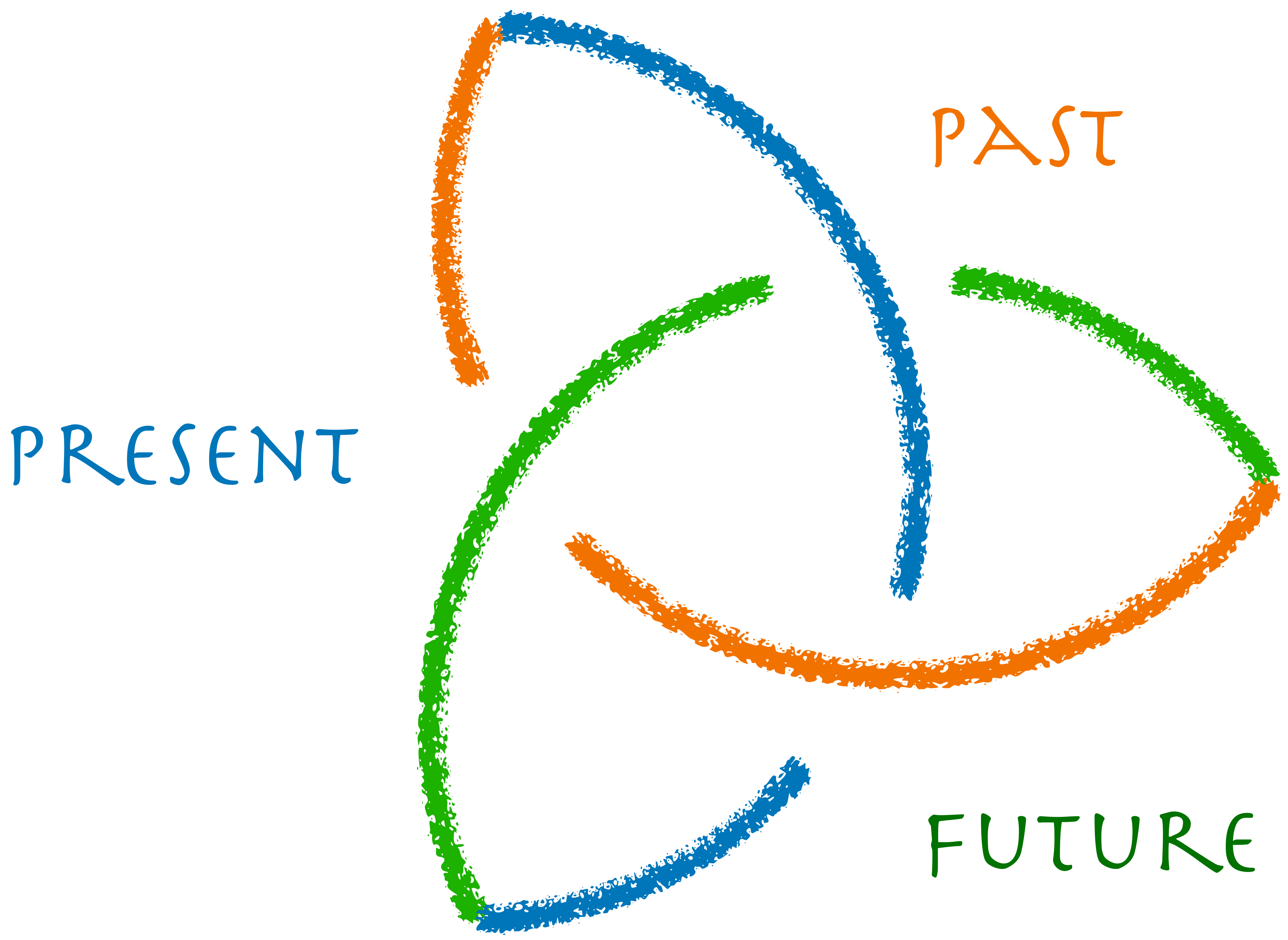
Fisica ai colliders

Fabio Maltoni
Sezione INFN di Bologna
Università di Bologna



Disclaimer

- Fairly representing past and present contributions of the Italian/INFN theory community to 60+ years of collider physics, and discuss the future is a task well beyond speaker's abilities.
- The speaker has just arbitrarily selected a minimal set to allow him to tell a story.
- The result clearly reflects several of the biases and limitations of the speaker.
- Apologies beforehand for mistakes and omissions (any feedback welcome).

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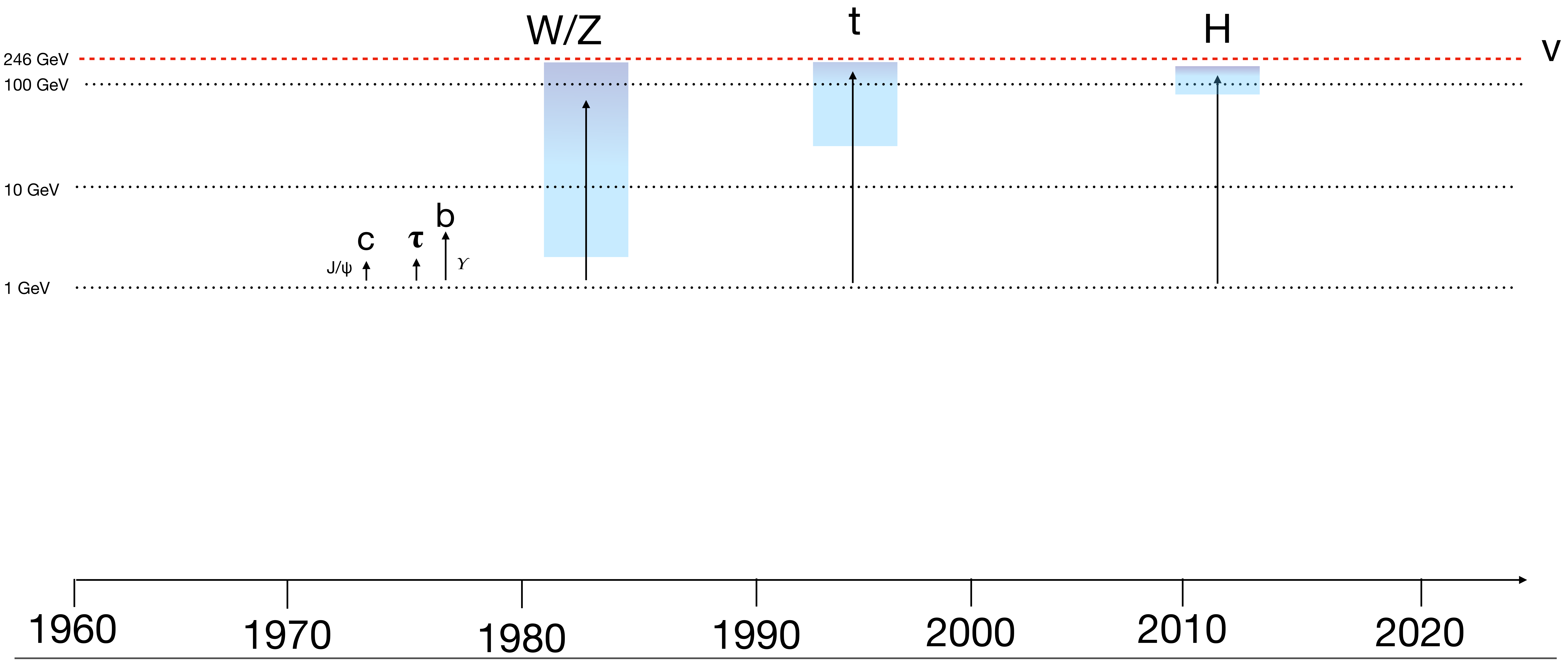
"Based on a true story"

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



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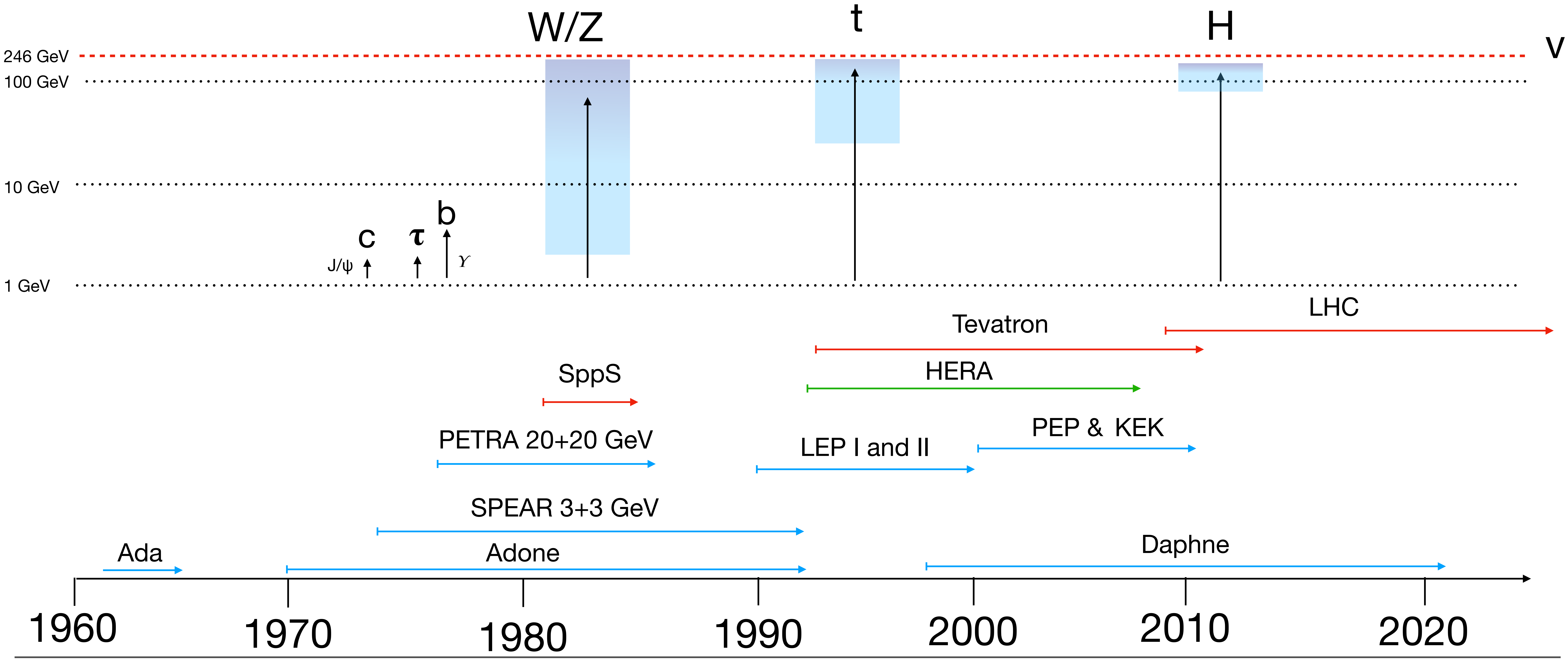
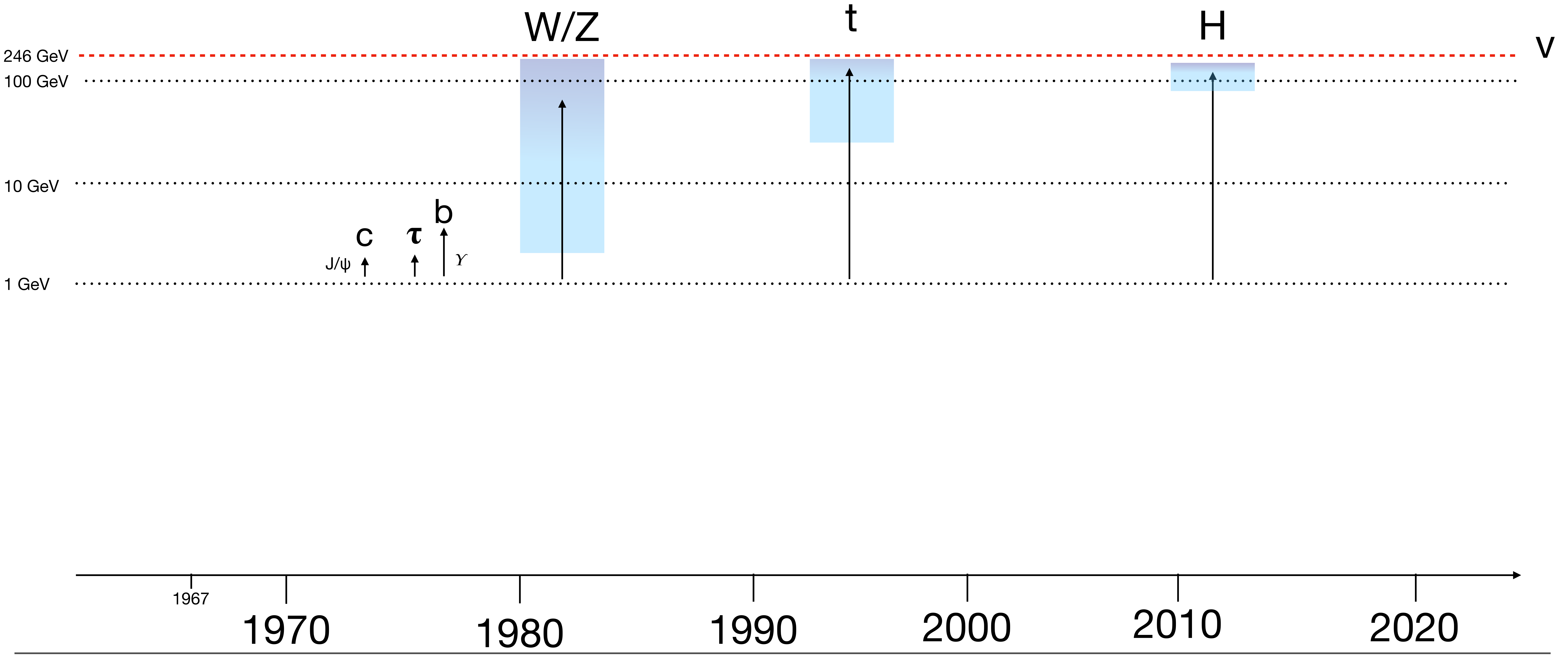


(A) theorist's point of view

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.



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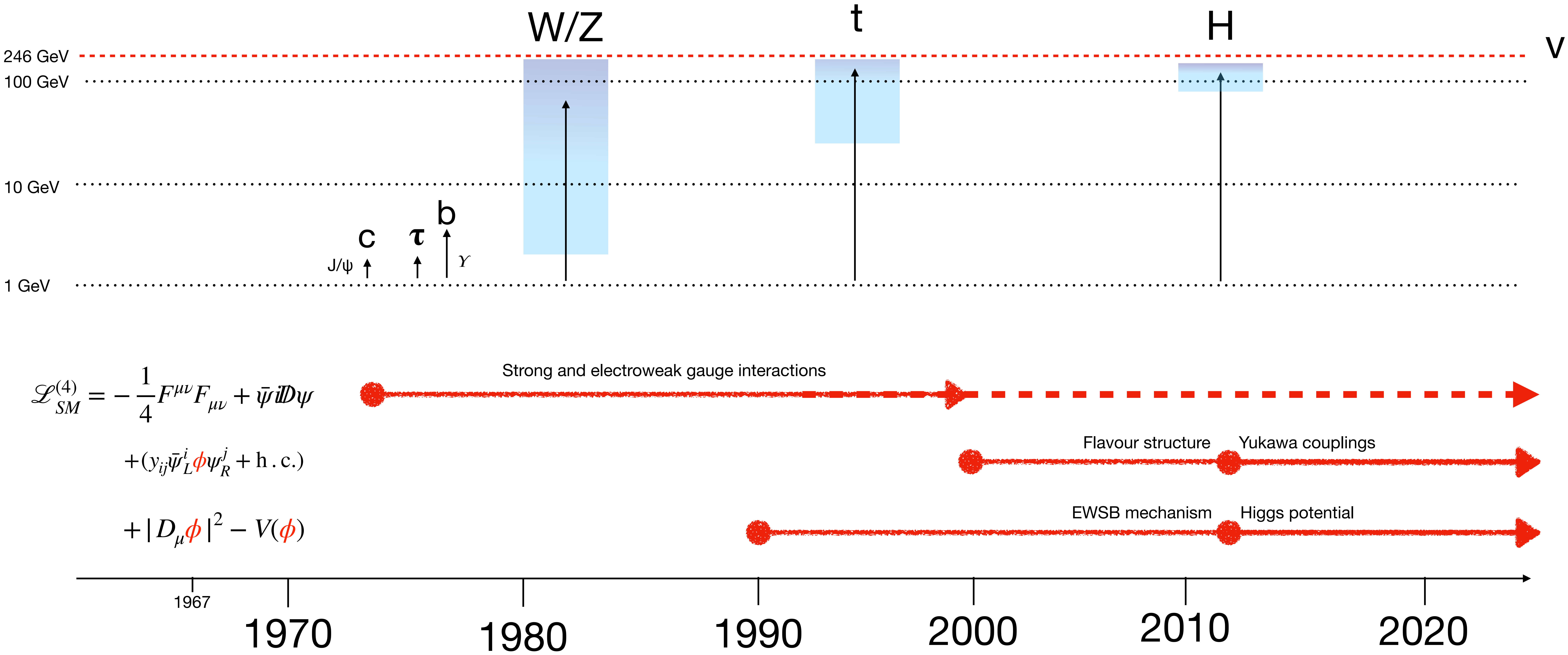
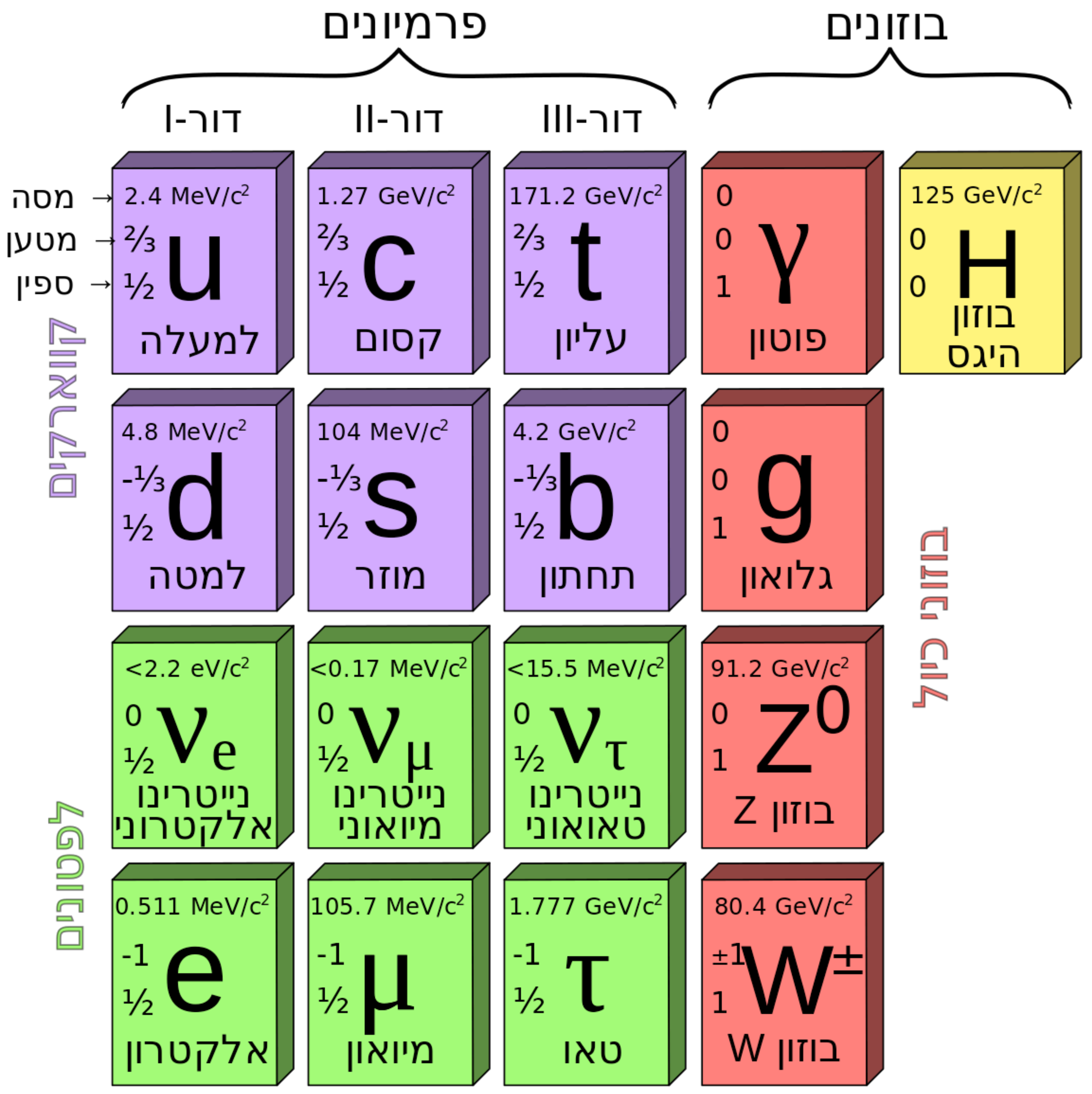


Present

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



- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- A number of accidental symmetries seen in Nature.
- Neutrino masses can be accommodated in two distinct ways.

Present

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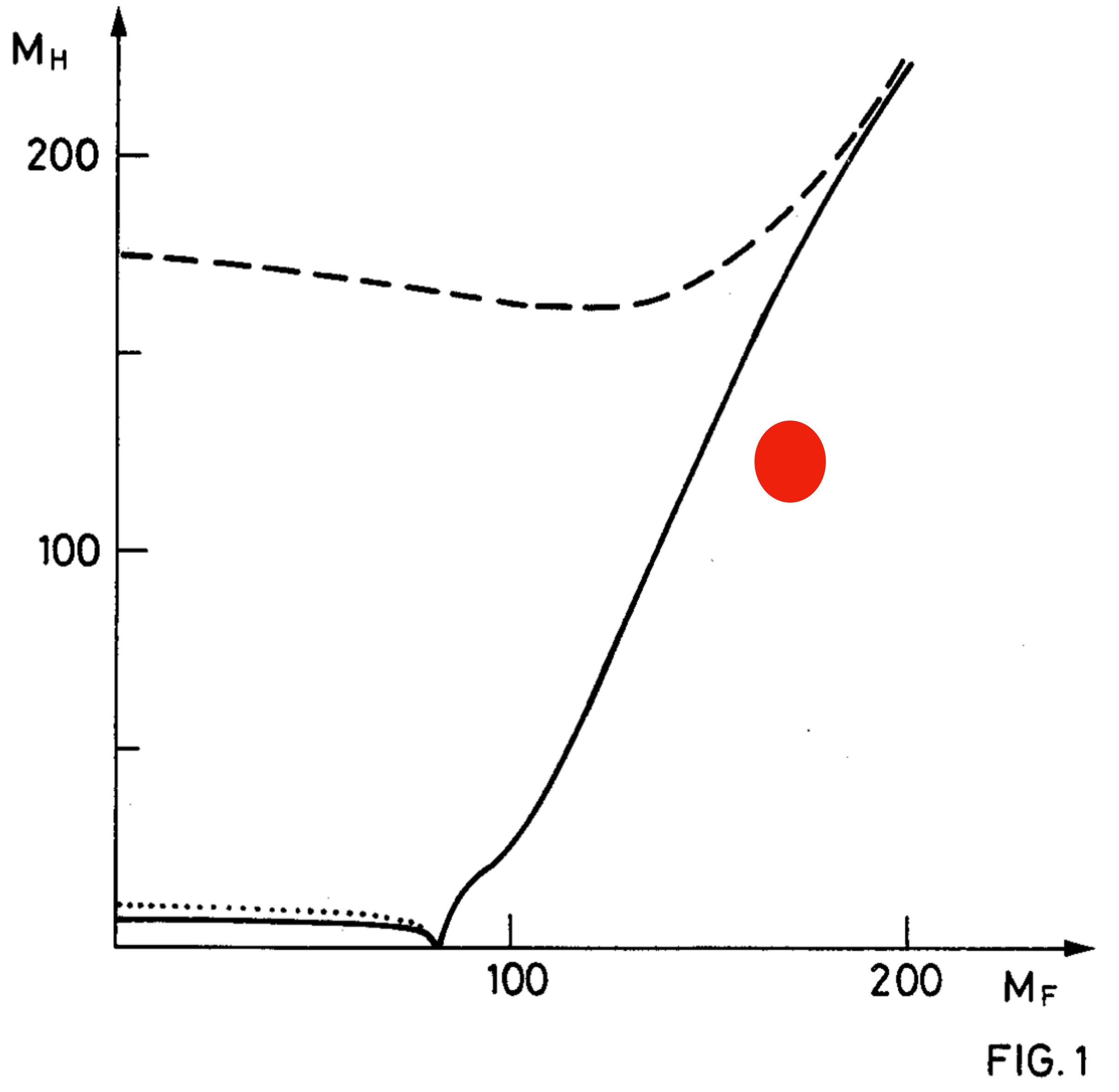
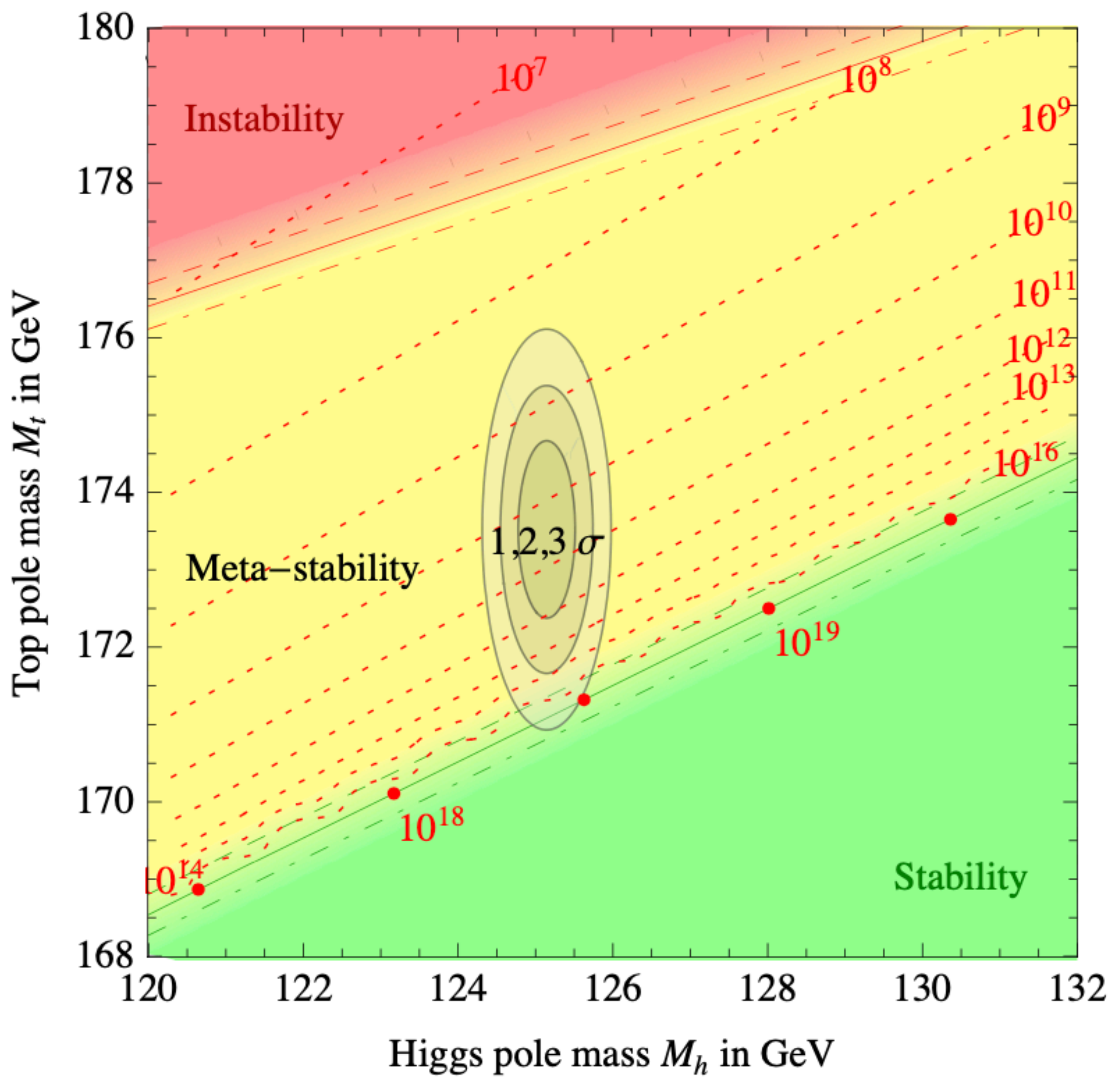
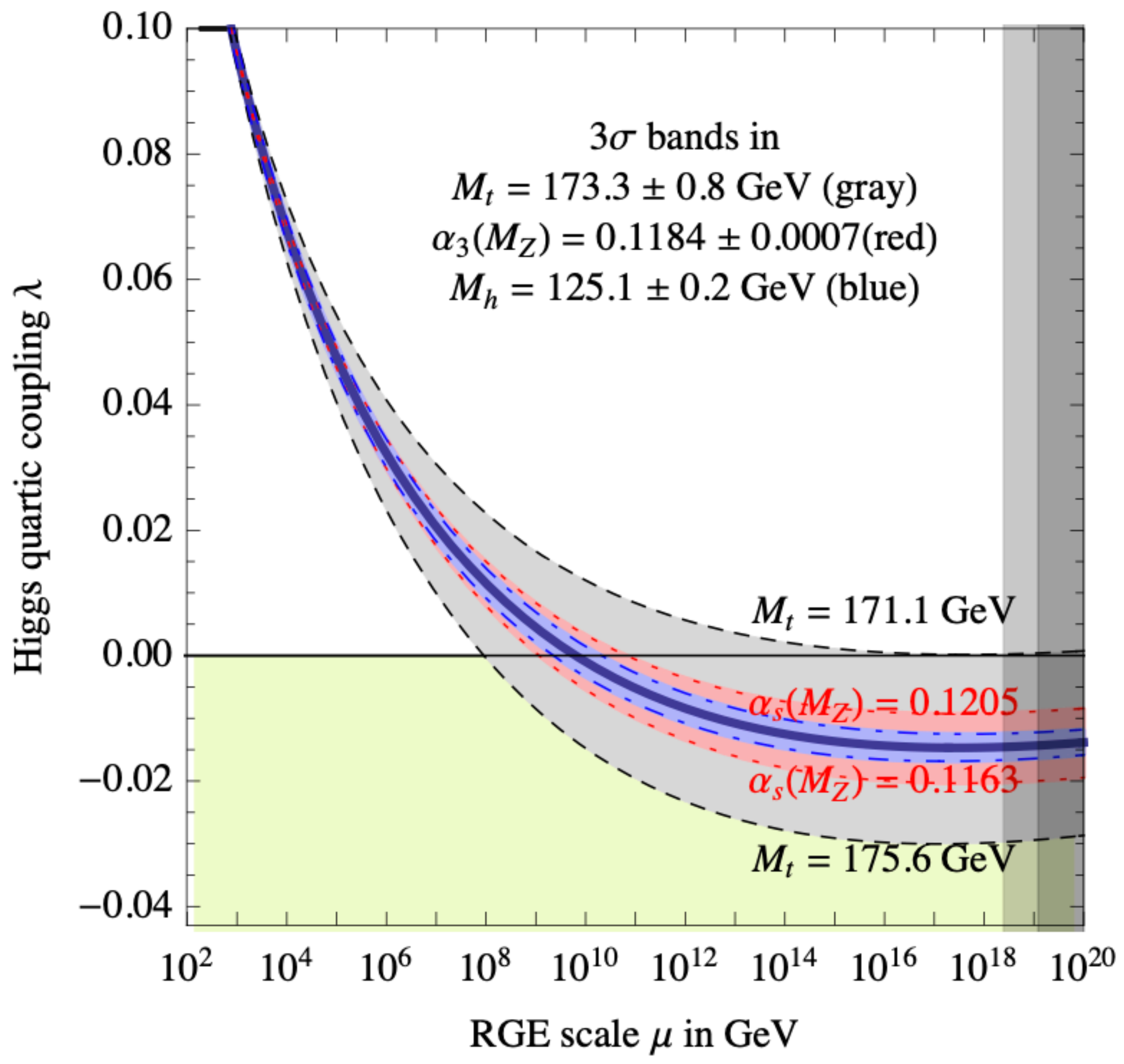


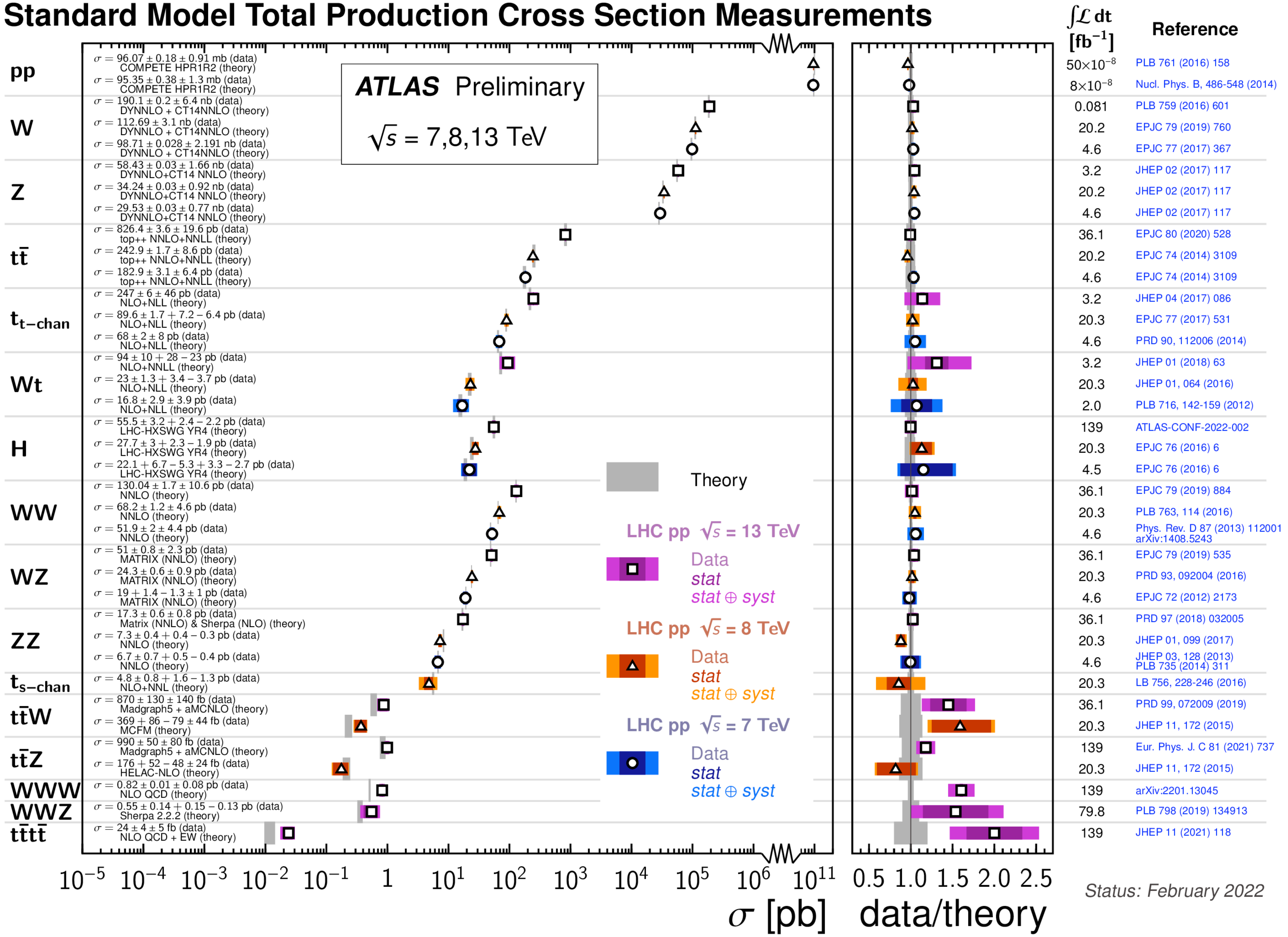
[Cabibbo, Maiani, Parisi, Petronzio, 1979]





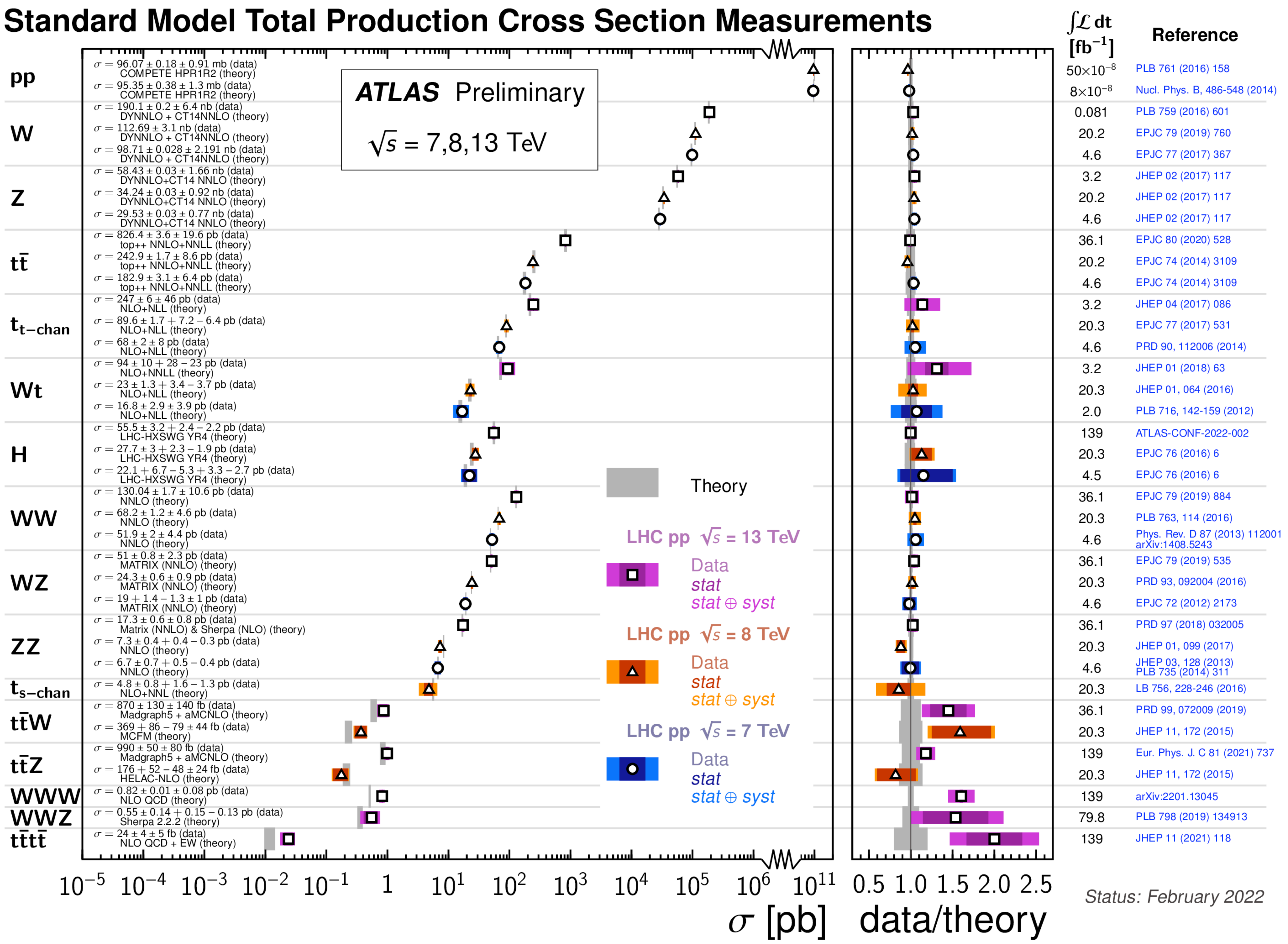
[G. Isidori, G. Ridolfi, A. Strumia, 2001]
[Degrassi, Di Vita, Miro, Espinosa, G. Giudice, 2012]
[D. Buttazzo, G. Degrassi, PP Giardino, G. Giudice, F. Sala, A. Salvio, A. Strumia 2013]
[Devoto, Devoto, Di Luzio, Ridolfi, 2022]

Present



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- So many processes test very different sectors of the SM.

Present



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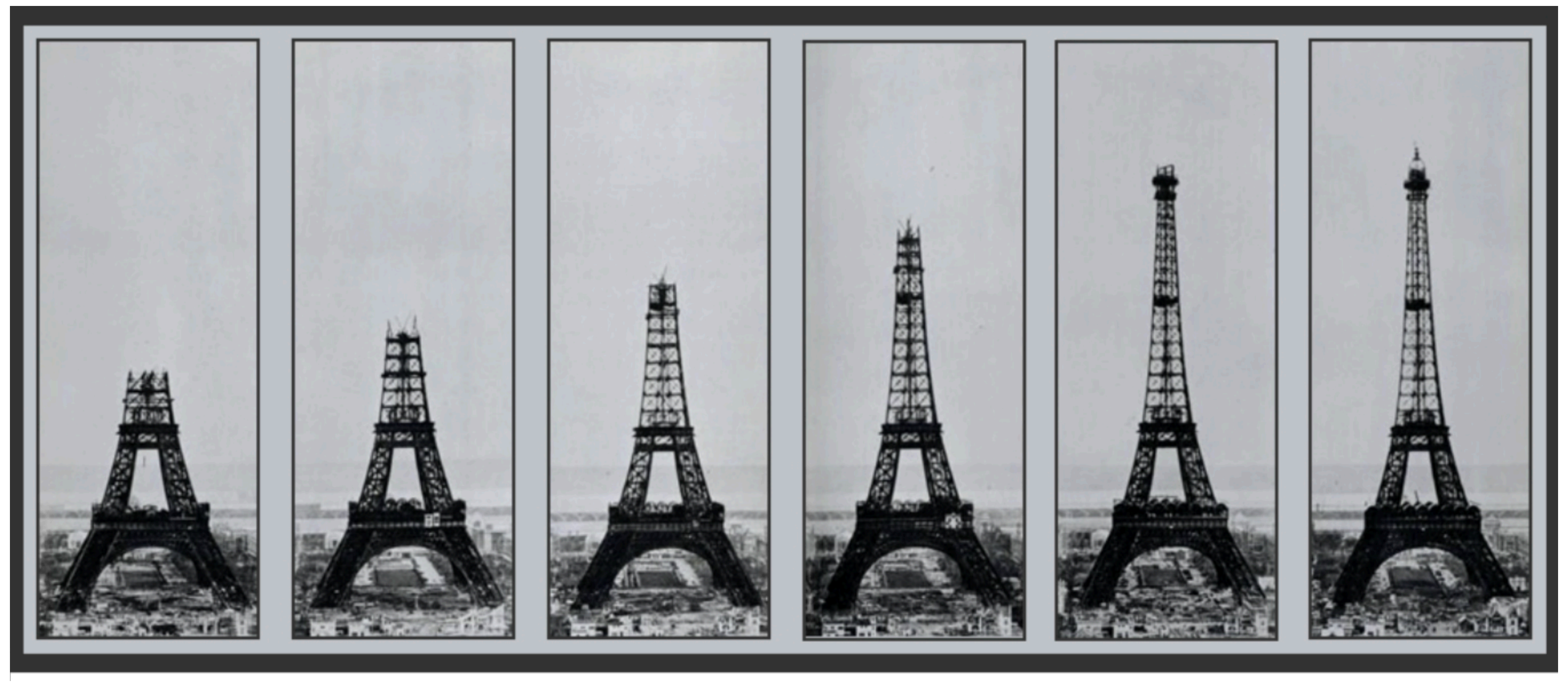

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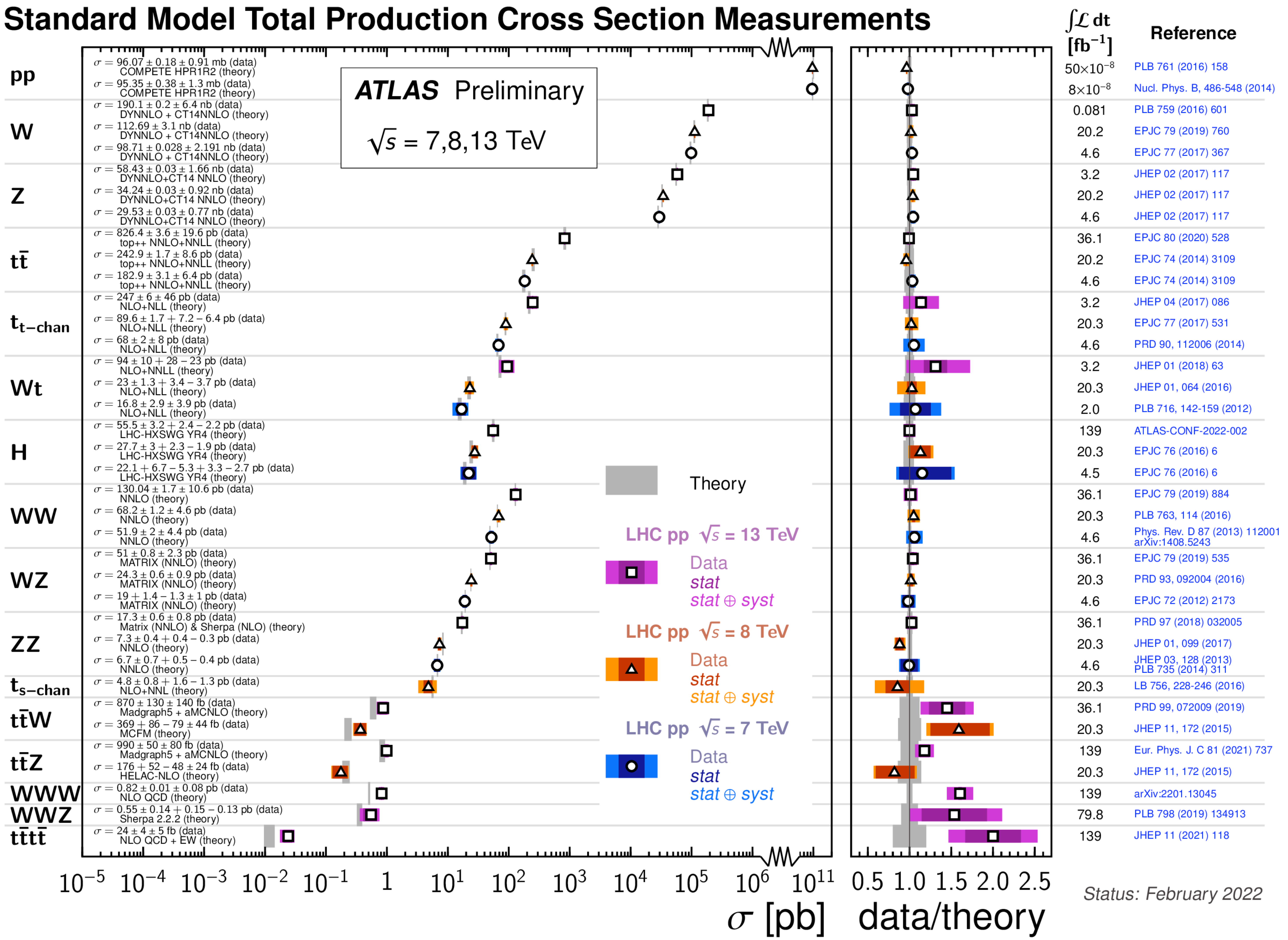

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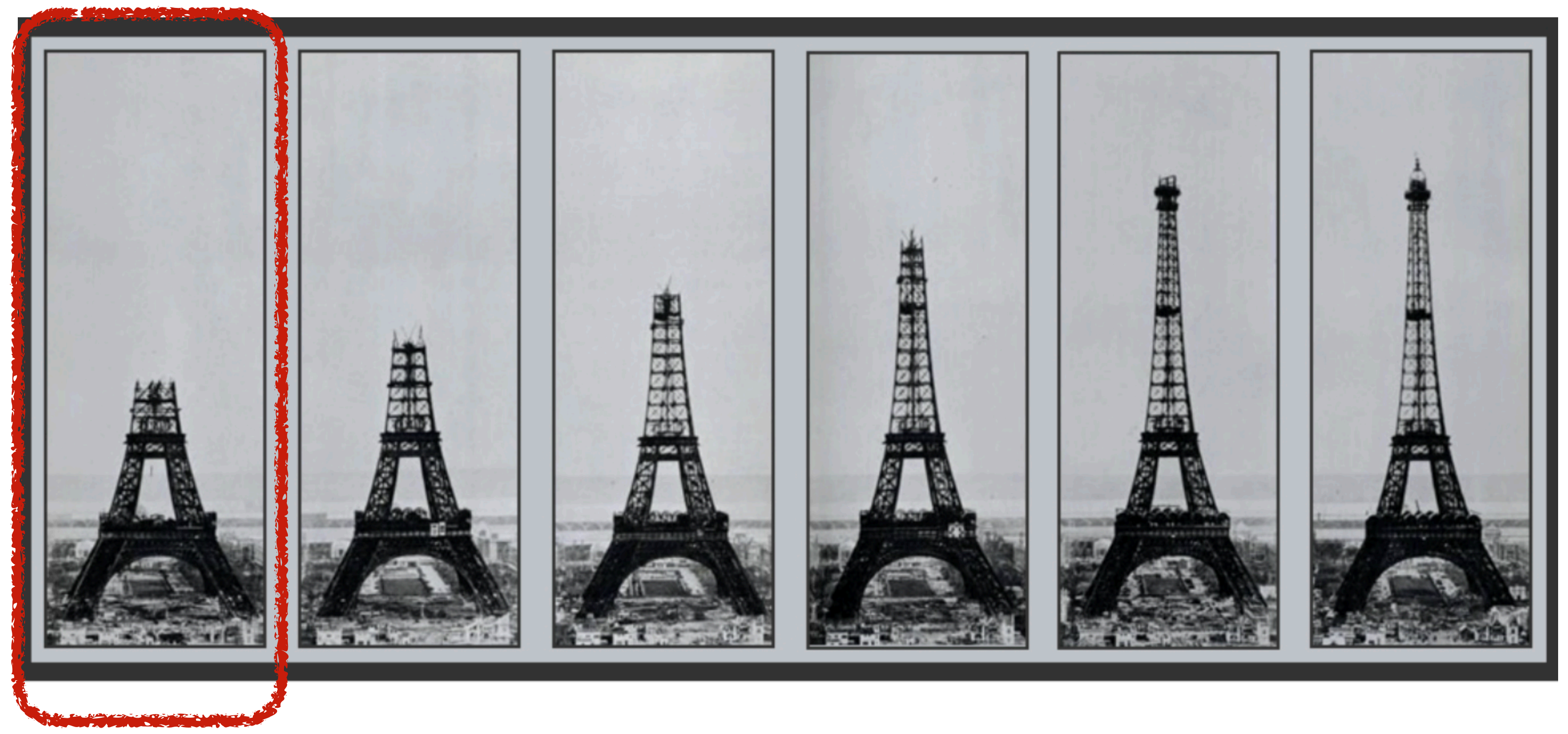
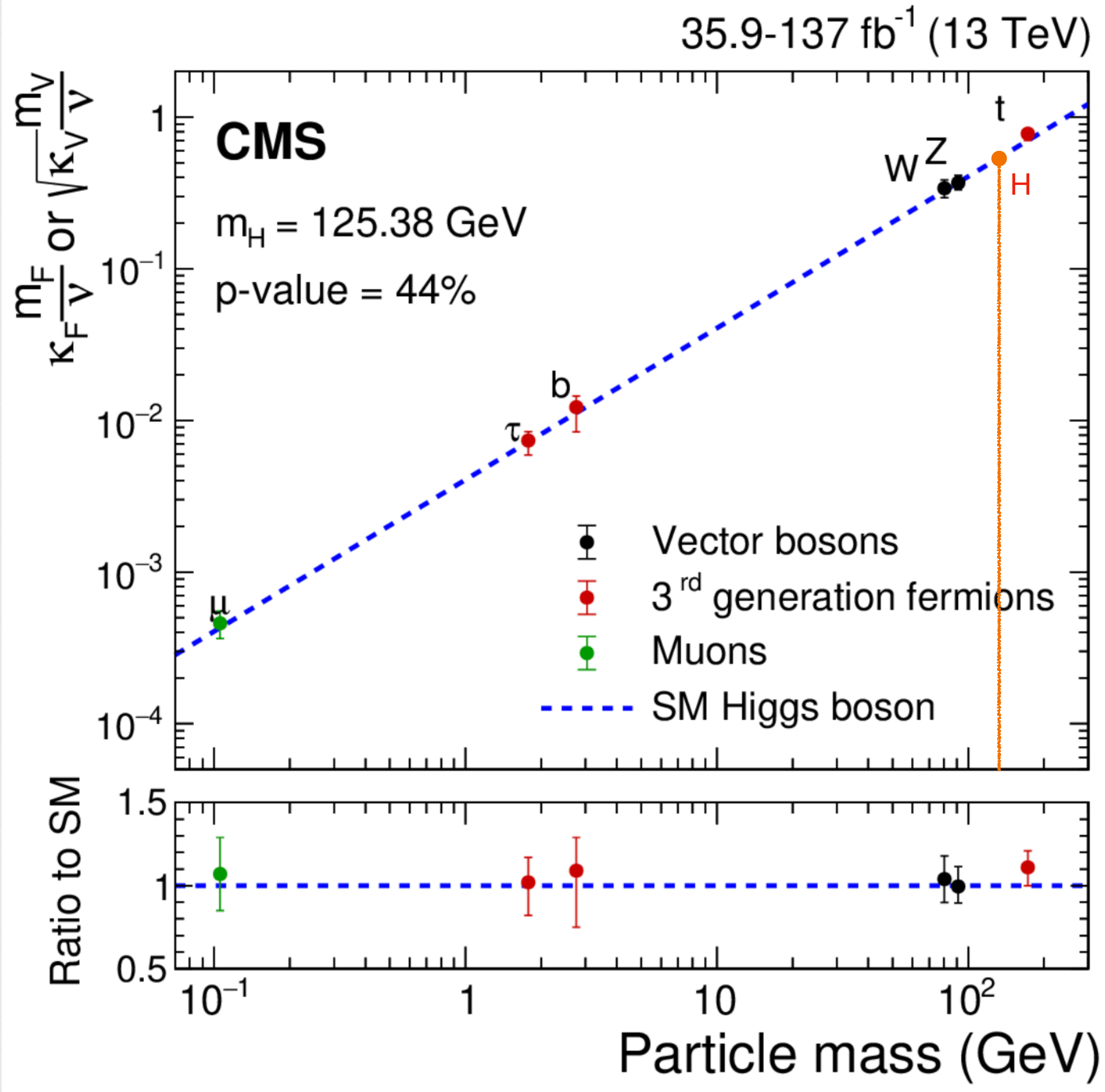
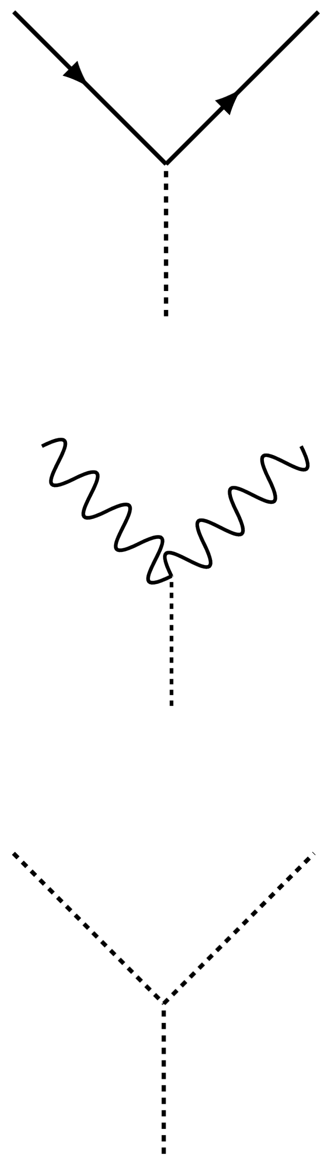


Present

Higgs couplings



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



$$i\, m_f/v$$

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

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

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

+ 4 point interactions.

