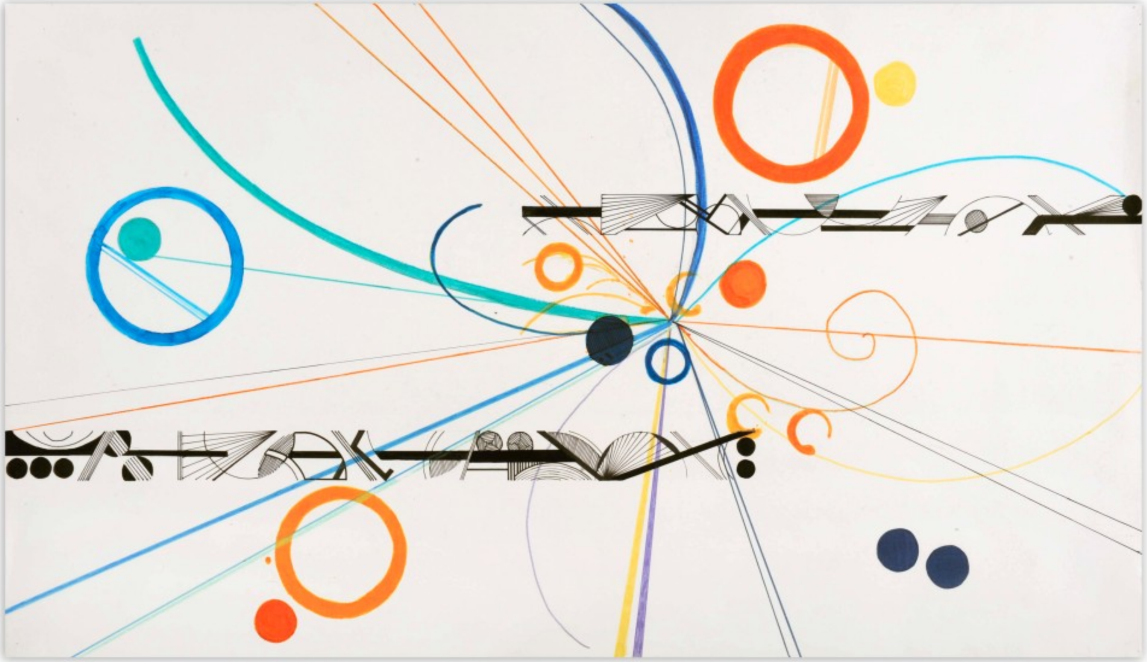
“My own visions of CLIC”
Artwork by Natasha de Heney, 2010



Introduction to CLIC

Erica Brondolin
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Students Seminar
8th August 2018

Main topics

- **Introduction**
  - Why is CLIC an interesting option for the future?

- **Physics potential**
  - Why has CLIC a unique physics potential?

- **CLIC accelerator**
  - Which are the key issues?

- **CLIC detector**
  - What is the role of each sub-detector?

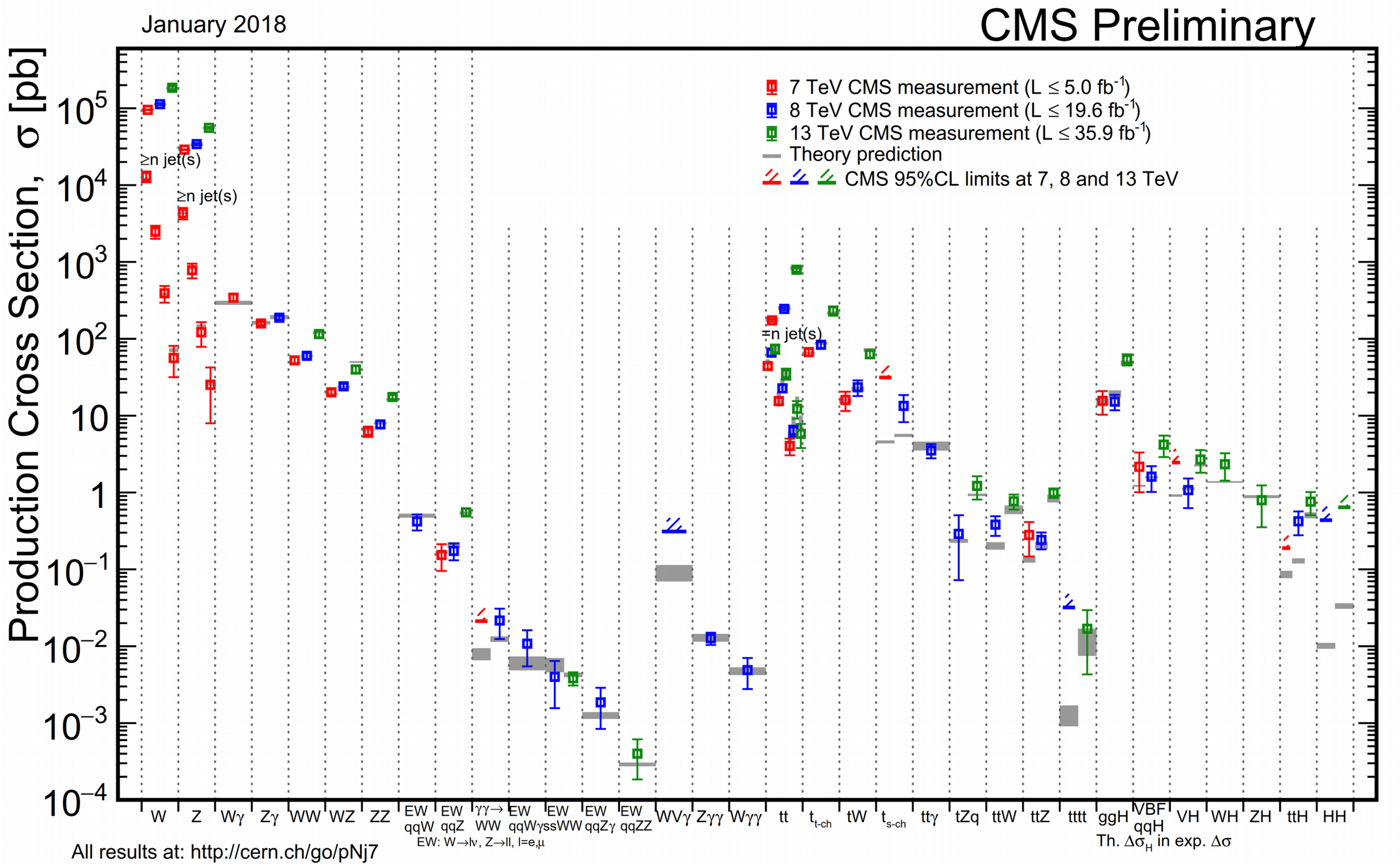
- **Conclusion**
  - Have I convinced you?

“My own visions of CLIC”
Artwork by Vilma Heiskaner, 2010

Introduction

Success of the LHC

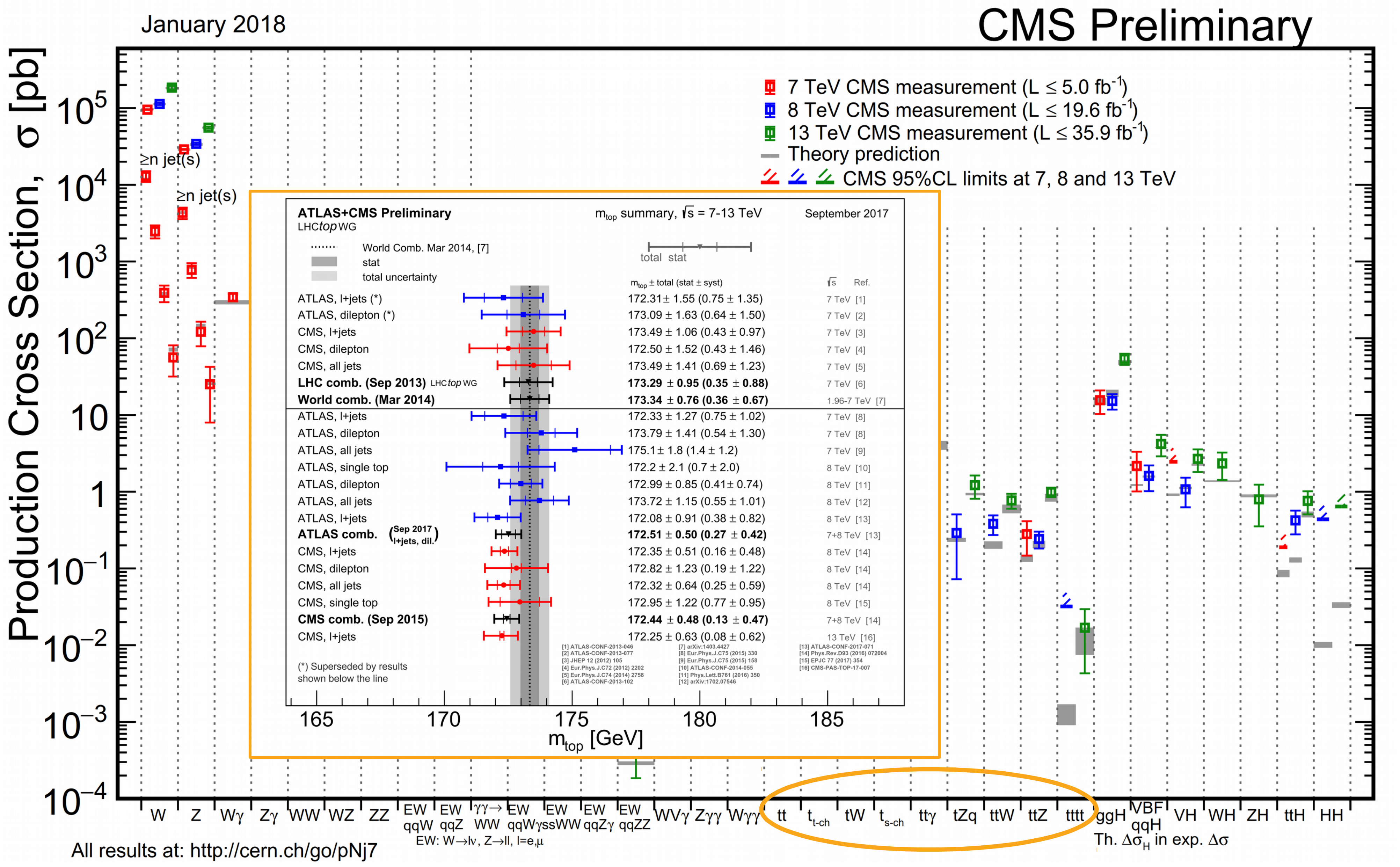
- **Standard Model results**



All results at: http://cern.ch/go/pNj7

Success of the LHC

- **Standard Model results**



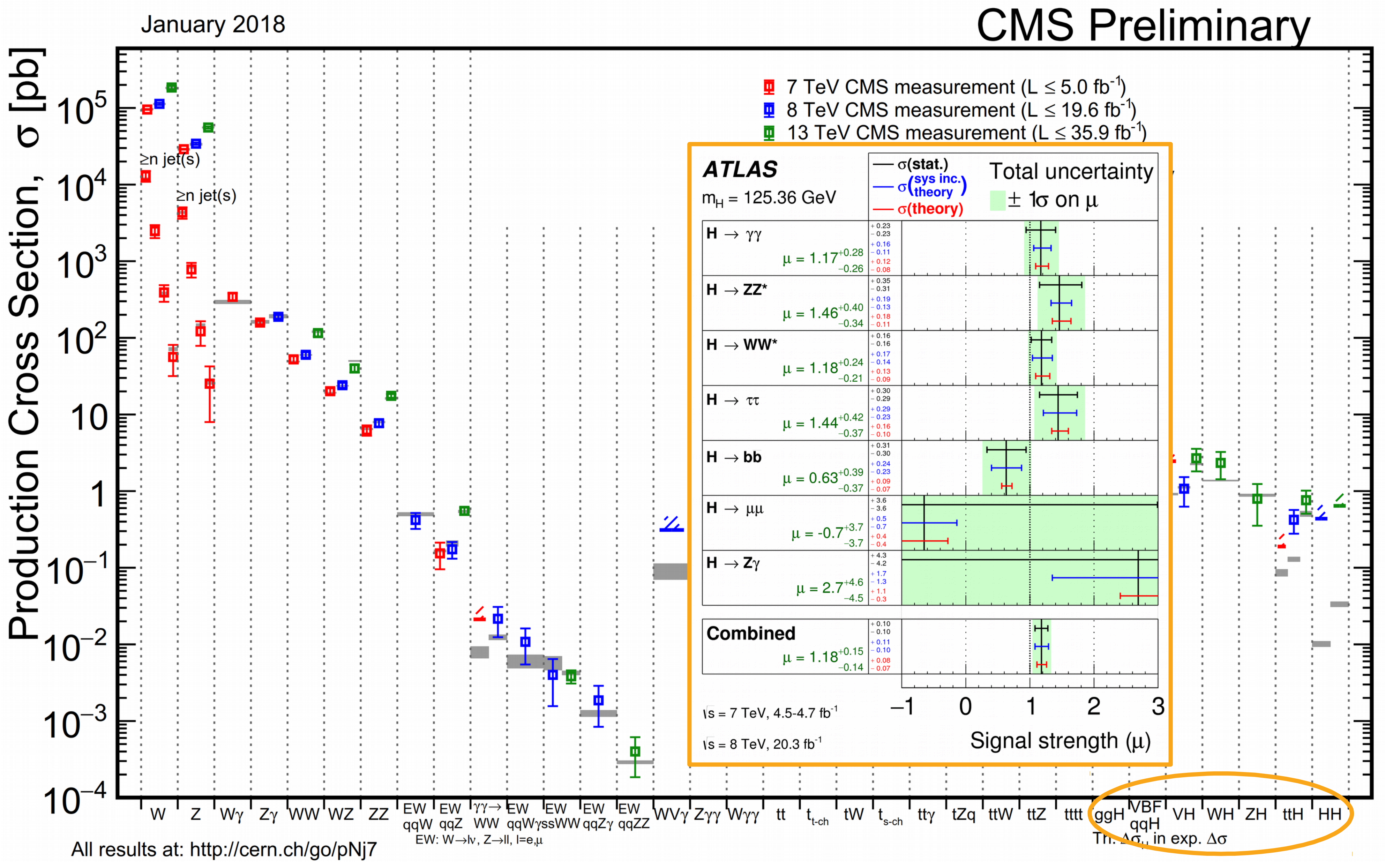
	m_{top} ± total (stat ± syst)	$\sqrt{s}$	Ref.
ATLAS, l+jets (*)	172.31± 1.55 (0.75 ± 1.35)	7 TeV	[1]
ATLAS, dilepton (*)	173.09 ± 1.63 (0.64 ± 1.50)	7 TeV	[2]
CMS, l+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV	[3]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV	[4]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV	[5]
LHC comb. (Sep 2013) LHC*top*WG	**173.29 ± 0.95 (0.35 ± 0.88)**	7 TeV	[6]
World comb. (Mar 2014)	**173.34 ± 0.76 (0.36 ± 0.67)**	1.96-7 TeV	[7]
ATLAS, l+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV	[8]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV	[8]
ATLAS, all jets	175.1± 1.8 (1.4 ± 1.2)	7 TeV	[9]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV	[10]
ATLAS, dilepton	172.99 ± 0.85 (0.41± 0.74)	8 TeV	[11]
ATLAS, all jets	173.72 ± 1.15 (0.55 ± 1.01)	8 TeV	[12]
ATLAS, l+jets	172.08 ± 0.91 (0.38 ± 0.82)	8 TeV	[13]
ATLAS comb. (Sep 2017 l+jets, dil.)	**172.51 ± 0.50 (0.27 ± 0.42)**	7+8 TeV	[13]
CMS, l+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV	[14]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV	[14]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV	[14]
CMS, single top	172.95 ± 1.22 (0.77 ± 0.95)	8 TeV	[15]
CMS comb. (Sep 2015)	**172.44 ± 0.48 (0.13 ± 0.47)**	7+8 TeV	[14]
CMS, l+jets	172.25 ± 0.63 (0.08 ± 0.62)	13 TeV	[16]

(*) Superseded by results shown below the line

[1] ATLAS-CONF-2013-046
[2] ATLAS-CONF-2013-077
[3] JHEP 12 (2012) 105
[4] Eur.Phys.J.C72 (2012) 2202
[5] Eur.Phys.J.C74 (2014) 2758
[6] ATLAS-CONF-2013-102
[7] arXiv:1403.4427
[8] Eur.Phys.J.C75 (2015) 330
[9] Eur.Phys.J.C75 (2015) 158
[10] ATLAS-CONF-2014-055
[11] Phys.Lett.B761 (2016) 350
[12] arXiv:1702.07546
[13] ATLAS-CONF-2017-071
[14] Phys.Rev.D93 (2016) 072004
[15] EPJC 77 (2017) 354
[16] CMS-PAS-TOP-17-007

