COMPUTATIONAL PARTICLE PHYSICS for EVENT SIMULATION and ANALYSIS

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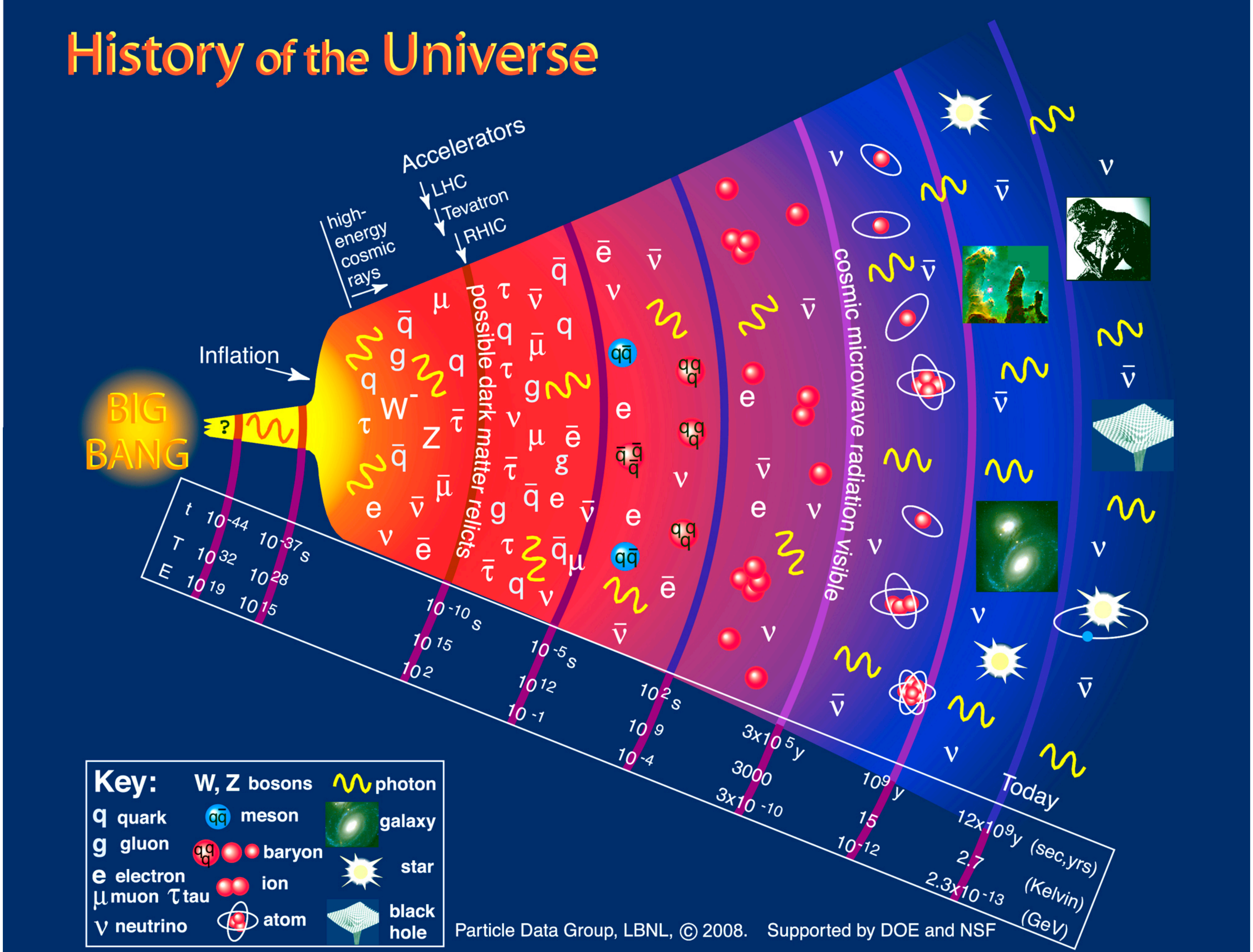
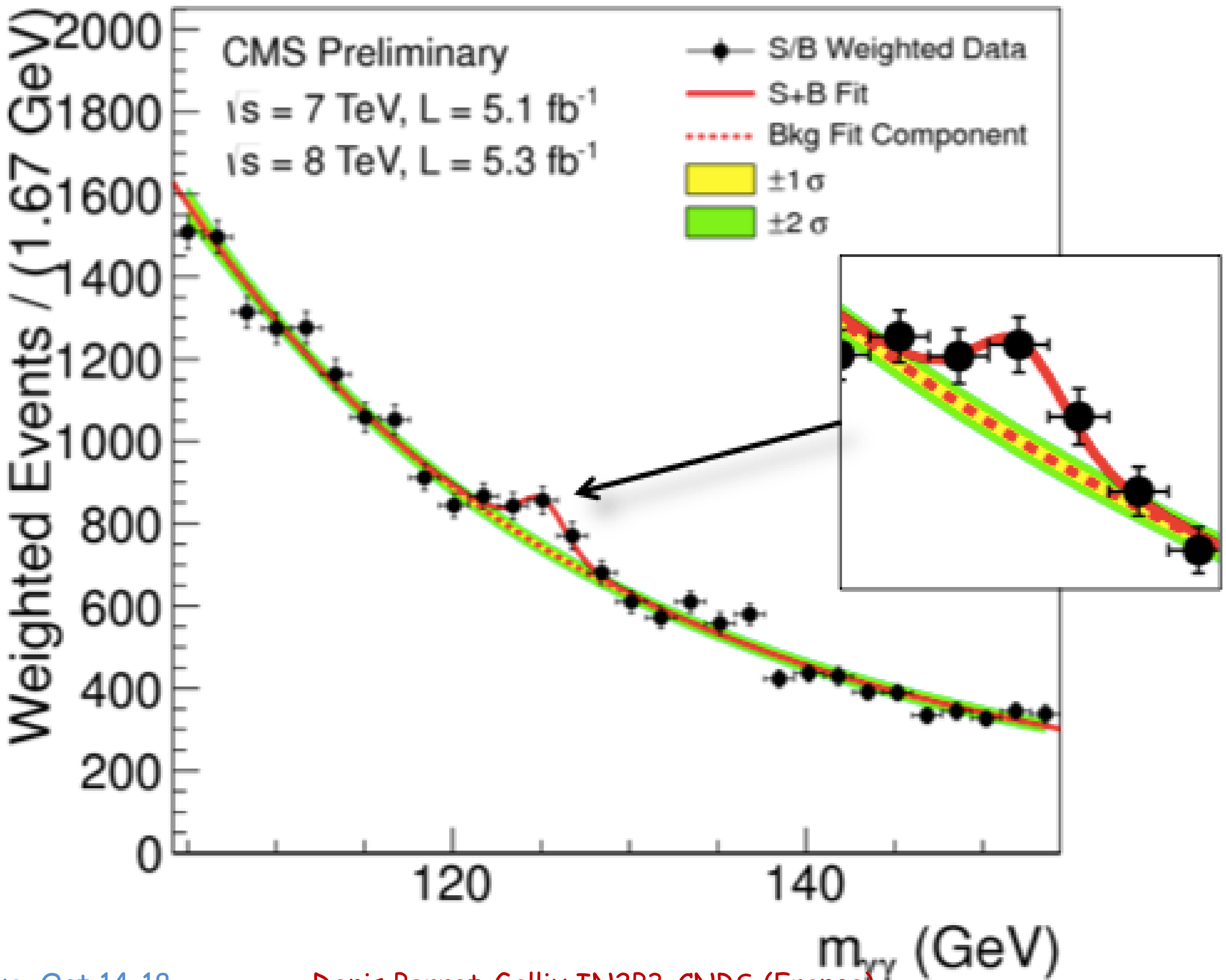
From Goals to Means

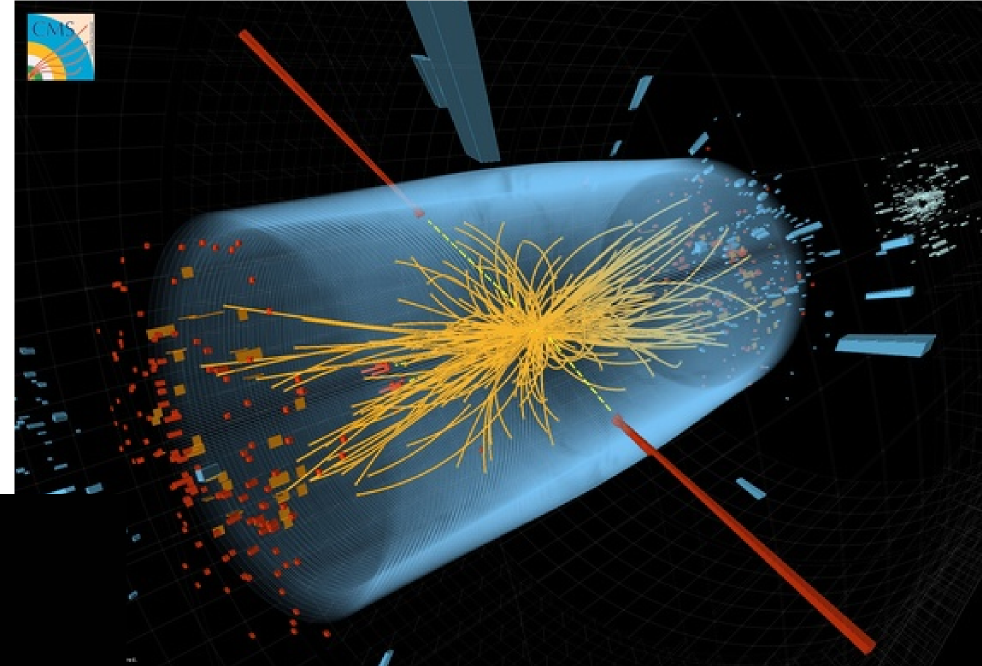


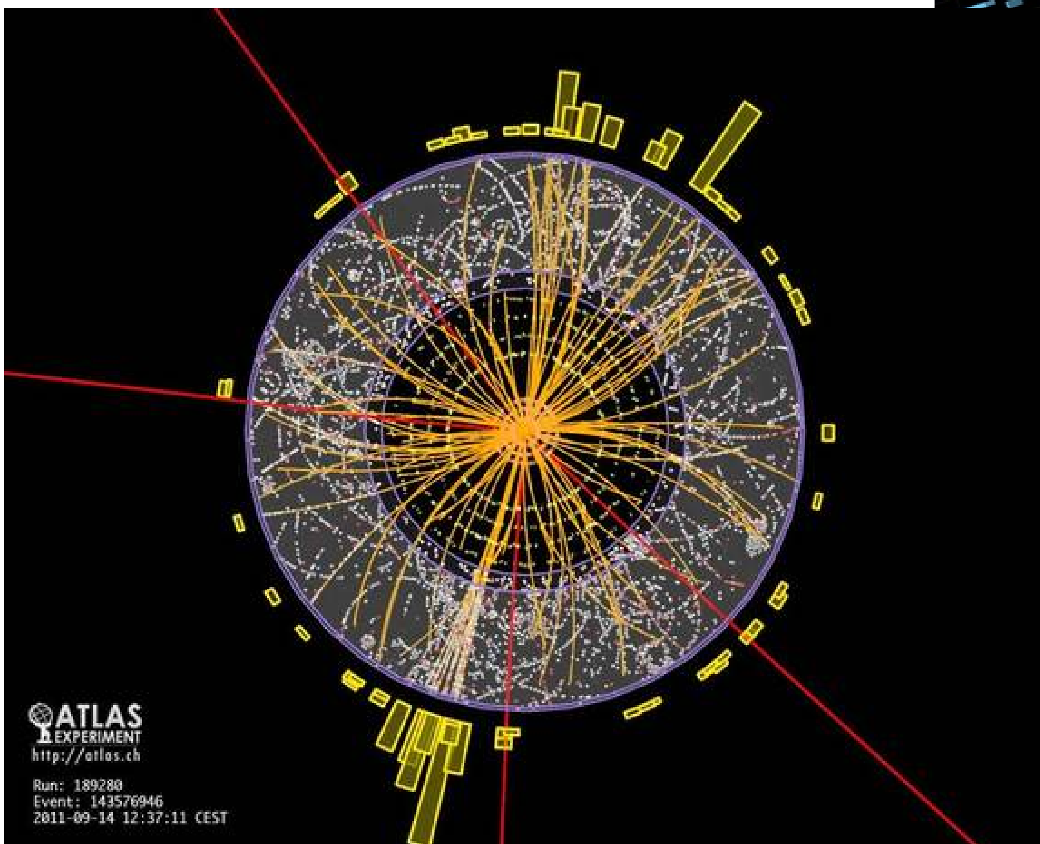
History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

