

Perspectives in High Energy Physics

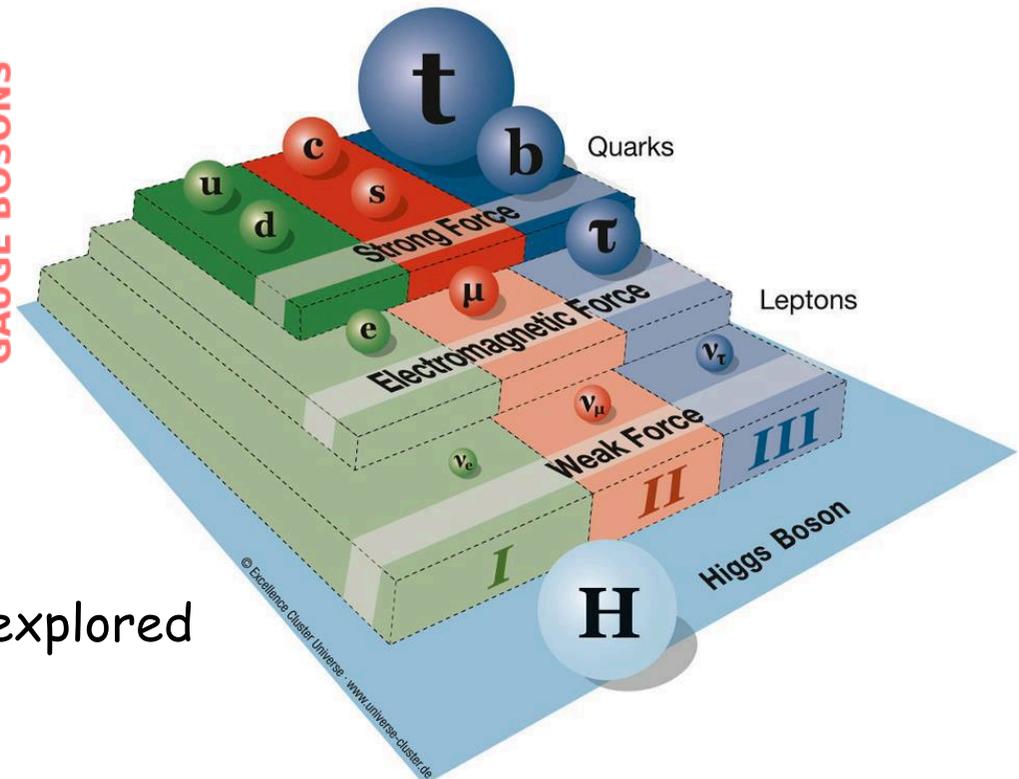
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Tel Aviv University



- Status of Standard Model of particle physics
- What is missing?
- Future options

Status of the Standard Model

| | | | | | |
|----------------|---|---------------------------------------|--------------------------------------|-------------------------|-------------------------|
| mass → | 2.4 MeV/c ² | 1.27 GeV/c ² | 171.2 GeV/c ² | 0 | ≈126 GeV/c ² |
| charge → | 2/3 | 2/3 | 2/3 | 0 | 0 |
| spin → | 1/2 | 1/2 | 1/2 | 1 | 0 |
| | u up | c charm | t top | γ photon | H Higgs boson |
| QUARKS | 4.8 MeV/c ² | 104 MeV/c ² | 4.2 GeV/c ² | 0 | |
| | -1/3 | -1/3 | -1/3 | 0 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | d down | s strange | b bottom | g gluon | |
| | 0.511 MeV/c ² | 105.7 MeV/c ² | 1.777 GeV/c ² | 91.2 GeV/c ² | |
| | -1 | -1 | -1 | 0 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | e electron | μ muon | τ tau | Z Z boson | |
| LEPTONS | <2.2 eV/c ² | <0.17 MeV/c ² | <15.5 MeV/c ² | 80.4 GeV/c ² | |
| | 0 | 0 | 0 | ±1 | |
| | 1/2 | 1/2 | 1/2 | 1 | |
| | ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | W W boson | |
| | | | | | GAUGE BOSONS |

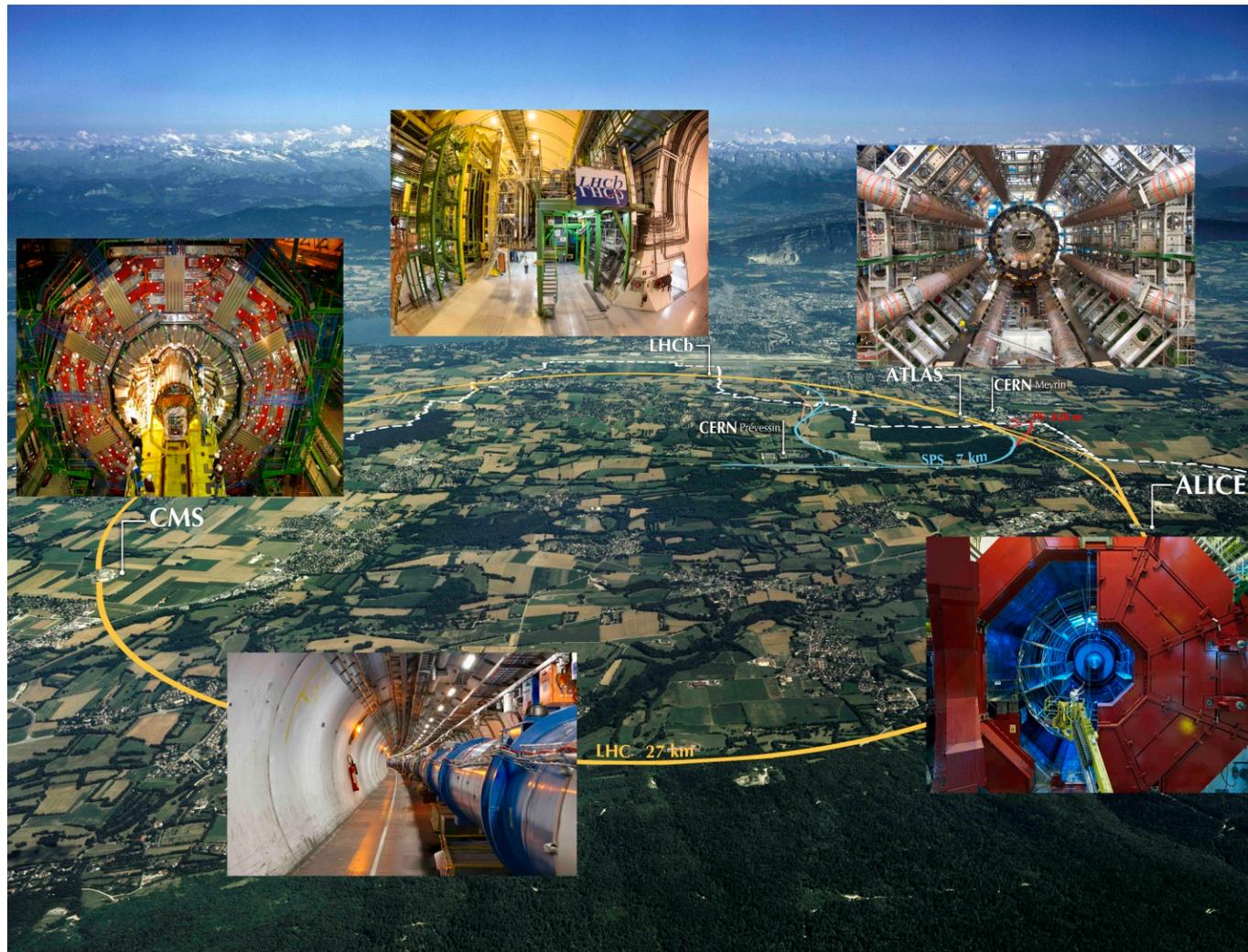


Higgs sector and top sector largely unexplored

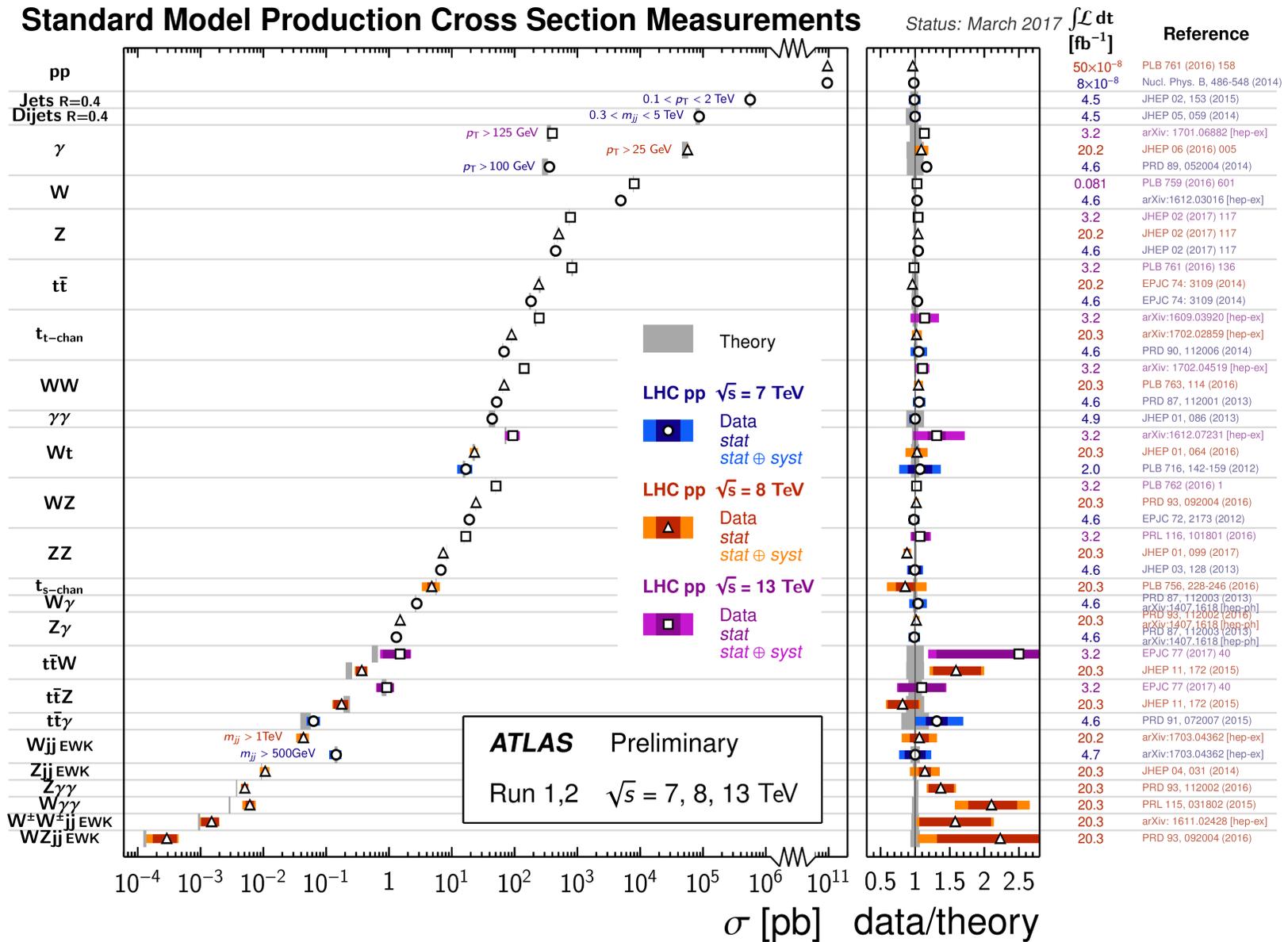
Present Energy Frontier - Large Hadron Collider at CERN

