Long Term Strategy Workshop – CSN1
Isola d’Elba, 22nd May

Standard Model Physics at the **F**uture **C**ircular **C**ollider **FCC-ee** / **FCC-hh**

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

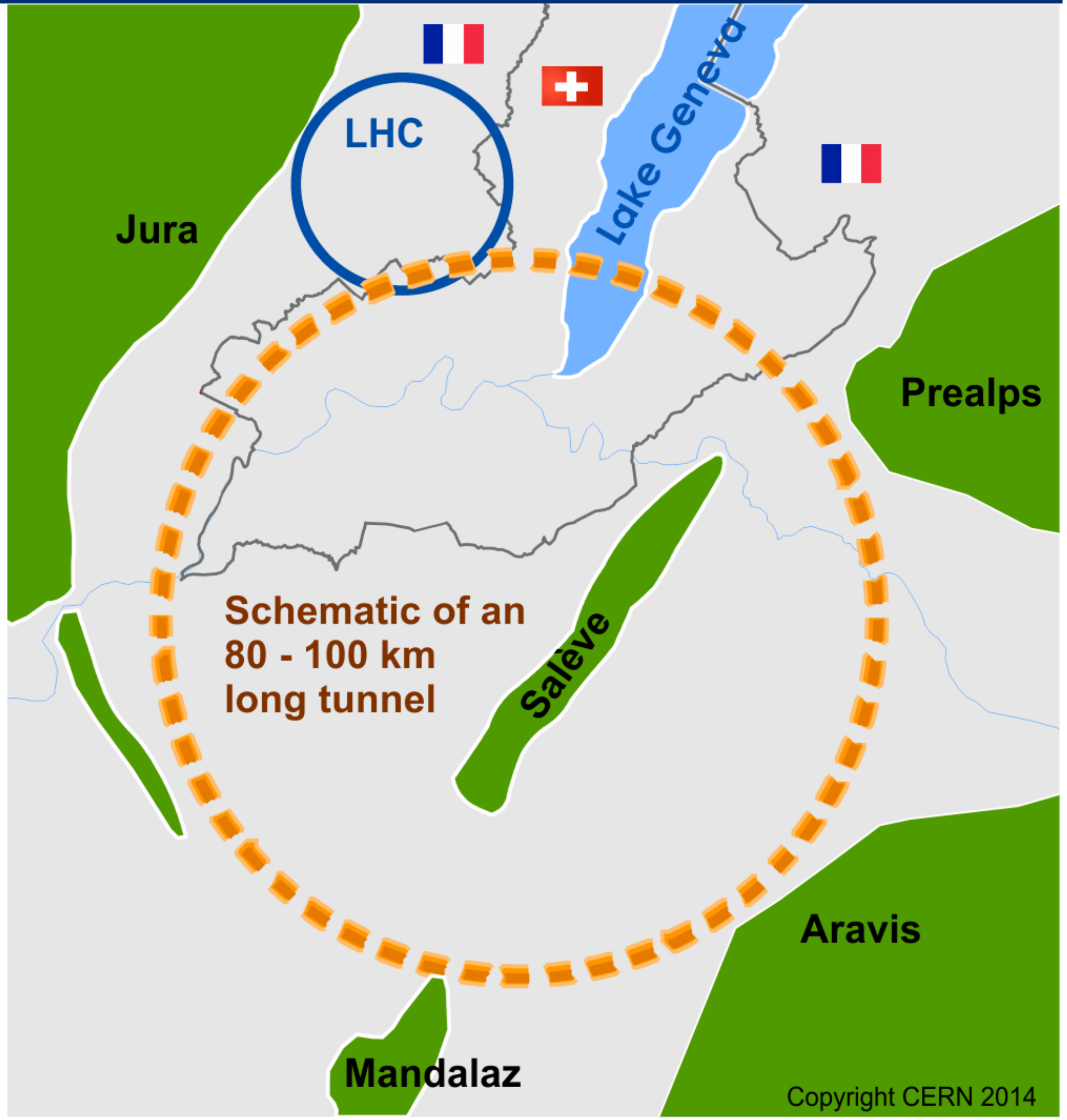
Forming an international collaboration to study:

•***pp*-collider (*FCC-hh*)**
Ultimate goal
→ defining infrastructure requirements

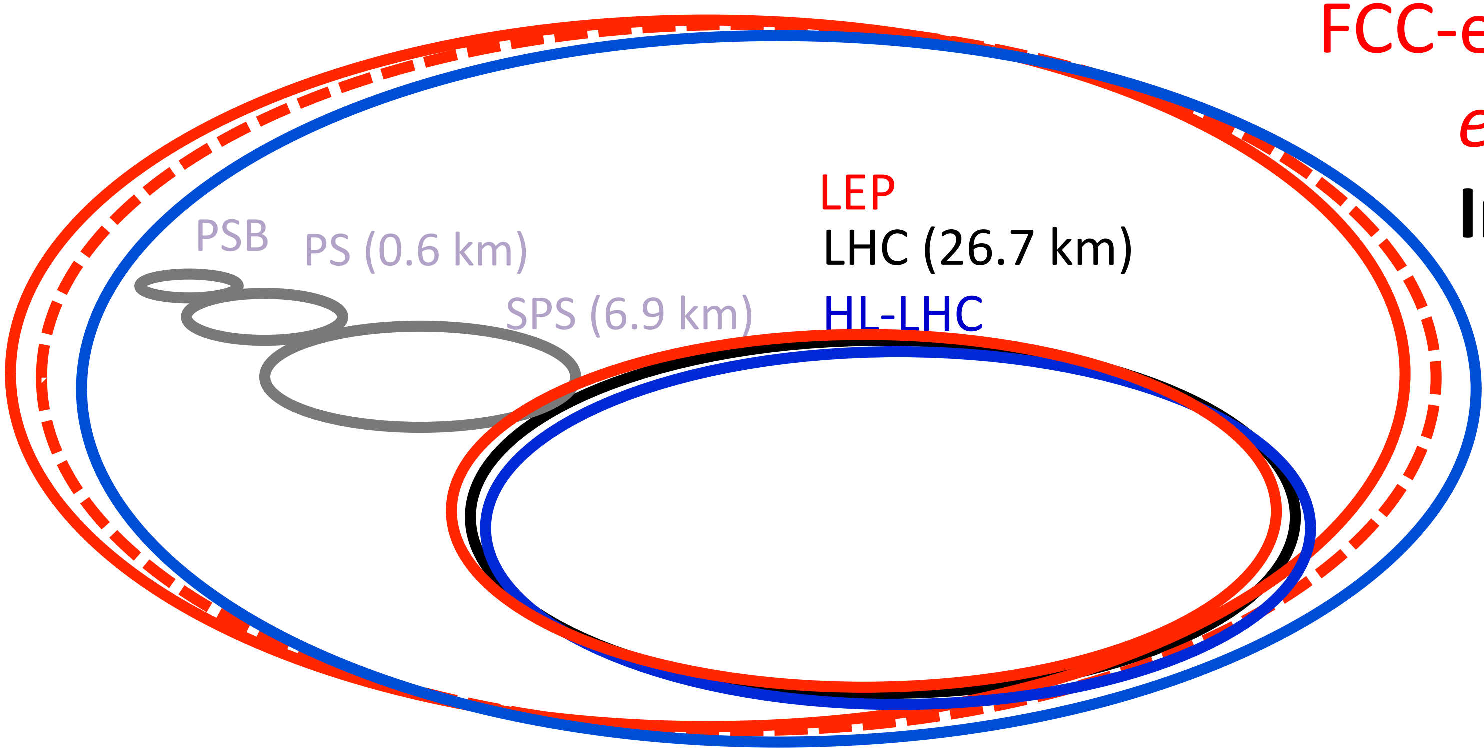
•***e^+e^-* collider (*FCC-ee*)** as potential intermediate step