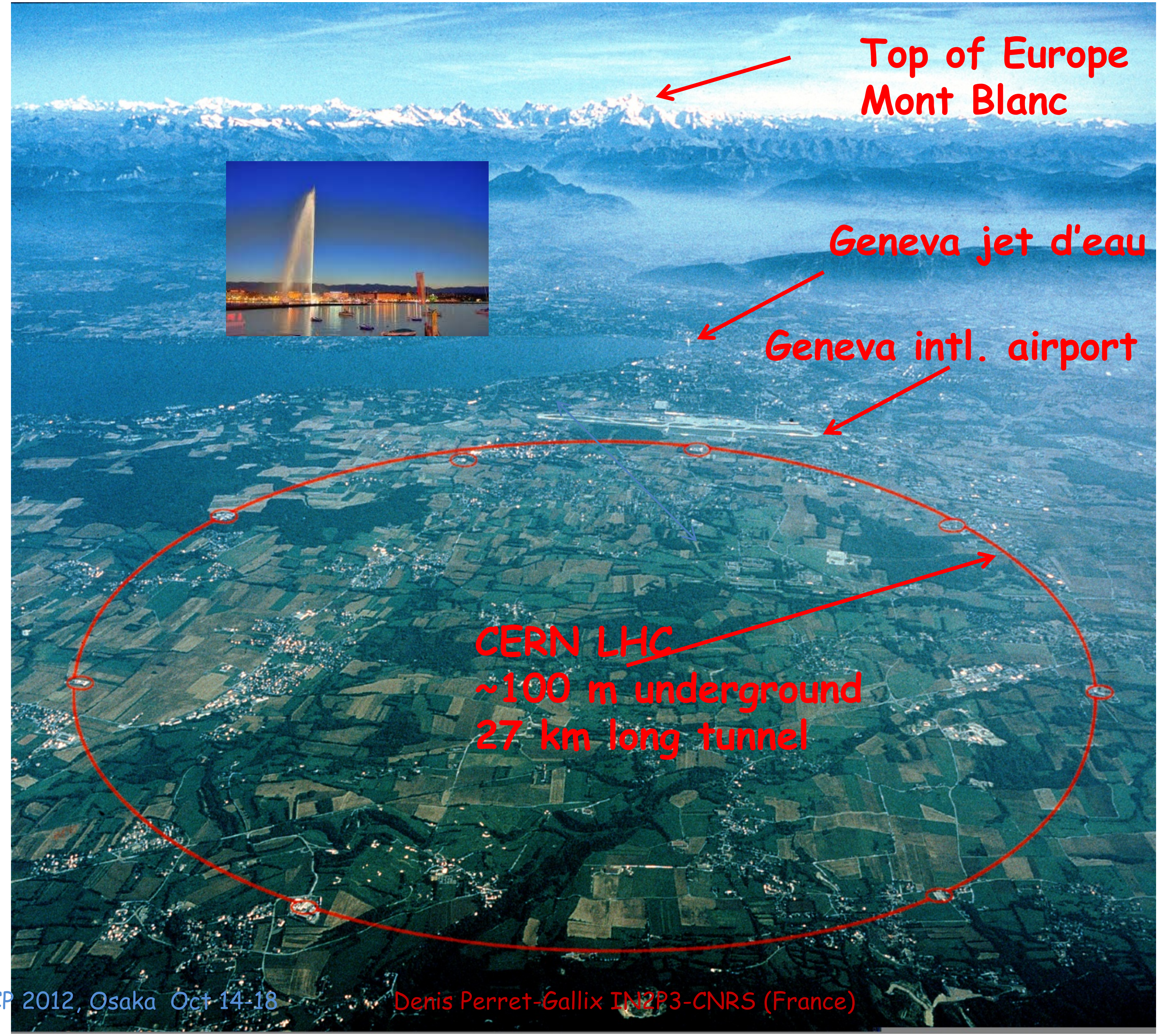
CERN-LHC "New Boson" discovery
PP -> H+X -> $\gamma\gamma$ +X



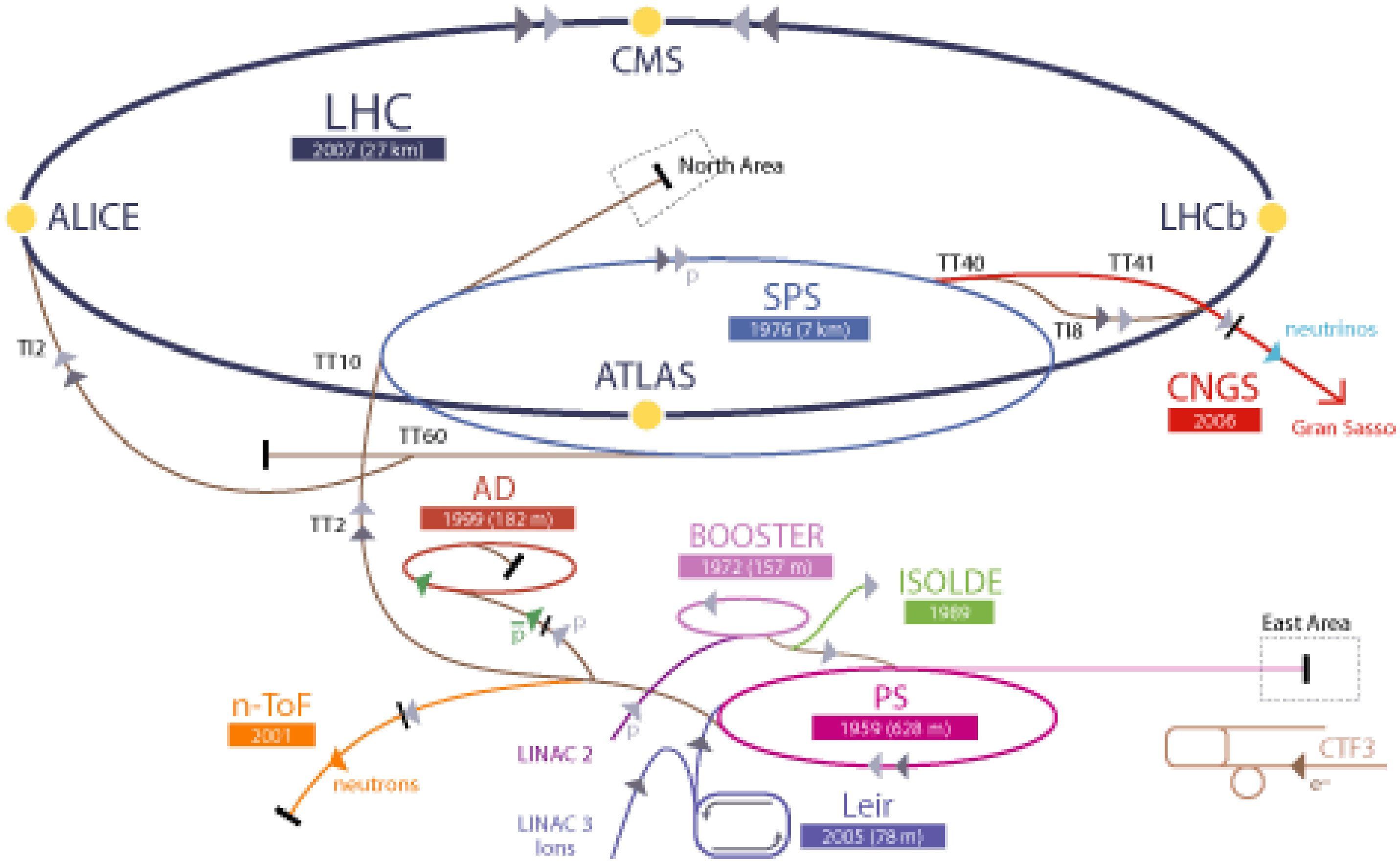
LHC Events @ 7.5 TeV






Top of Europe
Mont Blanc
Geneva jet d'eau
Geneva intl. airport
CERN LHC
~100 m underground
27 km long tunnel

CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) neutrinos electron

proton/antiproton conversion

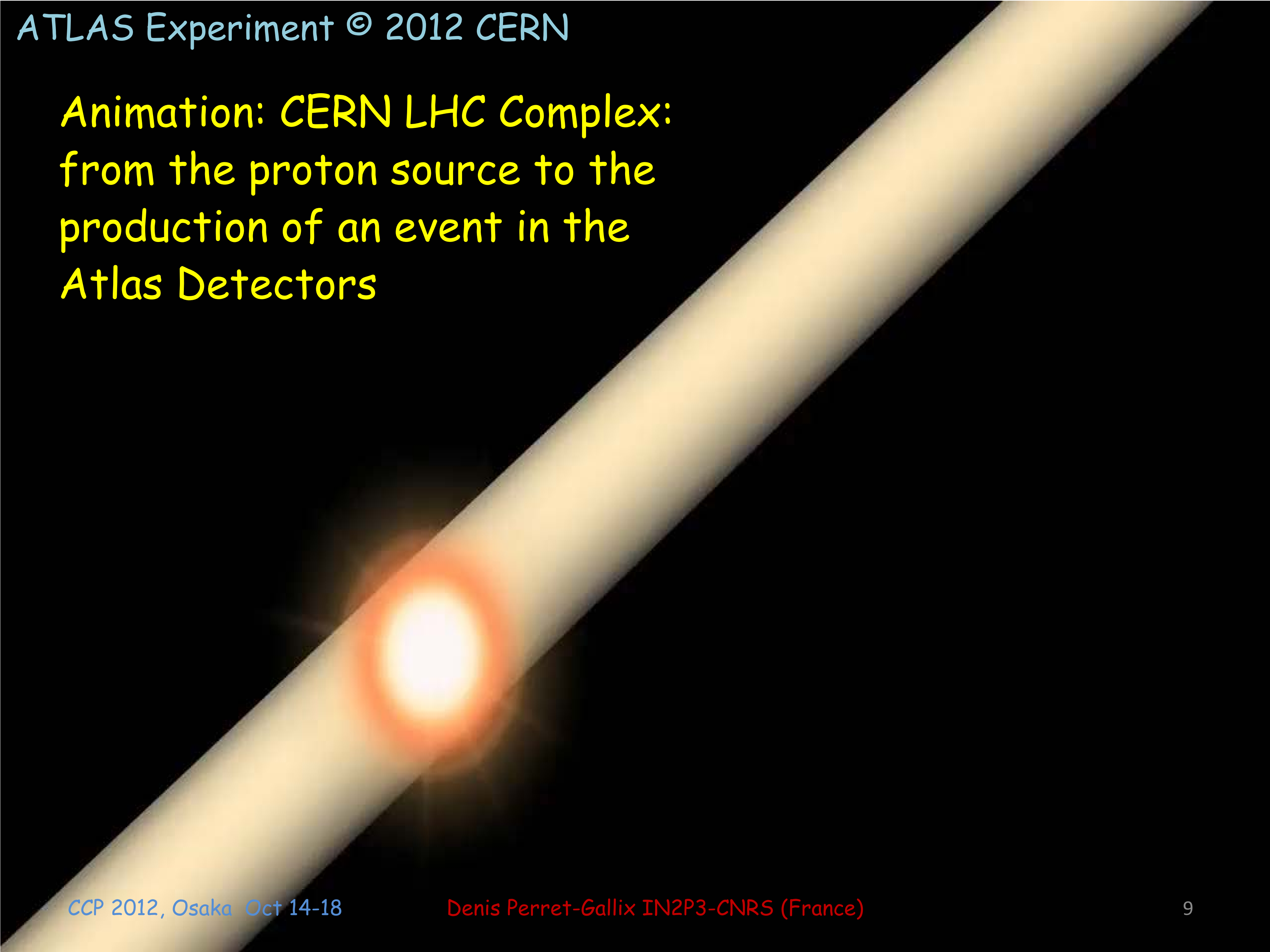
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility

CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

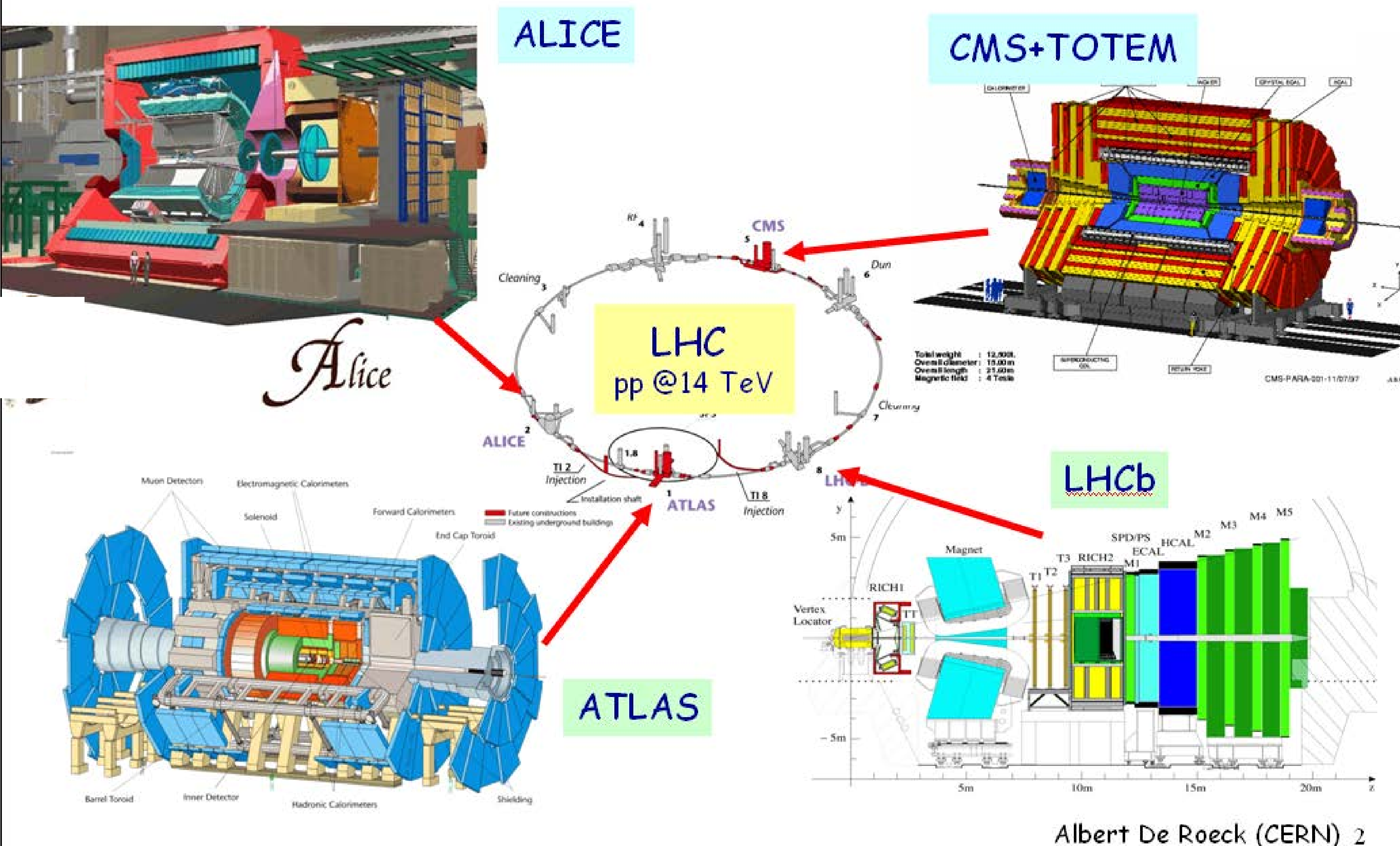
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Animation: CERN LHC Complex: from the proton source to the production of an event in the Atlas Detectors



Geant 4

The Large Hadron Collider Experiments



Computing needed at all stages

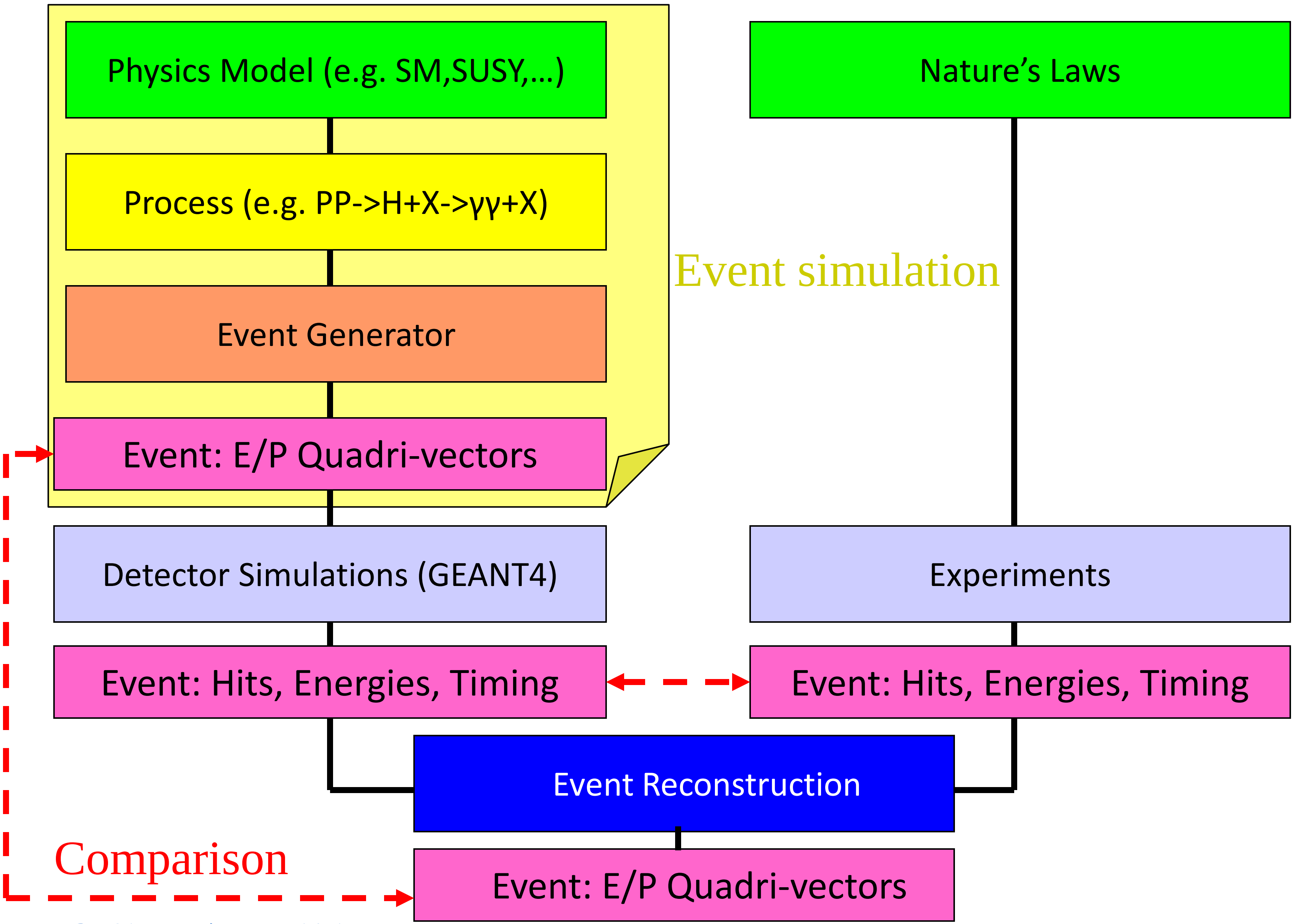
- Accelerator Design, monitoring, operation and optimization
- Data acquisition (150 million sensors)
- Detector design, acceptance/efficiency,
- Event reconstruction
- Event selection and classification
- Event analysis
- Theory interpretation

