Status, Open Questions and Future Perspectives of Particle Physics

physikus particulae --

– ubi es ?

– cui prodes ?

– quo vadis ?

MAX-PLANCK-GESELLSCHAFT

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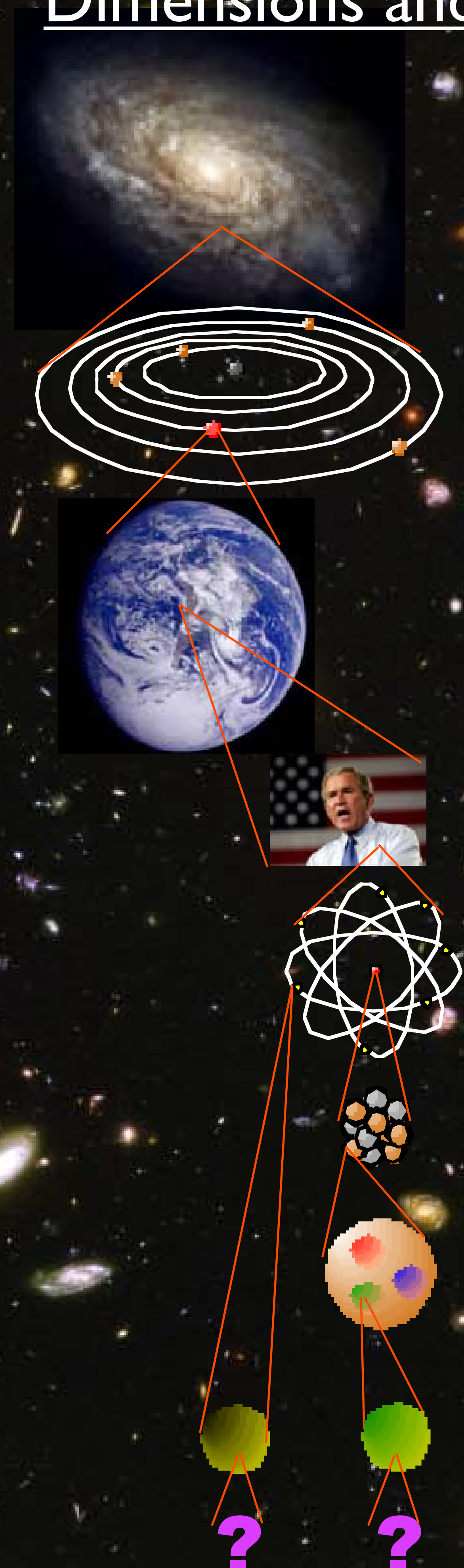
Dimensions and Structure of Matter



Universe 10^{26} m

Galaxy 10^{21} m

Solar System 10^{13} m

Earth 10^{7} m

Human 10^{0} m

Atom 10^{-10} m

Atomic Nucleus 10^{-14} m

Nucleon 10^{-15} m

Quark; Lepton $< 10^{-18}$ m

????? ???

Particle Physics

- ubi es

The „Standard Model" of Particle Physics

Elementary Particles	Generation 1	Generation 2	Generation 3
Quarks	**u** **d**	**c** **s**	**t** **b**
Leptons	ν_e e	ν_μ μ	ν_τ τ

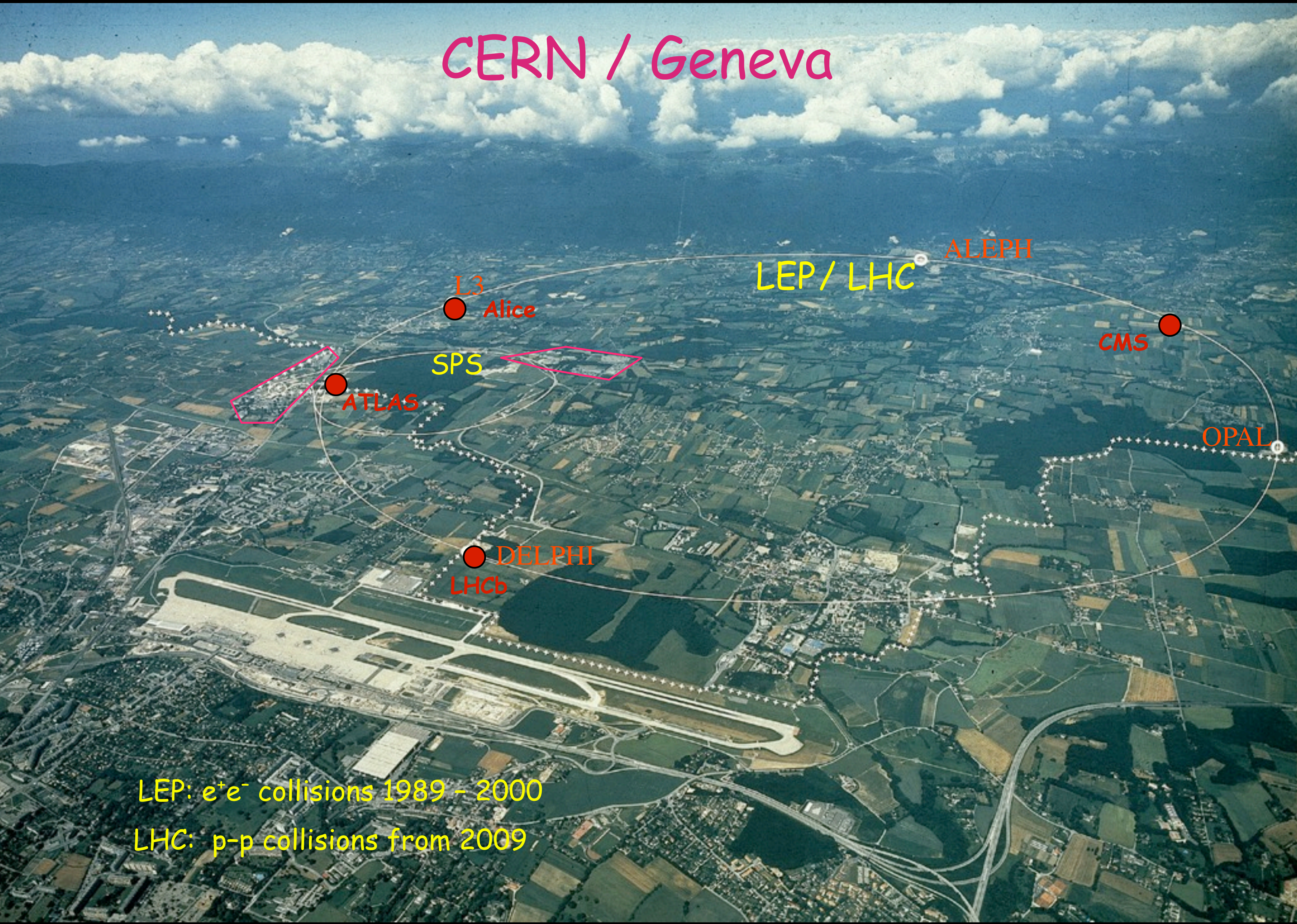
... as well as anti-particles

Elementary Forces	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	$W^\pm, Z^0$	10^{-14}
Gravitation	*G*	10^{-40}

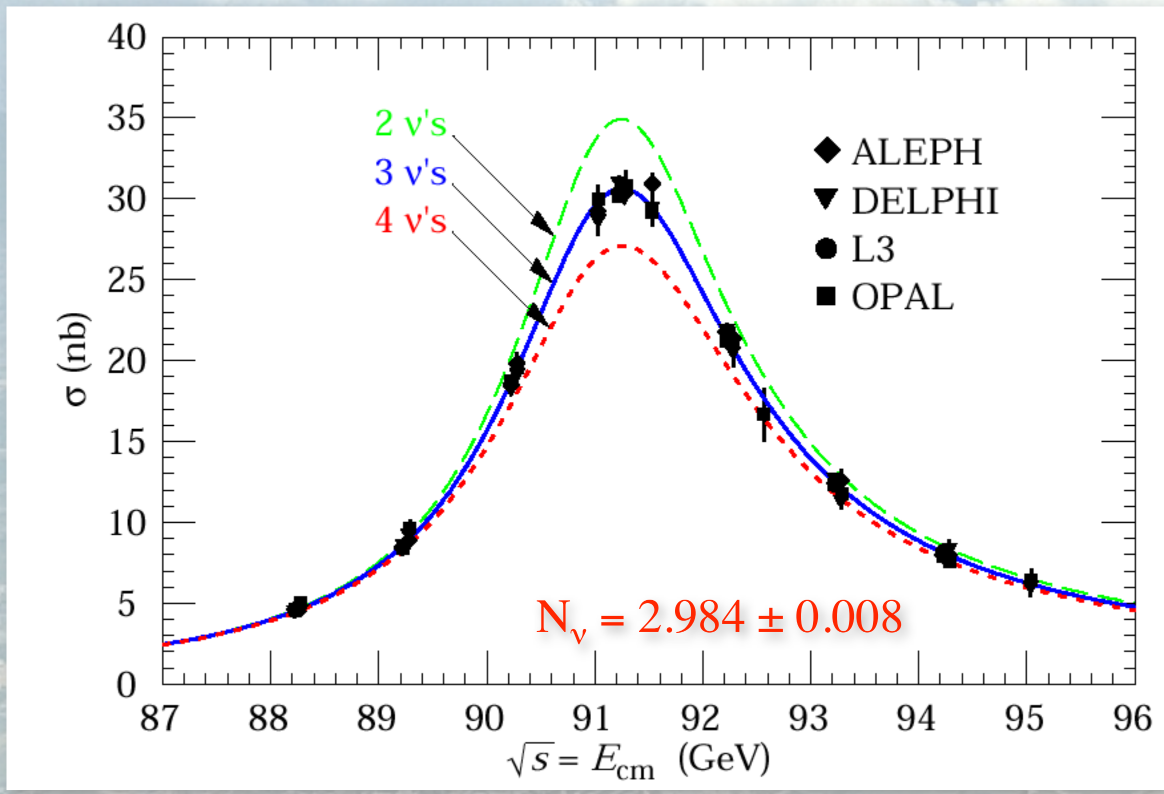
SM describes describes dynamics of all known particles and forces

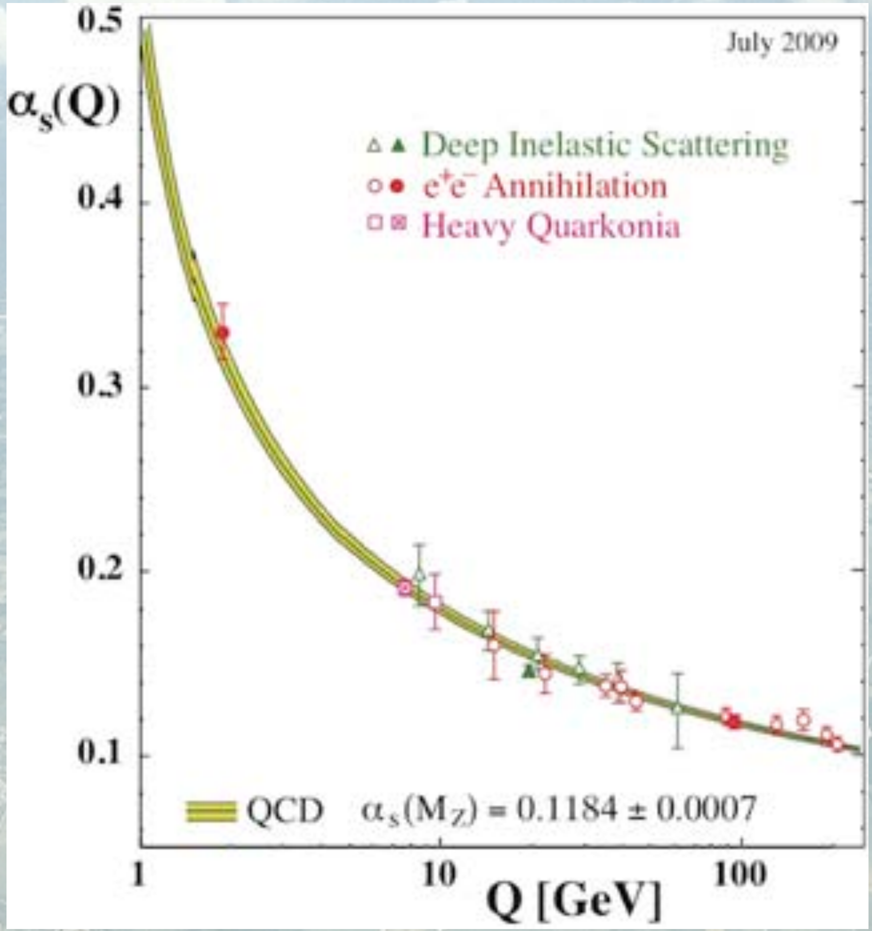
(known matter consists of members of 1^{st} generation)

theoretical predictions to explain origin of
the different masses of particles:
the HIGGS Boson
(unobserved)


CERN / Geneva
ALEPH
LEP/ LHC
L3
Alice
CMS
SPS
ATLAS
OPAL
DELPHI
LHCb
LEP: e+e- collisions 1989 – 2000
LHC: p–p collisions from 2009

Some Highlights from LEP & Co:





- resonance line of the Z^0 at LEP: there are exactly 3 generations of neutrinos (particles)

- M_Z = (91.1875 ± 0.0021) GeV (...after correcting for phases of moon and TGV train schedule)

- exp. tests of the Standard Model of particle physics at per-mille level

- precision measurement of strength of Strong Force: α_s „runs"; proof of Asymptotic Freedom, of Confinement and therefore, of QCD!

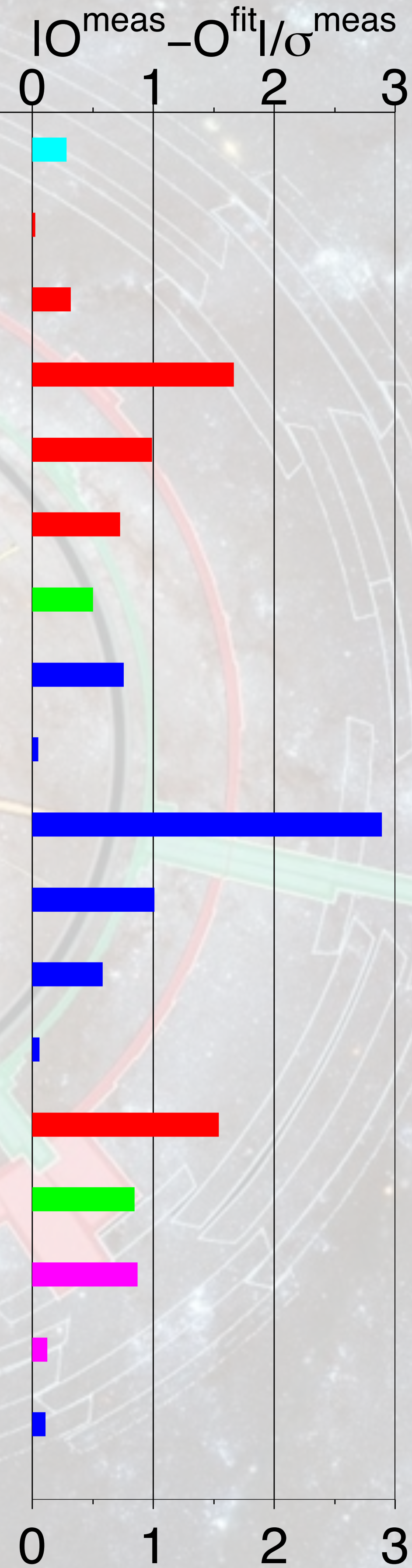
Nobel Price 2004

- limits on the mass of the Higgs-Boson (unobserved, but predicted by theory):

114.1 GeV < M_H < 185 GeV

Measurements and Fits of electro-weak parameters

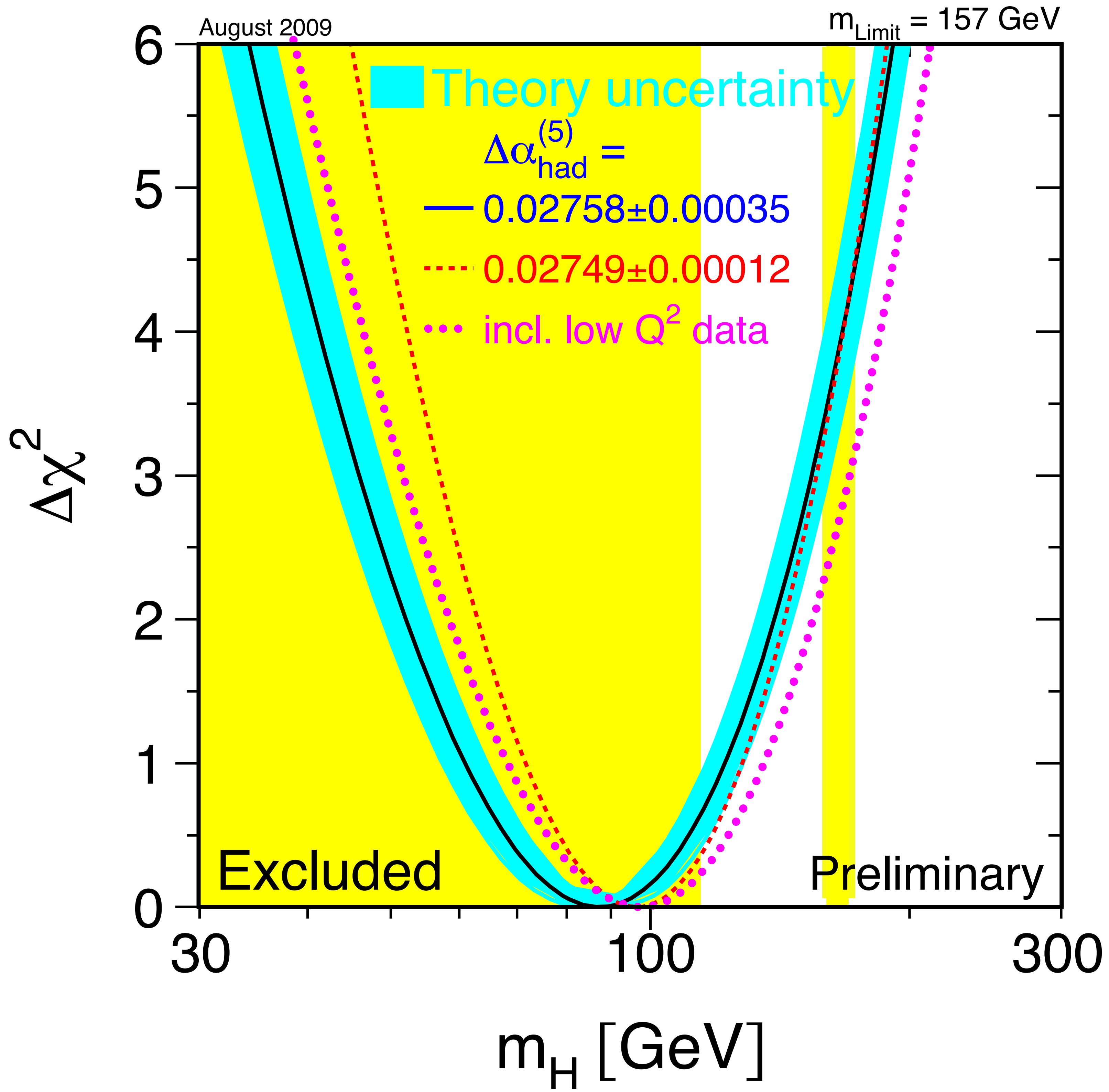
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

