Physics with ILD

Keisuke Fujii

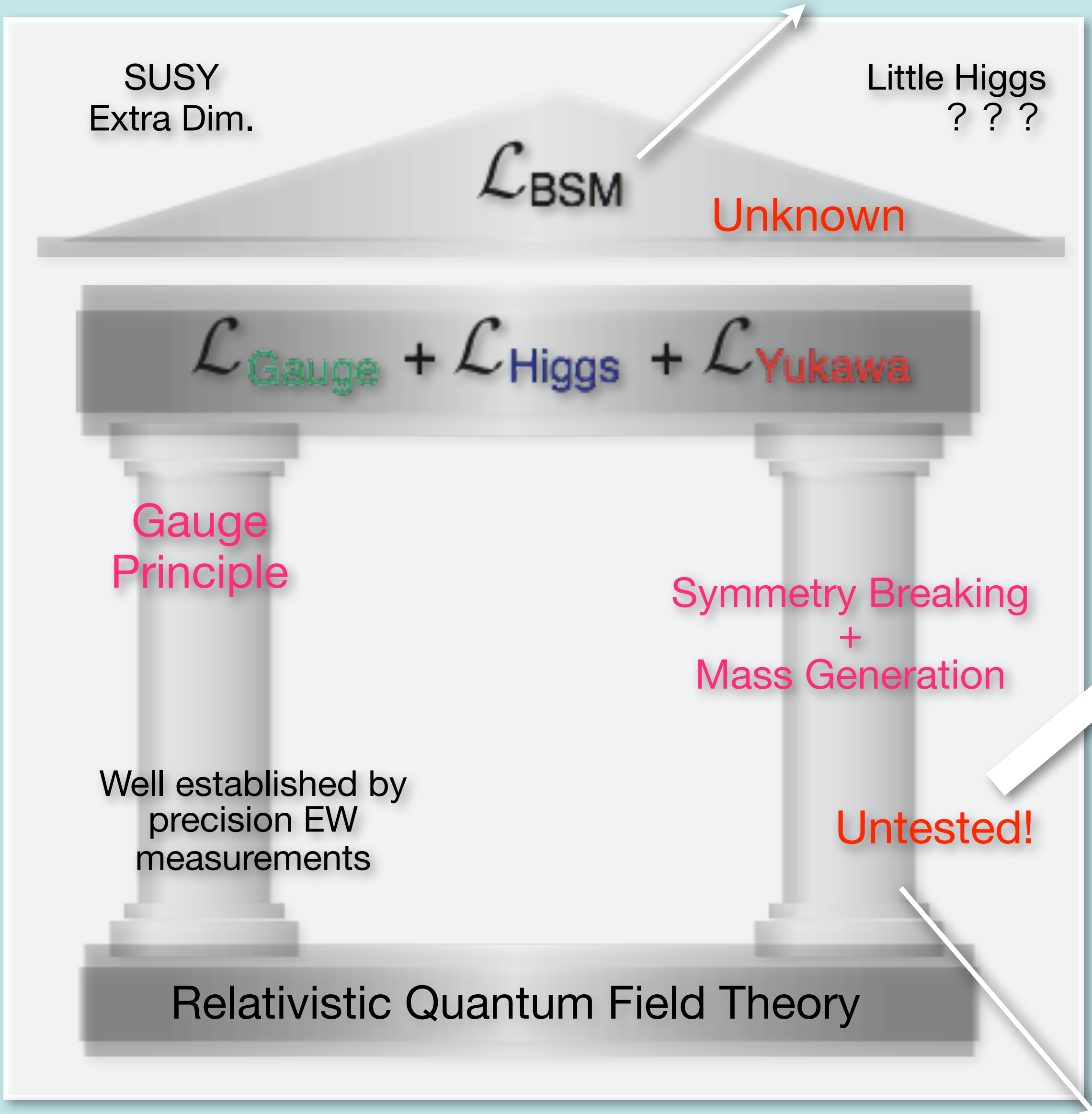
Why are we doing what we are doing?

Primary Goal

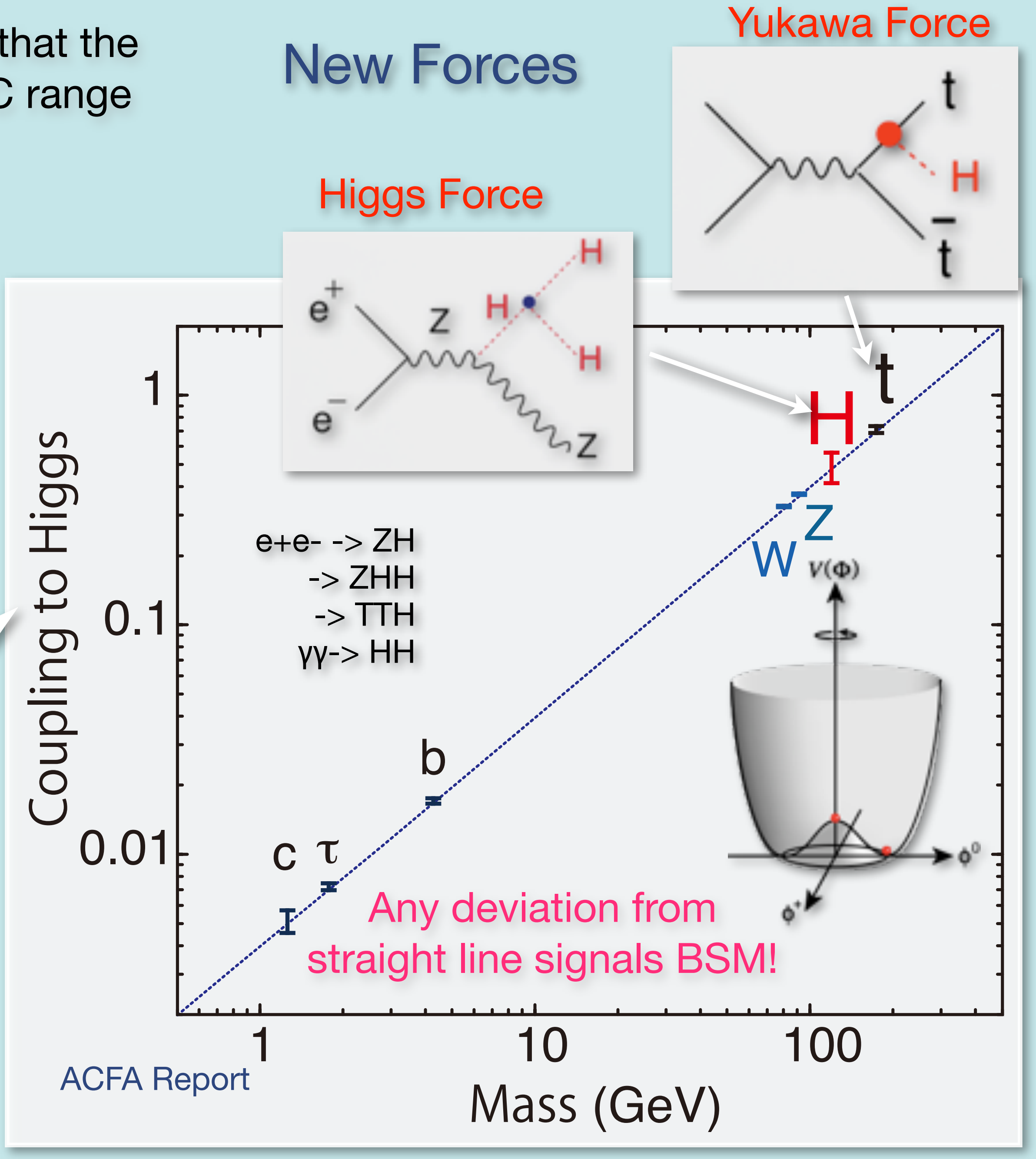
Test of the 2nd pillar, then BSM

2 Main Pillar of SM

There's a good chance that the dark matter is in the ILC range



New Forces



Wd do not know how firm this pillar is. The answer surely lines in the TeV Region