•***p-e* (*FCC-he*) option**

•**80-100 km infrastructure** in Geneva area



possible long-term strategy



FCC-ee (80-100 km,
e^+e^-, 90-350 GeV

Interm. step

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

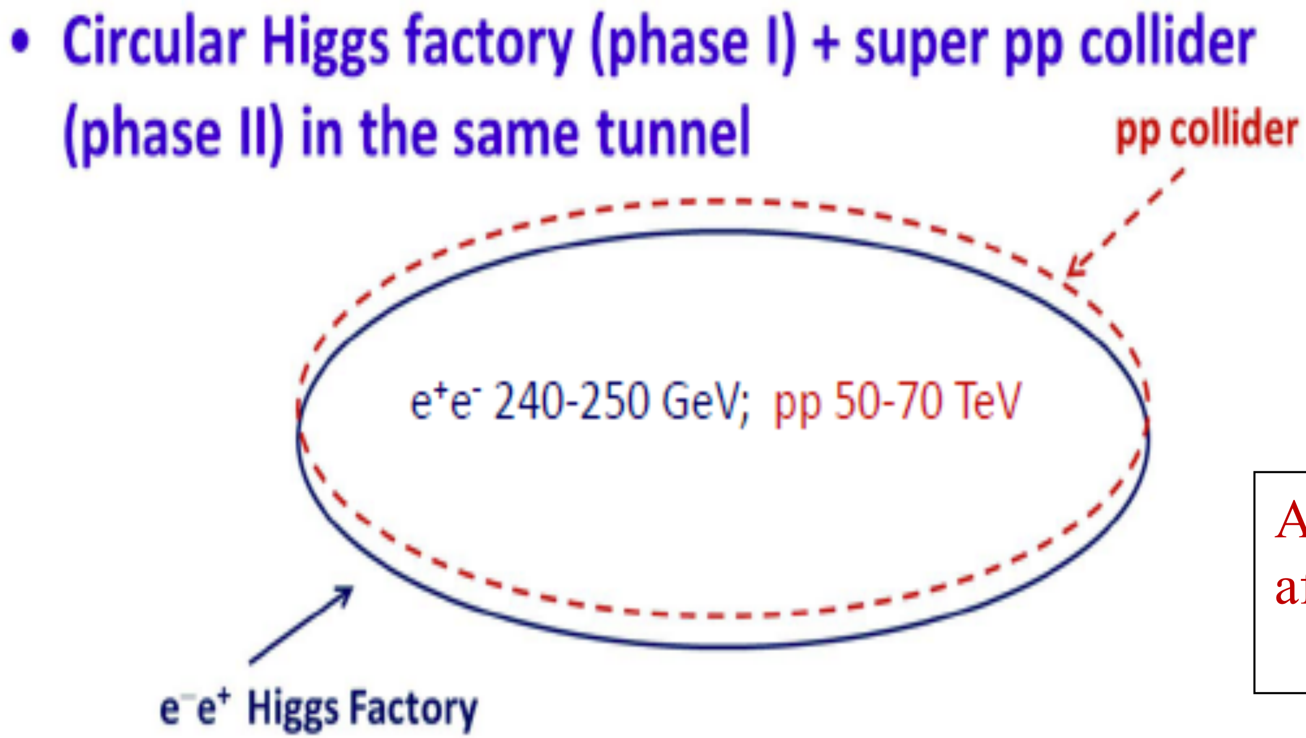
Ultimate goal

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

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

Chinese proposal: CEPC+SppC

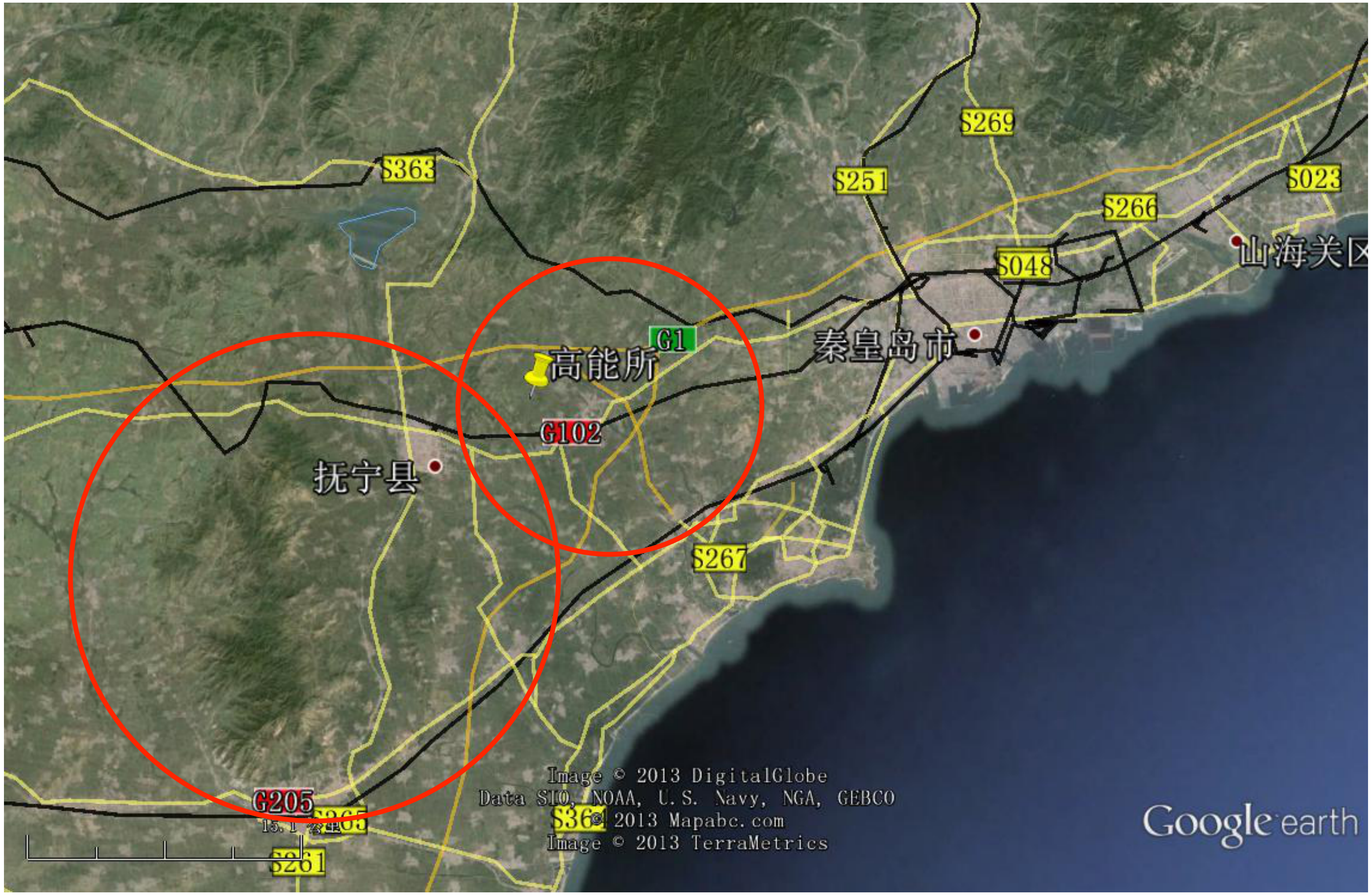
- “What can be done after BEPCII in China”
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC +SppC configuration was proposed in Sep. 2012



