FCC
hh ee he

Potentially the first step
in the FCC history

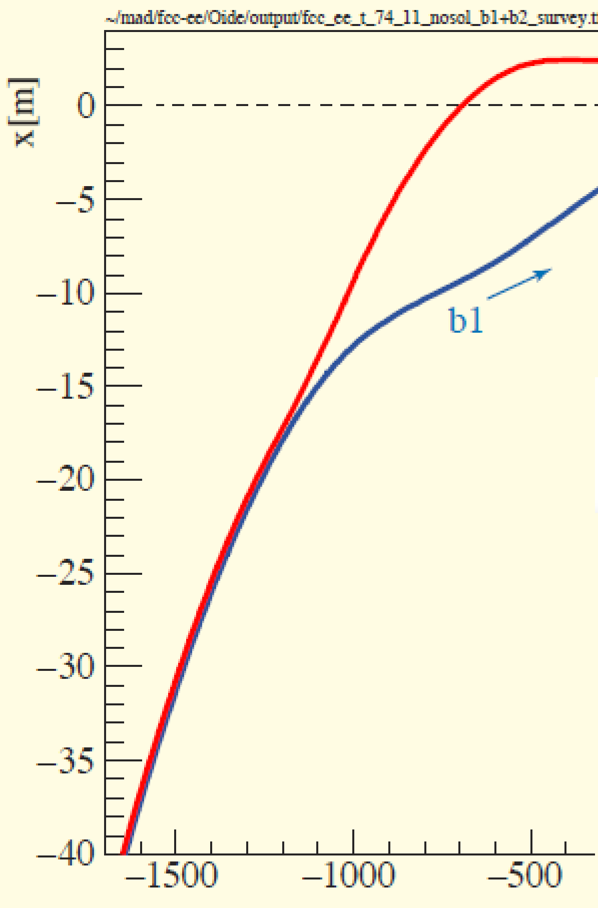
Experiments at FCC-ee

Sessions : -- MDI on Tuesday 8:30
-- FCC-ee experiments on Thursday 13:30-17:00

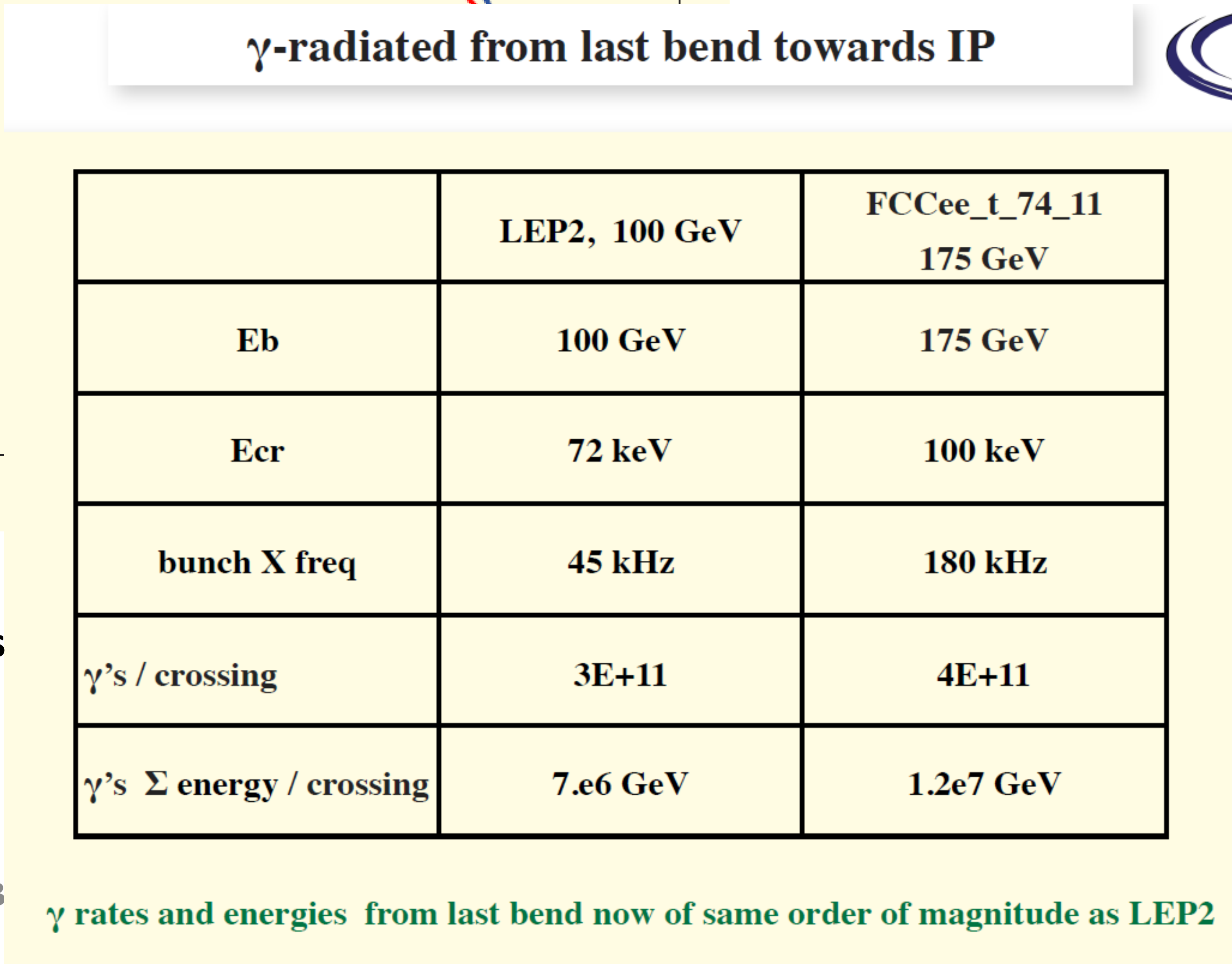
Some of the main Challenges

M. Boscolo

- Synchrotron Radiation is the main constraint for IR design and it drives the IR optics and layout.
- Feasibility of magnetic system -main detector magnet, final focus elements, compensation magnets- has to be investigated, also with R&D.
- Luminosity measurement, as well as other particle detectors, are part of the IR design, challenge: very close to IP.
- Accelerator and IP Backgrounds: full simulation to check detector sustainability and design proper masking.
- Underground infrastructure is a challenge it itself, of course, together with MDI group compatibility with FCC-hh option has to be assured.



H. Burkhardt



γ-radiated from last bend towards IP

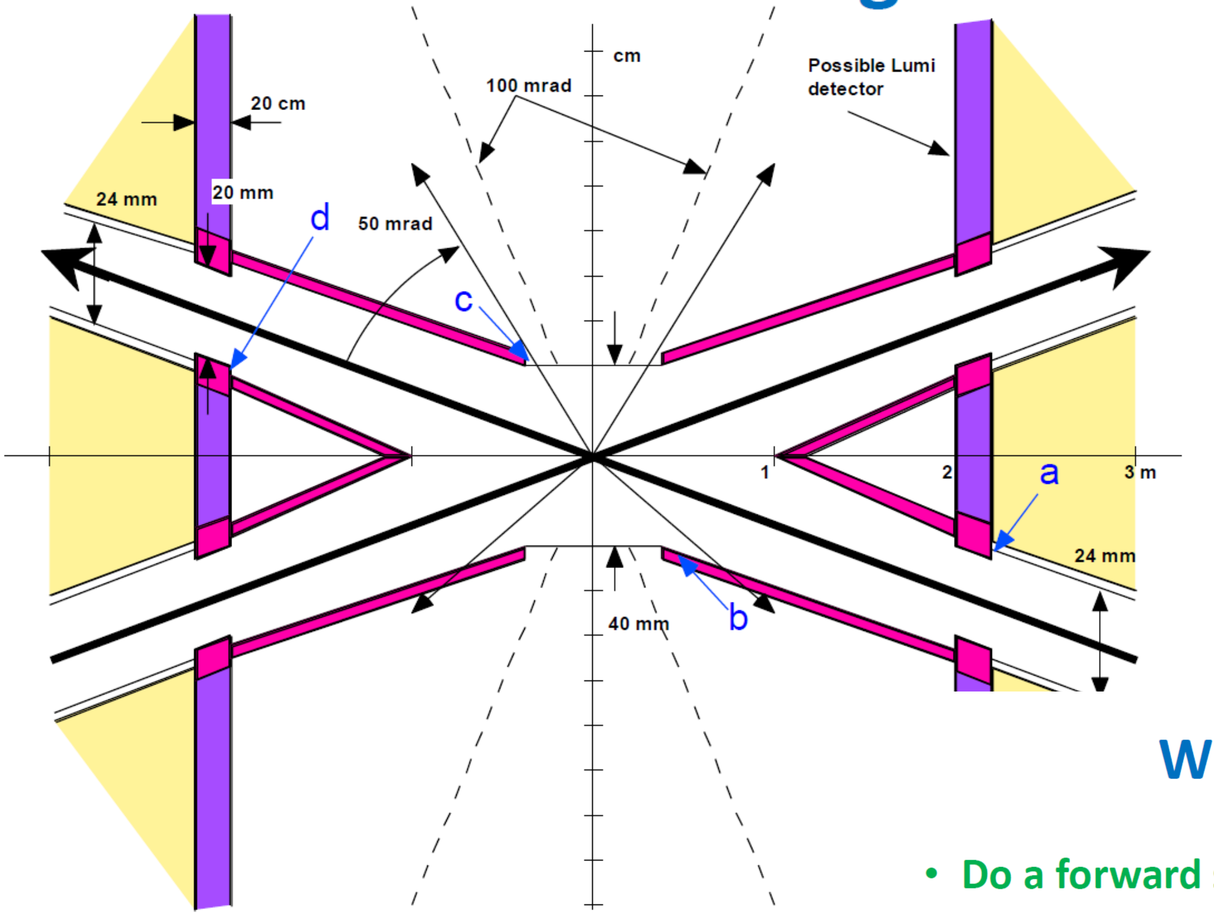
	LEP2, 100 GeV	FCCee_t_74_11 175 GeV
Eb	100 GeV	175 GeV
Ecr	72 keV	100 keV
bunch X freq	45 kHz	180 kHz
γ's / crossing	3E+11	4E+11
γ's Σ energy / crossing	7.e6 GeV	1.2e7 GeV

