Higgs and beyond at the LHC
with a little help from QCD

Gavin Salam

CERN, Princeton University & LPTHE/CNRS (Paris)

MIT Physics Colloquium
6 September 2012

The LHC has been colliding protons since late 2009

The world's largest fundamental physics endeavour

Involving $\mathcal{O}(10\,000)$ scientists and engineers
From about 60 countries across the world
At a cost of several billion US dollars

The New York Times

Late Edition

NEW YORK, THURSDAY, JULY 5, 2012

Physicists Find Elusive Particle Seen as Key to Universe

International Herald Tribune

THE GLOBAL EDITION OF THE NEW YORK TIMES

Discovery upends world of physics

CHINA DAILY

Le Monde

Science : la matière dévoilée

LA DÉPÊCHE

La «particule de Dieu» existe

le dauphiné

L'Univers livre enfin ses secrets

EL DIARIO

Libération

Physique des particules La masse est dite

L'ECHO

Particule élémentaire !

la Nouvelle République

La particule qui fait accélérer notre histoire

CORRIERE DELLA SERA

The New York Times

THE TIMES

Frankfurter Allgemeine

EL PAÍS

International Herald Tribune

LA RAZÓN

LA VANGUARDIA

El juez imputa a Rato y 32 consejeros de Bankia

Levante

DIE WELT

THE HINDU

Elusive particle found, looks like Higgs boson

la Repubblica

"Perché l'Italia deve farcela"

LA STAMPA

MK

The Telegraph

l'Unità

The Gazette

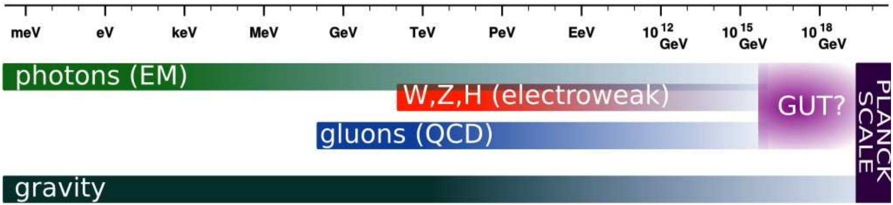
THE JERUSALEM POST

AD ALGEMEEN DAGBLAD

আনন্দবাজার পত্রিকা

বিজ্ঞানের 'ঈশ্বর' দর্শন

The scales at play



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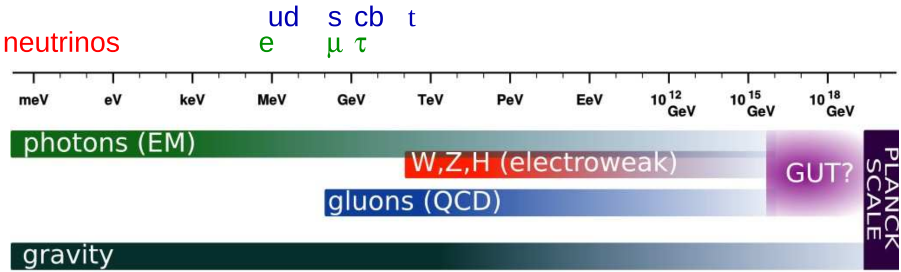

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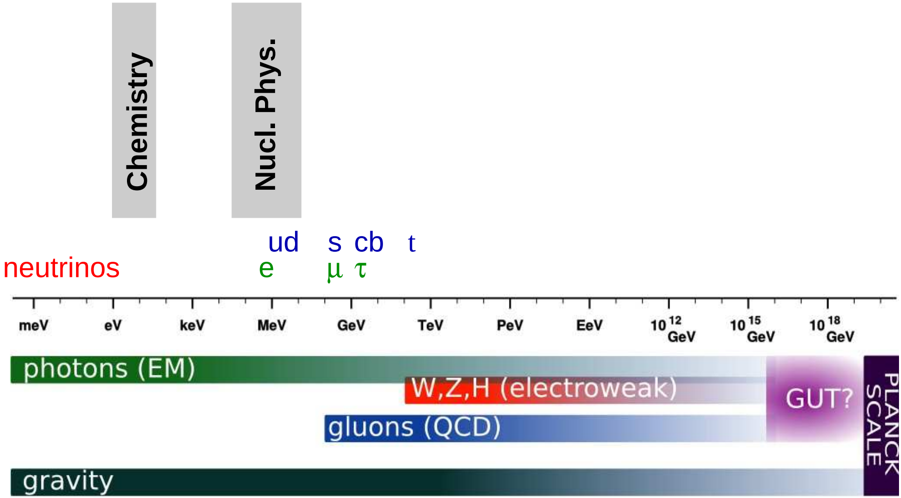

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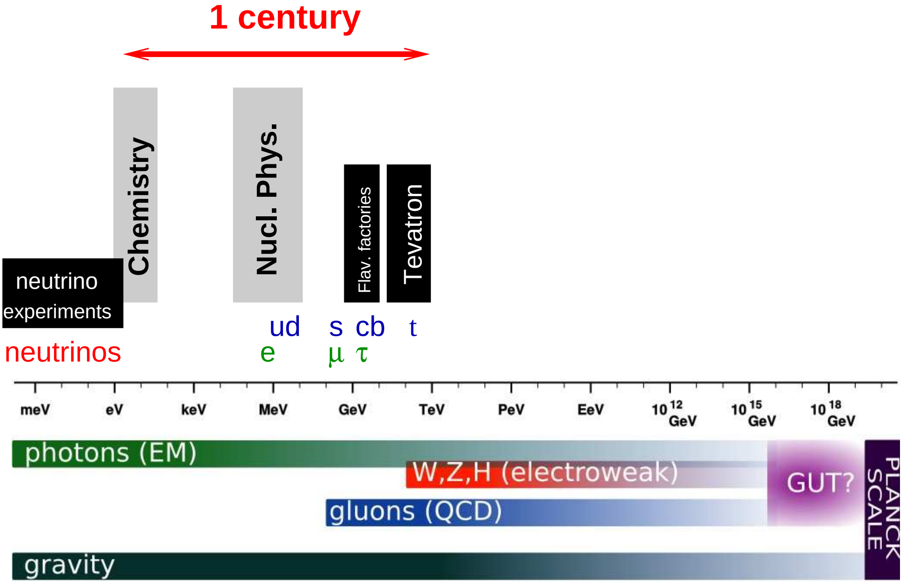

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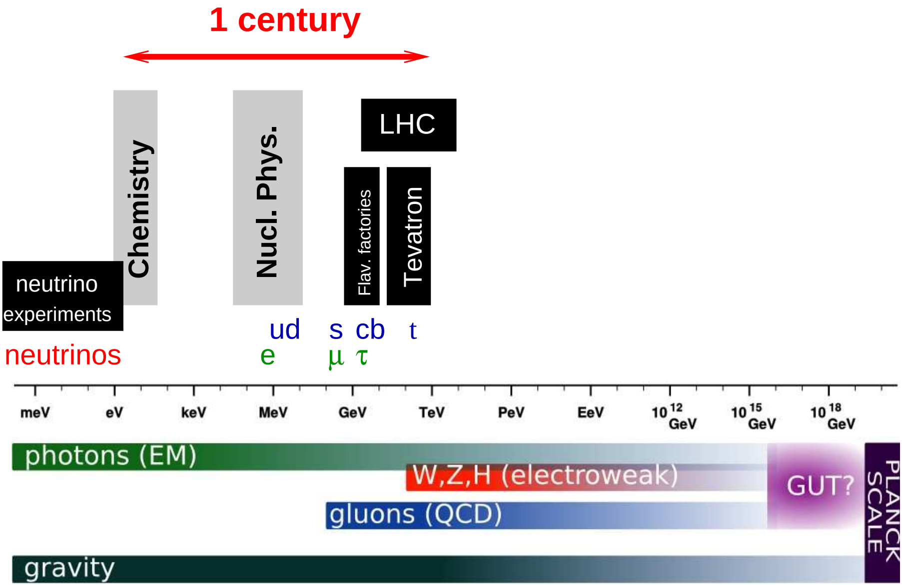

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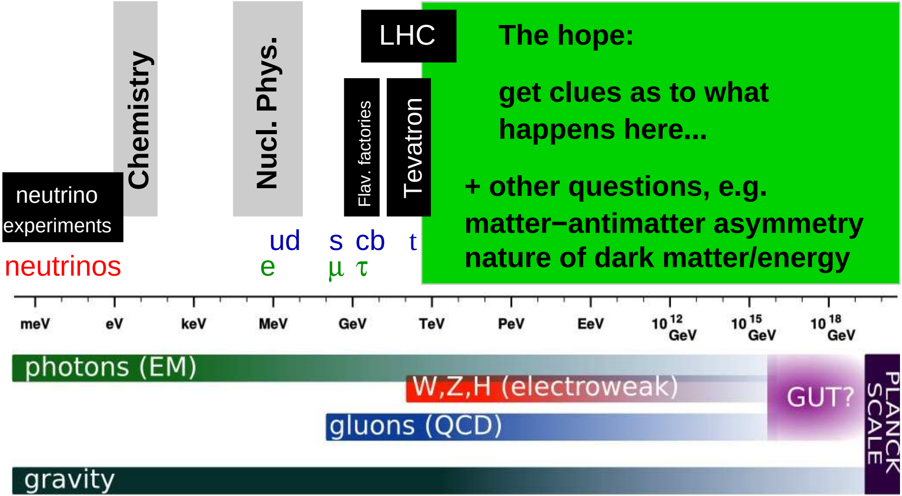
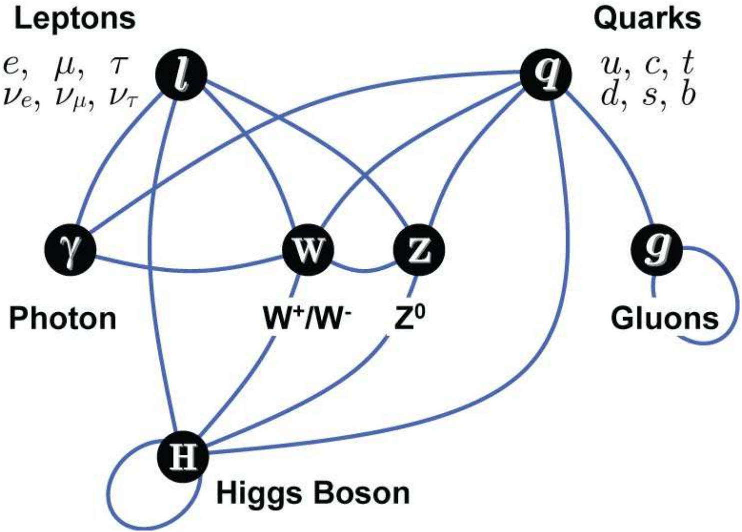


The hope:

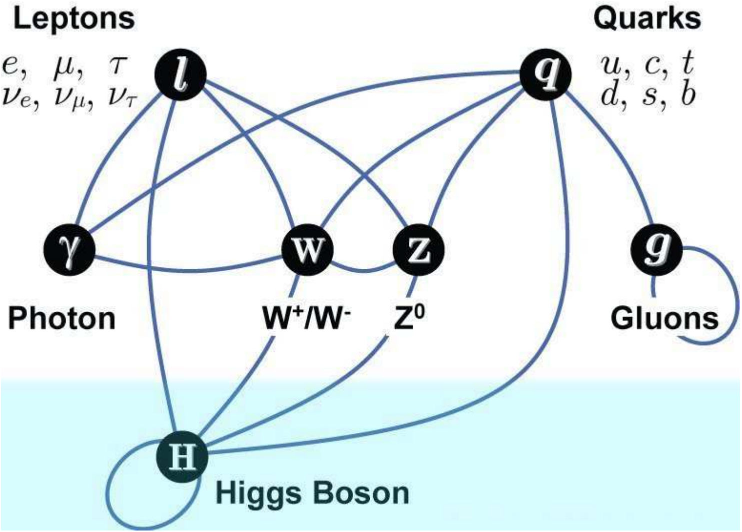
get clues as to what happens here...

