

Perspectives in High Energy Physics

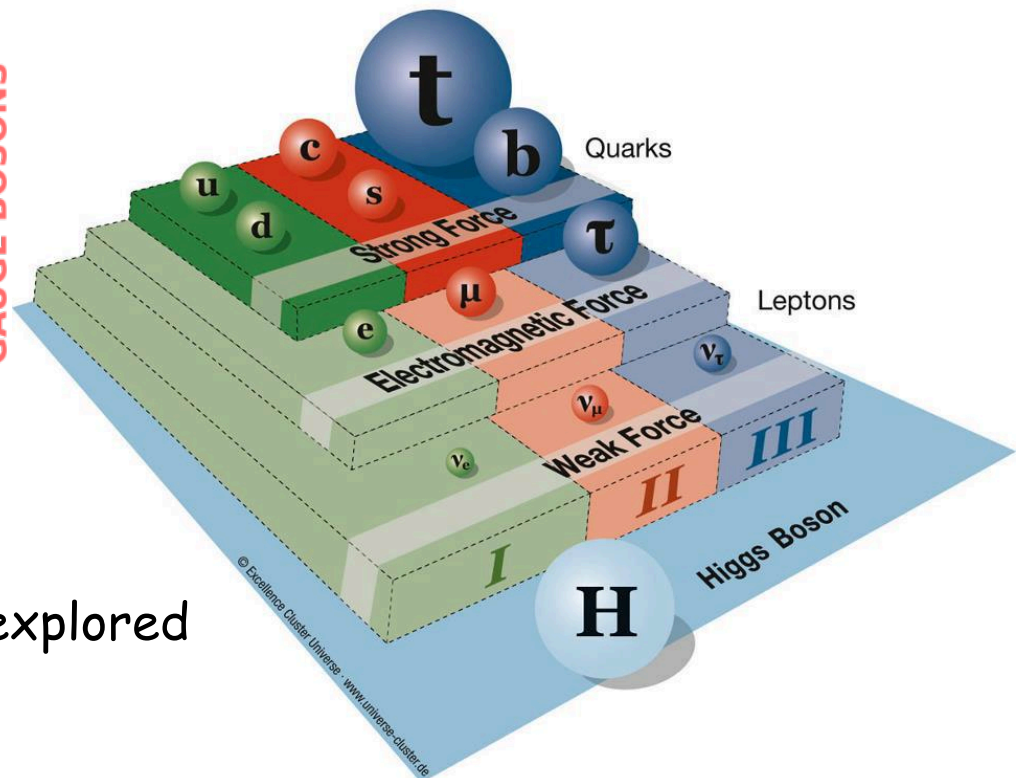
Halina Abramowicz
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- Status of Standard Model of particle physics
- What is missing?
- Future options

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	
LEPTONS	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	
GAUGE BOSONS	<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	

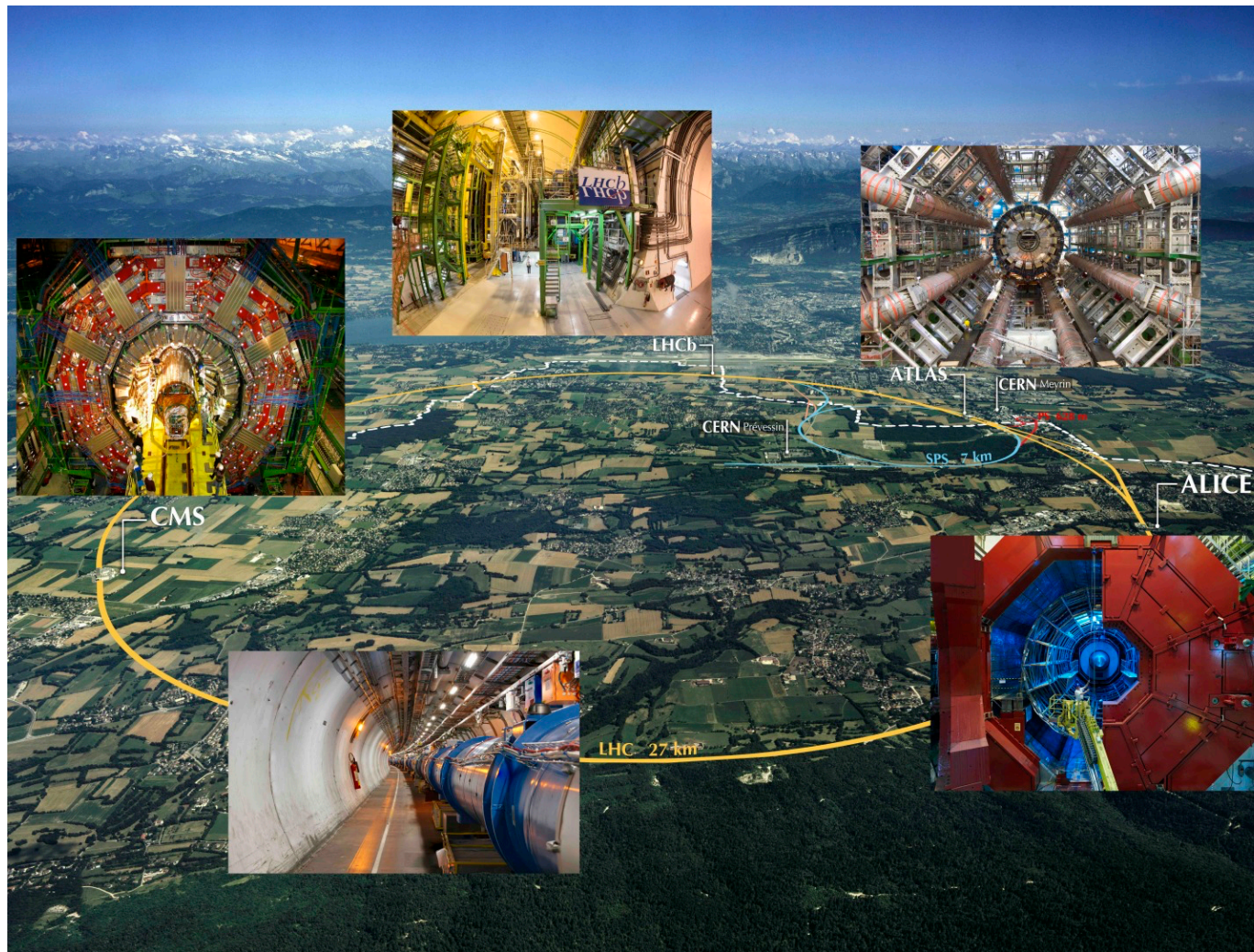


Higgs sector and top sector largely unexplored

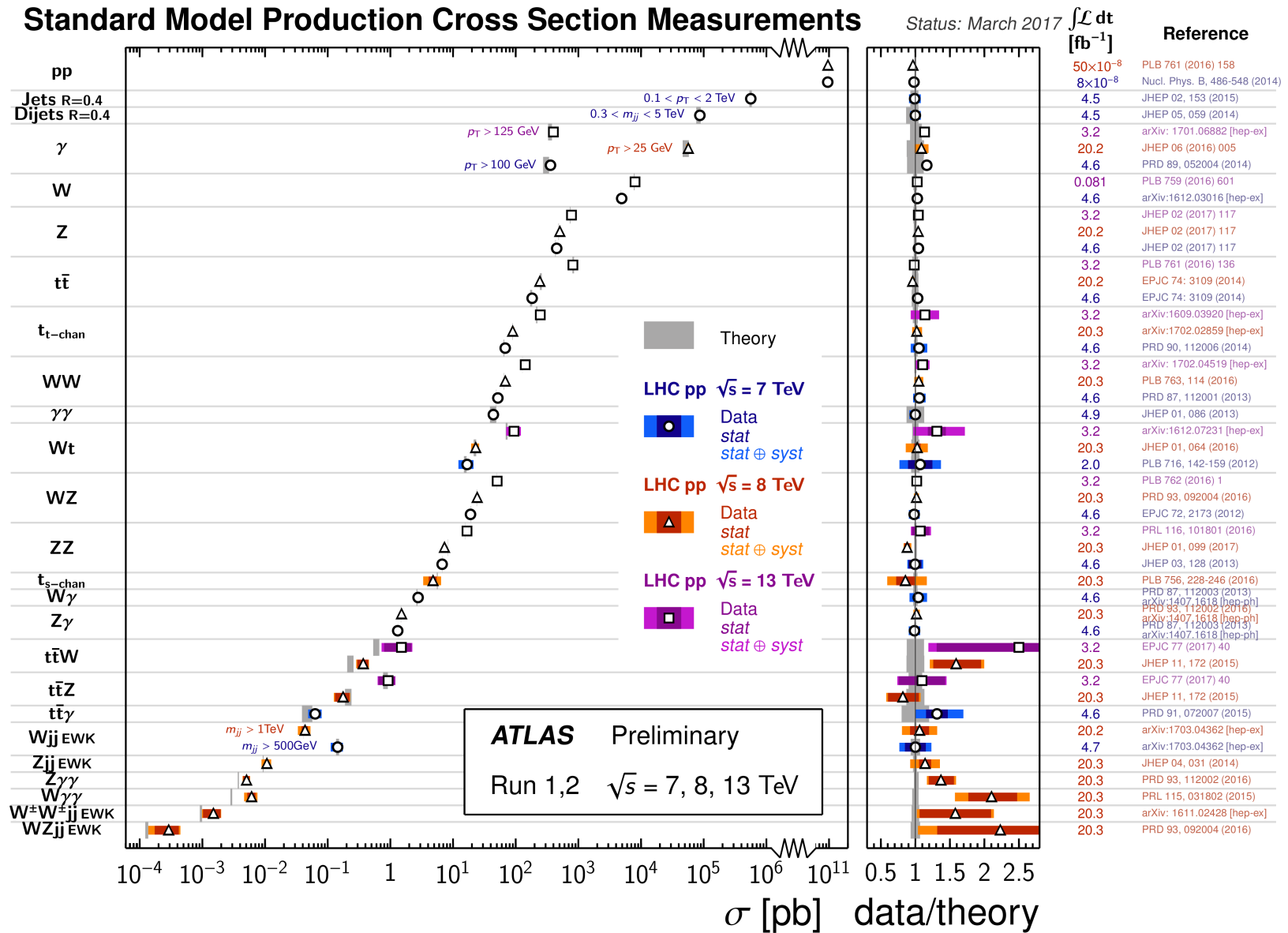
Present Energy Frontier - Large Hadron Collider at CERN