A 50-70 km tunnel is very affordable in China NOW

Site in China

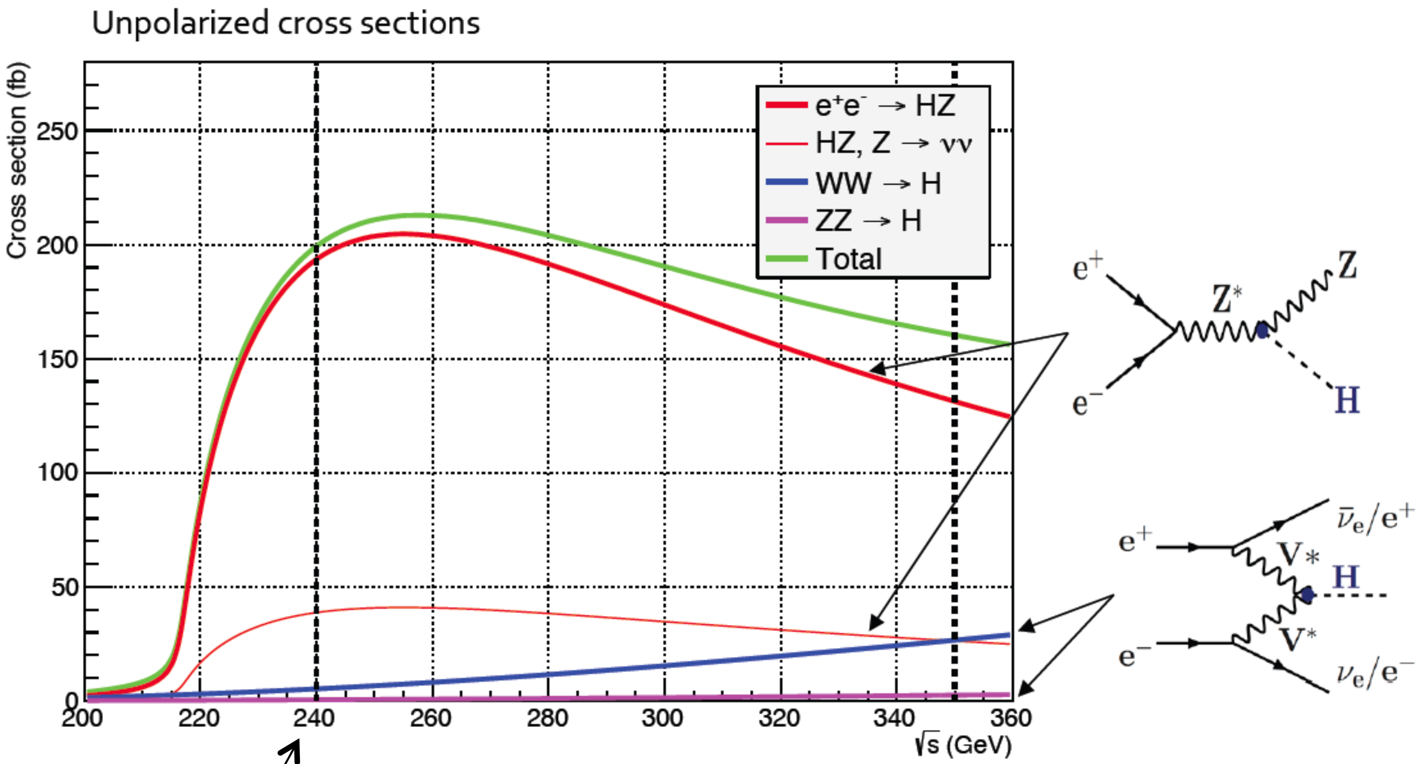
- Preliminary selected: Qinhuangdao (秦皇岛）
- Strong support by the local government



e+e- circular colliders revitalized by Higgs discovery

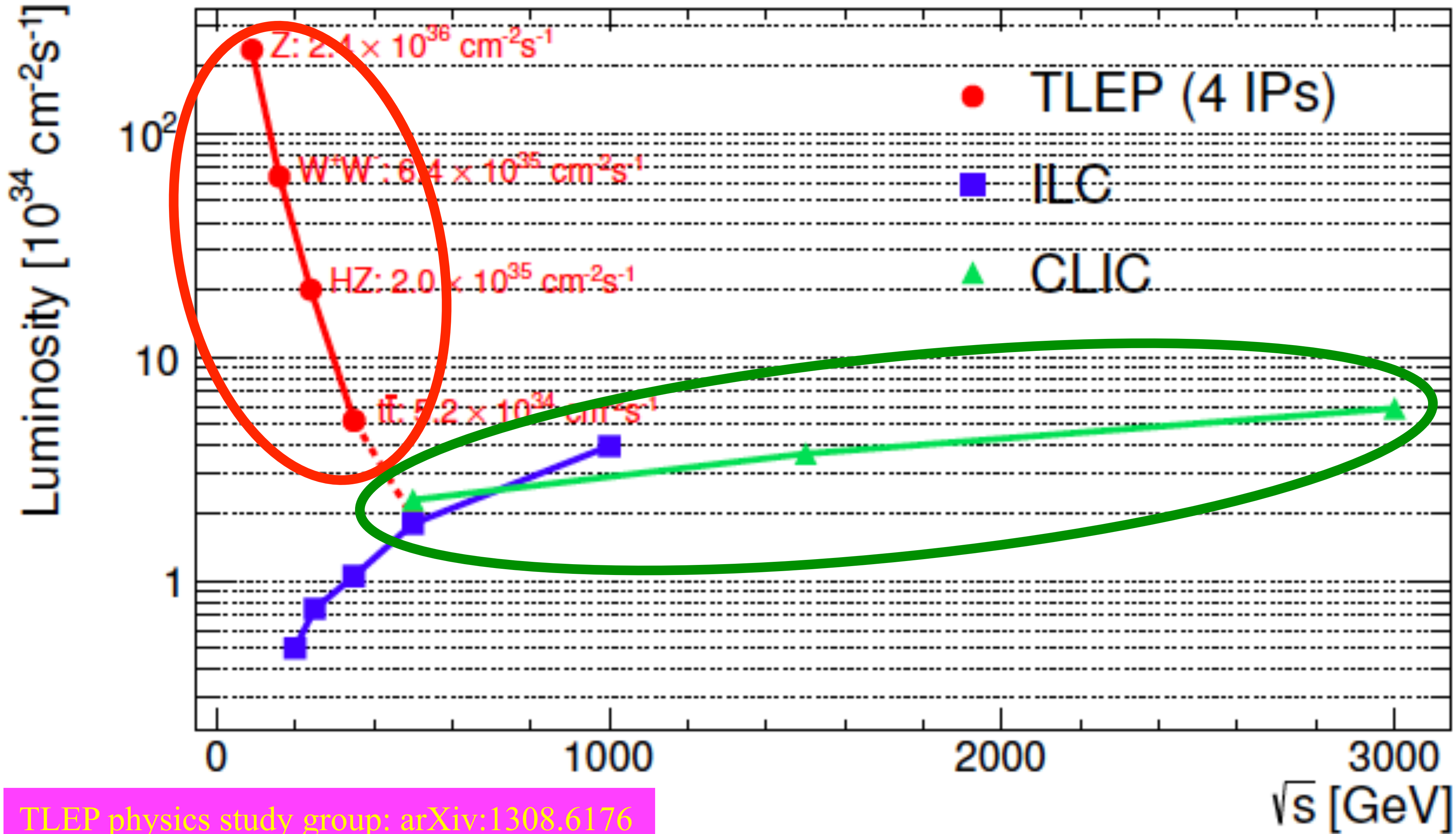
- The Higgs mass is low: at LEP we were close … sensitive up to 115 GeV, (125/115=1.09)
- Synchrotron energy loss per turn goes as E^4/ρ , if you increase the radius by a factor 3 you have $(1.09)^3/3=0.43$ showing that RF cavities "a la LEP" would be enough
- A two-step plan is rather natural
  - Build a tunnel and fill it with a e+e- circular collider
  - When 16 T (20 T) magnets can be produced use the tunnel for a 100 TeV pp collider

Optimal energy for Higgs factory operation



The optimal energy in a circular collider is a bit lower than the maximum because of the E^3 falling spectrum of luminosity

Projected e^+e^- Colliders: Luminosity vs Energy



TLEP physics study group: arXiv:1308.6176

FCC-ee main baseline parameters

- Different optimizations are possible within ΔL/L ~30-50%.
  - *No. bunches ⇔ bunch population, emittances …*

Parameter	**Z**	**W**	**H**	**t**	**LEP2**
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16’700	4’490	1’330	98	4
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (pm)	60	7	2	2	~250
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})	**28**	**12**	**6.0**	**1.8**	**0.012**

FCC-ee physics goals

- Provide highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold.
  - *Beam energy range from 45 GeV to 175 GeV.*

