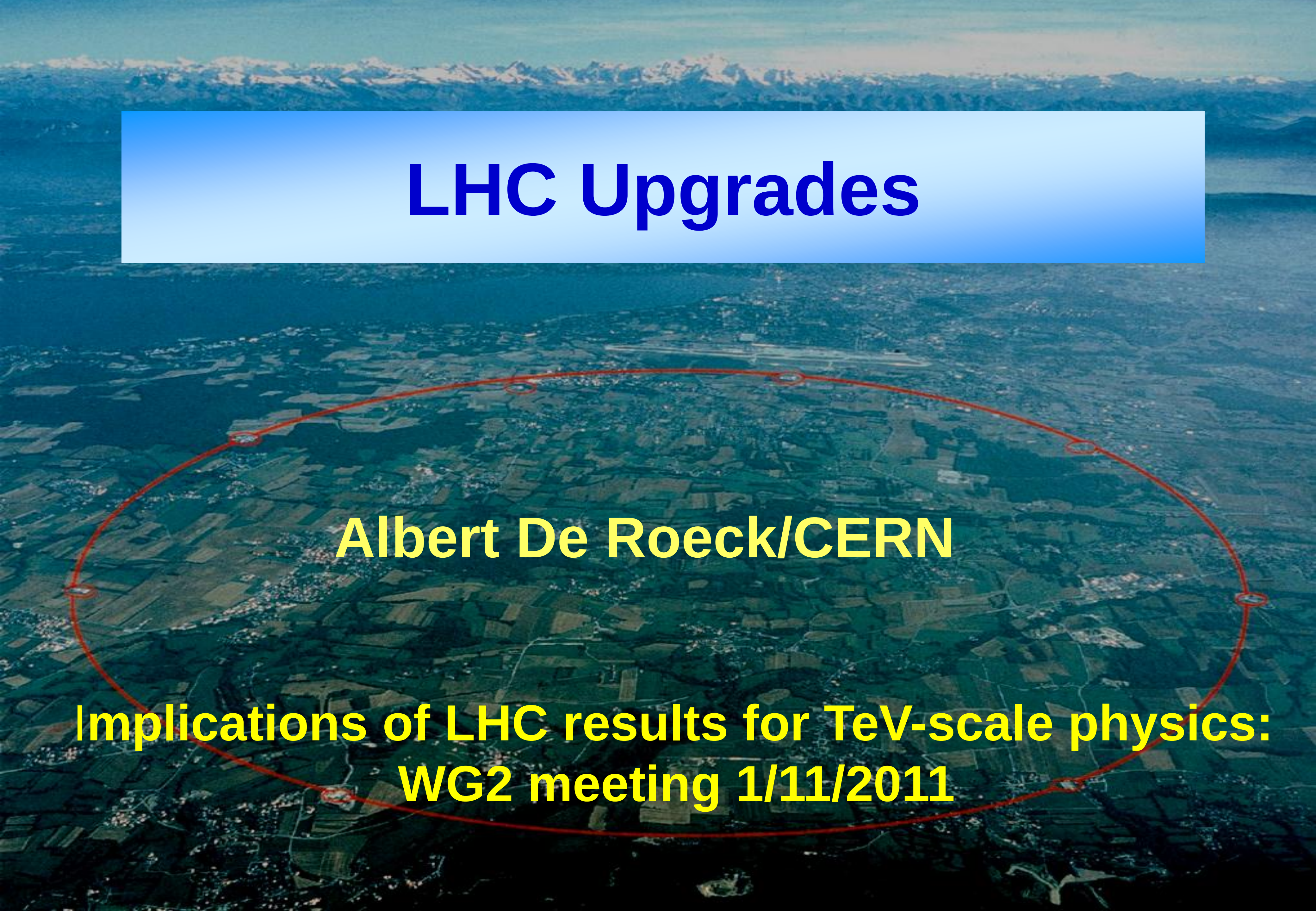


LHC Upgrades

Albert De Roeck/CERN

Implications of LHC results for TeV-scale physics: WG2 meeting 1/11/2011

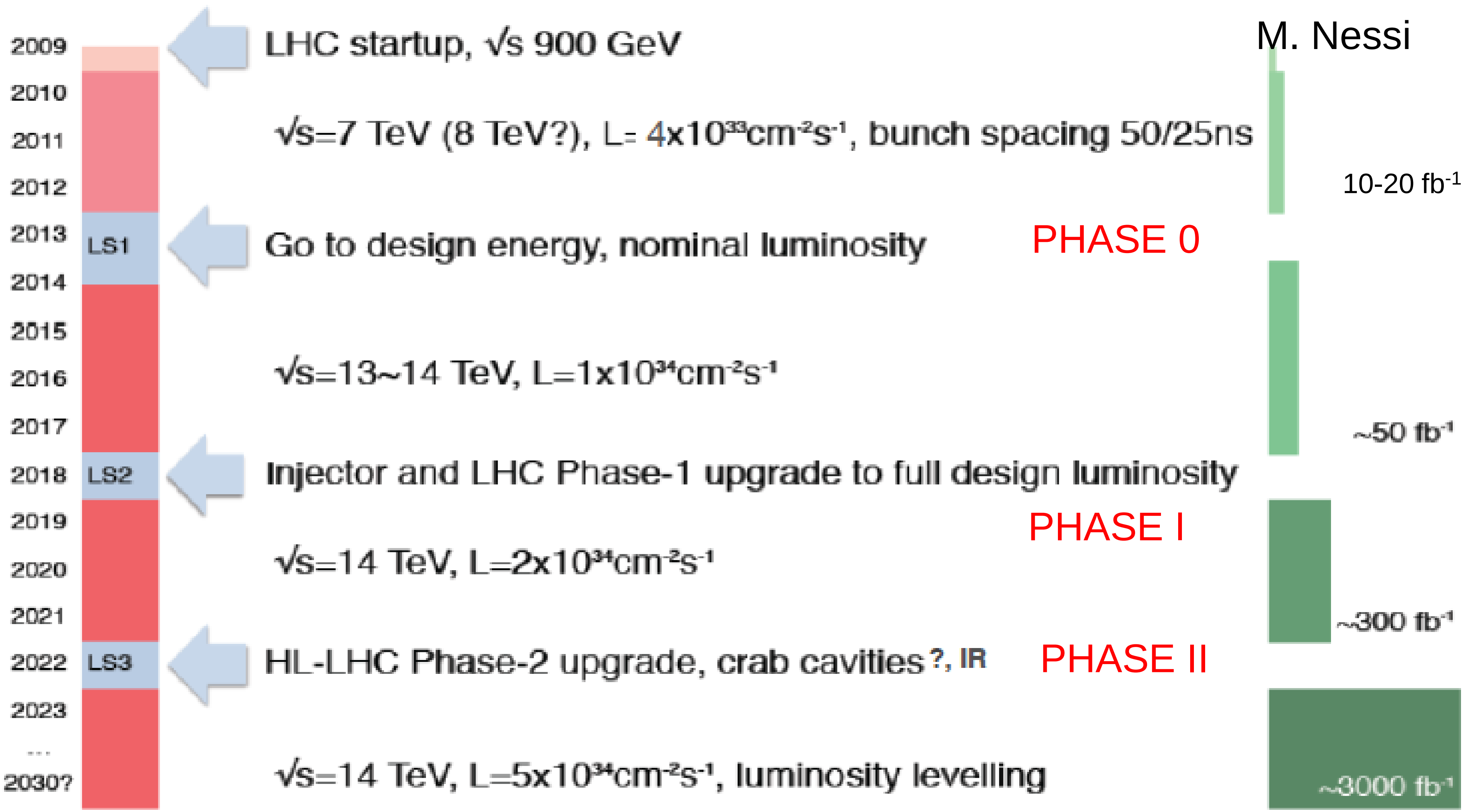
Contents

- Introduction
- Luminosity upgrade scenario for the LHC machine
  - High Luminosity: HL-LHC
  - Higher Energy: HE-LHC
  - Electron–proton LHeC
- Summary

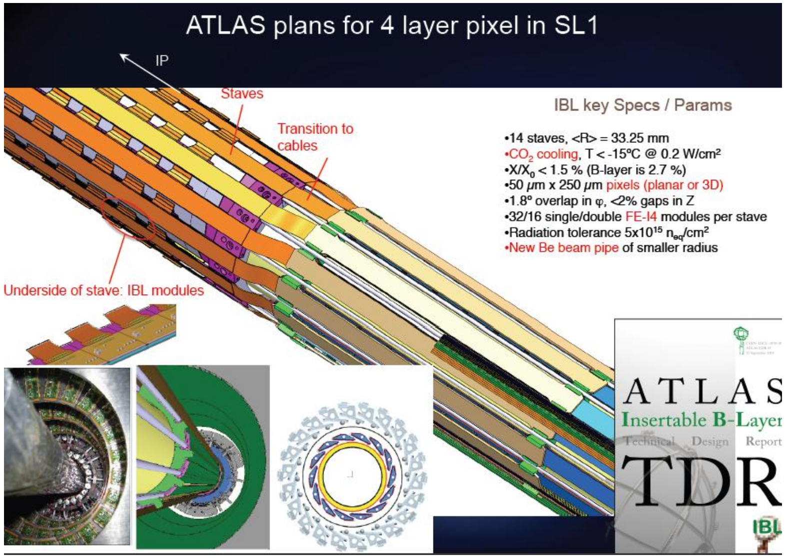
Note: Very little specific physics studies for the first two options since 2002.
Recently: some specific performance studies for the detector upgrades

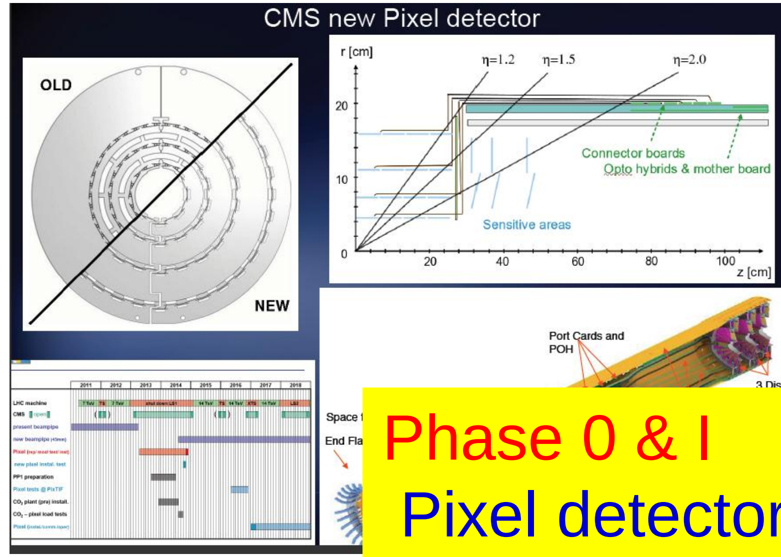
Maybe time to think of a special effort? Many new ideas have not been explored for higher energy/luminosity.