γ rates and energies from last bend now of same order of magnitude as LEP2

Asymmetric IR design solves

1. The booster bypass
2. The SR problem comes back to LEP levels.
3. can start looking in detail

Lumi detection angles



M. Sullivan

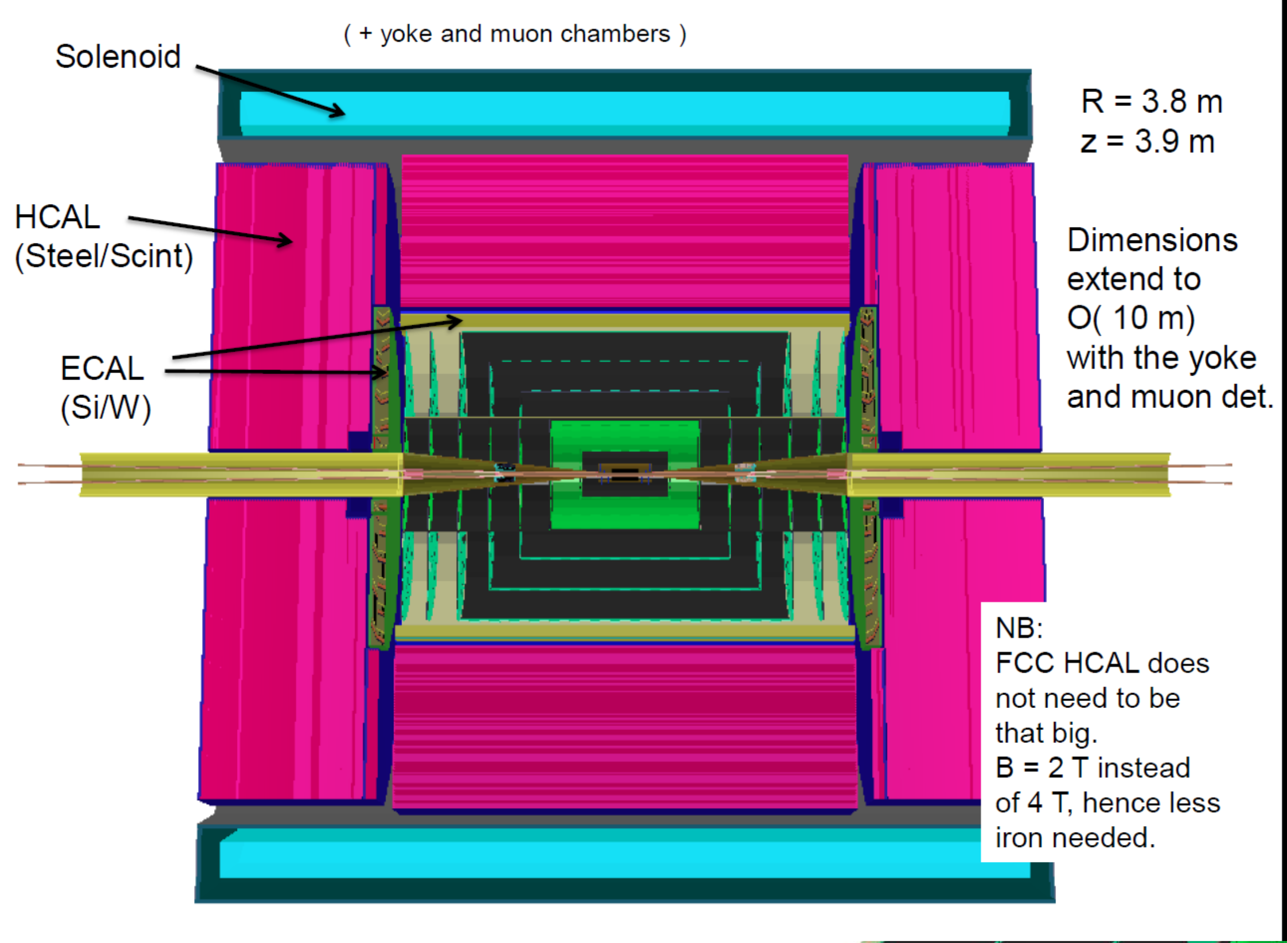
Started from hardest (tt machine)

What to do next

- Do a forward scatter simulation ✓
- Look at Z machine parameters ✓
- Check what a higher field soft bend does
  - Try this at the Z

Looks like it should be fine

- Look at Higgs machine parameters



Dimensions extend to O(10 m) with the yoke and muon det.

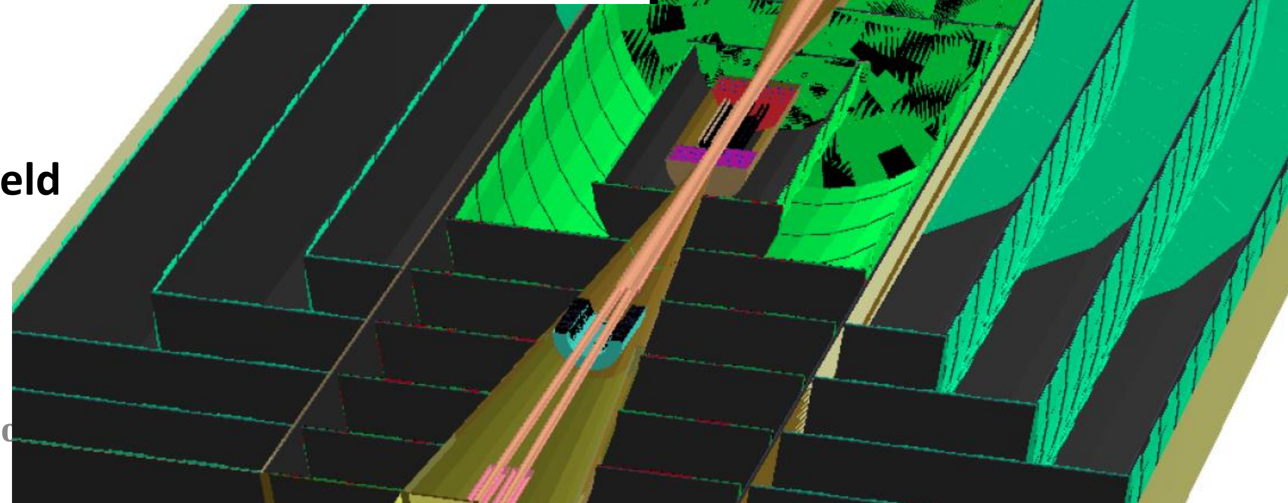
NB:
FCC HCAL does not need to be that big.
B = 2 T instead of 4 T, hence less iron needed.