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

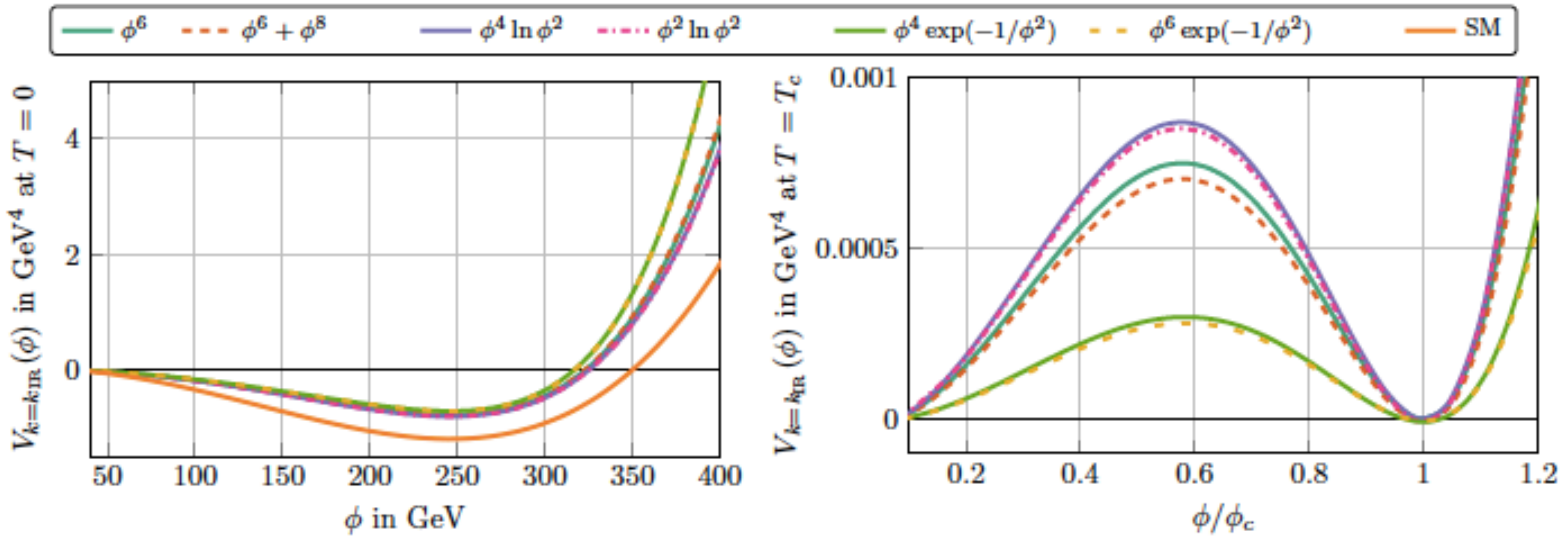
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

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

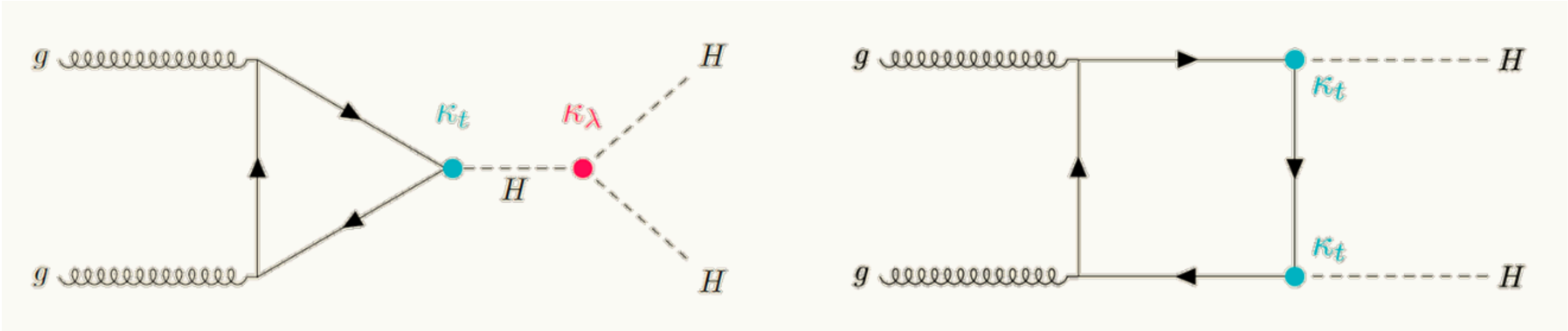
Present

Higgs potential

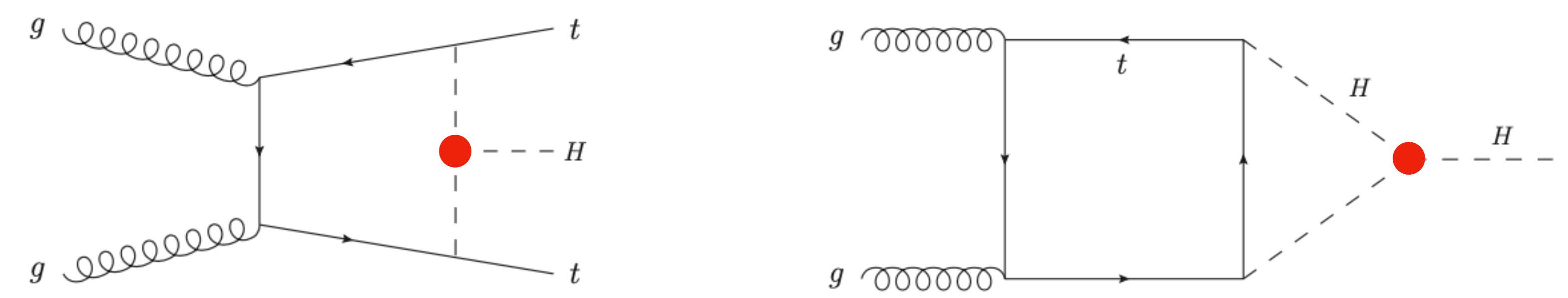
The experimental value for m_H gives a second order phase transition. Increasing λ_3 makes it first.



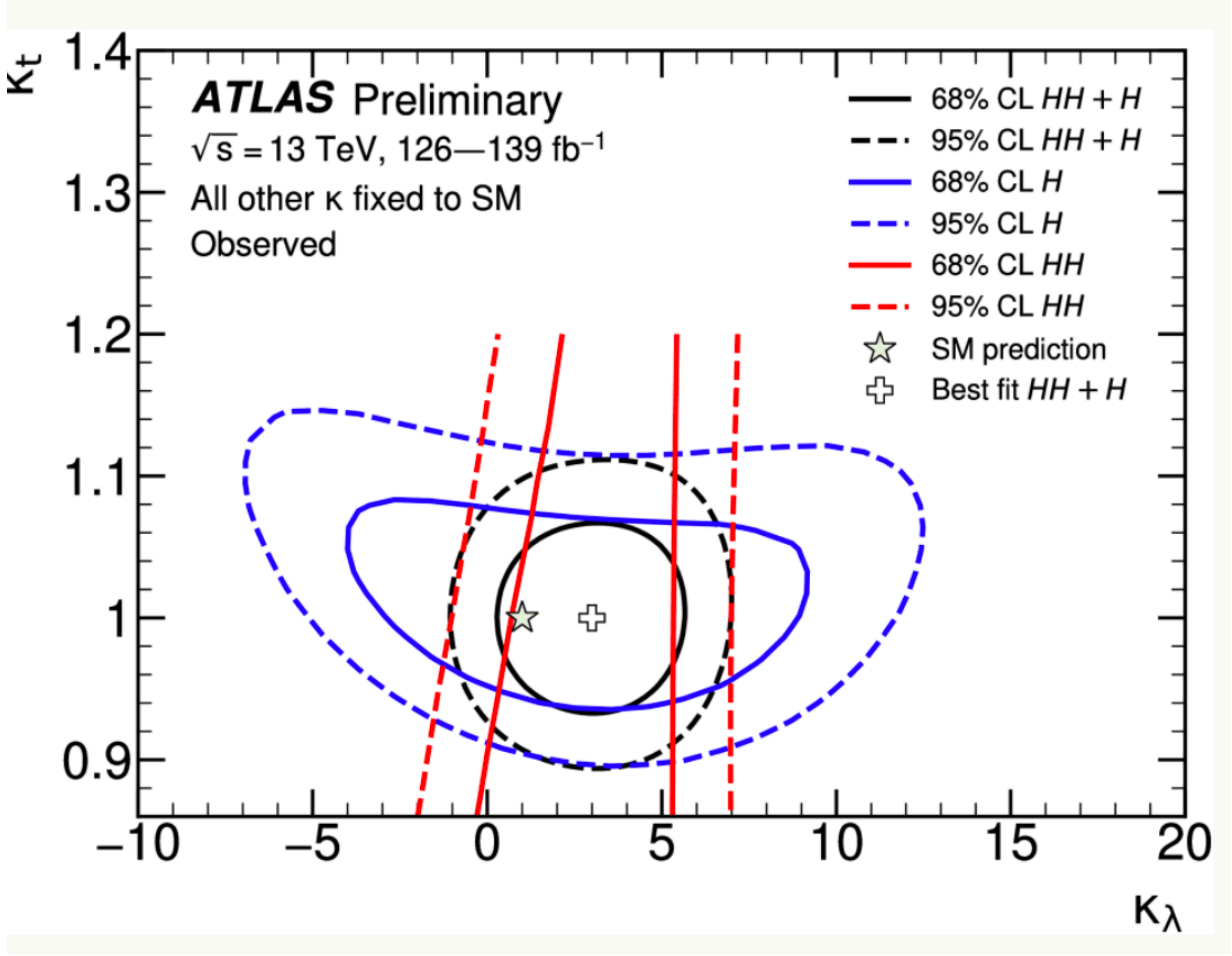
Reichert et al. 1711.00019



"Direct"



"Indirect"



Combining information from the direct search and from the indirect single Higgs production at one-loop one can maximise the constraints.[G. Degrassi, PP Giardino, FM, D. Pagani, 2016]

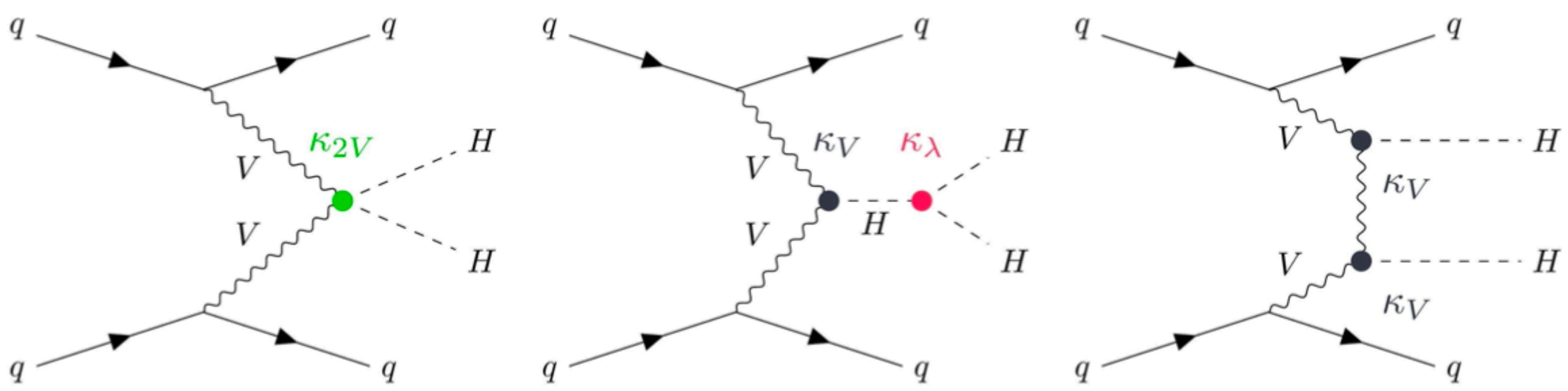
Present

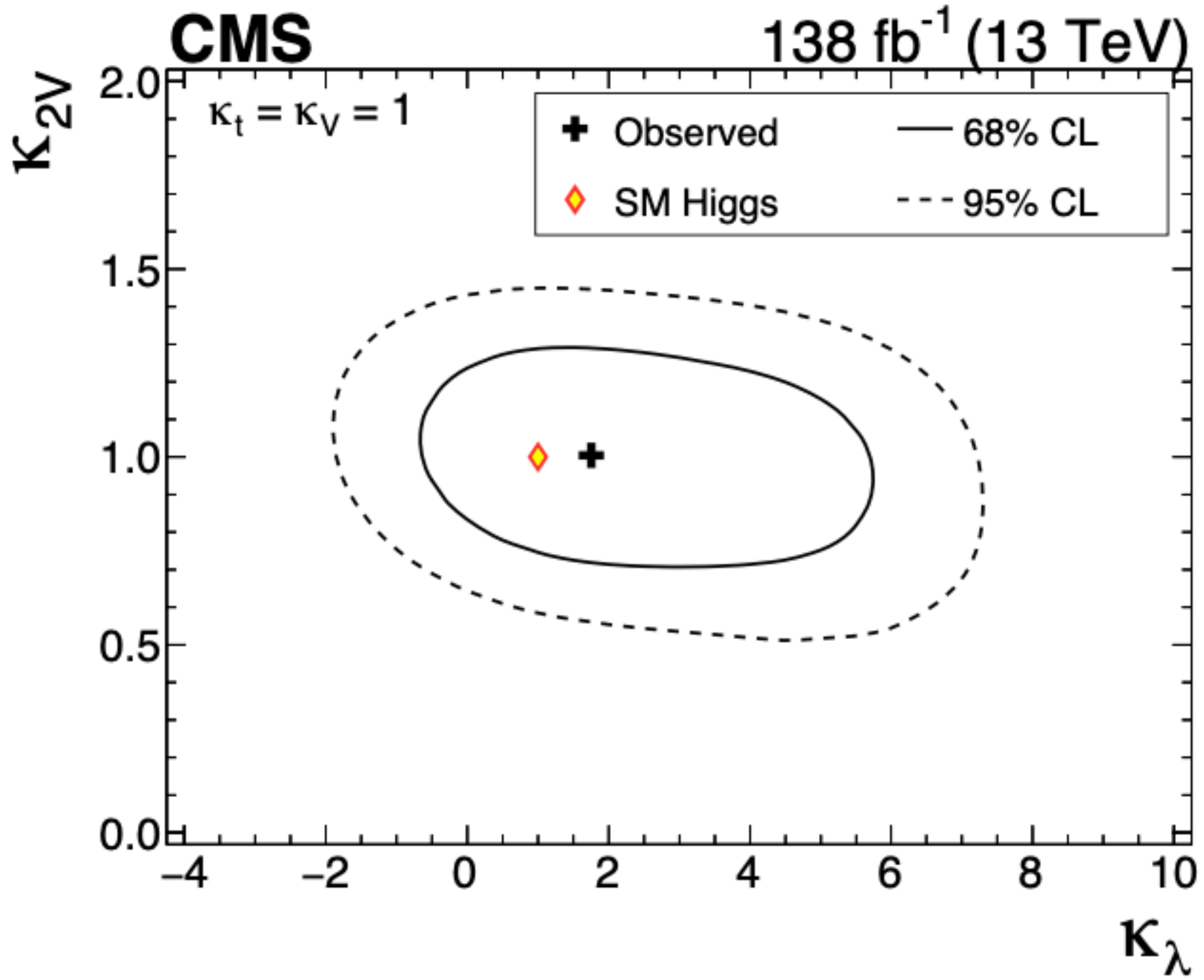
Unlocking the SM

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

$$\mathscr{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

Seagull vertex of scalar SU(2) or $(\phi^\dagger.\phi)^2$

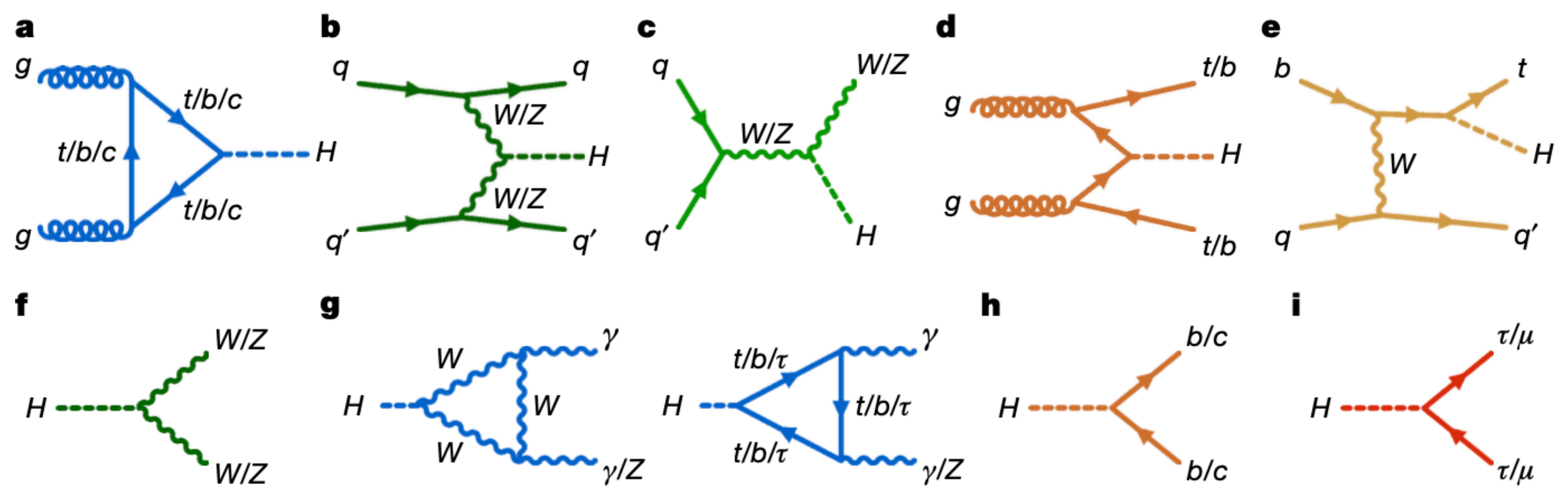


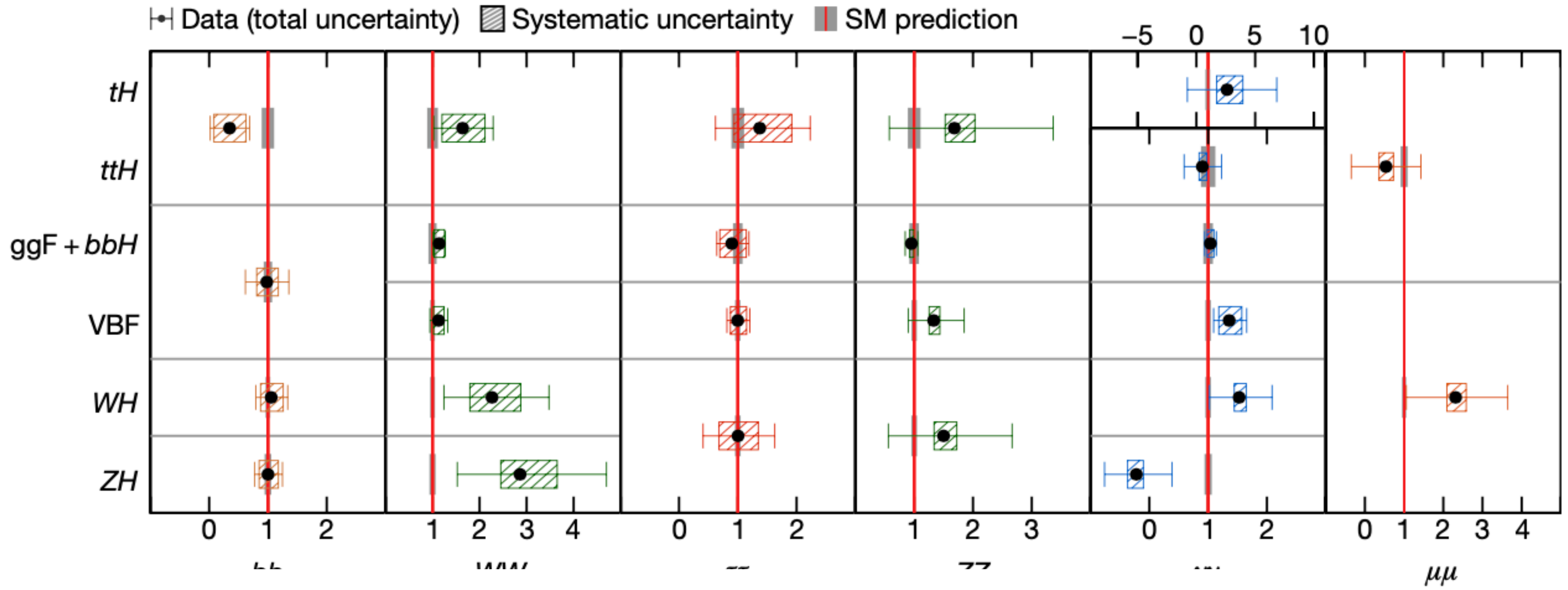


- $k_{2V} \leq 0$ excluded with 6.6σ assuming otherwise SM couplings

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.

How did we get here?

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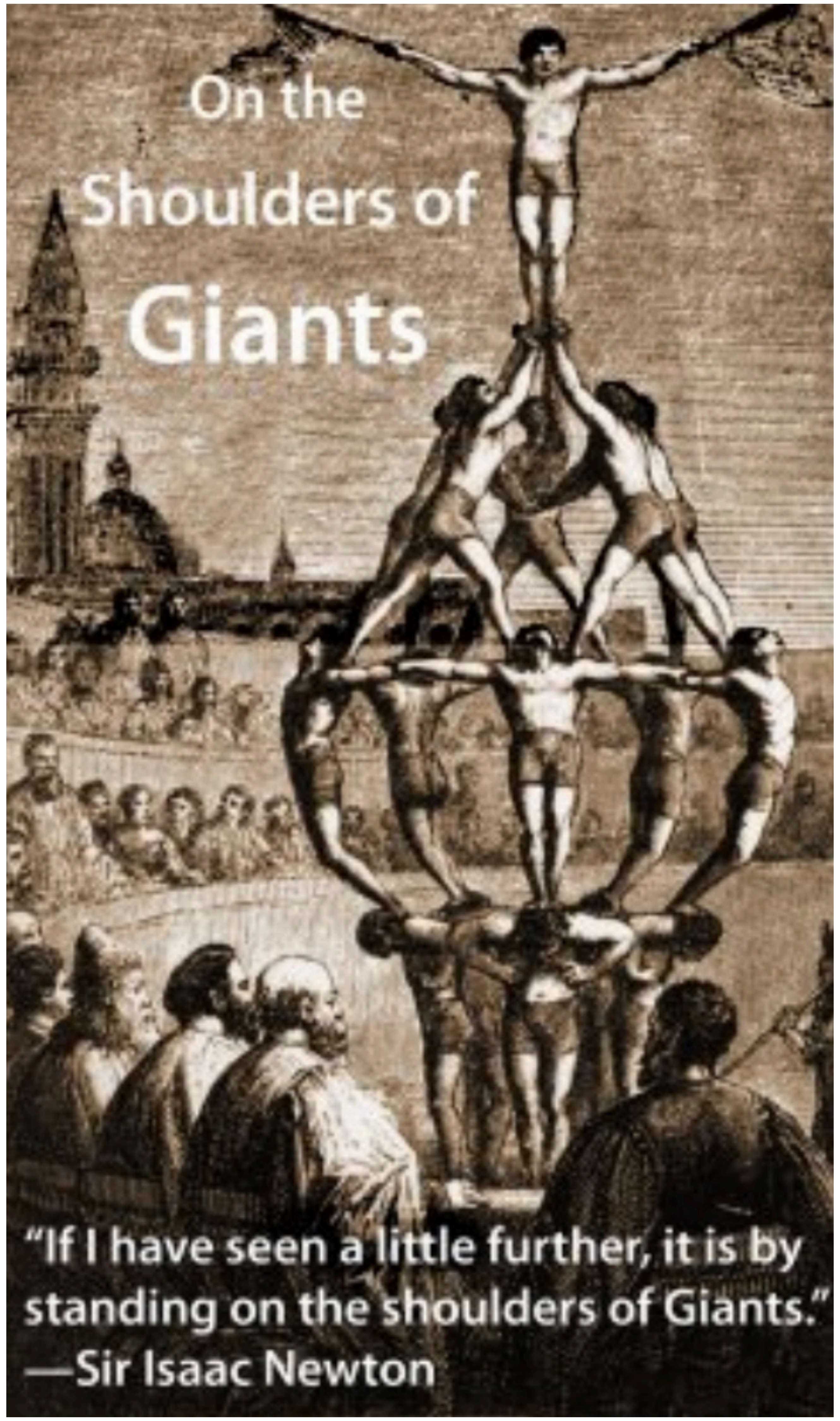

PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

Electron-Positron Colliding Beam Experiments

N. Cabibbo and R. Gatto
Istituti di Fisica delle Università di Roma e di Cagliari, Italy and
Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy

(Received June 8, 1961)

Possible experiments with high-energy colliding beams of electrons and positrons are discussed. The role of the proposed two-pion resonance and of the three-pion resonance or bound state is investigated in connection with electron-positron annihilation into pions. The existence of a three-pion bound state would give rise to a very large cross section for annihilation into $\pi^0+\gamma$. A discussion of the possible resonances is given based on consideration of the relevant widths as compared to the experimental energy resolution. Annihilation into baryon-antibaryon pairs is investigated and polarization effects arising from the nonreal character of the form factors on the absorptive cut are examined. The density matrix for annihilation into pairs of vector mesons is calculated. A discussion of the limits from unitarity to the annihilation cross sections is given for processes going through the one-photon channel. The cross section for annihilation into pairs of spin-one mesons is rather large. The typical angular correlations at the vector-meson decay are discussed.

A neutral weakly interacting vector meson would give rise to a strong resonant peak if it is coupled with lepton pairs. Effects of the local weak interactions are also examined. The explicit relation between the e^2 corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

[2] F. Amman, C. Bernardini, R. Gatto, G. Ghigo, and B. Touschek (unpublished). A smaller storage ring for electrons and positrons for maximum energy of 250 Mev is already at an advanced state of construction; see C. Bernardini, G. F. Corazza, G. Ghigo, and B. Touschek, Nuovo cimento **18**, 1293 (1960).

[3] Electron-positron colliding beams are also being considered at CalTech, Cornell, and Paris.

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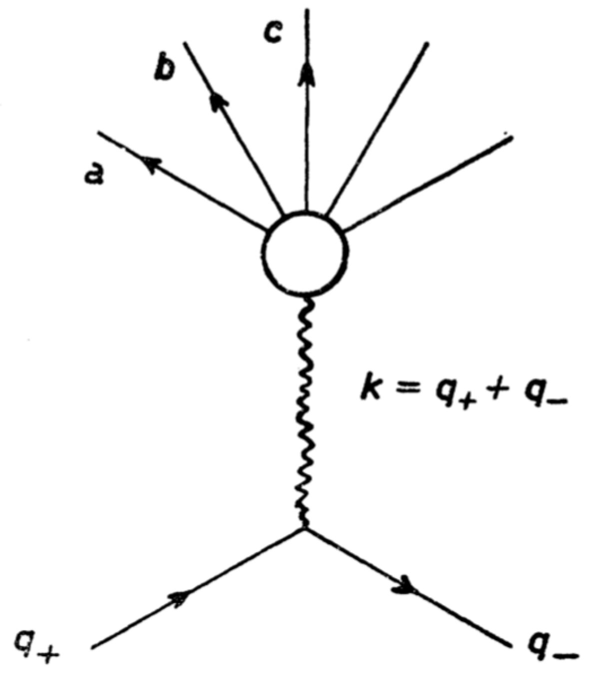

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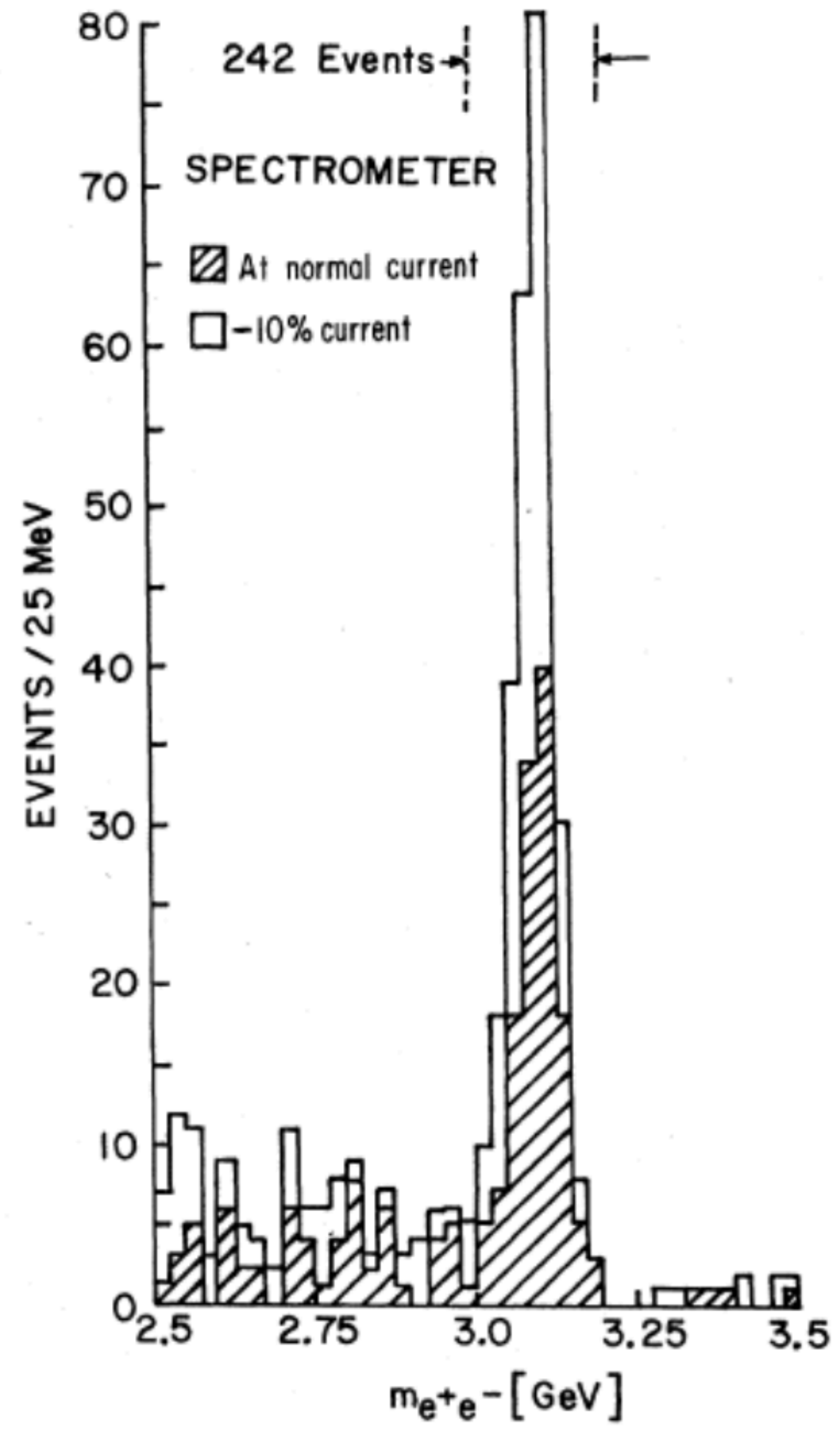
13 years later



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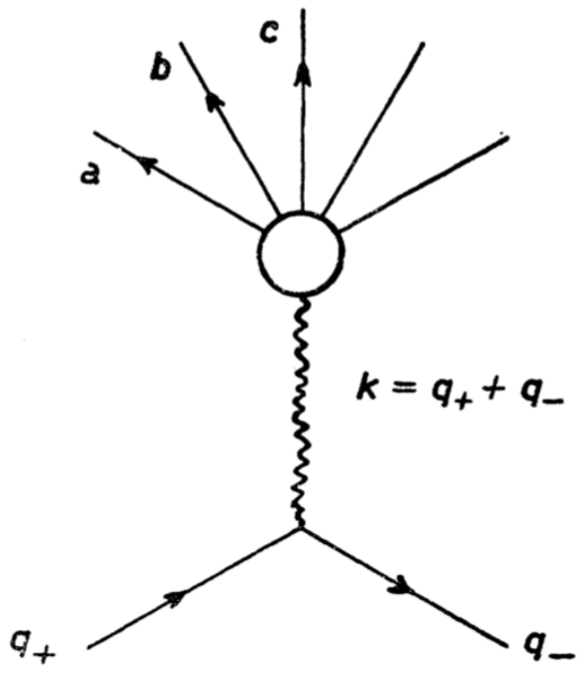


Unitary Symmetry and Leptonic Decays

Nicola Cabibbo (CERN) (Jun, 1963)

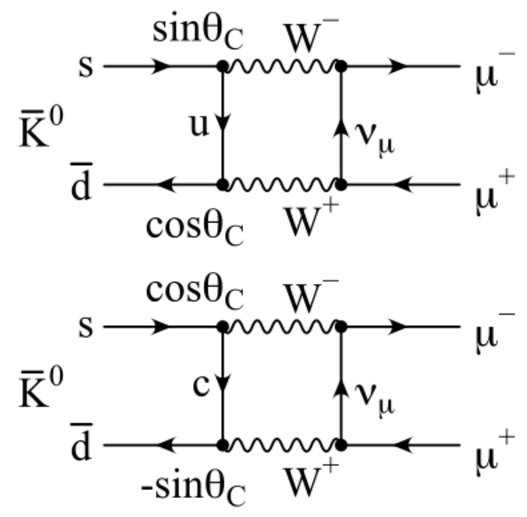
Published in: *Phys.Rev.Lett.* 10 (1963) 531-533 •

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

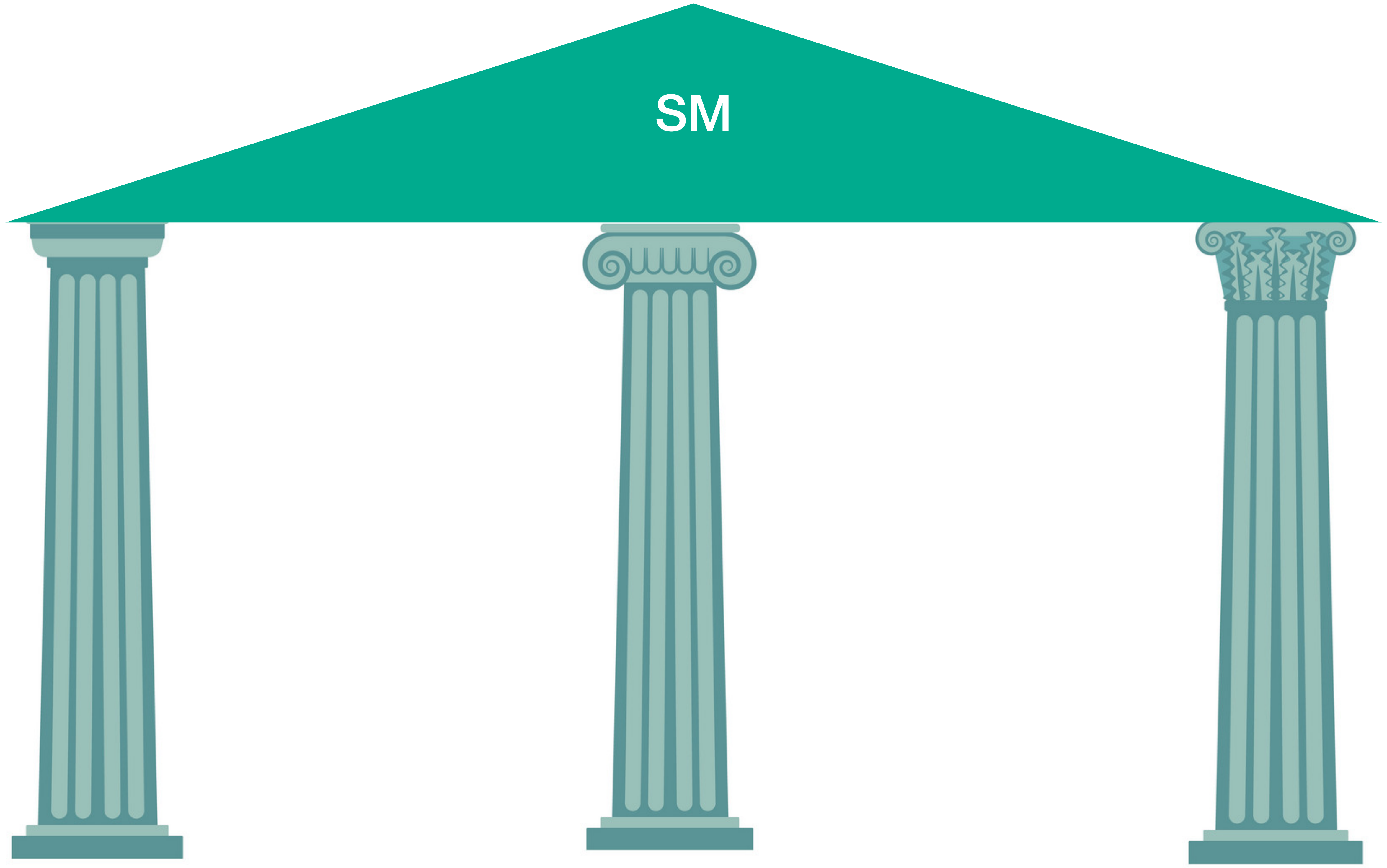
Weak Interactions with Lepton-Hadron Symmetry

S.L. Glashow (Harvard U.), J. Iliopoulos (Harvard U.), L. Maiani

Published in: *Phys.Rev.D* 2 (1970) 1285-1292



A model for EW interactions



BEH
1964

Weinberg
1967

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IL NUOVO CIMENTO VOL. XXIV, N. 1 1° Aprile 1962

Proton-Antiproton Annihilation into Electrons, Muons and Vector Bosons.

A. ZICHICHI and S. M. BERMAN (*)

CERN - Geneva

N. CABIBBO and R. GATTO

Università degli Studi - Roma e Cagliari
Laboratori Nazionali di Frascati del CNEN - Roma

(ricevuto il 20 Gennaio 1962)

Summary. — The possibility of achieving relatively high intensity antiproton beams has prompted some considerations on the rather rare annihilation channels of the proton-antiproton system. We propose i) to study the two-electron mode as a means of investigating the electromagnetic structure of the proton for time like momentum transfers; ii) to study the two-muon mode and compare with the two-electron mode to investigate whether the muon behaves like a heavy electron for large time like momentum transfers; iii) to investigate the existence of weak vector bosons by the modes $p+\bar{p}\to B+\bar{B}$ and $p+\bar{p}\to B+\pi$. Although no precise theoretical predictions can be made, crude estimates indicate that the cross-section for these four channels could be roughly of the same order of magnitude.