Success of the LHC

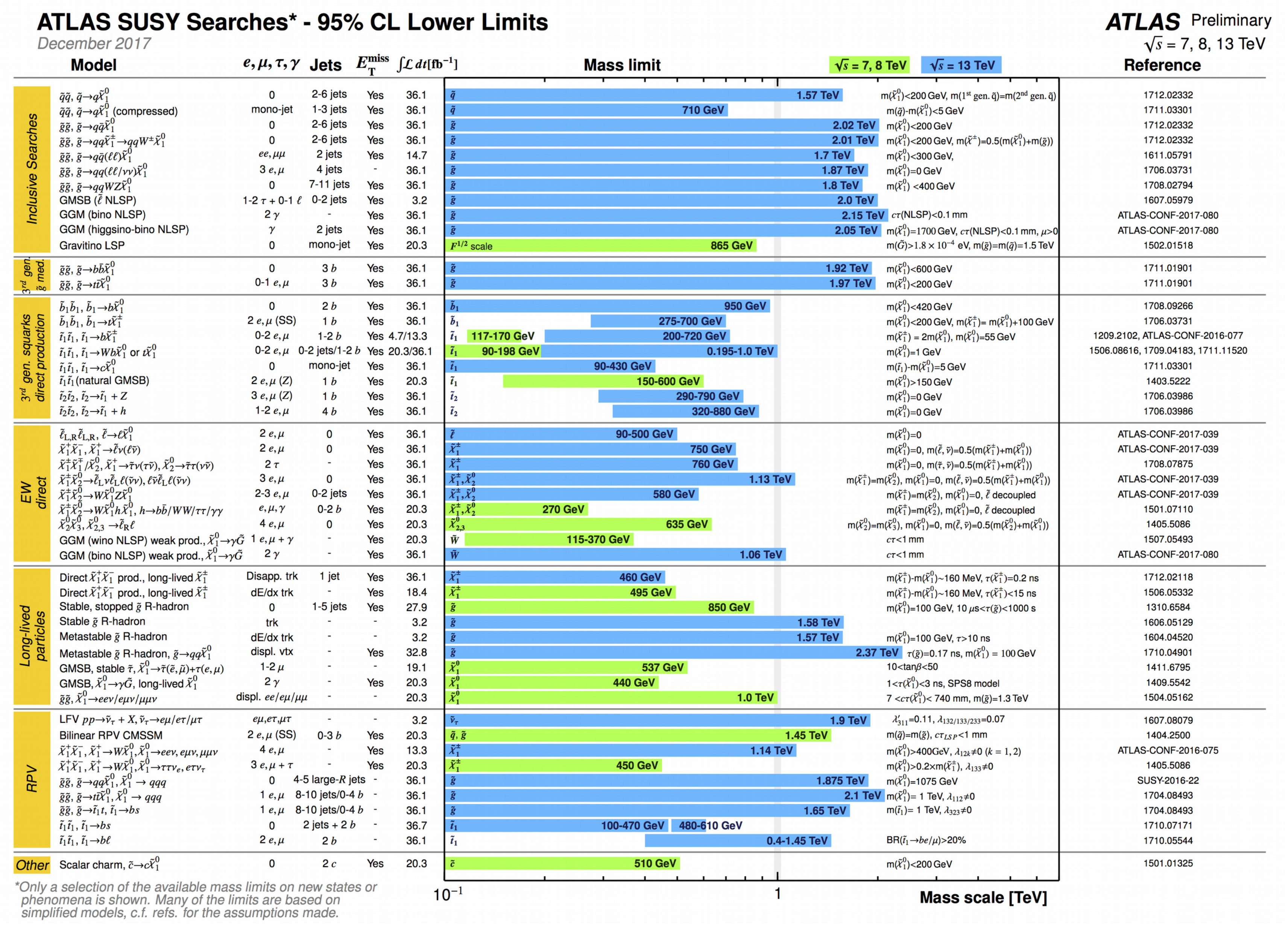
- **Standard Model results**



All results at: http://cern.ch/go/pNj7

BSM at the LHC

- **Limits on Physics Beyond Standard Model (BSM)**



ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

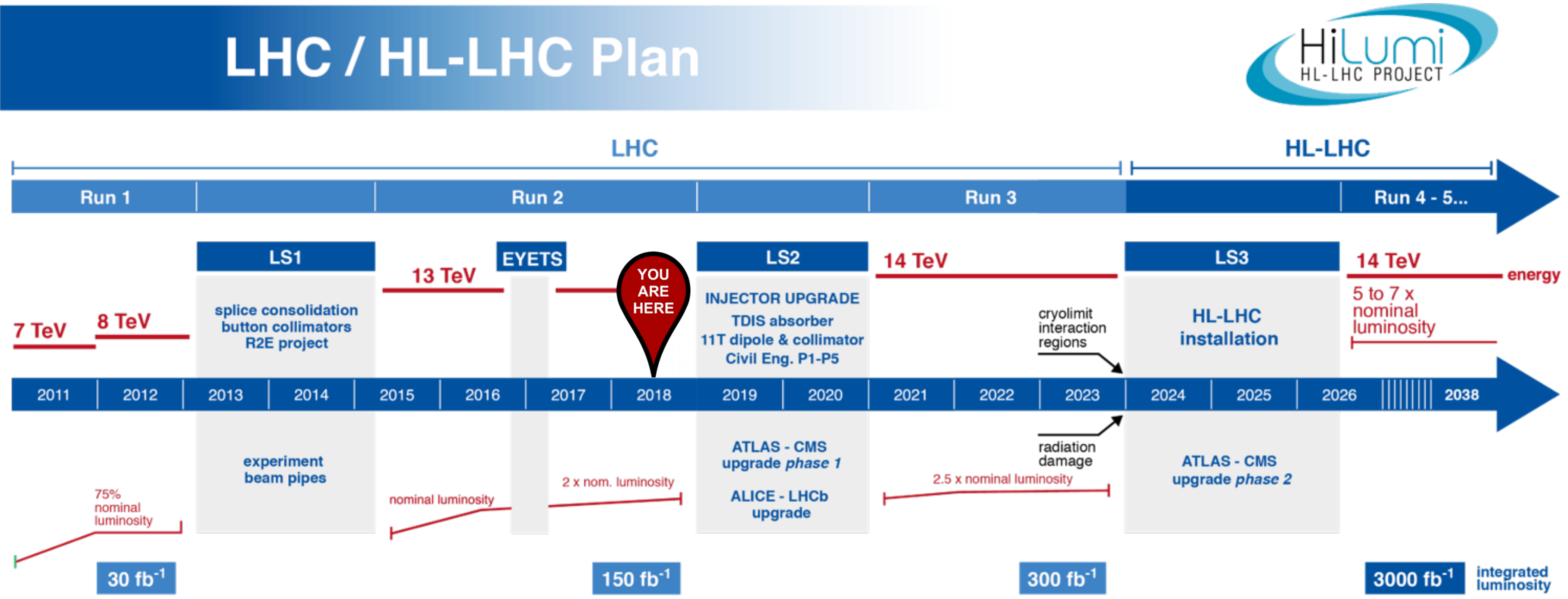
$\sqrt{s}$ = 7, 8, 13 TeV

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	🟦 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. q̃)=m(2nd gen. q̃)	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	🟦 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	🟦 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$	🟦 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$	🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$	🟦 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	🟦 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$	🟦 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	🟦 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	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	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	🟦 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$(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
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	🟦 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$	🟦 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	🟦 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟦 1.13 TeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟦 580 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟩 270 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$	🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 460 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	🟩 495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)<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 μs<τ($\tilde{g}$)<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	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	🟦 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	🟦 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	🟦 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$	🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

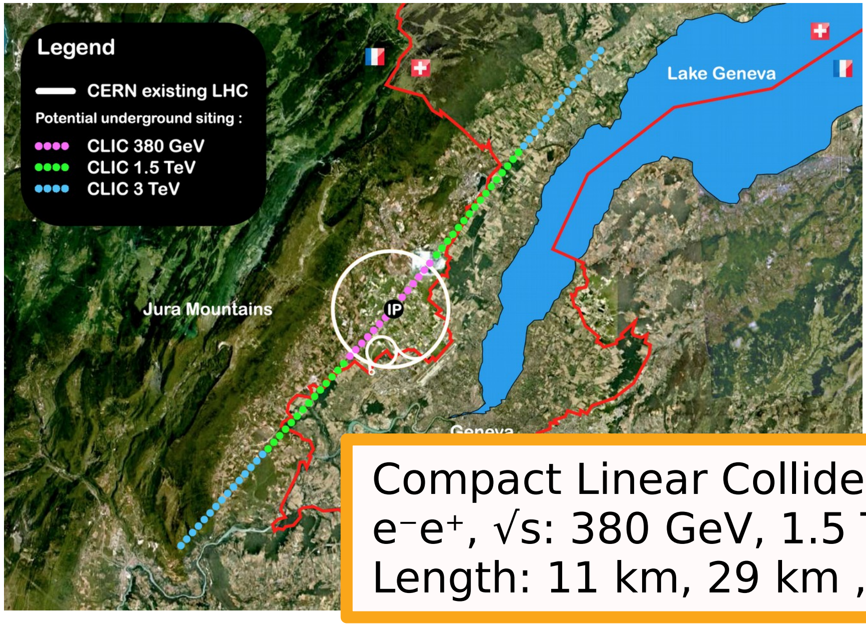
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

What’s next?



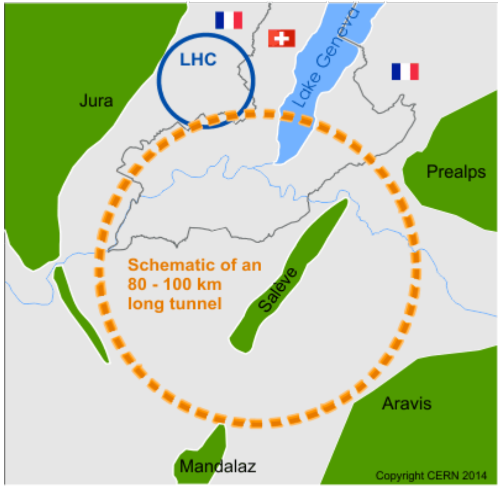
- **HL-LHC up to 2038**
- **What’s next-to-next?**
  - Future hadron collider
  - Future electron collider
  - Something that is not a collider
- **When do we have to start planning?** LEP was formally approved in 1981 and civil engineering work began on 13 September 1983. First beam circulated on 14 July 1989.

What’s next-to-next?

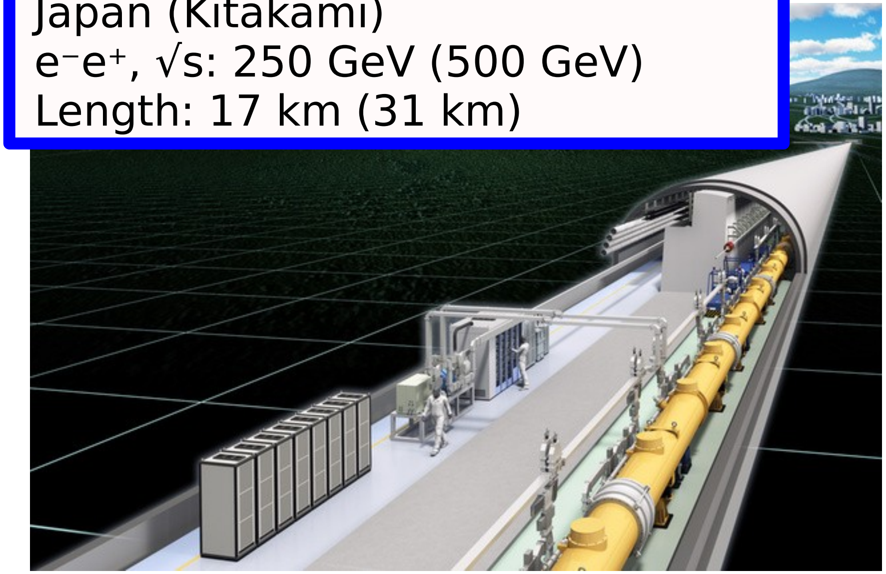


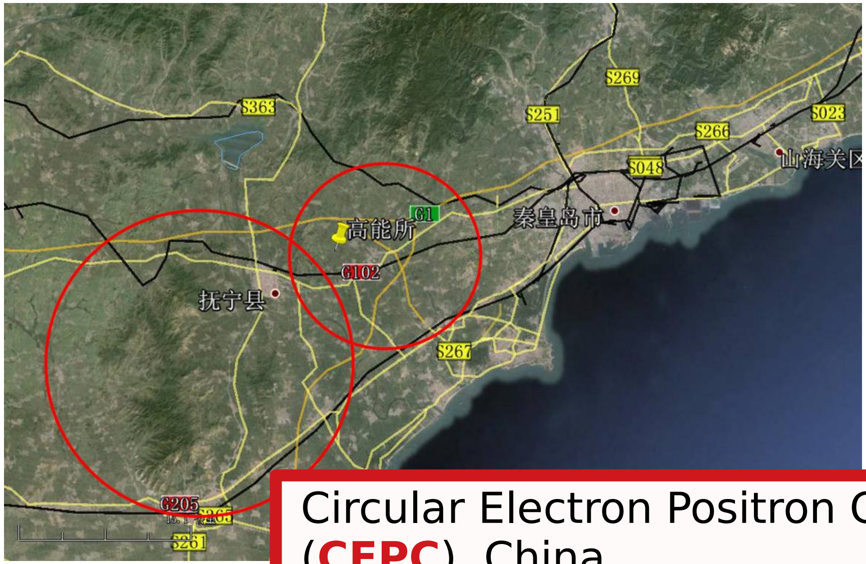
Compact Linear Collider (**CLIC**): CERN
e^-e^+, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

Future Circular Collider (**FCC**): CERN
e^-e^+, $\sqrt{s}$: 90 - 365 GeV; pp, $\sqrt{s}$: ~100 TeV
Circumference: 97.75 km



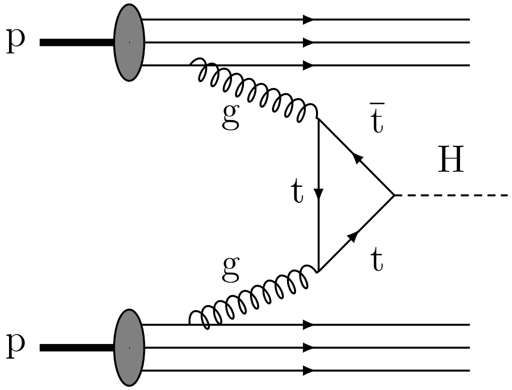
International Linear Collider (**ILC**):
Japan (Kitakami)
e^-e^+, $\sqrt{s}$: 250 GeV (500 GeV)
Length: 17 km (31 km)





Circular Electron Positron Collider
(**CEPC**), China
e^-e^+, $\sqrt{s}$: 90 – 240 GeV; SPPC pp,
Circumference: ~100 km

Hadron vs. e^+e^- colliders

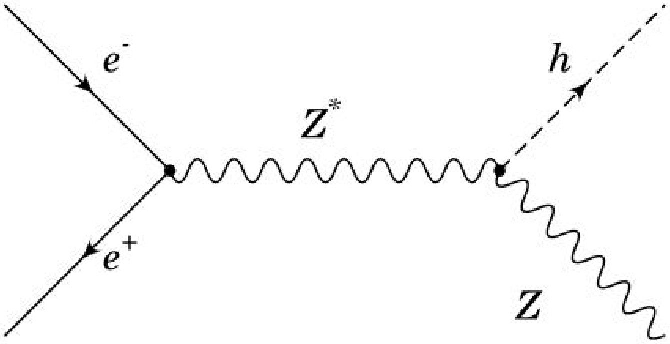


Hadron colliders:

- The proton is a compound object
  → Initial state unknown
  → Precision limited

- Higher energy reachable

- High rates of QCD background
  → Complex triggers
  → High levels of radiation



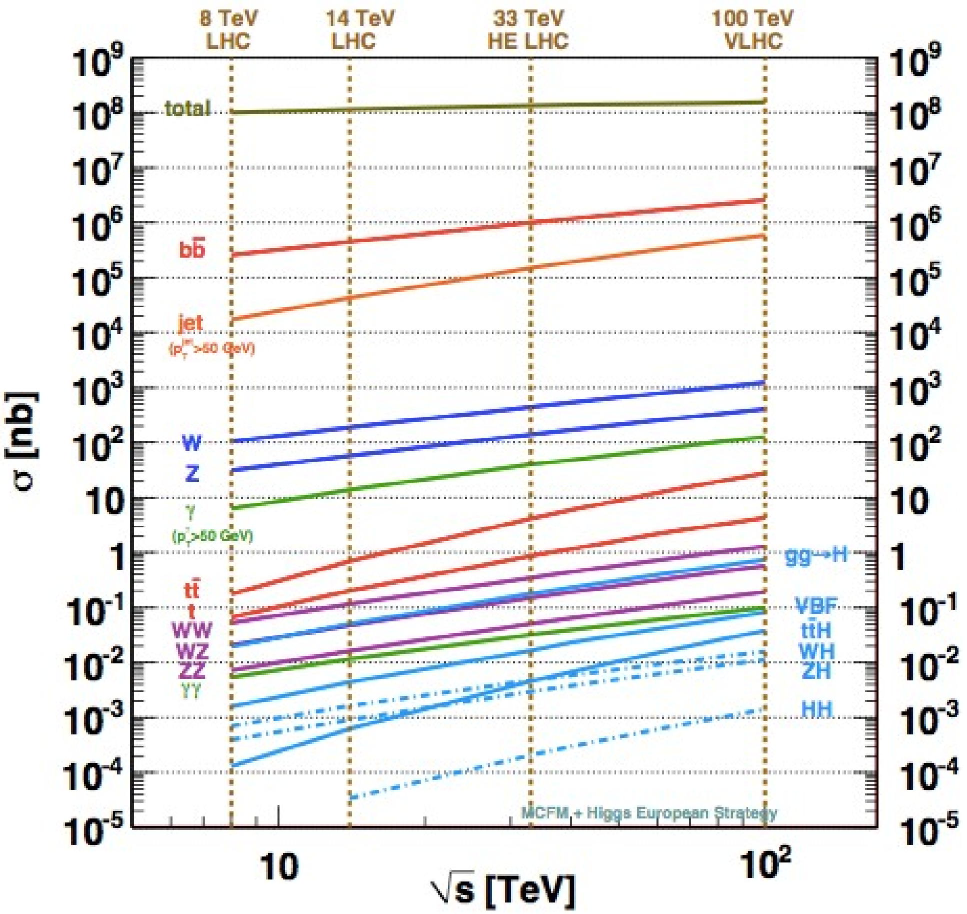
e^+e^- colliders:

- e^+e^- are point-like
  → Initial state well-defined
  → High-precision measurements

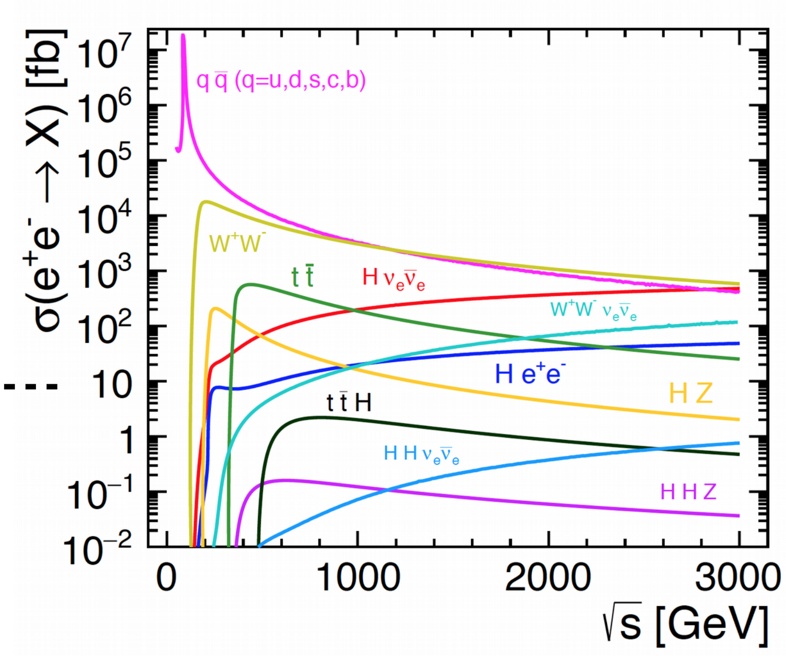
- Lower energy than hadron, but √s > 350 GeV is still possible with linear collider

- Clean experimental environment
  → Less, or even no, trigger
  → Lower radiation levels

Hadron vs. e^+e^- colliders



8 orders of magnitude!



