

Perspectives in High Energy Physics

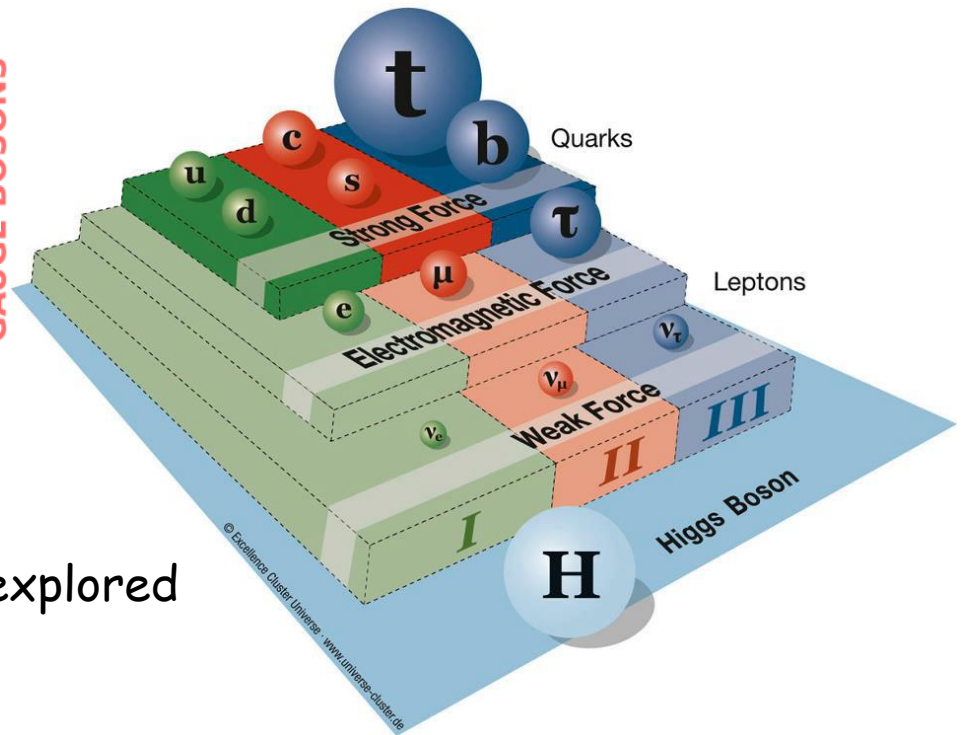
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- Status of Standard Model of particle physics
- What is missing?
- Future options
 - High energy colliders
 - Neutrino Physics (Ken Long)
 - Physics beyond colliders (Claude Vallee)

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	

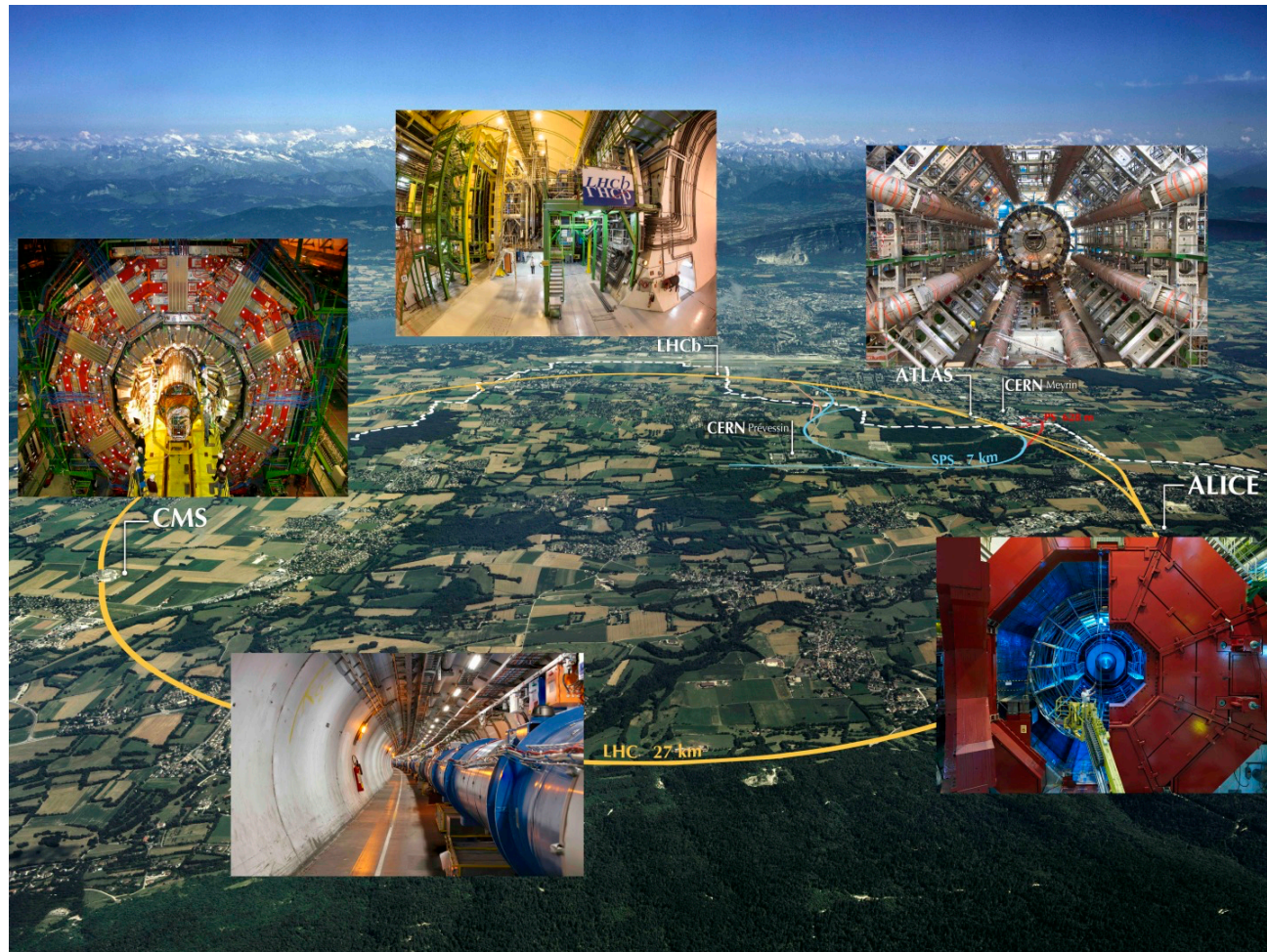


Higgs sector and top sector largely unexplored

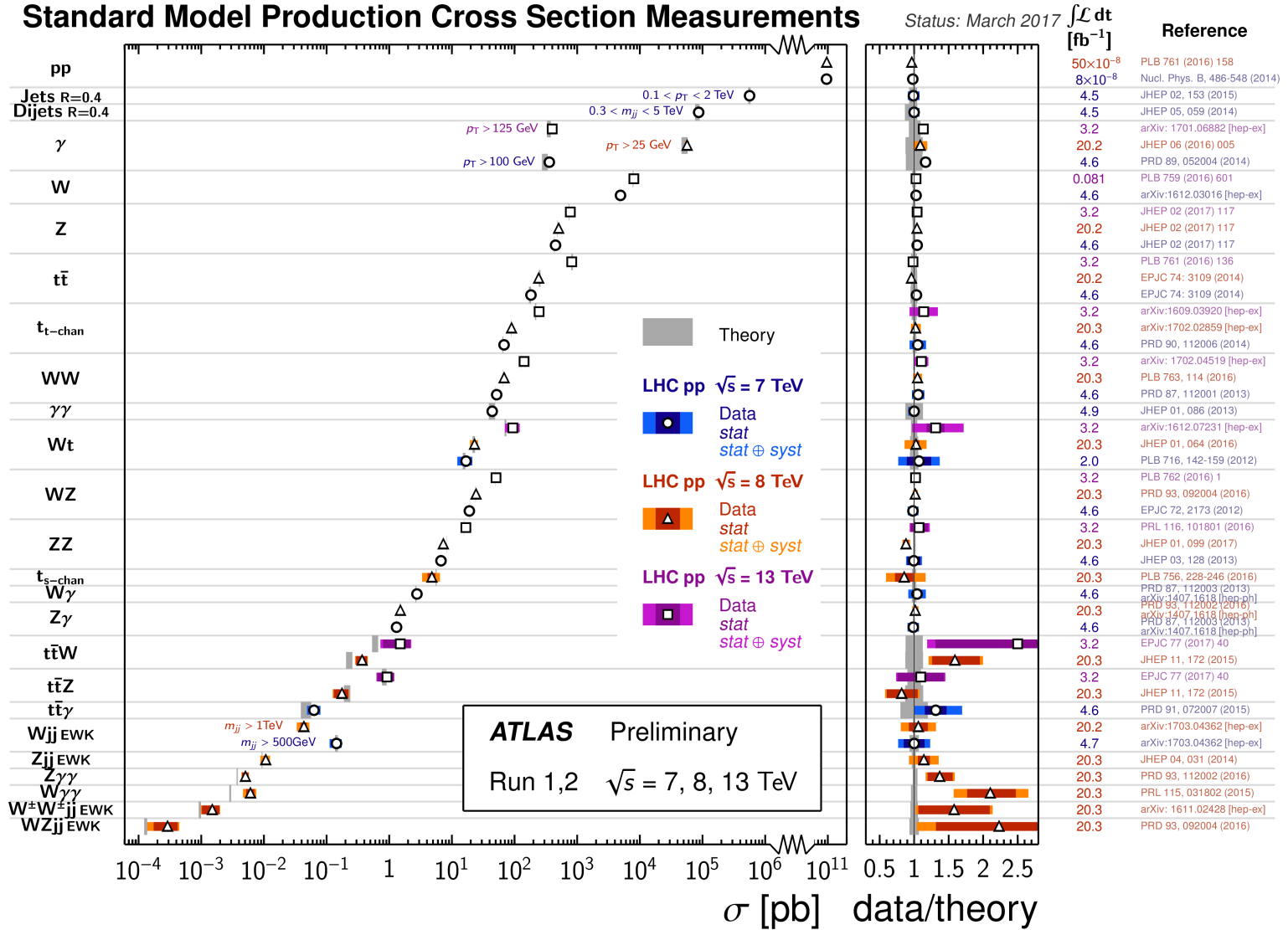
Present Energy Frontier - Large Hadron Collider at CERN

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

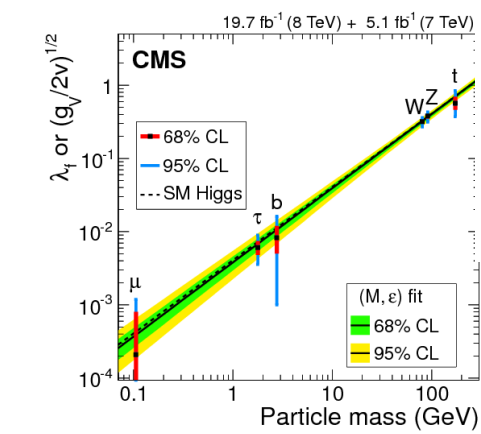
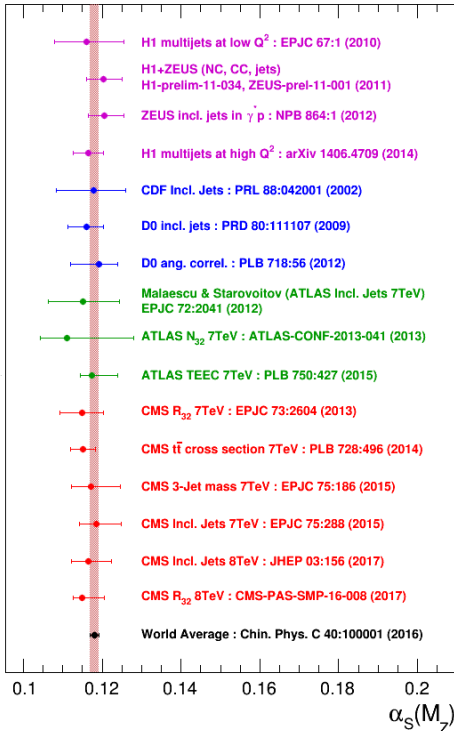
Collected pp data: 7TeV (2010/2011); 8TeV (2012); 13TeV (2015-now)



Stress test of SM at the LHC



Stress test of SM at the LHC



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

Model	e, μ, τ, γ	Jets	E_T^{miss}	$[L d(\text{fb}^{-1})]$	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	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	1.85 TeV	$m(\tilde{g})=m(\tilde{t})$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{\chi}_1^0$	1.57 TeV	$m(\tilde{t}_1^*) < 200 \text{ GeV}, m(\tilde{t}_2^*) = m(\tilde{g}) + m(\tilde{2}^{nd} \text{ gen. } \tilde{q})$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ (compressed)	0	mono-jet	Yes	3.2	$\tilde{\chi}_1^0$	608 GeV	$m(\tilde{g}) = m(\tilde{t}_1^*) < 5 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{\chi}_1^0$	$> 200 \text{ GeV}$	$m(\tilde{t}_1^*) < 200 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{\chi}_1^0$	2.02 TeV	$m(\tilde{t}_1^*) < 200 \text{ GeV}, m(\tilde{t}_2^*) = 0.5(m(\tilde{t}_1^*) + m(\tilde{g}))$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell/\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{\chi}_1^0$	1.825 TeV	$m(\tilde{t}_1^*) < 400 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{\chi}_1^0$	1.8 TeV	$m(\tilde{t}_1^*) < 400 \text{ GeV}$	
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{\chi}_1^0$	2.0 TeV	$m(\text{NLSP}) < 0.1 \text{ mm}$	
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{\chi}_1^0$	1.65 TeV	$m(\tilde{t}_1^*) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{\chi}_1^0$	1.37 TeV	$m(\tilde{t}_1^*) > 880 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	
3 rd gen. squarks & med.	GGM (higgsino NLSP)	γ	2 jets	Yes	13.3	$\tilde{\chi}_1^0$	1.8 TeV	$m(\text{NLSP}) < 430 \text{ GeV}$	
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{\chi}_1^0$	900 GeV	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{g}) - 1.5 \text{ TeV}$	
	Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g}/\tilde{t} scale	865 GeV		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{\chi}_1^0$	1.92 TeV	$m(\tilde{t}_1^*) < 600 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{\chi}_1^0$	1.97 TeV	$m(\tilde{t}_1^*) < 200 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.3	$\tilde{\chi}_1^0$	1.37 TeV	$m(\tilde{t}_1^*) < 300 \text{ GeV}$	
	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	$m(\tilde{t}_1^*) < 420 \text{ GeV}$
		$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{t}_1^*) < 200 \text{ GeV}, m(\tilde{t}_2^*) = m(\tilde{t}_1^*) + 100 \text{ GeV}$
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{t}_1^*) = 2m(\tilde{t}_2^*), m(\tilde{t}_1^*) = 55 \text{ GeV}$
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\chi}_1^0$ 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	$m(\tilde{t}_1^*) = 1 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\chi}_1^0$		0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 5 \text{ GeV}$	
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)		2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV		
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow Z\tilde{\chi}_1^0$		3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV		
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow t\tilde{h}$		1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{t}_1^*) = 0 \text{ GeV}$	
EW direct		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	\tilde{t}_1	90-440 GeV	$m(\tilde{t}_1^*) = 0$
		$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}\nu(\tilde{\nu})$	2 e, μ	0	Yes	36.1	\tilde{t}_1	710 GeV	$m(\tilde{t}_1^*) = 0, m(\tilde{\nu}, \tilde{\nu}) = 0.5(m(\tilde{t}_1^*) + m(\tilde{\chi}_1^0))$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}\nu(\tilde{\nu}), \tilde{t}_2\tilde{t}_2 \rightarrow \tilde{t}\nu(\tilde{\nu})$	2 τ	0	Yes	36.1	\tilde{t}_1, \tilde{t}_2	760 GeV	$m(\tilde{t}_1^*) = 0, m(\tilde{\nu}, \tilde{\nu}) = 0.5(m(\tilde{t}_1^*) + m(\tilde{\chi}_1^0))$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\chi}_1^0$	3 e, μ	0	Yes	36.1	\tilde{t}_1, \tilde{t}_2	580 GeV	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 0, m(\tilde{\nu}, \tilde{\nu}) = 0.5(m(\tilde{t}_1^*) + m(\tilde{\chi}_1^0))$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	\tilde{t}_1, \tilde{t}_2	270 GeV	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 0, \tilde{t}$ decoupled	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow h\tilde{t}$	e, μ, γ	0-2 b	Yes	20.3	\tilde{t}_1, \tilde{t}_2	635 GeV	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 0, m(\tilde{\nu}, \tilde{\nu}) = 0.5(m(\tilde{t}_1^*) + m(\tilde{\chi}_1^0))$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow h\tilde{t}$	4 e, μ	0	Yes	20.3	\tilde{t}_1	115-370 GeV	$c\tau < 1 \text{ mm}$	
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	590 GeV	$c\tau < 1 \text{ mm}$	
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	590 GeV		
	Long-lived particles	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	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 180 \text{ MeV}, c\tau(\tilde{\chi}_1^0) = 0.2 \text{ ns}$
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	$m(\tilde{t}_1^*) = m(\tilde{t}_2^*) = 180 \text{ MeV}, c\tau(\tilde{\chi}_1^0) < 15 \text{ ns}$	
Stable, stopped $\tilde{\chi}_1^0$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{\chi}_1^0$	850 GeV	$m(\tilde{t}_1^*) = 100 \text{ GeV}, 10 \mu\text{s} < c\tau < 1000 \text{ s}$	
Stable $\tilde{\chi}_1^0$ R-hadron		trk	-	-	3.2	$\tilde{\chi}_1^0$	1.58 TeV	1310.6584	
Metastable $\tilde{\chi}_1^0$ R-hadron		dE/dx trk	-	-	3.2	$\tilde{\chi}_1^0$	1.57 TeV	1606.05129	
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\nu}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$m(\tilde{t}_1^*) = 100 \text{ GeV}, \tau > 10 \text{ ns}$	
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	$10^{-4} < \text{tan}\beta < 50$	
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}\nu/\mu\tilde{\nu}\nu/\mu\tilde{\nu}\nu$		displ. $e/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$1 < c\tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$		displ. $\nu\nu + \text{jets}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	
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	$A_{111} = 0.11, A_{132}/A_{333} = 0.07$
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	1.45 TeV	$m(\tilde{g}) = m(\tilde{t})$	
	$\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}_e, e\tilde{\nu}_\mu, \mu\tilde{\nu}_\mu$	4 e, μ	0	Yes	13.3	$\tilde{\chi}_1^0$	1.14 TeV	$m(\tilde{t}_1^*) > 400 \text{ GeV}, A_{12k} \neq 0 (k = 1, 2)$	
	$\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu_\tau, e\nu_e, \tau\nu_\tau$	3 $e, \mu + \tau$	0	Yes	20.3	$\tilde{\chi}_1^0$	450 GeV	$m(\tilde{t}_1^*) > 0.2x m(\tilde{t}_2^*), A_{133} \neq 0$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}$	0	4-5 large-R jets	-	14.8	$\tilde{\chi}_1^0$	1.08 TeV	$\text{BR}(\tilde{g}) \rightarrow \text{BR}(\tilde{b}) \rightarrow \text{BR}(\tilde{c}) = 0\%$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	0	4-5 large-R jets	-	14.8	$\tilde{\chi}_1^0$	1.55 TeV	$m(\tilde{t}_1^*) < 800 \text{ GeV}$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{\chi}_1^0$	2.1 TeV	$m(\tilde{t}_1^*) = 1 \text{ TeV}, A_{112} \neq 0$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{\chi}_1^0$	1.65 TeV	$m(\tilde{t}_1^*) = 1 \text{ TeV}, A_{333} \neq 0$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{c}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	450-510 GeV	$\text{BR}(\tilde{t}_1 \rightarrow b\tilde{c}/\mu\tilde{\nu}) > 20\%$	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{t}_1^*) < 200 \text{ GeV}$	