mostly from LEP / SLC; also includes Tevatron: M_t, M_W

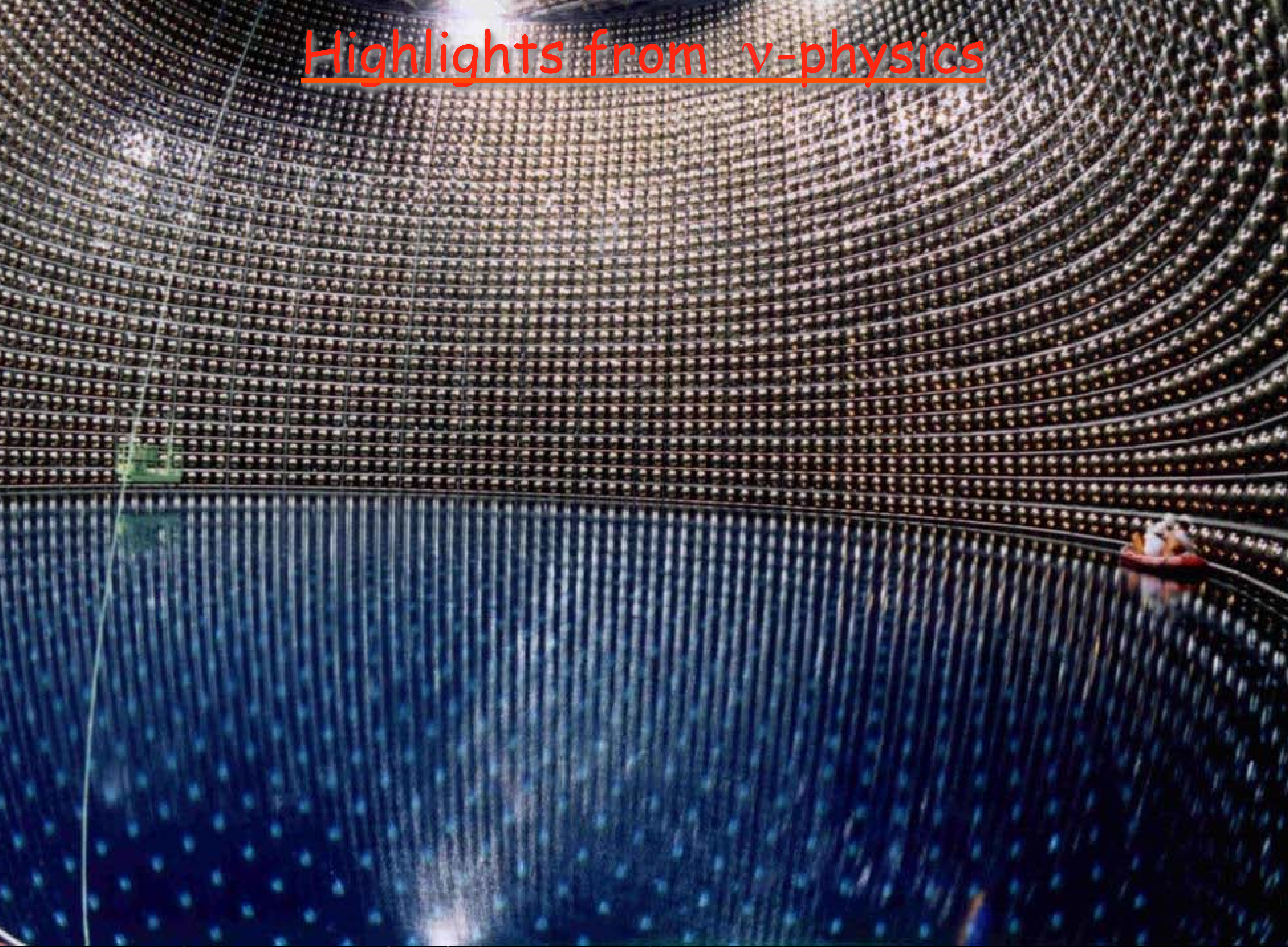
direct and indirect searches for the Higgs Boson



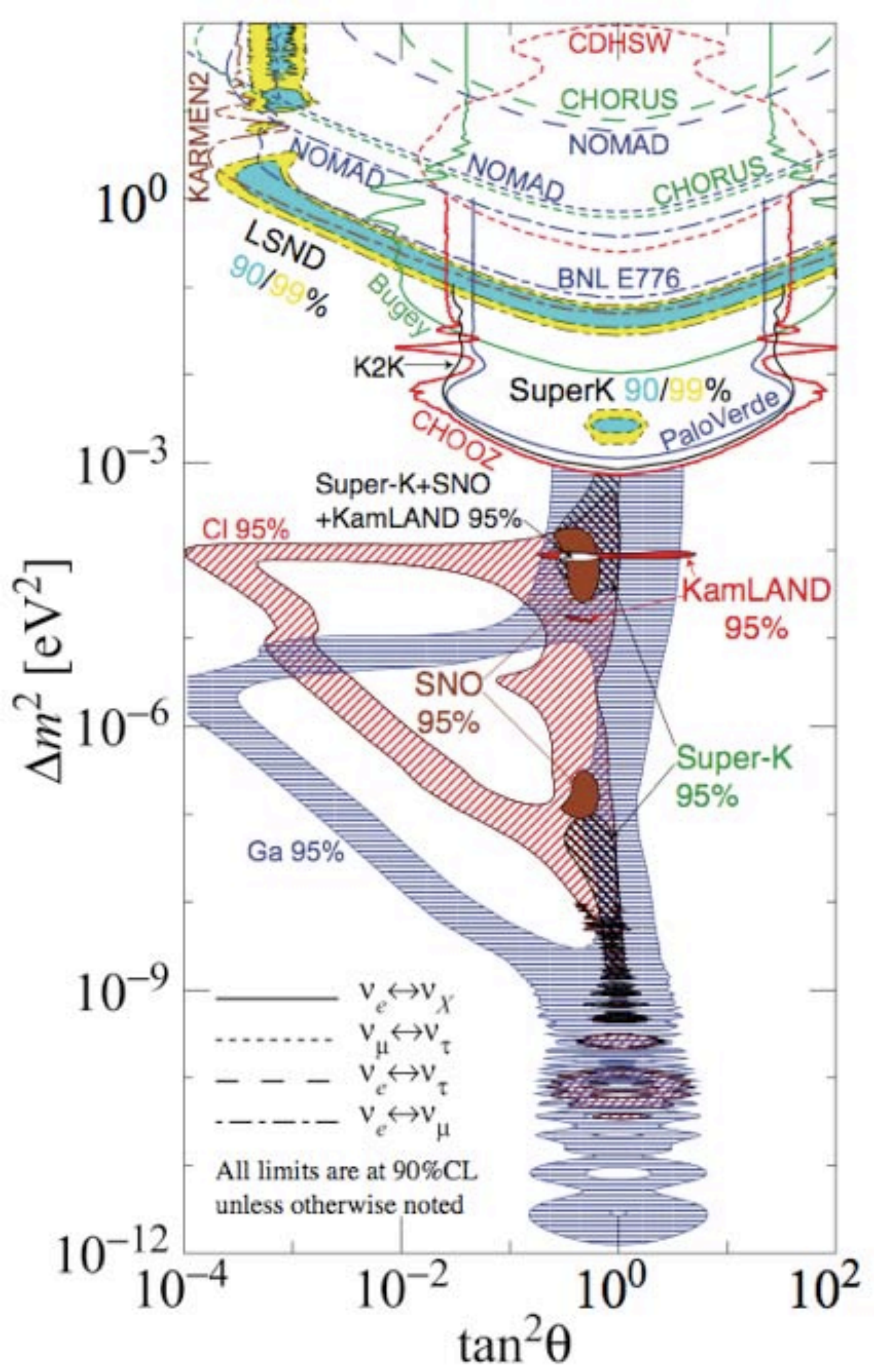
direct Higgs searches: $M_H > 114.1$ GeV/c²; $M_H \notin [158,175]$ (95% CL)

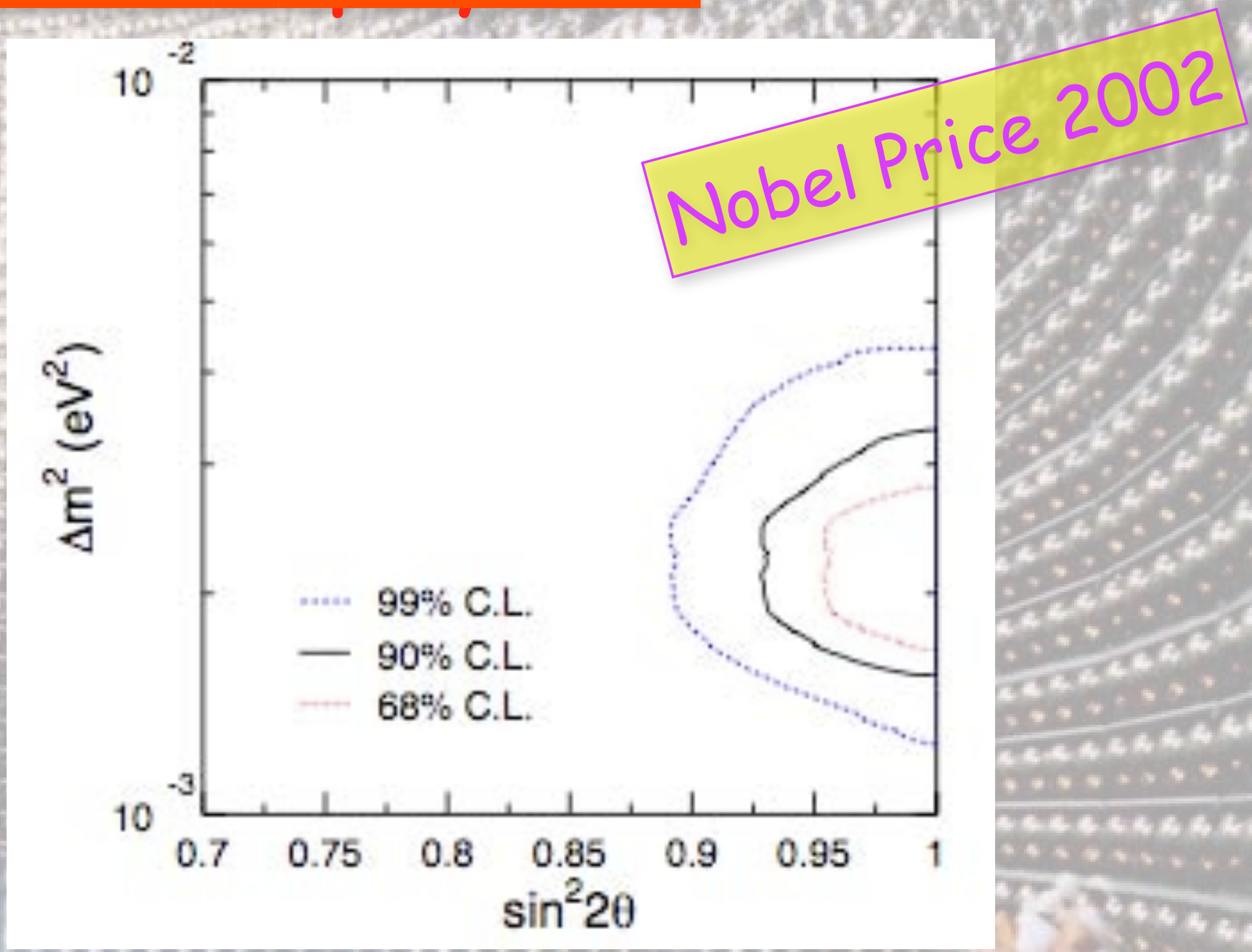
indirect from radiative corrections: $M_H < 186$ GeV/c^2 (95% CL)

Highlights from ν-physics



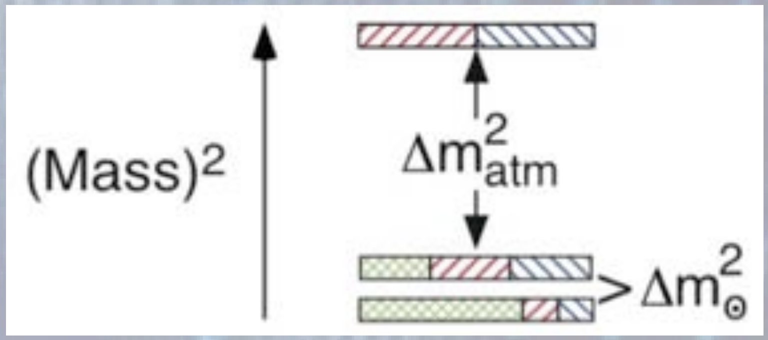
Highlights from ν-physics





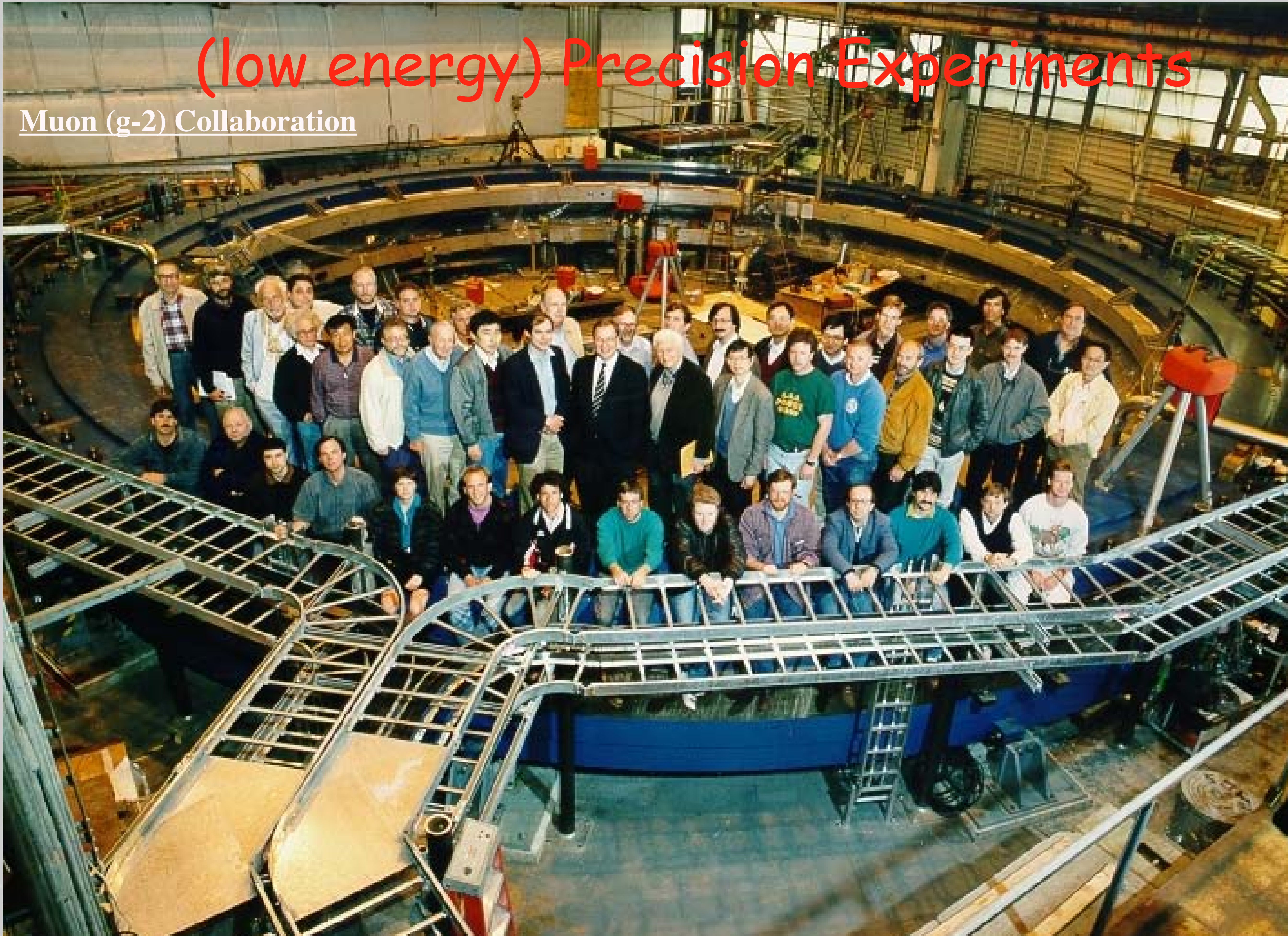
• atmospheric neutrinos: oscillation $\nu_\mu \to \nu_x$
=> neurinos have (different) masses.

• solar and reactor- neutrinos: oscillation $\nu_e \to \nu_x$
=> solution to the solar neutrino problem.

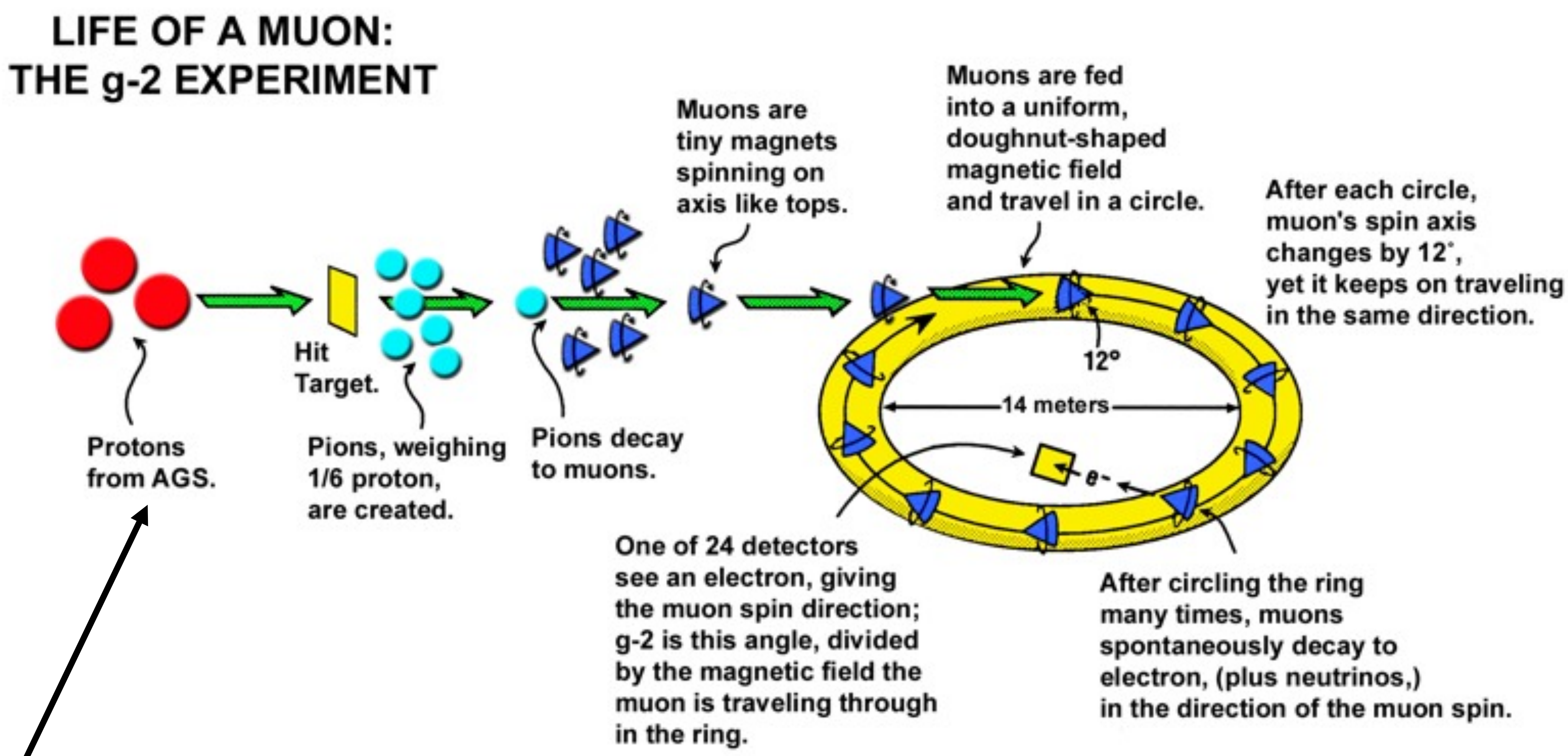


consistent explanation of mass-/flavour-eigenvalues of 3 neutrino families?

