中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Future Colliders

Lecture-1

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For the First International High Energy Physics School and Workshop in Western China, Aug 2018, Lanzhou, China

The Topic

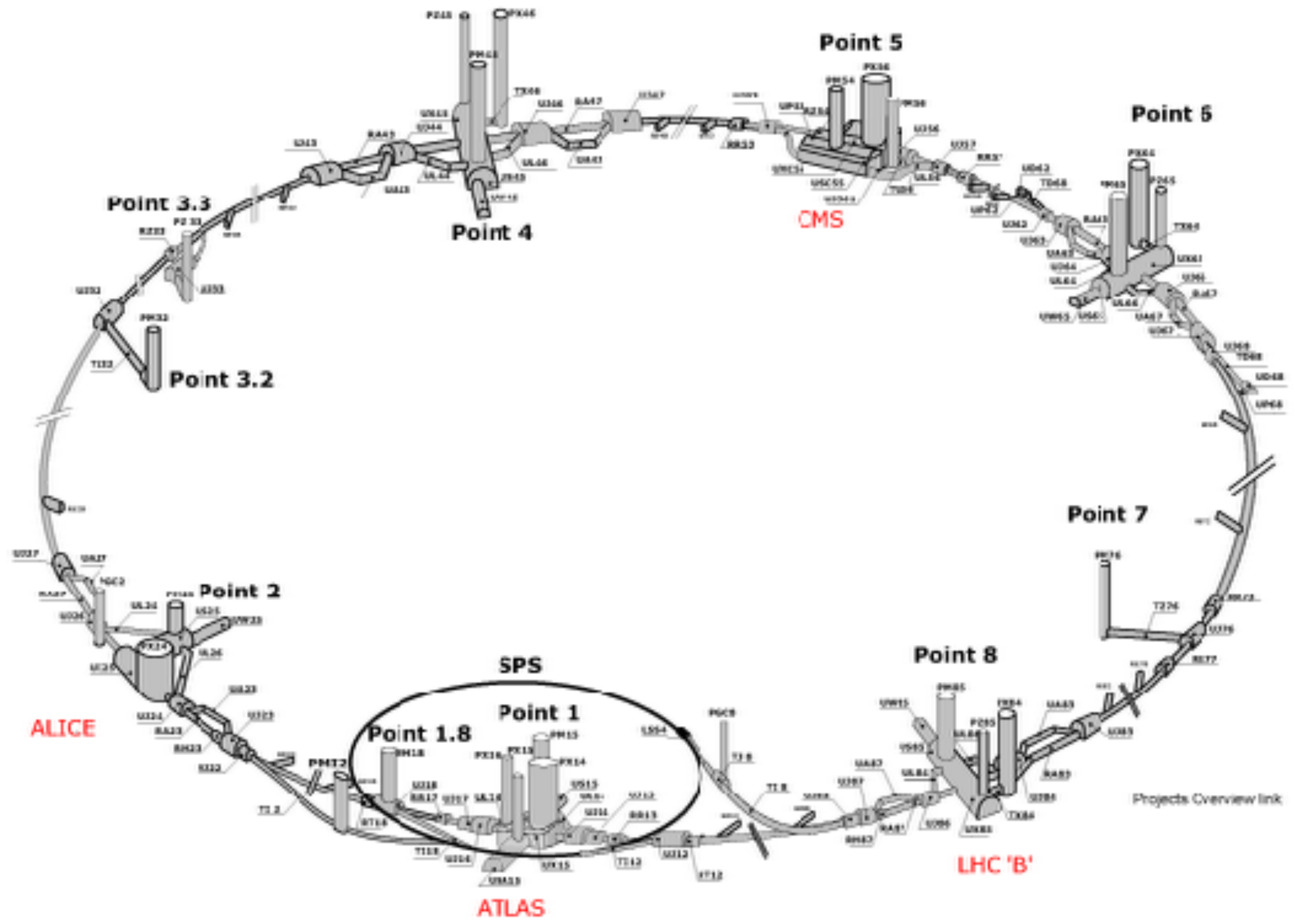
- Some review of the LHC exp (overlap with Prof. Rachid Mazini);
- Some review of the phenomenology at the LHC (overlap with Prof. Joey Huston and Prof. Tao Han);
- Some knowledge of the electroweak standard model, especially the Higgs physics (overlap with Prof. Shinya Kanemura);
- Phenomenology at the future lepton colliders and hadron colliders (overlap with Prof. Tao Han and Prof. Rachid Mazini);
- Search for new physics at future colliders (overlap with Prof. Andrea Romanino and Prof. Michael Ramsey-Musolf);
- … (more overlaps?)

Outline

- From the LHC to the future lepton colliders.
- (Higgs) Physics at future lepton colliders.
- Physics at future hadron colliders.
- Summary and outlook.

Lecture 1: From the LHC to the Future Lepton Colliders

A Review of the LHC



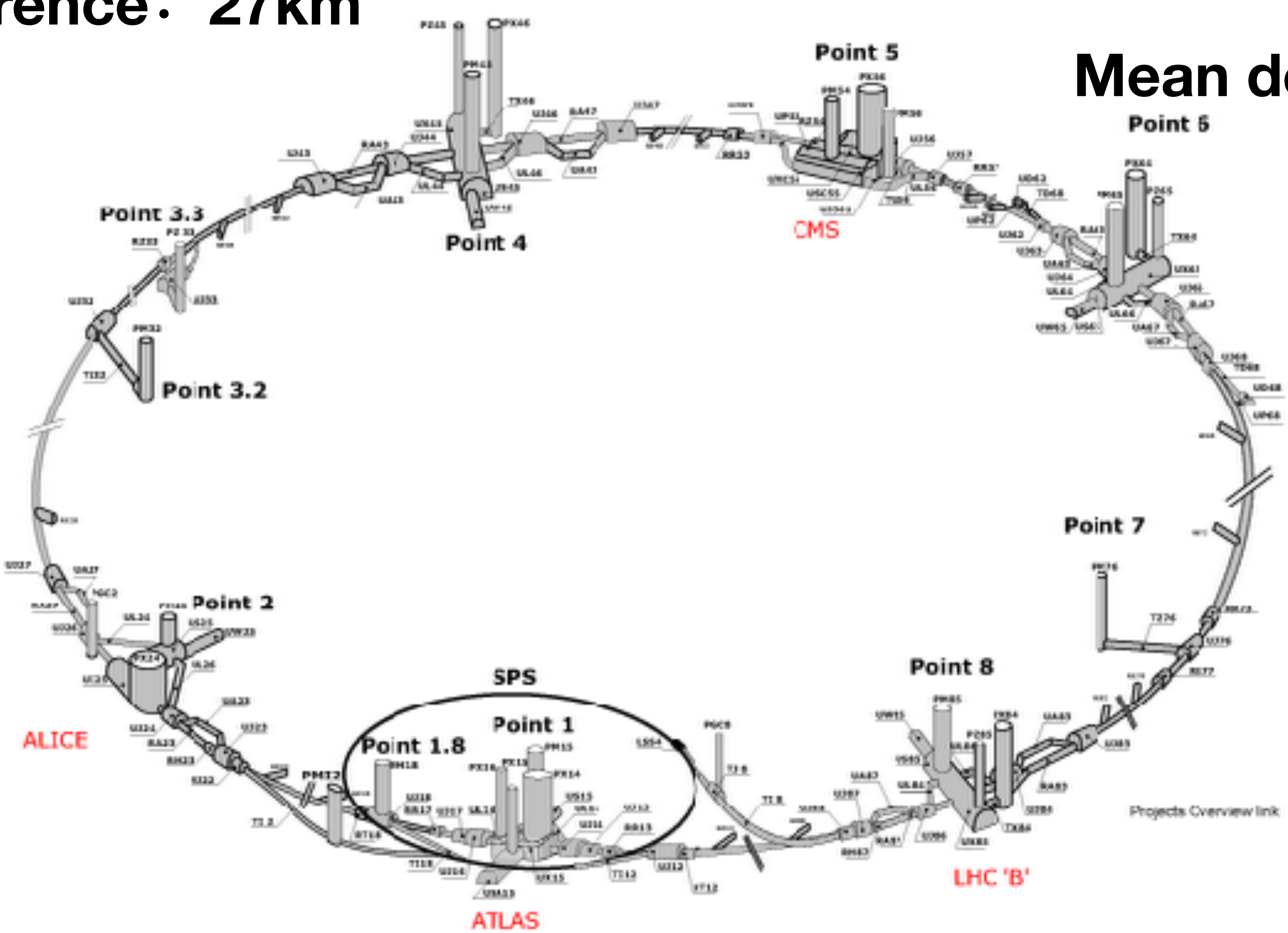
A Review of the LHC

Center of mass energy：14TeV=2.2×10^{-6}J, v=0.999999991c

Total cost: ~4 billion $

Circumference：27km

Mean depth：100m



A Review of the LHC

Center of mass energy： 14TeV=2.2×10^{-6}J, v=0.999999991c

Total cost: ~4 billion $

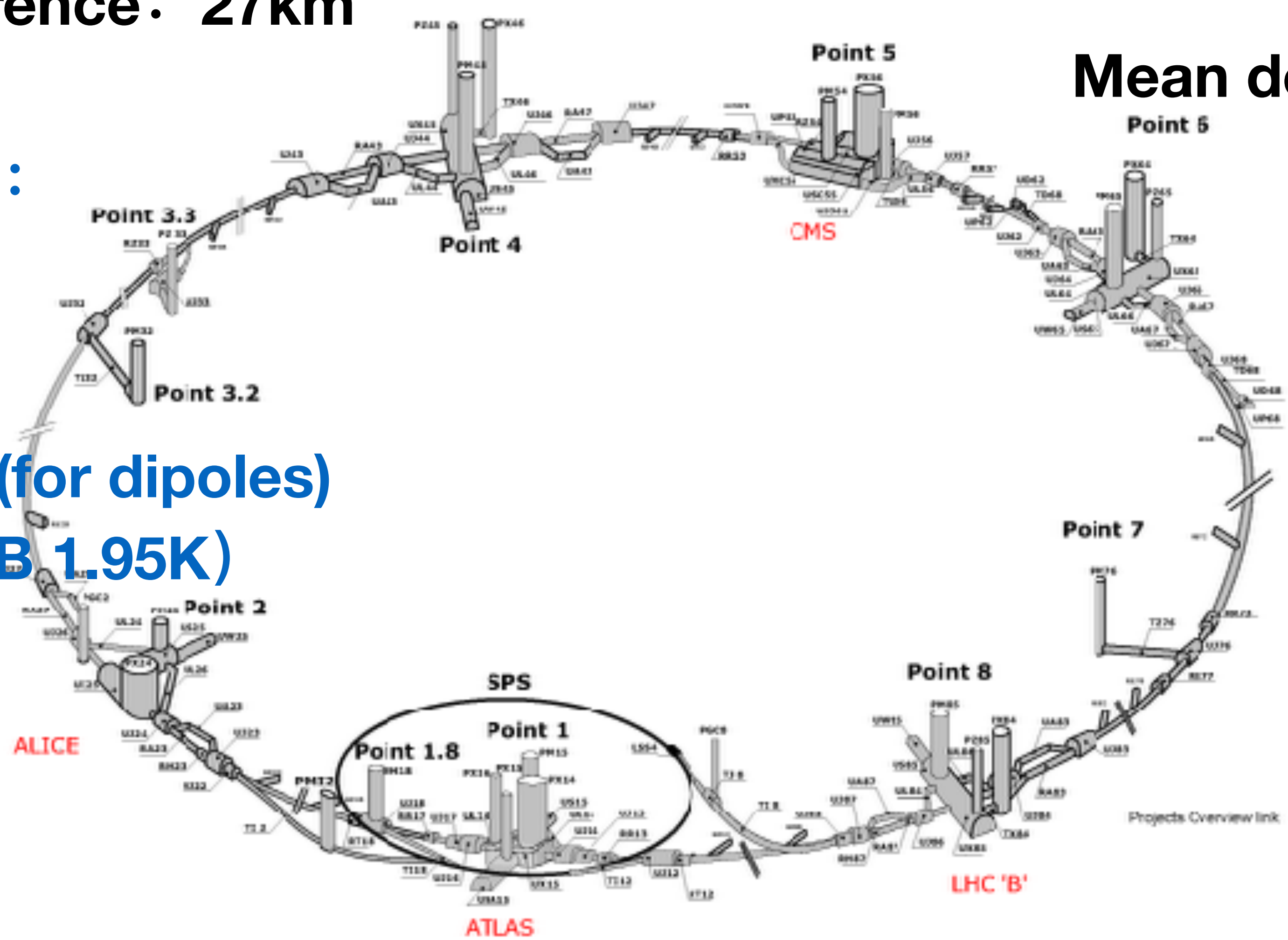
Effect from the (moon) tidal force: 1mm/27km

Circumference： 27km

Mean depth： 100m

Vacuum pressure：
10^{-13}atm

Temperature： 1.9K (for dipoles)
（CMB 2.71K, CNB 1.95K）



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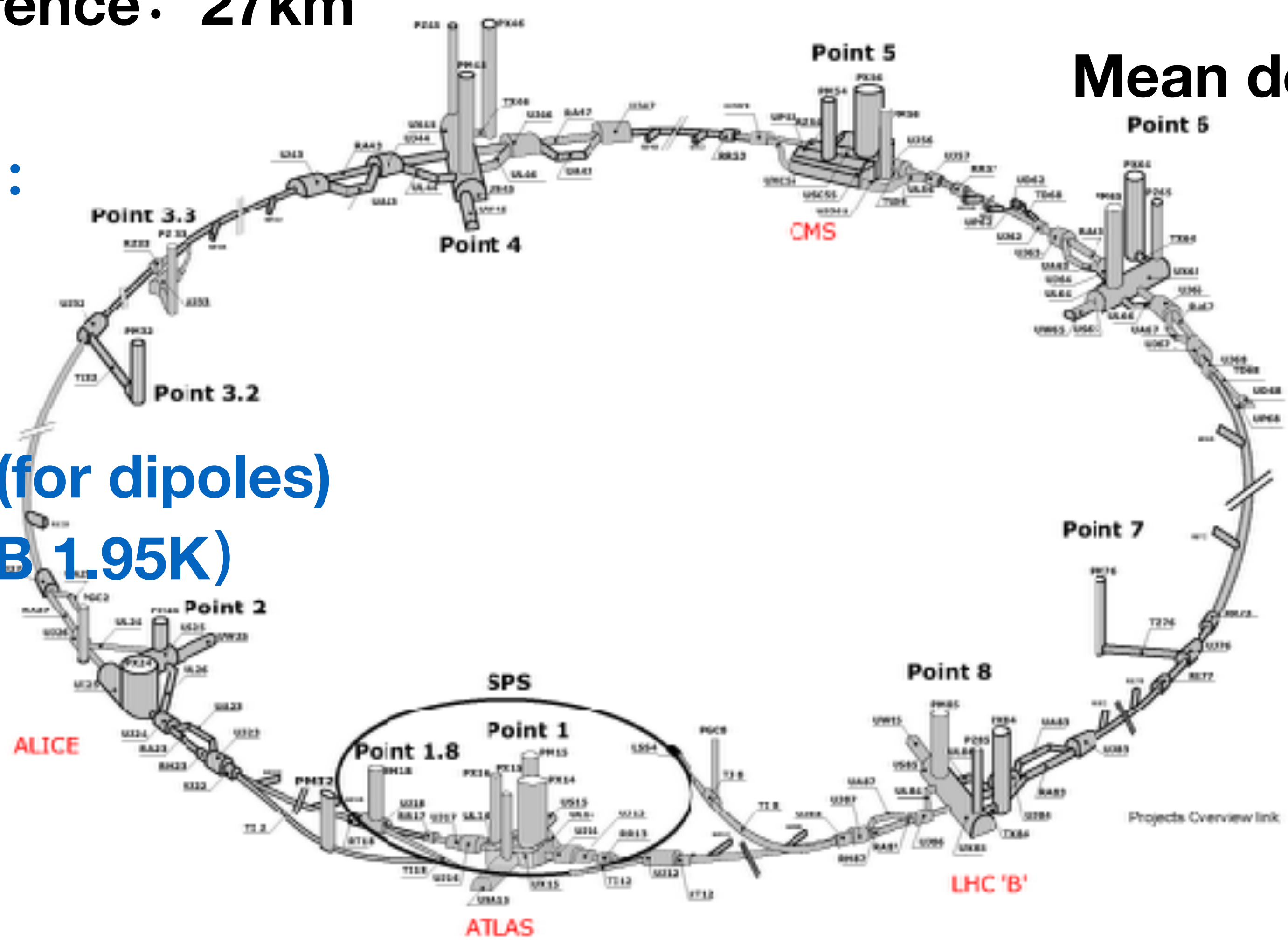
9593 magnets

1232 dipoles：15m，35t
（1.9K，I=11850A），~8T



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Effect from the (moon) tidal force: 1mm/27km

