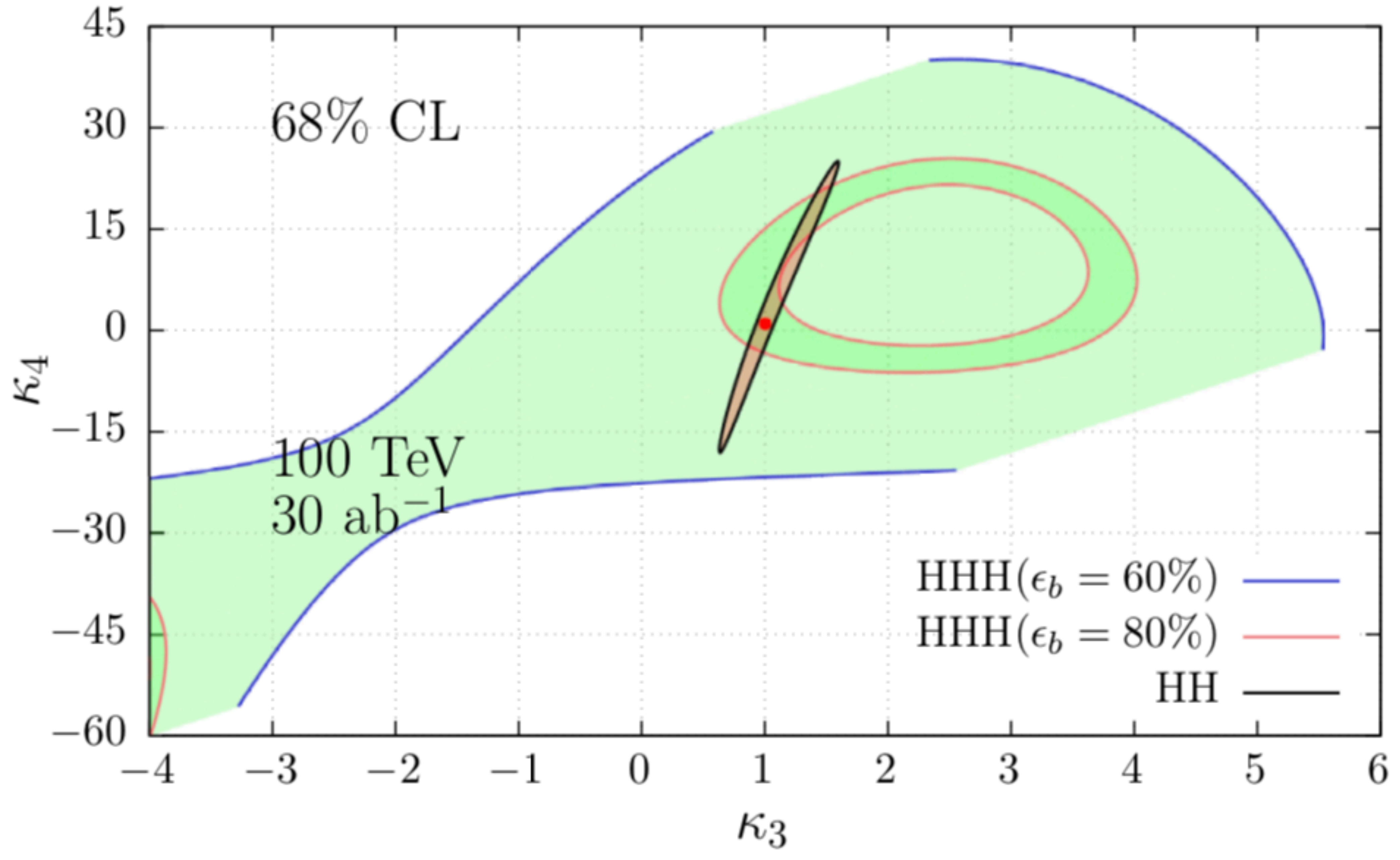
- An estimate for FCC-hh is based on the bbbbγγ signature, assuming an optimistic (80%) and a conservative (60%) scenarios on the b-tagging efficiency.
  - $\kappa_4 \in [-2.3, 4.3]$ at 68%CL

- At future e+e− colliders the SM rate for triple Higgs production can be accessed only at the very high energies.
  - the cross-section strongly depends on κ_4, and so it is possible to obtain significant constraints.
  - The constraints that can obtained at CLIC at 3 TeV via W boson fusion HHH production are similar to those that would be obtained at a FCC-hh 100 TeV

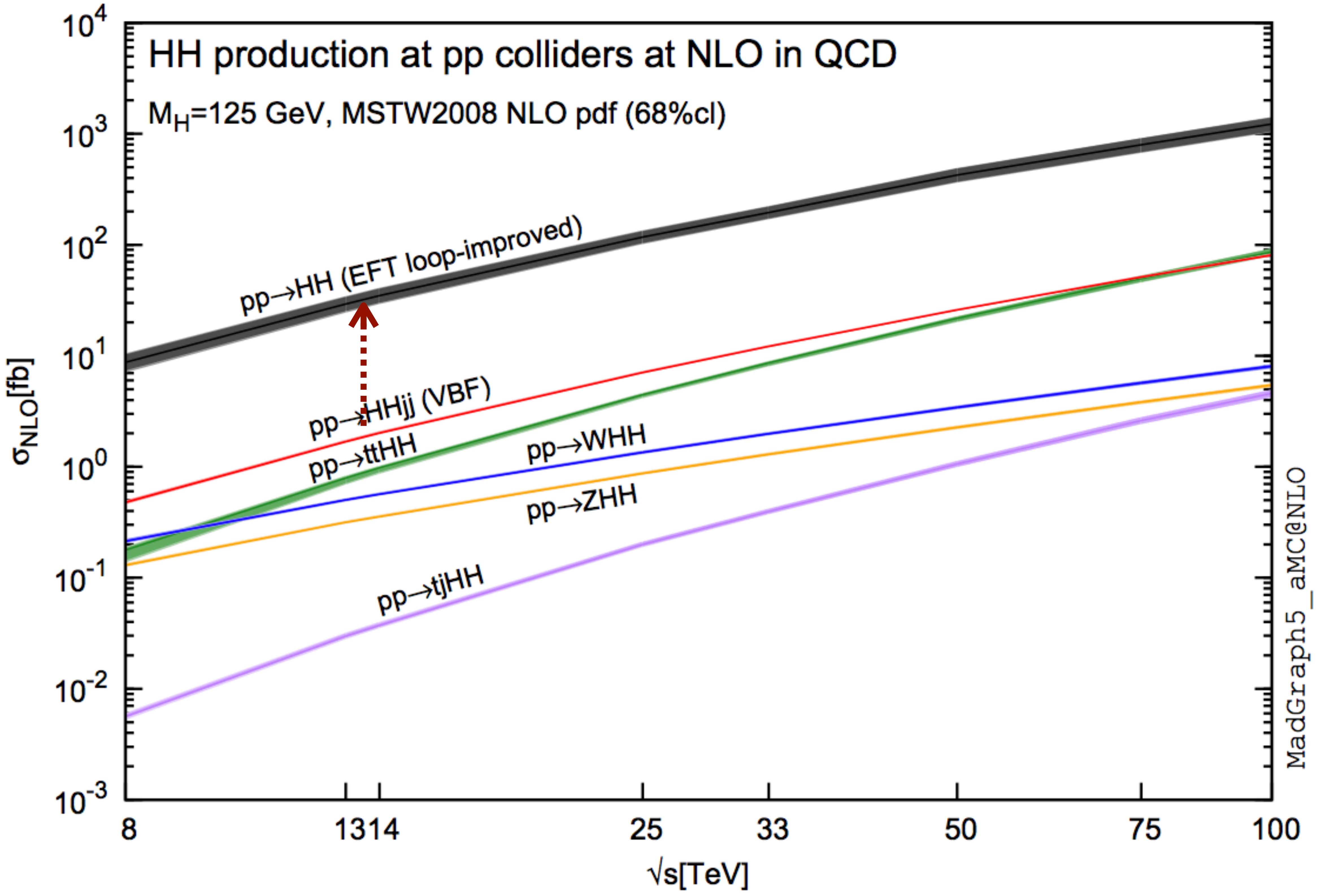
$$\Delta\mathscr{L} = -\frac{\bar{c}_6}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 - \frac{\bar{c}_8}{v^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4$$

