Early New Physics Detection Possibilities with CMS at the LHC

KITP Seminar

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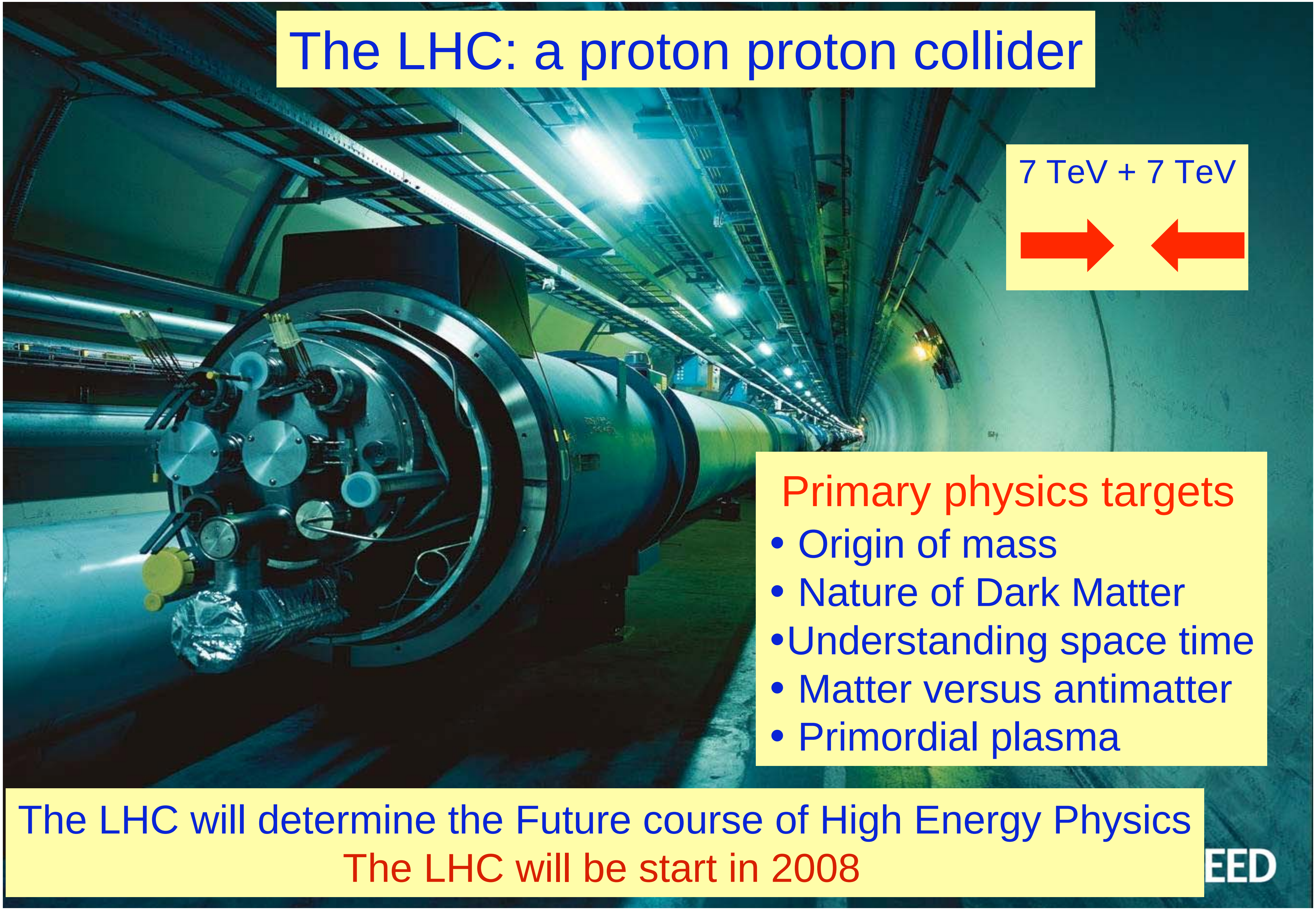
CERN
and University of Antwerp
and the IPPP Durham

Kavli Institute for Theoretical Physics

Contents

- Introduction
- Status of CMS
- First physics with CMS
  - Measuring the Standard Model at 14 TeV
  - Discovering the Higgs?
  - Discovering New Physics?
- Some new signatures (the unexpected?)
- Outlook

The LHC: a proton proton collider



7 TeV + 7 TeV

Primary physics targets

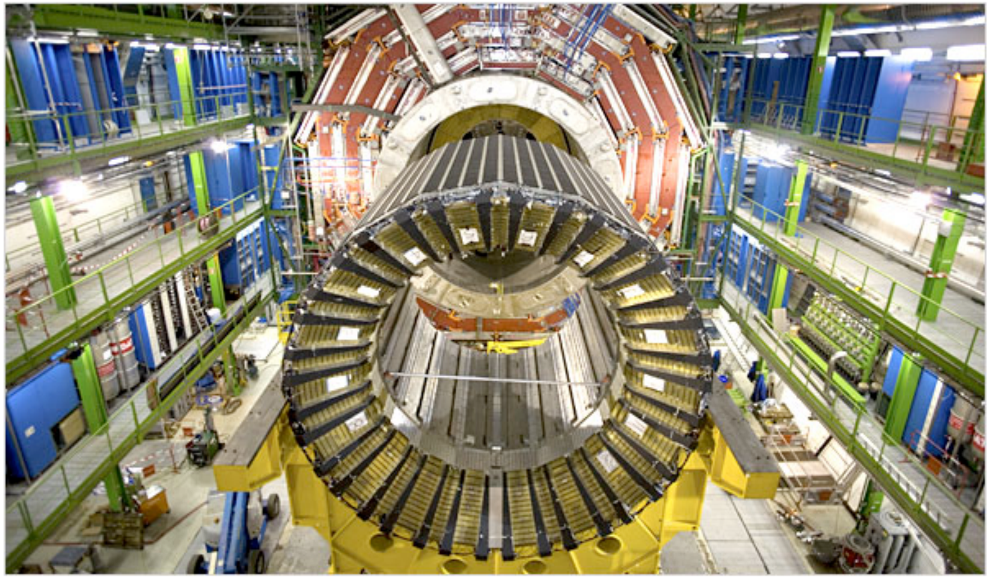
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC will determine the Future course of High Energy Physics

The LHC will be start in 2008

But… Saturday New York Times..

Asking a Judge to Save the World, and Maybe a Whole Lot More



Valerio Mezzanotti for The New York Times

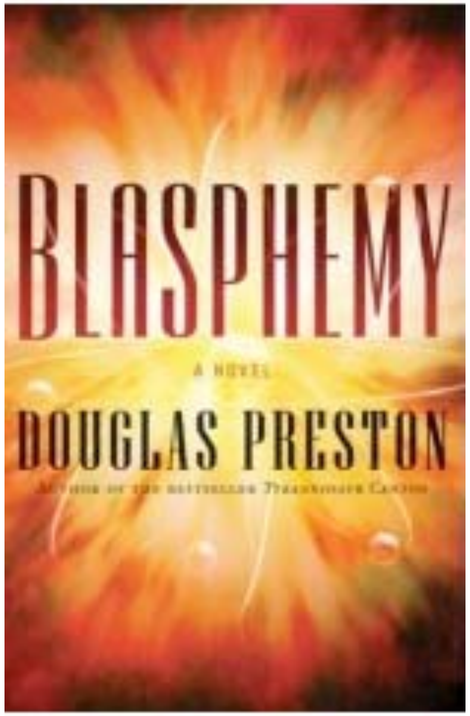
Part of a detector to study results of proton collisions by a particle accelerator that a federal lawsuit filed in Hawaii seeks to stop.

By DENNIS OVERBYE
Published: March 29, 2008

Stable black Hole production at the LHC:
A problem for the survival of mankind?
Giddings & Mangano: No! (probably)
Law suit against the LHC (Hawai)?

More Science Fiction…

Spotted (and bought) this last Saturday in downtown San Francisco…



The world's biggest supercollider, locked in an Arizona mountain, was built to reveal the secrets of the very moment of creation: the Big Bang itself.

The Torus is the most expensive machine ever created by humankind, run by the world's most powerful supercomputer. It is the brainchild of Nobel Laureate Gregory North Hazelius. Will the Torus divulge the mysteries of the creation of the universe? Or will it, as some predict, suck the earth into a mini black hole? Or is the Torus a Satanic attempt, as a powerful televangelist decries, to challenge God Almighty on the very throne of Heaven?

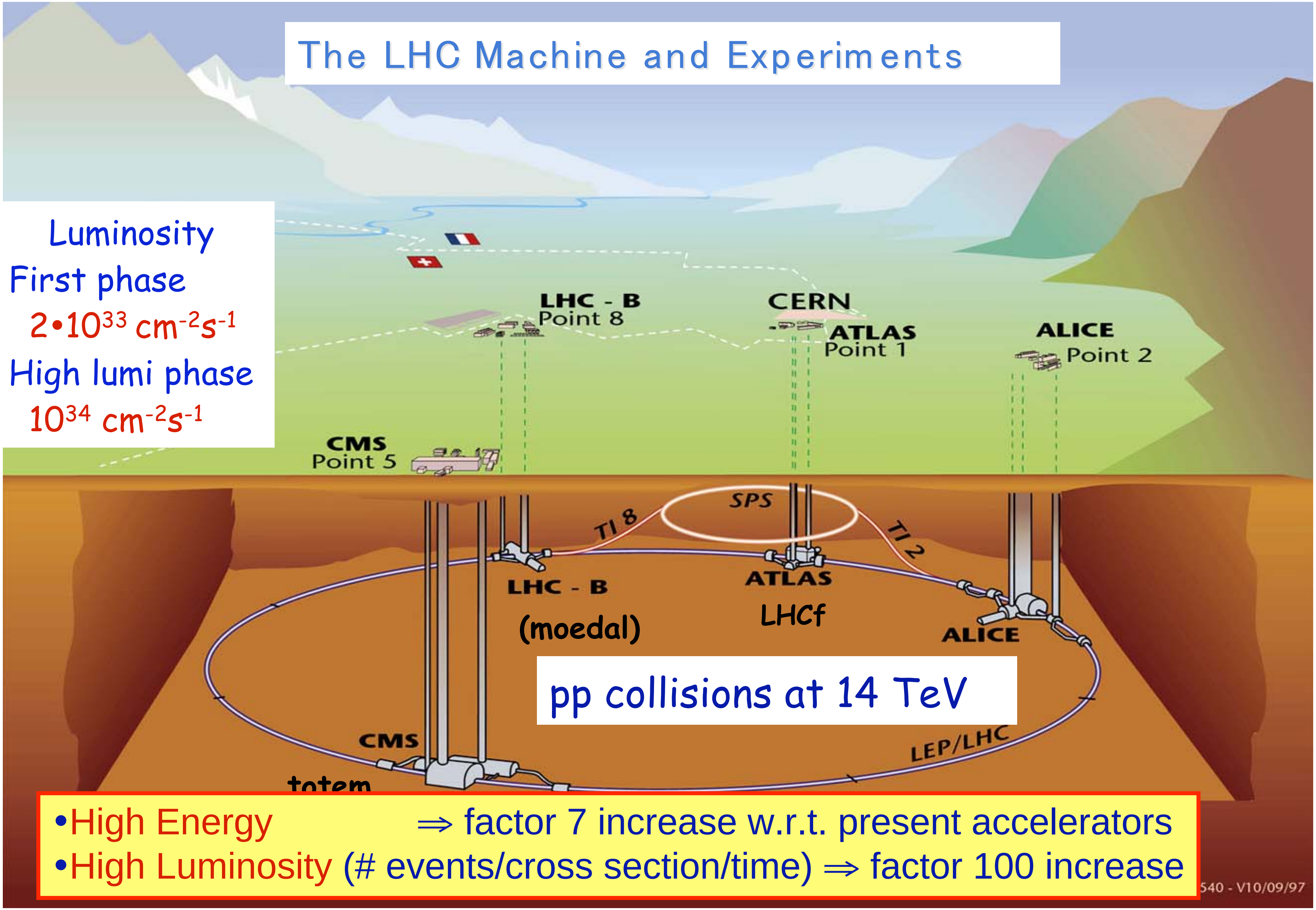
Appeared in 2007
with reference to the LHC

~47 miles long circular machine
"Isabella" (rings a bell?)

The LHC

7 November 2007:
Connecting the last Dipoles of the LHC

The LHC Machine and Experiments



Luminosity

First phase

$2 \cdot 10^{33}$ $cm^{-2}s^{-1}$

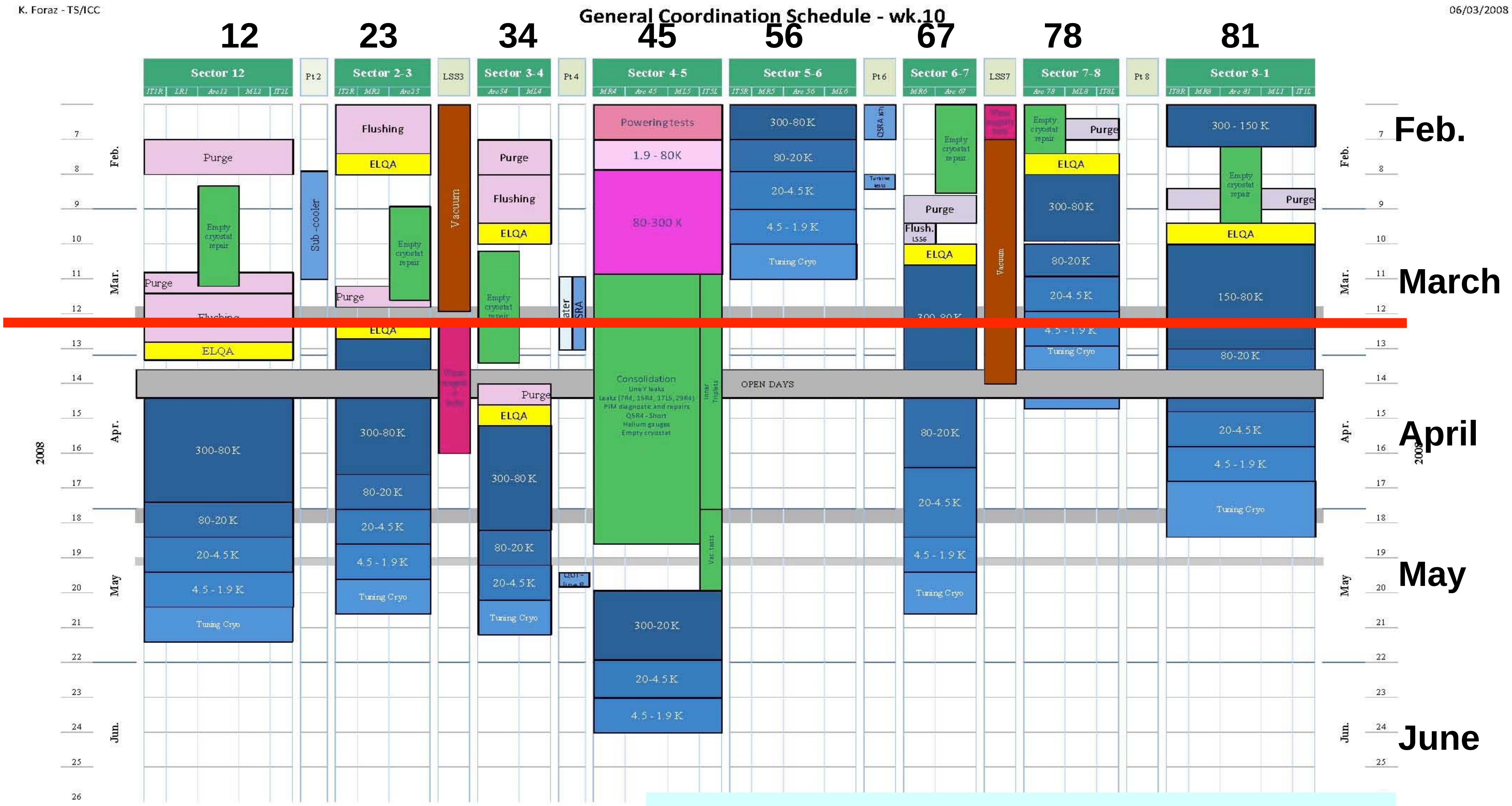
High lumi phase

10^{34} $cm^{-2}s^{-1}$

pp collisions at 14 TeV

- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

LHC cool-down schedule



Collisions like middle of June+ 2 months

LHC 2008

Anticipated luminosity in 2(

- Approx 30 days of beam time to establish first collisions
- 1 to N to 43 to 156 bunches per beam
- N bunches displaced in one beam for LHCb
- Pushing gradually one or all of:
  - Bunches per beam
  - Squeeze
  - Bunch intensity

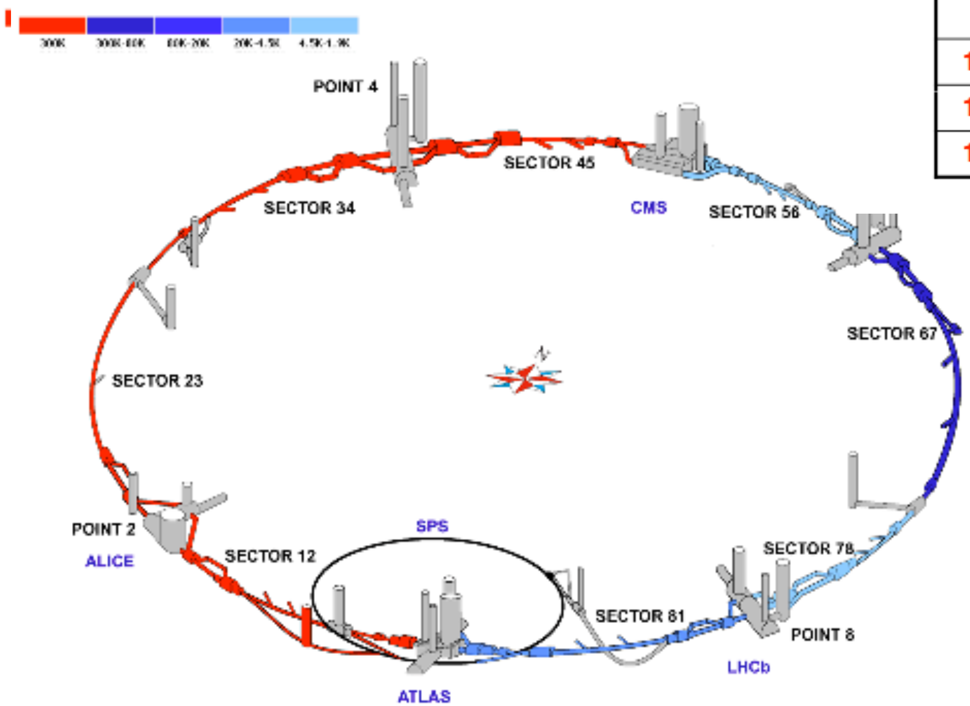
Each step lasts ~week

IP 1 & 5

Bunches	β*	I_b	Luminosity	Pileup	Minbias rate
1 x 1	18	10^{10}	10^{27}	Low	55 in ~10^4 xings
43 x 43	18	3 x 10^{10}	3.8 x 10^{29}	0.05	20 kHz in 5.10^5
43 x 43	4	3 x 10^{10}	1.7 x 10^{30}	0.21	60 kHz in 5.10^5
43 x 43	2	4 x 10^{10}	6.1 x 10^{30}	0.76	200 kHz in 5.10^5
156 x 156	4	4 x 10^{10}	1.1 x 10^{31}	0.38	400 kHz in ~10^7
156 x 156	4	9 x 10^{10}	5.6 x10^{31}	1.9	2MHz in ~10^7
156 x 156	2	9 x 10^{10}	1.1 x10^{32}	3.9	4MHz in ~10^7

All CMS5 Feb08 tsv 10

Sector cooldown status
Tuesday evening 4/1/08



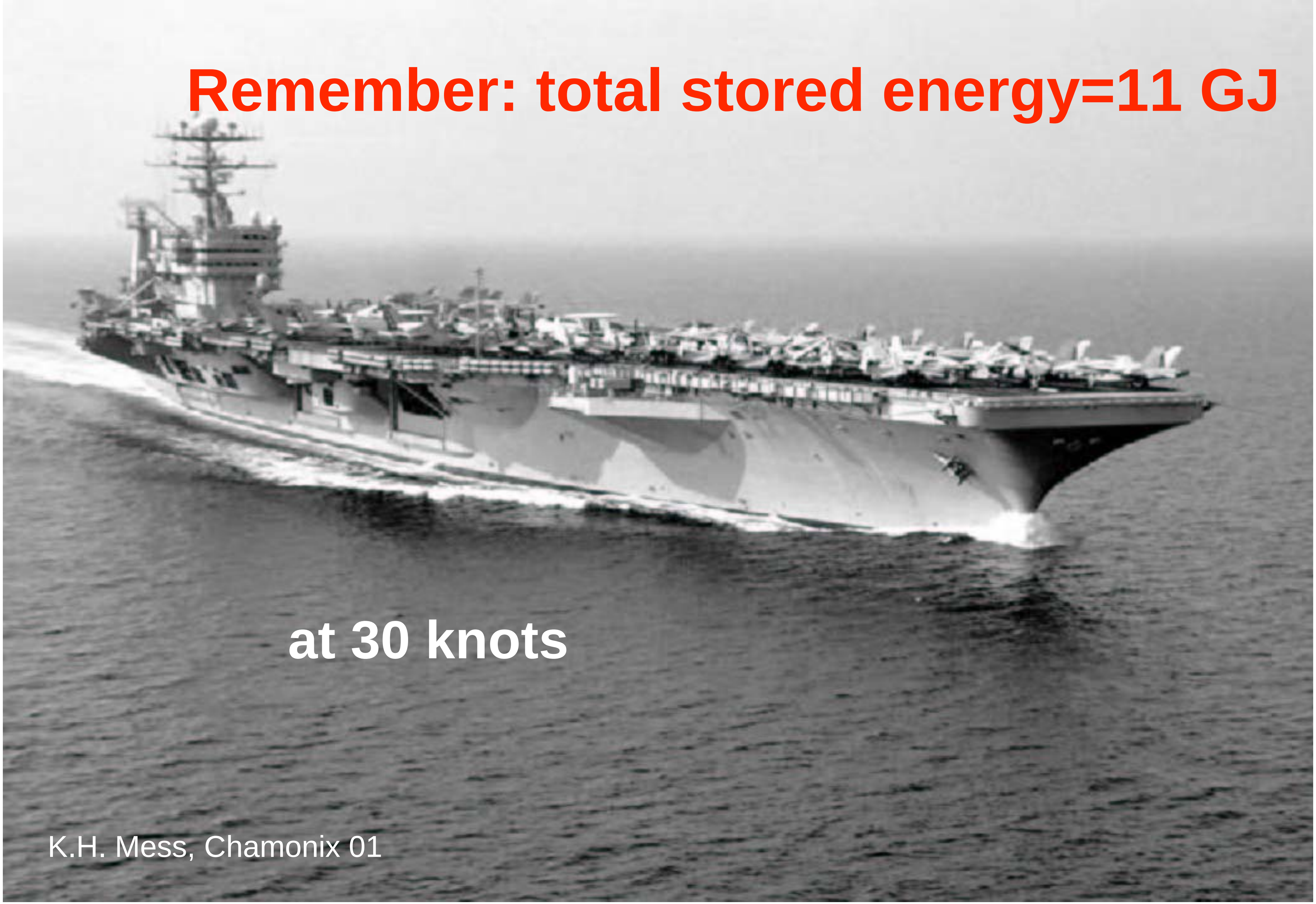
O(10-100) pb^{-1} in the first year

Presently the big question is
What energy will we start???
10 TeV? 12 TeV? Not 14 TeV!!!

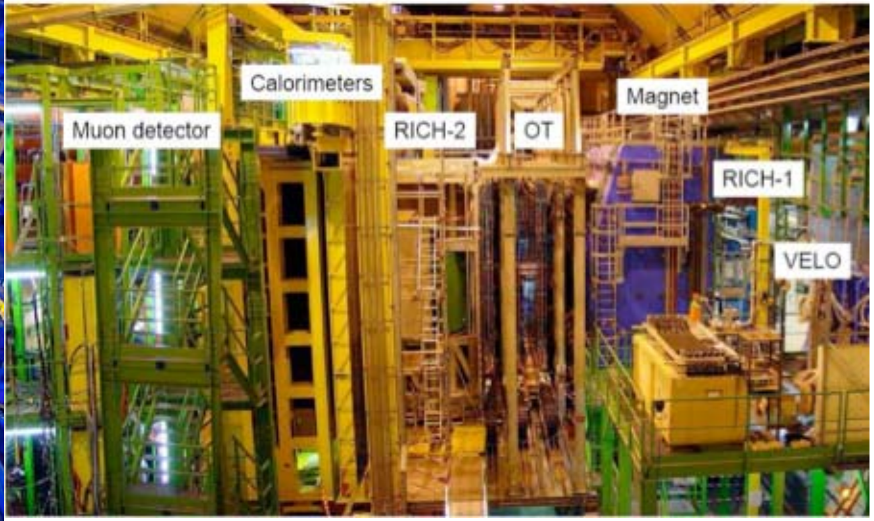
optimistic LHC schedule

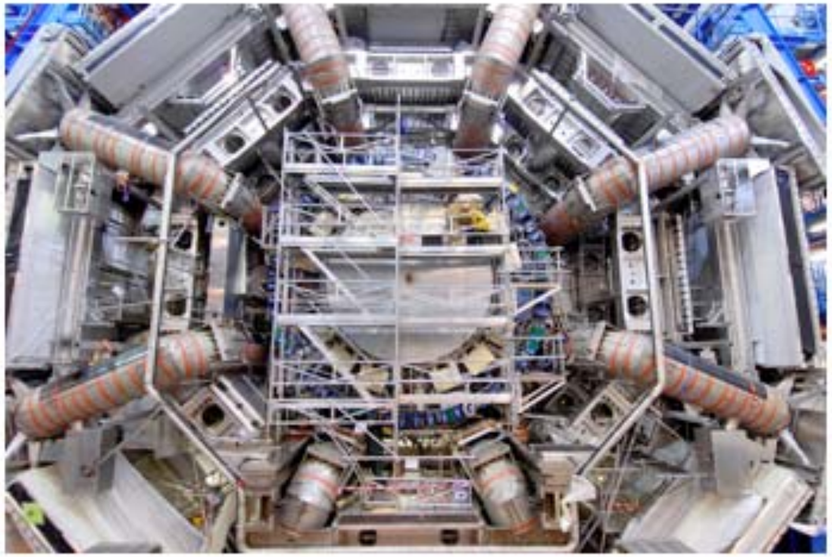
F. Zimmerman
Japanese physics soc.
March 24 '08

- whole ring cold by mid June
- inject first beam in early July
- make compromise between speed of commissioning & collision energy in order to get to physics as early as possible & to give operations teams some margin for error during early operation
- beam energy between 5 and 6 TeV; value to be decided by end of April
- if all goes well, collisions in late August or September?!


