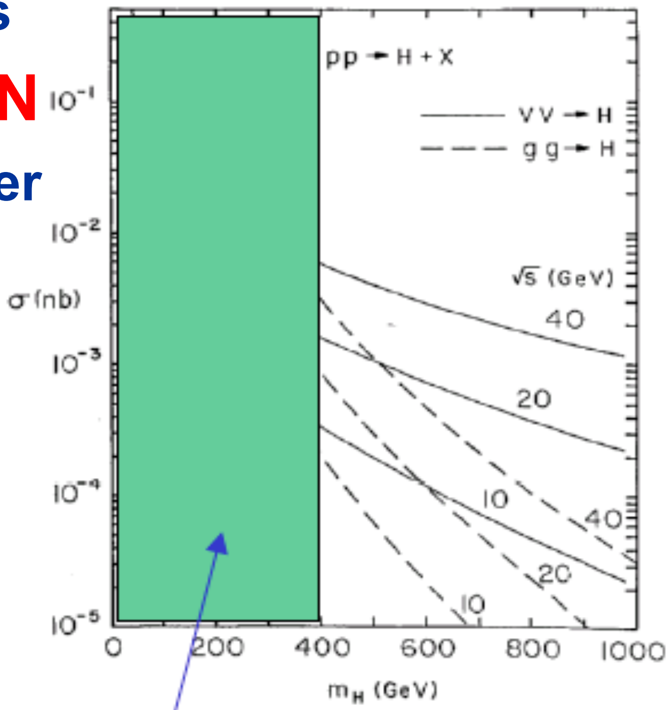
Introduction

Short historical prelude (aka how we got to here)

Why ATLAS/CMS look the way they do

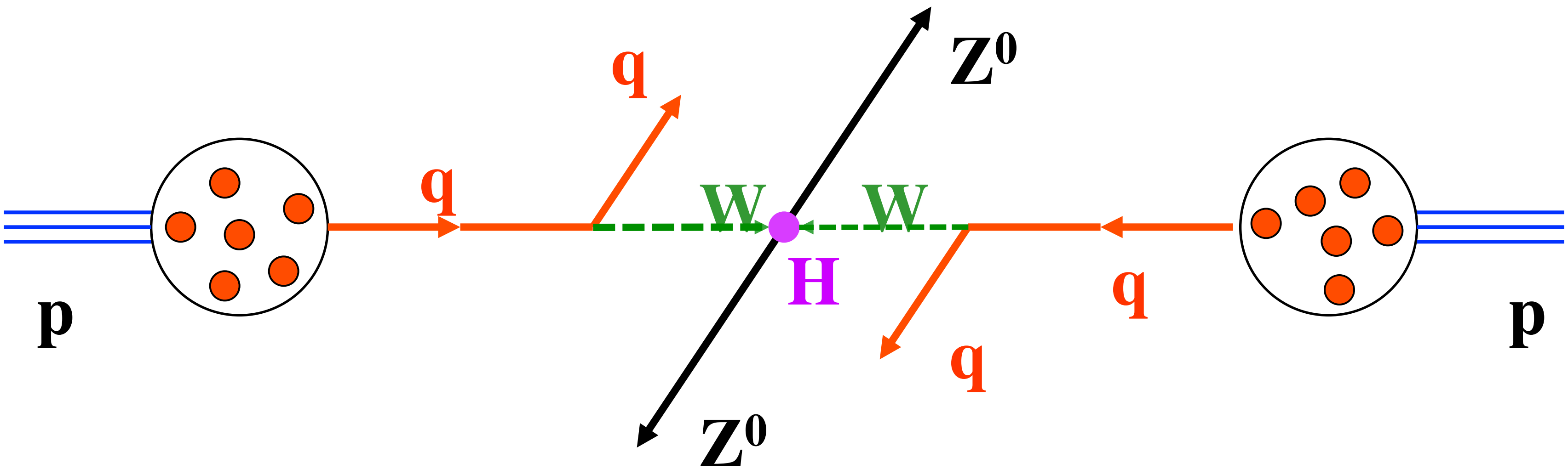
A machine for EWSB

- **Superconducting Supercollider (SSC) √s=40 TeV...**
  - **By now: would have had 3rd-gen results**
- **So: use existing LEP tunnel at CERN**
  - **Replace: e by p; increase bending power**
    - ➨ Large Hadron Collider



D.Dicus, S. Willenbrock
Phys.Rev.D32:1642,1985

Higgs Production in pp Collisions



M_H ~ 1000 GeV

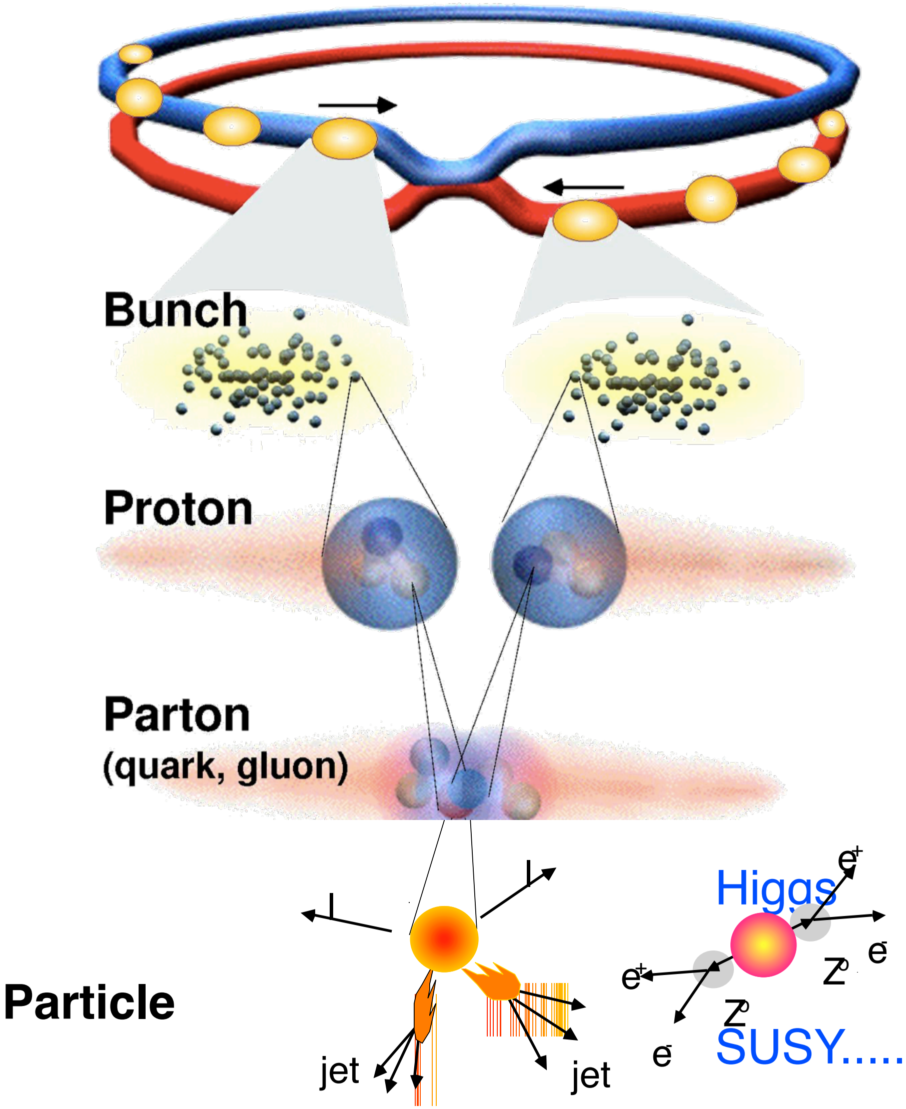
$E_W \geq$ 500 GeV

$E_q \geq$ 1000 GeV (1 TeV)

$E_p \geq$ 6000 GeV (6 TeV)

→ **Proton Proton Collider with $E_p \geq$ 6-7 TeV**

Collisions at the LHC: summary



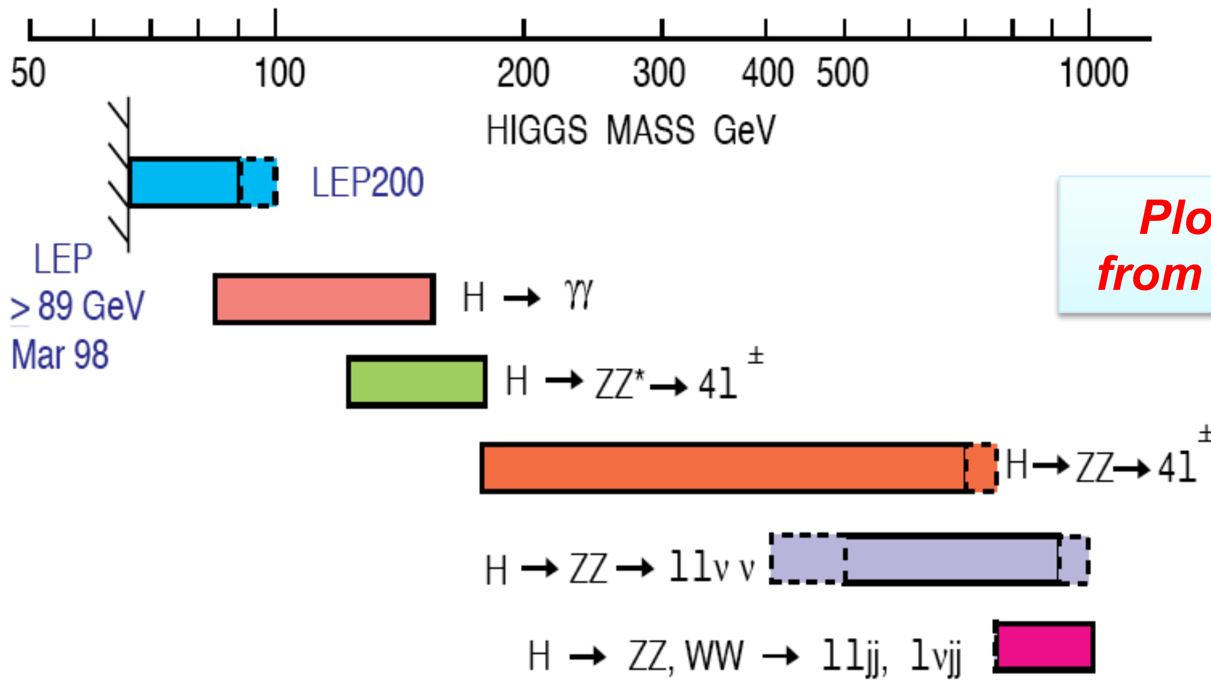
Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^7-10^9

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

Designing LHC detectors

- **Using Higgs boson as driver of requirements:**
  - **SM did not provide information on MH, so a broad range of masses – and thus signatures – had to be considered**



Plot/slide from the 90's

- **Need "4π, general-purpose detectors"**

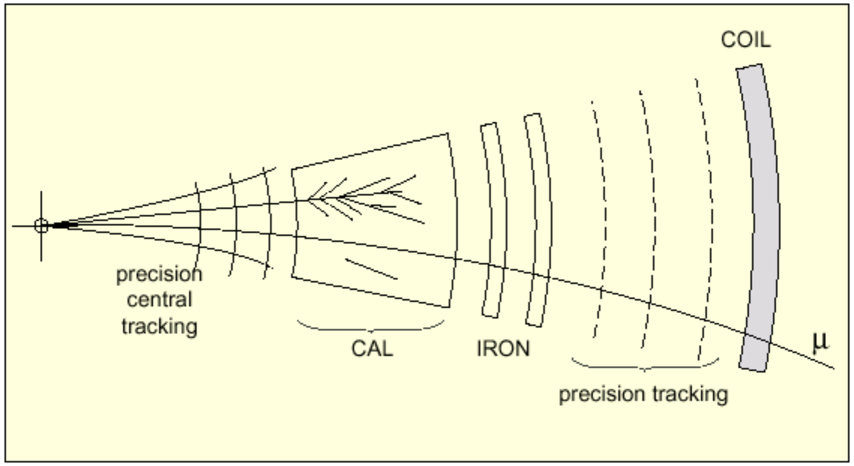
Timeline (example: CMS; ATLAS ~same)

- LHC Workshop, Aachen 1990
  - Concept of a compact detector based on 4T superconducting solenoid
- Expression of Interest, Evian 1992
  - Conceptual Design
- Letter of Intent, October 1992 [CERN/LHCC 92-3]
- Technical Proposal, Dec 1994 [CERN/LHCC 94-38]
- Interim Memorandum of Understanding (IMoU) 1995
- Memorandum of Understanding (MoU) 1998
- Detector Technical Design Reports: 1997-98; Lvl-1 Trigger: 2000; DAQ/HLT: 2002
- Computing & Physics TDR: 2005-06
- First data taking: 2008. LHC Incident. Restart in 2009.
- High-energy data taking [Run I]: 2010–2012
  - pp at 7 TeV: 2010 and 2011 (5 fb^{-1}); 8 TeV in 2012 (20 fb^{-1})
- High-energy data taking [Run II]: 2015–present
  - pp at 13 TeV: 2015 (4 fb^{-1}); 2016 (40 fb^{-1}); 2017 (starts spring 2017)

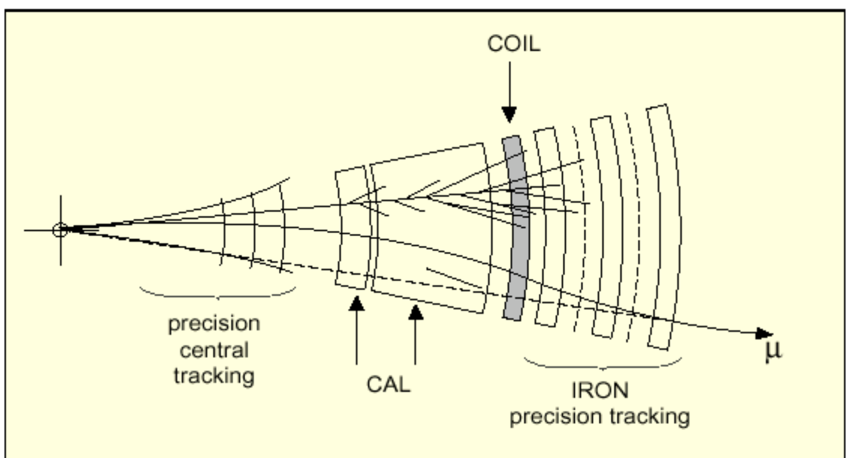
Designing an LHC experiment

- **THE issue: measure momenta of charged particles (e.g. muons); so which measurement "architecture"?**

Note: B in z in both cases



Standalone p measurement; safe for high multiplicities;
Air-core torroid
Property: σ flat with η

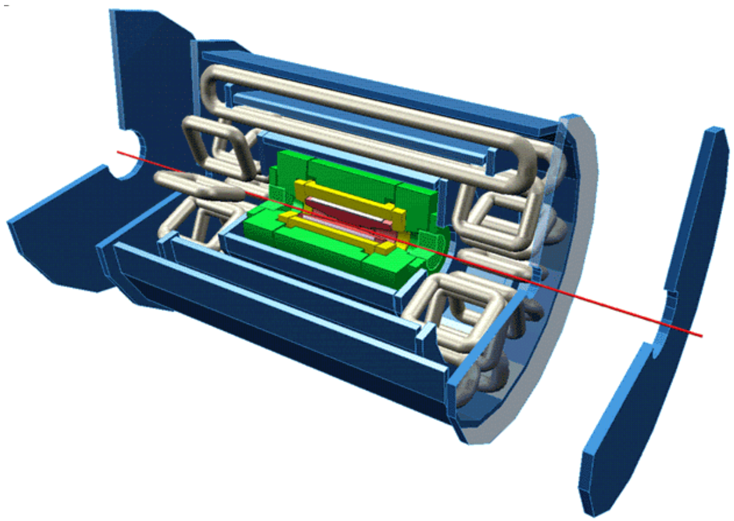


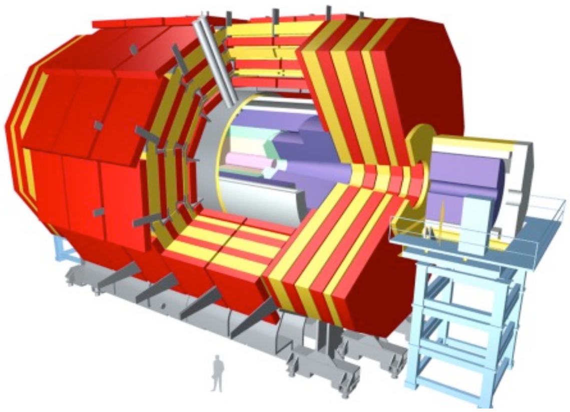
Measurement of p in tracker and B return flux;
Iron-core solenoid
Property: muon tracks point back to vertex

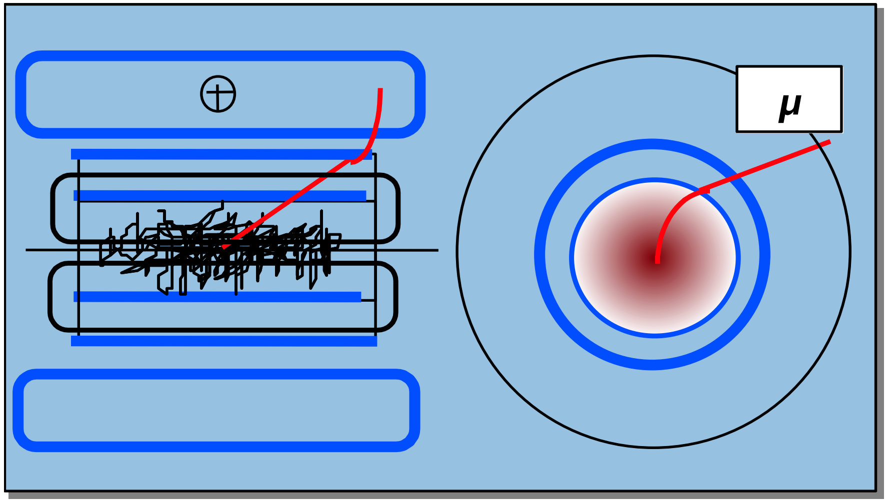
LHC: pp general-purpose experiments

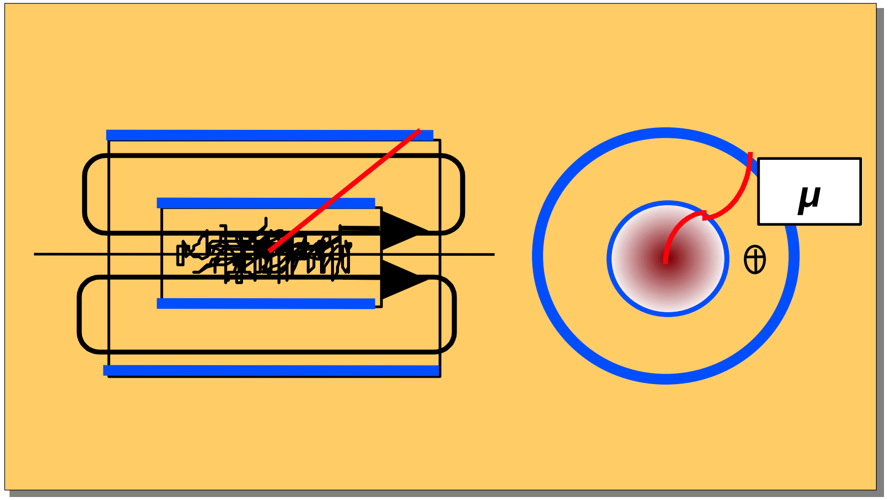
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid



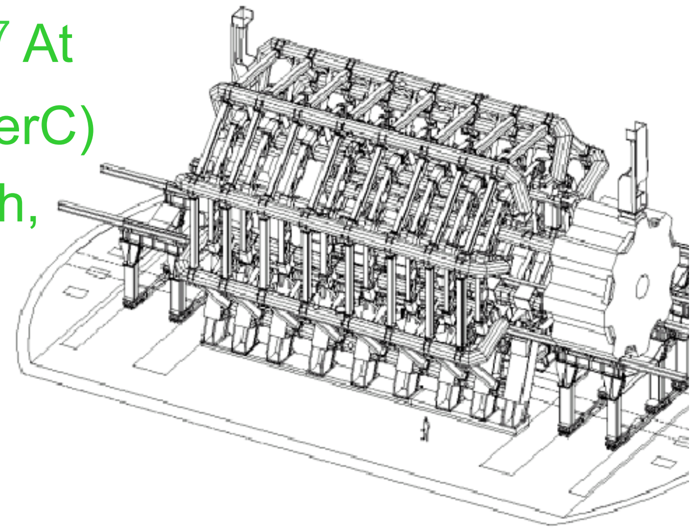




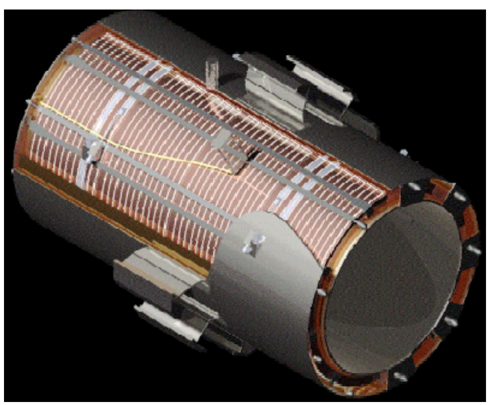


Choice of magnet (I)

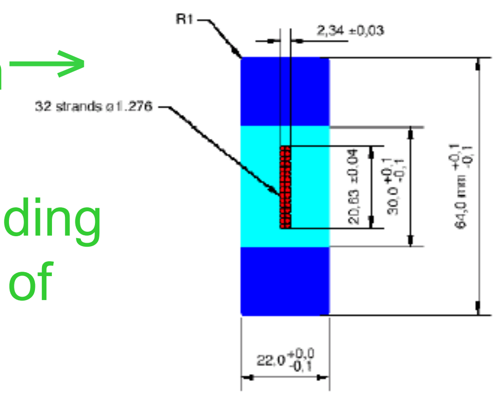
- **Basic goal: measure 1 TeV muons with 10% resolution**
  - **ATLAS: <B>~0.6T over 4.5 m → s=0.5mm → need σ_s=50μm**
    - Ampère's thm: $2\pi RB=\mu_0 nI$ ⟶ $nI=2x10^7$ At
    - With 8 coils, 2x2x30 turns: I=20kA (superC)
    - Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area



  - **CMS: B=4T (E=2.7 GJ!)**

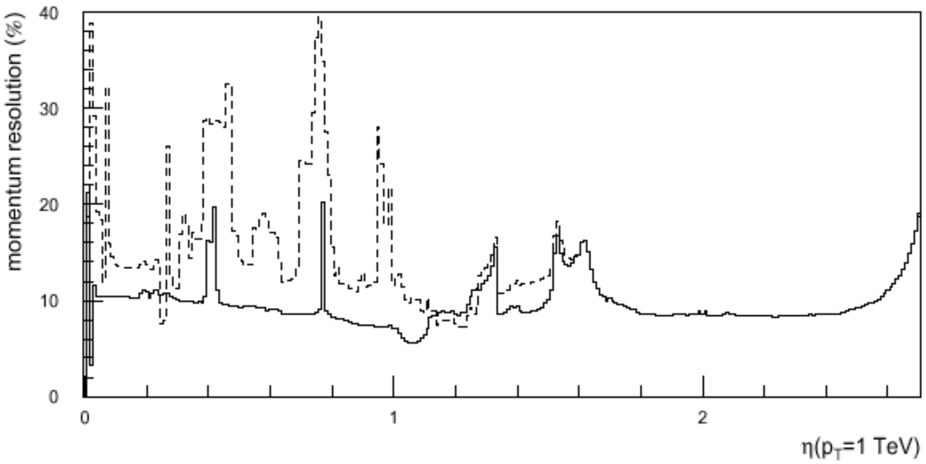


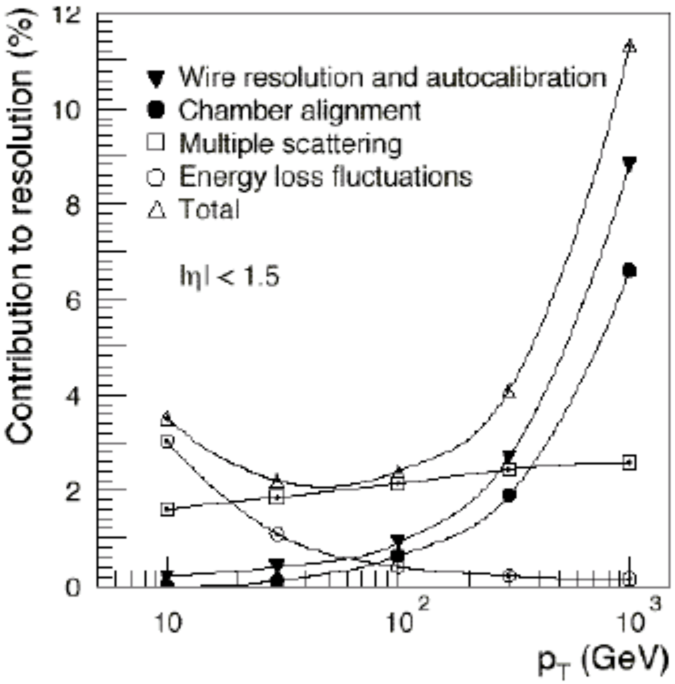
- $B=\mu_0 nI$; @2168 turns/m ⟶ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable



