Exploring the Terascale:
The CMS Experiment at the LHC and the First Results.

The Royal Society of Edinburgh

Higgs-Maxwell Workshop

9 Feb. 2011

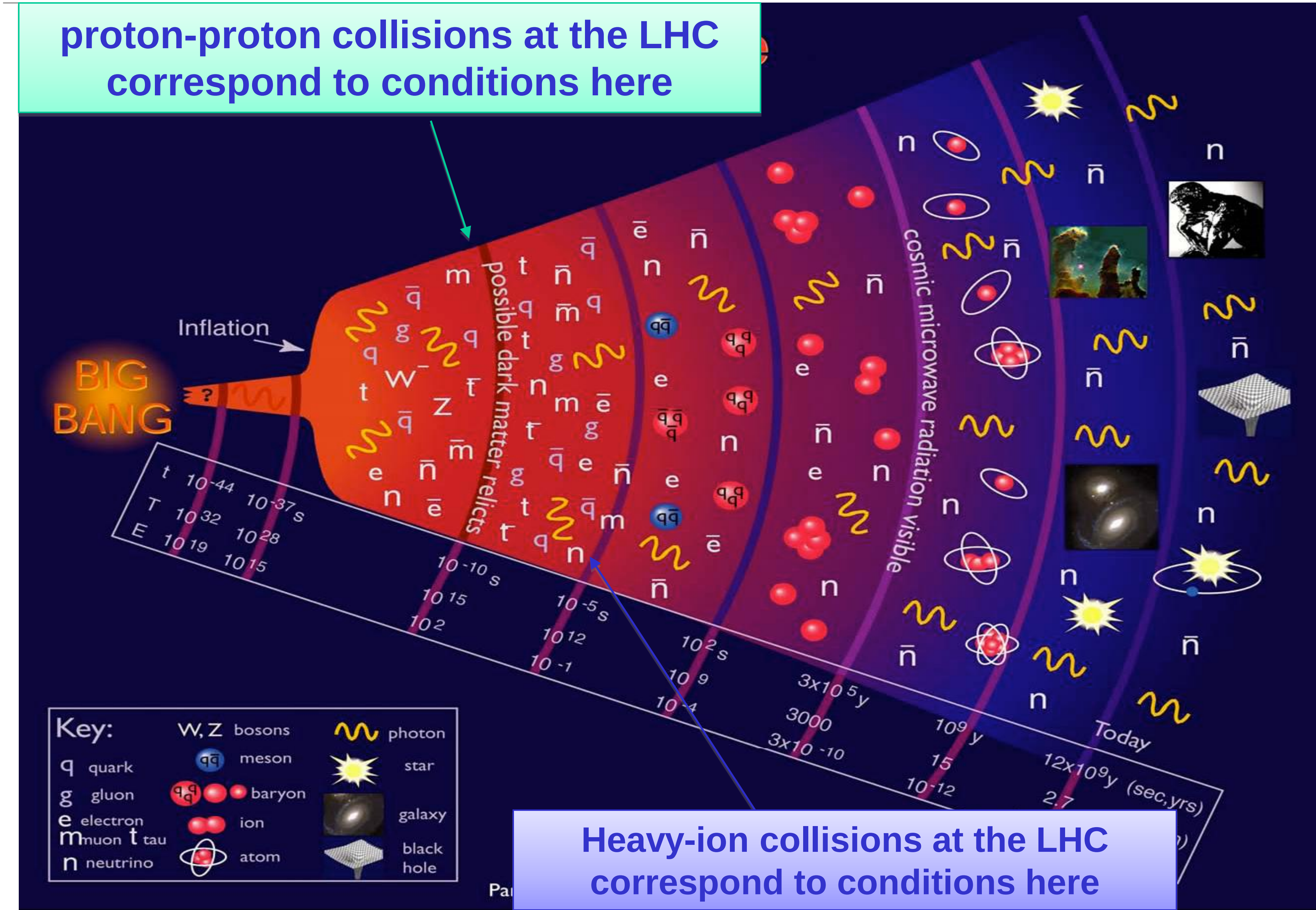
Brief Physics Introduction
The CMS Experiment
First Results from CMS
Outlook

Acknowledgements
G. Landsberg – CERN EP/PP/LPCC Seminar (Jan11)
P. Sphicas: CERN Academic Training (Jan/Feb'11)
Many CMS Coleagues

Tejinder S. Virdee, Imperial College/CERN
On behalf of CMS Collaboration

Exploring the Terascale

proton-proton collisions at the LHC correspond to conditions here



Heavy-ion collisions at the LHC correspond to conditions here

Prologue

Lepton-Photon Conference 2009 G. Altarelli

The LHC physics run will soon start, ... hopefully!

After the incident on Sept.19 '08 we must wait till Nov. '09
[LEP was closed at the end of 2000] Start at 3.5 TeV per beam

Top physics priorities at the LHC (ATLAS&CMS):

- Clarify the EW symmetry breaking sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

Also:

- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

At this point, fresh input from experiment is badly needed

Experimentally at LHC

Find new particles/new symmetries/new forces?

- ⇨ **Origin of Mass -** Higgs boson(s)
- ⇨ **Supersymmetric particles** - a new zoology of particles, dark matter particle? …
- ⇨ **Extra space-time dimensions:** gravitons, Z' etc. ?
- ⇨ **The Unexpected !!**

Studies of CP Violation (LHC*b*) and Quark Gluon Plasma (ALICE)

Summarising 2010 …

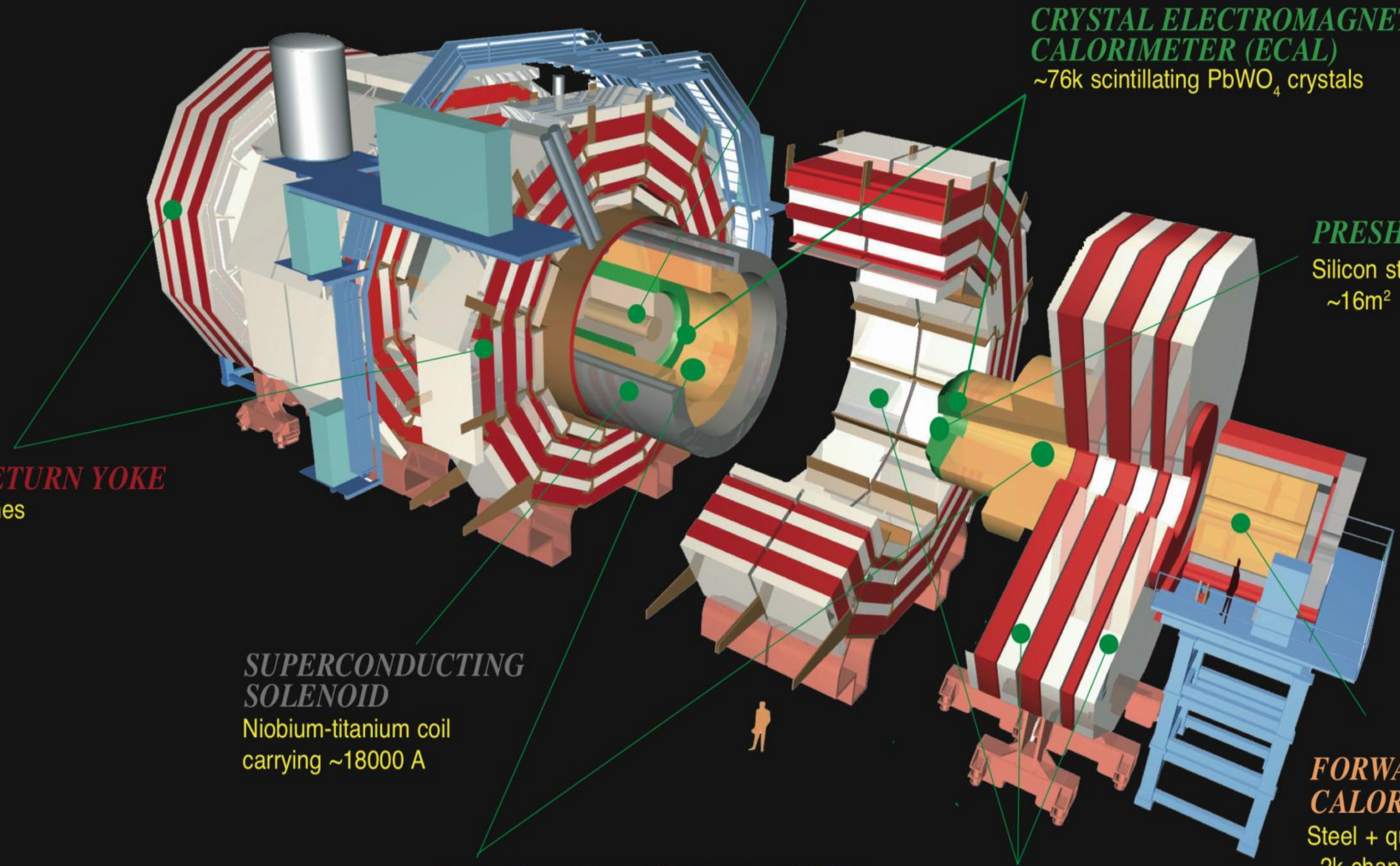
1. **The LHC accelerator performed marvelously well - running in proton mode at $\sqrt{s}$=7TeV and heavy-ions mode at $\sqrt{s}$=2.76TeV/nucleon. Many thanks.**
   - During the year the p-p interaction rate increased from 10^2 to around 10^7 !
   - The stored energy in the machine reached around 6% of the design value!
   - The transition to heavy-ion running was smooth
   - The machine conditions were "clean" and about 40 pb^{-1} ($10\mu b^{-1}$) in pp (PbPb) mode were delivered.

2. **CMS (+ other LHC experiments) also performed marvelously well**
   - The unprecedented and high level of preparation led to quality results streaming out very soon after startup.
   - CMS is very well described in the simulation codes
   - Much "physics commissioning" has been done. The precision of some measurements is already approaching that of theoretical uncertainties.
   - New subtle effects are being seen and in many areas the LHC experiments are exploring territory beyond what has been explored at the Tevatron or RHIC.

" an unprecedented state of readiness"
PS: several years of delay were well spent

CMS Detector

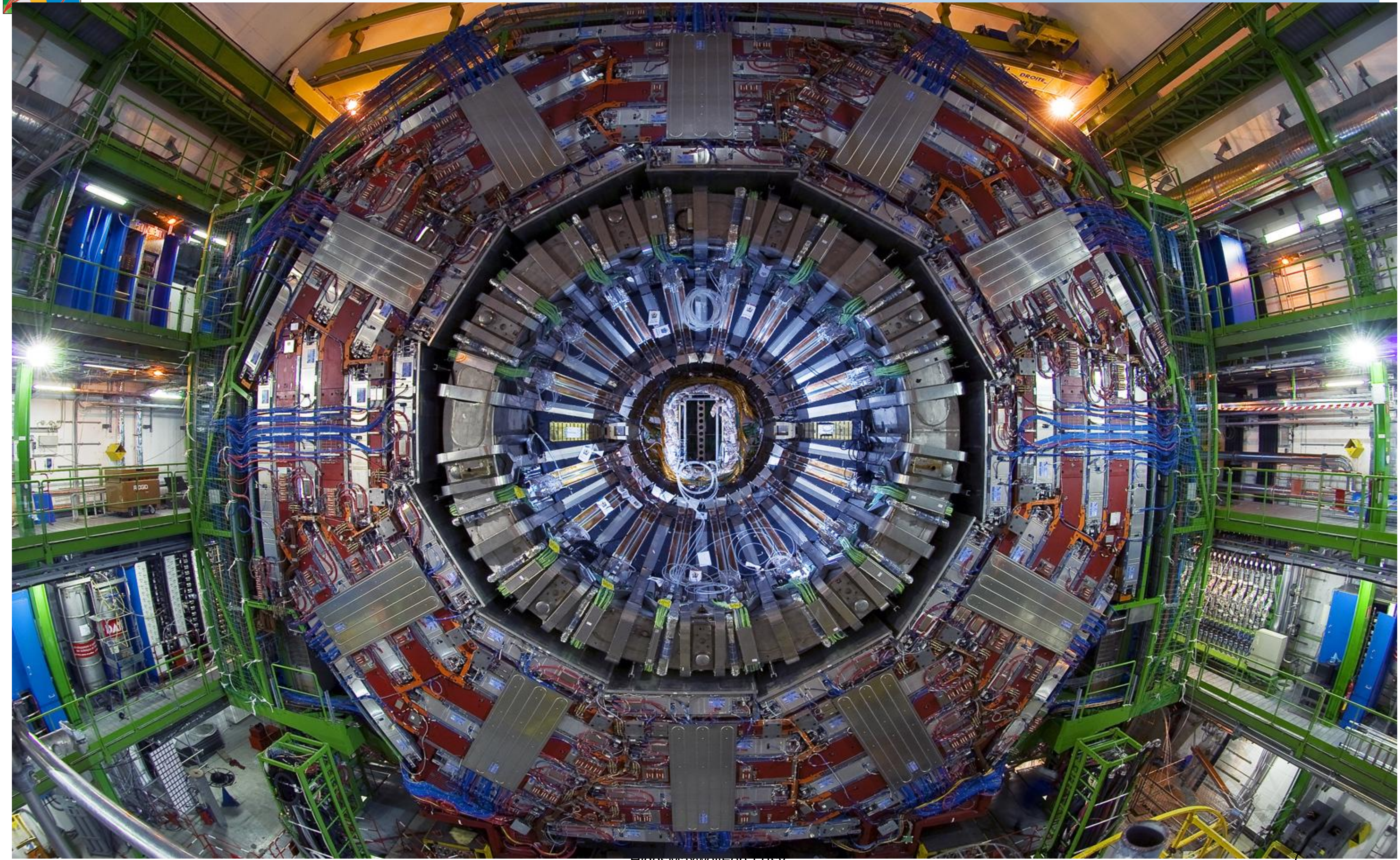
39 Countries,169 Institutions
3170 Scientists and Engineers
(800 Ph.D Students)
Bristol, Brunel, Imperial, RAL



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Imperial College London

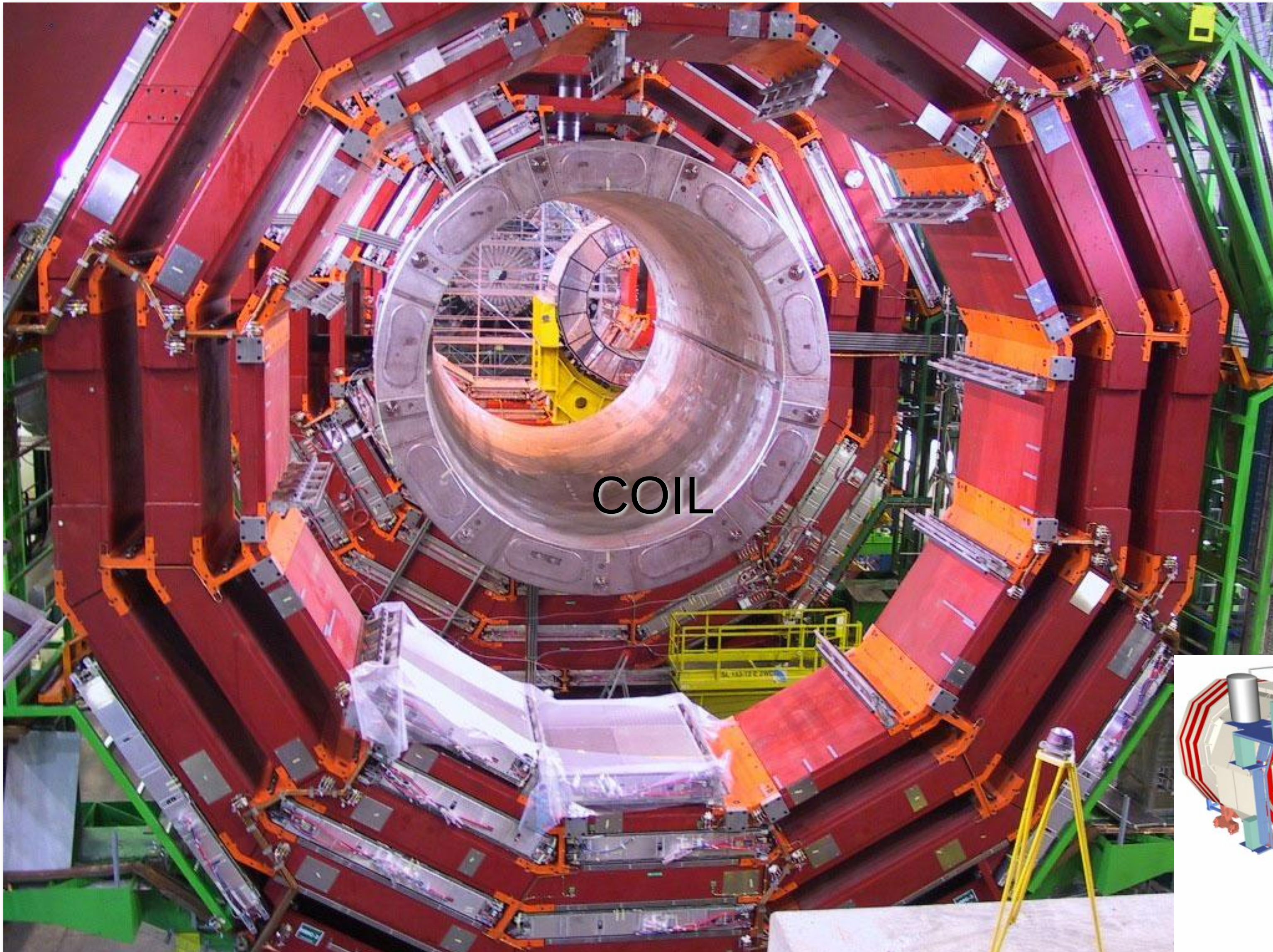
CMS Detector

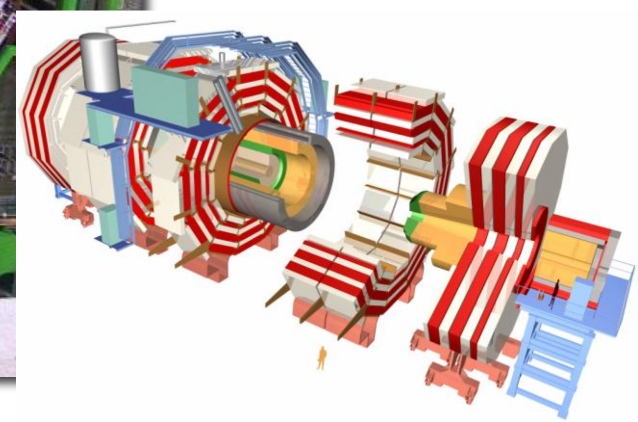


Imperial College London

CMS: Surface Site in 2000

CMS: Surface Hall in Feb 2006





Spectacular Operations (Feb. 2007)

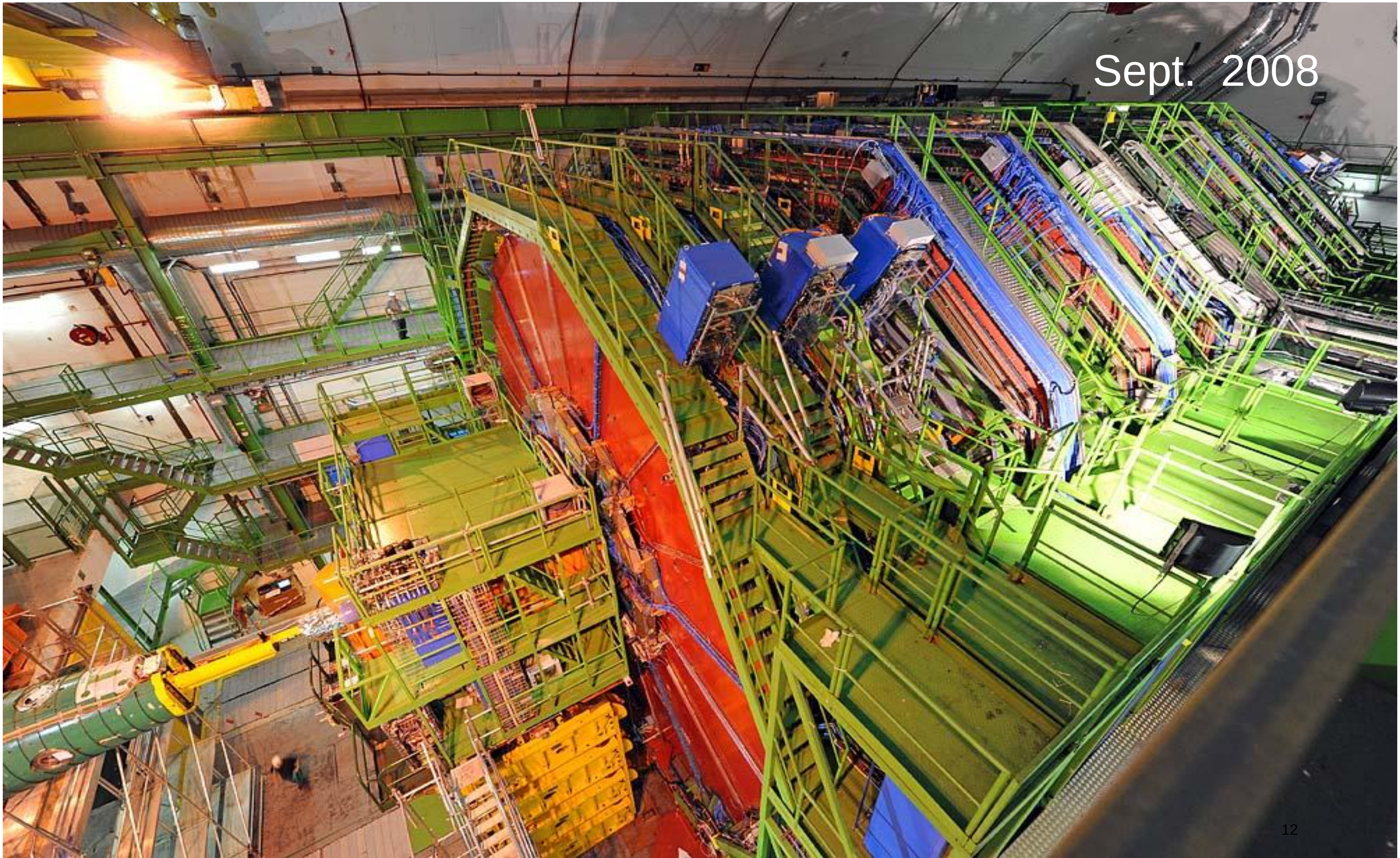
Cables, Pipes and Oprical Fibres !

Nov 2007

Took 50’000 man hours

Imperial College London

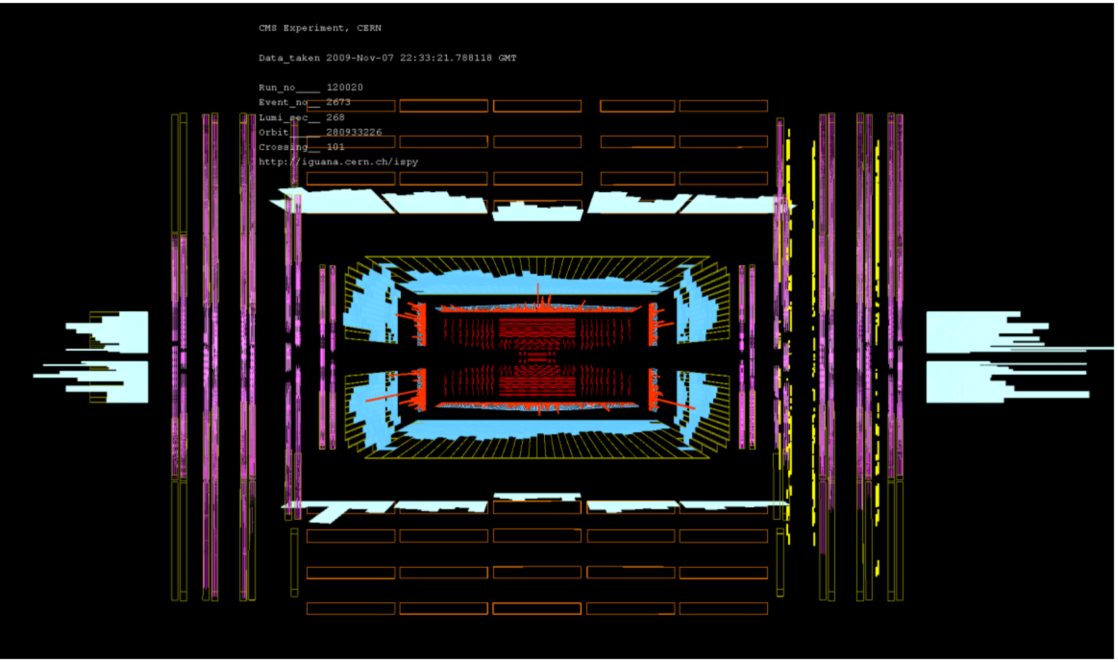
CMS Detector Closed



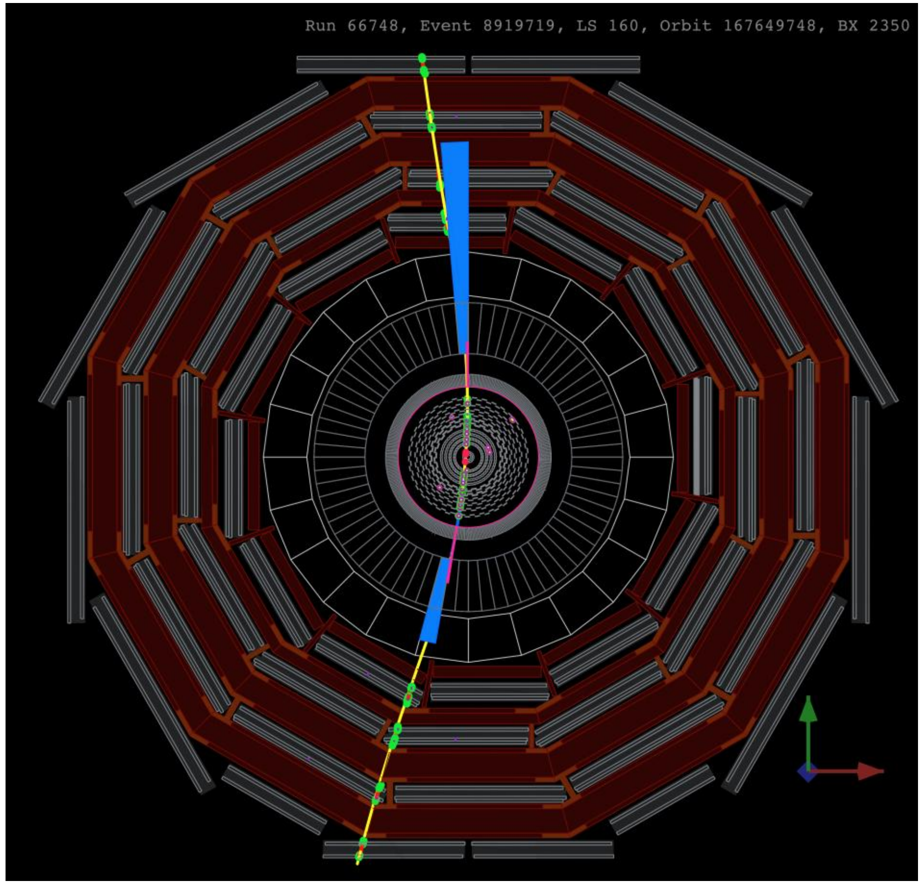
Imperial College London

Commissioning using cosmics & beam “splashes”

LHC Beam 10 Sep 2008



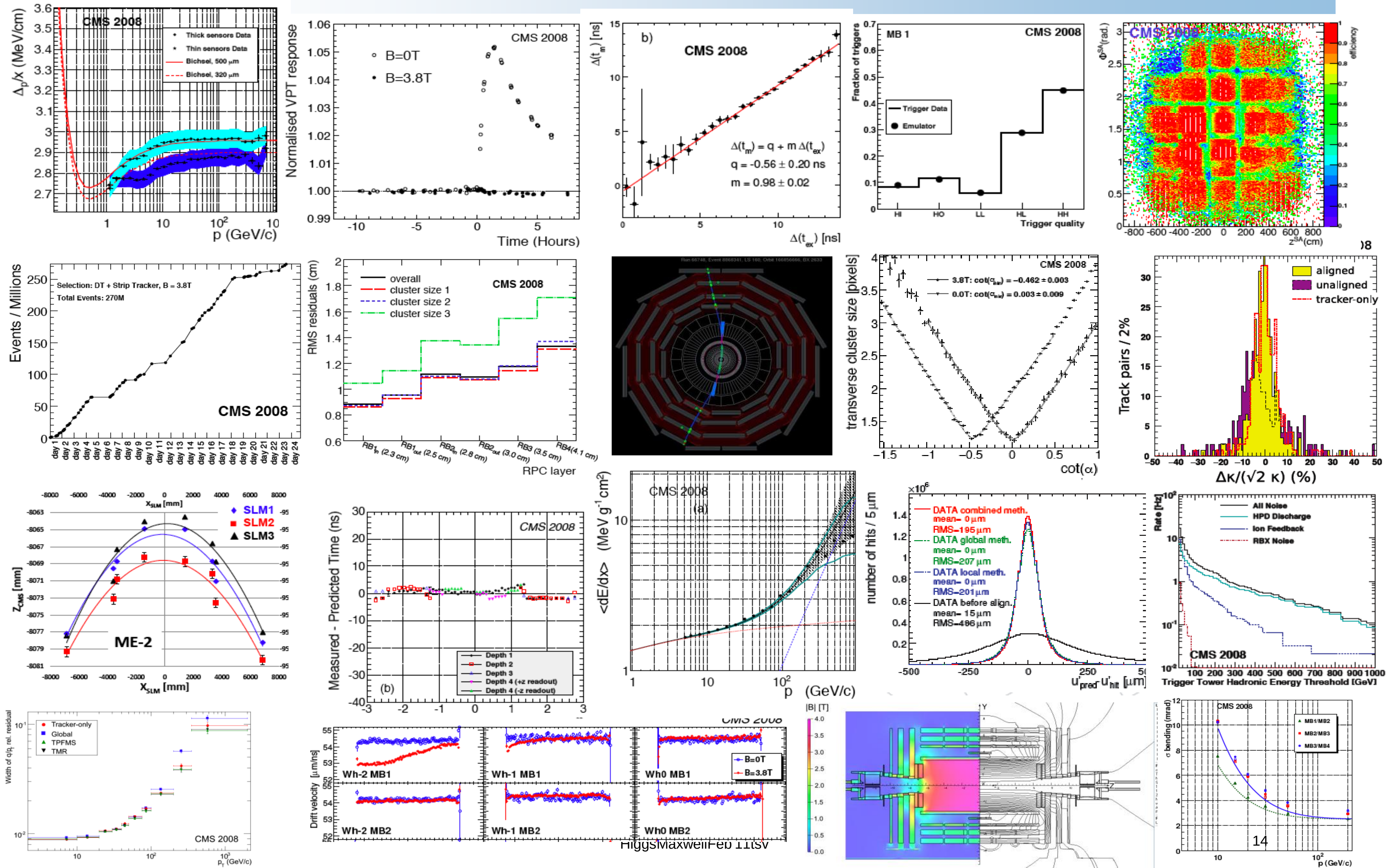
LHC Incident 19 Sep 2008



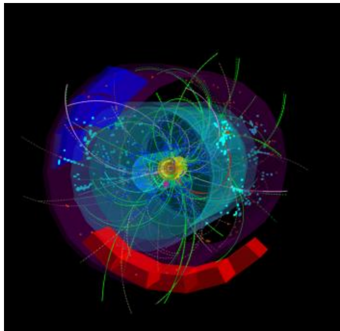
Great state of readiness at start of run thanks to extensive studies with ~1G cosmic μ events (2008-09), beam splash events (2009), and detector description in MC.