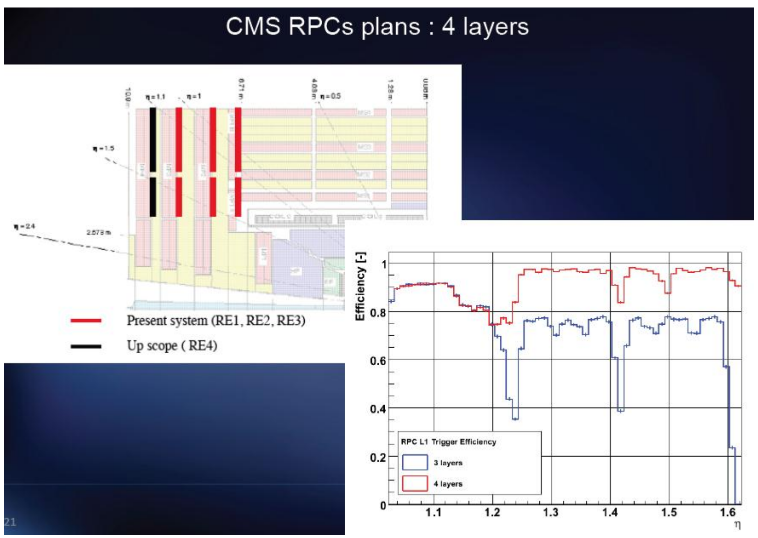
LHC History/Schedule

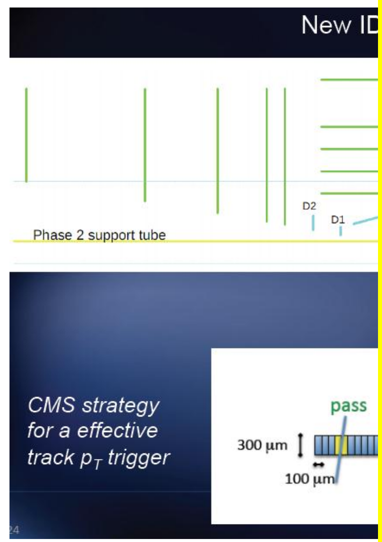


Detector Upgrades: Examples









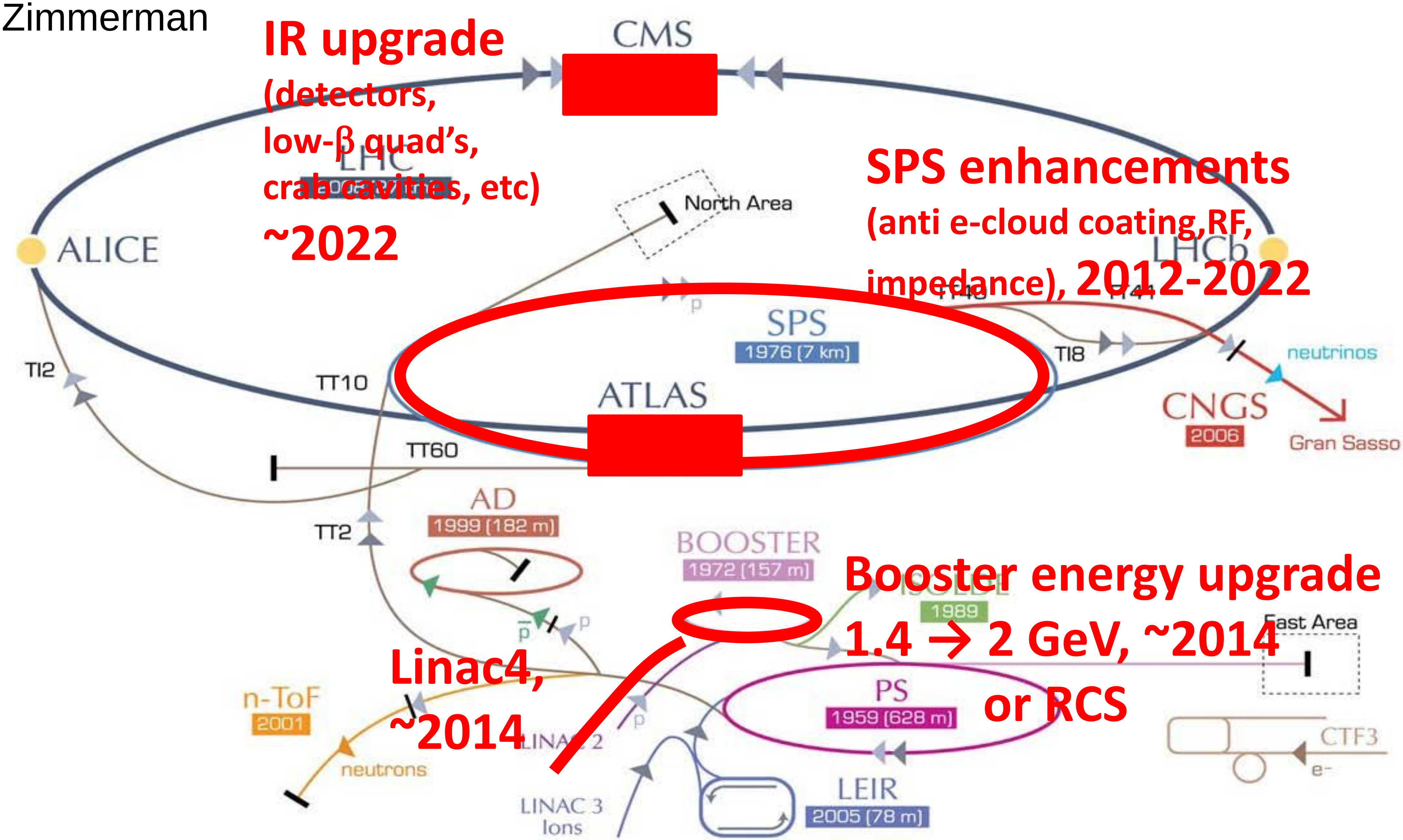
Phase 0 & I
- Pixel detectors
- Hadron calorimeters
- Muon detectors
- Trigger, DAQ

Phase II
- New trackers
- Trigger, DAQ…

Phase-0 & I upgrades. Phase-II upgrades (high lumi) still in design

HL-LHC – LHC modifications

F. Zimmerman



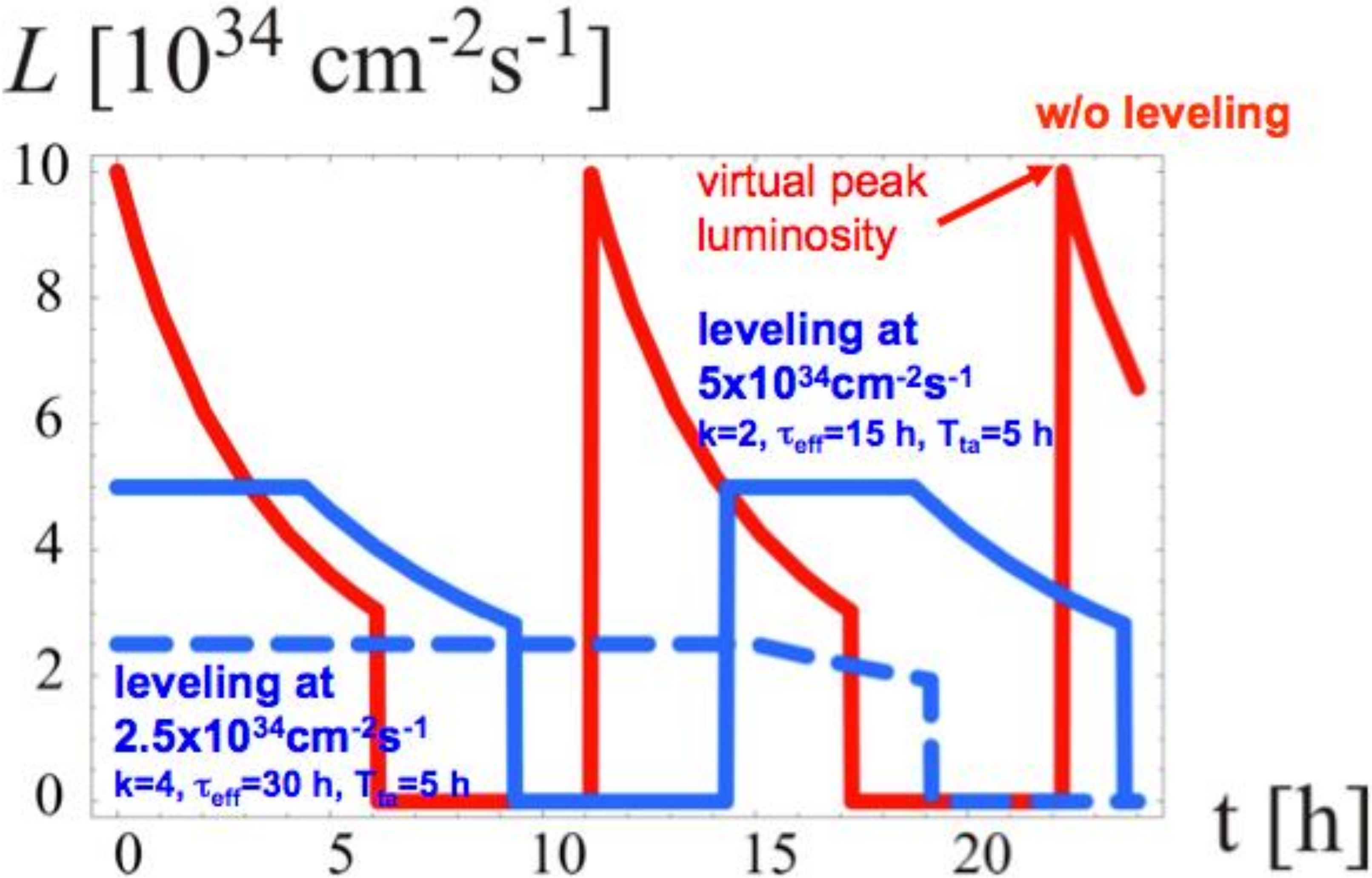
HL-LHC Targets

- Leveled peak luminosity: $L = 5\ 10^{34}\ cm^{-2}\ s^{-1}$
- Virtual peak luminosity: $L \geq 10\ 10^{34}\ cm^{-2}\ s^{-1}$
- Integrated luminosity: 200 fb^{-1} to 300 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1} by 2030

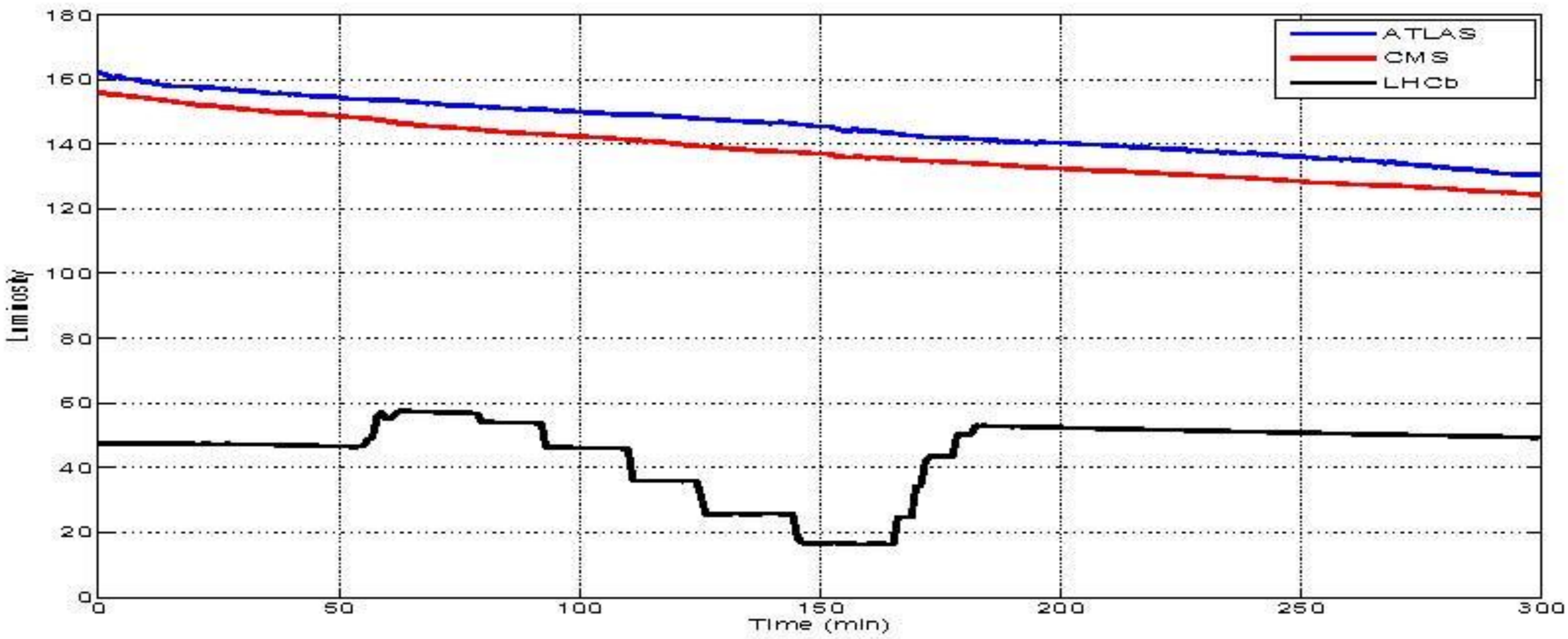
Example Parameters

parameter	symbol	nom.	nom.*	25 ns, crab, lrc	50 ns, crab, lrc
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	3.4
bunch spacing	Δt [ns]	25	50	25	50
beam current	I [A]	0.58	0.43	0.86	0.86
rms bunch length	σ_z [cm]	7.55	7.55	7.55	7.55
beta* at IP1&5	β* [m]	0.55	0.55	0.15	0.15
full crossing angle	θ_c [μrad]	285	285	425	425
normalized mittance	γε [μm]	3.75	3.75	2.8	2.8
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.65	2.13	2.13
tune shift	ΔQ_{tot}	0.009	0.0136	0.006-0.011	0.012-0.015
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	9.6	19.3
actual (leveled) pk luminosity	L_{lev} [10^{34} cm^{-2}s^{-1}]	1	1.1	5	5 (2.5)
events per #ing		19	40	95	190 (95)
effective lifetime	τ_{eff} [h]	44.9	30	13.3	13.3 (26.6)
level time / run time	$t_{level,run}$ [h]	15.2	12.2	3.7 / 8.6	6.5 / 10.1 (16.4)
e-c heat SEY=1.2	P [W/m]	0.2	0.1	0.4	0.3
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	0.32	0.30	0.58	0.91
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	58, 104	39, 70	71, 60	36, 30
annual luminosity	L_{int}[fb^{-1}]	57	58	259	317 (204)