Choice of magnet (II): air-core torroid

- **Torroid: gives flat σ vs η:**





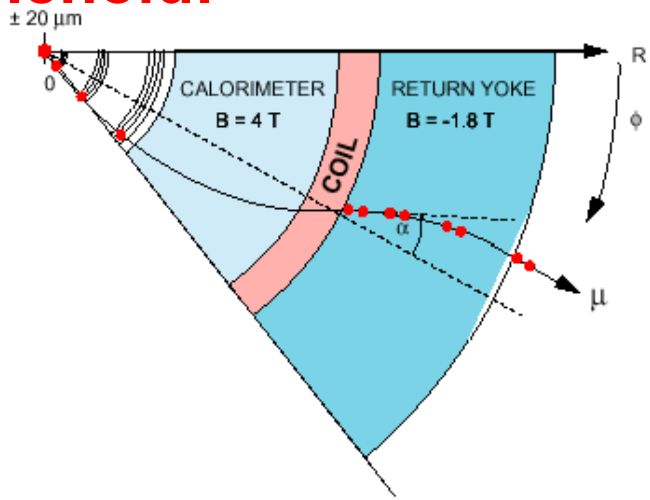
(a) External meas. does not benefit From beam spot (20 μm @ LHC)

(b) need additional solenoid for internal track measurement

- **ATLAS: B=2T solenoid**

- **Calorimetry: a new question: inside or outside solenoid?**
  - **ATLAS: outside; CMS: inside**

Choice of magnet (III): iron-code solenoid

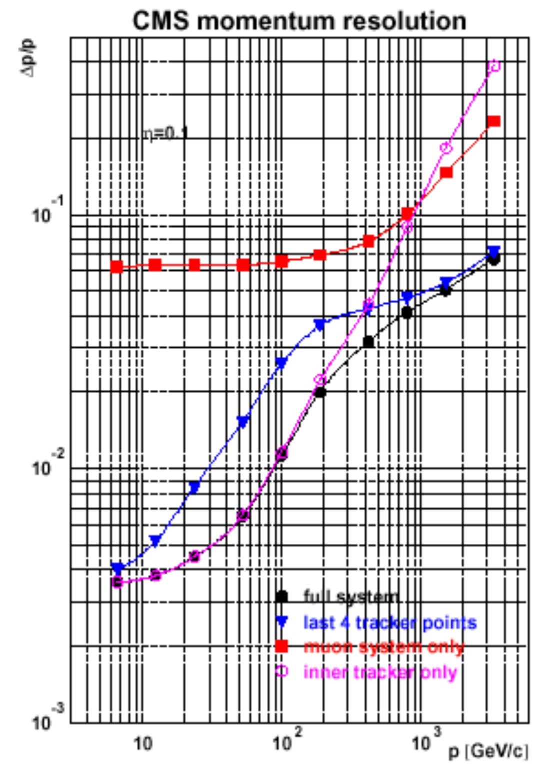
- **Solenoid:**
  - 

Bending in transverse plane

Use 20μm beam spot

BUT: 4T brings problems

(e.g. cannot use PM tubes)



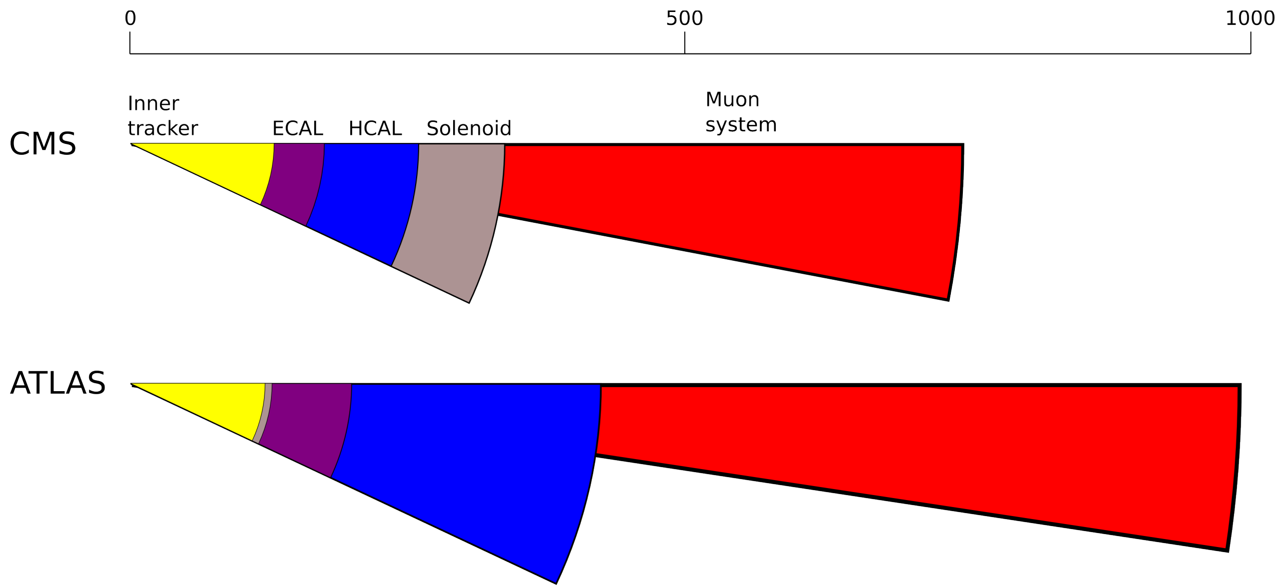
- **Iron-core → multiple scattering**
  - **Tracking in magnetized iron:**

$$\frac{\Delta p}{p} = \frac{40\%}{B\sqrt{L}}$$

  - **BUT measurement much better when combined with the tracker**
  - **Insufficient bending at large |η|...**

Choice of magnet (IV)

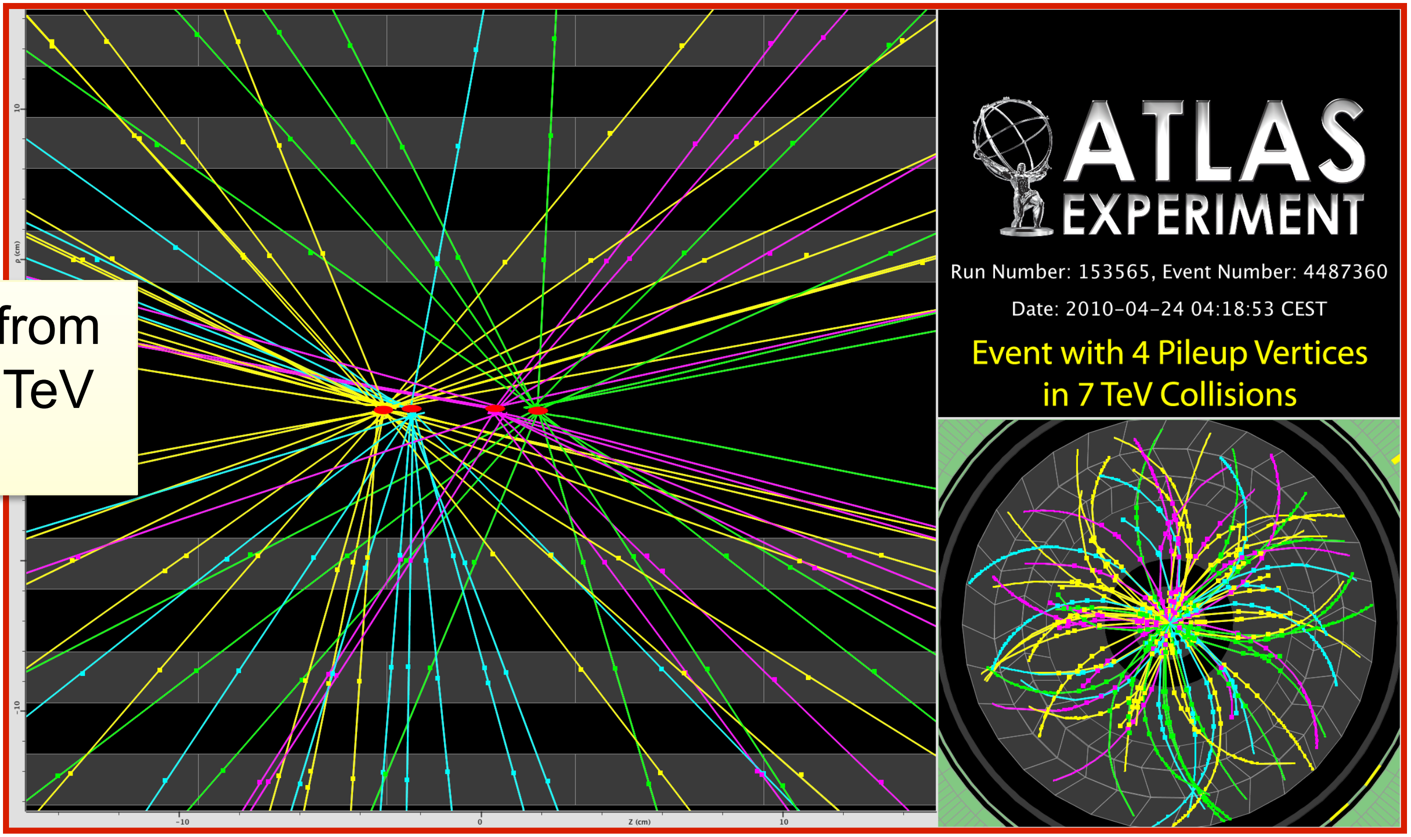
- **Side effects: size of things...**
  - **External measurement:**
    - **Need space: solenoid + toroids → complicated field configuration**
    - **Lower field in tracker (2T)**
  - **Internal measurement:**
    - **Very compact ® no space**



  - **HCAL: shallow in CMS; deep (and better) in ATLAS**
    - **ATLAS: 60%/√E; CMS: 120%/√E → naively expect, ATLAS ~twice better for jets and ME_T**

The environment

- **Lower cross section ® need higher luminosity.**
  - **But then, probability that two protons interact rises**



Example from earliest 7 TeV collisions

- **This is referred to as "pileup".**

The environment (II)

# of interactions/crossing:

Interactions/s:

- **Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}$Hz**
- **σ(pp) = 80 mb**
- **Interaction Rate, R = 8×10^8 Hz**

Events/beam crossing:

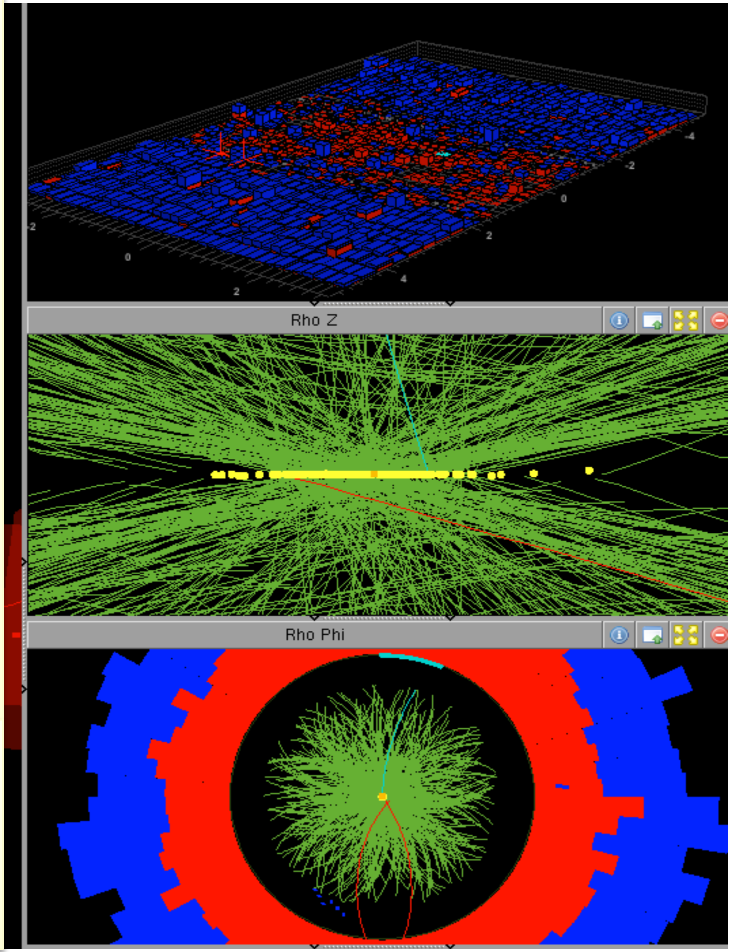
- **Δt = 25 ns = 2.5×10^{-8} s**
- **Interactions/crossing=20**
  - **For 50 ns operation: 40!**

Not all p bunches full

- **2835 out of 3564 only**
- **Interactions/"active" crossing = 20 x 3564/2835 = 25**

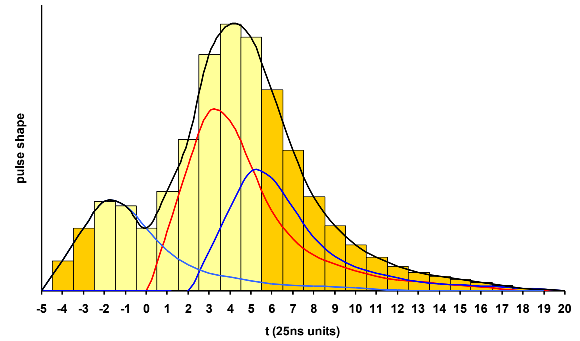
Operating conditions (summary):
(1) A "good" event containing a Higgs or SUSY decay +
(2) ~ 25 extra "bad" (minimum bias) interactions

CMS event with 78 reconst-ructed vertices and 2 muons…

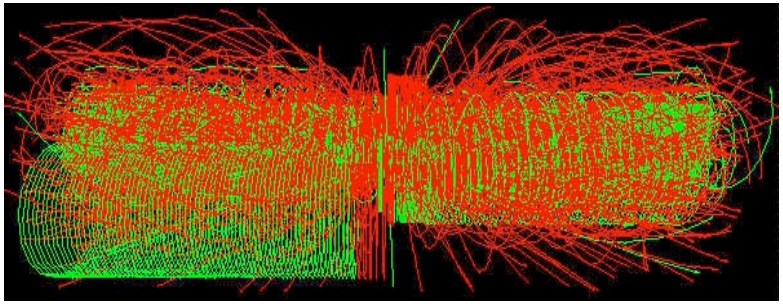


LHC challenges: detector design

- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns
    - → challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object
    - → large number of electronic channels; high cost
- **LHC detectors must be radiation-resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters in 10 yrs of LHC:
    - up to 10^{17} n/cm^2 [10^7 Gy; 1 Gy = 1 Joule/Kg)



100 million channels per detector!



Muon system

Muon-ID should be easy at L=10^{34}cm^{-2}s^{-1}

Muons can also be identified inside jets

Factors that affect performance

Level-1 trigger

Very high rate from genuine muons (b,c→μ). Must make P_T cut with very high efficiency and flexible threshold (P_T in the range 5-75 GeV)

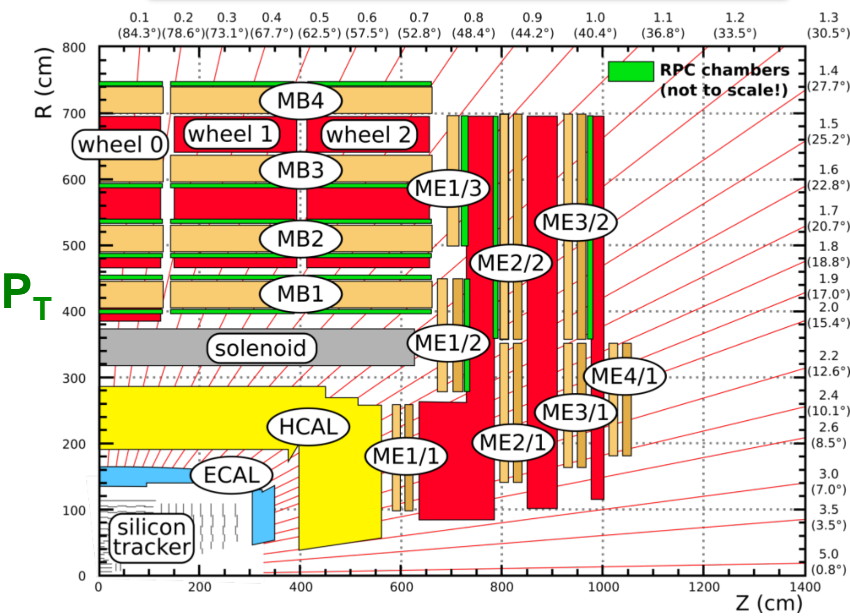
Pattern recognition

Hits can be spoiled by correlated backgrounds: δ' s, EM showers, punchthrough. Uncorrelated bkgs: neutrons and associated photons

Momentum resolution

High p_T: need large int(B.dl); good chamber resolution (<100μm) and alignment. Low p_T: inner tracking better

Multiple stations with multiple hits



14 ktons of iron absorber and B-field flux return
Bending in iron + muon tracking: trigger info; and link with main tracker

Tracking

Resolution goal:

$\Delta p_T/p_T = 0.1 p_T$ [TeV] $|\eta|<2$;

plus narrow signals: $H\rightarrow 4\mu$ & match Z width

- Lepton charge up to p~2 TeV
- Match calo resolution (electrons)
- Calo calibration (ECAL)

Pattern recognition:

- Large-p_T leptons: μ (isolated/in jets); e (isolated)
- + large-p_T tracks around lepton
- Identify all tracks with p_T>2GeV

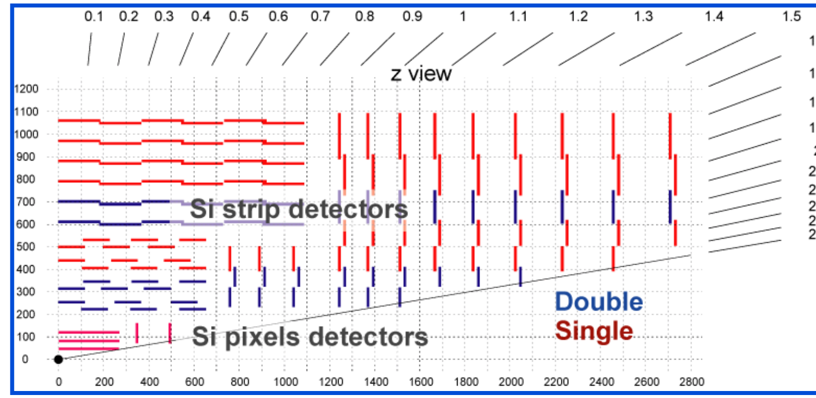
CMS solution: few, very accurate points

- ATLAS: "continuous" tracking

Post LoI: add pixels for vertex tagging. Extremely important!

3 Si Pixel & 10 (4 double) Si Strip Measurement Layers

Radius ~ 110cm, Length ~ 270cm



12 hits; B=4T; R=110 cm; spatial resolution: (pitch/ √12); resolution:

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\mu m}\right)^1 \left(\frac{1.1m}{L}\right)^2 \left(\frac{4T}{B}\right)^1 \left(\frac{p}{1Tev}\right)$$

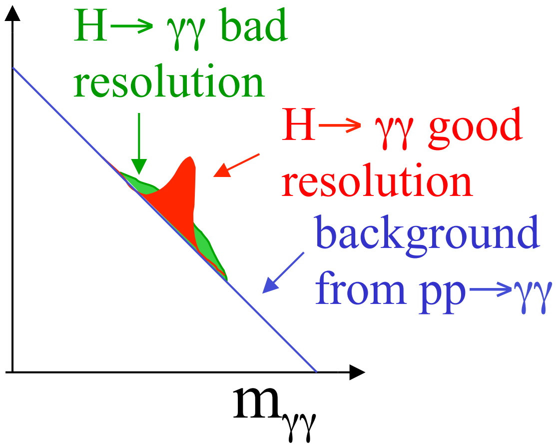
→ Need pitch ~100μm.

Low occupancy: 66M pixels, 10M strips

Rad-tolerance: keep at -10°C (x100 wrt to 25°C)

Electromagnetic calorimeter

Need excellent energy resolution of EM calorimeters for e/γ; Example: $H \to \gamma\gamma$ for low-mass Higgs



- Higgs width very small, → S/N ∝ to signal resolution
- Initial QCD background: x100 larger
- π^0 rejection: strips (ATLAS), crystal size (isolation) (CMS); preshower in the endcap

ATLAS: liquid argon.

CMS: not enough space for cryogenics. Need something more compact → crystal ECAL

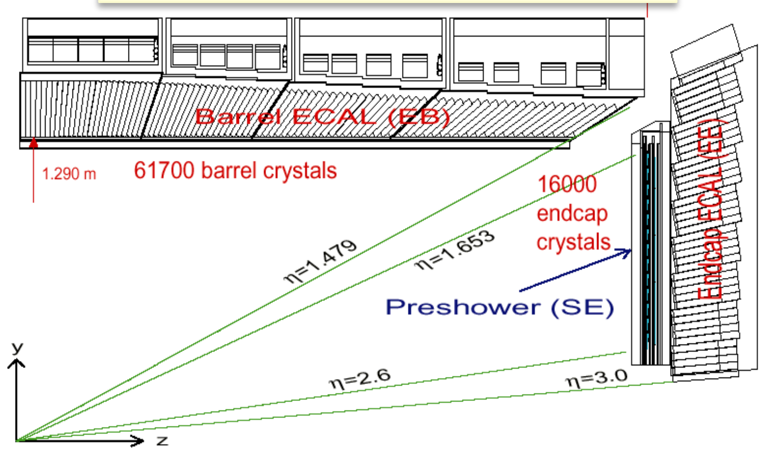
Properties of some crystals

Crystal	X_0 (cm)	R_M (cm)	Light Yield Gammas/MeV	Peak (nm)	Decay (ns)
BaF_2	2.06	3.4	2000	210	0.6
			6500	310	620
CeF_3	1.68	2.6	2000	300	5
				340	20
$PbWO_4$	0.89	2.2	250	440	5-15

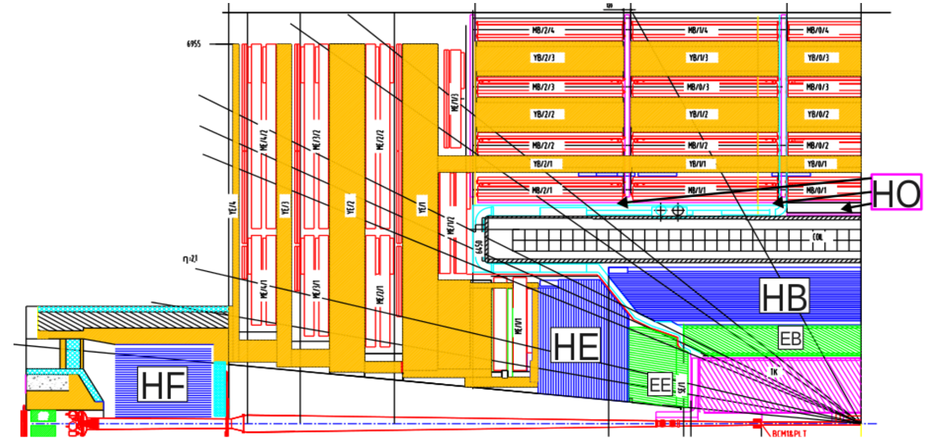
Need new photo-detector type: APD

~76 k Lead tungstate ($PbWO_4$) crystals: 2.3 X 2.3 X 23 cm^3

$\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$



Hadron calorimeter



HCAL requirements

Jet energy resolution: limited by jet algorithm, fragmentation, magnetic field and pileup at high luminosity

Figure-of-merit used: width of the jet-jet mass distribution

- Low-p_T jets: W, Z → Jet–Jet, e.g. in top decays
- High-p_T jets: Z ' → Jet–Jet (M(Z'))~1 TeV)

At very high-p_T: need fine lateral granularity (for very collimated jets

$$\frac{\sigma_E}{E}(\%) \sim \frac{100-150\%}{\sqrt{E}}$$

Missing transverse energy resolution

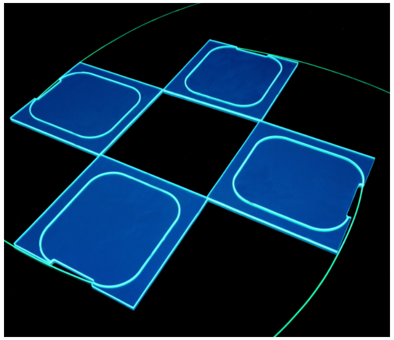
- Gluino and squark production/decay
- Forward coverage to $|\eta|<5$
- Hermeticity – minimize cracks and dead areas

Absence of tails in energy distribution: more important that a low value in the stochastic term