27km tunnel, up to 175m deep, 1232 SC bending magnets 1.9K, 14.3m long, 8T

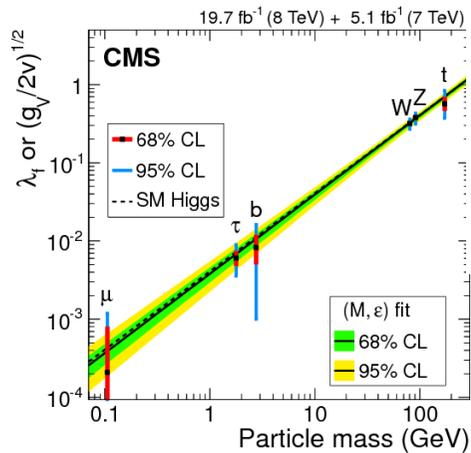
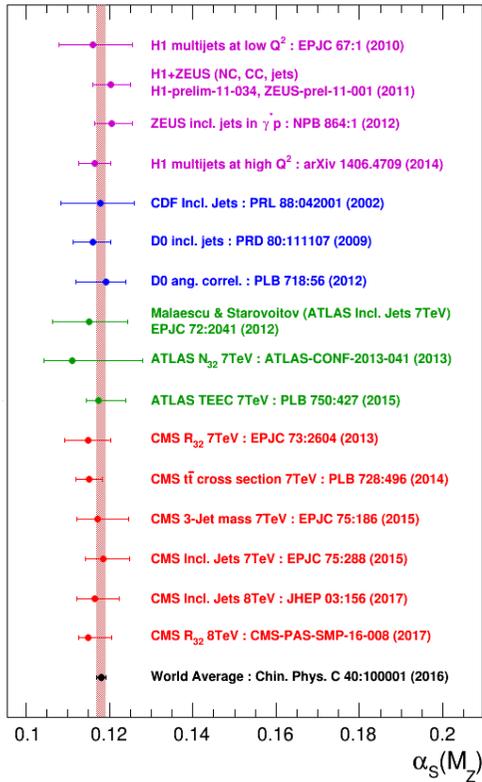
Collected pp data: 7TeV (2010/2011); 8TeV (2012); 13TeV (2015-now)



Stress test of SM at the LHC



Stress test of SM at the LHC



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

| Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L} d\tau [fb^{-1}]$ | Mass limit | $\sqrt{s} = 7, 8$ TeV | $\sqrt{s} = 13$ TeV | Reference | | |
|---|--|--|------------------------|------------------------------------|--------------------|------------------------|--|--|--|---------------------------------|
| Inclusive Searches | MSUGRA/CMSSM | 0-3 $e, \mu/1-2 \tau$ | 2-10 jets/3 b | Yes | 20.3 | \tilde{g}, \tilde{g} | 1.85 TeV | $m(\tilde{g})=m(\tilde{g})$ | 1507.05525 | |
| | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | \tilde{q} | 1.57 TeV | $m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{st} \text{ gen. } \tilde{q})=m(2^{nd} \text{ gen. } \tilde{q})$ | ATLAS-CONF-2017-022 | |
| | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | \tilde{q} | 608 GeV | $m(\tilde{q})=m(\tilde{\chi}_1^0) < 5$ GeV | 1604.07773 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | \tilde{g} | | $m(\tilde{g}) < 200$ GeV | ATLAS-CONF-2017-022 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | \tilde{g} | | $m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | ATLAS-CONF-2017-022 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | \tilde{g} | | $m(\tilde{\chi}_1^0) < 400$ GeV | ATLAS-CONF-2017-030 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$ | 3 e, μ | 4 jets | Yes | 36.1 | \tilde{g} | | $m(\tilde{\chi}_1^0) < 400$ GeV | ATLAS-CONF-2017-033 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | \tilde{g} | | | 1607.05979 | |
| | GMSB (bino NLSP) | 1-2 $\tau, 0-1 \ell$ | 0-2 jets | Yes | 3.2 | \tilde{g} | | $ct\tau(NLSP) < 0.1$ mm | 1606.09150 | |
| | GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 20.3 | \tilde{g} | 1.37 TeV | $m(\tilde{\chi}_1^0) < 950$ GeV, $ct\tau(NLSP) < 0.1$ mm, $\mu < 0$ | 1507.05493 | |
| 3 rd gen. squarks & med. | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 36.1 | \tilde{g} | 1.92 TeV | $m(\tilde{\chi}_1^0) < 600$ GeV | ATLAS-CONF-2017-021 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ | 0-1 e, μ | 3 b | Yes | 36.1 | \tilde{g} | 1.97 TeV | $m(\tilde{\chi}_1^0) < 200$ GeV | ATLAS-CONF-2017-021 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} | 1.37 TeV | $m(\tilde{\chi}_1^0) < 300$ GeV | 1407.06000 | |
| | 3 rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 36.1 | \tilde{b}_1 | 950 GeV | $m(\tilde{\chi}_1^0) < 420$ GeV | ATLAS-CONF-2017-038 |
| | | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$ | 2 e, μ (SS) | 1 b | Yes | 36.1 | \tilde{b}_1 | 275-700 GeV | $m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_1^0) + 100$ GeV | ATLAS-CONF-2017-030 |
| | | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$ | 0-2 e, μ | 1-2 b | Yes | 4.7/13.3 | \tilde{t}_1 | 117-170 GeV | $m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^{\pm}), m(\tilde{\chi}_1^{\pm}) = 55$ GeV | 1209.2102, ATLAS-CONF-2016-077 |
| | | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}_1\tilde{t}_1$ | 0-2 e, μ | 0-2 jets/1-2 b | Yes | 20.3/36.1 | \tilde{t}_1 | 90-198 GeV | $m(\tilde{\chi}_1^0) = 1$ GeV | 1506.08616, ATLAS-CONF-2017-020 |
| | | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | \tilde{t}_1 | 90-323 GeV | $m(\tilde{\chi}_1^0) = 5$ GeV | 1604.07773 |
| | | $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_1 | 150-600 GeV | $m(\tilde{\chi}_1^0) < 150$ GeV | 1403.5222 |
| | | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{\chi}_1^0 + Z$ | 3 e, μ (Z) | 1 b | Yes | 36.1 | \tilde{t}_2 | 290-790 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2017-019 |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{\chi}_1^0 + h$ | | 1-2 e, μ | 4 b | Yes | 36.1 | \tilde{t}_2 | 320-880 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2017-019 | |
| EW direct | | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 36.1 | \tilde{t}_1 | 90-440 GeV | $m(\tilde{\chi}_1^0) = 0$ | ATLAS-CONF-2017-039 |
| | | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 36.1 | \tilde{t}_1 | 710 GeV | $m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{t}_1))$ | ATLAS-CONF-2017-039 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 36.1 | \tilde{t}_1 | 760 GeV | $m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{t}_1))$ | ATLAS-CONF-2017-035 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 3 e, μ | 0 | Yes | 36.1 | \tilde{t}_1 | | $m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{t}_1))$ | ATLAS-CONF-2017-039 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 2-3 e, μ | 0-2 jets | Yes | 36.1 | \tilde{t}_1 | 580 GeV | $m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{t}_1))$ | ATLAS-CONF-2017-039 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | e, μ, γ | 0-2 b | Yes | 20.3 | \tilde{t}_1 | 270 GeV | $m(\tilde{\chi}_1^0) = 0, \tilde{t}_1$ decoupled | 1501.07110 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 4 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 | 635 GeV | $m(\tilde{\chi}_1^0) = 0, \tilde{t}_1$ decoupled | 1405.5086 | |
| | GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma G$ | 1 $e, \mu + \gamma$ | - | Yes | 20.3 | \tilde{W} | 115-370 GeV | $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^{\pm}), m(\tilde{\chi}_1^{\pm}) = 0, m(\tilde{t}_1) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{t}_1))$ | 1507.05493 | |
| | GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma G$ | 2 γ | - | Yes | 20.3 | \tilde{W} | 590 GeV | $ct\tau < 1$ mm | 1507.05493 | |
| | Long-lived particles | Direct $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$ prod., long-lived $\tilde{\chi}_1^0$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^0$ | 430 GeV | $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^{\pm}) = 160$ MeV, $\tau(\tilde{\chi}_1^0) = 0.2$ ns | ATLAS-CONF-2017-017 |
| Direct $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$ prod., long-lived $\tilde{\chi}_1^0$ | | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^0$ | 495 GeV | $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^{\pm}) = 160$ MeV, $\tau(\tilde{\chi}_1^0) < 15$ ns | 1506.05332 | |
| Stable, stopped \tilde{g} R-hadron | | 0 | 1-5 jets | Yes | 27.9 | \tilde{g} | 850 GeV | $m(\tilde{\chi}_1^0) = 100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s | 1310.6584 | |
| Stable \tilde{g} R-hadron | | trk | - | - | 3.2 | \tilde{g} | 1.58 TeV | | 1606.05129 | |
| Metastable \tilde{g} R-hadron | | dE/dx trk | - | - | 3.2 | \tilde{g} | 1.57 TeV | | 1604.04520 | |
| GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ | | 1-2 μ | - | Yes | 19.1 | $\tilde{\chi}_1^0$ | 537 GeV | $m(\tilde{\chi}_1^0) = 100$ GeV, $\tau > 10$ ns | 1411.6795 | |
| GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma G$, long-lived $\tilde{\chi}_1^0$ | | 2 e, μ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ | 440 GeV | $1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model | 1409.9542 | |
| $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/\mu\nu$ | | displ. ee/ μ/μ | - | - | 20.3 | $\tilde{\chi}_1^0$ | 1.0 TeV | $7 < \tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV | 1504.05162 | |
| $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ZG$ | | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ | 1.0 TeV | $6 < \tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g}) = 1.1$ TeV | 1504.05162 | |
| RPV | | LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu/\tau/\mu/\tau$ | $e\mu, e\tau, \mu\tau$ | - | - | 3.2 | $\tilde{\nu}_e$ | 1.9 TeV | $\lambda_{111} = 0.11, \lambda_{132/133/233} = 0.07$ | 1607.08079 |
| | Bilinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{g}, \tilde{g} | 1.45 TeV | $m(\tilde{g}) = m(\tilde{g}), ct\tau_{LSP} < 1$ mm | 1404.2500 | |
| | $\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, e\mu\nu, \mu\mu\nu$ | 4 e, μ | Yes | 13.3 | $\tilde{\chi}_1^0$ | 1.14 TeV | $m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ($k = 1, 2$) | ATLAS-CONF-2016-075 | | |
| | $\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu_e, e\nu_e$ | 3 $e, \mu + \tau$ | Yes | 20.3 | $\tilde{\chi}_1^0$ | 450 GeV | $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{133} \neq 0$ | 1405.5086 | | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 0 | 4-5 large- R jets | - | 14.8 | \tilde{g} | 1.08 TeV | $BR(\tilde{g}) = BR(\tilde{b}) = BR(\tilde{c}) = 0\%$ | ATLAS-CONF-2016-057 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 0 | 4-5 large- R jets | - | 14.8 | \tilde{g} | 1.55 TeV | $m(\tilde{\chi}_1^0) = 800$ GeV | ATLAS-CONF-2016-057 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 1 e, μ | 8-10 jets/0-4 b | - | 36.1 | \tilde{g} | 2.1 TeV | $m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{112} \neq 0$ | ATLAS-CONF-2017-013 | |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 1 e, μ | 8-10 jets/0-4 b | - | 36.1 | \tilde{g} | 1.65 TeV | $m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{123} \neq 0$ | ATLAS-CONF-2017-013 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$ | 0 | 2 jets + 2 b | - | 15.4 | \tilde{t}_1 | 410 GeV | $BR(\tilde{t}_1 \rightarrow b\tilde{e}/\mu) > 20\%$ | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084 | |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}$ | 2 e, μ | 2 b | - | 36.1 | \tilde{t}_1 | 0.4-1.45 TeV | | ATLAS-CONF-2017-036 | |
| Other | Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$ | 0 | 2 c | Yes | 20.3 | \tilde{c} | 510 GeV | $m(\tilde{\chi}_1^0) < 200$ GeV | 1501.01325 | |