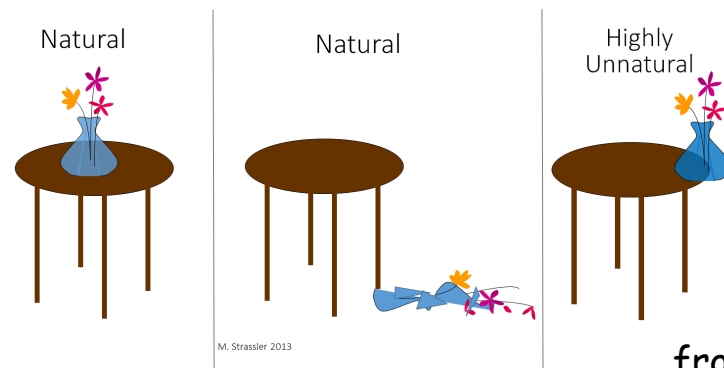
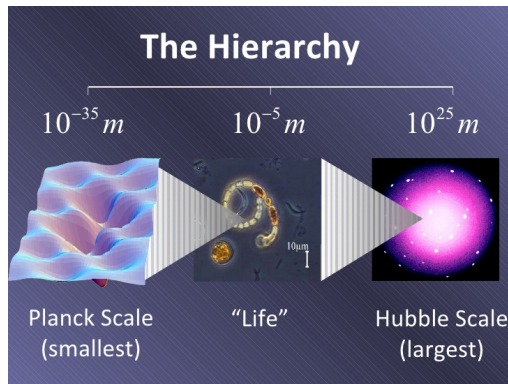
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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
- Lepton/flavor conservation - hints from LHCb in c/b-decays???

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???)
- Prevalence of matter over anti-matter
- Theorists believe that the theory is not complete

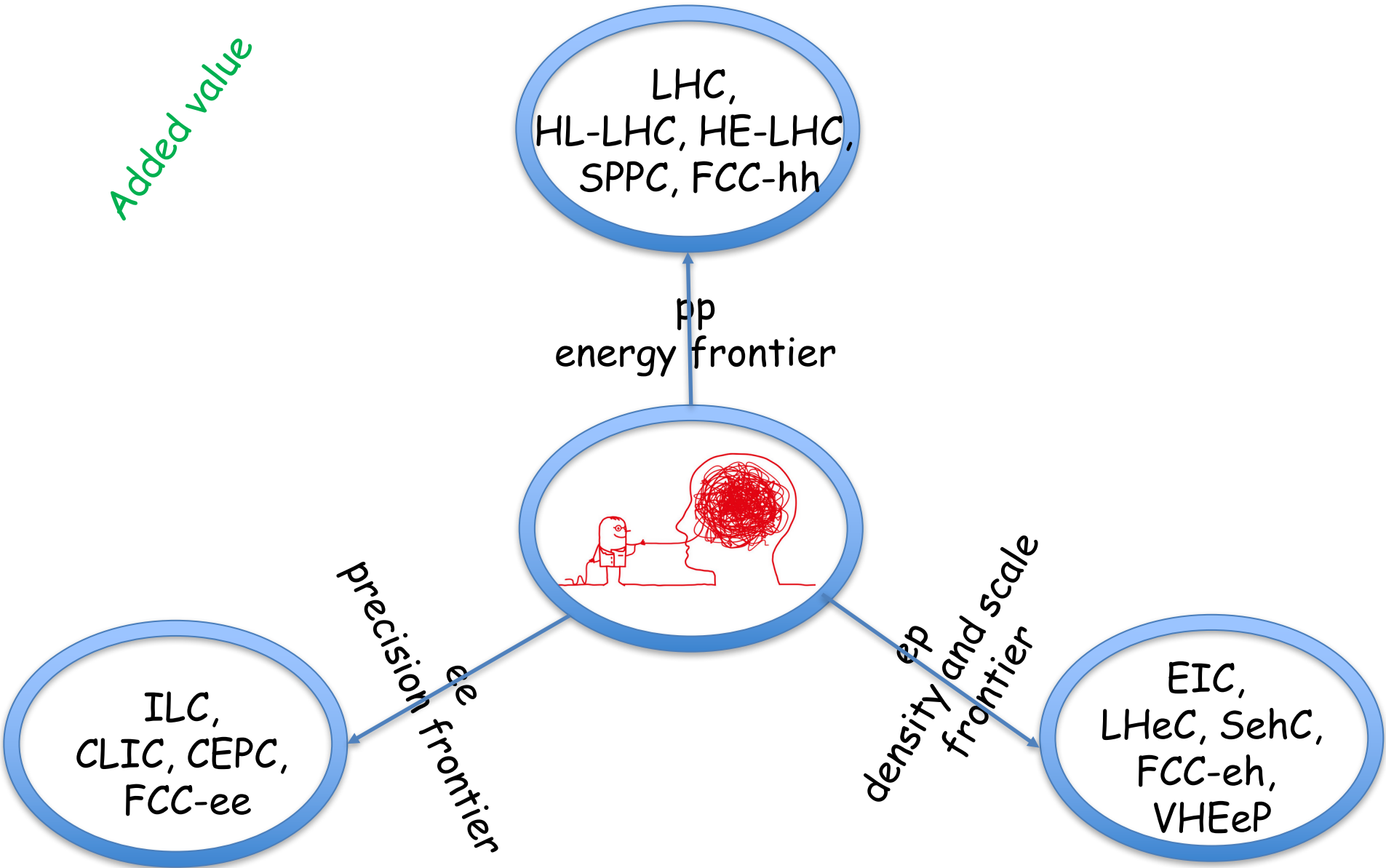


from M. Strassler

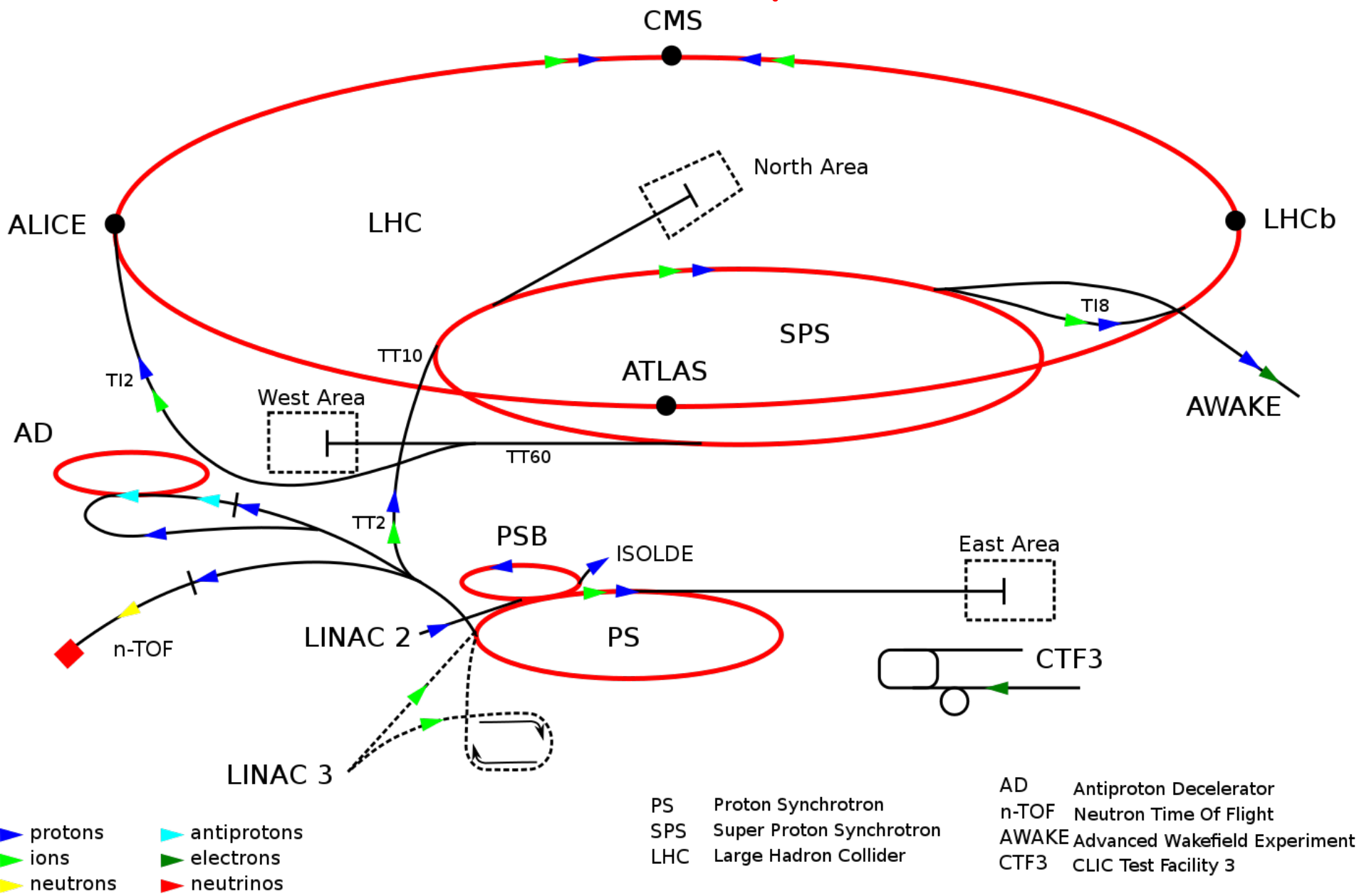
How should we go about understanding all these issues ?