E. Perez

acker

o 100 mrad.

ones used

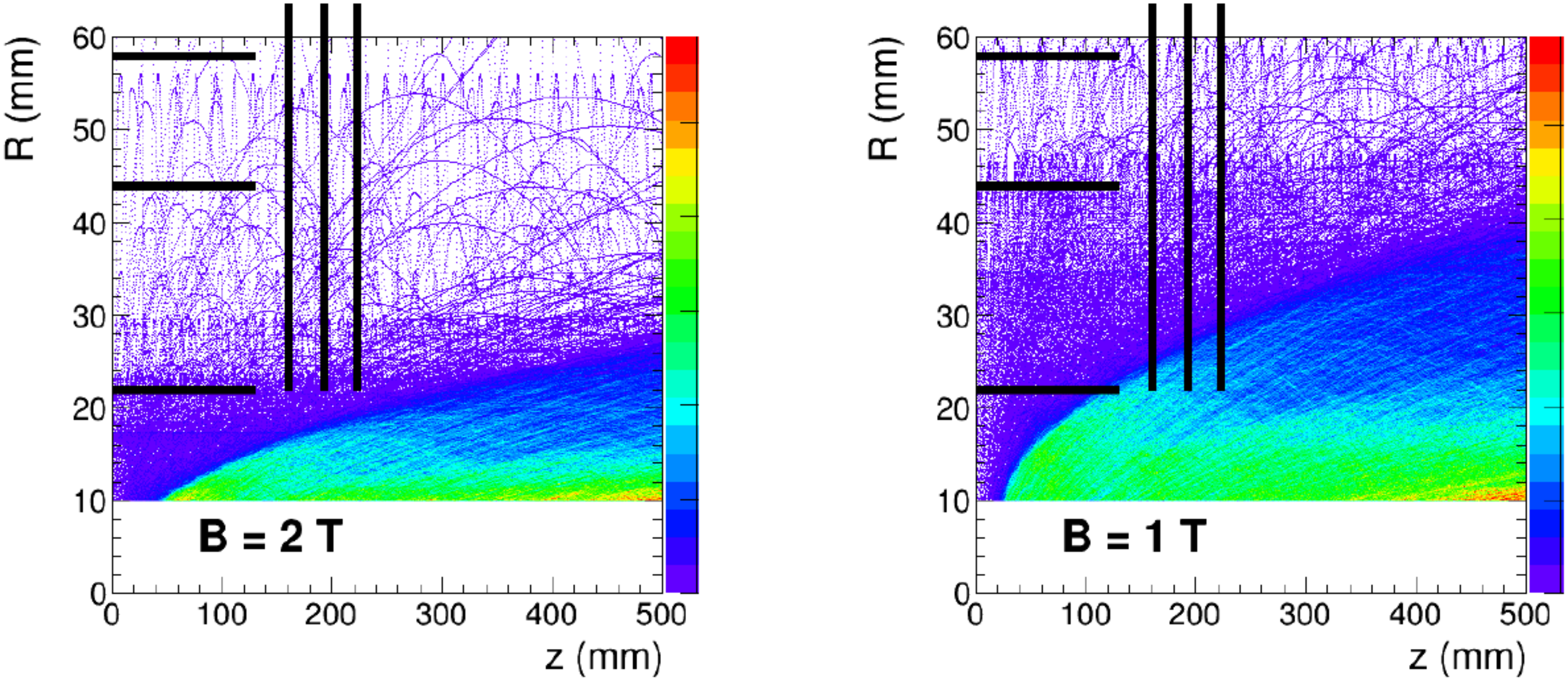


A good start
-- will need to decrease B-field
-- will need to reoptimize relative weight of tracker and calorimeter
(physics cost and MDI)

Conclusions similar to M. Sullivan: VTX detector at ~2cm from IP.

Trajectories of e+/- pairs in the 2T field

Helicoidal trajectories of the e+/- pairs in the field of the experiment :



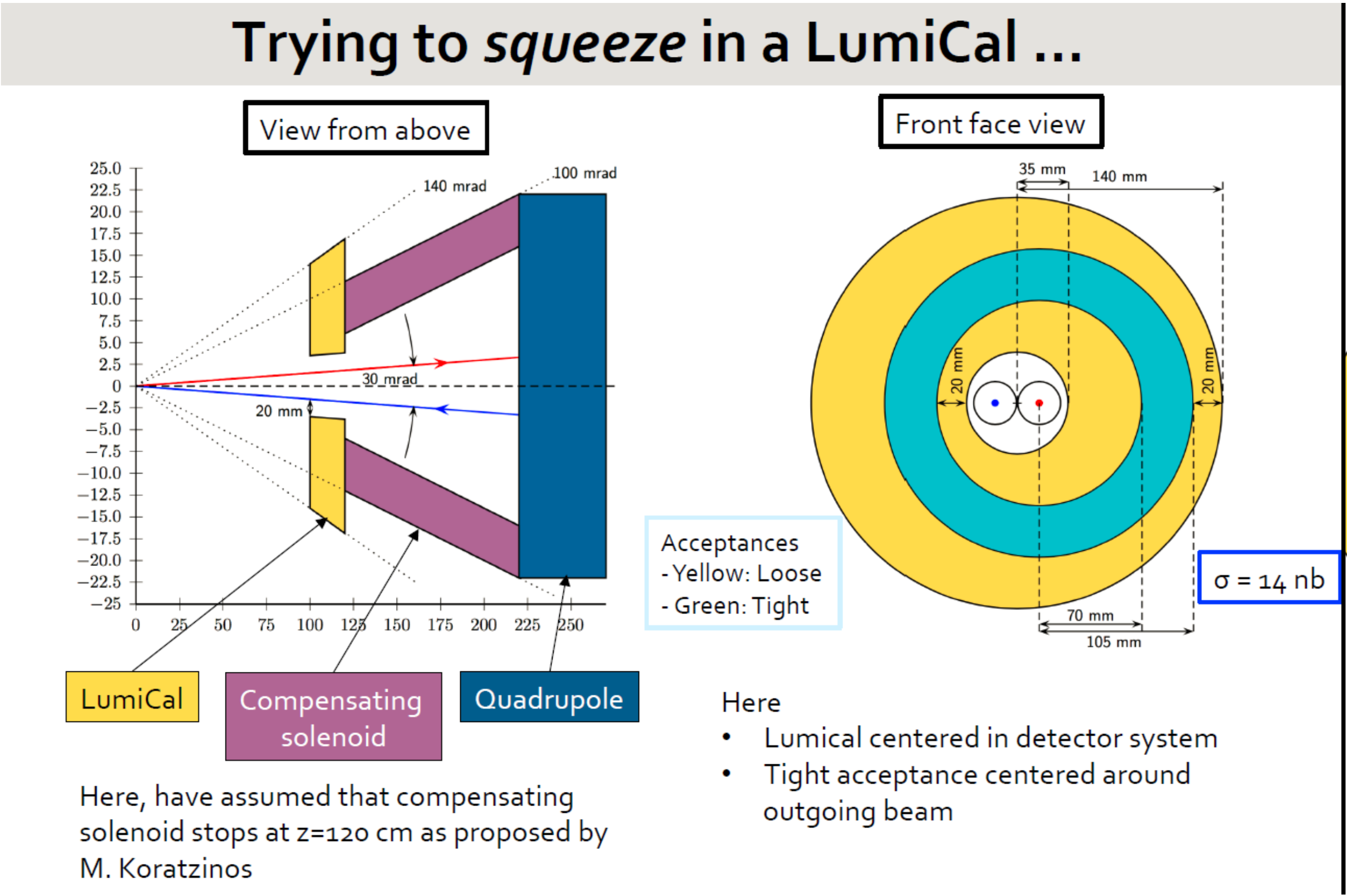
With the nominal value of B = 2 T and innermost layer of VXD at 2.2 cm :
VXD avoids the hot region

Luminosity measurement

M. Dam

-- thanks to high luminosity can use two large angle QED processes
e+e- → $\gamma\gamma$ and e+e → e+e-
-- need theoretical evaluation of e+e- → $\gamma\gamma$ @ 10^{-4} precision

-- at and around Z pole need low angle Bhabha :



Trying to *squeeze* in a LumiCal ...