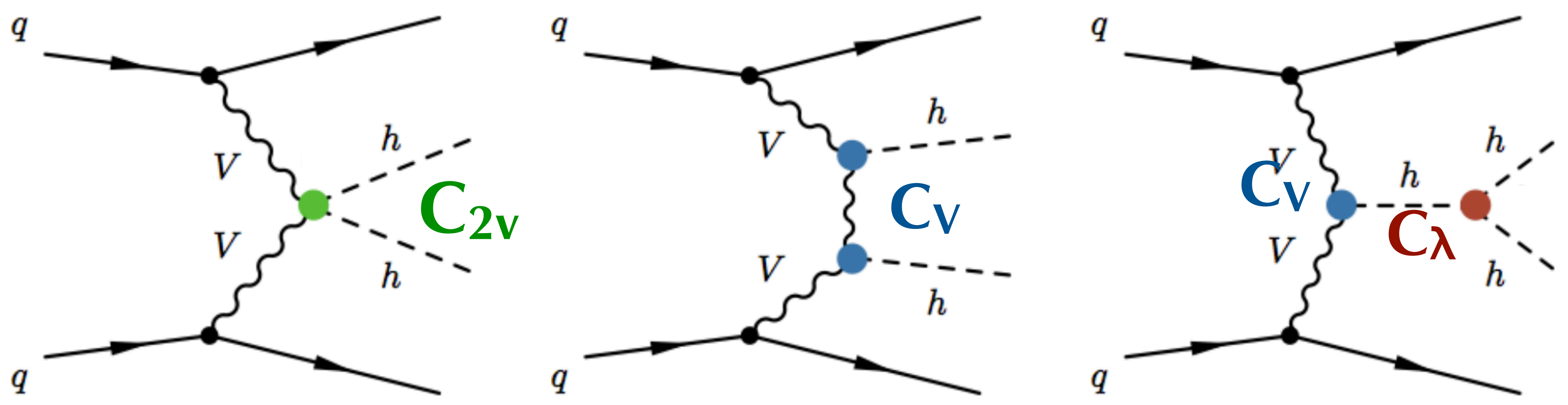
$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}} = 1 + c_6$$

$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{SM}} = 1 + 6c_6 + c_8\,.$$



VBF production





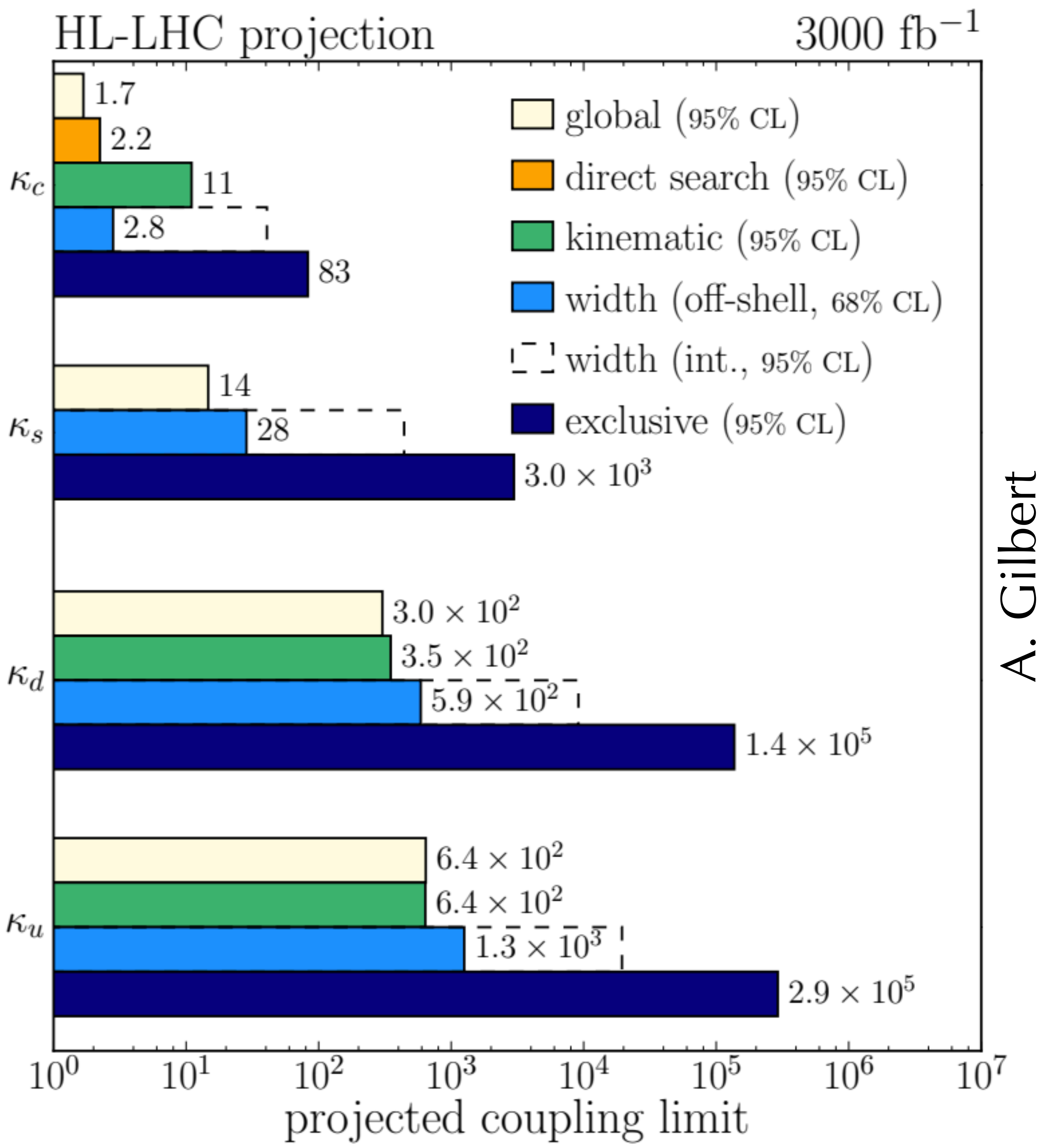
VBF production has a small cross-cross-section (1.73 fb)

- two high p_T forward jets provide a very specific topology
- allow to probe C_{2V} (VVHH), C_V and C_λ

Prospects for light quark couplings at HL-LHC

CERN-LPCC-2018-04

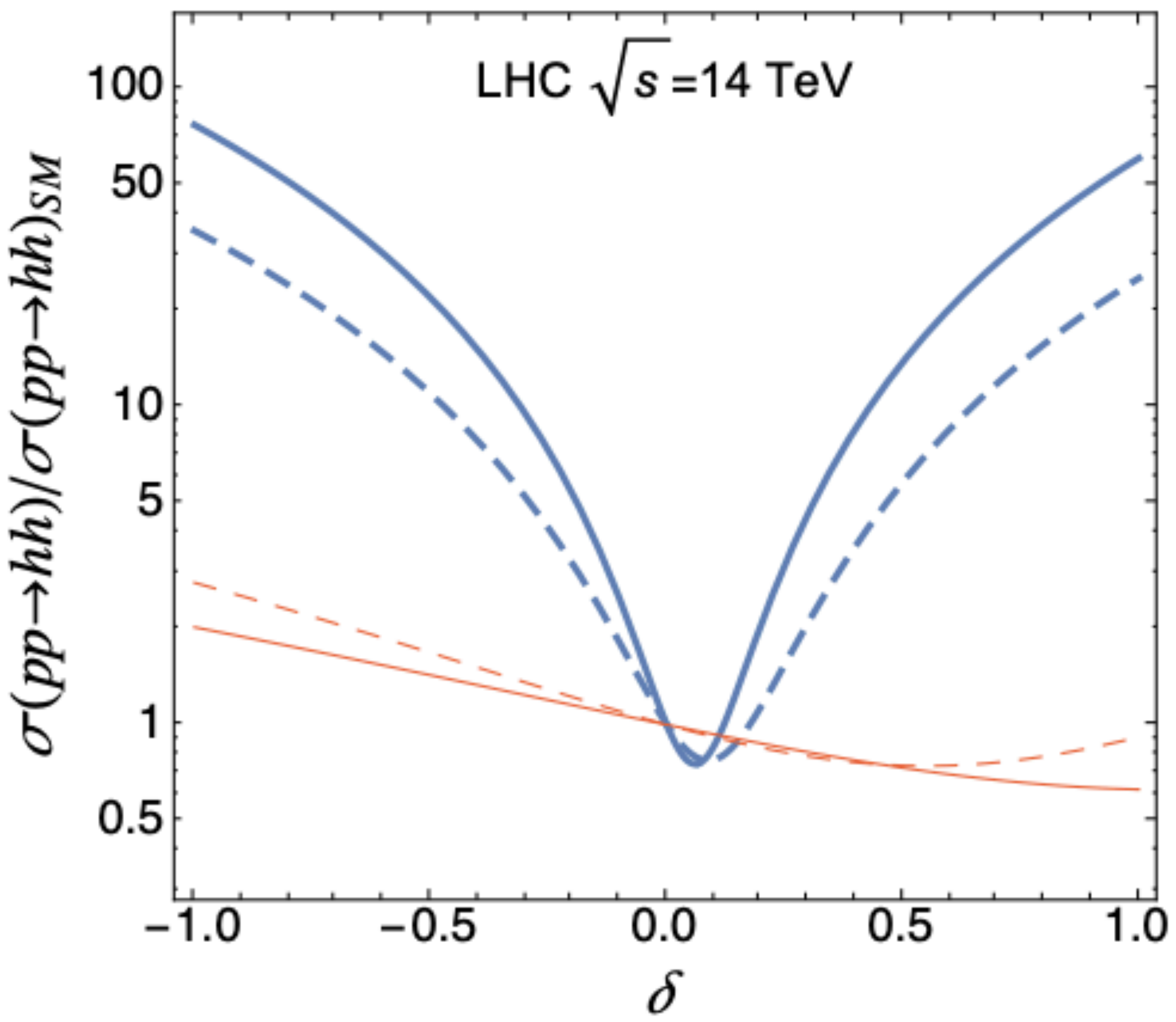
- Exclusive decays to γ+meson include contributions from light quark Yukawa couplings
- Interpretation of Higgs width constraint: direct measurement and via off-shell
- Interpretation of kinematic distributions
- Direct search for H→cc
- Global fit of all Higgs couplings (assuming no other BSM decays)