Circumference：27km

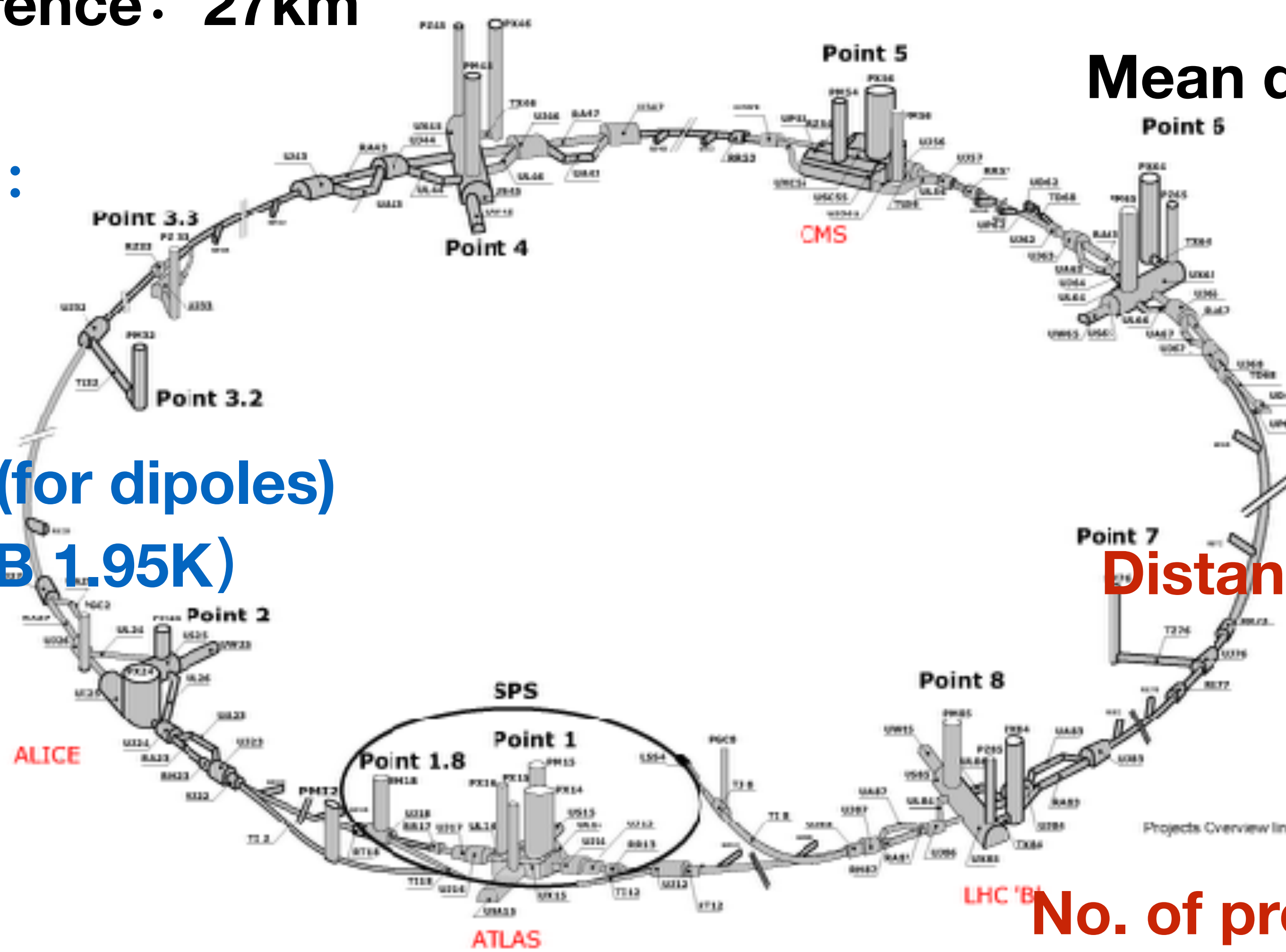
Mean depth：100m

Vacuum pressure：
10^{-13}atm

No. of bunches per proton beam：2808

Temperature：1.9K (for dipoles)
（CMB 2.71K, CNB 1.95K）

Distance between bunches：
7.5m（25ns）



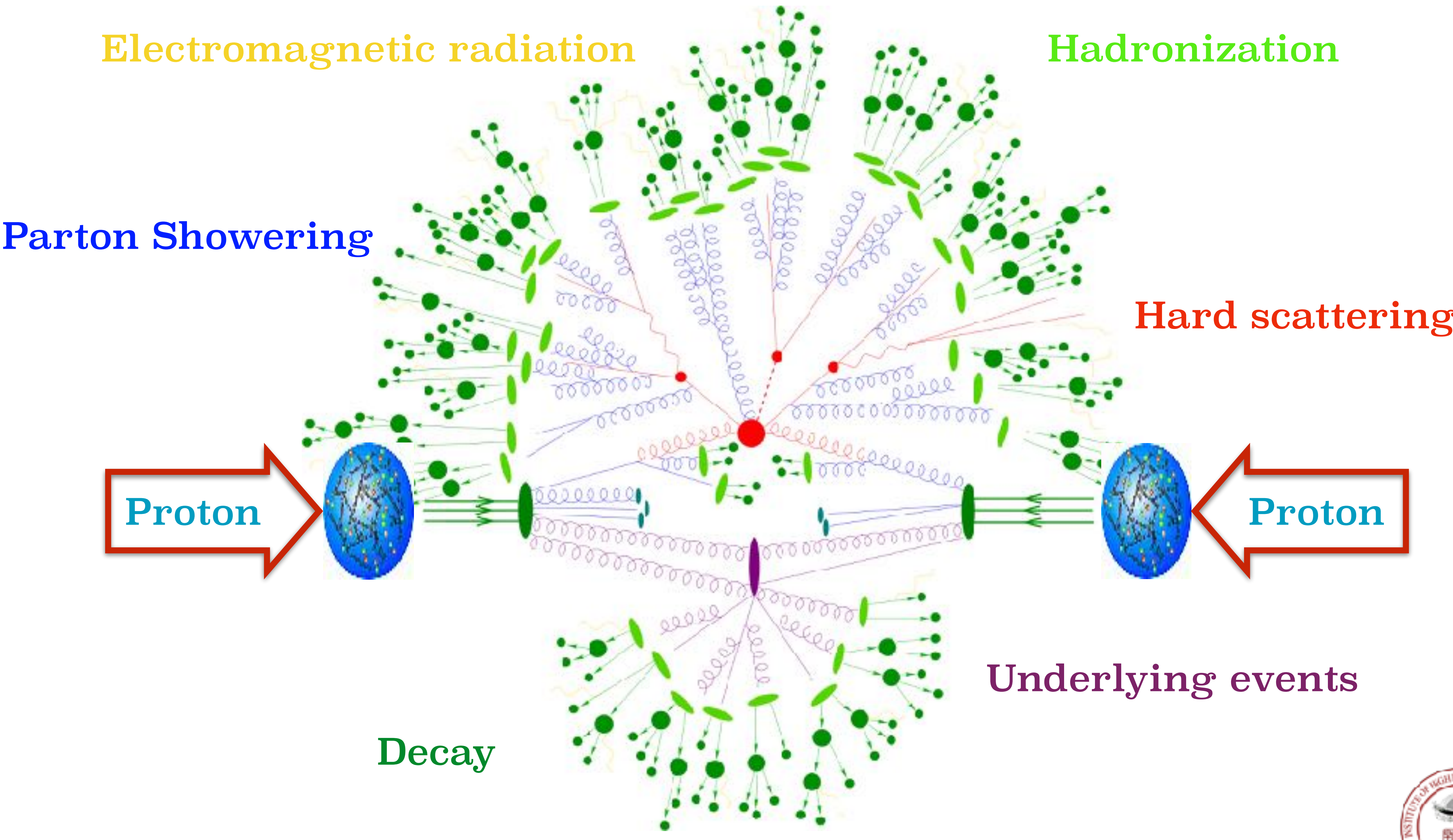
9593 magnets

No. of protons per bunch：
1.2×10^{11}

1232 dipoles：15m，35t
（1.9K，I=11850A），~8T

No. of collisions per second: ~1 billion

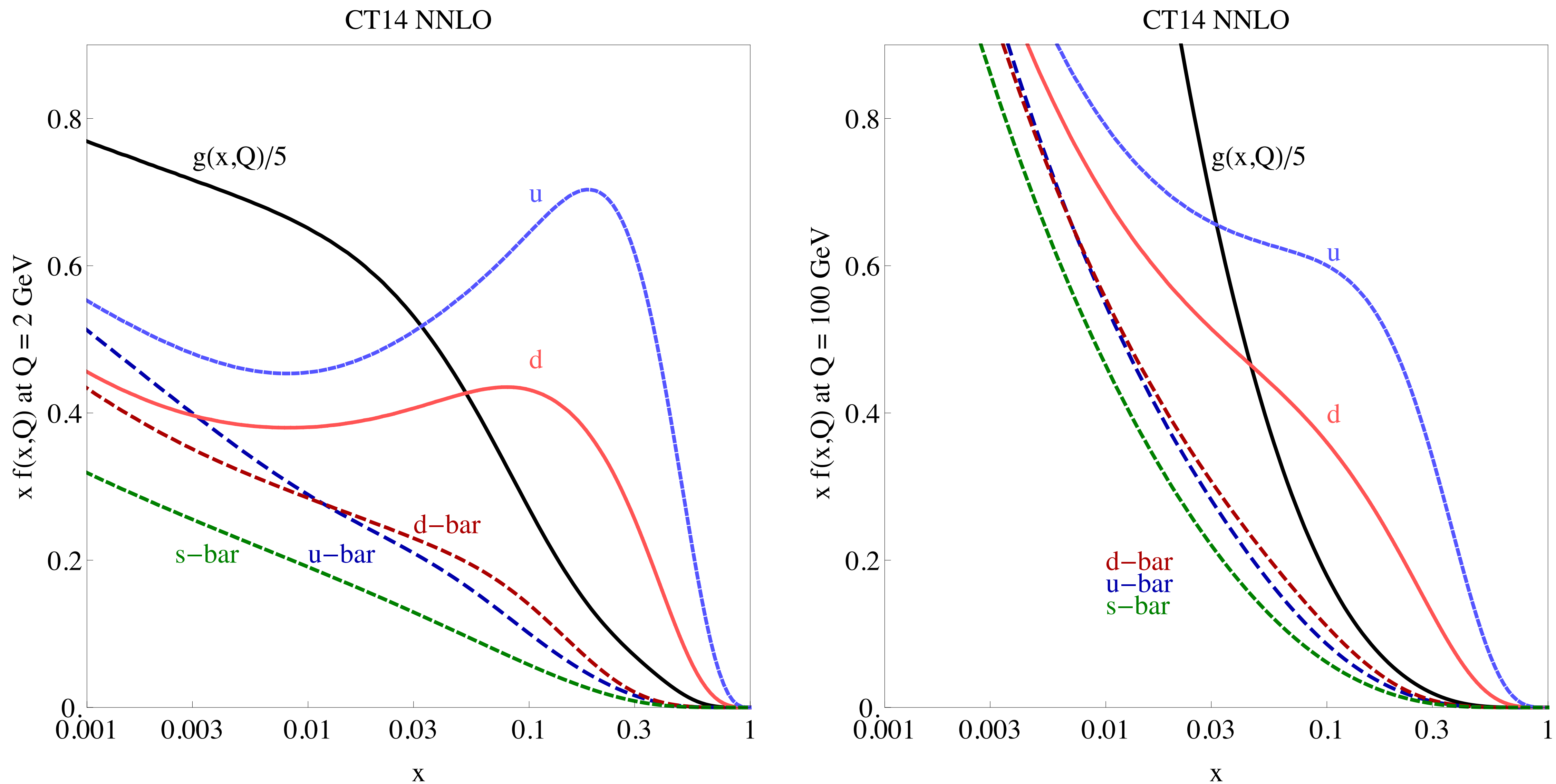
A Review of the LHC



A Review of the LHC

- Parton distribution function (PDF).

$$N(\sqrt{S}) = \mathcal{L}\sigma(\sqrt{S}) = \mathcal{L}\sum_{a,b}\int dx_1 dx_2 \sigma_H(\sqrt{x_1 x_2 S}) f_{a/P}(x_1) f_{b/P}(x_2)$$



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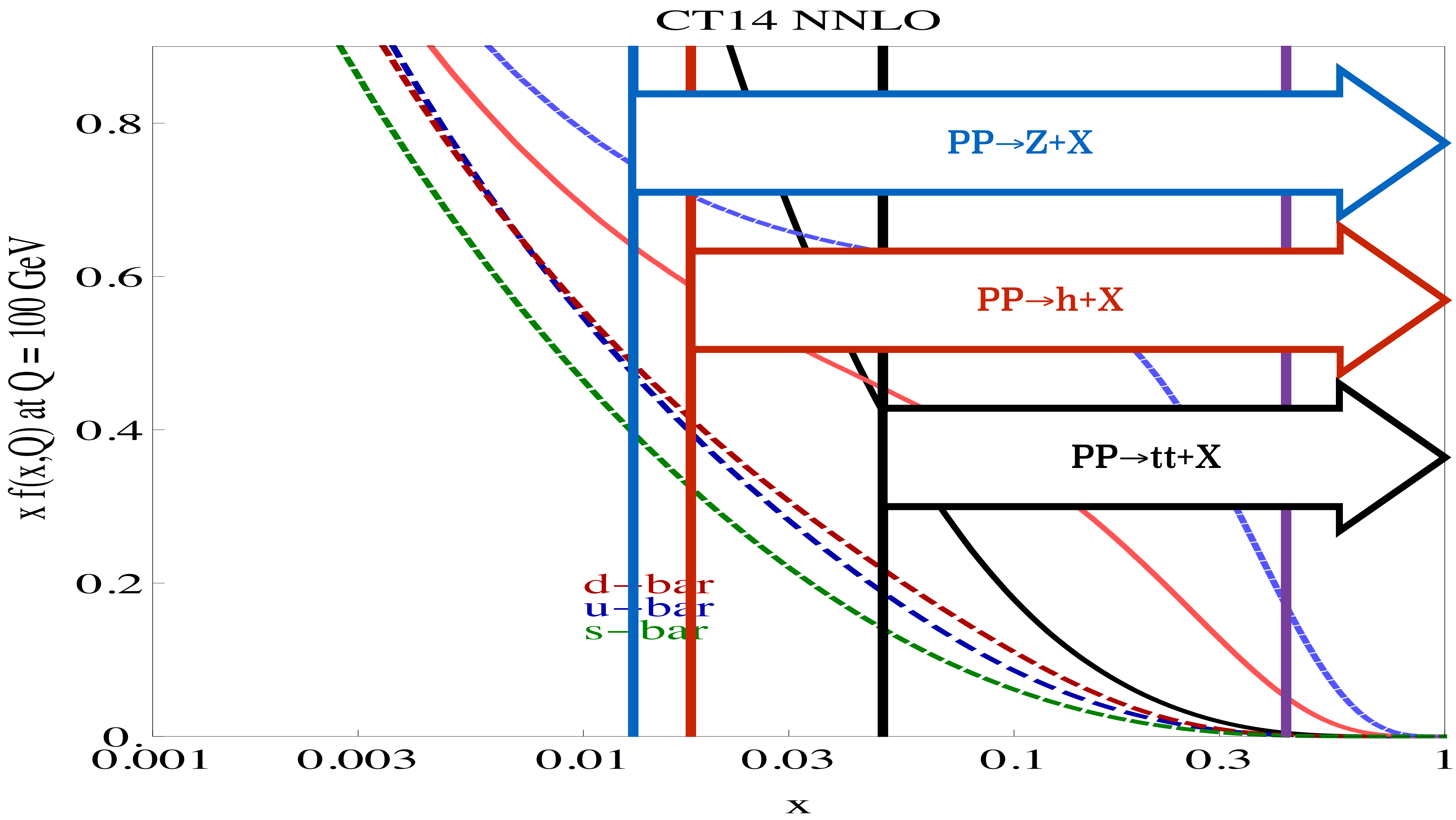
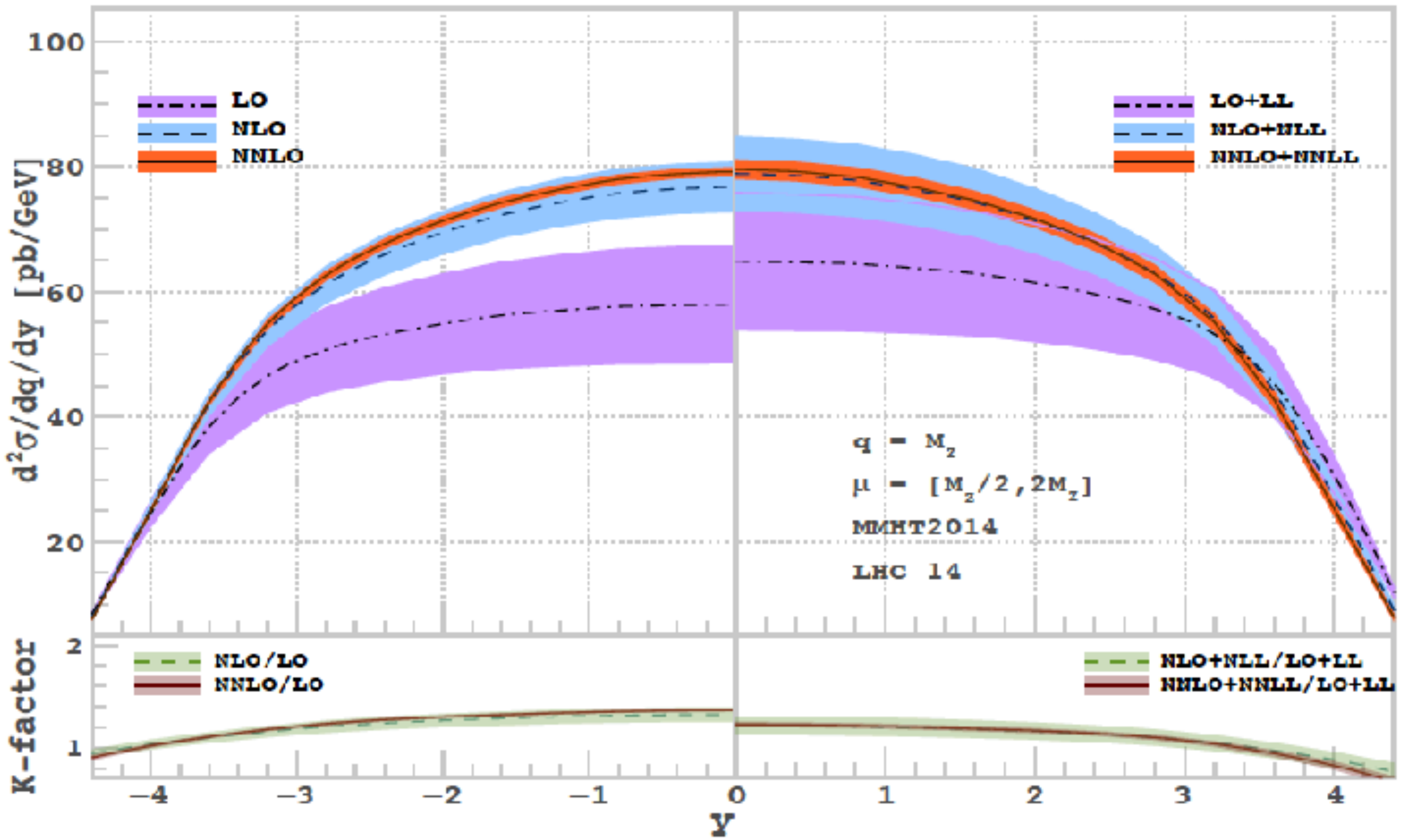


A Review of the LHC

- Large coupling constant α_S.
- Large higher order corrections from both real and virtual processes.



Drell-Yan rapidity distribution for 14 TeV LHC, arXiv:1805.01186

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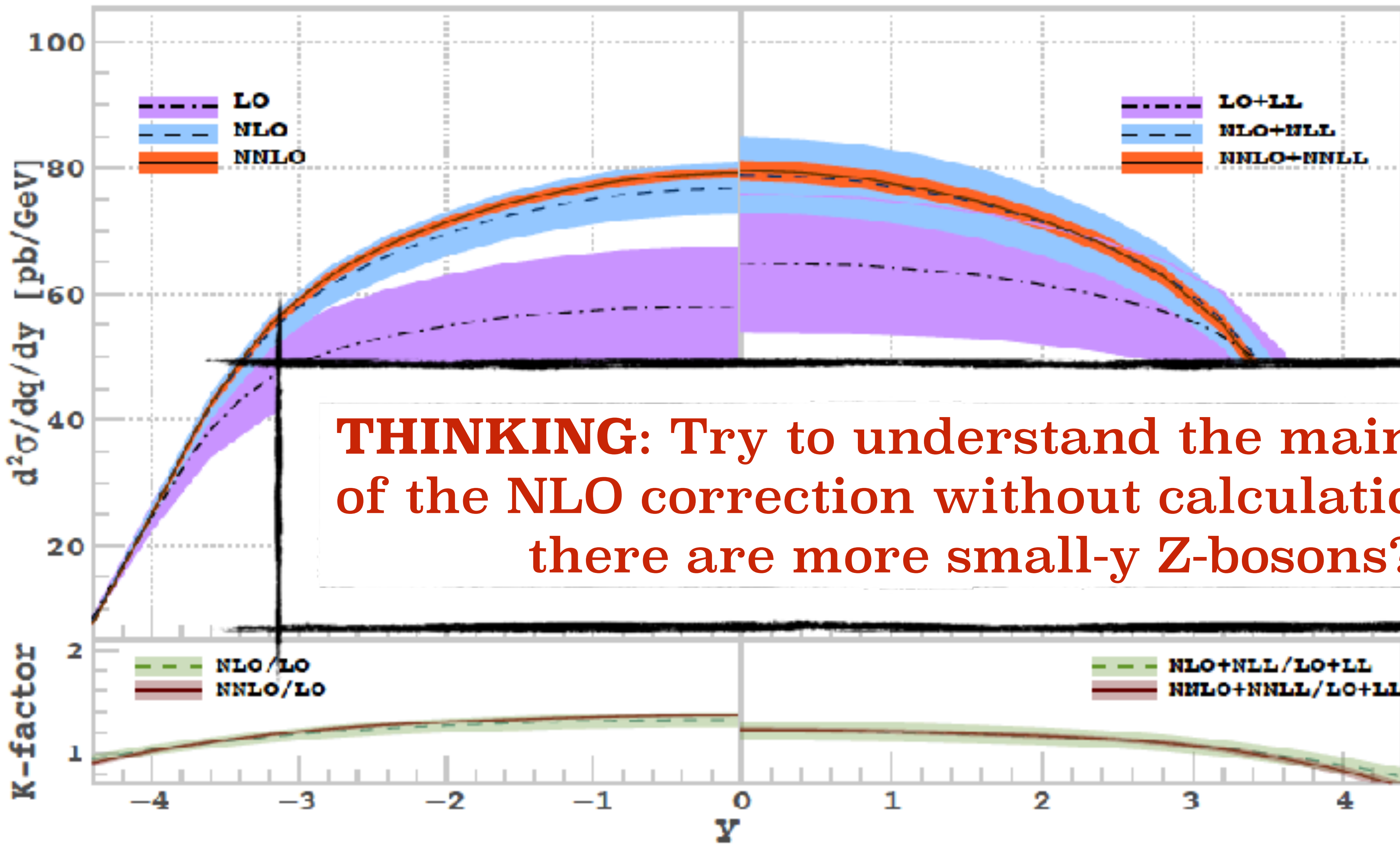

THINKING: Try to understand the main source of the NLO correction without calculation. Why there are more small-y Z-bosons?

