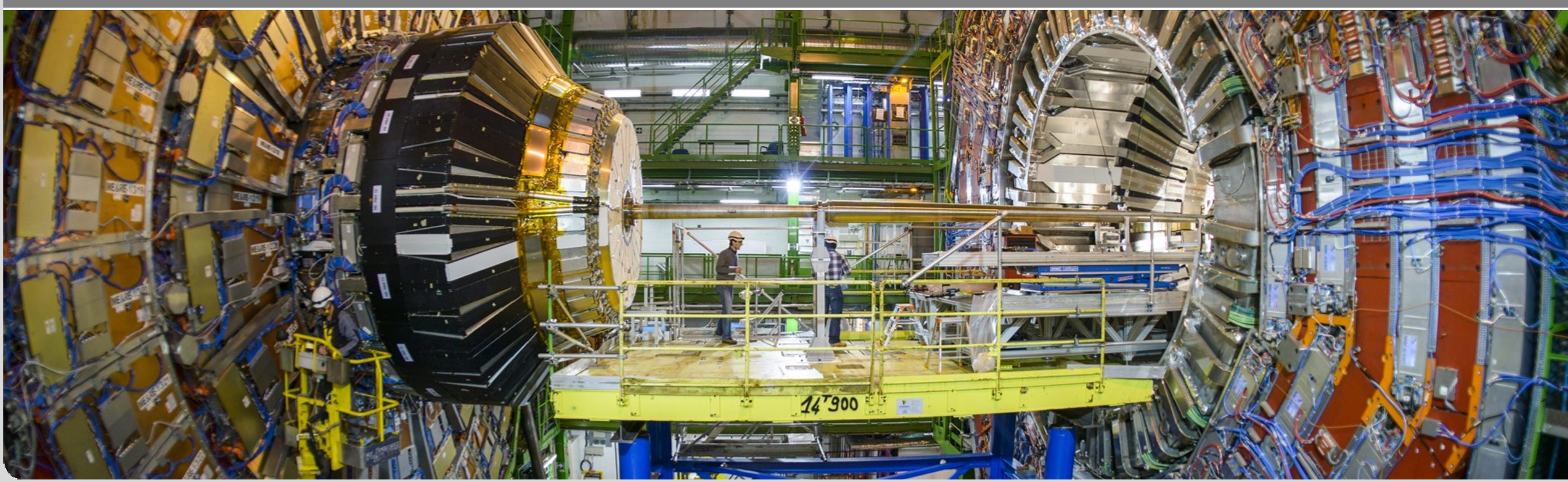
Karlsruhe Institute of Technology

Physics at the TeV Scale
(aka Introduction to the Terascale)

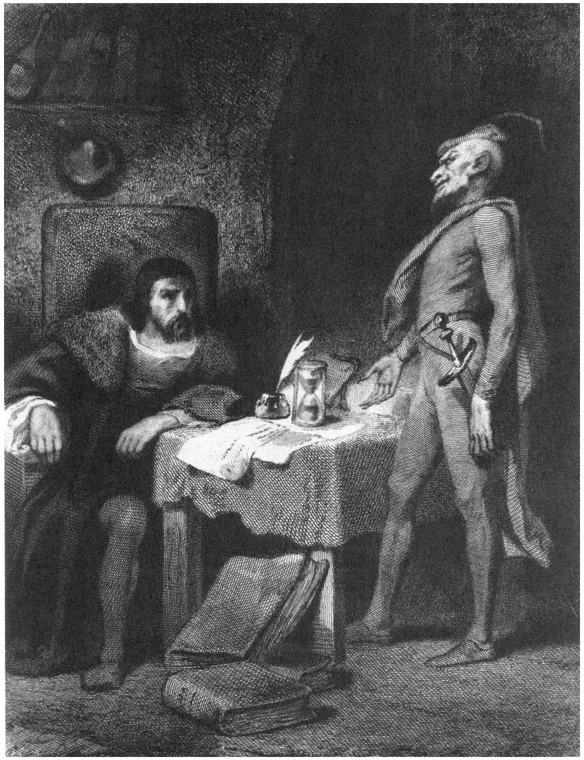
Roger Wolf

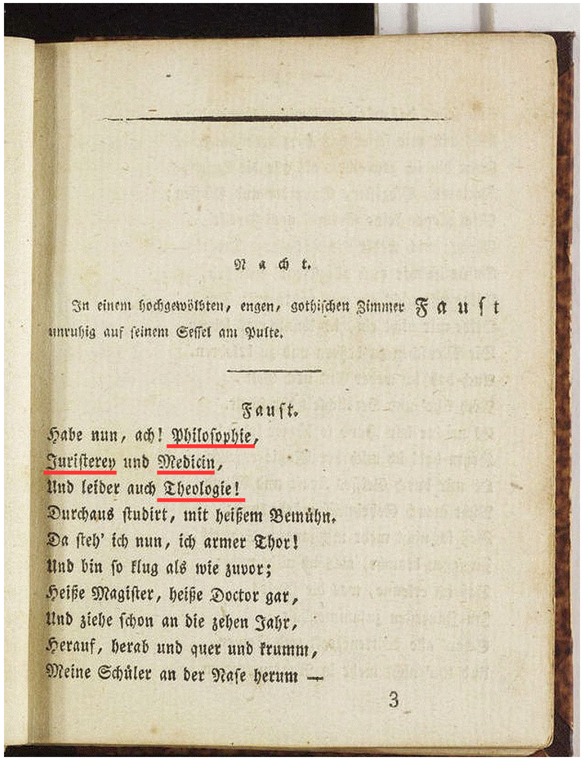
20. April 2015

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Nobel Aims





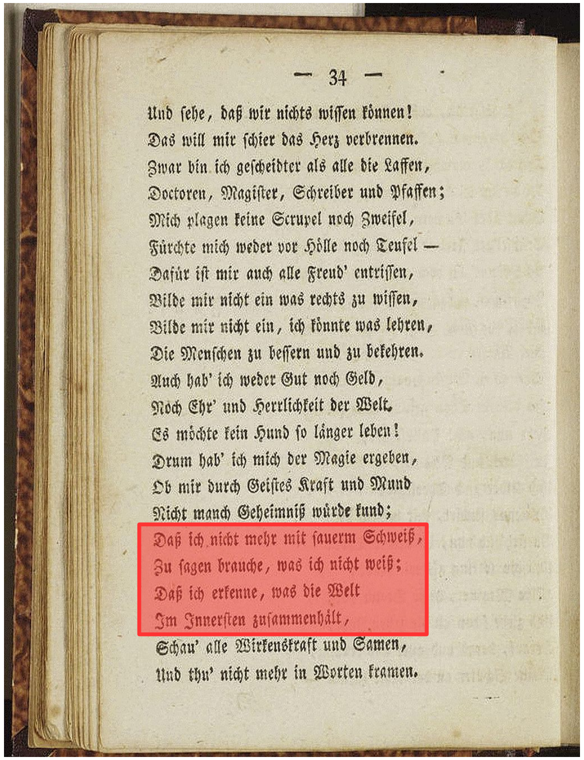
Nacht.

In einem hochgewölbten, engen, gothischen Zimmer Faust unruhig auf seinem Sessel am Pulte.

Faust.

Habe nun, ach! Philosophie,
Juristerey und Medicin,
Und leider auch Theologie!
Durchaus studirt, mit heißem Bemühn.
Da steh' ich nun, ich armer Thor!
Und bin so klug als wie zuvor;
Heiße Magister, heiße Doctor gar,
Und ziehe schon an die zehen Jahr,
Herauf, herab und quer und krumm,
Meine Schüler an der Nase herum —

3



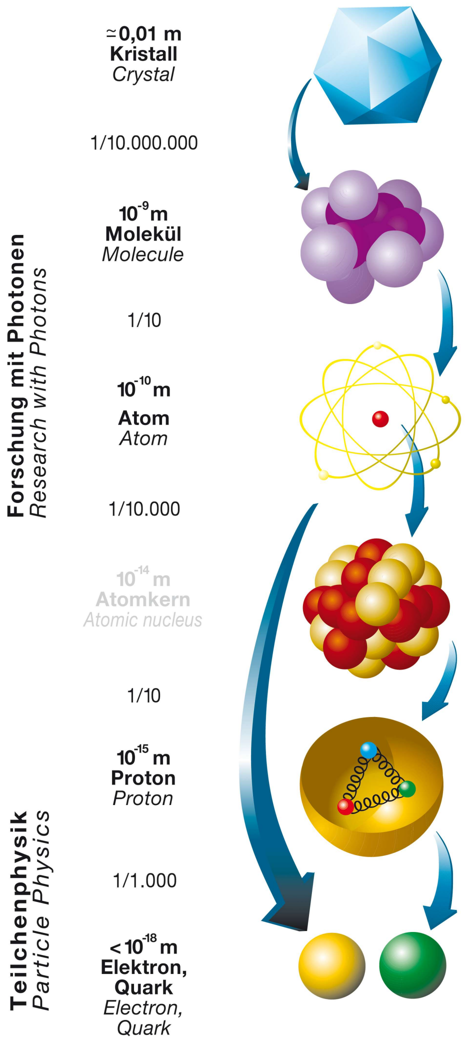
— 34 —

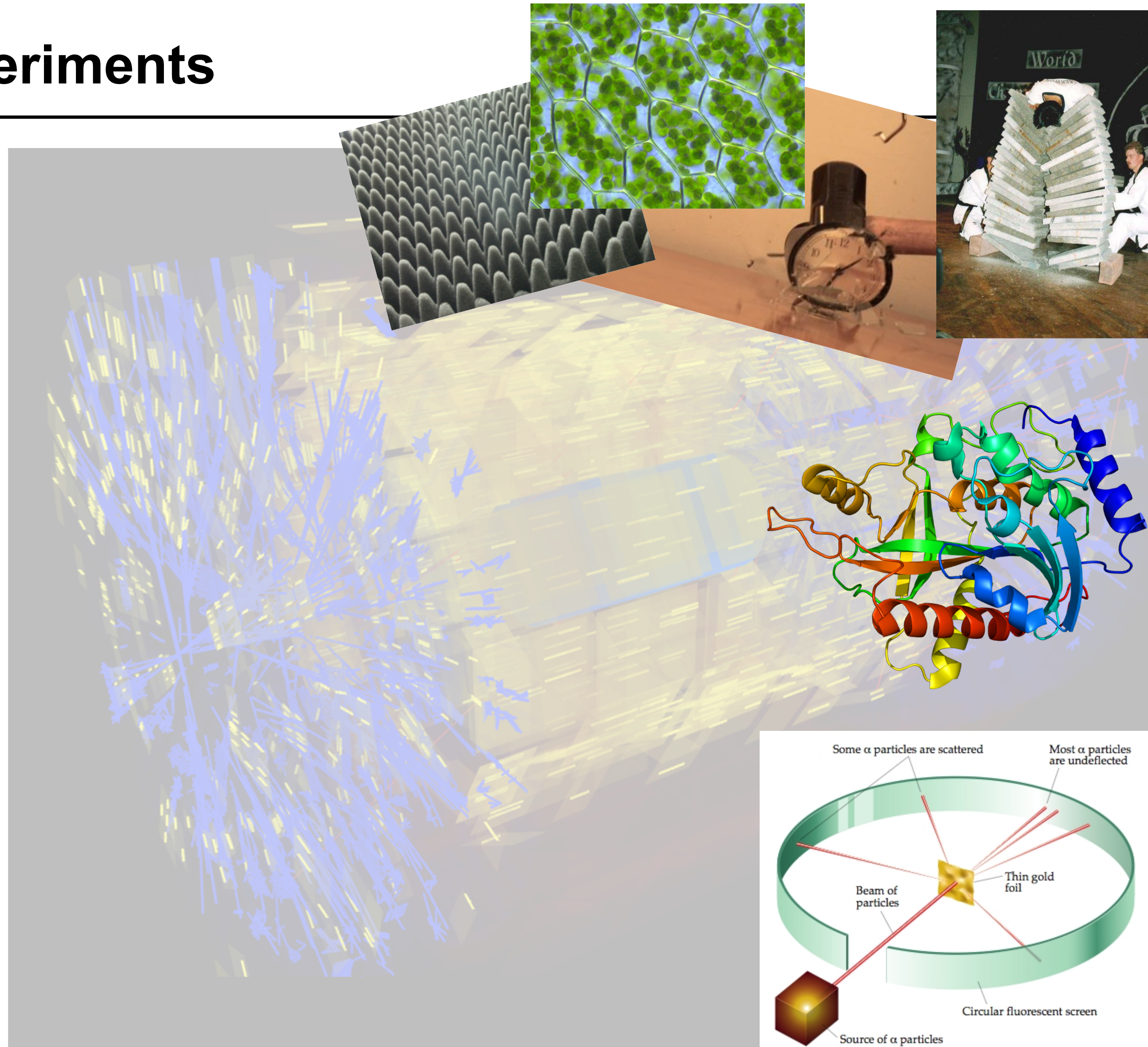
Und sehe, daß wir nichts wissen können!
Das will mir schier das Herz verbrennen.
Zwar bin ich gescheidter als alle die Laffen,
Doctoren, Magister, Schreiber und Pfaffen;
Mich plagen keine Scrupel noch Zweifel,
Fürchte mich weder vor Hölle noch Teufel —
Dafür ist mir auch alle Freud' entrissen,
Bilde mir nicht ein was rechts zu wissen,
Bilde mir nicht ein, ich könnte was lehren,
Die Menschen zu bessern und zu bekehren.
Auch hab' ich weder Gut noch Geld,
Noch Ehr' und Herrlichkeit der Welt.
Es möchte kein Hund so länger leben!
Drum hab' ich mich der Magie ergeben,
Ob mir durch Geistes Kraft und Mund
Nicht manch Geheimniß würde kund;
Daß ich nicht mehr mit sauerm Schweiß,
Zu sagen brauche, was ich nicht weiß;
Daß ich erkenne, was die Welt
Im Innersten zusammenhält,
Schau' alle Wirkenskraft und Samen,
Und thu' nicht mehr in Worten kramen.

J. W. von Goethe, Der Tragödie erster Teil, Tübingen: Cotta, 1808

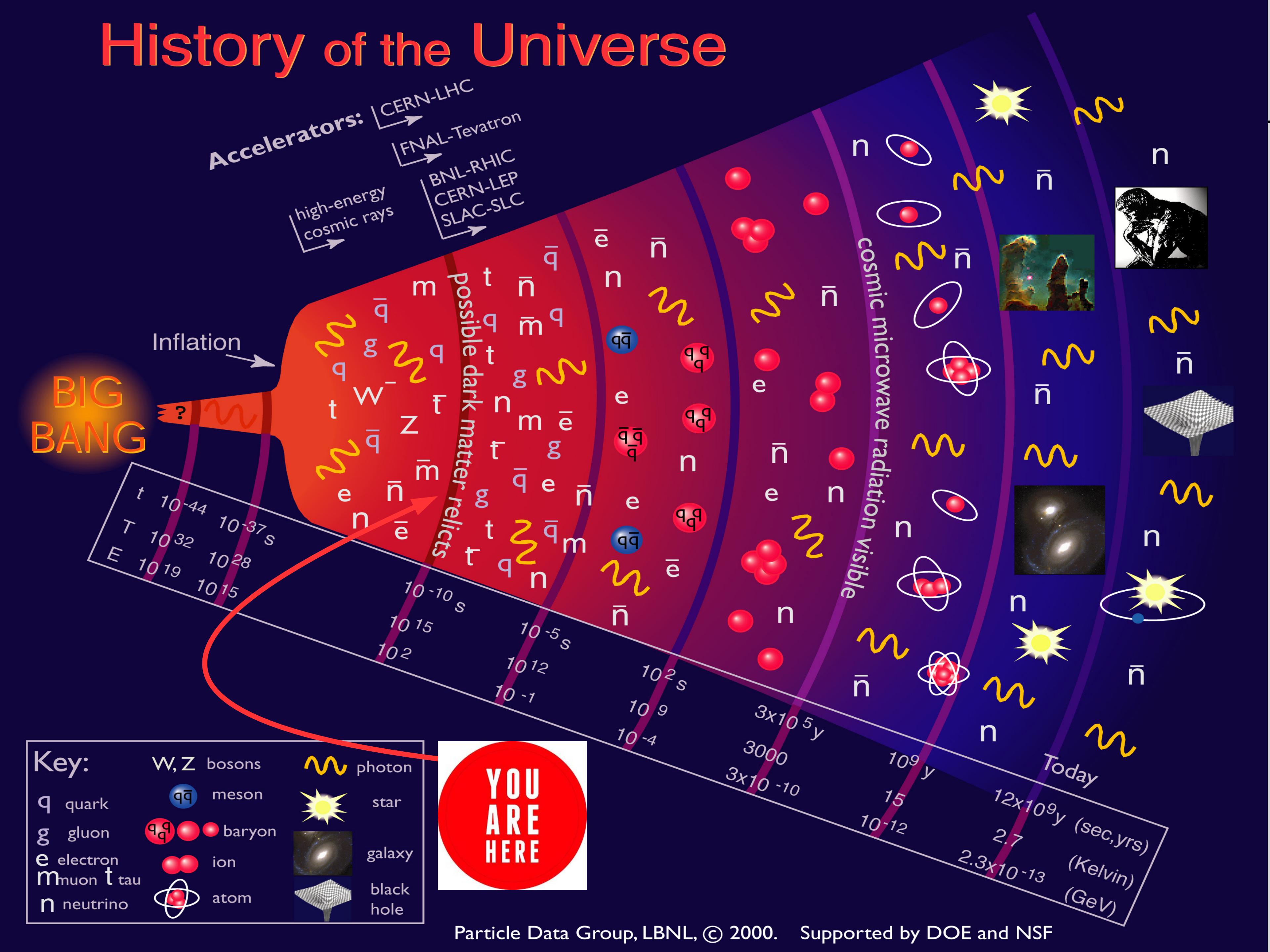
- 207 years later.
- Same questions.
- More success oriented ansatz.