Controlled experiments at accelerators

Added value



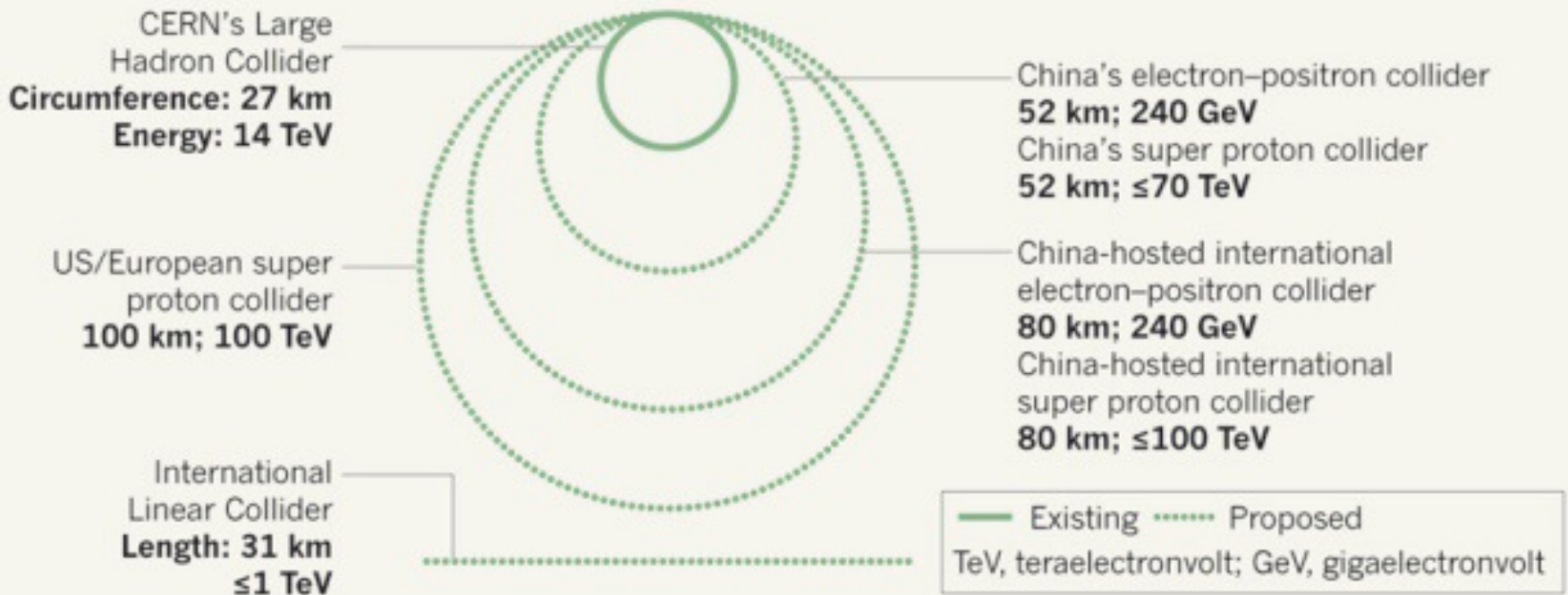
Present Accelerator Complex at CERN



Collision Course

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



Energy frontier

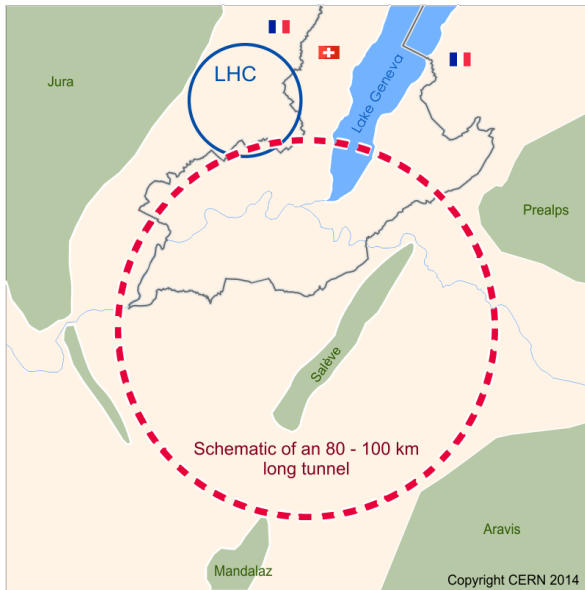
- Hadron colliders

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

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

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

Geneva



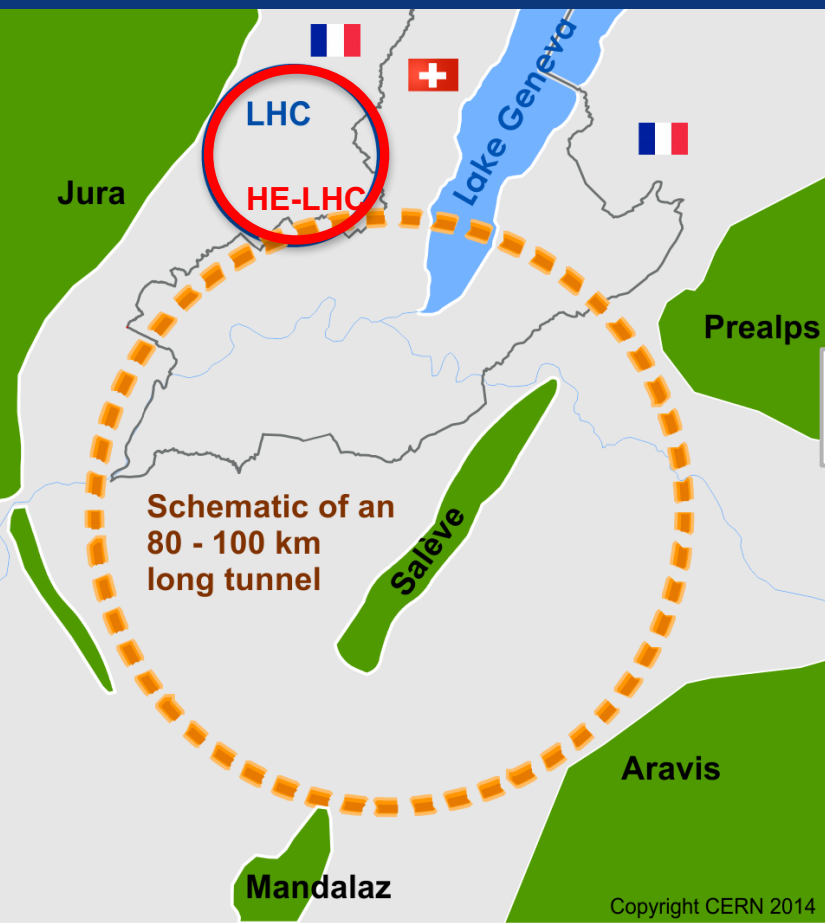
Qinghuada



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



Future Circular Collider (FCC) Study

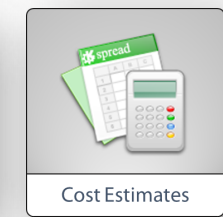
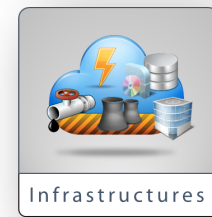
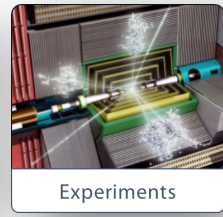
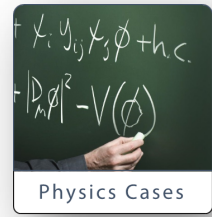


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (FCC-*hh*)**
→ main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- ~100 km tunnel infrastructure in Geneva area, site specific
- ***e⁺e⁻* collider (FCC-*ee*)**, as potential first step
- **HE-LHC** with *FCC-*hh** technology
- ***p-e* (FCC-*he*) option**, IP integration, *e⁻* from ERL



From M. Benedikt, PECFA Nov. 2017, CERN



FCC study: physics and performance targets

FCC-ee:

- Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_Z , m_W , m_{top} , $\sin^2 \theta_w^{\text{eff}}$, R_b , $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z)$, $m_Z m_W m_\tau$), Higgs and top quark couplings)
- Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks
- Machine design for 100 TeV c.m. energy & integrated luminosity $\sim 20\text{ab}^{-1}$ within 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV $\sim 14 \text{ TeV} \times 16 \text{ T}/8.33\text{T}$, target luminosity $\geq 4 \times \text{HL-LHC}$
- Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies

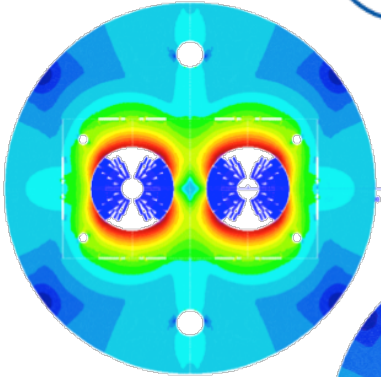
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16 T dipole design activities and options

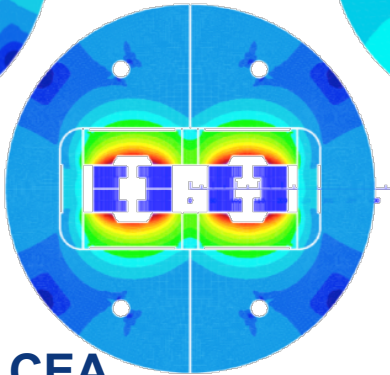


Cos-theta



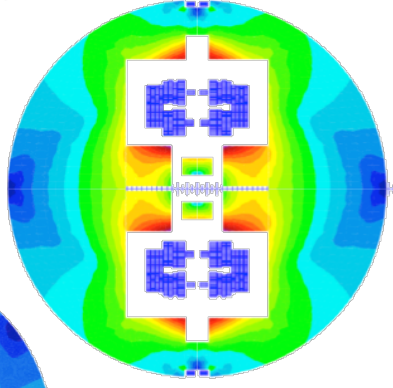
INFN

Blocks



CEA

Common coils

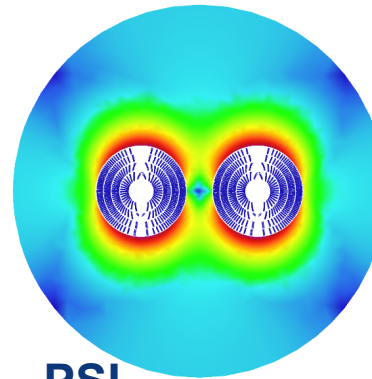


CIEMAT

Swiss contribution



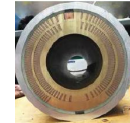
Canted Cos-theta



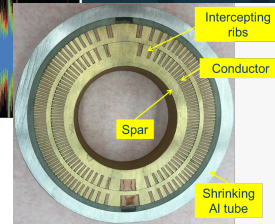
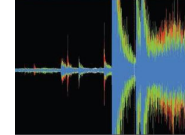
PSI



The U.S. Magnet Development Program Plan

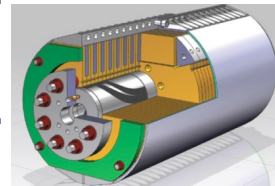


S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510
D. Larbaestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310



LBLN

FNAL



Short model magnets (1.5 m lengths) will be built from 2017 - 2022

From M. Benedikt, PECFA Nov. 2017, CERN



HE-LHC integration aspects

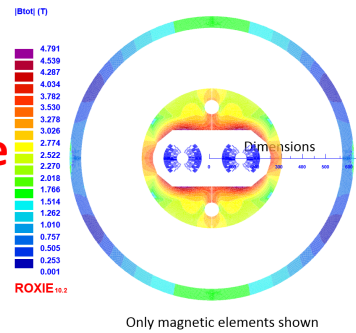
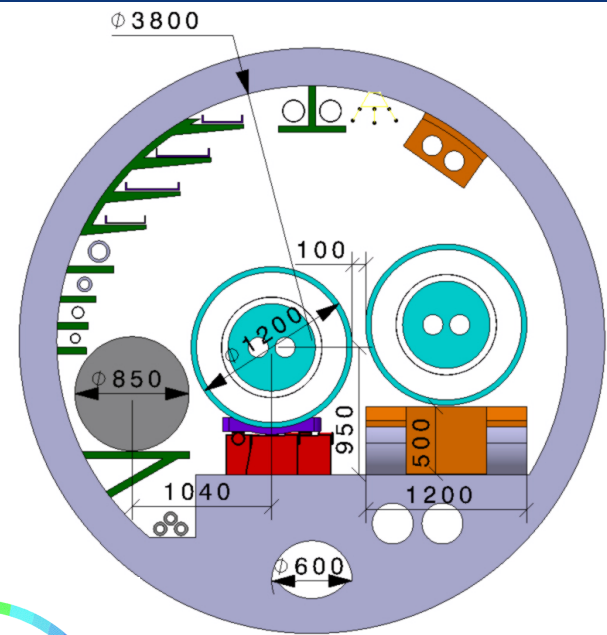
Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical cryostat design gives ~1500 mm diameter!**

Strategy: develop optimized 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
 - **Optimization of inter-beam distance (compact)**
- Smaller diameter also relevant for FCC-hh cost

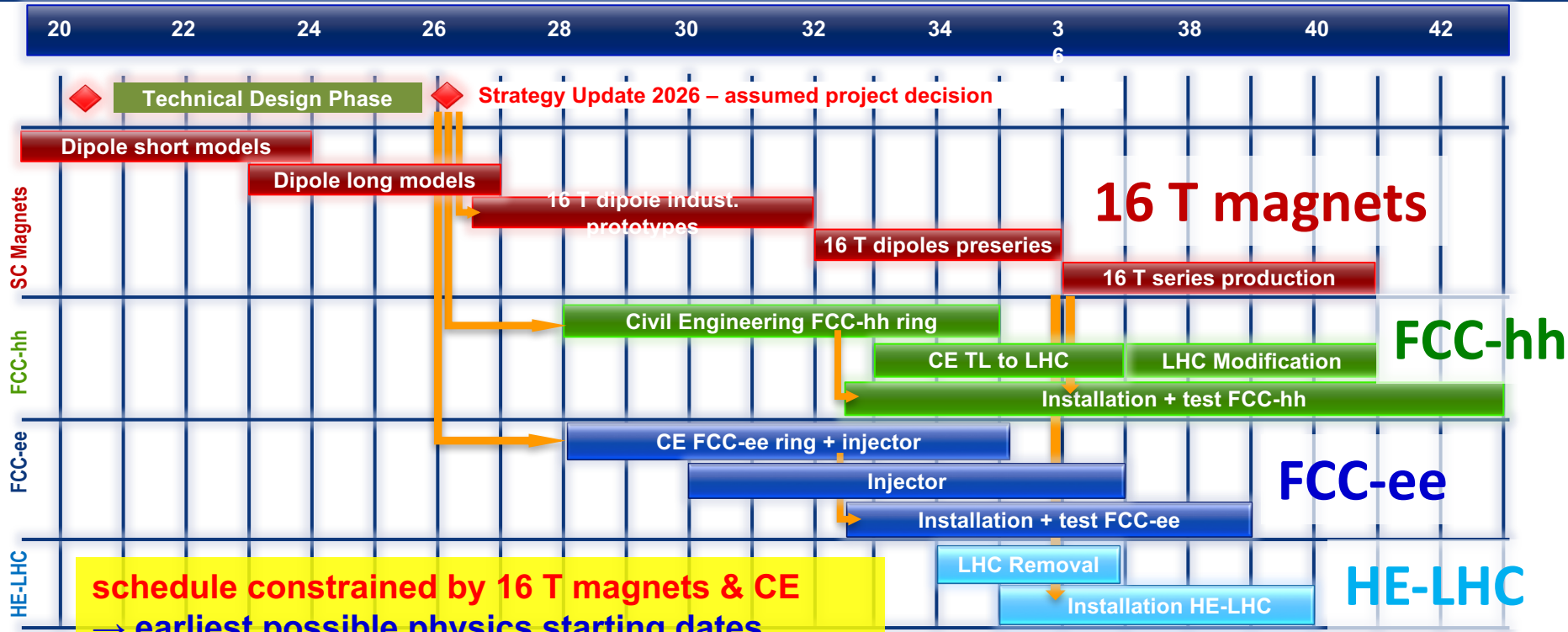


Description	OD in mm
Iron yoke	600
Aluminium shrinking cylinder	740
Stainless steel He tight shell	760
Al radiation shield	940
Vacuum vessel (magnetic steel)	1220

From M.Lemont, PECFA Nov. 2017, CERN



Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE
 → earliest possible physics starting dates

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

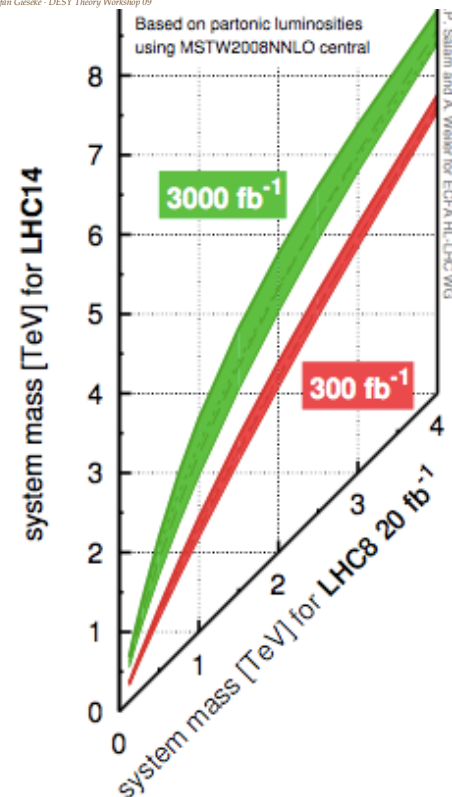
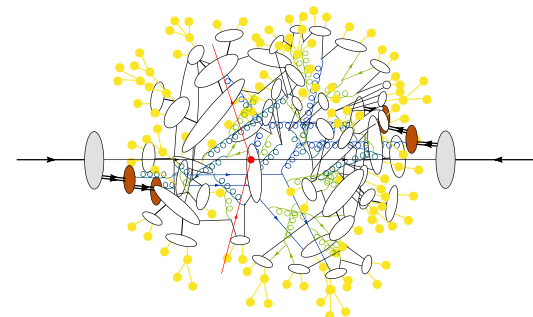
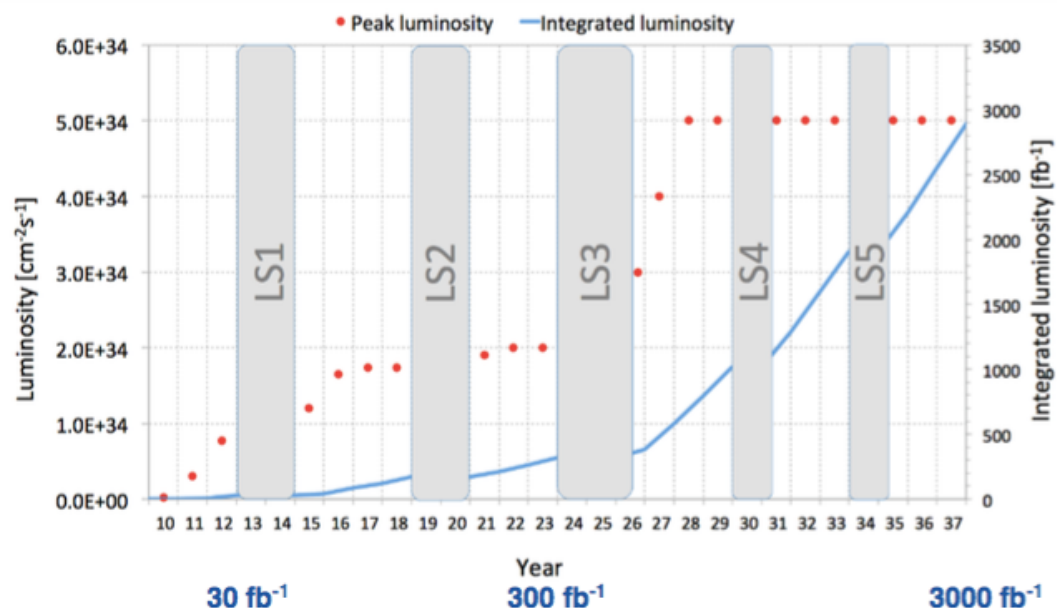
From M. Benedikt, PECFA Nov. 2017, CERN

Energy Frontiers

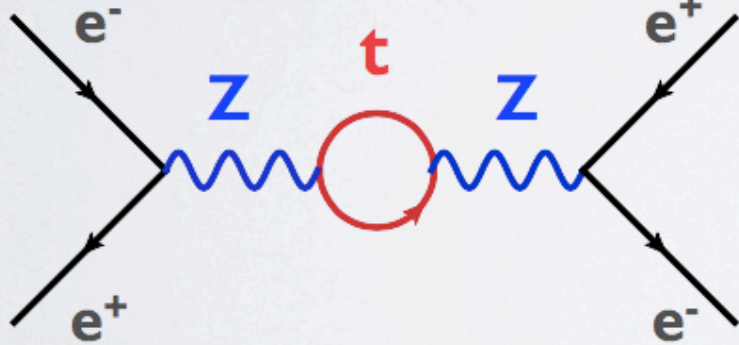
pp interactions are not very efficient energy-wise but no-alternative