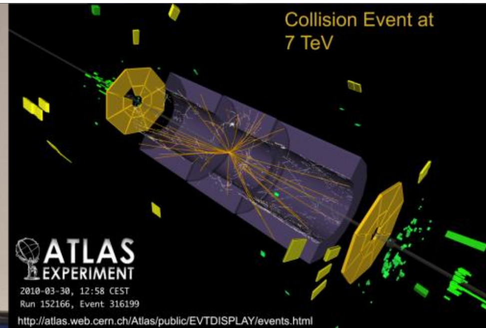
Imperial College London

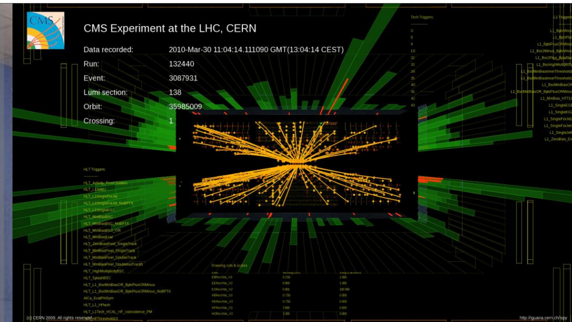
CRAFT: Publishing 23 Papers in JINST



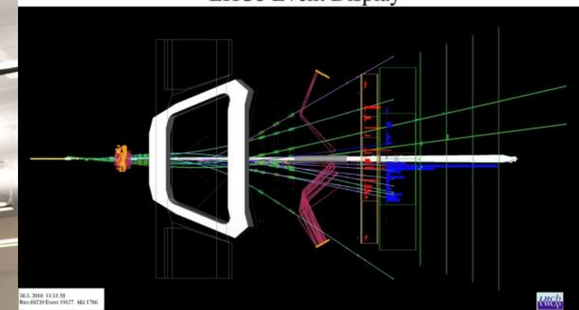
March 30 2010: Collisions at 7 TeV
A Big Step Up in Energy



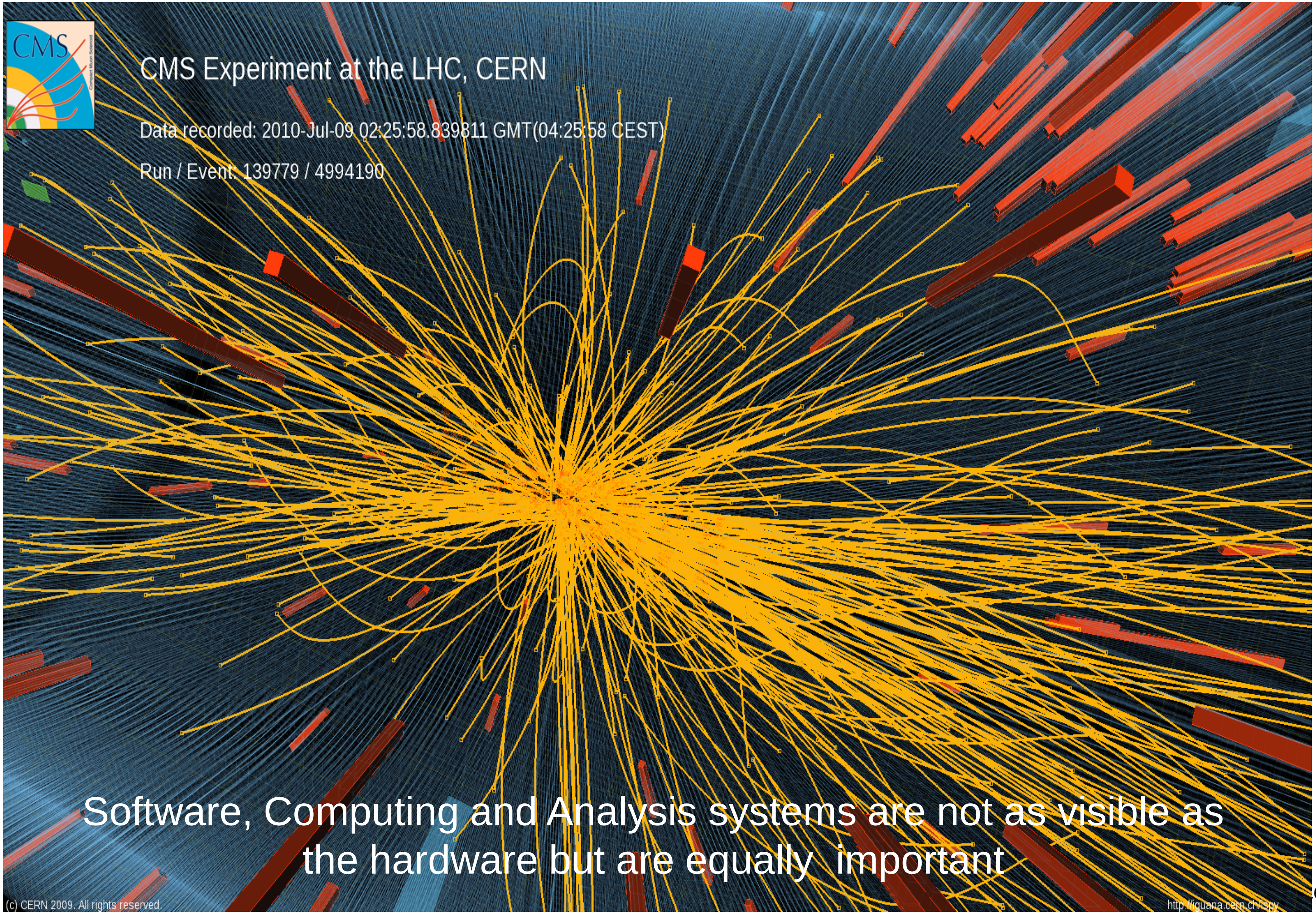




LHCb Event Display



Collisions at 7 TeV: A Big Step Up in Energy

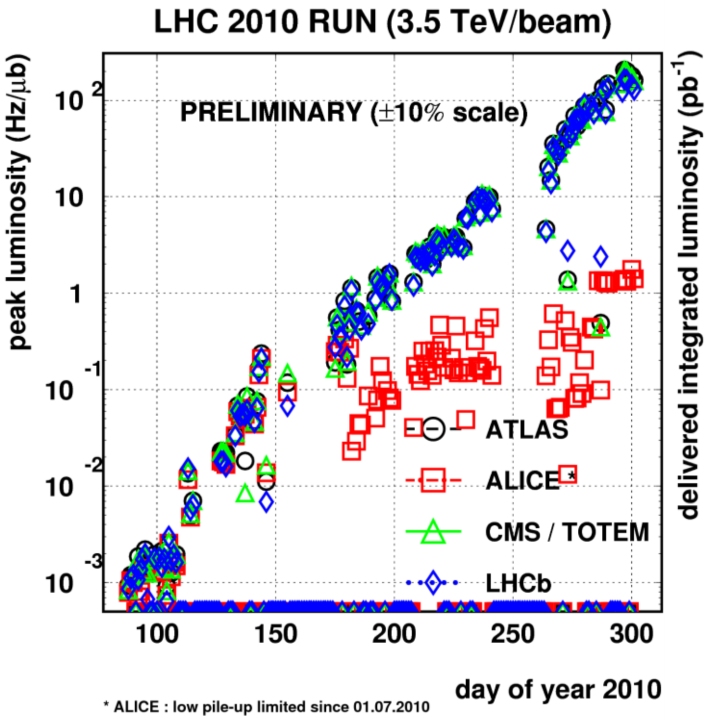


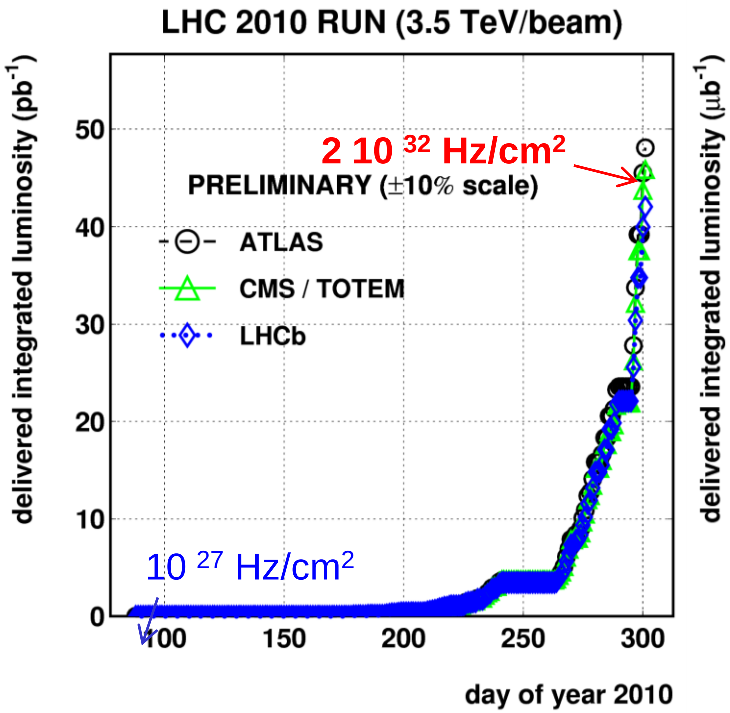
Software, Computing and Analysis systems are not as visible as the hardware but are equally important

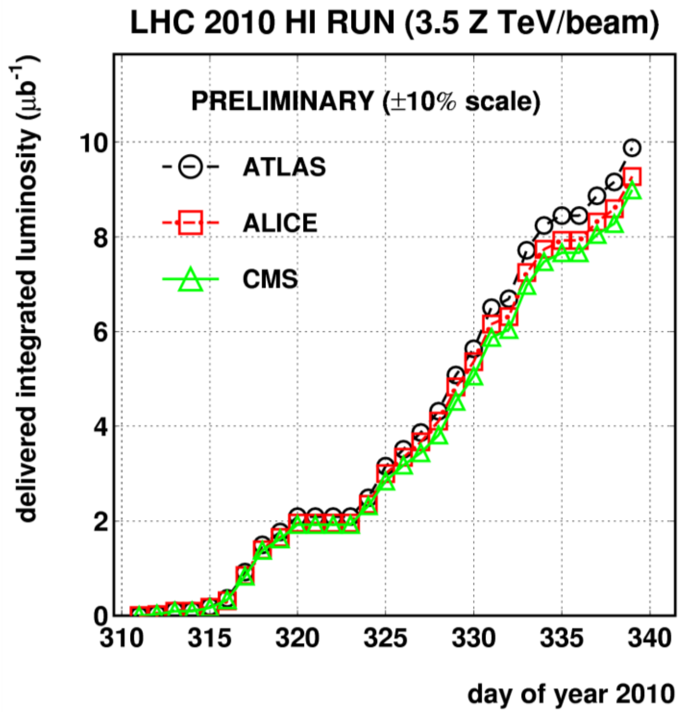
The Luminosity Evolution in 2010

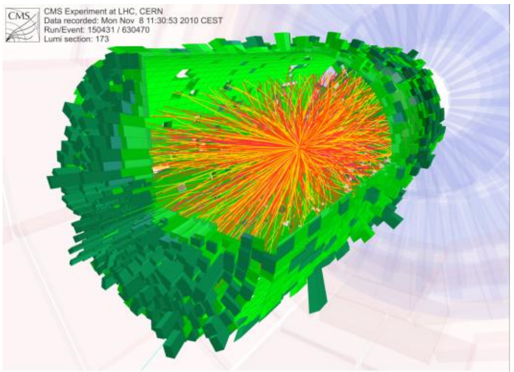
Proton-proton running

Pb-Pb Running





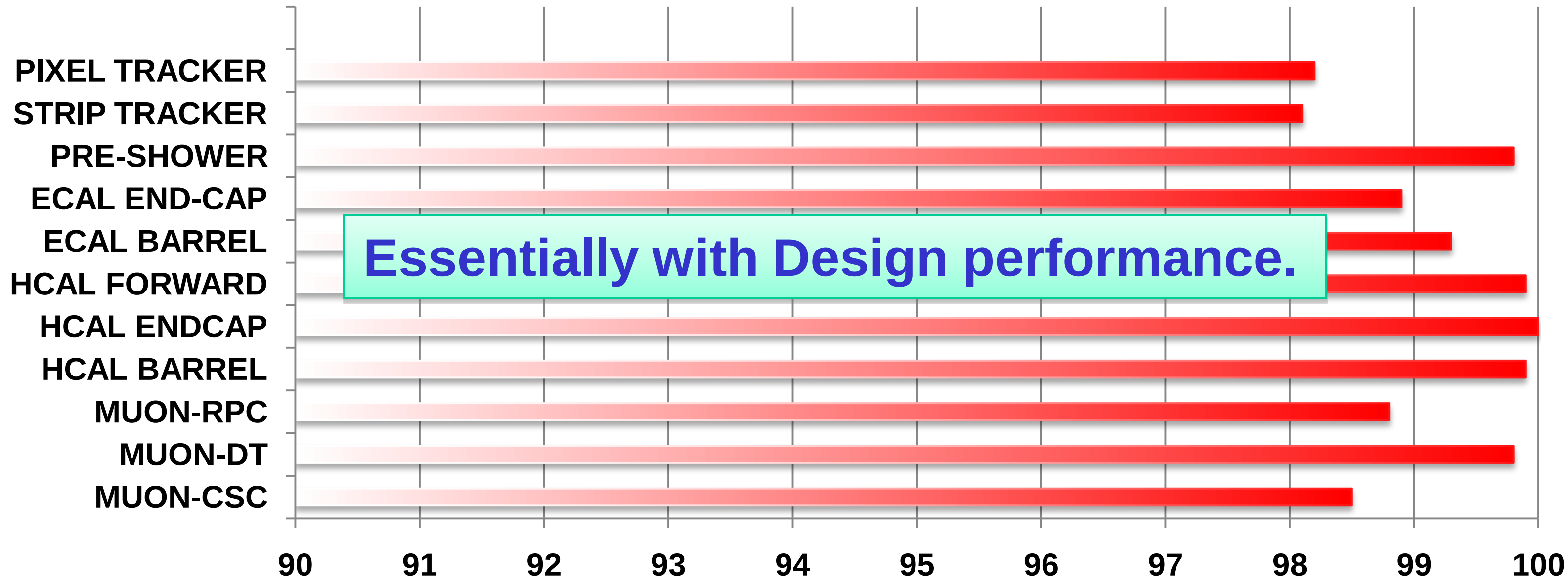




Luminosity increased by 5 orders of magnitude
half of integrated luminosity delivered in the last week!

Level-1 and HLT were rapidly changing !

CMS: Good Operational Status in 2010



Essentially with Design performance.

	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

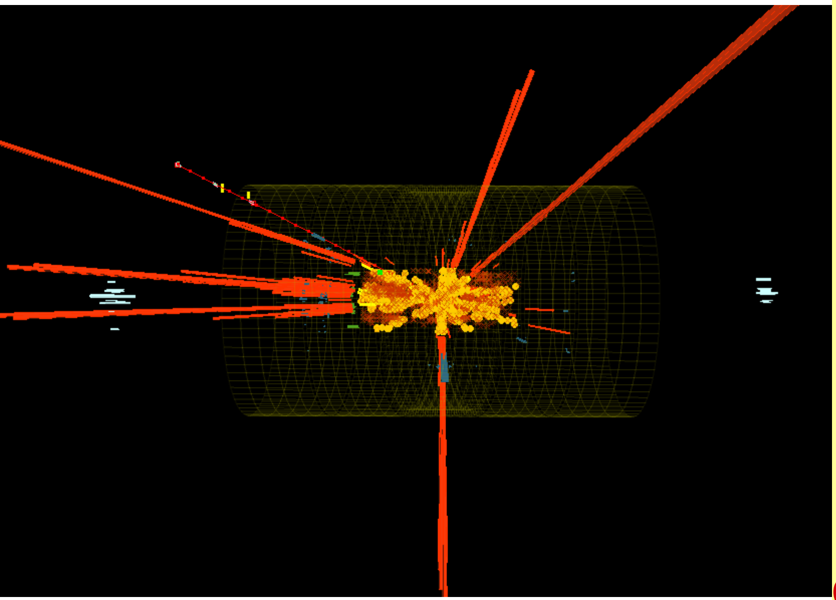
Proton-proton
LHC Delivered 47 pb^{-1},
CMS recorded 43 pb^{-1}
Overall data taking efficiency 92%
~85% with all subdetectors fully operational

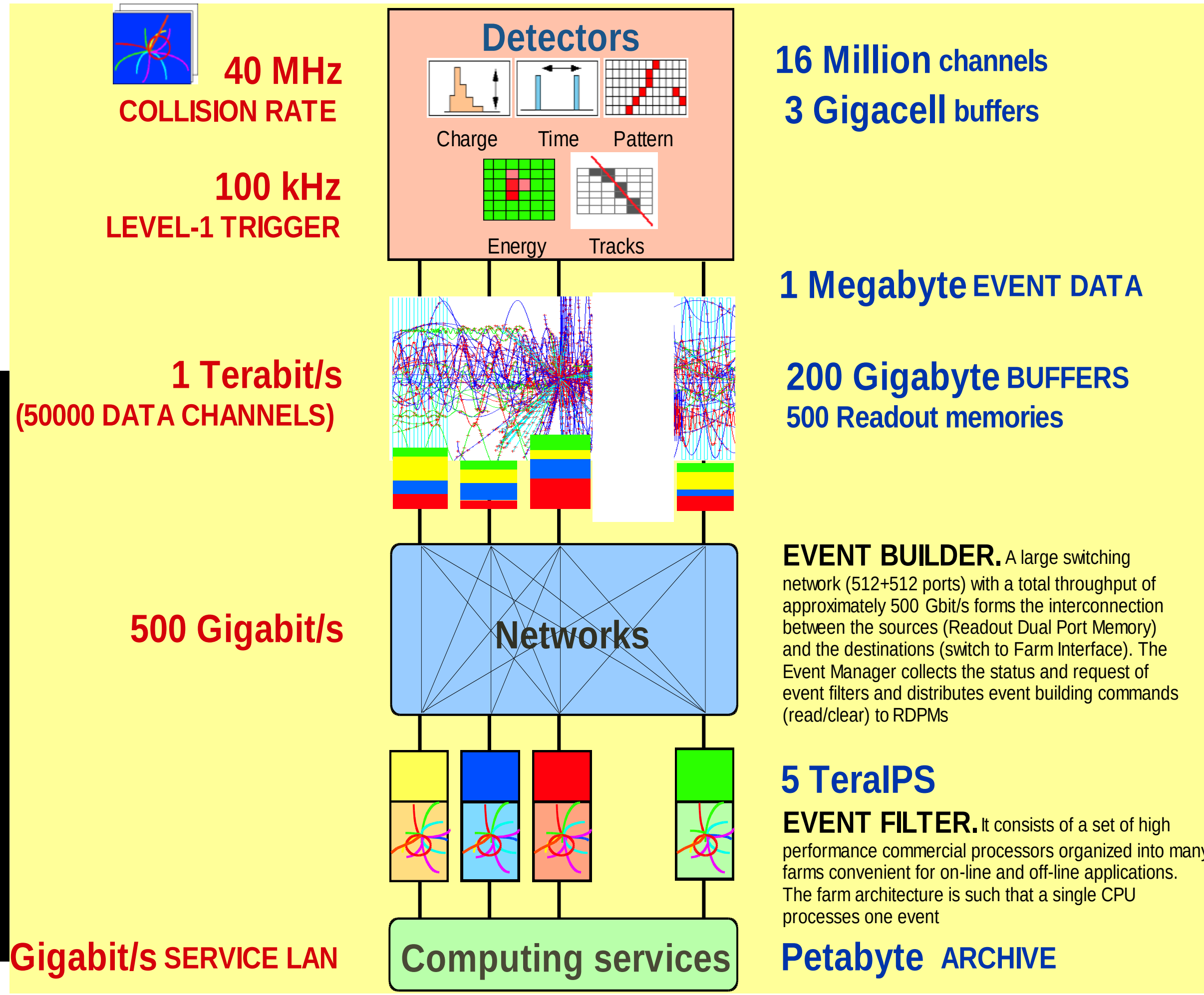
Heavy (Pb-Pb) Ions
LHC delivered ~ 10 μb^{-1},
CMS efficiency > 95%

Selection of Interesting Events

CMS uses a 2-tier "trigger" system to select interesting pp collision events for use in physics analysis.

A collision is considered interesting if it contains high p_T objects (electrons, muons, jets, E_t^{miss})



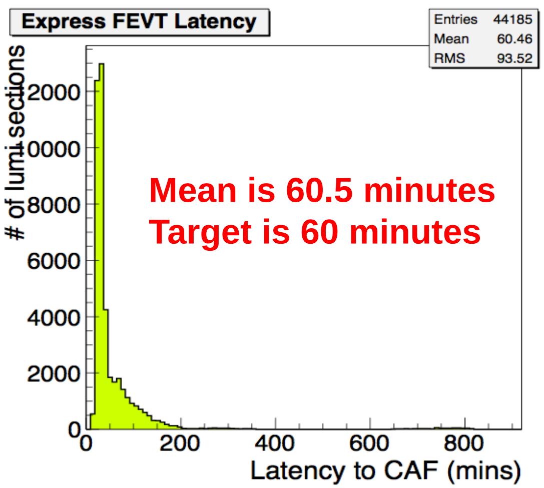


Few hundred Hz to mass storage

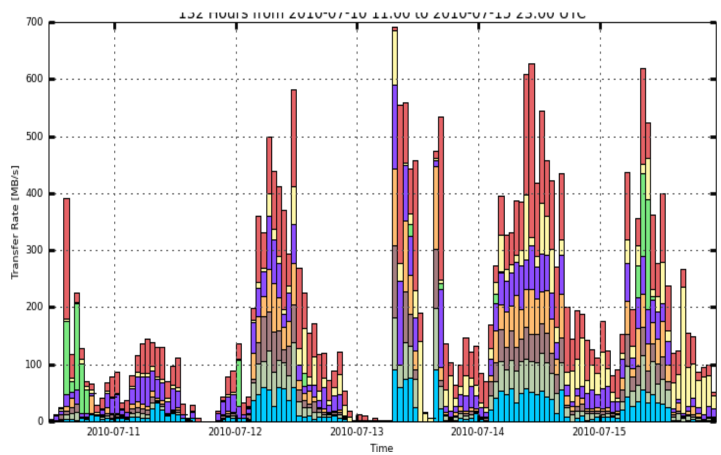
Imperial College London

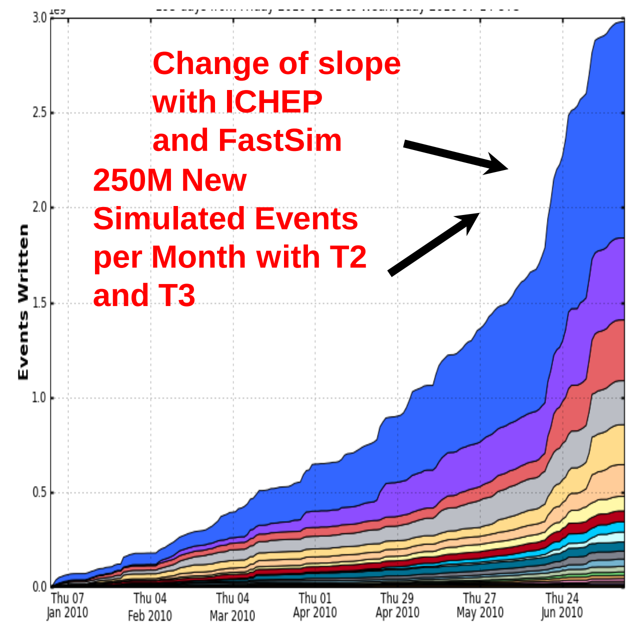
Data Transfers, CPU, Analysis (jobs, people,..) ...

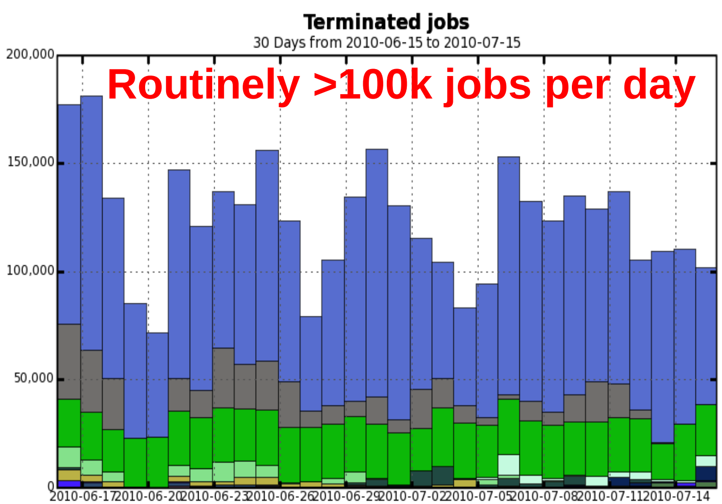
The whole offline and Computing organization + GRID infrastructure performed very well.

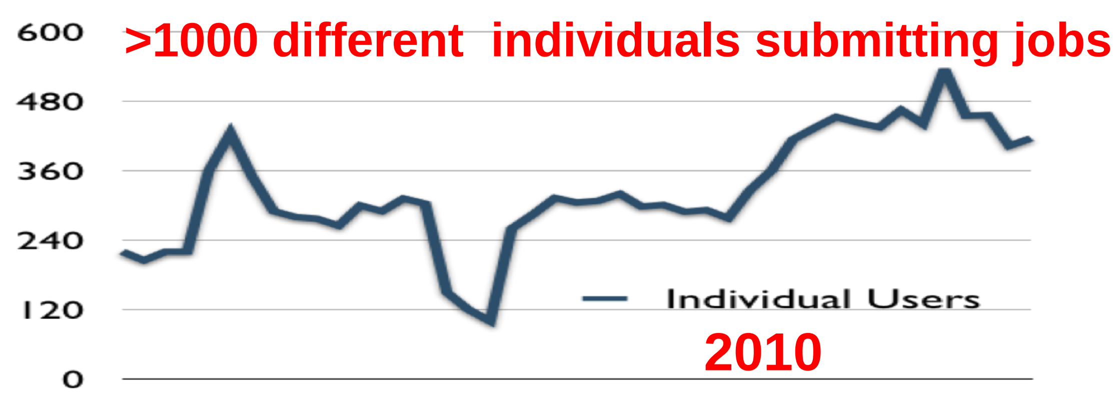


Hourly Peaks to Tier-1s of 600MB/s

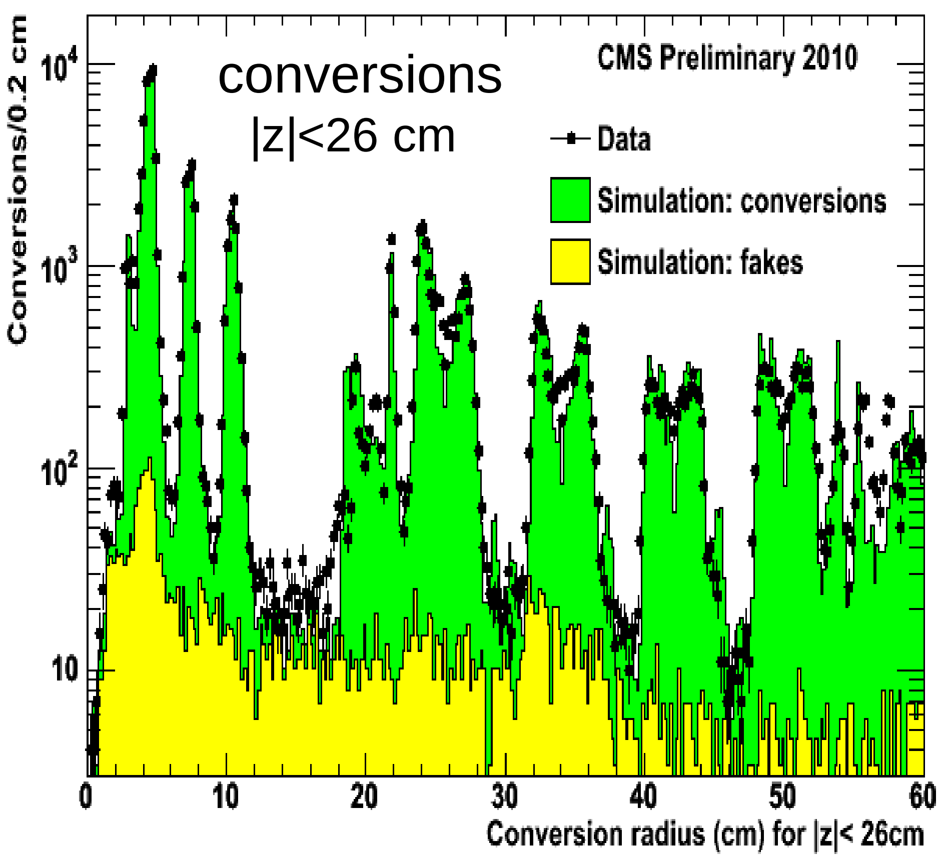


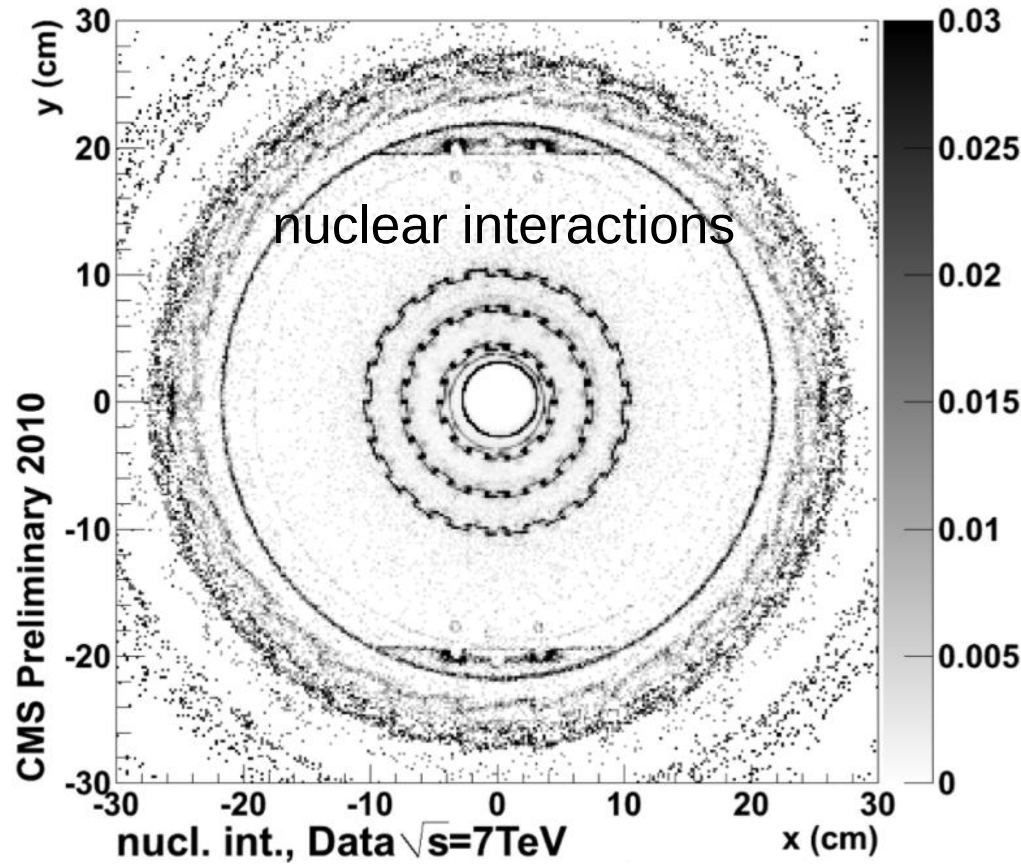






CMS is well-described in computer code
e.g. comparison in the Tracker

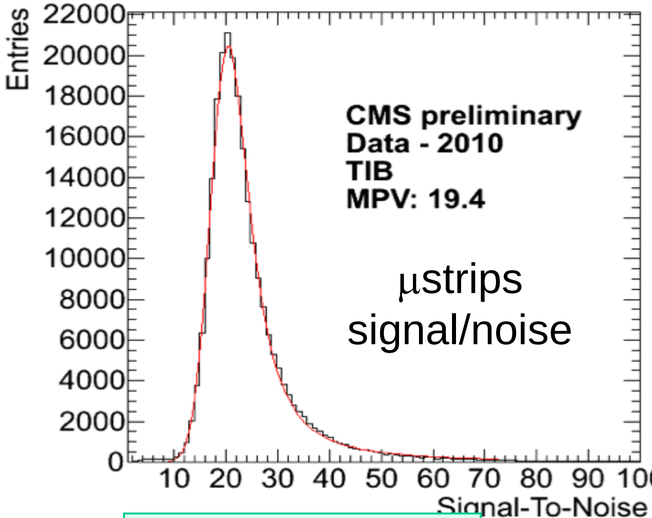


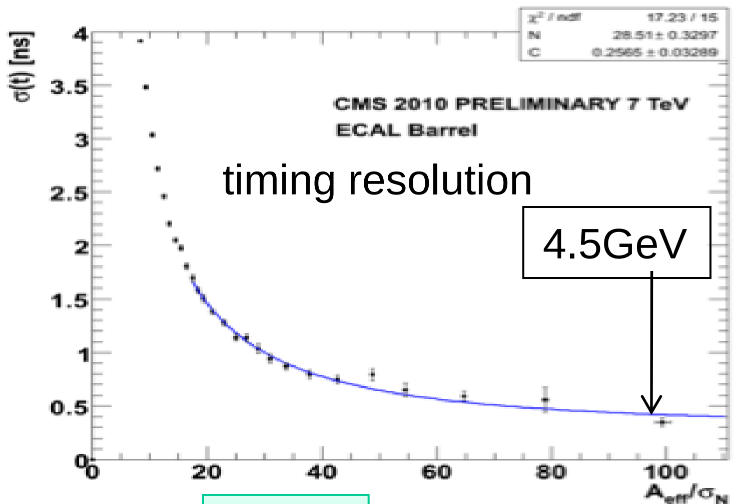


Monte Carlo events are simulated using GEANT-4 based model of the CMS detector and reconstructed & analysed using the same software used to process collision data