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

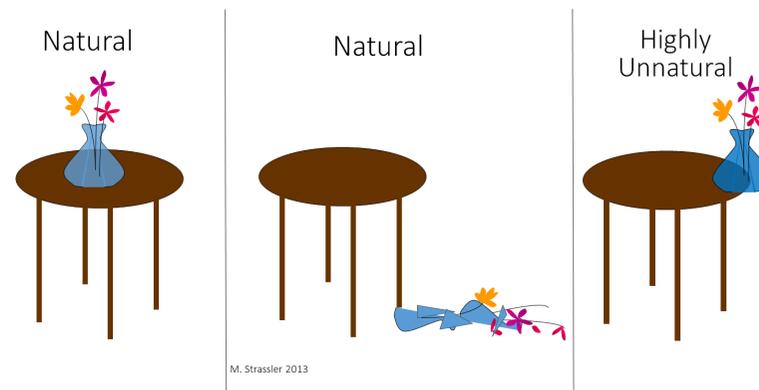
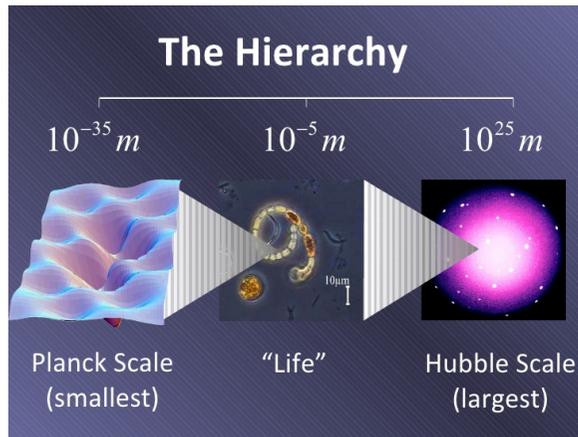
Guidelines from LHC results

- The Standard Model is doing amazingly well
- The Higgs scalar is very much like expected in the Standard Model
- There is no indication of physics BSM up to scales of the order of 1 to 3 TeV

however

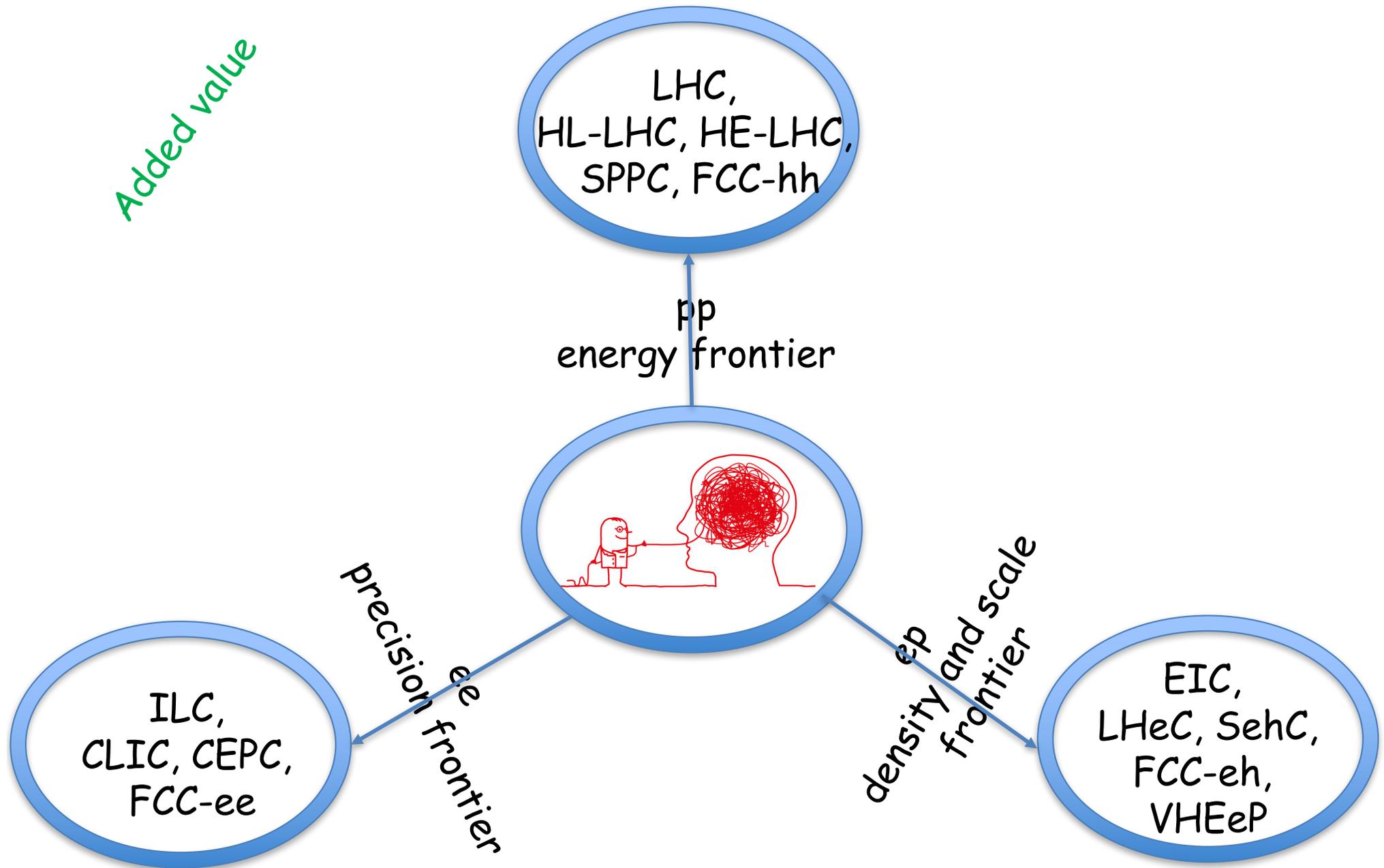
Guidelines from outside LHC

- Neutrinos have masses (oscillations) - not acquired in the SM
- There is dark matter in the Universe with no candidates within the SM (axions???)
- There are theoretical arguments that theory is not complete



How should we go about understanding all these issues ?

Controlled experiments at accelerators



Energy frontier

- Hadron colliders

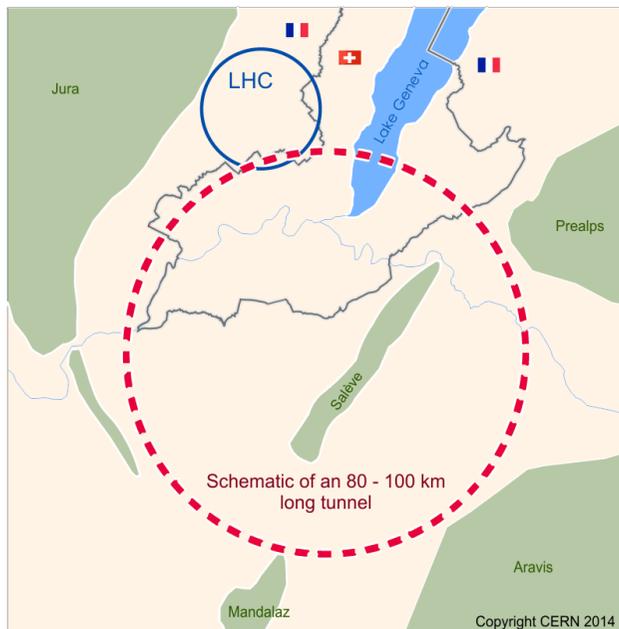
CERN: HE - LHC, pp 28 TeV - replace dipoles with 16 T HTS Nb₃Sn → 20 T

CERN: FCC - pp 100 TeV, 80 to 100 km tunnel, 16 to 20 T magnets

China: SppC - pp 35 to 65 TeV, 60 km to 100 km tunnel with 12 T HTS → 24 T

US: SSC - pp 100 to 300 TeV, 270 km tunnel, 5 T to 15 T magnets

Geneva



Qinghuada

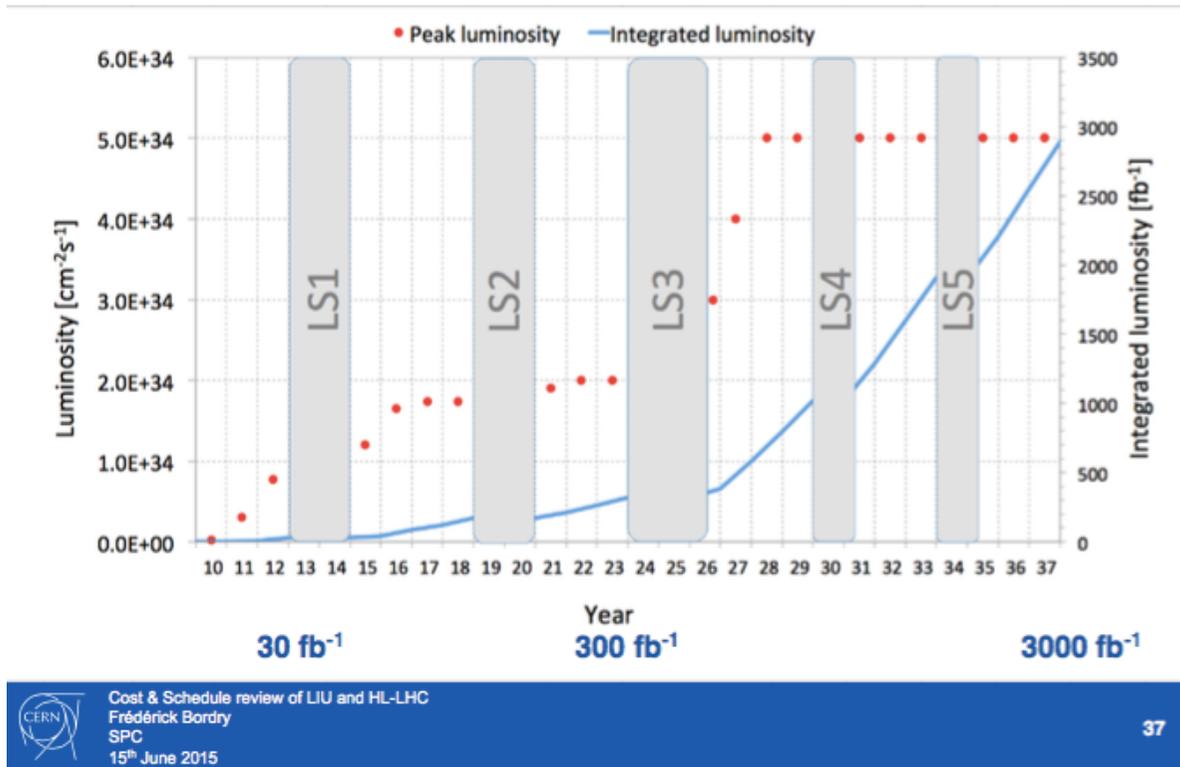


Energy Frontiers

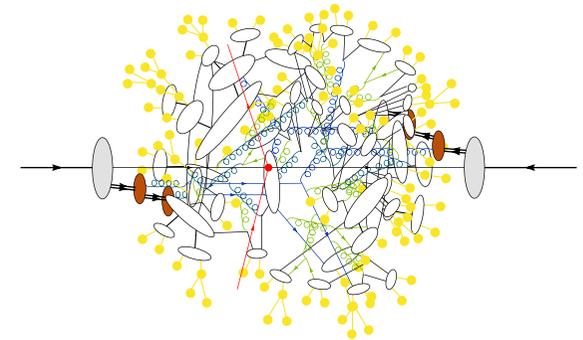
pp interactions are not very efficient energy-wise but no-alternative