First test the 2nd pillar by precision Higgs study and then put

Beyond the Standard Model **roof!**

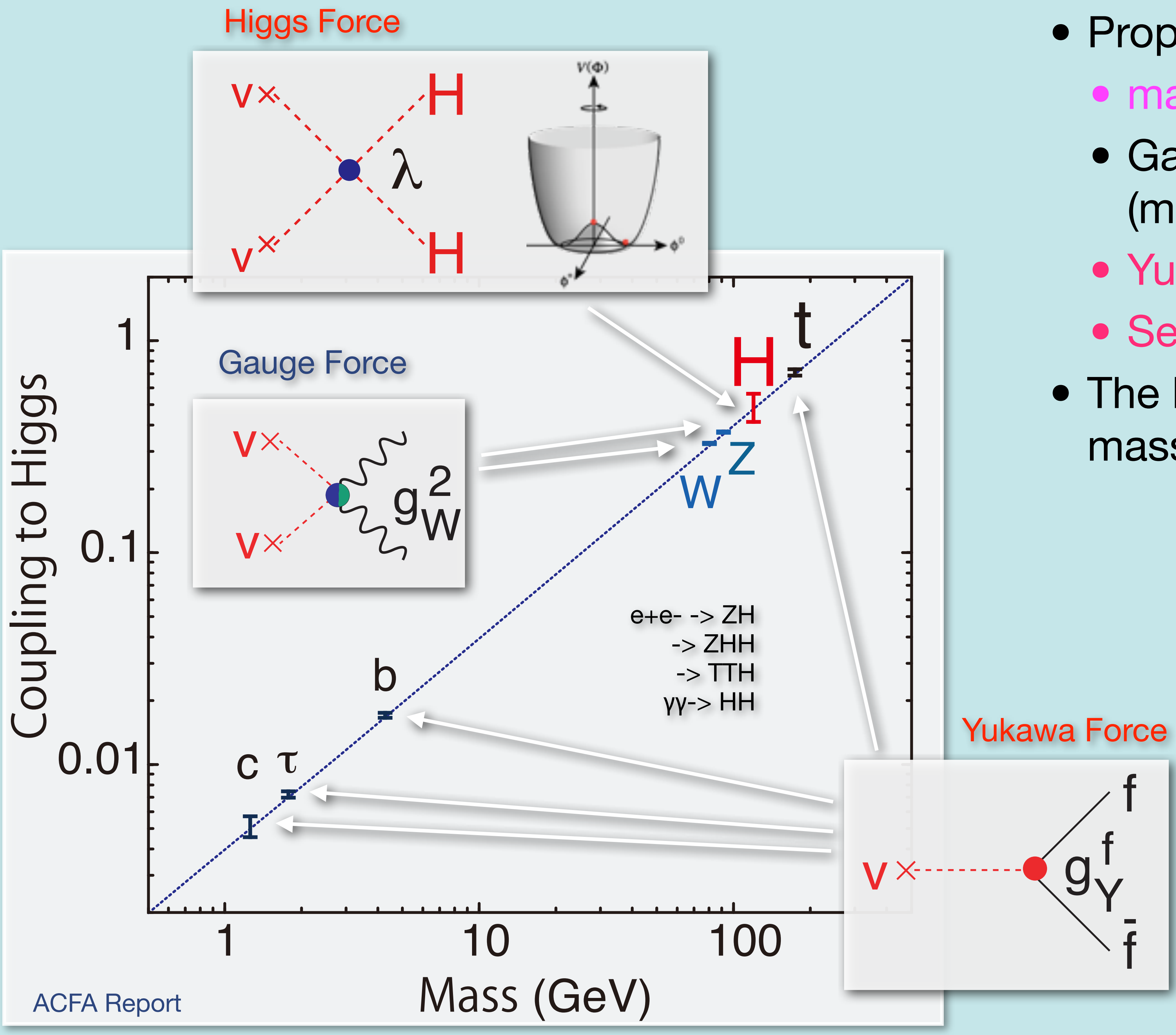
Has the climate changed?

- Success of SM = Success of Gauge Principle

  W_T and Z_T = gauge fields of the EW gauge symmetry
- We knew there must be "something (electro-weakly charged) condensed in the vacuum" to break SU(2)xU(1) thus giving masses to W and Z and inducing L-R mixing/ flavor mixing of matter fermions.
- We knew it's there in the vacuum with a vev of 245GeV. But other than that we did not know almost anything about it until July 4th, 2012.
- Since the July 4th the world has changed!
- We now have H(125), which looks very much like a Higgs boson.
- We need to check this ~125GeV boson in detail to see if it has indeed all the required properties of the something in the vacuum.

What Properties to Measure?

The Key is the Mass-Coupling Relation



ACFA Report

- Properties to measure are
  - mass, width, J^{PC}
  - Gauge quantum numbers (multiplet structure)
  - Yukawa couplings
  - Self-coupling
- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!

The Higgs is a window to BSM physics!

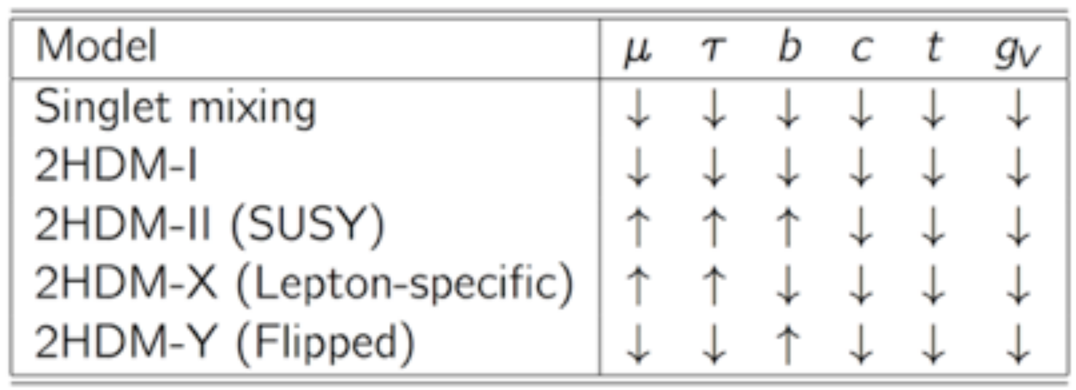
Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- Multiplet structure :
  - Additional singlet?
  - Additional doublet?
  - Additional triplet?
- Underlying dynamics :
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other questions of HEP :
  - DM
  - EW baryogenesis
  - neutrino mass
  - inflation?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!



Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

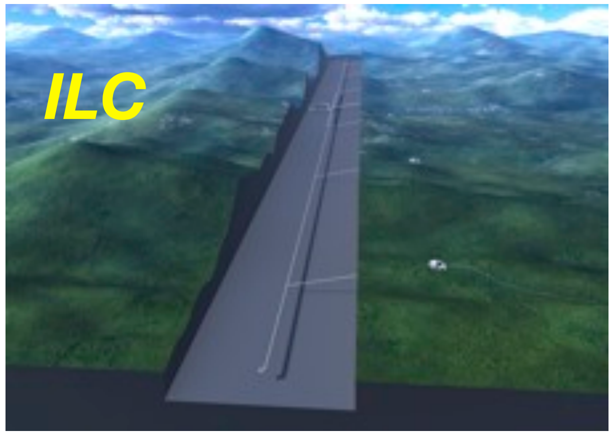
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}). \end{cases}$$

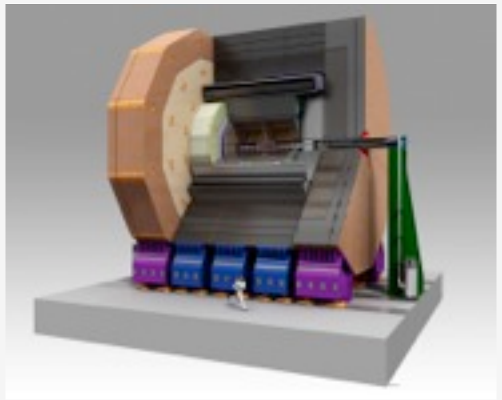
SUSY

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Expected deviations are small --> Precision!



ILD



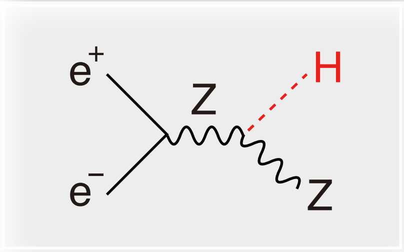
For the precision we need a 500GeV LC and a high precision detector

Why 250-500 GeV?

Three well known thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

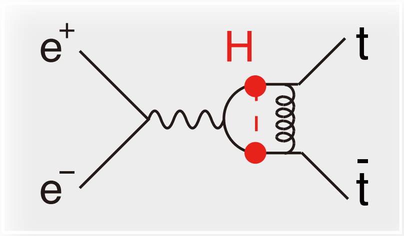
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass)   -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

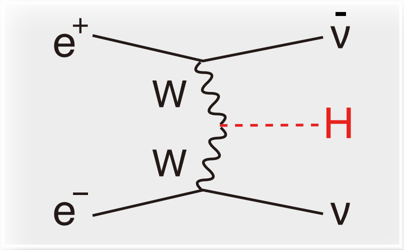


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> theoretically clean mt measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



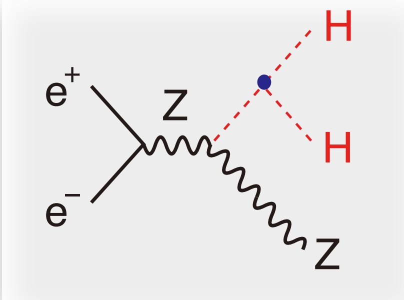


vvH @ 350 - 500GeV :

- HWW coupling -> total width --> absolute normalization of Higgs couplings

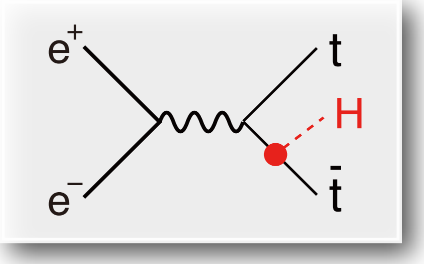
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling



ttbarH @ 500GeV (~2mt+M_H+30GeV) :

- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling



We can complete the mass-coupling plot at ~500GeV!

Has the climate changed?

So the answer is YES indeed!

