FCC-ee : physics program for 5,10 or 20 years?

more info: http:cern.ch/fcc-ee

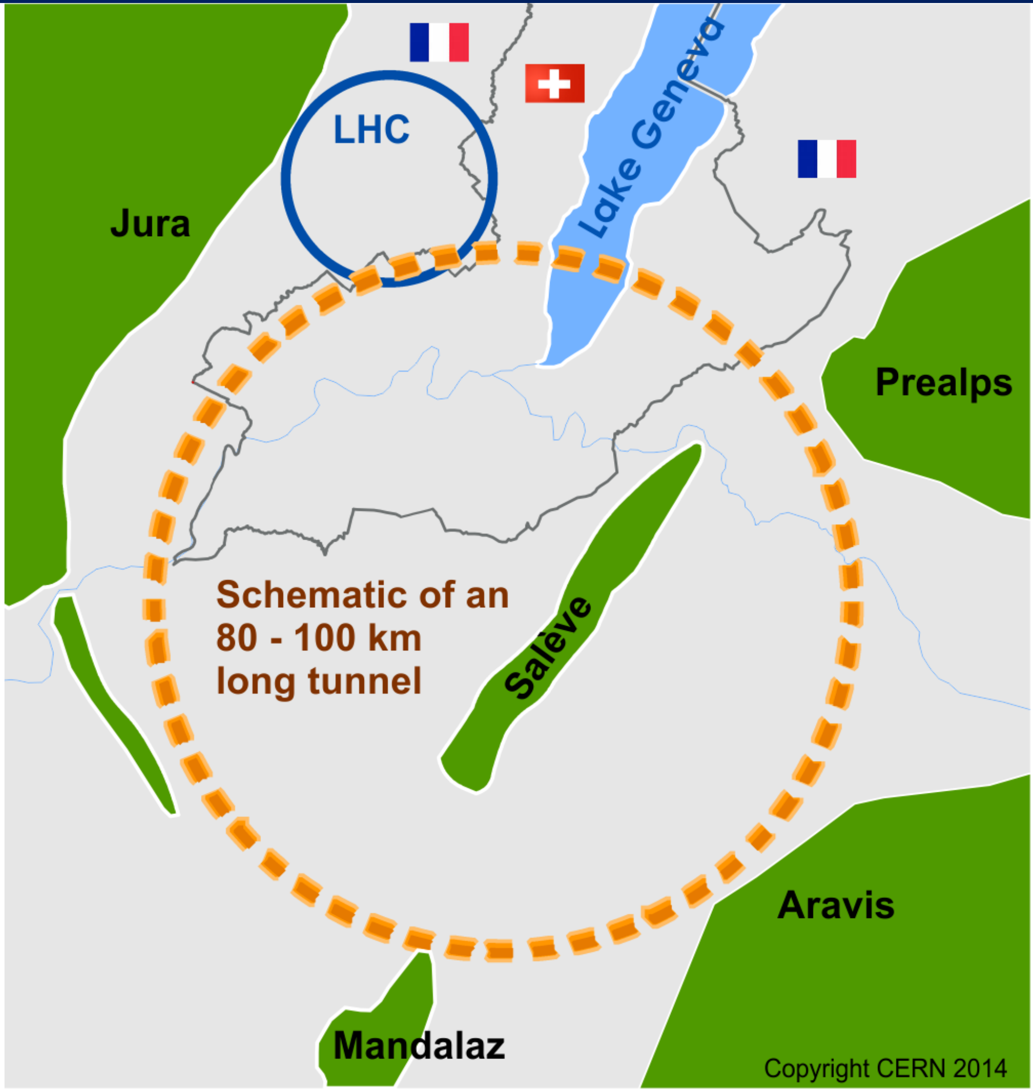
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*) → defining infrastructure**

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*) as potential intermediate step ECM=90-350+ GeV**
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure in Geneva area**



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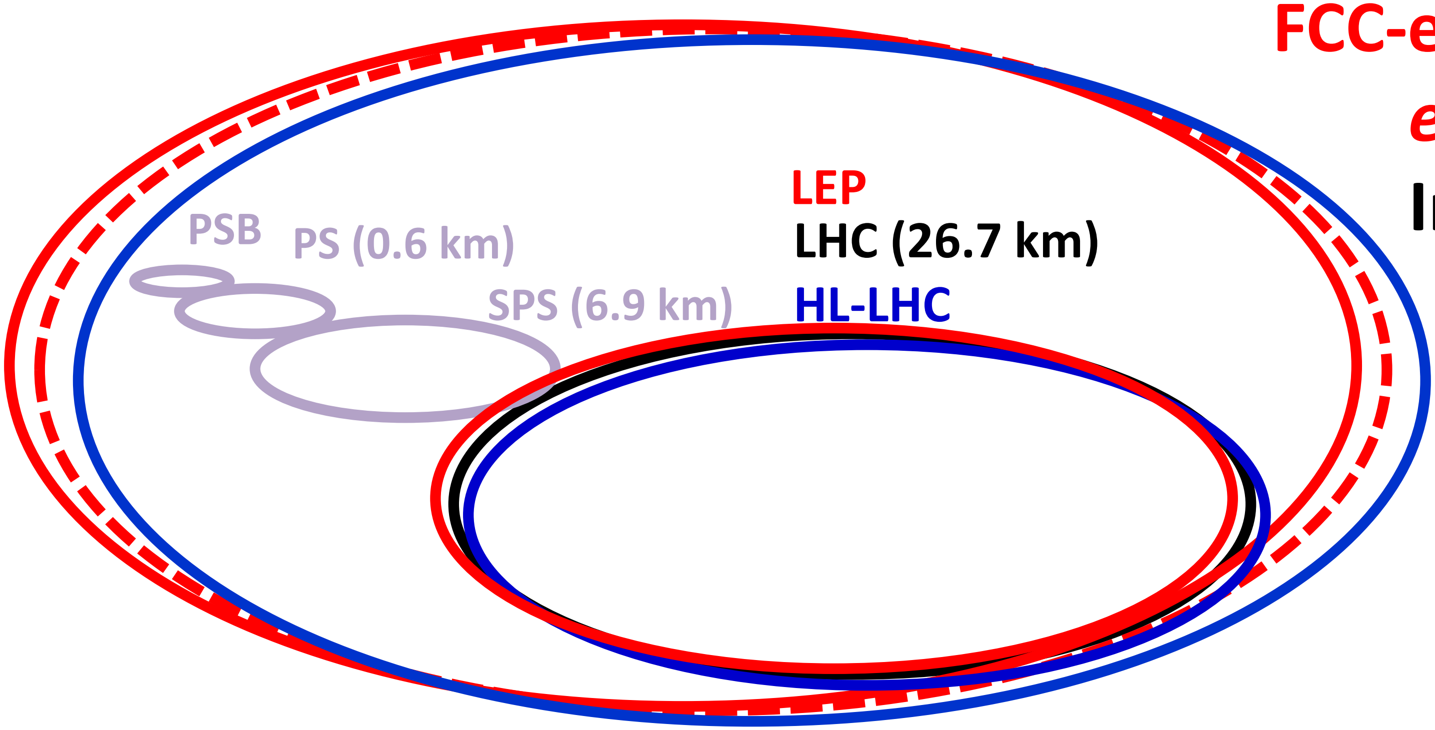
possible long-term strategy



FCC-ee (80-100 km,
e^+e^-, 90-400 GeV
Interm. step

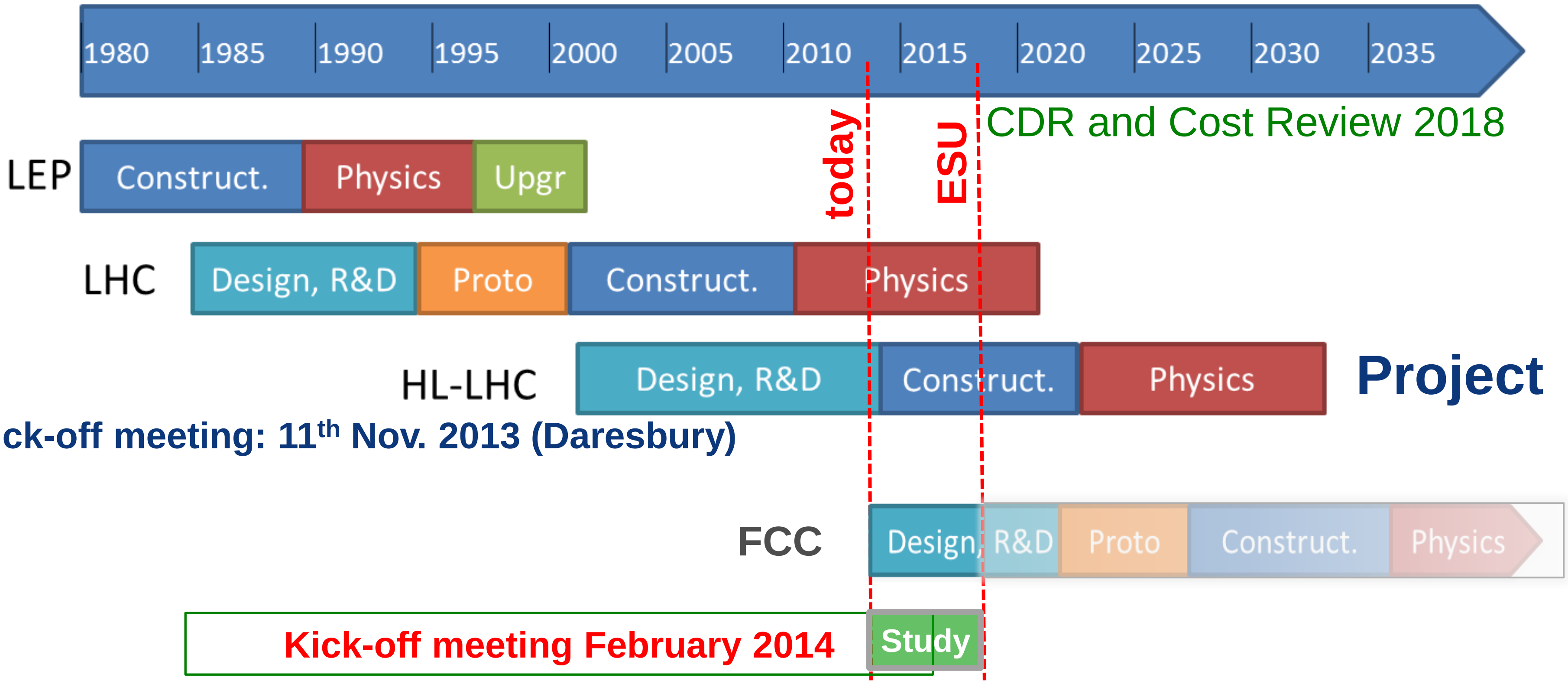
FCC-hh
(*pp*, up to
100 TeV c.m.)

Ultimate goal

& ***$e^\pm$* (120 GeV)–*p* (7, 16 & 50 TeV)** collisions FCC-eh)

≥60 years of *e^+e^-*, *pp*, *ep/A* physics at highest energies

CERN roadmap and FCC planning

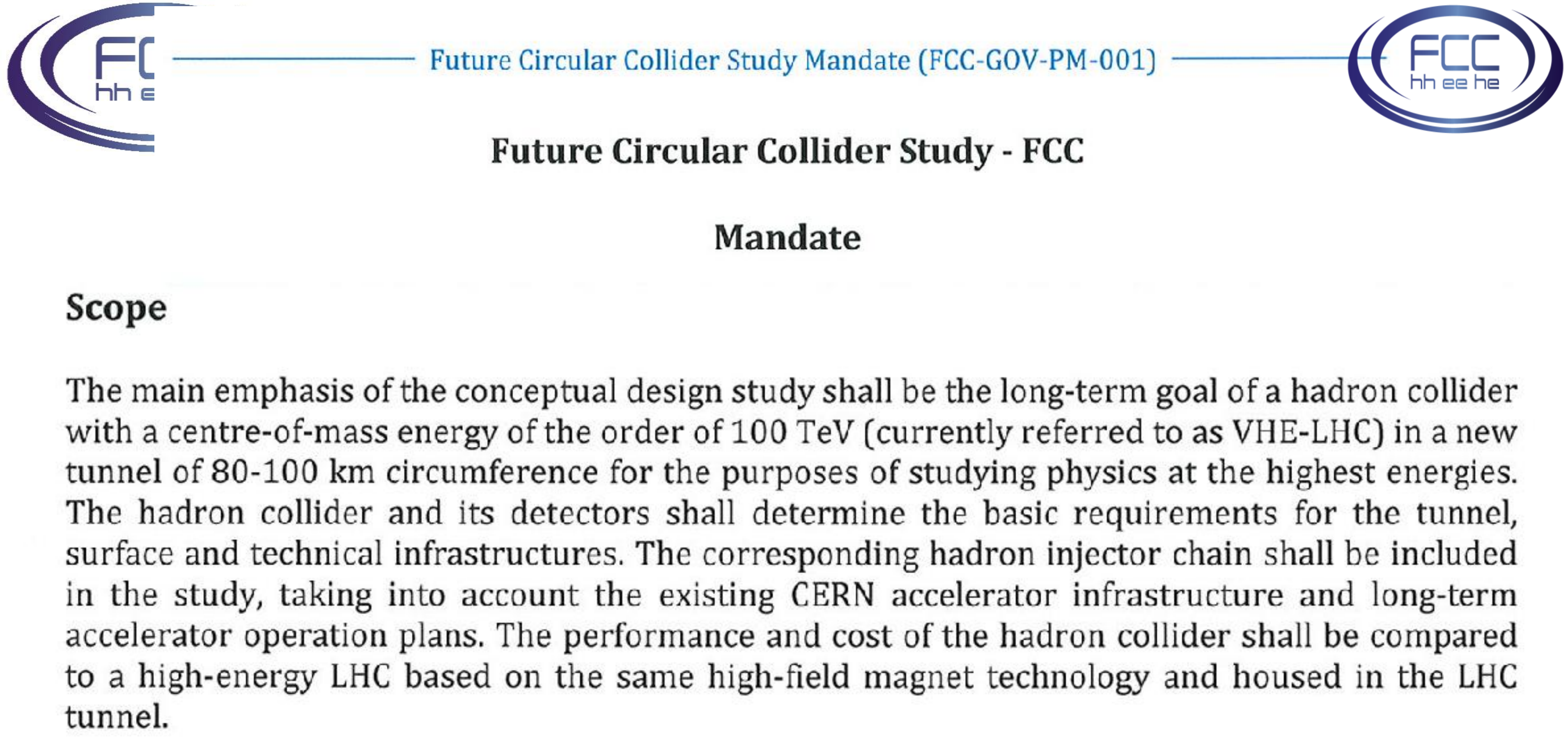


Project

Kick-off meeting: 11th Nov. 2013 (Daresbury)

Kick-off meeting February 2014

CDR and Cost Review for 2018



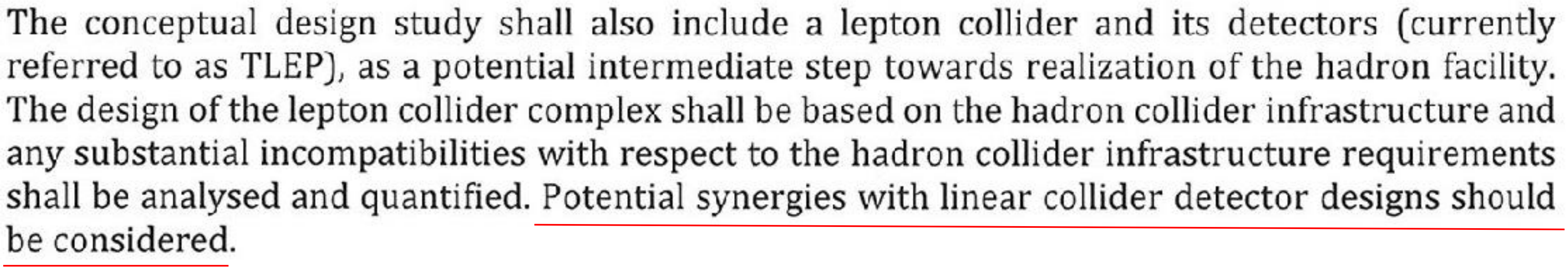
Future Circular Collider Study Mandate (FCC-GOV-PM-001)

Future Circular Collider Study - FCC

Mandate

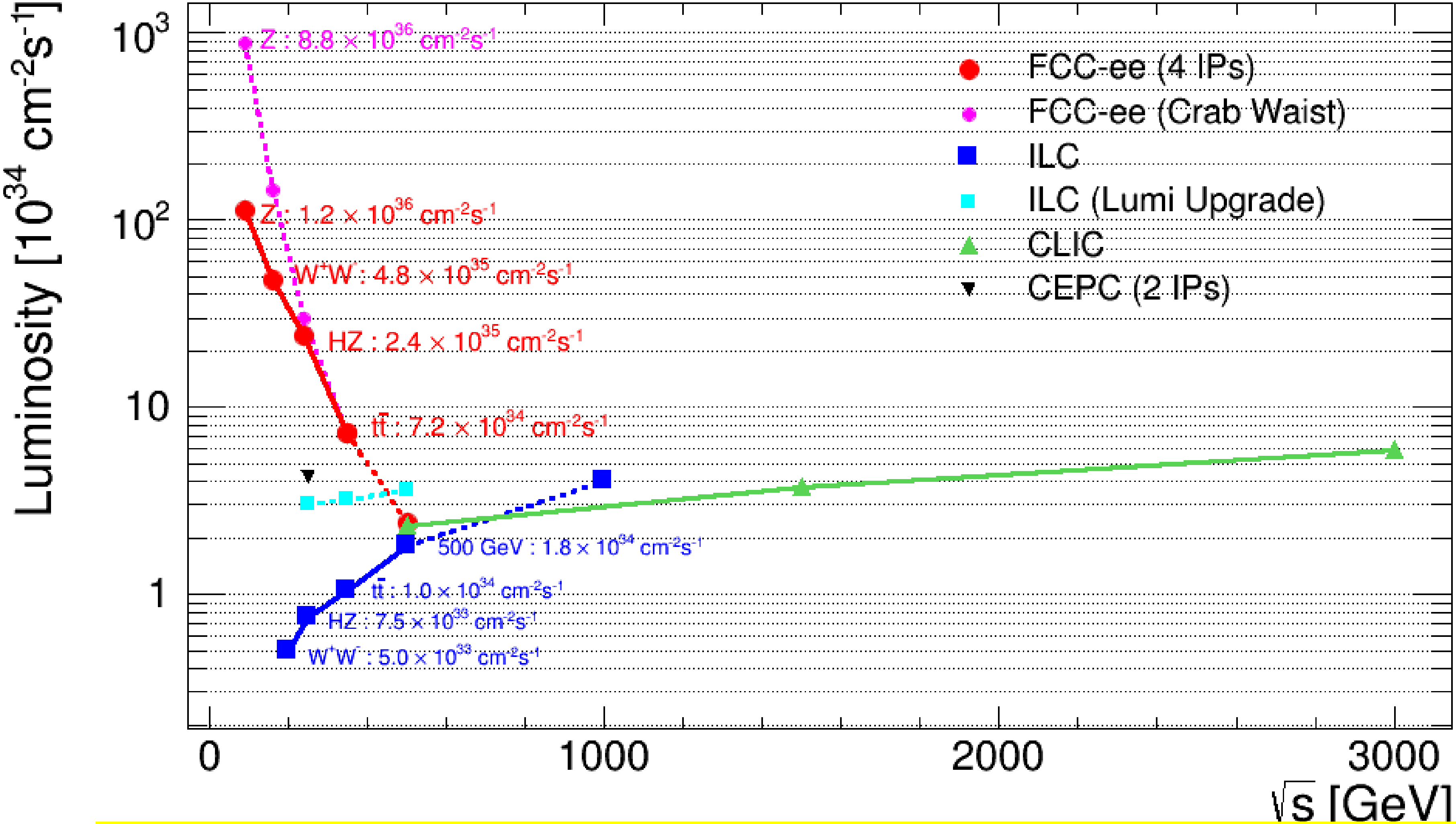
Scope

The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV (currently referred to as VHE-LHC) in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies. The hadron collider and its detectors shall determine the basic requirements for the tunnel, surface and technical infrastructures. The corresponding hadron injector chain shall be included in the study, taking into account the existing CERN accelerator infrastructure and long-term accelerator operation plans. The performance and cost of the hadron collider shall be compared to a high-energy LHC based on the same high-field magnet technology and housed in the LHC tunnel.



