
(some) Experimental conditions at FCC-ee and differences with CLIC

E. Perez (CERN)

CLIC Workshop, March 10, 2017

Material from this talk comes mostly from :

- the FCC-ee MDI group
 - two-weeks workshop in January, lead to a new baseline for the IR
 - not implemented yet in the simulations shown here
- the FCC-ee detector group
- CLICdp-note-2017-001 and the CLIC CDR

Thanks in particular to Nilou Alipour, Nicola Baccheta, Manuela Boscolo, Konrad Elsener, Patrick Janot, Emilia Leogrande, Lucie Linsen, Georgios Voutsinas

Linear or circular electron-positron colliders : several projects

Linear: ILC & CLIC



- only way to go to very high \sqrt{s} : reach = 3 TeV for CLIC
- natural longitudinal polarisation
- possibility to operate as a $\gamma\gamma$ collider
- low repetition rate (beam is lost !), i.e. high luminosity requires
 - Very small beam size (nm)
 - Negative effects: large beamstrahlung, energy spread
- deliver data to only one detector at the time



Circular : FCC & CEPC

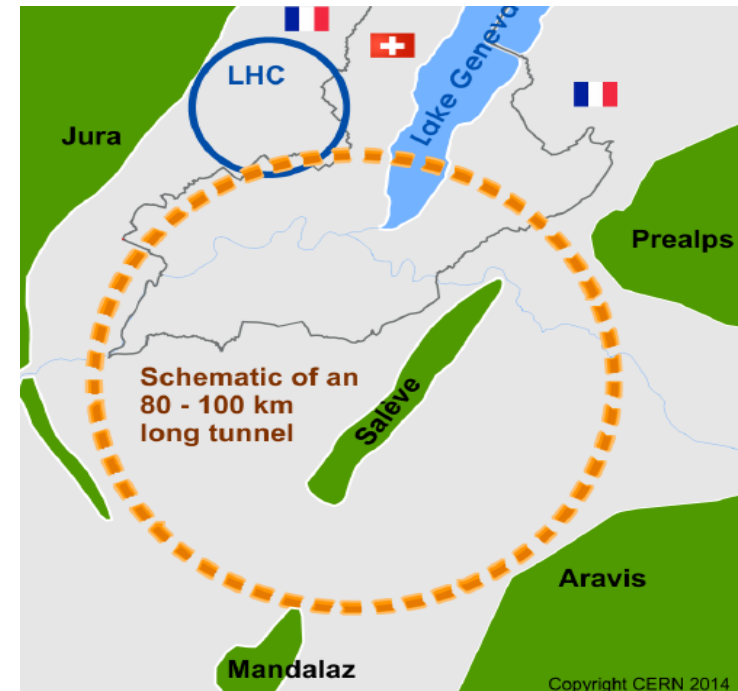


- \sqrt{s} limited by synchrotron radiation (goes as E^4 / R) i.e. by RF power
- large number of bunches allows high luminosity
- possibility of several interaction regions
- natural transverse polarisation: very precise measurement of Ebeam (resonant depol)
- Big synergy with future high energy pp colliders

FCC : Future Circular Colliders

Design study: **CDR end of 2018**, for the next European Strategy Update (2019)

- Ultimate goal: pp collider O(100) TeV (FCC-hh)
- 100 km tunnel, in Geneva area, LHC as injector
- ee as a possible first step (FCC-ee)
 - Same infrastructure
 - range : **from M_Z and below, to O(365 GeV)**



Kickoff meeting in 2014. Some challenges :

- Large **Synch. Radiation** (SR) at $\sqrt{s} = 2mt$ (intense radiation, impact on the vacuum and on the RF)
- **Large momentum acceptance** of 2% required for the ZH and $t\bar{t}$ points (else beamstrahlung leads to a too short lifetime)

Much progress since then :

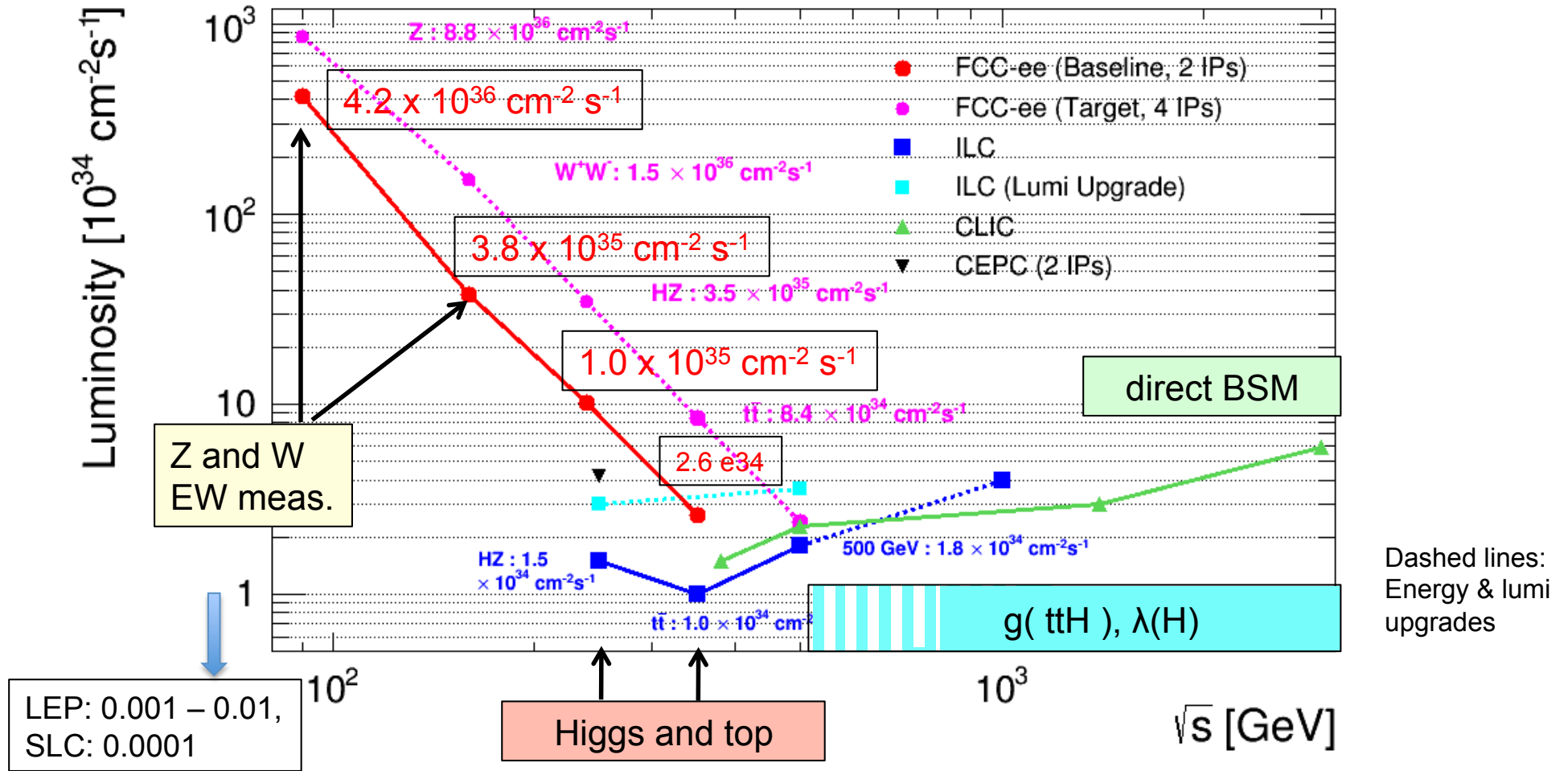
- A design optics that complies with the requirements

Technology ready (cf SuperKEKB)

- ongoing R&D aims at improving efficiency and reducing the costs

e+e- future colliders : luminosity vs energy

From Patrick Janot



- FCC : “baseline” updated 2016 = conservative optics & 2 IPs only (red curve)
 - optics with 4 IPs under study, as well as smaller β^* optics (pink curve)
 - L rises with decreasing \sqrt{s} : less SR -> RF power can be used to accelerate more bunches
- linear : L rises with increasing \sqrt{s} due to adiabatic damping (radiation induced beam size reduction)



FCC-ee key parameters

F. Zimmermann

parameter	FCC-ee				CEPC	LEP2
energy/beam [GeV]	45		120	175	120	105
bunches/beam	30180	91500	770	78	50	4
Bunch spacing [ns]	7.5	2.5	400	4000		22000
beam current [mA]	1450		30	6.6	16.6	3
luminosity/IP x 10 ³⁴ cm ⁻² s ⁻¹	207	90	5.1	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03		1.67	7.55	3.1	3.34
synchrotron power [MW]	100				103	22
RF voltage [GV]	0.4	0.2	3.0	10	6.9	3.5
rms bunch length (SR,+BS) [mm]	1.2, 6.7	1.6, 3.8	2.0, 2.4	2.1, 2.5	2.1, 2.6	12, 12
rms emittance $\epsilon_{x,y}$ [nm, pm]	0.2, 1	0.1, 1	0.6, 1	1.3, 2.5	6, 18	22, 250
longit. damping time [turns]	1320		72	23	39	31
crossing angle [mrad]	30		30	30	0	0
beam lifetime [min]	94	185	67	57	61	434



FCC-ee key param

F. Zimmermann

Large number of bunches : Need crossing angle : $\theta_c = 30$ mrad to avoid parasitic crossings