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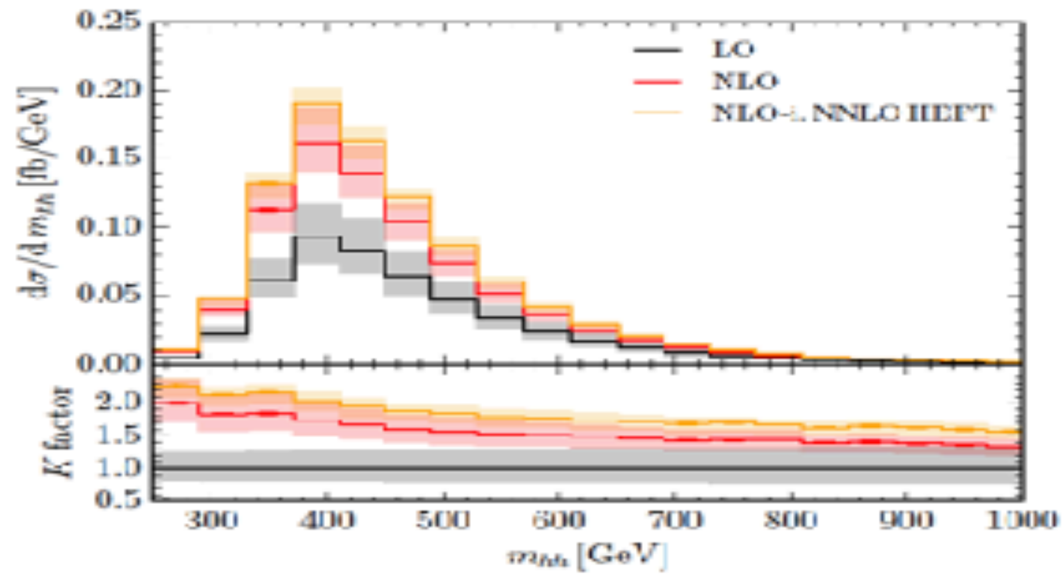
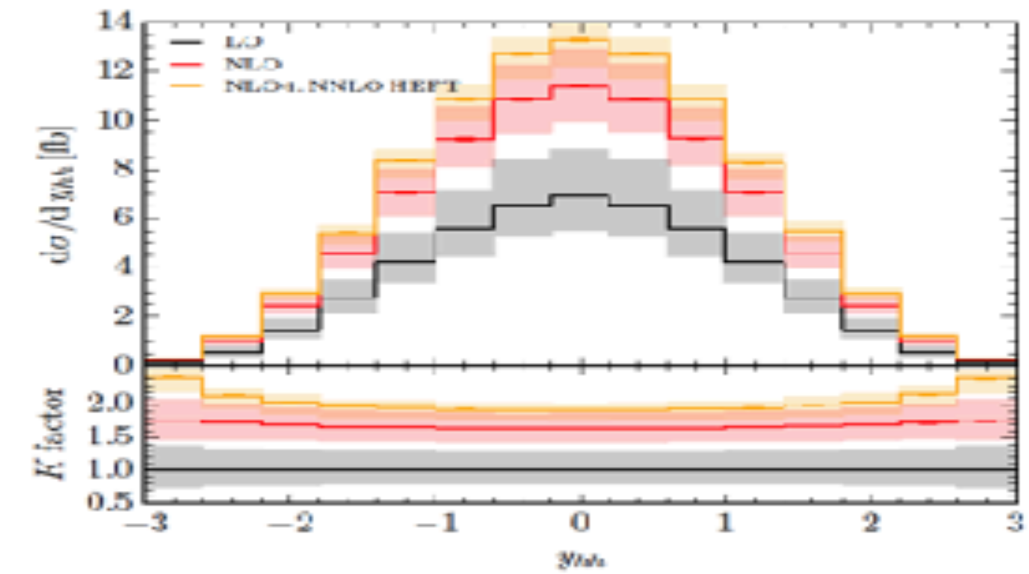
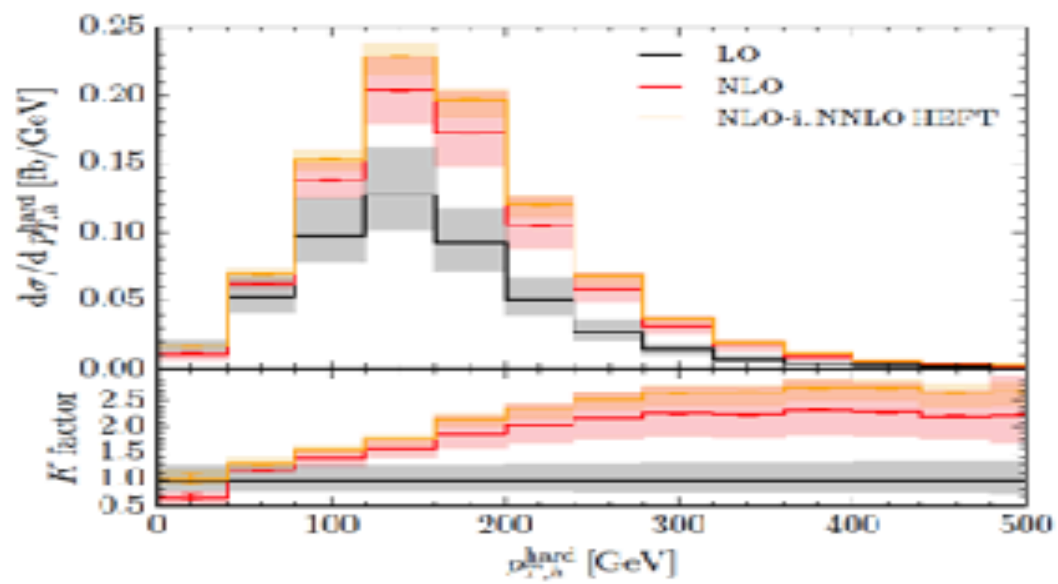


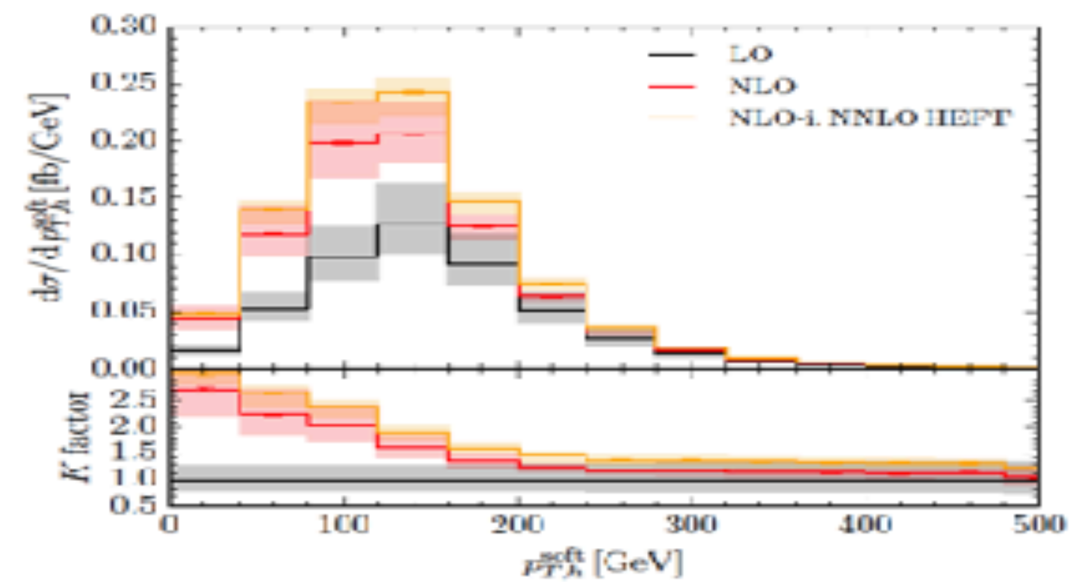
(a) 14 TeV, m_{hh}.



(b) 14 TeV, y_{hh}.



(c) 14 TeV, leading p_T.



(d) 14 TeV, subleading p_T.

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A Review of the LHC

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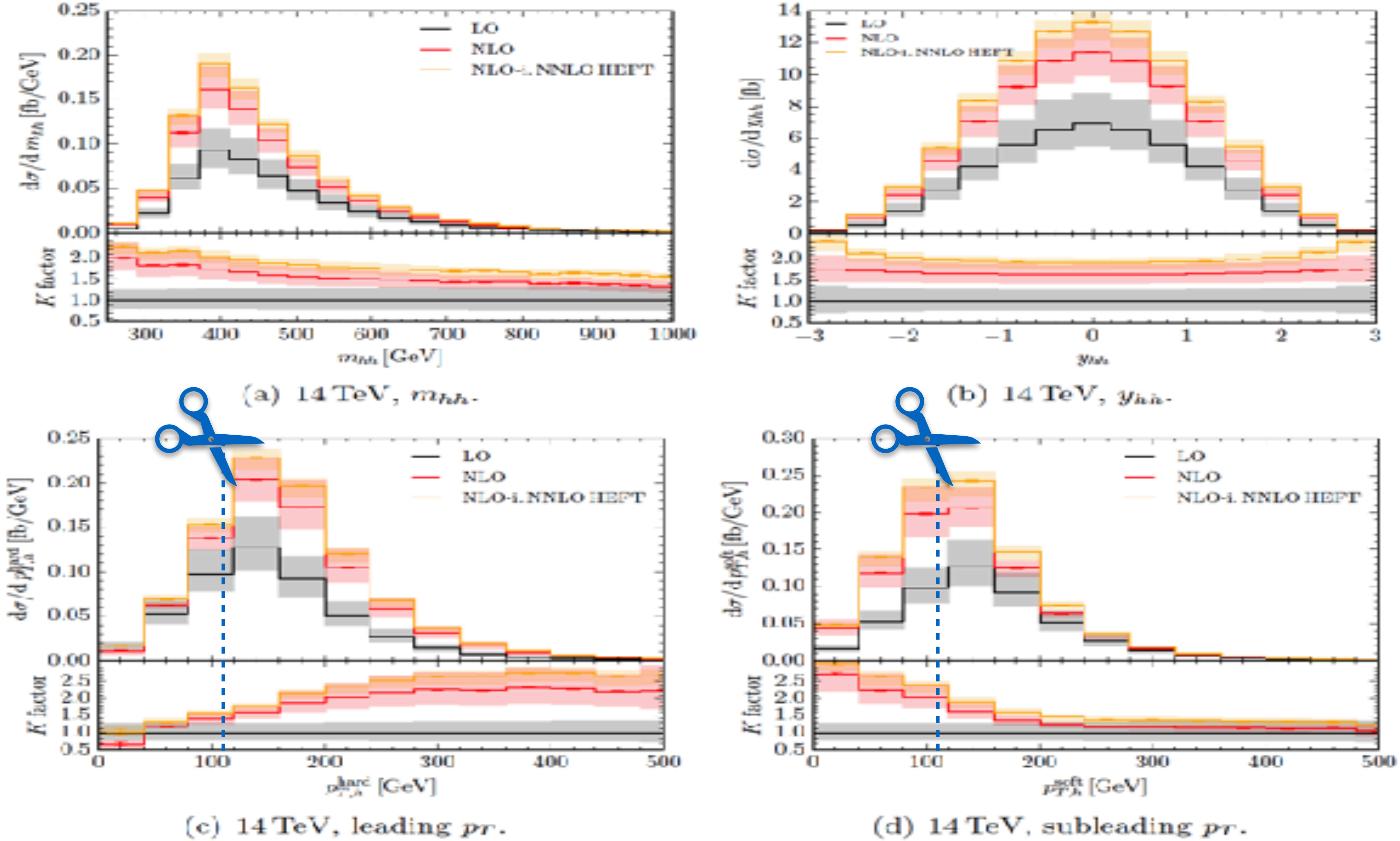

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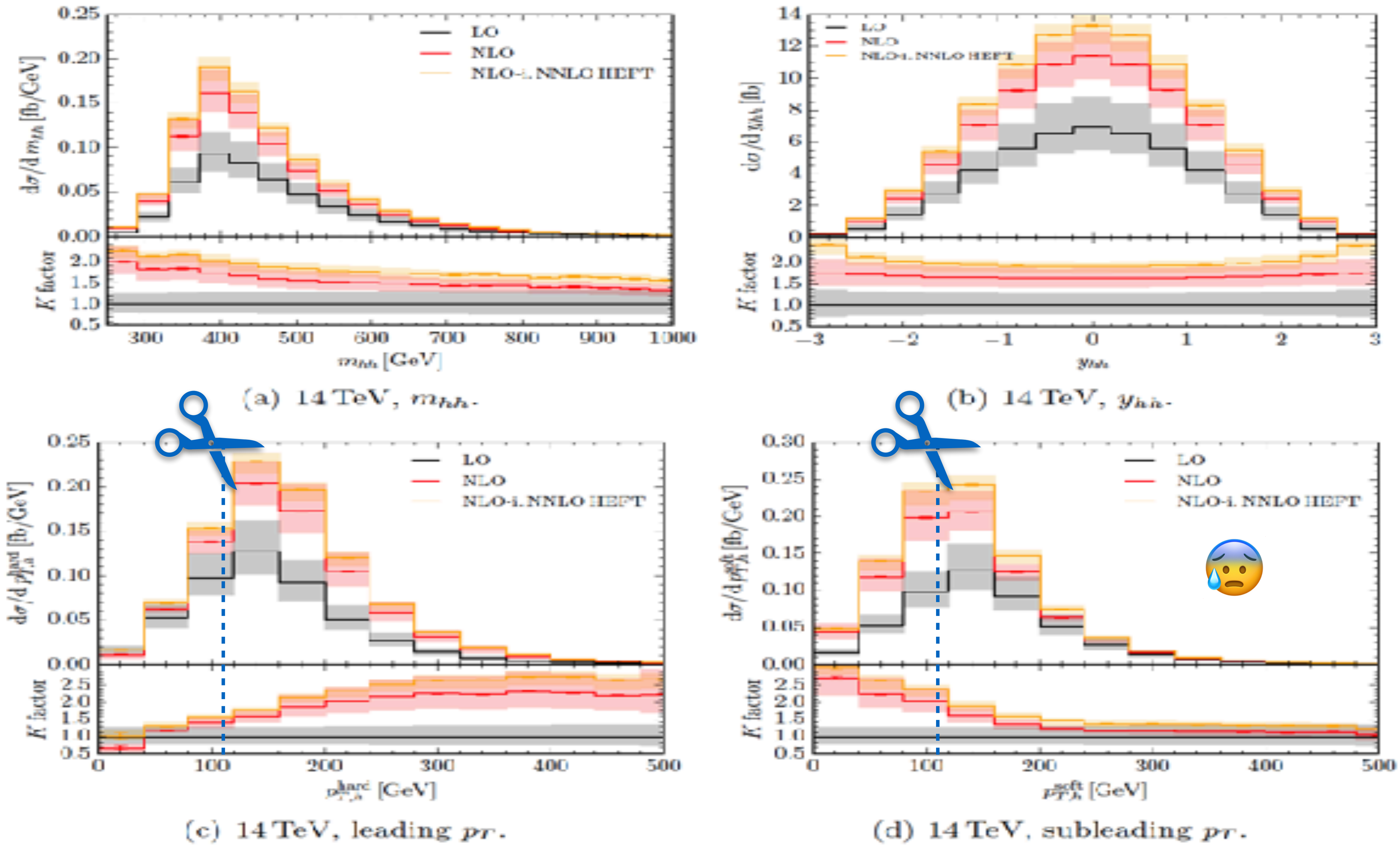

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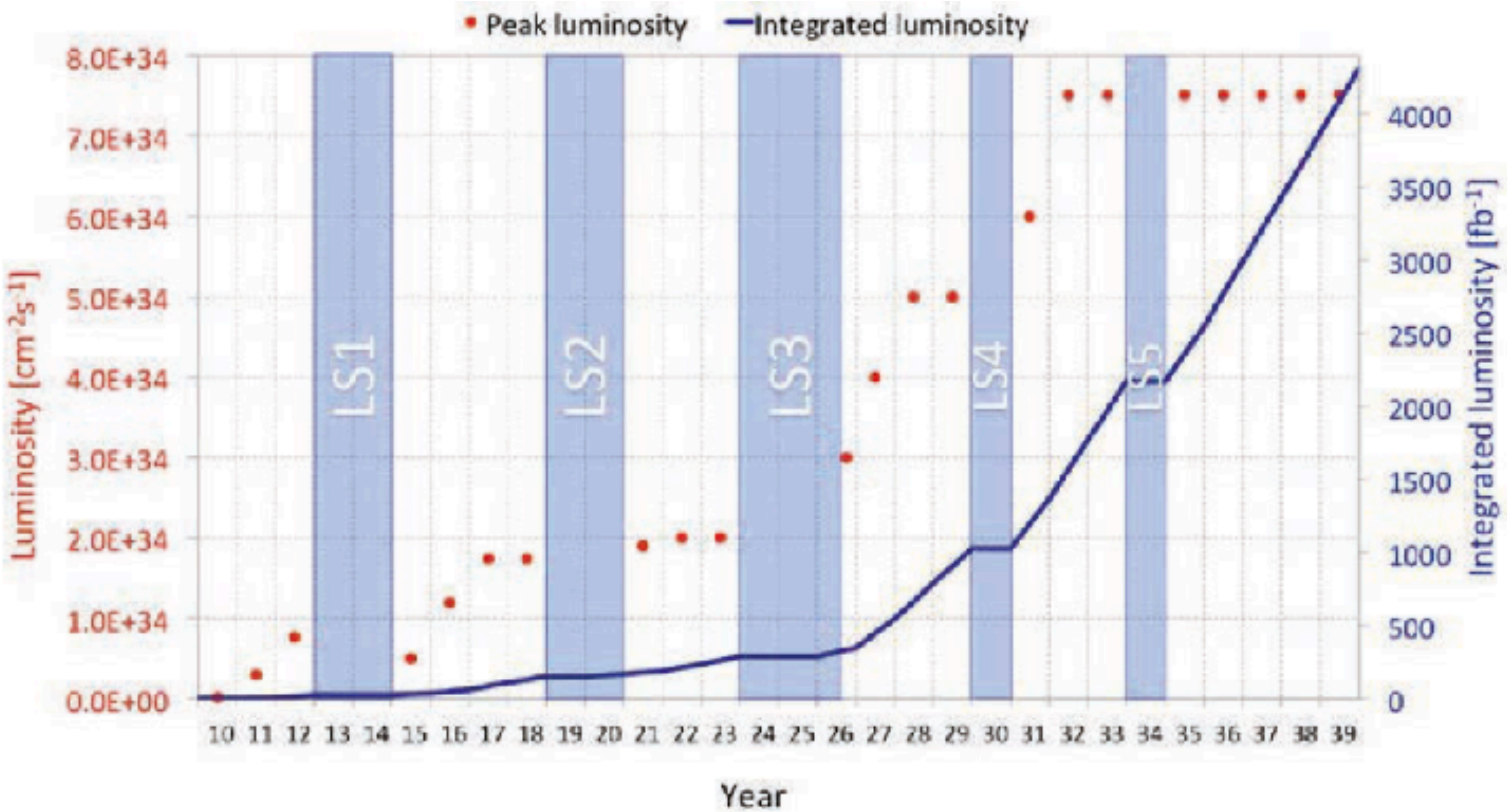
A Review of the LHC

- Quasi-future collider: High Luminosity LHC (HL-LHC).
- More data, lower statistic error.
- More data can probably help us reduce the systematic error.
- High luminosity, high pile-up…

