FCC WEEK 2017
Berlin, 29 May – 2 June

FCC-ee physics & experiments
CDR plan and status

Roberto Tenchini

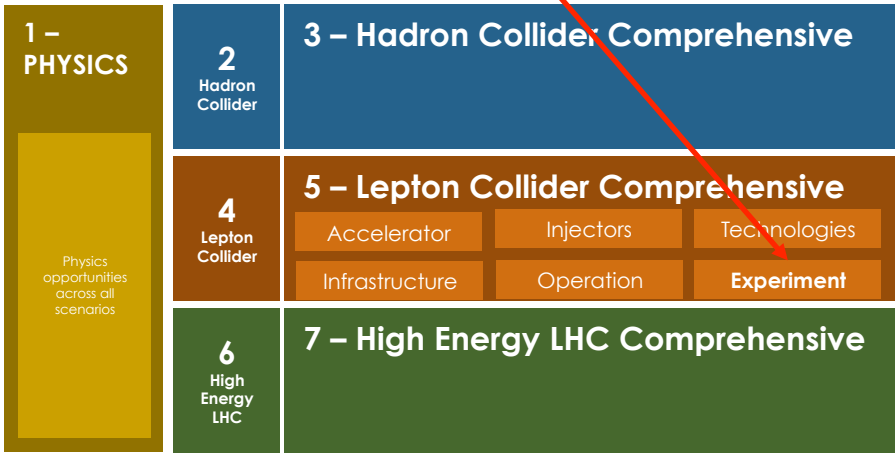
INFN Pisa

See Acknowledgements for long list of people that helped for this talk, thanks !

CDR FCC-ee physics & experiments – outline

- Vol. "FCC-ee: Physics & Experiments"
  - Introduction (running plan, history, motivation, …)
  - Electroweak physics with Z's and W's
  - Higgs physics
  - Top quark physics
  - QCD and $\gamma\gamma$ physics
  - Flavours
  - BSM (Physics behind precision, global fits, direct searches)
  - MDI and experimental environment
  - Polarization and beam energy measurement
  - Detector designs
  - Summary and outlook

An entire day dedicated to this subject tomorrow: this is essentially an executive summary



Physics and Experiments Studies Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z's and W's
R. Tenchini, F. Piccinini
S. Heinemeyer, A. Freitas

Higgs properties
M. Klute, K. Peters
S. Heinemeyer, A. Freitas

Top quark physics
P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas

Synergies with FCC-hh physics, LC studies, LEP legacy

QCD and γγ physics
D. d'Enterria
P. Skands

Flavours physics
S. Monteil
J. Kamenik

New physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis
Synergies
J. Ellis

Physics software
C. Bernet, B. Hegner,
C. Helsens

Synergy with FCC-hh, LC, LHC

Online selection & DAQ
C. Leonidopoulos
E. Perez

Polarization, √s measurments
A. Blondel
J. Wenninger

Joint with FCC-ee Accelerator

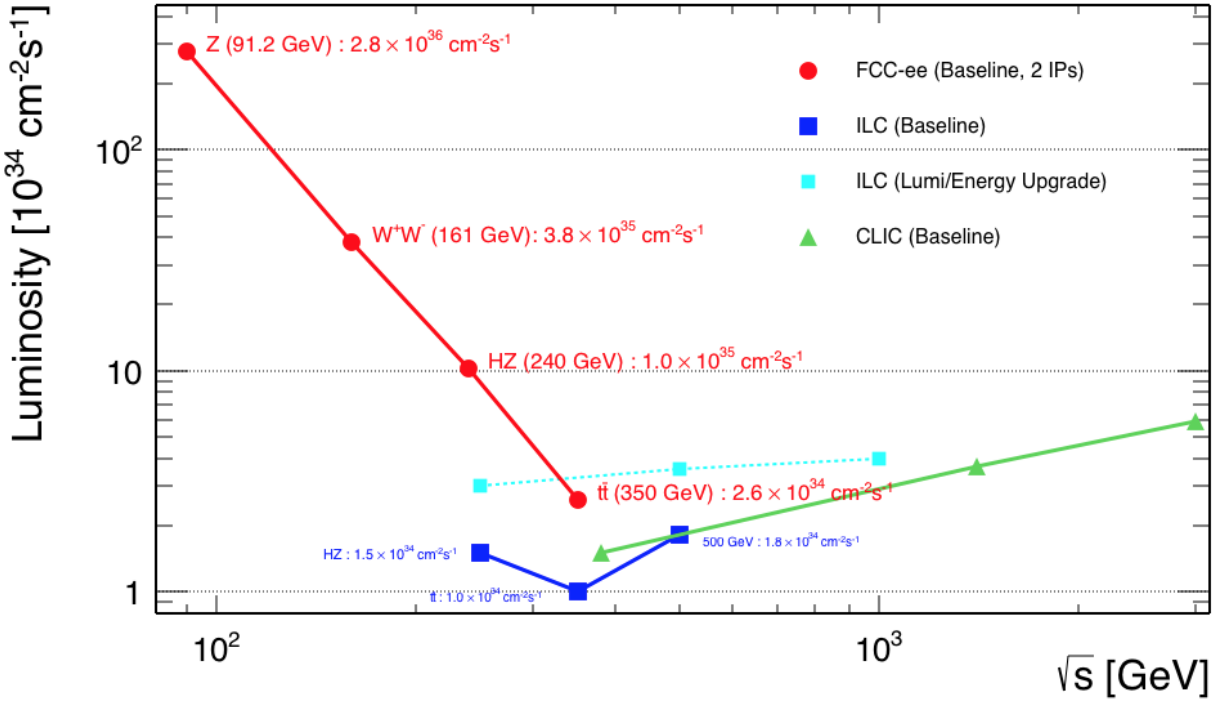
MDI, Exp'tal environment
M. Boscolo
N. Bacchetta

Adapt (to) the interaction region
Joint with FCC-ee Accelerator

Detector designs
A. Cattai, G. Rolandi,
M. Dam

Synergy with LC and CEPC
Set constraints on designs
to match statistical precision
Propose detector designs

Luminosities and centre-of mass energies



LEP record at the Z
$2.3 \cdot 10^{31}$ cm^{-2}s^{-1}

LEP2 record
$\approx 10^{32}$ cm^{-2}s^{-1}

Operation model assumed for the CDR

- Physics goals (see next slides)
  - 150 ab^{-1} around the Z pole (~ 25 ab^{-1} at 88 and 94 GeV, 100 ab^{-1} at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - 5 ab^{-1} at the HZ cross section maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the top threshold (a fraction at ~350 GeV, the rest at ~370 GeV)

  - Benchmark run plan with 2 IP and the baseline optics
    - Numbers of years are soft numbers that can be revised in view of the physics panorama at the time

√s (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	15, then 30	4	1	0.3
Events/year	1.2×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}
Runtime (years)	6	2	5	5

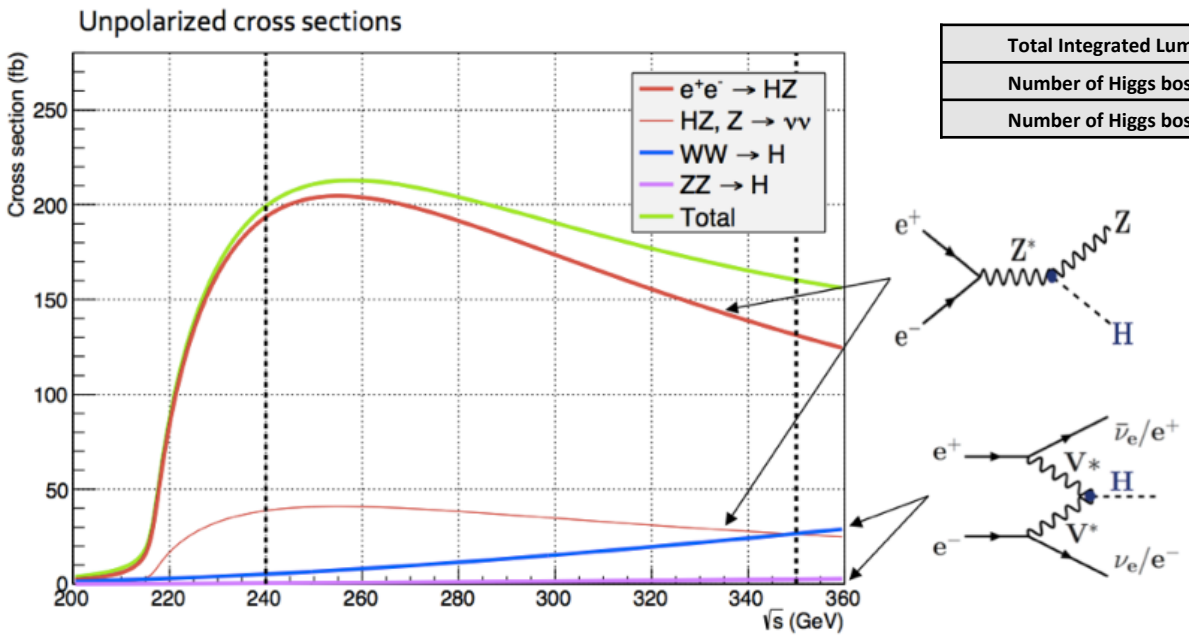
M. Benedikt
May 2017

200 scheduled physics days per years, Hübner factor ~ 0.6

Physics opportunities at FCC-ee

(short summary, more at the dedicated session tomorrow)

