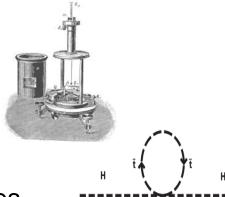
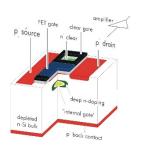
Towards the Next Standard Model – Experimental Challenges



Christian Kiesling
Max-Planck-Institut für Physik and
Ludwig-Maximilians-Universität, München

- Historical Reflections
- Theoretical Guide Lines
- Trends in Particle Detection Techniques
- Conclusions



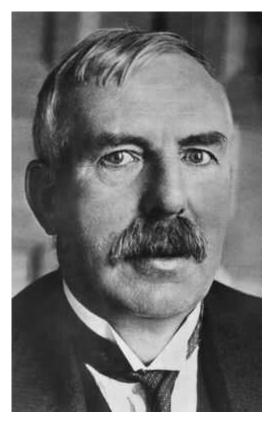




What can we learn from E. Rutherford ...

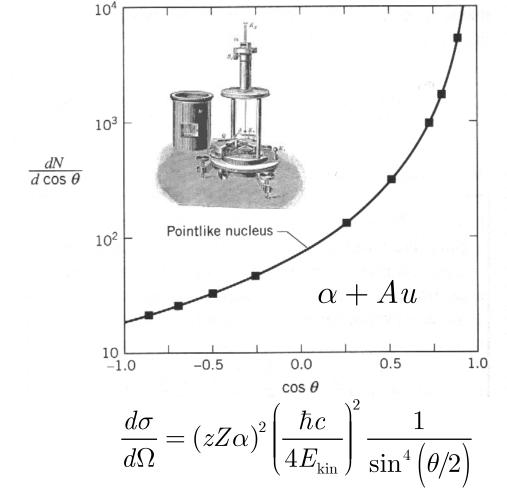


Structure of the atom



NP 1908 (for chemistry!)

structure revealed in scattering experiments



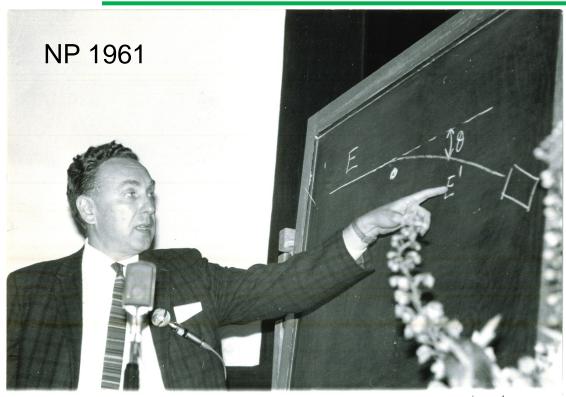


structure "explained" by theoretical models



Pioneer of Electron Scattering: Bob Hofstadter



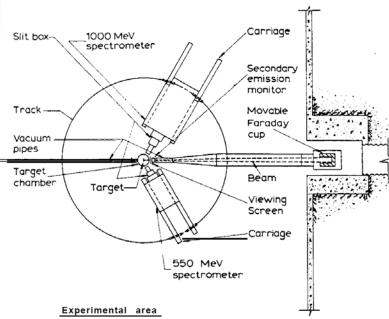


- electrons are elementary
- are sensitive only to charge
- can be easily produced and accelerated to high energy

$$hc = 200 \text{ [MeV fm]}$$

typical setup for an electron scattering experiment

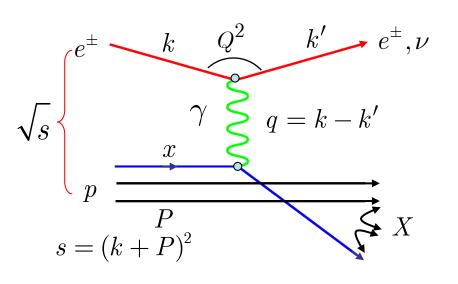
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Rath} \left(\frac{E'}{E}\right) \cos^2 \frac{\theta}{2} \left| F(q) \right|^2$$





Deep Inelastic Scattering: Quarks are Real





$$E \longrightarrow k' E'$$

$$Q^2 = 4E\mathbf{E'}\sin^2\left(\frac{\theta}{2}\right)$$

$$y = \frac{Q^2}{sy}$$
 $y =$

$$y = 1 - \frac{E'}{E} \cos^2 \left(\frac{\theta}{2}\right)$$

fraction of the proton momentum carried by the scattering partner (=,,parton") of the electron

$$\frac{d^2\sigma(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \Big(1 + (1-y)^2\Big) F_2(x)$$

valid, if the parton is an electrically charged, point-like spin = ½ particle

$$F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x) \quad \text{parton densities} \quad \text{(pdf)}$$

 e_i : charge of the parton



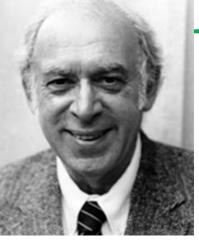
J. Friedman

R. Taylor

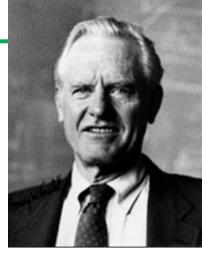
H. Kendall



NP 1990

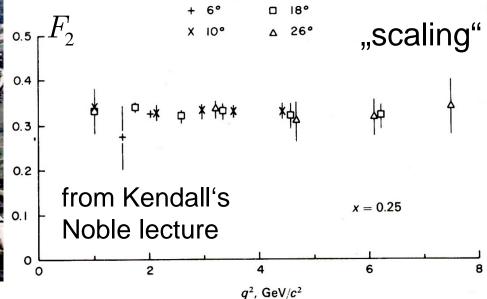






SLAC 2 mile linear accelerator 20 GeV electrons

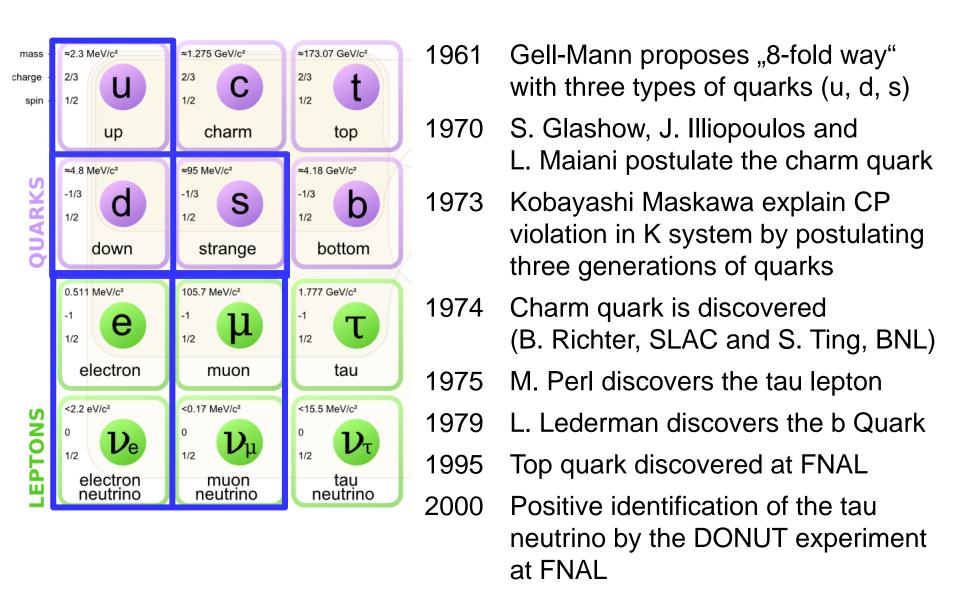
The proton is made out of structureless spin ½ quarks (1967-1972)





The Constituents of Matter

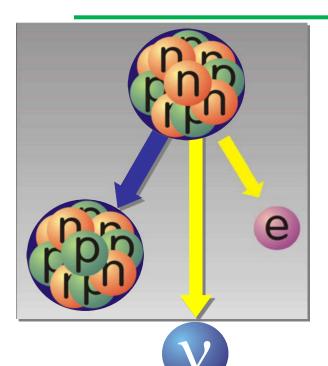


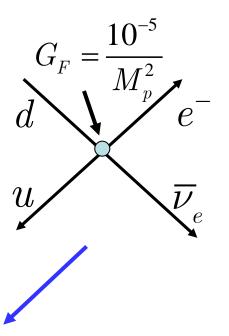




Weak Interactions: Nuclear Decay and more ...



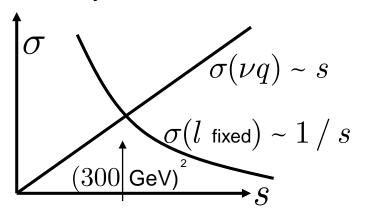


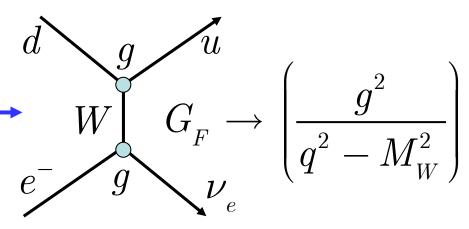


4-fermion theory

describes low-energy weak interactions satisfactorily, Including parity violation (V-A structure of currents, introduced in 1958 by Feynman and Gell-Mann)

But: unitarity is violated at V. H.E.

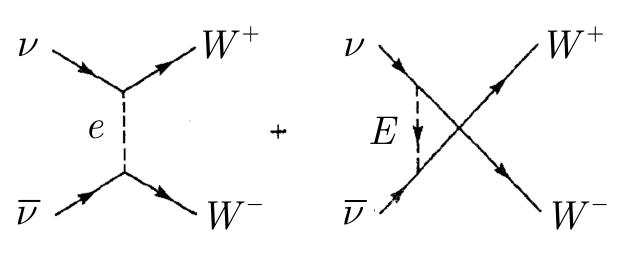






Vector Boson Production: Theory





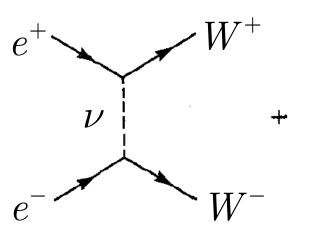
Unitarity (again) requires an additional exchange:

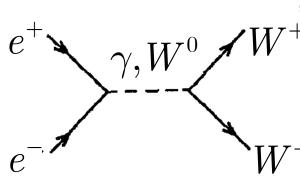
many different models, e.g.