The conceptual design study shall also include a lepton collider and its detectors (currently referred to as TLEP), as a potential intermediate step towards realization of the hadron facility. The design of the lepton collider complex shall be based on the hadron collider infrastructure and any substantial incompatibilities with respect to the hadron collider infrastructure requirements shall be analysed and quantified. Potential synergies with linear collider detector designs should be considered.

parameter	**LEP2**	**FCC-ee**				
		Z	**Z (c.w.)**	**W**	**H**	**t**
E_{beam} [GeV]	104	**45**	**45**	**80**	**120**	**175**
beam-beam par. ξ_y/IP	**0.06**	**0.03**	**0.175**	**0.06**	**0.093**	**0.092**
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	**100**	**100**	**100**	**100**	**100**
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	**29**	**0.14**	**3.3**	**0.94**	**2**
ε_y [pm]	250	**60**	**1**	**1**	**2**	**2**
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	**1**	**1**	**1**	**1**	**1**
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	**11.5**	**1.64**	**2.7**	**1.01**	**0.81**	**1.16**
$\sigma_{z,tot}$ [mm] (w beamstr.)	**11.5**	**2.56**	**5.9**	**1.49**	**1.17**	**1.49**
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	**28**	**212**	**12**	**6**	**1.7**
τ_{beam} [min]	434	**298**	**39**	**73**	**29**	**21**



Overlapp in Higgs/top region, but differences and complementarities between linear and circular machines: luminosity, experimental environment E_{CM} calibration and longitudinal polarization

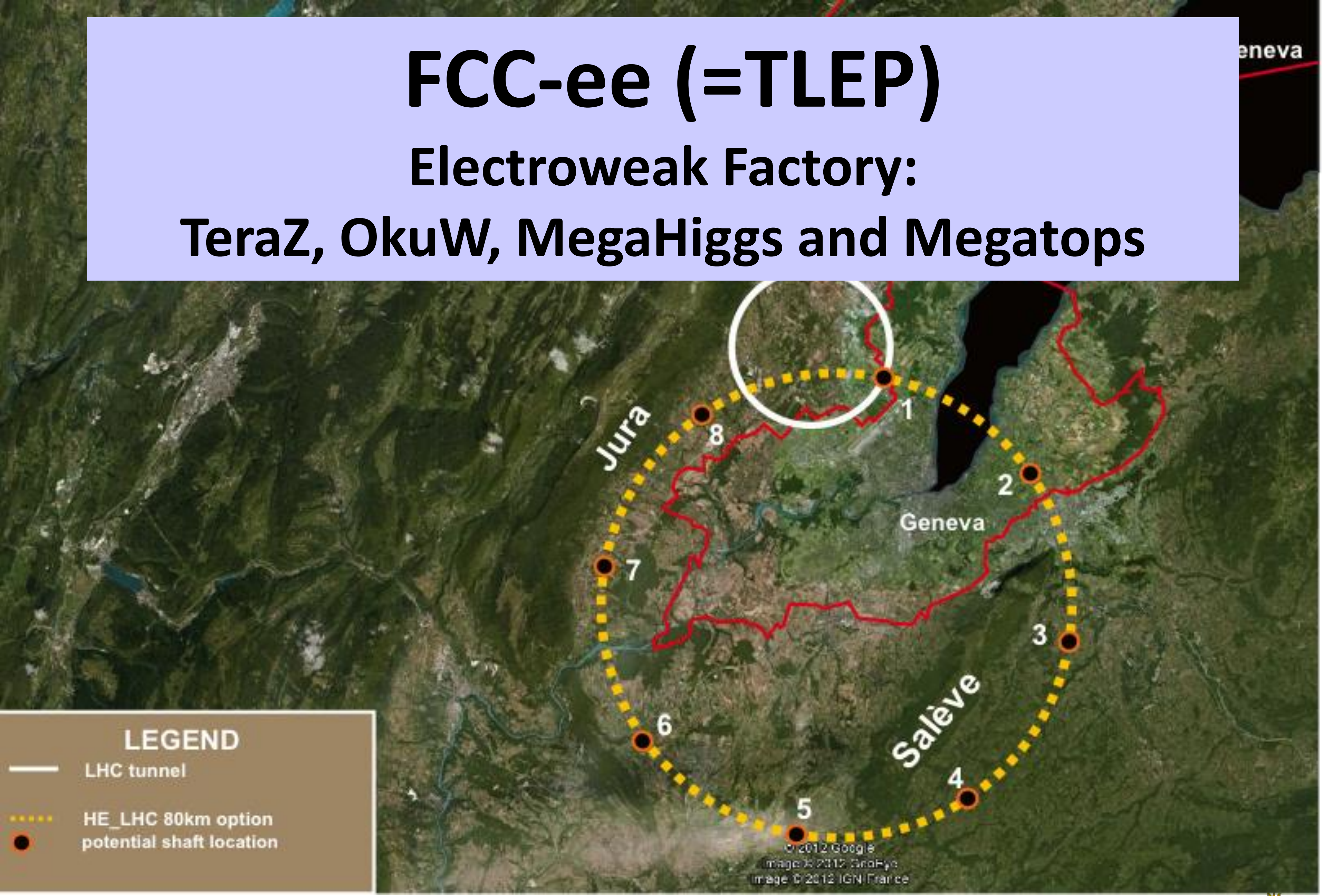
FCC-ee: PARAMETERS & STATISTICS

	TLEP-4 IP, per IP	statistics
circumference	80-100 km	
max beam energy	175 GeV	
no. of IPs	4	
Luminosity/IP at 350 GeV c.m.	$1.3\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{6} $\bar{t}t$ pairs
Luminosity/IP at 240 GeV c.m.	$6.0\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2 10^{6} ZH evts
Luminosity/IP at 160 GeV c.m.	$1.6\mathrm{x}10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{8} WW pairs
Luminosity/IP at 90 GeV c.m.	2. $10^{35/36}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$10^{12/13}$ Z decays

FCC-ee (=TLEP)

Electroweak Factory:

TeraZ, OkuW, MegaHiggs and Megatops



Original motivation (end 2011): now that m_H and m_top are known,
explore EW region with a high precision, affordable, high luminosity machine

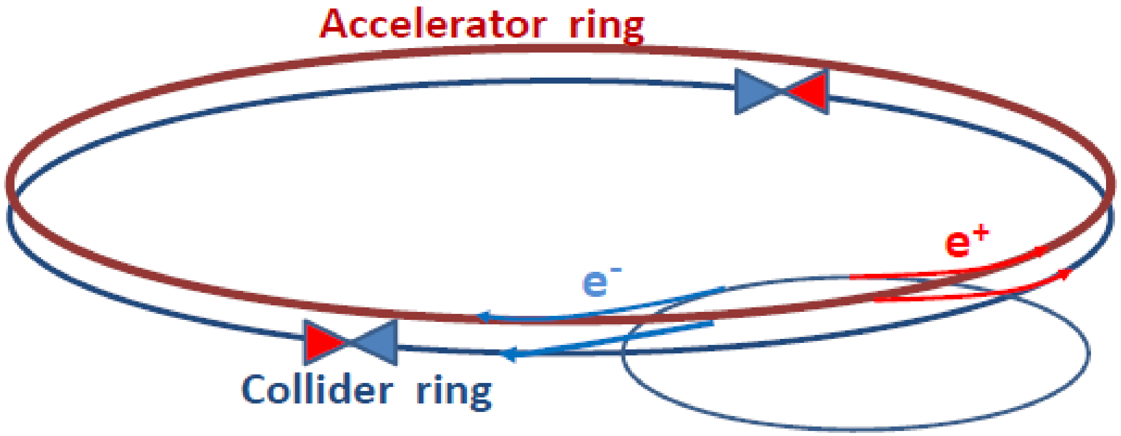
→ Discovery of New Physics in rare phenomena or precision measurements

ILC studies → need increase over LEP 2 (average) luminosity by a factor 1000
How can one do that without exploding the power bill?

Answer is in the B-factory design: a low vertical emittance ring with
higher intrinsic luminosity, and small β^*_y (1mm vs 5cm at LEP) 50
Electrons and positrons have a much higher chance of interacting
→ much shorter lifetime (few minutes)
→ top up continuously with booster ==> increase operation efficiency 5
Increase SR beam power to 50MW/beam 4

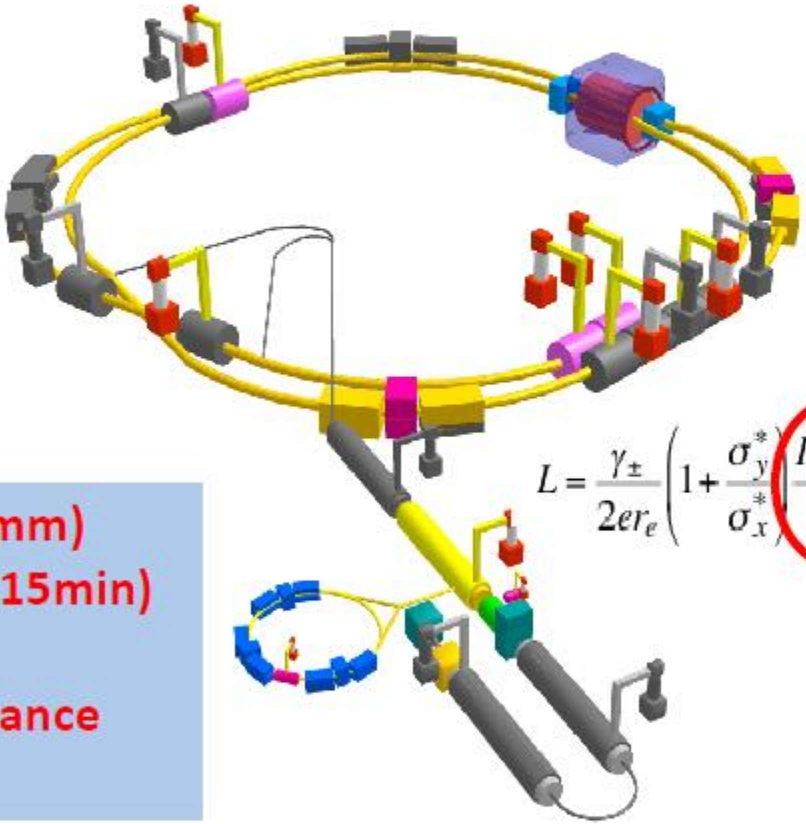
1000

at ZH threshold
in LEP/LHC tunnel
X 4 in FCC tunnel
X2-4 interaction points
EXCITING!



SuperKEKB – TLEP demonstrator!

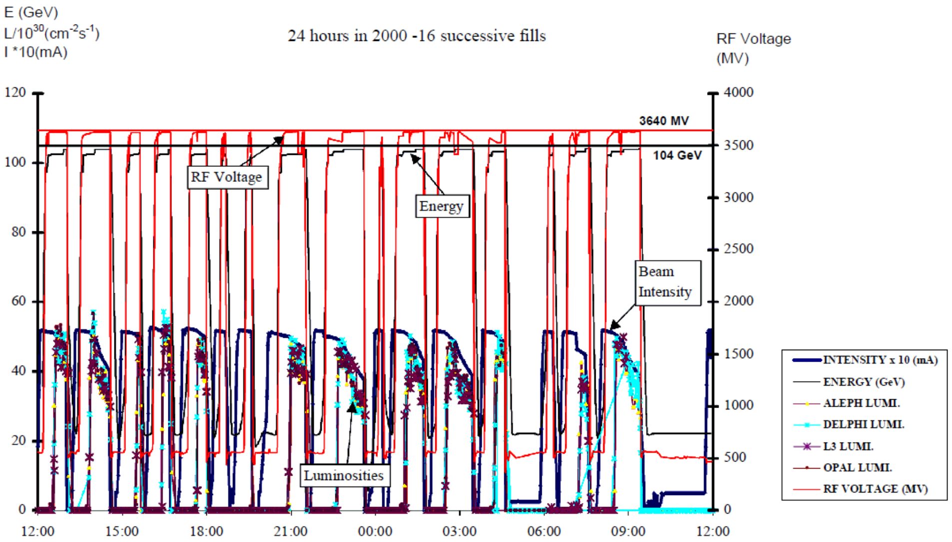
beam commissioning will start in early 2015



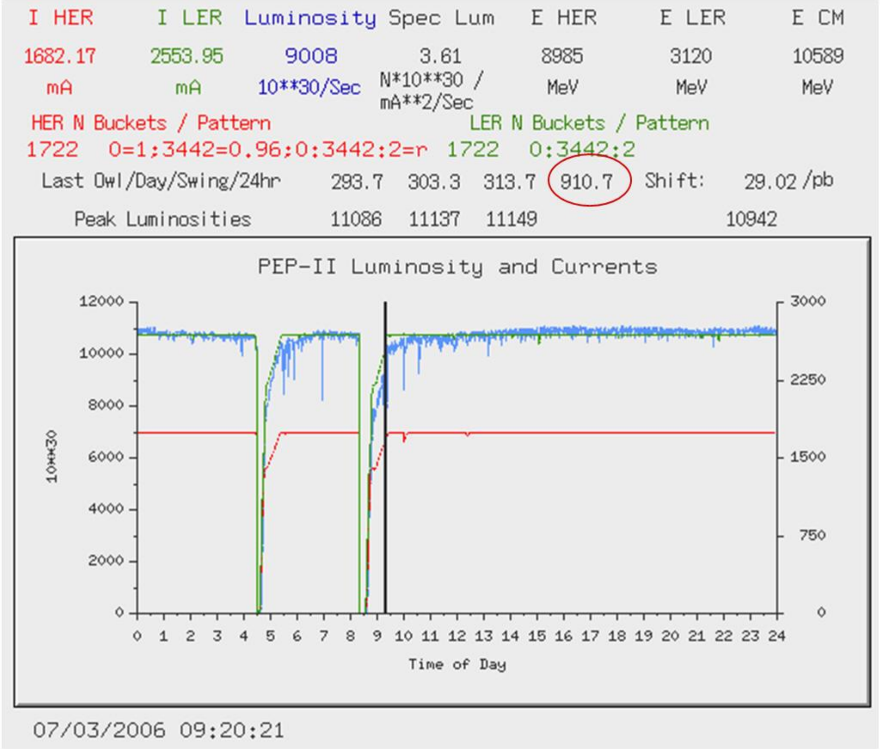
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\boxed{\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)}\left(\frac{R_L}{R_y}\right)$$

- **β_y*=300 μm (TLEP: 1 mm)**
- **lifetime 5 min (TLEP: ~15min)**
- **$\varepsilon_y/\varepsilon_x$=0.25% (~TLEP)**
- **off momentum acceptance**
- ***e^+* production rate**

Toping up ensures constant current, settings, etc... and greater reproducibility of system



LEP2 in 2000 (12th year!):
fastest possible turnaround but
average luminosity ~ 0.2 peak luminosity



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1682.17	2553.95	9008	3.61	8985	3120	10589
mA	mA	10**30/Sec	N*10**30 / mA**2/Sec	MeV	MeV	MeV

HER N Buckets / Pattern
1722 0=1;3442=0.96;0:3442:2=r

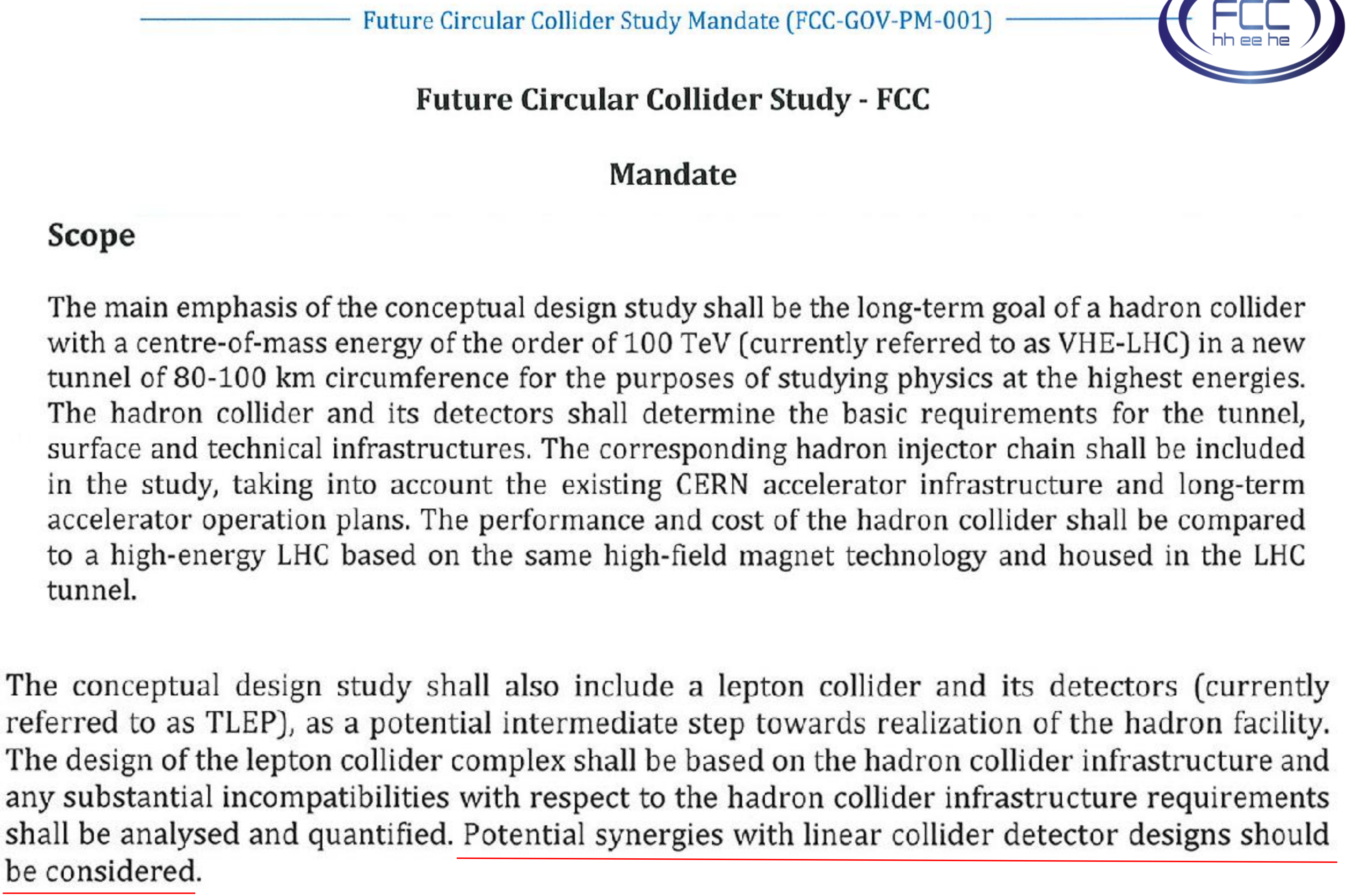
LER N Buckets / Pattern
1722 0:3442:2

Last Owl/Day/Swing/24hr 293.7 303.3 313.7 910.7 Shift: 29.02 /pb

Peak Luminosities 11086 11137 11149 10942

07/03/2006 09:20:21

B factory in 2006 with toping up
average luminosity ≈ peak luminosity



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Experimental Studies: Conveners

- **Coordinators A. Blondel, P. Janot**
  - **Study the properties of the Higgs and other particles with unprecedented precision**

EW Physics (Z pole)
R. Tenchini
F. Piccinini

Diboson physics, m_W
R. Tenchini
F. Piccinini

H(126) Properties
M. Klute
K. Peters

Top Quark Physics
P. Azzi

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P. Skands

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini
C. Rogan

- **Develop the necessary tools**

Understand the experimental conditions

Physics Software
C. Bernet
B. Hegner

Synergy with FCC-hh,,
LHC, Linear Colliders

Online & Trigger
E. Perez
C. Leonidopoulos

Exp'tal Environment
N. Bacchetta

Synergy with FCC-hh
and Linear Colliders

- **Set constraints on the possible detector designs to match statistical precision**

Detector Designs
A. Cattai
G. Rolandi

Synergy with Linear Collider detectors and others

Phenomenological Studies: Conveners

- Coordinators: J. Ellis, C. Grojean
  - Set up a long-term programme to match theory predictions to experimental precisions