At 14 TeV and 3 ab^{-1} mass reach $< 10 \text{ TeV}$

Integrated luminosity

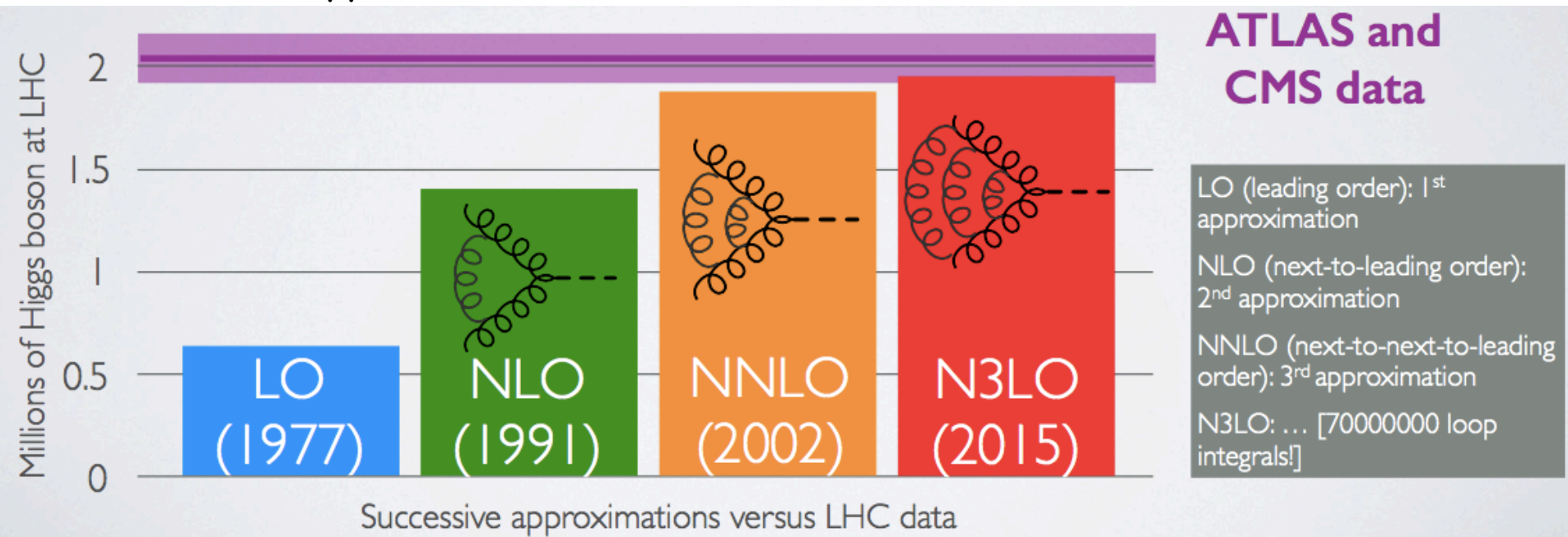


Precision Frontier



- 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 $pp \rightarrow H + X$

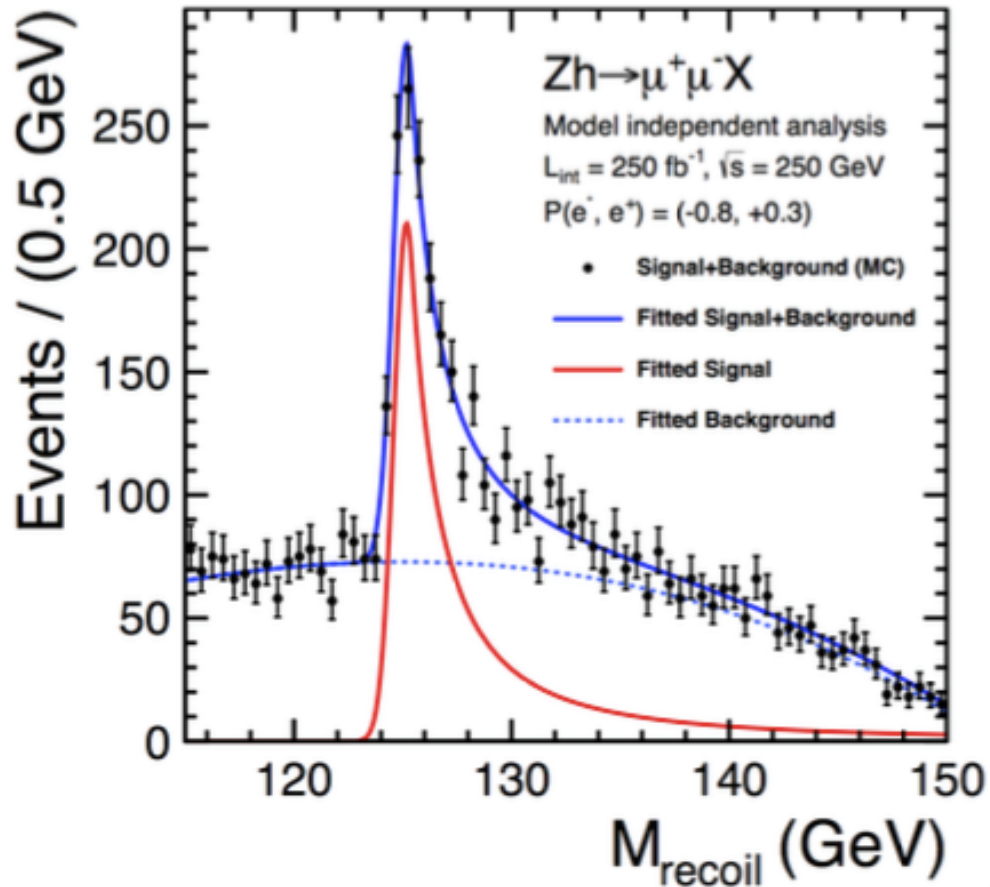
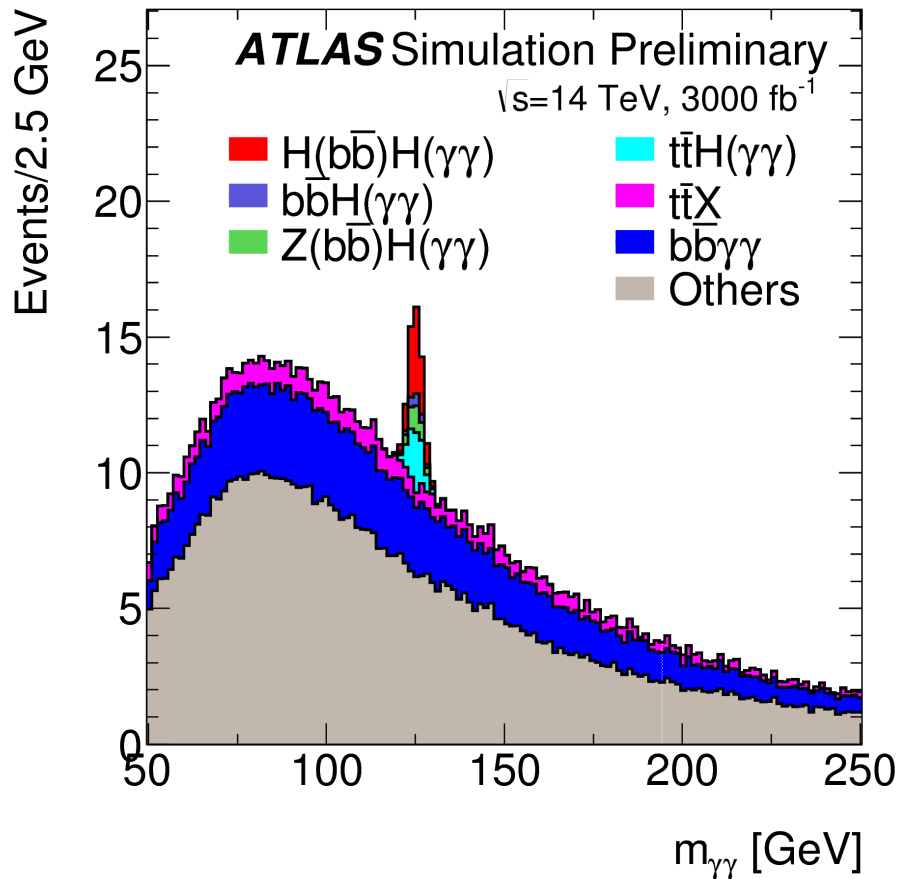


Precision Frontier

Precision Higgs

HL-LHC

ILC



Precision frontier

- Electron-positron machines

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

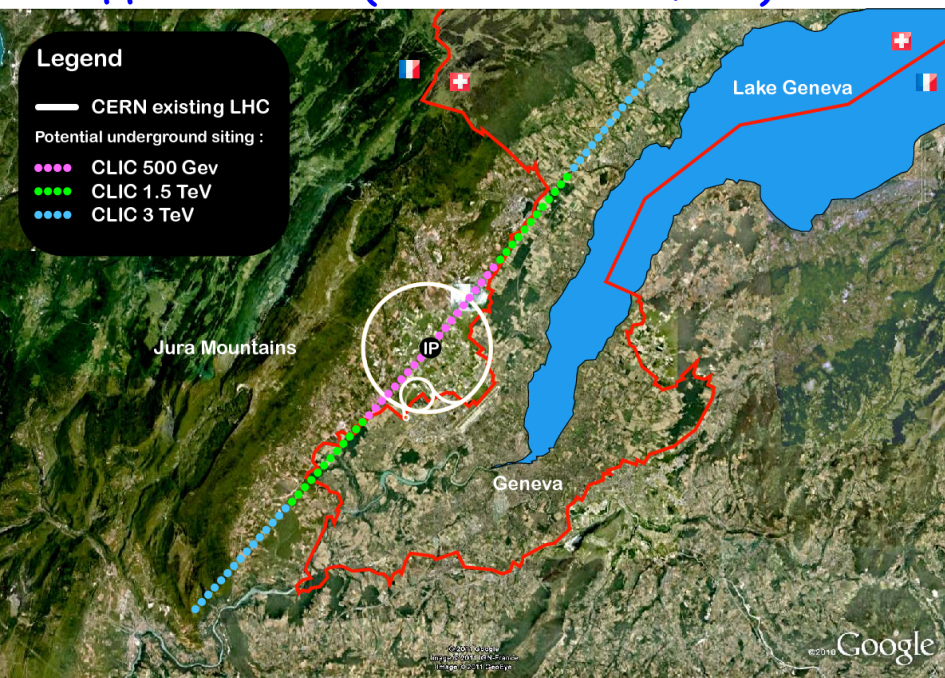
CERN: CLIC - linear collider, 380 GeV to 3 TeV (up to 50 km)

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

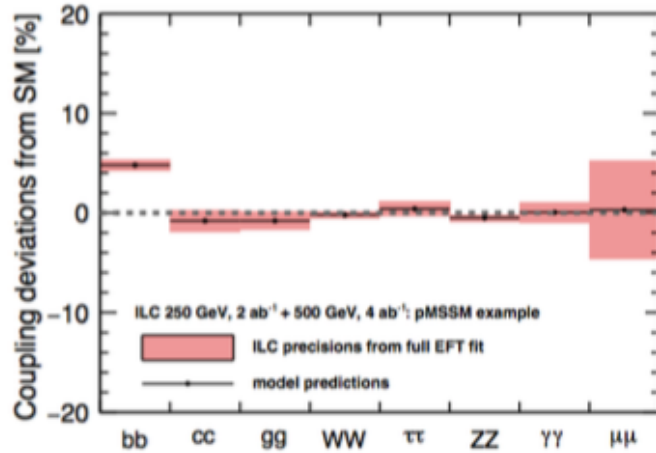


ILC (upgrade)
 31km (50km), 30V/m (45V/m)
 500 GeV (1 TeV)

