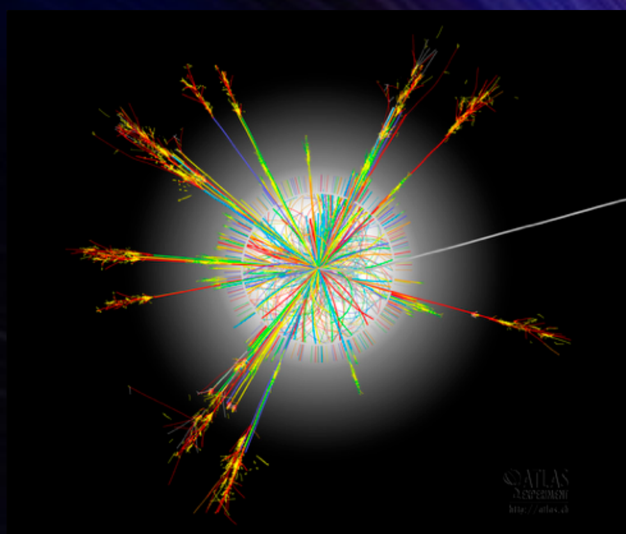
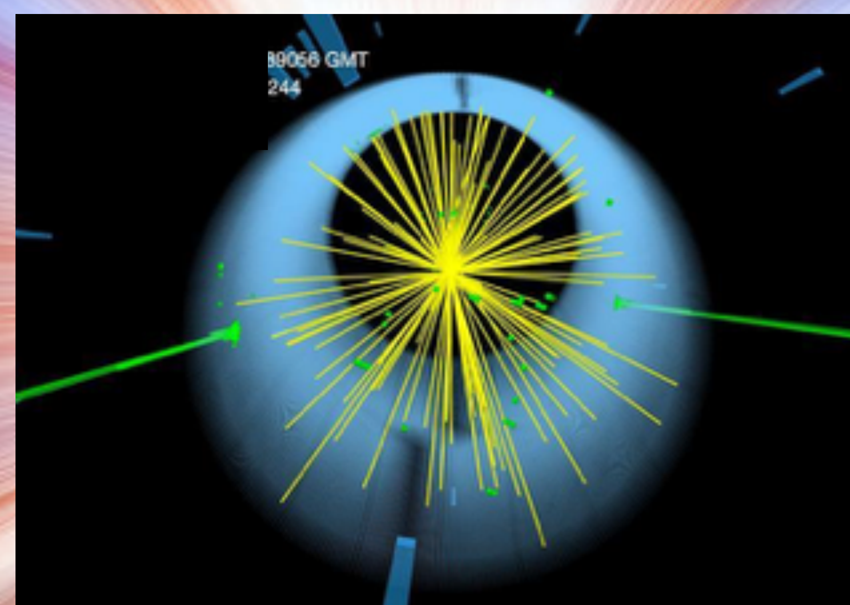
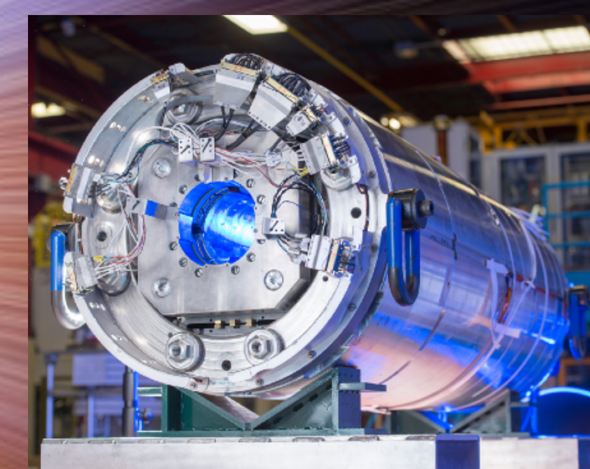
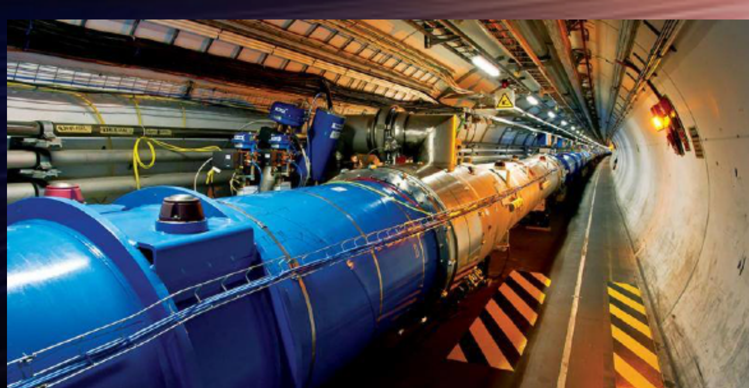
Les expériences du futur : potentiel de physique

Avant-propos introductif









École de Gif 2019

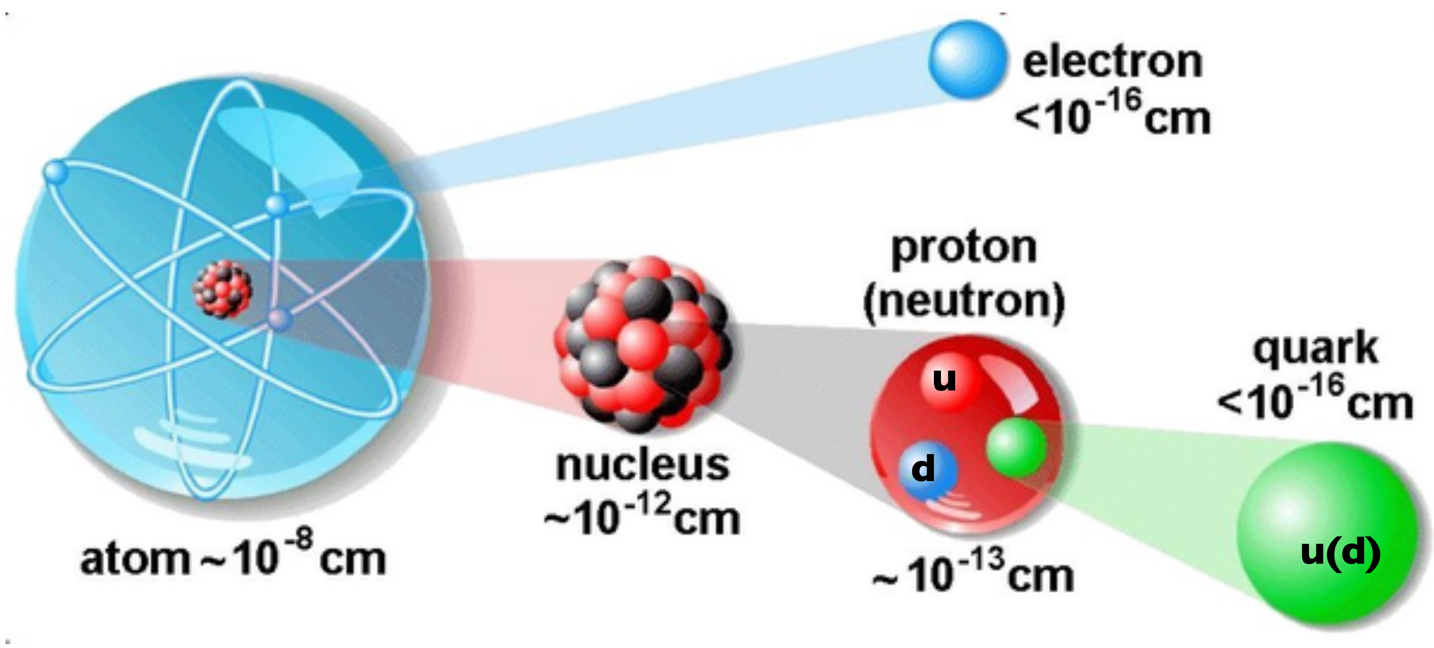
Questions ouvertes en physique des particules

2-6 septembre 2019

École polytechnique, Palaiseau

Gautier Hamel de Monchenault

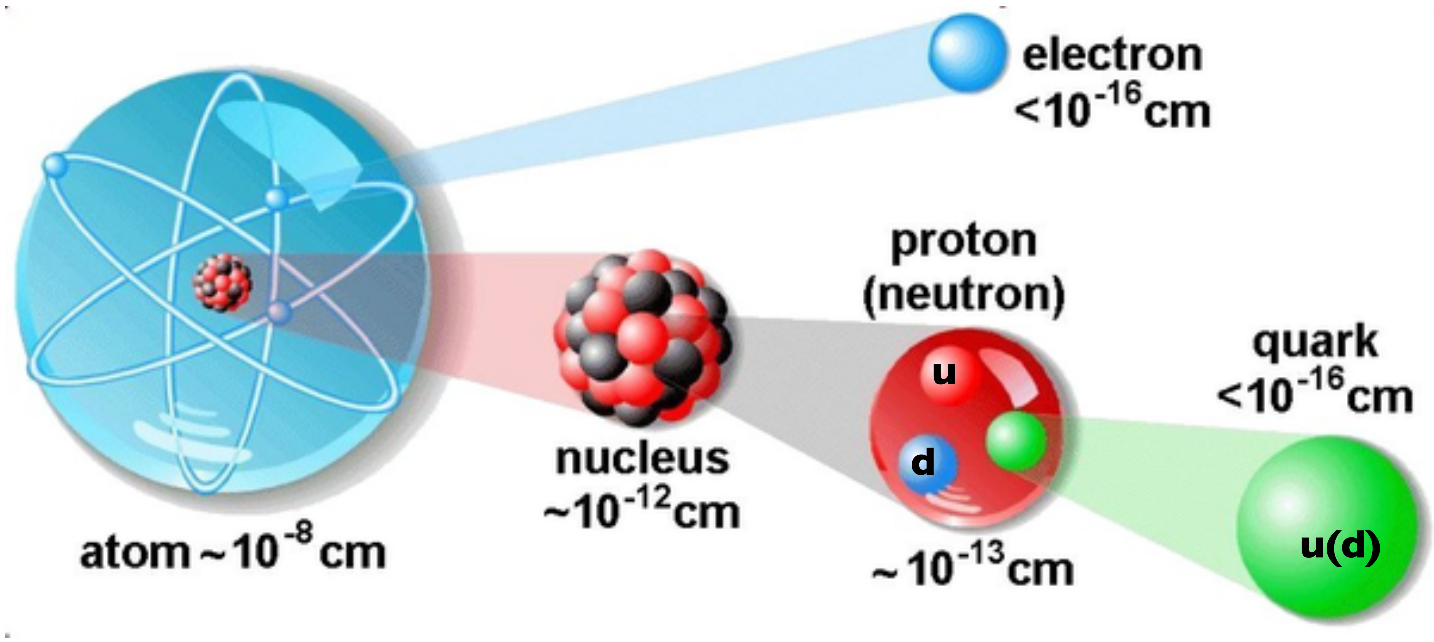
The Standard Model



The **Standard Model** (MS) of particle physics describes les elementary particles and their interactions

- matter particles: quarks and leptons
- vectors of force: gauge bosons

The Standard ~~Model~~ Theory



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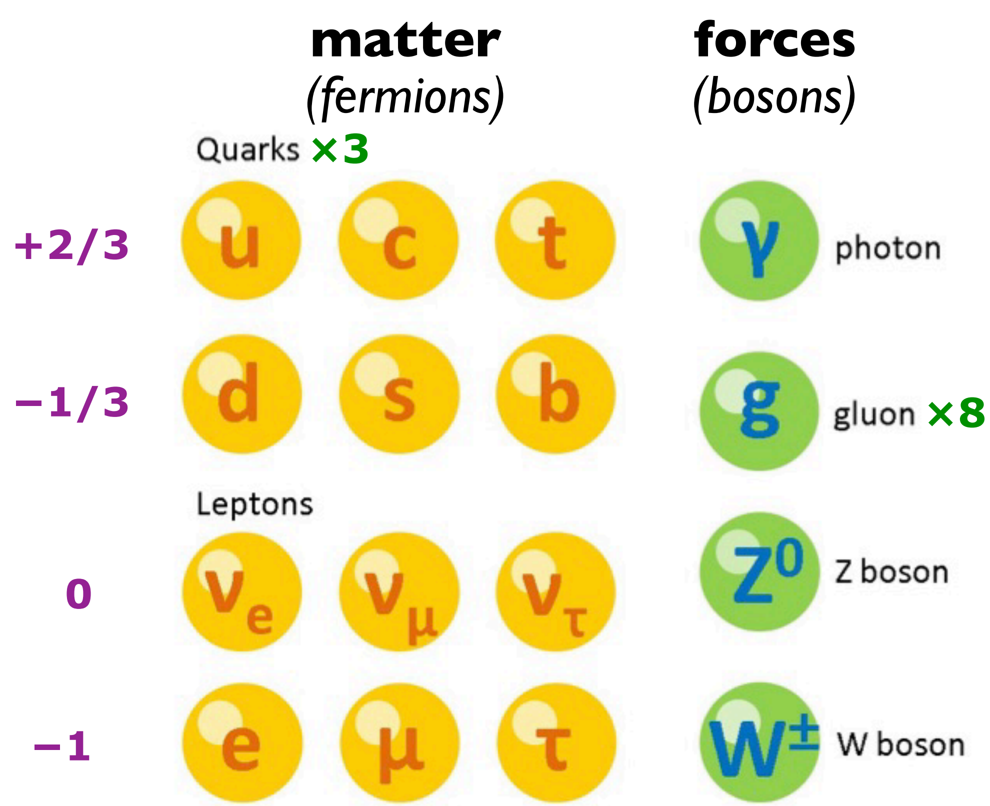
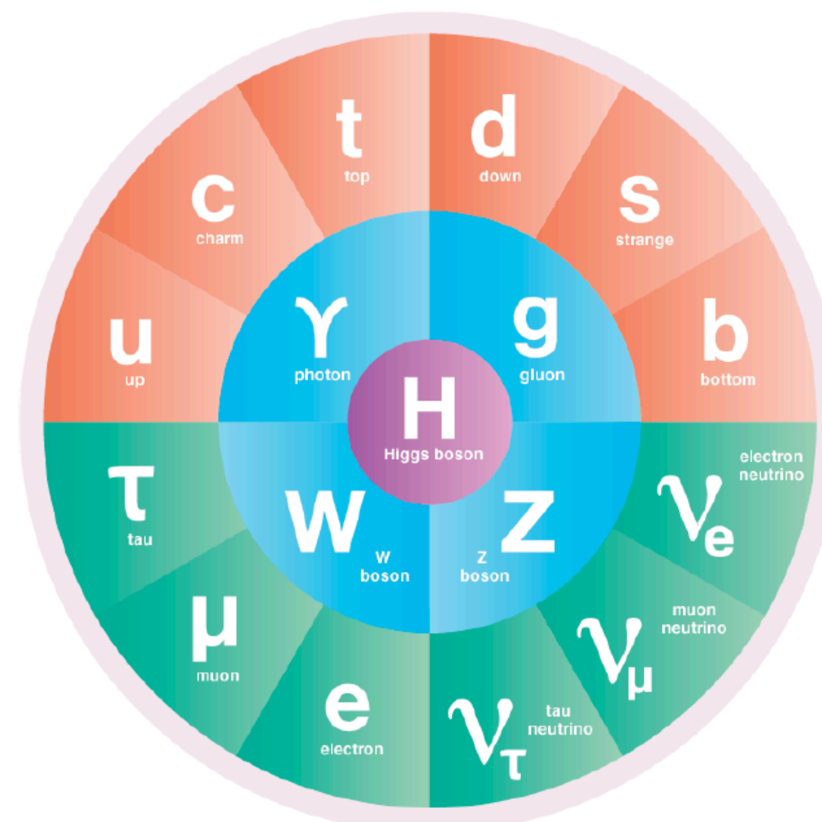


3 families

☞ 12 particles (+ antiparticles)

… and the **Higgs boson**

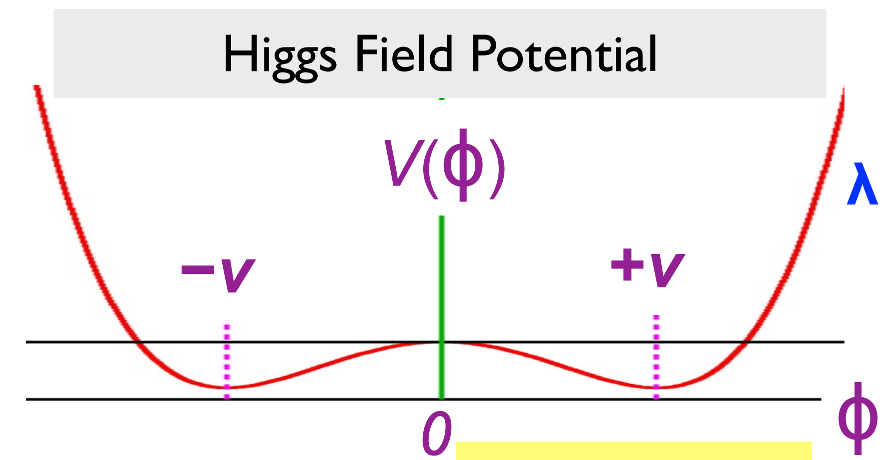


the Higgs boson plays a central role in the SM as it is linked to the origin of mass

The Origin of Mass

The Higgs field ϕ

- its non-zero vacuum expectation value breaks spontaneously the $SU(2)_L \otimes U(1)_Y$ symmetry into the $U(1)_{EM}$ symmetry of electromagnetism: massless photon
- it gives massive W and Z bosons
- by connecting left- and right-handed fields, it allows massive fermions



v = 246 GeV

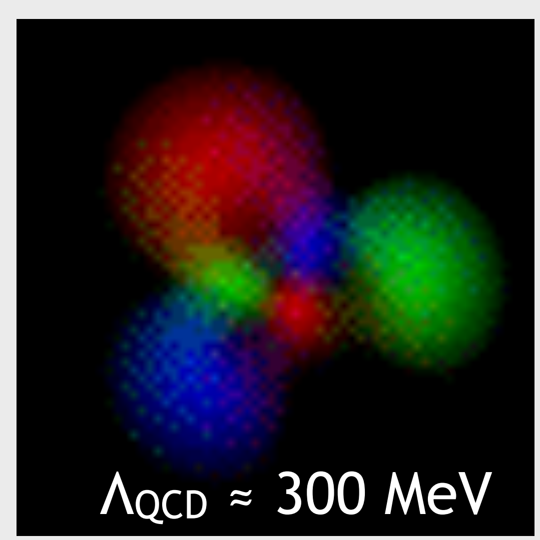
SSB = Spontaneous Symmetry Breaking

non-zero vacuum expectation value

Higgs field = 4 degrees of freedom (ddl)
☛ After SSB:
- 3 ddl → long. polar. of W^+, W^- and Z bosons
- 1 ddl → Higgs boson
- Yukawa couplings → fermion masses

To be honest, "our" mass comes from QCD
but Higgs Yukawa couplings play essential roles:
- mass of the electron → atom size → chemistry
- m(d) > m(u) → m(neutron > m(proton)
- m(t) and m(H) → stability of the EW vacuum

➠ LIFE!

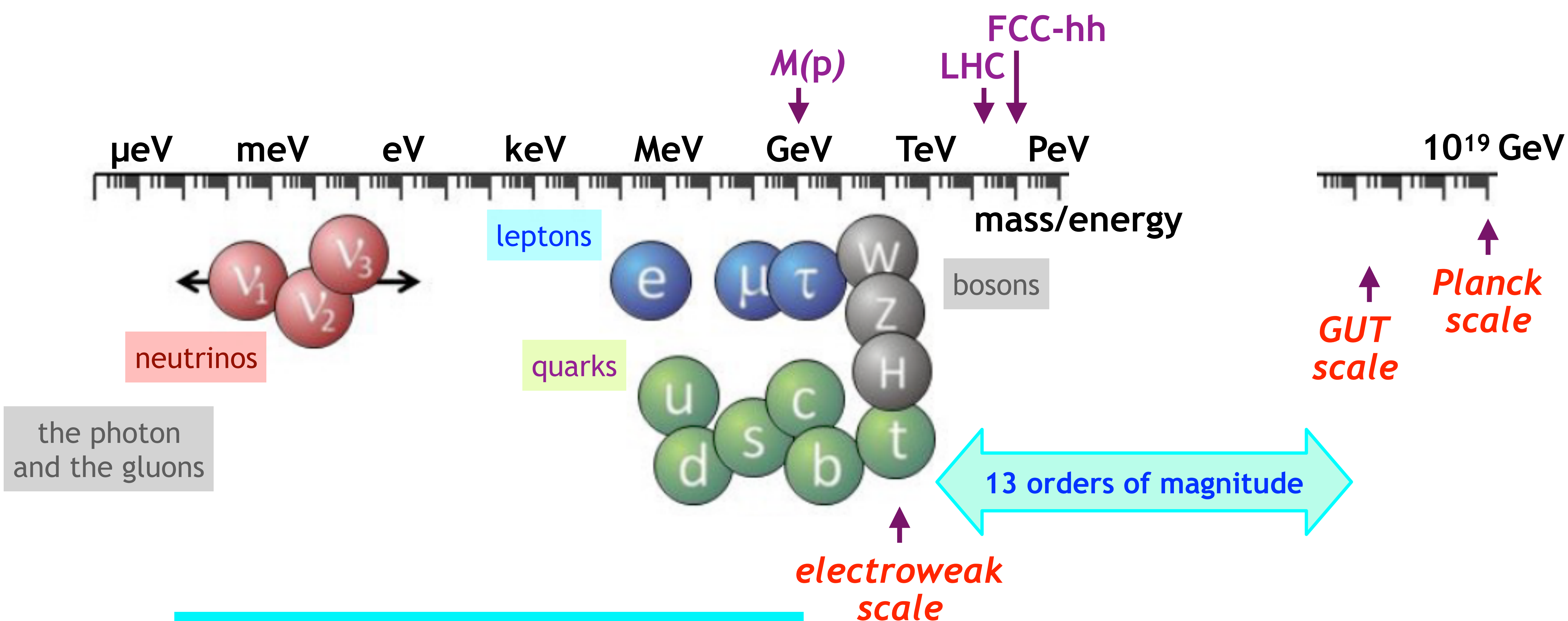


Contribution of quarks to the proton mass <10%

Most of the mass of the proton comes from the binding energy that ensures its cohesion (gluons)

Mass Hierarchy

Natural units:
M(proton) ≈ 1 GeV

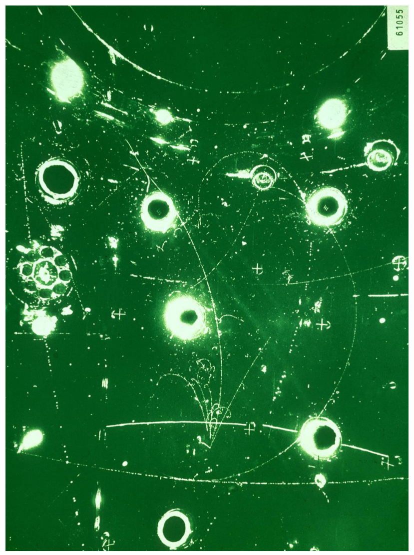


We live in the **Electroweak Oasis**

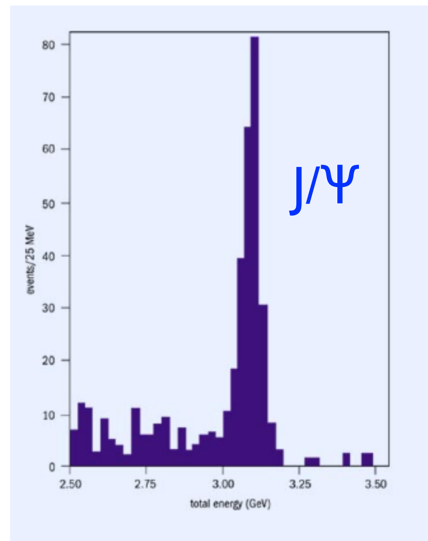
- we know that the desert around us does not exceed 1000 km
- we suspect that something new has to happen within 10 km

Three Decades of Discoveries

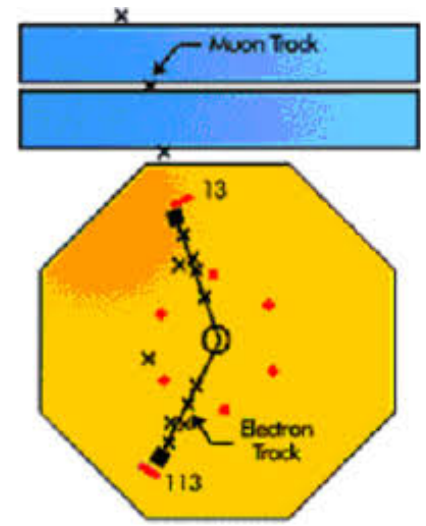
1972 — CERN
neutral currents



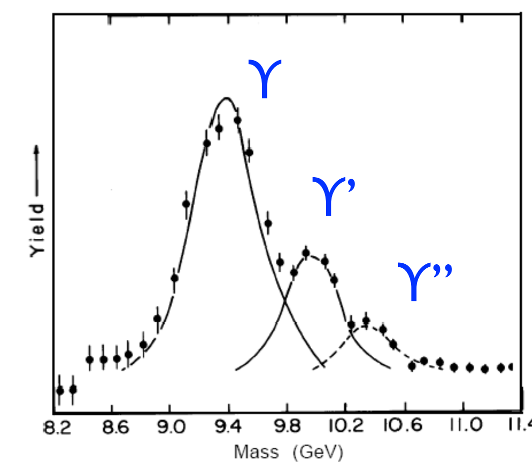
1974 — BNL, SLAC
charm



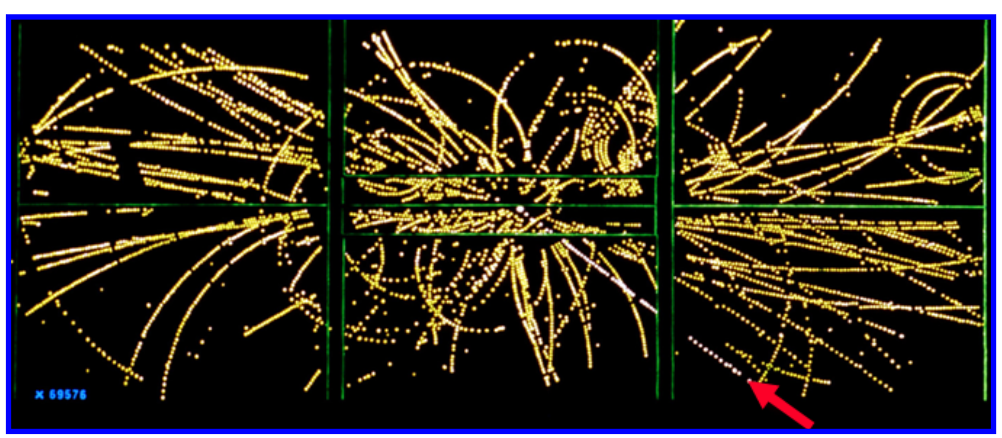
1976 — SLAC
tau lepton



1979 — Fermilab
beauty

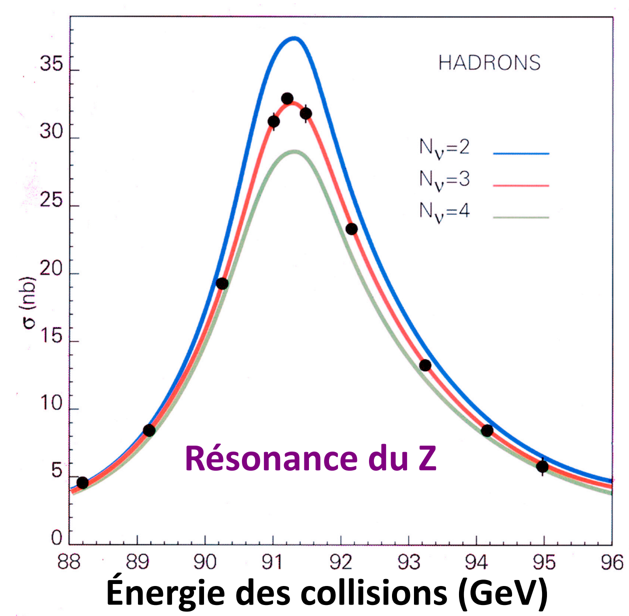


1983 — CERN/SppS
W and Z boson



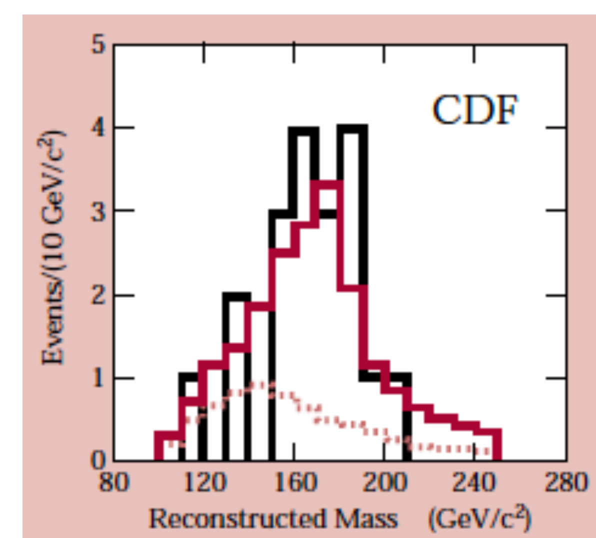
UA1, UA2

1990 — CERN/LEP
3 families of neutrinos



ALEPH, DEPHI, L3, OPAL

1994 — Fermilab/TeVatron
top quark



CDF, D0

Three Decades of Discoveries

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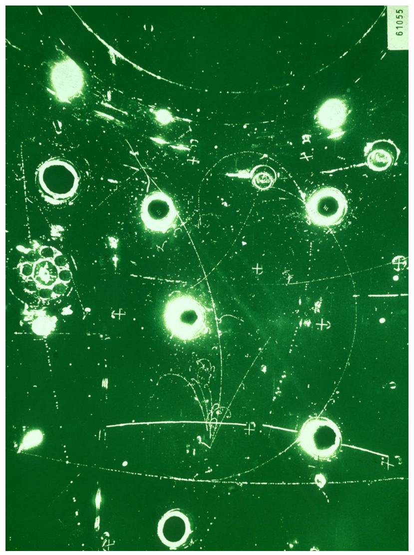
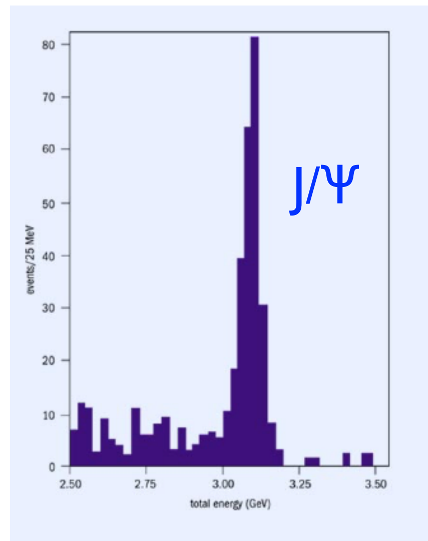
neutral currents



1974 — BNL, SLAC
charm



1976 — SLAC
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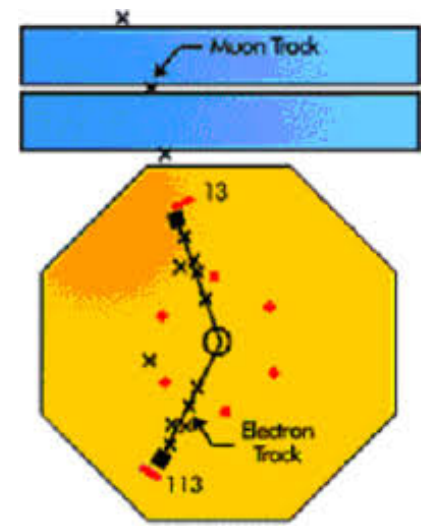
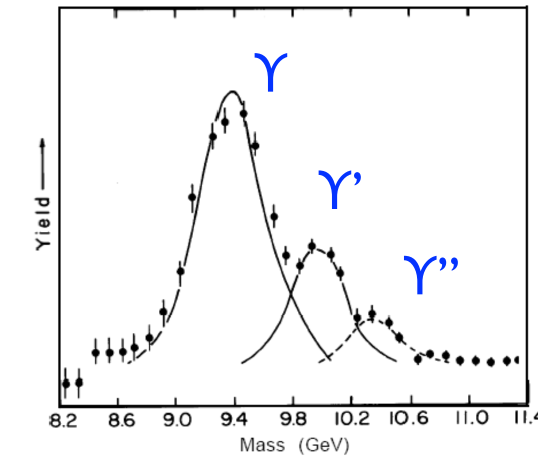


1979 — Fermilab
beauty



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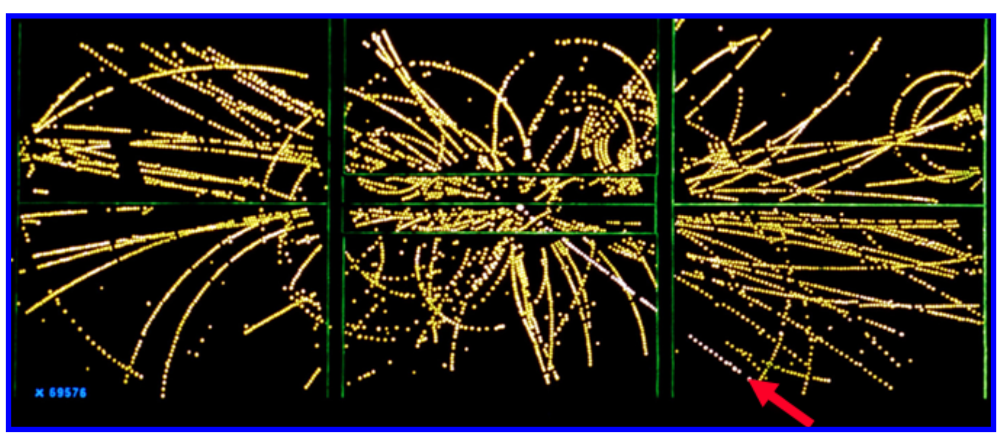

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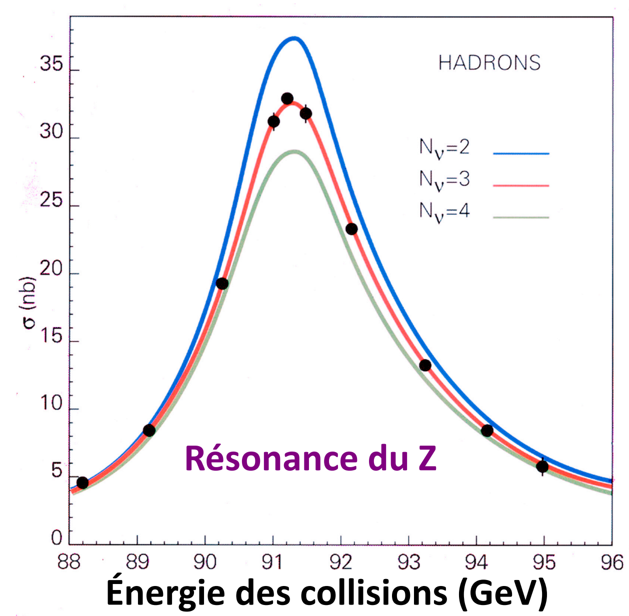

ALEPH, DEPHI, L3, OPAL

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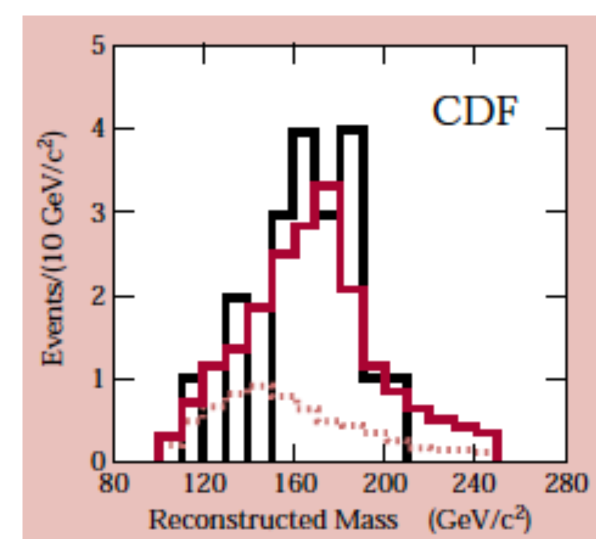
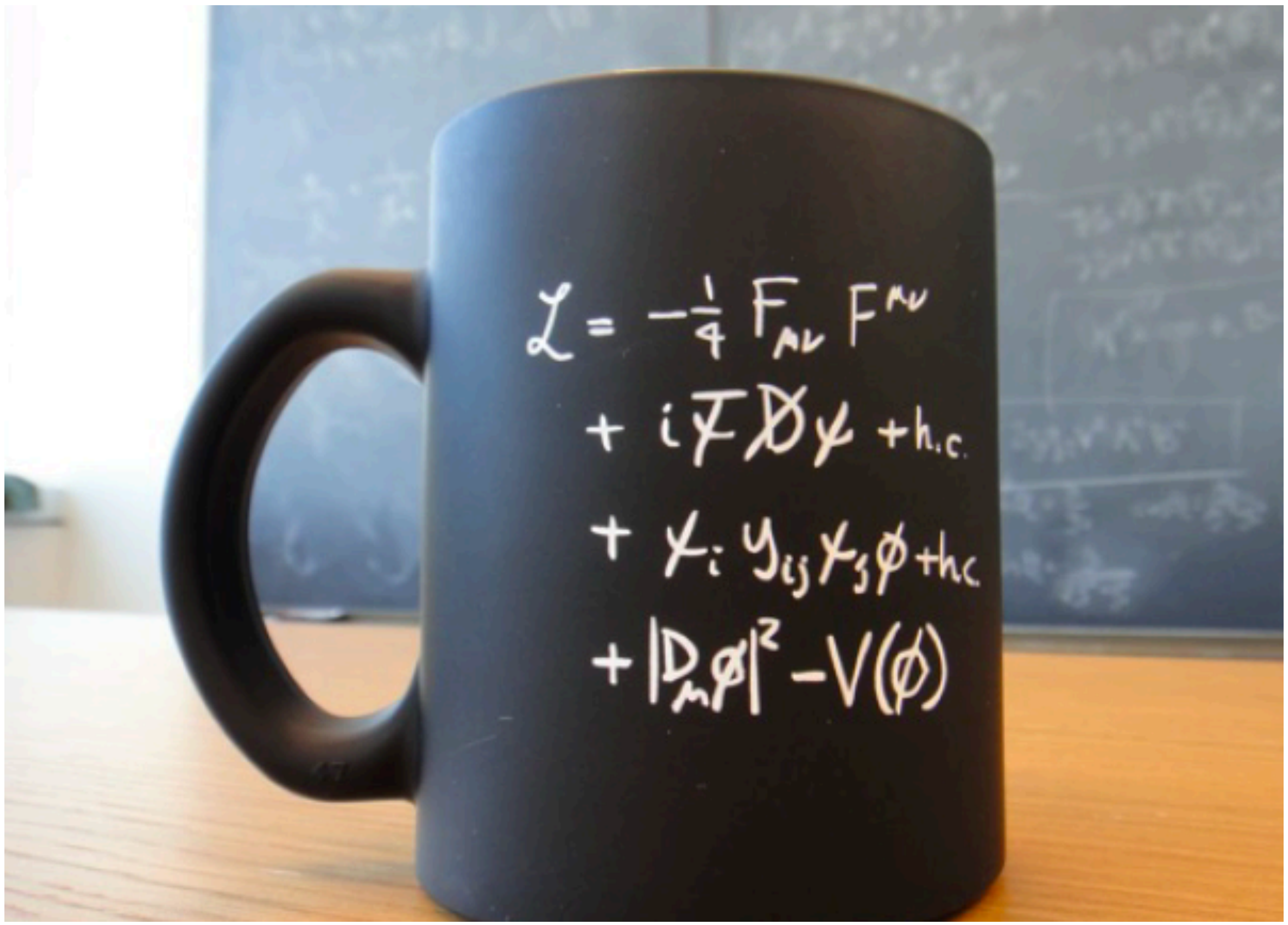