QCD and $\gamma\gamma$ Physics
(Joint exp/th)
P. Skands

Precision EW calculations
S. Heinemeyer

Flavour Physics
(Joint exp/th)
J. Kamenik

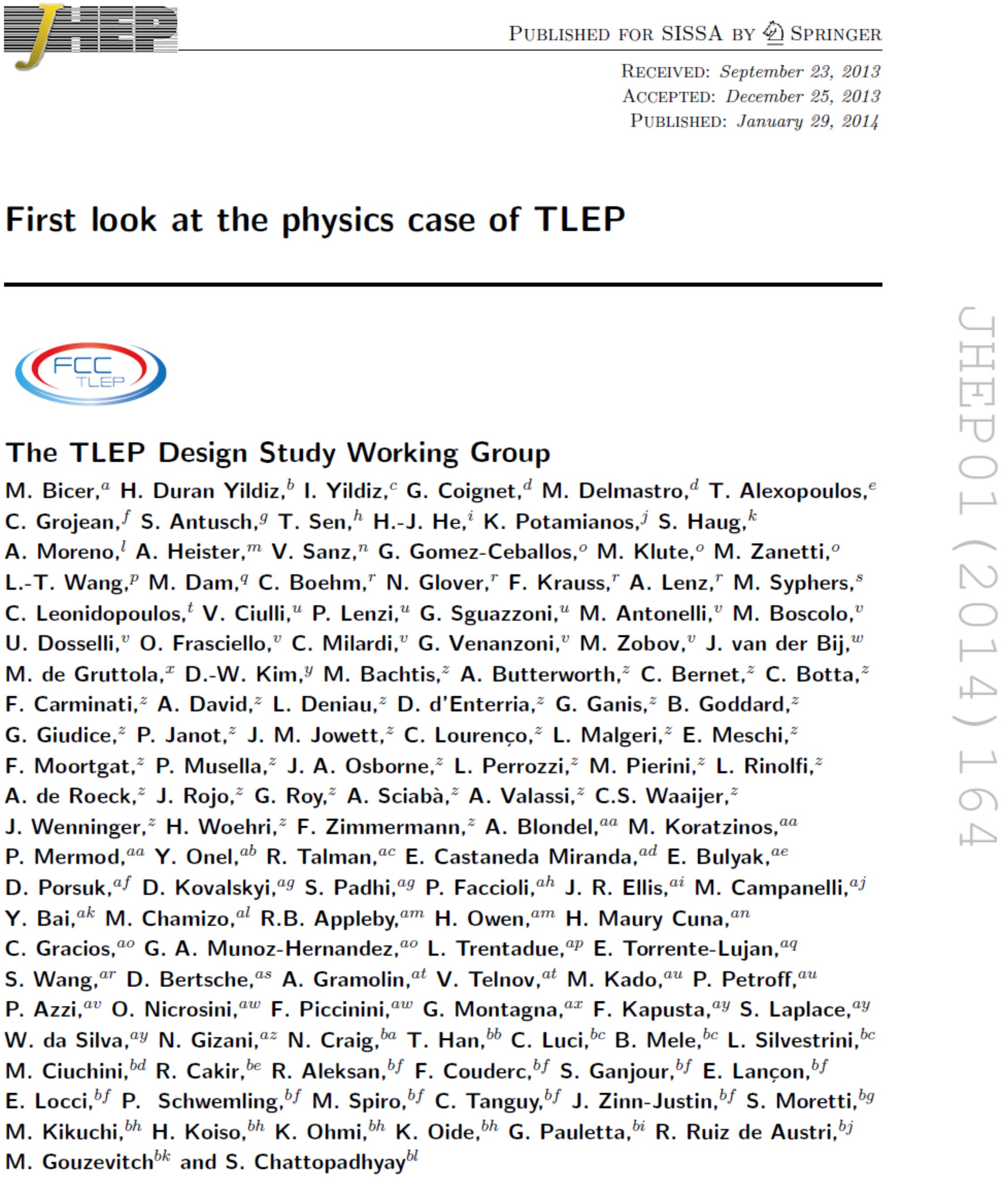
  - Understand how new physics would show up in precision measurements, and in searches for rare decays (Z, W, t, H, b, c, τ, …) and rare processes

Model Building and New Physics
A. Weiler

Synergy with
FCC-hh physics
Linear collider physics,
LEP physics

  - Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)

Global Analysis, Combination, Complementarity
J. Ellis



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First look at the physics case of TLEP

The TLEP Design Study Working Group

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JHEP01(2014)164

http://arxiv.org/abs/1308.6176

1. Higgs Physics

invisible and exotic widths, subpercent measurements of partial widths etc.

2. Precision EW and QCD measurements

one to two orders of magnitude improvements over present results

new precision tests using W H top
tests of the closure of the Standard Model , α_s (m_Z)

3. Rare phenomena

FCNC, LFV, RH neutrinos, single top

4. Complete searches in LHC ‘holes’

A possible TLEP running programme (07/2013)

from http://arxiv.org/abs/1308.6176

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^{35} /cm2/s => 210^{6} ZH events

   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

Higgs boson HZ studies
+ WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @ 7 10^{34} /cm2/s → 10^{6} ttbar pairs ++Zpeak

Top quark mass
Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration → 10^{12} Z decays
   → transverse polarization of ‘single’ bunches for precise E_beam calibration
   2 years

Mz, Γ_Z R_b etc…
Precision tests and
rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years → 10^8 W pairs ++Zpeak

M_{W}, and W properties
etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

A_{LR}, A_{FB}^{pol} etc

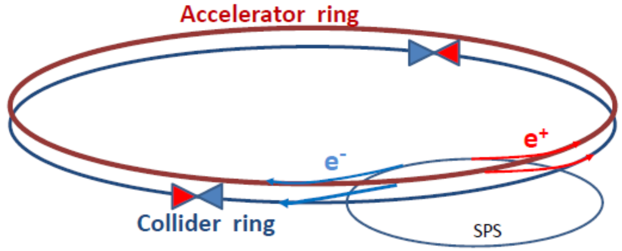
Thus the answer is....

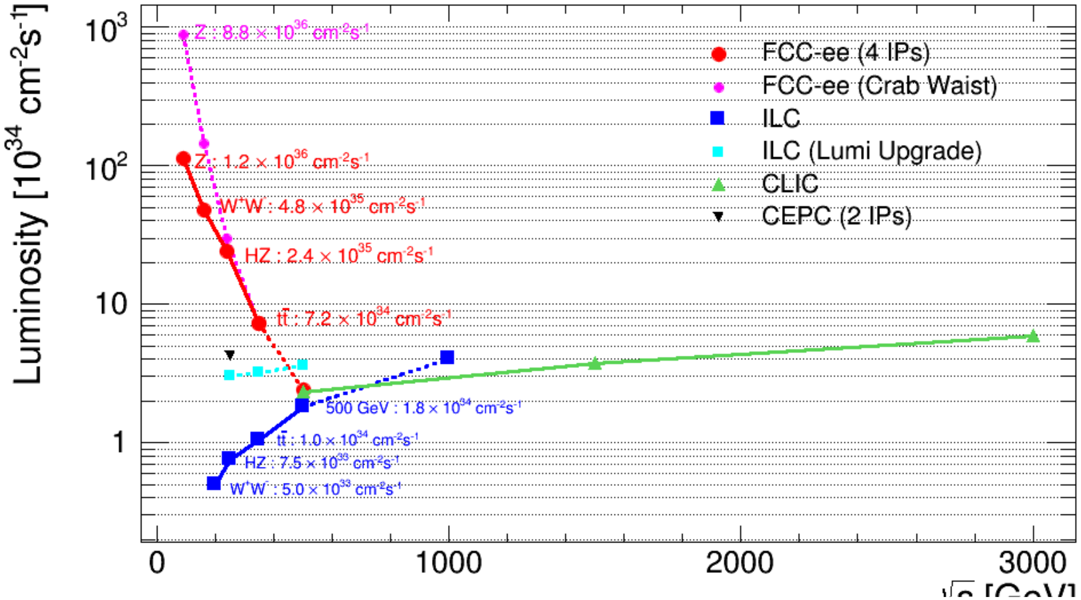
20 years of operation

numbers assume 10^7 s/year at peak luminosity
➔~6 months/year @ 60% operation efficiency

No optimization between various energies yet
but should assume 1 year of commissioning/Energy point

Is longitudinal polarization essential?
(At first sight not). DS will answer this question.





First look at the physics case of TLEP, arXiv:1308.6176v3 scoped the precision measurements:

-- Model independent Higgs couplings and invisible width

-- Z mass (0.1 MeV), W mass (0.5 MeV) top mass (~10 MeV), $\sin^2{}_W^{\mathrm{eff}}$, R_b, N_ν etc...

➔ powerful exploration of new physics with EW couplings up to very high masses

➔ importance of luminosity and E_{beam} calibration by beam depolarization up to W pair

So far: simulations with CMS detector (Higgs) -- or «just» paper studies.

Snapshot of progress since

Higher luminosity prospects at W, Z with **crab-waist**

- ➔ sensitivity to right handed (sterile) neutrinos
- ➔ s-channel e+e- → H(125.2) production almost possible (➔ monochromators?)
- ➔ rare Higgs Z W and top decays, FCNCs etc...

➔ discovery potential for very small couplings

➔ precision event generators (Jadach et al)

http://cern.ch/FCC-ee

Higgs Physics

Higgs factory

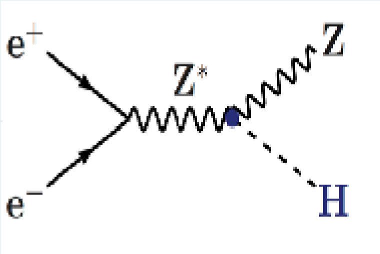
(constrained fit including 'exotic')

	4 IPs	TLEP (2 IPs)
g_{HZZ}	0.05%	(0.06%)
g_{HWW}	0.09%	(0.11%)
g_{Hbb}	0.19%	(0.23%)
g_{Hcc}	0.68%	(0.84%)
g_{Hgg}	0.79%	(0.97%)
$g_{H\tau\tau}$	0.49%	(0.60%)
$g_{H\mu\mu}$	6.2%	(7.6%)
$g_{H\gamma\gamma}$	1.4%	(1.7%)
BR_{exo}	0.16%	(0.20%)

➔ ***total width*** **<1%**

HHH **(best at FCC-hh)** 28% → from HZ thresh

Htt **(best at FCC-hh)** 13% → from tt thresh



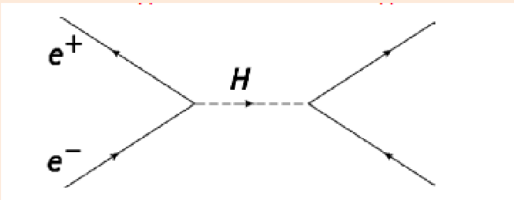
2 10^6 ZH events in 5 years

«A tagged Higgs beam».

sensitive to new physics in loops

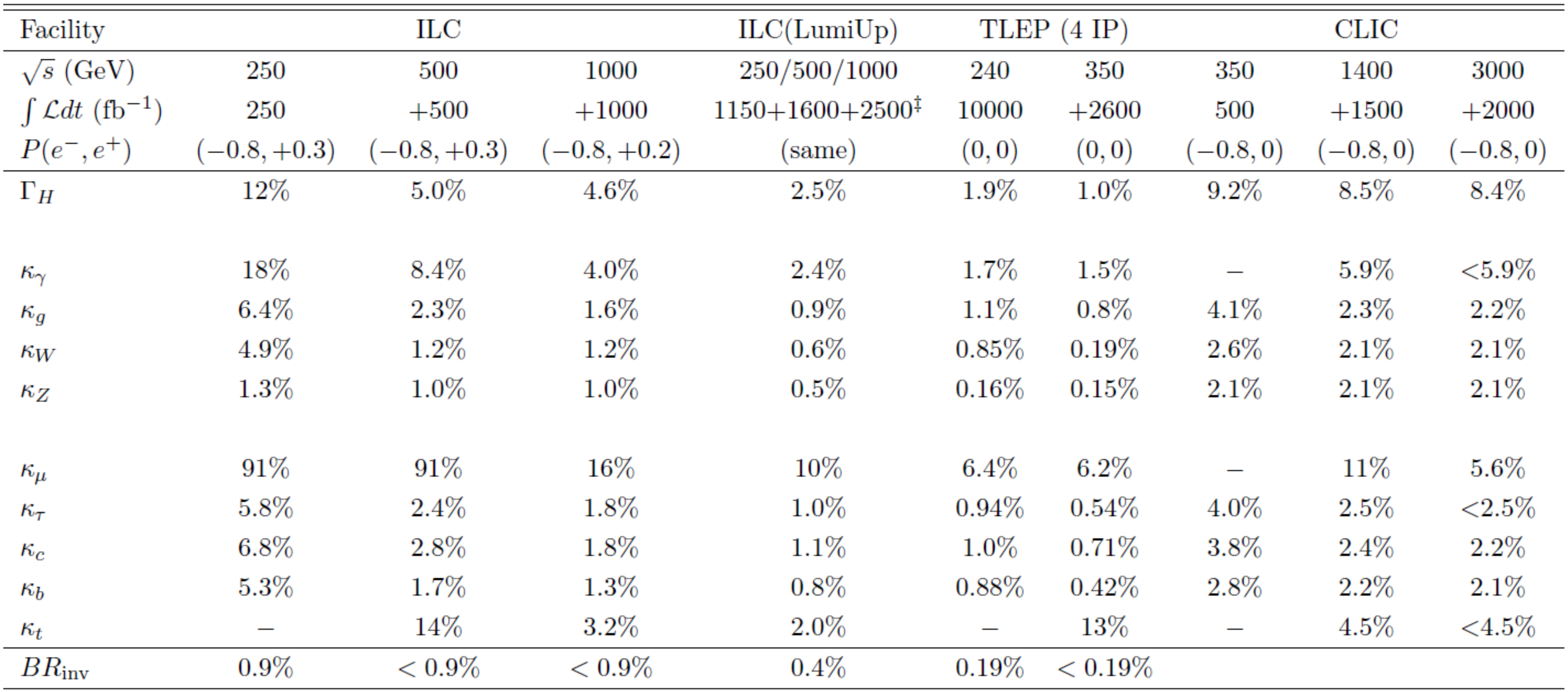
incl. invisible = (dark matter?)

A big challenge, but unique:
Higgs s-channel production at √s = m_H



10^4 events per year.
Very difficult because huge background and beam energy spread ~ 10 x Γ_H
limits or signal? monochromators?
Aleksan, D'Enterria, Woijcik

from snowmass report



Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

comments:

-- Invisible width to be improved by extending Z tagging to Z→ qq (expect <0.1%)

-- 350 GeV running improves κ_W (and Γ_H significantly)

-- complementarity: ttH and HHH are better done at hadron machine

once Γ_H is measured at e+e- collider

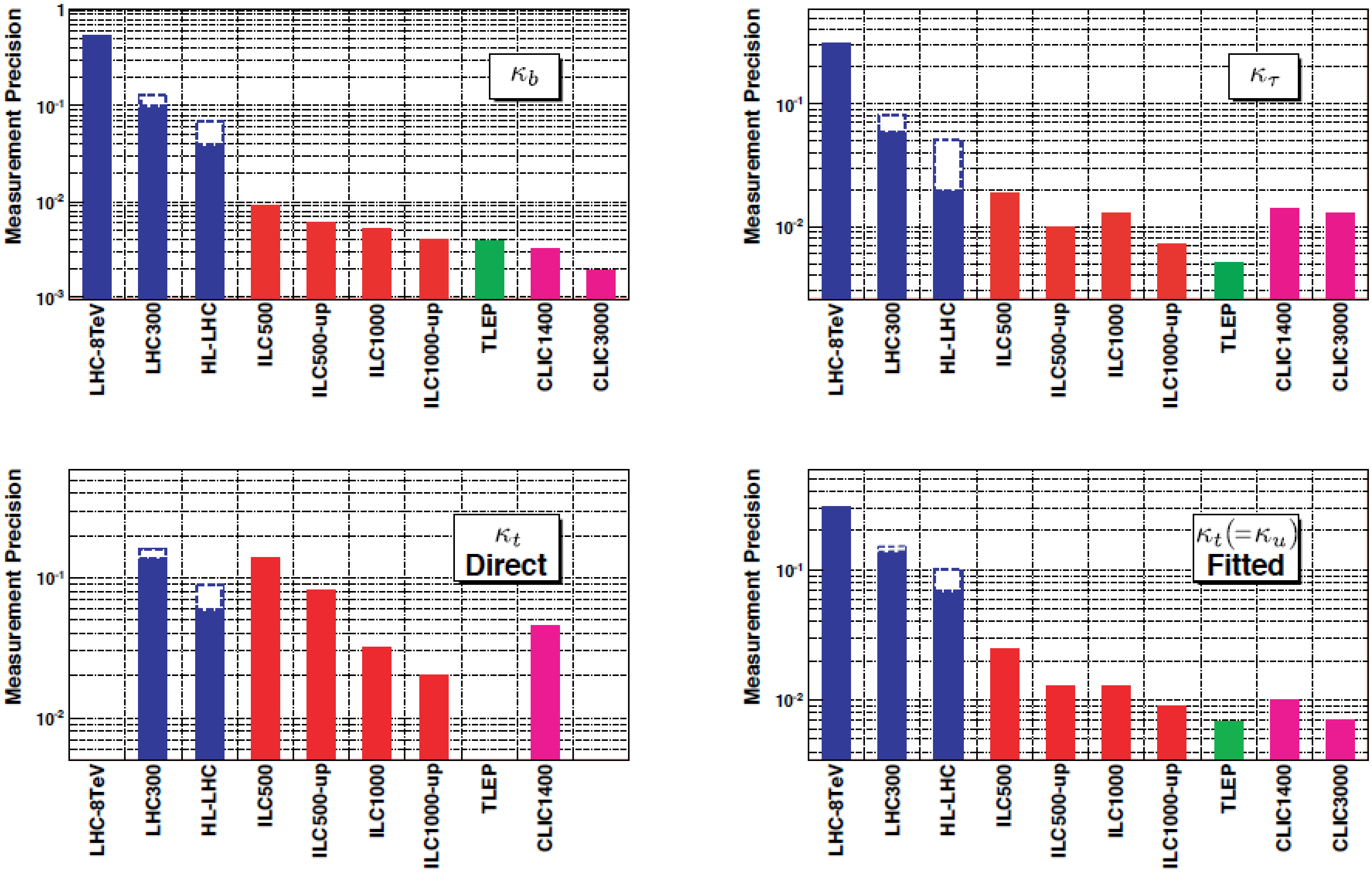
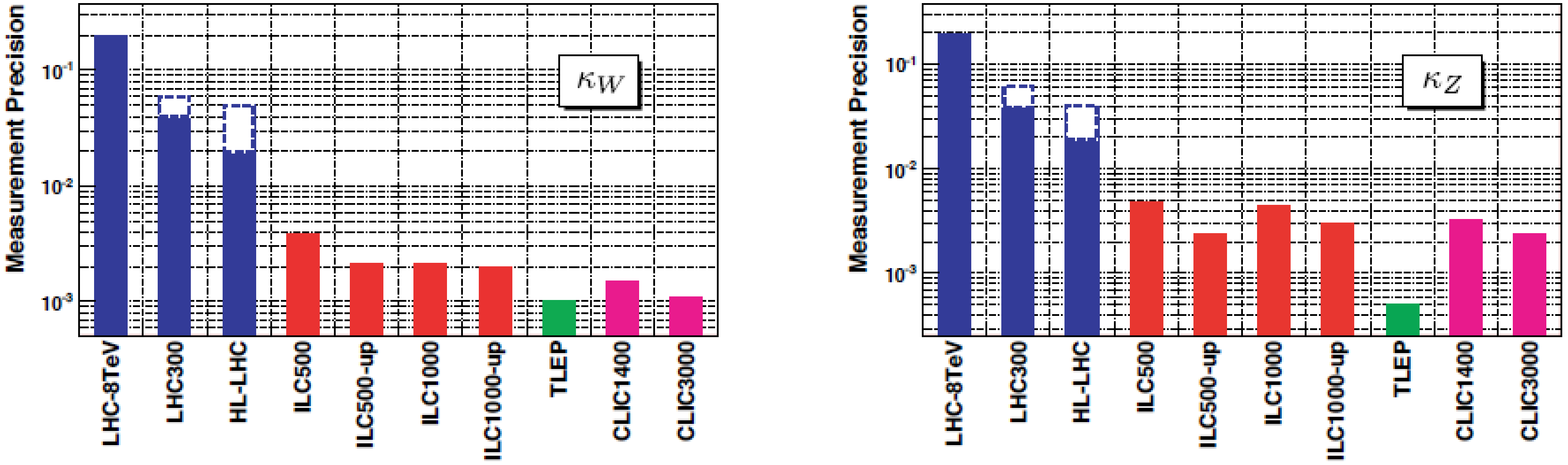


Figure 1-4. *Measurement precision on κ_b, κ_τ, and κ_t measured both directly via $t\bar{t}H$ and through global fits at different facilities.*