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

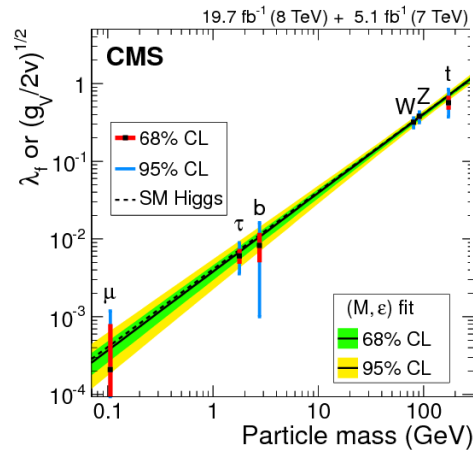
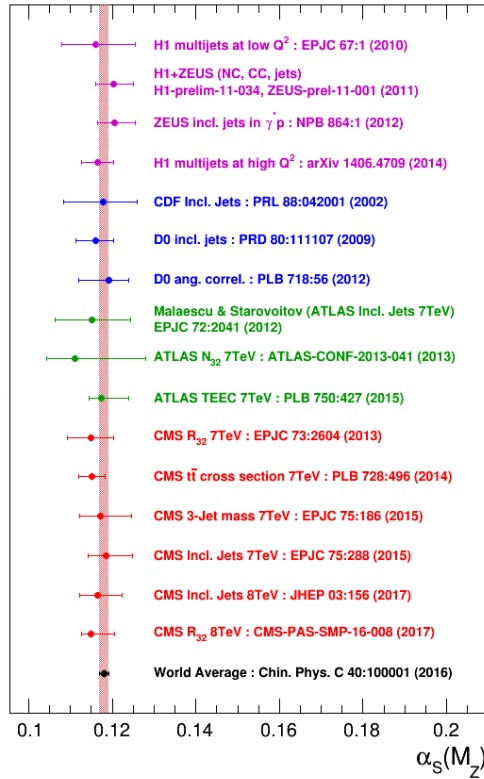
Collected pp data: 7TeV (2010/2011); 8TeV (2012); 13TeV (2015-now)



Stress test of SM at the LHC



Stress test of SM at the LHC



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

Model	e, μ, τ, γ	Jets	E_{miss}^T	$\int \mathcal{L} d(\sqrt{s})^{-1}$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	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	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	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	$m(\tilde{q})=m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^0)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\ell\ell/\nu\nu\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.825 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ/\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2017-033
	GMSB (if NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV	$\tau\tau(\text{NLSP}) < 0.1 \text{ mm}$	1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$m(\tilde{\chi}_1^0) < 950 \text{ GeV}, \tau\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) > 680 \text{ GeV}, \tau\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	1507.05493
3 rd gen. squarks	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$	ATLAS-CONF-2016-066
	Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}/1/2 \text{ scale}$	865 GeV	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	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	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	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	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1407.0600
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{\chi}_1^0) < 420 \text{ GeV}$	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0)+100 \text{ GeV}$	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	200-720 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$	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	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	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	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1604.07773
EW direct	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	ATLAS-CONF-2017-019
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	\tilde{t}_1	90-440 GeV	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	\tilde{t}_1	710 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1)+m(\tilde{t}_2))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 τ	0	Yes	36.1	\tilde{t}_1	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{t}_1, \tilde{t}_2) = 0.5(m(\tilde{t}_1)+m(\tilde{t}_2))$	ATLAS-CONF-2017-035
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	3 e, μ	0	Yes	36.1	\tilde{t}_1	1.16 TeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{t}_1, \tilde{t}_2)=0.5(m(\tilde{t}_1)+m(\tilde{t}_2))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	\tilde{t}_1	580 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, \tilde{t}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow W\tilde{b}\tilde{\chi}_1^0$	e, μ, γ	0-2 b	Yes	20.3	\tilde{t}_1	270 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, \tilde{t}$ decoupled	1501.07110
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_1 \rightarrow W\tilde{b}\tilde{\chi}_1^0$	4 e, μ	0	Yes	20.3	\tilde{t}_1	635 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{t}_1, \tilde{t}_2)=0.5(m(\tilde{t}_1)+m(\tilde{t}_2))$	1405.5086
Long-lived particles	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$\tau < 1 \text{ mm}$	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	590 GeV	$\tau < 1 \text{ mm}$	1507.05493
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^0$	430 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^0)=0.2 \text{ ns}$	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^0$	495 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) < 15 \text{ ns}$	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	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	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, \tau > 10 \text{ ns}$	1604.04520
	GMSB, stable $\tilde{t}_1, \tilde{\chi}_1^0 \rightarrow \tilde{t}(\tilde{t}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	\tilde{t}_1	537 GeV	$10 < \text{tan}\beta < 50$	1411.7795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$	displ. $e\bar{e}/\mu\bar{\mu}$	-	-	20.3	\tilde{g}	1.0 TeV	$7 < \tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162
RPV	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	\tilde{g}	1.0 TeV	$6 < \tau(\tilde{\chi}_1^0) < 480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\mathcal{L}_{111} = 0.11, A_{132/133/233} = 0.07$	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{g}	1.45 TeV	$m(\tilde{g}) = m(\tilde{g}), \tau_{\text{LSP}} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu, e\bar{\nu}\mu, \mu\bar{\mu}\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^0$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, A_{124} \neq 0 (k = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\bar{\tau}\nu_e, e\bar{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^0$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^0), A_{133} \neq 0$	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	$\text{BR}(\tilde{g})=\text{BR}(\tilde{g})=\text{BR}(\tilde{g})=0\%$	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	$m(\tilde{\chi}_1^0) = 800 \text{ GeV}$	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	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, A_{112} \neq 0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow b\tilde{b}\tilde{\chi}_1^0$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, A_{123} \neq 0$	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	$\text{BR}(\tilde{t}_1 \rightarrow b\tilde{e}/\mu) > 20\%$	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
Other	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	0.4-1.45 TeV		ATLAS-CONF-2017-036
	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

10⁻¹

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Mass scale [TeV]

*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.

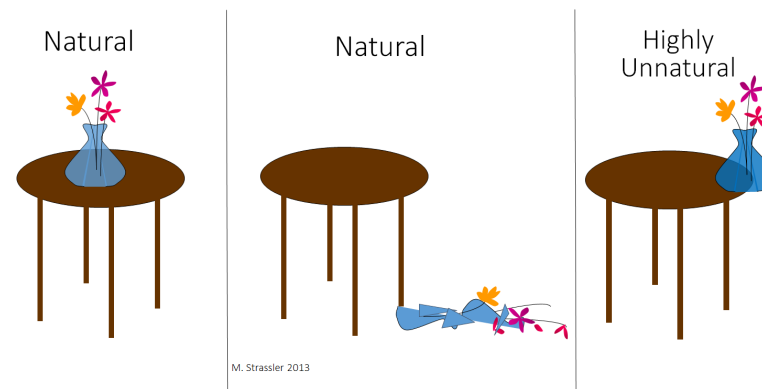
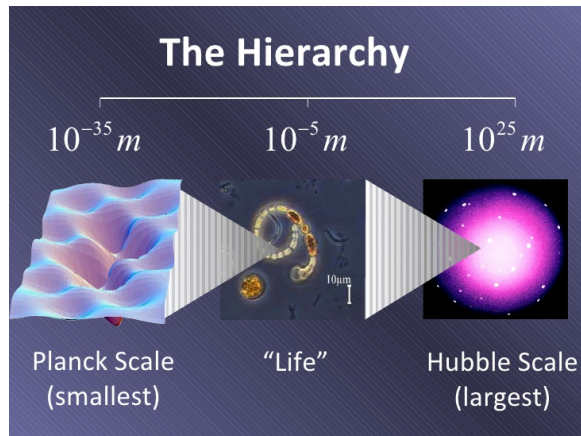
Guidelines from LHC results

- 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

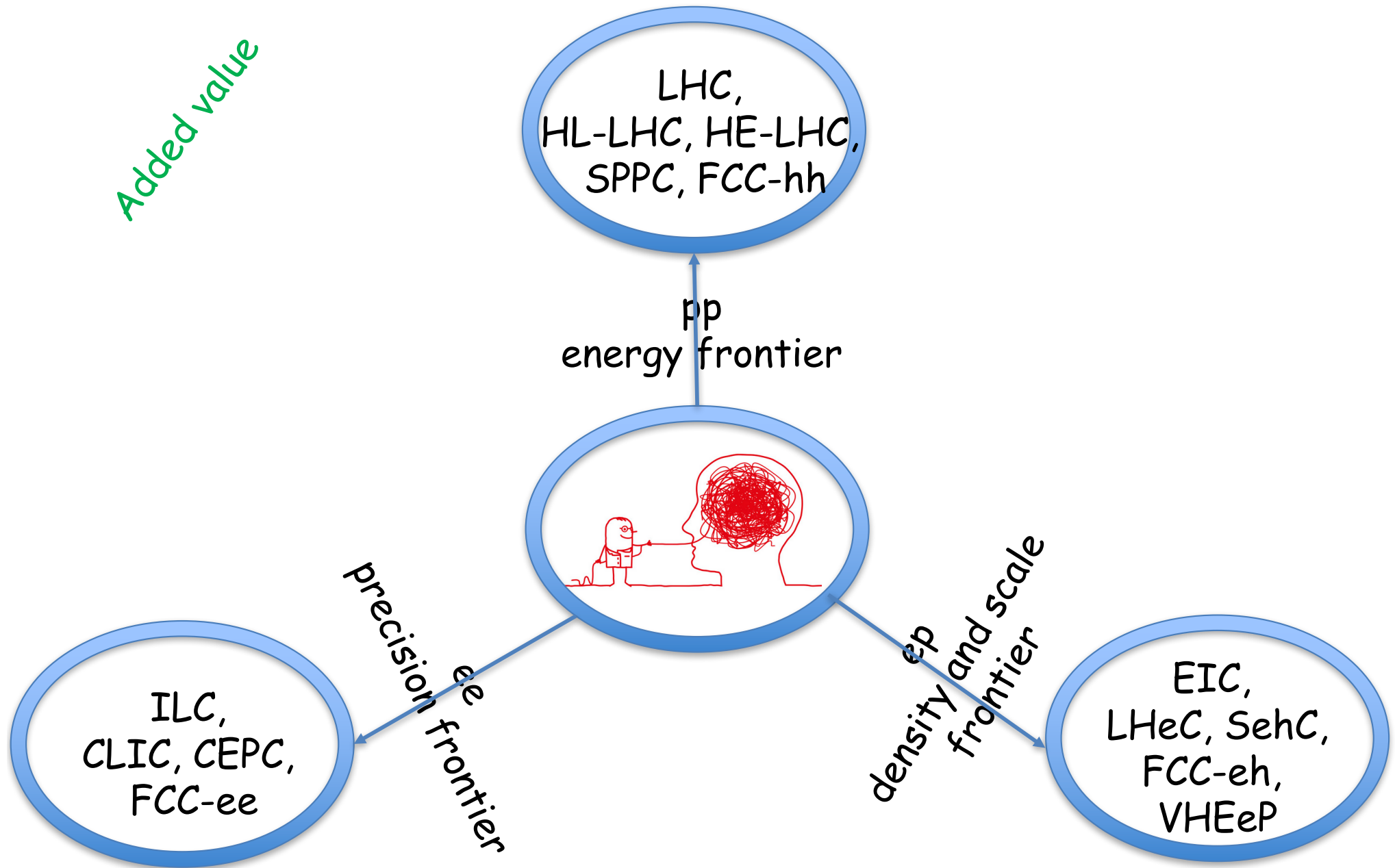
Guidelines from outside LHC

- 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

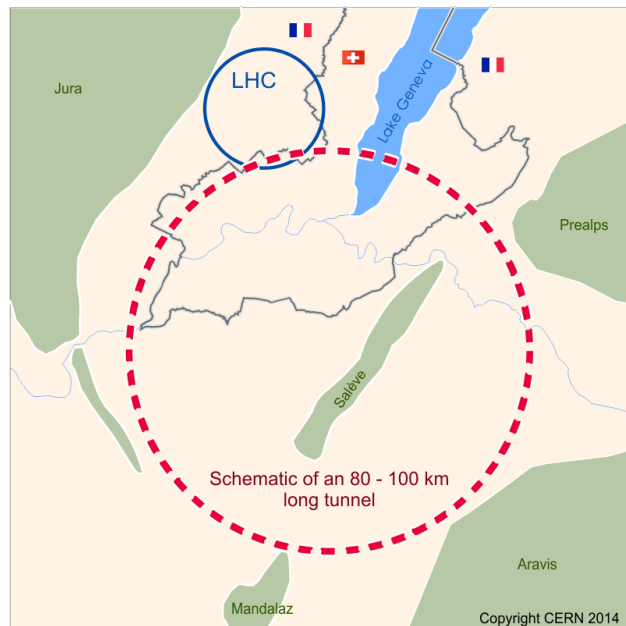
CERN: HE - LHC, pp 28 TeV - replace dipoles with 16 T HTS Nb₃Sn → 20 T