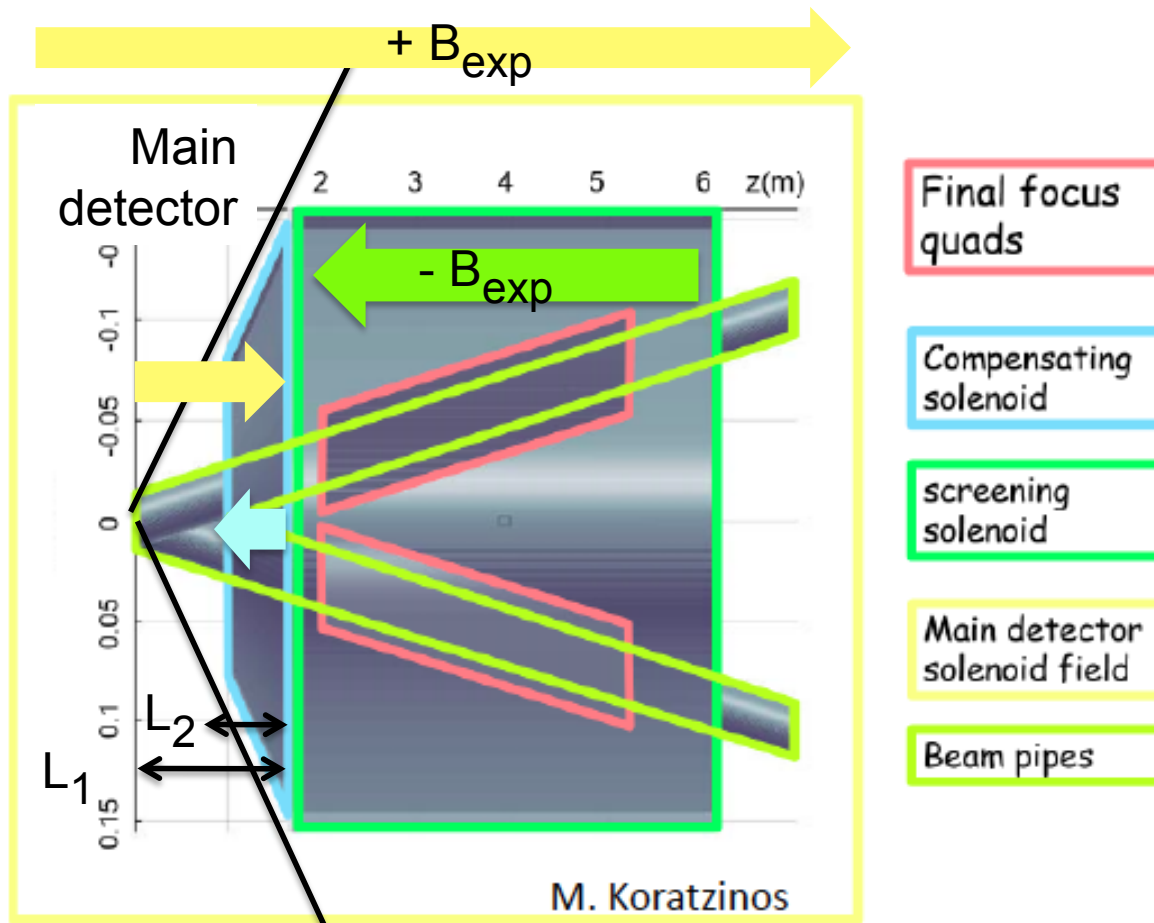
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energy loss/turn [GeV]				7.55		
synchrotron power [MW]	<p>Luminosity up to $2e36$ cm⁻² s⁻¹ :</p> <ul style="list-style-type: none"> - “crab-waist scheme” demands large θ_c - Need last focusing quadrupole very close to the IP <p>$L^* = 2.2$ m</p>					
RF voltage [GV]						
rms bunch length (SR,+BS) [mm]						
rms emittance $\epsilon_{x,y}$ [nm, pm]						
longit. damping time [turns]						
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Large amount of synchrotron radiation at the t \bar{t} bar energy
Impact on IR, RF

FCC-ee interaction region

Very strong focusing -> final quadrupole (QD0) within the detector volume, esp. within the solenoidal field of the experiment. Consequences :

- QD0 must be shielded such that net solenoidal field = 0 in QD0 (= screening)
- $\theta_c \neq 0$: Need to “undo” the effect of B_{exp} on the beam to prevent emittance blow-up (budget $\epsilon_y \sim 1 \text{ nm}$) -> compensating solenoid in front of QD0



integral of $B.L = 0$:

e.g. with $L_2 = L_1 / 2$,
 $B_{comp} \approx 2 B_{exp}$

B_{comp} can not be too high,
 sets a limit on B_{exp} !

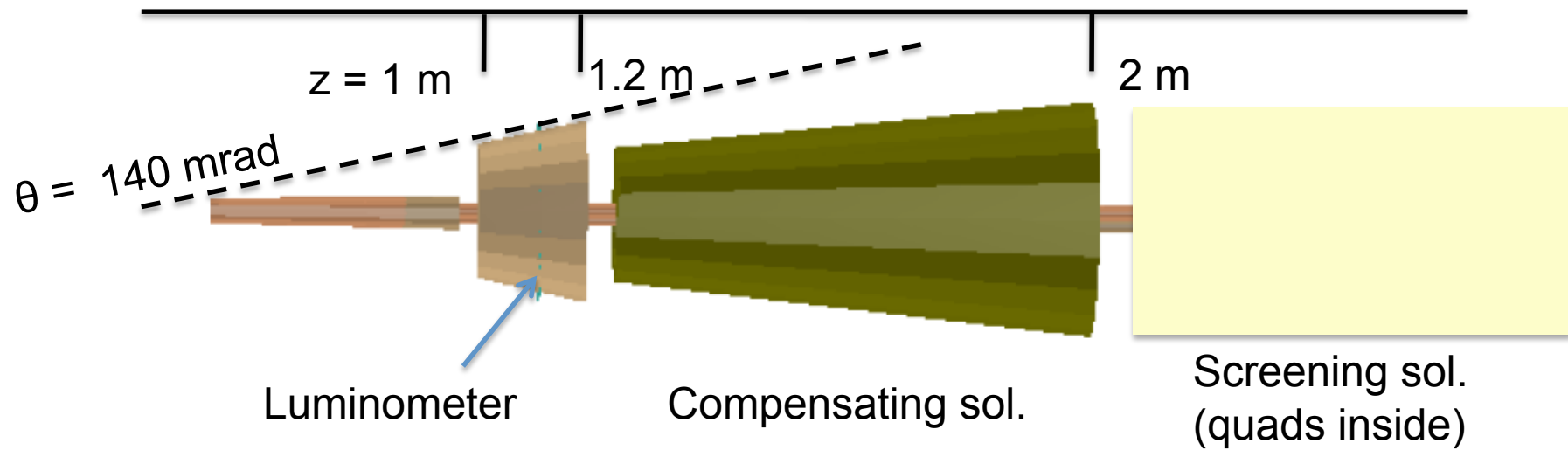
Baseline :

$L^* = 2.2 \text{ m}$

$1.25 \text{ m} < z(\text{comp}) < 2 \text{ m}$

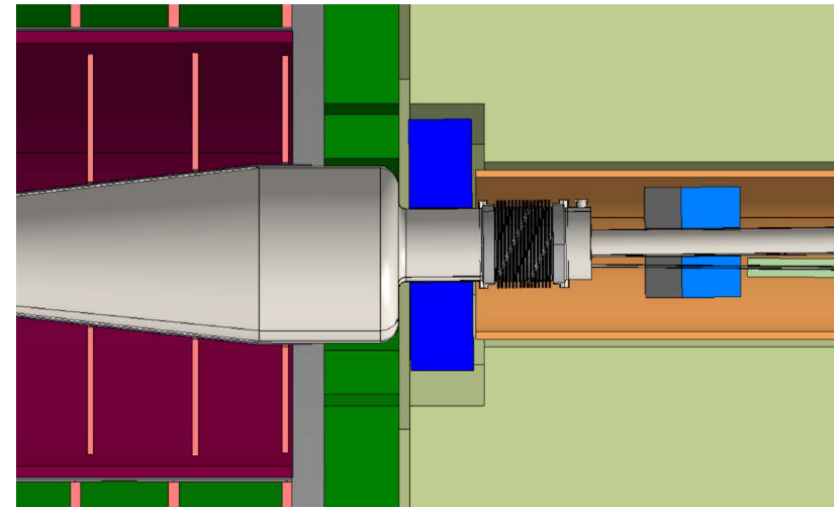
$B_{exp} = 2 \text{ T}$
 2x lower than CLIC

CLIC and FCC interaction regions

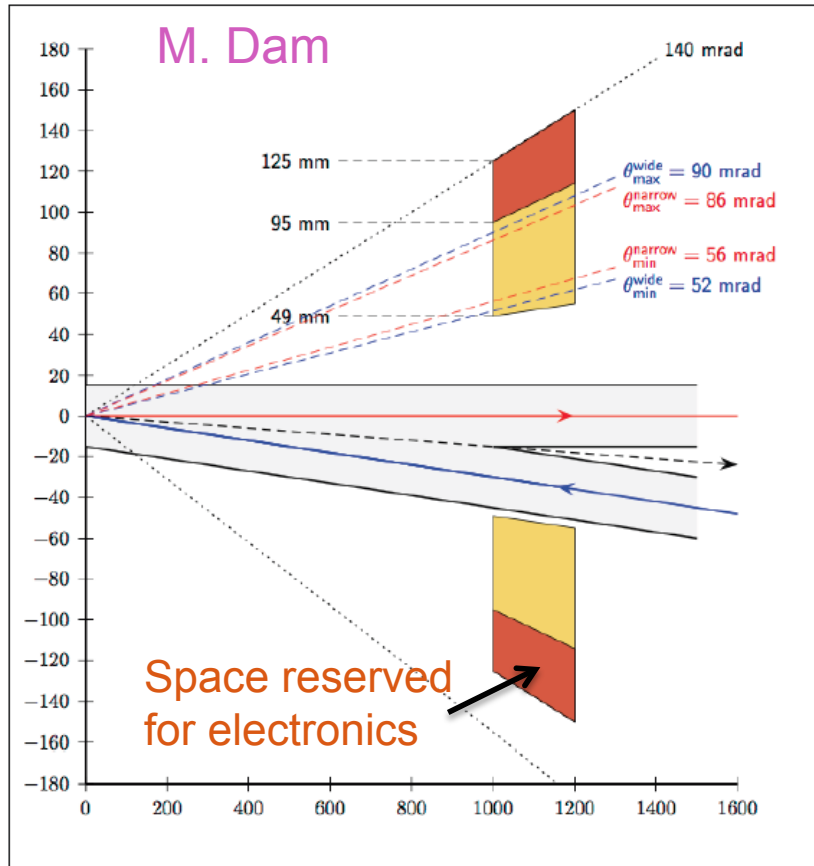


Very little space to squeeze in the luminosity calorimeter !