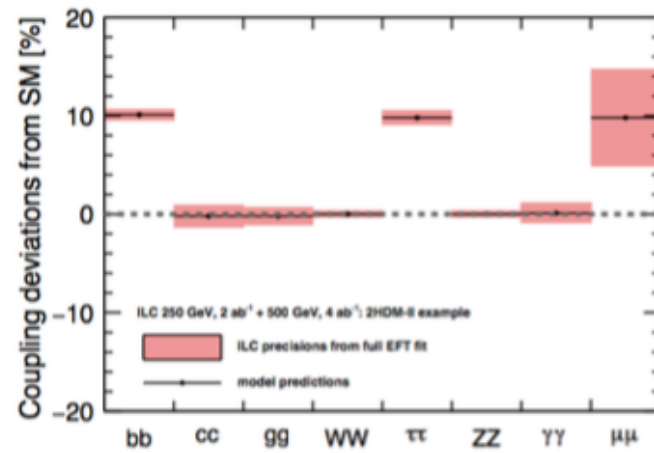
Accelerating structures 72 to 100 MV/m

Sensitivity of Higgs couplings to BSM

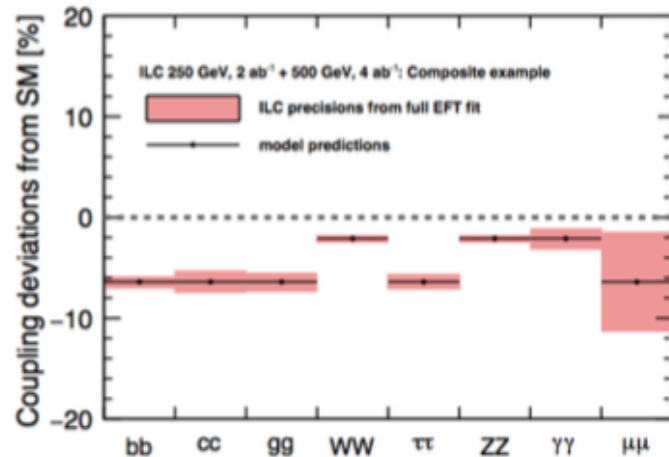
heavy SUSY



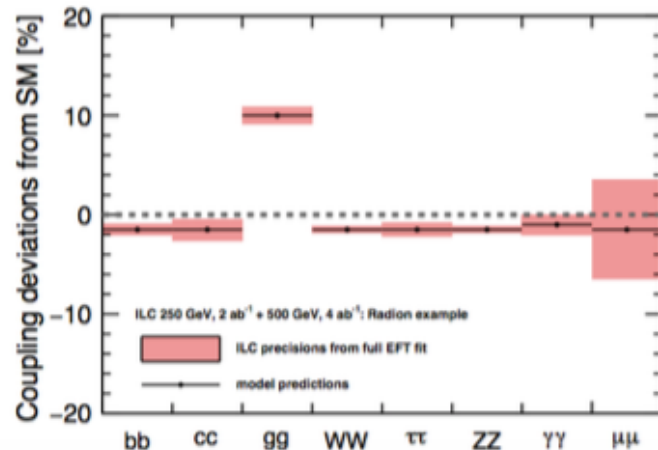
2 Higgs doublet



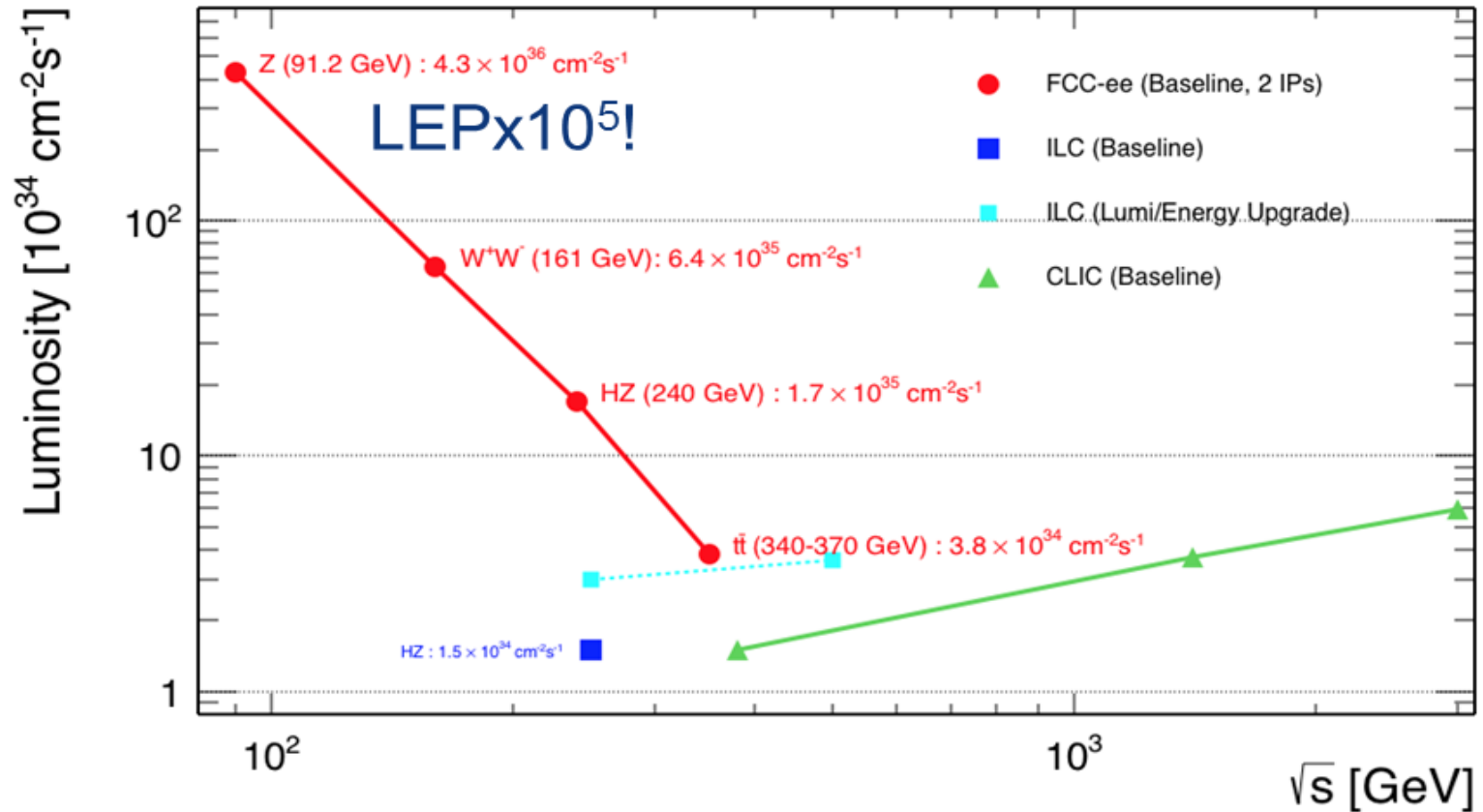
composite Higgs



Higgs-Radion mixing



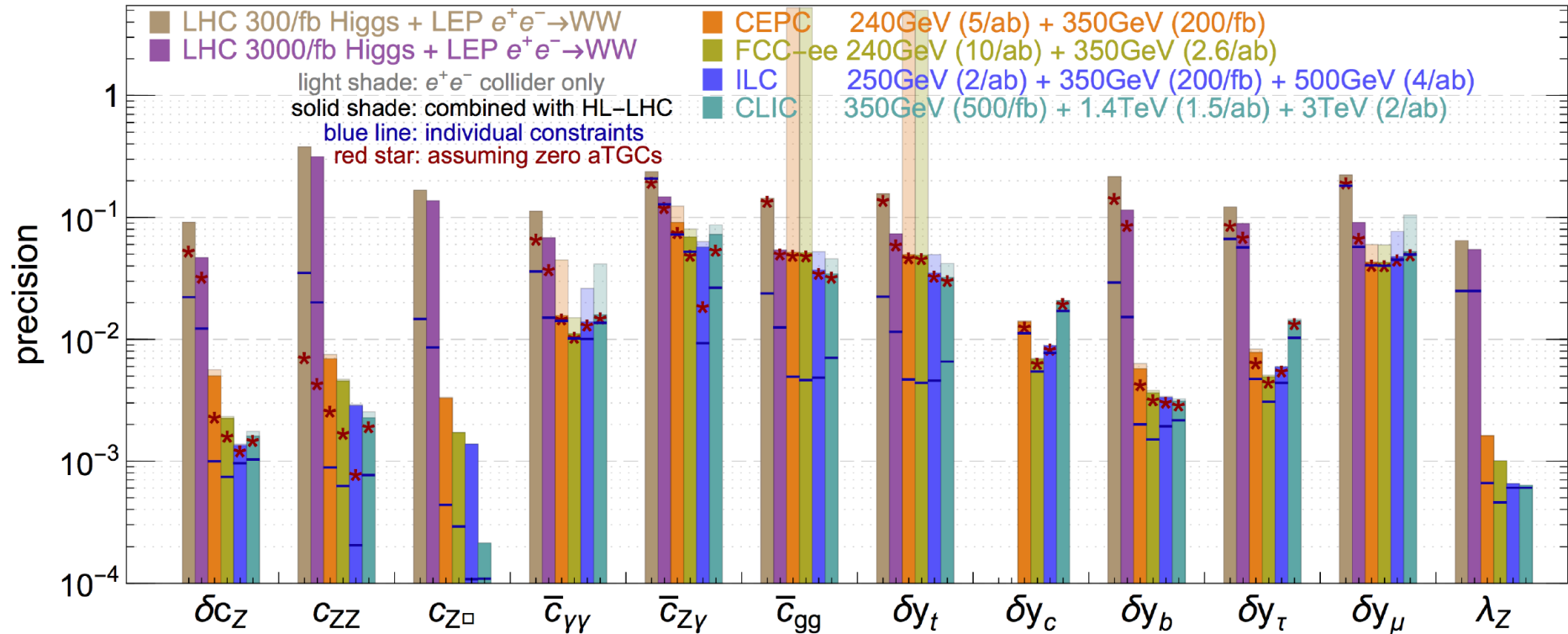
Precision Frontier



Luminosity vs energy for e^+e^- colliders

Comparison between collider options

Precision reach of the 12-parameter fit in Higgs basis



- Many EFT parameters can be measured **significantly better at CLIC than at HL-LHC**
- $H \rightarrow cc$ only accessible at lepton colliders

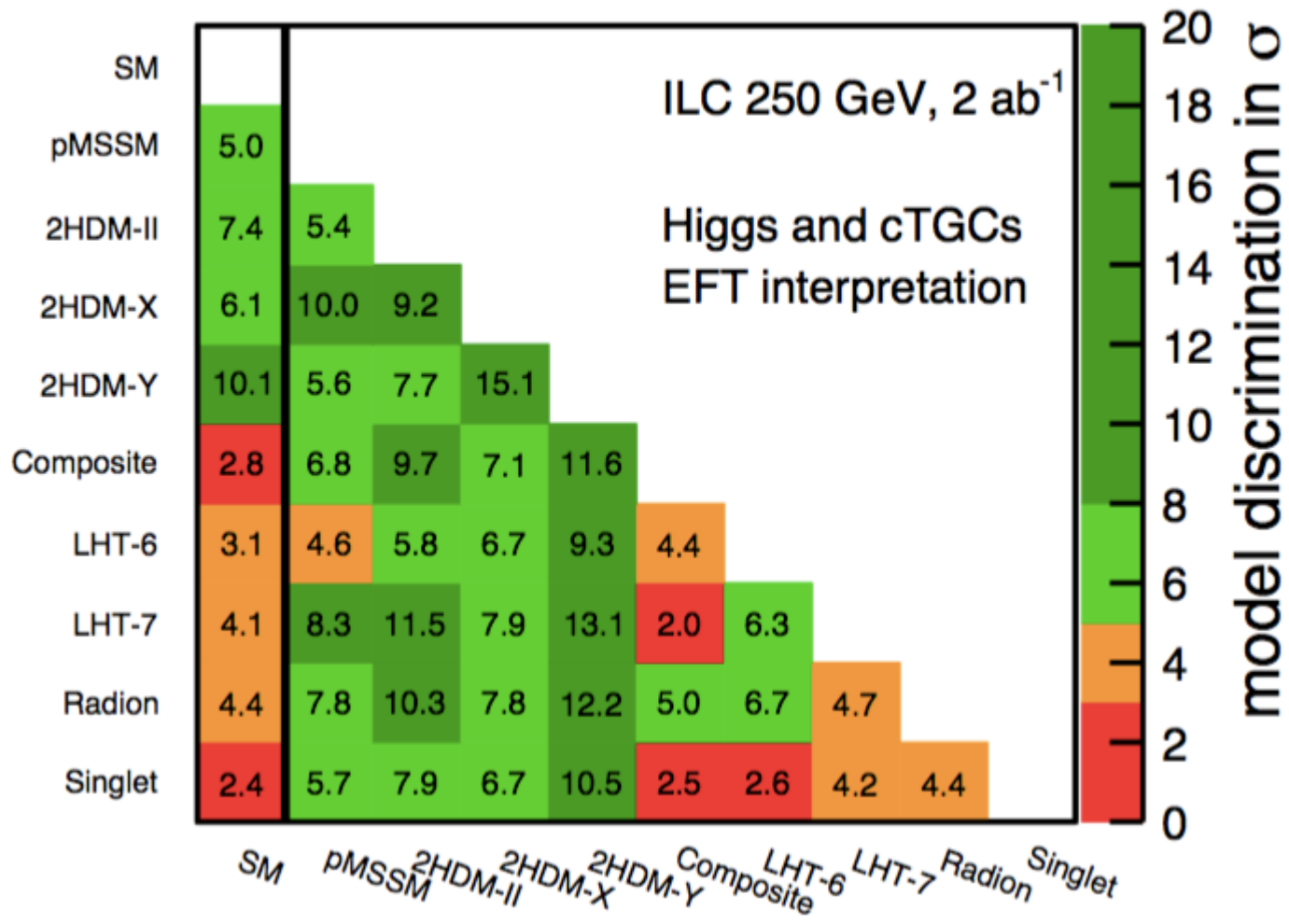
arXiv:1704.02333
See also [JHEP 1705, 096 \(2017\)](#)

Here are some final results for various proposed colliders:

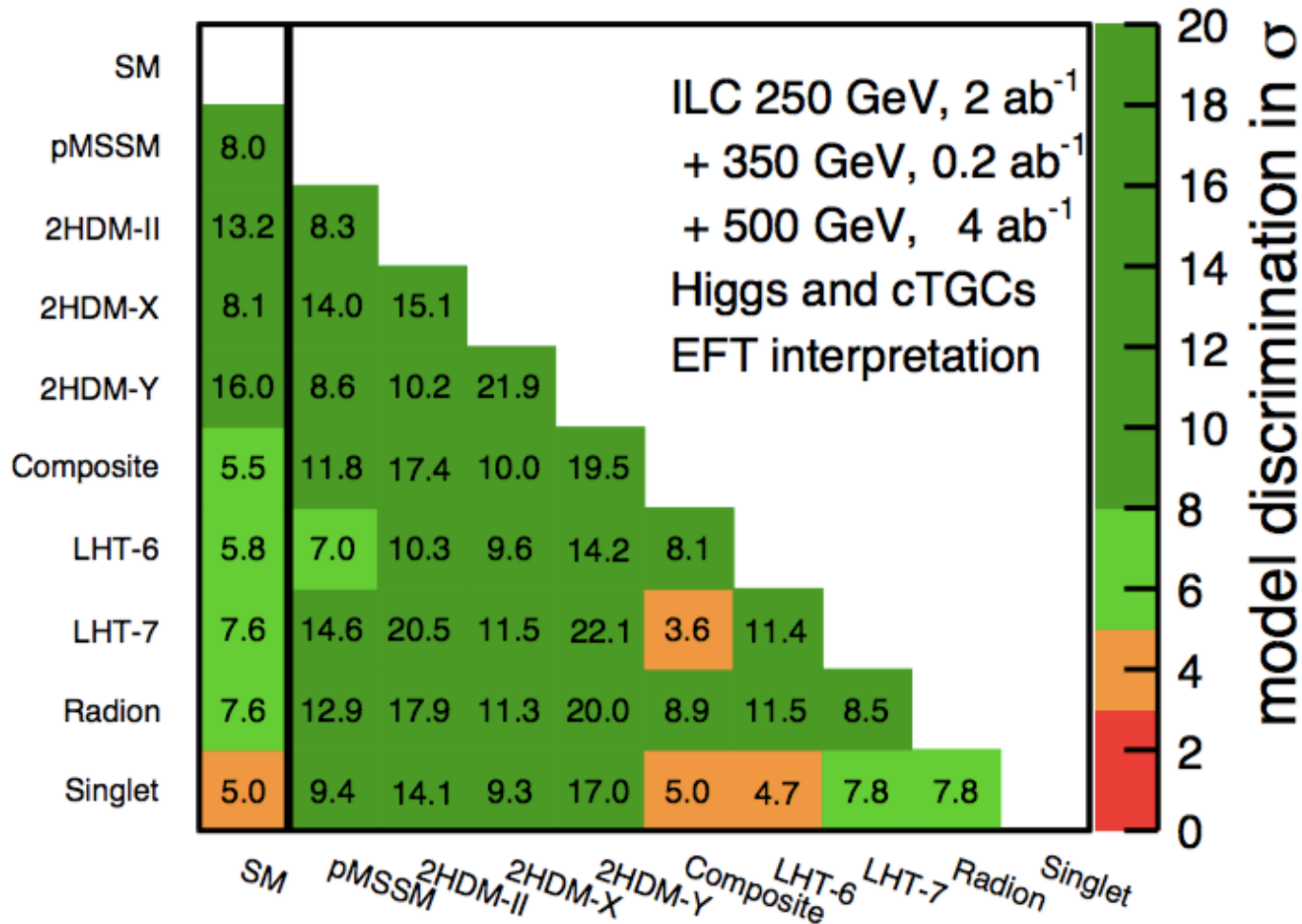
	ILC250 2 ab ⁻¹ w. pol.	CLIC350 2 ab ⁻¹ 350 GeV	CEPC 5 ab ⁻¹ no pol.	FCC-ee + 1.5 ab ⁻¹ at 350 GeV	ILC250+500 full ILC 250+500 GeV
$g(hb\bar{b})$	1.1	1.1	0.98	0.66	0.58
$g(hc\bar{c})$	1.9	2.3	1.4	1.2	1.2
$g(hgg)$	1.7	1.7	1.3	0.99	0.95
$g(hWW)$	0.67	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.2	1.4	1.1	0.75	0.74
$g(hZZ)$	0.68	0.57	0.80	0.42	0.35
$g(h\gamma\gamma)$	1.2	1.2	1.3	1.0	1.0
$g(h\mu\mu)$	5.6	5.7	5.1	4.87	5.1
$g(hb\bar{b})/g(hWW)$	0.88	0.90	0.58	0.51	0.46
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.5	2.5	2.1	1.5	1.6
$BR(h \rightarrow inv)$	0.32	0.56	0.30	0.27	0.29
$BR(h \rightarrow other)$	1.6	1.6	1.1	0.94	1.2

errors in %

results: ILC 250 GeV 2 ab⁻¹



results: ILC 250 GeV 2 ab⁻¹ + 500 GeV 4 ab⁻¹



Latest news from ICFA seminar in Ottawa

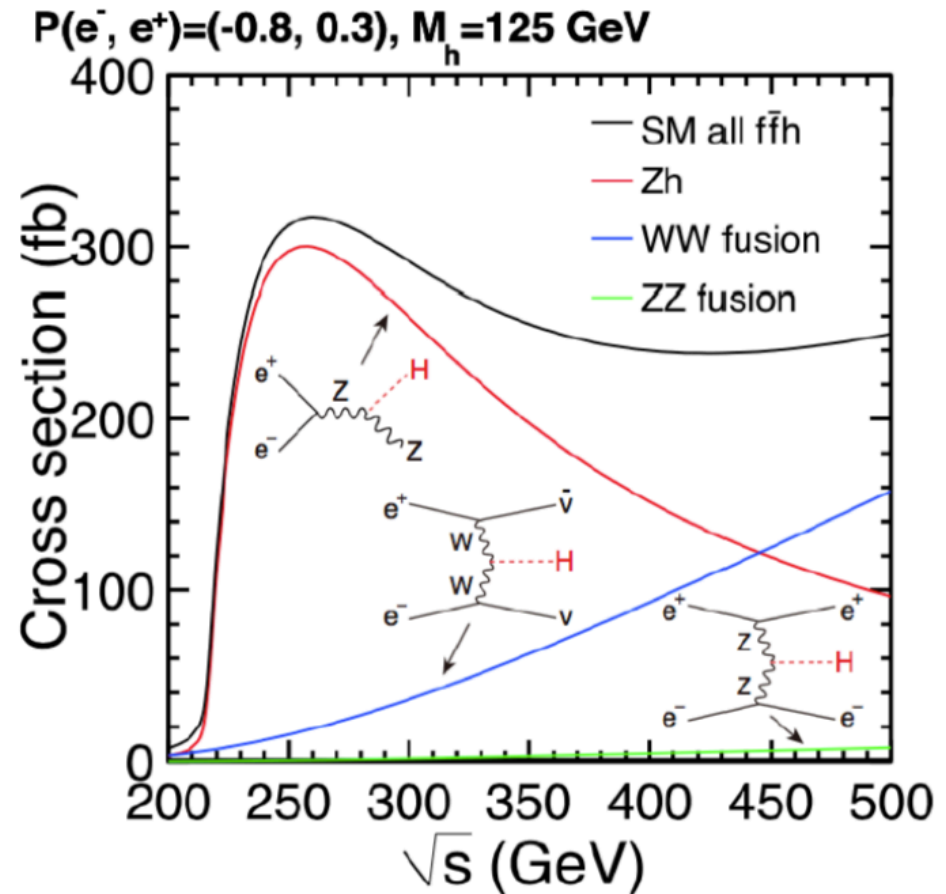
Japanese HEP community Statement

..., in light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan

Linear Collider Board statement

- Compelling case for a Higgs factory at 250 GeV
- Substantial cost reduction compared to the original 500 GeV ILC
- Technology is mature, thanks to the European XFEL
- Operation energy of a linear collider is intrinsically upgradable by extending the tunnel and accelerating structures