Luminosity Leveling

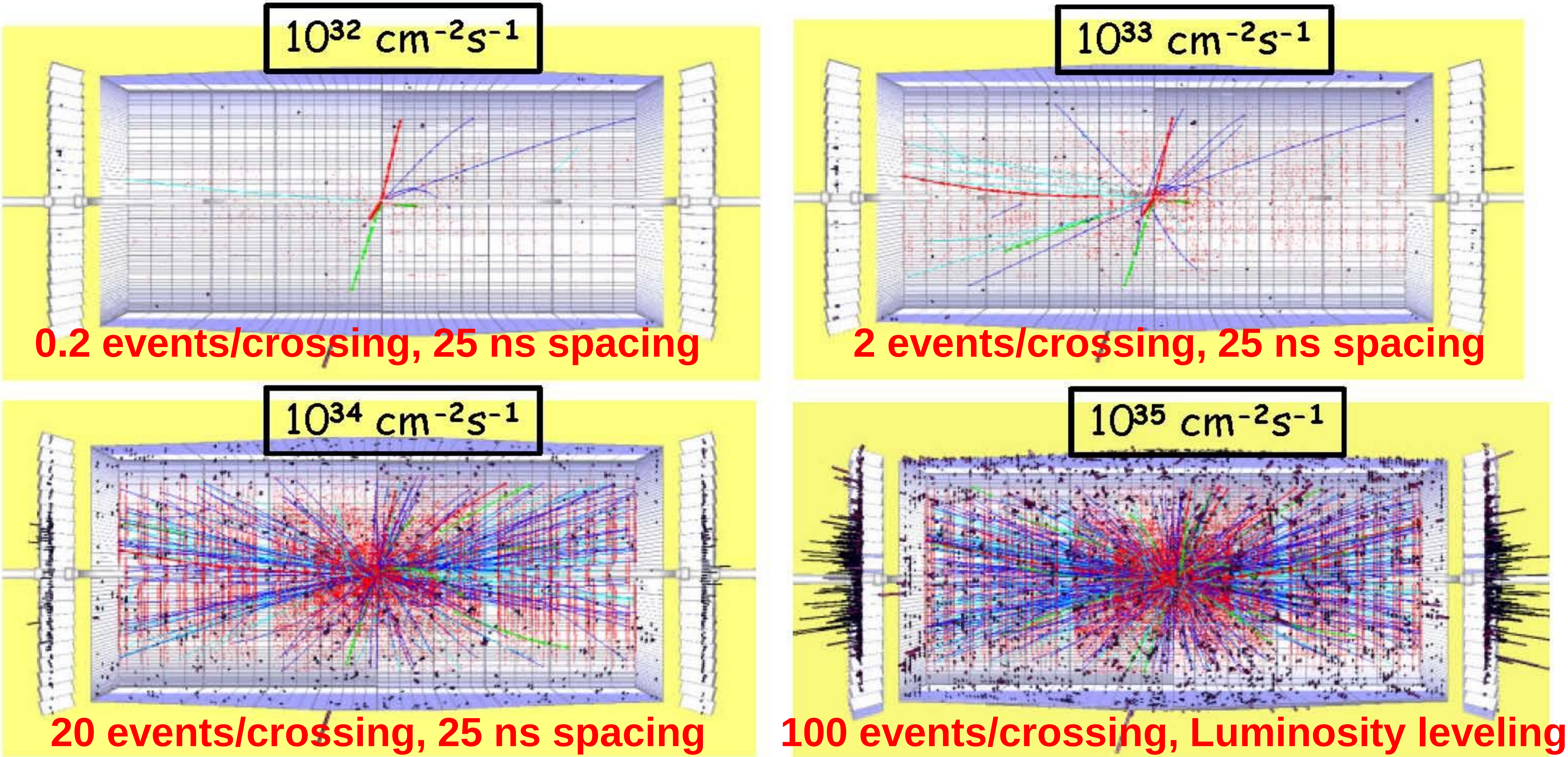


Luminosity leveling with beam-beam offset for LHCb



The luminosity can be successfully leveled using transverse offsets between 0 and a few s (here at IP8) without significant effects on the beam or the performance of the other experiments (IP1&5)

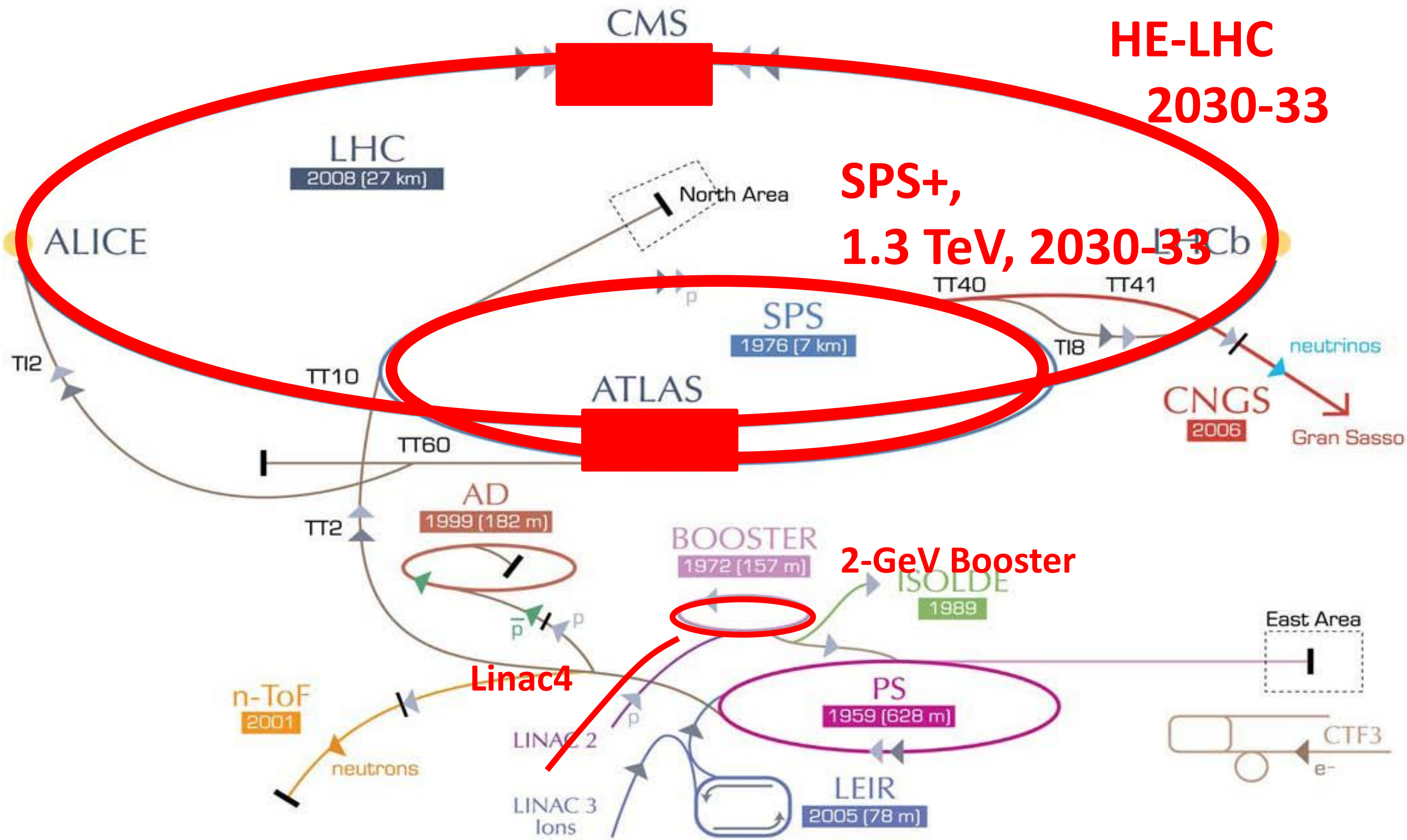
Event Pile-up!!



$H \rightarrow ZZ \rightarrow \mu\mu ee$ event with M_H= 300 GeV for different luminosities

p_T > 1 GeV/c cut, i.e. all soft tracks removed

HE-LHC – LHC modifications



HE-LHC

High Energy-LHC (HE-LHC)

CERN working group since April 2010

EuCARD AccNet workshop HE-LHC'10 , 14-16 October 2010

key topics

beam energy 16.5 TeV; 20-T magnets

cryogenics: **synchrotron-radiation heat**

radiation damping & emittance control

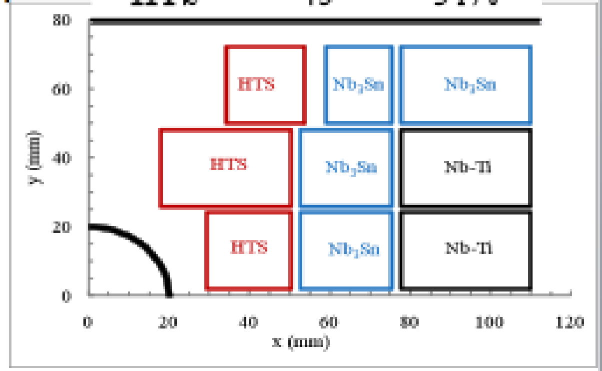
vacuum system: synchrotron radiation

new injector: energy > 1 TeV

parameters

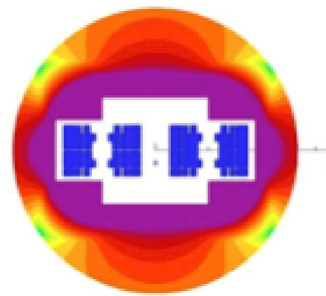
	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0

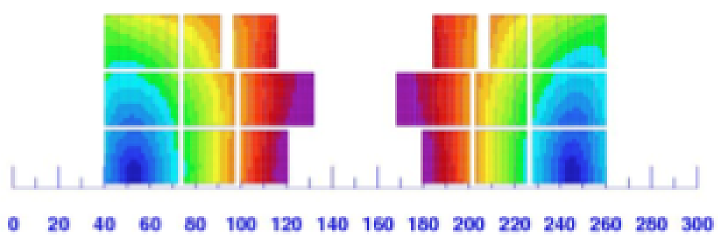
	Turns	%
Nb-Ti	40	28%
Nb_3Sn	58	41%
HTS	45	31%