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

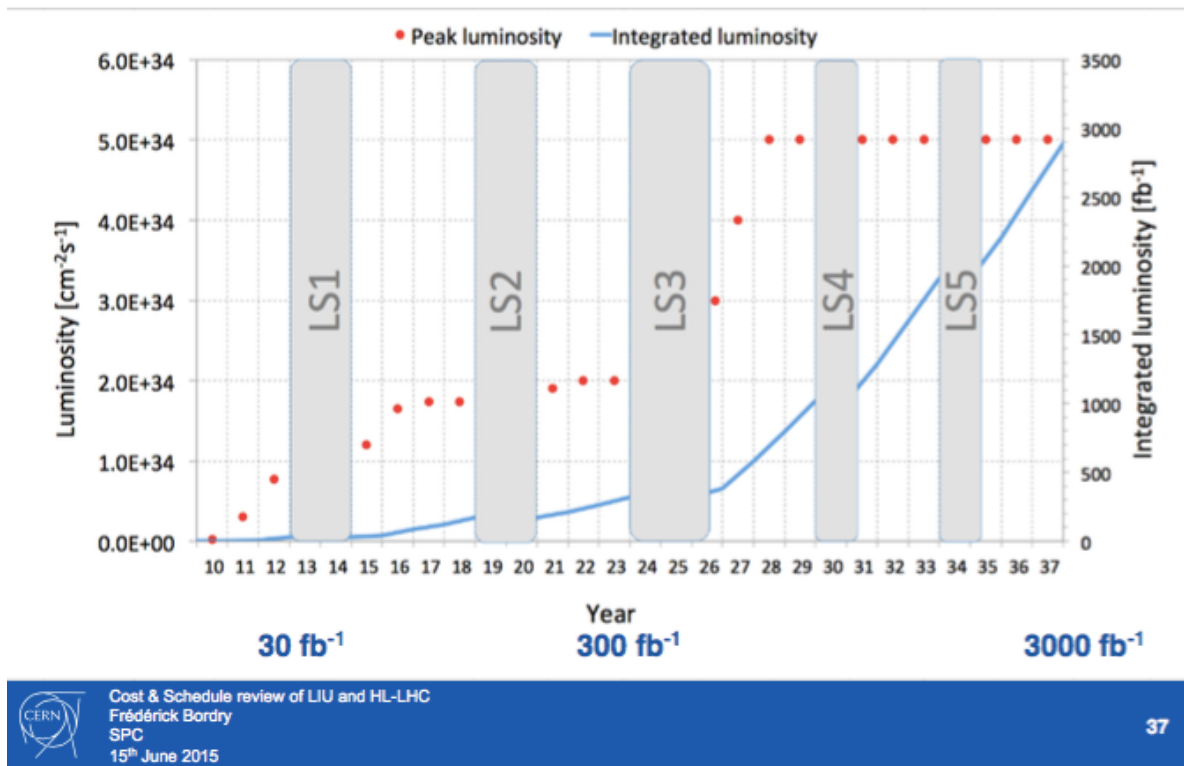


Energy Frontiers

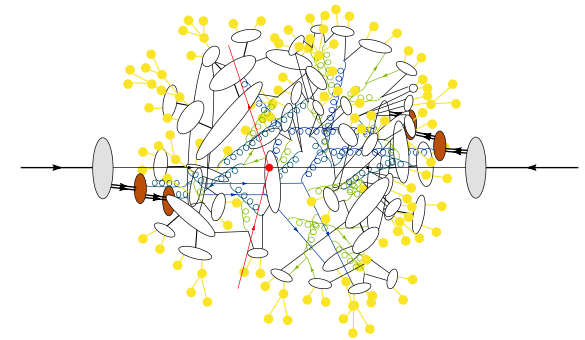
pp interactions are not very efficient
energy-wise but no-alternative

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

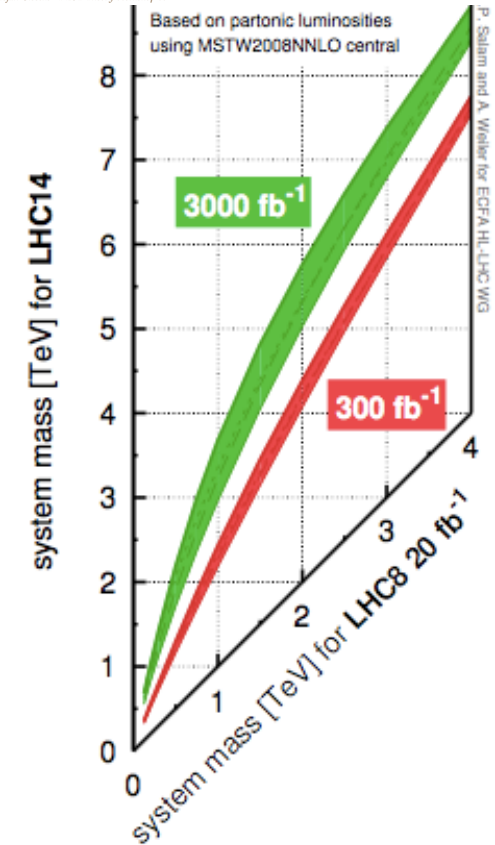
Integrated luminosity



pp Event Generator

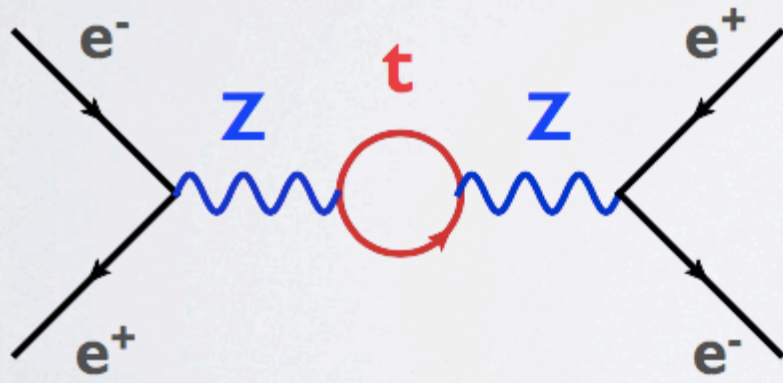


Stefan Gieseke - DESY Theory Workshop 09



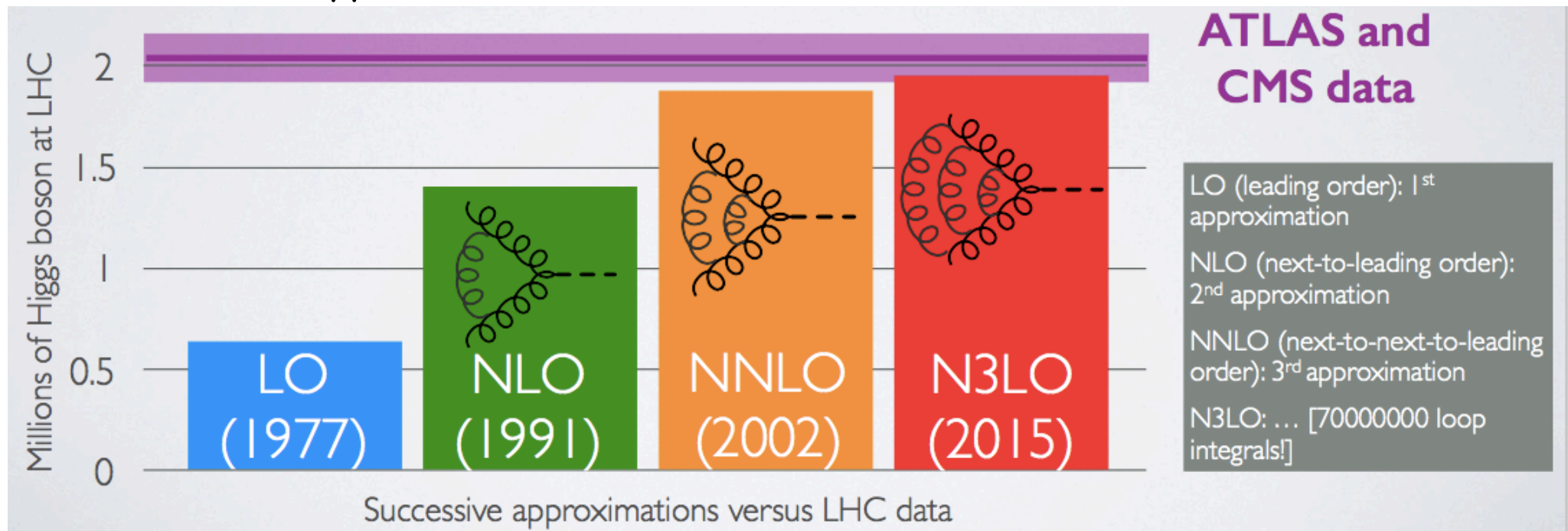
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Precision Frontier



- 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)