Good forward coverage required to tag processes from vector-boson fusion

Tile calorimeter

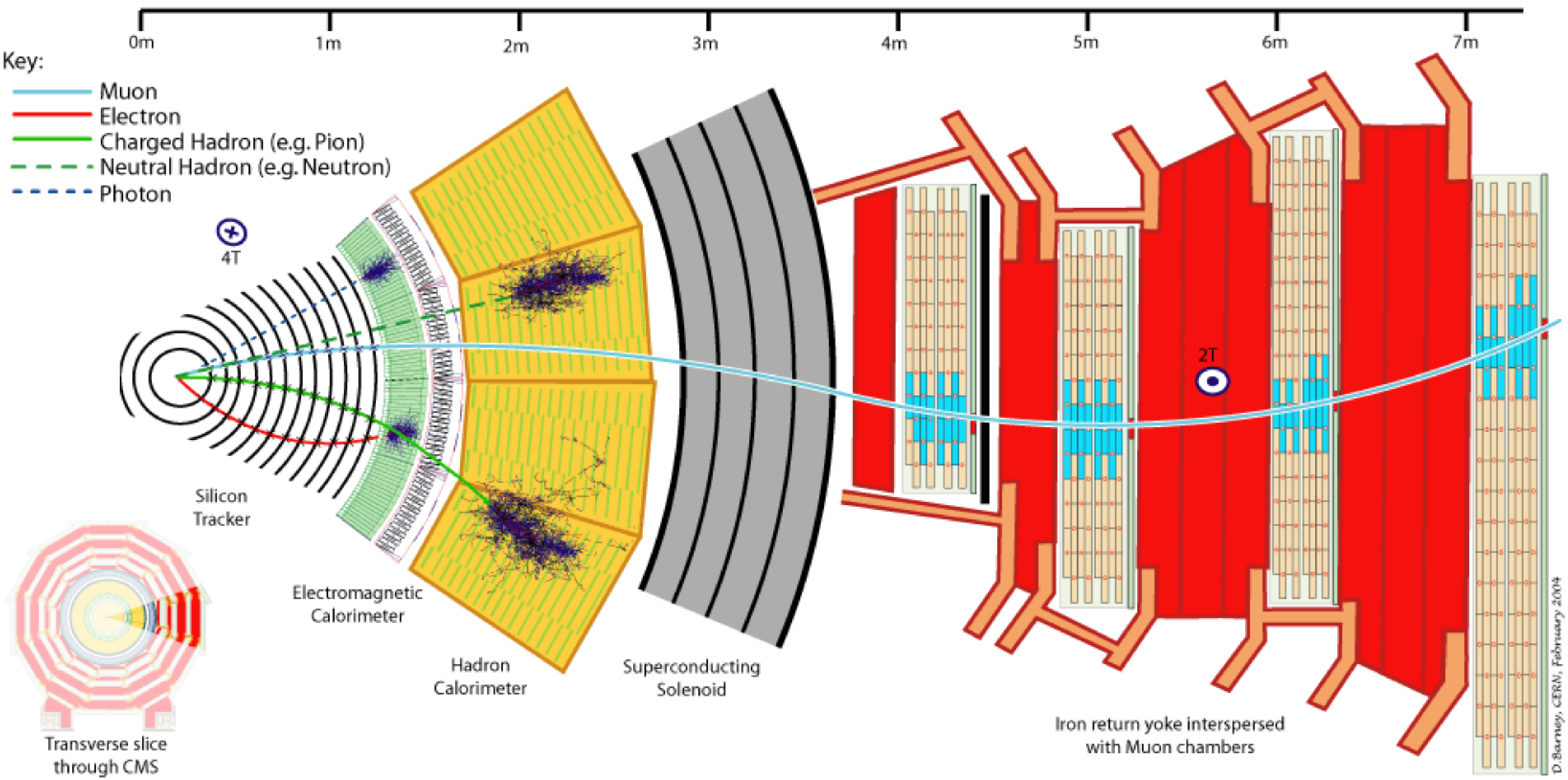
Scintillating tiles with wavelength shifting (WLS) fiber



Tower size: $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$

This is the basic trigger unit

Particle detection/identification in CMS



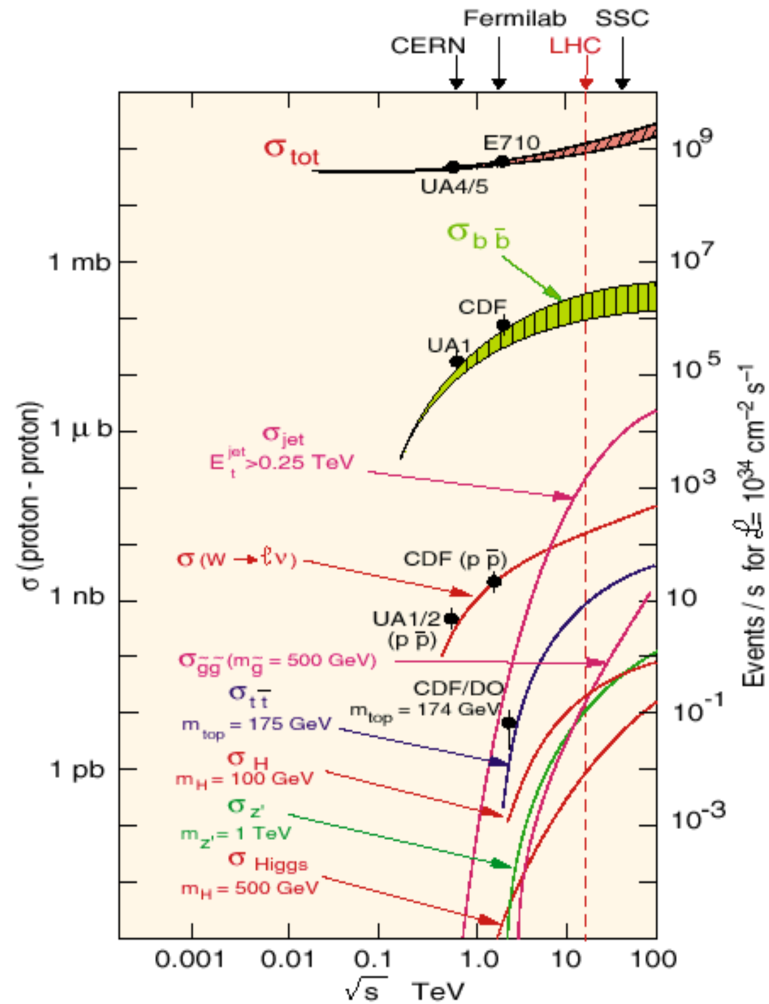
ATLAS & CMS magnet systems

TABLE 3 Main parameters of the CMS and ATLAS magnet systems

	CMS	ATLAS		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.7 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

Selectivity: the physics

- **Cross sections for various physics processes vary over many orders of magnitude**
  - Inelastic: 10^9 Hz
  - $W \to \ell \nu$: 10^2 Hz
  - t t production: 10 Hz
  - Higgs (100 GeV/c^2): 0.1 Hz
  - Higgs (600 GeV/c^2): 10^{-2} Hz
- **Selection needed: $1:10^{10-11}$**
  - Before branching fractions...



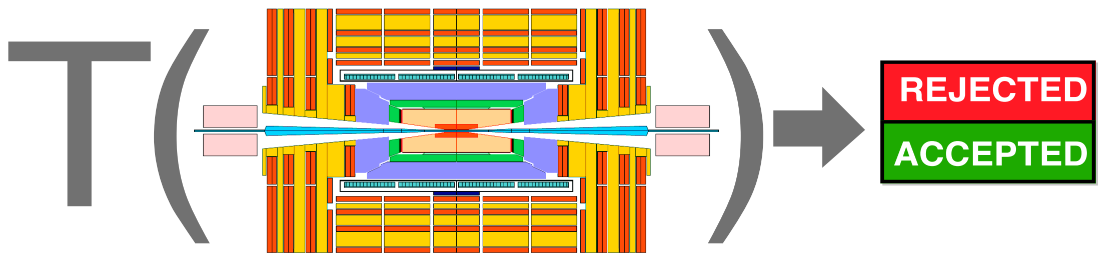
Triggering

Mandate:

"Look at (almost) all bunch crossings, select most interesting ones, collect all detector information and store it for off-line analysis"

P.S. For a reasonable amount of CHF

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

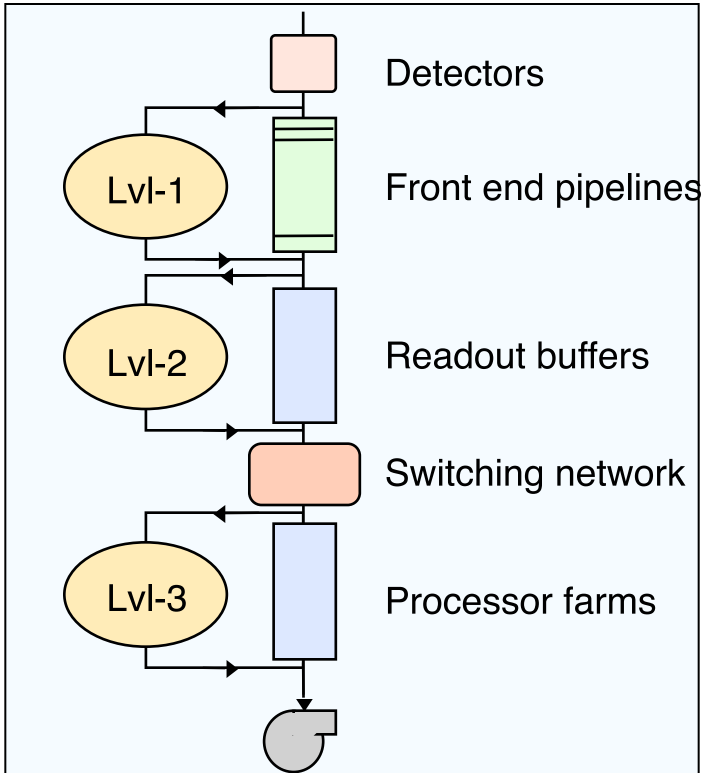
Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

TRIGGER LEVELS

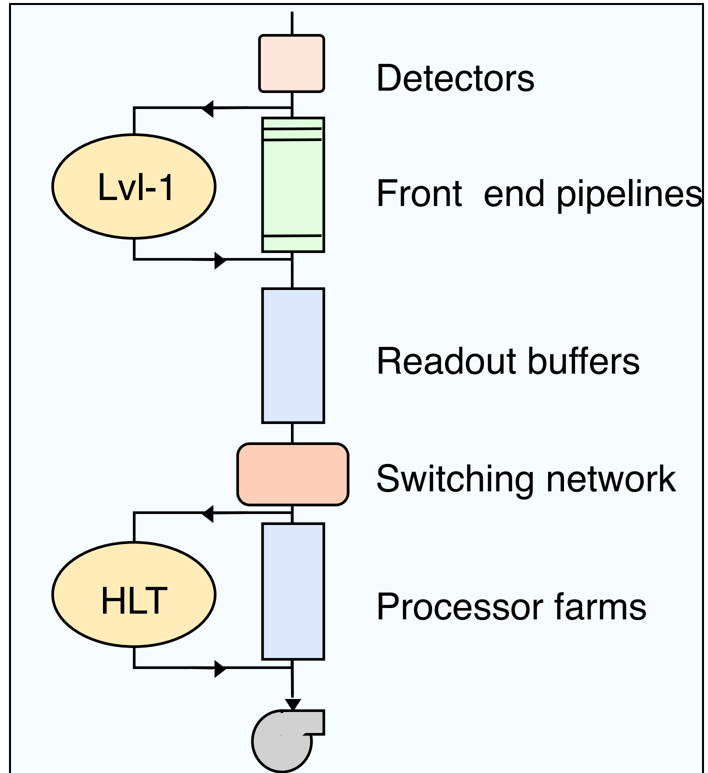
(possibly with zero dead time)

Online Selection Flow in pp

- **Level-1 trigger: reduce 40 MHz to 10^5 Hz**
  - **This step is always there**
  - **Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps**



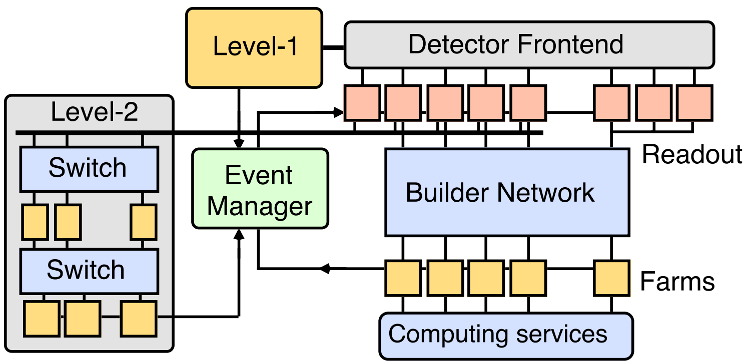
"Traditional": 3 physical levels

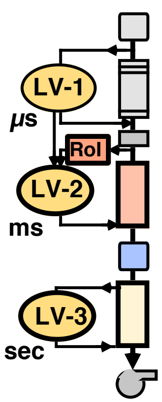


CMS: 2 physical levels

Three physical entities

- **Additional processing in LV-2: reduce network bandwidth requirements**





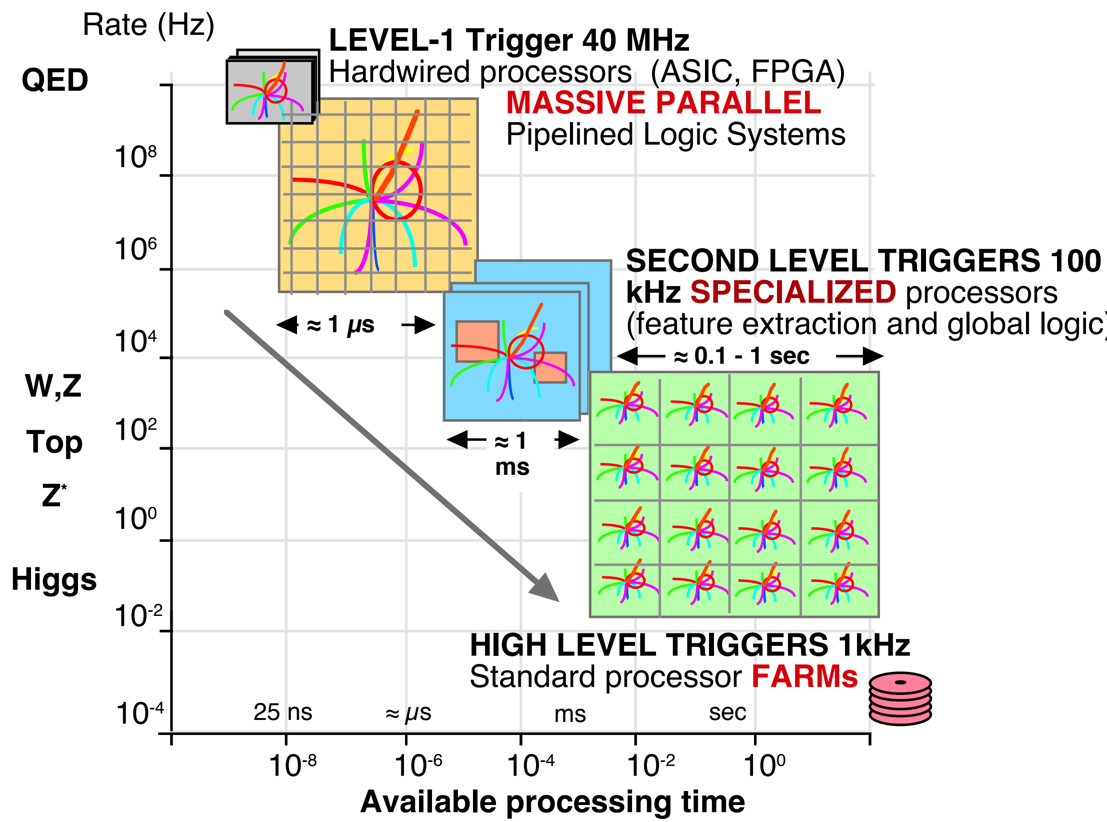
40 MHz

10^5 Hz

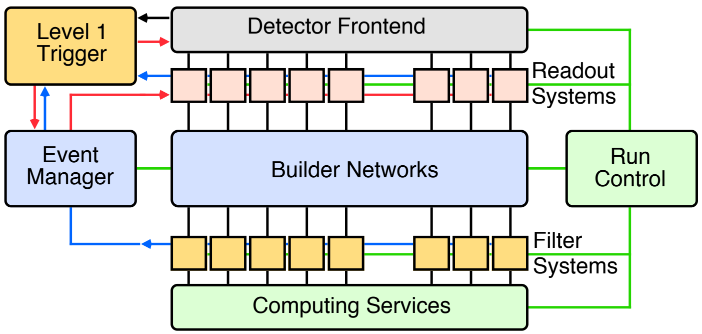
10^3 Hz

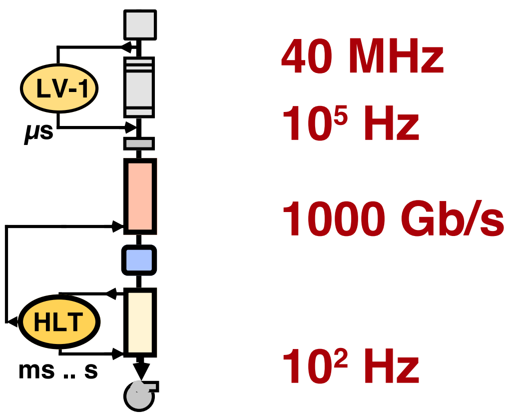
10 Gb/s

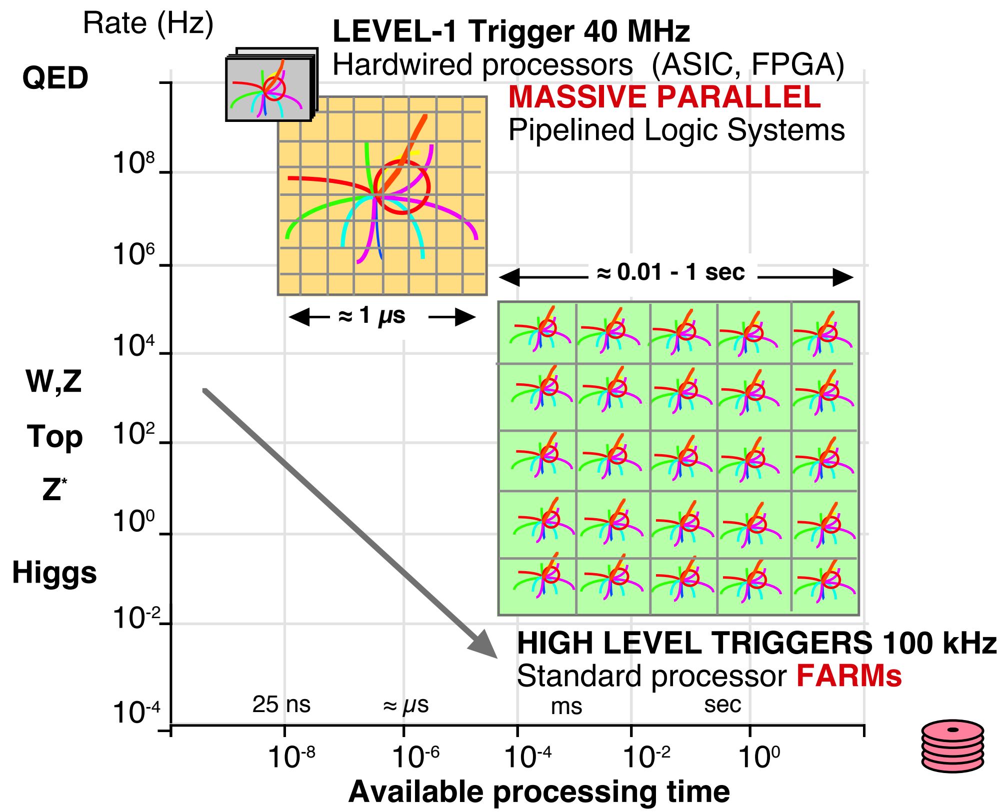
10^2 Hz



Two physical entities



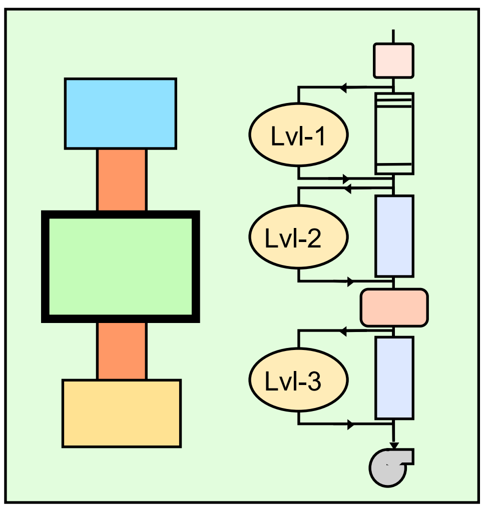




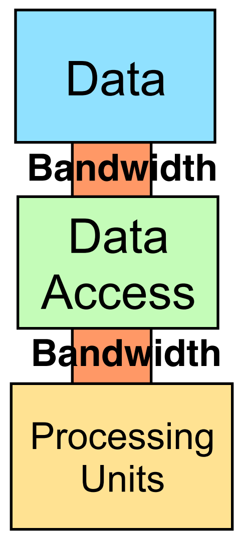
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Comparison of 2 vs 3 physical levels

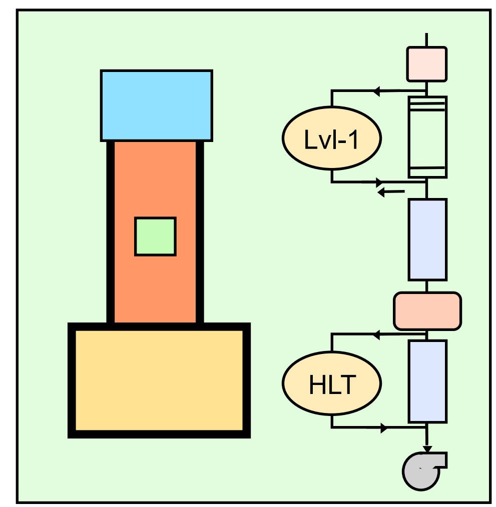
- **Three Physical Levels**
  - Investment in:
    - Control Logic
    - Specialized processors



Model

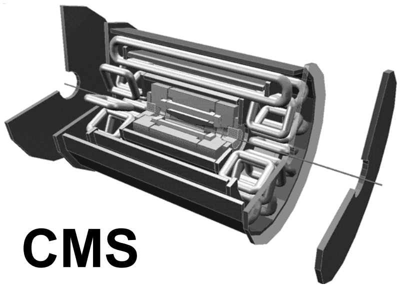


- **Two Physical Levels**
  - Investment in:
    - Bandwidth
    - Commercial Processors