	FCC	CLIC
$L^* \text{ (m)}$	2.2	6.0
$B \text{ exp (T)}$	2	4
LumiCal	$1 < z < 1.2 \text{ m}$	$2.5 < z < 2.7 \text{ m}$
BeamCal	-	$3.2 < z < 3.4 \text{ m}$



Luminosity measurement at FCC



Luminosity from the measurement of low angle Bhabha electrons. Calorimeter centered around the outgoing beam.

Challenging requirement at FCC : $\Delta L/L = 10^{-4}$

e.g. OPAL (exp. syst.) reached $3 \cdot 10^{-4}$

(esp. for Z line-shape)

- θ_{min} constrained by the incoming pipe ;
- θ_{max} constrained by main detector acceptance, down to $> 140 \text{ mrad} \approx 8 \text{ deg}$

Baseline design : LumiCal at $z = 1 \text{ m}$,
Measurement within $56 < \theta < 86 \text{ mrad}$

CLIC : easier requirement $\Delta L/L = \text{a few } 10^{-3}$

LumiCal at 2.5 m, i.e

- go to smaller θ : $39 < \theta < 134 \text{ mrad}$ (geom)
- much easier on metrology
- dominant systematics may be \neq from FCC

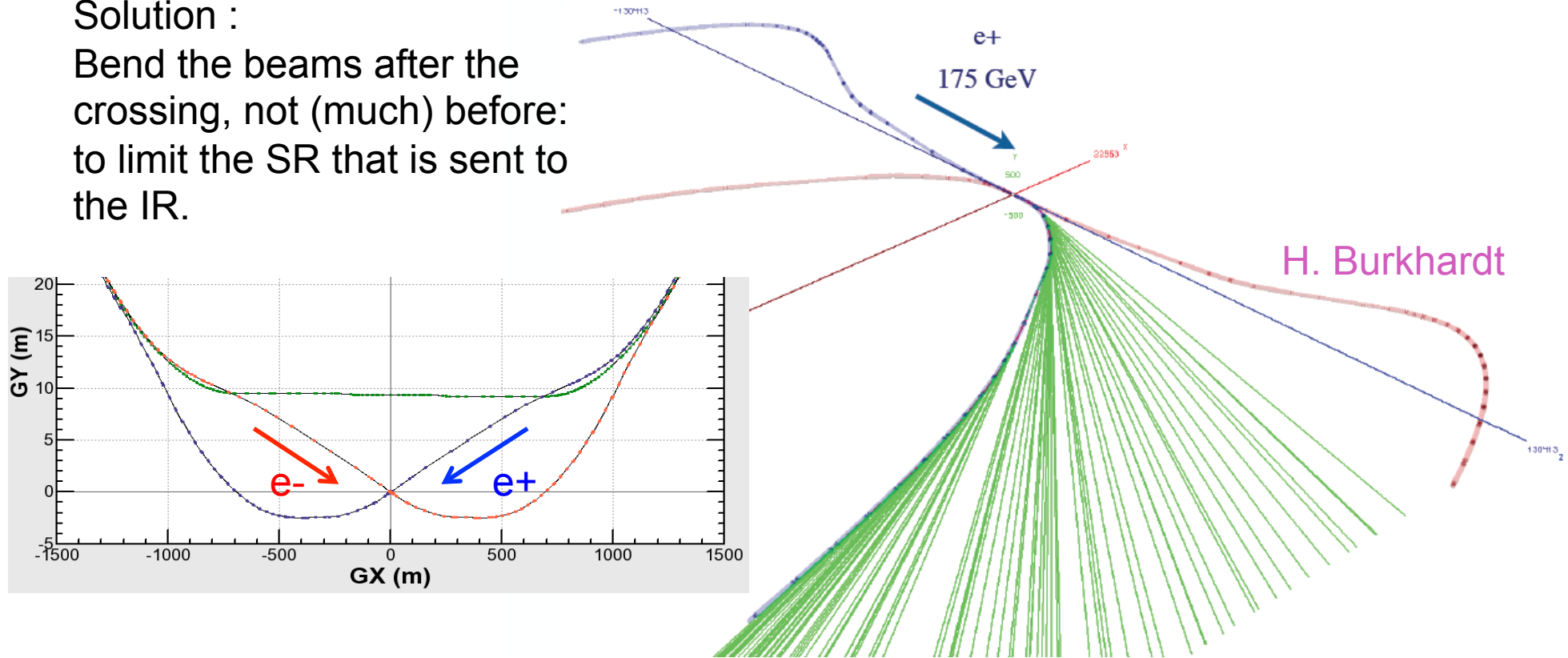
Cross section: $\sigma = 23 \text{ nb}$
Geometric precision needed for absolute normalization to 10^{-4}

- $\delta z = 50 \mu\text{m}$
- $\delta r_{min} = 1.6 \mu\text{m}$
- $\delta r_{max} = 5.8 \mu\text{m}$

Synchrotron radiation at FCC-ee

SR sets important constraints to the IR design and drives the IR optics and layout.

Solution :
Bend the beams after the crossing, not (much) before:
to limit the SR that is sent to the IR.



With this asymmetric layout:
at $\sqrt{s} = 2mt$, SR level is then similar to that of LEP2.
Still, careful design is required to limit SR sent into the detector.

FCC IR

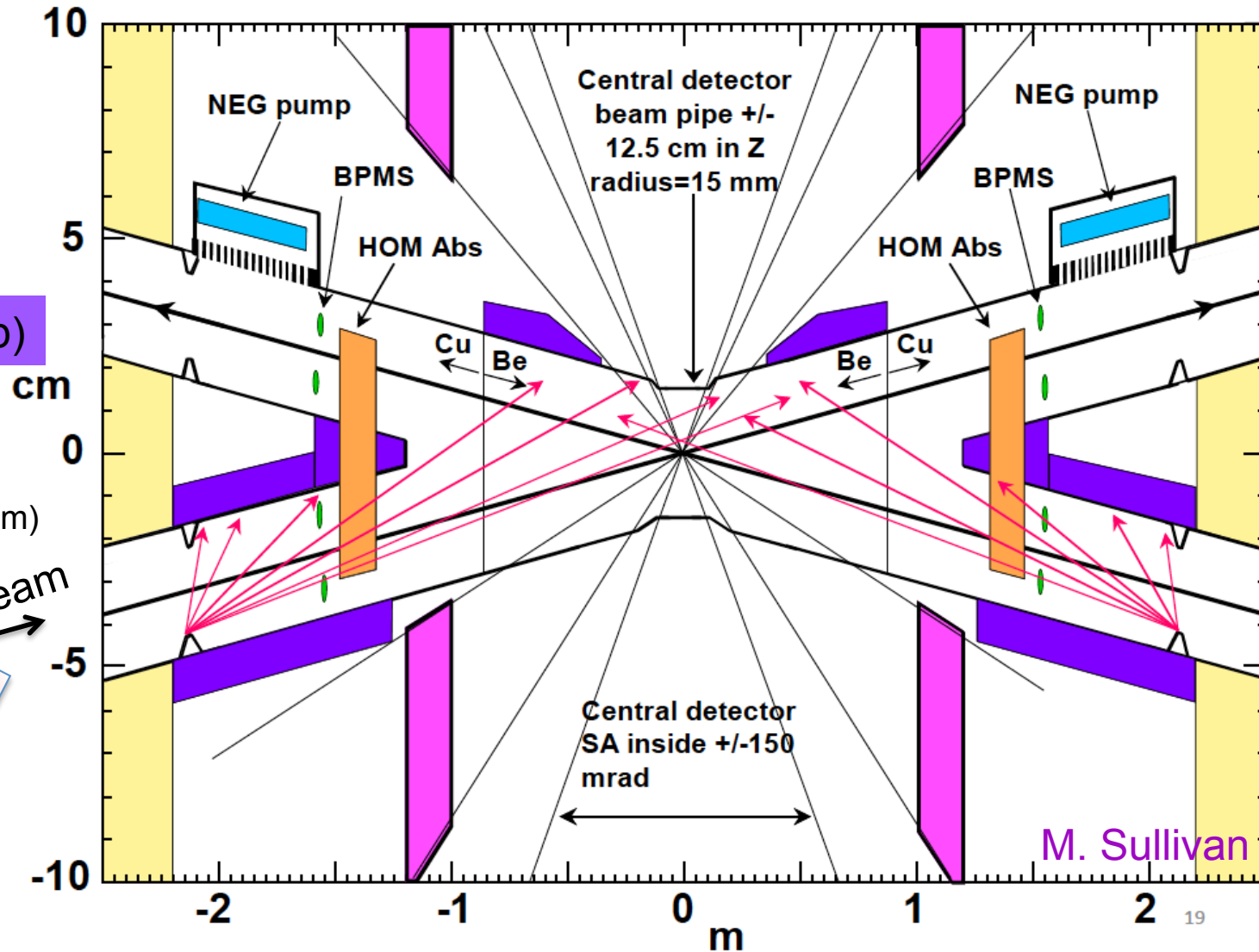
QD0

LumiCal

Shielding (Pb)

HOM abs
(only on top/bottom)

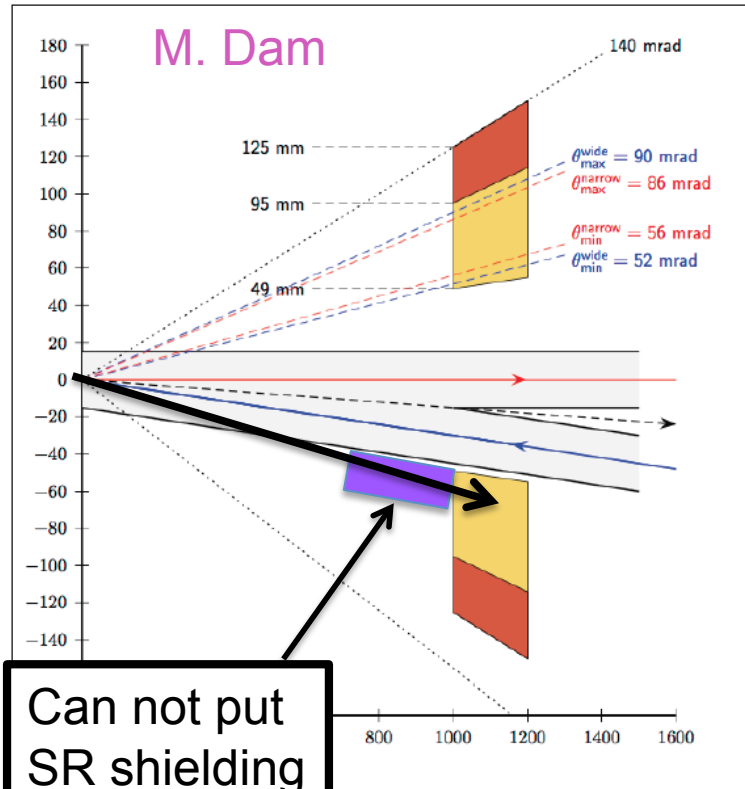
Incoming beam
SR γ s



At FCC : Synchrotron radiation largely determines the radius of the beam-pipe in the IR
While at CLIC, it is driven by beamstrahlung-induced backgrounds (see later)

FCC baseline : R = 1.5 cm
CLIC : R = 3 cm

SR shielding and LumiCal !