At 14 TeV and 3 ab⁻¹ mass reach < 10 TeV

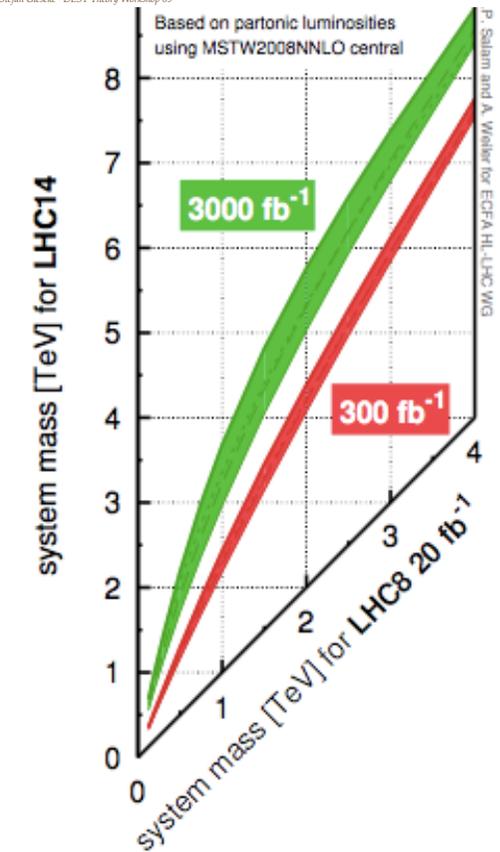
Integrated luminosity



pp Event Generator

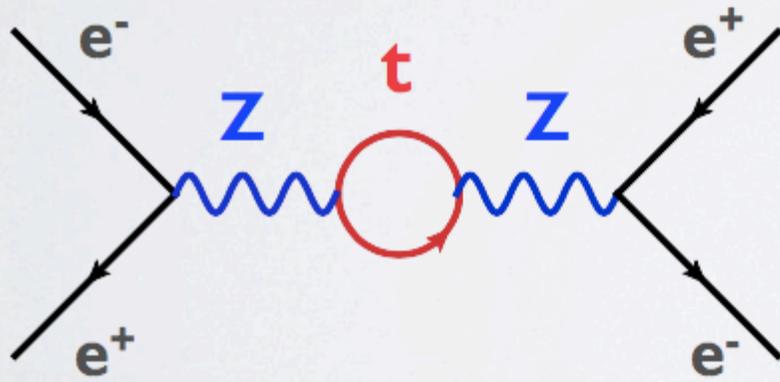


Stefan Gieseke - DESY Theory Workshop 09



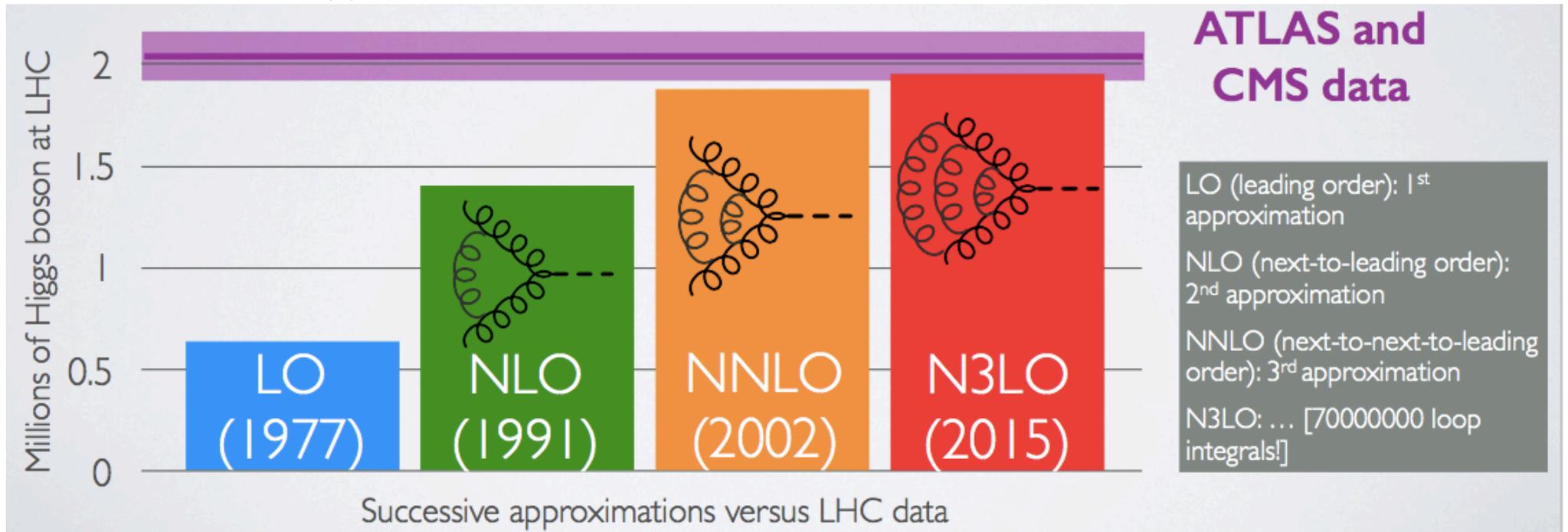
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Precision Frontier



- Mass of the top quark from *indirect* determinations at LEP1 and SLC in 1993: $m_{\text{top}} = (177 \pm 10) \text{ GeV}$
- First *direct* production at the Tevatron in 1994: $m_{\text{top}} = (174 \pm 16) \text{ GeV}$

In contrast to $pp \rightarrow H + X$



Precision frontier

- Electron-positron machines

Kitakami: ILC - linear collider, 250 GeV baseline (up to 31 km, expandable to 1 TeV)

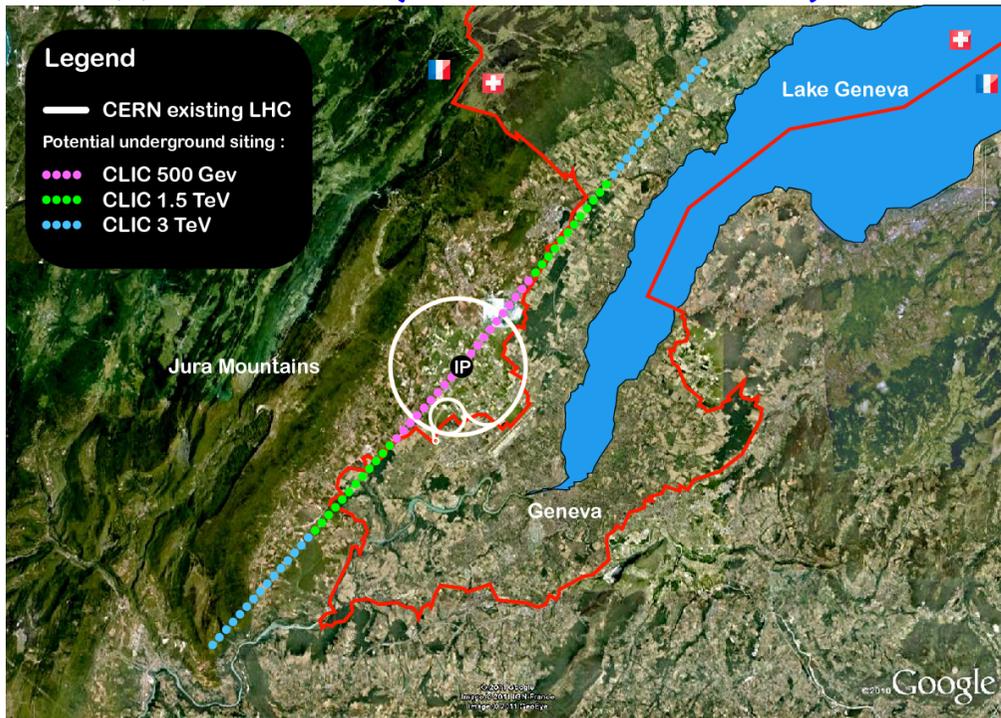
CERN: CLIC - linear collider, 380 GeV to 3 TeV (up to 50 km)

CERN: FCC ee - circular collider, 240 to 350 GeV

China: CEPC - circular collider, 240 GeV

US: SSC - resurrected 87 km tunnel for circular Higgs factory

- $\gamma\gamma$ colliders (derivatives of ee)



ILC Candidate site in Kitakami, Tohoku

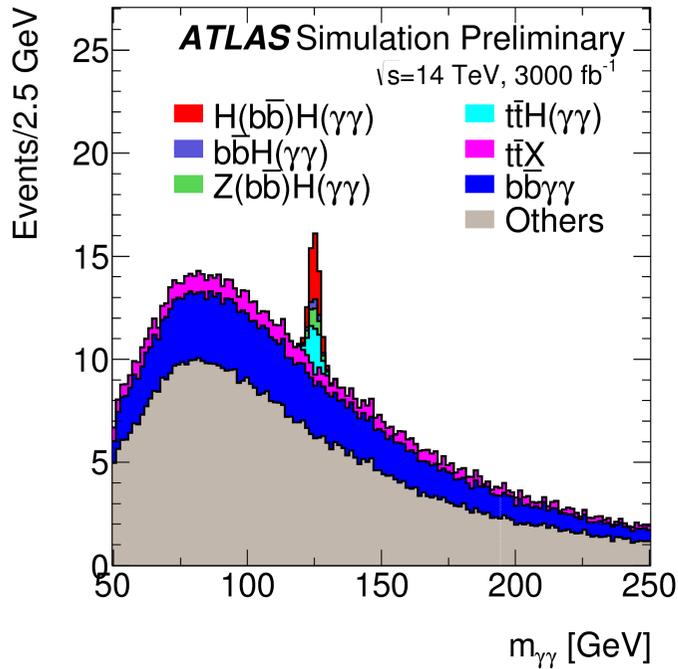


ILC (upgrade)
 31km (50km), 30V/m (45V/m)
 500 GeV (1 TeV)

Accelerating structures 72 to 100 MV/m

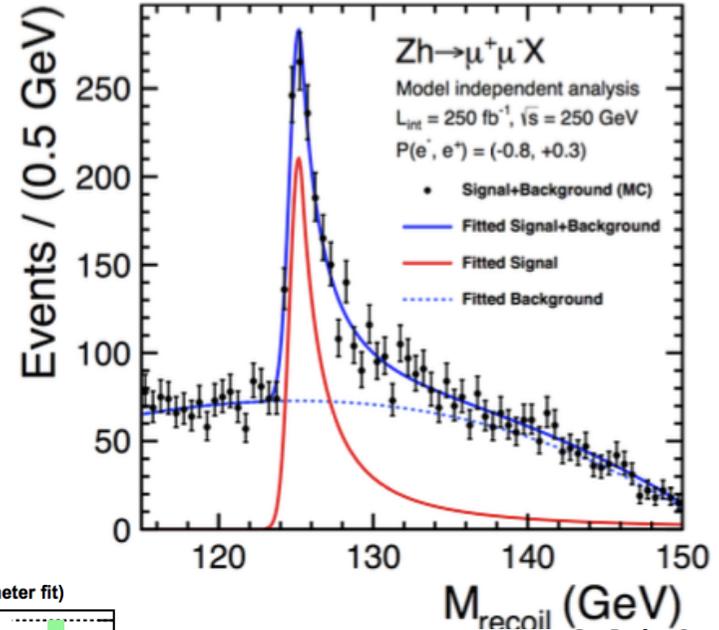
Precision Frontier

Precision Higgs/top physics

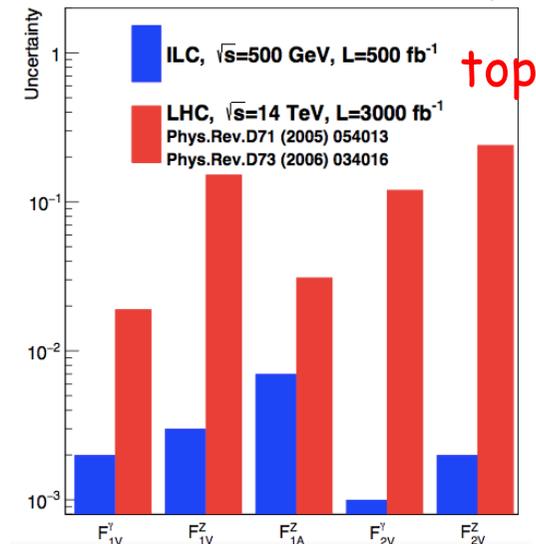
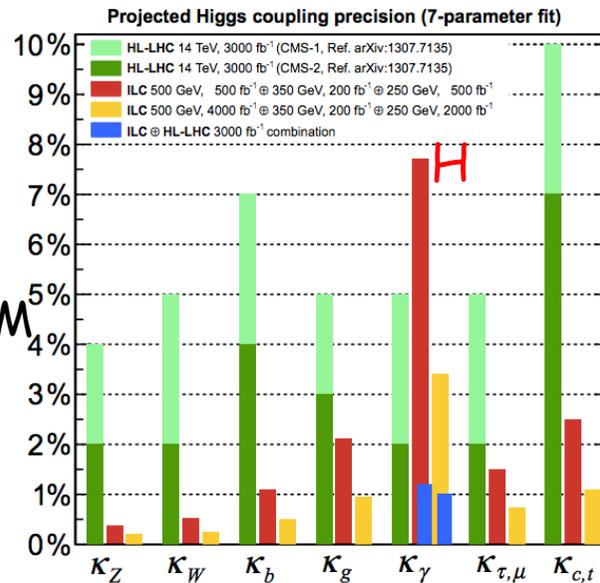