The Higgs program at √s=240 and 350 GeV



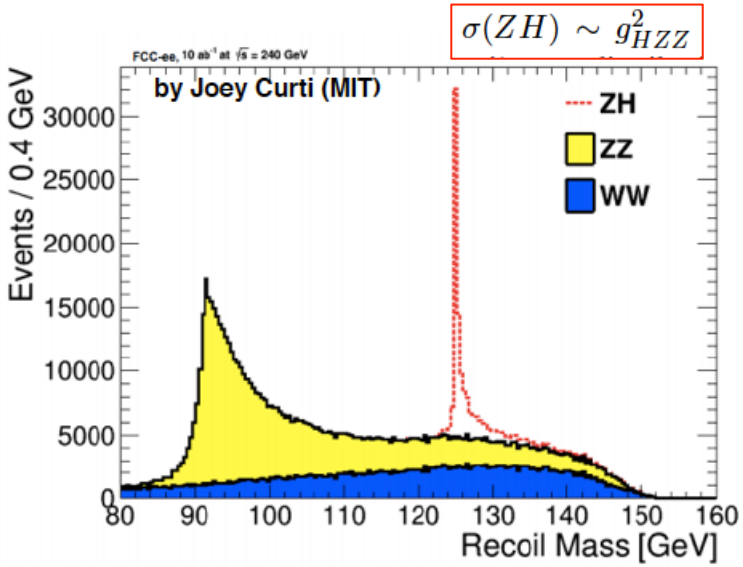
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
Number of Higgs bosons from $e^+e^- \to HZ$	1,000,000	200,000
Number of Higgs bosons form fusion process	25,000	40,000

Combining in an optimal way Higgstrahlung and Vector Boson Fusion at the two centre-of-mass energies

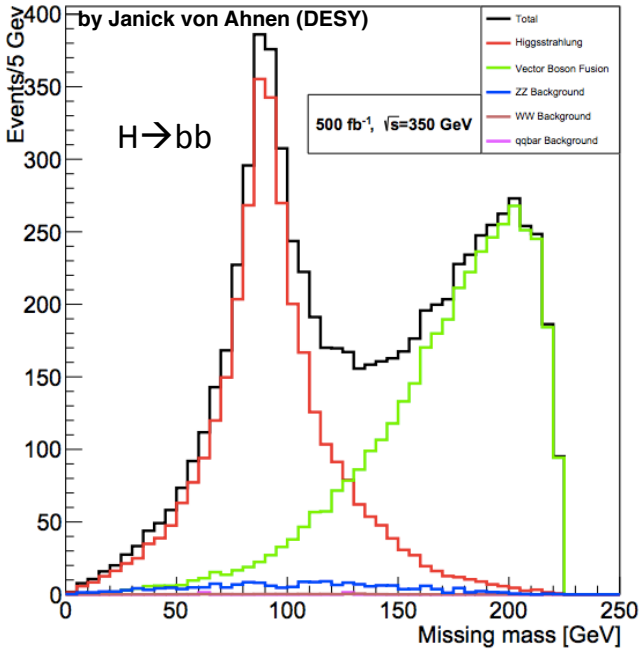
Talk of Markus Klute on Tuesday

Higgs model independent couplings and width

Recoil mass: Higgs events are tagged decay independent



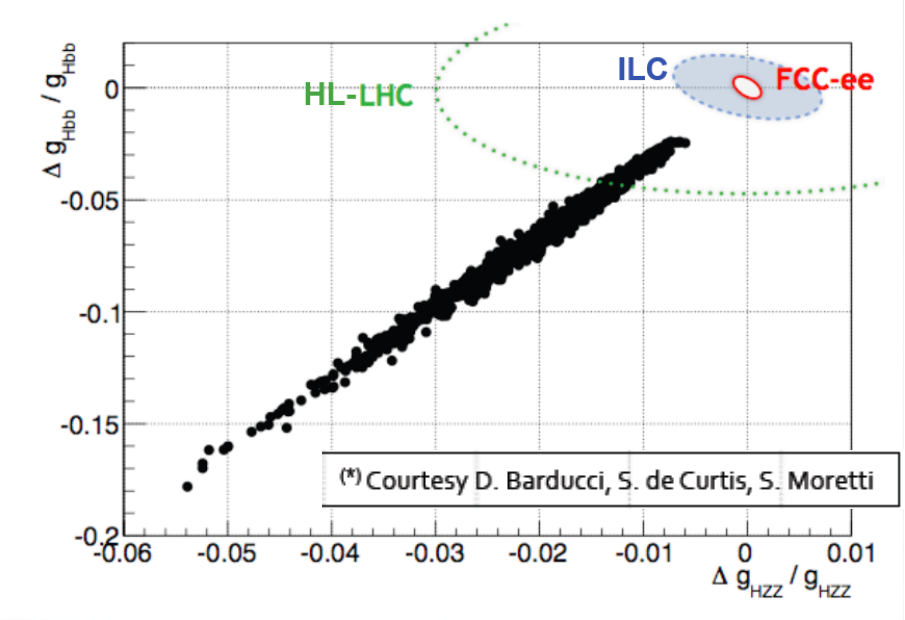
Extract couplings from combination of measurements



Tagging of a specific channel allows the total H width to be determined: $\Gamma_H = \Gamma(H \to ZZ)/\mathrm{BR}(H \to ZZ) \propto \sigma(ZH)/\mathrm{BR}(H \to ZZ)$

Higgs couplings precision and sensitivity

Example from Composite Higgs Models (4HDM)



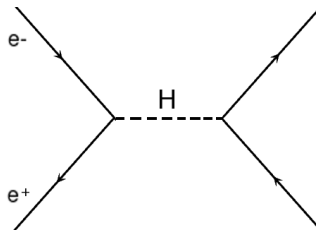
(HL- LHC measurements are model dependent)

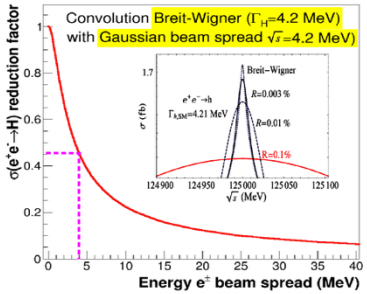
in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.0
g_{Hg}	3-5	1.2
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.8
$g_{H\gamma}$	2-5	2.1
Γ_H	5-8%	1.5

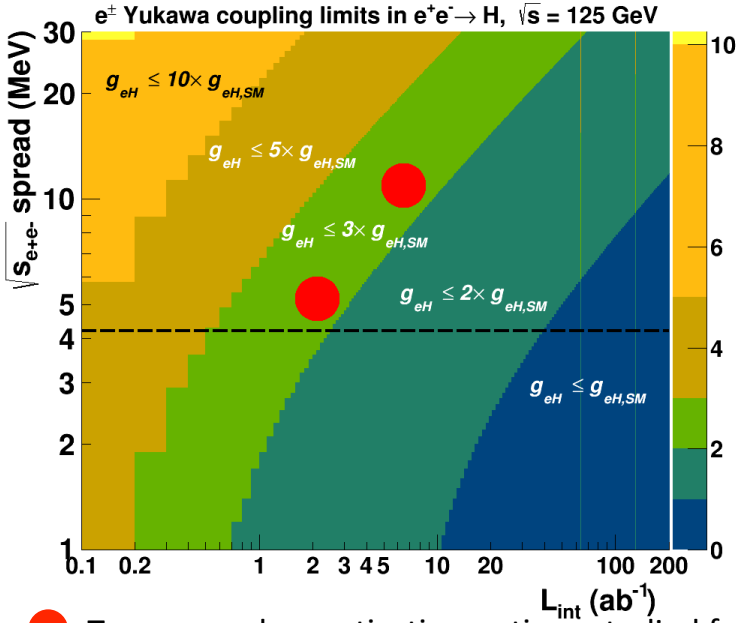
Higgs boson and first generation: s-channel production

Unique opportunity to measure the electron Yukawa coupling, highly challenging: σ(ee→H) = 1.6 fb, further reduced to ≈ 0.3 fb accounting for the finite energy spread and ISR of the e± beams.