Imperial College London

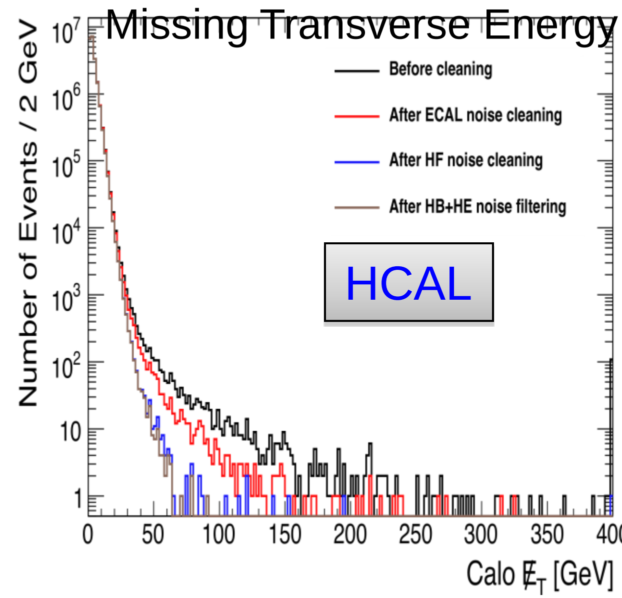
Examples of CMS Performance

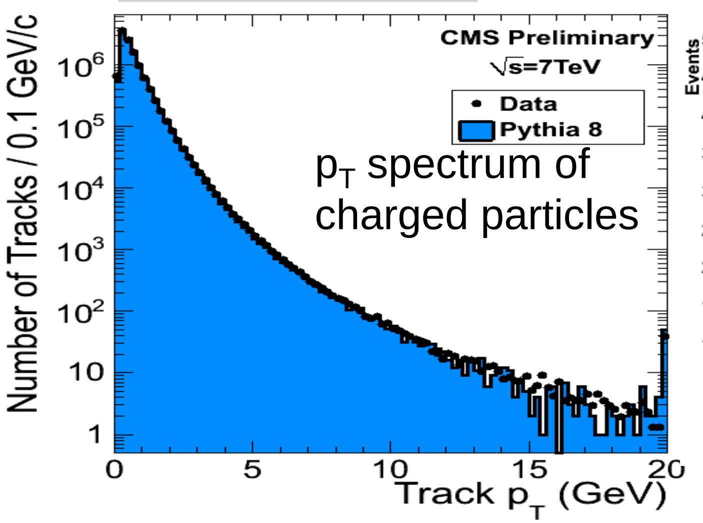


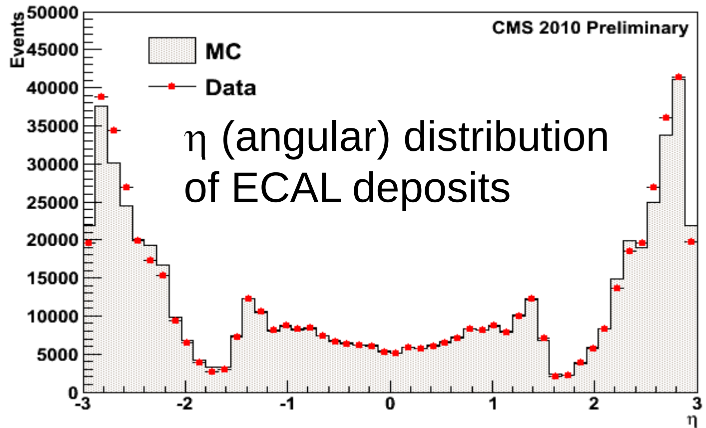


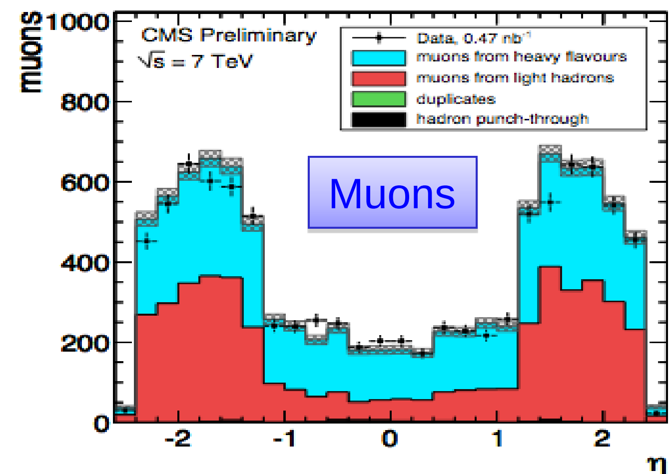
Silicon Tracker

ECAL









Physics "Commissioning" of CMS

2010 run 40 pb^{-1} collected

(corresponding to ≅ 3 trillion pp collisions examined)

Commissioning of Physics Objects very well advanced

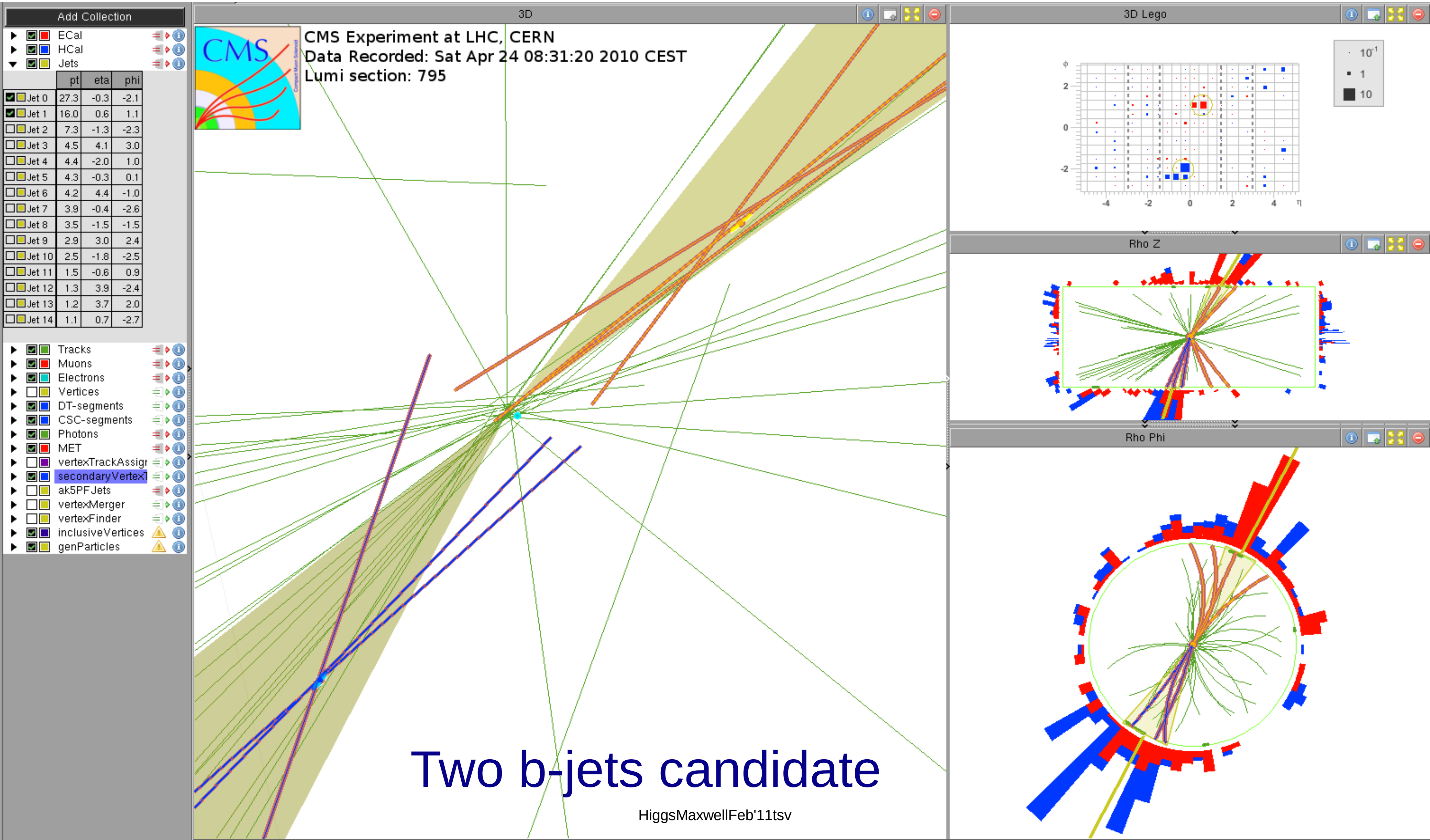
- **Charged track reconstruction, electrons, photons, muons and taus**
- **Jets & MET**
  - Refine noise filters, cleaning algo's
  - Optimization of jet algorithms for resolution, scale, lepton and γ fakes, etc.
- **Commission higher level algo's**
  - B tagging
  - Particle Flow

Also calibrate with known objects

- Study candles for leptons and photons
  - $\pi^0,\eta,..\Upsilon,\psi,\ldots$ initially to understand the detector, tracking, object id's
  - Extended to W, Z $\rightarrow$ leptons

Imperial College London

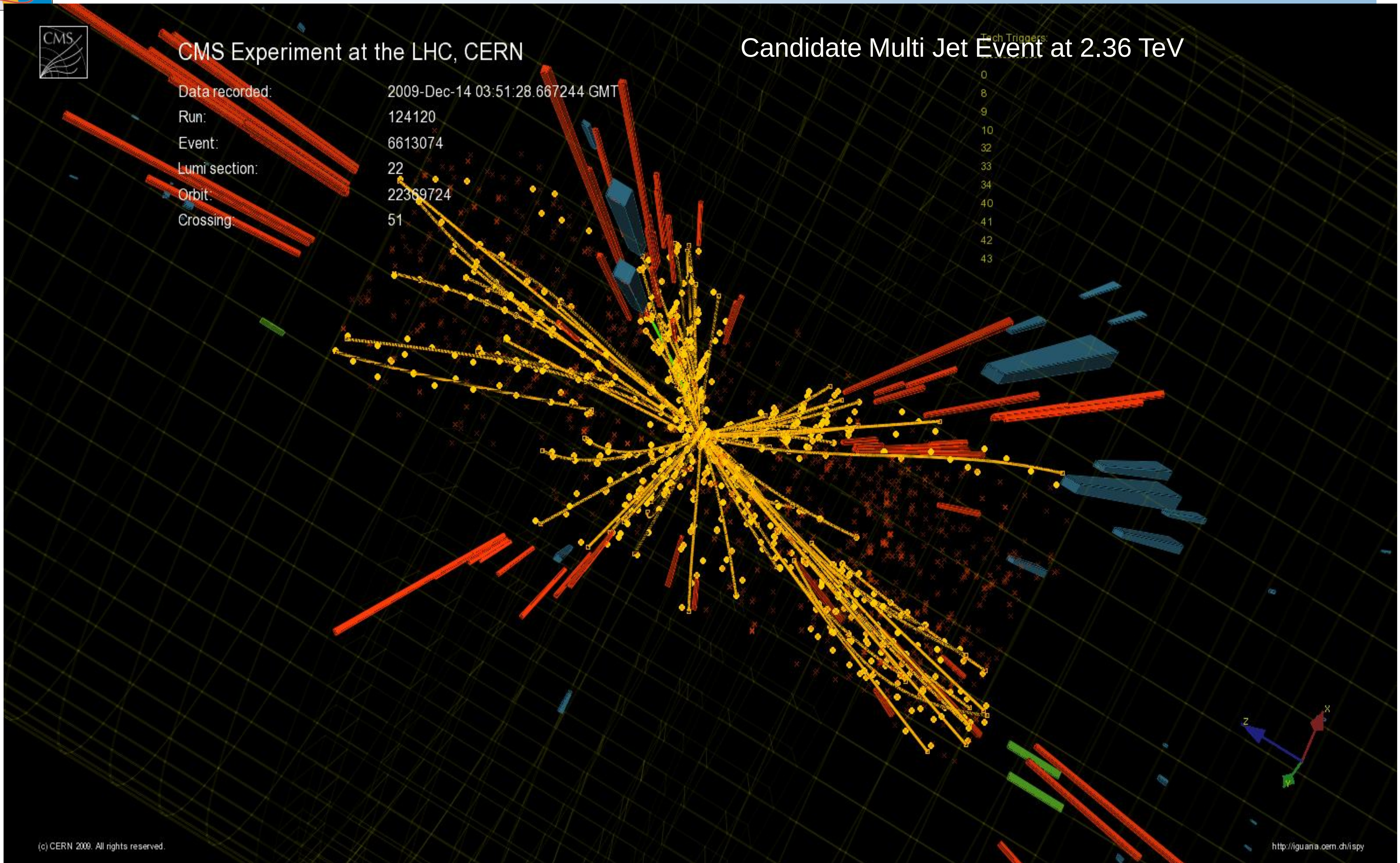
b-tagging



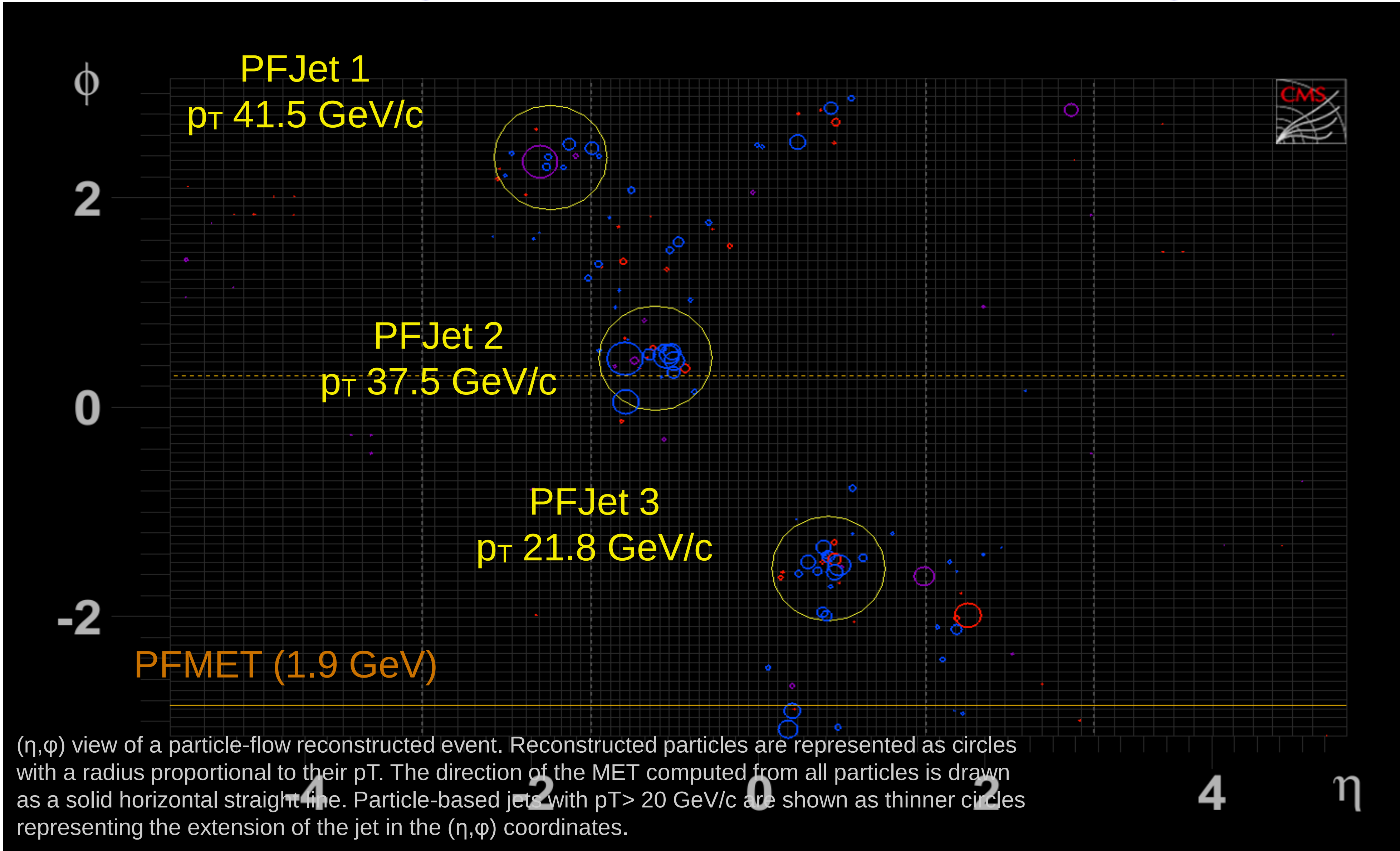
Two b-jets candidate

Imperial College London

Analysing Complex Events



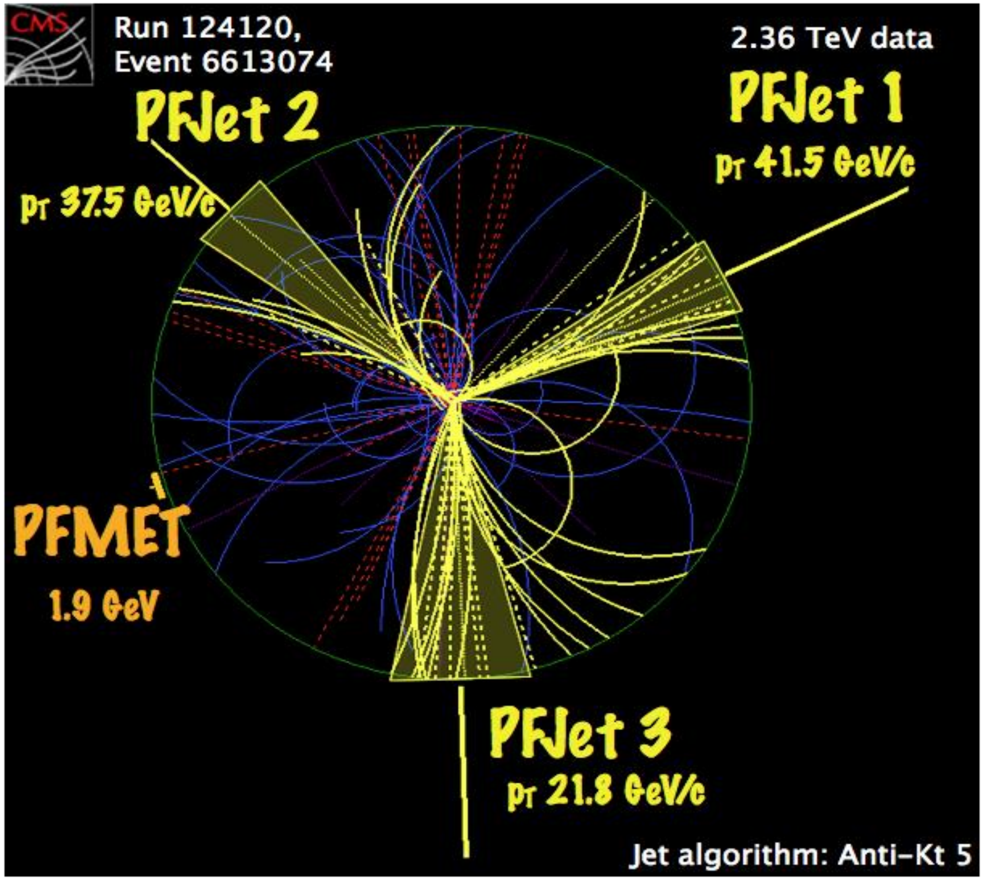
Analysing Complex Events Combining Calorimetry and Tracking

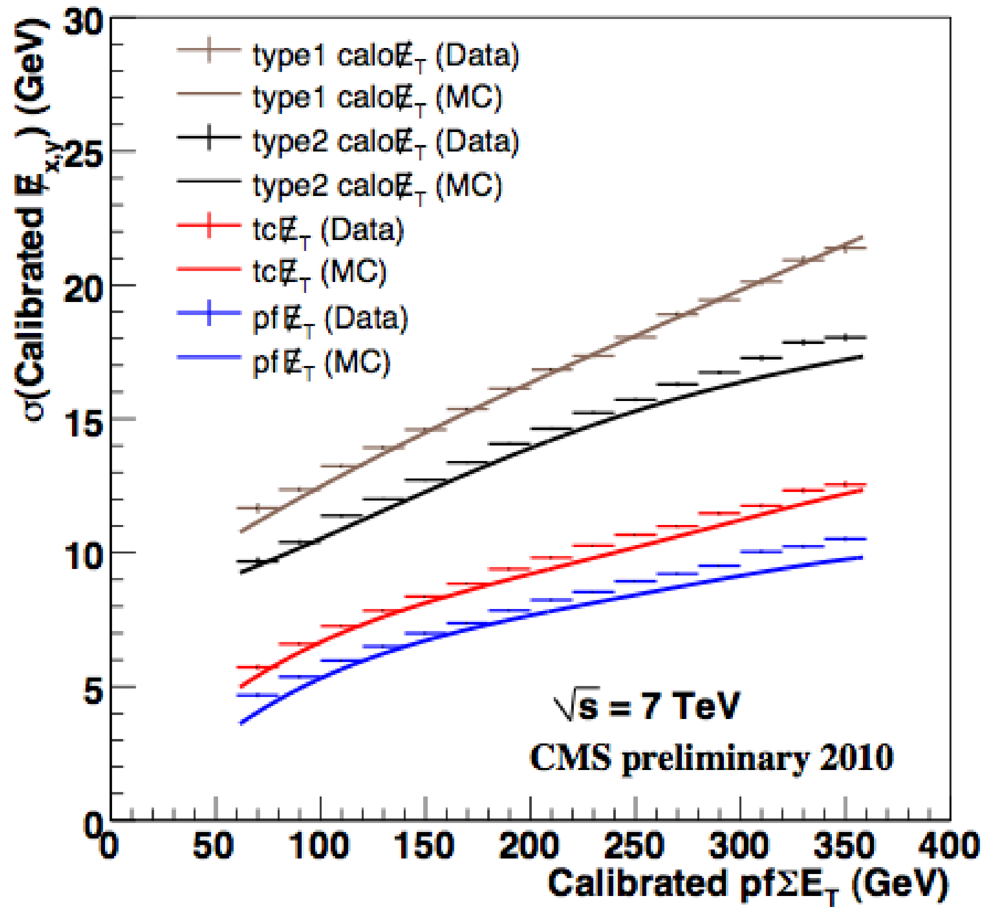


(η,φ) view of a particle-flow reconstructed event. Reconstructed particles are represented as circles with a radius proportional to their pT. The direction of the MET computed from all particles is drawn as a solid horizontal straight line. Particle-based jets with pT> 20 GeV/c are shown as thinner circles representing the extension of the jet in the (η,φ) coordinates.

Imperial College London

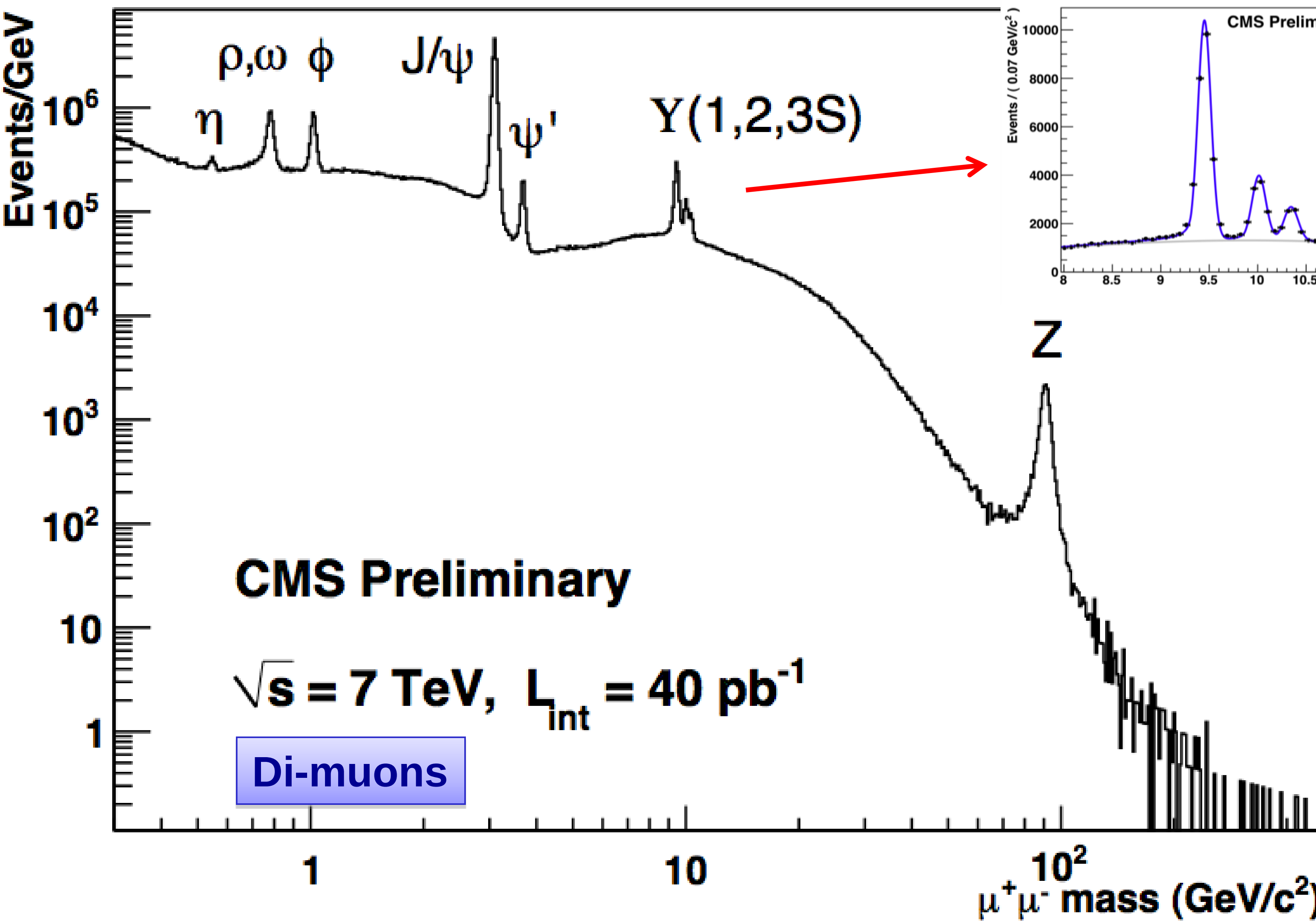
Missing E_T Peformance of CMS





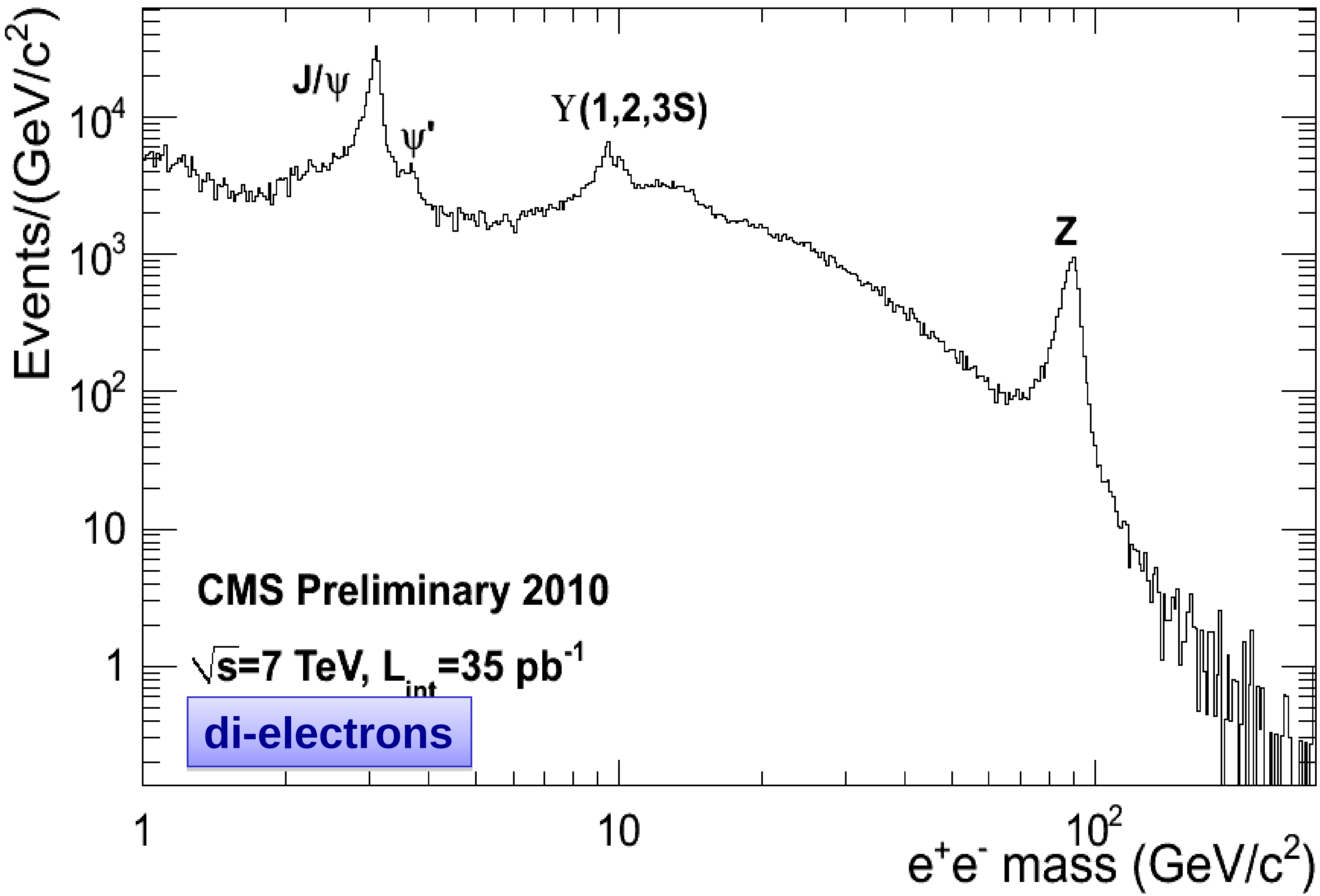
Excellent MET resolution and small non-Gaussian tails. Understanding all sources of erratic noise is very important for cleaning the distributions.