Scattering Experiments



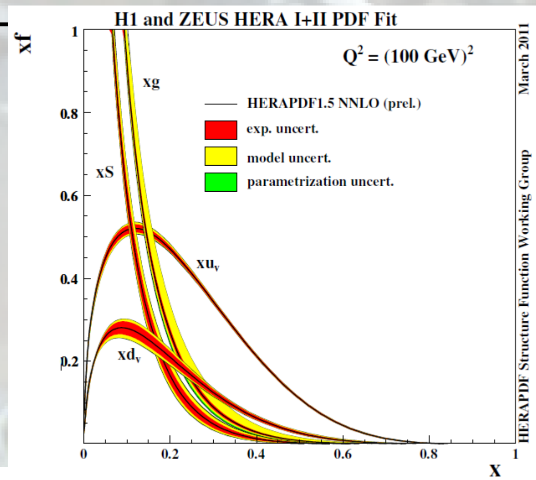


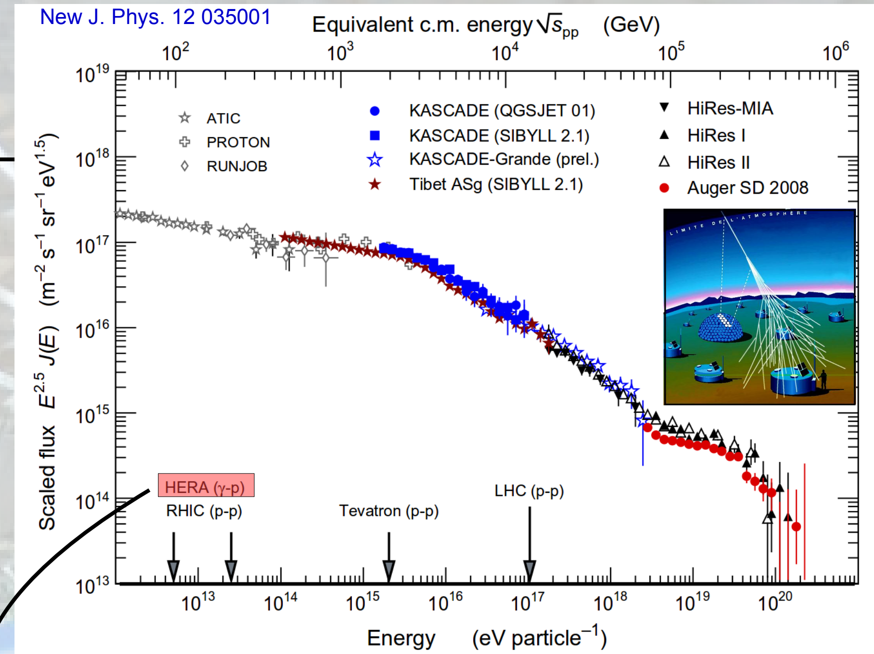
First LHC beam splash event recorded with CMS 2015



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
YOU ARE HERE
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

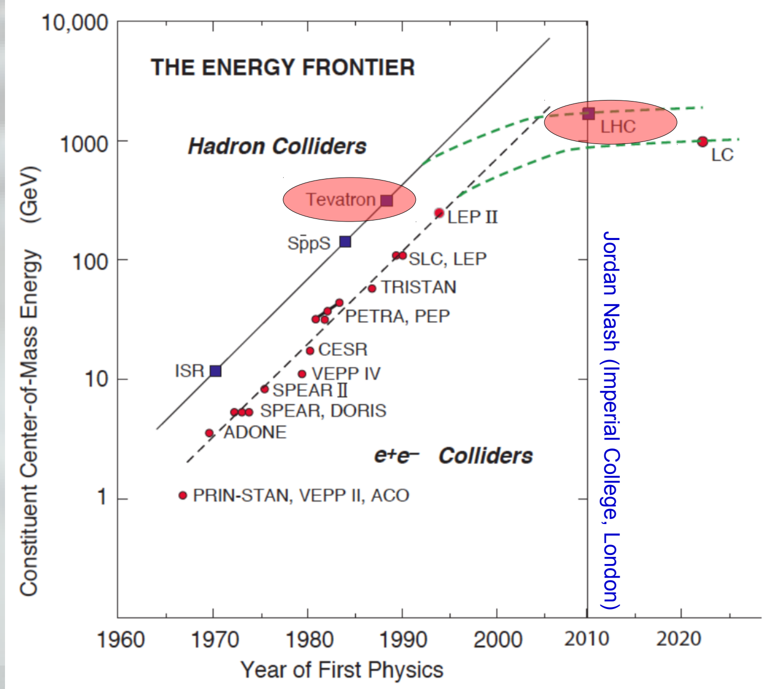
Physics at the TeV Scale



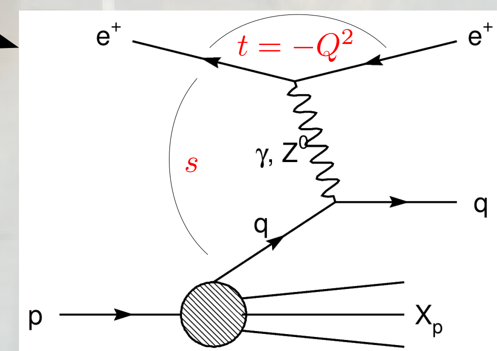


: first places to study physics @ the Terascale!

Livingston accelerator chart



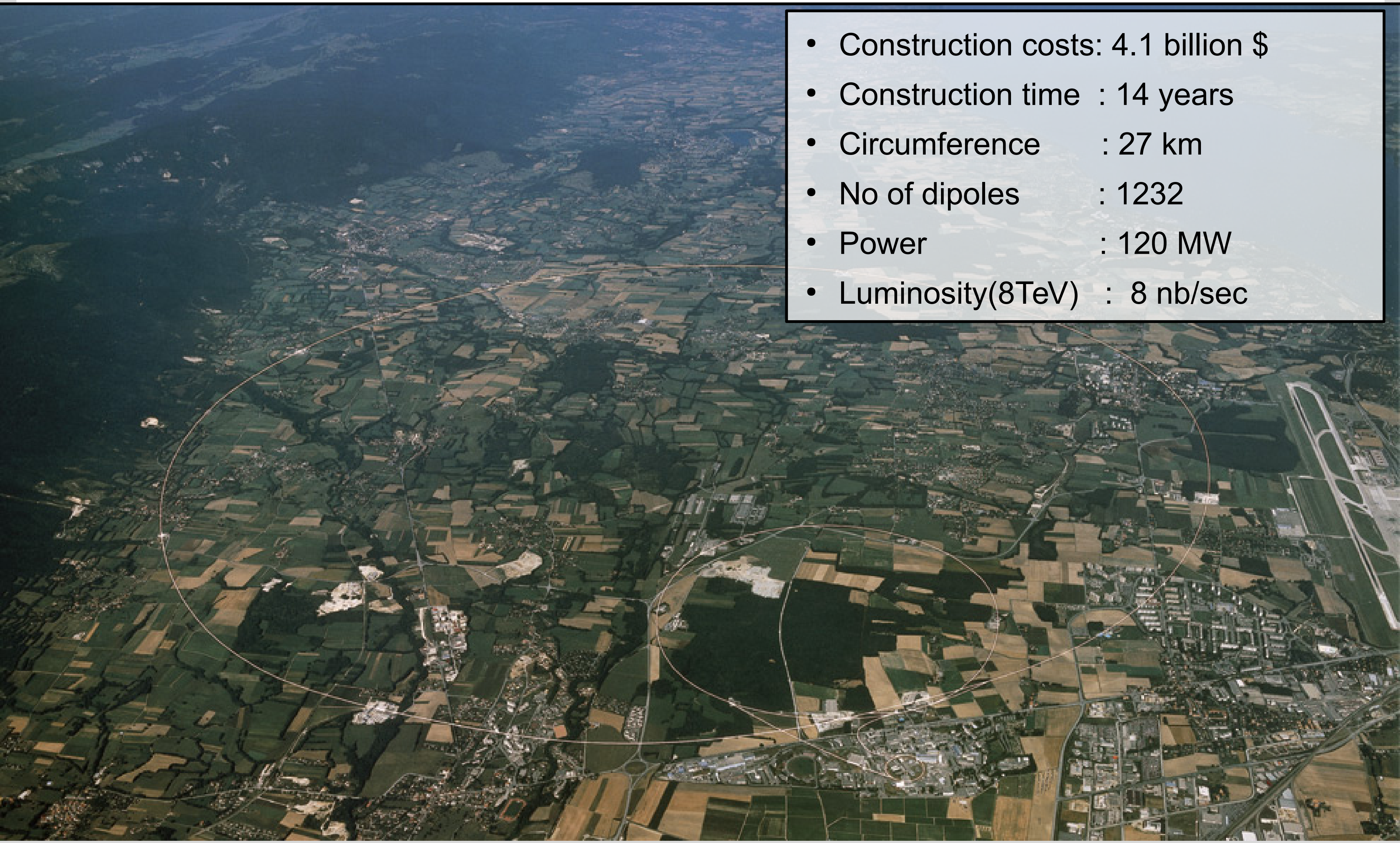
- Reminder *Mandelstam* variables: $s + t + u = \sum_i m_i^2$
- We are usually interested in t more then in s!



DIS @ HERA

The Large Hadron Collider

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



The Large Hadron Collider

Energy radiated off per rotation cycle:

$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0 \rho^2}\gamma^4 = \frac{e^4}{6\pi\epsilon_0 \rho^2}\frac{E^2 B^2}{m^4}$$

$$P(p|_{m_p=1\ \mathrm{GeV}}) = 280\ \mu\mathrm{W}$$

$$P(e|_{m_e=0.511\ \mathrm{MeV}}) = 450\ \mathrm{kW}$$

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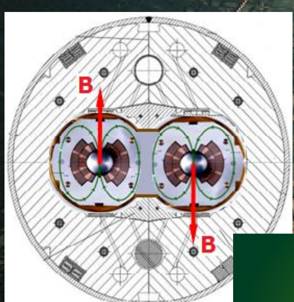
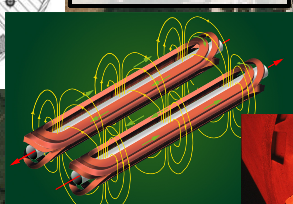


- 8.3 T
- 11.8 kA
- 160 cyc



- Energy density 500 kJ/m
- Tension 200'000 t/m

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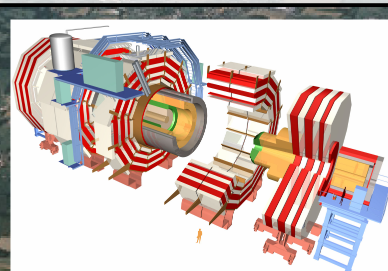

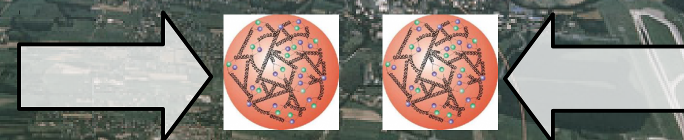

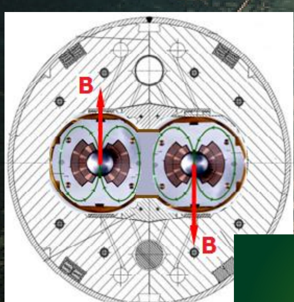

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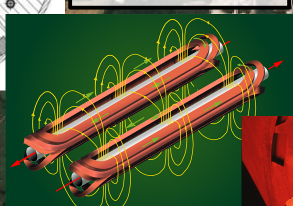

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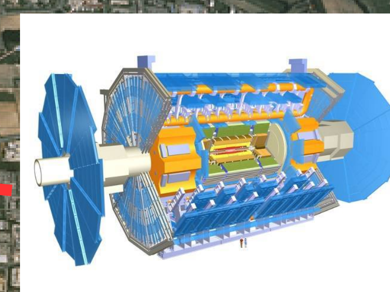
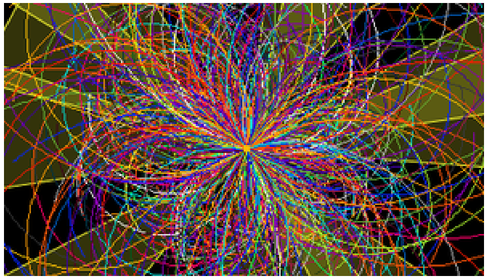
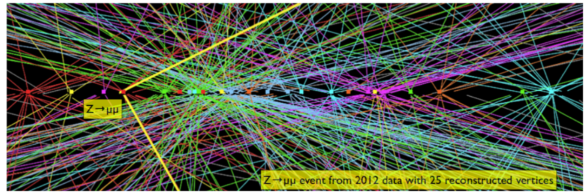
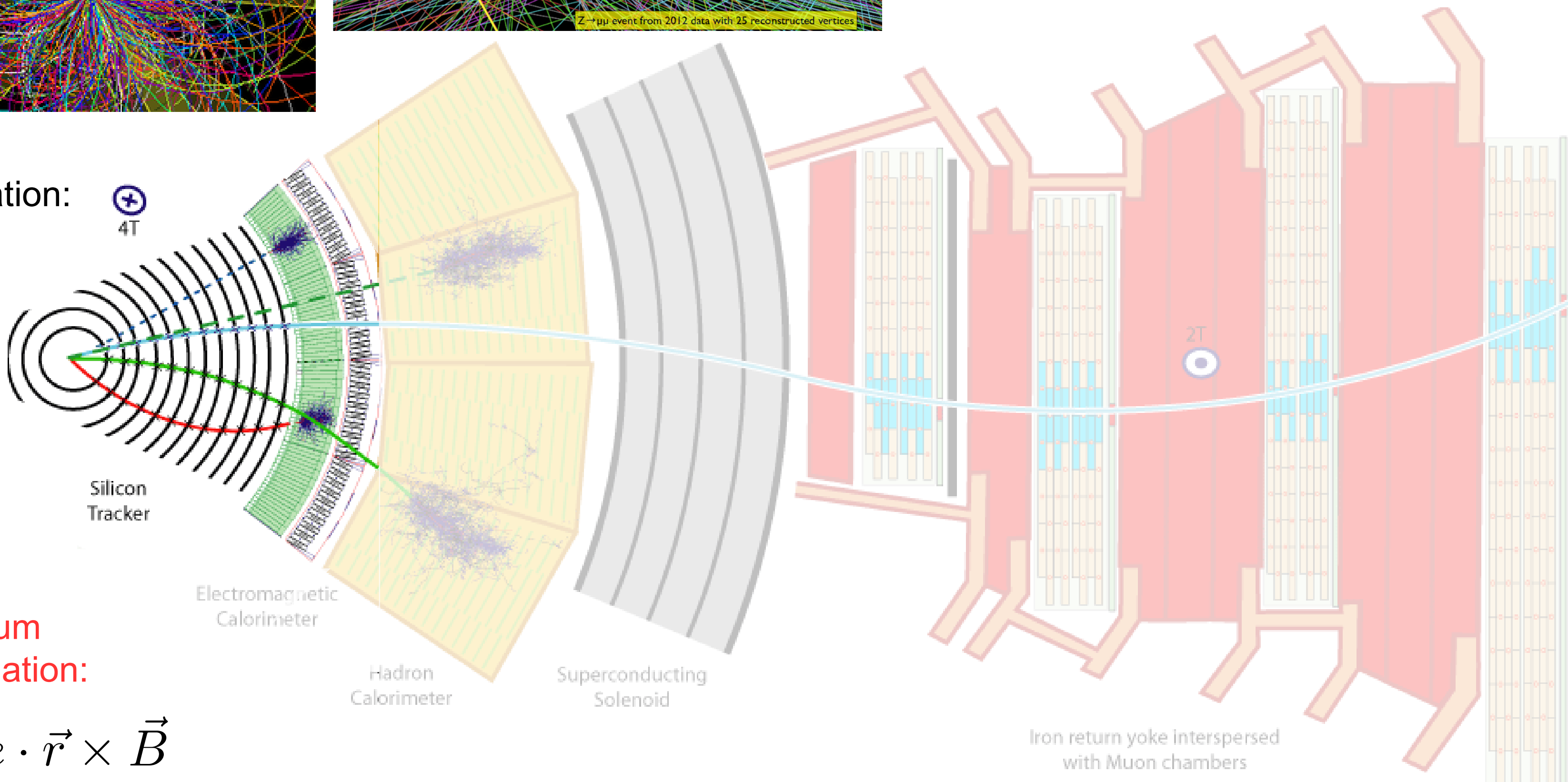


Key Demands on Experiments





Vertex identification:



Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

$$\frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

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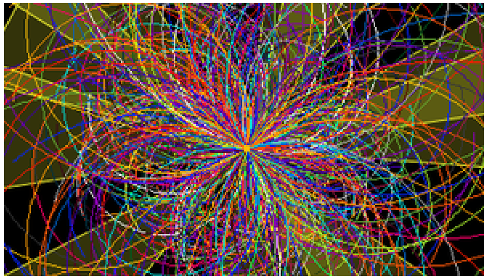

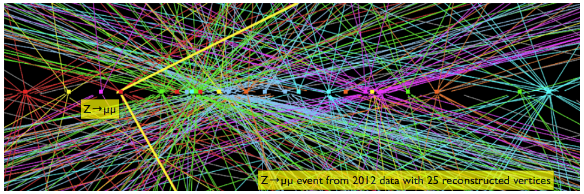

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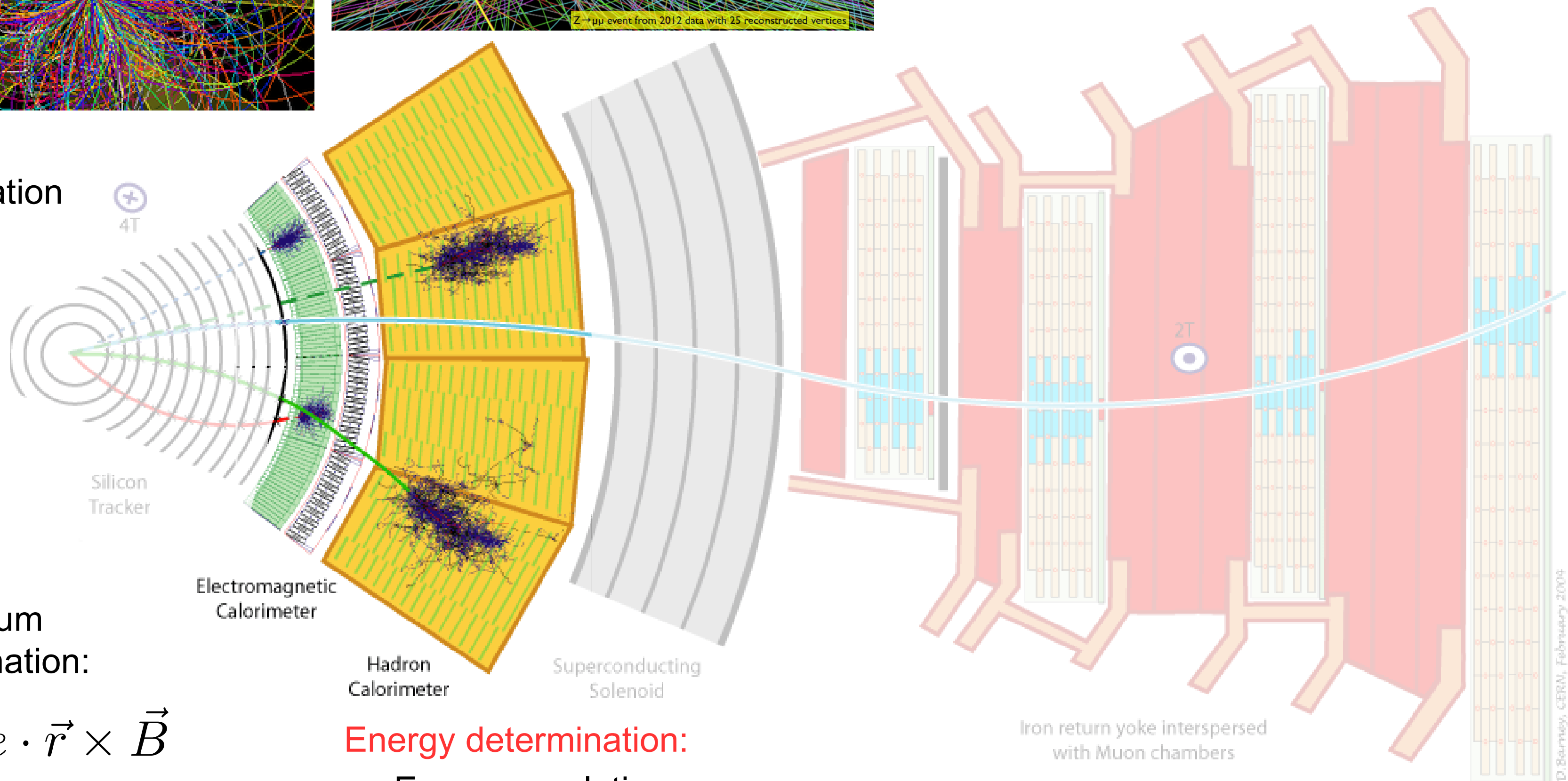

Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

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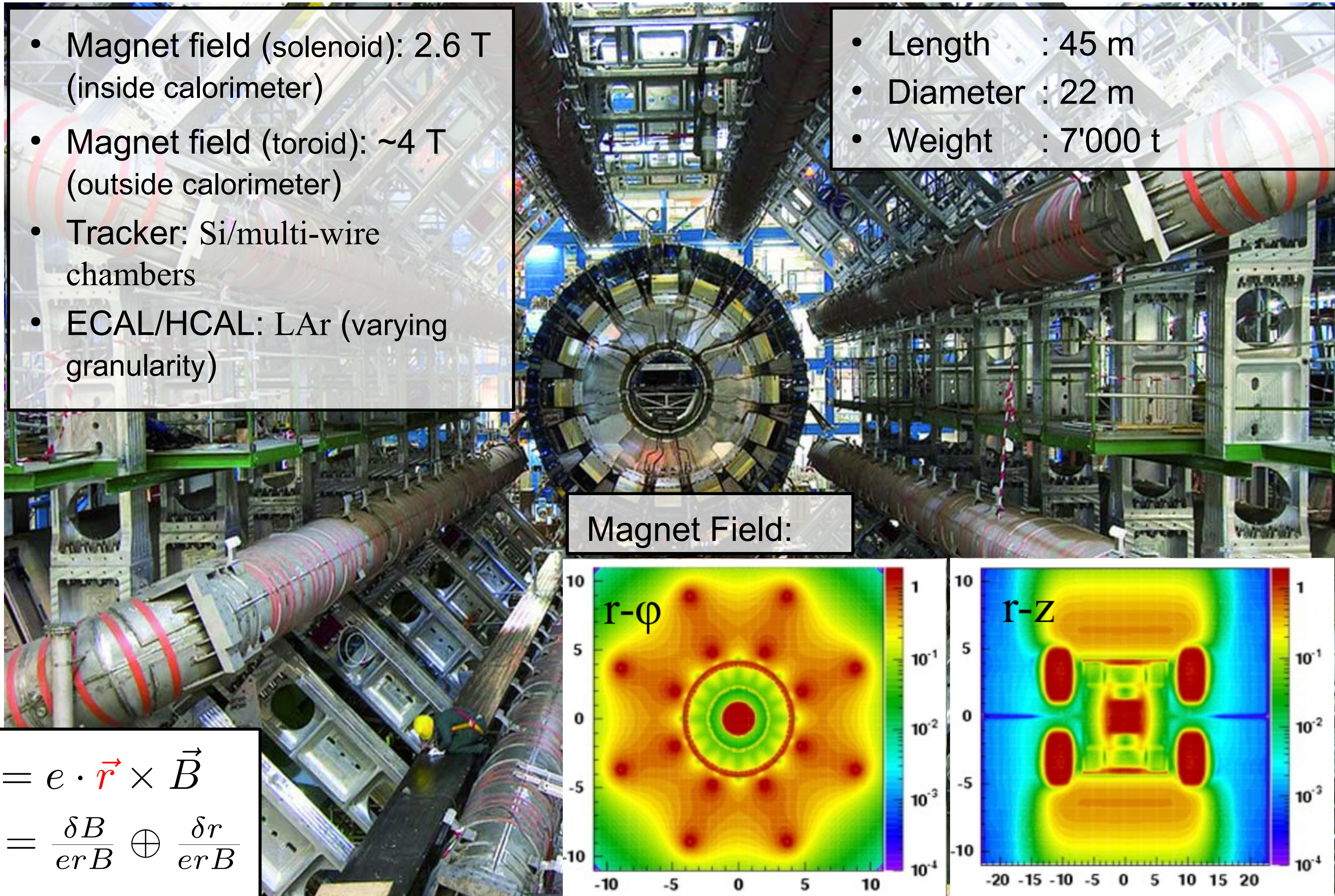
Energy determination:

- Energy resolution
- Stopping power

The Large Scale Solution (ATLAS)



- Magnet field (solenoid): 2.6 T (inside calorimeter)
- Magnet field (toroid): ~4 T (outside calorimeter)
- Tracker: Si/multi-wire chambers
- ECAL/HCAL: LAr (varying granularity)

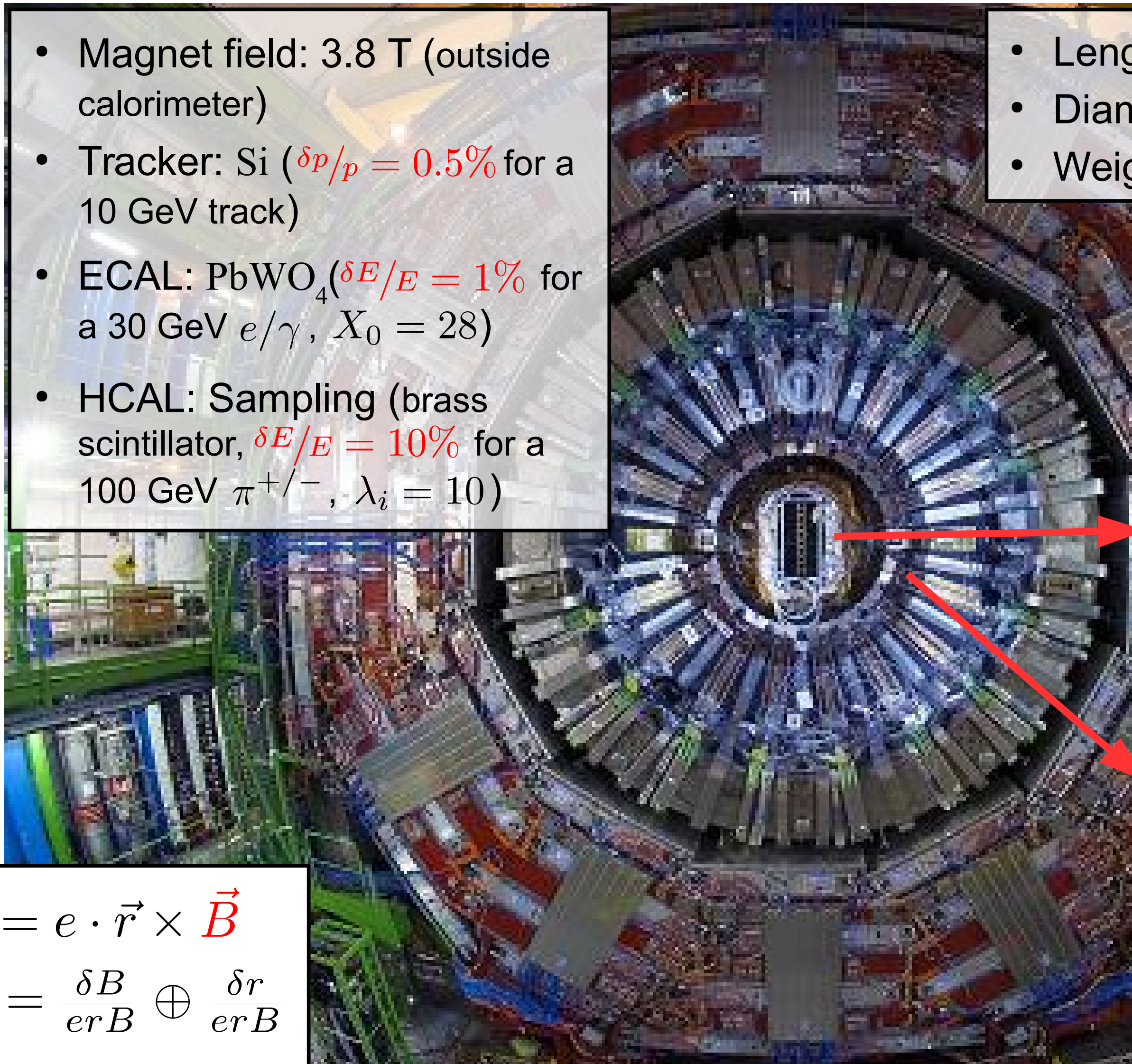
- Length : 45 m
- Diameter : 22 m
- Weight : 7'000 t

Magnet Field:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

$$\frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

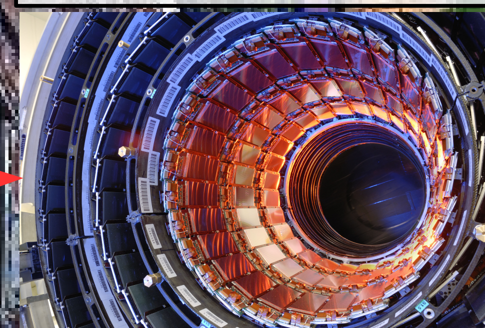
The Compact Solution (CMS)



- Magnet field: 3.8 T (outside calorimeter)
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track)
- ECAL: $PbWO_4$($\delta E/E = 1\%$ for a 30 GeV e/γ, $X_0 = 28$)
- HCAL: Sampling (brass scintillator, $\delta E/E = 10\%$ for a 100 GeV $\pi^{+/-}$, $\lambda_i = 10$)

- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

Silicon Tracker:

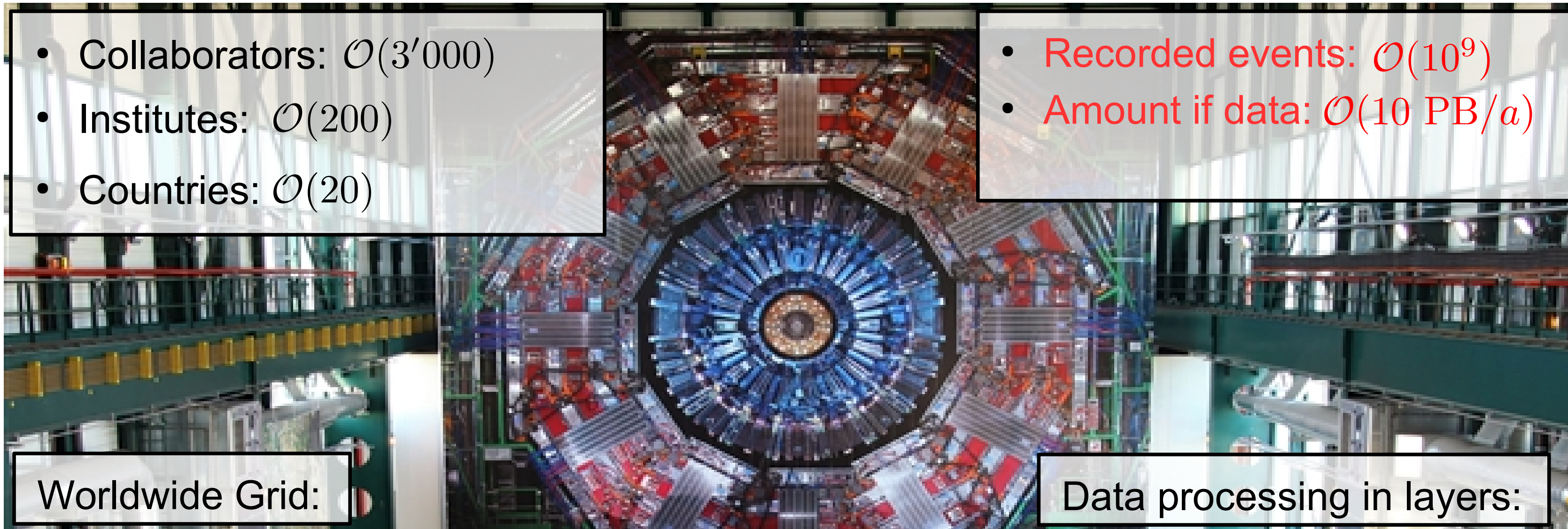


Electromagnetic Calo:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

$$\frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

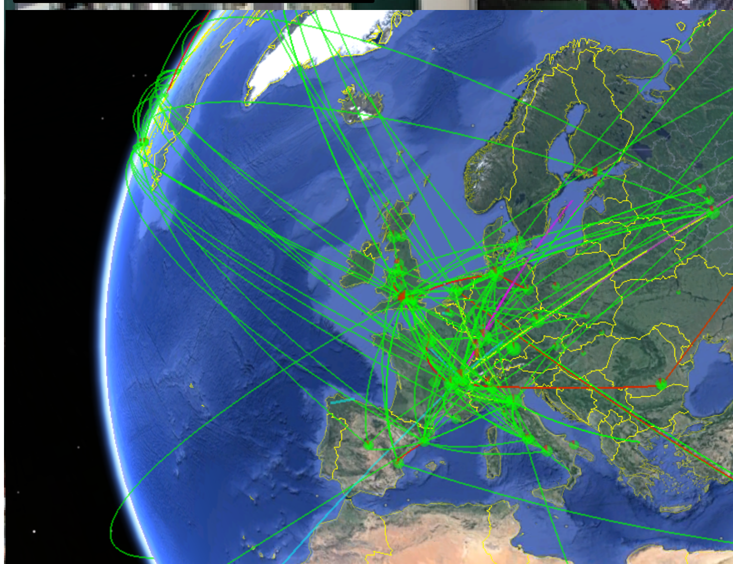
Worldwide Distribution of Data



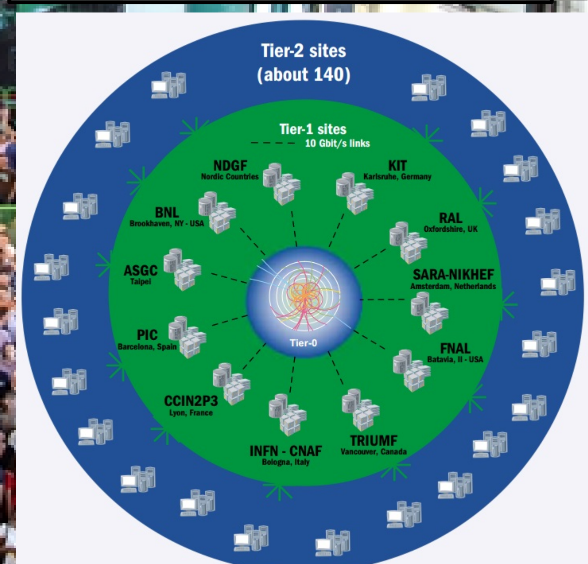
- Collaborators: $\mathcal{O}(3'000)$
- Institutes: $\mathcal{O}(200)$
- Countries: $\mathcal{O}(20)$

- Recorded events: $\mathcal{O}(10^9)$
- Amount if data: $\mathcal{O}(10\ \mathrm{PB}/a)$

Worldwide Grid:



Data processing in layers:



LHC History (represented in physics measurements)

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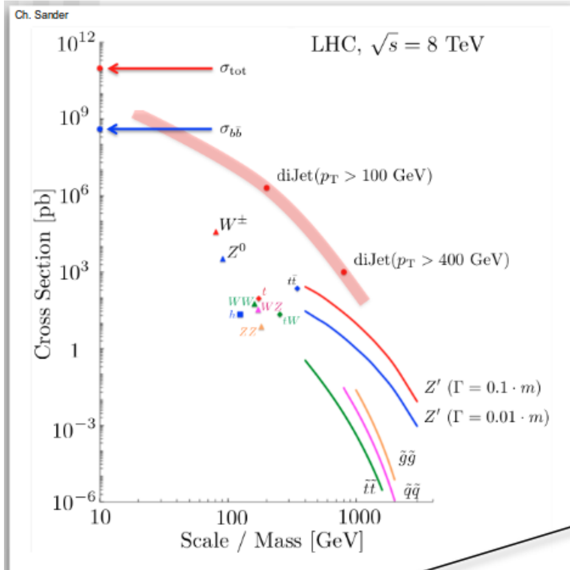
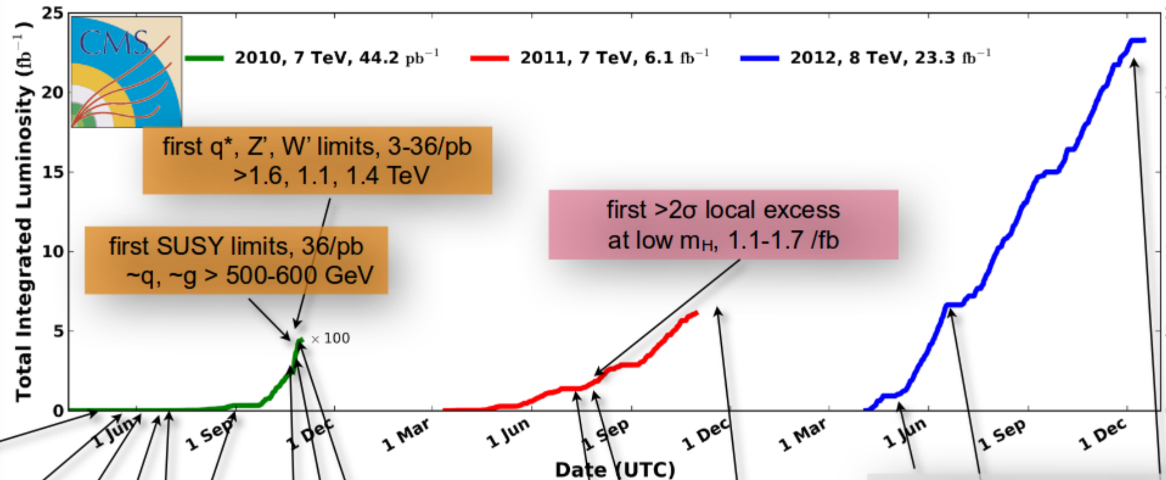




first q*, Z', W' limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb
~q, ~g > 500-600 GeV

first >2σ local excess
at low m_H, 1.1-1.7 /fb

first MinBias / UE
studies, particle multiplicities

first incl. b x-section, 8/nb
δ ~ 15 %

first incl. jet x-section, PF jets
60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb
δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb
δ ~ 20%

first top xsec, 3/pb
δ ~ 40%

first single top xsec,
t-chan., 36/pb
δ ~ 36%

first m_{top}, 36/pb
Δ ~ 6.5 GeV

first WW xsec, 36/pb
δ ~ 40%
first limit on HWW

first ZZ xsec, 1.1 /fb
δ ~ 40%

going more differential,
e.g. Z/W + j,b,c

first significant limit on
$B_s \rightarrow \mu\mu$, BR<1.9×10^{-8}

first particle discovered
by CMS: Ξ_b

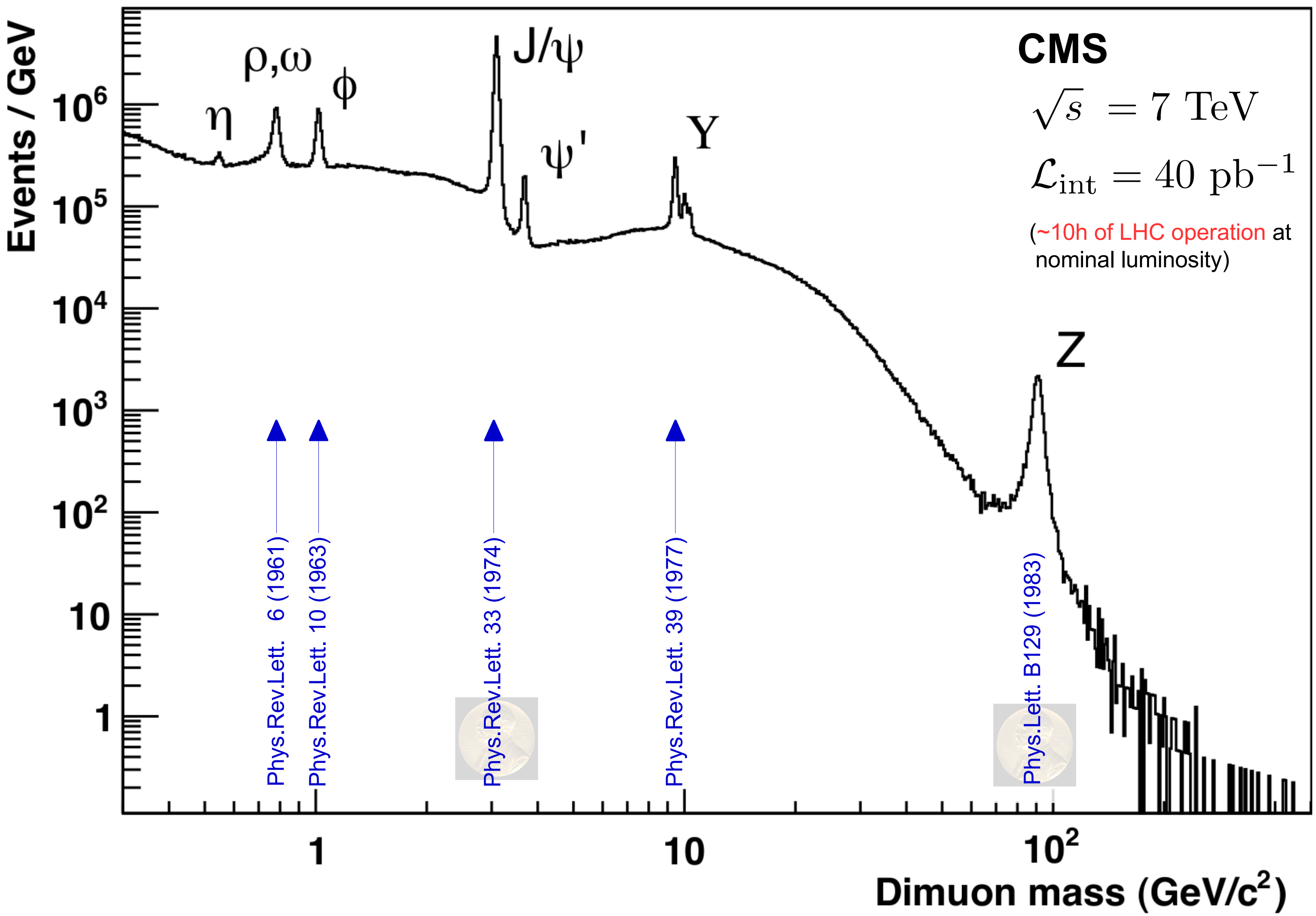
BSM searches continue,
limits pushed

repeating the program
at 8 TeV

a new boson is
announced, 5 /fb

first spin parity
analysis of the boson,
17 /fb

LHC Repeating History (in fast forward)