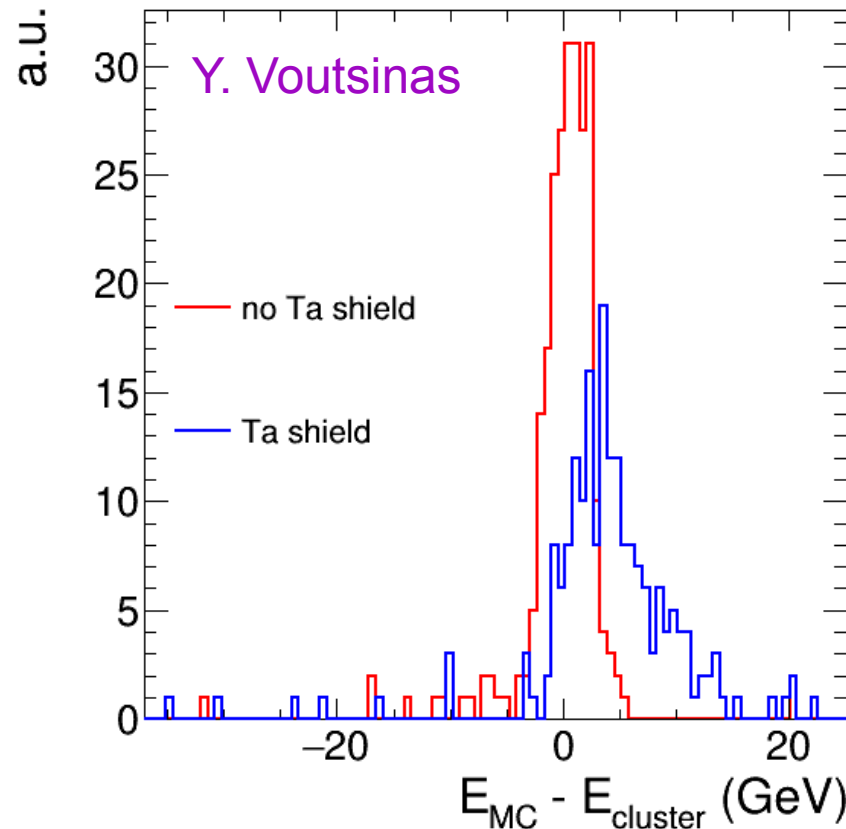


Can not put SR shielding here !!

Ex : GEANT4 simulation of Bhabha, CLIC-like LumiCal, in the FCC-ee interaction region

The Bhabha electrons for luminosity measurement should not see any shielding on their path to the LumiCal !

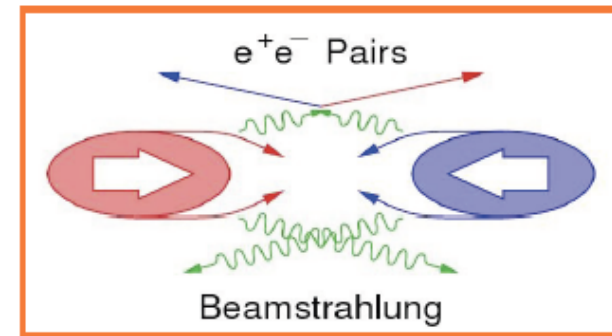
Else, shielding acts as a preshower and degrades dramatically the energy measurement in the LumiCal :



Beamstrahlung

	CLIC 380	CLIC 3 TeV	FCC Z	FCC tt
σ_x (nm) / σ_y (nm)	150 / 2.9	40 / 1	10000 / 32	36000 / 70
σ_z	70 μm	44 μm	6.7 mm (SR only: 0.9 mm)	2.5 mm
N / bunch	5.2e9	3.7e9	1.0e11	1.7e11

- **CLIC** : high luminosity demands **extremely small beams**. Consequence: large EM fields from the bunches, large beamstrahlung.
 - > luminosity profile ($\sqrt{s} \neq$ nominal \sqrt{s})
 - > $\gamma\gamma \rightarrow e^+e^-$, $\gamma\gamma \rightarrow$ had background



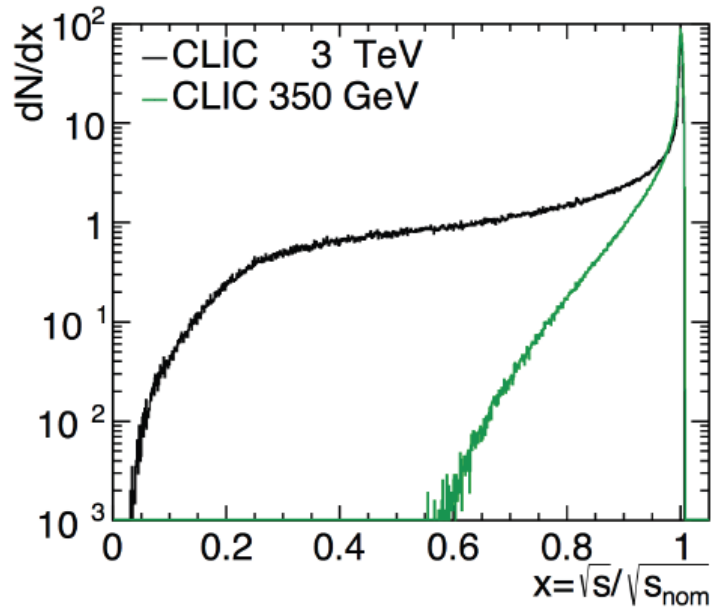
- **FCC** : mandatory to limit the effect of beamstrahlung. Beams are circulating !!
Much larger beam size limits the BS.
- Amount of Beamstrahlung driven by the **charge density** of the bunches :

$$Y_{ave} \approx cst \cdot \gamma N / \sigma_z \sigma_x$$

$$Y(\text{CLIC 380}) / Y(\text{FCC 350}) \approx 250$$

$$Y(\text{FCC 350}) / Y(\text{FCC 90}) \approx 5$$

Beamstrahlung and luminosity profile



Fraction $v_s/v_{s_{nom}}$	350 GeV	3 TeV
>0.99	68%	36%
>0.9	95%	57%
>0.8	99.1%	68%
>0.7	99.9%	77%
>0.5	~100%	88%

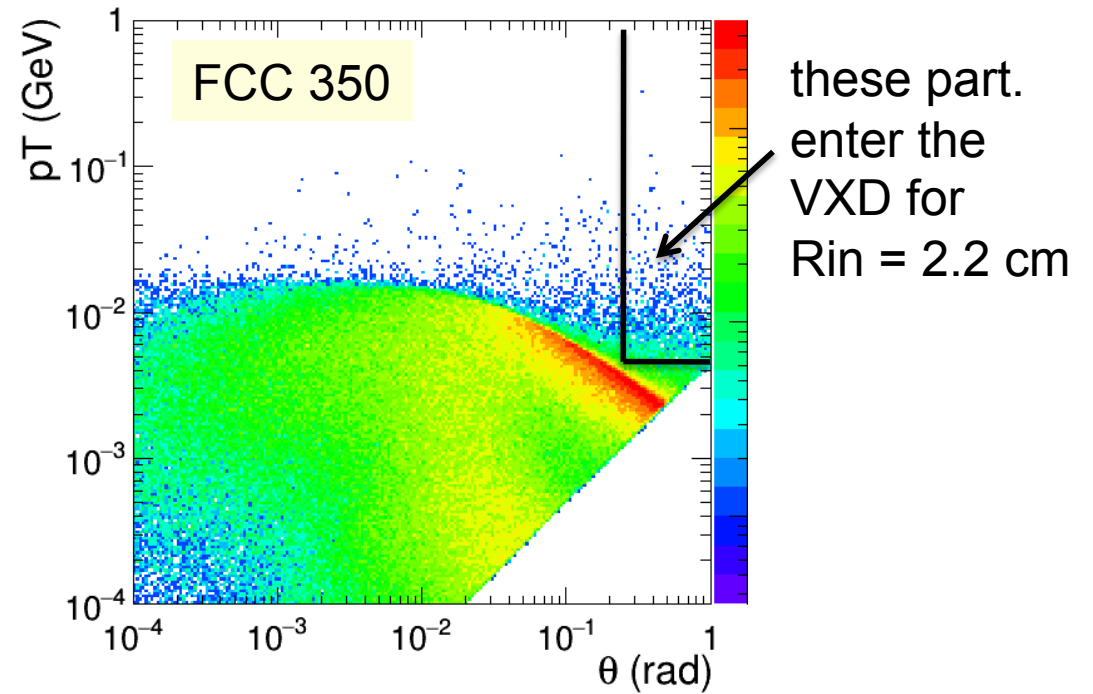
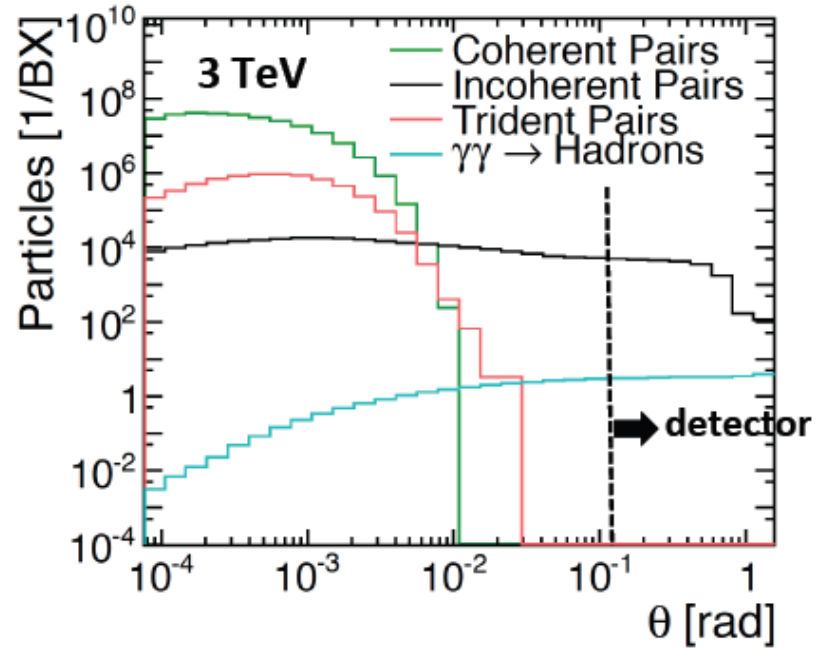
At FCC, energy spread induced by BS with design optics is limited to $< 0.2\%$.