Requires beam "monochromatization" at 62.5 GeV







Two monochromatization options studied for FCC-ee

http://jacow.org/ipac2016/papers/wepmw009.pdf

Talk of Paolo Azzurri on Tuesday

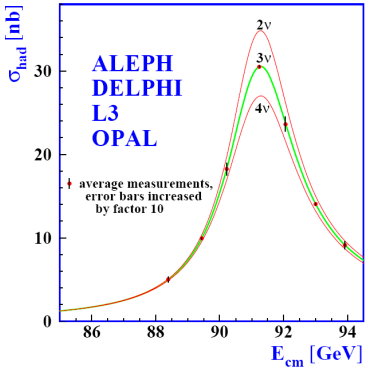
[from CDR in preparation and JHEP01(2014)164]

Tera Z: a new scenario for precision at the Z pole

L~2.8 10^{36} → ≈10^{12} Z events per year (**total at LEP 1.7 10^7 evts**)

The key for Z **mass** and **width**

→ continuous E_{CM} calibration (resonant depolarization)
$\Delta E_{beam} \approx 10$ KeV (stat) + 100 KeV (syst)



Precisions on observables[1]

- Z mass : $\Delta_{rel}(m_Z) \approx 10^{-6}$
- Z width : $\Delta_{rel}(\Gamma_Z) \approx 5\ 10^{-5}$
- R_l hadronic/leptonic width : $5\ 10^{-5}$ → $\Delta_{rel}\ \alpha_s(m^2_Z) \approx 2\ 10^{-3}$
- electroweak mixing angle from $A_{FB}(\mu\mu)$ at pole: $\Delta_{rel}\ \sin^2\theta_{eff} \approx 2\ 10^{-5}$
- from $A_{FB}(\mu\mu)$ off peak: $\Delta_{rel}\ \alpha_{QED}(m_Z^2) \approx 3\ 10^{-5}$
- invisible width : $10^{-3}\ N_\nu$ (from Z+photon at higher energy)

Improvement w.r.t. LEP

20
20
20
100 [just using $A_{FB}(\mu\mu)$]
not measured
8

(1) Δ_{rel} relative

[from CDR in preparation and JHEP01(2014)164]

Tera Z: precision for ewk heavy flavours measurements

tau polarization

Polarization vs the production angle allows A_e to be separated from A_τ :

➔ $\Delta A_\tau \approx$ **4** (**30**) 10^{-5} **stat** (**syst**)

➔ $\Delta A_e \approx$ **5** (**10**) 10^{-5} **stat** (**syst**)

Universality test and $\sin^2\theta_W$

Improvement w.r.t. LEP

10

30

bottom and charm couplings from FB asymmetries, R_b, R_c

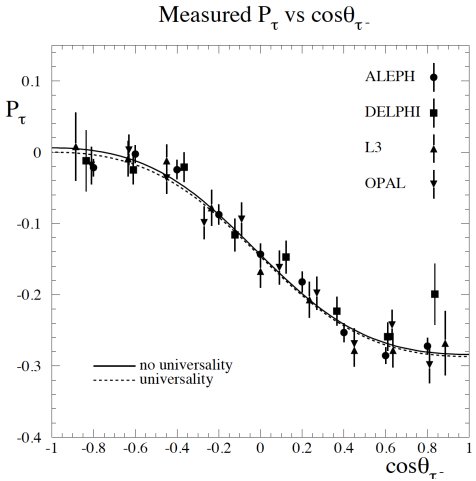
➔ $\Delta A_b \approx$ **2** (**40**) 10^{-5} **stat** (**syst**) $\Delta A_c \approx$ **3** (**40**) 10^{-5} **stat** (**syst**)

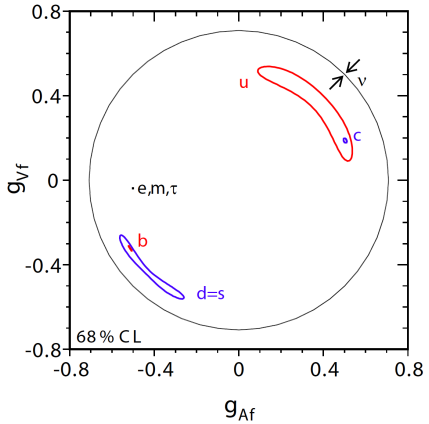
$\Delta R_b = \approx$ **1** (**5-20**) 10^{-5} **stat** (**syst**) $\Delta R_c = \approx$ **3** (**50**) 10^{-5} **stat** (**syst**)

Improvement w.r.t. LEP

5, 8

3-10, 6



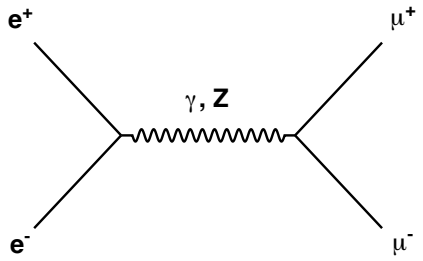


(1) here Δ absolute precision

Tera Z: Direct measurement of $\alpha_{QED}(m_Z^2)$

At LEP hadronic contributions to the vacuum polarization as external input (dispersion relations+ lower energy experiments) $\Delta_{rel} \approx 10^{-4}$

FCC-ee: direct measurement with better precision



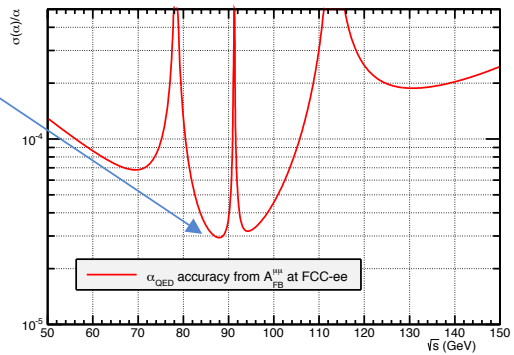
$$A_{FB}^{\mu\mu} = A_{FB,0}^{\mu\mu} + \frac{3}{4}\frac{a^2}{v^2}\frac{\mathcal{I}}{\mathcal{G}+\mathcal{Z}}.$$

Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED} : $\sqrt{s_-}$ = **87.9 GeV** and $\sqrt{s_+}$ = **94.3 GeV**

P. Janot: JHEP 2016(2) 1

Type	Source	Uncertainty
Experimental	E_{beam} calibration	1×10^{-5}
	E_{beam} spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
Theoretical	QED (ISR, FSR, IFI)	$< 10^{-6}$
	Missing EW higher orders	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

Work on EWK theoretical corrections required to reach $\approx 3\ 10^{-5}$



$\sigma(\alpha)/\alpha$ plot, for a year of running at any $\sqrt{s}$

Intrinsic th. uncertainties on EWPO

This is mandatory work that the community should support and consider it part of the full project !

- from the CDR draft contribution WG 2 write-up

"Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee"

Conveners: A. Freitas and S. Heinemeyer; Contributors: M. Beneke et al.
see talk by S. Heinemeyer

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	1–1.5[‡]	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b [10^{-5}]	6	15	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	7
R_l [10^{-3}]	1	5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	1.5

[‡]The pure experimental precision on M_W is ~ 0.5 MeV [3].

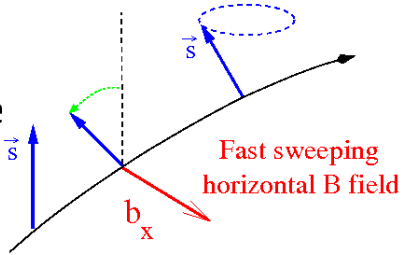
See talks of Gluza, Heinemeyer and Piccinini on tuesday evening

- with present and conceivable loop technology, the intrinsic th. uncertainties will be at the same level of the experimental errors
- new calculation methods should be introduced

see talk by J. Gluza

see e.g. the recent review on multi-loop integrals, A. Freitas, Prog. Part. Nucl. Phys. 90 (2016) 201

Key ingredient: transverse beam polarization provides beam energy calibration by resonant depolarization



- Low level of polarization is required (~10% is enough)
  - → at Z use of wigglers at beginning of fills otherwise very long polarisation time
  - → **at W pair threshold comes naturally** [NOTE: not available at LEP !]
  - → could be used also at ee → H(126) (depending on exact M_H!)
  - → not available at beam energies higher than ~90 GeV
    (but for H and top can use ee → Z γ or ee → ZZ, WW to calibrate E_CM at ~5 MeV level)

- **Must be done continuously during physics filly to avoid issues encountered at LEP** (Tides, TGV, etc.)
  - → this is possible with single bunches and Compton polarimeter (commercial laser)
    use 'single' non-colliding bunches
  - → must be complemented by analysis of «average E_beam» to E_CM relationship

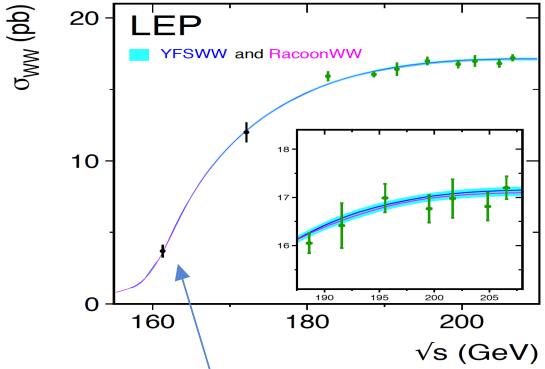
See talks of Blondel and Gianfelice-Wendt on Wednesday