+ other questions, e.g.
matter−antimatter asymmetry
nature of dark matter/energy

The Standard Model



The Standard Model



Higgs/ABEHGHK'tH in an (oversimplified) slide

Among the terms in the Standard Model Lagrangian:

$$g_{\mathrm{W}}^2 \;\; \phi^2 \;\; Z_\mu Z^\mu$$

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Z-boson fields

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gauge coupling

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Among the terms in the Standard Model Lagrangian:

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scalar field

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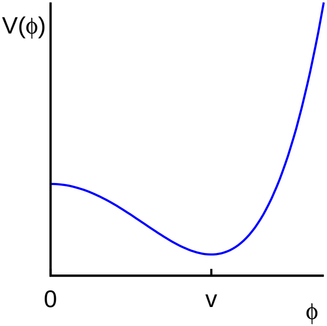
$$\underset{\text{gauge coupling}}{g_{\mathrm{W}}^2}\ \ \underset{\text{scalar field}}{\phi^2}\ \ \underset{\text{Z-boson fields}}{Z_\mu Z^\mu}$$

Potential for scalar field is

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Universe lives at minimum of potential, $\phi \simeq v$. Rewrite ϕ in terms of perturbations H around minimum



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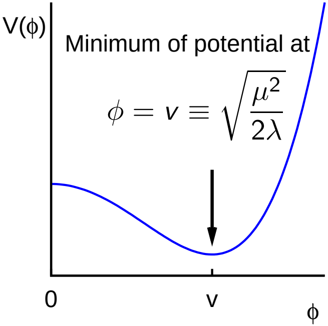

Minimum of potential at

$$\phi = v \equiv \sqrt{\frac{\mu^2}{2\lambda}}$$

Higgs/ABEHGHK'tH in an (oversimplified) slide

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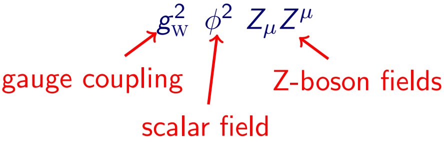

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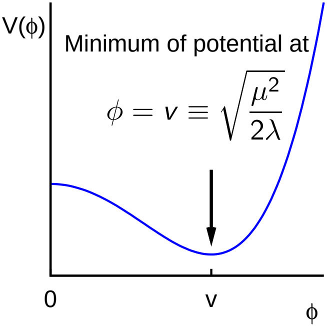

Minimum of potential at

$$\phi = v \equiv \sqrt{\frac{\mu^2}{2\lambda}}$$

$$\phi \equiv v + H \;\; \rightarrow \;\; \phi^2 = v^2 + 2vH + H^2$$

H is the **Higgs-boson** field

Higgs/ABEHGHK'tH in an (oversimplified) slide

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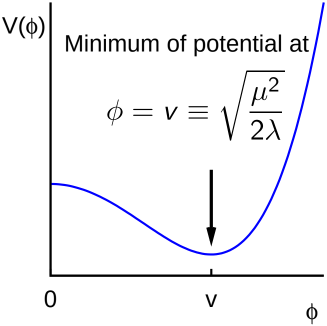

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$$\phi \equiv v + H \ \rightarrow\ \phi^2 = v^2 + 2vH + H^2$$

H is the **Higgs-boson** field

$$g_w^2\phi^2 Z_\mu Z^\mu \rightarrow \underbrace{g_w^2 v^2}_{\textbf{Z mass}^2} Z_\mu Z^\mu + \underbrace{2g_w^2 v}_{\textbf{HZZ coupling}} HZ_\mu Z^\mu$$

Mechanism generates particle masses

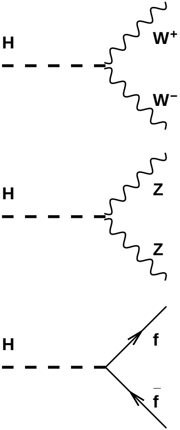
And a "Higgs" boson

A similar mechanism holds for fermions, with a Yukawa coupling y_f,

$$y_f \phi f\bar{f} \to \underbrace{y_f\, v\, f\bar{f}}_{\textbf{fermion mass}} + \underbrace{y_f\, H\, f\bar{f}}_{\textbf{interaction}}$$

Higgs mechanism gives mass to all fundamental particles (except maybe neutrinos).

It predicts characteristic relationship between their masses and their interactions with the Higgs boson.



$$2i\frac{M_W^2}{v}g_{\mu\nu}$$

$$2i\frac{M_Z^2}{v}g_{\mu\nu}$$

$$i\frac{m_f}{v}$$

$v \simeq 246$ GeV is known as vacuum expectation value of Higgs field

Higgs Mass ↔ no-lose proposition

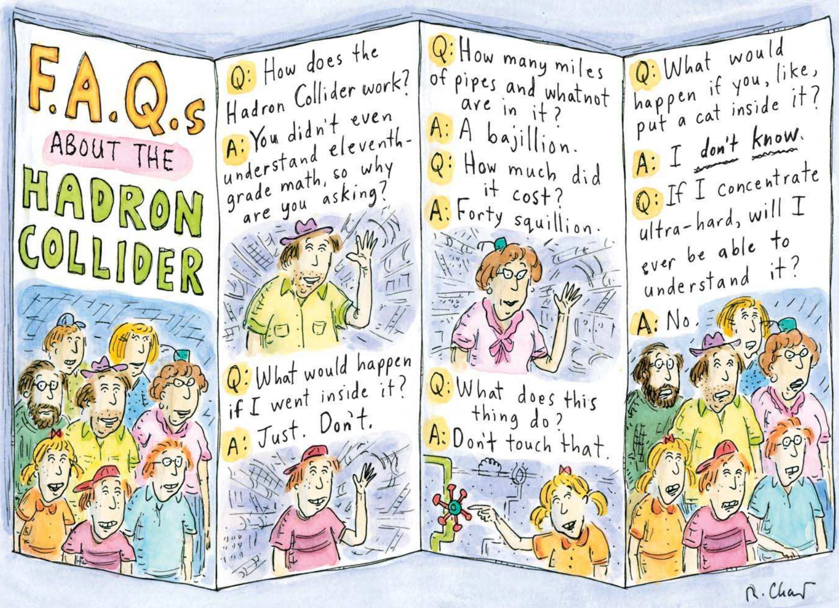
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \qquad \longrightarrow \qquad M_H = \sqrt{2\lambda}v$$

quartic coupling λ unknown, so **no prediction about Higgs mass**

Still, strong arguments say

- it cannot be below 70 GeV, because λ too small — renormalisation group evolution drives it negative and our universe is unstable
- if $M_H \gtrsim 800$ GeV, λ is large and we see new non-perturbative physics at ~ 1 TeV

So ideally build a collider that can discover Higgs-boson up to 800 GeV and perform WW scattering up to $\simeq 1$ TeV

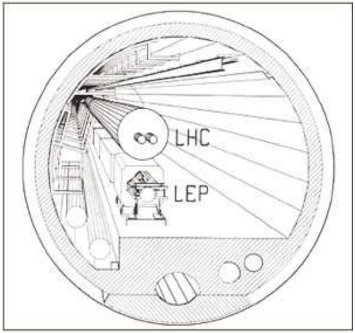

F.A.Q.s
ABOUT THE
HADRON
COLLIDER
Q: How does the Hadron Collider work?
A: You didn't even understand eleventh-grade math, so why are you asking?
Q: What would happen if I went inside it?
A: Just. Don't.
Q: How many miles of pipes and whatnot are in it?
A: A bajillion.
Q: How much did it cost?
A: Forty squillion.
Q: What does this thing do?
A: Don't touch that.
Q: What would happen if you, like, put a cat inside it?
A: I don't know.
Q: If I concentrate ultra-hard, will I ever be able to understand it?
A: No.
R. Chast

LHC concept got serious in first half of 80's

From the CERN Courier in **1984:**

The installation of a hadron collider in the [27km] LEP tunnel, using superconducting magnets, has always been foreseen by ECFA and CERN as the natural long term extension of the CERN facilities beyond LEP. [...]

Although the installation of such a hadron collider in the LEP tunnel might appear still a long way off [...], it [is] an opportune moment for ECFA, in collaboration with CERN, to organize a 'Workshop on the Feasibility of a Hadron Collider in the LEP Tunnel' [...]

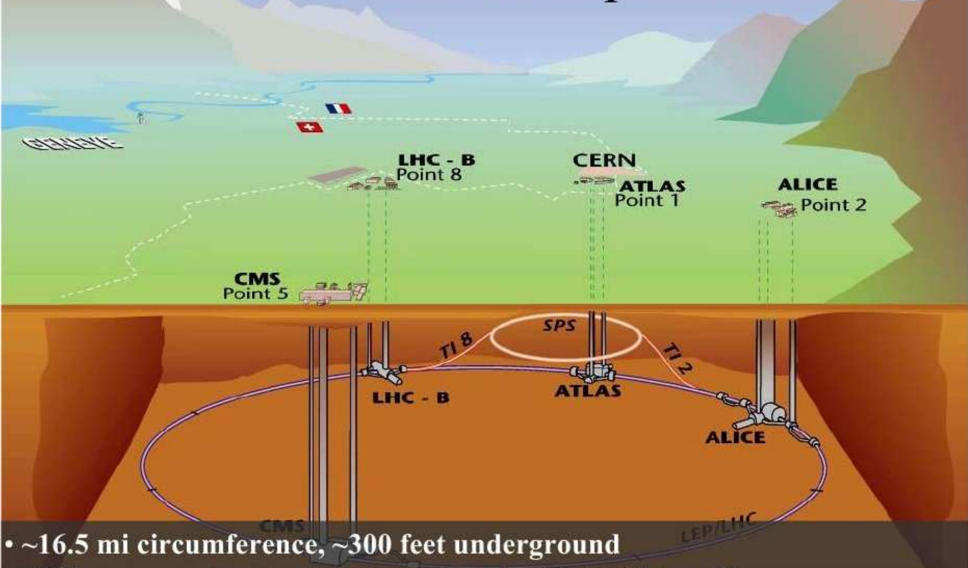


$$E \propto BR$$

ring radius $R \sim 4\times$Tevatron
superconduction magnets: $B = 8$ T
($2\times$ Tevatron)

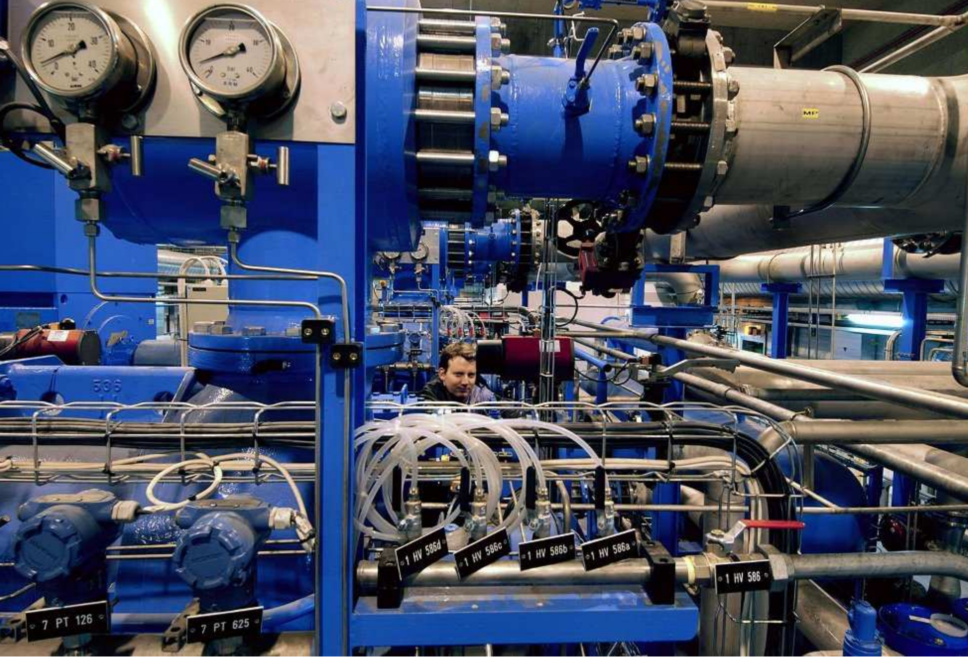
Tevatron ∼ 2 TeV ⟶ LHC ∼ 14 TeV

The LHC and its Experiments



- ~16.5 mi circumference, ~300 feet underground
- 1232 superconducting twin-bore Dipoles (49 ft, 35 t each)
- Dipole Field Strength 8.4 T (13 kA current), Operating Temperature 1.9K
- Beam intensity 0.5 A (2.2 10^{-6} loss causes quench), 362 MJ stored energy

Interconnection between two “dipoles” (bending magnets) in the LHC tunnel.