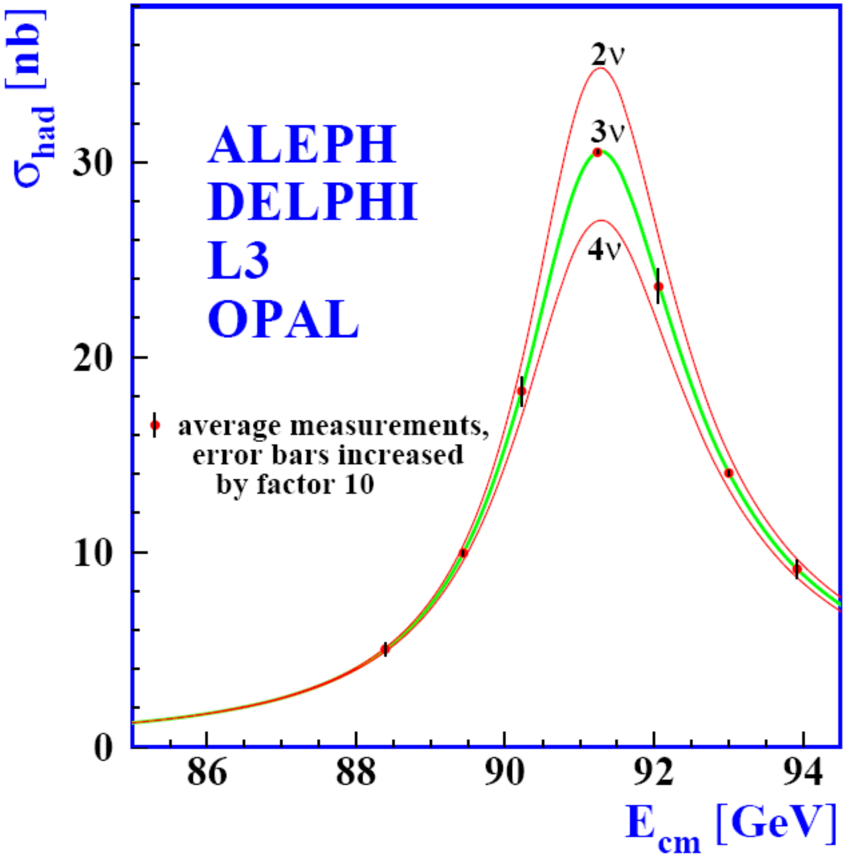
- Main physics programs / energies (+ scans around central values):
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production threshold,*
  - *t (175 GeV): $t\bar{t}$ threshold.*

↑

beam energy

TeraZ: high precision M_Z and Γ_Z

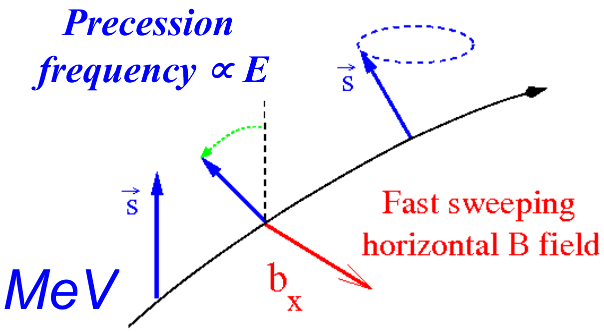
- Measure the Z lineshape by accumulating 10^{12} Z bosons in a energy scan
- At LEP reached $\sim 2 \cdot 10^{-5}$ and gained a lot of experience on **centre-of-mass energy determination with resonant depolarization**
- Could potentially reach $\sim 10^{-6}$ (100 keV on M_Z)



Polarization

Two main interests for polarization:

- Accurate energy calibration using resonant depolarization ⇒ measurement of M_Z, Γ_Z, M_W
  - *Nice feature of circular machines, δM_Z, $\delta \Gamma_Z$ ~ 0.1 MeV*



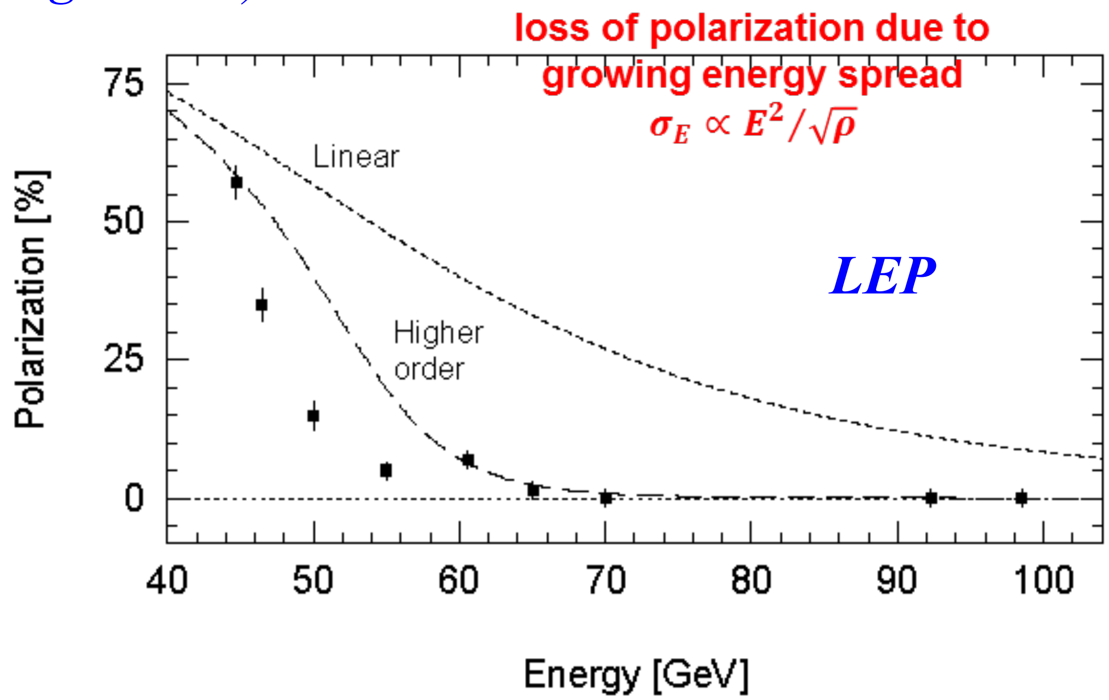
- Physics with longitudinally polarized beams.
  - *Transverse polarization must be rotated in the longitudinal plane using spin rotators (see e.g. HERA).*

Scaling the LEP observations :

polarization expected up to the WW threshold !

Integer spin resonances are spaced by 440 MeV:

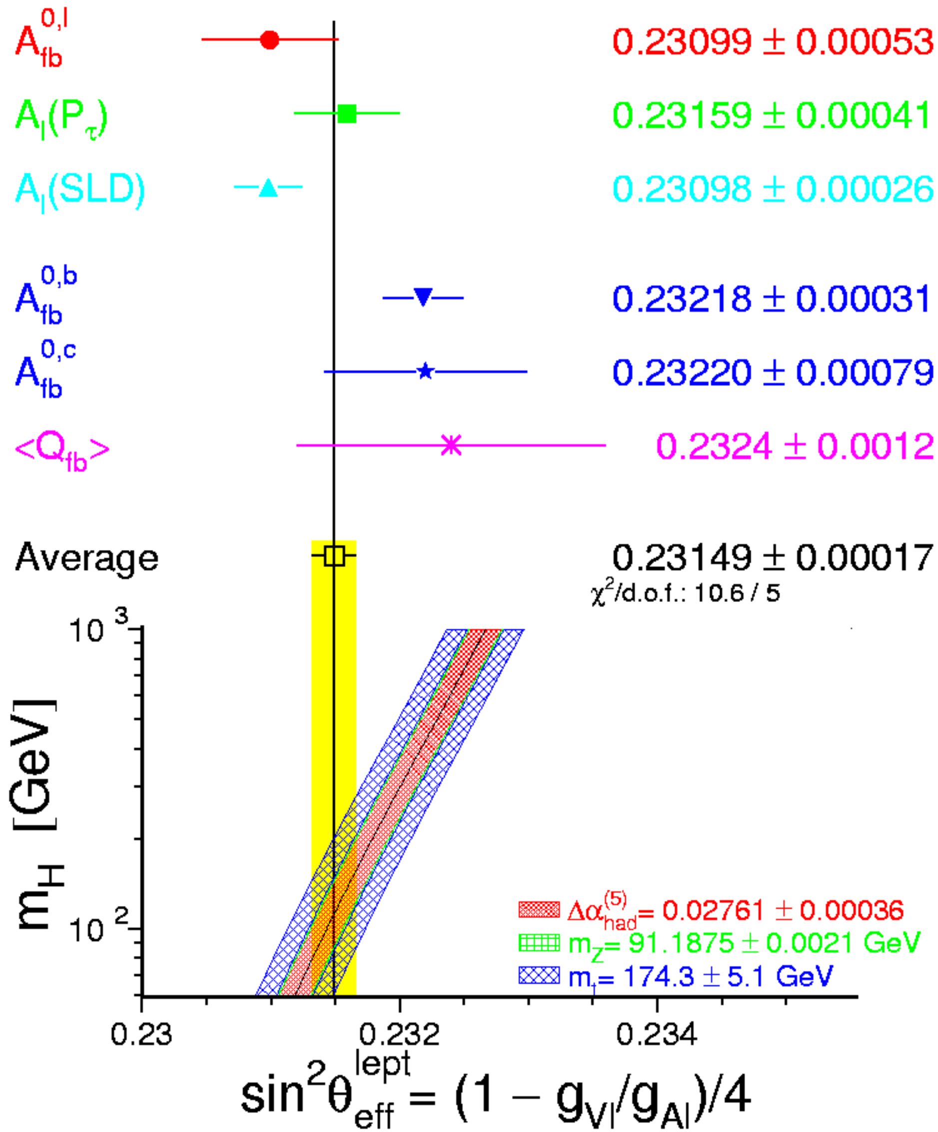
energy spread should remain below ~ 60 MeV



