

Non Liouvillian Colliders

Presentation on the occasion of Lagarrigue's prize
to

Michel della Negra

Carlo Rubbia

Senator for life of the Italian Republic

Original collider's patent by Wideröe, 8th Sept 1943

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WtGBL S. 175)

BUNDESREPUBLIK DEUTSCHLAND



DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 876 279

KLASSE 21g GRUPPE 36

W 687 VIII c / 21 g

AUSGEGEBEN AM
11. MAI 1953

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Kernreaktionen können dadurch herbeigeführt werden, daß geladene Teilchen von hoher Geschwindigkeit und Energie, in Elektronenvolt gemessen, auf die zu untersuchenden Kerne geschossen werden. Wenn die geladenen Teilchen in einem gewissen Mindestabstand von den Kernen gelangen, werden die Kernreaktionen eingeleitet. Da aber neben den zu untersuchenden Kernen noch die gesamten Elektronen der Atomhülle vorhanden sind und auch der Wirkungsquerschnitt des Kernes sehr klein ist, wird der größte Teil der geladenen Teilchen von den Hüllenelektronen abgebremst, während nur ein sehr kleiner Teil die gewünschten Kernreaktionen herbeiführt.

Erfindungsgemäß wird der Wirkungsgrad der Kernreaktionen dadurch wesentlich erhöht, daß die Reaktion in einem Vakuumgefäß (Reaktionsröhre) durchgeführt wird, in welchem die geladenen Teilchen hoher Geschwindigkeit gegen einen Strahl von den zu untersuchenden und sich entgegengesetzt bewegenden

Kernen auf einer sehr langen Strecke laufen müssen. Dies kann in der Weise durchgeführt werden, daß die geladenen Teilchen zum mehrmaligen Umlauf in einer Kreisröhre gezwungen werden, wobei die zu untersuchenden Kerne auf derselben Kreisbahn, aber in entgegengesetzter Richtung umlaufen. Da die geladenen Teilchen dabei nicht von bei der Reaktion unwirksamen Elektronen abgebremst werden und andererseits auf einer sehr langen Wegstrecke gegen die Kerne sich bewegen können, wird die Wahrscheinlichkeit für das Eintreten der Kernreaktionen wesentlich größer und der Wirkungsgrad der Reaktion sehr stark erhöht.

Um die bei der Kreisbewegung entstehenden Zentrifugalkräfte aufzuheben, müssen die umlaufenden Teilchen von nach innen gerichteten Ablenkkräften gesteuert werden, während eine Diffusion der Teile mittels stabilisierender, von allen Seiten auf den Bahnkreis gerichteter Kräfte verhindert wird. Falls die gegen-

Zu der Patentschrift 876 279
Kl. 21g Gr. 36

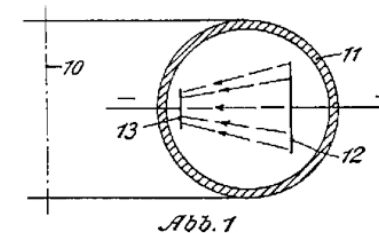


Abb. 1

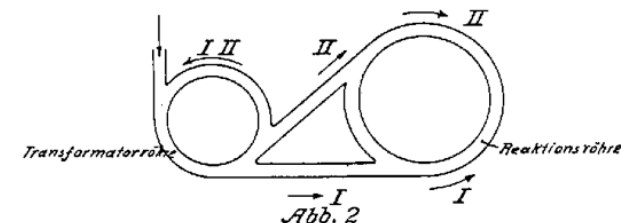


Abb. 2

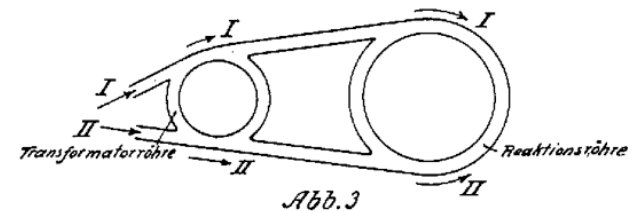


Abb. 3

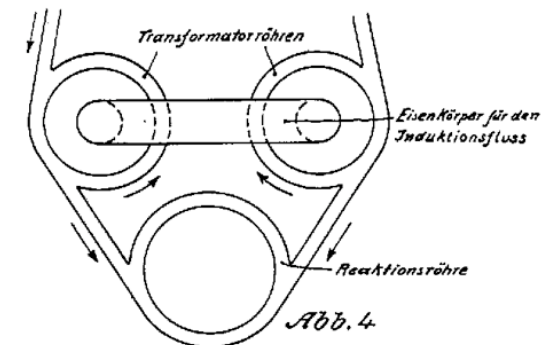


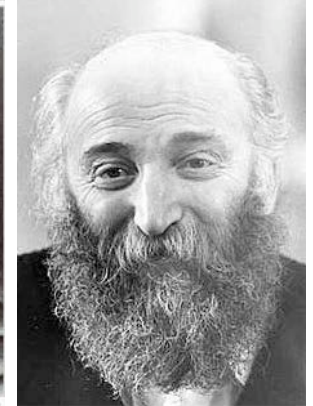
Abb. 4

From storage rings to colliders

- Main conceptual progress in the fifties
 - ➡ MURA
 - ➡ Frascati (Bruno Touschek)
 - ➡ Novosibirsk (Gersh Budker)
- **Two great skepticisms:**
 - ➡ Luminosity (rates) and
 - ➡ Beam-gas background
- The success of e^+e^- colliders at Frascati: ADA, ADONE
- The p-p collisions: ISR at CERN. The beginning of a far more "difficult" physics. "Two swiss watches" in collision !
- The p-pbar collisions: p-bar accumulation and the beam-beam tunes shift problem. *Fewer particles, higher tunes shift!*
- The pessimism about operability of the p-pbar collider was conjugated with a widespread lack of confidence in hadron collisions (ISR), when compared for instance with e^+e^- .



Photograph of Bruno Touschek.

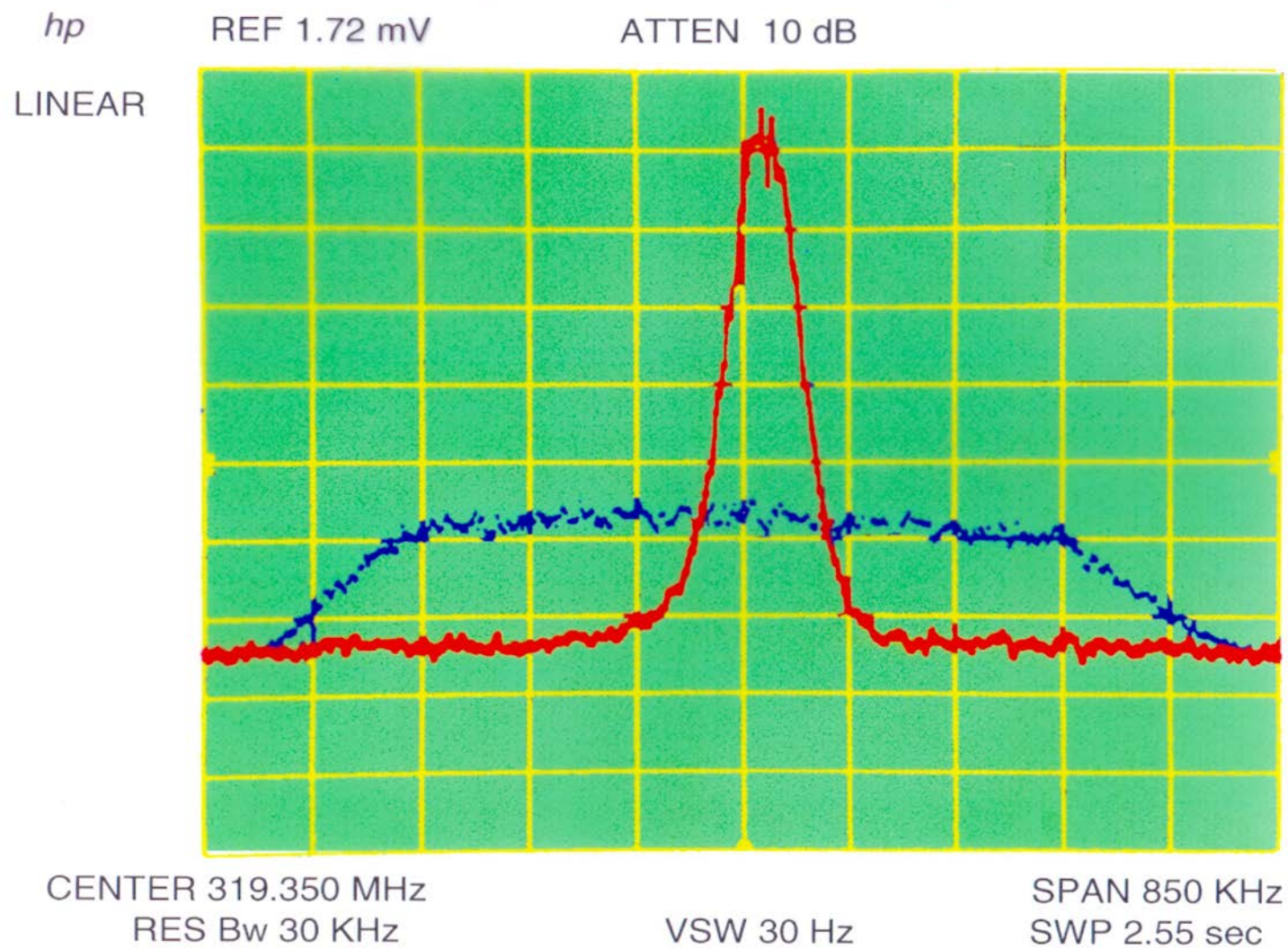


Gersh Itskovich Budker

Initial Cooling Experiment (ICE)

- In 1977, in a record-time of 9 months, the magnets of the g-2 experiment were modified and used to build a proton/antiproton storage ring: the "Initial Cooling Experiment" (ICE).
- It served for the verification of the cooling methods to be used for the "Antiproton Project". Stochastic cooling was proven the same year, electron cooling followed later.
- Electron cooling was provided by an "e-cooler" located in a straight section of the ring.
- With some modifications, the cooler was later transplanted into LEAR (Low Energy Antiproton Ring) and then, with further modifications, into the AD (Antiproton Decelerator), where it cools antiprotons to this day.

Antiproton cooling in 2 sec !



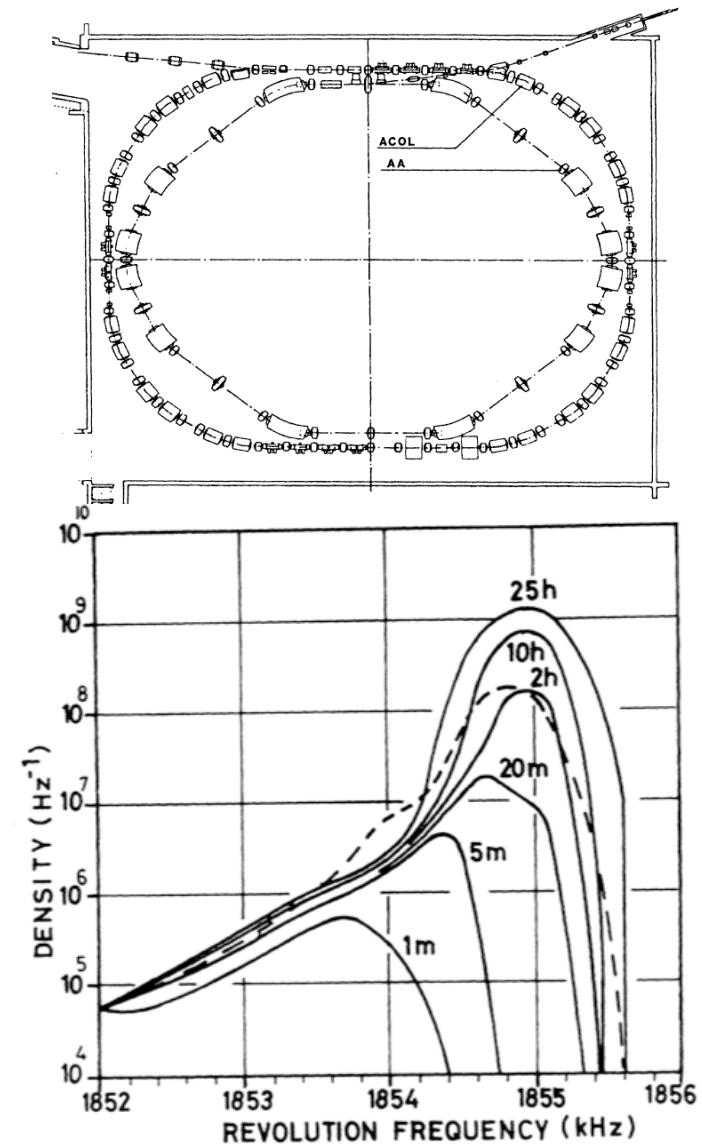
Precooling 6×10^6 \bar{p} 's in 2 seconds. Longitudinal Schottky band at the 170th harmonic (314 MHz) before and after cooling.

The CERN-AA accumulator

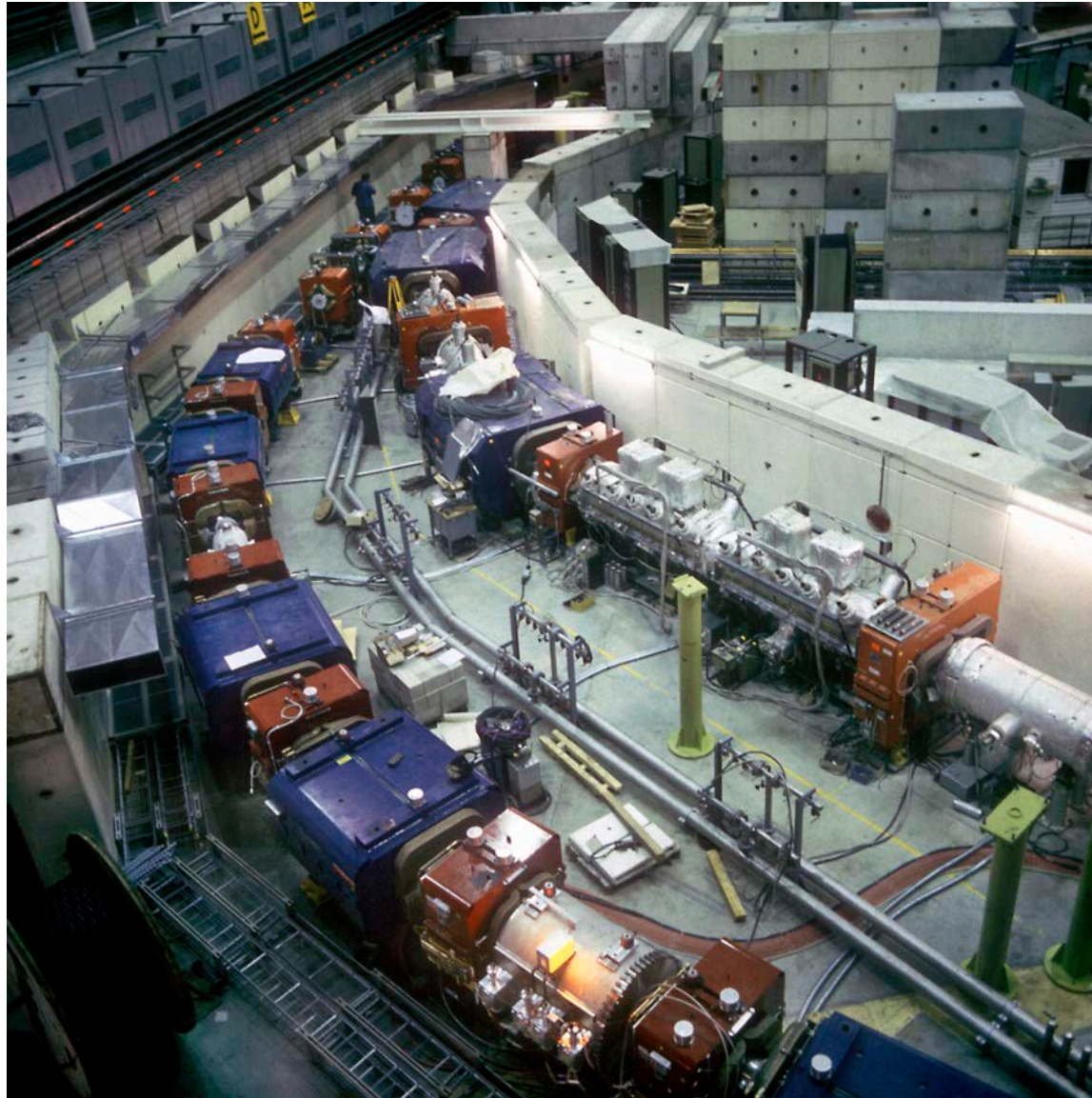
PARAMETERS

CENTRAL MOMENTUM	3.5 GeV/c
CIRCUMFERENCE	151.08 m at injection (CPS/4) 155.84 m at stack centre
WORKING POINT	$Q_x = 2.284$ $Q_y = 2.276$ at stack centre
TOTAL $\Delta p/p$	$\pm 30 \times 10^{-3}$
VACUUM PRESSURE	10^{-10} Torr
TARGET	Tungsten rod 110 mm long, 3 mm \varnothing followed by magnetic horn
PROTON/PULSE ON TARGET	1×10^{13} every 2.4 sec
ANTIPROTON/PULSE	2.5×10^7 in AA acceptance
ACCEPTANCE (INJECTION)	100 hor., 100 vert. mm mrad at $\Delta p/p = 7.5 \times 10^{-3}$
(TRANSFER TO CPS)	7.6 hor., 4.5 vert. mm rad at $\Delta p/p = 1.1 \times 10^{-3}$
FIRST FILL (1×10^{12} \bar{p})	50 000 pulses, 33 hrs
REFILL (6×10^{11} \bar{p})	30 000 pulses, 20 hrs

- 2 years after approval, the first antiprotons were accumulated in summer 1980.