Cryogenics plant: 96 000 kg of Helium circulate through the machine at 1.9K

The detectors:

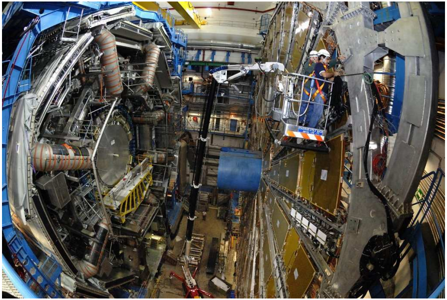
To accumulate 5×10^{16} collisions over a few years, they have to be able to handle a pp collision rate of 10^9 Hz

[25 collisions every 25 ns]

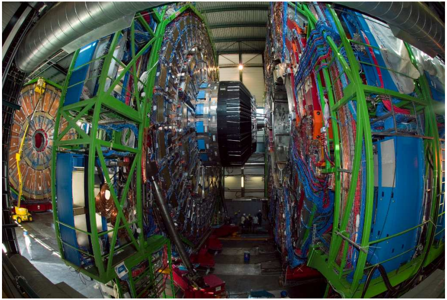
Typically, about 100 000 000 channels to read out.

[must be examined 40 000 000 times/s, interesting events written to long-term storage ∼400–1000 times/s]

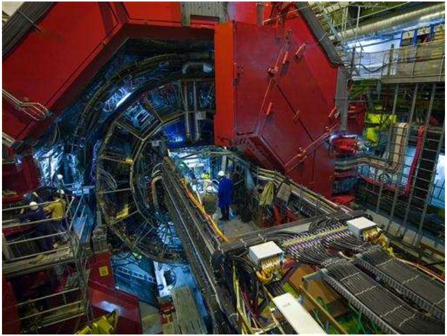
ATLAS: general purpose



CMS: general purpose



ALICE: heavy-ion physics



LHCb: B-physics

+ TOTEM, LHCf

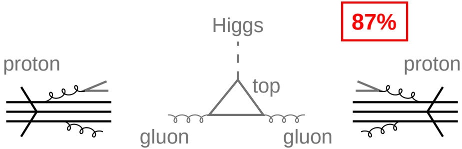
HIGGS PRODUCTION CHANNELS

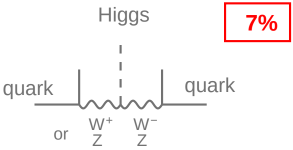
(always indirect, because H couples only weakly to light quarks)

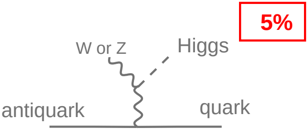
cross section $\simeq$ 20 pb

$\sim$ 1 Higgs every 5×10^9 pp collisions

[for $m_H = 125.5$ GeV]





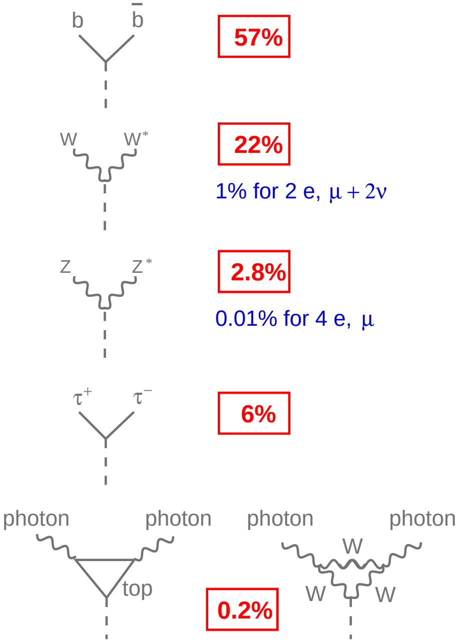


DECAY CHANNELS

[for $m_H = 125.5$ GeV]

WW and *ZZ* suppressed relative to simple coupling proportionality, because they cannot be produced on-shell

Best channels for detection are $\gamma\gamma$ and $ZZ^*(\rightarrow 4e, \mu)$, because of excellent experimental mass resolution and manageable backgrounds



57%

22%

1% for 2 e, $\mu + 2\nu$

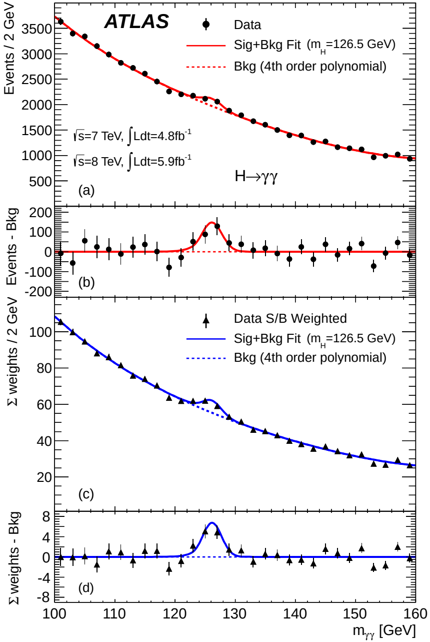
2.8%

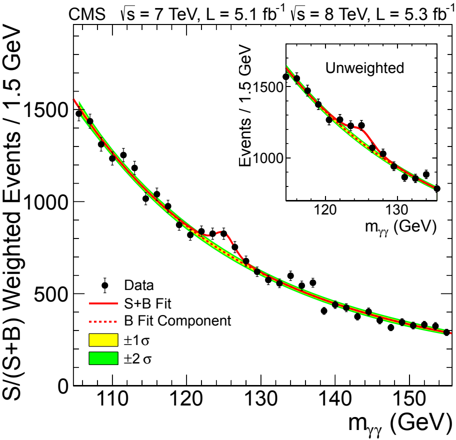
0.01% for 4 e, μ

6%

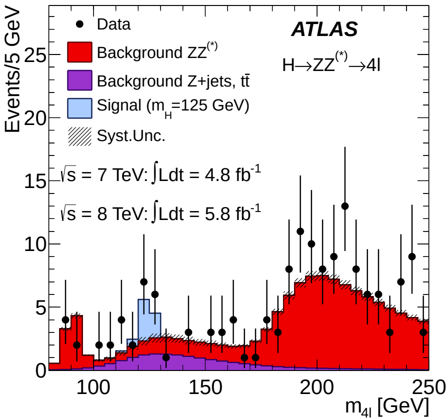
0.2%

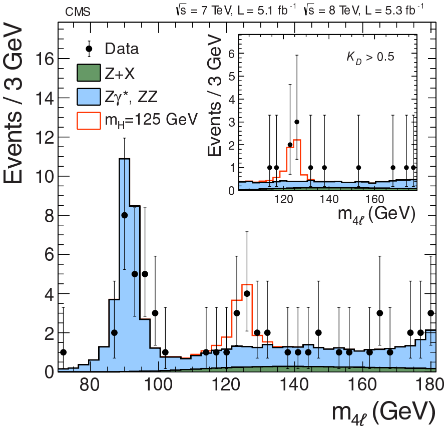
$\gamma\gamma$ pair invariant mass distribution





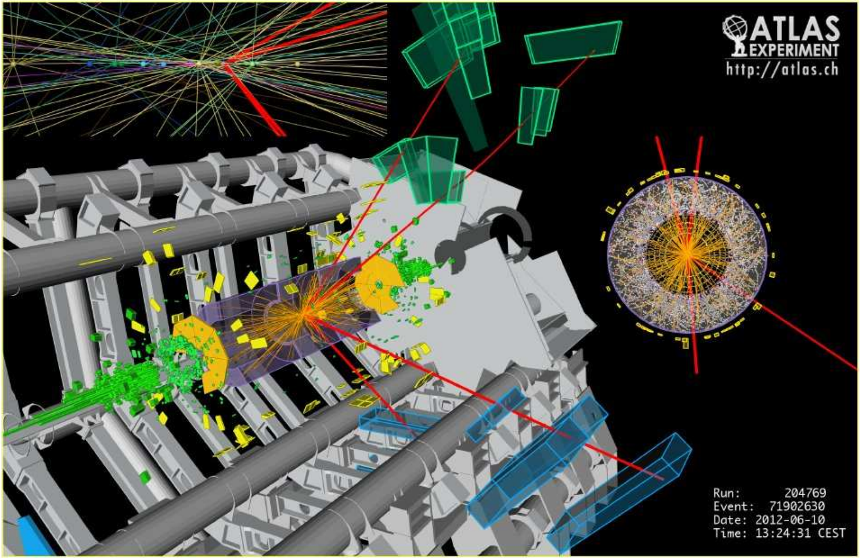
ZZ^* (4-lepton) invariant mass distribution



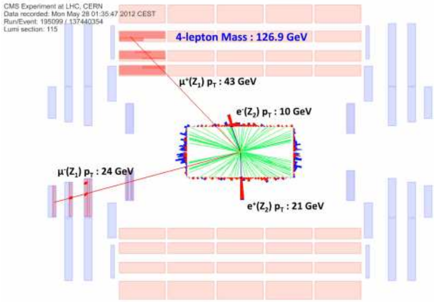


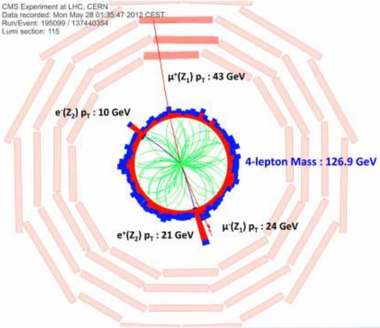
$m_{4\mu}$ = 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7 [GeV]
m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices



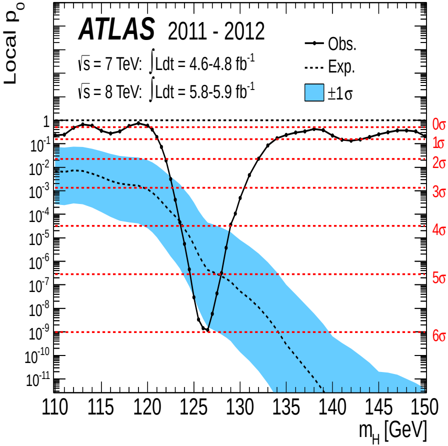
Event Display 2e2μ event

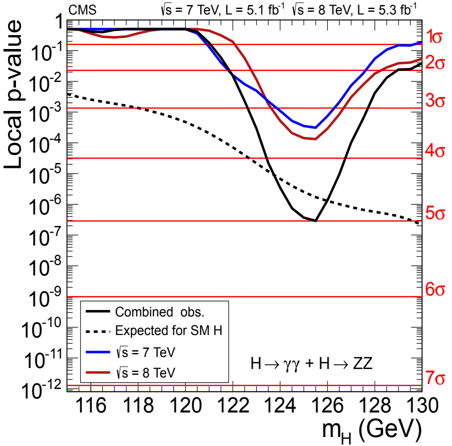




Significance of the "bumps"?

p_0 value = probability background fluctuated to produce observed "bumps".