IL NUOVO CIMENTO VOL. XXIV, N. 1 1° Aprile 1962

Discovery of the W and Z

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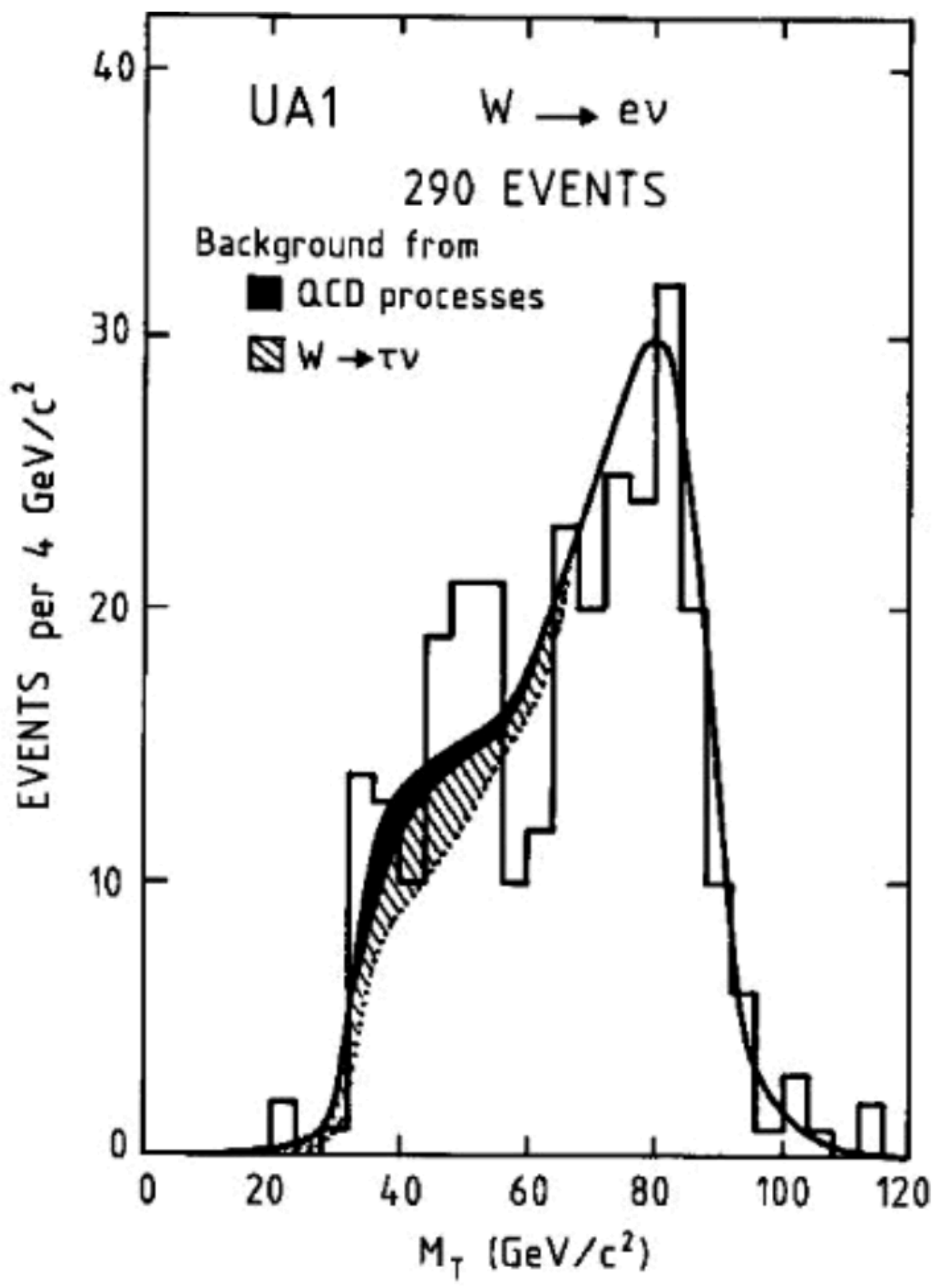
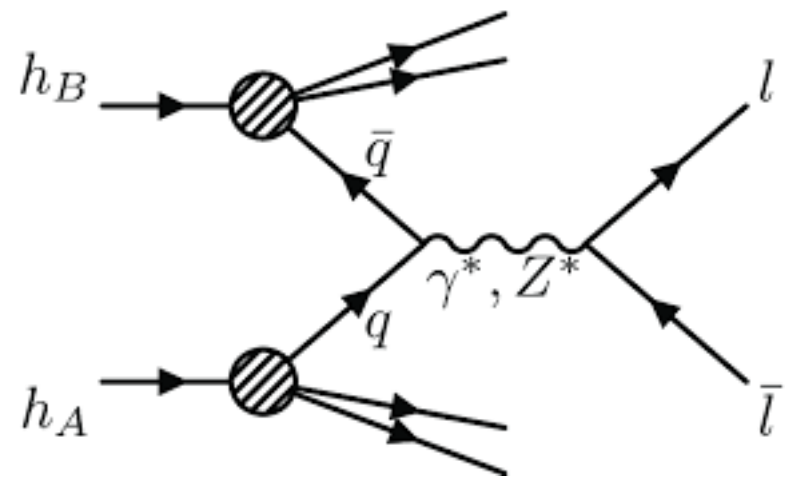
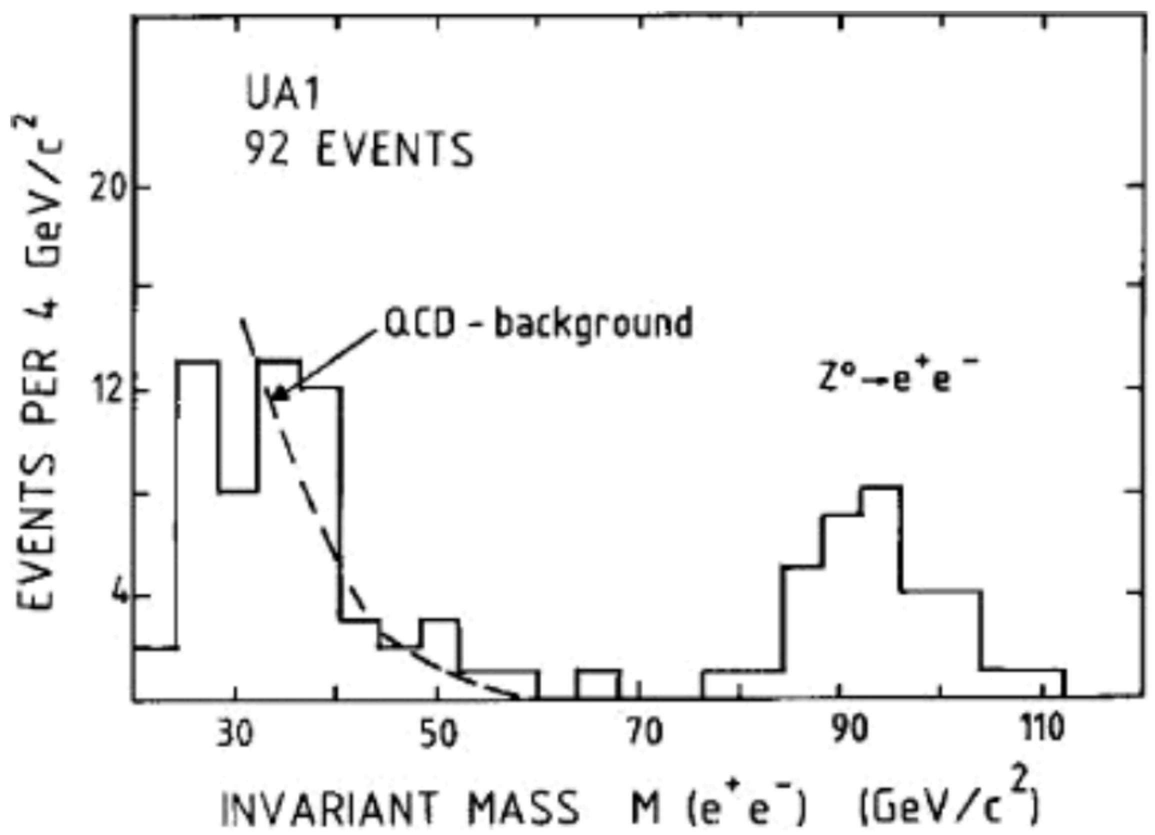
20 years later







pp collider

Leptoproduction and Drell-Yan Processes Beyond the Leading Approximation in Chromodynamics

Guido Altarelli (Rome U. and INFN, Rome), R.Keith Ellis (MIT, LNS), G. Martinelli (Frascati) (Jun, 1978)

Published in: *Nucl.Phys.B* 143 (1978) 521, *Nucl.Phys.B* 146 (1978) 544 (erratum)

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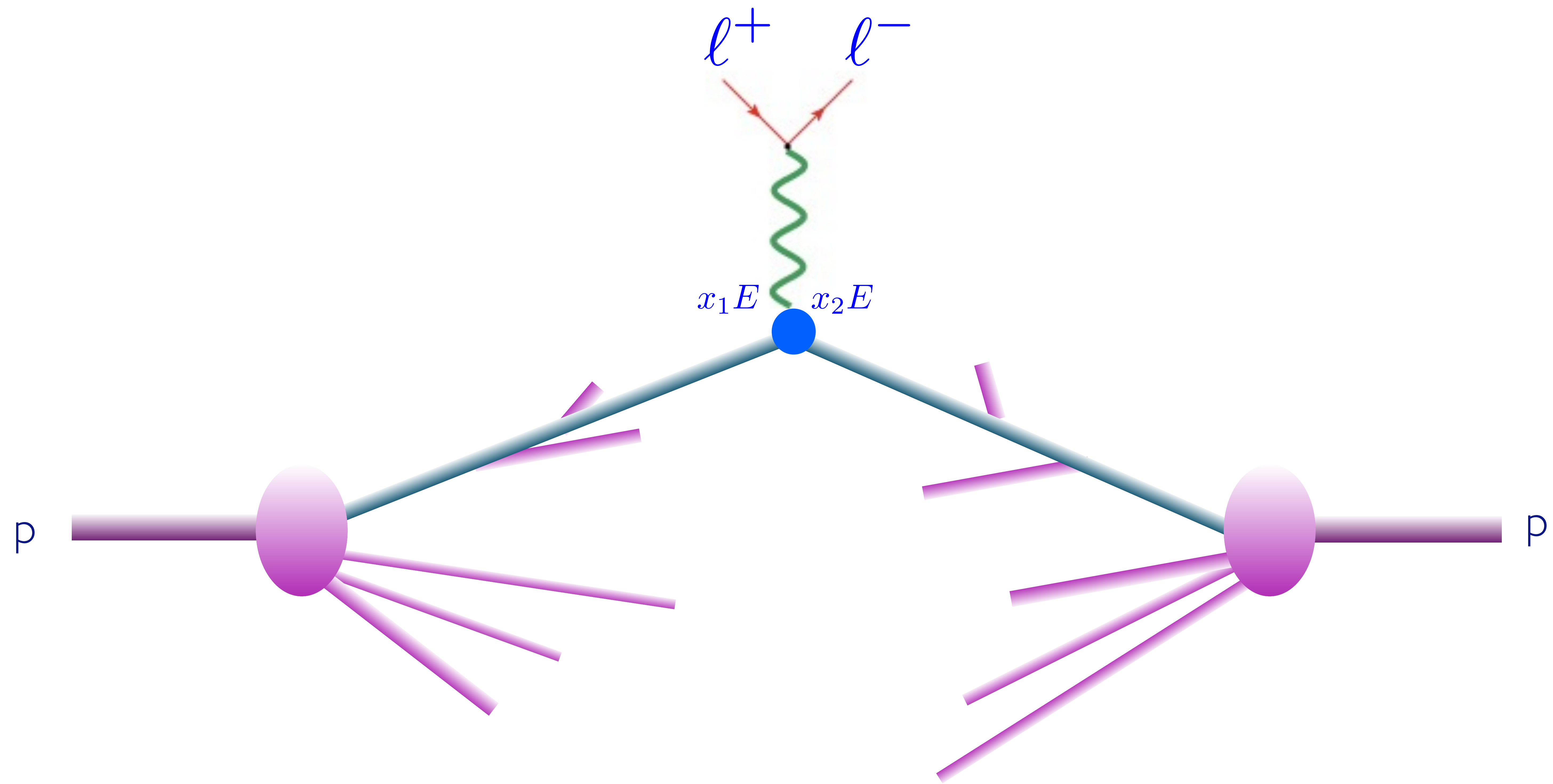

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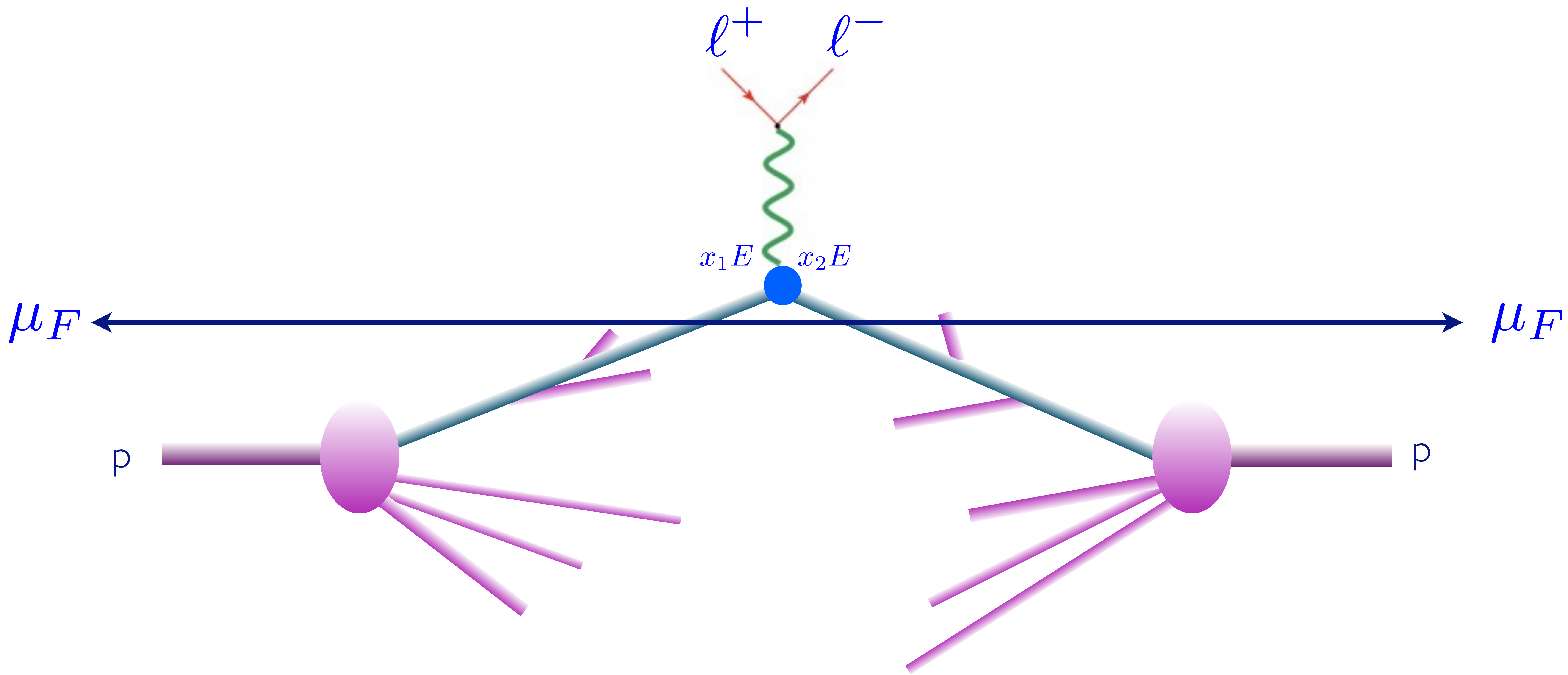

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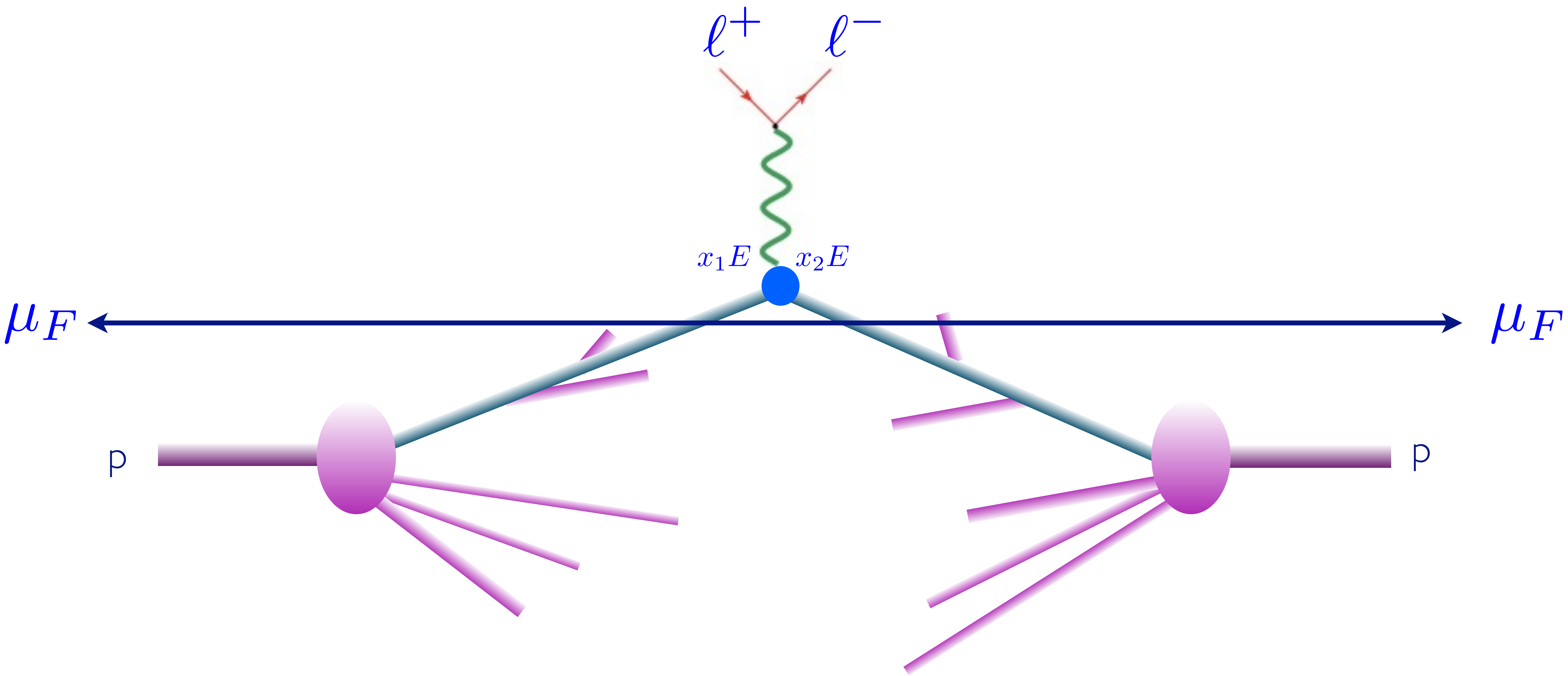

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

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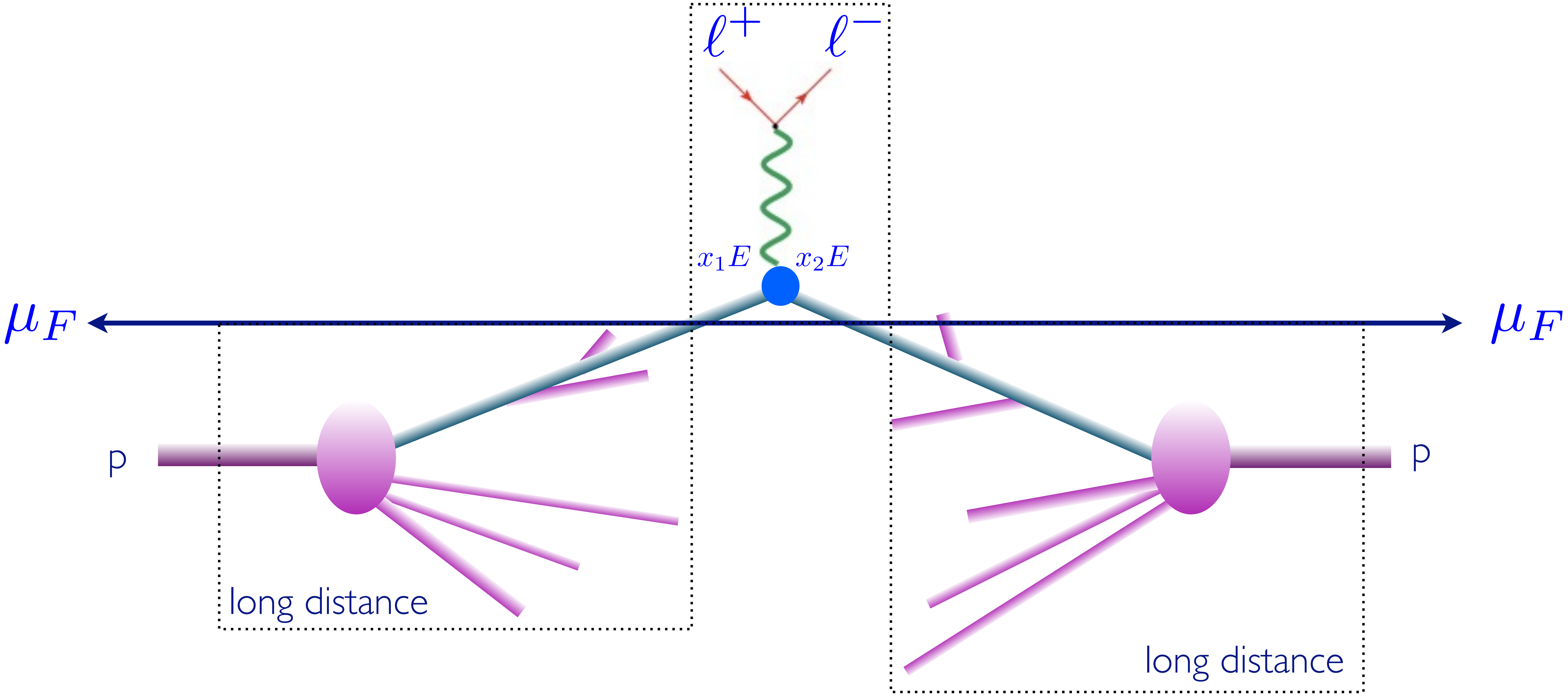
Leptoproduction and Drell-Yan Processes Beyond the Leading Approximation in Chromodynamics

Guido Altarelli (Rome U. and INFN, Rome), R.Keith Ellis (MIT, LNS), G. Martinelli (Frascati) (Jun, 1978)

Published in: *Nucl.Phys.B* 143 (1978) 521, *Nucl.Phys.B* 146 (1978) 544 (erratum)



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

pp collider

Relating Hard QCD Processes Through Universality of Mass Singularities

D. Amati (CERN), R. Petronzio (CERN), G. Veneziano (CERN) (Mar, 1978)

Published in: *Nucl.Phys.B* 140 (1978) 54-72
Published in: *Nucl.Phys.B* 146 (1978) 29-49

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution Functions (from exp, but evolution from th).

2. Short distance coefficients as an expansion in α_S (from th).

$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

Leading order

Next-to-leading order

Next-to-next-to-leading order

pp collider

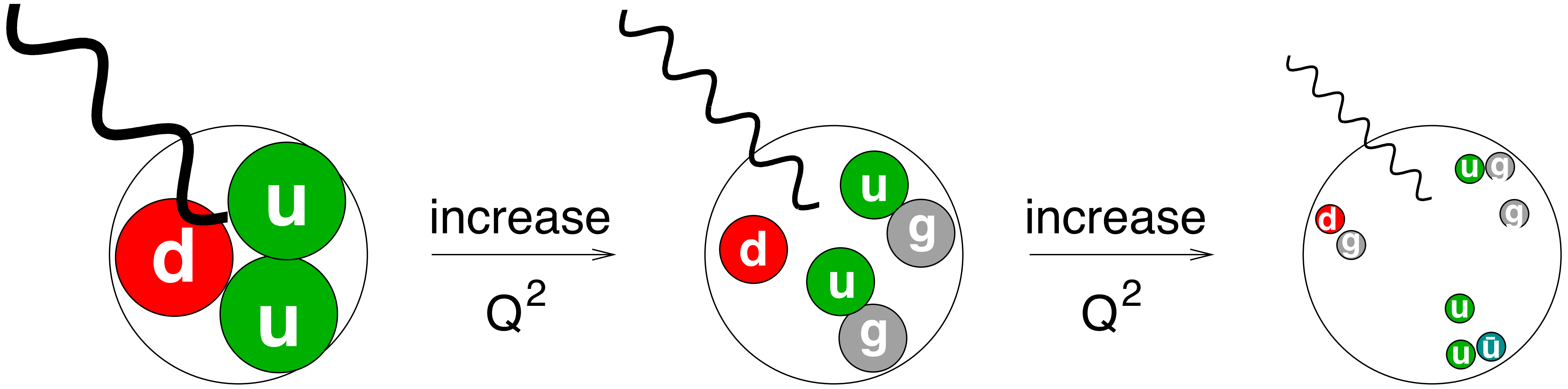
ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, *Paris, France*

G. PARISI ***
Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inleastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.



$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_{j=1}^{2f} q^j(y,t)\, P_{q^iq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^iG}\left(\frac{x}{y}\right)\right],$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_{j=1}^{2f} q^j(y,t)\, P_{Gq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right].$$

+

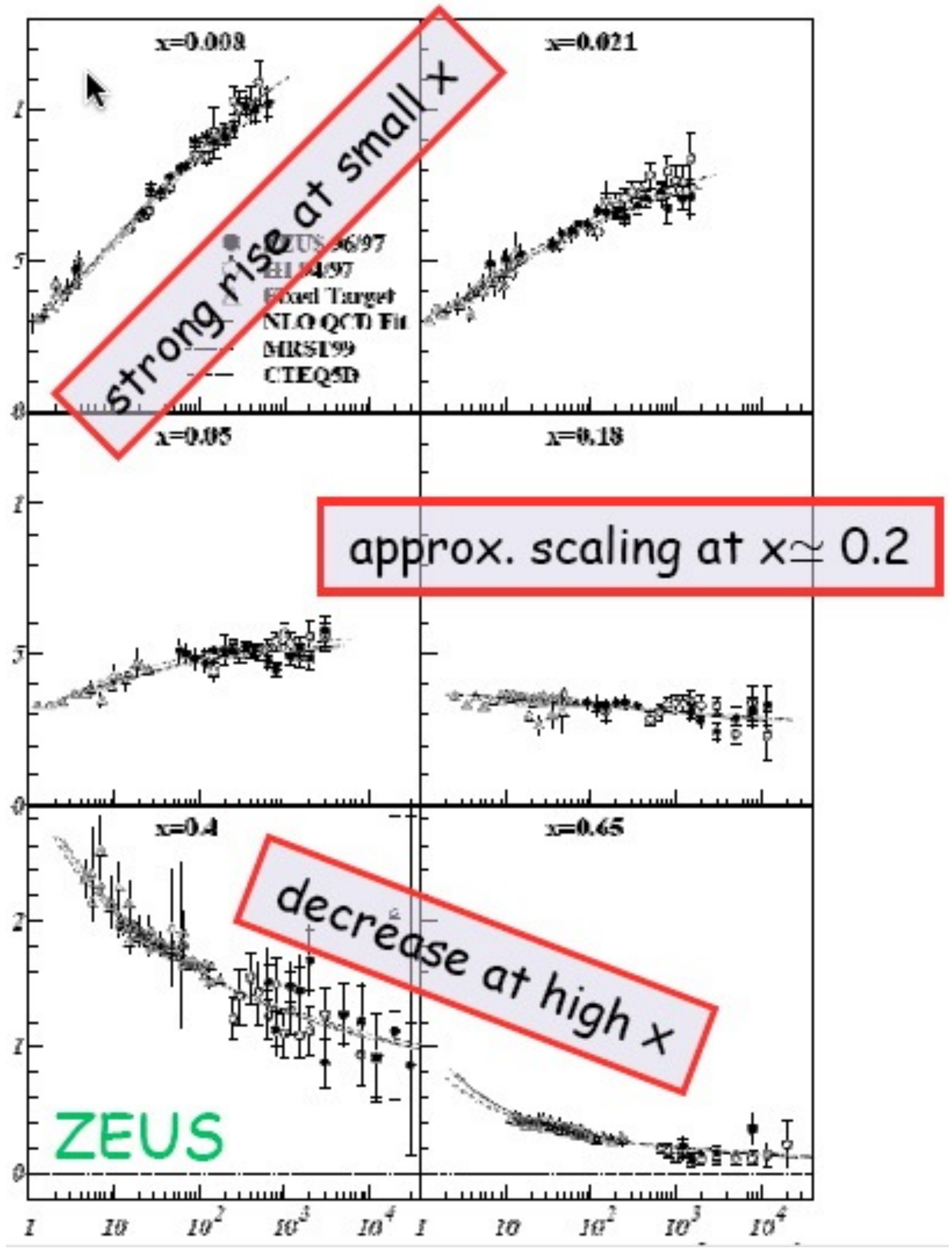
Evolution of Parton Densities Beyond Leading Order: The Nonsinglet Case

G. Curci (CERN), W. Furmanski (Jagiellonian U.), R. Petronzio (CERN) (Feb, 1980)

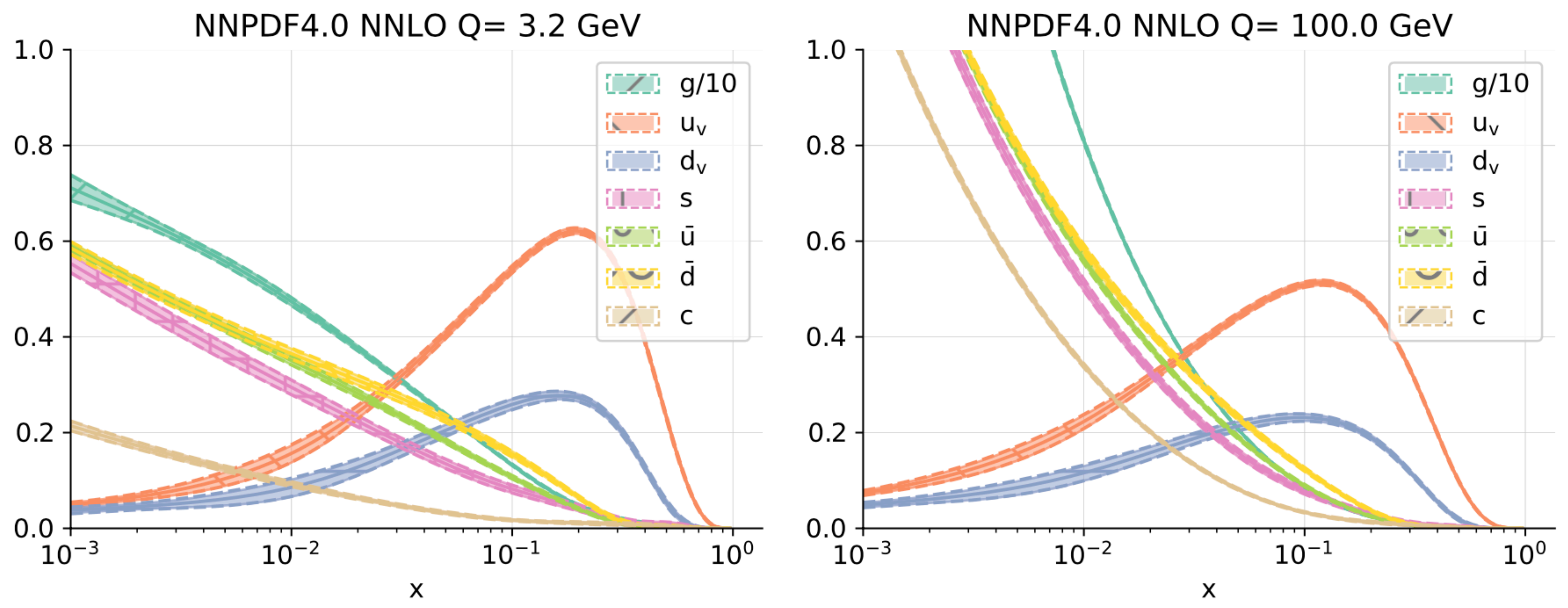
Published in: *Nucl.Phys.B* 175 (1980) 27-92

Scaling violations and PDF determination

DIS at HERA



30 years later



A first unbiased global NLO determination of parton distributions and their uncertainties

Richard D. Ball (Edinburgh U.), Luigi Del Debbio (Edinburgh U.), Stefano Forte (INFN, Milan and Milan U.), Alberto Guffanti (Freiburg U.), Jose I. Latorre (Barcelona U., ECM) et al. (Feb, 2010)

Published in: *Nucl.Phys.B* 838 (2010) 136-206 • e-Print: 1002.4407 [hep-ph]

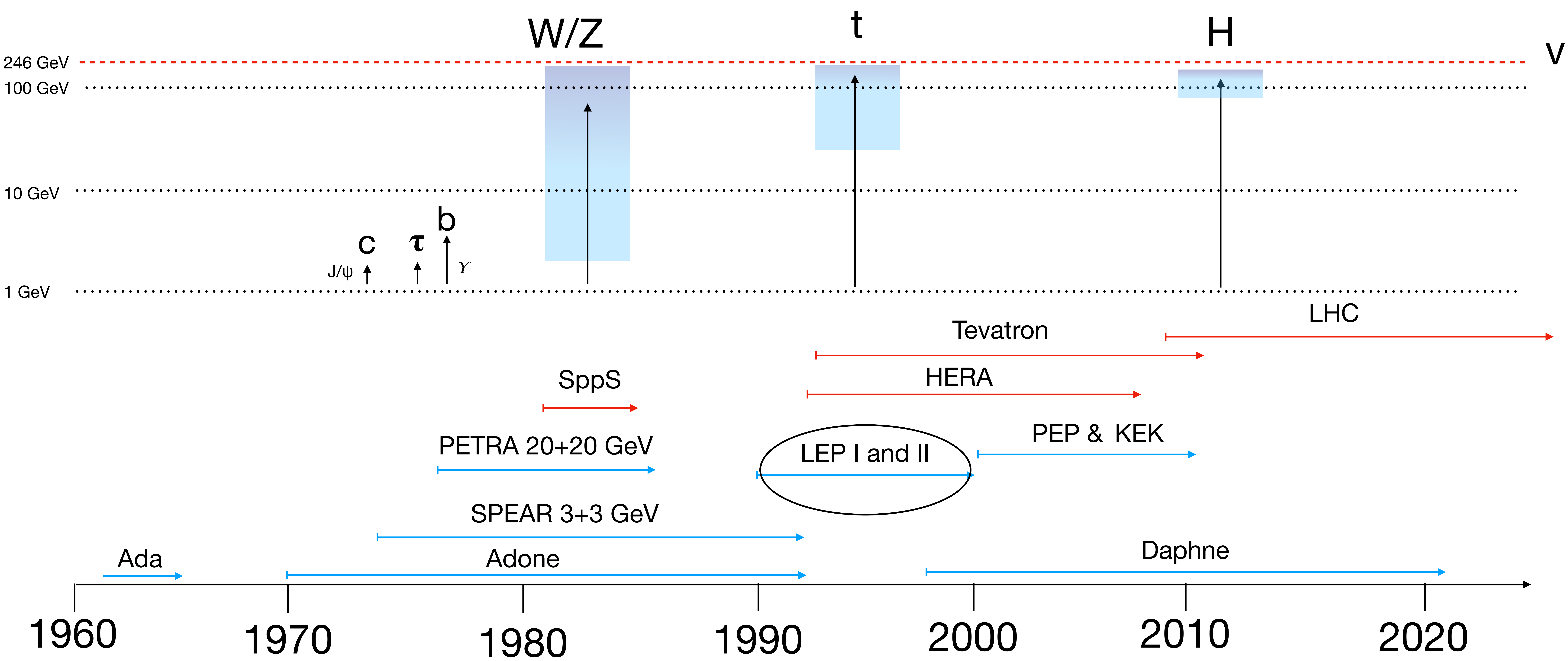
The path to proton structure at 1% accuracy

NNPDF Collaboration • Richard D. Ball (U. Edinburgh, Higgs Ctr. Theor. Phys.) et al. (Sep 6, 2021)

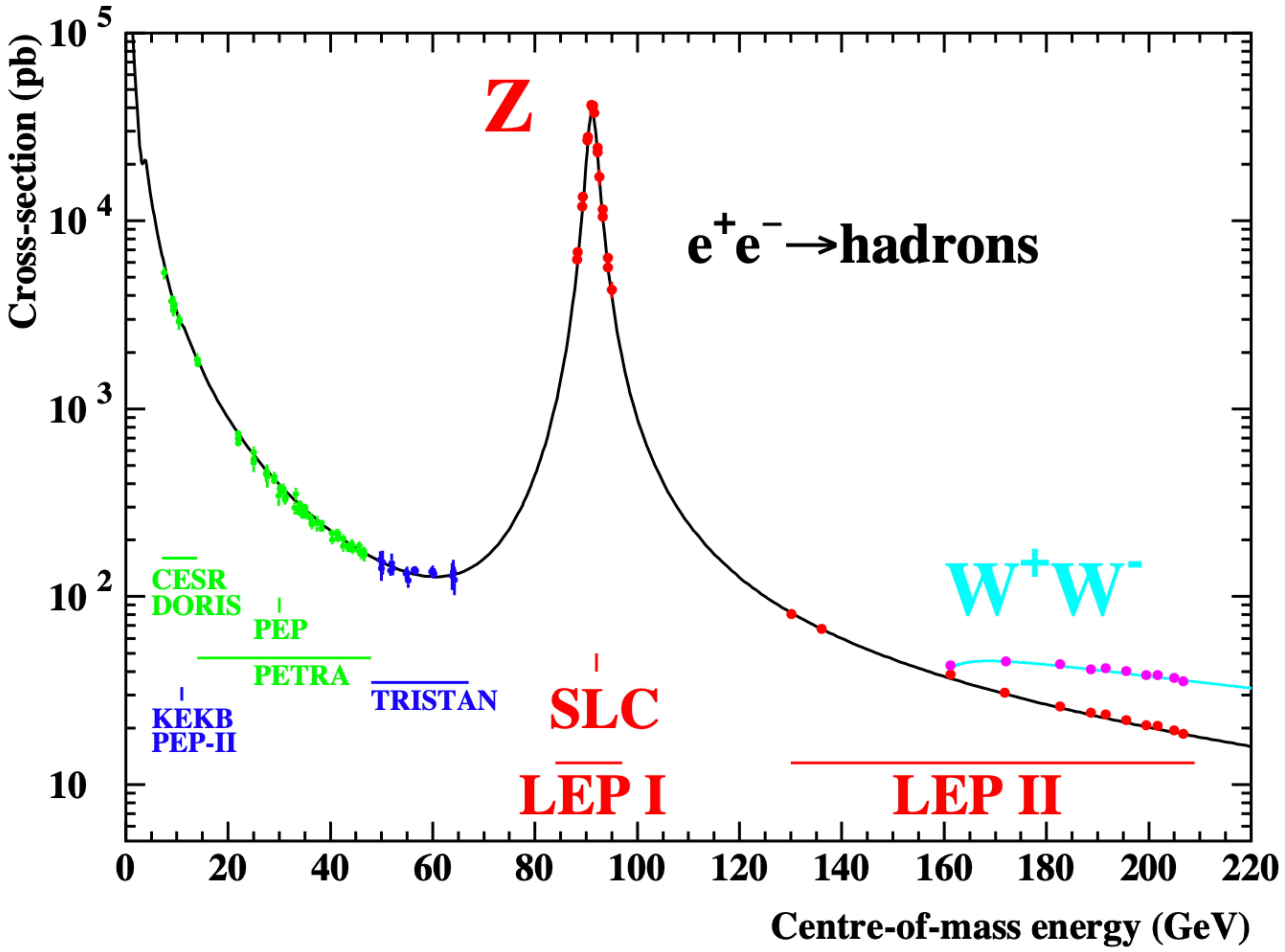
Published in: *Eur.Phys.J.C* 82 (2022) 5, 428 • e-Print: 2109.02653 [hep-ph]

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



LEP era



Even with a model-independent approach [Borrelli, Consoli, Maiani, Sisto, 1990] precision analysis for LEP1 and LEP2 would not been possible without precision predictions.

Lineshape:

TOPAZ0 [Montagna, Nicrosini, Passarino, Piccinini, Pittau, 1993] (also for LEP2)

Luminosity:

Bhabha scattering : Important contributions from the Parma-Pavia group [Cacciari, Deandrea, Montagna, Nicrosini, Trentadue, 1991] Pavia-Torino [Montagna, Nicrosini, Passarino, Piccinini, Pittau, 1993] (BABAYAGA) [Carloni Calame, Montagna, Nicrosini, Piccinini, 2000] Bologna group (BHAGEN) [Caffo, Czyz, Remiddi , 1993].

LEP era

RADIATIVE CORRECTIONS FOR COLLIDING BEAM RESONANCES

M. GRECO, G. PANCHERI-SRIVASTAVA * and Y. SRIVASTAVA * **
Laboratori Nazionali del CNEN, Frascati, Italy

Received 3 July 1975

Detailed expressions are presented for radiative corrections to colliding beam experiments in the presence of resonances, including interference effects. The derivation of our formulae is accomplished using perturbation theory methods as well as the coherent state formalism. These are then applied to determine the resonance parameters for $\psi(3.1)$ and $\psi(3.7)$.

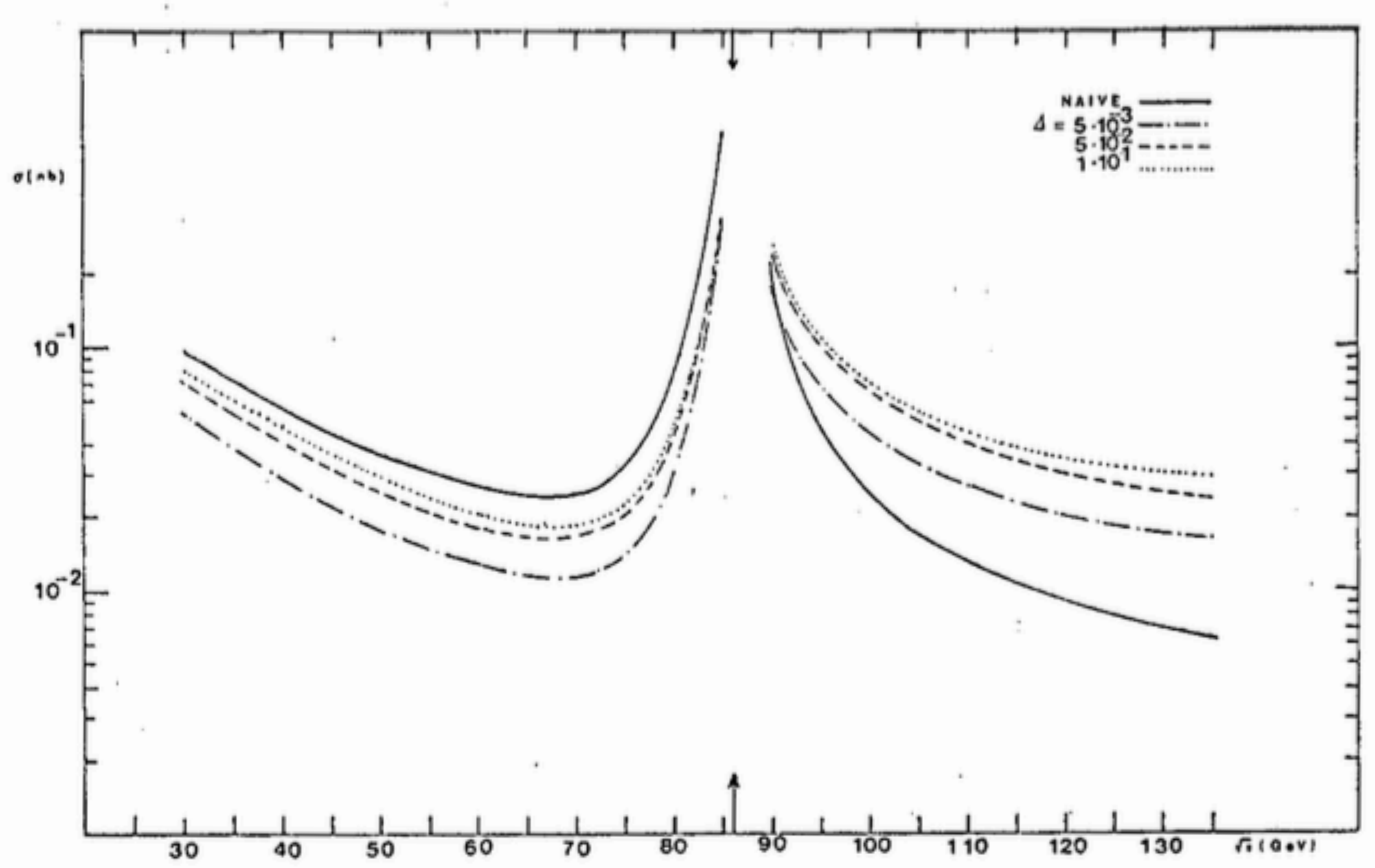


FIG. - 6 Total cross-section σ vs. $\sqrt{s}$ with and without radiative corrections (naive). Various values of the experimental resolution $\Delta\omega/E = \Delta$ are considered.

M. Greco, G. Pancheri-Srivastava and Y. Srivastava, *Radiative Corrections to $e^+e^- \to \mu^+\mu^-$ Around the Z^0*, *Nucl. Phys. B* **171** (1980) 118.

O. Nicrosini and L. Trentadue, *Soft Photons and Second Order Radiative Corrections to $e^+e^- \to Z^0$*, *Phys. Lett. B* **196** (1987) 551.

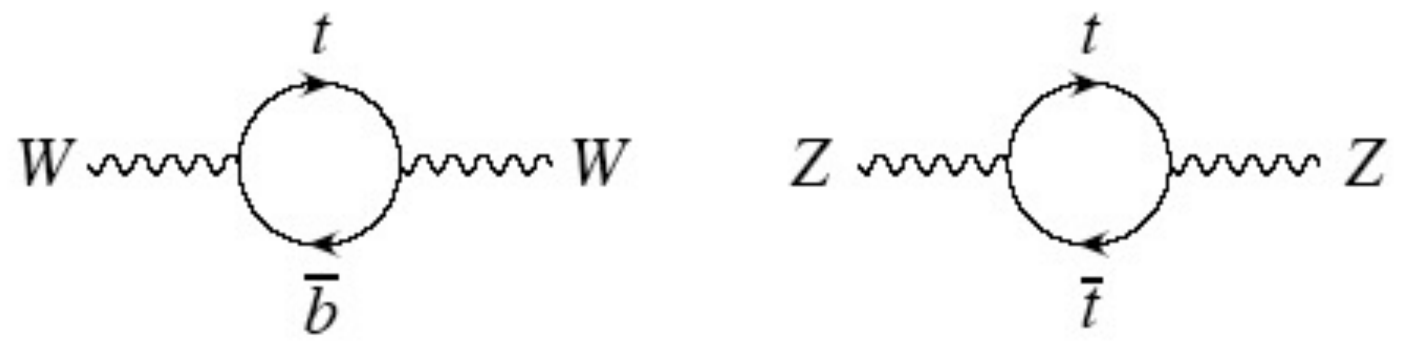
Another important electromagnetic effect is the presence of a substantial radiative tail. Due to the emission of a hard photon from the initial state, the radiative tail is expected to radically modify the angular asymmetries in $e^+e^- \to \mu^- \mu^+$. It follows therefore that a detailed calculation of the e.m. radiative corrections is of primary importance for the forthcoming experiments around the Z_o-mass.