TeraZ: final word on Asymmetries !

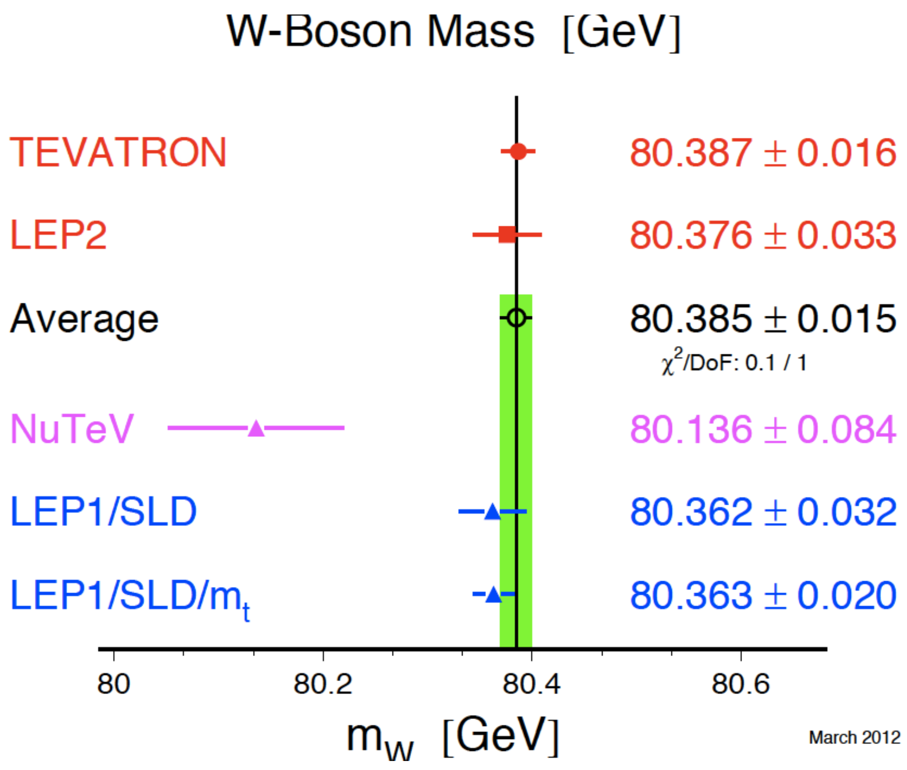
- Long standing difference between Alr and A_{FB}(b), **it must be sorted out**
- measurement of Alr with polarized beams (both beams, 4 measurements = no dependence on polarization)
- direct measurement of the b couplings (again need polarization)
- Could potentially reach $\sim 10^{-6}$ on sin2theta

$\sin^2\theta_{eff}^{l}$



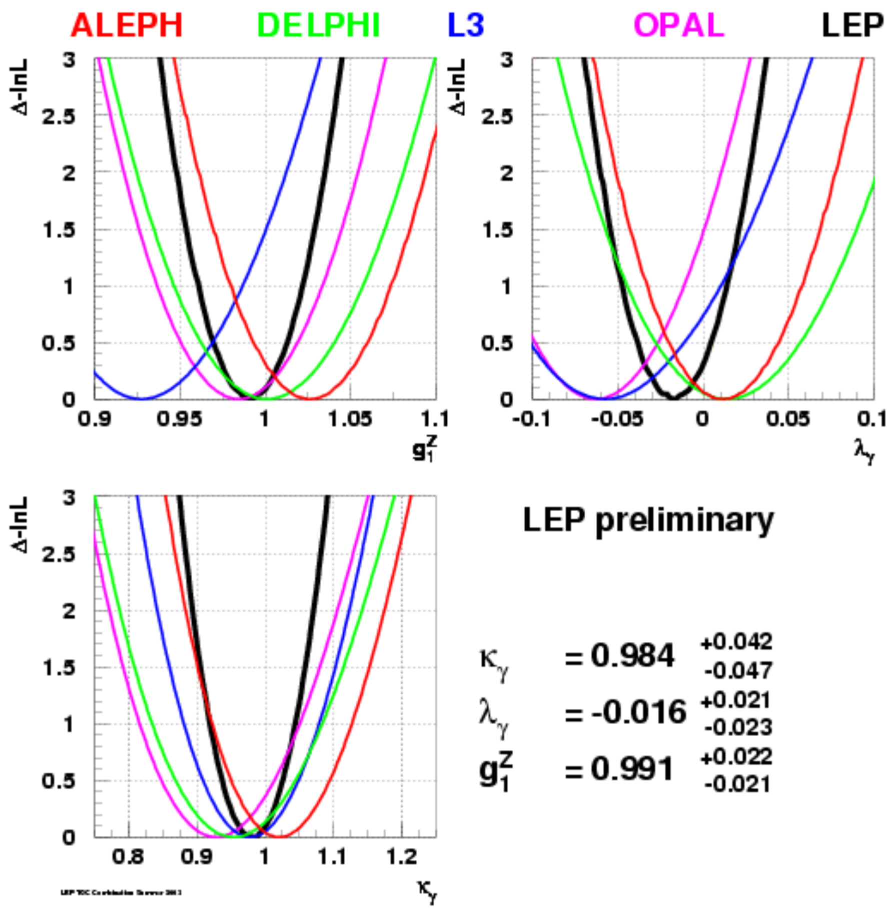
160 GeV: Measurement of the W mass

- Perform a precise measurement from the WW threshold scan
  Could potentially reach ~ 0.5 MeV
- Revisit the LEP2 method of direct reconstruction (there is room for improvement, e.g. beam energy, large statistics on semileptonic events, etc.)



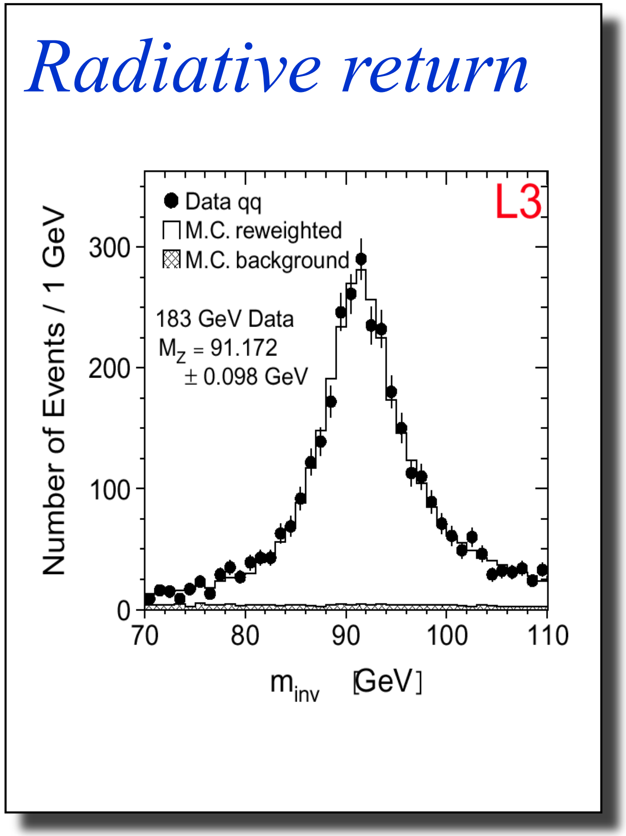
triple and quartic boson couplings

- Great potential for multi-gauge-boson production (di-boson WW, ZZ, Zγ or γγ production, but also tri-boson production like WWγ, WWZ, γγγ, WWH, etc.)