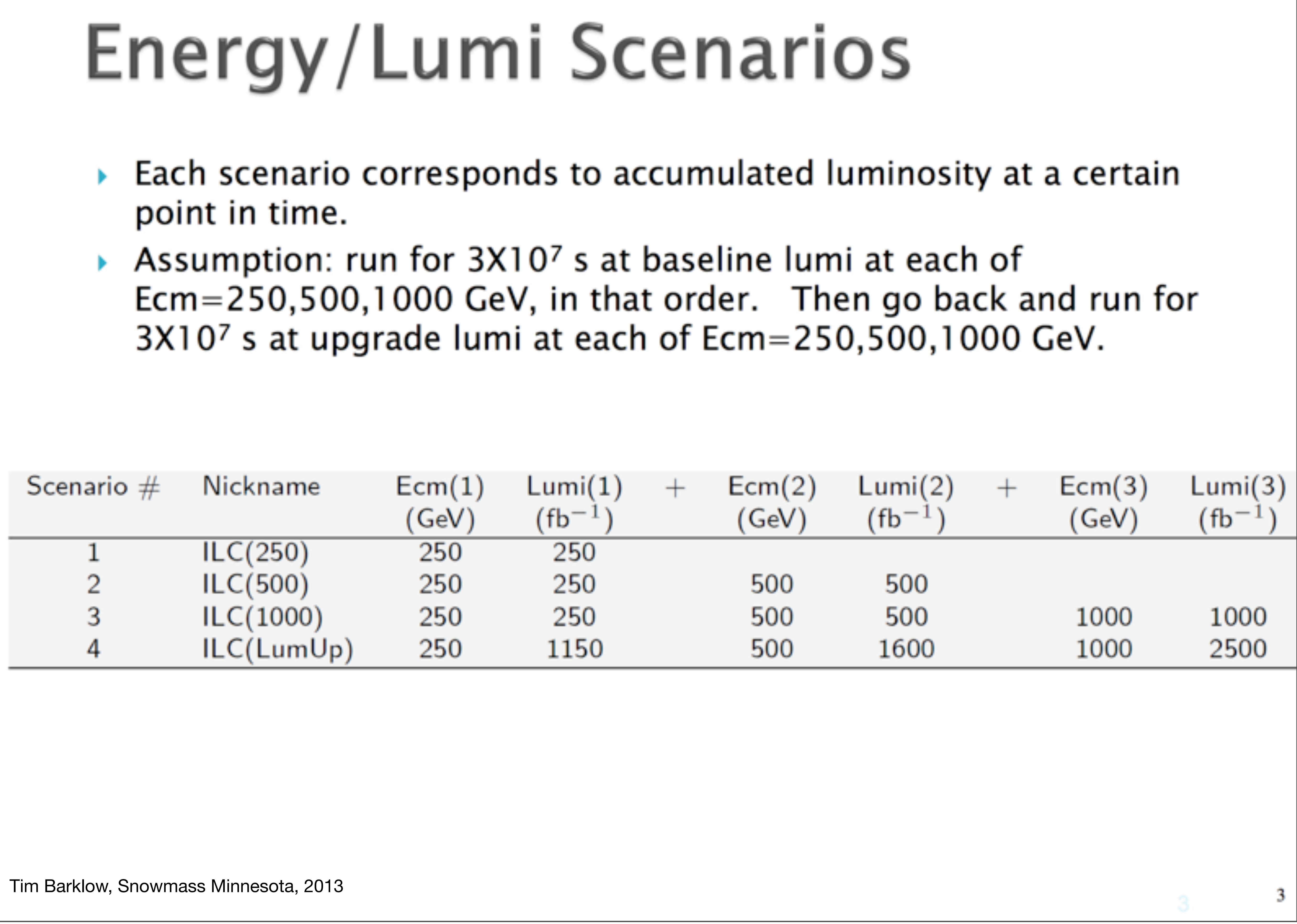
We now have H(125) as a probe of BSM physics.

We need O(1%) or hopefully sub-% precision since no clear BSM signal seen at LHC(8TeV) .

- LHC will study H(125) for at least decade before ILC will start running.

- We need to demonstrate that ILC will advance our understanding of particle physics, H(125) in particular, qualitatively beyond the information that will be available from the results expected from the future stages of the LHC.

Luminosity Upgrade



Energy/Lumi Scenarios

- Each scenario corresponds to accumulated luminosity at a certain point in time.
- Assumption: run for $3X10^7$ s at baseline lumi at each of Ecm=250,500,1000 GeV, in that order. Then go back and run for $3X10^7$ s at upgrade lumi at each of Ecm=250,500,1000 GeV.

Scenario #	Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})
1	ILC(250)	250	250						
2	ILC(500)	250	250		500	500			
3	ILC(1000)	250	250		500	500		1000	1000
4	ILC(LumUp)	250	1150		500	1600		1000	2500

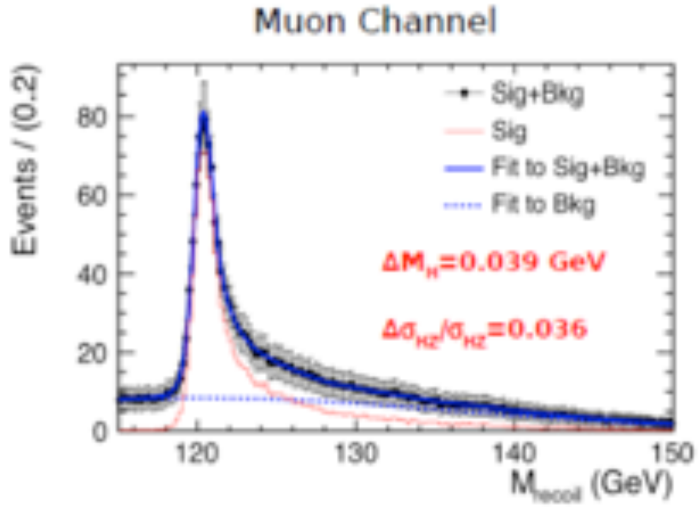
Tim Barklow, Snowmass Minnesota, 2013

QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

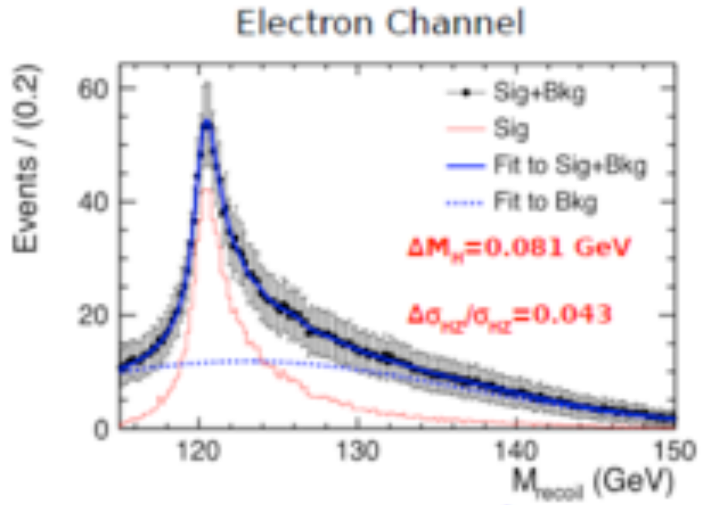
- Almost all ILC Higgs measurements are measurements of $\sigma \bullet BR$.
- One crucial measurement is different: the Higgs recoil measurement of $\sigma(e^+e^- \to ZH)$.
- σ_{ZH} is the key that unlocks the door to model independent measurements of the Higgs BR's and Γ_{tot} at the ILC.

- All LHC Higgs measurements are measurements of $\sigma \bullet BR$

and hence model-dependent!



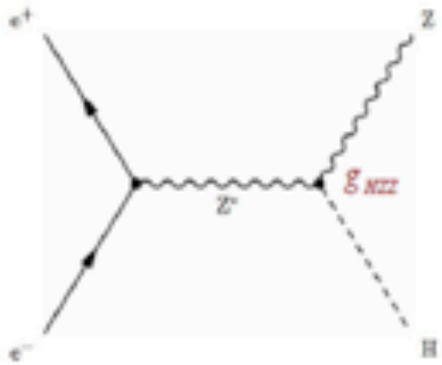
Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material

Combined: $\Delta M_H = .032$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=2.5% for L= 250 fb^{-1}

$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb^{-1}



$\sigma_{HZ} \sim g^2_{HZZ}$

$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\%$ (0.6%) for L=250 (1150) fb^{-1}

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THESE AND OTHER QUALITATIVE DIFFERENCES BETWEEN ILC & LHC LEAD TO QUANTITATIVE IMPROVEMENTS OVER LHC

7 Parameter HXSWG Benchmark *

Mode	LHC			
	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	$(5-7)\%$	$(2-5)\%$	3.8 %	2.3 %
gg	$(6-8)\%$	$(3-5)\%$	1.1 %	0.67 %
WW	$(4-5)\%$	$(2-3)\%$	0.21 %	0.13 %
ZZ	$(4-5)\%$	$(2-3)\%$	0.44 %	0.22 %
$t\bar{t}$	$(14-15)\%$	$(7-10)\%$	1.3 %	0.76 %
$b\bar{b}$	$(10-13)\%$	$(4-7)\%$	0.51 %	0.31 %
$\tau^+\tau^-$	$(6-8)\%$	$(2-5)\%$	1.3 %	0.72 %

* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays } i} \Gamma_i^{SM} \kappa_i^2$