Remember: total stored energy=11 GJ
at 30 knots
K.H. Mess, Chamonix 01

Detectors are well on their way

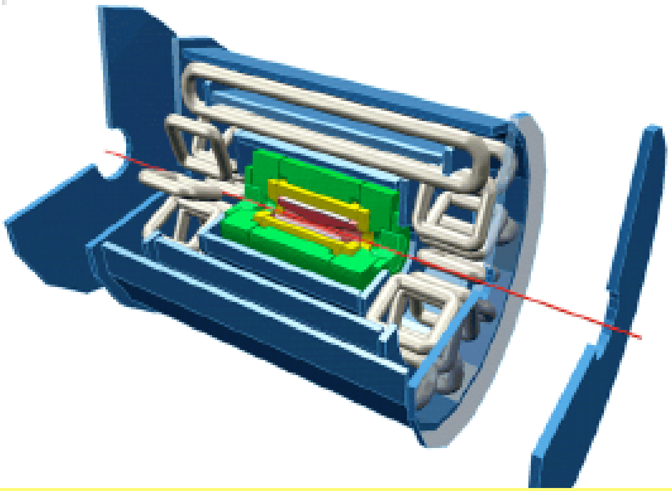


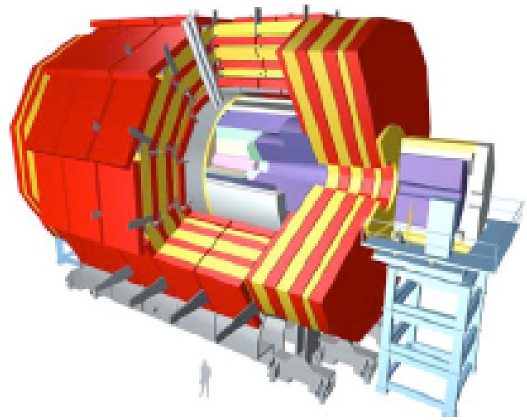


Gearing up for first collisions…

General Purpose Detectors at the LHC

ATLAS A Toroidal LHC ApparatuS **CMS** Compact Muon Solenoid





In total about

~100 000 000 electronic channels

Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

Amount of data of just one collisions

>1 500 000 Bytes

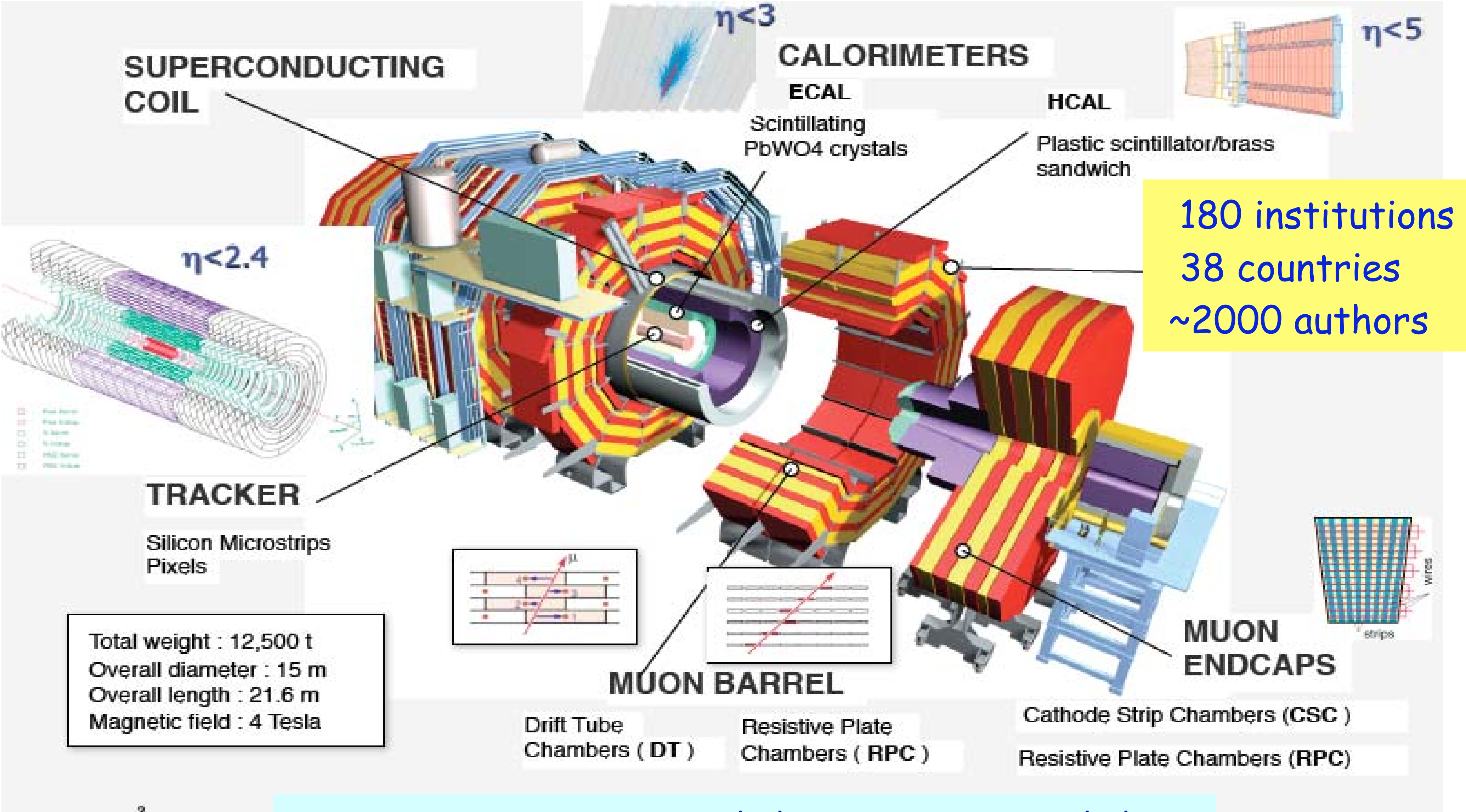
Trigger (online event selection)

Reduce 40 MHz collision rate to ~100 Hz data recording rate

Readout to disk

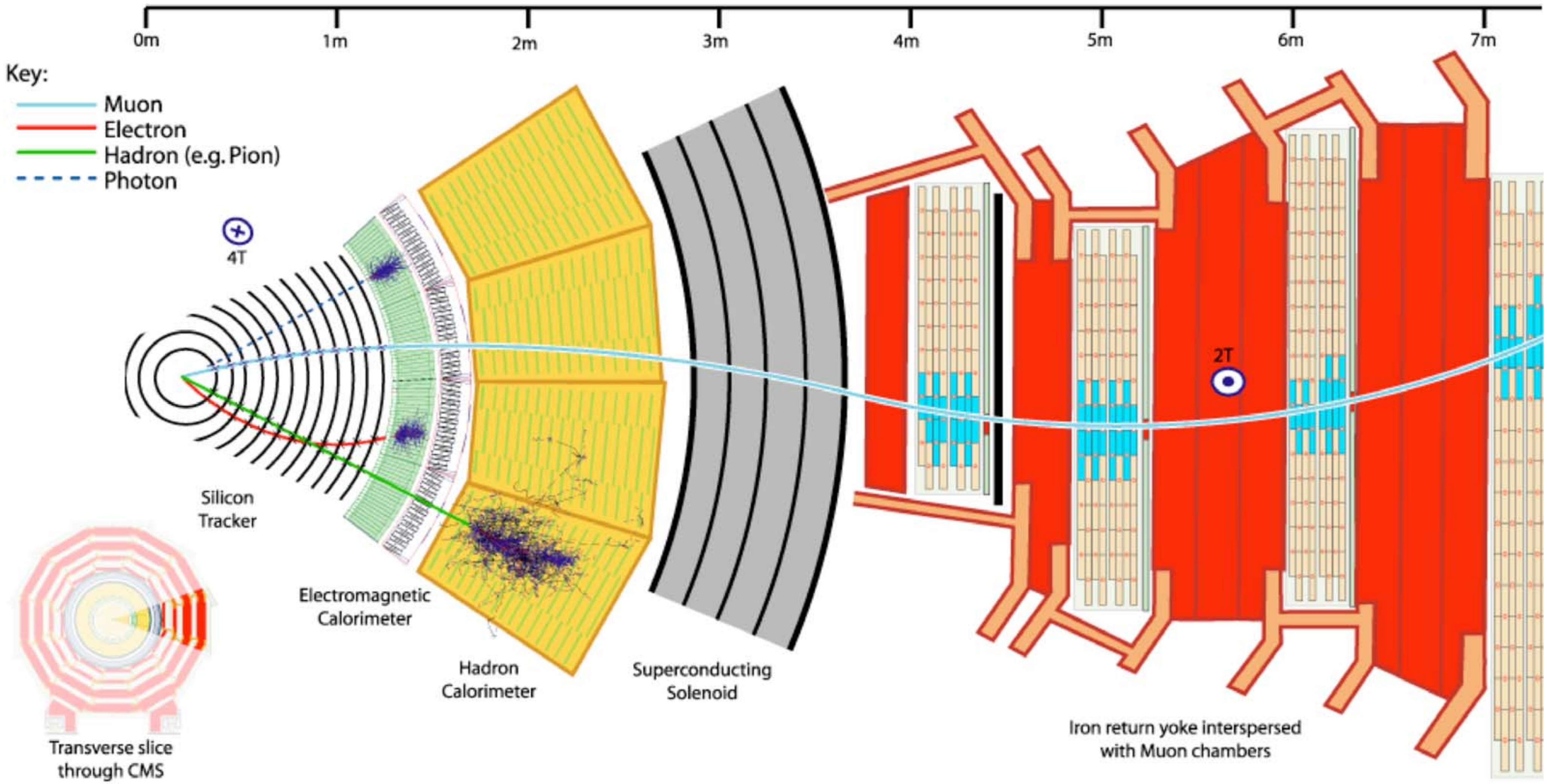
100 collisions/sec ⇒ pentaBytes of data/year

The CMS Experiment



Acceptance: Calorimetry |η| <5.0 Tracking |η|<2.4

A Collider Detector



CMS Status

Si Tracker ready

Pixel detector being completed

Barrel ECAL installed
Endcaps to be installed
April and June 08

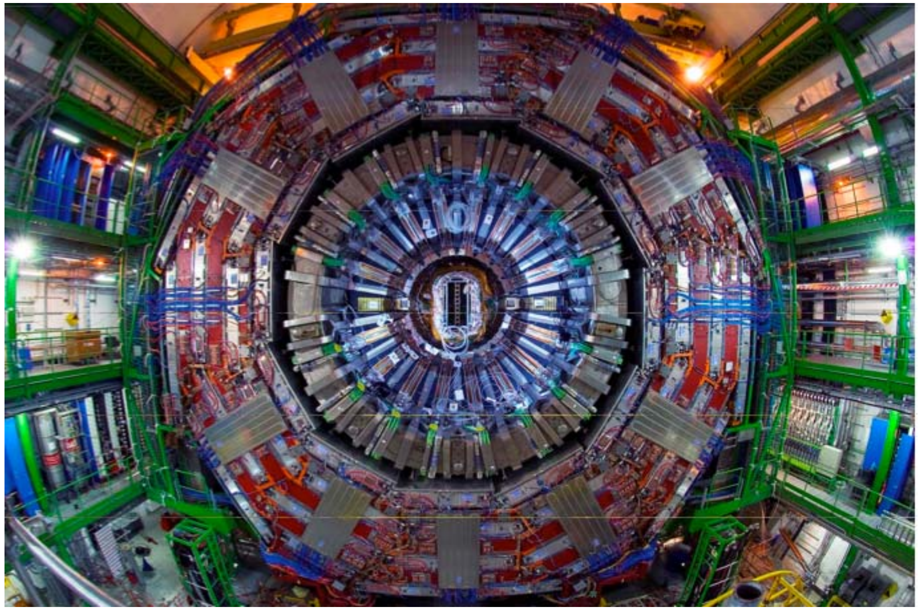
HCAL ready since 2006

Muon detectors installed

March 08
All elements have been lowered

180 institutions
38 countries
~2000 authors

The last pieces have been lowered

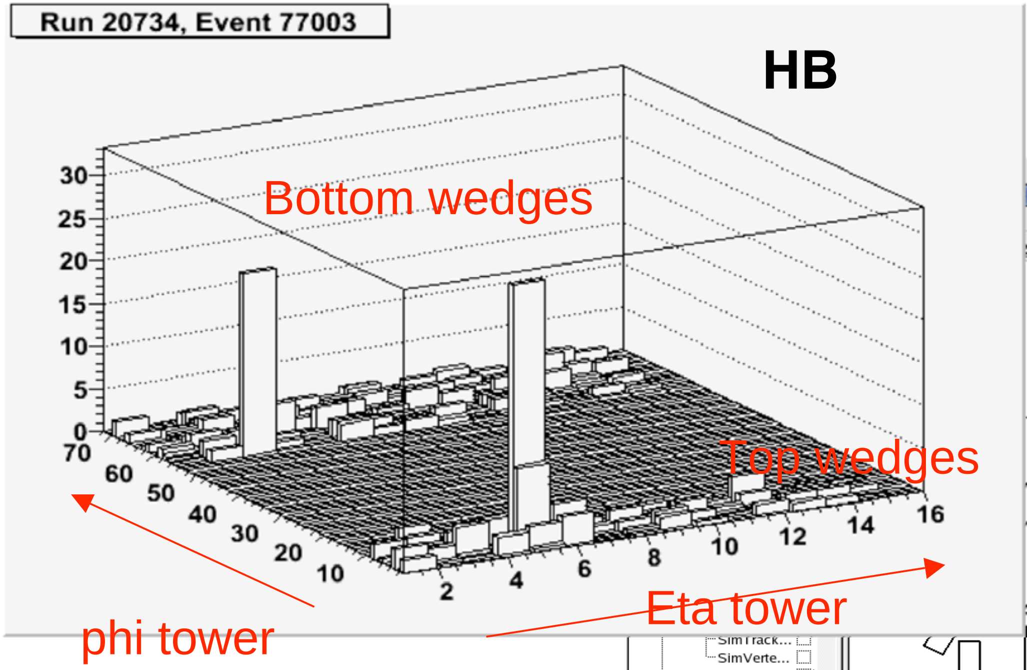


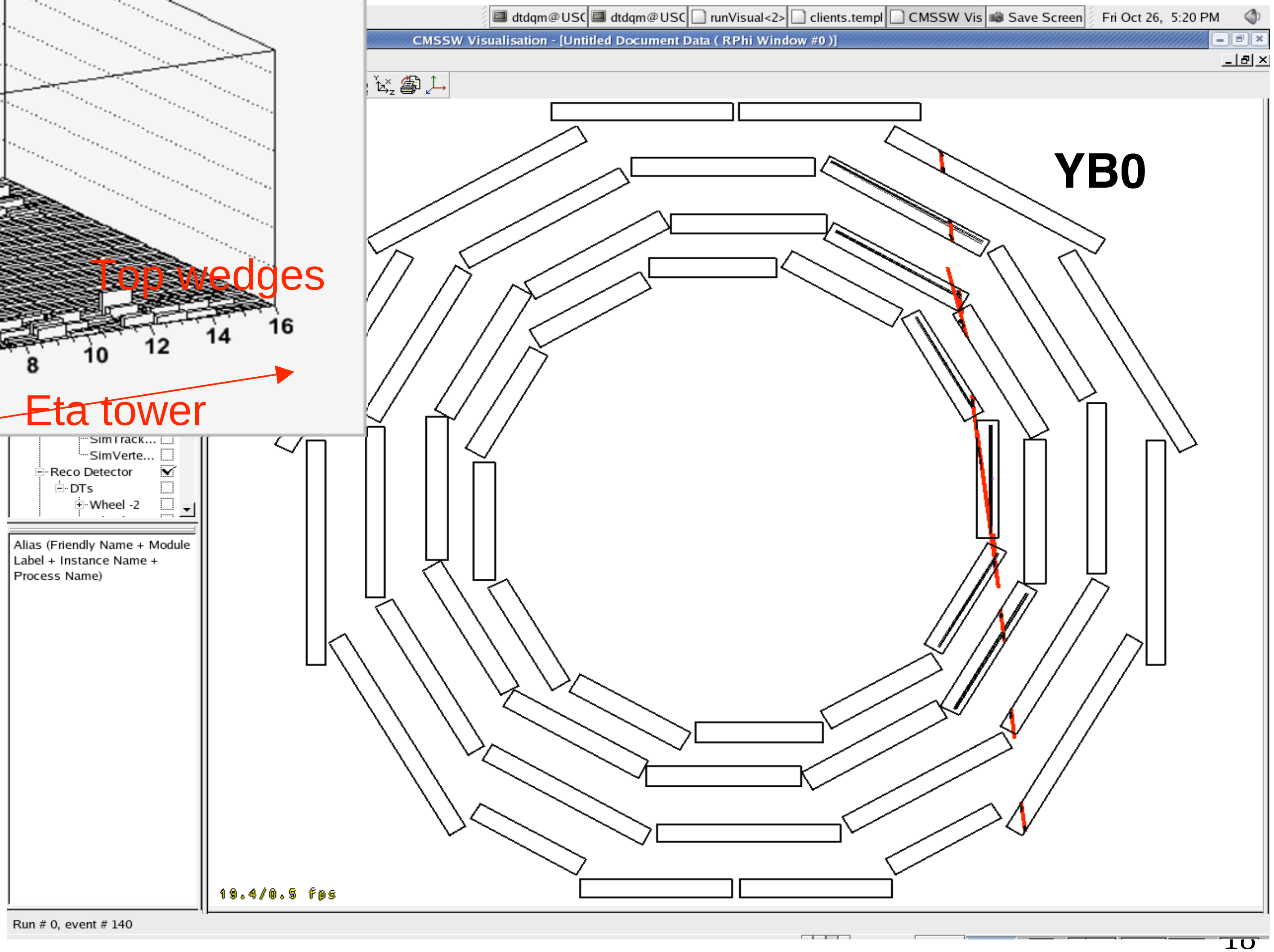
Central tracker installed

Final endcaps lowered

Still pixel detector/ECAL endcaps

Cosmics in central barrel ring:

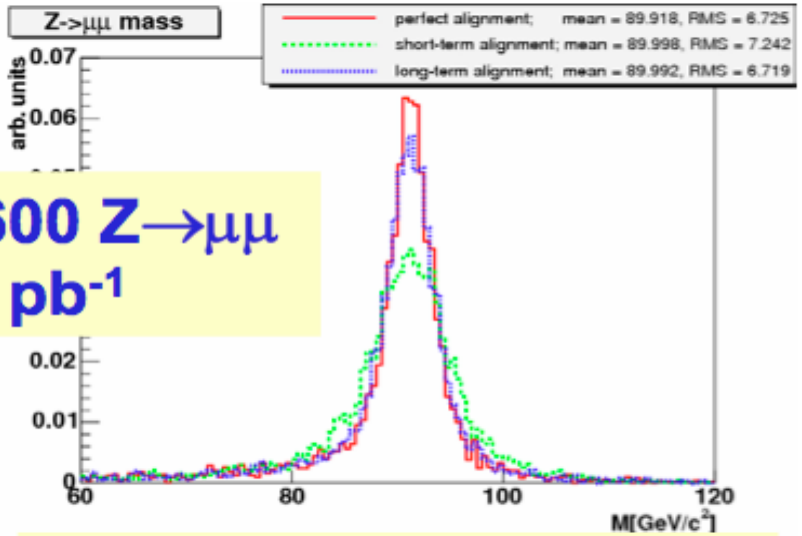




Detector Performance at Startup

- **Tracker Alignment**

	Expected Day 0	Goals for Physics
Tracker alignment	20-200 μm in Rϕ	$\mathcal{O}$(10 μm)



600 Z→μμ / pb^{-1}

Z peak visible even with initial (rough) alignment

- **Calorimeter calibration**

	Expected Day 0	Ultimate goals
ECAL uniformity	~4%	< 1%
Lepton energy	0.5-2%	0.1%
HCAL uniformity	2-3%	< 1%
Jet energy	<10%	1%

ECAL, HCAL: intercalibration using azimuthal symmetry (min bias).

ECAL: π^0 calibration, then electrons

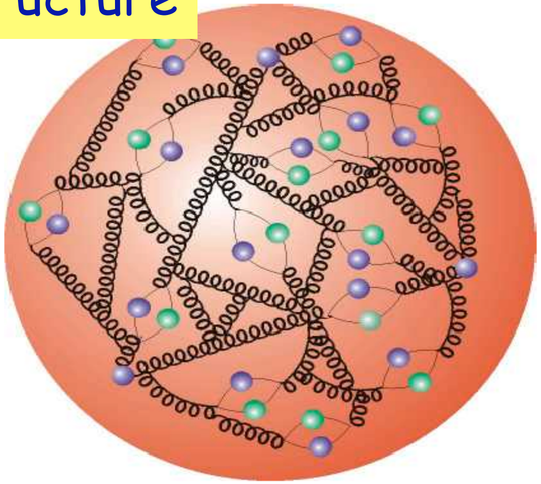
HCAL: di-jet balancing; check with photon+jets; Jet Energy Scale set by W→jj in top events

ATLAS ⇔ CMS

	ATLAS	CMS
Magnet(s)	Air-core toroids + solenoid in inner cavity	Solenoid
	Calorimeters in field-free region	Calorimeters inside field
	4 magnets	1 magnet
Inner detector	Si pixels and strips	Si pixels and strips
	TRT → particle identification	No particle identification
	B = 2 T	B = 4 T
	$\sigma/p_T \sim 3.4 \times 10^{-4} p_T(\text{GeV}) \oplus 0.01$	$\sigma/p_T \sim 1.5 \times 10^{-4} p_T(\text{GeV}) \oplus 0.008$
EM calorimeter	Lead-liquid argon	$PbWO_4$ crystals
	$\sigma/E \sim 10\%/\sqrt{E(\text{GeV})}$	$\sigma/E \sim 3-5\%/\sqrt{E(\text{GeV})}$
	Longitudinal segmentation	No longitudinal segmentation
HAD calorimeter	Fe-scintillator + Cu-liquid argon	Brass-scintillator
	$\geq 10\ \lambda$	$\geq 7.2\ \lambda$ + tail catcher
	$\sigma/E \sim 50\%/\sqrt{E(\text{GeV})} \oplus 0.03$	$\sigma/E \sim 100\%/\sqrt{E(\text{GeV})} \oplus 0.05$
Muon spectrometer	Chambers in air	Chambers in solenoid return yoke (Fe)
	$\sigma/p_T \sim 7\%$ at 1 TeV	$\sigma/p_T \sim 5\%$ at 1 TeV
	spectrometer alone	combining spectrometer and inner detector

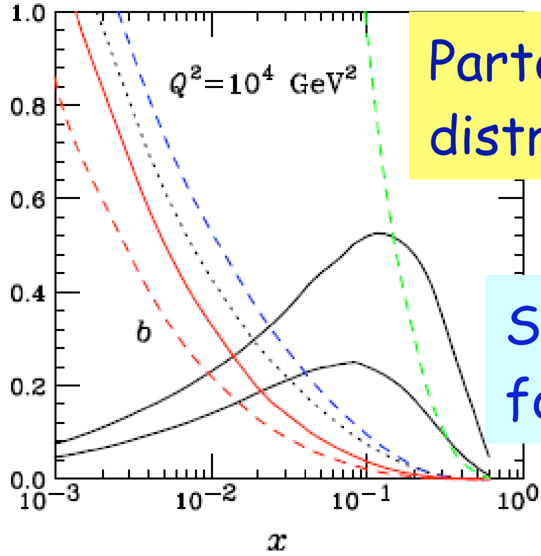
pp collisons : complications…

Protons have structure

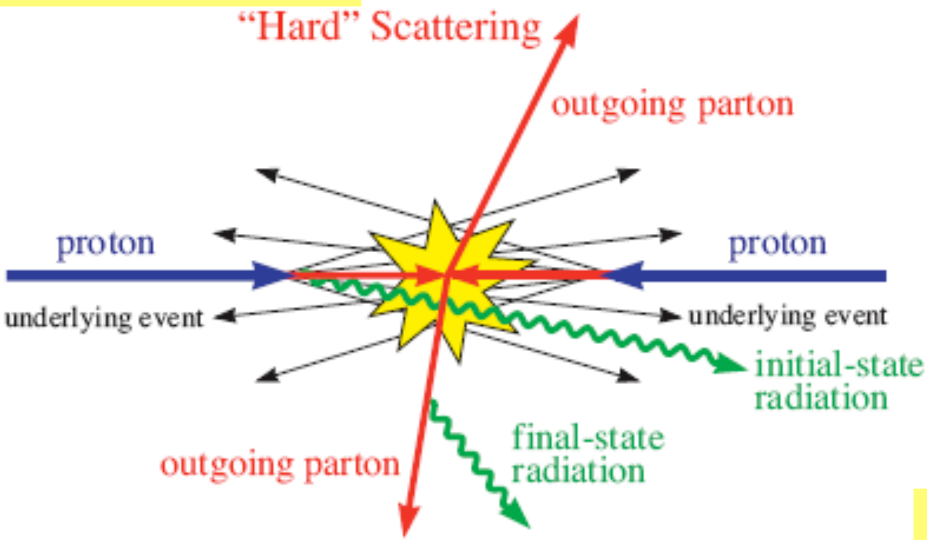


Parton distributions

Strong role for HERA



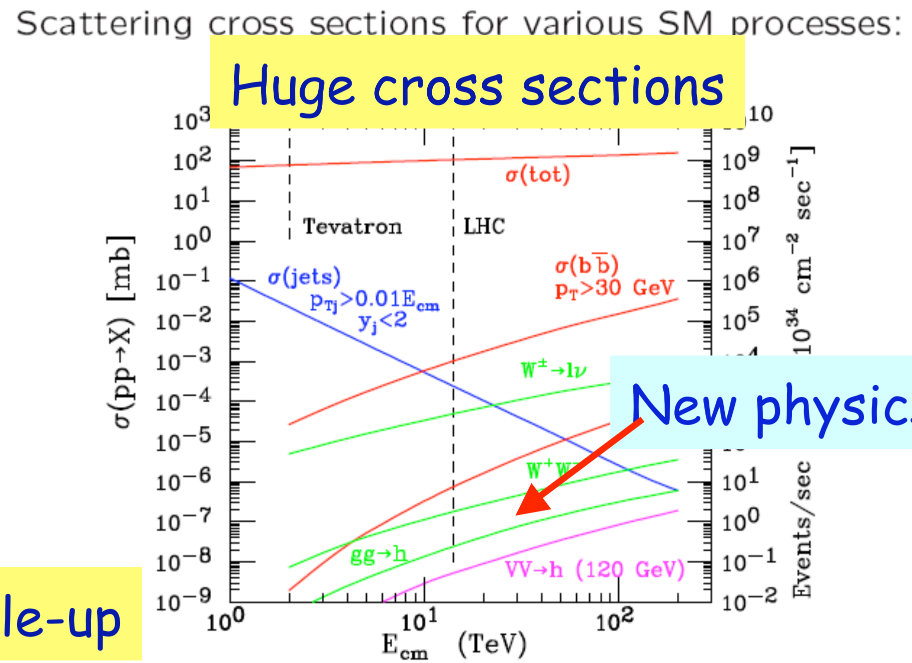
Underlying event



Huge cross sections

New physics ?

Pile-up



Start-up Physics 2008

With the first physics run in 2008 ($\sqrt{s}$ = 14 TeV) ....

Expect 0.1-1 fb^{-1}

1 fb^{-1} (100 pb^{-1}) ≡ 6 months (few days) at L= 10^{32} $cm^{-2}s^{-1}$
with 50% data-taking efficiency
→

Channels (examples ...)	Events to tape for 100 pb^{-1} (per expt: ATLAS, CMS)	Total statistics from some of previous Colliders
$W \to \mu \nu$	~ 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu \mu$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
tt → W b W b → $\mu \nu$ +X	~ 10^4	~ 10^4 Tevatron
QCD jets p_T > 1 TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	

With these data:

- Understand and calibrate detectors in situ using
  e.g. - Z → ee, μμ tracker, ECAL, Muon cham
  - tt → blν bjj jet scale from W → jj, b-
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, Q
  (also because omnipresent backgrounds to New Ph

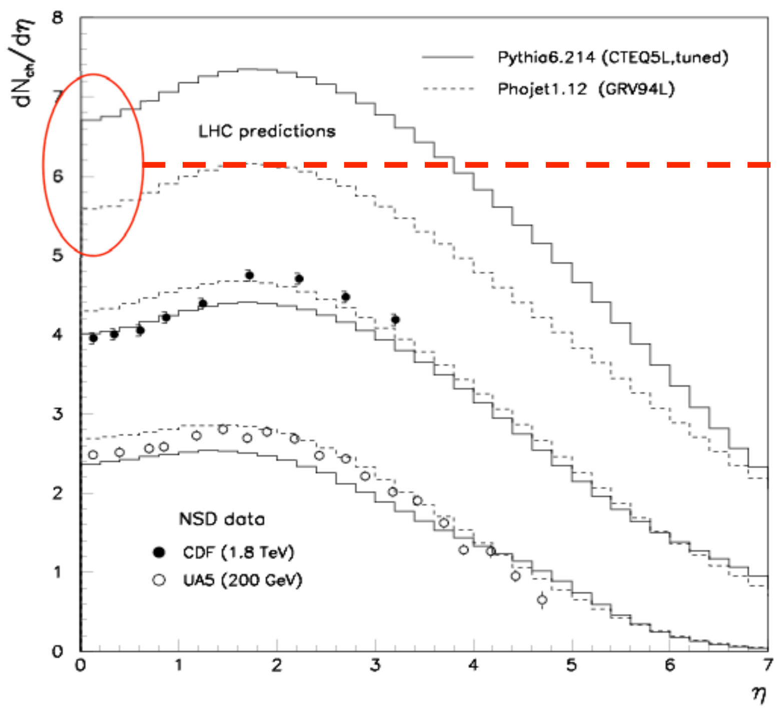
In 2008 we have to rediscover the Standard Model at >10 TeV and compare to calculations and generators.
...And tune generators

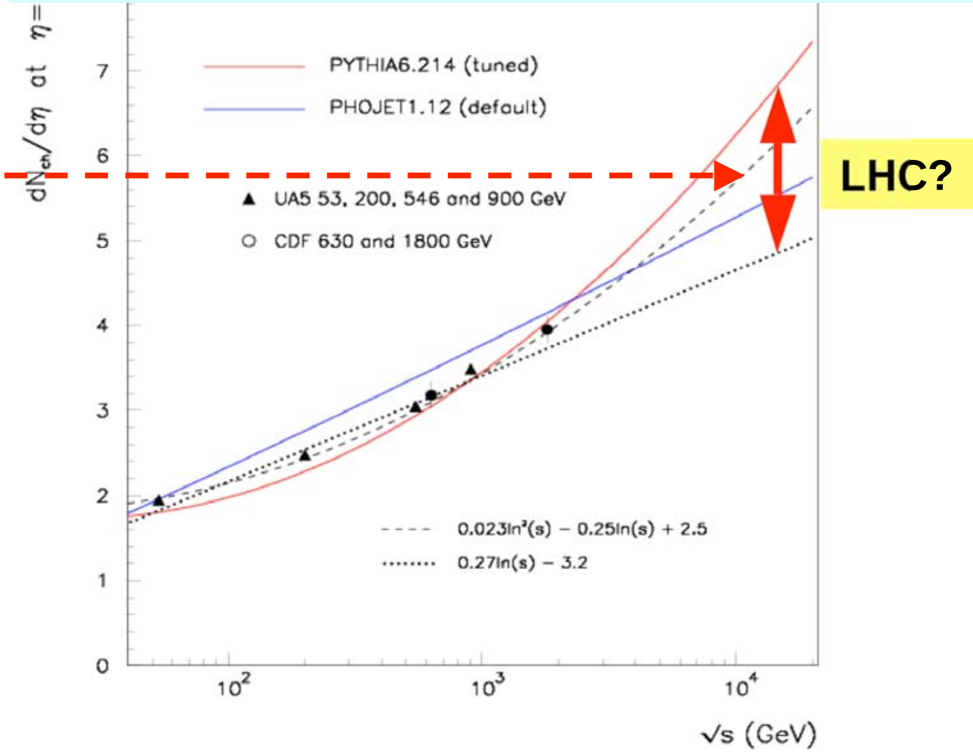
→ prepare the road to discovery ...... it will take time ...