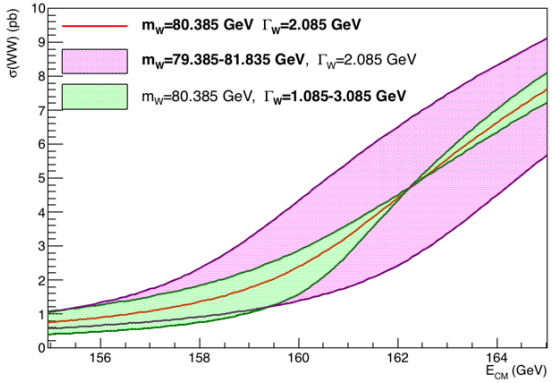
«EPOL» working group on polarization and beam energy:
J. Wenninger, E. Gianfelice, D. Barber, W. Hillert, A. Bogomyagkov, I. Kopp, N. Munchoi, M. Koratzinos, K. Oide, A.Blondel, et al
arXiv:1506.00933

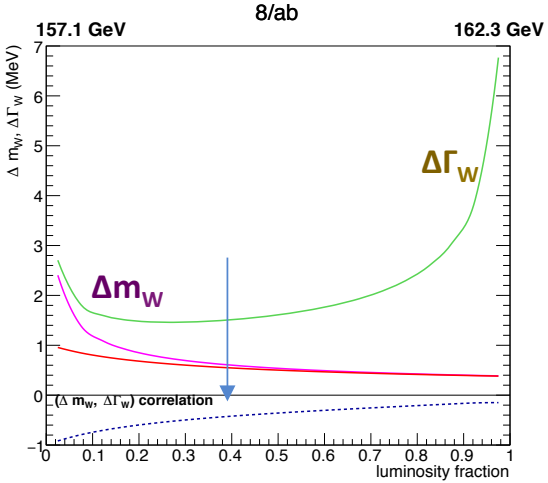
<< 100 keV beam en. calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

Talk of Paolo Azzurri on Tuesday

W mass (and width) from WW cross section







At LEP2 √s=161 GeV σ=4pb
ε=0.75, σ_B=300 fb
p=0.9 : εp≈0.68 (@161)
➔ m_W=80.40±0.21 GeV
with 11/pb @E_{CM}=161 GeV

Sensitivity to mass and width is different at different E_{CM}: can optimize measurement mass AND width choosing carefully two energy points.
<u>Same concept can be used to minimize systematics (e.g. due to backgrounds)</u>

with E_1=157.1 GeV E_2=162.3 GeV f=0.4
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

Goal: control acceptance and systematics at 10^{-4} level !

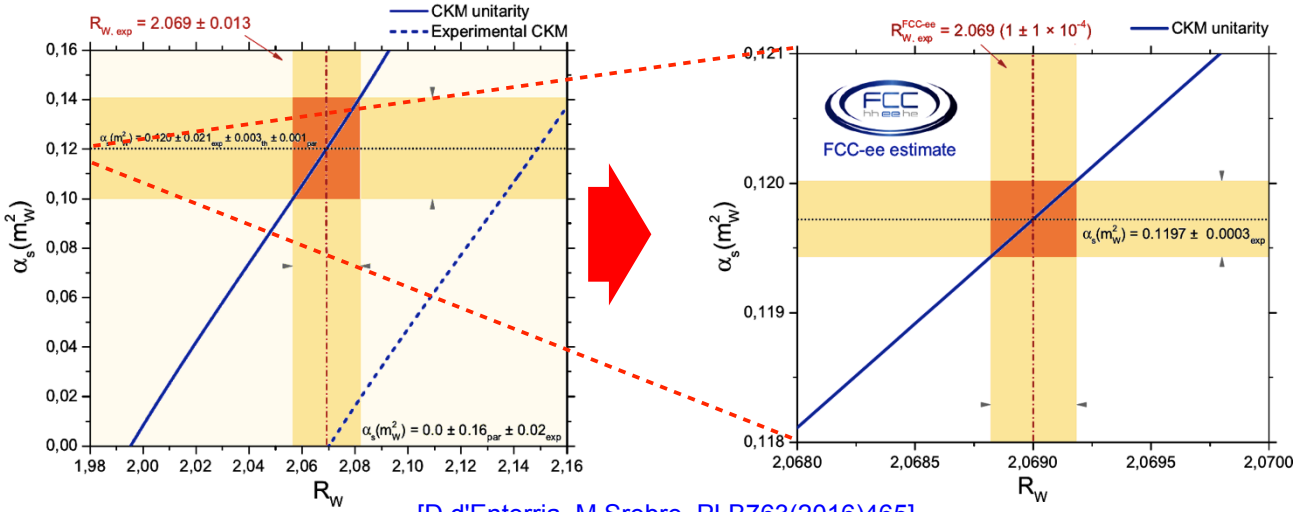
Talk of David d'Enterria on Tuesday

α_s via hadronic W decays

- Computed at $N^{2,3}LO$: $\Gamma_{W,had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi}\right)^k + \delta_{electroweak}(\alpha) + \delta_{mixed}(\alpha\alpha_s) \right]$
- LEP: Γ_W = 1405±29 MeV (±2%), BR_W = 0.6741±0.0027 (±0.4%)

  Extraction with large exp. & parametric (CKM V_{cs}) uncertainties today:

a_s (M_z) = 0.117 ± 0.040 (±35%)



[D.d'Enterria, M.Srebre, PLB763(2016)465]

- FCC-ee: – Huge W stats (×10^4 LEP) will lead to: : $\Delta_{rel}\ \alpha_s$ **< 0.3%**
  – TH uncertainty: $\Delta|V_{cs}|$ to be significantly improved (10^{-4})

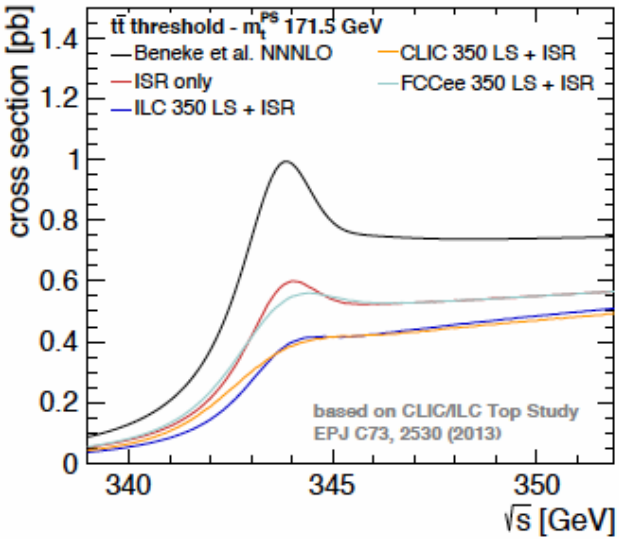
Can measure α_s at **< 0.1%** uncertainty combining Z, W, tau hadronic decays and jets rates & shapes

Talk of Patrizia Azzi on Tuesday

top mass from threshold scan

Cross section shape depends strongly on top quark mass, width, α_s and Y_t

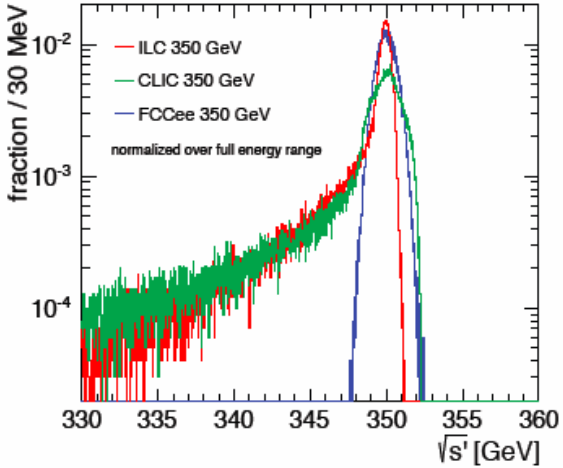
Top mass can then be extracted directly with a threshold scan



F. Simon arXiv:1611:03399 (2016)

The threshold shape is affected by ISR and machine beam energy spread

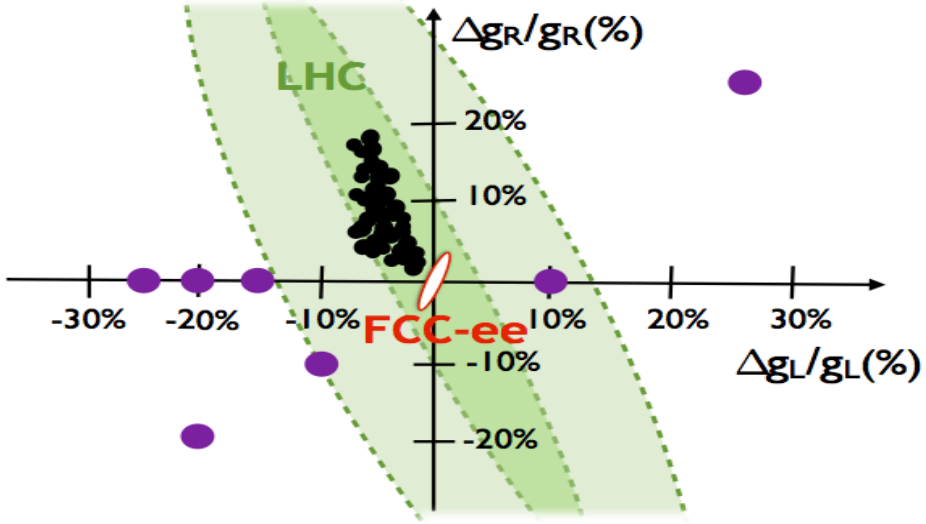
The FCC-ee has very steep luminosity profile, enhancing size of top sample

