

European Strategy







Istituto Nazionale di Fisica Nucleare Sezione di Pavia



Most slides from Iacopo Vivarelli's talk ...





Most slides from Iacopo Vivarelli's talk ...

Interpretation is mine ...





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Of course ...



Credits

Most slides from Iacopo Vivarelli's talk ...

Interpretation is mine ...

Of course ... mistakes are his



Physics we have

From LHC so far: universe is very SM-like



No significant deviation from SM with 140 fb⁻¹ of pp collisions (not promising for BSM at HL-LHC)

Standard Model Total Production Cross Section





on Measure	ments	∫£ dt [fb ⁻¹]	Reference
	[ED IC 00 (0000) 444
71	1 2 1	34×10-0	EFJC 63 (2023) 441
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	🖌	20.3	EP.IC 77 (2017) 531
$\sqrt{5} = 13.6 \text{ TeV}$		4.6	PRD 90 112006 (2014)
Data		4.0	arXiv:2310.01518
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5 10 E 11		21.0	orViv:2206 11270
$p_V s = 13 \text{ TeV}$		120	IHEP 05 (2023) 028
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$\sqrt{s} = 5 \text{ TeV}$		20.2	HEP 11 172 (2015)
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σ [pb]	data/theory		

Precision SM

- M_Z , Γ_Z , N_ν , R_I , A_{FB} , M_W , Γ_W
- $\alpha_{\rm s}$ (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD



ALPs, dark photons, Heavy Neutral Leptons, LLPs



Numbers for FCC-ee – original slide from C. Grojean

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Higgs width, Higgs to invisible, (self-)couplings











Numbers for FCC-ee – original slide from C. Grojean





Whole physics programme (not just "Higgs factory") makes the difference

- $\sin^2 \theta_W$ (mainly from $A_{FB}^{\mu\mu}$)
- M_W , Γ_W to O(1 MeV)
- M_{top} , Γ_{top} at O(10-50 MeV) •
- Auxiliary measurements ($\alpha_{QED}(M_Z^2)$, M_Z , Γ_Z , $\alpha_s(M_Z^2)$)
- Model-independent Γ_{H} , Higgs couplings, Higgs-to-invisible BR •
- BSM models (ALPs, dark photons, light dark matter, ...) ullet

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from FCC-ee CDR

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Physics case drivers

Higgs boson tagging and BR into invisibles sets requirements on:

- Tracking performance
- Material in the tracking volume
- Magnetic field (and thickness of solenoid)
- Higgs boson BR sets requirements on e, y and jet energy and angular resolutions
- Tagging sets requirements on tracking and vertexing

Requirements grow as more and more physics is explored

	Critical detector	Requirement	Comments
$ZH \to \ell^+ \ell^- X$	Tracker	$\frac{\sigma(p_{\rm T})}{p_{\rm T}^2} \sim \frac{0.1 \%}{p_{\rm T}} \oplus 2 \cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \rightarrow b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}[\mu \mathrm{m}]$	Additional case study: B→K [*] ττ
$H \rightarrow gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{\rm jet})}{E_{\rm jet}} \sim 4\% \text{ (at } E_{\rm jet} \sim 50 \text{ GeV})$	Also BSM and missing energy reconstruction
$H o \gamma \gamma$	ECAL	$\frac{\sigma(E_{\gamma})}{E_{\gamma}} \sim \frac{10 - 15\%}{\sqrt{E_{\gamma}}}$	But flavour physics may need better EM energy resolution

Benchmark physics channels for Higgs/Top/EW factories discussed in 2401.07564 will improve detector requirements by spring 2025

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0.5

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- Inner tracker with lowest possible mass and smallest possible inner radius ٠
- Low-mass outer tracker for excellent momentum resolution at high energies ٠
- Particle ID performance for flavour physics ٠
- High granularity, high resolution calorimetry •
- Large superconducting solenoid
- Muon system ٠