Build or tested by ***Monte-Carlo Physics Simulation***

Monte-Carlo Event Simulation

a major component of Particle Physics

Simulation and Data Analysis Chain



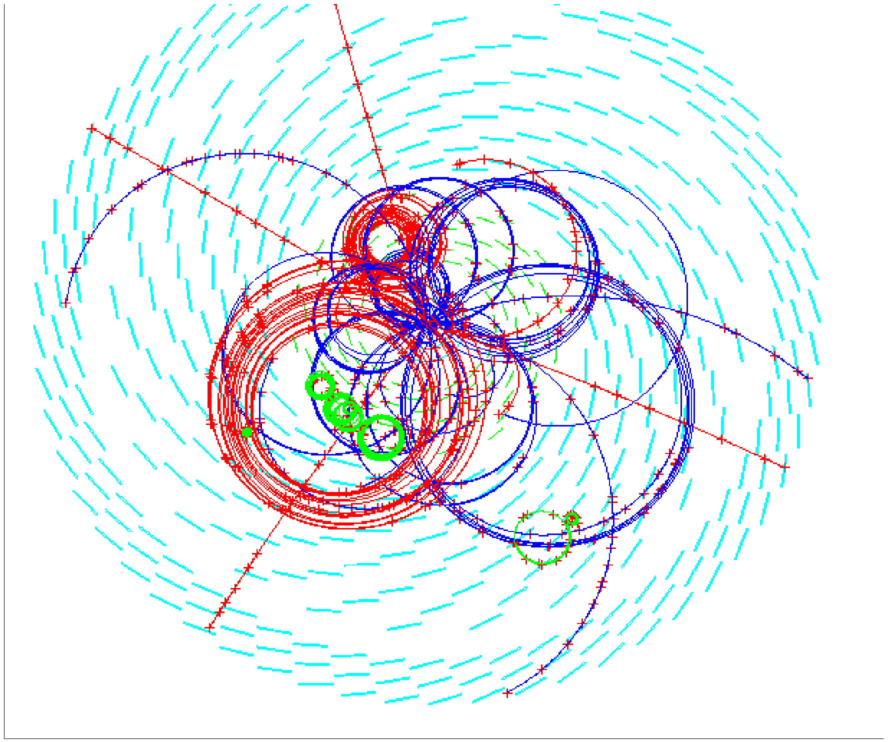
Frontier Computation

- Complexity
- Worldwide collaborations

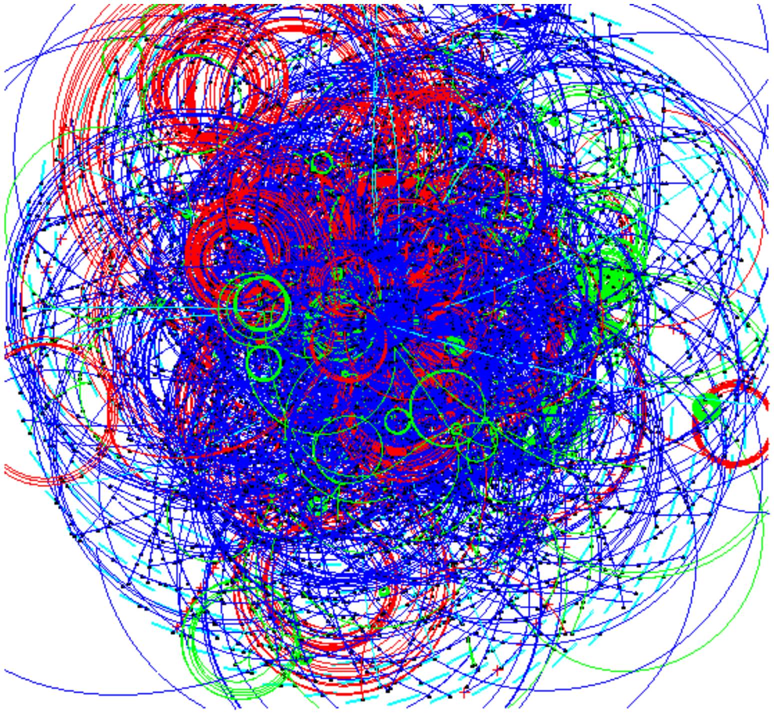
Complexity

Signal event is obscured by
~ 20 overlapping uninteresting collisions in same crossing

One event



One crossing (every 25 ns)

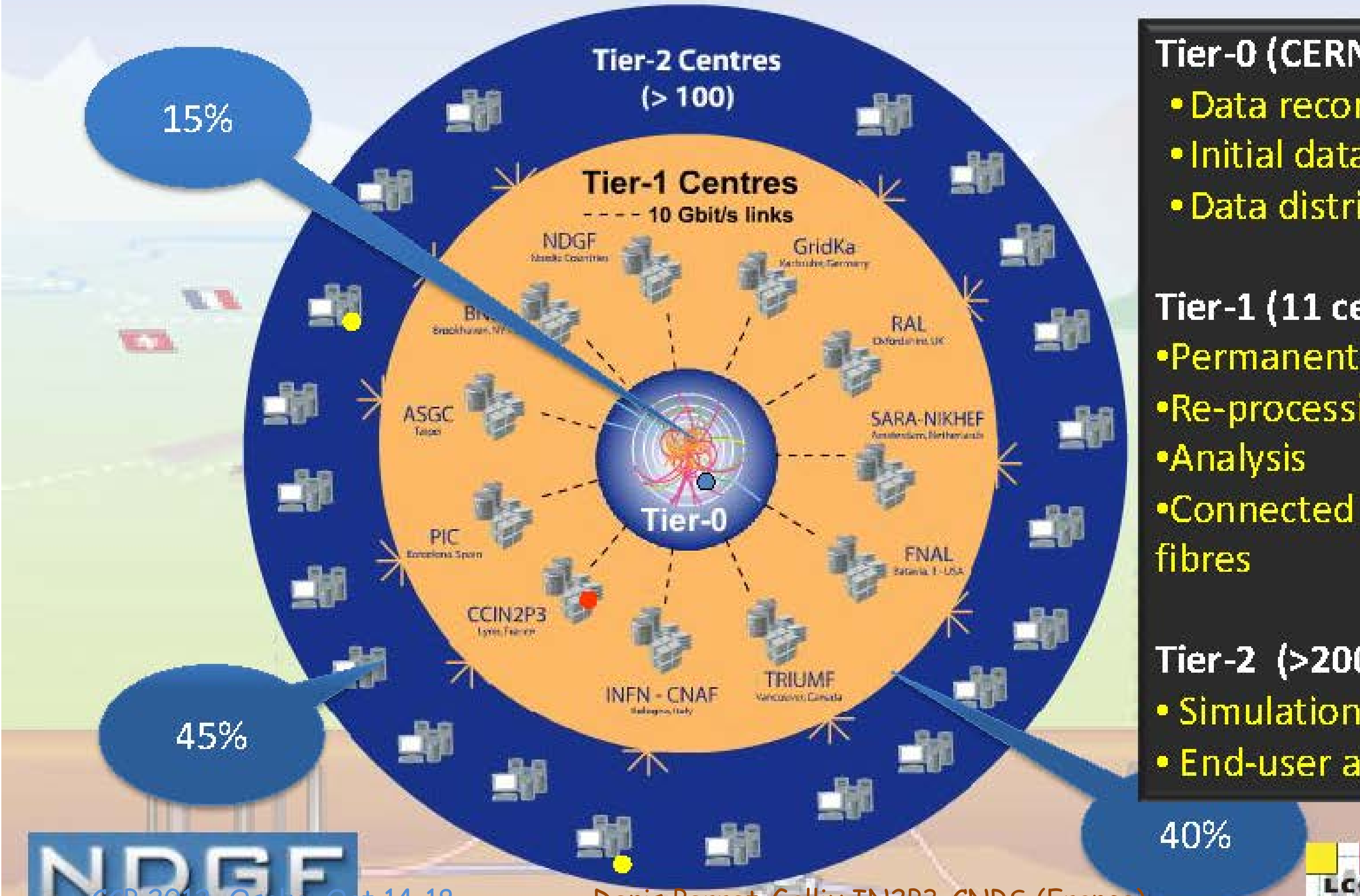


LCG Data Grid

World Wide Collaboration ⇒ distributed computing & storage capacity

Data Grid Architecture

F. Furano, CERN-IT

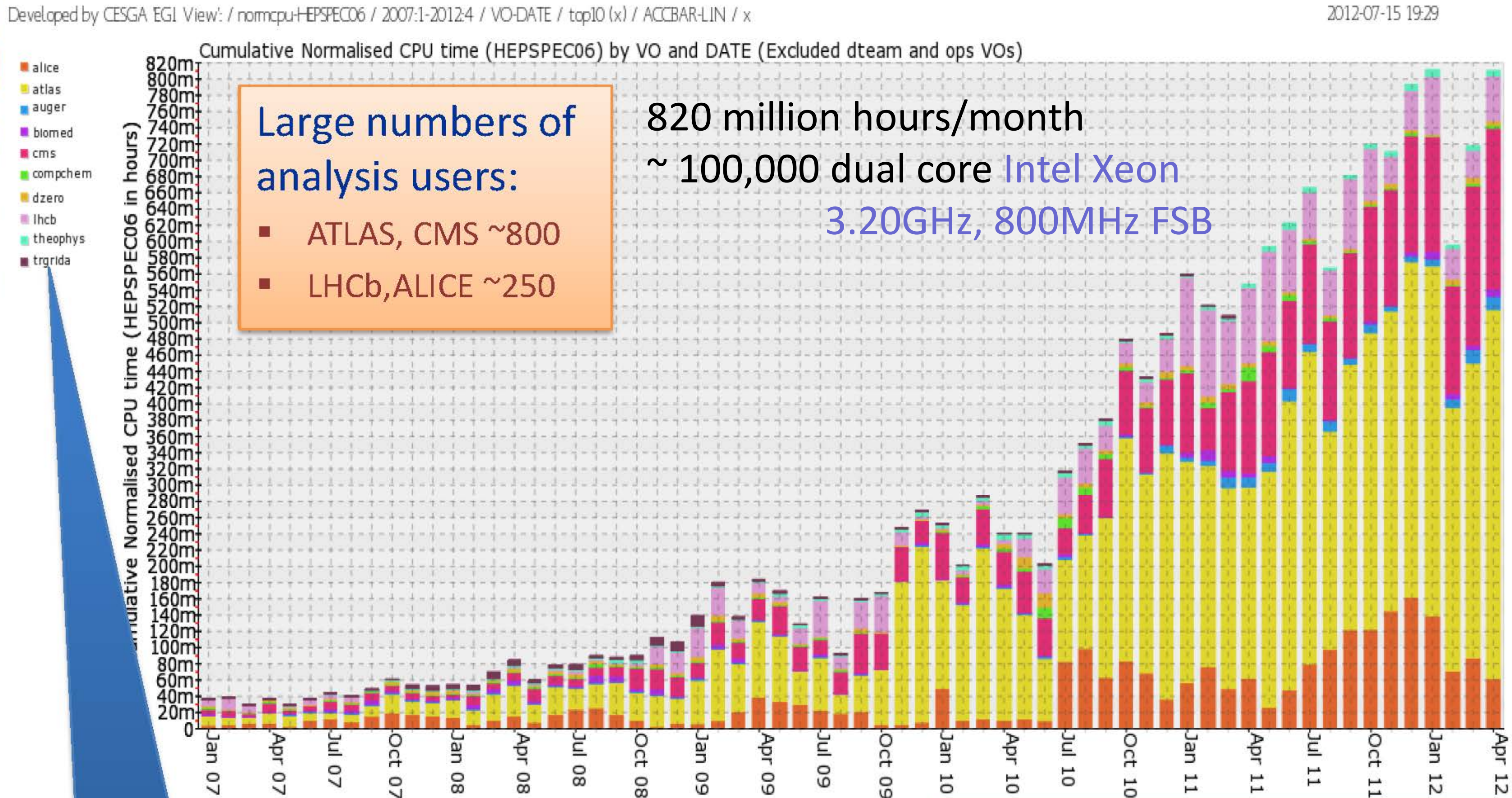


Tier-0 (CERN): (15%)
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres): (40%)
- Permanent storage
- Re-processing
- Analysis
- Connected by direct 10 Gb fibres

Tier-2 (>200 centres): (45%)
- Simulation
- End-user analysis

Grid Usage



Large numbers of analysis users:

- ATLAS, CMS ~800
- LHCb,ALICE ~250

820 million hours/month
~ 100,000 dual core Intel Xeon 3.20GHz, 800MHz FSB

The Grid is also used by non LHC VOs

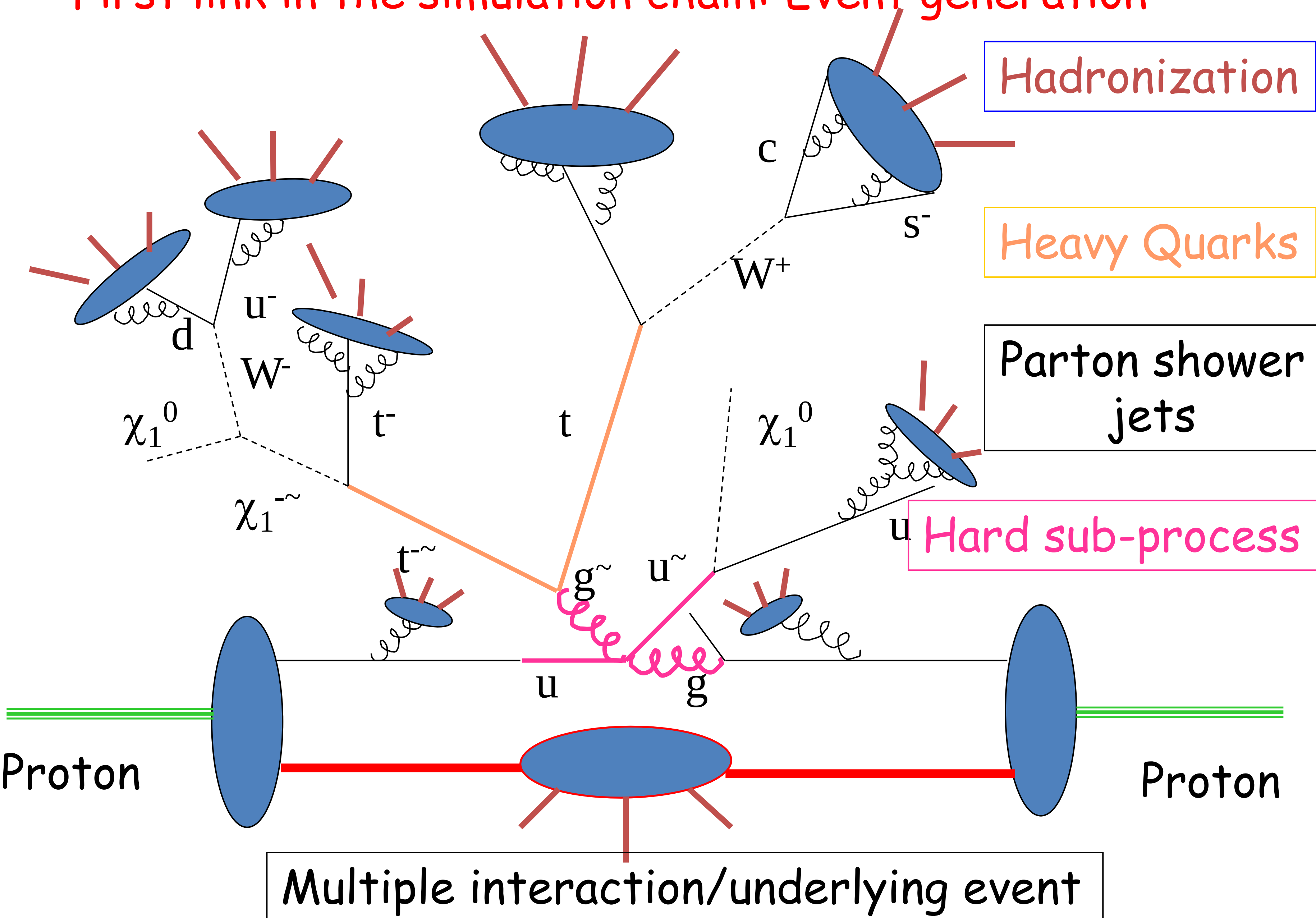
As well as LHC data, large simulation productions always on going

- II -

Monte-Carlo

Event simulation

First link in the simulation chain: Event generation



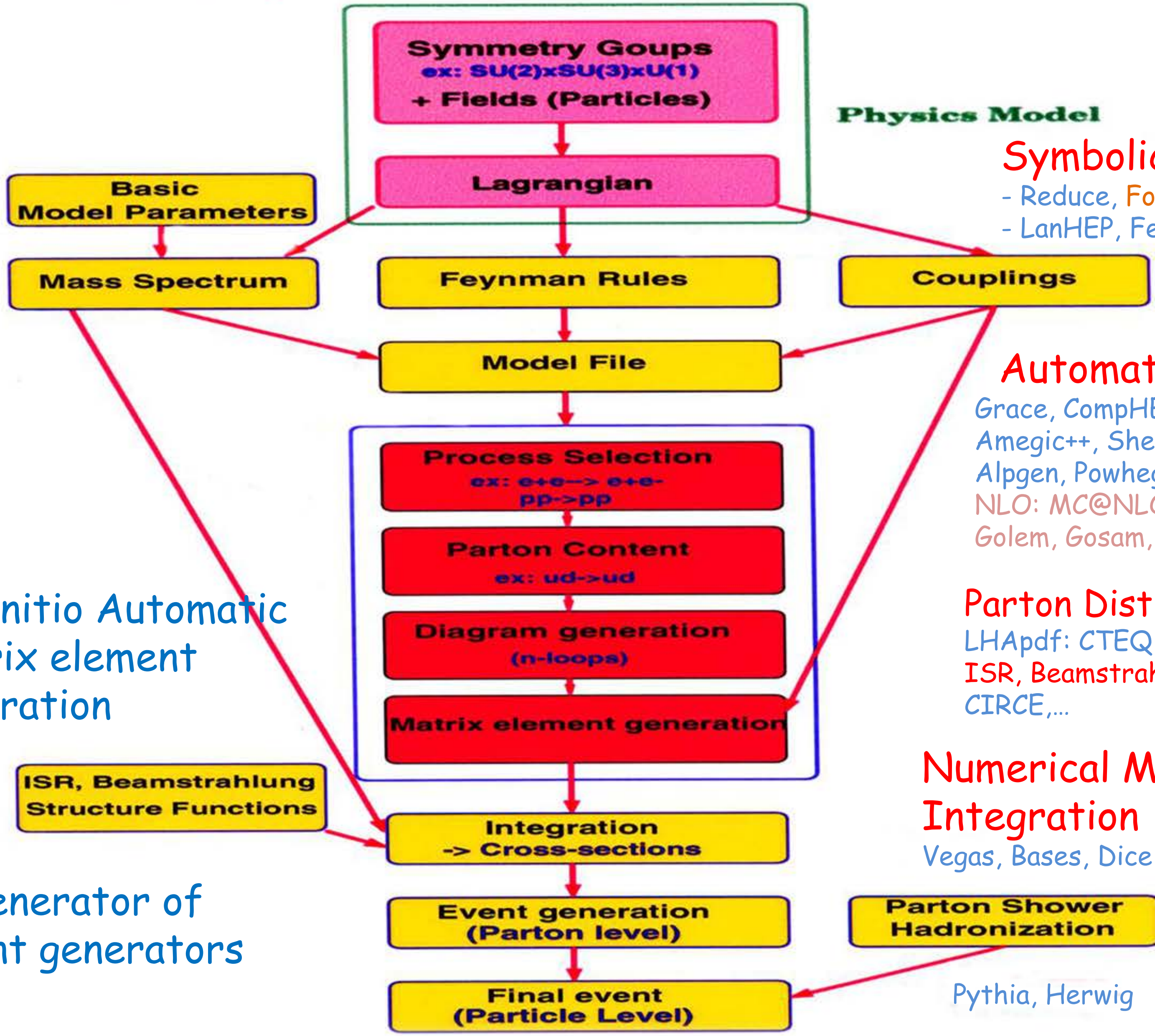
From Physics models to Simulation

Physics process probability (Matrix Element)

Event generators

Data Analysis by the Matrix Element Method

From Symmetries to event generation



Symbolic computation
- Reduce, Form, Maple, Mathematica, ..
- LanHEP, FeynRules

Automation
Grace, CompHEP, CalcHEP, FeynCalc, Amegic++, Sherpa, Madgraph, Whizard, Alpgen, Powheg, …,
NLO: MC@NLO, MCFM, Blackhat+Sherpa
Golem, Gosam, …

Parton Distribution Functions
LHApdf: CTEQ, MRST, …
ISR, Beamstrahlung
CIRCE,…

Numerical Multi-dimensional Integration
Vegas, Bases, Dice,Vamp, Parint,

Pythia, Herwig

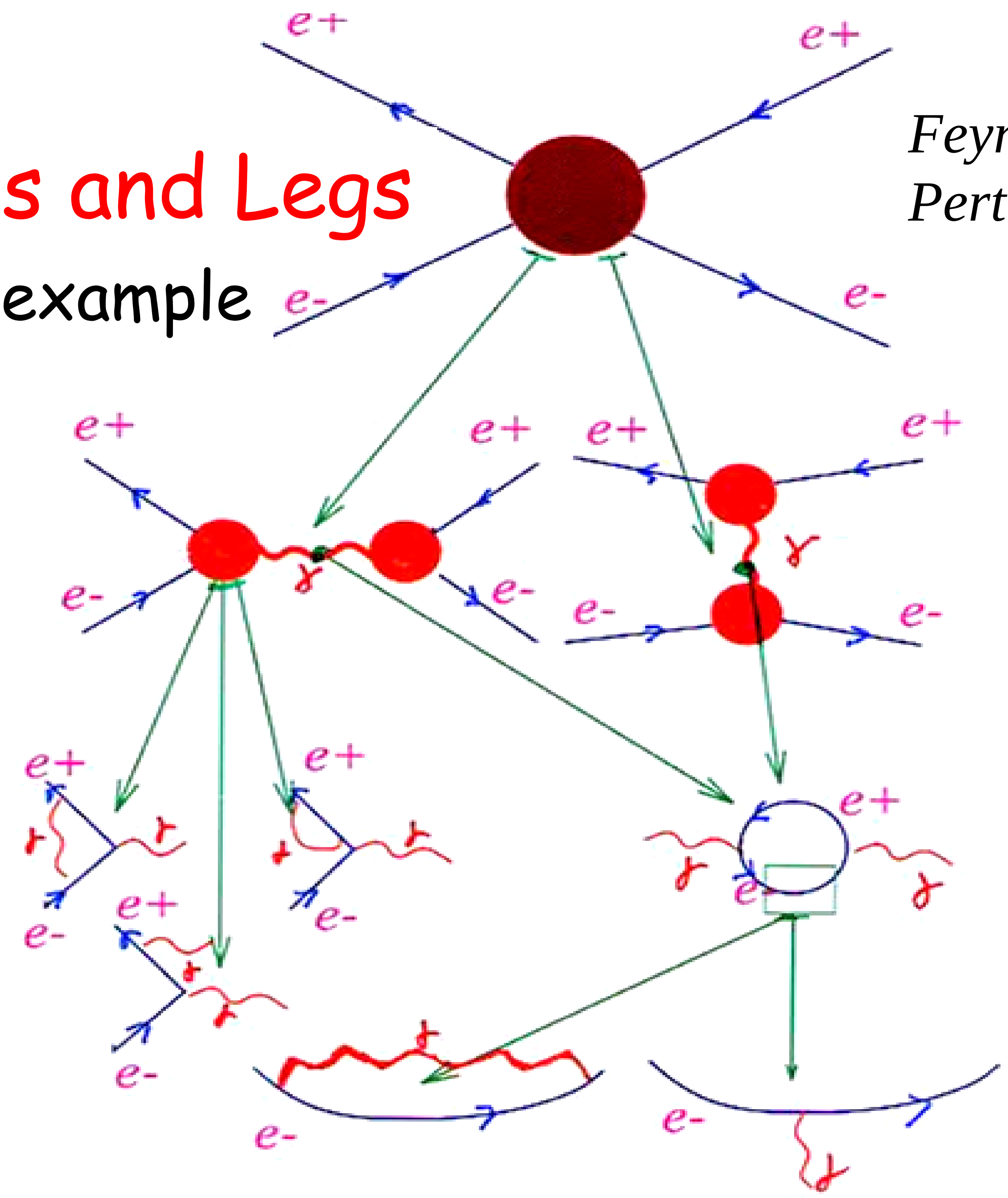
Ab Initio Automatic matrix element generation