Muons in CMS



Events/GeV
ρ,ω
φ
J/ψ
η
ψ'
Y(1,2,3S)
Z
CMS Preliminary
√s = 7 TeV, L_int = 40 pb^-1
Di-muons
μ+μ- mass (GeV/c2)
CMS Preliminary, √s = 7 TeV
L_int = 40 pb^-1
|η^μ| < 1
σ = 67 MeV/c2
Events / (0.07 GeV/c2)

Electrons in CMS



The Physics Reach - Startup

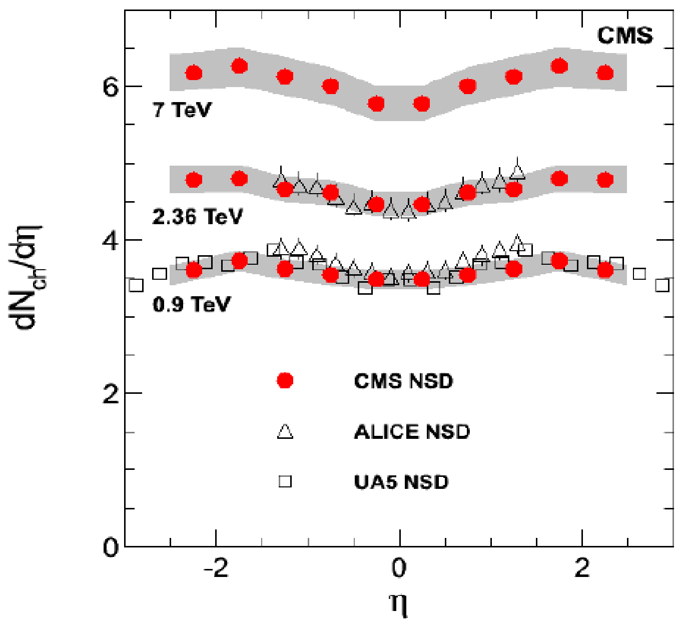
- **A number of signals both from the SM and from beyond are visible over a large part of the parameter space with a fraction of a fb^{-1}.**
  - **SUSY: 500 GeV sparticles: large production cross section, spectacular signatures.**
  - **Extra dimensions: significant reach for Z′ etc**
  - **Compositeness: reach multi-TeV very fast**
  - **(Higgs enters a little later with higher integrated luminosities)**

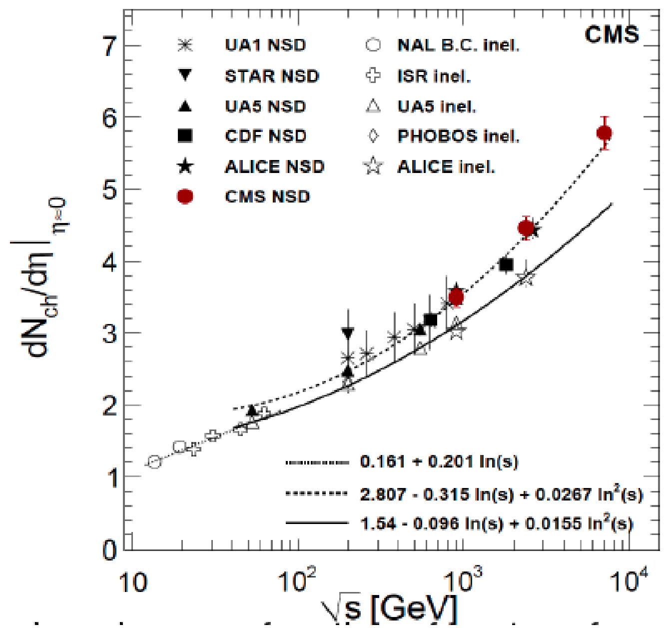
- **Of course, all these signals can be claimed after understanding Standard Model channels (as backgrounds)**
  - **QCD jets, prompt γ's, J/ψ, y, ….**
  - **b-quark production**
  - **Drell-Yan, W+Z production (plus jets); multi-IVB (WW,WZ,ZZ)**
  - **Top quark**

Imperial College London

Inelastic pp collisions: Characteristics

- **Minimum bias events**
  - Non single-diffractive event selection (correction 6%→2.5% systematic error)
- Soft QCD (P_T threshold on tracks: 50 MeV)



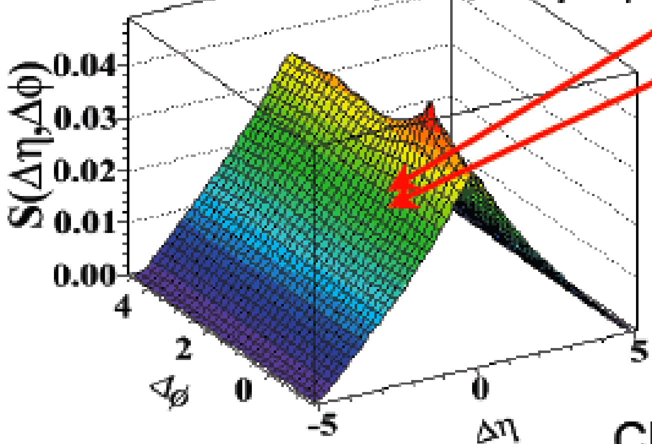


- Particle density in data rises faster stronger than in model predictions. Tuning effort of MC generators....
- Marginal impact on high-P_T physics

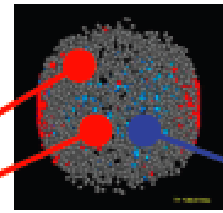
Two-particle Correlations I

Signal distribution:

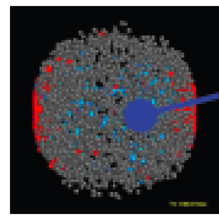
$$S_N(\Delta\eta,\Delta\varphi)=\frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Event 1

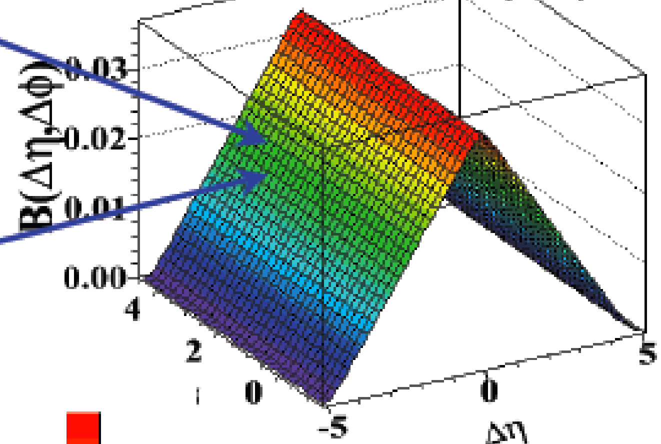


Event 2



Background distribution:

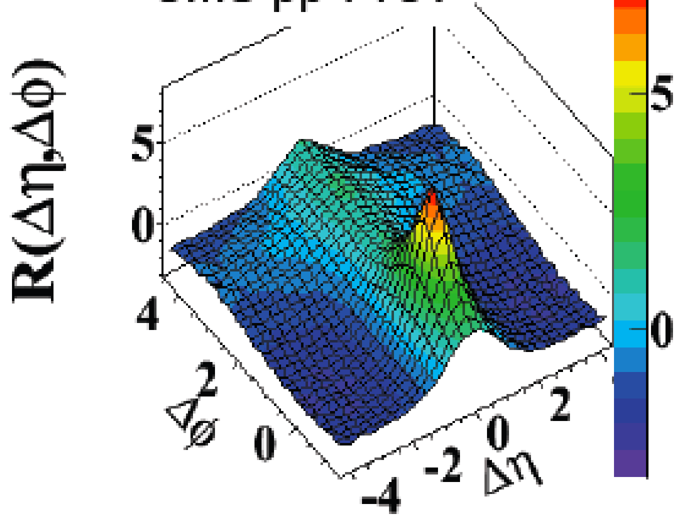
$$B_N(\Delta\eta,\Delta\varphi)=\frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



$$\Delta\eta=\eta_1-\eta_2$$

$$\Delta\varphi=\varphi_1-\varphi_2$$

CMS pp 7TeV



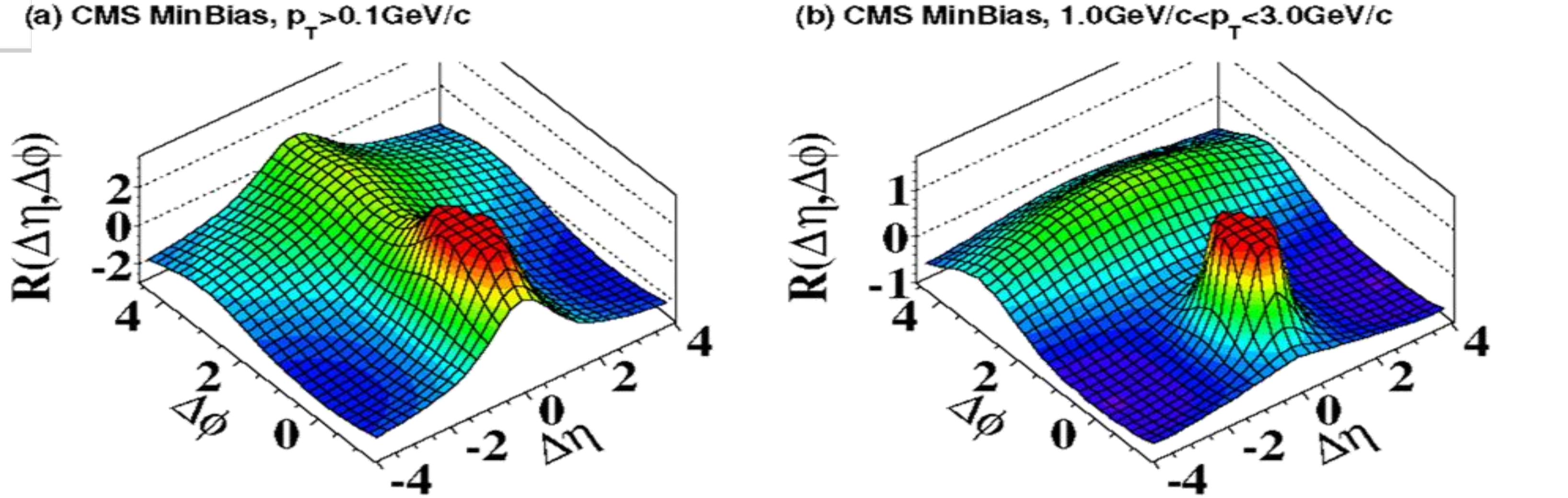
$$R(\Delta\eta,\Delta\varphi)=\left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)}-1\right)\right\rangle_N$$

p_T-inclusive two-particle angular correlations in MinBias collisions

Two-particle Correlations II

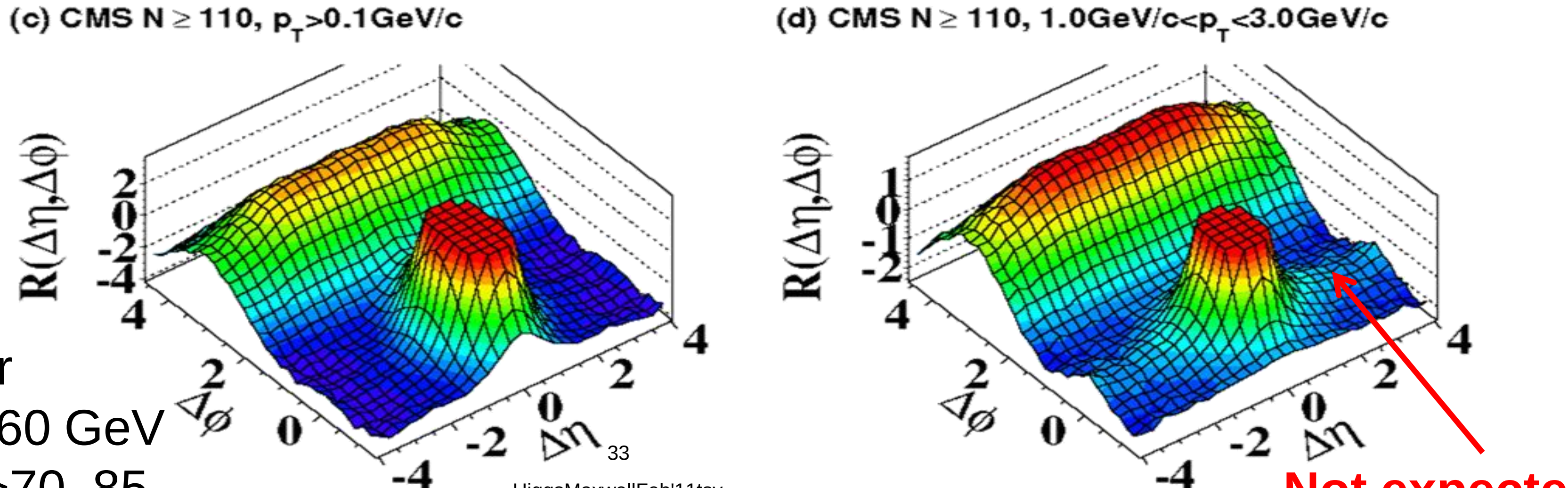
arXiv:1009.4122

Min Bias



p_T > 0.1 GeV/c **1.0 < p_T 3 GeV/c**

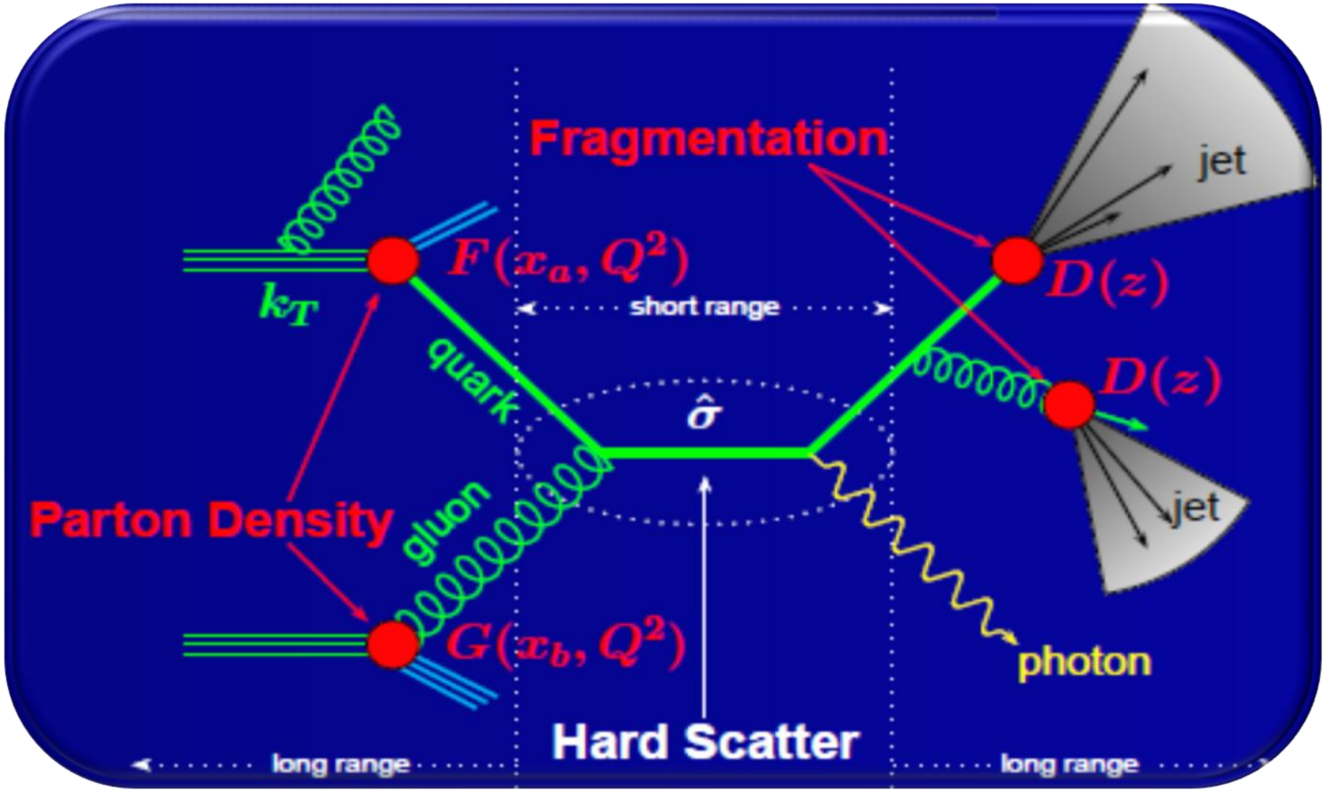
N > 110



Not expected

980 nb^{-1}
Special Trigger
Calo Sum E_T>60 GeV
$N_{pix\ trk}$ (online)>70. 85

The Hard Scatter



Jet Algorithm
Anti-k_T, R=0.5

Typical of hard scatter
e, μ, γ : E_T > 20 GeV
Jets: E_T > 20 GeV

Isolation
E_T,p_T < thresh in cone

$$\Delta R \equiv \sqrt{\Delta\eta + \Delta\phi}$$

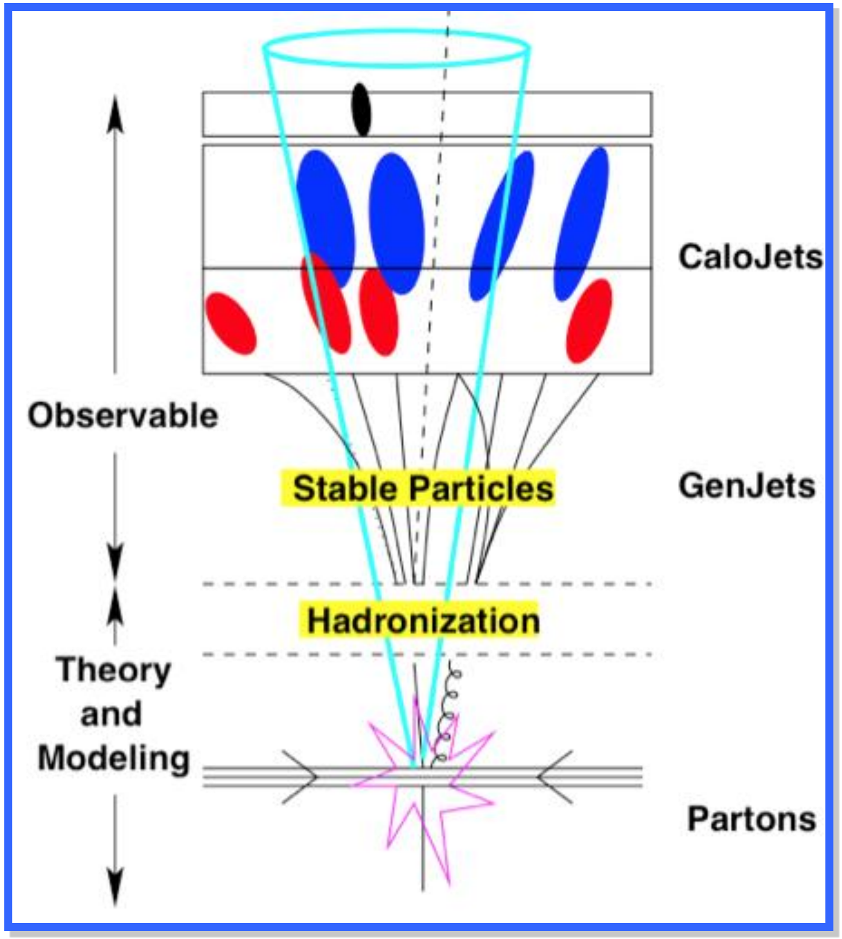
ΔR ~ 0.3

H_T - scalar sum of E_T of all jets with e.g. P_T > 30 GeV/c
S_T - scalar sum of E_T of N individual objects (jets, e, μ, γ) with e.g. E_T > 50 GeV/c

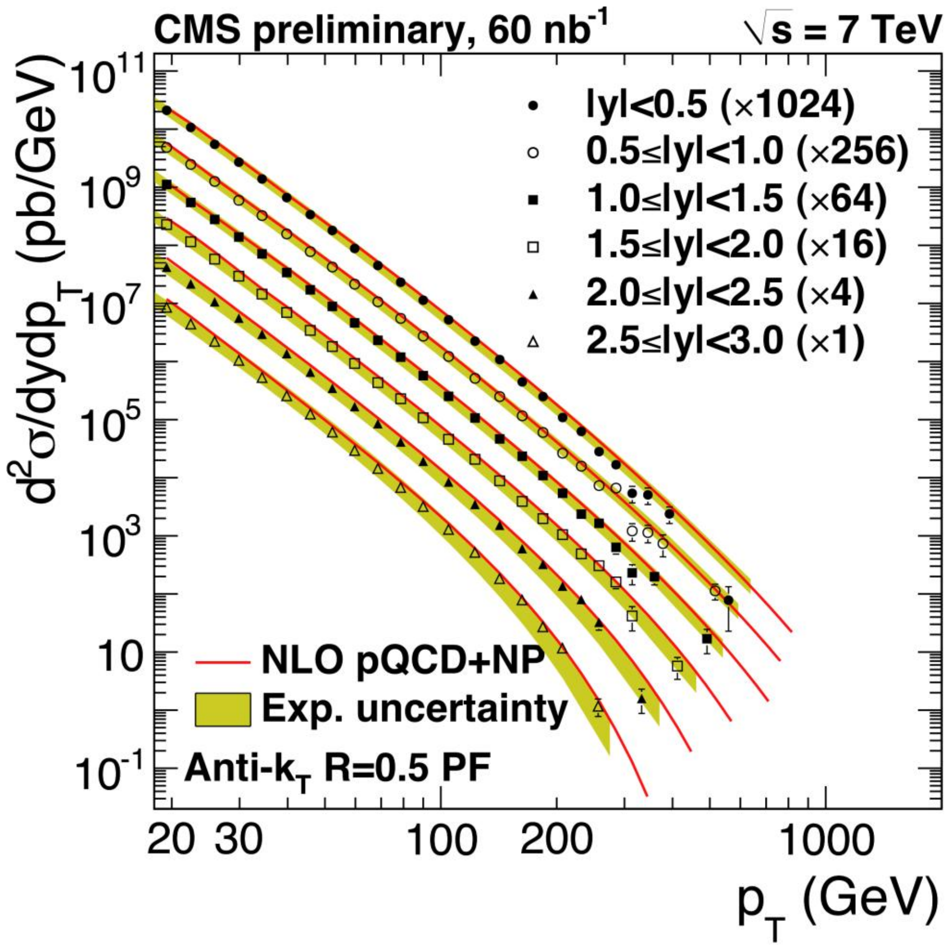
Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}} \qquad \alpha_T = \frac{E_{T2}}{M_T} \leq 0.5$$

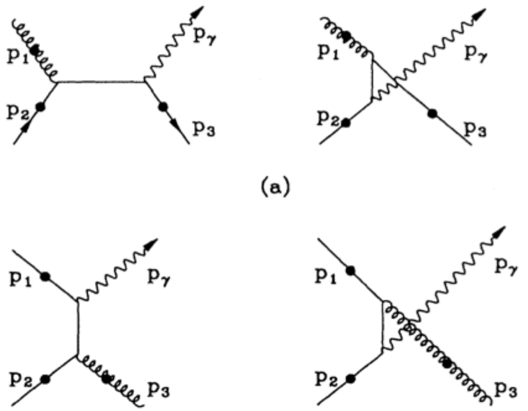
The Hard Scatter: Inclusive jet production

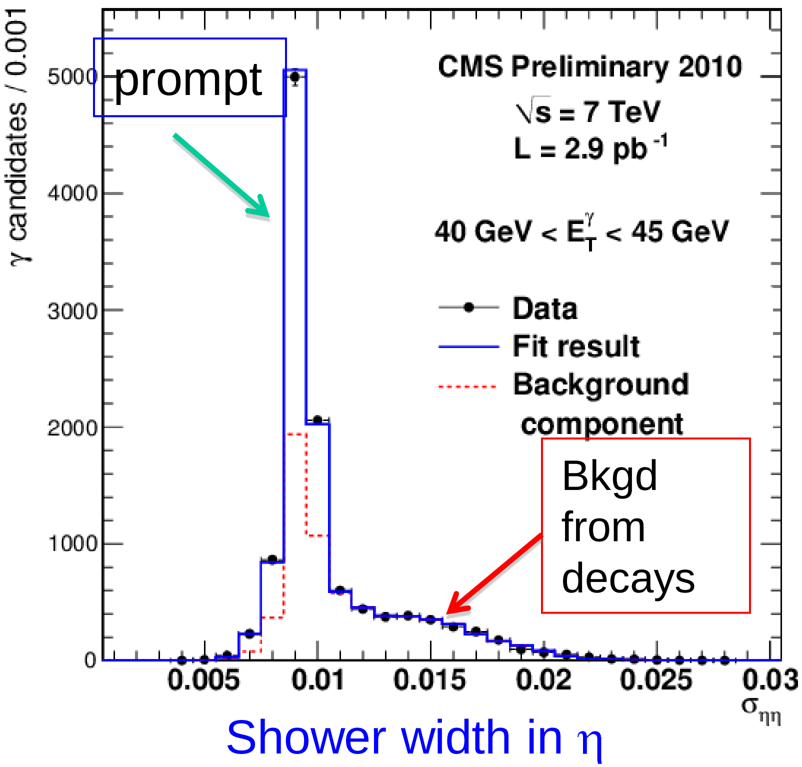


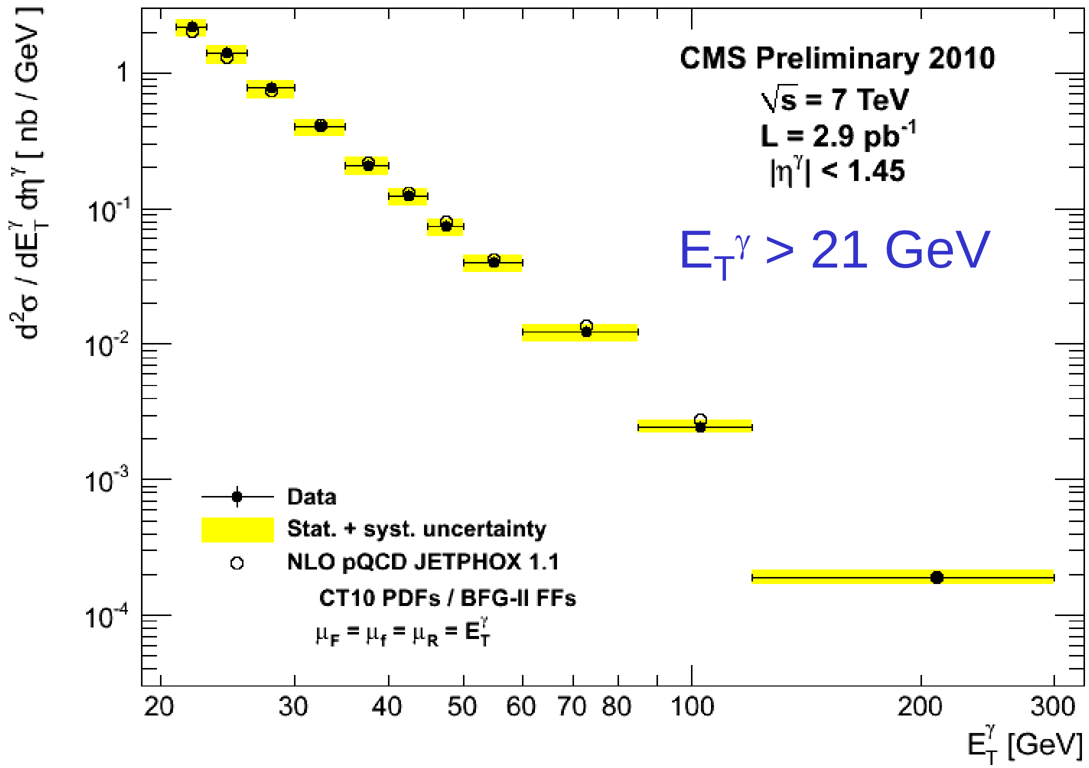
The measured jet production rate is in good agreement with theoretical predictions (within errors).