Early Soft Minimum-Bias Measurements

Charged particle density

The pile-up for the future: ~4 events at low and ~20 events at high luminosity





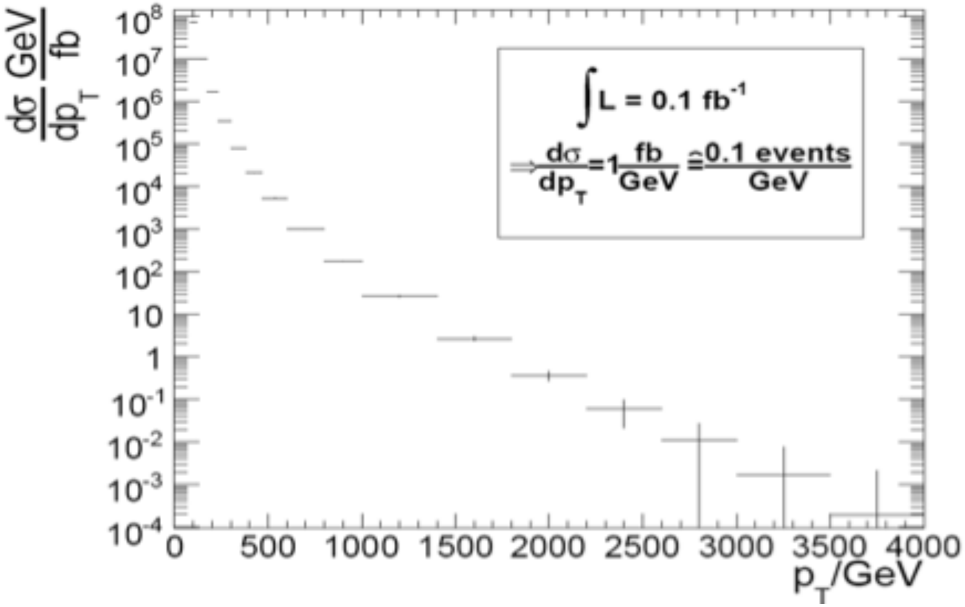
- Energy dependence of dN/dη ?
- Vital for tuning UE model
- Only requires a few thousand events.

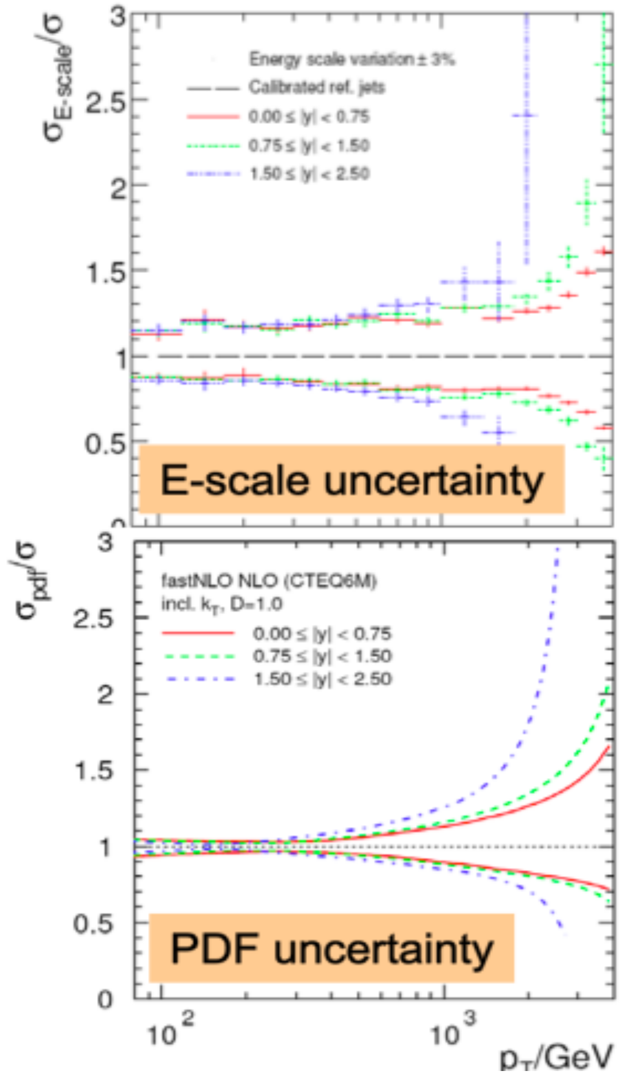
- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a ln(s) dependence.

At 14 TeV startup!!

Jets

- With 100 pb^{-1}: reach ~2 TeV (E_T)
- With 1fb^{-1}: reach ~3 TeV
  - ~10^4 events with E_T> 1 TeV
- Systematic uncertainties:
  - detector: jet energy scale
  - theory: PDFs



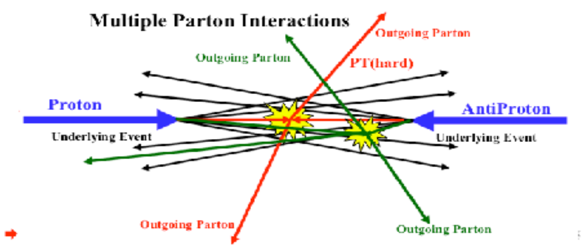


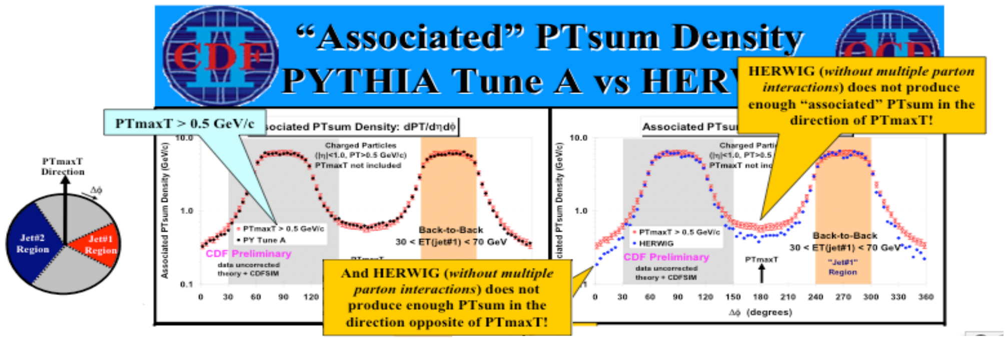
Underlying event at the LHC

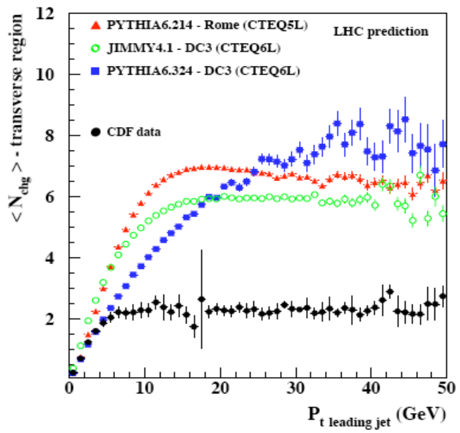
- There's also a great deal of uncertainty regarding the level of underlying event at 14 TeV, but it's clear that the UE is larger at the LHC than at the Tevatron
- Should be able to establish reasonably well with the first collisions in 2008
  - ~20M MB events will allow overlap with hard scatter regime (~30 GeV/c)
- We have a strategy in CMS to measure the underlying event properties

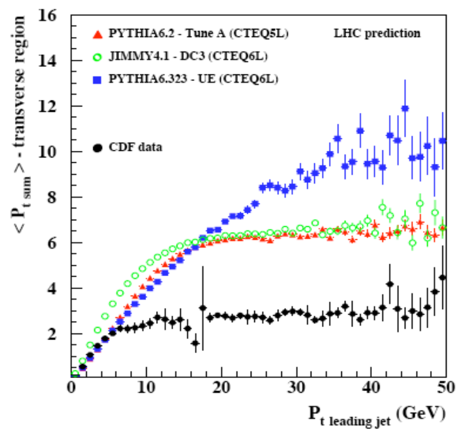
The structure of the underlying event

Mounting experimental evidence (R.Field, CDF) that the UE is the result of **multiple semi-hard (minijet-like) interactions**





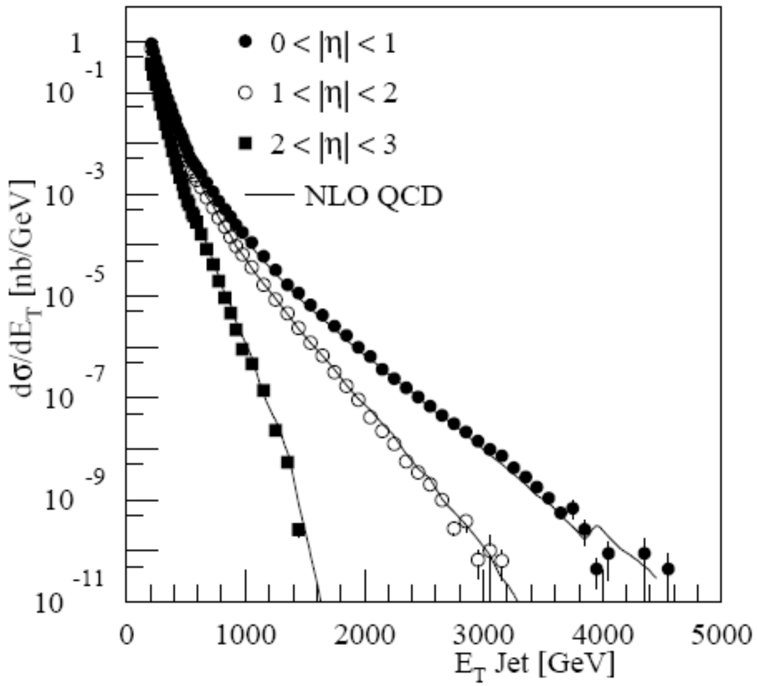




QCD Studies @ LHC

E.g. Jet Physics

Huge cross sections:
Eg for 1 fb^{-1} ~ 10000 events with E_T> 1 TeV
100 events with E_T> 2 TeV



- PDFs
- Jet shape
- Underlying event
- α_s?
- Diffraction
- BFKL studies
- low-x
- New physics?
-

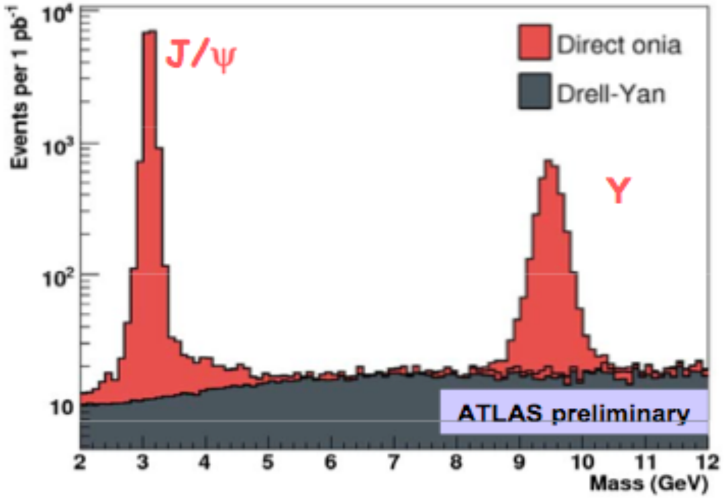
•Understanding QCD at 14 TeV will be one of the first topics at LHC

…and a whole b-physics and top-physics program

Resonances

The first peaks …

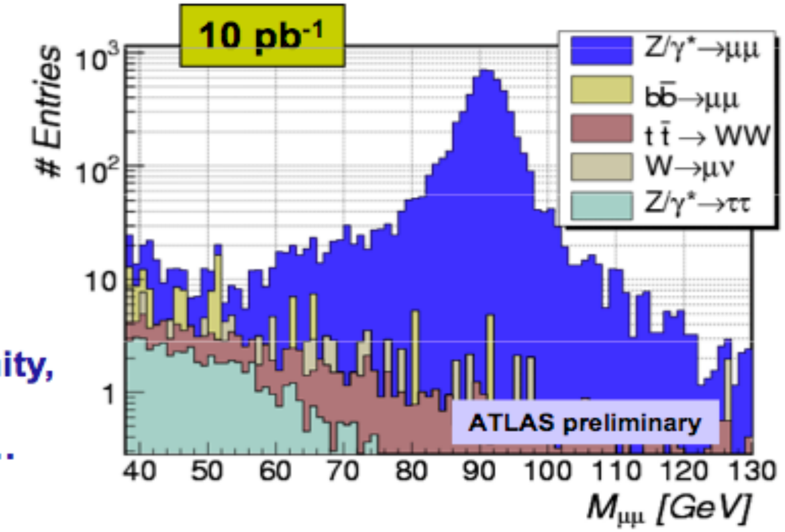
1 $pb^{-1} \equiv$ 3 days at 10^{31} at 30% efficiency



After all cuts:
~ 4200 (800) J/ψ (Y) → μμ evts per day at L = 10^{31}
(for 30% machine x detector data taking efficiency)
~ 15600 (3100) events per pb^{-1}

→ tracker momentum scale, trigger performance, detector efficiency, sanity checks, …

After all cuts:
~ 160 Z → μμ evts per day at L = 10^{31}
~ 600 events per pb^{-1}



→ Muon Spectrometer alignment, ECAL uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, …

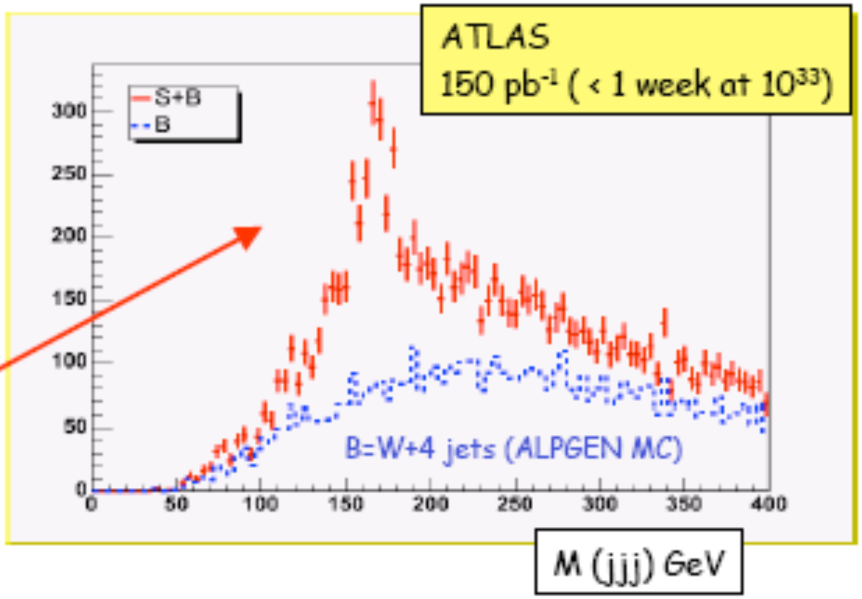
Precision on σ (Z→μμ) with 100 pb^{-1}: <2% (experimental error), ~10% (luminosity)

Top quarks

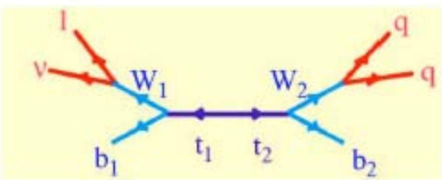
Example of initial measurement : top signal and top mass

First top quarks in Europe!

- Use gold-plated tt → bW bW → blν bjj channel
- Very simple selection:
  - -- isolated lepton (e, μ) p_T > 20 GeV
  - -- exactly 4 jets p_T > 40 GeV
  - -- no kinematic fit
  - -- no b-tagging required (pessimistic, assumes trackers not yet understood)
- Plot invariant mass of 3 jets with highest p_T



Time	Events at 10^{33}	Stat. error δM_{top} (GeV)	Stat. error $\delta\sigma/\sigma$
1 year	3×10^5	0.1	0.2%
1 month	7×10^4	0.2	0.4%
1 week	2×10^3	0.4	2.5%



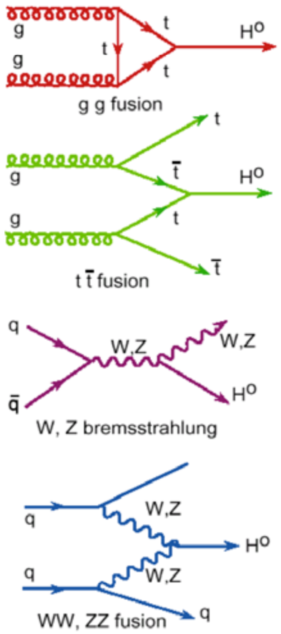
- top signal visible in few days also with simple selection and no b-tagging
- cross-section to ~ 20% (10% from luminosity)
- top mass to ~7 GeV (assuming b-jet scale to 10%)
- get feedback on detector performance :
  m_{top} wrong → jet scale ?
  gold-plated sample to commission b-tagging

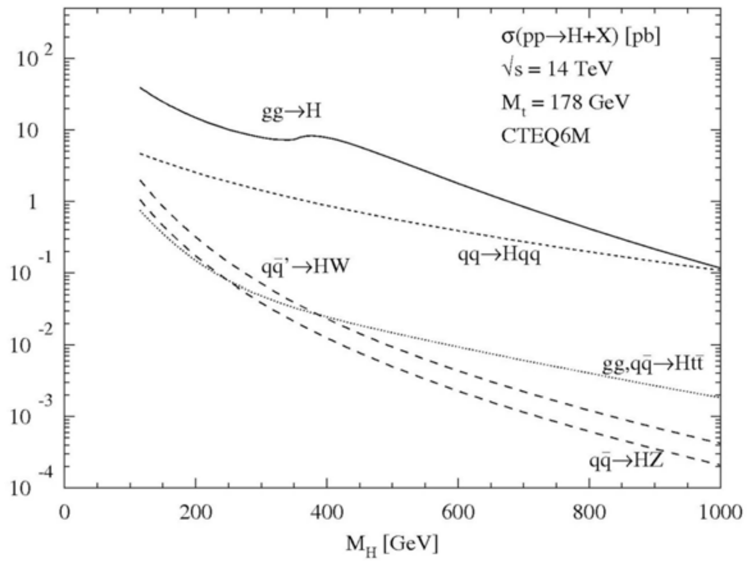
Higgs Physics

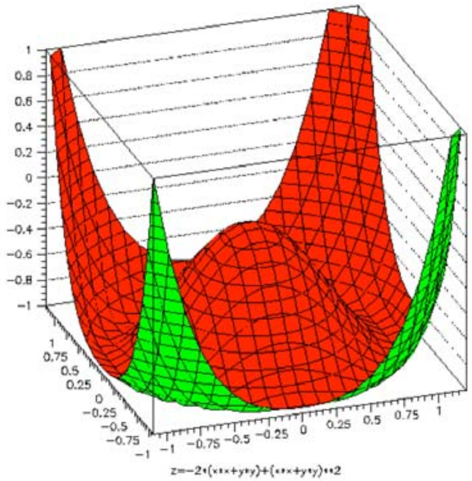
⇒ What is the origin of Electro-weak Symmetry Breaking?

⇒ If Higgs field at least one new scalar particle should exist: The Higgs

One of the main missions of LHC: discover the Higgs for m_H< 1 TeV





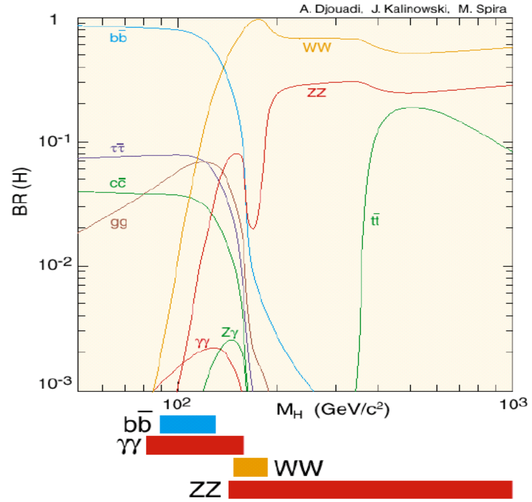


SM Higgs Search Channels

Recent Review:
G. Polesello and ADR
Comptes Rendus Physique 8: 1078-1097,2007.

Low mass $M_H \lesssim 200$ GeV

Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	YES
$H \to bb$			YES	YES
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*, Z \to \ell^+\ell^-$, ℓ=e, μ	YES			
$H \to Z\gamma, Z \to \ell^+\ell^-$, ℓ=e, μ	very low σ			



Intermediate mass
($200 \text{ GeV} \lesssim M_H \lesssim 700$ GeV)

inclusive $H \to WW$
inclusive $H \to ZZ$

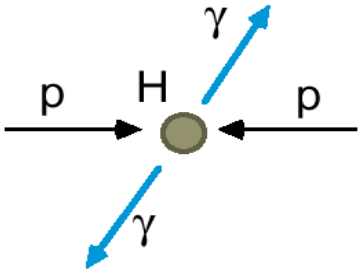
High mass ($M_H \gtrsim 700$ GeV)

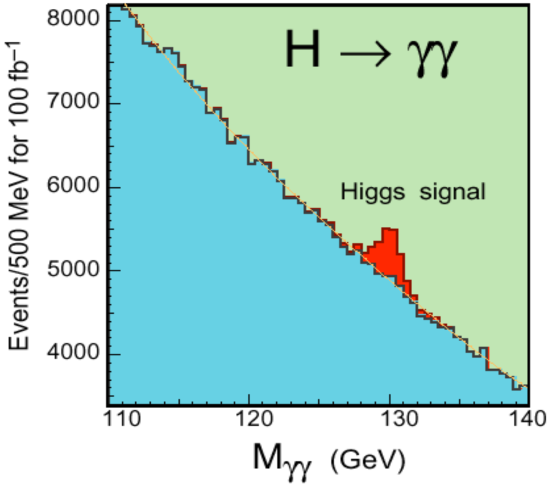
VBF $qqH \to ZZ \to \ell\ell\nu\nu$
VBF $qqH \to WW \to \ell\nu jj$

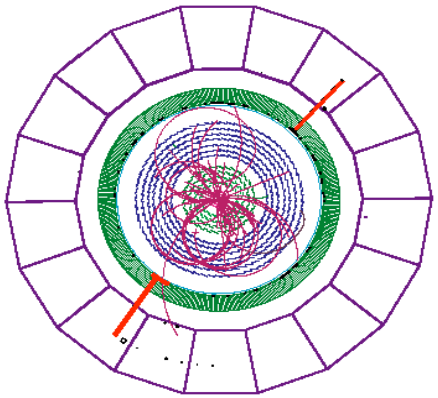
$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

Higgs Searches

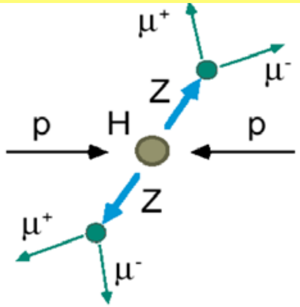
Low M_H < 140 GeV/c²

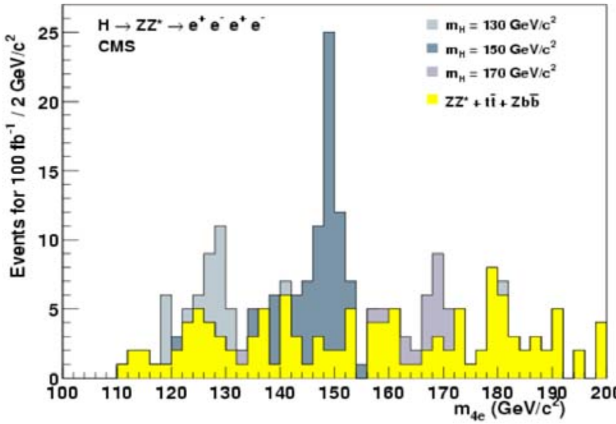


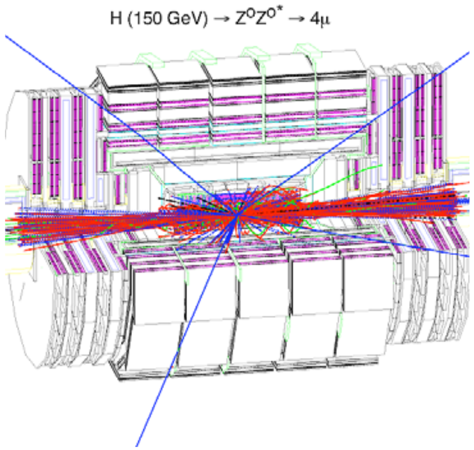




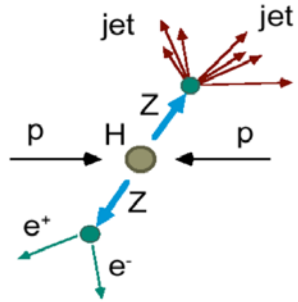
Medium 130<M_H<500 GeV/c²

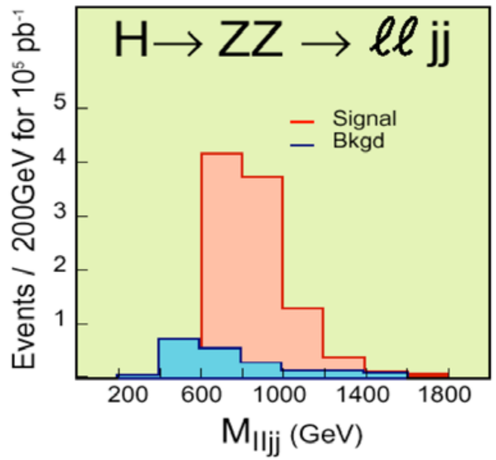


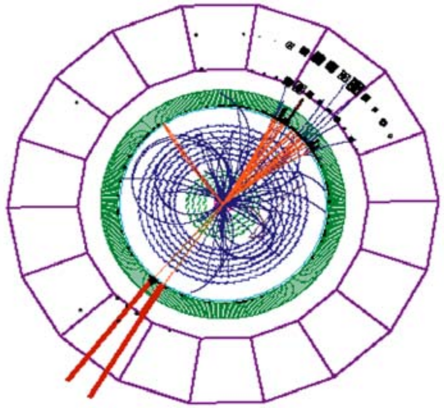




High M_H > ~500 GeV/c²

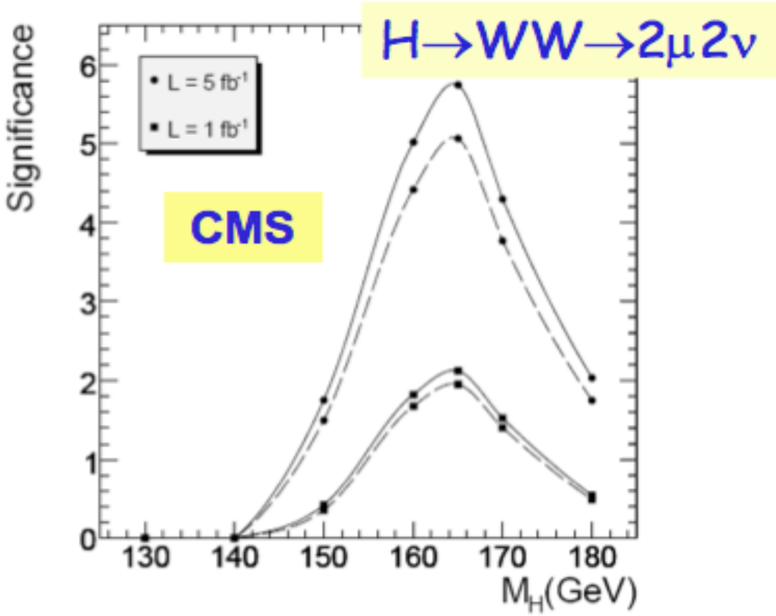


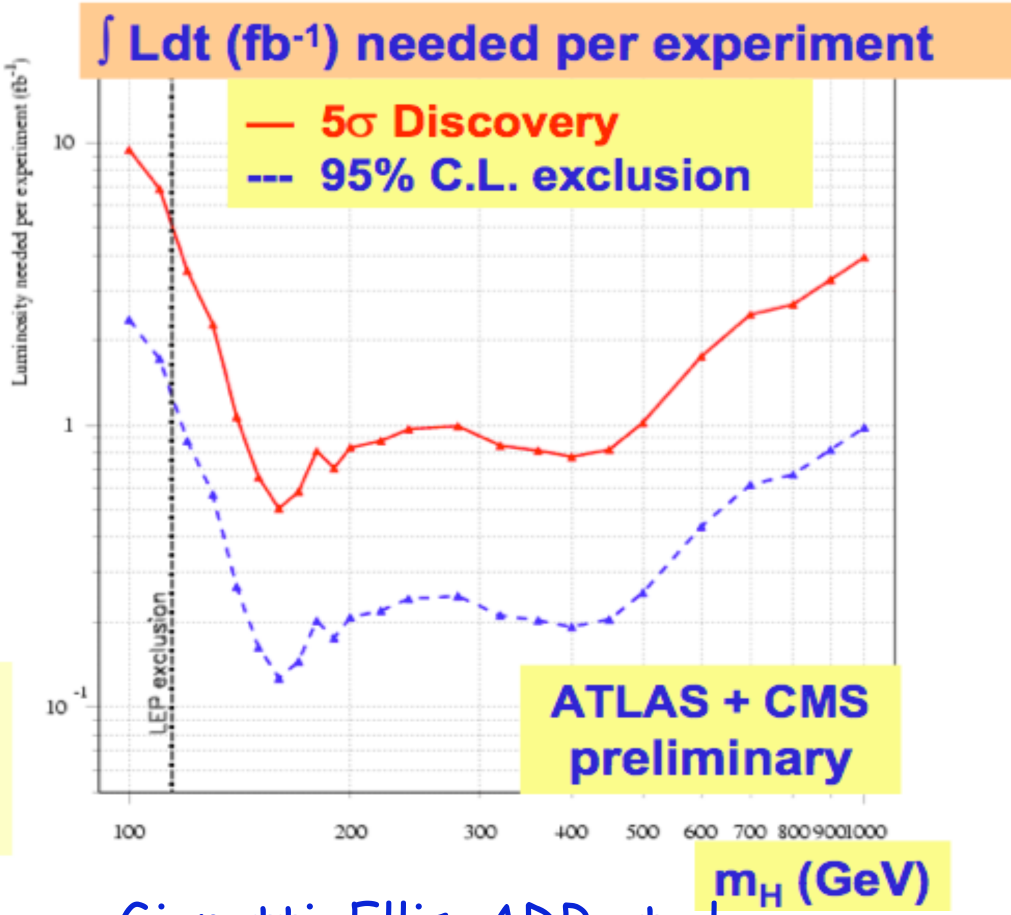




Higgs search with more luminosity

- Possible observation (around $2M_W$); limits over large part of parameter space





Race will be on understanding of detector, physics objects and bkg measurement

Gianotti, Ellis, ADR et al.