A Review of the LHC



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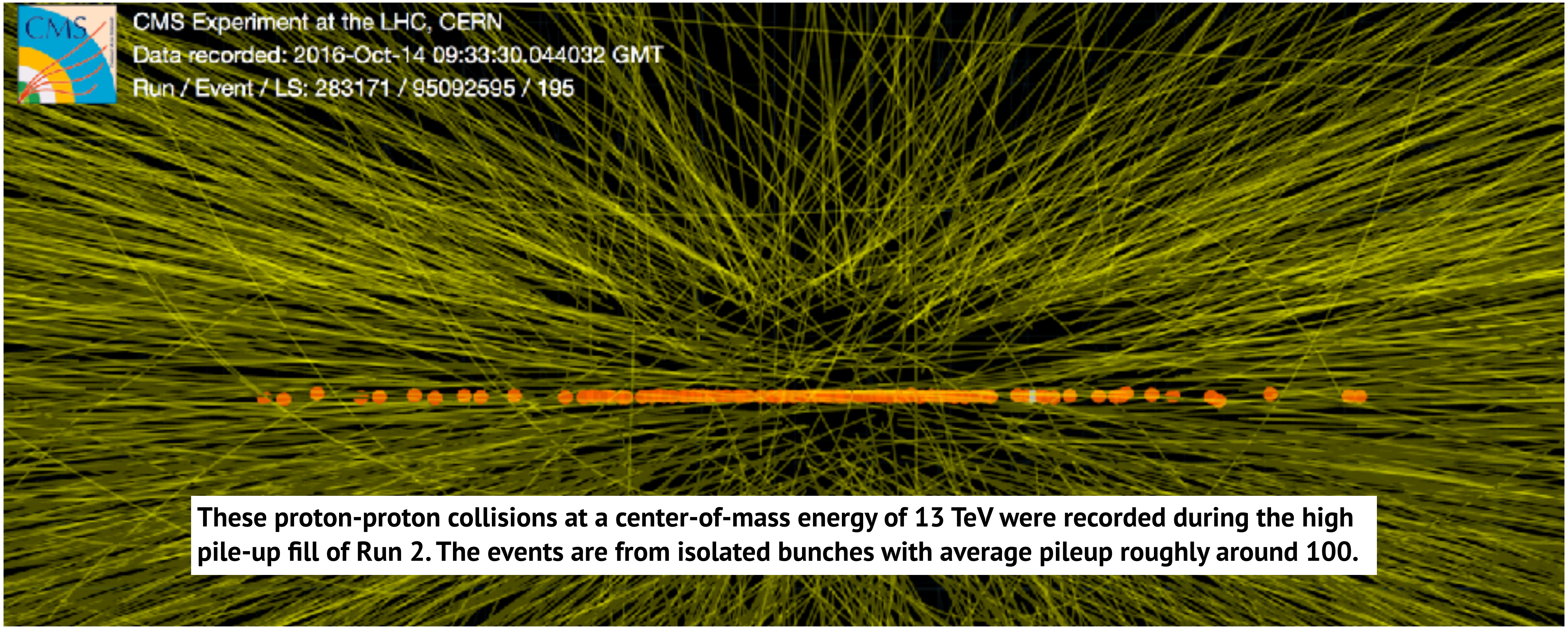

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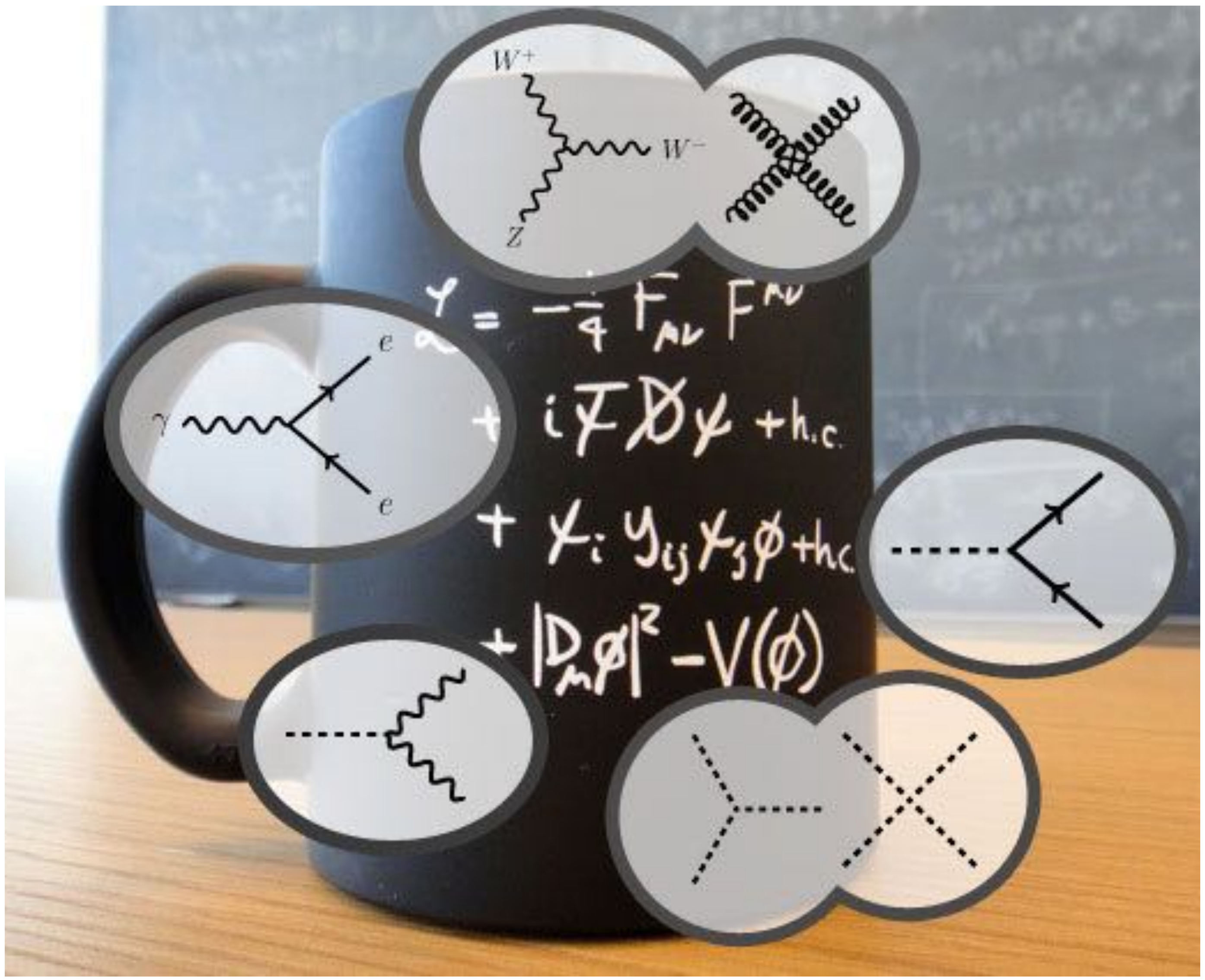
A Review of the LHC

- The LHC is a very powerful hadron collider.
- Advantages:
  - High energy;
  - High luminosity;
  - …
- Disadvantages:
  - The effective c.m. energy is ~TeV;
  - Large theoretical uncertainty, large SM backgrounds, large pile-up;
  - …
- It is designed for discovering physics at high energy scale, but not precisely measurements.
- Is TeV enough?

Some Challenges

- Do we really understand the SM well?



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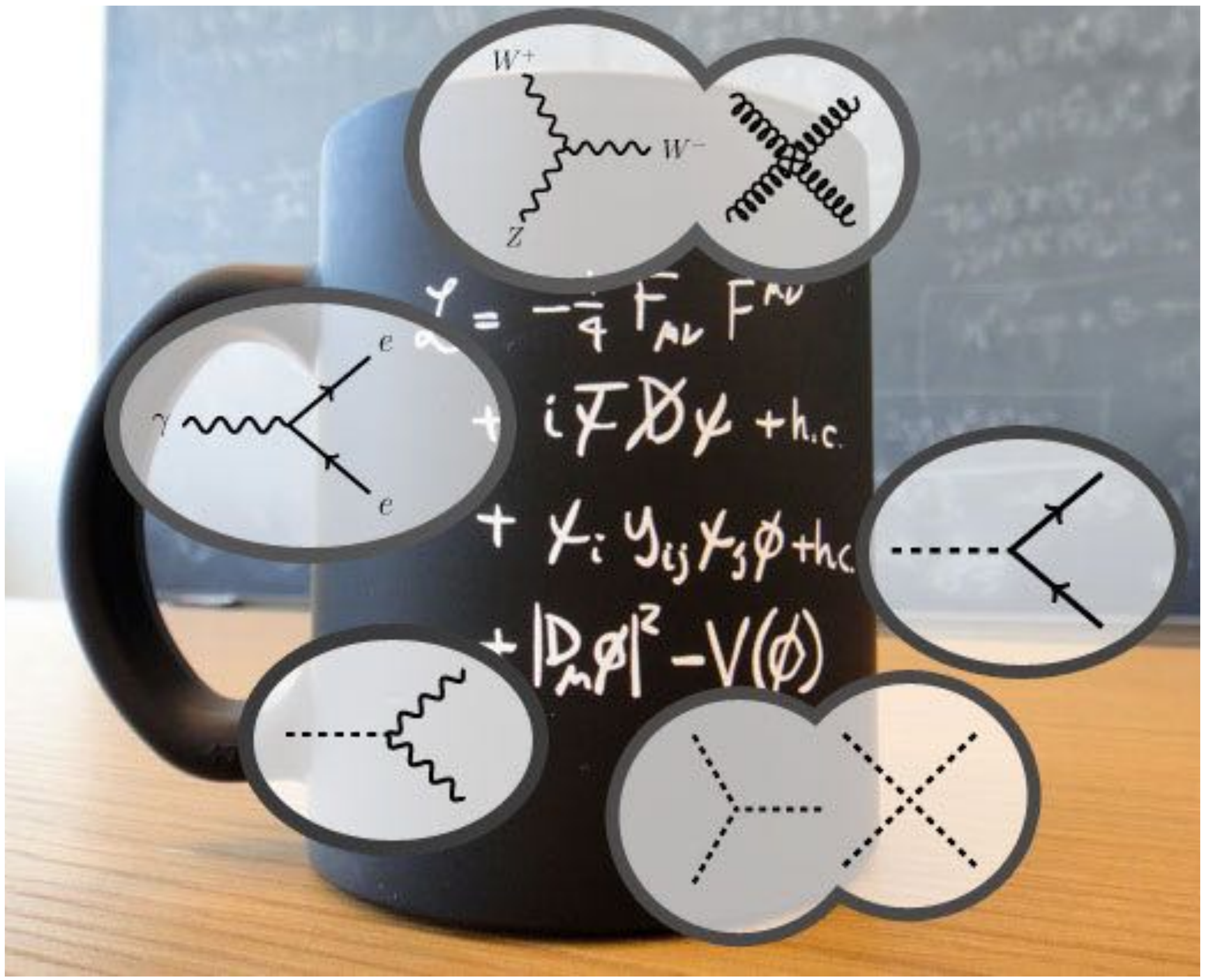
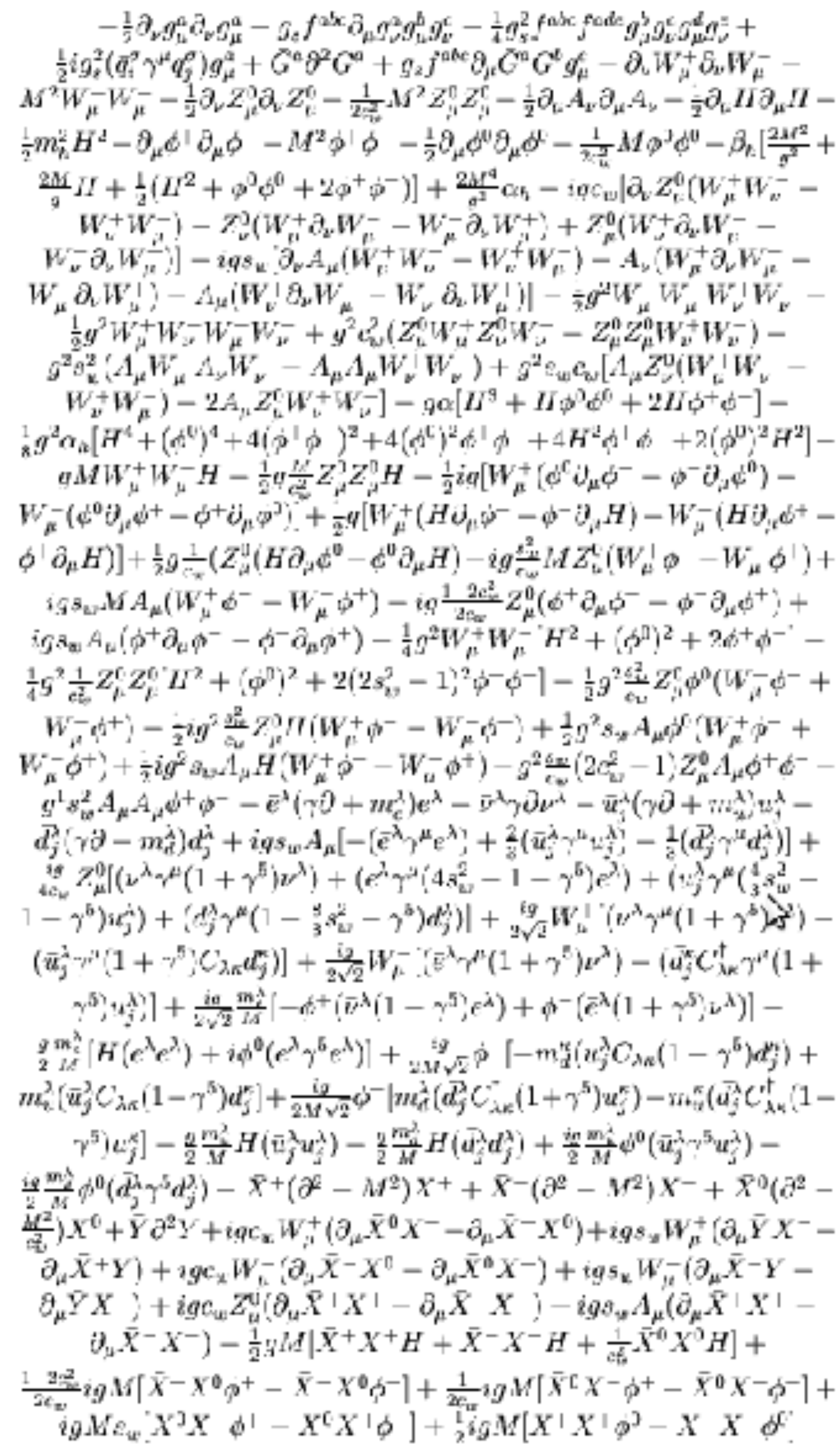
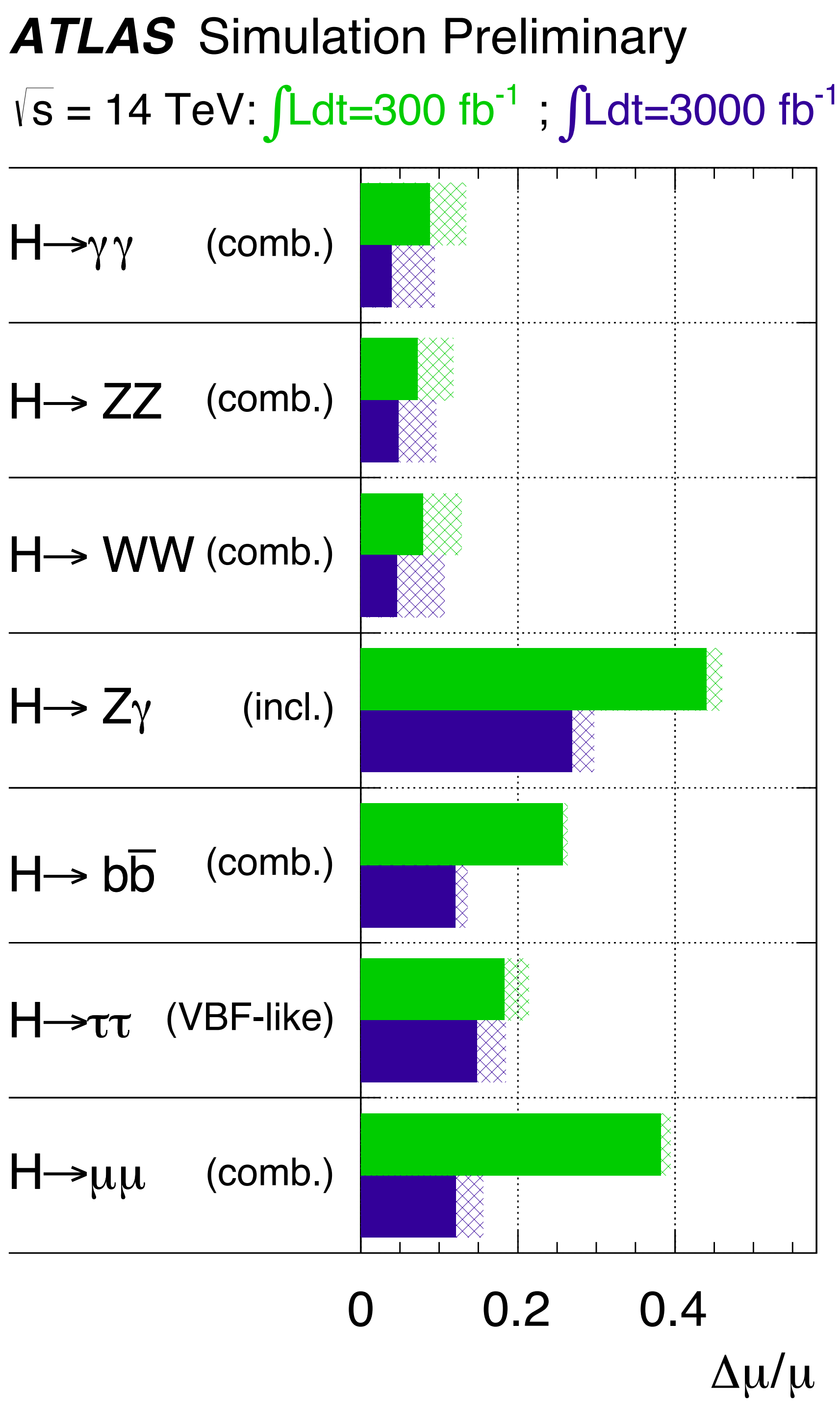
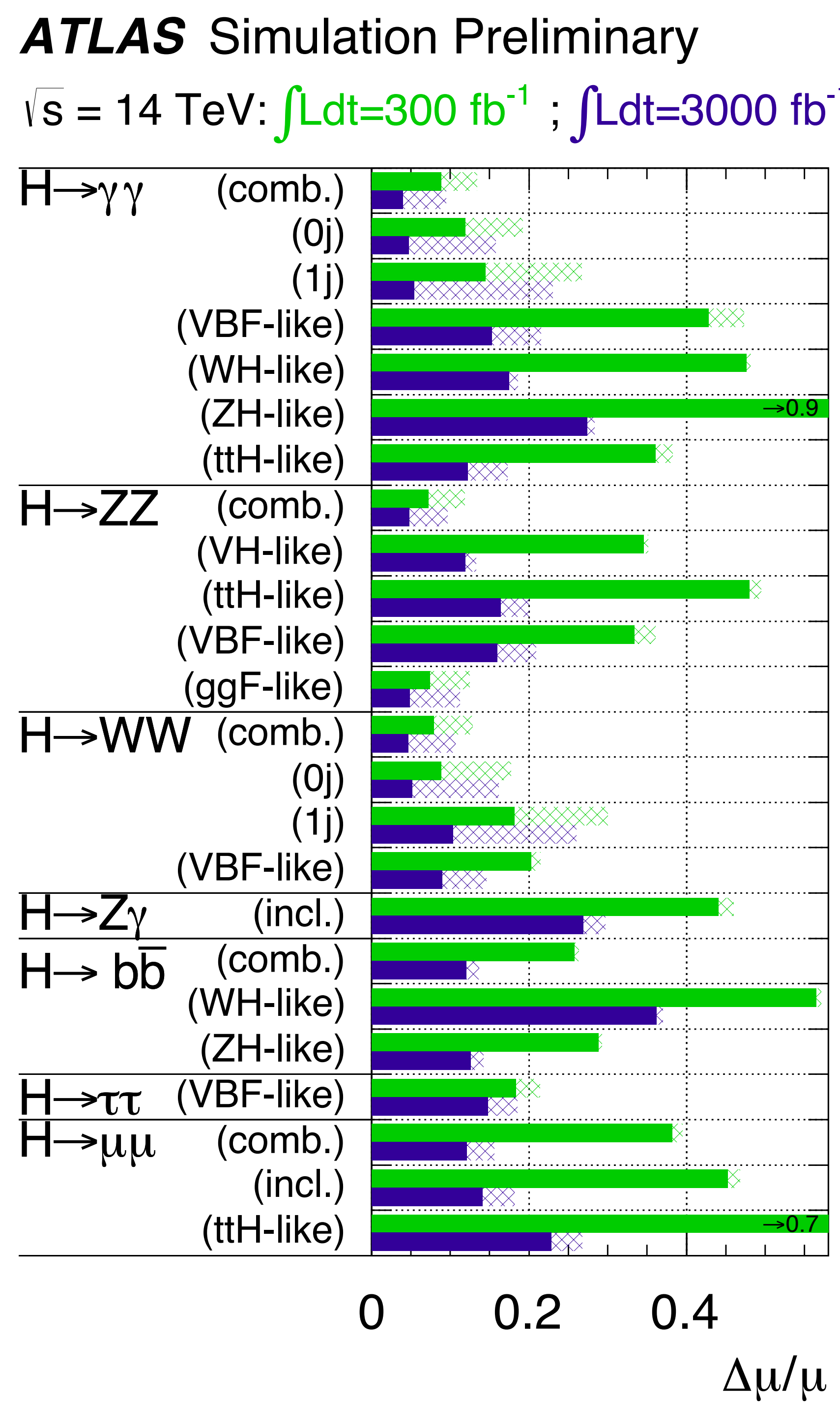




Some Challenges

- Example: precisely Higgs physics.