CDF, D0

The Electroweak Lagrangian



The electroweak Lagrangian after SSB

Gauge sector

Flavour sector

Higgs sector

The SM Lagrangian

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu\left[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4

$$+ \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j)$$

5

$$+ \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

from Symmetry Magazine, 2019

credit: T. Gutierrez, notations: M. Veltman

The SM Lagrangian

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4

$$+ \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j)$$

5

$$+ \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

1. kinematics and colour interactions of gluons (QCD)
2. kinematics and interactions of elementary bosons: W, Z, γ, and H
3. kinematics and interactions of elementary fermions: quarks and leptons (and massless neutrinos)
4. ghosts
5. more ghosts

from Symmetry Magazine, 2019

credit: T. Gutierrez, notations: M. Veltman

The Gauge Sector

Gauge fields before SSB (massless)

- $SU(2)_L$ (coupling = g) W^1, W^2 and W^3
- $U(1)_Y$ (coupling = g') B

Physical boson fields after SSB

- weak bosons (massive) W^+, W^- and Z
- photon (massless) γ

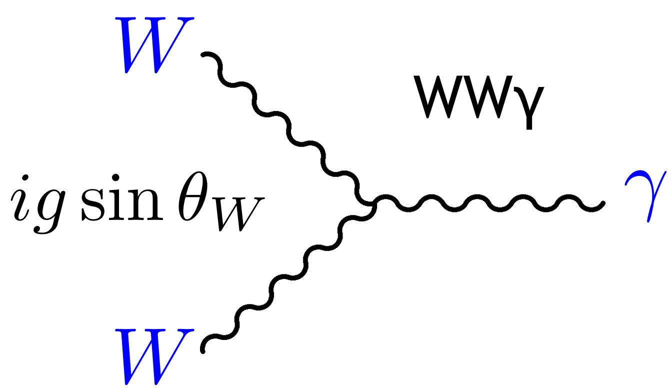
Weak mixing angle

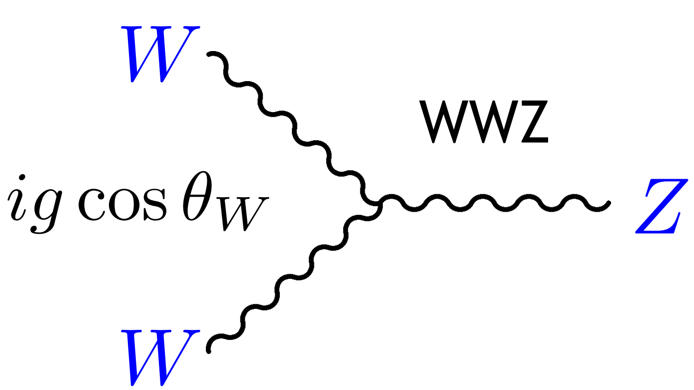
$$\tan\theta_W \equiv g'/g$$

Unit of electric charge

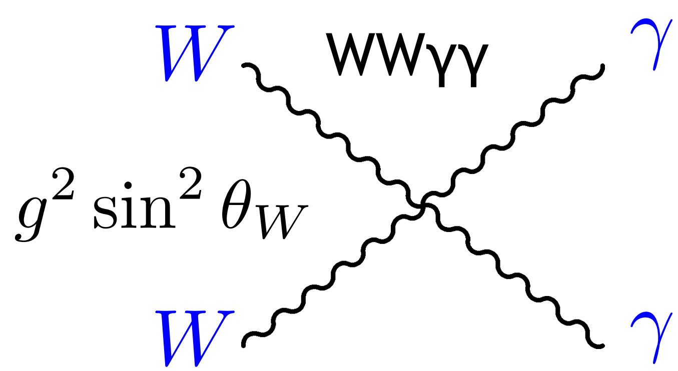
$$e \equiv g \ \sin\theta_W$$

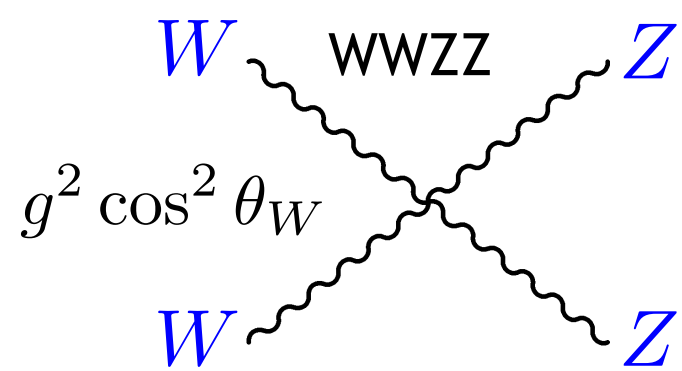
Triple gauge couplings

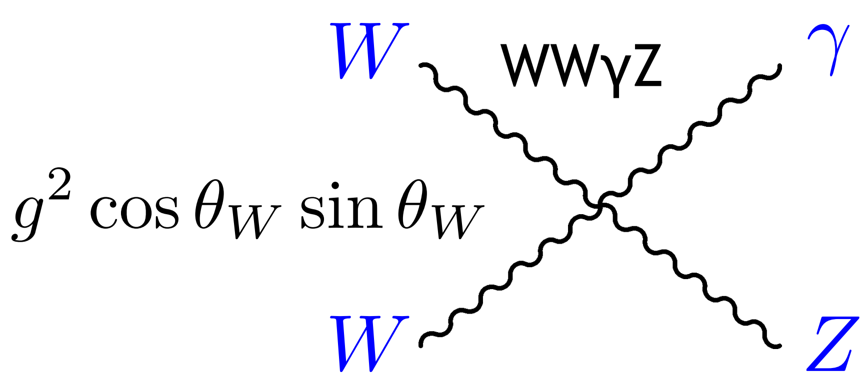


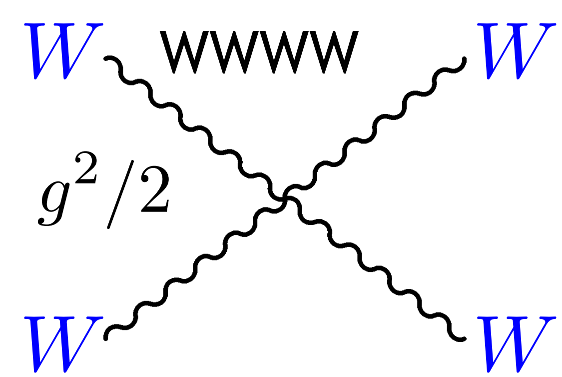


Quartic gauge couplings





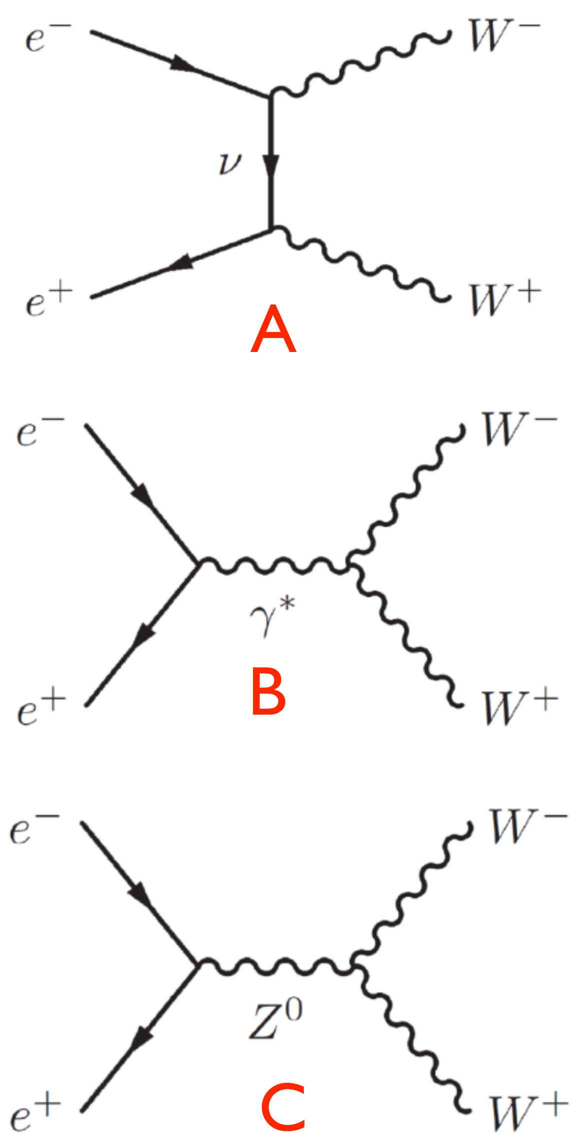


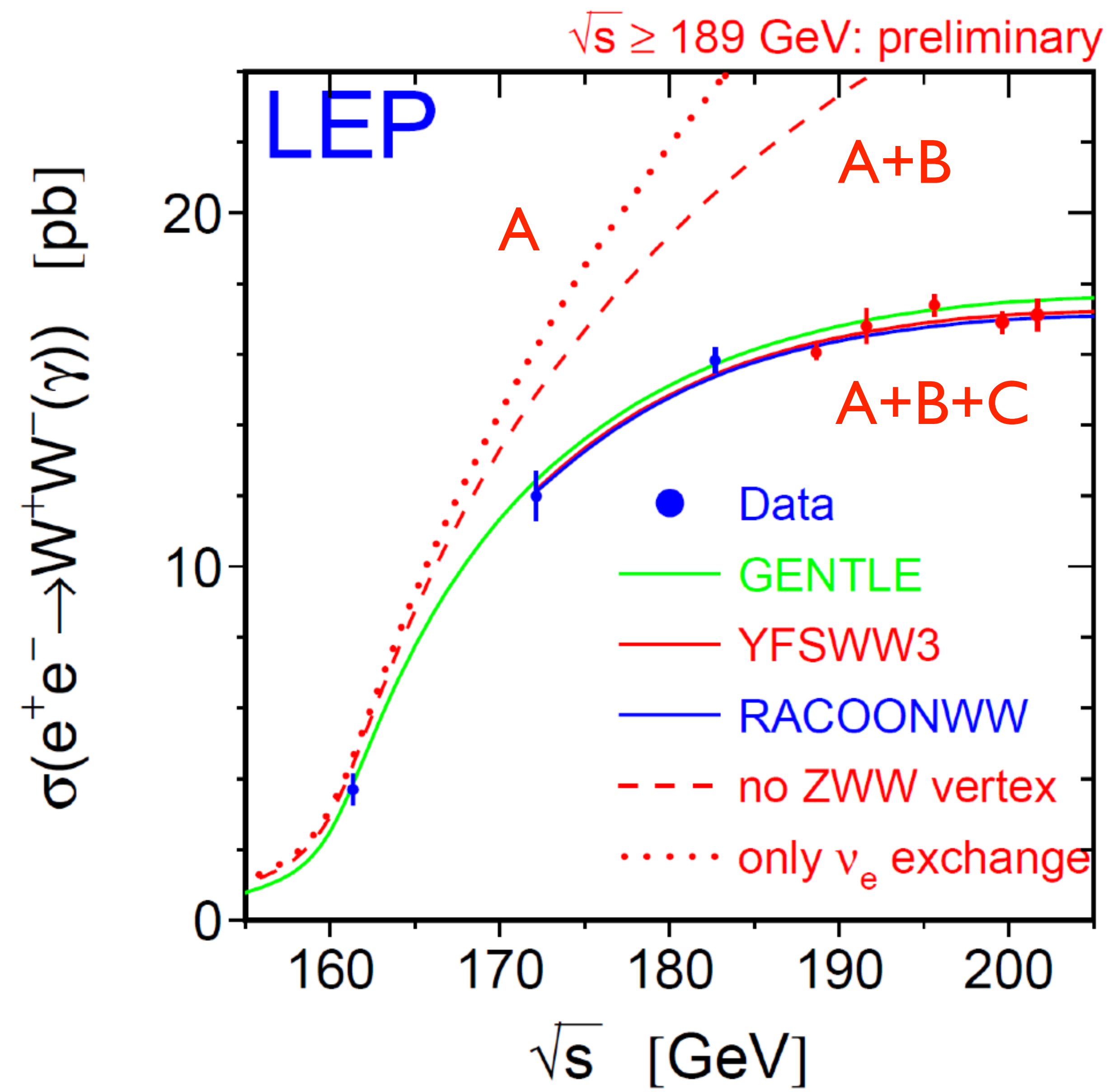


Triple and quartic gauge couplings
are central predictions of the Electroweak theory

LEP-2 : W Pair Production

W-pair production in e^+e^- collisions:





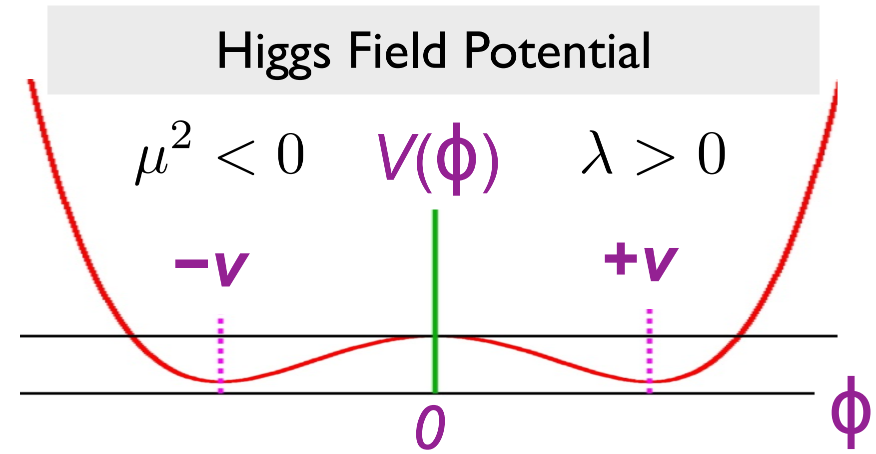
amplitudes B & C are essential to avoid an high-energy catastrophe (violation of unitarity)

Clear observation of triple gauge couplings (circa 2000 @ CERN)

The Higgs Sector

Higgs field v.e.v. $v = \sqrt{-\mu^2/2\lambda}$

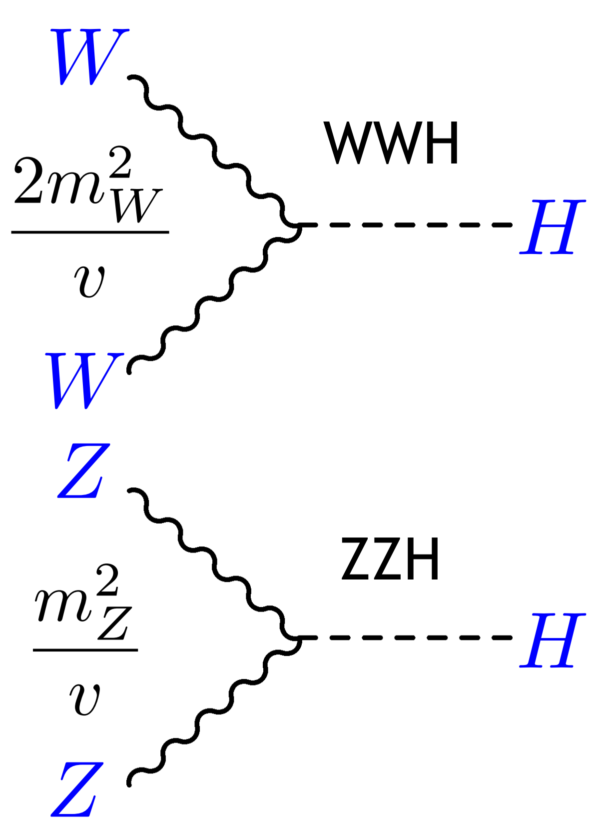
Higgs boson mass $m_H = \sqrt{2\lambda}v$

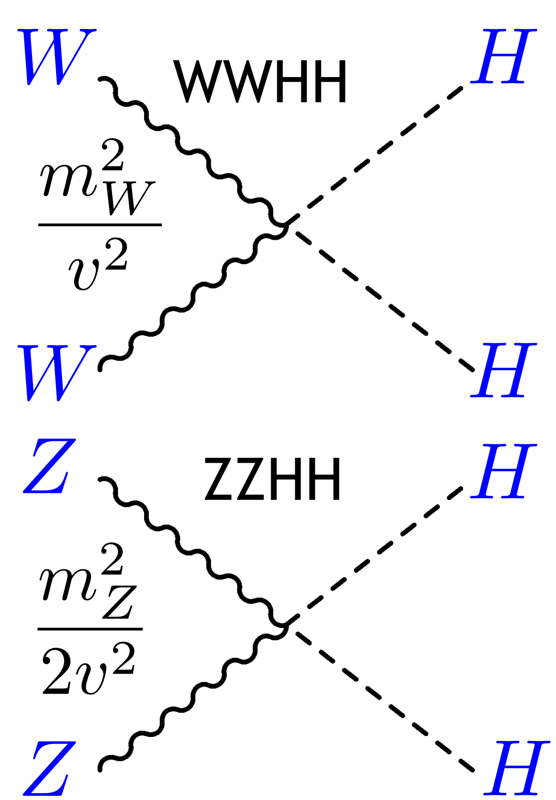


Weak boson masses

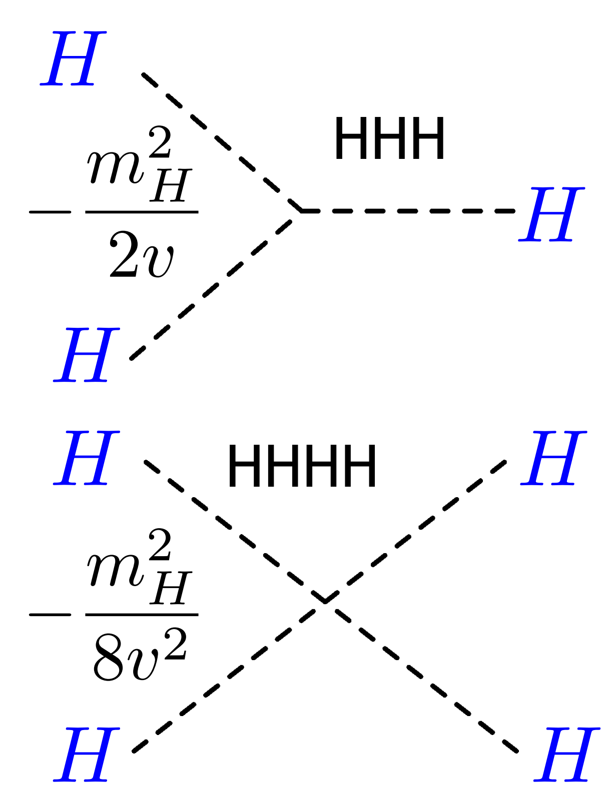
$$m_W \equiv \frac{gv}{2} \quad \text{and} \quad m_Z \equiv \frac{gv}{2\cos\theta_W}$$

Couplings to gauge bosons





Self couplings



EWK Radiative Corrections

Observables can be calculated in the SM in term of a finite number of parameters to be determined experimentally (coupling constants, masses of fermions, CKM and M_H)

Link with Fermi theory

$$m_W^2 = \frac{\pi}{\sqrt{2} G_F} \frac{\alpha}{\sin^2 \theta_W}$$

☛ Electroweak parameters (= at classical level)

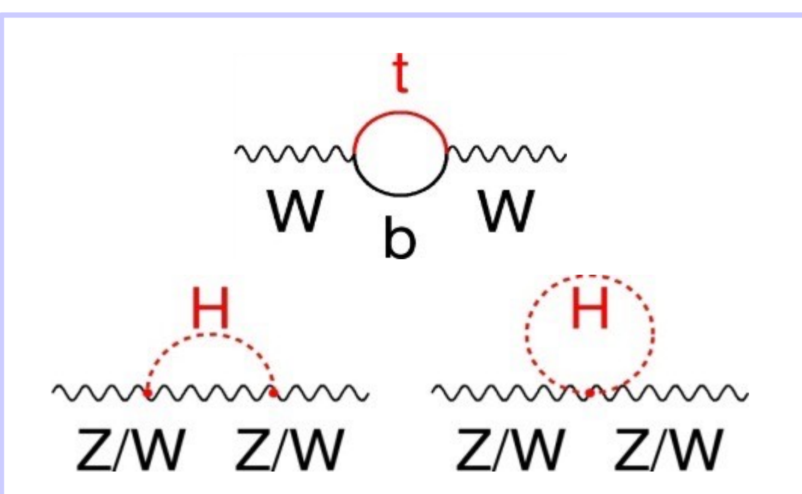
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \quad (= 1) \qquad s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2} \quad (= \sin^2\theta_W)$$

☛ Physical quantities

$$\bar{\rho} = 1 + \Delta\rho$$

$$M_W^2 = m_W^2 \, (1 + \Delta r) \qquad \text{and} \qquad \sin^2 \theta_W^{\text{eff}} = s_W^2 (1 + \Delta\kappa)$$

with $\quad \Delta r, \Delta\rho, \Delta\kappa = f(\, m_t{}^2, \ln(m_H), \ldots \,)$



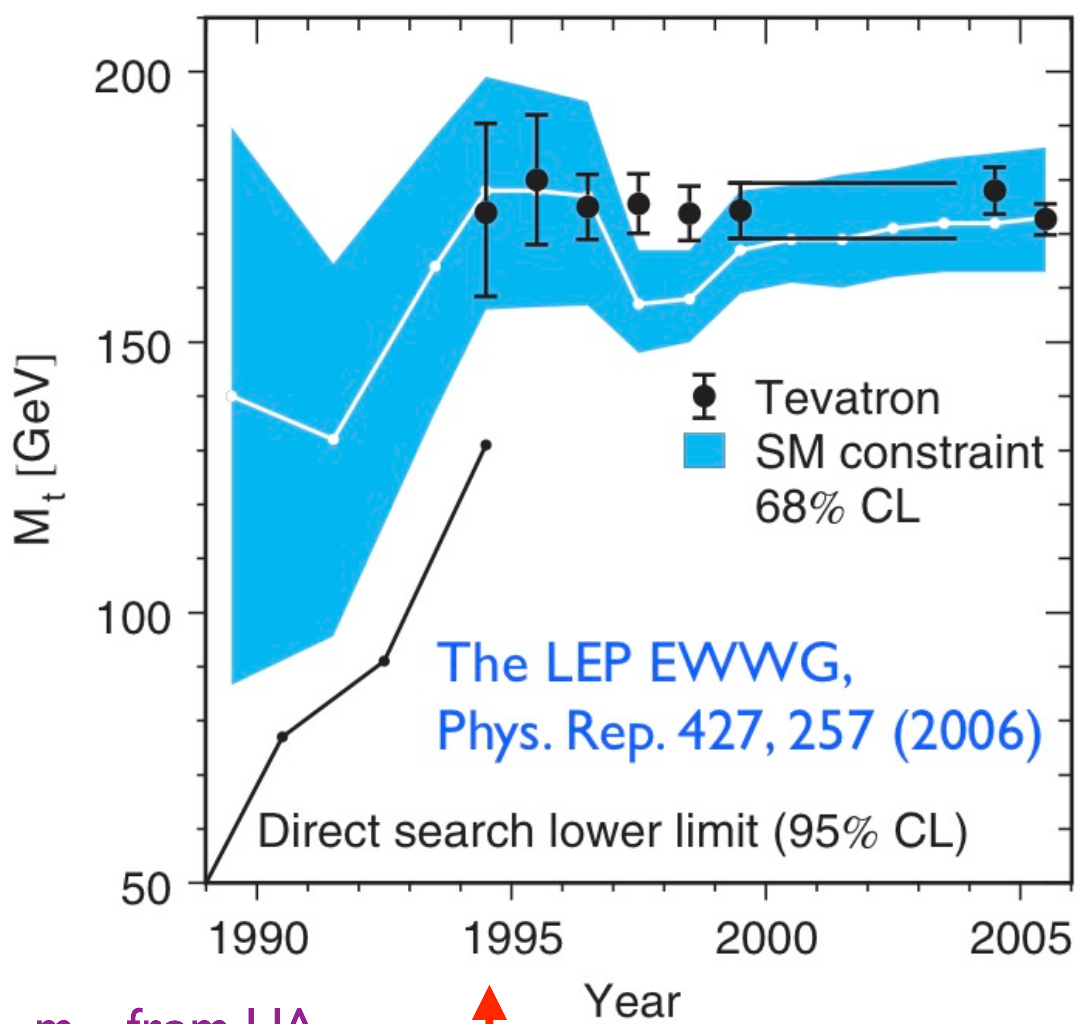
$$\Delta\rho_t \simeq 0.01 \times [\, m_t/(175 \text{ GeV}) \,]^2$$

$$\Delta\rho_H \simeq -0.0015 \times \log(\, m_H / M_W \,)$$

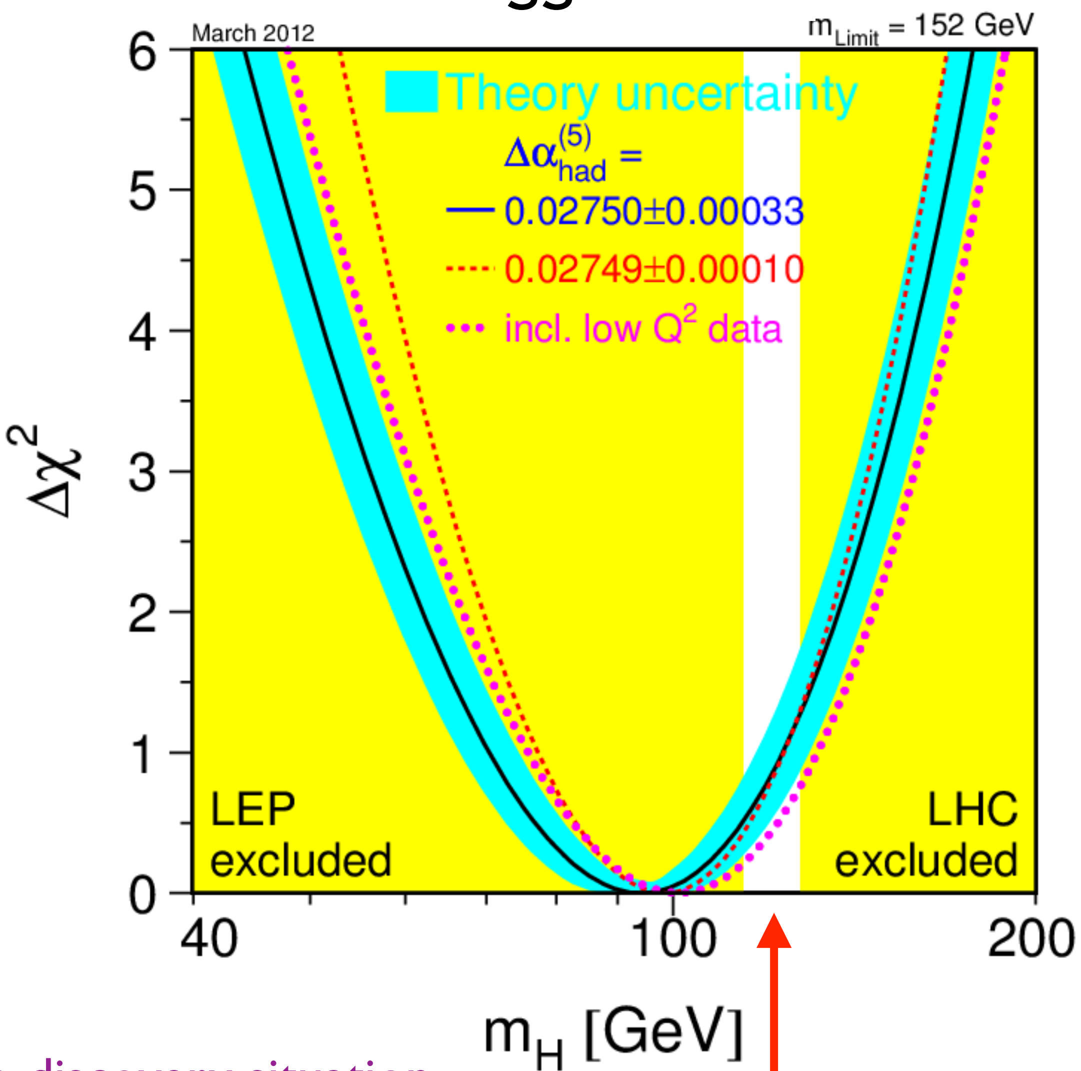
the electroweak radiative correction parameters are of the order of the percent and involve contributions from top quark and Higgs boson loops

Predictive Power of the SM

The Top Quark



The Higgs Boson



mW from UA
+ precision EW
from LEP/SLD

discovery
Tevatron
1994

W mass
from LEP-II

pre-discovery situation
(March 2012)

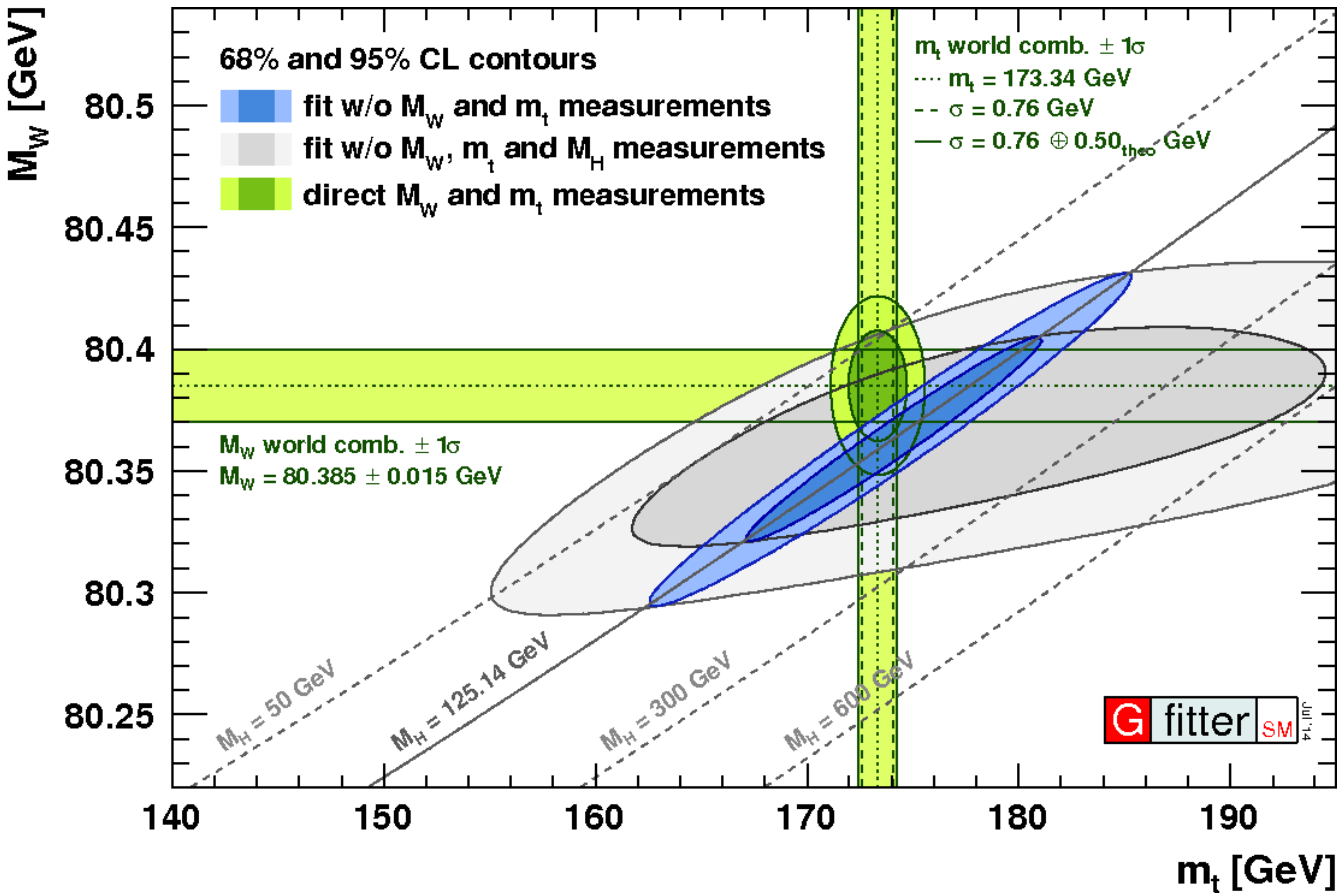
discovery LHC
2012

Successful experimental strategy

- precision at lepton machines
- discovery at hadron machines

The Electroweak Fit

Through quantum corrections, the theory establishes relations between measurable parameters

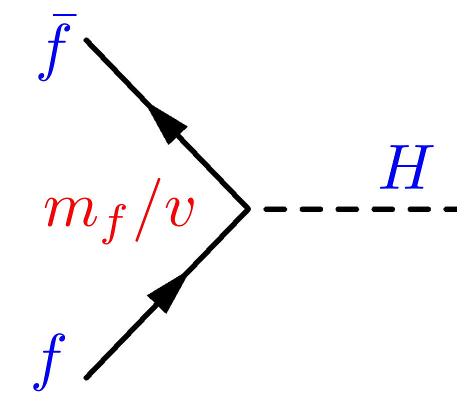


Fermion and Boson Masses

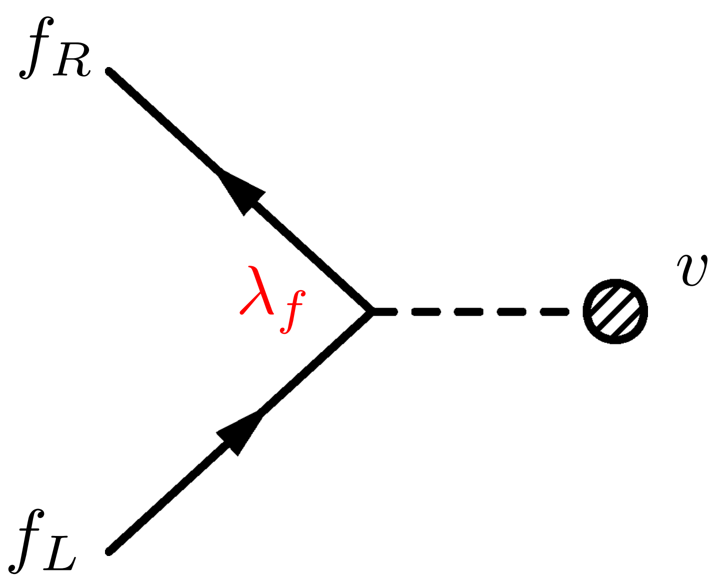
Yukawa interaction terms between fermions and the Higgs field

- Lorentz scalar
- gauge invariant

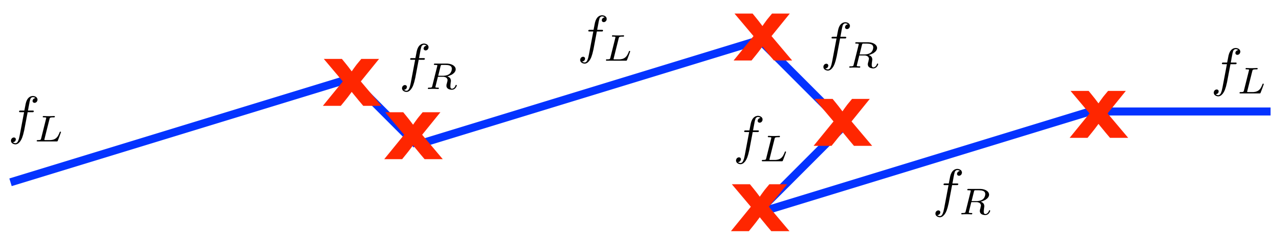
$$\lambda_f(\overline{F_L}\phi)f_R + \text{h.c.} \xrightarrow{\text{SSB}} m_f\,\overline{f}f + m_f/v\,\overline{f}fh$$



Fermions acquire mass

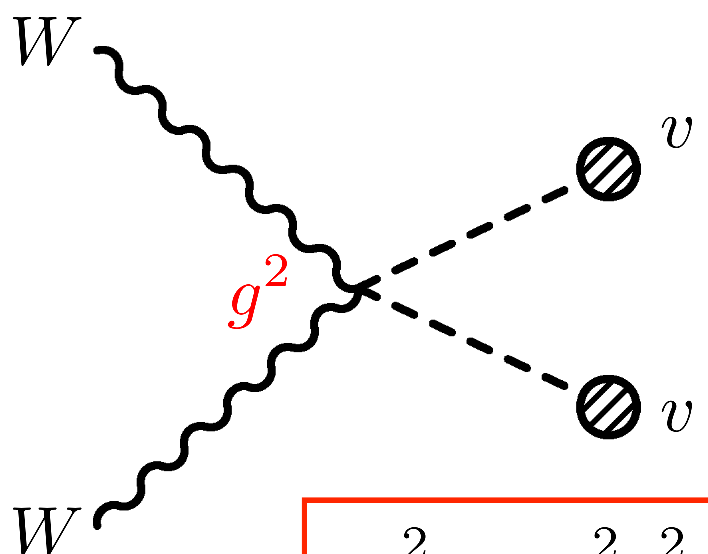


$$m_f = \lambda_f\, v/\sqrt{2}$$



Higgs condensate *connects* left- and right- components

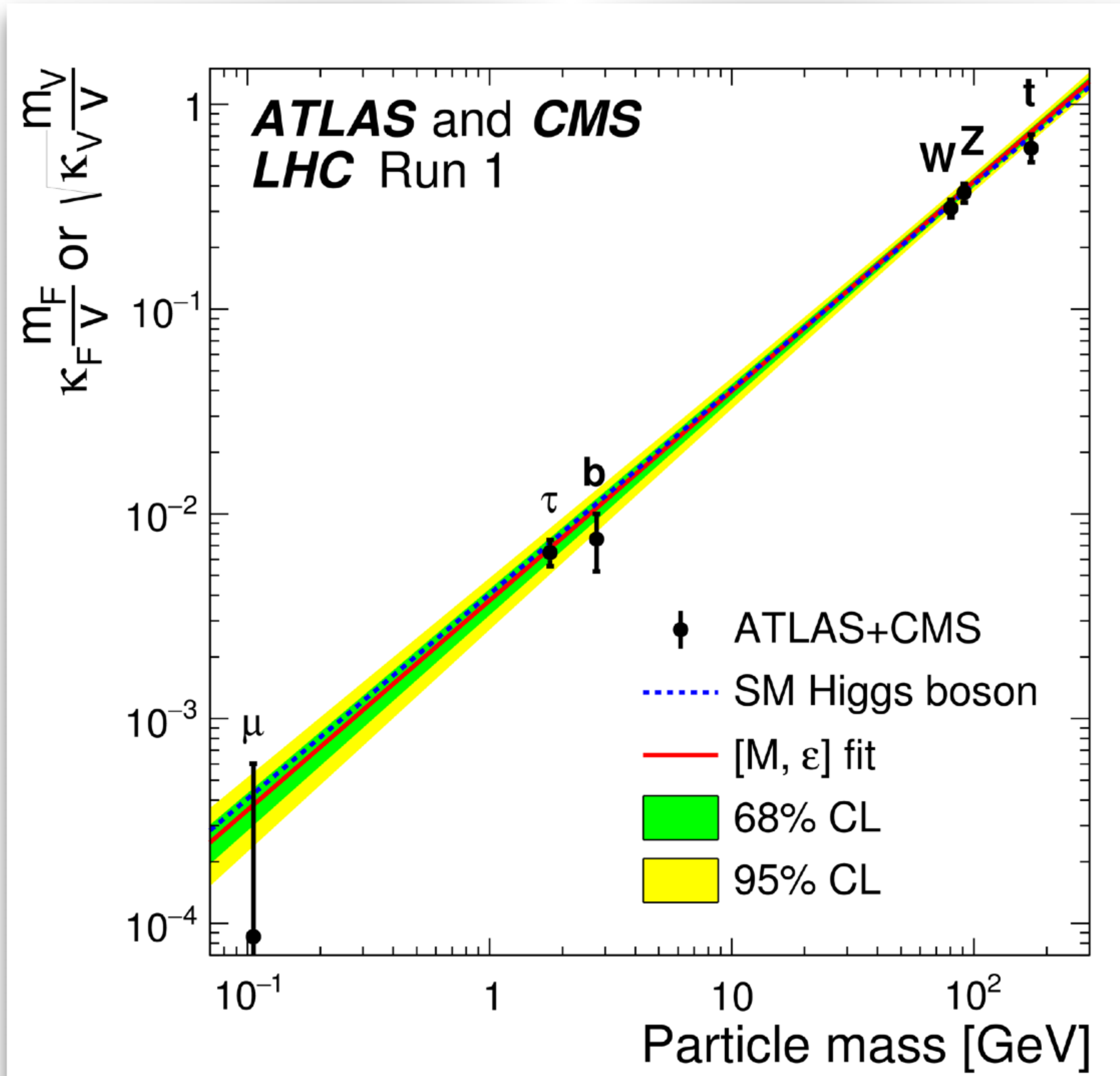
Bosons acquire mass



$$m_W^2 = g^2v^2/4$$

W and Z Bosons acquire a longitudinal polarisation through interaction with the Higgs condensate

The Higgs Boson's Signature



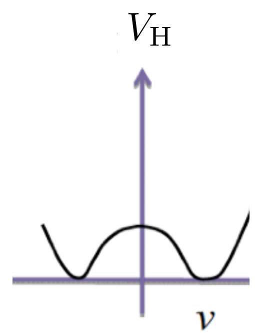
m_H = 125 GeV

exactly as predicted by the SM...