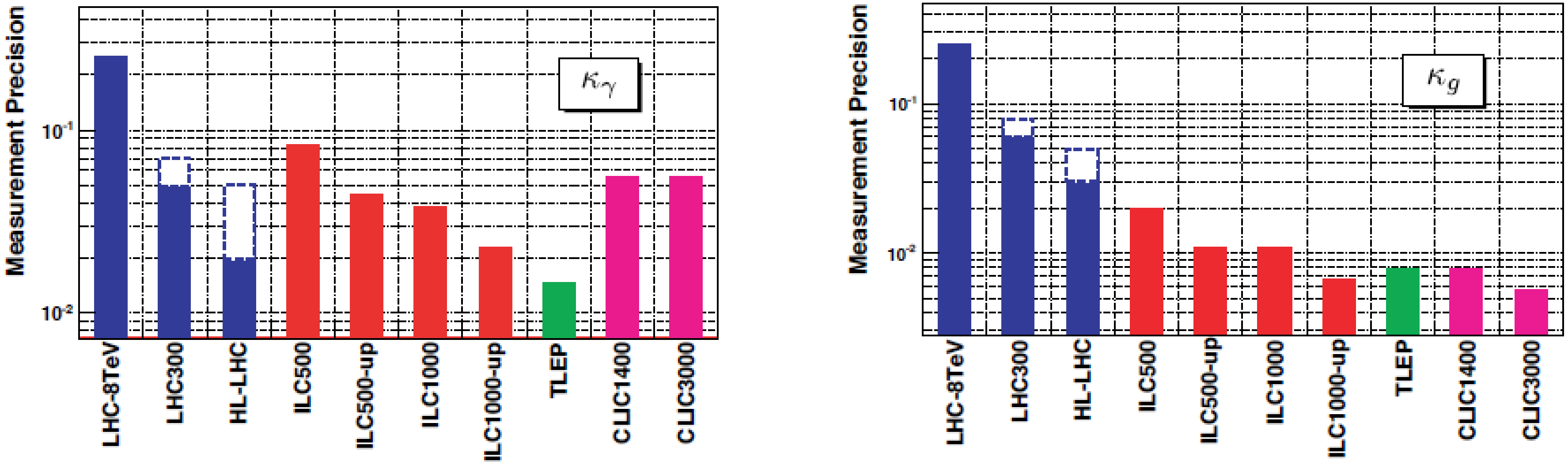
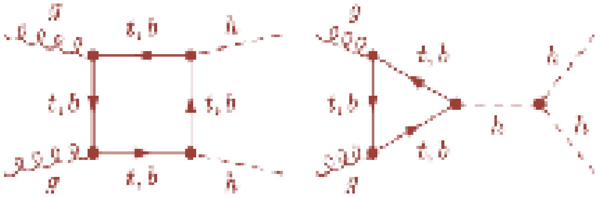


Figure 1-3. *Measurement precision on κ_W, κ_Z, κ_γ, and κ_g at different facilities.*

H^3 @ TLEP

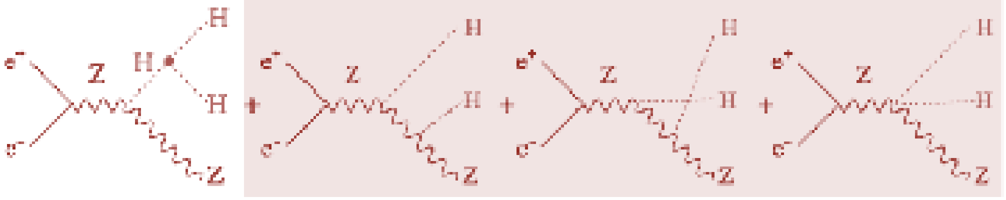
Grojean

- At LHC (Requires $E_{CM} > 2\, m_h$):



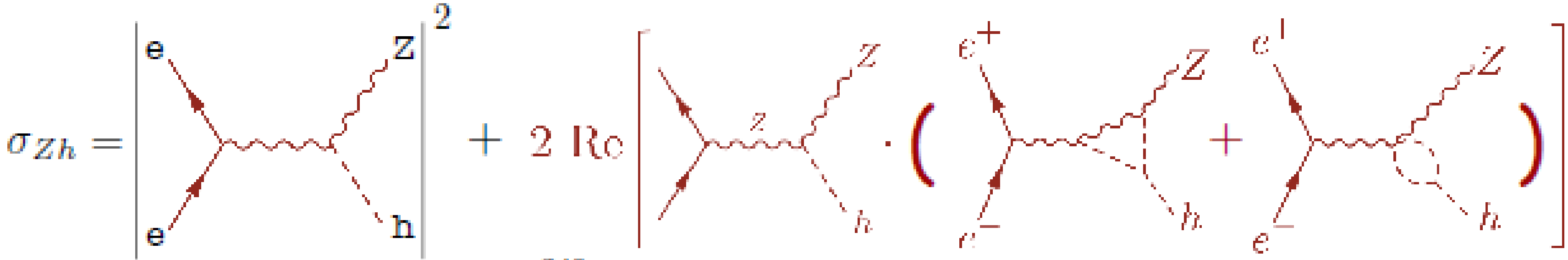
Dolan, Englert, Spannowsky

- At ILC (Requires $E_{CM} > 2\, m_h + m_Z$):



J. Tian, K. Fujii

- At TLEP 240 GeV: M. McCullough '14



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh **(0.05%)**

because of Luminosity FCC-ee (in combination with HL-LHC nd/or FCC-hh) is a very powerful Higgs Factory, but....

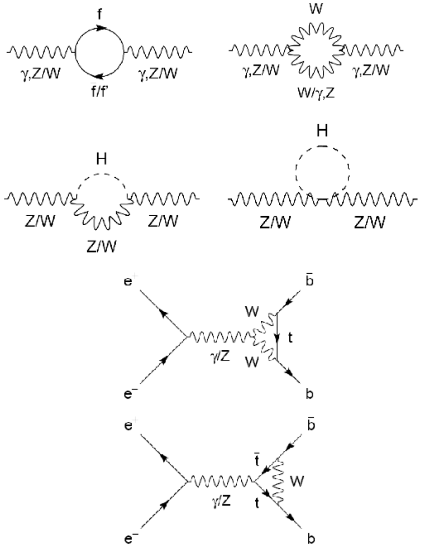
FCC-ee is MUCH more than a Higgs Factory!

Family Name	**FCC**
First name	**ee**
Middle name	**Higgs Factory**
Nick names	**TLEP, Electroweak Factory, the first step**

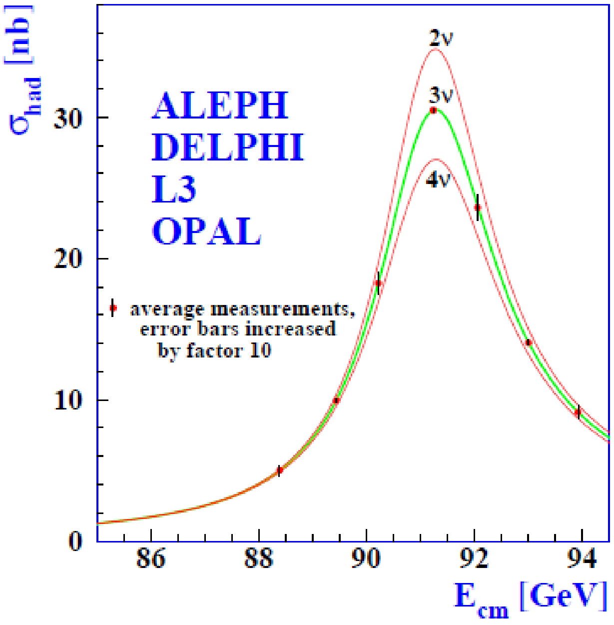
TERA-Z, Oku-W, Megatops

Precision tests of the closure of the Standard Model

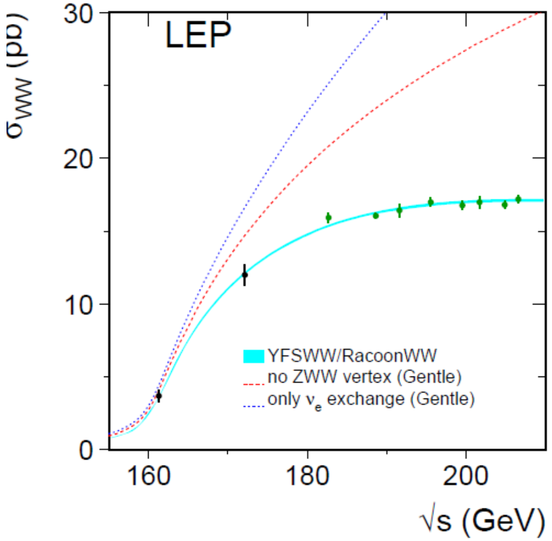
Precision tests of EWSB

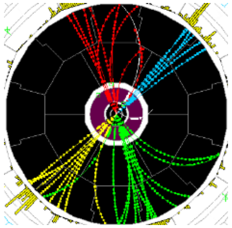


Z pole ssymmetries, lineshape

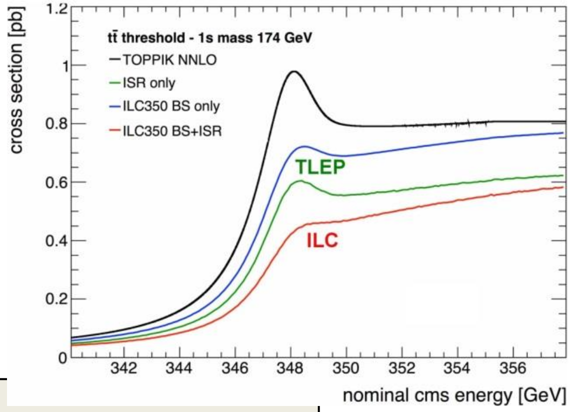


WW threshold scan





tt threshold scan



Frank Simon

TLEP : Repeat the LEP1 physics programme every 15 mn

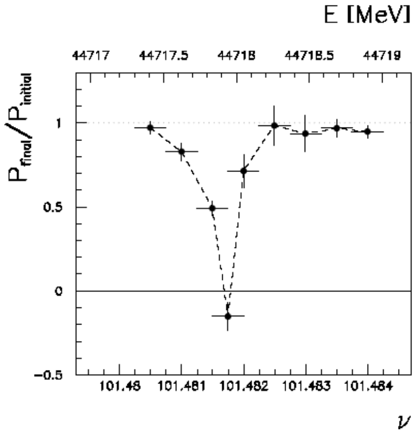
Transverse polarization up to the WW threshold

- Exquisite beam energy determination (10 keV)

Longitudinal polarization at the Z pole

- Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}
- Statistics, statistics: 10^{10} tau pairs, 10^{11} bb pairs, QCD and QED studies etc…

Beam polarization and E-calibration @ FCC-ee



Precise meast of E_{beam} by resonant depolarization

~100 keV each time the meast is made

At LEP transverse polarization was achieved routinely at Z peak.

instrumental in 10^{-3} measurement of the Z width in 1993

led to prediction of top quark mass (179+- 20 GeV) in March 1994

Polarization in collisions was observed *(40% at BBTS = 0.04)*

At LEP beam energy spread destroyed polarization above 60 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ **At FCC-ee transverse polarization up to at least 80 GeV**

to go to much higher energies requires spin rotators and siberian snake

FCC-ee: use 'single' bunches to measure the beam energy continuously

no interpolation errors due to tides, ground motion or trains etc…

but saw-toothing must be well understood! **require Wigglers to speed up pol. time**

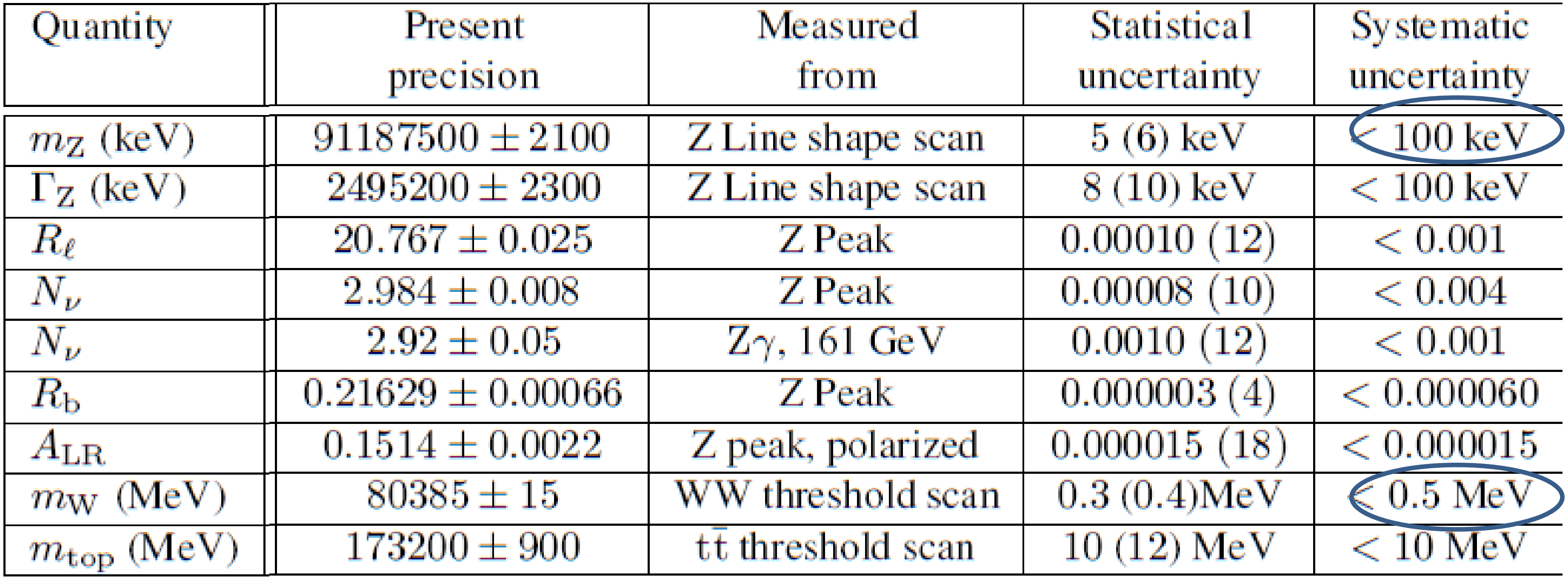
<< 100 keV beam energy calibration around Z peak and W pair threshold.

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

best-of ee-FCC/TLEP #2: Precision EW measts

Asset: -- high luminosity (10^{12} Z decays + 10^{8} Wpairs + 10^{6} top pairs)
-- exquiste energy calibration up and above WW threshold

target precisions



Quantity	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001
N_ν	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004
N_ν	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001
R_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060
A_{LR}	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} (MeV)	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV

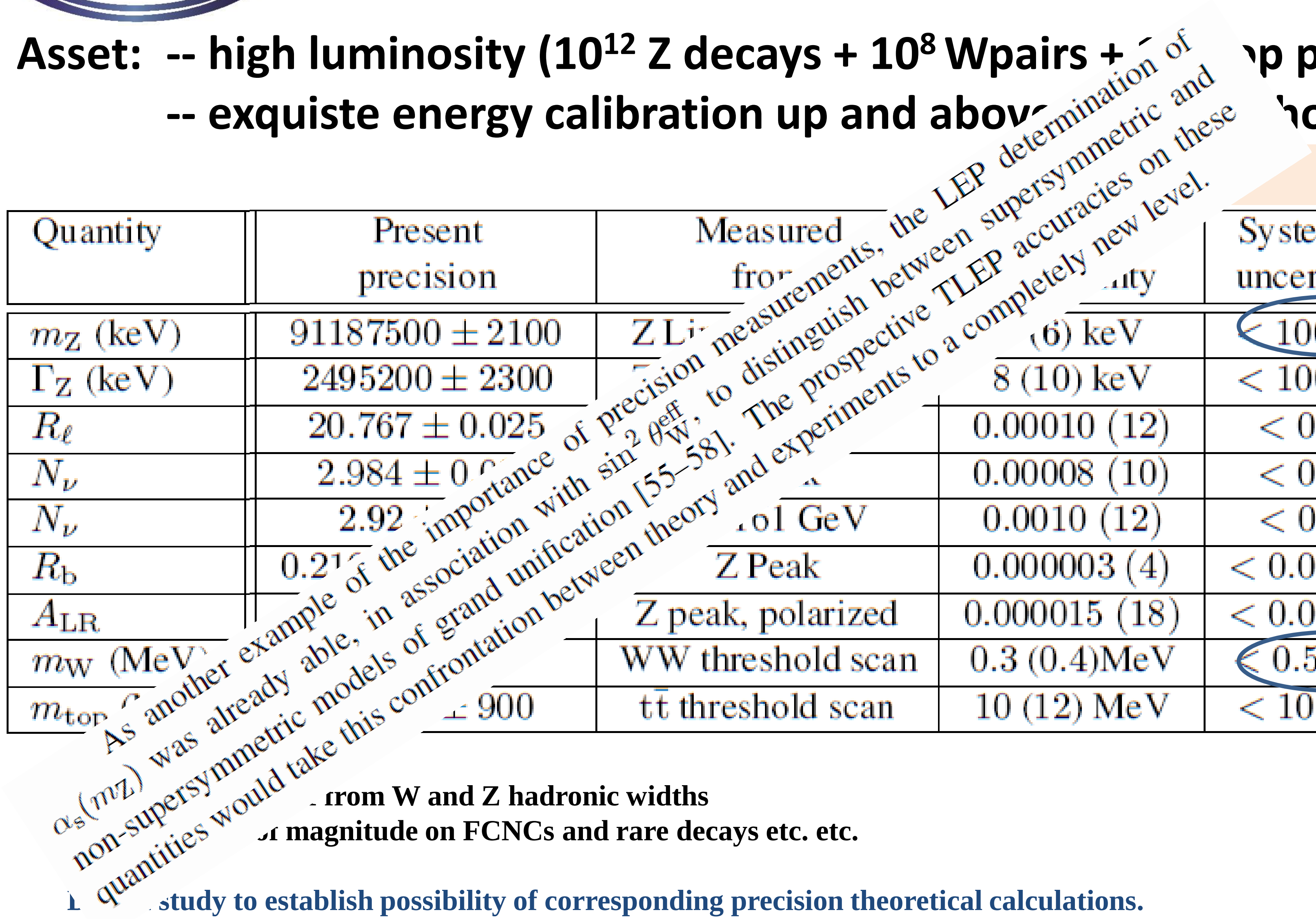
Also -- $\Delta\sin^2\theta_W \approx 10^{-6}$ from Z peak AFBs
-- $\Delta\alpha_S$= 0.0001 from W and Z hadronic widths
-- orders of magnitude on FCNCs and rare decays etc. etc.

Design study to establish possibility of achieving corresponding precision theoretical calculations.

best-of ee-FCC/TLEP #2: Precision EW measts

Asset: -- high luminosity (10^{12} Z decays + 10^{8} Wpairs + ...p pairs)
-- exquiste energy calibration up and abov... ...hold

Quantity	Present precision	Measured fro	...ity	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Li	(6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300		8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025		0.00010 (12)	< 0.001
N_ν	2.984 ± 0.0	k	0.00008 (10)	< 0.004
N_ν	2.92	161 GeV	0.0010 (12)	< 0.001
R_b	0.21	Z Peak	0.000003 (4)	< 0.000060
A_{LR}		Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV		WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top}	900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV



As another example of the importance of precision measurements, the LEP determination of $\alpha_s(m_Z)$ was already able, in association with $\sin^2\theta_W^{\rm eff}$, to distinguish between supersymmetric and non-supersymmetric models of grand unification [55–58]. The prospective TLEP accuracies on these quantities would take this confrontation between theory and experiments to a completely new level.

from W and Z hadronic widths

of magnitude on FCNCs and rare decays etc. etc.