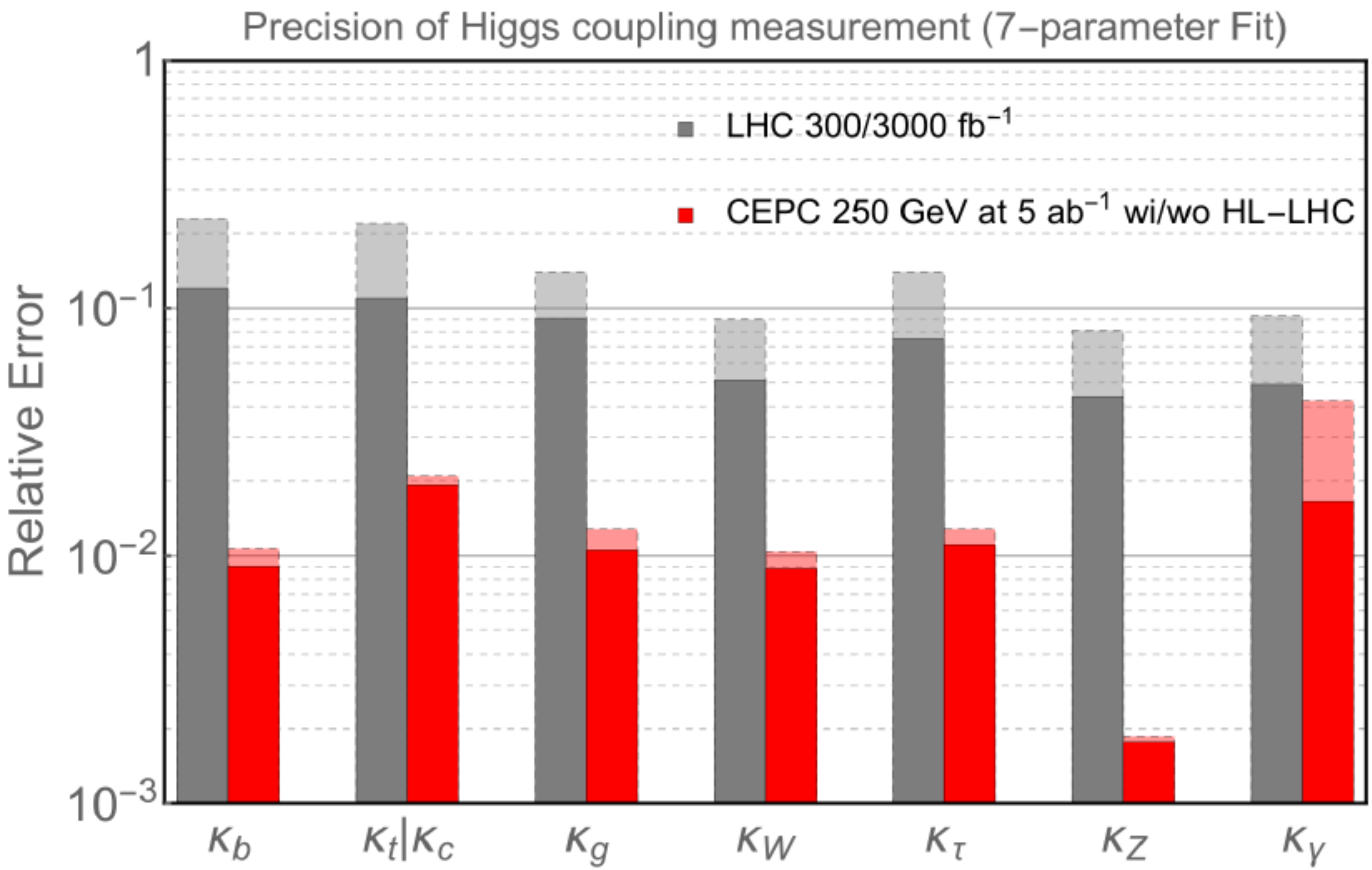
Some Challenges

- Example: precisely Higgs physics.

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23

Some Challenges

- Example: precisely Higgs physics.



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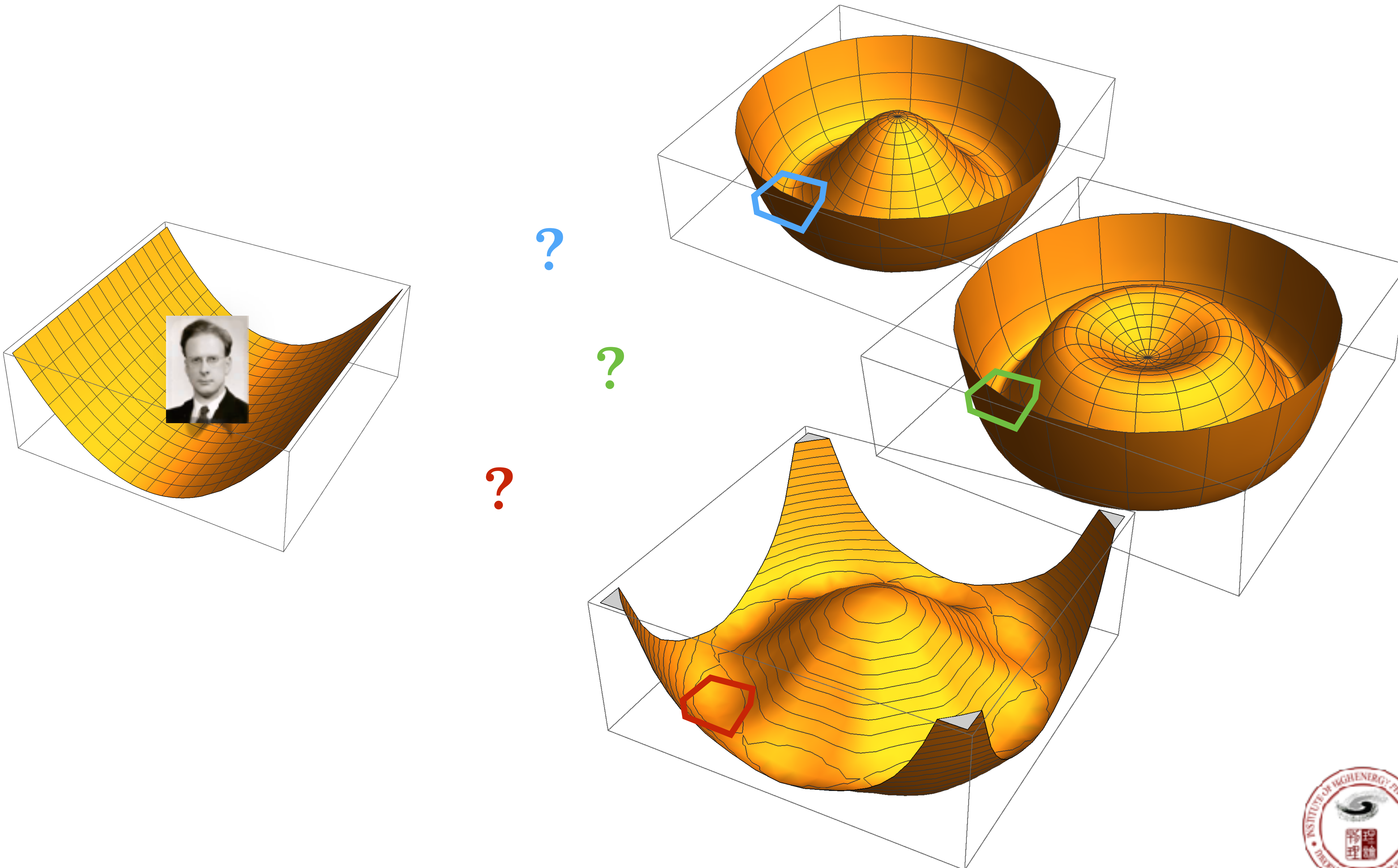
Some Challenges

- Example: understand the EWSB.



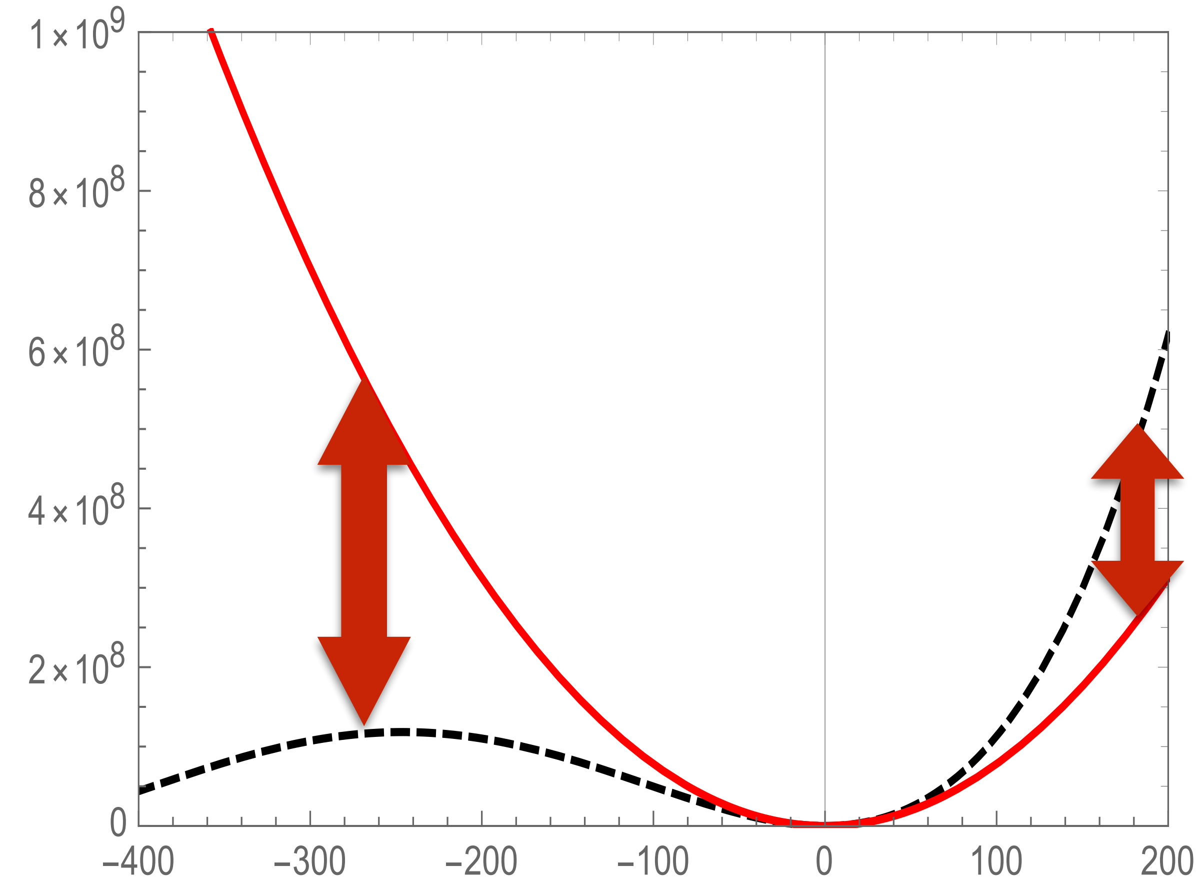
Some Challenges

- Example: understand the EWSB.

$$V(\Phi)_{SM} = \lambda\left(\Phi^\dagger\Phi - v^2\right)^2$$

$$\Phi(x) \sim \exp\left[ig'\alpha(x) + ig\sum_{j=1}^{3}\sigma^j\alpha_j(x)\right]\begin{pmatrix} 0 \\ v + \dfrac{h(x)}{\sqrt{2}}\end{pmatrix}$$

$$V(\Phi)_{SM} = \frac{1}{2}(4\lambda v^2)h^2 + \sqrt{2}\lambda v h^3 + \frac{\lambda}{4}h^4$$

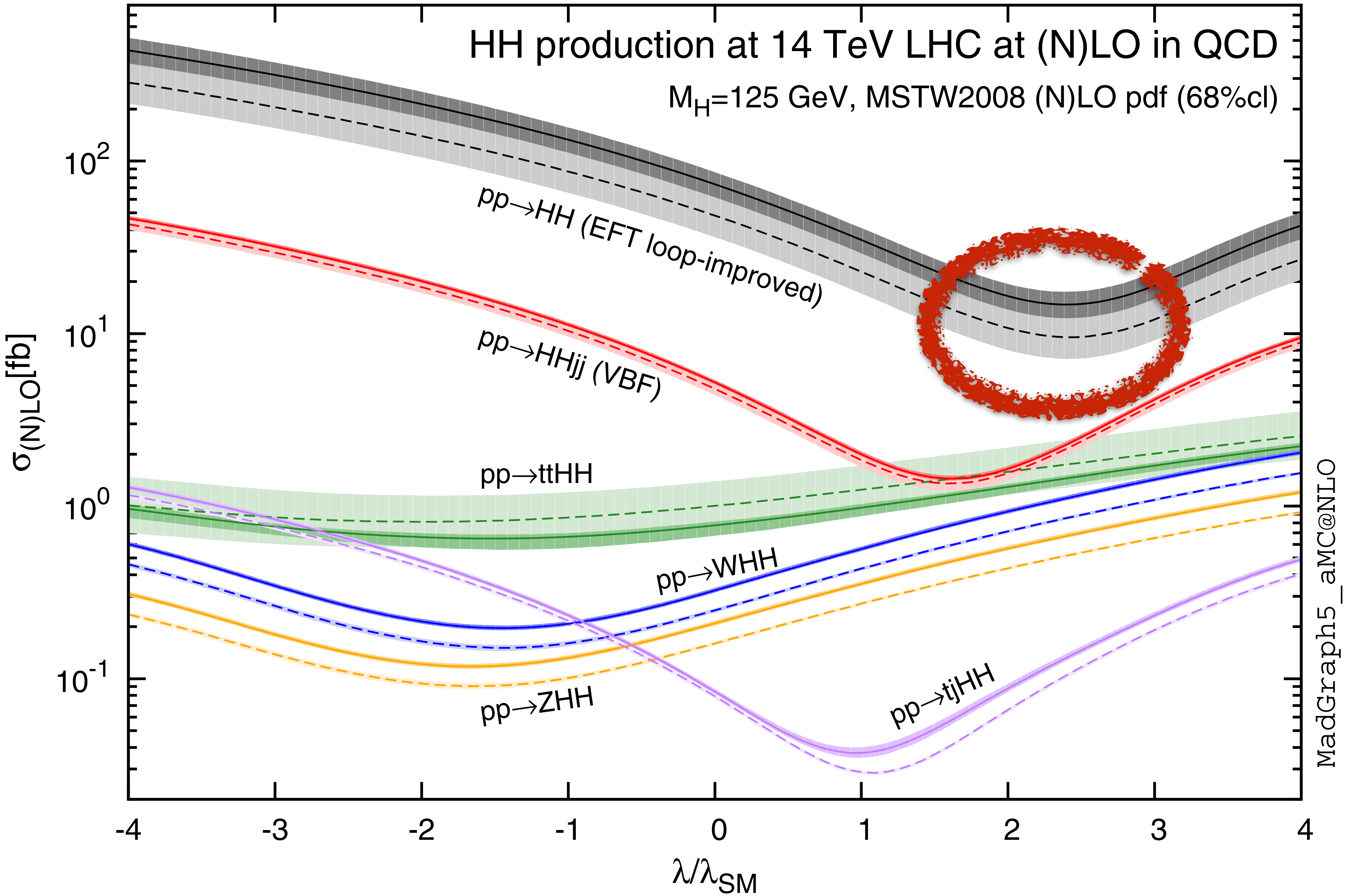


Zero temperature, tree level!

$$\lambda_{SM} = \frac{m_h^2}{4v^2} \sim 0.13$$

Some Challenges

- Example: understand the EWSB.