Other Higgs Couplings

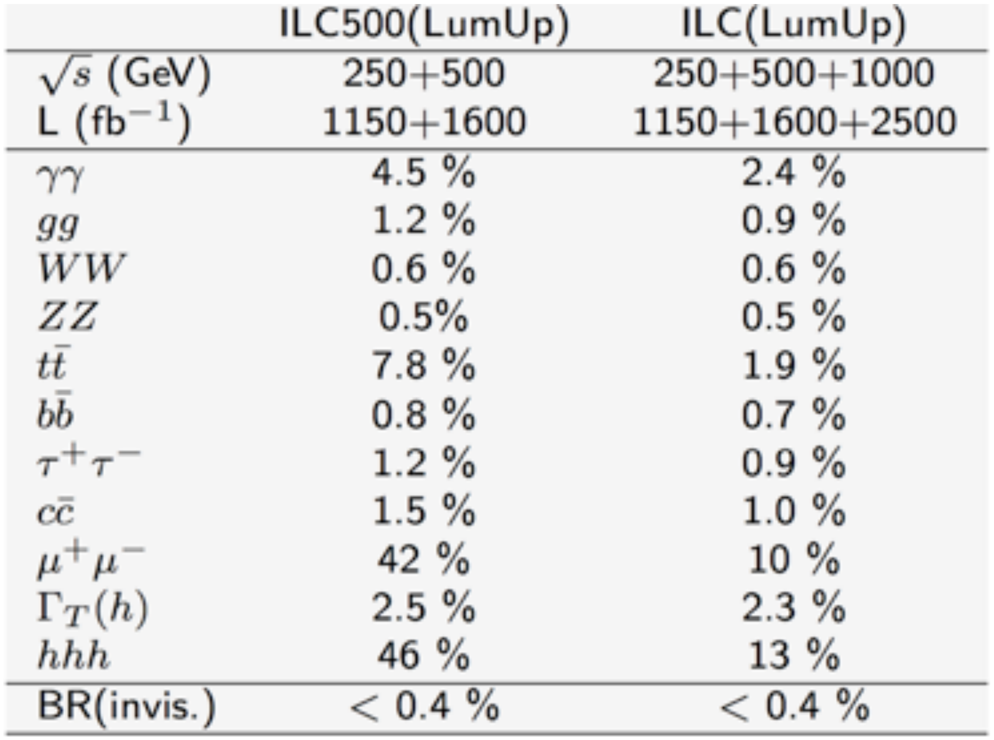
Mode	LHC 300 fb^{-1}	LHC 3000 fb^{-1}	ILC(1000)	ILC(LumUp)
$\mu^+\mu^-$	30%	10%	16 %	10 %
hhh	-	50%	21 %	13 % *
BR(invis.)	< (17 – 28)%	< (6-17)%	$<$ 0.69 %	$<$ 0.32 %
$c\bar{c}$	-	-	2.0 %	1.1 %
$\Gamma_T(h)$	-	-	5.6 %	2.7 %

* Current full simulation result using $H \to b\bar{b}$, WW^* only. Results will improve as more Higgs decay modes are added, and as jet combinatoric problems are solved.

More Recent Results

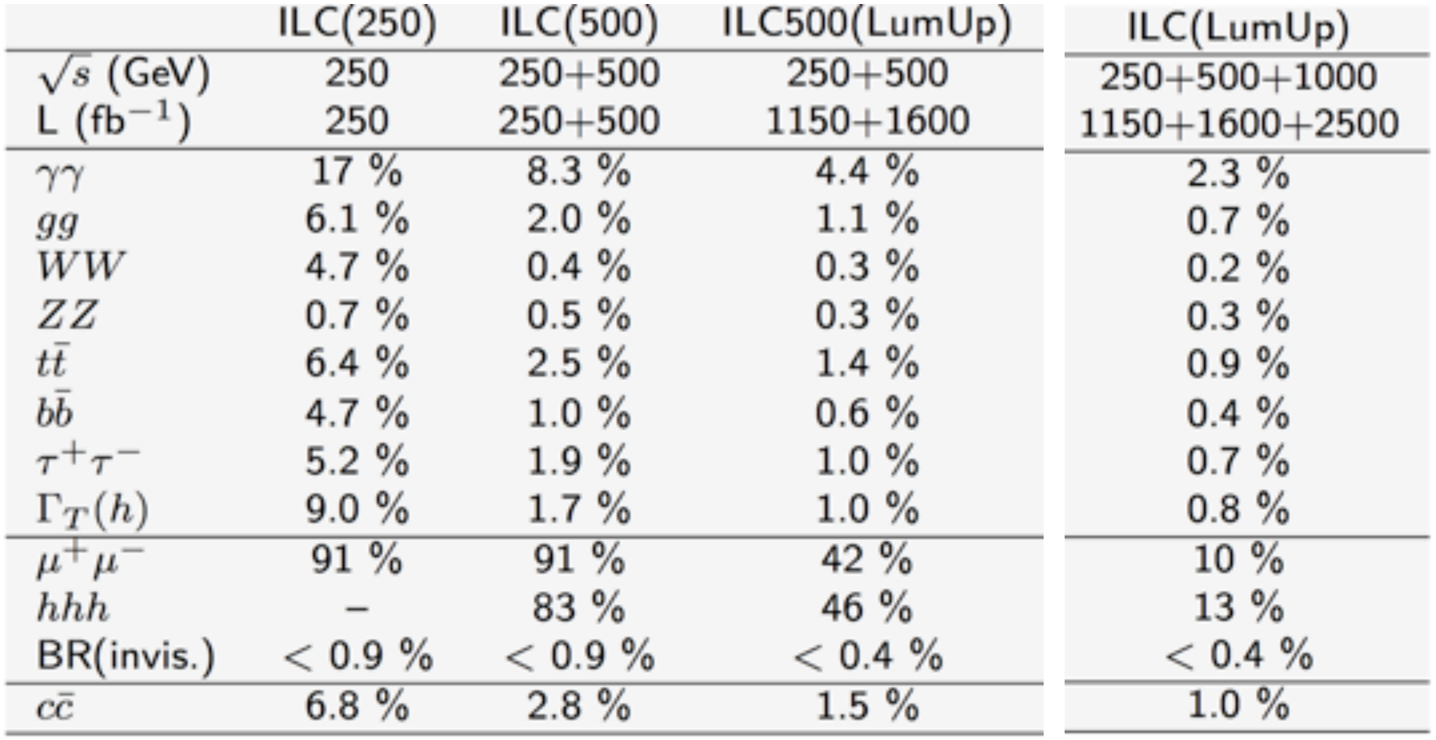
from Snowmass White Paper

Model independent fit



	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250+500	250+500+1000
L (fb^{-1})	1150+1600	1150+1600+2500
$\gamma\gamma$	4.5 %	2.4 %
gg	1.2 %	0.9 %
WW	0.6 %	0.6 %
ZZ	0.5%	0.5 %
$t\bar{t}$	7.8 %	1.9 %
$b\bar{b}$	0.8 %	0.7 %
$\tau^+\tau^-$	1.2 %	0.9 %
$c\bar{c}$	1.5 %	1.0 %
$\mu^+\mu^-$	42 %	10 %
$\Gamma_T(h)$	2.5 %	2.3 %
hhh	46 %	13 %
BR(invis.)	< 0.4 %	< 0.4 %

Model dependent 7-param. fit



	ILC(250)	ILC(500)	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500	250+500+1000
L (fb^{-1})	250	250+500	1150+1600	1150+1600+2500
$\gamma\gamma$	17 %	8.3 %	4.4 %	2.3 %
gg	6.1 %	2.0 %	1.1 %	0.7 %
WW	4.7 %	0.4 %	0.3 %	0.2 %
ZZ	0.7 %	0.5 %	0.3 %	0.3 %
$t\bar{t}$	6.4 %	2.5 %	1.4 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	1.9 %	1.0 %	0.7 %
$\Gamma_T(h)$	9.0 %	1.7 %	1.0 %	0.8 %
$\mu^+\mu^-$	91 %	91 %	42 %	10 %
hhh	–	83 %	46 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.4 %	< 0.4 %
$c\bar{c}$	6.8 %	2.8 %	1.5 %	1.0 %

More Exercises Needed

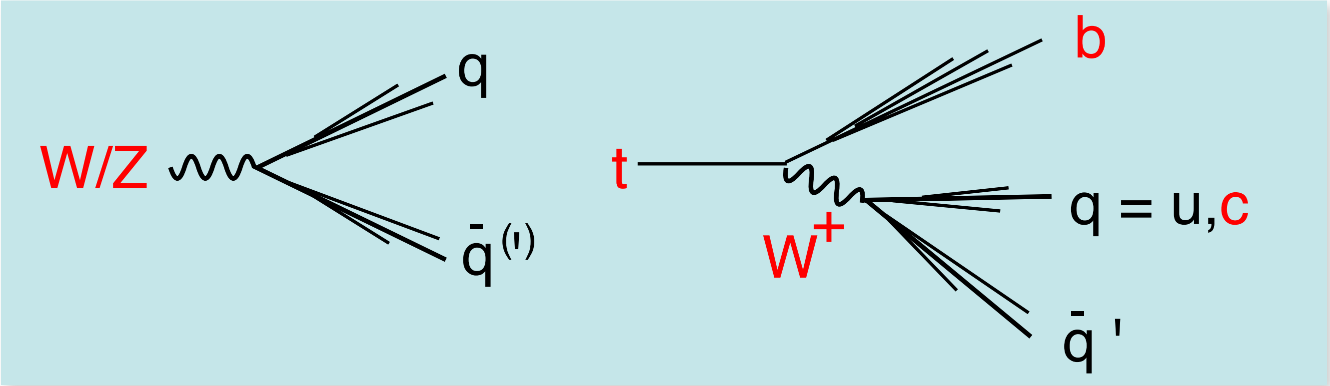
- For theorists:
  - ILC can measure various quantities such as mh, gamma_h, ghxx, mt, etc. far better than LHC. But how accurately do we really need to measure them?
    → partly done in the snowmass study
  - What will be the ultimate theoretical uncertainties in various predictions for LHC and ILC, respectively?
- For Experimentalists:
  - Update all the old analyses with mh=120 GeV to mh=125GeV → partly done
  - Complete the homework such as rare Higgs decays: → partly done but not fully yet
  - Improve the analyses such as self-coupling, H->gamma gamma where the results are not yet satisfactory. → being worked on
  - With the projected running scenarios described in DBD, the most measurements are still statistically limited and should improve by a luminosity upgrade or by running longer. Nevertheless, ILC, too, will hit systematics limits, eventually. It is probably the right time to start more serious studies of expected systematic errors.
    - Identify possible sources of systematic errors
    - Estimate to what degree we can control them → partly done but not fully yet

How would the climate change affect our detector?