The Standard Model of Particle Physics (SM)

- 18 free parameters
- 45 fermion fields
- 12 gauge fields

QCD

8 gluons

$SU(3)$

exact

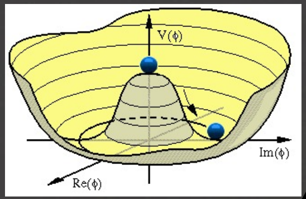
Best theory ever brought up by mankind!

Non-abelian (self interactions)

$m_t = 173.3 \text{ GeV}$

$\text{v} = 246.2 \text{ GeV}$

Abelian



(responsible for masses)

$W^{+/-}$ Z

$SU(2)$

broken

γ

$U(1)$

exact

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$$

$$\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}} \qquad \cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

QFT

QED

A Long Road of Theory Developments

$gg \to H$
- NNLO+NNLL(α_s)
- NLO(α)
- Precision 15%

$qq \to qqH$
- NNLO(α_s)
- NLO(α)
- Precision 3%

$qq \to VH$
- NNLO(α_s)
- NLO(α)
- Precision 4%

tt production
- NNLO+NNLL(α_s)
- Precision 4%

Single top production
- NNLO(α_s)
- Precision 4%

How this precision was obtained:

W + additional jets
- NNLO(α_s)
- Precision 5%

Z + additional jets
- NNLO(α_s)
- Precision 5%

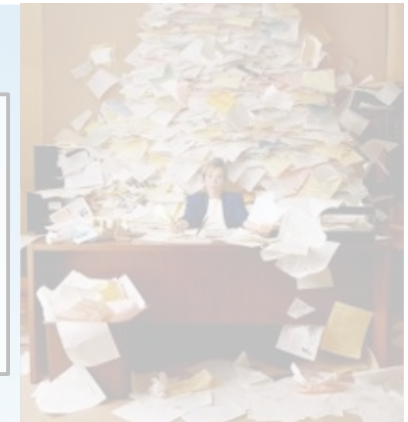
WW WZ ZZ
- NLO(α_s)
- Precision 10%

A Long Road of Theory Developments

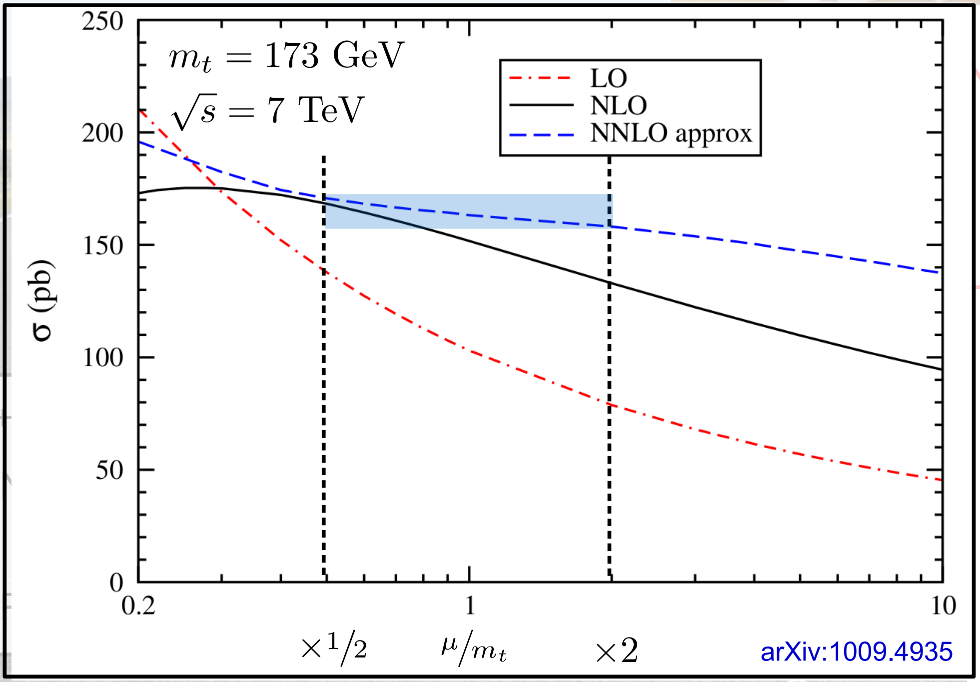
$gg \to H$
- NNLO+NNLL(α_s)
- NLO(α)
- Precision 15%

$qq \to qqH$
- NNLO(α_s)
- NLO(α)
- Precision 3%

$qq \to VH$
- NNLO(α_s)
- NLO(α)
- Precision 4%



tt production
- NNLO+NNLL(α_s)
- Precision 4%



W + additional jets
- NNLO(α_s)
- Precision 5%

Z +

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A Long Road of Theory Developments

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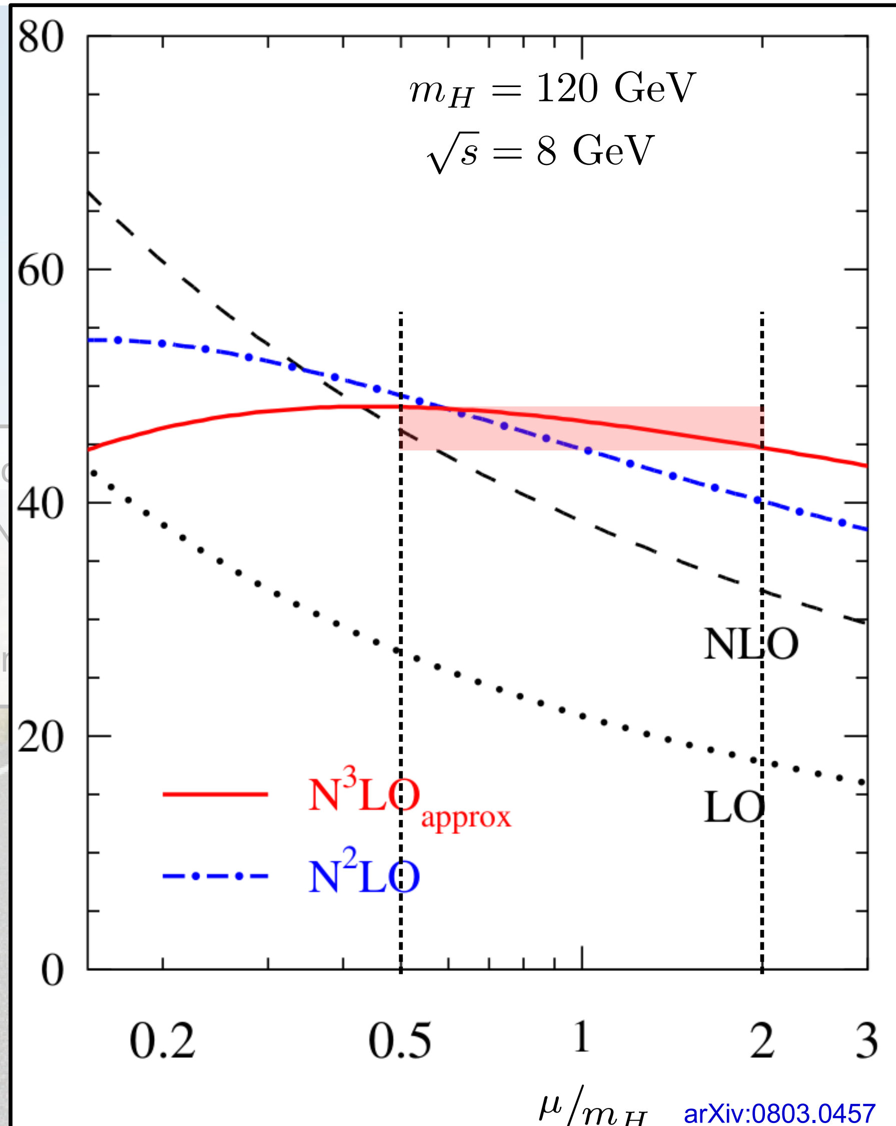
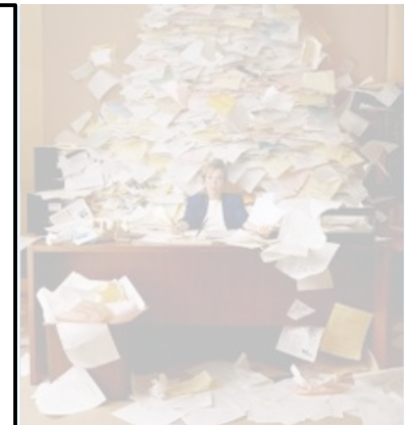
$gg \to H$

- NNLO+NNLL(α_s)
- NLO(α)
- Precision 15%





tt productio
- NNLO+N
- Precisio

W + additional jets
- NNLO(α_s)
- Precision 5%

is precision
otained:

WZ ZZ
- O(α_s)
- ecision 10%

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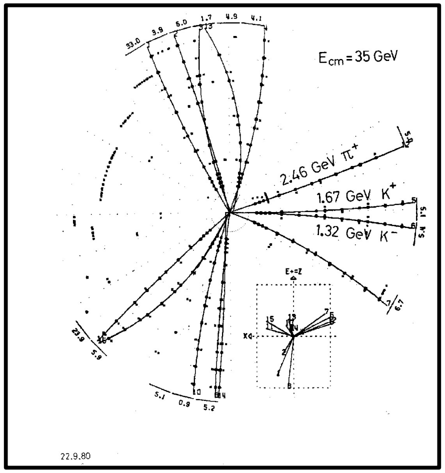
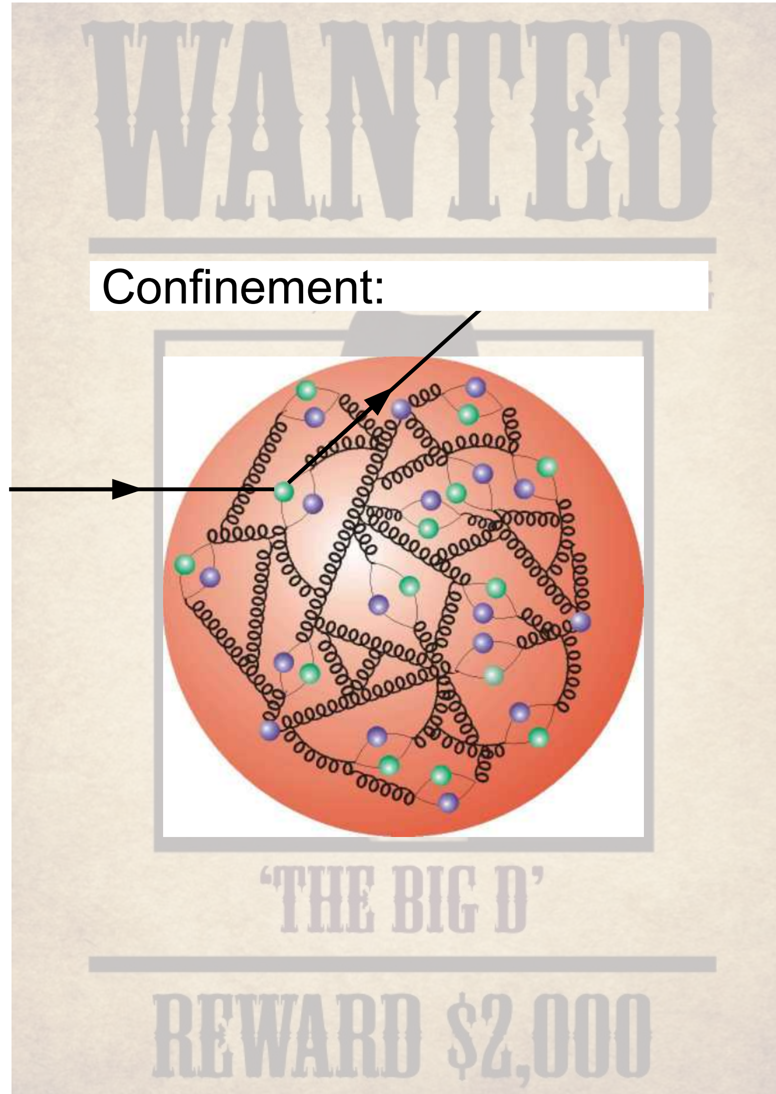
The Strong Sector of the SM

$SU(3)$ exact gauge symmetry:

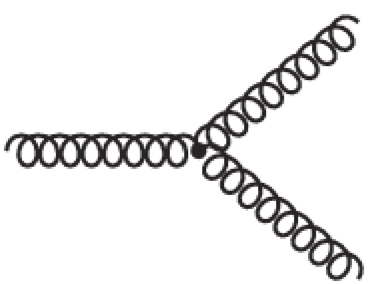
→ 8 massless gluons as gauge bosons.

Asymptotic freedom:





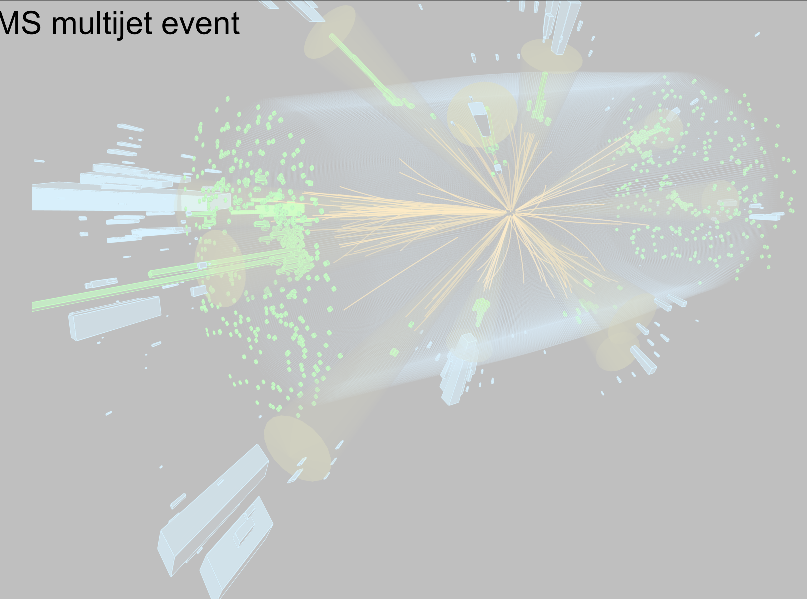
Non-Abelian gauge structure:

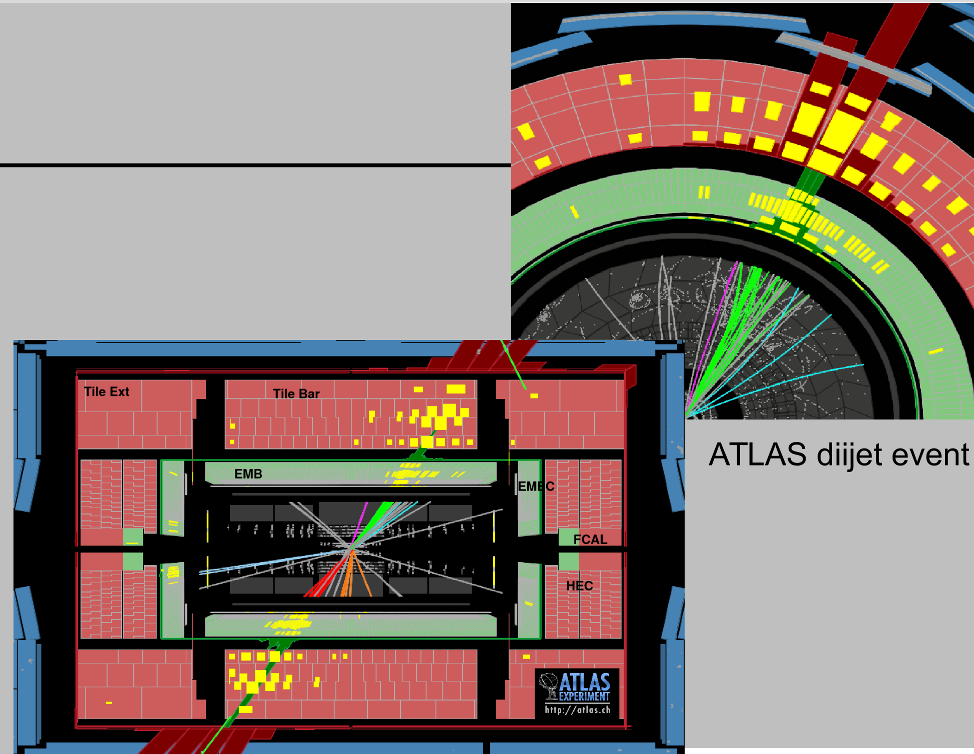


→ leads to gluon-gluon self-couplings.