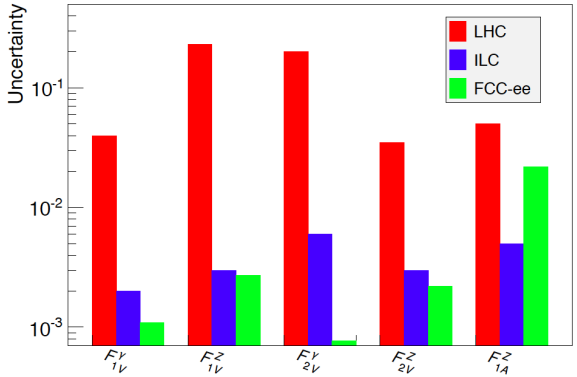


With 200 fb-1 FCC-ee can measure top quark mass with ~10 MeV statistical accuracy

Electroweak couplings of the top quark

- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**
- **Optimal √s= 365-370 GeV**

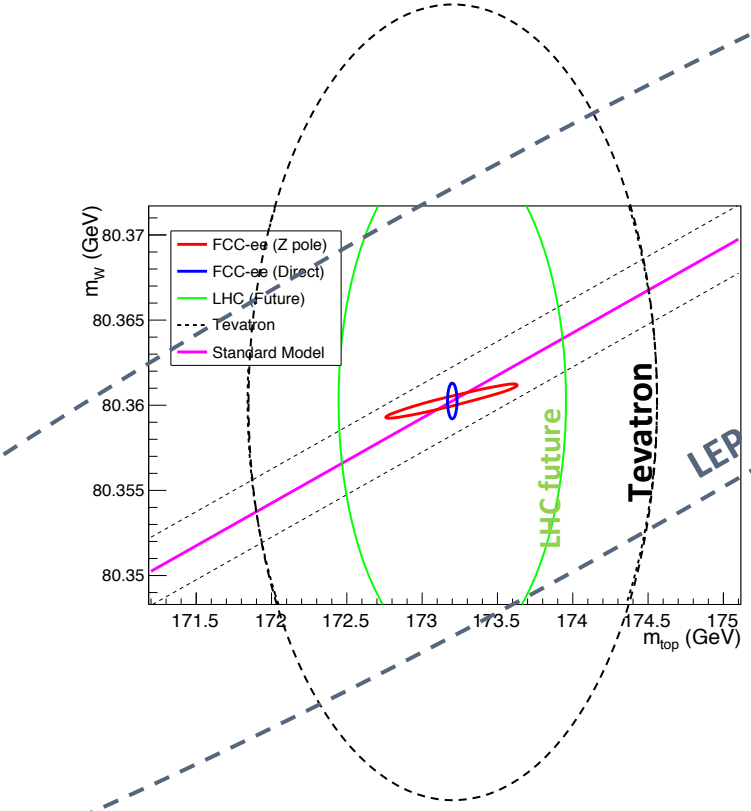




- ➤ Fit includes conservative assumptions detector performance
- ➤ Theory uncertainty on production mechanism dominates

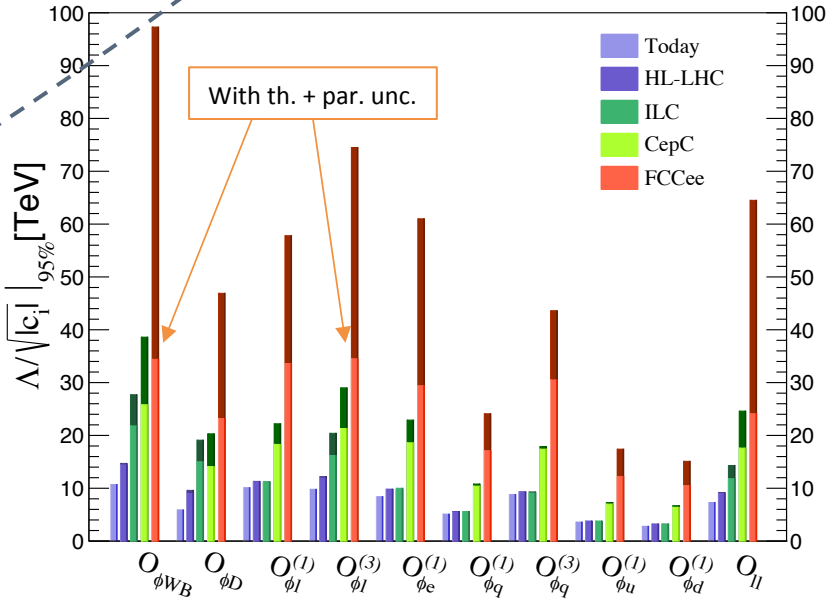
FCC-ee expected precision of order 10^{-2} to 10^{-3}

Global ewk fit and sensitivity to new physics



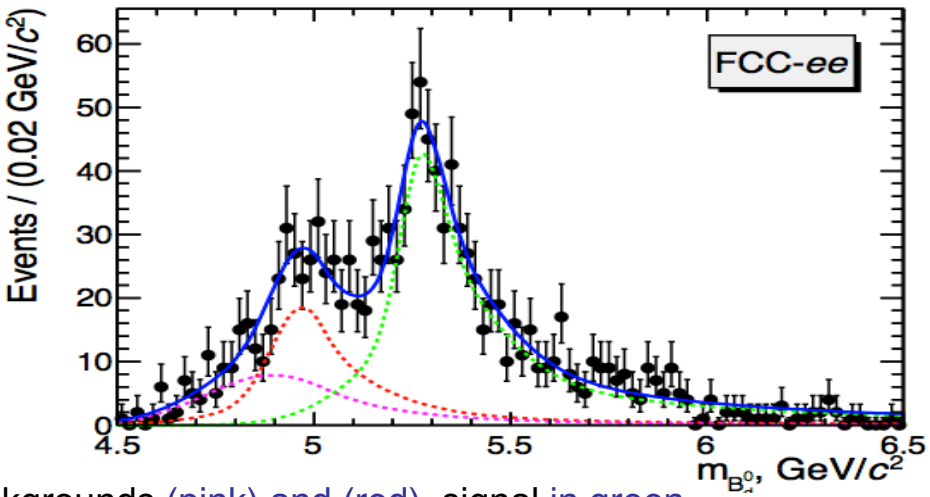
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Jorge de Blas
LHCP 2017



Example of B physics at FCC-ee - $B^0 \to K^{*0}\,\tau^+\tau^-$

- Persistent tensions seen in FCNC decays $b \to s\ \ell^+\ell^-$ w.r.t. SM / QCD, e.g. $B^0 \to K^{*0}\ \mu^+\mu^-$, $B^0 \to K^{*0}\ e^+e^-$
- A challenging channel: $B^0 \to K^{*0}\ \tau^+\tau^-$
- At baseline **Tera Z** luminosity, 10^3 events of reconstructed signal. Angular analysis possible.
- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance (crucial)
- *Another interesting and more challenging mode is $B_s \to \tau^+\tau^-$*
- *Also FCNC in Z decays: $Z \to \mu e,\ \mu\tau,\ e\tau$*



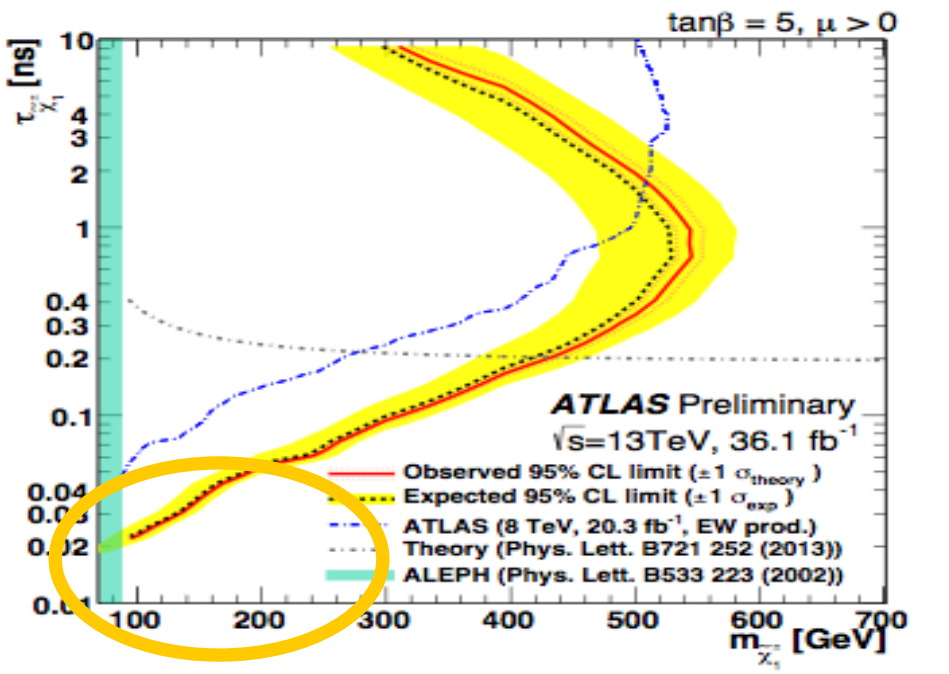
Backgrounds (pink) and (red), signal in green.
Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector.