Antiproton Accumulator (AA) and Antiproton Collector (AC)



UA1-The first of a new breed of detectors for hadron colliders

- The reason of lack of success of ISR -where most of the discoveries were missed - was due to insufficient quality of detectors
- Detection for e^+e^- was simple, since the events are already selected in the s-channel
- In the hadronic channel one is in presence of a high background, since for instance $\sigma_{inel} = 3 \times 10^{-26} \text{ cm}^2$ and $\sigma_{W,Z} = 10^{-34} \text{ cm}^2 \Rightarrow \text{signal/noise} = 3 \times 10^{-9}$.
- UA1 experiment has been the first of new "hermetic" and 4π detectors, later followed at LEP and LHC, solving:
 - ➡ *The trigger problem*
 - ➡ *The signature problem*

PROPOSAL

CERN/SPSC/78-06
SPSC/P92
30 January 1978

A 4 π SOLID ANGLE DETECTOR FOR THE SPS USED AS A PROTON-ANTIPROTON
COLLIDER AT A CENTRE OF MASS ENERGY OF 540 GeV

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P. Kalmus⁶, I. Kenyon¹, A. Kernan⁷, F. Lacava^{**)}⁴, J.Ph. Laugier⁵,
A. Leveque⁵, D. Linglin², J. Mallet³, T. McMahon³, F. Muller⁴, A. Norton⁴,
R.T. Poe⁷, E. Radermacher¹, H. Reithler¹, A. Robertson⁶, C. Rubbia^{†)}⁴,
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(Aachen-Annecy-Birmingham-CERN-Coll ge de France-Queen Mary College-
Riverside-Rutherford-Saclay Collaboration)

*) Visitor from University of Wisconsin, Madison, Wisconsin, USA.

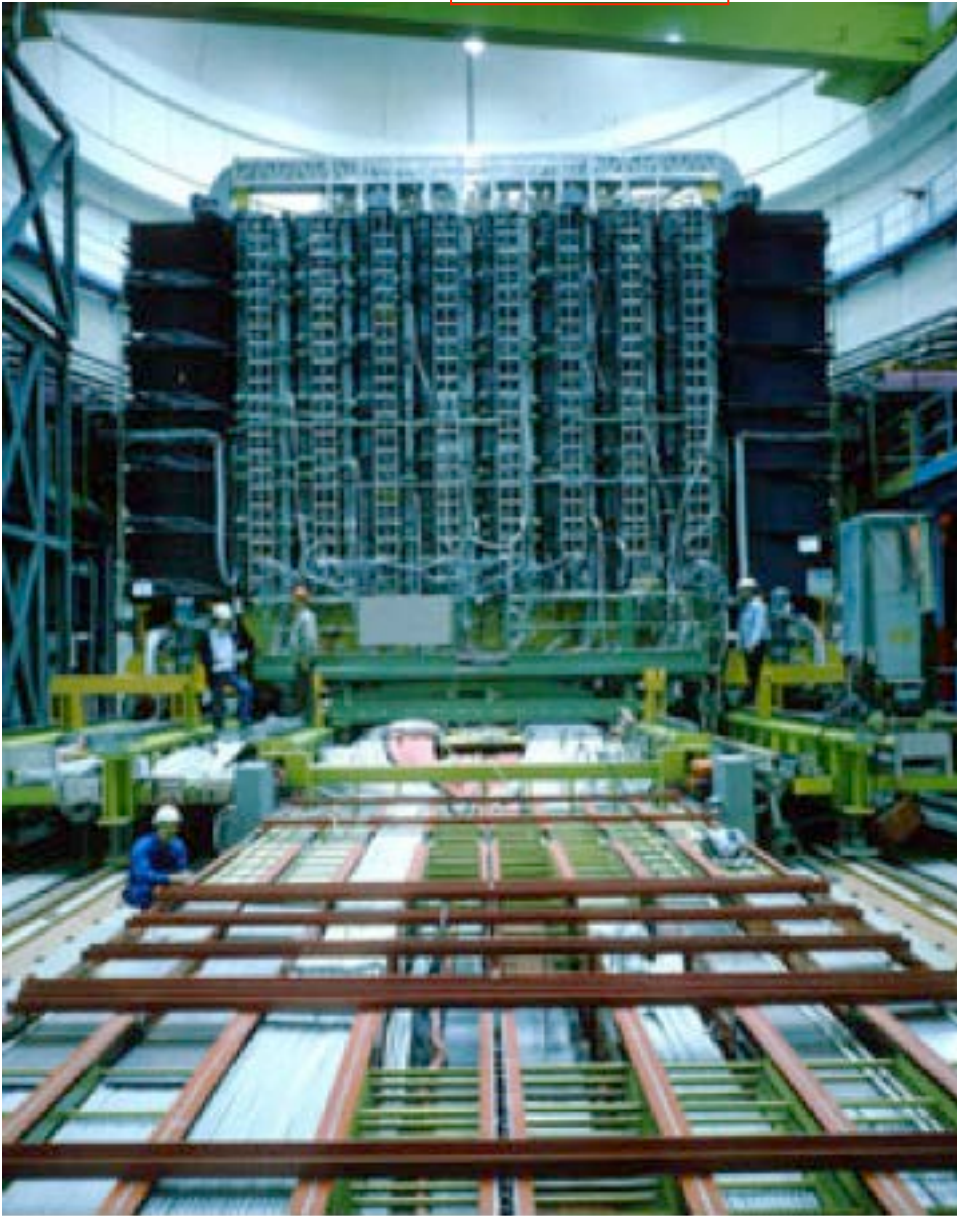
**) Visitor from University of Roma, INFN Roma, Italy.

***) Visitor from Harvard University, Cambridge, Mass., USA.

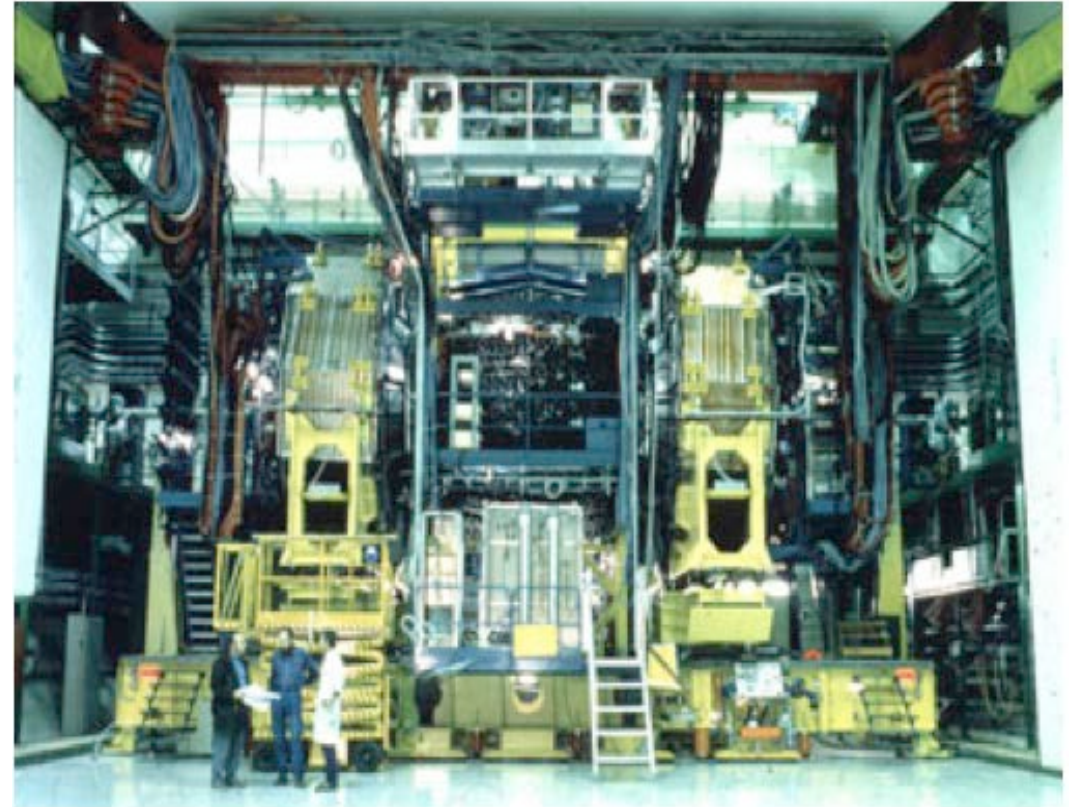
†) Spokesman.

52 authors
< 1/100 of LHC !

UA1



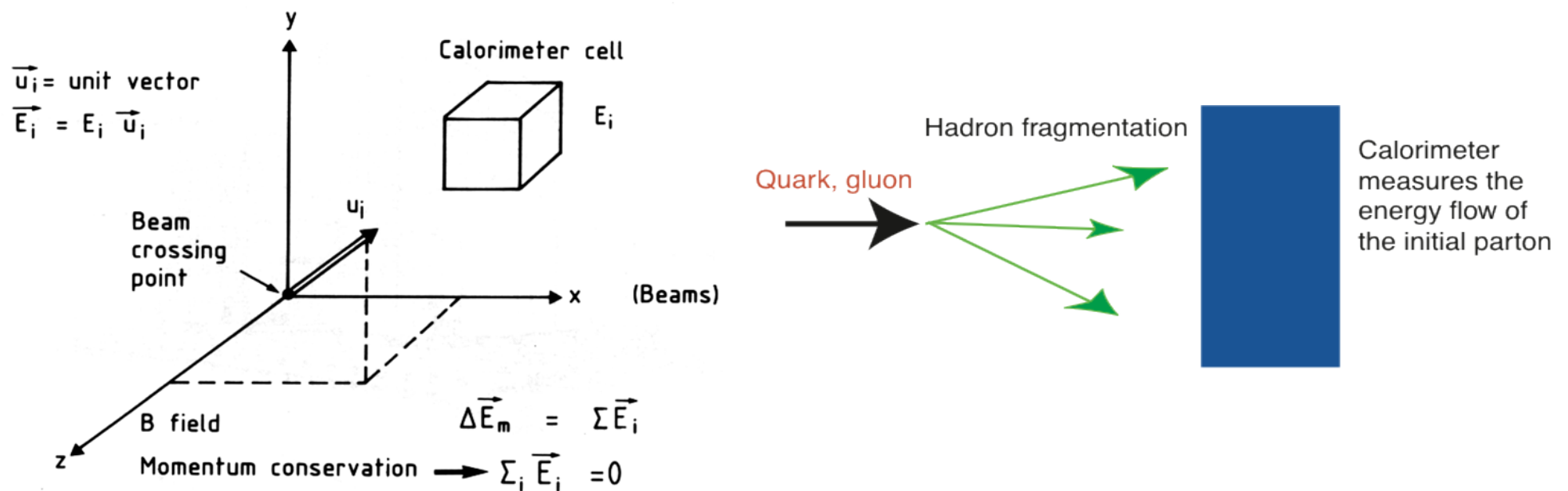
Della Negra_Dec.2015



UA2

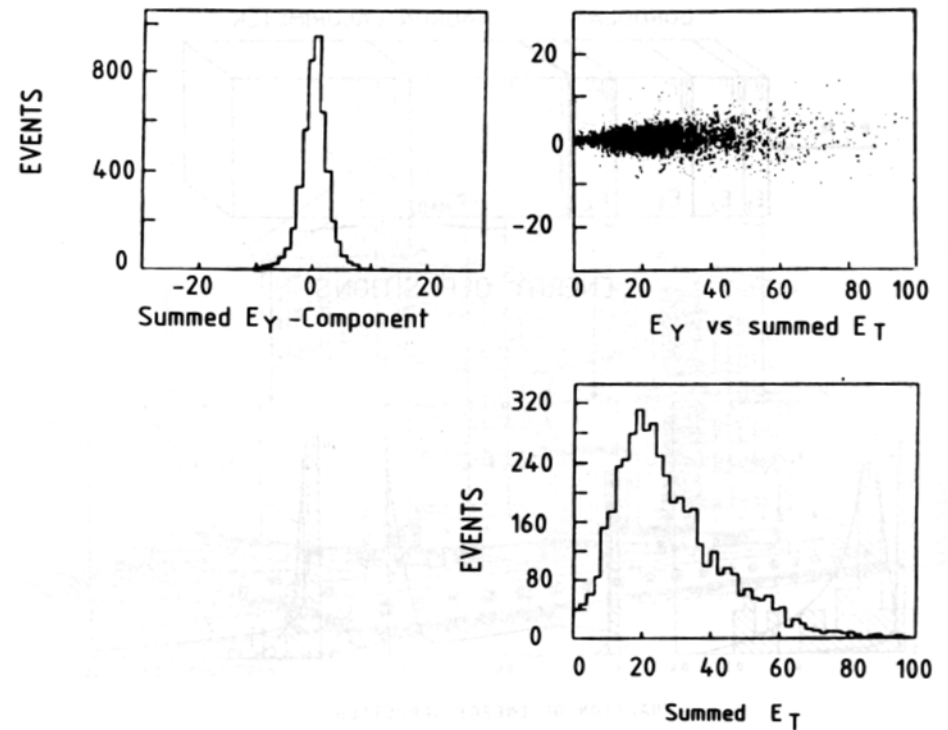
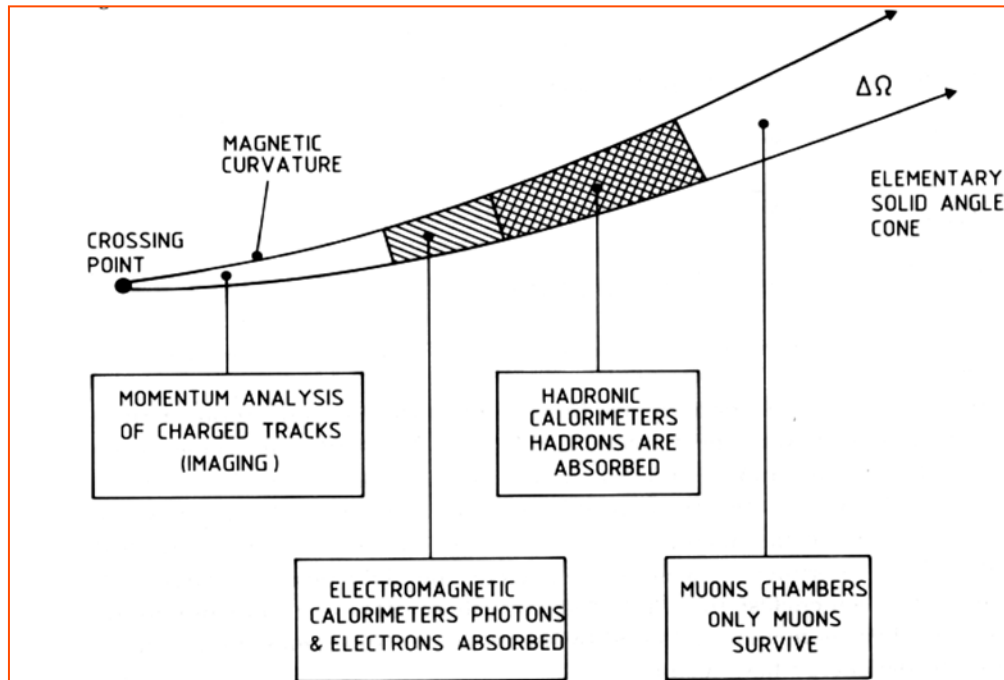
Two major innovations

- Look directly at constituents (quarks and gluons) beyond fragmentation, with the help of a sophisticated 4π calorimetry \Rightarrow *Energy flow*



- Missing energy to identify escaping neutrino or non interacting particles \Rightarrow *"Ermeticity" down to 0.2 °*

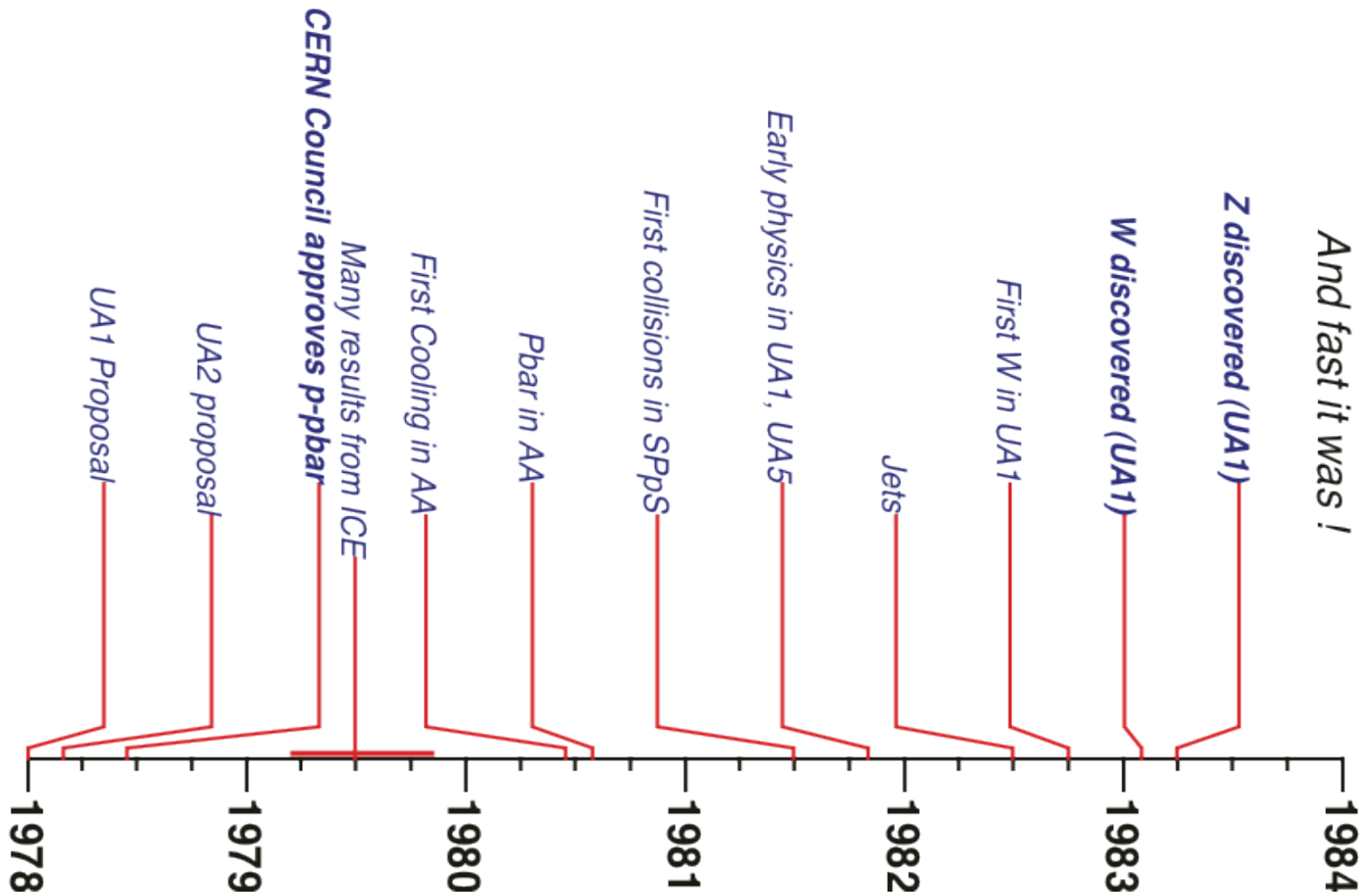
Hadronic events



Schematic function in each of the elementary solid angle elements constituting the detector's structure