$\geq 5\sigma$: OBSERVATION OF A NEW PARTICLE BY BOTH ATLAS AND CMS!

Properties of this new "Higgs-like" particle

- decay to $\gamma\gamma$ indicates either spin 0 or 2

  data by end of year should pin down spin and parity

- Mass:

  ATLAS: $126.0 \pm 0.4 \pm 0.4$ GeV
  CMS: $125.3 \pm 0.4 \pm 0.5$ GeV

- Couplings to other SM particles (key prediction of Higgs mechanism)

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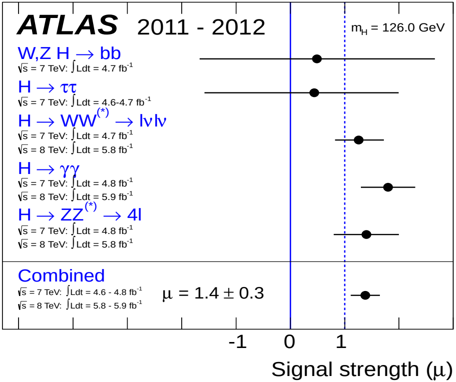
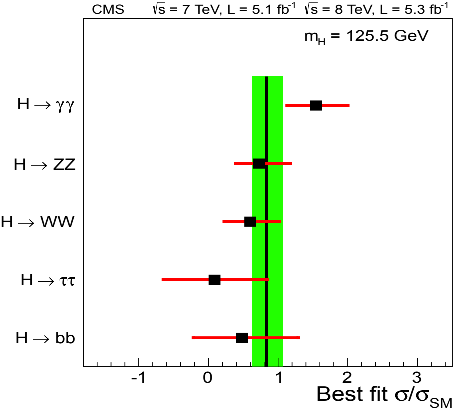
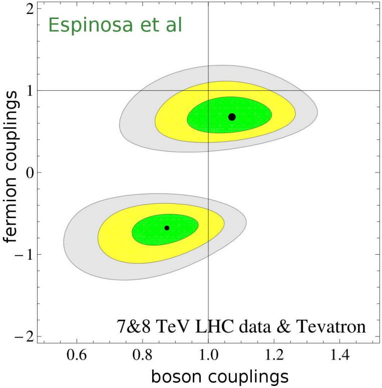


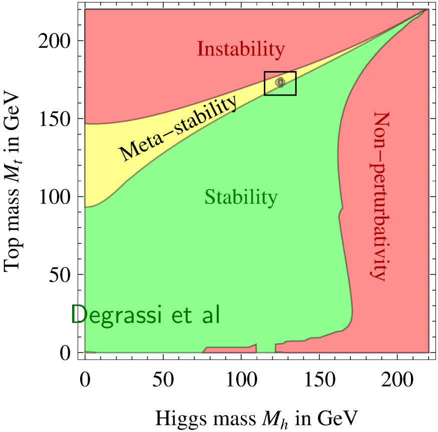


Interpretations. . .

Fits to underlying couplings



Stability of universe at M_{planck}



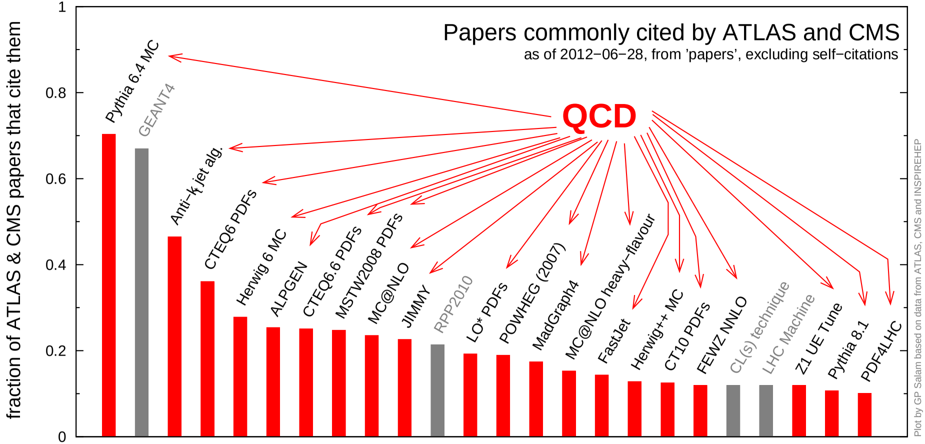
Since the discovery, a slew of papers have discussed couplings, proposed new physics explanations of deviations, etc.

The forthcoming installments of data will tell us more.

Behind the scenes…

One of the enablers for the LHC's success is our understanding of the strong interaction

Quantum Chromodynamics — QCD



Plot by GP Salam based on data from ATLAS, CMS and INSPIREHEP

Rough combination of ATLAS and CMS $H \to \gamma\gamma$ signal strengths: they see 1.6 ± 0.3 times the standard model expectation — a little high, but still consistent

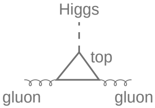
The standard-model cross section for gluon-fusion Higgs production is written as a perturbative expansion in powers of the strong coupling constant, with a leading-order (LO) term:

strong coupling constant ~ 0.11

number of colliding gluon pairs per pp collision ~ 100

Higgs production cross section

$$\sigma_{\mathrm{LO}} = \frac{\alpha_s^2}{576\pi v^2}\,\mathcal{L}_{gg}$$



Higgs field vacuum expectation value

If ATLAS and CMS had used the previous page's formula they would have found

$$\frac{\sigma_{\text{observed}}}{\sigma_{\text{LO}}} = 5.6 \pm 1.1$$

This would have been a strong sign (4σ) of physics beyond the standard model!

Where's the catch? Higher orders of QCD perturbation theory:

$$\begin{aligned} \sigma_{gg\to H} &= \sigma_{\text{LO}}\left(1 + 11.4\,\alpha_s + 63\,\alpha_s^2 + \cdots\right) \\ &= \sigma_{\text{LO}}\,(1 + \;1.27\quad + 0.79\quad + \cdots) \\ &\simeq \sigma_{\text{LO}} \times 3.4 \end{aligned}$$

NLO: Dawson '91; Djouadi, Spira & Zerwas '91

NNLO: Harlander & Kilgore '02; Anastasiou & Melnikov '02; Ravindran, Smith & van Neerven '03

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This would have been a strong sign (4σ) of physics beyond the standard model!

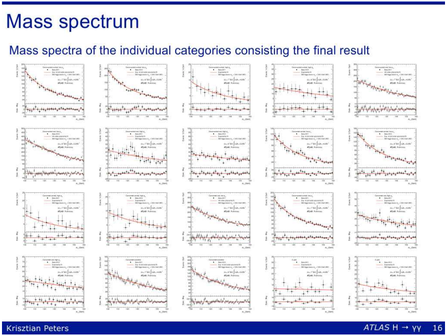
Where's the catch? Higher orders of QCD perturbation theory:

$$\begin{aligned}\sigma_{gg\to H} &= \sigma_{\text{LO}}\left(1 + 11.4\,\alpha_s + 63\,\alpha_s^2 + \cdots\right)\\ &= \sigma_{\text{LO}}\,(1 + \;\; 1.27 \quad + 0.79 \;\; + \cdots)\\ &\simeq \sigma_{\text{LO}} \times 3.4\end{aligned}$$

NLO: Dawson '91; Djouadi, Spira & Zerwas '91

NNLO: Harlander & Kilgore '02; Anastasiou & Melnikov '02; Ravindran, Smith & van Neerven '03

Corrections to total $\sigma_{gg\to H}$ are tip of QCD iceberg

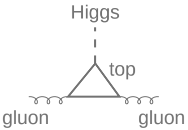


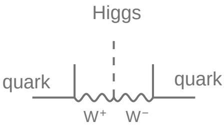
Mass spectrum

Mass spectra of the individual categories consisting the final result

Krisztian Peters ATLAS H → γγ 16

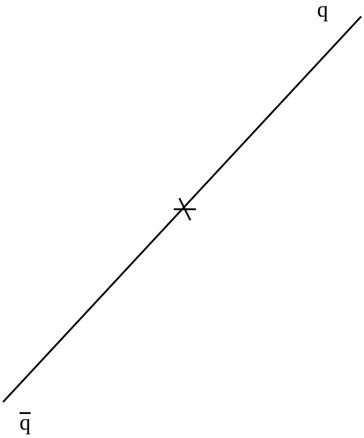
Experimental searches break analysis into sub-channels, which can differ in terms of signal process, backgrounds, resolutions, etc. Need QCD predictions in each sub-channel.





One or richest aspects of this kind of event characterization involves **jets**, which help count the number of energetic quarks and gluons in an event.

Quarks & gluons? We only ever see "jets"



Start off with quark and anti-quark, $q\bar{q}$

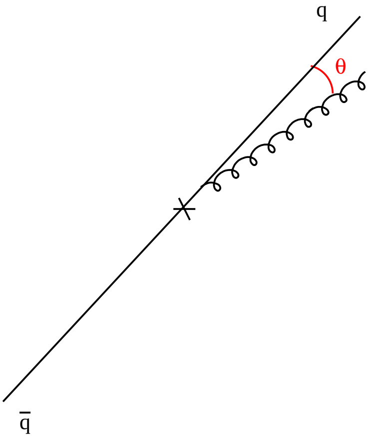
Quarks & gluons? We only ever see "jets"

In perturbative quantum chromodynamics (QCD), probability that a quark or gluon emits a gluon:

$$\sim \alpha_s \frac{dE}{E} \frac{d\theta}{\theta}$$

Diverges for small gluon energies E

Diverges for small angles θ



A quark never survives unchanged

it always emits a gluon (usually low-energy, at small angles)

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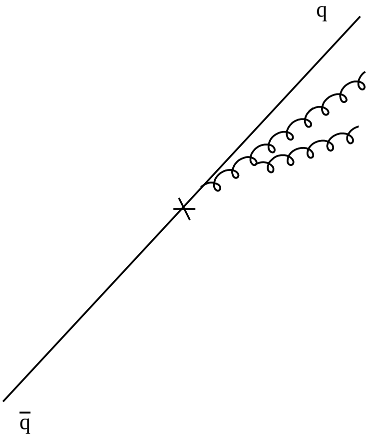

Each gluon radiates a further gluon

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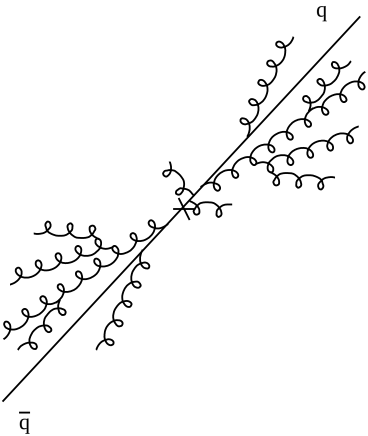

And so forth

Quarks & gluons? We only ever see "jets"