Design Principle: Intact!

Goal

- Reconstruct events in terms of fundamental particles such as quarks, leptons, gauge/higgs bosons
  --> View events as viewing Feynman diagrams



Jet invariant mass → W/Z/t/h ID → p^μ
→ angular analysis → s^μ

Missing momentum → neutrinos

Particle Flow Analysis

- Is this really limiting physics performances?
  - Yes, unless limited by jet-clustering
    - enW, nnZ, nnh, ..
  - Need to improve analysis methods: color-singlet clustering, flavor tagging, jet charge ID, etc. to fully take advantage of the potential of ILD

b/c ID with 2ndary/3tiary vertices

Thin and high resolution vertexing

Particle Flow Analysis

High resolution tracking

high granularity calorimetry

Hermeticity

down to O(10mrad) or better

Detector Evolution

From LHC to ILC

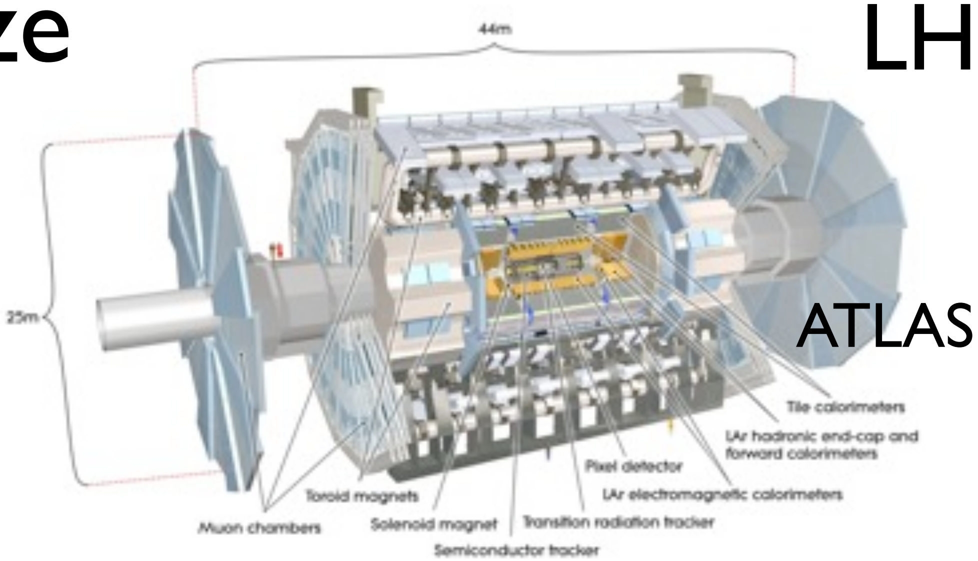
Size

LHC : current state of the art

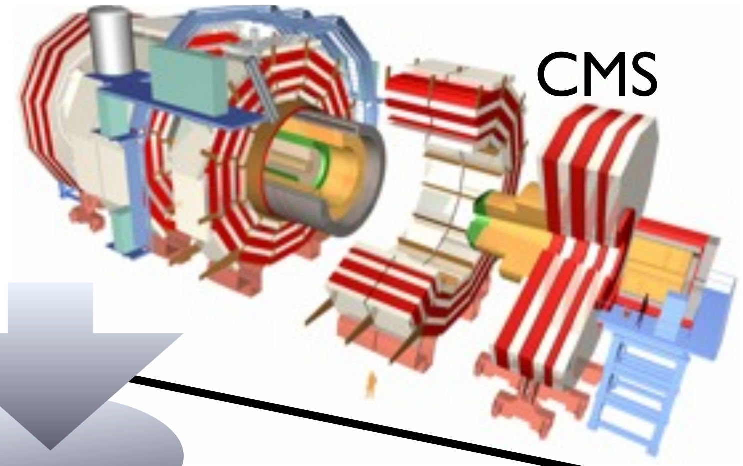
Use the cleanest modes to beat the huge QCD BG.

Moral

Energy Frontier Collider Detectors spearhead state-of-the-art detector technologies

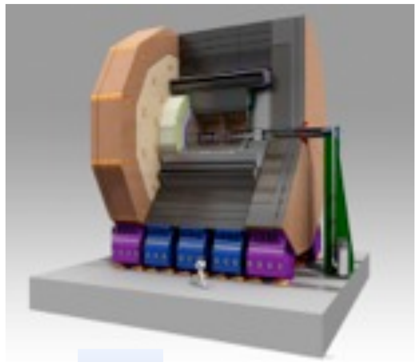


ATLAS



CMS

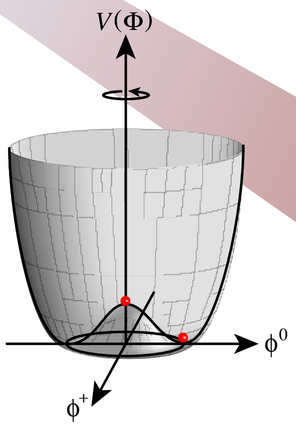
ILD



ILC : next generation

Use the dominant (jet) modes to take advantage of clean environment

LHC : Higgs Discovery



ILC : Full understanding of Higgs sector

Resolution

As compared to ATLAS

Vertex resolution	2-7 times better
Momentum resolution	10 times better
Jet energy resolution	2 times better

Granularity

As compared to ATLAS

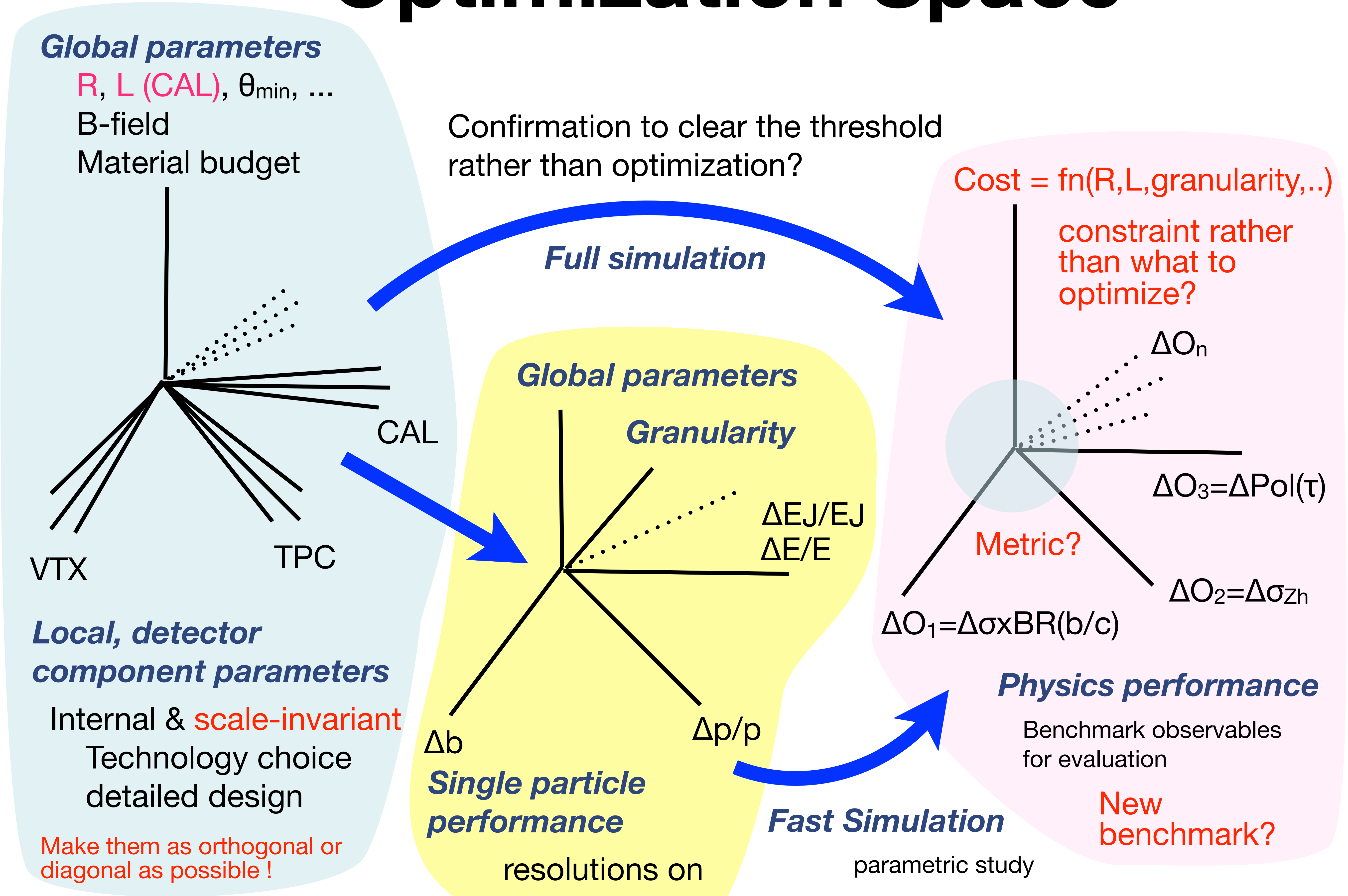
Vertex	x800
Tracker	x2
EM Cal	x61 (Si)
	x7 (Sci)

Boundary Conditions

Any climate change since the LoI?