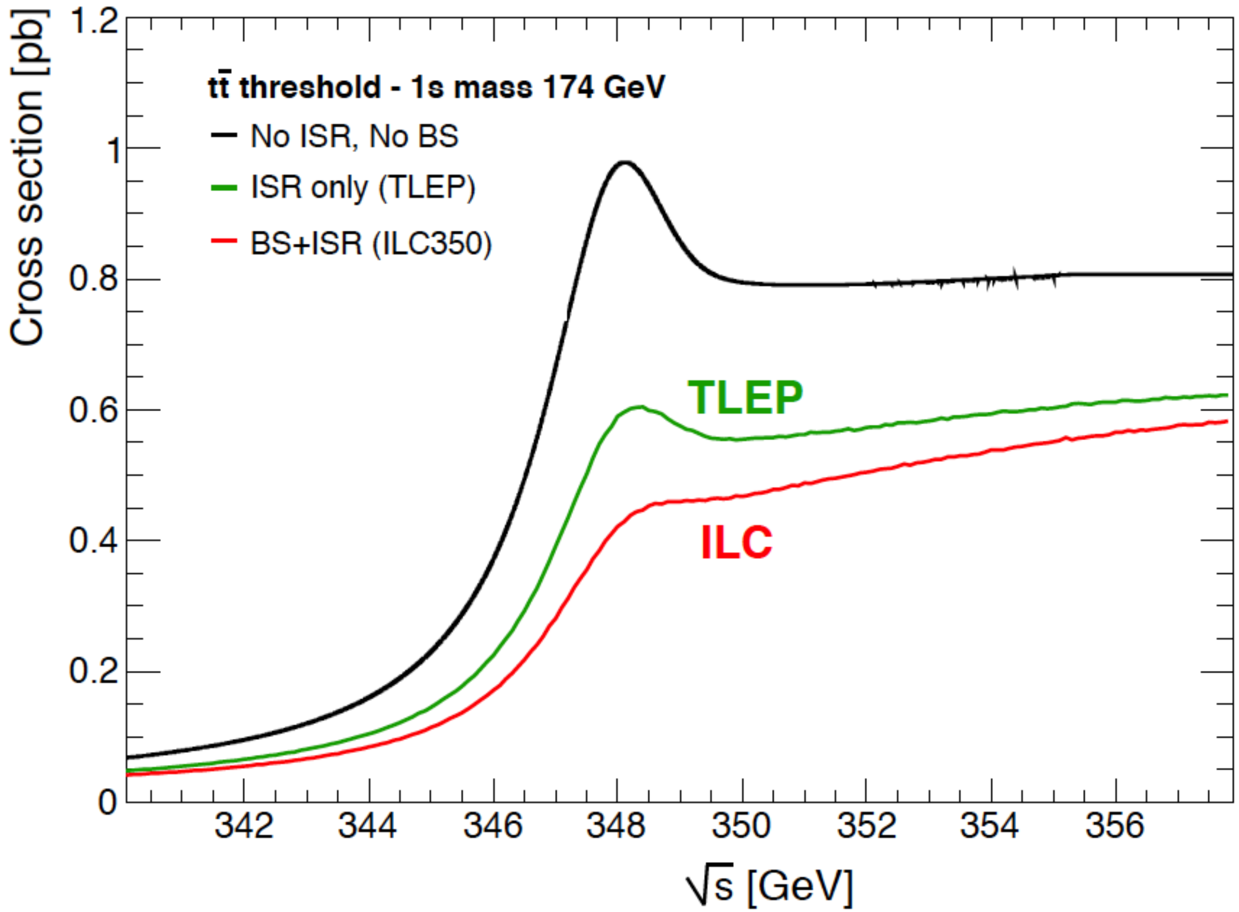
The Z invisible width and Z radiative returns

- Number of neutrino families from LEP Nv=2.984±0.008
- Potential to improve the measurement to ±0.001 with $e^+e^- \rightarrow Z\gamma$
- Include study of sterile neutrinos



350 GeV: the top mass

- Advantage of a very low level of beamstrahlung
- Could potentially reach 10 MeV uncertainty on m_top



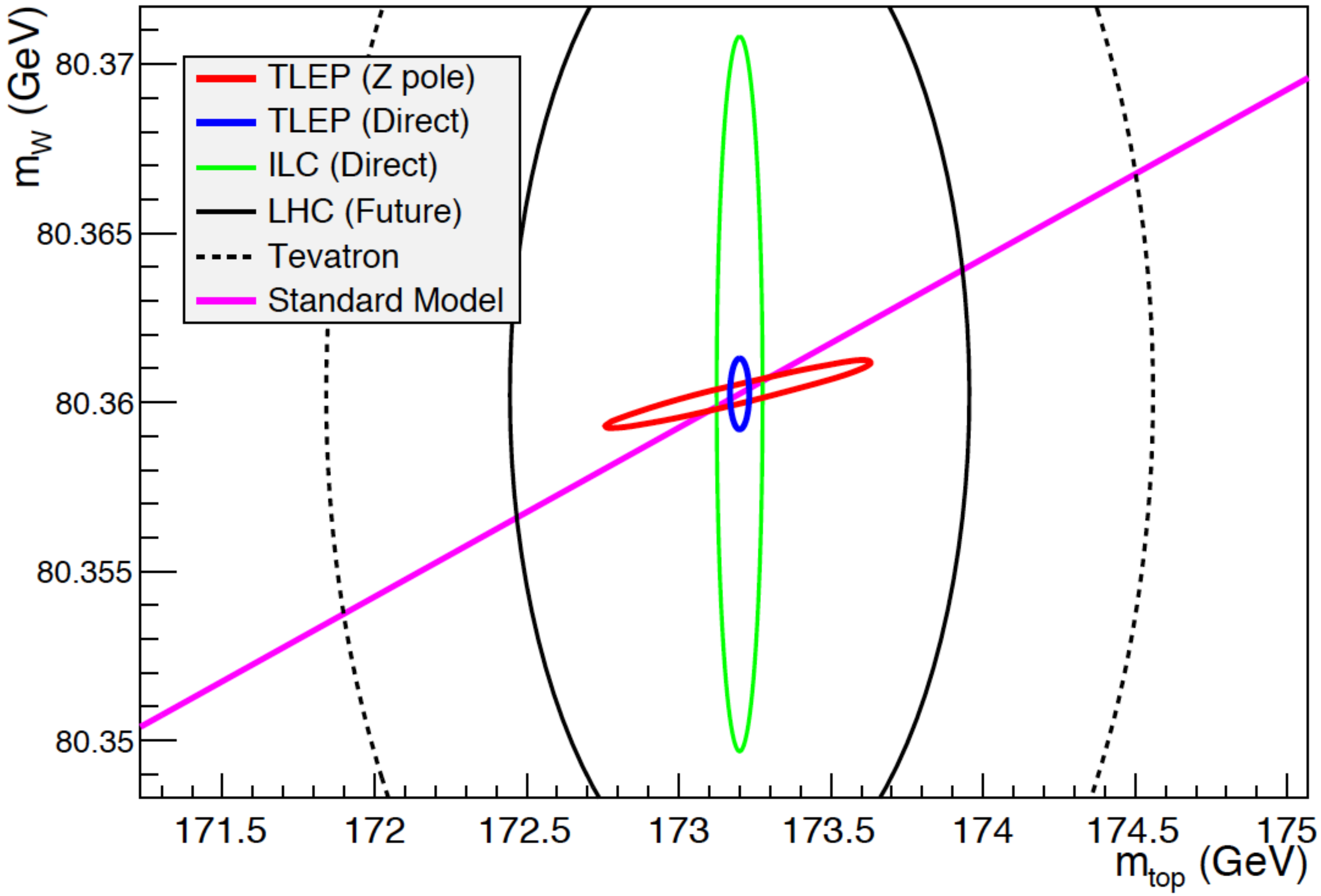
Summary for EWK precision measurements at FCC-ee