A generator of event generators

Loops and Legs

QED example

Feynman diagrams in Pertubative theory



Leading Order
LO,1st order or tree level

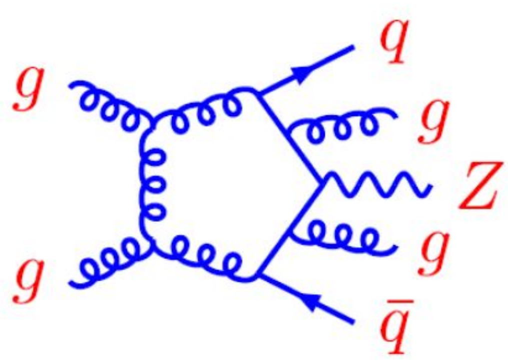
Next Leading Order
NLO

Next Next Leading Order
NNLO

Perturbative QCD requires higher orders calculations

- LO is not precise enough due to scale uncertainties
  - Renormalization (UV) $\alpha_s(\mu)$ and soft/collinear (IR) cone size
- NLO is the lowest order calculation that can lead to realistic evaluation (normalization and event shape): necessary for LHC
  - Decreases the scales arbitrariness
- Parton shower algorithm must also be NLO
- Many Many-legs diagrams must be calculated for new particle search

e.g. 2→ 5 at NLO



The Les Houches Wish List (2010)

2010

process wanted at NLO	background to
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
2. $pp \to H + 2$ jets	H in VBF Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ Melia, Melnikov, Rontsch, Zanderighi VBF: Bozzi, Jäger, Oleari, Zeppenfeld
7. $pp \to V + 3$ jets	new physics Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Feynman diagram methods

now joined by

unitarity based methods

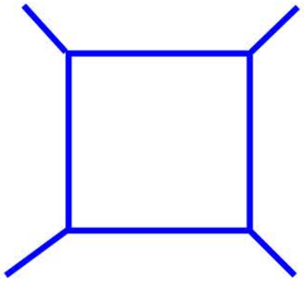
2005 list basically done. Amusingly *W,Z* + 4 jets was not on this list.

9

Zvi BERN, UCLA, 2011

Example of loop difficulty

Consider a tensor integral:



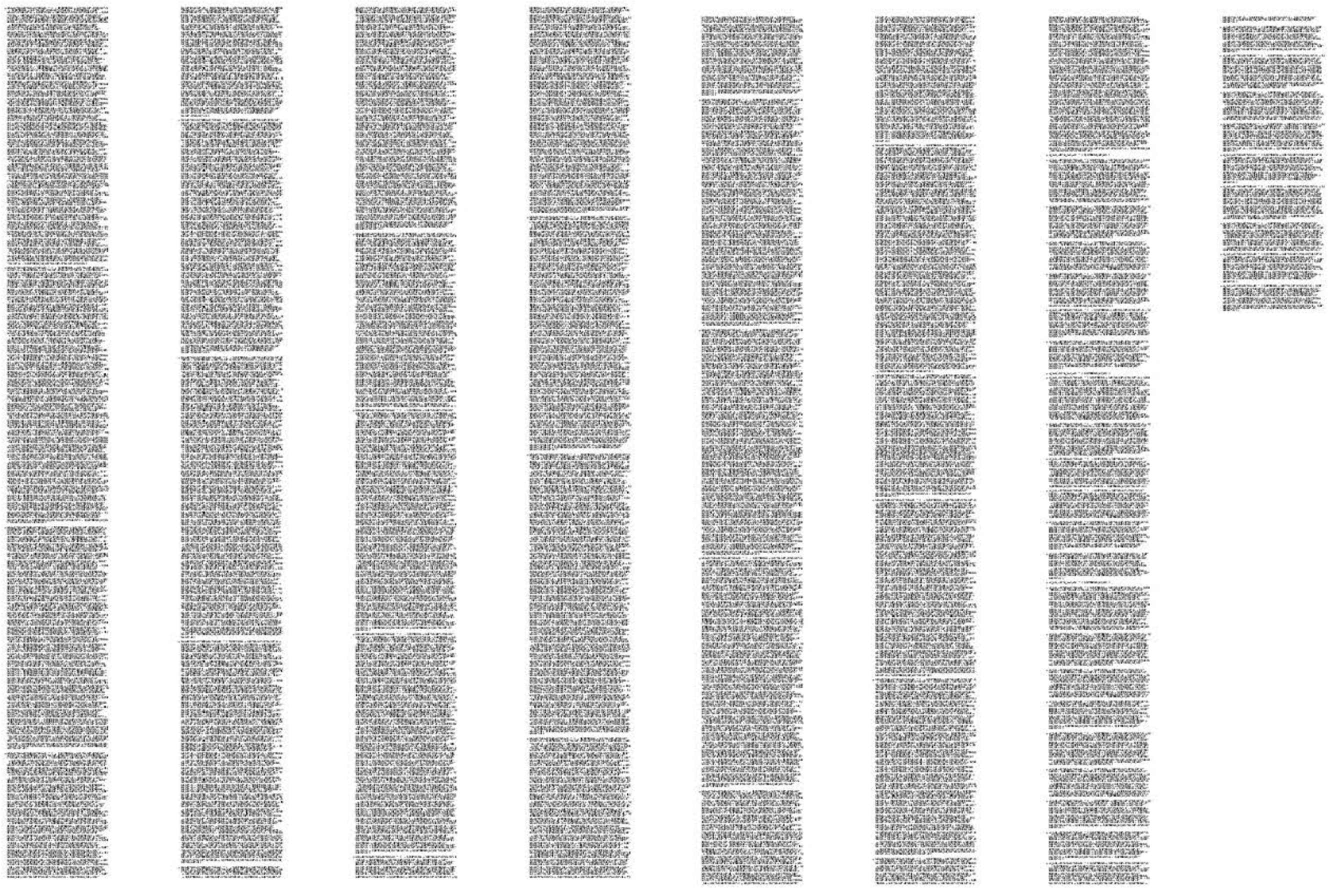
$$\int \frac{d^{4-2\epsilon}\ell}{(2\pi)^{4-\epsilon}} \frac{\ell^\mu \, \ell^\nu \, \ell^\rho \, \ell^\lambda}{\ell^2 \, (\ell - k_1)^2 \, (\ell - k_1 - k_2)^2 \, (\ell + k_4)^2}$$

Note: this is trivial on modern computer. Non-trivial for larger numbers of external particles.

Evaluate this integral via Passarino-Veltman reduction. Result is …

Zvi BERN, UCLA, 2011

Result of performing the integration



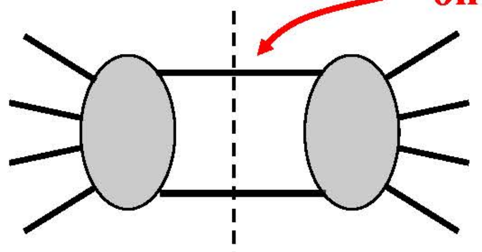
Calculations explode for larger numbers of particles or loops. Clearly, there should be a better way!

Zvi BERN, UCLA, 2011

On-shell Methods

Key idea: Rewrite quantum field theory so only gauge invariant on-shell quantities appear in intermediate steps.

Loops amplitudes constructed from tree amplitudes

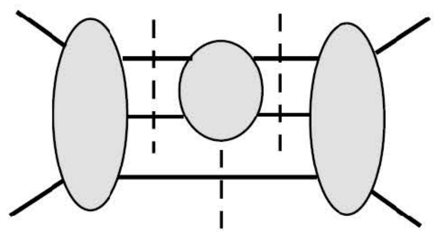


Unitarity method

Bern, Dixon, Dunbar and Kosower (BDDK)

Generalized unitarity as a practical tool

ZB, Dixon and Kosower (1998)