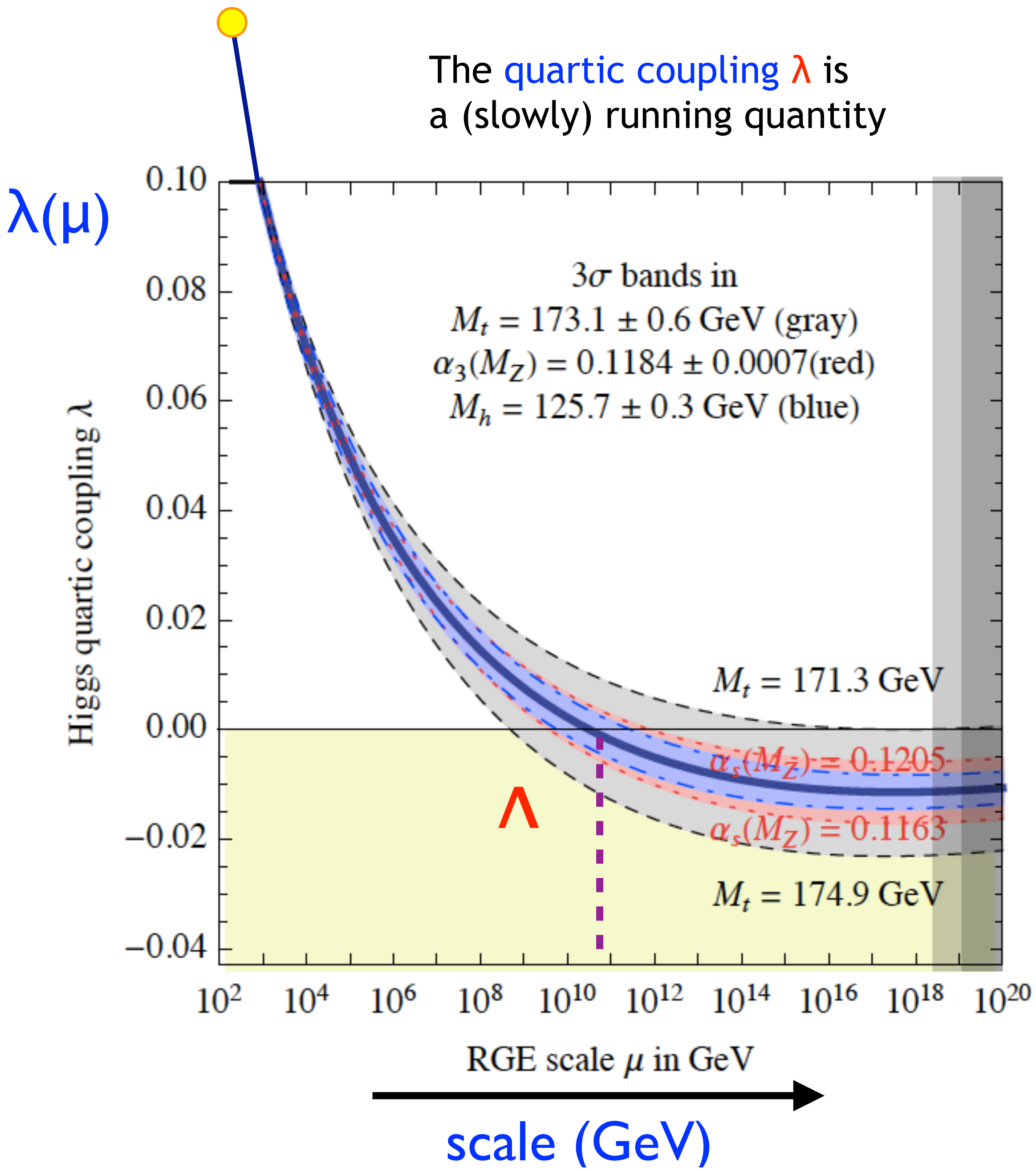
EW Vacuum Stability

Higgs potential

$$V_{\rm H} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\lambda(v) = M_{\rm H}^2/2v^2$$

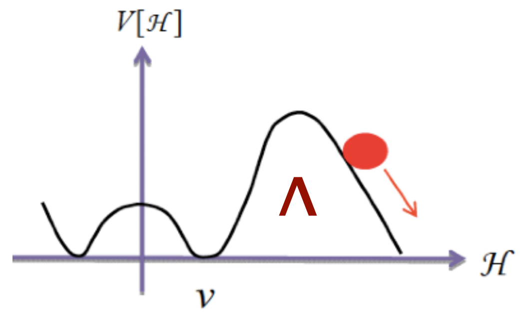


The *instability scale* of the SM, which depends on m_t , M_H, and α_s is of order $\Lambda \approx 10^{11}$ GeV !

EW Vacuum Stability

Higgs potential

$$V_{\rm H} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



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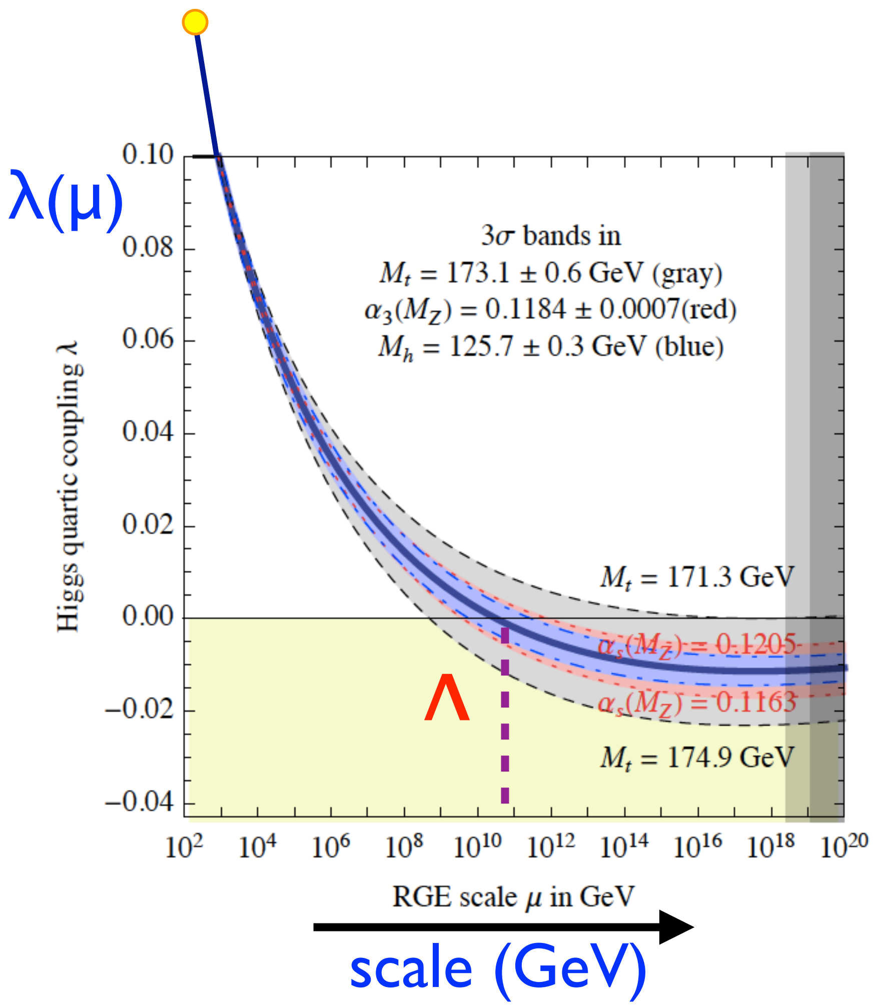
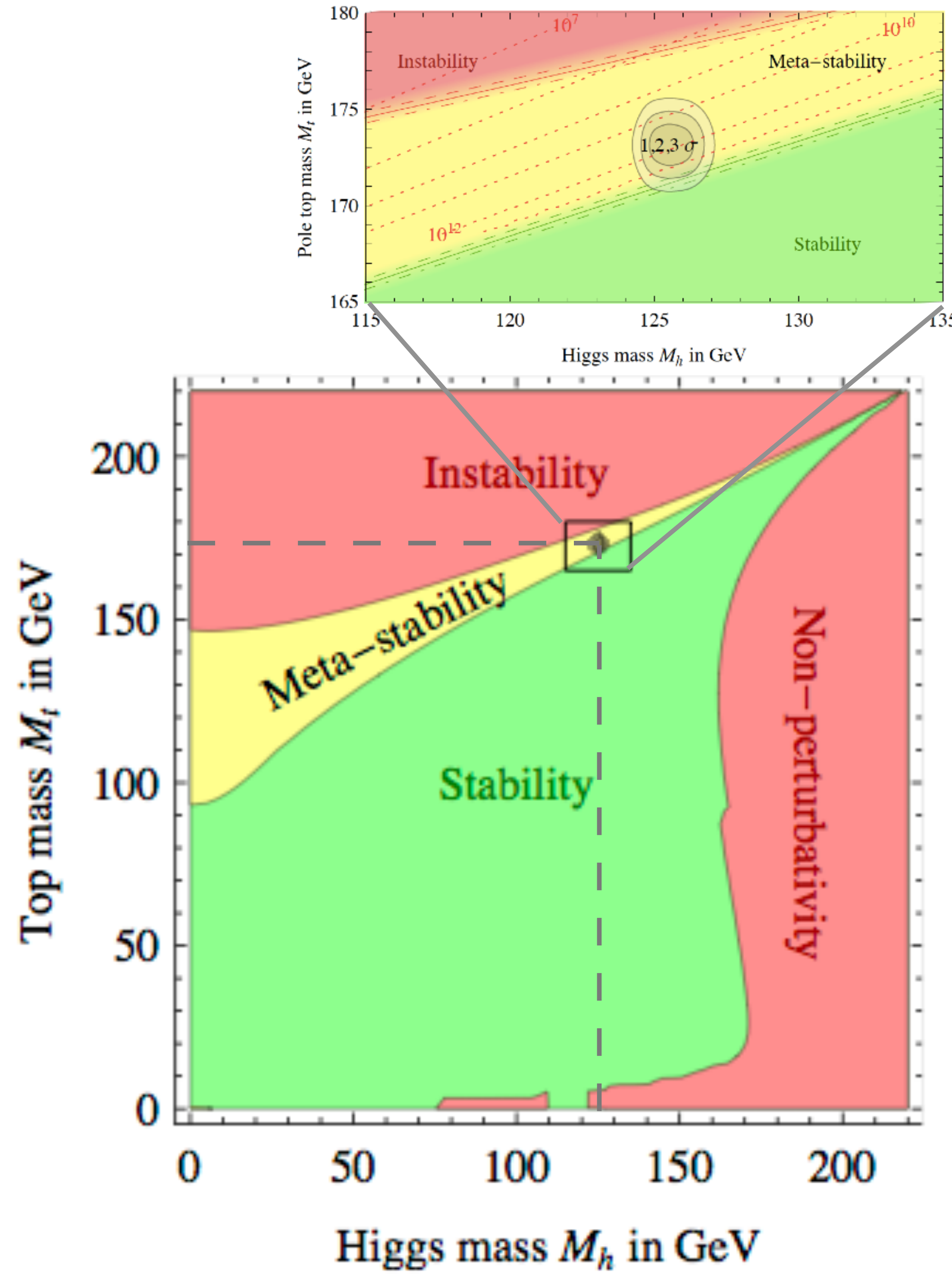


Instability scale Λ ≈ 10^{11} GeV



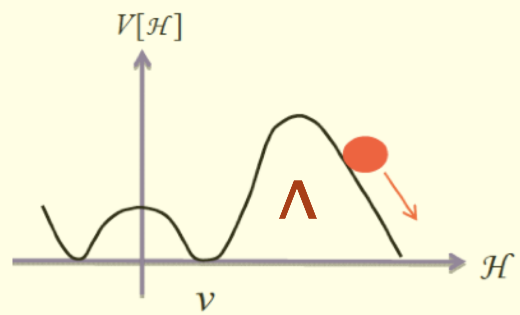
Our universe lives on the edge of the precipice

Numerical coincidence
or fundamental feature ?

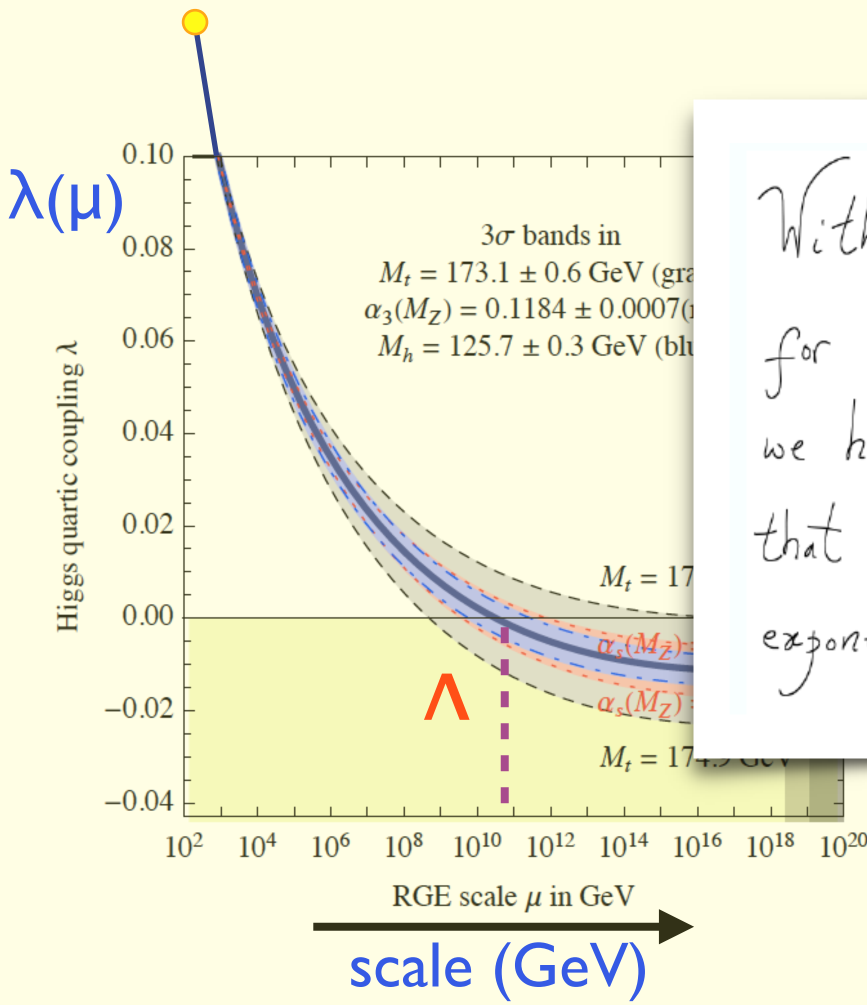
EW Vacuum Stability

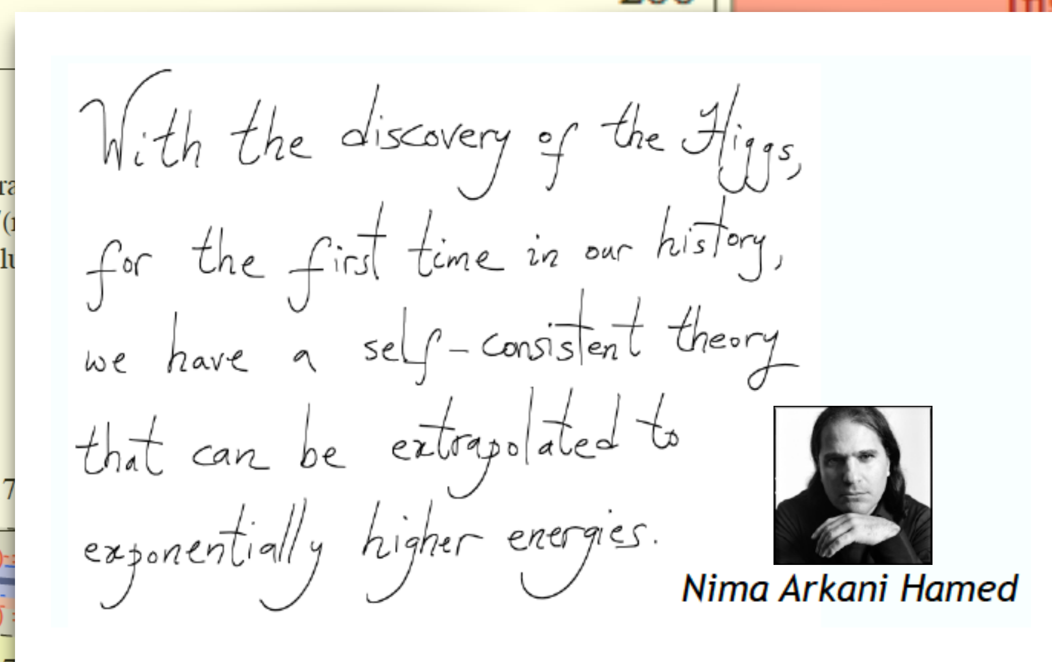
Higgs potential

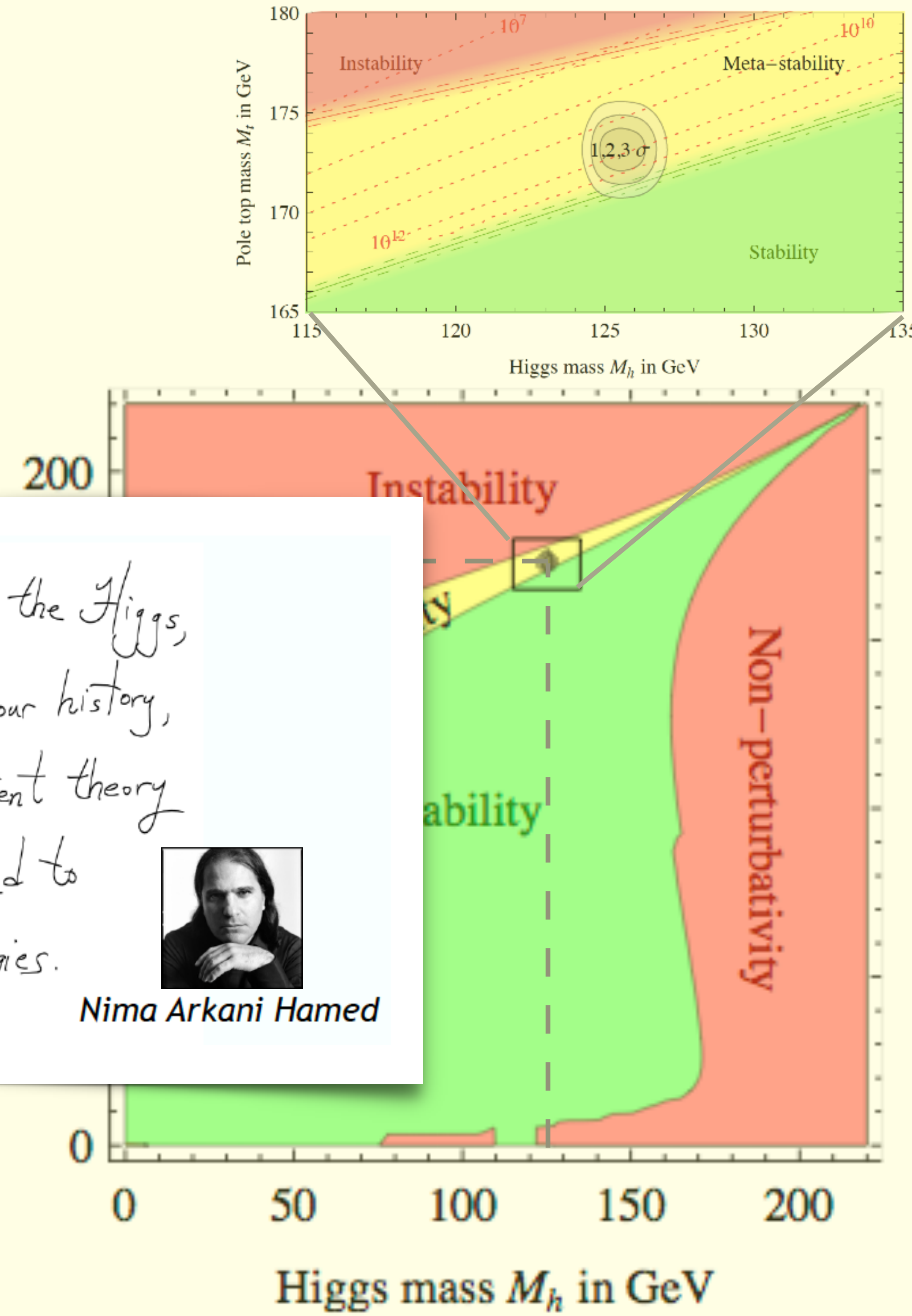
$$V_{\rm H} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\lambda(v) = M_{\rm H}^2/2v^2$$







Instability scale $\Lambda \approx 10^{11}$ GeV

Our universe lives on the edge of the precipice

Numerical coincidence
or fundamental feature ?

Is this the End of History?

PLB 683 (2010) 196

Asymptotic safety of gravity and the Higgs boson mass

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Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

12 January 2010

2010 !

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

In conclusion, we discussed the possibility that the SM, supplemented by the asymptotically safe gravity plays the role of a fundamental, rather than effective field theory. We found that this may be the case if the gravity contributions to the running of the Yukawa and Higgs coupling have appropriate signs. The mass of the Higgs scalar is predicted $m_H = m_{\min} \simeq 126$ GeV with a few GeV uncertainty if all the couplings of the Standard Model, with the exception of the Higgs self-interaction λ, are asymptotically free, while λ is strongly attracted to an approximate fixed point $\lambda = 0$ (in the limit of vanishing Yukawa and gauge couplings) by the flow in the high energy regime. This can be achieved by a positive gravity induced anomalous dimension for the running of λ. A similar prediction remains valid for extensions of the SM as grand unified theories, provided the split between the unification and Planck-scales remains moderate and all relevant couplings are perturbatively small in the transition region. Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

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2010 !

Abstract

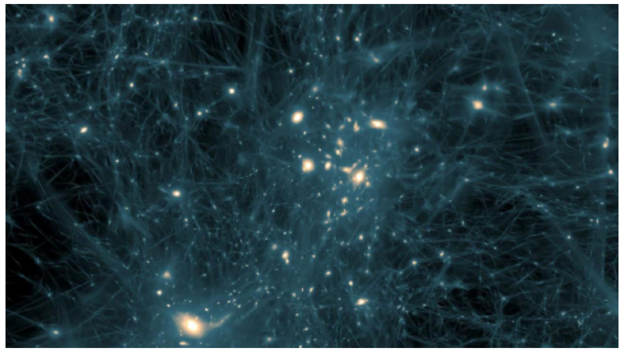
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

In conclusion, we discussed the possibility that the SM, supplemented by the asymptotically safe gravity plays the role of a fundamental, rather than effective field theory. We found that this may be the case if the gravity contributions to the running of the Yukawa and Higgs coupling have appropriate signs. The mass of the Higgs scalar is predicted $m_H = m_{\min} \simeq 126$ GeV with a few GeV uncertainty if all the couplings of the Standard Model, with the exception of the Higgs self-interaction λ, are asymptotically free, while λ is strongly attracted to an approximate fixed point $\lambda = 0$ (in the limit of vanishing Yukawa and gauge couplings) by the flow in the high energy regime. This can be achieved by a positive gravity induced anomalous dimension for the running of λ. A similar prediction remains valid for extensions of the SM as grand unified theories, provided the split between the unification and Planck-scales remains moderate and all relevant couplings are perturbatively small in the transition region. Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

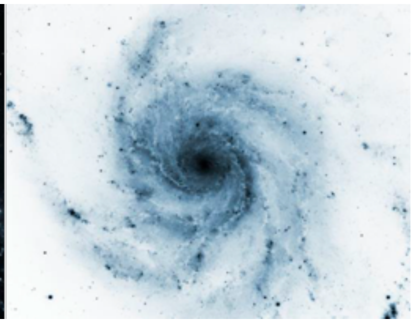
… the answer is: NO!

(I guess)

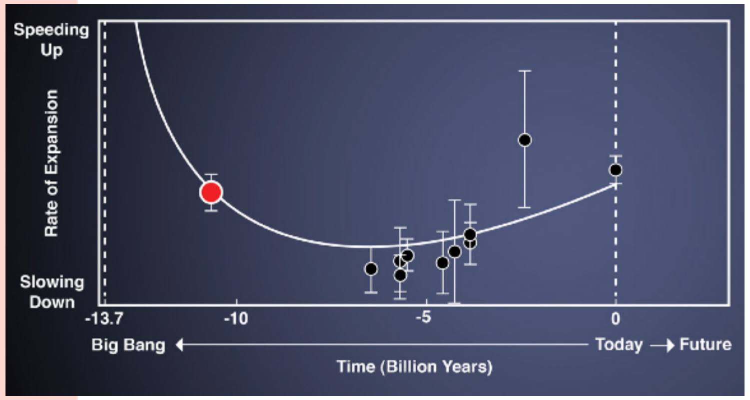
What the SM cannot explain

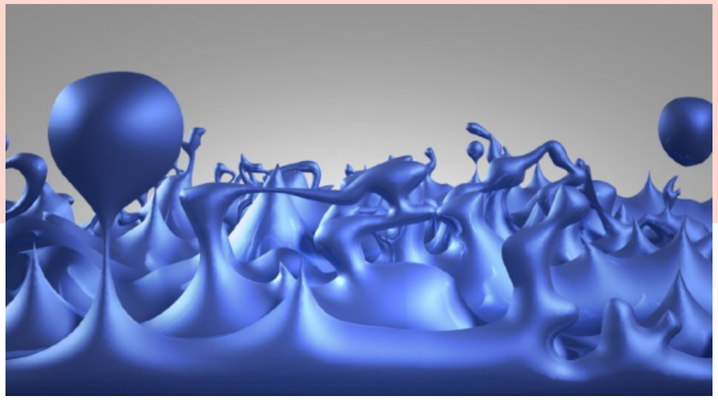


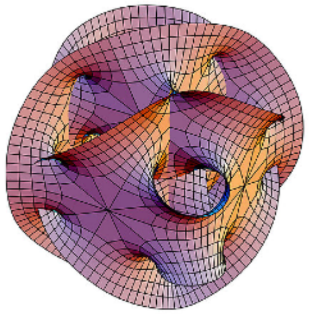
- ☛ the origin of Neutrino Masses
- ☛ the nature of Dark Matter
- ☛ the Baryonic Asymmetry of the Universe



- ☛ the Accelerated Expansion of the Universe
- ☛ the dynamics of the Primordial Inflation
- ☛ Gravitation



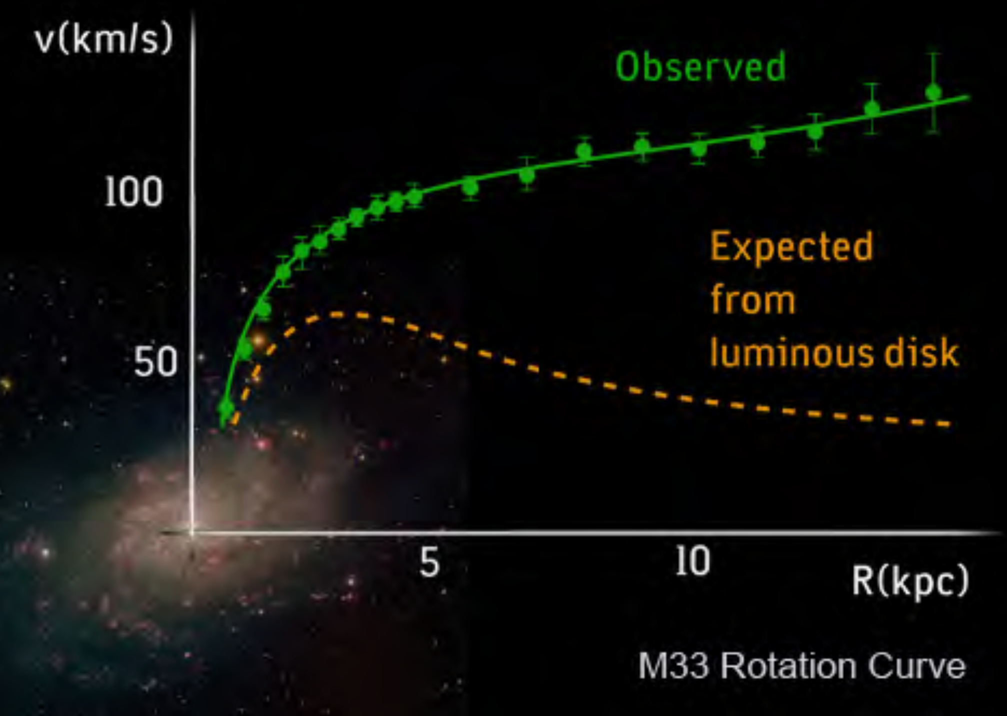




see lecture by G. Servant

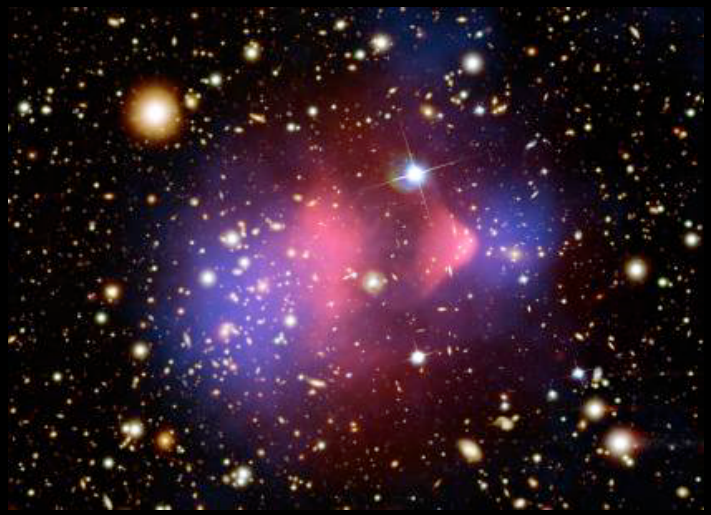
Dark Matter (DM)

Astrophysical Indications
all scales

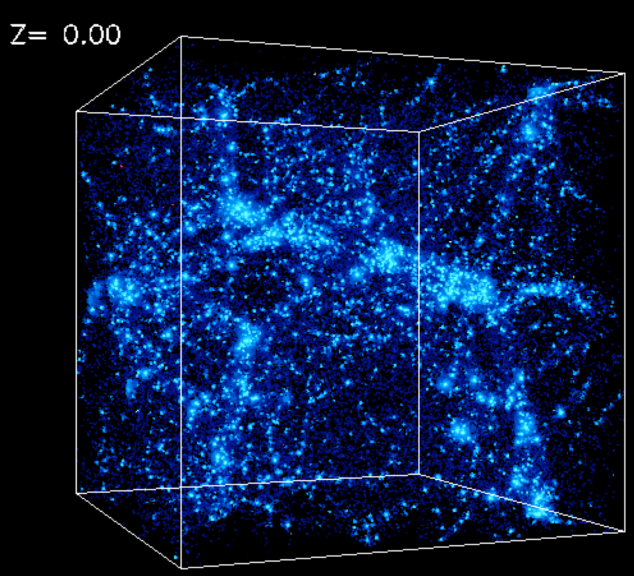


rotation curves of galaxies

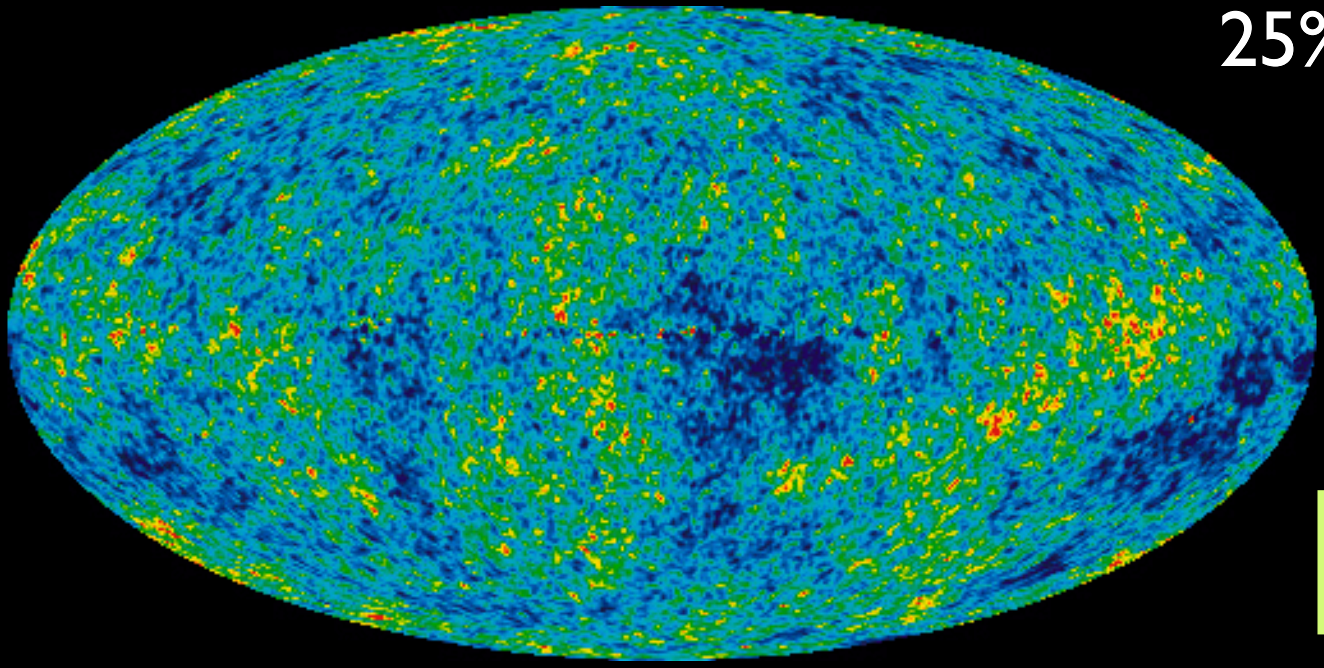
galaxy clusters
gravitational lensing



colliding galaxy clusters
(here: *bullet cluster*)



structure formation
at large scale

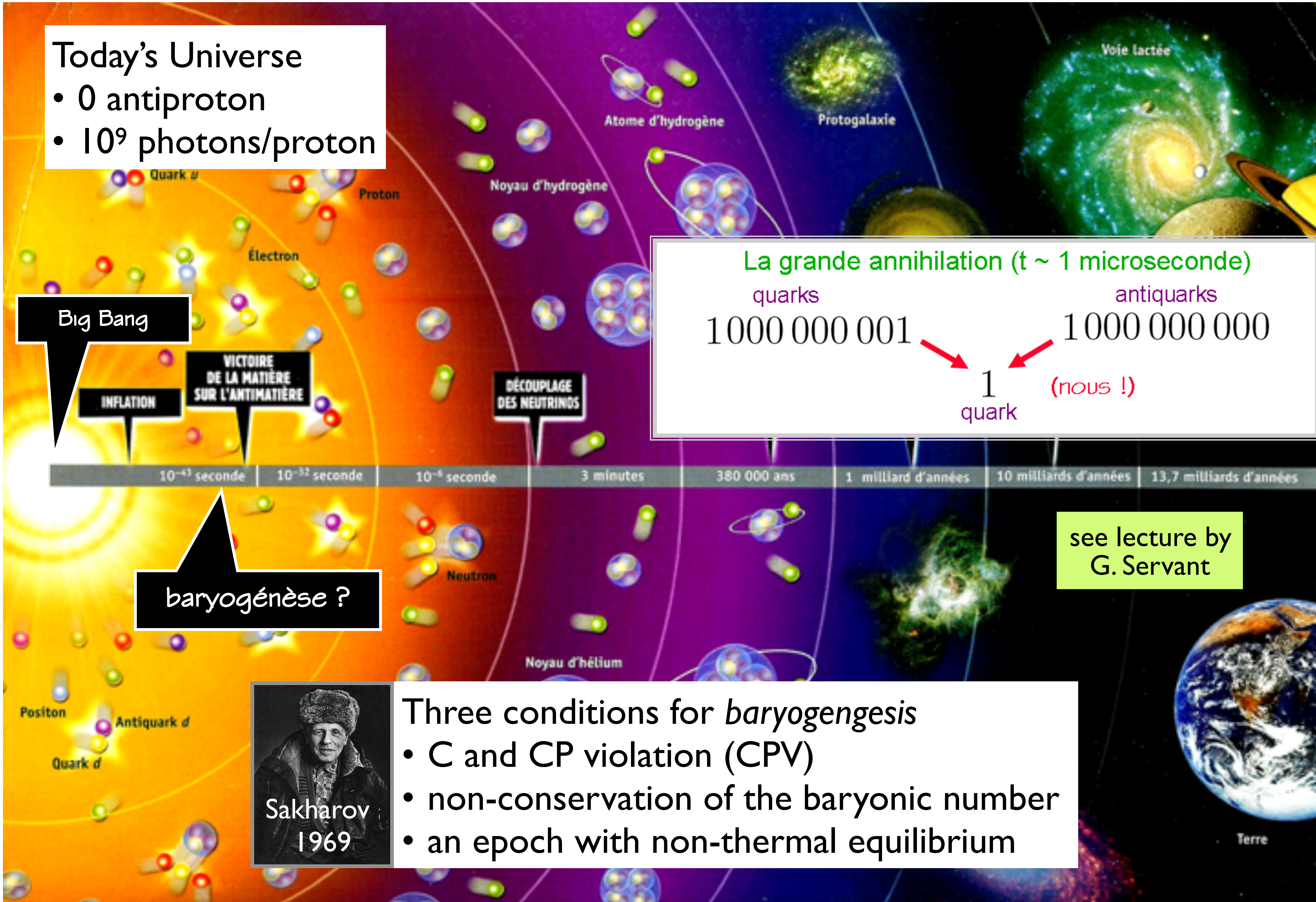


25%

anisotropies in the cosmic microwave radiation (CMB)

see lecture by
Ch. Yèche

Baryonic Asymmetry of the Universe



Today's Universe
- 0 antiproton
- 10^9 photons/proton

La grande annihilation (t ~ 1 microseconde)

quarks 1 000 000 001 → 1 quark ← antiquarks 1 000 000 000 (nous !)