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_{Z} (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV	E_{beam} calibration	QED corrections
Γ_{Z} (keV)	$\Delta\rho$ (not $\Delta\alpha_{\mathrm{had}}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV	E_{beam} calibration	QED corrections
R_{ℓ}	$\alpha_{\mathrm{s}}, \delta_{\mathrm{b}}$	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_{ν}	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_{ν}	... and sterile ν's	2.92 ± 0.05	$\mathrm{Z}\gamma$, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_{b}	δ_{b}	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\mathrm{had}}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_{W} (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\mathrm{had}}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$\mathrm{t\bar{t}}$ threshold scan	10 (12) MeV	< 10 MeV	Statistics	Theory interpretation

From arXiv:1308.6176

Possible evolution of EWK data

… it does not need to be centered to the SM, after predicting top and Higgs mass will we have predicting power for NP ?



240 GeV and above: Higgs Couplings and Properties

Coupling	TLEP
g_{HZZ}	**0.15%** (0.18%)
g_{HWW}	**0.19%** (0.23%)
$g_{Hb\bar{b}}$	**0.42%** (0.52%)
$g_{Hc\bar{c}}$	**0.71%** (0.87%)
g_{Hgg}	**0.80%** (0.98%)
$g_{H\tau\tau}$	**0.54%** (0.66%)
$g_{H\mu\mu}$	**6.2%** (7.6%)
$g_{H\gamma\gamma}$	**1.5%** (1.8%)
BR_{exo}	**0.45%** (0.55%)

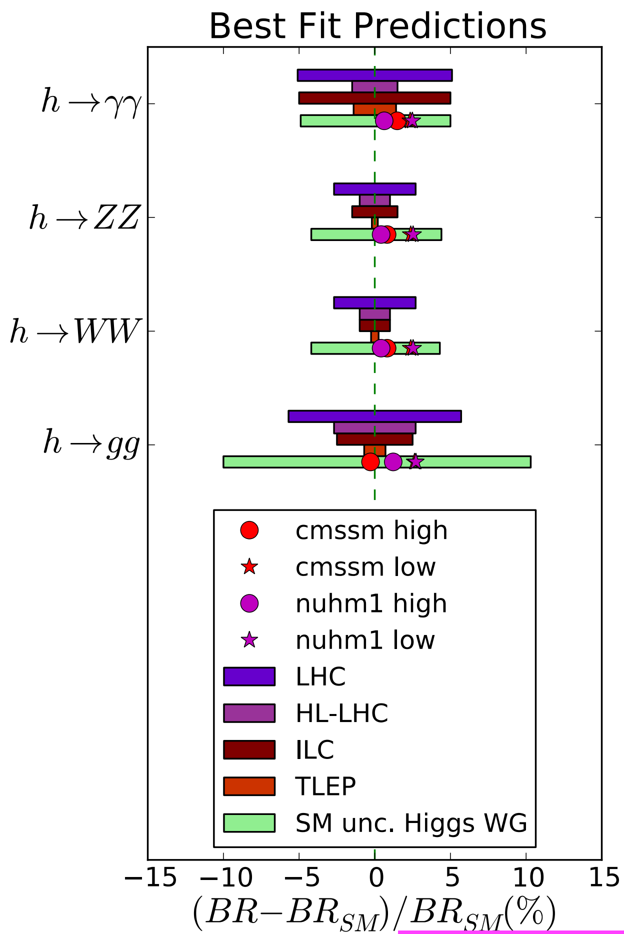
Relative statistical uncertainty on the Higgs boson couplings for data taken at 240 and above

- The numbers between brackets indicates the uncertainties expected with two detectors instead of four.
- The last line gives the absolute uncertainty on the Higgs boson branching fraction to exotic particles (invisible or not).

Impact of Higgs Measurements

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - LHC
  - HL-LHC
  - ILC
  - TLEP (= FCC-ee)

  (Able to distinguish from SM)



K. De Vries (MasterCode)

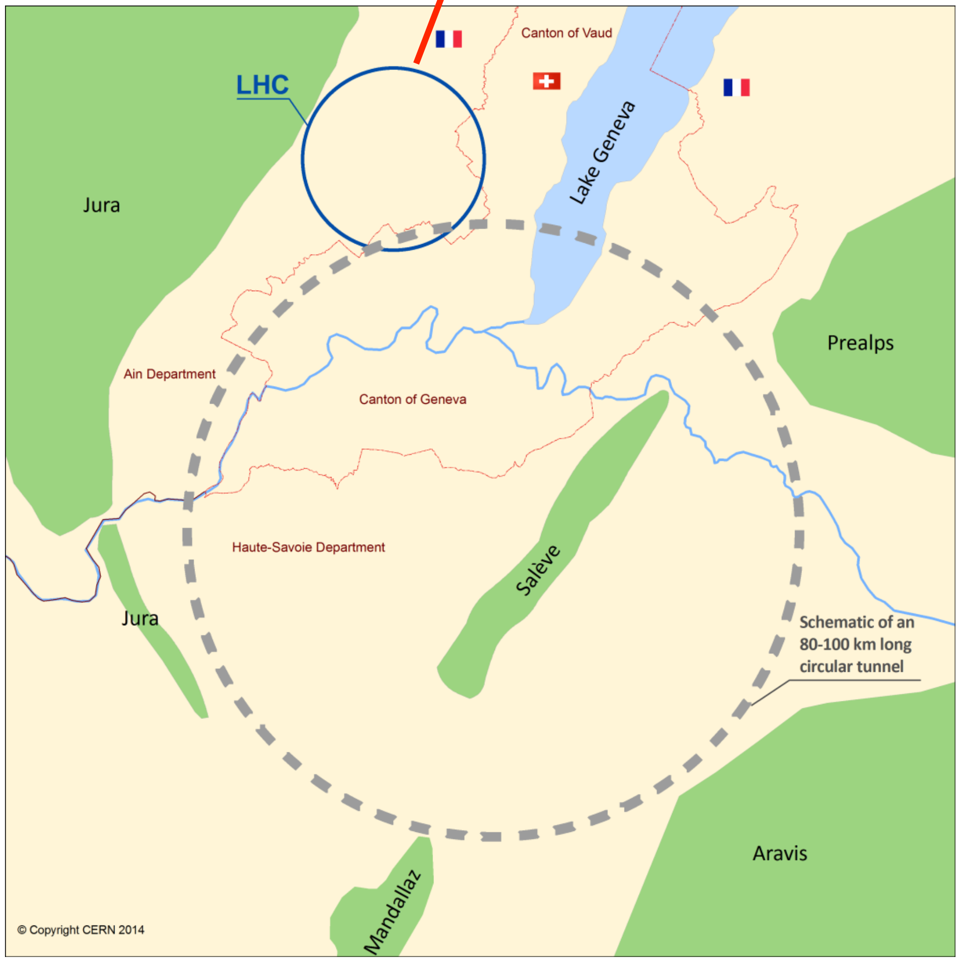
FCC-hh : "High Energy LHC"

HE-LHC :33 TeV with 20T magnets

First studies on a new 80 km tunnel in the Geneva area

- **42 TeV with 8.3 T using present LHC dipoles**
- **80 TeV with 16 T based on Nb_3Sn dipoles**
- **100 TeV with 20 T based on HTS dipoles**