- Physics inputs from LHC, etc.
    - required precisions for Higgs studies now sub-% level → performance threshold
        - We need good control of systematics
        - Need to improve analysis methods to take full advantage of PFA (it's too early to compromise PFA performance)
    - running scenarios (staging) and (energy/luminosity) upgrade
        - Optimization for Higgs physics
- New boundary conditions from the machine?
    - Luminosity upgrade: 10 Hz operation, higher BG
    - crossing angle?
- New results from component R&D
    - those outperformed the expected results
    - those failed the expectations
- Technology choices
    - showstopper found?
    - down selection at some point?
    - new better solutions found?
- Cost ceiling? Don't forget running cost, a better detector may save running time

Optimization Space



Global parameters

R, L (CAL), θ_{min}, ...

B-field

Material budget

Local, detector component parameters

Internal & scale-invariant

Technology choice

detailed design

Make them as orthogonal or diagonal as possible !

Confirmation to clear the threshold rather than optimization?

Full simulation

Global parameters

Granularity

Single particle performance

resolutions on x^{μ} and p^{μ}, etc.

Fast Simulation

parametric study

Cost = fn(R,L,granularity,..)

constraint rather than what to optimize?

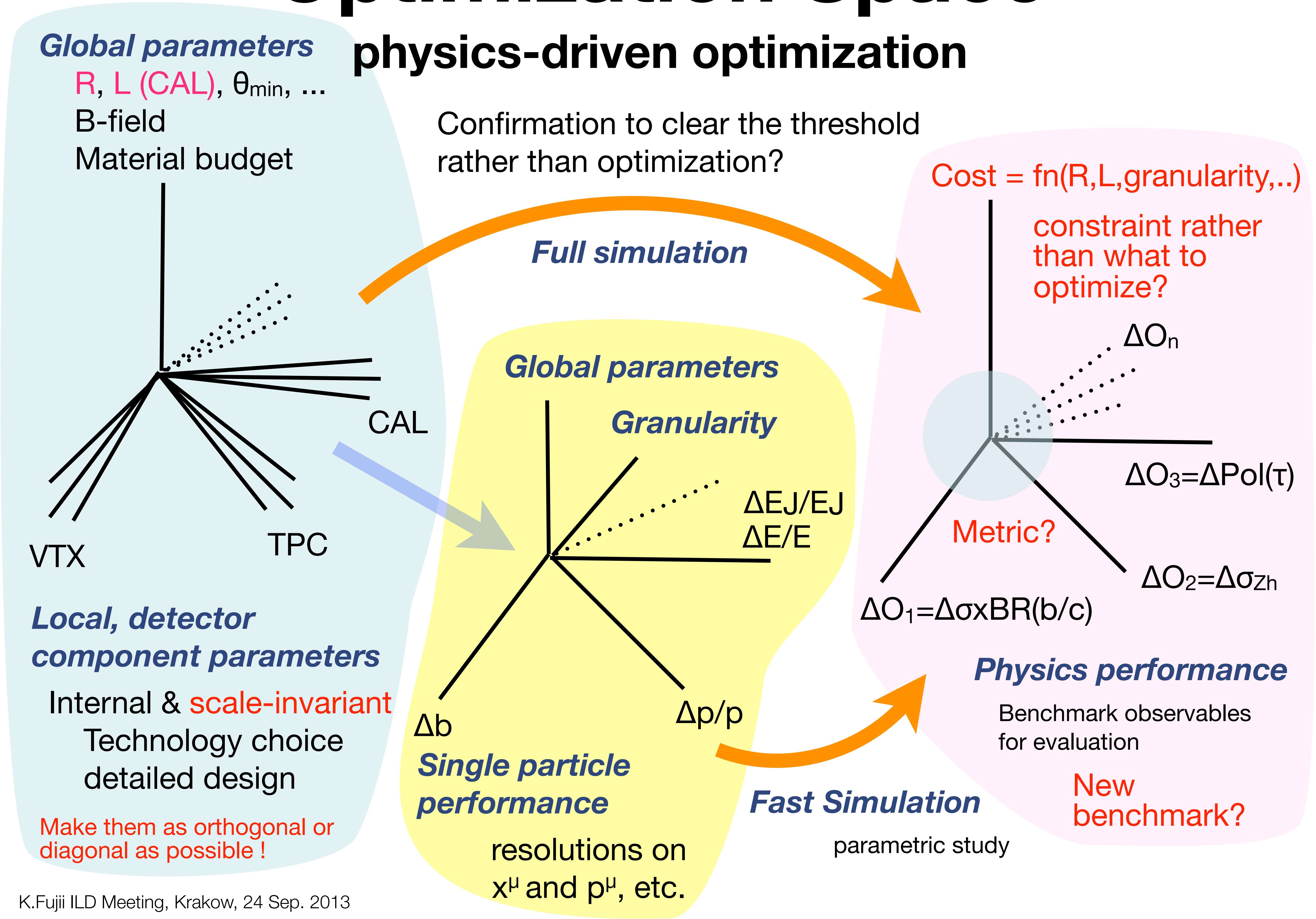
Physics performance

Benchmark observables for evaluation

New benchmark?

Optimization Space

physics-driven optimization



Global parameters

R, L (CAL), θ_{min}, ...

B-field

Material budget

CAL

VTX

TPC

Local, detector component parameters

Internal & scale-invariant

Technology choice

detailed design

Make them as orthogonal or diagonal as possible !

Confirmation to clear the threshold rather than optimization?

Full simulation

Global parameters

Granularity

$\Delta EJ/EJ$
$\Delta E/E$

Δb

$\Delta p/p$

Single particle performance

resolutions on x^μ and p^μ, etc.

Fast Simulation

parametric study

Cost = fn(R,L,granularity,..)

constraint rather than what to optimize?

ΔO_n

$\Delta O_3 = \Delta Pol(\tau)$

Metric?