Linear vs. circular specifics

Linear colliders:

- Bunch trains \rightarrow allow power pulsing \rightarrow cooling not needed
- Beamstrahlung:
 - 1) High magnetic field (> 3 T) desirable

 \rightarrow lower tracking volume \rightarrow solenoid could be outside calo volume

2) Inner tracking radius limited to greater than some (\sim 3) cm

Circular colliders:

- Continuous running → cooling required
- Preserve beam emittance @ Z pole:
 - Magnetic field limited to 2 T max
 - \rightarrow larger tracking volume needed
 - \rightarrow solenoid better inside calorimeter volume (or in between ECAL and HCAL)



A bit of advertising



Precise and continuous \sqrt{s} , \sqrt{s} spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors **Essential for precision measurements**



FCC-ee detectors



- Beam crossing angle + need to keep vertical beam emittance low \implies B field limited to 2 T @ Z pole •
- Lot of room for (even radical) changes
- Show already different approaches to tracking/calorimetry



Vertex detectors

General requirements

Flavour physics and tagging requires 3-5 μ m \rightarrow pixel size ~15 μ m Small material budget (0.1% of X₀/layer) \rightarrow thickness ~ 50 µm Low power consumption (especially inner layers) $\rightarrow 10-30 \text{ mW/cm}^2$

Solution: CMOS MAPS

high spacial resolution and **small material** (integrated circuitery)

- Used in LHC upgrades (ALICE ITS, ATLAS ITK, etc.)
- No need for bump-bonding: allow smaller pixel size
- Overall affordable



IDEA design





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Bent silicon sensors (ALICE ITS3 R&D)

Full silicon tracking – CLD approach







Light weight tracking - IDEA

Vertex technologies

Depleted Monolithic Active Pixel detectors

3 Inner Vertex (ARCADIA based):

- Lfoundry 110 nm process
- 50 µm thick
- Dimensions:
- Power density 30 mW/cm²
- 100 MHz/cm²

Target high granularity Low power consumption required

compromise with time-resolution

Middle and Outer Vertex plus disks (ATLASPIX3 based):

- TSI 180 nm process
- 50 μm thick Module dimensions:
- Power density 150 mW/cm² Up to 1.28 Gb/s downlink

Alternative: curved MAPS (inspired by ALICE ITS3 design)

~0.05% X/X_0 material budget per layer 5 times less than baseline option

13.7 mm radius: mechanics ok, does electrically work?

Active pixels < 95% of covered area (chip service zones) Impact on physics?





Precision points connecting vertex with Drift Chamber Low-p_T tracking **Bunch-crossing ID**



Light weight tracking - ALLEGRO

ALLEGRO: VTX similar to CLD

- Tracking with drift chamber (as in IDEA similar in concept to MEG II chamber)
- Minimising multiple scattering, adding only 2% X₀ to material in front of calorimeter
- Drift time O(300 ns)
- Cluster counting (12.5 cm⁻¹ clusters) improves spacial resolution and dE/dx measurement
- Single point precision (with cluster counting) better than $\sim 100 \,\mu m$, many points per track





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IDEA: Material vs. $cos(\theta)$



Drift chamber

Total thickness: 1.6% of X_0 at 90° (W wires dominant contribution)

max drift time: 350 ns $\sigma_{xv} \sim 100 \ \mu\text{m}; \ \sigma_{z} < 1 \ \text{mm}$

Open issues:

- Complete mapping of dN/dx data in all relevant background regions
 - Understand details of cluster counting performance
- Build large mechanical prototype

 - Inner radius R_{in} = 35 cm, outer radius R_{out} = 200 cm
 Spoke (wire support) mechanical deformation due to wire mechanical tension
- Build full length functioning prototype with few cells
- Develop on-detector cluster counting electronics