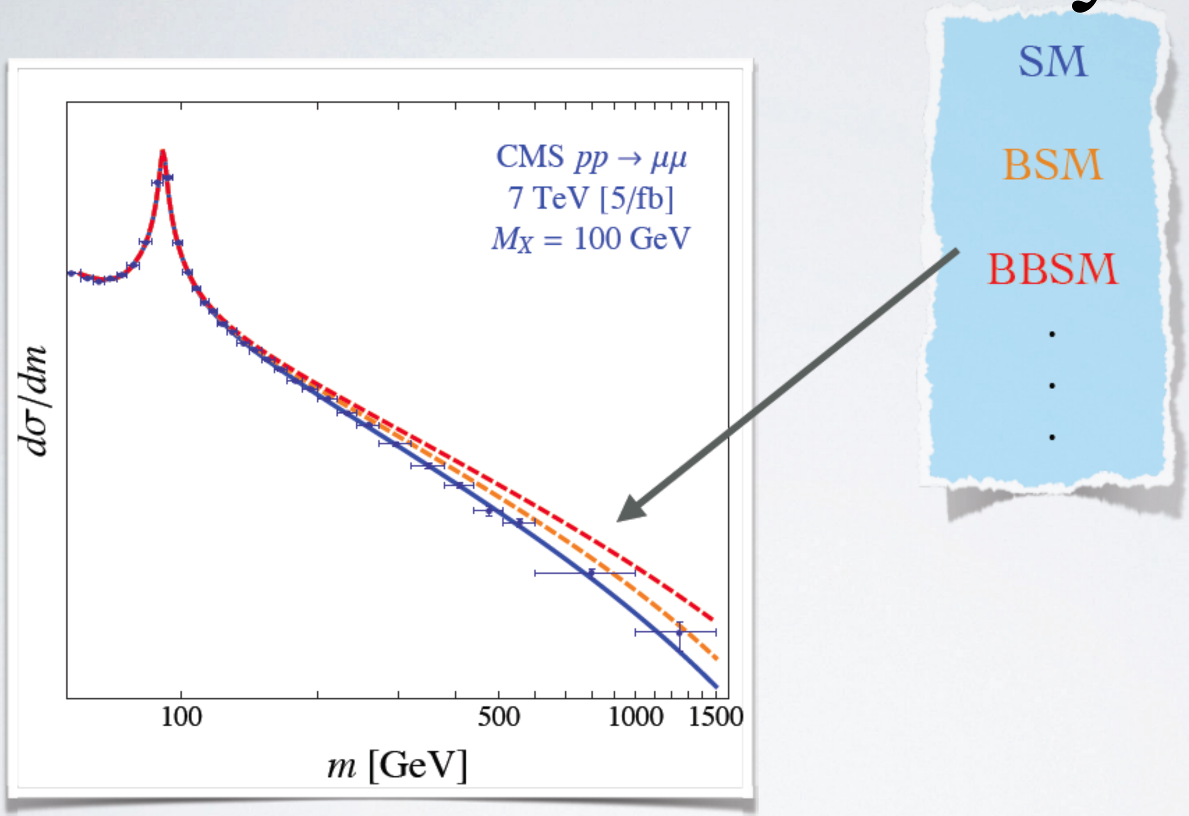
16 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km



Standard Model Physics at FCC-pp

- Clearly, FCC-pp is a **discovery** machine
- Nevertheless there is a great potential to complement discovery with SM measurements, e.g.
  - Use of DY production to study the running of the EWK coupling constants
  - Study of top properties (including single top) and rare top decays
  - Study of "hyper-boosted objects", e.g. W, top, higgs
  - Cross section ratios to measure Higgs couplings at the permil level

Coupling evolution in Drell Yan: effect of New Physics

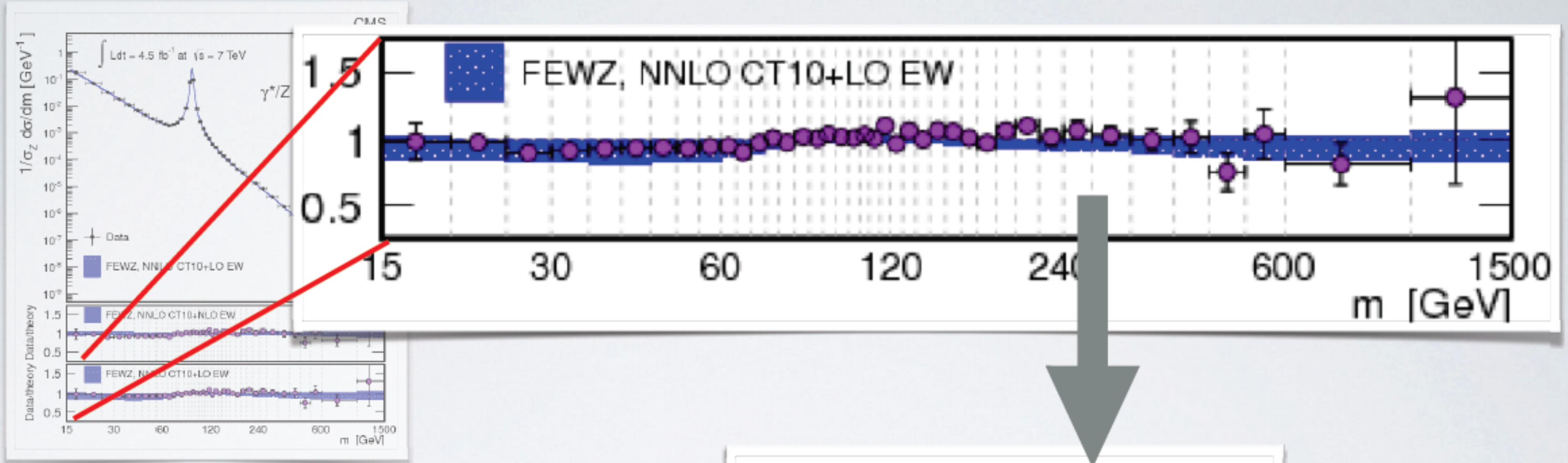


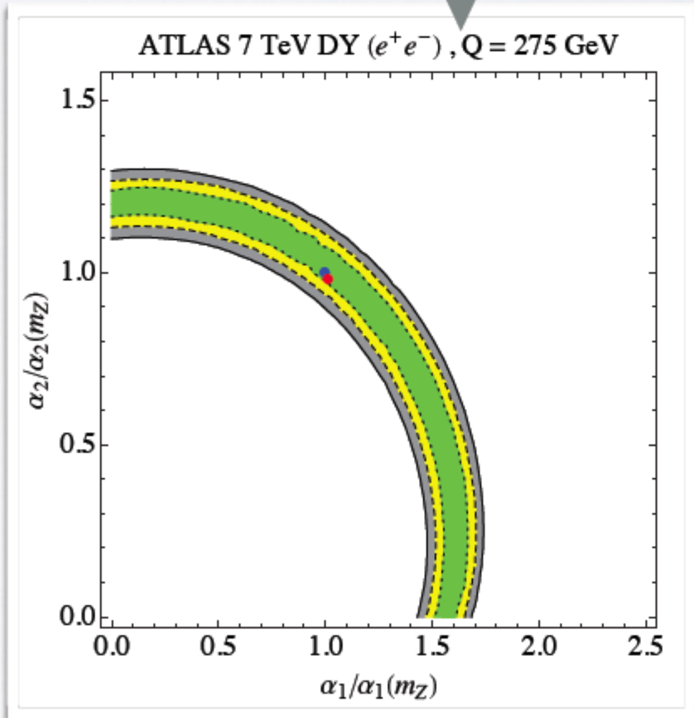
Jamison Galloway

Workshop on Physics at a 100 TeV Collider
SLAC: April 23-25, 2014

GAUGE COUPLINGS AT A HADRON MACHINE

Drell-Yan: clean final state, sensitive to $\alpha_{1,2}$ (and deviations therein)





Starting simple:
fit couplings within
a given bin

Personal Final Remarks

- We are not facing a "standard", but an "exceptional" model, it must be challenged with higher precision.
- We hope to see soon signals of new physics, but is unlikely that a full scenario will appear at short-medium term.
- At this point an e^+e^- machine, allowing very high precision measurements of electroweak observables and a very detailed study of the Higgs boson is a mandatory NEXT to pave the way to NEXT high energy hadron collider