Precision for discovery

ρ parameter

Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level mW=mZ cos θW. At one loop:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

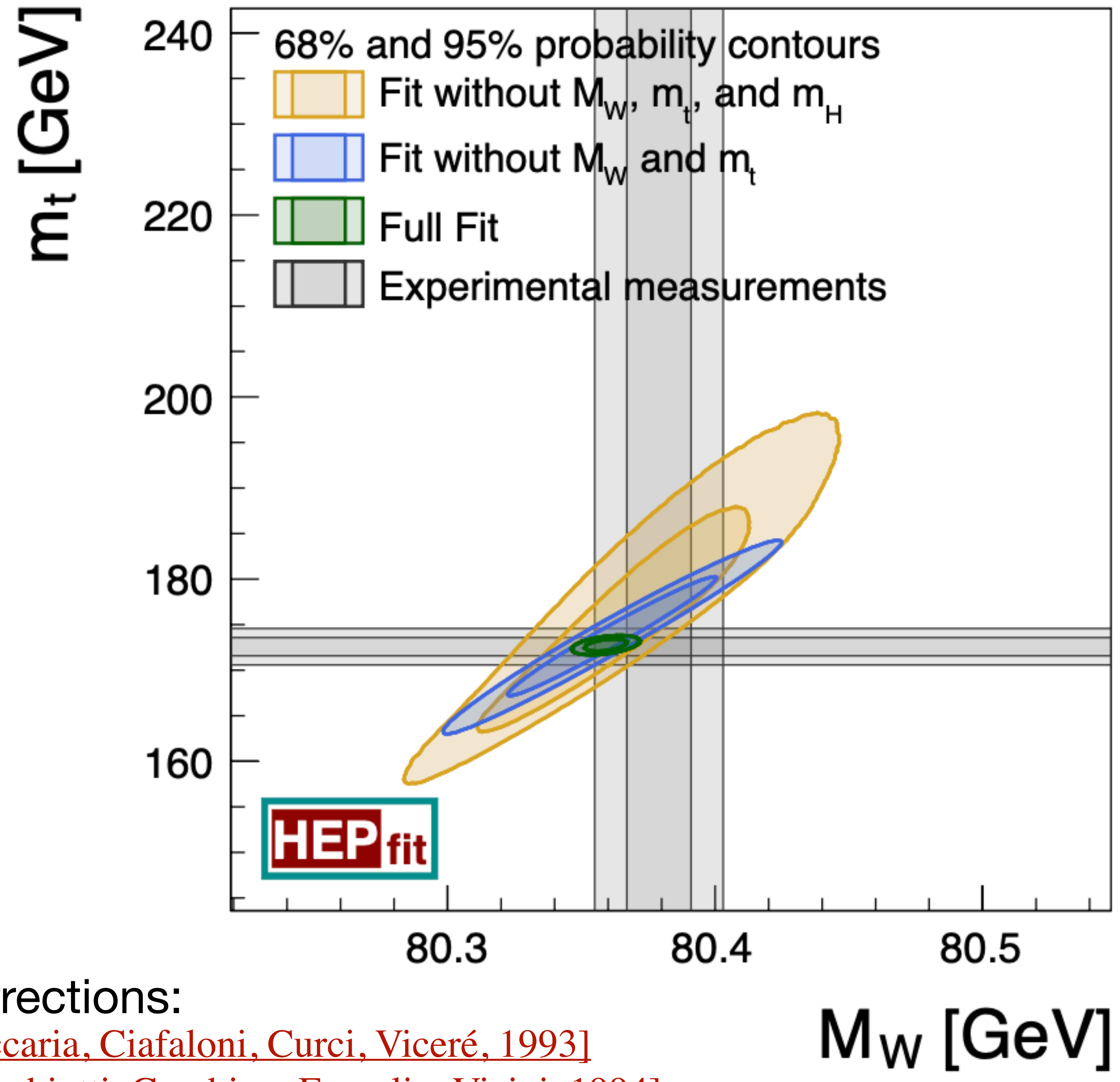


$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

Long tradition of groups doing EWPO fits

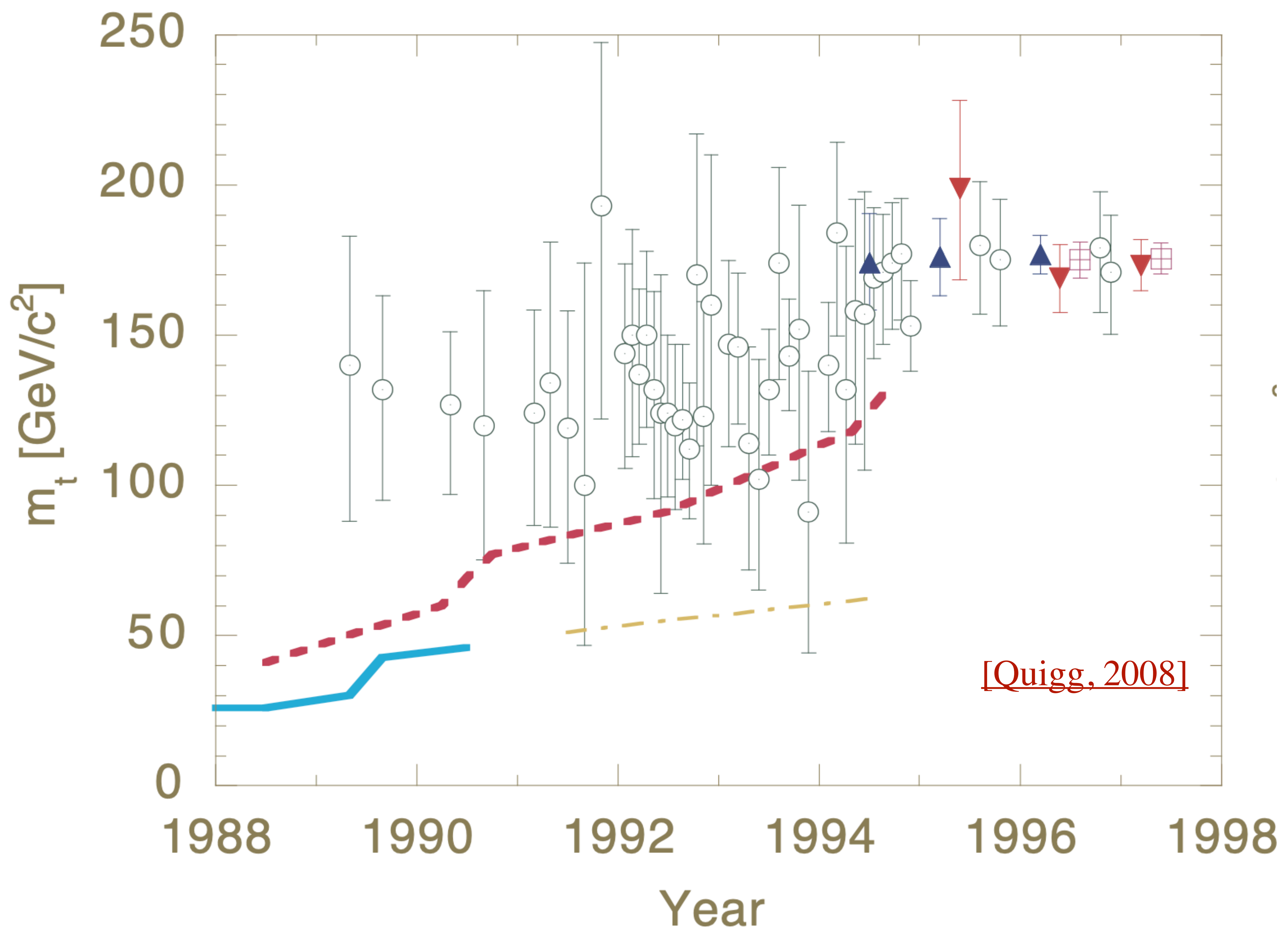
[Consoli, Hollik Jegernelher, 1983]
[Doujadi, Verzegnassi, 1987]
[Ellis, Fogli, Lisi, 1992/3/4/5/6]
[Montagna, Nicrosini, Passarino, Piccinini, 1993]
[De Blas, Ciuchini, Franco, …Pierini, Reina, Silvestrini, 2021]



Two-loop corrections:

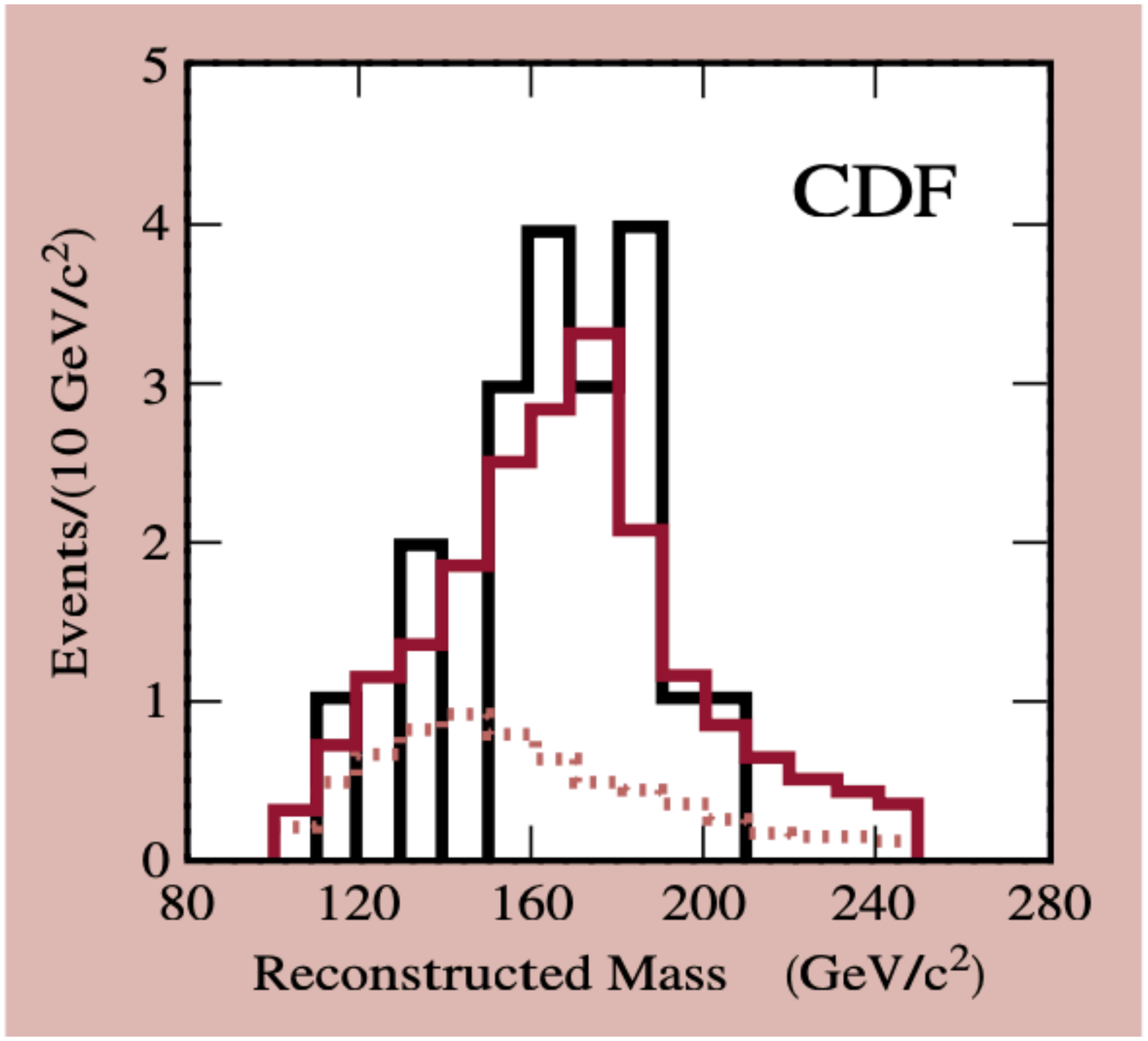
[Barbieri, Beccaria, Ciafaloni, Curci, Viceré, 1993]
[Degrassi, Fanchiotti, Gambino, Feruglio, Vicini, 1994]

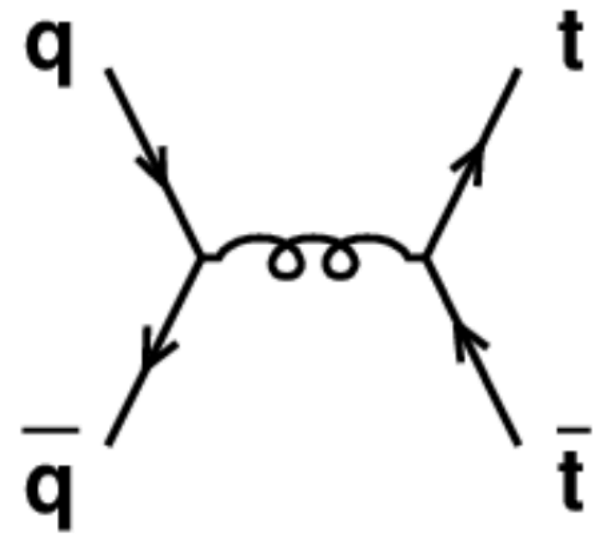
Precision for discovery : the top



Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \to (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and 1997. The 1997 world average from direct observations is shown as the crossed box.

Top discovery at FNAL





b-tagged. This establishes the existence of the top quark. The preliminary mass and cross section measurements yield $M_{top} = 176 \pm 8 \pm 10$ GeV/c^2 and $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb.

The Total Cross-Section for the Production of Heavy Quarks in Hadronic Collisions

P. Nason (Brookhaven), S. Dawson (Brookhaven), R.Keith Ellis (Fermilab) (Dec, 1987)

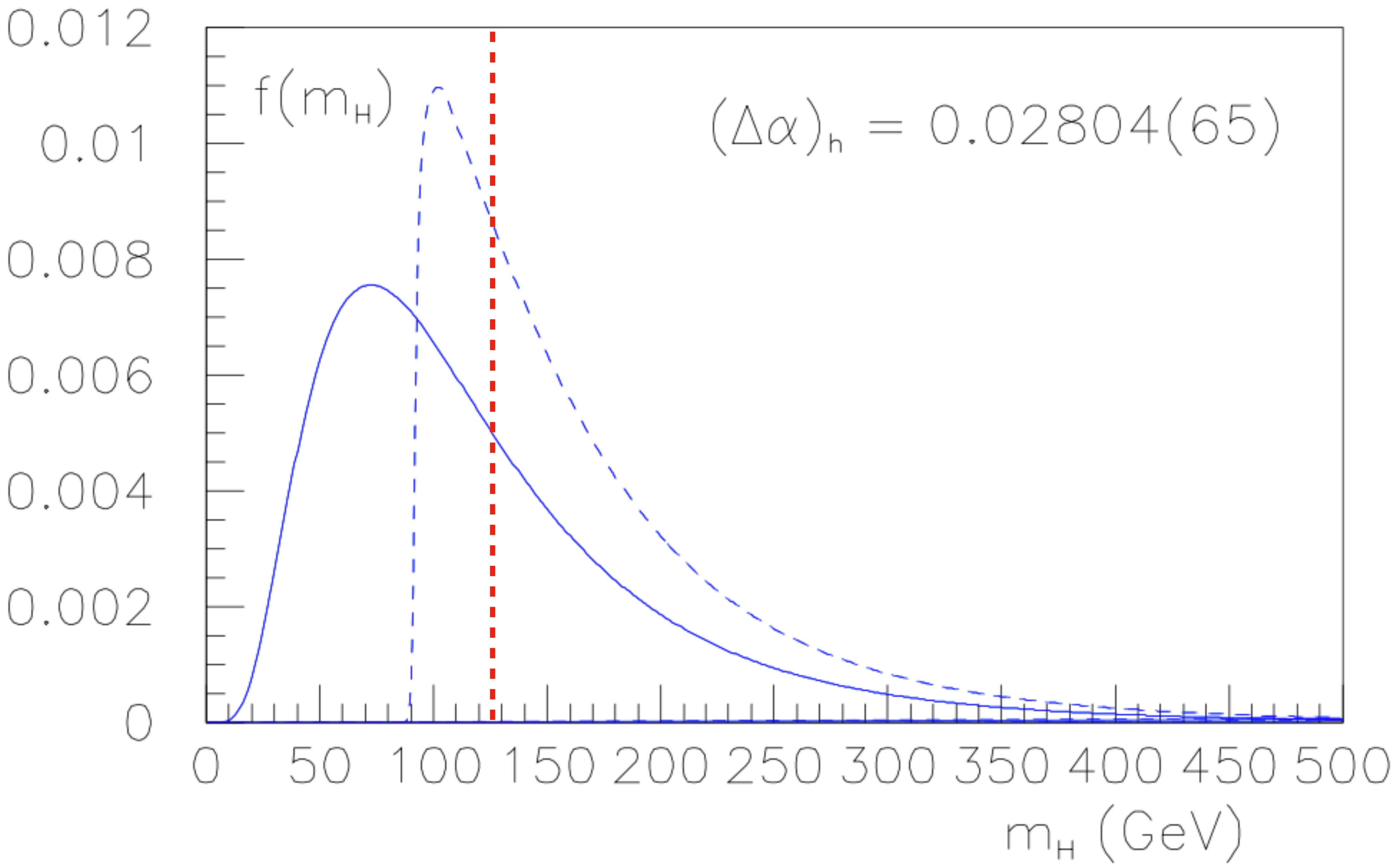
Published in: *Nucl.Phys.B* 303 (1988) 607-633

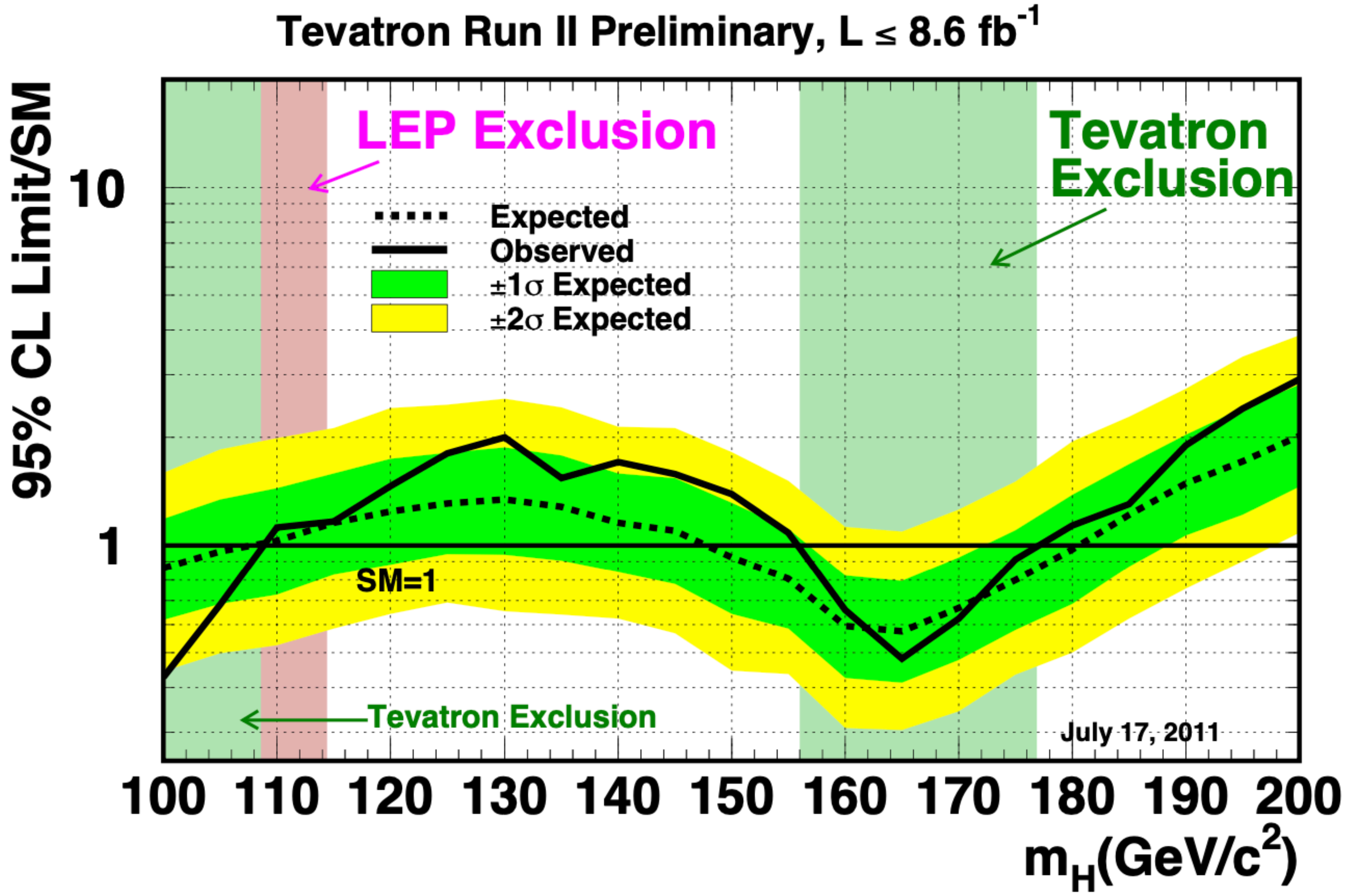
Heavy quark correlations in hadron collisions at next-to-leading order

Michelangelo L. Mangano (INFN, Pisa and Pisa, Scuola Normale Superiore), Paolo Nason (INFN, Parma), Giovanni Ridolfi (INFN, Genoa) (Sep 24, 1991)

Published in: *Nucl.Phys.B* 373 (1992) 295-345

Precision for discovery : the Higgs





[D'Agostini, G. Degrassi, hep-ph/9902226]

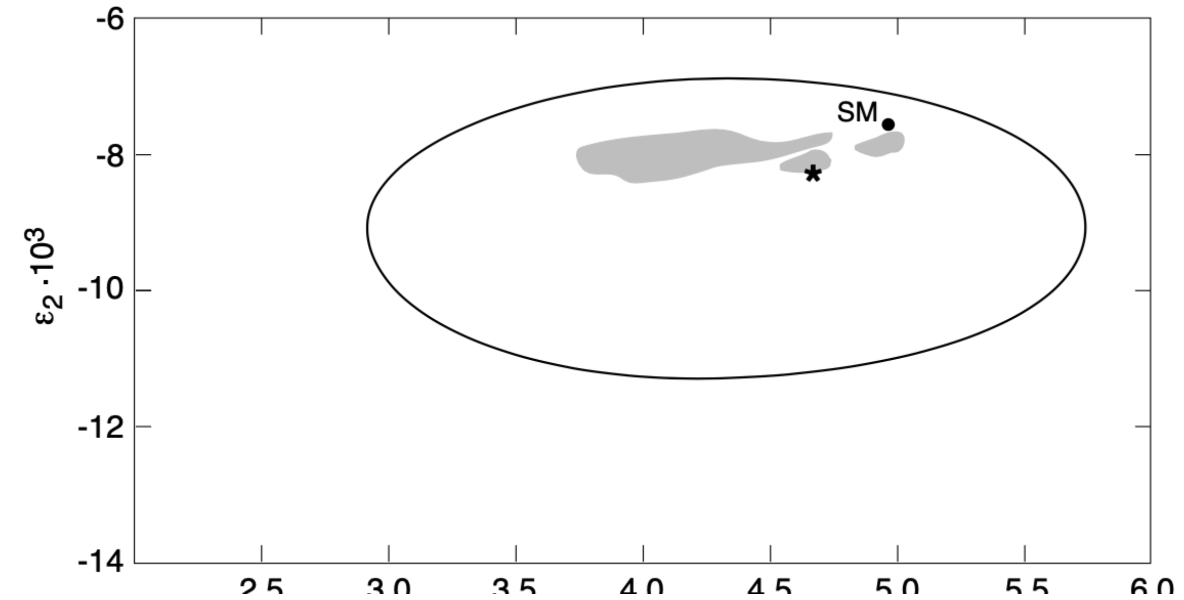
[CDF&D0, 2011]

Testing the unknown through precision

$\epsilon_1, \epsilon_2, \epsilon_3$

One can extend the idea of looking at rho to predict SM missing ingredients to the full set of self energies to probe new physics:

“…for a useful definition we choose a set of representative observables that are used to parametrize those hot spots of the radiative corrections where new physics effects are most likely to show up. “



$$
\begin{aligned}
\epsilon_1 &= \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} - \frac{3G_F m_W^2}{4\pi^2\sqrt{2}} \tan^2\theta_W \ln\frac{m_H}{m_Z} + \ldots., \\
\epsilon_2 &= -\frac{G_F m_W^2}{2\pi^2\sqrt{2}} \ln\frac{m_t}{m_Z} + \ldots., \\
\epsilon_3 &= \frac{G_F m_W^2}{12\pi^2\sqrt{2}} \ln\frac{m_H}{m_Z} - \frac{G_F m_W^2}{6\pi^2\sqrt{2}} \ln\frac{m_t}{m_Z} \ldots., \\
\epsilon_b &= -\frac{G_F m_t^2}{4\pi^2\sqrt{2}} + \ldots.
\end{aligned}
$$

[Barbieri, Maiani, 1983] [Ellis, Ridolfi, Zwirner, 1991]
[Altarelli, Barbieri, Caravaglios,1993, 1994, 1997]

$$
\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{v^2}\left[c_{WB}\mathcal{O}_{WB} + c_H\mathcal{O}_H + c_{WW}\mathcal{O}_{WW} + c_{BB}\mathcal{O}_{BB}\right]
$$

Adimensional form factors			operators		
$g^{-2}\widehat{S}$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB}$	$=$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}/gg'$
$g^{-2}M_W^2\widehat{T}$	$=$	$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$
$-g^{-2}\widehat{U}$	$=$	$\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)$	$-$		
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0) - \Pi''_{W^+W^-}(0)$	$-$		
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$	$-$		
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2g^2$
$2g_s^{-2}M_W^{-2}Z$	$=$	$\Pi''_{GG}(0)$	$\mathcal{O}_{GG}$	$=$	$(D_\rho G^A_{\mu\nu})^2/2g_s^2$

[Barbieri, Pomarol, Rattazzi, Strumia, hep/0405040]

What about new physics?

Multa novit vulpes, verum echinus unum magnum

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the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

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the hedgehogs view the world through the lens of a single defining idea

What about new physics?

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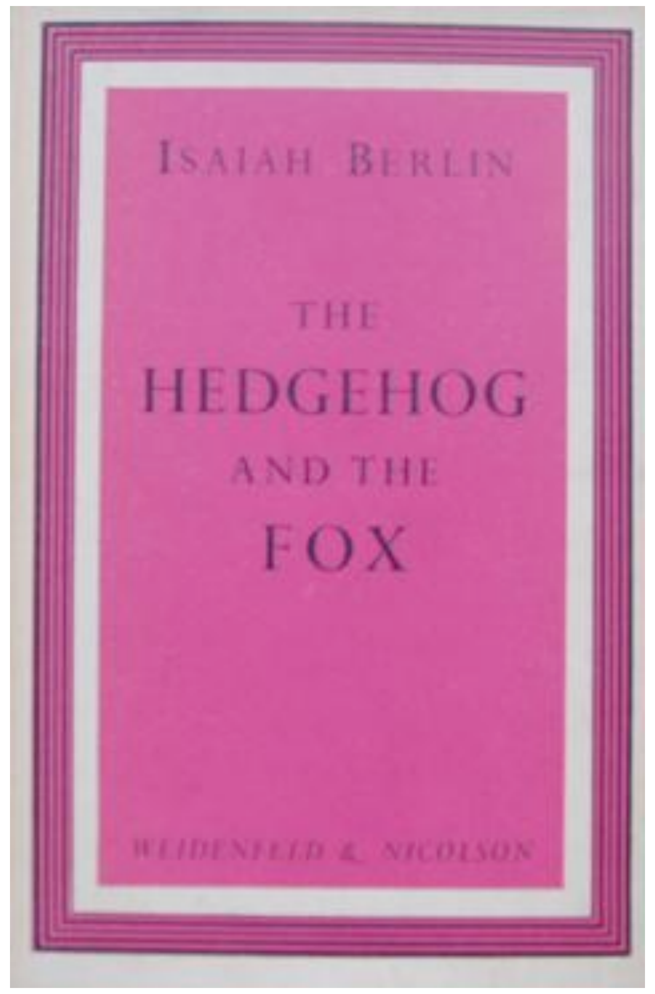


[Archilocus]

[Erasmo]

[Berlin]

the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

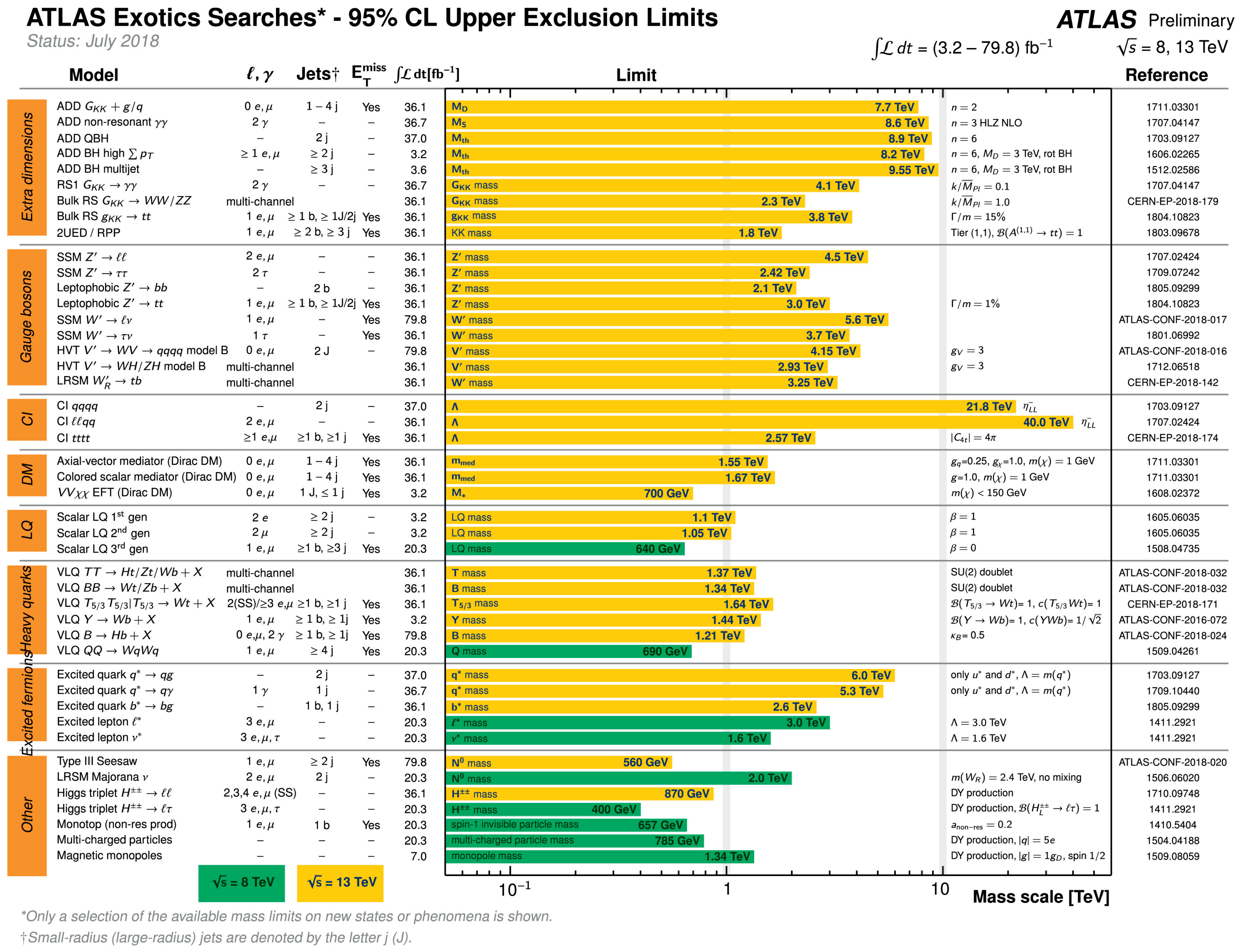
the hedgehogs view the world through the lens of a single defining idea

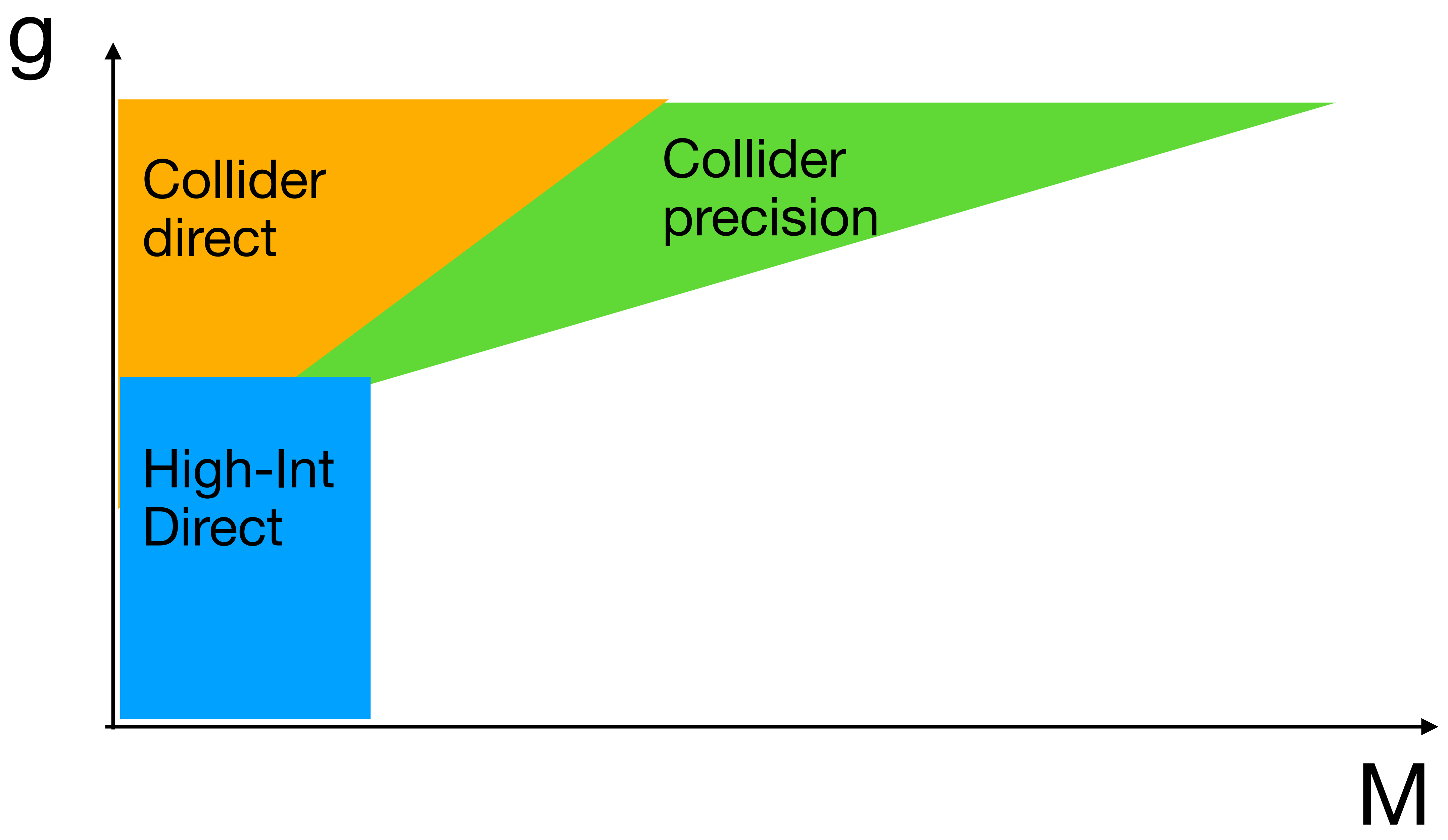
What about new physics?

Direct searches

- Apart from periodic hints, no tension between accelerator data and SM predictions has survived the test of time and scrutiny, at least so far. At the LHC no evidence for BSM phenomena has emerged. Indications from lower energy (g-2, LFUV) are still being considered.

- Schematically current collider direct searches exclude the existence of new states at the weak scale interacting with SM-like couplings. High-intensity low energy experiments cover low couplings, low masses.





What about new physics?

Effective field theory

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

Rattazzi®GGI tea break

What about new physics?

Effective field theory

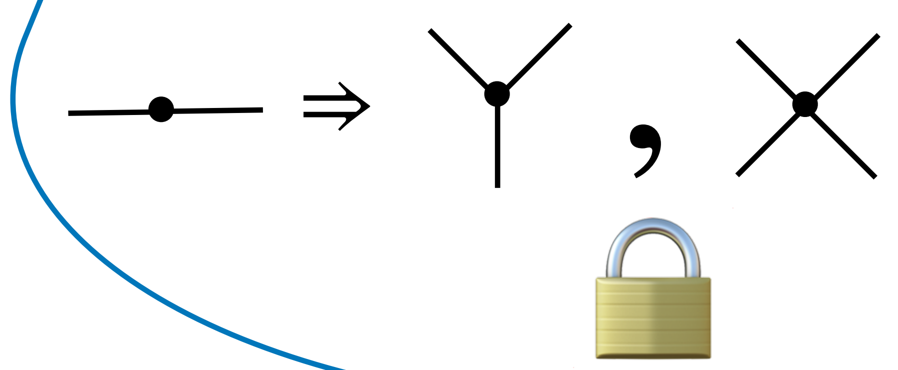
$$\mathscr{L} \quad = \quad \mathscr{L}^{(2)} \quad + \quad \mathscr{L}^{(4)} \quad + \quad \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \ldots$$

$$m_\nu = 0$$

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

GIM

$Y_u, Y_d, Y_l \Rightarrow$ Fla$\cancel{\text{vo}}$r & $\cancel{\text{CP}}$



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$m_\nu = 0$

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GIM

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

$\Rightarrow$,

$\cancel{U(1)}_L \to m_\nu \neq 0$

~~Flavor~~ $\Rightarrow \mu \to e\gamma, \Delta m_K, \dots$

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

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

$U(1)_B \Rightarrow p \to \pi^0 e^+$

$\not\Rightarrow_6$ $\not\Rightarrow_8$

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Effective field theory

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

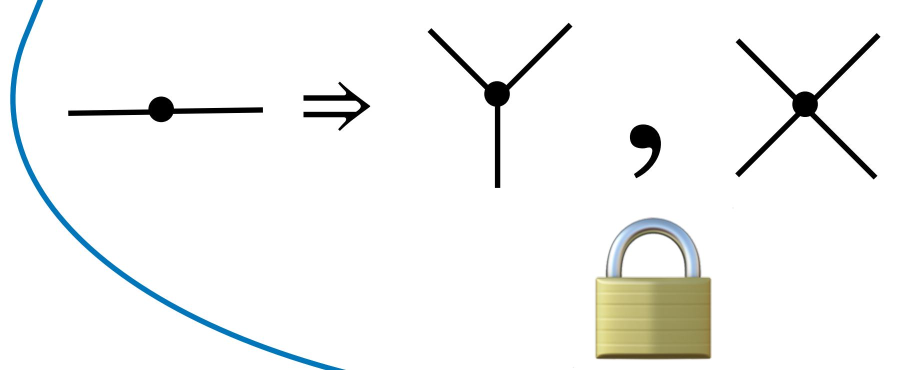
$m_h^2 \simeq \Lambda^2$

$m_\nu = 0$

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

GIM

$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}}\ \&\ \cancel{CP}$



$\cancel{U(1)}_L \to m_\nu \neq 0$

$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \ldots$

$\cancel{CP} \Rightarrow \text{edm's}$

$\text{Dipoles} \Rightarrow (g-2)_\mu$

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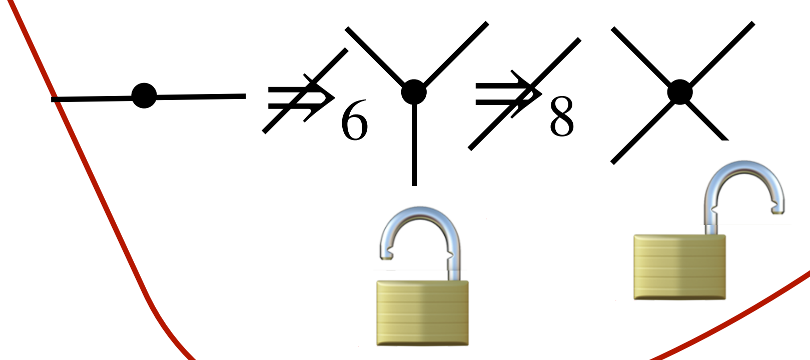

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What about new physics?

Effective field theory

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

$m_h^2 \simeq \Lambda^2$

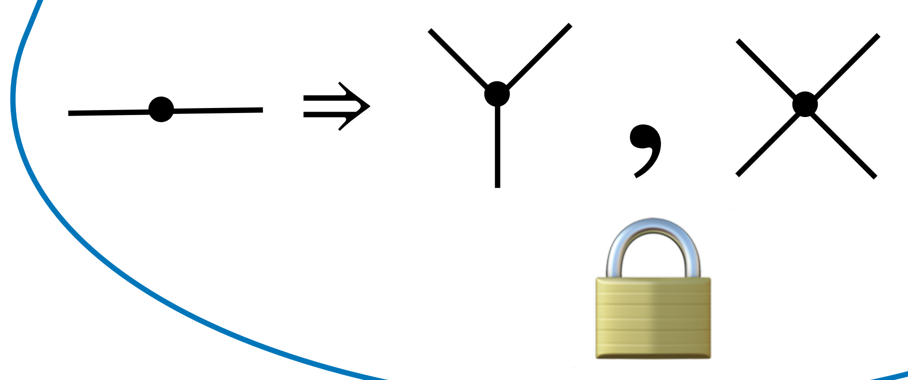
$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

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

GIM

$Y_u, Y_d, Y_l \Rightarrow$ ~~Flavor~~ & $\cancel{CP}$



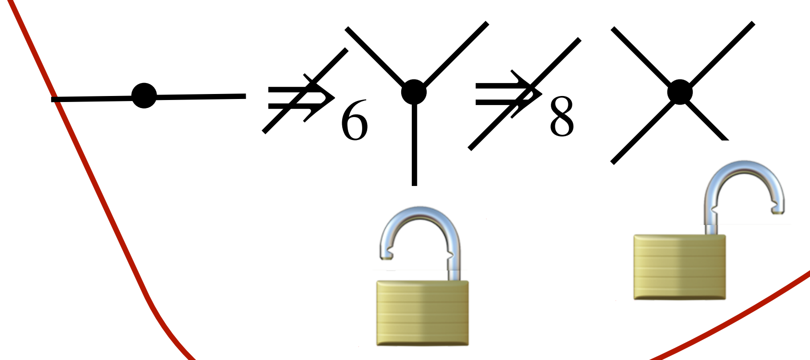
$U(\cancel{1})_L \to m_\nu \neq 0$ $\quad \Rightarrow \Lambda \geq 10^{14}$ GeV

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

$\cancel{CP} \Rightarrow$ edm's

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

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



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

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What about new physics?

Effective field theory

Λ_{UV}

TeV

TeV Λ_{UV}

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

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GIM

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

$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \dots \quad \Rightarrow \Lambda \geq 10^6$ GeV

$\cancel{CP} \Rightarrow$ edm's

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

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

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

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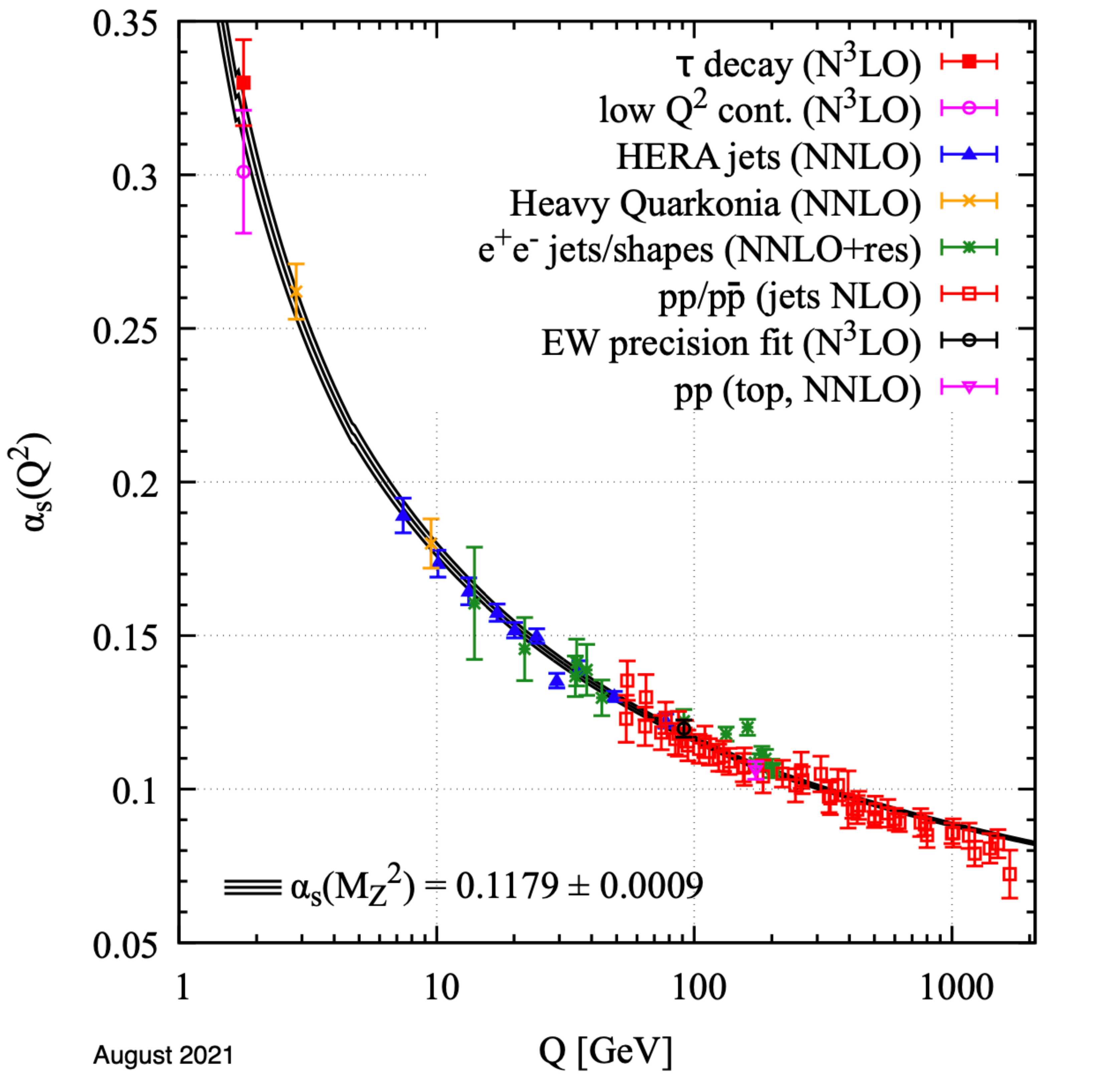
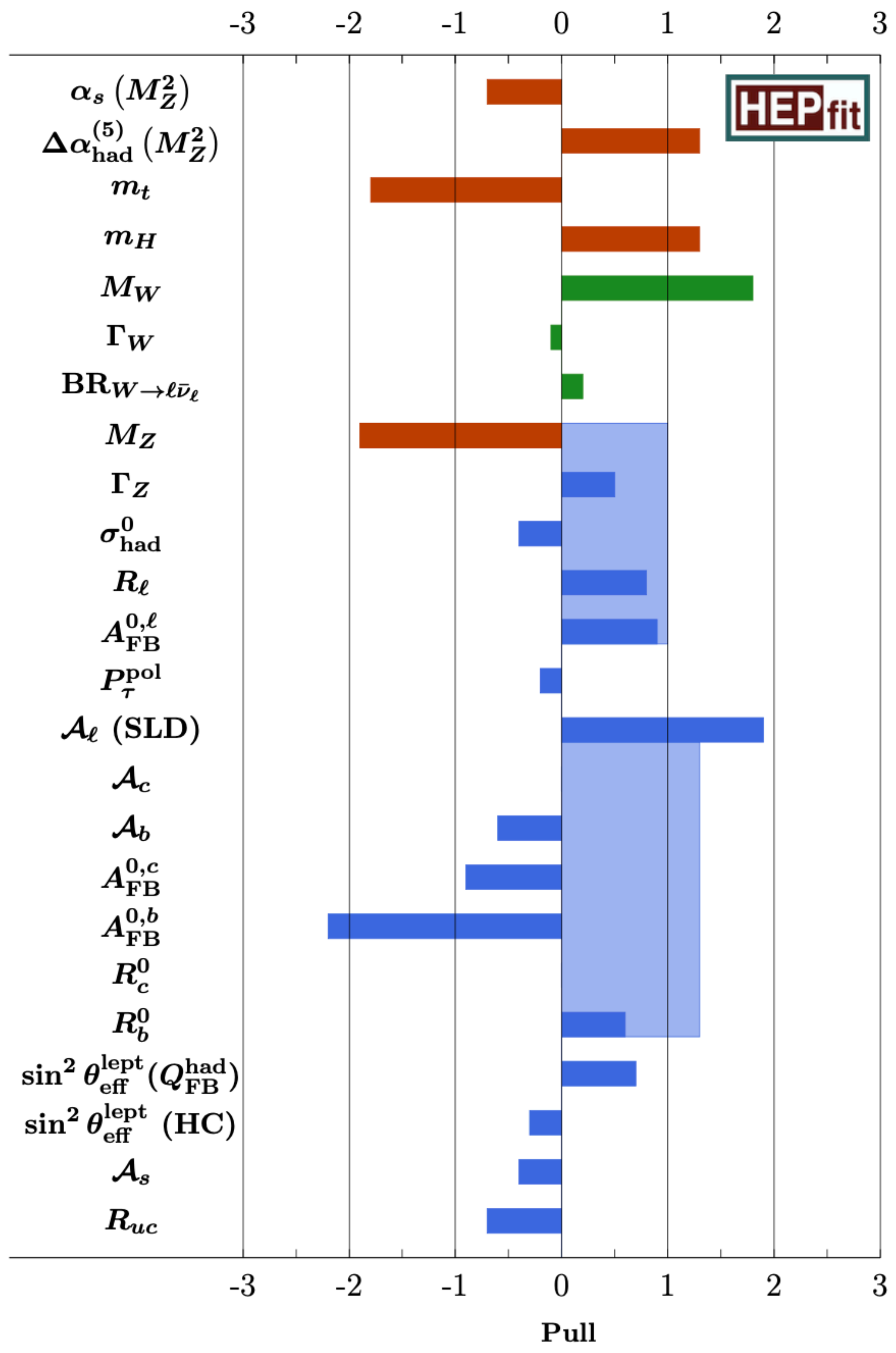
Precision for discovery





At LEP, QCD and EW physics were loosely connected. At hadron colliders they are intrinsically connected. **No QCD? ⇒ no EW!**

Improving the QCD accuracy for the LHC

A General algorithm for calculating jet cross-sections in NLO QCD

S. Catani (Florence U. and INFN, Florence), M.H. Seymour (CERN) (May, 1996)

Published in: *Nucl.Phys.B* 485 (1997) 291-419, *Nucl.Phys.B* 510 (1998) 503-504 (erratum) • e-Print: hep-ph/9605323 [hep-ph]

Three jet cross-sections to next-to-leading order

S. Frixione (Zurich, ETH), Z. Kunszt (Zurich, ETH), A. Signer (SLAC) (Dec, 1995)

Published in: *Nucl.Phys.B* 467 (1996) 399-442 • e-Print: hep-ph/9512328 [hep-ph]

General methods to compute IR safe observables at NLO.

The Singular behavior of QCD amplitudes at two loop order

Stefano Catani (CERN and Orsay, LPT) (Feb, 1998)

Published in: *Phys.Lett.B* 427 (1998) 161-171 • e-Print: hep-ph/9802439 [hep-ph]

NNLO Structure

An NNLO subtraction formalism in hadron collisions and its application to Higgs boson production at the LHC

Stefano Catani (INFN, Florence and Florence U.), Massimiliano Grazzini (INFN, Florence and Florence U.) (Mar,

Published in: *Phys.Rev.Lett.* 98 (2007) 222002 • e-Print: hep-ph/0703012 [hep-ph]

A Subtraction scheme for computing QCD jet cross sections at NNLO: Regularization of doubly-real emissions

Gabor Somogyi (Debrecen, Inst. Nucl. Res.), Zoltan Trocsanyi (Debrecen, Inst. Nucl. Res.), Vittorio Del Duca (INFN, Turin) (Sep, 2006)

Published in: *JHEP* 01 (2007) 070 • e-Print: hep-ph/0609042 [hep-ph]

Local analytic sector subtraction at NNLO

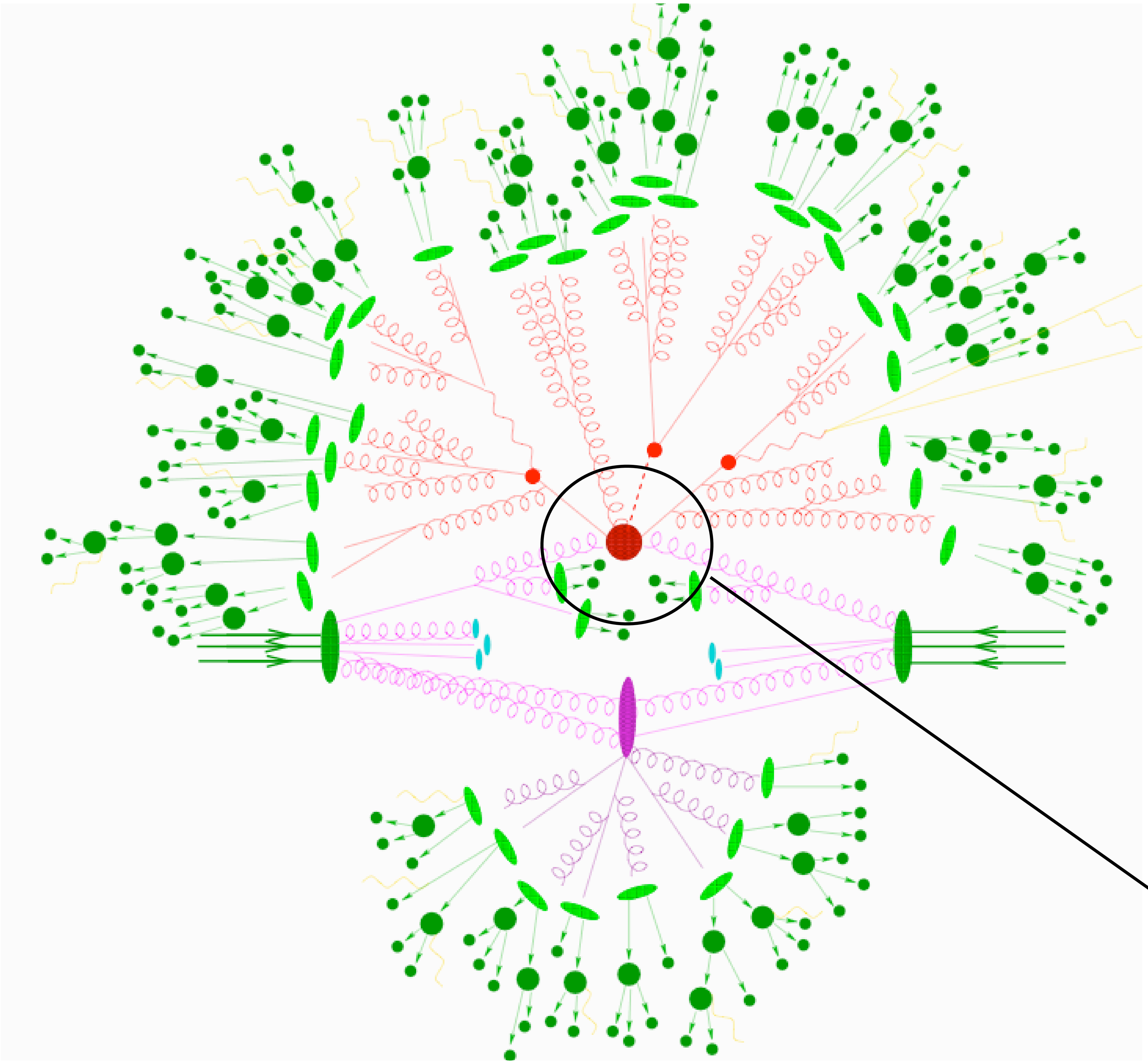
L. Magnea (INFN, Turin and Turin U.), E. Maina (INFN, Turin and Turin U.), G. Pelliccioli (INFN, Turin and Turin U.), C. Signorile-Signorile (INFN, Turin and Turin U.), P. Torrielli (INFN, Turin and Turin U.) et al. (Jun 25, 2018)

Published in: *JHEP* 12 (2018) 107, *JHEP* 06 (2019) 013 (erratum) • e-Print: 1806.09570 [hep-ph]

General methods to compute IR safe observables at NNLO.