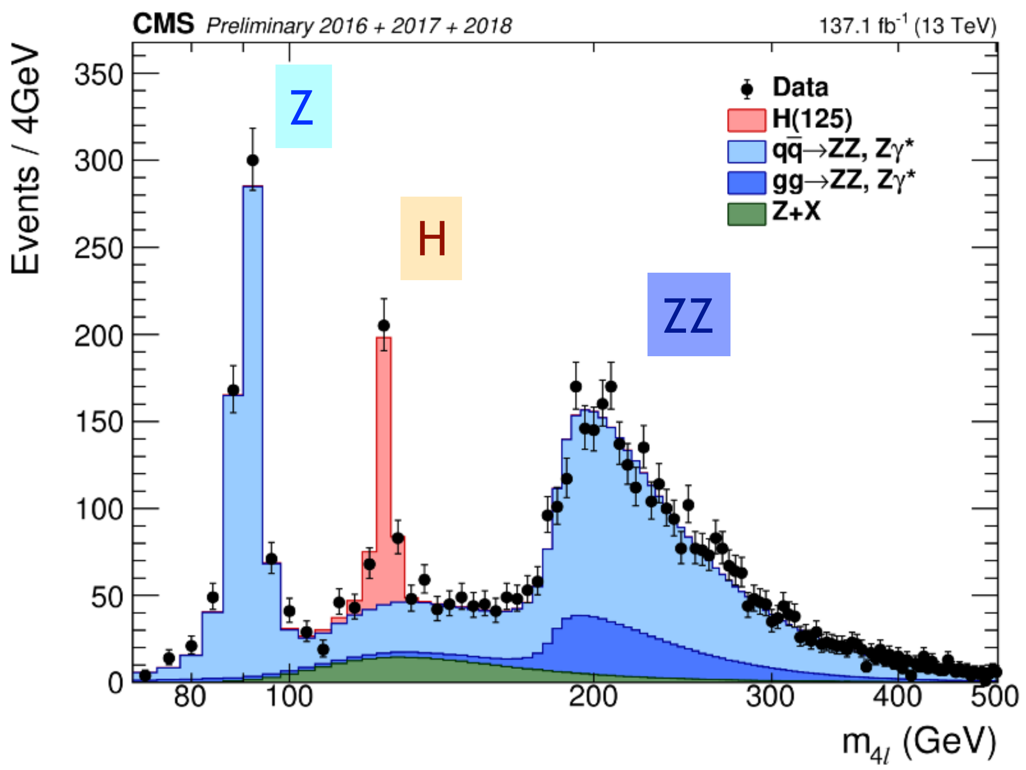
see lecture by G. Servant

Three conditions for *baryogengesis*
- C and CP violation (CPV)
- non-conservation of the baryonic number
- an epoch with non-thermal equilibrium

The Unbearable Lightness of the Higgs

The SM of particle physics is theoretically consistent and incredibly successful at

- describing (almost) all experimental facts
- making non-trivial falsifiable predictions



Still, the SM is not the Theory of Everything (clearly) and it has problems

☛ aesthetical problems

- large number of arbitrary parameters (19)
- failure at unifying gauge couplings at high energy

☛ the hierarchy/naturalness problem

- radiative corrections to M_H^2 in the SM with cut-off $\Lambda \gg M_H$ of order Λ^2
- mind-blowing fine tuning for $\Lambda = M_{Plank}$

Is there a fundamental symmetry protecting the Higgs mass and linking the Z and H bosons?

How much fine tuning can we bear?
➙ HL-LHC (no NP) ≈ 1%
➙ FCC-hh (no NP) ≈ 0.01%

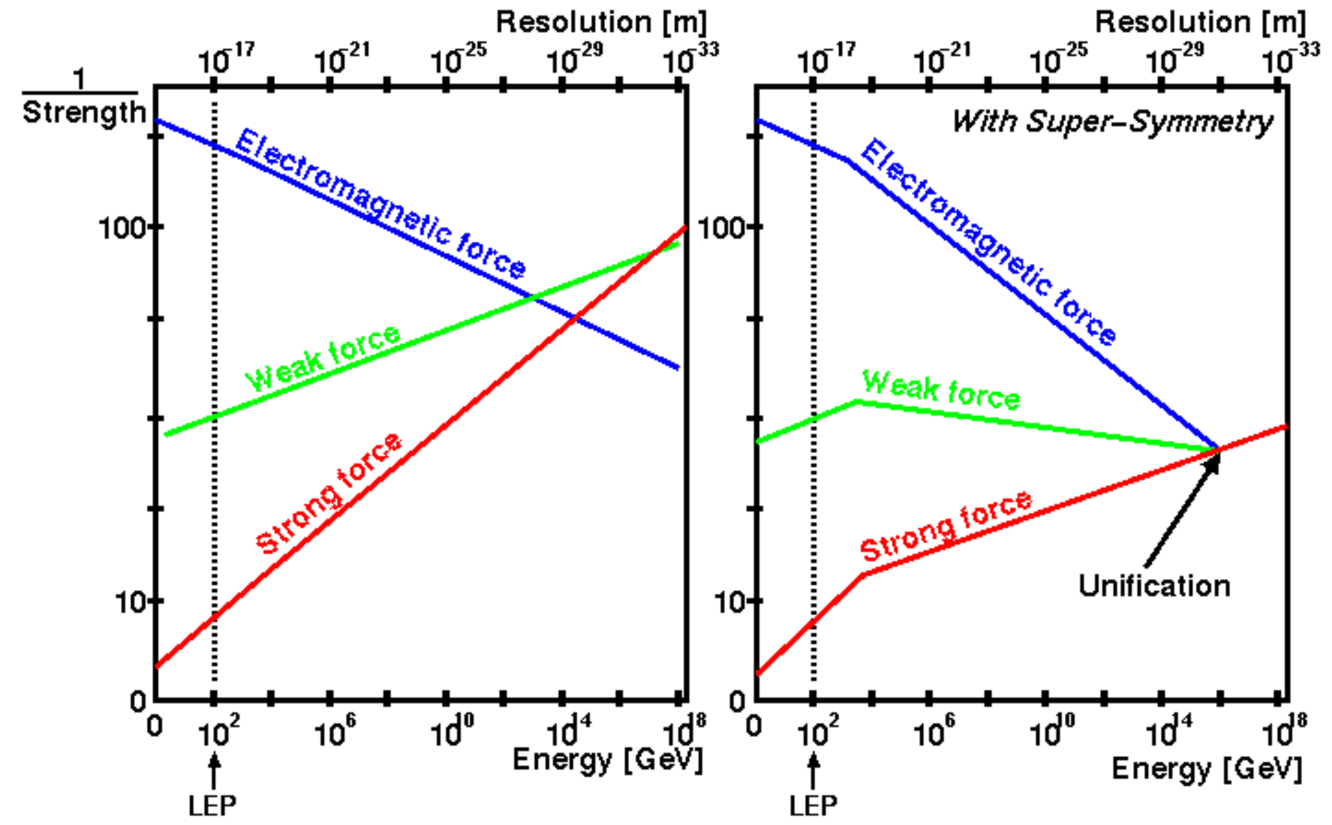
see lecture by J. Zinn-Justin

Physics Beyond the Standard Model

There are convincing reasons to believe that the SM is "only" a low-energy manifestation of a more fundamental theory

Mains goals of most models of physics beyond the SM (BSM):

1. solve the Naturalness problem
2. provide a Dark Matter candidate
3. realise Unification of coupling constants at high energy



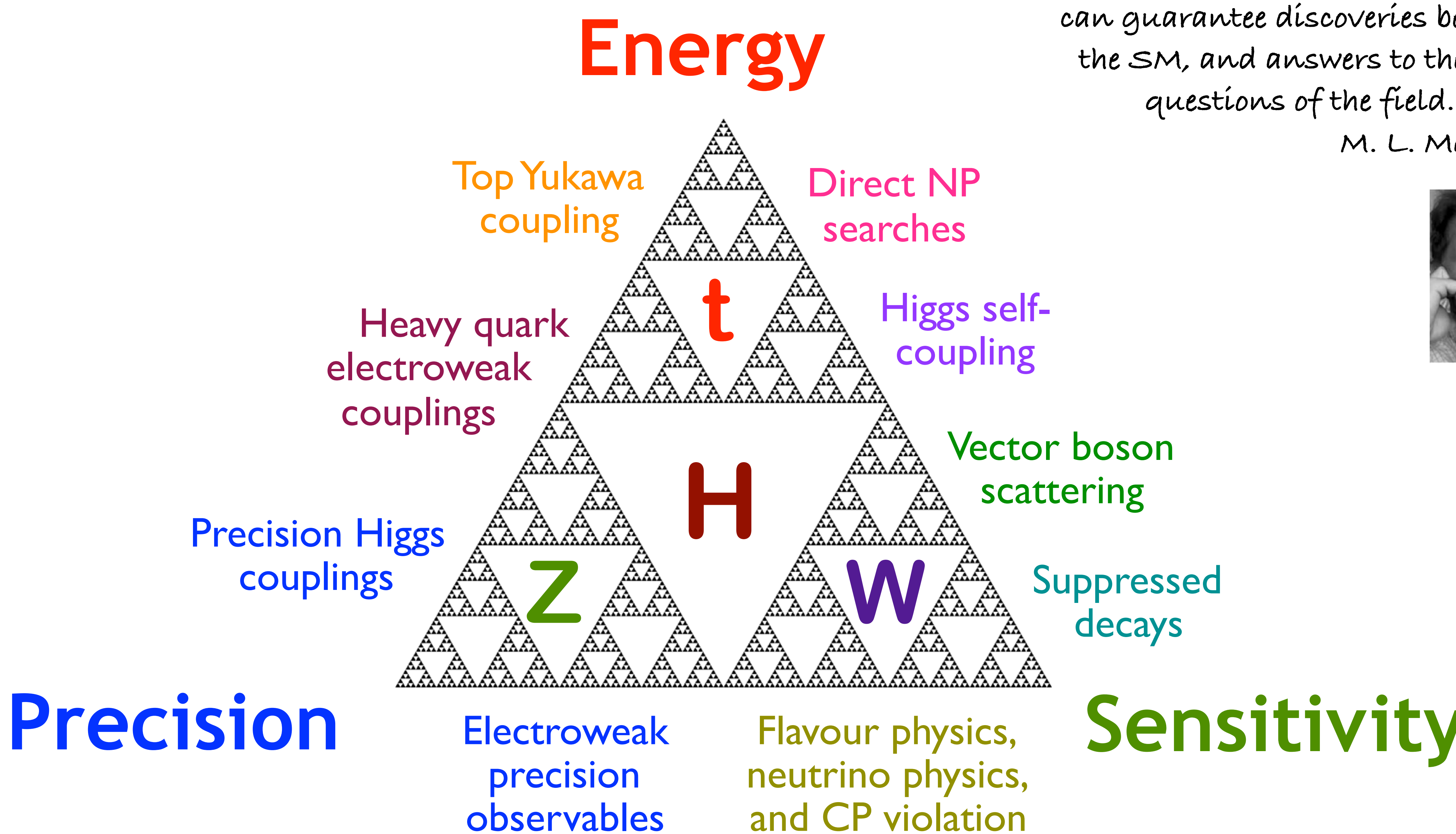
Three BSM avenues for naturalness

- Compositeness
  Higgs as a bound state of fermions (pseudo Goldstone boson)
- Extra space-time dimensions
  where at least spin-2 gravitons propagate (bring gravity scale down to the EW scale)
- Supersymmetry (SUSY)

Pre-LHC
➠ SUSY models use to address 1, 2, and 3

Post-LHC
➠ surviving SUSY models are mostly guided by Naturalness

Experiments to the Rescue?



...there is no experiment/facility, proposed or conceivable (...) which can guarantee discoveries beyond the SM, and answers to the big questions of the field.

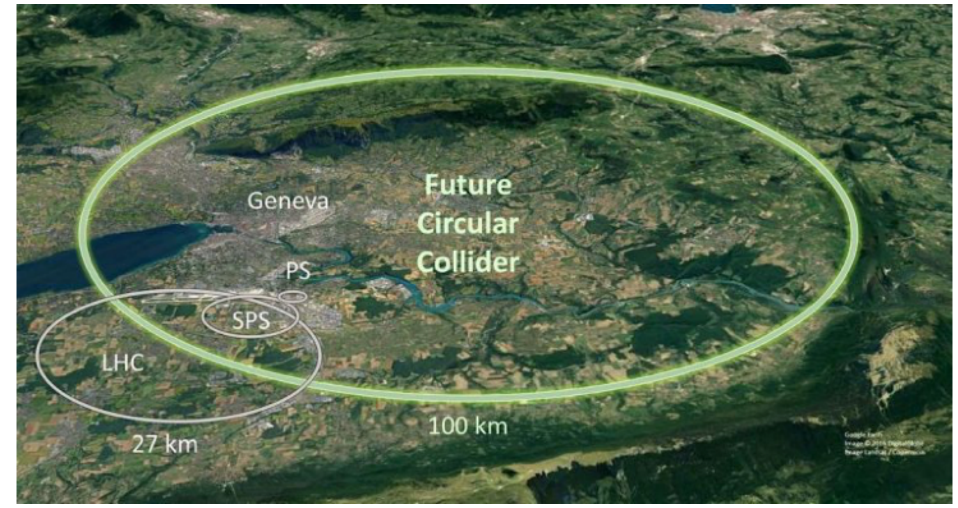
M. L. Mangano

Which Colliders for Particle Physics?

High-Luminosity LHC

Approved

- luminosity×5 starting 2026
- 3000 fb^{-1} per experiment in 10 years



Project

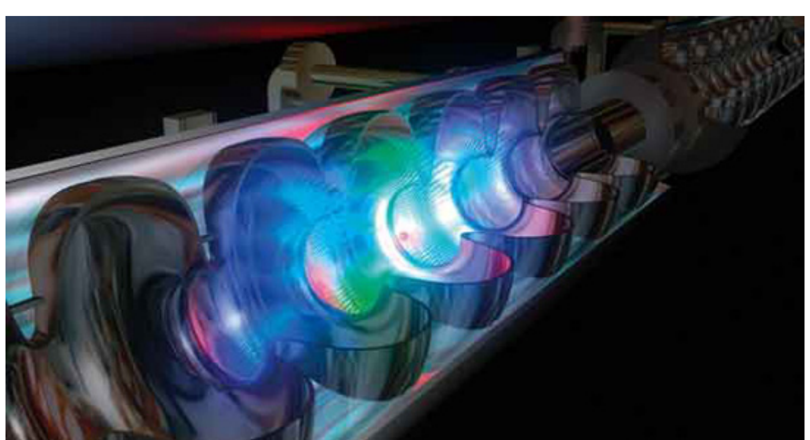
FCC	CM energy	collisions	tunel
HE-LHC	27 TeV	pp	LHC
FCC-ee	90-365 GeV	e^+e^-	100-km
FCC-hh	100 TeV	pp	

Update of the European Strategy in Particle Physics (EPPSU) in progress (2019-2020)

ILC in Japan

Project

- e^+e^- linear collider
- 250 GeV → 550 GeV



en attente de décision politique

see lecture by F. Zimmermann

CEPC in China

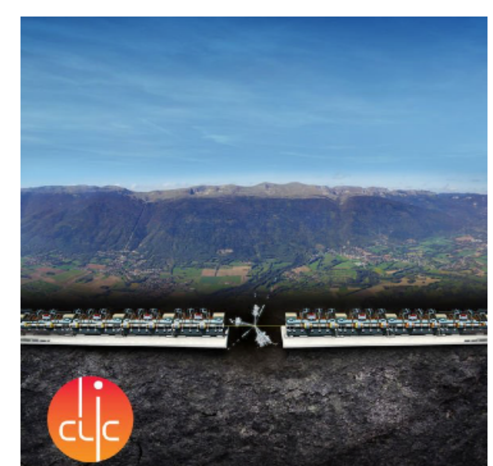
- e^+e^- circular collider
- tunnel 100 km
- 90-250 GeV

Project

CLIC

- e^+e^- linear collider
- 380 GeV → 3 TeV

Project



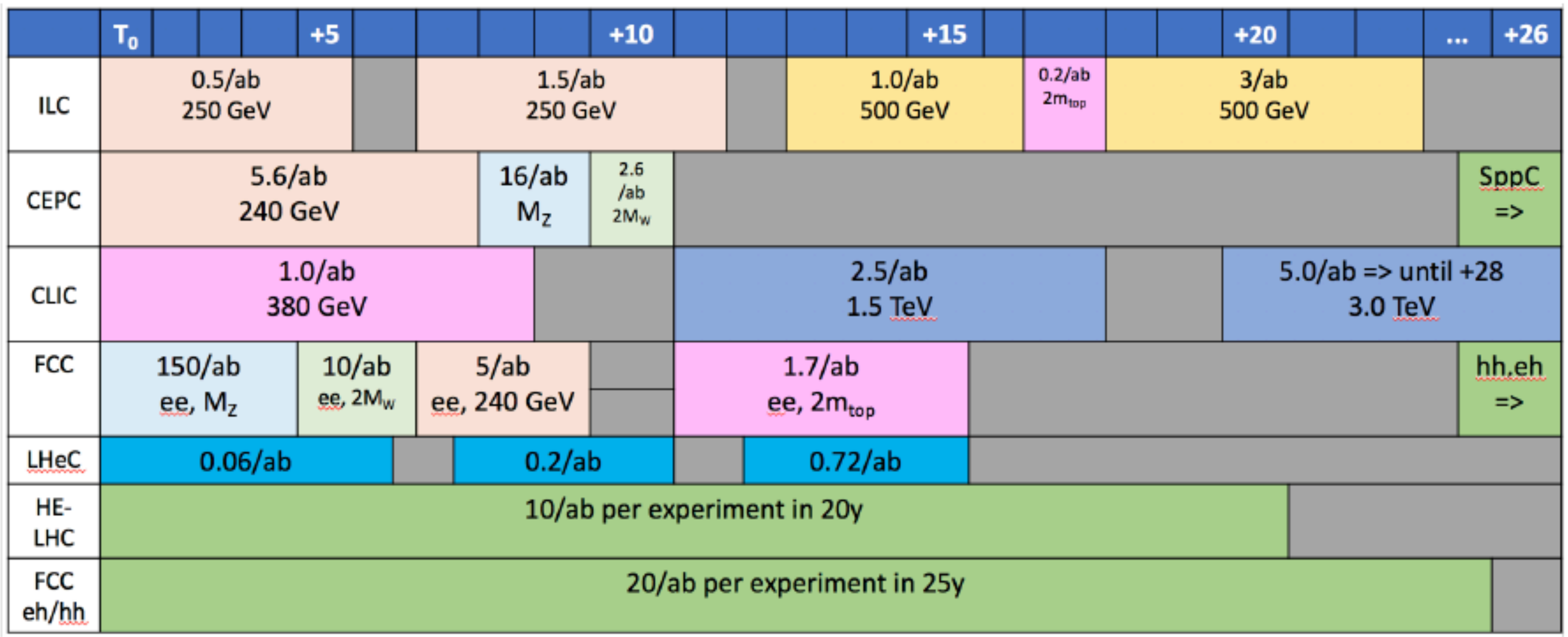
Future Collider: Official Parameters

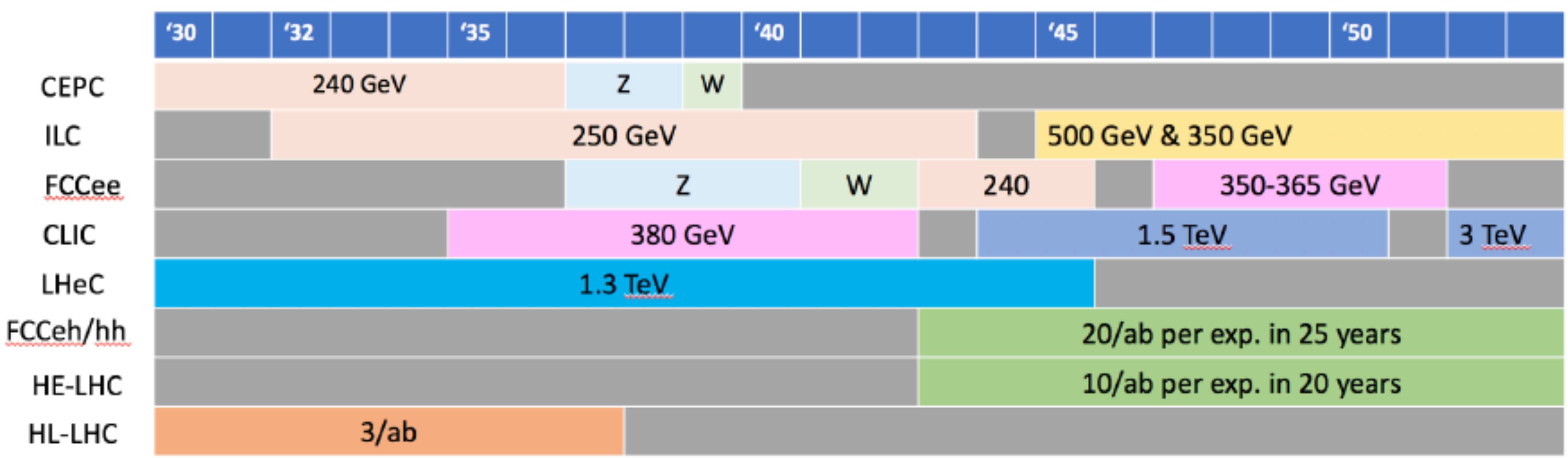
For performance studies, the EPPSU considers conventional sets of machine parameters

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5 (+1)
ILC	ee	250 GeV	$\pm80/\pm30$	1	1.35/2.7	2.0	11.5
		350 GeV	$\pm80/\pm30$	1	1.6	0.2	1
		500 GeV	$\pm80/\pm30$	1	1.8/3.6	4.0	8.5 (+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	$\pm80/0$	1	1.5	1.0	8
		1.5 TeV	$\pm80/0$	1	3.7	2.5	7
		3.0 TeV	$\pm80/0$	1	6.0	5.0	8 (+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

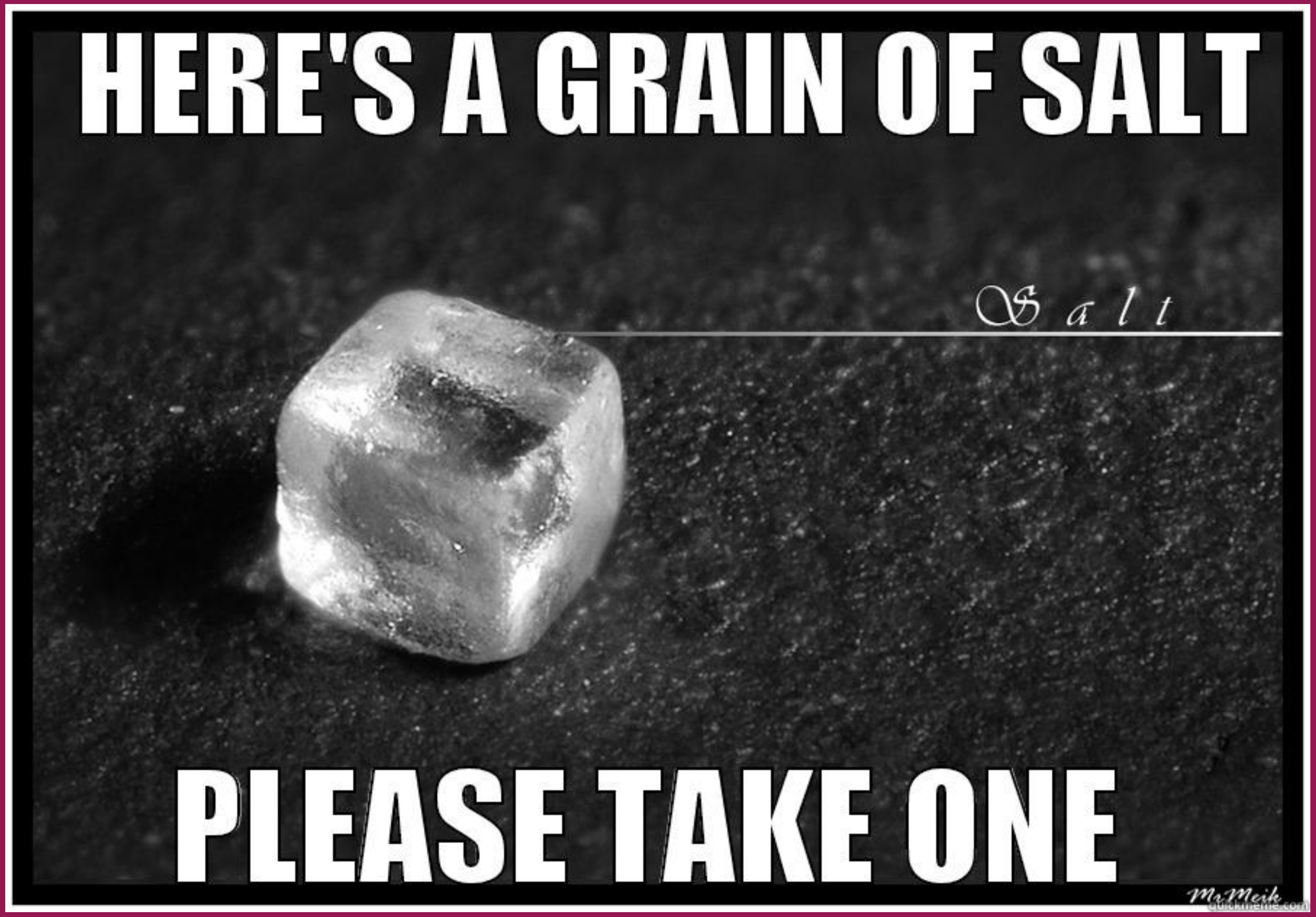
see lecture by F. Zimmermann

Future Colliders: Official Timelines





U. Bassler, H. Abramovitch @ Granada 2019


HERE'S A GRAIN OF SALT
Salt
PLEASE TAKE ONE

Hadron Colliders

<2010

Pre-LHC
LEP, HERA, Tevatron, Belle/Babar, etc.

2010-2018

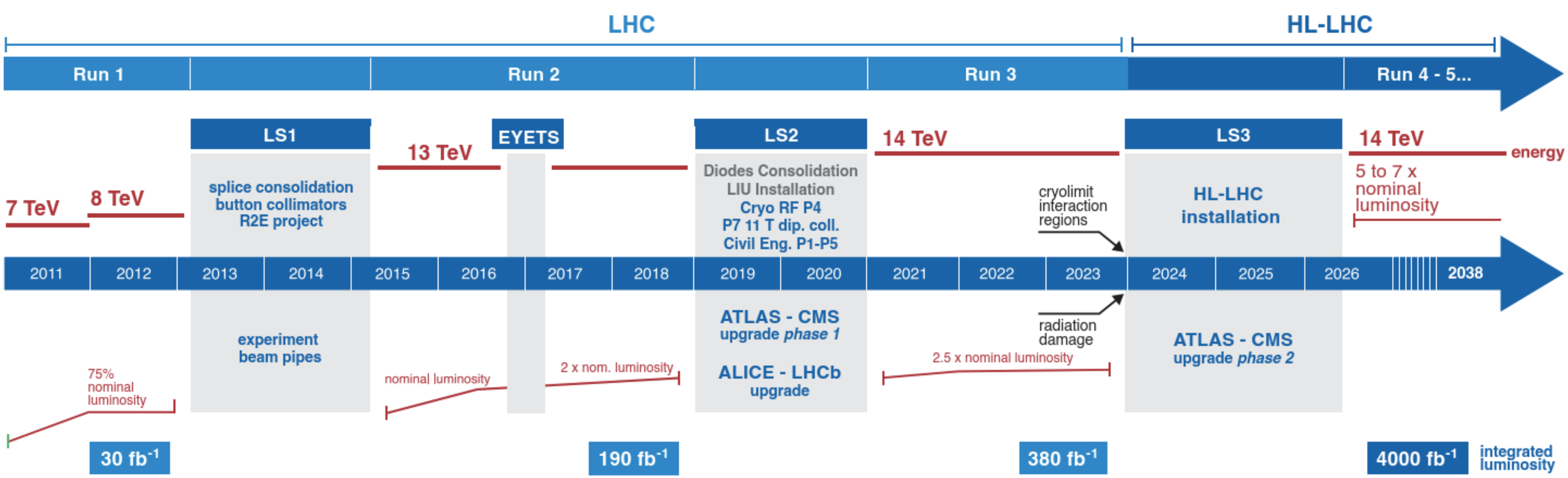
LHC Run-1 & 2
$\sqrt{s}$ = 7, 8, 13 TeV
ATLAS, CMS
L up to 140 fb^{-1}

2021-2023

LHC Run-3
$\sqrt{s}$ = 14 TeV
ATLAS, CMS
L = 300 fb^{-1}

2027-2039?

HL-LHC
$\sqrt{s}$ = 14 TeV
upgraded ATLAS, CMS
L = 3 ab^{-1} in 10y

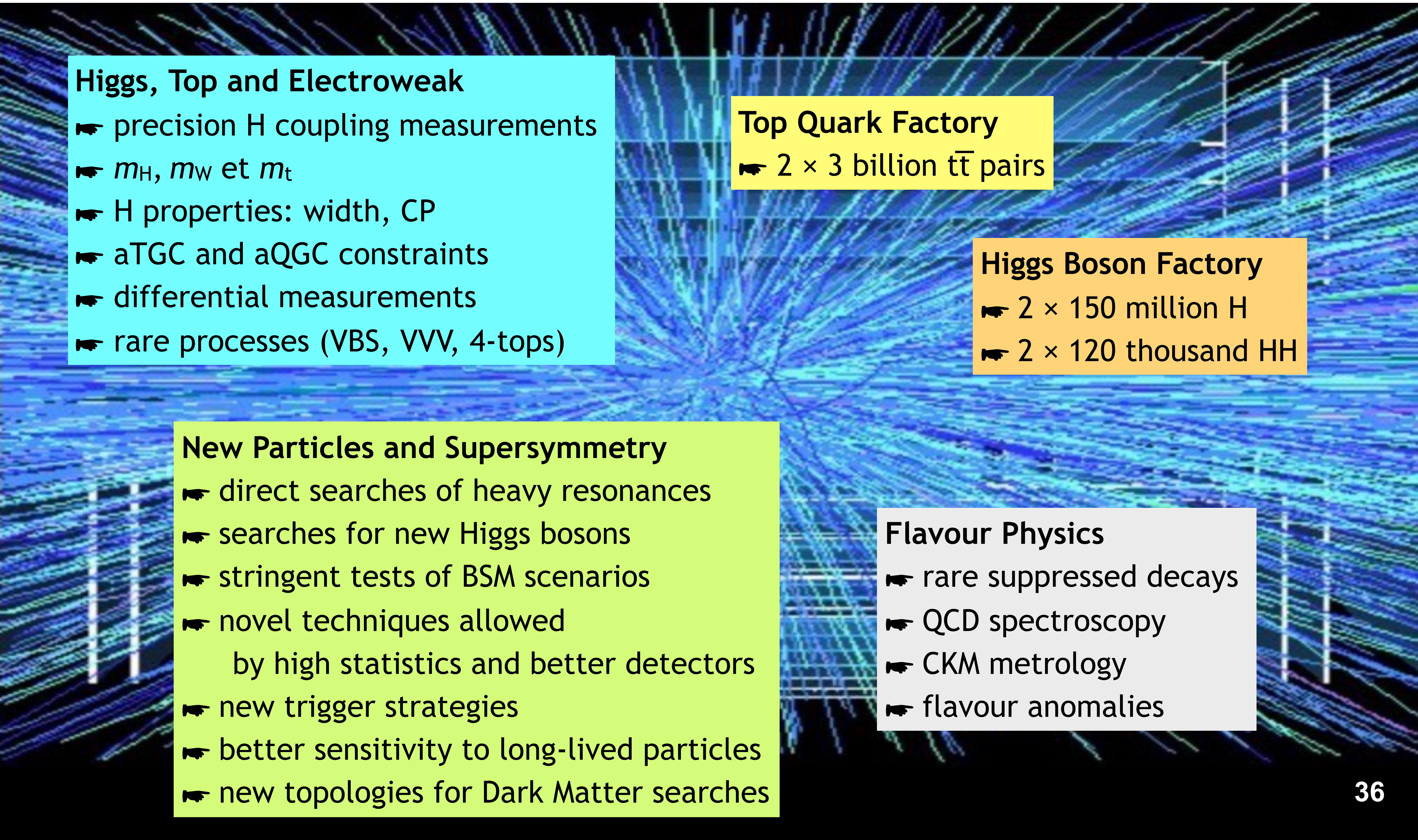


from F. Bordry, RRB CERN 29/10/2018

High-Lumi LHC: the only future collider one can say with certain confidence it will actually exist

Maximilien Brice, CERN

HL-LHC Physics in a Nutshell



Higgs, Top and Electroweak

- precision H coupling measurements
- m_H, m_W et m_t
- H properties: width, CP
- aTGC and aQGC constraints
- differential measurements
- rare processes (VBS, VVV, 4-tops)

Top Quark Factory

- 2 × 3 billion $t\bar{t}$ pairs

Higgs Boson Factory

- 2 × 150 million H
- 2 × 120 thousand HH

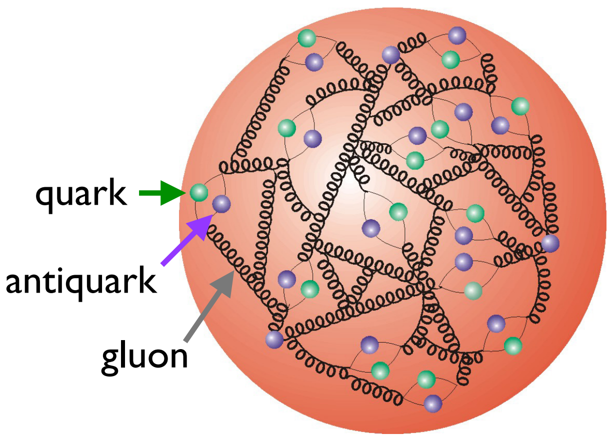
New Particles and Supersymmetry

- direct searches of heavy resonances
- searches for new Higgs bosons
- stringent tests of BSM scenarios
- novel techniques allowed by high statistics and better detectors
- new trigger strategies
- better sensitivity to long-lived particles
- new topologies for Dark Matter searches

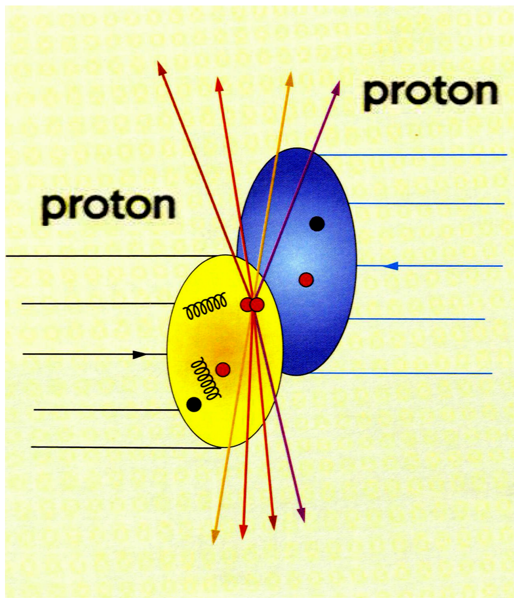
Flavour Physics

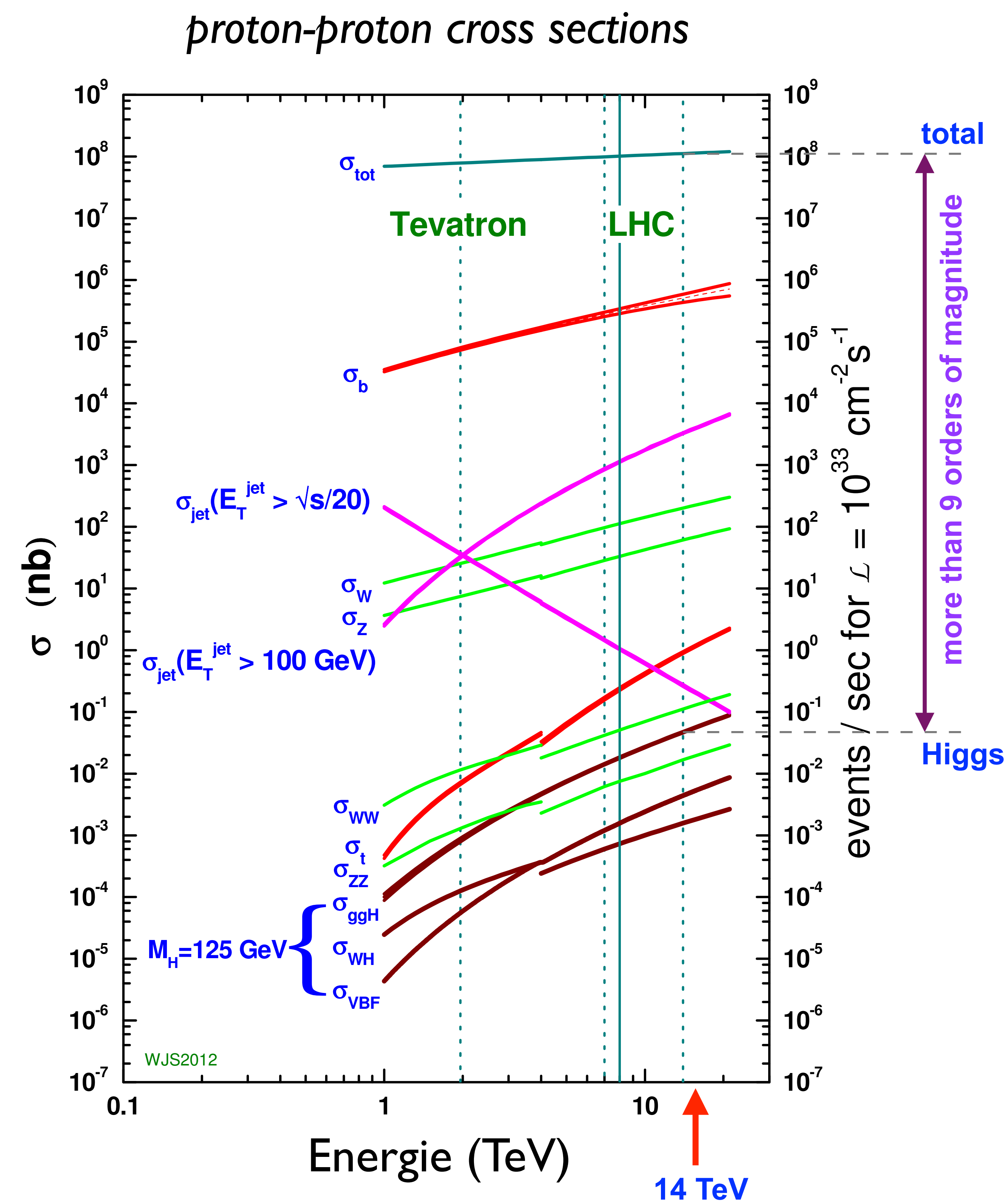
- rare suppressed decays
- QCD spectroscopy
- CKM metrology
- flavour anomalies

A Quark Gluon Collider



the proton “seen”
at short distance
(= high energy)

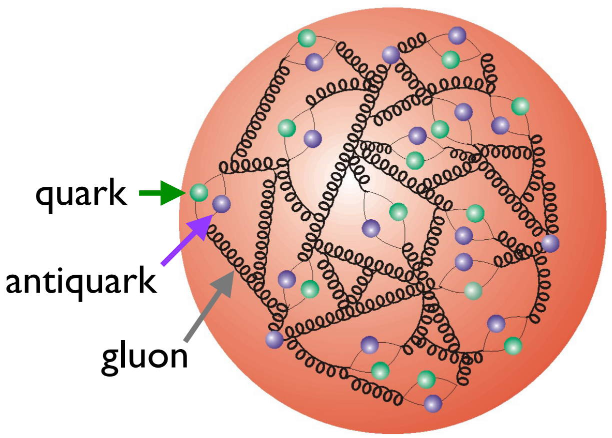




Study of hard interactions
- gluon & gluon *(dominant)*
- quark & antiquark
- (anti)quark & gluon
- etc.