Challenges

- Full silicon tracking:
 - Keep material down, despite cooling and services
 - Particle identification may require additional detectors (RICH?)
- Drift chamber:
 - Mechanical stability, cluster-counting compatible electronics





Detector occupancy driven by incoherent pair creation and synchrotron radiation photons

Estimated < 1% for full silicon detectors Almost **NO GO** for TPC (see here) OK (but need to **keep eye on**) for DWC



Taken from <u>here</u>

Particle-flow oriented calorimeters

- Basic idea: for charged particles, measure energy by using tracker rather than calorimeter
- Requirements: High granularity compactness (small Molière radius)
- Drawbacks: confusion term (when calo-cluster subtraction goes wrong \rightarrow tails in jet energy distributions)
- Studied in detail for linear colliders

SiW ECAL



Active area: silicon PiN Diodes Typical segmentation: 0.5x0.5 cm²

Analogue Scintillator HCAL and ECAL



Scintillator tiles/strips + SiPM Typical segmentation: 3x3cm²











Challenges:

Cooling despite challenging environment (no power pulsing possible) Large area of silicon detectors Timing for 5D particle flow?

Calorimetry @ **CLD**

CLD paradigm: calorimeter optimised for particle flow (emphasis on granularity rather than quality of energy measurement)













Calorimetry @ ALLEGRO

EM Calorimeter:

- Noble liquid calorimeters: good energy resolution, long-term stability, easy to calibrate
 - Ideas to **achieve high granularity** targeting particle flow
- Solution heavily inspired by ATLAS: LAr + copper but different geometry
- Hadronic section with increased granularity scintillator tile + steel







Calorimetry @ IDEA

- Simultaneously measure:
 Scintillation signal (S)
 Cherenkov signal (C)
- Calibrate both signals with e-
- Unfold event by event f_{em} to obtain corrected energy

$$S = E[f_{em} + (h/e)_{S}(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_{C}(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_{S}}{1 - (h/e)_{C}}$$

Two options currently under study:

- Longitudinal unsegmented dual-readout fibre calorimeter (combined EM+HAD calorimeter)
- Dual-readout crystal (EM calo) + dual-readout fibre calorimeter (HAD calo) \rightarrow boost flavour physics performance





✦ ECAL ~20 cm PbWO₄

- ✤ 2 layers: 6+16 X₀
- DR with filters
- $\sigma_{\rm EM} \approx 3\% / \sqrt{E}$
- timing layer
 - LYSO:Ce crystals
 - $\sigma_t \sim 20 \text{ ps}$
- HCAL layer
 - + $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$







Geant4 simulation of $Z \rightarrow jj$ events: • magnetic field ON but NO tracker Gaussian smearings of MC tracks according • to expected IDEA tracker performance • for each track extrapolate impact point • remove and store tracks not reaching calo





Geant4 simulation of $Z \rightarrow jj$ events: magnetic field ON but NO tracker • Gaussian smearings of MC tracks according to expected IDEA tracker performance for each track extrapolate impact point • remove and store tracks not reaching calo • identify EM neutral clusters (photons) by

- cluster radius

 $R_{\rm transv}$

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$$e_{\text{rese}} = \frac{E_{\text{seed}}}{\sum_{i} E_{\text{hit},i} (\Delta R_i < 0.013)}$$

remove and store photons (R<0.9)



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 remove and store photons (R<0.9) • for each track, rank calo hits by distance



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R_{transv}

- collect hits in cone

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R_{transv}

- collect hits in cone
- compare with E_{target}(track)



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- cluster radius

 $R_{\rm transv}$

- for each track, rank calo hits by distance collect hits in cone
- compare with E_{target}(track)
- if "good" agreement remove hits and track



$$erse = \frac{E_{seed}}{\sum_{i} E_{hit,i} (\Delta R_i < 0.013)}$$

remove and store photons (R<0.9)

- ... continue
- apply k_t algorithm (e.g. Durham) for two jets





finally ...