Talk of Stephane Monteil on Tuesday

Example FCC-ee filling LHC corners: flying gauginos

- LHC experiments are searching for long-living particles. Typical example: chargino decaying to almost-degenerate neutralino

- Search limited not only by beam/statistics → difficult to probe short lifetimes in a hadronic environment



FCCee can probe the small-mass/small-lifetime scenario (motivated by naturalness for many BSM models)

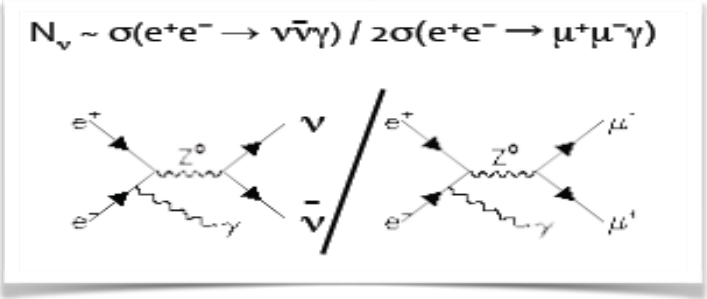
Talk of Maurizio Pierini on Tuesday

Search for Sterile Neutrinos at FCC-ee

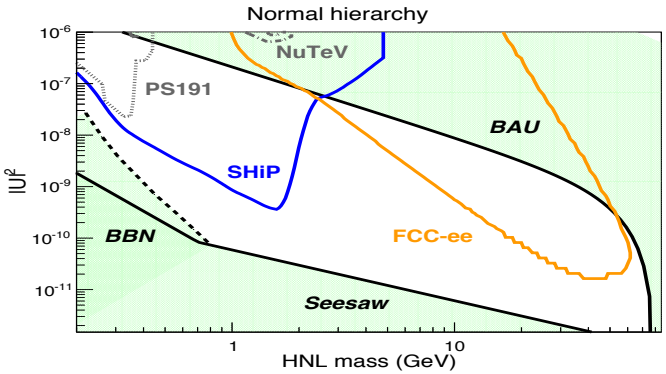
- **Number of neutrino families from LEP Nν=2.984±0.008**
  - potential to improve to ±0.001 using e+e—>Zγ (not enough statistics at LEP)
- **Search for sterile neutrinos in Z decays:**

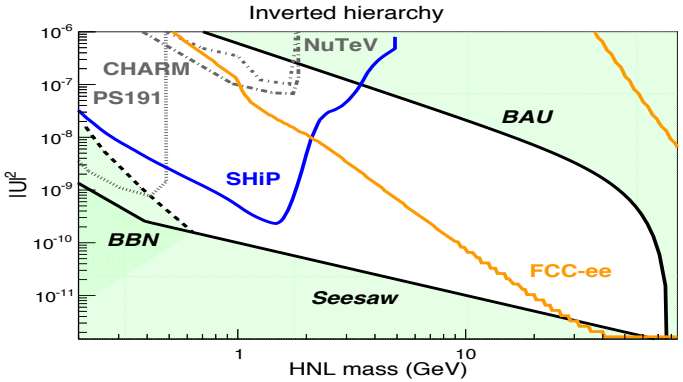
$$Z \rightarrow N\nu_i, \text{ with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j$$

  - Number of events depends on mixing between N and ν, and m_N

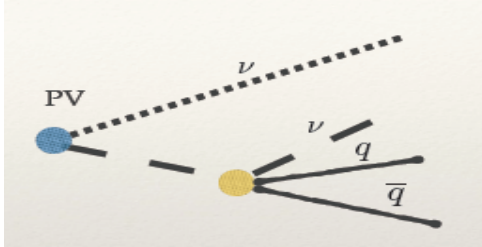


arXiv:1411.5230





(Very) Displaced SV

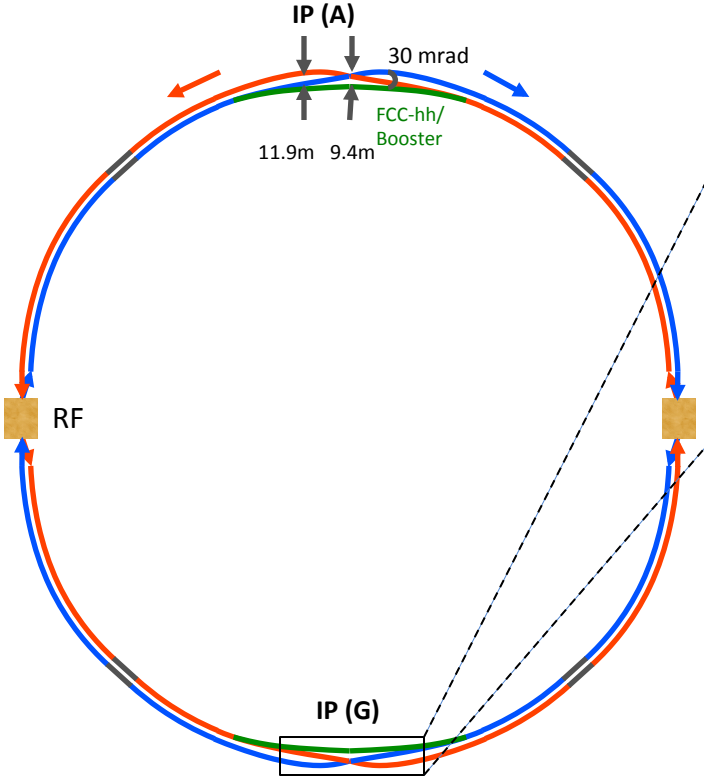


two plots correspond to different luminosity and detector size

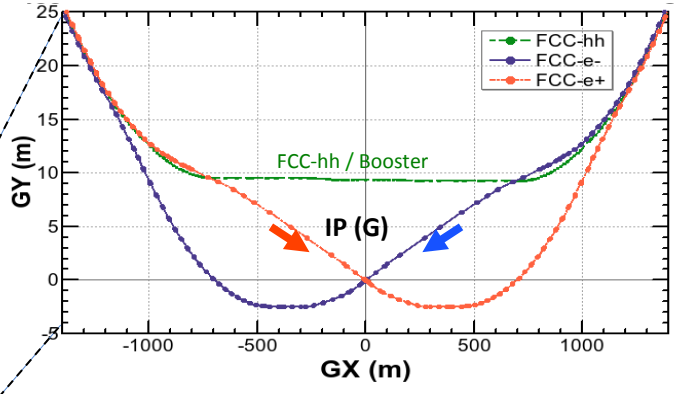
Concepts for experiments at FCC-ee

(short summary, more at the dedicated session tomorrow)

FCC-ee baseline layout



Asymmetric beam crossing at the IPs
Minimize synchrotron radiation



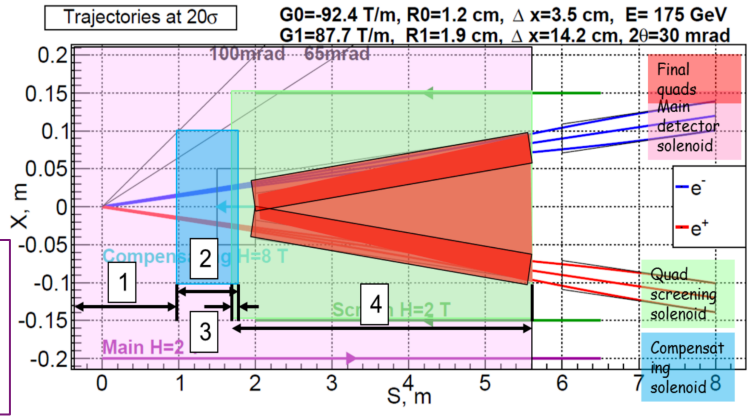
Conservative optics:
Two IPs – Relaxed β*
Integrated time needed twice smaller with four detectors than with two

Detector and MDI general requirements at FCC-ee

- Be suitable for high precision measurements
  → precise tracking in a low X0 tracker
- Excellent lepton id and momentum resolution
- Excellent photon id and energy/direction res.
- Precise angular (and energy) jet measurement
- Particle flow friendly
  → adequate calorimeter granularity
- High granularity vertex detector with b and c tagging capabilities

→ in a low occupancy environment maximum event rate 20 kHz @ Z peak

- Asymmetric optics with beam crossing angle of 30 mrad
- IP displaced by about 9.4 m wrt proton beam line
- Maximum magnetic field 2T (compensation)
- Beam pipe radius 15 mm
- Last quadrupole L* =2.2 m
- Detector has to "stay above" the 100 mrad line