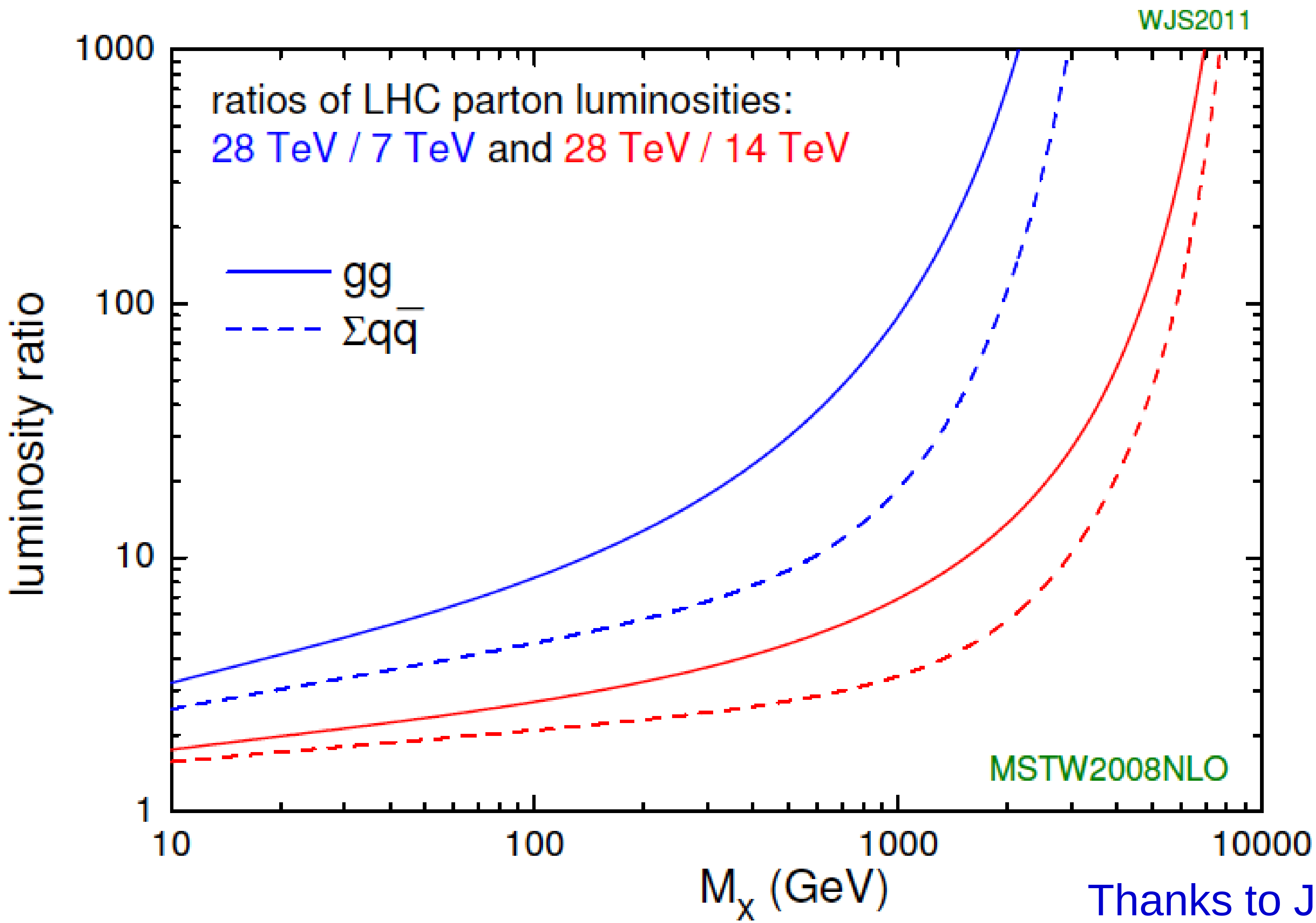
E. Todesco

hybrid magnet





Higher Energies



Thanks to James Stirling

Physics Studies for the LHC upgrade

- Electroweak Physics
  - Production of multiple gauge bosons ($n_V \geq 3$)
    - triple and quartic gauge boson couplings
  - Top quarks/rare decays
- Higgs physics
  - Rare decay modes
  - Higgs couplings to fermions and bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- Supersymmetry
- Extra Dimensions
  - Direct graviton production in ADD models
  - Resonance production in Randall-Sundrum models TeV^{-1} scale models
  - Black Hole production
- Quark substructure
- Strongly-coupled vector boson system
  - $W_L Z_L$ g $W_L Z_L$, $Z_L Z_L$ scalar resonance, $W^+_L W^+_L$
- New Gauge Bosons

Examples studied in some detail

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtinen [1], K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

Include pile up, detector…

hep-ph/0204087

SUSY Reach: LHC, HL-LHC & HE-LHC

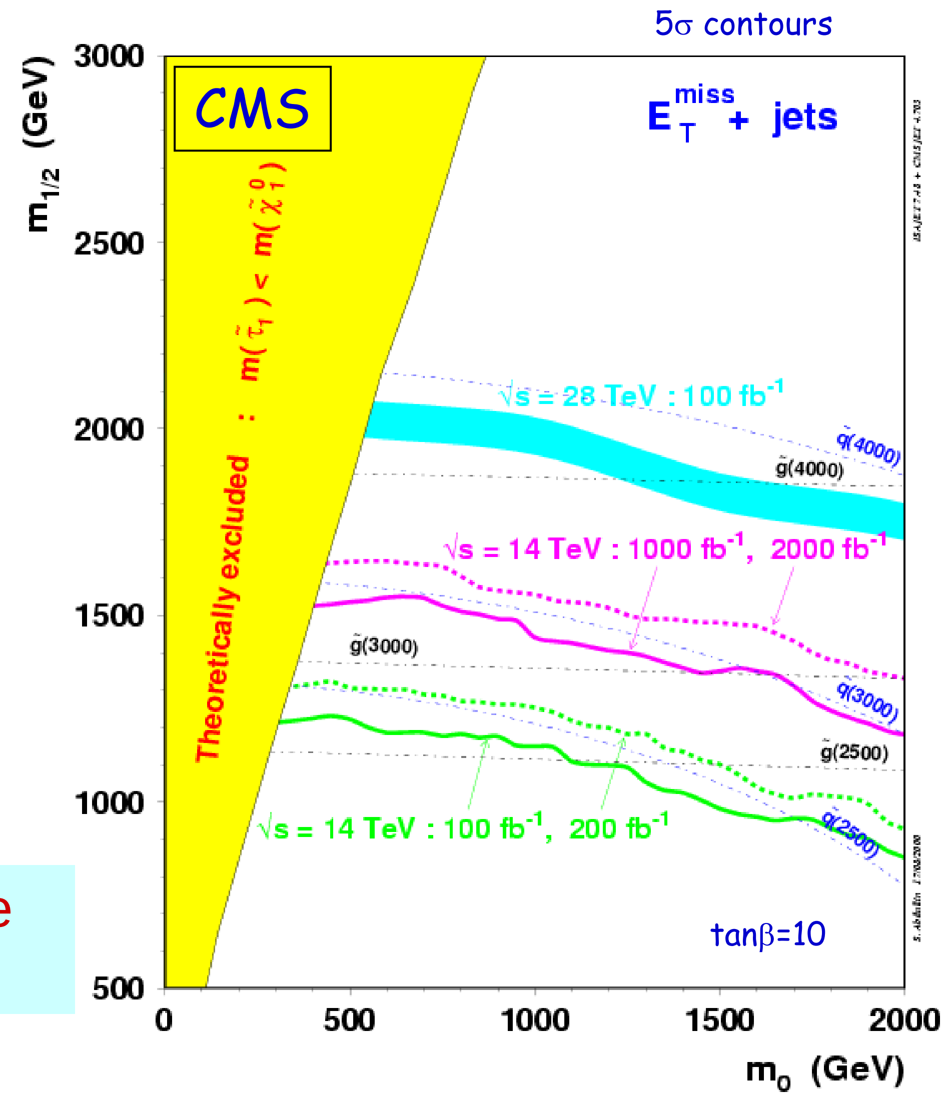
<u>Impact of the HL-LHC</u>

Extend the discovery region for squarks and gluinos by roughly 0.5 TeV, i.e. from

~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and large missing E_T

⇒ Not much compromised by increased pile-up at SLHC



$m_{1/2}$ universal gaugino mass at GUT scale

m_0: universal scalar mass at GUT scale

HL-LHC: tackle difficult SUSY scenarios

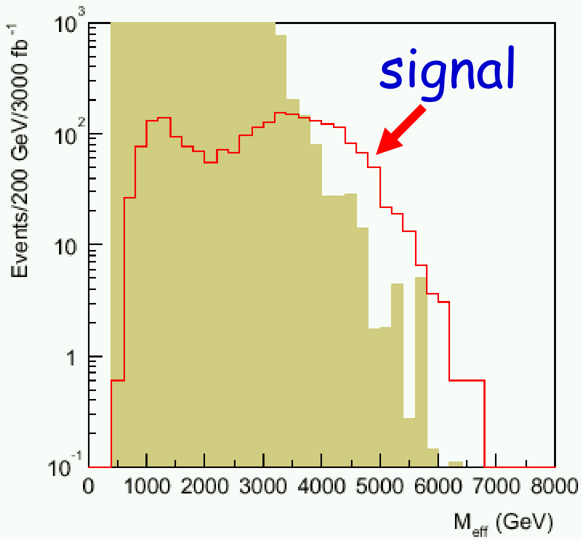
Squarks: 2.0-2.4 TeV Gluino: 2.5 TeV

Can discover the squarks at the LHC but cannot really study them

$$M_{eff} = E_T^{miss} + \sum_{jets} E_{T,jet} + \sum_{leptons} E_{T,lepton}$$

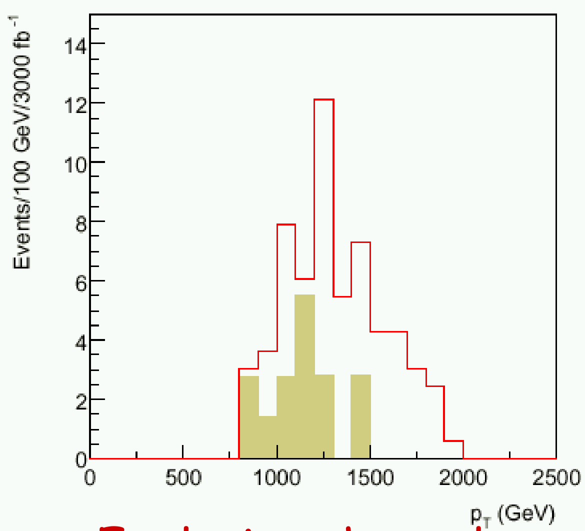
$P_T^1 > 700$ GeV & $E_T^{miss} > 600$ GeV

eg. Benchmark Point K in hep-ph/0306219 $m_{1/2}$=1300 GeV, m_0=1000 GeV, tanβ=35



Inclusive: M_{eff} > 4000 GeV

S/B = 500/100 (3000 fb^{-1})



Exclusive channel

$\tilde{q}\tilde{q} \rightarrow \chi_1^0\, \chi_1^0\, qq$

S/B =120/30 (3000fb^{-1})

Higgs in χ_2 decay

$\chi_2 \rightarrow \chi_1 h$ becomes visible at 3000 fb^{-1}

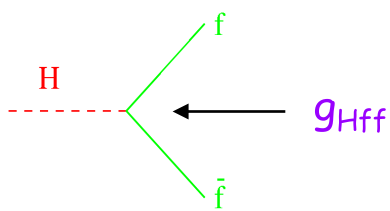
Measurements of some difficult scenarios become possible at the HL-LHC

Higgs Decays Modes

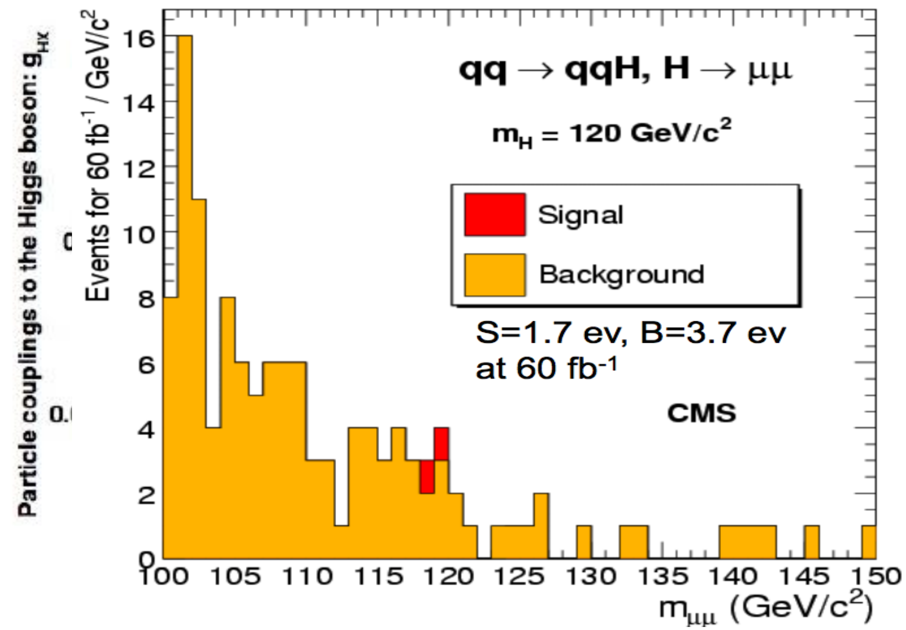
Rare Higgs Decays

Channels studied:

- $H \to Z\gamma \to \ell\ell\gamma$
- $H \to \mu\mu$



Branching ratio ~ 10^{-4} for these channels!
Cross section ~ few fb



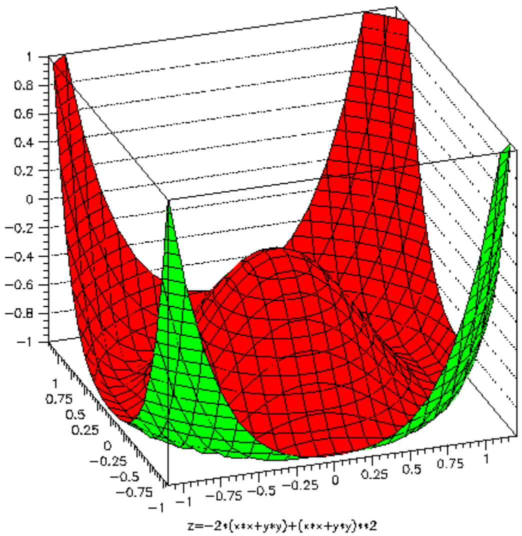
Channel	m_H	S/√B LHC (600 fb^{-1})	S/√B SLHC (6000 fb^{-1})
$H \to Z\gamma \to \ell\ell\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 9.5 (gg)

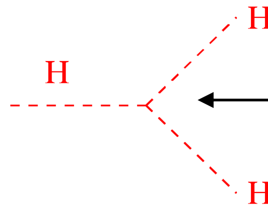
Higgs Couplings (ratios)

Can be improved with a factor of 2: 20%→10% at HL-LHC

Higgs Self Coupling Measurements

$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

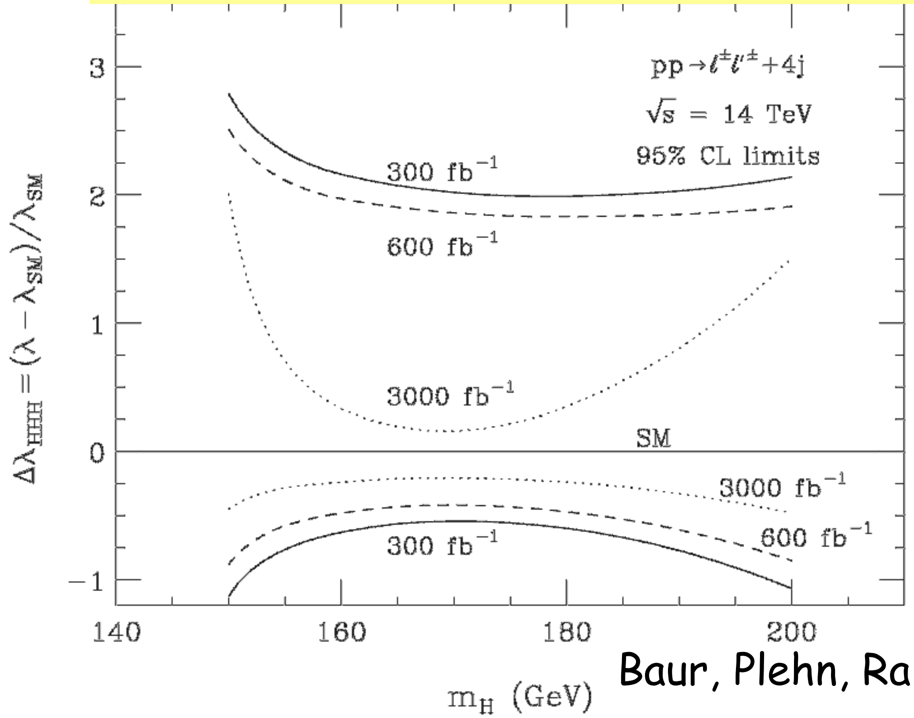




~ λv

$m_H^2 = 2\,\lambda\, v^2$

$HH \to W^+ W^- W^+ W^- \to \ell^\pm \nu jj \;\; \ell^\pm \nu jj$

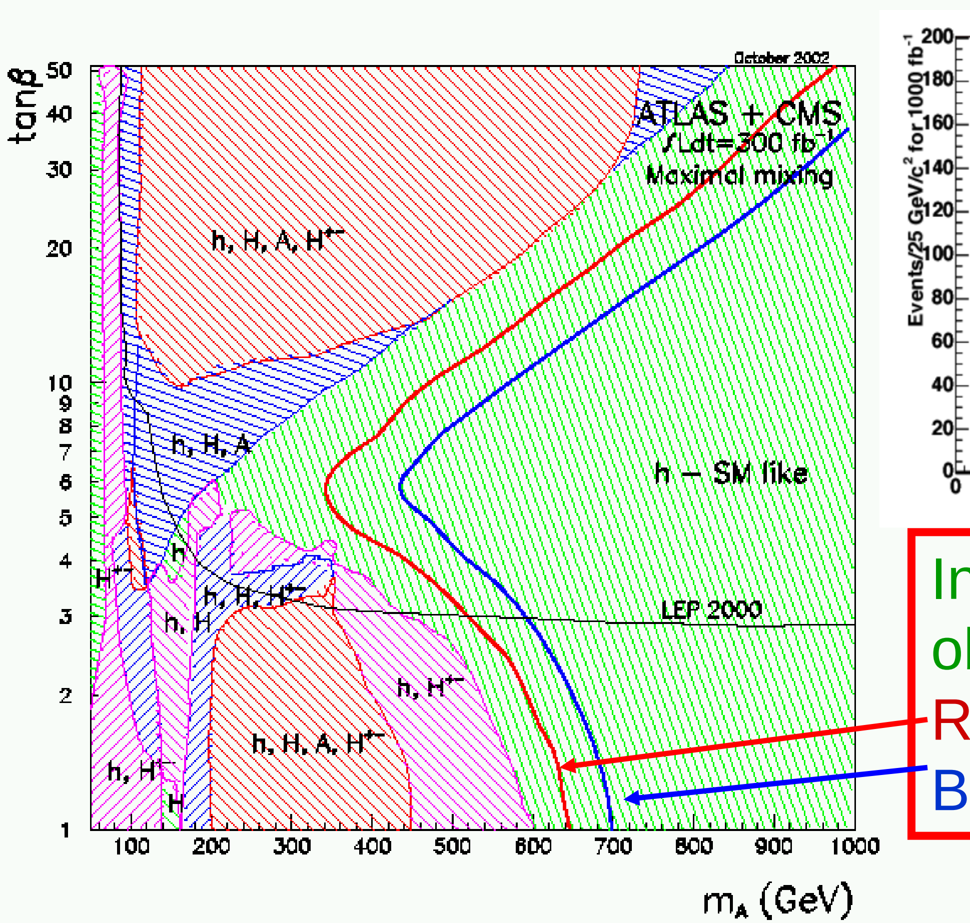


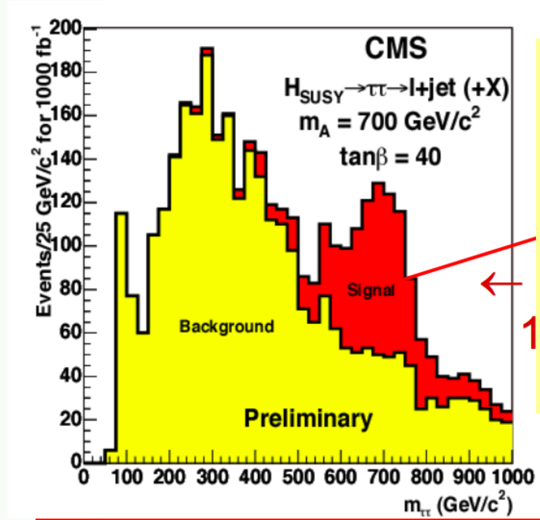
Baur, Plehn, Rainwater

- LHC: λ= 0 can be excluded at 95% CL.
- HL-LHC: λ can be determined to 20-30% (95% CL)

Note: Different conclusion from ATLAS study ⇒Jury is still out

SUSY Higgs Particles: h,H,A,H$^{\pm}$





Dominated in the green wedge by signal/background.
⇒ Increase in statistics helps!!

In the green region only SM-like h observable with 300 fb^{-1}/exp
Red line: extension with 3000 fb^{-1}/exp
Blue line: 95% excl. with 3000 fb^{-1}/exp

Heavy Higgs reach increased by ~100 GeV at the HL-LHC.

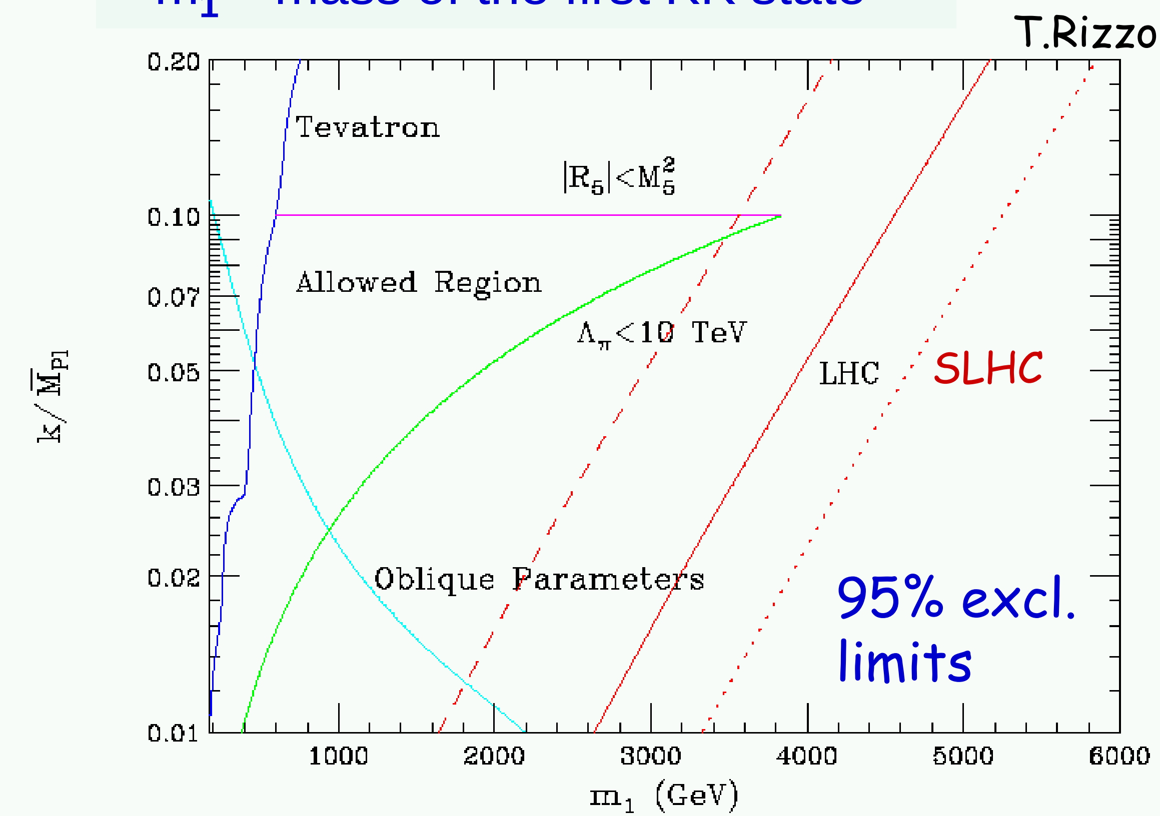
HL-LHC: KK Gravitons

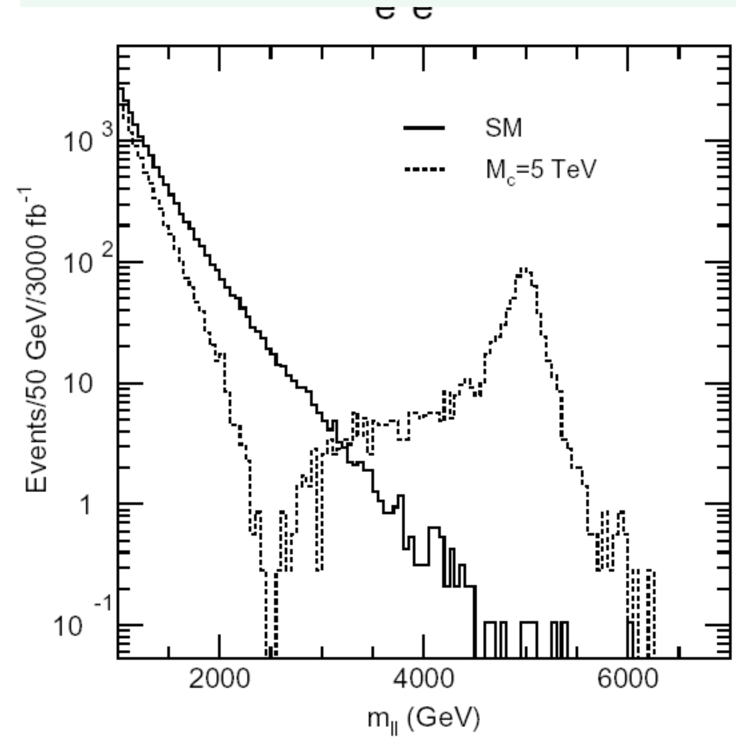
Randall Sundrum model

- Predicts KK graviton resonances
- k= curvature of the 5-dim. Space
- m_1 = mass of the first KK state

TeV scale ED's

- KK excitations of the γ,Z





100→1000 fb^{-1}: Increase in reach by 25%

Direct: LHC/600 fb^{-1} 6 TeV
HL-LHC/6000 fb^{-1} 7.7 TeV

Spin Analysis (Z'⇔Randall Sundrum gravitons)

Luminosity required to discriminate a spin-1 from spin-2 hypothesis at the 2σ level

Needs statistics!