Improving the QCD accuracy for the LHC

Showers



Simulation of QCD Jets Including Soft Gluon Interference

G. Marchesini (Parma U. and INFN, Milan), B.R. Webber (CERN) (Feb, 1983)

Published in: *Nucl.Phys.B* 238 (1984) 1-29

Monte Carlo Simulation of General Hard Processes with Coherent QCD Radiation

G. Marchesini (Parma U. and INFN, Parma), B.R. Webber (Cambridge U.) (Dec, 1987)

Published in: *Nucl.Phys.B* 310 (1988) 461-526

QCD coherent branching and semiinclusive processes at large x

S. Catani (Cambridge U.), B.R. Webber (Cambridge U.), G. Marchesini (Parma U. and INFN, Parma) (May, 1990)

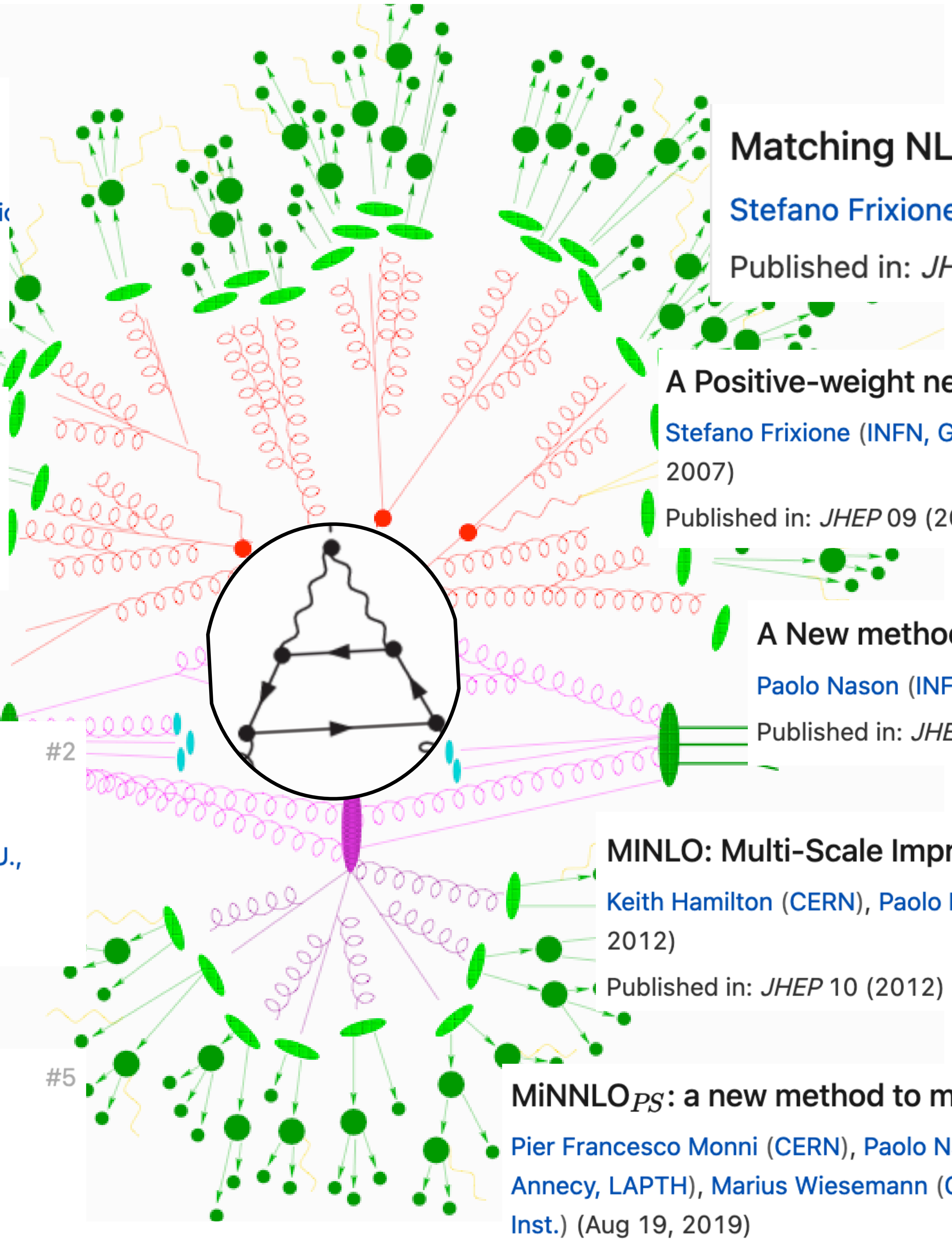
Published in: *Nucl.Phys.B* 349 (1991) 635-654

...

Hard scattering at the lowest order.

Improving the QCD accuracy for the LHC

Methods and tools



A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX

Simone Alioli (DESY, Zeuthen and INFN, Milan Bicocca), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (Milan Bic U. and INFN, Milan Bicocca), Emanuele Re (Durham U., IPPP and INFN, Milan Bicocca) (Feb, 2010)

Published in: *JHEP* 06 (2010) 043 • e-Print: 1002.2581 [hep-ph]

Matching NLO QCD computations and parton shower simulations

Stefano Frixione (Annecy, LAPP), Bryan R. Webber (Cambridge U.) (Apr, 2002)

Published in: *JHEP* 06 (2002) 029 • e-Print: hep-ph/0204244 [hep-ph]

Matching NLO QCD computations with Parton Shower simulations: the POWHEG method

Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (INFN, Milan Bicocca and Milan Bicocca U.) (Sep, 2007)

Published in: *JHEP* 11 (2007) 070 • e-Print: 0709.2092 [hep-ph]

A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction #5

Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan Bicocca), Giovanni Ridolfi (Genoa U. and INFN, Genoa) (Jul, 2007)

Published in: *JHEP* 09 (2007) 126 • e-Print: 0707.3088 [hep-ph]

A New method for combining NLO QCD with shower Monte Carlo algorithms

Paolo Nason (INFN, Milan) (Sep, 2004)

Published in: *JHEP* 11 (2004) 040 • e-Print: hep-ph/0409146 [hep-ph]

The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations #2

J. Alwall (Taiwan, Natl. Taiwan U.), R. Frederix (CERN), S. Frixione (CERN), V. Hirschi (SLAC), F. Maltoni (Louvain U., CP3) et al. (May 1, 2014)

Published in: *JHEP* 07 (2014) 079 • e-Print: 1405.0301 [hep-ph]

MINLO: Multi-Scale Improved NLO

Keith Hamilton (CERN), Paolo Nason (CERN and INFN, Milan Bicocca), Giulia Zanderighi (Oxford U., Theor. Phys.) 2012)

Published in: *JHEP* 10 (2012) 155 • e-Print: 1206.3572 [hep-ph]

ALPGEN, a generator for hard multiparton processes in hadronic collisions #5

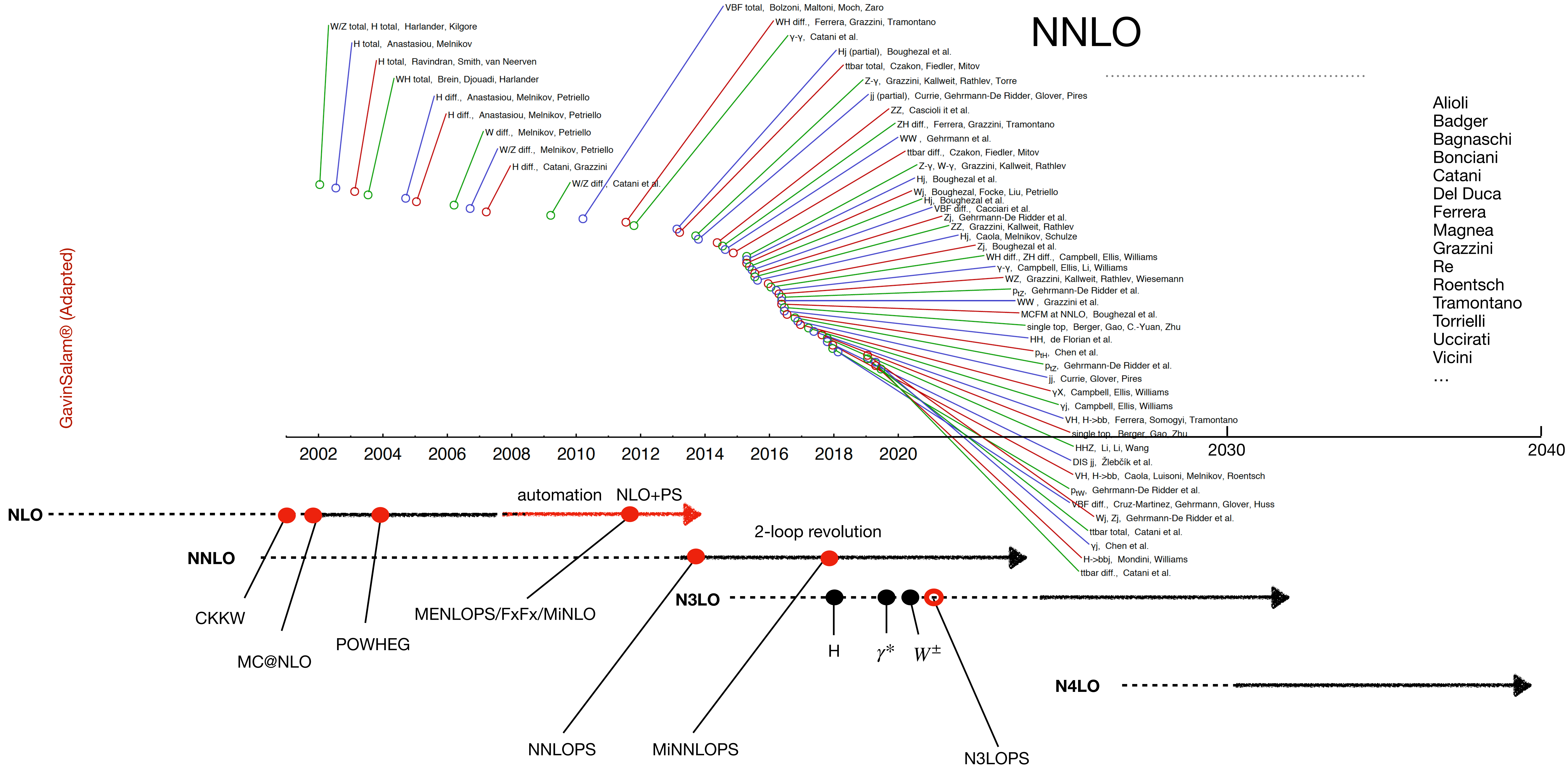
Michelangelo L. Mangano (CERN), Mauro Moretti (Ferrara U. and INFN, Ferrara), Fulvio Piccinini (CERN), Roberto Pittau (Turin U. and INFN, Turin), Antonio D. Polosa (CERN) (Jun, 2002)

Published in: *JHEP* 07 (2003) 001 • e-Print: hep-ph/0206293 [hep-ph]

MiNNLO$_{PS}$: a new method to match NNLO QCD to parton showers

Pier Francesco Monni (CERN), Paolo Nason (INFN, Milan Bicocca and Milan Bicocca U.), Emanuele Re (CERN and Annecy, LAPTH), Marius Wiesemann (CERN and Munich, Max Planck Inst.), Giulia Zanderighi (Munich, Max Planck Inst.) (Aug 19, 2019)

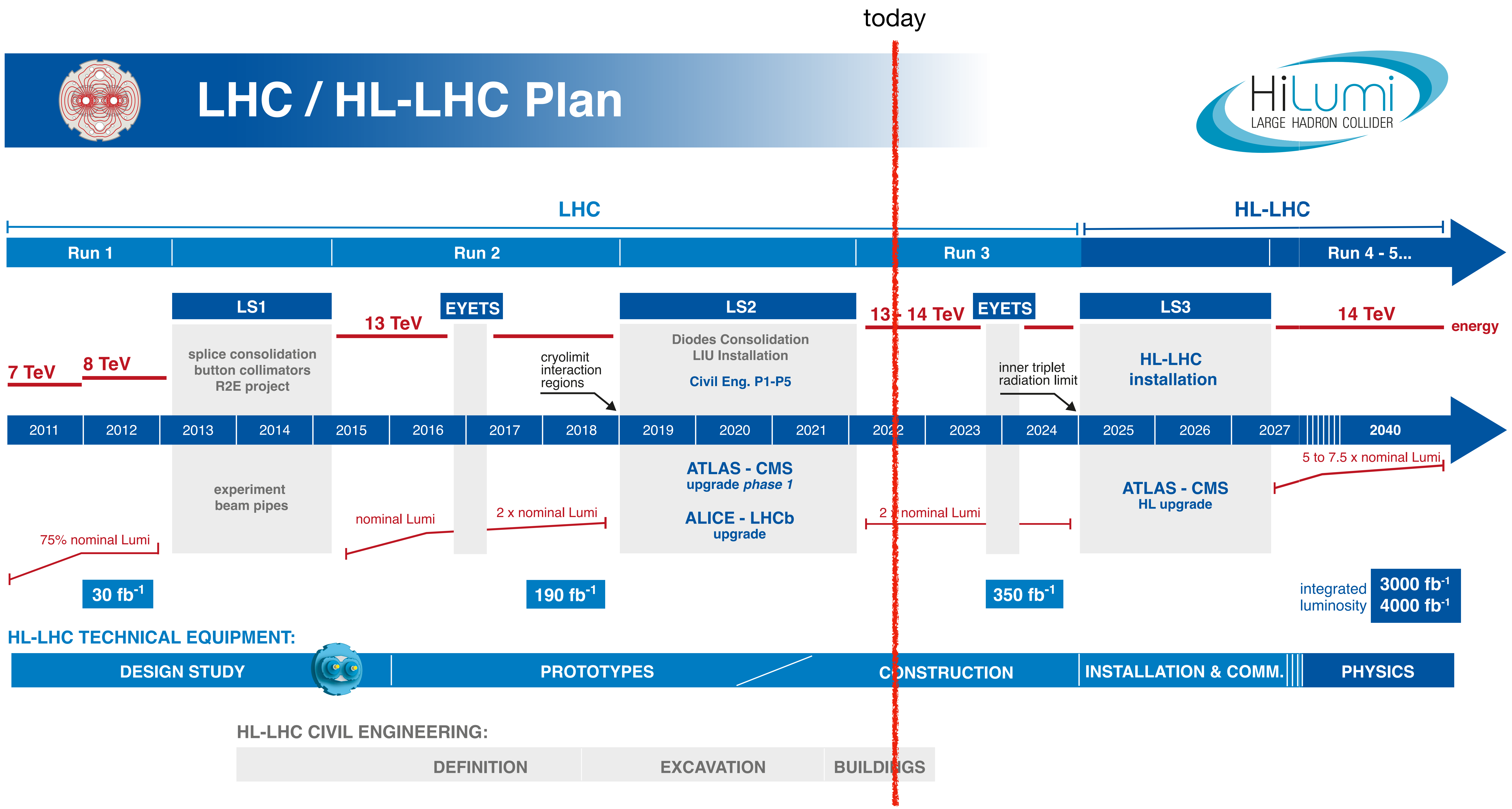
Published in: *JHEP* 05 (2020) 143, *JHEP* 02 (2022) 031 (erratum) • e-Print: 1908.06987 [hep-ph]



NNLO
W/Z total, H total, Harlander, Kilgore
H total, Anastasiou, Melnikov
H total, Ravindran, Smith, van Neerven
WH total, Brein, Djouadi, Harlander
H diff., Anastasiou, Melnikov, Petriello
H diff., Anastasiou, Melnikov, Petriello
W diff., Melnikov, Petriello
W/Z diff., Melnikov, Petriello
H diff., Catani, Grazzini
W/Z diff., Catani et al.
VBF total, Bolzoni, Maltoni, Moch, Zaro
WH diff., Ferrera, Grazzini, Tramontano
γ-γ, Catani et al.
Hj (partial), Boughezal et al.
ttbar total, Czakon, Fiedler, Mitov
Z-γ, Grazzini, Kallweit, Rathlev, Torre
jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires
ZZ, Cascioli it et al.
ZH diff., Ferrera, Grazzini, Tramontano
WW, Gehrmann et al.
ttbar diff., Czakon, Fiedler, Mitov
Z-γ, W-γ, Grazzini, Kallweit, Rathlev
Hj, Boughezal et al.
Wj, Boughezal, Focke, Liu, Petriello
Hj, Boughezal et al.
VBF diff., Cacciari et al.
Zj, Gehrmann-De Ridder et al.
ZZ, Grazzini, Kallweit, Rathlev
Hj, Caola, Melnikov, Schulze
Zj, Boughezal et al.
WH diff., ZH diff., Campbell, Ellis, Williams
γ-γ, Campbell, Ellis, Li, Williams
WZ, Grazzini, Kallweit, Rathlev, Wiesemann
p_{tZ}, Gehrmann-De Ridder et al.
WW, Grazzini et al.
MCFM at NNLO, Boughezal et al.
single top, Berger, Gao, C.-Yuan, Zhu
HH, de Florian et al.
p_{tH}, Chen et al.
p_{tZ}, Gehrmann-De Ridder et al.
jj, Currie, Glover, Pires
γX, Campbell, Ellis, Williams
γj, Campbell, Ellis, Williams
VH, H->bb, Ferrera, Somogyi, Tramontano
single top, Berger, Gao, Zhu
HHZ, Li, Li, Wang
DIS jj, Žlebčík et al.
VH, H->bb, Caola, Luisoni, Melnikov, Roentsch
p_{tW}, Gehrmann-De Ridder et al.
VBF diff., Cruz-Martinez, Gehrmann, Glover, Huss
Wj, Zj, Gehrmann-De Ridder et al.
ttbar total, Catani et al.
γj, Chen et al.
H->bbj, Mondini, Williams
ttbar diff., Catani et al.
Alioli
Badger
Bagnaschi
Bonciani
Catani
Del Duca
Ferrera
Magnea
Grazzini
Re
Roentsch
Tramontano
Torrielli
Uccirati
Vicini
...
GavinSalam® (Adapted)
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2030
2040
NLO
automation
NLO+PS
NNLO
2-loop revolution
N3LO
N4LO
CKKW
MC@NLO
POWHEG
MENLOPS/FxFx/MiNLO
NNLOPS
MiNNLOPS
H
γ^*
$W^\pm$
N3LOPS

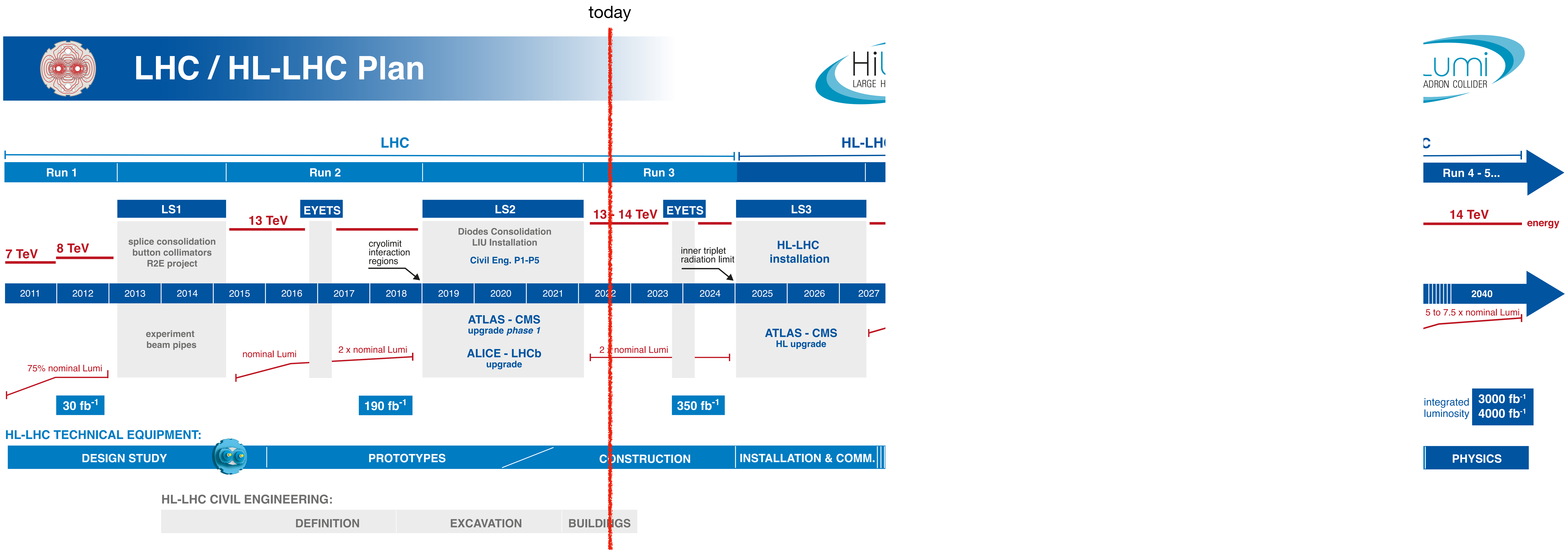
The future

The LHC reference frame and unit of time



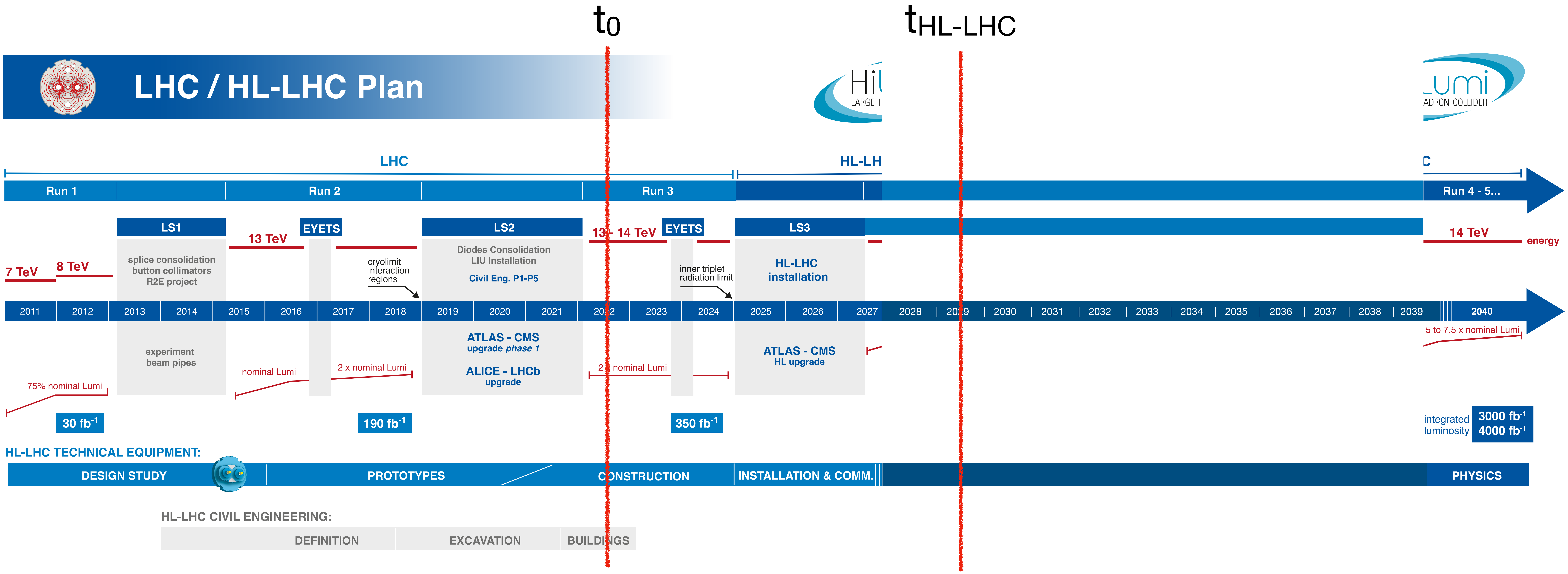
The future

The LHC reference frame and unit of time



The future

The LHC reference frame and unit of time



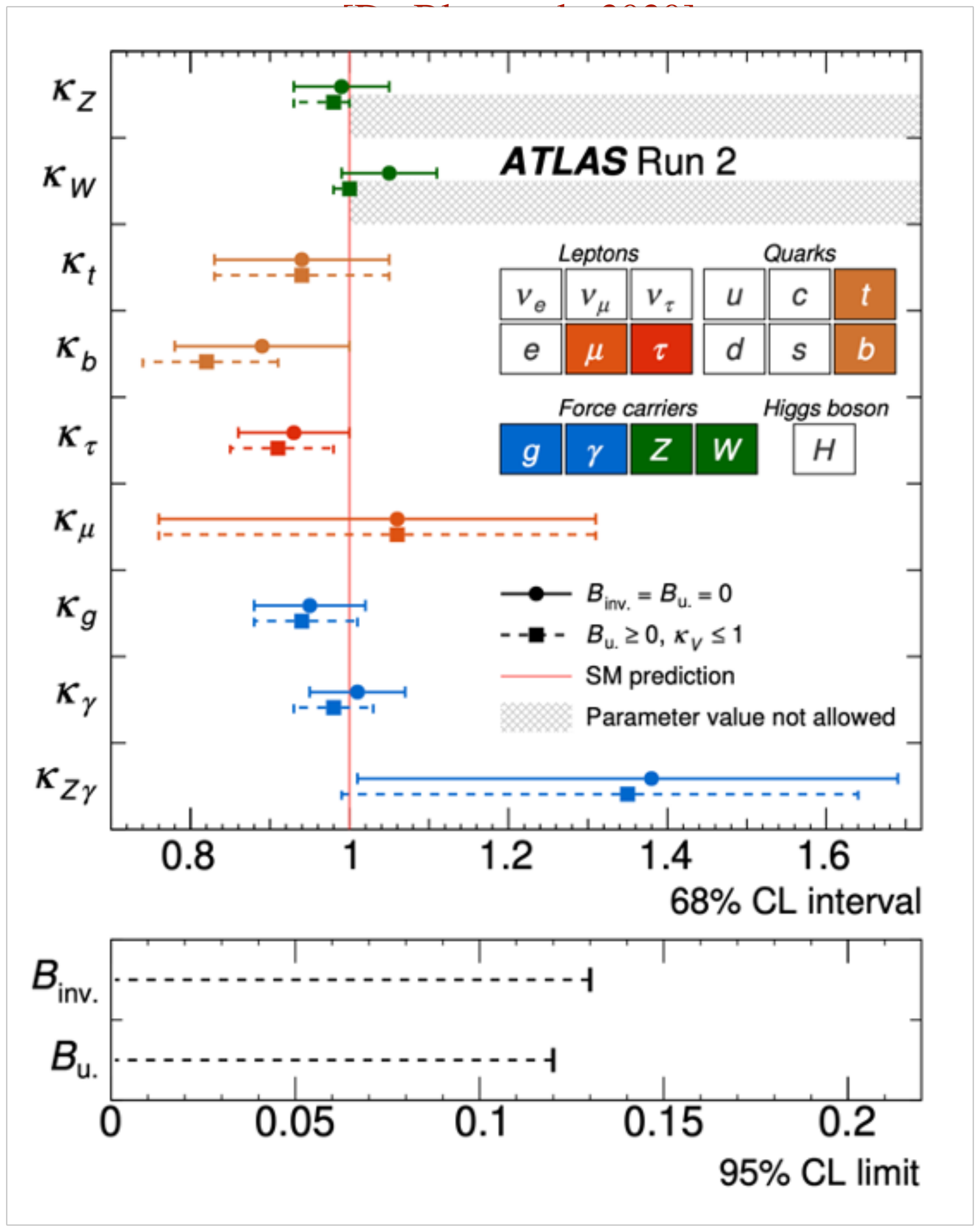
We are at 1/3 of our adventure with 1/20 of the expected data

The Higgs future

Couplings at HL-LHC

The Higgs future

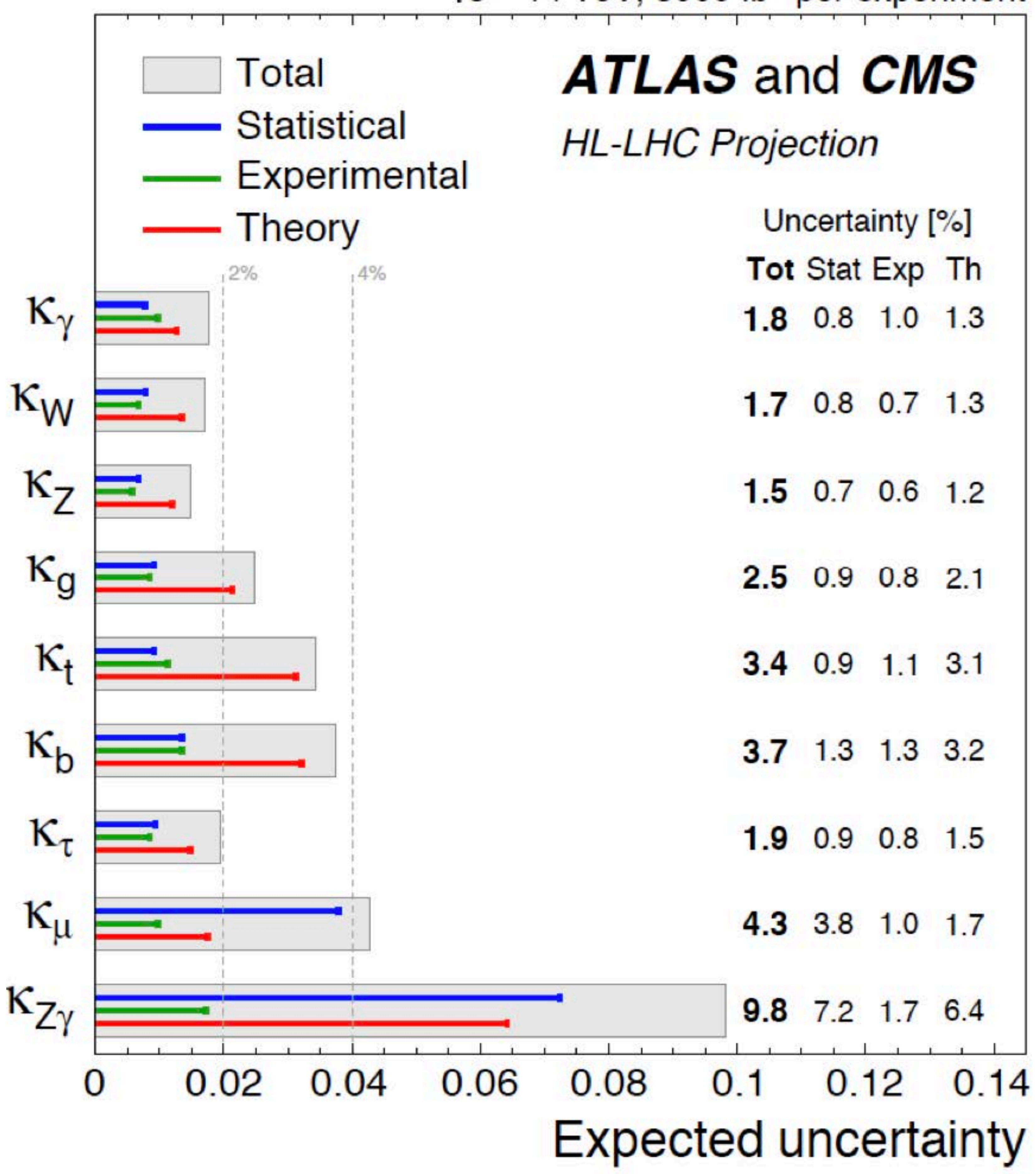
Couplings at HL-LHC



10-20%

2-4%

[De Blas et al., 2020]



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

The importance of being the Higgs boson

- Many questions and mysteries remain open that call for a deeper understanding.

- The first elementary (?) scalar interaction => a force not from a gauge symmetry (?).

- A scalar particle opens the gates to New Worlds:

$$(\Phi^\dagger \Phi) \qquad (\bar{L}\Phi_c)$$
$$\text{dim}=2 \qquad \text{dim}=5/2$$

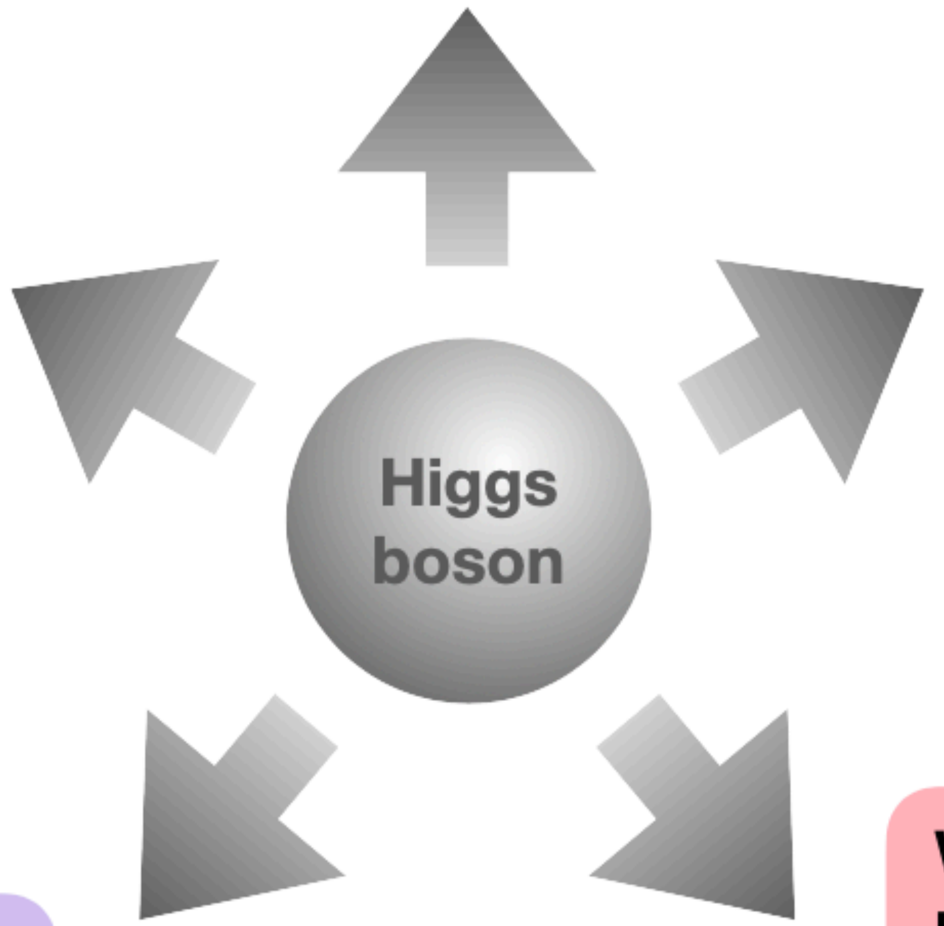
- Provide a template for: inflation modelling, extension of gravity, dark matter,

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

The importance of being the Higgs boson

- Many questions and mysteries remain open that call for a deeper understanding.
- The first ele
=> a force no
- A scalar par
Worlds:

$(\Phi^\dagger\Phi$
dim=

- Provide a template for: inflation modelling, extension of gravity, dark matter,

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions

What is the origin of the early-universe inflation?

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W and Z?

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antimatter in
?

rge-parity
s decays?
malies in the
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- Are there multiple Higgs sectors?

consistent with the Standard Model?
- Are there new decay modes of the Higgs?

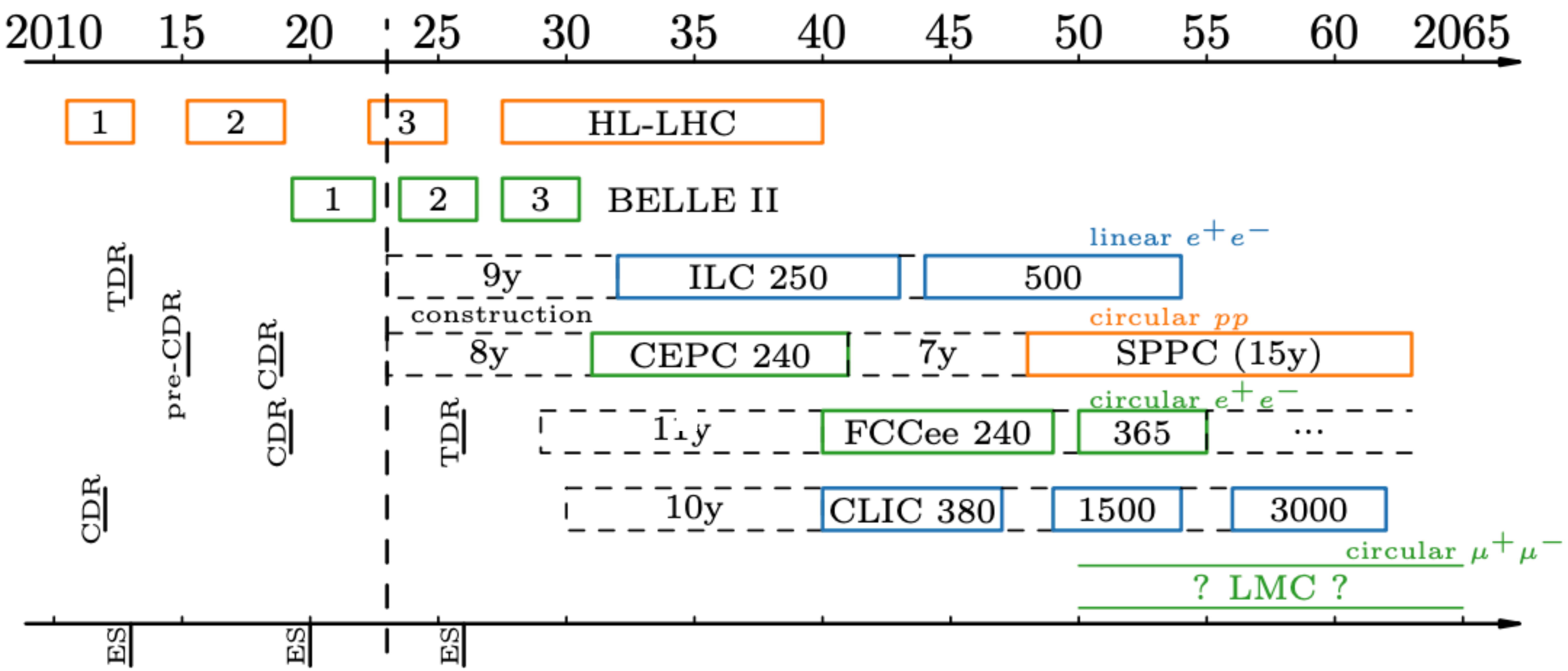
PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH!

NHA@ 10 years HIGGS boson discovery

Our leptonic future(s)

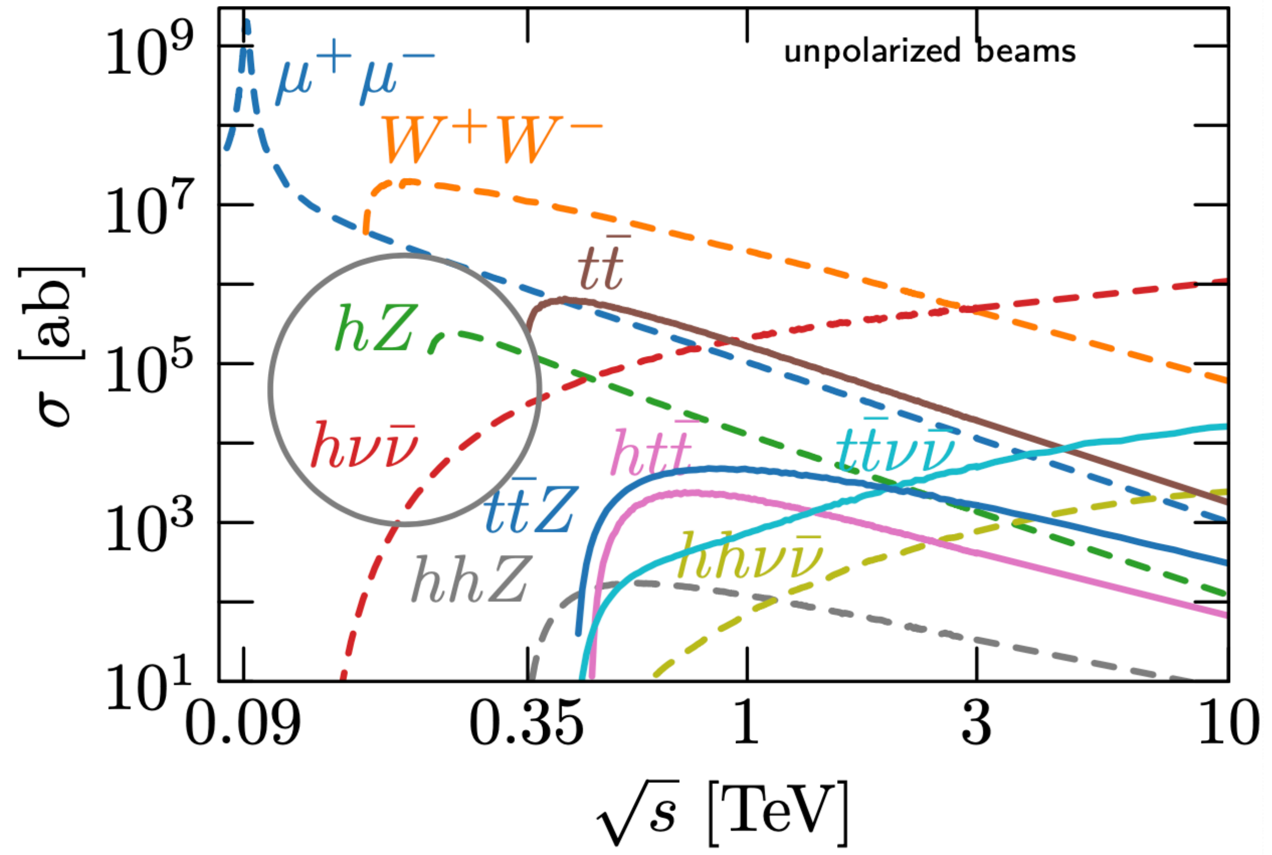
Higgs-and-more factories



Extensive studies with ESU & Snowmass and now in ECFA w/ 10^6 Higgs bosons

Our leptonic future(s)

Higgs-and-more factories



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

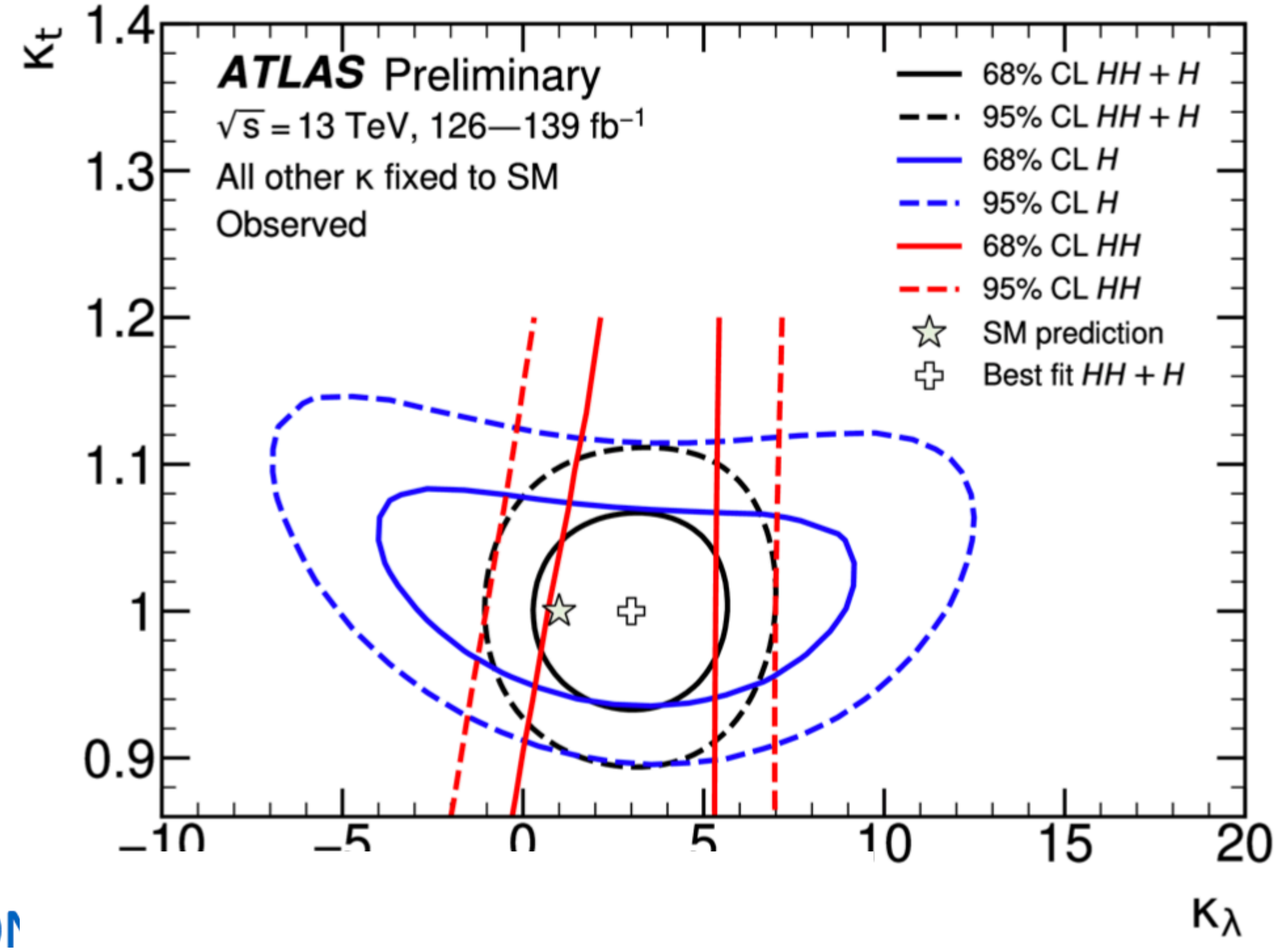
Extensive studies with ESU & Snowmass and now in ECFA w/ 10^6 Higgs bosons

HL-LHC projections

Higgs self-coupling

Now

[ATLAS, 2022]