HL-LHC

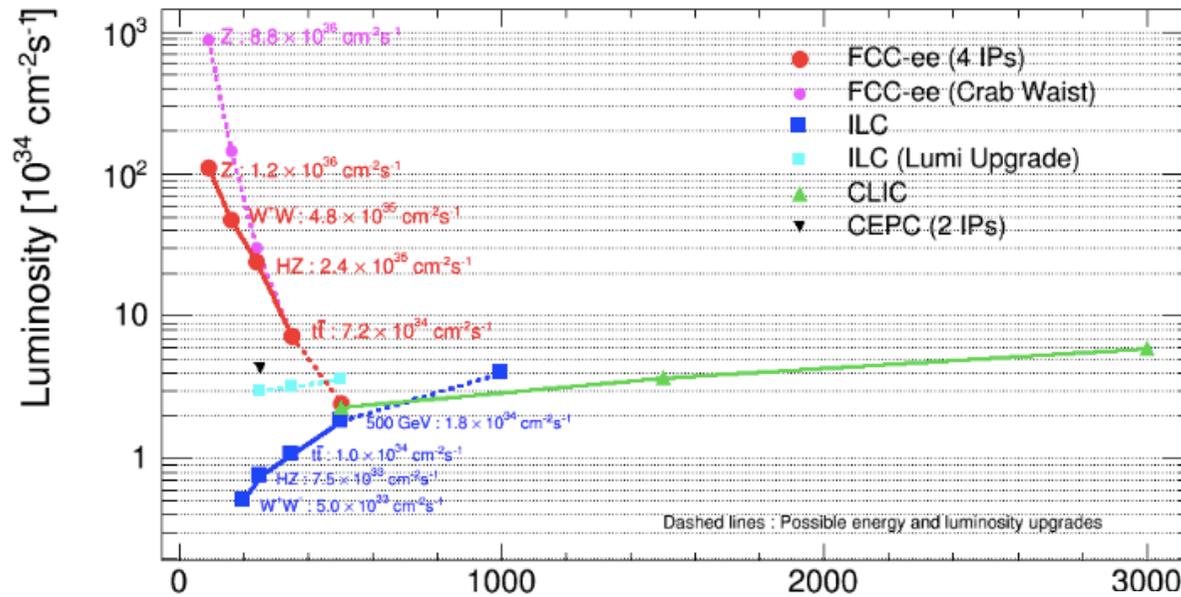
ILC



Higgs couplings - sensitive to BSM
 ILC below 1%, except $\gamma\gamma$
 LHC 2% to 3% except $bb \ cc \ tt$



Precision Frontier



Luminosity vs energy for ee colliders

Comparison of expected Precision on H couplings

| Coupling vs (TeV) → L (fb ⁻¹) → | LHC 14 3000(1 expt) | CepC 0.24 5000 | FCC-ee 0.24+0.35 13000 | ILC 0.25+0.5 6000 | CLIC 0.38+1.4+3 4000 | FCC-hh 100 40000 |
|--|---------------------------|-----------------------------|------------------------------|-------------------------|----------------------------|------------------------|
| K_W | 2-5 | 1.2 | 0.19 | 0.4 | 0.9 | |
| K_Z | 2-4 | 0.26 | 0.15 | 0.3 | 0.8 | |
| K_g | 3-5 | 1.5 | 0.8 | 1.0 | 1.2 | |
| K_γ | 2-5 | 4.7 | 1.5 | 3.4 | 3.2 | < 1 |
| K_μ | ~8 | 8.6 | 6.2 | 9.2 | 5.6 | ~ 2 |
| K_c | -- | 1.7 | 0.7 | 1.2 | 1.1 | |
| K_t | 2-5 | 1.4 | 0.5 | 0.9 | 1.5 | |
| K_b | 4-7 | 1.3 | 0.4 | 0.7 | 0.9 | |
| K_{ZY} | 10-12 | n.a. | n.a. | n.a. | n.a. | |
| Γ_h | n.a. | 2.8 | 1. | 1.8 | 3.4 | |
| BR_{invis} | <10 | <0.28 | <0.19 | <0.29 | <1 | |
| K_t | 7-10 | -- | 13% ind. tt scan | 6.3 | <4 | ~ 1 ? |
| K_{HH} | ? | 35% from K_Z model-dep | 20% from K_Z model-dep | 27 | 11 | 5-10 |

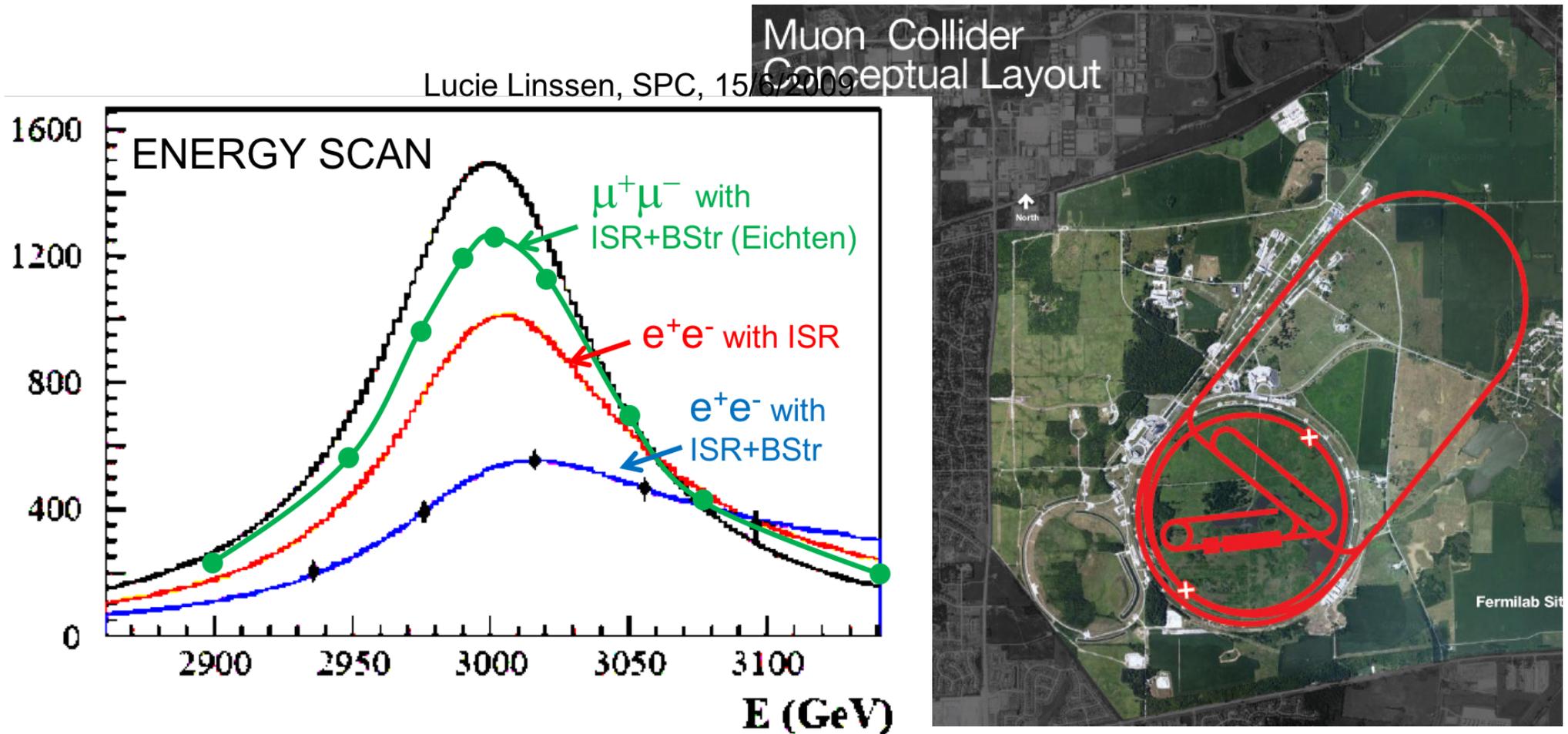
Units are %

summary table from Fabiola Gianotti LP15

Precision Frontier - muon collider

- Muon collider - Higgs factory and energy frontier

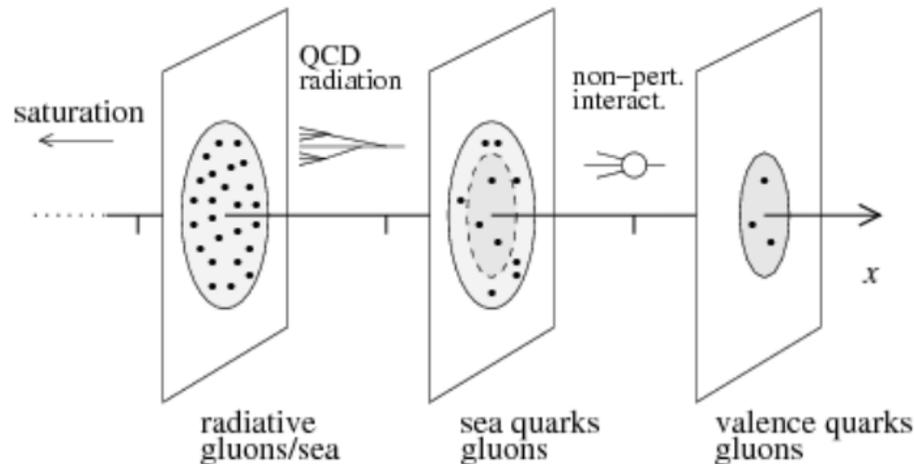
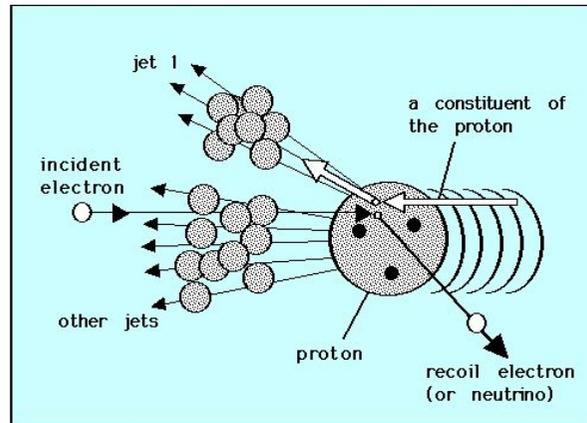
Circular collider - 120 GeV to 5 TeV, 300 m long (neutrino factory as added bonus)



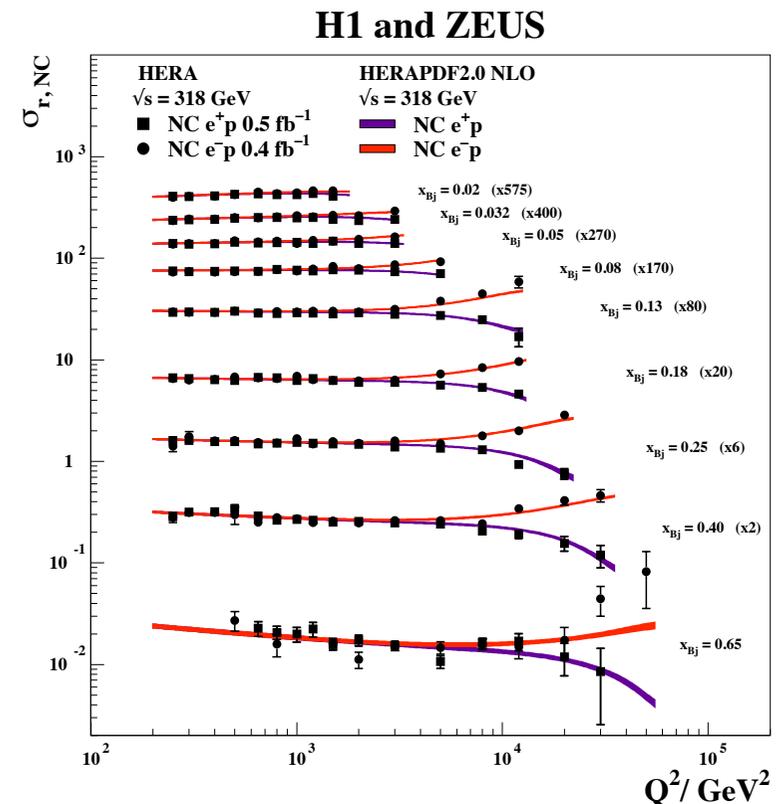
Challenges: to produce enough muons, cool them and compress the beam and all very fast