- energy well known, advantageous for energy scans

Already sets a **demanding requirement of 2% on the momentum acceptance**, such that the **lifetime** due to BS is not smaller than that due to the burn-off of the beam.

	Z	Z	W	H	tt
Energy spread [%]					
- Synchrotron radiation	0.04	0.04	0.07	0.10	0.14
- Total (including BS)	0.22	0.09	0.10	0.12	0.17

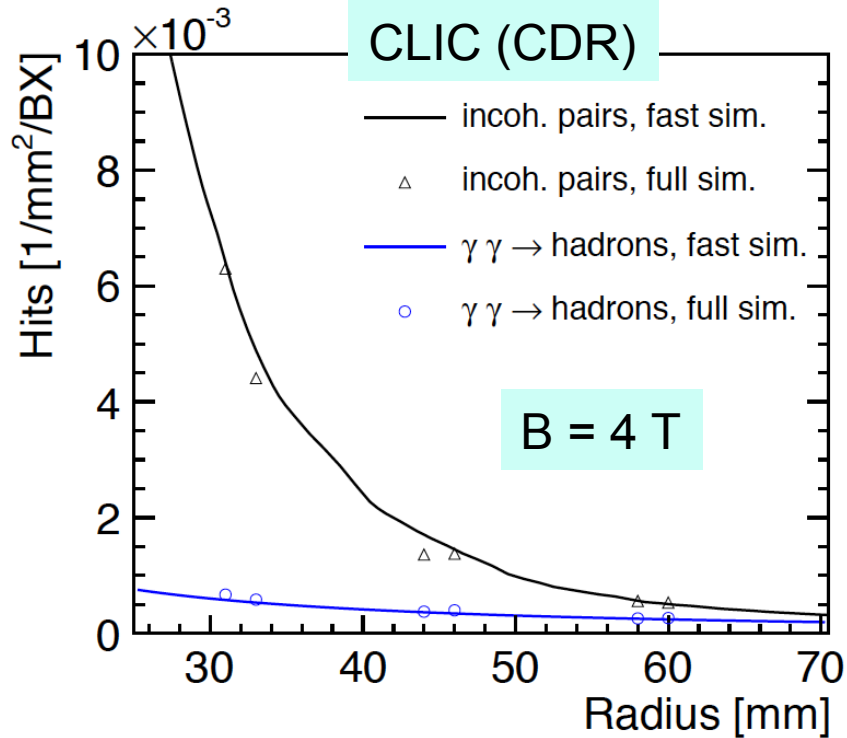
Beamstrahlung and backgrounds in the detector



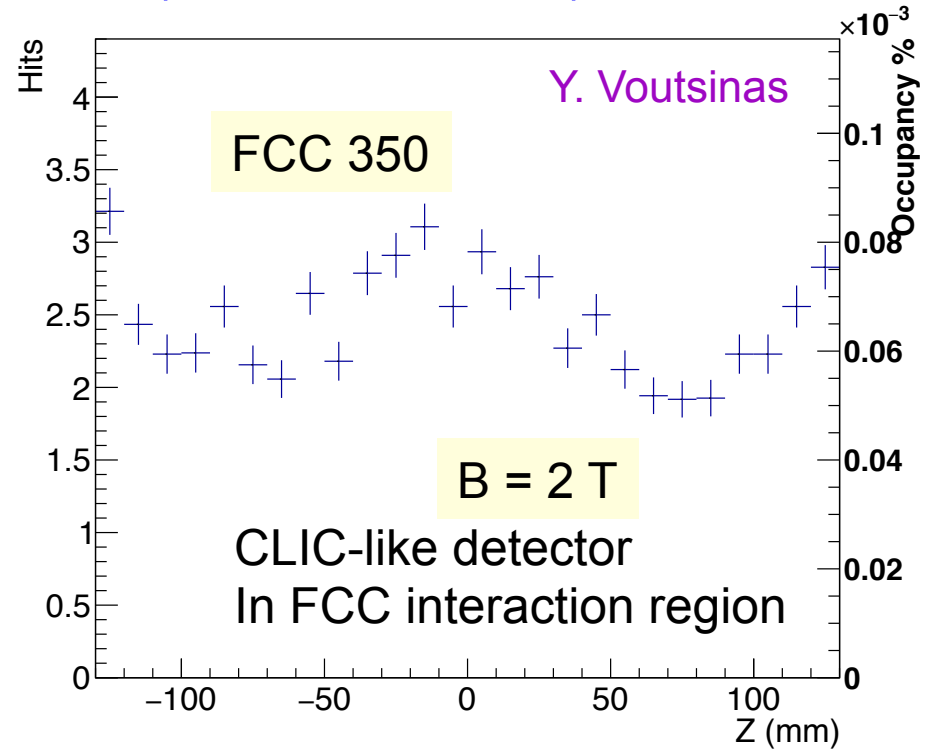
	CLIC 3 TeV		FCC 350		FCC Z	
Npart / BX	Total	$\Theta > 7.3^\circ$, $p_T > 20$ MeV	Total	$\Theta > 7.6^\circ$, $p_T > 6.6$ MeV	Total	$\Theta > 7.6^\circ$, $p_T > 6.6$ MeV
Incoh. e+e-	$3.3 \cdot 10^5$	60	4000	12	350	1
$\gamma\gamma \rightarrow$ had	102	54	t.b.a.		t.b.a.	

The cuts in the table correspond to the (p_T , θ) needed to cross $R \approx 3$ cm (CLIC, 4 T) or $R \approx 2.2$ cm (FCC, 2 T, old baseline) at $|z| < 26$ cm - i.e. (approx.) enter the VXD.

Occupancies in the vertex detector. Ex: barrel (GEANT4, ddsim)



CLIC 3 TeV : first layer $R = 3$ cm
 $6 \cdot 10^{-3}$ hit / mm^2 / BX
 300 hits per BX
 x 5 (CS) x 5 (safety) = 7500 / BX
 x 312 BXs = $2.3 \cdot 10^6$
 Occupancy = 2% [still very efficient reco]



FCC 350 : first layer $R = 2.2$ cm
 $2 \cdot 10^{-3}$ hit / mm^2 / BX
 (would be O(x4) lower at $R = 3$ cm)
 70 hits per BX
 x 5 (CS) x 5 (safety) = 1750 / BX
 Occupancy $< 10^{-4}$ %

Much less severe conditions at FCC. Margin to go closer to the beam ($R = 1.7$ cm is the new baseline).

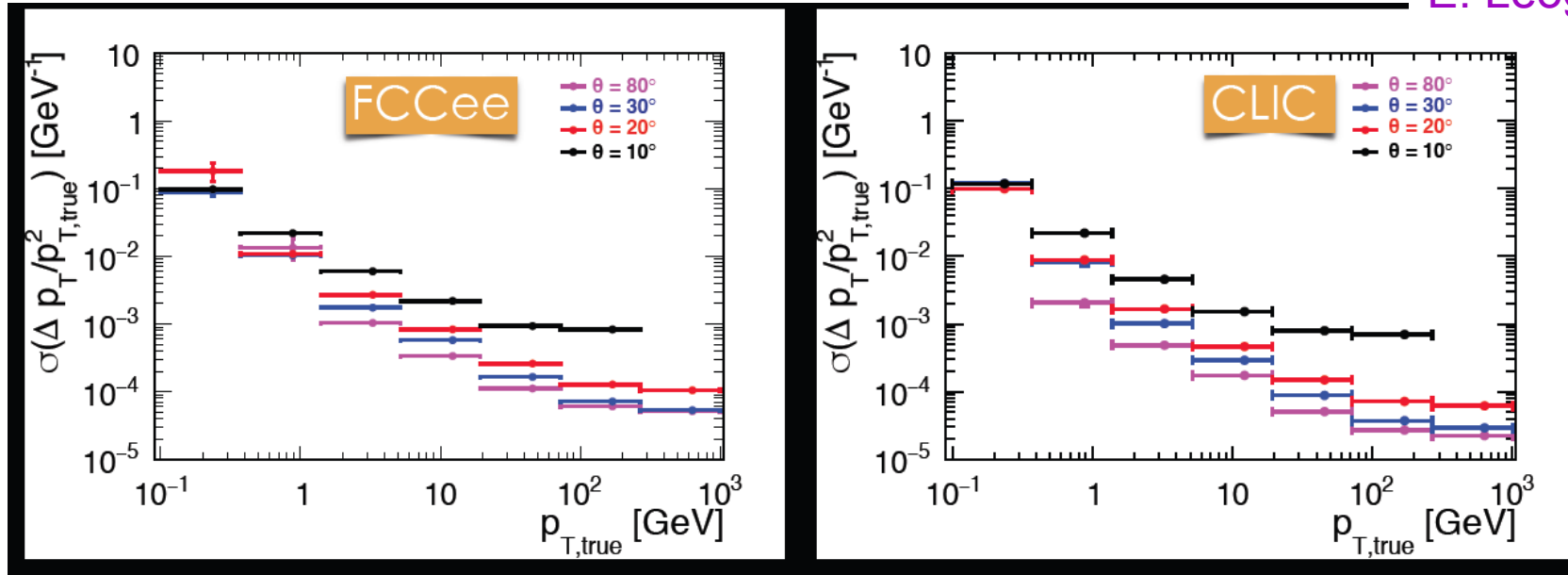
Detector concepts for FCC (1) : CLIC-like

$B = 2 \text{ T}$: constrained by the need for compensating solenoid.