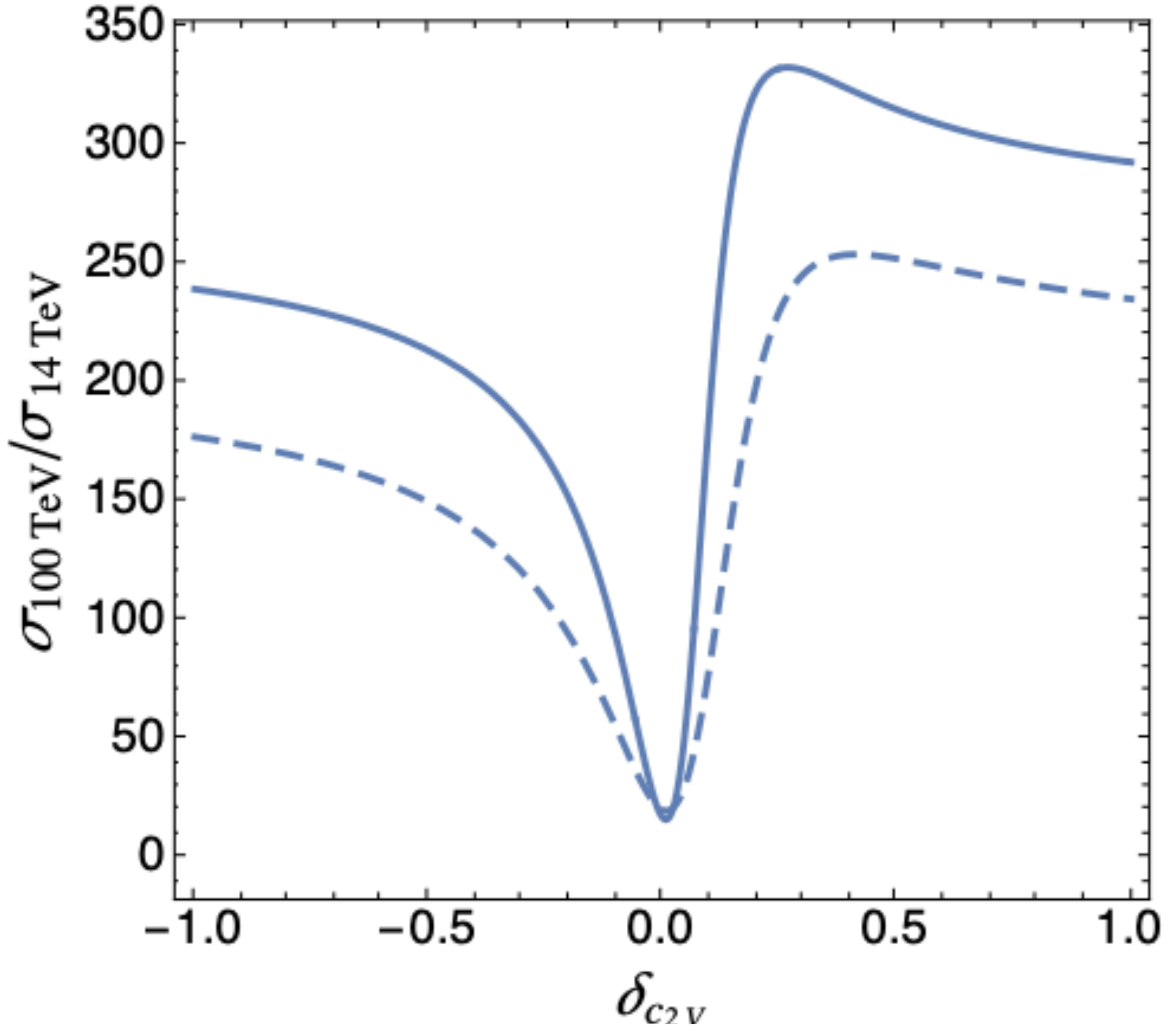


Perspective on c_{2V} at FCC-hh

arXiv:1611.03860

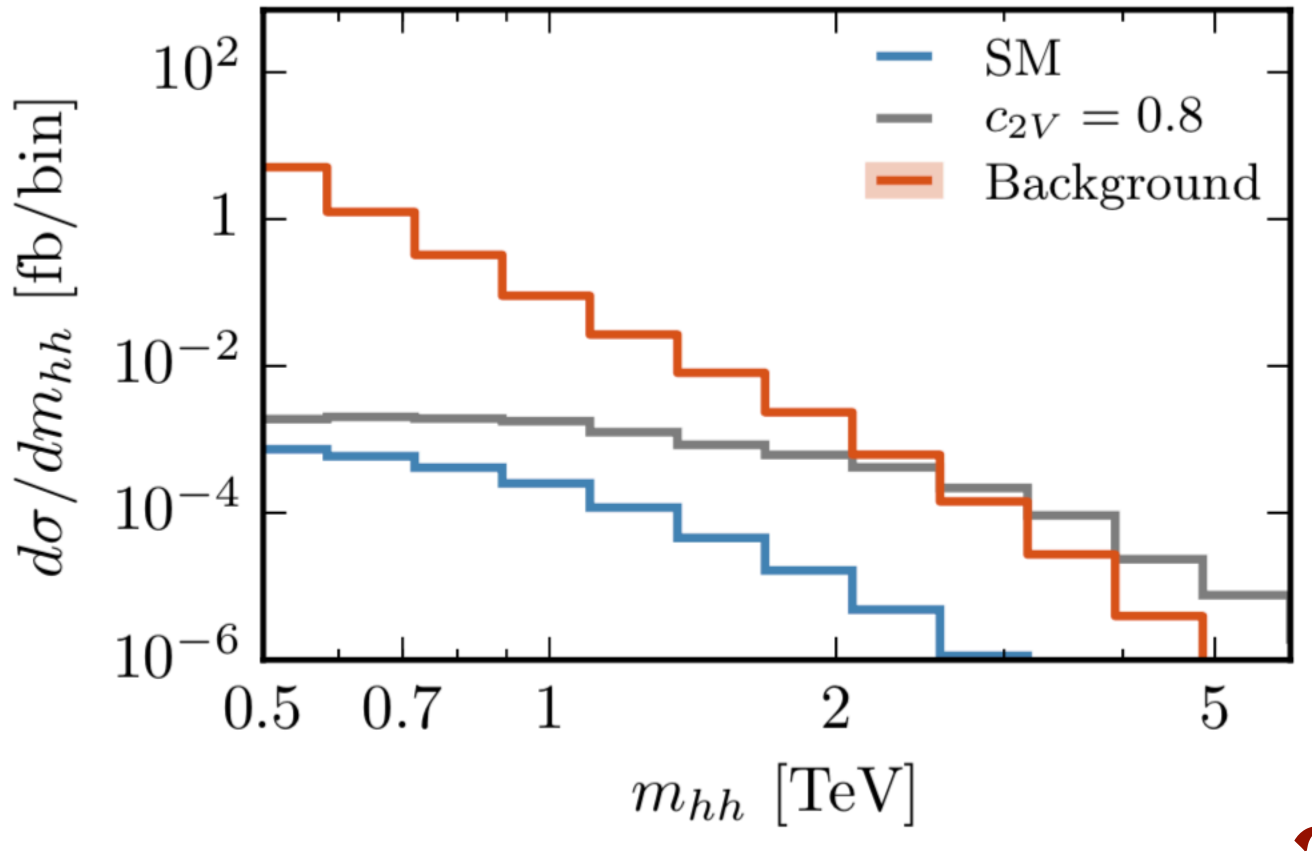
- c_V will be measured with a few per-mille precision at e+e-
- the cubic Higgs self-coupling contribution is suppressed at the multi-TeV mass values
- the constraints on δc_{2V} at **FCC-hh is expected to be better than ±1%**
  - a large improvement compared to the precision that can be obtained at the HL-LHC.