Density frontier and more

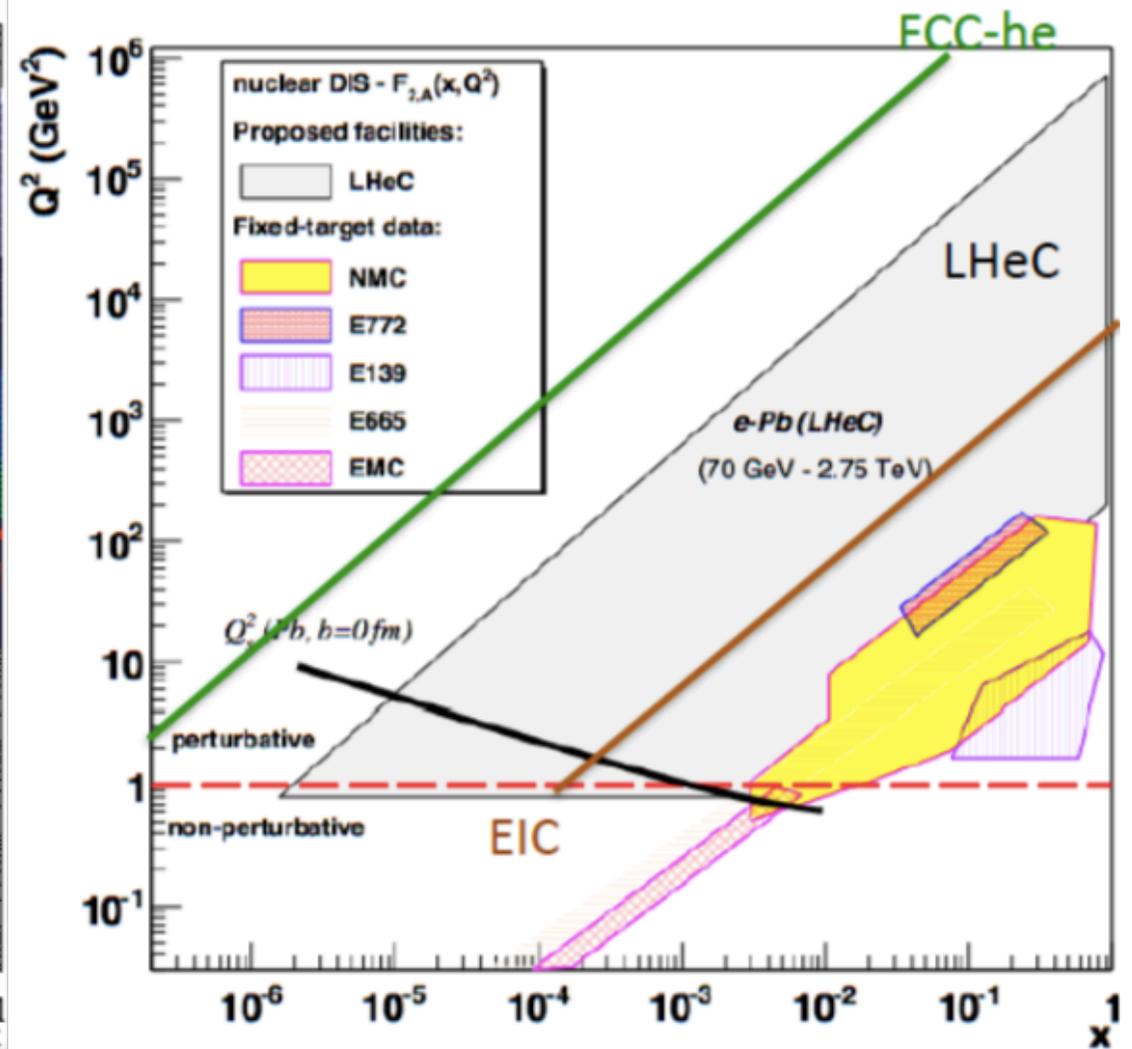
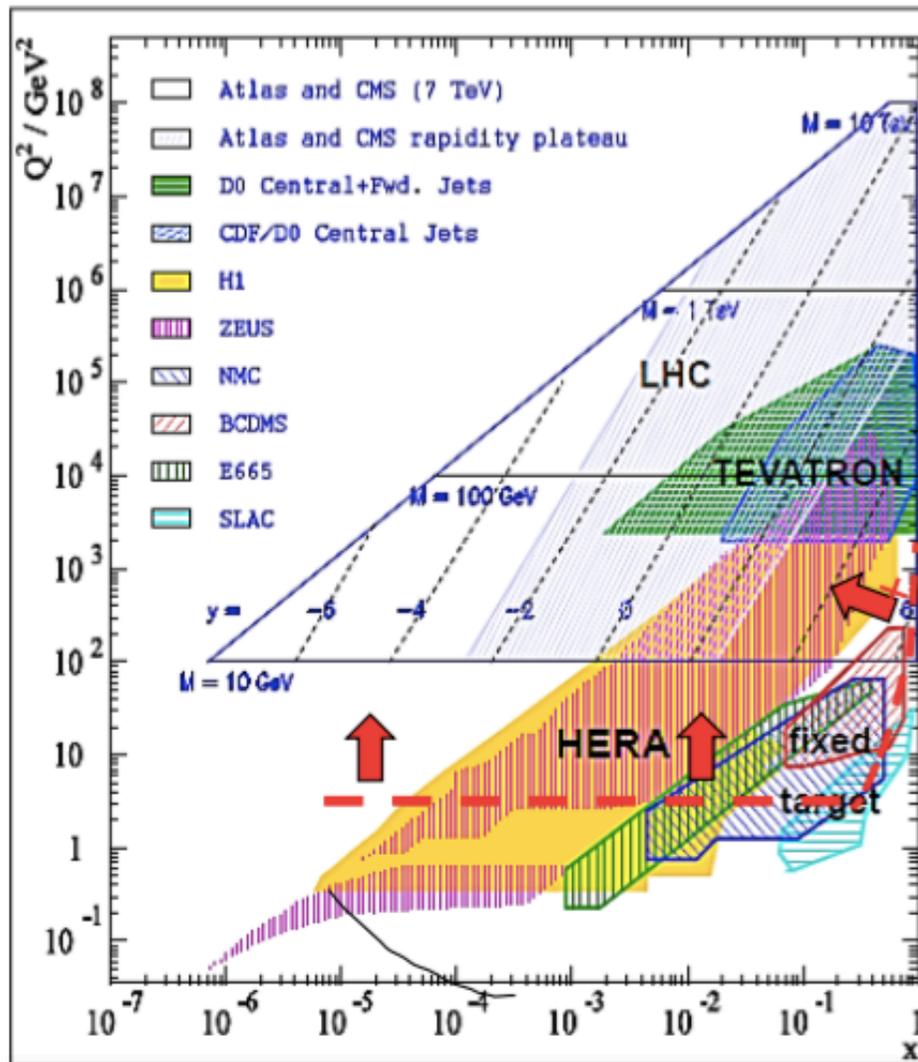
- Proton - composite object consisting of quarks and gluons
- only **5%** of its mass is generated through the Higgs mechanism
 - **95%** of its mass is due to **QCD**
 - structure cannot be calculated (yet) from first principles