Achtung! Tevatron Approaching!!

Remigius Mommsen

[Dec 2007]

- for m_H=115, obs. (exp.) 95% CL relative to σ_{SM} = 5.1 (3.3) [6.2 (4.3)]
- for m_H=160, obs. (exp.) 95% CL relative to σ_{SM} = 1.1 (1.6) [1.4 (1.9)]

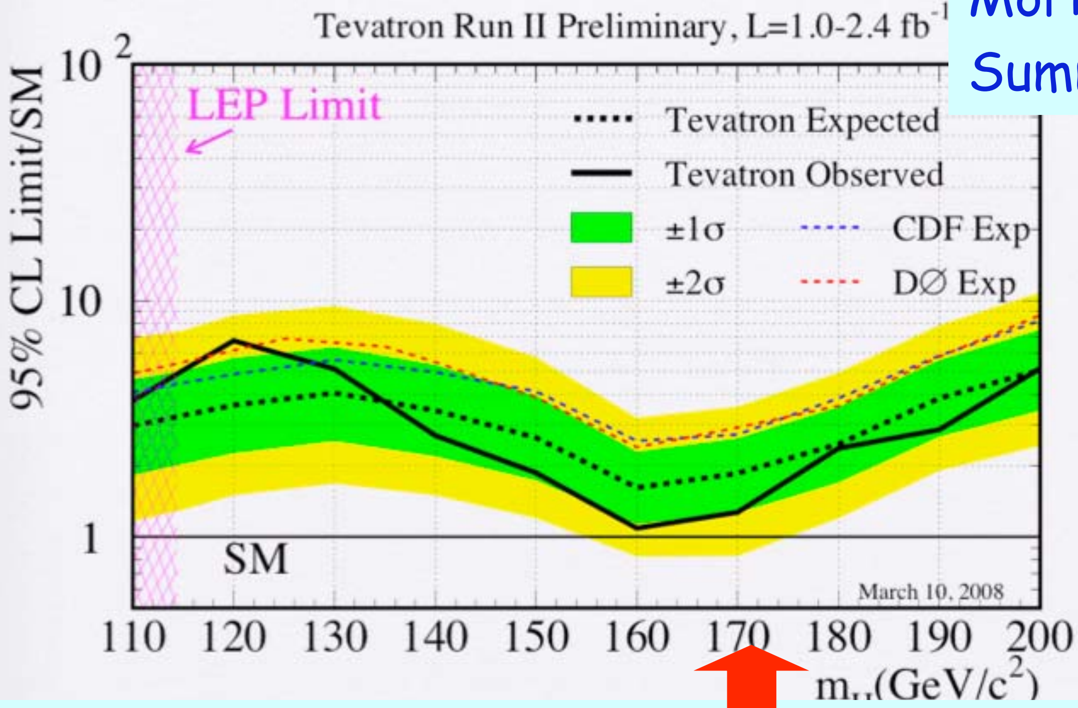
Channels

- WH→eν/μν+bb
- ZH →ee/μμ +bb
- ZH →νν +bb
- H→→γγ
- H→ττ
- H→WW→lνlν

New results for most channels!!

Tevatron Combination

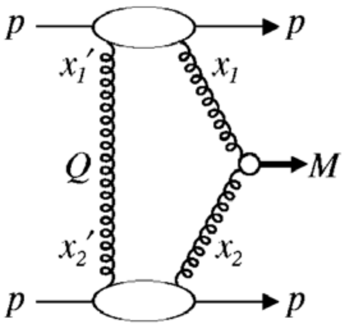
From the Moriond08 QCD Summary speaker

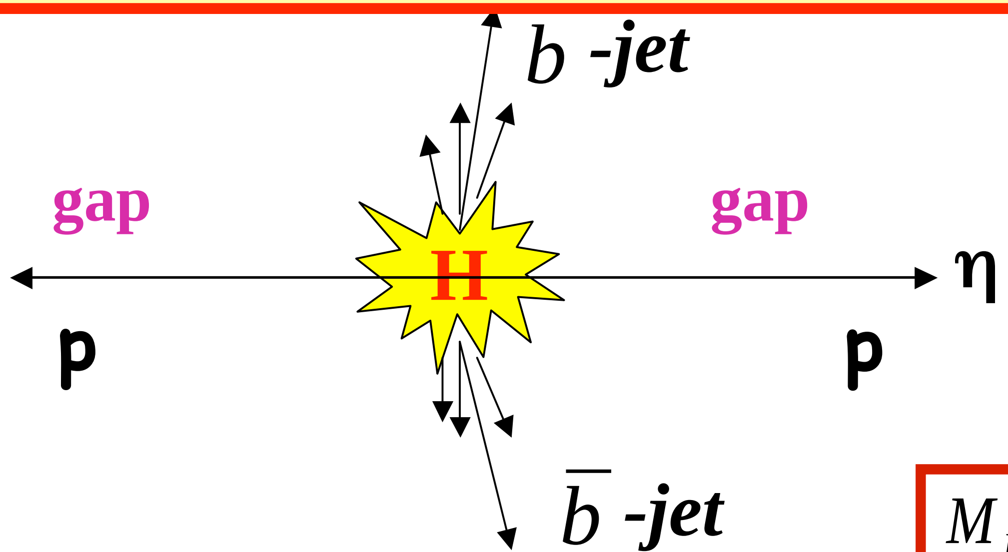


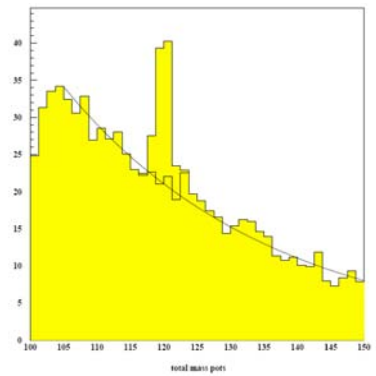
Note: this is coming close to the LHC "early discovery range"

Central Exclusive Higgs Production

Exclusive central Higgs production pp→ p H p : 3-10 fb SM
>100 fb MSSM (high tanβ)

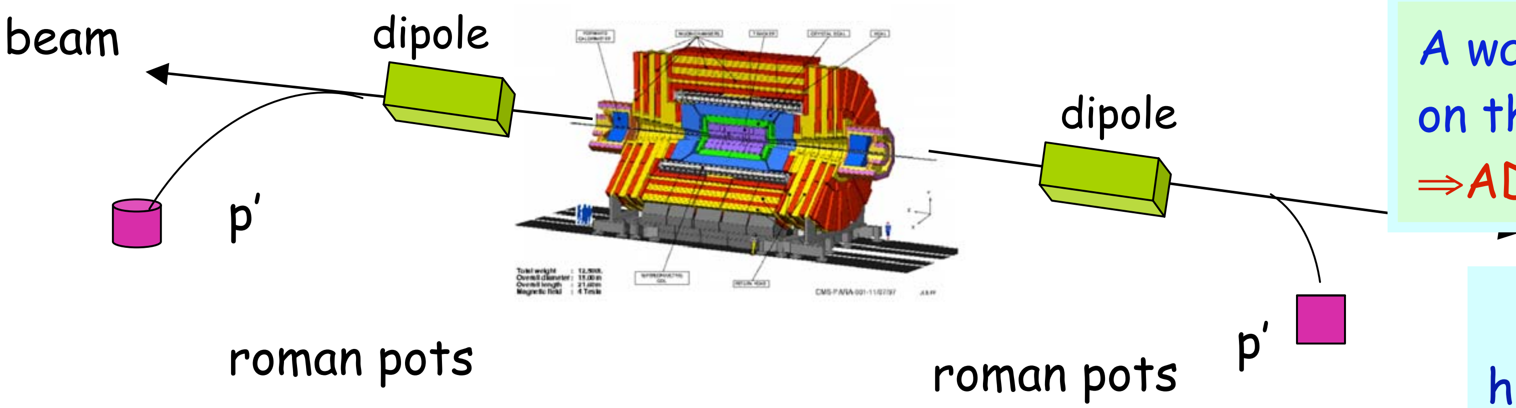






$$M_H^2 = (p + \overline{p} - p' - \overline{p}')^2$$

ΔM = O(1.0 - 2.0) GeV

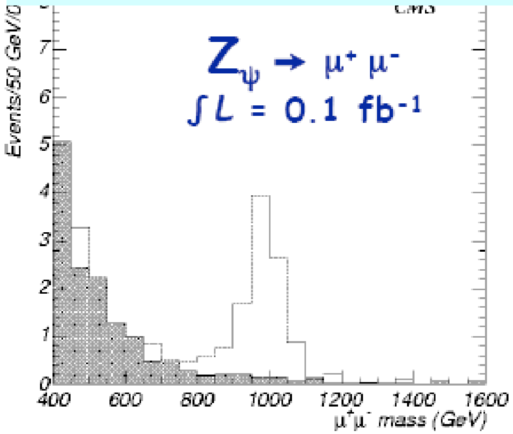


A way to get information on the spin of the Higgs
⇒ADDED VALUE TO LHC

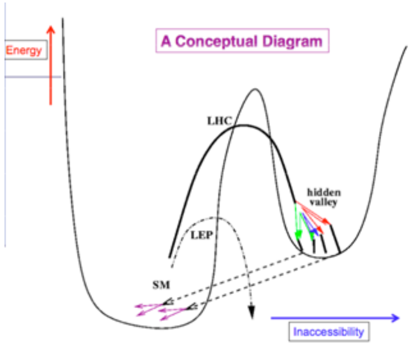
FP420 R&D Project
http://www.fp420.com

BSM Physics at the LHC

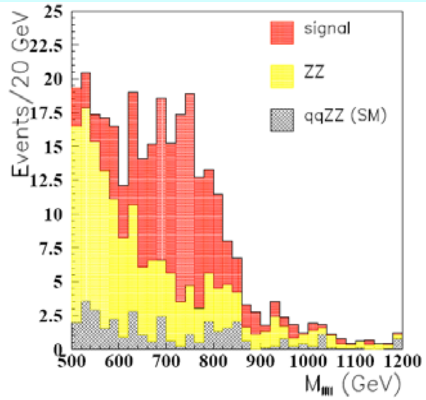
New Gauge Bosons?



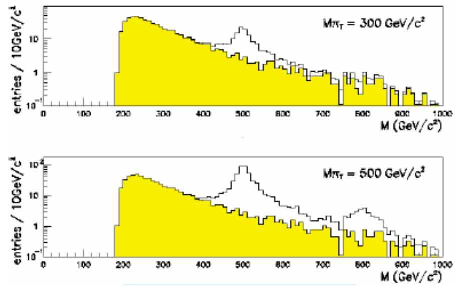
Hidden Valleys?



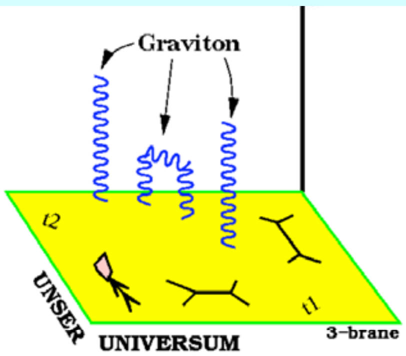
ZZ/WW resonances?



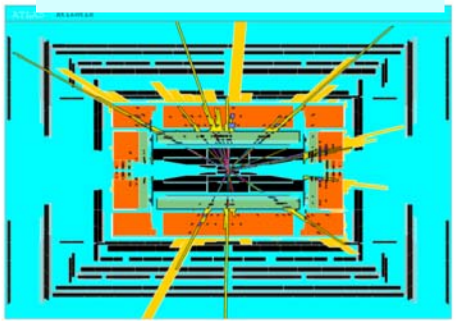
Technicolor?



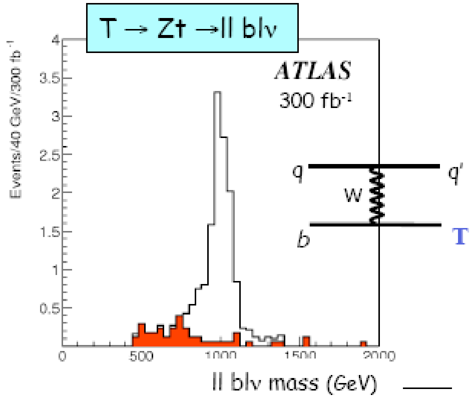
Extra Dimensions?



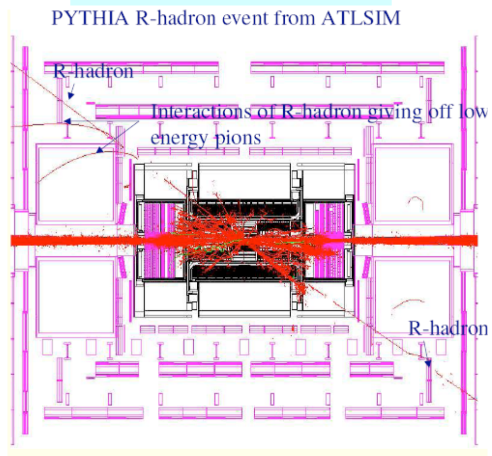
Black Holes???



Little Higgs?



Split Susy?



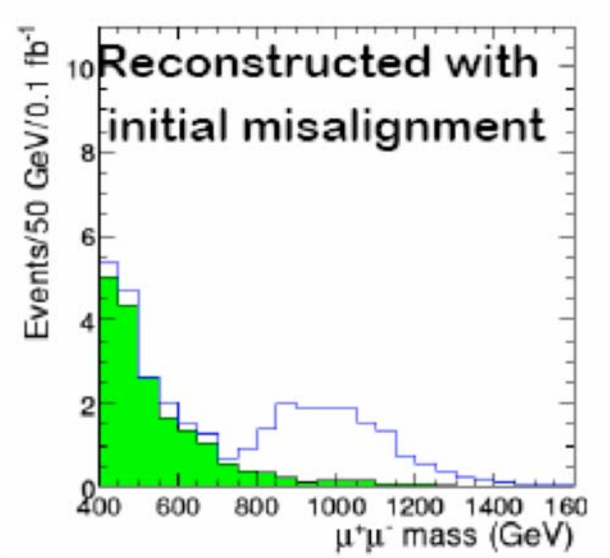
We do not know what is out there for us…

New Physics Signatures

- Many channels in New Physics :Typical signals
  - Di-leptons (like sign/same sign)
  - Leptons + MET
  - Photons + MET
  - Multi-jets (2 → ~10)
  - Multi-jets +MET (few 10 → few 100 GeV)
  - Multi jets + leptons + MET…
  - B/τ final states…
- Also: new unusual signatures
  - Large displaced vertices
  - Heavy ionizing particles (heavy stable charged particles)
  - Non-pointing photons
  - Special showers in the calorimeters
  - Unexpected jet structures
  - Very short tracks (stubs)…

Early discoveries? E.g. Di-lepton Resonance

If we are lucky:
a signal could be
seen very early on



First months of operation

CMS PTDR

Example : The Di-lepton channel

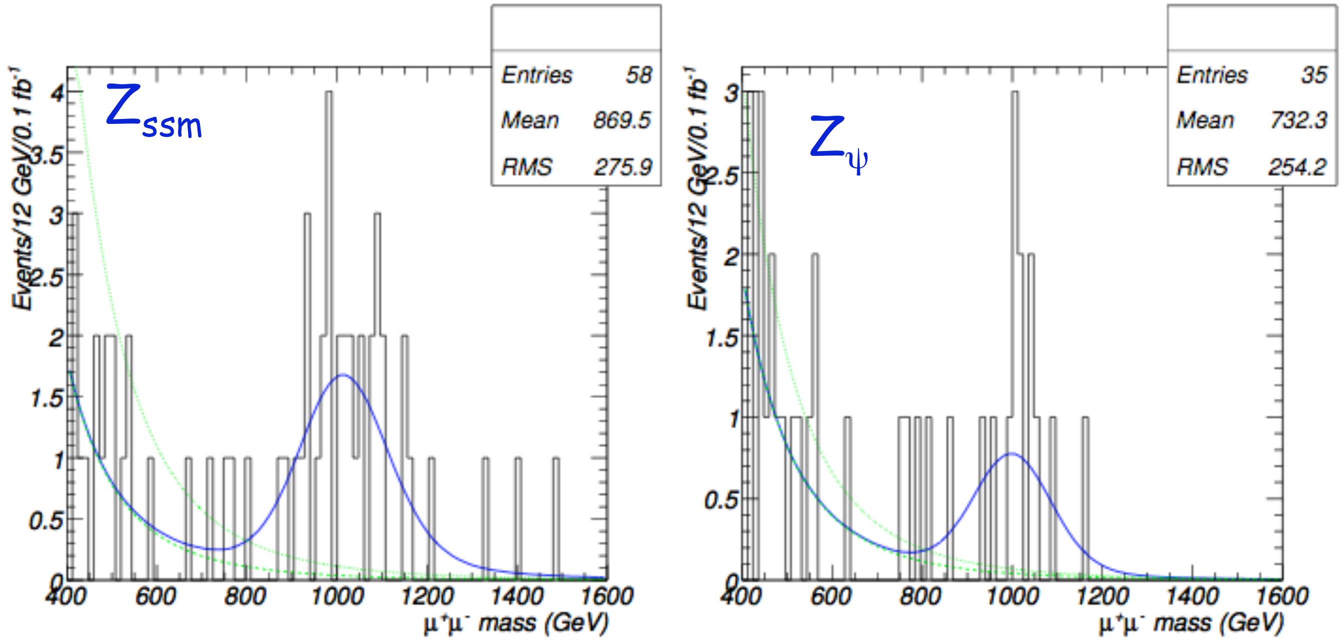
- Z' (New gauge bosons)
- A_H, Z_H (Little Higgs)
- $G^{(1)}$ (Randall-Sundrum)
- $\gamma^{(1)}/Z^{(1)}$ (TeV^{-1} Extra Dimensions)
- $G^{(KK)}$ (ADD)
- ...

Background under a signal

Eg: Z'→μμ high mass

Use data (normalization in side band) + Theory (extrapolation)

100 fb^{-1}

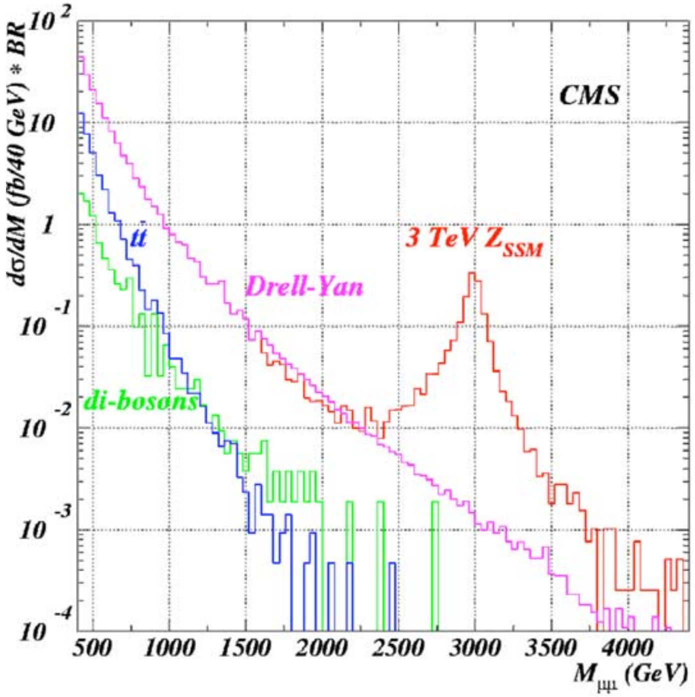


Use as much as possible data driven methods, but theory or Monte Carlo input often cannot be avoided. Hence we need good & tuned tools. This means tools with higher order QCD AND EW corrections!

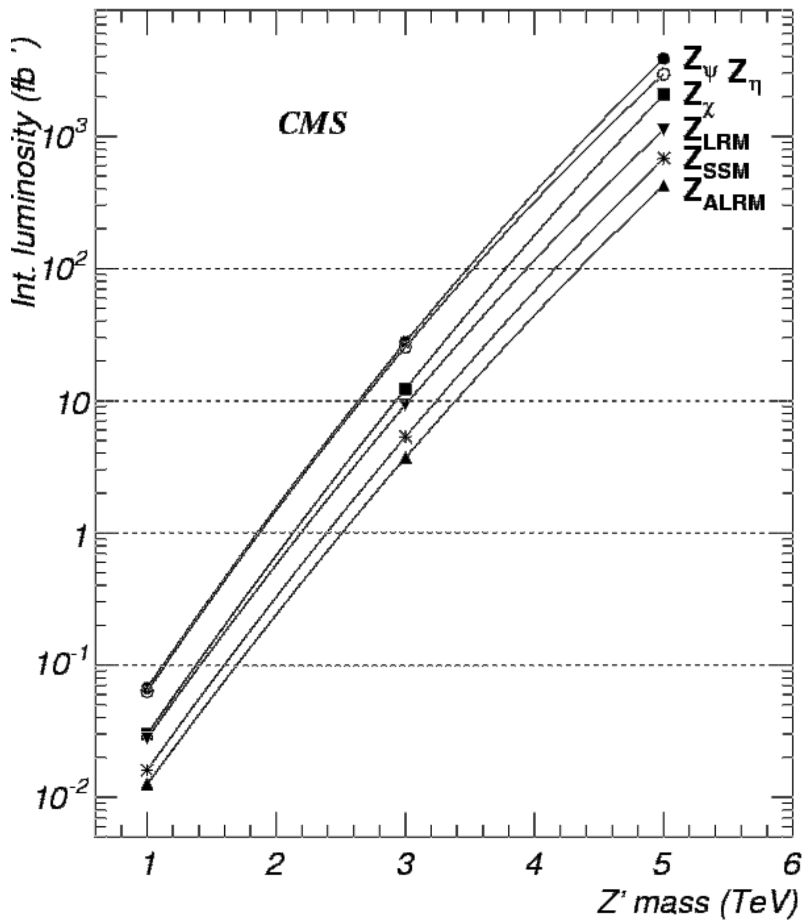
New Gauge Bosons

R. Cousins et al.

$Z' \rightarrow \mu\mu$ production



$Z' \rightarrow \mu^+ \mu^-$: 5σ significance curves

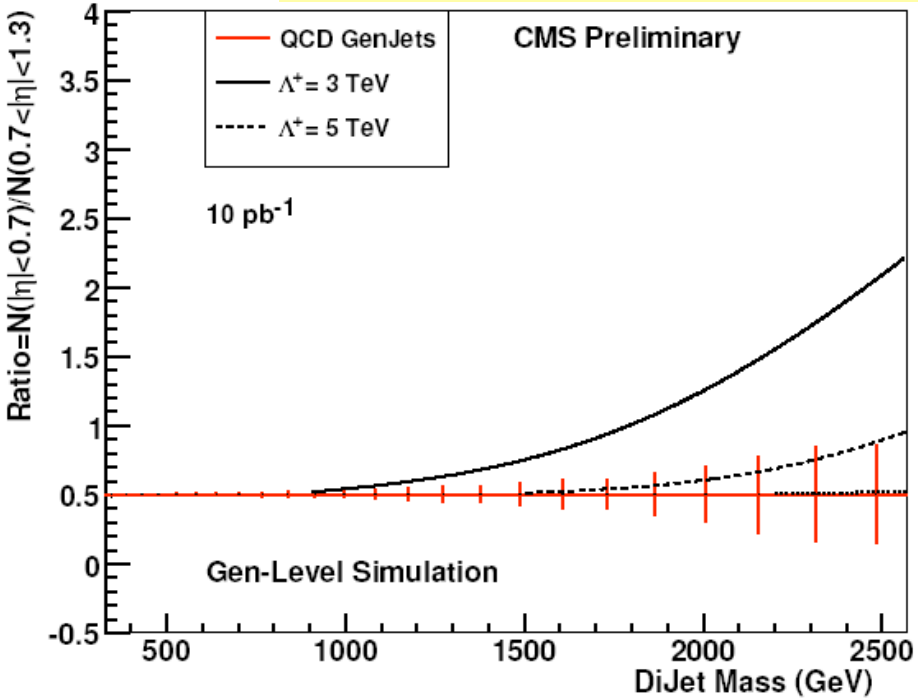


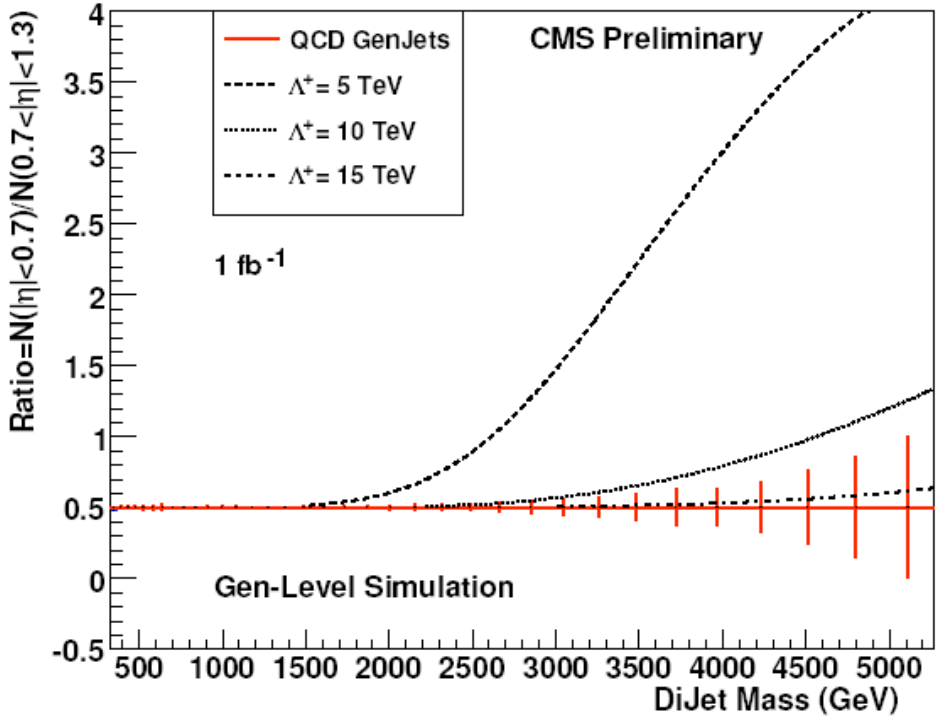
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

- Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron run-II
- High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

New Physics with Jets

Eg Contact Interactions
⇒ Using dijet event ratios in η





	Excluded Λ (TeV)			Discovered Λ (TeV)		
	10 pb^{-1}	100 pb^{-1}	1 fb^{-1}	10 pb^{-1}	100 pb^{-1}	1 fb^{-1}
DØ and PTDR η cuts	< 3.8	< 6.8	< 12.2	< 2.8	< 4.9	< 9.1
Optimized η cuts	< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