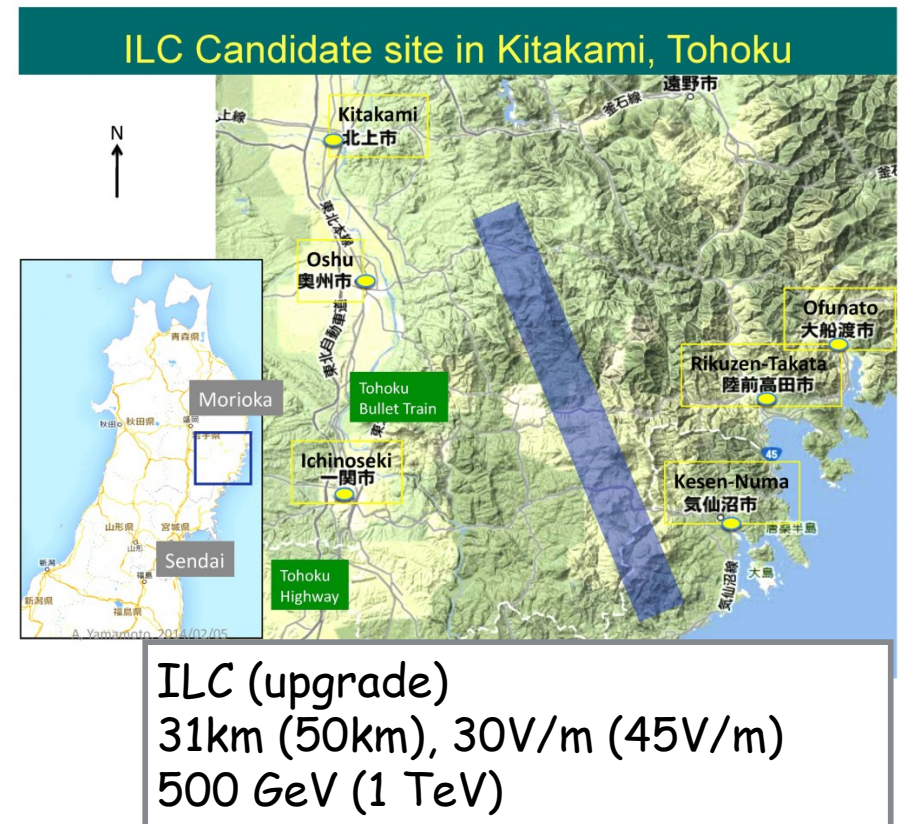
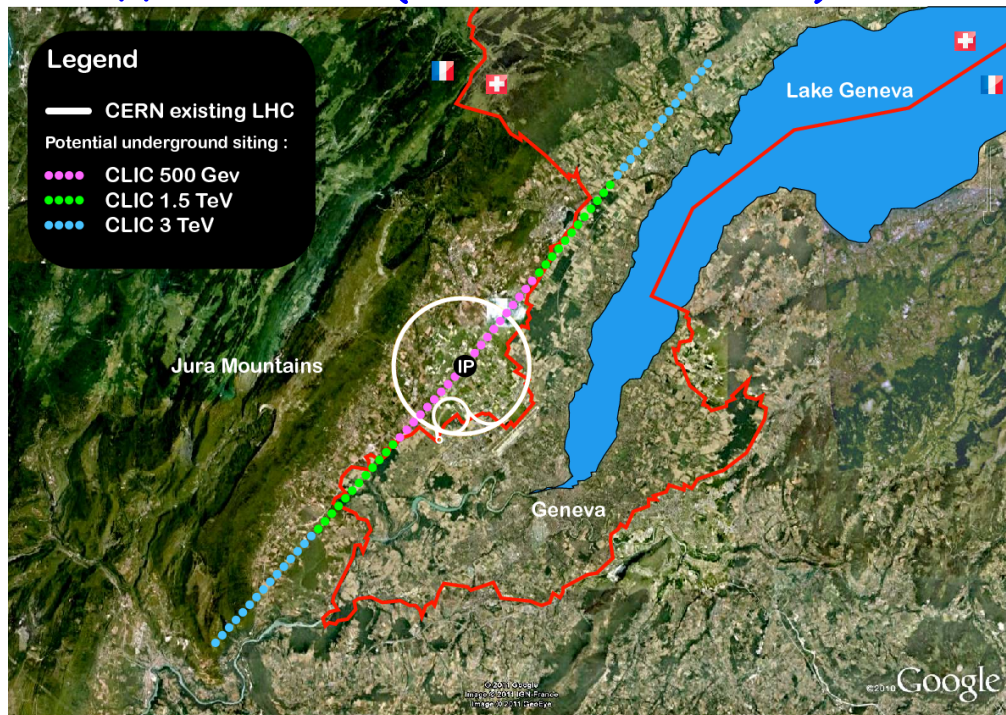
CERN: CLIC - linear collider, 380 GeV to 3 TeV (up to 50 km)

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

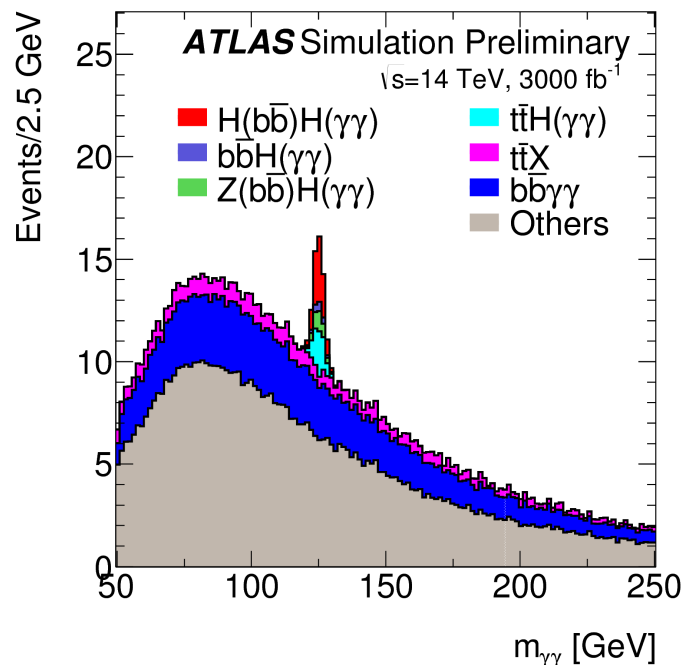
- $\gamma\gamma$ colliders (derivatives of ee)



Accelerating structures 72 to 100 MV/m

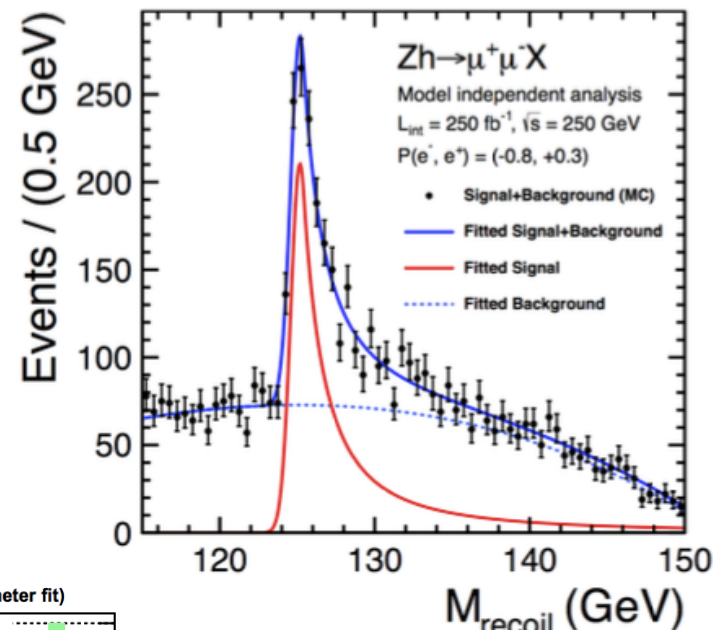
Precision Frontier

Precision Higgs/top physics

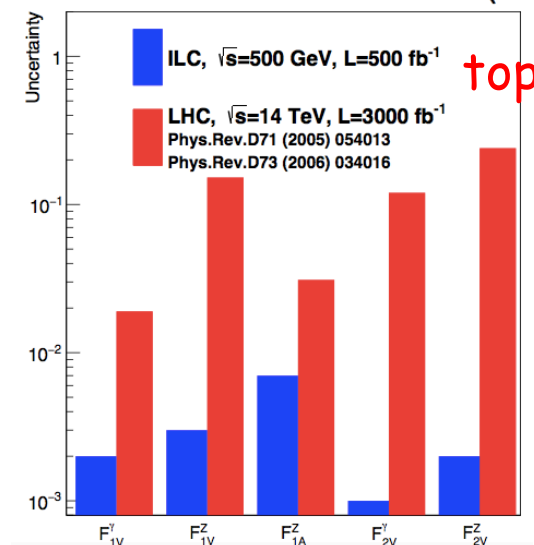
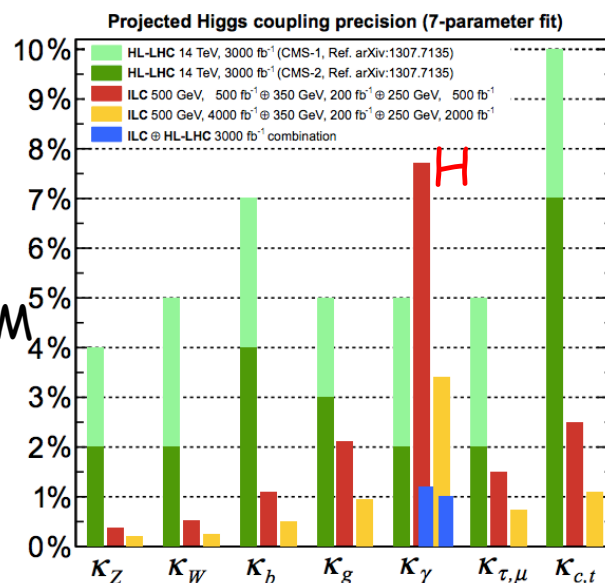


HL-LHC

ILC



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

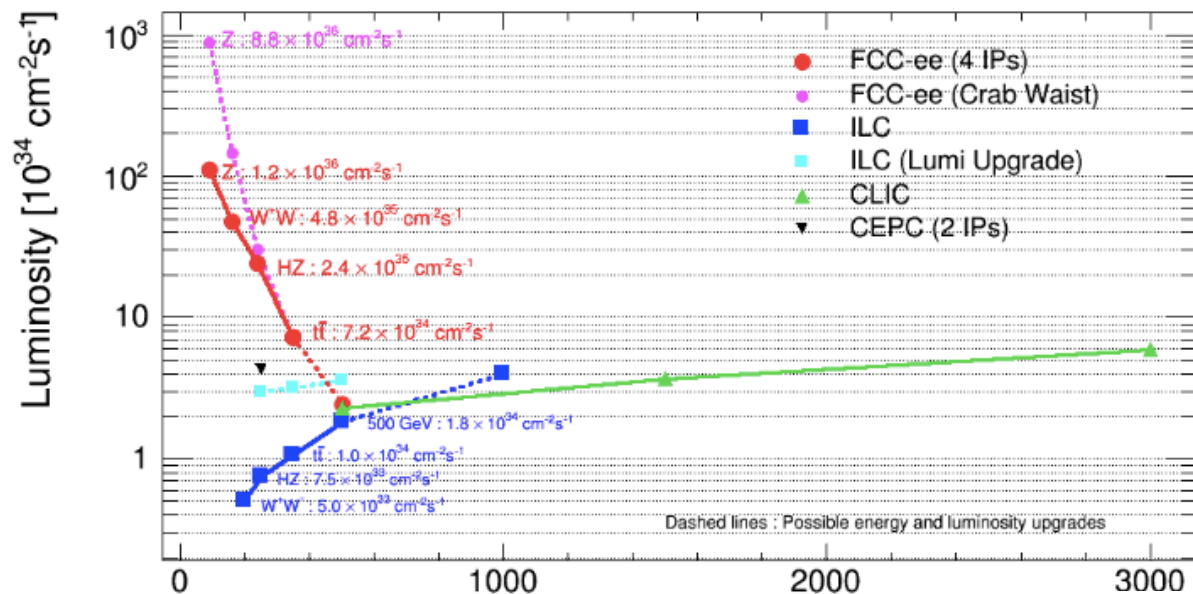


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H. Abramowicz - Passion for Physics
2017