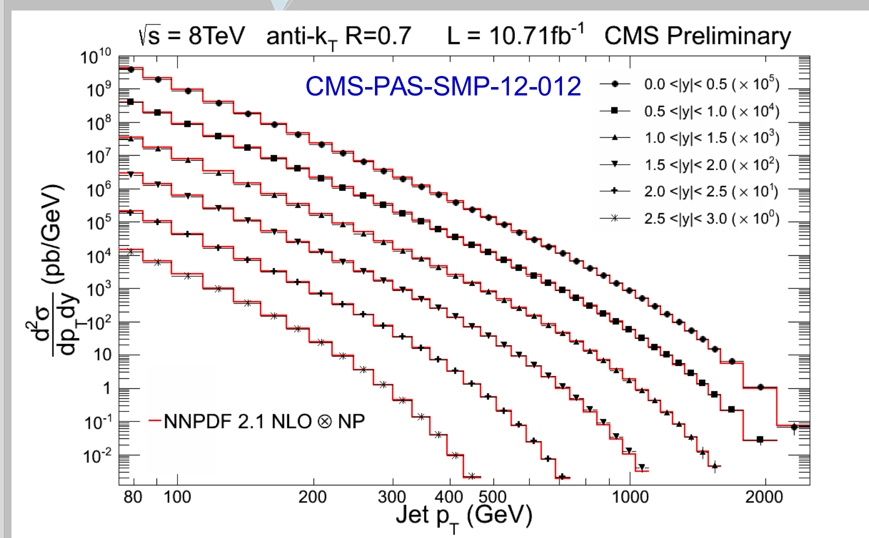
The Strong Sector of the SM

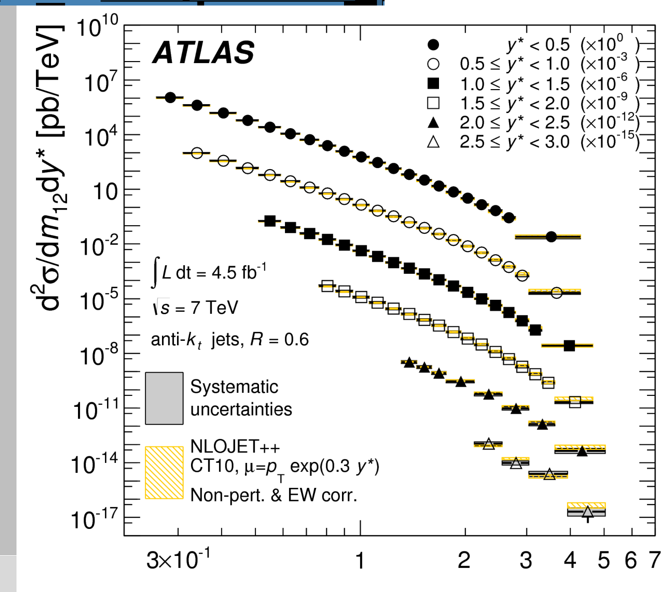
CMS multijet event





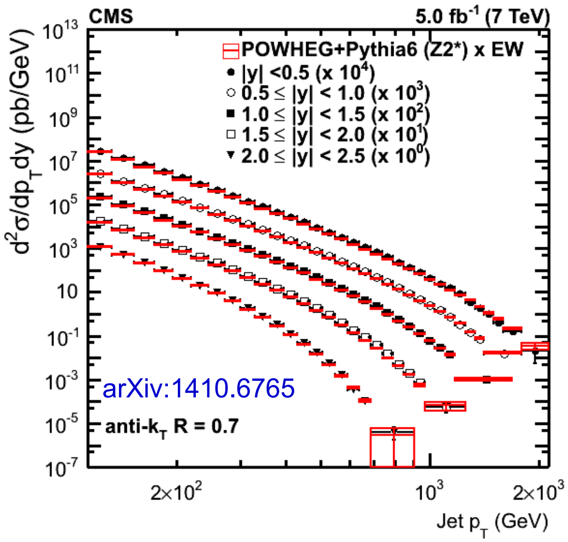
ATLAS diijet event

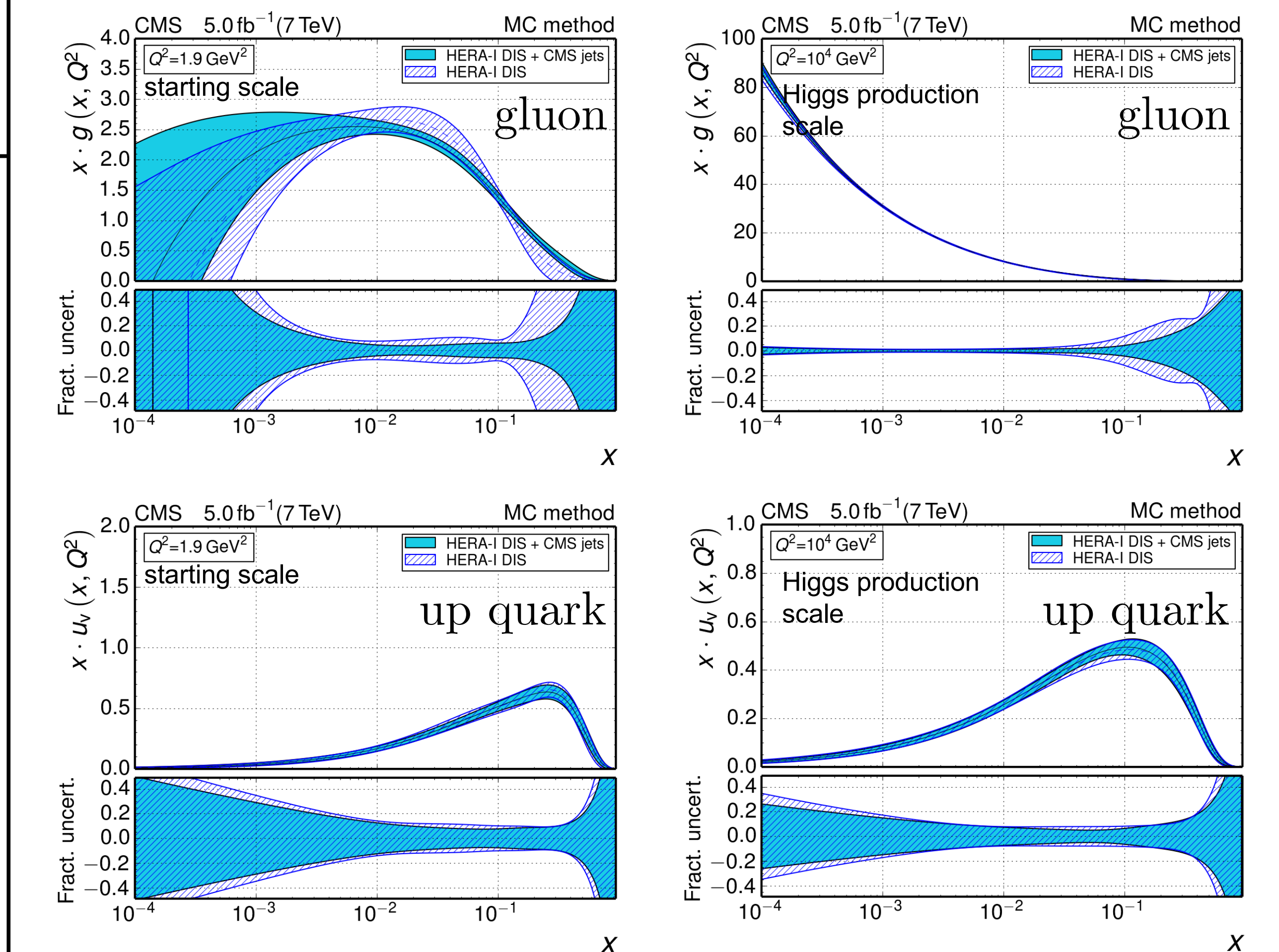




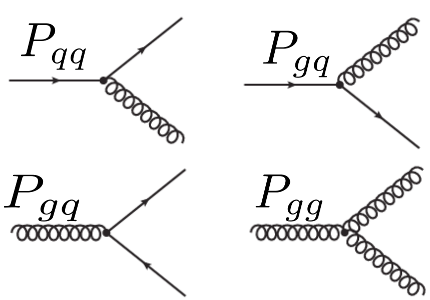
JHEP 05 (2014)

PDFs @ the LHC





Splitting functions (@LO):



$$\frac{dq_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left[\quad q_i(\xi,Q^2)P_{qq}\left(\frac{x}{\xi}\right) + g(\xi,Q^2)P_{qg}\left(\frac{x}{\xi}\right)\right]$$

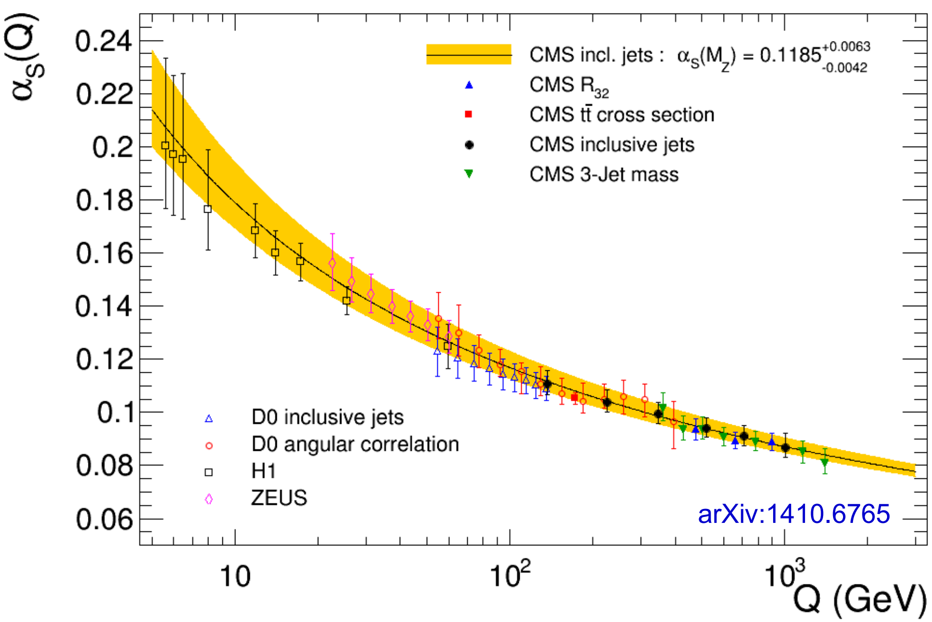
$$\frac{dg_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left[\sum_i q_i(\xi,Q^2)P_{gq}\left(\frac{x}{\xi}\right) + g(\xi,Q^2)P_{gg}\left(\frac{x}{\xi}\right)\right]$$

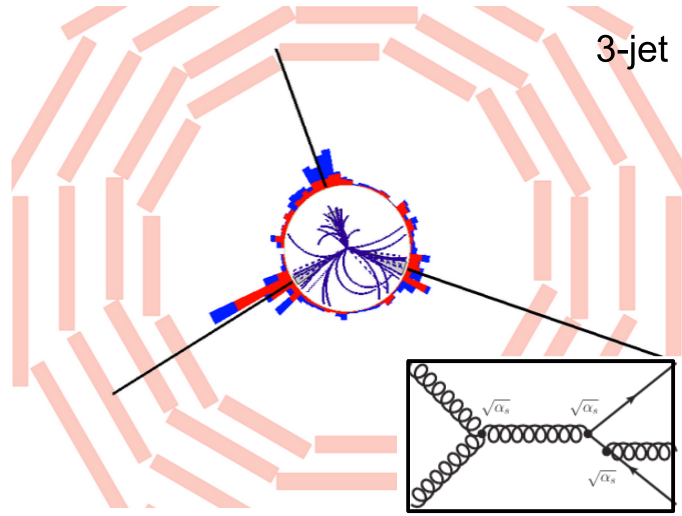
The Running of α_s

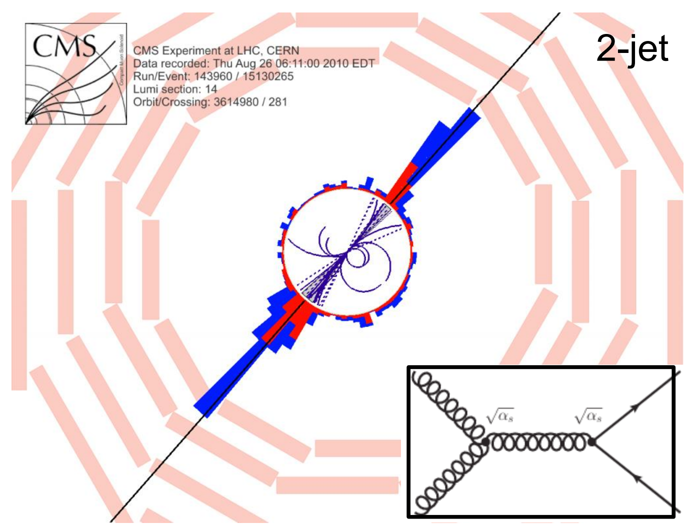
Running $\alpha_s(\mu^2)$ (e.g. from 1-loop RGE):

$$\alpha_s(\mu^2) = \frac{g_s^2(\mu^2)}{4\pi} = \frac{1}{\beta_0 \ln\left(\mu^2/\Lambda_{\mathrm{QCD}}^2\right)}$$

Measure $\alpha_s(\mu^2)$ from ratio of 3-jet over 2-jet events at given scale:

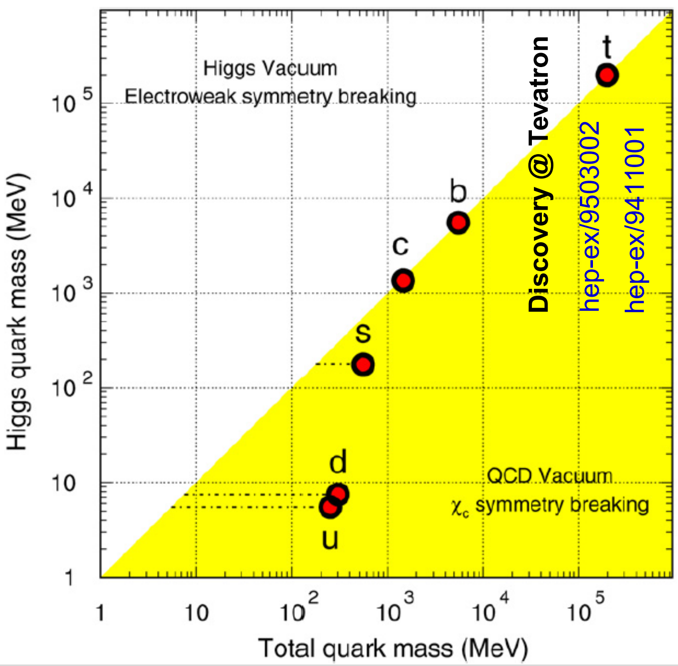


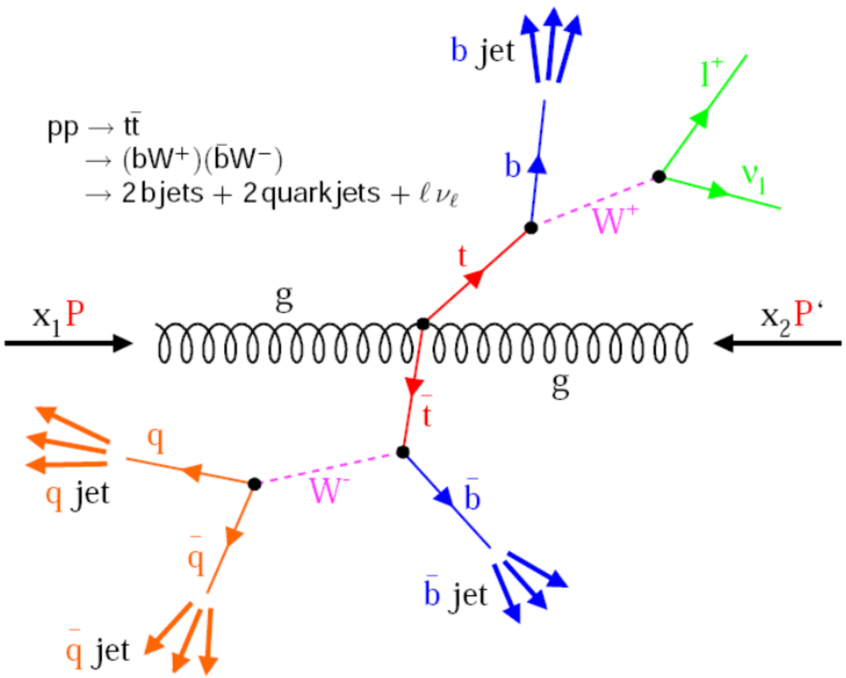




Physics of the Top Quark

- Weak decay nearly exclusively via $t \to b$ ($BR \approx 0.998$).
- Lifetime $t = 5 \times 10^{-25}$ s (hadronization time scales $\delta t \approx \frac{\hbar}{\Lambda_{QCD}} \approx 3 \times 10^{-21}$ s).