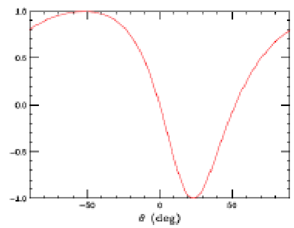
- May well be a case for the HL-LHC
- Also: SUSY particle spin analysis (Barr, Webber, Smiley) need > 100 fb^{-1}

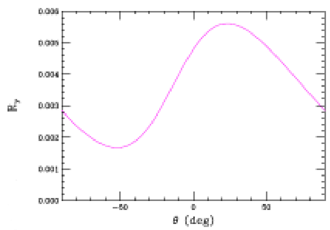
Z’ Studies and Searches

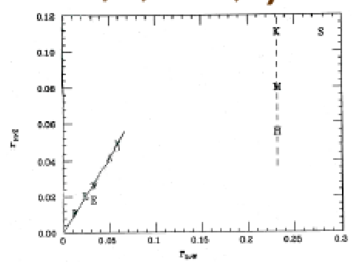
T. Rizzo

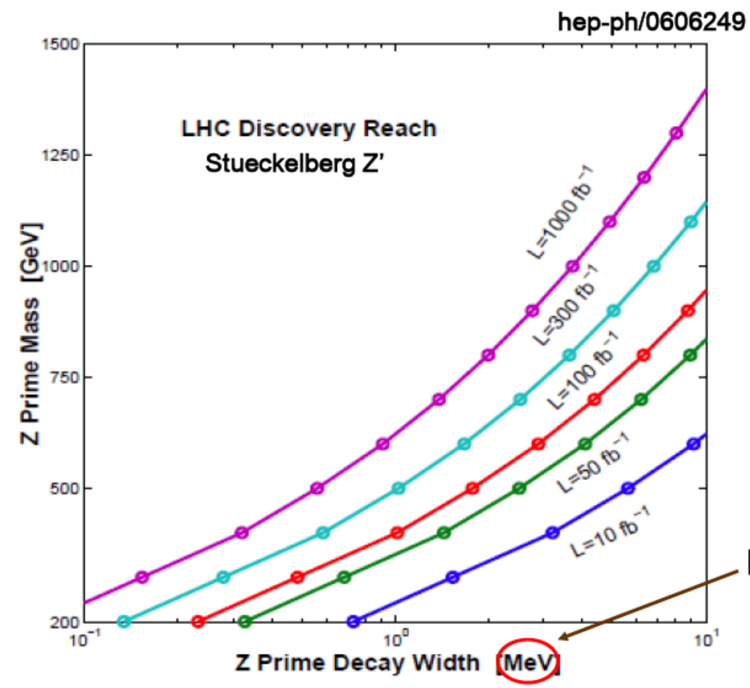
Eg Z’ detailed studies will likely require very high luminosities

- Z’ →ττ polarization measurement
- Associated on-shell Z’ + (W,Z,γ) production
- Rare Decays: Z’ → $\bar{f}$ f ’V (V = W,Z; f = l,ν)
- Z’ → WW, Zh
- Z’ →$\bar{b}$b, $\bar{t}$ t









These have not been studied in any detail for the LHC but all will require quite high luminosity even for a light Z’

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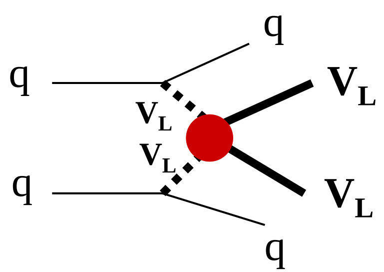
Strongly Coupled Vector Boson System

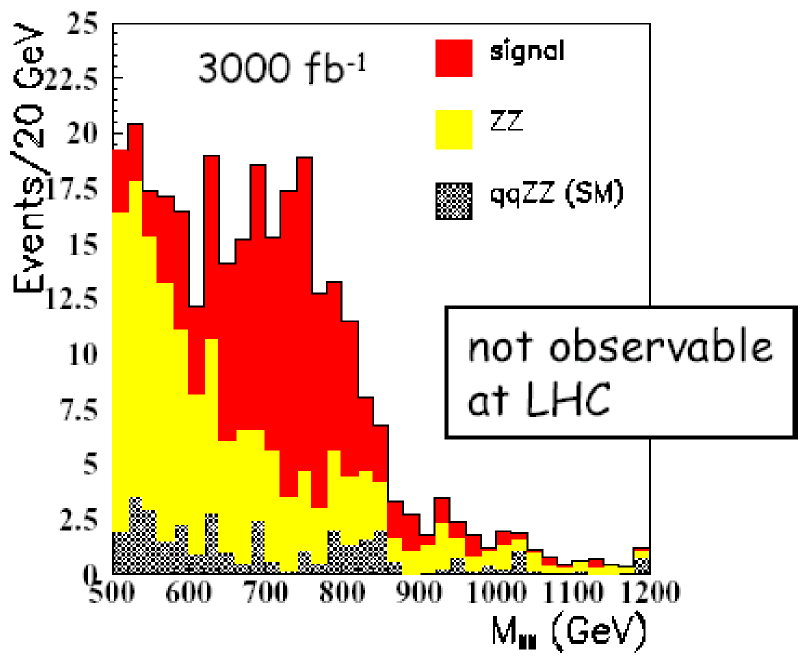
If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at ~ 1TeV



Could well be difficult at LHC. What about HL-LHC?

- degradation of fwd jet tag and central jet veto due to huge pile-up
- BUT : factor ~ 10 in statistics → 5-8σ excess in $W^+_L W^+_L$ scattering
  → other low-rate channels accessible

Scalar resonance $Z_L Z_L \rightarrow 4\ell$



Indicative Physics Reach

Ellis, Gianotti, ADR
hep-ex/0112004+ few updates

Units are TeV (except $W_L W_L$ reach)

☝ Ldt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	LH-LHC 14 TeV 1000 fb^{-1}	HE-LHC 28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	ILC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z'	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λcompositeness	30	40	40	50	100	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

Should be redone…

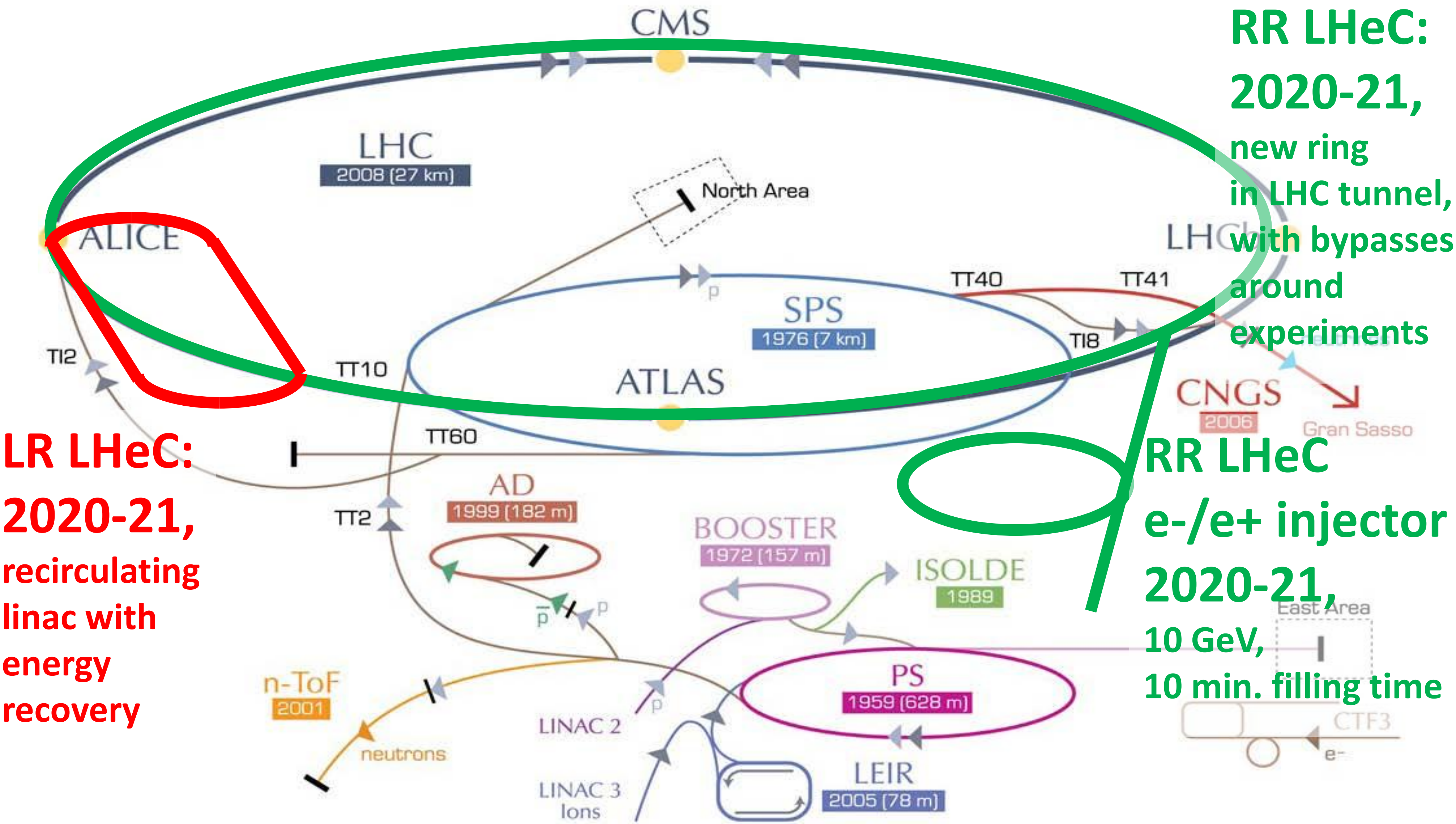
Approximate mass reach machines:

$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV

$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV

$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV

Large Hadron electron Collider



LHeC Parameters

Table 1: Parameters of the RR and RL Configurations

	Ring	Linac
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e $[10^9]$	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) $[10^{32}\text{cm}^{-2}\text{s}^{-1}]$	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ $[10^{32}\text{cm}^{-2}\text{s}^{-1}]$	0.3	1

Both the ring and the linac are feasible and both come very close to the desired performance. The pleasant challenge is to soon decide for one.