(low energy) Precision Experiments



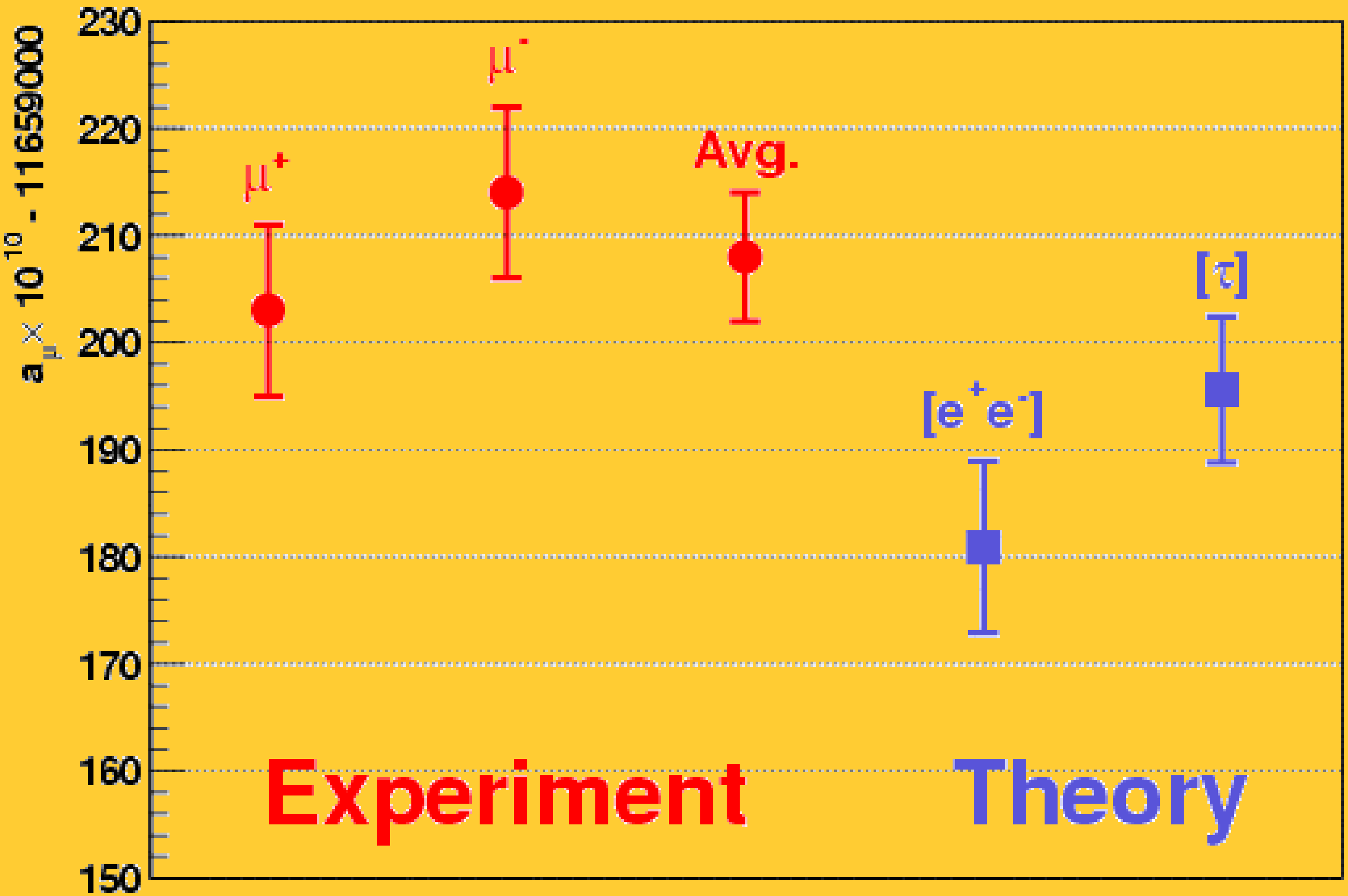
the anomalous magnetic moment of the muon (g–2)



Brookhaven alternate gradient synchrotron

The (g-2) value of the negative muon was announced January 8, 2004!

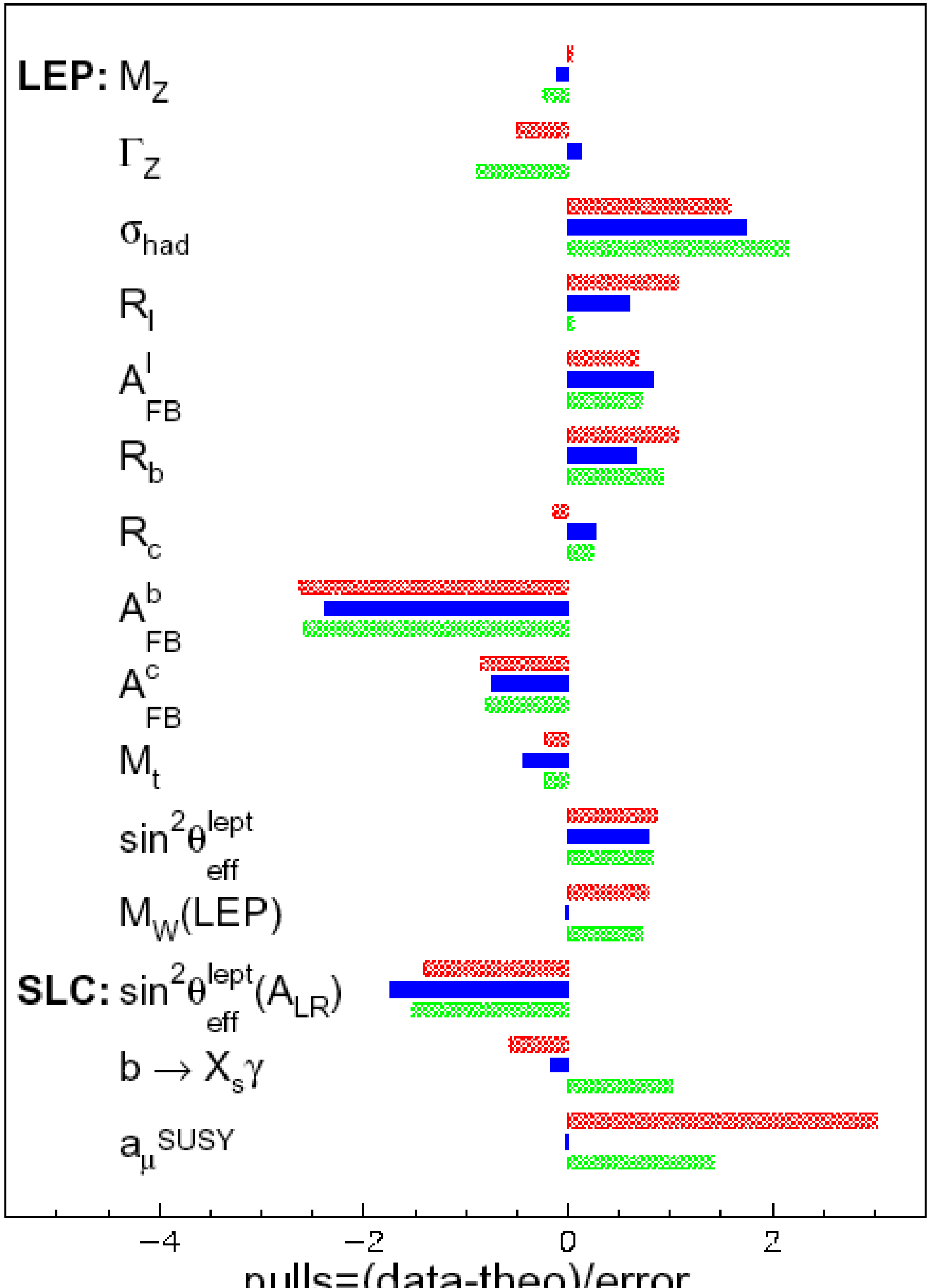
a_{μ^-} (BNL'01) = 11 659 214 (8)(3) $\times 10^{-10}$ (0.7 ppm)



a_μ (exp) = 11 659 208 (6) $\times 10^{-10}$ (0.5 ppm)

Supersymmetry: indirect searches

Global fits to world precision ew data



SM: χ^2/d.o.f = 27.2/16

MSSM: χ^2/d.o.f = 16.4/12

CMSSM: χ^2/d.o.f = 23.2/16

- slightly improved fit quality of SUSY-models

– however –

- mostly due to a_μ measurement (anomalous magnetic moment of μ)

de Boer & Sander, PLB585 (2004) 276

ubi es ?

so far, no significant signal for physics beyond the Standard Model of Particle Physics !

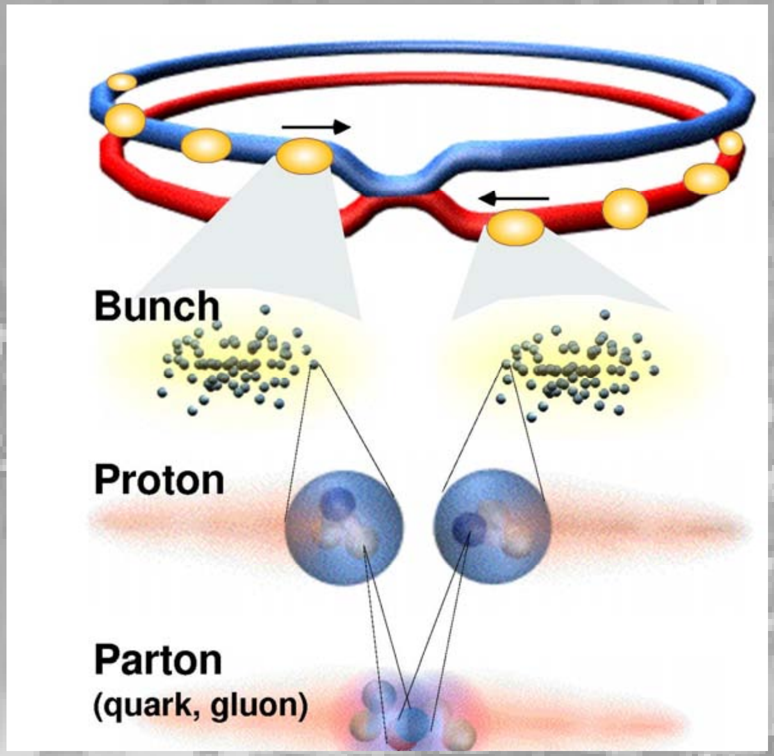
however, the future has just begun:

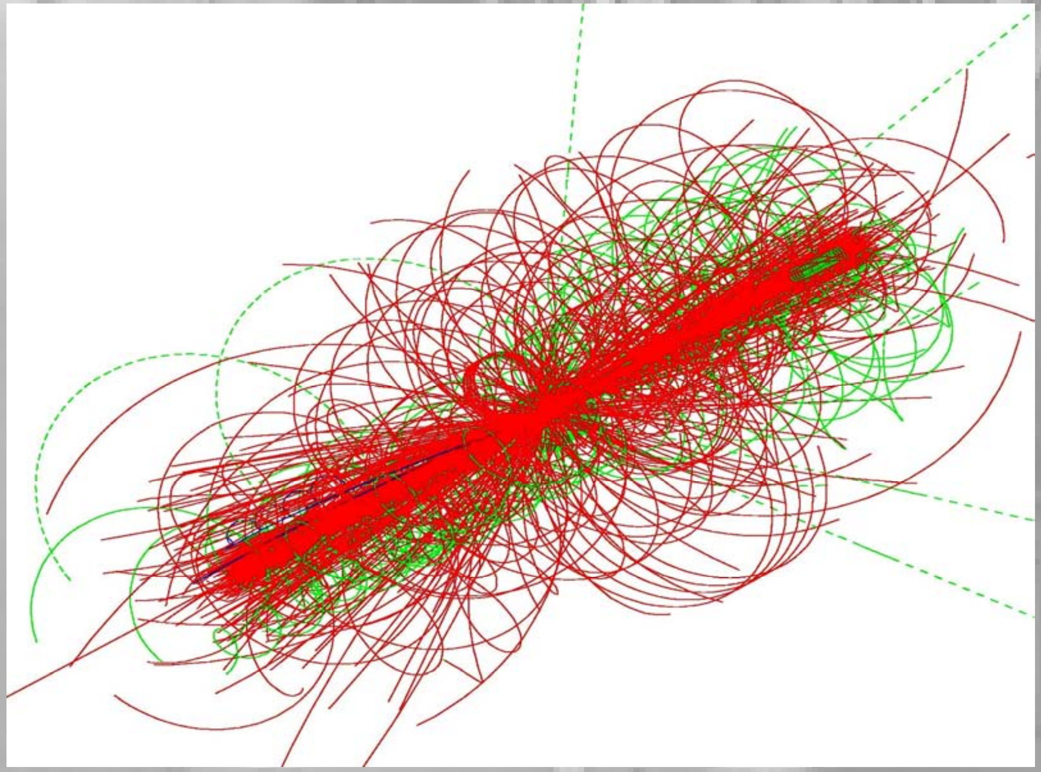
high energy operation of the Large Hadron Colllider started in March 2010

since March 2010, the LHC collides protons at 7 TeV c.m. !

ATLAS control room; 30.3.2010 13:01

The Large Hadron Collider (LHC)





Proton – Proton Collisions:

2835 x 2835 bunches
distance: 7.5 m (25 ns)

10^{11} Protons / bunch
Collision rate: 40 million / sec.
Luminosity: $L = 10^{34}$ cm^{-2} sec^{-1}

Proton-Proton collisions: ~10^9 / sec
(about 23 pp-interactions per bunch crossing)

~1600 charged particles in detector

high demands on detectors

LHC

the largest scientific project ever attempted

- 30,000 tons of 8.4 Tesla s.c. dipole magnets cooled to 1.9 degrees K by 90 tons of liquid helium

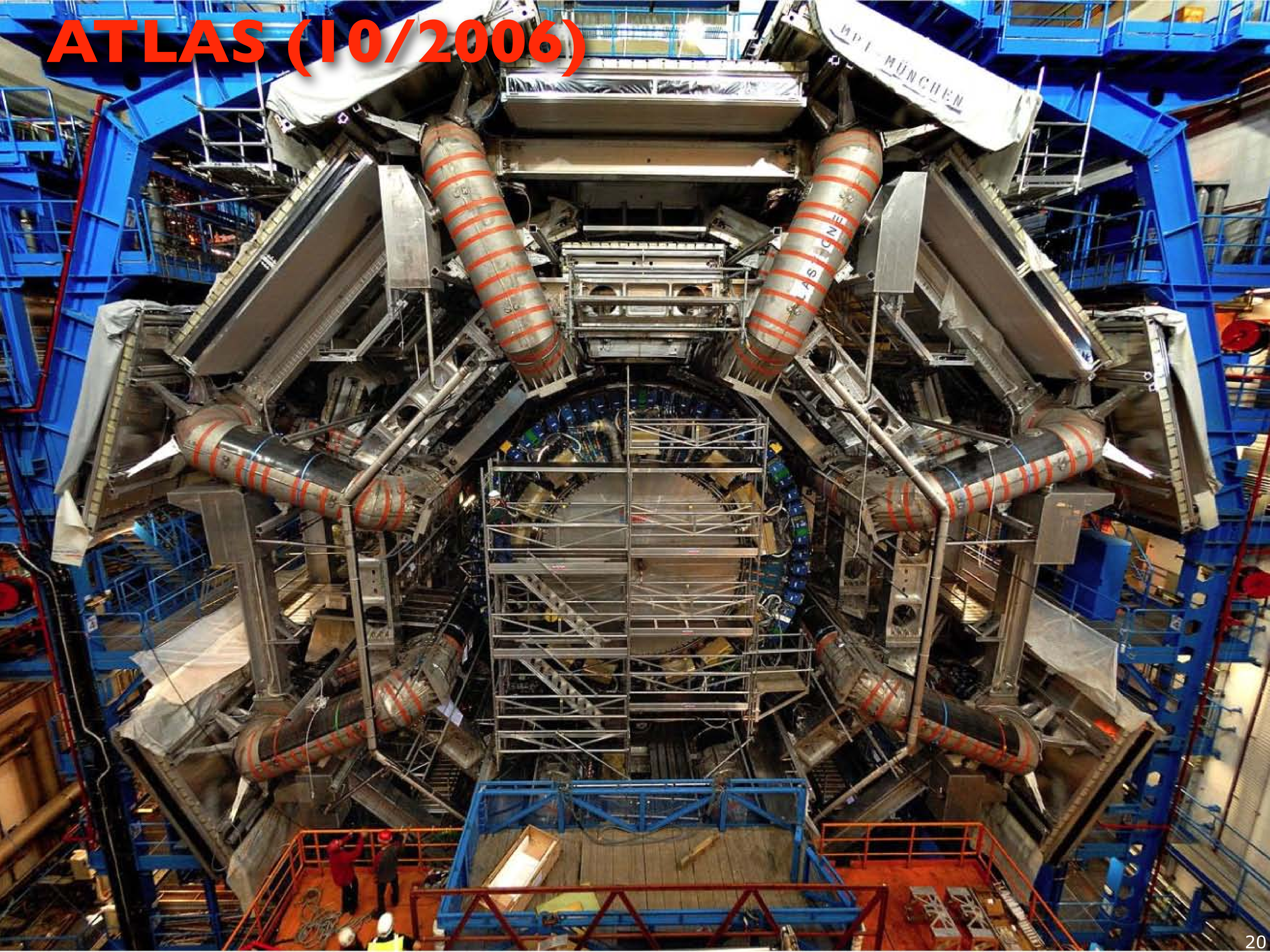
- 40 MHZ collision rate = 1 Terabyte/sec raw data rate from the CMS and ATLAS particle detectors

- 7000 tons (ATLAS) and 12.500 tons (CMS) of high precision particle detector technology

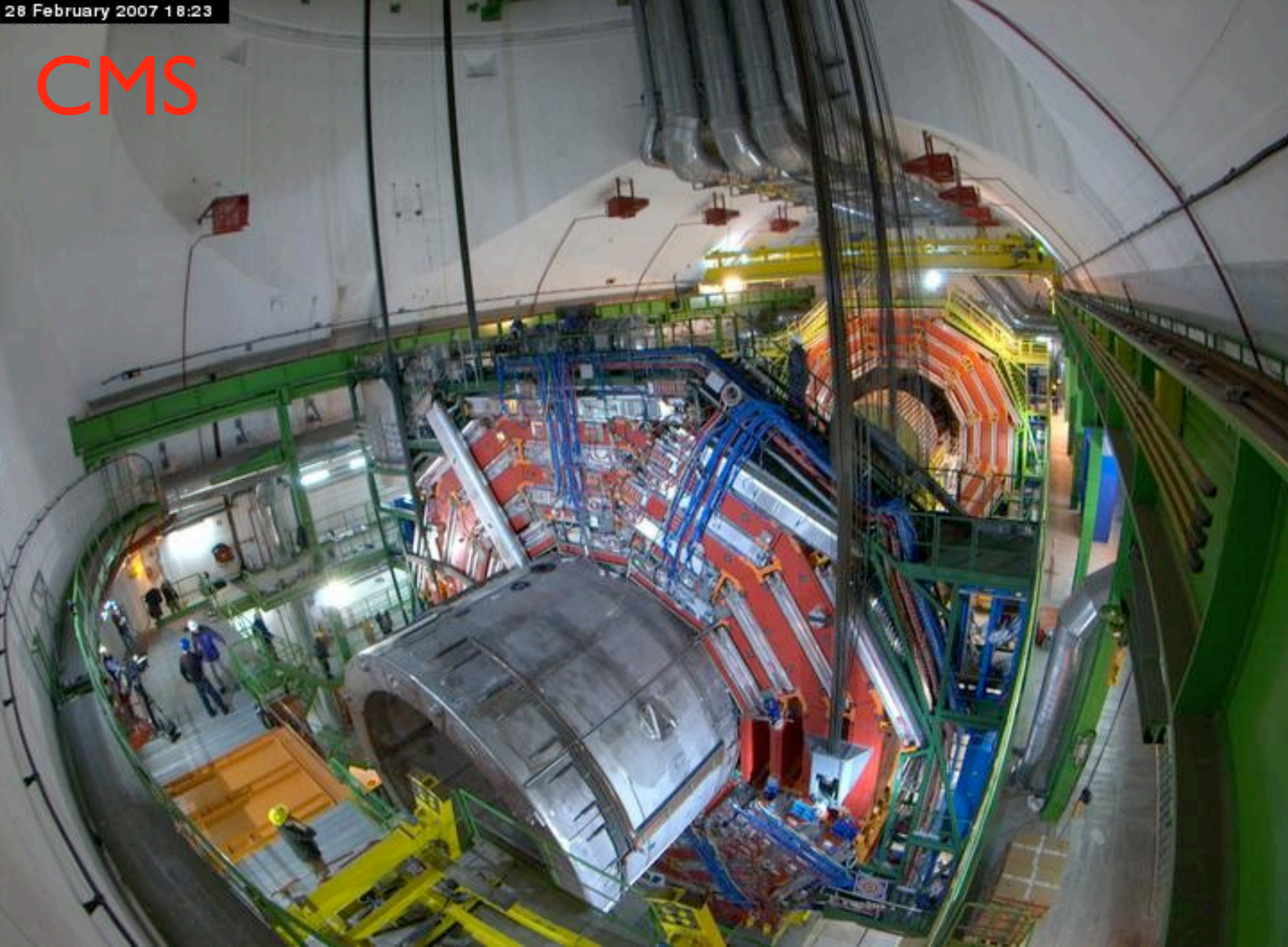
(for comparison: – weight of fully loaded Boeing 747: 200 tons
– Eiffel tower: 7.300 tons
- USS John McCain (warship): 8.300 tons)