Cross sections in nanobarn (nb)
☛ 1 nb = 10^{-33} cm^2
☛ at 14 TeV : $\boldsymbol{\sigma_{tot} = 10^8}$ **nb**, $\boldsymbol{\sigma_H = 0.05}$ **nb**
Instantaneous luminosity LHC : $\mathcal{L}$ **= 1×10^{34} cm^{-2}s^{-1}**
☛ 1 billion inelastic collisions per second
☛ 1 Higgs boson every 2 seconds

A Quark Gluon Collider



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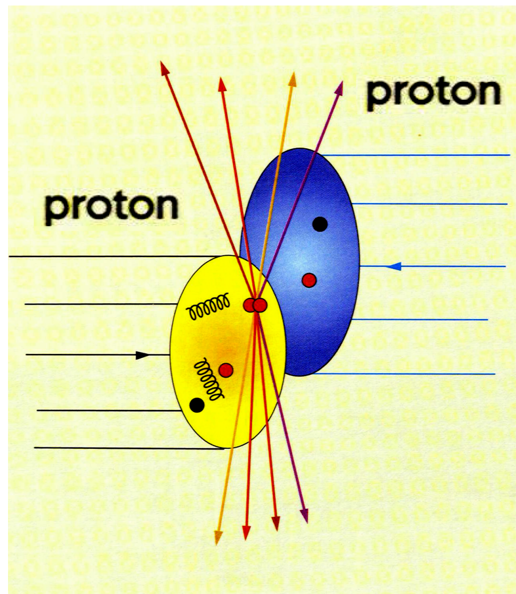

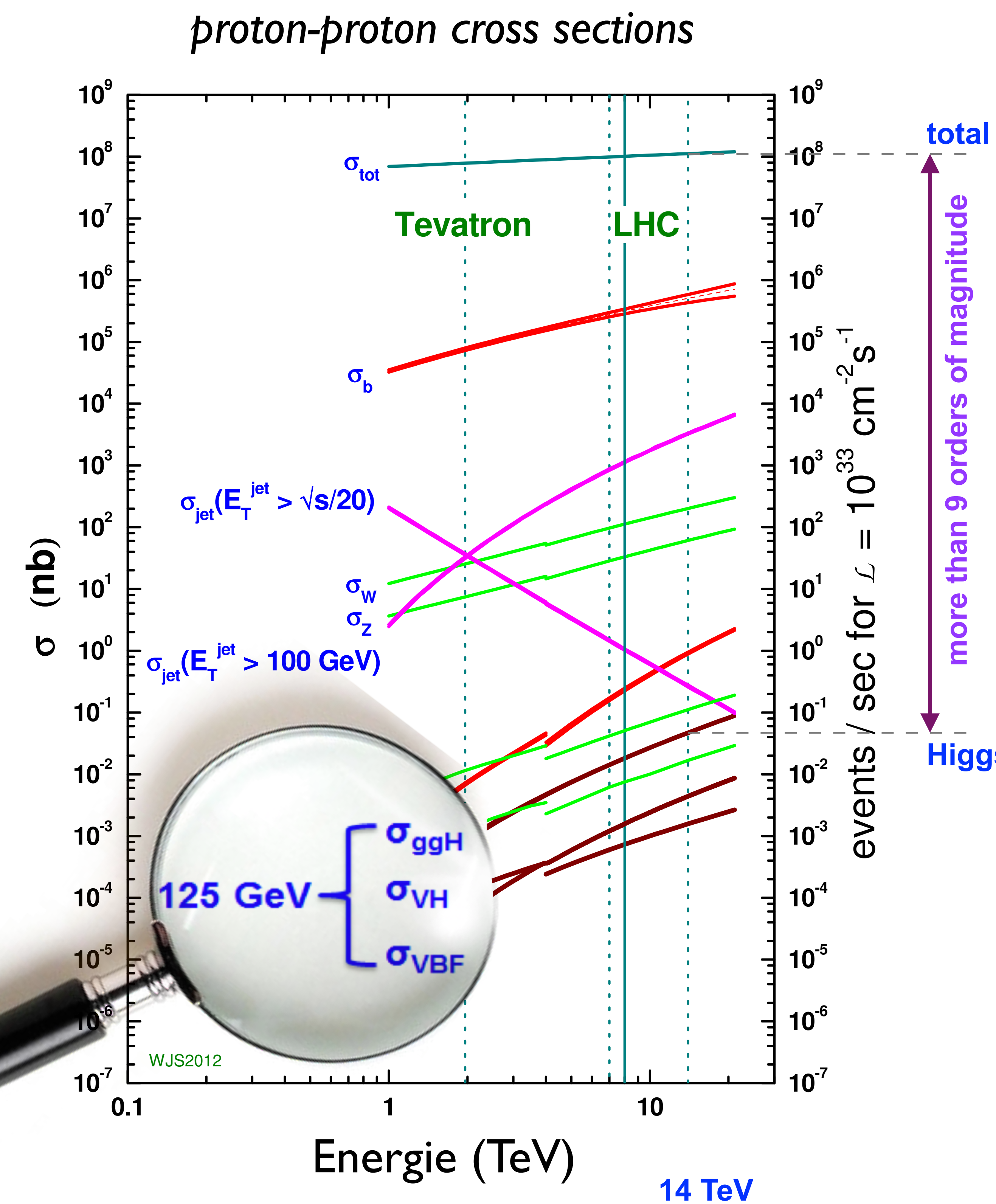

Study of hard interactions
- gluon & gluon *(dominant)*
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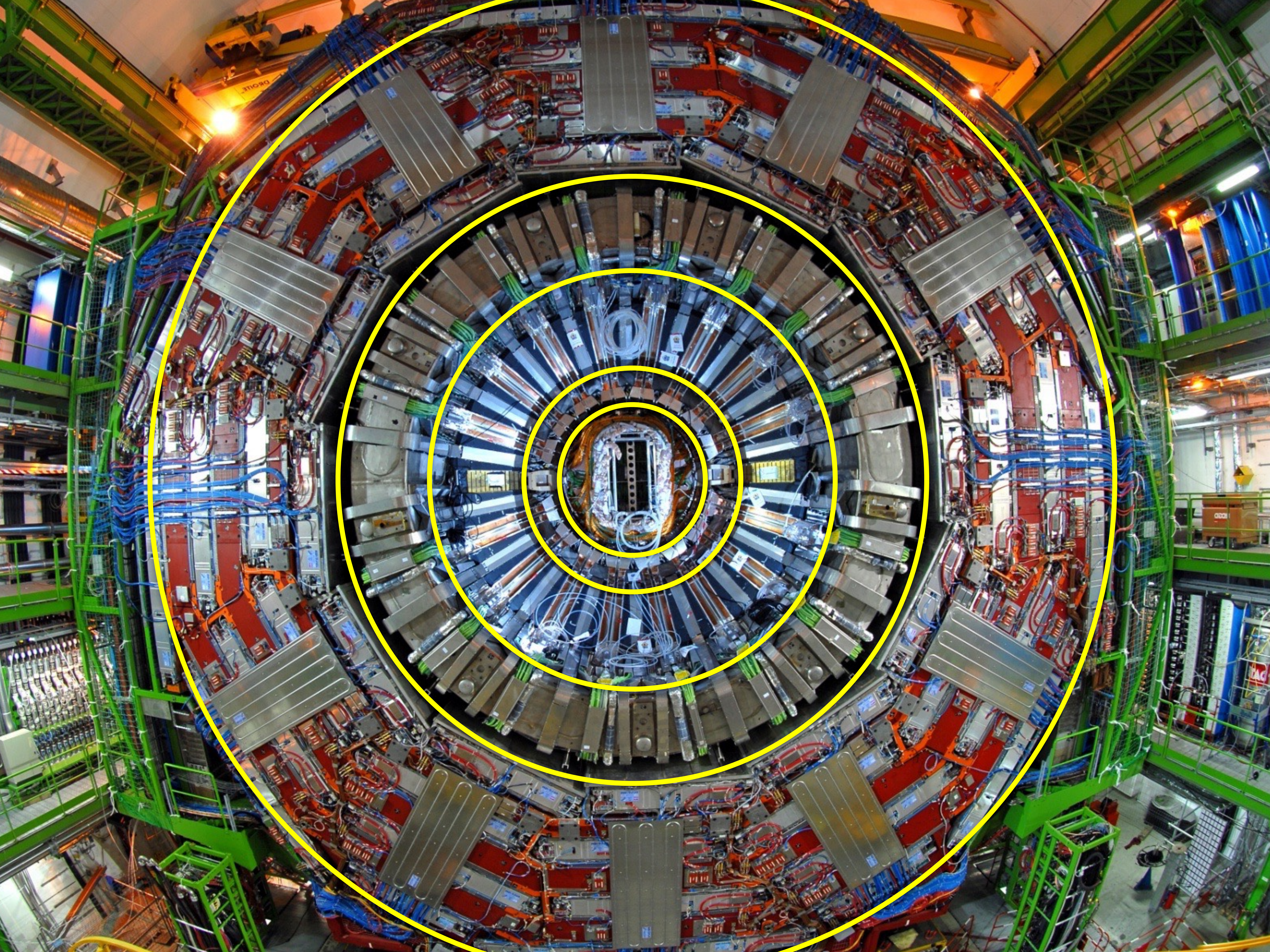
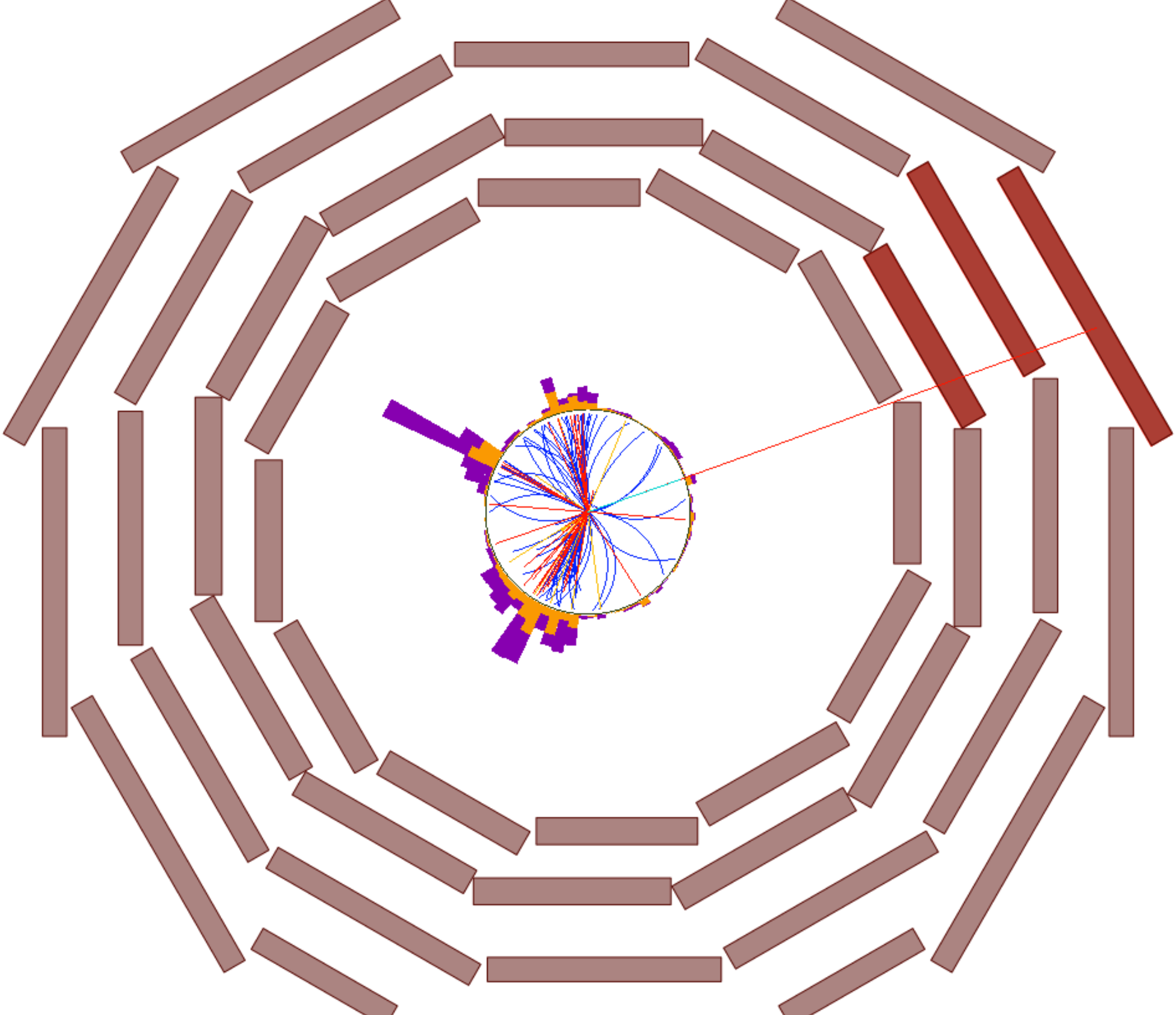
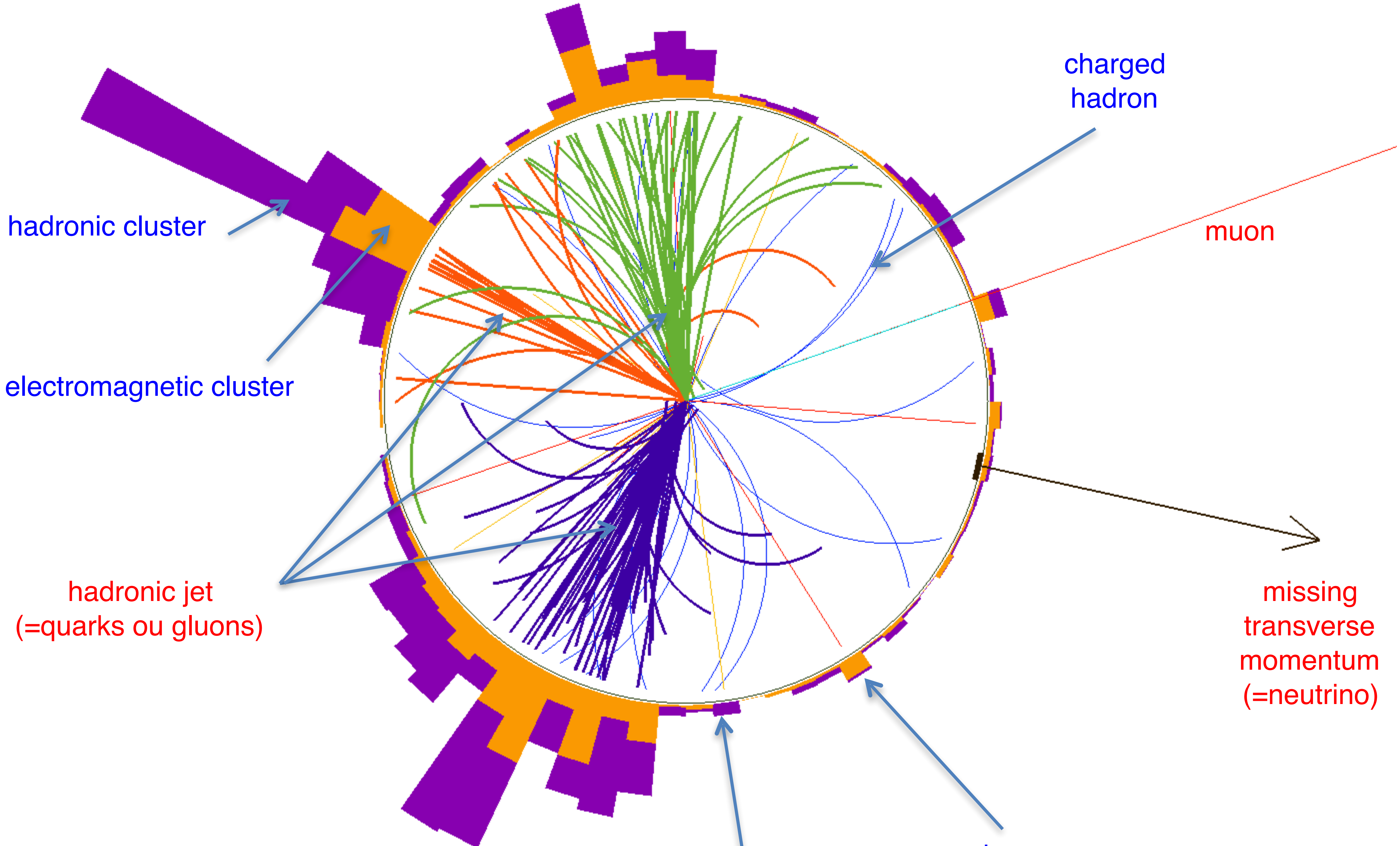
- etc.

Cross sections in nanobarn (nb)
☛ 1 nb = 10^{-33} cm²
☛ at 14 TeV : σ_{tot} **= 10⁸ nb,** σ_H **= 0.05 nb**
Instantaneous luminosity LHC : $\mathscr{L}$ **= 1×10³⁴ cm⁻²s⁻¹**
☛ 1 billion inelastic collisions per second
☛ 1 Higgs boson every 2 seconds





“Object” Reconstruction



W(→μν)+3 jets

A Dantesque Environment

Integrated luminosity expressed in **inverse-femtobarn** (fb^{-1})
☛ at 14 TeV : 1 fb^{-1} corresponds to one hundred thousand billion proton collisions

Integrated luminosities at ATLAS and CMS

Run-1

✓ 5 fb^{-1} at 7 TeV (2011)
✓ 20 fb^{-1} at 8 TeV (2012)

Run-2

✓ 140 fb^{-1} at 13 TeV (2015-2018)

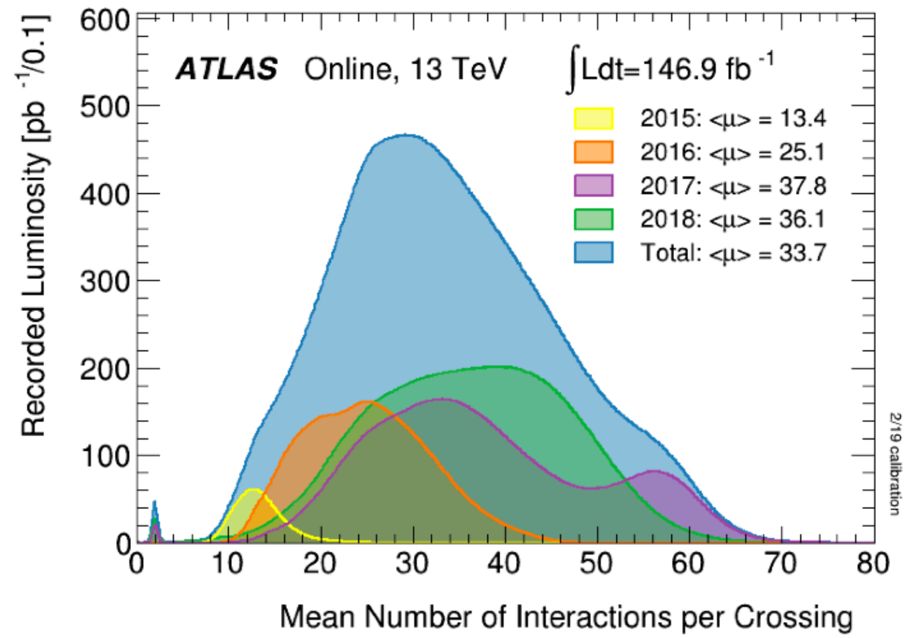
Run-3

- 300 fb^{-1} at 14 TeV (2021-2023)

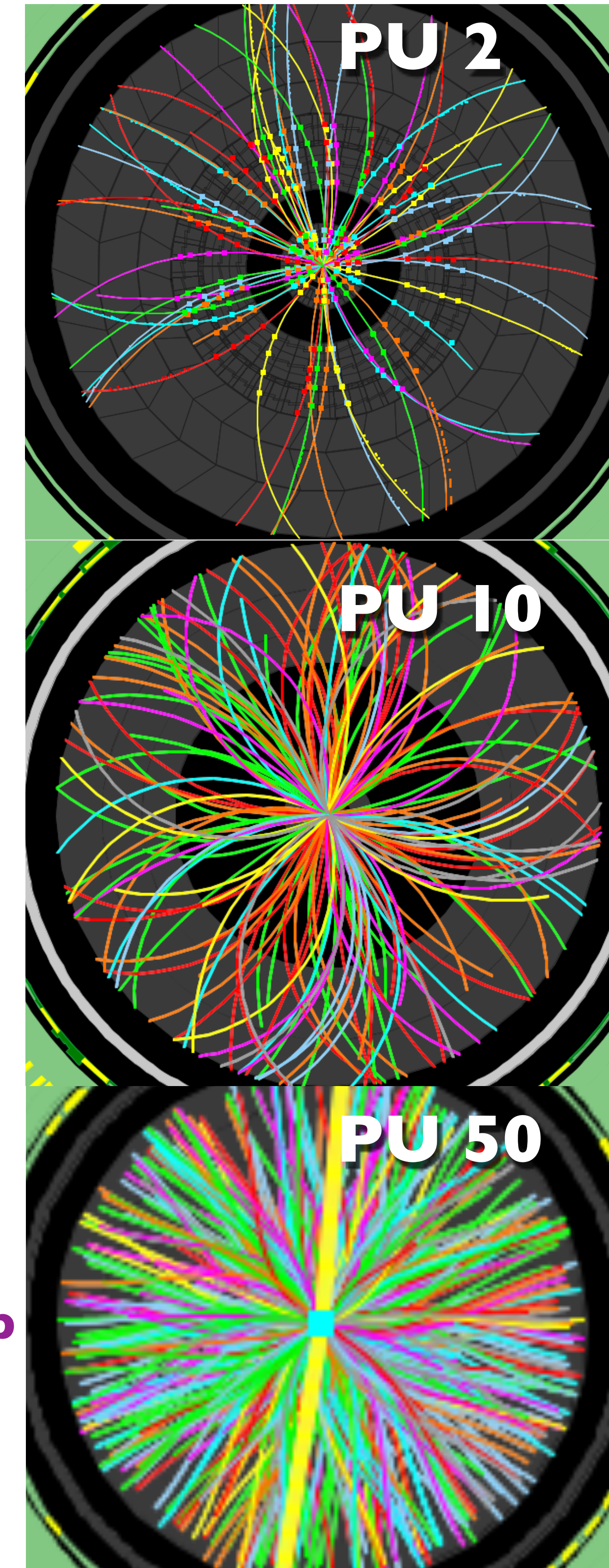
HL-LHC

- 3000 fb^{-1} at 14 TeV (2026-2035+)

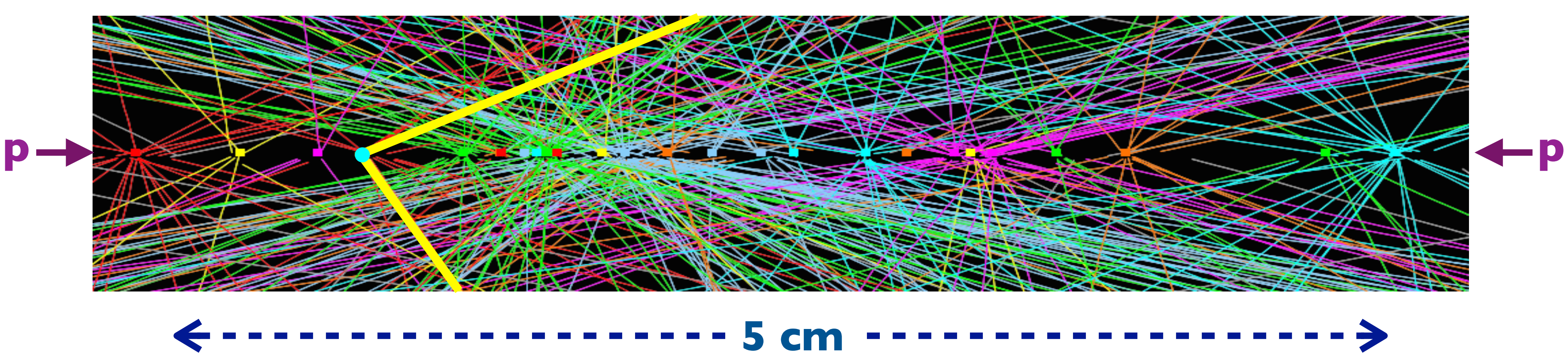
pile-up (PU) = number of inelastic interactions per bunch crossing (every 25 ns)

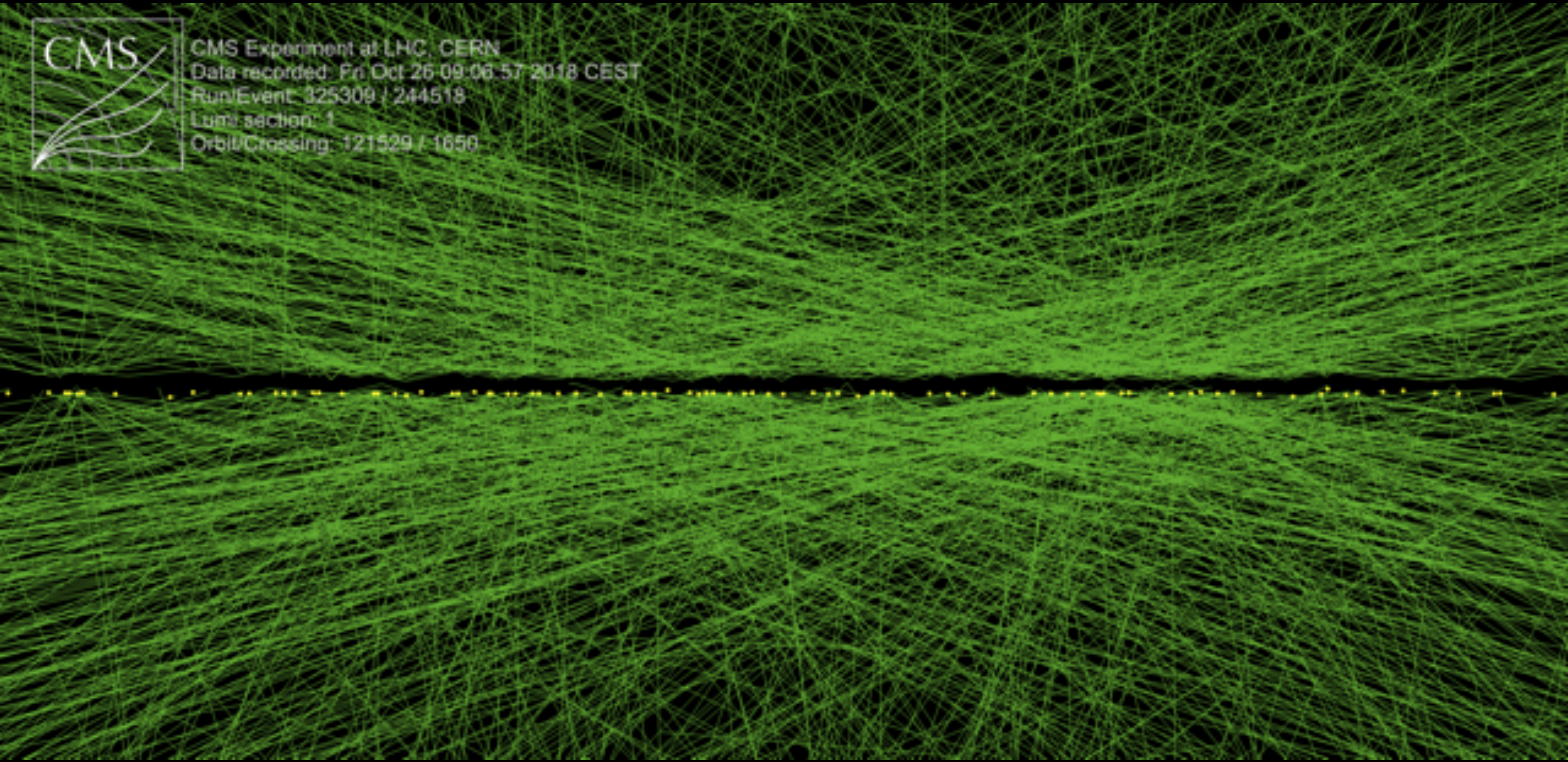


PU at HL-LHC: 200 !



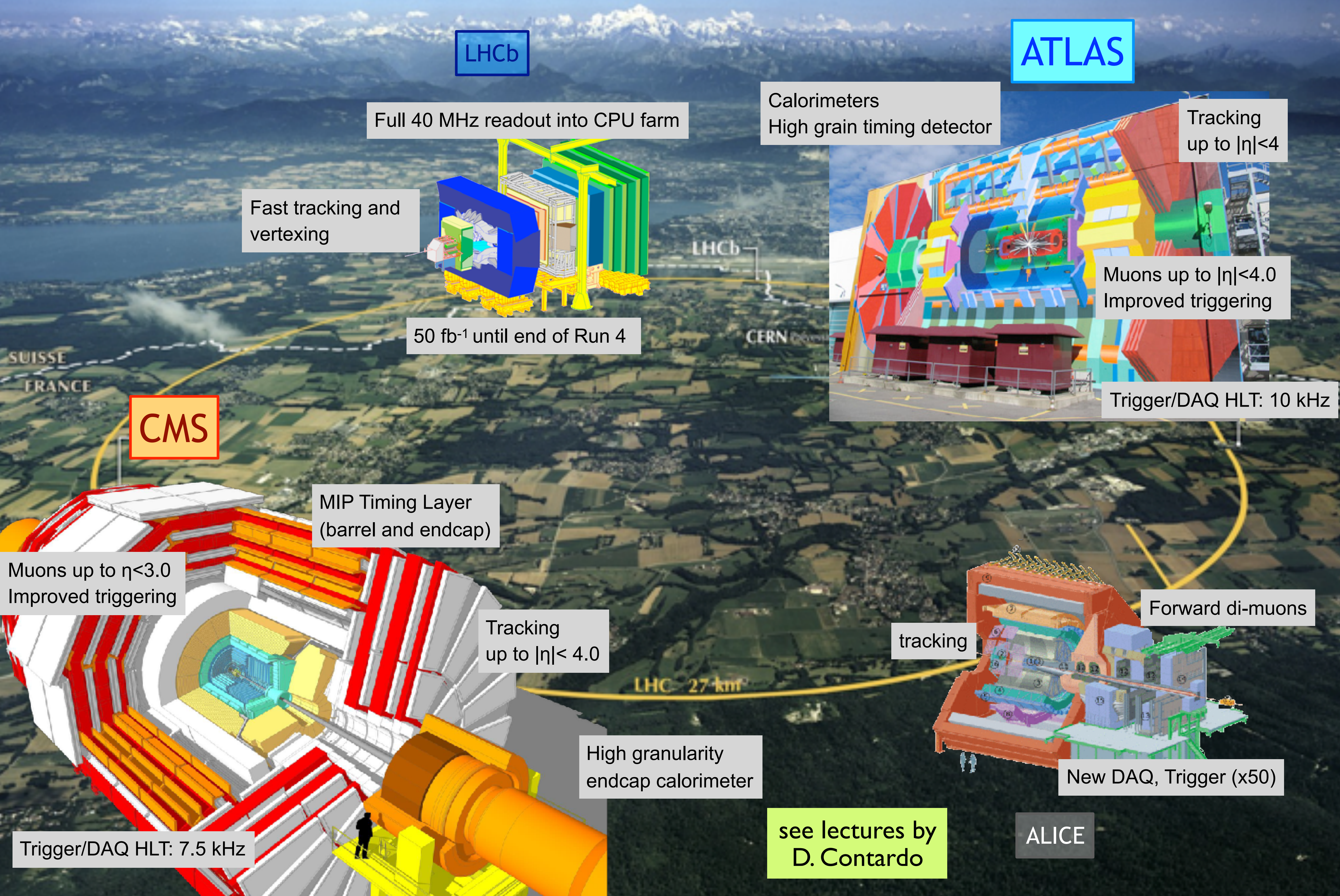
A tremendous experimental challenge





136 pile-up event BX
(CMS, October 2018)