Compared to CLIC (for similar performance requirements) :

- the tracker volume could extend to larger radius ($B L^2$)
- no TeV showers: calo can be smaller. Also lower B: less iron

E. Leogrande



Starting point : CLIC model out-of-the-box (nearly), adapted to IR, smaller $R_{\text{innermost}}$

- full simulation studies with the CLIC software framework

Muon momentum resolution in central region at high p_T : worse by $O(2)$ compared to CLIC, as expected due to $\times 2$ lower B .

For 100 (10) GeV muons : momentum resolution for FCC is already 0.8% (0.4 %)

Detector concepts for FCC (2) : other IDEAs

L. Rolandi,
A. Blondel,
F. Bedeschi et al

“International Detector for Electron-positron Accelerator”

- Light Si vertex 2cm → 20-40 cm
 - Light Drift chamber: 20-40 cm → 1.8 m
 - 100 meas. per track, < 1% X0
 - preshower (+ PID ?) : 1.8 → 1.9 m
 - dual readout calorimeter : 1.9 → 3.3 m
 - coil for 2T : 3.3 – 3.55 m
 - outer tracking : 3.55 – 10 m !
 - coil for 0.23 T ?
- } for detached vertices
(RH neutrinos, dark sector, etc)

Very low mass $\sim 0.03 X_0$ before the pre-shower

Muon momentum resolution of 0.3% at $p=100$ GeV

E/γ energy resolution $\sim 1\%$ at $E=100$ GeV

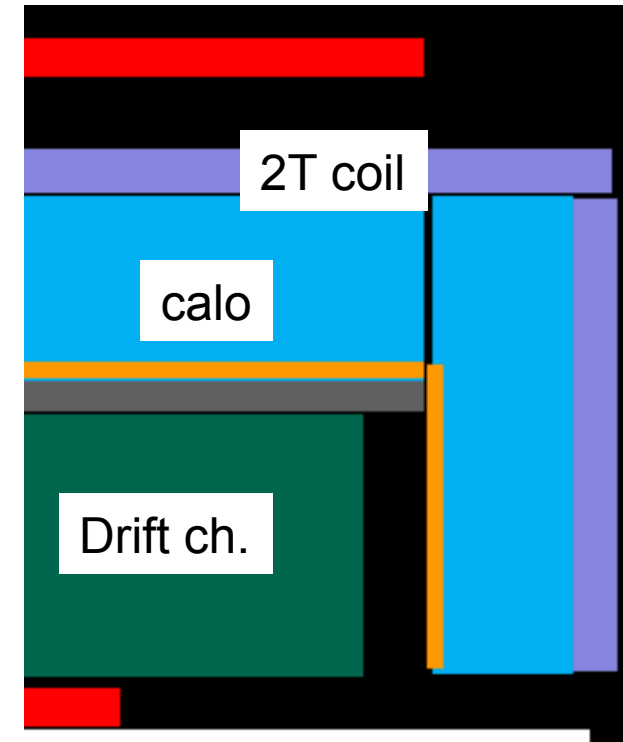
Jet energy resolution \sim few % at $E=100$ GeV

Acceptance defined at $\sim 2 \mu\text{m}$ over few meters

Excellent $e-\mu-h$ separation

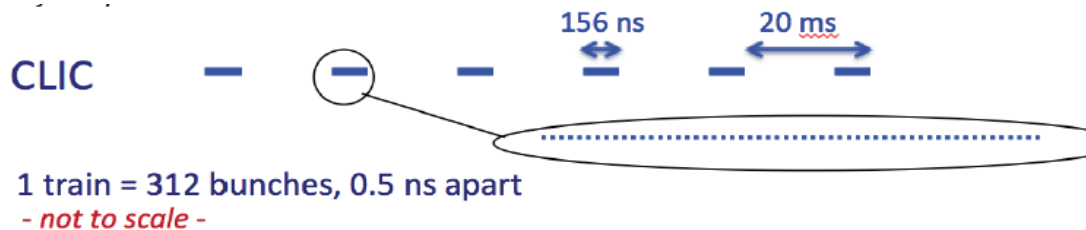
More than 3σ π/k separation over a wide momentum range

Very good b and c tagging (to be quantified)



Performances to be quantified
better once implemented in a
full simulation

Time structure of the beams, trigger and readout



FCC : regularly spaced bunches,
 $\Delta t \approx 3$ ns (Z peak) up to
 $\Delta t \approx 4$ μ s (top threshold)

- Time structure of CLIC beam allows **power-pulsing of the electronics**
 - Much less power dissipation, hence cooling is less demanding : can use **air-flow cooling** for the tracker, allows to **minimize the material !**
 - Ex : CLIC inner tracker barrel modules: with water-cooling instead of air-flow cooling : increases from 0.2% X0 to 0.8% X0 [from Konrad E.]
 - air-flow cooling probably insufficient at FCC ?
- **Trigger and readout :**
 - CLIC : readout takes place at the end of the train
 - Repetition rate = 20 ms = 50 Hz is low: can read all trains : no need for a hardware level-1 trigger system
 - Timing requirements 1 – 10 ns to suppress bkgd offline
 - FCC : at the Z pole : $\Delta t \approx 3$ ns i.e. 300 MHz (Z rate : ~ 100 kHz).
“Trigger-less” mode desirable...
 - Data volume from FE to event builder does not seem to be a show-stopper
 - but requirements on the readout electronics...

Conclusion

Several differences between the experimental conditions at CLIC and FCC

- FCC interaction region sets constraints on
 - B of the experiment
 - the position of the Luminosity monitor
 - FCC : large Synchrotron Radiation
 - effect on detector at the top energy to be quantified
- while CLIC : large Beamstrahlung

Still several synergies between the two communities, especially around the detector and the software.

Backup

For the Top running

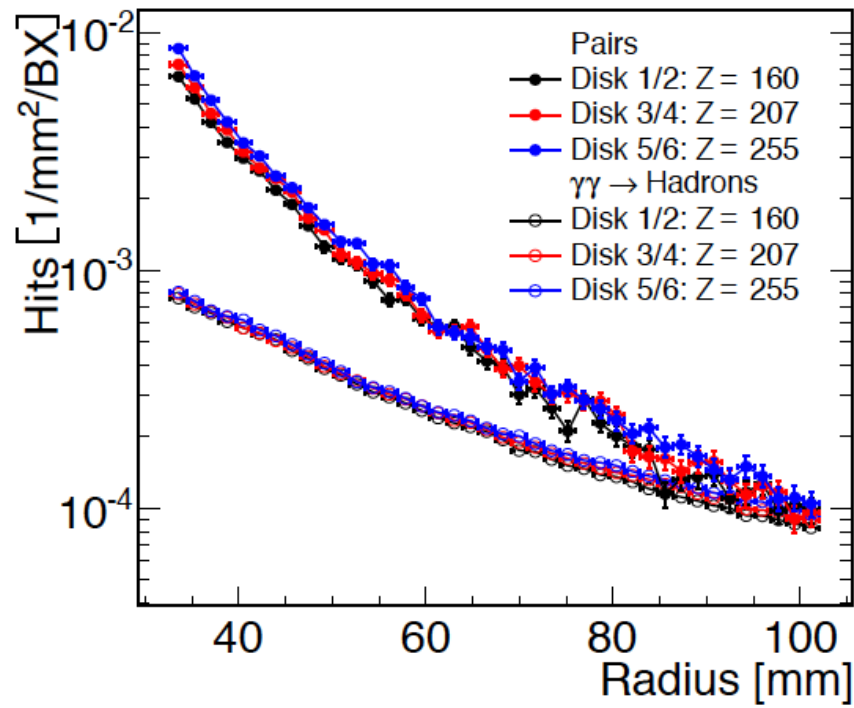
- 1.9×10^9 photons incident on the mask tip every beam bunch
- 3.87% scatter through the mask tip
- About 1% can scatter through 2 cm of Ta
- This means about 700,000 photons go into the central detector region every beam crossing – too many
- We will need to add as much shielding as we can in order to cut this rate down
- We may need to ask for a yet softer bend magnet for the last 10% of the current soft bend

What about the Higgs?