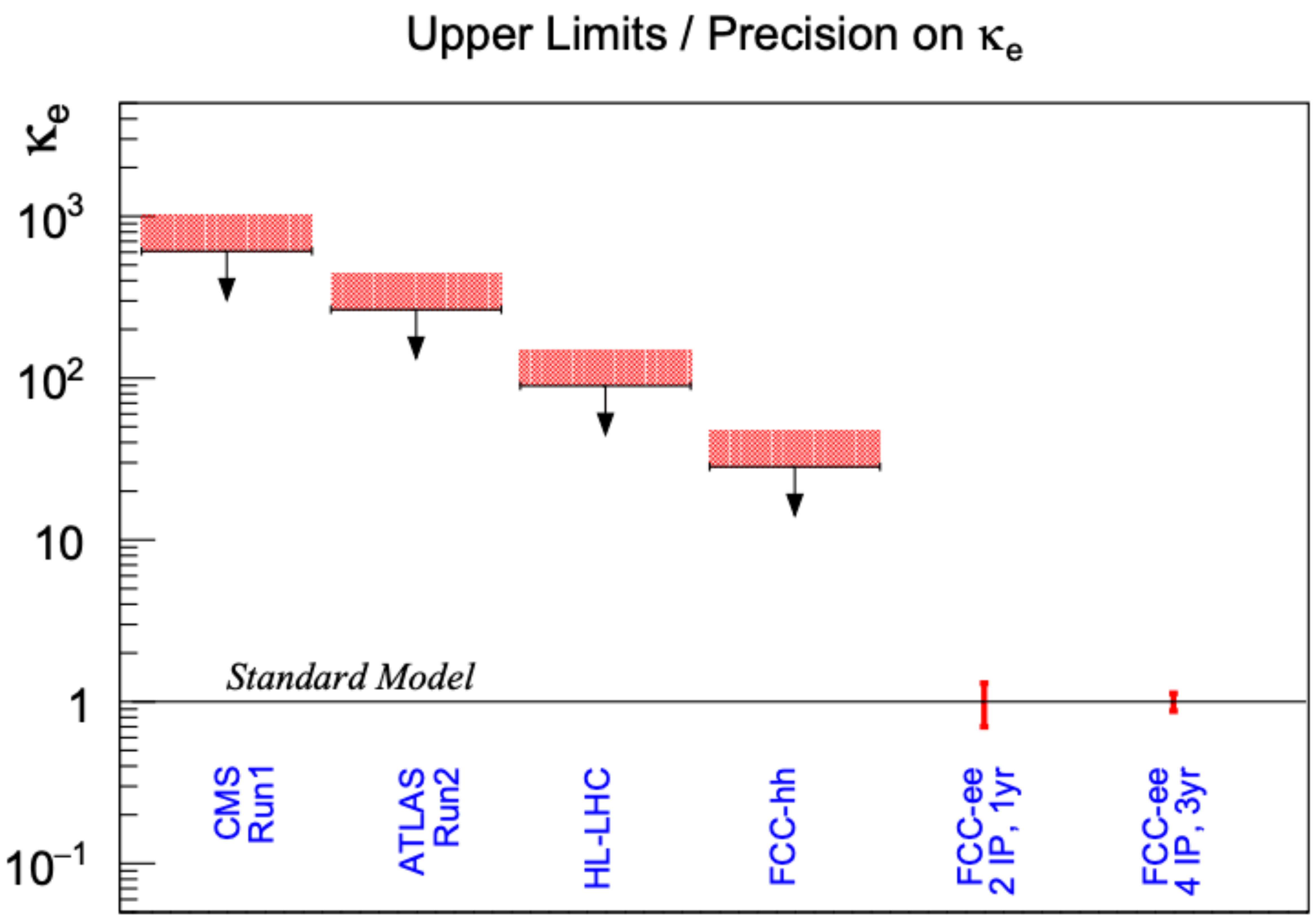
$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}(\delta_c) + \mathcal{O}(m_W^2/\hat{s})$$