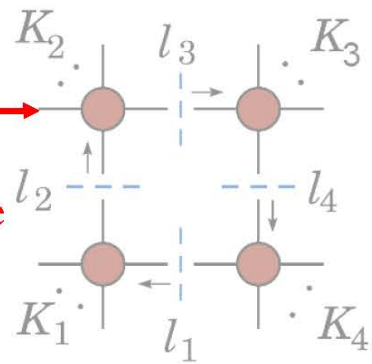


Rules for assembling *n*-point amplitudes from tree ampltiudes

Use of complex momenta

Britto, Cachazo and Feng,

tree amplitude

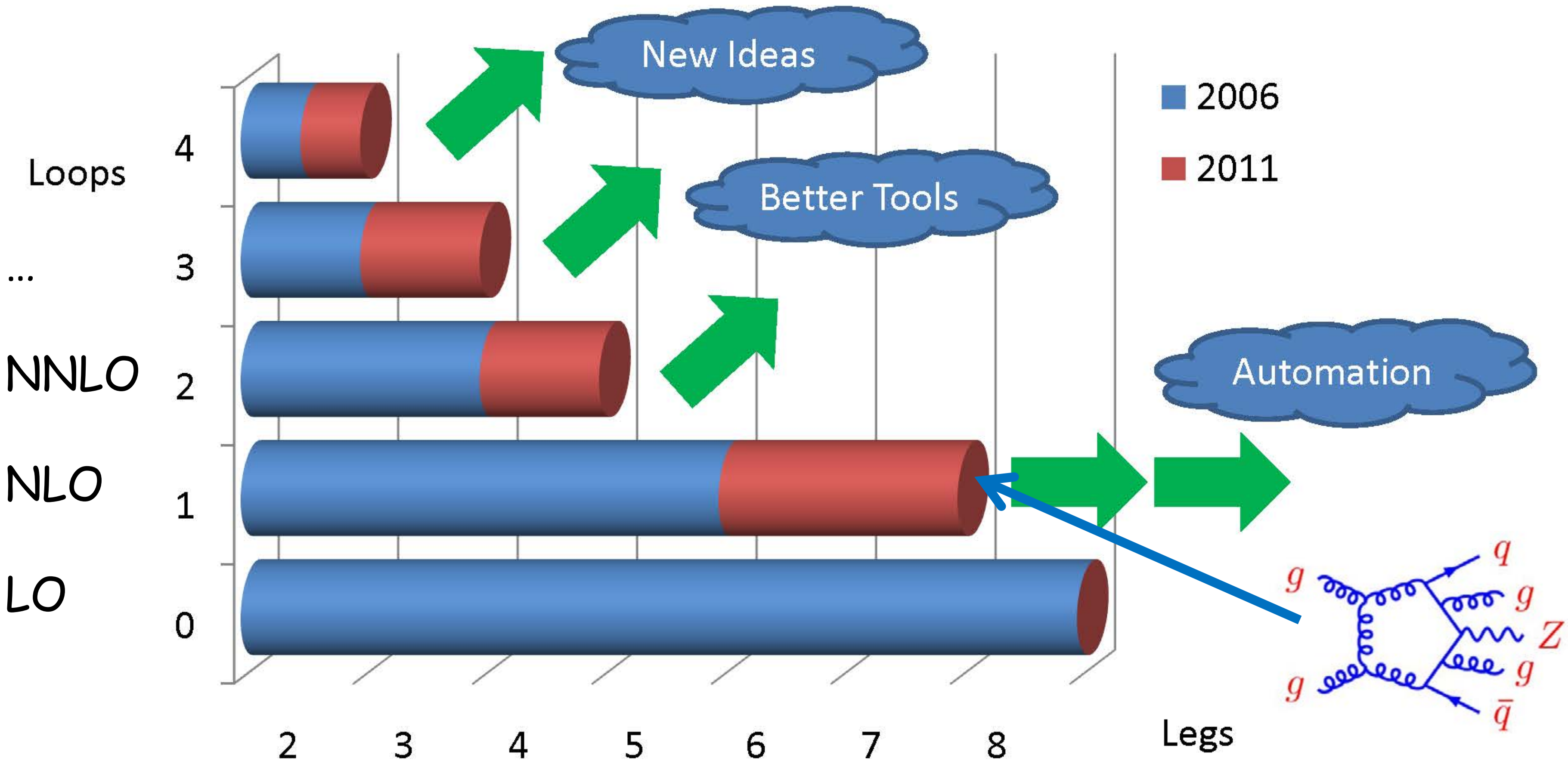


many new advances

Bern, Dixon and Kosower
Britto, Cachazo and Feng,
Ossola, Papadopoulos, Pittau;
Giele, Melniokov, Kunszt,
Forde ;Badger

Zvi BERN, UCLA, 2011

NLO Revolution



N. Glover Durham Univ. UK, ACAT'2011

Multi-dimensional integration

Vegas, Bases, Dice, Vamp, Parint

- Large number of dimensions
  - @LO: $N_{d} = 3N_{legs} - 5$
  - More at higher orders
- Singularities and kinematics
  - Intensive and High Precision floating-point (quad or more)
  - Specific manual variable transforms (sometime necessary)
- Monte-Carlo technique: CPU time consuming
  - Adaptive grid segmentation (
    - Importance sampling (region of largest integrant)
    - Stratified sampling (region of the largest variance)
  - Multi-channel sampling (sum of well behaved functions) (Vamp)
  - Parallel quasi-Monte Carlo techniques and extrapolation (Parint)
  - Parallelism (many-core, GPU, …)

See:

Poster 7: E. De Doncker (Western Michigan Univ.,USA),
Shared memory iterated numerical integration for Feynman loop integrals

Poster 166: F. Yuasa (KEK, Japan):
Acceleration of Feynman loop integrals in HEP on many core GPUs.

New Use of Matrix Elements

- III -

Event Analysis

Matrix Element Likelihood Method

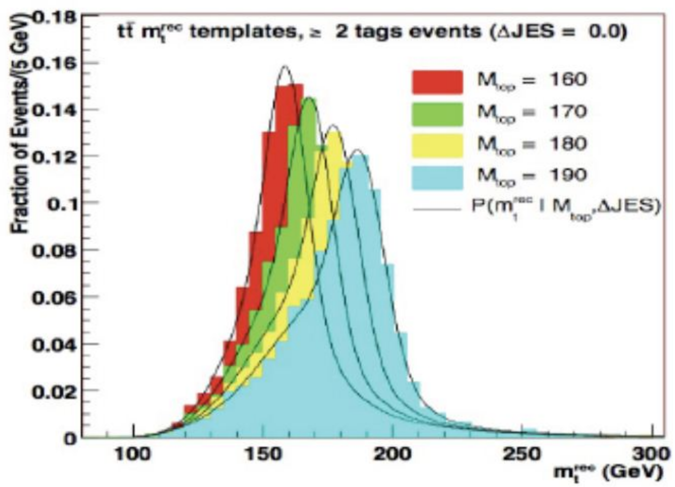
Template Methods

e.g. Higgs mass in γγ

1. Select events based on cuts defined by MC studies
2. Build histograms on estimator (i.e. γγ mass)
3. Compare histograms with MC simulation for different values of the Higgs mass
4. Likelihood on histogram fit

Easy to implement, but

- Full event info not used



Matrix Element Methods

e.g. Higgs mass in γγ

1. Select events based on cuts defined by MC studies
2. Use matrix element to weight events for each similar process (signal and backgrounds)
3. Build and maximize likelihood of mass hypothesis

More involved and CPU intensive, but

- Full event kinematics information is used
- Improvement of statistical uncertainty
- Separation between theory and experimental inputs
- Complementary to template methods (different statistical significance)

For Precision measurement and search for new phenomena

K. Kondo 90 (top mass)
D0, CDF,
Madweight,
ATLAS, CMS Mela

Matrix Element Method in a nutshell

e.g. Top mass evaluation

For each event:

$$P_{sig}(x, mt) = \frac{1}{N} \int_{y,q_1,q_2} d\Phi_6 \, |\mathcal{M}_{t\bar{t}}|^2 \, W(x,y) \, f_{pdf}(q_1) \, f_{pdf}(q_2) \, dq_1 dq_2$$

Measured kinematics

Top mass hypothesis

Matrix element for $t\bar{t}$ production and decay into y partonic state

Transfer Function between x and y state with detector resolution and hadronization.

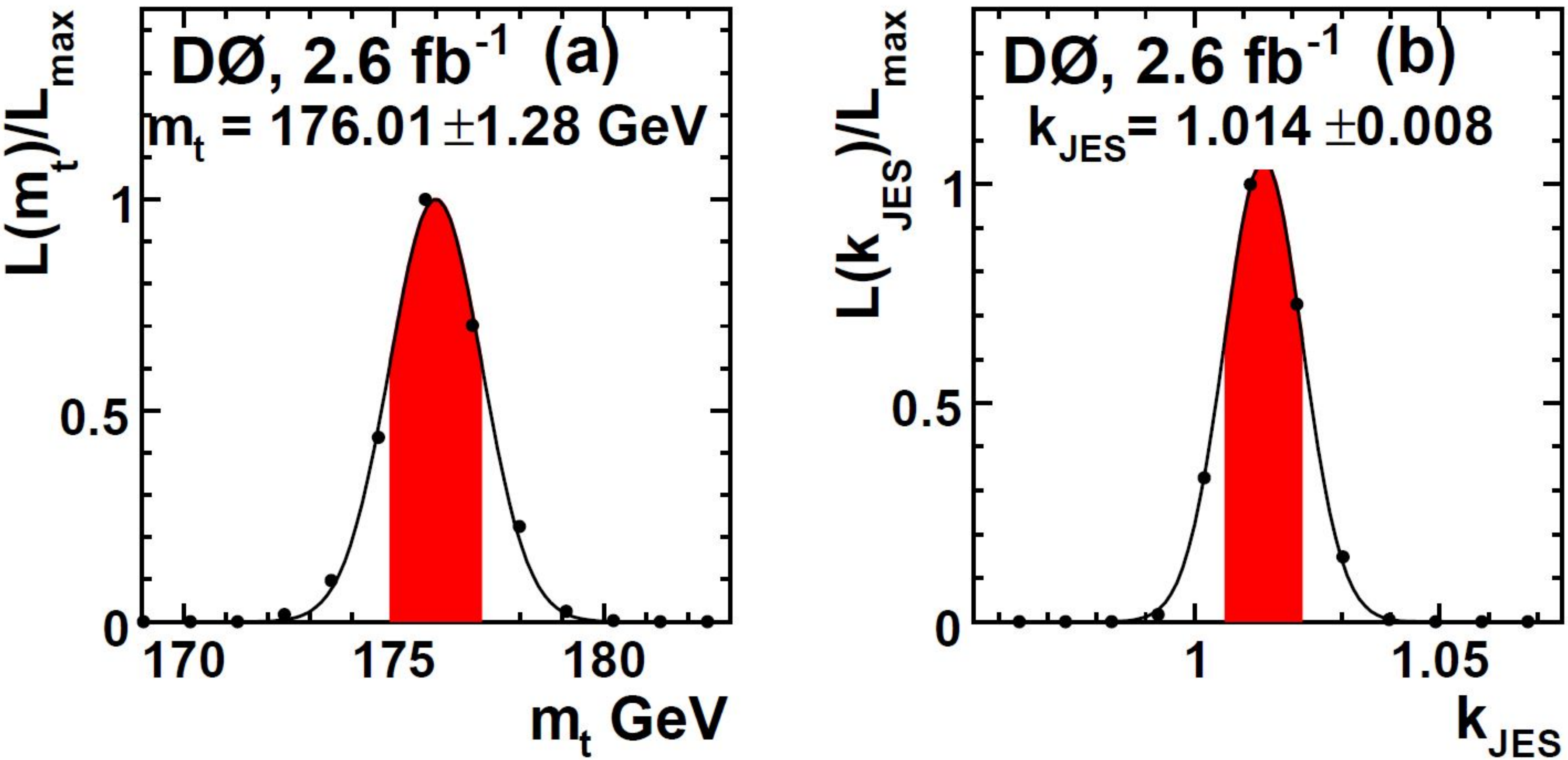
For each event, all possible processes (matrix elements):

$$P_{evt} = f_{sig} P_{sig} + f_{bkg_1} P_{bkg_1} + \ldots + f_{bkg_n} P_{bkg_n}$$