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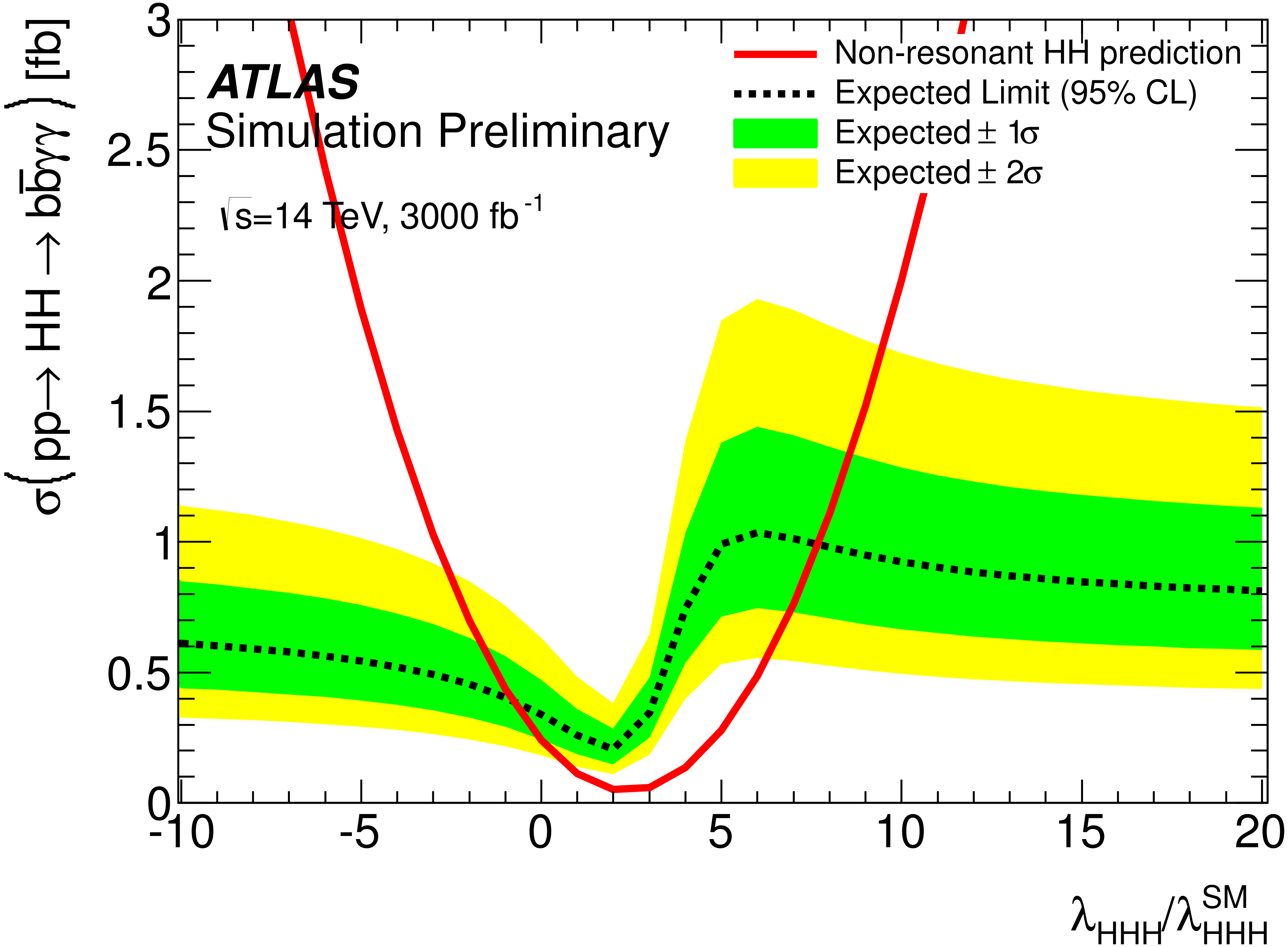

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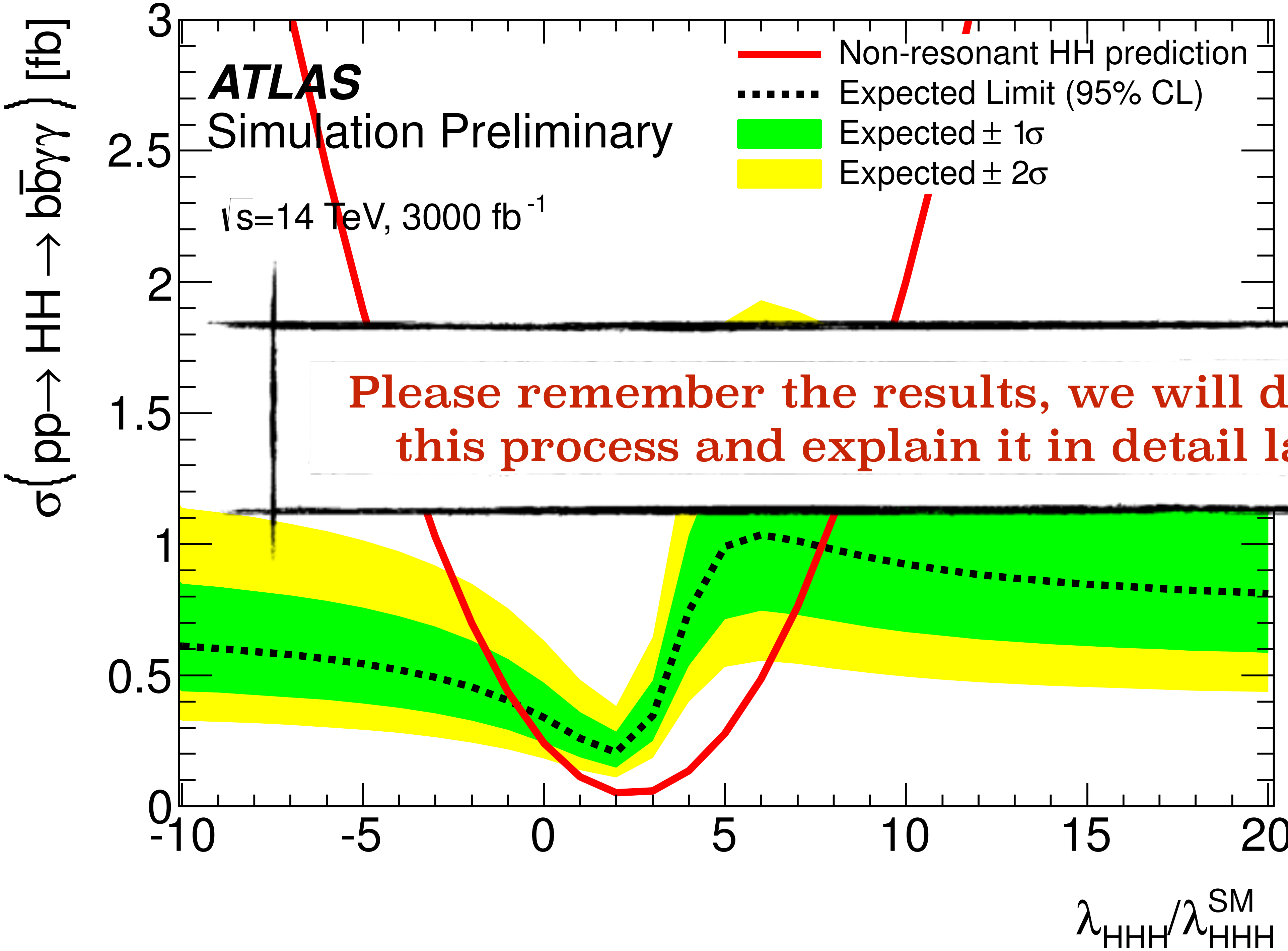
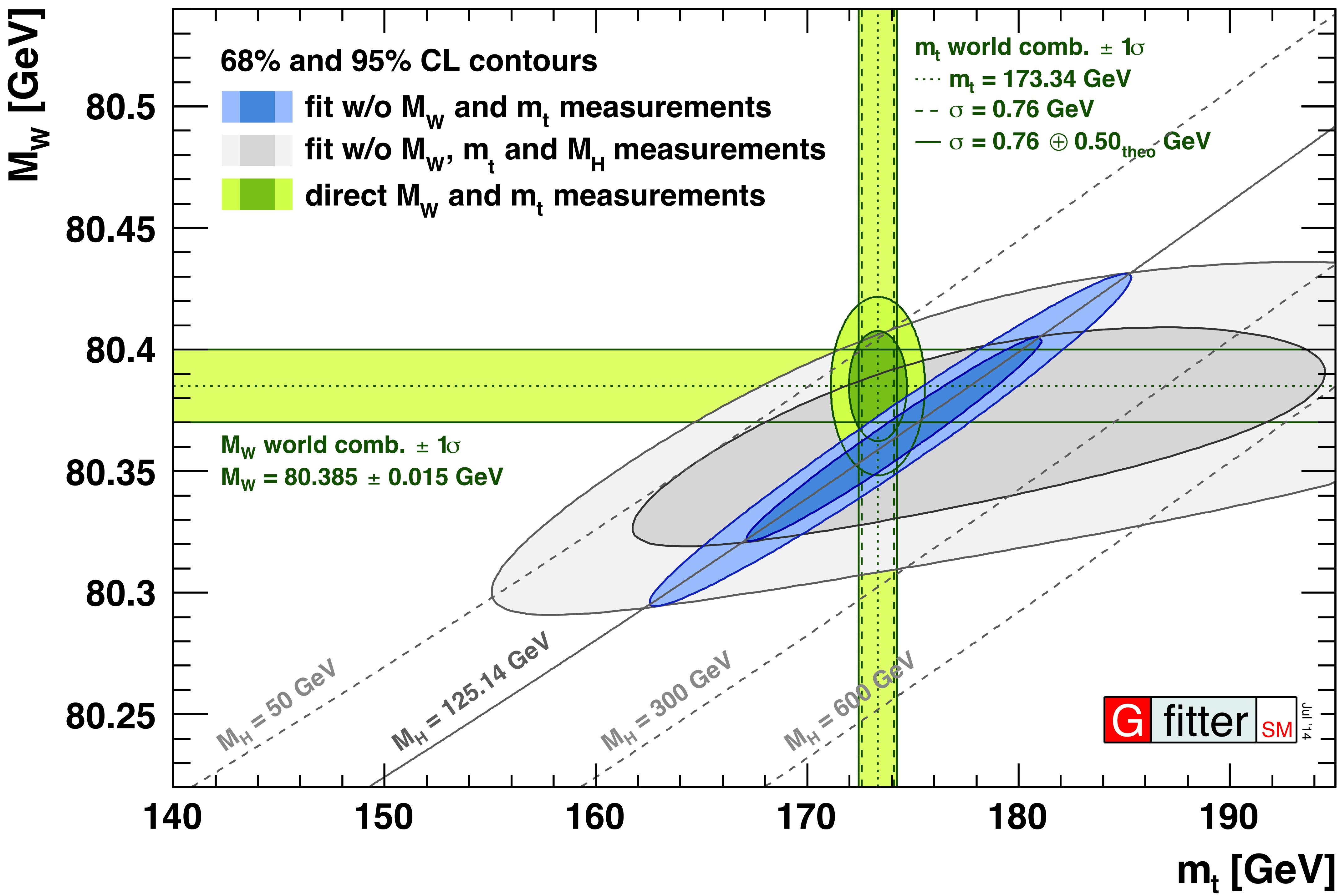


Please remember the results, we will discuss this process and explain it in detail later.

Some Challenges

- Example: top quark “mass”.



Some Challenges

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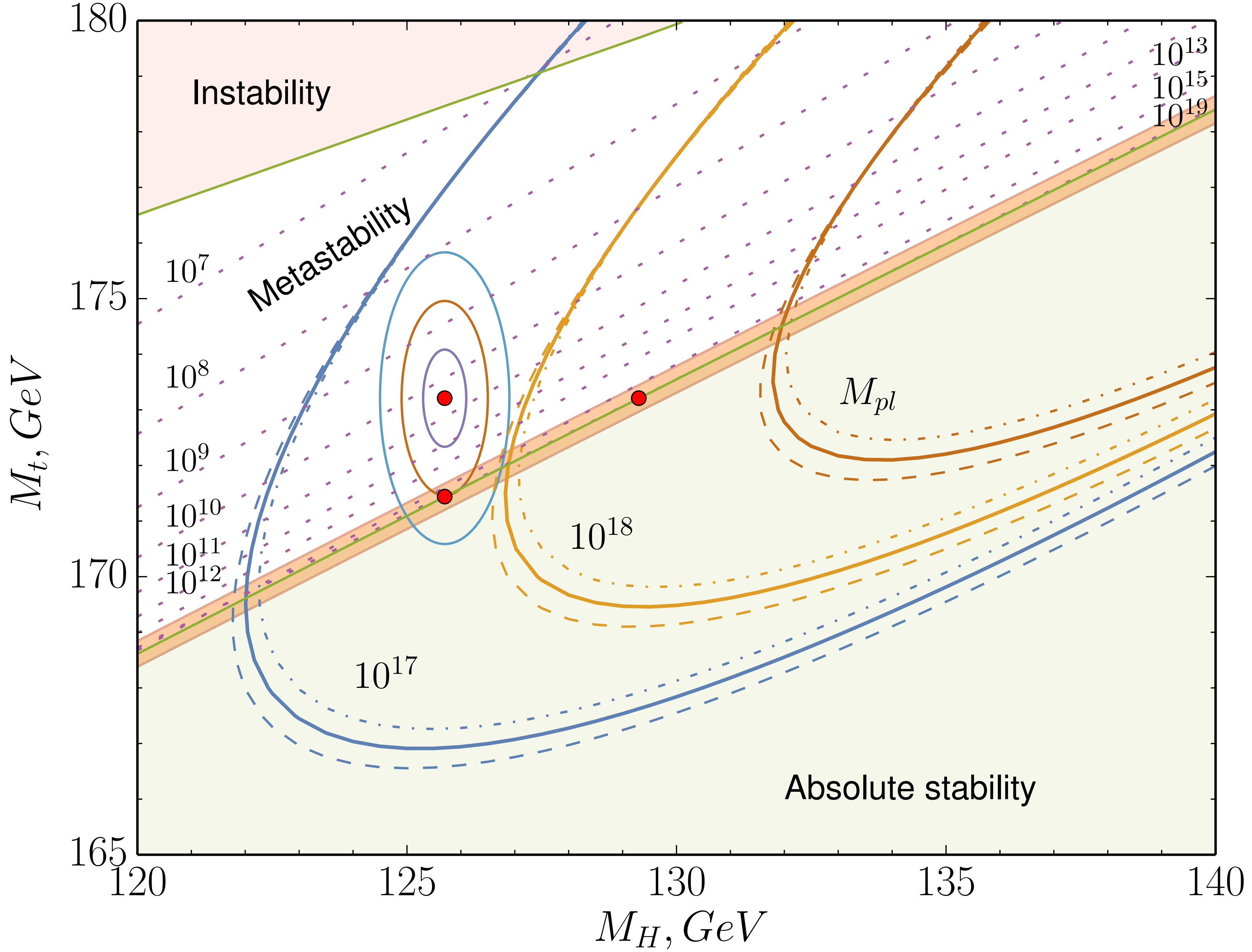
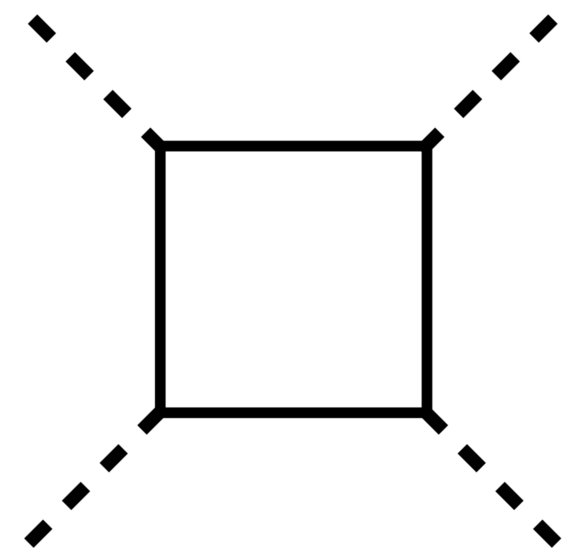
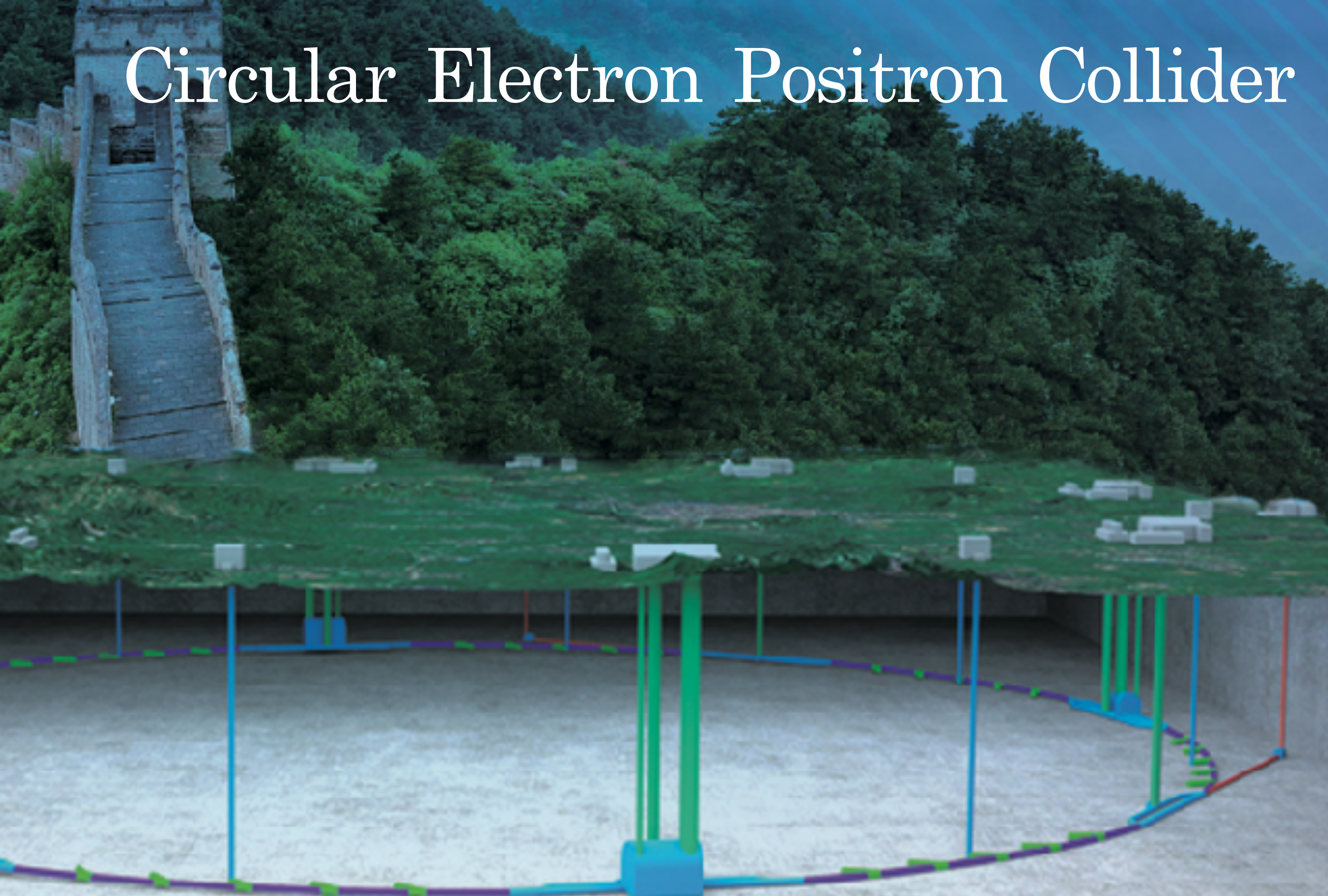