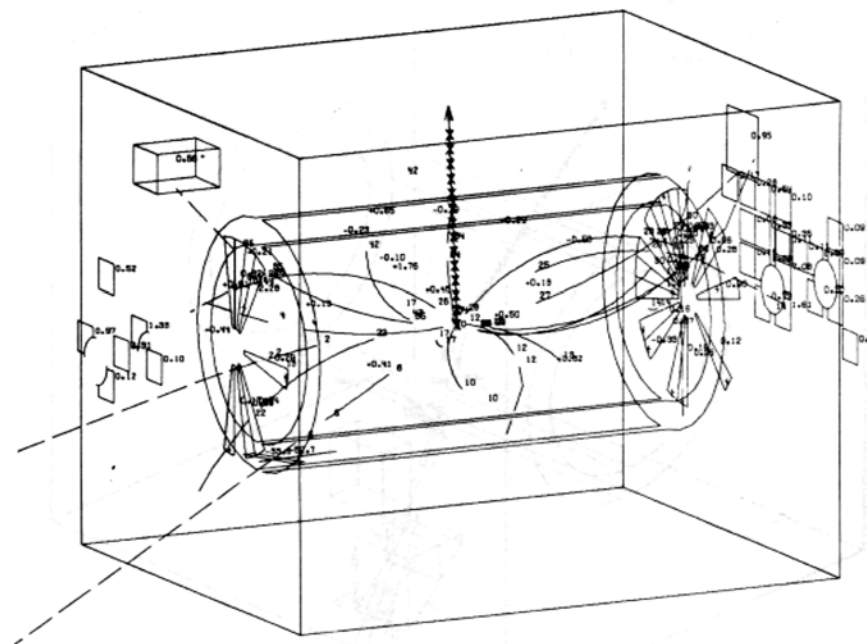
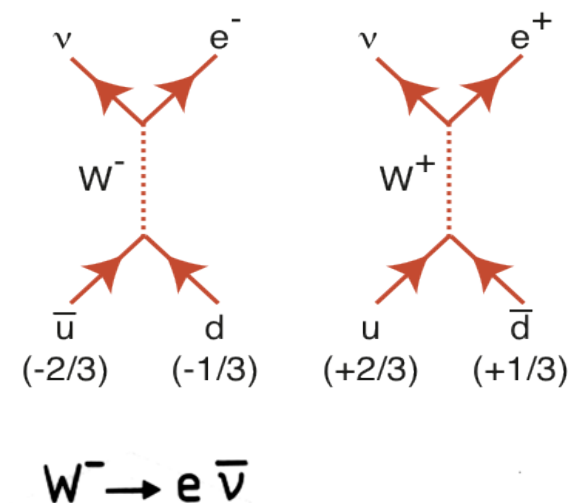
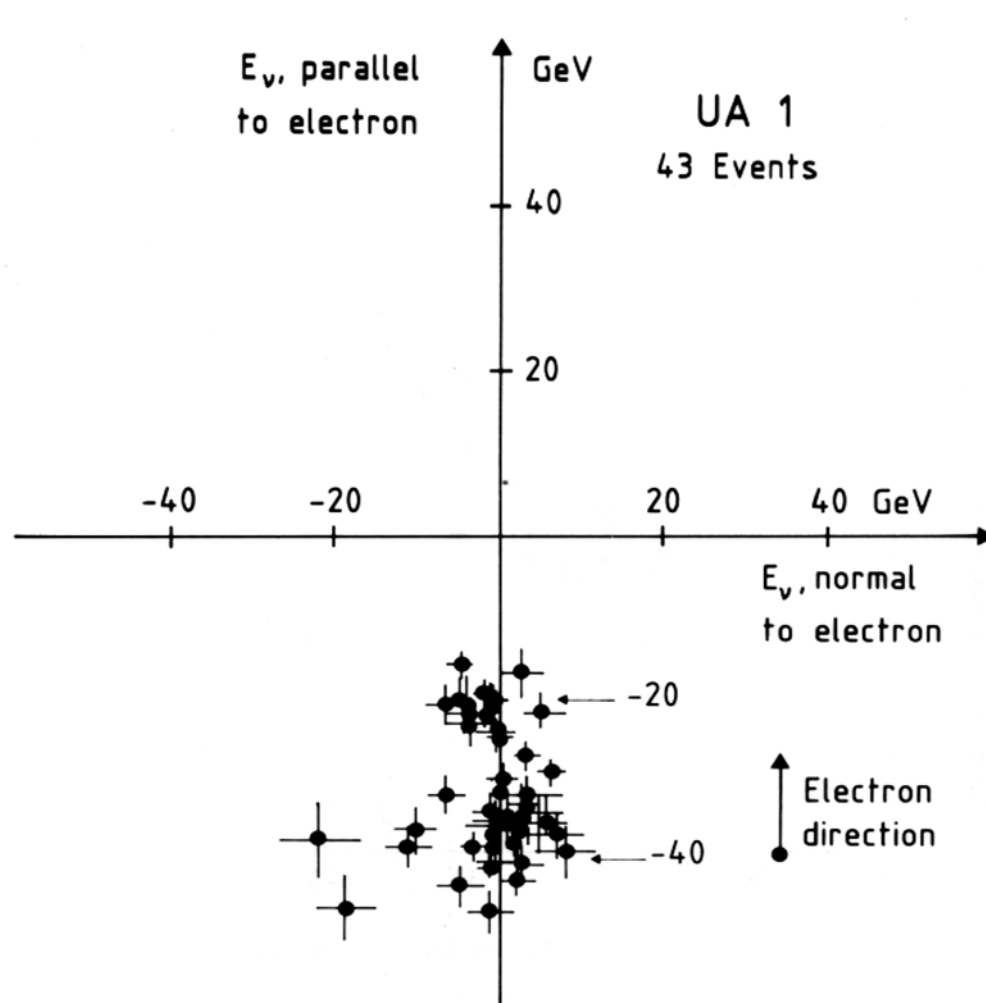
Over all energy balance for ordinary events

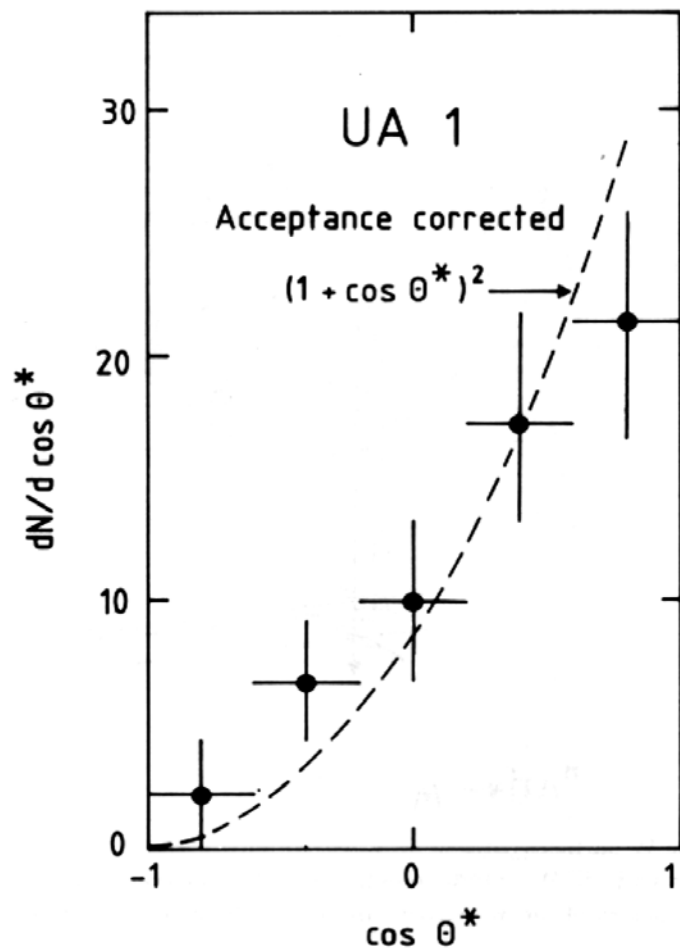
And fast it was !



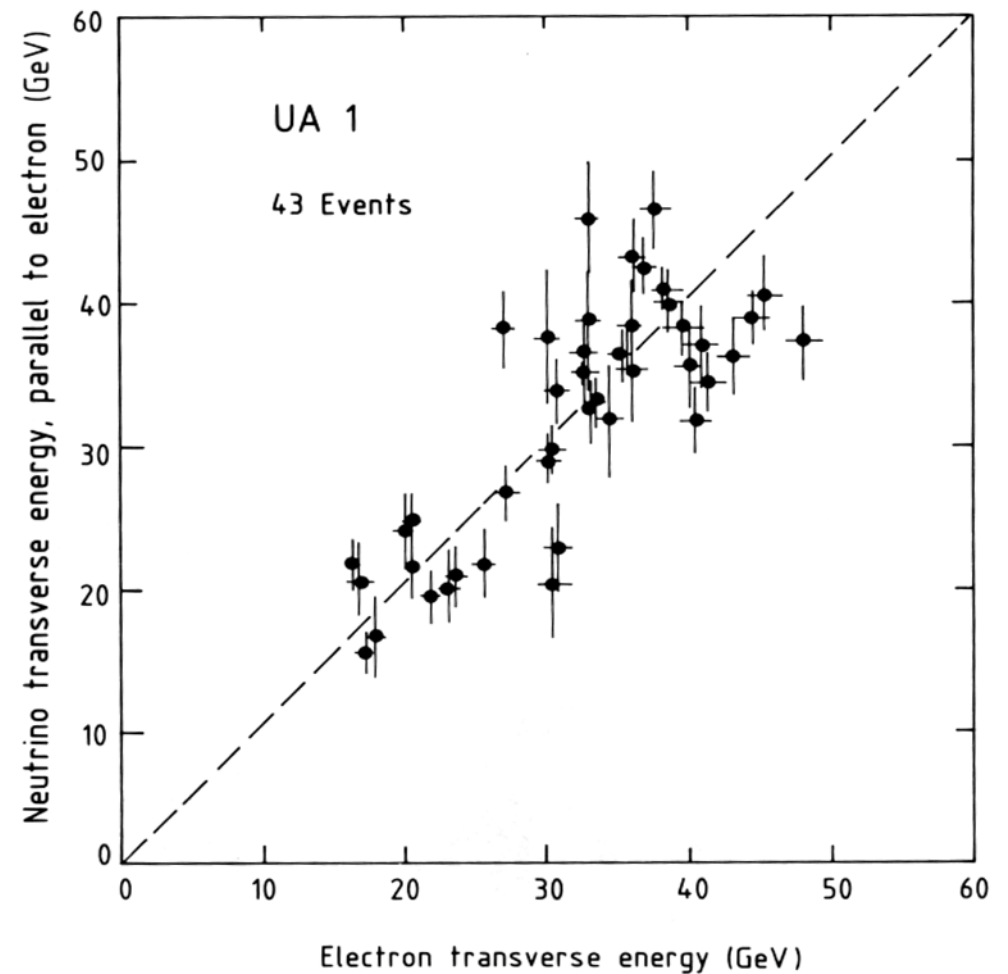
The initial discovery of the W signal

Neutrino detection by missing energy balance



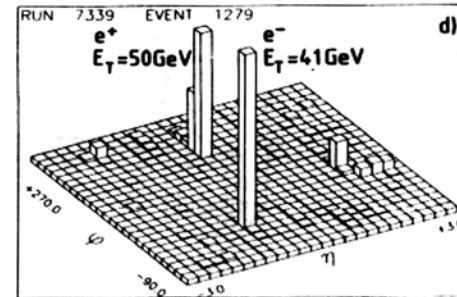
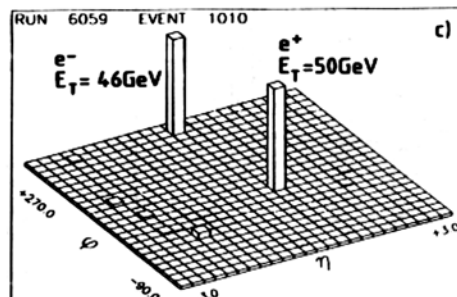
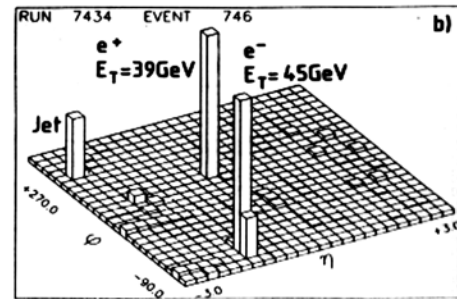
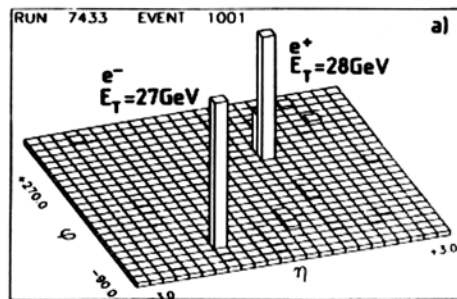


Decay angular asymmetry of the electron in the rest frame of the W (Parity violation)