Subsequently endorsed by ICFA

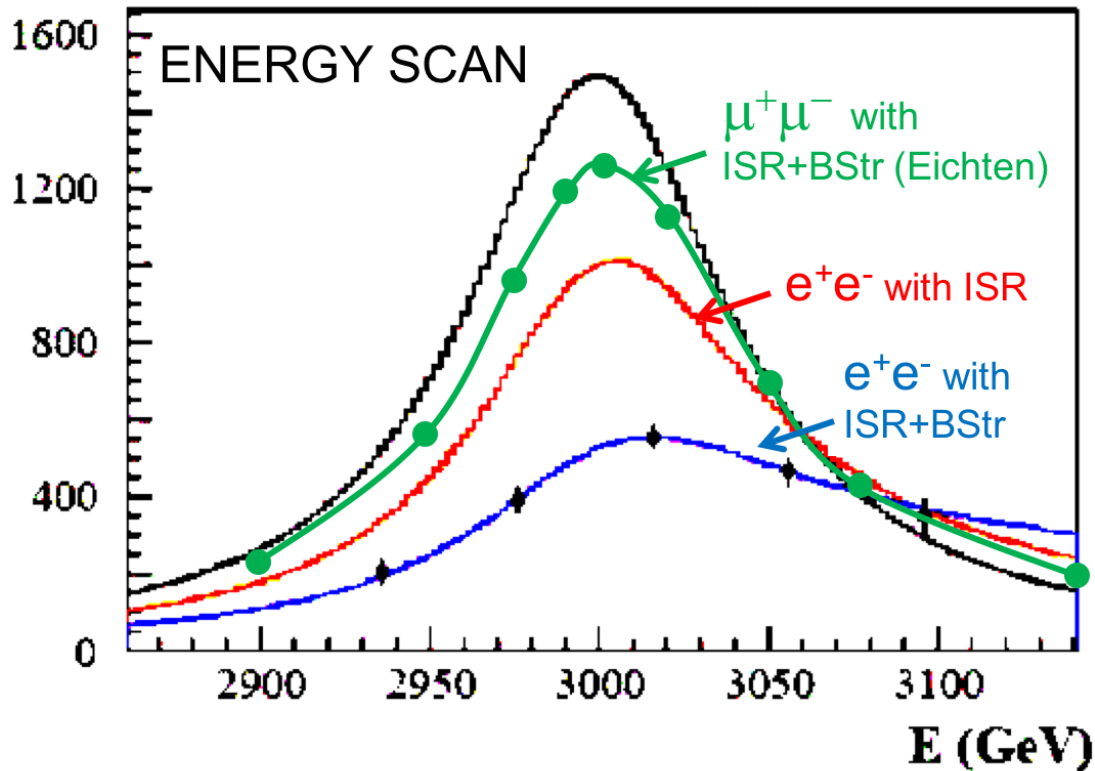


Precision Frontier - muon collider

- Muon collider - Higgs factory and energy frontier
- Circular collider - 120 GeV to 5 TeV, 300 m long (neutrino factory as added bonus)

Lucie Linssen, SPC, 15/6/2009

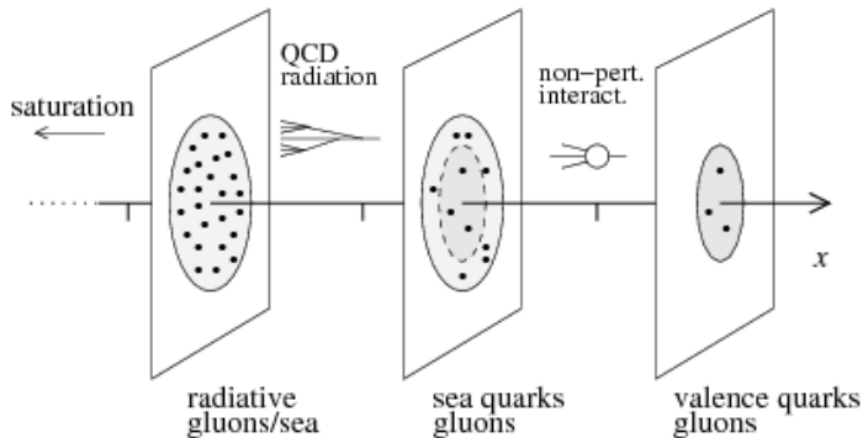
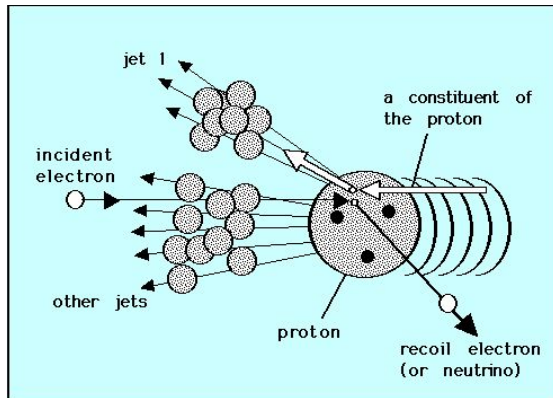
Muon Collider
Conceptual Layout



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

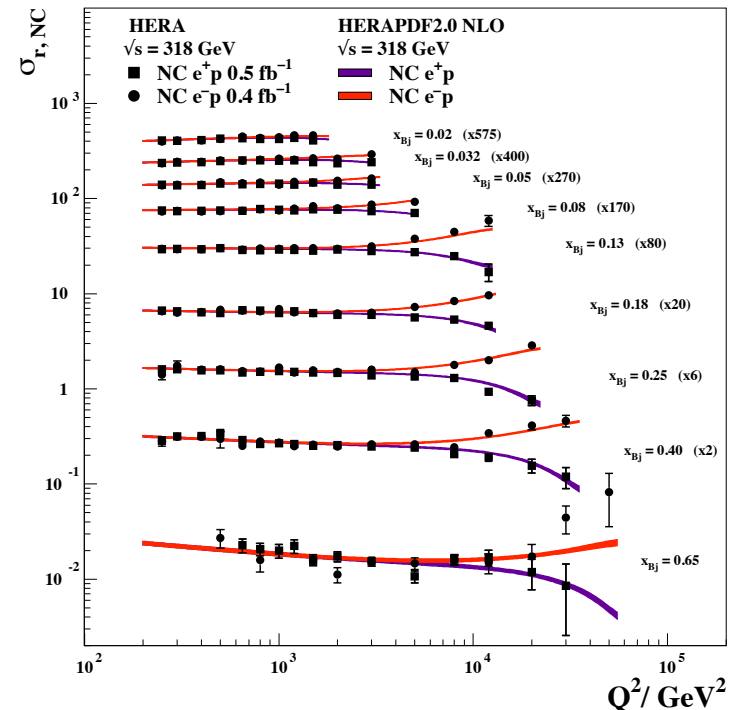
Density frontier and more

- 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

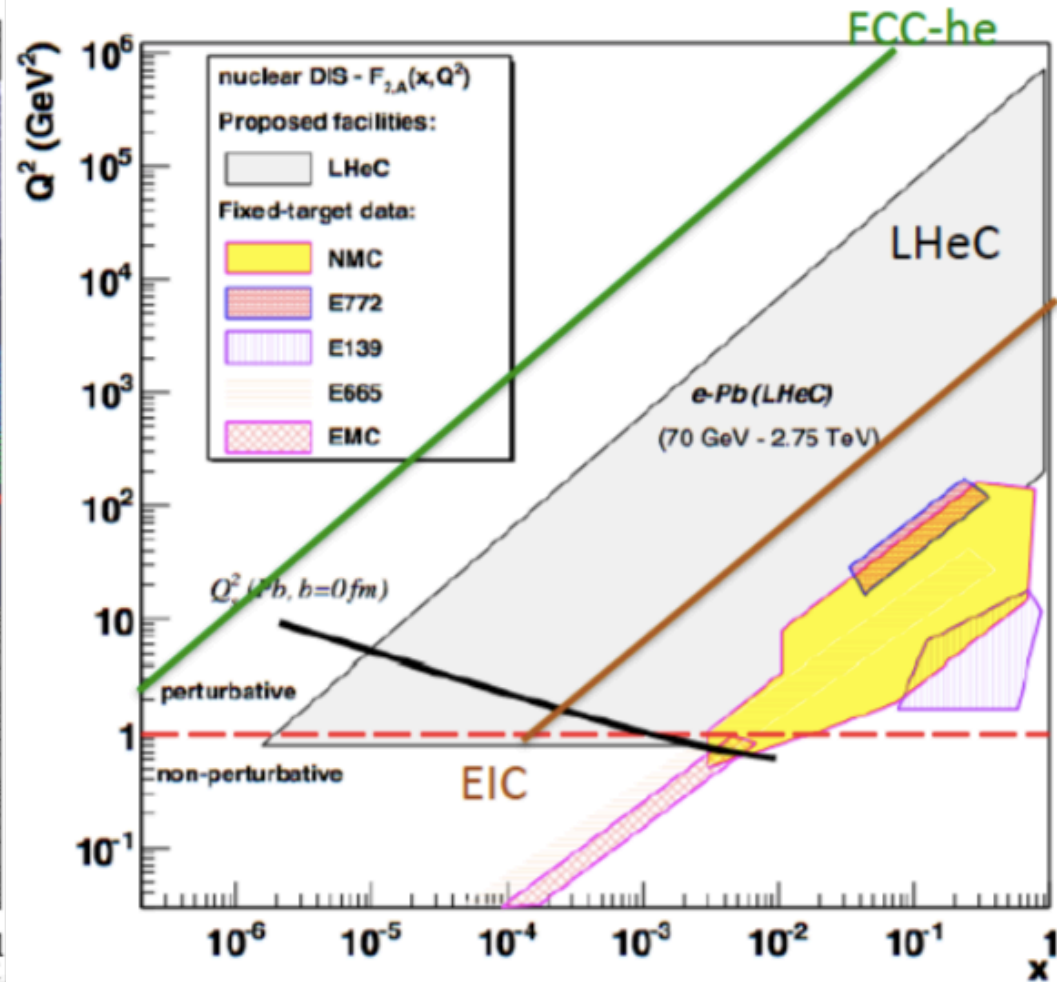
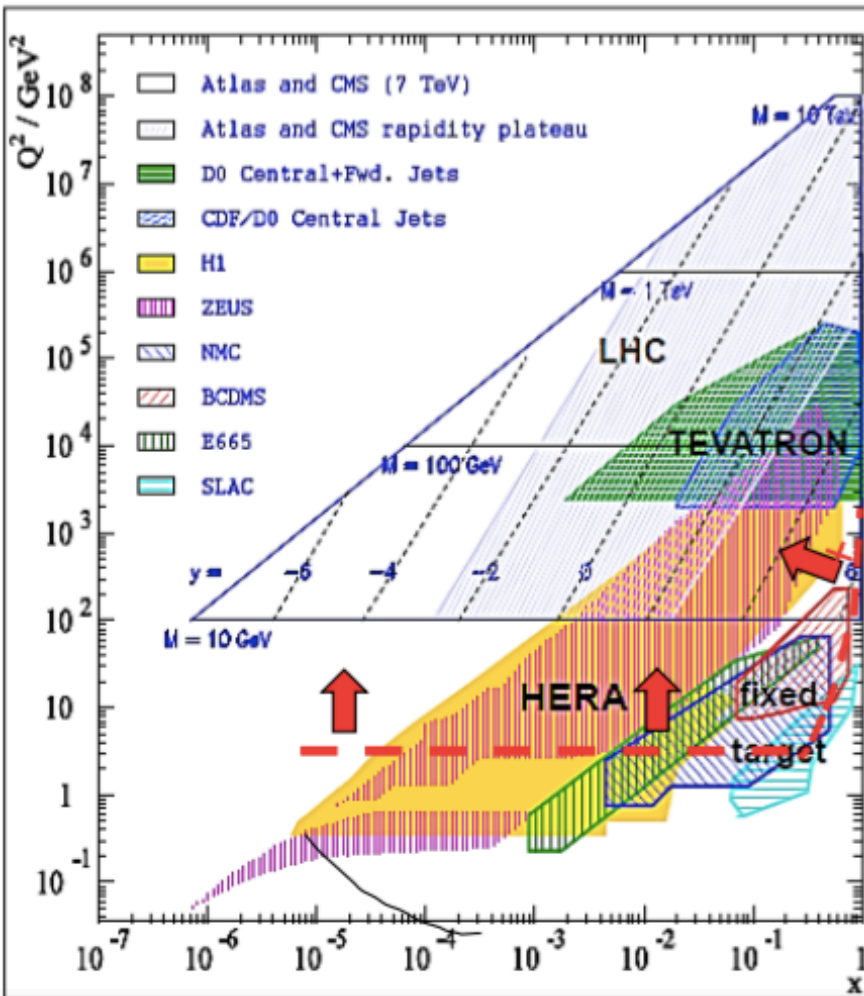