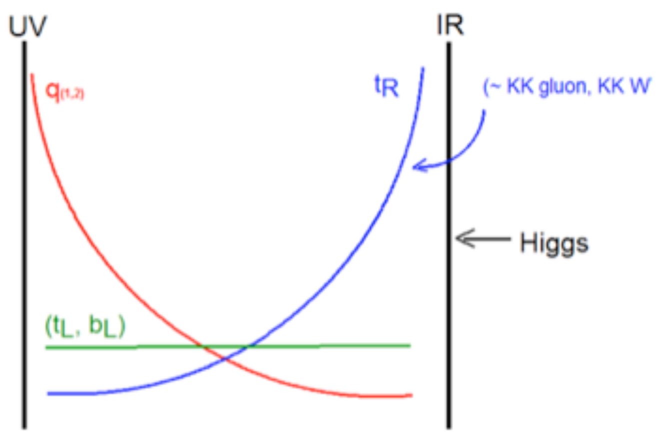
Test up to Λ ~ 10 TeV during 08/09 already

Highly boosted top

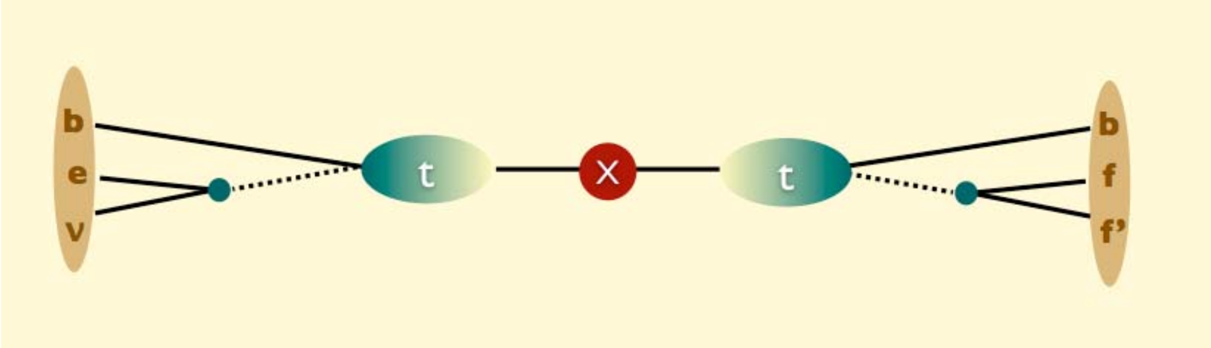
Recent developments in models: the prominent role of top production
Top co-anihilation SUSY, top resonances, RS→top top etc.
Often this leads to 'boosted top' ie the hadronic decay jets merge

T. Han et al.

- Eg RS → t tbar

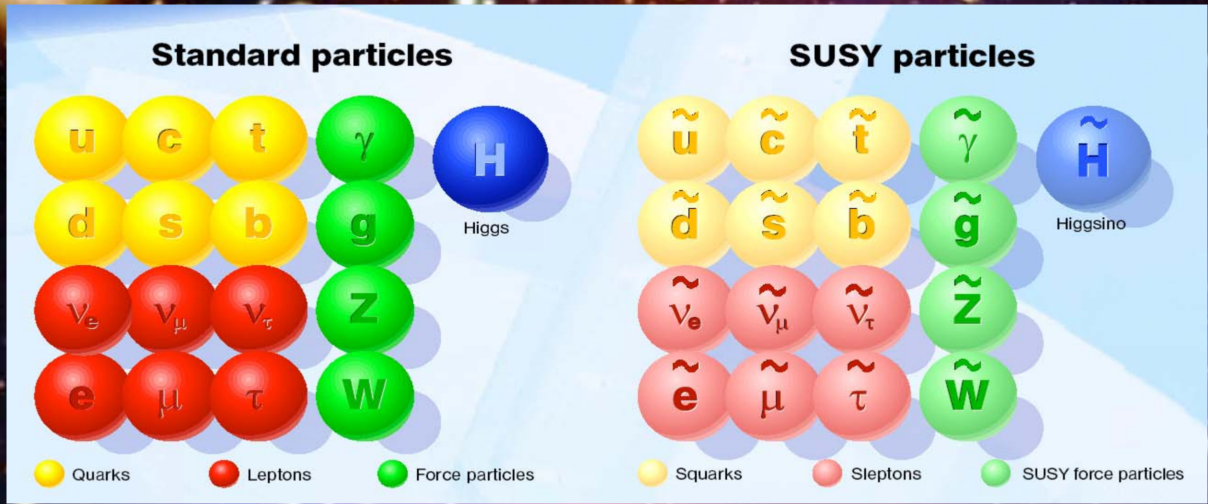


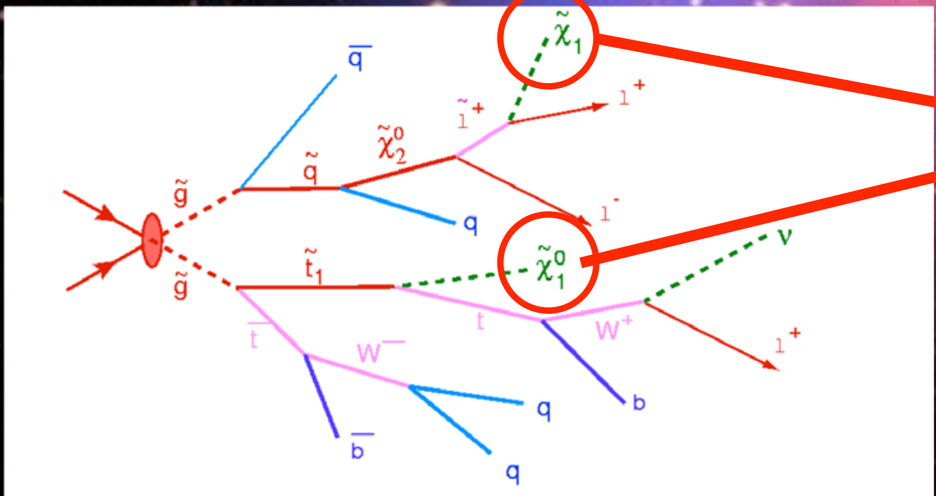
⇒High P_T tops



The jets typically appear as 'fat' jets
with internal structure
⇒ Can be studied with SM top production
→ Tool development
⇒ Needs input for SM 'jet structure' studies

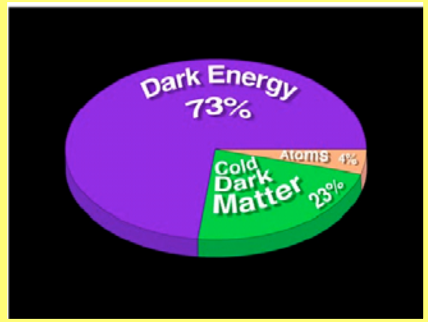
Supersymmetry: a new symmetry in Nature





SUSY particle production at the LHC

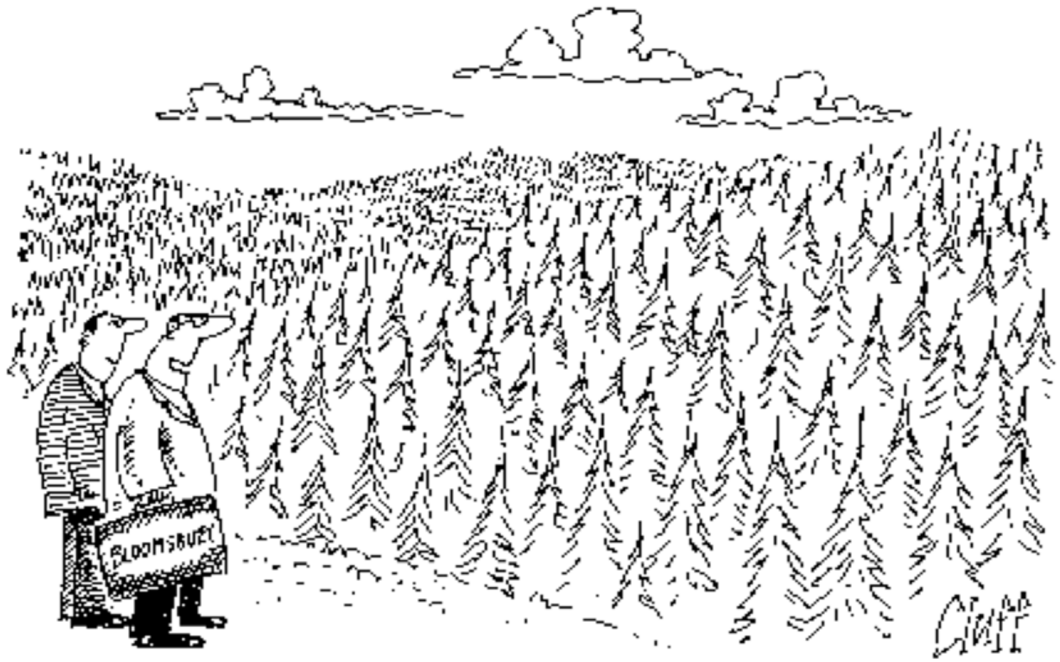
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab



Supersymmetry

A VERY popular benchmark…

More than 7000 papers since 1990 (Kosower)



"One day, all of these will be supersymmetric phenomenology papers."

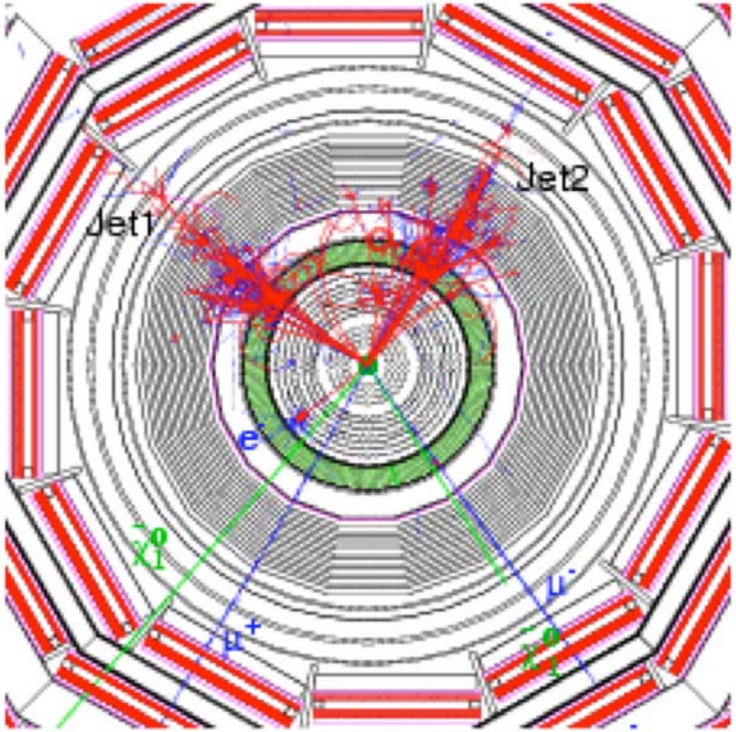
Considered as a benchmark for a large class of new physics models

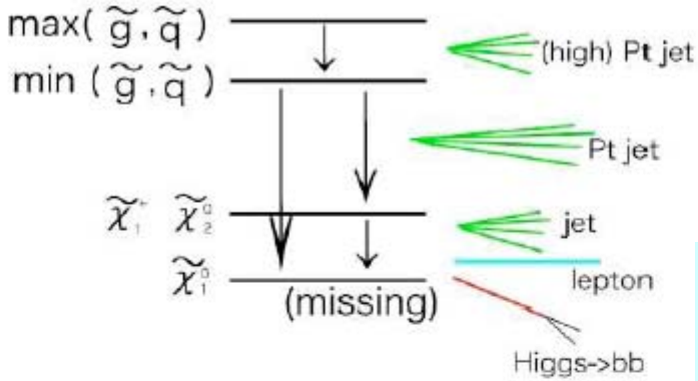
Supersymmetry

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10 fb^{-1}$





event topologies of SUSY

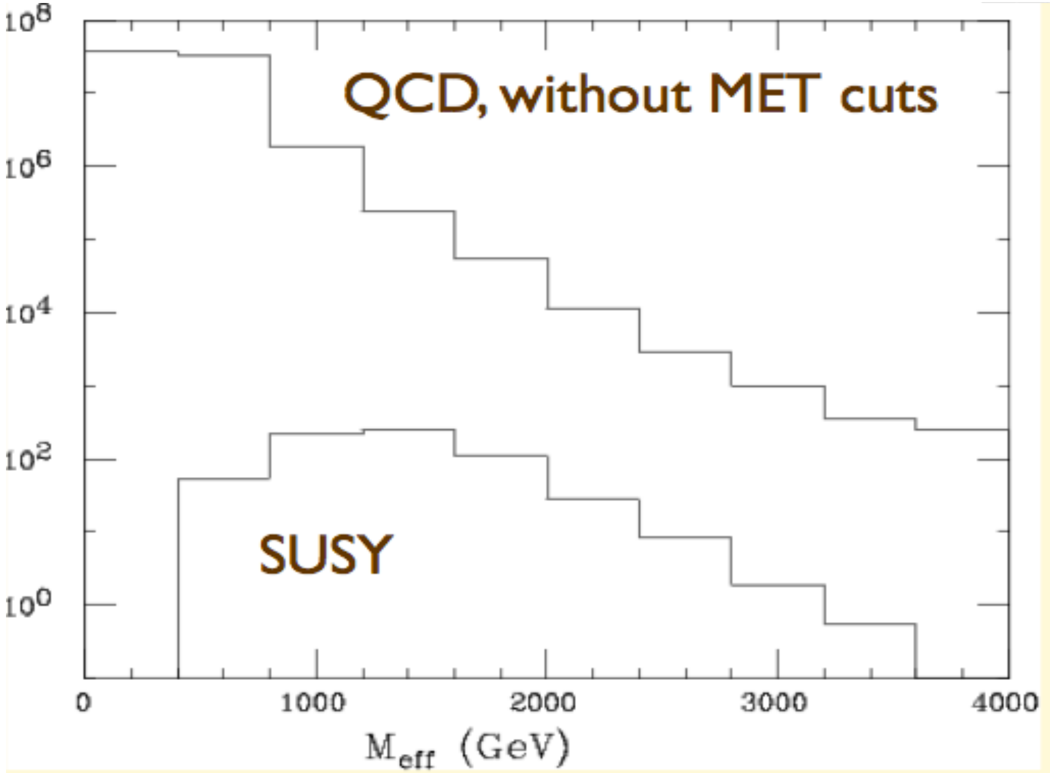
	multi	leptons
$\not{E}_T$ +	High P_T jets +	b-jets
		τ-jets

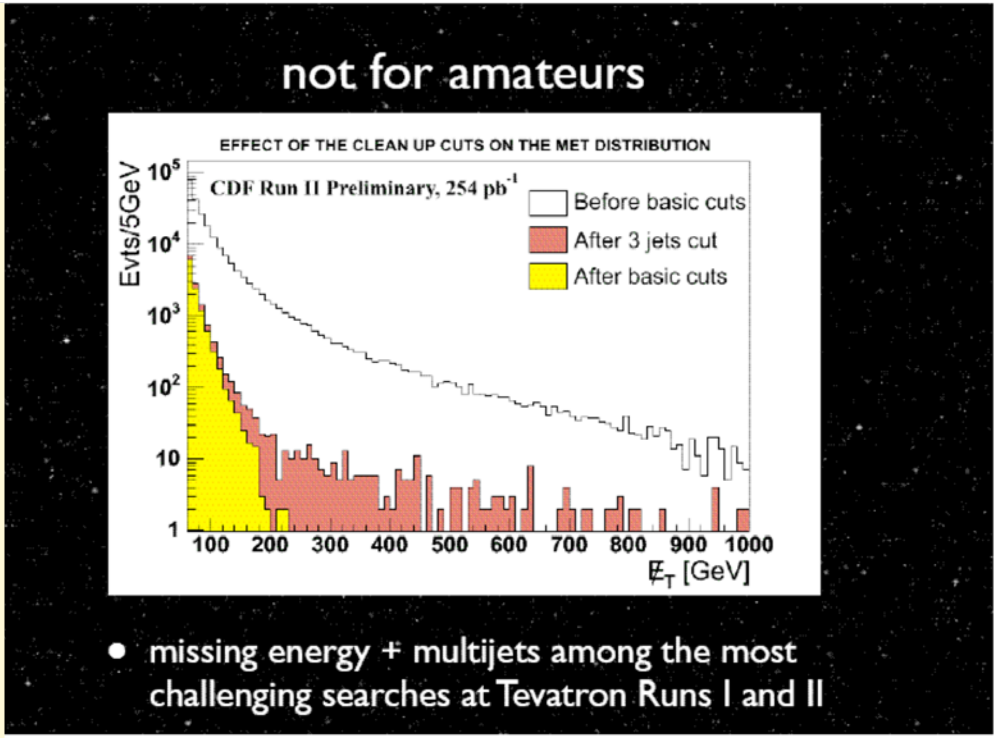
Therefore:
SUSY one of the priorities of the "search" program

Main signal: lots of activity (jets, leptons, taus, missing E_T)
Needs however good understanding of the detector & SM processes!!

Missing Transverse Energy

A difficult quantity to measure!



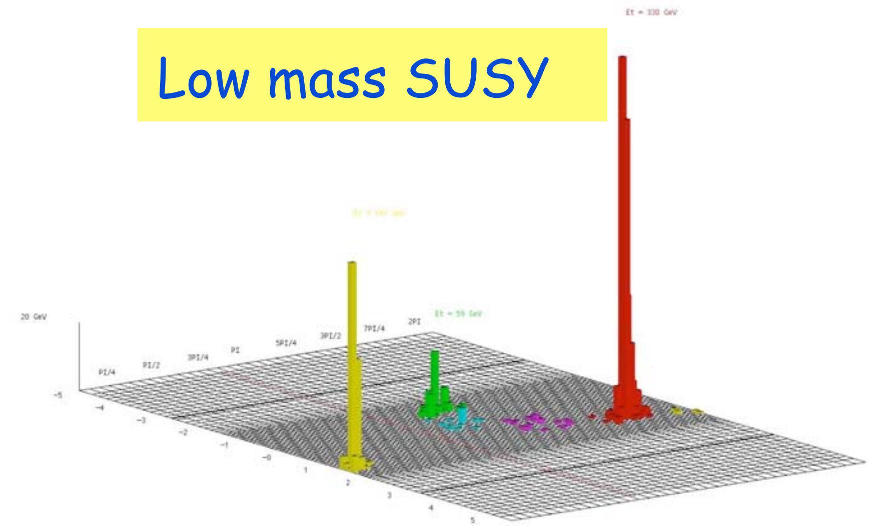


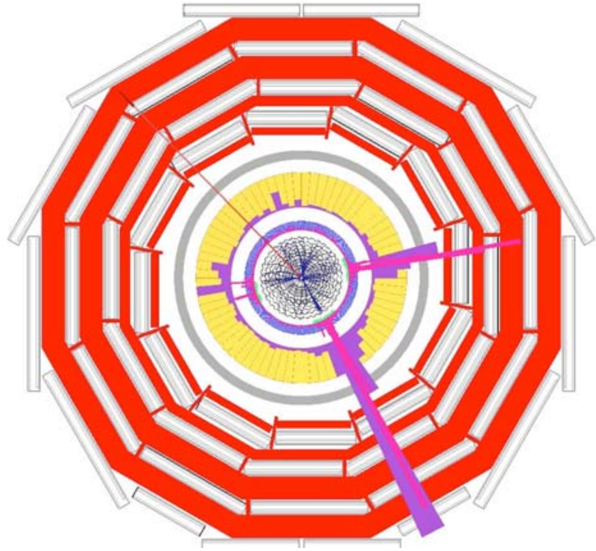
Tevatron experience!

Clean up cuts: cosmics, beam halo, dead channels, QCD

Detailed Simulation: Missing E_T

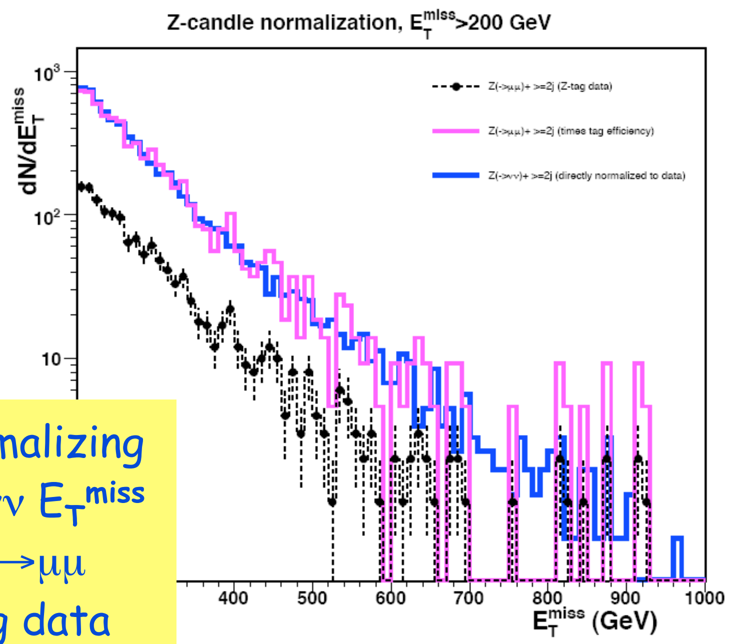
Low mass SUSY



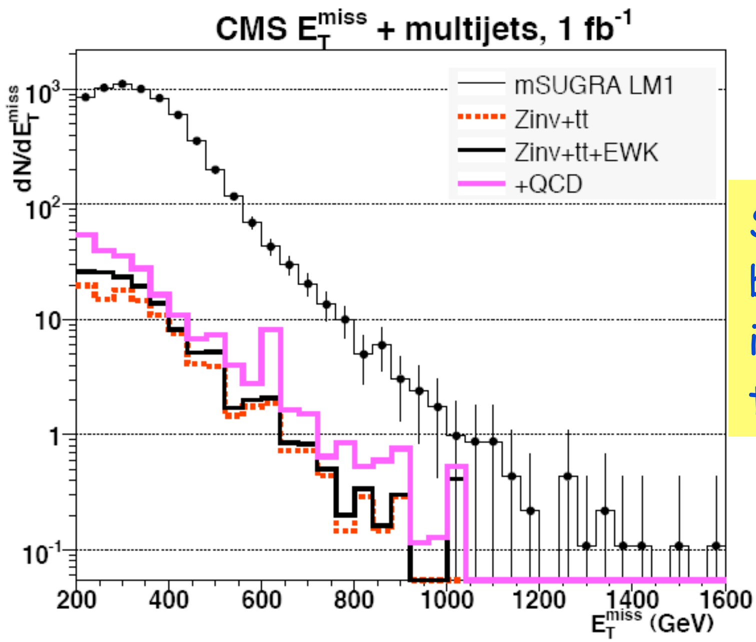


Missing E_T is a difficult measurement for the experiments

CMS PTDR



Normalizing $Z \to \nu\nu$ E_T^{miss} to $Z \to \mu\mu$ using data



Signal over background in E_T^{miss} for the LM1 point

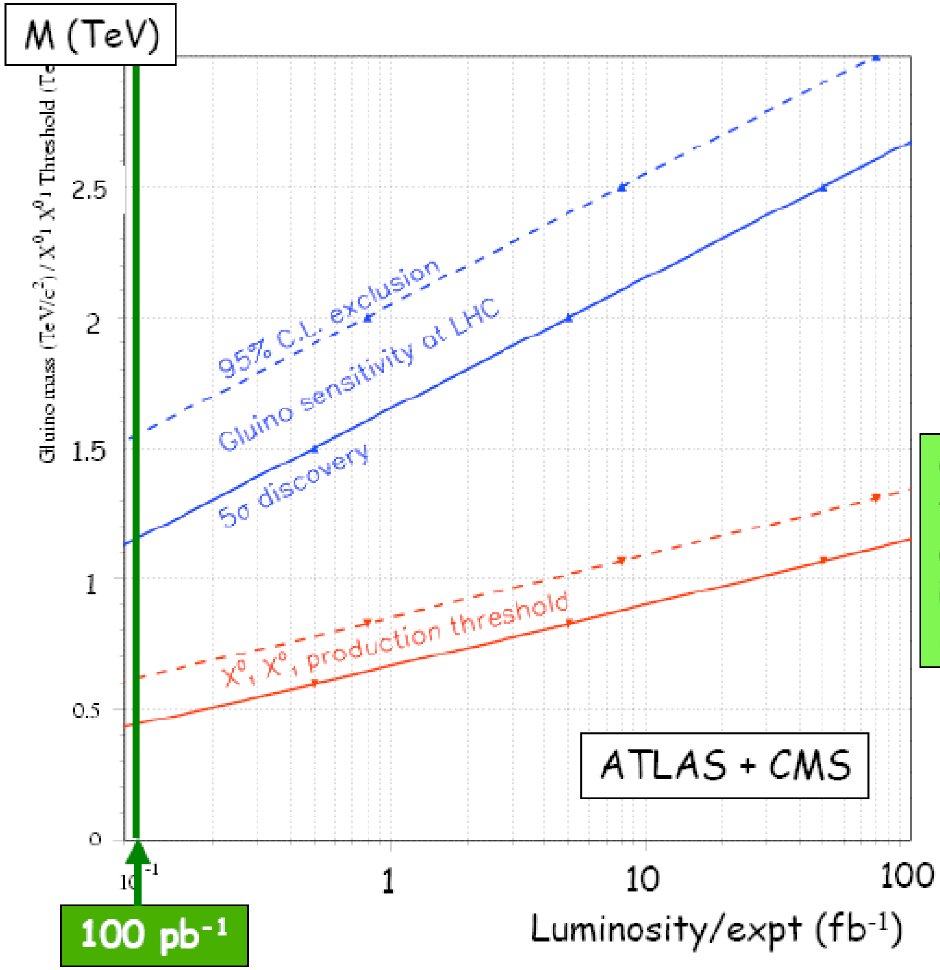
Early SUSY?

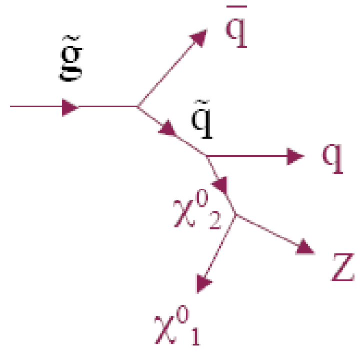
F. Gianotti, J. Ellis, ADR et al.

Example of "early" discovery: Supersymmetry ?

If SUSY at TeV scale → could be found "quickly" .... thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for $m(\tilde{q},\tilde{g}) \sim 1$ TeV
- spectacular signatures (many jets, leptons, missing E_T)





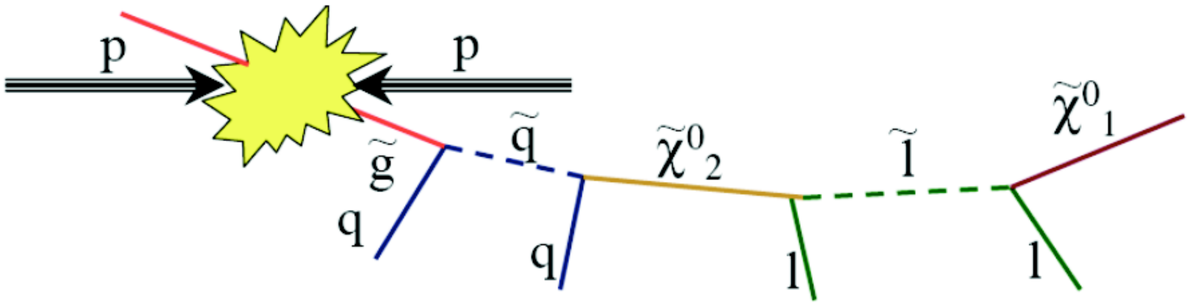
Something to watch for the ILC...