For the selected event sample: minimize the negative likelihood

$$\mathcal{L}(m_t) = - \ln \Pi_{evt} P_{evt}(x, m_t)$$

Top mass measurement



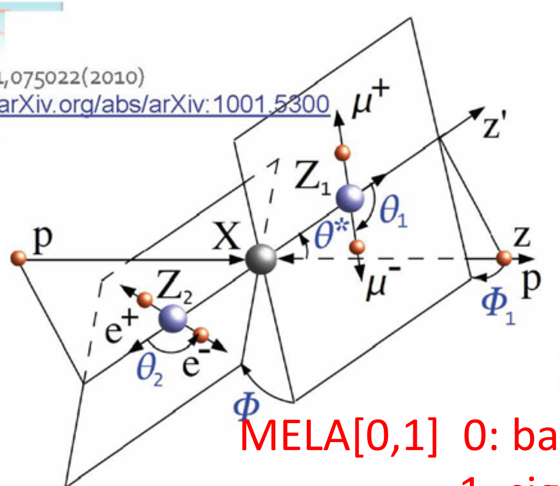
H->ZZ*

MELA

J. Incandela for the CMS COLLABORATION

July 4th 2012 The Status of the Higgs Search

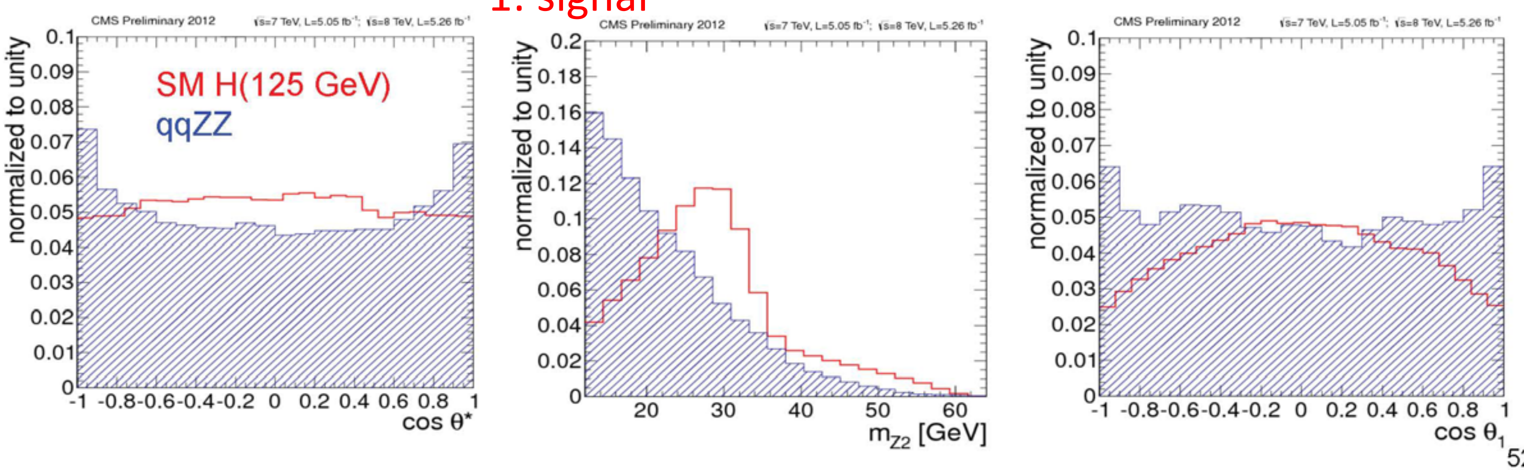
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300



Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

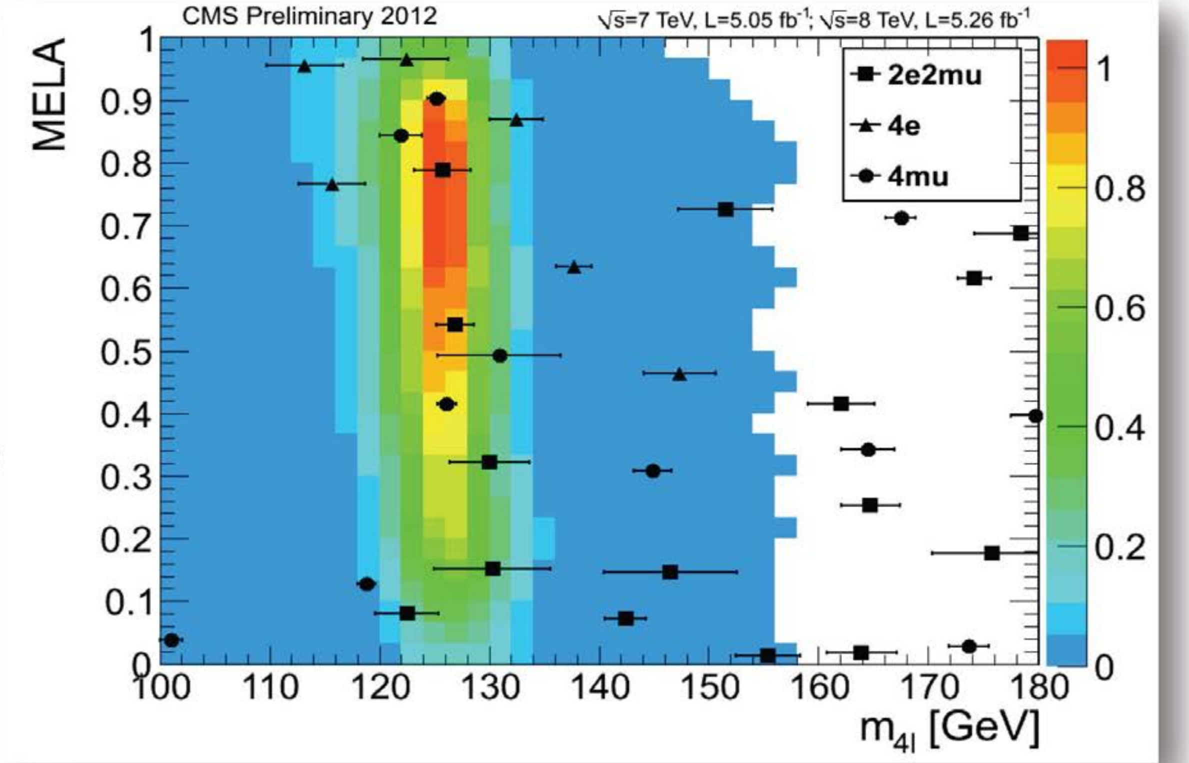
MELA[0,1] 0: background
1: signal



Results: MELA 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties

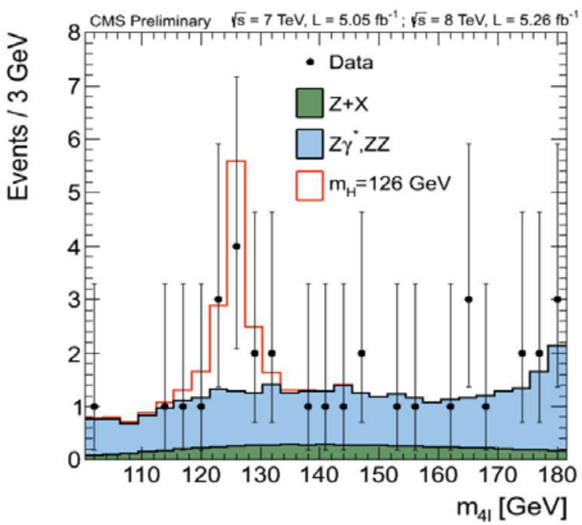


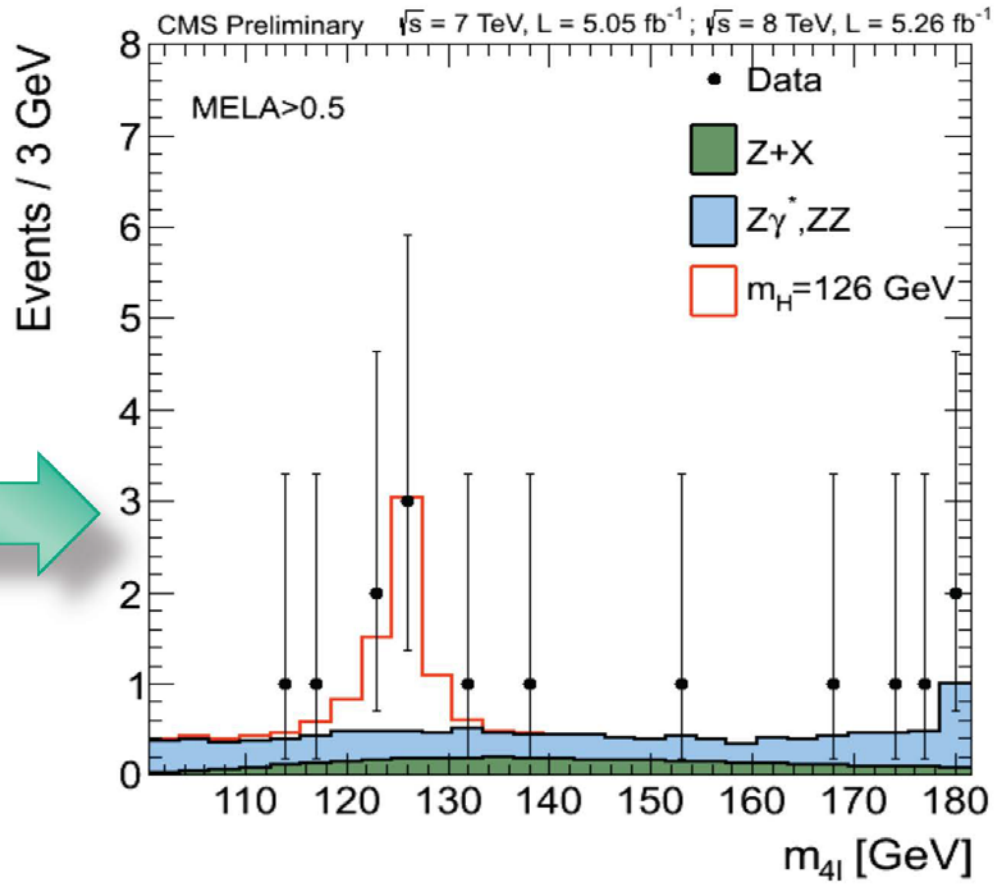
Data w.r.t 126 GeV Higgs Expectation

59

For illustration: Low mass region with MELA cut

- Enrich the signal content
  - Cut: MELA > 0.5
    - Cut value chosen such that signal probability > background probability





61

July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION

Cross disciplinary Issues

- Symbolic manipulation packages (mathematica, maple, reduce,…)
  - Form
    - Expression size: only limited by disk space and cpu time
    - Parallel form
- Numerical multi-dimensional integration packages
  - Large integrands
  - Singularities
- Parallel computation (symbolic, automation, integration, ..)
  - Efficient use of many-core (long term trend of the industry)
  - Portable enough for other architectures (GPU, …)
- Floating point high precision
  - Quad, Octuple precision, … sometime reduces le nb of iteration
- Automation and gluing different packages (perl, python, java, …)
- Large computing world-wide infrastructures (Data grid, Clouds,..)
- Data Analysis toolkits (root) and statistical methods: NN, multivariate analysis, …

ACAT 2013, 15th Int. Workshop on Advanced Computing and Analysis Techniques for Research Beijing (May 16-21, 2013) http://acat2013.ihep.ac.cn/

Conclusions I
Physics simulations

- Monte-Carlo event simulations: mandatory for Experimental Design and Data Analysis in HEP
- Automatic calculation of physics processes is now the rule
  - NLO calculations are needed for LHC(QCD) studies.
  - NLO revolution open widely the field of possible new needed calculations.
  - But computing time and memory size become an issue

Conclusions II
Automatic Matrix elements or amplitude calculations

- Event generators
  - Process automatic calculations
    - Many Physics Models, many processes, many diagrams, higher orders
  - Matrix element automatic construction:
    - tree level done but needs kinematics tuning for efficiency
    - 1-loop processes in (big) progress
  - Many event generators available
- Data Analysis for precision and new physics
  - Matrix Element Method
    - Full use of event information, best error estimate
    - complementary to the template method
    - but cpu time consuming

15th International Workshop on
advanced computing and analysis techiques in physics
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http://acat2013.ihep.ac.cn