Legacy of ep collider HERA

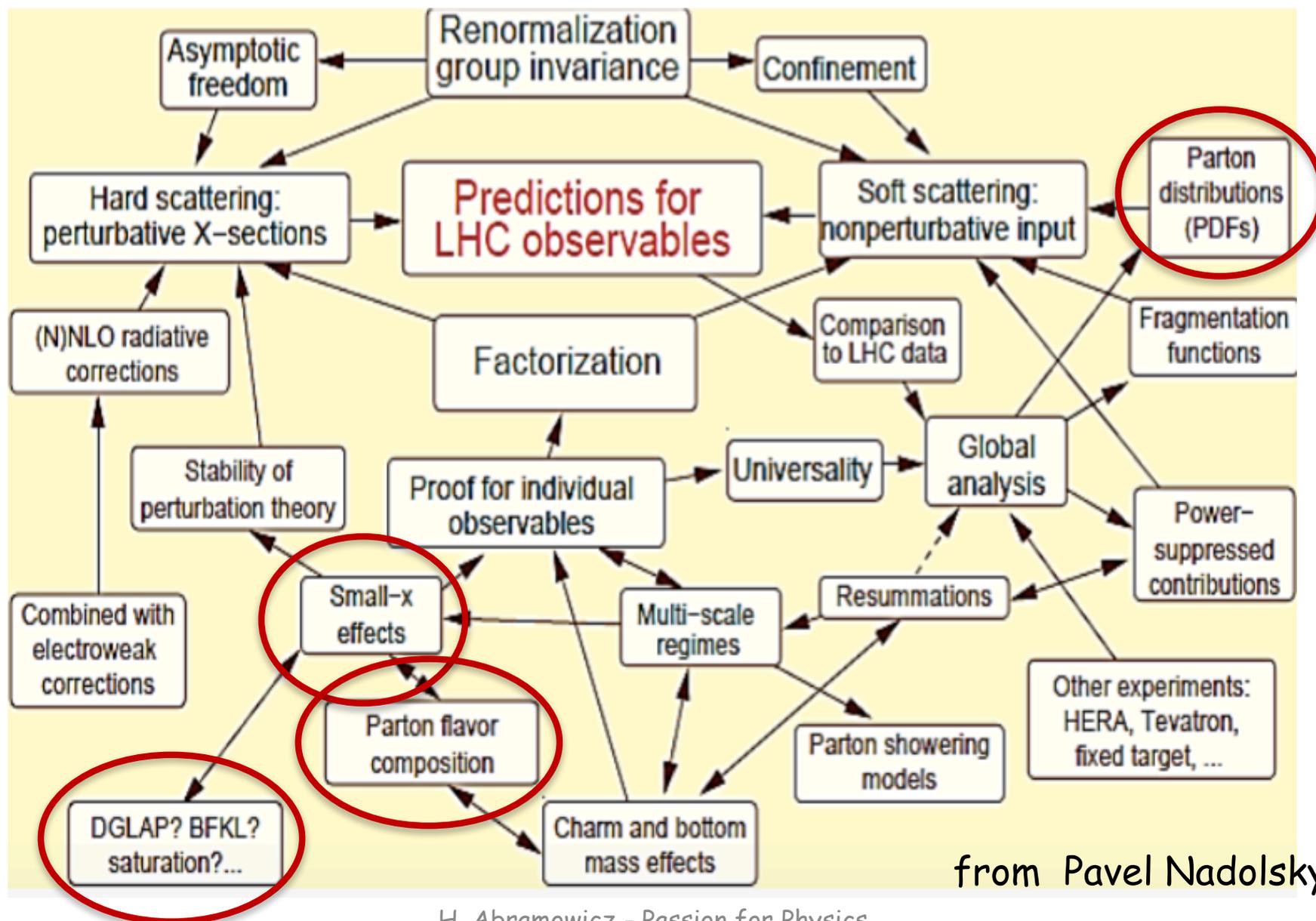


Density frontier and more



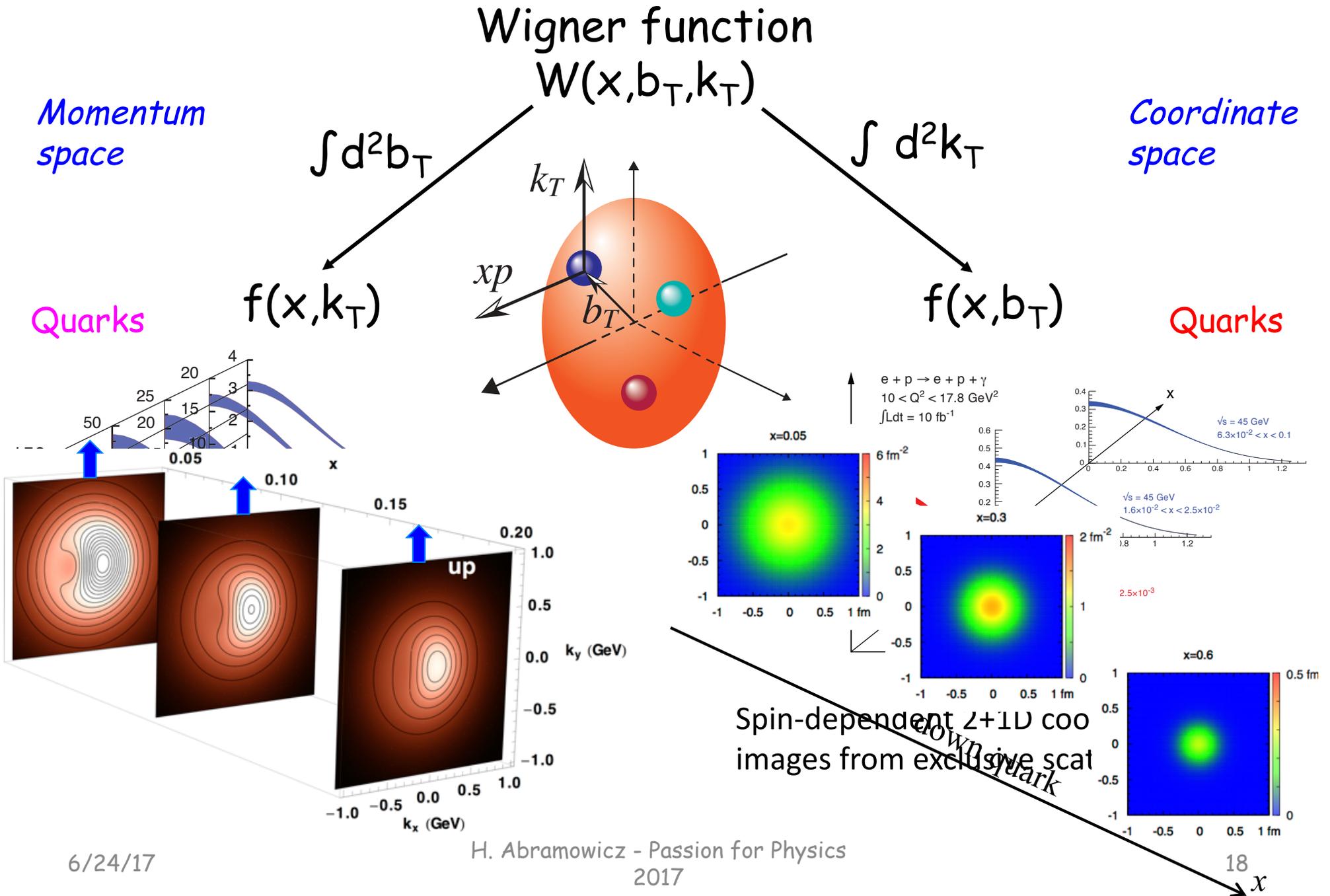
Proton structure and QCD

What it takes to get SM predictions for LHC



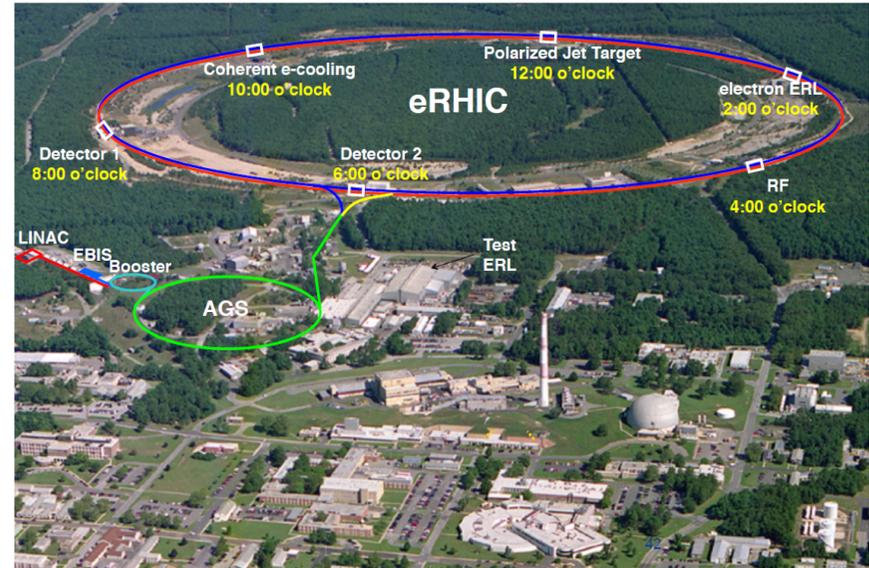
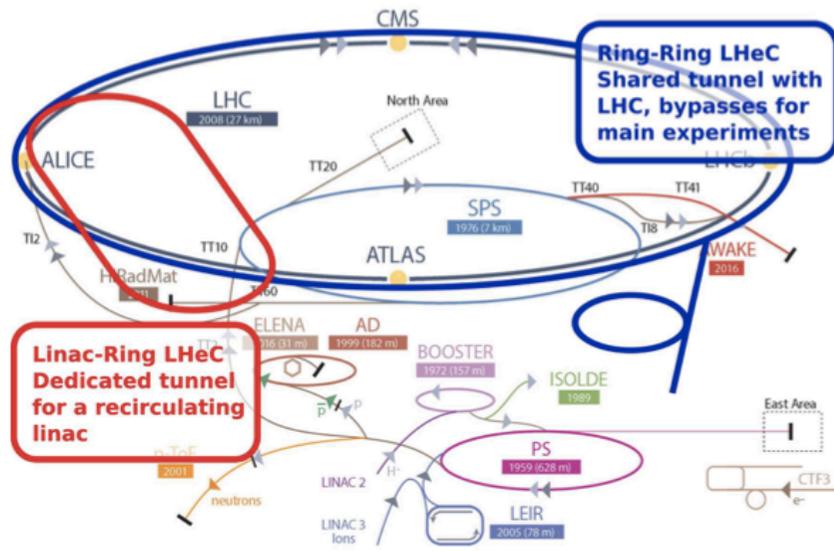
from Pavel Nadolsky

2+1 dimensional Imaging of Quarks & Gluons

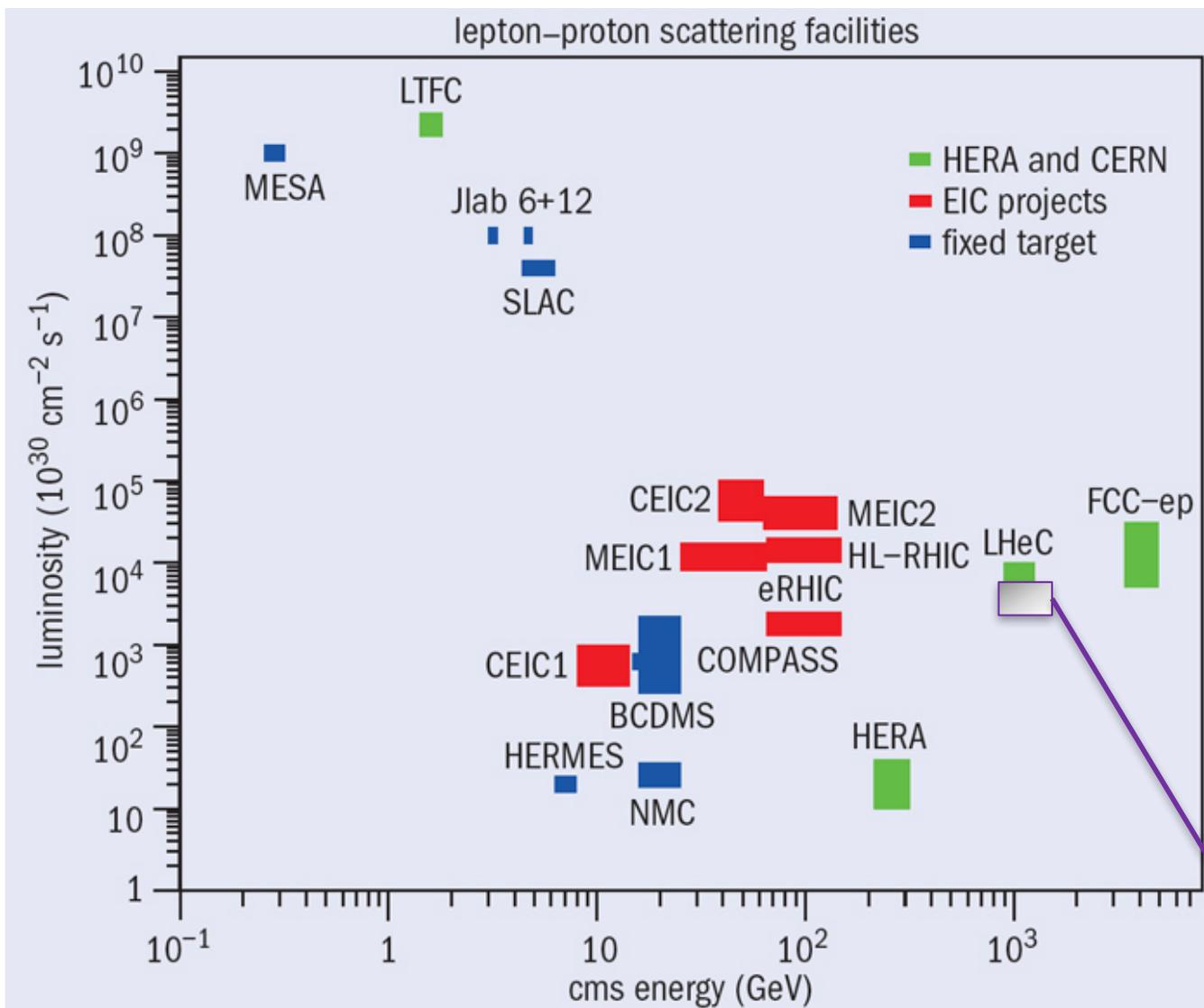


ep/eA colliders

Ring-Ring or (Energy Recovery) Linac-Ring



ep/eA colliders



CEIC1 = Chinese version of Electron-Ion Collider
 ("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