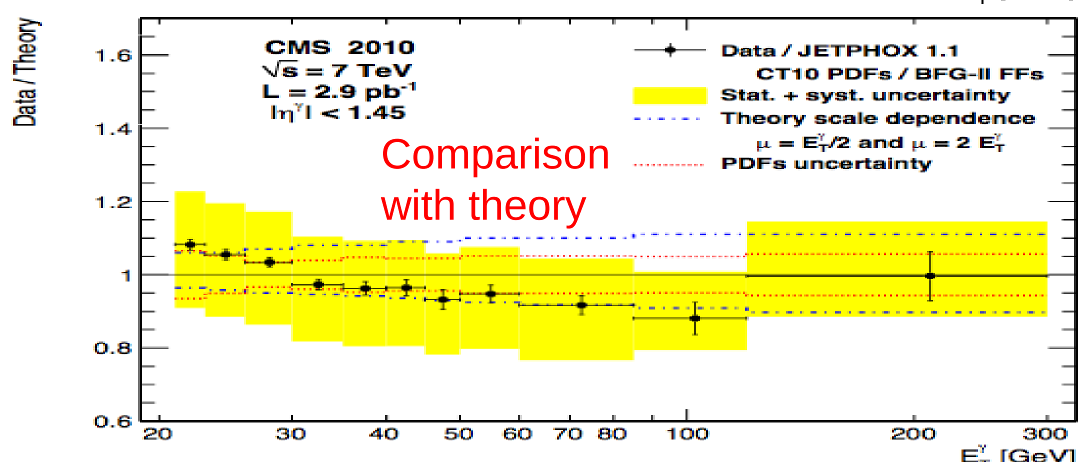


Prompt Photon Production



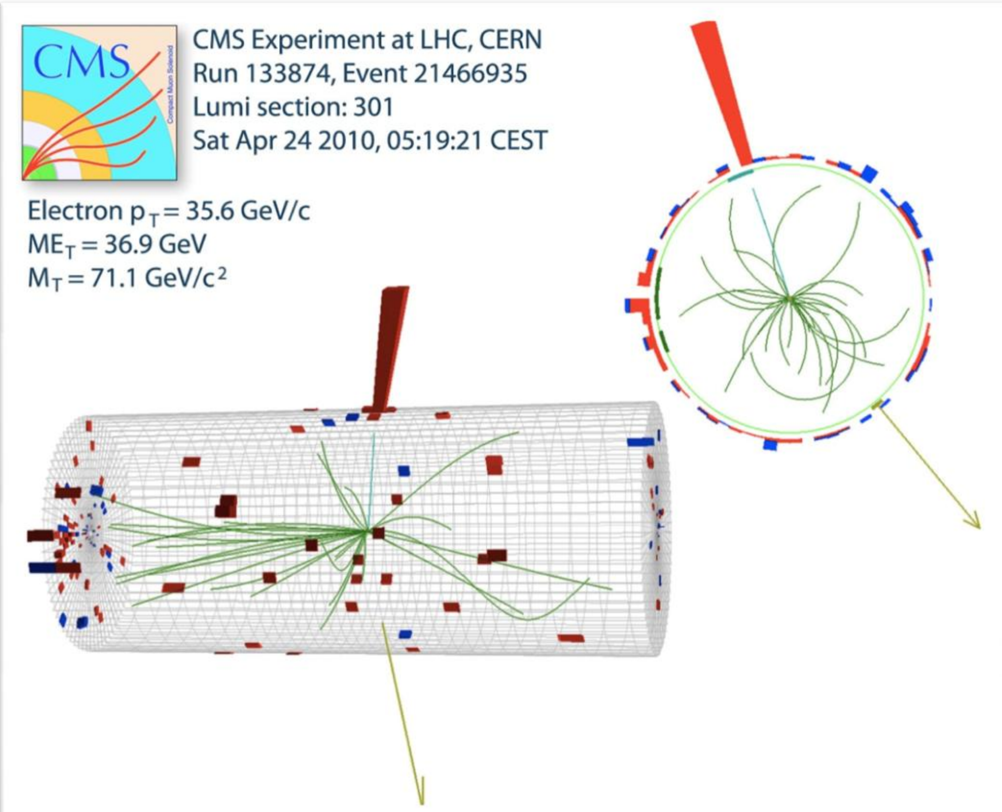




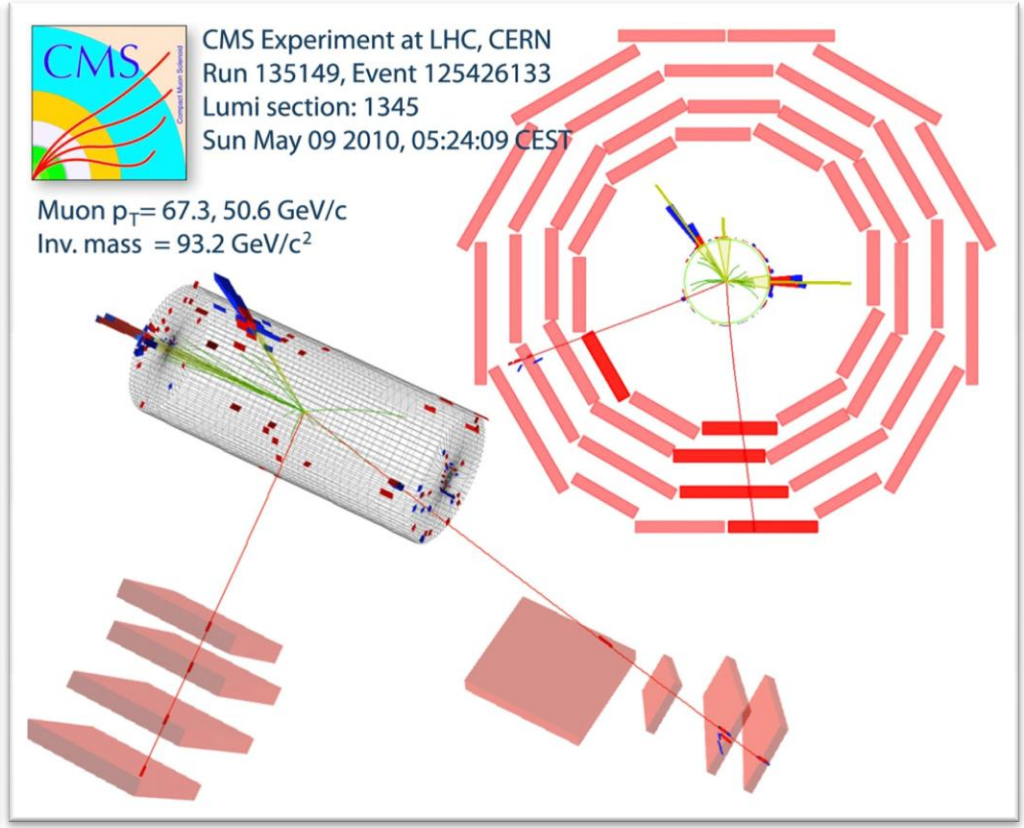


Intermediate Vector Bosons

$W \rightarrow e\ \nu$



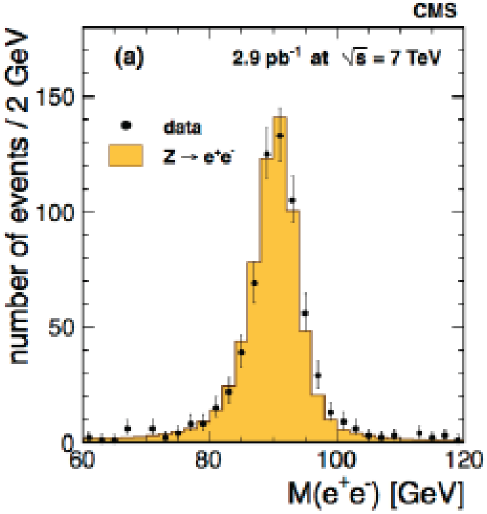
$Z \rightarrow \mu\ \mu$

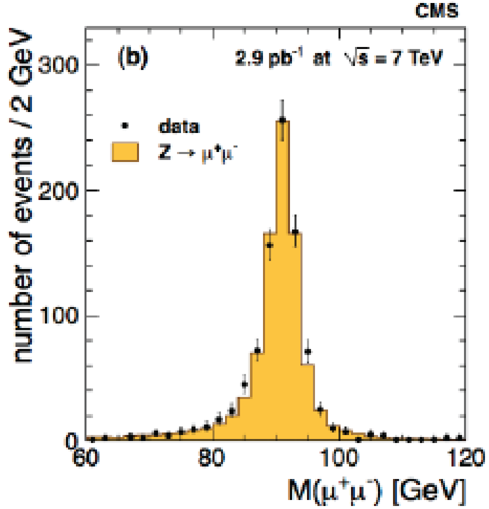


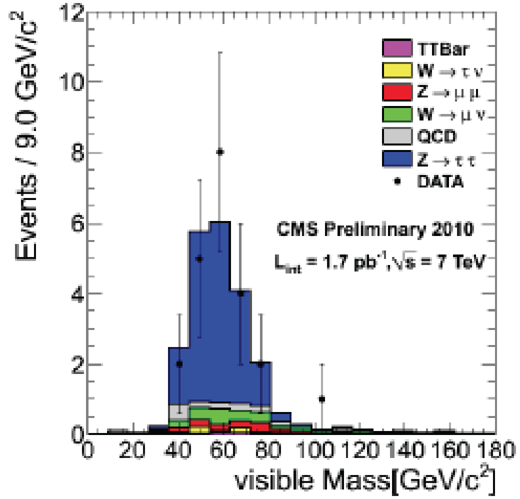
Intermediate Vector Boson production $W^{\pm}$ and Z^0

	electron(s)	muon(s)	tau(s)

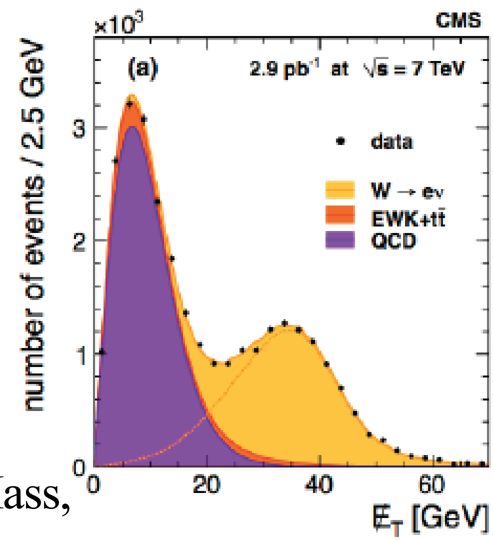
Z Boson

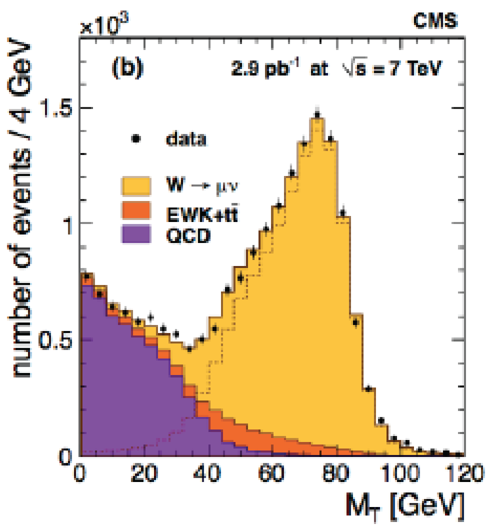


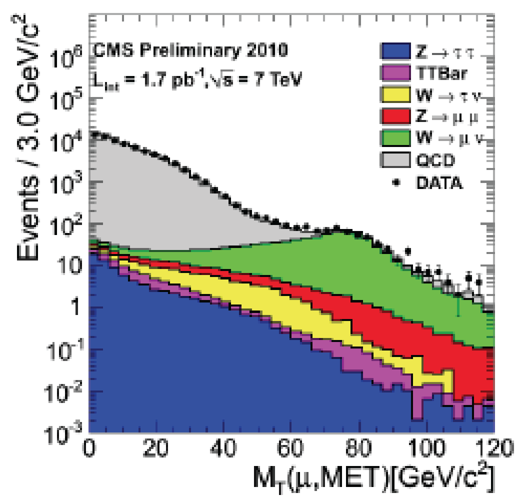




W Boson





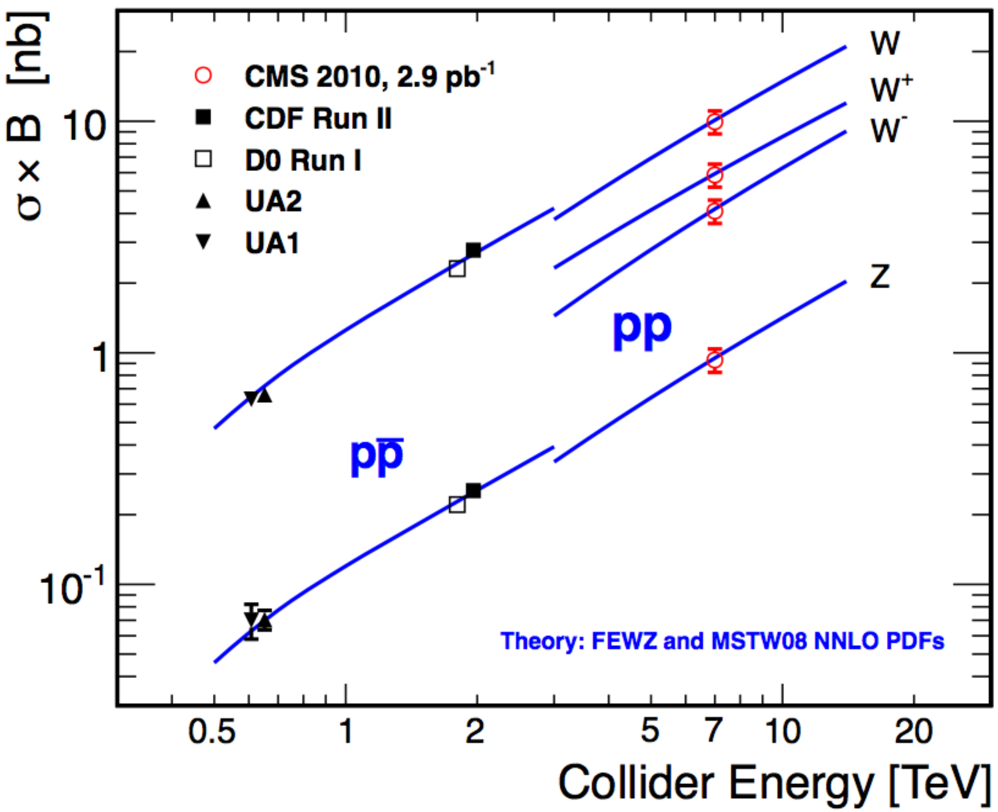


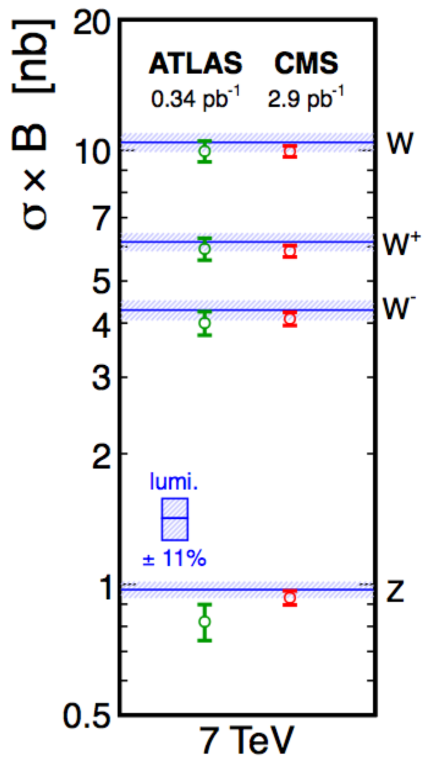
Transverse Mass,

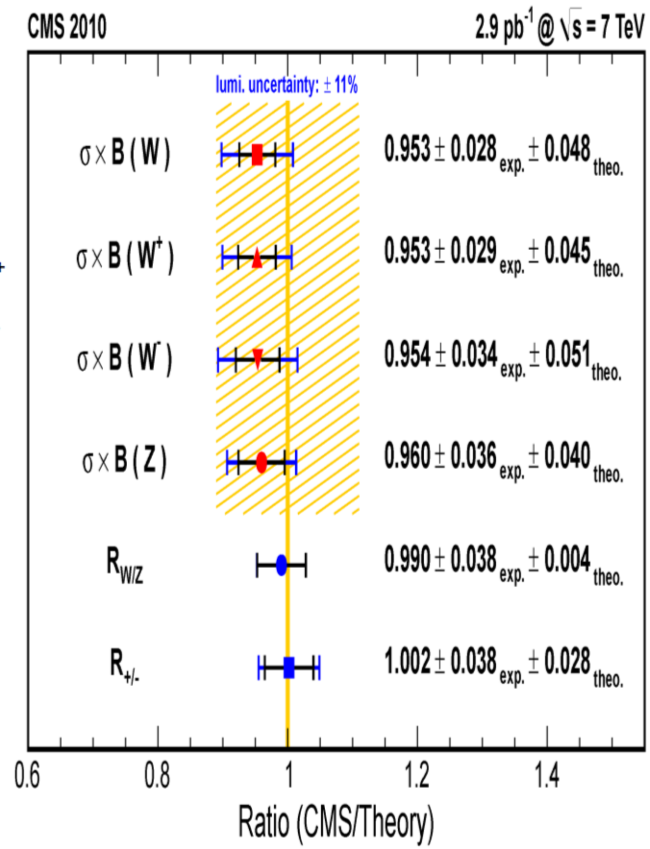
$$M_T = \sqrt{2E_T^{\mu} E_T^{miss}(1 - \cos\Delta\phi_{e,miss}}$$

$W^{\pm}$, Z^{o} production: Confronting Predictions

arXiv:1012.2466

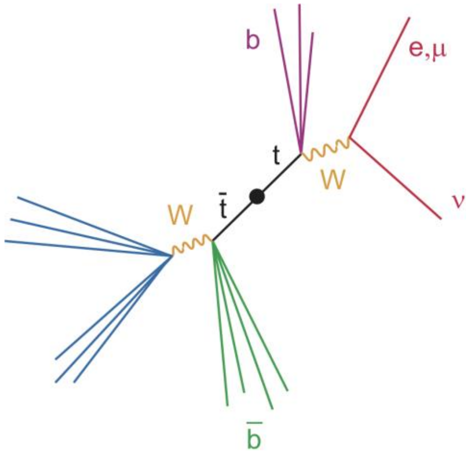


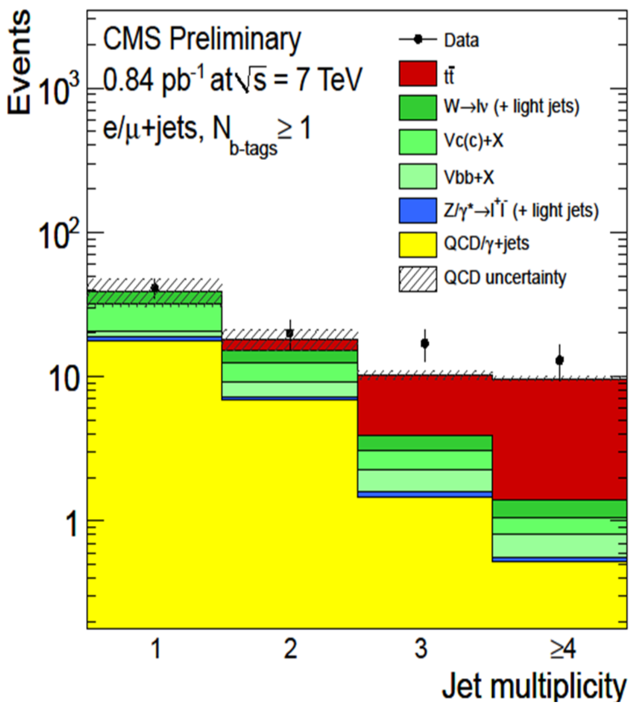


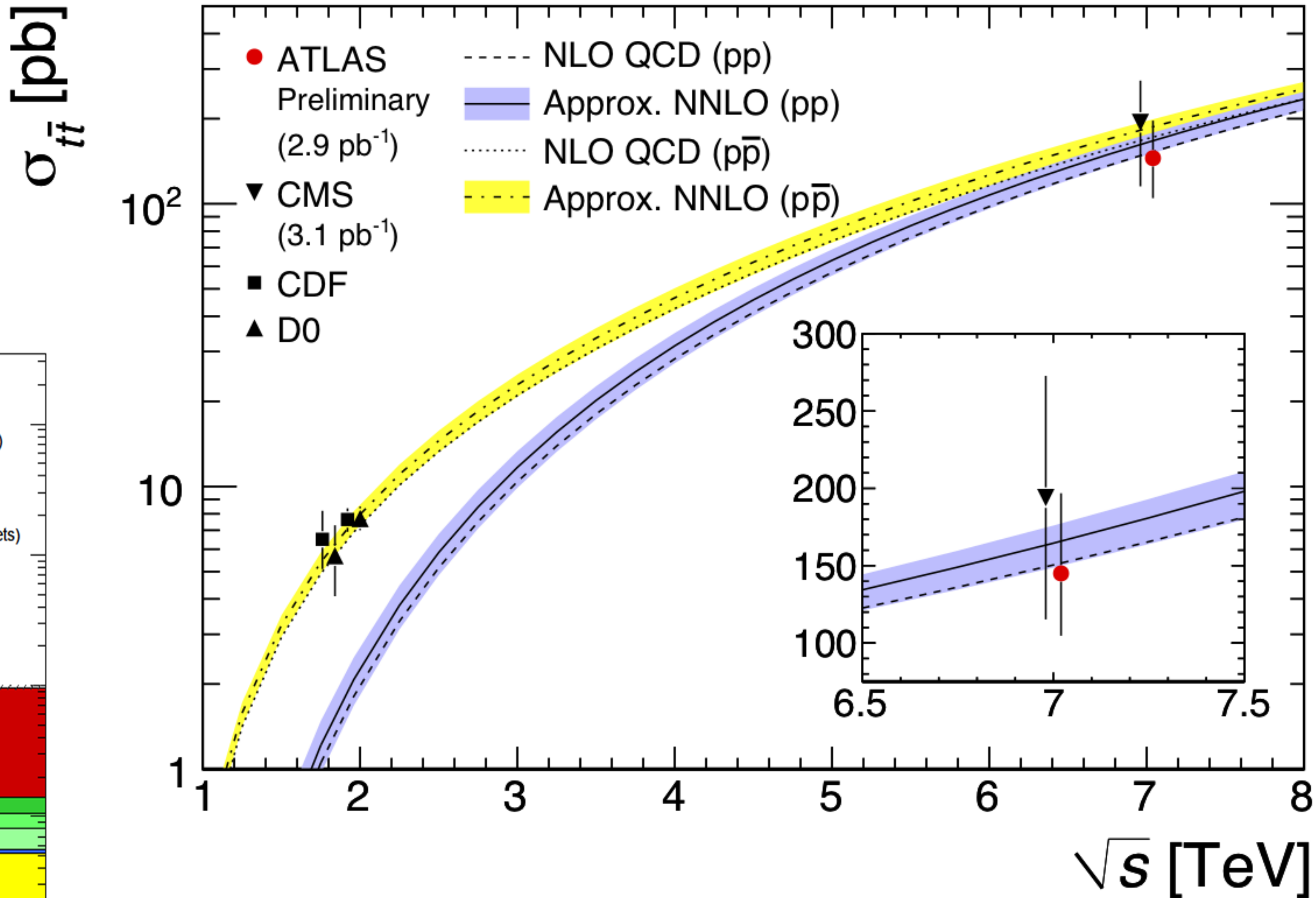


$$\sigma(pp \rightarrow WX) = \frac{N_{Signal}}{A_W \times \epsilon_W \times \int L dt}$$

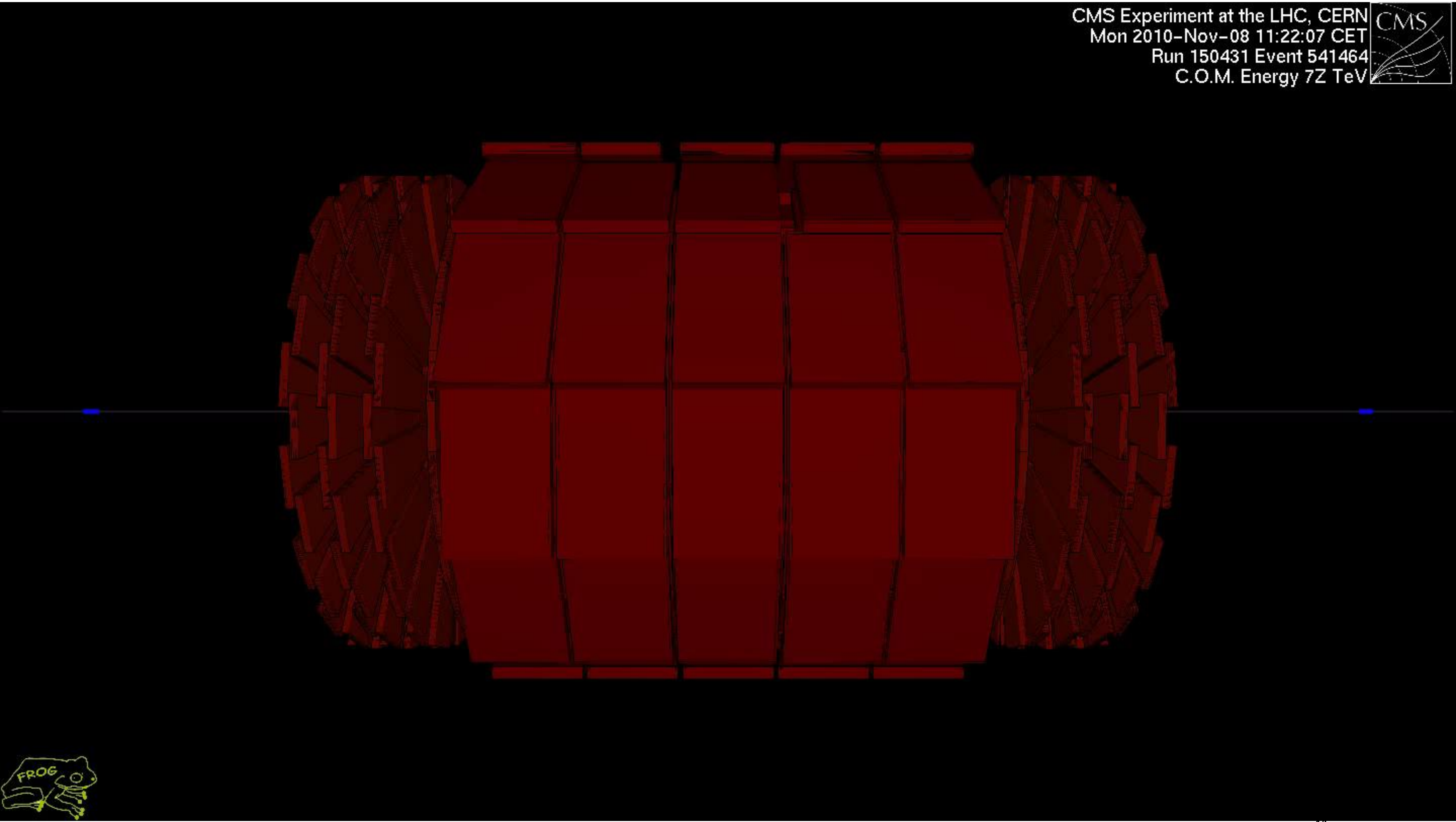
Top quark production: Confronting Predictions







Central Heavy Ion Event

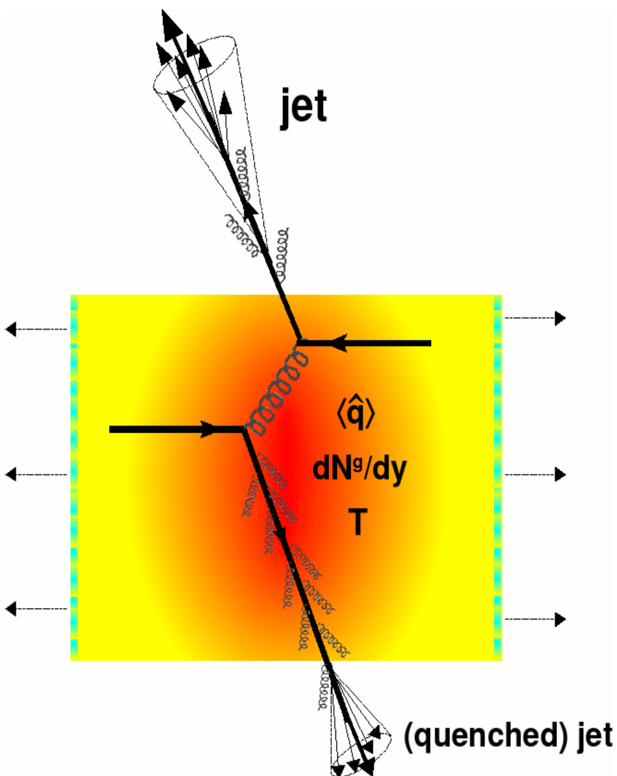


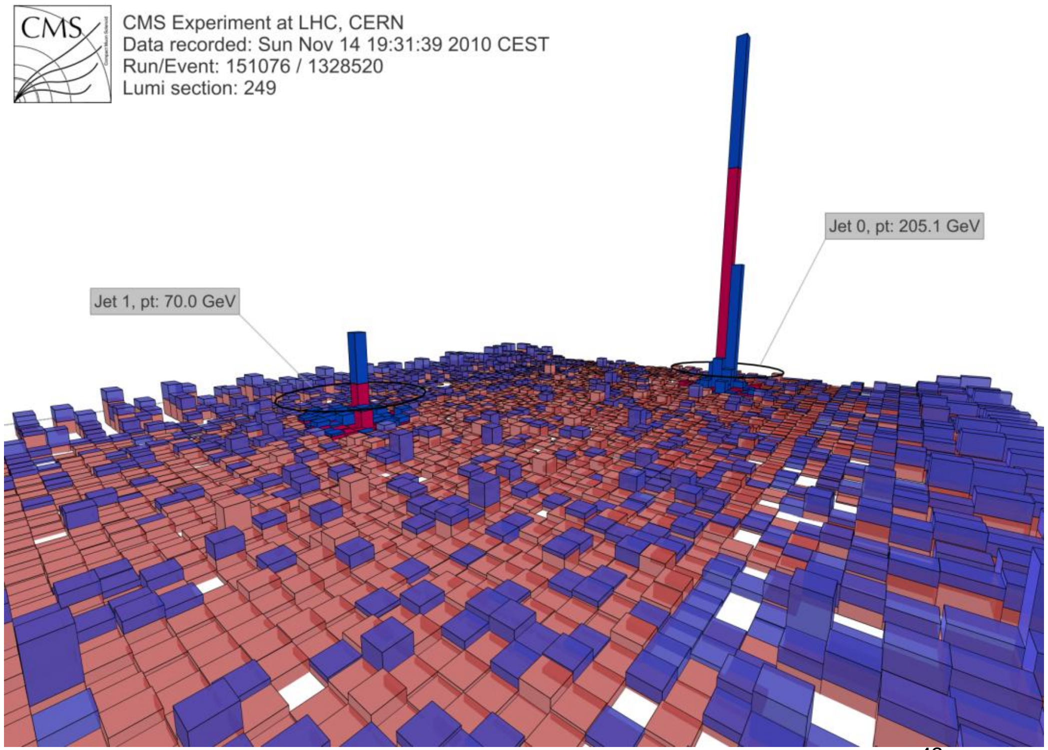
Quarks and Gluons in a Dense Medium

• Fragmentation of quarks and gluons into jets is strongly modified as they traverse the quark-gluon medium created in head-on (central) high energy Pb-Pb collisions - labeled **"jet quenching"**.

• Such effects were observed in at RHIC for single particle spectra and particle correlations.

• At the LHC one can fully reconstruct the jets!