New "heavy" lepton ${\cal E}$

or

Hypothetical processes ("real" for theorists)





"neutral current exchange":

Bludman-Schwinger, GWS etc.

or

"hybrid" models ($E\!+\!W^0$)



The Discovery: Neutral Currents



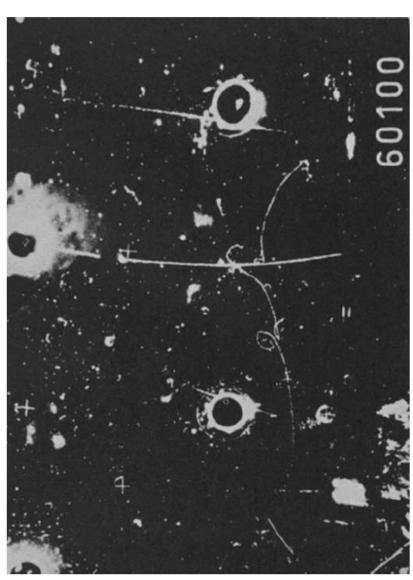
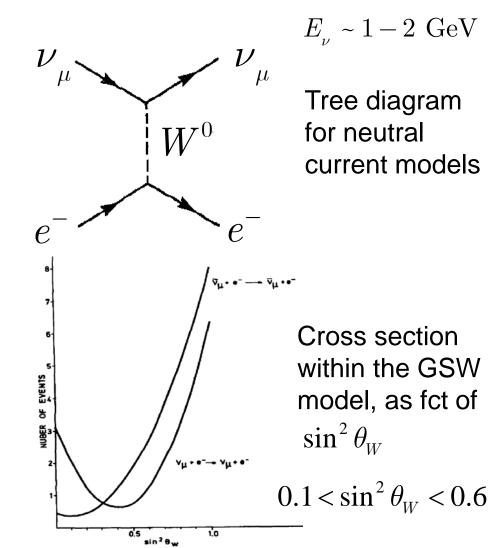


Fig. 1. Possible event of the type $\overline{\nu}_{\mu} + e^{-} \rightarrow \overline{\nu}_{\mu} + e^{-}$.

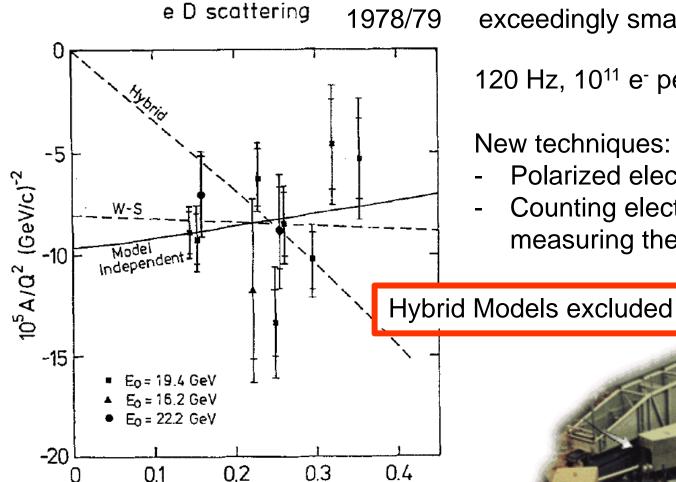
Gargamelle Heavy Liquid bubble chamber, 1973





The "SLAC Massacre": Parity Violation in epol d



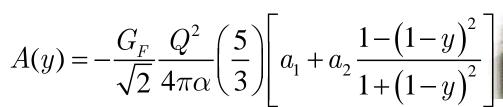


exceedingly small effect!

120 Hz, 10¹¹ e⁻ per pulse

New techniques:

- Polarized electron beam
- Counting electrons -> measuring the electron current

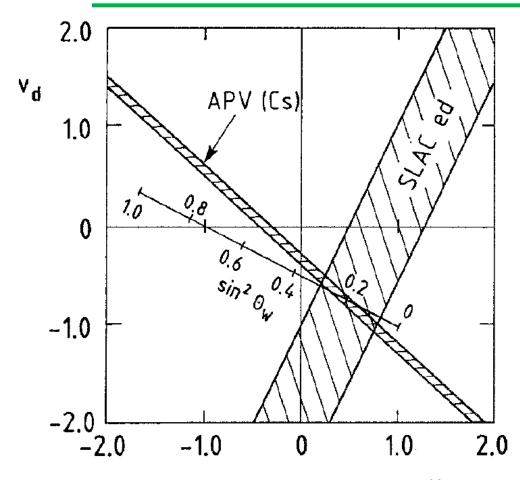


"Endstation A" spectrometers



The "SLAC Massacre", Part 2





$$A(y) = -\frac{G_F}{\sqrt{2}} \frac{Q^2}{4\pi\alpha} \left(\frac{5}{3}\right) \left[a_1 + a_2 \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right]$$

GSW model:

$$a_{1} = -a_{e} (2v_{u} - v_{d})$$
 $a_{2} = -v_{e} (2a_{u} - a_{d})$

Electron scattering

$$\begin{aligned} v_e &= -1 + 4\sin^2\theta_W \\ a_e &= -1 \end{aligned}$$

Atomic parity violation

$$v_A = (1 - 4\sin^2\theta_W)Z - N$$

$$a_e = Z - N$$

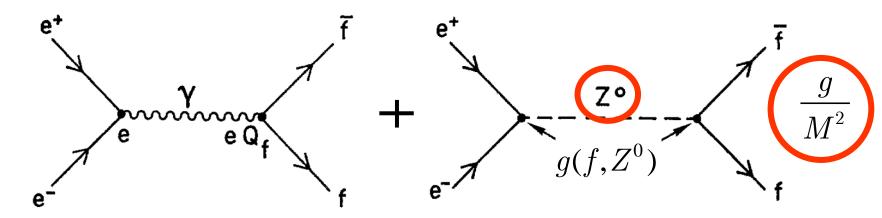
Only GSW Model survives

$$\sin^2 \theta_W = 0.218 \pm 0.012 \pm 0.008$$



Essentials of the Standard Model

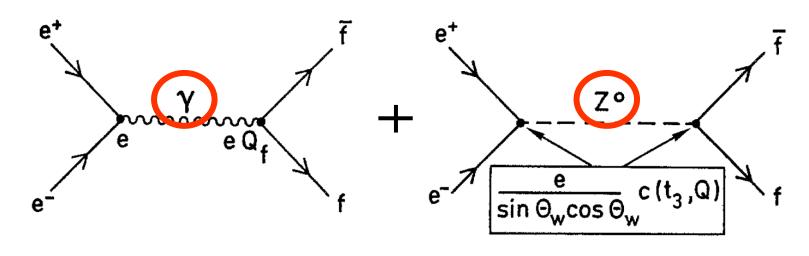




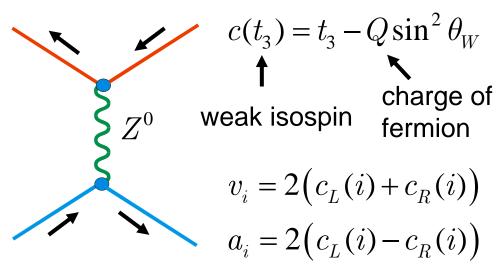


Essentials of the Standard Model





Electroweak unification: $e = g \sin \theta_W$



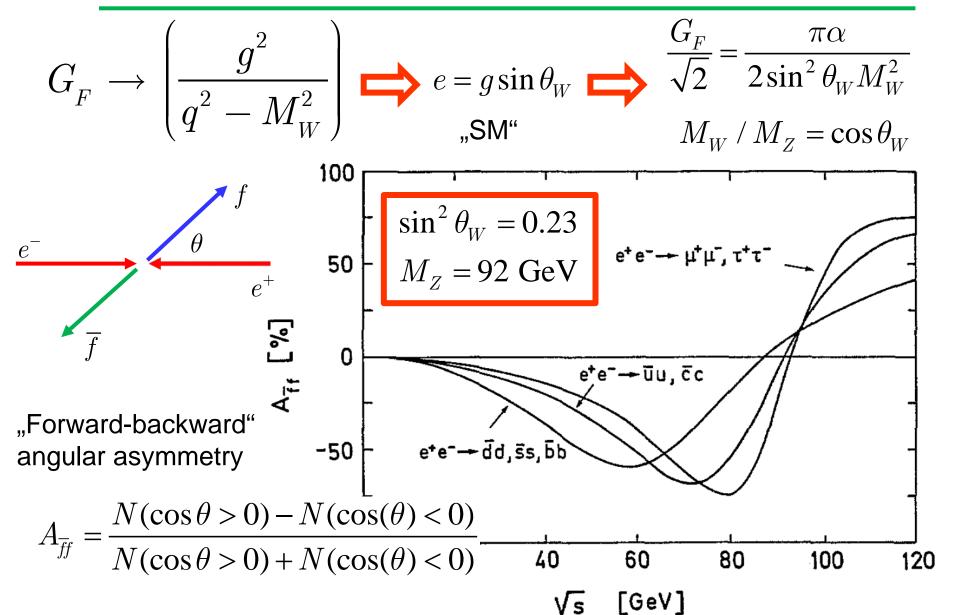
left-handed (L): $t_3 = \pm 1/2$ right-handed (R): $t_3 = 0$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \cdots \begin{pmatrix} v \\ e \end{pmatrix}_{L-1/2}^{+1/2}$$