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Precision Frontier



Luminosity vs energy for ee colliders

Comparison of expected Precision on H couplings

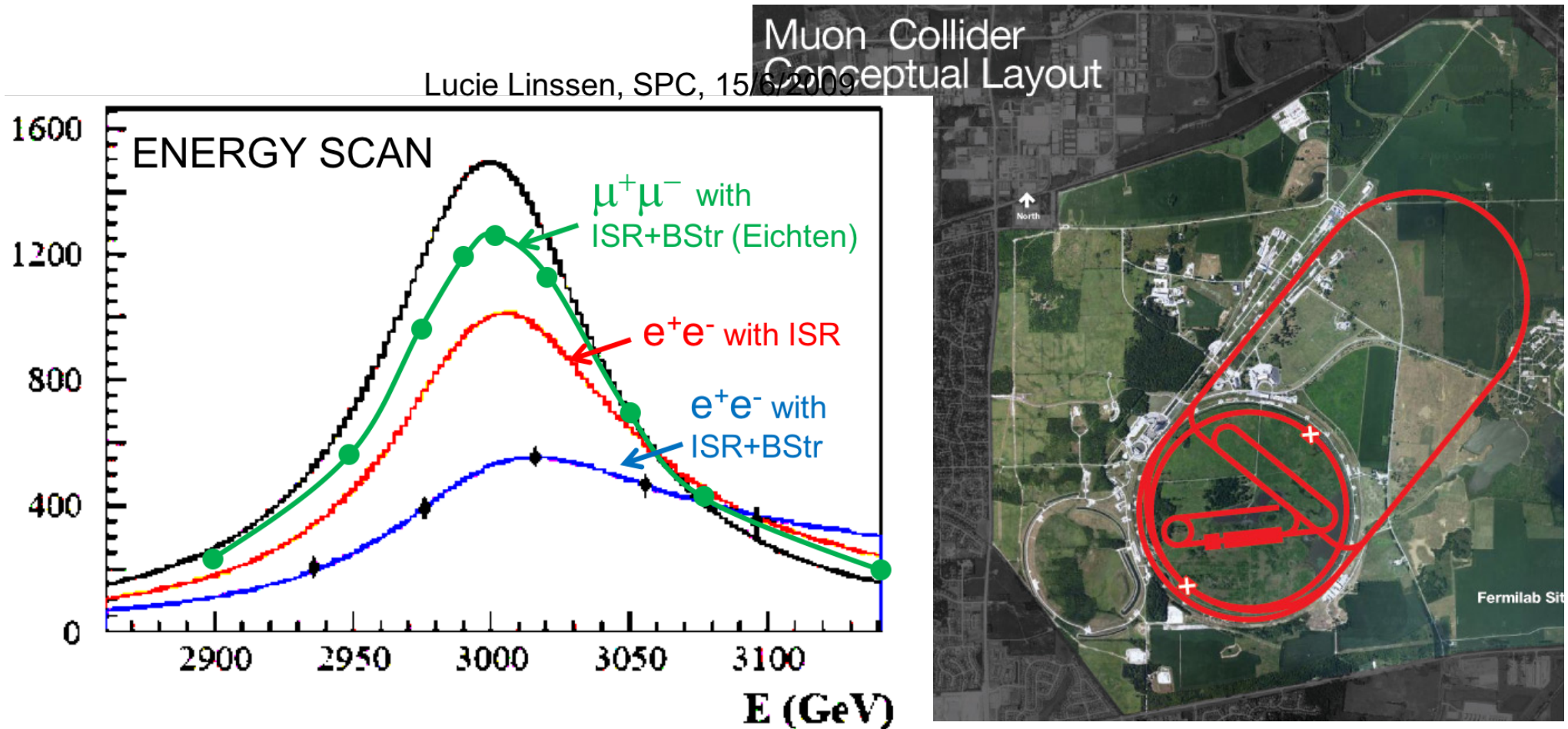
Coupling vs (TeV) → L (fb ⁻¹) →	LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24+0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000	Units are %
K_W	2-5	1.2	0.19	0.4	0.9		
K_Z	2-4	0.26	0.15	0.3	0.8		
K_g	3-5	1.5	0.8	1.0	1.2		
K_γ	2-5	4.7	1.5	3.4	3.2	< 1	
K_μ	~8	8.6	6.2	9.2	5.6	~ 2	
K_c	--	1.7	0.7	1.2	1.1		
K_τ	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	

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)

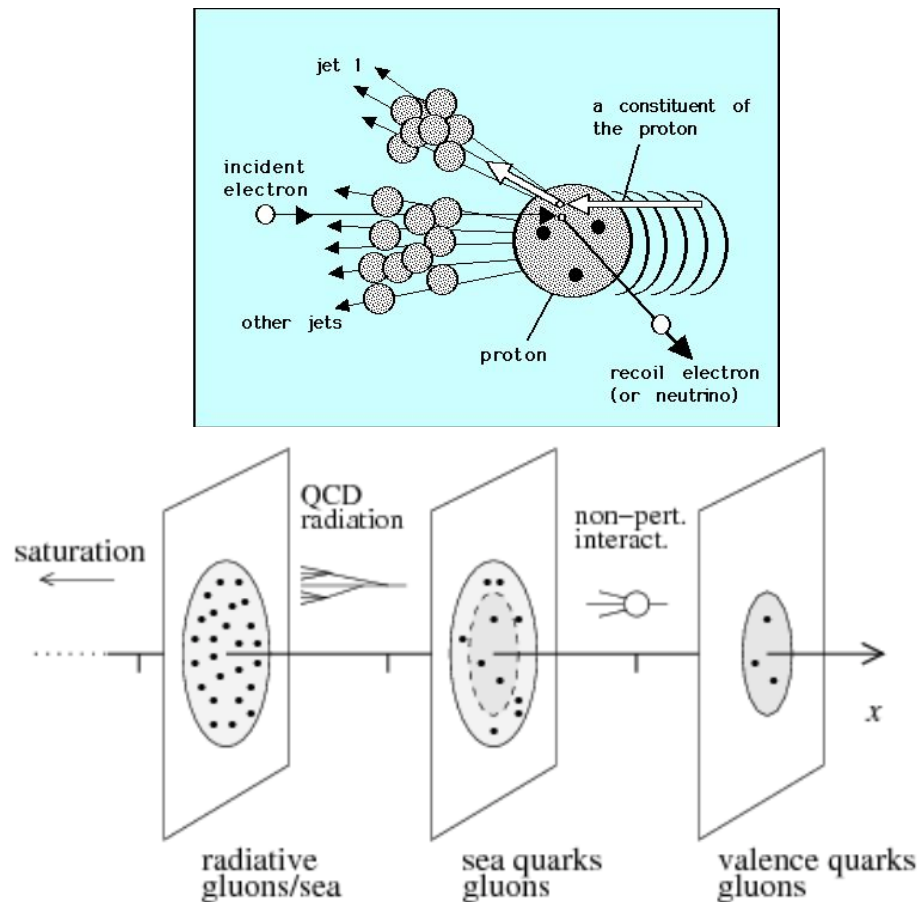


Challenges: to produce enough muons, cool them and compress the beam and all very fast