Other ongoing R&D on calorimetry

GRAINITA



DECAL - Ultra-high granularity CMOS Ecal High-density digital CMOS readout - count hits rather than measure energy



Scintillator grains and absorber suspended in liquid Trapped light extracted with WLS fibres

High density EM calorimeter



Crystal calorimeter for FCC-ee?

Traditionally achieve superb EM resolution but w/ limited granularity

Recent R&D shows potential for particle flow







Synergies: consortia and ECFA DRDs



- and proto-collaborations
- **ECFA DRDs**







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• Lot of leverage done in past within **consortia**

Challenges connected with detector R&D find common framework (aimed at increasing coherence and optimising resources) with

AIDA

Synergies: common tools

Nice sub-products of these collaborations already widely used

Key4HEP

Common software framework used for FCC and for many of other future collider projects

Includes common event data model, tools for easy and portable **detector geometry** handling, consistent set of tags of most used **HEP software packages**



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EUDAQ

Common data acquisition and online monitoring software, often used in conjunction with **common hardware** for beam monitor (EUDET), and data quality tools

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Lost and found

1. Timing



Timing

All detectors developments address timing issues:

- Trackers and muon chambers
- PID and ToF detectors
- Calorimeters

with sensitivities that cover quite different time domains \rightarrow see table below for calorimeters (!)









Solid state detectors

"Technica dates are r	I" Start Date	of Facility he earliest	(This means, where the technically feasible start			< 2030				2	030-203	5	ſ	2035	2040-	2045		>2045	
date is ind the delayir	icated - such ng factor)	that detec	tor R&D readiness is not	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 ¹⁾	ALICE 3	LHCb (≳LS4) ^{1]}	ATLAS/CMS (≳ LS4) ¹⁾	EIC	LHeC	ILC ²⁾	FCC-ee	CLIC ²⁾	FCC-hh	FCC-eh	Muon Collider
			Position precision σ_{hit} (µm)		≃5		≲5	≃3	≲3	≲10	≲15	≲3	≃ 5	≲3	≲3	≲3	≃7	≃ 5	≲5
		4.4	X/X ₀ (%/layer)	≲0.1	≃ 0.5	≃ 0.5	≲0.1	≃ 0.05	≃ 0.05	≃1		≃ 0.05	≲0.1	≃ 0.05	≃ 0.05	≲0.2	≃1	≲0.1	≲0.2
ie_	CMOS	RDT 3. RDT 3.	Power (mW/cm ²)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
etecto	APS Passive ADs		Rates (GHz/cm ²)		≃ 0.1	≃1	≲0.1		≲0.1	≃6		≲0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	
ertex D	M/ r/3D/F LG		Wafers area (") ⁴⁾					12	12			12			12		12		12
>	Plana	DRDT 3.2	Timing precision $\sigma_t (ns)^{5)}$	10		≲0.05	100		25	≲0.05	≲0.05	25	25	500	25	≃ 5	≲0.02	25	≲0.02
		0T3.3	(x 10 ¹⁶ neq/cm ²)							≃6	≃ 2						$\simeq 10^2$		
		DRC	Radiation tolerance TID (Grad)							≃1	≃ 0.5						≃ 30		
			Position precision σ _{hit} (μm)						≃6	≃ 5		≃6	≃6	≃6	≃6	≃7	≃ 10	≃6	
		4 1	X/X _o (%/layer)						≃1	≃1		≃1	≃1	~ 1	≃1	~1	≲2	~ 1	
	CMOS	RDT 3. RDT 3.	Power (mW/cm²)						≲100	≃ 100		≲100		≲100	≲100	≲150			
ker ^{6]}	vPS assive ADs		Rates (GHz/cm²)							≃ 0.16									
Trac	M/ 1/3D/P		Wafers area (") ⁴⁾						12			12		12	12	12	12		12
	Planar	DRDT 3.2	Timing precision $\sigma_t (ns)^{5)}$						25	≲25		25	25	≲0.1	≲0.1	≲0.1	≲0.02	25	≲0.02
		JT3.3	(x 10 ¹⁶ neq/cm ²)							≃ 0.3							≲1		
		DRC	Radiation tolerance TID (Crod)							≃ 0.25							≲1		
tter ⁷⁾	S Passive SADs	DRDT 3.2	Timing precision $\sigma_t (ns)^{5)}$											≲0.05	≲0.05	≲0.05	≲0.02		≲0.02
lorime	MAP ar/3D/ AOS LG	0T 3.3	(x 10 ¹⁶ neq/cm ²)														≳10 ²		
ë	e Plana	DRC	Radiation tolerance TID (Crad)														≃ 50		
light ⁸⁾	s /Passive 5ADs	DRDT 3.2	Timing precision $\sigma_t (ns)^{5)}$				≃ 0.02		≃ 0.02		≲0.03	≃ 0.02	≃ 0.0		≲0.01		≲0.01	≃ 0.02	
ne of F	MAP ar/3D/ MOS L(DT 3.3	(x 10 ¹⁶ neq/cm ²)														≃ 10 ²		
μ	Plan CI	DRI	(Grad)														≃ 30		