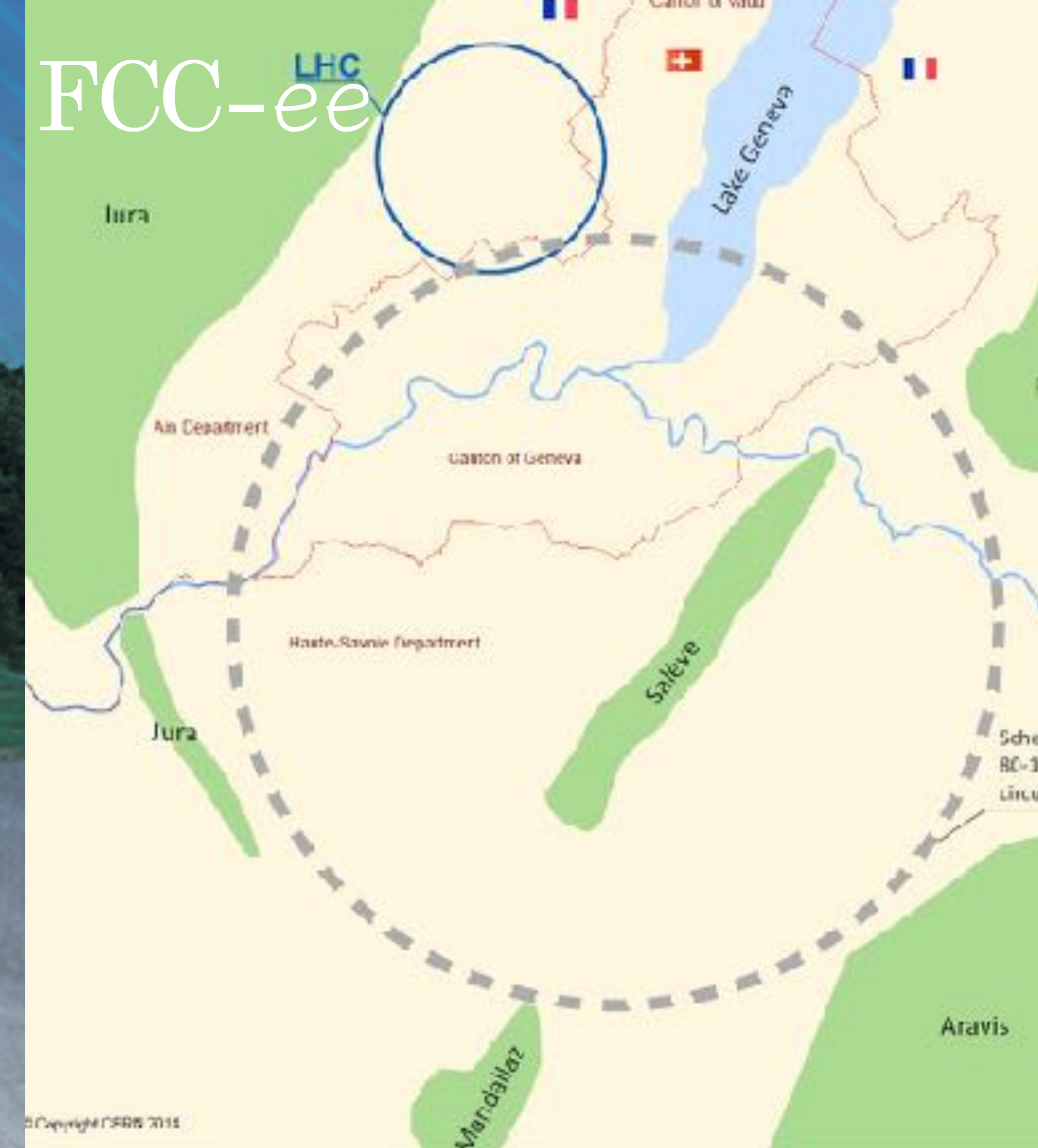


$$\beta_\lambda \ni -\frac{(M_t^{\overline{MS}})^4}{16\pi^2 v_0^4}$$

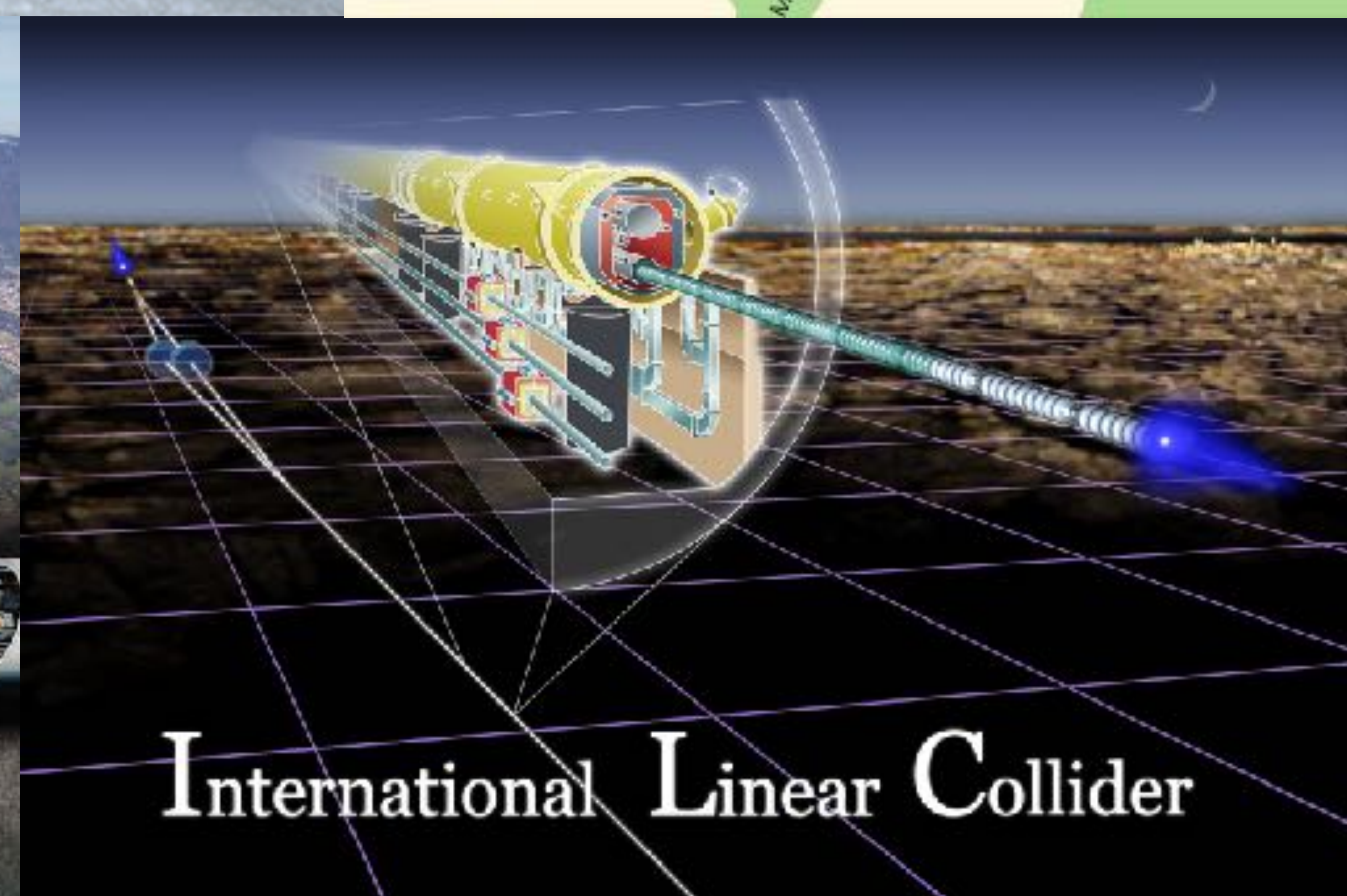
Future Collider Plans

- Future lepton collider plans (in alphabetical order):
  - Circular Electron Positron Collider (CEPC)
  - Compact Linear Collider (CLIC)
  - Future Circular Collider - e^+e^- (FCC-ee, TLEP)
  - International Linear Collider (ILC)
- Future hadron collider plans:
  - Future Circular Collider - hadron-hadron (FCC-hh)
  - Super Proton Proton Collider (SPPC)
- Other plans:
  - Future Circular Collider - eh (FCC-eh)
  - Muon Collider?
  - Gamma-Gamma Collider?
  - …

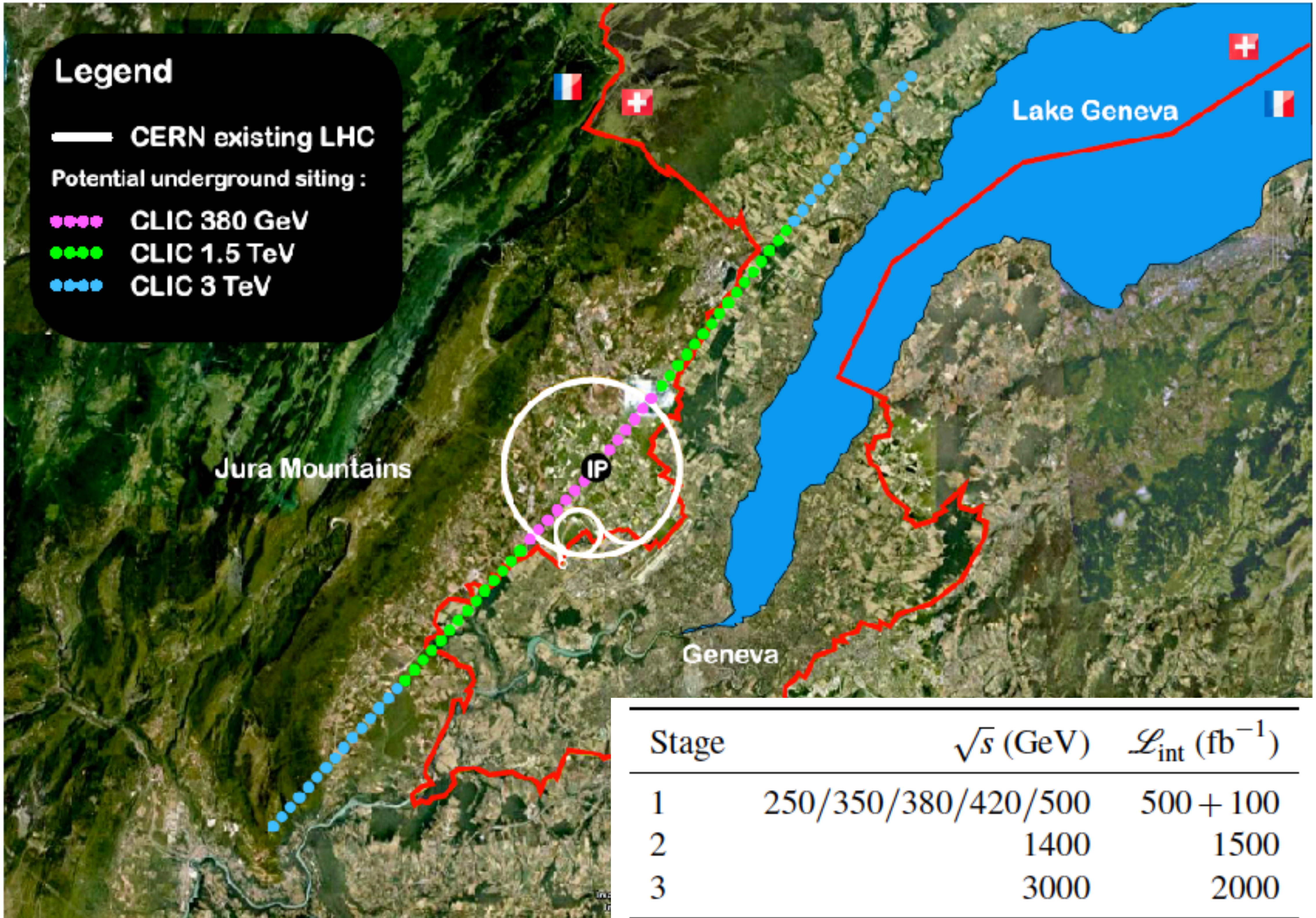

Circular Electron Positron Collider


FCC-ee
LHC
Lake Geneva
Jura
Ain Department
Canton of Geneva
Haute-Savoie Department
Salève
Jura
Aravis
Mandallaz


Compact Linear Collider

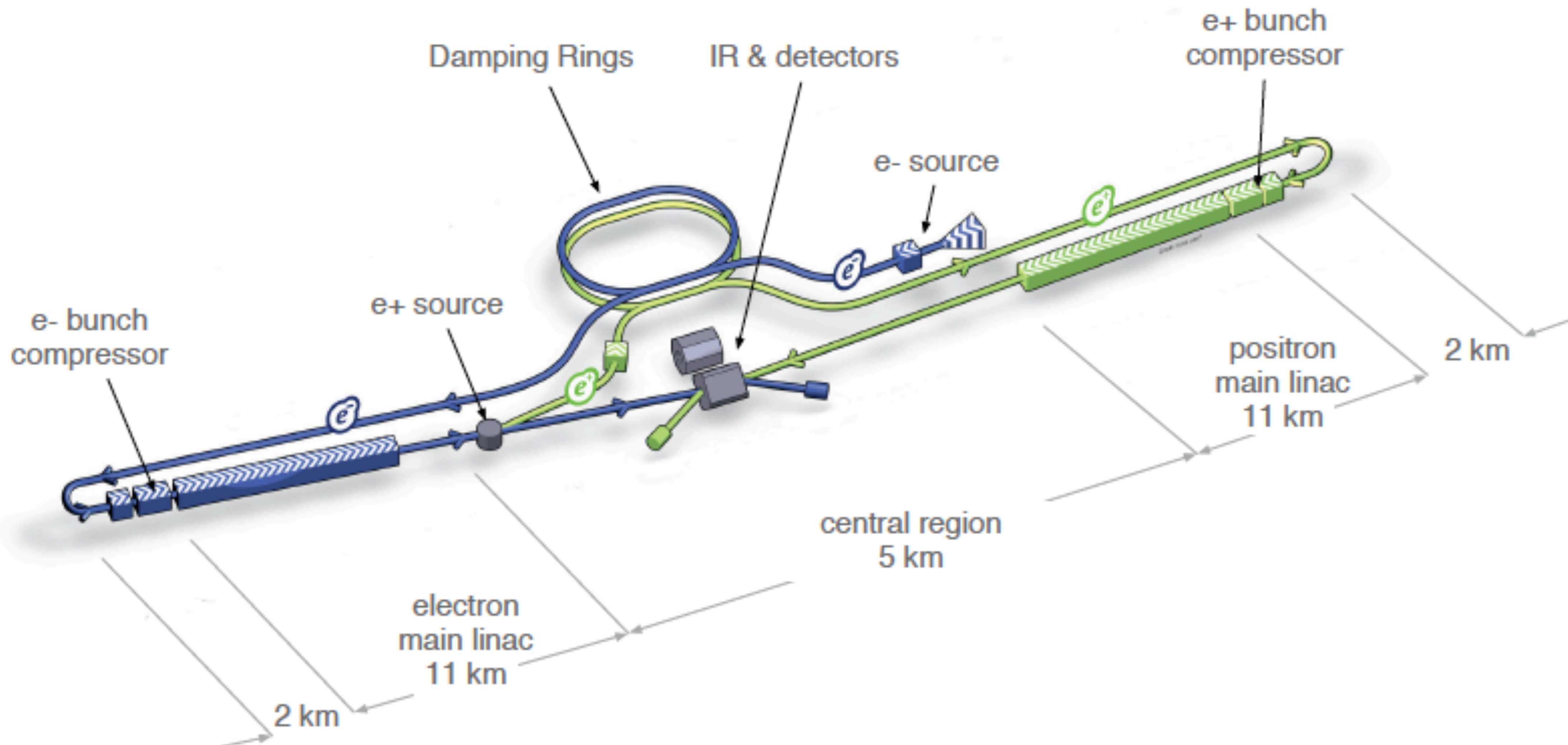

International Linear Collider

The Linear Colliders

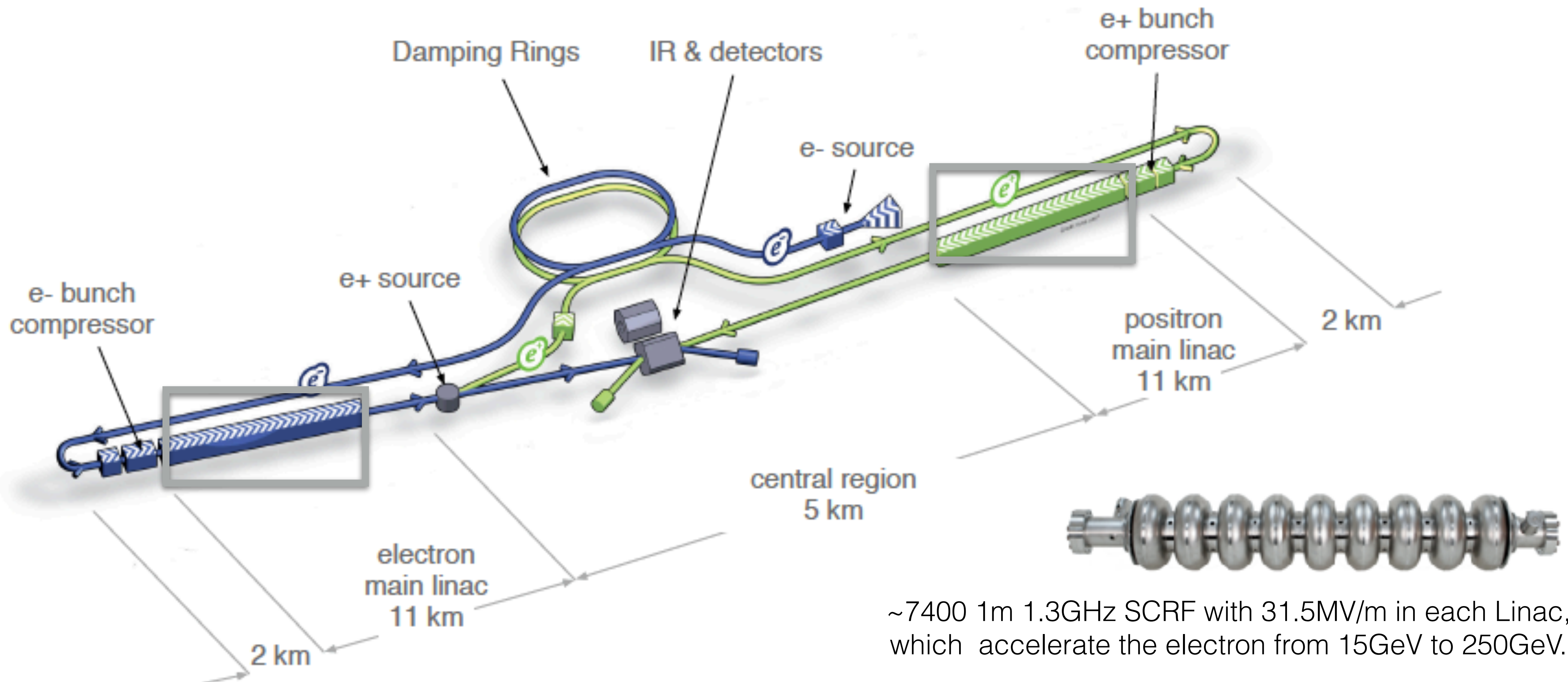


Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	250/350/380/420/500	500 + 100
2	1400	1500
3	3000	2000

The Linear Colliders

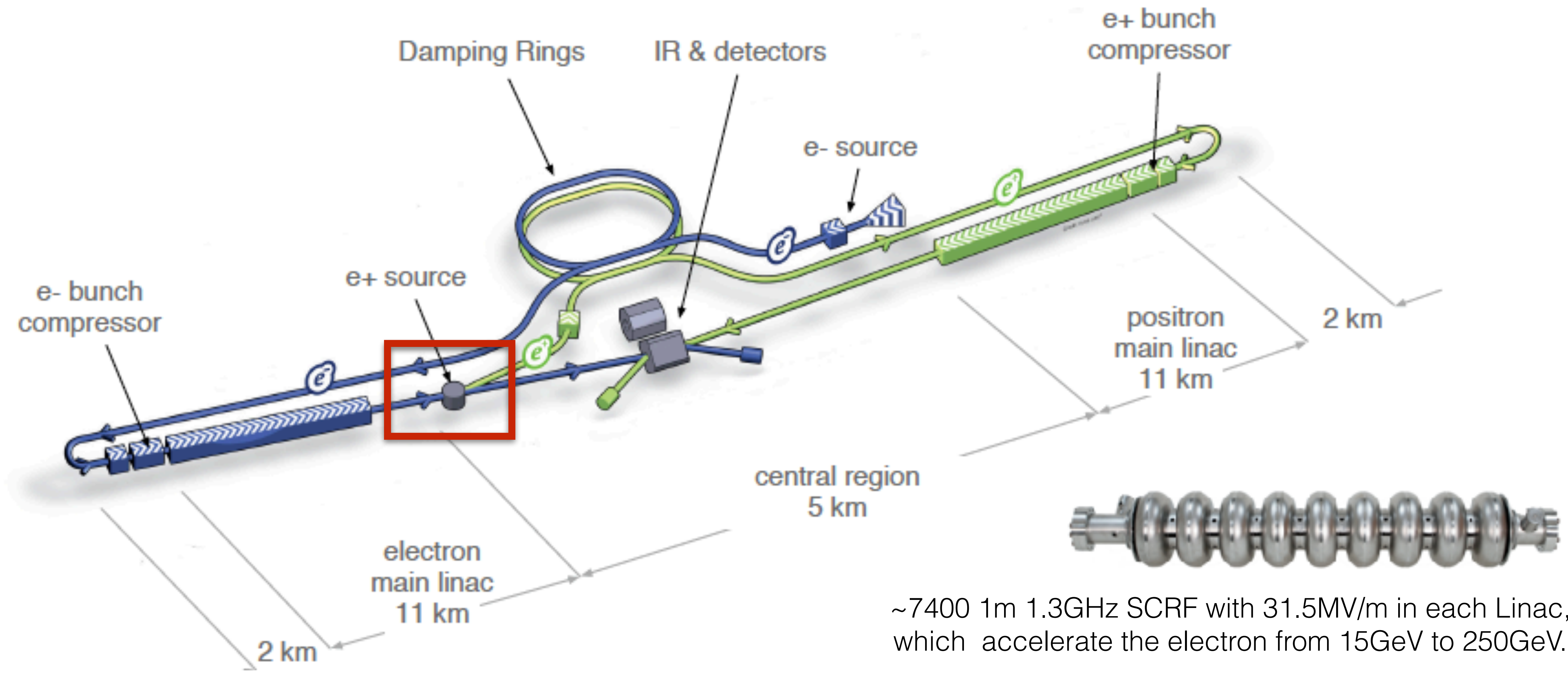


The Linear Colliders



~7400 1m 1.3GHz SCRF with 31.5MV/m in each Linac, which accelerate the electron from 15GeV to 250GeV.