$$\delta_c = c_{2V} - c_V^2$$



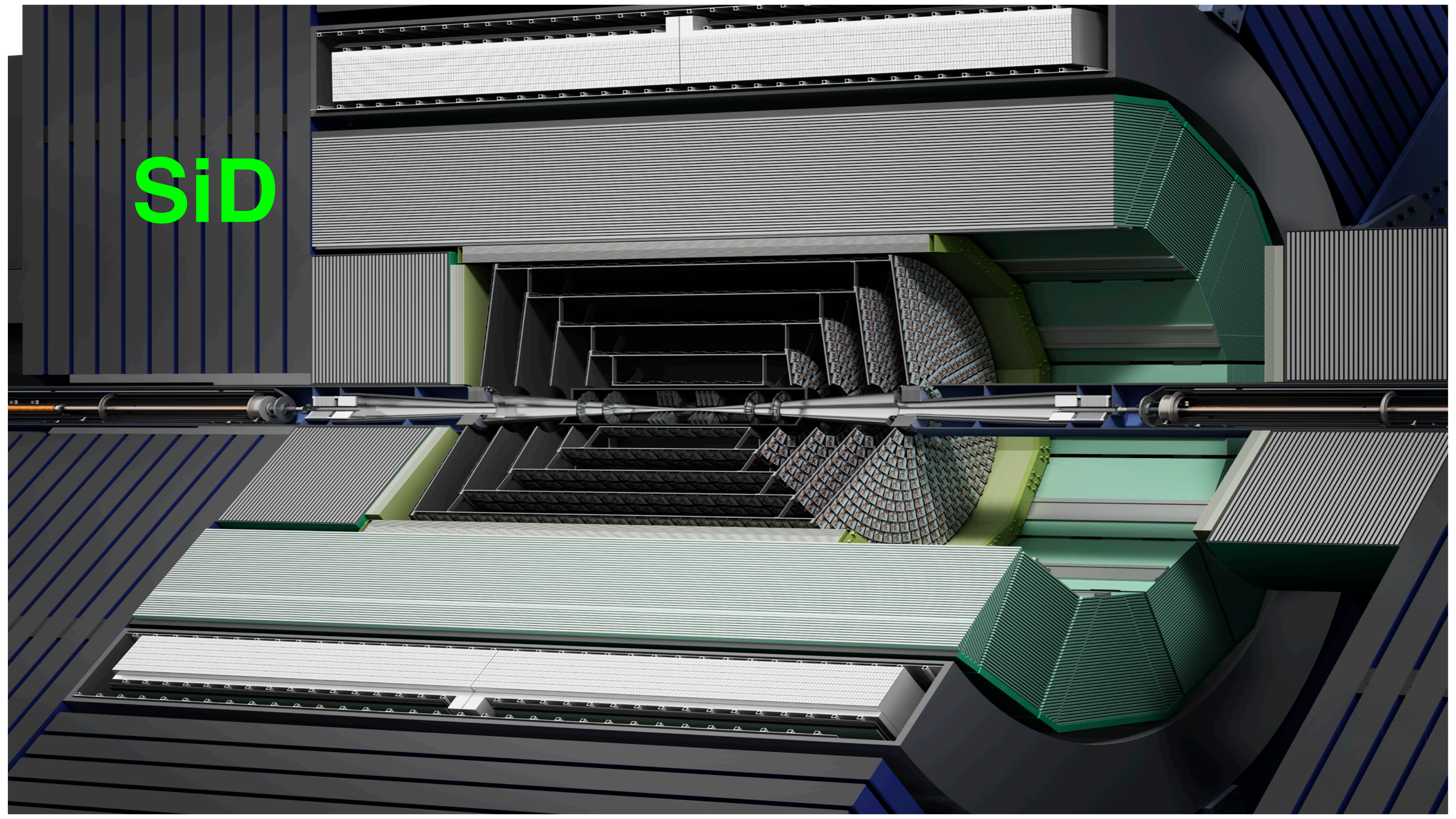
Higgs at e+e-

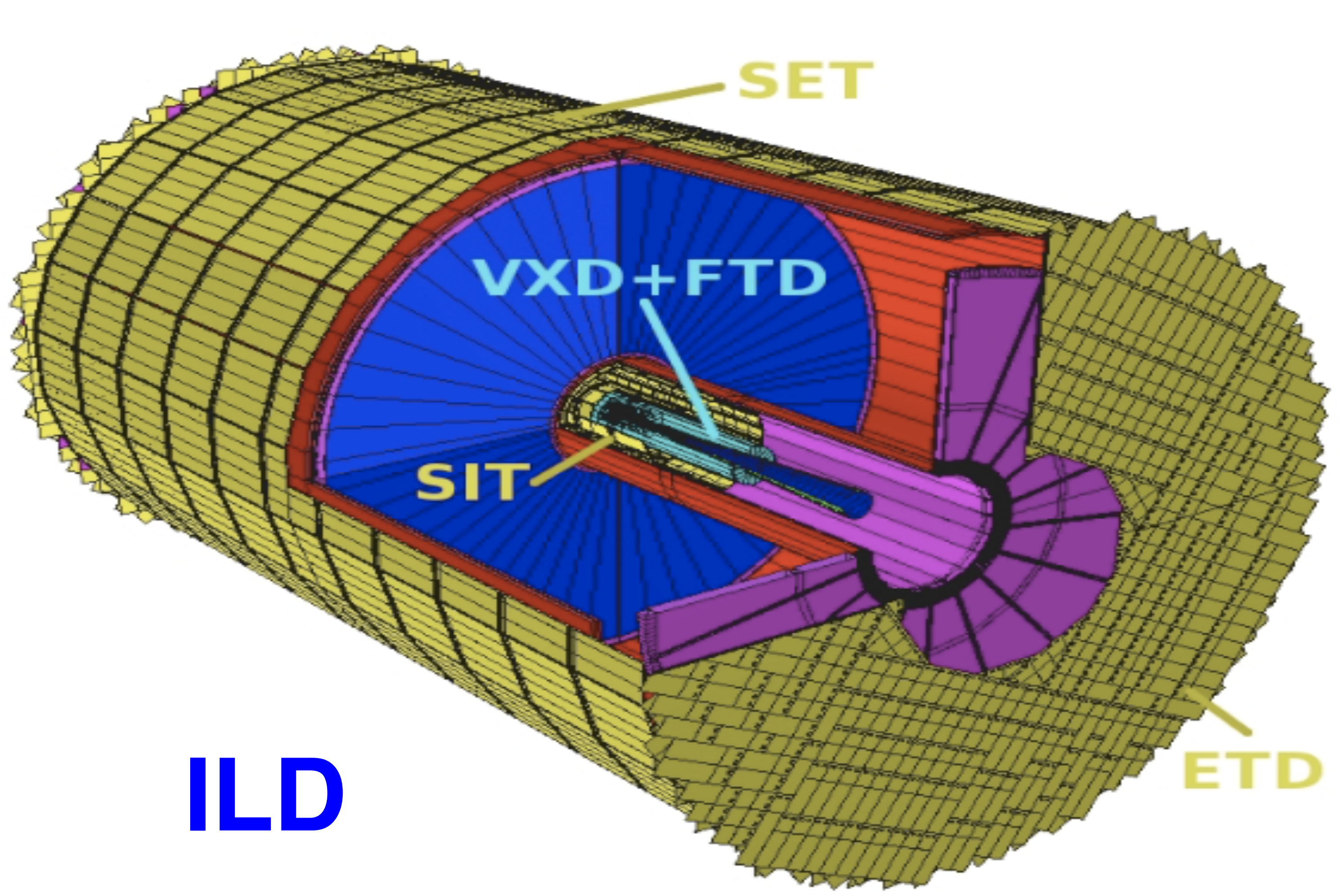
1912.11871



- Circular lepton colliders - FCC-ee - provide the highest luminosities at lower centre-of-mass energies
  - Unique opportunity to measure the Higgs boson coupling to electrons through the resonant production process $e^+e^- \rightarrow H$ at $\sqrt{s} = 125$ GeV
  - FCC-ee running at H pole-mass with 20/ab would produce O(30.000) H's reaching SM sensitivity
    - Requires control of beam-energy spread

ILC silicon detectors





- Future lepton colliders target unprecedented precision on physics ↔ extremely high precision detectors
- Silicon strip and pixel detectors are **key** for precision charged particle tracking, secondary vertexing, and as input to Particle Flow reconstruction - which is assumed as baseline
- Minimizing material budget is vital → Exciting Si pixel & strip technologies in development

Physics drivers for tracking detectors

ILC TDR Vol. 4
arXiv:2003.01116

Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%
$Zh \to \ell^+\ell^- X$ $\mu^+\mu^-(\gamma)$ $Zh + h\nu\bar{\nu} \to \mu^+\mu^- X$	Higgs recoil mass Luminosity weighted E_{cm} BR($h \to \mu^+\mu^-$)	μ detector Tracker	Charged particle Momentum Resolution $\Delta p_t/p_t^2$	$5 \times 10^{-5}(GeV/c)^{-1}$
$Zh, h \to b\bar{b}, c\bar{c}, b\bar{b}, gg$	Higgs branching fractions b-quark charge asymmetry	Vertex	Impact parameter	$5\mu m \oplus 10\mu m/p(\text{GeV/c})\sin^{3/2}\theta$

Physics requirements for future detectors at colliders

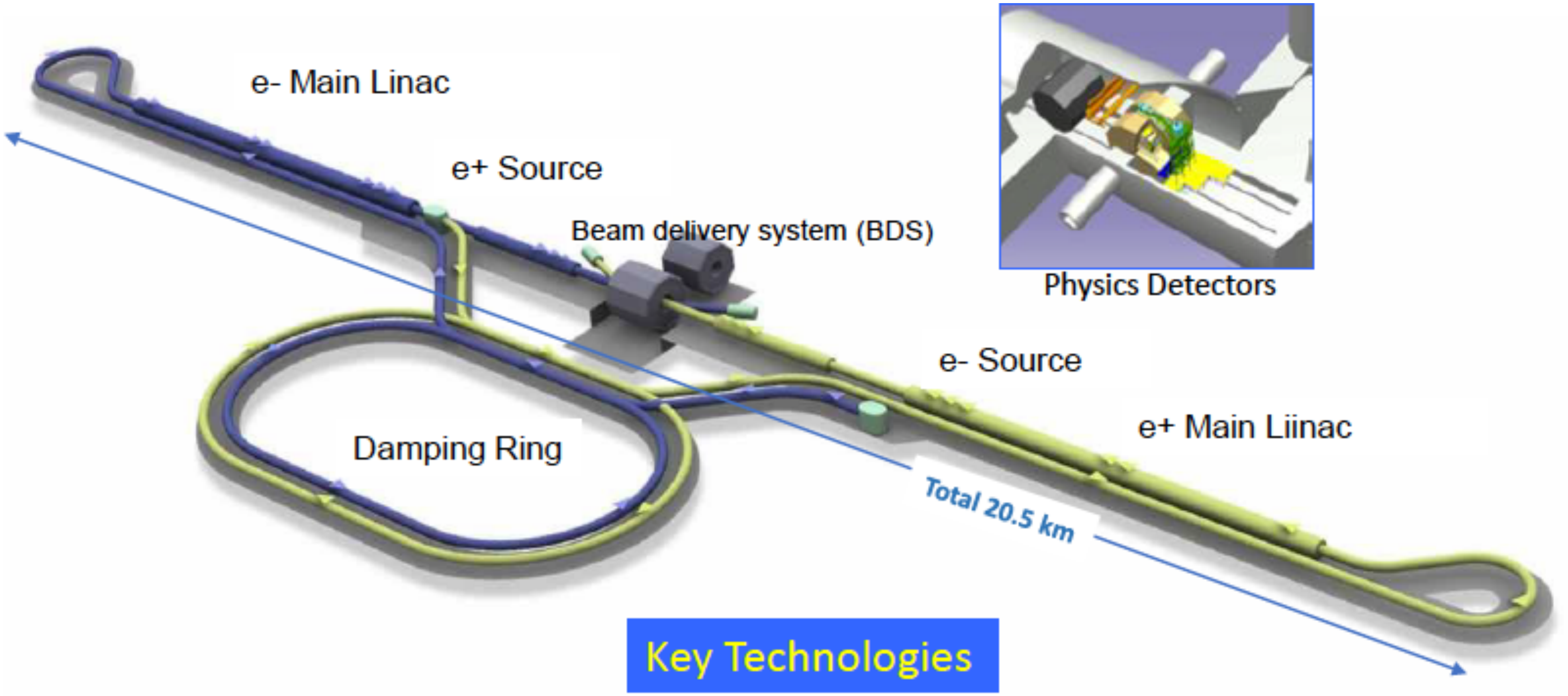
DOE Basic Research Needs Study on Instrumentation