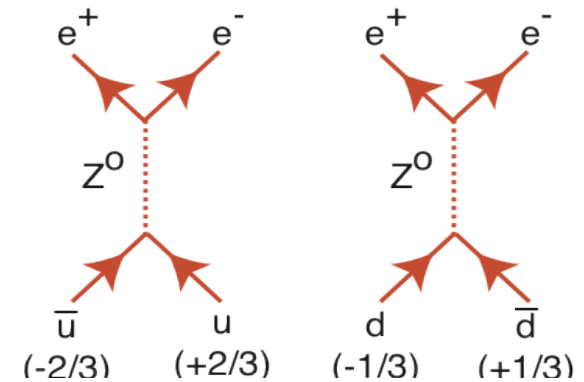


Correlation of electron and neutrino energies

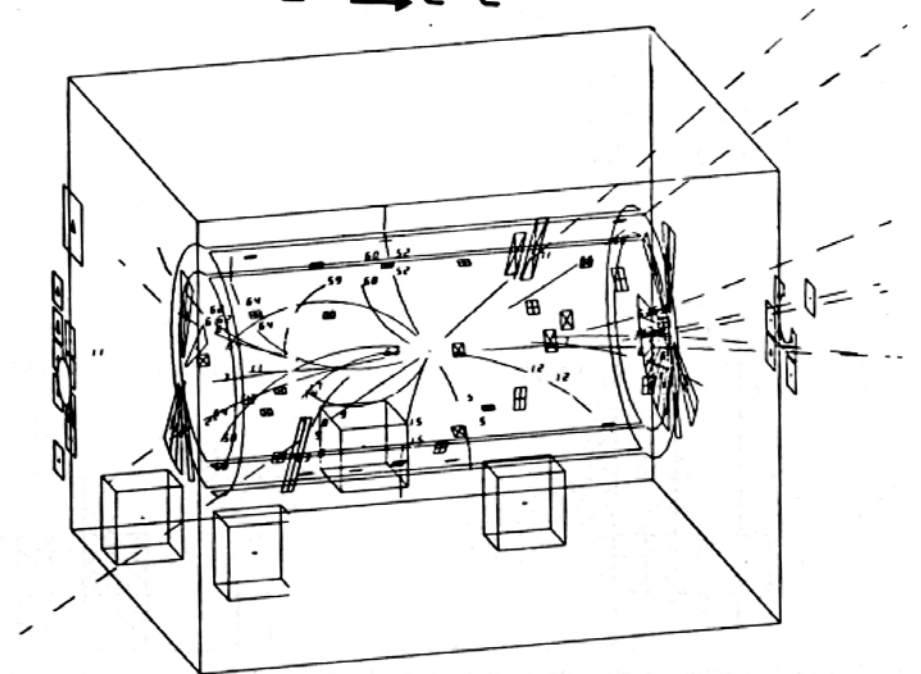
The initial discovery of the Z signal



Lego plots of Z events



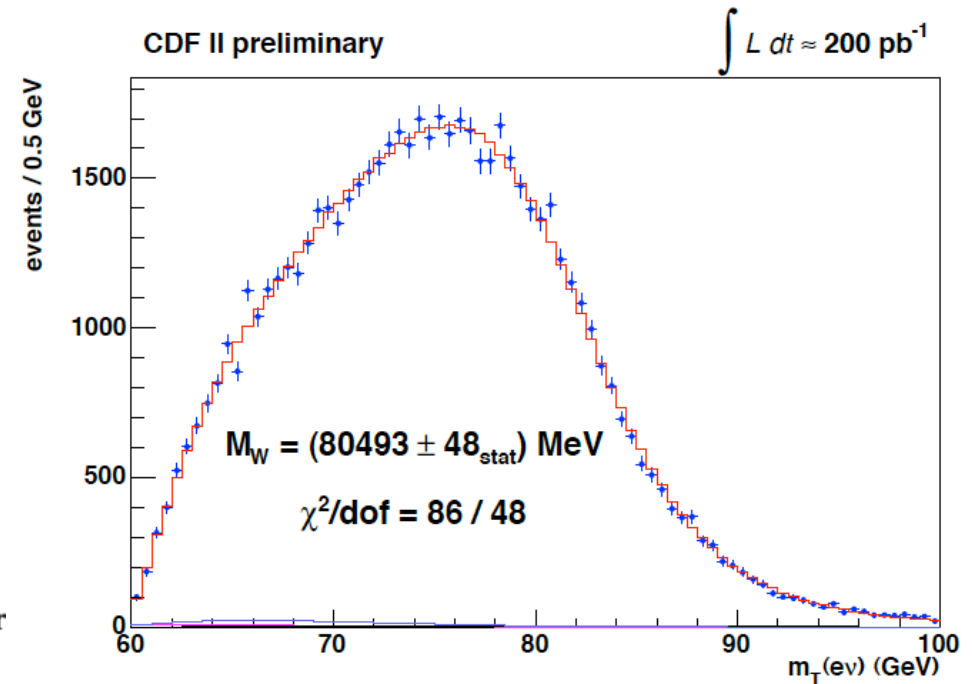
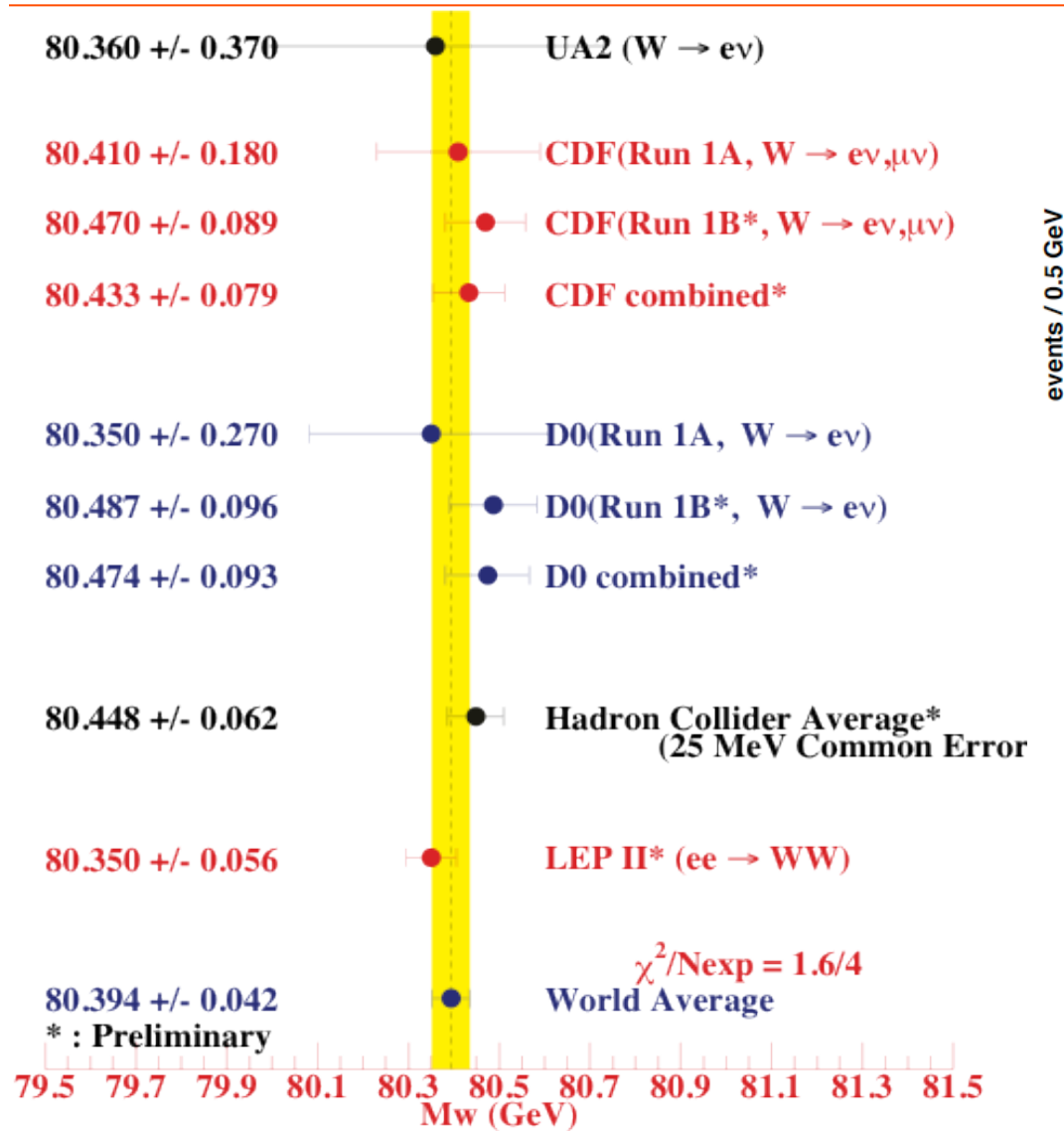
$$Z^0 \rightarrow e^+ e^-$$



Somewhere in Sweden.....



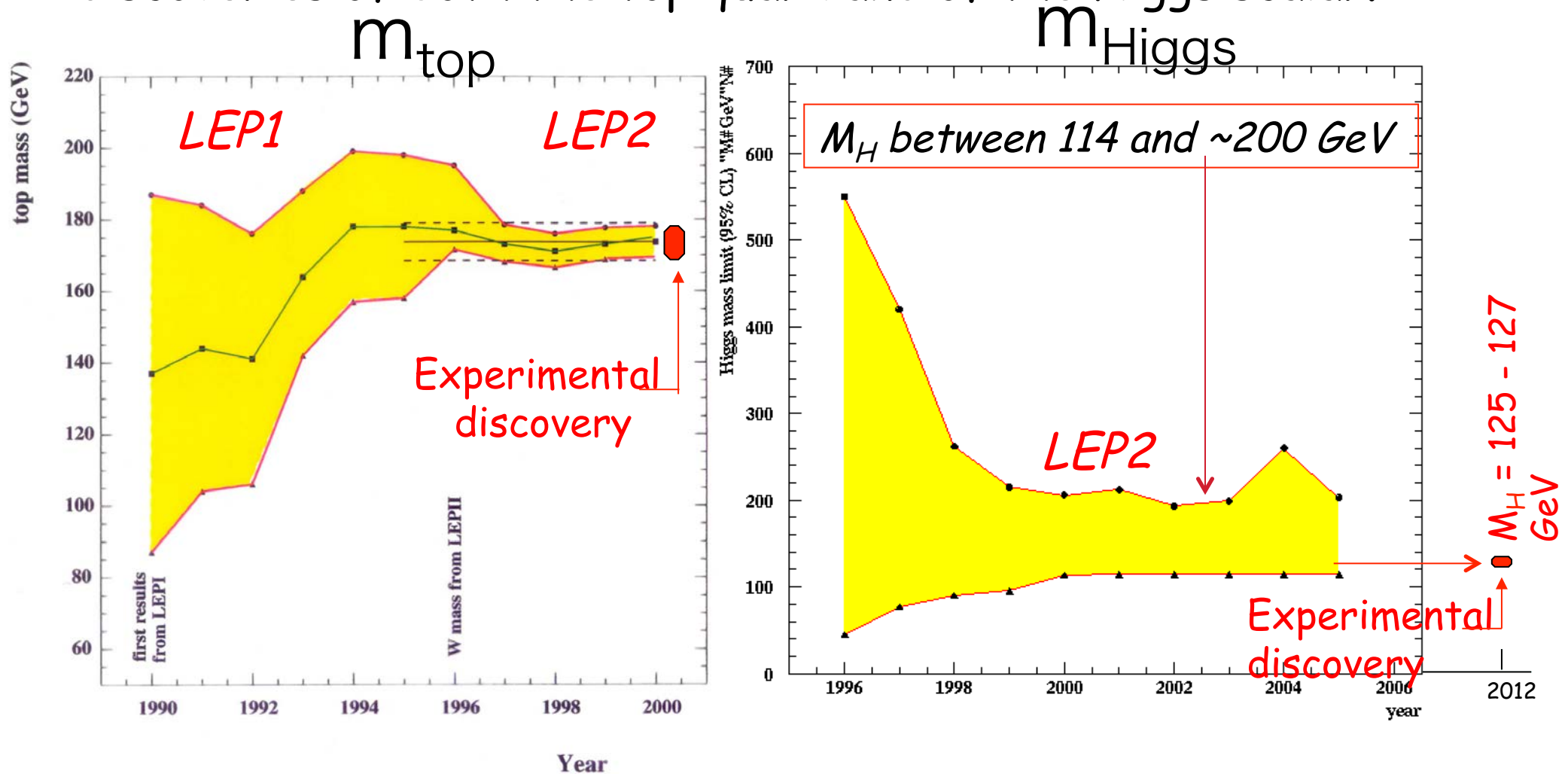
W-mass determinations



W → eν channel

Anticipating discoveries with higher order diagrams ?

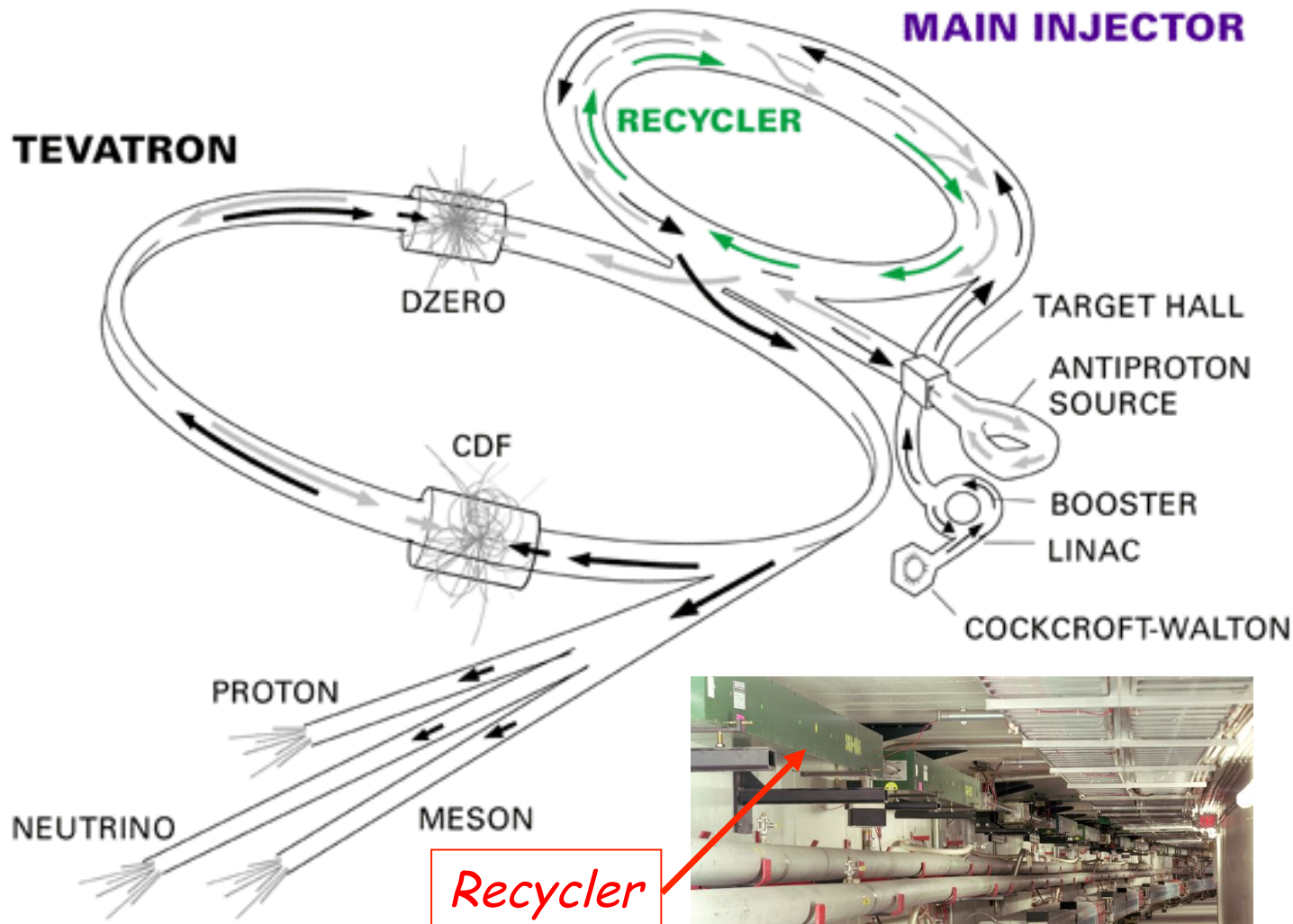
- After the Z^0 discovery with p-pbar, its detailed studies of the Z^0 at LEP in very clean conditions have been an essential phase.
- Higher order QM corrections at LEP have anticipated the discoveries of both the top quark and of the Higgs scalar.



The Fermilab Tevatron



Fermilab Accelerator chain

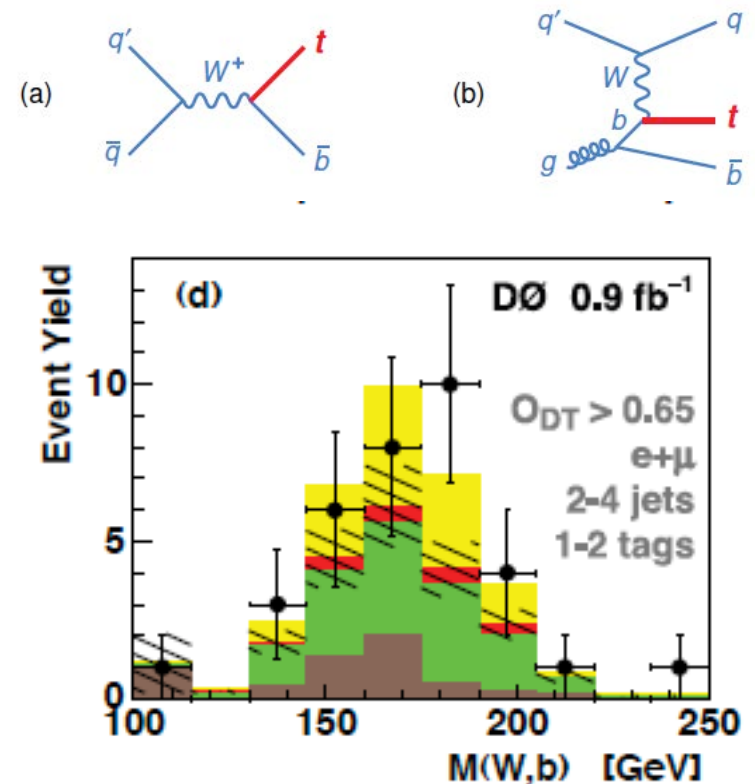


- Main p injector (120 GeV)
- Target: p-bars with a nickel target
- Antiproton source: triangular shaped ring accumulating p-bar with stochastic cooling at 8.9 GeV/c
- Recycler: permanent magnet ring with electron cooling for additional pbar storage at 8.9 GeV/c
- Tevatron: the p-pbar storage ring at 980 GeVx2 in c. of m.



The discovery of the top quark

- The first observation of single top quark production using 3.2 fb^{-1} of pbar-p collision data with $\sqrt{s} = 1.96 \text{ TeV}$ collected by the Collider Detector at Fermilab (61 institutions).
- The significance of the observed data is 5.0 s.d. The cross section is $2.3 \pm 0.6 \text{ pb}$.
- First evidence for the production of single top quarks at the Fermilab Tevatron pbar-p collider and 0.9 fb^{-1} dataset (84 institutions)
- The cross section is $4.9 \pm 1.4 \text{ pb}$, corresponding to a 3.4 standard deviation significance.



W+highest- p_T b-tagged jet
The expected signal is shown from the measured cross section

Conclusion: Impact of p-pbar on HEP

- Since its initial introduction in HEP in 1982, the p-pbar technology firstly at CERN and later at Fermilab has dominated the highest energy sector over the last 27 years, transforming with the help of pbars the two major existing accelerators into colliders with remarkable luminosities: $L_{\text{init}}(\text{ppbar}) = 2.78 \times 10^{32} \text{ cm}^{-2}$, $\text{ISR}(\text{pp}) = 1.4 \times 10^{32} \text{ cm}^{-2}$.
- The cooling technologies have been generalized and the accumulation rate has been greatly increased mostly with the help of Van Der Meer cooling and later also with Budker's cooling both at CERN and at FermiLab.
- On the other end of the energy spectrum, very low energy pbar (LEAR) have permitted very fundamental discoveries.
- Equally revolutionary have been the associated development of instrumentation with the 4π "hermetic" detectors (UA1), hadron calorimetry (Schopper) and drift chambers (Charpak) which have ensured even with "Swiss watches" a detection capability comparable to the one of e^+e^- .