Two benchmarks for CDR

- new IDEA from present state-of-the-art technology
- CLIC detector revisited for FCC-ee

Backgrounds studied with full Geant simulation

Synchrotron radiation mainly dictates the IR design

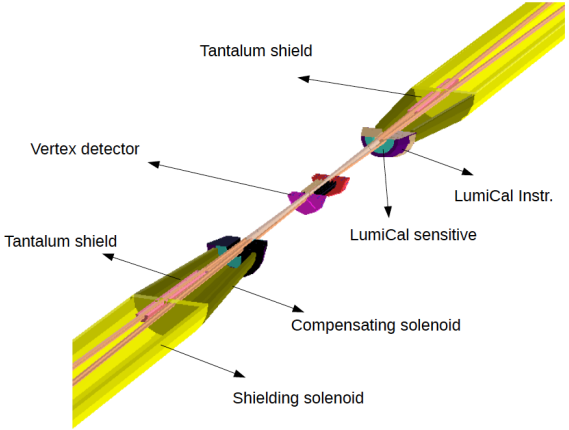
- Defines the beam pipe radius

Mask shields the detector from direct hits

- Some photons are scattered from the tips of the mask

Proper shielding can be optimized to keep rates low

- e.g. first layer of VTX occupancy < 10^{-5} can be achieved



Most unfavourable FCC-ee case (350 GeV) studied

Source	CLIC 3 TeV*		FCC 350 GeV	
	N / BX			
	total	P_T > 20MeV	total	P_T > 5MeV
IPC	3×10^5	60	2600	33
CPC	6×10^8	0	0	0
hadrons	102	54	0.05	~0.05
Syn. rad			$\sim5\times10^6$ †	

For more details see talk of Y. Voutsinas on Tuesday

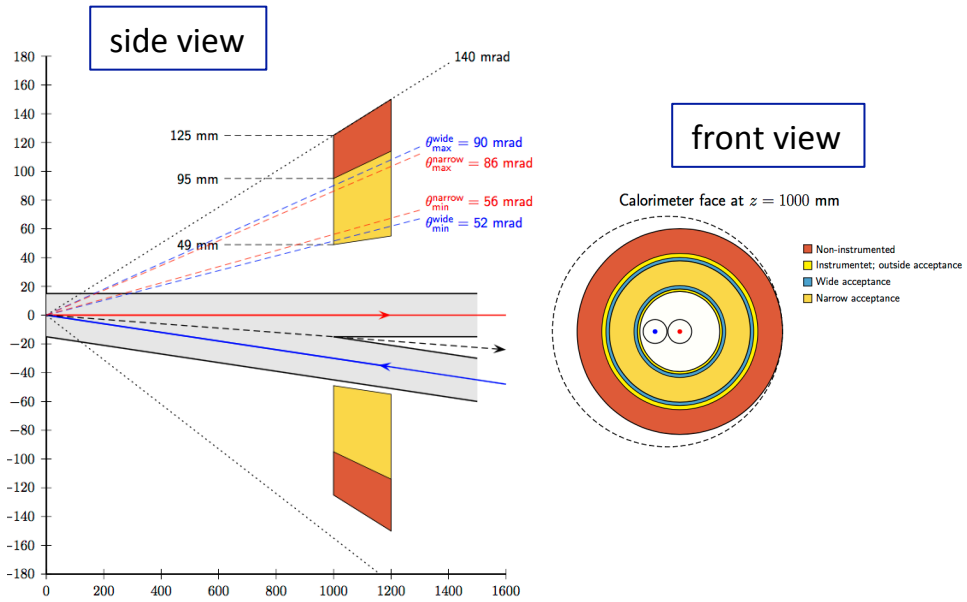
IPC=Incoherent Pair Creation
CPC=Coherent Pair Creation

Synchrotron radiation refers to photons scattered through the mask with " >10keV" energy per BX per beam

Luminosity measurement

- Alternate “tight” and “loose” fiducial regions in the two luminometers to make the measurement independent from beam position
- Luminometers centered on the outgoing beams
- Current limitation on absolute luminosity precision is from low angle Bhabha scattering theoretical cross section 10^{-3} aim at improving it for FCC-ee to reach a combined theory+exp uncertainty 10^{-4}
- Consider also γγ final state as a possible channel
- Challenges
  - Very fast readout (few ns)
  - Electronic not pulsed – heat dissipation
  - Maintain mechanical stability at 1 micron level

$$\sigma_{bh}^{th} \sim \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right)$$

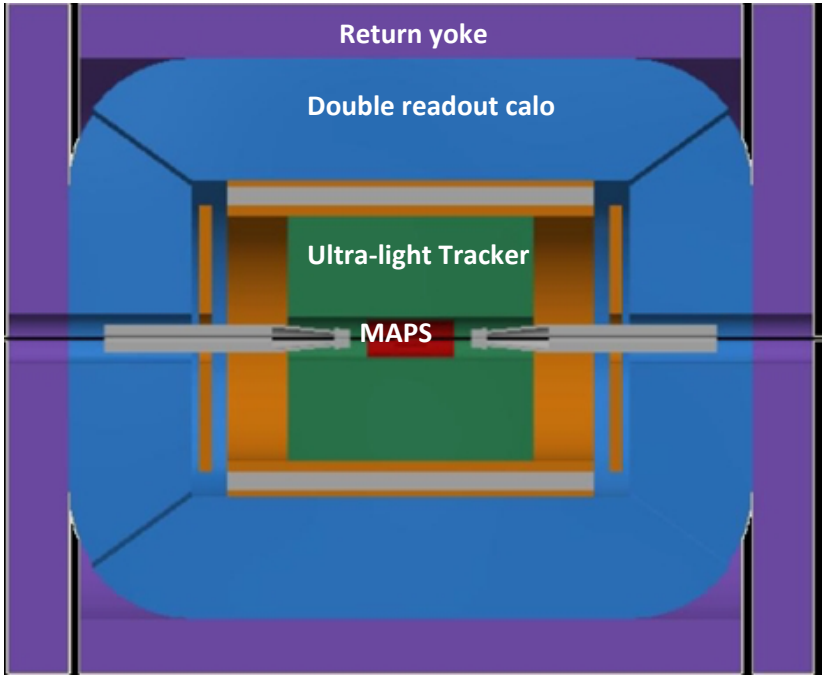


the IDEA concept

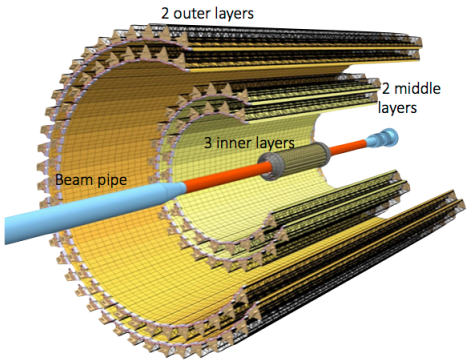
Talk of Mogens Dam on Tuesday

- Vertex detector, MAPS (a la ALICE)
- Ultra-light drift chamber with PID (a la MEG2)
  - **≈ 0.04 X0 up to the preshower face**
- Pre-shower counter
  - **defines acceptance ≈ 10-20 μm precision**
- Double read-out calorimetry (RD52 - DREAM)
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke
- Possibly surrounded by large tracking volume (R = 8m) for very weakly coupled (long-lived) particles

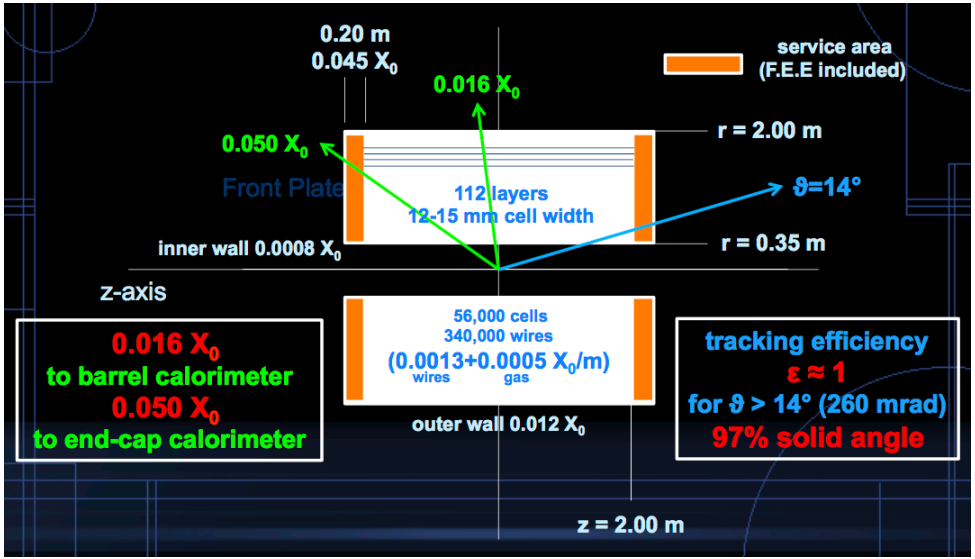
Two Options: Calorimetry inside or outside coil