Physics of the Top Quark

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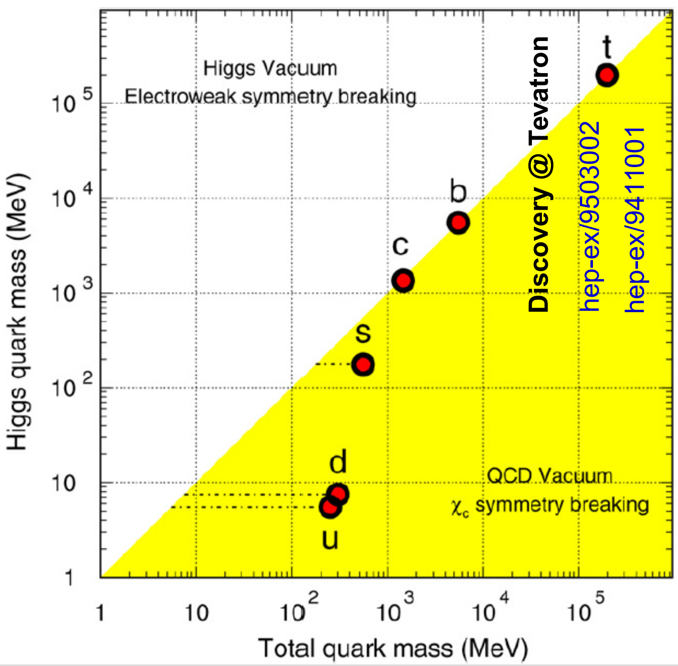
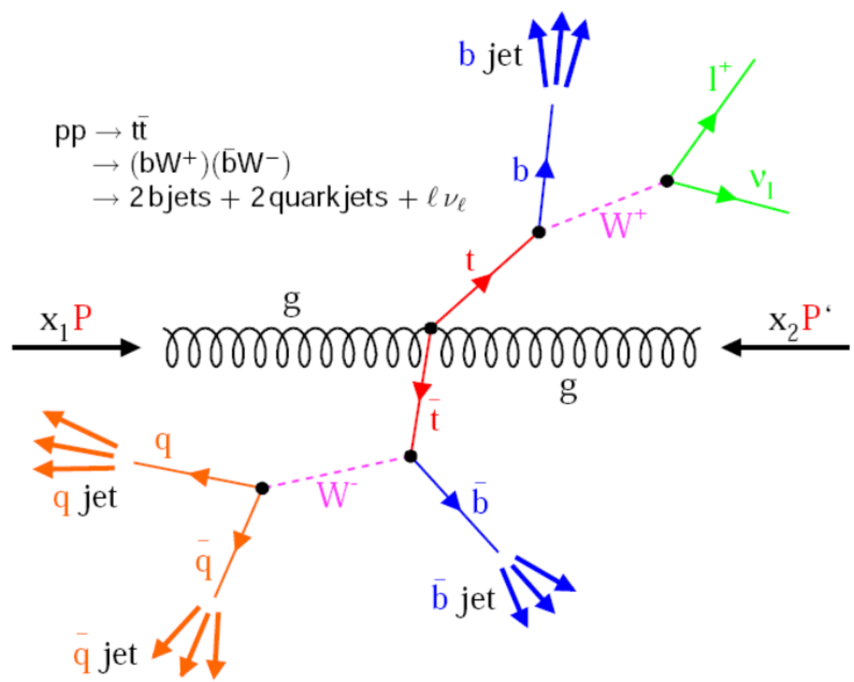
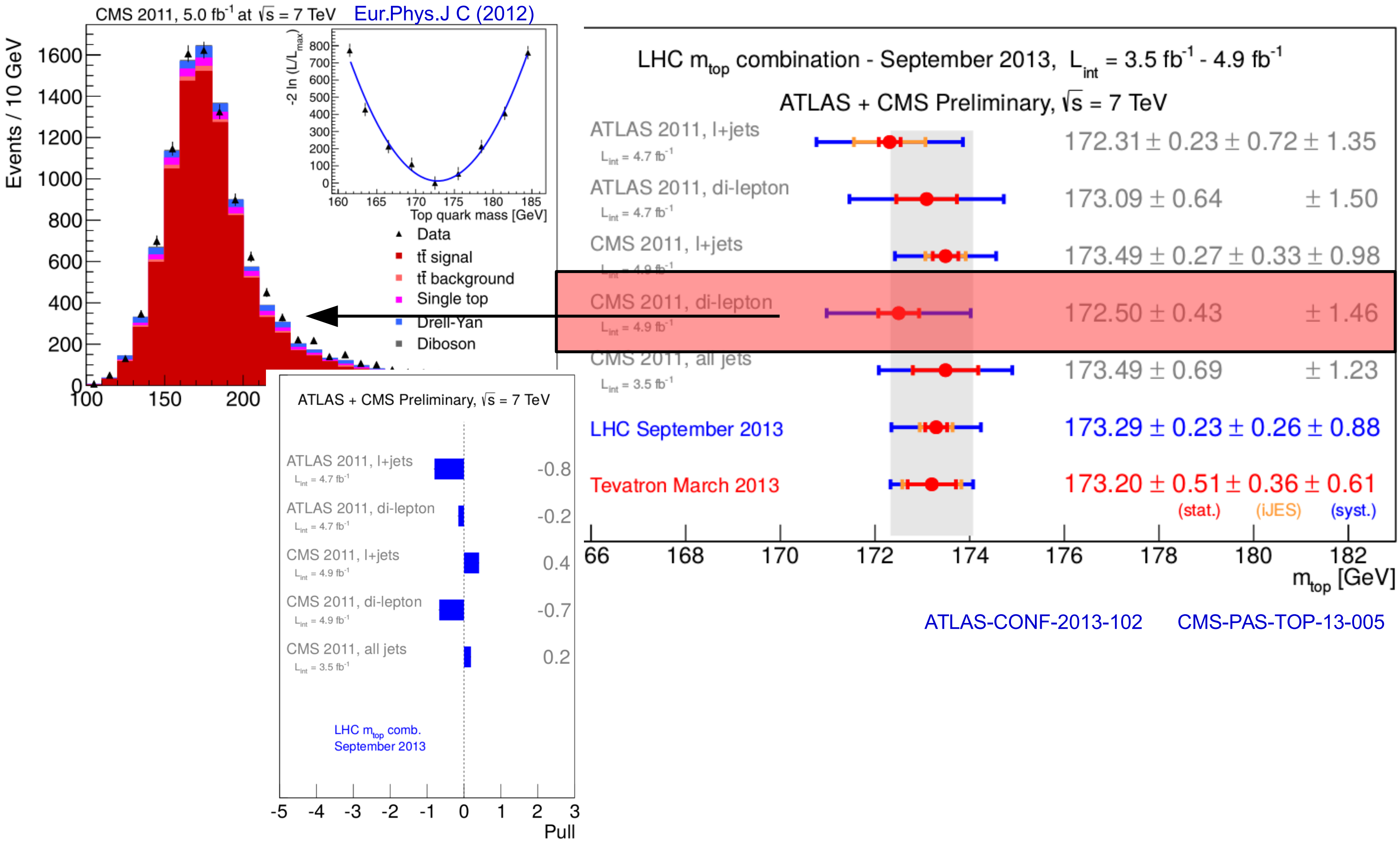
- Lifetime $t = 5 \times 10^{-25}$ s (hadronization time scales $\delta t \approx \frac{\hbar}{\Lambda_{QCD}} \approx 3 \times 10^{-21}$ s).
- Fermi's Golden Rule: $\lambda_{if} = \frac{2\pi}{\hbar} |\mathcal{M}_{if}|^2 \cdot \rho(E_f)$



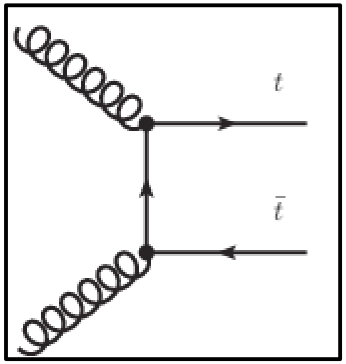


The Mass of the Top Quark

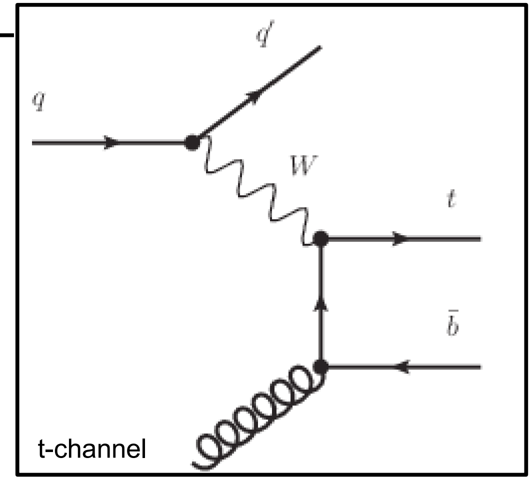


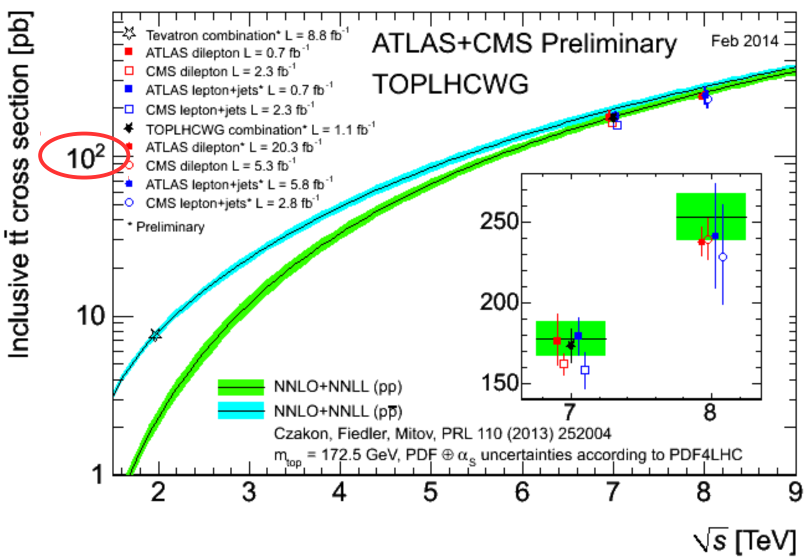
Top Quark Production

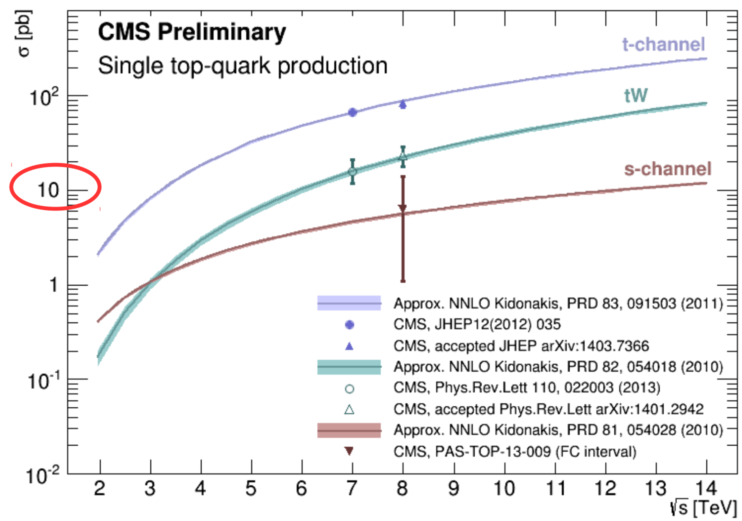
Top quark pair production:



Single top quark production:





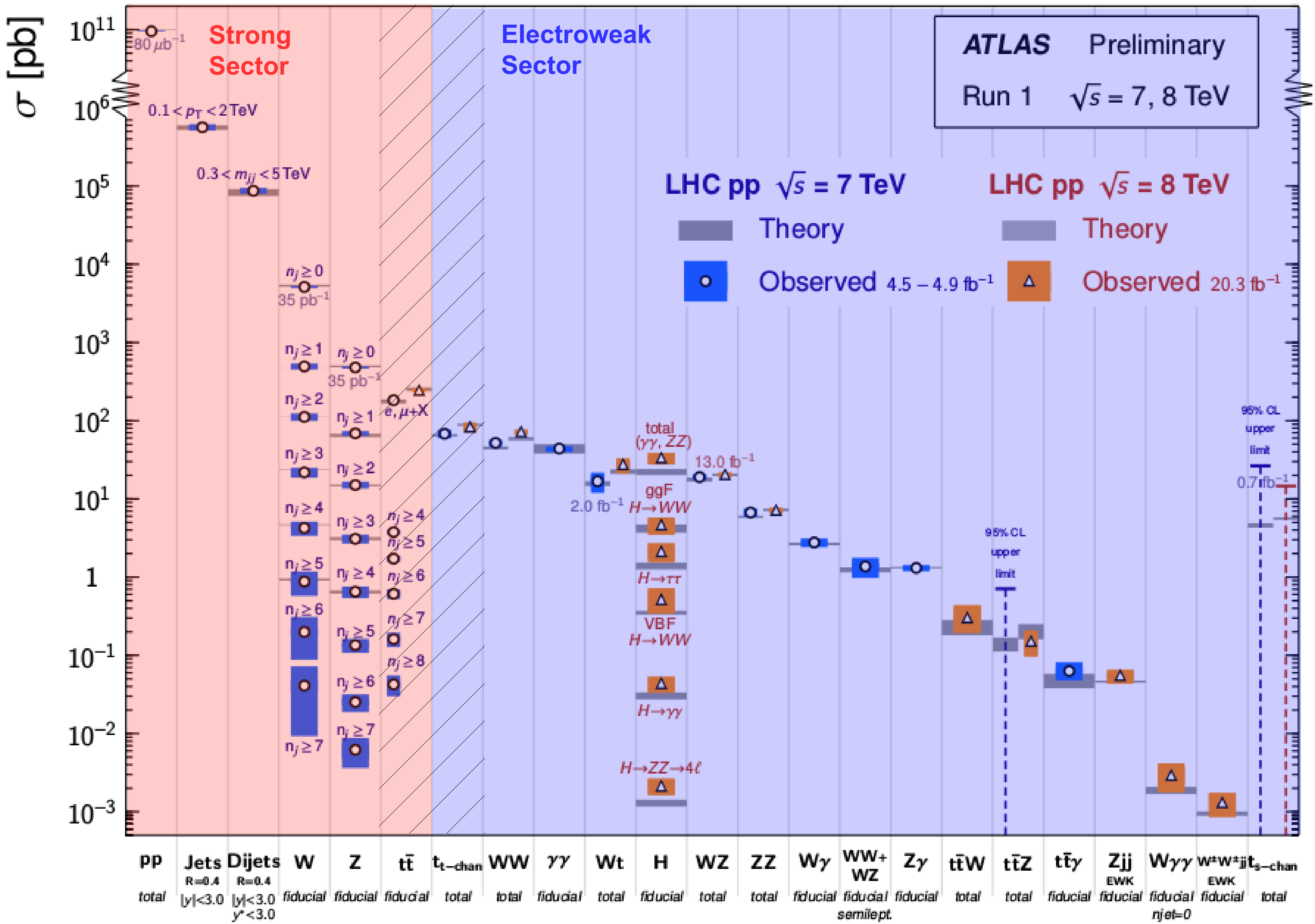


Typical DGLAP/Regge like high energy behavior ($\rightarrow \log(s)$).

Single top over top quark pair production: $^1/_{10}$.

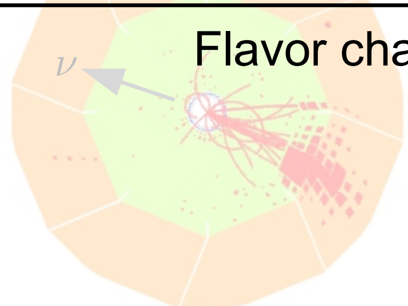
Standard Model Production Cross Section Measurements

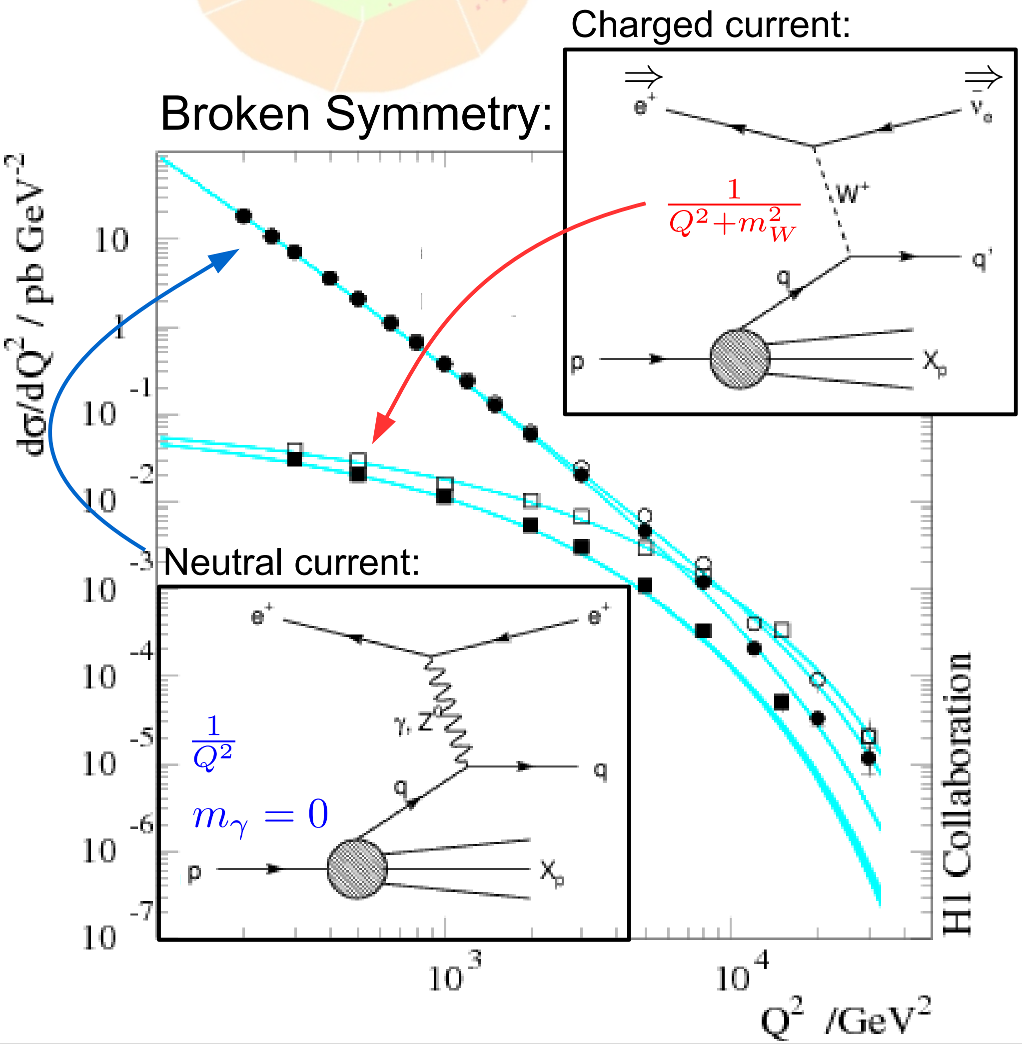
Status: March 2015

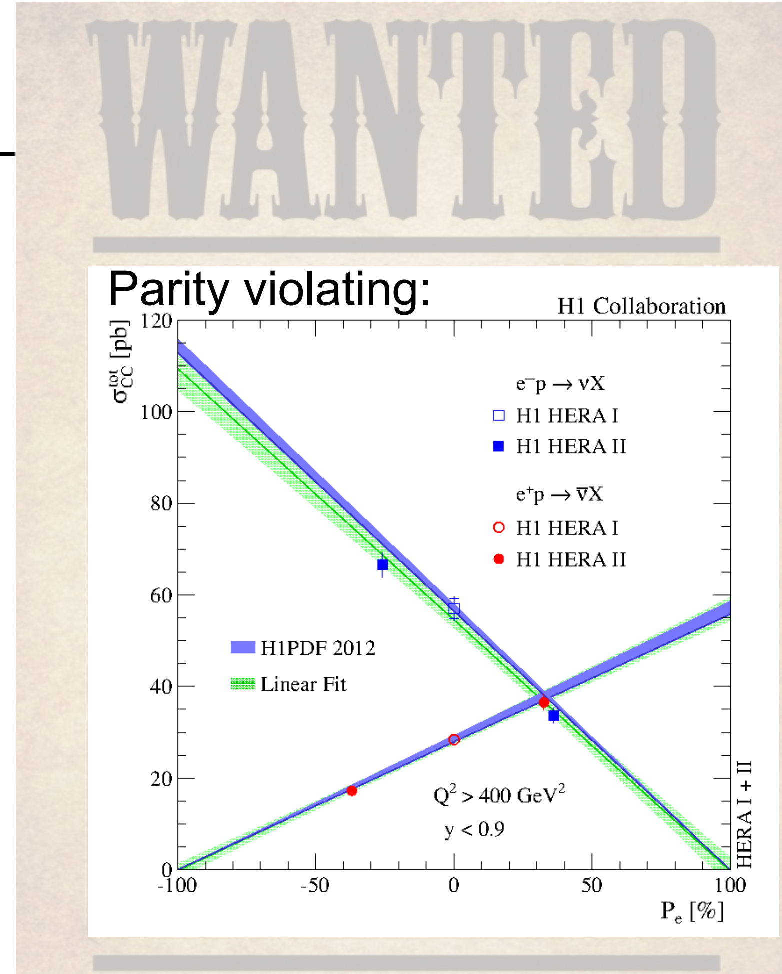


The Weak Sector of the SM

Flavor changing:



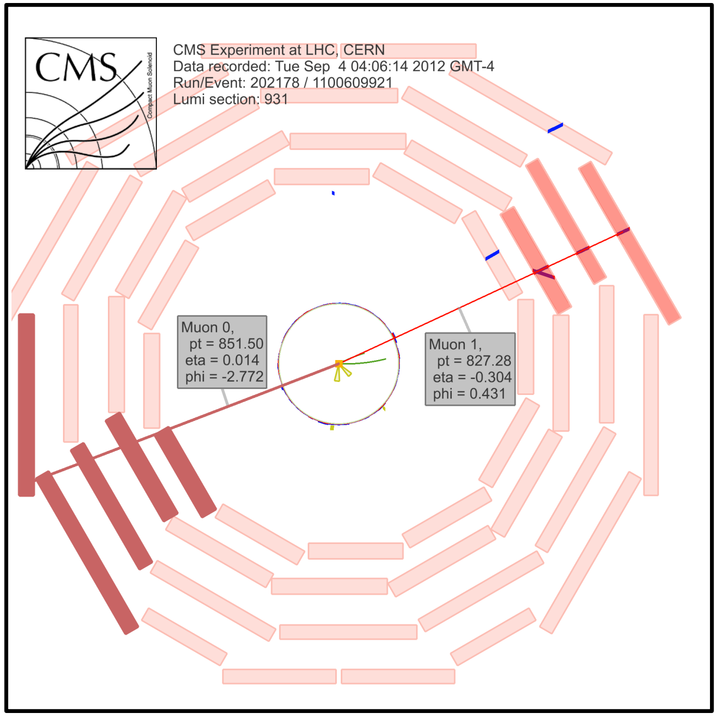




Non-Abelian gauge structure!