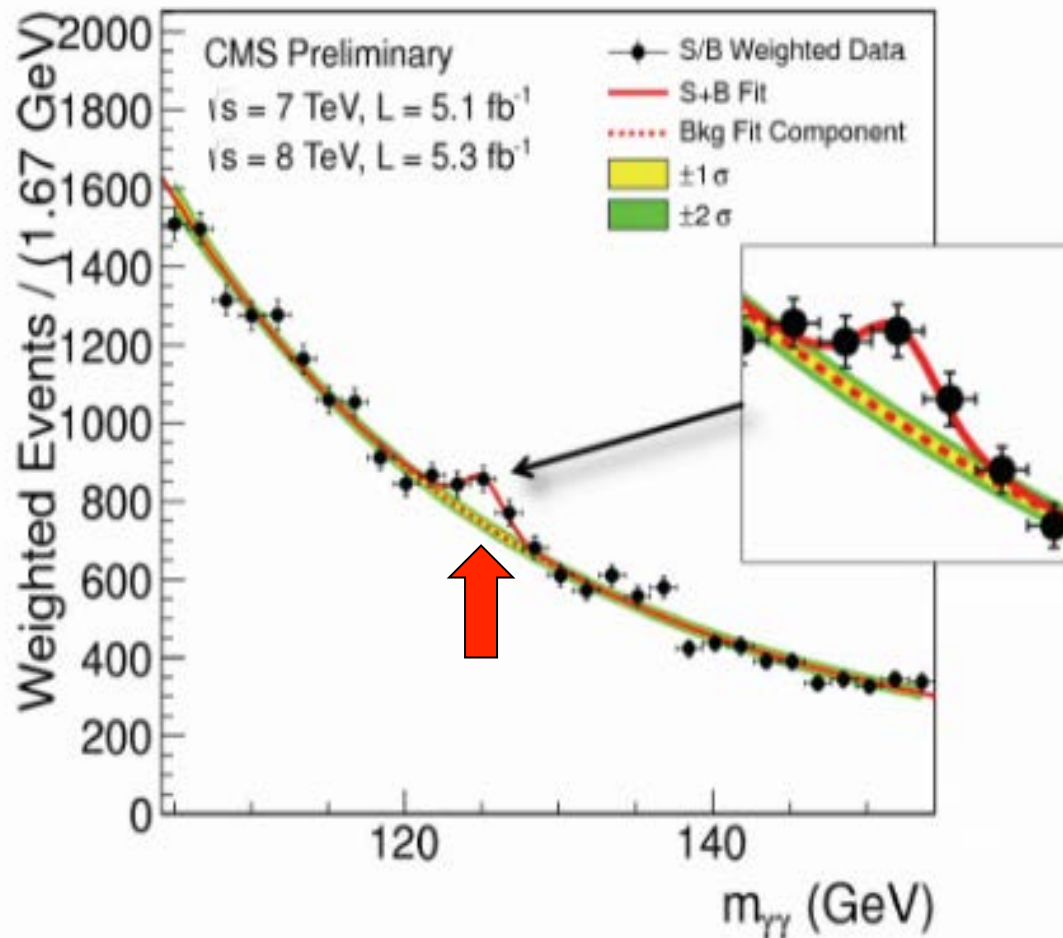
The Higgs, the latest Nobel winning discovery !

- CMS and Atlas have observed in 2012 with LHC a narrow line of high significance at about 125 GeV mass, compatible with the Standard Model Higgs boson.
 - ⇒ ATLAS: $m_H = 125.5 \pm 0.2 \text{ (stat)} \pm 0.6 \text{ (sys)} \text{ GeV}$
 - ⇒ CMS: $m_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (sys)} \text{ GeV}$
- Their data are consistent with fermionic and bosonic coupling expected from a SM Higgs particle.
- Searches have been performed in several decay modes, however in the presence of very substantial backgrounds.
- Experimental energy resolutions have been so far much wider of any conceivable intrinsic Higgs width.
- Results of both experiments also exclude other SM Higgs bosons up to approximately 600 GeV.

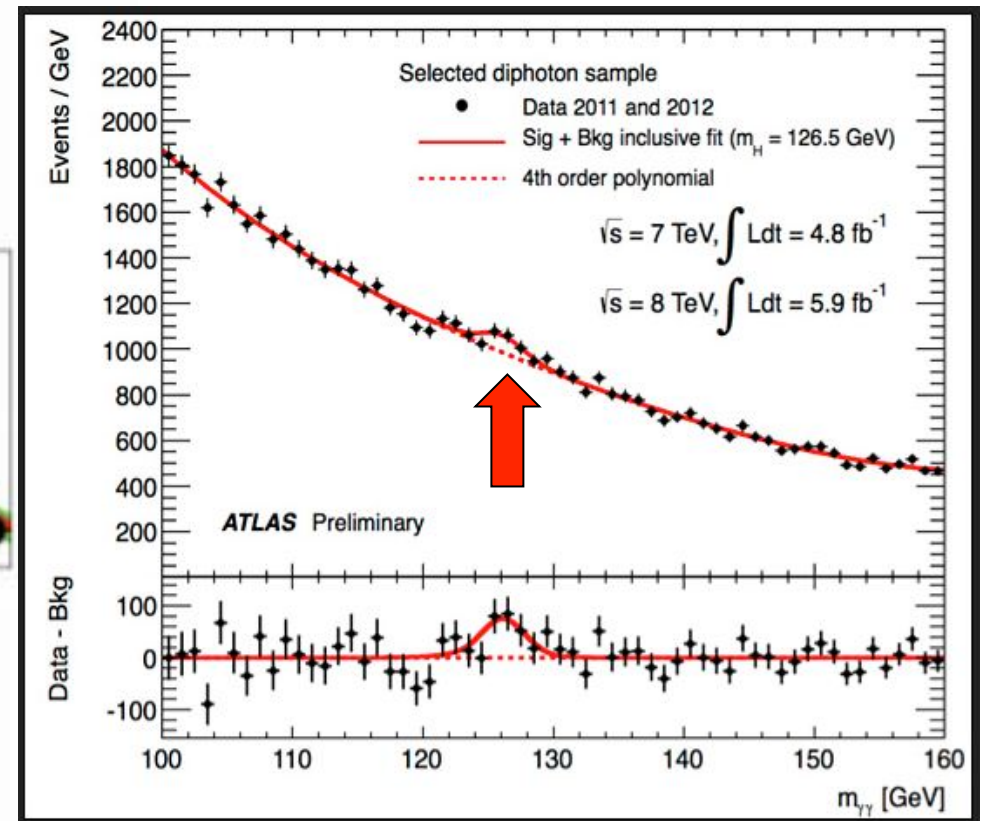
The LHC observation of the Higgs at 125 GeV

Signal and background in the $H \rightarrow 2\gamma$ channel

CMS

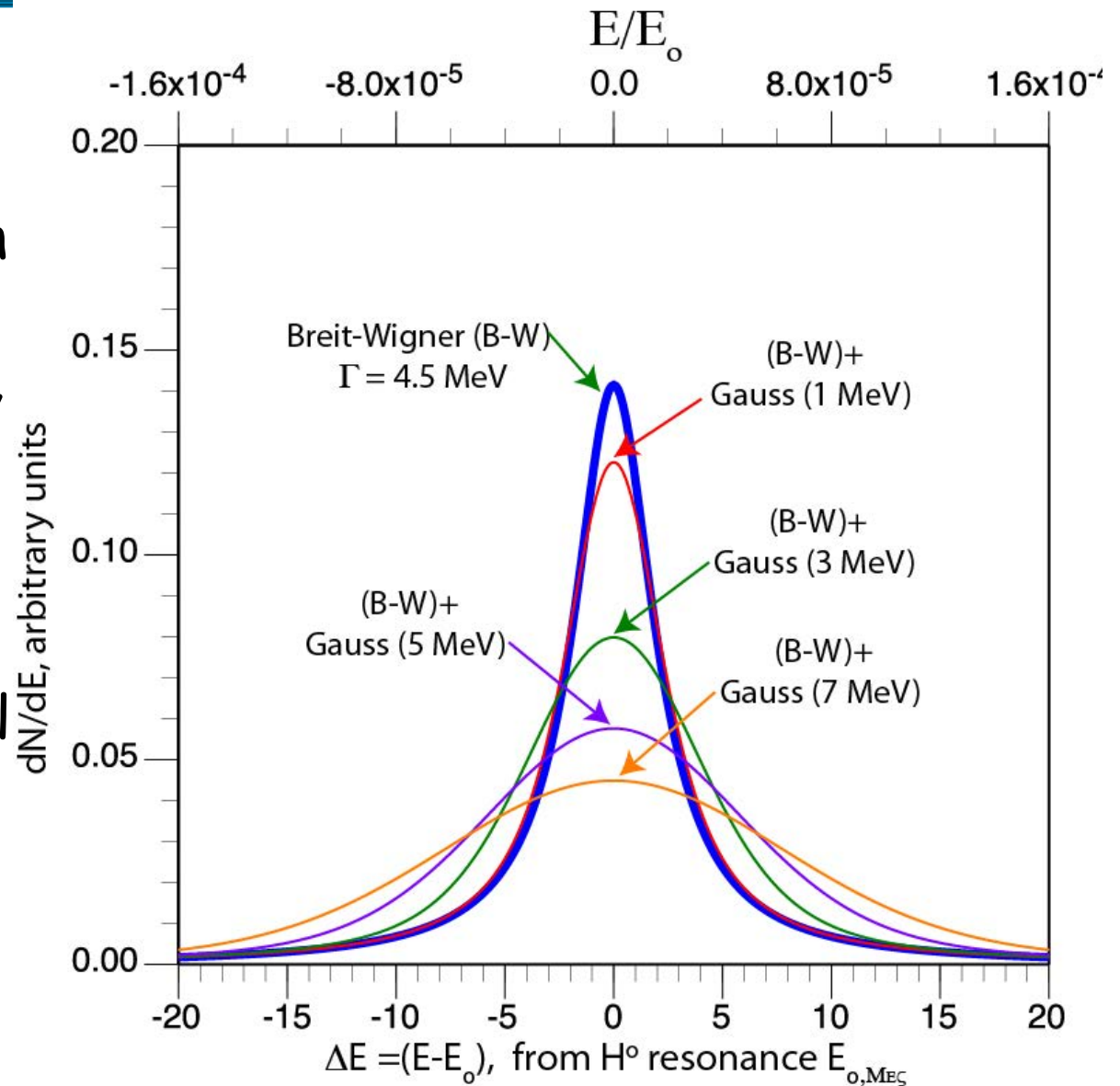


ATLAS



The Higgs width according to the Standard Model

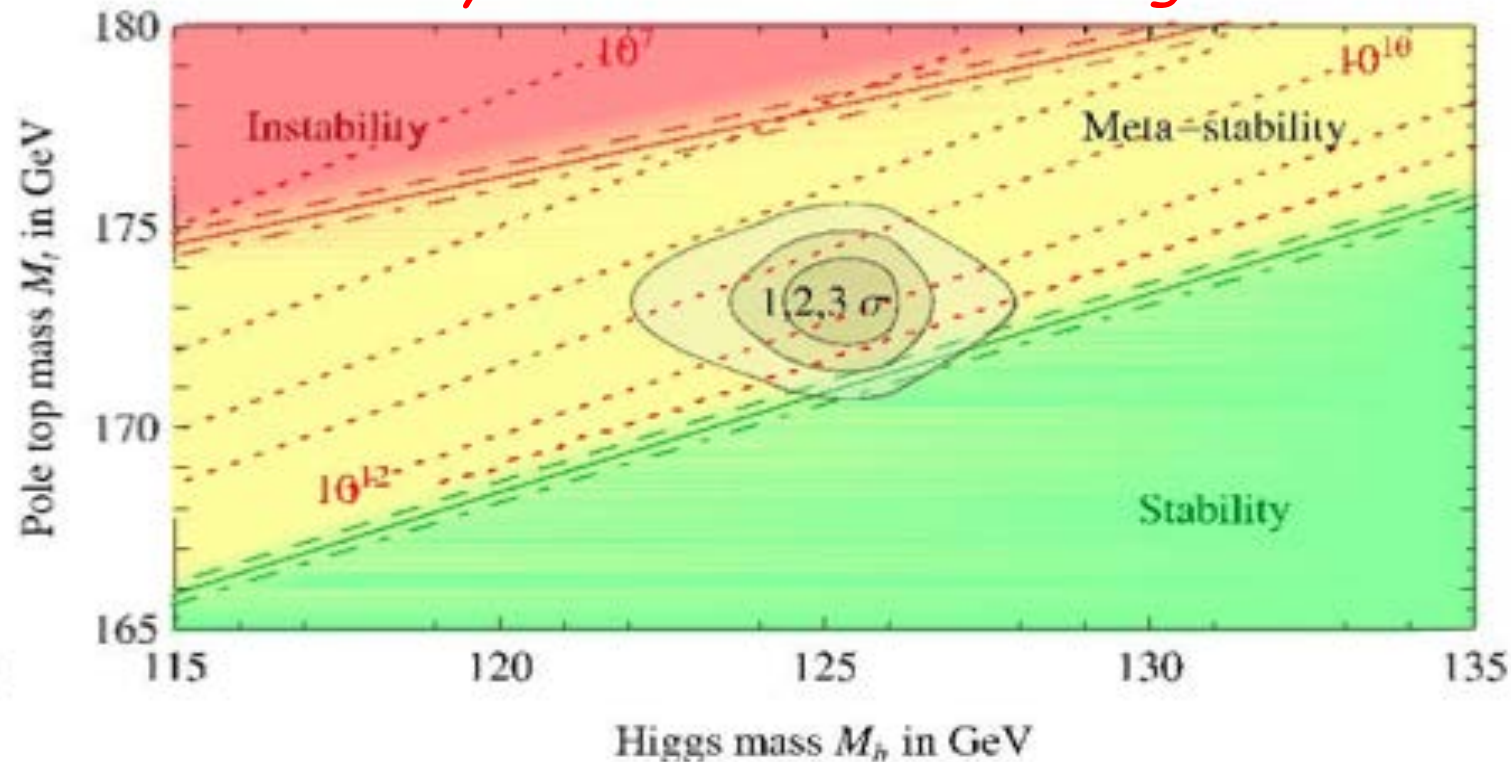
- Cross section for the Higgs is shown here, convoluted with a Gaussian beam distribution.
- Signal is not affected only if the rms beam energy width is \leq a few MeV.
- Like in the case of the Z_0 , the H_0 width will be crucial in the determination of the nature of the particle and of the associated underlying phenomenology



4.5 MeV width: The very demanding resolution $R \approx 0.003\%$ is required

Stability of the Higgs sector

- For the experimental value, the electroweak vacuum is meta-stable, but with a lifetime longer than the age of the Universe.
- The Standard Model may be valid without new physics all the way up to the Planck scale. *Thus, there may be only one standard model (SM) Higgs and no need for the "no fail theorem" and no immediate necessity of SUSY at LHC energies.*

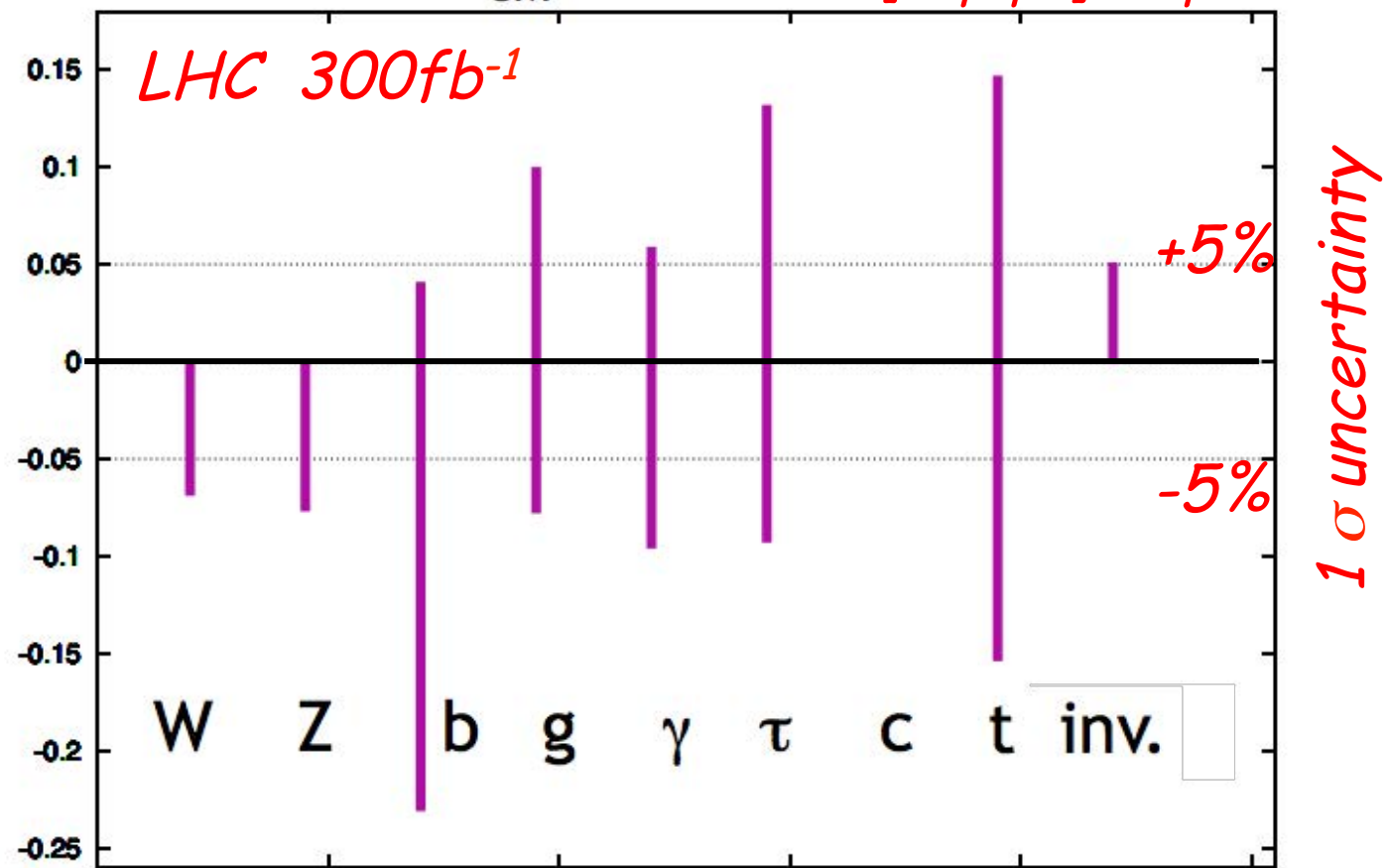


Ultimate LHC uncertainties are due to systematic effects

- The estimates reflect one of LHC detectors accumulating 300 fb⁻¹ of data, dominated at this level by systematic errors of the ATLAS and CMS collaborations at the best understanding.

arXiv:1207.2516v3 [hep-ph] 1 Apr 2013

- ATLAS and CMS have estimated errors also for 3000 fb⁻¹ from the High-L LHC.
- However such estimates can hardly be a straightforward extrapolation of the current performances.