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5 \times 0.5\ \text{cm}^2$, hadronic cells of $1 \times 1\ \text{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and $3 \times 10^{16}\ (5 \times 10^{18})\ \text{n}_{\text{eq}}/\text{cm}^2$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

The Central Role of Tracking

- Tracking detectors provide the primary measurements for charged particle momentum and impact parameter
  - Momentum and IP resolution are limiting factors in key precision measurements
- Detector systems at Lepton Colliders designed for **Particle Flow reconstruction**. Precision tracking needed for:
  - Calorimeter charged / neutral particle energy deposition separation
  - Limiting factor: “confusion” in energy deposition to particle assignment
- Primary, Secondary, and Tertiary vertex reconstruction
  - Key for identifying and separating heavy flavour jets
- Bunch crossing time stamping, leading to reduction of beam backgrounds

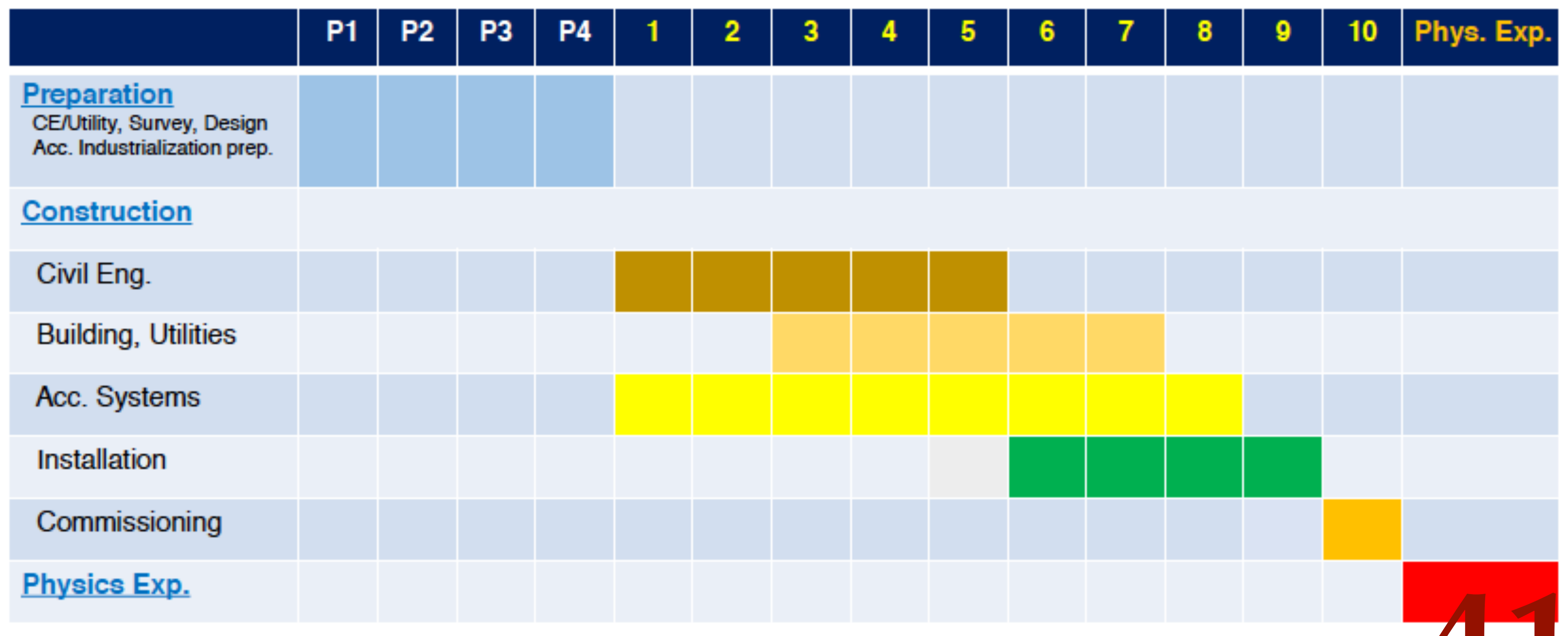
ILC and SRF Technology



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35×10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

- Experience with LCLS-II construction commissioning
- Future SRF high brightness injector development
- Cost reduction, higher gradient, higher Q
- Efficient rf sources and lower cost modulators

Now we are at pre-preparation phase (waiting for the preparation phase).
Four years preparation and 9 years construction.



C^3 - Cool Copper Collider

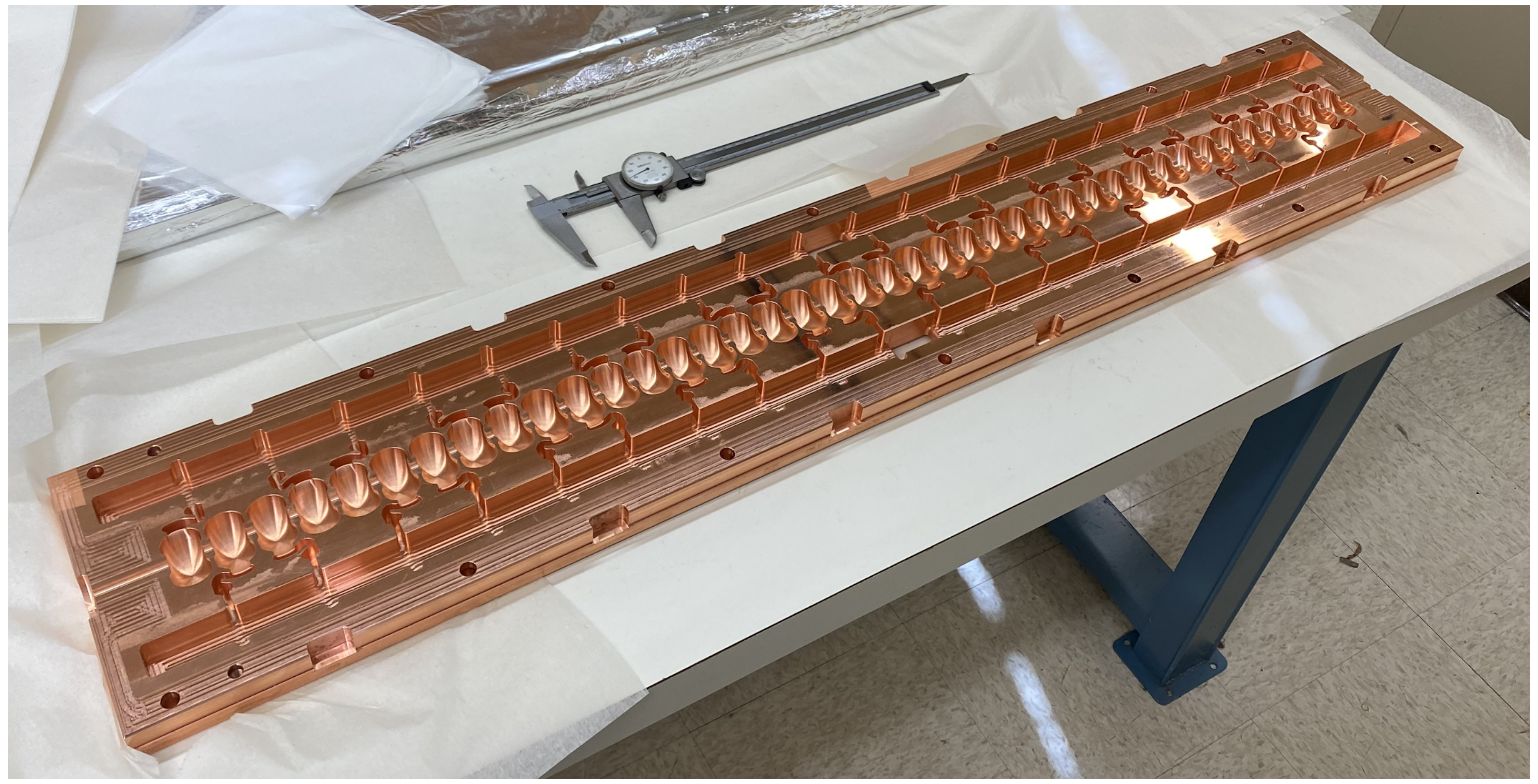
More Details See: Bane et al., *ArXiv* 1807.10195 (2018)