Impact of timing ... e/π discrimination



Combination of cuts: >99% *electron efficiency*, <0.2% *pion mis-ID*





Impact of timing ... energy reconstruction



CMS HGCAL measurements

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Highly granular Cu-Si calorimeter 30 & 100 GeV pion simulations

Impact of timing ... Iongitudinal segmentation



Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

Timing Resolution $\Delta(t)$, ps	Position Resolution $\Delta(z)$, cm	Energy Resolution σ/E , %		
0	0.0	3.6		
100	5.0	3.9		
150	7.5	4.0 VV/		
200	10.0	4.2		

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Cherenkov fibres only

Impact of timing ... ToA measurements (simulations)





Waveform digitisation

Results with SensL (MicroFC-30020SMT): SiPM with both fast and standard output



Two-photon event (simultaneous)

Two-photon event (5 ns apart)



NALU Scientific AARDVARC v3

Sampling rate 10-14 GS/s
12 bits ADC
4-8 ps timing resolution
32 k sampling buffer
2 GHz bandwidth
System-on-Chip (CPU)



Lost and found

2. DNNs



DNNs

Significant performance improvements expected in many domains:

- Triggering (whenever needed)
- Data reduction (feature extraction)
- Final state identification
- Event reconstruction

• ...



IDEA layout

→ information: fibre signal output (# p.e.) (no time information)

3-class classification: $\tau_{lep}, \tau_{had}, QCD$ jet

8-class classification:

 $T_0, T_1, T_2, T_3, T_4, T_5, T_6, QCD jet$

[τ from Z $\rightarrow \tau\tau$ decays]

3-class label	8-class label	
0	0	
0	1	
1	2	
1	3	
1	4	
1	5	
1	6	
2	7	





DGCNN w/ geometrical information only

DGCNN optimised but w/o #pe as input feature

B field and material in







0.62	0.03	0.00	0.00	1.58	0.03			
3.48	0.41	2.02	0.39	1.44	0.14			
80.45	9.25	1.61	1.67	0.16	0.25			
10.43	84.55	0.16	3.87	0.05	0.25			
1.38	0.35	84.82	8.79	0.03	0.95			
1.98	2.60	10.19	82.60	0.08	2.20			
0.11	0.00	0.03	0.00	96.82	0.03			
0.19	1.05	2.54	4.08	0.06	91.75			
1	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	<u>`</u>	く	-4			
- 3	2 ?	3 T	JN .3	3_1	2 5	200		
Predicted BR 2								

input: fibre coordinates + type avg accuracy: 88.3% (w/ #p.e. 90.8%)

Where are we?