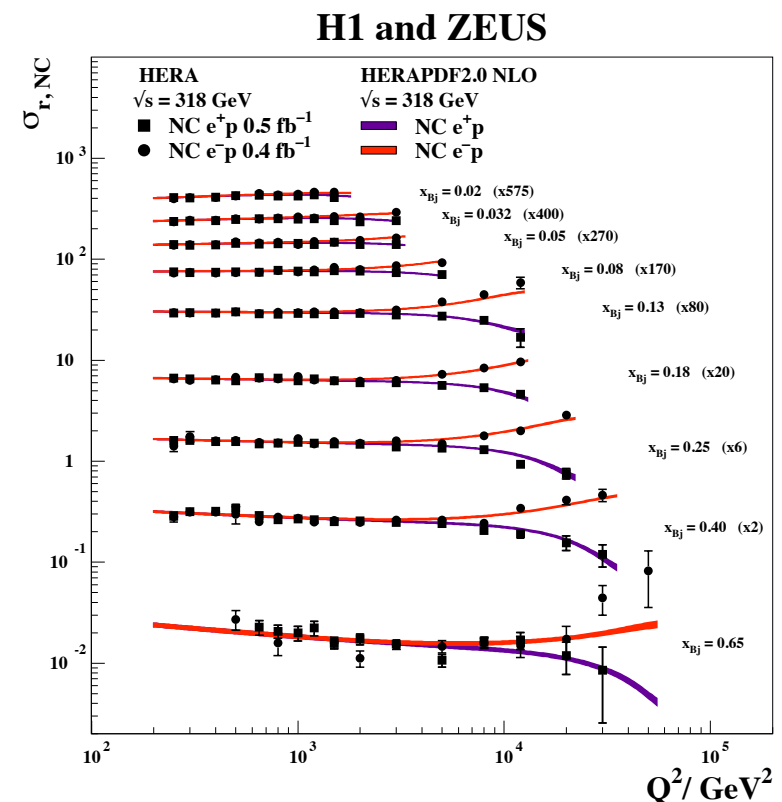
Density frontier and more

Proton - composite object consisting of quarks and gluons

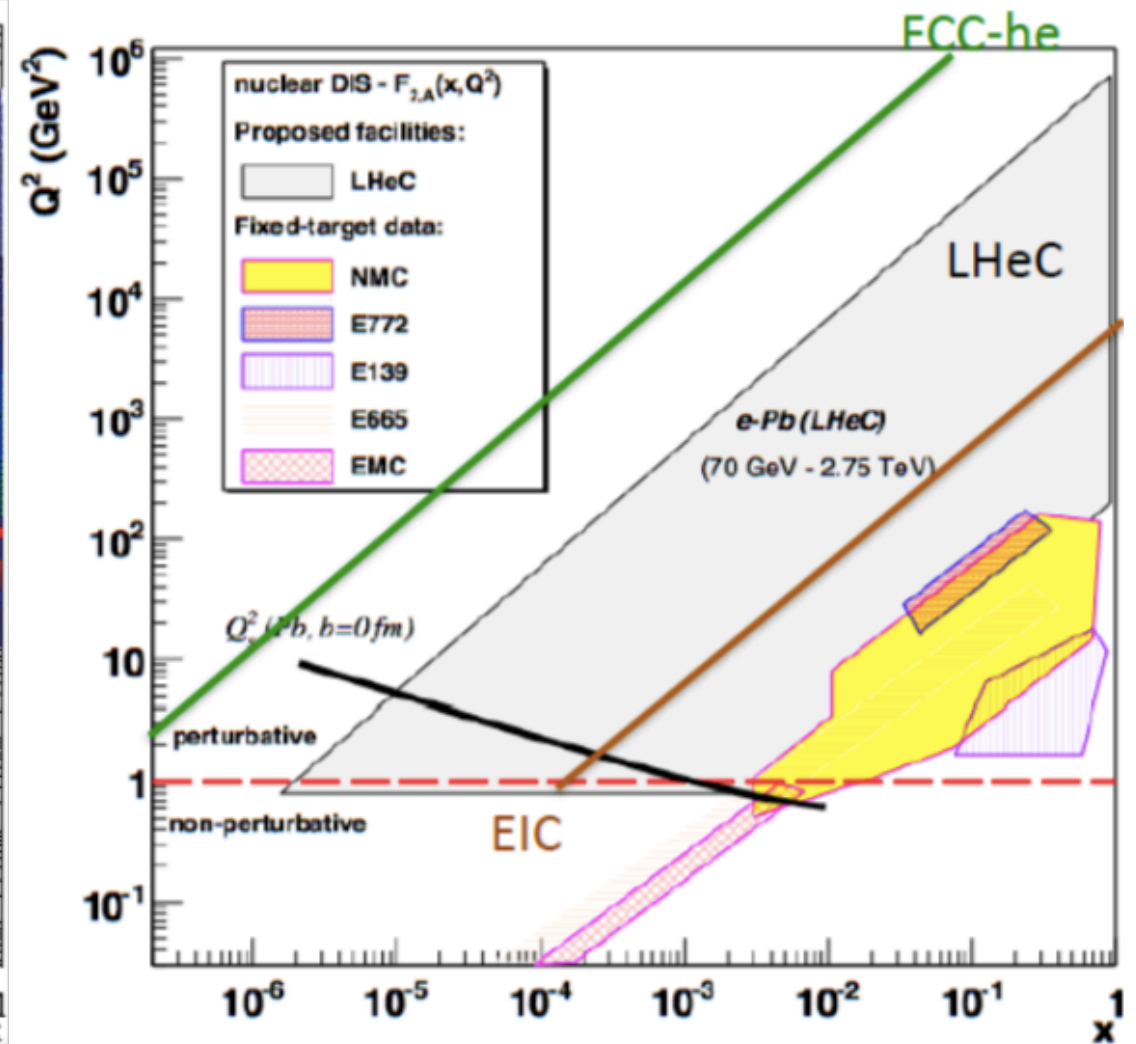
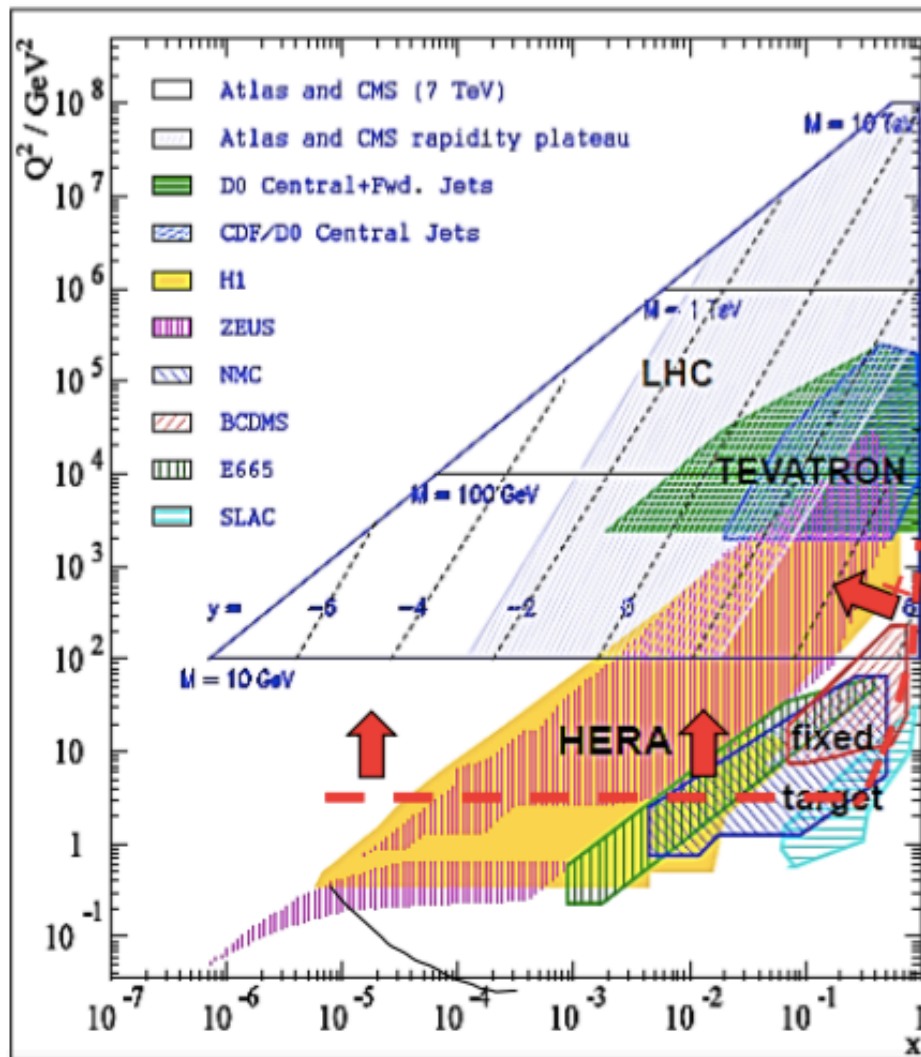
- only **5%** of its mass is generated through the Higgs mechanism
- **95%** of its mass is due to **QCD**
- structure cannot be calculated (yet) from first principles