Standard Model: Electroweak Interference

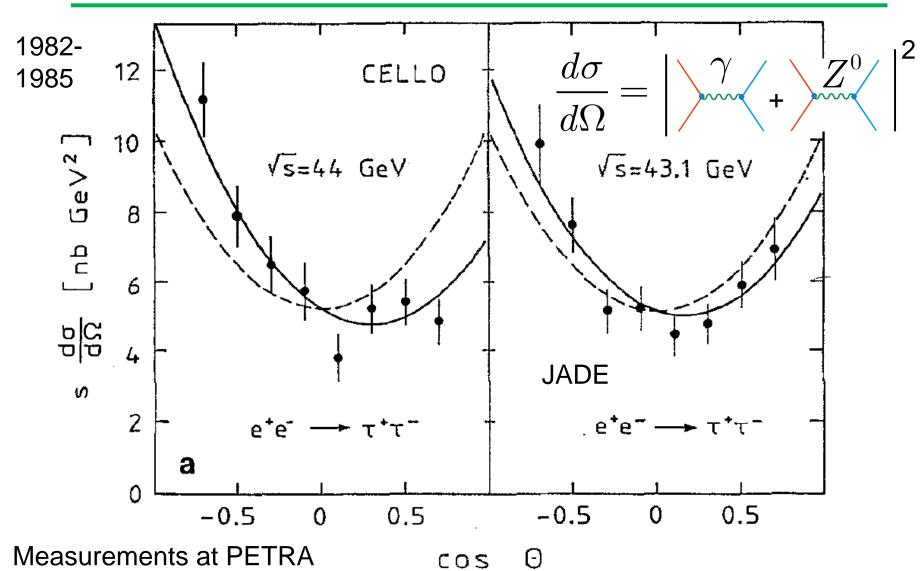






Electroweak Interference





(highest energy at that time)

clear evidence for the Z⁰

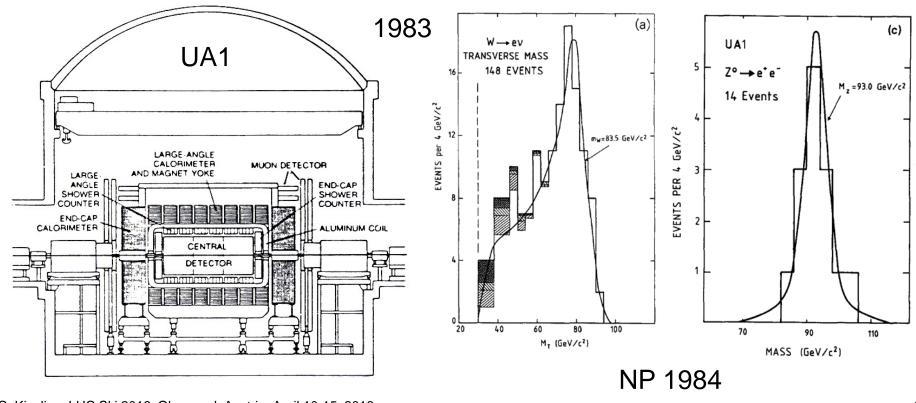


The Proof



Important machine developments:

- SPS changed to proton-antiproton storage ring -> SppS (C. Rubbia)
 (magnet cooling: had to limit the energy to 270 GeV per beam)
- Stochastic cooling of anti-protons in AA (S. v. d. Meer) otherwise no adequate luminosity could be made

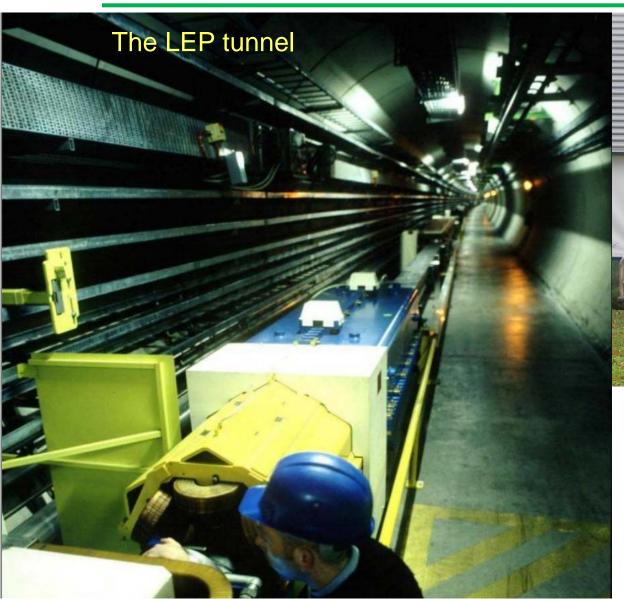






The Biggest Civil Engineering Project ever





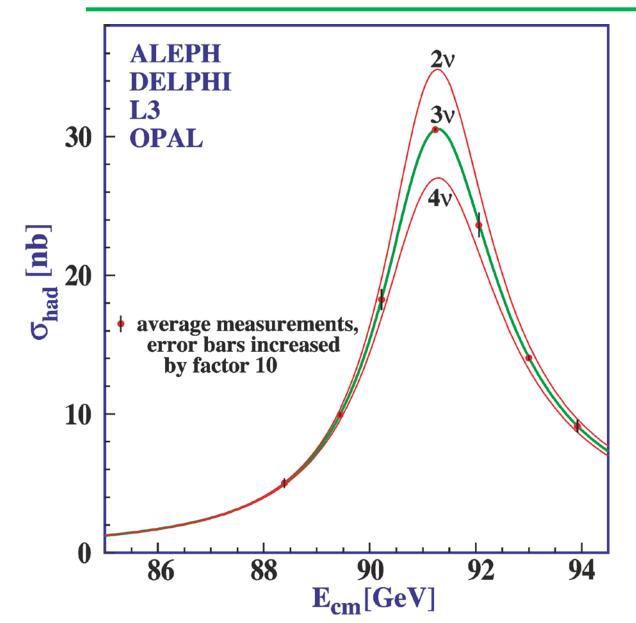


Essential: resonant cavities (with storage cavity on top) provide necessary acceleating field (compensate synchrotron losses)



LEP: Rich Physics Harvest ...





"Clean" experimental environment (in contrast to hadronic machines)

High precision results

among them:

Number of light neutrinos is "3"

Standard Model proven to be correct (at low E),

no significant deviations



LEP: "Finding" the Top and the Higgs (I)



$$M_W^2 = \frac{\pi\alpha}{G_F \sqrt{2} \sin^2 \theta_W (1 - \Delta r)}$$

 $\frac{\Delta r}{r} = \frac{\Delta r(\text{had}) + \Delta r(\text{top}) + \Delta r(\text{Higgs})}{\gamma}$ "known" from loop corrections L.E.measurements

$$\Delta r(\text{top}) = \frac{3G_F}{8\sqrt{2}\tan^2\theta_W} m_t^2$$

Small, but very sensitive to the top mass

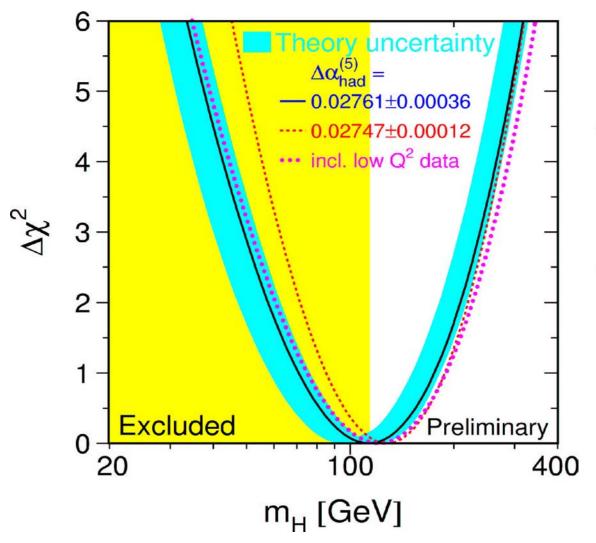
$$\Delta r(\text{Higgs}) = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2} \left(\ln \frac{m_H^2}{m_Z^2} - \frac{5}{6} \right)$$

Small, logarithmic sensitivity, but"measurable" when the top mass is known precisely

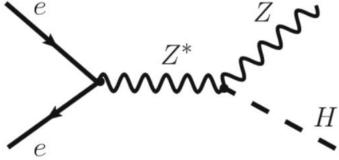


LEP: "Finding" the Top and the Higgs (II)





LEP fits suggested a very light Higgs



LEP 2 used to look for "Higgs-Strahlung",

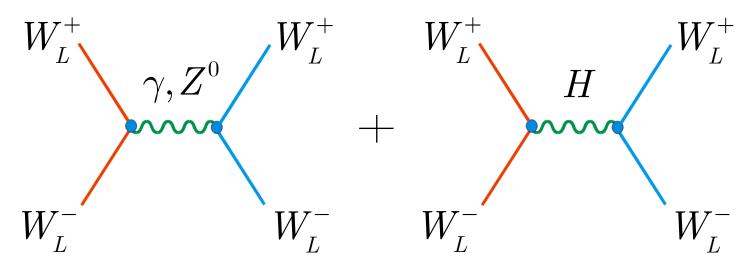
But no signal found ...