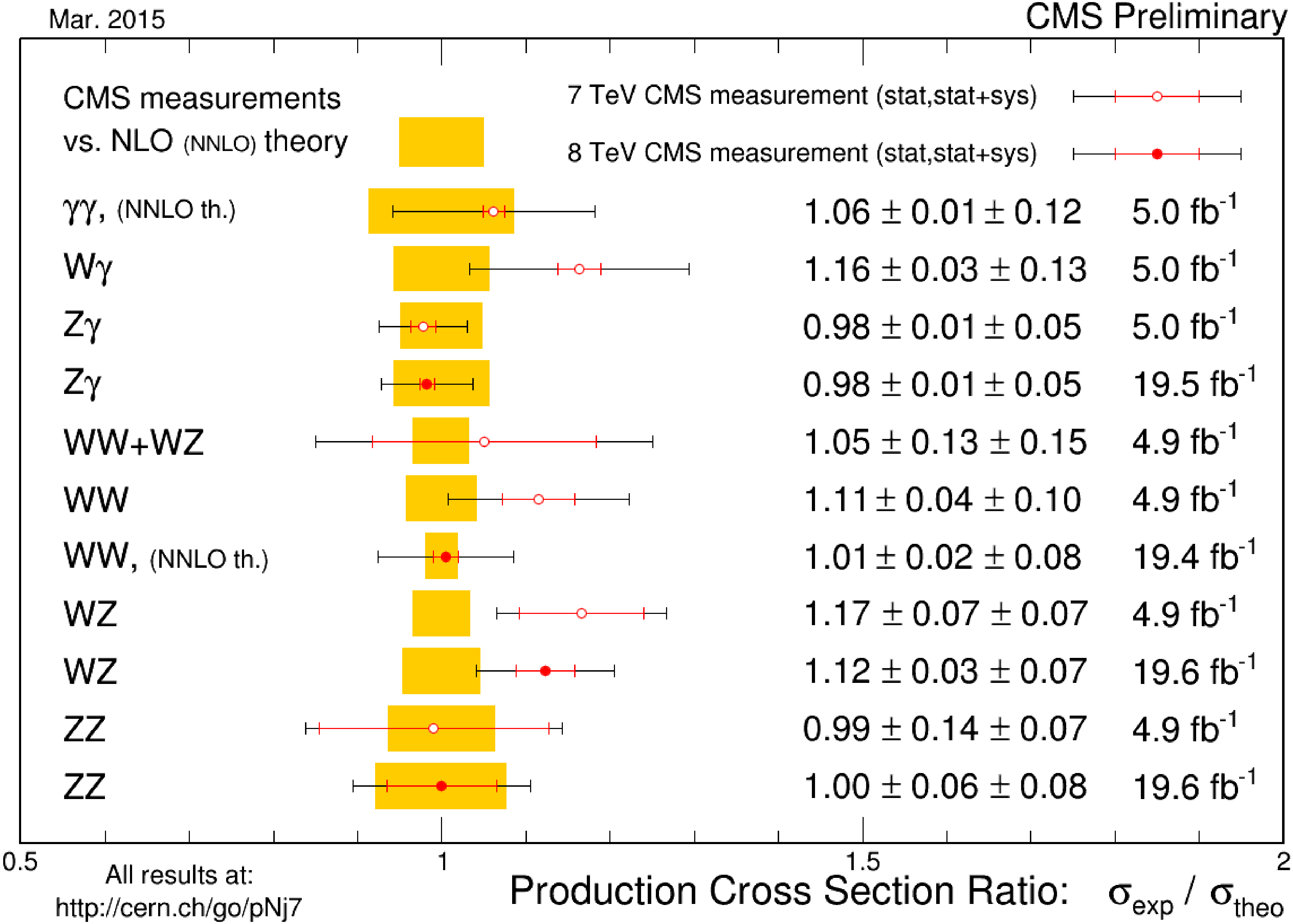
Lepton universality!

Z Bosons (abused) as Calibration Tools



- Tag & Probe to validate ℓ reconstr. efficiencies:
- Tag:
  - Strictly selected, isolated ℓ.
  - Well defined vertex with m_Z requirement.
- Probe:
  - Non-isolated ℓ.
  - Non-ID'ed ℓ.
  - A track pure track or cluster (validate linking efficiency).

- Tool to validate MET resolution (from recoil of $Z \to \mu\mu$): $\vec{U} + \vec{\mu}_1 + \vec{\mu}_2 = \vec{0}$
- Tool to validate efficiency to find hard interaction vertex.



Mar. 2015
CMS Preliminary
CMS measurements
vs. NLO (NNLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
γγ, (NNLO th.) 1.06 ± 0.01 ± 0.12 5.0 fb-1
Wγ 1.16 ± 0.03 ± 0.13 5.0 fb-1
Zγ 0.98 ± 0.01 ± 0.05 5.0 fb-1
Zγ 0.98 ± 0.01 ± 0.05 19.5 fb-1
WW+WZ 1.05 ± 0.13 ± 0.15 4.9 fb-1
WW 1.11 ± 0.04 ± 0.10 4.9 fb-1
WW, (NNLO th.) 1.01 ± 0.02 ± 0.08 19.4 fb-1
WZ 1.17 ± 0.07 ± 0.07 4.9 fb-1
WZ 1.12 ± 0.03 ± 0.07 19.6 fb-1
ZZ 0.99 ± 0.14 ± 0.07 4.9 fb-1
ZZ 1.00 ± 0.06 ± 0.08 19.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

Non-Abelian Gauge Structure of $SU(2)$

$$\mathcal{L}^{\text{gauge}} = -\frac{1}{2}\text{Tr}\left(W^a_{\mu\nu}W^{a\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

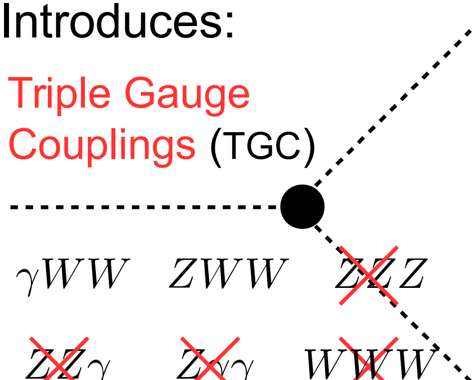
$$B_\mu \to A_\mu \qquad W^3_\mu \to Z_\mu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

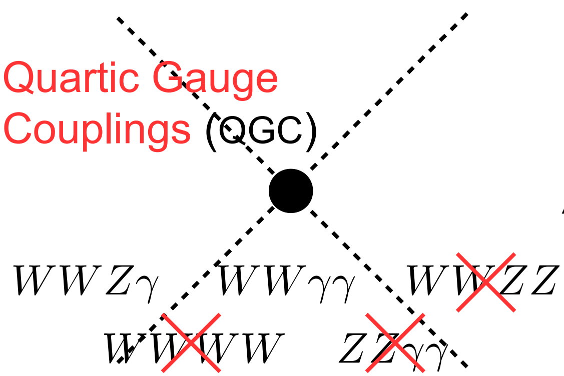
$$W_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + ig\left[W^a_\mu, W^a_\nu\right]$$

- Implies lepton universality of weak interaction. (→extensively tested @ LEP)
- Introduces:

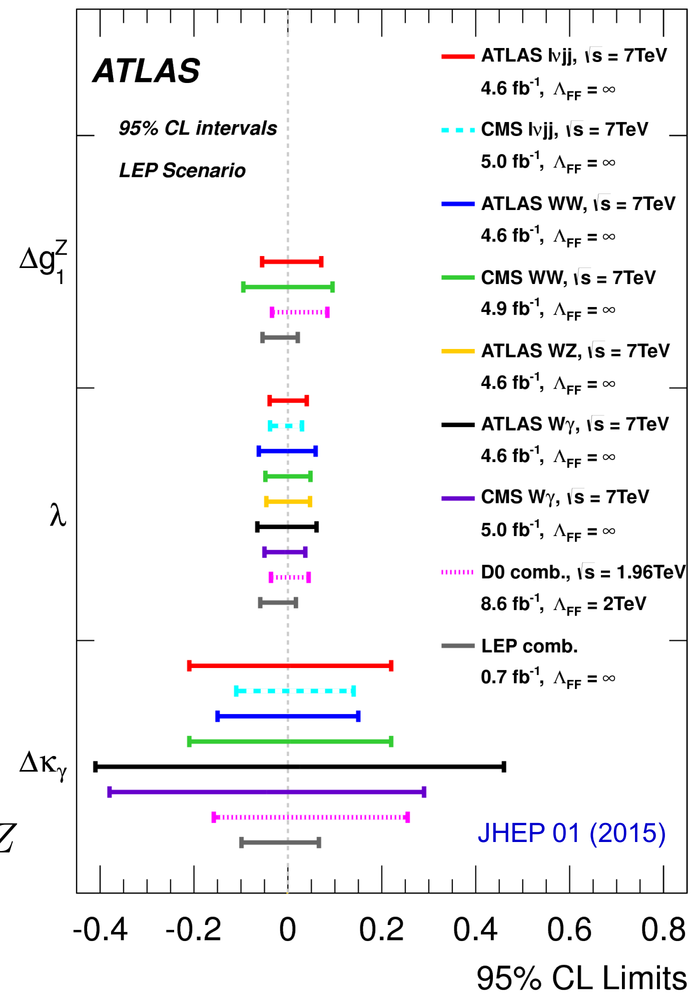
Triple Gauge Couplings (TGC)



Quartic Gauge Couplings (QGC)

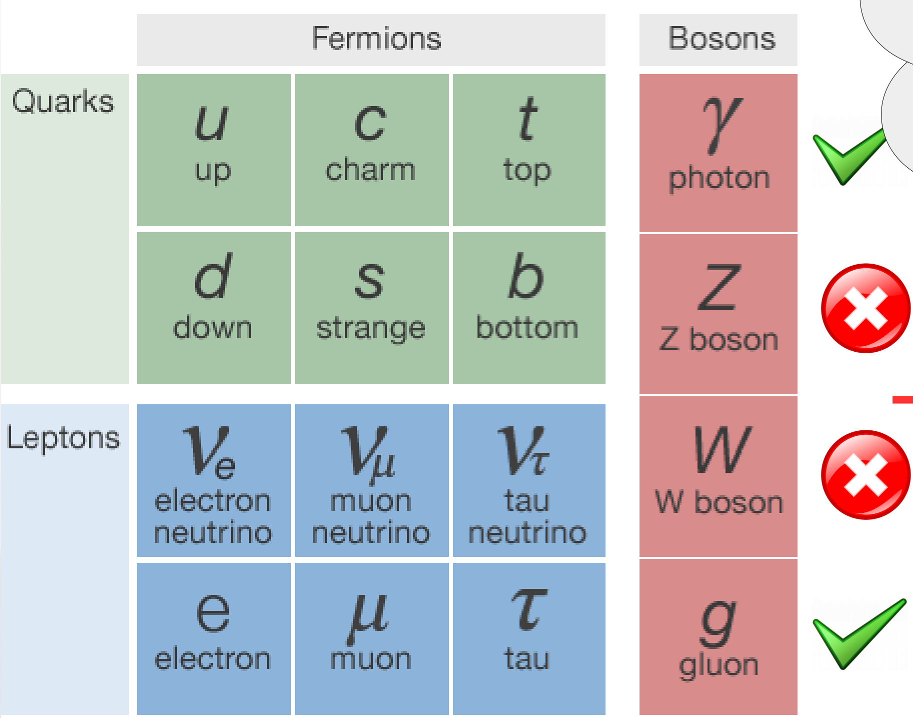


Searches for aTGC:



The Case of Electroweak Symmetry

- Local gauge symmetries **strictly require** force mediating particle to have $m = 0$:



$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
$$m_W = 85.385 \pm 0.015 \text{ GeV}$$

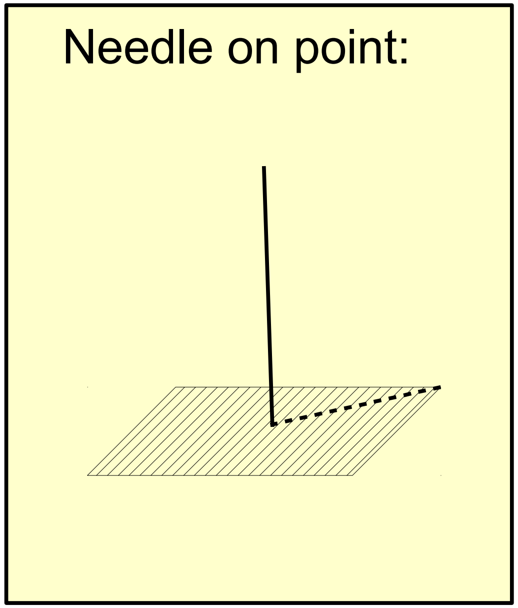
- Weak interactions are described by weak gauge symmetries! → symmetry exists.
- Force mediating particles explicitly break symmetry! → symmetry not realized in nature.

- Weak interaction makes a difference between left- & right-handed coordinate systems.
- This property destroys local gauge invariance for all weak interactions if fermions have mass $m \neq 0$.

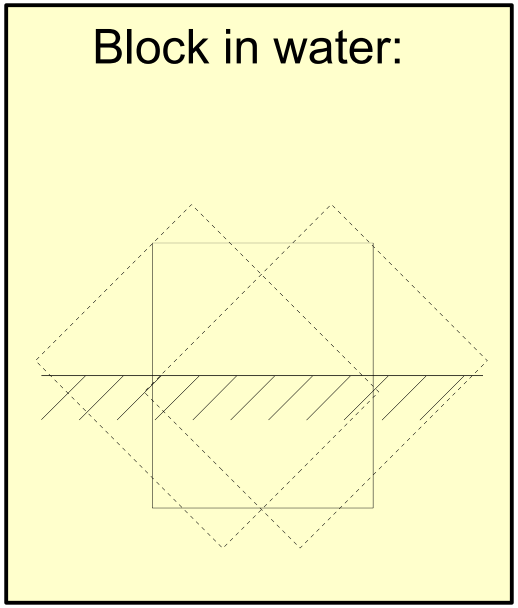
Spontaneous Symmetry Breaking

- Symmetry present in the system (i.e. in Lagrangian density $\mathcal{L}$).
- BUT symmetry broken in energy ground state of the system (i.e. quantum vacuum).

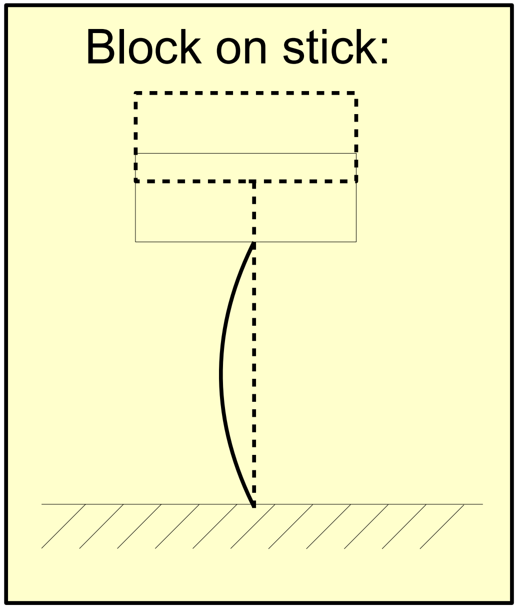
- Three examples from classical mechanics:



φ symmetry



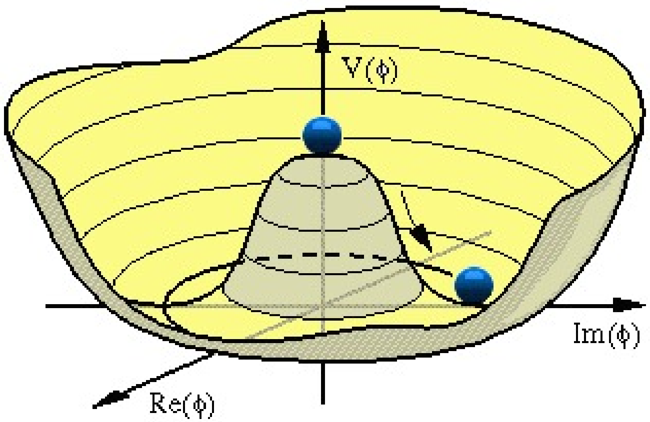
axis-symmetry



φ symmetry

The Higgs Mechanism

- Incorporation of spontaneous symmetry breaking in gauge field theory = Higgs mechanism:
- Introduce new field ϕ with characteristic interaction potential.
- Leads to prediction of new particle: $\rightarrow$ Higgs boson!
- Allows to incorporate mass terms in the theory.