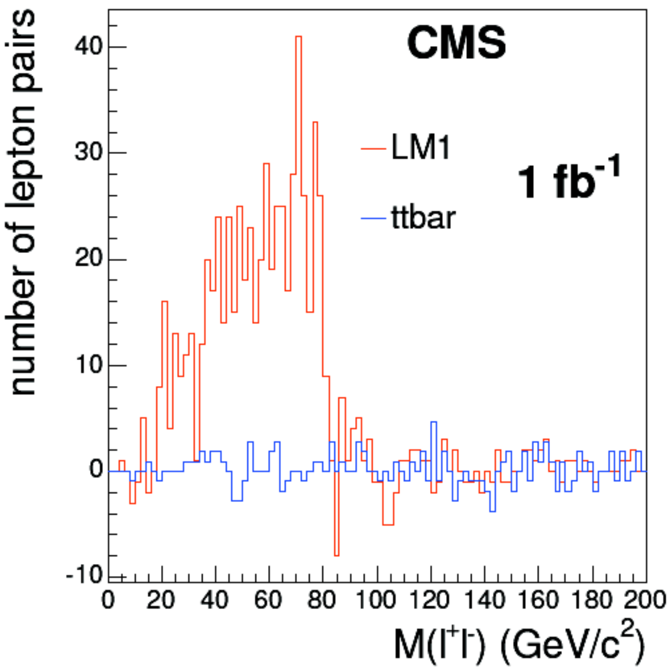
Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

Sparticle Mass Reconstruction

First Mass Clues (dileptons)

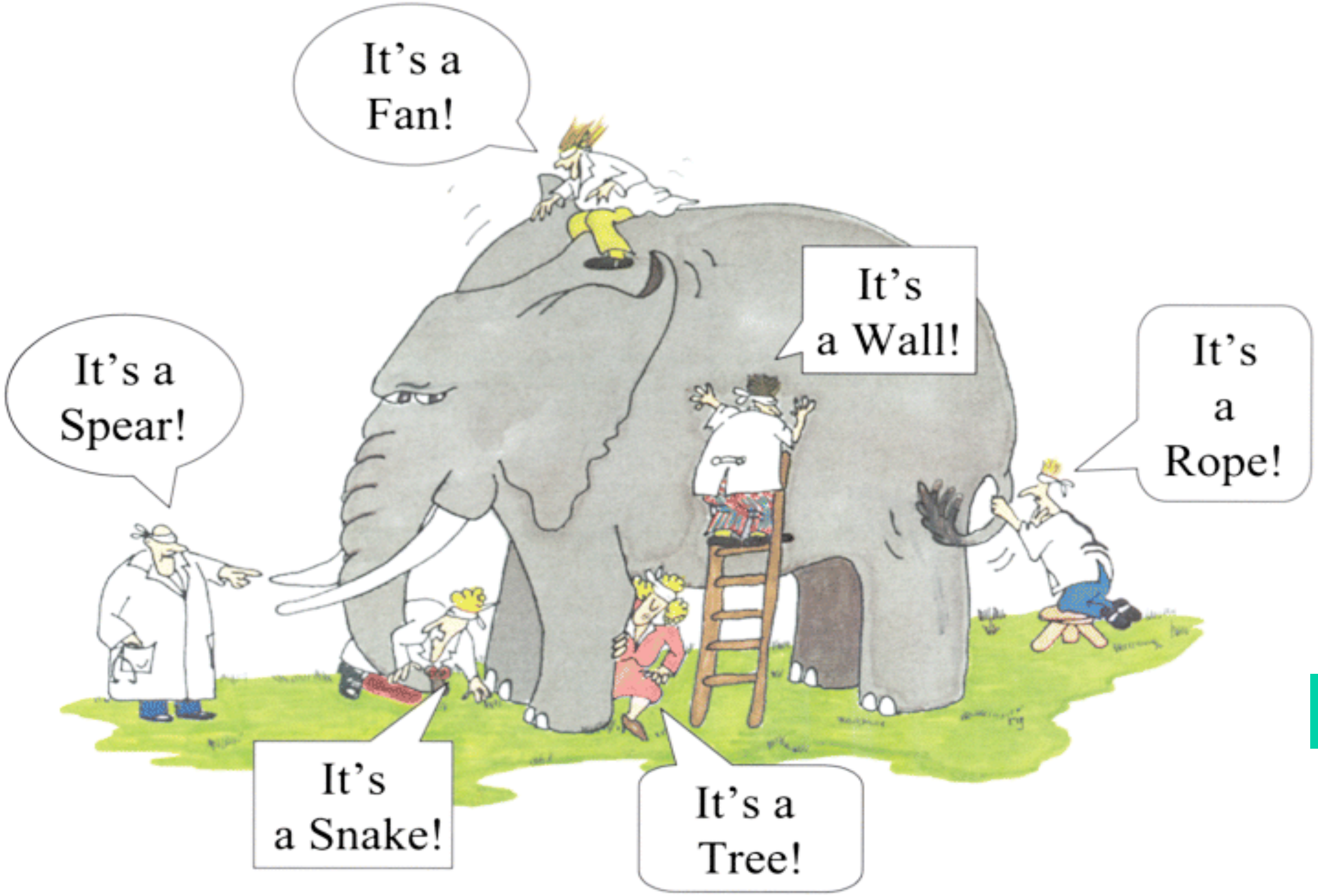




- $M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1 - \frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$
- $M_{\ell\ell}^{max}$(meas)= 80.42 $\pm$ 0.48 GeV/c^2, *cfr* with
- expected $M_{\ell\ell}^{max}$= 81 GeV/c^2 [given $M(\tilde{\chi}_1^0)$ = 95, $M(\tilde{\chi}_2^0)$= 180 and $M(\tilde{\ell}_R)$ = 119 GeV/c^2]

D. Miller et al: Scot Thomas et al.
⇒ use also the shapes

Since we do not know what we will find…



Nature.com

…we will look at it from all angles….

Close interaction between Experiment and Theory will be important

Is it SUSY?

Example: Universal Extra Dimensions

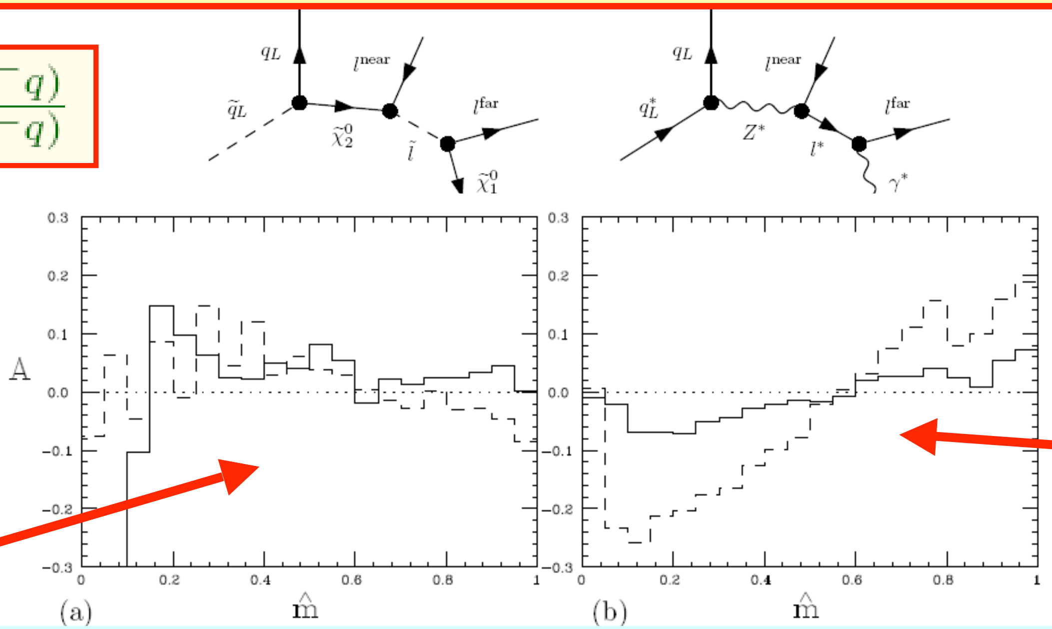
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:

Can the LHC distinguish?

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

Look for variables sensitive to the particle spin eg. lepton charge asymmetries in squark/KKquark decay chains Barr hep-ph/0405052; Smillie & Webber hep-ph/0507170

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$



KK like spectrum (small mass splitting)

SPS1a benchmark type spectrum

Method works better or worse depending on (s)particles spectrum

More discriminating variables needed!!

Spin measurements

Recently: lot of new ideas being proposed (see T. Plehn HCP07, Elba)
Most still need the detailed test of the 'experimental reality'

Kilic-Wang-Yavin:
Spin measurements in cascade decays
Angular correlations in decays…

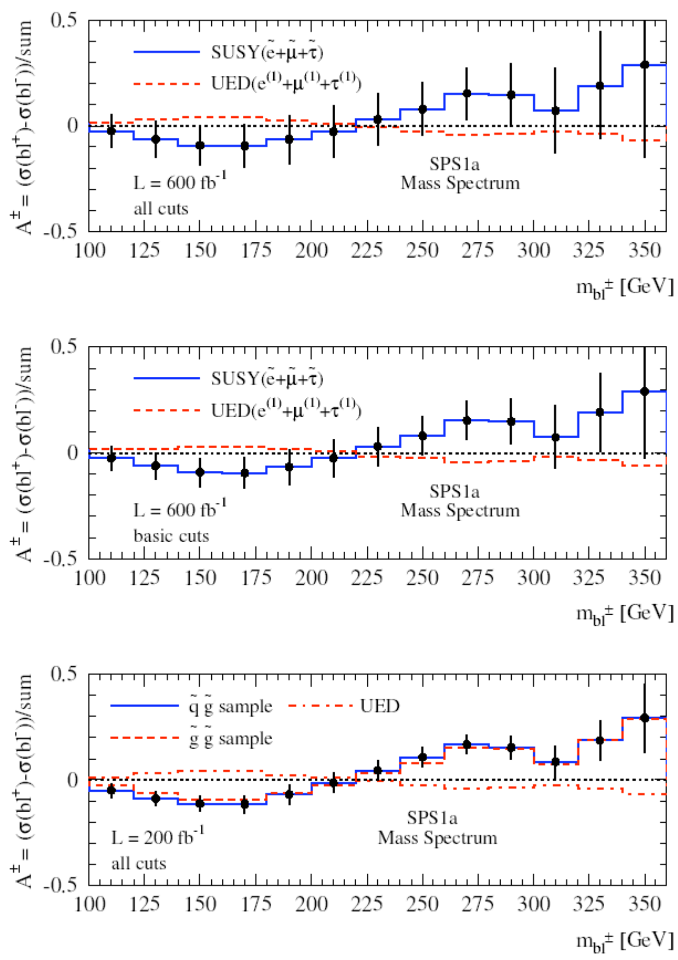
Alves-Eboli
Sbottom spin

Alves-Eboli-Plehn
Spins in Gluino Decays

Athanasiou-Lester-Smillie-Webber
Distinguishing spins in decay chains at the LHC

Choi-Hagiwara-Kim-Mawatari-Zerwas
Tau polarization in SUSY cascade decays

Further: Wang & Yavin, S. Thomas et al,



Spin ⇔ Cross Section

- For example, consider the mass of a new color octet to be $M = 800\text{GeV}$. If we choose scales $\mu_F = \mu_R = M_Z$, then the cross section for the spin-$\frac{1}{2}$ and spin-1 are given

F by

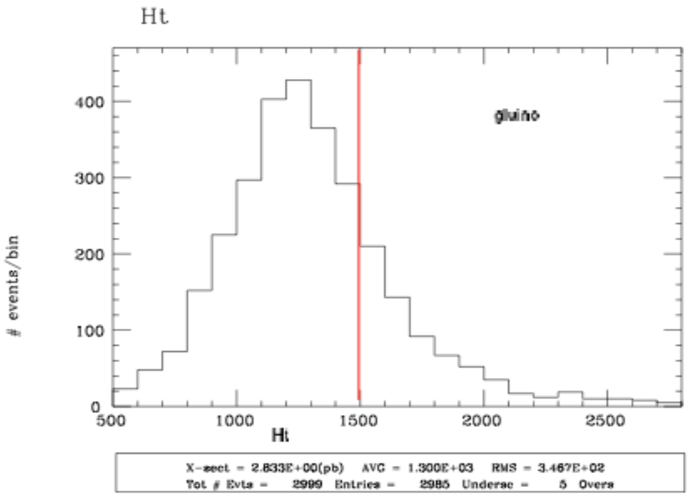
$$\sigma_{pp\to\tilde{g}\tilde{g}} \approx 2.8\text{pb}, \quad \sigma_{pp\to g_V g_V} \approx 24.1\text{pb}. \quad \text{ratio} \approx 8.5$$

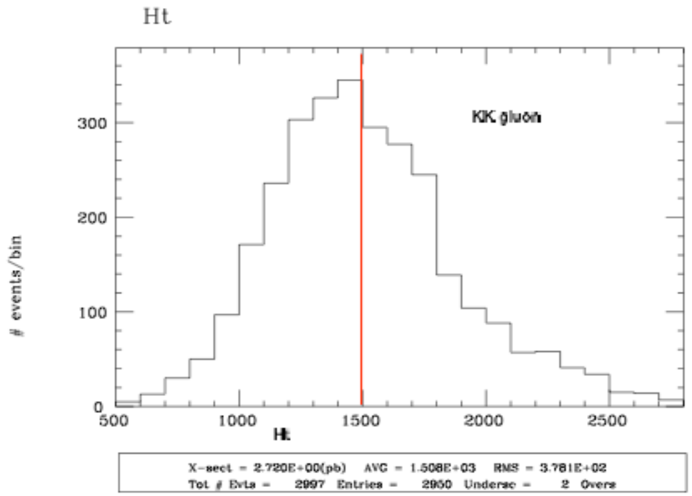
- For scales $\mu_F = \mu_R = M$

$$\sigma_{pp\to\tilde{g}\tilde{g}} \approx 0.95\text{pb}, \quad \sigma_{pp\to g_V g_V} \approx 7.79\text{pb}. \quad \text{ratio} \approx 8.2$$

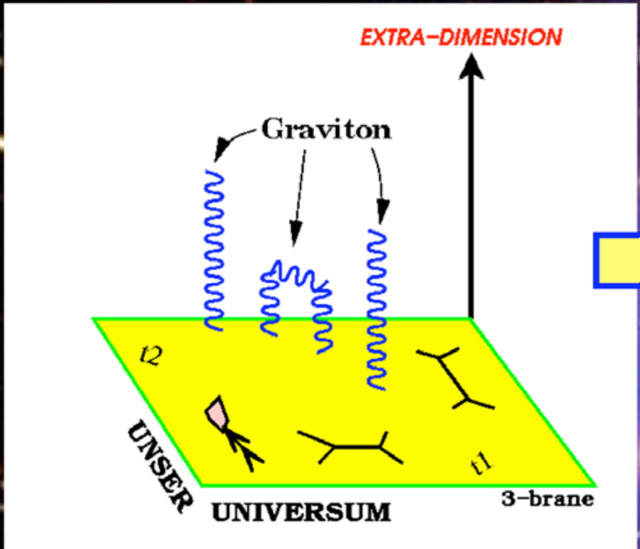
Shao, Kane
Petrov, Wang
(Ann Arbor
Jan '08)

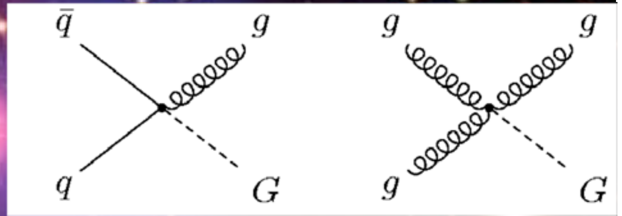
What if cross sections ~ same? M_{gluino} = 800 GeV M_{KK} =1100 GeV





Extra space dimensions?





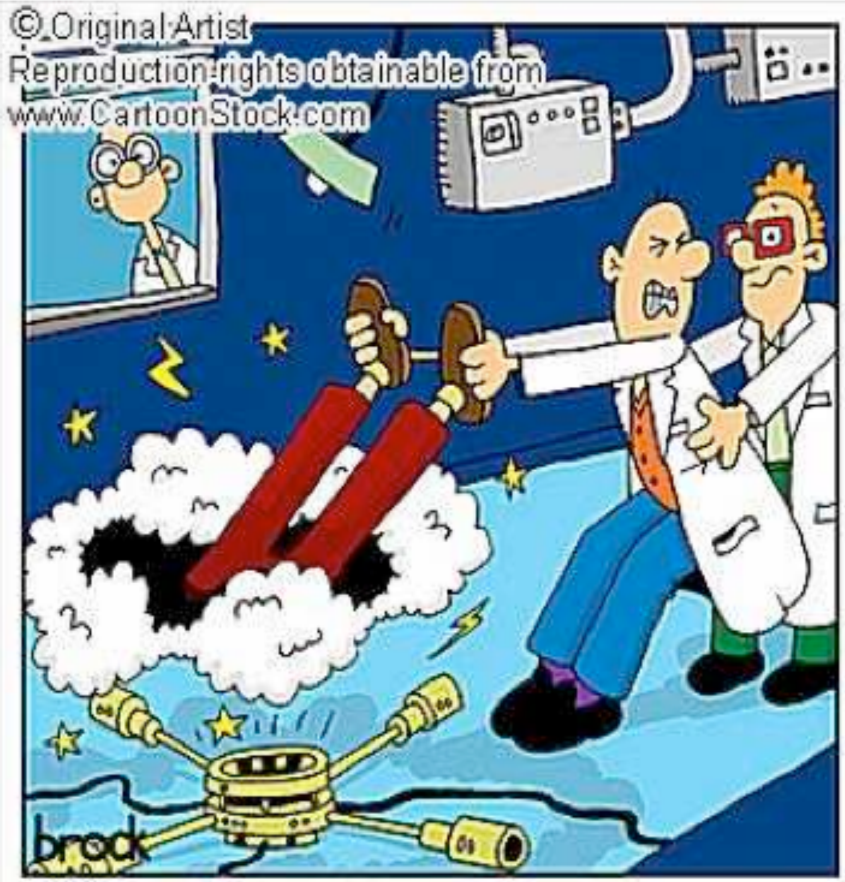
Signatures

Eg monojet events
monophoton events
Z′ like resonances
KK excitations
…

The Gravity force becomes strong!

Production of Mini Black Holes @LHC

- We are sorry but this section is closed for the time being. It will be re-opened soon



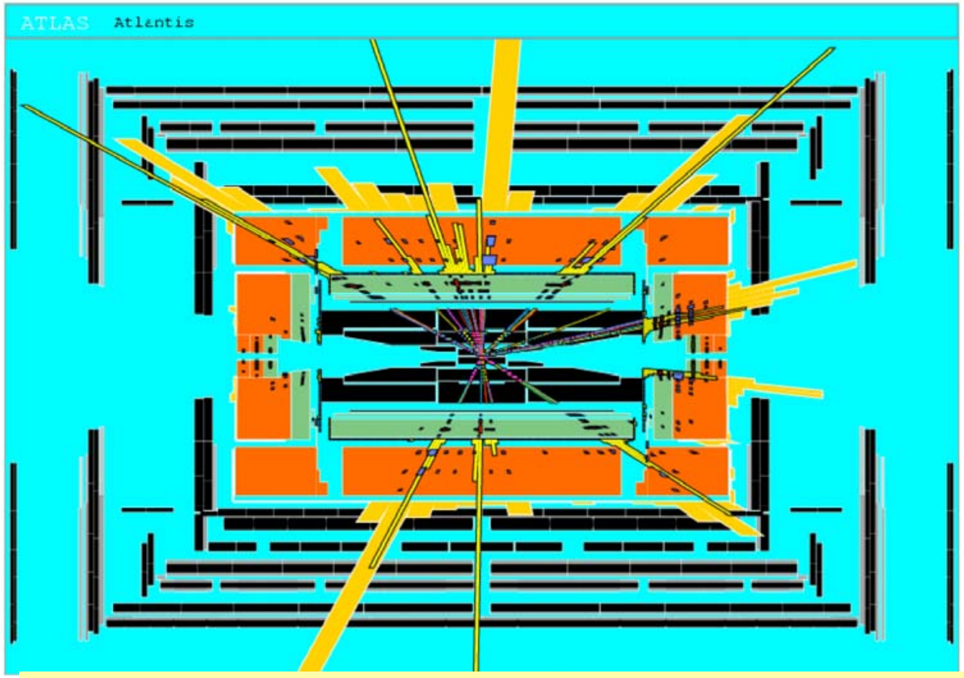
Professor Landsberg was fast regretting becoming the first man to successfully create a mini black hole in the laboratory.

Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production

4 dim. : $R_s \rightarrow \ll 10^{-35}$ m
4+n dim. : $R_s \rightarrow \sim 10^{-19}$ m
R_S = schwartzschild radius



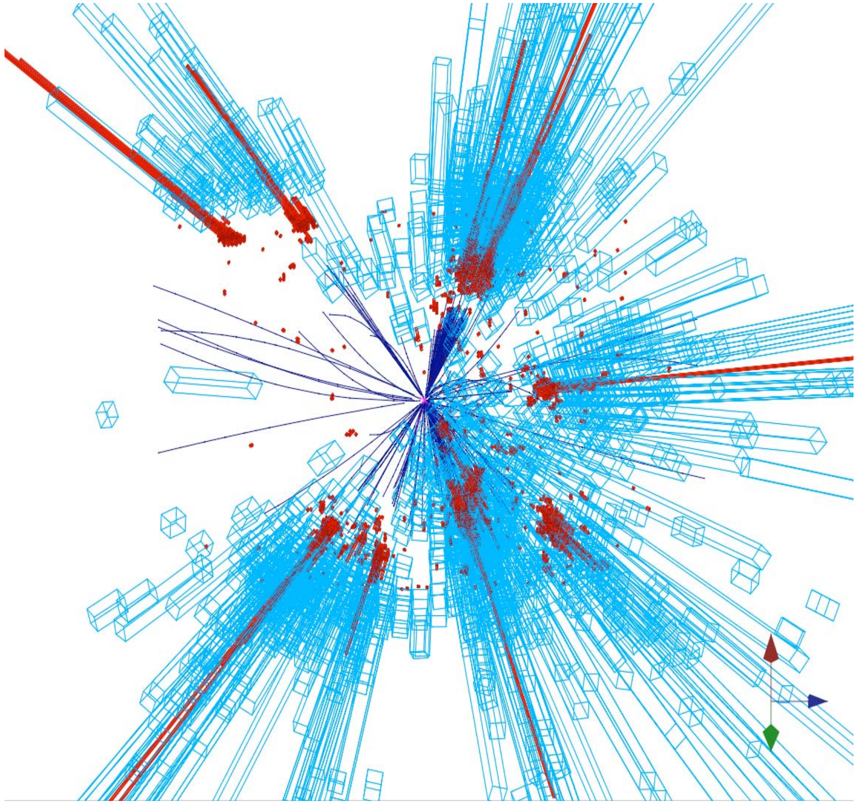
Simulation of a Quantum Black Hole event

Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

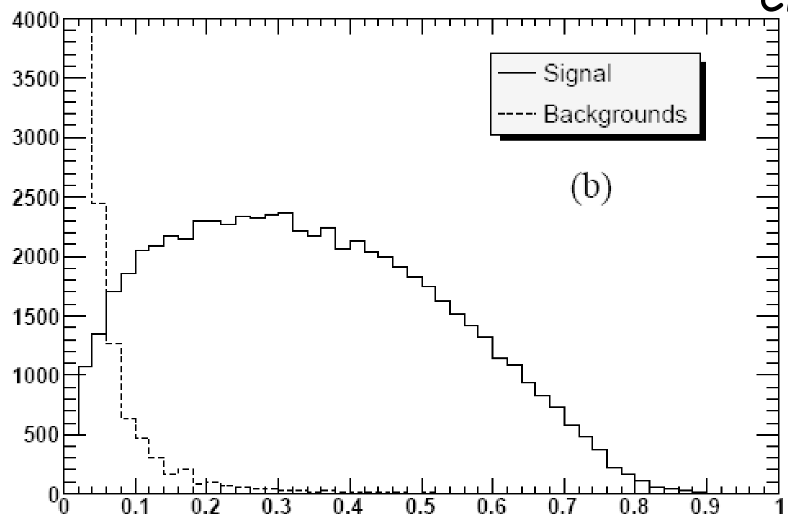
Black Holes Production

If the Planck scale in ~TeV region: can expect Black Hole production



Simulation of a black hole event with M_{BH} ~ 8 TeV in CMS

CMS PTDR



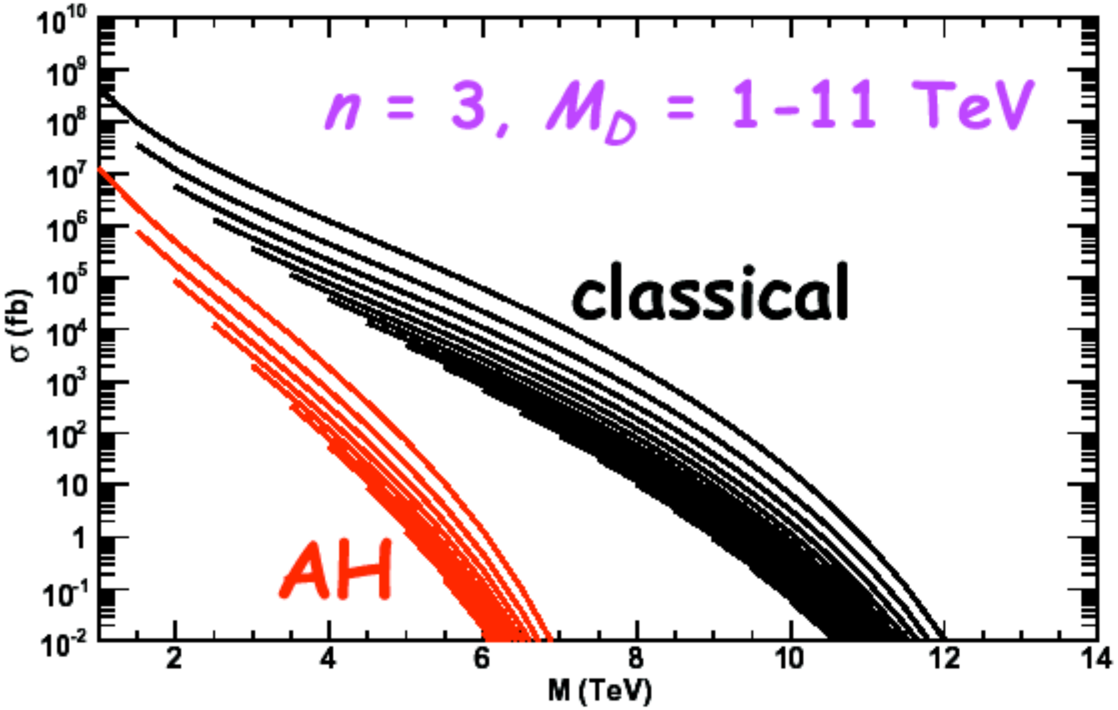
sphericity

~ Spherical events: Many high energy jets leptons, photons etc.

Ecological comment: BH's will decay within ~ 10^{-27} secs
Detectors, electronics (and rest of the world) are safe!!

Black Holes

Warning: cross section could be much less than optimistic estimates



$$\sigma_{BH} \sim \pi r_h^2$$

For 10 fb^{-1}

- Classical approximation to cross-section: large! Black Holes up to 8-10 TeV
- Apparent horizon (AH), not all energy trapped; see eg. hep-ph/0609055
  Black holes up to 4-5 TeV

Recent Studies: New Signatures

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

  - Gluino can live long: sec, min, years!

  - R-hadron formation: slow, heavy particles containing a heavy gluino.