$$m_{\scriptscriptstyle H} > 113~{
m GeV}$$



Unitarity once more



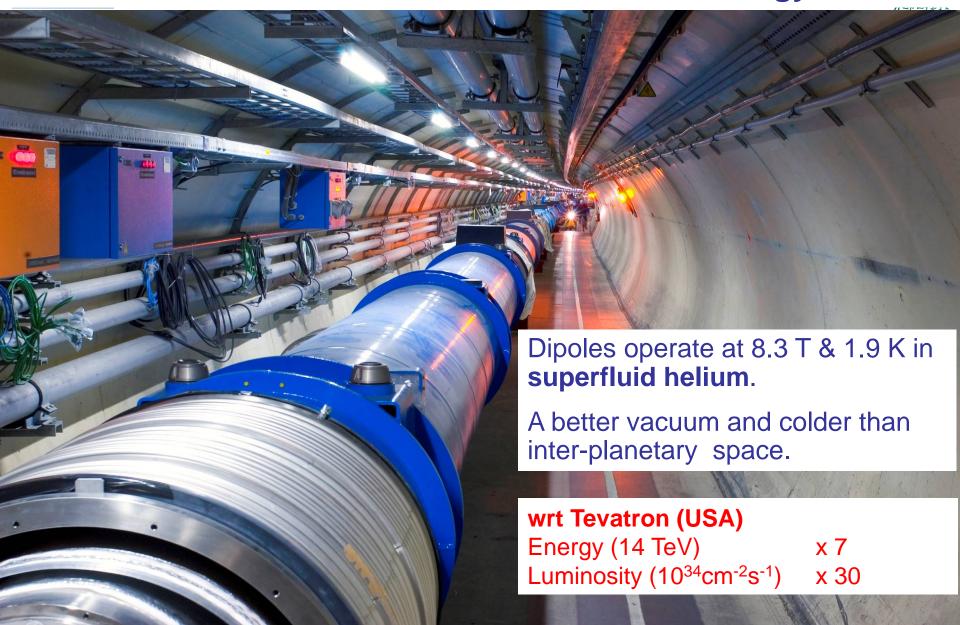


without an additional (scalar) *H* exchange, unitarity would be violated for c.m. energies > 1.5 TeV

A machine, which could produce cms energies (on the parton level) of order 1.5 TeV, with sufficient luminosity, would surely find the Higgs (or whatever it replaces to save unitarity)

Need a proton-proton machine to produce ~ 15 TeV total cms energy

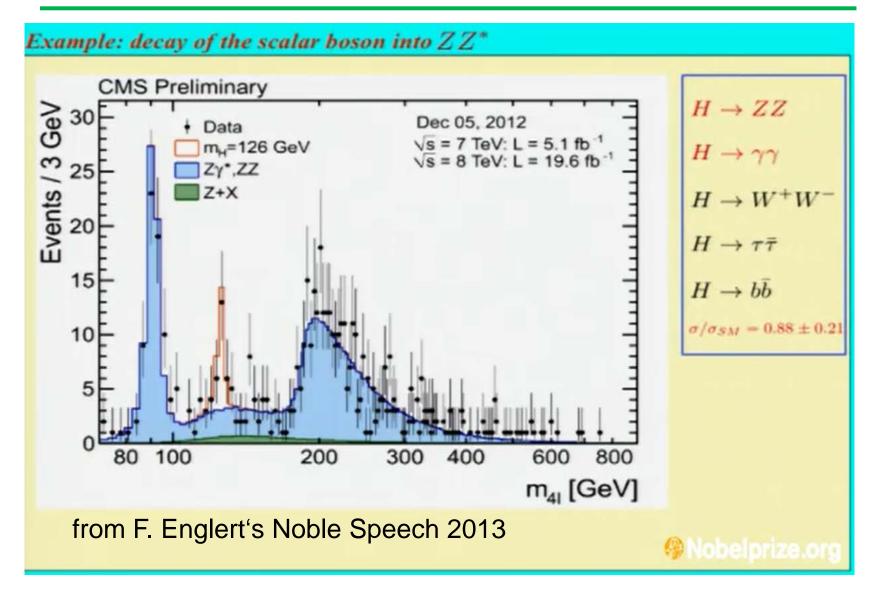
The LHC Machine is a marvel of technology.





Discovery of the Higgs Particle





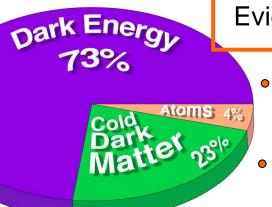
The Standard Model is complete!



Why do we Expect New Physics?



The Standard Model SU₃ x SU₂ x U₁ (SM) describes all data so far yet: cannot be the correct theory, SM only a "low energy" approximation



Evidence for Physics beyond the Standard Model:

- Dark Matter exists
 (only 4% of the Universe accounted for by SM)
- Neutrinos have mass (Dirac, Majorana?)
- Baryon Asymmetry in the Universe is much too large (by 10 orders of magnitude)

need
very high energy
(LHC) or
very high precision
(e.g. LHCb,
SuperKEKB

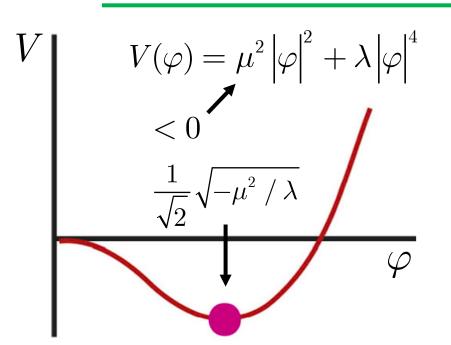
At least two of them have to do with CP Violation

∠P : One of the so-called Sakharov-conditions



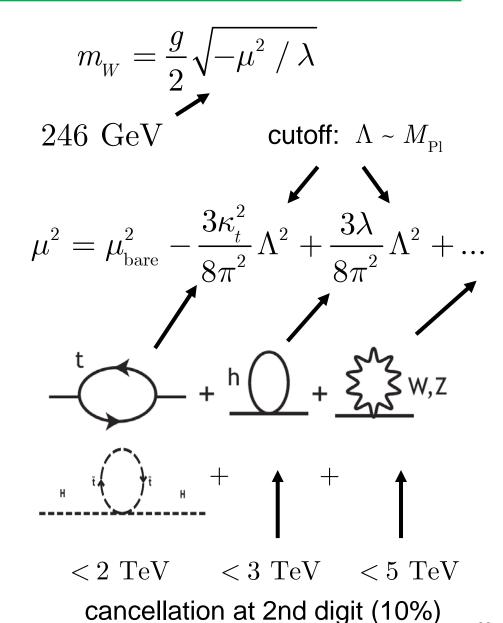
New States at High Energy?





no New States: cancellation requires precision of couplings up to 30 decimal places ("Gauge Hierarchy Problem")

Higgs vacuum stability requires counter terms to tame loop divergencies, e.g. SUSY





What do we learn from the past?



The way our science is conducted, is extremely successful

Interplay between theory and experiment essential

Basic theoretical concepts serve as excellent guides

The success is our problem:

We have verified the present theory, the SM, to an extremely high degree of accuracy. Still, we know the SM is only approximating "reality", cannot be the correct theory.

The SM has several serious short comings, solutions most likely found in new, higher energy regimes.

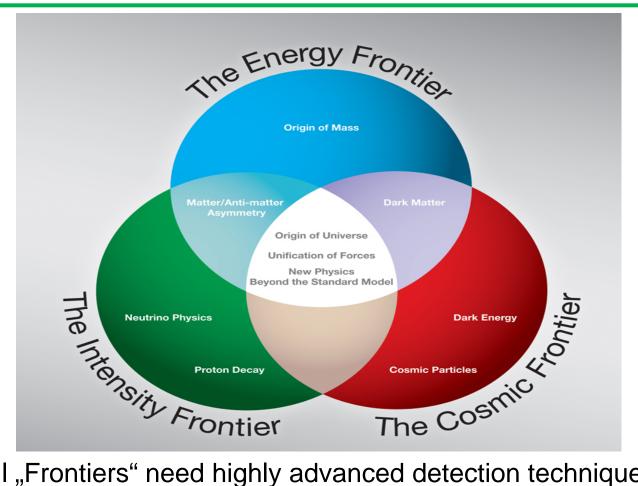
In contrast to the last decades we have NO clear theoretical guidance:

This coming decade is all "experiment"



How to Tackle ",the Next Round"?





all "Frontiers" need highly advanced detection techniques

PRECISION is the name of the game: Luminosity (Machine) and Resolution (Detector)



Task of a Particle Detector (in HEP)



Measure 4-momentum and vertex of each particle produced, with highest possible precision

Energy: "Calorimeter" (separated in EM & Had)

Momentum: "tracker"

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \otimes b \otimes \frac{c}{E}$$

$$\frac{\sigma}{p_{\perp}} = \frac{\sigma(x)}{0.3BL^2} \sqrt{\frac{720}{N+4}} p_{\perp}$$

Mass: "Particle Identification"

all technology-dependent



Calorimetry



Design principles:

Homogeneous (em only):

Noble liquids

charge { - Cerenkov glasses- Scintillating crystals

optimal energy resolution

Sampling (em & had):

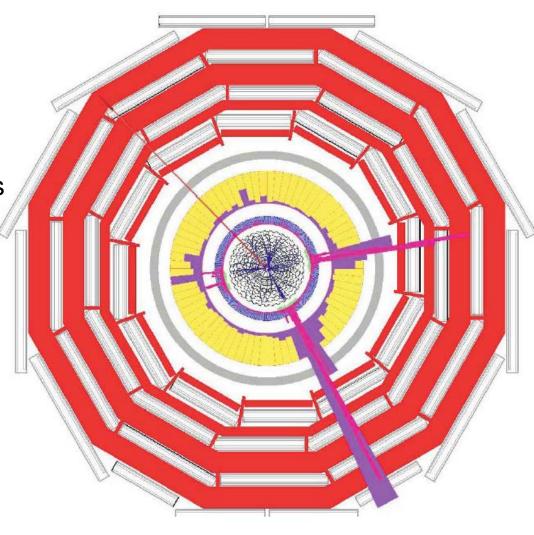
charge

Noble liquidsSi diodes

light

plastic scintillatorquartz fibers

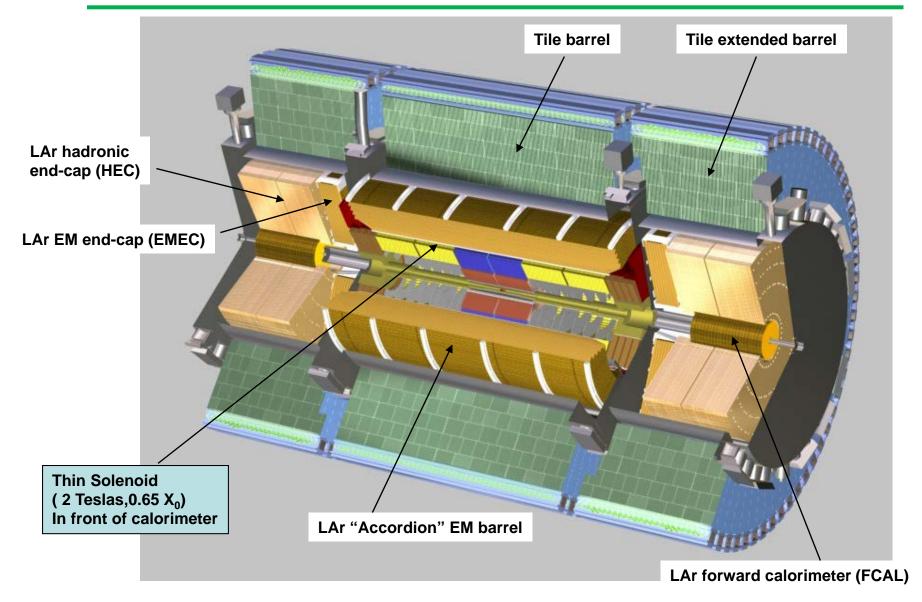
"economic" solution only way for hadronic (and all future) calorimeters