The Linear Colliders



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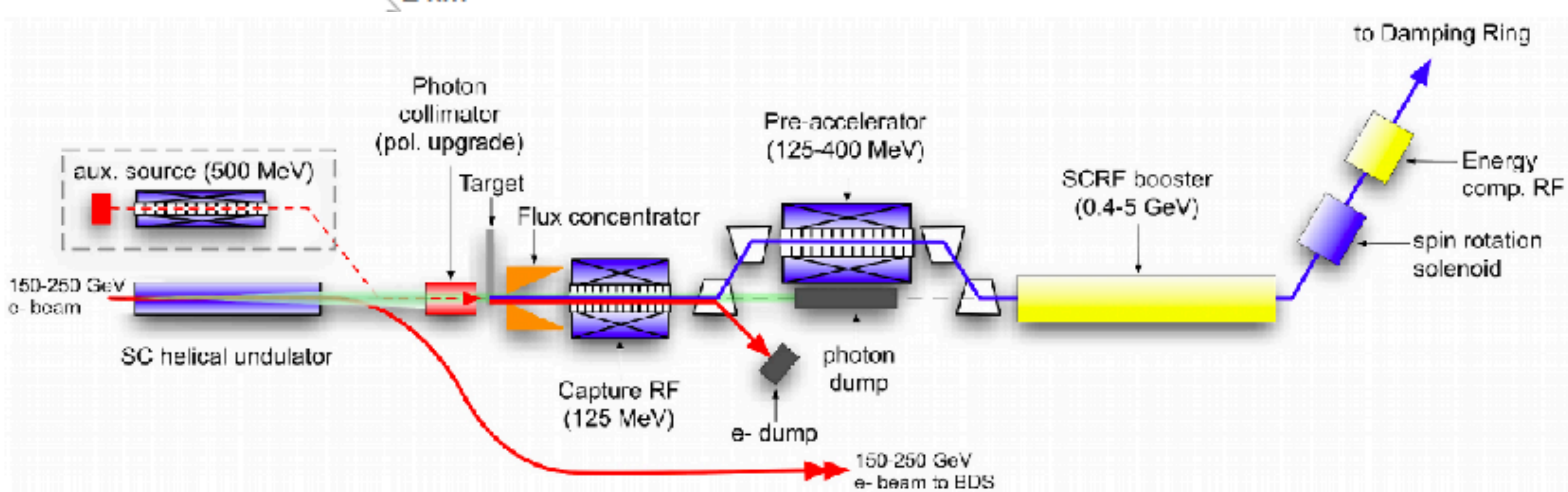

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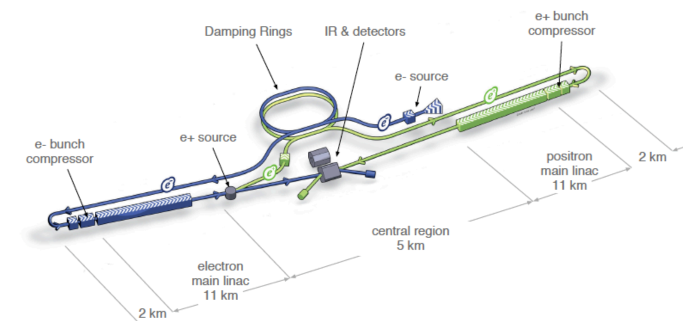
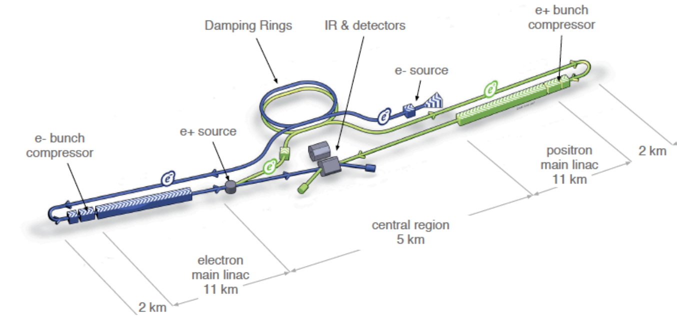


			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ $cm^{-2}s^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

The Linear Colliders



C.M energy: 250GeV, 350GeV, 500GeV, 1TeV

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade A	E_{CM} Upgrade B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	4
Electron linac rate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	4
Number of bunches	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2450	2450
Bunch population	N	[illegible]	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
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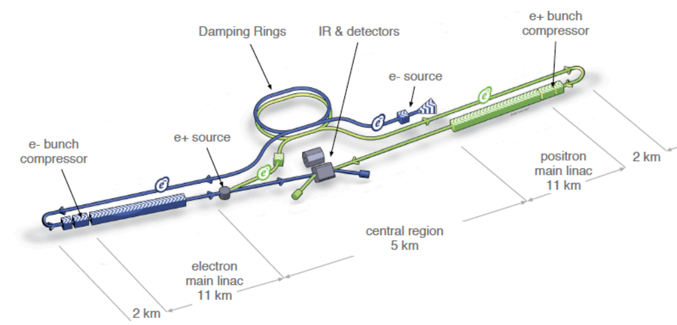
The Linear Colliders



			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
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Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
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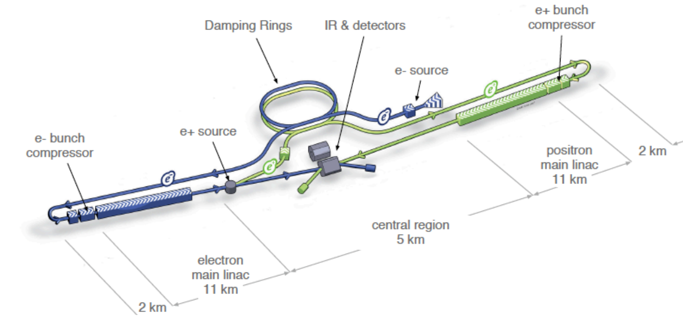
C.M energy: 250GeV, 350GeV, 500GeV, 1TeV

Electron polarization: 80%
Positron polarization: 30%

The Linear Colliders



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H			10	10	10	10	10	10	10
V			35	35	35	35	35	30	30
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C.M energy: 250GeV, 350GeV, 500GeV, 1TeV

Electron polarization: 80%
Positron polarization: 30%

Luminosity:
0.75×10^{34}cm^{-2}s^{-1} at 250GeV;
1.0×10^{34}cm^{-2}s^{-1} at 350GeV;
1.8×10^{34}cm^{-2}s^{-1} at 500GeV;

$$10^{34}\text{cm}^{-2}\text{s}^{-1} = 10^{34} \times \frac{10^{-39}\text{cm}^2}{1\text{fb}} \times \frac{365.25 \times \times 24 \times 60 \times 60\text{s}}{1\text{y}} = 315.6\text{fb}^{-1}\text{y}^{-1}$$

The Linear Colliders

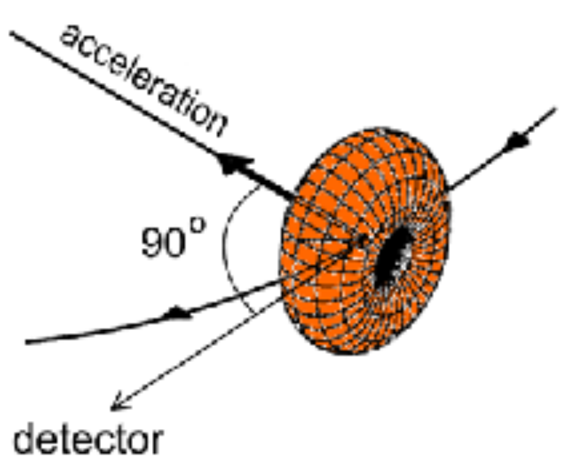
- The C.M. energy can be large.
- The luminosity increases when the C.M. energy increases.
  - The undulator-based positron source must have an electron-beam energy of at least 150 GeV to produce the requisite positron intensity;
  - The beam divergence at the interaction point is constrained by the allowable synchrotron radiation fan generated by the final doublet.
- The initial state electron and positron can be polarized.
- Typical energy is from 250GeV to several TeV.

The Circular Colliders

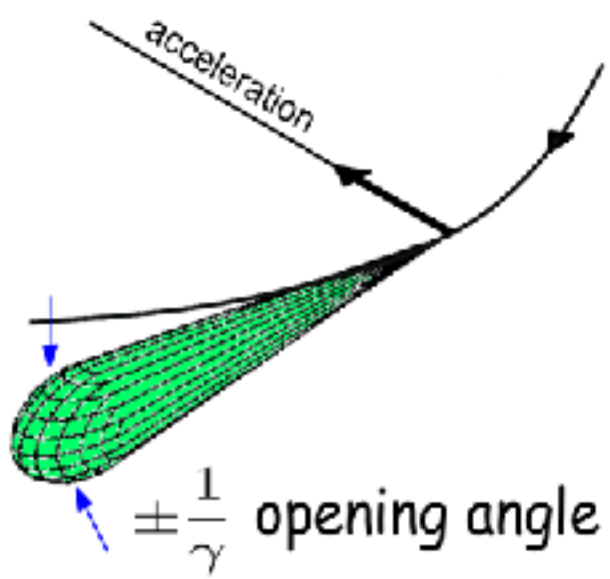
- Classical electrodynamics: synchrotron radiation.

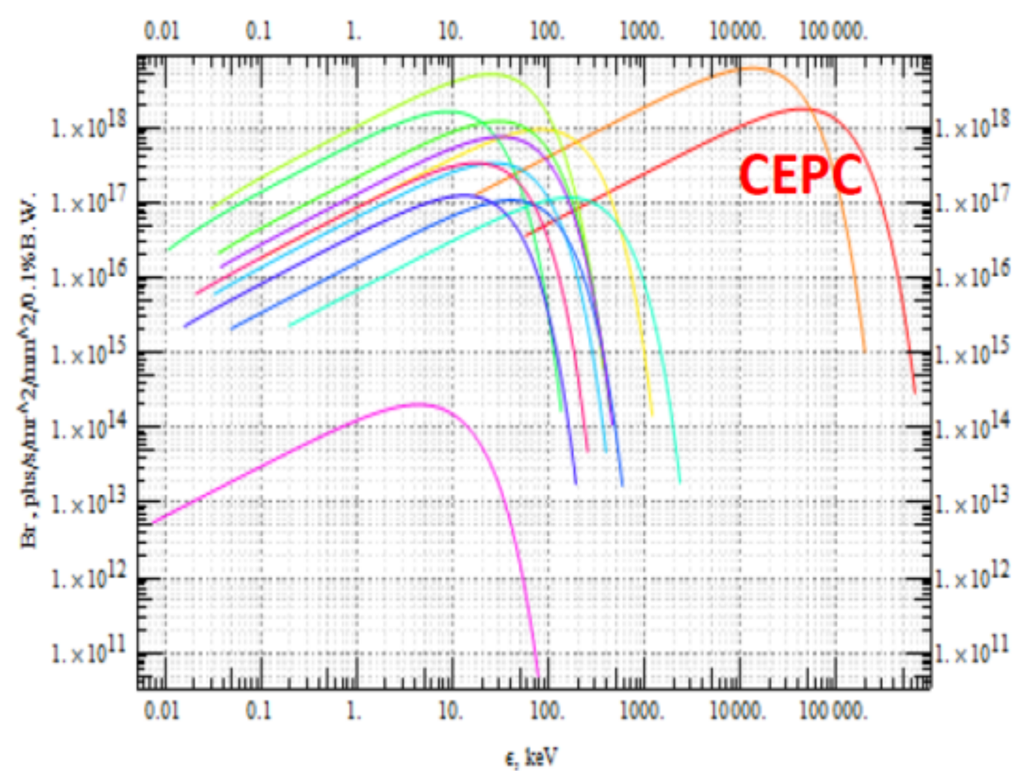
$$P = \frac{e^2 c}{6\pi\epsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$$

$$= \frac{\pi e^2 c}{24\epsilon_0}\frac{E_{c.m.}^4}{m^4 L^2} = \frac{e^4}{24\pi\epsilon_0 c^5}\frac{E_{c.m.}^2 B^2}{m^4}$$



$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1-(\frac{v}{c})^2}$$





The Circular Colliders

- Classical electrodynamics: synchrotron radiation.

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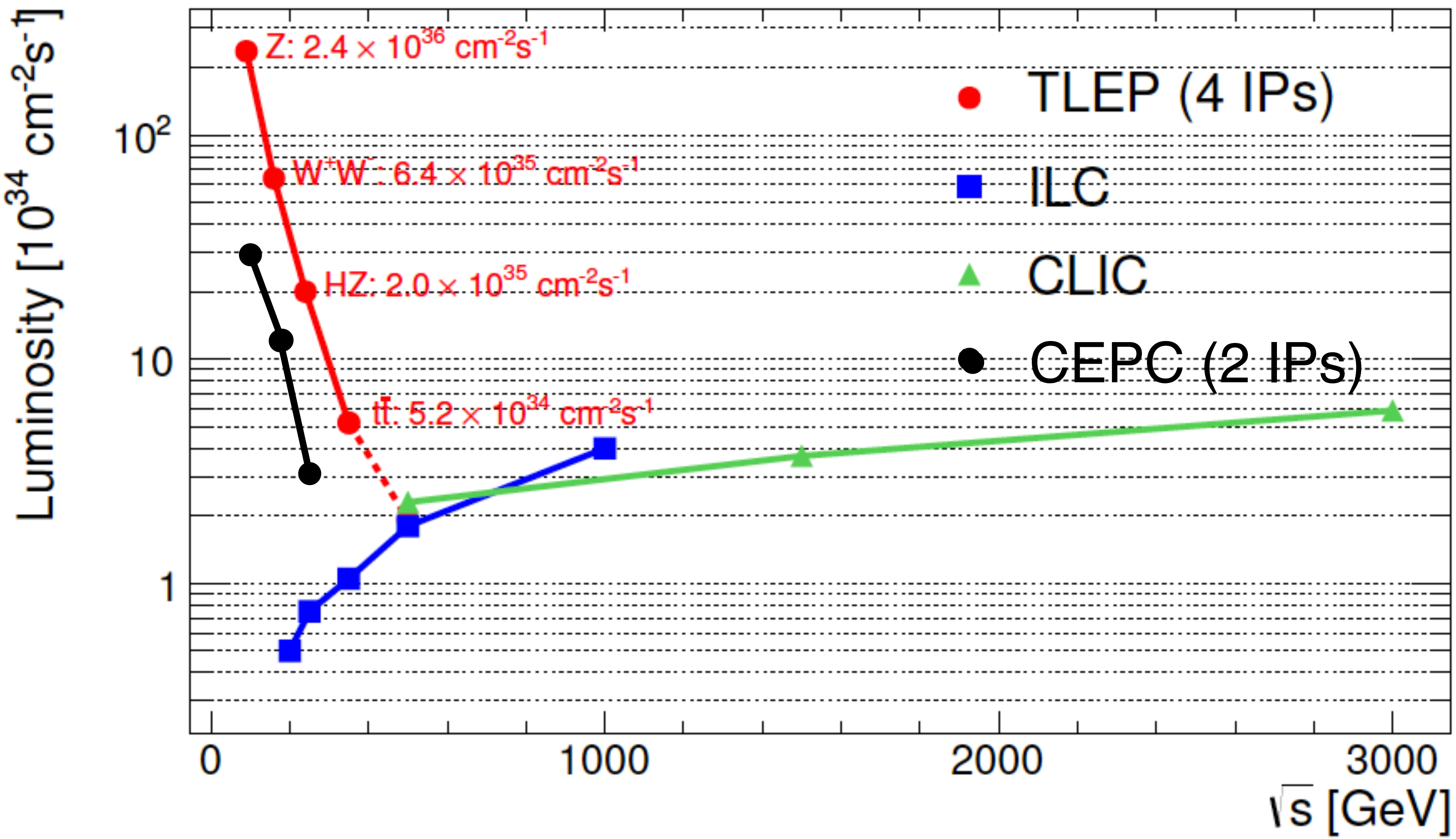
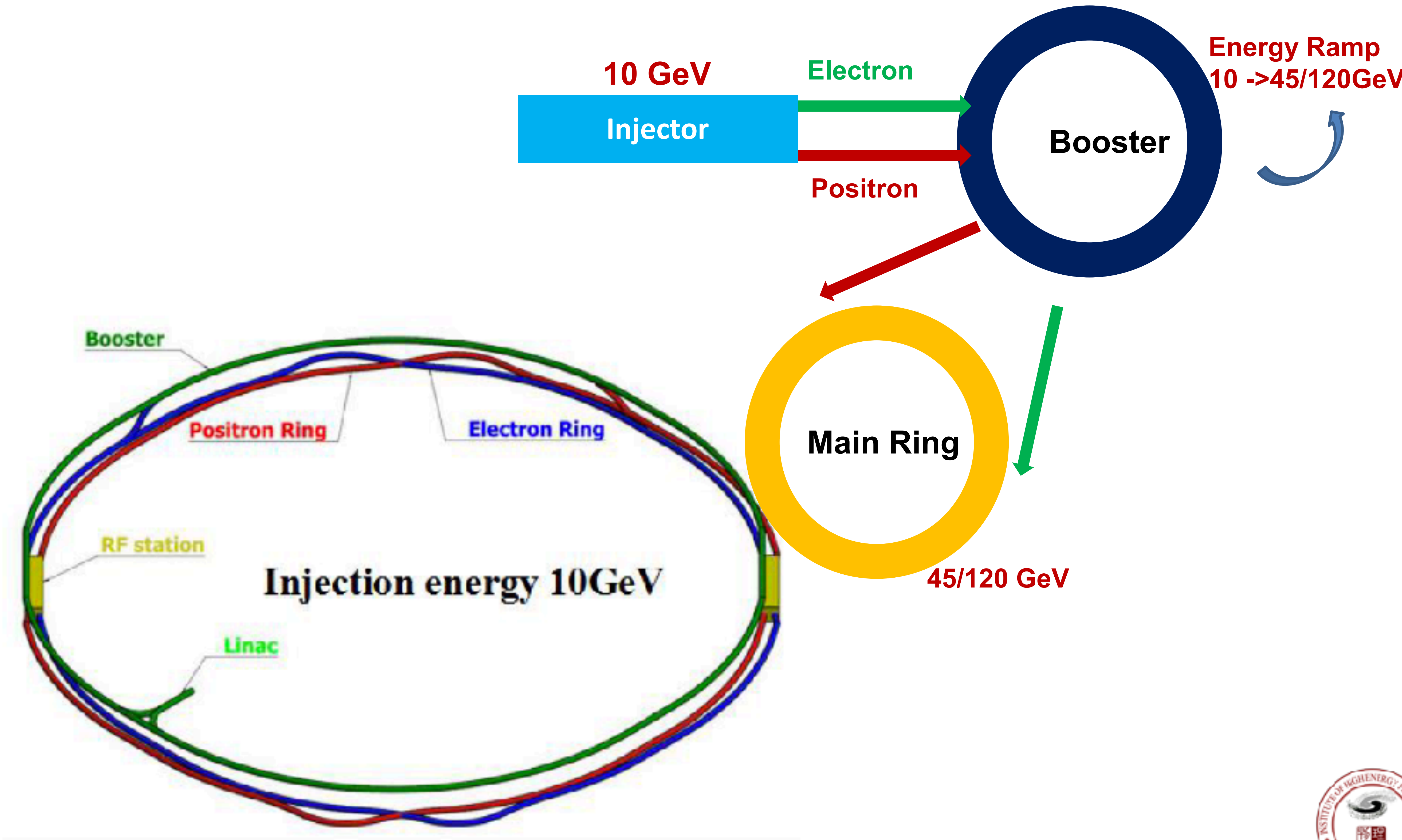
- For lower E_{cm}, the RadioFrequency cavities' power can use to accelerate much more electron and positron.

$$\mathscr{L} \sim \frac{1}{E_{c.m.}^3}$$

The Circular Colliders



The Circular Colliders



Next Lecture

- A review of the SM Higgs physics.
- Higgs physics at future lepton colliders and the phenomenology.