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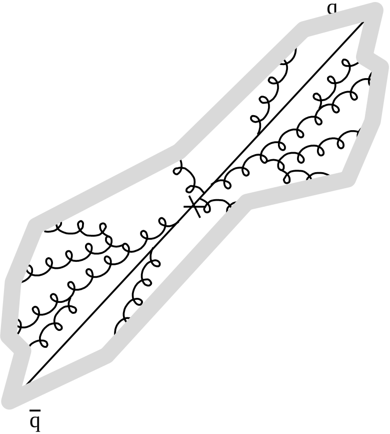
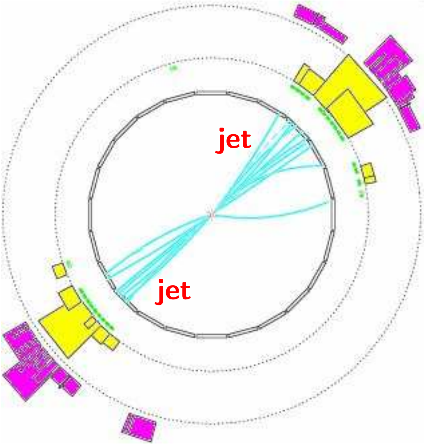
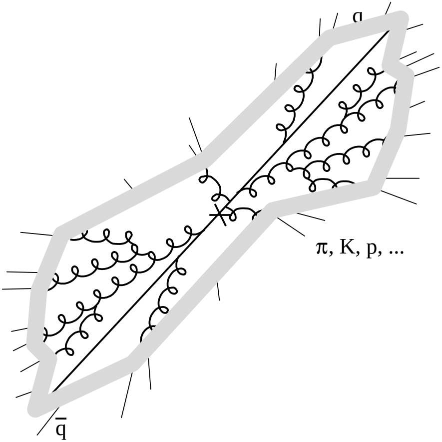


And then a non-perturbative transition occurs

Quarks & gluons? We only ever see "jets"

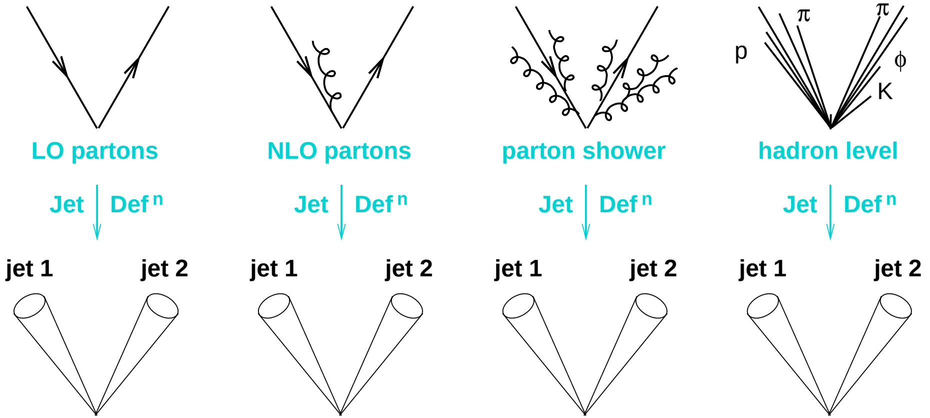




Giving a pattern of hadrons that "remembers" the gluon branching

Hadrons mostly produced at small angle wrt $q\bar{q}$ directions or with low energy

Jets made systematic: jet definitions



LHC events may be discussed in terms of quarks, quarks+gluon, or hadrons

A **jet definition** provides common representation of different "levels" of event complexity.

A \$100 000 000, 20-year old problem

QCD theorists have spent the past 10–15 years making accurate calculations of signals and backgrounds at the LHC, many of them with jets (with remarkable advances in field theory on the way)

$\mathcal{O}(100)$ people × 10 years $\simeq$ \$100 000 000

Problem 1: the jet definitions originally foreseen by LHC experiments were not compatible with these calculations — they "leaked" infinities:

$$\sigma = \sigma_{\mathrm{LO}} \left(1 + c_1\, \alpha_s + c_2\, \alpha_s^2 + \infty\, \alpha_s^3 + \cdots\right)$$

Problem 2: the jet definitions advocated by theorists since 1990's had been mostly shunned by proton-collider experiments

a) bad response to experimental noise

b) severe computational issues (1 minute/event $\times 10^{10}$ recorded events)

Solving the jets problem

Discovered a link between QCD jet-finding and problems of 2D computational geometry

Cacciari & GPS '05

Jet clustering reduces to 2D dynamic nearest neighbour problem

time to cluster N particles reduced from $N^3 \rightarrow N \ln N$ (or $N^{\frac{3}{2}}$)

Developed a theory of the interplay between jet-finding, QCD radiation and experimental noise

Cacciari, GPS & Soyez '08

A crucial element was linearity of response

Spin-off applications for γ and lepton ID in Higgs searches

Proposed a new jet-definition based on what we'd learnt

anti-k_t

Cacciari, GPS & Soyez '08

Anti-k_t algorithm

simple agglomerative clustering algorithm

repeatedly cluster objects with smallest $d_{ij} = \dfrac{\Delta R_{ij}^2}{\max(k_{ti}^2, k_{tj}^2)}$

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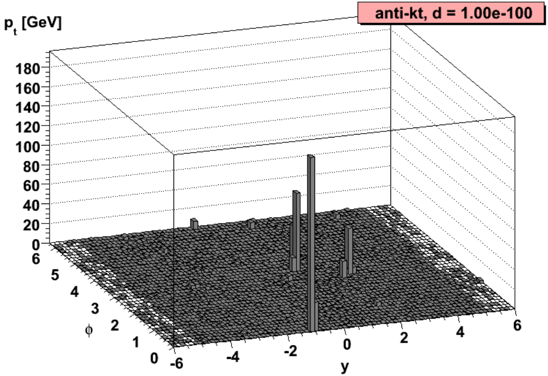

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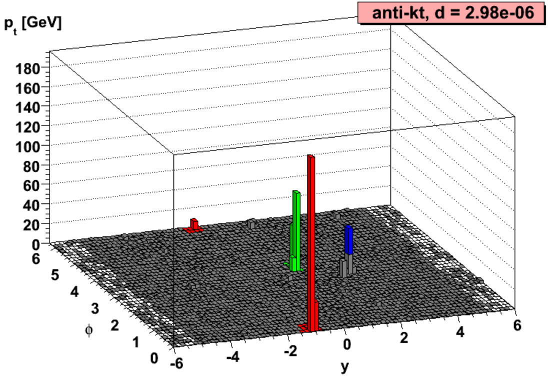

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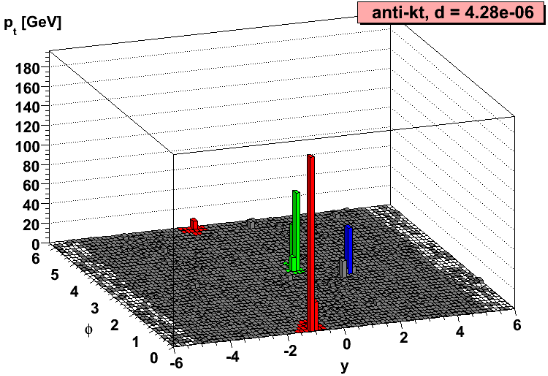

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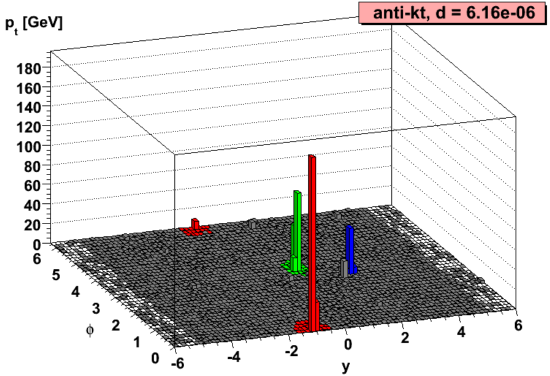

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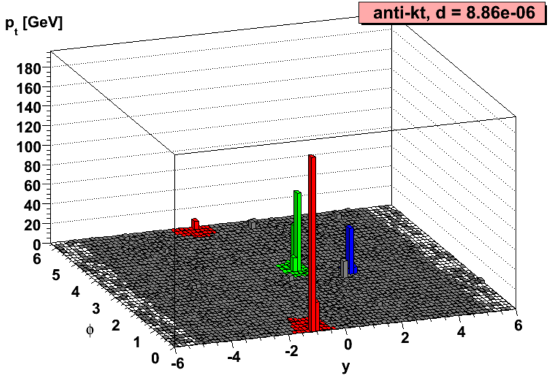

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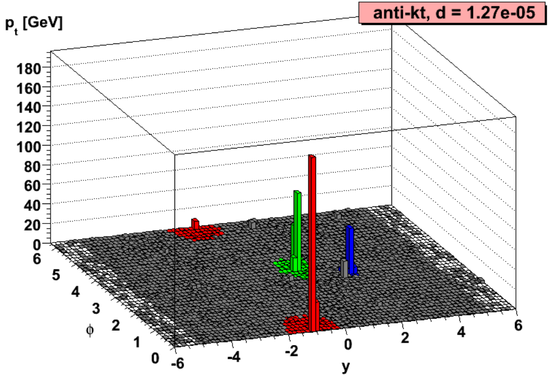

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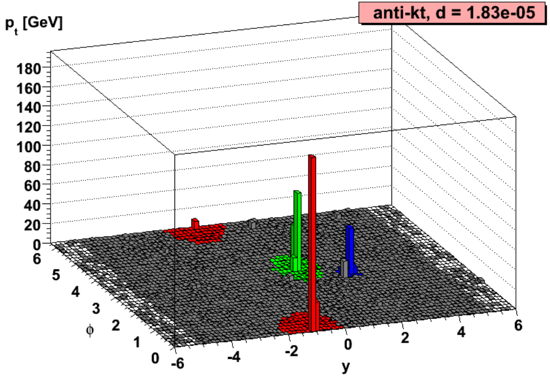

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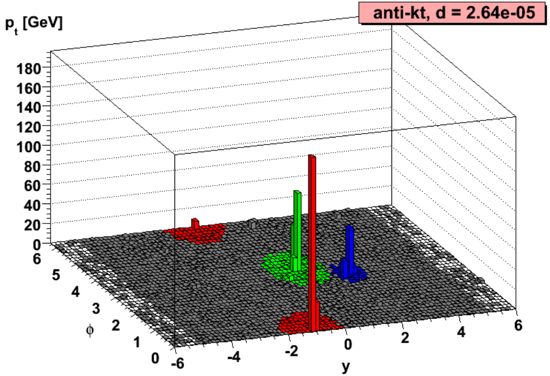

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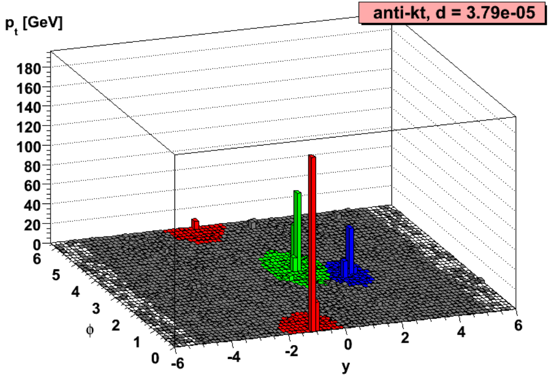

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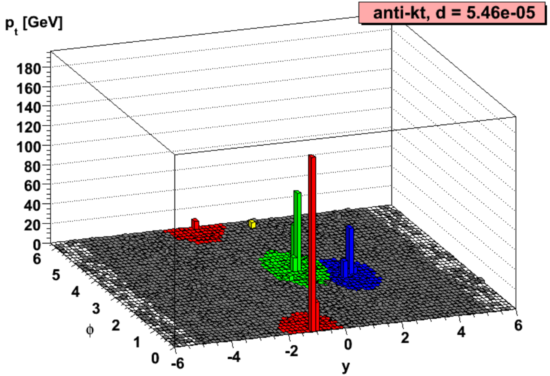