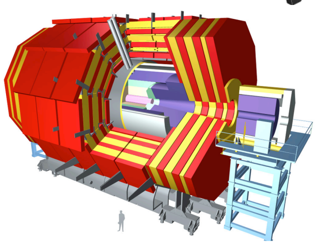


Trigger/DAQ parameters: summary

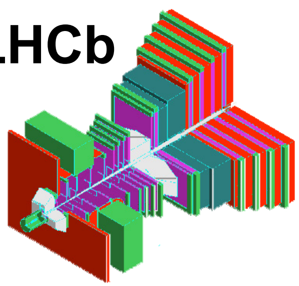
ATLAS



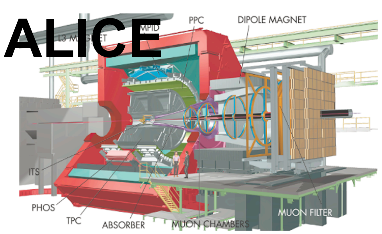
CMS



LHCb

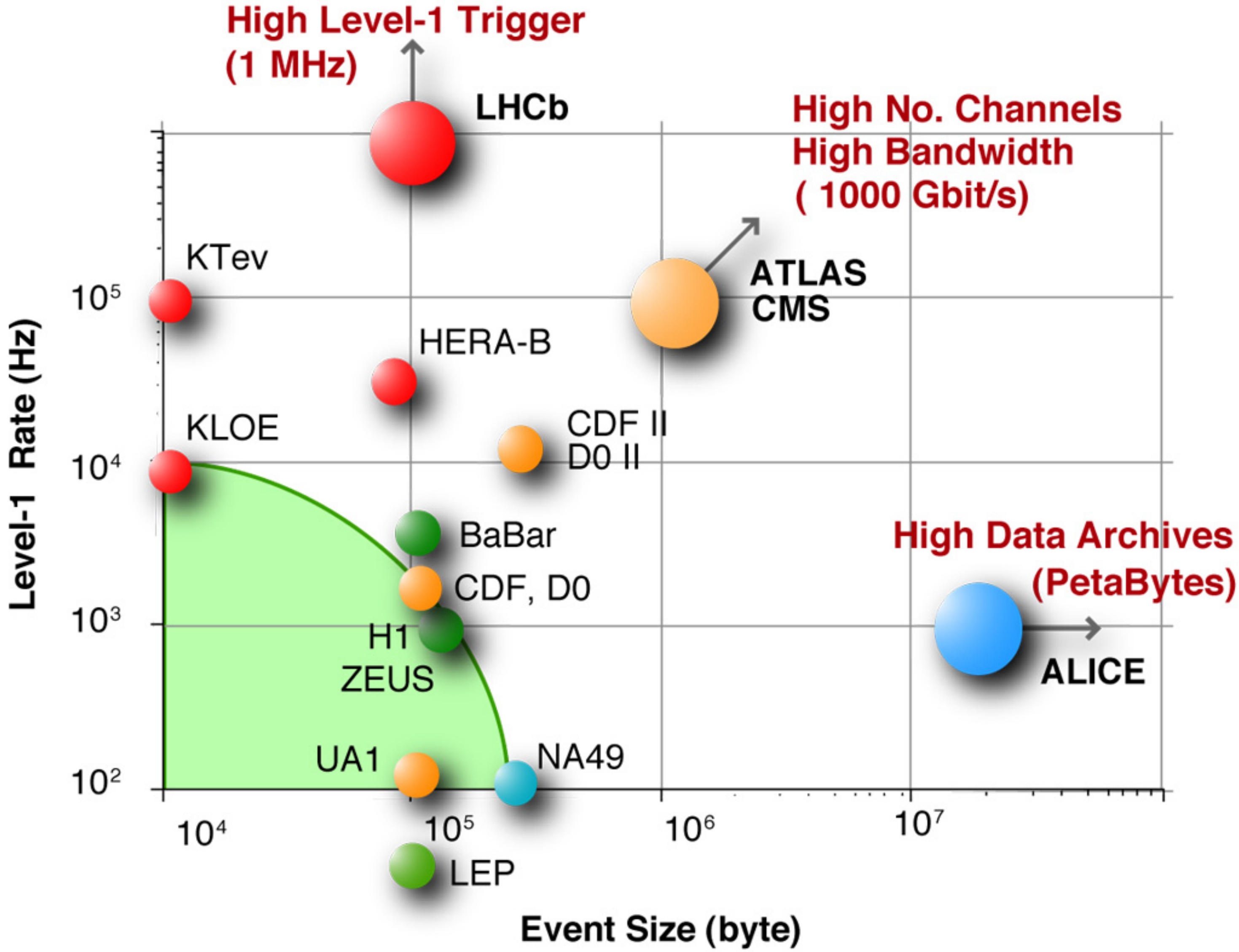


ALICE

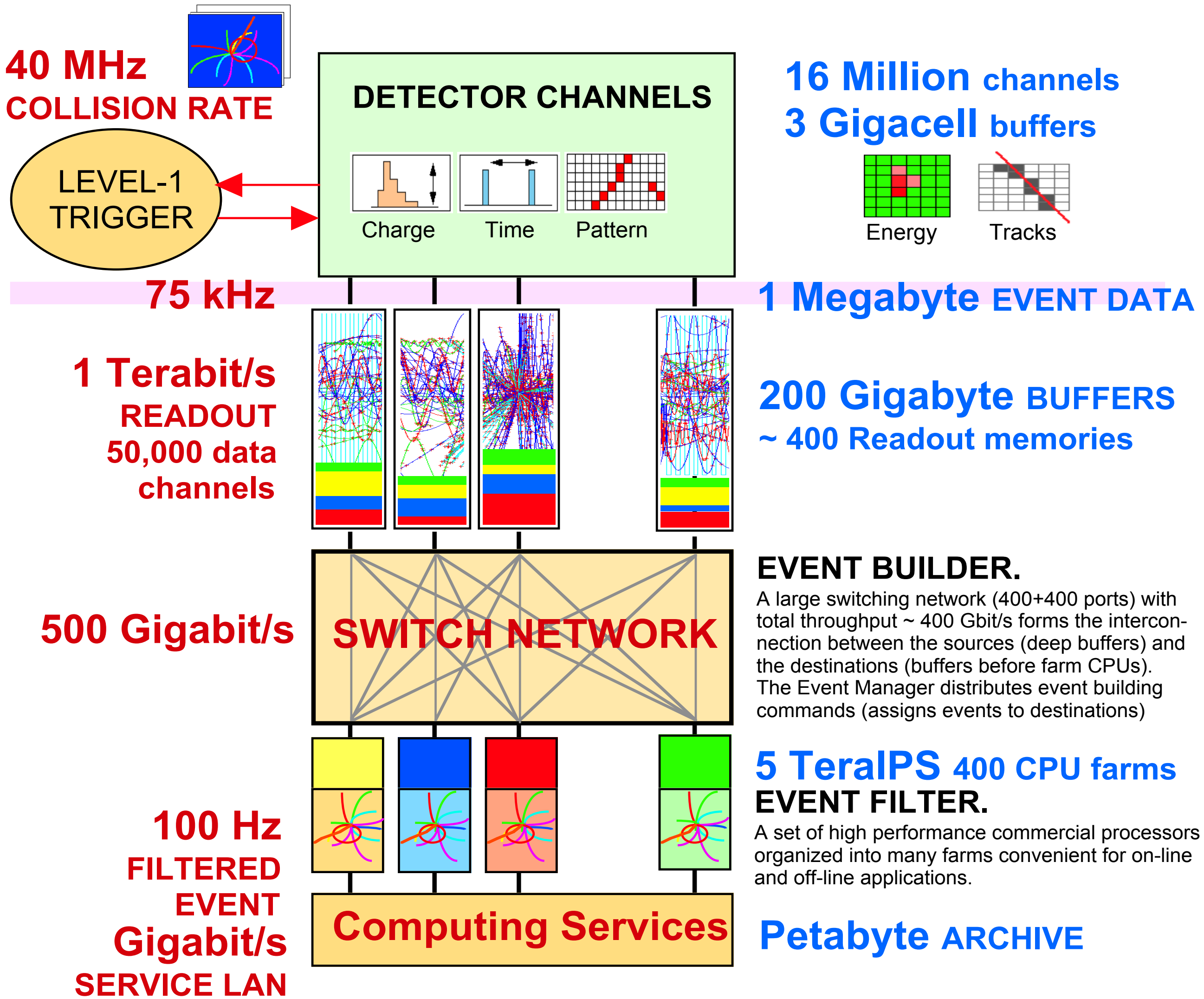


	No.Levels Trigger	Level-1 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS	**3**	**10^5** LV-2 **10^3**	**10^6**	**10**	**100** (10^2)
CMS	**2**	**10^5**	**10^6**	**100**	**100** (10^2)
LHCb	**3**	LV-0 **10^6** LV-1 **$4\ 10^4$**	**$2x10^5$**	**4**	**40** ($2x10^2$)
ALICE	**4**	Pp-Pp **500** p-p **10^3**	**$5x10^7$** **$2x10^6$**	**5**	**1250** (10^2) **200** (10^2)

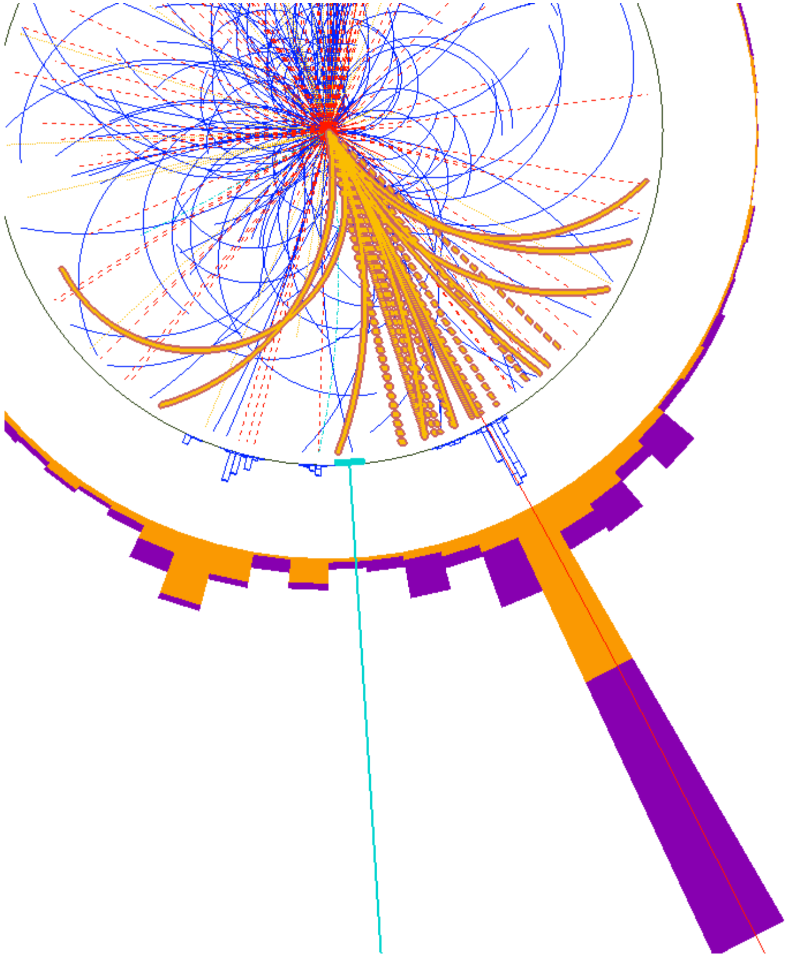
Trigger/DAQ systems: present & future



Online Selection Flow in pp (II)



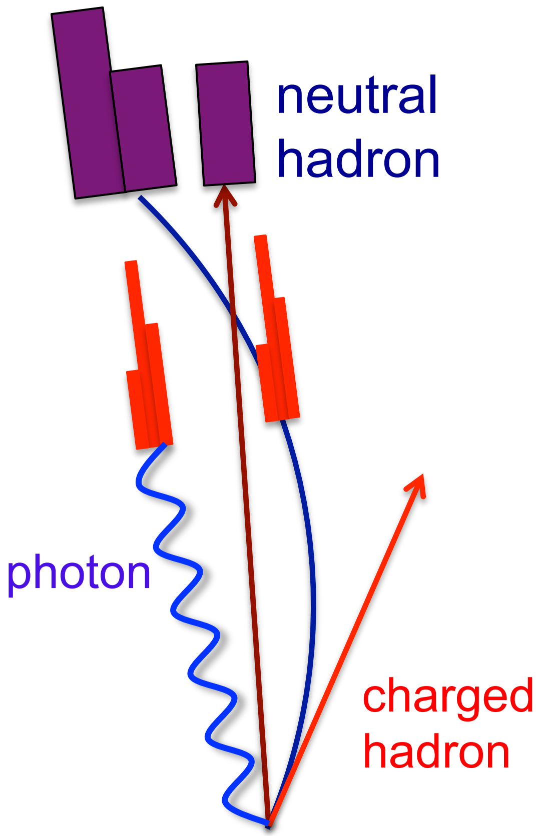
Bending power



- Bending power (inner):
  - CMS: 3.8x1.3 = 4.9 T.m
  - ALEPH: 1.5x1.8 = 2.7 T.m
  - ATLAS: 2.0x1.2 = 2.4 T.m
  - CDF: 1.5x1.5 = 2.25 T.m
  - DO: 2.0x0.8 = 1.6 T.m

What has to be reconstructed: particle flow

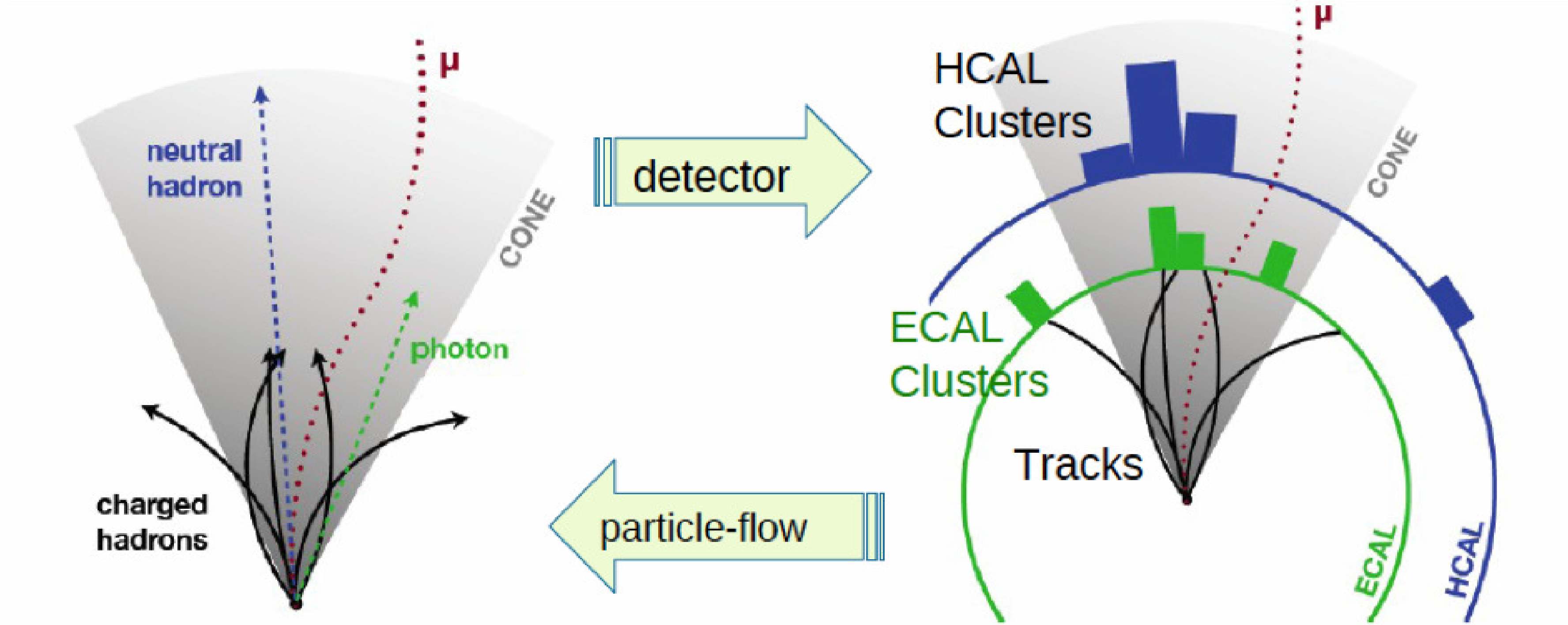
- **Types of particles**



- **Calorimeter jet:**
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- **Particle flow jet:**
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 5-10% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E
  - Need to resolve the energy deposits from the neutral particles…

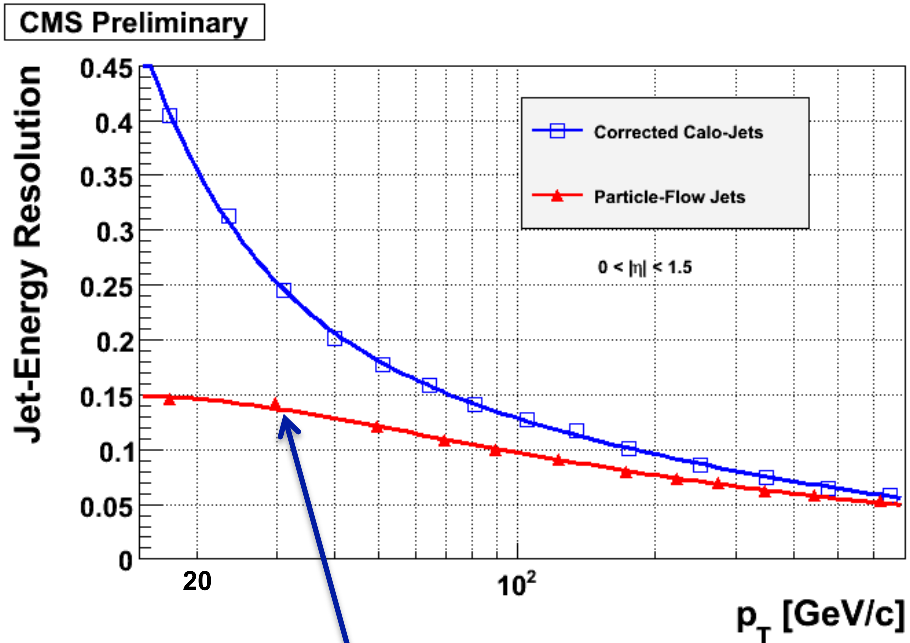
A new (and unforeseen in the 90's) element: particle flow

- **Principle: combine information from all detectors. Trade information from low-res detectors to high-res detectors, depending on object**



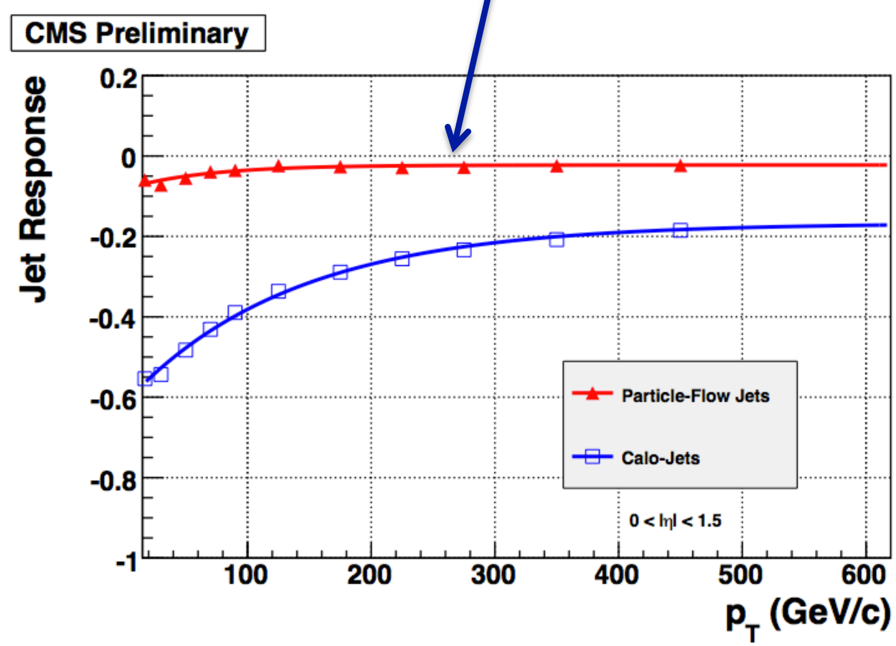
- **Nowadays, the large majority (~all) CMS analyses use p-flow reconstruction (and the associated objects)**

Improvement in jet resolution



Large improvement at low p_T

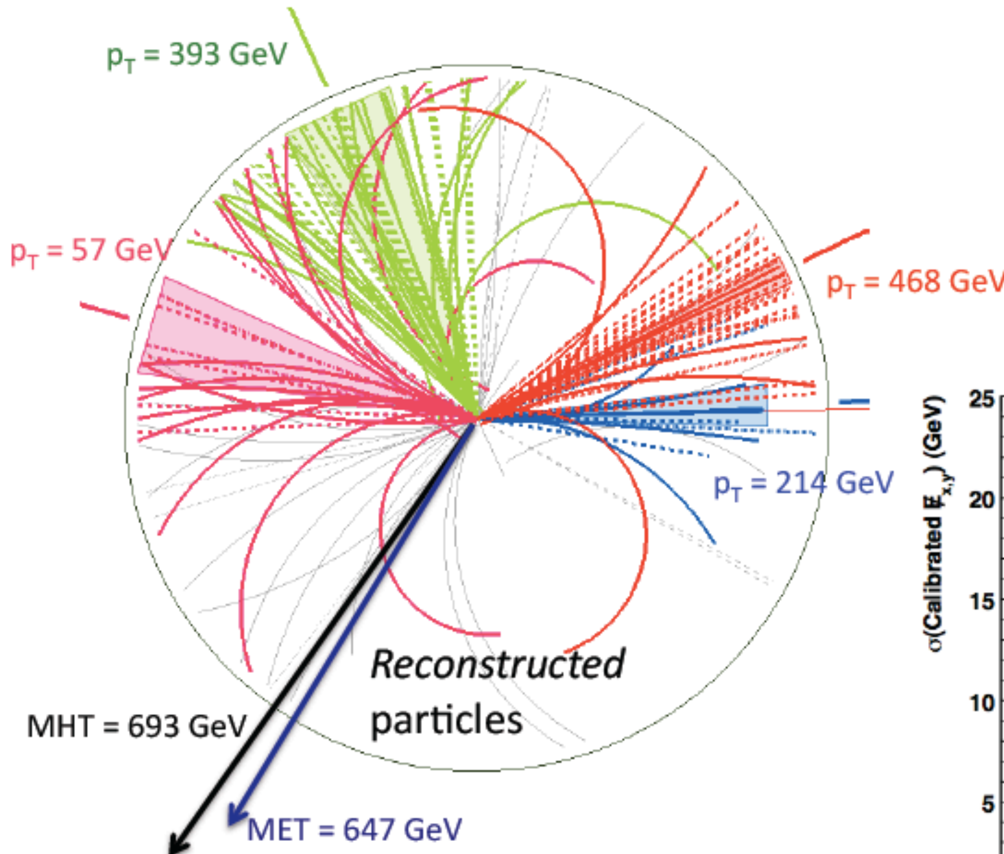
Jet particles were calibrated → response close to 1 *before* any jet energy correction



CMS-PAS-PFT-09-001
CMS-PAS-PFT-10-002

Hadronic variables: definition

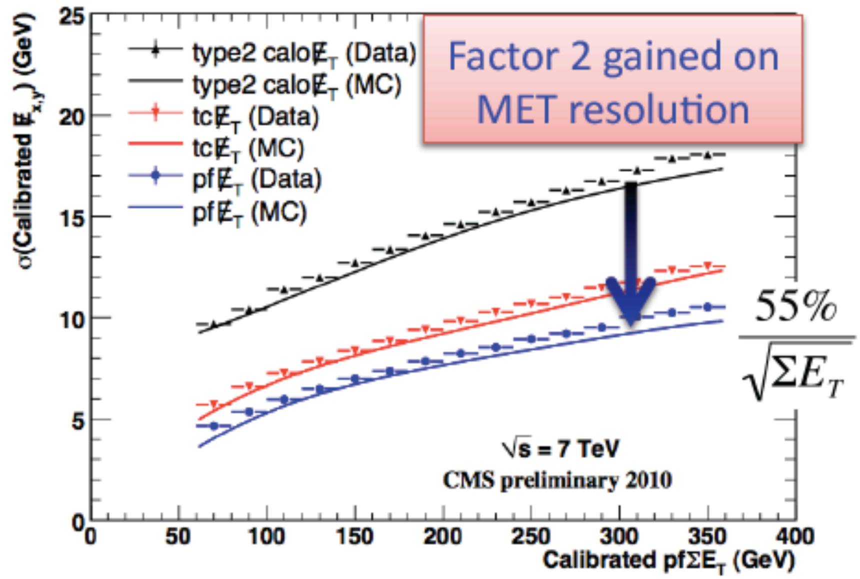
Highest MET multi-jet event recorded in 2010



$$\vec{E}_T^{miss} = \overrightarrow{MET} = -\sum_{\text{All particles}} \vec{p}_T$$

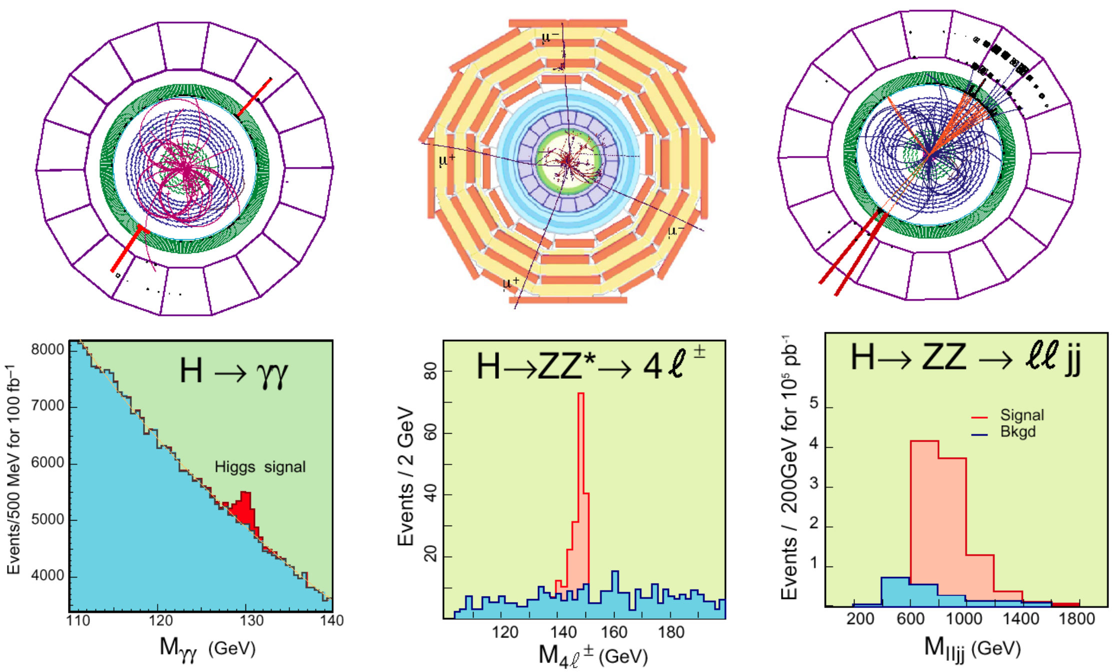
$$\overrightarrow{MHT} = -\sum_{\text{Jets}} \vec{p}_T$$

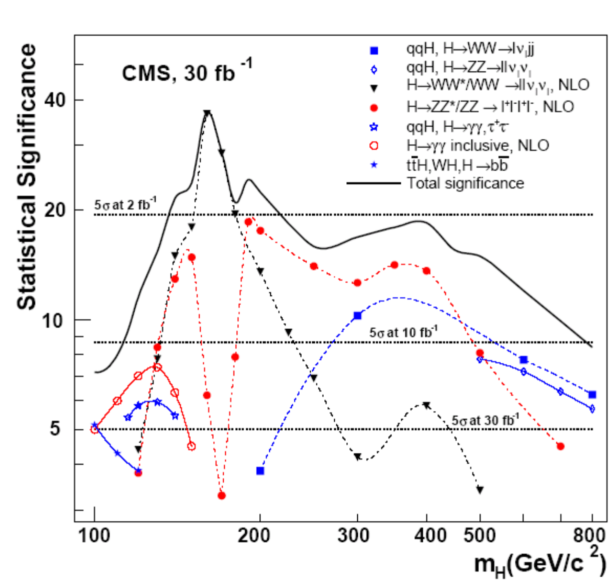
$$HT = \sum_{\text{Jets}} p_T$$



Higgs reach

- **CMS can probe the entire set of “allowed” Higgs mass values;**
  - **in most cases a few months at 2×10^{33} $cm^{-2}s^{-1}$ are adequate for a 5σ observation**





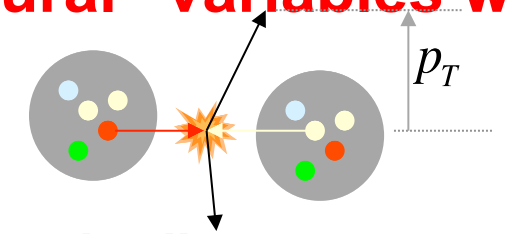
Text & simu from 1999

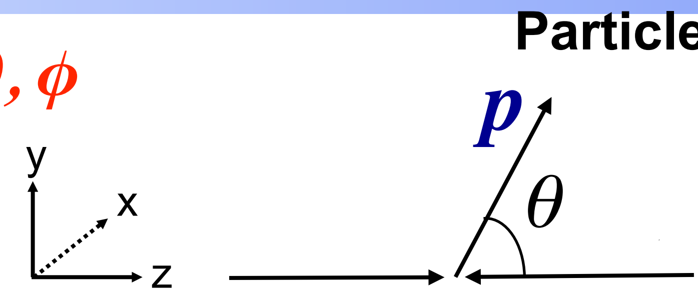
Introduction

pp collisions:
characteristics and kinematics;
the environment and event reconstruction

pp collisions: kinematics (I)