LHC Phase 2 Detector Upgrades



Tracking Detectors

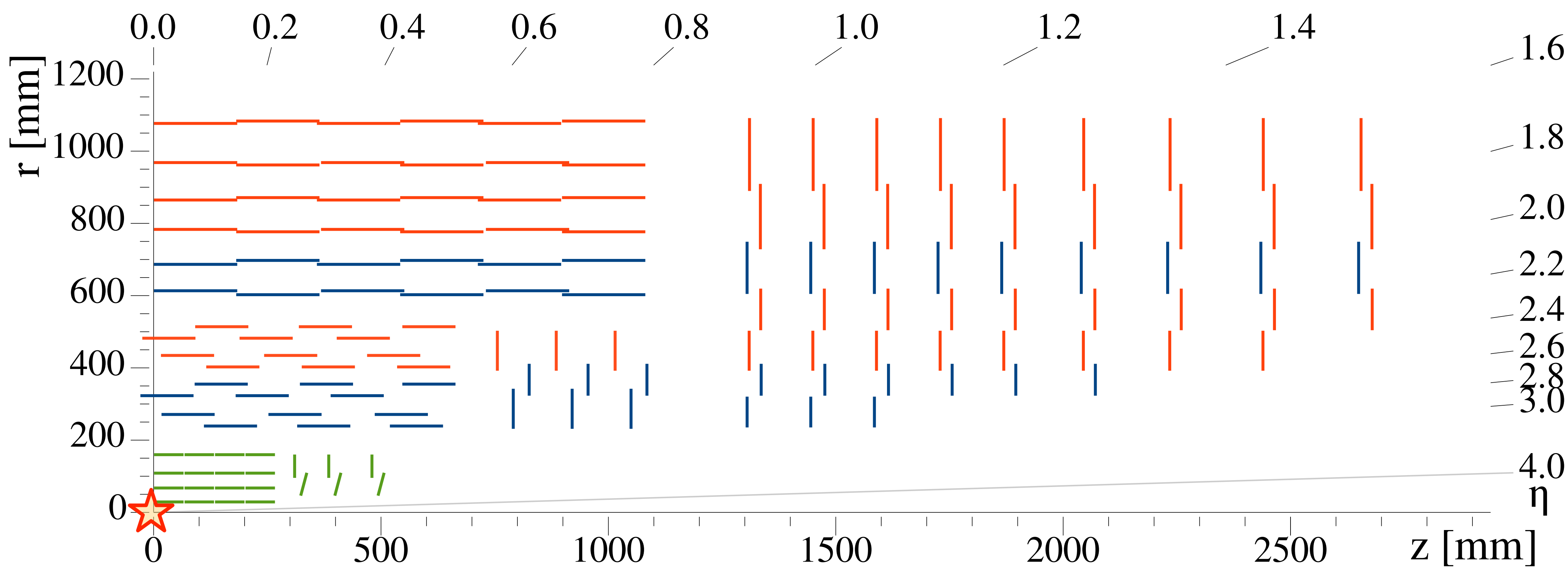
kinematical variables at colliders

transverse momentum $p_{\mathrm{T}} \equiv \sqrt{p_x^2 + p_y^2}$

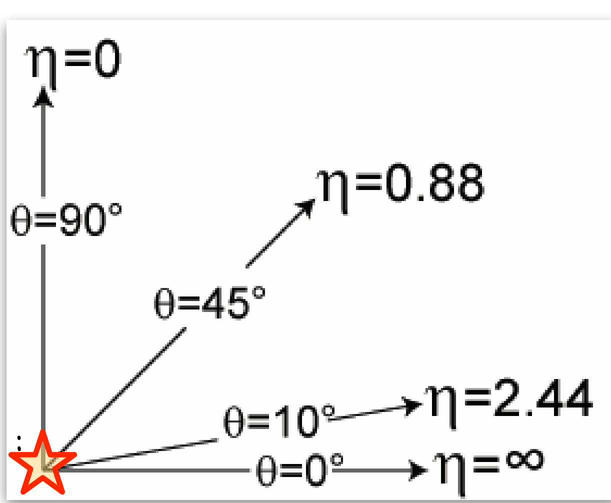
rapidity $y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$

invariant under Lorentz boost along z

CMS Run-2



☛ acceptance: |η| < 2.5



pseudo-rapidity η
= rapidity for the massless

$$\eta \equiv -\ln \tan \theta/2$$

Tracking Detectors

kinematical variables at colliders

transverse momentum $p_\mathrm{T} \equiv \sqrt{p_x^2 + p_y^2}$

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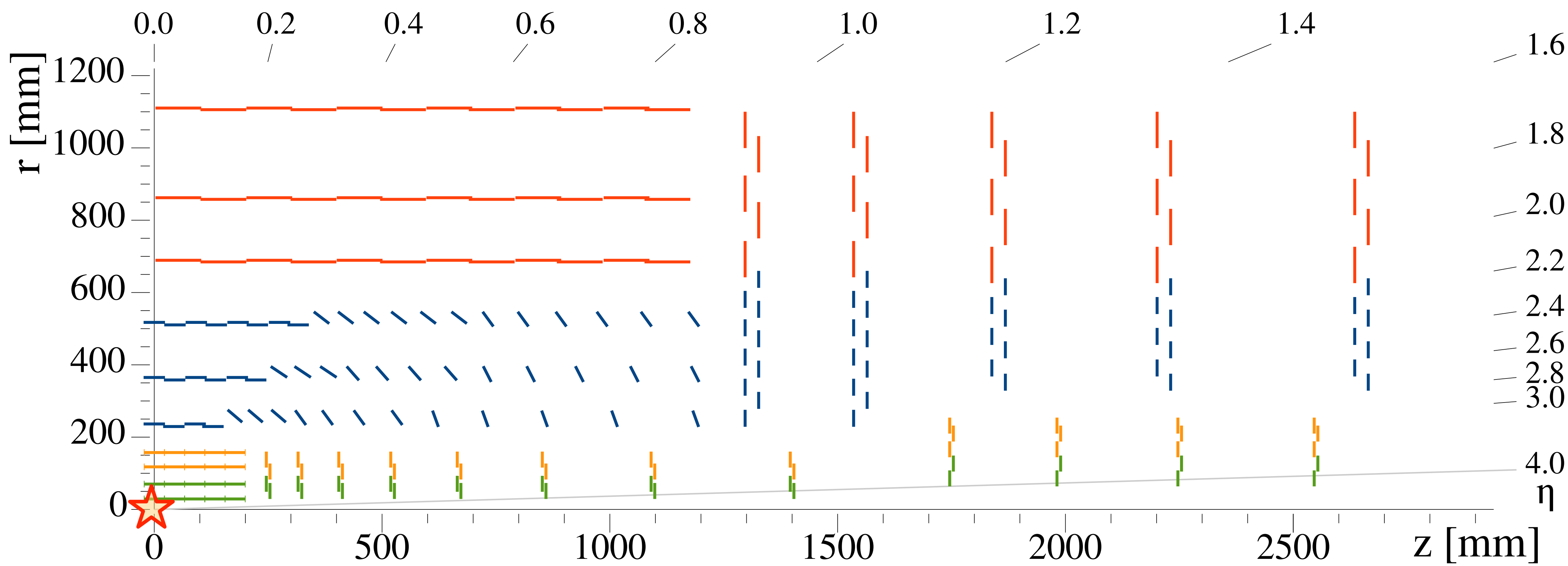
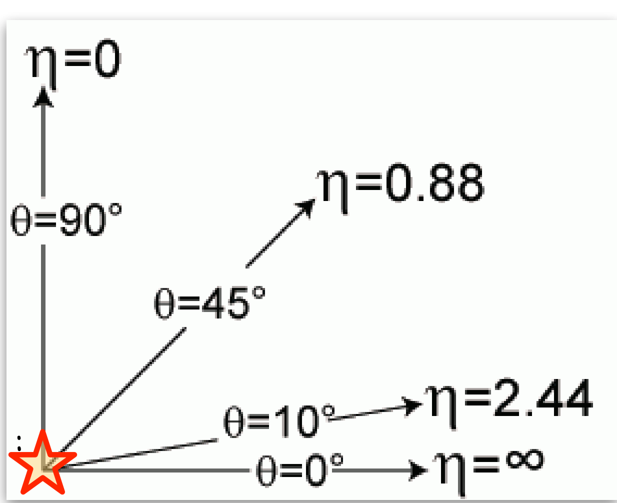
CMS HL-LHC



- larger acceptance: |η| < 4
- less detector material
- better resolution



pseudo-rapidity η
= rapidity for the massless

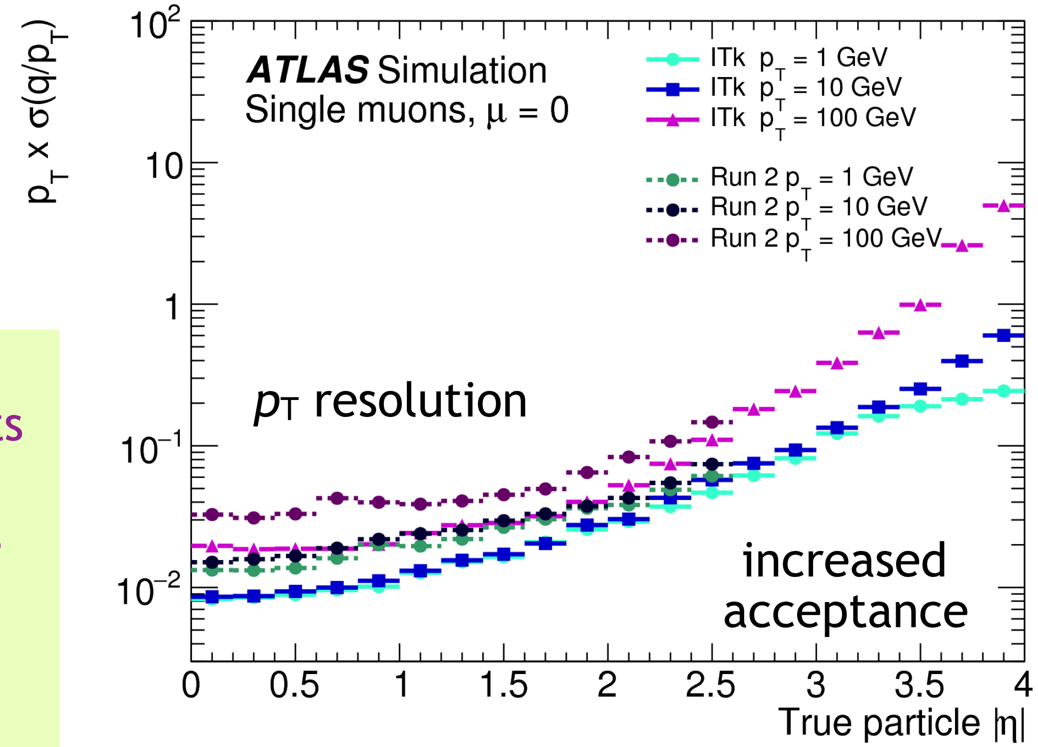
$$\eta \equiv -\ln \tan \theta/2$$

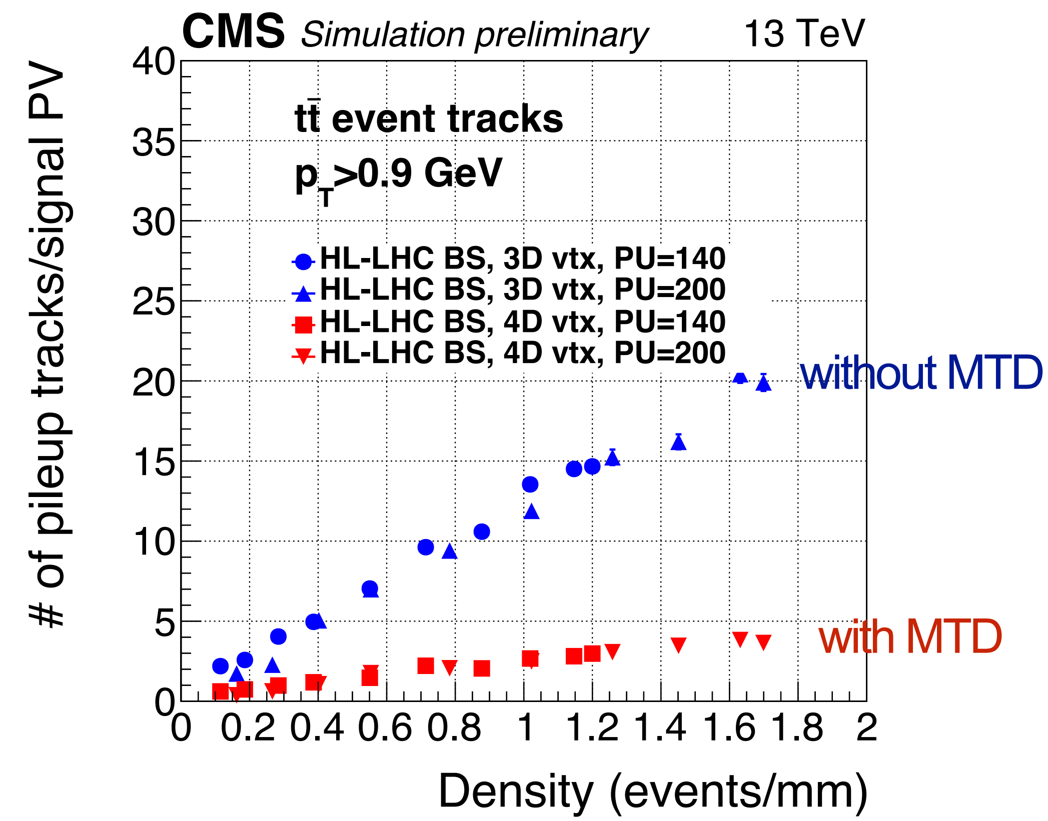
see lectures by D. Contardo

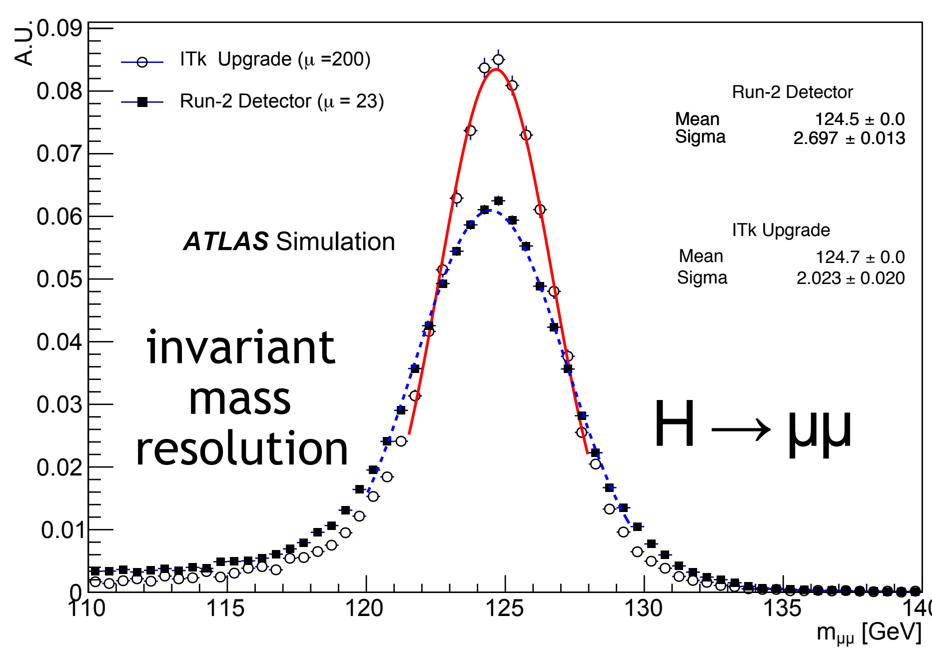
Improved Performance

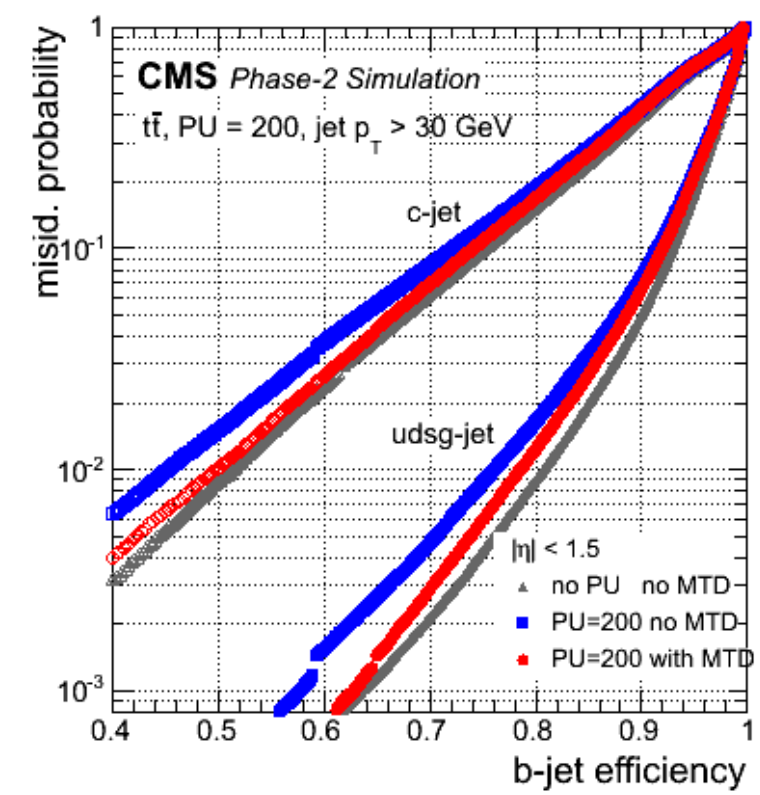
ATLAS: tracking

CMS: mitigation of PU with *timing* (MTD)









Main targets

- mitigate the effects of increased PU to perform at least as well as for Run-II
- cope with high radiation dose
- improve forward calorimetry and extend tracking at high rapidity
- gain in acceptance and efficiency
- add precision timing detectors (mostly to mitigate PU effects)

see lectures by D. Contardo

Projected Uncertainties at HL-LHC

Scale statistical uncertainties as $1/\sqrt{\mathscr{L}}$

☛ **Run-2 scenario (S1)** *conservative*

- systematic uncertainties as for Run-2

Common ATLAS/CMS strategy

☛ **Baseline scenario YR18 (S2)** *more realistic*

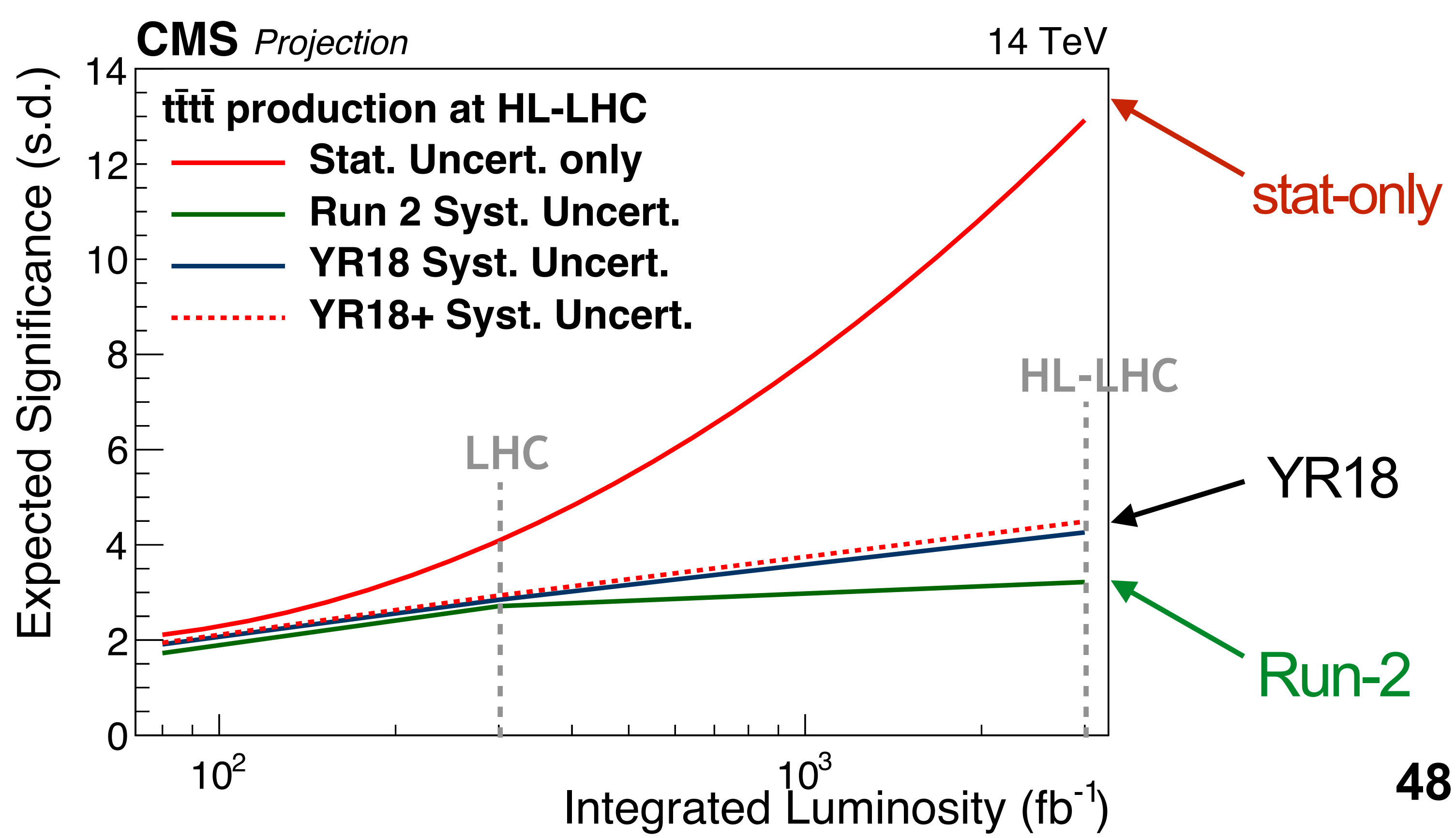
- uncertainties on methods as of latest Run 2 published results
- for each physics object:
  - detector: unchanged or revised from TDR studies
  - systematic uncertainty: scale as $1/\sqrt{\mathscr{L}}$ up to some agree-upon *floor*
- MC statistics uncertainty: neglected, luminosity uncertainty: 1%
- theory uncertainty: factor 2 in reduction (normalisation & modelling)

HL-LHC and HE-LHC Yellow Report 2018

1. Standard Model
2. Higgs Physics
3. BSM
4. Flavour Physics
5. High-density QCD

Systematic uncertainties will the limiting factor for most analyses

Example: CMS, four top production



CMS-PAS-FTR-18-031

S2 Experimental Systematics

Example of systematic *floors* used in S2 (here: ATLAS)

Source	Component	Run 2 unc.	Projection minimum unc.
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic τ ID		6%	Same as Run 2
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
$\vec{p}_T^{\text{miss}}$ scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Theory ½

Hadron Colliders

2010-2018

LHC Run-1 & 2
$\sqrt{s}$ = 7, 8, 13 TeV
ATLAS, CMS
L up to 140 fb^{-1}

2021-2023

LHC Run-3
$\sqrt{s}$ = 14 TeV
ATLAS, CMS
L = 300 fb^{-1}

2027-2039?

HL-LHC
$\sqrt{s}$ = 14 TeV
upgraded ATLAS, CMS
L = 3 ab^{-1} in 10y

2030+

?

LHeC
7 TeV p vs 60 GeV e
???
L = 1 ab^{-1} in 13y

2040+

?

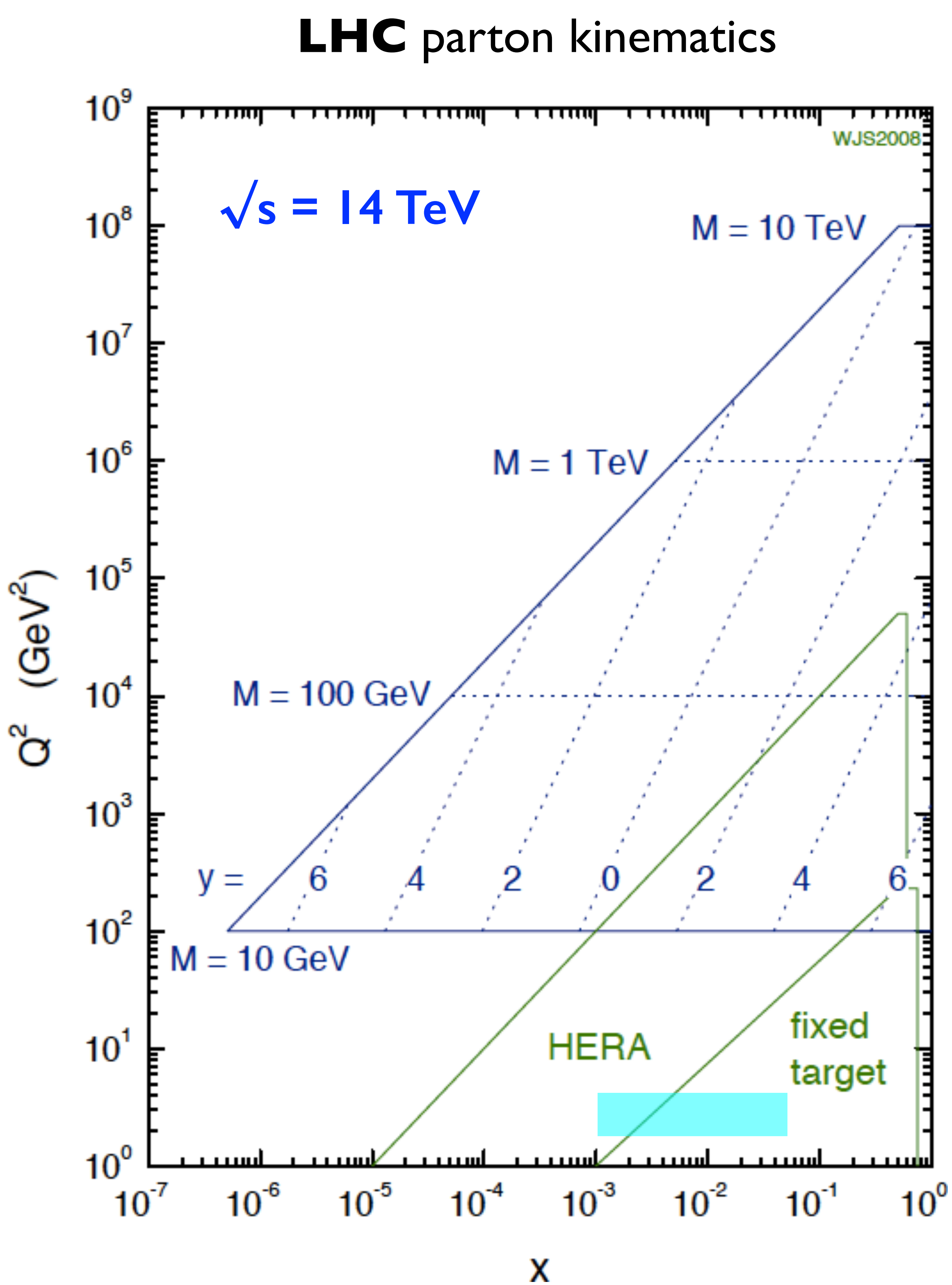
HE-LHC
$\sqrt{s}$ = 27 TeV
super ATLAS, CMS ?
L = 15 ab^{-1} in 20y

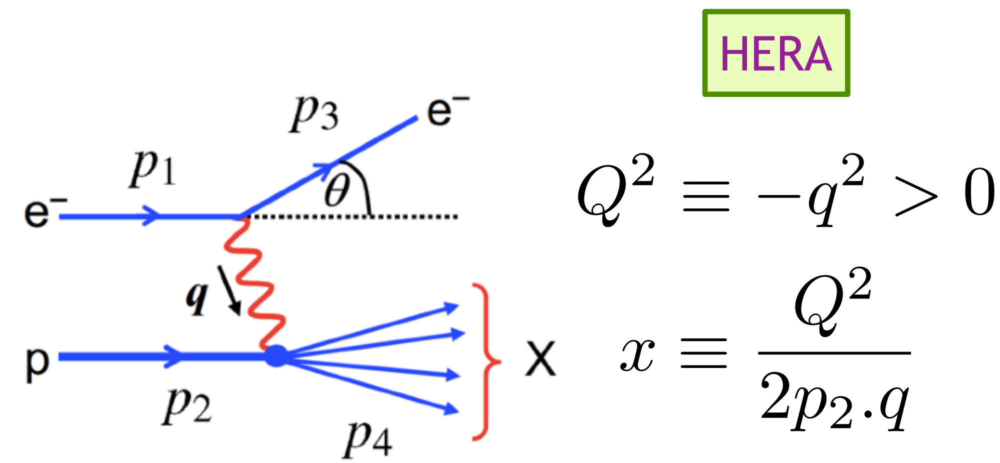
2045+

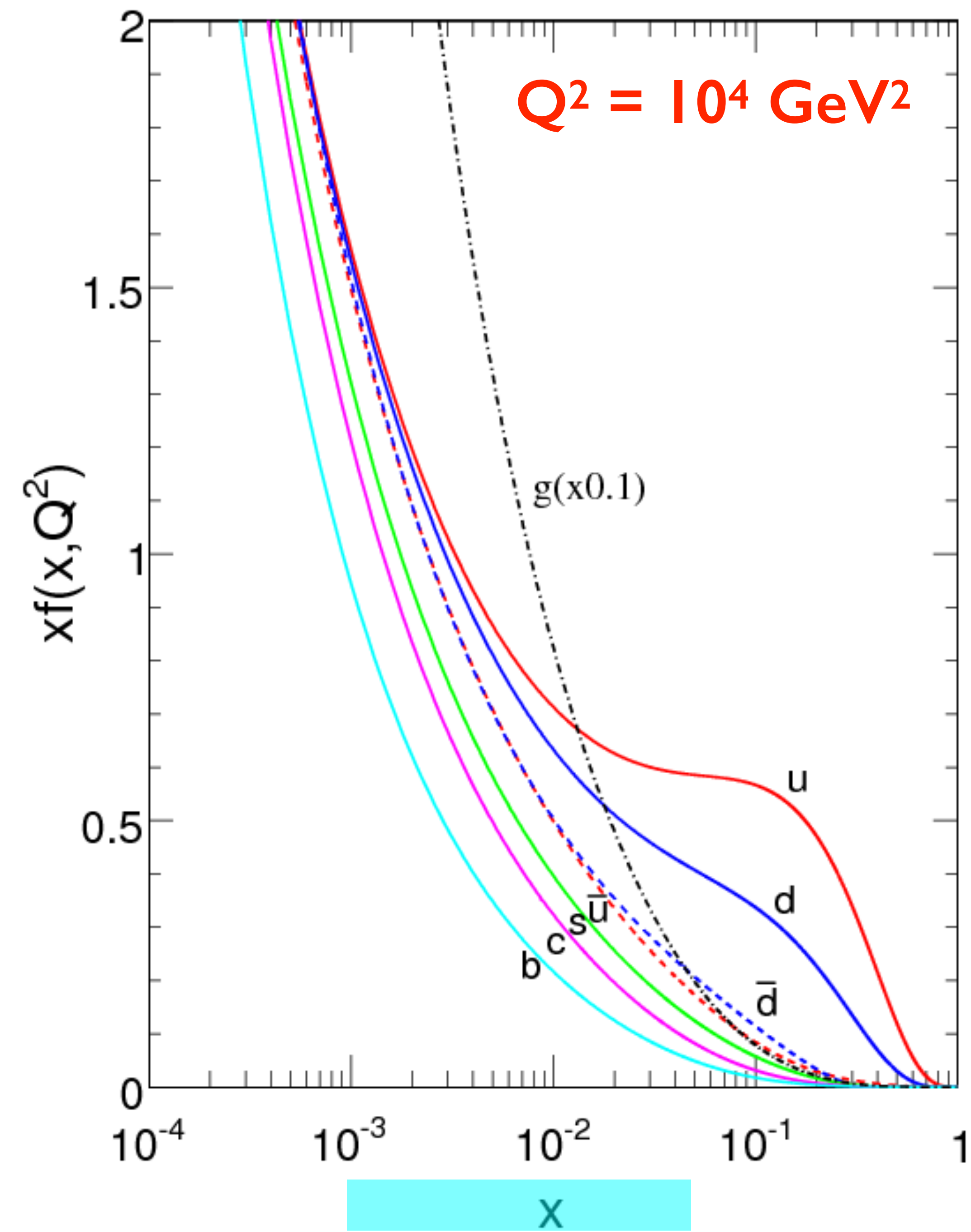
?

FCC-hh
$\sqrt{s}$ = 100 TeV
???
L = 30 ab^{-1} in 30y

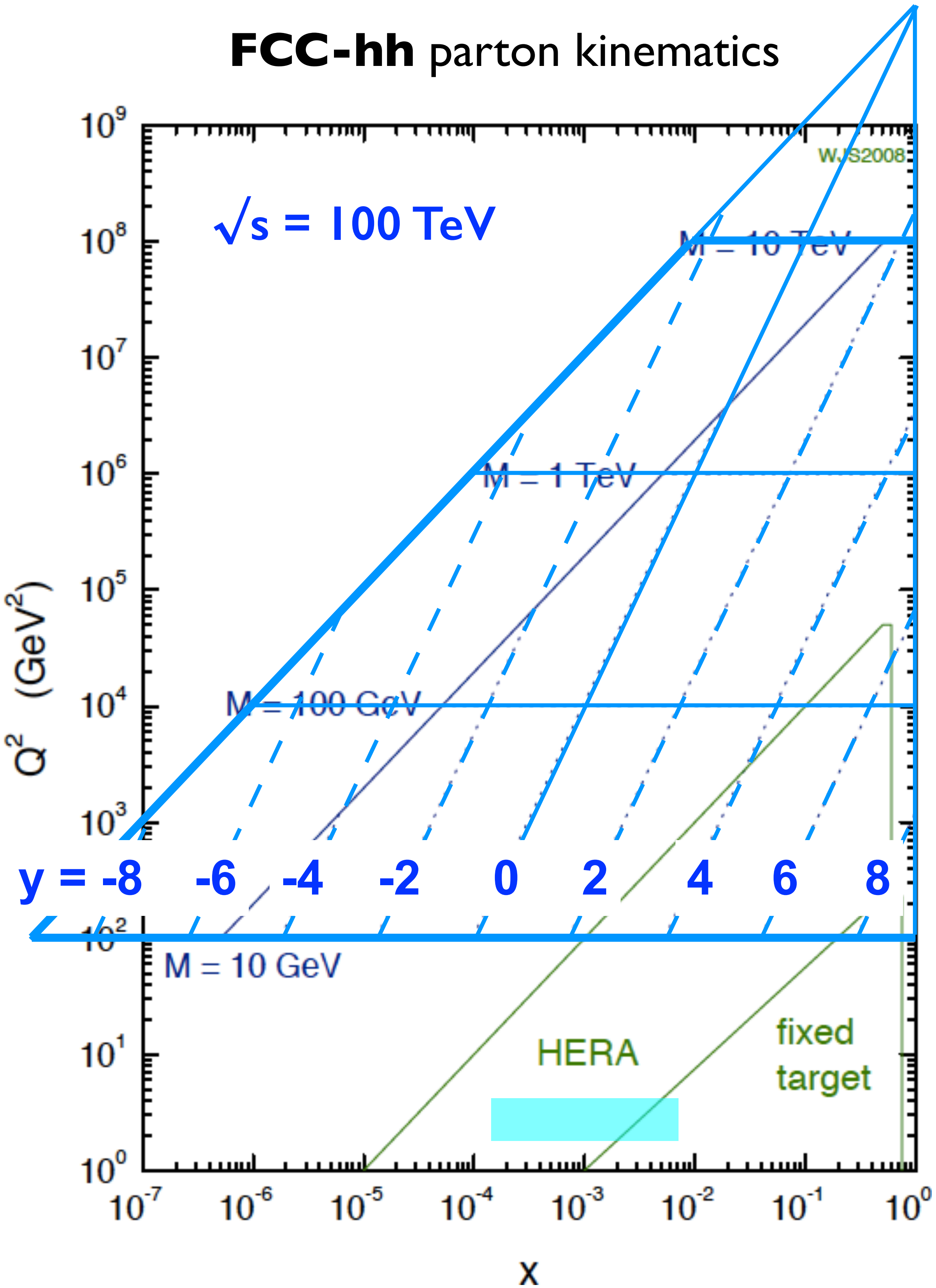
Parton Kinematics

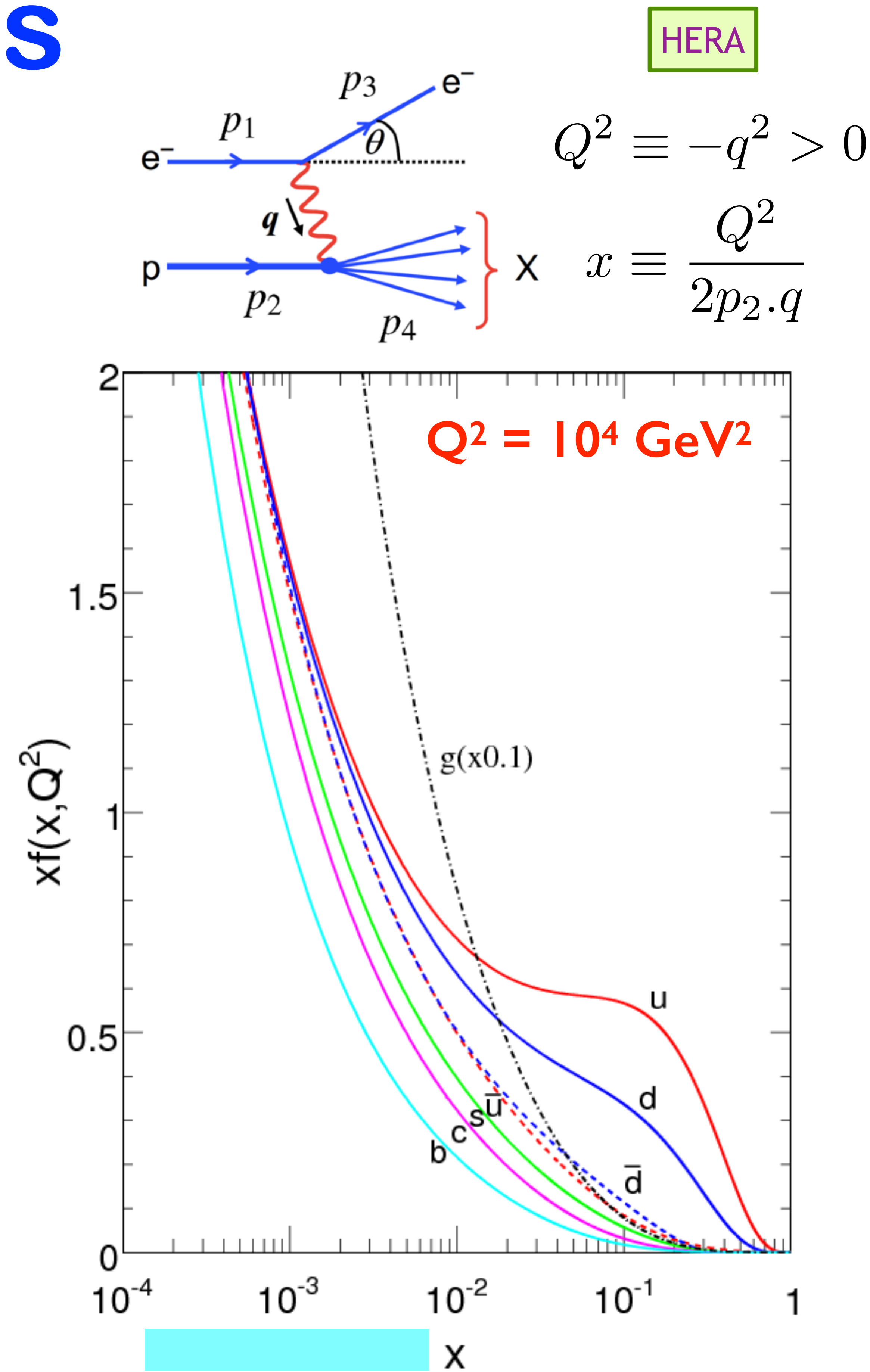






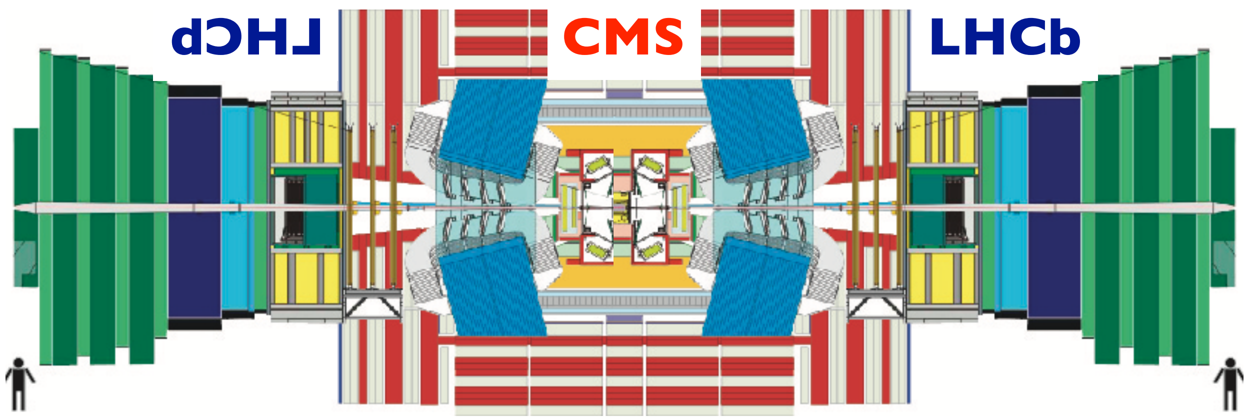
Parton Kinematics





FCC-hh Reference Detector

Starting point

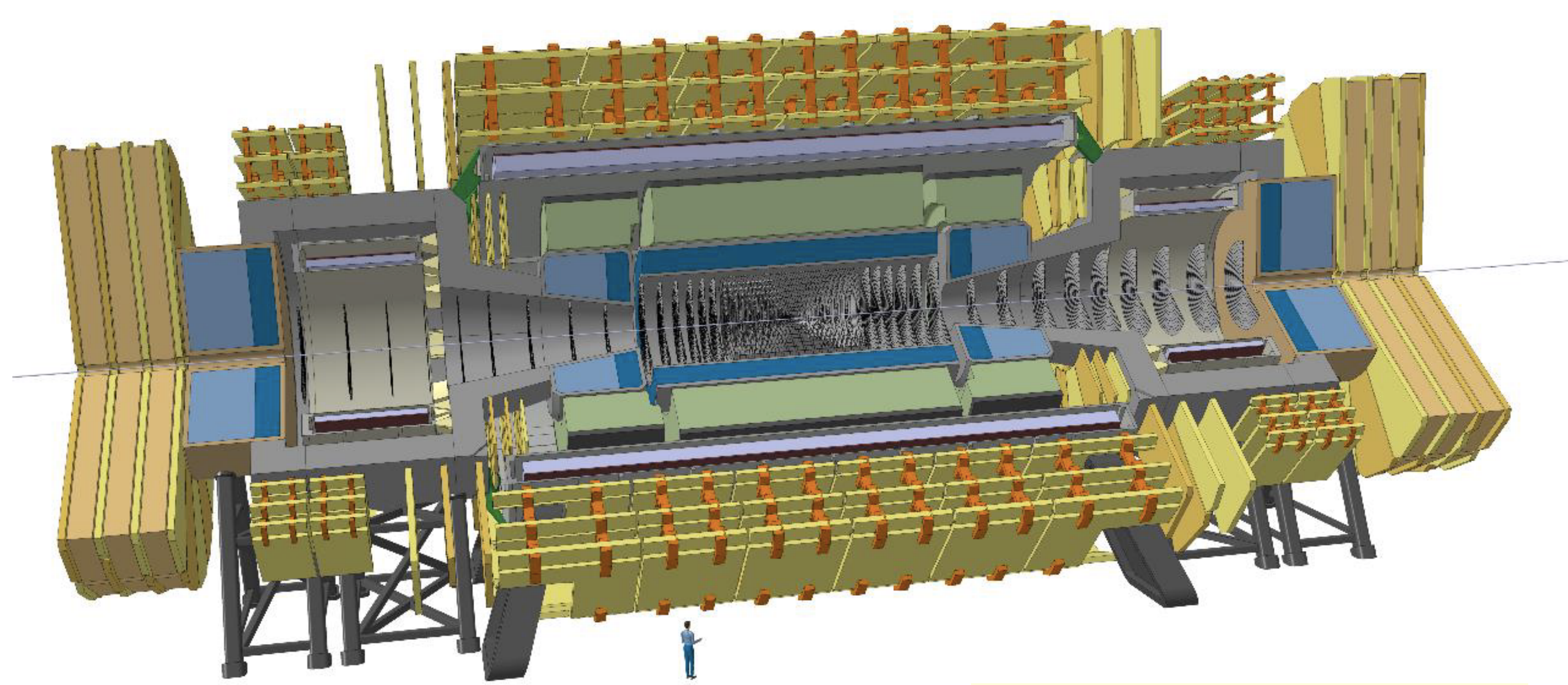


Main features

- 4T solenoid, 10-m bore solenoid
- Two forward 4T, 5-m bore solenoids
- no shielding
- ~14 GJ stored energy
- EM and H calorimetry up to η = 6
- high granularity (×4 ATLAS or CMS)
- trigger includes muon system