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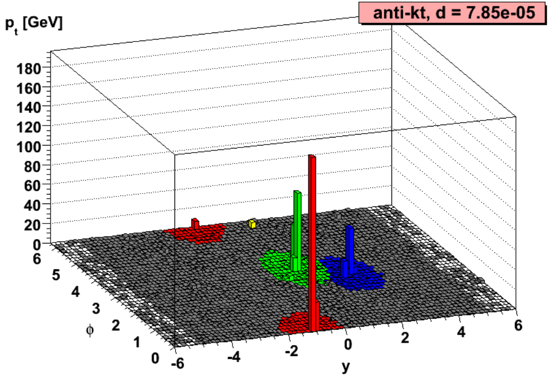

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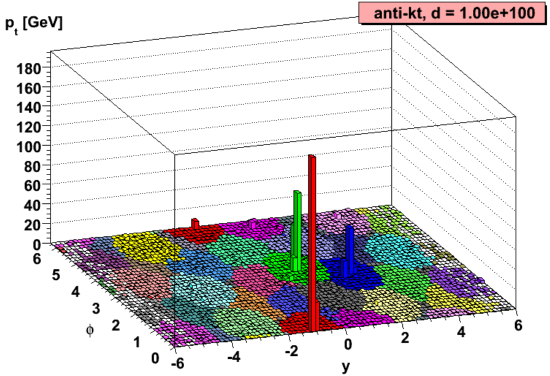
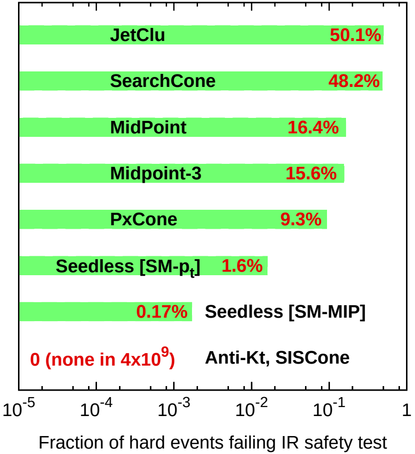


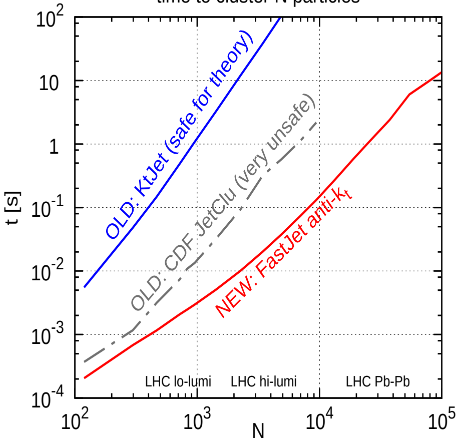
Coefficient of "infinity"



Safe for perturbative QCD:
No infinities

Speed

time to cluster N particles

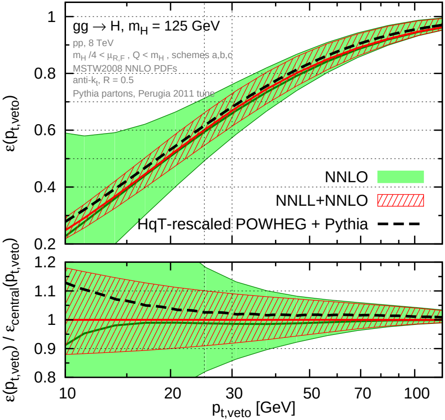


$\sim$ 1000 times faster than previous codes e.g.: fraction of Higgs events that pass a "jet veto," which matters for measuring $H \to WW$

anti-k_t used in nearly all jet measurements at the LHC

→ possible to make accurate predictions for range of measurements, including Higgs

allowing the experiments to pin down Higgs couplings more accurately in years to come



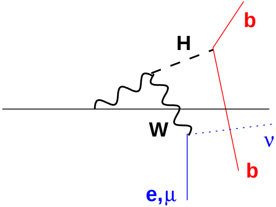
Banfi, Monni, GPS & Zanderighi '12
cf. talk tomorrow by Pier Monni

QCD is, in part, about predicting properties of collisions

But also about devising techniques to carry out more effective searches

$H \to b\bar{b}$ (57% of decays) v. hard to see

Best hope is $pp \to W^{\pm}H$ (and ZH), $W^{\pm} \to \ell^{\pm}\nu$, $H \to b\bar{b}$.



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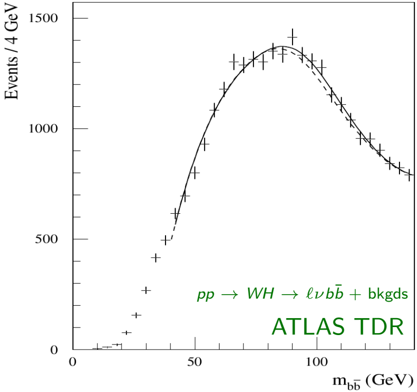
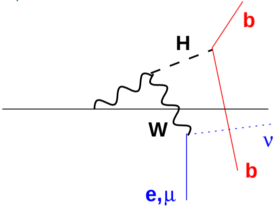


Conclusion (ATLAS TDR):

> *"The extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]"*

Low efficiency, huge backgrounds, e.g. $t\bar{t}$

NB: Evidence of this channel seen recently at Tevatron, but similar difficulties



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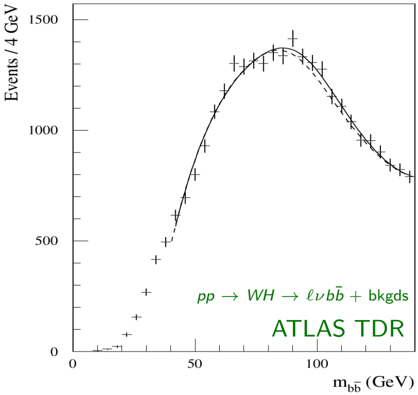

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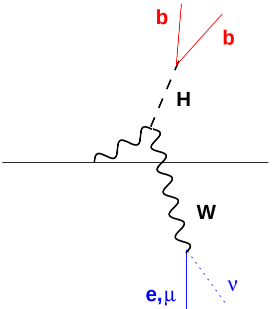
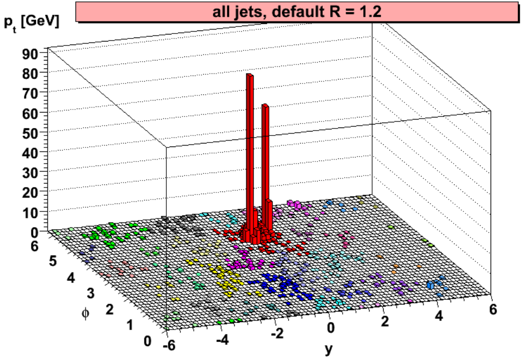


Analysis of signal/bkgd suggests:

- Go to high p_t ($p_{tH}, p_{tW} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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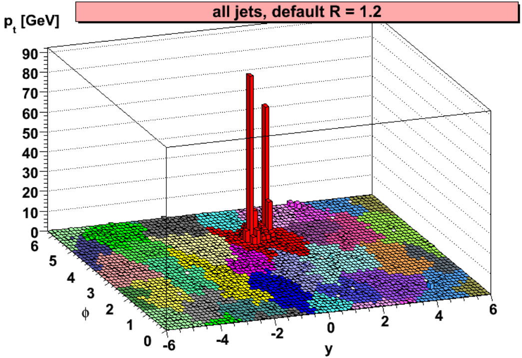

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

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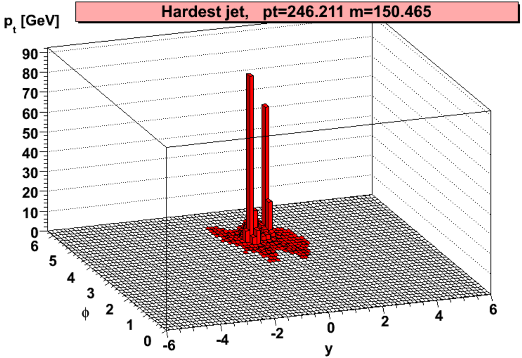

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

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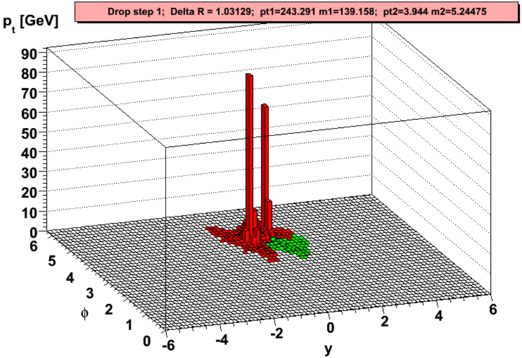


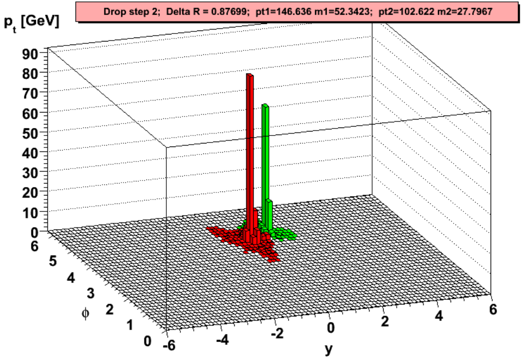
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



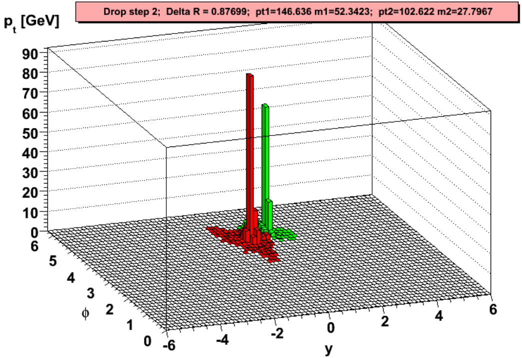
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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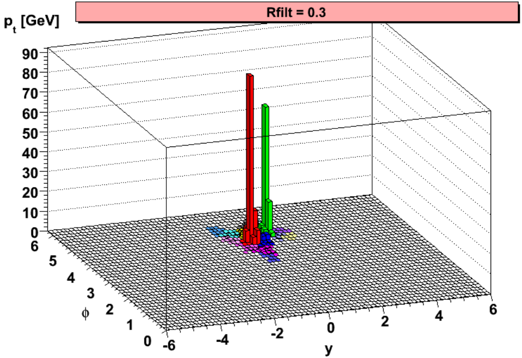

$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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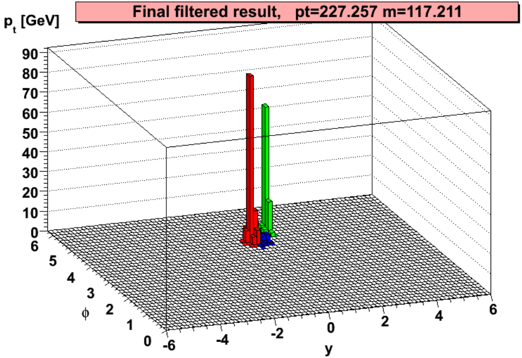