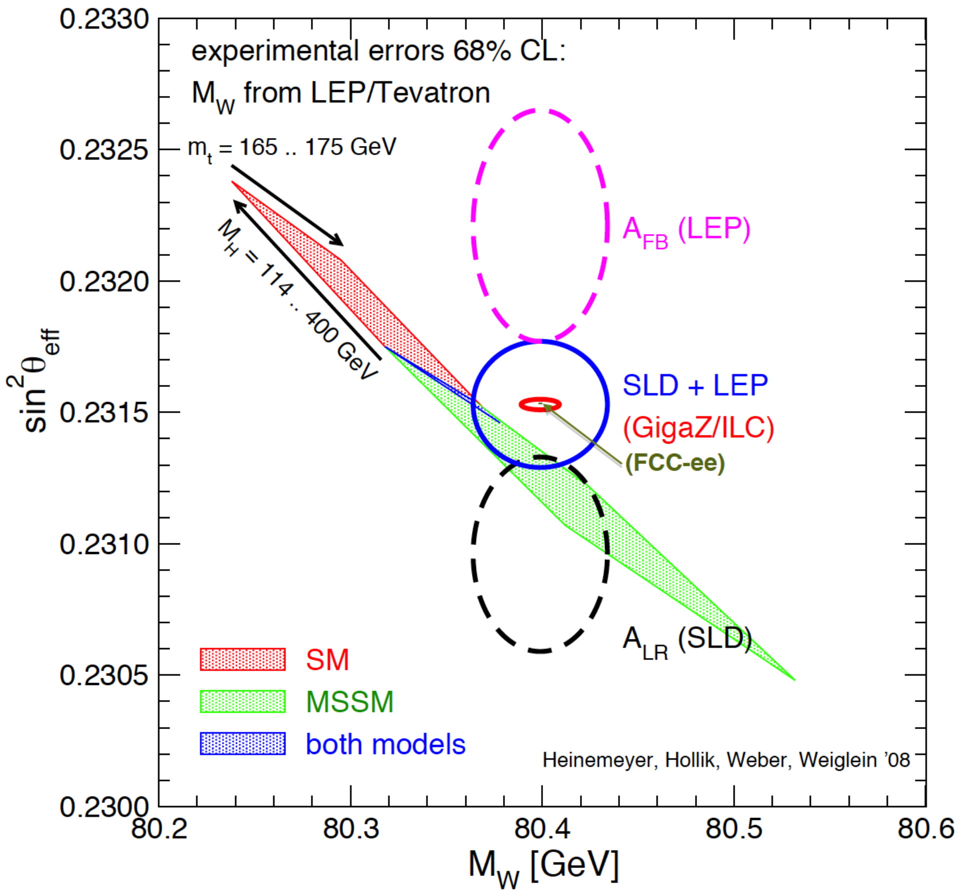
I ... study to establish possibility of corresponding precision theoretical calculations.

A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(105/161)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho$, ε_3, $\Delta\alpha$** **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	**$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$** **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

Precision Measurements and New Physics

- **With the Higgs discovery the SM has nowhere to go!**
- **Any deviation is now 'new physics'**
- **Indirect but inclusive information on new physics with ~weak couplings**
- **Precise knowledge of m_{top} is essential**
- **full analysis of discovery power including all observables is missing.**



Example (from Langacker& Erler **PDG 2011**)

$\Delta\rho = \varepsilon_1 = \alpha(M_Z)\ .\ T$

$\varepsilon_3 = 4 \sin^2\theta_W\ \alpha(M_Z)\ .\ S$

$\Delta\rho$ today = 0. 0004+0.0003–0.0004

-- is consistent with 0 at 1σ

-- is sensitive to non-conventional Higgs bosons (e.g. in SU(2) triplet with ‘funny v.e.v.s)

-- is sensitive to Isospin violation such as $m_t \neq m_b$ or **ibid for stop-sbottom**

$$\rho_0 = 1 + \frac{3\,G_F}{8\sqrt{2}\pi^2}\sum_i \frac{C_i}{3}\,\Delta m_i^2\ , \qquad (10.63)$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-degenerate vector-like fermion doublets (with an extra factor of 2), and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in Supersymmetry (in the absence of L–R mixing).

Present measurement implies

$$\sum_i \frac{C_i}{3}\,\Delta m_i^2 \leq (52\ \mathrm{GeV})^2.$$

Most e.g. SUSYmodels have these symmetries embedded from the start

Similarly:

$$S = \frac{C}{3\pi}\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2,$$

Rare decays

-- FCNC: Z→ e + τ   Z → μ + τ   ,

-- Heavy RH neutrinos

-- other final states with single or double photons and jets

-- flavour physics... single top production, top couplings etc...

-- and many others (Z→ γγγ etc)

-- How far can one go with 10^{12} or 10^{13} Z decays?

N. Lockyer was speaking at the ICFA seminar in Beijing in October

Higgs discovery has dramatically changed the landscape…

- Higgs discovery motivates a precision Higgs factory…not going to make three….what is the right direction?

- China wants to build a Higgs factory
- Europe wants to build a Higgs factory

- ILC higher energy (500 GeV), both beams polarized, mature design & machine ready to go technically e.g., Euro-XFEL~500 cavities built…together 3 regions can build ILC
  - (significant energy increase possible with further R&D on Nb3Sn)
- Strategy for FCC and CECP is however attractive
- Neither FCC or CECP as high energy as Linear Collider(s) but have an attractive growth path just as LEP grew into LHC.

Note that this is not based on physics comparisons but values FCC-ee as launching pad for FCC-hh

FCC-ee is a wonderful first step towards the Ultimate goal of a 100 TeV hadron collider and this is one of the reasons it is attracive.

But...

FCC-ee is MUCH more than a launching pad!

FCC-ee and FCC-hh:
Synergy and complementarity

As first step, the lepton collider would provide
-- a home (the tunnel, shafts, caverns etc...)
-- cryogenics, power connections etc.
-- can start taking data as HL-LHC finishes (2035)

-- A dramatically improved baseline of precision measurements
-- hopefully new discovery(ies) to guide the hh program
-- and a large amount of very complementary knowledge

Complementarity

Proposed physics topics to be used in the study of **synergy/complementarity** among experiments **at FCC-hh/ee/eh**

Subject		**ee**	**hh**	**he**
Higgs Physics	precision studies higher dimension operators composite Higgs rare and exotic decays multiple Higgs production extra Higgs bosons			
Interface with Cosmology	Dark matter baryogenesis right-handed/(almost) sterile neutrinos			
Electroweak Sym. Breaking	WW scattering supersymmetry extra dimensions composite models			
Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts (m_Z,m_W,m_t,α,$\alpha_s(m_Z)$,$\sin^2\theta_W$.R_b... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

What we believe now and work to demonstrate in a few years:

The combination of the FCC machines offers outstanding discovery potential by exploration of new domains of
-- precision
and
-- direct search,

both at high energy and at very small couplings

CONCLUSIONS

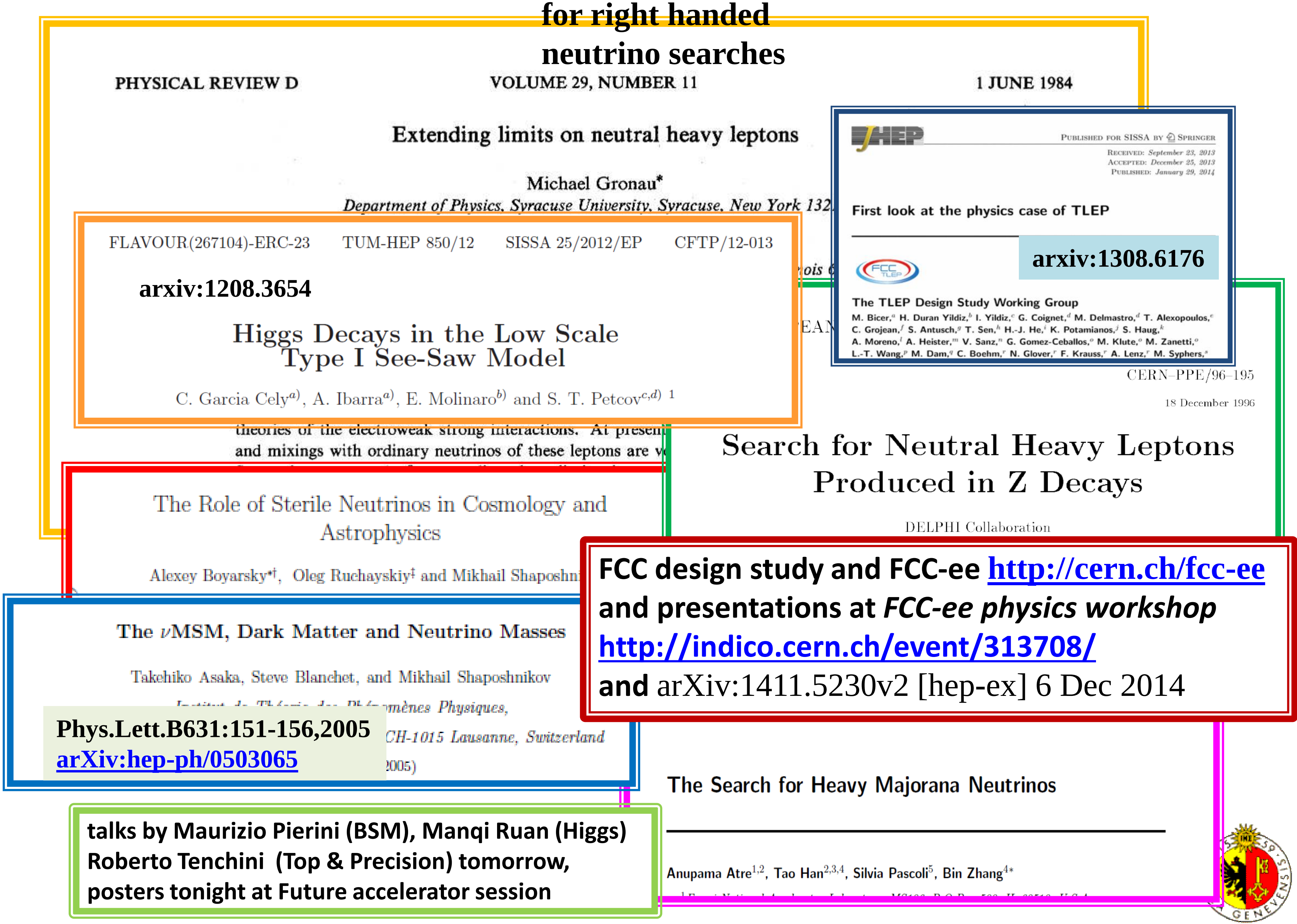
Kick-off Meeting of the Future Circular Colliders Design Study

12 - 15 February 2014, University of Geneva / Switzerland

photo by Michael.Hoch@cern.ch

330 registered participants

some REFERENCES for right handed neutrino searches



PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

Department of Physics, Syracuse University, Syracuse, New York 132

theories of the electroweak strong interactions. At presen

and mixings with ordinary neutrinos of these leptons are v

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a)], A. Ibarra[a)], E. Molinaro[b)] and S. T. Petcov[c,d)] [1]

JHEP PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *September 23, 2013*
ACCEPTED: *December 25, 2013*
PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s]

CERN–PPE/96–195

18 December 1996

Search for Neutral Heavy Leptons Produced in Z Decays

DELPHI Collaboration

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhni

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

mènes Physiques,

CH-1015 Lausanne, Switzerland

005)

Phys.Lett.B631:151-156,2005
arXiv:hep-ph/0503065

The Search for Heavy Majorana Neutrinos

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

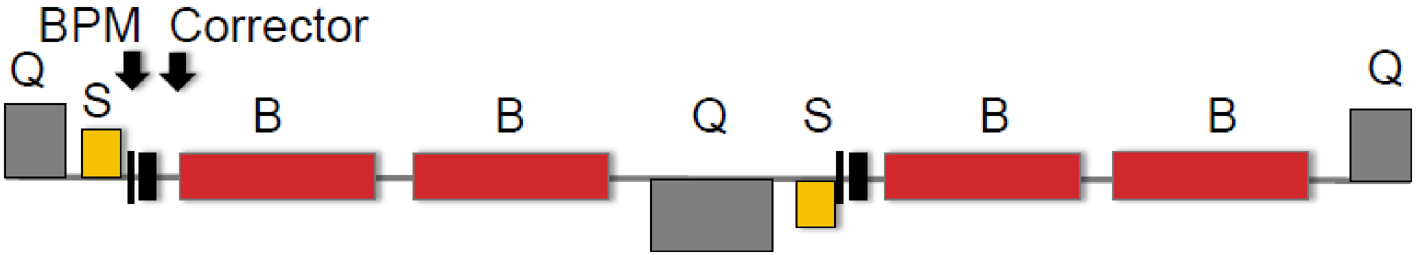
FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshop*
http://indico.cern.ch/event/313708/
and arXiv:1411.5230v2 [hep-ex] 6 Dec 2014

talks by Maurizio Pierini (BSM), Manqi Ruan (Higgs)
Roberto Tenchini (Top & Precision) tomorrow,
posters tonight at Future accelerator session

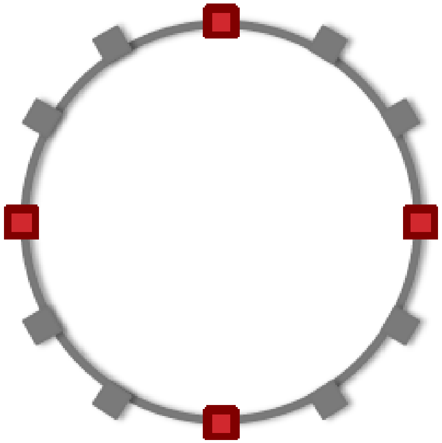
Arc lattice (circular machine)

LATTICE V12B-S

arc cell layout

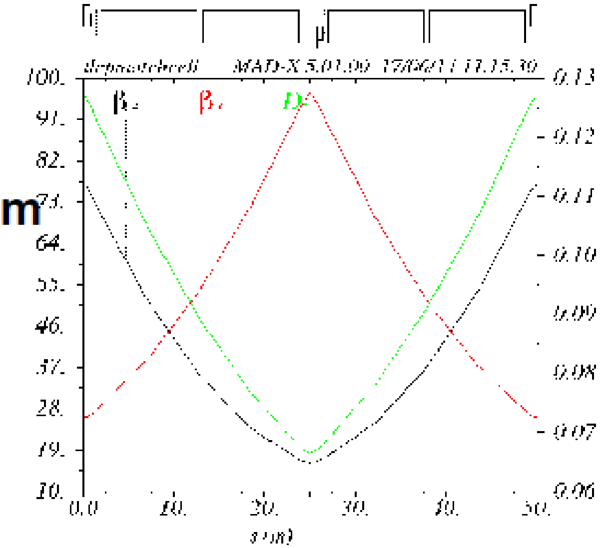


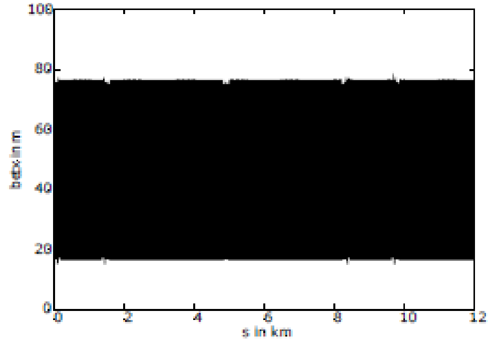
B = bending magnet, Q = quadrupole, S = sextupole

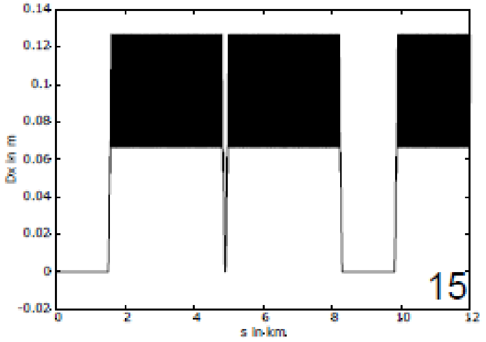


Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

FODO cell optics
cell length 50 m

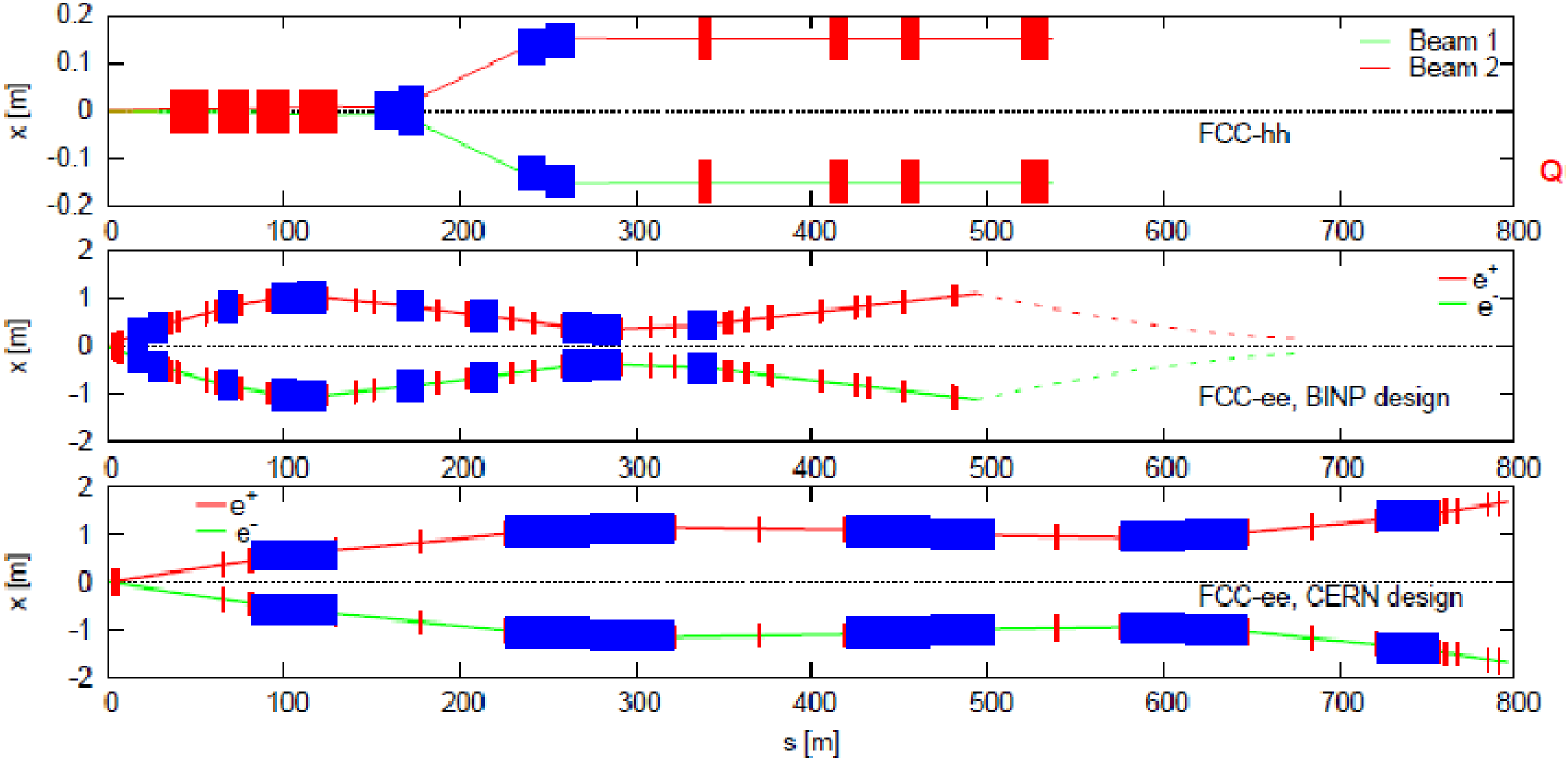






B. Harer, B. Holzer

IR layouts

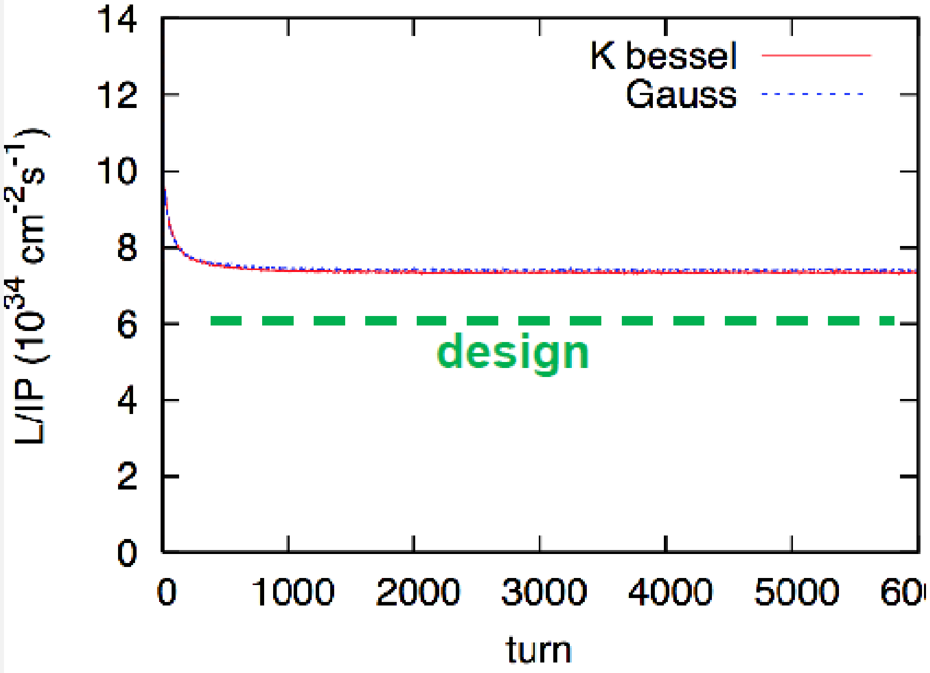


Dipoles in blue

Quadrupoles in red

- ❑ Tunnel transverse width of both FCC-ee designs ~3-4 m.
- ❑ Additional length is required to bend beams back, plus room for RF.
- ❑ Synchrotron rad. power per IP: CERN 140 kW, BINP 1400 kW.
  - ○ *Optimum between length and power loss to be identified !*
  - ○ *93 km racetrack IR straights of 1400 m may be too short for ee !*