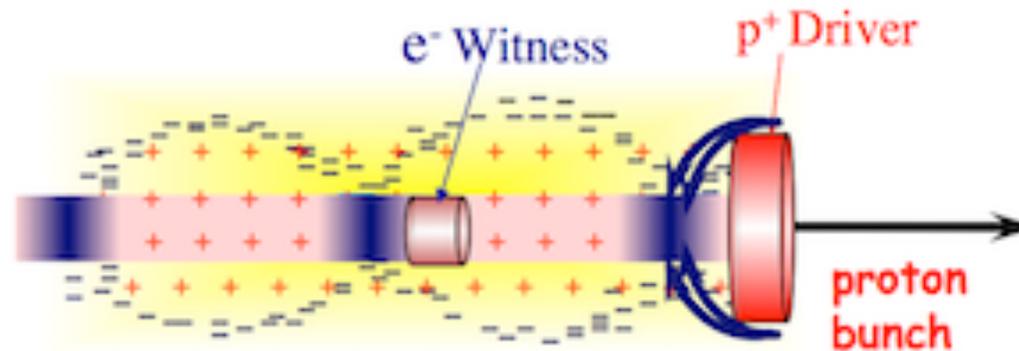
LHeC = ep/eA collider @ CERN

CEIC2
 MEIC2
 HL-eRHIC
 FCC-he

SehC

New Accelerator Technologies

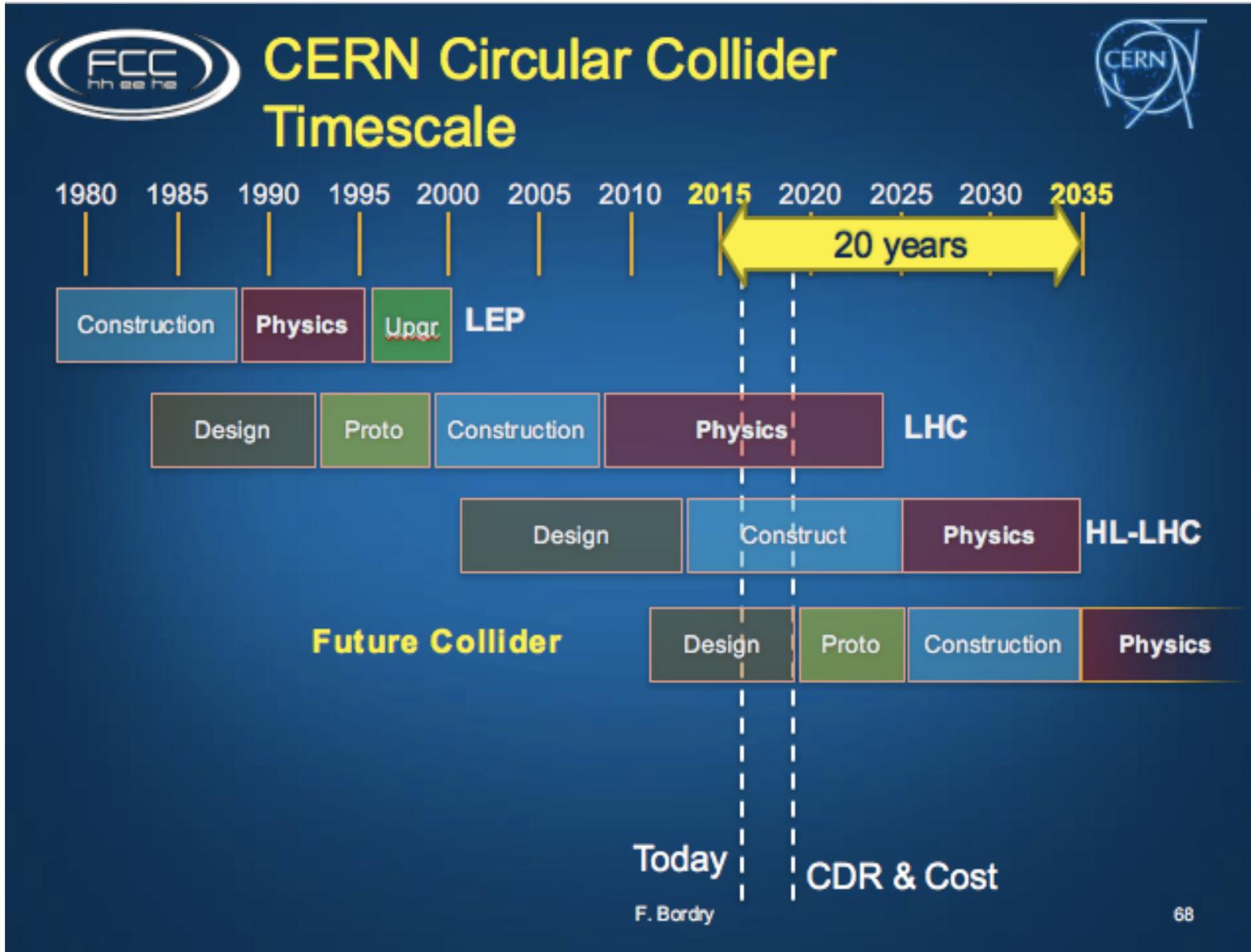
- Accelerators using RF cavities limited to ~ 100 MV/m; high energies \Rightarrow long accelerators
- Gradients in plasma wakefield acceleration of ~ 100 GV/m measured



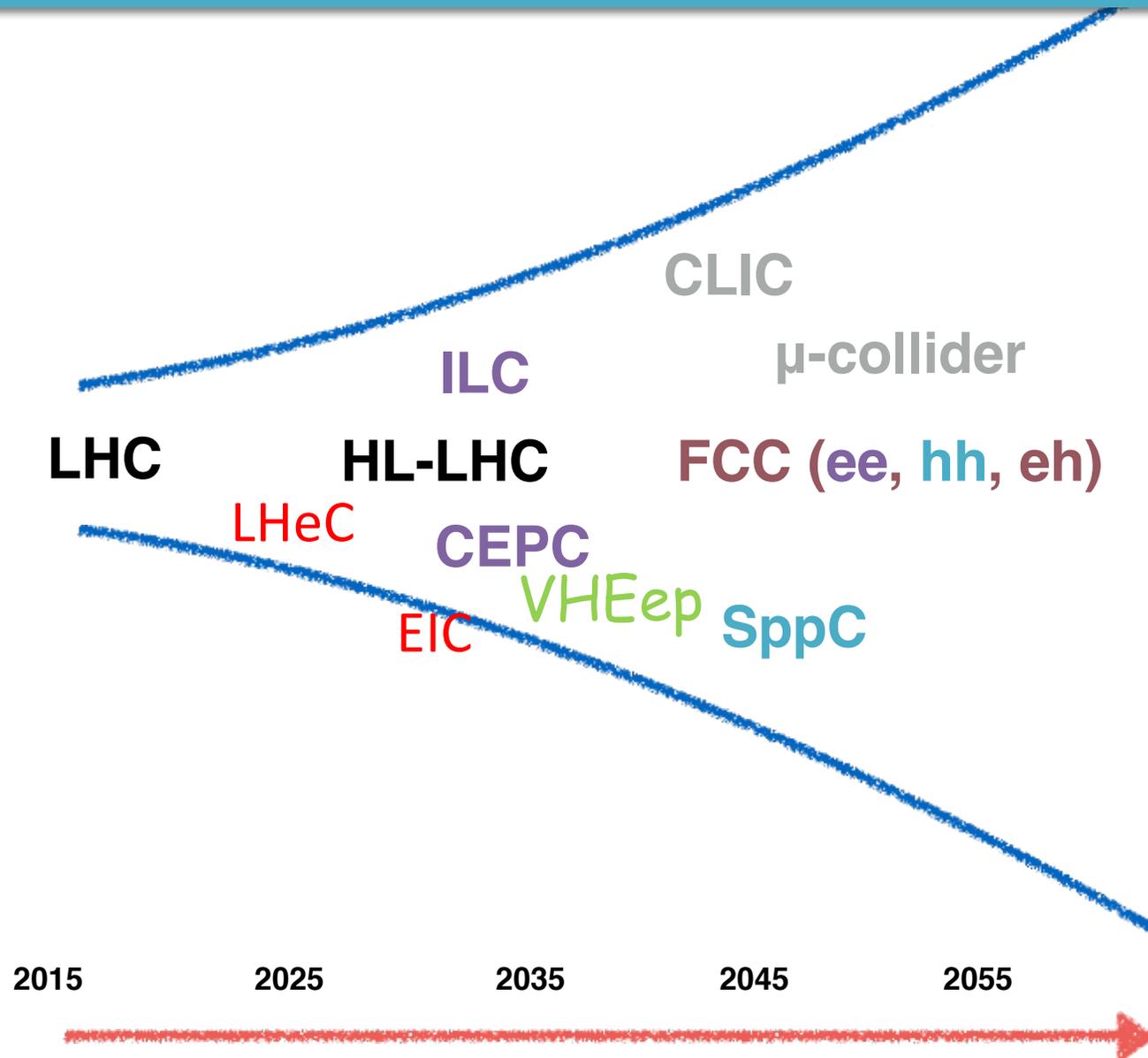
- ❖ ILC-CLIC, 0.5 TeV bunch with $2 \times 10^{10} e^-$ - about 1.6 kJ
- ❖ SPS, 400 GeV bunch with $10^{11} p$ - about 6.4 kJ
- ❖ LHC, 7 TeV - 112 kJ
- ❖ A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage
- ❖ Large average gradient (> 1 GV/m, 100's m)

Proof of principle under way at the SPS at CERN

Time scales



Colliders of the 21st Century

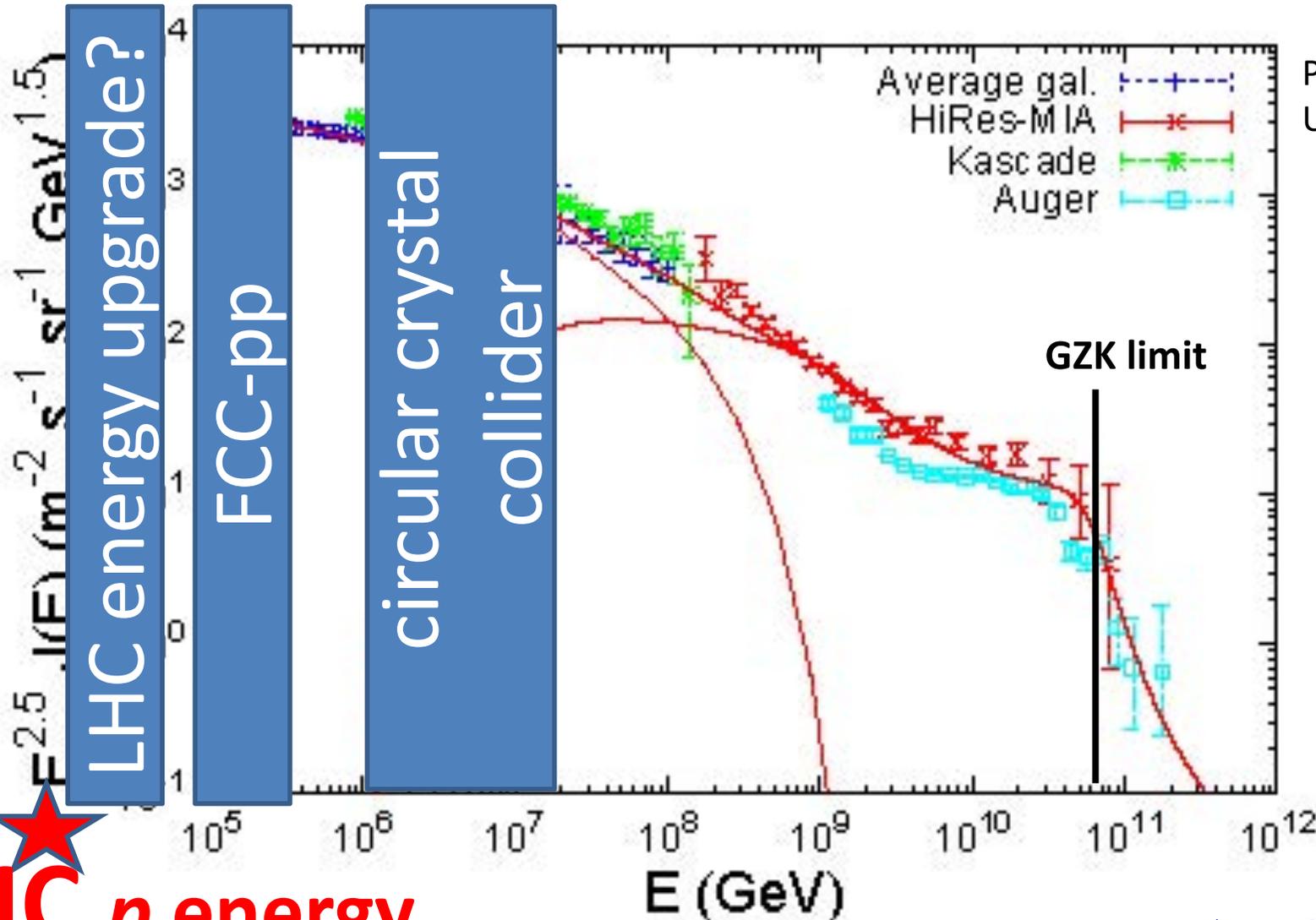


European Strategy 2013 - next update 2020

- Europe's top priority should be the exploitation of the full potential of **the LHC**, including the **high-luminosity upgrade** of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. (HL-LHC)
- CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator R&D programme (CLIC, FCC hh,ee,ep ... AWAKE)
- There is a strong scientific case for **an electron-positron collider**... The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation... Europe looks forward to a proposal from **Japan** to discuss a possible participation. (Waiting for Japanese Gov. decision)
- CERN should develop a **neutrino programme** to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects **in the US** and Japan. (LBNF in FNAL - DUNE in S. Dakota)

$10^{45} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{1.5}!$

cosmic-ray energy spectrum



P. Blasi,
UHECR2012

LHC p energy

6/24/17

H. Abramowicz - Passion for Physics
2017

$\times 10^8$

25

Outlook

- The community is busy thinking about the future, driven by the physics case
- Many exciting developments
- The timelines of the various projects very uncertain
 - Technology issues
 - Funding issues
- **HL-LHC approved**
- **For the near future EIC looks like the most realistic project**
- Expect heated discussions during the ESU



If curious why HEP should be supported
feel invited to
Special ECFA-EPS/HEPP session
"Particle Physics and Society:
Extending our Vision and Reach"
July 8th, afternoon

The European Physical Society Conference on High Energy Physics (EPS-HEP) is one of the major international conferences that reviews the field every second year since 1971. It is organized by the High Energy and Particle Physics Division of the European Physical Society. The latest conferences in this series were held in Vienna, Stockholm, Grenoble, Krakow, Manchester, Lisbon and Aachen.

In 2017 the EPS-HEP will take place in Venice, Italy on 5-12 July. The conference is organized by Istituto Nazionale di Fisica Nucleare (INFN) and the Department of Physics and Astronomy of the Padua University.