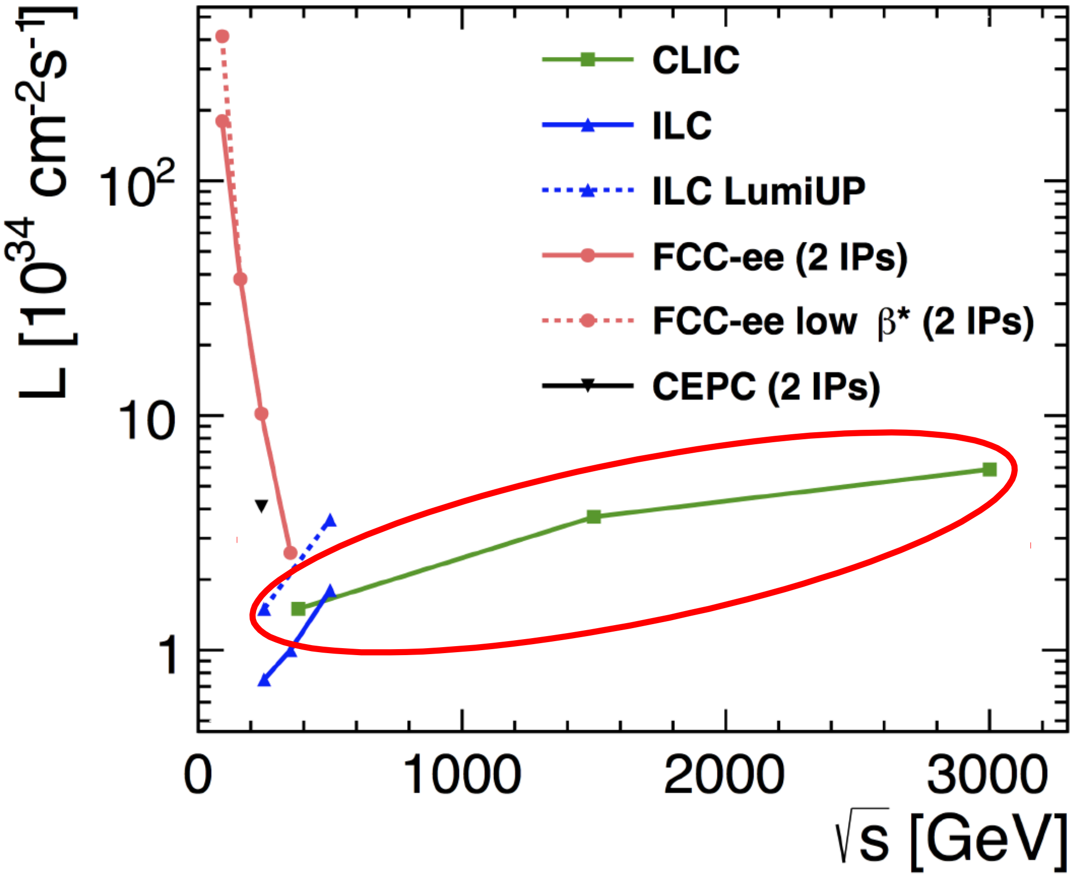
pp collisions:

Interesting events need to be found in a huge number of collisions

e^+e^- collisions:

More “clean” environment, all events usable

Luminosity performance (e^+e^-)



Circular colliders:

Large instantaneous luminosity at lower energies
Luminosity decreases with energy

Linear colliders:

- Can reach the highest energies
- Luminosity rises with energy
- Beam polarization possible

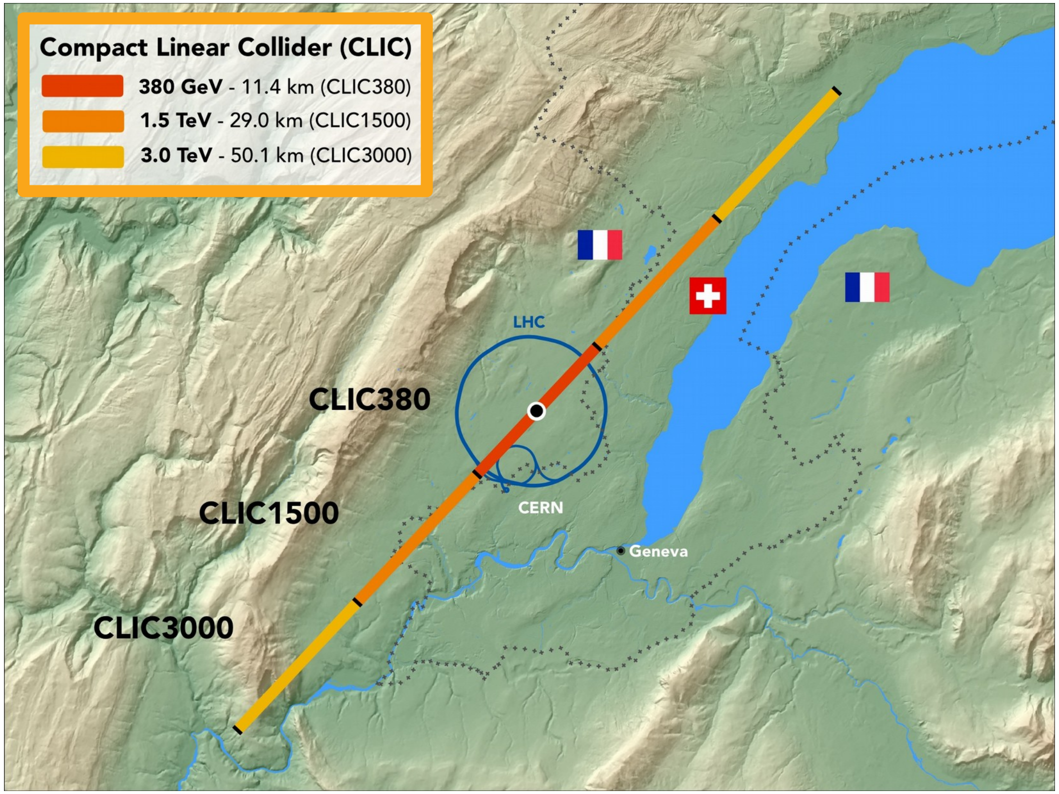
Note: Peak luminosity at LEP2 (209 GeV) was ~10^{32} $cm^{-2}s^{-1}$

CLIC in a nutshell

- **CLIC = Compact Linear Collider**
- High-luminosity linear e^+e^- collider
- Centre-of-mass energy from few hundred GeV up to 3 TeV

- Staged construction

- **The CLIC studies are carried by two international collaborations:**
  → CLIC accelerator collaboration
  → CLIC detector and physics collaboration
  Together ~80 institutes



- **Physics goals:**
  → Precision measurement of SM processes
  → Precision measurement of new physics (discovered at LHC or CLIC)
  → Search for BSM

CLIC timeline

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

“My own visions of CLIC”
Artwork by Sean Steed, 2010

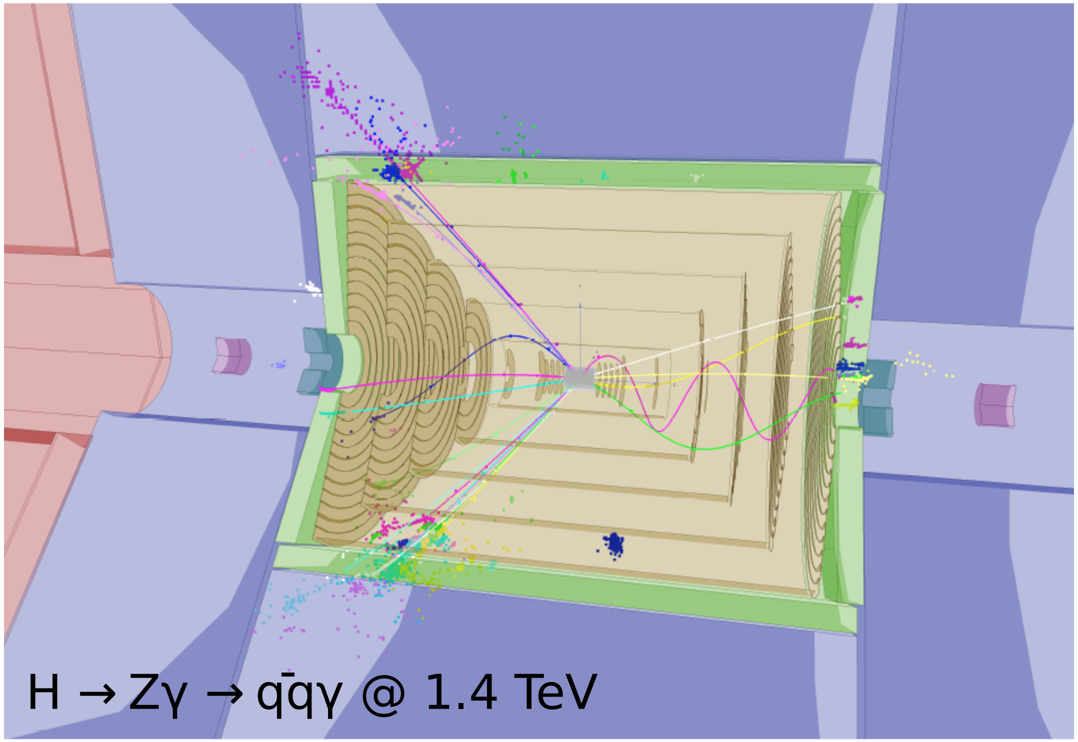
Physics potential

Main physics topics

- **Higgs boson**
- **Top quark**
- **BSM (direct and indirect)**

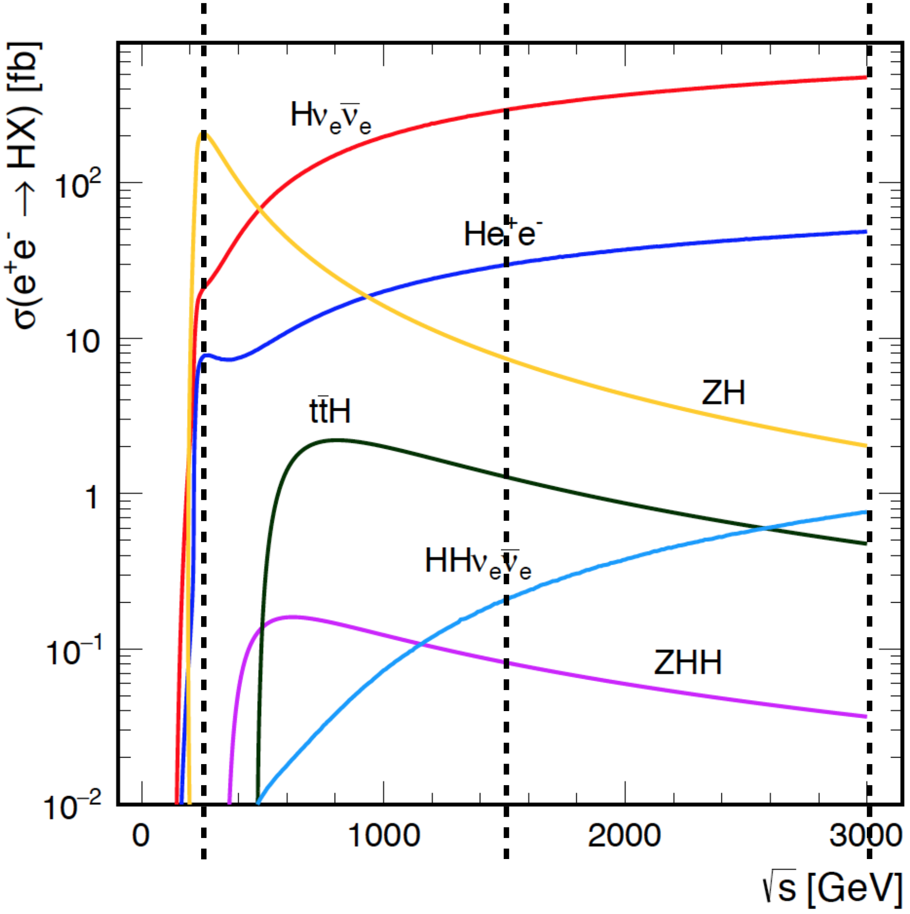
- What can we learn by studying the Higgs boson and the top quark in collisions?
- Which precision measurements can hint to new physics at very high scales?
- Can CLIC make direct observations although the LHC has found nothing so far?

Stage	**$\sqrt{s}$**	**L_{int} (fb^{-1})**
1	380 GeV 350 GeV	500 100
2	1.5 TeV	1500
3	3 TeV	3000



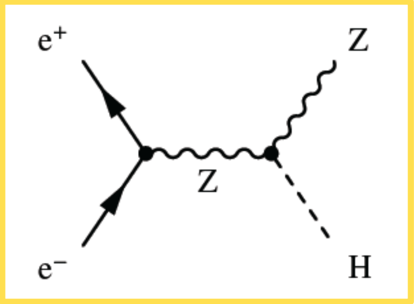
$H \to Z\gamma \to q\bar{q}\gamma$ @ 1.4 TeV

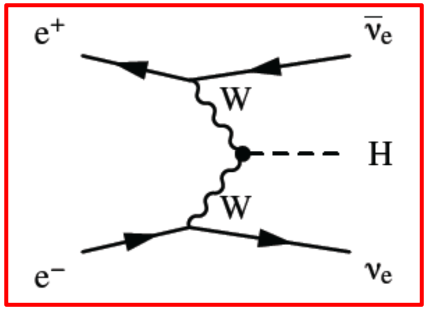
Higgs physics at CLIC

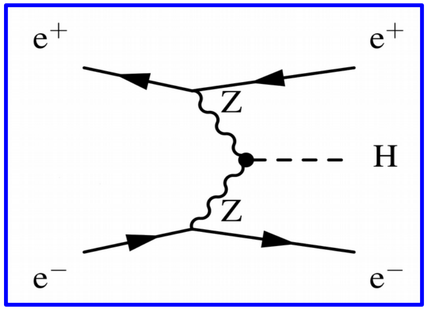


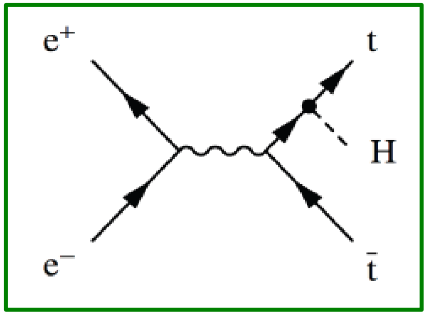
Single Higgs production:

- **Higgsstrahlung: $e^+e^- \rightarrow ZH$**
  $\sigma \sim 1/s$, dominant up to ~ 450 GeV
  Higgs identification from recoil
- **WW fusion: $e^+e^- \rightarrow H\nu_e\bar{\nu}_e$**
  $\sigma \sim \log(s)$, dominant above ~ 450 GeV
  Large statistics at high energy
- **$t\bar{t}H$ production: $e^+e^- \rightarrow t\bar{t}H$**
  Accessible > 500 GeV, maximum ~ 800 GeV
  Direct extraction of the top Yukawa coupling





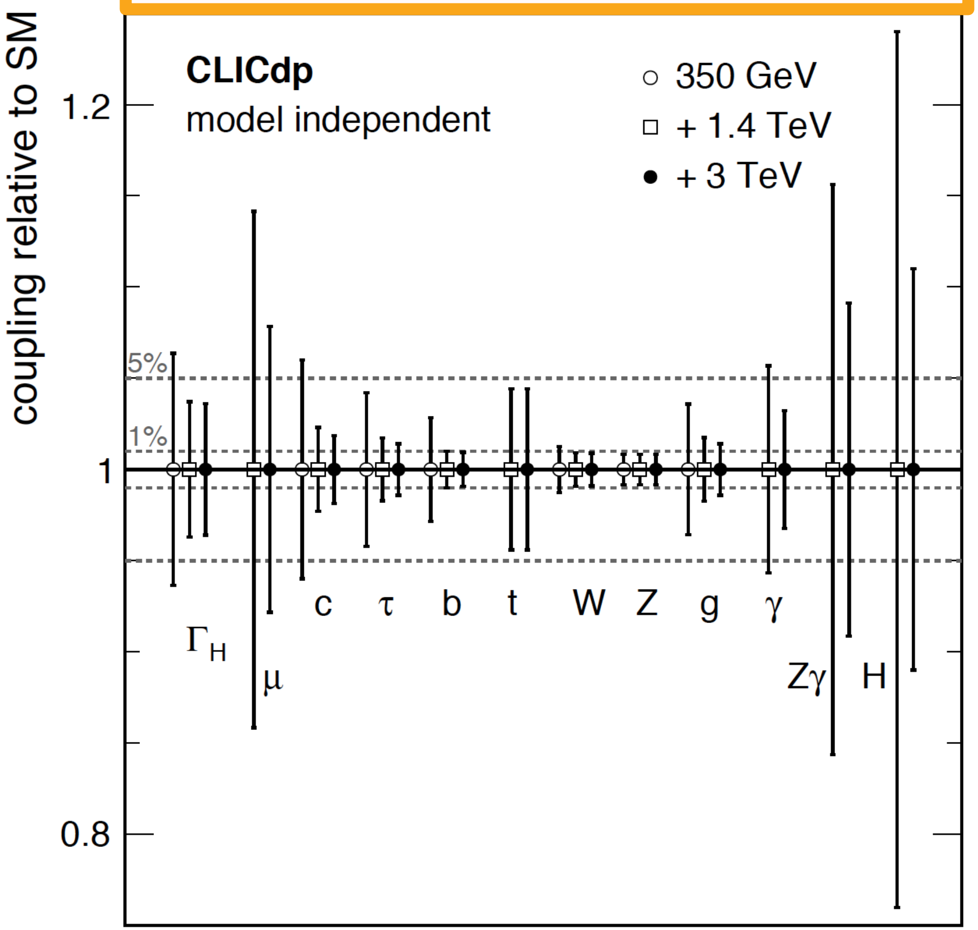


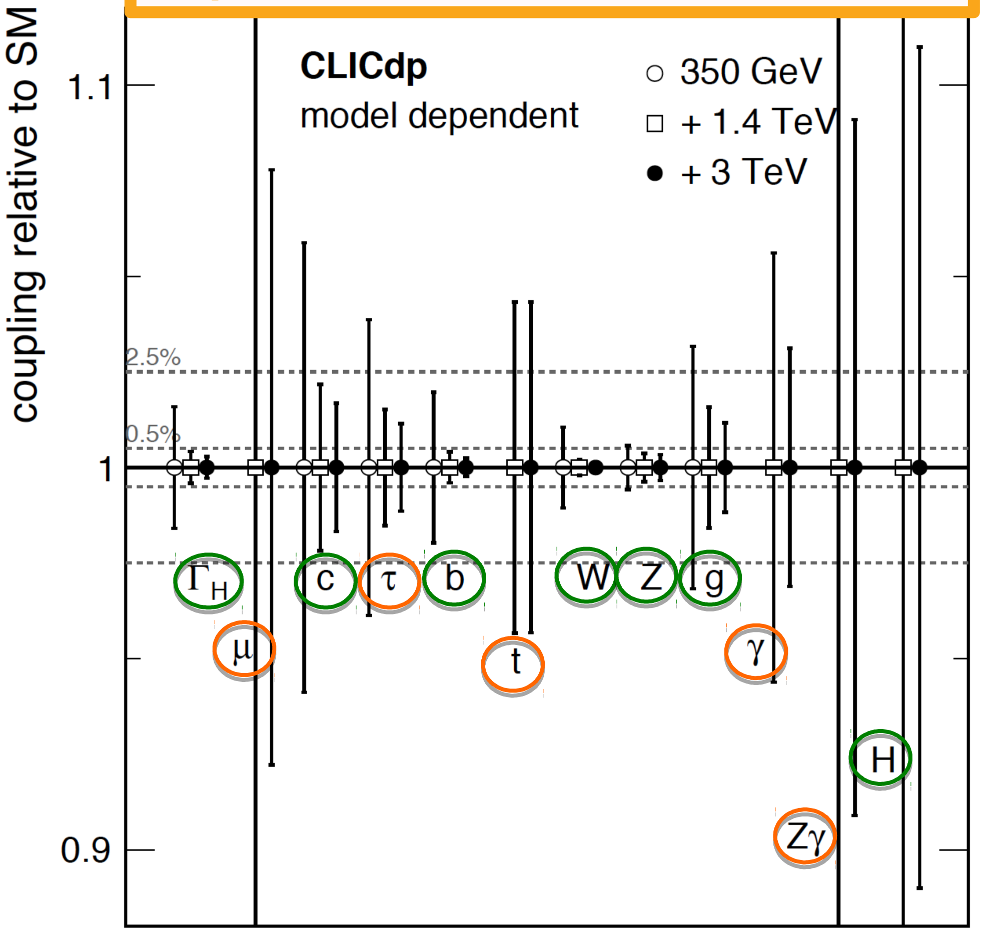


Higgs physics at CLIC

Fully model-independent analysis only possible at lepton colliders

Indicative comparison with LHC capabilities





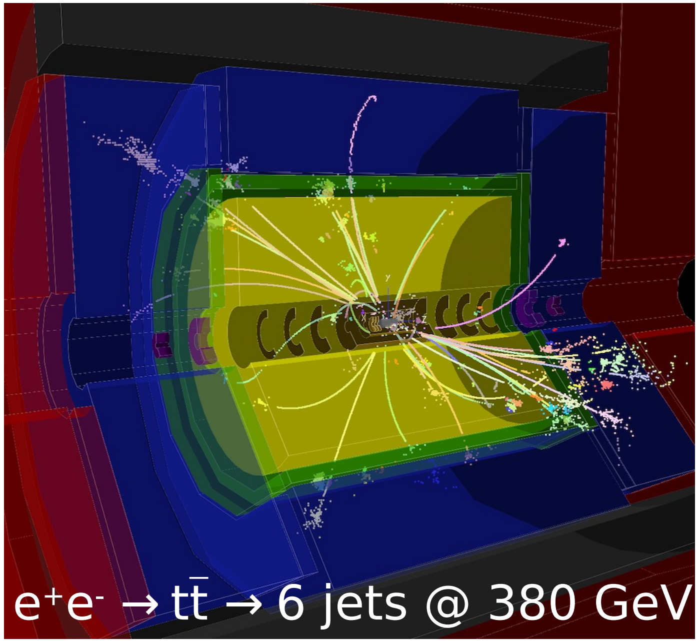
High precision measurements:
- Couplings with sub-1% level (at 1% for rare decays)
- Higgs width: 3.4%