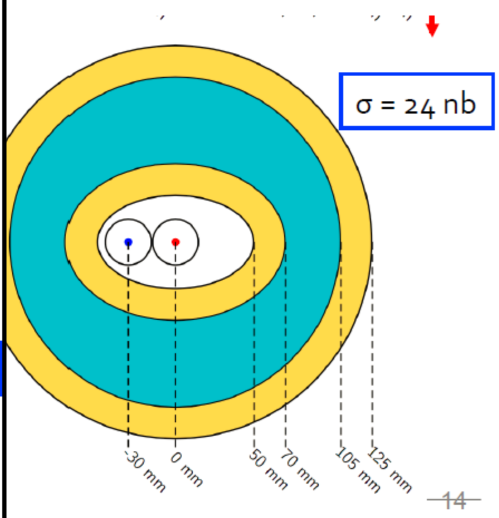
View from above

Here, have assumed that compensating solenoid stops at z=120 cm as proposed by M. Koratzinos

Front face view

Acceptances
- Yellow: Loose
- Green: Tight

Here
- Lumical centered in detector system
- Tight acceptance centered around outgoing beam



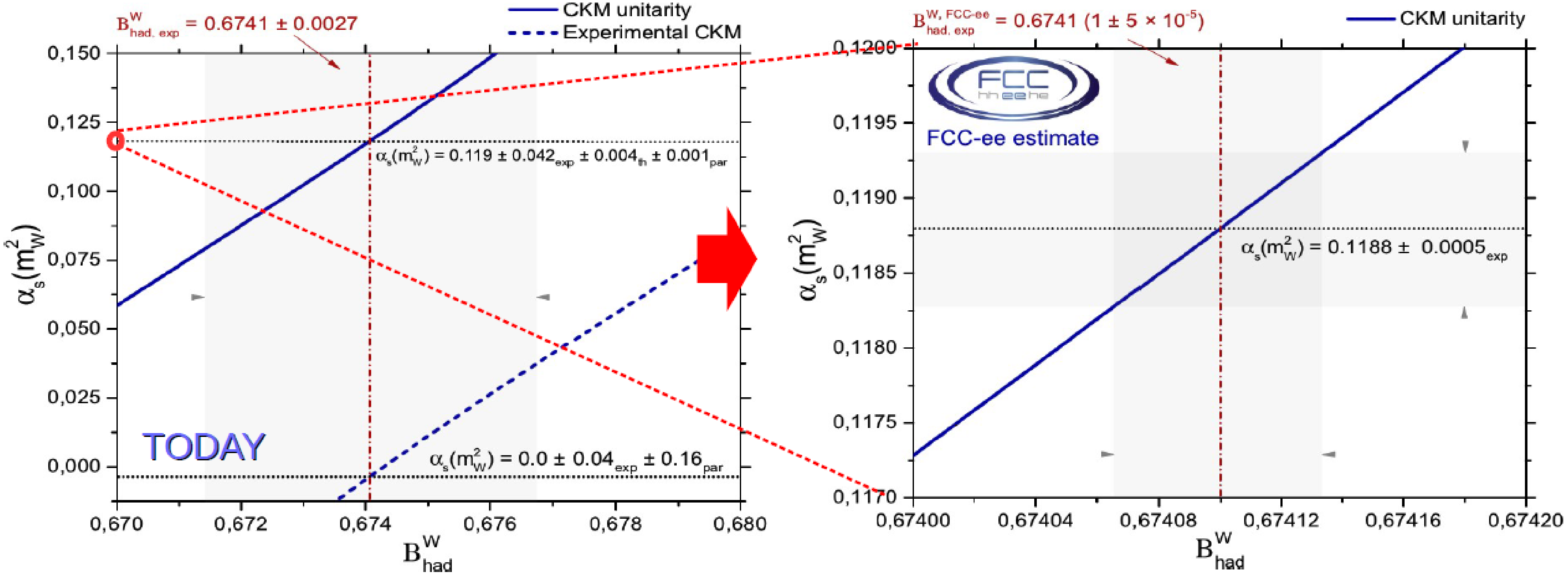
α_s from hadronic W decays at FCC-ee

[d'Enterria,Srebre, arXiv:1603.06501]

- Hadronic W width (BR) known at N^{3}LO (NNLO). Sensitivity to α_s (only beyond Born) requires exquisite experimental uncertainties:

$$\Gamma_{\rm W,had} = \frac{\sqrt{2}}{4\pi} G_{\rm F} m_{\rm W}^3 \sum_{\rm quarks\ i,j} |V_{\rm i,j}|^2 \left[1 + \sum_{\rm k=1}^{4} \left(\frac{\alpha_{\rm s}}{\pi}\right)^k + \delta_{\rm electroweak}(\alpha) + \delta_{\rm mixed}(\alpha\alpha_{\rm s})\right]$$

- Current Γ_W measurement yields poor extraction: $\delta\alpha_s$~25%
- FCC-ee prospects: Huge $e^+e^-\to WW$ stats (10^8, ×10^3 LEP): $\delta\alpha_s < 0.2\%$



$\alpha_s(M_Z) = 0.117 \pm 0.030_{\rm (exp)}$
$\pm 0.003_{\rm (th)} \pm 0.001_{\rm (par,CKM=1)}$

$\alpha_s\,(M_Z) = 0.1188 \pm 0.0002_{\rm (exp)}$

$R_{\rm W} \equiv \mathcal{B}^{\rm W}_{\rm had}/\mathcal{B}^{\rm W}_{\rm lep} = \mathcal{B}^{\rm W}_{\rm had}/(1-\mathcal{B}^{\rm W}_{\rm had})$ in three $e^+e^- \to {\rm W^+W^-}$ final states ($\ell\nu\,\ell\nu$, $\ell\nu\,{\rm qq}$, ${\rm qq\,qq}$)

Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise $\alpha_s(m_Z)$ measurement was derived from the Z decay ratio $R_l = \Gamma_{had}/\Gamma_l$.
Reinterpreting this measurement in light of: i) new N_3LO calculations; ii) improved m_{top} ; and iii) knowledge of the m_{Higgs}, the uncertainty is now something like:

$$\boxed{\delta\ (\alpha_s(m_Z)\ )_{LEP} = \pm\ 0.0038\ (exp.) \pm 0.0002\ (others)}$$

R_l measurement was statistics dominated: Foresee a factor ≥25 improvement at FCC-ee.
From the Z-pole, therefore a resonable experimental target is

$$\boxed{\delta\ (\alpha_s(m_Z)\ )_{FCC\text{-}ee} = \pm\ 0.00015}$$

Similarly, from the WW threshold, $\alpha_s(m_W)$ can be derived from the high stats measurement of $B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$

$$\boxed{\delta\ (\alpha_s(m_W)\ )_{FCC\text{-}ee} = \pm\ 0.00015}$$

Combining the two above, a realistic target precision would be

$$\boxed{\delta\ (\alpha_s(m_Z)\ )_{FCC\text{-}ee} = \pm\ 0.0001}$$

Present W.A.

$\alpha_s(M_Z) = 0.1181 \pm 0.0013$

D. Enterria

Workshop on α_S sept 2015

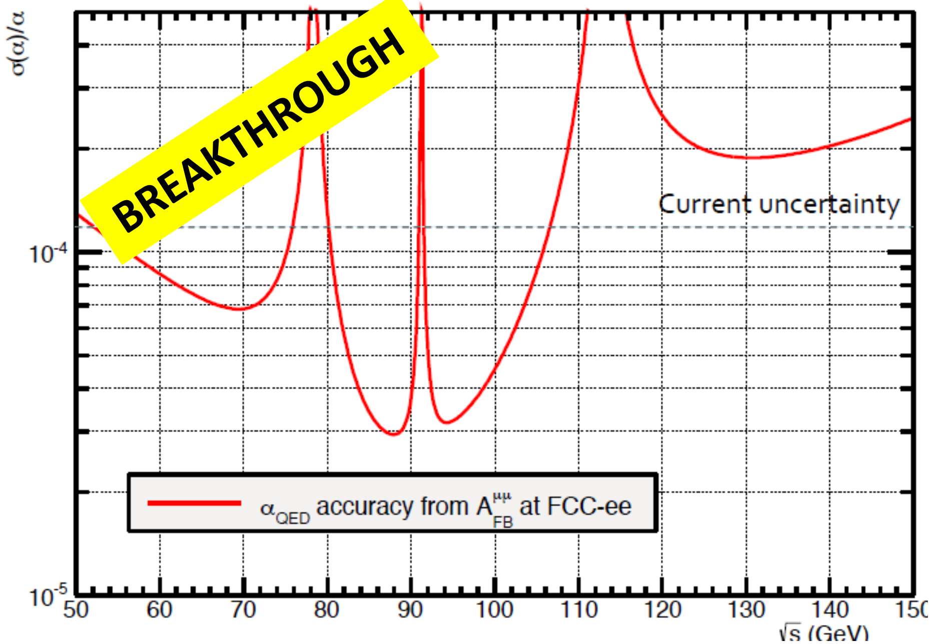
D. d'Enterria, P.Z. Skands (eds.)