IDEA: tracking



Tracker inspired by MEG2 Drift Chamber under construction



Courtesy of F. Grancagnolo

Vertex inspired by new ALICE ITS based on MAPS technology

- Pixels 30 × 30 μm^2

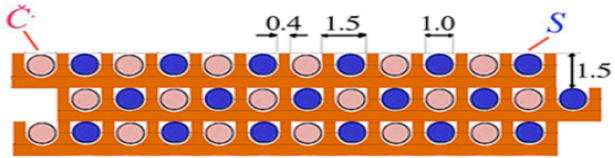
- Light
  - Inner layers: 0.3% X_0 / layer
  - Outer layers: 1% X_0 / layer
- Performance:
  - Point resolution about 5 μm
  - Efficiency of 100%
  - Extremely low fake rate hit rate

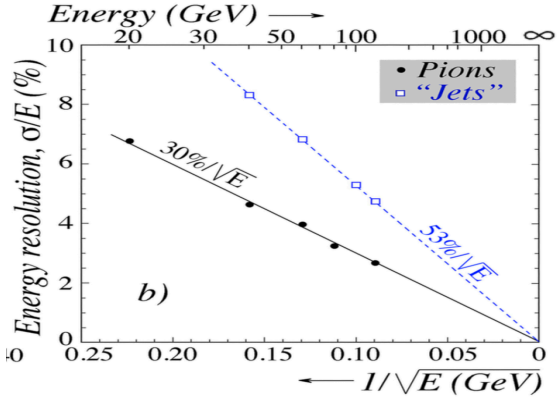
$\Delta P_T/P_T \approx 0.3\%$ at 100 GeV

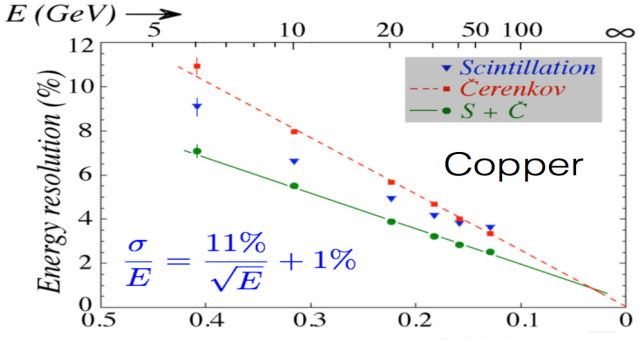
IDEA: dual readout calorimeter

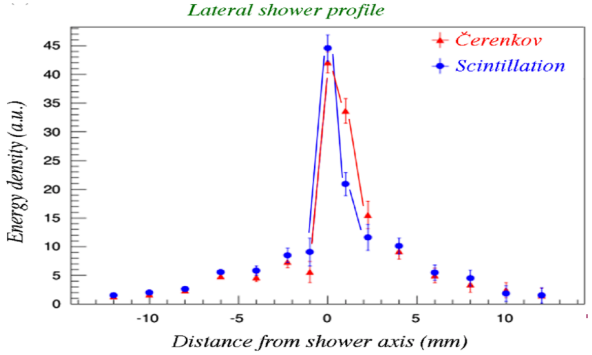
arXiv:1307.5538
arXiv:1703.09120

- As a possibility, investigating dual readout copper calorimeter of 160 cm radial depth
  - One compartment, no longitudinal segmentation
    - Longitudinal segmentation may be possible
  - ≈5.6 λ_{int} (coil outside option) - ≈8 λ_{int} (coil inside option)
- Separate readout of scintillation and Cerenkov signal
  - Very good electromagnetic performance
    - ≈2 GeV resolution on Higgs mass in H → γγ
  - Promising resolution also for hadrons









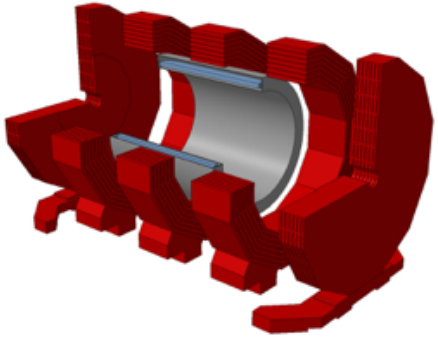
Talk of Emilia Leogrande on Tuesday

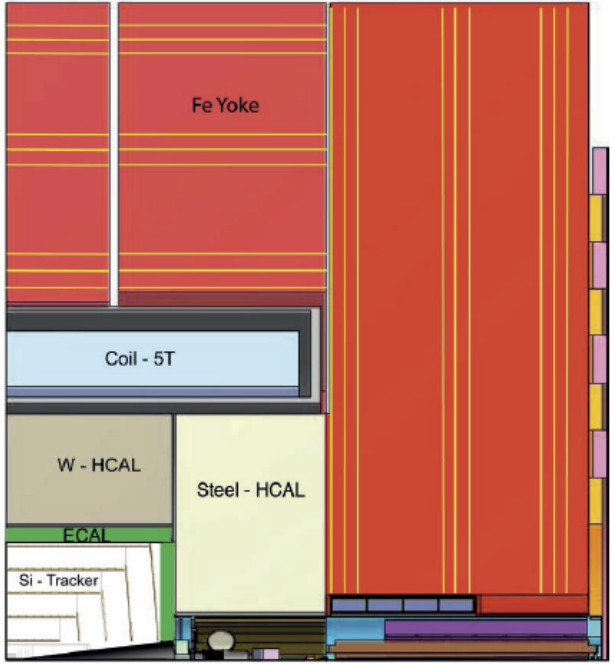
A CLIC-inspired detector for FCC-ee

Adapted from CLIC_SiD

- Pixel Vertex detector - pix 25x25 μm^2 – 0.4% X_0/d. layer
- Silicon Strips Tracker – 6 layers < 0.1 X0 barrel
- High Granularity Calorimetry
  - ECAL silicon-tungsten – 22 X_0
  - HCAL barrel scintillator tiles-tungsten – 5.5 λ_{int}
  - HCAL endcap scintillator tiles-steel

STRUCTURE unchanged: Fe yoke equipped with muon chambersRPCs 30x30 mm2

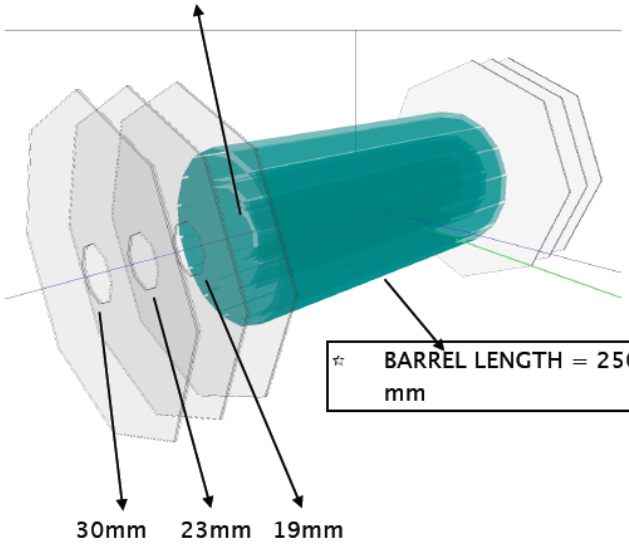




For more details talk of Emilia Leogrande on Tuesday

CLIC-detector scaled and adapted for FCC-ee

- INNER LAYER closer to the beam pipe
  - depends on SR photon background



- BARREL LENGTH = 250 mm

- DISKS INNER RADIUS closer to the beam pipe

Scale all the barrel layers*

double layer radius [mm]	CLIC	FCC
1st	31–33	17–19
2nd	44–46	37–39
3rd	58–60	57–59

*layer thickness may need to be increased to accomodate water cooling

Disks to replace spirals (no need for air flow)

	double disk z [mm]
1st	159–161
2nd	229–231
3rd	299–301

- OUTER BARREL RADIUS to be increased to 2.14 m
  - to compensate for the lower B

Scale all the barrel layers*

layer radius [mm]	CLIC	FCC
ITB1	127	127
ITB2	340	400
ITB3	554	670
OTB1	819	1000
OTB2	1153	1568
OTB3	1486	2136

*layer thickness may need to be increased to accomodate more water cooling

Support tube*

radius [mm]	CLIC	FCC
inner	575	675
outer	600	700

*diameter to be checked for mechanical stability

SUMMARY, not conclusions, yet

- The FCC-ee CDR describing a vibrant program of key measurements at e^+e^- centre-of-mass energies around 90, 160, 240 and 350 GeV is in preparation
- It will include perspectives for significant progress in the realm of W, Z and Higgs boson physics, QCD, Heavy Flavours and searches for BSM physics
- Discussions on realistic detectors and MDI considerations will be an essential part of the volume

Acknowledgements

P. Azzi, P. Azzurri, N. Bacchetta, F. Bedeschi, M. Boscolo, A. Blondel, M. Dam, J. De Blas, D. d'Enterria, F. Grancagnolo, P. Janot, M. Klute, A. Kolano, E. Leogrande, S. Monteil, F. Piccinini, E. Perez, M. Pierini, G.Rolandi, Y. Voutsinas