- **"Natural" variables would be p, θ, ϕ**



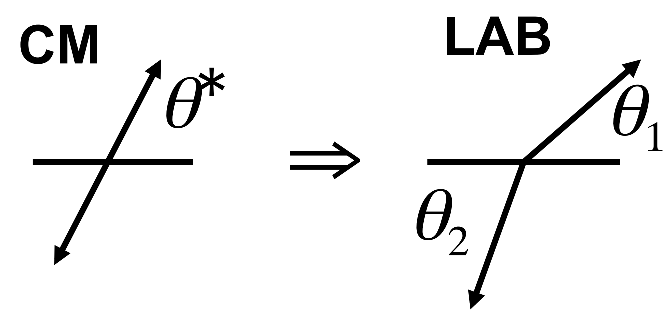


  - Longitudinal momentum & energy, p_z & E: not useful
    - Particles escaping detection have large p_z; visible p_z not conserved: $\sum_i p_{z,i} \neq 0$
  - More useful: transverse momentum, p_T
    - Particles escaping detector (low θ) have $p_T \approx 0$; visible p_T conserved: $\sum_i p_{T,i} \approx 0$

- **LAB ≠ parton-parton CM system**

Parton CM $(\text{energy})^2 \rightarrow \hat{s} = x_1 x_2 s$

Worse: p, θ not invariant under Lorentz boosts along z (not good, especially in two-particle correlations)

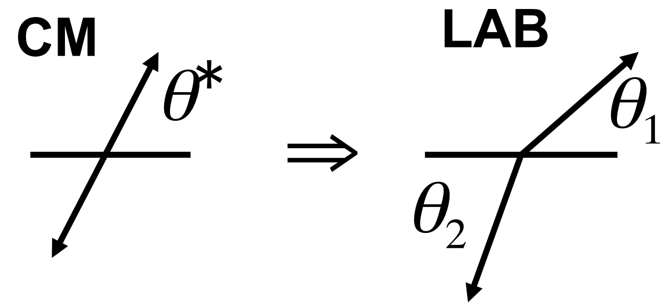


pp collisions: kinematics (II)

- **LAB ≠ parton-parton CM system**

$$\text{Parton CM (energy)}^2 \rightarrow \hat{s} = x_1 x_2 s$$

$$p_z(\text{parton-parton}) = x_1 - x_2\sqrt{\hat{s}}$$



- **And since we cannot use $\sum_i p_{z,i}=0$, we cannot infer the overall boost in z of the parton-parton system**
  - **New problem: boost in z → p_T is invariant; p_z is not; since**

$$\tan\theta = p_z / p_T;\; p = \sqrt{p_T^2 + p_z^2}$$

→ so p, θ not invariant under Lorentz boosts along z

  - **Not good, especially in two-particle correlations: e.g. angle between two particles not the same in CM and LAB frames. We measure in LAB (but we to connect to calculation, we need z boost – to connect to the CM frame)**

pp collisions: kinematics (III)

- **Need to introduce another "measure" of θ; rapidity:**

Rapidity (y)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

Pseudo-rapidity (η)

$$\beta \to 1 \ (m << p_T): \ \eta \equiv -\ln\tan\frac{\theta}{2}$$

  - **Lorentz boost in z direction:**

$$y \to y' = y + \log\sqrt{\frac{1-\beta}{1+\beta}} = y - \tanh^{-1}(\beta) \Rightarrow \Delta y' = \Delta y$$

- **Angular distance(two particles): use Δy(or Δη) and Δϕ**

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

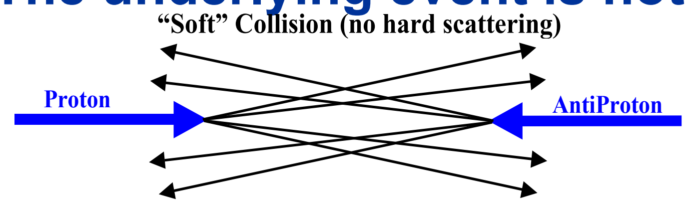
- **Particle description: p_T, y, φ**

$Edy = dp_z \Rightarrow$ **LI factor:**

$$\frac{d^3p}{E} = p_T dp_T dy d\varphi = \pi dy dp_T^2$$

The “underlying event"

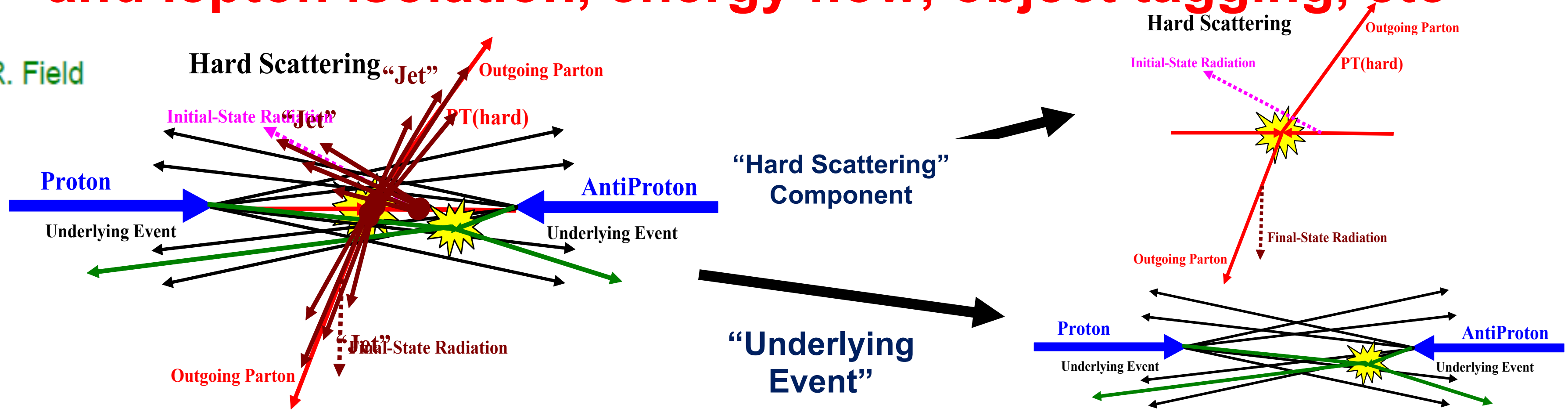
- The UE consists of the “beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI)
  - The underlying event is not the same as a minimum bias event



No hard scattering
“Min-Bias” event

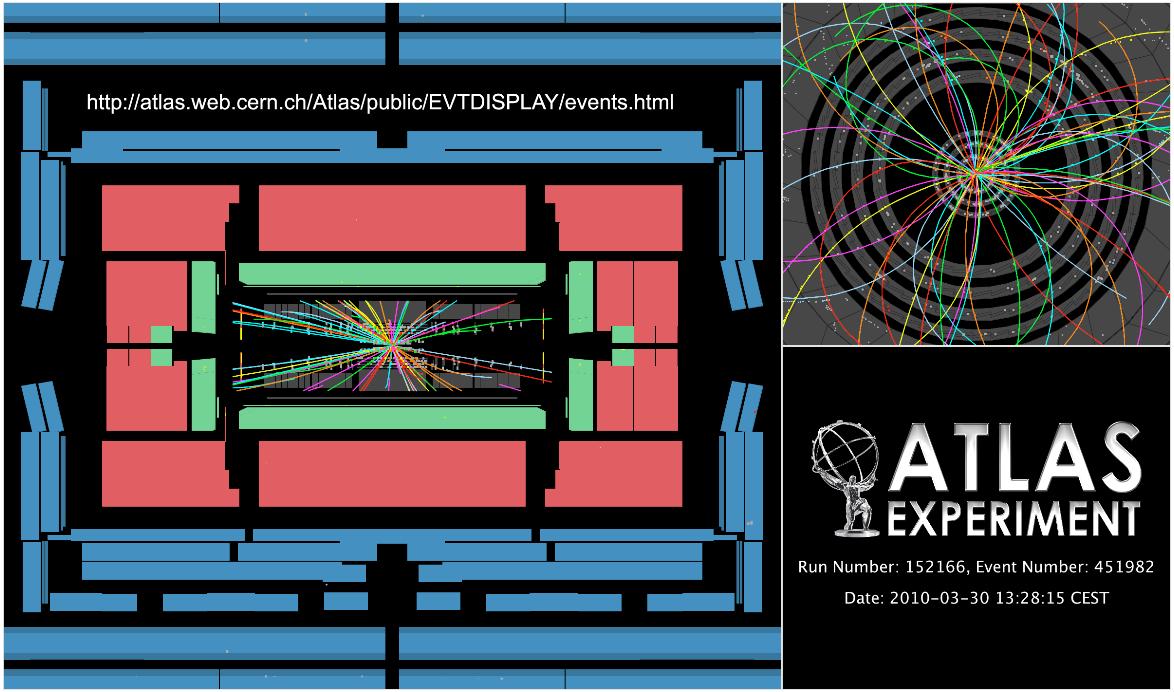
- Modeling of UE: important ingredient for jet physics and lepton isolation, energy flow, object tagging, etc

à la R. Field



Inelastic pp collisions: characteristics

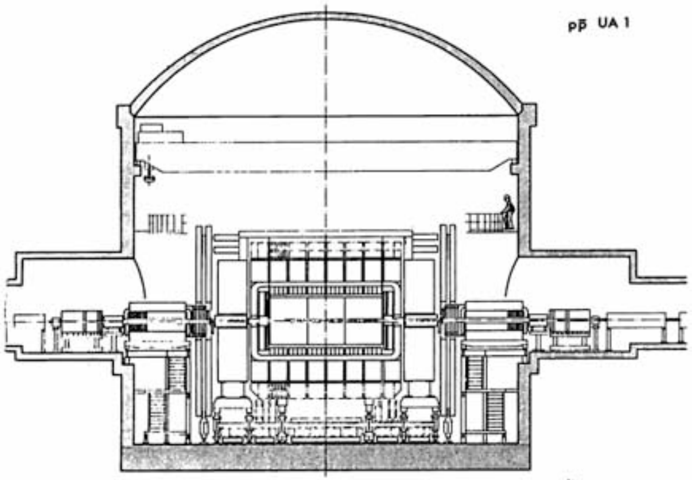
- **One of the earliest collisions at 7 TeV**



- **Minimum-bias collisions ~ model/input for "underlying event"**
- **Properties to study: particle multiplicities; particle momenta and correlations; energy flow, especially in transverse plane**

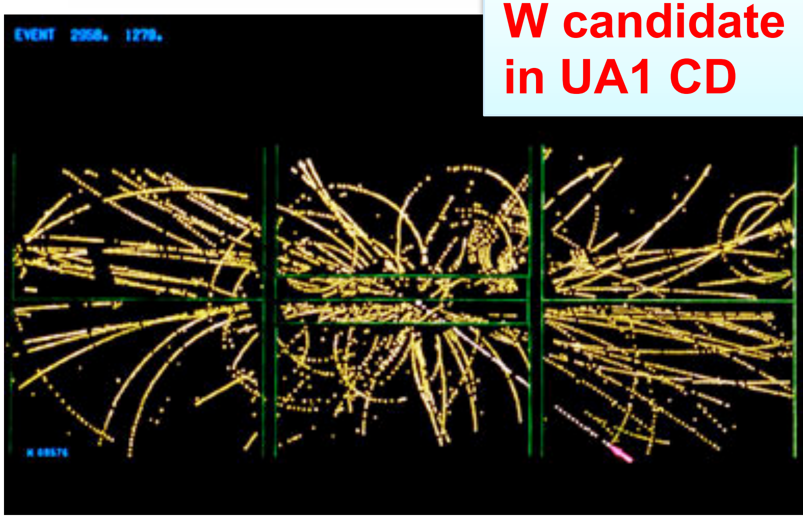
Defeating the underlying event (the 80's)

- **Short parenthesis** (history of "dirtiness" in hadron collisions)

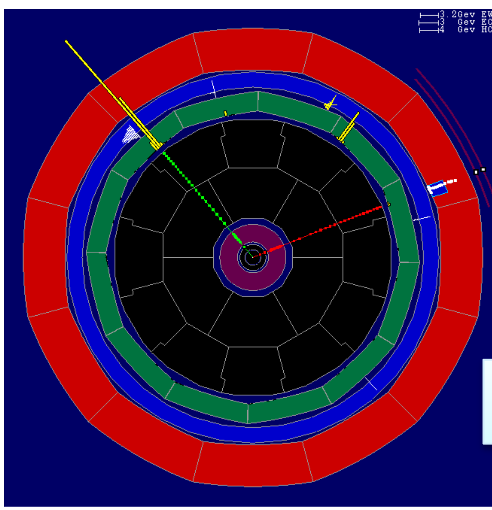


LEP (ALEPH)

Z→e⁺e⁻



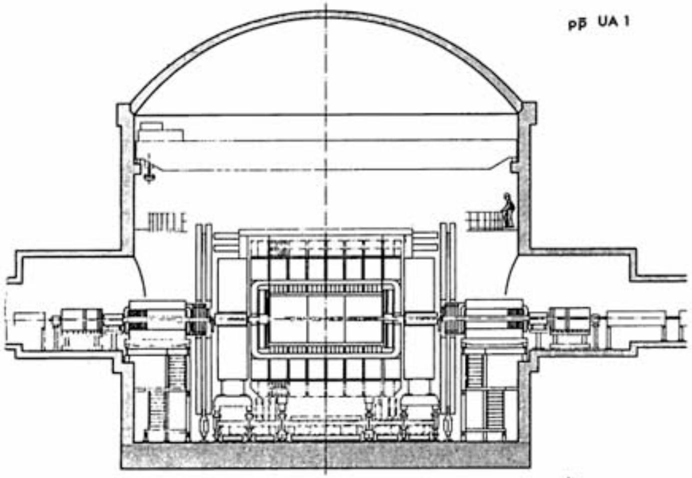
W candidate in UA1 CD

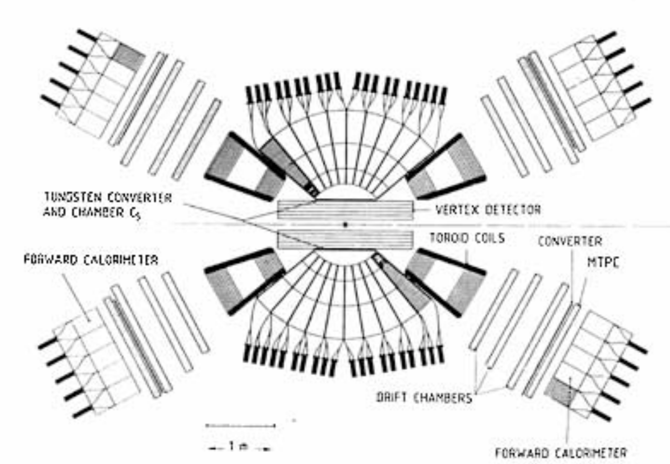


WW→eμνν

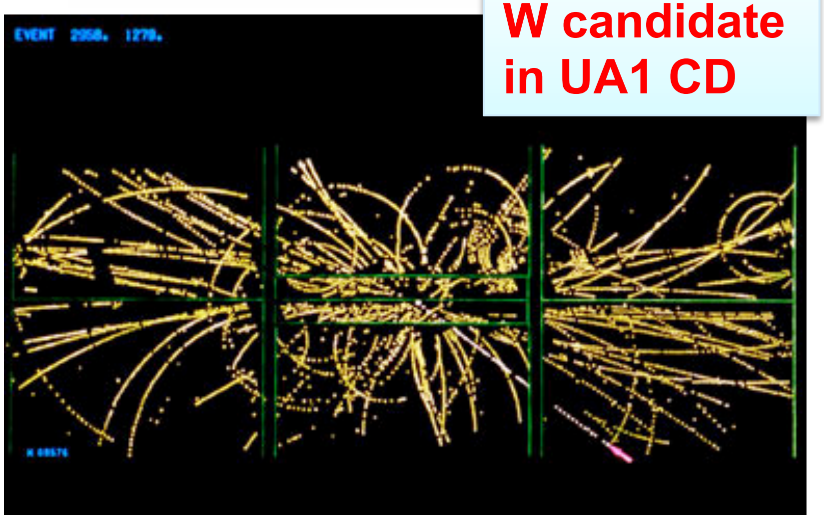
Defeating the underlying event (the 80's)

- **Short parenthesis** (history of "dirtiness" in hadron collisions)

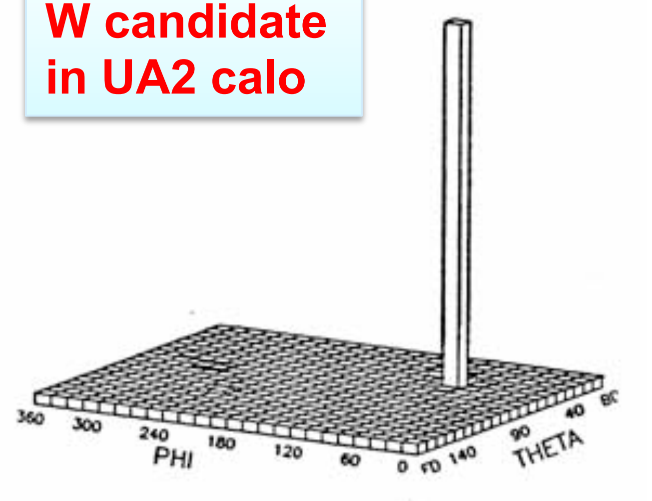




W candidate in UA1 CD

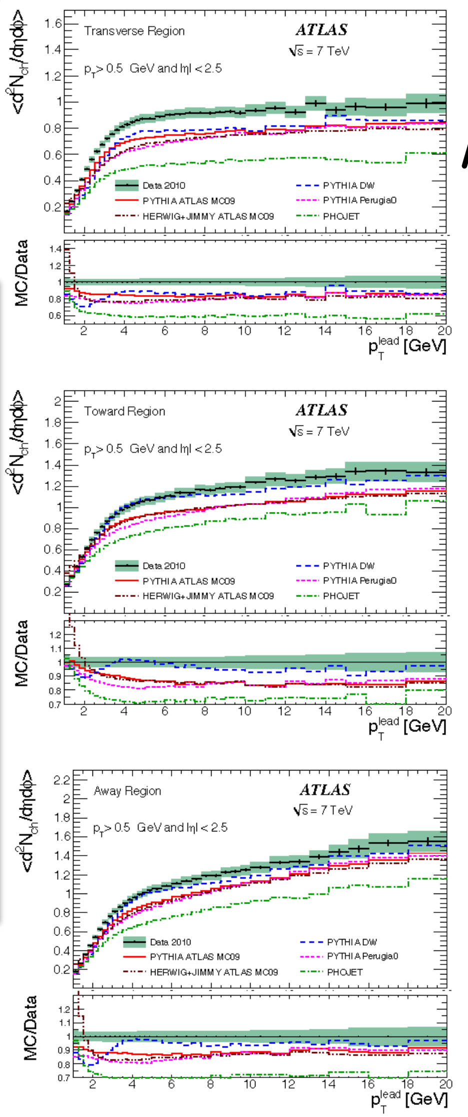


W candidate in UA2 calo

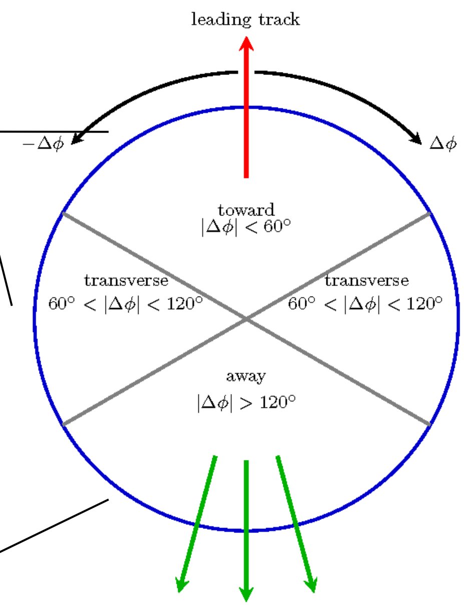


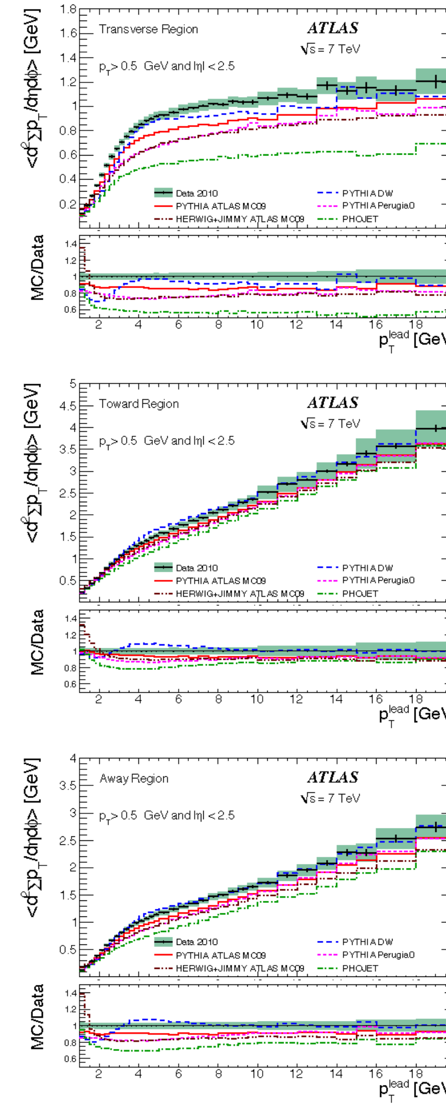
Underlying event (I)

Multiplicity vs P_T



Particle momentum flow in regions defined wrt leading track



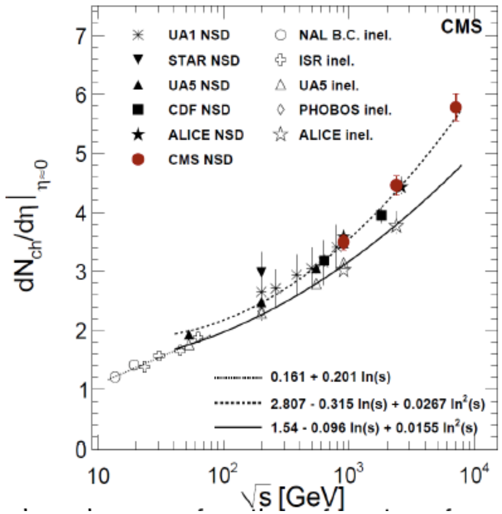


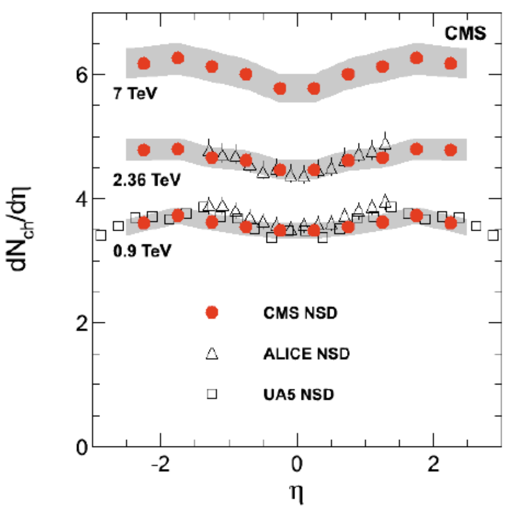
Sum P_T vs P_T

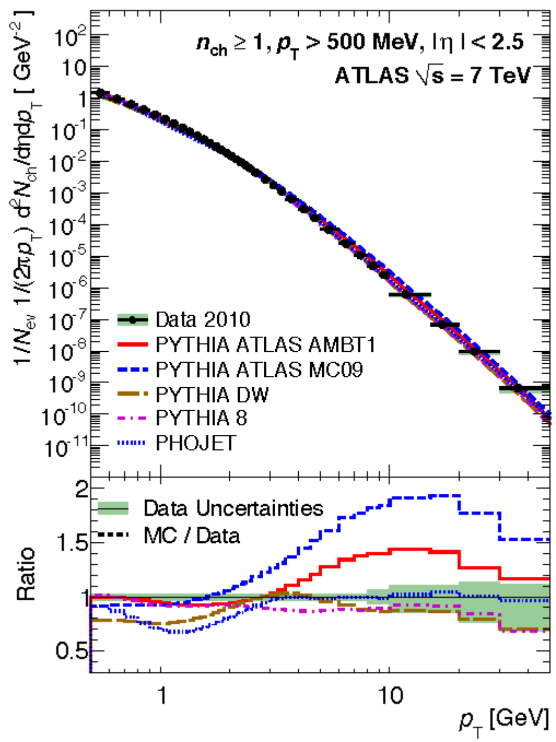
arXiv:1012.0791

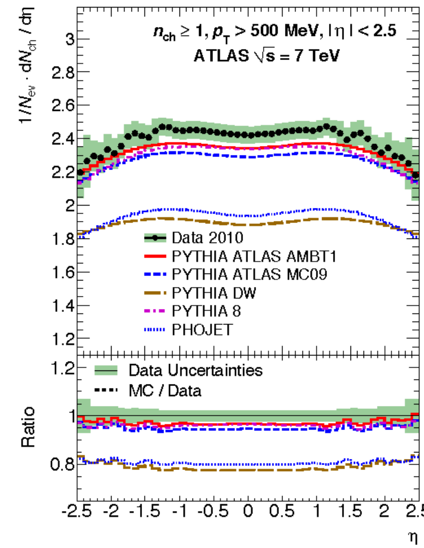
Minimum bias interactions

- Inelastic collisions (protons break)

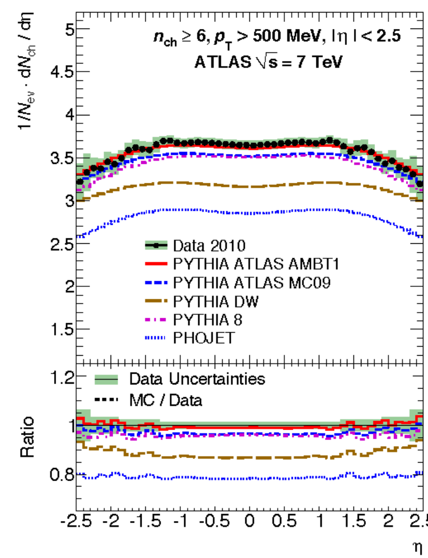








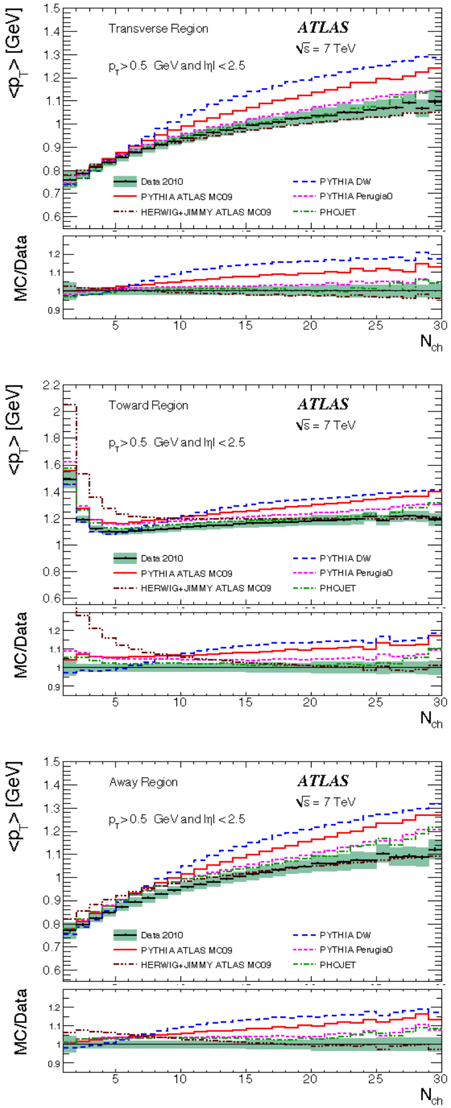
$N_{ch} \geq 1$



$N_{ch} \geq 6$

Underlying event (II)

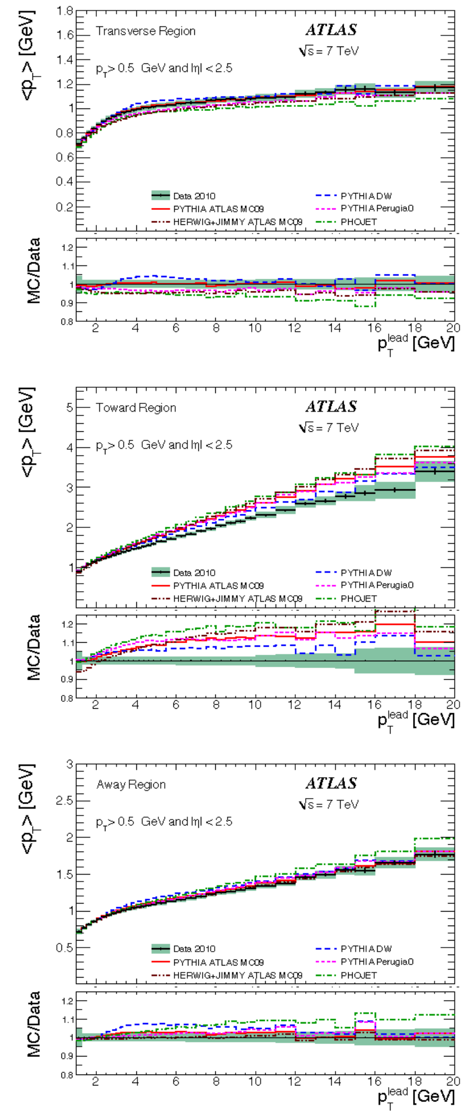
Mean P_T vs Multiplicity



From these comparisons: determine best "tunes" for underlying event.