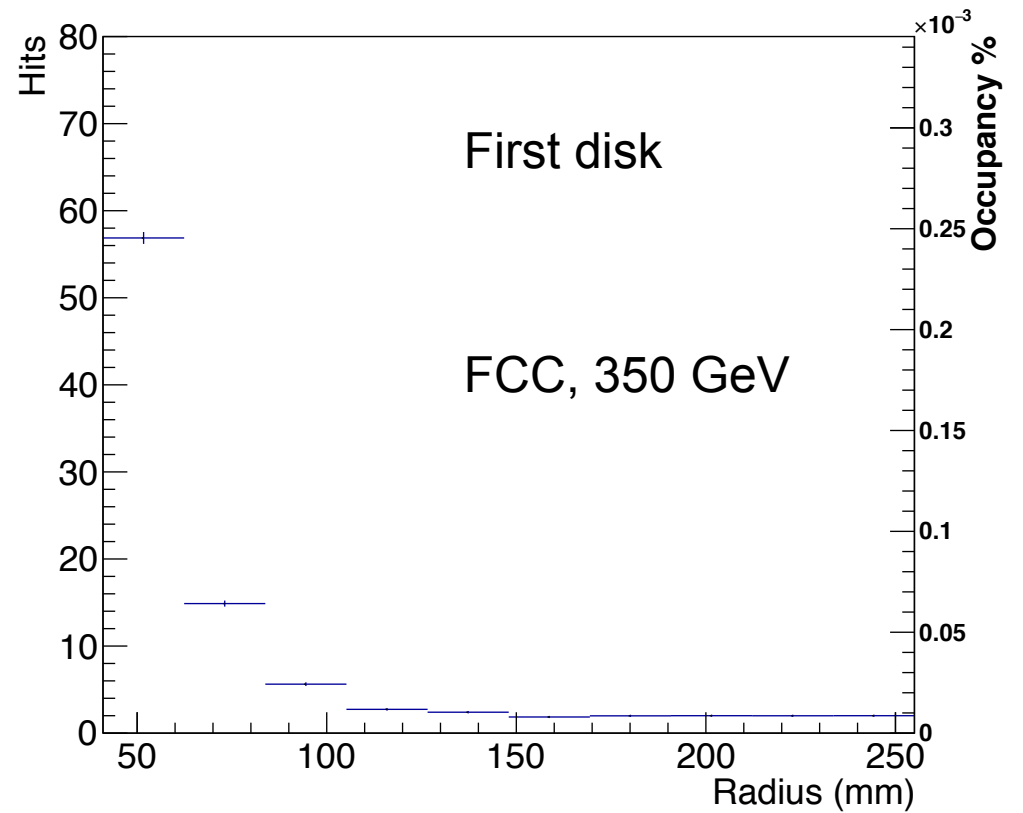
- Scattered SR photon energies will increase from the Z
 - The critical energy of the last soft bend magnet
 - For the Top – 100 keV
 - For the Higgs – 40 keV
 - For the Z – 1.7 keV
- Needs to be looked at as a separate case
- More simulation runs with the GEANT4 model of the beam pipe
- Do we want/need the LumiCal for the Higgs?
- Stay tuned.....

Occupancies inner tracker

CLIC, 3 TeV



ITE D1



Running scenarios (2)

\sqrt{s}	Z	WW	ZH	$\geq tt$	total
FCC-ee : Baseline scenario (2 IPs, conservative optics)					
Lumi / year [ab ⁻¹]	42	3.8	1	0.25	
#years	3	2	5	5.5	15 yrs
#events	5 10¹² Z	30 M WW	1 M Higgs	800 k tt	

<i>Tera-Z</i>	<i>“Oku”-W</i>	<i>Mega-Higgs</i>	<i>Mega-top</i>
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- with the “target” scenario (4 IPs, smaller β^*) : program would take O(10) years and statistical errors would be smaller by 40%
- running at $\sqrt{s} \approx 125$ GeV may allow a unique measurement of H_{ee} via **resonant ee \rightarrow H** (challenging, need mono-chromaticity & high luminosity !)

CEPC : at 240 GeV, about 0.5 fb⁻¹ / year \rightarrow 1M Higgs in O(10) years.

Higgs measurements in e+e- (examples)

With O(1-2M) Higgs in a clean environment with S/B >> LHC : measure the Higgs couplings with a much better precision than HL-LHC (few %), in a **model-indep. way by exploiting ee -> ZH (recoil mass)** : unique to lepton colliders.

	ILC (*)	CLIC (a)	FCC (**)	CEPC
g(HZZ)	0.31%	0.8%	0.15%	0.26%
g(HWW)	0.42%	0.9%	0.19%	1.2%
g(Hγγ)	3.4%	3.2%	1.5%	4.7%
g(Hcc)	1.2%	1.9%	0.71%	1.7%
Γ _{tot}	1.8%	3.6%	1%	2.8%
BR _{inv}	< 0.3%	< 1%	< 0.2%	< 0.3%
g(Hμμ)	9.2%	7.8%	6.2%	8.6%
g(Htt)	6.3%	4%	model-dep.	-
λ(HHH)	27%	10%	meas.	Moddep

(*) [ILC](#) includes lumi upgrade – errors are x2 larger without the upgrade
 (**) Numbers from [TLEP paper](#), approx. the “baseline” configuration
 (a) Comprehensive paper on [Higgs at CLIC](#) about to be released

CLIC: lower stat in ZH -> Larger error, affects all other g's.

CEPC worse: no WW -> H . Also affects Γ_H & all other g's.

Low stat ! Combining with HL-LHC (BR ratios) -> 1%

Won't be done at LHC !

% level means 40 keV !

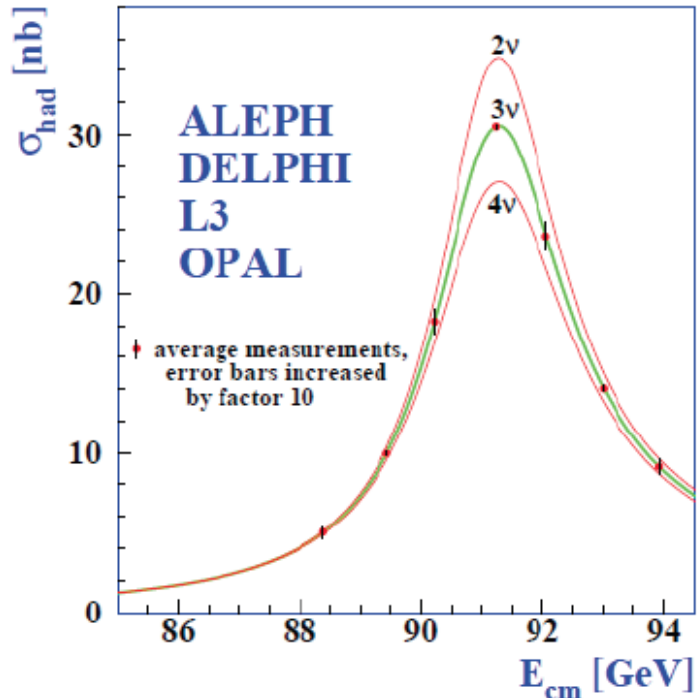
HL-LHC : O(10%)

If λ = λ(SM). CLIC benefits from ee -> ννHH.

- ee will access observables that won't be accessible at LHC : Γ_{tot}, BR_{inv}, g(Hcc), g(Hgg)
- Will improve, by a factor of up to 10, the precision of ~ all couplings w.r.t HL-LHC
- best precision (up to a few 0.1% !) at FCC (luminosity !)
- ttH and λ(HHH) call for higher energy: CLIC (ILC ?) or FCC-hh (LHC ?)

Precision measurements of the EW sectors (Z, WW) - only at FCC

Z resonance: TeraZ



- Lineshape

- ➔ Exquisite E_{beam}
- ➔ m_Z, Γ_Z to 100 keV

- Asymmetries $A_{\text{FR}}^{\mu\mu}$

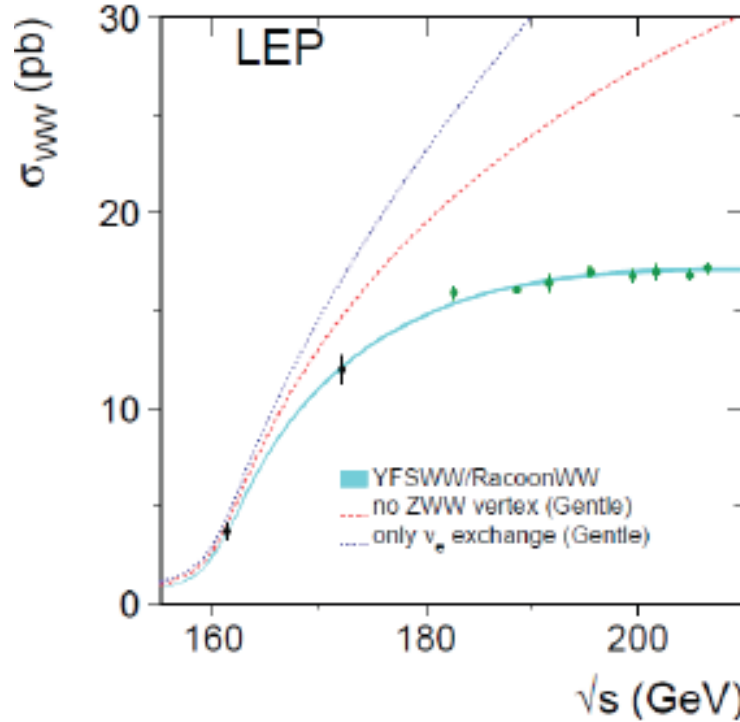
- ➔ $\sin^2\theta_W$ to 6×10^{-6}
- ➔ $\alpha_{\text{QED}}(m_Z)$ to 3×10^{-5}

- Branching ratios, R_l, R_b

- ➔ $\alpha_s(m_Z)$ to 0.0002

[P. Janot, JHEP1602 \(2016\) 053](#)

WW threshold scan: OkuW



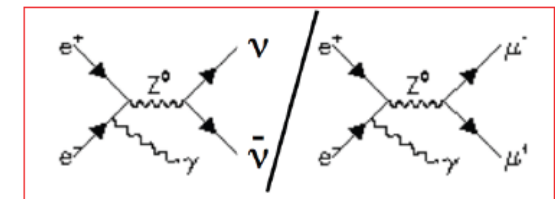
- Threshold scan

- ➔ m_W to 500 keV

- Radiative returns $e^+e^- \rightarrow \gamma Z$ ($Z \rightarrow \nu\nu, \mu^+\mu^-$)

- ➔ N_ν to 0.0004 $N_\nu \sim \sigma(e^+e^- \rightarrow \nu\nu\gamma) / \sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)$

$B(W \rightarrow \text{had})/B(W \rightarrow l\nu)$ @WW
reduces further $\Delta\alpha_s(m_Z)$



Keys:

- Huge stat
 - Ebeam known to < 100 keV via resonant depol. method (unique to circ. ee machines).
- Capital as drives the syst. uncert. in many cases.