Some of the challenges

- pileup = 1000 (×10 / HL-LHC)
- radiation = 10^{18} part (1MeV)/cm2 (×100 / HL-LHC)
- forward SM physics
- high-p_T jets and leptons
- 1-1.5 PB/s

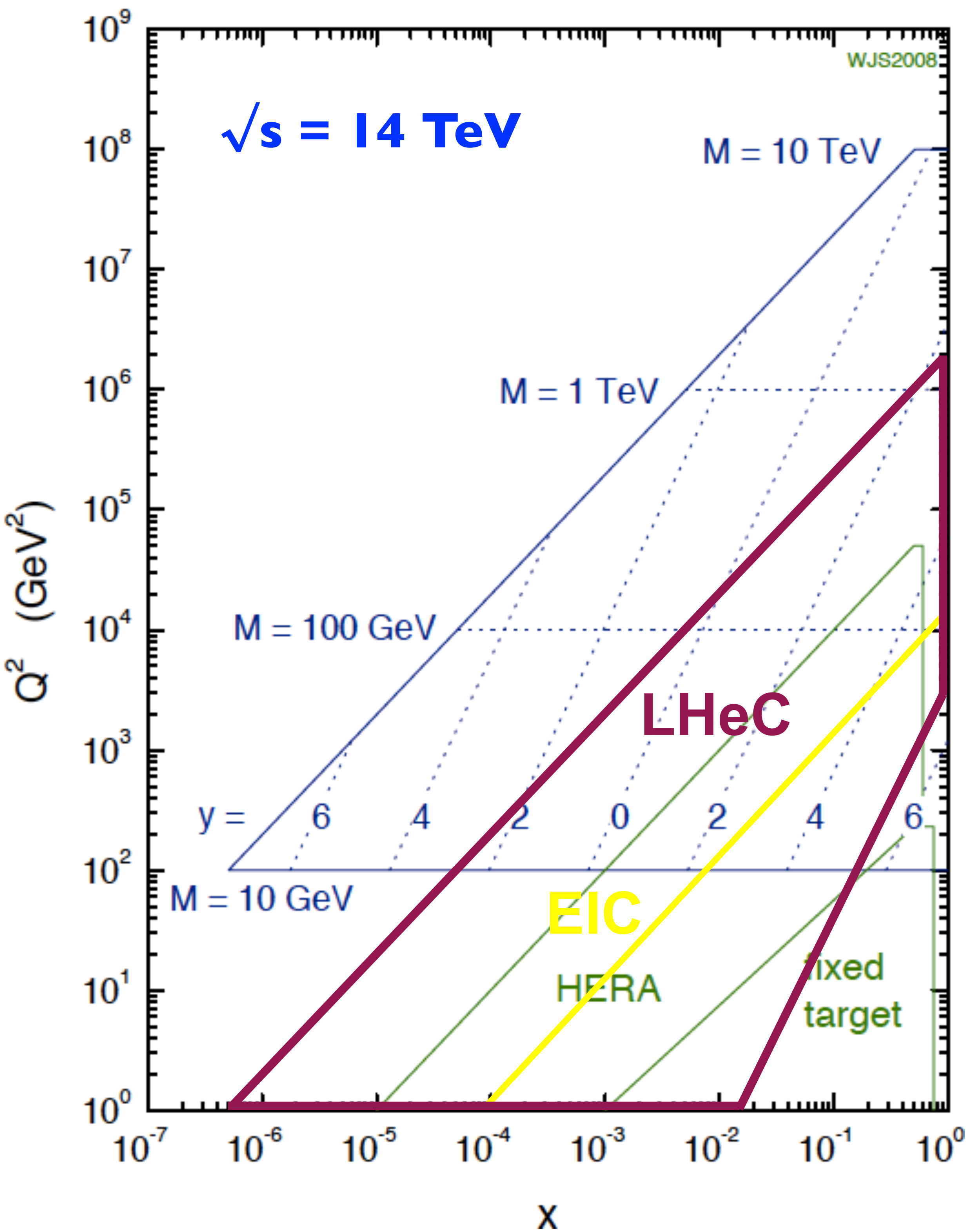


see lectures by D. Contardo

one billion € project

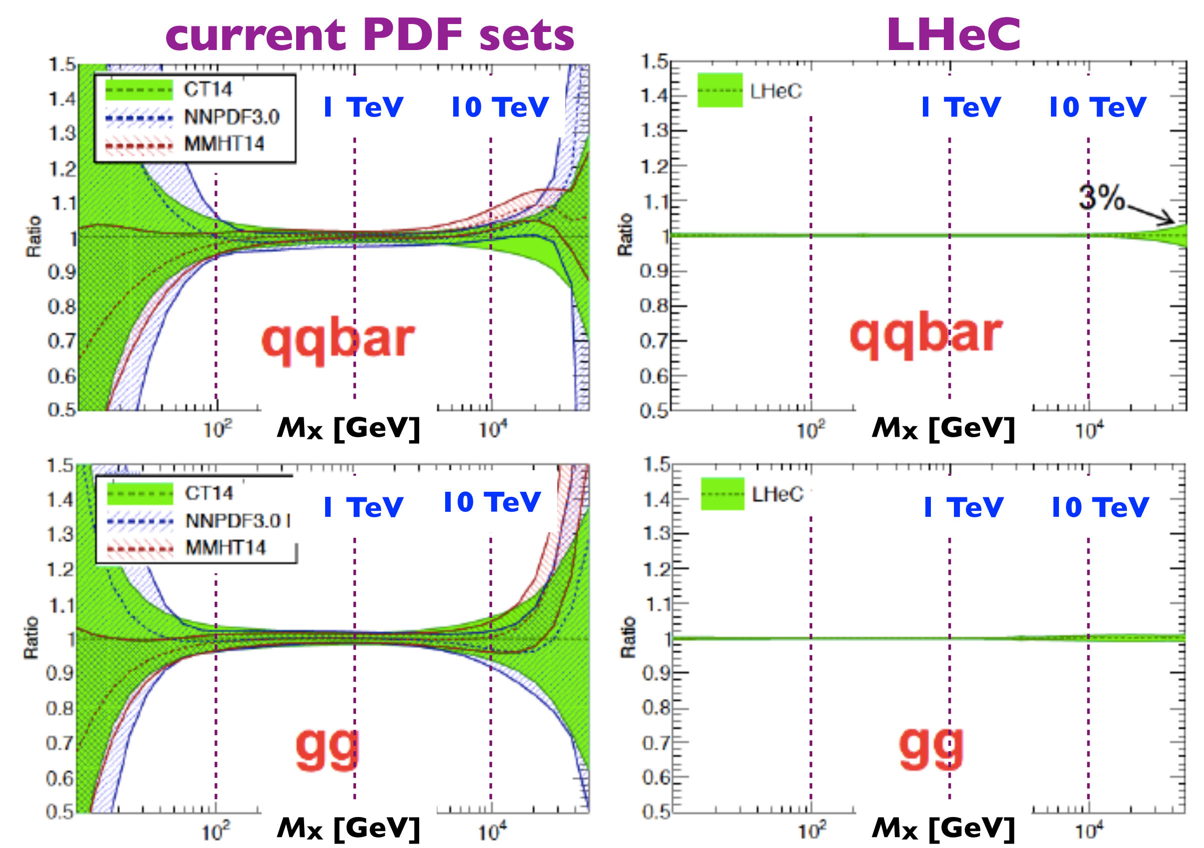
LHeC: e±p at HL-LHC

LHC parton kinematics



Electrons for the LHC

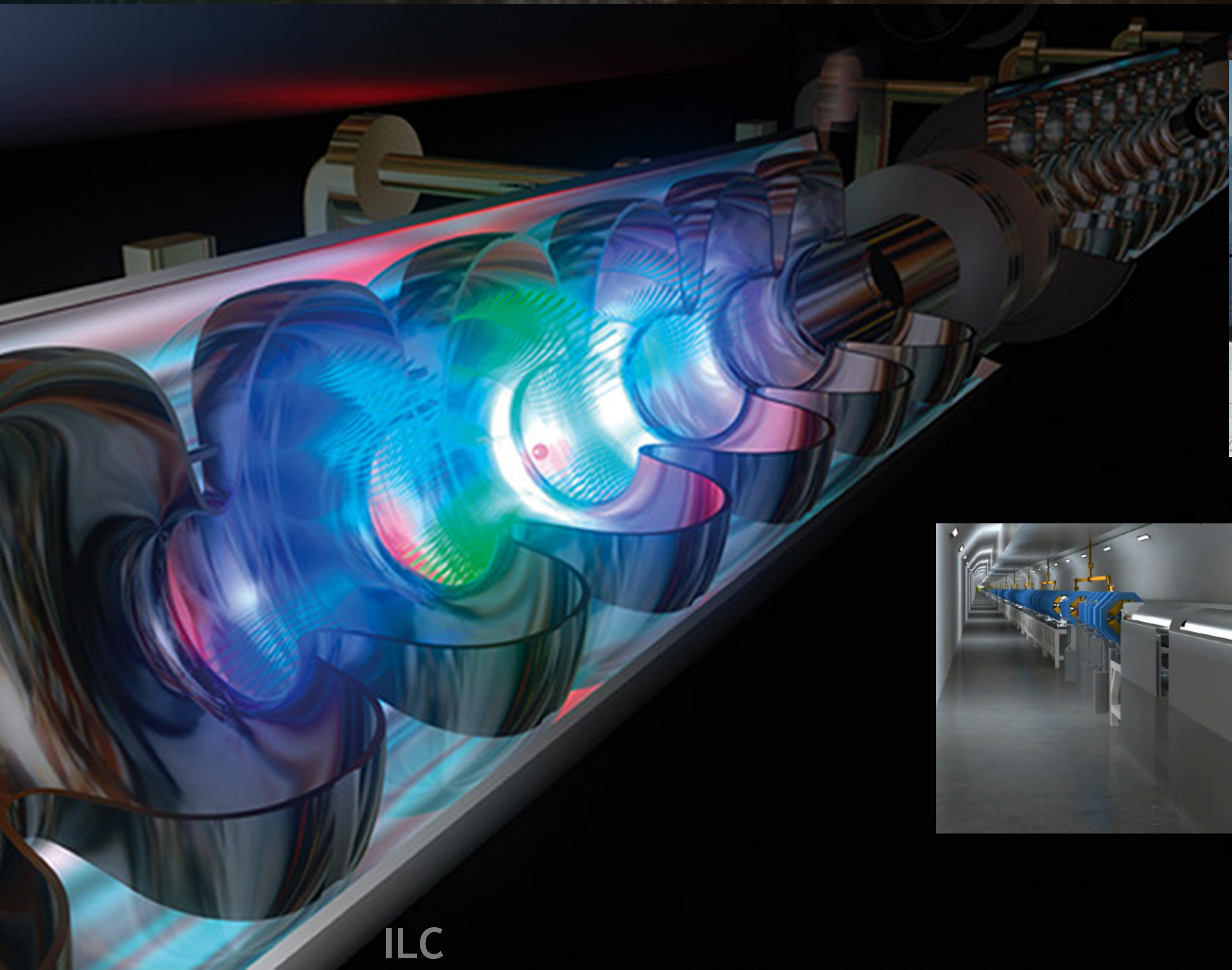
- Energy Recovery Linac (ERL) <100 MW
- 10-60 GeV e^- *vs* 1-7 TeV p
  → $\sqrt{s}$ = 200 GeV-1.3 TeV
- concurrent ep and pp (LS4-LS6): 225 fb^{-1}
- dedicated $e^\pm p$ (4 years): +650 fb^{-1}



Reduction of theory uncertainties by large factors at the (HE-)(HL-)LHC and FCC-hh

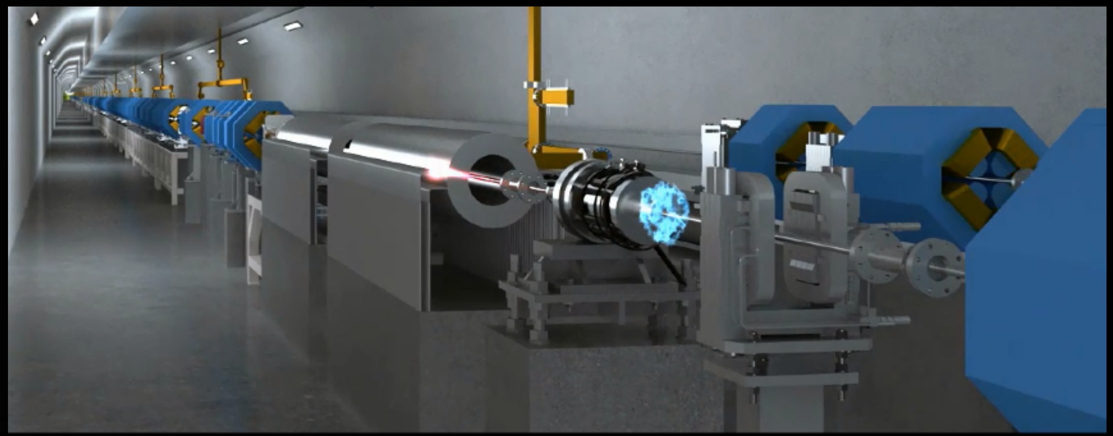
from M. Klein, DPhP seminar

CLIC



ILC

FCC-ee



CEPC

Lepton Colliders

2031+
? **ILC**
$\sqrt{s}$ = 250 GeV
ILD + ?
L = 500 fb^{-1} in 5y

2039+
? **ILC**
$\sqrt{s}$ = 350 GeV
ILD + ?
L = 2 ab^{-1} in 6y

2048+
? **ILC**
$\sqrt{s}$ = 500 GeV
ILD + ?
L = 4 ab^{-1} in 10y

2036+
? **CLIC**
$\sqrt{s}$ = 380 GeV
CLiC-D
L = 1 ab^{-1} in 8y

2046+
? **CLIC**
$\sqrt{s}$ = 1.5 TeV
CLiC-D
L = 2.5 ab^{-1} in 8y

2056+
? **CLIC**
$\sqrt{s}$ = 3 TeV
CLiC-D
L = 5 ab^{-1} in 8y

2039+
? **FCC-ee**
Z-WW-ZH
2 or 4 IR
L = 150-10-5 ab^{-1} in 9y

2049+
? **FCC-ee**
tt-365 GeV
2 or 4 IR
L = 0.2-1.5 ab^{-1} in 5y

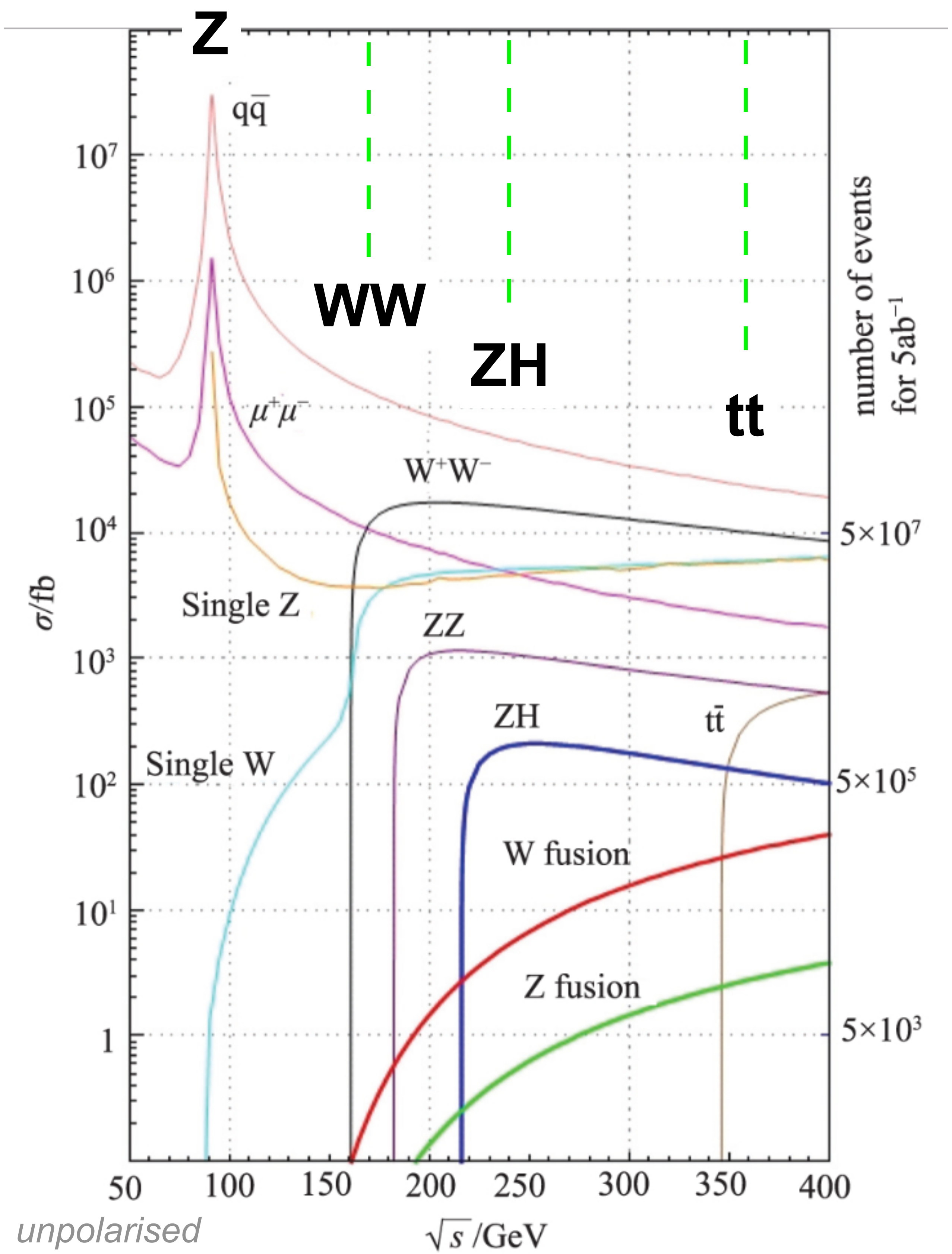
2060+
? **FCC-hh**

2031+
? **CEPC**
Z-WW-ZH
2 or 4 IR
L = 10-5-2 fb^{-1} in 10y

2046+
? **SppC**

2070 ??
?? muon collider

SM Cross Sections at e^+e^- Colliders



unpolarised

At $\sqrt{s}$ = 250 GeV

- $e^+e^- \rightarrow ZH$ **200 fb** *(Higgstrahlung)*
- $e^+e^- \rightarrow H\nu\nu$ **8 fb** *(W fusion)*

Cross sections decreasing as 1/s:

- $e^+e^- \rightarrow qq(\gamma)$ **60 pb** *(incl. Z return)*
- $e^+e^- \rightarrow W^+W^-$ **16 pb**
- $e^+e^- \rightarrow ZZ$ **1 pb**

Slowly increasing cross sections:

- $\gamma\gamma \rightarrow qq, \ell\ell$ **30 pb** *(m > 30 GeV)*
- $e\gamma \rightarrow Ze$ **3.8 pb**
- $e\gamma \rightarrow W\nu$ **1.5 pb** *(WWγ)*
- $ee \rightarrow Z\nu\nu$ **32 fb** *(WWZ)*

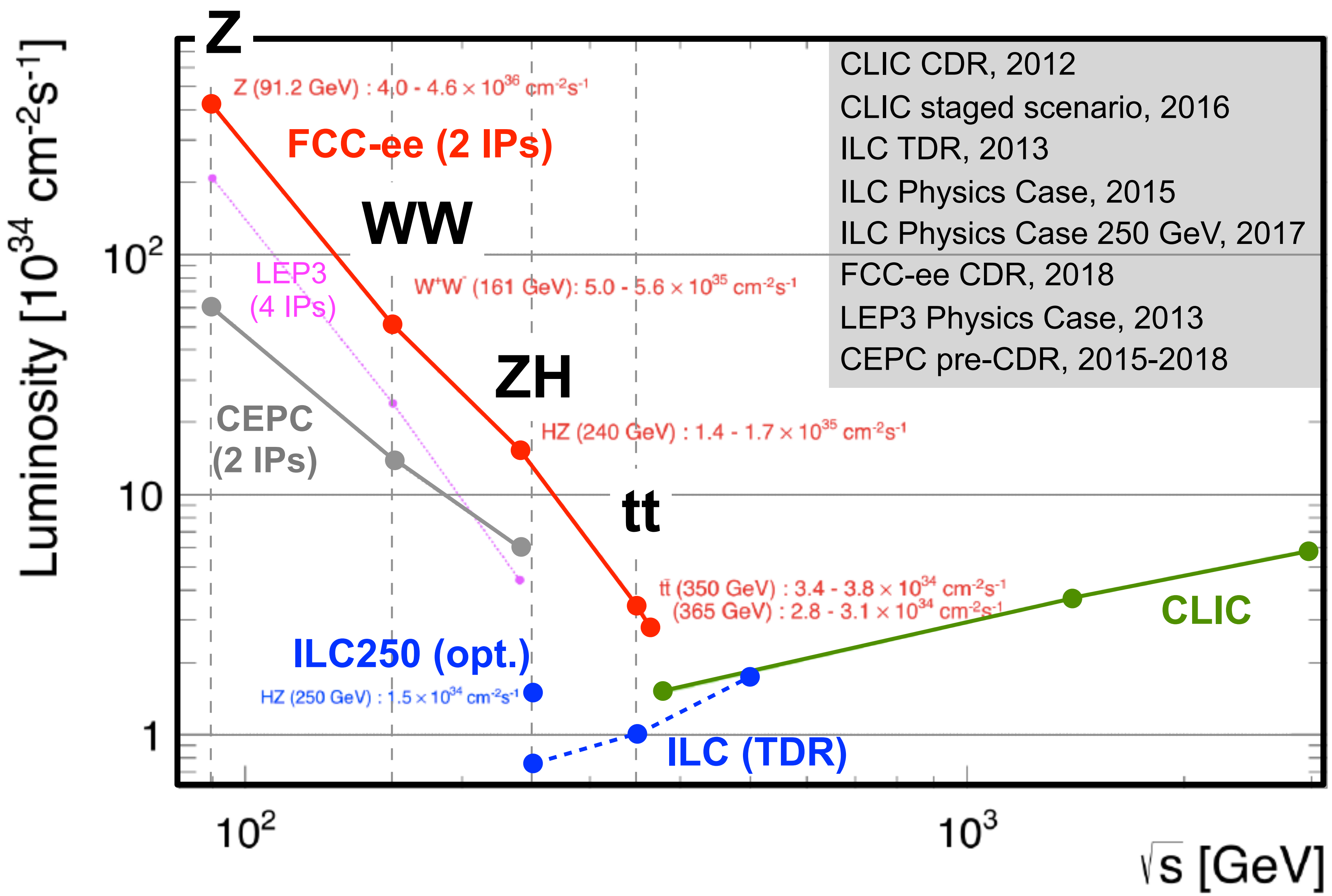
At $\sqrt{s}$ = 380 GeV

- $e^+e^- \rightarrow tt$ **500 fb**
- $e^+e^- \rightarrow ZH$ **100 fb**
- $e^+e^- \rightarrow H\nu\nu$ **40 fb**

SM Physics at e^+e^- Colliders

$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to qq, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to tt$	ultra-precision top mass	m_t
>360 GeV	• $e^+e^- \to tt$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to ttH$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to ff$ • $e^+e^- \to \chi\chi$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for Supersymmetry search for new Higgs bosons	y_{top} λ_{HHH}

Luminosity of e^+e^- Colliders



Circular colliders

☛ high-luminosity from Z peak to top pair threshold

Linear colliders

☛ extendability at high energy and beam L-polarisation

Linear or Circular? Pros & Cons

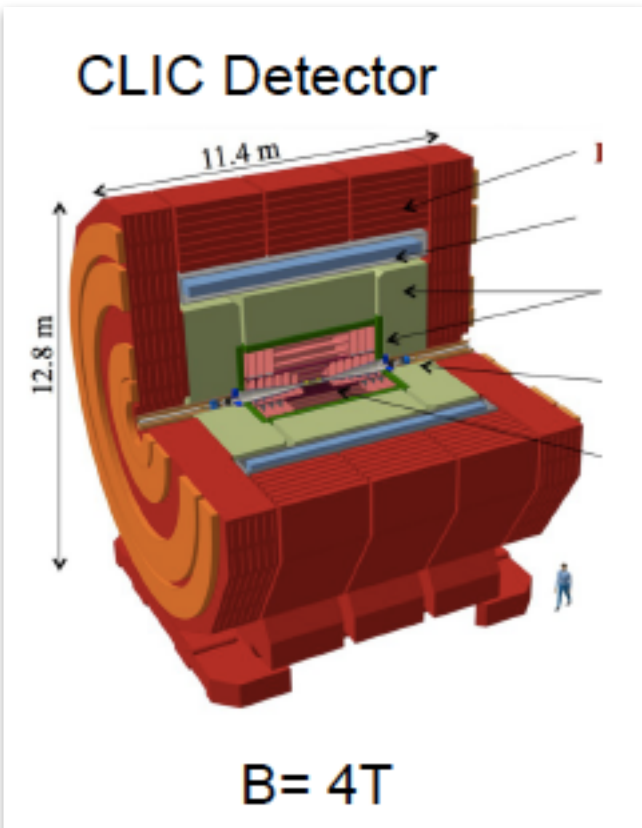
	Circular Colliders (FCC-ee)		Linear Colliders (ILC)	
	pros	cons	pros	cons
$\sqrt{s}$		• **limited by synchrotron radiation** (SR), which increases as E^4_{beam}/R • 100 km → 365 GeV max	• **extendable in energy** • large potential $\sqrt{s}$ reach 250→500→1000 GeV (access to ttH, ZHH, Hee)	• running at $\sqrt{s}$ smaller than 250 GeV would require optimisation
beam-strahlung		• **strong**: affects beam lifetime (typically 30 min.) • **top-up injection** needed to compensate for fast $\mathscr{L}$ burn-off		• **strong** due to beam size at interaction point (IP) • increasing with energy
energy spread	• **small energy spread** (<0.1% at 240 GeV) • with top-up injection: **mean $\mathscr{L}$ = 95% of peak**			• **larger energy spread** (86% within 1% of nominal at 250 GeV)
lumi	• **high-lumi** obtained with **large number of bunches** • **increasing at lower $\sqrt{s}$** due to less SR (spare RF used to accelerate more bunches) • **crab waist** scheme • **several interaction regions** possible	• **limited by SR power** at higher energies	• **high-lumi** obtained with **nanometer-size beams** • **increasing naturally with energy** thanks to beam dynamics at IP • **luminosity upgrade** (1312 → 2625 bunches)	• **low repetition rate** • **only one interaction region** (ILD and SLD detectors in push-pull)
L-polar		• **no L-polarisation**, except perhaps at Z peak	• **e^- beam: ±80%** • **e^+ beam: ±30% (±60%)**	
misc	• precise E_{beam} from **resonant depolarisation** (Z peak and perhaps WW threshold)		• nm-beams at IP allow for **very small beam pipe** (superior for b/c tagging)	

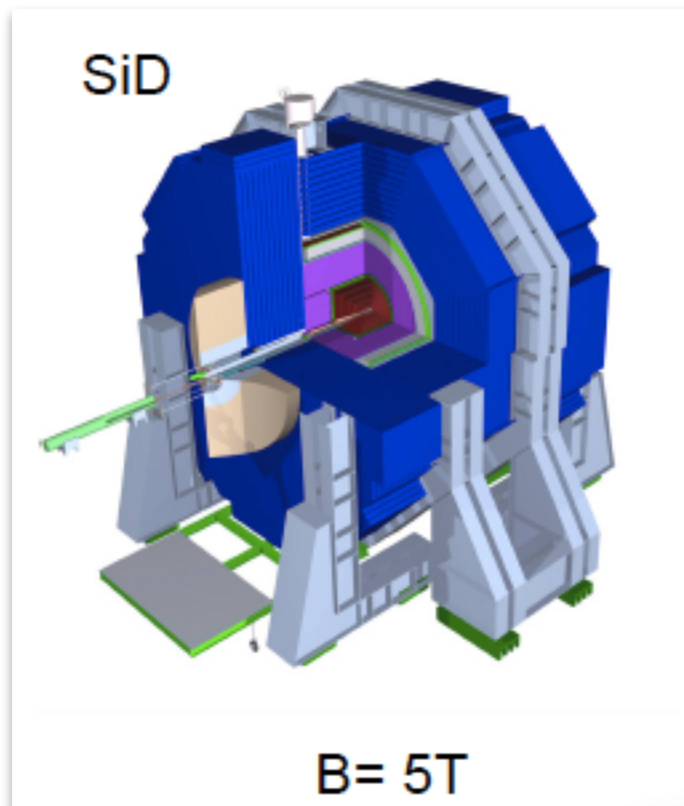
Detector Concepts for ee Colliders

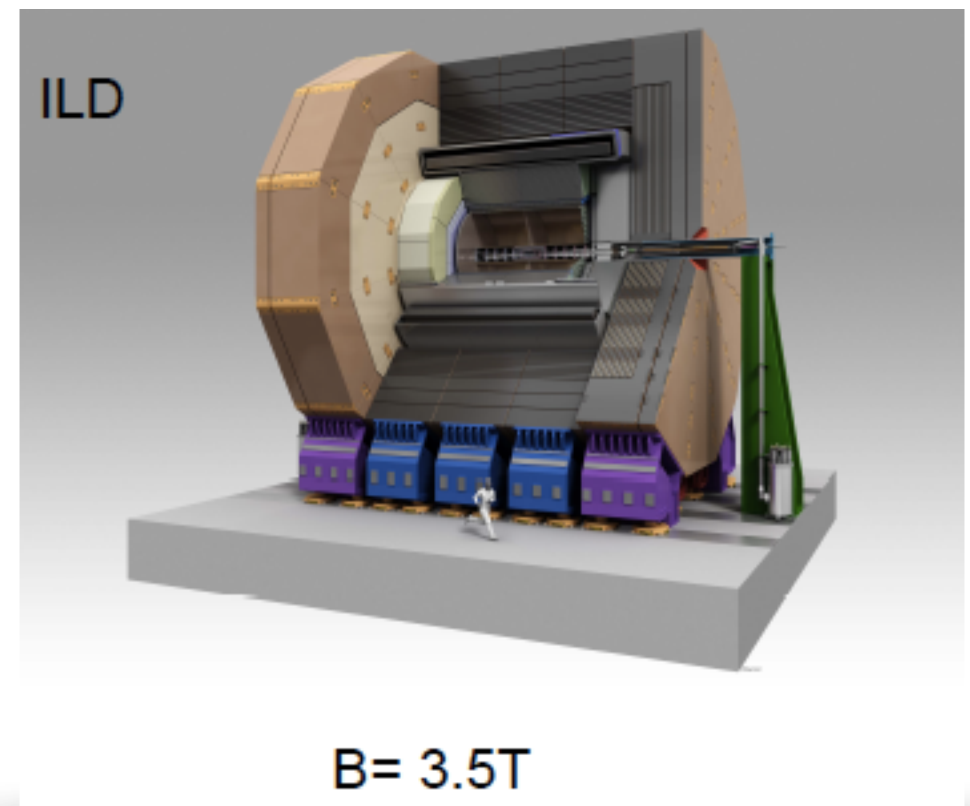
Particle Flow Detectors
- high hermiticity
- high granularity
- momentum resolution
- high separation power

FCC-ee 2 detector concepts
- CLD: inspired from CLIC detector
- IDEA: from present state-of-the-art

CEPC 2.5 detector concepts
- baseline: ILD/SiD concept (3T)
- IDEA concept (2T)







inner tracking with silicon

central tracking with silicon

central tracking with TPC

highly-granular calorimeters

see lectures by D. Contardo

ILC DBD (2013)

CLIC CDR (2012) (revised since)

physicsworld

“Discoveries make the front pages of the newspapers, while precise measurements of known particle don’t, but scientifically they are just as important."

quote borrowed from A. Blondel @ FCC symposium 2019

Selected References

CERN

- Machine parameters and project luminosity performance of proposed future colliders at CERN, CERN/SPC/1114
- European Particle Physics Strategy Update

HL-LHC and HE-LHC

- Yellow Book, Report on the physics at HL-LHC and perspectives for HE-LHC

FCC

- Future Circular Collider Study, Conceptual Design Report, 2019, Volume 1, *Physics Opportunities*
- Physics at a 100 TeV pp collider: Beyond the Standard Model phenomena, arxiv:1606.00947
- Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies, arxiv:1606.09408
- Physics at a 100 TeV pp collider: Standard Model processes, arxiv:1607.01831

LHeC

- A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector, arxiv:1206.2913

CLIC

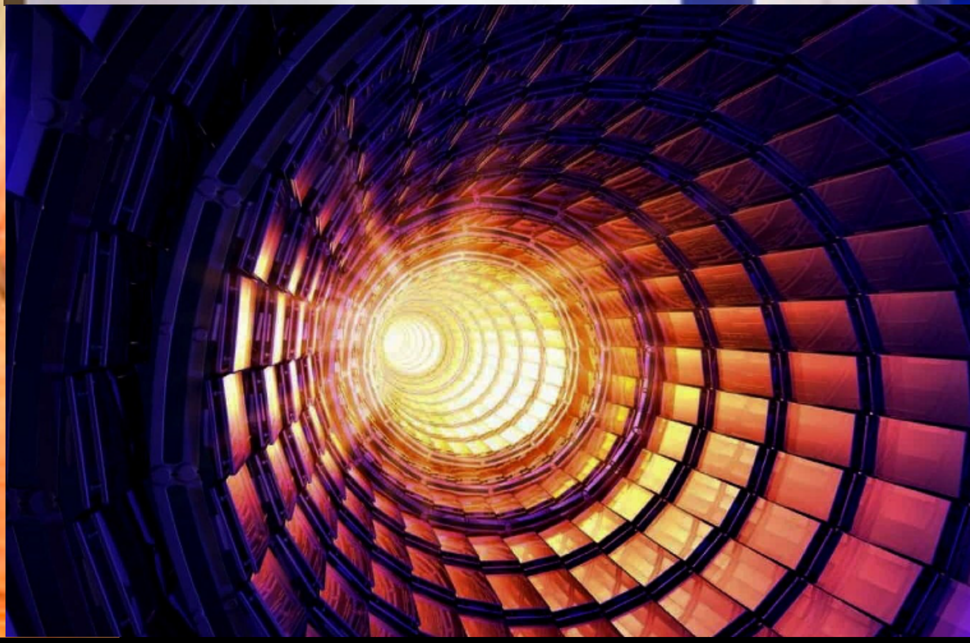
- Updated baseline for a staged Compact Linear Collider, arxiv:1608.07537

ILC

- The International Linear Collider Technical Design Report - Volume 1: Executive Summary, arxiv:1306.6327
- Physics Case for the 250 GeV Stage of the International Linear Collider, arxiv:1710.07621