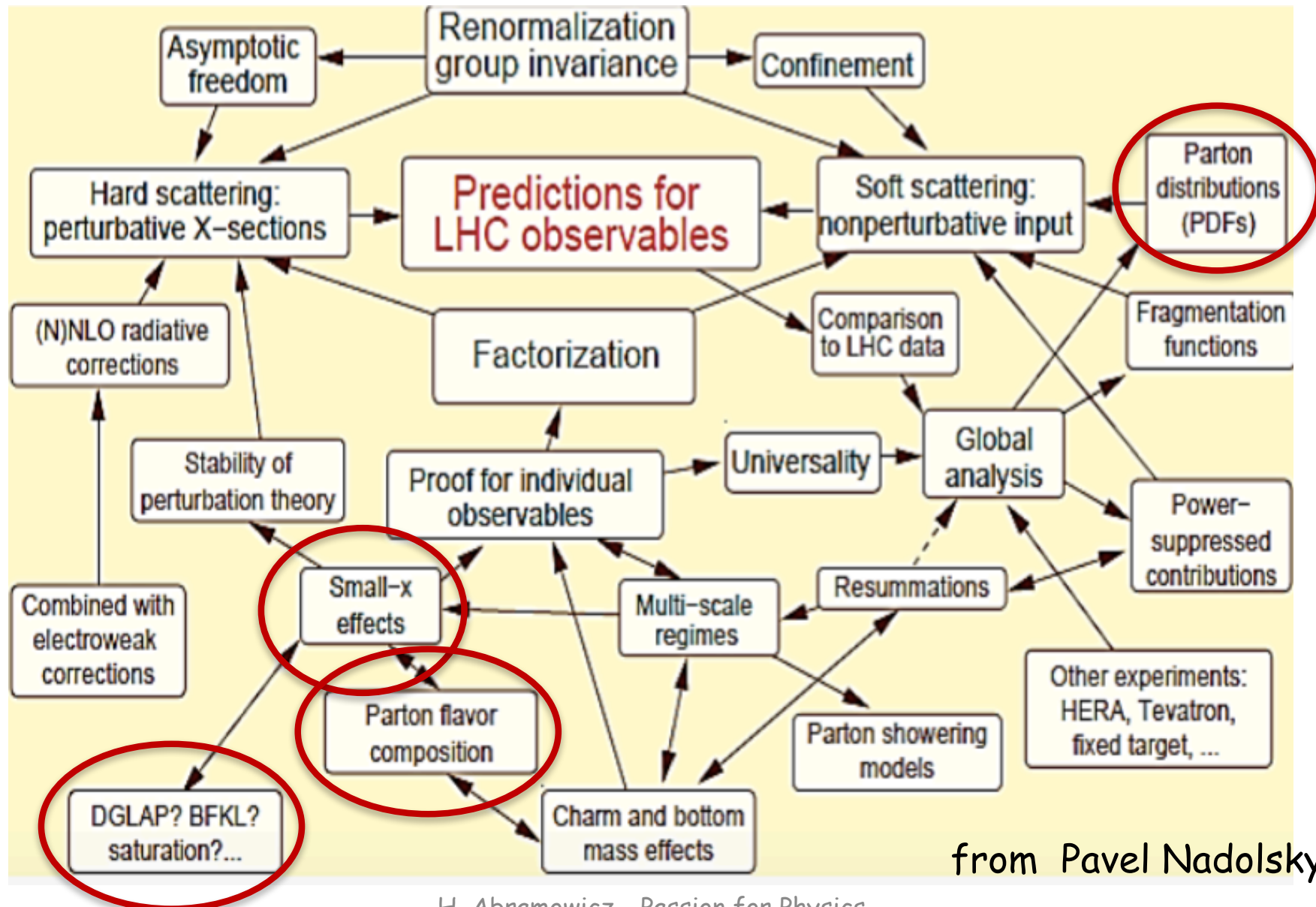
Legacy of ep collider HERA



Density frontier and more

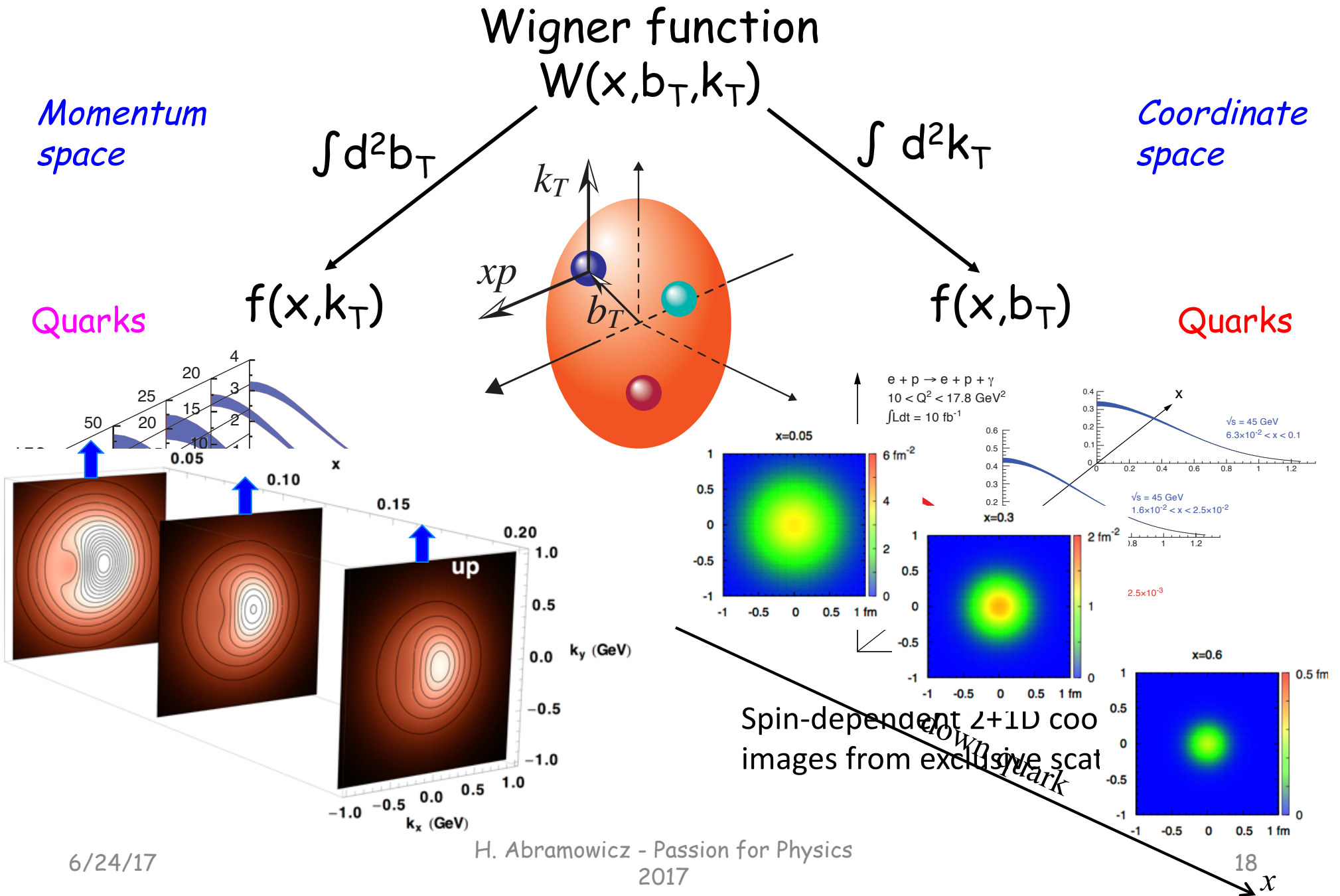


What it takes to get SM predictions for LHC



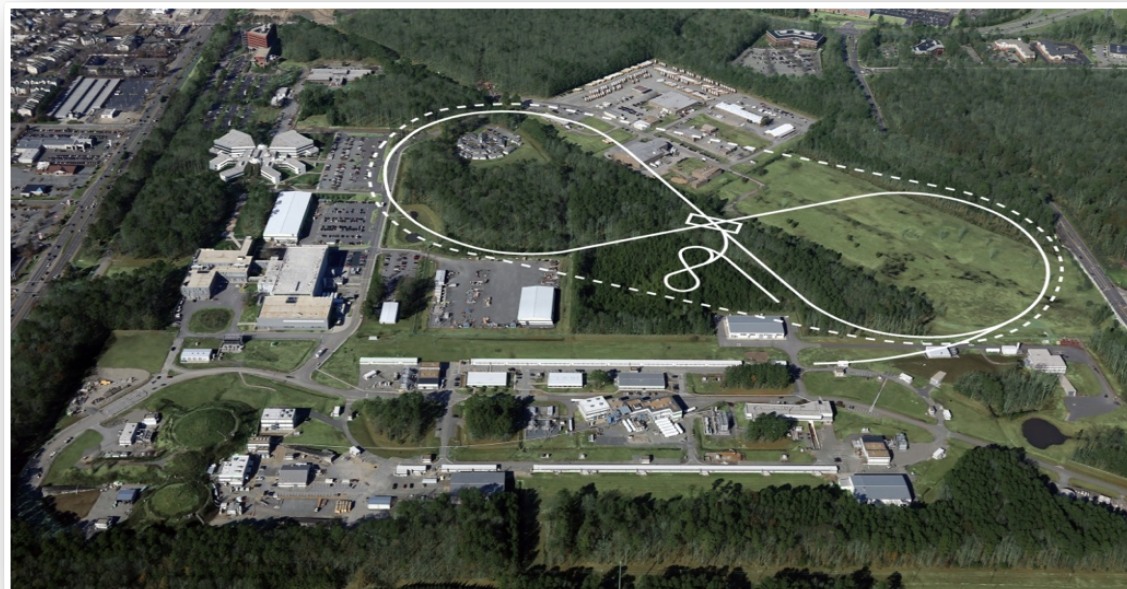
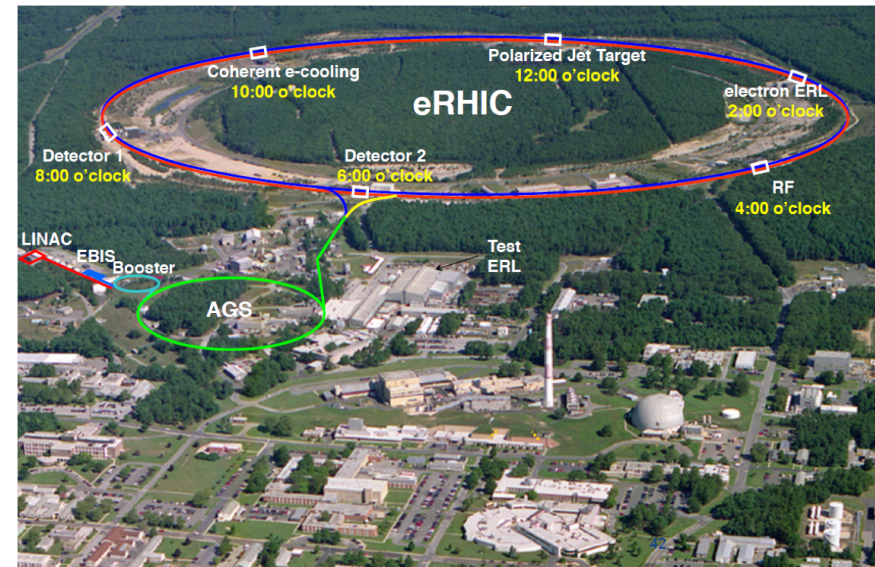
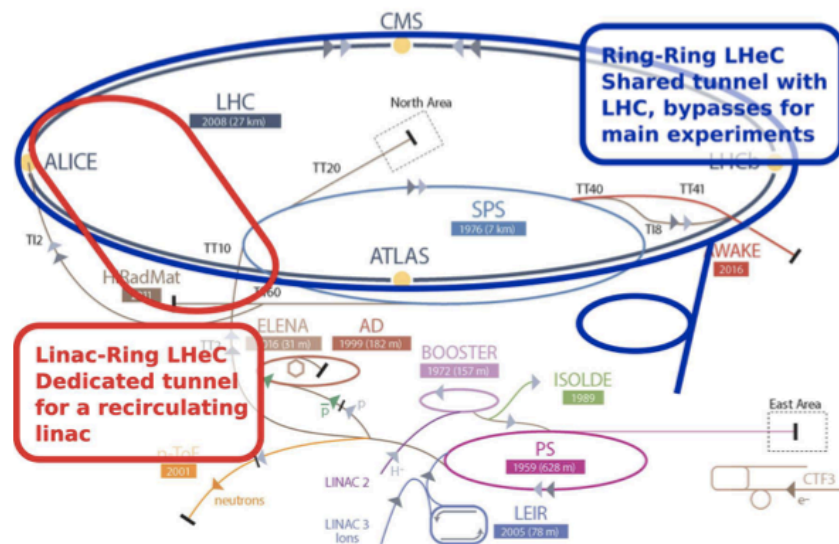
from Pavel Nadolsky

2+1 dimensional Imaging of Quarks & Gluons

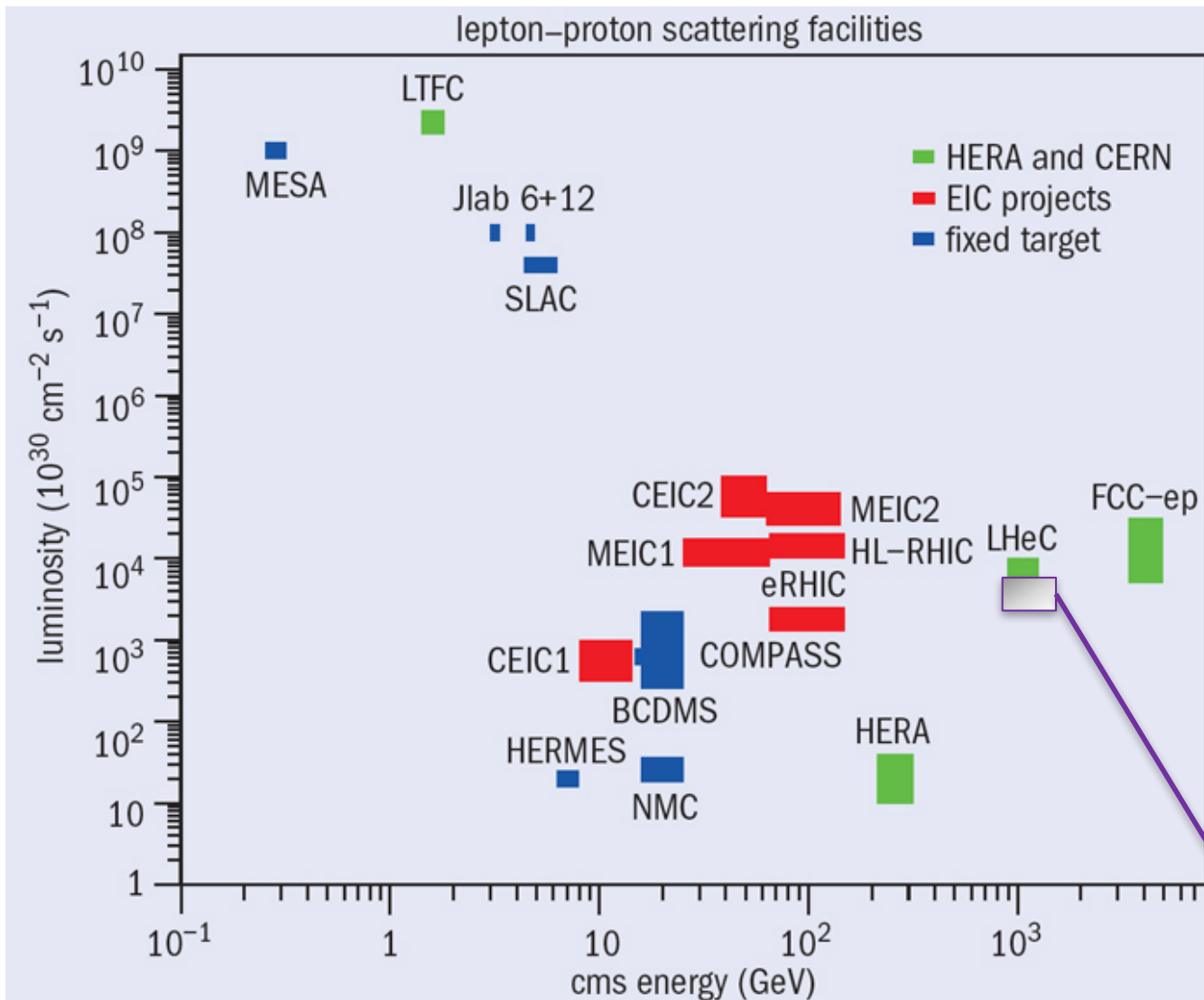


ep/eA colliders

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

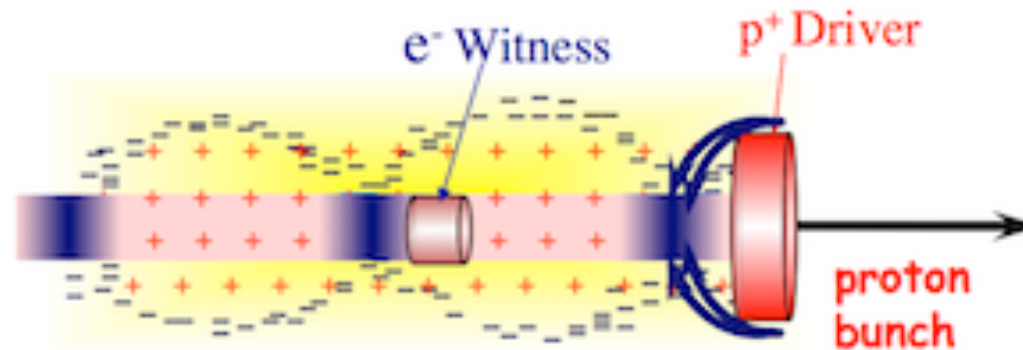
LHeC = ep/eA collider
@ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