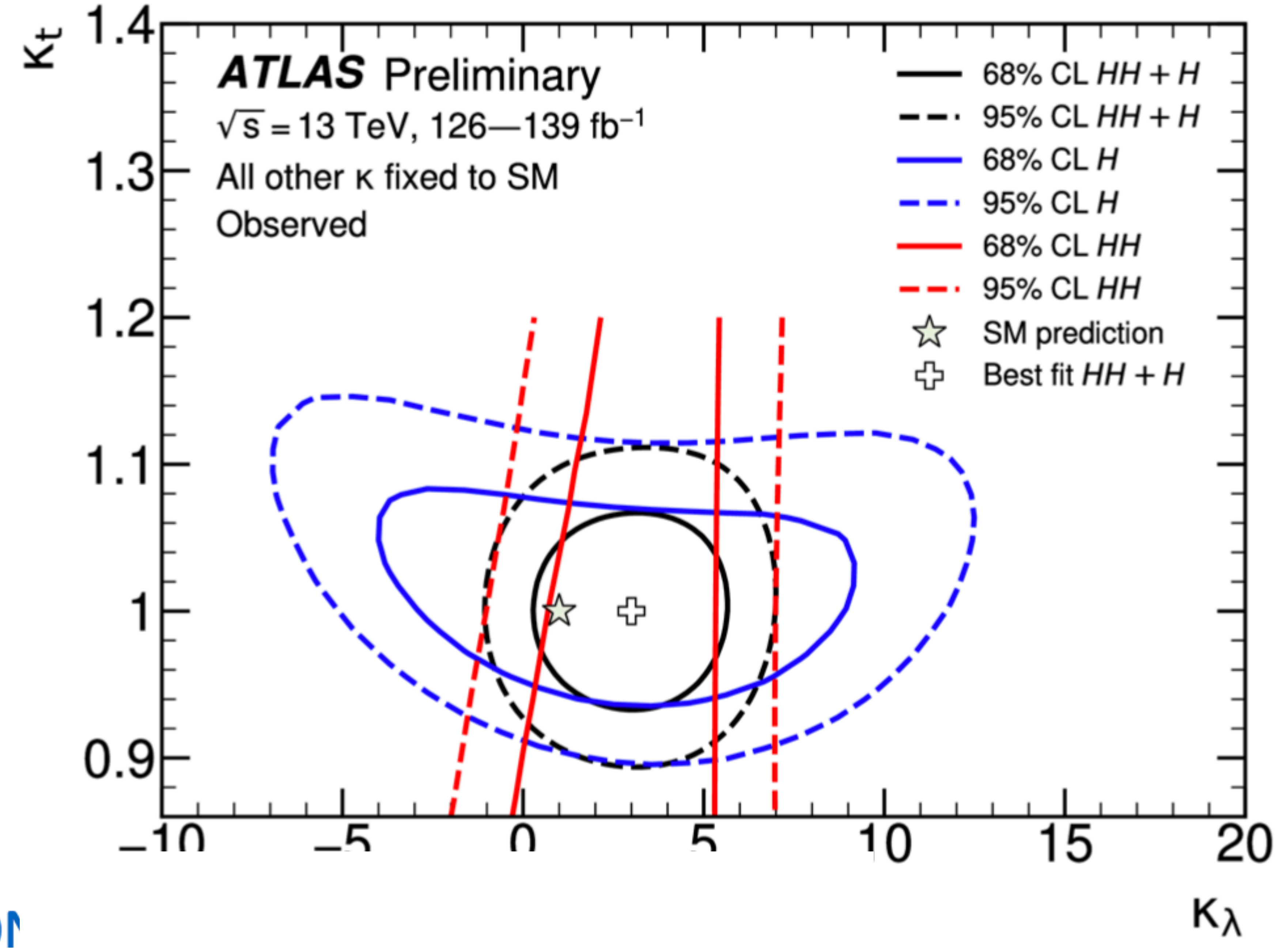


HL-LHC projections

Higgs self-coupling

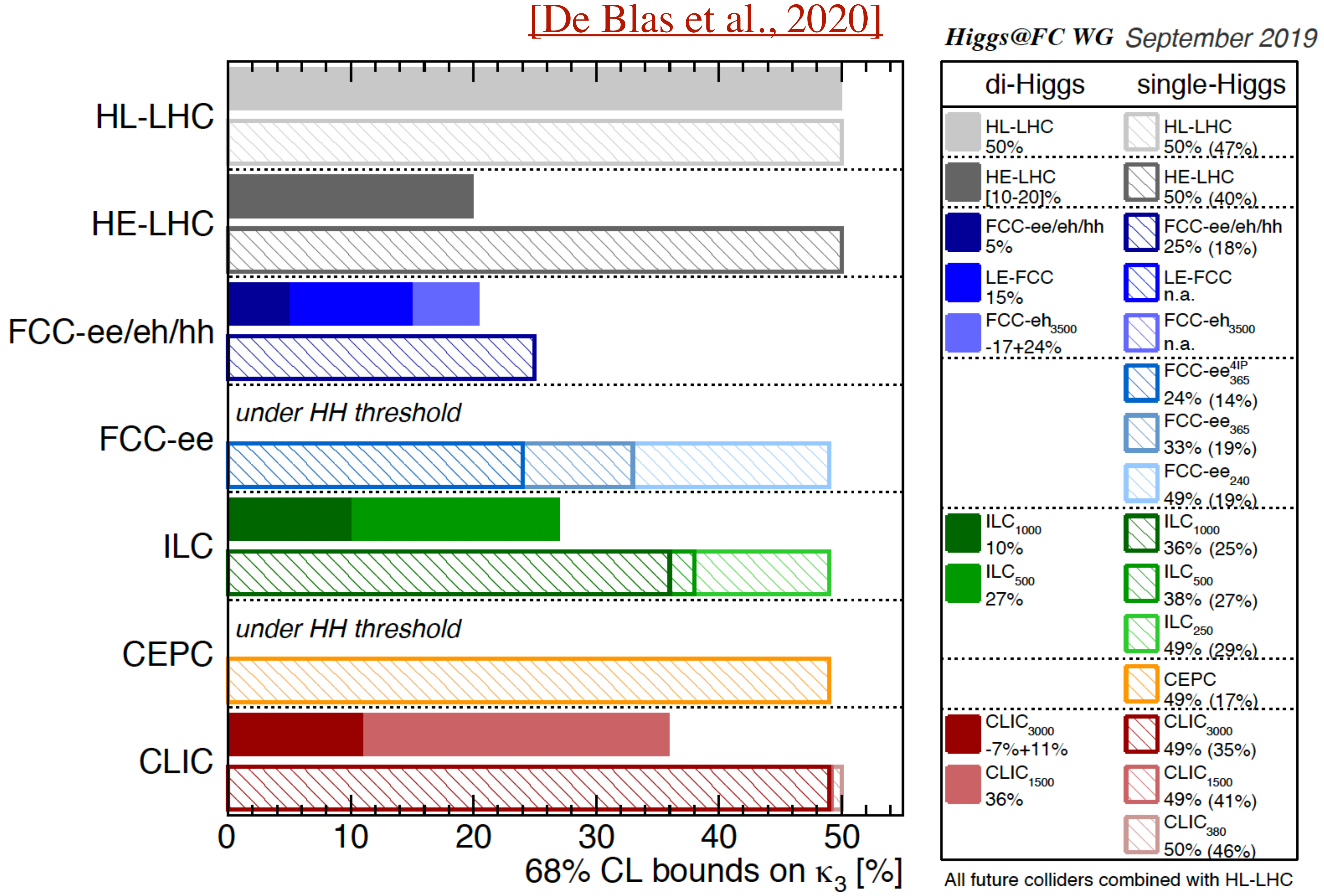
Now

[ATLAS, 2022]



Future

[De Blas et al., 2020]

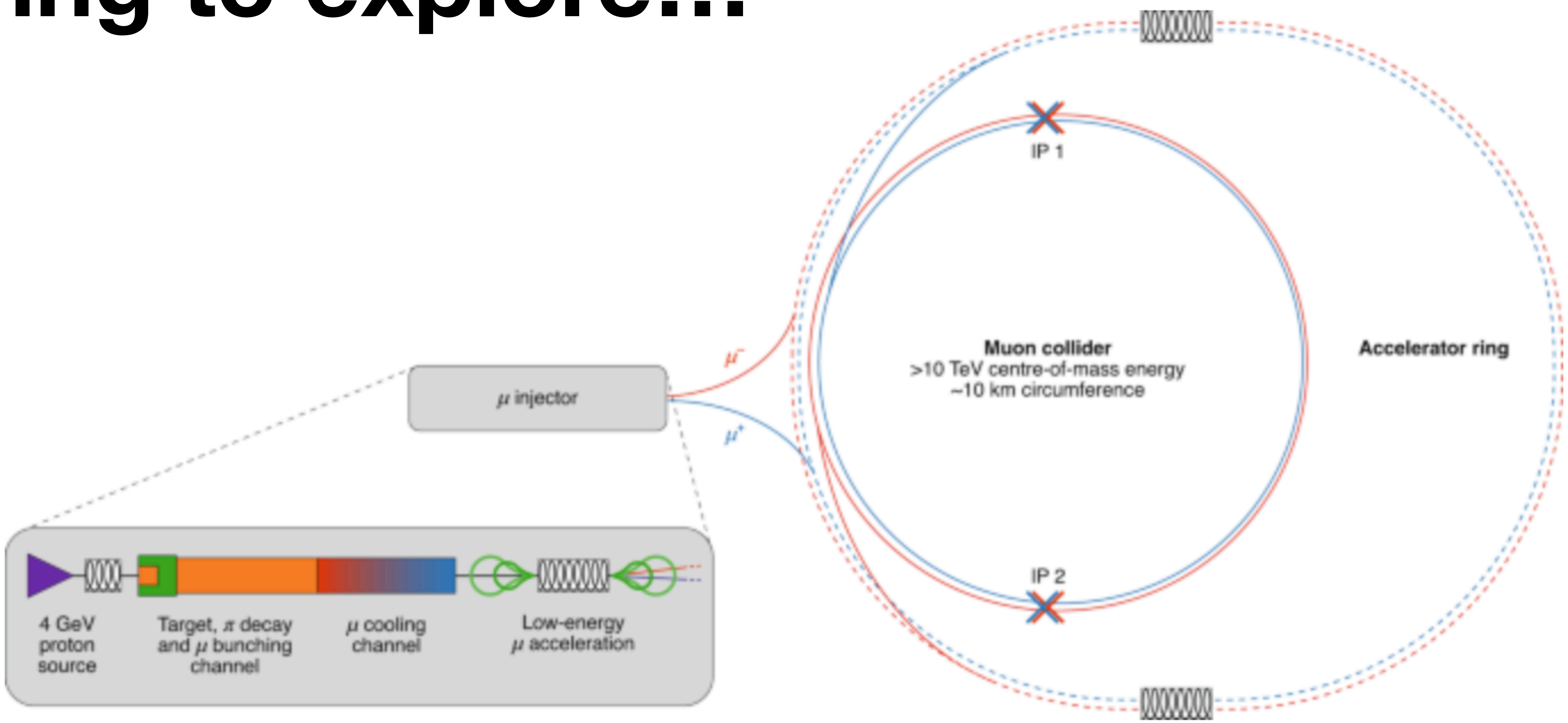


Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.
Borderline sensitivity to say something about EW baryogenesis…

Daring to explore…

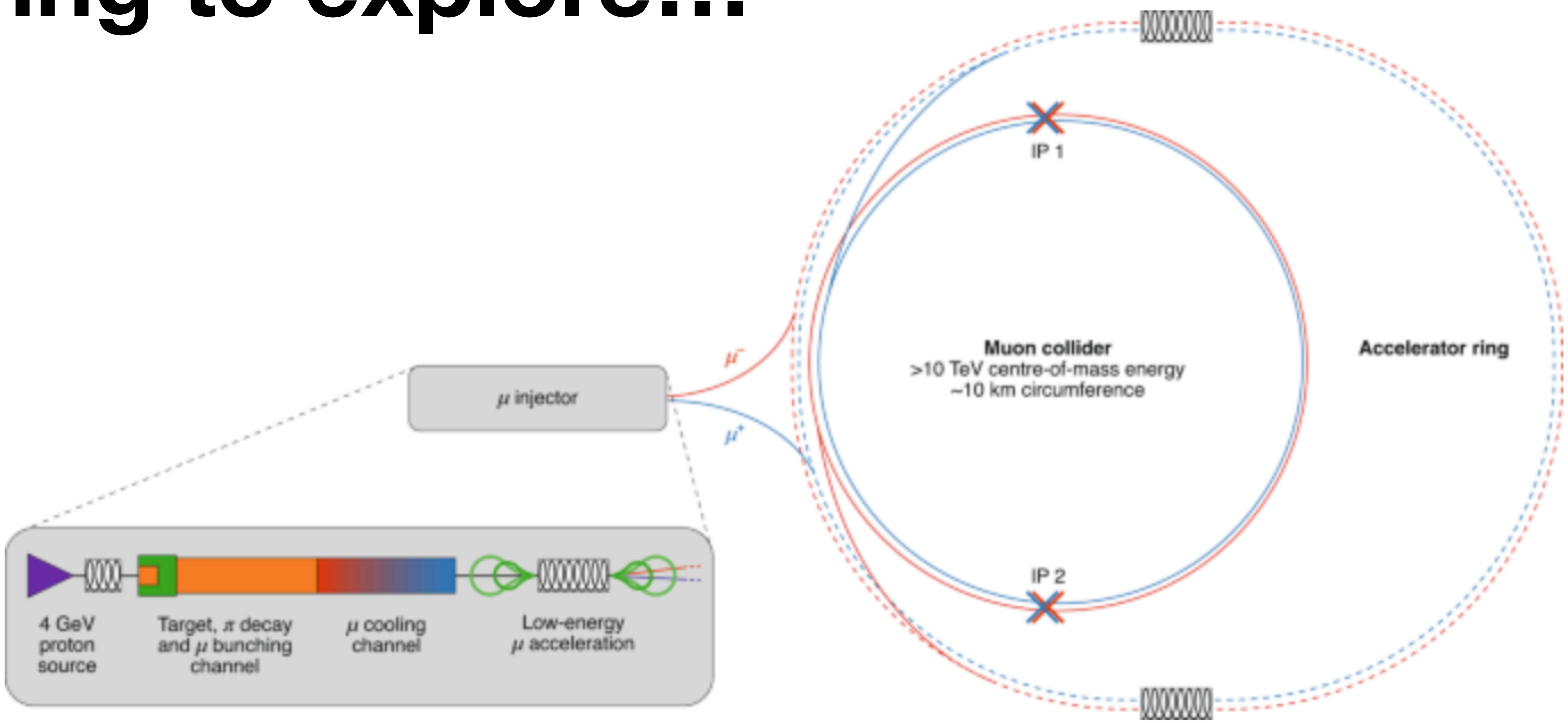
International MUON Collider Collaboration

Daring to explore…



International MUON Collider Collaboration

Daring to explore…

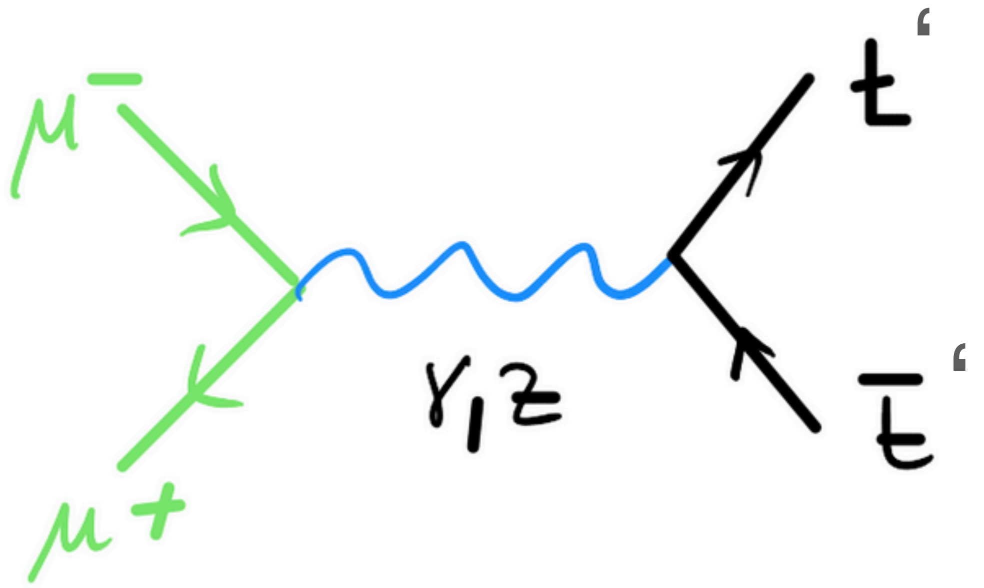


…the muon collider option

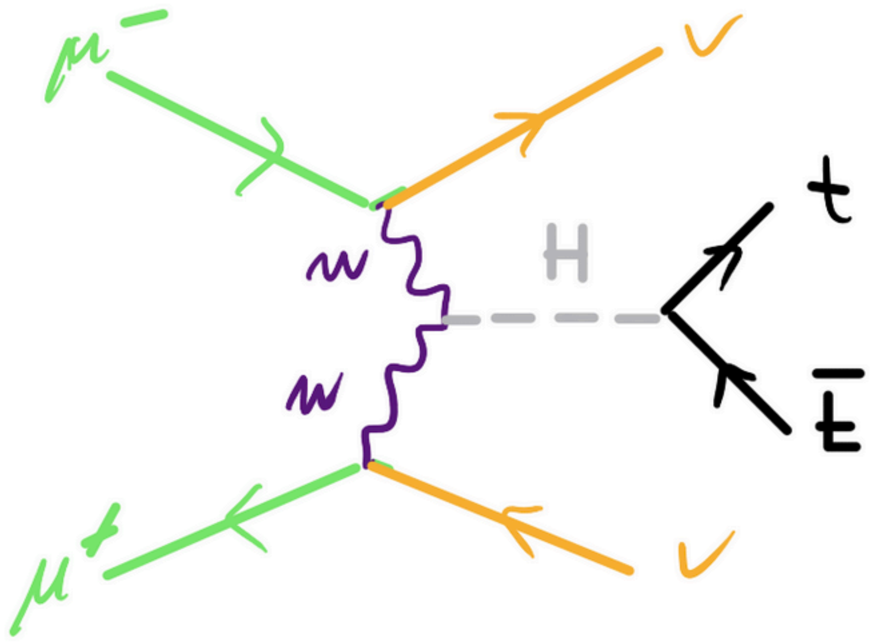
Muon collider physics

The essentials #1 : two colliders in one

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



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



Energetic final states
(either heavy or very boosted)

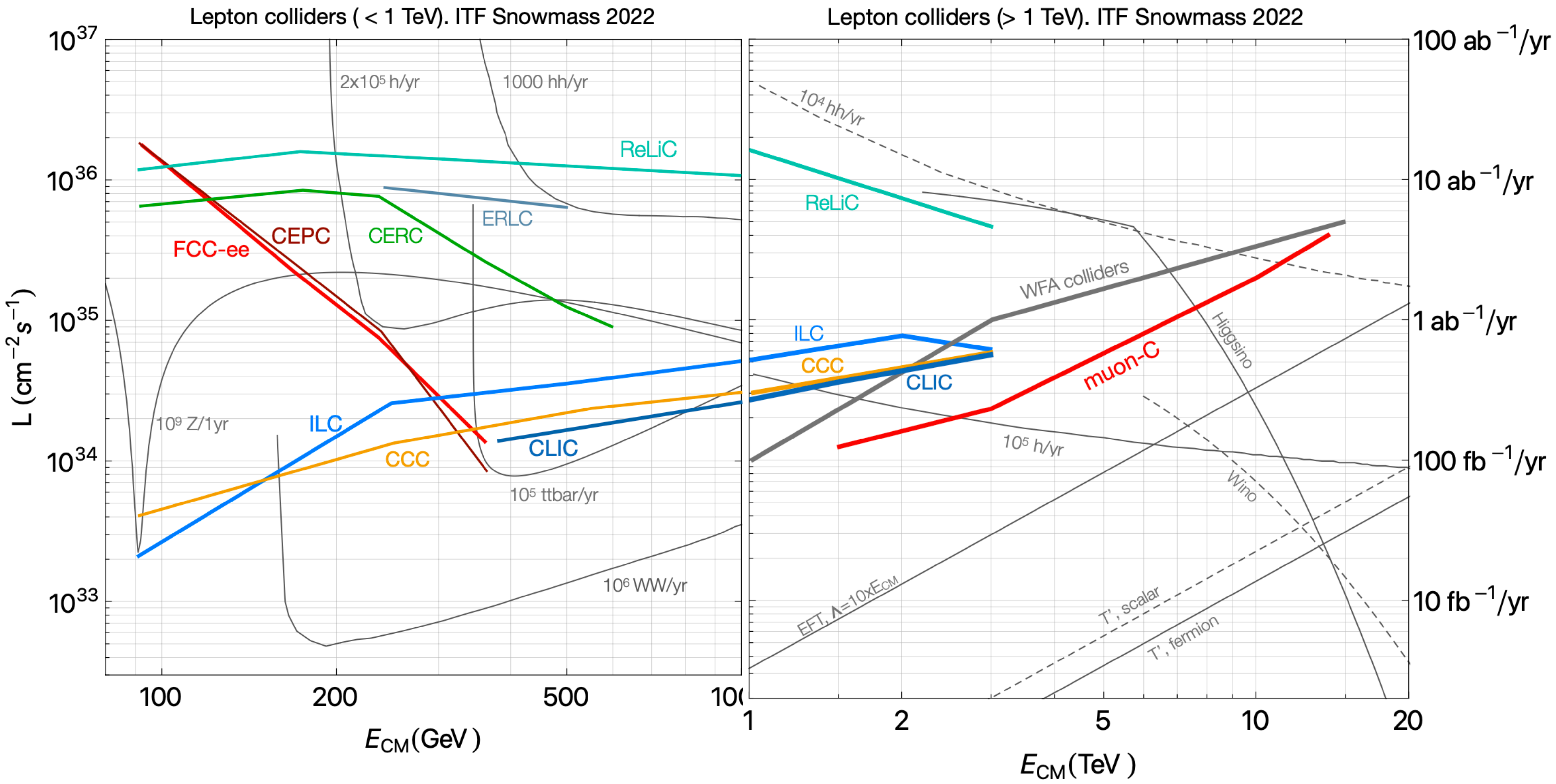
Large production rates,
SM coupling measurements
Discovery light and weakly interacting

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

Different physics being probed in the two channels

Muon collider physics

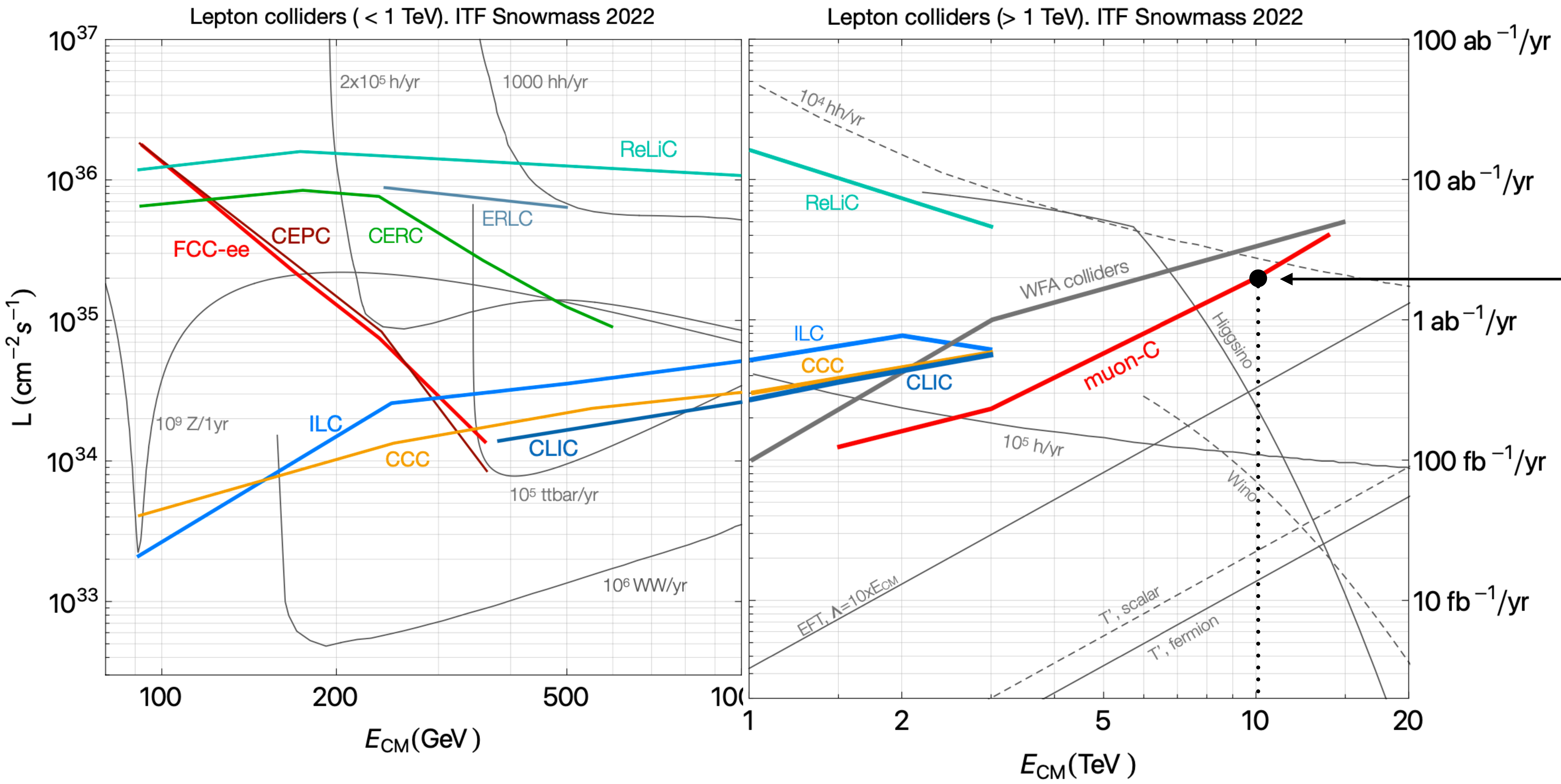
The essentials #2 : luminosity with energy



arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #2 : luminosity with energy



10 ab^{-1} in 5 years

arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #3: compactness

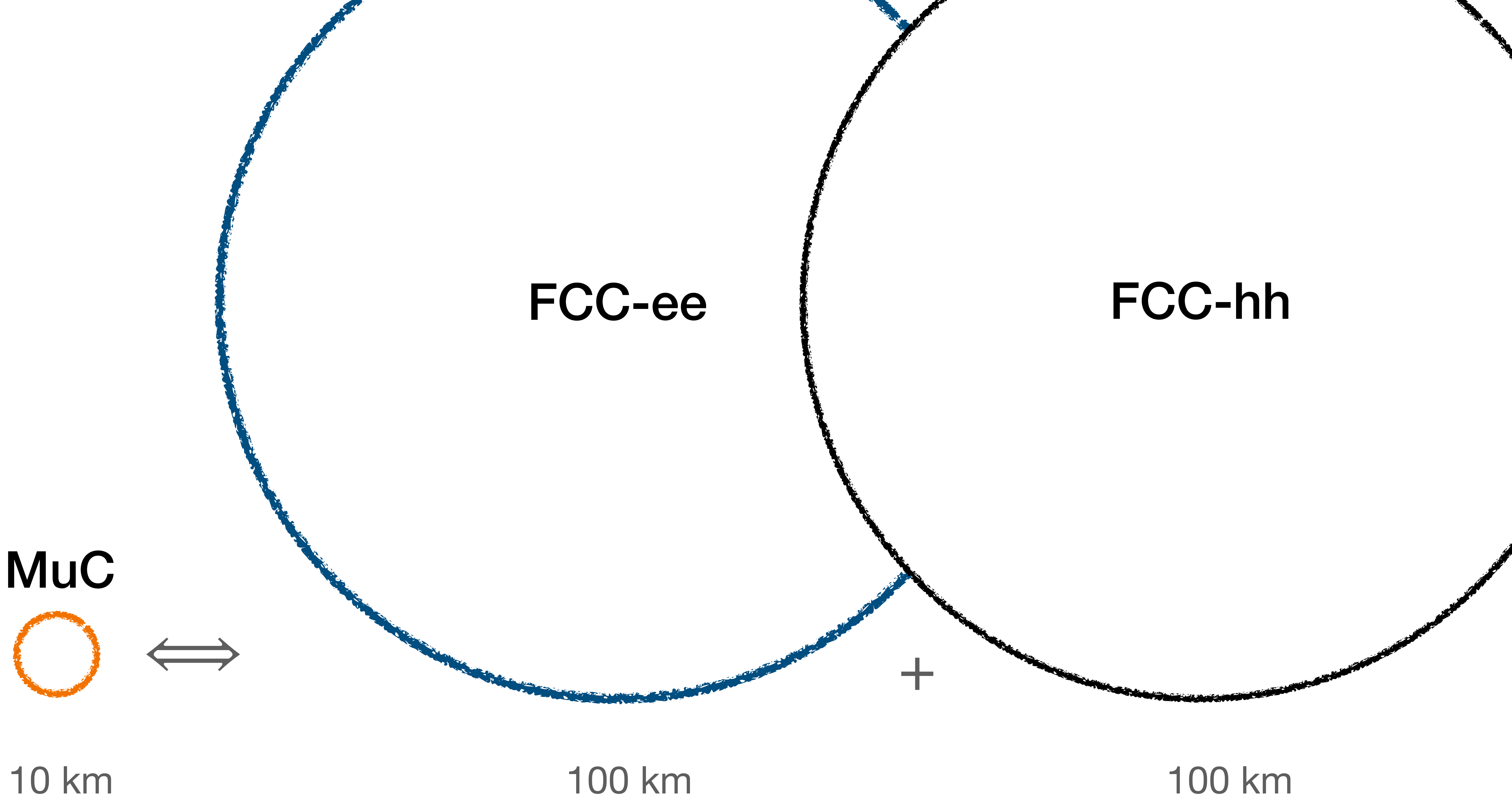
x

t

Muon collider physics

The essentials #3: compactness

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



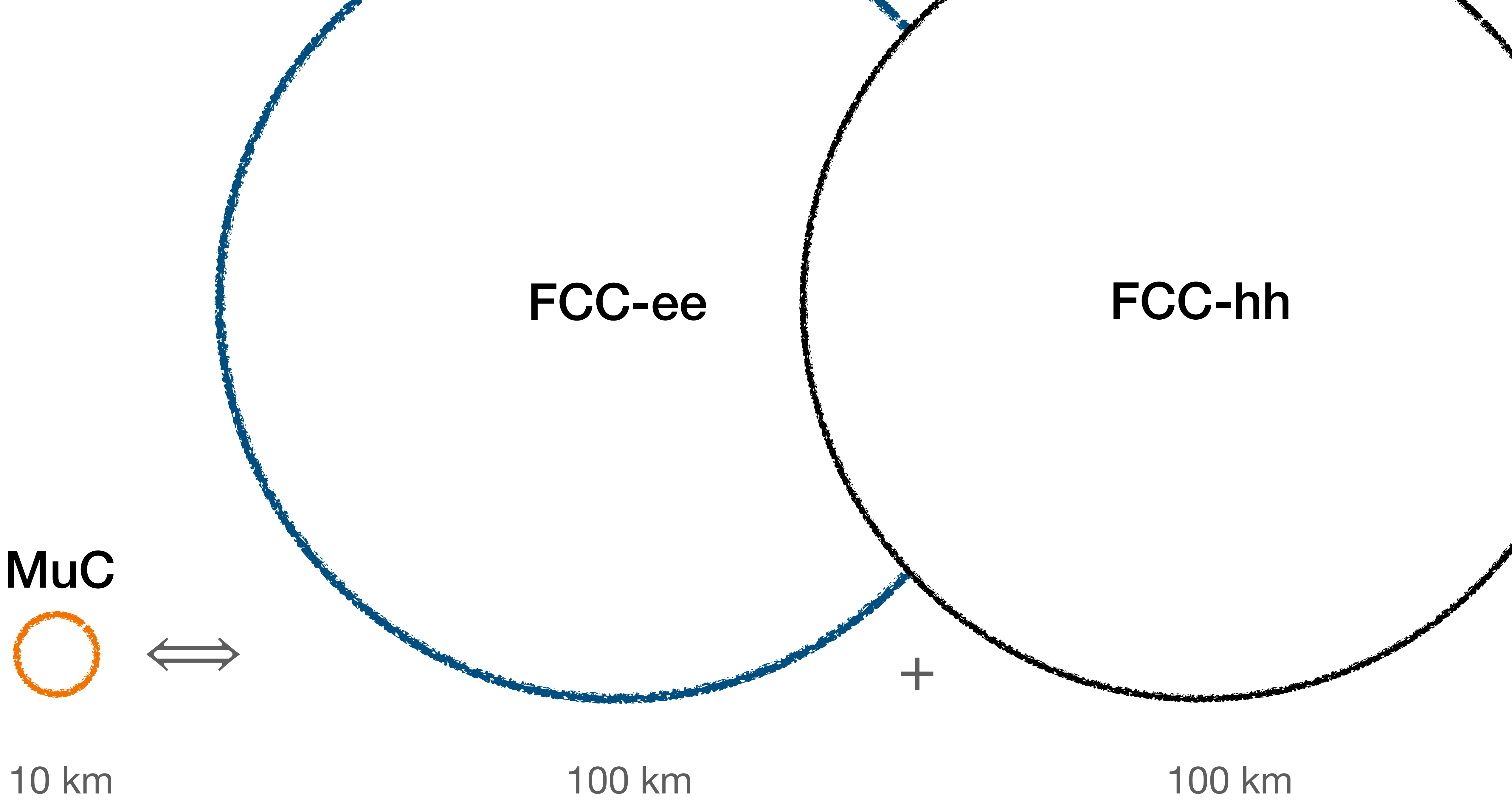
x

t

Muon collider physics

The essentials #3: compactness

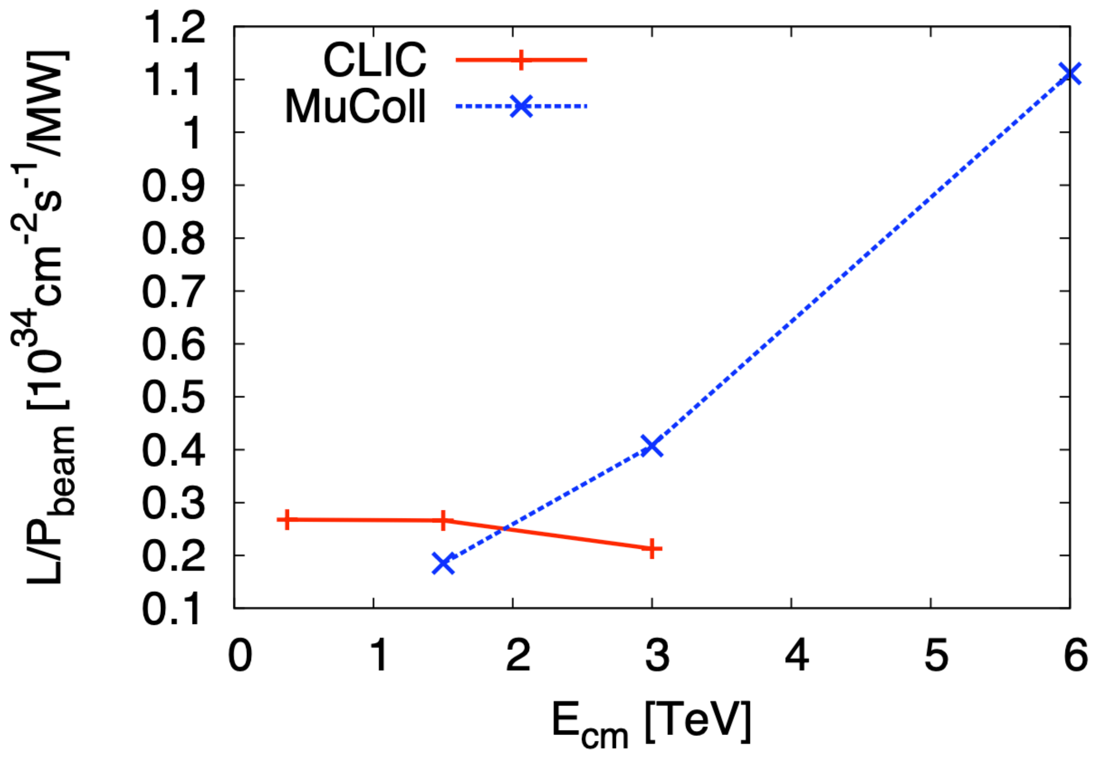
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:



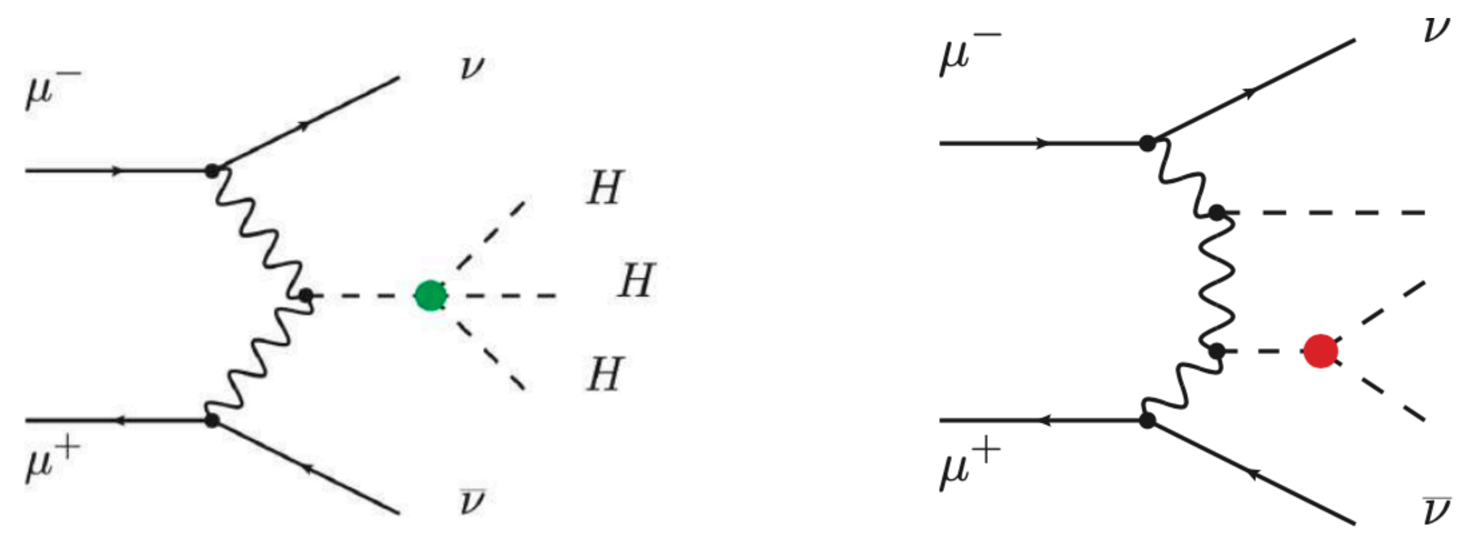
⇒MuC is an STCC = Space-Time-Compact Collider

⇒ Goal of the tens:

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

[Chiesa, Mele, Piccinini et al. 2020]

Higgs precision physics
The essentials #4: Higgs physics

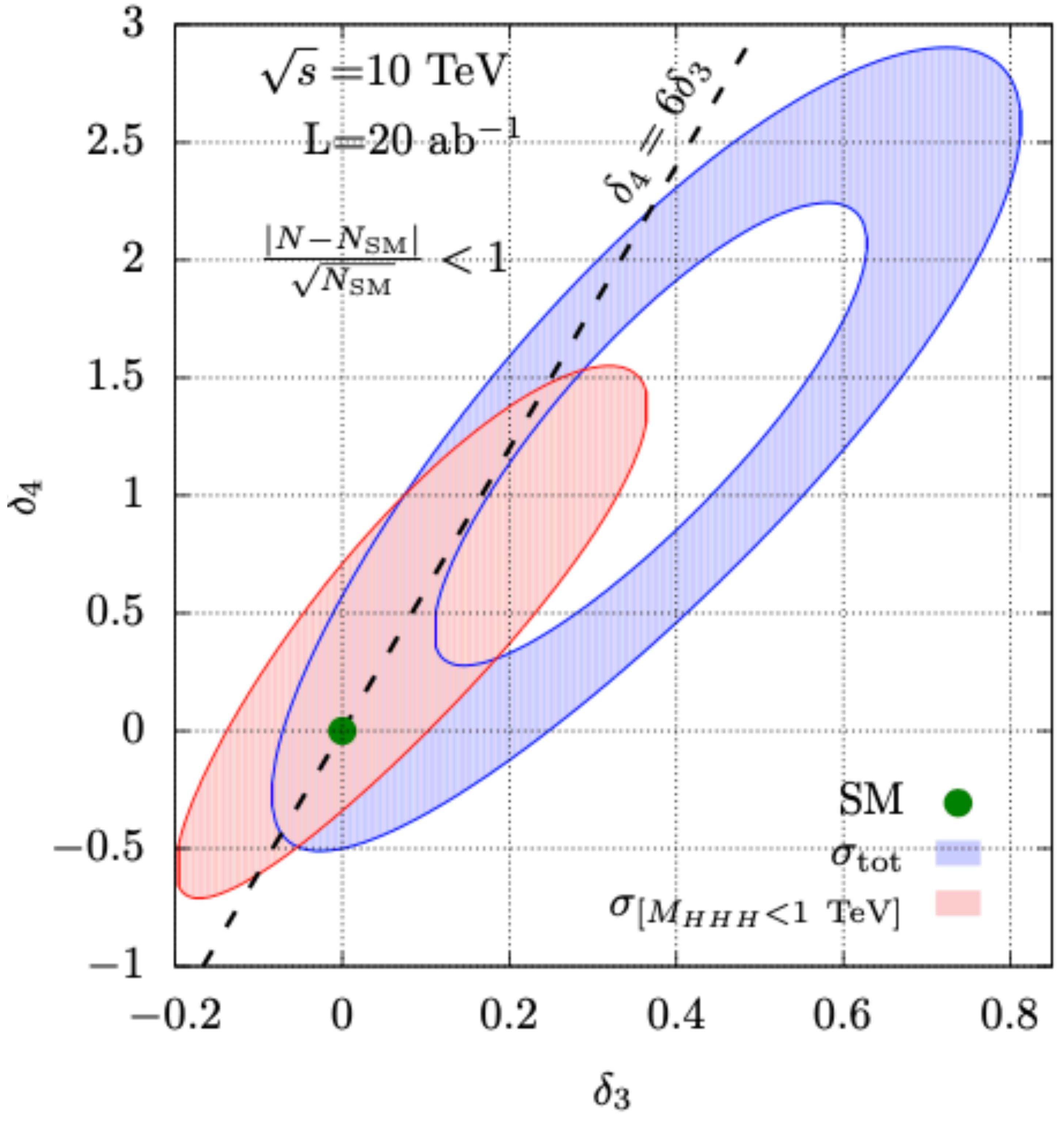


arXiv:2203.07256v1

	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

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



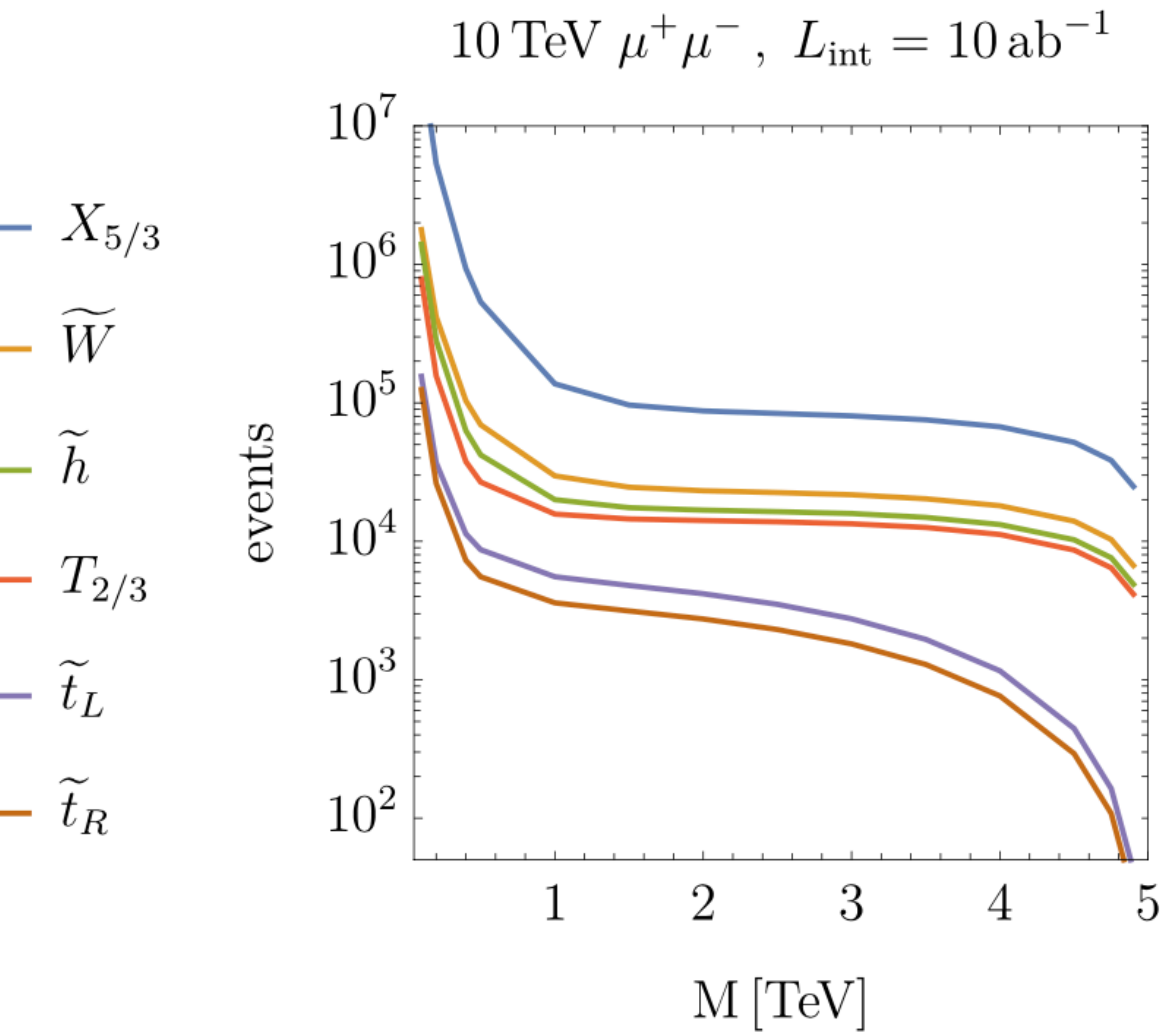
$$10\,\text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

Similar constraining power of
a ee Higgs factory

Muon collider physics

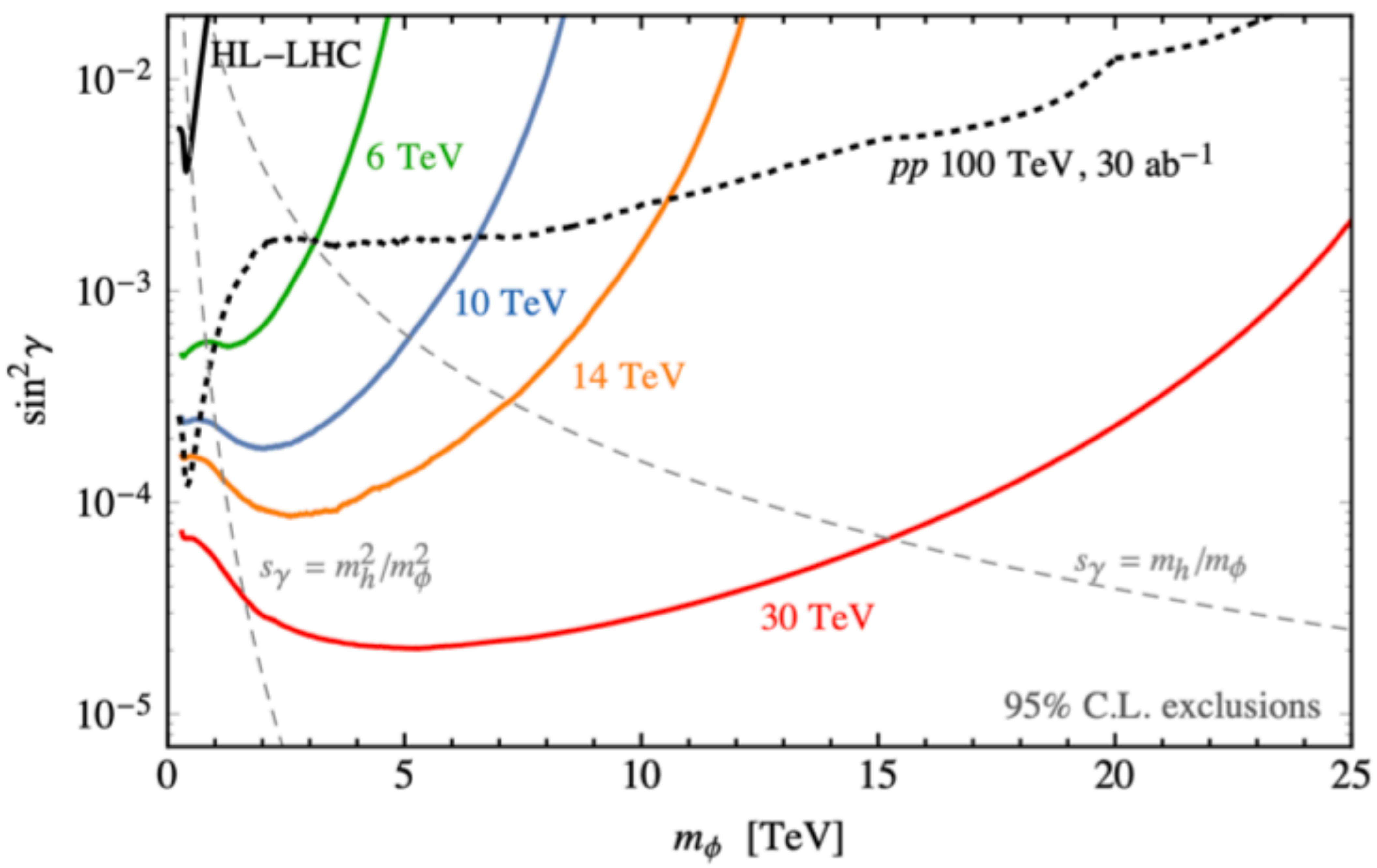
The essentials #5: New Physics

[Franceschini, Wulzer, 2021]



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

[Buttazzo, Redigolo, Sala, Tesi, 1807.04743]



Exclusion contour for a scalar singlet of mass m_φ mixed with the Higgs boson with strength $\sin\gamma$.

Final considerations

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- We have gone a long way and established a Standard Theory for matter and strong+electroweak interactions.