CEPC

- Conceptual Design Report, Volume 2 — Physics and Detector, IHEP-CEPC-DR-2018-02



Gautier Hamel de Monchenault

Gauge Sector

$$
\begin{aligned}
\mathcal{L}_{\text{gauge}} &= -\frac{1}{4}\,\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \frac{1}{4}\,B_{\mu\nu}B^{\mu\nu} \\
&= -\frac{1}{2}\,W^{-}{}_{\mu\nu}W^{+\mu\nu} - \frac{1}{4}\,Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} \\
&\quad + ig\cos\theta_W \left[\left(W^{-}{}_{\mu\nu}W^{+\mu} - W^{+}{}_{\mu\nu}W^{-\mu} \right) Z^{\nu} + Z_{\mu\nu}W^{+\mu}W^{-\nu} \right] \\
&\quad + ig\sin\theta_W \left[\left(W^{-}{}_{\mu\nu}W^{+\mu} - W^{+}{}_{\mu\nu}W^{-\mu} \right) A^{\nu} + F_{\mu\nu}W^{+\mu}W^{-\nu} \right] \\
&\quad + g^2\cos^2\theta_W \left[Z_\mu Z_\nu\, W^{-\mu}W^{+\nu} - Z_\mu Z^\mu\, W^{-}{}_{\nu}W^{+\nu} \right] \\
&\quad + g^2\sin^2\theta_W \left[A_\mu A_\nu\, W^{-\mu}W^{+\nu} - A_\mu A^\mu\, W^{-}{}_{\nu}W^{+\nu} \right] \\
&\quad + g^2\cos\theta_W\sin\theta_W \left[\left(Z_\mu A_\nu + Z_\nu A_\mu \right) W^{-\mu}W^{+\nu} - 2\, Z_\mu A^\mu\, W^{-}{}_{\nu}W^{+\nu} \right] \\
&\quad + \frac{g^2}{2}\, W^{-}{}_{\mu}W^{+}{}_{\nu} \left[W^{-\mu}W^{+\nu} - W^{-\nu}W^{+\mu} \right]
\end{aligned}
$$

gauge kinetic terms

vector boson kinetic terms

ZWW

γWW

ZZWW

γγWW

γZWW

WWWW

EWSB Sector

$$\begin{aligned}
\mathcal{L}_{\text{EWSB}} &= (\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi) - \lambda\left[(\phi^\dagger\phi)^2 - v^2\phi^\dagger\phi\right] \\
&= \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_H^2 h^2 \\
&\quad + m_W^2 W^-{}_\mu W^{+\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \\
&\quad + \frac{2m_W^2}{v}W^-{}_\mu W^{+\mu}h + \frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{m_W^2}{v^2}W^-{}_\mu W^{+\mu}h^2 + \frac{m_Z^2}{2v^2}Z_\mu Z^\mu h^2 \\
&\quad - \frac{m_H^2}{2v}h^3 - \frac{m_H^2}{8v^2}h^4 + \left(\text{Cte} = \frac{m_H^2 v^2}{8}\right)
\end{aligned}$$

Higgs boson kinetic and mass terms

electroweak boson mass terms

coupings to bosons and self-couplings of the Higgs boson

Quark Sector

left-handed doublets

$$Q^j{}_L \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix} u_j \\ d'_j \end{pmatrix}$$

right-handed singlets

$$u_{jR} \equiv \frac{1}{2}(1+\gamma^5)\, u_j$$

$$d'_{jR} \equiv \frac{1}{2}(1+\gamma^5)\, d'_j$$

(3 families)

$$\begin{aligned}
\mathcal{L}_{\text{kin-quarks}} &= \sum_j \; i\,\overline{Q^j}{}_L \gamma^\mu \mathcal{D}_\mu Q^j{}_L \;+\; i\,\overline{u}_{jR}\gamma^\mu \mathcal{D}_\mu u_{jR} \;+\; i\,\overline{d}_{jR}\gamma^\mu \mathcal{D}_\mu d_{jR} \\
&= \; i\,\overline{\mathbf{u}}\gamma^\mu \partial_\mu \mathbf{u} + i\,\overline{\mathbf{d}}\gamma^\mu \partial_\mu \mathbf{d} \;+\; \frac{2}{3} e\,\overline{\mathbf{u}}\gamma^\mu \mathbf{u} A_\mu \;-\; i\,\frac{1}{3} e\,\overline{\mathbf{d}}\gamma^\mu \mathbf{d} A_\mu \\
&\quad + \frac{g}{2\sqrt{2}} \left[\, \overline{\mathbf{d}}\mathbf{V}_{\text{CKM}}{}^\dagger \gamma^\mu (1-\gamma^5)\mathbf{u}\, W^-{}_\mu + \overline{\mathbf{u}}\gamma^\mu(1-\gamma^5)\mathbf{V}_{\text{CKM}}\mathbf{d}\, W^+{}_\mu \,\right] \\
&\quad + \frac{g}{2\cos\theta_W}\left[-\frac{2}{3}\sin^2\theta_W\, \overline{\mathbf{u}}\gamma^\mu(1+\gamma^5)\mathbf{u} + \left(+\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) \overline{\mathbf{u}}\gamma^\mu(1-\gamma^5)\mathbf{u} \right] Z_\mu \\
&\quad + \frac{g}{2\cos\theta_W}\left[\;\frac{1}{3}\sin^2\theta_W\, \overline{\mathbf{d}}\gamma^\mu(1+\gamma^5)\mathbf{d} + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W\right) \overline{\mathbf{d}}\gamma^\mu(1-\gamma^5)\mathbf{d} \right] Z_\mu
\end{aligned}$$

Lepton Sector

left-handed doublets

$$L^{\ell}{}_L \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$$

right-handed singlets

$$\ell_R \equiv \frac{1}{2}(1+\gamma^5)\,\ell$$

(3 families)

$$\begin{aligned}
\mathcal{L}_{\text{kin-leptons}} &= \sum_\ell \; i\,\overline{L^\ell}{}_L\gamma^\mu\mathcal{D}_\mu L^\ell_L \;+\; i\,\overline{\ell}_R\gamma^\mu\mathcal{D}_\mu\ell_R \\
&= \sum_\ell \; i\,\overline{\nu}_\ell\gamma^\mu\partial_\mu\nu_\ell \;+\; i\,\overline{\ell}\gamma^\mu\partial_\mu\ell \;-\; e\,\overline{\ell}\gamma^\mu\ell\,A_\mu \\
&\quad + \frac{g}{2\sqrt{2}}\left[\,\overline{\ell}\gamma^\mu(1-\gamma^5)\nu_\ell\,W^-{}_\mu + \overline{\nu}_\ell\gamma^\mu(1-\gamma^5)\ell\,W^+{}_\mu\,\right] \\
&\quad + \frac{g}{2\cos\theta_W}\,\overline{\nu}_\ell\gamma^\mu\frac{1}{2}(1-\gamma^5)\nu_\ell\,Z_\mu \\
&\quad + \frac{g}{2\cos\theta_W}\left[\sin^2\theta_W\,\overline{\ell}\gamma^\mu(1+\gamma^5)\ell + \left(-\frac{1}{2}+\sin^2\theta_W\right)\overline{\ell}\gamma^\mu(1-\gamma^5)\ell\right] Z_\mu
\end{aligned}$$

neutrinos are massless in the SM

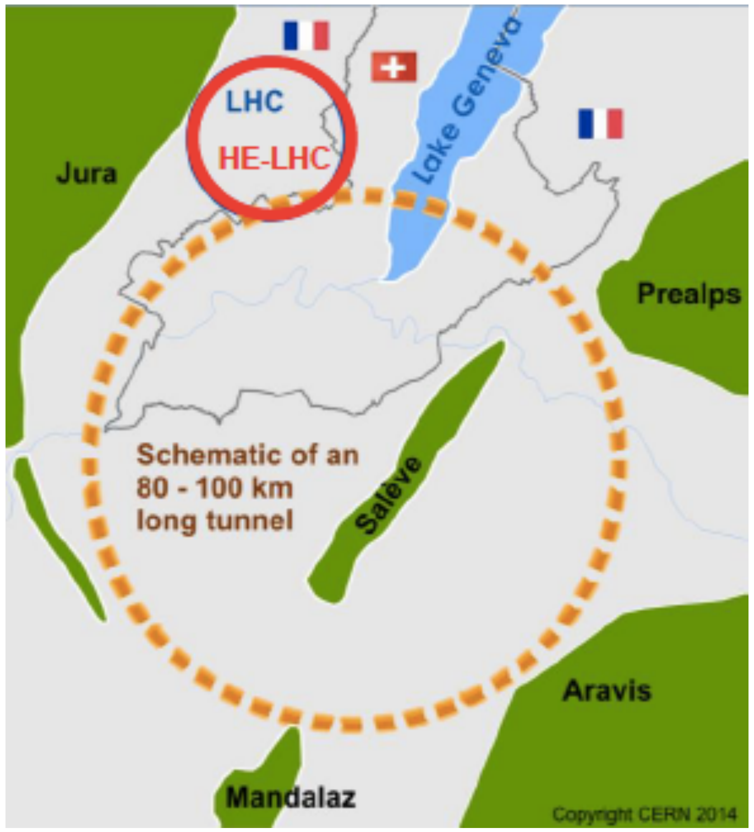
Yukawa Sector

$$\mathcal{L}_{\text{Yukawa}} = \sum_j \left(\Gamma_{uj}\, \overline{Q^j}_L \tilde{\phi}\, u_{jR} + \Gamma_{dj}\, \overline{Q^j}_L \phi\, d'_{jR} \right) + \sum_\ell \Gamma_\ell\, \overline{L^\ell}_L \phi\, \ell_R \;\; + \;\text{h. c.}$$

$$= \sum_f \left(m_f\, \overline{f} f \; + \; \frac{m_f}{v}\, \overline{f} f h \right)$$

fermion mass terms and couplings of the Higgs boson to fermions

FCC: Future Circular Colliders



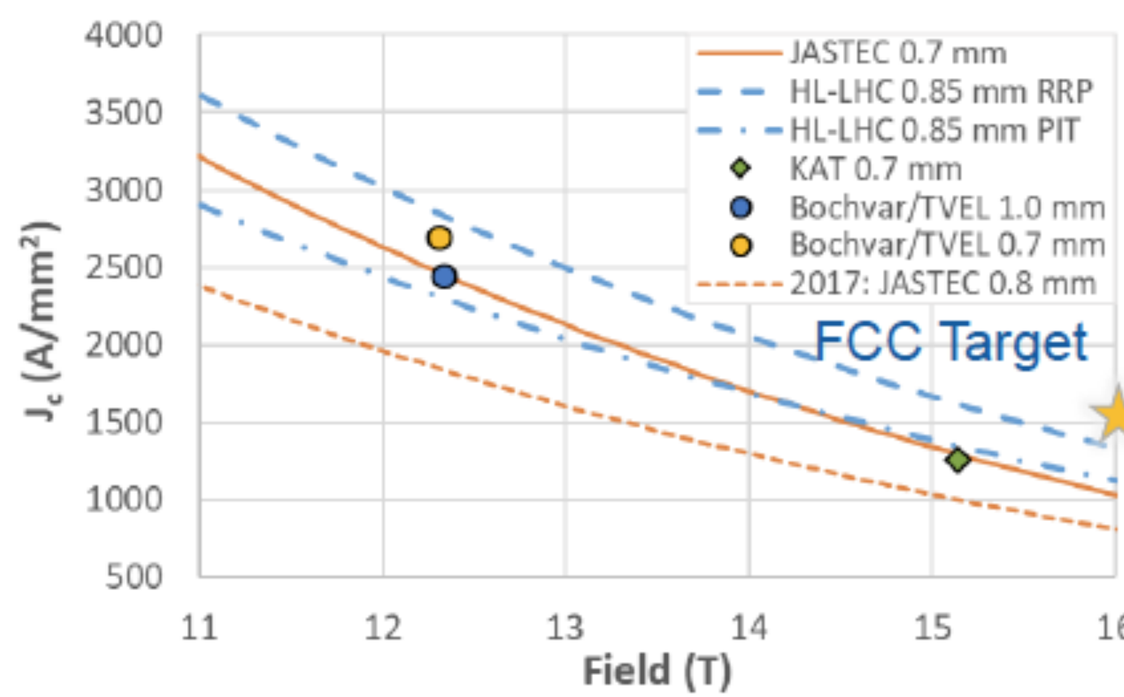
100-km tunnel in Geneva area

	$\sqrt{s}$	$\mathscr{L}$ (cm^{-2}s^{-1})	first beams (technically)	tunnel
HE-LHC	27 TeV	1.6×10^{35}	2040	LHC
FCC-ee	90-365 GeV	$200\text{-}1.5\times10^{34}$	2039	
FCC-eh	3.5 TeV	1.5×10^{34}	2043	100-km
FCC-hh	100 TeV	3×10^{35}	2043	

	$\sqrt{s}$	L (ab^{-1})	years
HE-LHC	27 TeV	12	20
FCC-hh	100 TeV	30	25

Major focus at CERN:
development of 16-T Nb_3Sb SC magnets

- on-going R&D on SC high-field magnets
- prepare industrialisation



FCC CDR fall 2018

CERN/SPC/1114 (2018)

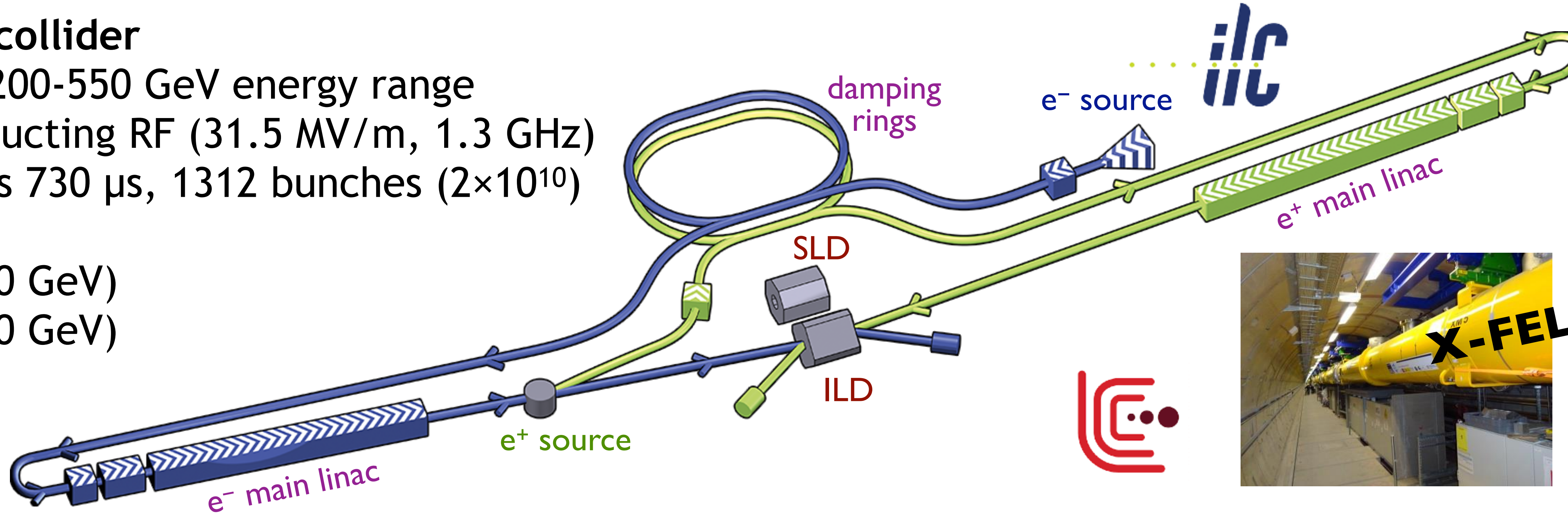
cf presentation by **Barbara Dalena**

ILC: International Linear Collider

Linear e⁺e⁻ collider

in the 200-550 GeV energy range

- super conducting RF (31.5 MV/m, 1.3 GHz)
- 5 Hz, trains 730 μs, 1312 bunches (2×10^{10})
- footprint:
  20 km (250 GeV)
  31 km (500 GeV)

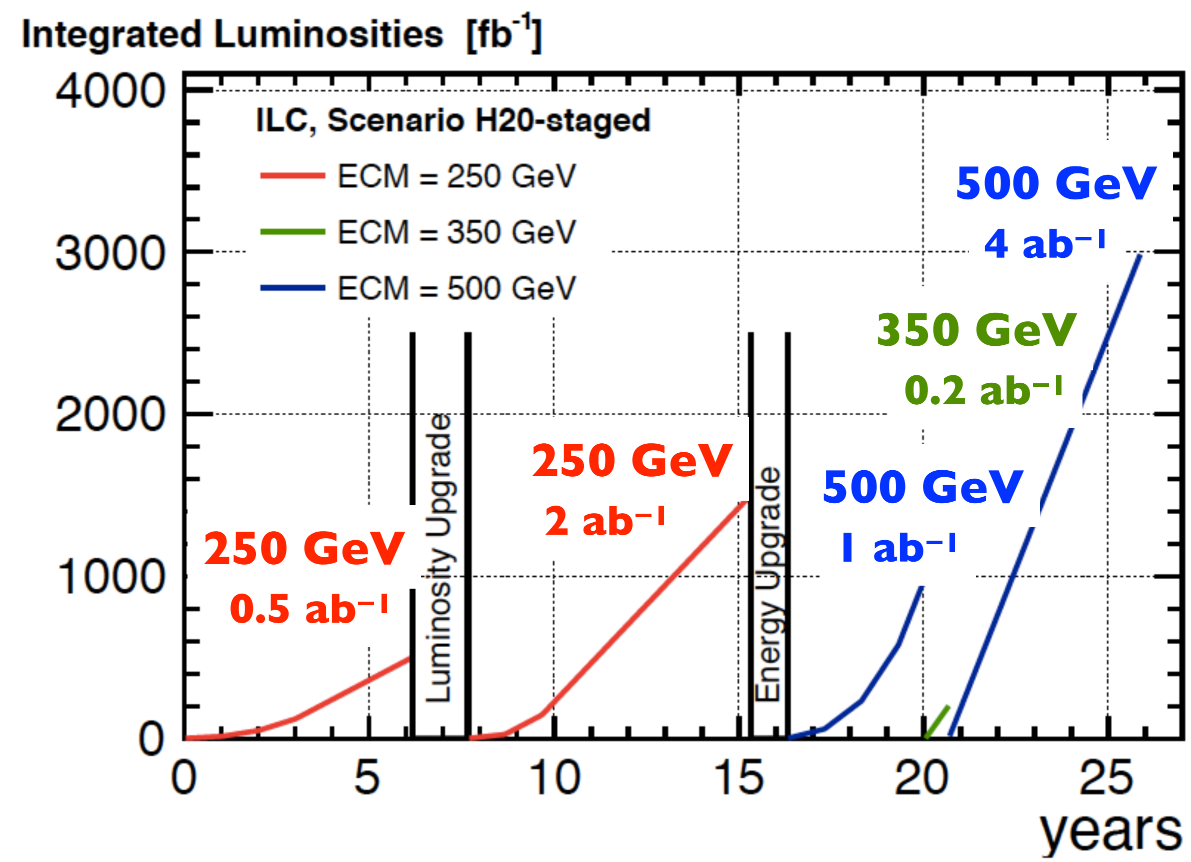


ILC TDR (2013)
ILC-250 Physics Case (2017)

Staging scenario

- $\sqrt{s}$ = 250 GeV
- optimised luminosity: $\mathscr{L} = 1.5\times10^{34}$ $cm^{-2}s^{-1}$
- ±80% (±30%) e⁻ (e⁺) beam polarisation
- (LR, RL, LL, RR) = (45%, 45%, 5%, 5%)

Strong effort by Japanese community to host ILC

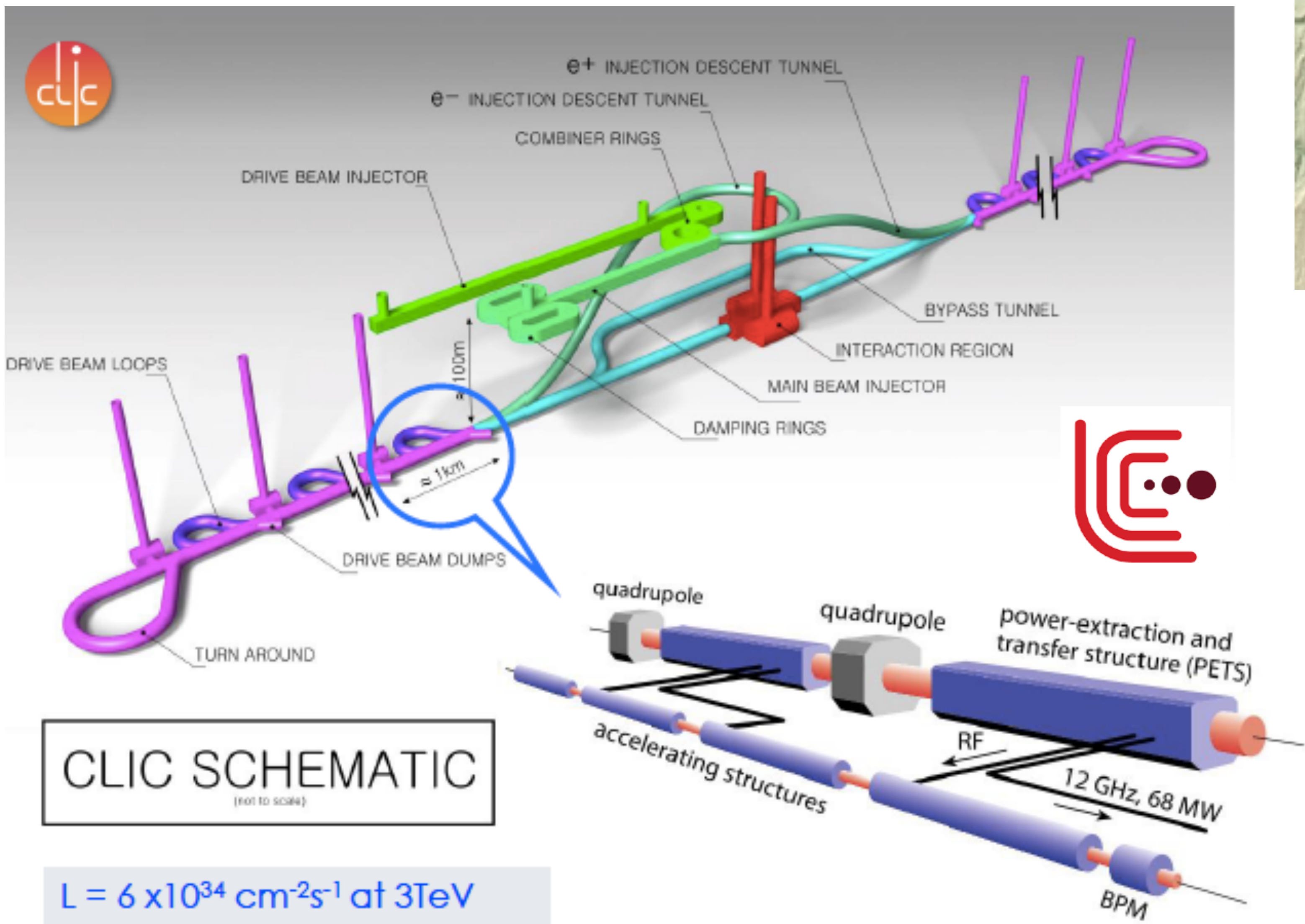


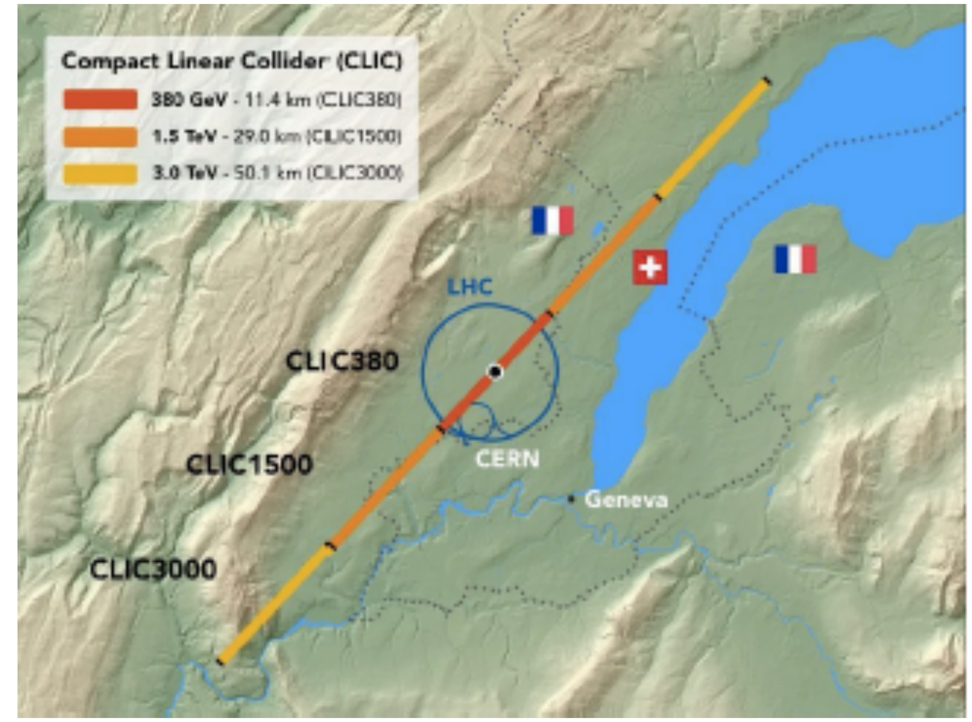
CLIC: Compact Linear Collider

Linear e^+e^- collider at CERN

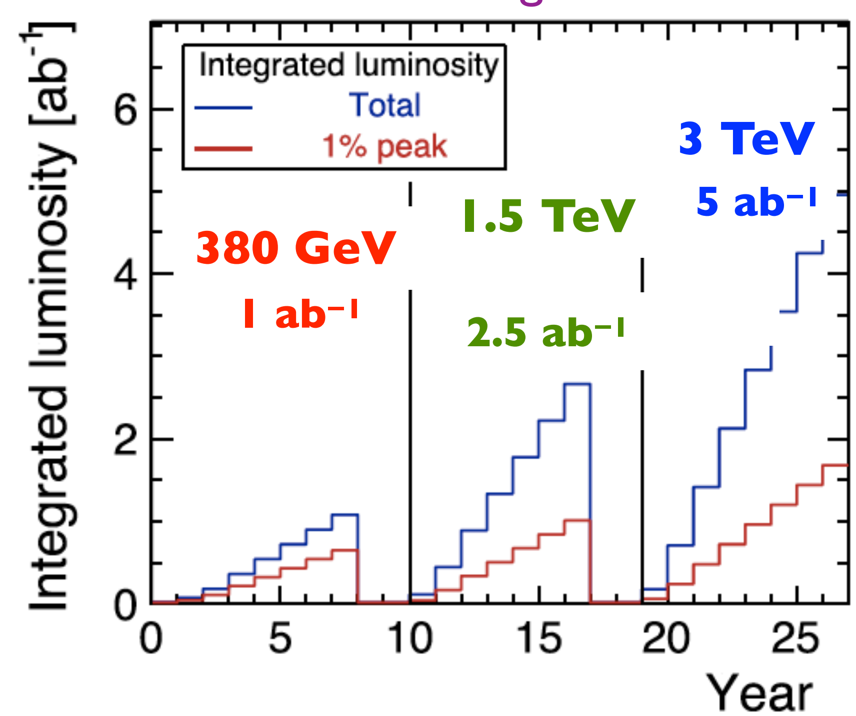
in the up-to multi-TeV energy range

- normal conducting high-frequency RF (X-band, 12 GHz)
- e^- drive beam for RF power generation





Scenario in 3 stages

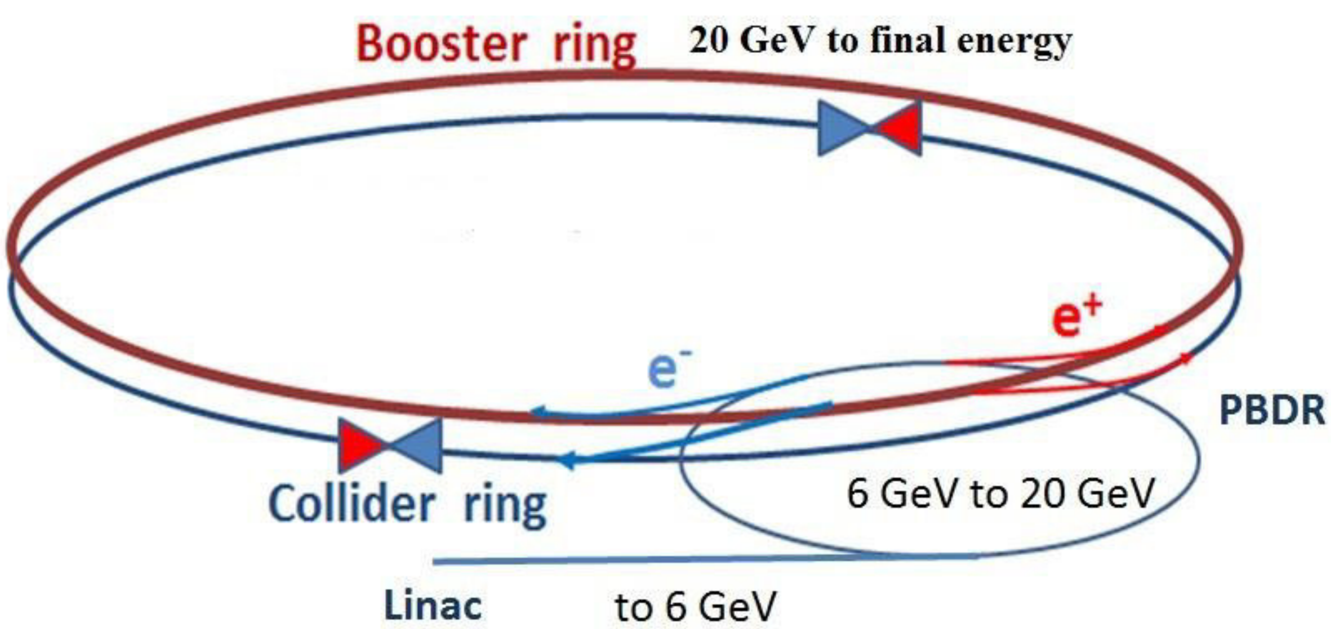


L = 6 x10^{34} $cm^{-2}s^{-1}$ at 3TeV
Beam power 30MW at 3TeV

Beam polarisation: (±80%, ∓80%)
LR / RL = 50% / 50%

CERN/SPC/1114 (2018)

FCC-ee: e^+e^- Circular Collider



First-phase machine in the **100-km tunnel** built to host eventually FCC-hh

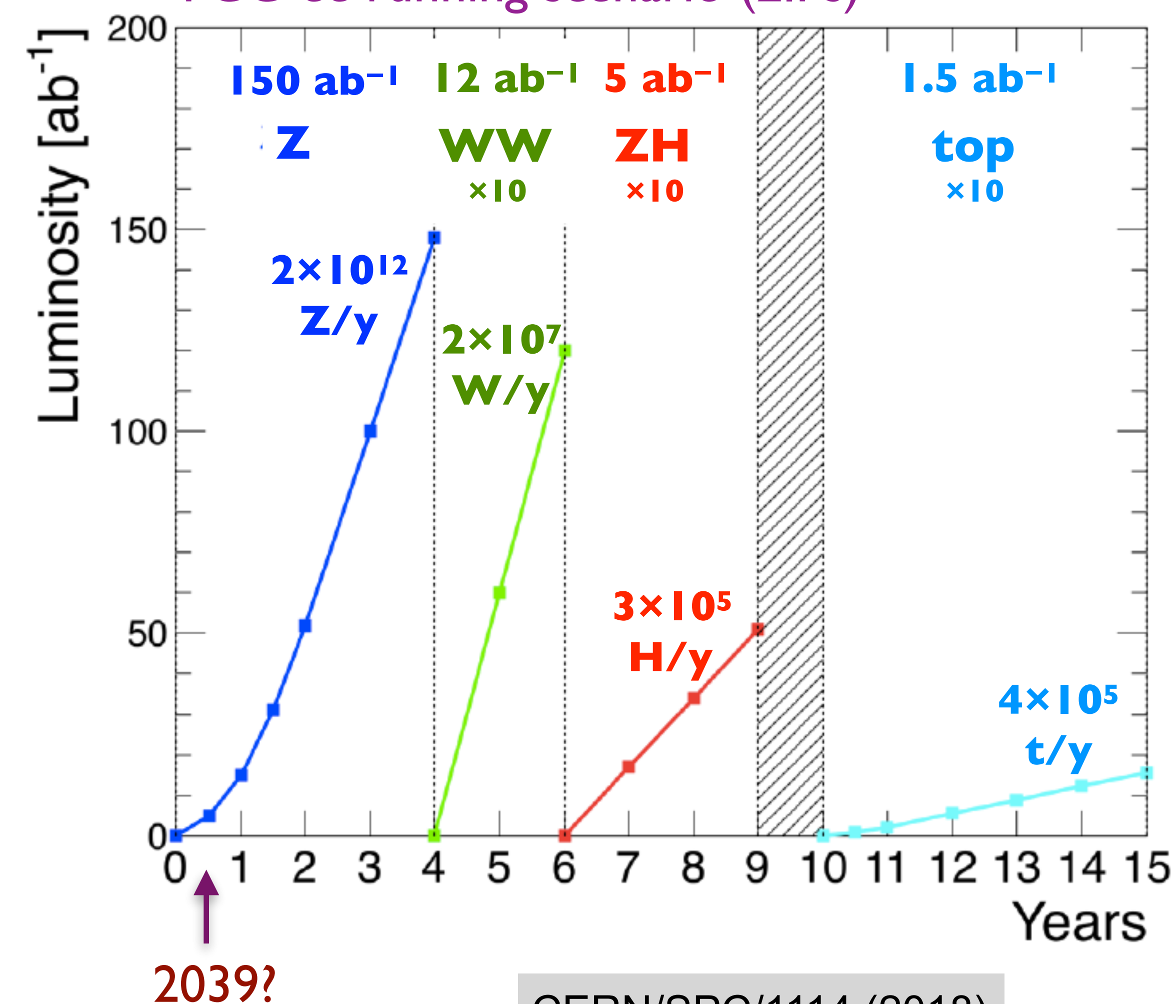
Luminosity limited by SR
- top-up injection (once per minute)
- 50 MW power/beam
- 2 interaction points

RF system: high-current → high gradient
3 sets of RF cavities

	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0,1	16640	1390
WW	0,44	2000	147
ZH	2,0	393	29
top	10,9	48	5,4

Asymmetric optics with beam crossing angle of 30 mrad

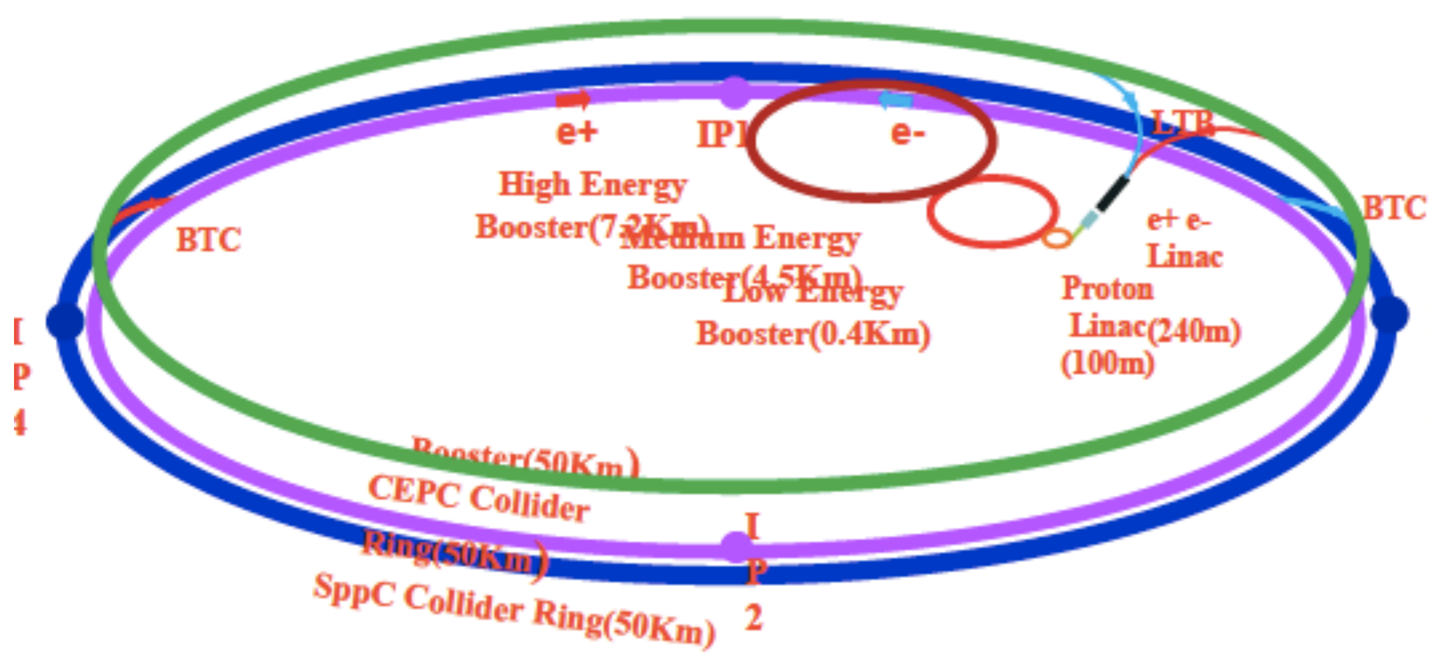
FCC-ee running scenario (2IPs)



FCC-ee CDR fall 2018

CERN/SPC/1114 (2018)

CEPC: Chinese e^+e^- Collider



Project similar to FCC-ee in China
- two colliding rings and a booster
- $\sqrt{s}$ = 90-240 GeV

- Hosted in a 100-km tunnel which could eventually host a 70-TeV pp collider
- several possible sites

Peak luminosity (2 IPs) (CDR parameters)
- at the Z: 1.7×10^{35} $cm^{-2}s^{-1}$ (3T)
- at the W: 1.0×10^{35} $cm^{-2}s^{-1}$
- at the H: 3×10^{34} $cm^{-2}s^{-1}$

Physics goals:
- $>3\times10^{11}$ Z bosons (8 ab^{-1})
- 2×10^{7} W pairs (2.6 ab^{-1})
- 10^{6} Higgs bosons (5.6 ab^{-1})

Timeline

2013-2015	pre-studies
2016-2022	R&D Engineering Design
2022-2030	Construction
2030-2040	data taking

- Starts before the end of the HL-LHC
- possibly concurrent with the ILC

CEPC CDR in preparation (2019)

CEPC symposium (Nov. 2018)