CERN-ECFA-NuPECC:
CDR Draft (530pages) being refereed
Publish early 2012

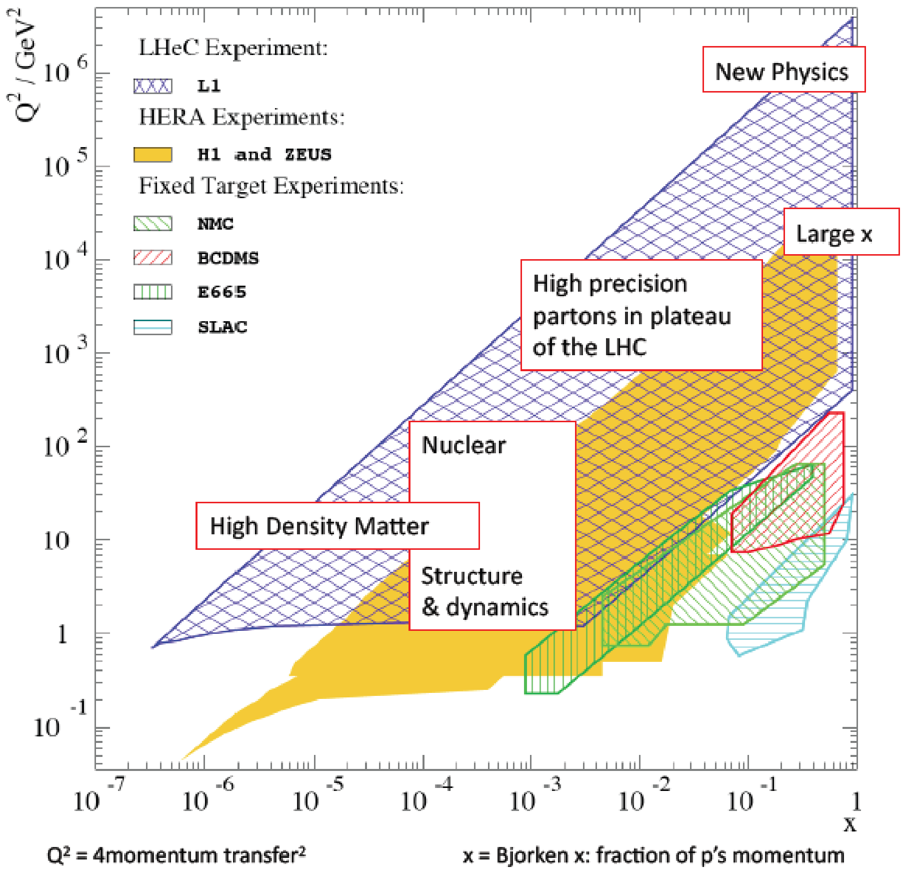
Steps towards TDR (tentative)
-Prototype IR magnet (3 beams)
-Prototype Dipole (1:1)
-Develop Cavity/Cryomodule
-Civil Engineering, …

Build international collaborations
for the accelerator and detector development. Strong links to ongoing accelerator and detector projects.

The LHC offers the unique perspective for a further TeV scale collider. The LINAC's are of about 2mile length, yet the Q^2 is 10^5 times larger than was achieved when SLAC discovered quarks. Particle physics needs pp, ll and ep.
Here is a realistic prospect to progress.

M Klein et al.

Physics Program



Physics

- eQ states
- GUT ($\delta\alpha_s$=0.1%)
- Excited fermions
- Hot/cold spots
- Single top
- Higgs
- PDFs
- Multi-Jets
- DVCS
- Unintegrated partons
- Saturation
- Vector Mesons
- IP - graviton
- Odderons
- NC couplings
- $\sin^2\Theta$
- Beauty
- Charm
- Partons in nuclei
- Shadowing
- ....

DRAFT 1.0
Geneva, August 5, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

CDR 530 pages

Leptoquarks & leptogluons, excited electrons, contact interactions, 4th lepton family, Z', quark substructure, extra dimensions, diquarks, Higgs CP studies…

Very little (so far) on SUSY; only RPV SUSY $eq \rightarrow \tilde{e}\tilde{q}$ via t-exchange of $\tilde{\chi}$

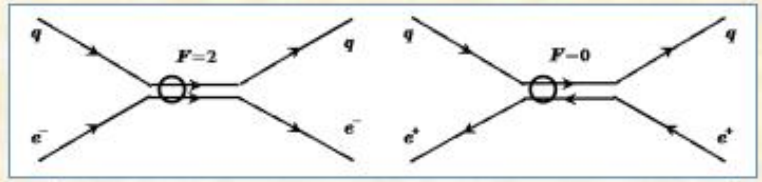
Leptoquark Studies

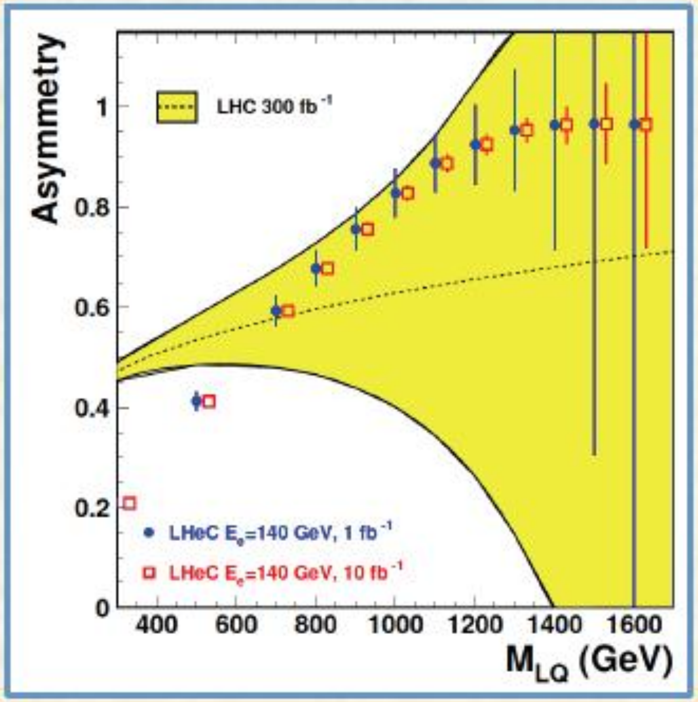
U. Klein

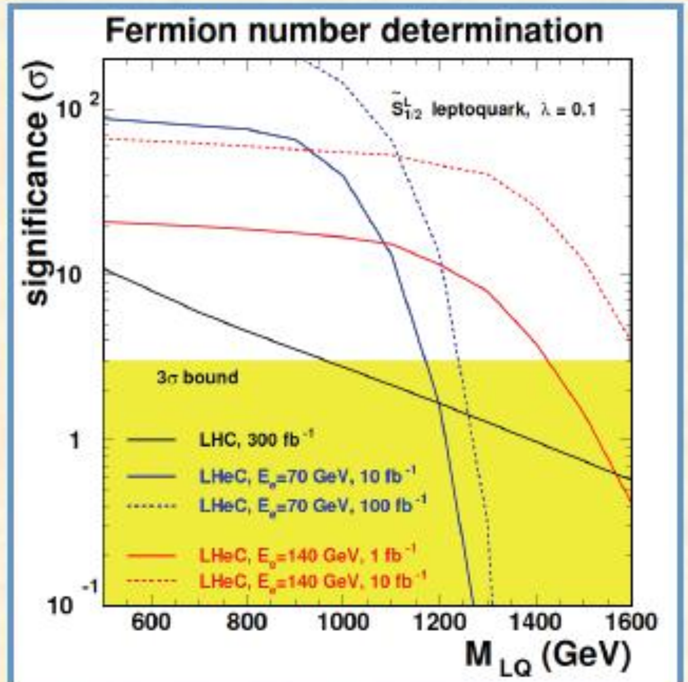
LQ Quantum Numbers and Couplings

- Fermion number *F* from asymmetry in e+/e-p cross sections
- Much cleaner accessible in DIS

$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} > 0 \text{ for F=2} \\ < 0 \text{ for F=0} \end{cases}$$







Studies for "low`` lumi assumptions for pp and ep

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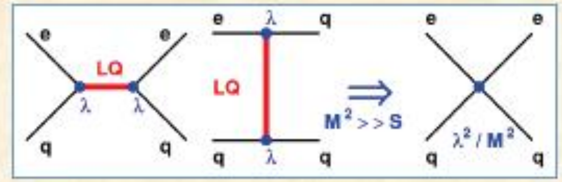
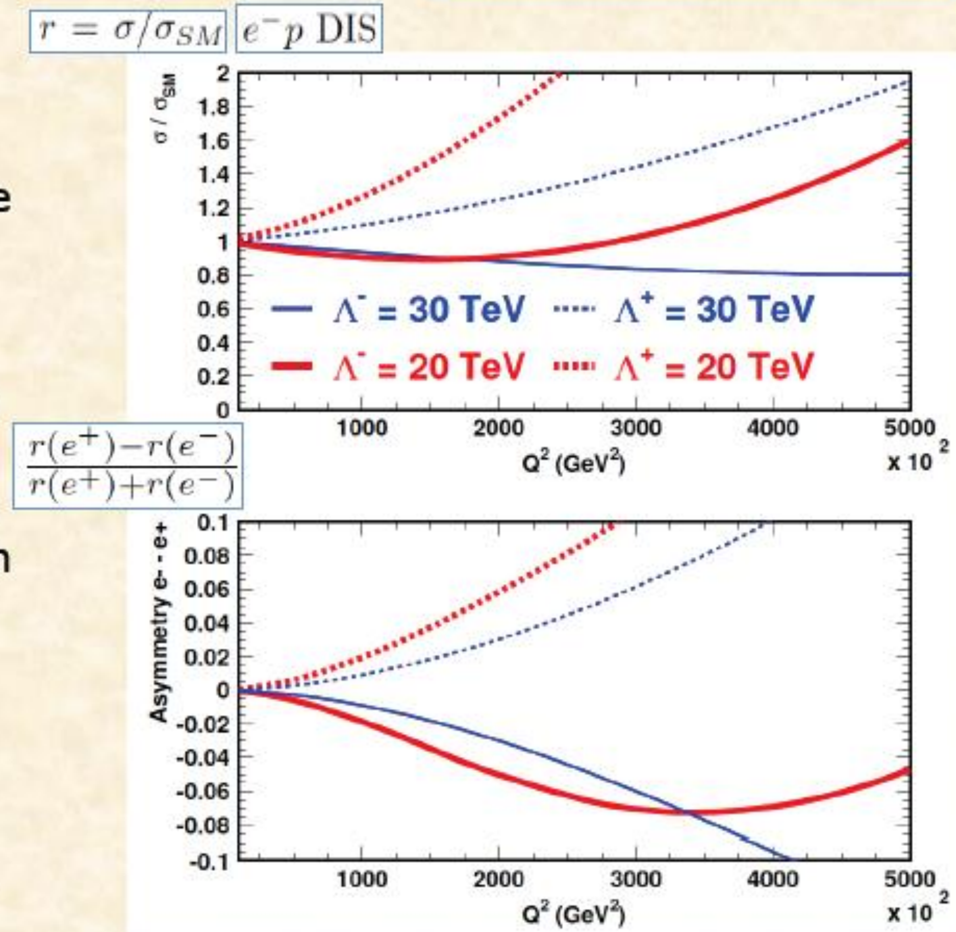
Contact Interaction Studies

Contact Interactions

Effective 4 fermion interaction to access scales beyond s. Substructure but as well KK gravitons: could study ED for different charge polarisation and quark flavour



- Probe deviations in the SM DIS cross section for ***eeqq*** contact interactions
- LHeC could test scales between 20-45 TeV
- *Polarised* lepton beam would help to establish the chiral structure of a new interaction ➔ very likely that a **combination of *pp* and *ep data*** will be needed to underpin the chiral structure of the new interaction