🟢 Accuracy significantly better than HL-LHC
🟠 Accuracy comparable to HL-LHC

Top-quark physics at CLIC

Motivations:

- Top quark is the heaviest known particle
- Yukawa coupling to Higgs boson y_t~1 → key to understanding Electroweak Symmetry Breaking
- Top quark decays before hadronising → test ground of QCD
- Large loop contribution to many precision measurements
- Sensitive to many BSM scenarios a window to BSM
- So far top quark only measured at hadron colliders



Production:

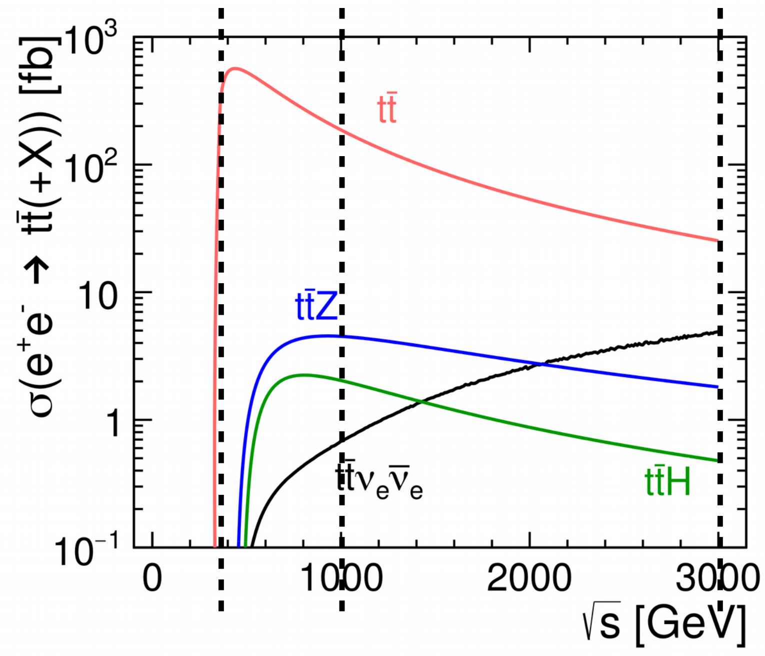
- **$e^+e^- \to t\bar{t}$:**

  Production threshold at √s ~ $2m_{top}$

  Large event sample at 380 GeV
- **$e^+e^- \to t\bar{t}H$:**

  Maximum near 800 GeV
- **$e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$ (Vector Boson Fusion):**

  Benefits from highest energies



Top-quark physics at CLIC

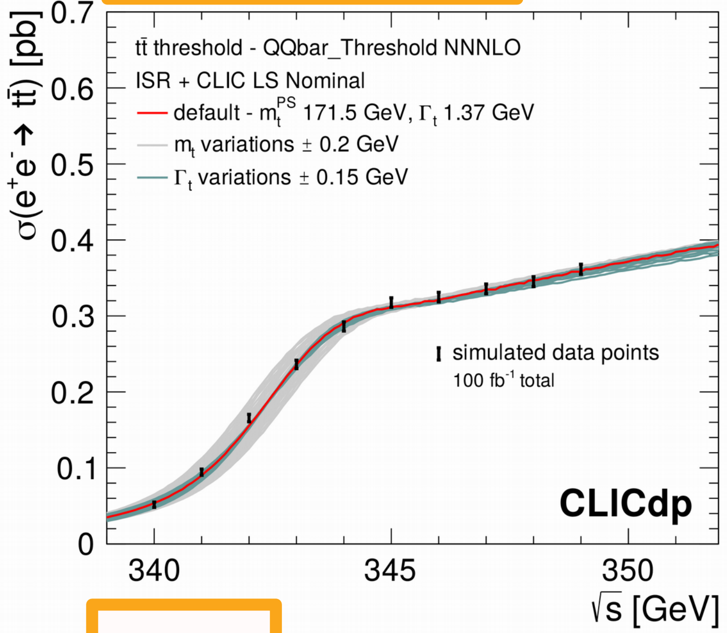
Dedicated measurements:

- Top quark mass:
  → Threshold scan at 350 GeV (100 fb^{-1})
  Best experimental and theoretical precision on its mass
  → Direct reconstruction

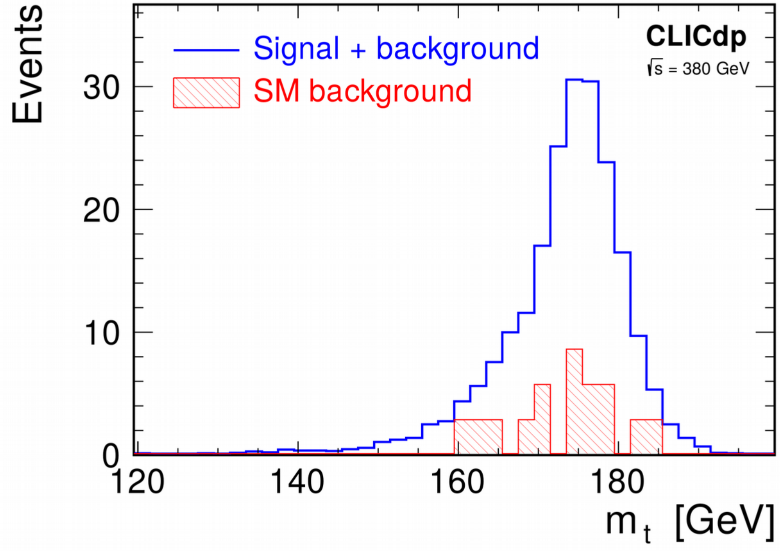
- Top-Yukawa coupling:
  → Precision measurement of the top EW couplings
  → Indirect searches of BSM physics

- Probe of new physics:
  → Measurement of V_{tb} in single top production
  → Top quark production asymmetries
  → FCNC top-quark decays
  High statistics in continuum at 380 GeV (500 fb^{-1})

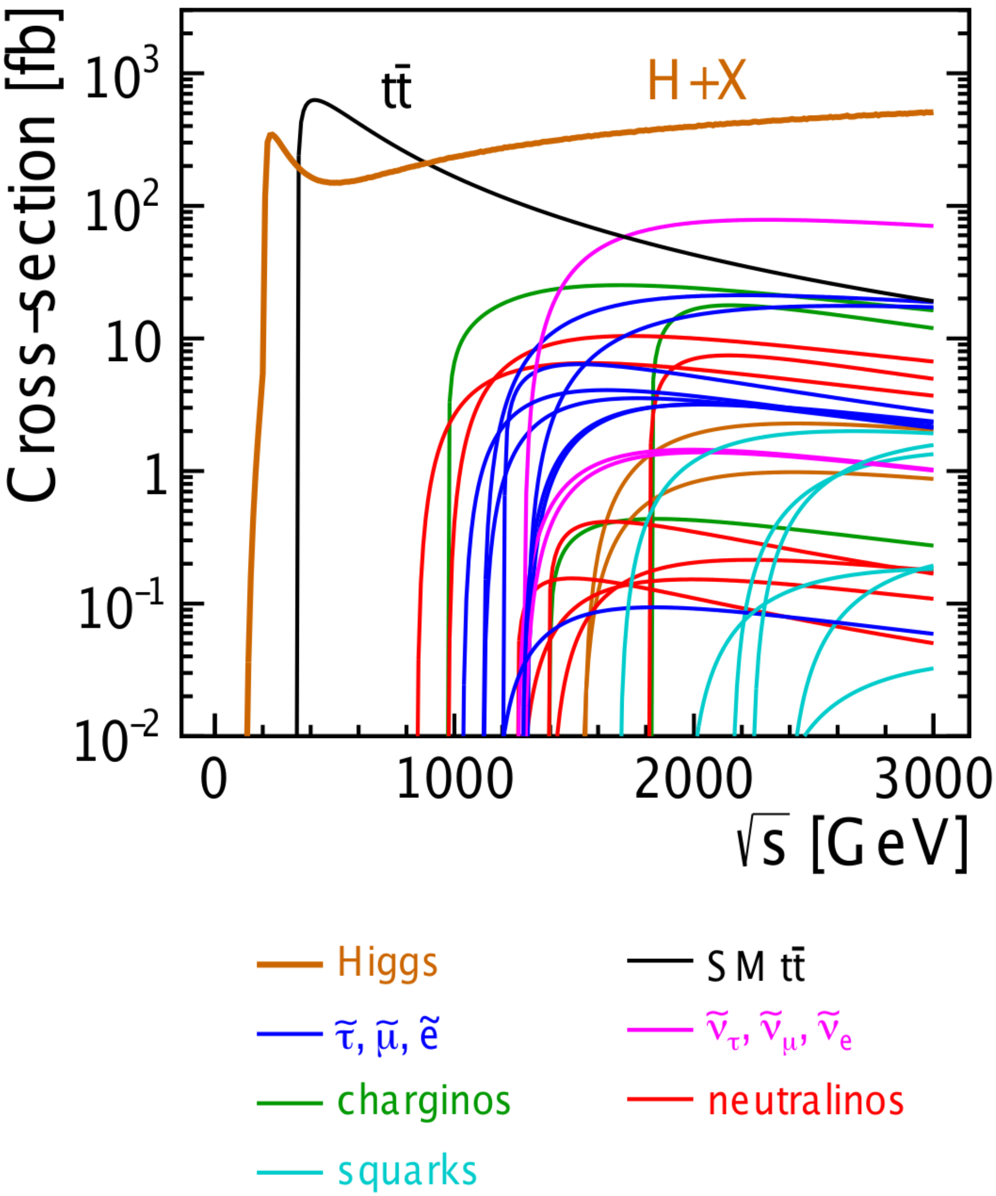
Threshold scan



t→ cγ



Beyond Standard Model at CLIC

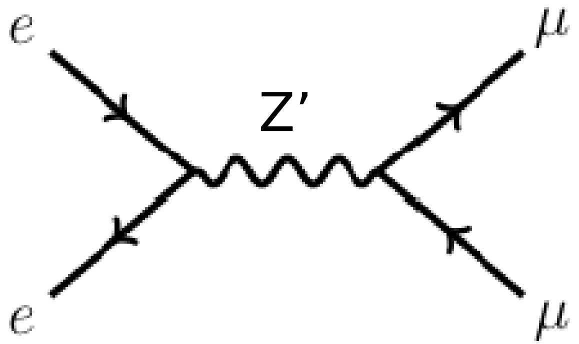


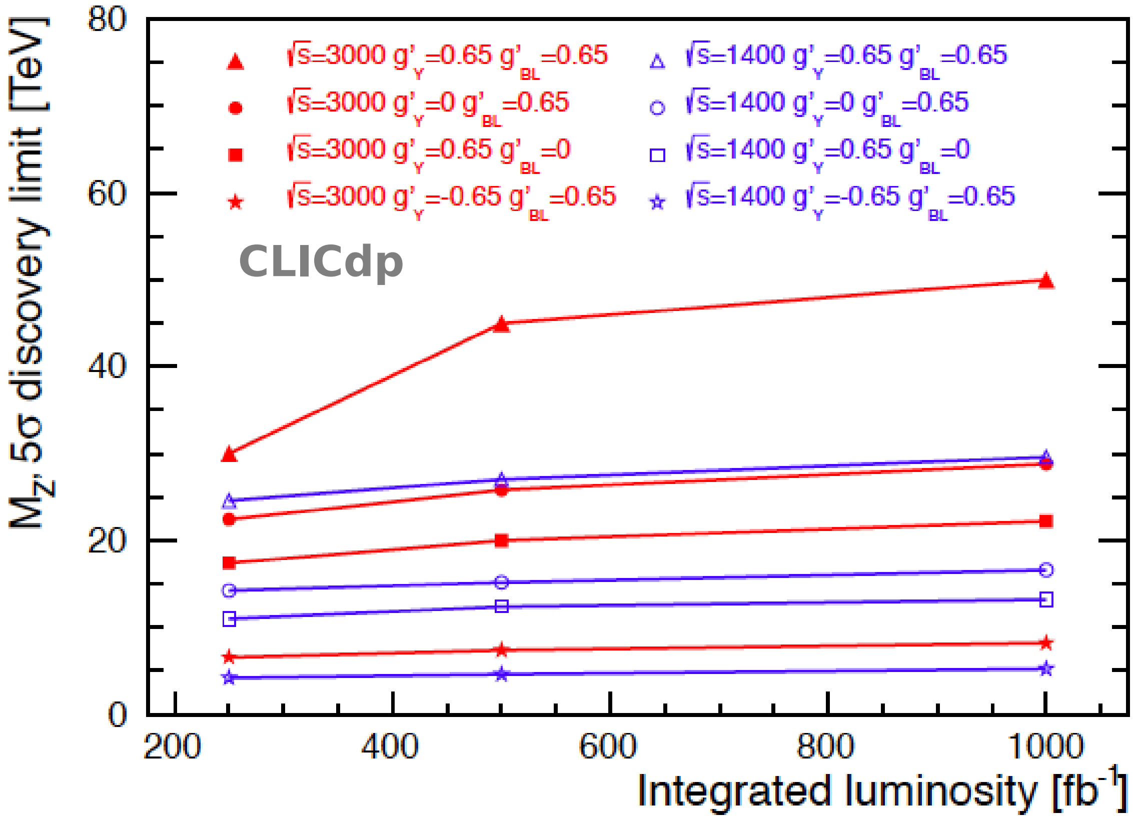
- CLIC operating at high energy provides significant discovery potential for BSM physics
- **Direct searches** of new particles:
  → Possible observation of the new phenomena thanks to the low background (no QCD)
  → Precision measurements of new particle properties (also for the ones discovered in (HL-)LHC)
  → Sensitivity often extends up to the kinematic limit (e.g. m ≤ √s / 2 for pair production)
- **Indirect searches** of new physics:
  → Precision measurements of sensitive observables reveal a signs of new physics, comparing to the SM expectations
  → The reach is higher – several tens of TeV

Beyond Standard Model at CLIC

Example of indirect measurement:

$Z' \rightarrow \mu^+\mu^-$





- **Observables:**
  - → Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
  - → Forward-backward asymmetry
  - → Left-right asymmetry (with ±80% e^- polarisation)

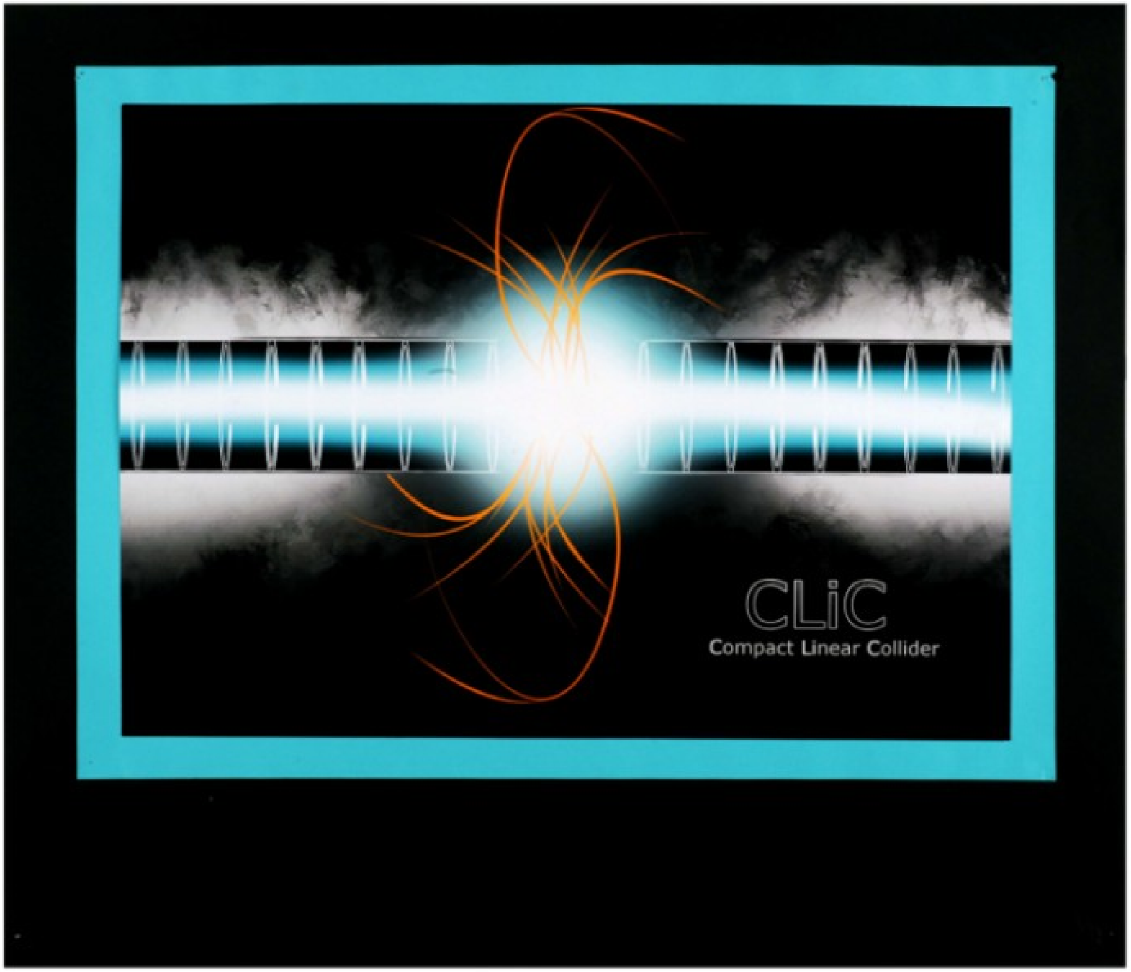
- **If LHC discovers Z' (e.g. for $M_{Z'}$=5 TeV)**

→ CLIC precision measurement of effective couplings

otherwise:

→ CLIC discovery reach up to tens of TeV (depending on the couplings)

“My own visions of CLIC”
Artwork by Alexander Duncan, 2010



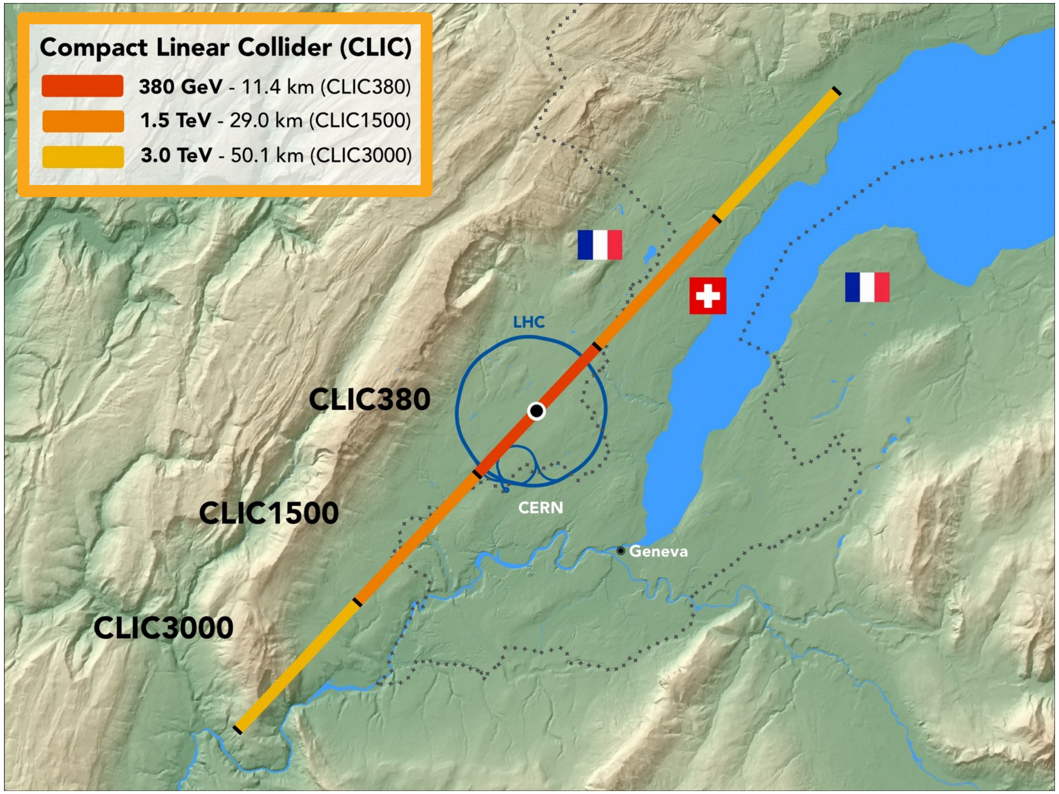
CLIC accelerator

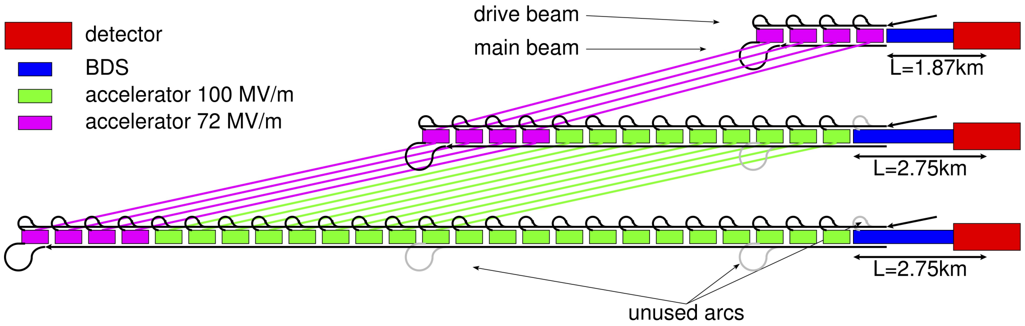
CLIC accelerator

- **CLIC = Compact Linear Collider**
- High-luminosity linear e^+e^- collider
- CLIC would be implemented in several energy stages
- Baseline scenario:

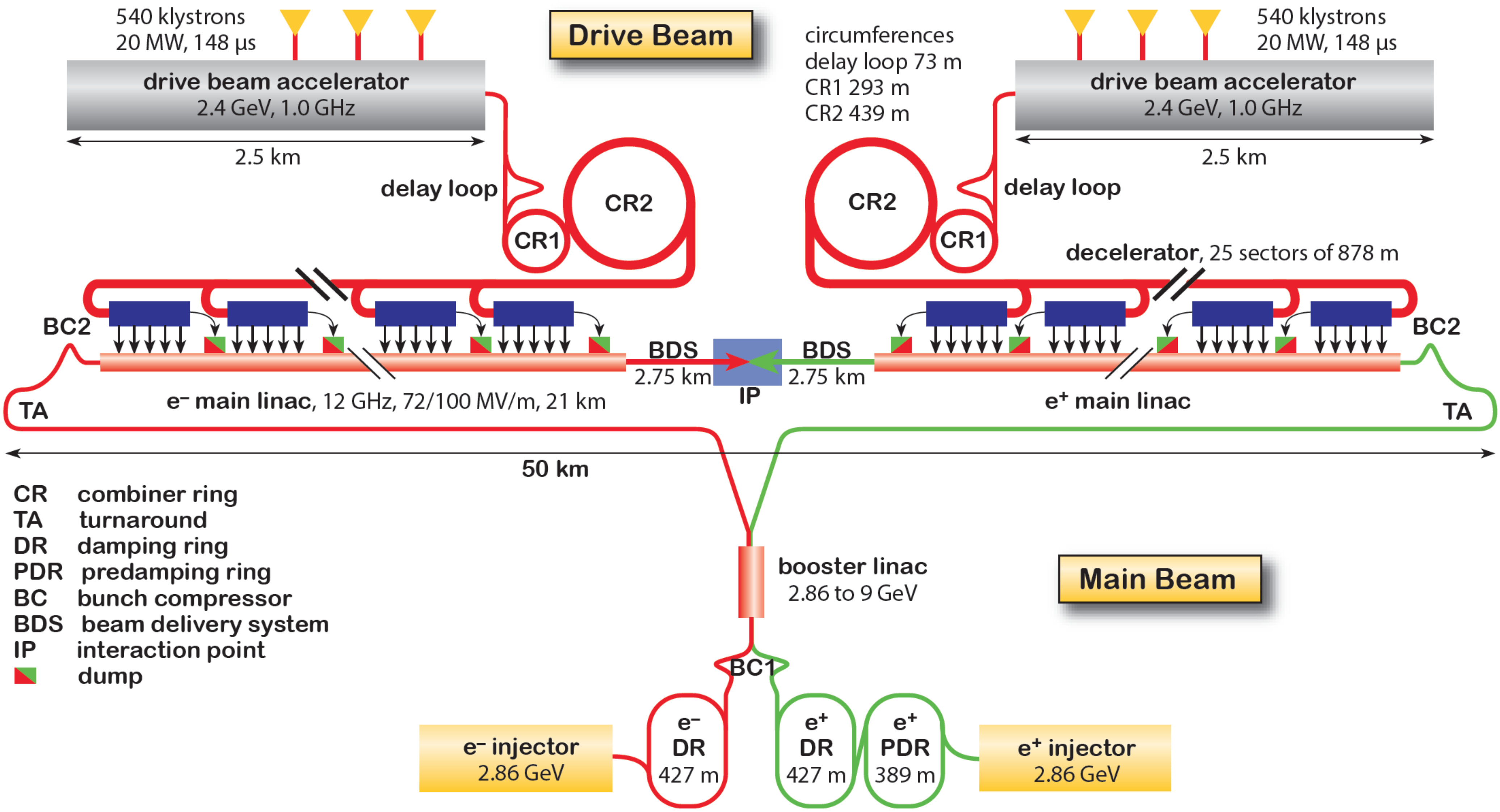
Stage	√s	L_{int} (fb^{-1})
1	380 GeV 350 GeV	500 100
2	1.5 TeV	1500
3	3 TeV	3000

- Possible polarization of the beam
- Possibility to adapt the stages to new LHC discovery!



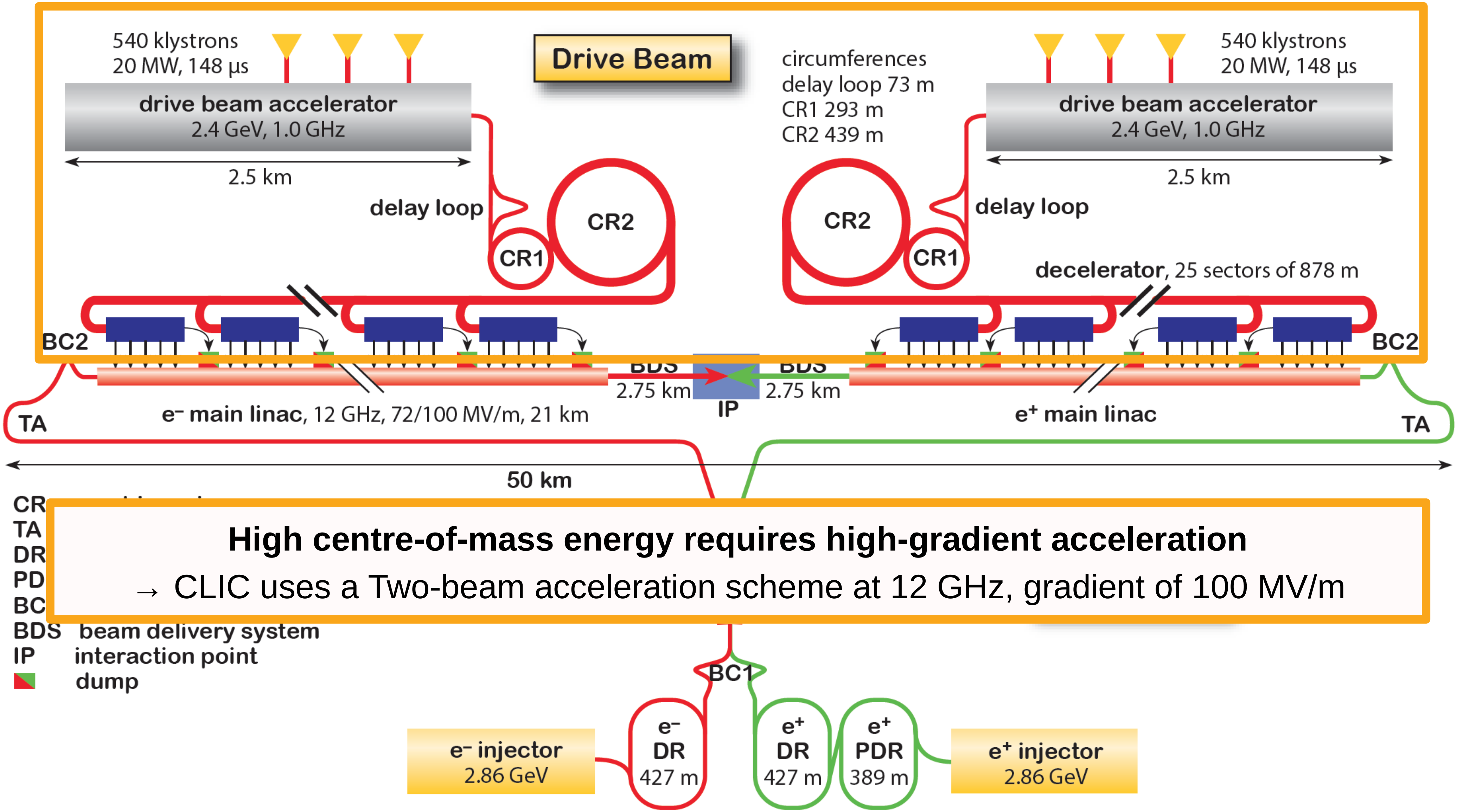


CLIC layout at 3 TeV



CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**

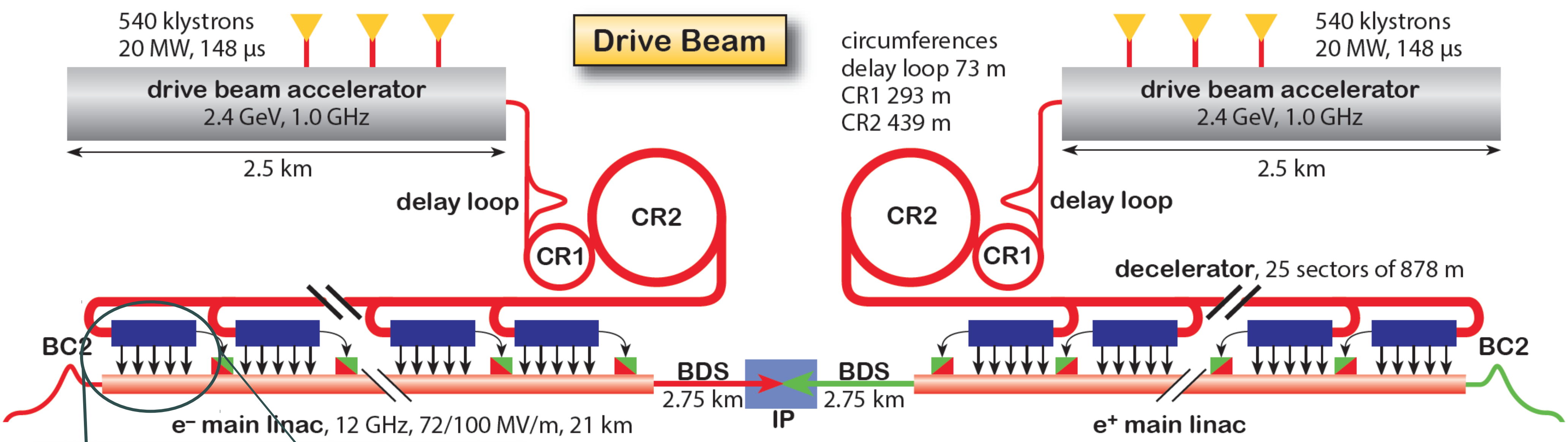
CLIC layout at 3 TeV

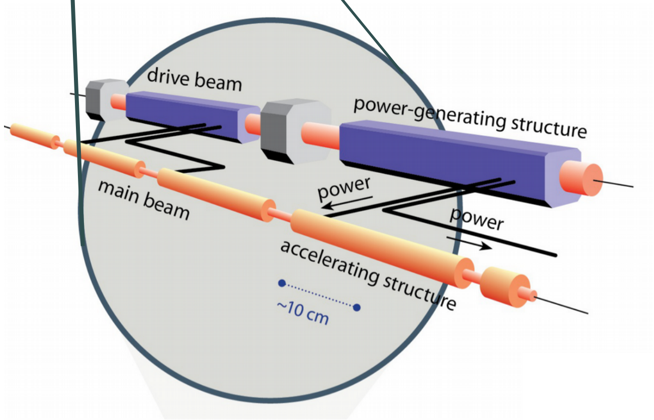


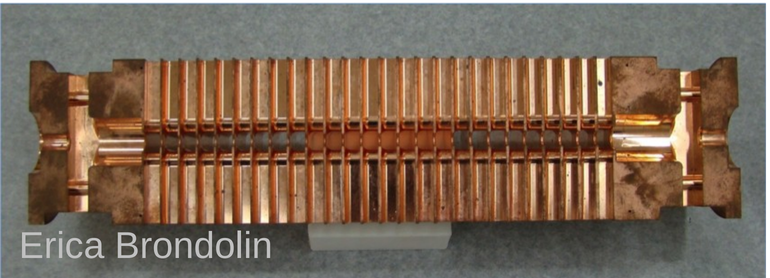
High centre-of-mass energy requires high-gradient acceleration

→ CLIC uses a Two-beam acceleration scheme at 12 GHz, gradient of 100 MV/m

CLIC layout at 3 TeV





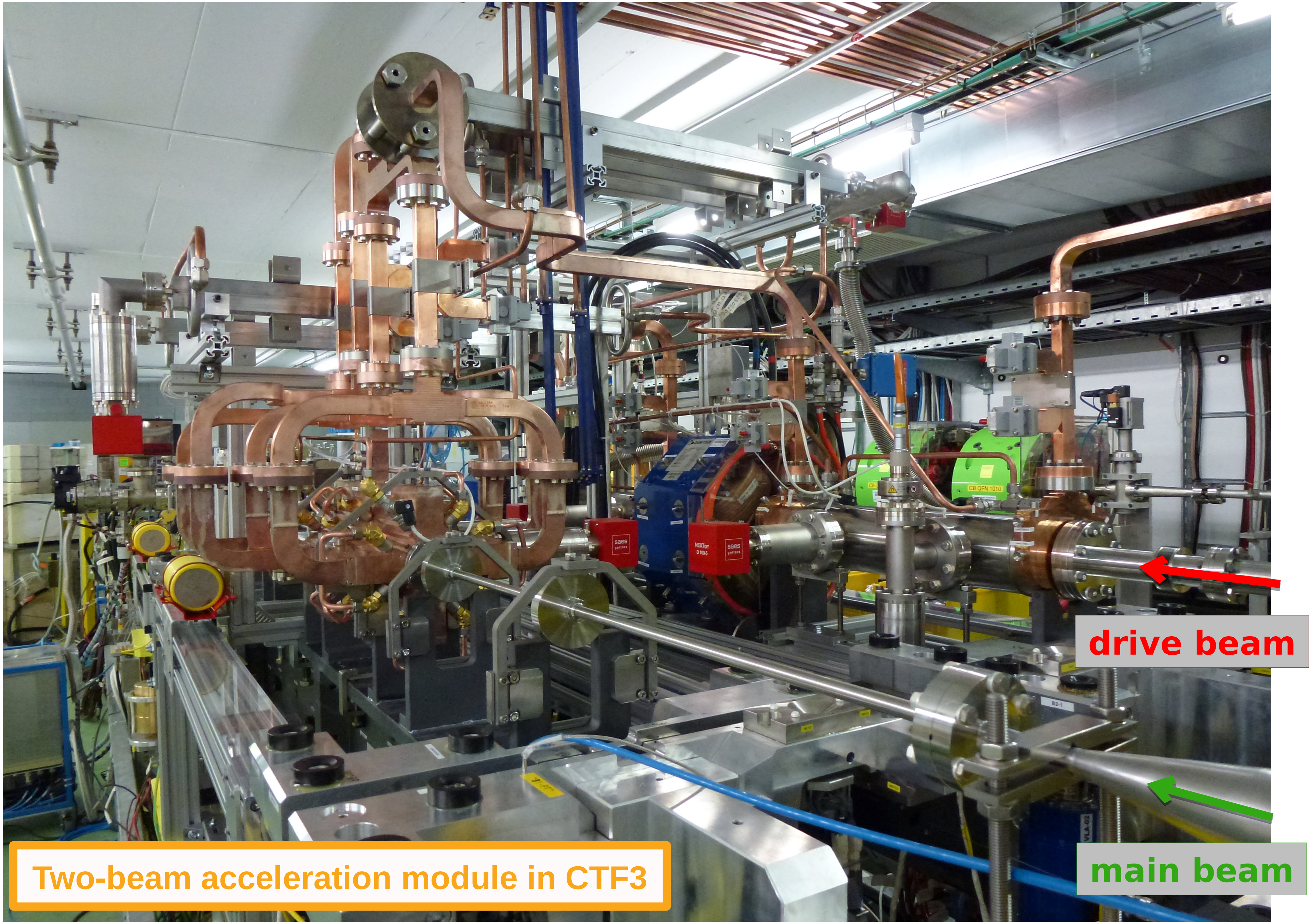


- RF power source using “Two-beam technique”

  Drive beam: high current (100 A), low energy (2.4 GeV - 240 MeV), klystron acceleration

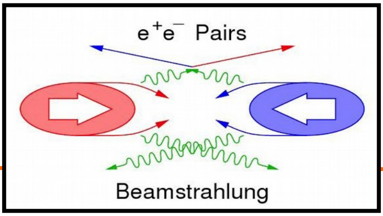
  Main beam for physics: lower current (1.2 A), high energy (9 GeV-1.5 TeV), accelerated by the RF cavities powered by the deceleration of the drive beam in special RF structures (PETS)
- Two beam technique demonstrated at CERN, CLIC CTF3 test facility

Two-beam setup



Two-beam acceleration module in CTF3

Beam-induced backgrounds



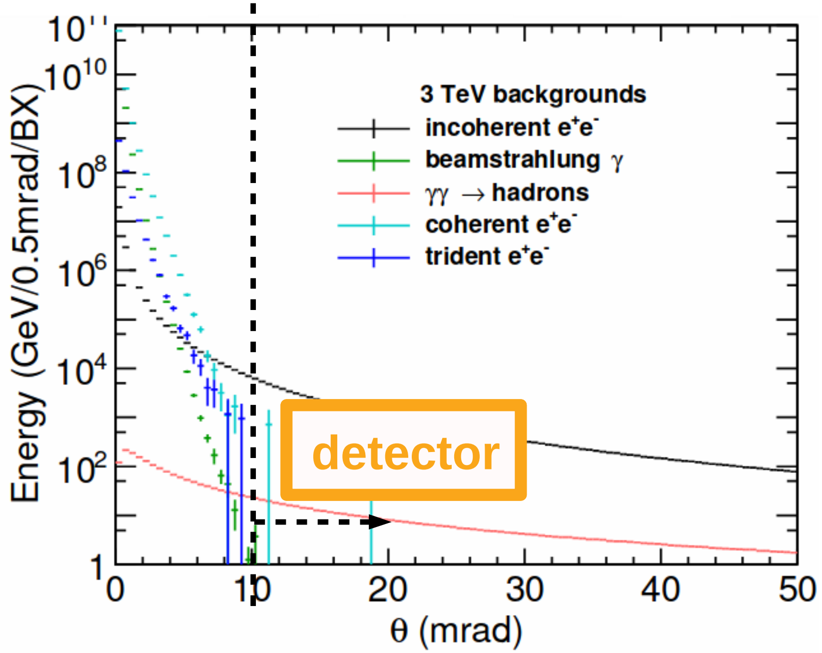
CLIC achieves high luminosities by using extremely small beam sizes