ATLAS Calorimeters

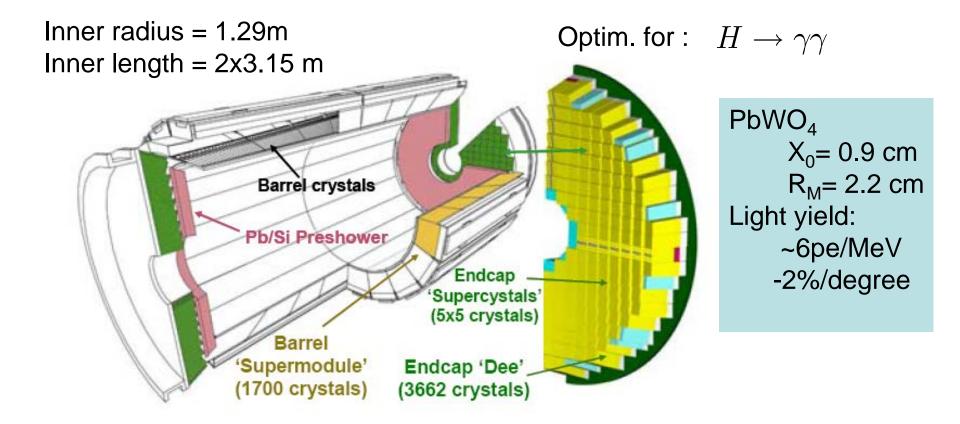






CMS EM Crystal Calorimeter



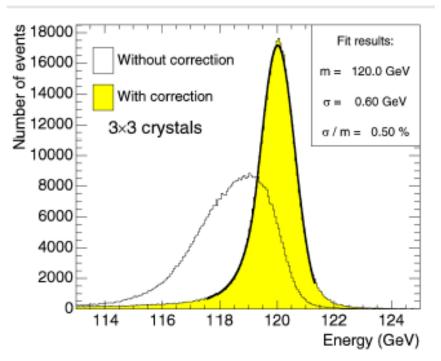


Barrel: 1700*36 = 61200 crystals readout by 2 APD (5x5 mm) End-caps 3662*4 =14648 crystals readout by vacuum photo-triodes Presampler(1.65<η<2.6) 1.9 X_0 lead-X plane of Si strips- 0.9 X_0 lead-Y strips 138 000 channels: pitch 1.9 mm, length 63mm,thickness 320 μm



CMS-Ecal: Energy resolution

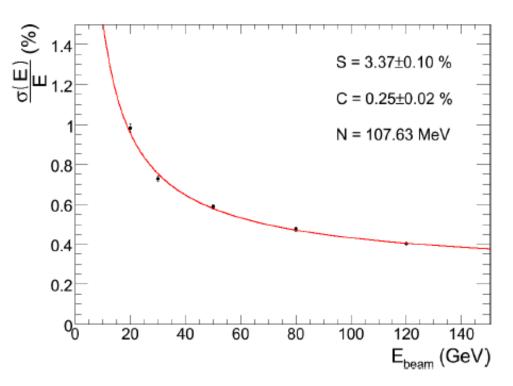




Correction for radial loss

The sampling term is 3 times smaller than ATLAS; other terms are similar

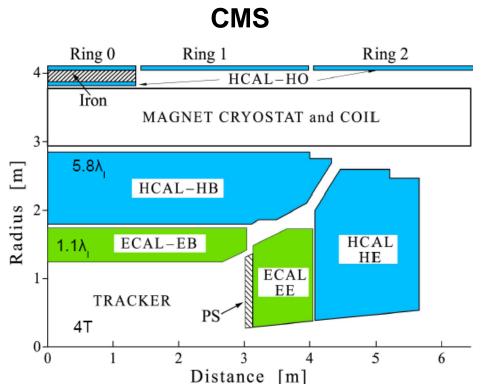
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + \left(0.25\%\right)^2$$
 stoch. noise const.



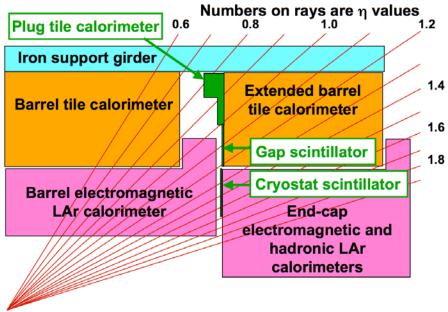


Hadronic Calorimeters





ATLAS



5 cm brass / 3.7 cm scint. Embedded fibres, HPD readout

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6 \text{ GeV}}{E} \oplus 3.3\%$$

14 mm iron / 3 mm scint. sci. fibres, read out by phototubes

Jet resolution with weighting:

$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$



Calorimetry for the ILC



 ILC physics requires jet energy resolution of 3-4 % @ 100 GeV (need to resolve W and Z from jet-jet masses)

- Classical calorimetry method:
 add E_{EM} and E_{HAD}
- Calorimeter resolution for hadrons intrinsically limited (losses by nuclear bindung energy)
- Energy resolution for jets worse than for single hadrons

 $e^+e^- @ \sqrt{s} \sim 500 \text{ GeV}$

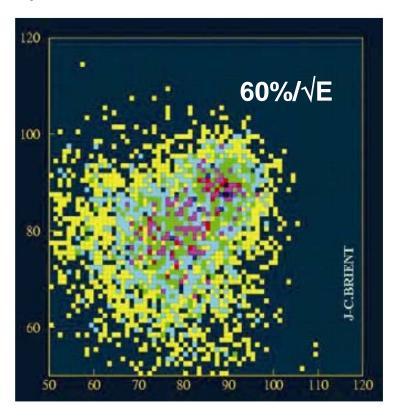
How to improve the jet resolution?

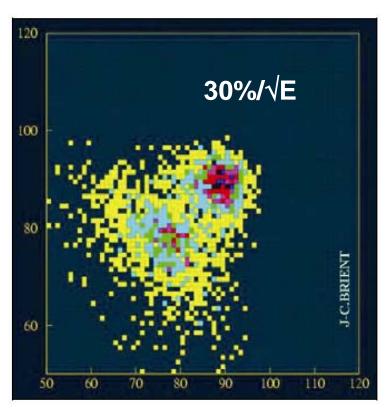


ILC: relevance of jet energy resolution



Dijet masses in vvWW and vvZZ events at \sqrt{s} = 500 GeV



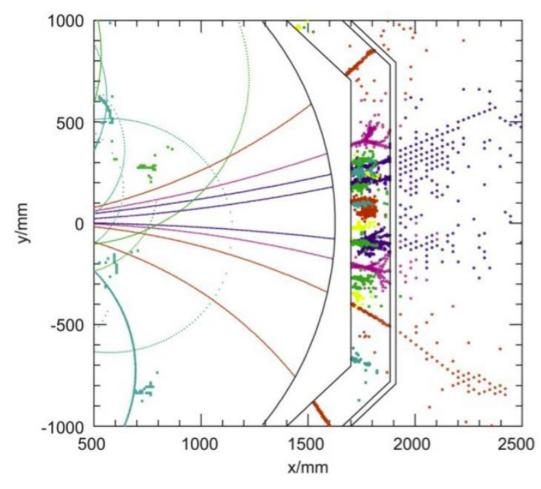


- From 60%/ \sqrt{E} to 30%/ \sqrt{E} jet energy resolution, the purity of final states (WW or ZZ) increases significantly
- Important bonus: separation of tau decay modes $(\pi, \rho, A1,...)$ possible



Particle Flow Calorimetry





"Imaging Calorimetry"

need high granularity (in 4D) and efficient software (PFA)

Energy share in a typical jet:

60 % charged hadrons 30 % photons (from π^0) 10 % neutral hadrons (mainly n, K_L)

- Particle Flow Concept
- Tracking for charged particles
- ECAL for photons (π^0)
- Neutral hadrons from HCAL (identify E_{dep} from other hads.)

Issues: double-counting wrong association



Particle Flow Detectors



Tracker: large radius, large magnetic field (-> TPC, e.g.)