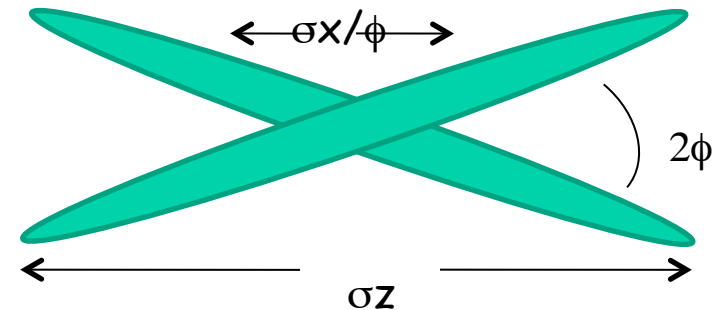


The future: studying the Higgs signal beyond LHC

- A comprehensive Higgs study requires \sqrt{s} energies of up to ≈ 1.0 TeV, and adequate luminosities. Two main alternatives are:
- *e^+e^- colliders* at $L > 10^{34}$, with huge dimensions and cost, namely
 - ⇒ a ≈ 100 km ring (4xLHC), but limited to $\sqrt{s} < 250$ GeV, thus missing many Higgs-strahlung and Higgs-Higgs boson diagrams
 - ⇒ a Linear Collider (ILC), eventually to $\sqrt{s} \approx 1$ TeV and ≈ 50 km. This is a major new technology which needs to be developed.
- These projects will largely exceed LHC costs and time schedule.
- *$\mu^+\mu^-$ rings*, with a much lower cost and of a much shorter time schedule and which may easily fit within the existing CERN site, but requiring the compression in phase space of muon beams, with two potential main alternatives:
 - ⇒ the s-channel resonance and $L > 10^{32}$ at $\sqrt{s} = 126$ GeV in order to observe its 4 MeV wide Higgs width without backgrounds;
 - ⇒ A higher energy collider ring, eventually up to 1 TeV and a $L > 10^{34}$ and luminosity comparable to a e^+e^- Linear Collider.

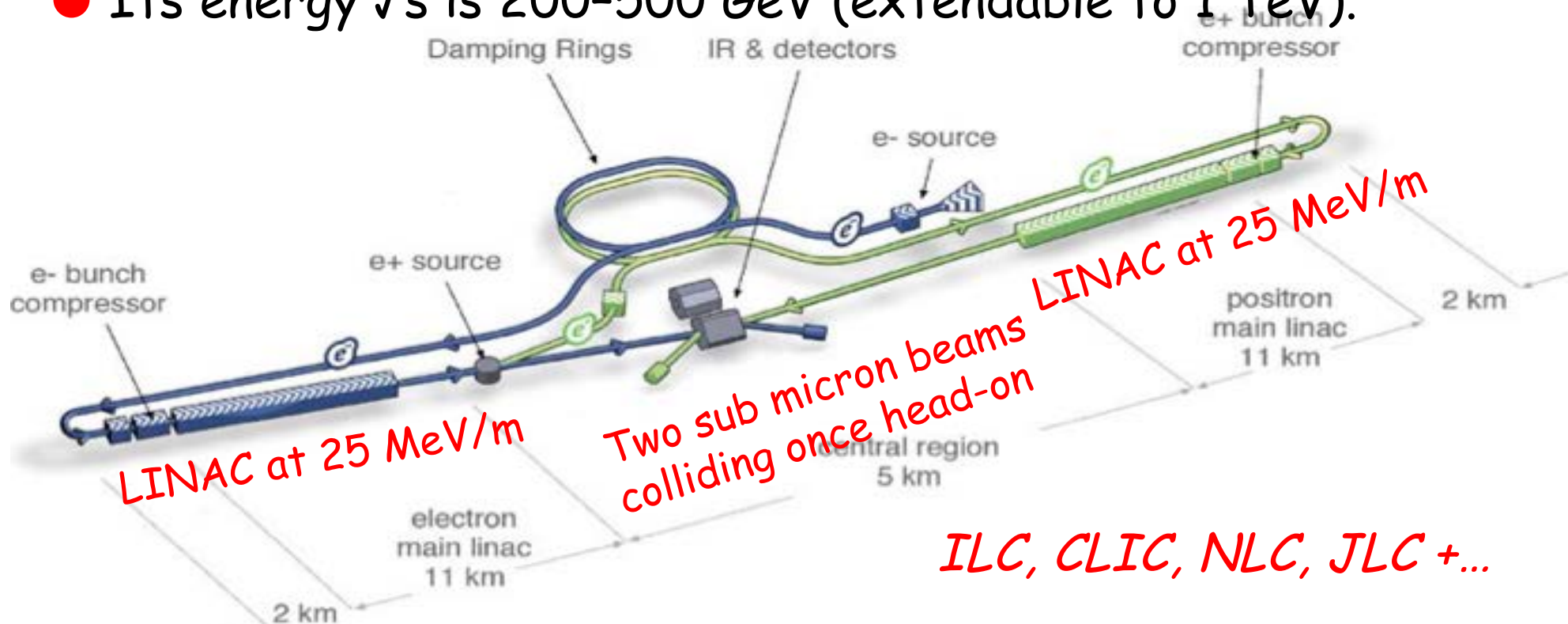
Requirements for the Higgs with a e^+e^- ring collider

- The luminosity is pushed to the beam-strahlung limit.
- Collisions are at an angle, but with fewer bunches than for a B-Factory: a nano-beam scheme
- Luminosity (several $\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), costs and power consumption ($\approx 100 \text{ MW}$) are comparable to those of a linear collider ILC.
- In order to reach luminosity (factor $\approx 500 \times \text{LEP2}$) and power consumptions (factor $5 \times \text{LEP2}$) the main cures are
 - Huge ring (80 km for SuperTristan or for T-LEP)
 - Extremely small vertical emittance, with a beam crossing size the order of 0.01μ (it has been 3μ for LEP2)
- *The performance is at the border of feasibility ($E_{cm} \approx 250 \text{ GeV}$).*
- *The Higgs width, H-strahlung and double Higgs diagrams cannot be studied by any acceptable e^+e^- ring collider.*



The Linear collider option

- The International Linear Collider (ILC) is a high-luminosity linear electron-positron collider based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology.
- Its energy \sqrt{s} is 200-500 GeV (extendable to 1 TeV).



ILC, CLIC, NLC, JLC +...

The total footprint for 500 GeV is ~31 km. To upgrade the machine to $E_{\text{cms}} = 1$ TeV, the linacs and the beam transport lines would be extended by another ~ 22 km.

Main parameters of ILC

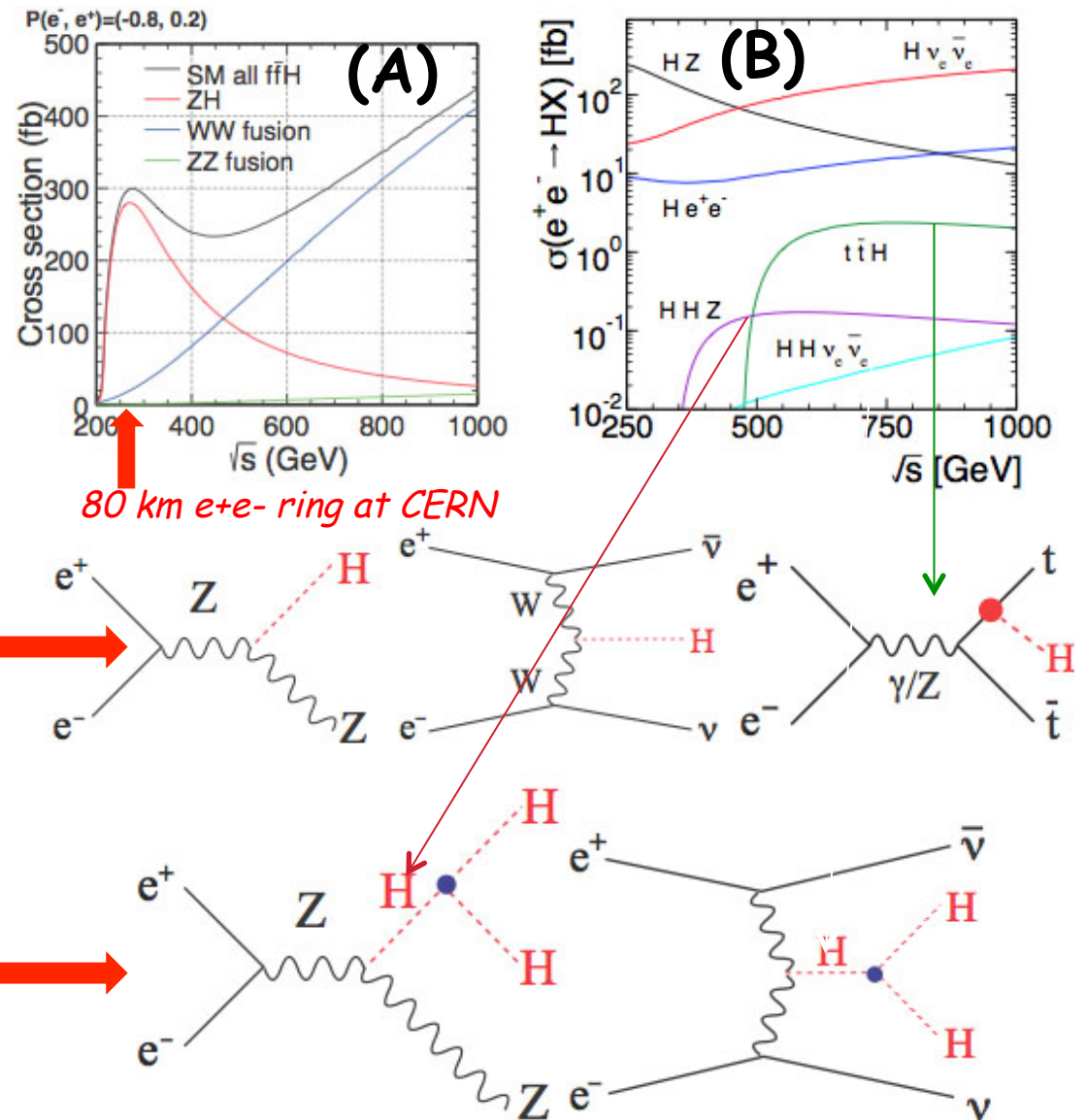
- Collisions between electrons and positrons, with many bunches of 5 nanometres ($0.005 \mu\text{m}$) in height, each containing 2×10^{10} particles and colliding 14,000 times per second.
- 16,000 SC accelerating cavities made of pure niobium.
- Temperature: 2 K (-271.2°C); Accelerating Gradient: 31.5 MV/m
- Length: 31 km for 500 GeV extended to 50 km for 1 TeV plus two damping rings, each with a circumference of 6.7 km (1/4 LHC).
- Nearly 300 laboratories and universities around the world are involved in the ILC: more than 700 people are working on the accelerator design, and another 900 people on detector development.
- The accelerator design work is coordinated by the Global Design Effort, and the physics and detector work by the World Wide Study.
- The estimated cost for the 500 GeV option is ≈ 8 Billion \$(2012).

Higgs related higher order electroweak processes

- (A) Production cross sections of Higgs boson from e^+e^- or $\mu^+\mu^-$ as a function of the energy \sqrt{s}
- (B) Production cross sections from e^+e^- or $\mu^+\mu^- \rightarrow HX$ as a function of the \sqrt{s} energy

⇒ The Higgs-strahlung diagram (Left), the W-boson fusion process (Middle) and the top-quark association (Right).

⇒ Double Higgs boson diagrams via off-shell Higgs-strahlung (Left) and W-boson fusion (Right) processes



In order to study comprehensively all these processes energies of 0.6-1 TeV are needed

The alternative: cooling with non Liouvillian Accelerators

- Already at MURA in the fifties it was realised that some beam phase-space compression may be often necessary from the source to the collision point (O'Neill, Piccioni, Symon).
- *Liouville theorem*: whenever there is an *Hamiltonian* (i.e. any force derivable from a potential) then the six dimensional phase space is preserved, namely, at best $\Delta V/dt = 0$.
- Therefore we need some kind of *dissipative non-Liouvillian drag force* working against the particle speed and not derived from an Hamiltonian. Several alternatives are possible:
 - ⇒ *Synchrotron radiation*: but only for electrons and positrons;
 - ⇒ *Electron cooling*: an electron beam bath travelling with a speed equal to the one of the circulating beam (Budker)
 - ⇒ *Stochastic cooling*: statistical fluctuations (Van Der Meer)
 - ⇒ *Ionization cooling*: dE/dx losses are added to the beam
- With any of such methods and with accelerating cavities replacing the losses, one can compress the phase-space volume.

From antiprotons to muons

- Phase compression (cooling) is essential whenever secondary particles are produced from initial collisions and later accelerated, to be accumulated in a storage ring.
- A well known case is the one of antiprotons, in which both stochastic and electron cooling have been vastly used. P-pbar colliders have permitted the discoveries of W/Z and the Top.
- Ionization cooling is specific for muons, since they have only electromagnetic interactions with matter
- The muon lifetime may be long enough to offer with the help of ionization cooling a reasonable number of $\mu^+ \mu^-$ collisions in a ring in which they interact head-on.
- The idea has been discussed by Budker and Skrinsky in the seventies. A comprehensive analysis has been given f.i. by Neuffer in the early nineties.

*T. Neuffer Particle Accelerators 1983 Vol.
14 pp. 75-90*

The development of ionization cooling

- This method, called “ dE/dx cooling” closely resembles the synchrotron compression of relativistic electrons — with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.
- The main feature of this method is that it produces an extremely fast cooling, compared to other traditional methods. This is a necessity for the muon case.
- Transverse betatron oscillations are “cooled” by a target “foil” typically a fraction of g/cm^2 thick. An accelerating cavity is continuously replacing the lost momentum.
- Unfortunately for slow muons the specific dE/dx loss is increasing with decreasing momentum. In order to “cool” also longitudinally, chromaticity has to be introduced with a wedge shaped “ dE/dx foil”, in order to reverse (increase) the ionisation losses for faster particles.

Muon cooling ring: transverse emittance

- The emittance ε_N evolves whereby dE/dx losses are balanced by multiple scattering (Neuffer and McDonald):

$$\frac{d\varepsilon}{dz} \approx \frac{\varepsilon}{\beta^2 E} \frac{dE}{dz} + \frac{\overset{\text{Cooling}}{\beta^* (13.6)^2}}{\overset{\text{Scattering}}{2\beta^3 E m_\mu X_o}} \rightarrow 0$$

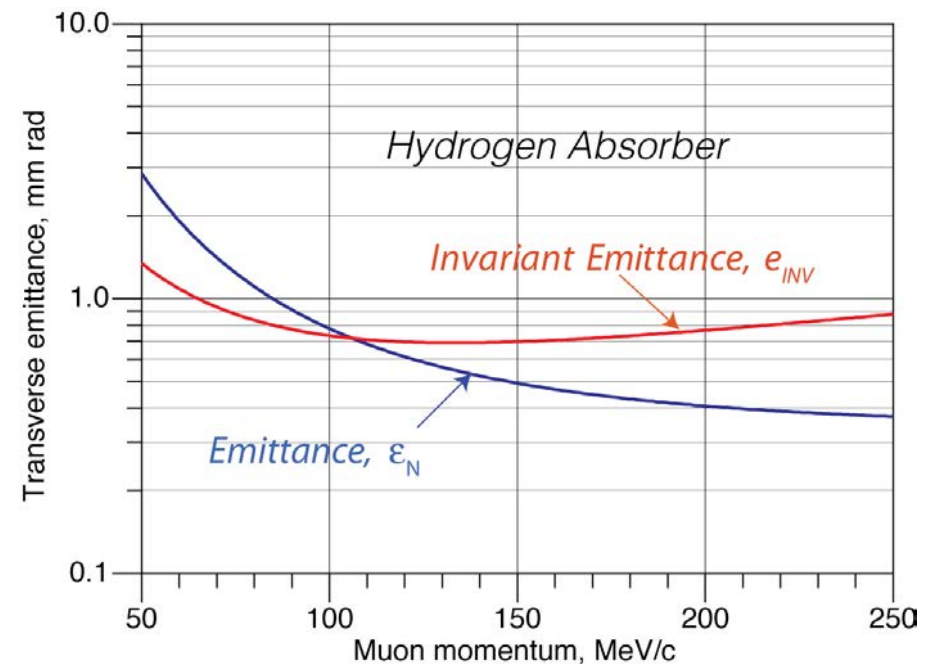
$\beta^* = \text{beta at cross}$
 $m_\mu \beta_\mu = \text{mu values}$

$X_o = \text{Rad. Length}$
 $dE/dz = \text{ioniz. Loss}$

- The cooling process will continue until an equilibrium transverse emittance has been reached:

$$\varepsilon_N \rightarrow \frac{\beta^* (13.6 \text{ MeV}/c)^2}{2\beta_\mu m_\mu} \frac{1}{(X_o dE/dz)}$$