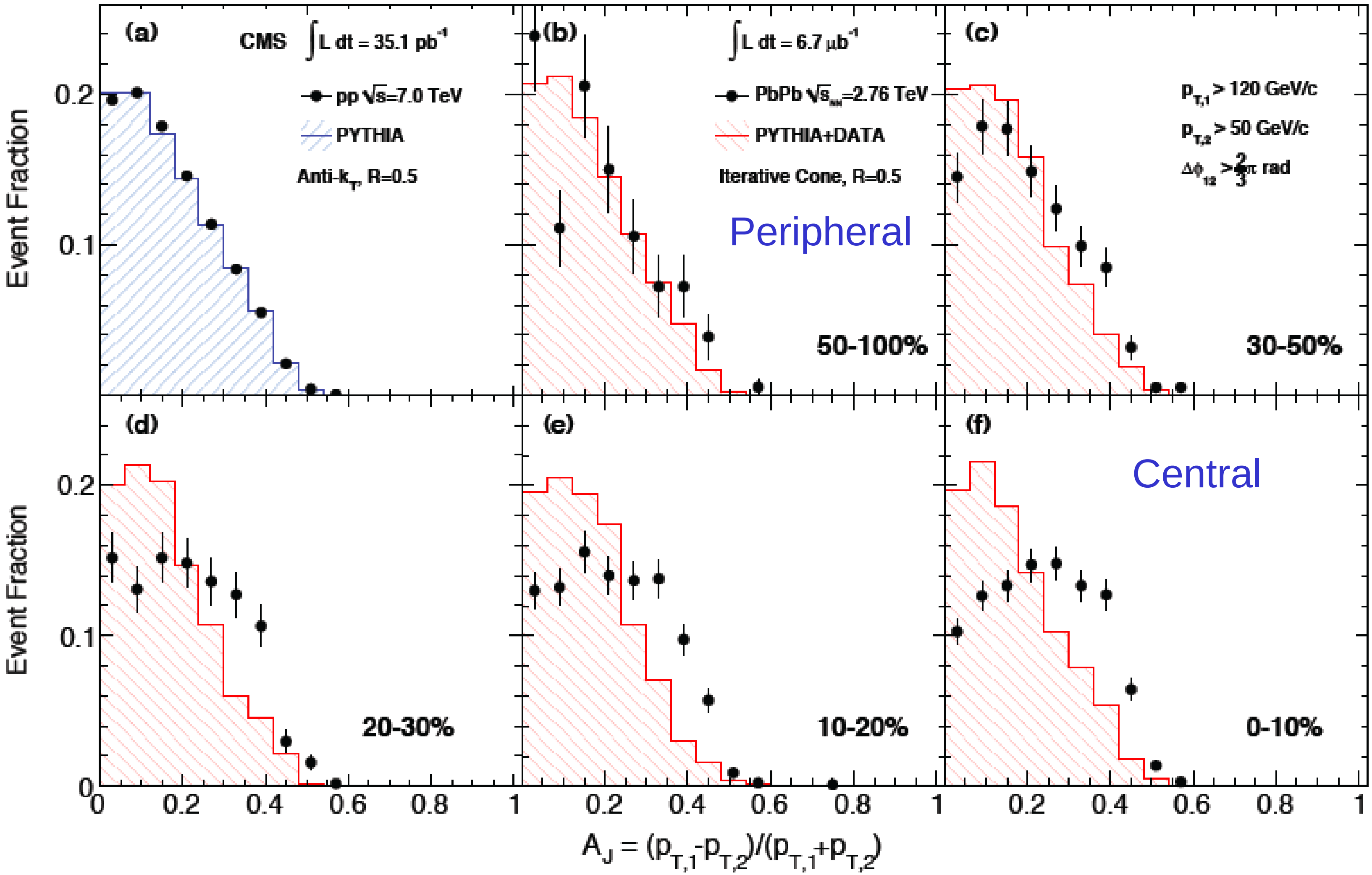




Quarks and Gluons in a Dense Medium

p_T (leading jet (1)) > 120 GeV,
p_T (sub-leading jet (2)) >50 GeV

Asymmetry $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$



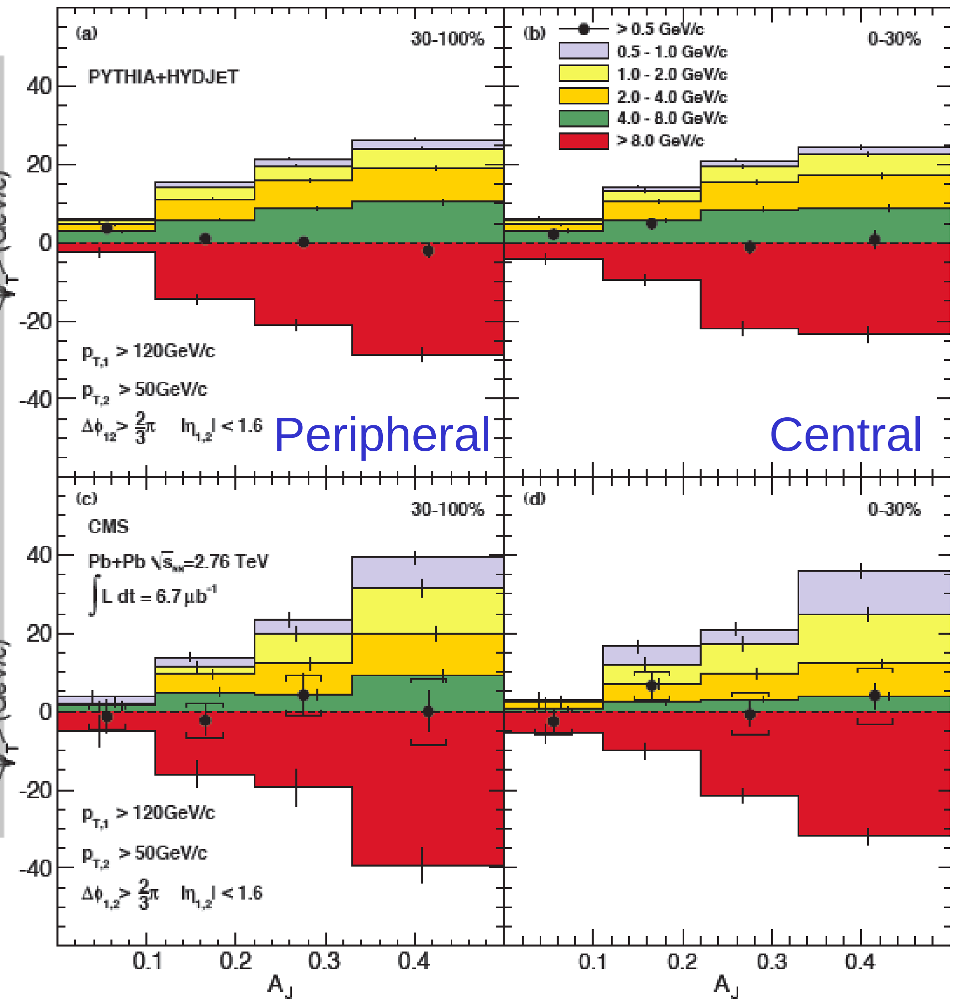
Imperial College London

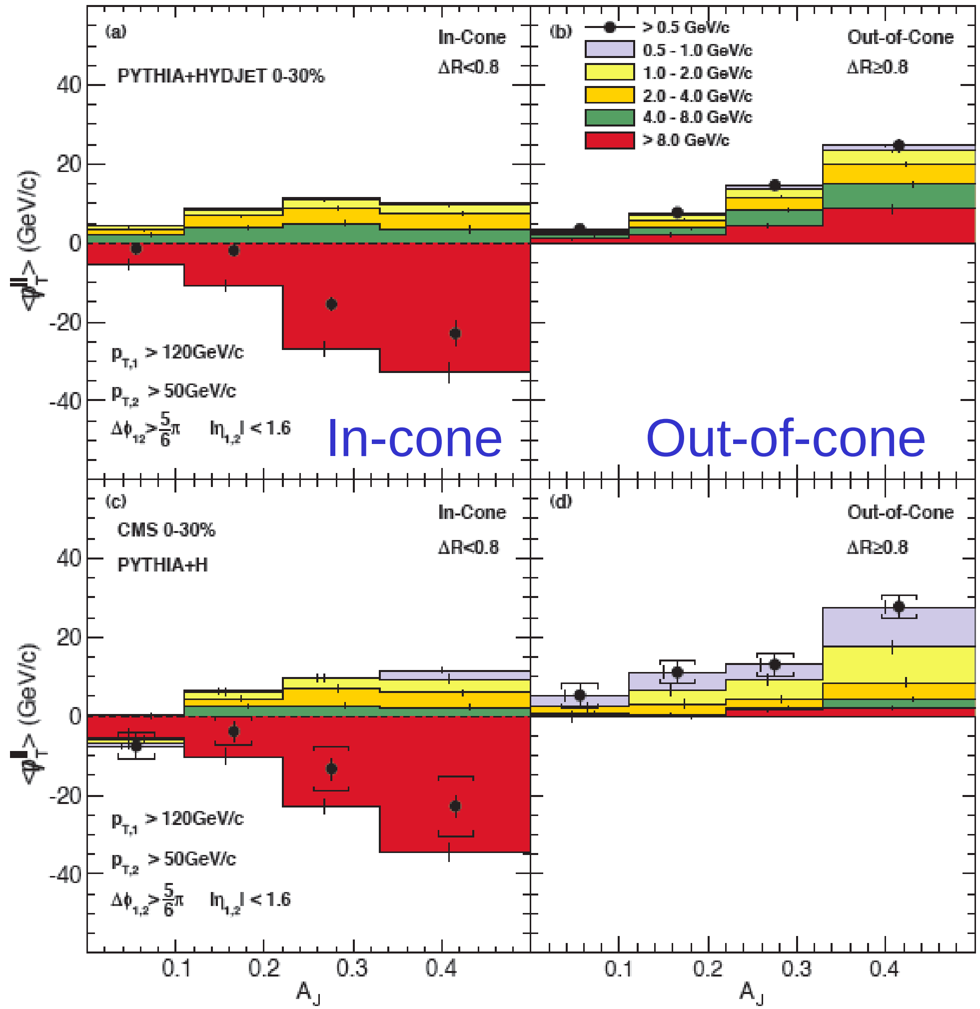
Quarks and Gluons in a Dense Medium
Where does the 'quenched' energy go?

A large fraction of the negative imbalance from high p_T is recovered in low momentum tracks

Out-of-cone contribution is carried almost entirely by tracks with $0.5 < p_T < 4$ GeV/c

$$\not{p}_T^{\parallel} = \sum_{\mathrm{Tracks}} -p_T^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$





Start Exploring the Unknown!

Numerous possibilities (examples below)

Sub-structure

Exotica:

- **Leptoquarks**
- New gauge bosons (W', **Z'**)
  - New resonances (W-Z-like)
- Fourth generation (b')
- Large Extra Dimensions
- **Microscopic Evaporating Black Holes**

Supersymmetry

- Squarks and gluinos
  - **Decays into jets and MET**
  - Decays into photons (GMSB)

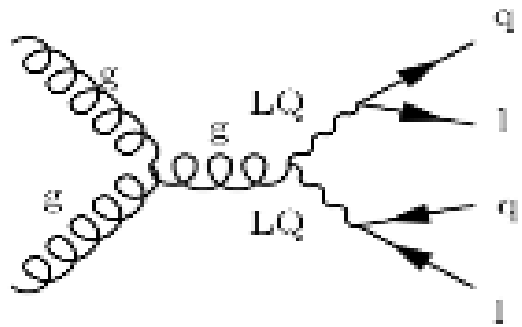
SUSY-based exotica:

- Long-lived particles

Leptoquarks (I)

- **As name implies, they are both "leptons" and "quarks": i.e. carry baryon and lepton number – & color (large σ!)**
  - GUT-inspired models, with (hypothetical) proton decay acting as one of the main motivations
  - Decay: into ℓq (branching ratio β) and νq (BR=1-β)
  - Easier searches (e/μ): first two generations, LQ1 and LQ2

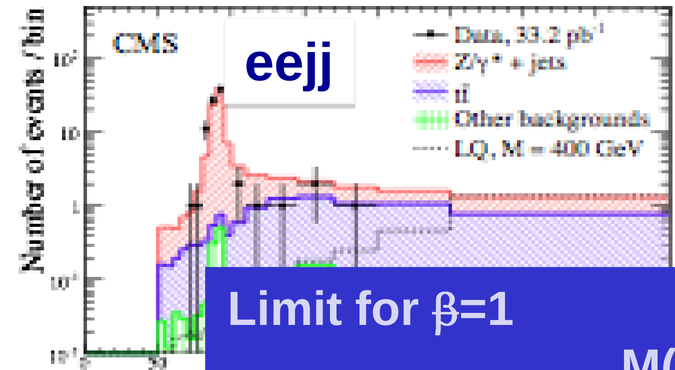
- **Pair-produced (gluon fusion)** **final state: (** **look for: pe**

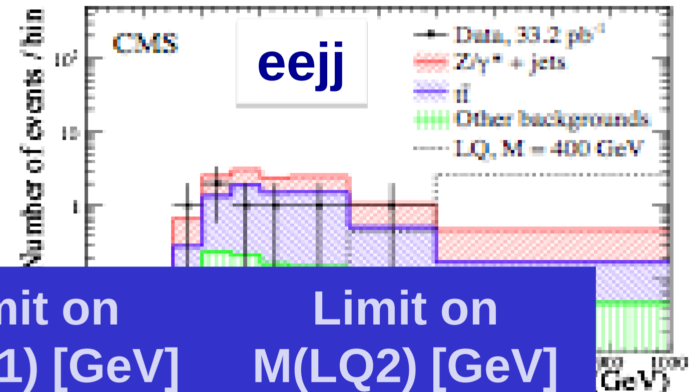


Use variable S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV

Leptoquarks (II)

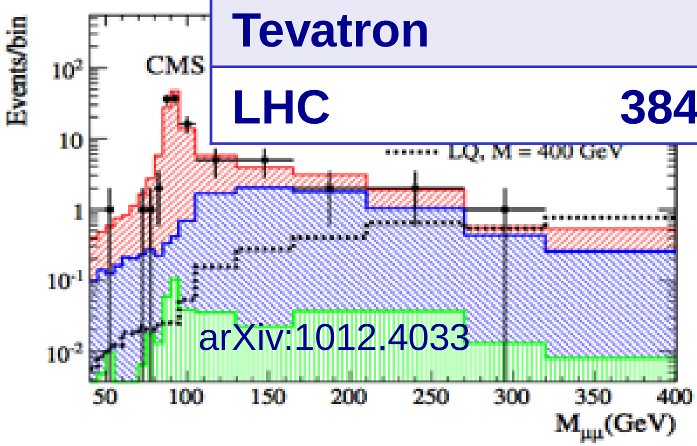
- Main irreducible bkg: DY+jets; 2nd: top production
  - In situ Z+jets measurement + measured top cross section in the dilepton channel to estimate both bkgs



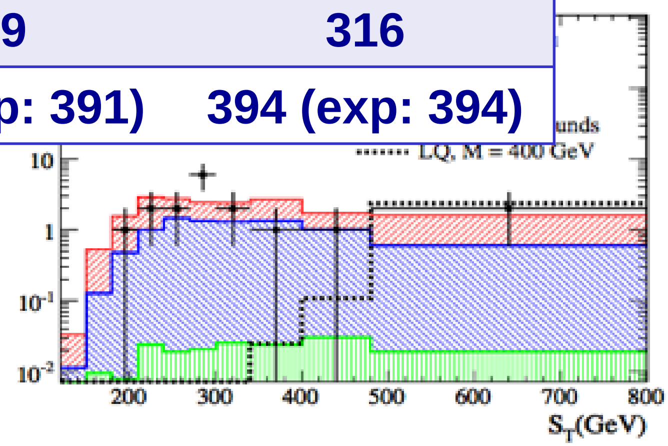


LQ1: S_T > 340-660 GeV for M_{LQ1} = 200-500 GeV, 2 events observed; consistent with bkg estimate

Limit for β=1	Limit on M(LQ1) [GeV]	Limit on M(LQ2) [GeV]
Tevatron	299	316
LHC	384 (exp: 391)	394 (exp: 394)



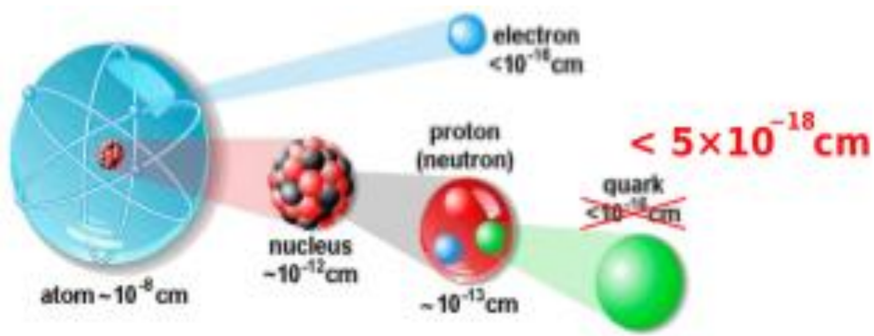
arXiv:1012.4033



LQ2: S_T > 310-700 GeV for M_{LQ1} = 200-500 GeV, 5 events observed; consistent with bkg estimate

Compositeness: do quarks have sub-structure?

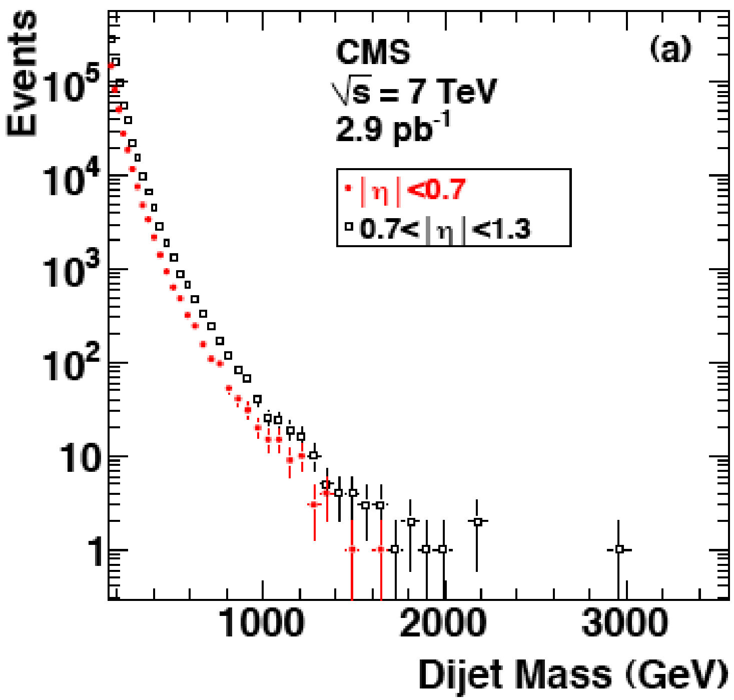
Search based on ratio of hadronic jet pairs (leading dijets)

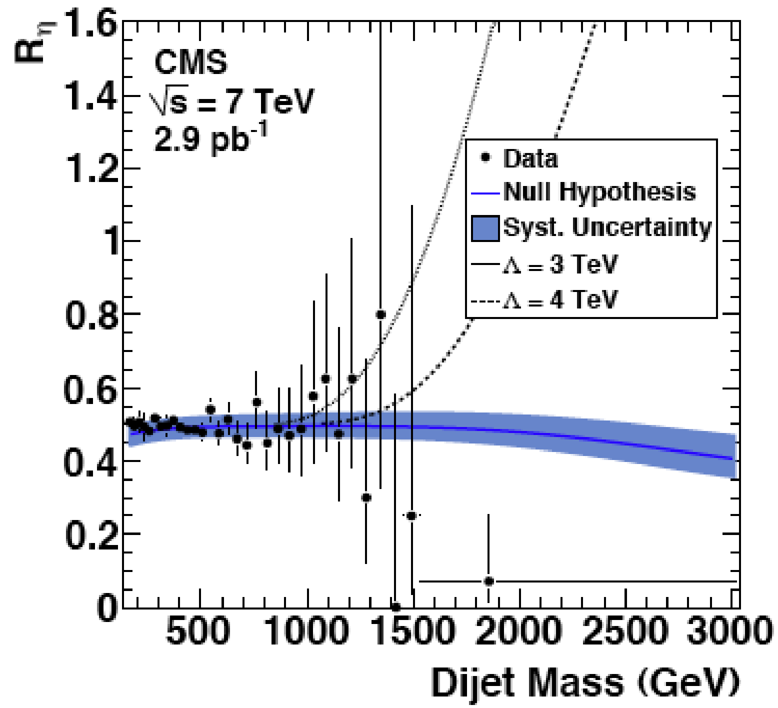


$$R_\eta = \frac{\sum_{|\eta|<0.7} Dijets}{\sum_{0.7<|\eta|<1.3} Dijets}$$

Anti-k_T5

p_T(Jet)>25 GeV





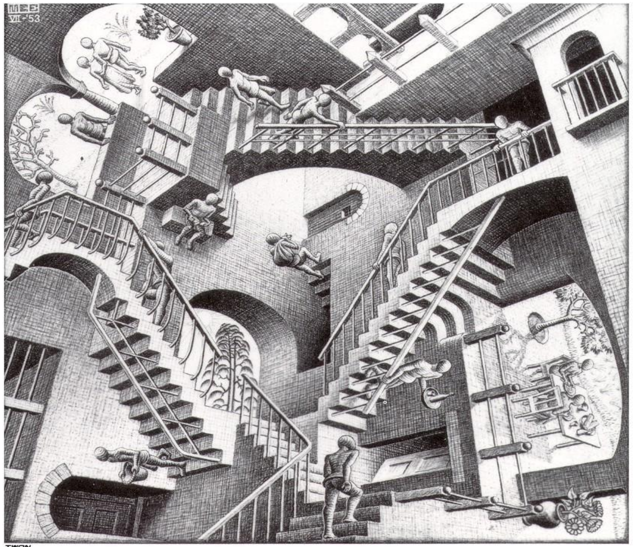
The observed limit is Λ < 4.0 TeV at the 95% CL
(expected limit is 2.9 TeV, previous limit is 3.4 TeV)

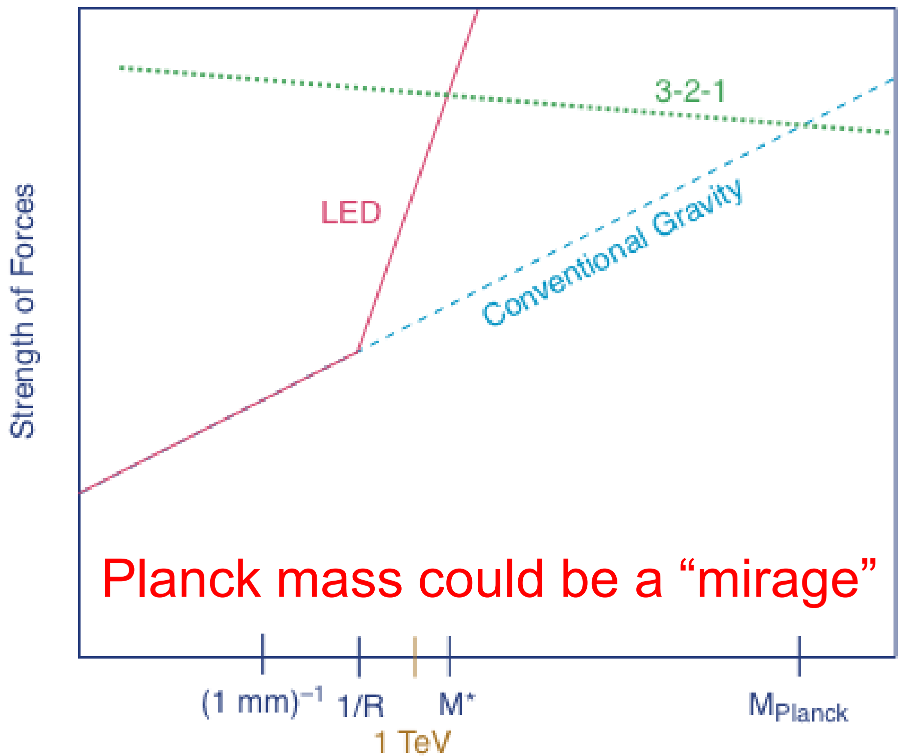
How many space-time dimensions are there?

Law of Gravity
In 3-D(∞ large dim): $F = \frac{GMm}{r^2}$

e.g. in 2-D (∞ large dim): $F \propto \frac{1}{r}$

Gravity may propagate in 4+n dimensions, would see effects only at very small distances, perhaps reachable in pp LHC Collisions e.g. New particles – Z-like



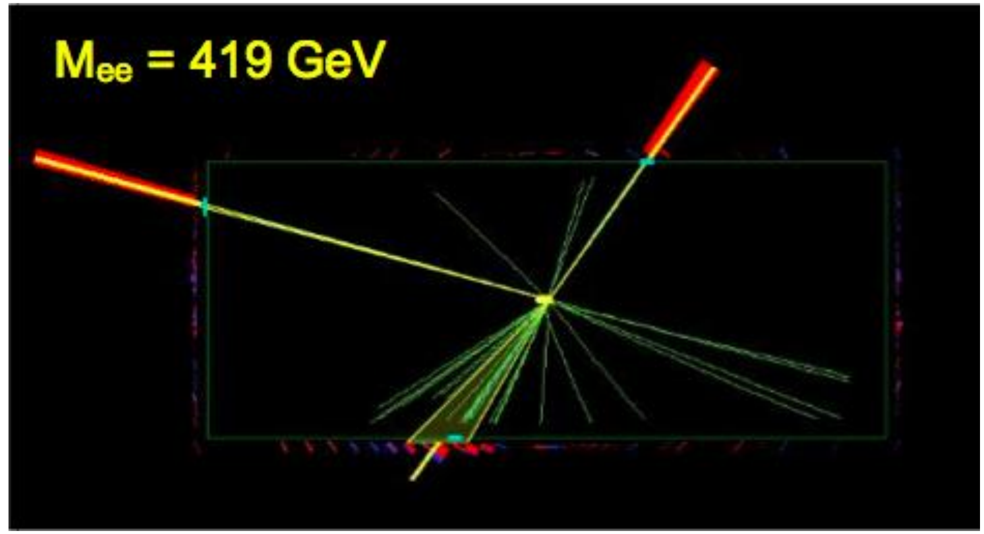


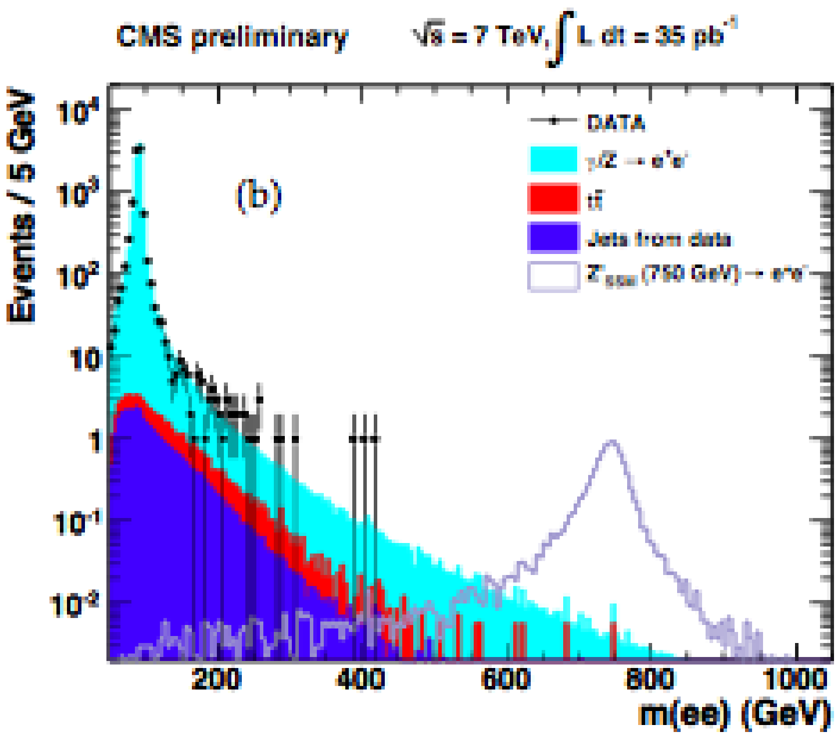
Number of space-time dimensions determines form of force observed

Imperial College London

Search for Heavy Vector Bosons: Z’ → e+e-

Heavy vector bosons could arise from
- spin 1: predicted by grand unified theories, Kaluza-Klein (KK) models
- spin 2: graviton excitations GKK arising in the Randall-Sundrum (RS) model of extra dimensions





Channel	μμ	ee	Combined
Z_{SSM}	1027 GeV	958 GeV	1140 GeV
Z_{ψ}	792 GeV	731 GeV	887 GeV
G_{KK}, k/M_{Pl} = 0.05	778 GeV	729 GeV	855 GeV
G_{KK}, k/M_{Pl} = 0.10	987 GeV	931 GeV	1079 GeV

Tevatron update on Jan 24 (!)

TABLE I: Mass limits on specific spin-1 Z' models [12] in data with 4.6 fb^{-1} of integrated luminosity at 95% confidence level.

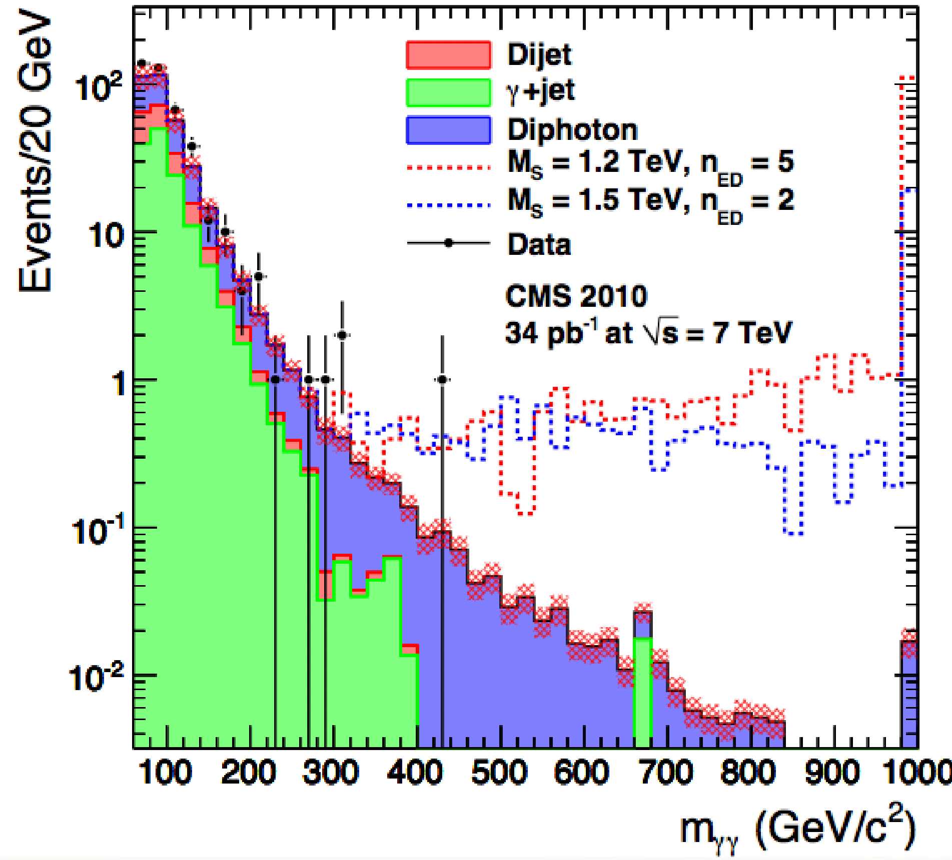
Model	Z'_I	Z'_{sec}	Z'_N	Z'_ψ	Z'_χ	Z'_η	Z'_{SM}
Mass Limit (GeV/c^2)	817	858	900	917	930	938	1071

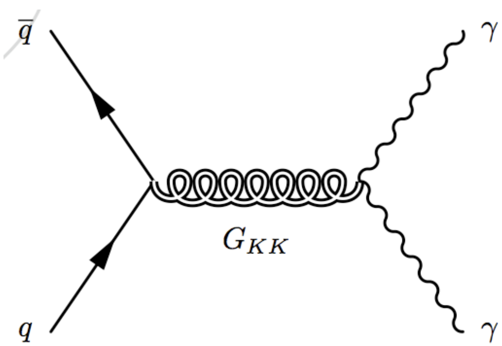
Search for Virtual Graviton Effects

e.g. Probe models with Large Extra Dimensions where gravity alone is allowed to propagate

-Offer a solution to the heirarchy problem by "lowering" the apparent Planck scale MPl ~ 10^{16} TeV to MD ~ 1 TeV

-Signature studied: non-resonant enhancement of di-photon cross-section due to virtual graviton effects





GRW	Hewett		HLZ (limits in TeV)					
	λ > 0	λ < 0	n=2	n=3	n=4	n=5	n=6	n=7
1.93	1.72	1.70	1.88	2.29	1.93	1.74	1.62	1.53
1.82			1.79	2.22	1.82	1.61	1.45	1.29

Figures highlighted in green are the highest to date

Microscopic Evaporating Black Holes

THE signature of low-scale quantum gravity ($M_D << M_{Pl}$)

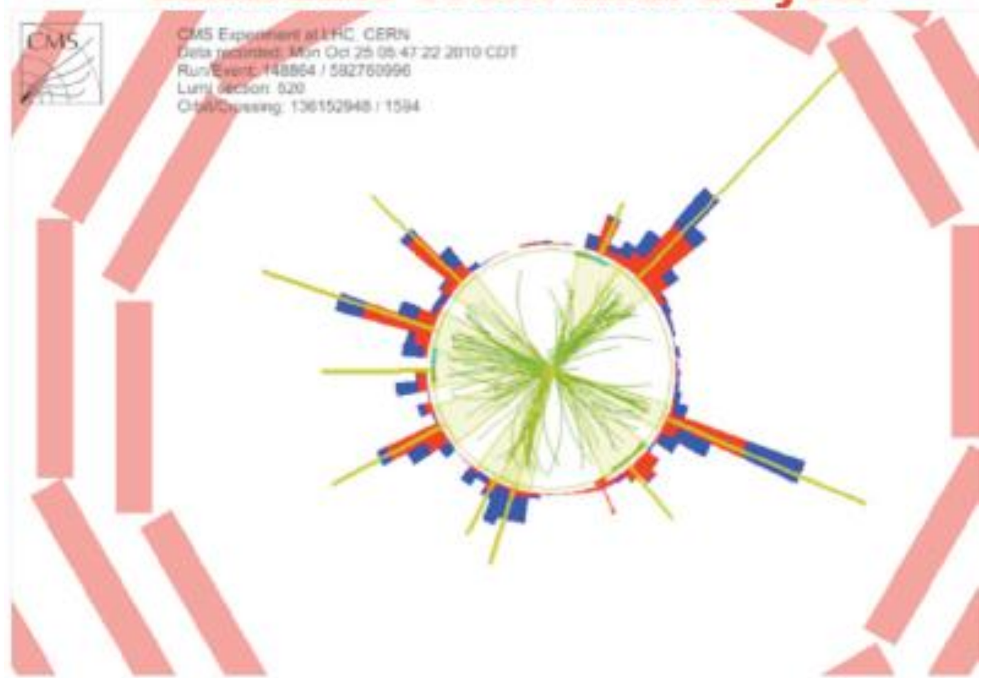
BH formation when the two colliding partons have distance smaller than R_S,, the Schwarzschild radius corresponding to their invariant mass

Cross section from geometry: $\sigma = \pi R_S^2 \sim \text{TeV}^{-2}$ (up to ~100 pb!)

Microscopic BHs decay instantaneously via Hawking evaporation
emitting “democratically” a large number of energetic quarks, gluons, leptons, photons, W/Z, h, etc.