ECAL and HCAL must be inside the coil: compact design

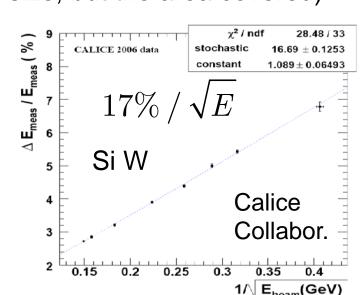
Sampling calorimeter mandatory (W for ECAL and HCAL, Fe for HCAL)

Very high granularity

- ECAL: cell size of order Moliere radius: 0.5 1 cm, 10⁸ cells
- HCAL: 1 3 cm, 10⁷-10⁸ cells (cost driver is not so much the cell size, but the area covered)

Sensing technologies:

- High res. silicon diodes (ECAL)
- Scintillator read out by SiPM (ECAL, HCAL)
- Micro Pattern Gas Detectors, such as RPCs, GEMs, MicroMegas





Particle Indentification



PID means to determine the particle's mass

$$p[GeV/c] = 0.3 \cdot \rho[m] \cdot B[T]$$

from the trackers

$$m = p \cdot \sqrt{\frac{1}{\beta^2} - 1}$$

particles with same p discrminated by B

measure the velocity

Methods to measure β :

 π/K

$$TOF = L/\beta \cdot c$$

 $TOF = L/\beta \cdot c$ (1m/1GeV: $\Delta TOF \sim 350 \text{ ps}$)

$$dE/dx \propto \frac{1}{\beta^2} \left(\frac{1}{2} \cdot \ln \frac{2m_e \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right)$$

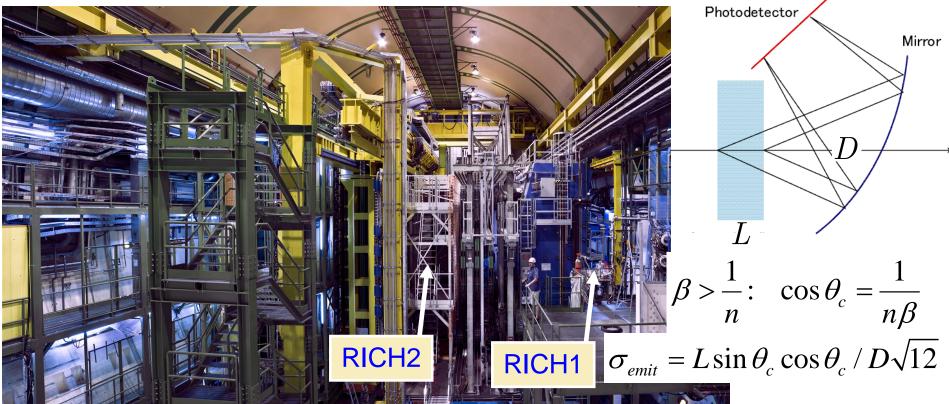
Cherenkov effect photons ...

PID crucial for Precision Frontier (LHCb, Belle II)



The LHCb RICH Counters





Hadron ID from 1-100GeV/c

2 radiators: C₄F₁₀, CF₄ (2-40, 15-100 GeV)

484 HPDs: 2.8m² with 2.5 x 2.5mm² pixels

Allows rare B-decay to be cleanly identified





New Developments in RICH Optics



Is there any way to increase L and hence improve N_{pe} without deteriorating $\sigma(emission)$?

Aerogel features

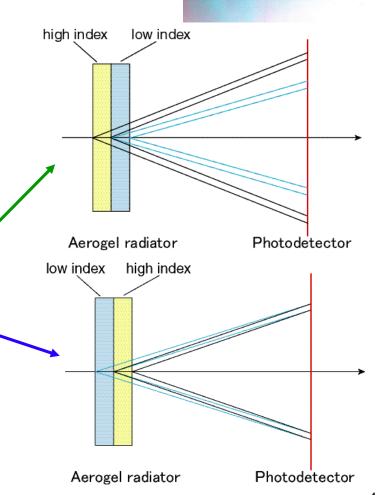
Index controllable at production time $\rightarrow \Theta_{C}$ can be chosen at will.

Idea: stack (more than) 2 aerogel with different refractive indices

n1>n2 → completely separated rings (velocity measured twice).

n1<n2 → focusing to compensate the increased thickness.

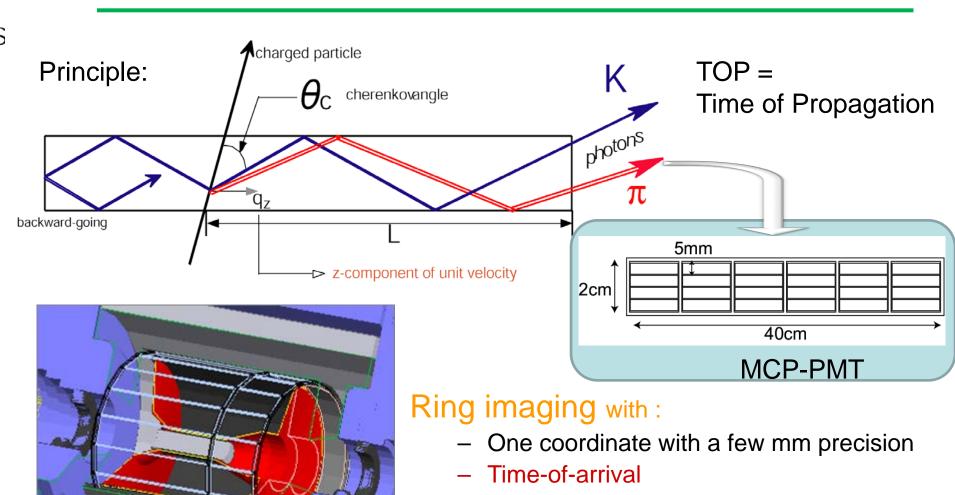
Dual Aerogel RICH installed in Belle II





Design for Barrel PID (TOP)



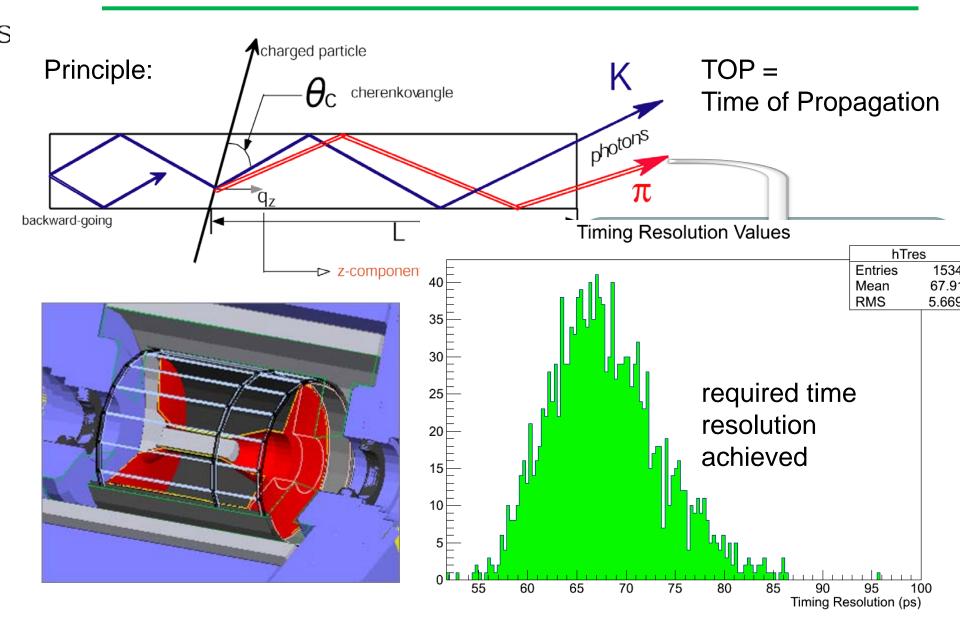


→ Excellent time resolution < ~70ps required for single photon in 1.5T B field



Design for Barrel PID (TOP)

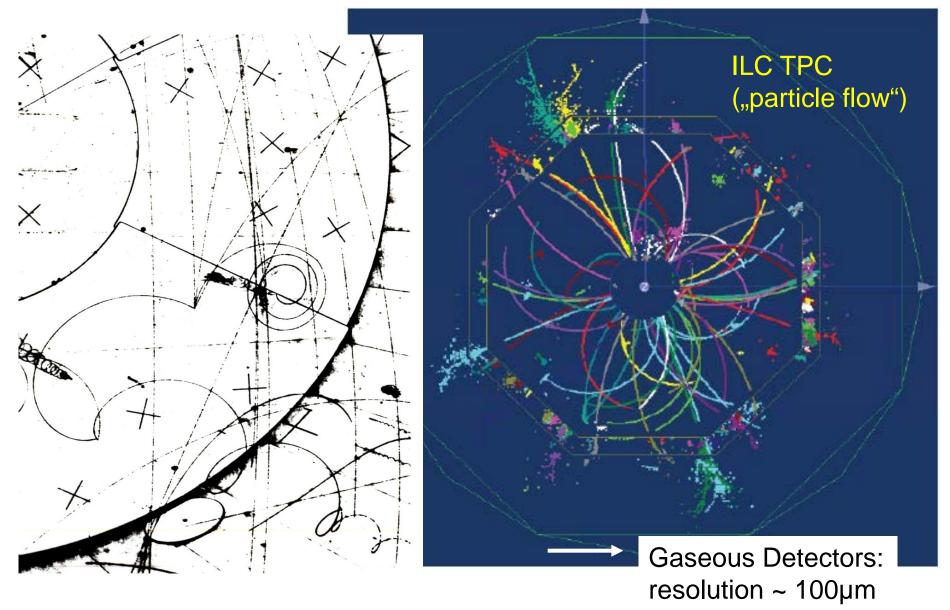






Tracking



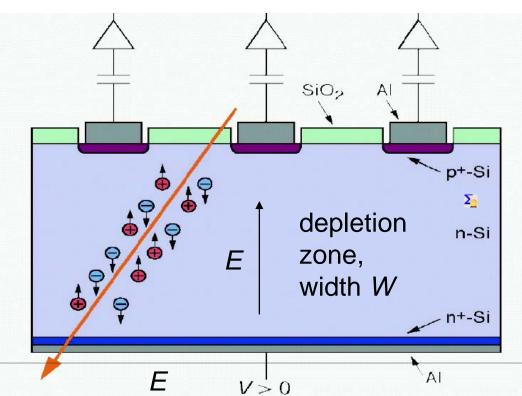


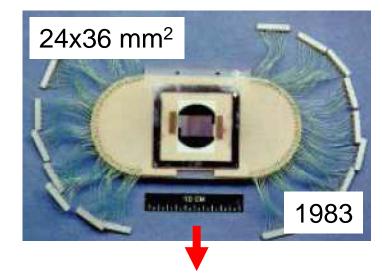


Solid State Detectors: Ultimate Resolution



Priniciple of Si-Strip Detectors:





essentially a reverse-biased p-n diode

$$W \sim \sqrt{\frac{V}{Ne}}$$

 $W \sim \sqrt{\frac{V}{Ne}}$ N: doping concentration



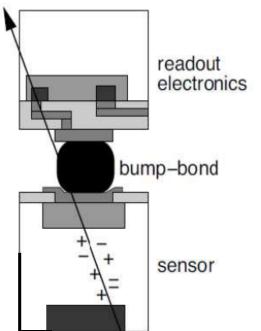


Si-Pixel-Sensors

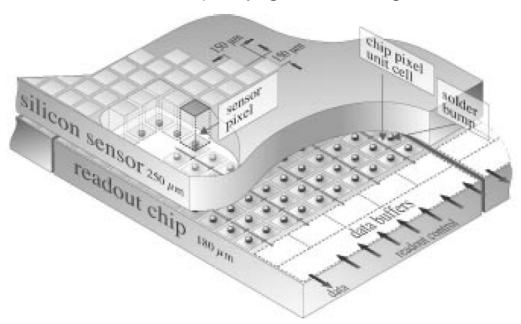


Particle flux scales like 1/r²

Solution: Pixel Sensors



Inner layers (< 20 cm radius) not usable with strip detectors at the LHC: occupany gets too high



Drawback: "thick" pixel detectors, material budget can be $O(X_0)$ for full (multilayer) detector

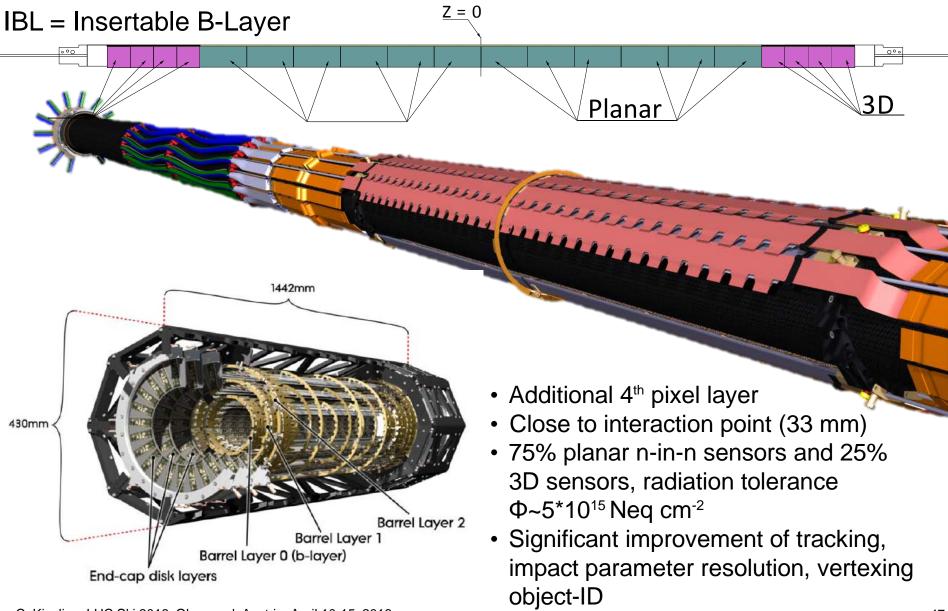
Si sensors need cooling -10° to -20°

track



ATLAS Upgrade: IBL

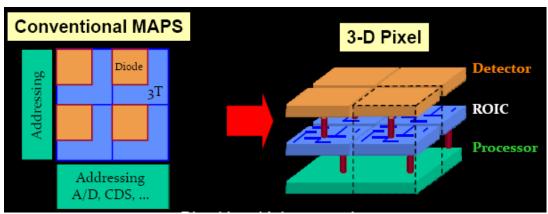


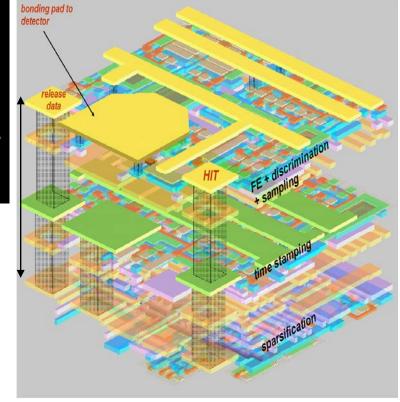




..and beyond: 3D Silicon Devices









22µm

Key Technologies:

- via formation and metallization
- vertical interconnections & bonding
- thinning

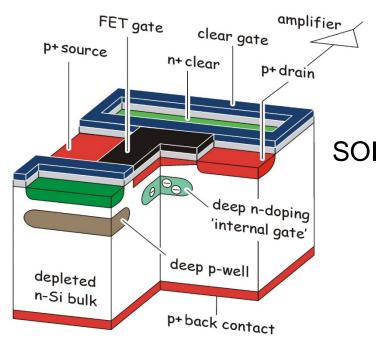
ongoing research



Reality today: Thin Pixel-Sensors



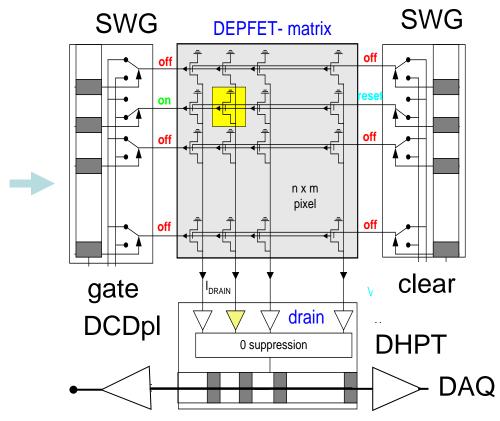
Low material budget extremely important at SuperKEKB (and ILC)



Monolithic pixel detector "DepFET" (MPI/HLL)

Depleted p-channel FET

"PXD" @ Belle II



ASICs: SWG (Switcher)

DCD (drain current digitizer)

DHP (data handling processor)

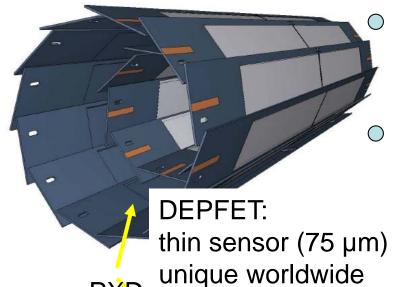


Silicon Tracking System @ Belle II



SuperKEKB: Nano beam option, 1 cm radius of beam pipe ____,"PXD"

SVD

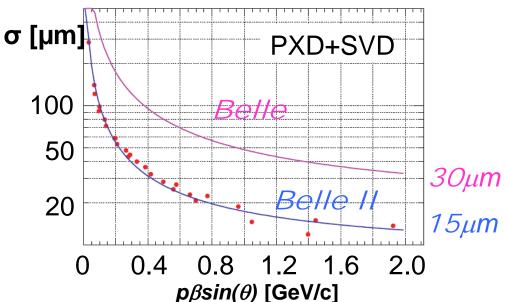


PXD

2 layer Si pixel detector (DEPFET technology) (R = 1.4, 2.2 cm) monolithic sensor thickness 75 μ m (!), pixel size ~50 x 50 μ m²

4 layer Si strip detector (DSSD) ← "SVD" (R = 3.8, 8.0, 11.5, 14.0 cm)

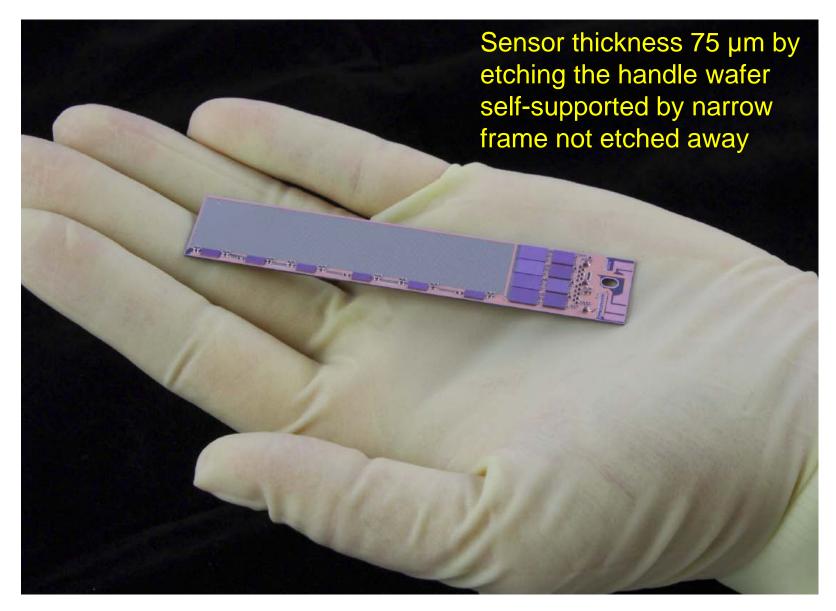
Significant improvement in z-vertex resolution