Beam-beam simulations



BBSS strong-strong simulation with beamstrahlung

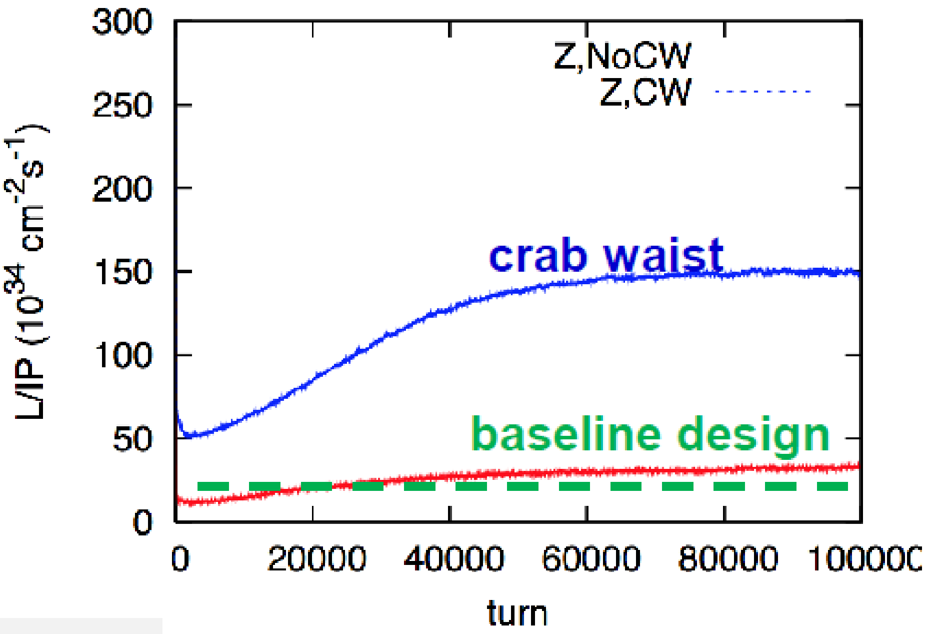
FCC-ee at 120 GeV:

$L≈7.5\text{x}10^{34}$ cm^{-2}s^{-1} per IP

FCC-ee in crab-waist mode at the Z pole (45.5 GeV):

$L≈1.5\text{x}10^{36}$ cm^{-2}s^{-1} per IP

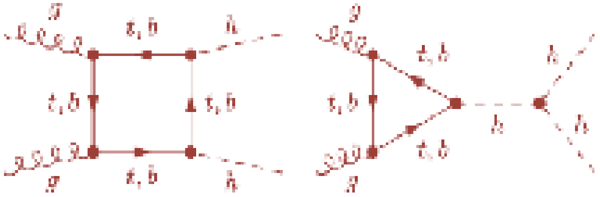
Tracking confirms assumptions!



K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

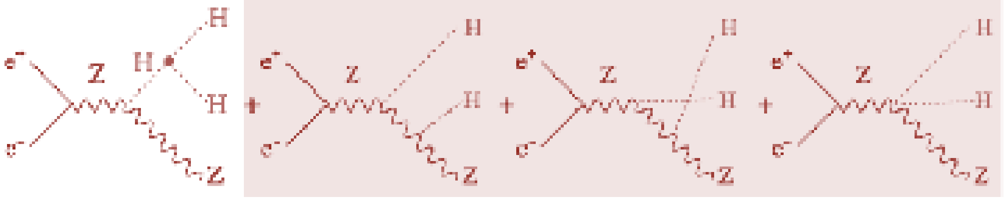
H^3 @ TLEP

- At LHC (Requires $E_{CM} > 2\ m_h$):



Dolan, Englert, Spannowsky

- At ILC (Requires $E_{CM} > 2\ m_h + m_Z$):



J. Tian, K. Fujii

- At TLEP 240 GeV: M. McCullough '14

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

tiny effect but visible thanks to the extraordinary TLEP sensitivity on Zh **(0.05%)**

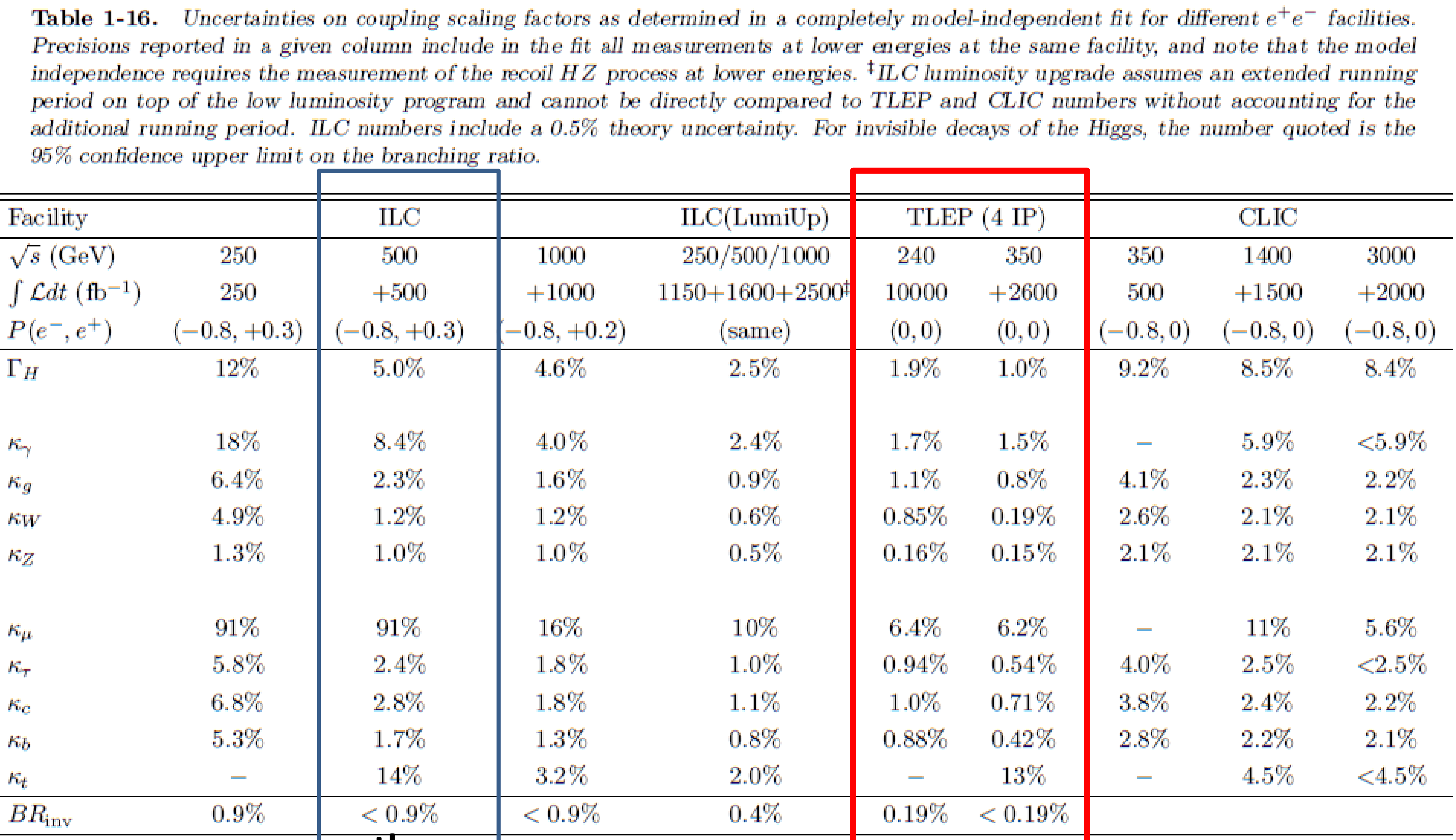
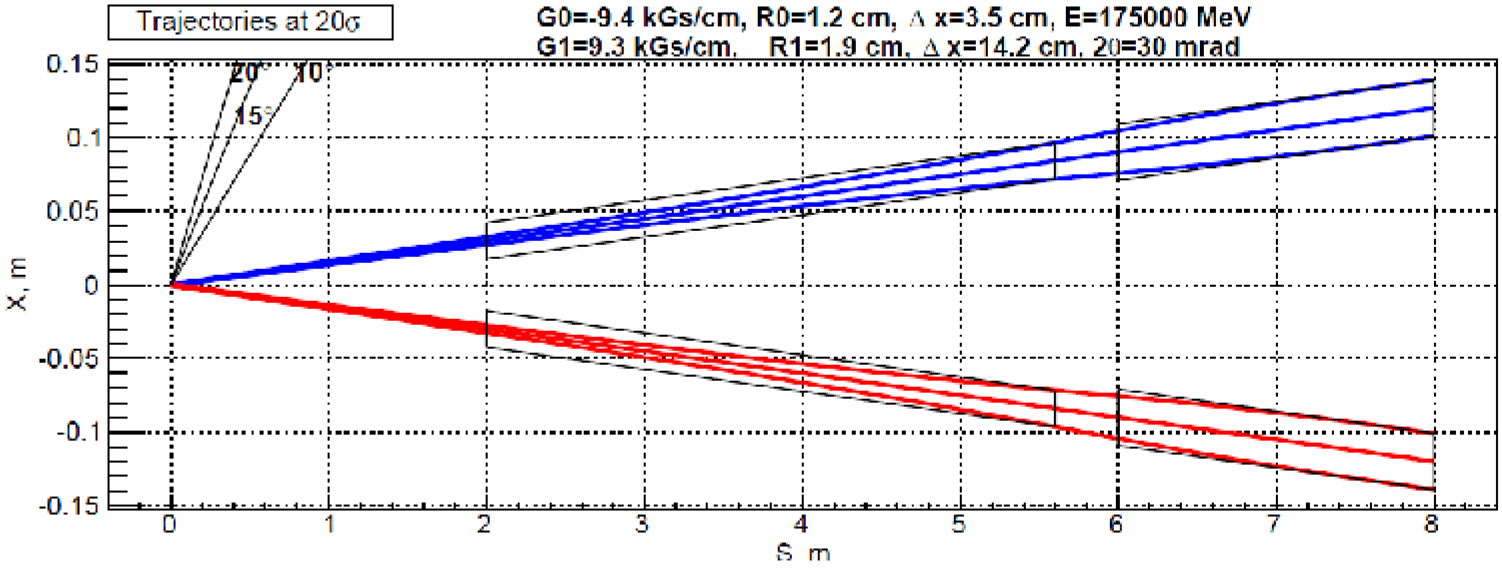


Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

the 10B$ ILC

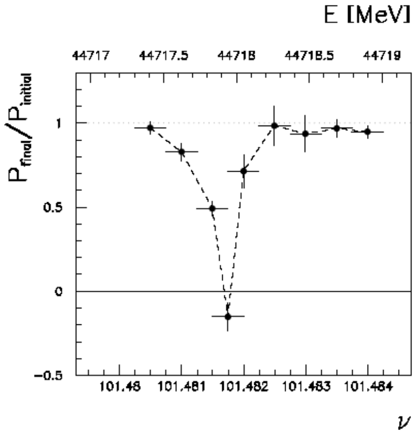
Trajectories L*=2m



Mogens Dam

example of challenge: crab crossing to increase further luminosity? (Novosibirsk) emittance and polarization compensation, etc

Beam polarization and E-calibration @ TLEP



Precise meast of E_{beam} by resonant depolarization

~100 keV each time the meast is made

At LEP transverse polarization was achieved routinely at Z peak.

instrumental in 10^{-3} measurement of the Z width in 1993

led to prediction of top quark mass (179+- 20 GeV) in March 1994

Polarization in collisions was observed *(40% at BBTS = 0.04)*

At LEP beam energy spread destroyed polarization above 60 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ *At TLEP transverse polarization up to at least 80 GeV*

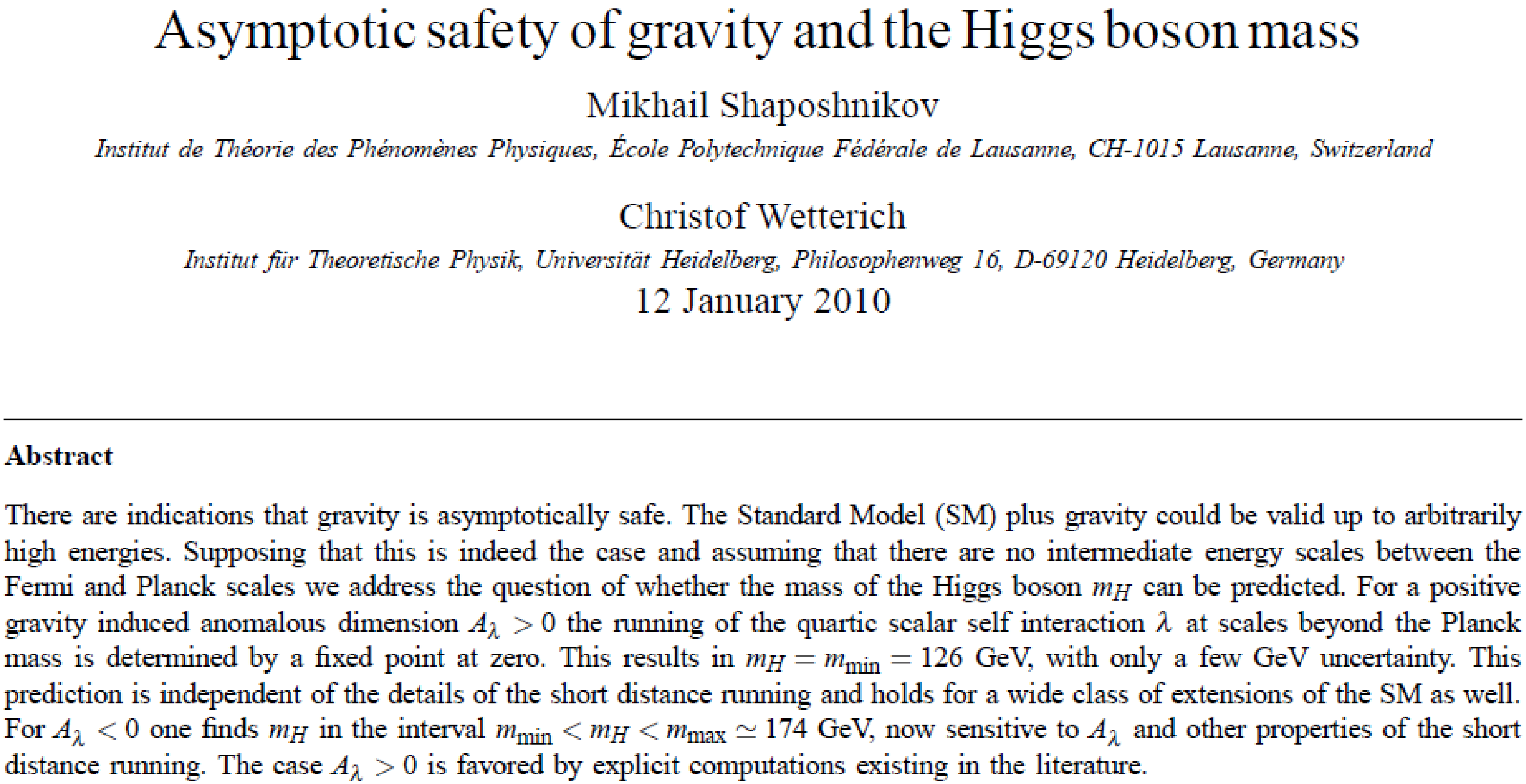
to go to higher energies requires spin rotators and siberian snake

TLEP: use ‘single’ bunches to measure the beam energy continuously

no interpolation errors due to tides, ground motion or trains etc…

<< 100 keV beam energy calibration around Z peak and W pair threshold.

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV



Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov
Institut de Théorie des Phénomènes Physiques, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Christof Wetterich
Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

in 2010 Shaposhnikov and Wetterich predict m_H=126 GeV
if there is no intermediate energy scale between the Fermi and Planck scales...

FCC Work and Organisation (i)

Work/meeting structures established based on INDICO, see:

- **FCC Study: https://indico.cern.ch/category/5153/**
- **http://cern.ch/FCC-ee (more developed, for FCC-ee)**

In particular:

- **FCC-hh Hadron Collider Physics and Experiments VIDYO meetings**
  - **https://indico.cern.ch/category/5258/**
  - **Contacts: michelangelo.mangano@cern.ch, fabiola.gianotti@cern.ch, austin.ball@cern.ch**

- **FCC-ee Lepton Collider (TLEP) Physics and Experiments VIDYO meetings**
  - **https://indico.cern.ch/category/5259/**
  - **Contacts: alain.blondel@cern.ch, patrick.janot@cern.ch**

FCC Work and Organisation (ii)

- **FCC-hh Hadron Collider VIDYO meetings**
  - **https://indico.cern.ch/category/5263/**
  - **Contacts: daniel.schulte@cern.ch**

- **FCC-hadron injector meetings**
  - **https://indico.cern.ch/category/5262/**
  - **Contacts: brennan.goddard@cern.ch**

- **FCC-ee (TLEP) Lepton Collider VIDYO meetings**
  - **https://indico.cern.ch/category/5264/**
  - **Contacts: jorg.wenninger@cern.ch,**

- **FCC infrastructure meetings**
  - **https://indico.cern.ch/category/5253/**
  - **Contacts: philippe.lebrun@cern.ch, peter.sollander@cern.ch**

FCC Week 2015

IEEE International Future Circular Collider Conference

March 23 - 27, 2015 | Washington DC, USA

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Jamieaddams99

Further information and registration
http://cern.ch/fccw2015

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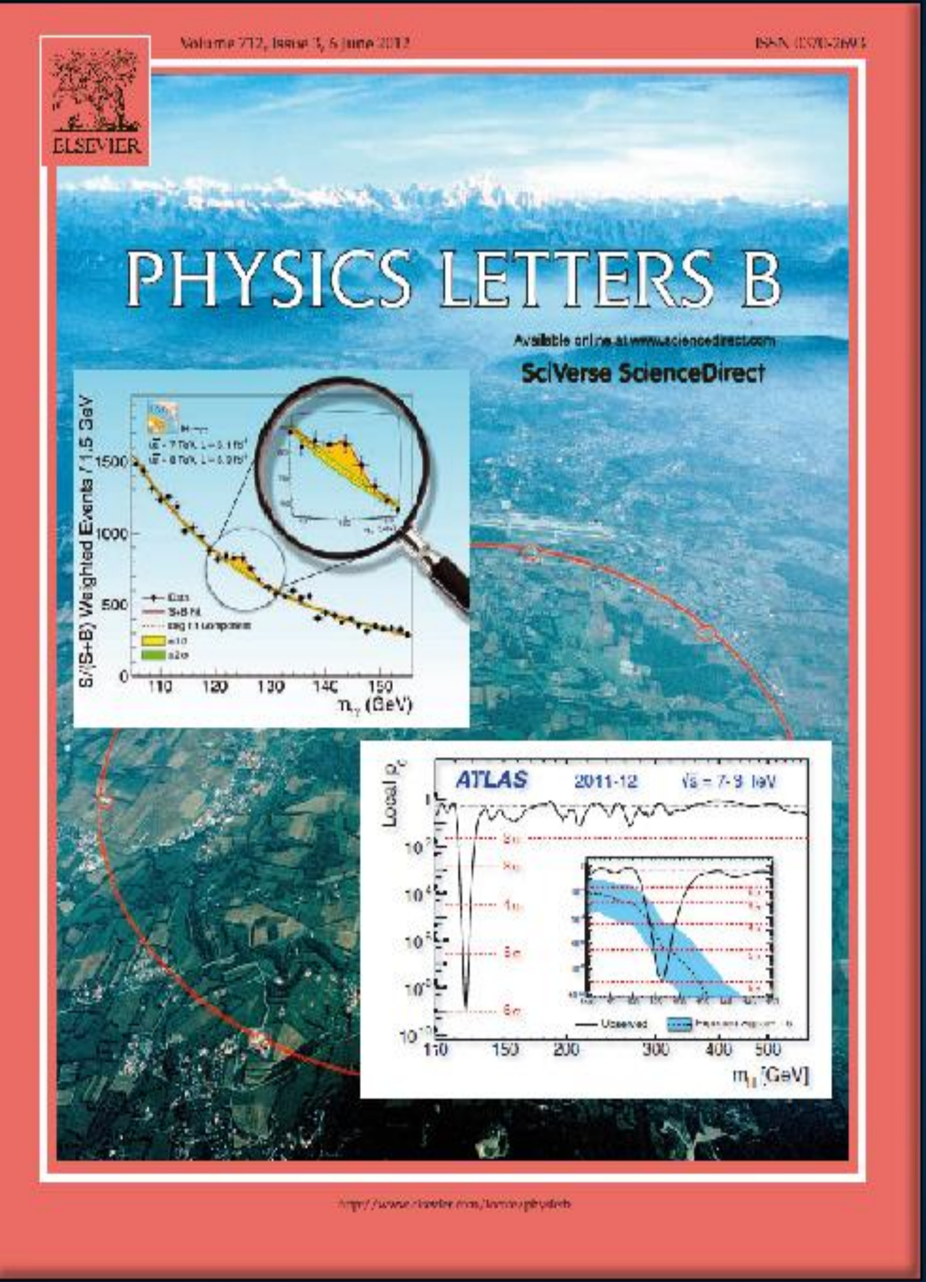
First FCC Week