LHC Tunnel (12/2005)

ATLAS (10/2006)

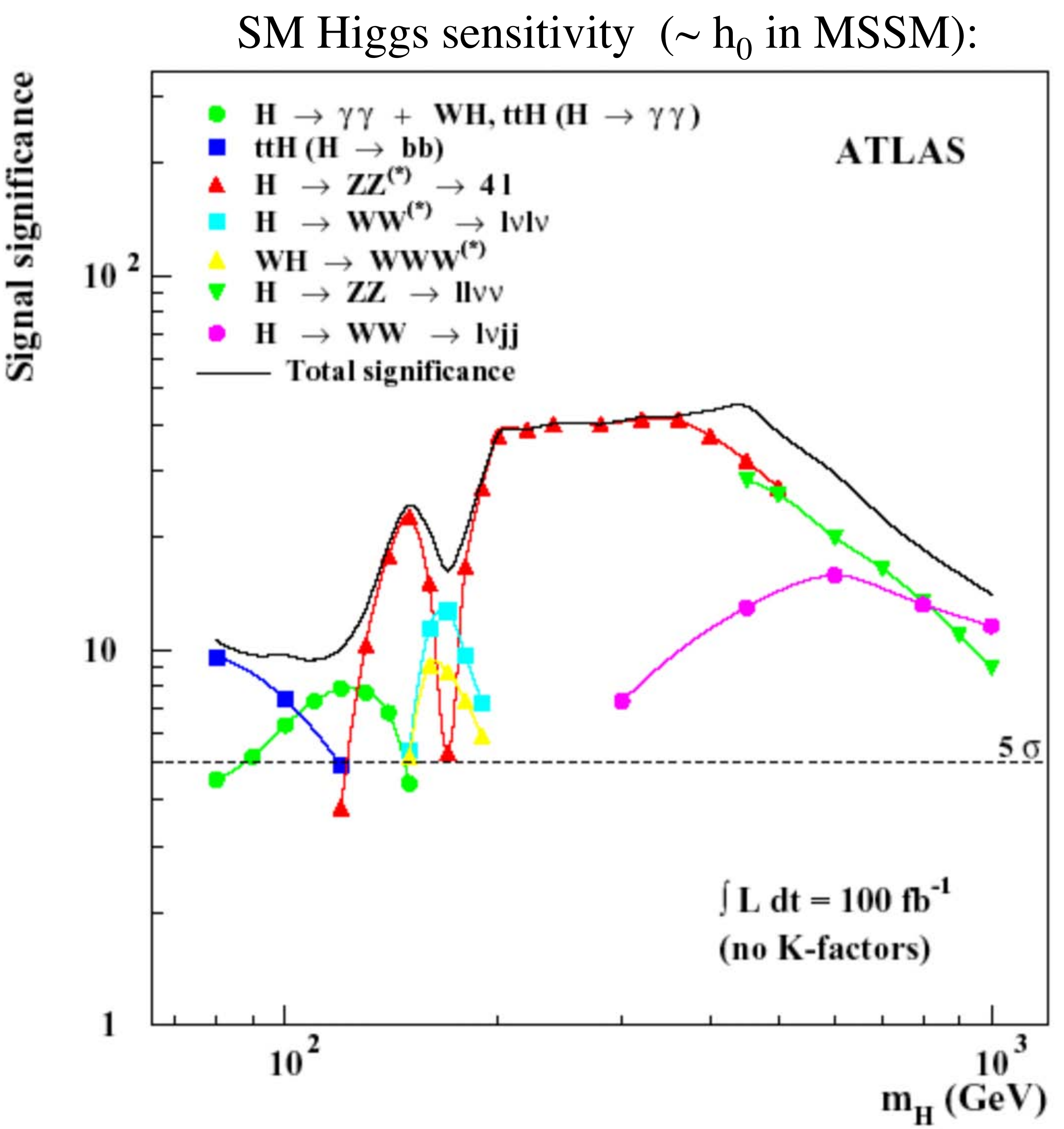


CMS

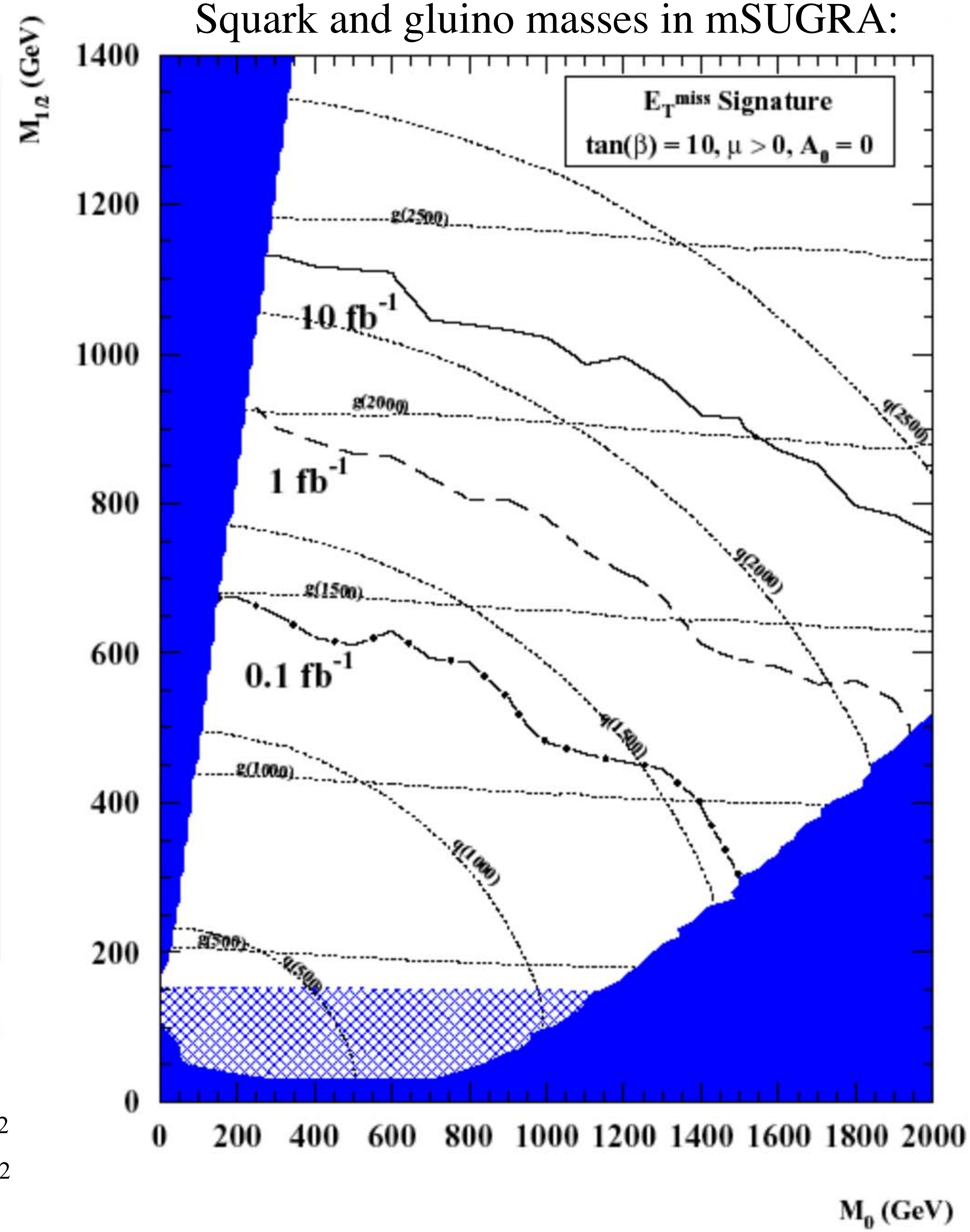


Higgs & SUSY Searches at the Large Hadron Collider

SM Higgs sensitivity (~ h_0 in MSSM):



Squark and gluino masses in mSUGRA:

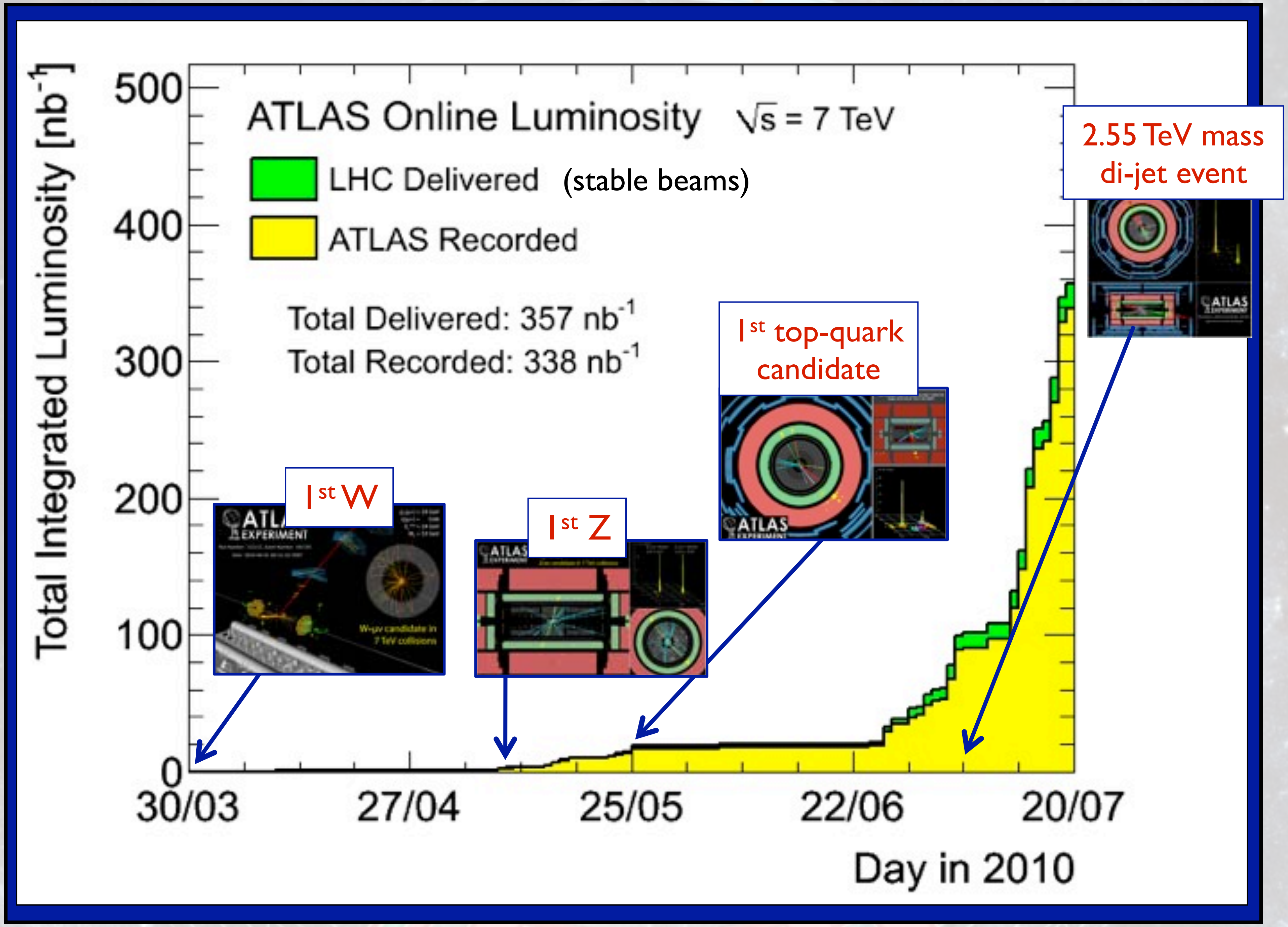


$10\ fb^{-1}$ —> 1^{st} year at initial Luminosity of $10^{33}\ s^{-1}\ cm^{-2}$

$100\ fb^{-1}$ —> first 3 years with Luminosity –> $10^{34}\ s^{-1}\ cm^{-2}$

• if standard Higgs exists, or if SUSY is realised at ~TeV scale, LHC will find it!

LHC: Integrated luminosity until July 22



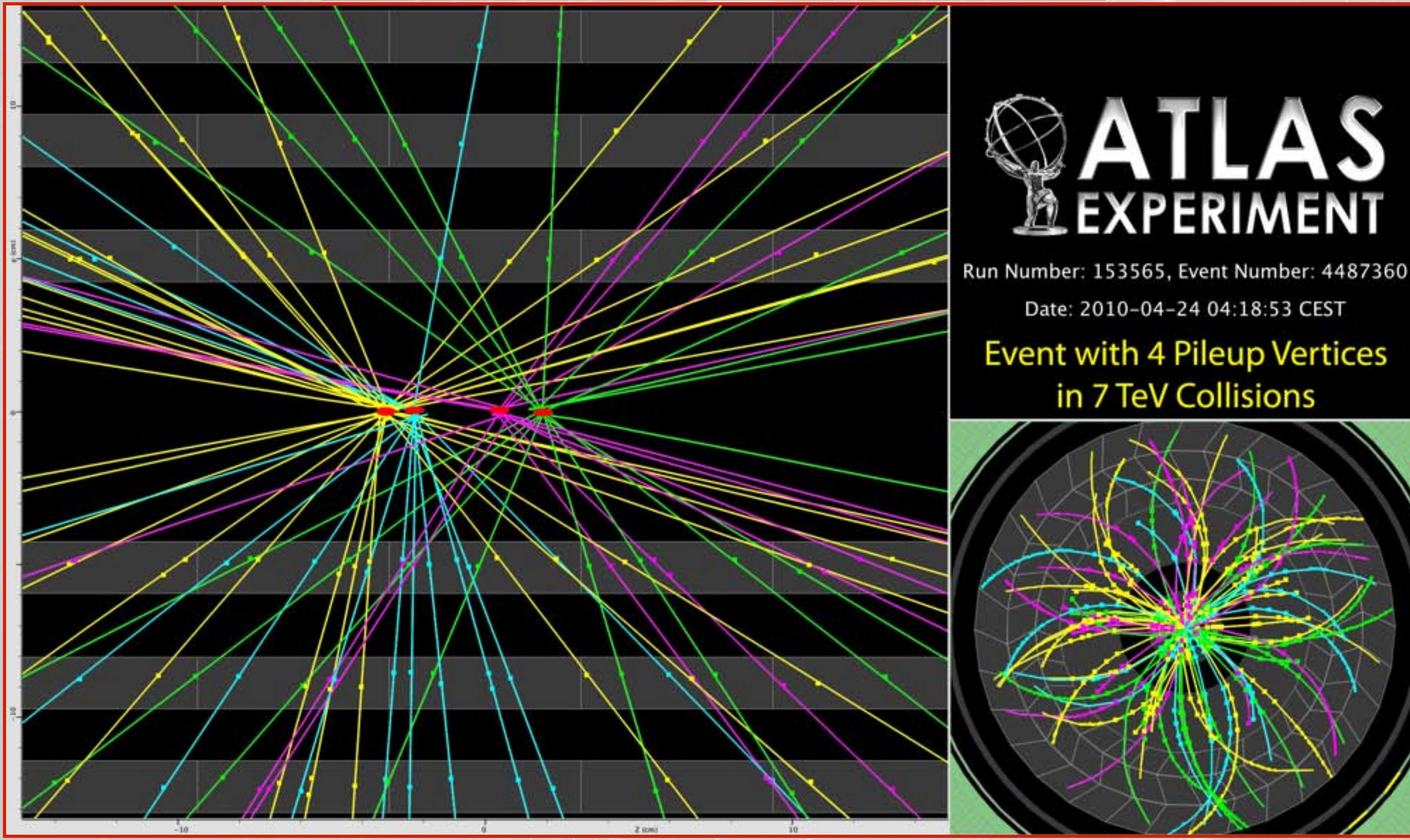
Overall data taking efficiency (with full detector on): 95%

Peak luminosity in ATLAS
$L \sim 1.6 \times 10^{30}\ cm^{-2}\ s^{-1}$

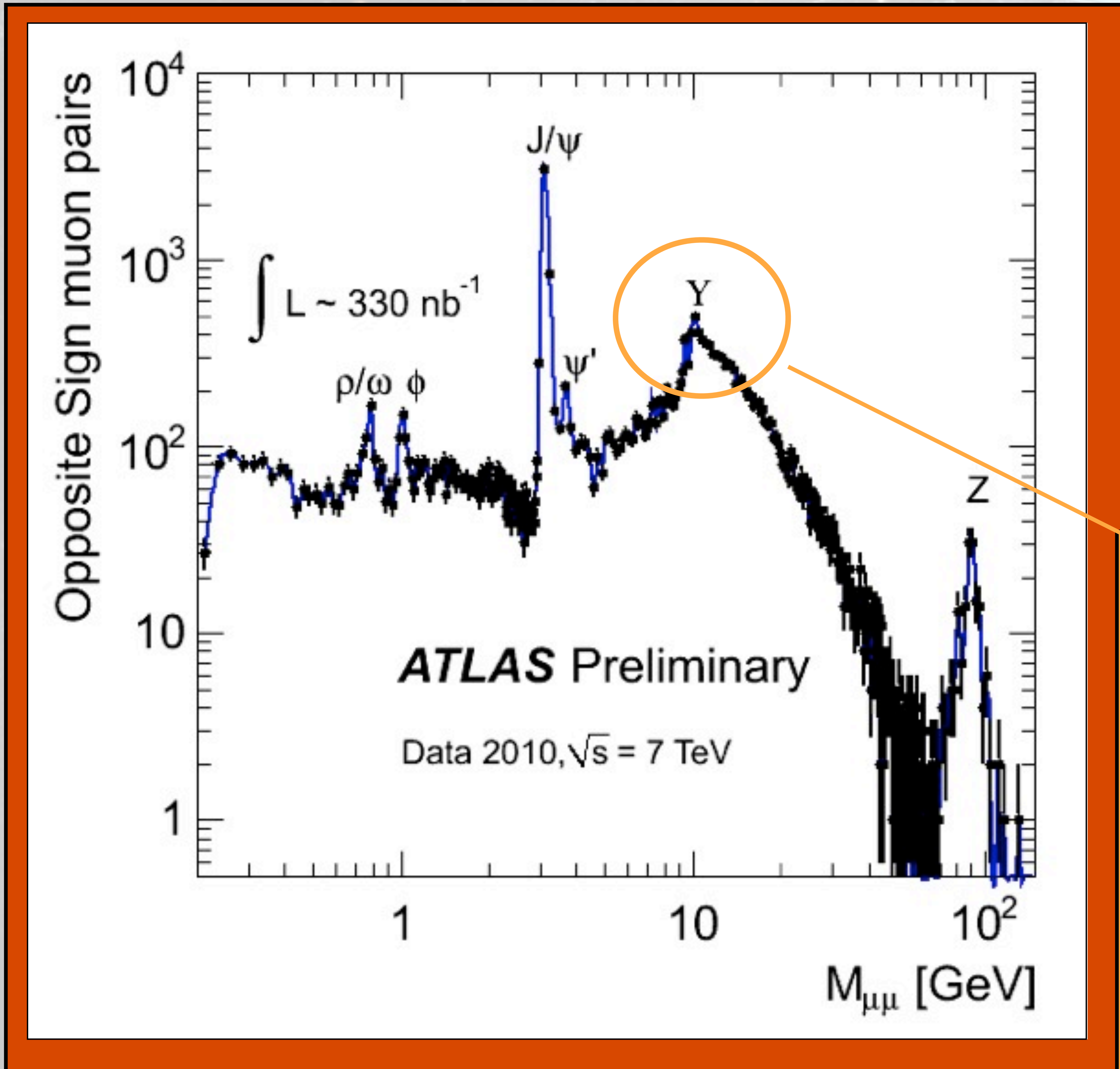
Luminosity known today to 11%
(error dominated by knowledge of beam currents)