[TLEP paper, JHEP 1401 \(2014\) 164](#)

Precision measurements in the top sector

Top mass and width via threshold scan

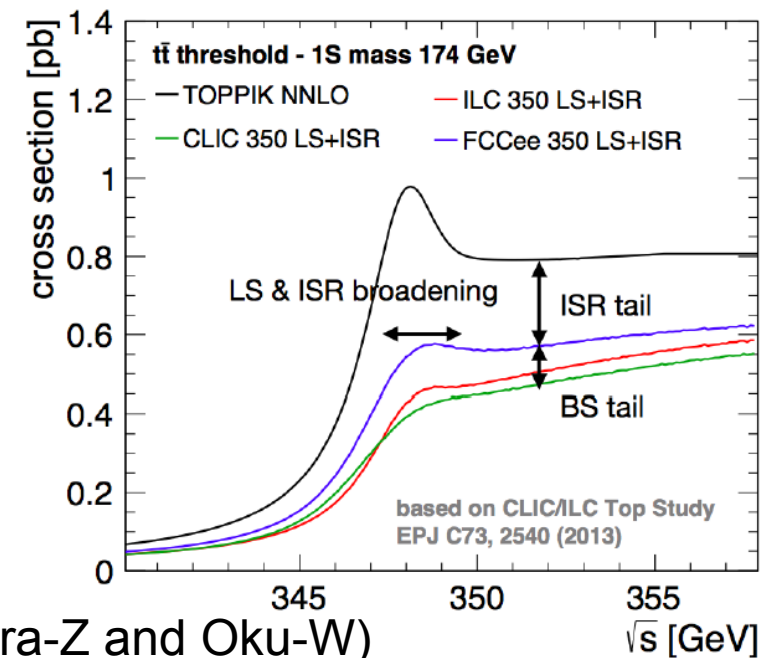
A few points around $2m_t$, total $O(100 \text{ fb}^{-1})$

Threshold shape affected by ISR and lumi spectrum

$$\delta_{\text{stat}} \sim 10 - 20 \text{ MeV on } m_{\text{top}}, \delta_{\text{tot}} < 50 \text{ MeV}$$

Current $\delta(\alpha_s(m_Z))$ leads to $\delta = 30 \text{ MeV}$,

reduced to $\sim \text{negl.}$ at FCC (improved $\alpha_s(m_Z)$ from Tera-Z and Oku-W)



Electroweak couplings of the top : sensitive to new physics (cf LEP and Rb !)

Observables sensitive to the $t\bar{t}V$ vertex and its chiral structure :

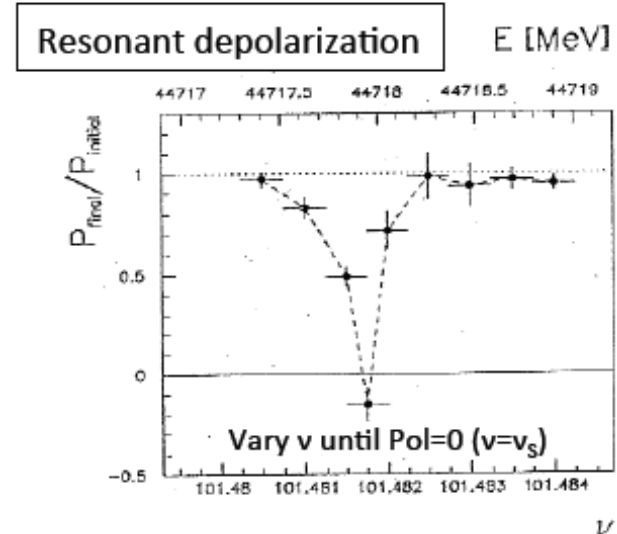
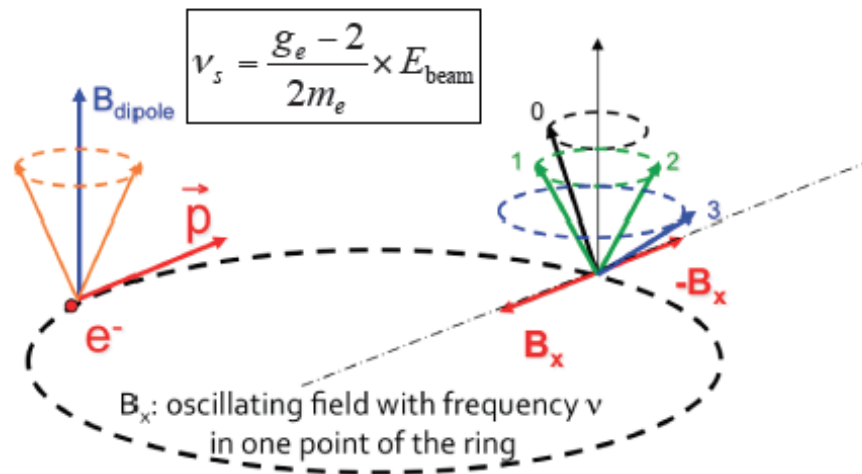
- $t\bar{t}$ σ 's and A_{FB} , exploiting the longitudinal polarisation of e^\pm , at ILC and CLIC
- event rates and energy & angular distribution of top decay products
 - Exploiting the polarisation of the produced top quarks
 - cf tau polarisation at LEP [P. Janot, JHEP 1504 \(2015\) 182](#)
 - long. polarisation of the incoming beams not mandatory !
 - realized recently in the context of a FCC study ($\sqrt{s} \sim 365 \text{ GeV}$)

Precision of 1% or better can be achieved – typically 10x better than HL-LHC.

Precision electroweak physics at FCC-ee (3)

Measurement of the beam energy at LEP (cont'd)

- The spin precesses around \mathbf{B} with a frequency proportional to $|\mathbf{B}|$ (Larmor precession)
 - Hence, the number of revolutions ν_s for each LEP turn is proportional to BL (or $\oint \mathbf{B}dL$)



Intrinsic precision of the method: $\Delta E_{\text{beam}} < 100 \text{ keV}$!

- However, m_Z and Γ_Z measured at LEP with a precision of 2.2 MeV
 - Extrapolation uncertainty from measurement performed w/o collisions

Measurement of the beam energy at FCC-ee

- LEP was colliding 4 bunches of e^+ and e^- ; FCC-ee will have 10.000's of bunches.
- Use ~ 100 "single" bunches to measure E_{beam} with resonant depolarization
 - Measure E_{beam} directly in physics runs
 - Each measurement gives 100 keV precision; no extrapolation uncertainty

m_Z to $< 100 \text{ keV}$



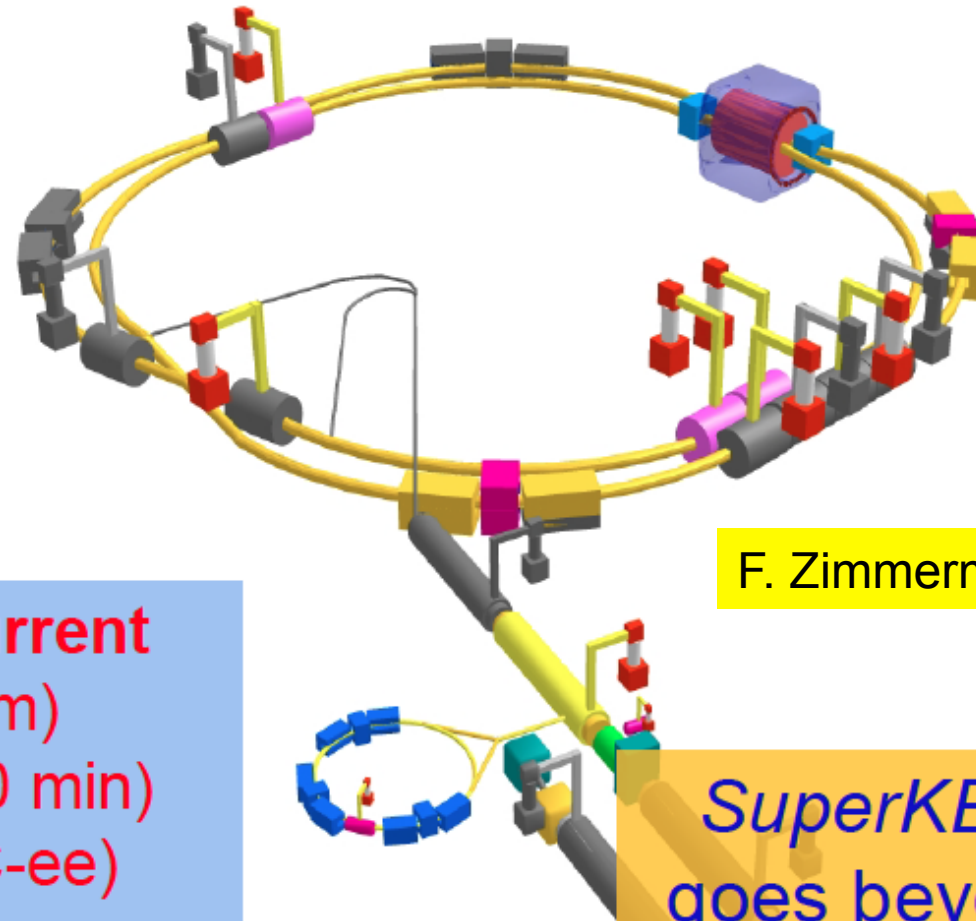
SuperKEKB: FCC-ee demonstrator

$$I_{e^+} = 3.6 \text{ A}, I_{e^-} = 2.6 \text{ A}$$

$$P_{\text{SR}} \sim 13 \text{ MW}$$

$$C = 3 \text{ km}$$

beam commissioning
started this year



F. Zimmermann

top up injection at high current

$\beta_y^* = 300 \mu\text{m}$ (FCC-ee: 1 mm)

lifetime 5 min (FCC-ee: ≥ 20 min)

$\varepsilon_y/\varepsilon_x = 0.25\%$ (similar to FCC-ee)

off momentum acceptance

($\pm 1.5\%$, similar to FCC-ee)

e^+ production rate ($2.5 \times 10^{12}/\text{s}$,
FCC-ee: $< 1.5 \times 10^{12}/\text{s}$ (Z cr.waist))

SuperKEKB
goes beyond
FCC-ee,
testing all
concept