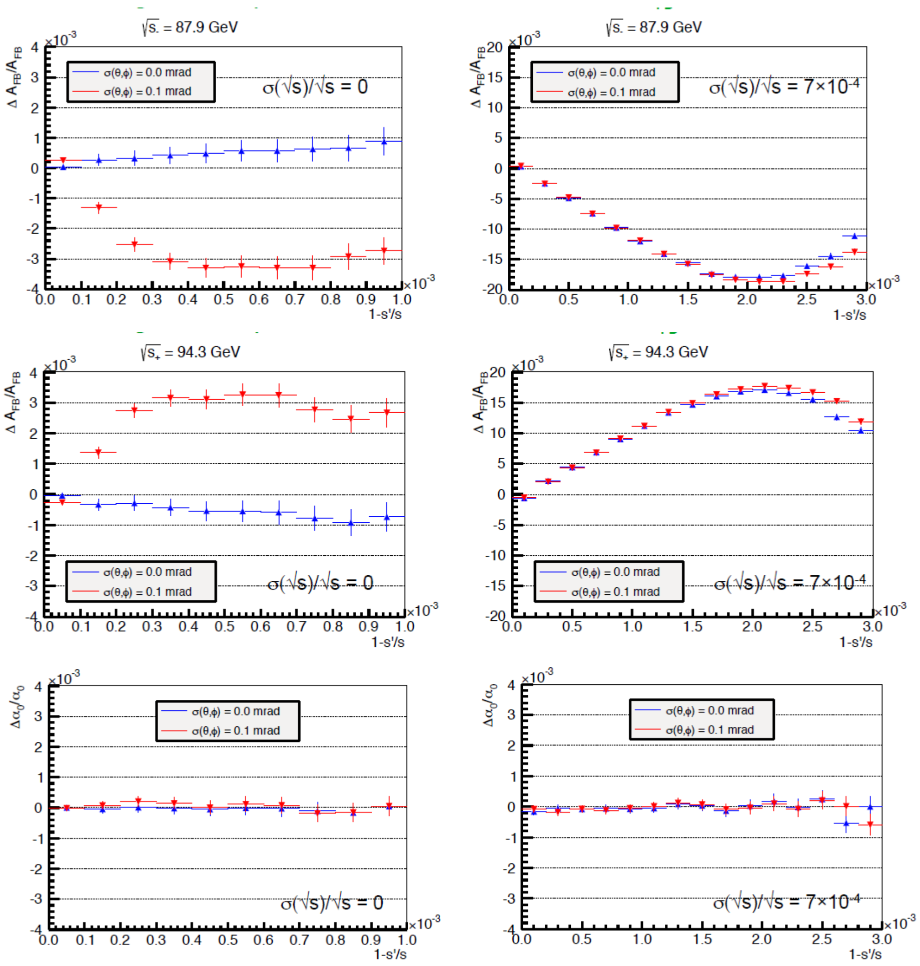
arXiv:1512.05194

$$\sin^2\theta_w^{eff}\cos^2\theta_w^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,M_Z^2}\,\frac{1}{1+\Delta\rho}\,\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_w}}$$

Unwanted error

Physics discoveries





- Total bias on $\alpha_{QED}(m_Z^2)$ of the order of 8×10^{-6}

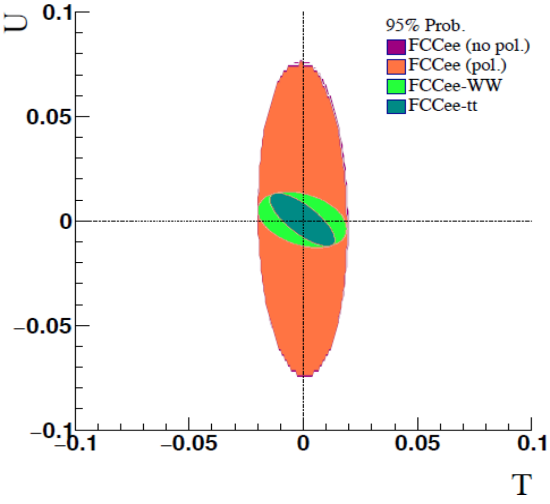
P. Janot discovered that one can measure $\Delta\alpha_{QED}(m_z)$ from measuring $A_{FB}^{\mu\mu}$ at +- 3 GeV from the Z peak. (Nice Z lineshape scan)

Further studies with S. Jadach shows error cancellation of +3 vs -3 points.

DO WE NEED LONGITUDINAL POLARIZATION?

A.Blondel

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC
visible Z decays	10^{12}	visible Z decays	10^{9}
muon pairs	10^{11}	beam polarization	90%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$
$\Delta\ E_{cm}$ (MeV)	0.1		2.2
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	ΔA_{LR} (E_{CM})	$4.1\ 10^{-5}$
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	ΔA_{LR}	$5.9\ 10^{-5}$
$\Delta \sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$



J. De Blas

	from $A_{FB}^{\mu\mu}$ LEP 2.10^7Z	SLC, 5.10^5 Z	$\Delta\alpha = 0.00035$	$\Delta\alpha = 0.00003$
$\Delta \sin^2\theta^{lept}_W$	$5.3\ 10^{-4}$	$2.6\ 10^{-4}$	$1.2\ 10^{-4}$	$1.\ 10^{-5}$

W.A. $1.6\ 10^{-4}$

All exceeds the limitation given by $\Delta\alpha(m_Z)$ ($3 10^{-5}$) or the needed precision for comparison with m_W (500keV)

But this precision on $\Delta \sin^2\theta^{lept}_W$ can only be exploited at FCC-ee!

At FCC-ee longitudinal polarization is more difficult and implies a significant reduction of luminosity. As far as we can tell today it is not justified

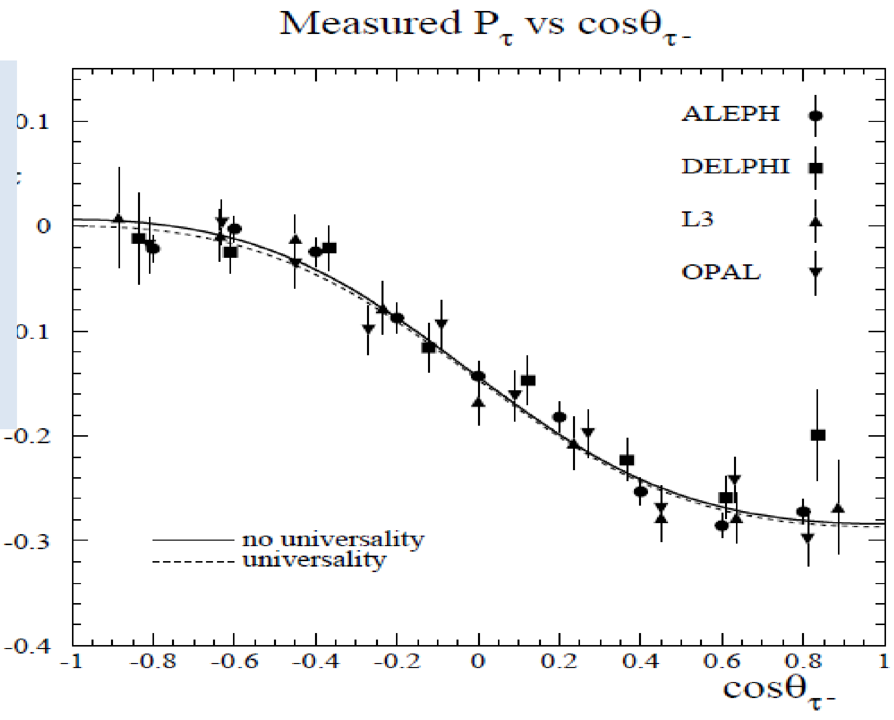
(similar conclusion by J. De Blas in pheno session)

The forward backward tau polarization asymmetry is very clean.
Dependence on E_{CM} same as A_{LR} negl.
At FCC-ee

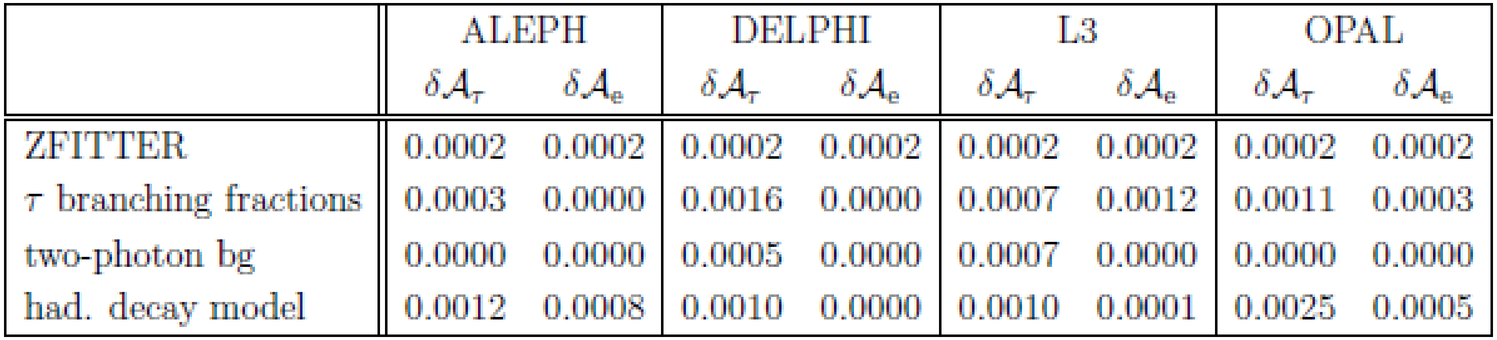
ALEPH data 160 pb^{-1} (80 s @ FCC-ee !)