$R_{filt} = 0.3$: take 3 hardest, **$\mathbf{m = 117}$ GeV**

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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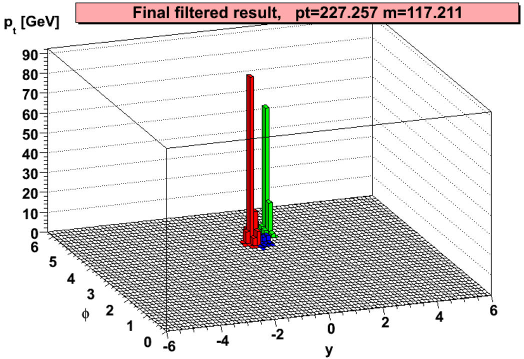

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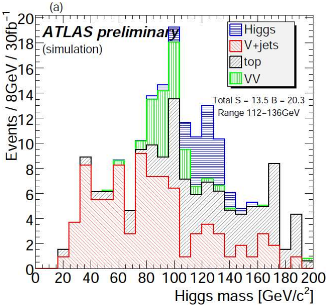
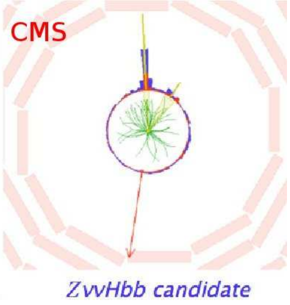
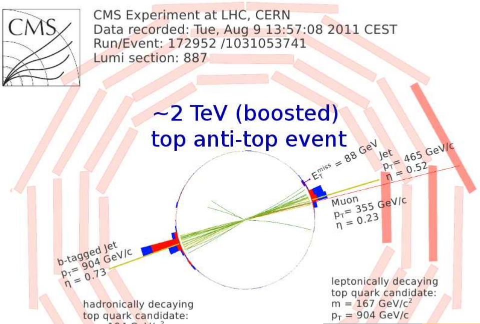


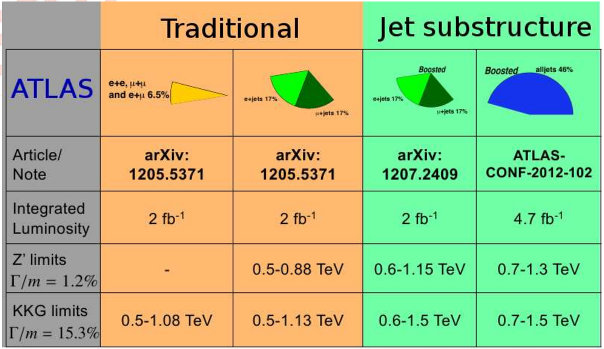




~2 TeV (boosted)
top anti-top event

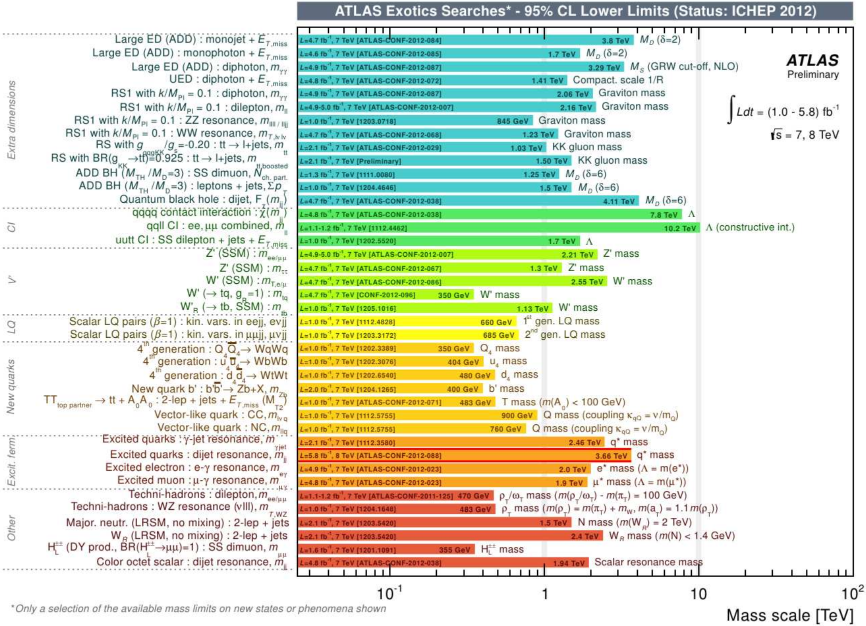
"substructure" techniques have applications in many searches, e.g. $t\bar{t}$ resonances

very active field,
(including MIT group!)



	Traditional		Jet substructure	
ATLAS	e+e, μ+μ and e+μ 6.5%	e+jets 17% μ+jets 17%	Boosted e+jets 17% μ+jets 17%	Boosted alljets 46%
Article/ Note	arXiv: 1205.5371	arXiv: 1205.5371	arXiv: 1207.2409	ATLAS-CONF-2012-102
Integrated Luminosity	2 fb^{-1}	2 fb^{-1}	2 fb^{-1}	4.7 fb^{-1}
Z' limits $\Gamma/m = 1.2\%$	-	0.5-0.88 TeV	0.6-1.15 TeV	0.7-1.3 TeV
KKG limits $\Gamma/m = 15.3\%$	0.5-1.08 TeV	0.5-1.13 TeV	0.6-1.5 TeV	0.7-1.5 TeV

An overview of some new-physics searches



LHC Outlook

rest of 2012

continue running at 8 TeV to reach $\sim 30\ \text{fb}^{-1}$ per experiment (a factor of 3 more data than used for discovery). Higgs features should emerge more clearly

2013

short proton-lead run
followed by ∼18 month shutdown to complete LHC repairs

late 2014-

Running at $13 - 14$ TeV

Accumulating several 100 fb^{-1} over a few years

Cover a large chunk of LHC's potential to search for new physics

Beyond

LHC luminosity upgrades: factor 5-10?

Linear collider (to study Higgs in detail)?

Higher-energy LHC?

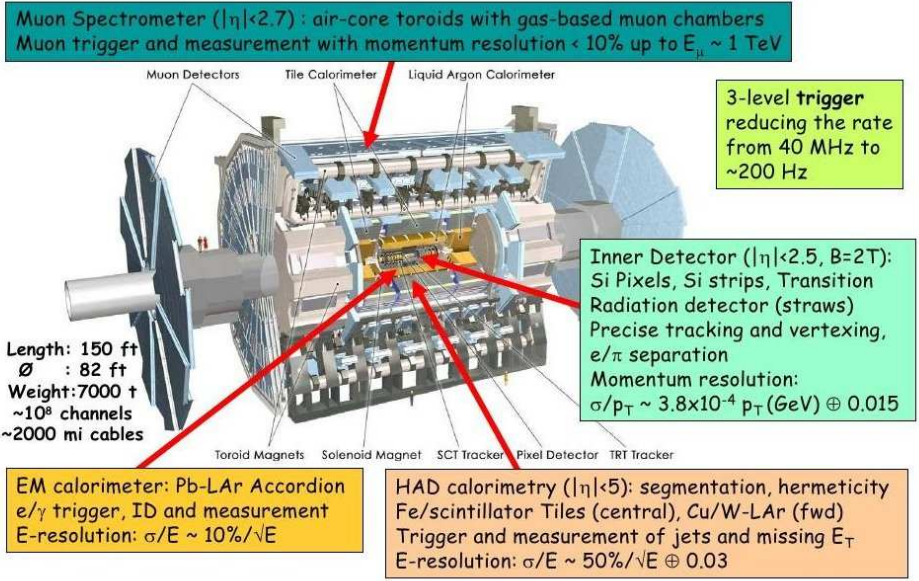
EXTRAS

Energy–frontier colliders of the past 25 years

Collider	Lab	Date	Collided		C.o.M. Energy
Tevatron	Fermilab/USA	1987 –	$p\bar{p}$	@	1960 GeV
SLC	SLAC/USA	1989 – 1998	e^+e^-	@	100 GeV
LEP	CERN/Europe	1989 – 2000	e^+e^-	@	209 GeV
HERA	DESY/Germany	1992 – 2007	$e^\pm p$	@	330 GeV

Protons are made of quarks, anti-quarks and gluons. It's the individual quarks and gluons that collide. Only a fraction of the proton's energy is actually available in a single *quark/gluon* collision.

ATLAS



Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

3-level **trigger** reducing the rate from 40 MHz to ~200 Hz

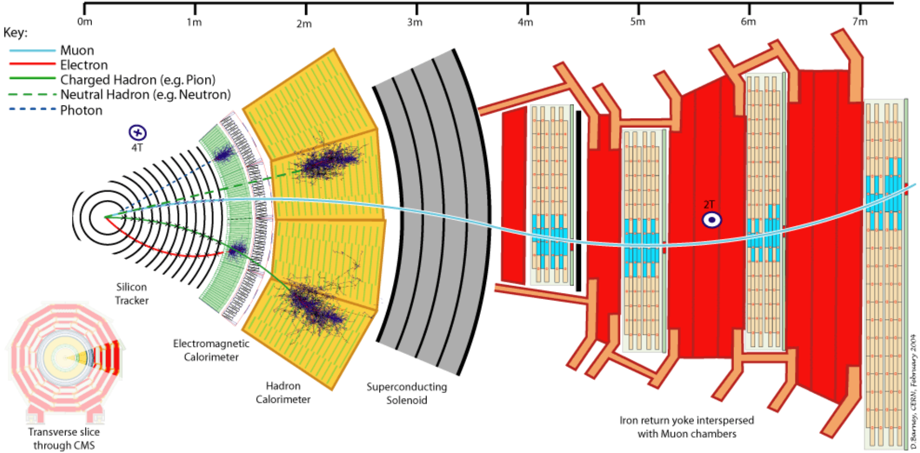
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\, p_T(\text{GeV}) \oplus 0.015$

Length: 150 ft
Ø : 82 ft
Weight: 7000 t
~10^8 channels
~2000 mi cables

EM calorimeter: Pb-LAr Accordion
e/γ trigger, ID and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

A slice of CMS



LHC has now been operating for three years

1995: LHC approved
2000: LEP closed

2008/09: LHC beams circulated
2008/09: severe "incident"

poor electrical connection, arc, catastrophic Helium release, much damage
Followed by reviews, the fixes that could be made in $\sim$ 1 year

2009/11: LHC starts up again, 900 GeV pp collisions
2009/12: 2360 GeV pp collisions
2010/03: 7000 GeV pp collisions ($\sim$ 50 pb^{-1})

"reduced-energy" target for safe operation

2010/11: 2760 GeV PbPb collisions
2011/03: 7 TeV pp collisions ($\sim$ 5 fb^{-1})
2011/11: 2760 GeV PbPb collisions
2012/03: 8 TeV pp collisions ($\sim$ 6 fb^{-1} published, $\sim$ 14 fb^{-1} delivered)

The challenges in reaching high energies

Circular e^+e^- collider. Basic issue is synchrotron radiation

$$\text{Energy loss per orbit} \sim \frac{E^4}{m^4 R}$$

At LEP the numbers are $\mathcal{O}(10\%)$ of the electron's energy per orbit.

Circular *pp* collider

Proton mass 2000 times larger, so synchrotron radiation not a problem. The limitation is magnetic field needed to bend the protons round

$$B \sim \frac{E}{R}$$

Tevatron: $R \sim 1\,\text{km}$, $E_{c.o.m} \sim 2$ TeV $\implies$ $B = 4$ TeV.