  Unusual interactions with material

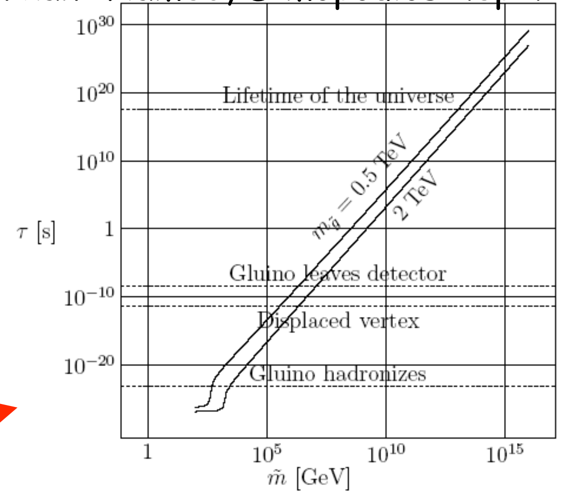
  eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

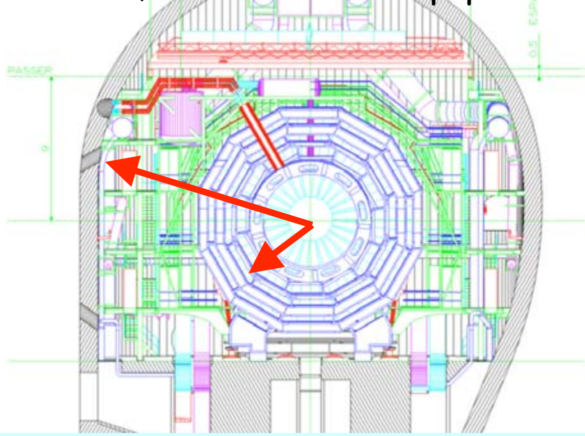
- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



K. Hamaguchi,M Nijori,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198



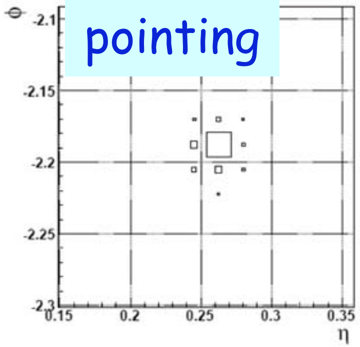
Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

New CMS Analyses

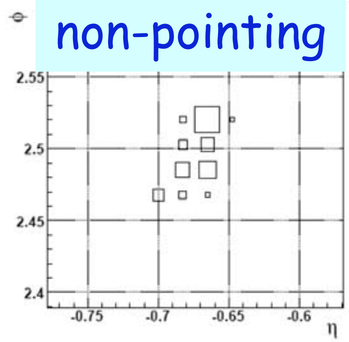
• GMSB: Non-pointing photons

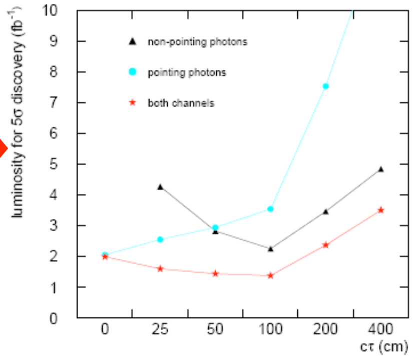
GMSB parameters $N = 1 \quad \tan\beta = 1 \quad \mathrm{sgn}\,\mu = 1 \quad M_m = 2\Lambda$

pointing



non-pointing

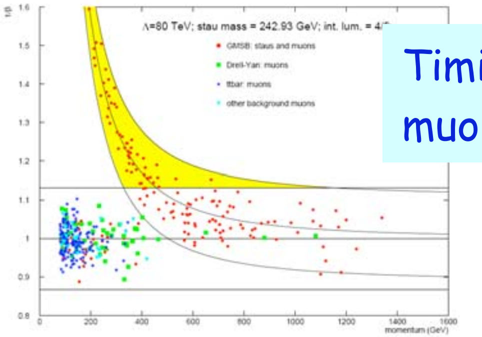




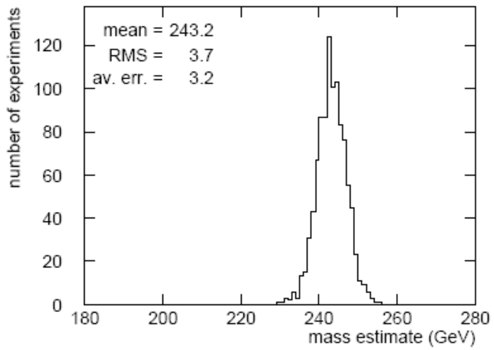
χ cτ lifetime extraction with ~20% precision

• GMSB: long living staus

GMSB parameters $N = 3 \quad \tan\beta = 3 \quad \mathrm{sgn}\,\mu = 1 \quad M_m = 2\Lambda$



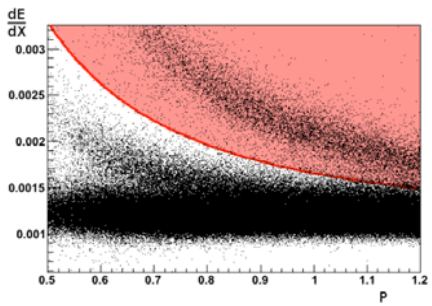
Timing (β) in muon detectors



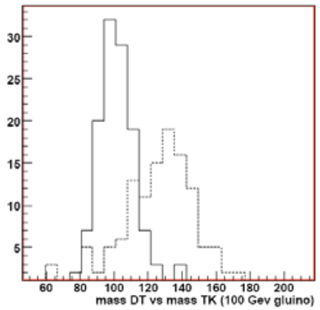
stau mass extraction with a few % precision

• R-hadrons

trigger/mass meas. for region β > 0.6



de/dx in the tracker

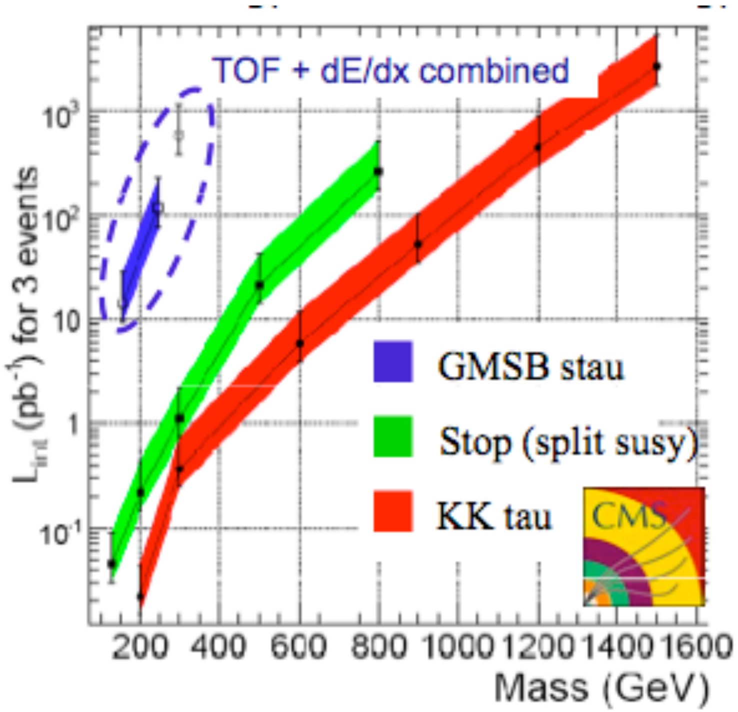


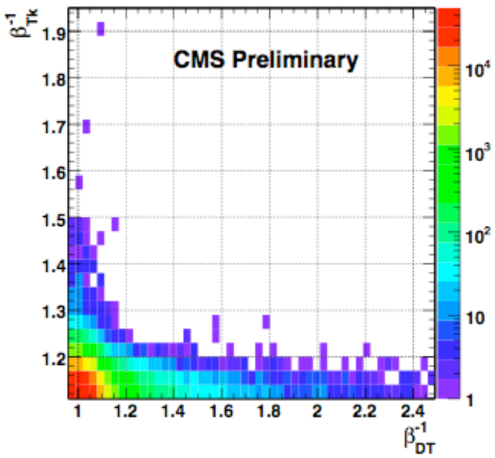
β-tracker
β-muons

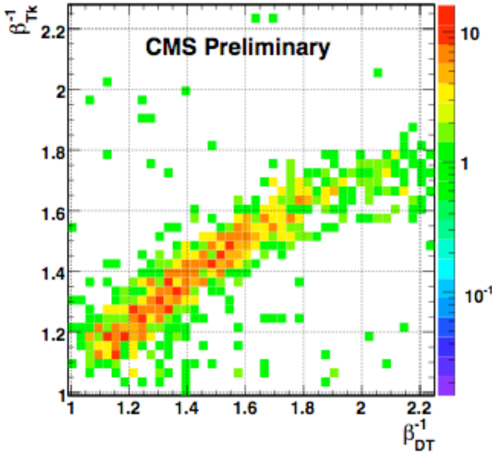
New: Heavy Stable Charged Particles

Data Sample	Cross section (pb)	HSCP in $\|\eta\| < 2.4$ (%)	HSCP in $\|\eta\| < 0.9$(%)
$\tilde{\tau}_1$ (156 GeV)	1.19	97.6	72.6
$\tilde{\tau}_1$ (247 GeV)	0.097	97.5	70.9
KK tau (300 GeV)	0.020	84.7	40.9
$\tilde{g}$ (200 GeV)	2.2×10^3	89.7	47.4
$\tilde{g}$ (300 GeV)	100	91.7	50.0
$\tilde{g}$ (600 GeV)	5.00	93.7	55.5
$\tilde{g}$ (900 GeV)	0.46	92.6	57.7
$\tilde{g}$ (1200 GeV)	61×10^{-3}	91.4	53.9
$\tilde{g}$ (1500 GeV)	10×10^{-3}	90.4	55.8
$\tilde{t}_1$ (130 GeV)	1.11×10^3	87.8	43.1
$\tilde{t}_1$ (200 GeV)	1.77×10^2	90.9	47.3
$\tilde{t}_1$ (300 GeV)	27.4	92.8	50.4
$\tilde{t}_1$ (500 GeV)	1.27	95.3	54.7
$\tilde{t}_1$ (800 GeV)	7.81×10^{-2}	96.9	61.9

New extended HCSP study







Split SUSY

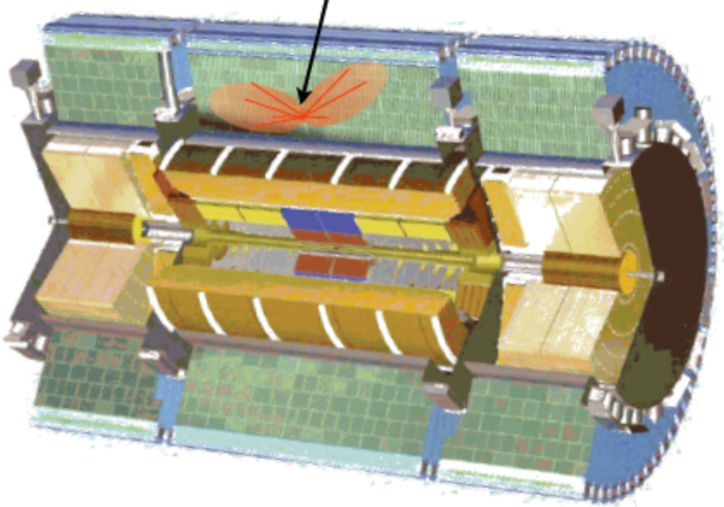
Arvanitaki et al.

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

100s GeV Unbalanced $= \not{E}_T$

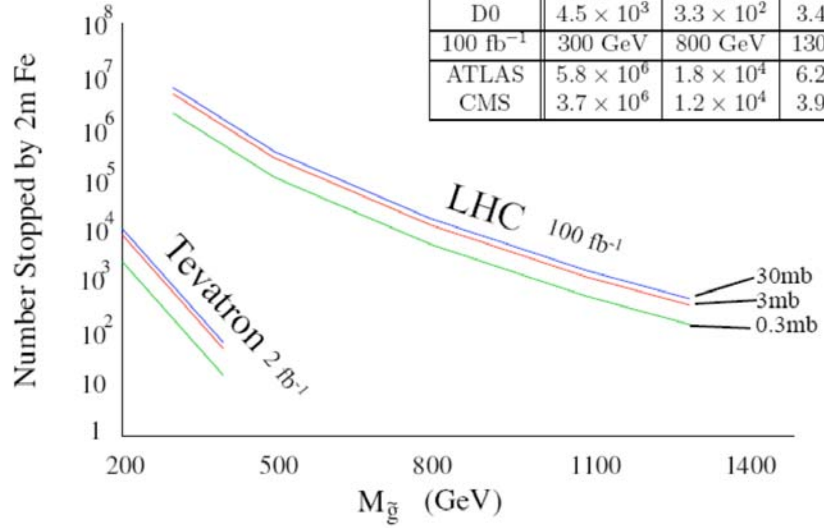


Uncorrelated with any beam crossing
No tracks going to or from activity

Total Number of Stopped Gluinos

Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242

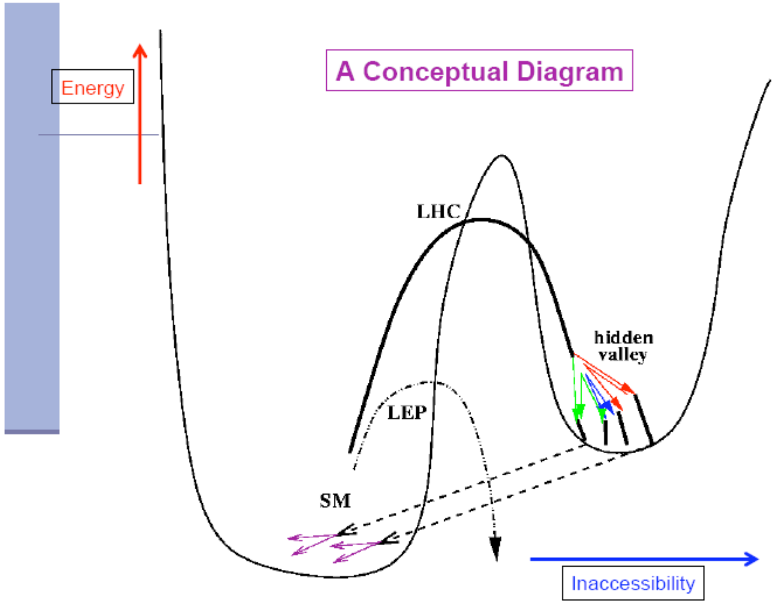
2 fb^{-1}	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
100 fb^{-1}	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2



⇒ Requires special triggers/analysis

Other new signatures:
Hidden valley particles, quirks, unparticles

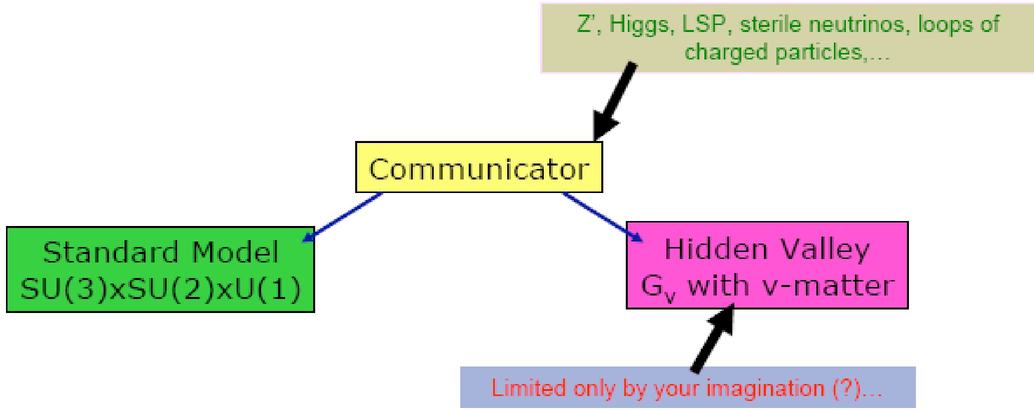
Hidden Valley Physics?



String Theory inspired

Eg. Strassler & Zurek hep-ph/0604261

- Basic minimal structure

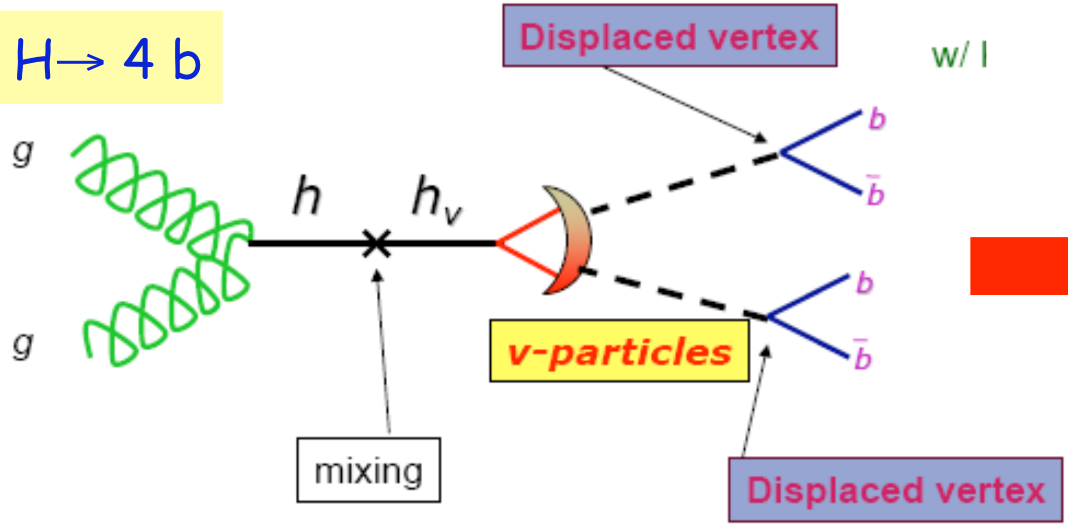


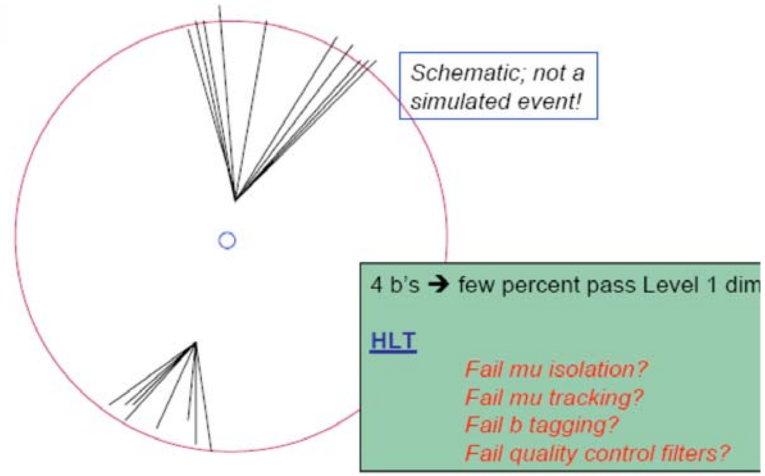
New possible phenomena that could occur in these models

- Higgs decays to two [or more] long-lived particles
  - ***Aside*** *on classes of possible decays of new particles*
- Z' decays to the v-sector:
  - *Final state with many particles, possibly long-lived*
- LSP decays to the v-sector
  - *Degradation of MET signal*
  - *Wide array of complex final states*

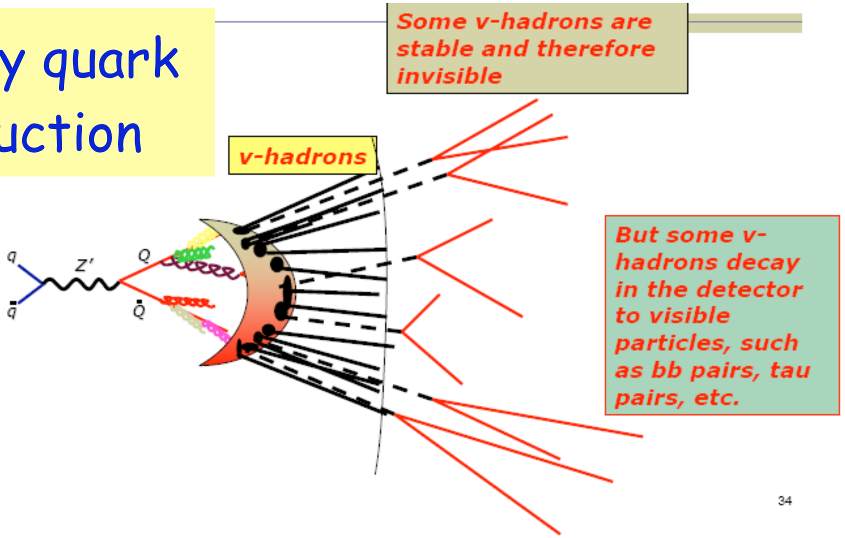
Some Hidden Valley Signals

H→ 4 b

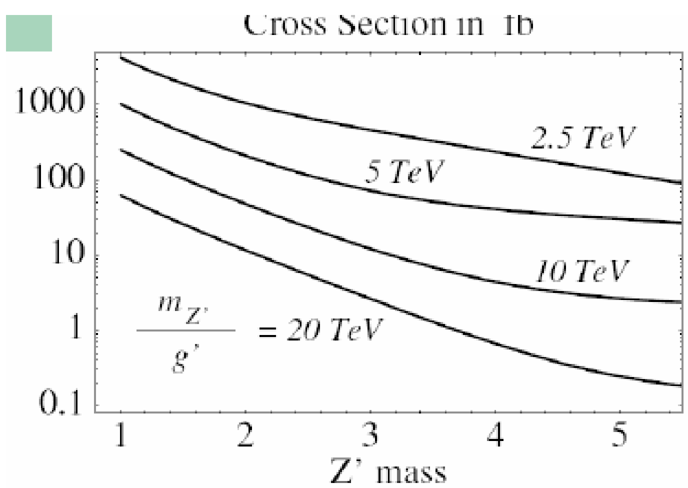




Valley quark production

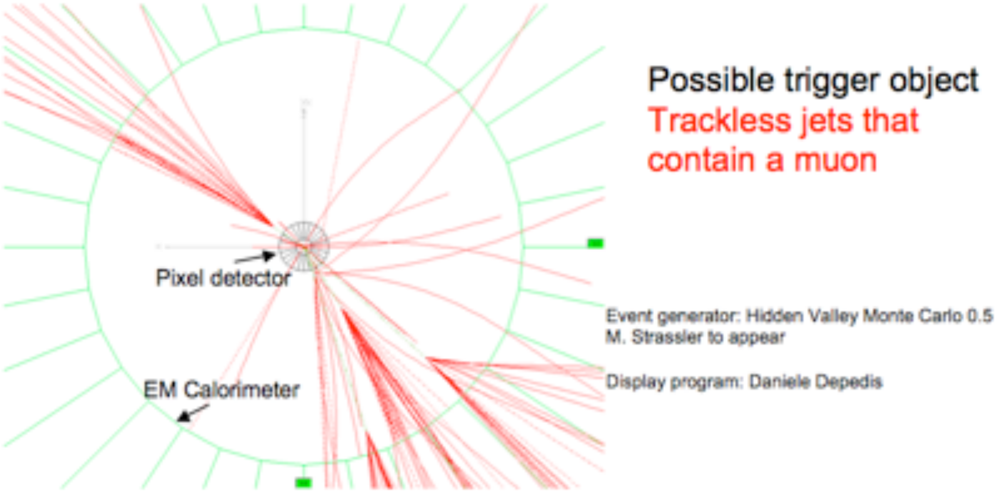


Production rates for v-hadrons



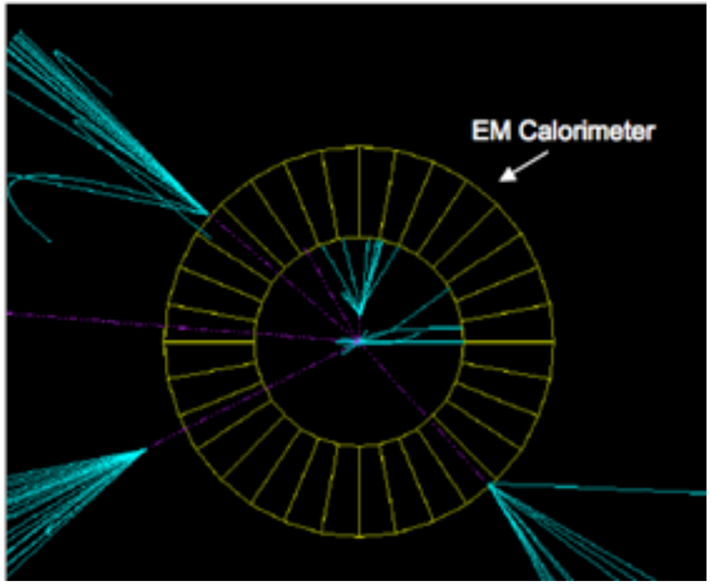
The Fear Factor: A real challenge for the triggers at the LHC

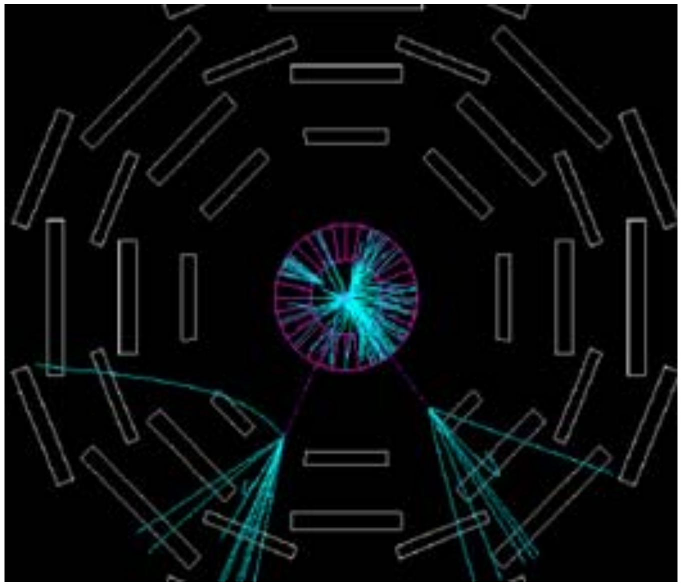
Hidden Valley events



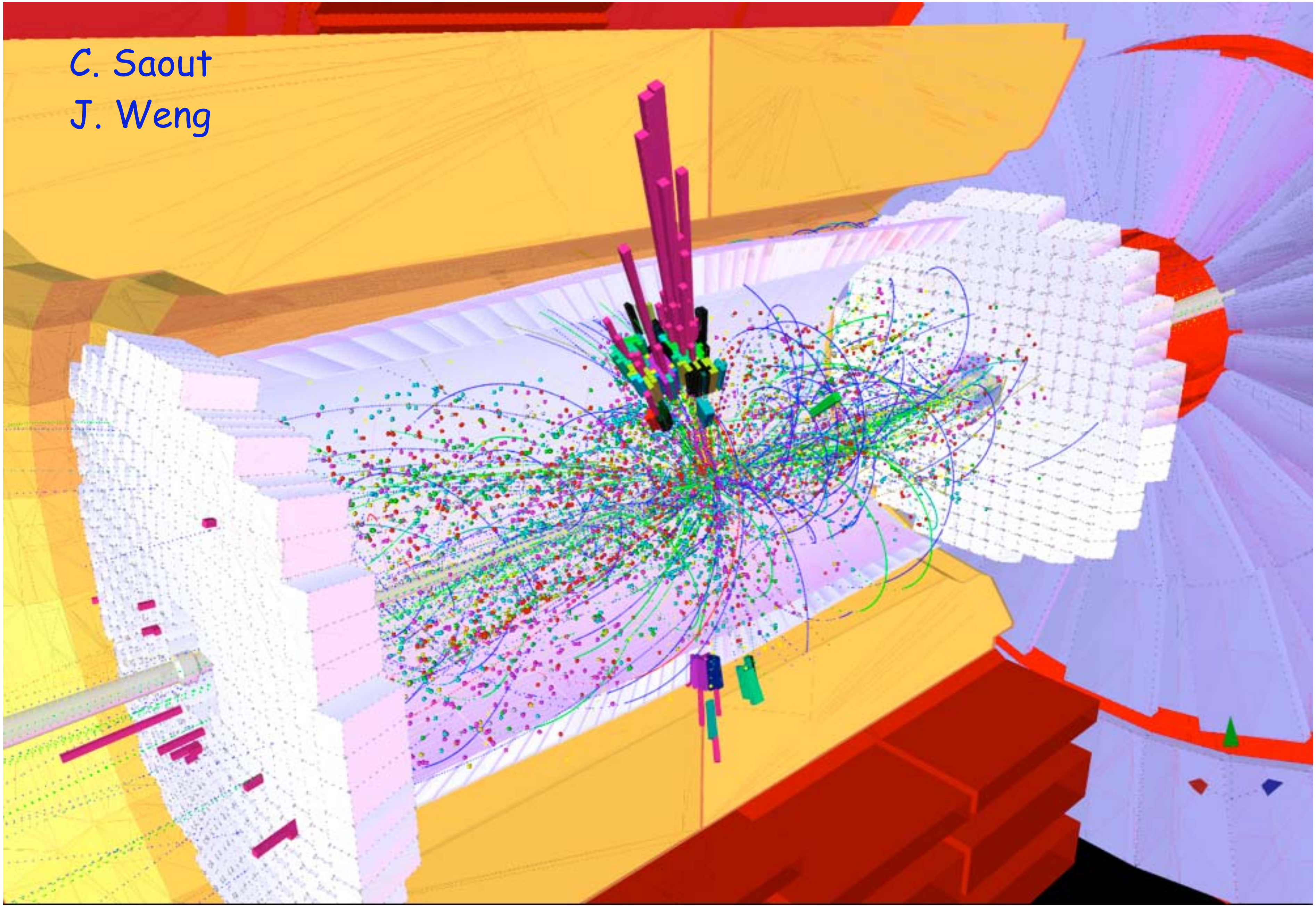
ATLAS: Trigger issues for events with large displayed vertices