LINUX
$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$+ i\bar{\psi}D\psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

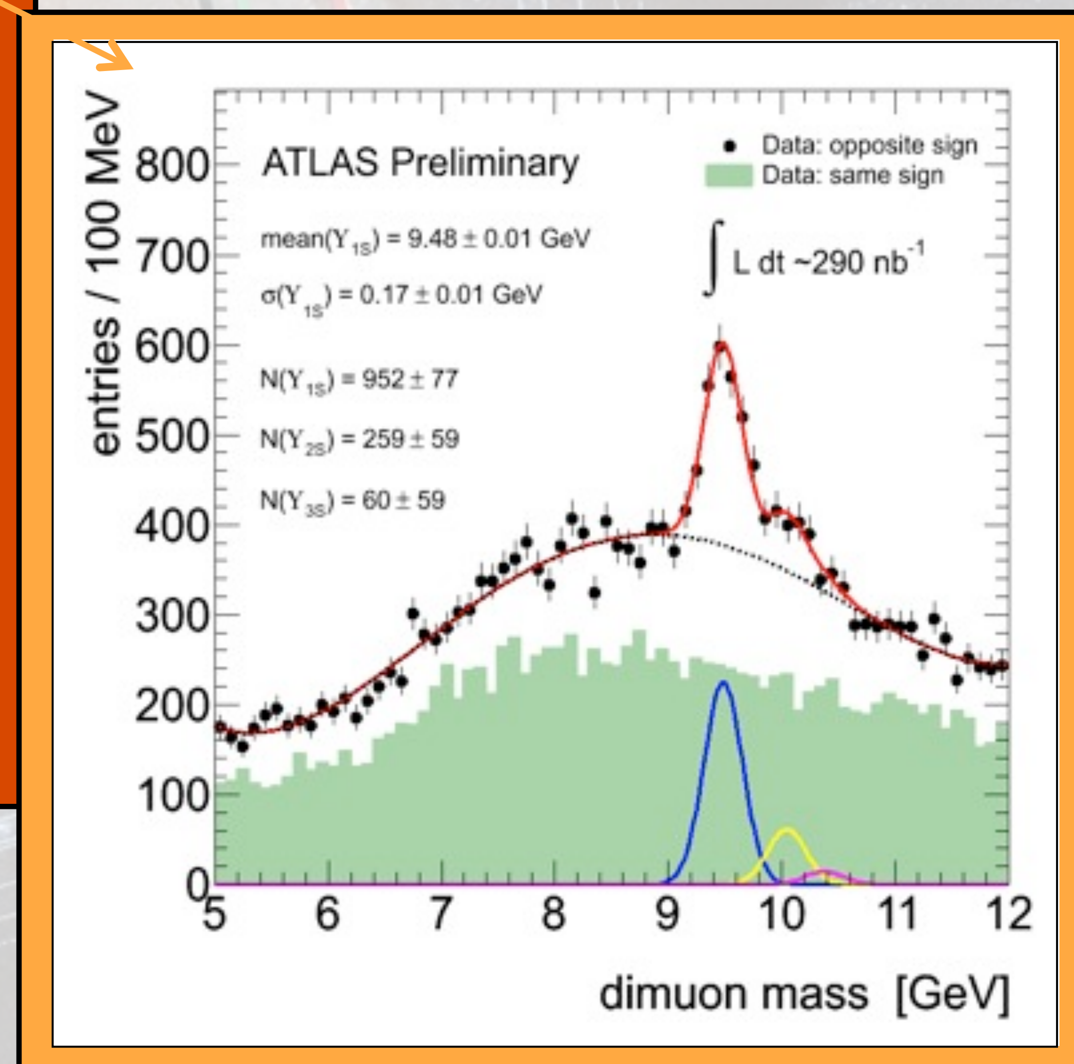
Event with 4 pp interactions in the same bunch-crossing

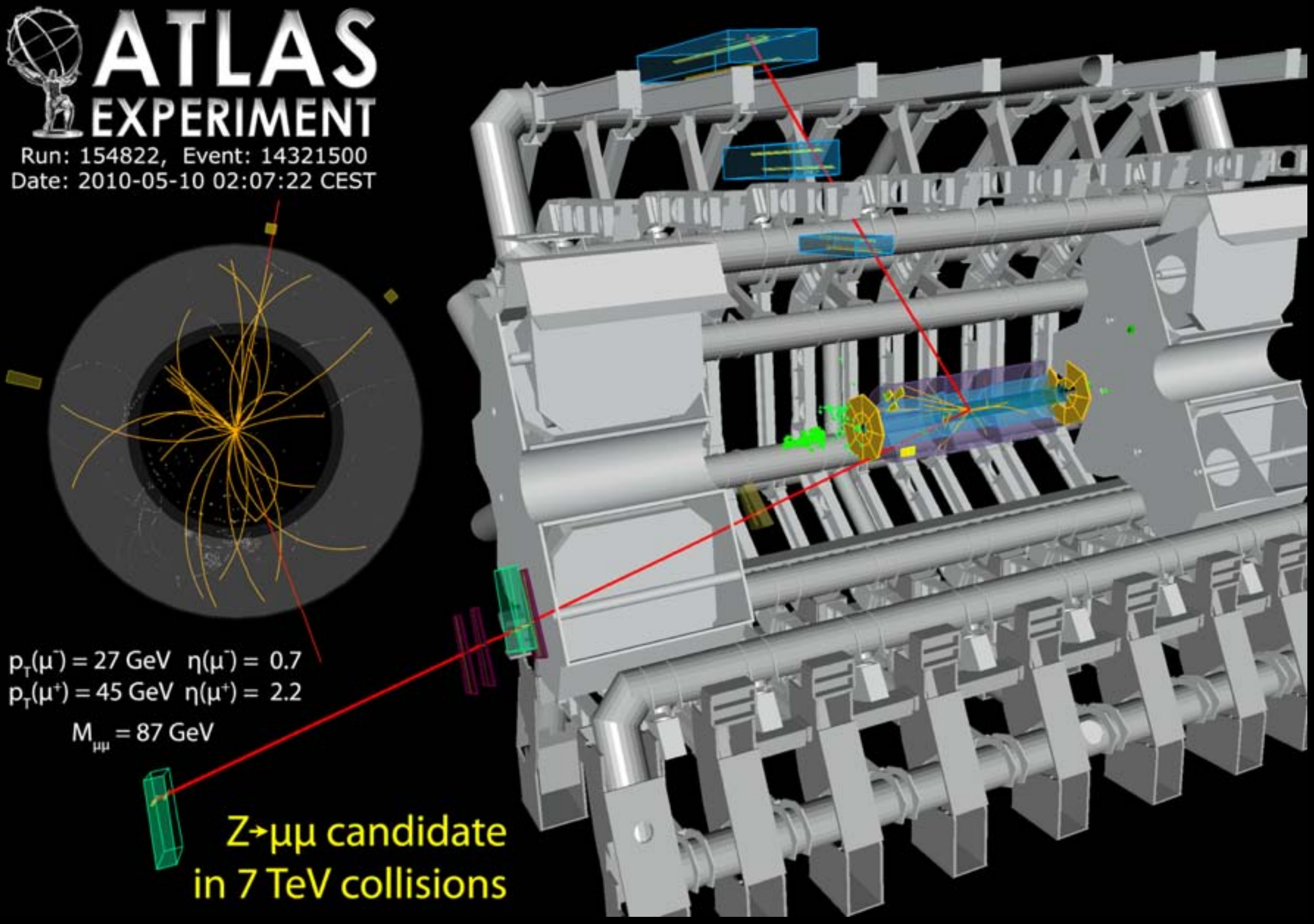


LHC: the re-discovery of the Standard Model

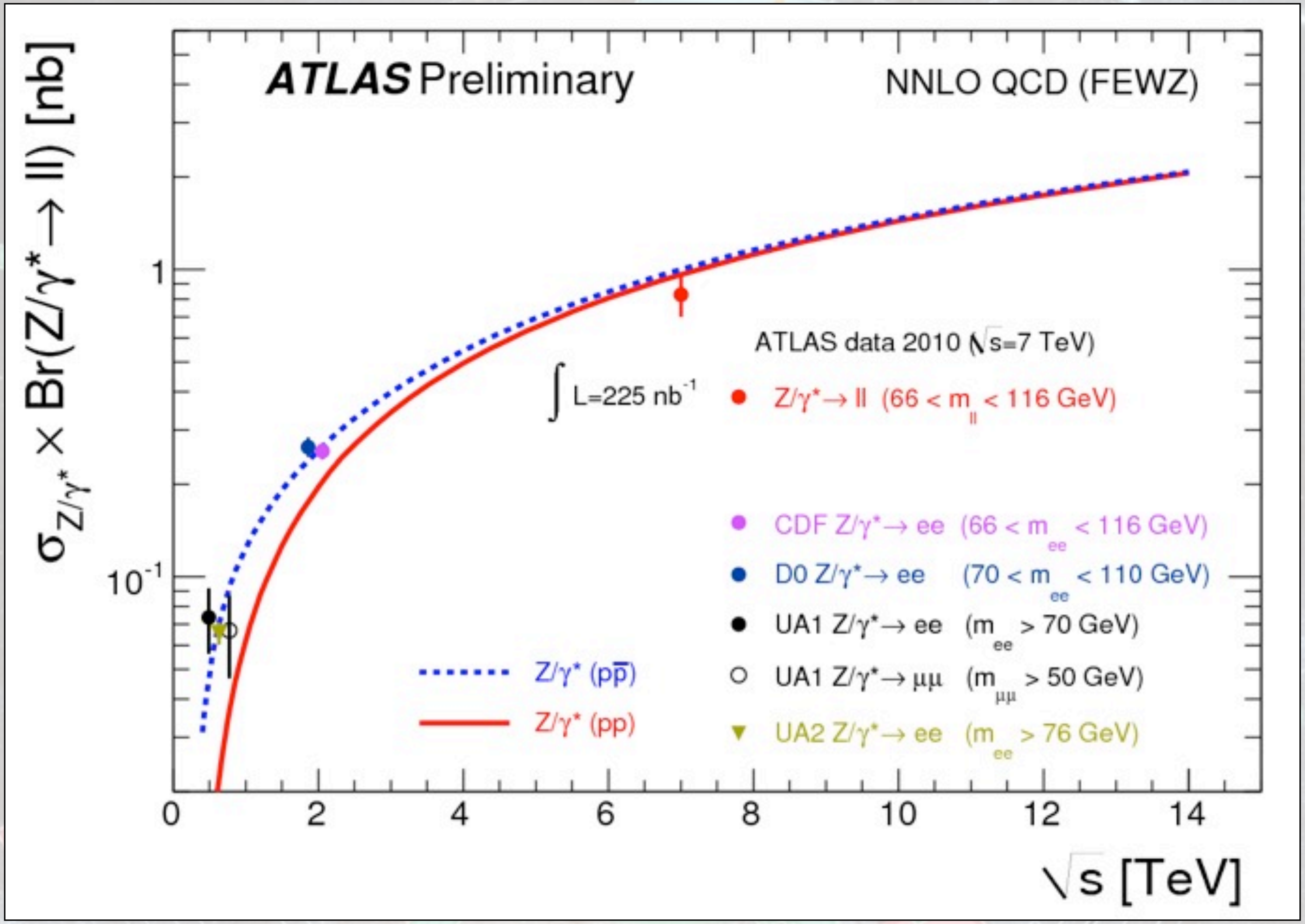


Di-muon resonances




ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

ATLAS: Z cross-section measurement

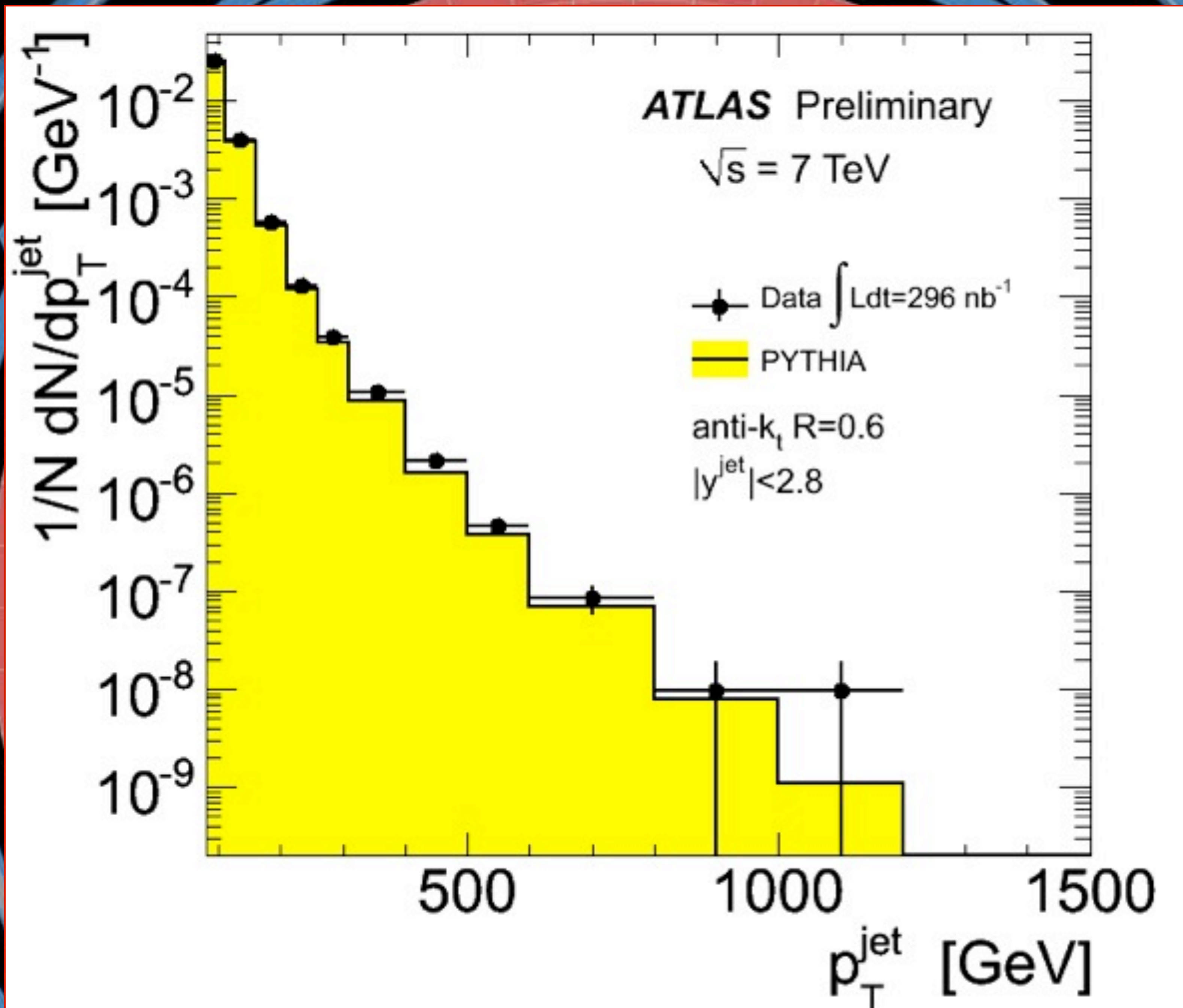


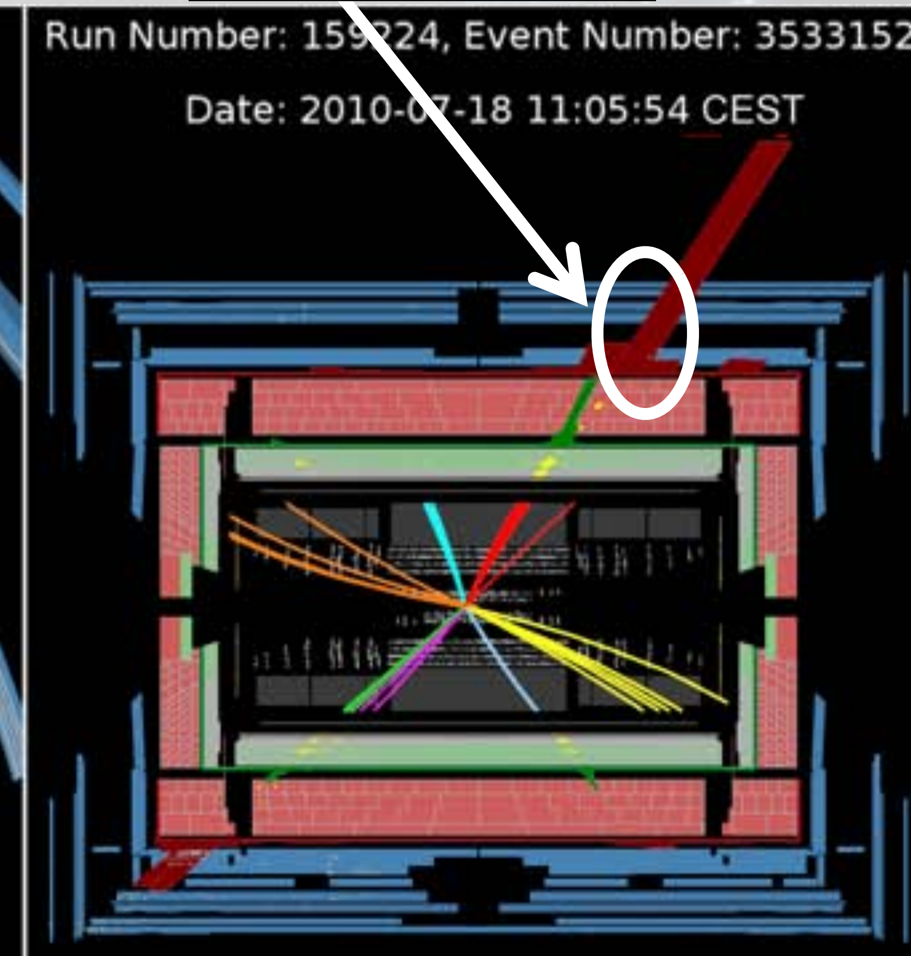
125 events:
46 Z→ ee
79 Z→ μμ

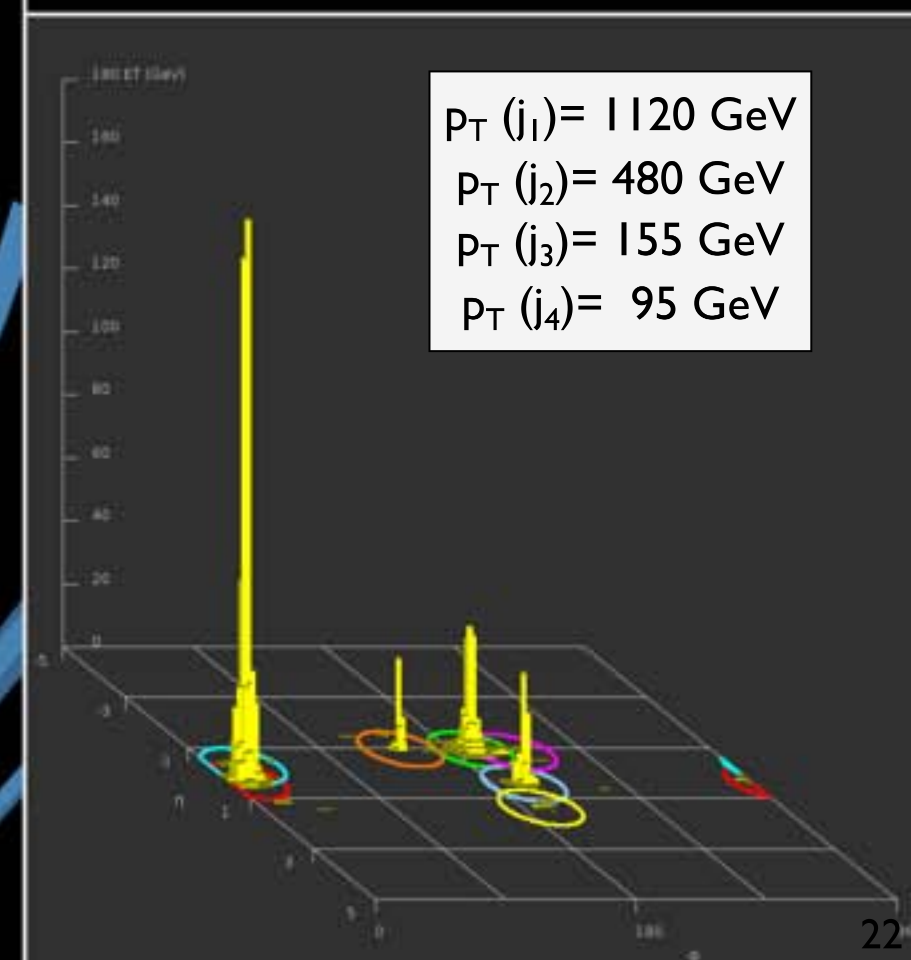
σ (Z → ll) = 0.83 ± 0.07 (stat) ± 0.06 (syst) ± 0.09 (lumi) nb