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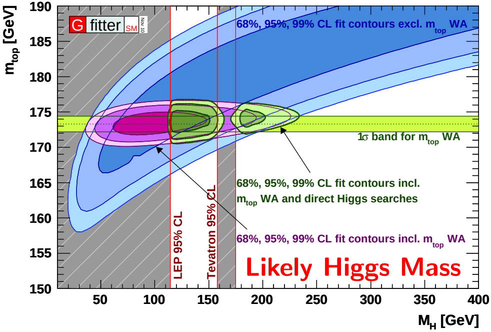
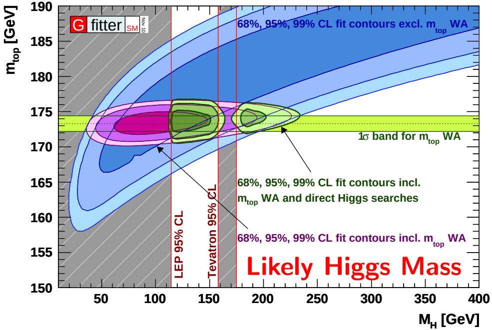
So what energy do you need?

Higgs mass and Higgs decays?



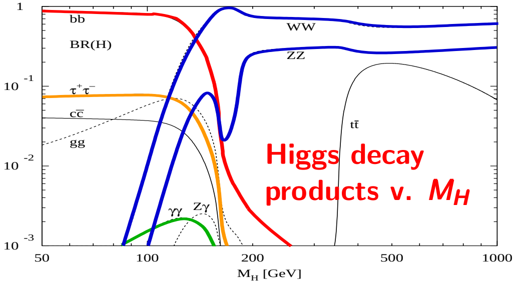
There's some likelihood that the Higgs boson will be "light", $M_H \sim 120$ GeV

Higgs mass and Higgs decays?



Likely Higgs Mass

There's some likelihood that the Higgs boson will be "light", $M_H \sim 120$ GeV

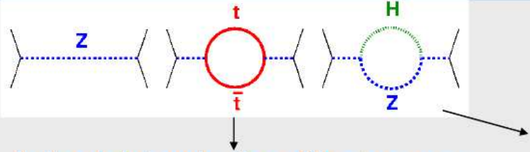


Higgs decay products v. M_H

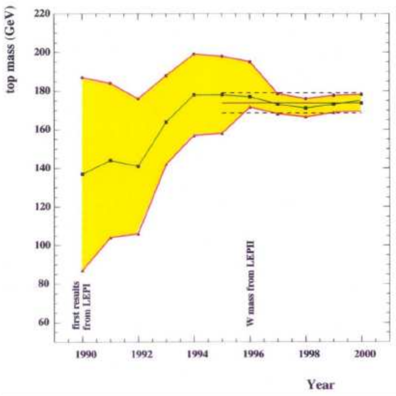
If it is, crucial test of whether it **is** the Higgs, will come from measuring several different decays

Remember: Higgs couplings intimately related to origin of particle masses

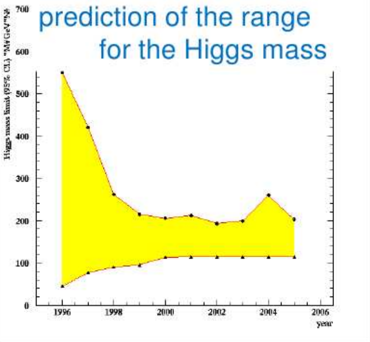
Test of the SM at the Level of Quantum Fluctuations



indirect determination of the top mass



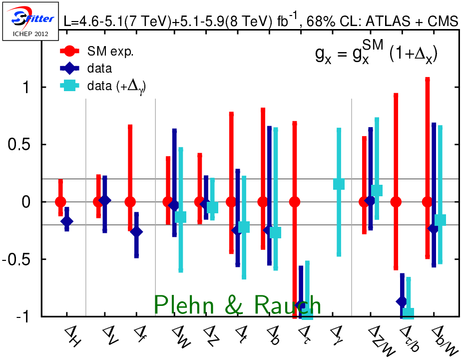
prediction of the range
for the Higgs mass

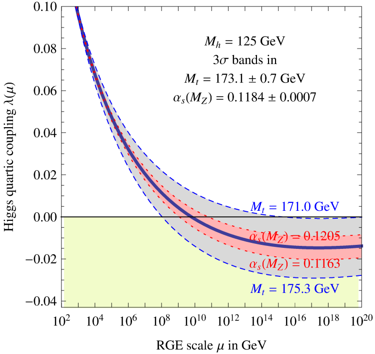


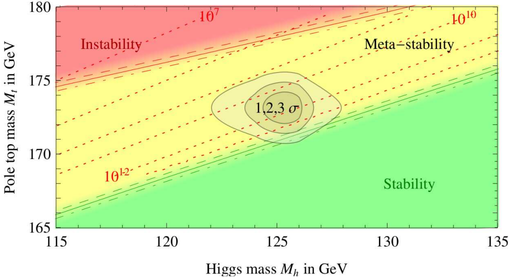
possible due to

- precision measurements
- known higher order electroweak corrections

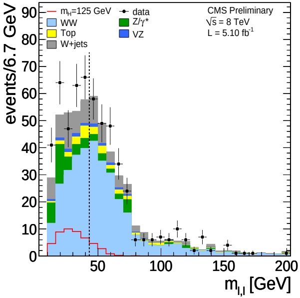
$$\propto \left(\frac{\boxed{M_t}}{M_W}\right)^2, \ln\left(\frac{\boxed{M_h}}{M_W}\right)$$


SFitter
ICHEP 2012
L=4.6-5.1(7 TeV)+5.1-5.9(8 TeV) fb^{-1}, 68% CL: ATLAS + CMS
SM exp.
data
data (+Δ_γ)
$g_x = g_x^{SM}\,(1+\Delta_x)$
1
0.5
0
-0.5
-1
Δ_H
Δ_V
Δ_f
Δ_W
Δ_Z
Δ_t
Δ_b
Δ_τ
Δ_γ
$\Delta_{Z/W}$
$\Delta_{\tau/b}$
$\Delta_{b/W}$
Plehn & Rauch


M_h = 125 GeV
3σ bands in
M_t = 173.1 ± 0.7 GeV
$\alpha_s(M_Z)$ = 0.1184 ± 0.0007
M_t = 171.0 GeV
$\alpha_s(M_Z)$ = 0.1205
$\alpha_s(M_Z)$ = 0.1163
M_t = 175.3 GeV
Higgs quartic coupling $\lambda(\mu)$
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
RGE scale μ in GeV

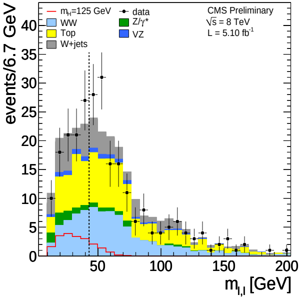

Instability
10^7
10^{10}
Meta−stability
1,2,3 σ
10^{12}
Stability
Pole top mass M_t in GeV
180
175
170
165
115
120
125
130
135
Higgs mass M_h in GeV

0-jet events



mainly WW^* background

1-jet events



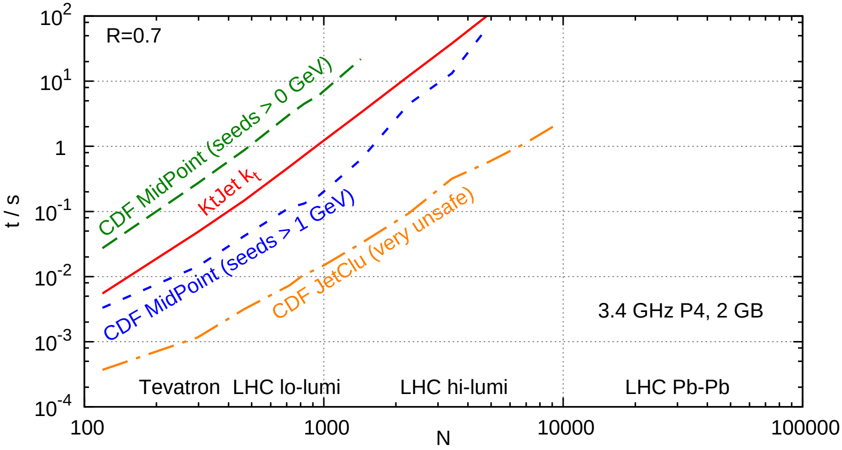
also some $t\bar{t}$ background

$\geq$ 2-jet events

not used
too much background

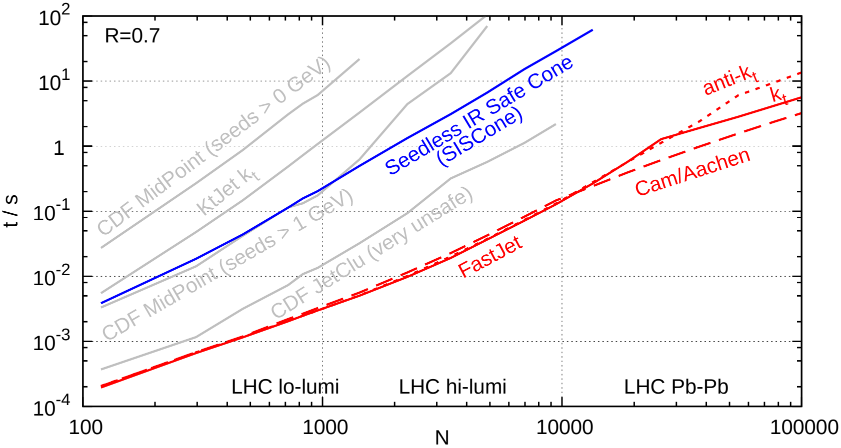
How does anti-k_t fare?

Timing v. particle multiplicity 2005



How does anti-k_t fare?

Timing v. particle multiplicity 2008

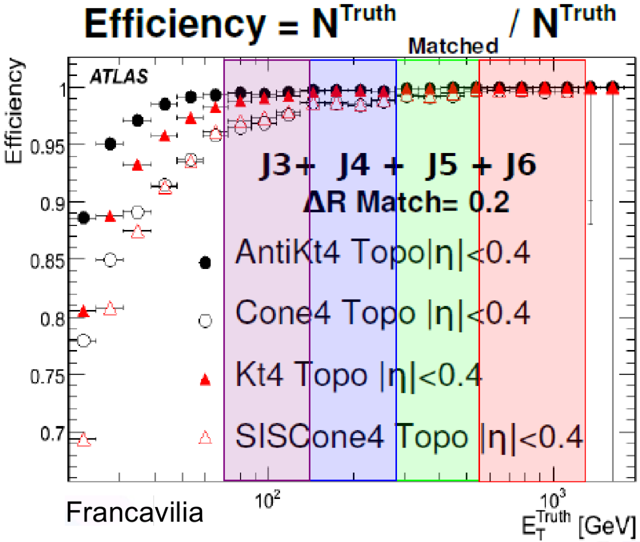


in critical region of $N \sim 2000 - 4000$

1000 times faster than previous attempts with similar jet algorithms

How does anti-k_t fare?

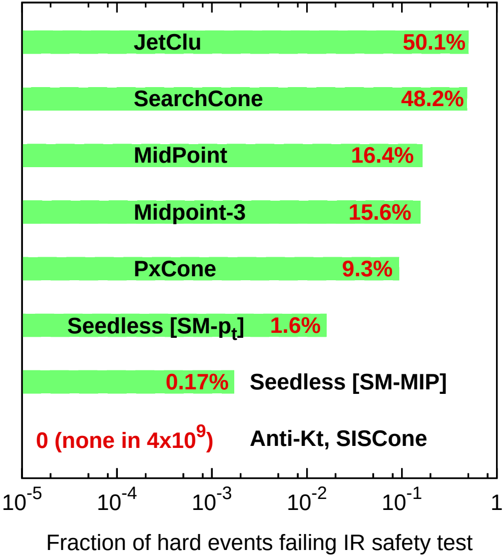
Experimental sensitivity to noise



As good as, or better than all previous experimentally-favoured algorithms

How does anti-k_t fare?

Coefficient of “infinity”



Safe for perturbative QCD predictions:

No “leakage” of infinities to higher orders