Already syst. level of 610^{-5}on $\sin^2\theta_W$

much improvement possible
by using dedicated selection
e.g. tau→ π ν to avoid had. model



ure 4.7: The values of $\mathcal{P}_\tau$ as a function of $\cos\theta_{\tau^-}$ as measured by each of the LEP ex- riments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The dashed curve overlays Equation 4.2 under the assumption of lepton universality for the LEP value of $\mathcal{A}_\ell$.



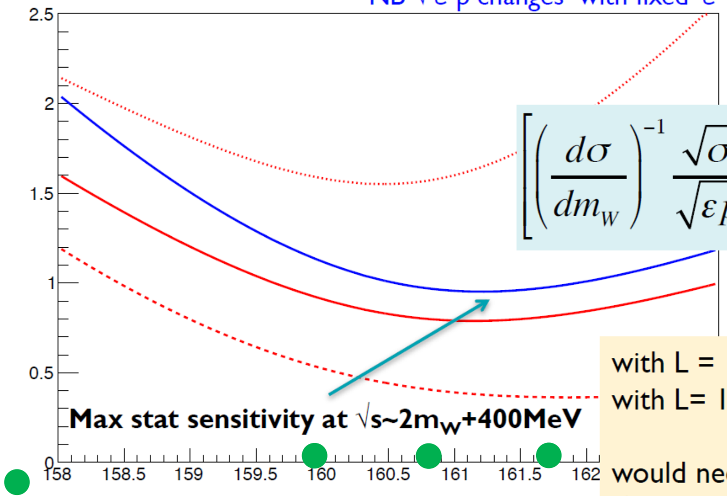
	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

Table 4.2: The magnitude of the major common systematic errors on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ by category for each of the LEP experiments.

m_W from σ_{WW}

P. Azzuri started optimizing
The W threshold scan
for measurement of
m_W and Γ_W
Smooth, plenty of points
with half integer spin tunes ●

NB $\sqrt{\varepsilon p}$ changes with fixed ε =0.75 and σ_B=0.3pb



$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{\min} \approx 0.95\frac{GeV}{pb^{1/2}}$$

Max stat sensitivity at $\sqrt{s}\sim 2m_W$+400MeV

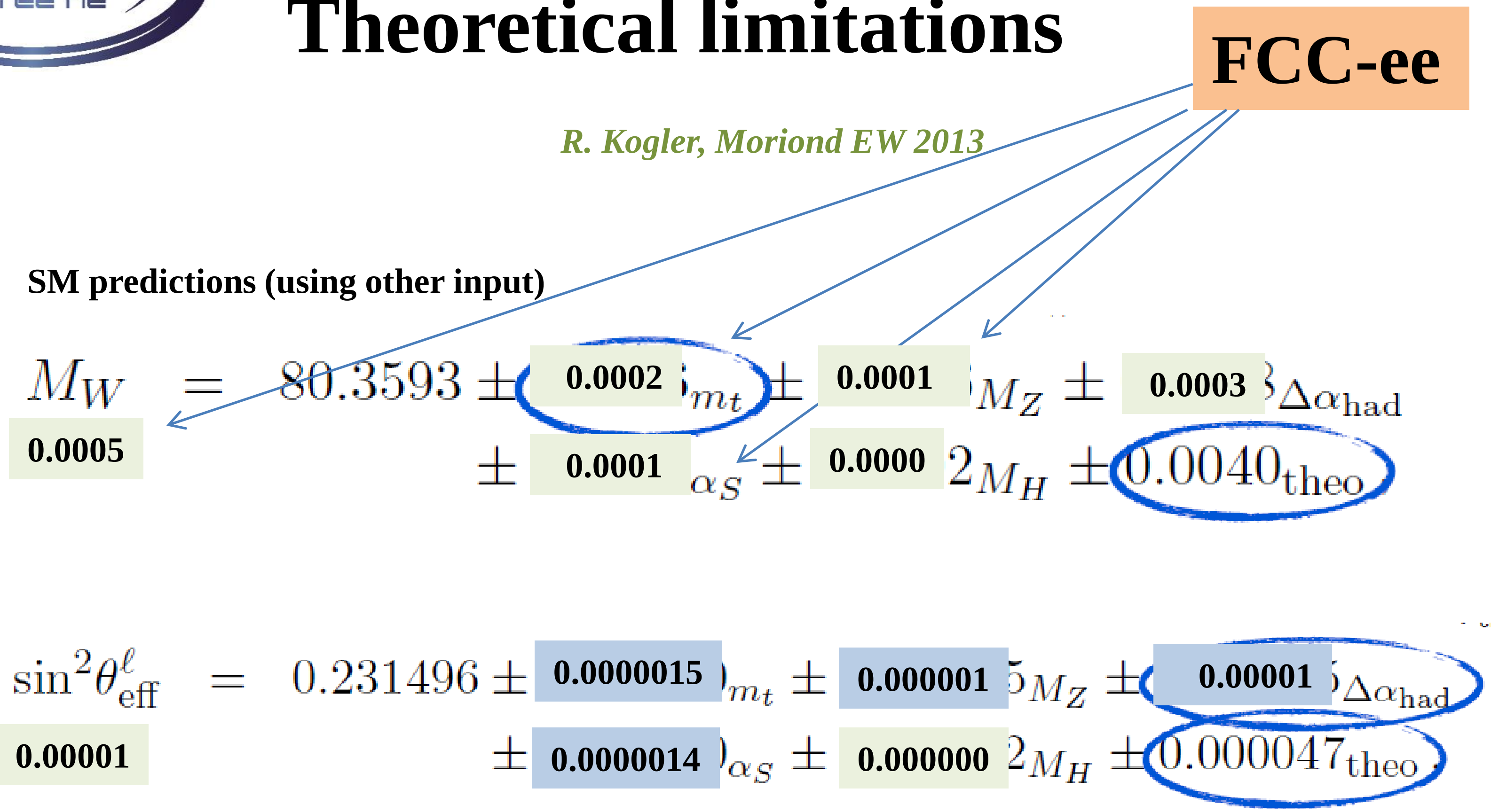
↓
$2m_W$

with L = 11/pb → Δmw≈380MeV
with L= 15/ab → Δmw≈0.25 MeV

would need
ΔE(beam)<0.25 MeV (3x10-6)
$\Delta\varepsilon/\varepsilon$, ΔL/L < 10-4
$\Delta\sigma_B$<0.5 fb (10-3)

Statistical error on m_W will be O(300 keV)
next: background and *signal* cross-sections!

Theoretical limitations



FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

M_W = 80.3593 ± **0.0002** $_{m_t}$ ± **0.0001** $_{M_Z}$ ± **0.0003** $_{\Delta\alpha_{\rm had}}$

± **0.0001** $_{\alpha_S}$ ± **0.0000** 2_{M_H} ± $0.0040_{\rm theo}$

0.0005

$\sin^2\theta^\ell_{\rm eff}$ = 0.231496 ± **0.0000015** $_{m_t}$ ± **0.000001** 5_{M_Z} ± **0.00001** $5_{\Delta\alpha_{\rm had}}$

± **0.0000014** $_{\alpha_S}$ ± **0.000000** 2_{M_H} ± $0.000047_{\rm theo}$

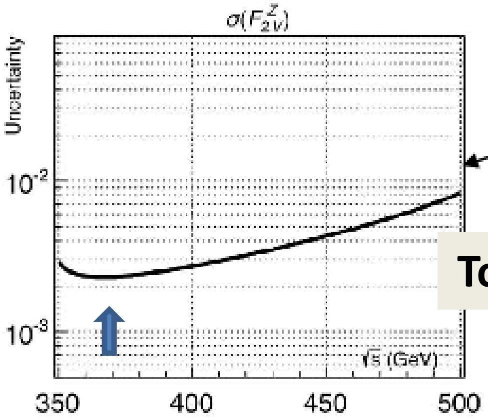
0.00001

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
Suggest including manpower for theoretical calculations in the project cost.