In practice: tuning of soft QCD model in PYTHIA

Tuning is important for data-MC agreement further down; particle isolation (e.g. in lepton identification) and missing energy (ME_T)



Mean P_T vs P_T

Some Standard Model processes

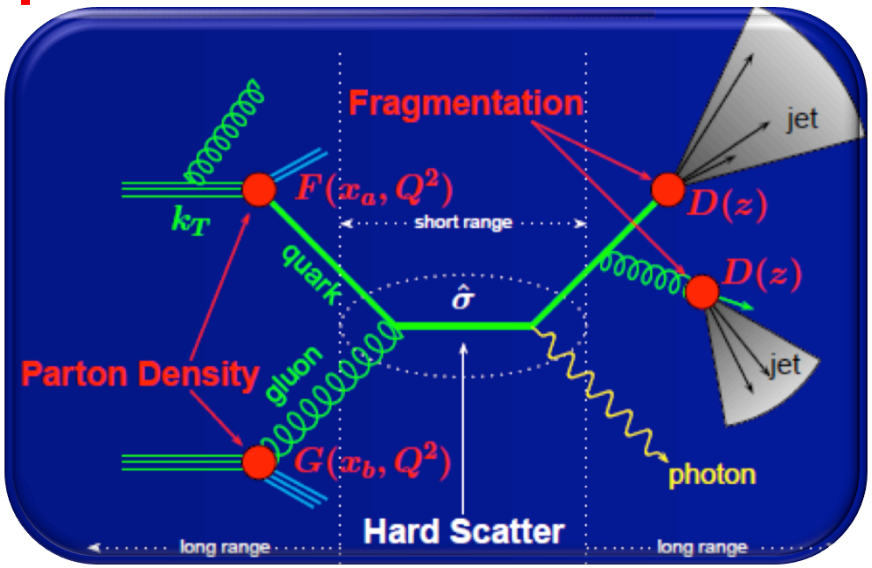
Jet production

W/Z production

top production

QCD: parton-parton scattering

- **Picture of pp interactions:**

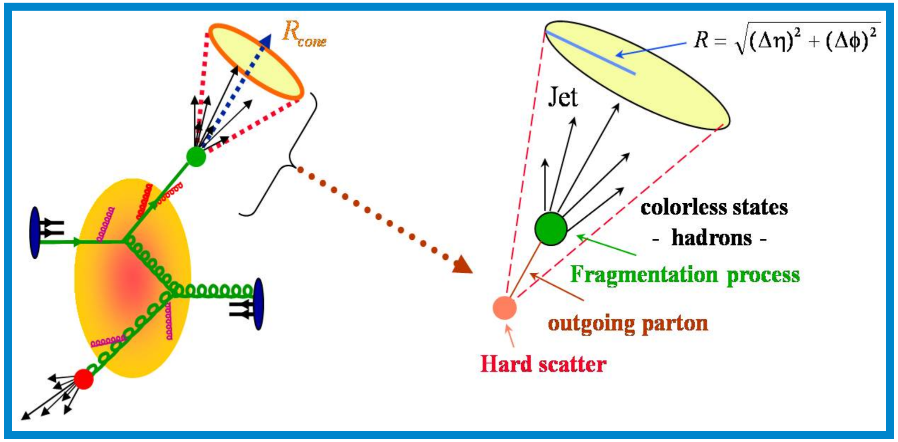


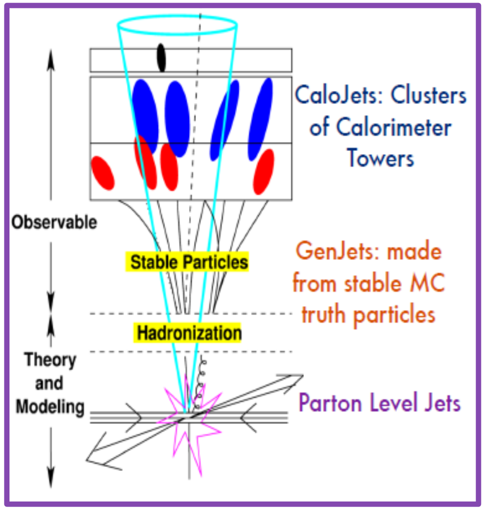
- **Basis of all calculations & Monte Carlo simulations: the QCD factorization theorem**

$$d\sigma_{pp}\left(p_1,p_2,M\right) = \sum_{a,b}\int_0^1 dx_a dx_b \;\; d\hat{\sigma}_{ab\to F+X}\left(x_a p_1, x_b p_2, M, \mu\right)$$
$$\times F_{a/p}\left(x_a,\mu\right)\; F_{b/p}\left(x_b,\mu\right)$$

Jets

- Colored partons from hard scatter "evolve" via soft quark and gluon radiation and and then hadronize to form a "spray" of roughly collinear colorless hadrons –> Jets
  - Jets: localized clusters of energy (or particles)
  - Jets: experimental signature of quarks & gluons



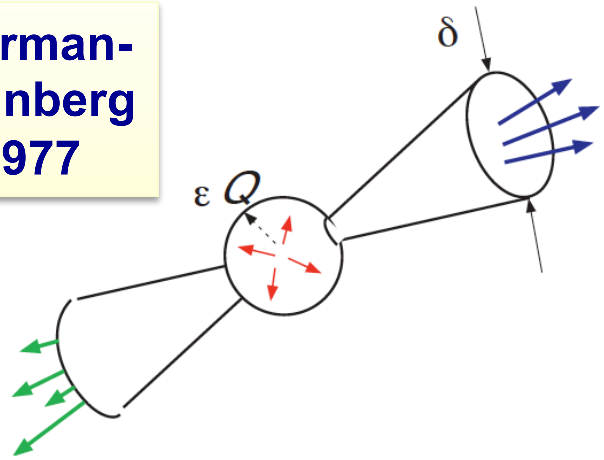


- Two types of measurements, probing:
  - The hard scatter: jet P_T and η, dijet correlations, dijet mass,…
  - Jet internals: energy flow, comparison of quark vs gluon jets,…

Definition of "jet"

- **Cone jets in e^+e^- annihilation:**
  - Hadronic events: all but a fraction $\varepsilon \ll 1$ of the energy inside two cones of opening $\delta \ll 1$.

Sterman-Weinberg 1977



$$\sigma_{2J}(Q,\delta,\epsilon) = \frac{3}{8}\sigma_0(1+\cos^2\theta) \times \left(1 - \frac{4\alpha_s}{\pi}\left[4\ln\delta\ln\epsilon + 3\ln\delta + \frac{\pi^2}{3} + \frac{5}{2}\right]\right)$$

- **In practice: combine final-state particles into "jets"**
  - "Separation" variable: $y_{ij} = \left(M_{ij}/E_{vis}\right)^2$
  - Form particle k from particles i,j:

$$y_{ij} < y^{cut} \rightarrow p_k = p_i + p_k \quad \text{or} \quad E_k = E_i + E_j$$

massive or *massless*

  - Combine until all combinations have $y_{ij} > y^{cut}$

pp collisions:

Most of the "energy" in the beam remnants; so use E_T flow (instead of E)

Definition of “jet” (II)

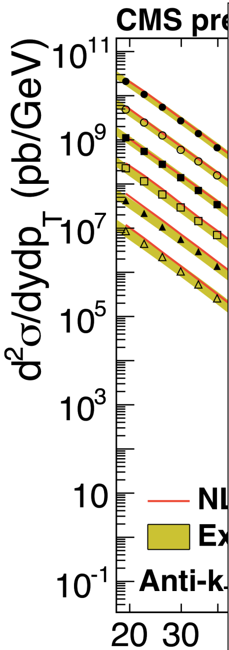
- **Since those early (e^+e^-) days, significant evolution:**
  - JADE: $M_{ij}^2 = 2E_iE_j\left(1-\cos\theta_{ij}\right)$
  - Durham (k_T): $M_{ij}^2 = 2\min\left\{E_i^2, E_j^2\right\}\left(1-\cos\theta_{ij}\right) \xrightarrow{\theta\to 0} \min\left\{k_{T,i}^2, k_{T,j}^2\right\}$
- **Hadronic collisions:**
  - Cone algorithms: merge everything inside a cone ΔR
  - kT & Generalizations:

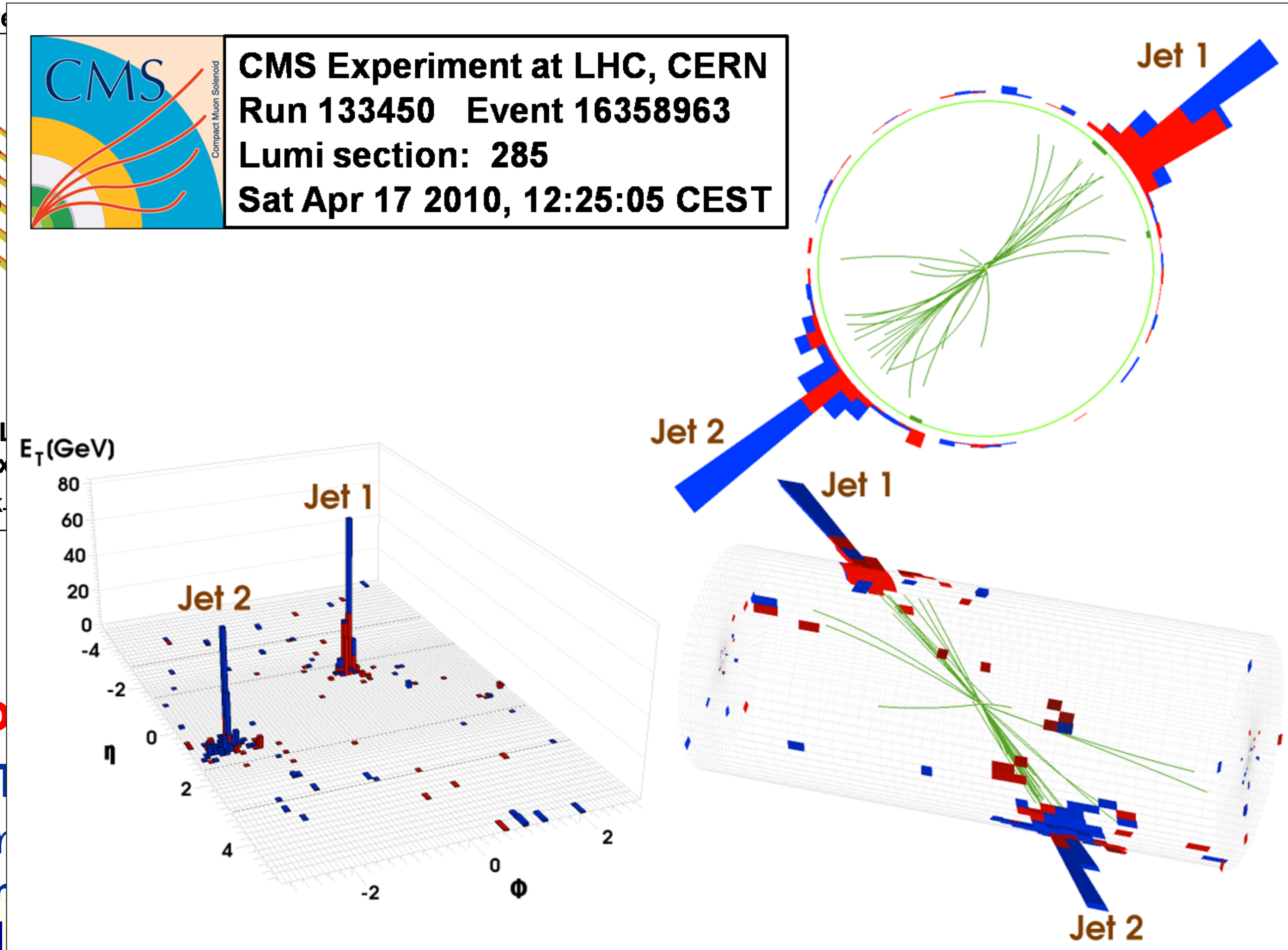
$$d_{ij} = \min\left\{p_{T,i}^{2\rho}, p_{T,j}^{2\rho}\right\}\frac{\Delta R_{ij}^2}{D^2}$$

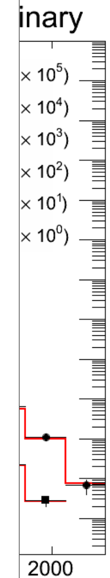
$$(D \sim 0.4 - 1)$$

    - p=1 → regular k_T jet algorithm
      - S.D.Ellis & D.Soper (1993)
    - p=0 → Cambridge/Aachen jet algorithm
      - Dokshitzer, Leder, Moretti, Webber ’97 (Cambridge) – Wobisch, Wengler ’99 (Aachen)
    - p=–1 → “Anti-k_T” jet algorithm
      - Cacciari, Salam, Soyez ’08
      - Soft particles will first cluster with hard particles before among themselves [almost a cone algo for hard partons]

Jets







c.

- Pro
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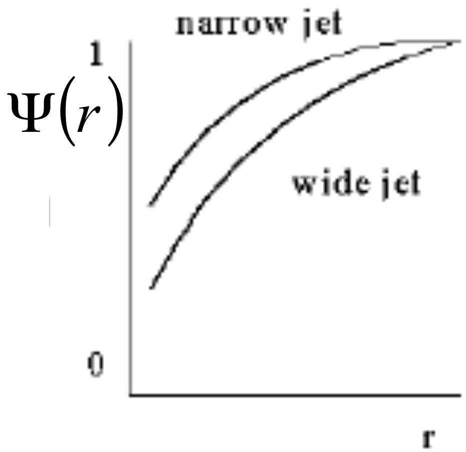
    ed
    1-2%)

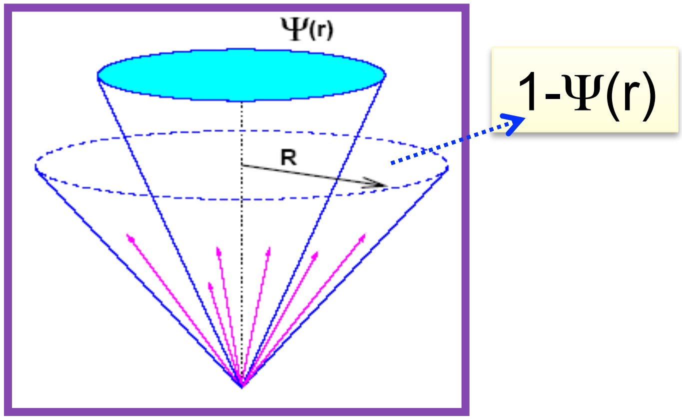
Excel

Jet shapes

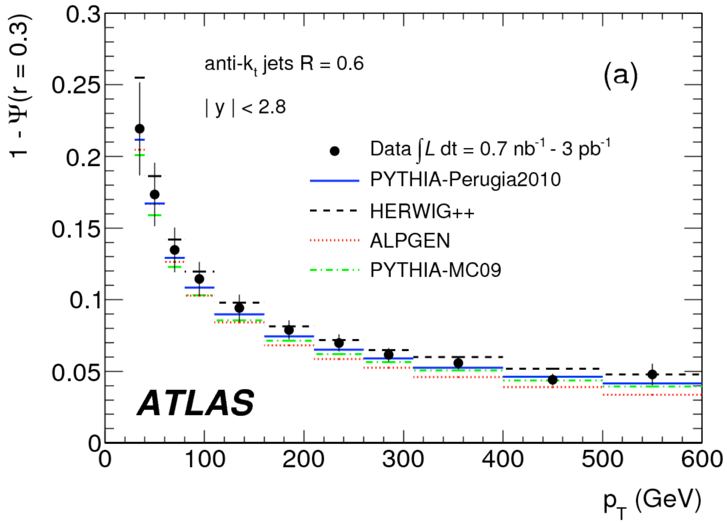
- **Integrated Jet Shape definition: average fraction of jet transverse momentum inside a cone of radius R concentric to the jet axis; measure of jet "narrowness"**

$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}; \quad (\Psi(R) = 1)$$



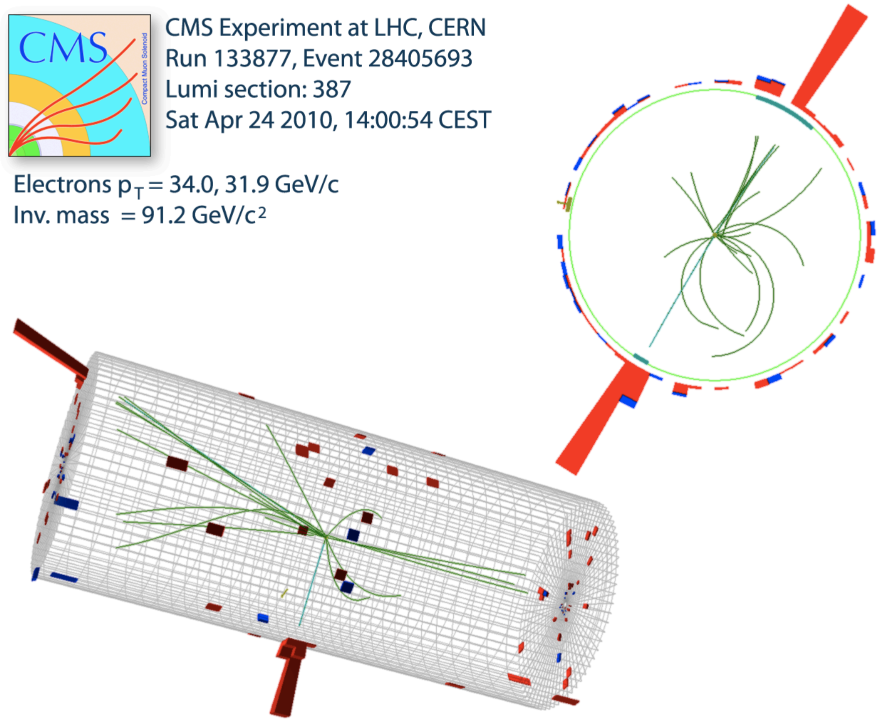


Quark jets are narrower than gluon jets

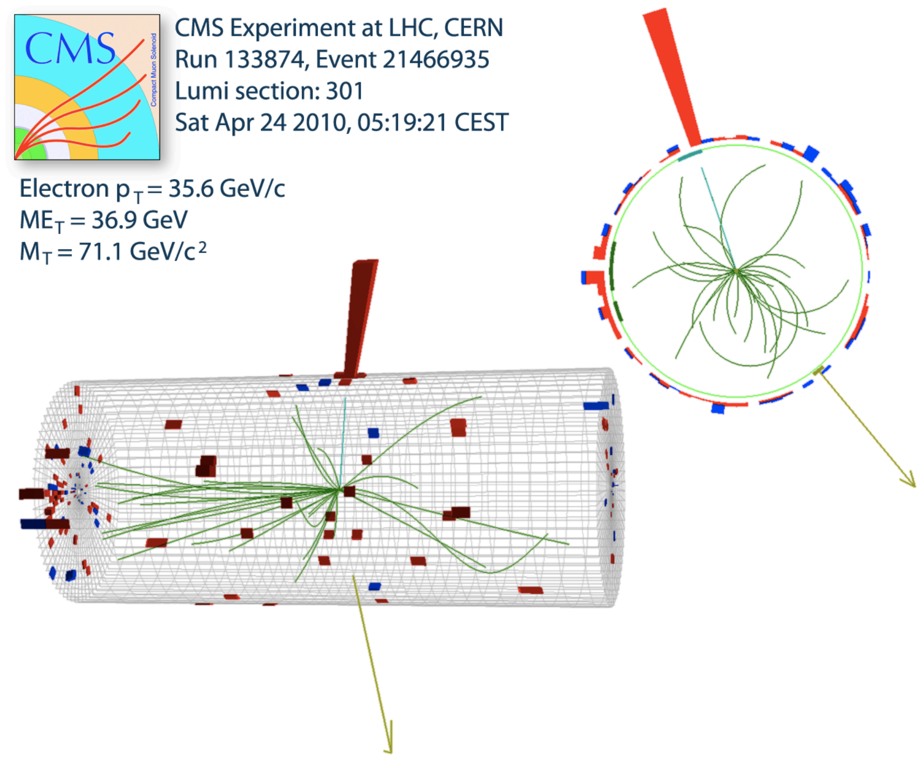


Mass, MET & transverse mass

Z → electron + positron



W → electron + neutrino



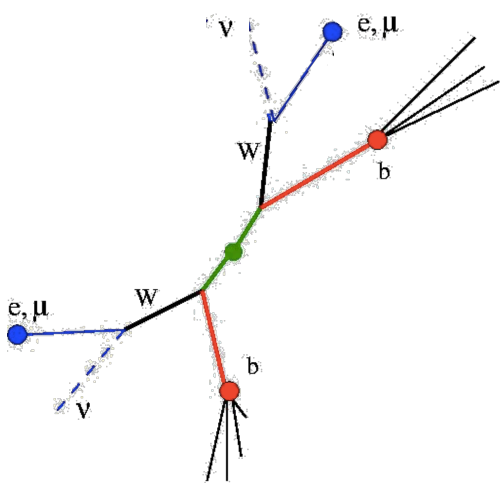
Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1 - \cos\Delta\phi_{e,miss}}$$

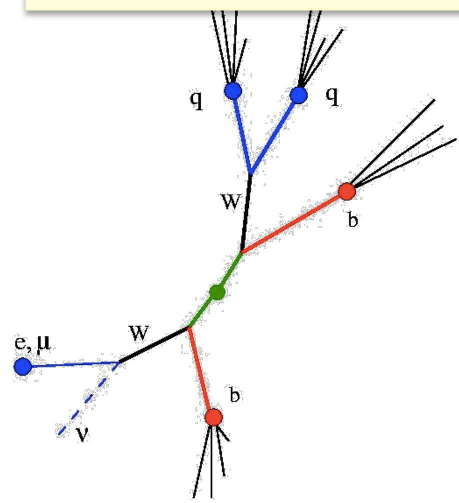
The top

- If the J/ψ, Y, W and Z are standard candles, then the top is a candelabra*
  - Leptons, missing E_T, additional jets; and b-tagging
  - Analysis requires all that has gone into the W and Z, plus increased QCD background (because of higher jet multiplicity).
    - Plus interplay with W/Z+jets production