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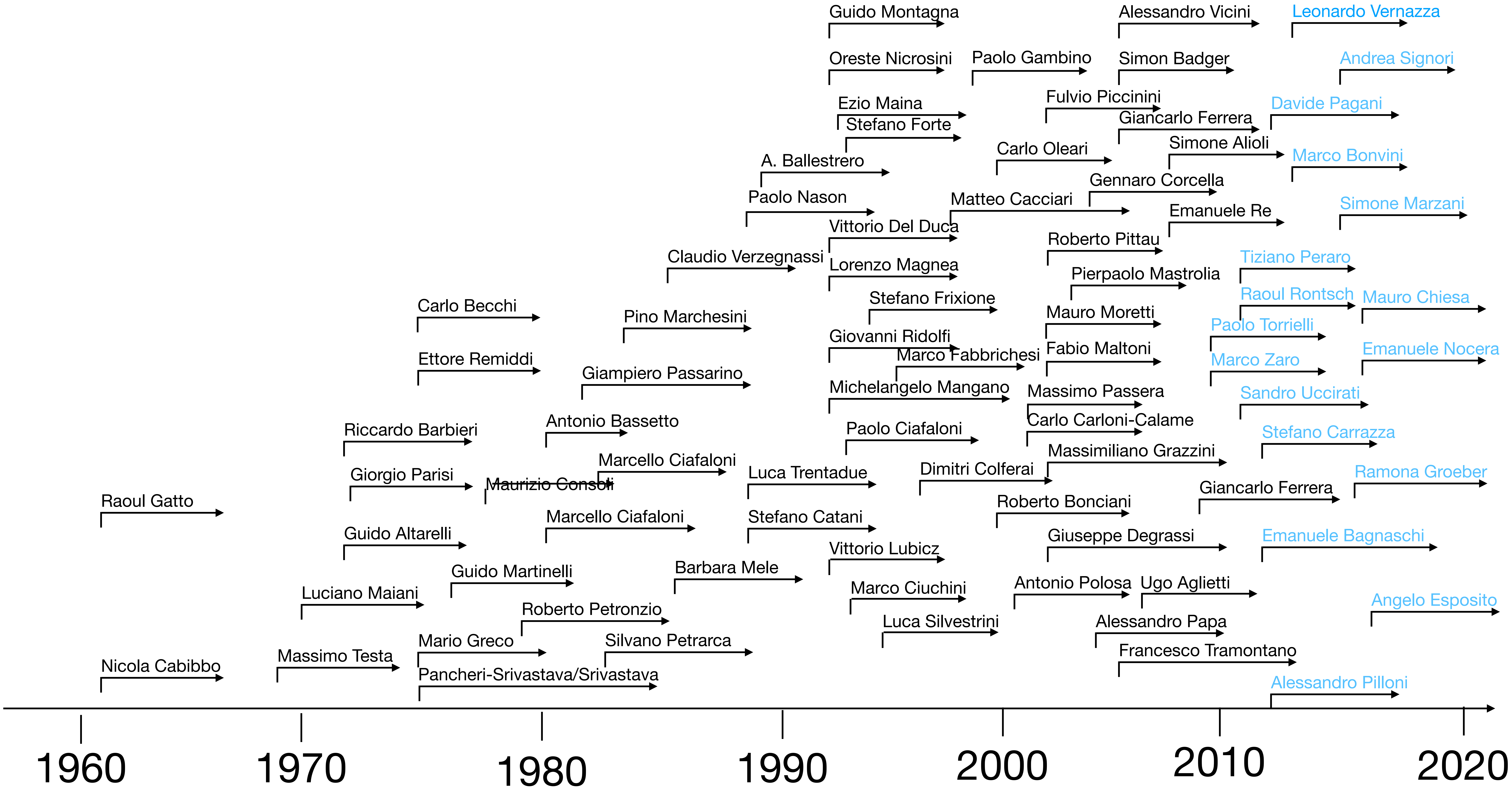
Disclaimers: Illustrative only. Incomplete. Affected by memory bias. Date indicative of the first very important contribution.

Precision predictions for colliders



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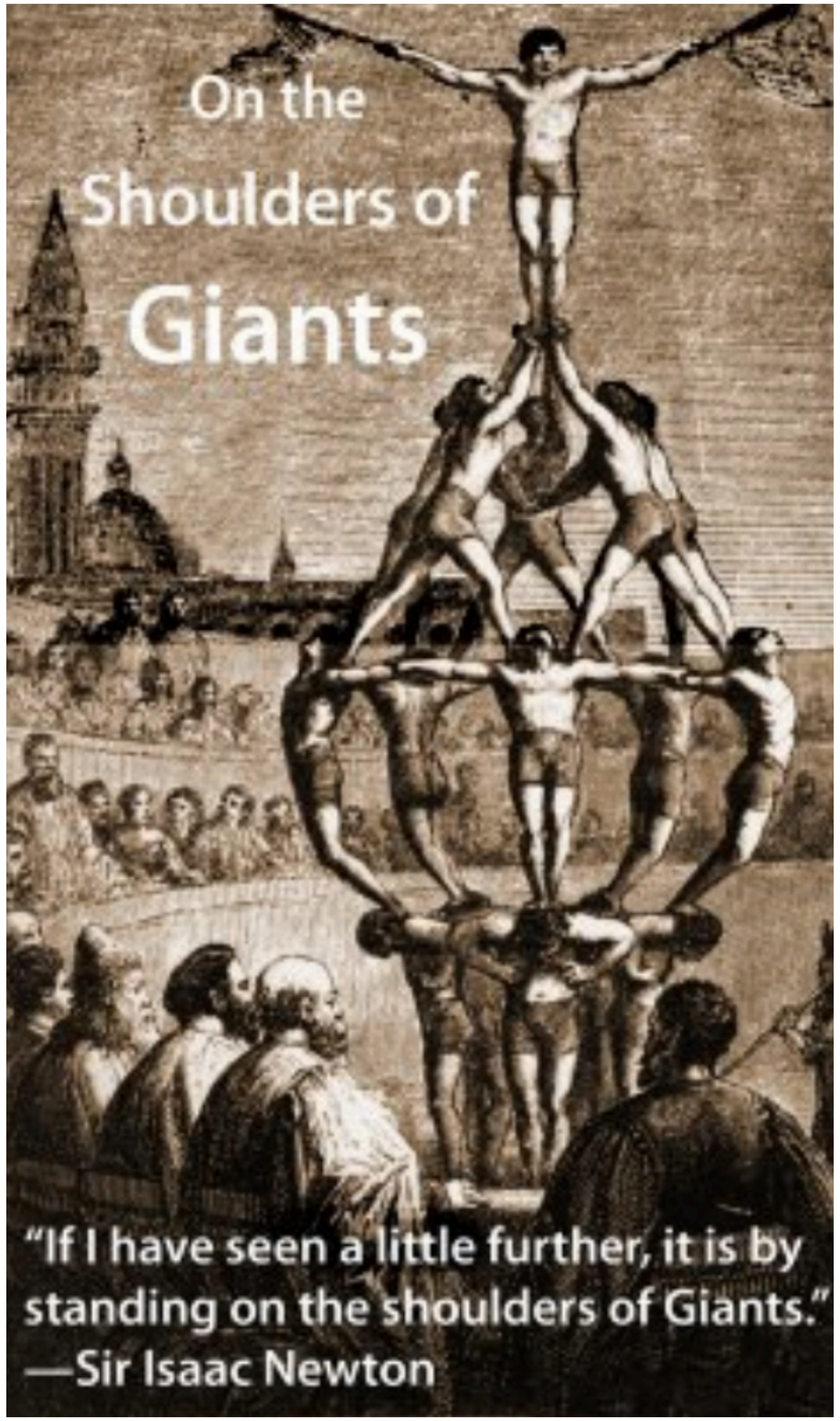
Beyond the SM for colliders

Final considerations

- We have gone a long way and established the Standard Theory for strong and electroweak interactions.
- Our story has been made by many enthusiastic and passionate theorists and experimentalists aligned to the same goals.
- Our future is in the hands of a strong and ambitious new generation of young theorists.



Final considerations

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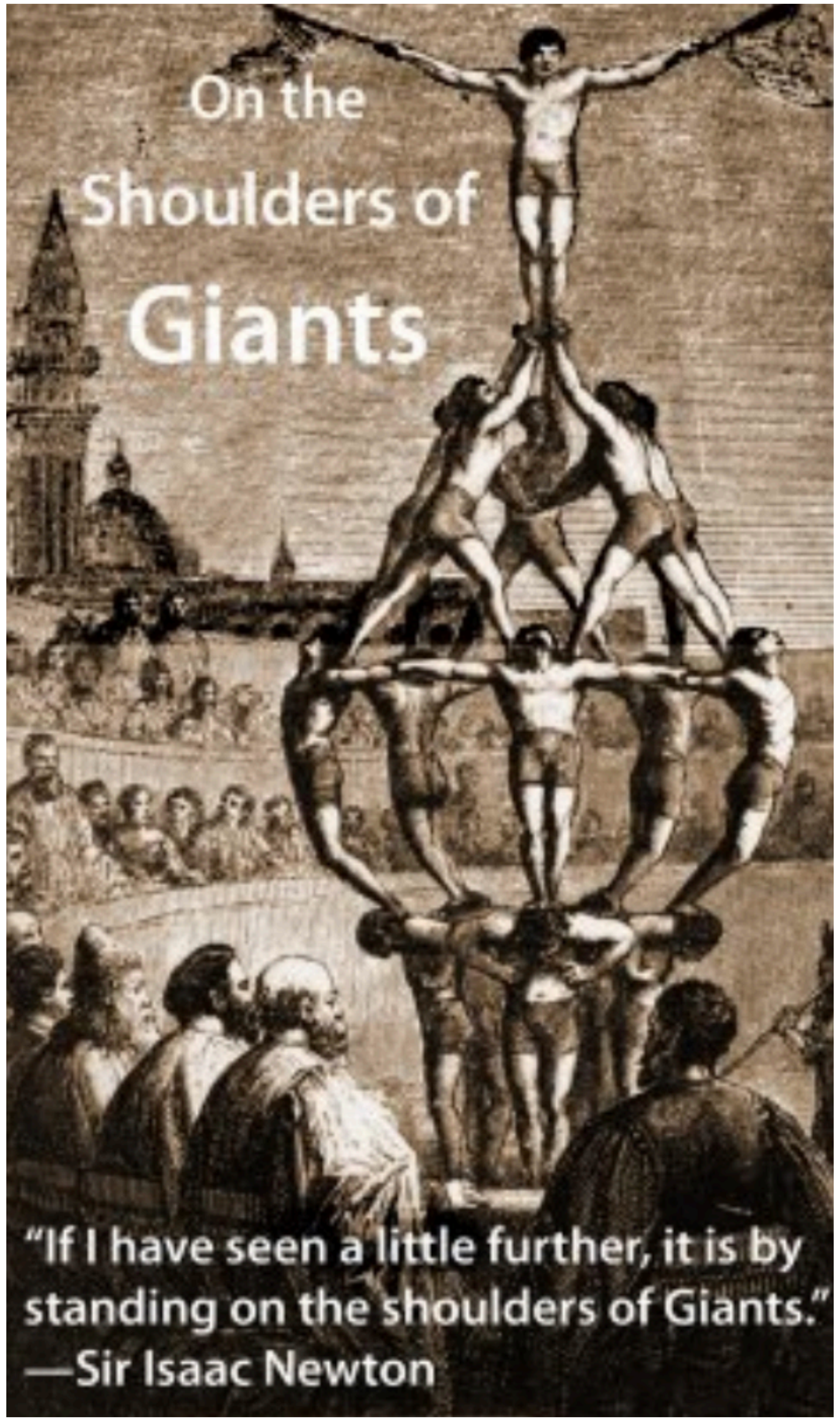
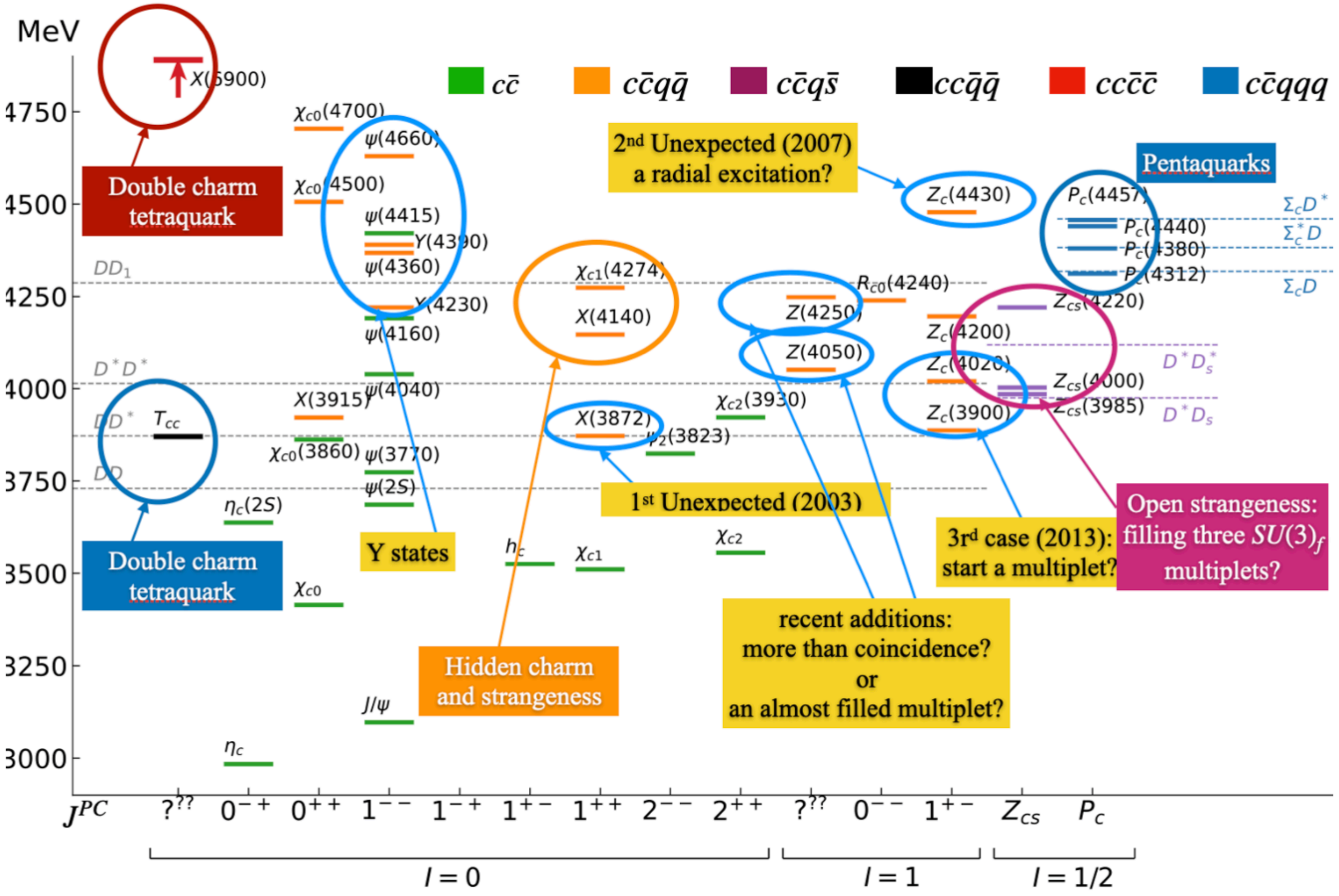
Thanks!

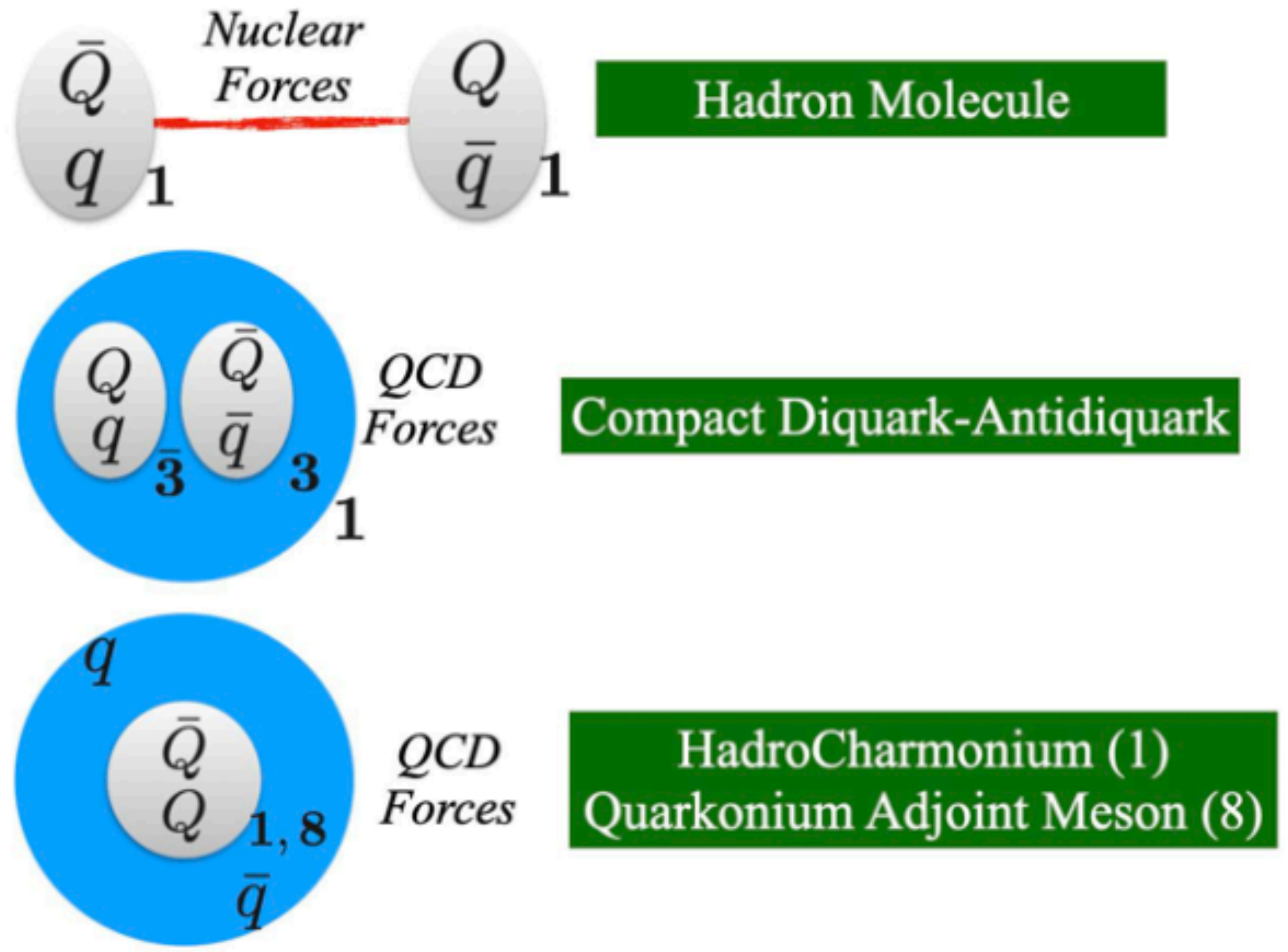


Some additional material

QCD bound states are still hot

Excitement in the hadron community

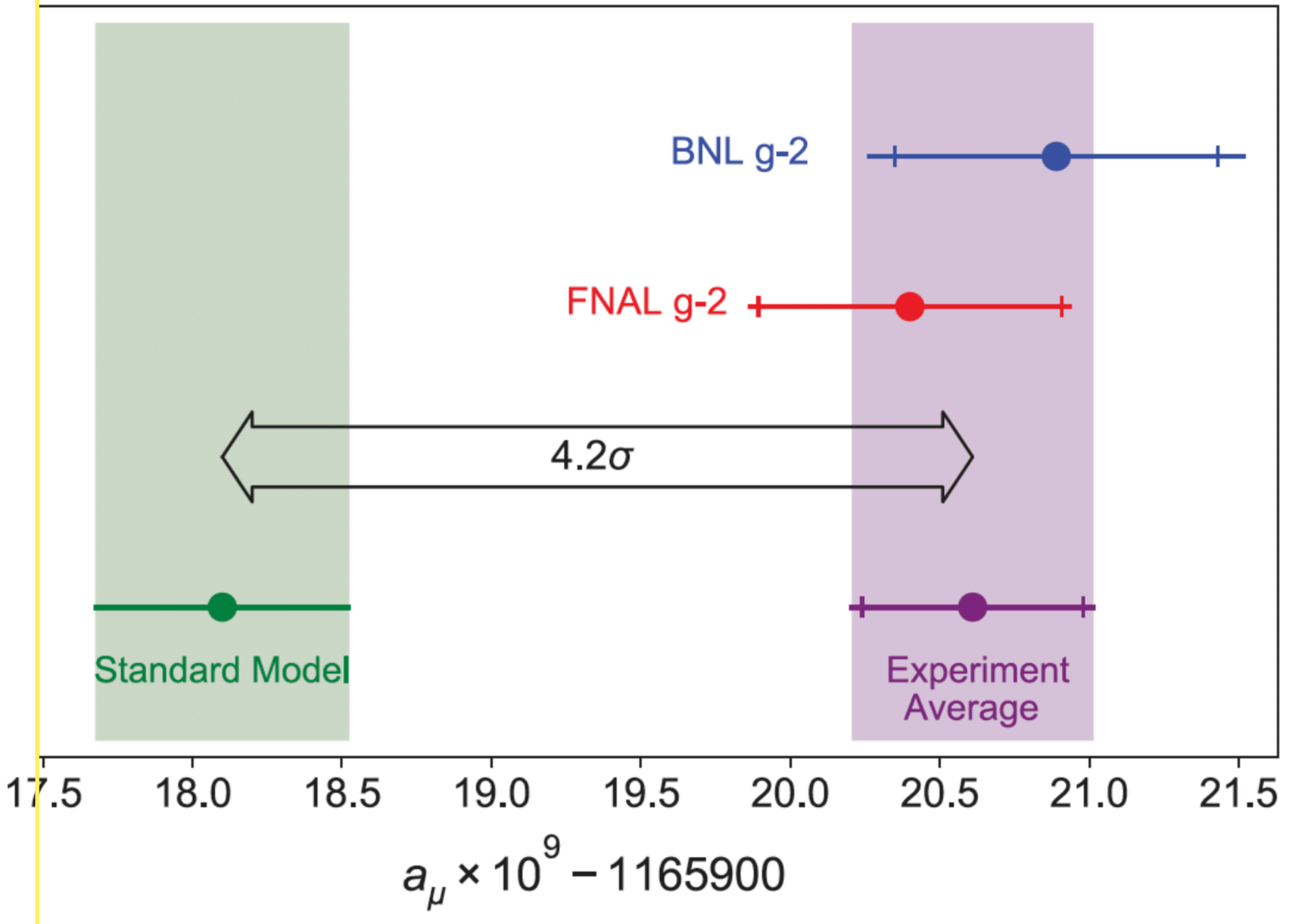




[Maiani, Polosa, Piccinini, Riquer, 2004/2005/2014/2015]
[Maiani, Pilloni,2022]

G-2

QED



3.7 σ

3.3 σ

4.2 σ

a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [0.54ppm] BNL E821

a_μ^{EXP} = (116592040 ± 54) x 10^{-11} [0.46ppm] FNAL E989 Run 1

a_μ^{EXP} = (116592061 ± 41) x 10^{-11} [0.35ppm] WA

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
Experiment (E989 – Run I)	116592040(54)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	279(76)

$a_\mu^{\rm QED} = (1/2)\,(\alpha/\pi)$ [Schwinger, 1948]

$+\,0.765857426\ (16)\ (\alpha/\pi)^2$

[Sommerfield; Petermann; Suura&Wichmann '57; Elend '66]

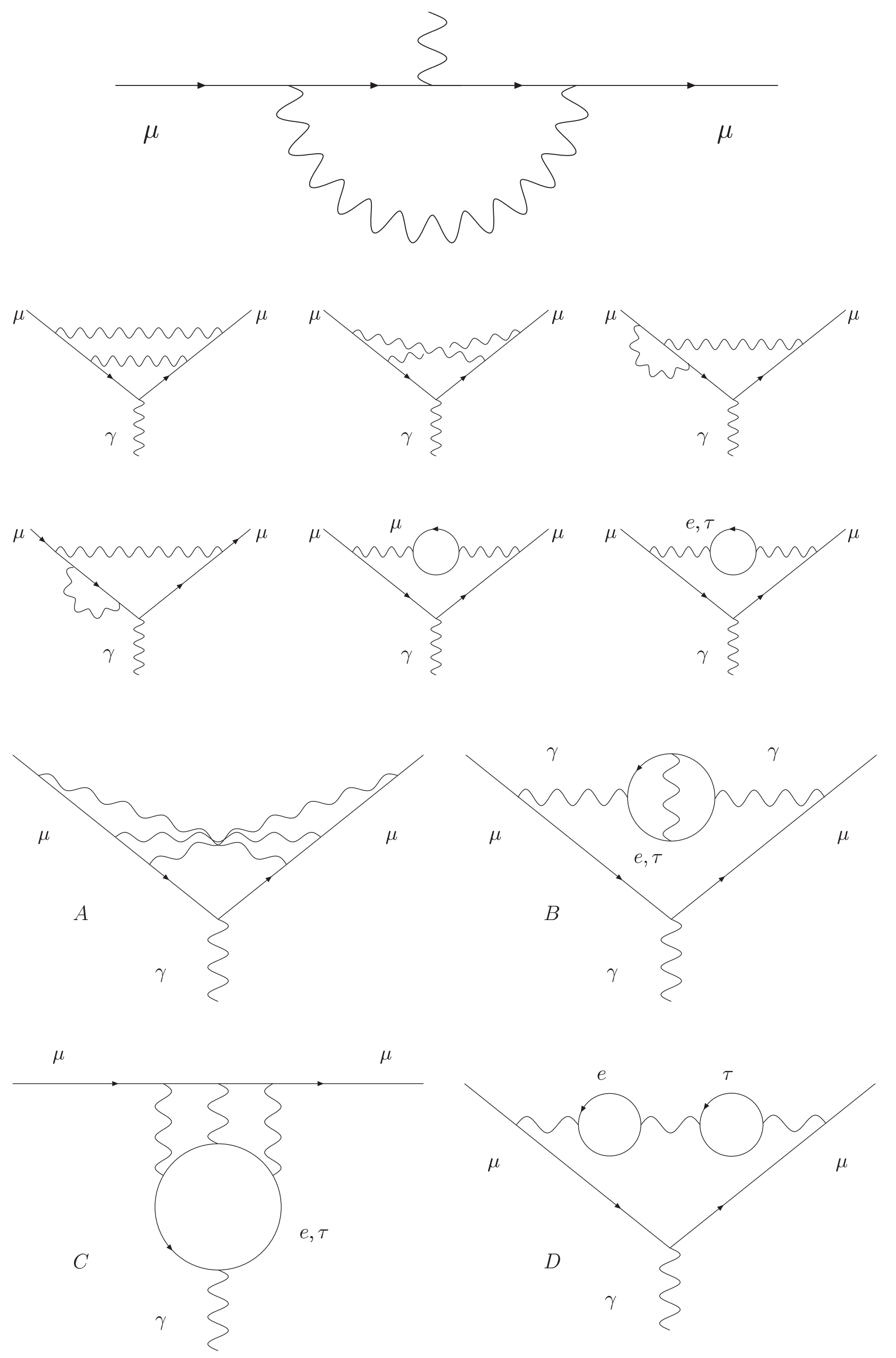
$+\,24.05050988\ (28)\ (\alpha/\pi)^3$

[Remiddi, Laporta, Barbieri...; Czarnecki, Skrzypek '99]

$+\,130.8780\ (60)\ (\alpha/\pi)^4$

[Kinoshita et al. '81-'15; Steinhauser et al. '13-'16; Laporta '17]

$+\,750.86\ (88)\ (\alpha/\pi)^5$ [Kinoshita et al. '90-'19]



a_μ^{QED} = 116584718.931 (19)(100)(23) x 10^{-11}

mainly from 4-loop coeff. unc. 6-loop from α(Cs)

α = 1/137.035999046(27) [0.2ppb] Parker et al 2018 WP20 value

[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]

G-2

HVP

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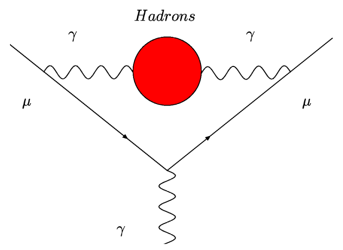
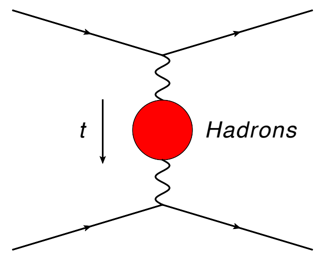
the timelike formula:



$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\text{had}}(s)$$

$$K(s) = \int_0^1 dx\, \frac{x^2(1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

- Alternatively, simply exchanging the x and s integrations:



$$a_\mu^{\text{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\text{had}}[t(x)]$$

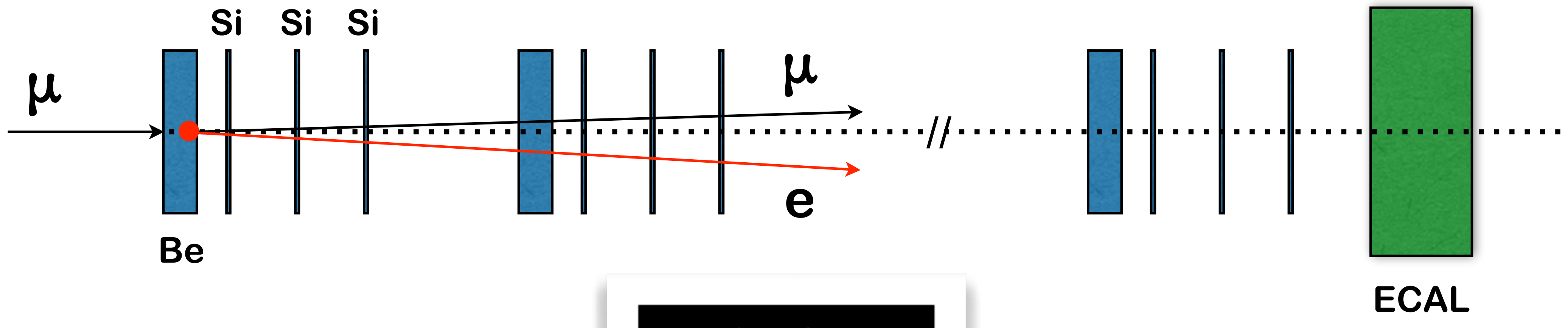
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region: a_μ^{HLO} can be extracted from scattering data!

MUonE: Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can be measured via the elastic scattering $\mu\, e \to \mu\, e$.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each station has one layer of Beryllium (target) followed by several thin Silicon strip detectors.



Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

TEO-EXP proposal in the best tradition of the INFN initiatives

The way of SMEFT

Interpretation needs precision

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\text{EXP}} - \mathrm{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2}\sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

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Most precise/accurate experimental measurements with uncertainties and correlations

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Most precise SM predictions for observables:
NLO, NNLO, N3LO…

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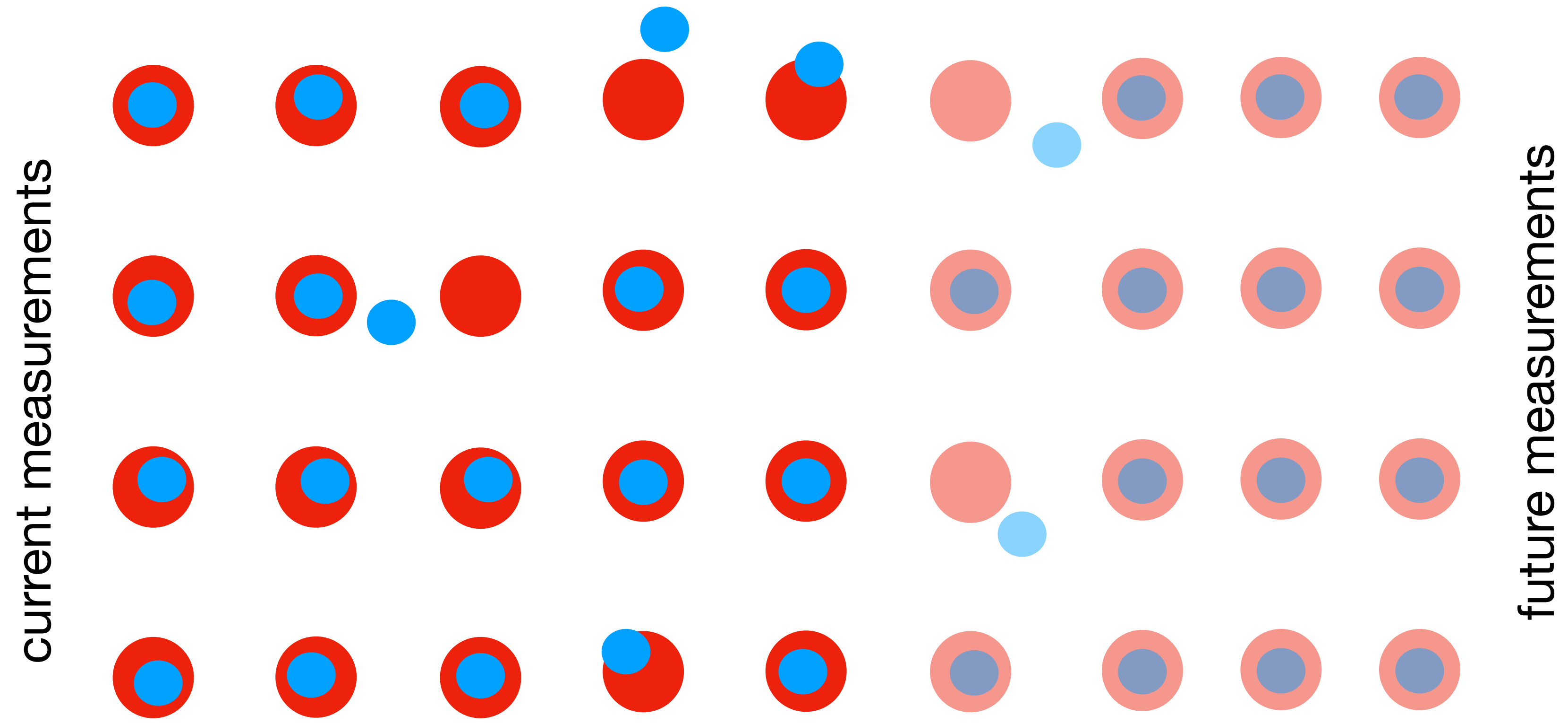

$\Rightarrow$ increased NP Sensitivity

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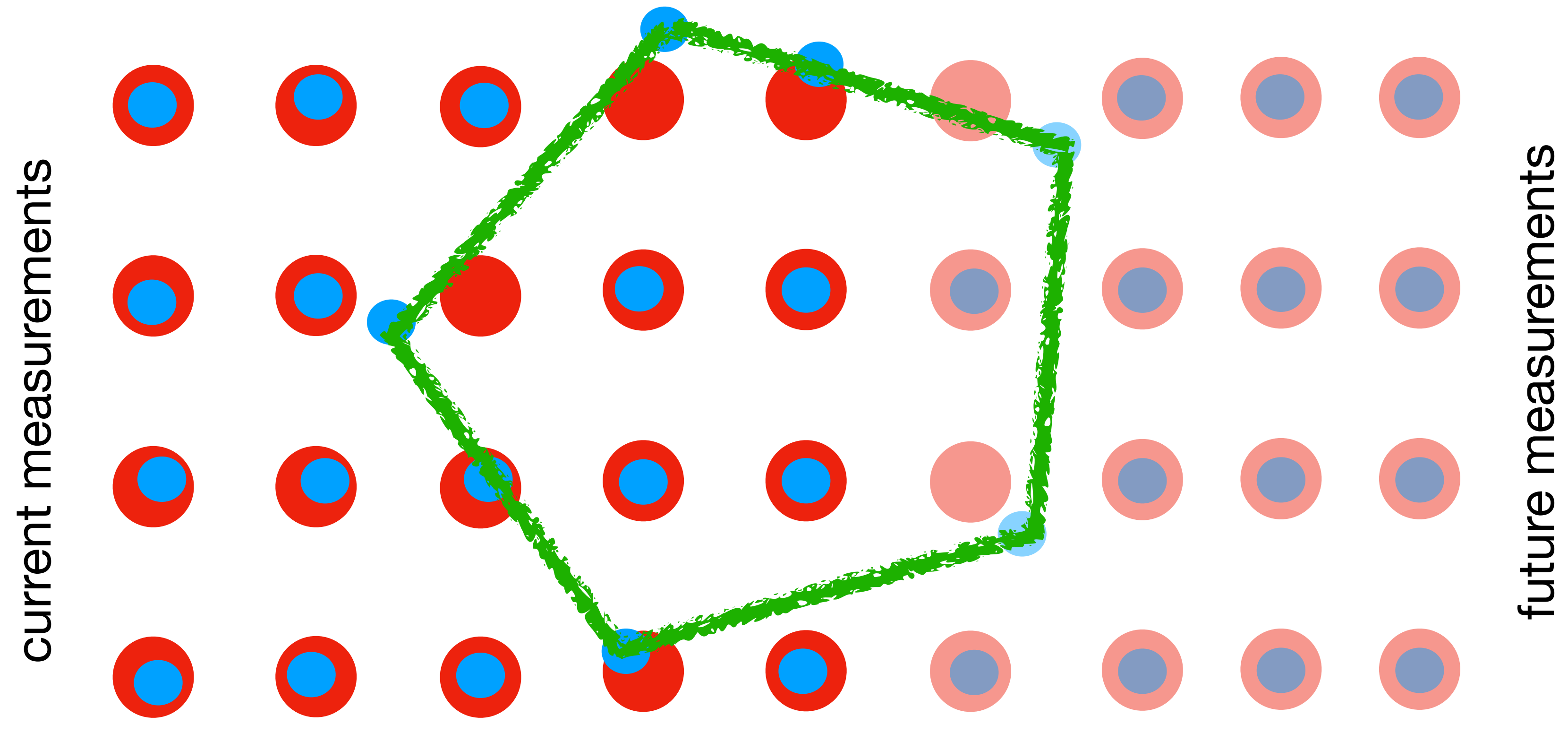

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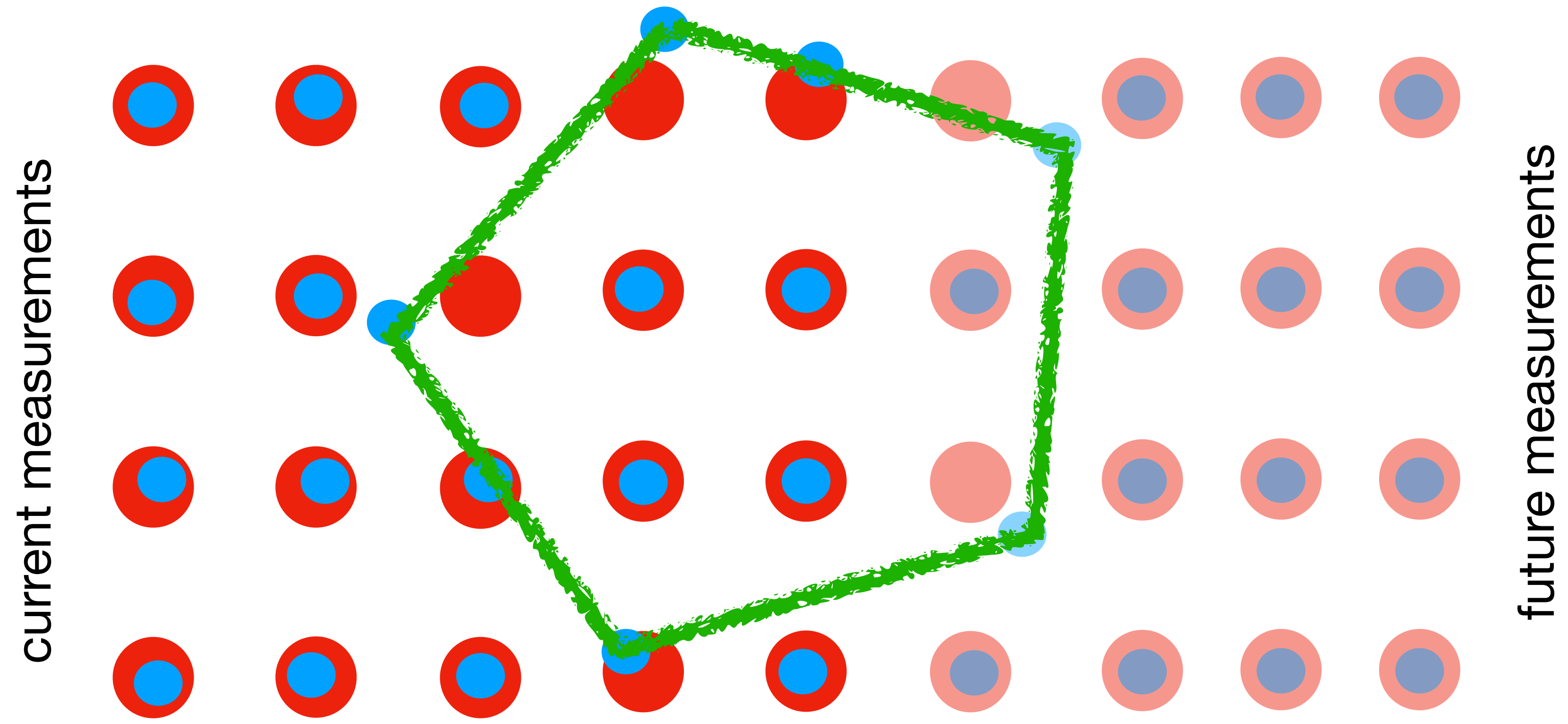
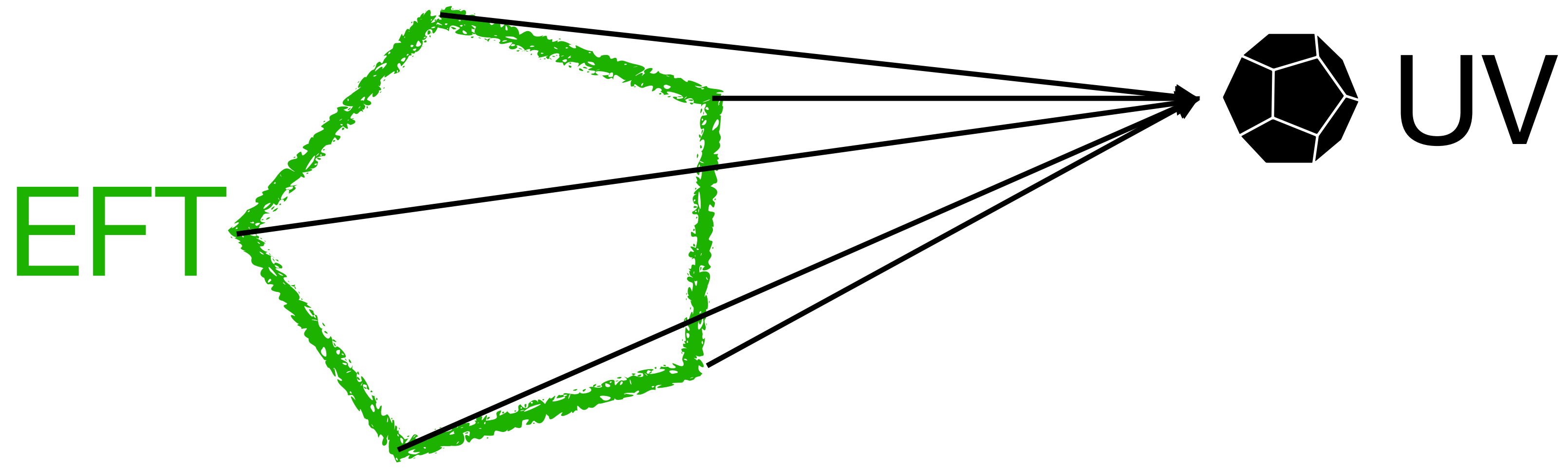


$\Rightarrow$ increased NP Sensitivity

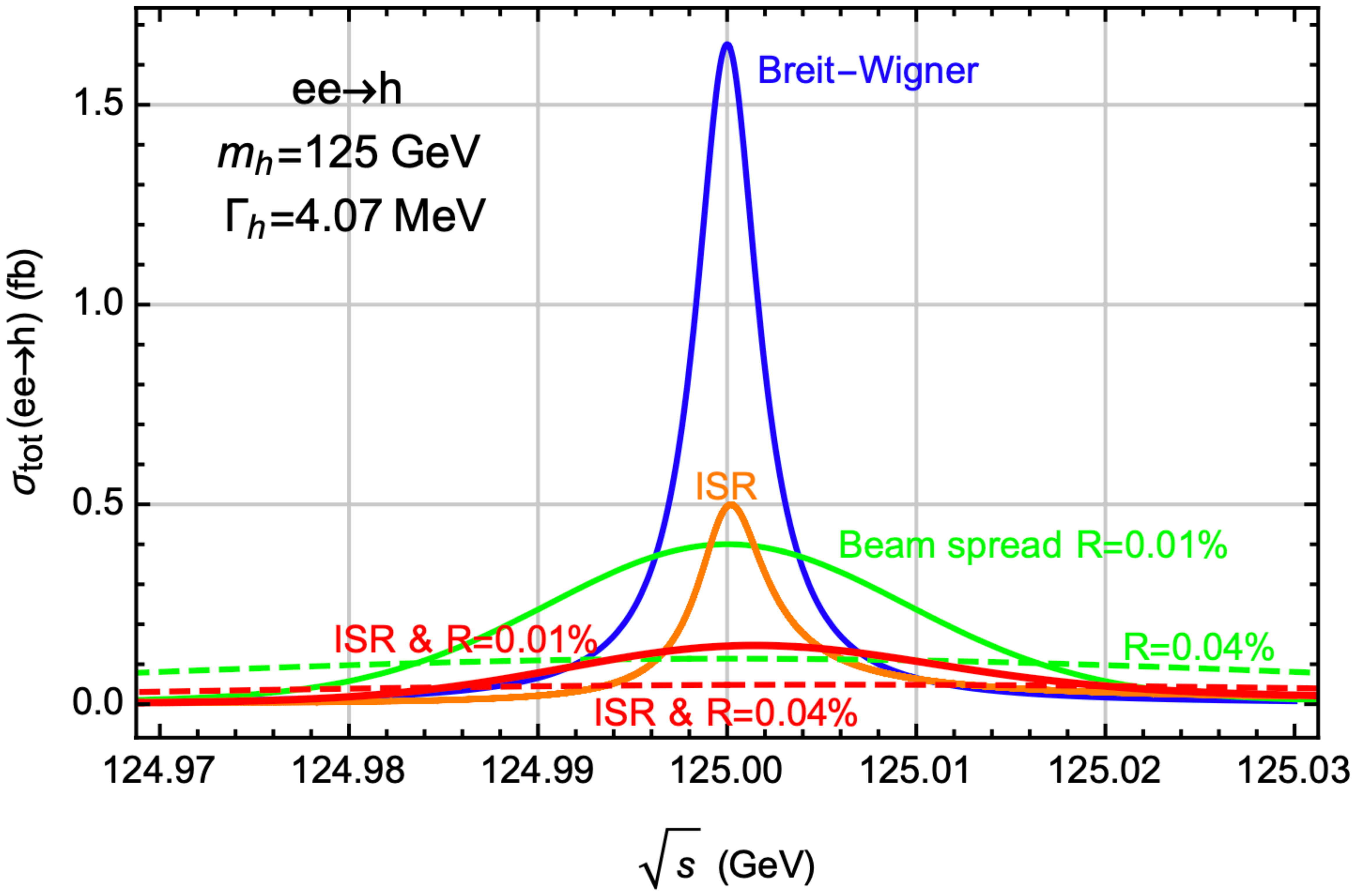
$\Rightarrow$ increased UV identification power



Future ee collider

Tera-Z option and Higgs factory

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times 10^3$)	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}$($\times 10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

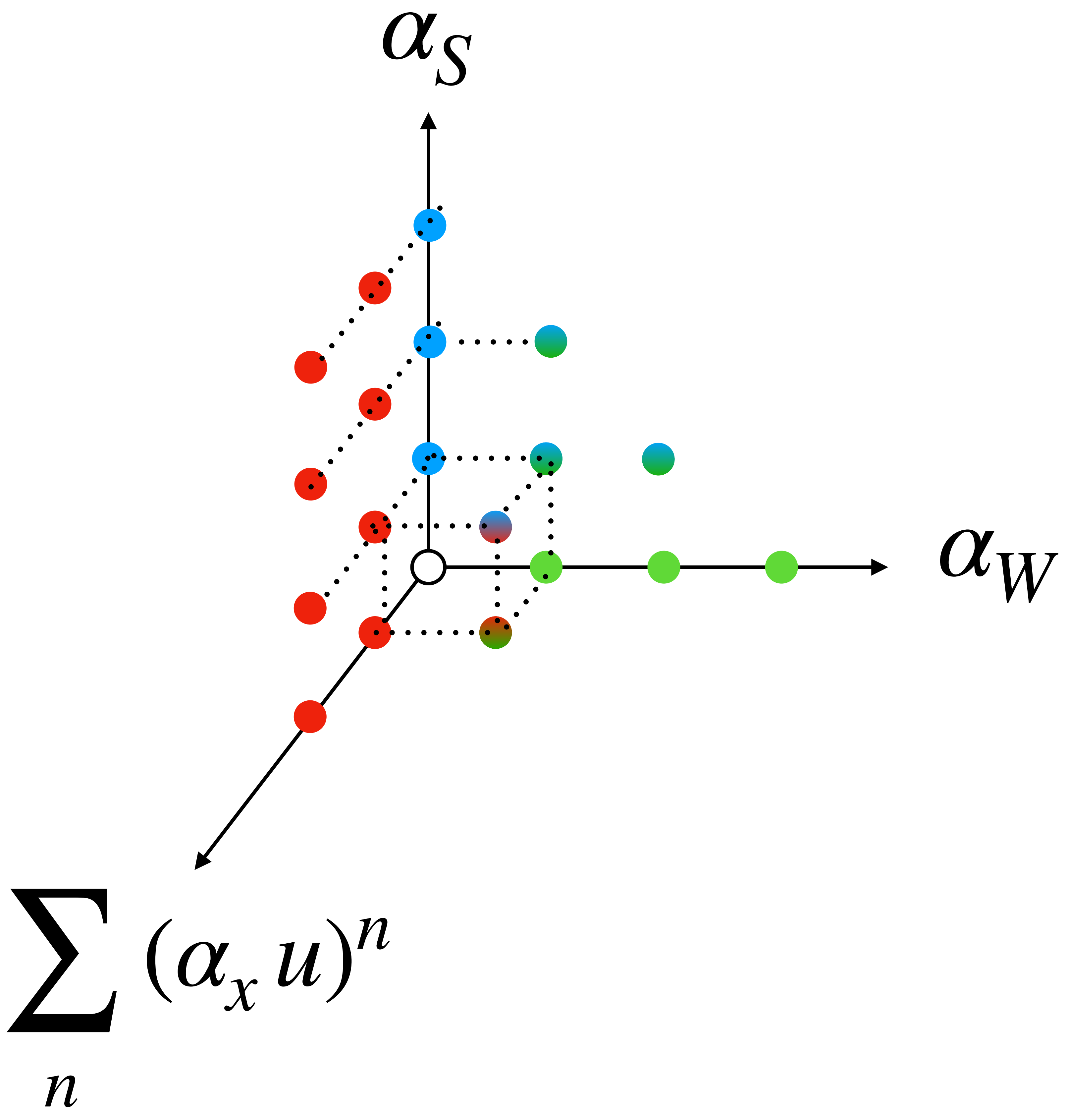


Precision calculations for the LHC

The path

"Rules of thumb at the LHC":

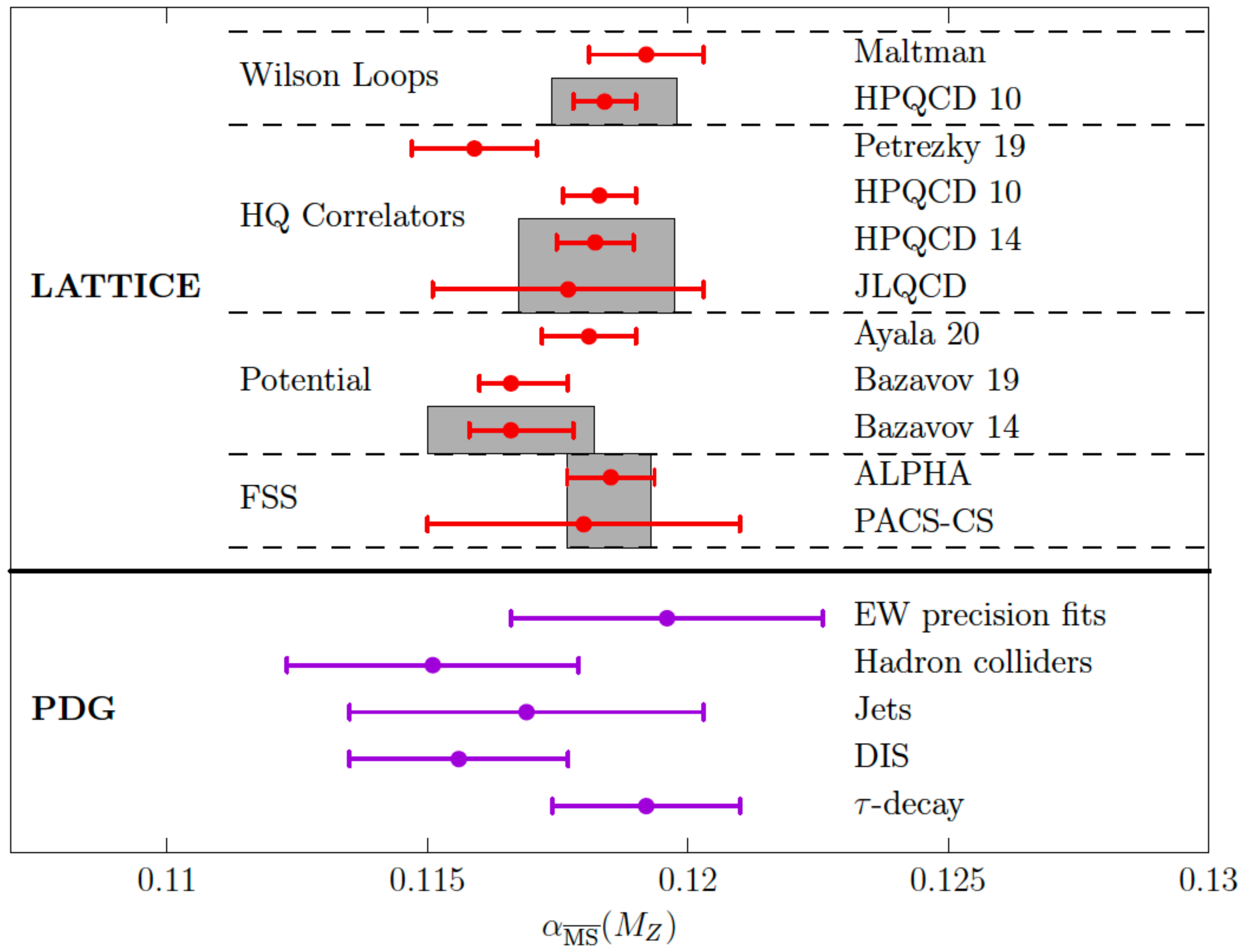
- Predictions must be calculated at least to **NLO QCD** to control the central value at 10-20%.
- **N2LO QCD** provides control at 5% level and on the uncertainties stabilizing the perturbative expansion.
- **N2LO QCD** is expected to be of the **same order** as **NLO EW** $\alpha_S^2 \sim \alpha_W$**, yet EW** corrections grow large and negative at high energies (Sudakov logs).
- **N3LO QCD** is the frontier of precision aiming ~1% of MHO uncertainties.
- **Resummation** Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. They might refer to global or non-global observables. Resummation leads to mprovements in precision and accuracy.