First PXD (Belle II) Module

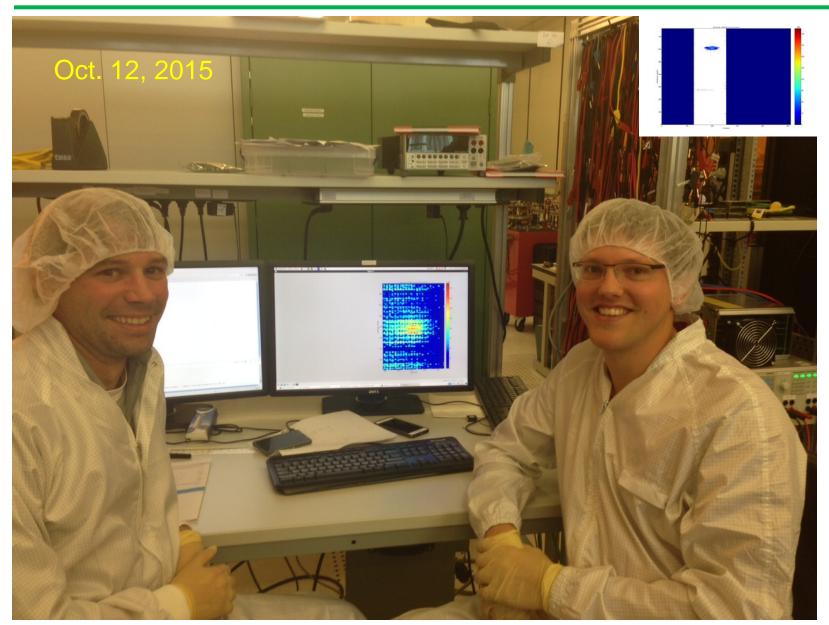






First PXD (Belle II) Module

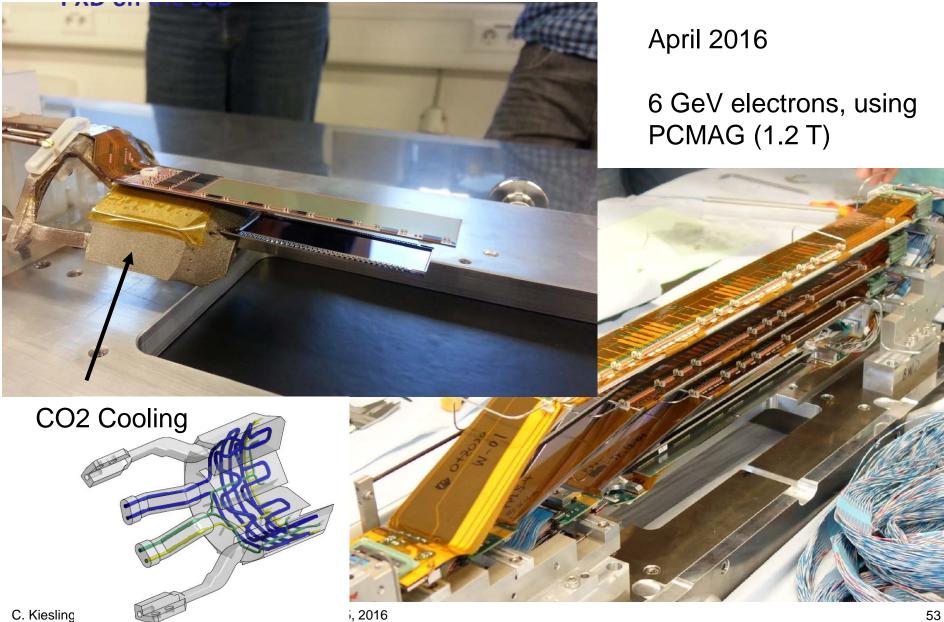






Final PXD Modules in DESY Test Beam

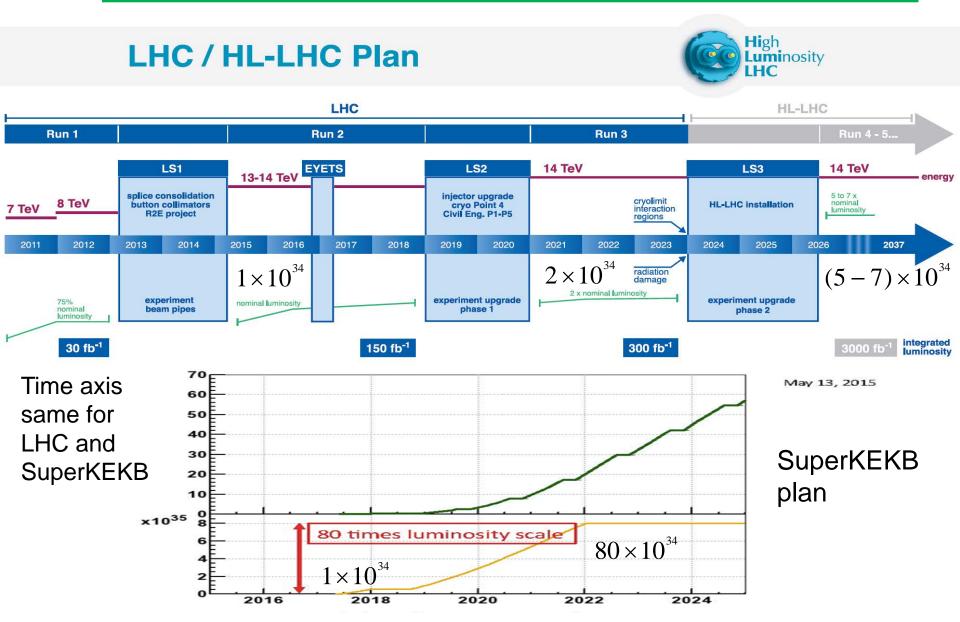






LHC and SuperKEKB Schedules







Conclusions



- The next 10 years are crucial for our science, they must be devoted to experimental search for new phenomena.
 We need a clear "hint" towards the Next Standard Model
- More precise detection techniques have proven to be essential in pushing further our knowledge about the laws of Nature
- Frontiers of precision measurement are being pushed further and further, new methods and analyses are emerging
- Overall, the tools seem in hand to master the coming challenges in experimental particle physics at present and future machines
- Last, not least, the advanced techniques in HEP have always provided useful applications in many fields of basic science, such as neutrino physics, dark matter searches, astrophysics, and other spin-offs.





Backup

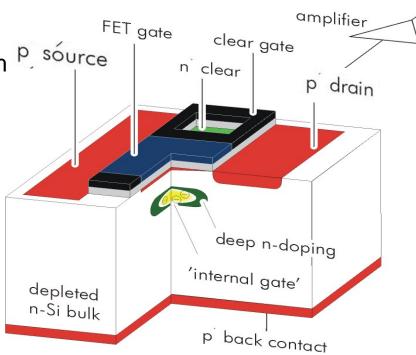


DEPFET Principle



- p-channel FET on a completely depleted bulk invented at MPI, produced at HLL
- A deep n-implant creates a potential minimum for electrons under the gate ("internal gate")
- Signal electrons accumulate in the internal gate and modulate the transistor current (g_q ~ 400 pA/e⁻)
- Accumulated charge can be removed by a clear contact ("reset")

Depleted p-channel FET



Fully depleted:

large signal, fast signal collection

Low capacitance, internal amplification low noise

Transistor on only during readout:

low power



Trends in Track-Triggers



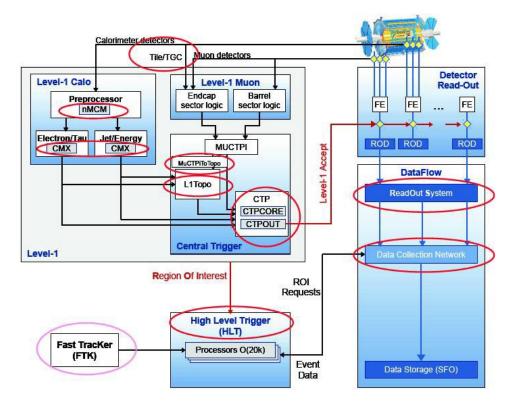
Any interest in (hardware) triggers in the future at the first level (L1) ??

- LHCb will only do HLT (SW)
- ILD will run without trigger (only HLT)

Still: high interaction rates need early data reduction

Upgrade plans for ATLAS and CMS at HL-LHC include also the tracker information (Si) at L1:

LHC: ATLAS & CMS use muons and calo so far at L1



Concepts: Pattern recognition + track fit (iterative algorithm in priniciple)

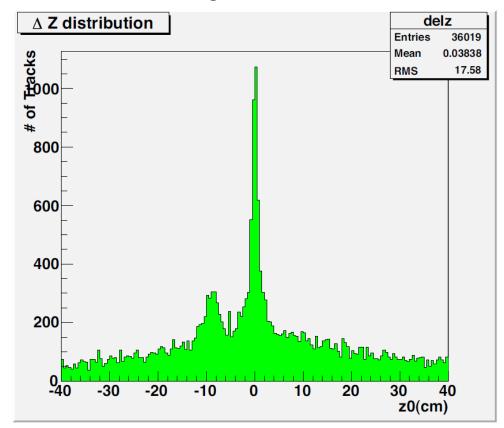
Issues: L1 latency, background



Track Triggers @ Belle II



The Background Problem:



vertex distribution along beam axis (from Belle experiment)

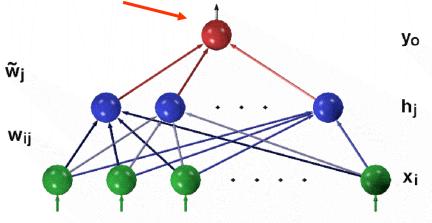
- Majority of events are coming from outside the interaction region
- These events will increase at Belle II due to the much larger beam background (Touschek effect)
- Need to open trigger for NP,
 + need to reduce trigger rate
 (reduce dead time and data rate to DAQ systems)
- Build a level 1 "z-vertex" trigger using the Belle II CDC:
 - → need resolution O(2cm)



Neural Approach to (z-)Vertex Trigger



output: z-impact parameter of track



input: subset of CDC SL wires (i), arranged in topological order, digital drift times x_i as input

Data (pre)processing:

- sectorize phase space in (θ, ϕ, p_T)
- select network by coarse 3D trigger
 Determine z-impact for track in given sector, using associated SL wire set