Legacy of ep collider HERA

H1 and ZEUS

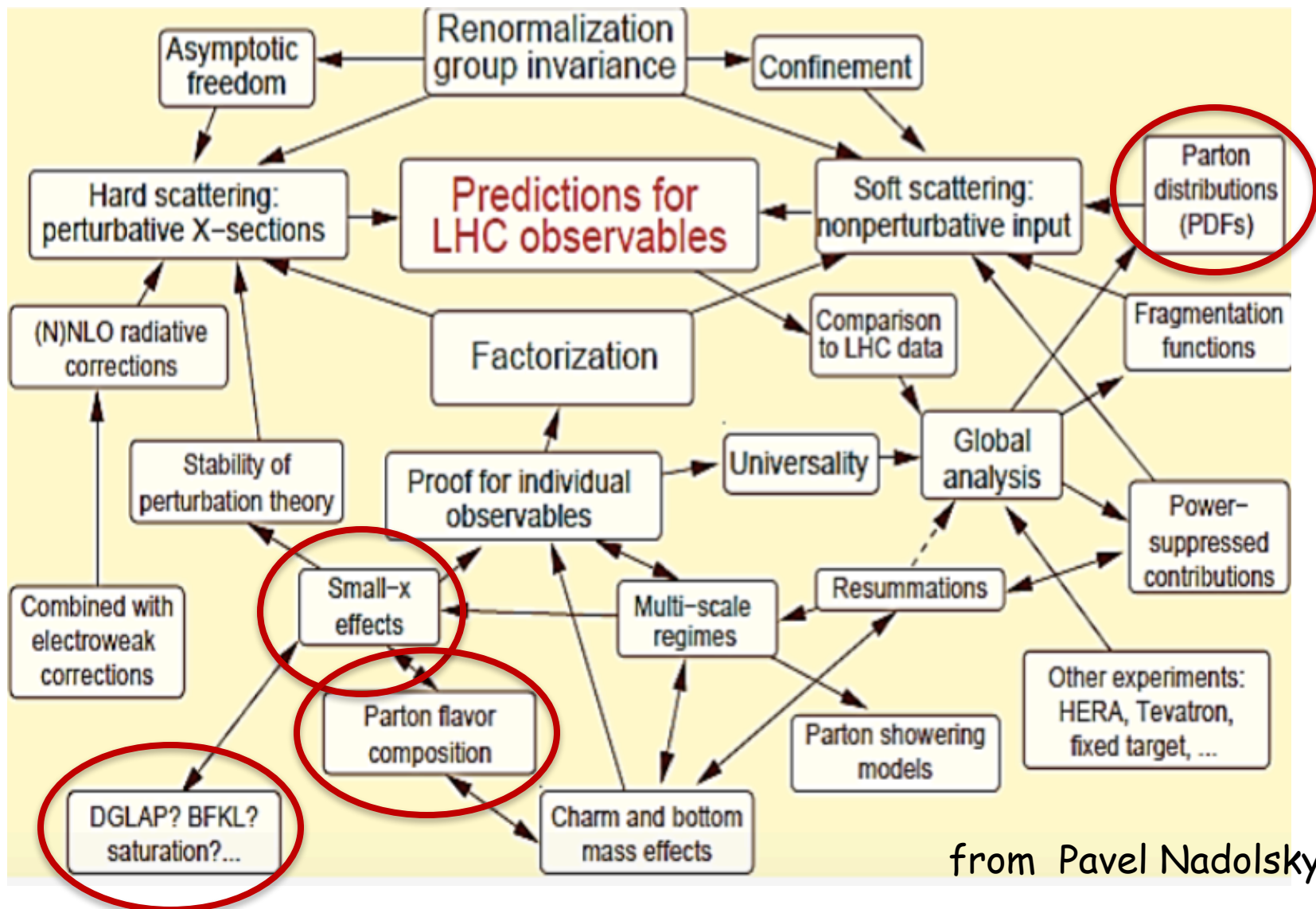


Density frontier and more



Proton structure and QCD

What it takes to get SM predictions for LHC



from Pavel Nadolsky

2+1 dimensional Imaging of Quarks & Gluons

Wigner function
 $W(x, b_T, k_T)$

Momentum space

Coordinate space

$$\int d^2 b_T$$

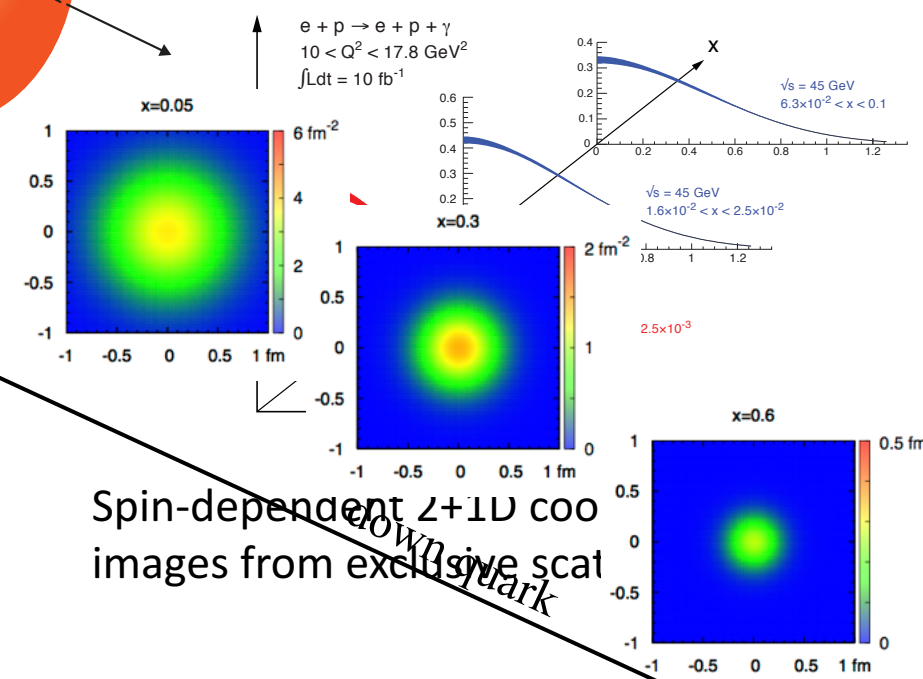
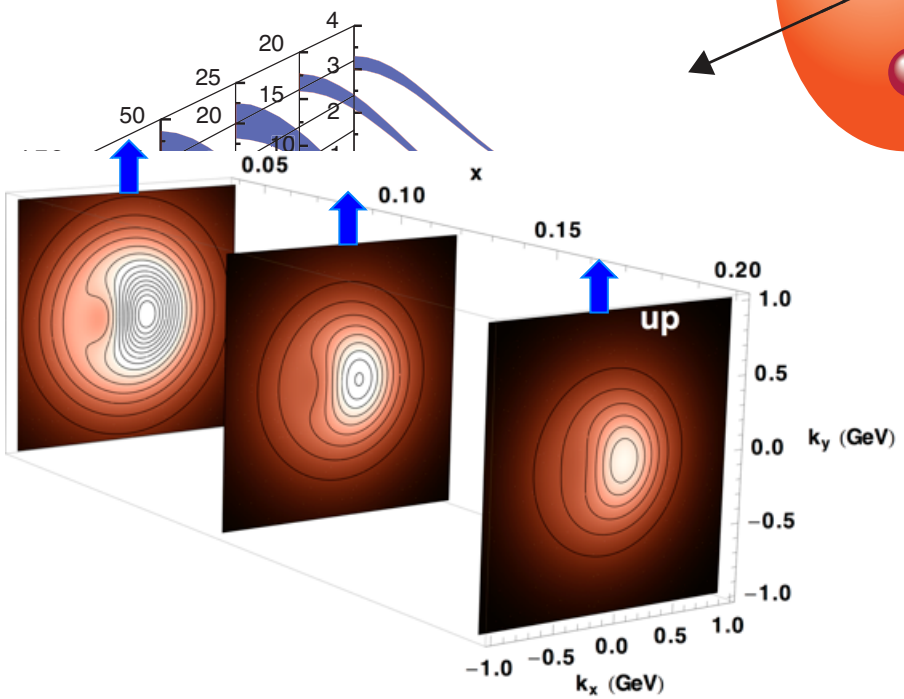
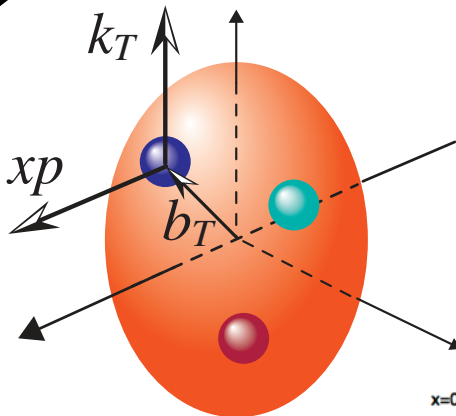
$$\int d^2 k_T$$

$$f(x, k_T)$$

$$f(x, b_T)$$

Quarks

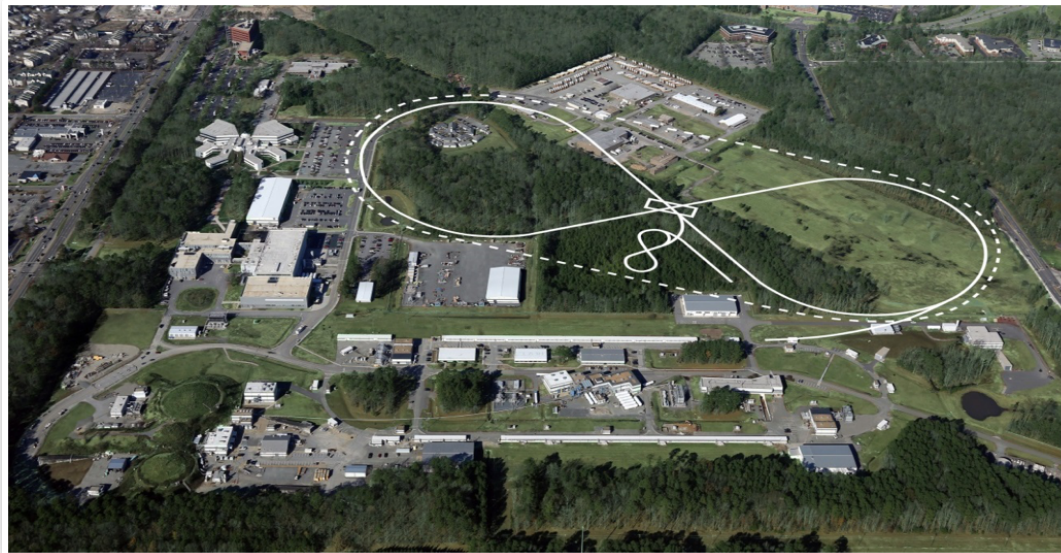
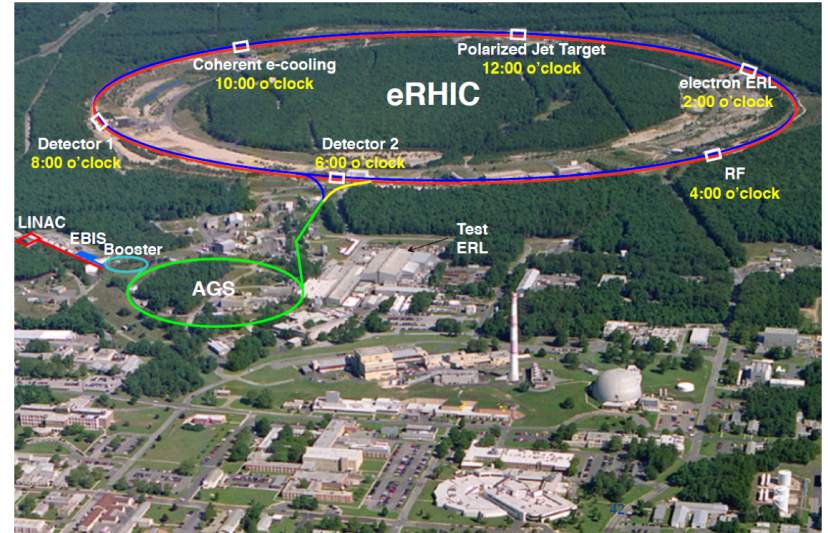
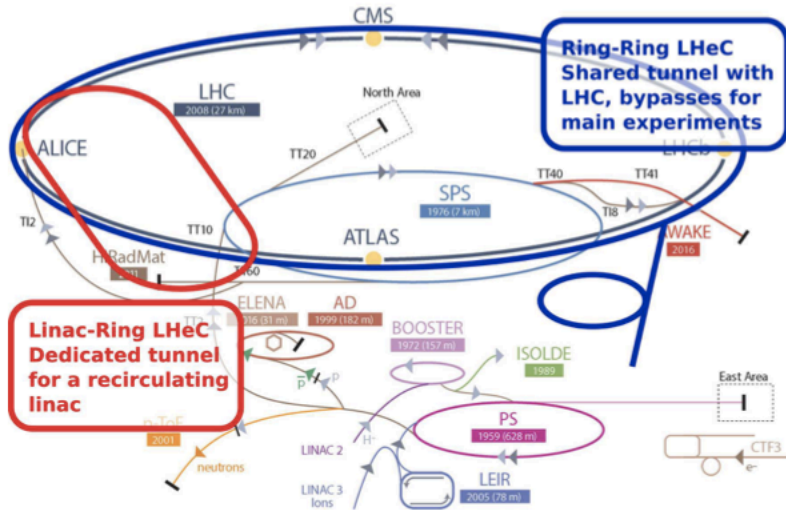
Quarks



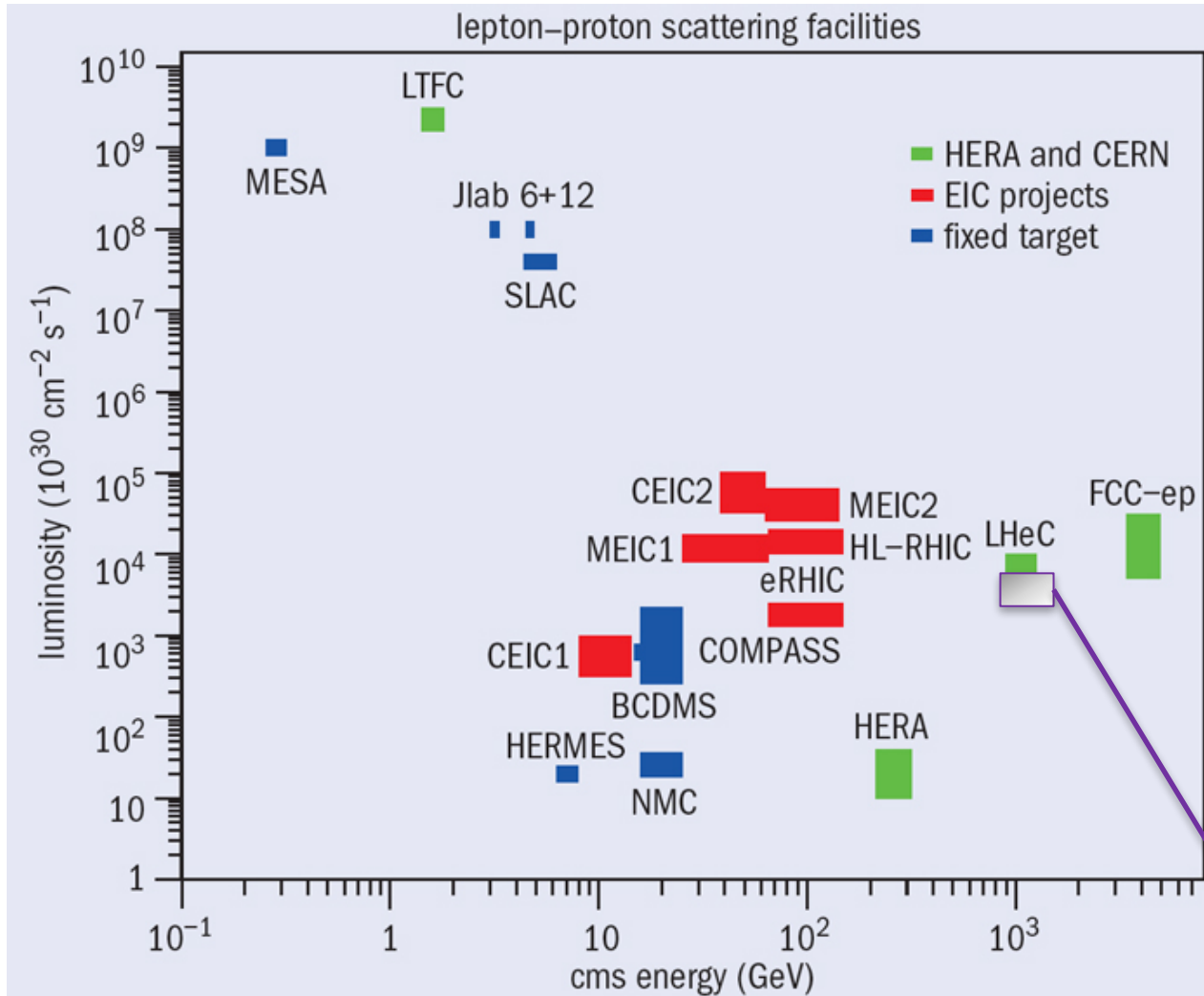
Spin-dependent 2+1D coordinate space images from exclusive scattering

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

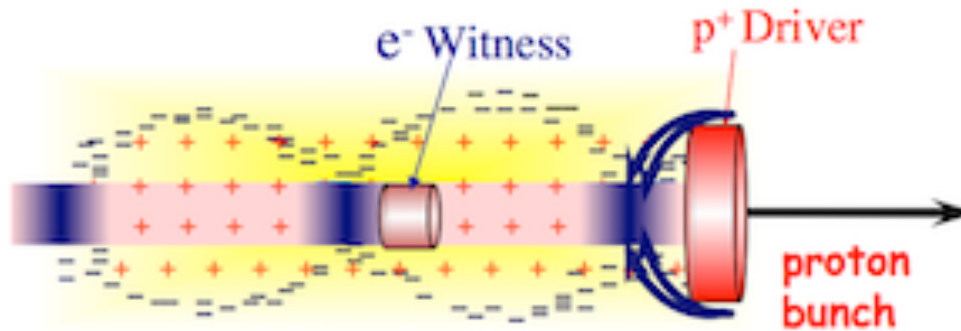
LHeC = ep/eA collider @ CERN

CEIC2
 MEIC2
 HL-eRHIC
 FCC-he

SehC

New Accelerator Technologies

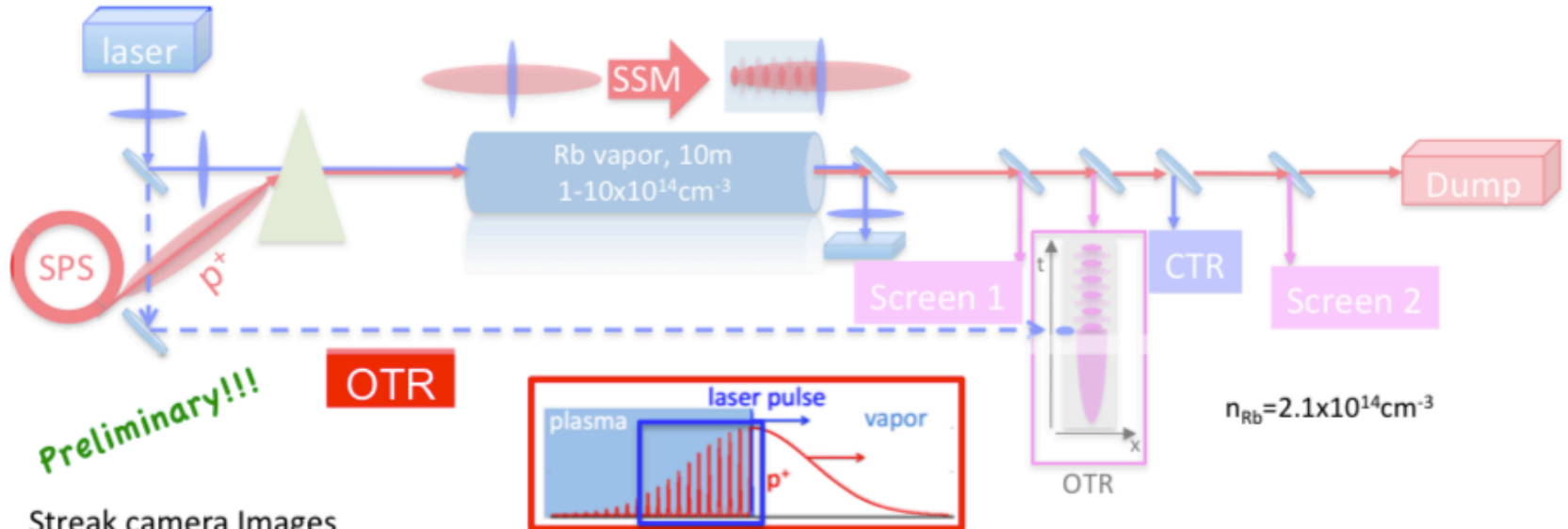
- Accelerators using RF cavities limited to ~ 100 MV/m; high energies \Rightarrow long accelerators
- Gradients in plasma wakefield acceleration of ~ 100 GV/m measured