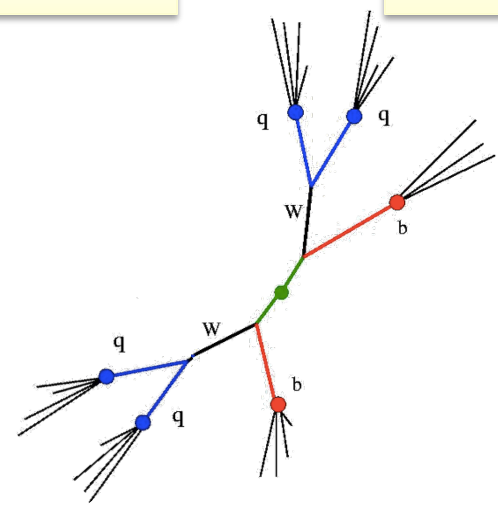
Dilepton: cleanest but Br~4/81



1-lepton: semi-clean; Br~8/27



0-lepton: not-clean; Br~4/9

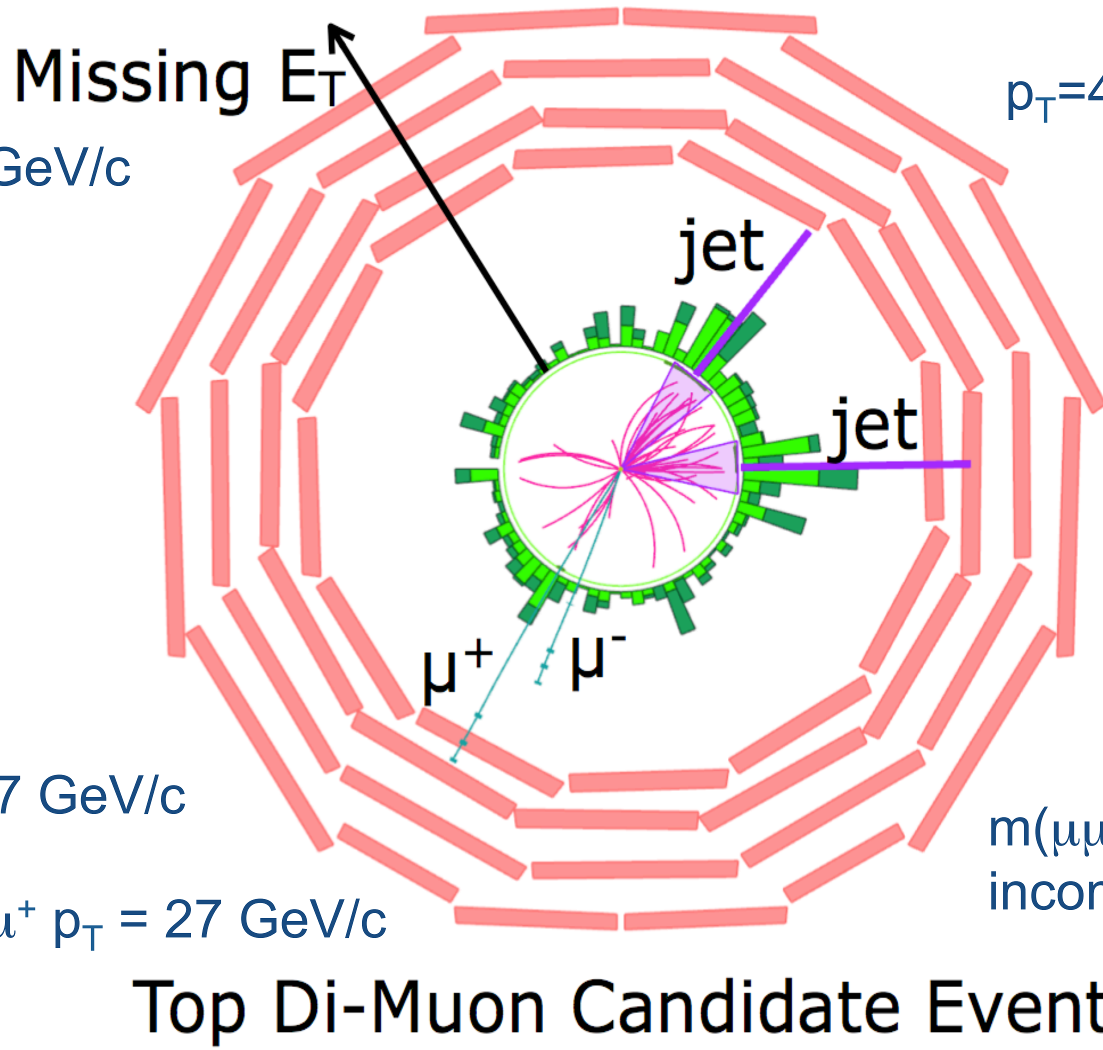


*: first heard this from Ken Bloom, U of Nebraska

top quark candidates: dilepton

MET= 57 GeV/c

p_T=45 GeV/c



p_T = 56 GeV/c

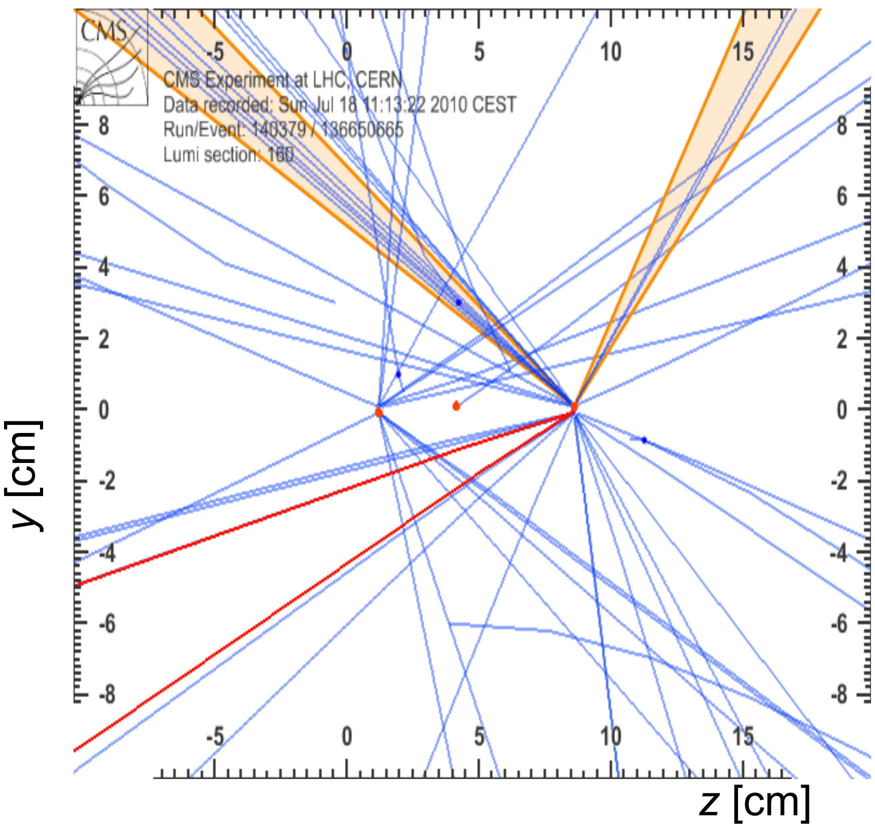
μ^- p_T = 57 GeV/c

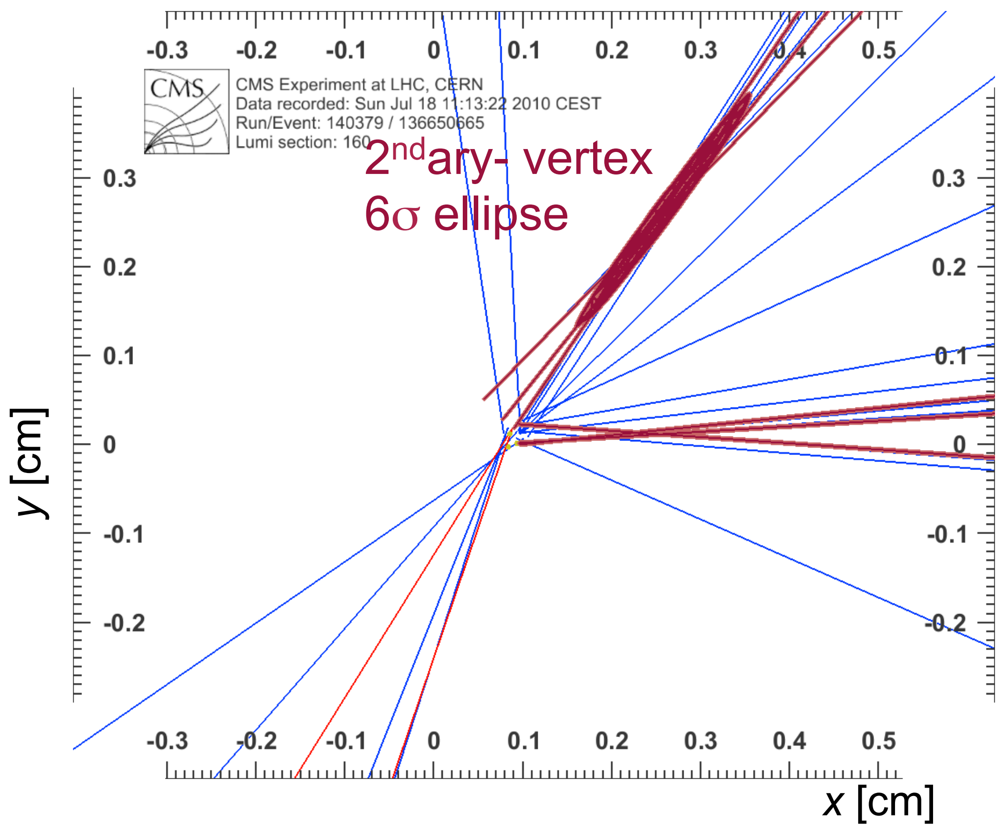
μ^+ p_T = 27 GeV/c

m($\mu\mu$) = 26 GeV/c^2
incompatible with Z

top quark candidates: dilepton (cntd)

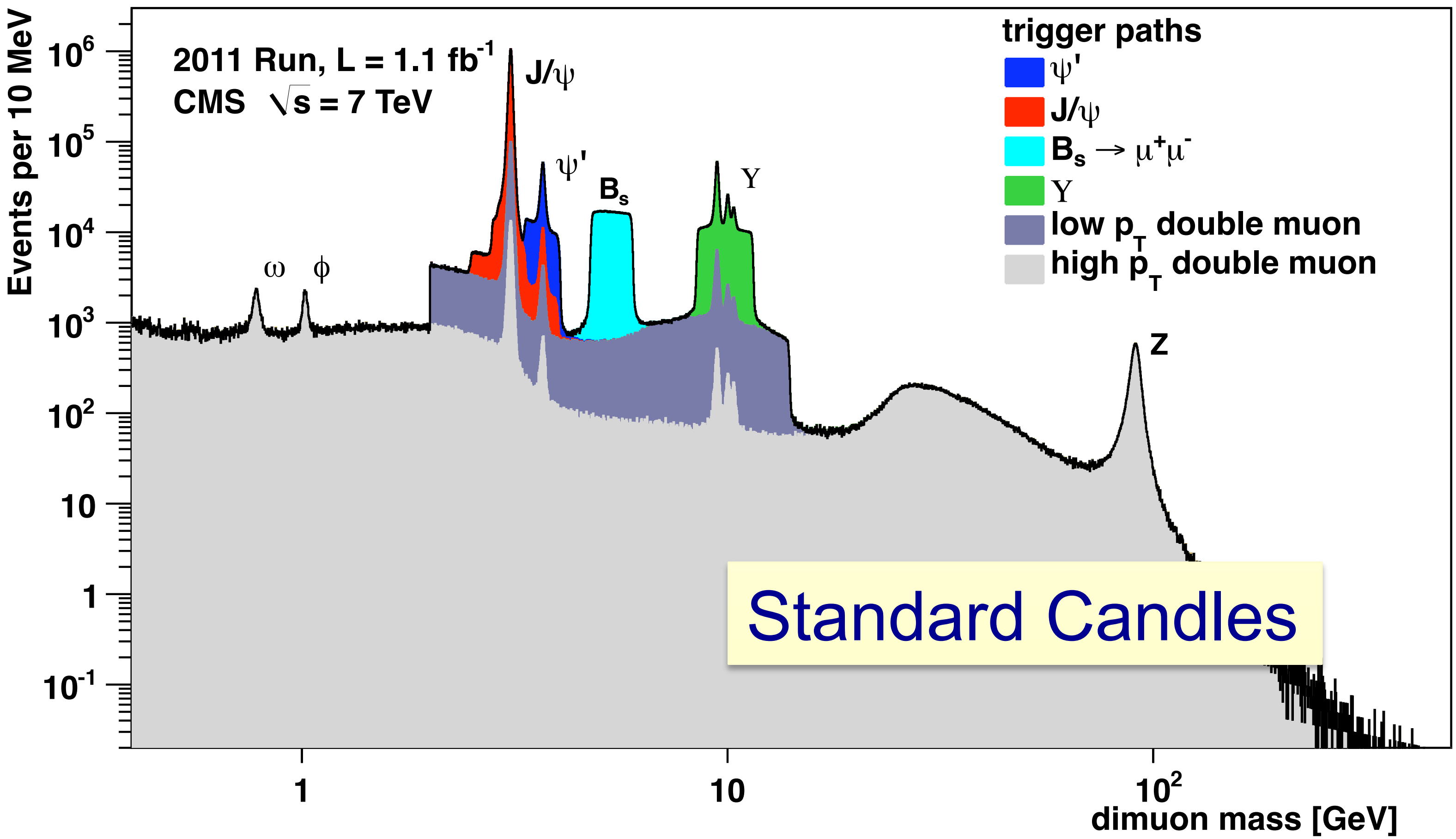
- **In addition: the two jets have good/clear *b*-tags**
- **Important cross check: muons and jets coming from the same interaction vertex.**



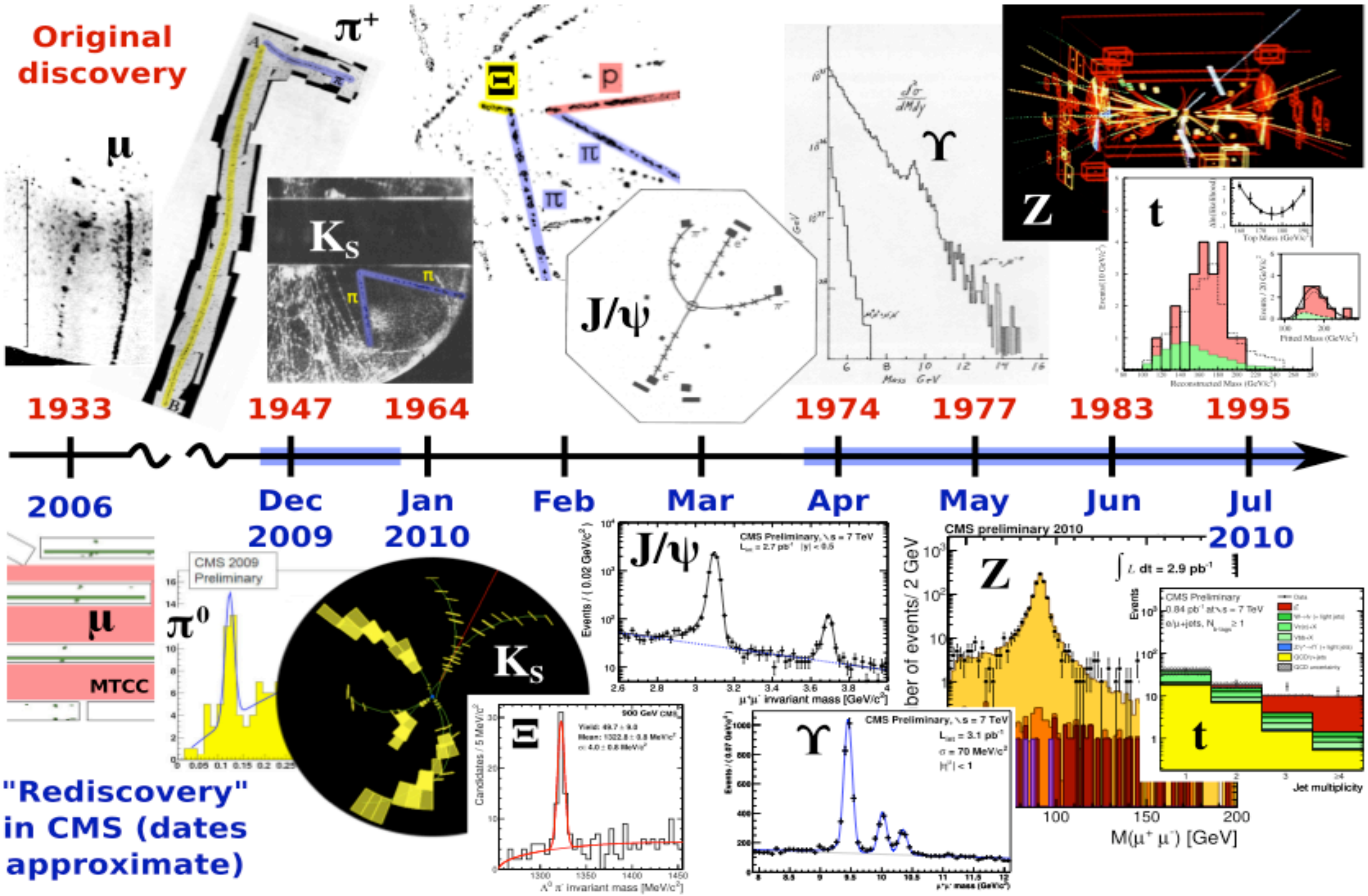


Detector performance

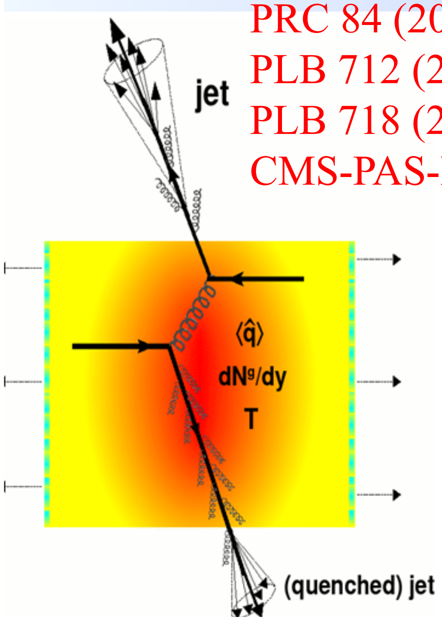
- **The startup of the experiments was the biggest discontinuity with the past: it was fast and efficient.**



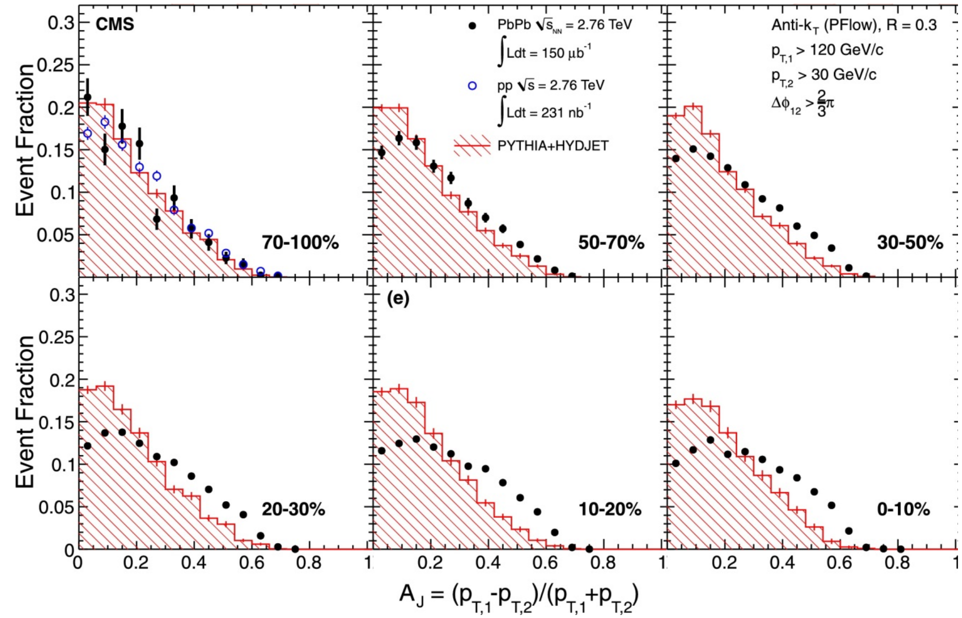
Around the standard model in 7 months

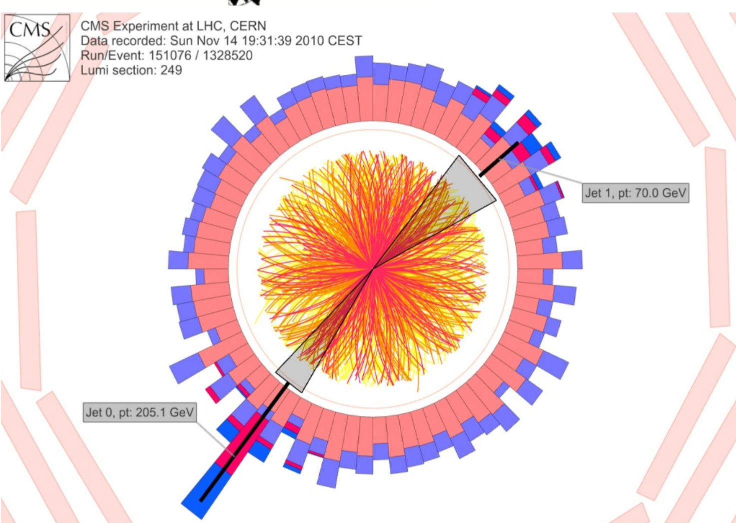


The ultimate: heavy-ion detector (!)

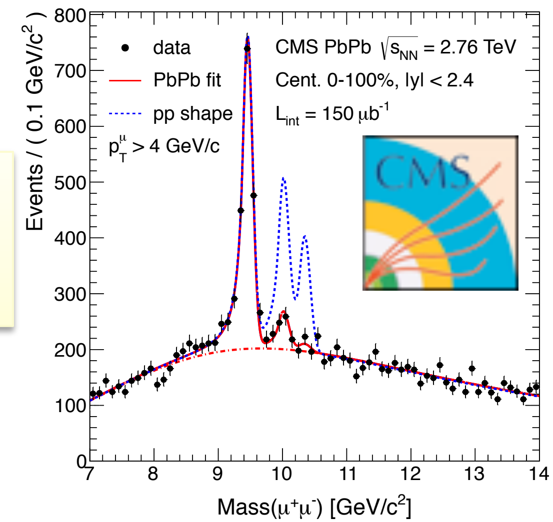


PRC 84 (2011) 024906
PLB 712 (2012) 176
PLB 718 (2013) 773
CMS-PAS-HIN-12-003





+ Melting Upsilons…

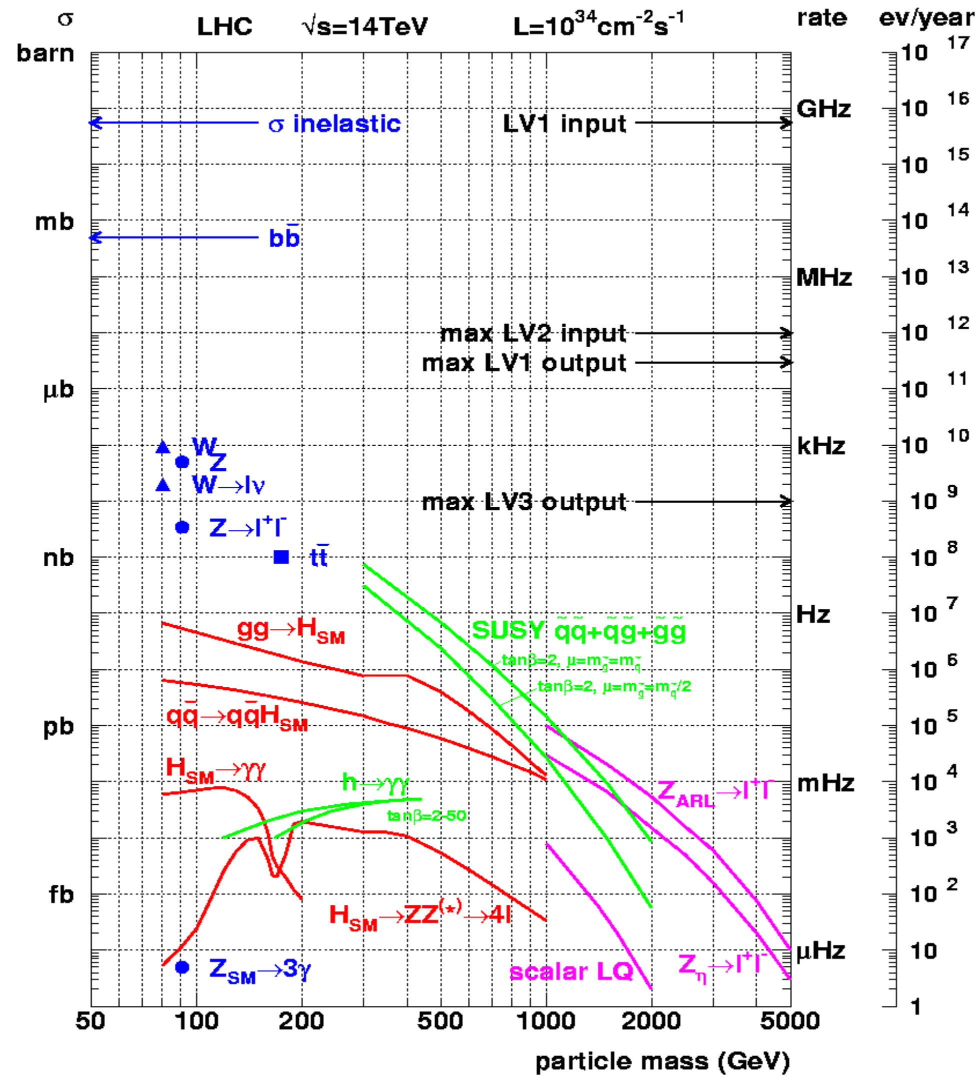


Challenges in searching for new physics

The case for using the data AMAP

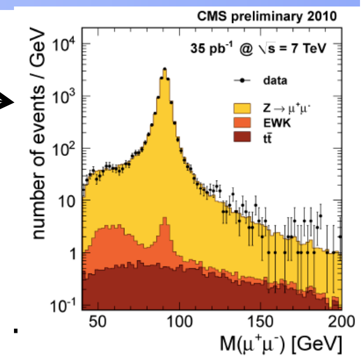
The LHC: signals much smaller than “bkg”

- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’



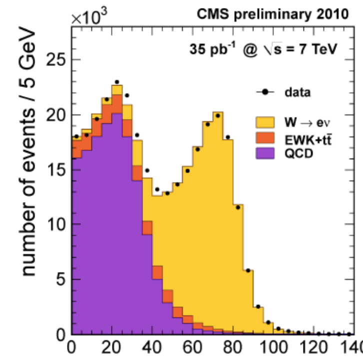
Summary of high-P_T & high-mass probes

- **High-P_T di-objects: jets, leptons and photons**
  - Mass(jet-jet), Mass($\ell\ell$), Mass($\gamma\gamma$)

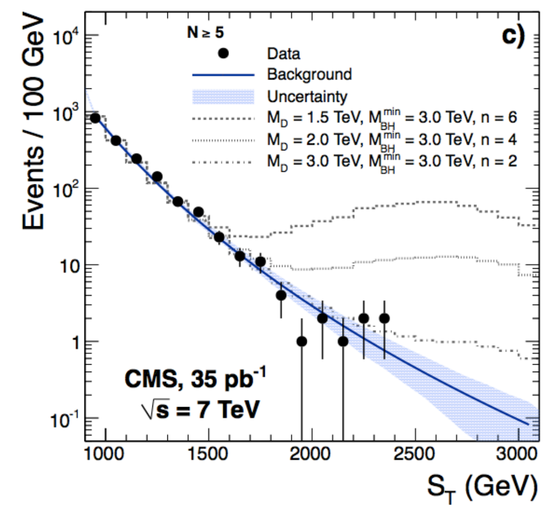


- **High-P_T lepton + ME_T (e.g. from ν)**
  - Transverse mass

$$M_T = \sqrt{2E_T^{\mu} E_T^{miss}\left(1 - \cos\Delta\phi^*\right)}$$



- **Combination of objects, e.g. as in SUSY and BH searches**
  - Various sums of transverse energies in the event
  - H_T: sum of all hadronic jets
  - S_T: sum of E_T of all objects (add leptons, photons, ME_T)
    - Also called "effective mass" (M_{eff}) in past LHC publications

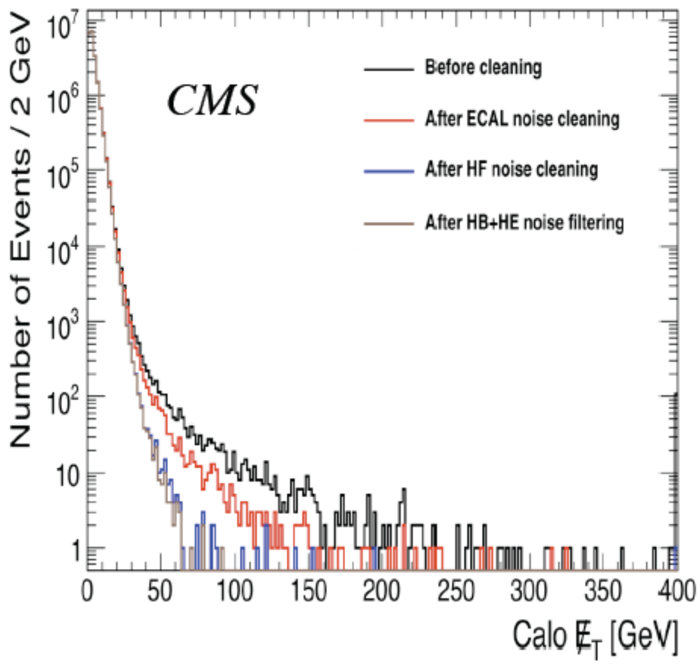


Understanding the detector (I)

- **Example 1: understand reconstruction of physics objects [e.g. for electrons or muons]**
  - **Suppose Grand Theory X342 implies that we should be looking for a signature of one muon, plus 3 jets**
    - **Naturally: use a combination of Monte Carlo simulation of all known processes [e.g. W+3 jets; $W \to \mu\nu$] that give this signature plus data events with 1μ+3jets**
    - **But what about another background: Z+3 jets, for which we lose one lepton from the $Z \to \mu\mu$ decay?!**
  - **Worse: we can only get a *feeling* for the size of the effect from Monte Carlo and detector simulation**
    - ***But this [MC+simu] will never get the answer quite right***
    - **One needs to find a way of calculating this efficiency from the only source that speaks the absolute truth: the data!**
- **Thus, we refer to "data-driven" methods / techniques**

Understanding the detector (II)

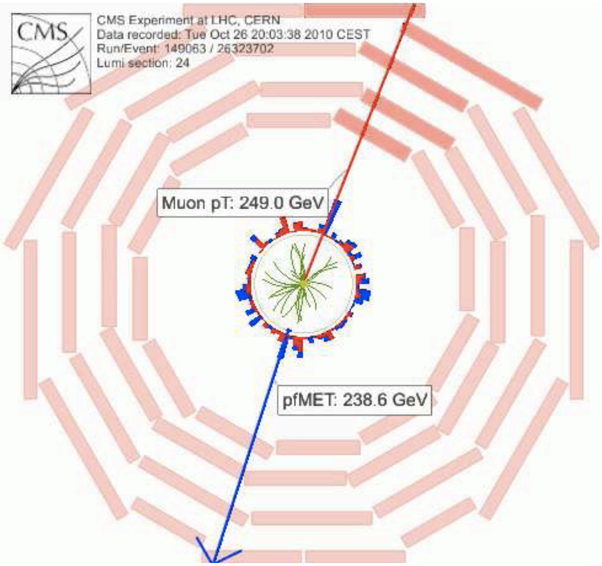
- **Example 2: understand missing transverse energy**
  - There are many instrumental sources of MET!
  - Calorimeter Noise
    - Need "noise filter"
  - Beam halo [particles from the beams]
    - Need "halo filter"
  - Cosmic muons traversing detector!
    - Can shower in the calorimeter!
    - Use tracks, topological cuts



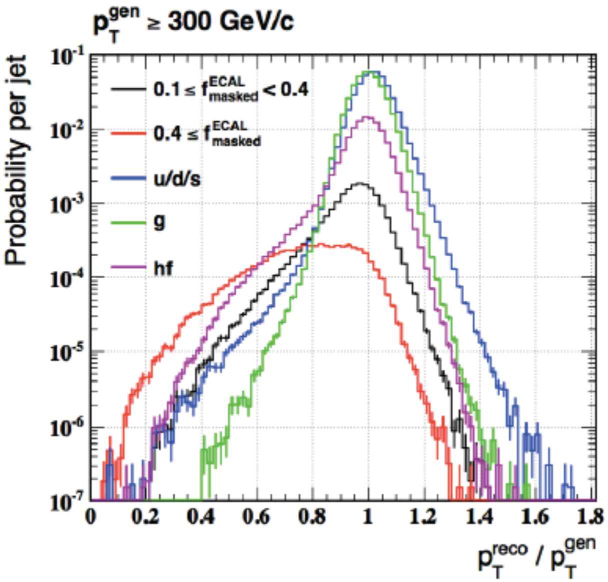
  - Here, for certain, simulation is of little help!
- **Again, one needs to rely on data**

Understanding the detector – ME_T (III)

- **Even worse: "honest mistakes"**
  - A misreconstructed muon can do damage: since muons leave only MIP energy in the calorimeter, in correcting the MET from the calos, one has to add the muon momentum! But if the muon is fake, one is correcting in error!



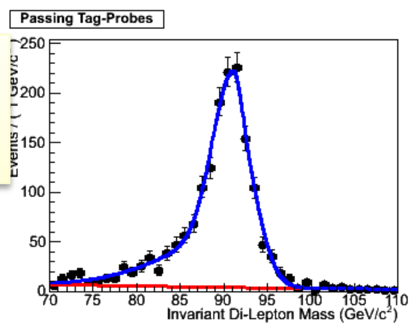
- **Tails of jet response!**
  - Effects of 1:10,000?
  - Detector cracks!
    - A jet that's heading straight into a detector crack will lose quite a bit of energy – and thus there will be a fake ME_T reconstructed [because the E_T will not be reconstructed!]

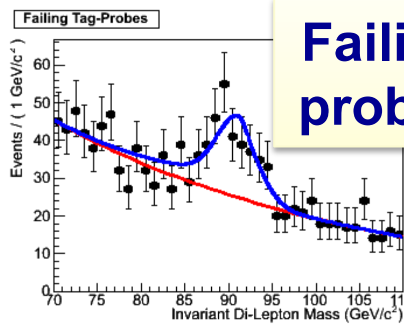


Obtaining (in)efficiencies from data

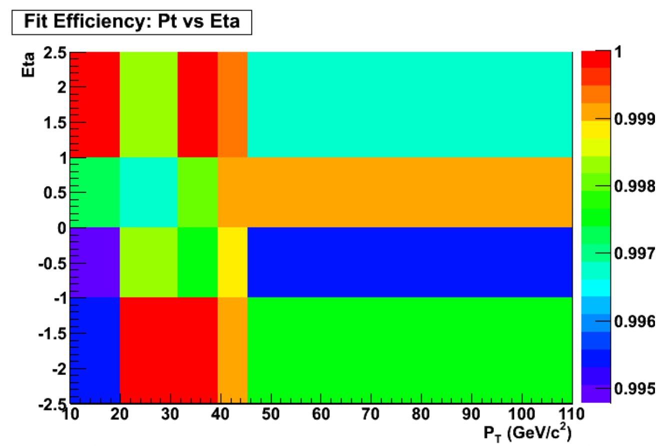
- What is the efficiency of the tight muon identification cuts? Or of the trigger? Use "tag and probe" method in, e.g. $Z \to \mu\mu$ decays:
  - Make a selection based on one muon that "tags" the type of event (e.g. passes tight cuts; or passes the trigger)
  - Then demand that second muon does the same

Passing probes

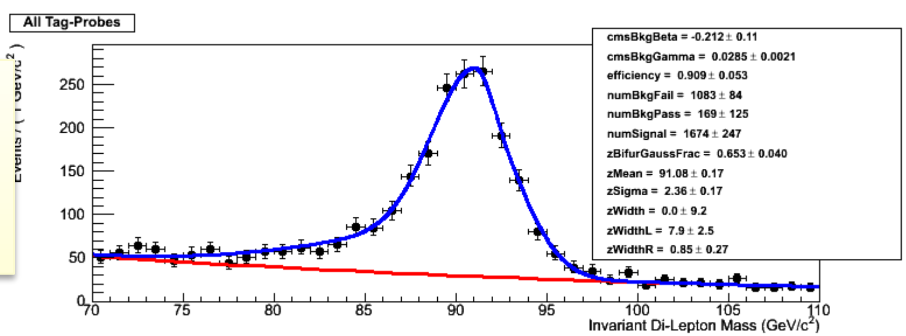




Failing probes



All combi-nations



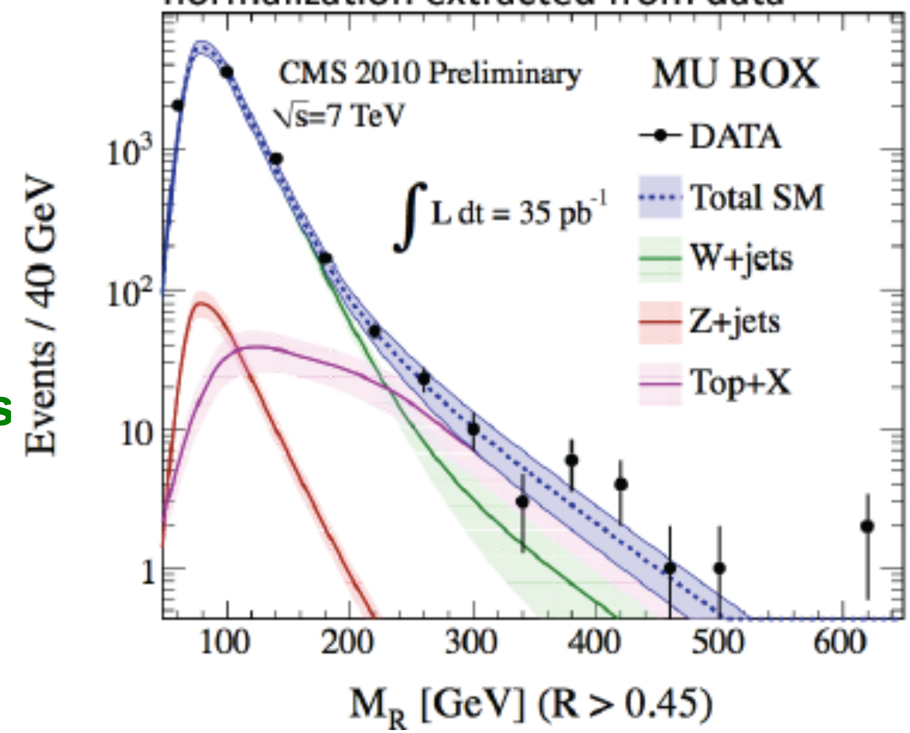
Obtain efficiency map

Understanding the physics background!

- **Suppose one is searching in the "jets + MET" signature**
  - We will encounter this later in the SUSY searches
  - Even after understanding the "reducible backgrounds" – i.e. detector response, the filters, etc, -- there are "irreducible backgrounds" from physics processes which give the same signature

Prime example 1: Z+jets
And the Z decays to neutrinos
So the MET is genuine!
Prime example 2: t-tbar
And one of the two W's decays to a tau and a neutrino

Background Shapes and normalization extracted from data



- **Cannot rely (only) on MC+simu!**

The problem: the background

Huge background: implications

- Very difficult to select the "right" event(s); what are the criteria? Cannot interview every single person
  - Need an automated procedure; by necessity, it will rely on a set of successive approximations
  - One has to design these selection steps; and one has to ensure that they are unbiased!
    - Very difficult to avoid biases in the selection process!
    - Particularly important in the online trigger system!
- Number of "input" events is so large that one expects all abnormalities to show up
  - Even with a probability of occurrence of 1:10,000, in a crowd of 1,000,000 people, there will be 100 "cases"!
  - In practice, implies a new level of understanding – cannot rely on Monte Carlo to simulate things at this level of detail

Pseudo-summary I

Pseudo-summary I

- The LHC was conceived to probe the physics of the ~TeV region
  - Energy at 14 TeV → need for higher luminosity
    - Several unprecedented challenges to detectors
- ATLAS & CMS: two different solutions for the same mission
  - With similar physics reach
- Hadron colliders: despite complexity of events, the interesting ones do stand out
  - Some limitations (e.g. $\Sigma p_z \neq 0$) but ways around it
  - Reconstruction: a huge job, to which we have done no justice
- Searches for New Physics: looking for processes hat are quite rare (compared to SM)
  - Selectivity so high that one must ensure that malfunctions and detector inefficiencies use the best simulation of reality aka data)

LHC t_0=2009

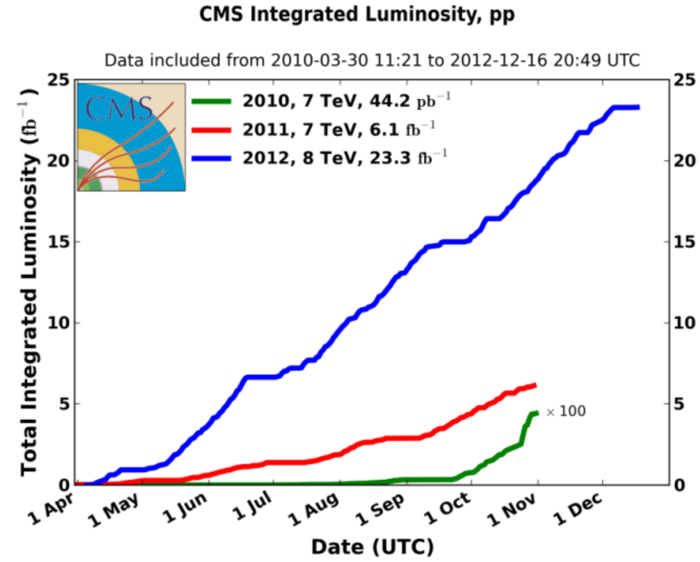
Run I:

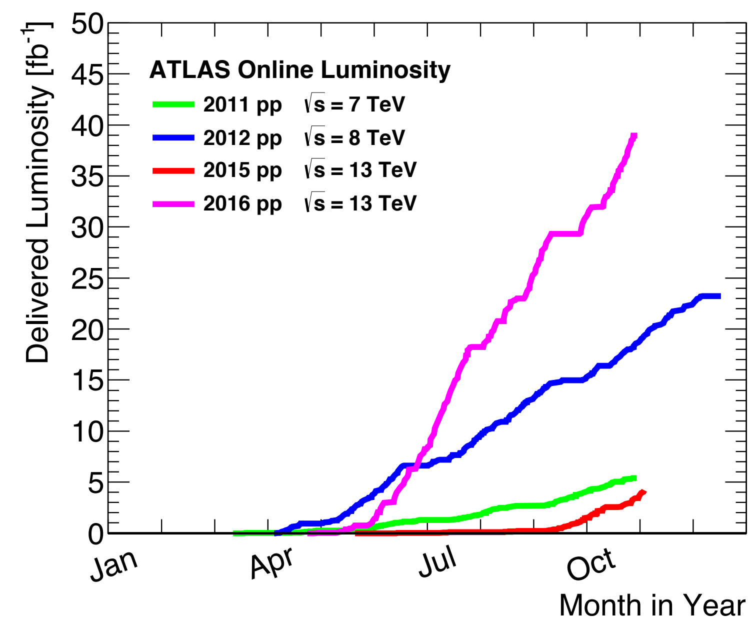
2010–11: 7 TeV
2012: 8 TeV

2013–14: LS1

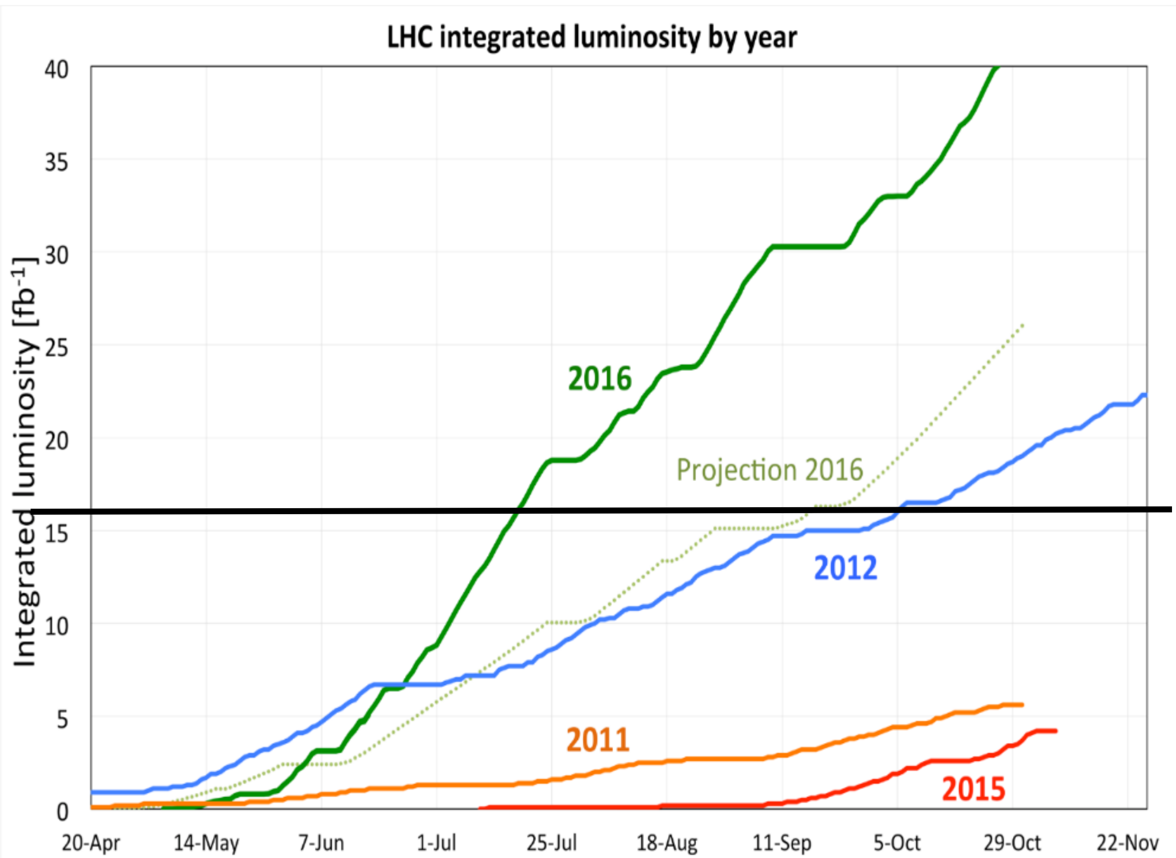
Run II:

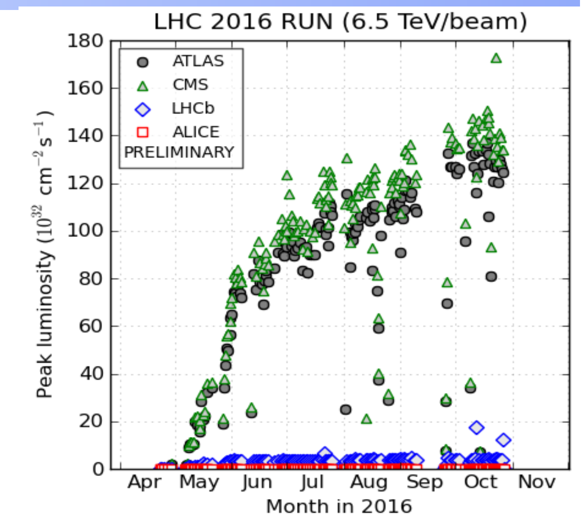
2015–16: 13 TeV

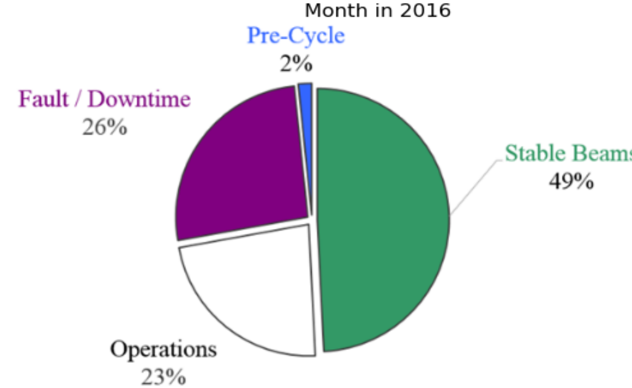




A great five years; an amazing 2016







≈153 days physics ≈3738.7 hours

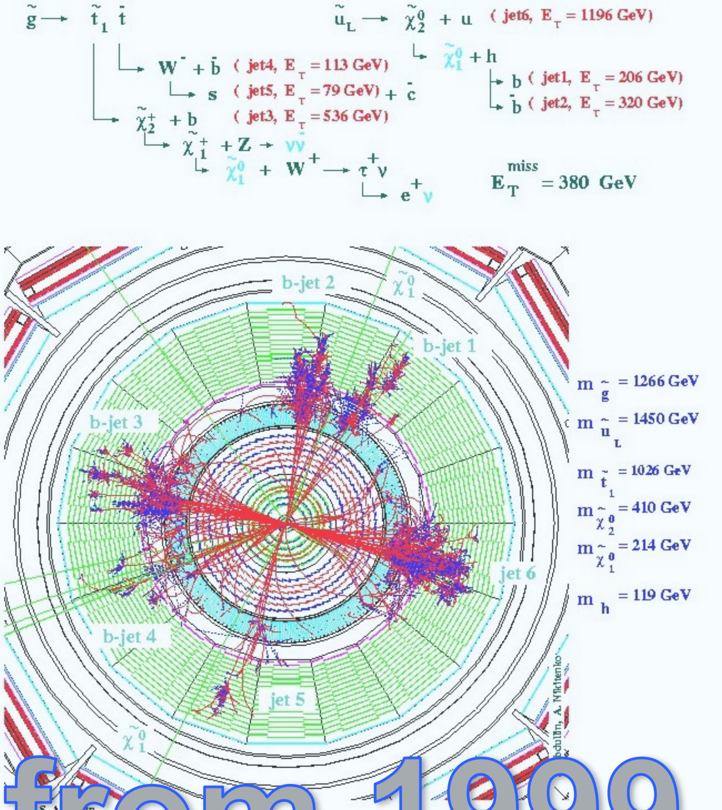
	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

Run I: 2010-2012; total L~25 fb^{-1}.
Run II: 2015-2016 (4 fb^{-1}; 40 fb^{-1})
2016: Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

"Turn on the LHC and… find Higgs & SUSY"

- **ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away**
  - **In fact: SUSY is strongly produced, so will be observed first**
    - **For the "impatient": join SUSY physics group**

- **Many hard Jets**
- **Large missing energy**
  - **2 LSPs**
  - **Many neutrinos**
- **Many leptons**
- **In a word Spectacular!**



Text & simu from 1999

So what has transpired?

- **Next three lectures!**
- **Lecture 2: Standard Model Physics**
  - **Jets and QCD measurements**
  - **Electroweak Theory**
  - **Top physics**
- **Lecture 3: EWSB Physics**
  - **The scalar sector, the great discovery**
  - **Searches for an extended scalar sector**
  - **Measurement of the W and top-quark masses; overall consistency of SM**
- **Lecture 4: Searches for New Physics**
  - **Supersymmetry**
  - **Exotica**
  - **Summary**