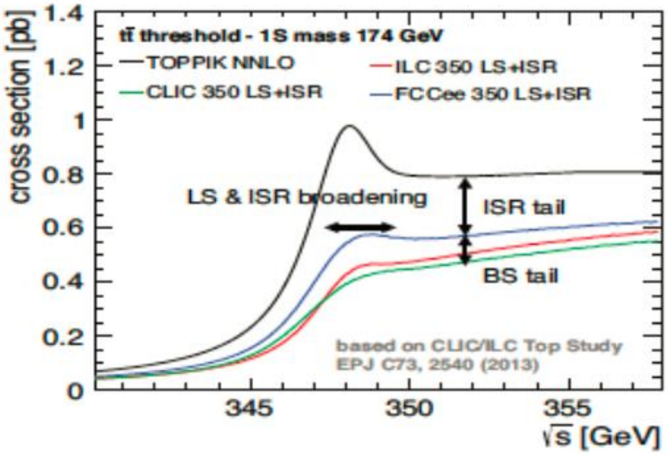
Top physics *Moftaba*

Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle



Typically best sensitivity just above production threshold

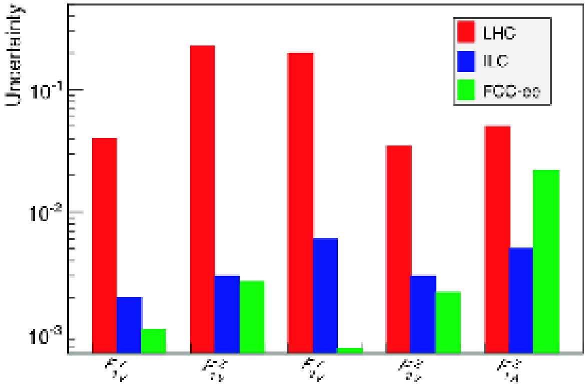
Top beam energy is 185 GeV



Top mas can be measured to O(10 MeV)
Beam energy calibration from WW, γZ, ZZ
Reduce th. errors due α_S meast @FCC-ee

Also:
CKM measurements
FCNC decays down to 10^{-6}
All luminosity can be used!

Patrick Janot
arXiv:1503.01325v2



FCC-ee discovery potential

Of course discovery depends on the goodwill of nature.
A few things that FCC-ee could discover if is there :

EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z), Higgs and top couplings

DISCOVER a violation of flavour conservation
-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.
+ flavour physics (10^{12} bb events)

DISCOVER dark matter as «invisible decay» of H or Z

DISCOVER very weekly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

…..

S. Monteil

Leptonic FCNCs

SM from neutrino oscillations:

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

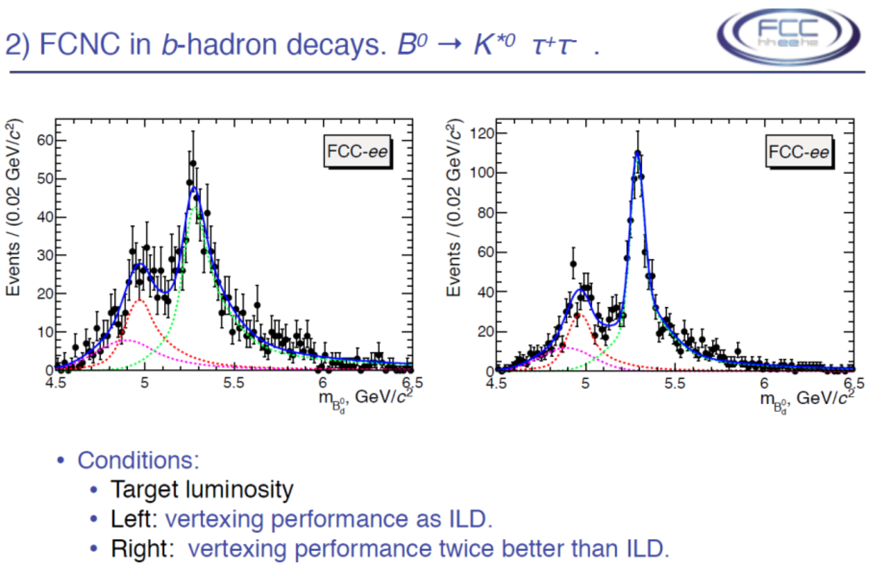
FCC-ee is highly competitive for $Z \to e\tau, \mu\tau.$

potential sensitivity 10^{-12} How far can we go?

First investigation of backgrounds. Z→ ππ Z→ W*W

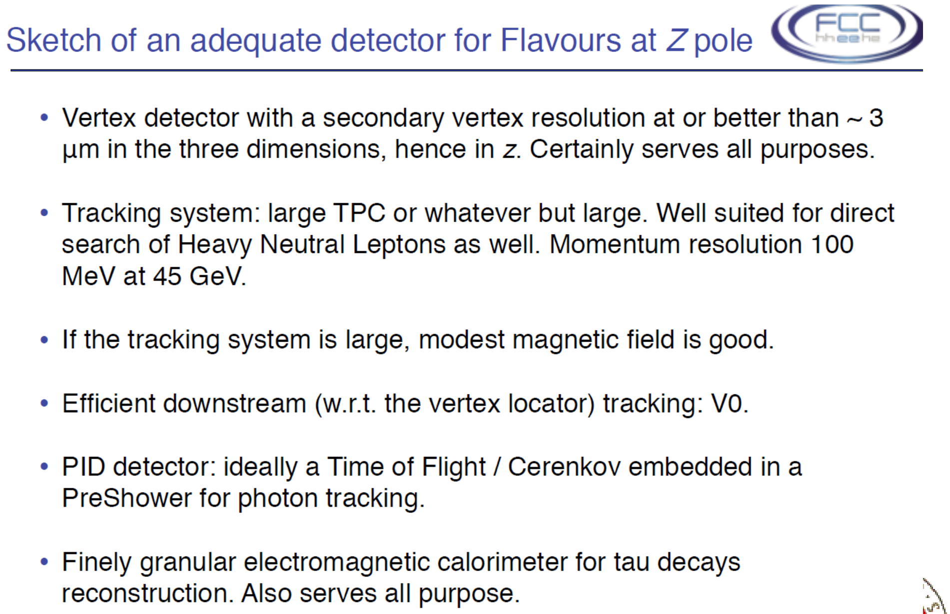
Backgrounds at level of 10^{-8} , but do not have life time (unlike taus)

Further analysis will need simulation.



2) FCNC in *b*-hadron decays. $B^0 \to K^{*0}\ \tau^+\tau^-$.

- Conditions:
  - Target luminosity
  - Left: vertexing performance as ILD.
  - Right: vertexing performance twice better than ILD.

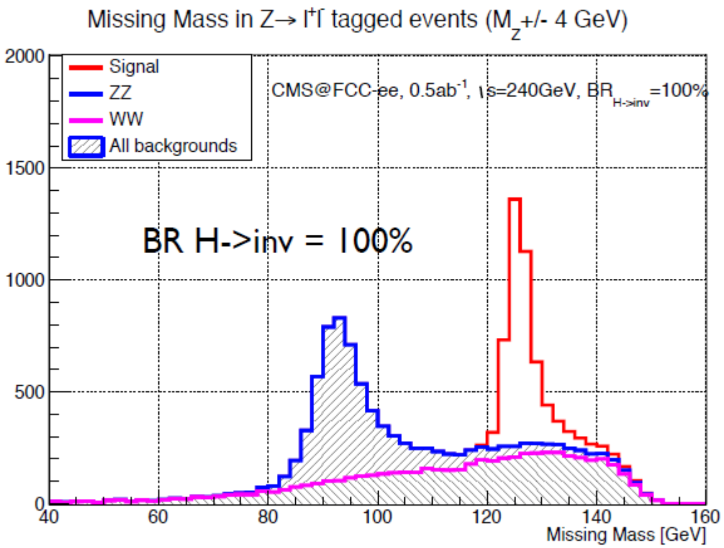


Sketch of an adequate detector for Flavours at *Z* pole

- Vertex detector with a secondary vertex resolution at or better than ~ 3 µm in the three dimensions, hence in *z*. Certainly serves all purposes.
- Tracking system: large TPC or whatever but large. Well suited for direct search of Heavy Neutral Leptons as well. Momentum resolution 100 MeV at 45 GeV.
- If the tracking system is large, modest magnetic field is good.
- Efficient downstream (w.r.t. the vertex locator) tracking: V0.
- PID detector: ideally a Time of Flight / Cerenkov embedded in a PreShower for photon tracking.
- Finely granular electromagnetic calorimeter for tau decays reconstruction. Also serves all purpose.