ATLAS: observed event with hardest jet

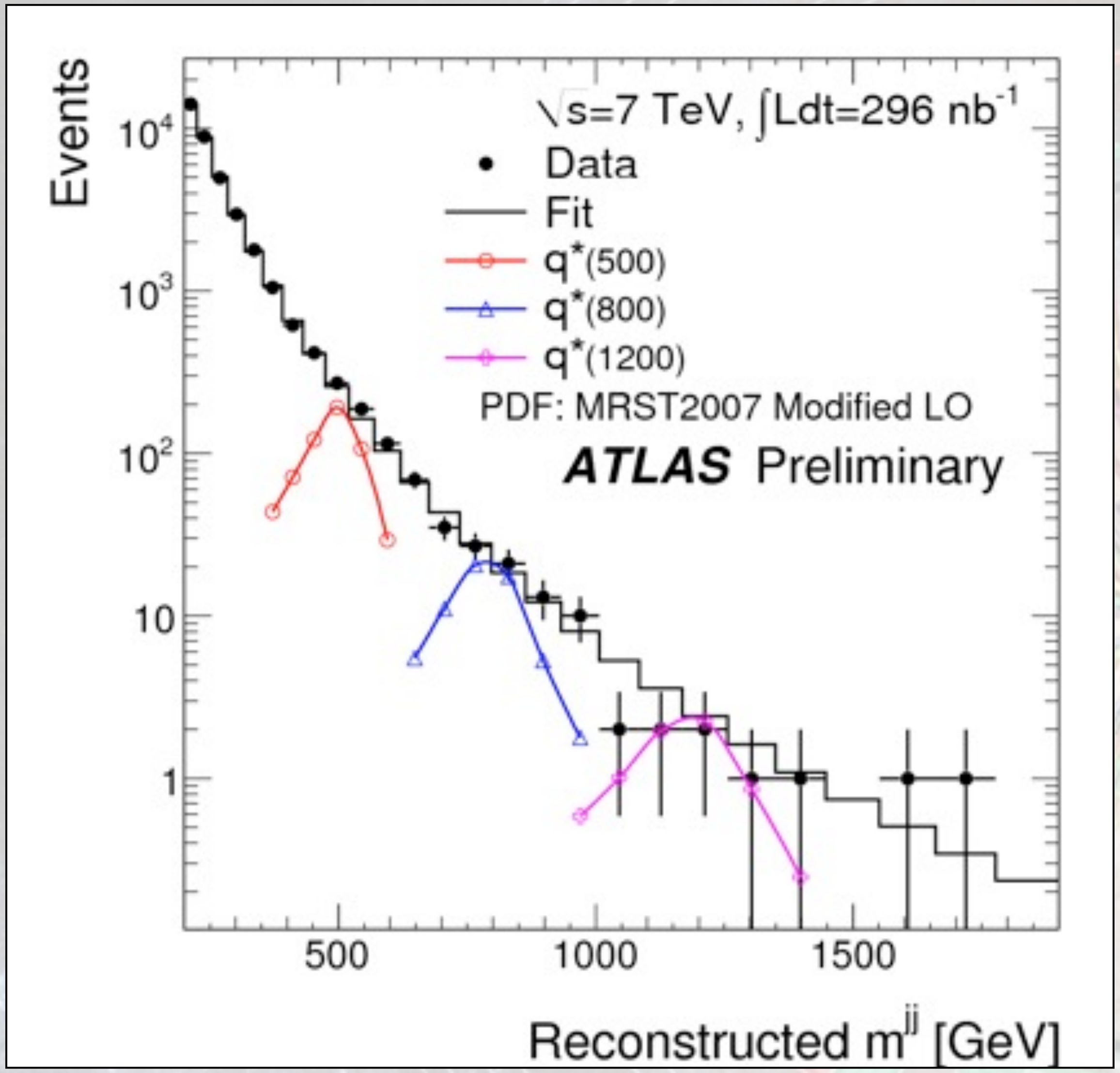
p_T (jet) > 1.1 TeV

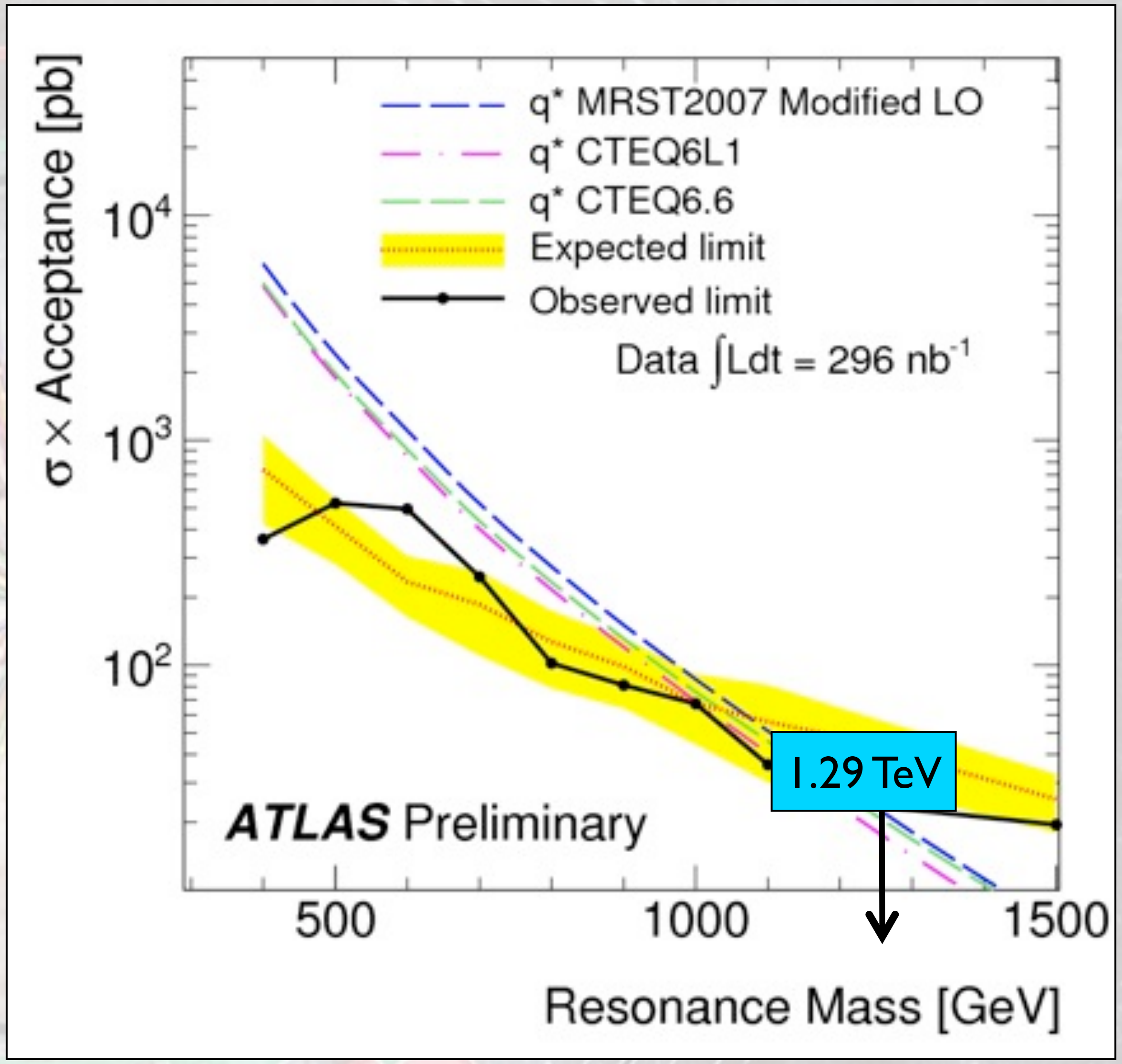






Searches for excited quarks: q* -> jj





0.4 < M (q*) < 1.29 TeV excluded at 95% C.L.

Latest published limit:
CDF: 260 < M (q*) < 870 GeV

ubi es ?

the Standard Model of Particle Physics ...

- describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;
- is extremely successful in consistently and precisely describing all particle reactions observed to date
- shows no *significant* discrepancies between data and theorie -- however it leaves open fundamental questions and problems which cannot be answered by the SM.

Particle Physics

- cui prodes

CNN contest (Nov. 2006): *„greatest wonders of the modern world"*

1: World Wide Web (50%)

2: particle accelerators at CERN (16%)

3: - none - (8%)

4: Dubai (7%)

5: the bionic arm (6%)

6: 3-Canyon Dam, China (5%)

particle physics

– is knowledge oriented basic research.

– has no direct relation to every-day applications .

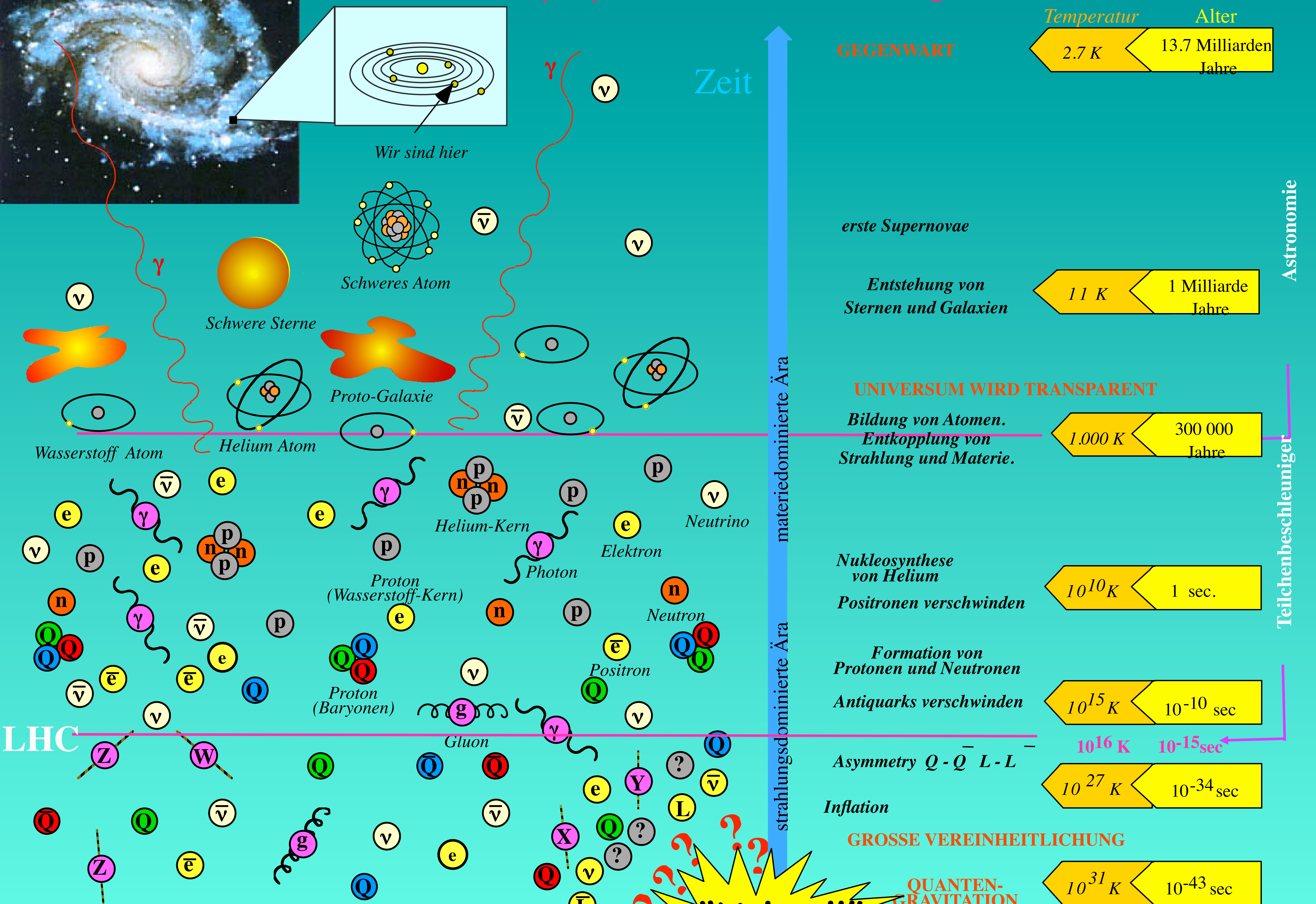
– bundels scientific interest world-wide and avoids duplication of projects

– initiates technological and theoretical developments at the limit of feasibility.

– provides significant spin-off technologies in medical science, engineering, in other natural sciences and culture.

– provides comprehensive scientific education in an international und kompetitive environment.

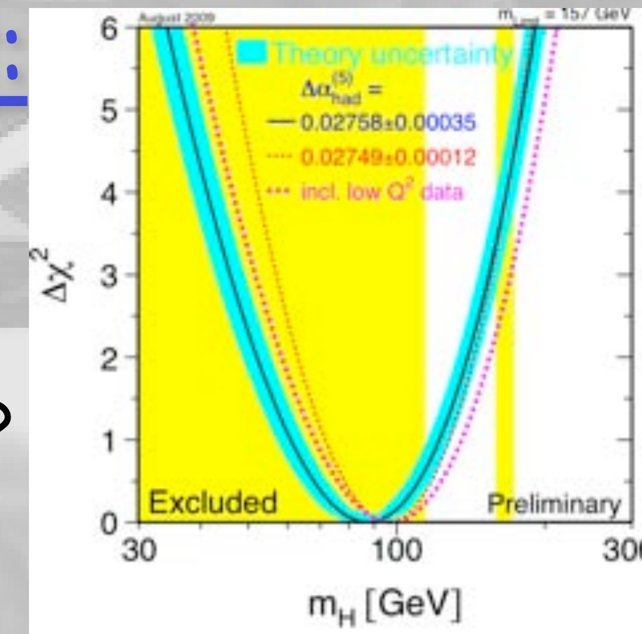
Teilchenphysik und Kosmologie



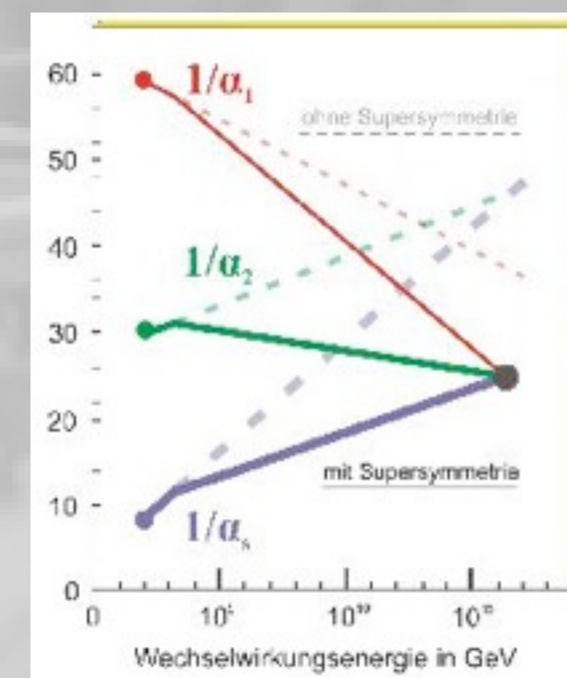
Particle Physics

- quo vadis

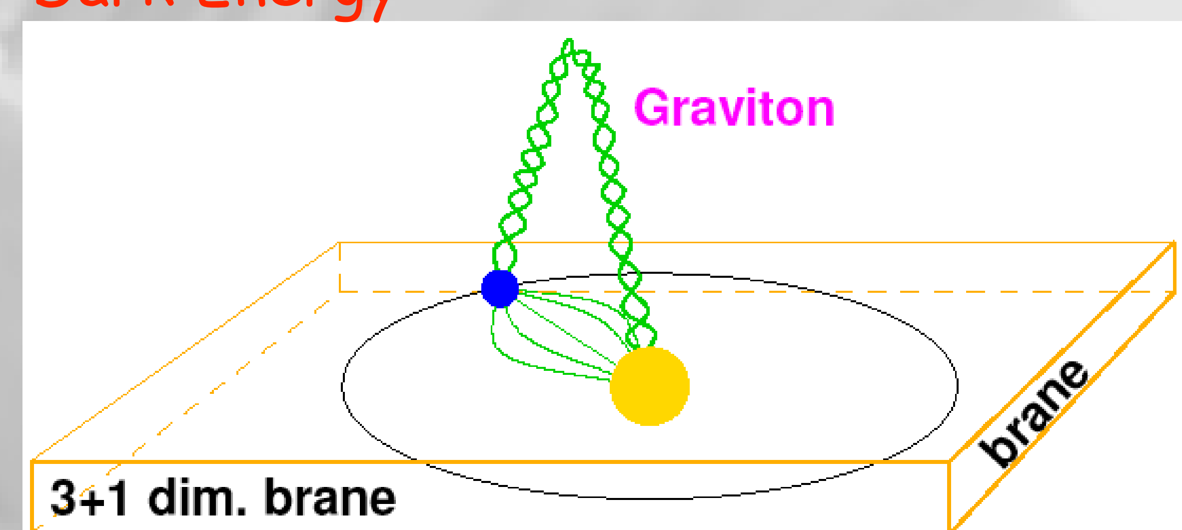
the SM - fundamental open questions:



1. what is the origin of mass ?
   - does the Higgs particle exist ?
   - if not, what is the mechanism of ew symmetry braking ?
2. why are there 3 families of quarks and leptons ?
   why is (electron charge) = -(proton charge) ?



3. where is the anti-matter in the universe?
4. is there one universal fundamental force ?
   -> GUT
5. are there unknown forms of matter ?
   - is our world supersymmetric ?
   - what is the origin of Dark Matter and Dark Energy which make up 95% of the universe ?
6. are there hidden extra dimensions ?
   - why is Gravitaty so much weaker than the other forces?