Conference

Washington DC
23-27 March 2015

http://cern.ch/fccw2015



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The Economist

JULY 7TH–13TH 2012

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Britain's banking scandal spreads

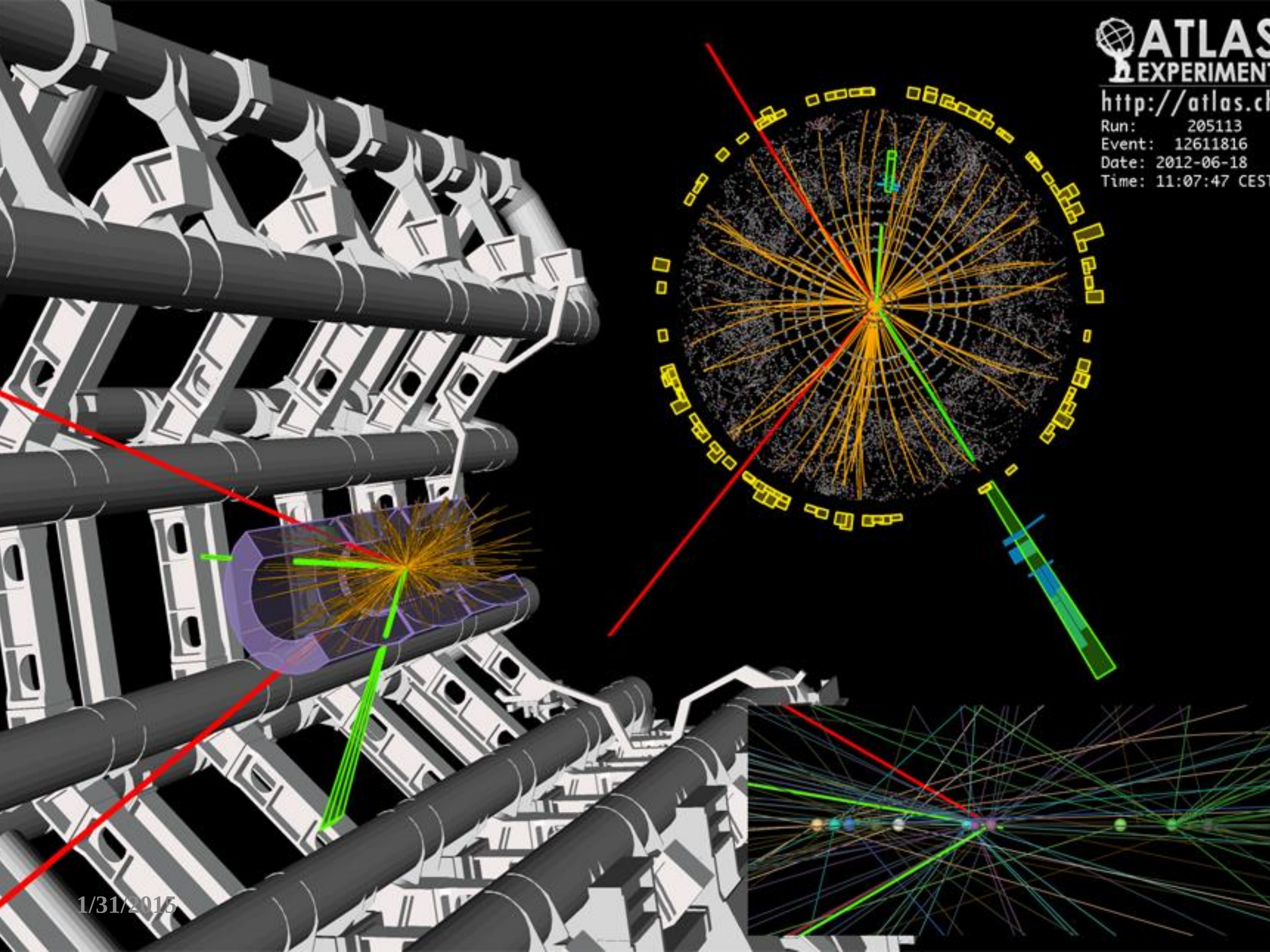
Volkswagen overtakes the rest

A power struggle at the Vatican

When Lonesome George met Nora

A giant leap for science

Finding the Higgs boson


ATLAS
EXPERIMENT
http://atlas.c
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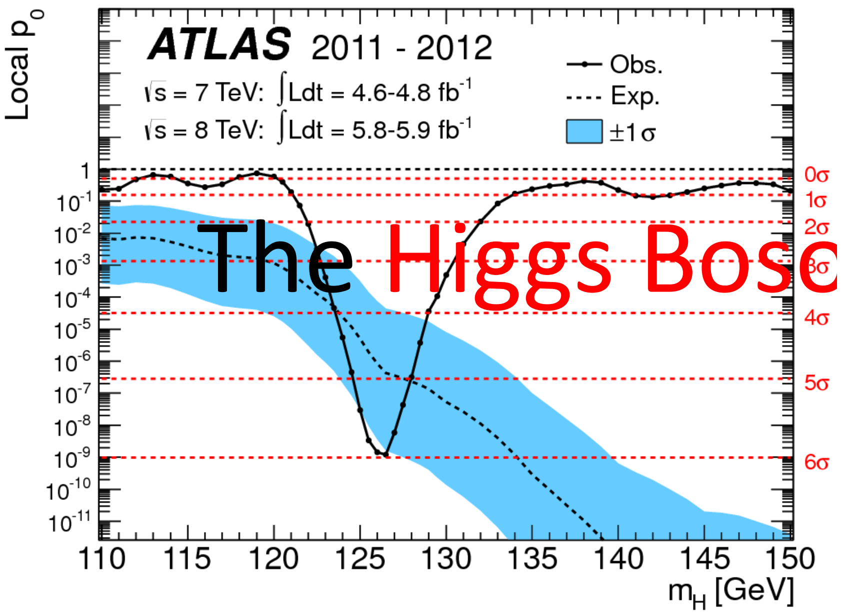
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

The Higgs Bos



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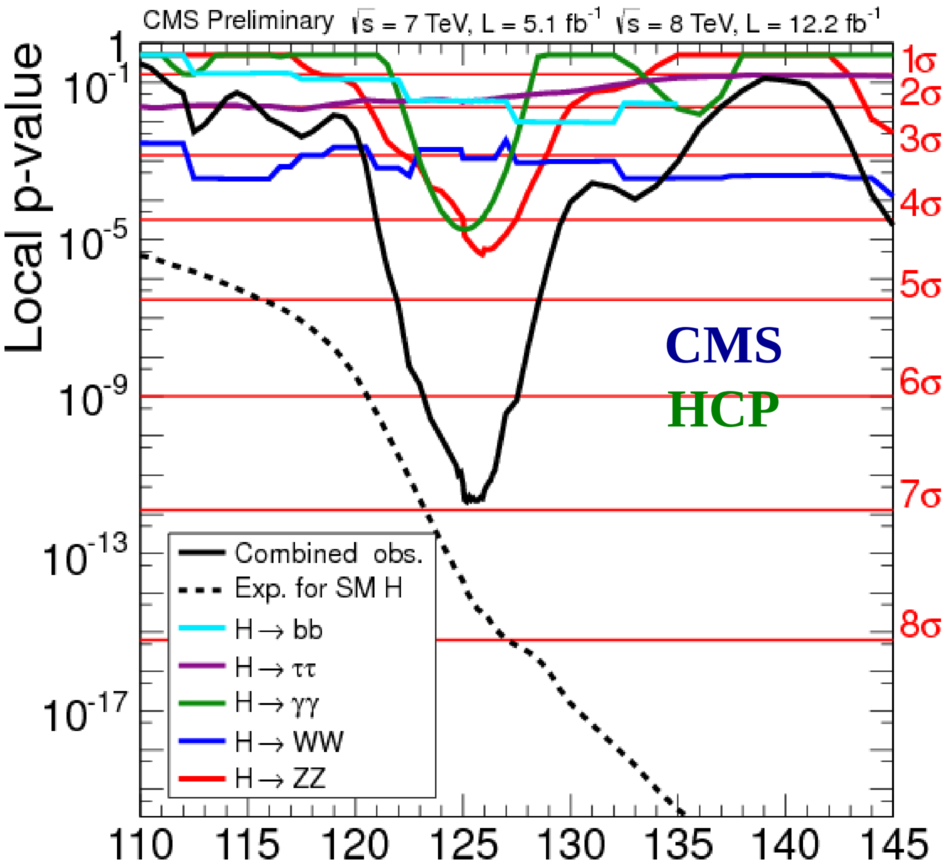
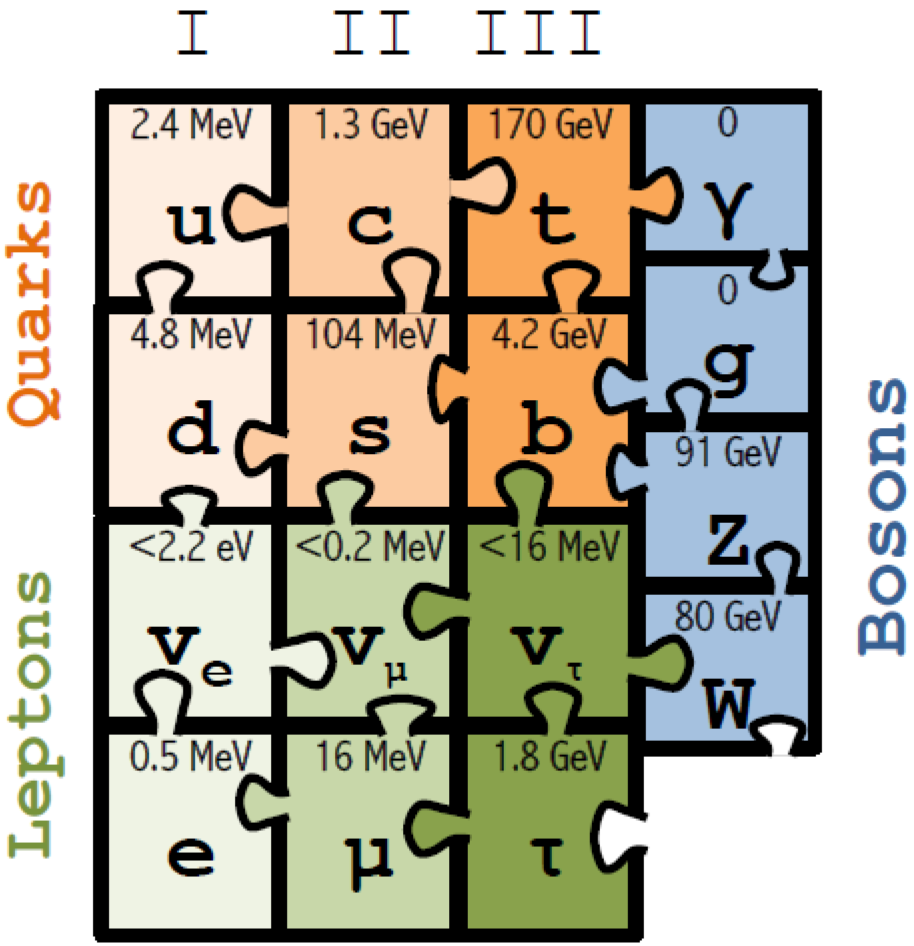


observed: 6.9; expected: 7.8

Discovered Higgs-like Boson: Clear mass peak in γγ and ZZ*→4ℓ

Is this the SM one ? From searches to measurements

1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t’Hooft and Veltman get Nobel Prize

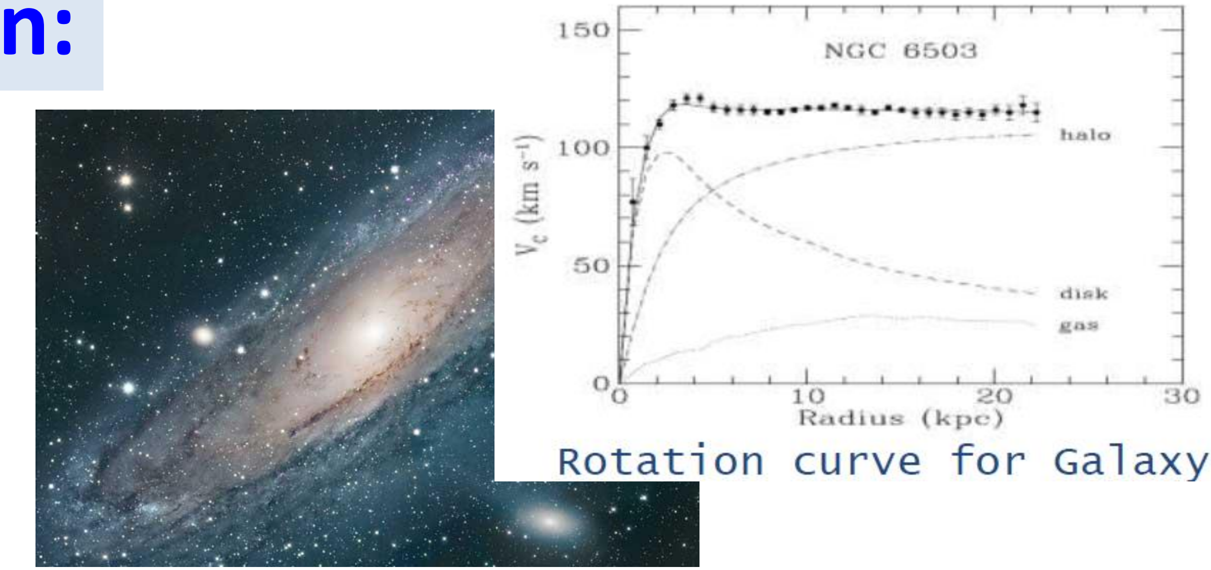


(c) Sfyrla

We cannot explain:

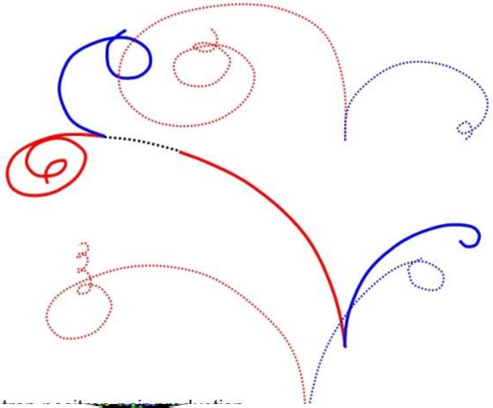
Dark matter

Standard Model particles constitute only 5% of the energy in the Universe



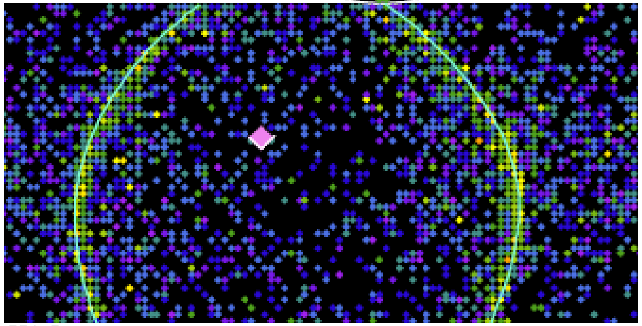
Rotation curve for Galaxy

Were is antimatter gone?



What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (how?)
Both (the preferred scenarios, see-saw...)
➔ heavy right handed neutrinos?



we cannot explain:

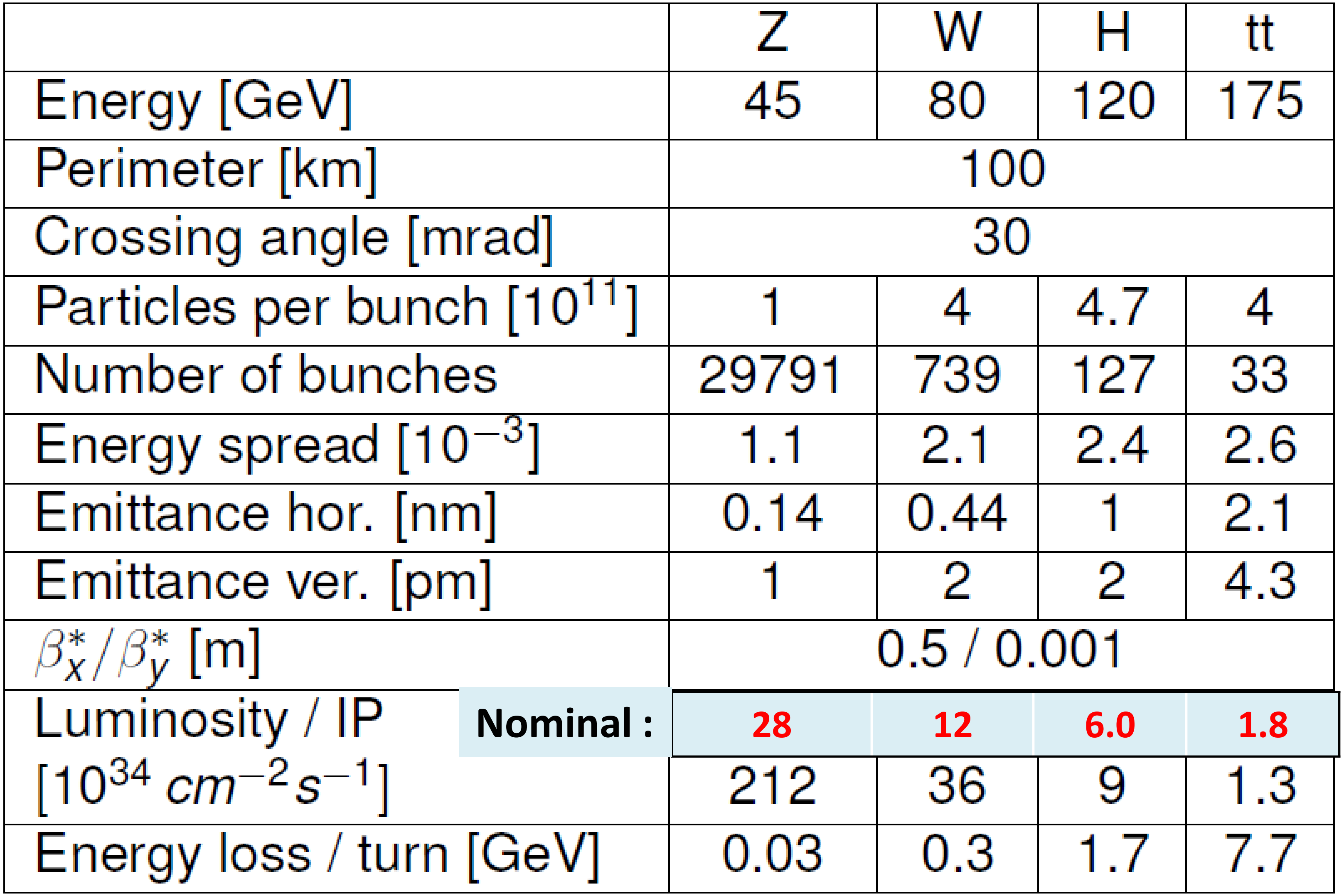
charge of proton = - charge of electron

$$|q_p + q_e|/e \quad < 1 \quad \times 10^{-21}$$

we have no explanation for this, except ...
that it is necessary for the stability of

1. the universe
2. the Standard Model calculations

PARAMETERS FOR CRAB WAIST OPERATION



	Z	W	H	tt
Energy [GeV]	45	80	120	175
Perimeter [km]	100			
Crossing angle [mrad]	30			
Particles per bunch [10^{11}]	1	4	4.7	4
Number of bunches	29791	739	127	33
Energy spread [10^{-3}]	1.1	2.1	2.4	2.6
Emittance hor. [nm]	0.14	0.44	1	2.1
Emittance ver. [pm]	1	2	2	4.3
β^*_x / β^*_y [m]	0.5 / 0.001			
Nominal :	28	12	6.0	1.8
Luminosity / IP [$10^{34}\ cm^{-2} s^{-1}$]	212	36	9	1.3
Energy loss / turn [GeV]	0.03	0.3	1.7	7.7

Important scope for improvement in luminosity.