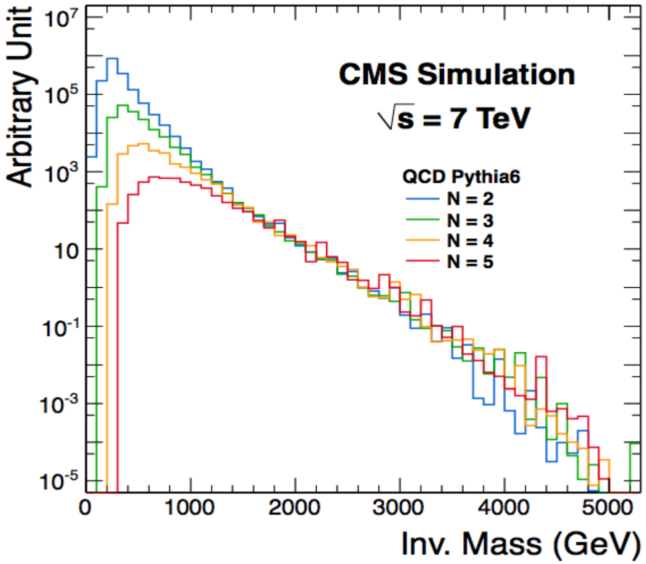
Expect lots of activity in the event, so
Use S_T = Sum E_T of all objects
(including ME_T) with E_T>50 GeV
(good for avoiding pileup – also in the future)

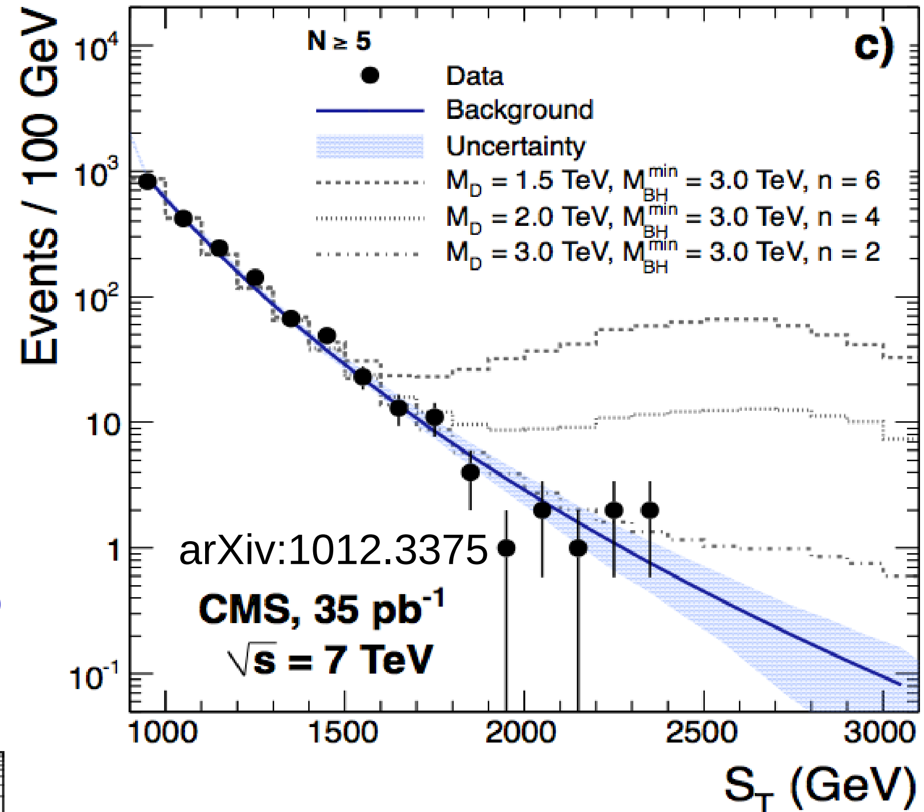
Candidate event with 10 jets



Imperial College London

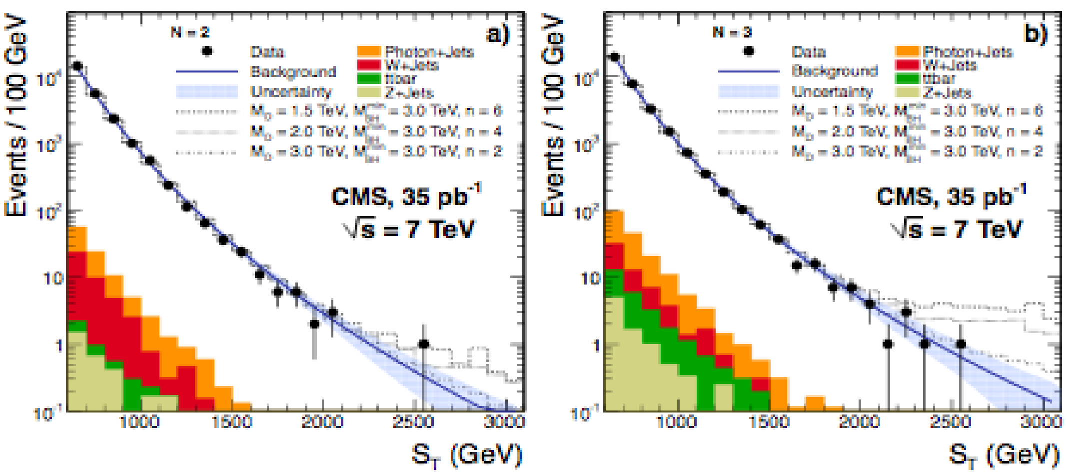
Search for Microscopic BHs





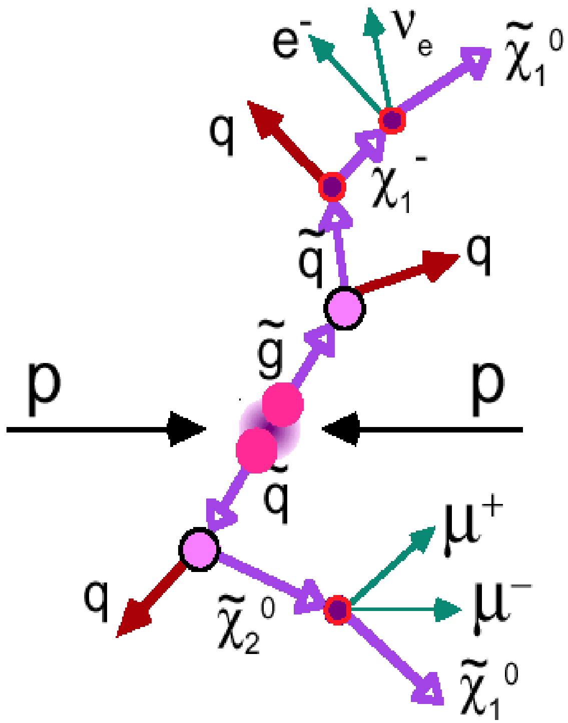
The shape of the S_T distribution is expected to be independent of event object multiplicity N

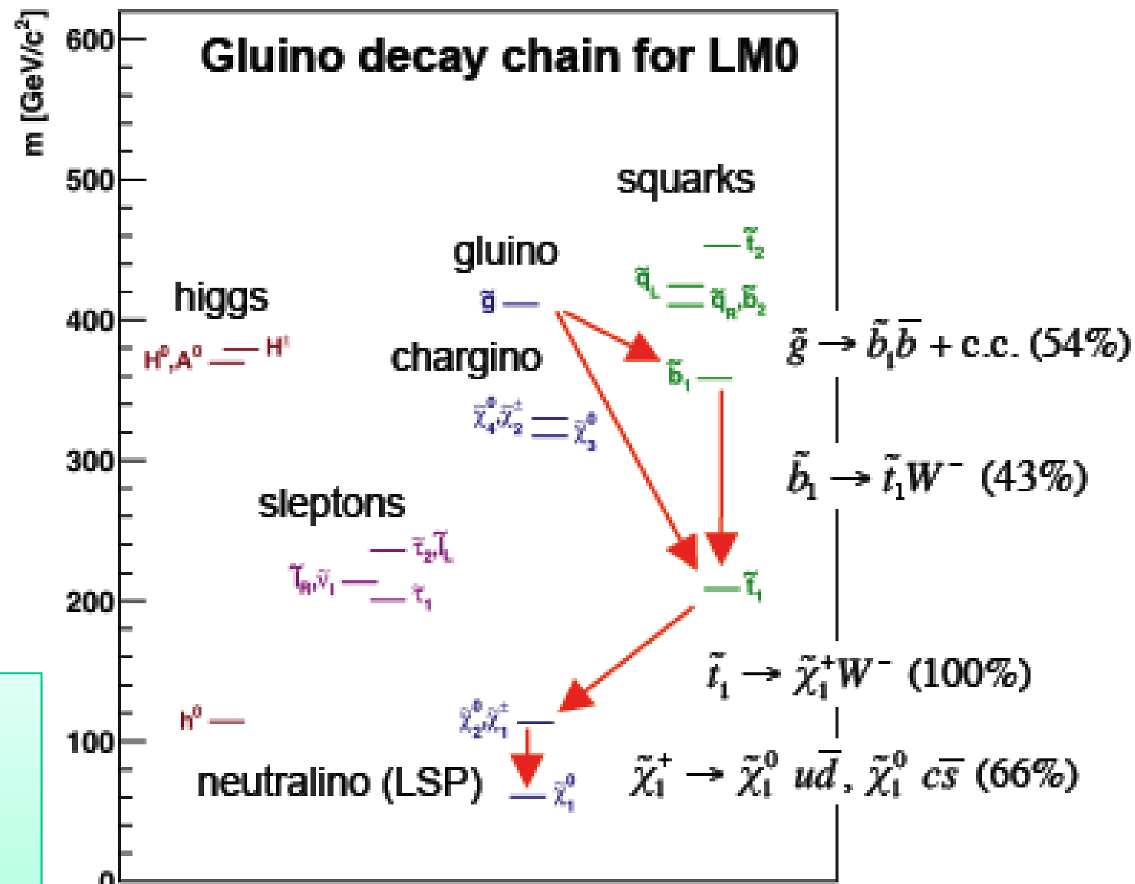
Normalized to $1000 < S_T < 1100$ GeV



No excess, so set limits
M_{BH} > 3.5-4.5 TeV
(semi-classical approximation)

Supersymmetry: a New Zoology of Particles?





Searches require (high-P_T) jets + (high) ME_T and charged leptons:

- 0ℓ (all-hadronic);
- 1ℓ
- 2ℓ (and break down into OS and SS)

Imperial College London

SUSY: jets+ME_T

- **Strongly-produced squarks and gluinos with M>400 GeV**
  - Decaying into SM particles (e.g. quarks) plus LSP; either directly or after a long chain
  - Huge background from QCD (several orders of magnitude).
  - Strategy: use kinematics (α_T) to reduced it to negligible level, then tackle next bkg
    - Veto leptons to avoid EWK backgrounds with MET arising from neutrinos
  - Largest remaining bkgs: Z($\rightarrow\nu\nu$)+jets, W($\rightarrow\ell\,\nu$)+jets, t-tbar

α_T for 2 jets:

$$\alpha_T = \frac{E_{T2}}{M_T} \leq 0.5$$

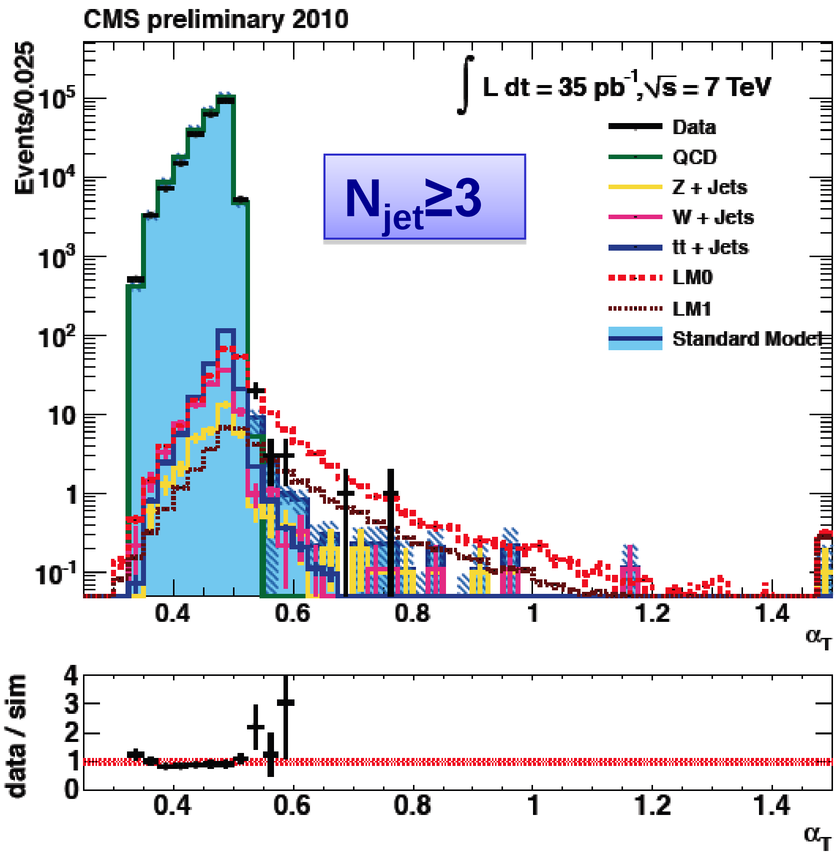
Expectation for QCD: α_T = 0.5
Jet mismeasurements: α_T<0.5

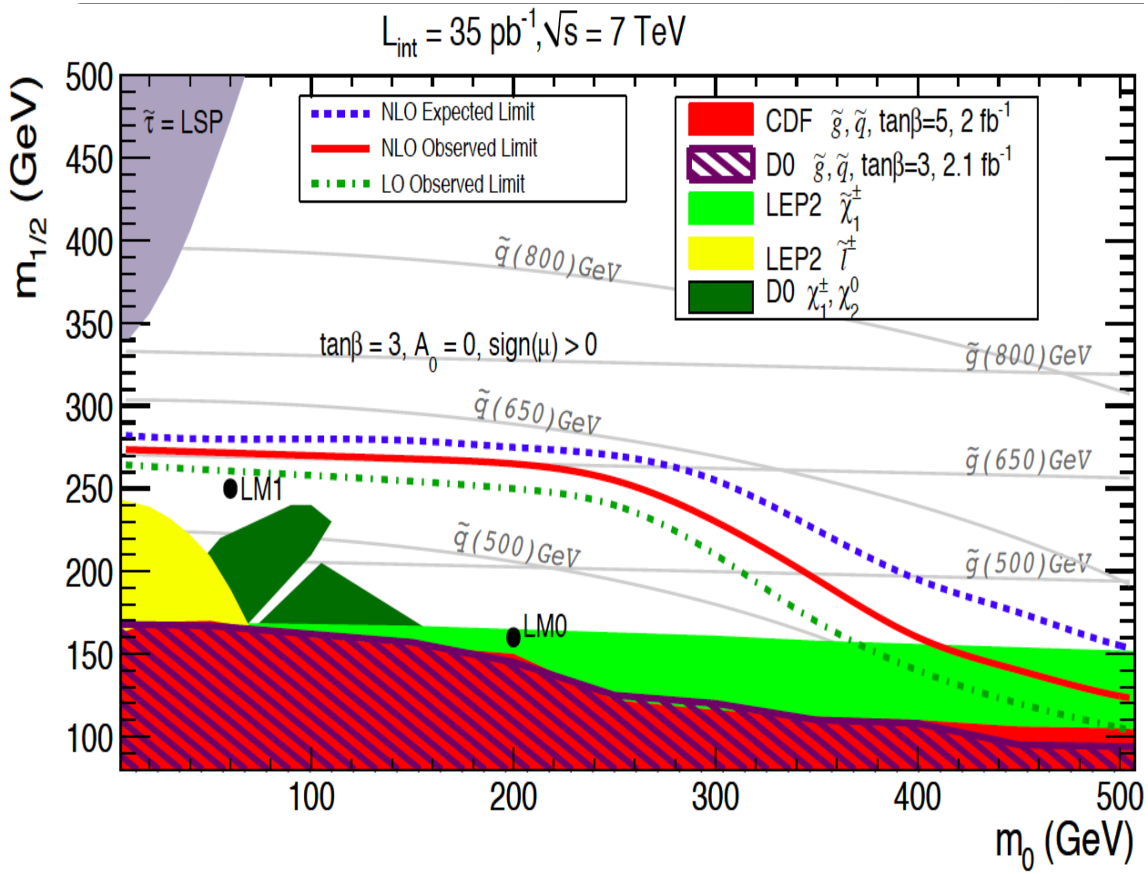
α_T for n jets:

$$\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{M_T}$$

(form two pseudo-jets – defined by balance in “pseudo-jet” $H_T = \sum E_T$)

SUSY: jets+ME$_T$





13 events observed but consistent with background estimates, so set limits

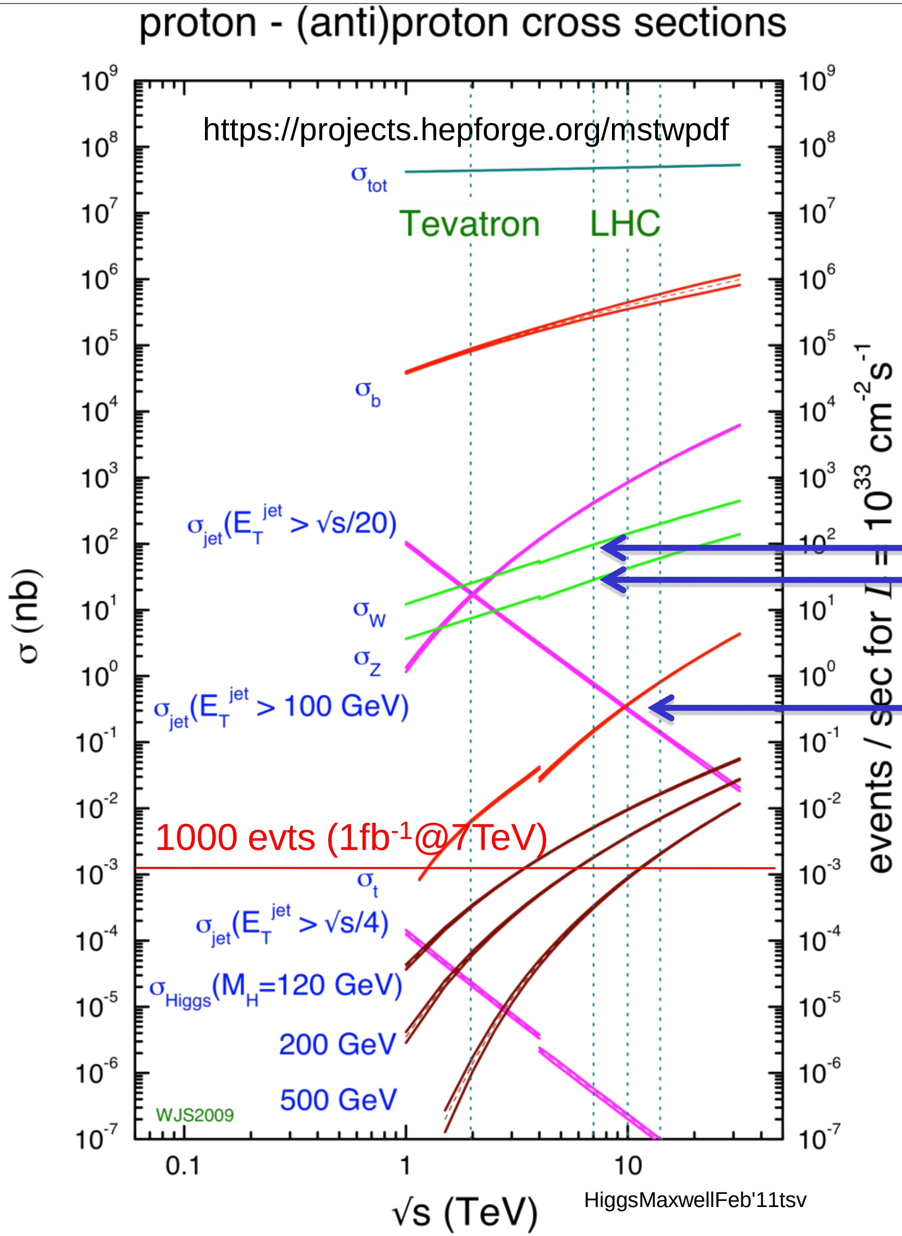
Already with 35 pb^{-1}: significant extension of previous reach

Outlook 2011-2012

by mid-2011 1 fb^{-1} ?
2-3 fb^{-1} at 7 TeV by end 2011?
10 fb^{-1} at ≥ 7 TeV by end 2012 ?

Make more precise SM measurements & confront theory
Search for the Higgs Boson
Search for Supersymmetry
Search for Exotica
Look for the unexpected

LHC Reach 2011-2012



per fb^{-1} at 7 TeV

100 million W's
20 million Z's

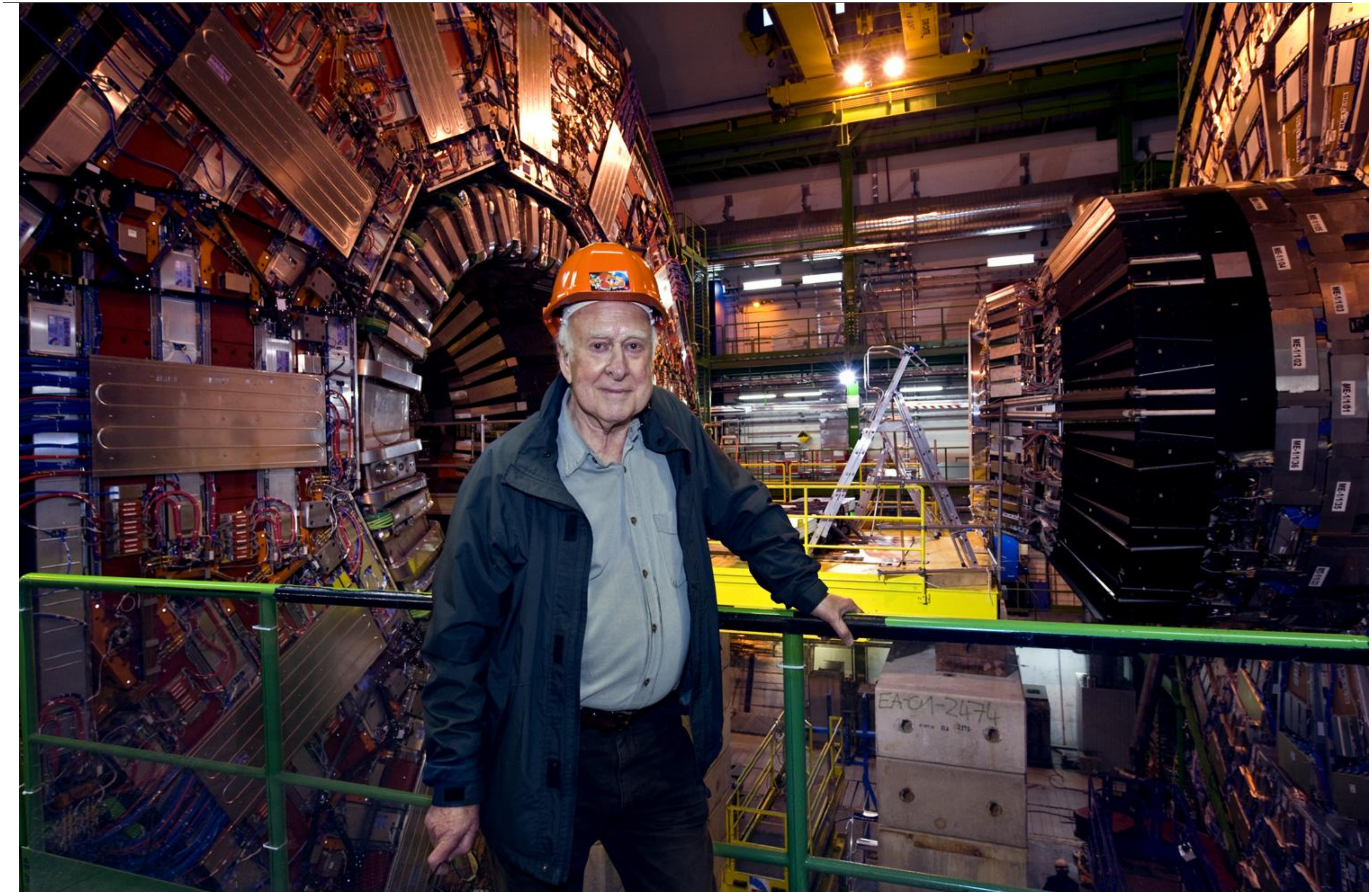
500k ttbar

ATLAS or CMS with 1fb^{-1}
~ 0.5 million Z →ee

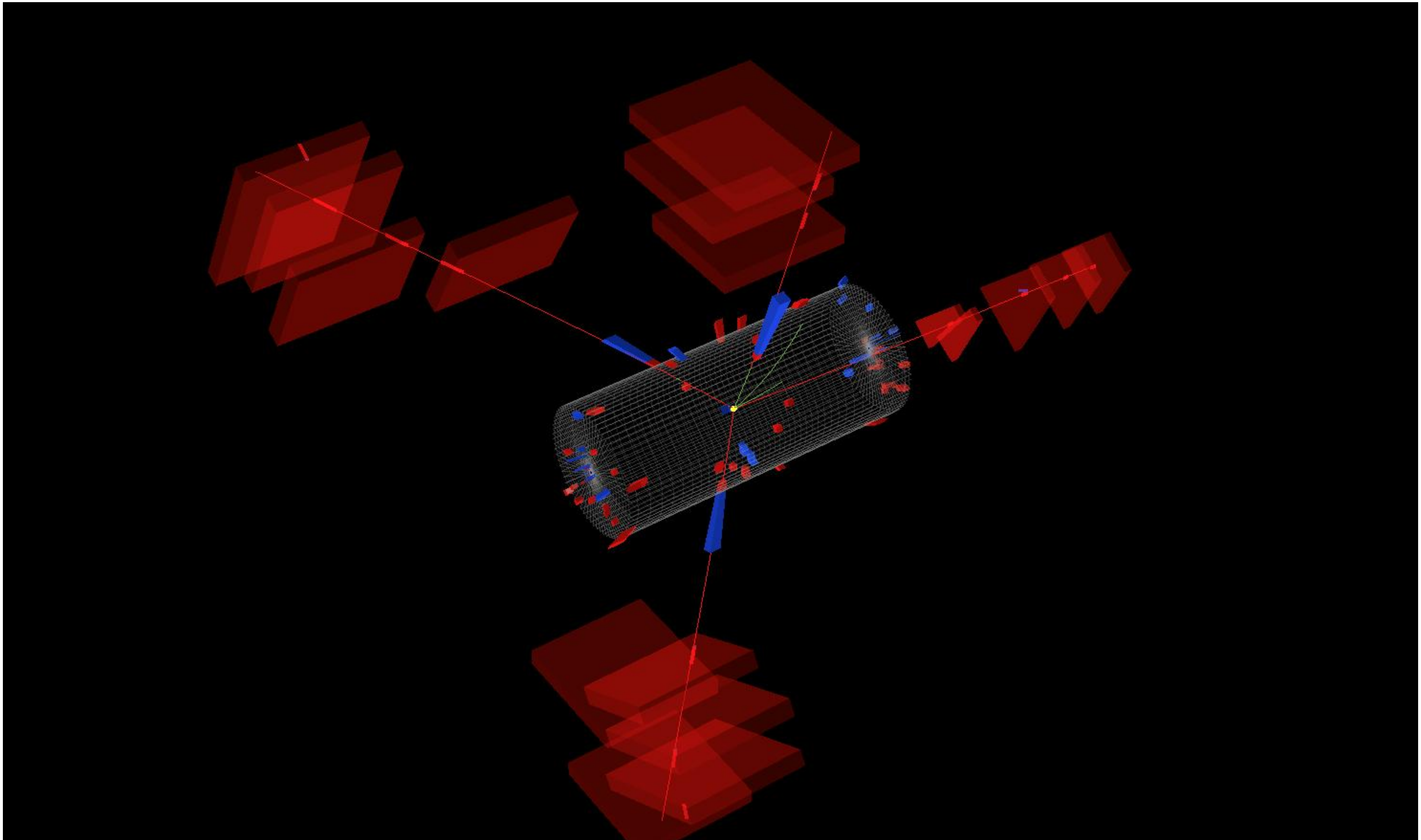
cf CDF or D0 with 10fb^{-1}
~ 0.5 million Z →ee

Imperial College London

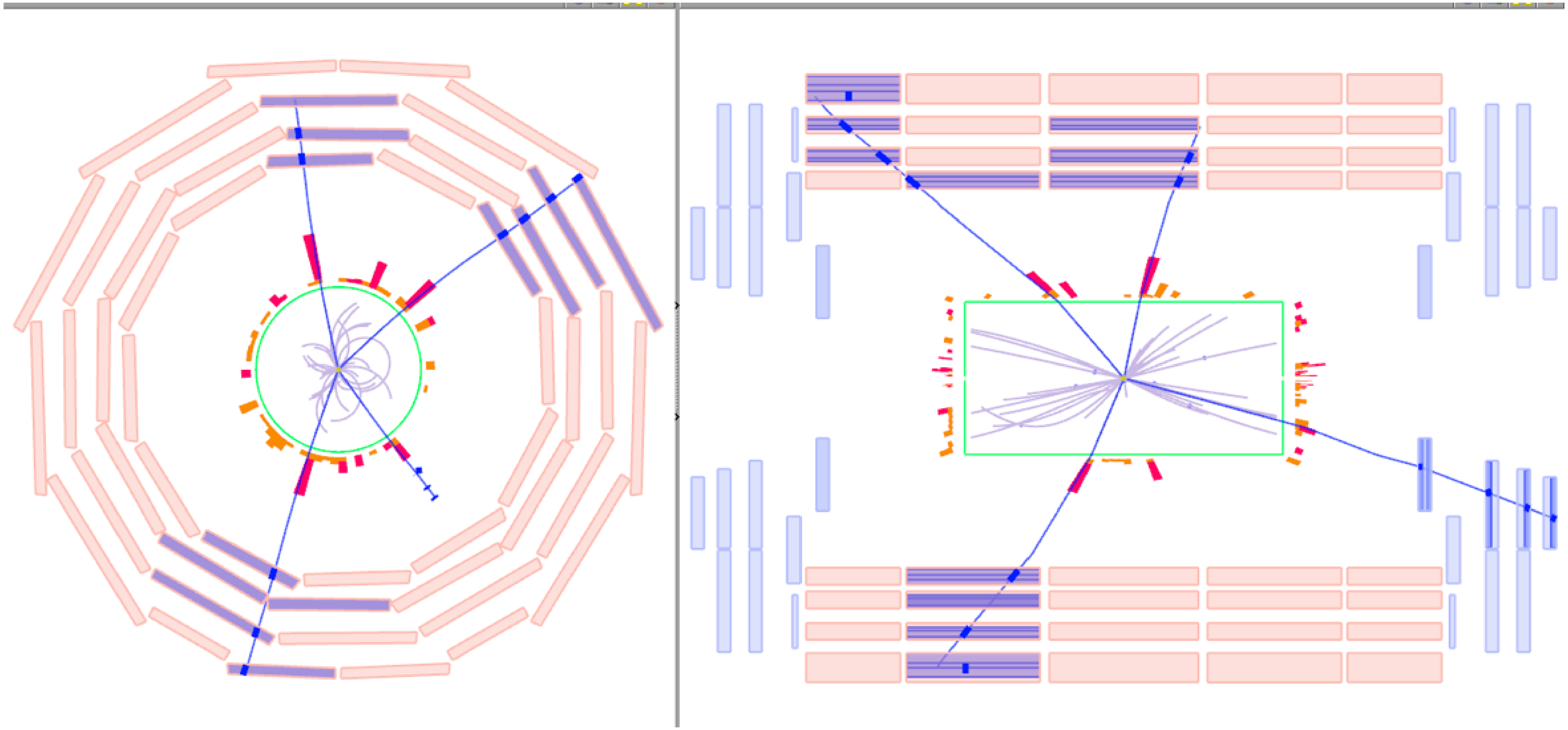
Higgs Seen in CMS



An Interesting 4-muon Event I



An Interesting 4-muon Event II



Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),

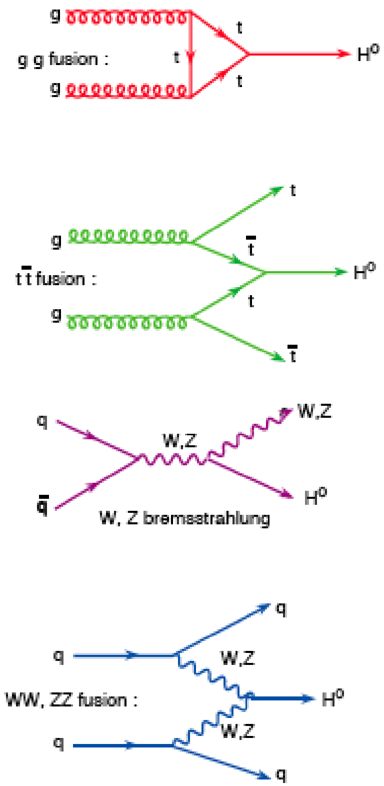
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),