M. De Gruttola

The Higgs invisible width



Potential: discovery of Dark Matter

Target: limit at 10^{-3} level

UNIQUE to e+e- : ability to tag event as ZH even if do not see the Higgs decay

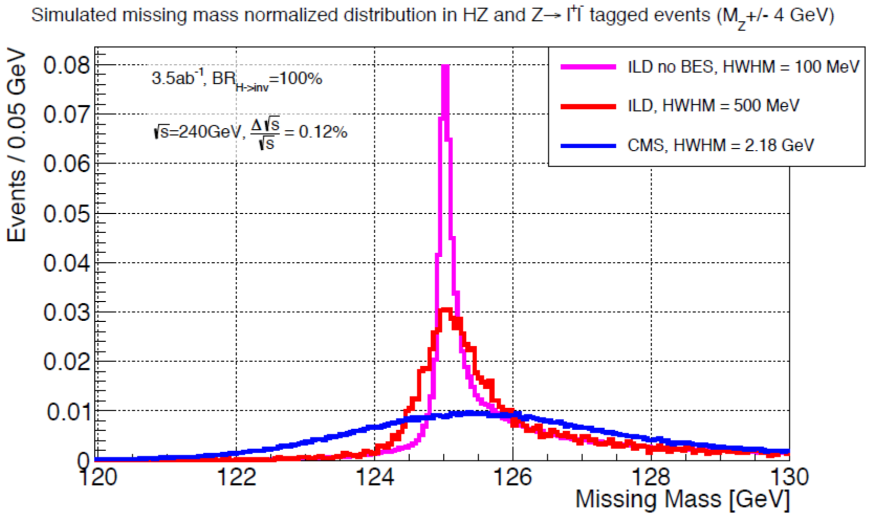
Started with Z-> leptons

Studied the effect of detector resolution

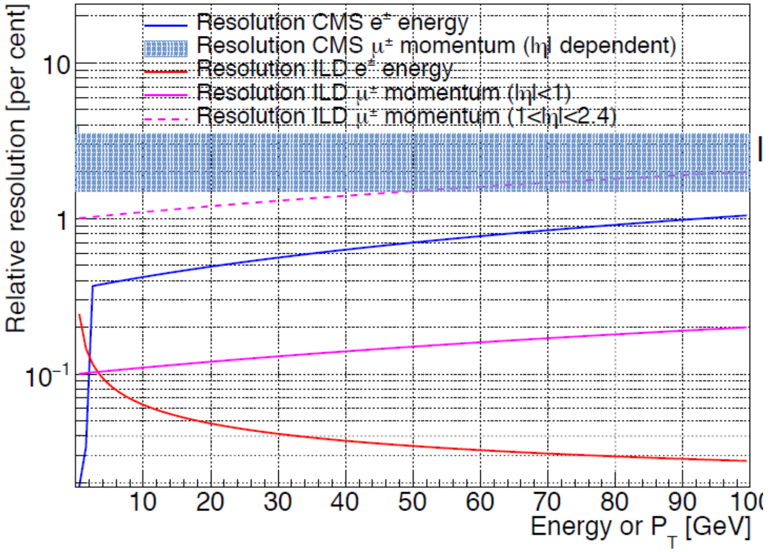
Compare CMS with ILD

Study effect of beam energy spread

Next step : look at Z→ qq tag (evts X 20)



CMS vs ILD (2)



ummary

Main conclusions

MDI acc-exp working group started and *working* !

-- asymmetric beam crossing has brought SR problem back to real axis
-- soon will be in position to attack magnet integration
-- Luminosity measurement requires attention but problem is well posed
-- detector simulation study (with great help from CLIC work!) started

Detectors and experiments will take usefully all luminosity the machine can give (pile-up< 10^{-3})

-- «baseline» is a good start, more welcome (we won't do anything that prevents it!)
-- discovery potential is in precision measurements, rare decays, invisible width (detector!)
-- top beam energy needs to be set to 185 GeV for top couplings measurements

Continuous beam energy calibration at O(10^{-6}) precision @ Z and W (resonant depolarization)

➔ central to precision measurements
➔ need a joint acc-exp working group to converge on strategy.

No obvious need identified so far for longitudinal polarization at any energy

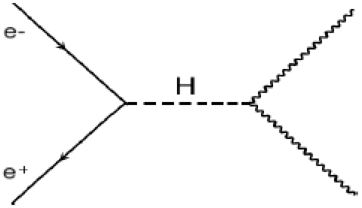
-- top quark couplings can be measured well using top quark polarization
-- high statistics @ Z (and e.g. final state polarization (tau))
should allow precision on $\sin^2\theta^{\ell ept}_W$ with more than adequate precision < 10^{-5}
-- high luminosity brings much much more $\Delta\alpha_{QED}(m_z)$ @ 3$10^{-5}$, $\Delta\alpha_S(m_z)$ @ ~10-^{4}

Monochromatization for s-channel e+e- → Higgs @ 125.2 GeV looks promising (off sessions)

Electron Yukawa via s-channel $e^+e^- \rightarrow H$ at FCC-ee

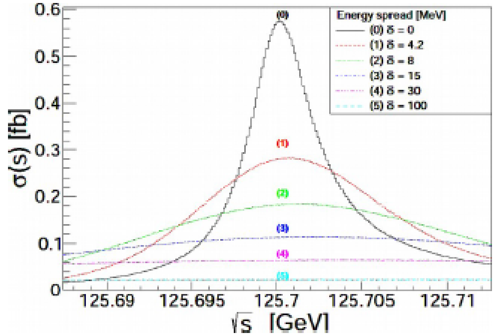
[d'Enterria, Wojcik, Aleksan]

- Resonant s-channel Higgs production at $\sqrt{s}$ = 125 GeV has tiny cross sections:



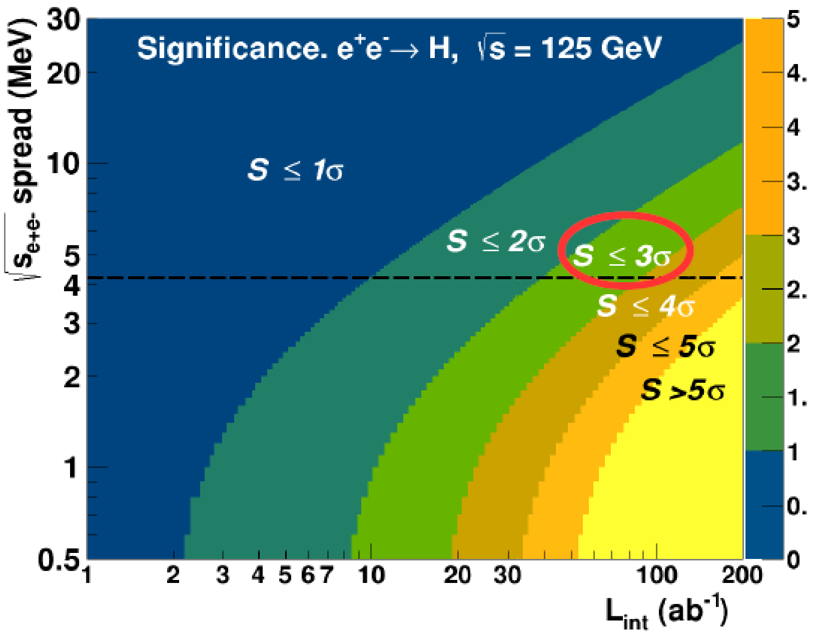
$\sigma(e^+e^- \rightarrow H)_{\text{Breit-Wigner}} = 1.64$ fb

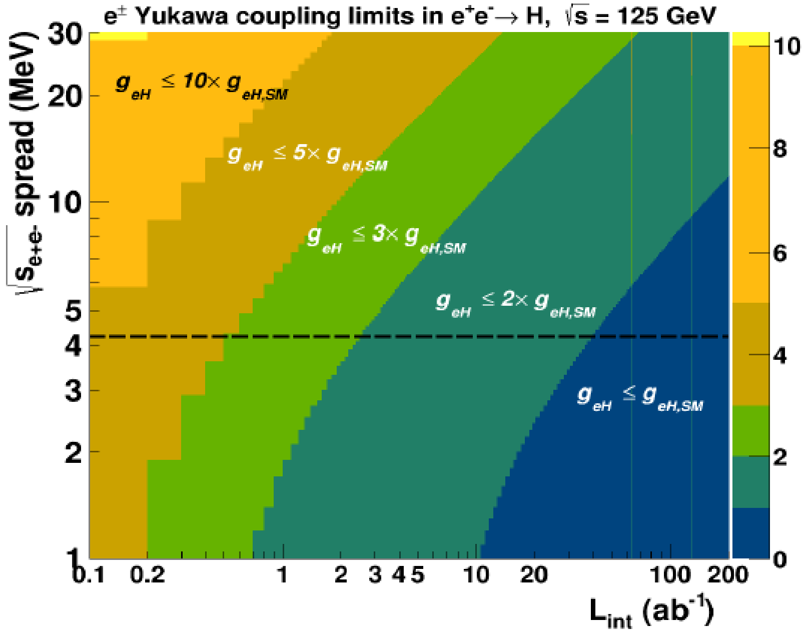
$\sigma(e^+e^- \rightarrow H)_{\text{visible}} = 290$ ab (including ISR + $\sqrt{s}_{\text{spread}} = \Gamma_H = 4.2$ MeV)



Mono-chromatization required to achieve $\sqrt{s}_{\text{spread}} \sim \Gamma_H$

- Preliminary study for signal + backgrounds in 10 Higgs decay channels.
- Significance & limits on e-Yukawa coupling:





3σ observation requires $L_{\text{int}} = 90$ ab^{-1}

$L_{\text{int}} = 10$ ab^{-1}: S ≈ 0.7, BR(Hee) < $2.8\times\text{BR}_{\text{SM}}$

$g_{eH} < 1.7\times g_{eH,SM}$ (95% CL)