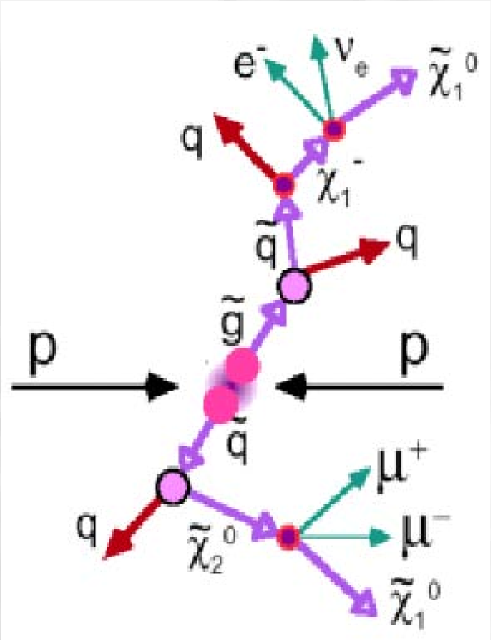


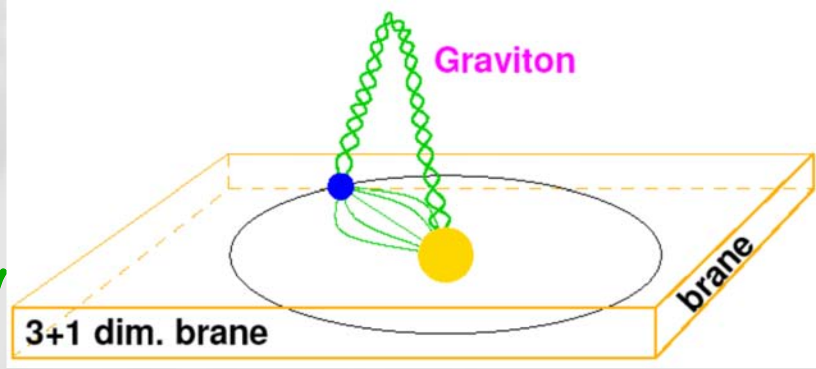
...


if it's not
dark
it doesn't
matter

the most *en vogue* candidates to solve (some of) these problems:

- Supersymmetry (SUSY)
  + fully compatible with and supported by GUT's
  + offers excellent Dark Matter candidates
  + theory finite and computable up to Planck Mass
  + essential for realisation of string theory (including quantum gravity)
  - no SUSY signals seen yet (LEP, Tevatron)
  - (too) many free parameters, large parameter space

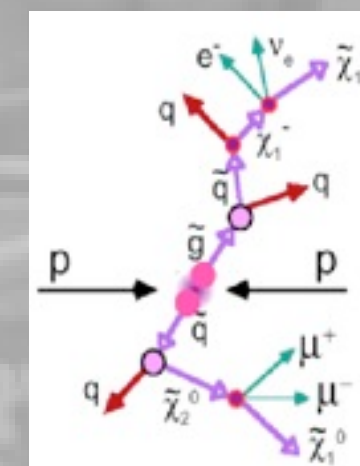




- Extra Space Dimensions
  + would solve hierarchy problem (M_{Planck} -> O(1 TeV
  + inspired by string theory: compactified extra dimensions
  +- exciting scenarios, but cannot solve many of above problems?
  - large model dependences

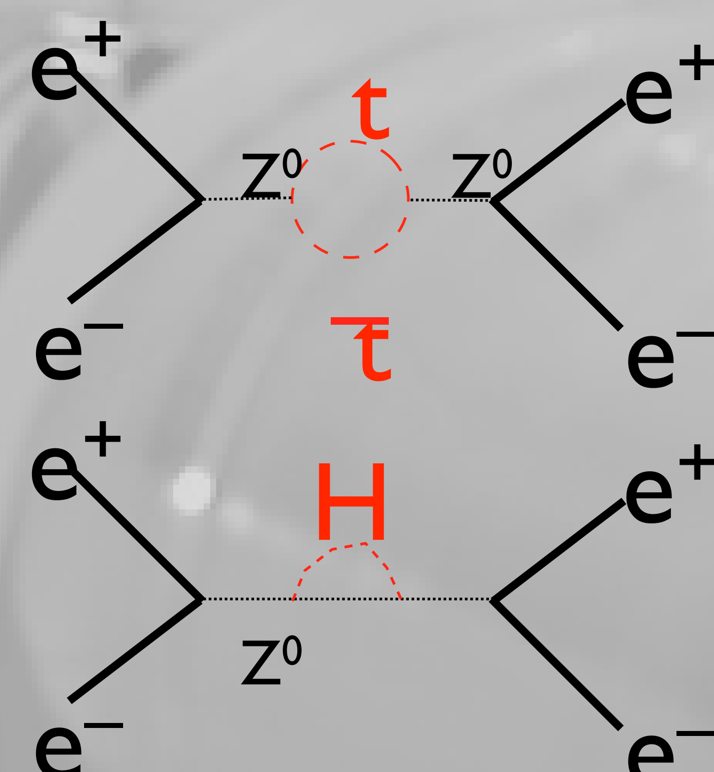
there are 2 principle ways to search for physics beyond the Standard Model:

- direct production of new particles in highest energy collisions

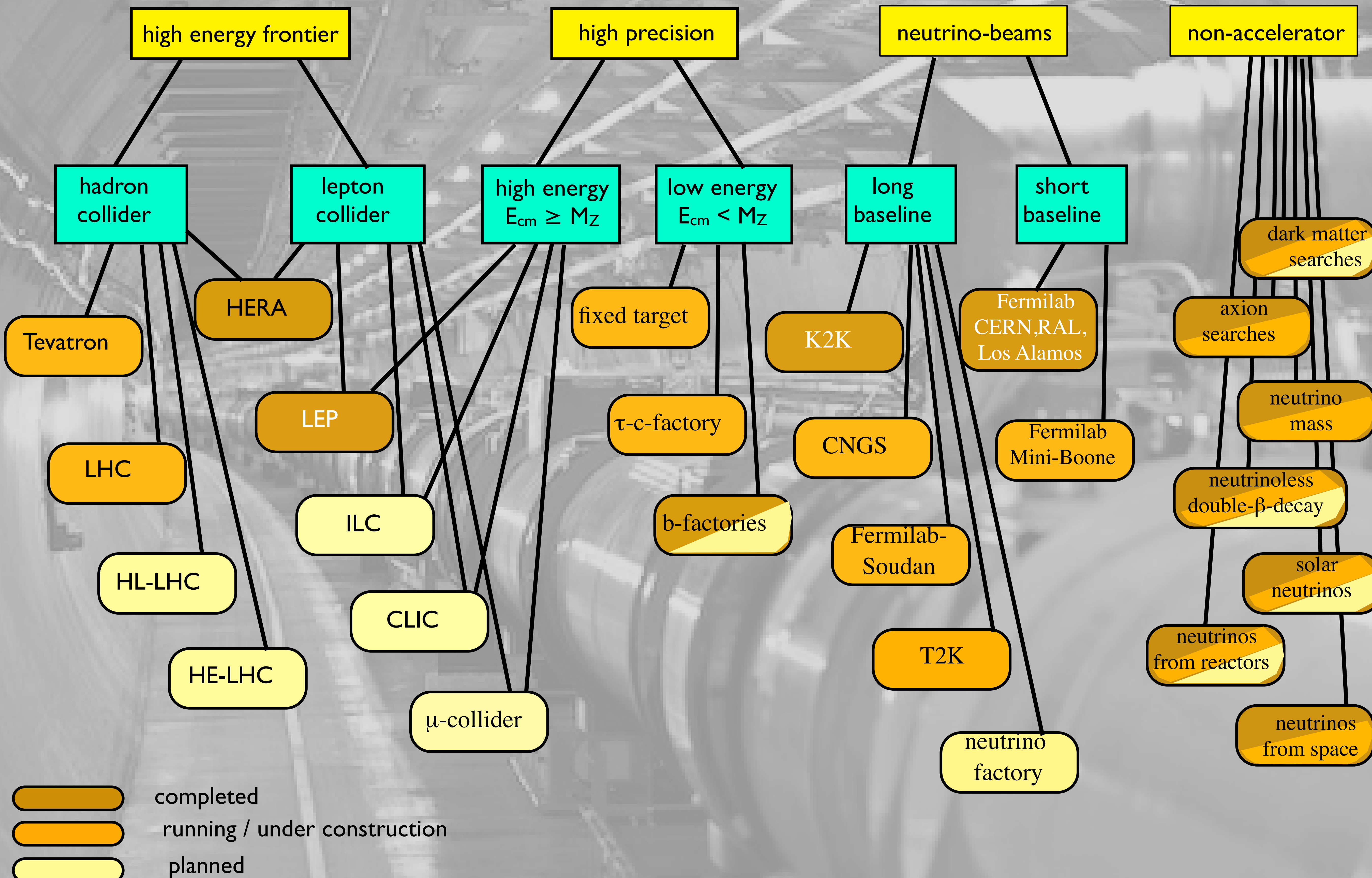


- indirect evidence for new phenomena in high precision experiments

(through radiative corrections; virtual loops...)



Particle Physics Projects



LHC - further plans:

2010 & 2011:

- continuous collisions at 7 TeV (-> 10 TeV ?); int. L ~ 1 fb-1
- higher beam currents (when reaching „safe beam conditions“: controlled beam-dump!)
- first sensitivity for „new physics“
- standard model physics (~ comparable with 20 years of Tevatron: top-Quark, ...)

2012:

- 1 year of shut-down (installation of full safety systems high magnet currents)

from 2013:

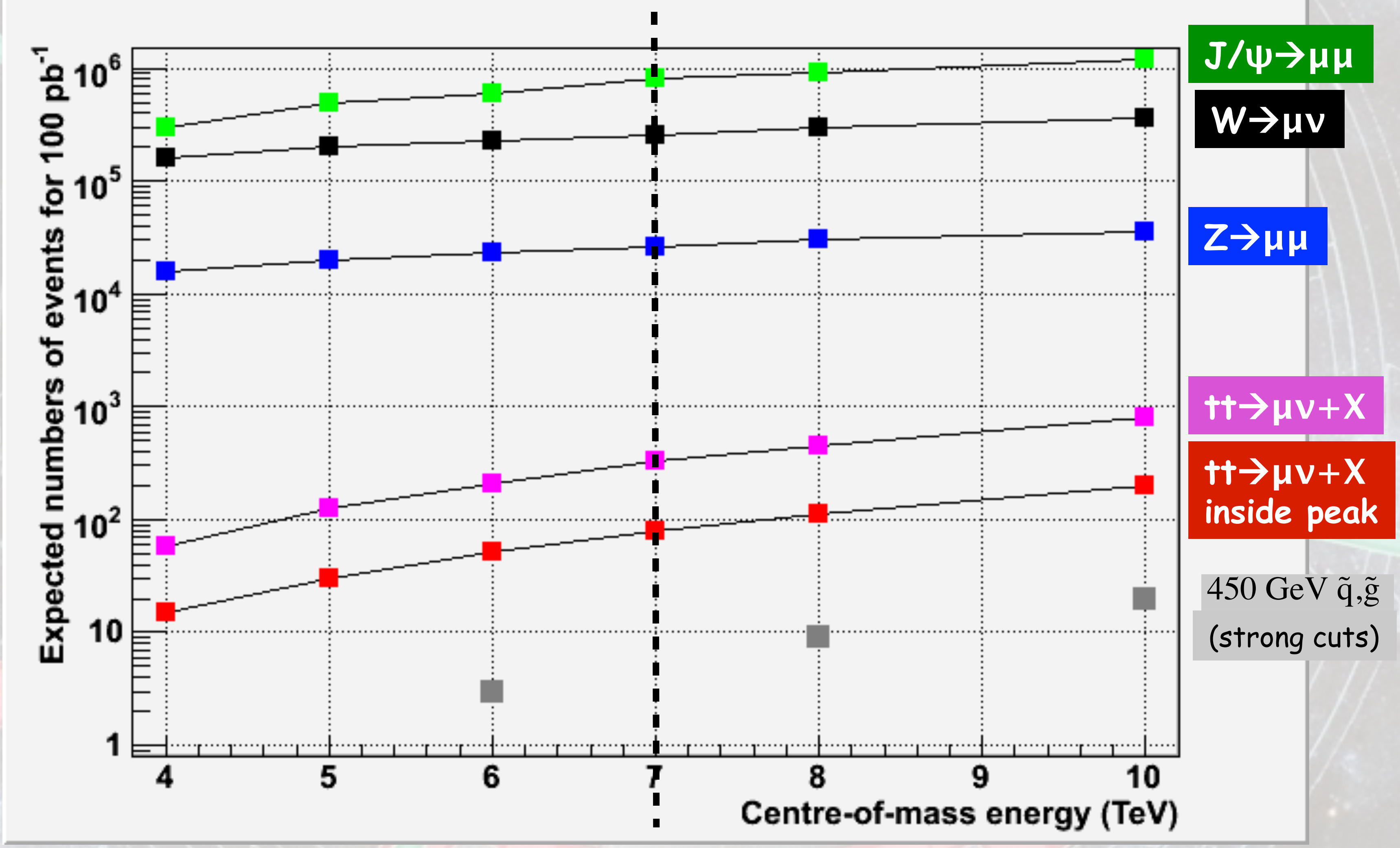
- full energy (14 TeV) and Luminosity (up to 10^{34} cm^{-2} s^{-1})

ab ca. 2017:

- ugrade of LHC (and detectors) to „HL-LHC“ (~10-fold Luminosity)

expectations until end of 2010:

Expected number of events in ATLAS for 100 pb^{-1} (Fall 2010 ?) after cuts for some representative processes



until end of 2010: about factor 10 more (1 fb^{-1})

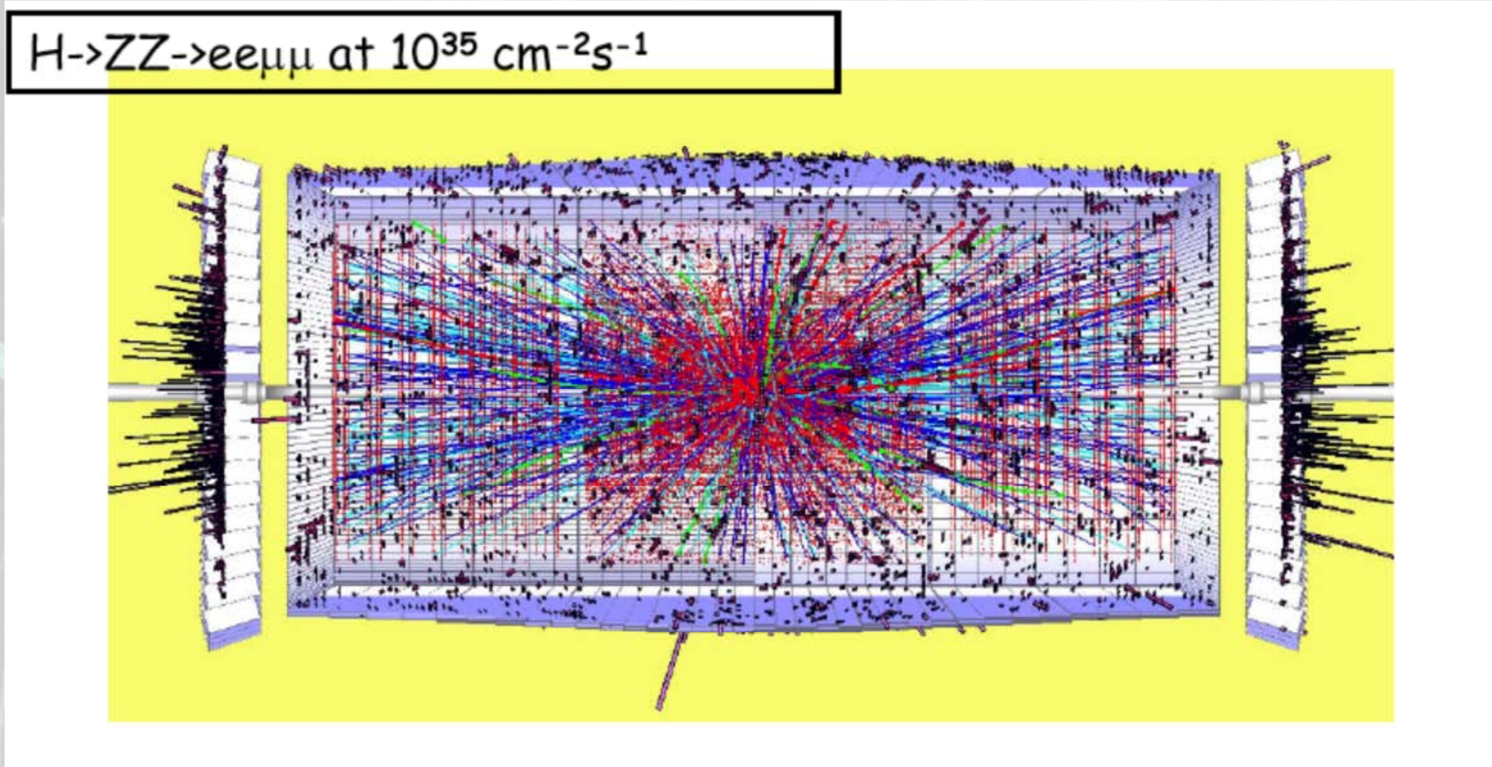
Super LHC Physics Menu

- Improvements from LHC: triple/quartic gauge couplings, top quark, Z' & compositeness, but LC can generally do better. (although SLHC will be there first ?)
- Higgs physics:
  - Main strength: wide m_H range coverage for ttH Yukawa coupling and Higgs self-coupling.
  - Improved coupling measurements, but LC will do better.
- SUSY:
  - Main strength: squark, gluino reach: -> 3 TeV.
  - Some extended reach of MSSM Higgs not covered by LC.
- Extra dimensions:

  Improved reach for black-hole production, KK states.
- Strongly coupled vector bosons (if no Higgs):

  Can have first significant signal (LHC stat. insufficient).

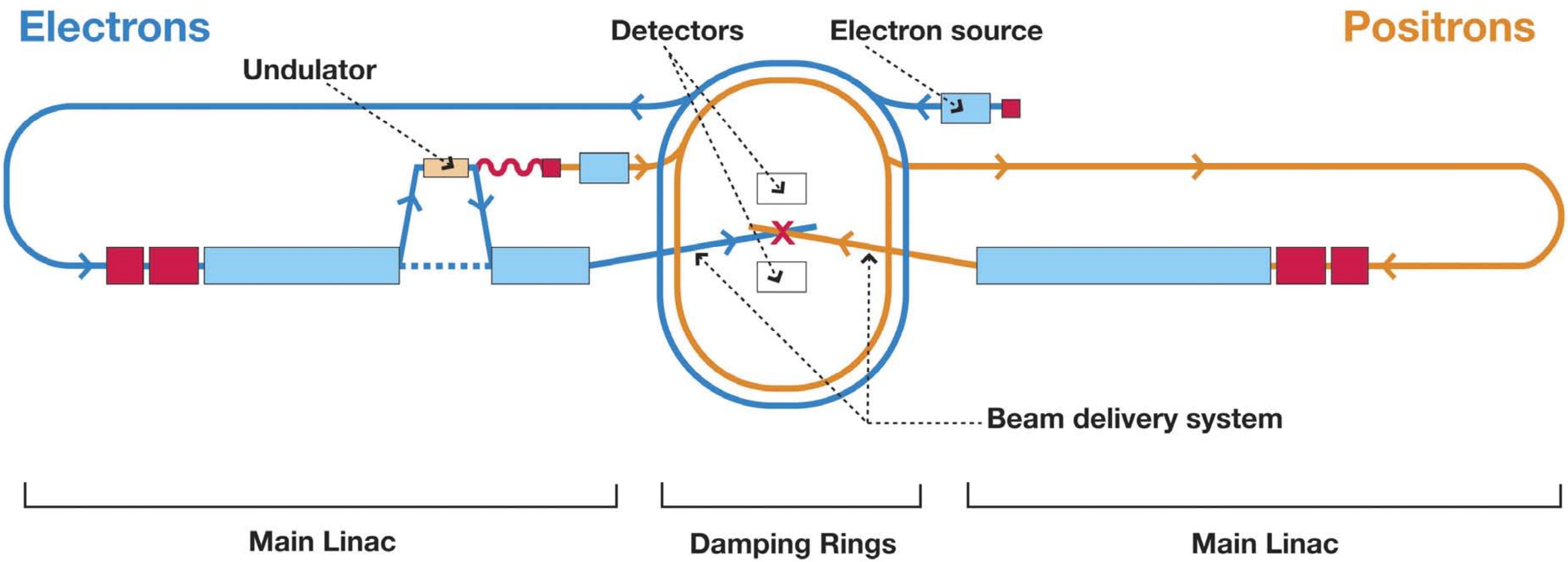
HL LHC



- radiation damage (tracker, electronics)
- increased levels of space charge in detecting media (solid, liquid, gas)
  -> signal degradation, reduced efficiencies and resolutions.
- reduced lifetime of detectors and electronics due to high particle rates
- larger data & background rates to be processed ->
  exceed bandwith -> data loss

Challenge: maintain efficiency, resolution and reliability!