SehC

New Accelerator Technologies

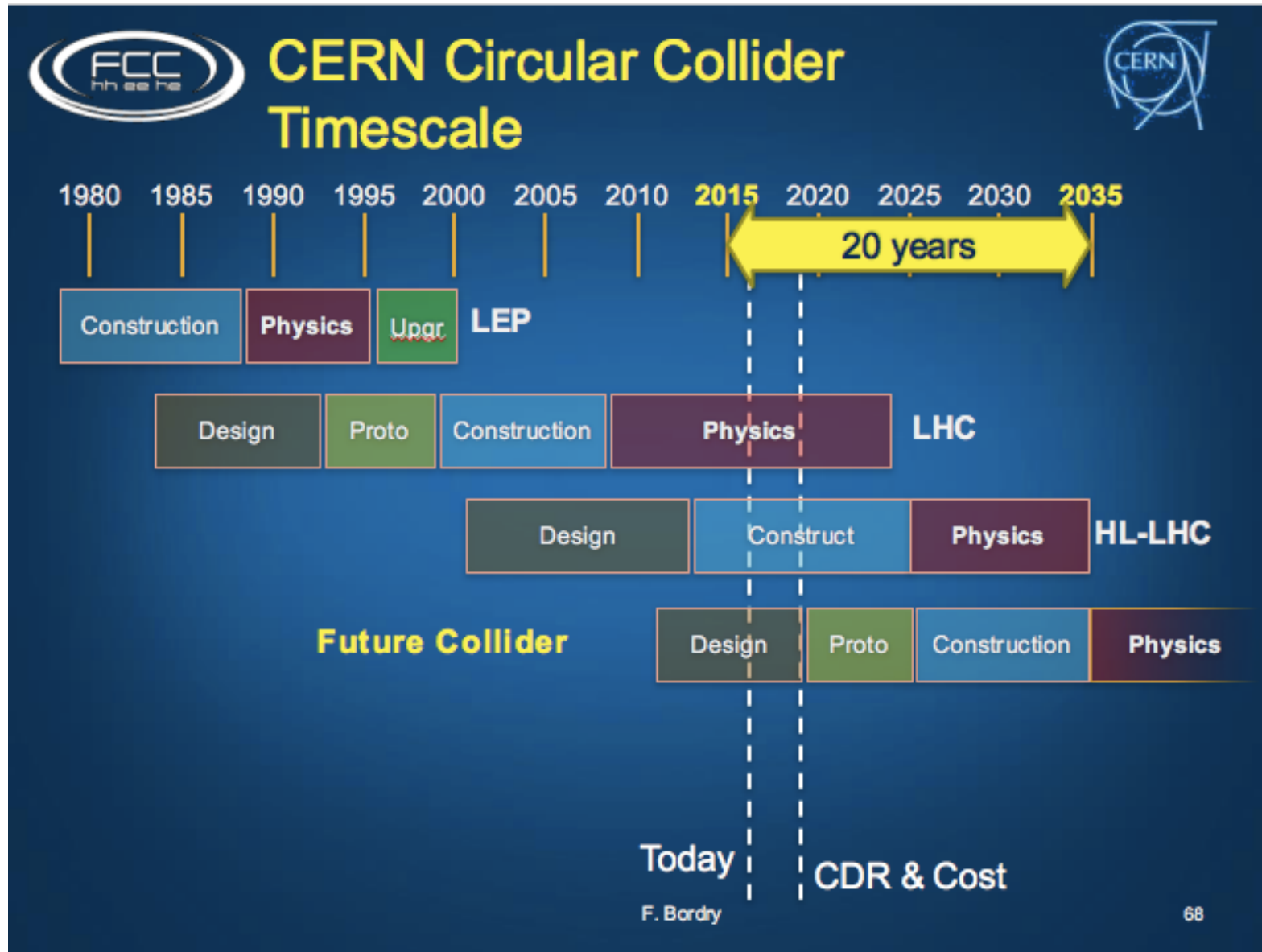
- Accelerators using RF cavities limited to $\sim 100 \text{ MV/m}$; high energies \Rightarrow long accelerators
- Gradients in plasma wakefield acceleration of $\sim 100 \text{ GV/m}$ measured



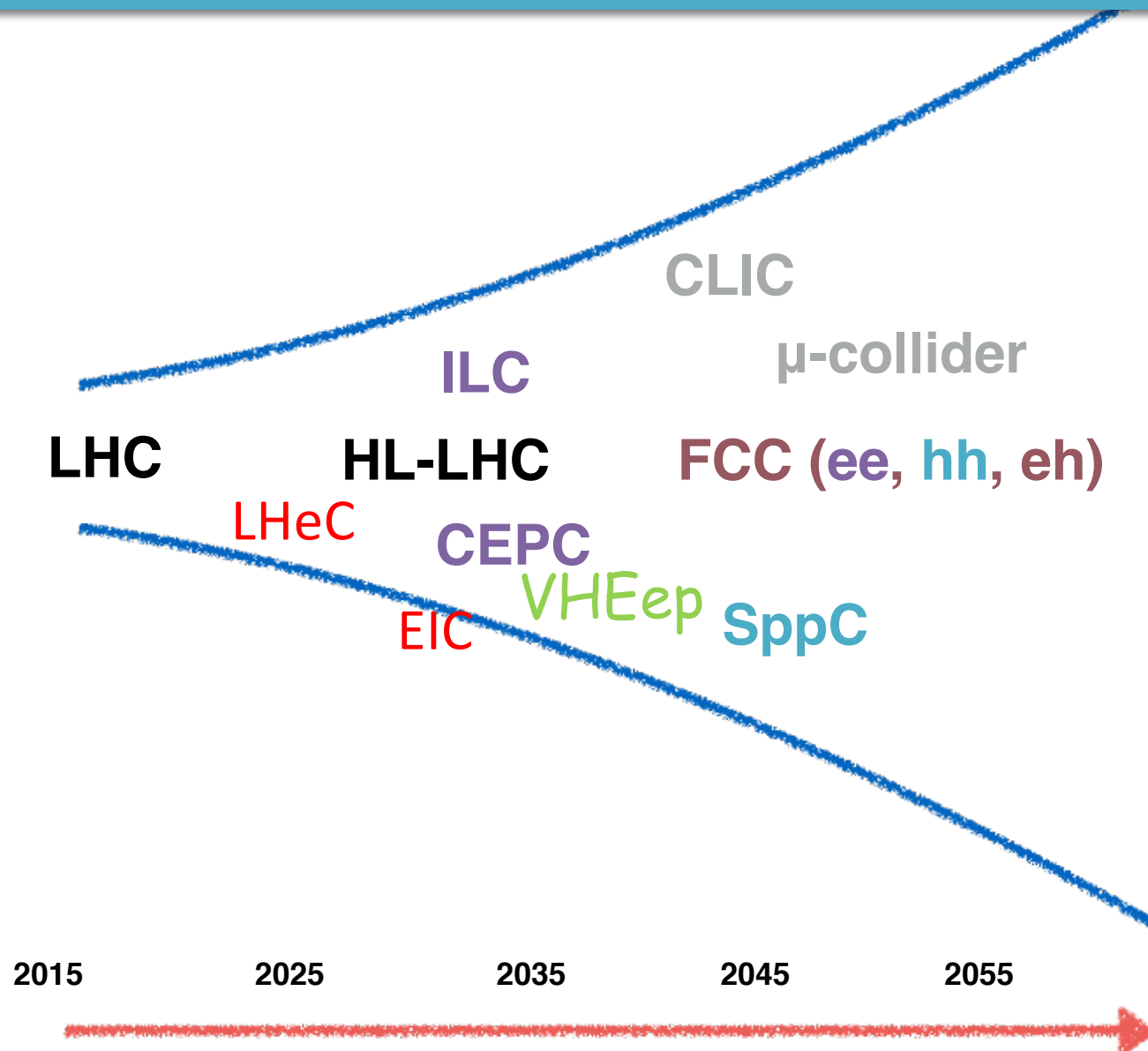
- ❖ ILC-CLIC, 0.5 TeV bunch with $2 \times 10^{10} e^-$ - about 1.6 kJ
- ❖ SPS, 400 GeV bunch with $10^{11} p$ - about 6.4 kJ
- ❖ LHC, 7 TeV - 112 kJ
- ❖ A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage
- ❖ Large average gradient ($> 1 \text{ GV/m}$, 100's m)

Proof of principle under way at the SPS at CERN

Time scales



Colliders of the 21st Century

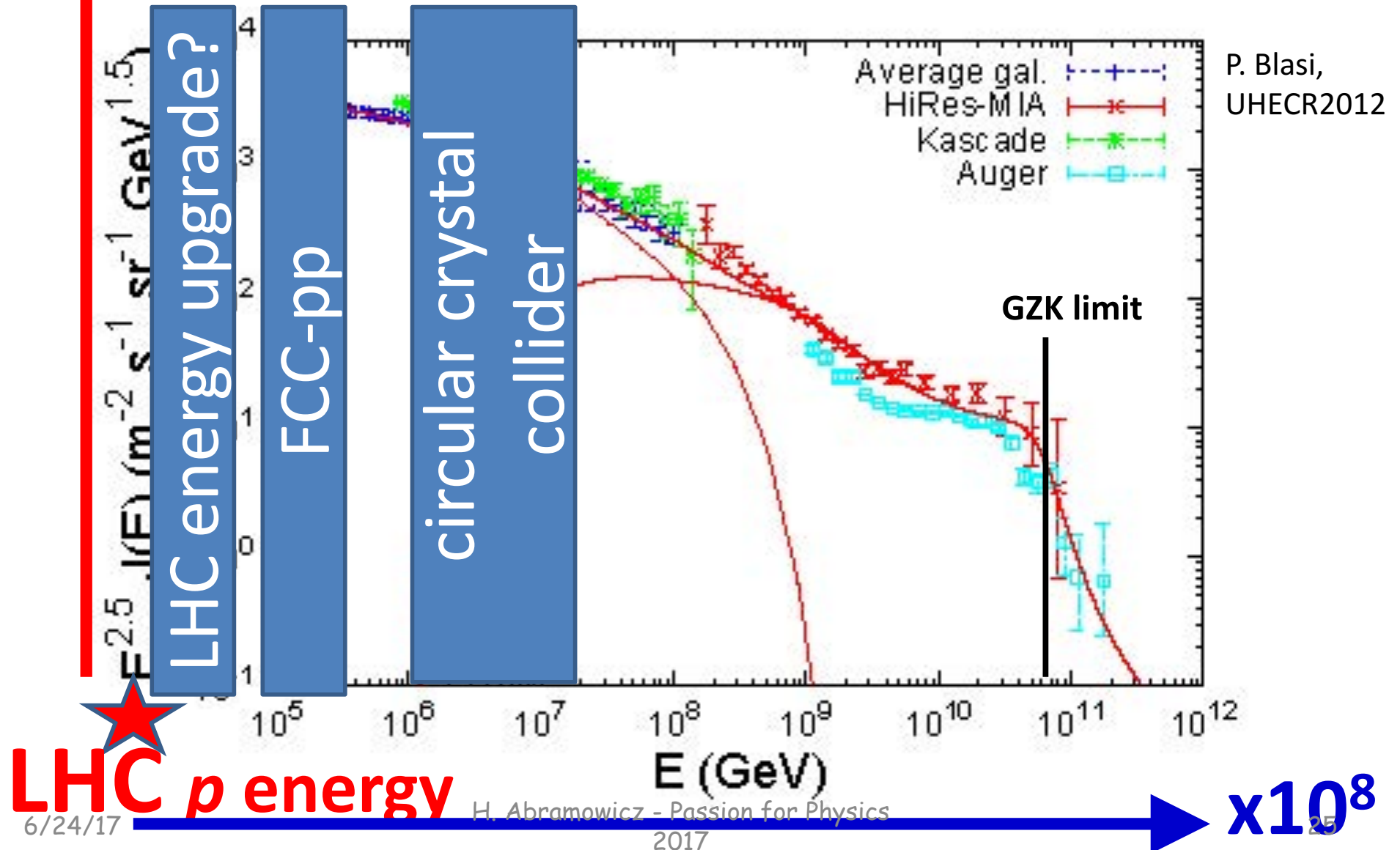


European Strategy 2013 - next update 2020

- 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



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.