→ 3 TeV CLIC bunch size: $\sigma_{x,y,z}$ = {40 nm, 1nm, 44um} (at LHC $\sigma_{T,z}$ = {16.7 μm, 7.55 cm})

→ very high EM-fields → beam-beam interactions

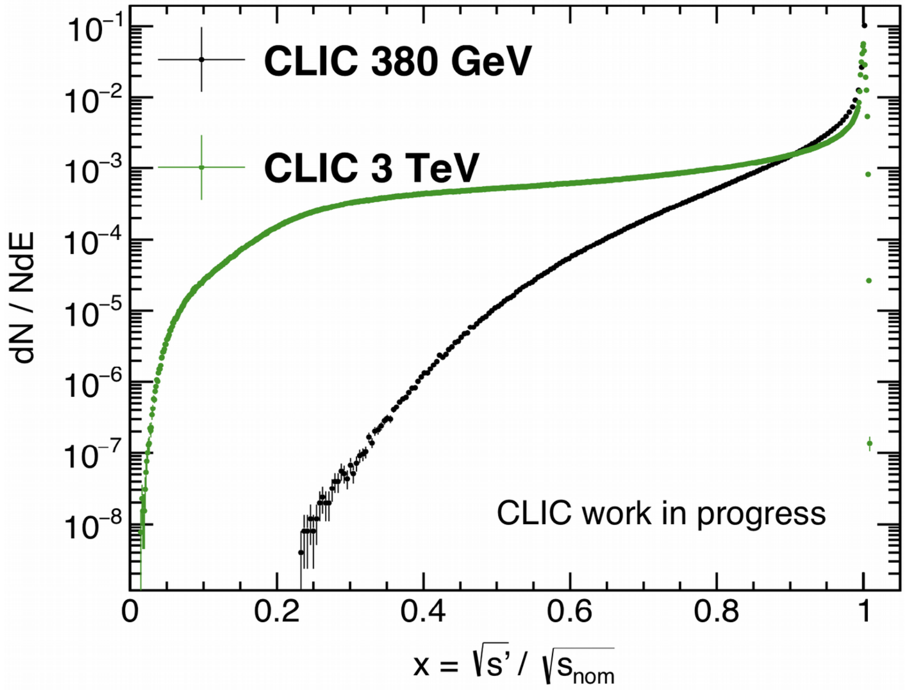
Main backgrounds:

- **Coherent e^+e^- pairs**
  Real γ interacts with beam field
  → Very forward region
- **Trident e^+e^- pairs**
  Virtual γ interacts with beam field
  → Very forward region
- **Incoherent e^+e^- pairs**
  Virtual or real γs interact with individual particles
  → High occupancy
  → Impact on detector granularity and design (in particular for the forward region)
- **γγ → hadrons**
  Virtual or real γs interact with each other
  → High energy deposits
  → Impact on detector granularity, design and physics measurement



- **Effect is dependent on √s**
- **Main effects:**
  → Background particles
  → Reduces √s

Luminosity spectrum at CLIC



Fraction √s’/√s	380 GeV	3 TeV
> 0.99	63%	36%
> 0.9	91%	57%
> 0.8	98%	69%
> 0.7	99.5%	77%
> 0.5	≈100%	89%

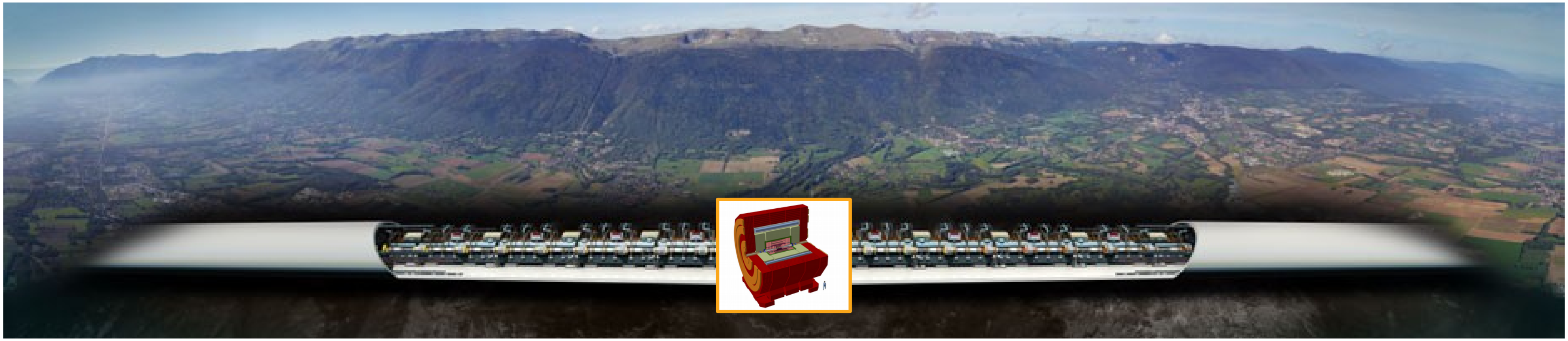
- Due to beamstrahlung, important energy losses right at the interaction point
- Collision energy is reduced by the amount lost in beamstrahlung before collision
- Most physics processes are studied well above production threshold

→ Can profit from almost full luminosity

“My own visions of CLIC”
Artwork by Lukas Molketin

CLIC detector

Detector technology R&D



CLIC detector layout and technology has to be optimized for:

- Physics program at CLIC:
  - → Precision measurements
  - → Searches for New Physics
- Experimental conditions at CLIC:
  - → Colliding system
  - → Collision energy and energy spread
  - → Beam-induced backgrounds
- Affordability and feasibility

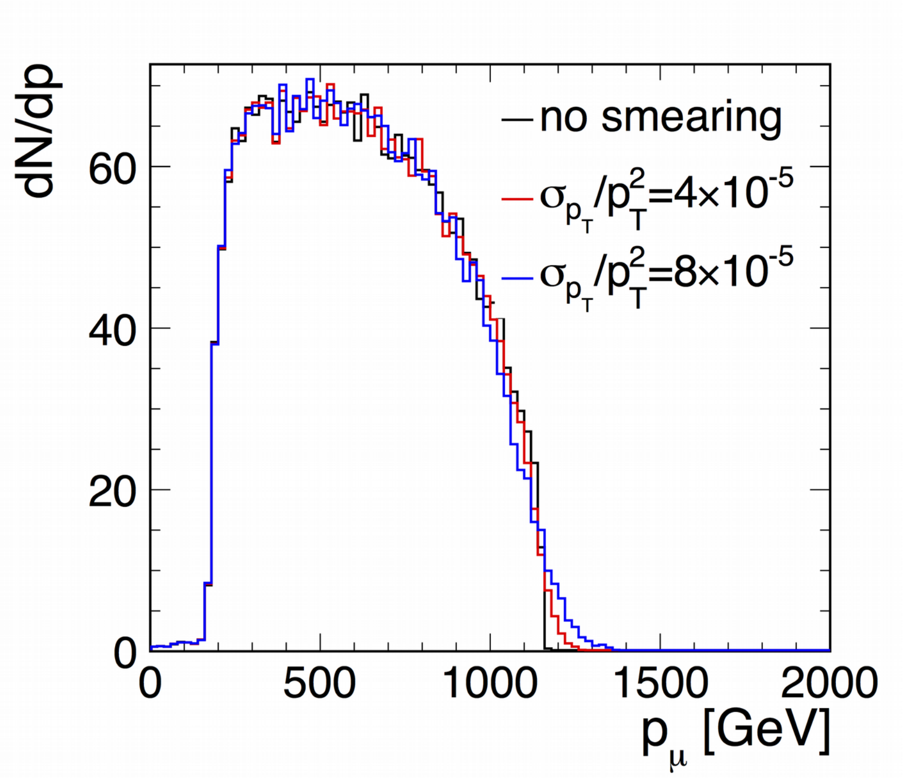
Detector requirements

Momentum resolution

(e.g. H → $\mu^+\mu^-$, leptons from BSM processes)

$$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\,\mathrm{GeV}^{-1}$$

above 100 GeV



$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

Energy resolution for light-quark jets

(e.g. W/Z/h di-jet mass separation)

$$\frac{\sigma_E}{E} \sim 3.5 - 5\,\%$$

for E = 50 GeV – 1 TeV

Impact parameter resolution

(e.g. b/c tagging, Higgs couplings)

$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$

Lepton identification efficiency > 95 %

Very forward electron tagging

Detector requirements

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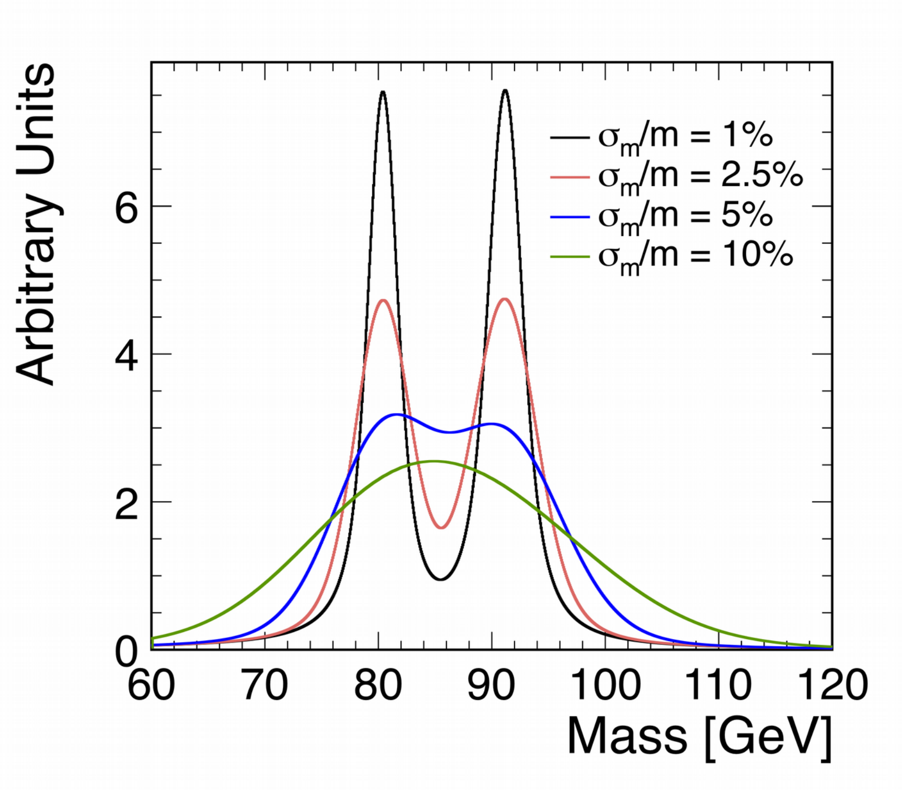

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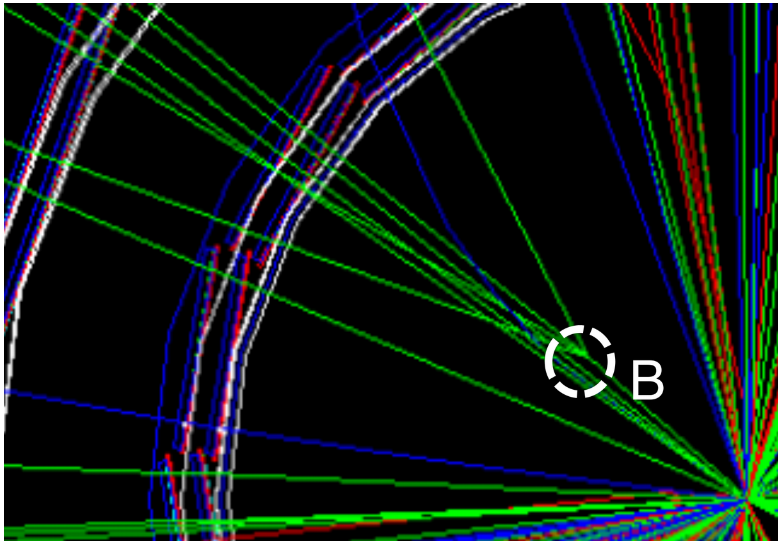


CLIC detector concept

Designed for Particle Flow Analysis (PFA) and optimised for CLIC environment

Basic characteristics:

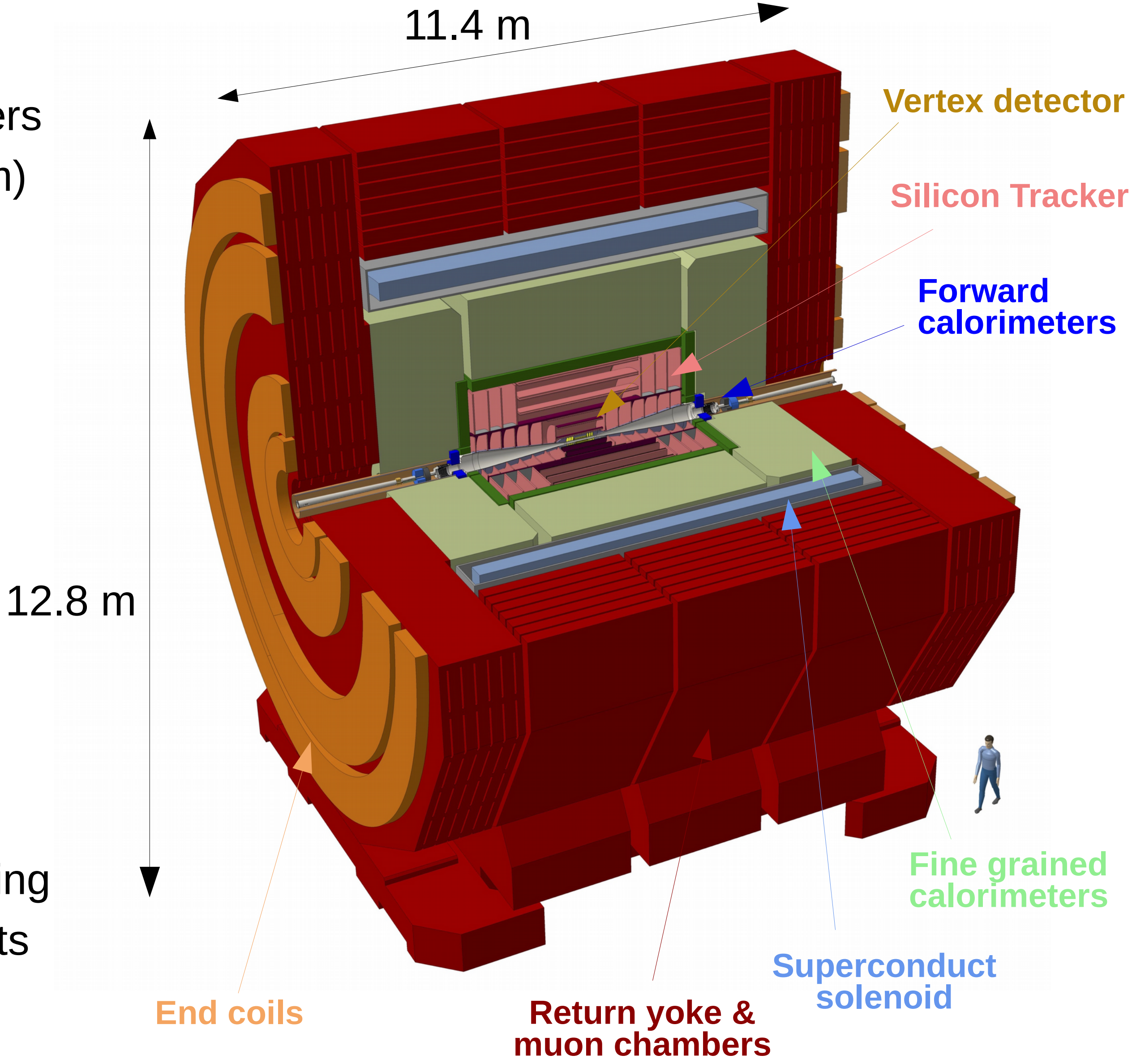
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (R ~ 1.5 m)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ_I)
- Muon chambers for Muon ID
- Last focusing magnet QD0

outside detector: increased HCAL forward acceptance

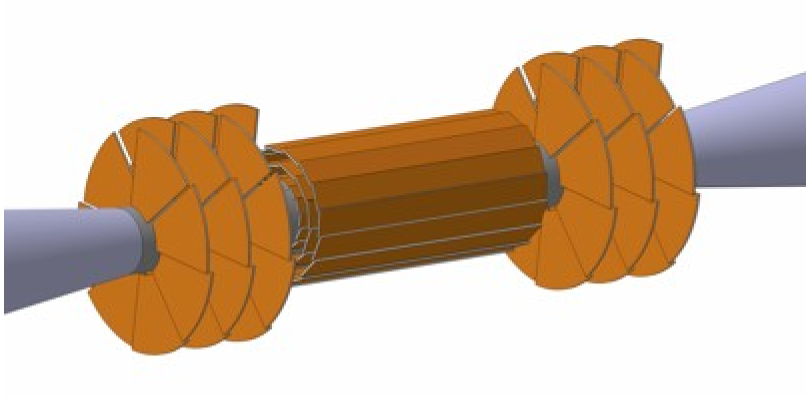
Precise timing for background suppression

(bunch crossings 0.5 ns apart)**:**

- < 10 ns hit time-stamping in tracking
- < 1 ns accuracy for calorimeter hits

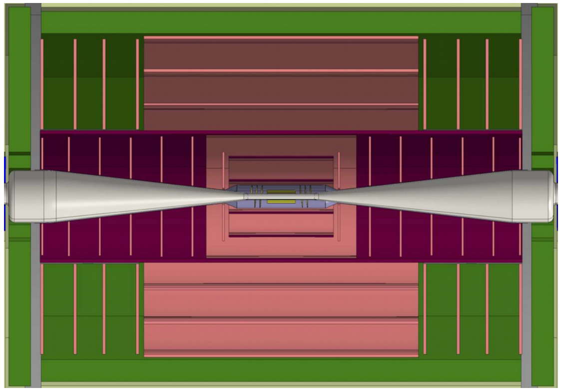


Vertex and tracking detectors



Vertex detector

- Flavor tagging capabilities drive the design of the vertex detector
  → Precise determination of displaced vertices
- Detector composed of 25 × 25 µm^2 pixels
- Total surface area ∼ 0.84 m^2
- Extremely accurate and light
- Main features:
  → Single point resolution: $\sigma < 3$ µm
  → Inner radius: $R = 31$ mm
  → Material budget: < 0.2 % X_0 per layer
- Time stamping: < 10 ns



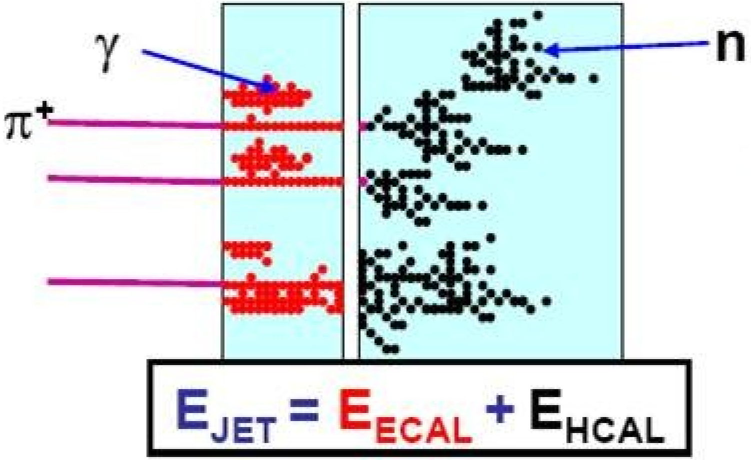
Silicon Tracker

- Very good momentum resolution drives the design of the tracker
  → Requires large $B \cdot R^2$
  → Many layers
- Tracker composed of large pixels/strips:
  50-300 µm thick
  50 µm − (1 mm or 10 mm) layout sizes
- Total surface area ~ O(100 m^2)
- Main features:
  → Single point resolution: $\sigma \sim 7$ µm
  → Larger radius: $R = 1.5$ m
  → Material budget: ~ 1-2 % X_0 per layer
- Time stamping: < 10 ns