$\Delta O_2 = \Delta\sigma_{Zh}$

$\Delta O_1 = \Delta\sigma x BR(b/c)$

Physics performance

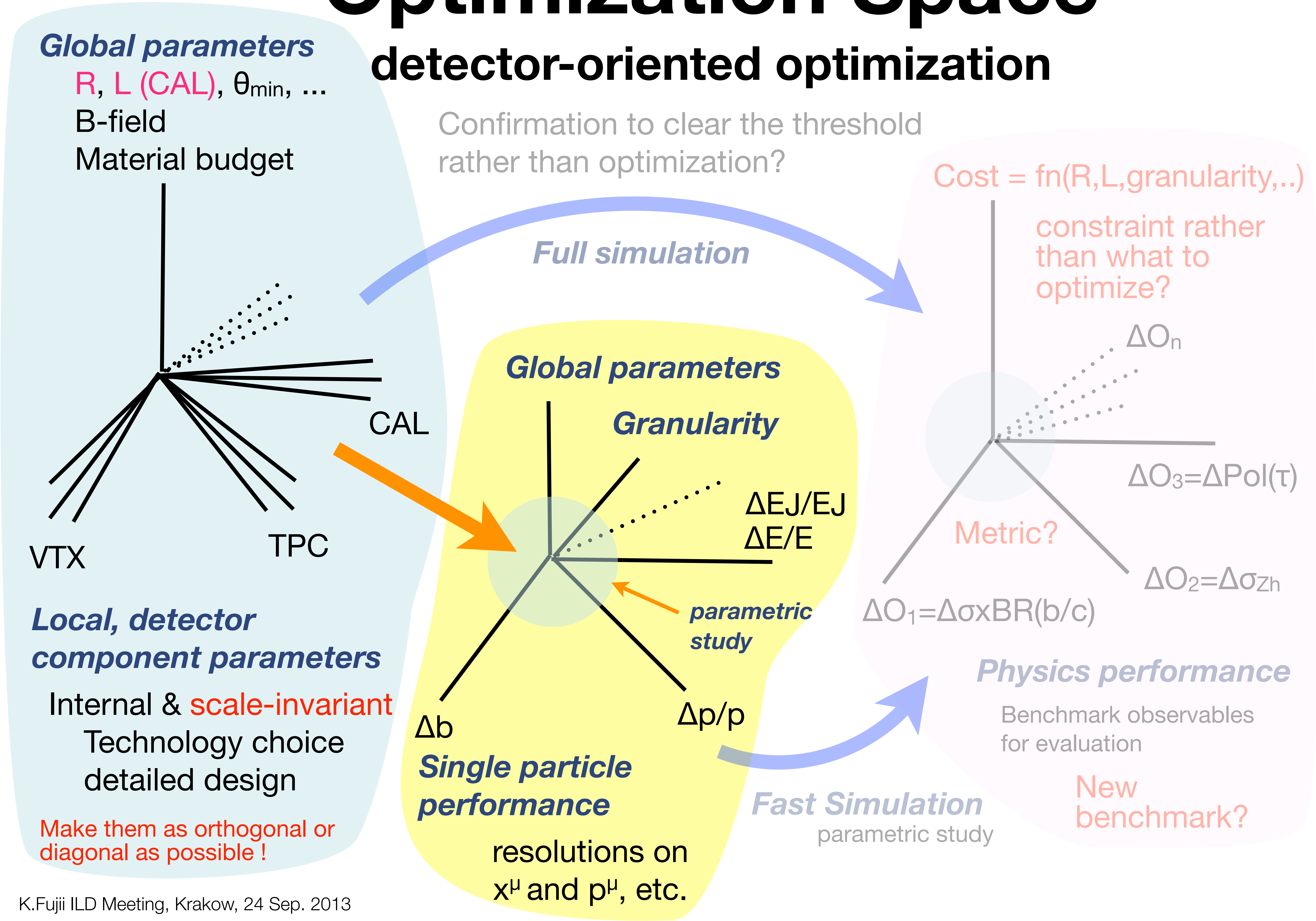
Benchmark observables for evaluation

New benchmark?

K.Fujii ILD Meeting, Krakow, 24 Sep. 2013

Optimization Space

detector-oriented optimization



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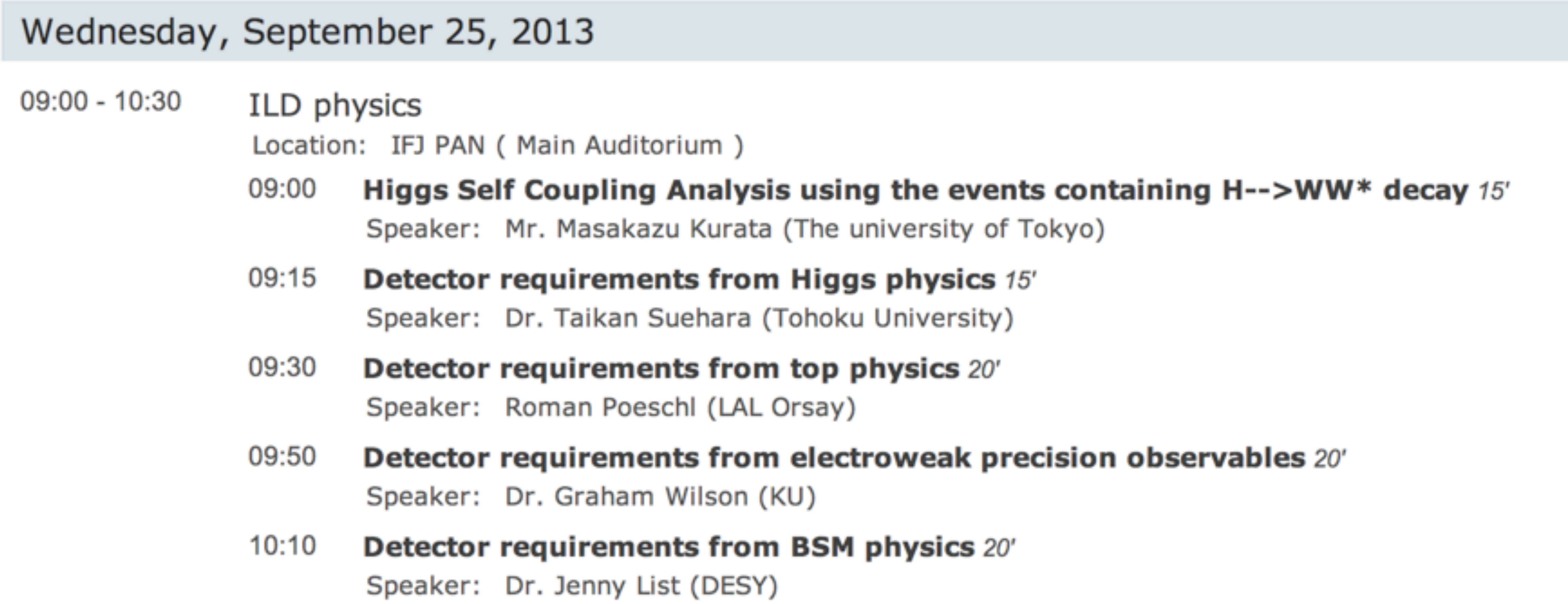
Summary

- Have boundary conditions changed?
  - H(125)
    → staging: 250, 350, 500, eventually to 1000 GeV
    → higher precision (sub-%)
      → luminosity upgrade
        →x2 increase of #bunches/train
        →x2 rep. rate (10 Hz operation) at 250 GeV
  - Machine upgrade v.s. detector upgrade
    → Optimize ILD for the early stage and then upgrade for >500GeV later?
  - Inputs from detector component R&D (boundary set in the input space)
- We need to set the detector parameter space (input) and the evaluation space (output): We need to ask right questions as Mark said in May!
  → Choose the axes properly and orthogonalize / diagonalize them!
    - In the detector parameter space (input space):
      - Separate global parameters from detector component parameters (which are usually determined by technology and detector physics and more or less scale-invariant)
    - In the evaluation space (output space):
      - Overall cost is driven by CAL, Mag, Mech → Cost = fn(R,L, ..)
        Cost axis: orthogonal to the base space spanned by observables
      - Choose appropriate benchmark observables

- How to optimize?
  - Detector R&D → single particle performances :
    good tools to optimize detector parameters, but need reliable parametric studies to judge how they affect physics performance
  - We need a metric for the evaluation space for optimization, we now know that we had better enough weight to precision Higgs studies and BSM scenarios with mass degeneracy
- Cost issue
  - Cost is a constraint rather than what to optimize?
  - Cost = fn(R,...) → Prepare for the adjustment
  - We want the best detector that we can afford, right?
    → Slice the image of the input space (the domain bounded by detector boundary conditions) in the evaluation space with a cost=const plane, and find the optimum in the slice or at least make sure the chosen point clear the threshold required by physics.
  - A better detector in principle saves running time (=running cost)
- Analysis improvements
  - We need to control systematics more than ever for H(125)
  - If the physics performance is limited by analysis rather than the detector performance, improve the analysis!
  - Don’t easily compromise PFA performance but improve jet (color-singlet) clustering (crucial for self-coupling measurement)!

Other Climate Changes in Physics Requirements?

Top / PEW / BSM and more on Higgs
We will discuss this tomorrow morning



Wednesday, September 25, 2013

09:00 - 10:30 ILD physics

Location: IFJ PAN (Main Auditorium)

09:00 **Higgs Self Coupling Analysis using the events containing H-->WW* decay** *15'*
Speaker: Mr. Masakazu Kurata (The university of Tokyo)

09:15 **Detector requirements from Higgs physics** *15'*
Speaker: Dr. Taikan Suehara (Tohoku University)

09:30 **Detector requirements from top physics** *20'*
Speaker: Roman Poeschl (LAL Orsay)

09:50 **Detector requirements from electroweak precision observables** *20'*
Speaker: Dr. Graham Wilson (KU)

10:10 **Detector requirements from BSM physics** *20'*
Speaker: Dr. Jenny List (DESY)

We should not forget that ILC, too, is an energy-frontier machine that will probe the energy region never probed by any lepton colliders before!

New Boundary Conditions from Detector R&D?