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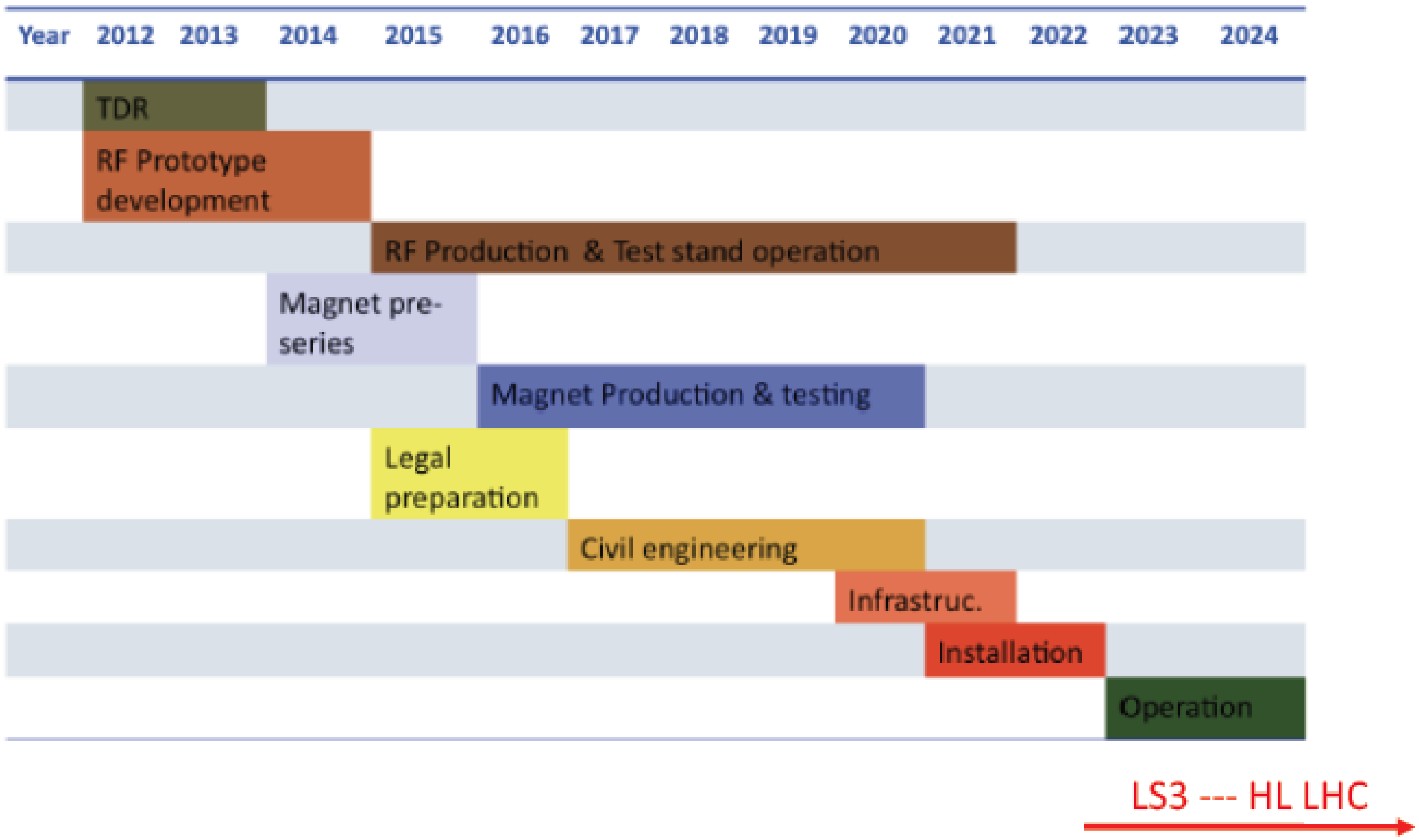
Possible Schedule

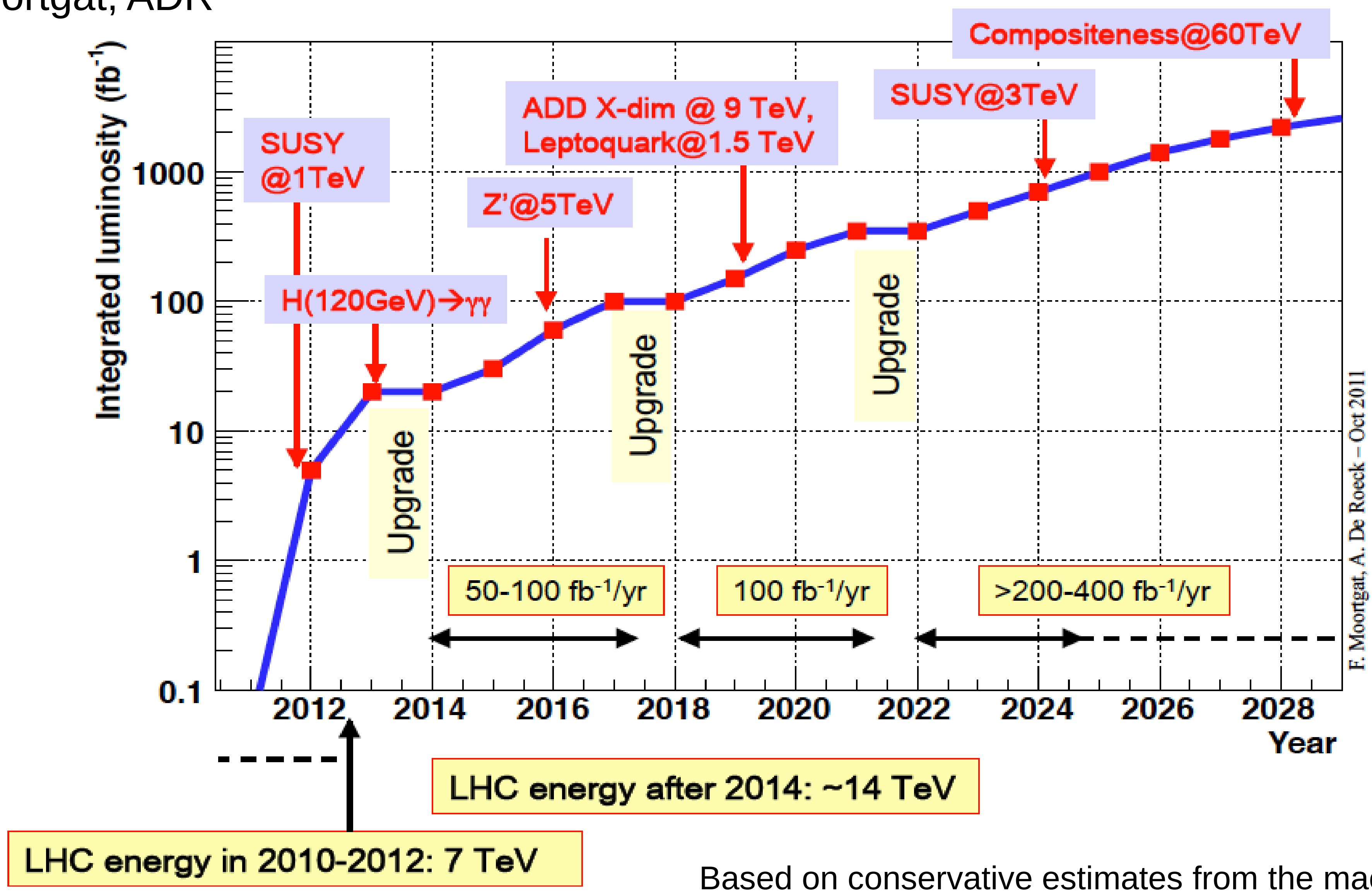
LHeC Tentative Time Schedule



We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

The Future?

F. Moortgat, ADR



Based on conservative estimates from the machine

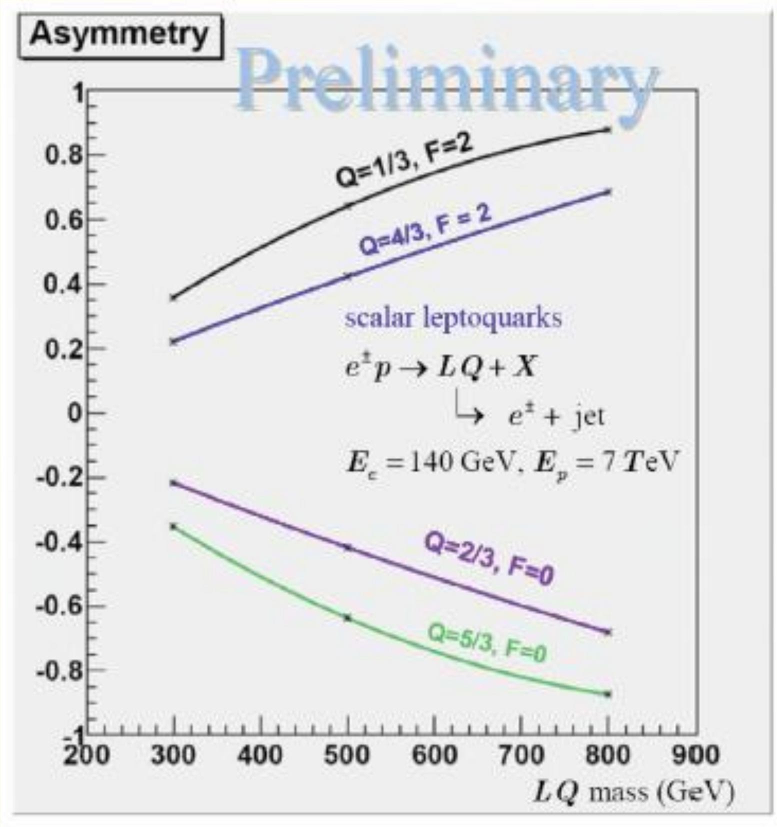
Summary

- Detector upgrade preparations in the experiments are well under way, making use of 3 foreseen long technical stops.
- HL-LHC: High Luminosity operation expected to start around 2022. Expect ~ 3 ab^{-1}/exp or more by 2030.
- HE-LHC: CM Energy discussed now 33 TeV, but magnets still in R&D. Not starting before well into the 2030's, according to present planning...
- LHeC: Technically feasible. CDR in review
- Physics case for the HL-LHC and HE-LHC have not been revisited since quite some time. Maybe something to think about for 2013-14…

Leptoquark Studies

Flavour Structure of LQ Coupling

- Using the charge asymmetry and the PDF sensitivity of the interacting quark, the flavour structure of the LQ coupling can be probed
- *Leptogluons* are not widely discussed in literature, but similar measurements than for the leptoquarks can be performed for them as well



LG's predicted in all models with coloured preons. Result: e.g.: For scale Λ of 10 TeV have mass reach of 1.1 TeV in M_{e8}. L ~ 1/2Λ ...

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ATLAS plans for LS1 and LS2

- *New Aluminum beam pipes to prevent activation problem and reduce muon BG*
- New insertable pixel b-layer (IBL) + new pixel services (nSQP) + new small Be pipe
- *New evaporative cooling plant for Pixel and SCT + IBL CO_2 cooling plant*
- Replace all calorimeter Low Voltage Power Supplies
- *Finish the installation of the EE muon chambers staged in 2003 + additional chambers in the feet and elevators region*
- Upgrade the magnets cryogenics with a new spare main compressor and decouple toroid and solenoid cryogenics
- *Add specific neutron shielding where necessary (behind endcap toroid, USA15)*
- Revisit the entire electricity supply network

- *New muon small wheels with more trigger granularity and trigger track vector information*
- Fast track trigger (FTK) using SCT and pixel hits (just after LVL1)
- *Higher-granularity calorimeter LVL1 trigger and associated front-end electronics*
- Topological trigger processors combining LVL1 information from different regions of interest
- *Readapt central LVL1 trigger electronics to the new needs (central processors, ….)*
- New forward physics detection station at 220 m for new diffractive physics
- *Add specific neutron shielding where necessary*

CMS plans for LS1 and LS2

Common system consolidation

New small radius Be beam pipe

New Pixel system

- Replacement of the current system with a 4-layer barrel, 3-disk endcap system for four hit coverage
- Ultra-lightweight support
- Development of a new readout chip with reduced data loss at higher collision rates
- Development of high bandwidth readout electronics and links as well as DC-DC converters

Calorimeters inside the solenoid

- Replacement of the HPDs in all three detectors with Silicon Photomultipliers (SiPM)
- Implementation of depth segmentation
- Use of timing to clean up backgrounds
- New back-end electronics designed to provide enhanced information to the upgraded Regional Calorimeter Trigger (RCT)

Forward Calorimeters

- Replacement of the photomultipliers of the Forward Hadron Calorimeter with new PMTs
- Replacement of the PMTs of the CASTOR detector
- Improvements to CASTOR's mechanical support system to prevent movements

Trigger

- Rebuilding the Regional Calorimeter Trigger (RCT) Rebuilding the CSC Trigger Track-Finder
- Rebuilding the RPC track finder
- Modification of the DT track finder
- Eventual implementation of a new Timing and Trigger Control system based on modern techn.

Construction of the Pixel Luminosity Telescope

RPCs: Endcap Resistive Plate Chambers

- Addition of a fourth layer of RPCs to extend coverage to *h* = 1.6
- R&D to develop detectors that can extend coverage to the region 1.6 < |η| < 2.1 or higher

DTs: barrel muon drift tubes

- Generation of a supply of BTIM chips (DT front end trigger primitive chip
- Relocation of the Sector Collector boards from the periphery of the detector

CSC: cathode strip chambers

- Addition of a fourth layer of chambers (ME4/2) and associated readout and triggering electronics Upgrade of the layer 1 (ME1/1) electronics with a new CSC "Digital" Front End Board (DCFEB)
- Deployment of new muon trigger primitive electronics to deliver the additional track segments