The Particle Flow approach

Main idea of Particle Flow approach:

- **Average jet composition:**
  60% charged particles
  30% photons
  10% neutral hadrons



The Particle Flow approach

Main idea of Particle Flow approach:

- **Average jet composition:** → Use the best information

  60% charged particles → tracker

  30% photons → ECAL

  10% neutral hadrons → HCAL

- **Hardware:**

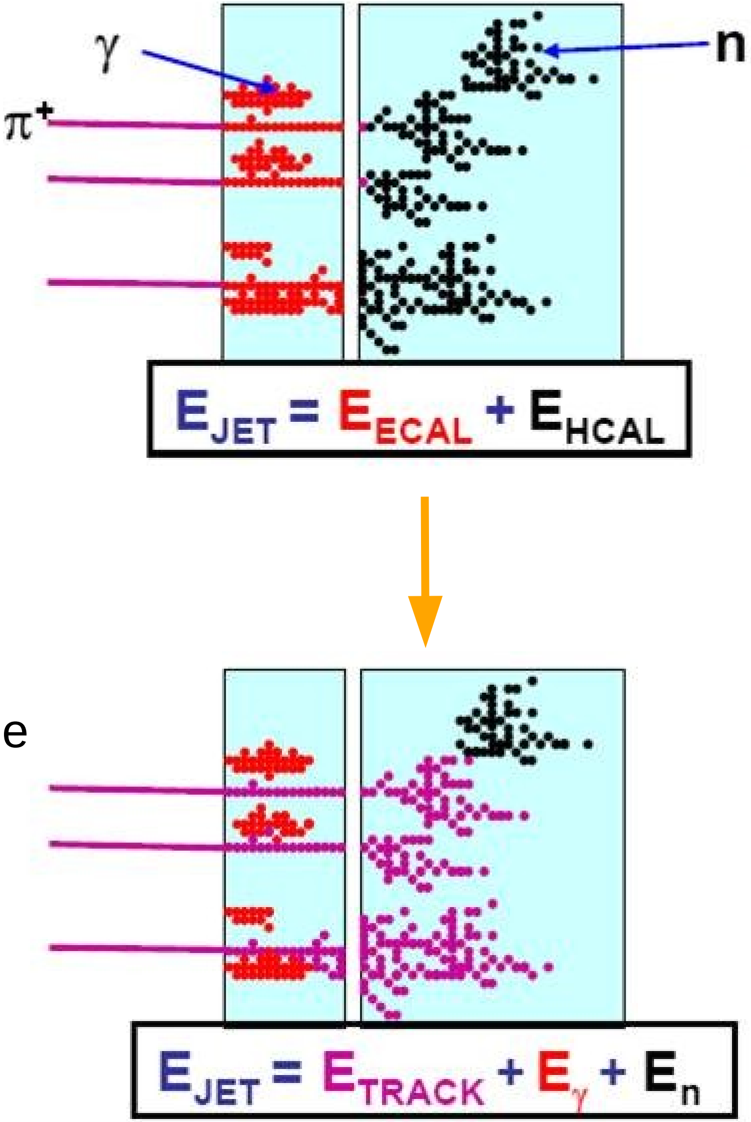
  Resolve energy deposits from different particles

  → High granularity calorimeters

- **Software:**

  Associate energy deposits to the correct individual particle

  → Sophisticated reconstruction software

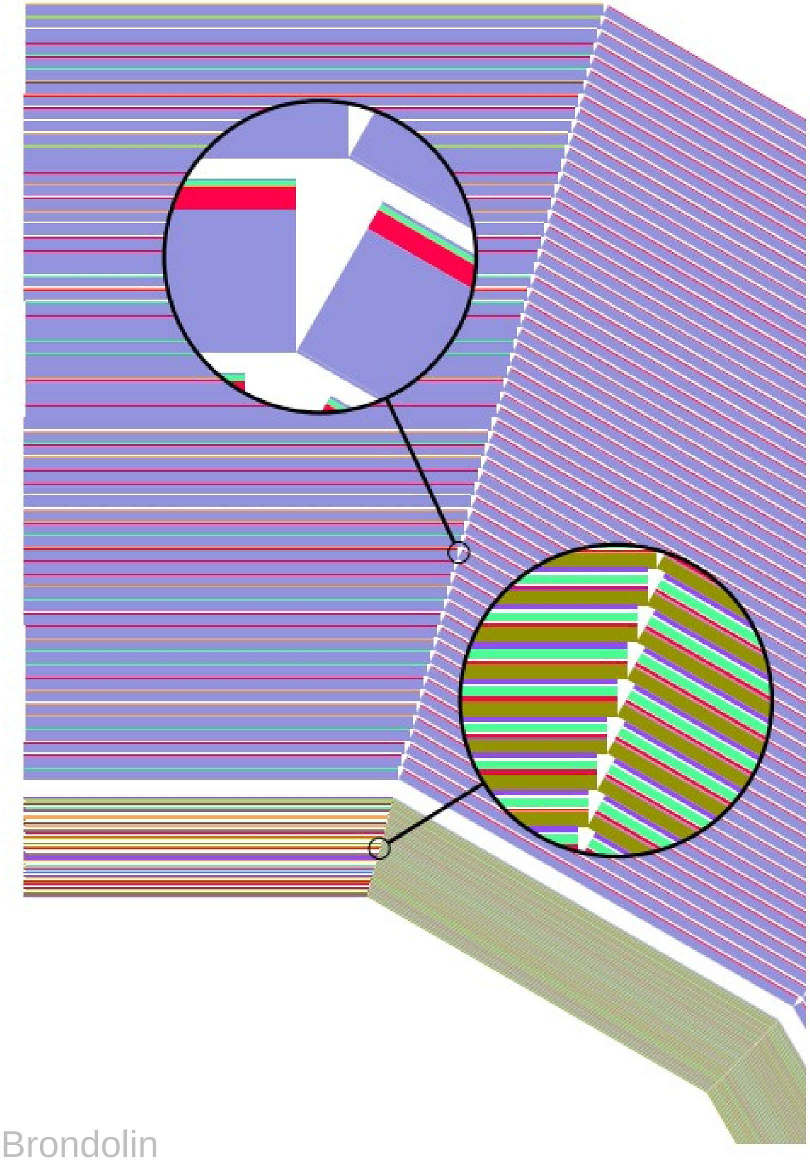


$$E_{JET} = E_{ECAL} + E_{HCAL}$$

$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

PFA calorimeters

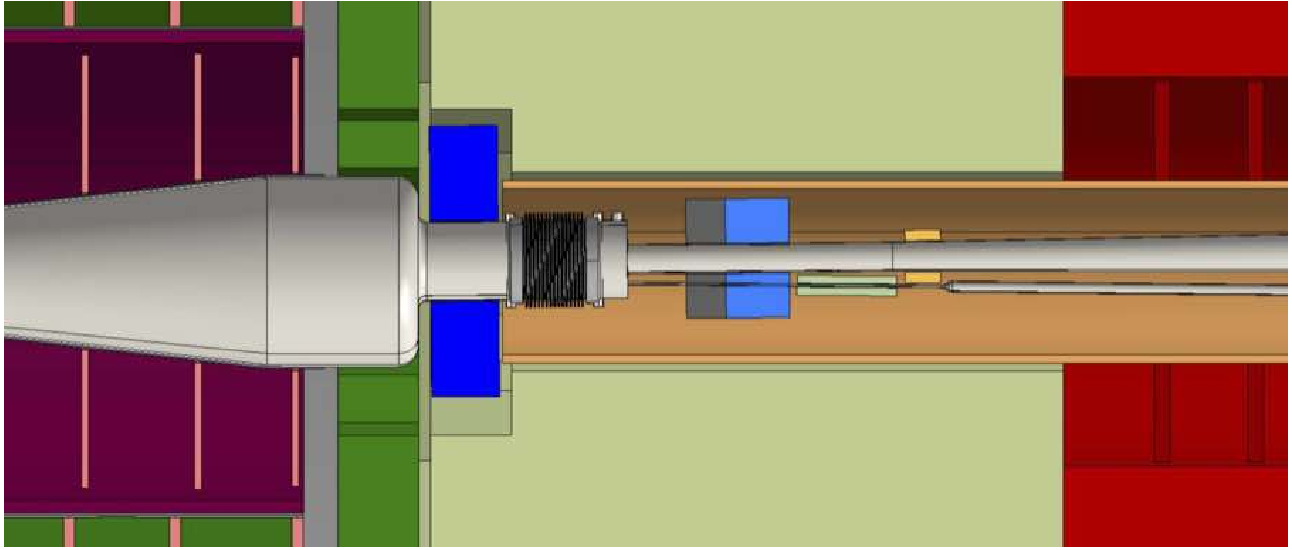
- Jet energy resolution drives the design of the calorimeters
  → Highly granular calorimeters



- **ECAL composed of Si-W**:
  2 mm thick tungsten plates interleaved with 500 µm thick silicon sensors
  40 layers 22 X_0 and 1 λ_I
  5 × 5 mm^2 silicon cell size
  Active area ~ 2500 m2 silicon
  ~ 100 million channels
- **HCAL composed of Scint-Fe**:
  19 mm thick steel plates interleaved with 3 mm thick plastic scintillator + SiPMs
  60 layers: 7.5 λ_I
  30 × 30 mm^2 scintillator cell size
  Active area ~ 9000 m^2 scintillator
  → ~ 10 million channels / SiPMs
- Compact design of all components
- Time stamping: < 1 ns

Forward CALorimetry: FCAL

LumiCal R_{out} = 34 cm, **BeamCal** R_{out} = 15 cm



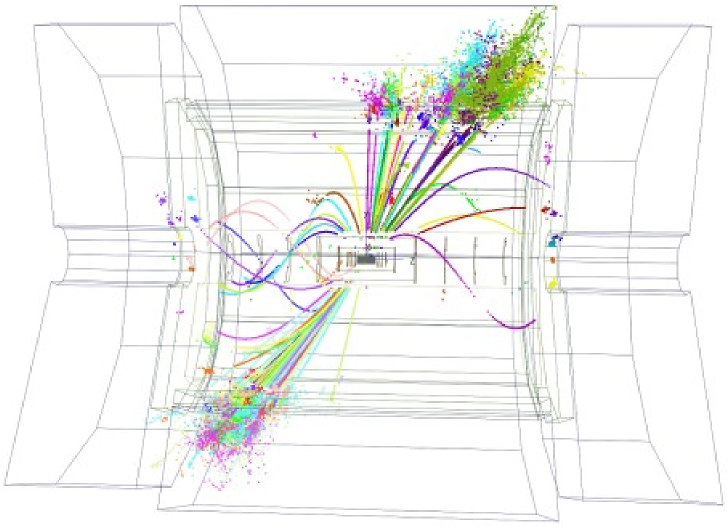
- e and γ acceptance to small angles
- Very compact design (sensors, read-out, absorber)
  → small Molière radius

- Luminosity measurements drive the design of the LumiCal
- LumiCal composed of Tungsten/Silicon

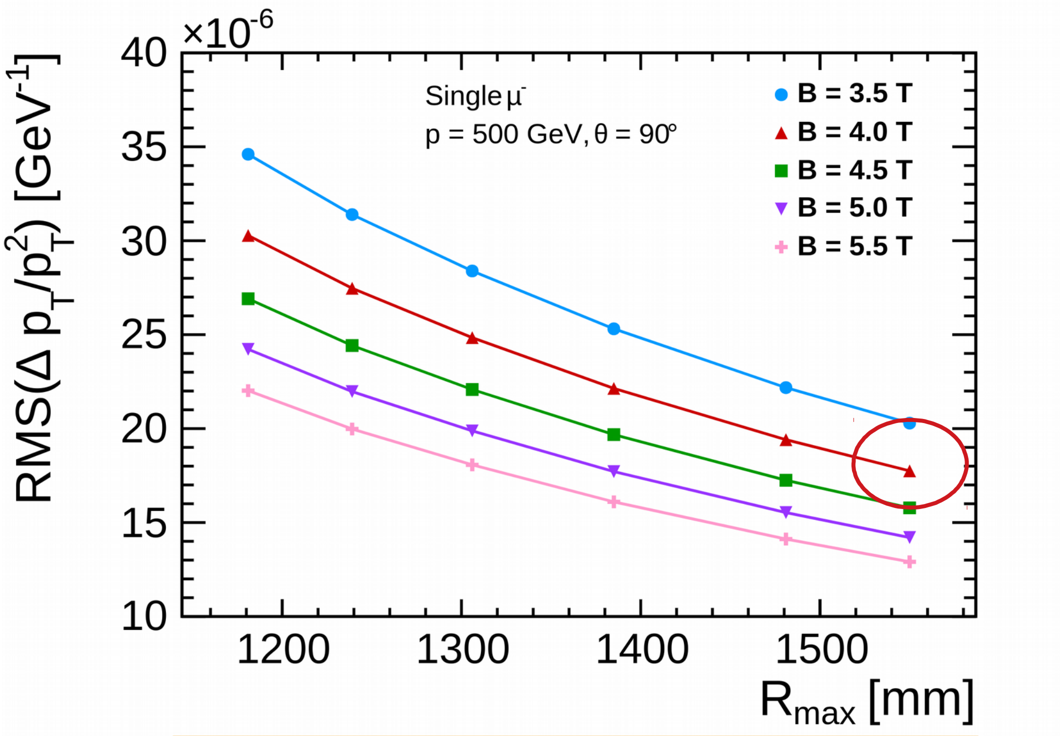
- Very forward electron tagging drives the design of the BeamCal
- BeamCal composed of Tungsten/GaAs

Full det simulation and optimization

- Full Geant4 detector simulation including overlay of beam-induced backgrounds
- Full reconstruction chain including
  reconstruction of tracks and clusters → particle flow objects → jets → flavor tagging
- Optimization of CLIC detector model in full detector simulations
  → Ensure that detector performance meets requirements
  → Validate full software chain



$e^+e^- \to t\bar{t}$ @ 3 TeV



Tracker radius and
B-Field ↔ momentum resolution

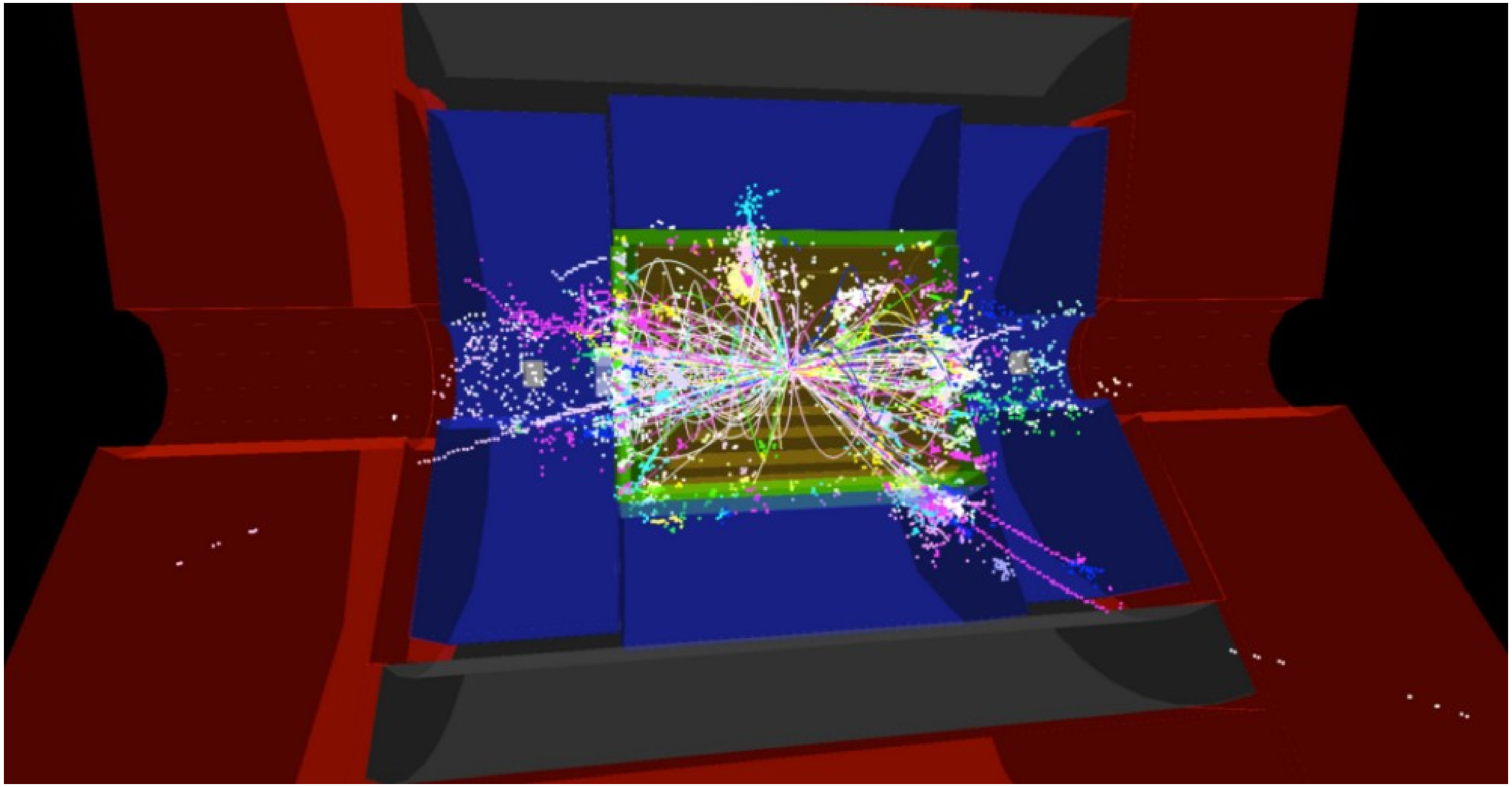
Beam-induced background rejection

Beam-induced background from γγ → hadrons can be efficiently suppressed by applying p_t vs. time selections on individually reconstructed particles (particle flow objects)