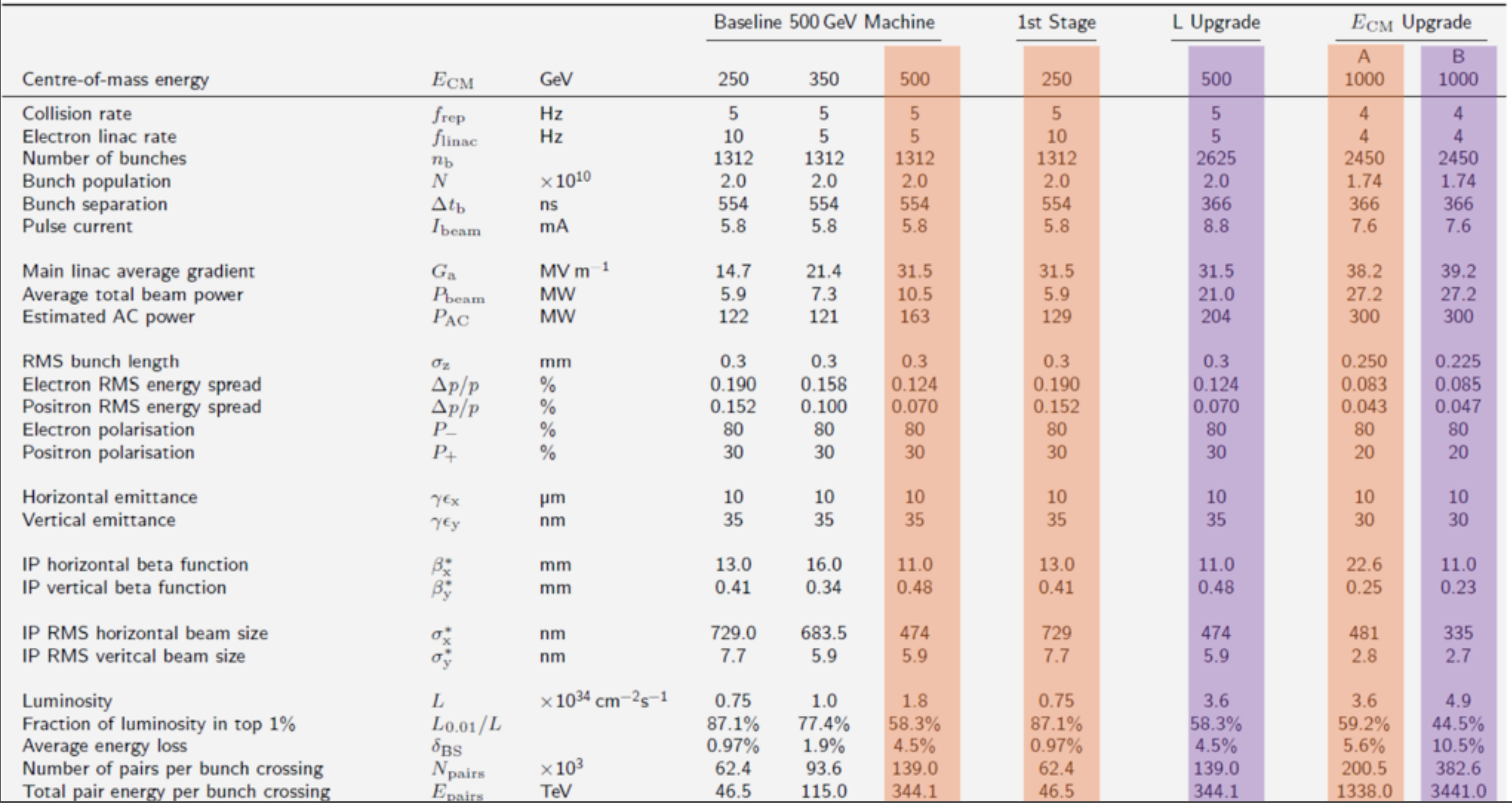
We will hear on this in various detector sessions of this meeting

Backup

ILC Accelerator Parameters from TDR

🟧 Baseline Luminosity

🟪 Upgrade Luminosity



			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	$\gamma\epsilon_{\mathrm{x}}$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_{\mathrm{y}}$	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

Lumi Upgrade at Ecm=250 GeV*

* not in TDR – private communication from Marc Ross and Nick Walker

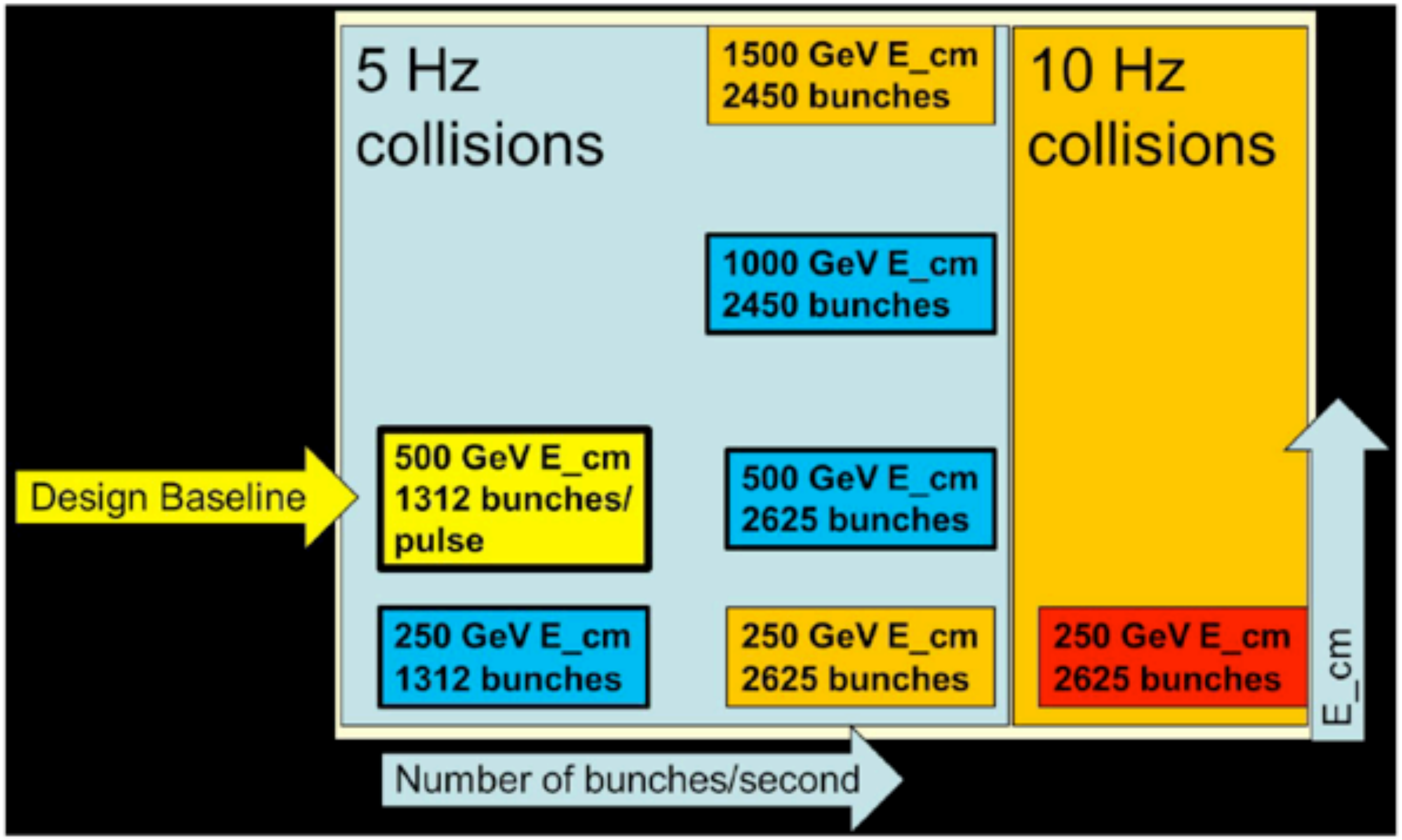
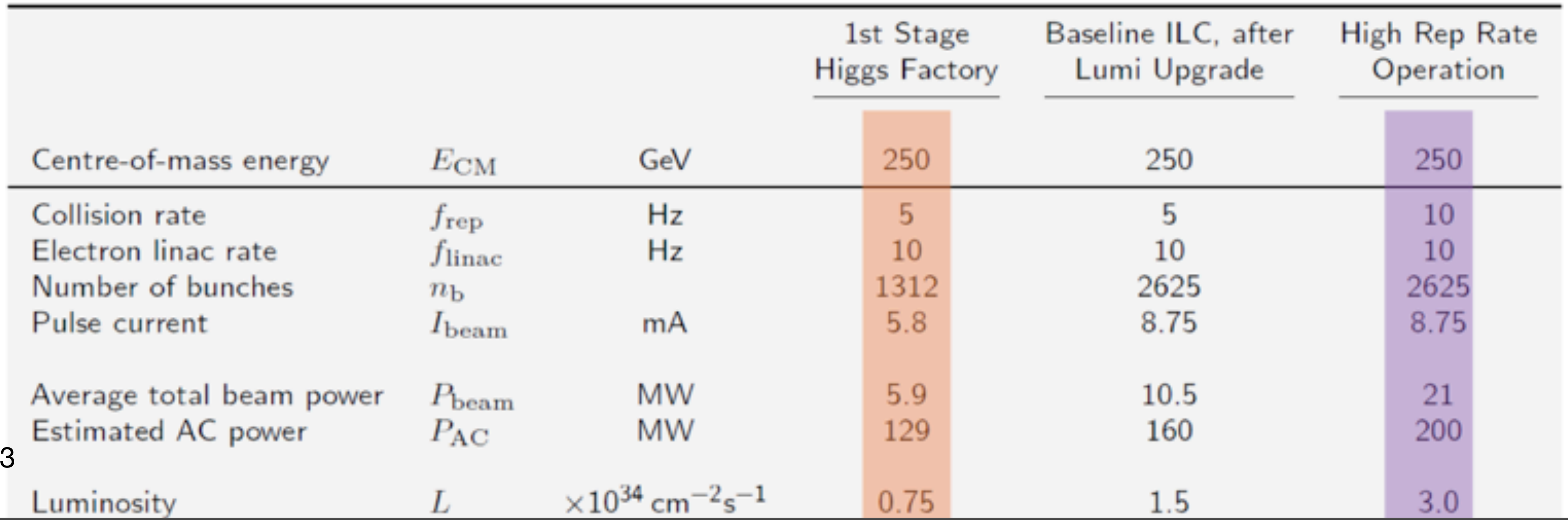


Table 1.2. ILC Higgs factory operational modes



			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Centre-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_{b}		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	P_{beam}	MW	5.9	10.5	21
Estimated AC power	P_{AC}	MW	129	160	200
Luminosity	L	$\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.5	3.0

🟧 Baseline Luminosity

🟪 Upgrade Luminosity

Tim Barklow, Snowmass Minnesota, 2013