Luminosity optimisation

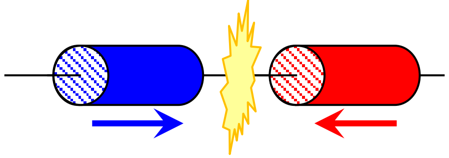
Ideal situation is that beam lifetime is driven by particle-particle interactions
-- dominated by radiative Bhabha scattering e+e- → e+e-γ (typically 150 mb)
with $e^{+/-}$ out of energy acceptance (improved with larger acceptance)

At high luminosity considered in FCC-ee, Beamstrahlung (particle-opp. beam interaction) becomes important.
-- requires very flat beams and +- 2% energy acceptance
-- reduces beam lifetime
-- increases energy spread and bunch length
This is the case in FCC-tt

At lower energy the beams are blowing eachother (beam-beam interaction)
-- this can be fought with ‘crab waist’ crossing
This is the case at all lower energies operating points

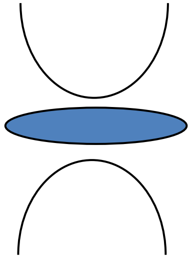
Numbers in main parameter list include beamstrahlung treatment, but have not considered crab waist operation.

Luminosity



$$e\,f\,k\,N = \text{beam current} \propto \frac{1}{E^4}$$

$$L = \frac{f\,k\,N^2}{4\pi\sigma_x\sigma_y}\,F\,H$$

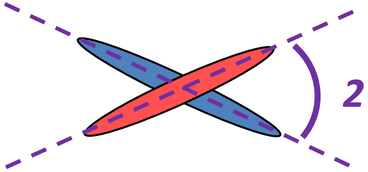


H ≤ 1

Hour-glass

F ≤ 1

Crossing angle



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{\max}(E)$$

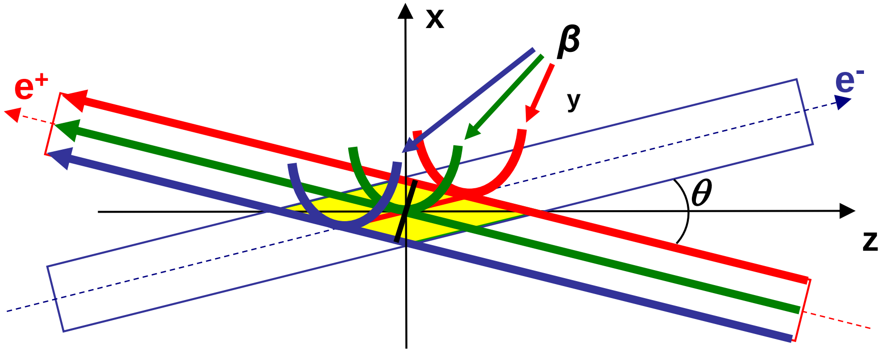
Beam-beam parameter

$$\boxed{L \propto \frac{P_{SR}}{E^3}\,\frac{\xi_y}{\beta_y^*}}$$

σ = beam size
k = no. bunches
f = rev. frequency
N = bunch population
P_{SR} = synch. rad. power
β^* = betatron fct at IP
(beam envelope)

Crab Waist Scheme

P. Raimondi, 2006



$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$$ **– Piwinski angle**

1) **Large Piwinski angle: $\phi >> 1$**

2) **β_y approx. equals to overlapping area: $\beta_y \sim \sigma_z / \phi$**

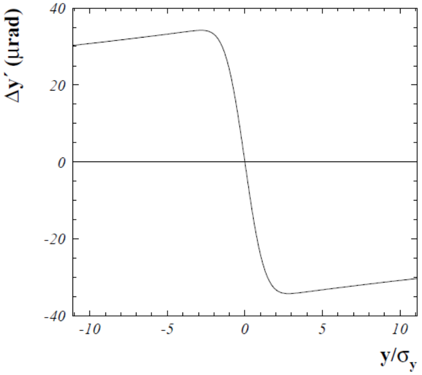
3) **Crab Waist: minimum of β_y along the axis of the opposite beam**

Advantages:

- ✓ **Impact of hour-glass is small and does not depend on bunch lengthening**
- ✓ **Suppression of betatron coupling resonances allows to achieve $\xi_y \sim 0.2$**
- ✓ **As a result, luminosity can be significantly increased especially at Z, otherwise $\xi_y \sim 0.03$**

Beam-beam parameter

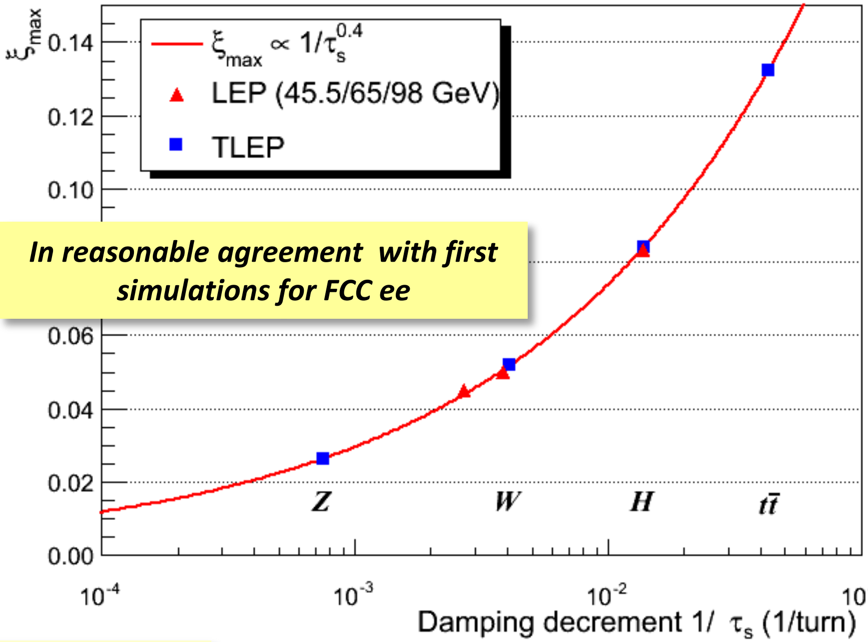
- **The beam-beam parameter ξ measures the strength of the field sensed by the particles due to the counter-rotating bunch.**
- **Beam-beam parameter limits are empirically scaled from LEP data (also 4 IPs).**



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{\max}(E)$$

$$\xi_y^{\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

$$\Rightarrow \quad L \propto \frac{P_{SR}}{E^{1.8}}\frac{1}{\beta_y^*}$$

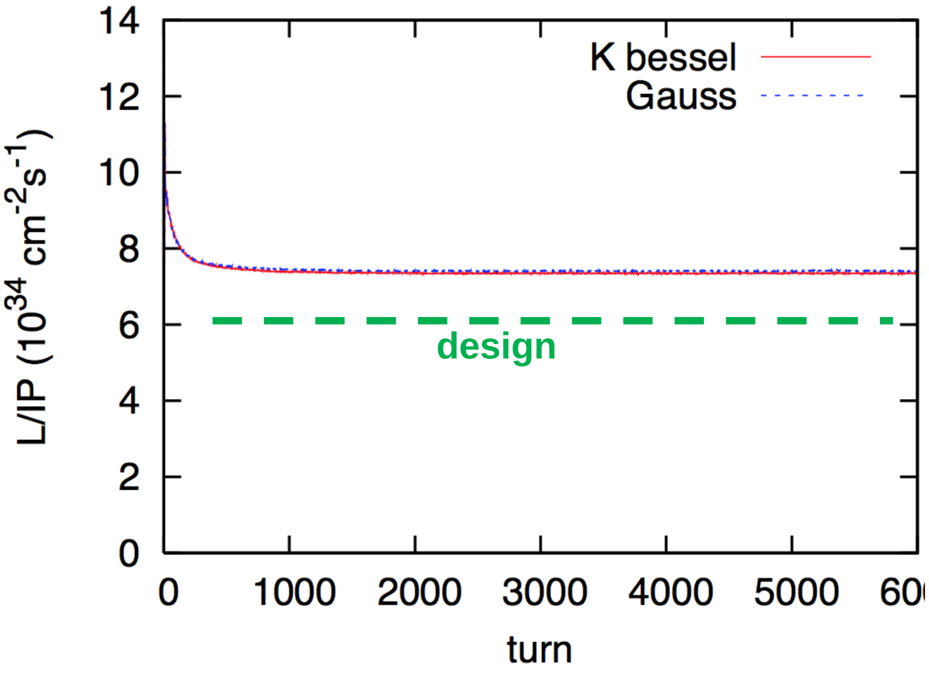


In reasonable agreement with first simulations for FCC ee

ξ_y and *L* may be raised significantly (x 4) with Crab-Waist schemes !

Beam-beam simulations

BBSS strong-strong simulation with beamstrahlung

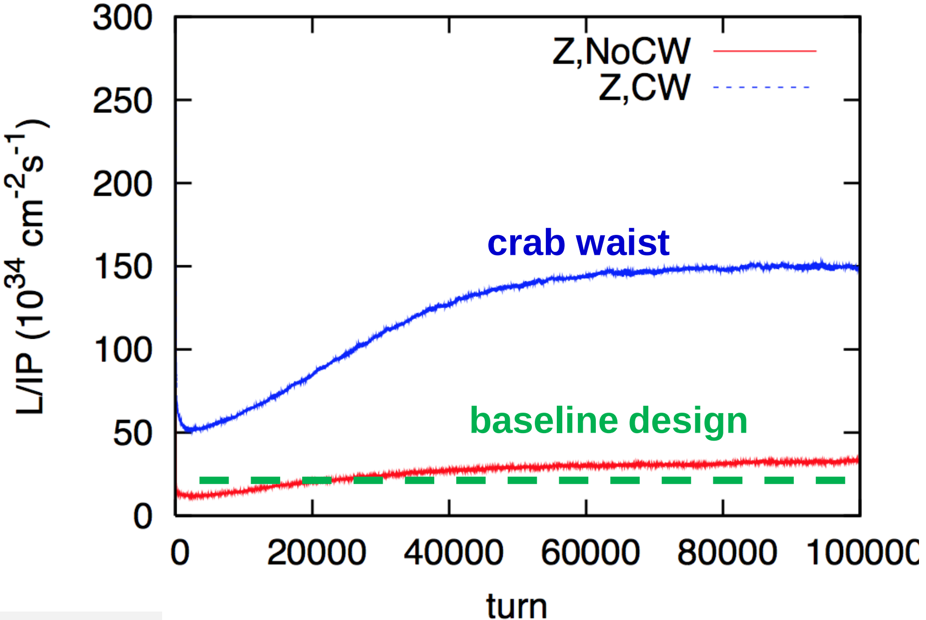


***FCC-ee* at 120 GeV:**

$L \approx 7.5 \times 10^{34}$ cm^{-2}s^{-1} per IP

***FCC-ee* in crab-waist mode at the Z pole (45.5 GeV):**

$L \approx 1.5 \times 10^{36}$ cm^{-2}s^{-1} per IP



Tracking confirms assumptions!

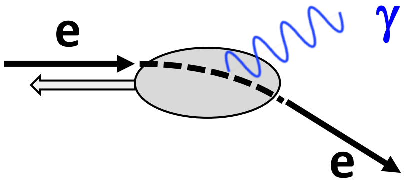
K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

Beamstrahlung

- **Hard photon emission at the IPs, '*Beamstrahlung*', can become a lifetime / performance limit for large bunch populations (N), small hor. beam size (σ_x) and short bunches (σ_s) .**

$$\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_s}\exp(A\eta\rho)$$

$$\frac{1}{\rho} \approx \frac{N r_e}{\gamma \sigma_x \sigma_s}$$



η : ring energy acceptance

$$L = \frac{f k N^2}{4\pi\sigma_x\sigma_y} F H$$

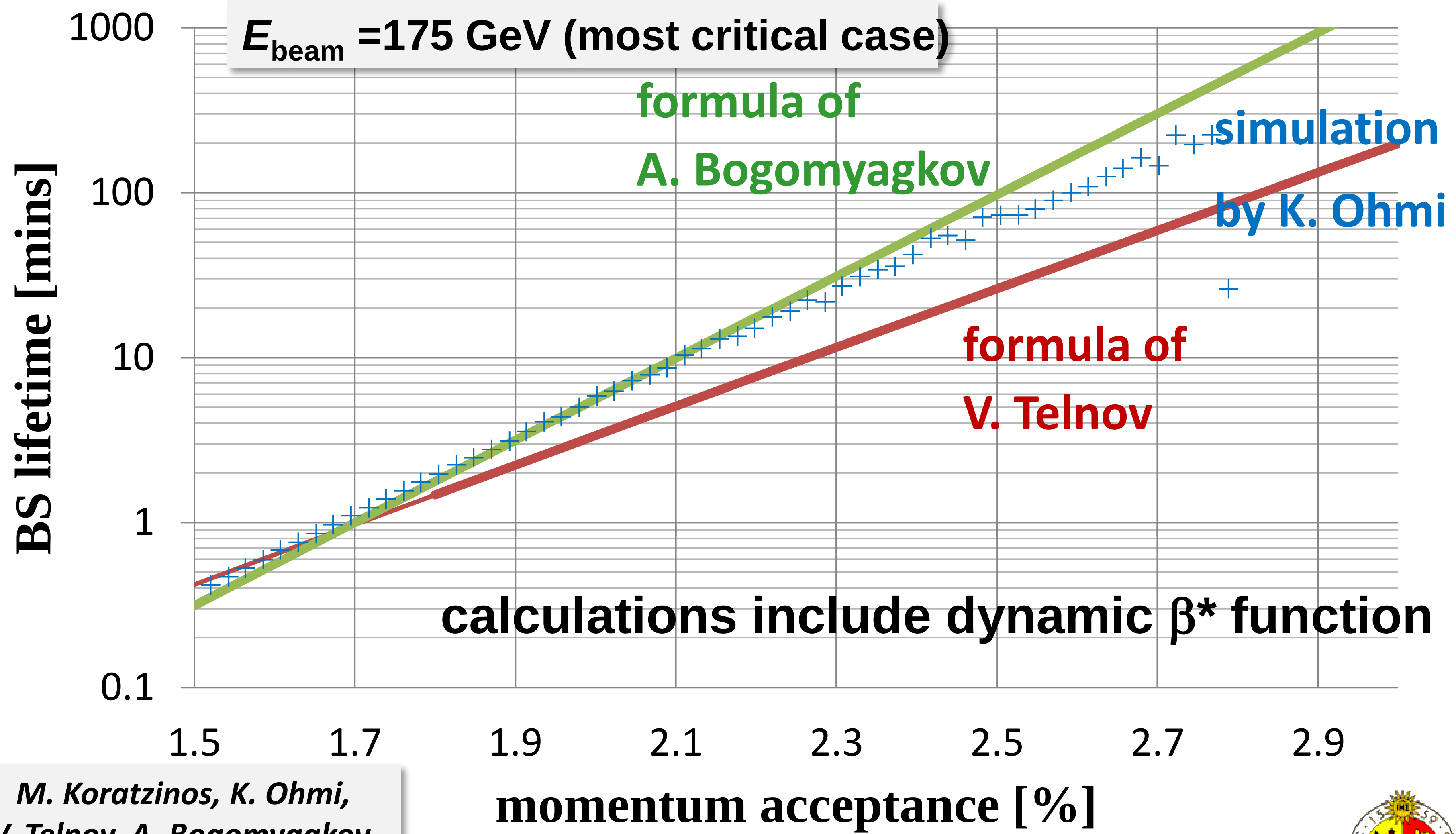
ρ : mean bending radius at the IP (in the field of the opposing bunch)

Lifetime expression by V. Telnov

- **To ensure an acceptable lifetime, ρ×η must be sufficiently large.**
  - **Flat beams : large σ_x and small σ_y !**
  - **Bunch length !**
  - **Large momentum acceptance of the lattice: 1.5 – 2% required.**
    - **LEP had < 1% acceptance, SuperKEKB ~ 1-1.5%.**

Beamstrahlung lifetime

Reasonable agreement between tracking and analytical estimates.



E_{beam} =175 GeV (most critical case)

calculations include dynamic β* function

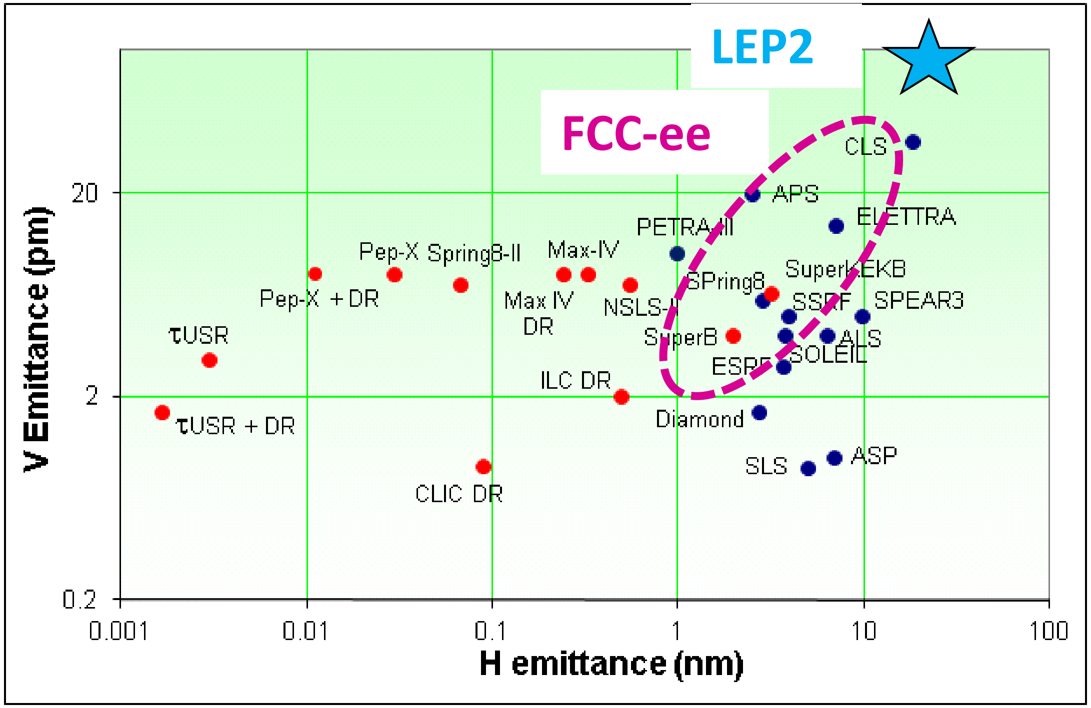
M. Koratzinos, K. Ohmi,
V. Telnov, A. Bogomyagkov,
E. Levichev, D. Shatilov

Emittances

- ❑ FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward.
  - **Coupling, spurious vertical dispersion.**
- ❑ Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings – beam-beam !

- ❑ FCC-ee parameters:
  - $\varepsilon_y/\varepsilon_x \geq 0.001$,
  - $\varepsilon_y \geq \approx 2$ pm

with a ring ~50-100 larger than a typical light source.



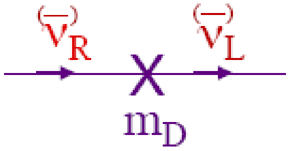
R. Bartolini, DIAMOND

- ❑ Very challenging target for a ring of that size!
- ❑ LEP2 achived routinely 0.004

beam corrections are much better now.

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

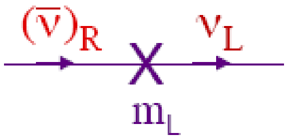
$m_D \nu_L \overline{\nu_R}$ $m_D \overline{\nu_L} \nu_R$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry </u>prevents adding then a term like

$$m_M \overline{\nu_R{}^c} \nu_R$$



and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

It is perfectly conceivable ('natural'?) that both terms are present ➔ 'see-saw'