C^3 Colloquium: https://sites.slac.stanford.edu/colloquium/node/159

C3 LOI Link

- SLAC technology for normal conducting accelerator at cryogenic temperature
- Aim to achieve high gradient (110 MeV/m real footprint) on short timescale
- Potential for high brightness polarized sources to eliminate damping rings
- Scalable technology optimizing for multi-TeV operation

First C3 structure at SLAC

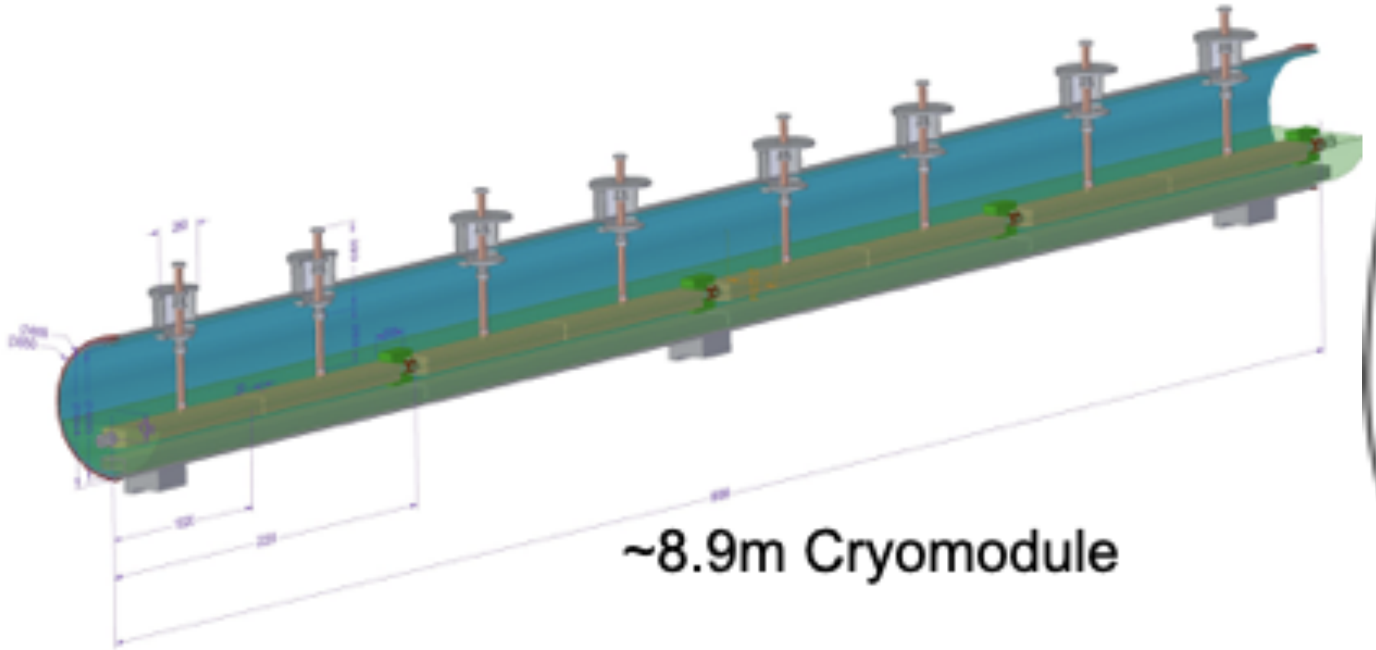


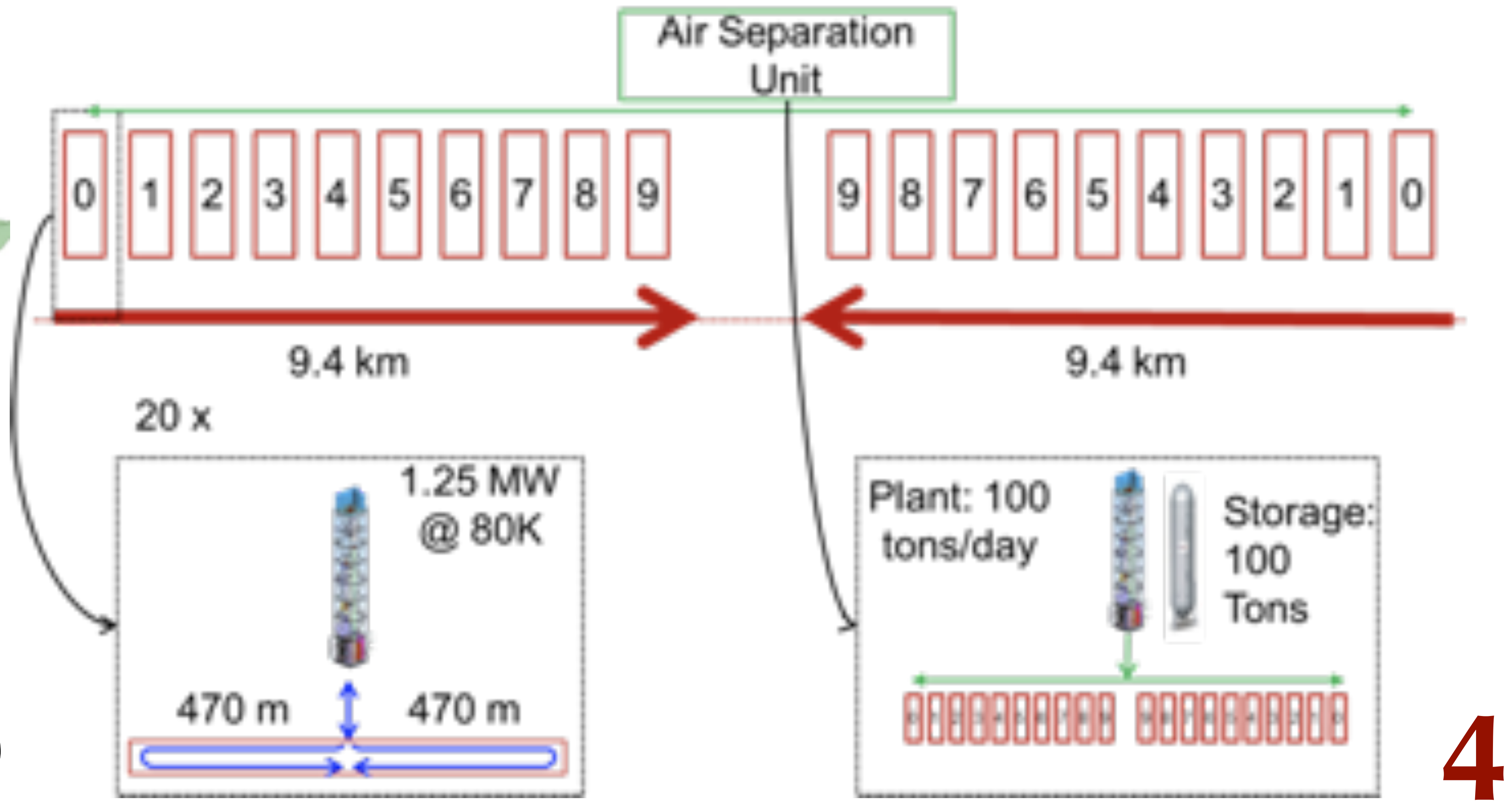
Timeline:

2 years - meter scale, wakefield damping, cryogenics

4 years - modular GeV units

Target operation in parallel w/ HL-LHC





Wakefield Accelerators

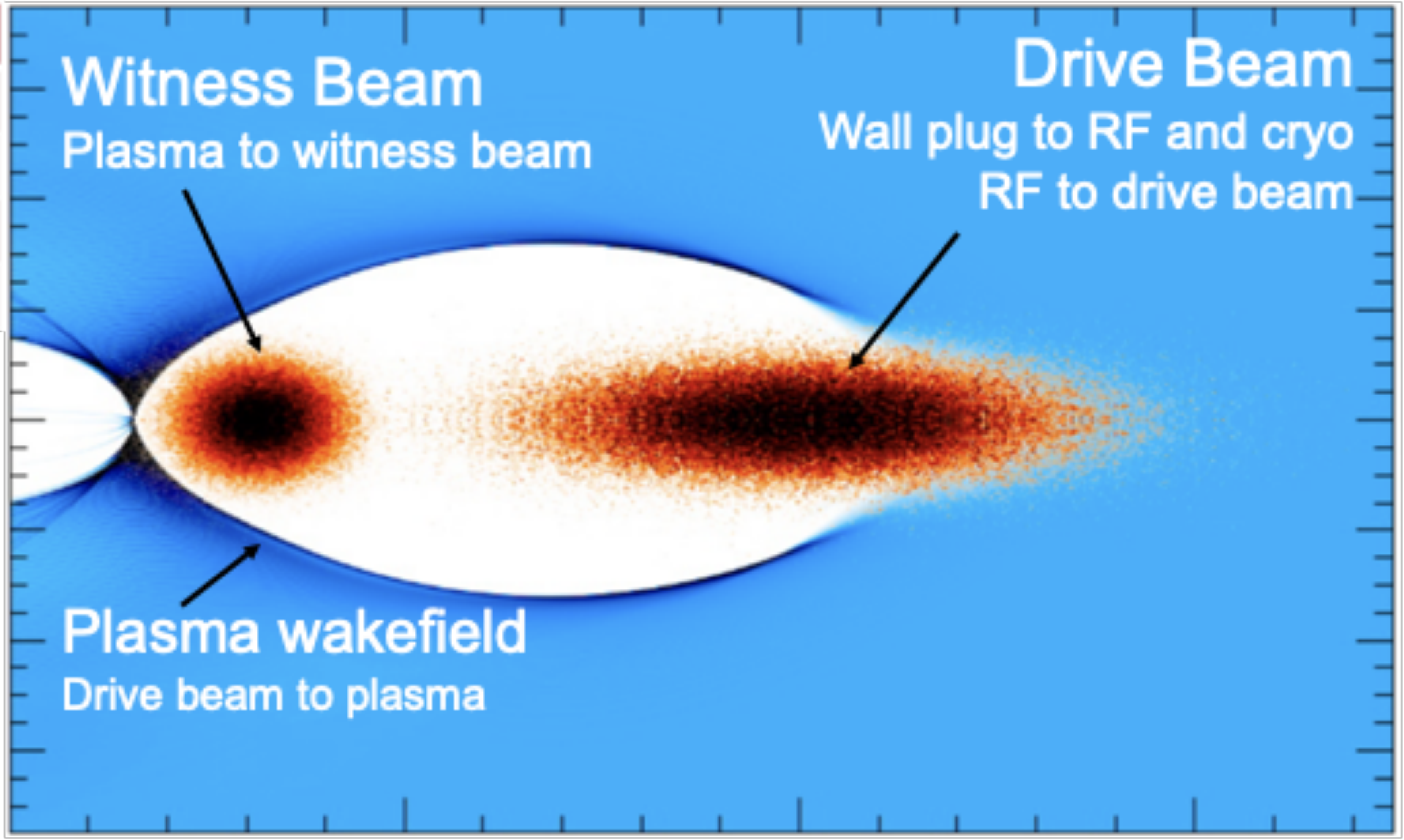
- Beam-driven, laser and structure wakefield accelerators
- Leading contributions to field with FACET-II
- Focus on stability, staging and first WFA facilities (light source?)
- Plasma components - e.g. lenses
- AAC roadmaps indicated a down-select on timescale of Snowmass discuss at (https://indico.fnal.gov/event/44088/)
- Structure WFA at 10s and 100s of GHZ; overlap with experiments and expertise at SLAC

Example LOI: SNOWMASS21-AF1-008.pdf219.03KB2020-06-26 17:47:14

250 GeV CM	MW	Eff.
Wall Plug→Drive	30→12	40%
Drive→Plasma	12→9	75%
Plasma→Witness	9→6	66%
Site Power	133	

10 TeV CM	MW	Eff.
Wall Plug→Drive	205→81	40%
Drive→Plasma	81→61	75%
Plasma→Witness	61→40	66%
Site Power	537	

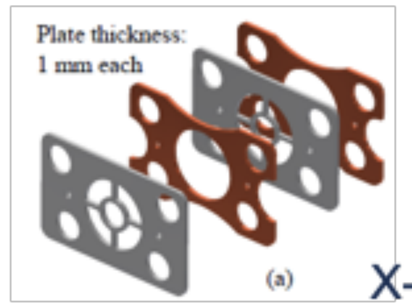
E. Adli *et. al.*, arXiv:1308.1145 [physics.acc-ph]



QuickPIC Simulation, W. An, UCLA

DRIVE BEAM POWER GENERATION

1 GW | >>1 GW



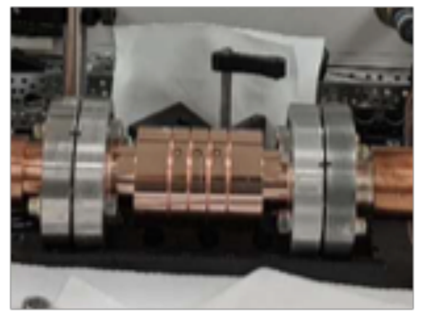
Metamaterial >1 GW

X-band 100-cell MTM

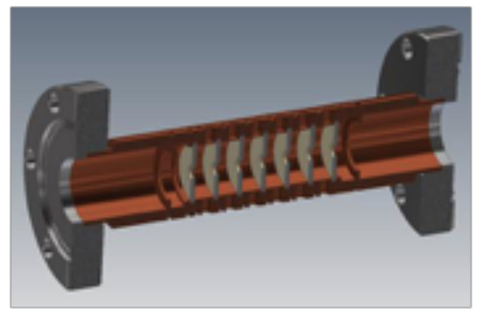
X. Lu, et al. Phys. Rev. Lett. **122**, 014801 (2019)

MAIN BEAM ACCELERATION GRADIENT

267 MeV/m | GeV/m

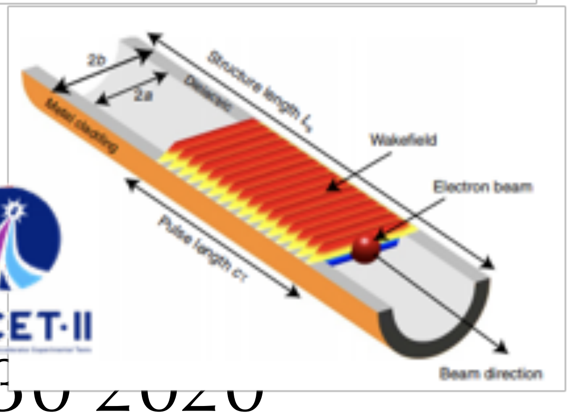


X-band short metallic



K-band DDA

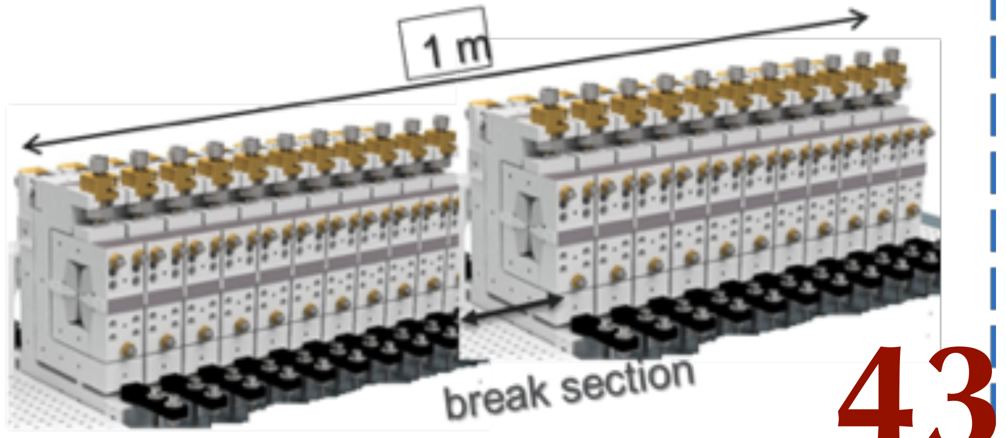
NOVEL RESEARCH



FACET-II

THz Acceleration >1 GV/m

B. O'Shea, et al. Nat. Comm. 7, 12763 (2016)



Collinear Wakefield Acceleration