UC Davis workshop on
The unexpected at the LHC
November 07

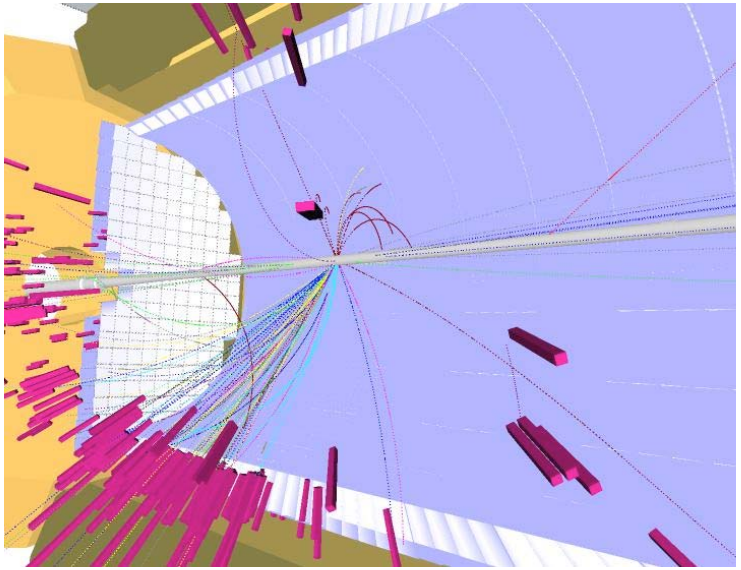


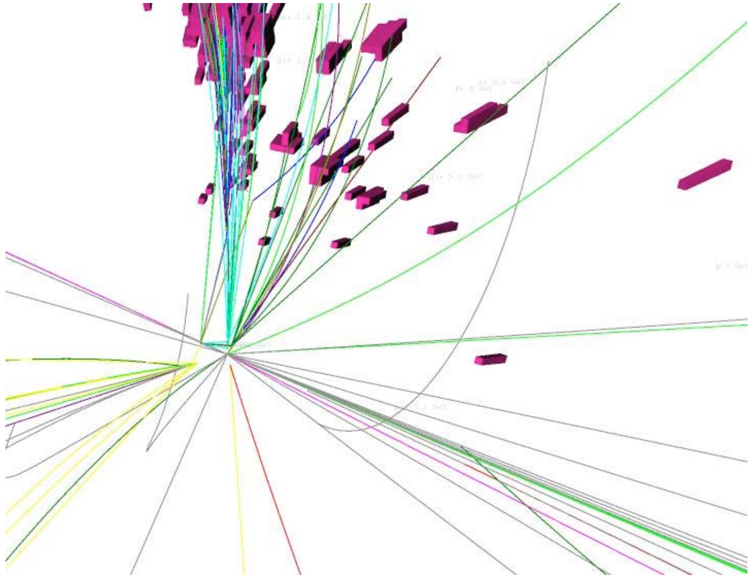


⇒Needs special triggers

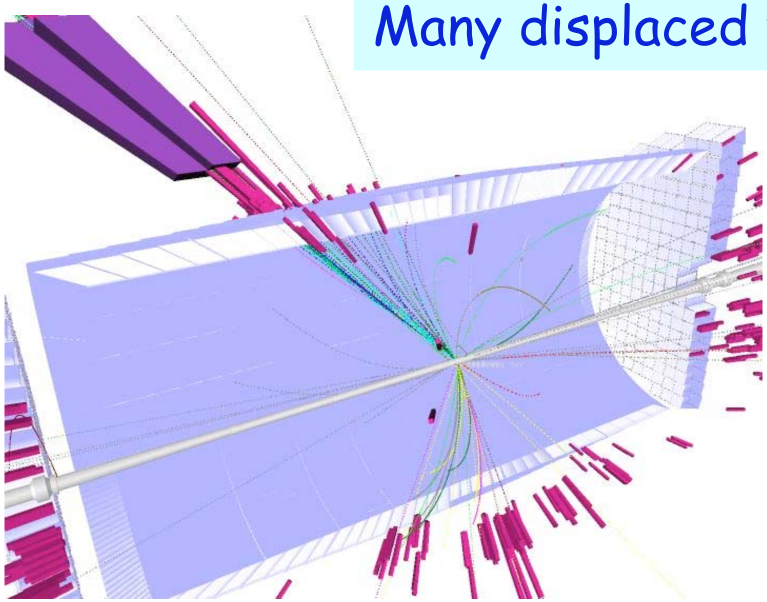

C. Saout
J. Weng

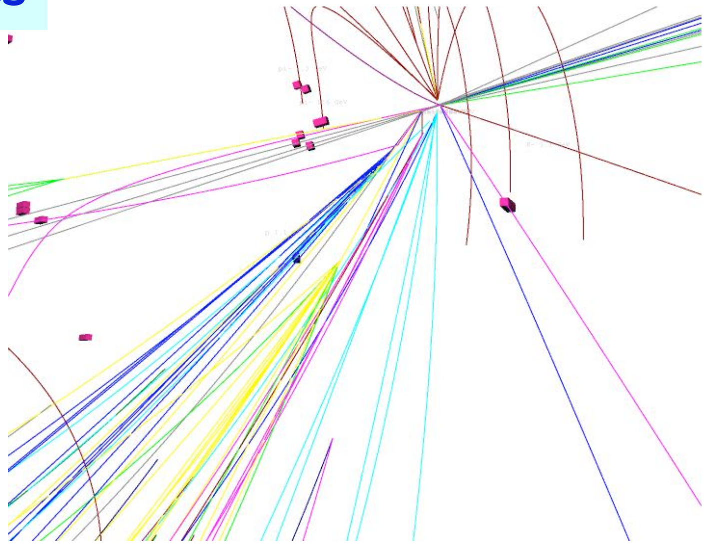
Hidden Valley Events





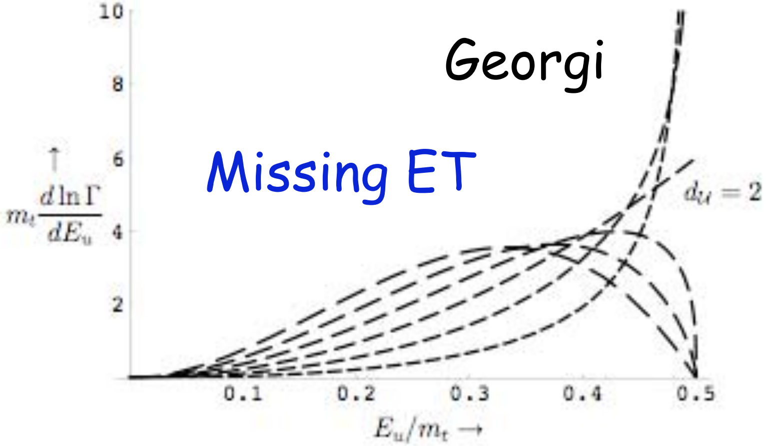
Many displaced vertices



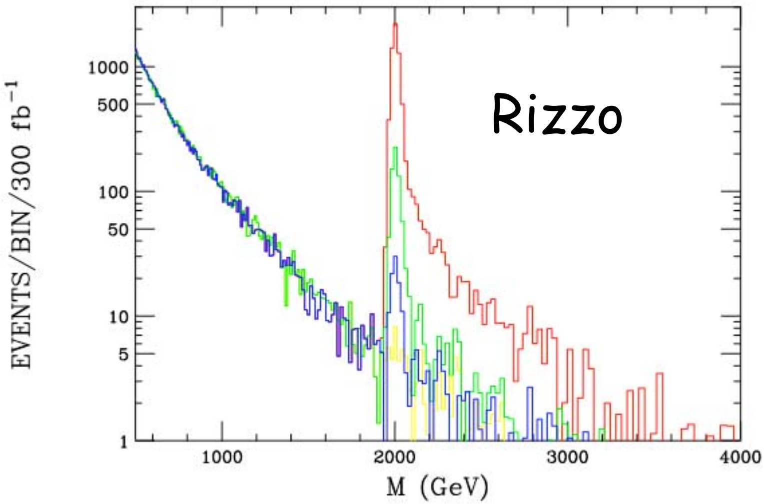


Unparticles

Top decay $t \to u + \mathcal{U}$



Decaying unparticles



- QFT possibility: sector that is scale invariant leading to new physics weakly coupled to SM through heavy mediators

⇒Unparticle stuff (Georgi, '07 + >100 new papers)
arXiv:hep-ph/0703260

- Real unparticle production
  - –Monophotons at LEP: $e^+e^- \to \gamma$ U
  - –Monojets at Tevatron, LHC: g g → g U
- Virtual unparticle exchange
  - –Scalar unparticles: f f → U → $\mu^+\mu^-$, $\gamma\gamma$, ZZ,... [No interference with SM]
  - –Vector unparticles: $e^+e^- \to U^\mu \to \mu^+\mu^-$, qq, ...

Other signatures: "funny jets"
high multiple photon rates

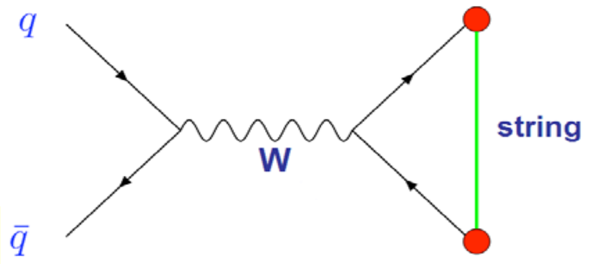
What are good unparticle signatures??

Quirks!

Quirks are exotic vector-like fermions that transform as a fundamental under a hidden confining group, but also carry Standard Model charges.

The quirk mass M is much larger than the confinement scale Λ.

⇒Macroscopic strings!?!

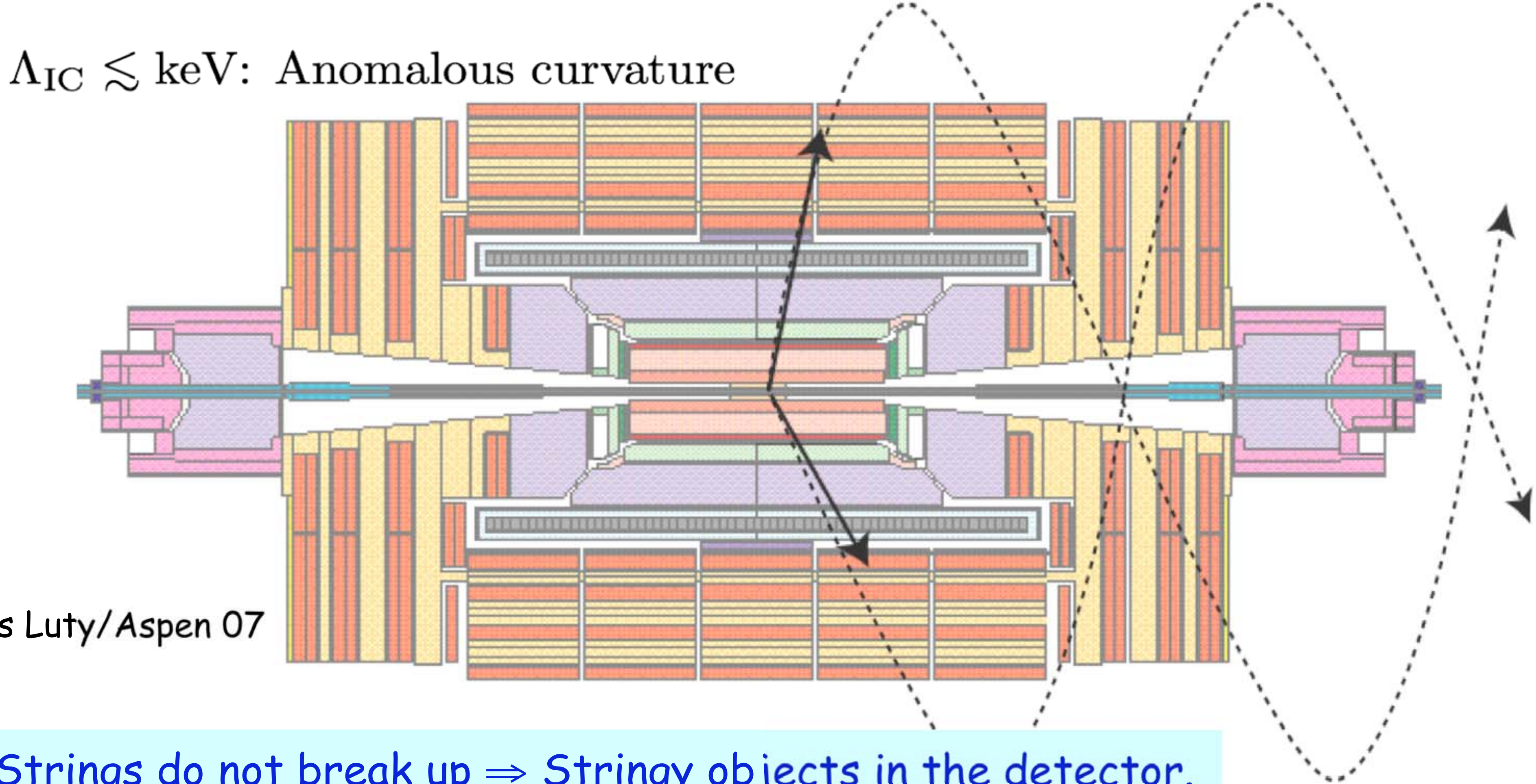


- Signatures Catalogue
  - Quirks with strange curvature in the B-field of the detectors
  - Quirks emitting many soft photons
  - Quirks emitting many soft hadrons
  - Quirks emitting glueballs
  - Quirks loosing energy in the detector (like R-Hardons?)
  - Quirks causing displaced vertices
  - Quirk pairs causing unusual ionization.
  - Timing of the signals?

M. Luty

Macro-Strings at the LHC?

New strong interactions with small Λ & new quarks m_Q> several hundered GeV



Markus Luty/Aspen 07

- Strings do not break up ⇒ Stringy objects in the detector.
- End points are massive quarks (quirks)
- The strings can oscillate⇒ strange signature in detectors

What should we do with this?

An Exceptionally Simple Theory of Everything

A. Garrett Lisi
SLRI, 722 Tyner Way, Incline Village, NV 89451
E-mail: alisi@hawaii.edu

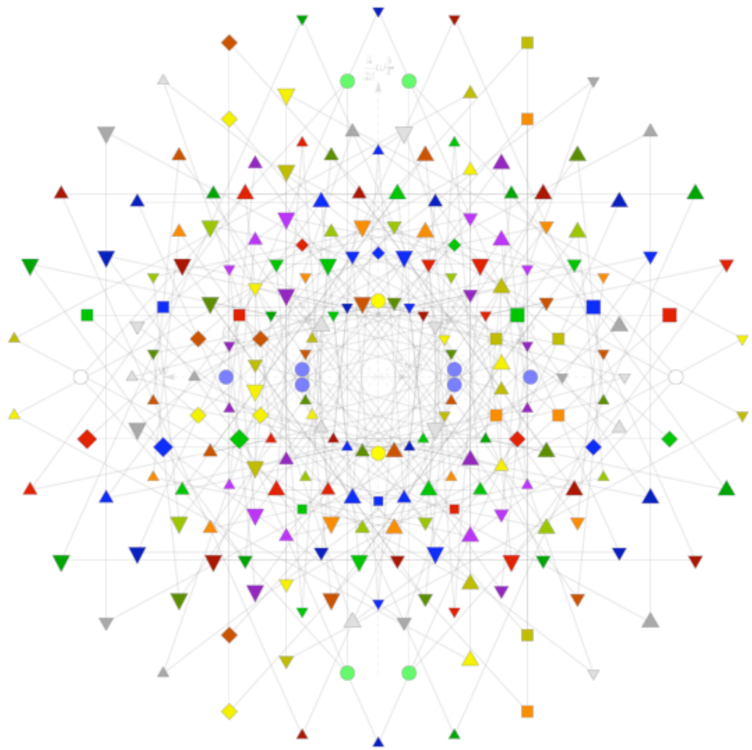
Abstract: All fields of the standard model and gravity are unified as an E8 principal bundle connection. A non-compact real form of the E8 Lie algebra has G2 and F4 subalgebras which break down to strong su(3), electroweak su(2) x u(1), gravitational so(3,1), the frame-Higgs, and three generations of fermions related by triality. The interactions and dynamics of these 1-form and Grassmann valued parts of an E8 superconnection are described by the curvature and action over a four dimensional base manifold.

Keywords: ToE.

A number of new particles predicted..

$E8$		$\frac{1}{2i}\omega_T^3$	$\frac{1}{2}\omega_S^3$	U^3	V^3	w	x	y	z	$F4$	$G2$	#
● ●	$\omega_L^{\wedge/\vee}$ $\omega_R^{\wedge/\vee}$	±1	±1	0		0	0			$D2_G$	1	4
● ○	$W^\pm$ $B_1^\pm$	0		±1	±1	0	0			$D2_{ew}$	1	4
■ ◆ ◆ ■	$e\phi_+$ $e\phi_-$ $e\phi_1$ $e\phi_0$	±1		±1		0	0			4×4	1	16
▲ ▲ ▲ △	ν_{eL} e_L ν_{eR} e_R	±1/2 ... even#>0				−1/2	−1/2	−1/2	−1/2	8_{S+}	l	8
▼ ▼ ▼ ▽	$\bar\nu_{eL}$ $\bar e_L$ $\bar\nu_{eR}$ $\bar e_R$	±1/2 ... even#>0				1/2	1/2	1/2	1/2	8_{S+}	$\bar l$	8
▲ ▲ ▲ ▲	u_L d_L u_R d_R	±1/2 ... even#>0				−1/2	±1/2 ... two>0			8_{S+}	q_I	24
▼ ▼ ▼ ▼	$\bar u_L$ $\bar d_L$ $\bar u_R$ $\bar d_R$	±1/2 ... even#>0				1/2	±1/2 ... one>0			8_{S+}	$\bar q_I$	24
▲ ▲ ▲ △	$\nu_{\mu L}$ μ_L $\nu_{\mu R}$ μ_R	±1/2 ... odd#>0				−1/2	1/2	1/2	1/2	8_{S-}	l	8
▼ ▼ ▼ ▽	$\bar\nu_{\mu L}$ $\bar\mu_L$ $\bar\nu_{\mu R}$ $\bar\mu_R$	±1/2 ... odd#>0				1/2	−1/2	−1/2	−1/2	8_{S-}	$\bar l$	8
▲ ▲ ▲ ▲	c_L s_L c_R s_R	±1/2 ... odd#>0				1/2	±1/2 ... two>0			8_{S-}	q_I	24
▼ ▼ ▼ ▼	$\bar c_L$ $\bar s_L$ $\bar c_R$ $\bar s_R$	±1/2 ... odd#>0				−1/2	±1/2 ... one>0			8_{S-}	$\bar q_I$	24
▲ ▲ ▲ △	$\nu_{\tau L}$ τ_L $\nu_{\tau R}$ τ_R	±1				1	0			8_V	1	8
▼ ▼ ▼ ▽	$\bar\nu_{\tau L}$ $\bar\tau_L$ $\bar\nu_{\tau R}$ $\bar\tau_R$	±1				−1	0			8_V	1	8
▲ ▲ ▲ ▲	t_L b_L t_R b_R	±1				0	−1			8_V	q_{II}	24
▼ ▼ ▼ ▼	$\bar t_L$ $\bar b_L$ $\bar t_R$ $\bar b_R$	±1				0	1			8_V	$\bar q_{II}$	24
●	g	0				0	1 −1			1	$A2$	6
■ ◆	$x_1\Phi$	0				−1	±1			1	q_{II}	6
■ ◆	$x_2\Phi$	0				1	±1			1	q_{II}	6
■ ◆	$x_3\Phi$	0				0	±(1 1)			1	q_{III}	6

Table 9: The 240 roots of $E8$ assigned elementary particle labels according to $F4$ and $G2$ subgroups.



Talking about weird things…

Search for Future Influence from L.H.C.

Holger B. Nielsen [1]
The Niels Bohr Institute, University of Copenhagen, Copenhagen ϕ, DK2100, Denmark
and
Masao Ninomiya [2]
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Abstract

We propose an experiment which consists of pulling a card and use it to decide restrictions on the running of L.H.C. at CERN, such as luminosity, beam energy, or total shut down. The purpose of such an experiment is to look for influence from the future, backward causation. Since L.H.C. shall produce particles of a mathematically new type of fundamental scalars, i.e. the Higgs particles, there is potentially a chance to find hitherto unseen effects such as influence going from future to past, which we suggest in the present paper.

Does the future affect the Present (backward causation)?

We suggest that our theoretical model building [3–5] especially calls for such an experiment. When the Higgs particle shall be produced, we shall retest if there could be influence from the future so that, for instance, the potential production of a large number of Higgs particles in a certain time development would cause a pre-arrangement so that the large number of Higgs productions, should be avoided. Such prearrangements may be considered influence from the future. One of us

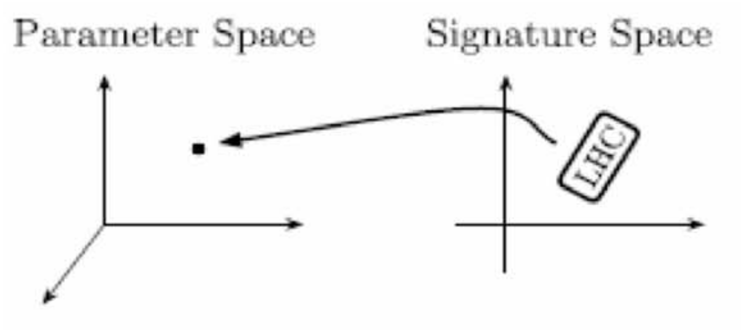
☺

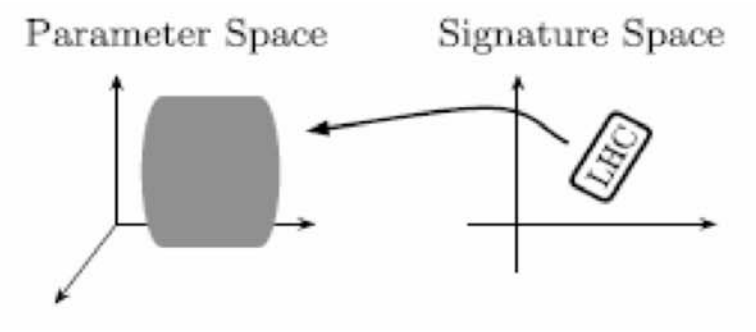
After the Champagne…

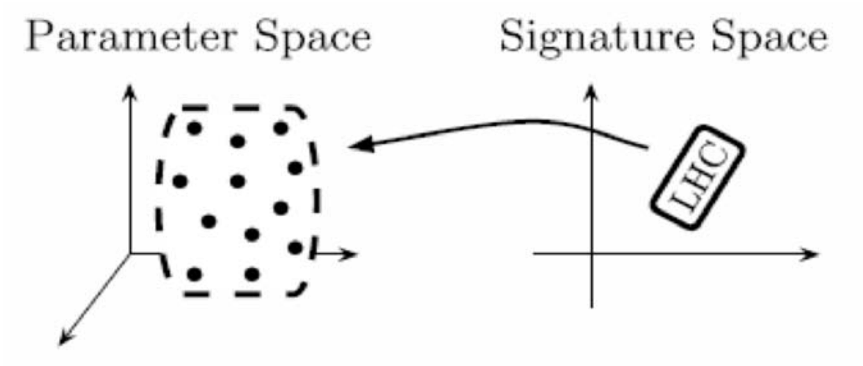
- WHEN new physics is discovered at the LHC, how well can we determine what it is? Does a specific experimental signature map back into a unique theory with a fixed set of parameters?

- Even within a very specific context, e.g., the MSSM, can one uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?

The Inverse Mapping of Data: there are many possible outcomes….







Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space… → model degeneracy

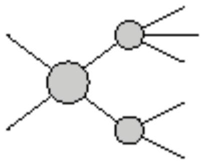
Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190
Kane, Kumar and Shao, arXiv:0709.4259

The efforts to understand the problems and design strategies - even before data- are very important!

The Inverse Problem

MARMOSET

LHC Signatures ⇔ **OSET** ⇔ $\mathcal{L}$

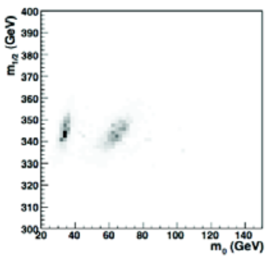


hep-ph/0703088, N. Arkani-Ahmed et al

Looks like an interesting communication tool with theorist

Other

Lester et al., hep-ph/0508143



Attempts to Map Measurements to the Parameter Space

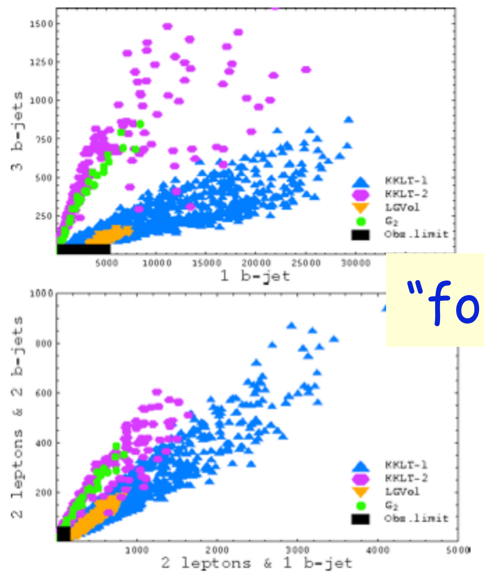
Inclusive+Exclusive

Inclusive [counting/cross section] and exclusive [end-point type] of measurements ⟶ a-posteriori probabilities of mapping back to the parameter space (*cf* references last slide and "Olympics" series)

Example

[3] a-posteriori probability distribution of mSUGRA parameters using cross-section + end-point measurements in a Markov Chain Monte Carlo sampling of the parameter space. The two regions reflect the lack of knowledge of which slepton is involved in the decay chain.

Kane et al., arXiv:0709.4259



"footprints"

⇒ Common ground of interest for theorist and experimentalists

Tools & Theoretical Estimates

The LHC will be a precision and hopefully discovery machine
But it needs strong collaboration with theorists

Examples

- Precision predictions of cross sections
- Estimates for backgrounds to new physics
- Monte Carlo programs (tuned) for SM processes: W,Z,t.. + njets and more..
- Monte Carlo programs for signals (ED's,…)
- Evaluation of systematics due to theory uncertainties
- Higher order calculations
- New phenomenology/signatures to look for
- Discriminating variables among different theories
- Getting spin information from particles
- Tools to interprete the new signals in an as model independent way as possible (MARMOSET, footprints?)
- …

In any case:

The only place where you find success before work is in the dictionary

LHC: machine in place, now being commissioned… A big challenge
Experiments: Detectors being completed in the next few months
Preparing for collisions!!

Theorists et al.: (please) be patient…

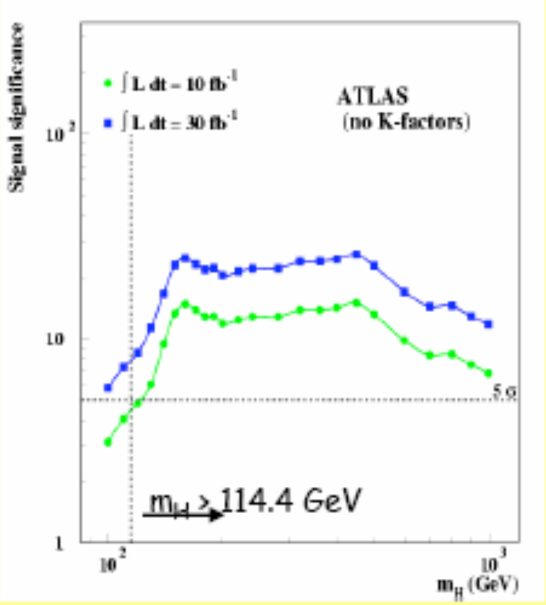
Summary

- CMS is on track for collisions at 14 TeV starting middle 2008 onwards.
  - Challenge: commissioning of machine and detectors of unprecedented scale, complexity, technology and performance
- The LHC will break new ground in exploring the TeV scale and hunt for the Higgs particle and new physics (SUSY?, EDs? Z'? Quirks? Hidden Valleys, Unparticles...)
  - Will it be easy and fast with the first luminosities as we all hope, or shall we have to sweat through years of data taking and hard work before we can claim a discovery ?
  - Watch out for weird signatures!
- In 2008(+) we will finally know!

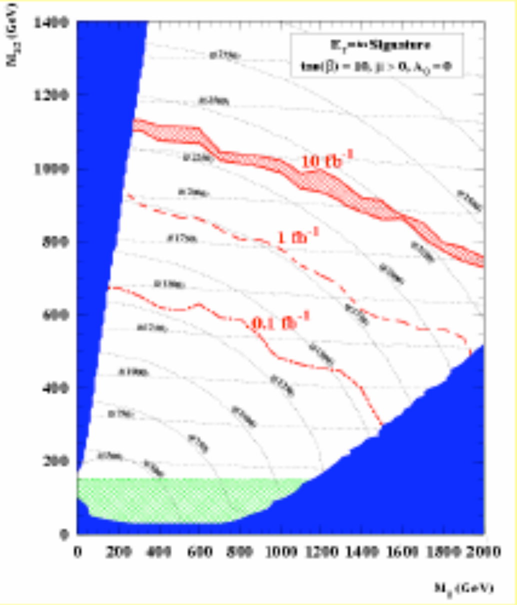
What can we expect in 2010 with 10 fb^{-1}?

"Early discoveries" at LHC

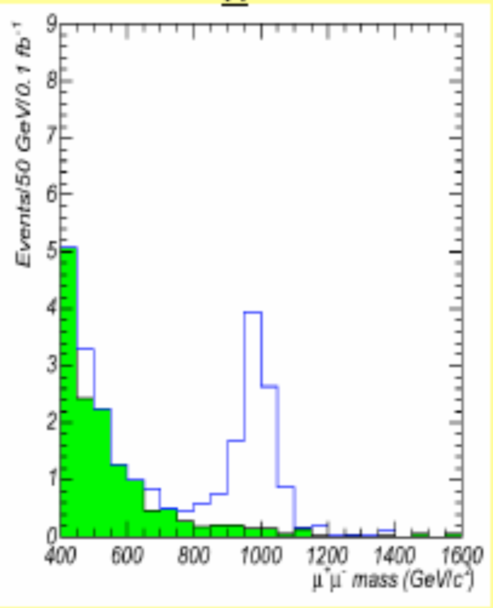
SM/MSSM Higgs



inclusive SUSY



di-lepton resonance (Z′,RS,Z_H,...)



with 10 fb^{-1}:

full range

$m_{sq,gl}$<2-2.5 TeV in mSugra

m<~3 TeV dep. on model