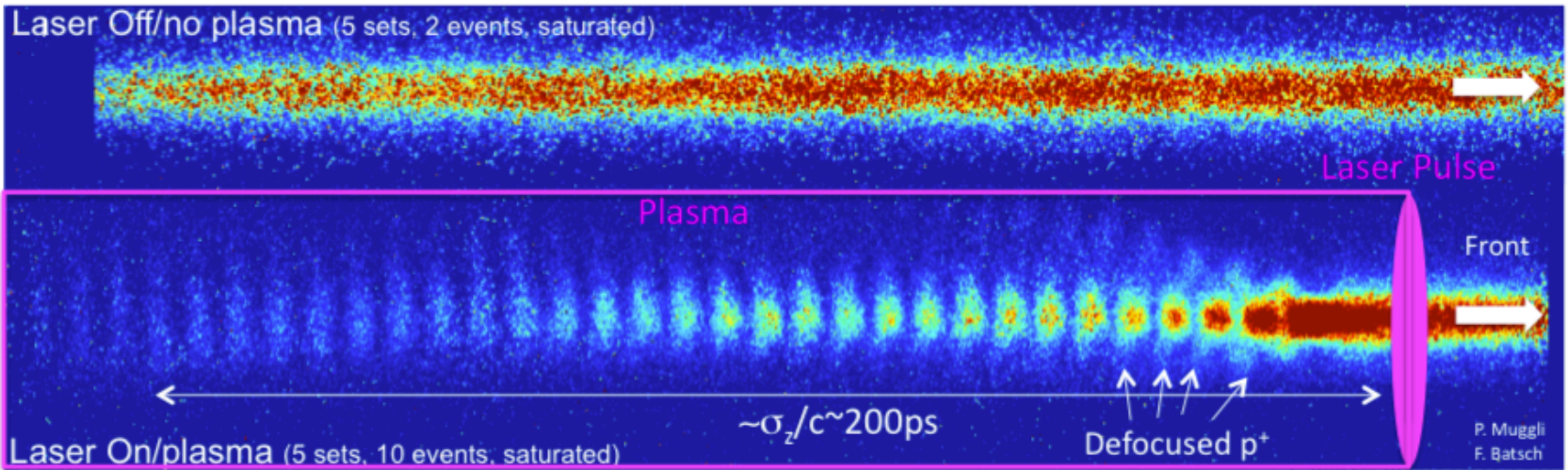
- ❖ ILC-CLIC, 0.5 TeV bunch with $2 \times 10^{10} e^-$ - about 1.6kJ
- ❖ SPS, 400 GeV bunch with $10^{11} p$ - about 6.4kJ
- ❖ LHC, 7 TeV - 112kJ
- ❖ A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage
- ❖ Large average gradient (>1 GV/m, 100's m)

Proof of principle under way at the SPS at CERN

μBUNCH TRAIN

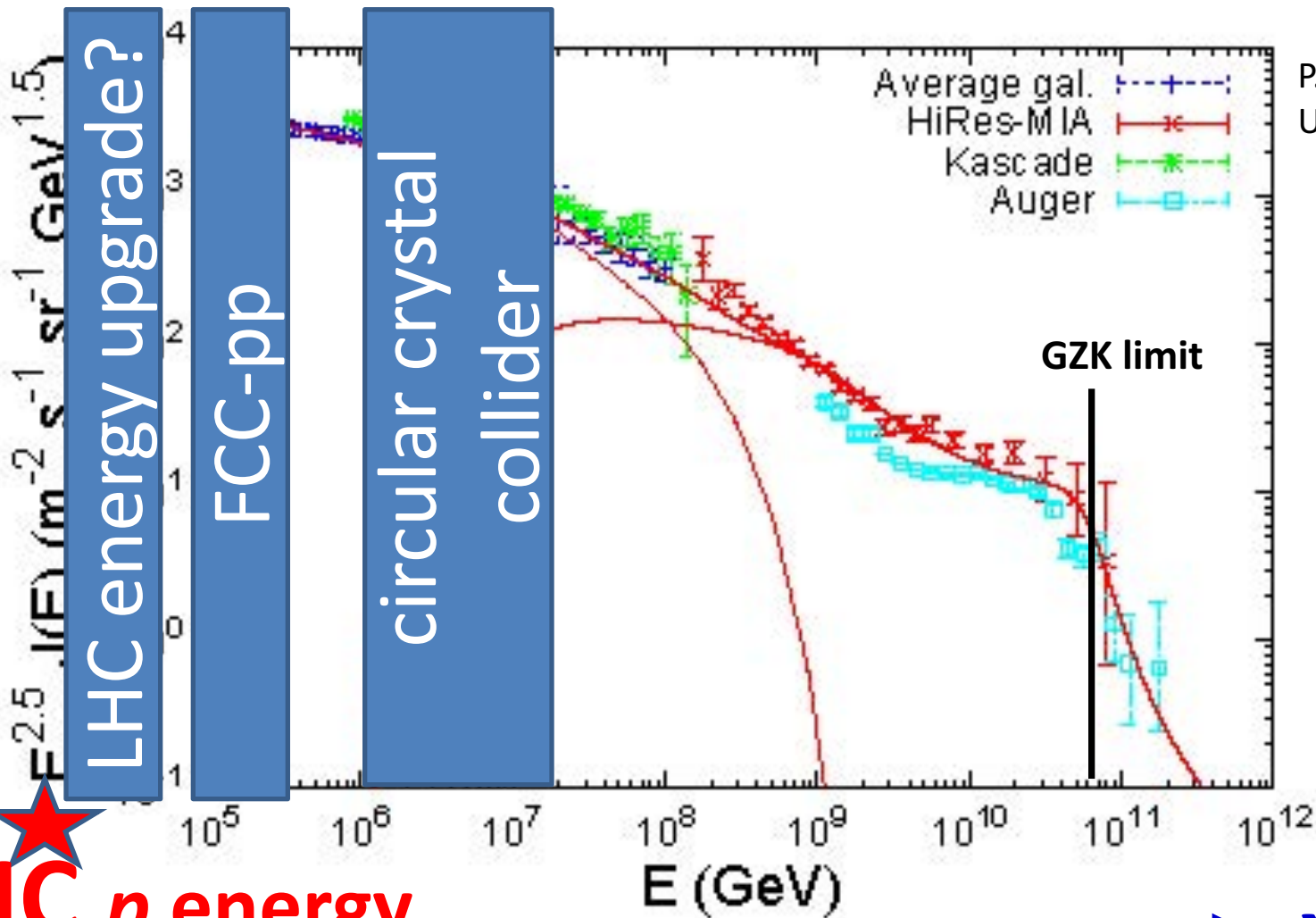


Streak camera Images



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

cosmic-ray energy spectrum

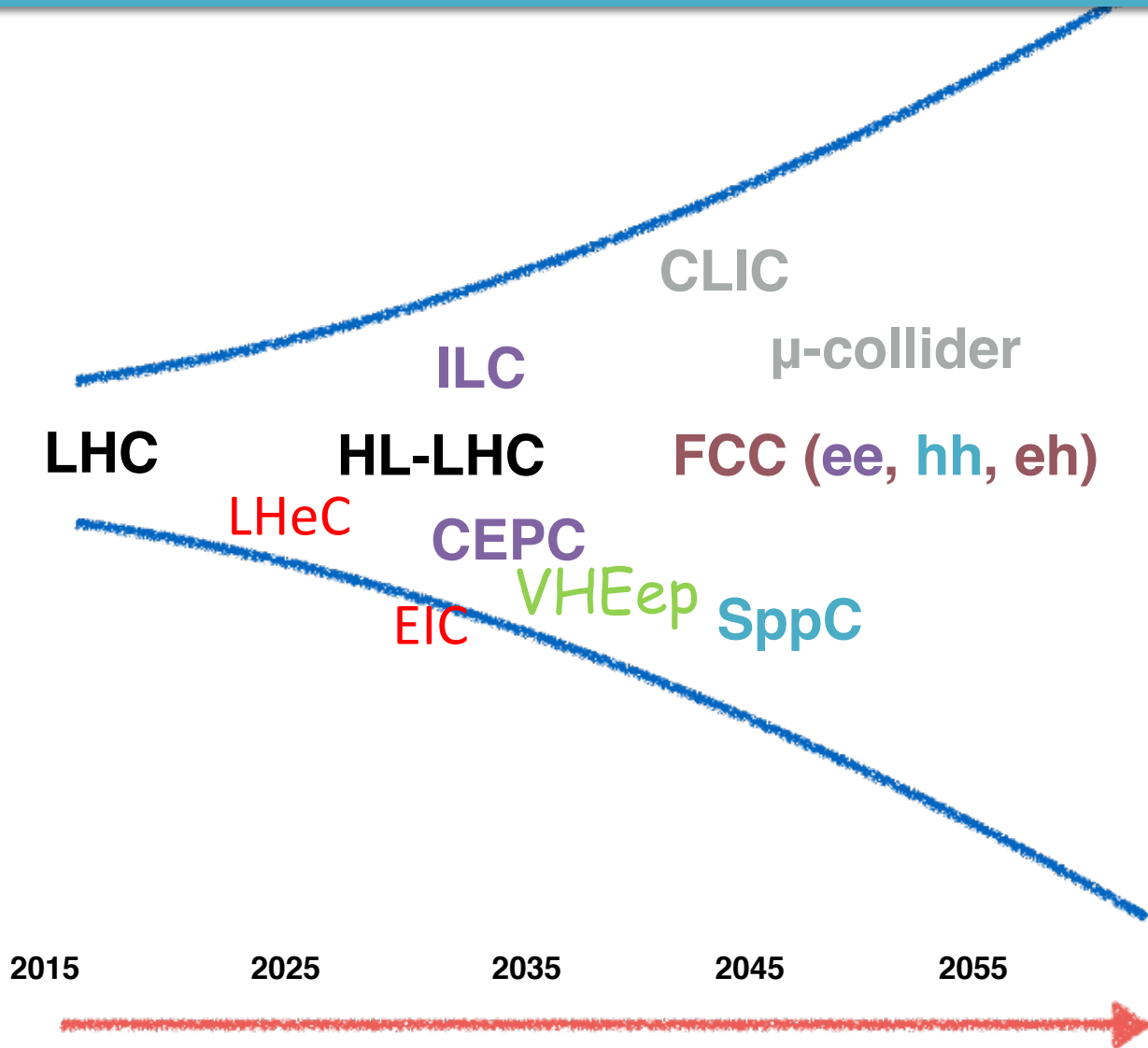


P. Blasi,
UHECR2012

LHC p energy

$\times 10^8$

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)

Structure of the EPPSU process

- Strategy update **approval by Council** (date fixed, May 2020)
- The strategy update is drafted by the European Strategy Group (**ESG**)
- The drafting is based on **input from the community** - collaborations, projects, national institutes, national roadmaps, individuals
- The input is collected by the Physics Preparatory Group (**PPG**)
- The PPG organizes the **Open Symposium** to discuss the proposals
- The PPG summarizes the input, the discussions and their conclusions in a **Briefing Book**
- The Briefing Book constitutes the input for the ESG for drafting the update
- The drafting of the strategy update takes place during a dedicated **Drafting Session** (the conclave of the EPPSU process)
- The organization is handled by the **Strategy Secretariat**
- All the groups are chaired by the **Strategy Secretary**

Members

- The Strategy Secretary - HA
- SPC chair - Keith Ellis
- ECFA chair - Jorgen D'Hondt
- Chair of *the European Laboratory Directors Group* - Lenny Rivkin

The European Laboratory Directors Group

- CERN
- CIEMAT
- DESY
- IRFU
- LAL
- NIKHEF
- LNF
- LNGS
- PSI
- STFC-RAL

Members

- The Strategy Secretary (chair)
- Four members recommended by the SPC
- Four members recommended by ECFA
- SPC chair
- ECFA chair
- Chair of the the European Laboratory Directors Group
- One representative appointed by CERN
- Representative(s) from Asia (≤ 2)
- Representative(s) from the Americas (≤ 2)

15 to 17 people

Members

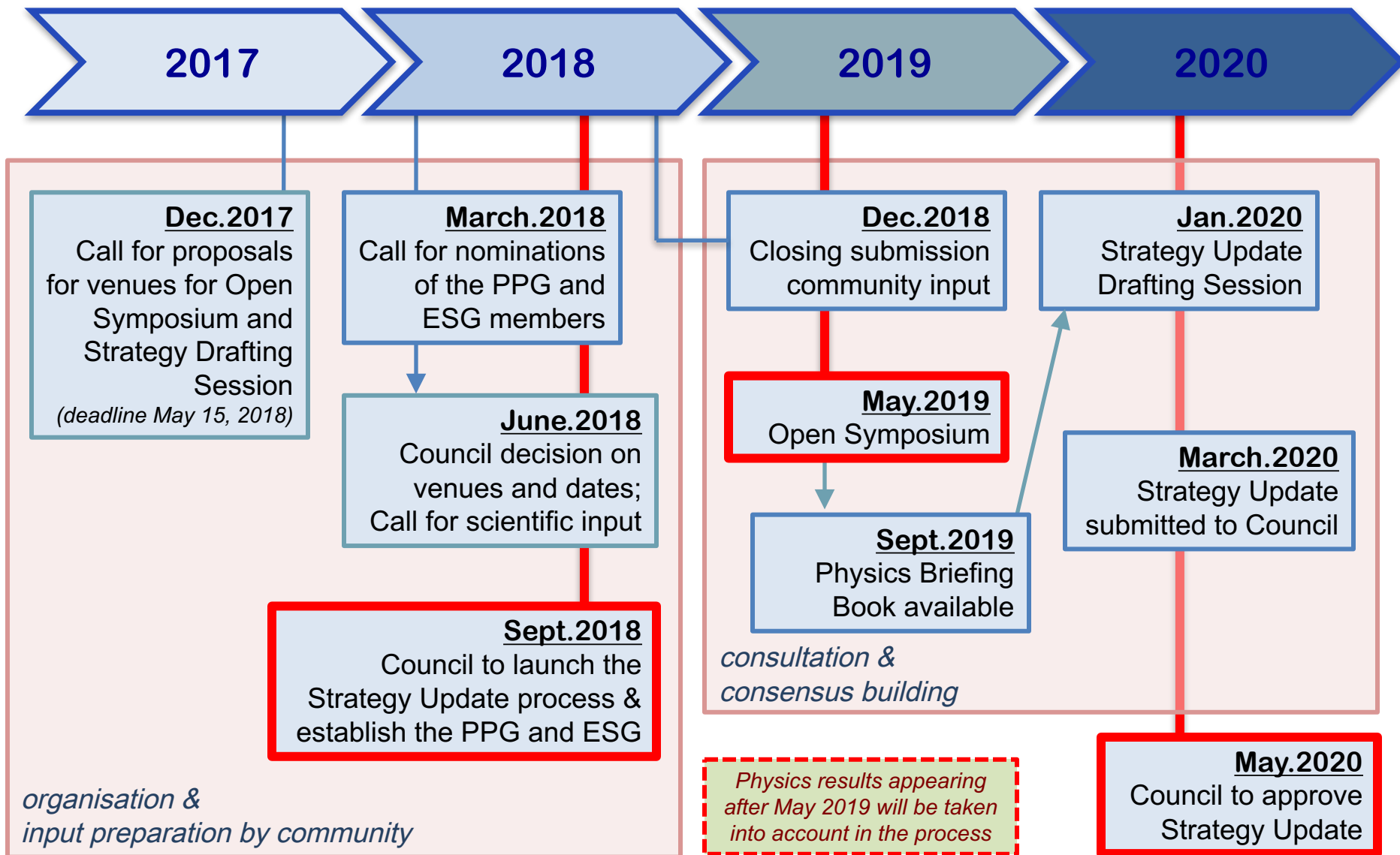
- The Strategy Secretary (chair)
- One representative appointed by each CERN MS (22)
- One representative appointed by each of the Labs participating in the European Laboratory Directors Group including its Chairperson (9)
- CERN DG
- SPC chair
- ECFA chair

Invitees

- President of CERN Council
- One representative from each AMS and OS (7+3)
- One representative from the European Commission
- Chairs of ApPEC, NuPECC, FALC, ESFRI
- Members of the PPG (17 - Secretariat)

62 to 64 people

European Particle Physics Strategy Update



References

ILC - [Technical Design Report](#)

CLIC - [Conceptual Design Report](#)

CepC - [pre-Conceptual Design report](#)

FCCee - [The Fcc-ee Design Study](#)

SSC - [Higgs Factory and 100 TeV Hadron Collider: Opportunity for a New World Laboratory within a Decade](#)

FCC - [Web pages](#)

SppC - [pre-Conceptual Design report](#)

HE-LHC – high field magnetic design

EIC – JLAB ([MEIC Design Summary](#))

EIC – BNL ([eRHIC Design Study: An Electron-Ion Collider at BNL](#))

VHEep - [VHEeP: A very high energy electron-proton collider](#)

Muon Collider - [A muon collider as a Higgs factory](#)

Image of M. Strassler from [“Conversations about Science with theoretical physicist Matt Strassler”, Of Particular Significance](#)

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 EPPSU