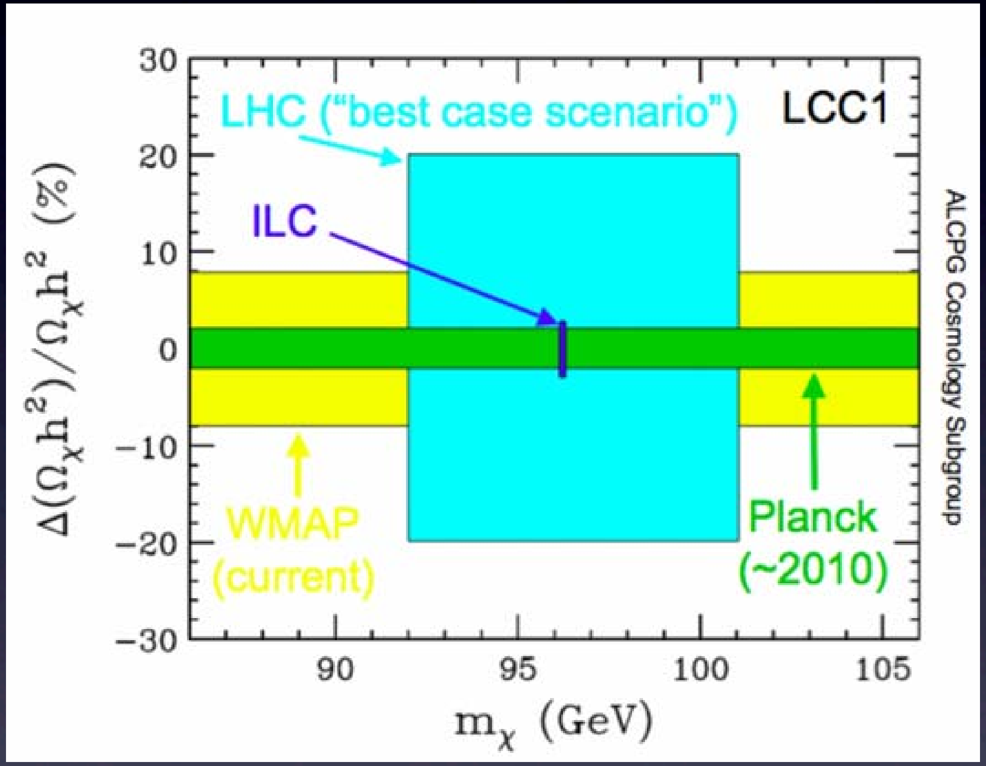
International Linear e+e- Collider



- E_{cm} = 0.5 ... 1.0 TeV
- super conducting cavities made of pure Niobium ; 31.5 MV/m
- length ~ 31 km, plus 2 damping rings with 6 km diameter
- costs: 6.65 Mrd $ plus 13.000 FTE's

Estimate 7 years of construction for accelerator and experiments after formal approval

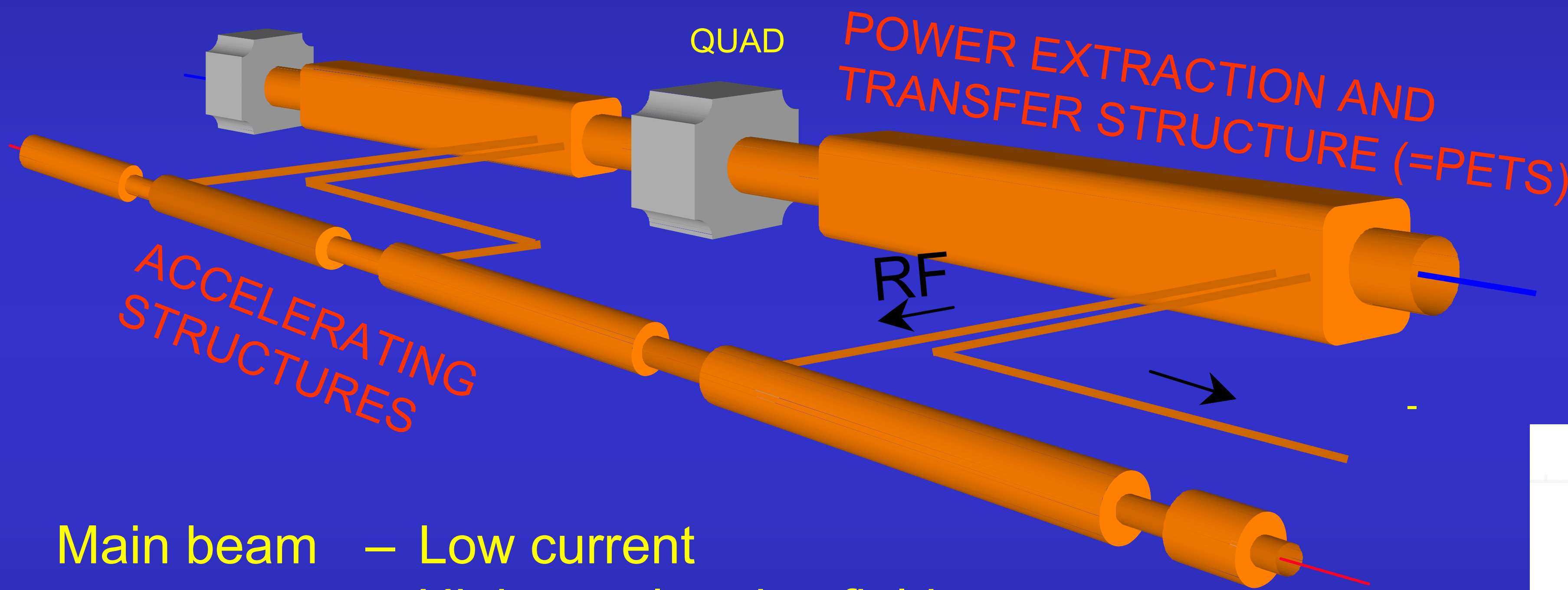
ILC: Precision!



Precision of determination of cosmic abundance
of Dark Matter and of the mass of DM-particles

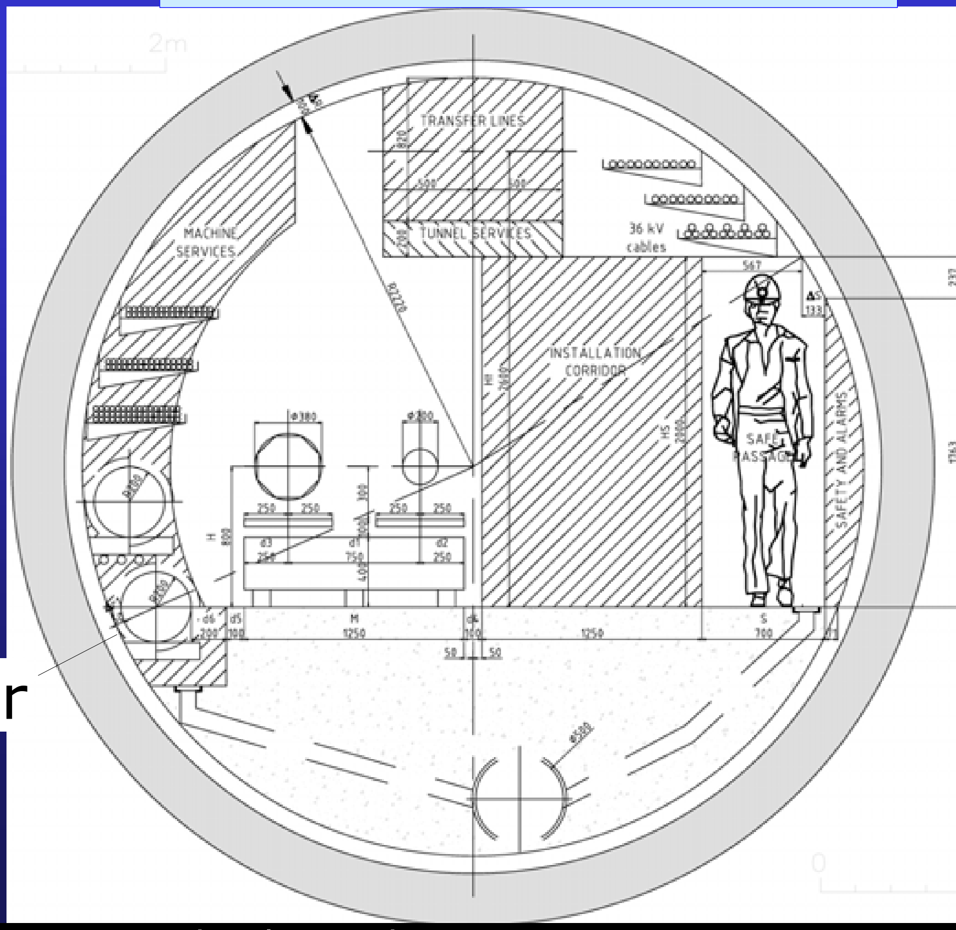
CLIC TWO-BEAM SCHEME

Drive beam - High current
- Low decelerating field



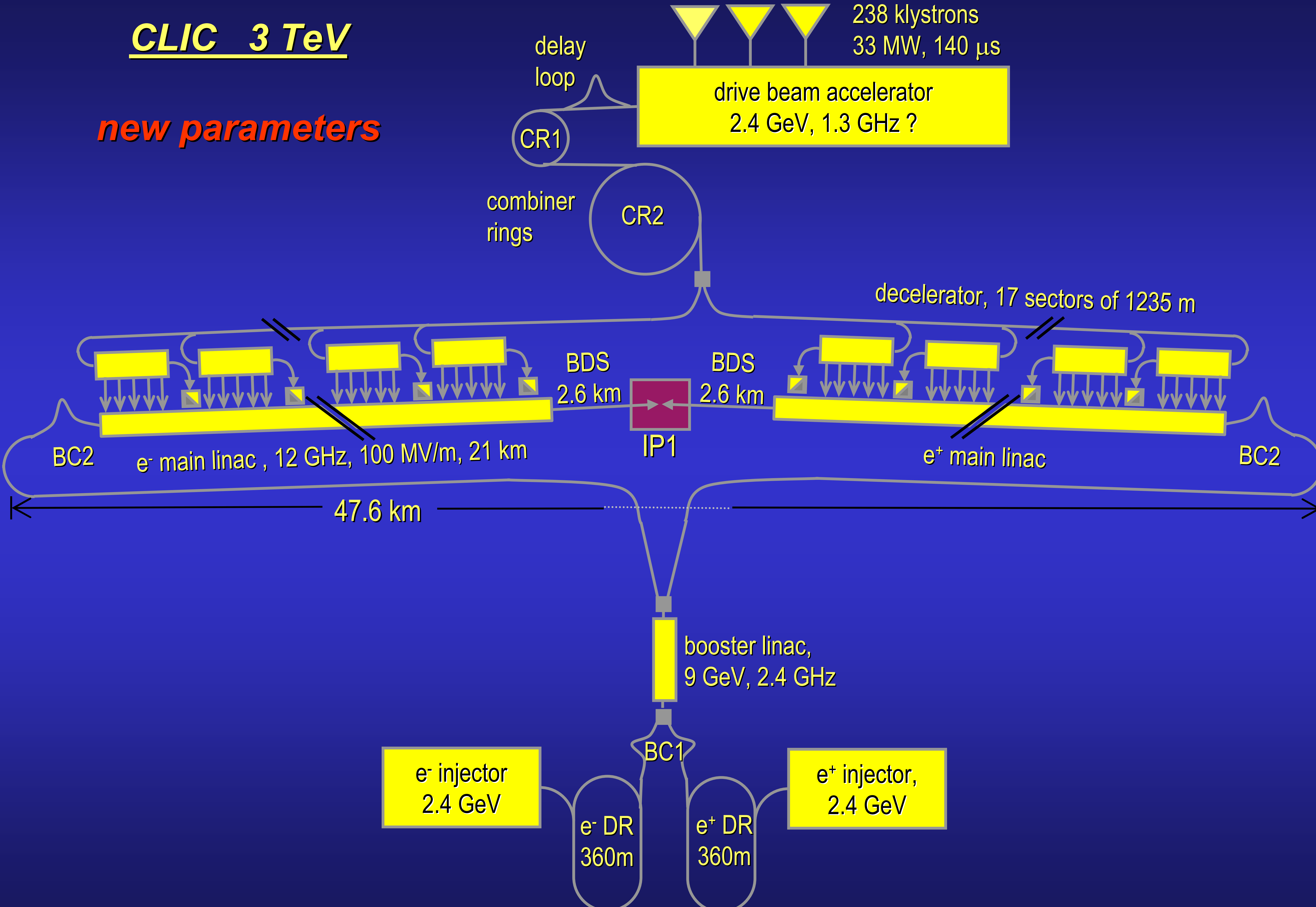
Main beam – Low current
- High accelerating field

CLIC TUNNEL CROSS-SECTION

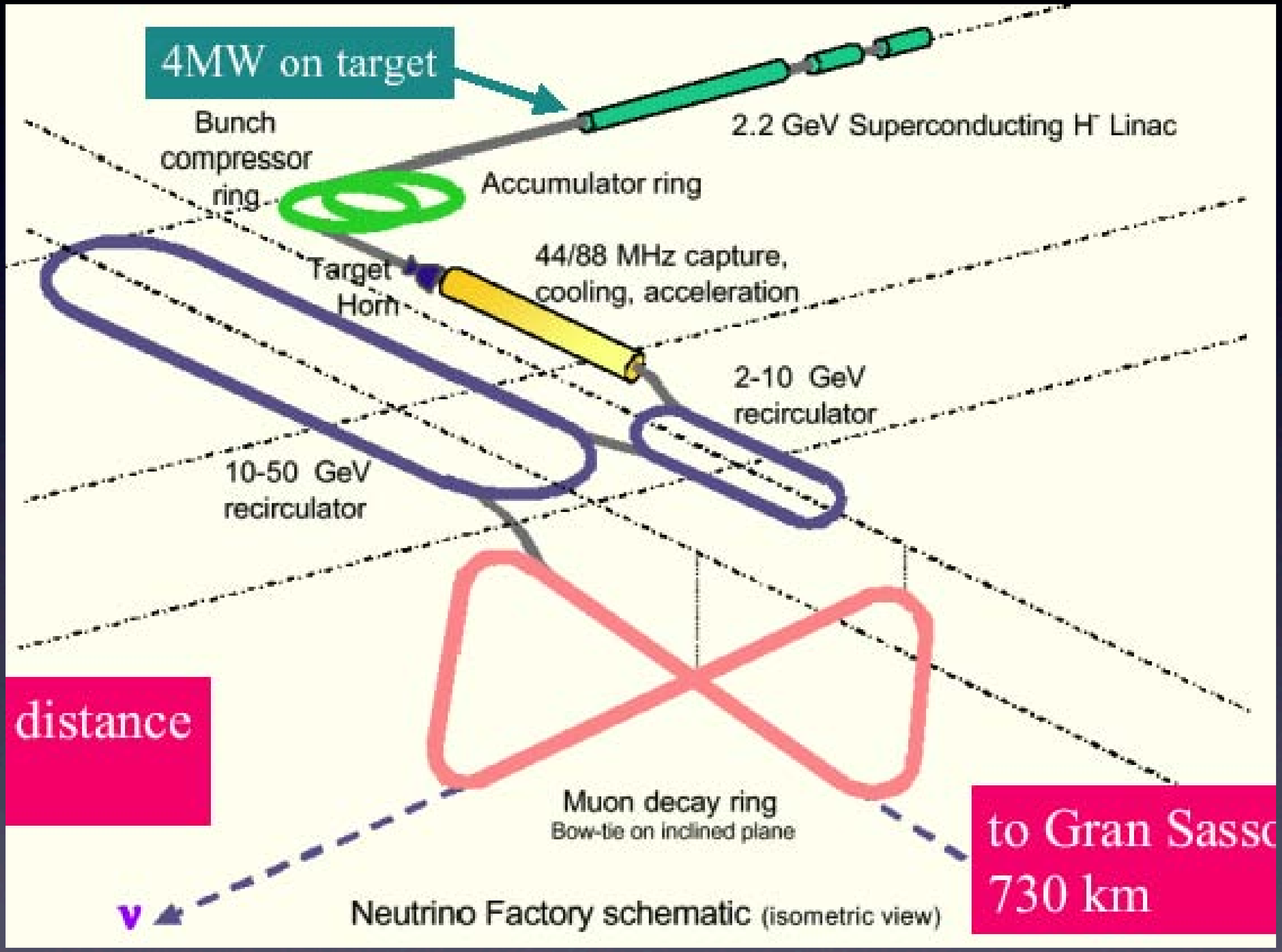


CLIC 3 TeV

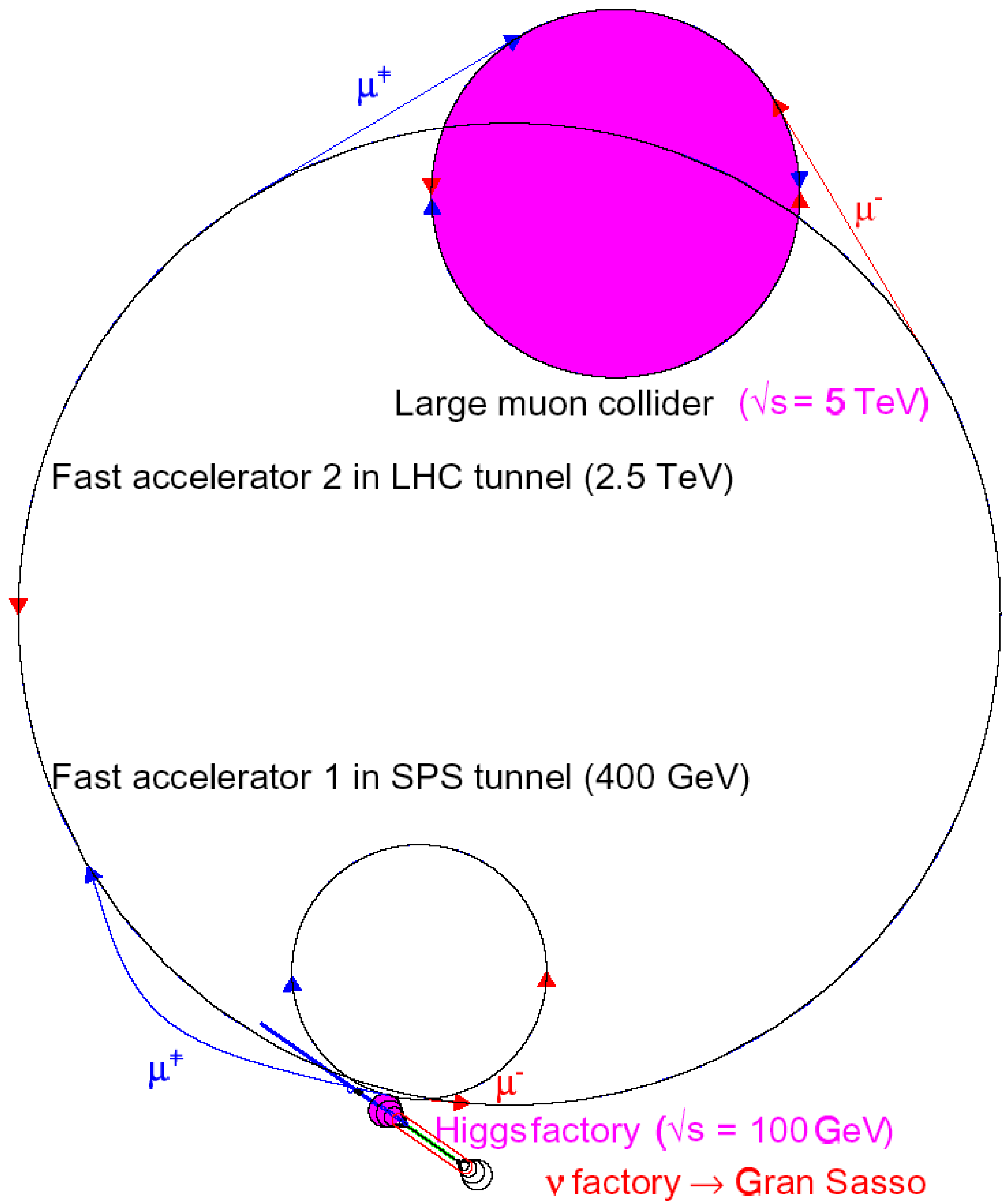
new parameters



Neutrino-Factory (CERN-study)



μ-Collider Complex (CERN-Study)



1. the highest priority is to fully exploit the physics potential of the LHC ... and centrally organize towards a luminosity upgrade by around 2015 (SLHC).
2. develop the CLIC technology and high performance magnets for future accelerators, and ... study and develop a high intensity neutrino facility.
3. complement the results of the LHC with measurments at a linear collider within the energy range of 0.5 to 1 TeV, the ILC; coordinated through the Global Design Effort.
4. European participation in a global neutrino programme.
5. Coordinated European strategy for non-accelerator experiments.

update planned for 2011/2012

similar roadmaps exist for U.S., Japan, ...

The End

http://www.mppmu.mpg.de