- The equilibrium emittance ε_N and its invariant $\varepsilon_N/\beta\gamma$ are shown as a function of the muon momentum.
- For H_2 and $\beta^* = 10 \text{ cm}$, $\varepsilon_N/\beta\gamma \leq 700 \text{ mm mr}$ from 80 to 300 MeV/c



Muon cooling ring: longitudinal emittance

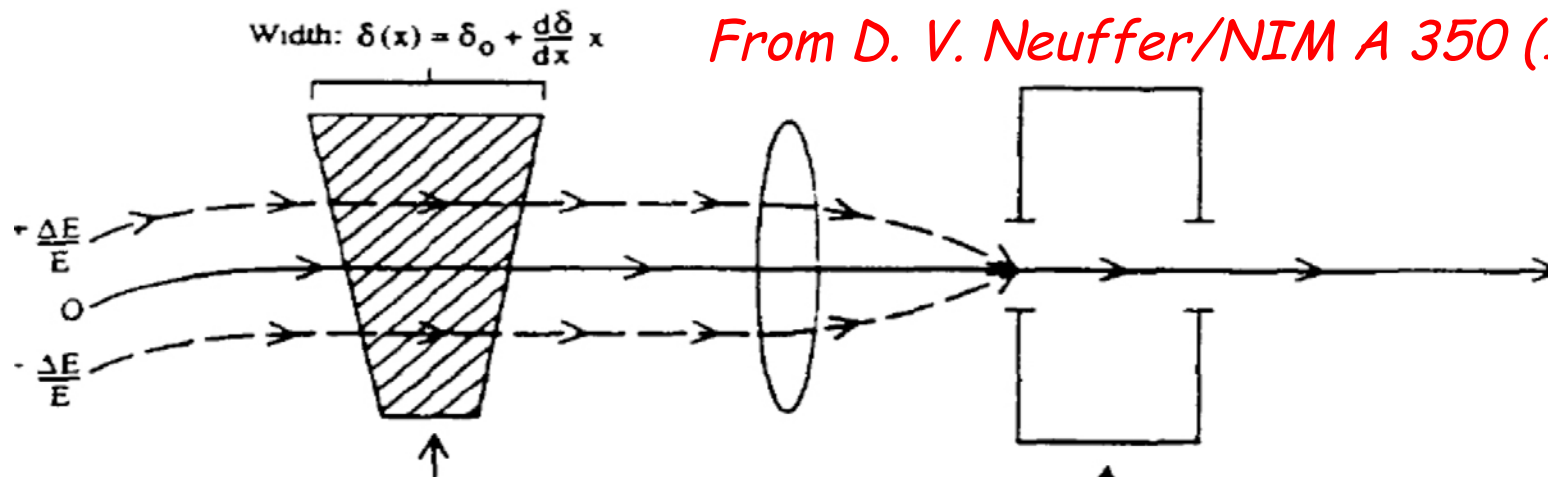
- *Longitudinal* balance is due to heat producing straggling balancing dE/dx cooling. A dE/dx radial wedge is needed in order to exchange longitudinal and transverse phase-spaces.
- Balancing heating and cooling for a Gaussian distribution limit:
Intrinsic Energy loss *Wedge shaped absorber* *Straggling*

$$\frac{d(\Delta E)^2}{dz} = -2(\Delta E)^2 \left[f_A \frac{d}{dE} \left(\frac{dE_o}{ds} \right) + f_A \frac{dE}{ds} \left(\frac{d\delta}{dx} \right) \frac{\eta}{E\delta} \right] + \frac{d(\Delta E)_{straggling}^2}{dz}$$

- $dE/dz = f_A dE/ds$, where f_A is the fraction of the transport length occupied by the absorber, which has an energy absorption coefficient dE/ds
- η is the chromatic dispersion at the absorber and δ and $d\delta/dx$ are the thickness and radial tilt of the absorber
- the straggling (H2) is given by $\frac{d(\Delta E)_{straggling}^2}{dz} = \frac{\pi(m_e c^2)^2 (\gamma^2 + 1)}{4 \ln(287) \alpha X_o}$

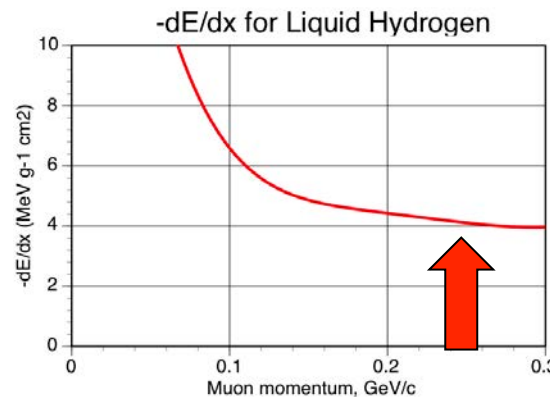
Longitudinal balance (cont.)

- The thickness of the absorber must vary with the transverse position, producing the appropriate energy dependence of energy loss, resulting in a decrease of the energy spread



- Energy cooling will also reduce somewhat the transverse cooling, according to the Robinson's law on sum of damping decrements.

$$2g_{\perp} + g_L \cong 2$$



dE/dx loss as a function of the muon momentum for hydrogen (very near to min for 250 MeV/c)

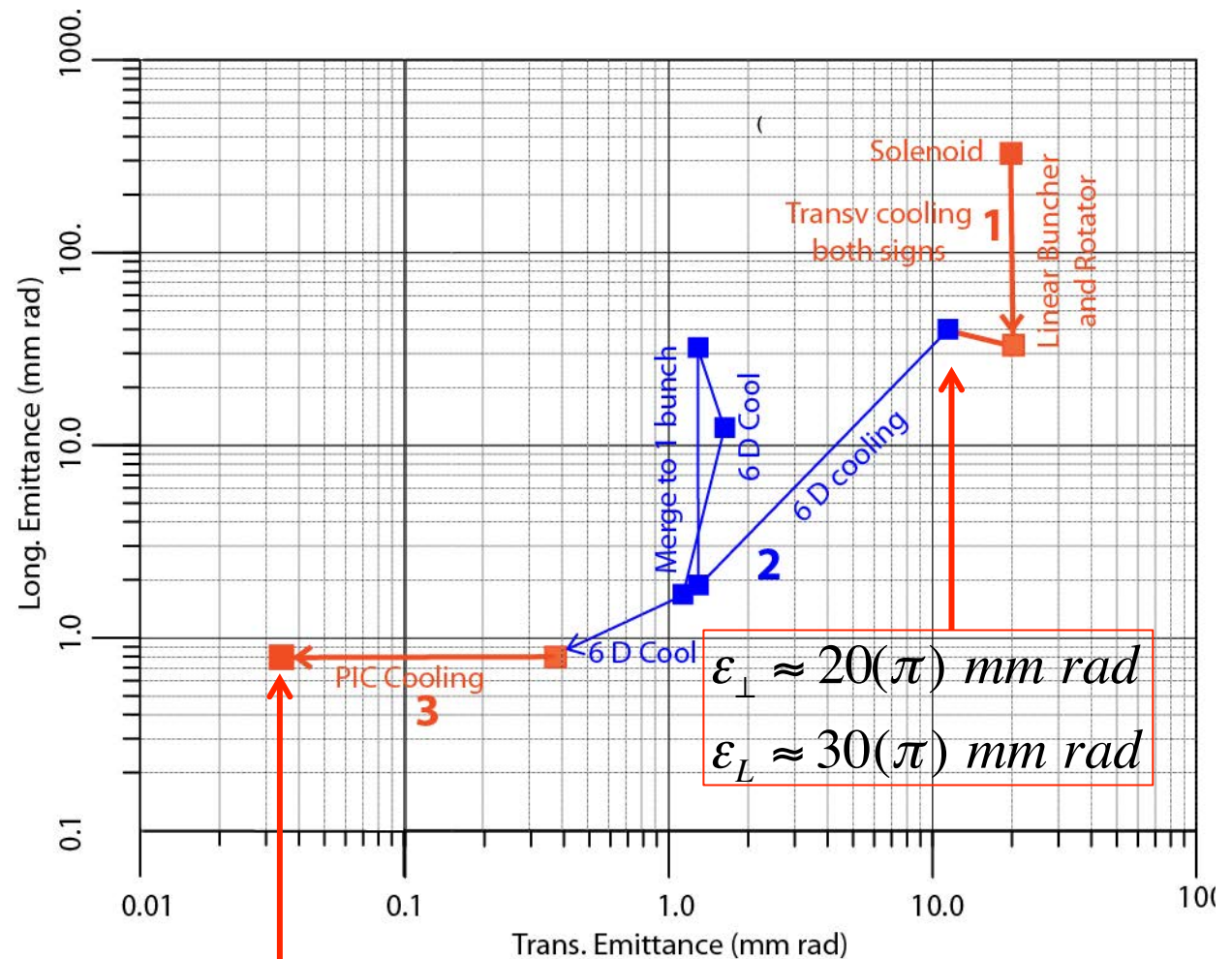
$\mu^+\mu^-$ colliders for Higgs factories ?

- Cooled muons may offer two alternative experiments:
 - ⇒ A Higgs ring in the narrow s-channel resonance at $\sqrt{s} = 126$ GeV, where most decay channels may be accurately measured.
 - ⇒ A higher energy collider ring eventually up to 0.6÷1.0 TeV. of luminosity comparable to one of a e^+e^- linear collider
- These rings can easily fit within the CERN site.
 - ⇒ For $\sqrt{s} = 126$ GeV the ring radius is ≈ 50 m (about 1/2 of the CERN PS or BNL AGS) and the *resolution $\approx 0.003\%$*
 - ⇒ For $\sqrt{s} = 1$ TeV the corresponding ring radius is ≈ 400 m (less than $\frac{1}{2}$ of the CERN SPS) and the *resolution $\approx 0.1\%$*
- Both alternatives must cool two bunches, each with 2×10^{12} μ^+ and μ^- , starting with 5 MWatt protons at ≥ 5 GeV and $10/50$ s $^{-1}$.
- After cooling, both μ^+ and μ^- must be accelerated.
- Packed recirculating LINAC structures to 62.5 and 500 GeV may be studied such as also to fit within the existing CERN site.

The full muon cooling process at $\sqrt{s} = 126$ GeV

- Three successive steps are required in order to bring the cooling process at very low energies, after capture and bunching + rotation.

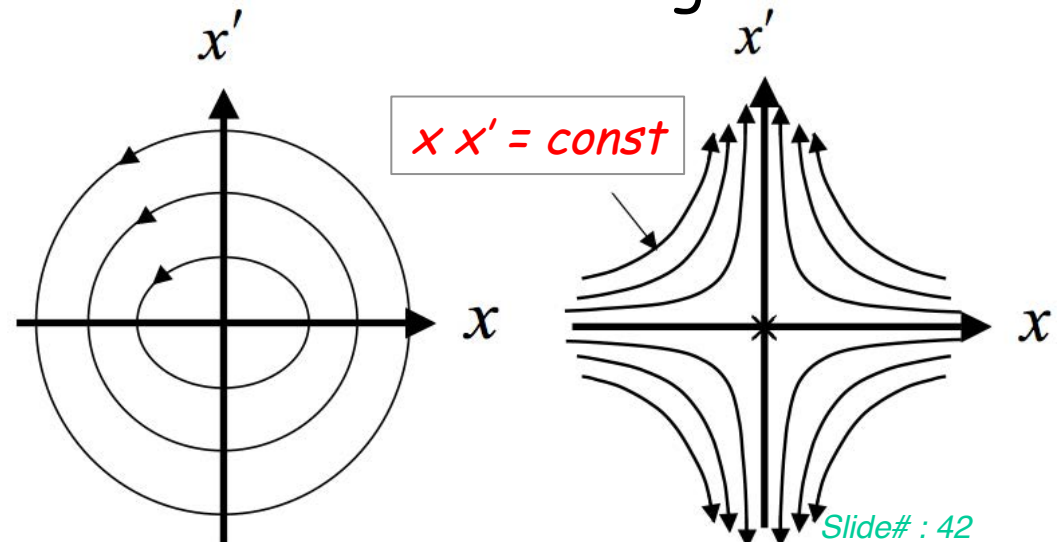
1. Linear transverse cooling of both signs and small Δp increase.
2. Ring cooling in 6D with B brings the μ^+ and μ^- to a reasonable size Merging and cooling to single bunches
3. Parametric Resonance Cooling (PIC), where the elliptical motion in $x-x'$ phase space has become hyperbolic.



PIC, the Parametric Resonance Cooling of muons

- Combining ionization cooling with parametric resonances is expected to lead to muon with much smaller transv. sizes.
- A linear magnetic transport channel has been designed by Ya.S. Derbenev et al where **a half integer resonance** is induced such that the normal elliptical motion of particles in x - x' phase space becomes **hyperbolic**, with particles moving to smaller x and larger x' at the channel focal points.
- Thin absorbers placed at the focal points of the channel then cool the angular divergence by the usual ionization cooling.

*LEFT ordinary oscillations
RIGHT hyperbolic motion
induced by perturbations
near an (one half integer)
resonance of the betatron
frequency.*



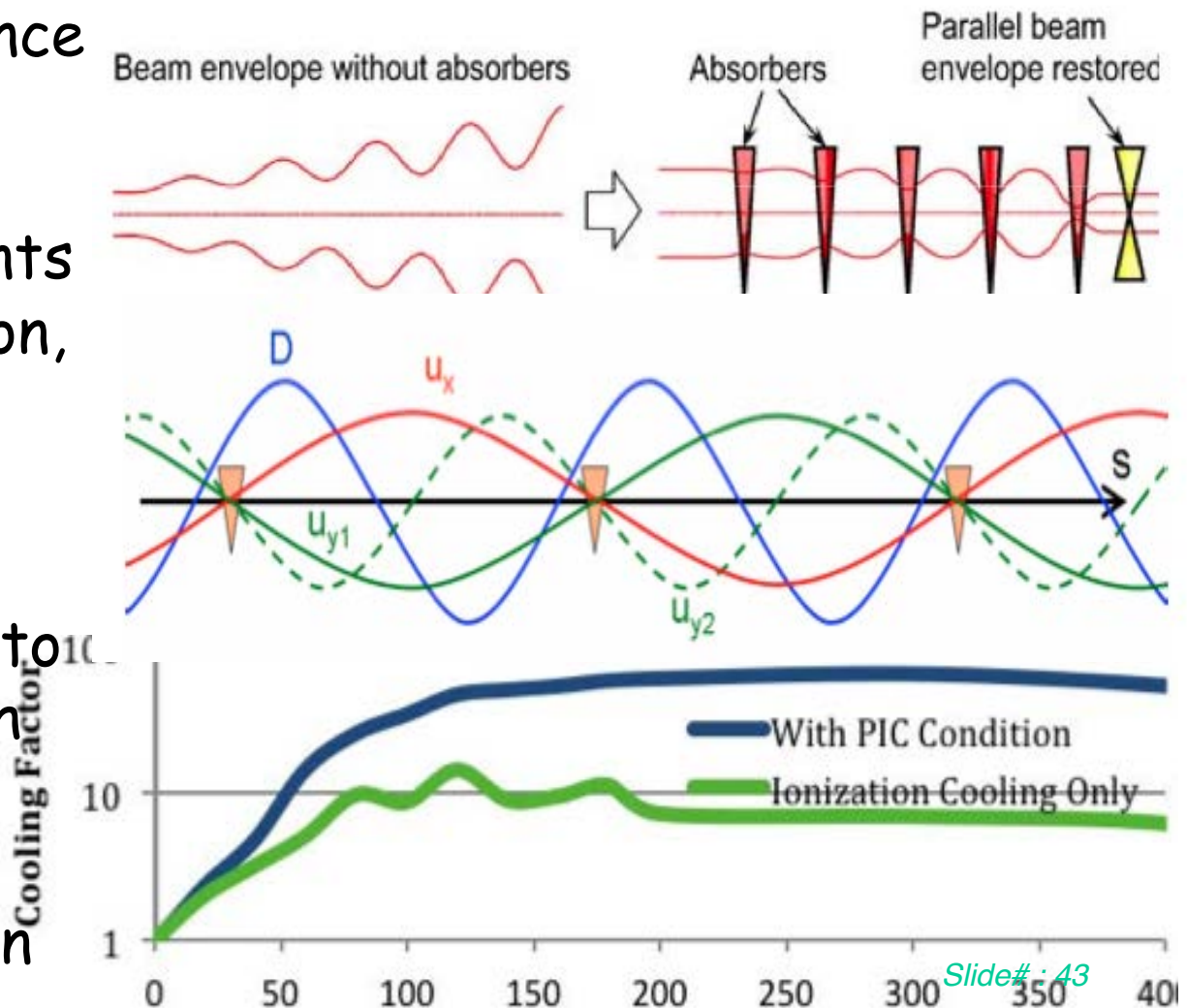
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V. S. Morozov et al, AIP 1507, 843 (2012);

Slide# : 42

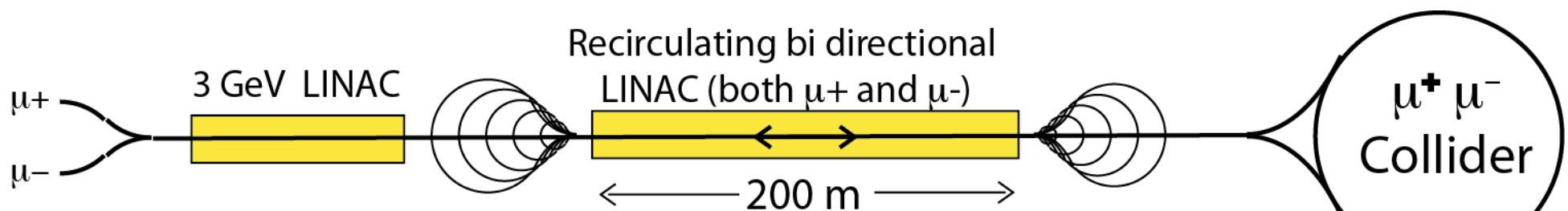
Details of PIC

- Without damping, the beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points stabilize the beam through the ionization cooling.
- The longitudinal emittance is maintained constant tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β .
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: more than 10x gain