The lattice frontier

α_S and PDF's

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

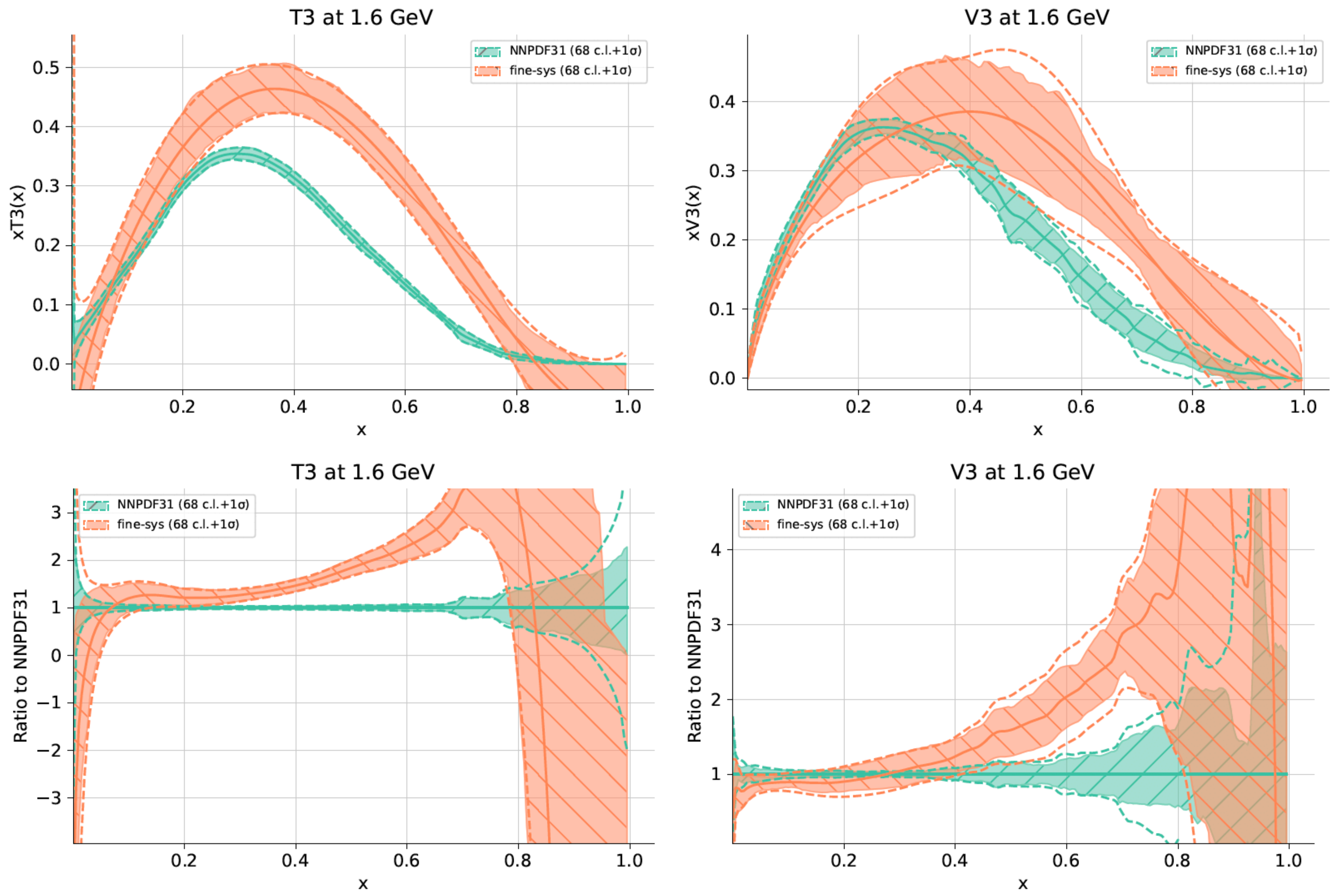


$$P(Q) = \sum_{k=0}^{n} c_k(s)\alpha^k_{\overline{\rm MS}}(\mu) + \mathcal{O}(\alpha^{n+1}_{\overline{\rm MS}}(\mu)) + \mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right), \qquad (s=\mu/Q)\,.$$

MHO PC

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.

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



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

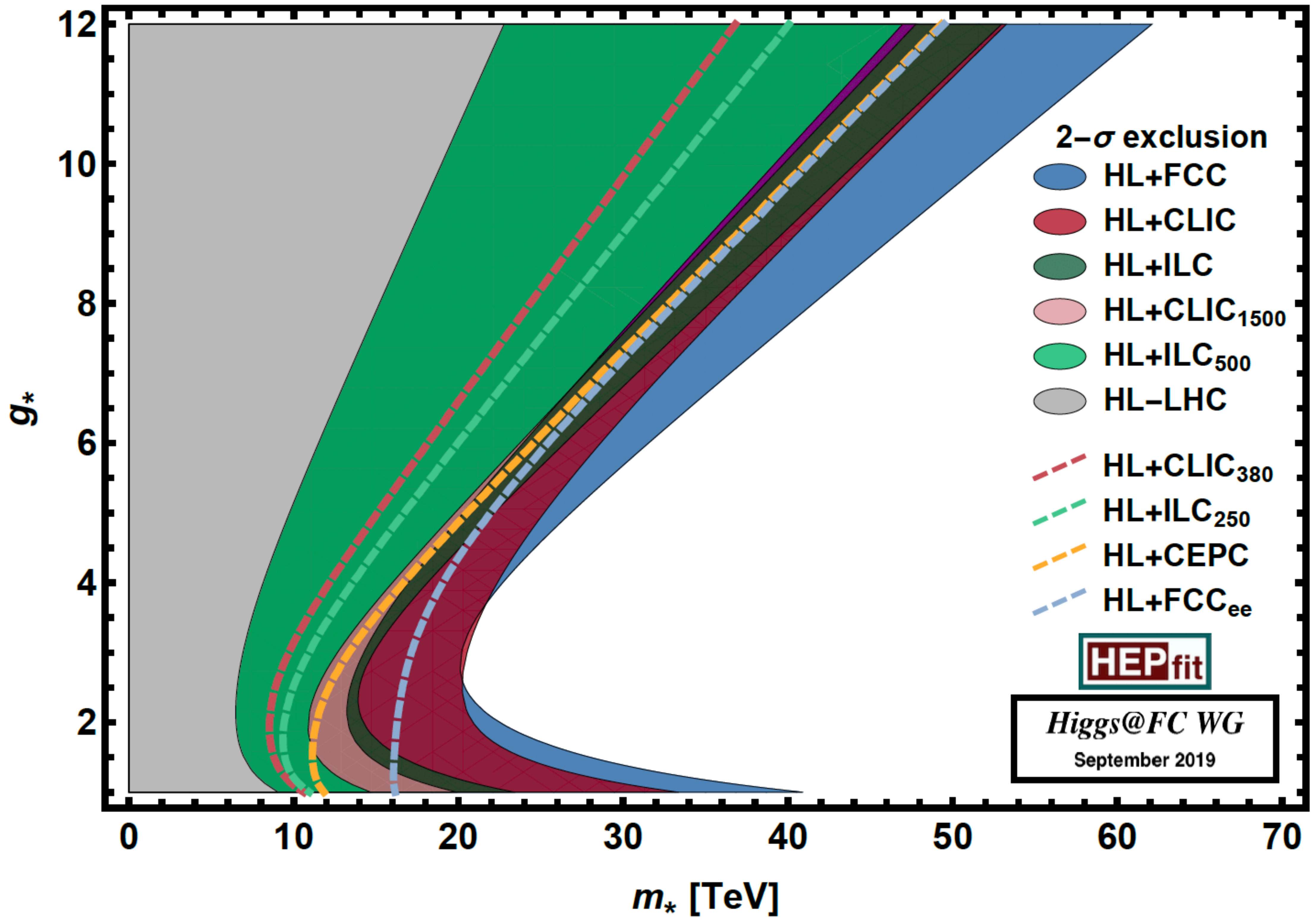
$T_3(x) = u(x) - \bar{u}(x) + [d(x) - \bar{d}(x)]$

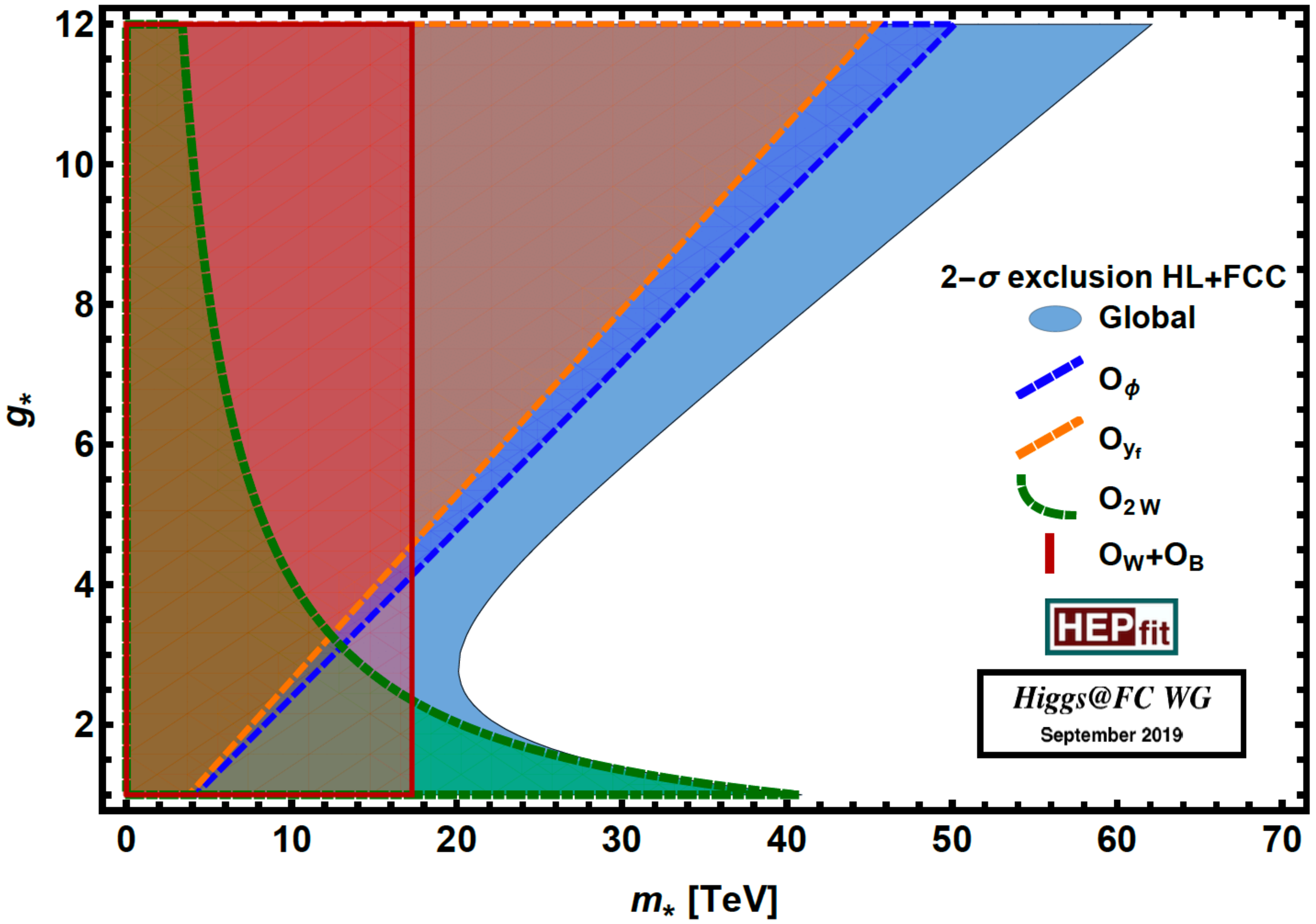
$$\mathfrak{M}\left(\nu, z_3^2\right) = \int_{-1}^{1} dx\, C\left(x\nu, \mu^2 z_3^2\right) f\left(x, \mu^2\right) + \mathcal{O}\left(z_3^2 \Lambda^2\right)$$

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

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.

HL-LHC projections
Simple model interpretation



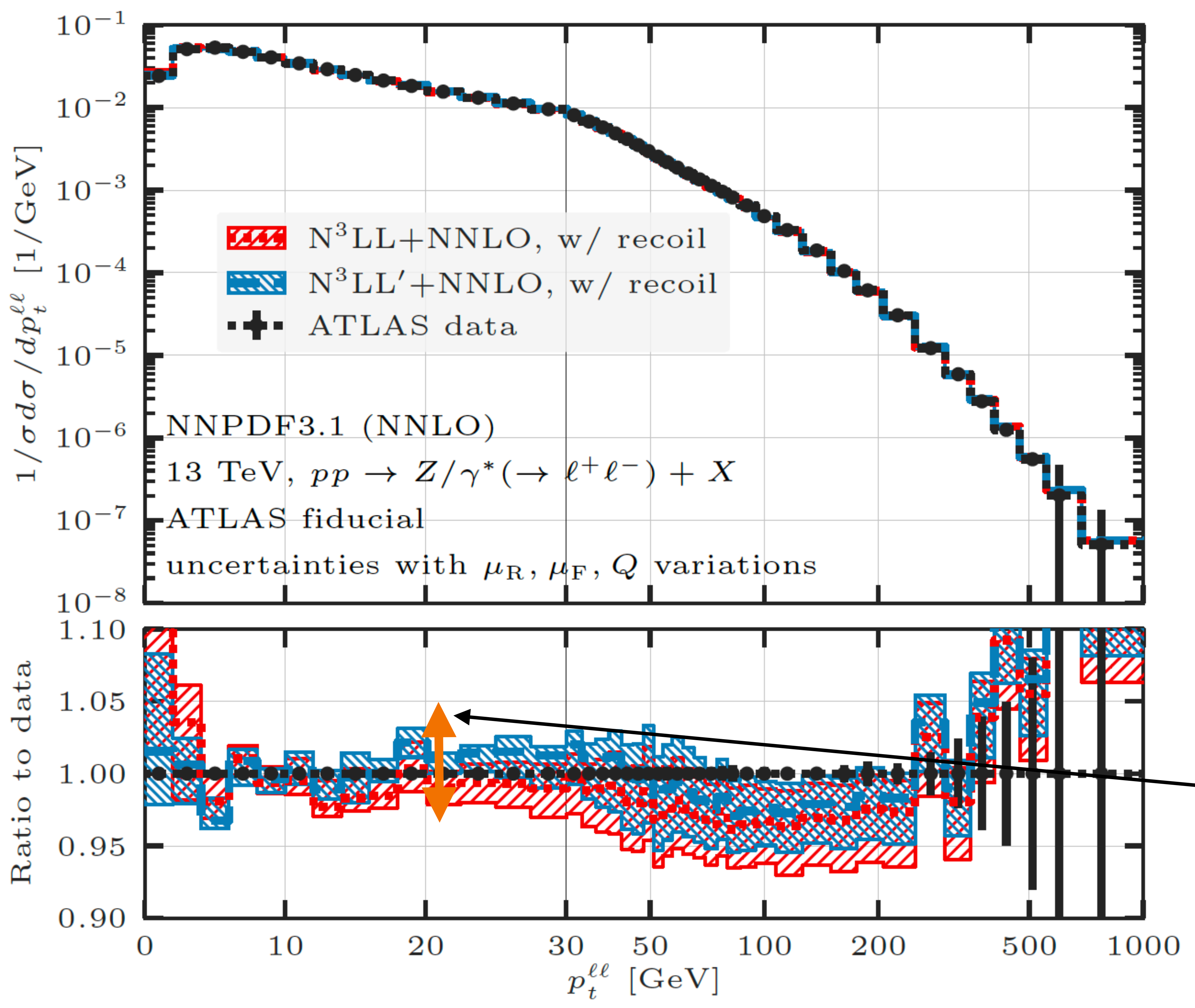


[De Blas et al., 2020]

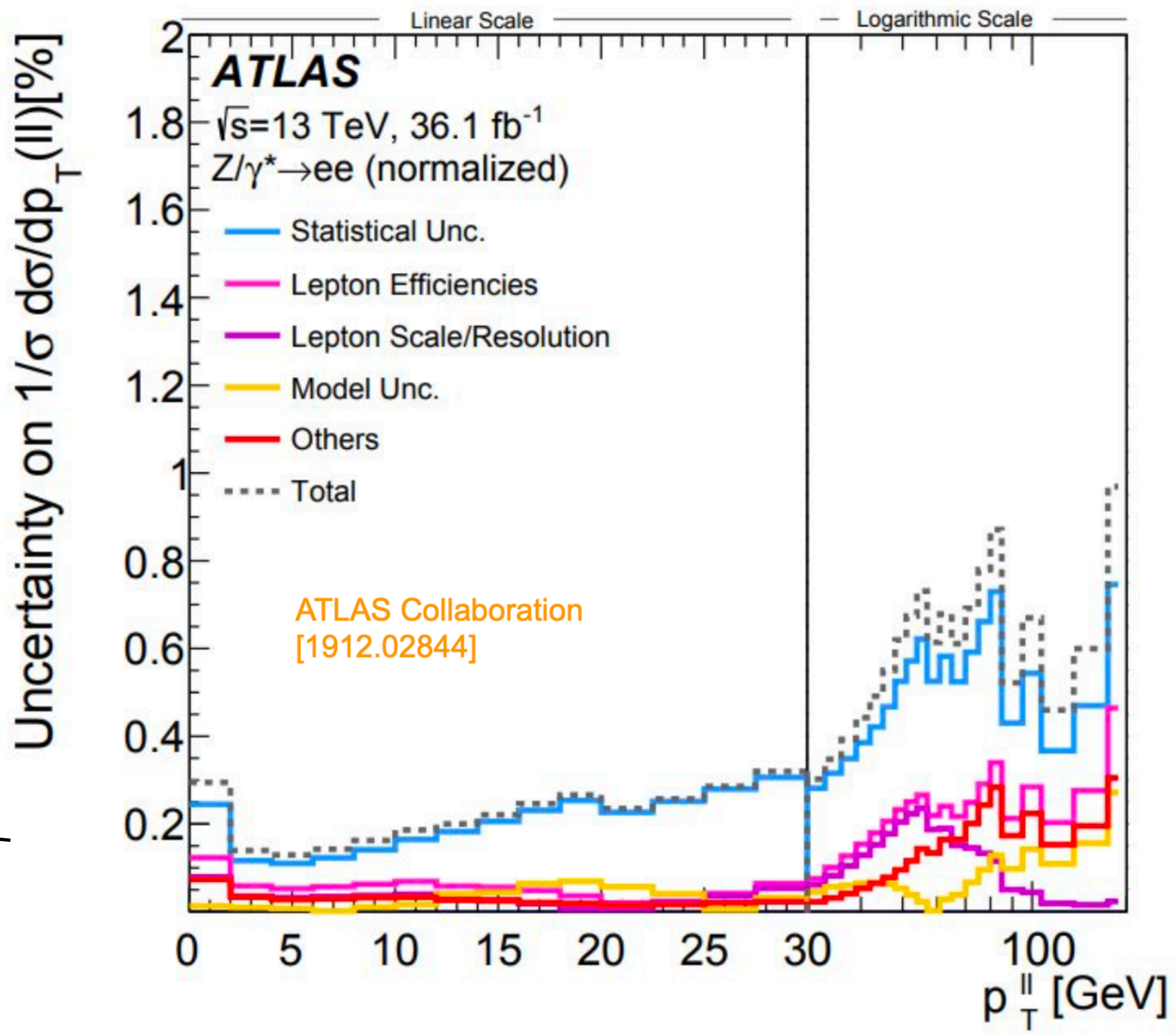
Precision calculations for the LHC

NNLO+N3LL : already not enough

[Billis et al. et al, 2102.08039]



Resummation improves the stability of the cross section predictions even in presence of cut-induced log effects.



EXP (way) better than TH already now!!

Algorithmic challenges

Machine Learning techniques

A survey of machine learning-based physics event generation

[Y. Alanazi, et al. 2106.00643]

Understanding Event-Generation Networks via Uncertainties

[M. Bellagente et al 2104.04543]

Phase Space Sampling and Inference from Weighted Events with Autoregressive Flows

[B. Stienen et al. , 2011.13445]

i-flow: High-dimensional Integration and Sampling with Normalizing Flows

[Christina Gao et al. 2001.05486]

How to GAN Event Unweighting

[M. Backes et al. : 2012.07873]

Generative Networks for LHC events

[Anja Butter and Plehn 2008.08558]

Invertible Networks or Partons to Detector and Back Again

[M. Bellagente et al. e-Print: 2006.06685]

How to GAN away Detector Effects

[M. Bellagente et al, 1912.00477]

How to GAN LHC Events

Anja Butter et al. 1907.03764 [hep-ph]

MLEGs	Data Source	Detector Effect	Reaction/Experiment	ML Model
[Hashemi *et al.*, 2019]	Pythia8	DELPHES + pile-up effects	$Z \to \mu^+\mu^-$	regular GAN
[Otten *et al.*, 2019]	MadGraph5 aMC@NLO	DELPHES3	$e^+e^- \to Z \to l^+l^-$, $pp \to t\bar{t}$	VAE
[Butter *et al.*, 2019]	MadGraph5 aMC@NLO		$pp \to t\bar{t} \to (bq\bar{q}')(\bar{b}\bar{q}q')$	MMD-GAN
[Di Sipio *et al.*, 2019]	MadGraph5, Pythia8	DELPHES + FAST-JET	$2 \to 2$ parton scattering	GAN+CNN
[Ahdida *et al.*, 2019]	Pythia8 + GEANT4		Search for Hidden Particles (SHiP) experiment	regular GAN
[Alanazi *et al.*, 2020b] [Velasco *et al.*, 2020]	Pythia8		electron-proton scattering	MMD-WGAN-GP, cGAN
[Martínez *et al.*, 2020]	Pythia8	DELPHES particle-flow	proton collision	GAN, cGAN
[Gao *et al.*, 2020]	Sherpa		$pp \to W/Z + n$ jets	NF
[Howard *et al.*, 2021]	MadGraph5 + Pythia8	DELPHES	$Z \to e^+e^-$	SWAE
[Choi and Lim, 2021]	MadGraph5 + Pythia8	DELPHES	$pp \to bb\gamma\gamma$	WGAN-GP

Impressive progress in the exploration of different methods and in identifying the most relevant questions in last couple of years!

- Can the ML-MC go beyond the statistical precision of the training event samples?
- Can they faithfully reproduce the physics?
- Can they provide new physics insights?

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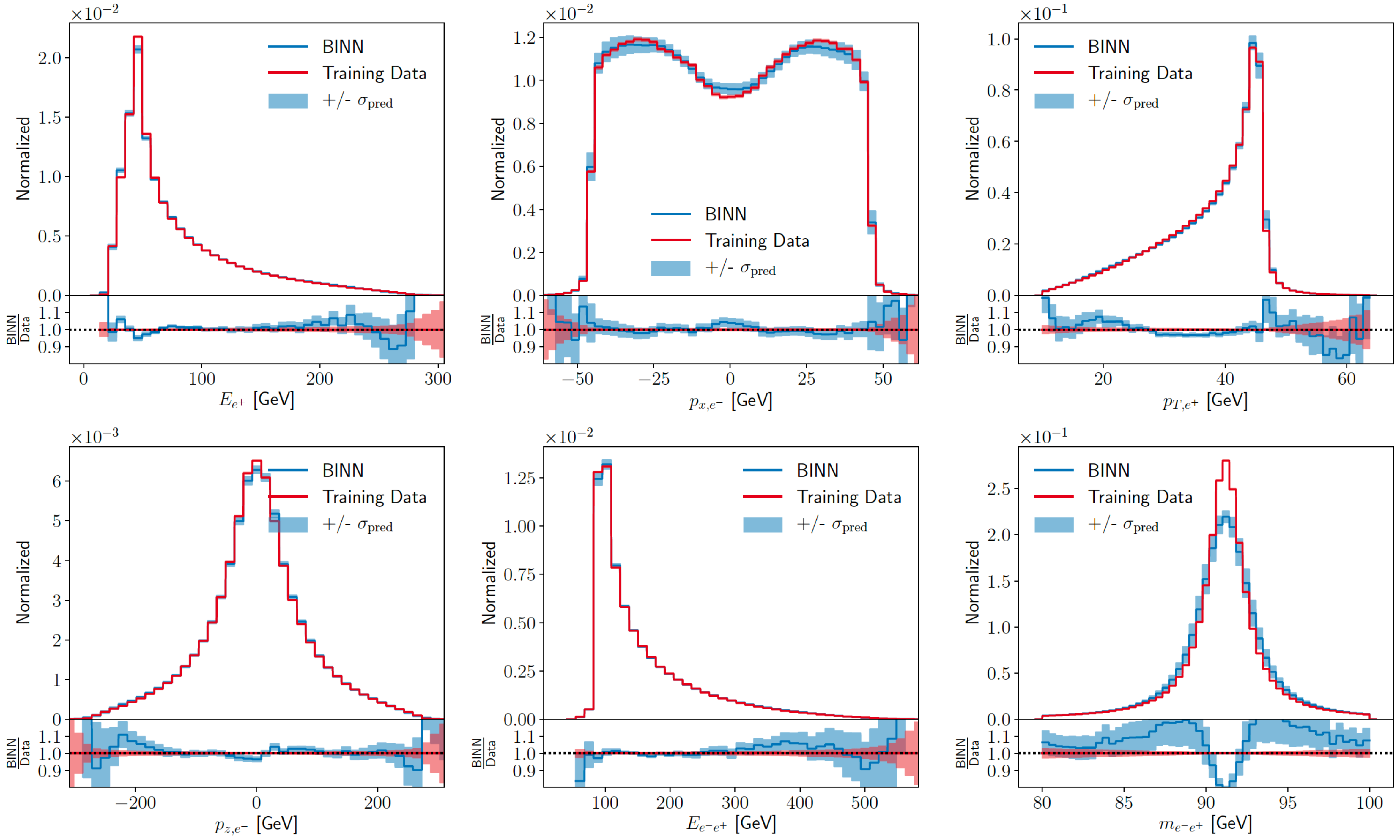

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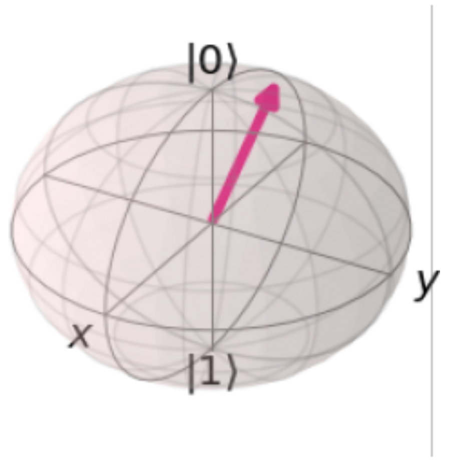
Algorithmic challenges
Quantum Computing

Growing interest in quantum computations for HEP:



$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle = \begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix},$$

(a) $|p\rangle^{\dot{a}}$

[Quantum Algorithm for High Energy Physics Simulations](#)
[C. W. Bauer et al. 1904.03196]

[Quantum Algorithms for Jet Clustering](#)
Annie Y. Wei et al. 1908.08949 [hep-ph]

[Towards a quantum computing algorithm for helicity amplitudes and parton showers](#)
Khadeejah Bepari et al. 2010.00046 [hep-ph]

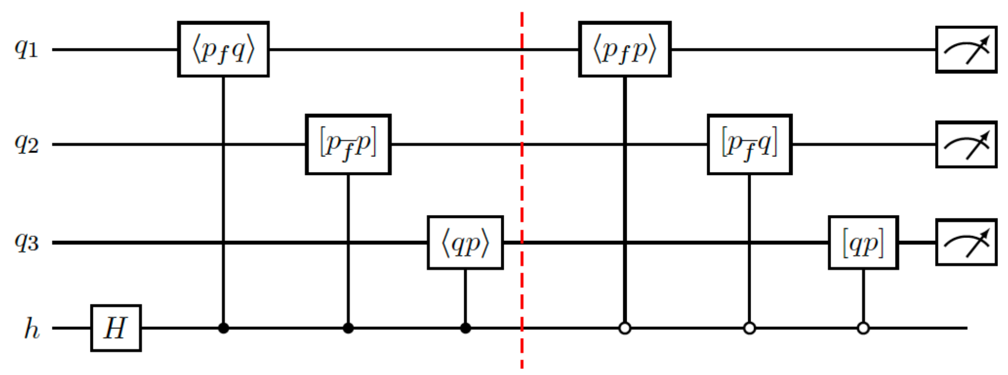
[Determining the proton content with a quantum computer](#)
Adrián Pérez-Salinas et al. 2011.13934

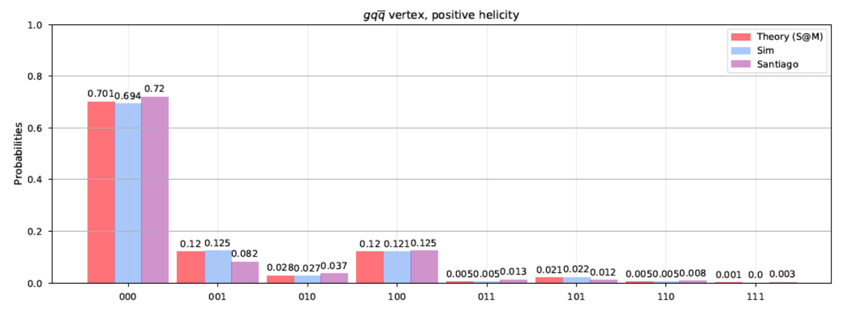
[Simulating collider physics on quantum computers using effective field theories](#)
C. W. Bauer et al. 2102.05044 [hep-ph]

[Quantum algorithm for Feynman loop integrals](#)
Selomit Ramírez-Uribe et al. 2105.08703

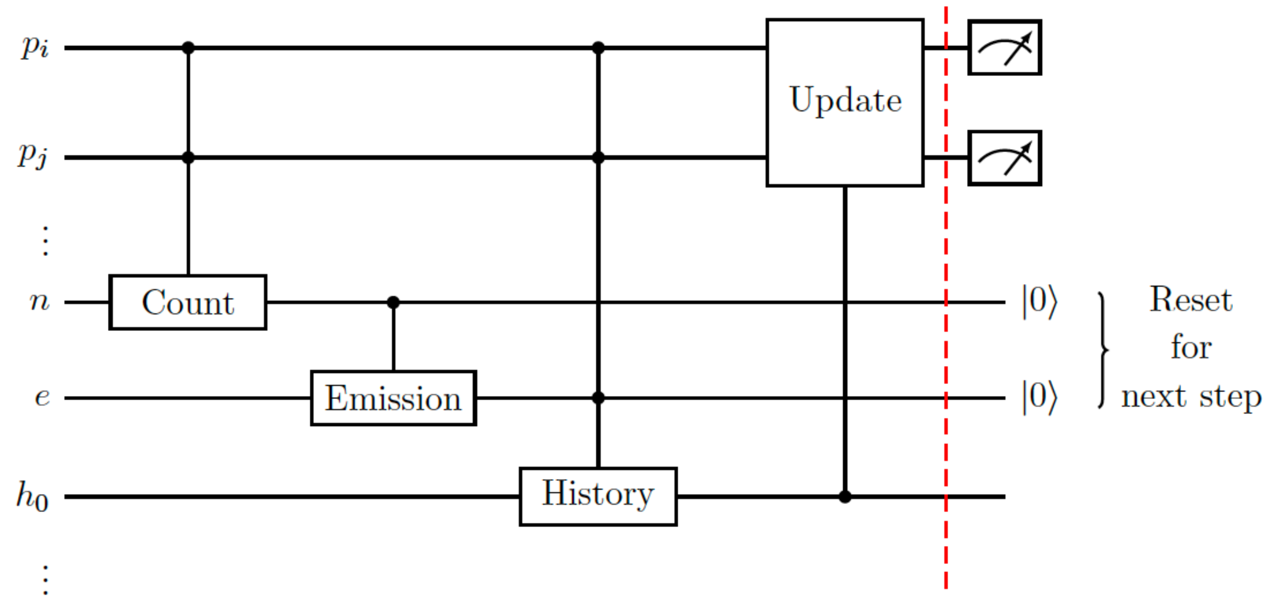
sum over helicities

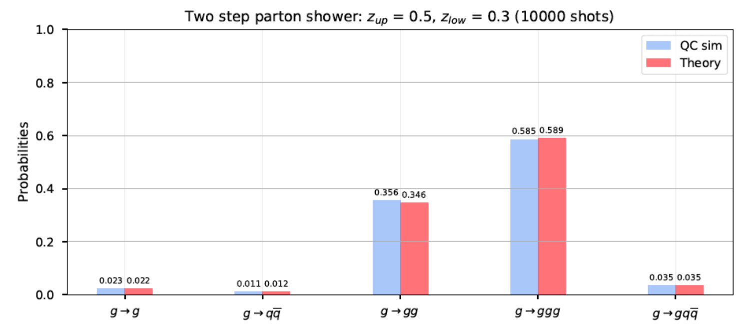
$$\mathcal{M}_+ = -\sqrt{2}\frac{\langle p_f q\rangle[p_{\bar f}p]}{\langle qp\rangle}, \qquad \mathcal{M}_- = -\sqrt{2}\frac{\langle p_f p\rangle[p_{\bar f}q]}{[qp]}.$$





sum over PS histories

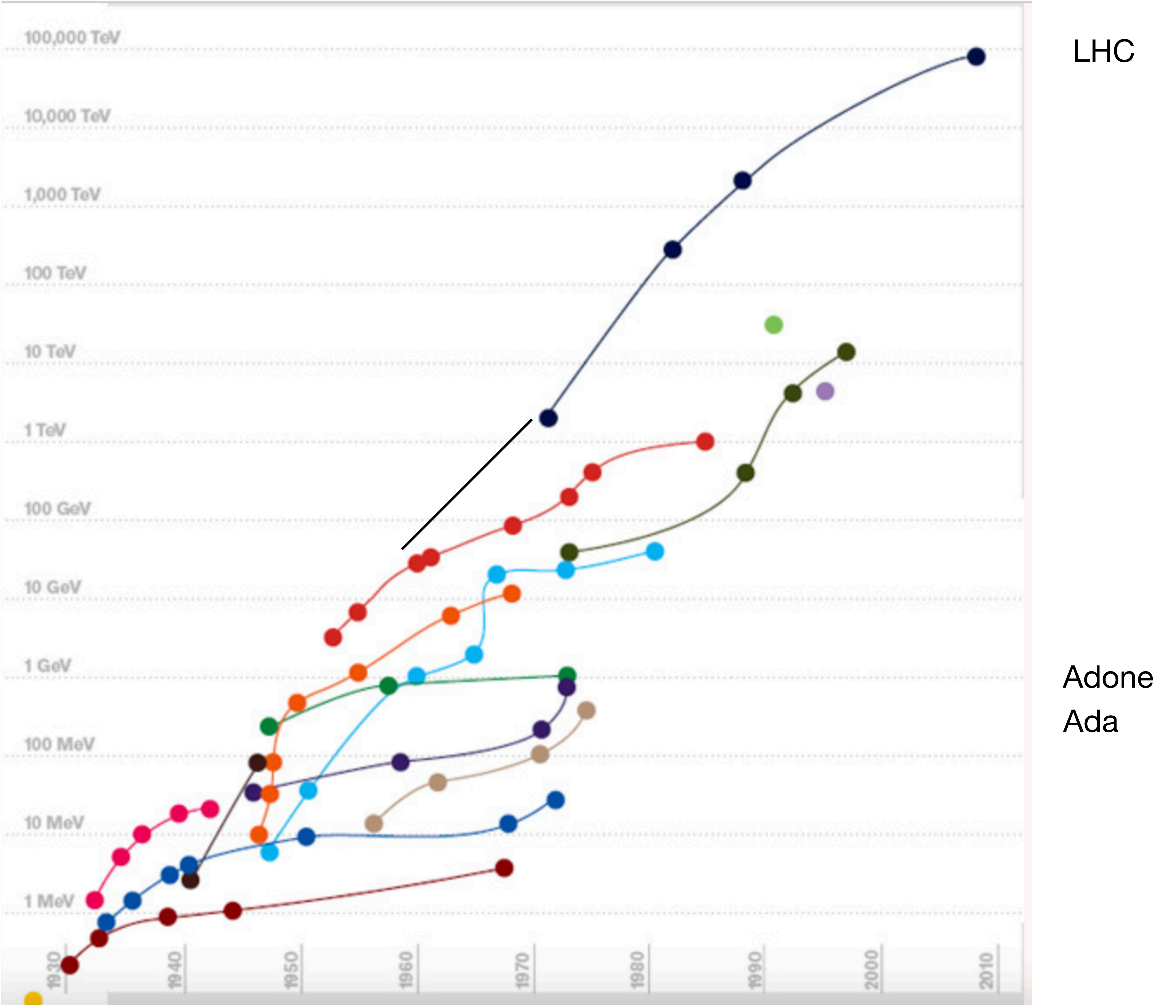




Many initiatives (see e.g. https://quanthep.eu/)

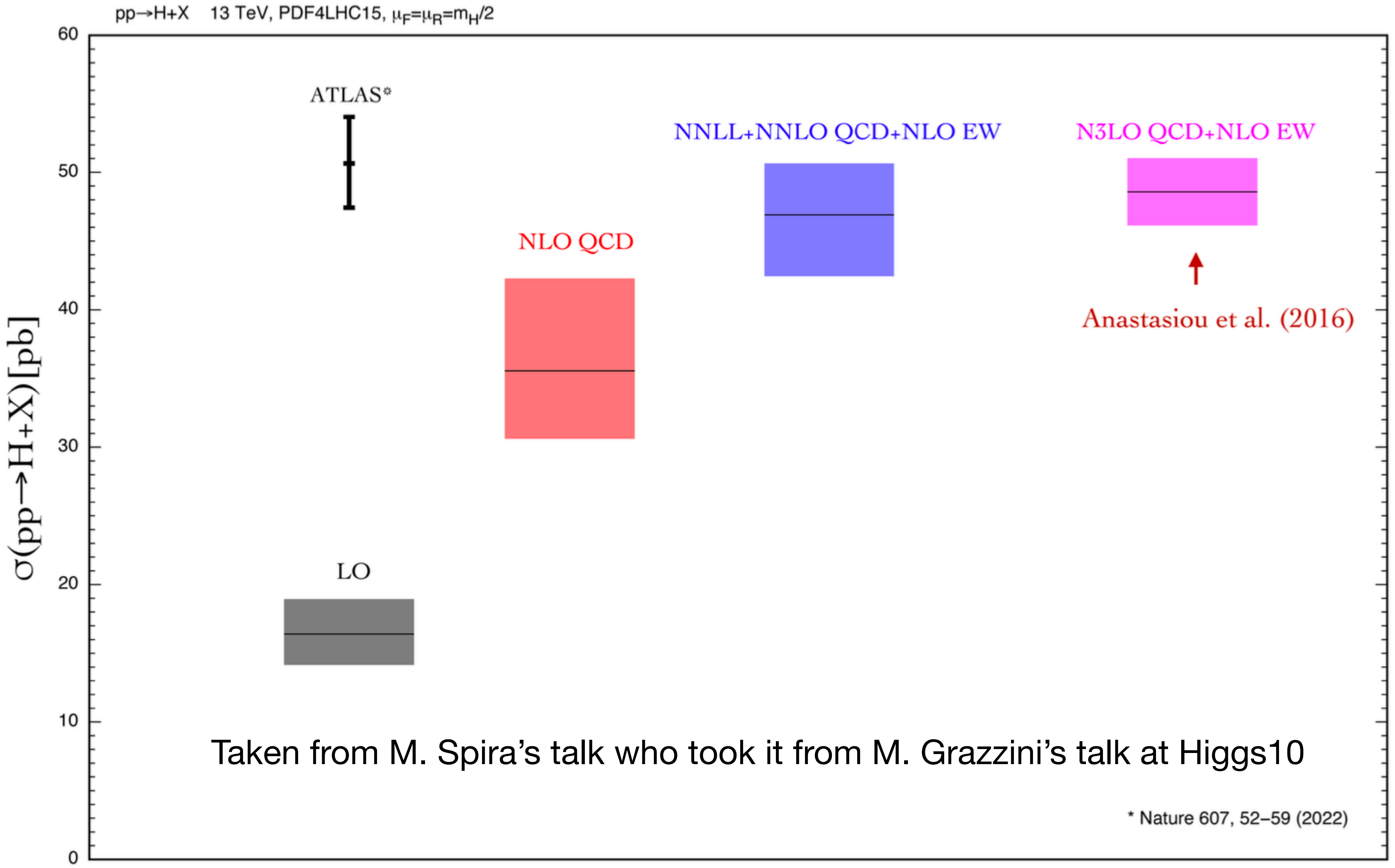
https://www.symmetrymagazine.org/article/october-2009/deconstruction-livingston-plot

Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

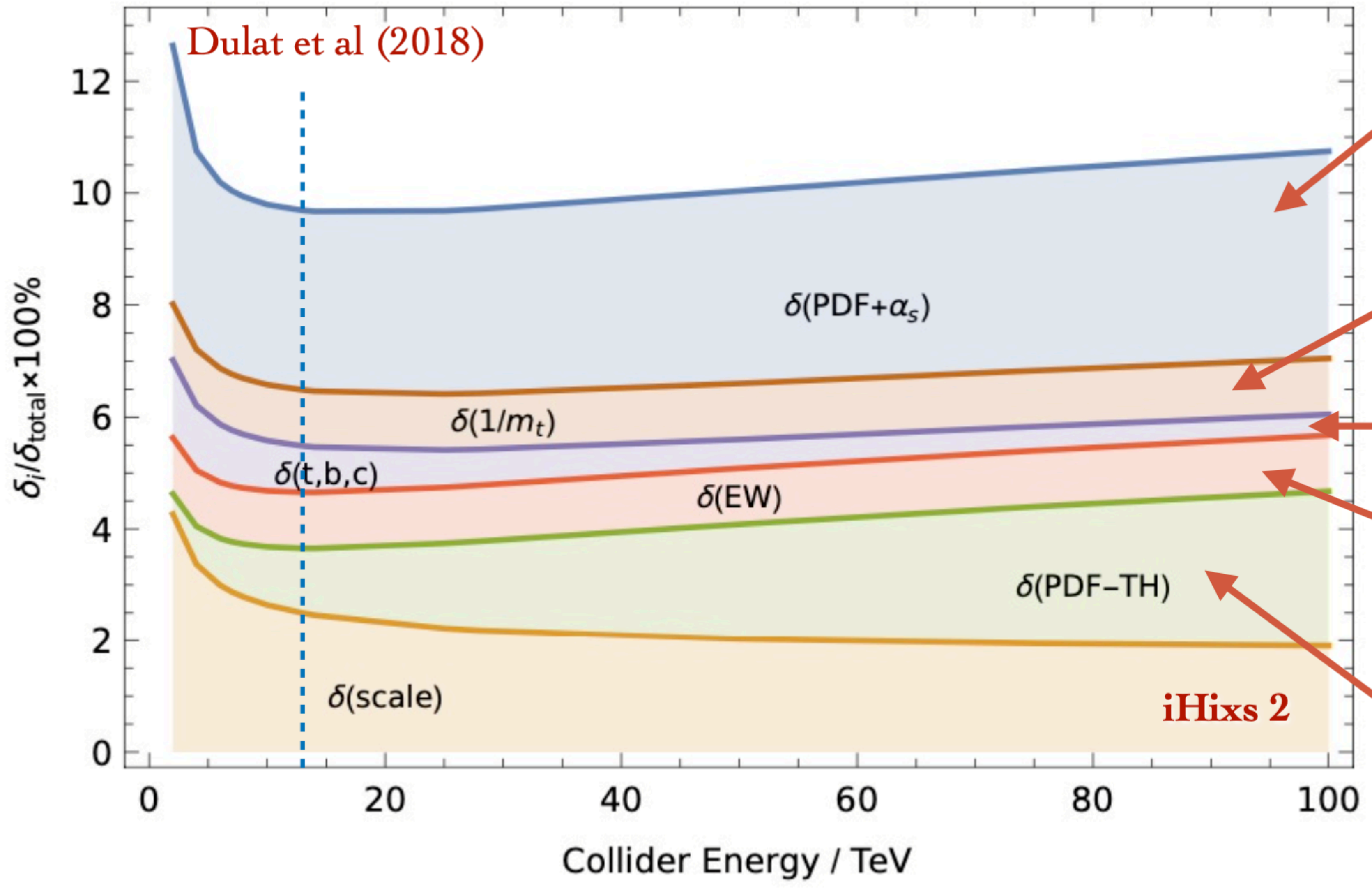


Precision calculations for the LHC

N3LO revolution



ggF known at N^{3}LO in HEFT ~ 1-2% uncertainty



$\alpha_s = 0.118 \pm 0.001 \rightarrow \mathcal{O}(2\%)$ uncertainty on x-section

Exact top mass dependence

Bottom mass contribution

QCD+EW mixed contributions

requires N^{3}LO PDFs