- Lot of work done, but way more ahead not exhaustive list:
 - Detector concepts are **nice frameworks** fresh ideas and redesign are **more than welcome** ... and at FCC-ee there are 3 detector concepts and 4 IPs....
 - **New technologies** (timing for optimal particle flow? UV/digital light sensors for crystals/fibres?)
 - **Software is in development** (starting from detector simulations) better software means more opportunities for improved physics requirements
- "Detector communities" fairly compact (o(20) people) a lot of room for new collaborators)
 - Opportunities for **younger colleagues** (maybe while spending most of their time on LHC experiments):
 - Doing "core" HEP detector/software work after highly optimised LHC detectors
 - Talks and proceedings
 - Fundamental for "knowledge transfer" (forming future detector experts) \rightarrow detector R&D need to be better "recognised" ... we form and loose people w/ quite impressive rate (my two cents)



Summary

- Work for definition of detectors for next high-energy collider is **in full swing**
- **FCC-ee** is gaining momentum also at international level (e.g. P5 endorsement and signing of Sol from US)
- Game of ideas (already at play for most, if not all, e+e- collider options):
 - Full-silicon or ultra-low material tracking? Calorimeter with high granularity or high energy • resolution? Or both? Lot of room for improvements!
- International collaboration in detector R&D being shaped by **ECFA DRD initiative**
- Long time before first collisions
 - ...but **big push happening now**! FCC-ee feasibility study + European Strategy update key ingredients for next steps



FCC-ee in pills

	Z pole	WW pole	ZH pole	Top pair pole	
Beam energy (GeV)	45.6	80	120	182.5	Saint-Jean de-Gonvil
Beam current (mA)	1270	137	26.7	4.9	Peron
Number of bunches	11200	1780	440	60	
Luminosity (per IP - 10 ³⁴ cm ⁻² s ⁻¹)	140	20	5	1.25	Duga/
Integrated luminosity (per IP - ab ⁻¹ /year)	17	2.4	0.6	0.15	uitens PJ: Dray-en-Vlache ce Vunche
Planned running time	4	2	3	5	
Which translates in	$5 \times 10^{12} \text{ Z}$ (LEP $\times 10^5$)	$\sim 10^8{\rm WW}$ (LEP $\times10^4$)	$2 imes 10^6$ H unprecedented at e^+e^-	$2 \times 10^6 t \bar{t}$ unprecedented at e^+e^-	Francy Multiple

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sergy PA: Poulity	eregnin Centhod Experiment Volfaire Believue Chambesy	Corsier Collonge-Bellerive Mei	V. Mertens, J. Gutleber
Thory Bois Perred Sister	Le Grând-Saconney Meyrin Contrin Le Petit Saconney Vernier 5 Châtelaine Les Pâquis	Vandosuvres Cht ogny Pupili	B: technical
PL: technica Ruser Li Kiane Certigny	Genève Planplais Chène Les Acatas Champel Onex Carouge Bernex Grand Lancy	Bougeries Anne Thonex Gaillard Etrember	Ville La Grand Marse Marse Bruchin Vétraz Monthous
Avulty	Number of surface sites	8	tomer Bome Arthar-Pont- Notre-Dame
Avusy ancy Sézegnin	Surface requirements	~40 ha	PD: experiment
X MAN	LSS@IP (PA, PD, PG, PJ)	1400 m	Reignier
A 40	LSS@TECH (PB, PF, PH, PL)	2032 m	Scientrer
vperiment	Arc length	9.6 km	Pers-Jussy
Maisonneuve	Sum of arc lengths	76.9 m	ssous
pagny Arr	Total length	90.7 km	Chapelle Arr
Jonzier Minzer Chavannaz Martior Contemer	Crany Cerrer Saint-Blase Vovray-en-Bornes 19 Copponer D15 Menthome en-Bornes Vity-le-Bouvert Crustelles	PF	La Joche-sur- Foron san
Sallenoves	technical	DIZ	03

PG: experiment