Bunch acceleration to 62.5 GeV

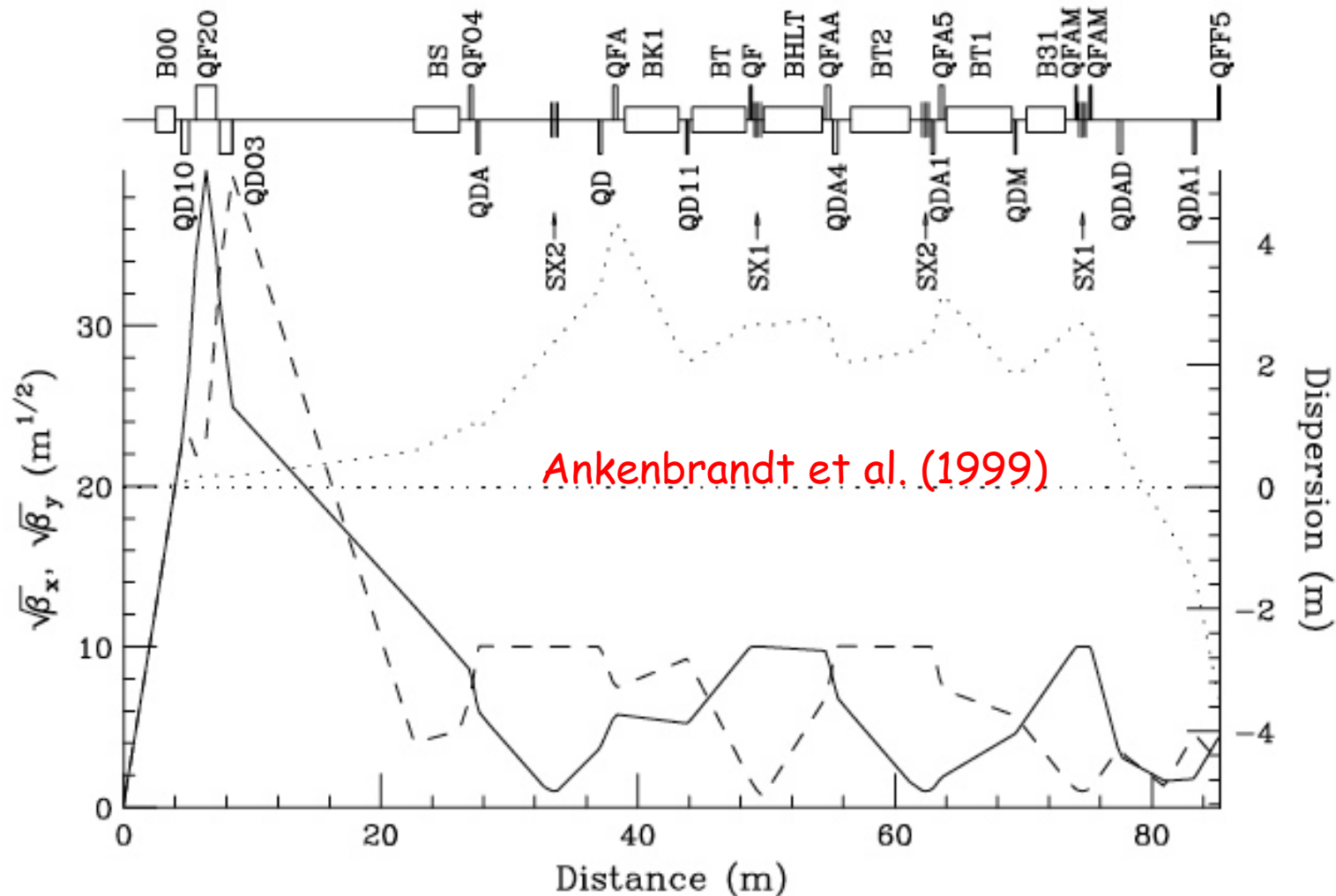
- In order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{H_0}/2$
- Adiabatic longitudinal Liouvillian acceleration to $p_f = 62.5 \text{ GeV}/c$.
- Both μ^+ and μ^- are accelerated sequentially in the same LINAC with opposite polarity RF buckets
- A recirculating LINAC and 25 MeV/m with f.i. 5 GeV energy/step + multiple bi-directional passages to 63 GeV ($\approx 200 \text{ m}$ long)
- A similar layout for the second phase with $\sqrt{s} \approx 1 \text{ TeV}$ will require a recirculating length of 1.6 km, still well within CERN site.



D. Neuffer, 2013

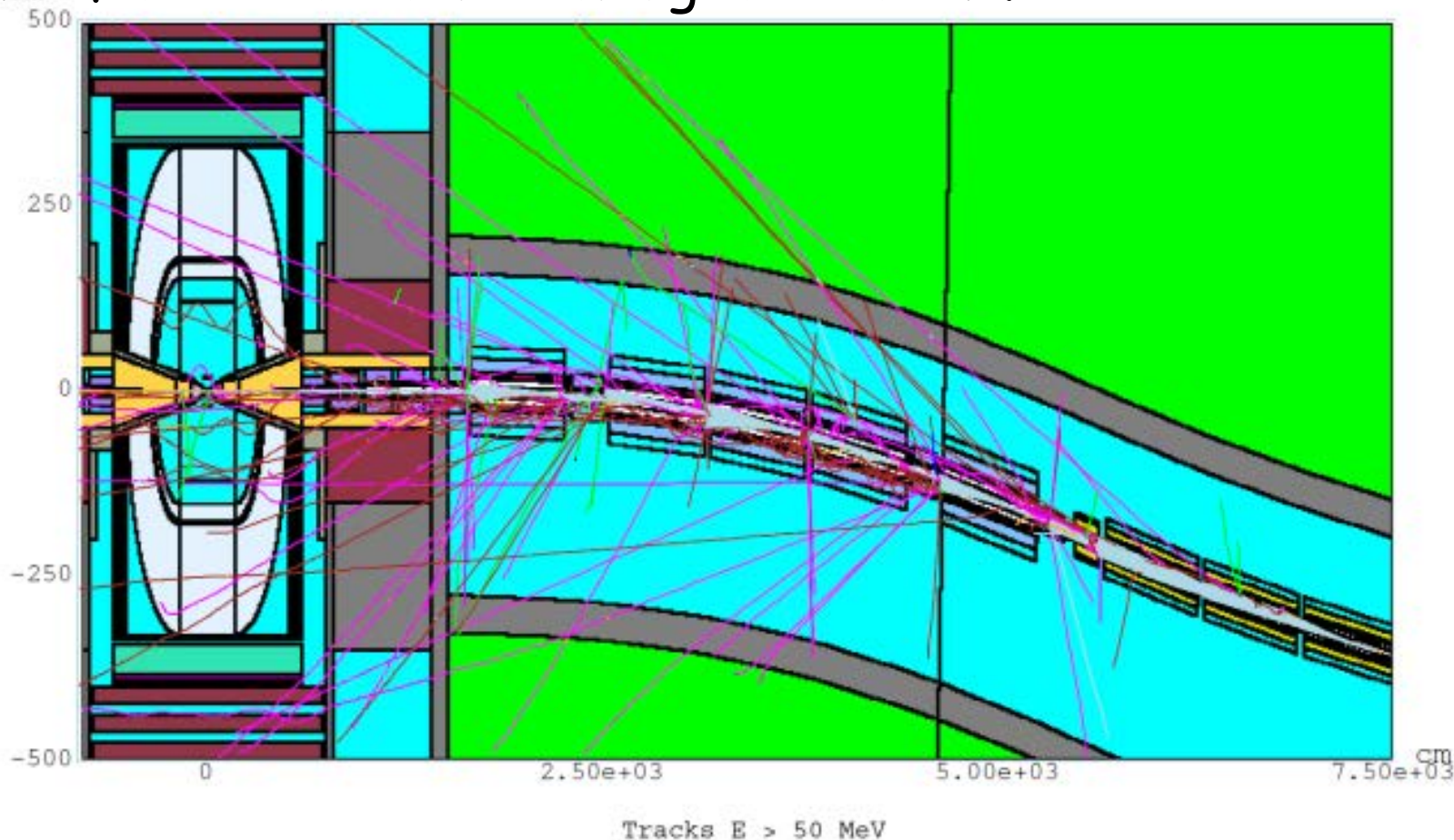
Muons collide in a storage ring of $R \approx 60$ m

- Lattice structure at the crossing point, including local chromaticity corrections with $\beta_x = \beta_y = \beta^* = 5$ cm.



Muon related backgrounds

- A major problem is caused by muon decays, namely electrons from μ decay inside the detector with $\approx 2 \times 10^3$ e/meter/ns, however collimated within an average angle of 10^{-3} rad.
- A superb collimation is required with the help of absorbers in front of the detector's straight sections.



Drozhdin, Mokhov et al.

Estimated performance of the H⁰-factory

- Two asymptotically cooled μ bunches of opposite signs collide in two low-beta interaction points with $\beta^* = 5$ cm and a free length of about 10 m, where the two detectors are located.
- The bunch transverse rms size is 0.05 mm and the μ - μ tune shift is 0.086.
- A luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is achieved with $1 \times 10^{12} \mu/\text{bunch}$.
- The SM Higgs rate is $\approx 44'000$ ev/year in each detector.
- An arrangement with at least two detector positions is recommended

Proton energy	5	GeV
Proton power	4	MW
Event rate	50	c/s
Protons/pulse	10^{14}	ppp
Muons, each sign	6×10^{12}	pp
Cooled fraction	0.16	
Final momentum	62.5	GeV/c
Final gamma	589.5	
Final muon lifetime	1.295	ms
Colliding, each sign	1×10^{12}	pp
Collider circumf.	360	m
Transverse emittances	0.04	mm rad
Bunch transv, rms	51.	μ
Long emittance	1	mm rad
No of turns	1110	
No effective turns	555	
Crossing/sec	27760	
Luminosity	5×10^{32}	$\text{cm}^{-2} \text{ s}^{-1}$
Cross section	1.0×10^{-35}	cm ²
Ev/y(10^7 s)	44'000	

The s-channel Higgs production colliders

● Advantages

- Large cross sections $\sigma(\mu^+\mu^- \rightarrow h) = 41 \text{ pb}$ in s-channel resonance and $\mu^+\mu^- \rightarrow ZH$ of 0.2 pb at 250 GeV .
- Small size footprint: it may fit within the CERN site
- No synchrotron radiation and beamstrahlung problems
- Precise measurements of line shape and total decay width Γ
- Exquisite measurements of all channels and tests of SM.
- ⇒ The cost of the facility, provided cooling will be successful, is less than 1/10 of one of the LHC.

● Challenges.

- ⇒ A low cost demonstration of muon cooling must be done first.
- Muon 2D and 3D cooling needs to be demonstrated
- Need ultimately very small c.o.m energy spread (0.003%)
- Backgrounds from constant muon decay
- Significant R&D required towards end-to-end design

Proving the muon cooling : the Initial Cooling Experiment

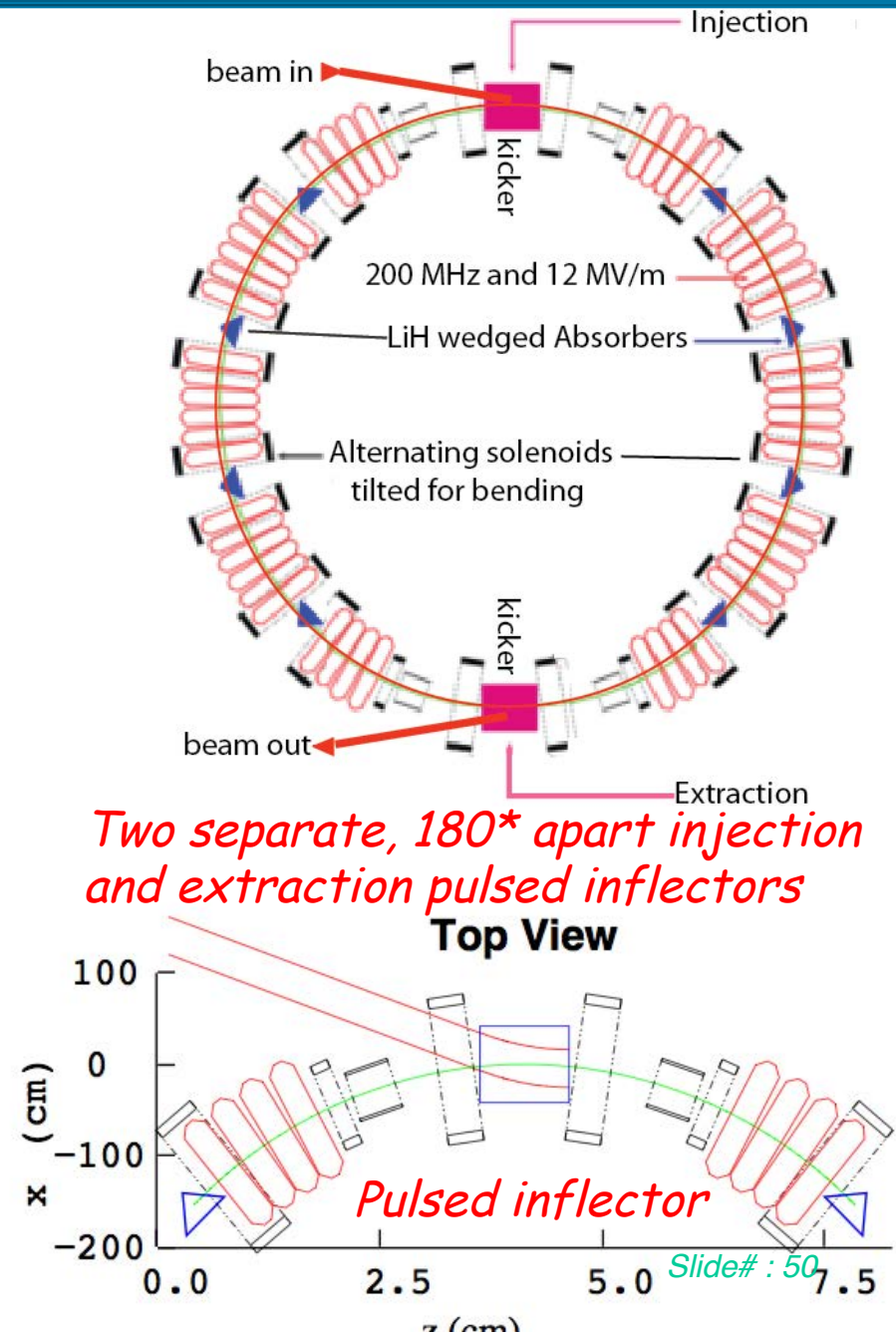
- Physics requirements and the studies already undertaken with muon cooling suggest that a next step, prior to but adequate for a specific physics programme *could be the practical realization of an appropriate cooling ring demonstrator.*
- Indicatively this corresponds to the realization of unconventional *tiny ring of 20 to 40 meters circumference* in order to achieve the theoretically expected longitudinal and transverse emittances of asymptotically cooled muons.
- The injection of muons from pion decays could be coming from some existing accelerator at a reasonable intensity.
- The goal is to prove experimentally the full 3D cooling.
- The other facilities, namely (1) the pion/muon production, (2) the final, high intensity cooling system (3) the subsequent muon acceleration and (4) the accumulation in a storage ring could be constructed later and only after the success of the initial cooling experiment has been confirmed at a low cost.

The RFOFO Ionization Cooling

- The design is based on solenoids tilted in order to ensure also bending. The LiH absorbers are wedge shaped to ensure longitudinal cooling.

Circumference	33	m
Total number of cells	12	
Cells with rf cavities	10	
Maximum axial field	2.77	Tesla
Coil tilt angle (degree)	3	degr
Average vertical field (T)	0.125	Tesla
Average momentum	220	MeV/c
Minimum transverse beta function	38	cm
Maximum dispersion function	8	cm
Wedge opening angle	100	degr
Wedge thickness on-axis	28	cm
Cavities rf frequency)	201.25	Mhz
Peak rf gradient	12	MV/m
Cavities rf phase from crossing	25	degr

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Comments

- A conventional muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involves instead the balance between a strong resonance growth and ionization cooling and it may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling may be a premise for an optimal luminosity, since the expected Higgs rate is proportional to the inverse of the transverse emittance,
- Up to one order of magnitude transverse decrement may be expected from PIC.

Conclusion

- Astro-particle Physics accelerators have reached with LHC a construction time of $\frac{1}{4}$ century and investment of ≈ 10 billion \$.
- A e^+e^- Linear Collider with ≈ 50 km in length (ILC) and $\sqrt{s} \approx 1$ TeV is a likely novel option, but with very long timescale and huge costs. *Short term approval and construction are rather unlikely.*
- In our view, cooling of muons in view of a $\mu^+\mu^-$ ring represents a very attractive alternative which should be carefully tested with the help of the tiny and cheap **Initial Cooling Experiment**.
- If successful, it should permit to proceed with muon cooling at a level suitable for high energy $\mu^+\mu^-$ colliders both for
 - ➡ single Higgs production in the s-state and $\sqrt{s} \approx 126$ GeV with a single conventional ring of ≈ 50 m radius ($\approx 1.2\%$ of LHC) and
 - ➡ $\sqrt{s} \approx 1$ TeV with a ring of ≈ 400 m radius ($\approx 10\%$ of LHC) and luminosity comparable to the one of the 50 km long e^+e^- ILC.
- *Provided muon cooling is demonstrated, both options can be constructed within the existing sites for a cost and timescale that are realistic and financially feasible.*

*Thank you
and congratulations
to you
Michel !*