→ Cuts optimized for detector regions

→ Cluster time obtained by combining hit timing information

Before the pt vs. time selections



Example: e+e− → ttH → Wb Wb H → qqb τνb bb at 1.4 TeV

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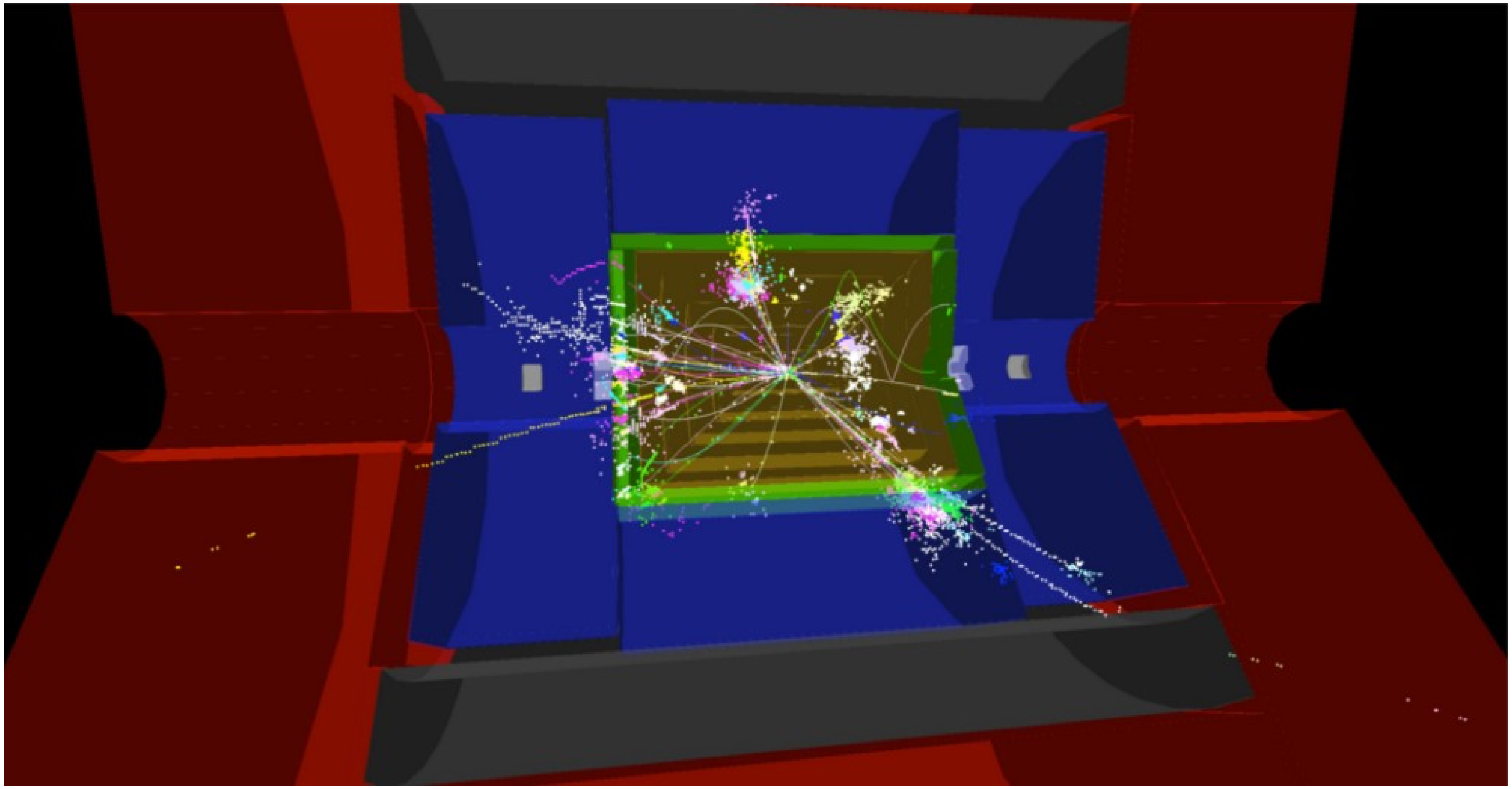
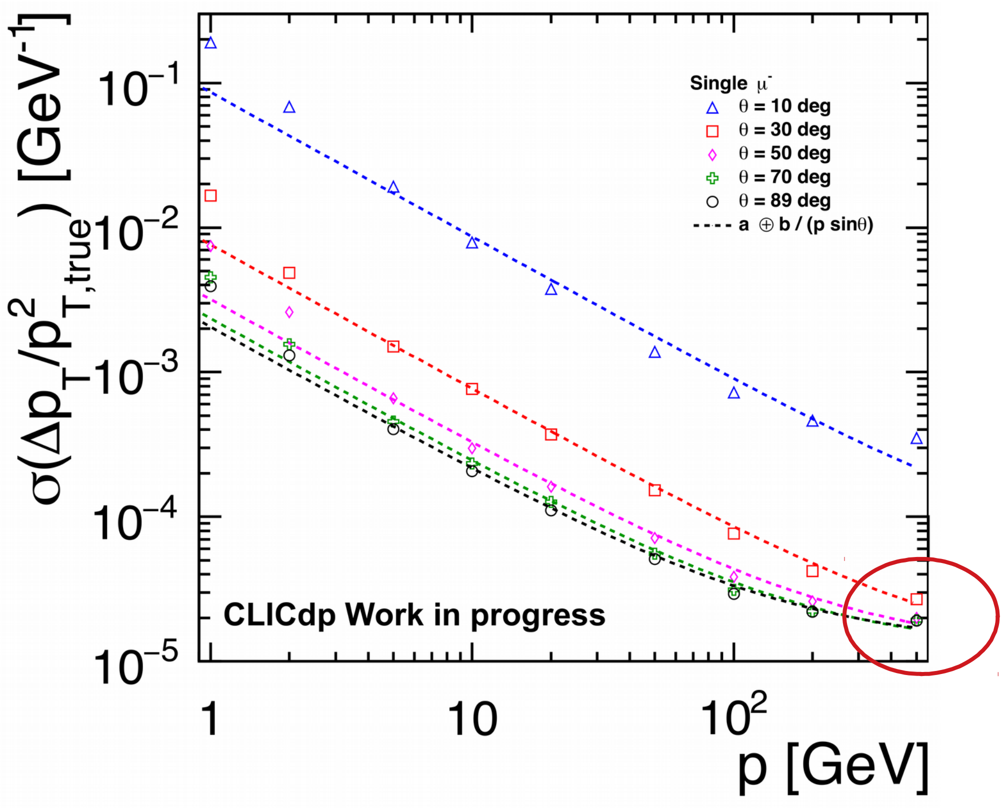


Example: e+e− → ttH → Wb Wb H → qqb τνb bb at 1.4 TeV

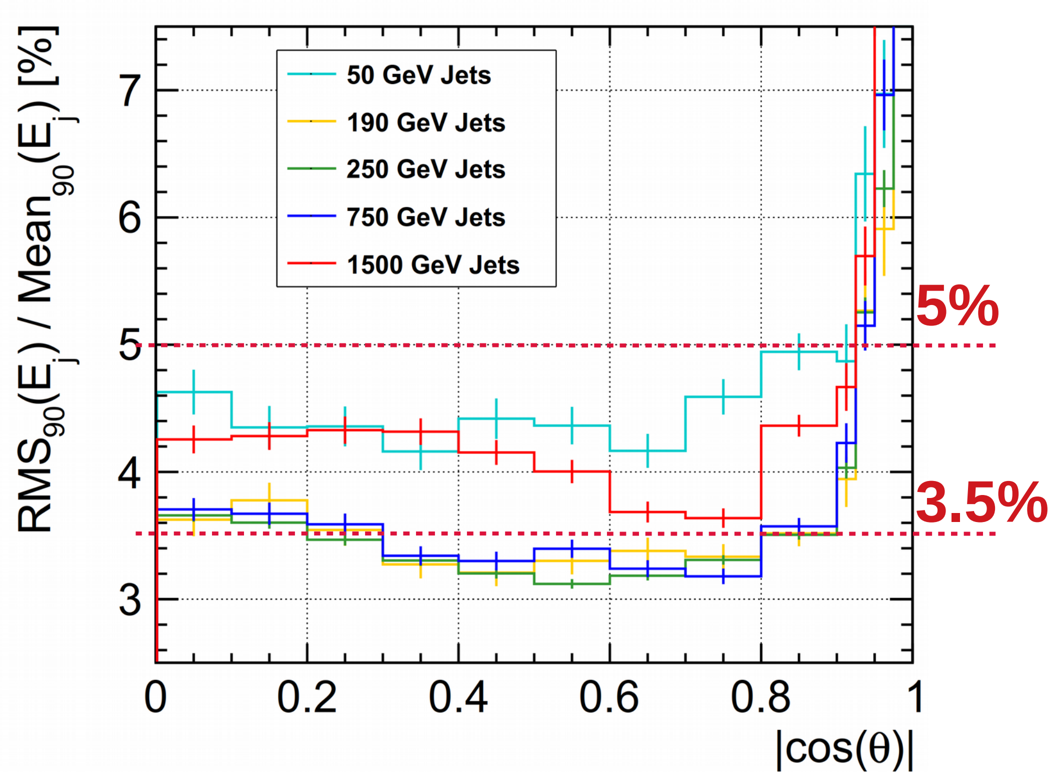
CLICdet performance (I)

Tracking



- Transverse momentum resolution of 2×10^{-5} GeV^{-1} achieved for high-energy tracks in the barrel

Jet energy resolution

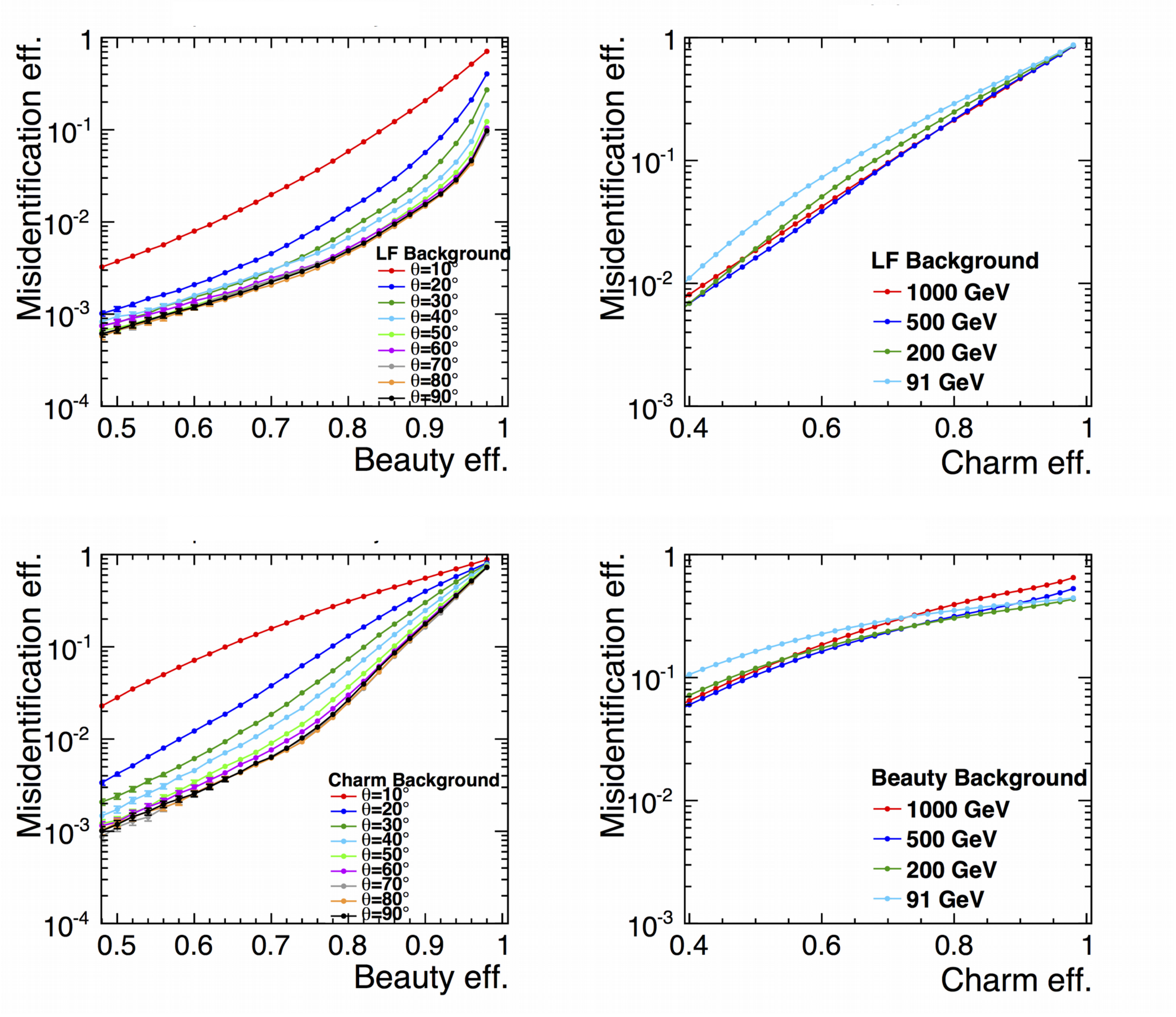


- Jet energy resolution of 3.5 – 5 % achieved for E = 50 GeV – 1 TeV using particle flow analysis and software compensation
- Requires detailed calibration and optimization for all detector regions

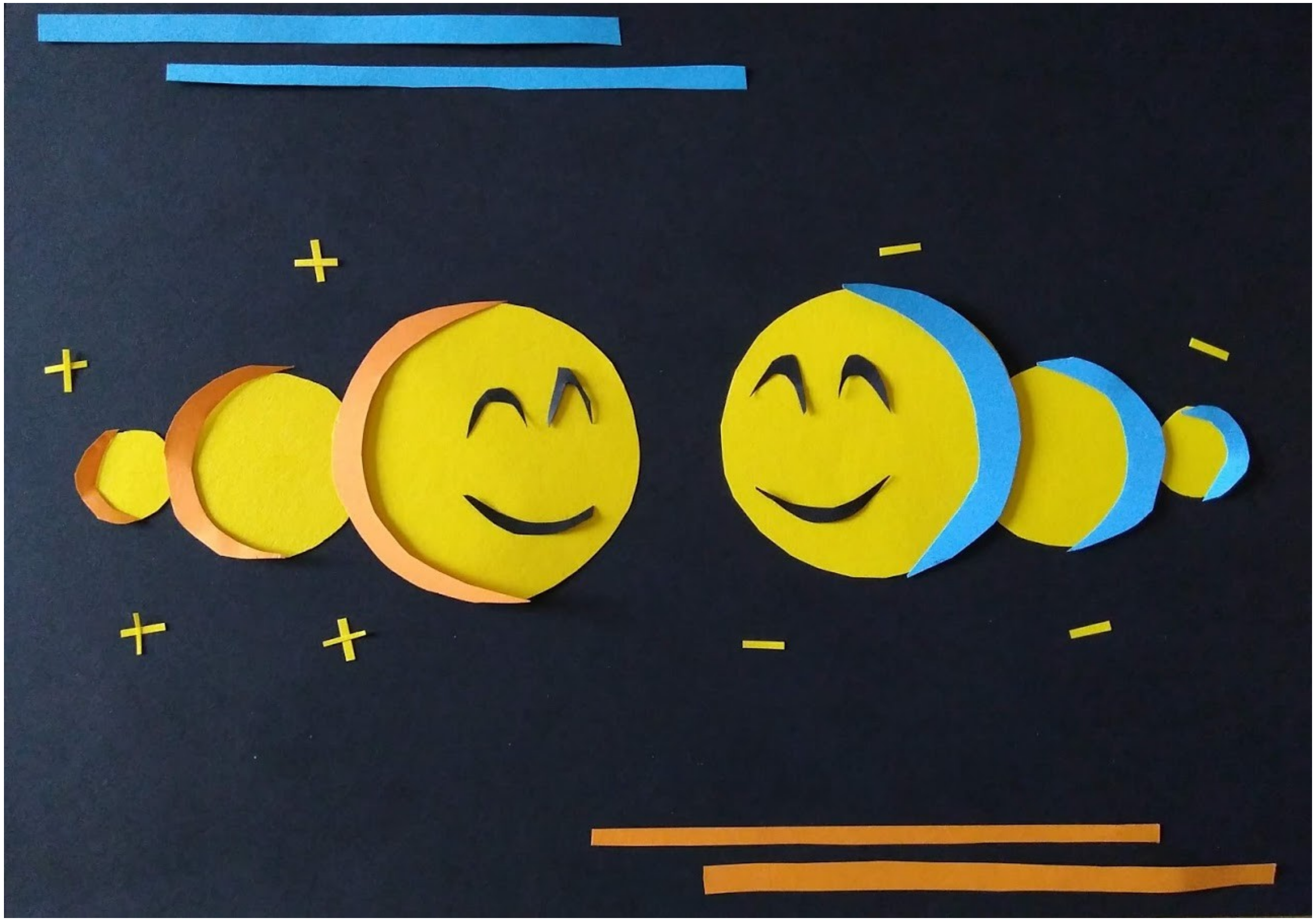
CLICdet performance (II)

- Vertex finder reconstructs primary and secondary vertices
- Jet reconstruction using jet clustering algorithm

b- and c-tagging in $e^+e^- \rightarrow qq$ events



“My own visions of CLIC”
Collage by Erica Brondolin



Conclusions

Have I convinced you?

- **CLIC is e^+e^- collider from a few hundred GeV up to 3 TeV**
- **CLIC is a mature international project**
- **CLIC is a precision machine with a unique physics potential**
  → Allows for precision Higgs boson and $t\bar{t}$ measurements and searches for physics beyond the Standard Model at the TeV scale
- **The accelerator feasibility issues have been addressed up to this date**
- **CLIC machine environment and physics goals lead to challenging requirements for detector and software**
  → Ultra-light vertex and tracking detectors
  → Fine-grained calorimeters and Particle Flow Analysis
  → Full detector simulation studies for detector optimization
  → Proof-of-concepts of most-challenging detector concepts

- **A statement about CLIC as a future option for CERN is expected from the 2019-2020 update to European Strategy of Particle Physics → stay tuned!**

Thank you for the attention!

Bibliography and sources

- CLIC Conceptual Design Report: http://clicdp.web.cern.ch/content/conceptual-design-report
- CLIC accelerator and artworks:
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- LEP story: https://press.cern/press-releases/2000/10/lep-story
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- Academic Training Lecture about CLIC: https://indico.cern.ch/event/668147/
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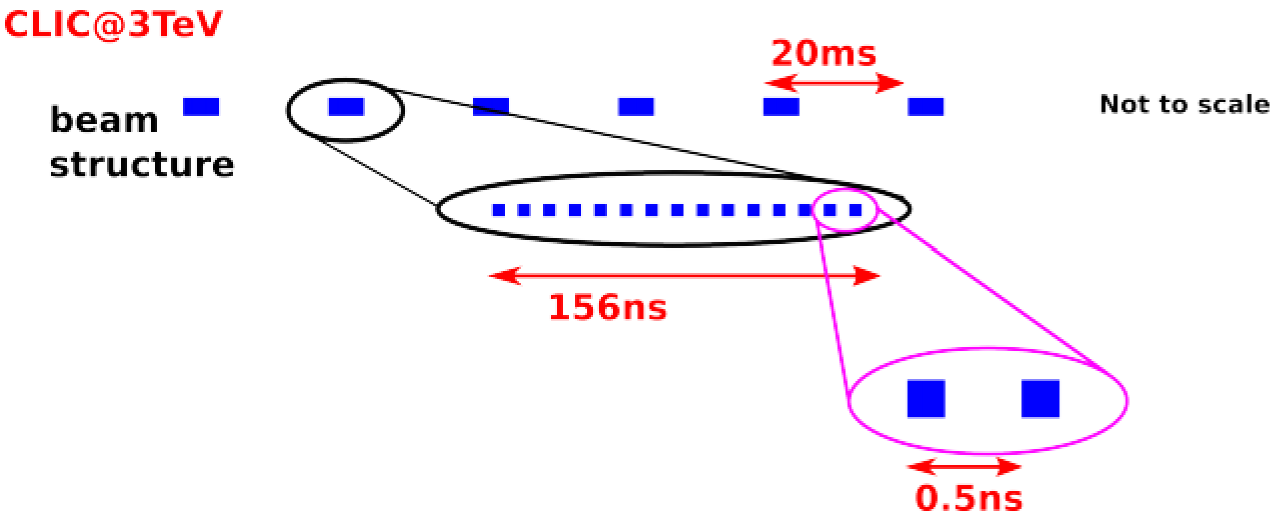
- CLICdet: The post-CDR CLIC detector model: https://cds.cern.ch/record/2254048

Duty cycle and bunch separation



Property √s	380 GeV	1.5/3 TeV
Train repetition rate	50 Hz	50 Hz
Bunches / train	356	312
Train duration	178 ns	156 ns
Bunch separation	0.5 ns	0.5 ns
Duty cycle	0.00089%	0.00078%

Linear colliders operate in bunch trains:

- Bunch separation drives timing requirement of detector:
  < 10 ns hit time-stamping in tracking
  < 1 ns accuracy for calorimeter hits
- Low duty cycle:
  Possibility of power pulsing of detectors

High Accelerating Gradient Challenge

- State of the art superconducting cavities can provide 35 MV/m but require costly cryogenics installation
- Widely used accelerator power sources - klystrons - cannot efficiently provide pulses at required frequency (12 GHz), pulse duration (152 ns)
- Required 9.2 TW peak RF power, 244 ns pulse length repeated at 50 Hz would need 35 000 klystrons to provide enough power - unfeasible and cost ineffective
- Klystrons can be used to give power to classical low frequency cavities and accelerate a so-called drive beam
- This beam with low energy (2.4 GeV) and high current (100 A) is used as a power source for high frequency RF cavities
- Drive beam is thus decelerated in special Power Extraction and Transfer Structures (PETS) to only 10% of its initial energy