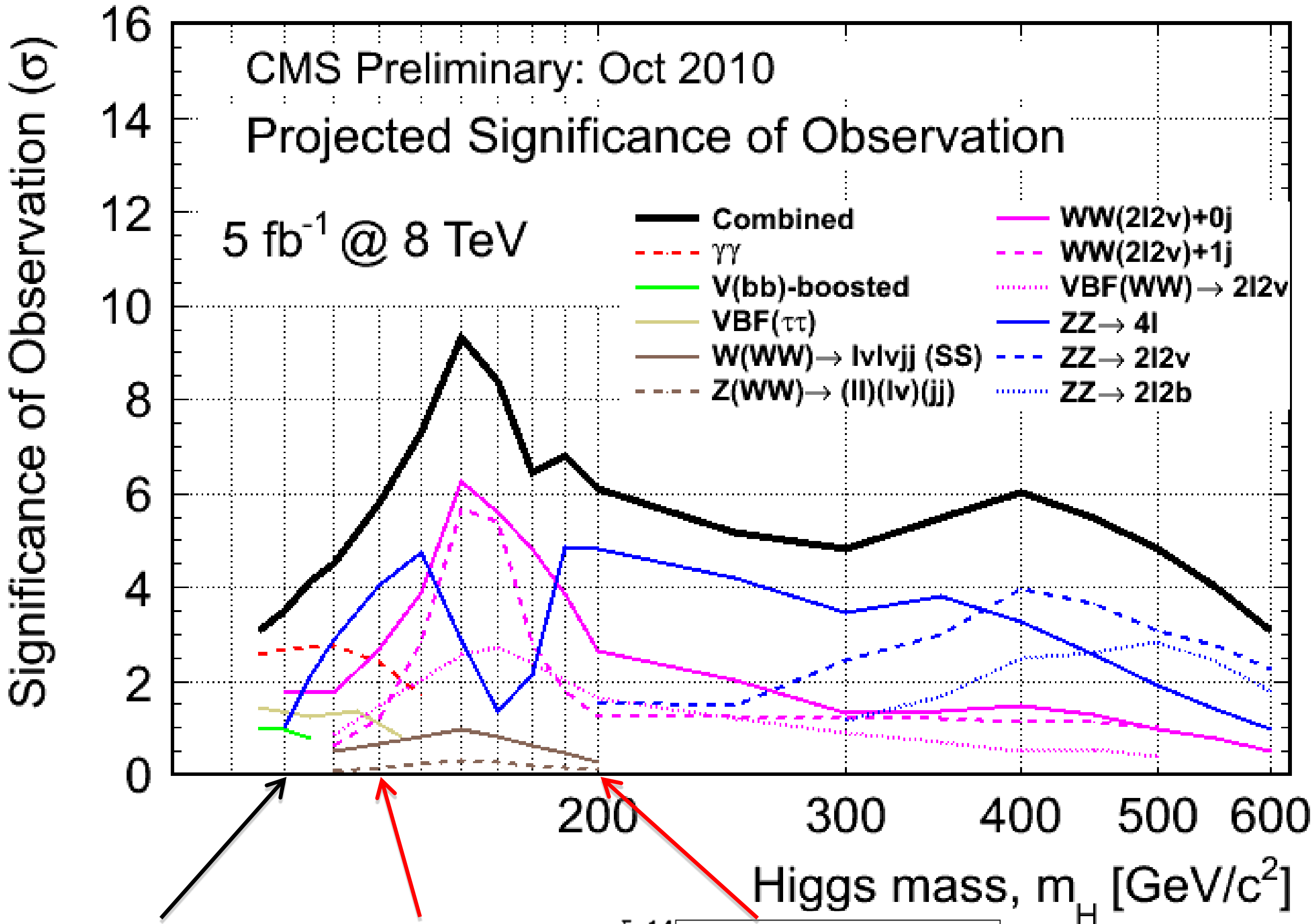
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),

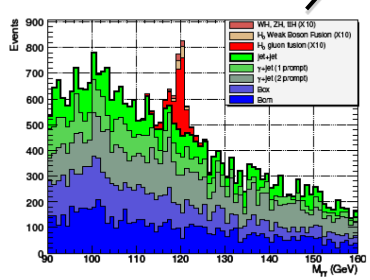
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

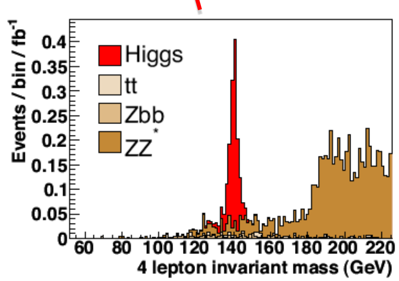
Invariant Mass of 4μ: 201 GeV

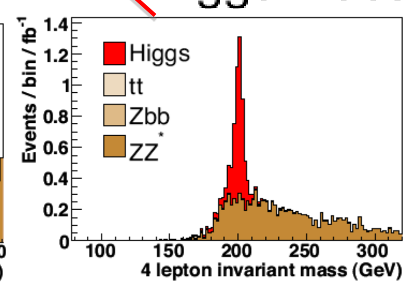
Standard Model (like) Higgs: LHC at 7/8 TeV





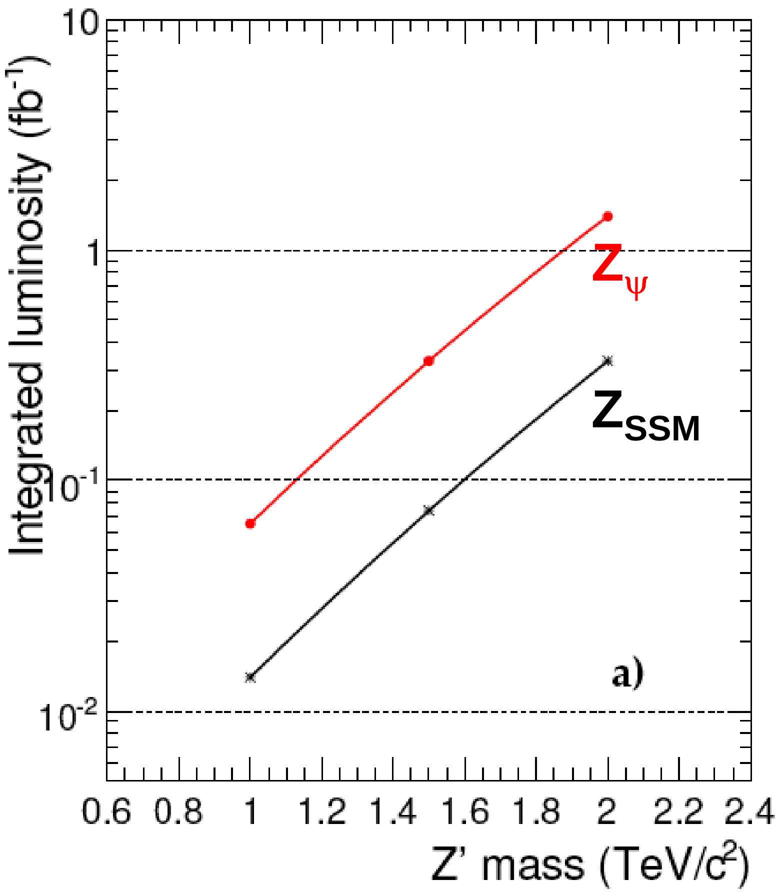




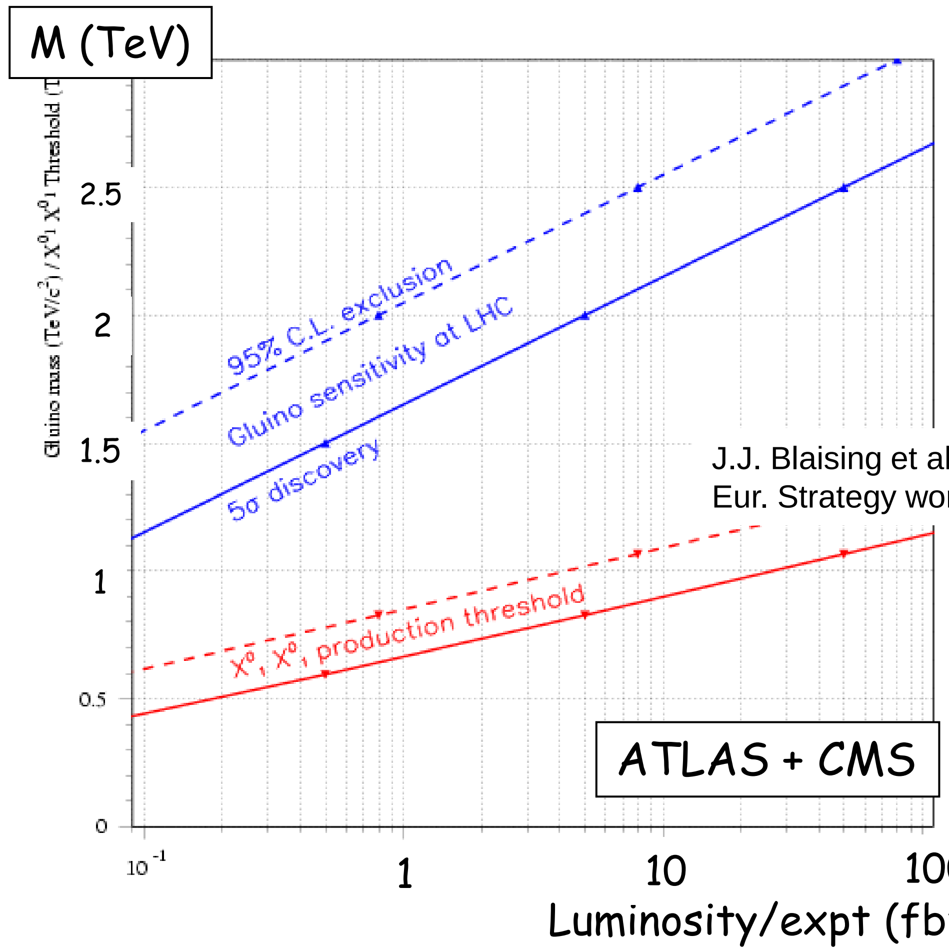


ATLAS / CMS: Supersymmetry @ 14 TeV

5σ discovery in the μμ channel



Luminosity needed at 7 TeV wrt 14 TeV
X ~ 5 (10) for M(Z') =1 (2) TeV



J.J. Blaising et al, input to
Eur. Strategy workshop

Summary

LHC and CMS (and the other LHC experiments) have made a truly impressive start after twenty years spent on the design, R&D, prototyping, construction, assembly and commissioning

The thorough preparation of CMS detector, the offline and computing systems, and physics analysis work-flows has allowed very rapid extraction of physics results.

CMS is already approaching design performance in many areas!
CMS has become a physics producing engine!

With ~ 40pb^{-1} the CMS has observed all particles of the standard model (save for neutrinos directly). Solid basis for understanding the "background" to searches at higher mass and transverse energy scales
CMS is already exploring new territory in many areas.

Much to look forward to in 2011/20112 and beyond.

But we are just at the beginning - the expectations still are that we shall find at the LHC will alter the way we view the universe at the fundamental level.

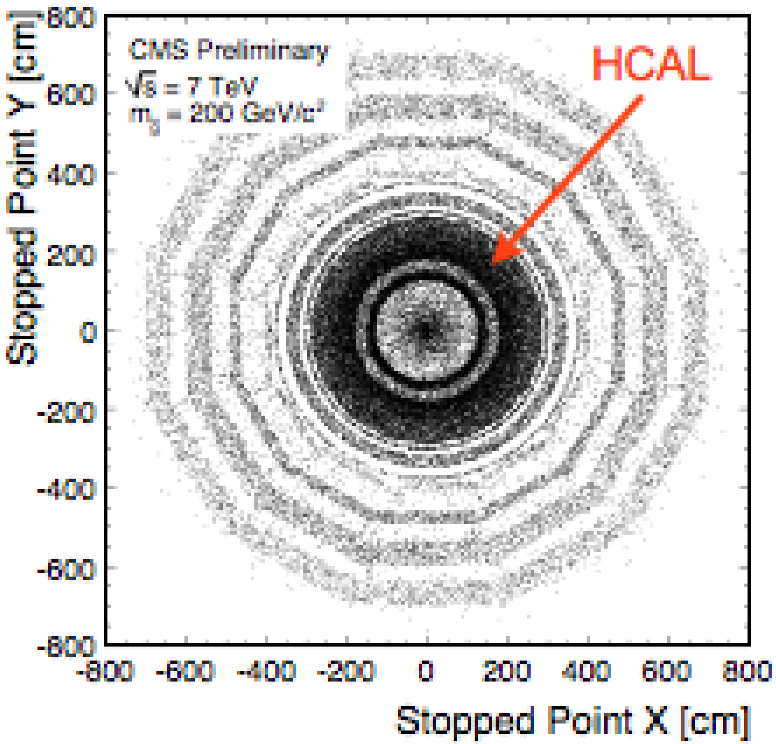
Dijet searches: summary

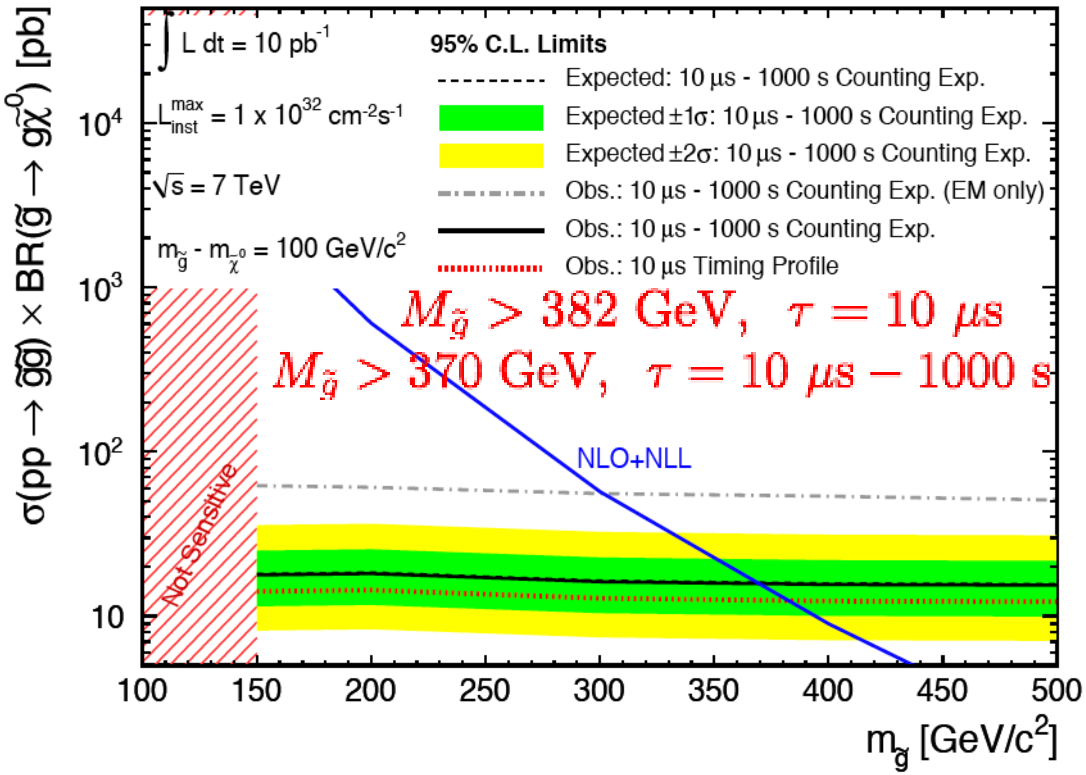
Particle	CMS, 2.9 pb^{-1} PRL **105**, 211801 (2010)	ATLAS, 0.32 pb^{-1} PRL **105**, 161801 (2010)	CDF, 1130 pb^{-1} PRD **79**, 112002 (2009)
q*	M > 1.58 (1.32) TeV	M > 1.26 (1.06) TeV	M > 0.87 TeV
S	M > 2.50 (2.40) TeV		M > 1.4 TeV (our estimate)
Axigluon/ Coloron	M > 1.17 TeV (M > 1.23 TeV) and not (1.42 < M < 1.53)		M > 1.25 TeV
E6 diquark	Exclude 0.50-0.58 & 0.97-1.08 & 1.45-1.60 TeV (M > 1.05 TeV)		M > 0.63 TeV

Quark Compositeness (left-handed quarks)		
CMS Centrality PRL **105**, 262001 (2010)	2.9 pb^{-1}	Λ > 4.0 (2.9) TeV actual (observed)
CMS Angular Distributions (to be submitted soon)	36 pb^{-1}	Λ > 5.6 (5.0) TeV
ATLAS (Angular Distributions) (Centrality) PLB **694**, 327 (2011)	3.1 pb^{-1}	Λ > 3.4 (3.5) TeV Λ > 2.0 (2.6) TeV
D0 (Angular Distriburions) PRL **103**, 191803 (2009)	700 pb^{-1}	Λ > 2.84-3.06 (2.76-2.91) TeV

Search for Stopped Gluinos

- **Predicted in many extensions of the SM: SUSY, hidden-valley models,..**
- Search for slow-moving (β<0.4) long-lived gluinos that stop in CMS and then decay μsec, sec or days later producing a signal (in HCAL) when there is no beam passing through CMS. Designed a special trigger.





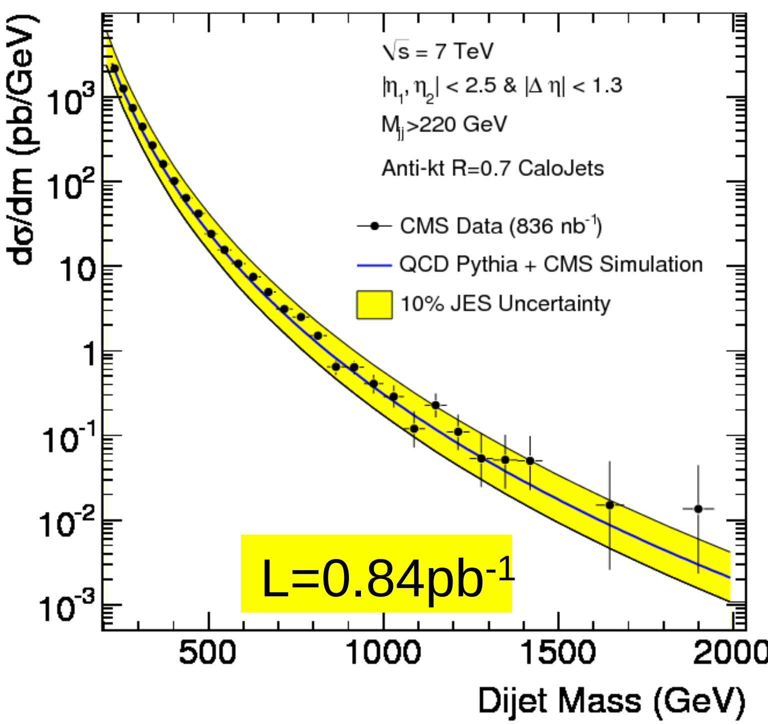
Most stringent limits to date.

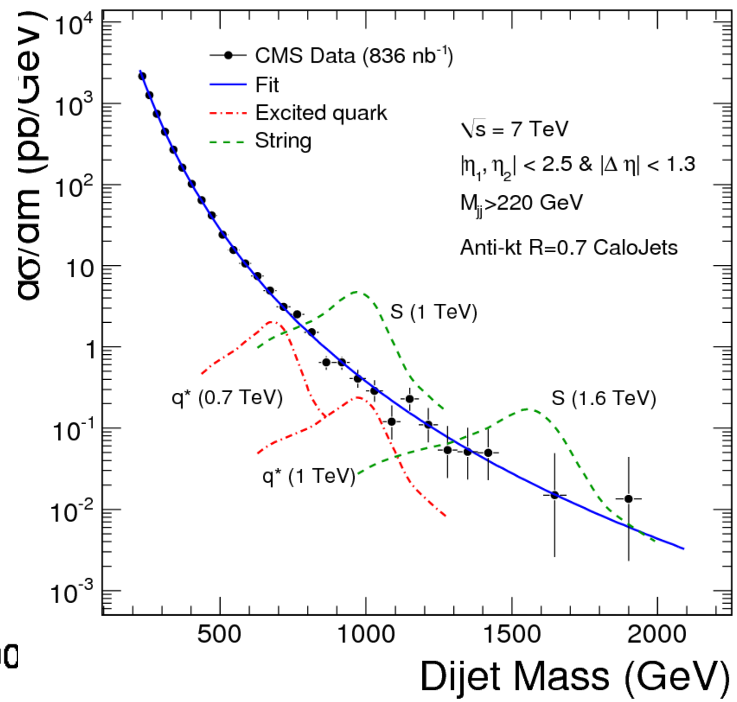
Imperial College London

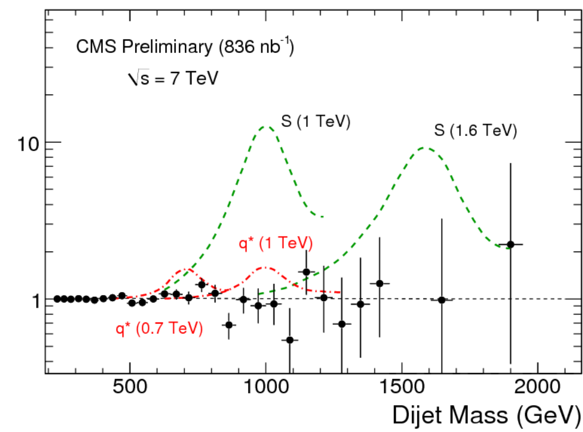
Exploring new territory

Search for narrow resonances in di-jet final states.

We have measured, in 0.84pb^{-1} of data, the dijet mass differential cross section for $|\eta_1,\eta_2|<2.5$ and $|\Delta\eta_2|<1.3$. The distribution is sensitive to the coupling of any new massive object to quarks and gluons.







95% CL mass limits for String resonances >2.1TeV; Excited quarks >1.14TeV; Axigluons/Colorons >1.06TeV; E_6 Diquarks >0.58

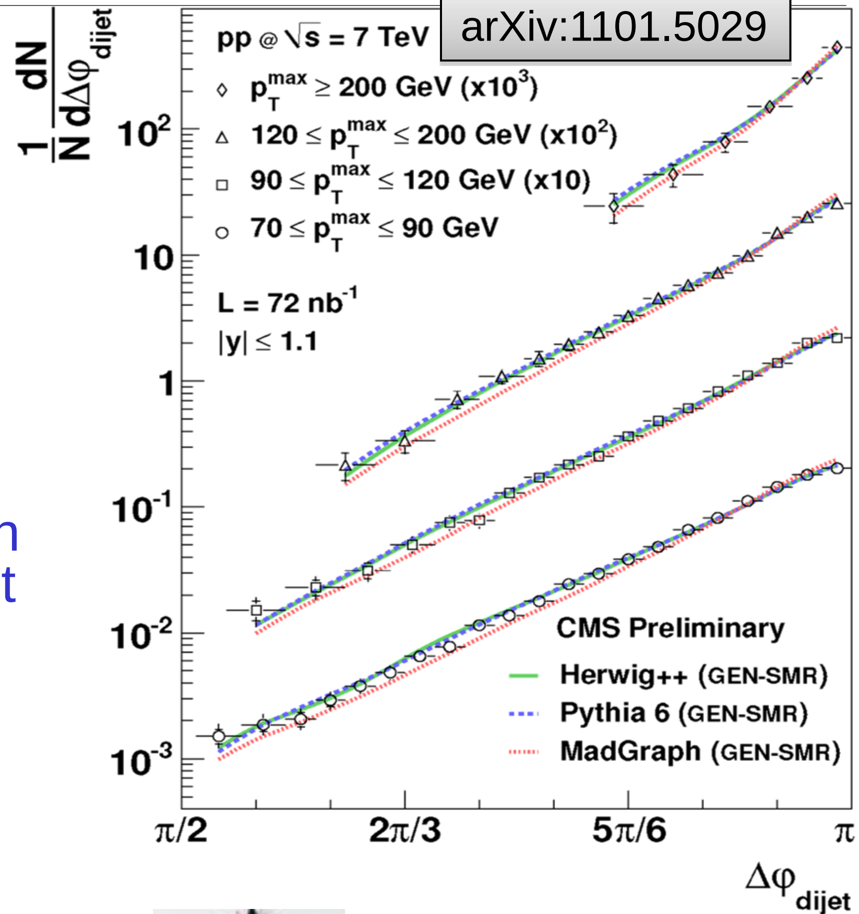
The Hard Scatter: Jet angular correlations

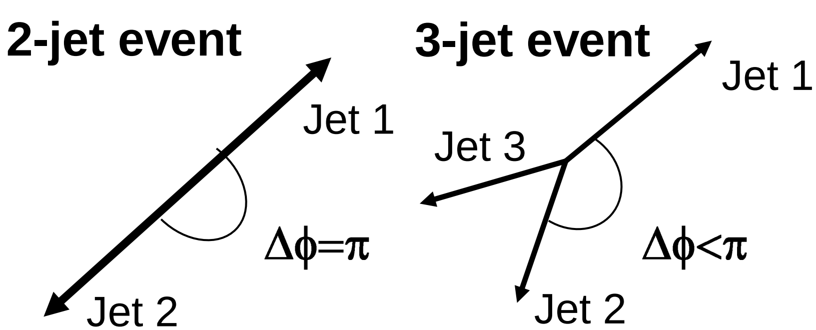
- Difference in azimuth:

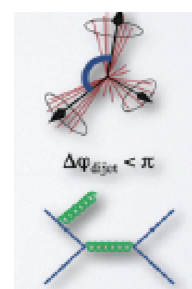
$$\Delta\phi = \left|\phi_{jet\,1} - \phi_{jet\,2}\right|$$

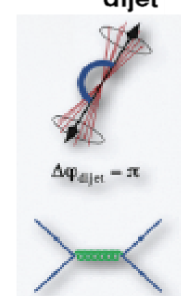
- Probe of QCD higher-order processes
  - Mostly sensitive to ISR (sentivitity to FSR low)
- Advantages
  - Very slight dependence on JES (main source of systematic uncertainty in jet measurements)
  - No dependence on luminosity

arXiv:1101.5029



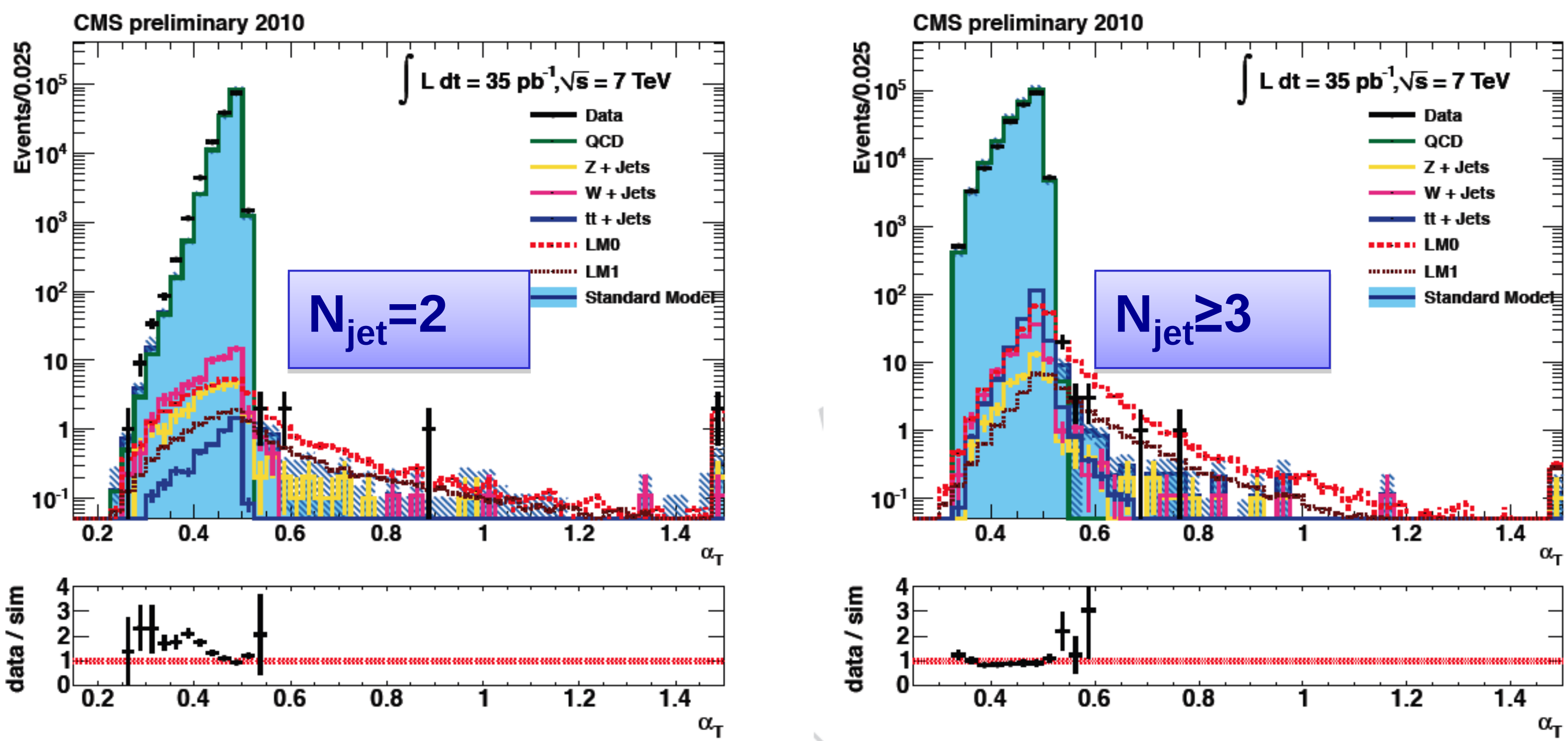






SUSY: jets+MET

- Apply a cut at α_T>0.55, QCD is negligible

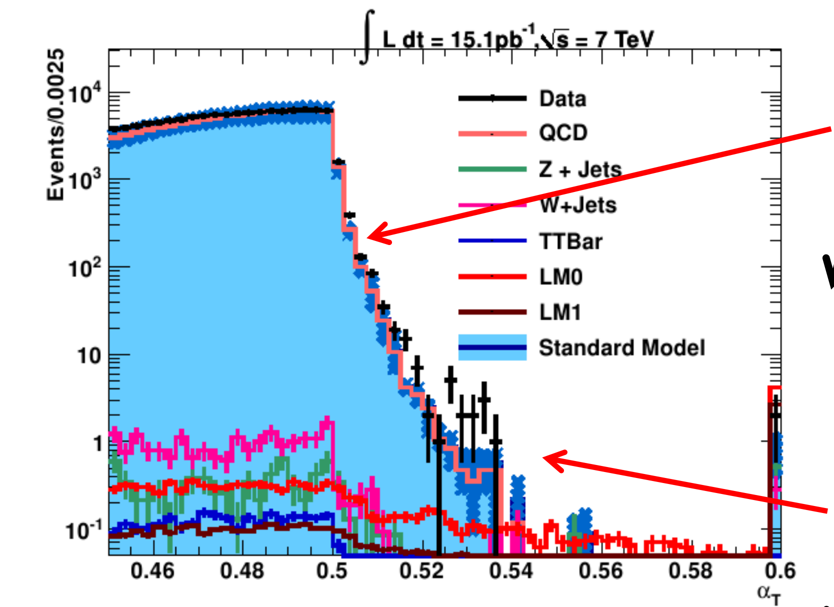


- For remaining bkgs (estimate): two data-driven methods
  – Direct estimate of EWK bkg using W+jets and g+jet events
  – Inclusive estimate using extrapolation from lower-HT

Imperial College London

SUSY: jets+MET

Spill-over in a_T>0.5 from:
(a)Processes with genuine MET (EWK, TOP, and SUSY ☺)
(b)Some remnant QCD



Core of resolution function:
Jet loss due to jet min p_T cut

Tail of resolution function:
Catastrophic mismeasurement of leading jet up to jet p_T cut