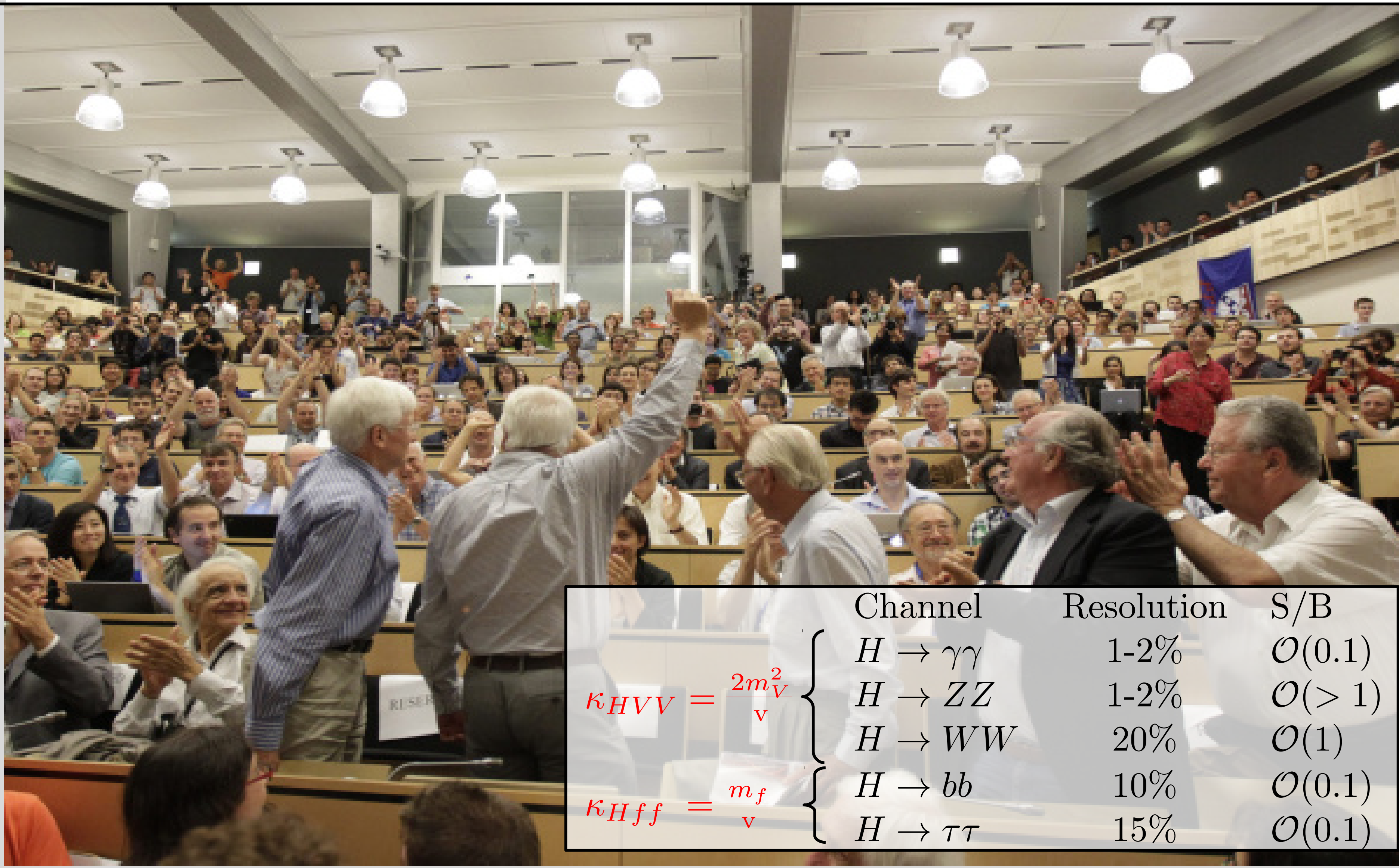
- Gauge symmetry compromising mass terms compensated by characteristic couplings to Higgs particle:

$\kappa_V = \frac{2m_v^2}{\text{v}}$ (for force mediating W & Z boson).

$\kappa_f = \frac{m_f}{\text{v}}$ (for weakly interacting fermions).

The Discovery of a New Particle 4th July 2012

Karlsruhe Institute of Technology



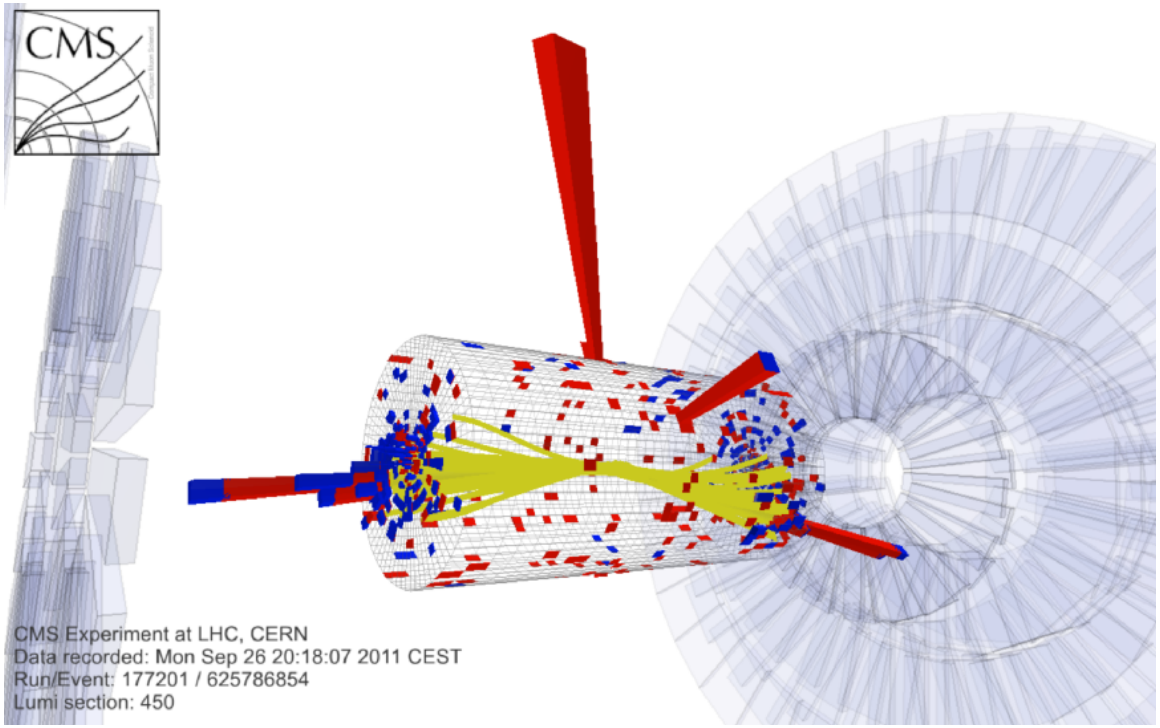
$$\kappa_{HVV} = \frac{2m_V^2}{v} \quad (H \to \gamma\gamma,\ H \to ZZ,\ H \to WW)$$

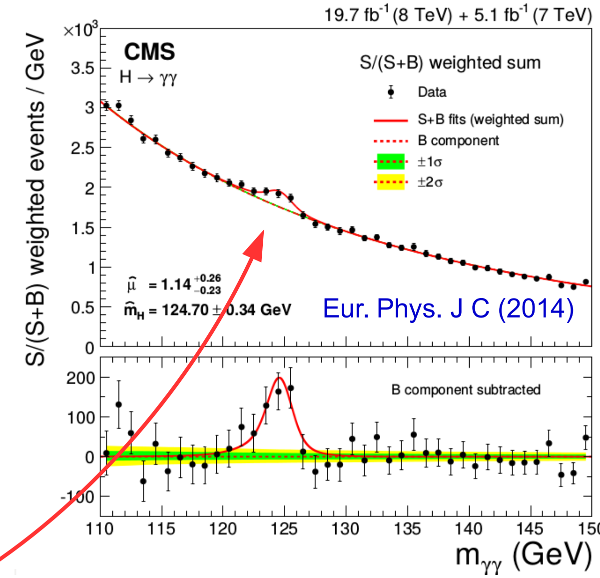
$$\kappa_{Hff} = \frac{m_f}{v} \quad (H \to bb,\ H \to \tau\tau)$$

Channel	Resolution	S/B
$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$H \to ZZ$	1-2%	$\mathcal{O}(> 1)$
$H \to WW$	20%	$\mathcal{O}(1)$
$H \to bb$	10%	$\mathcal{O}(0.1)$
$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

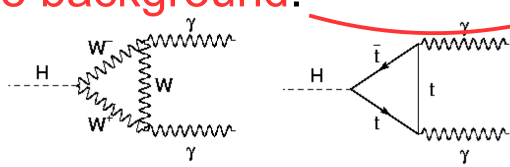
$H \to \gamma\gamma$ Decay Channel

Karlsruhe Institute of Technology

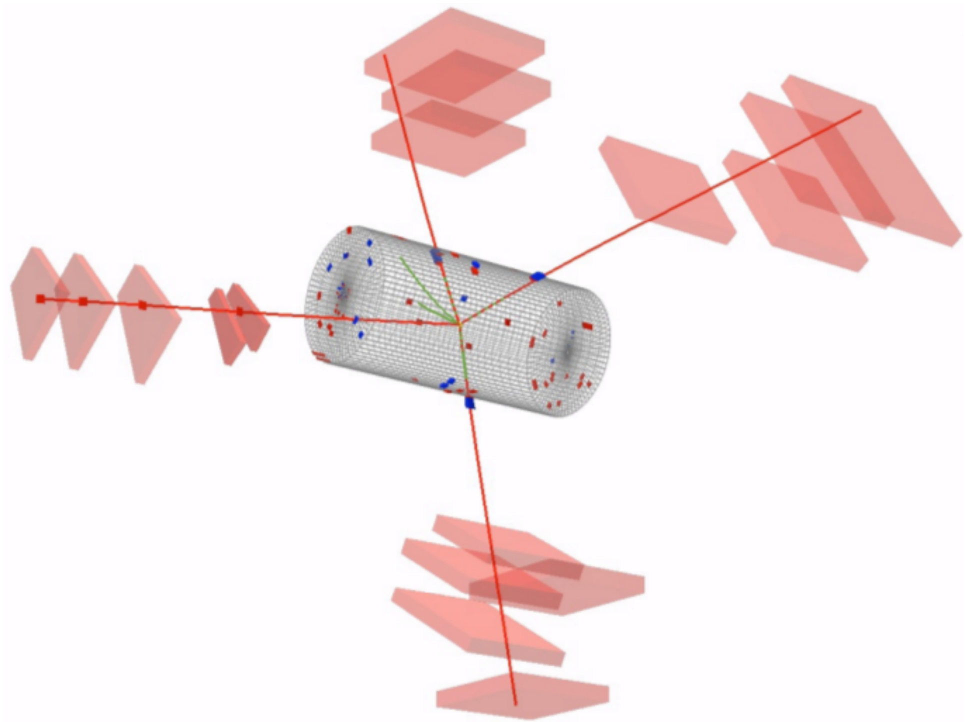


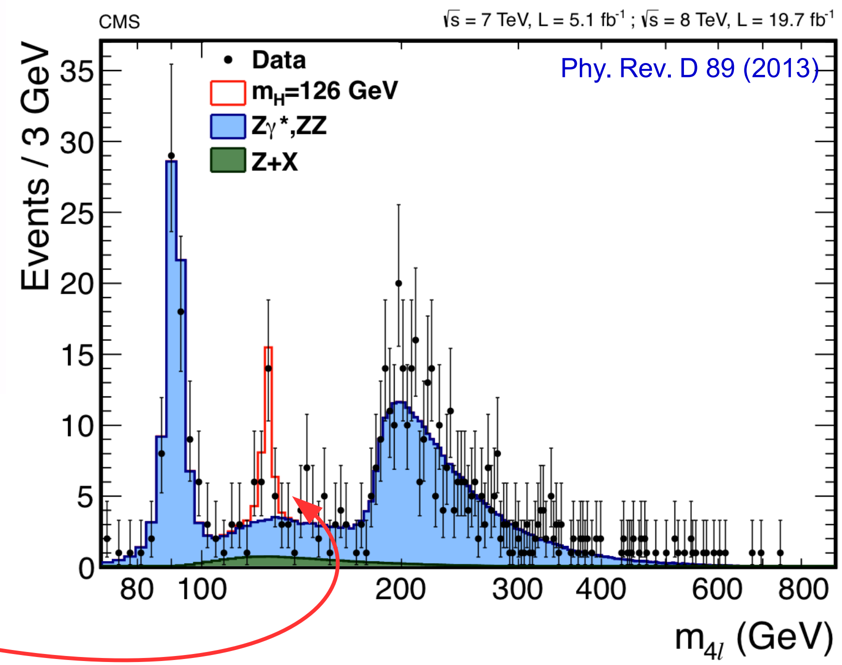


- High mass resolution ($\mathcal{O}(1\text{-}2\%)$). Simple reconstruction and event selection.
- Tiny signal on huge background.
- Decay via loops:



$H \to ZZ$ Decay Channel





- High mass resolution ($\mathcal{O}(1\text{-}2\%)$). Simple reconstruction and event selection.
- Obvious signal on small background.
- Most important search channels: 4μ $2\mu 2e$ $4e$

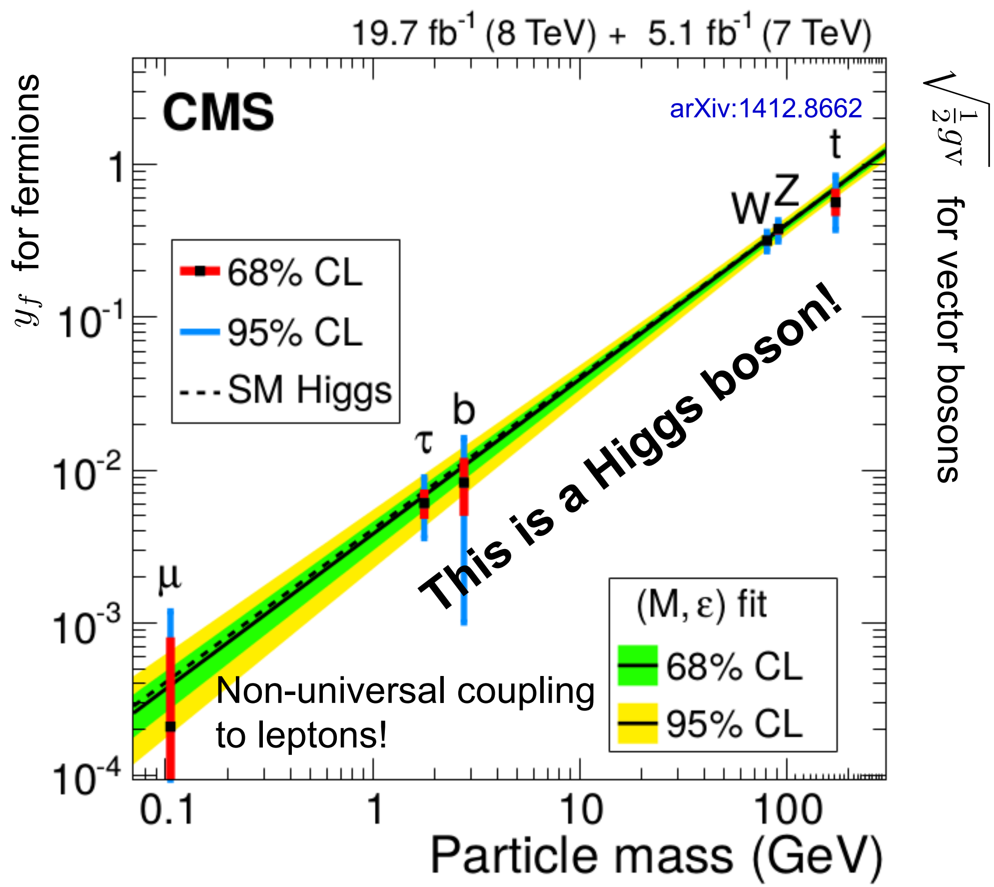
		$10\ \text{fb}^{-1}$ Significance (σ)		$25\ \text{fb}^{-1}$ Significance (σ)		$\hat{\mu}$
ATLAS	$H \to \gamma\gamma$	4.5 (2.5)	[25]	5.2 (4.6)	[97]	1.17 ± 0.27
	$H \to ZZ$	3.6 (2.7)	[25]	8.1 (6.2)	[98]	1.44 ± 0.37
	$H \to WW$	2.8 (2.3)	[25]	6.1 (5.8)	[99]	1.09 ± 0.21
CMS	$H \to \gamma\gamma$	4.1 (2.8)	[27]	5.7 (5.2)	[89]	1.14 ± 0.25
	$H \to ZZ$	3.2 (3.8)	[27]	6.8 (6.7)	[90]	0.93 ± 0.27
	$H \to WW$	1.6 (2.5)	[27]	4.3 (5.8)	[91]	0.72 ± 0.19

		$10\ \text{fb}^{-1}$ Significance (σ)		$25\ \text{fb}^{-1}$ Significance (σ)		$\hat{\mu}$
ATLAS	$H \to \tau\tau$	–		4.5 (3.4)	[113]	1.43 ± 0.40
	$H \to b\bar{b}$	–		1.4 (2.6)	[114]	0.52 ± 0.40
	$t\bar{t}H(\gamma\gamma)$	–		–	[115]	1.30 ± 2.20
CMS	$H \to \tau\tau$	– (1.4)	[27]	3.2 (3.7)	[92]	0.78 ± 0.27
	$H \to b\bar{b}$	0.7 (1.9)	[27]	2.1 (2.5)	[93]	0.84 ± 0.44
	$t\bar{t}H$	–		3.4 (1.2)	[111]	2.80 ± 0.95

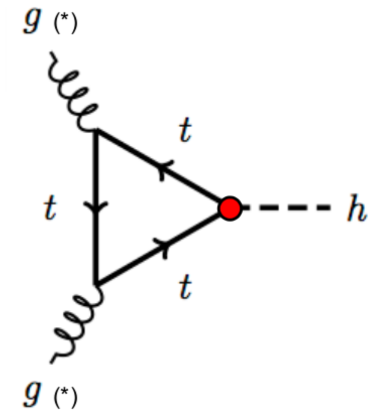
Taken from “The Higgs Boson Discovery at the Large Hadron Collider” Springer Tract of Modern Physics (tbp soon).

Analysis of the Coupling Structure

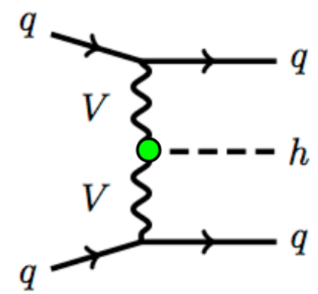
- Six free parameters for each tree-level coupling, m_H fixed to best fit value, γ and g vtx resolved.



$gg \to H$ production:



$qq \to qqH$ production:

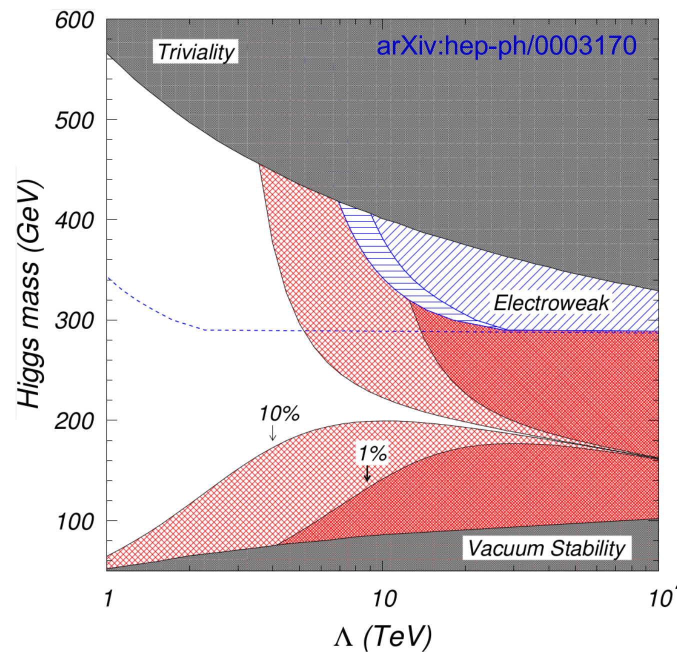


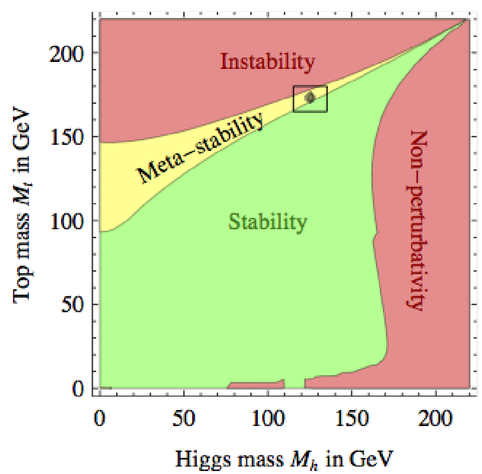
$f \; : \; \kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}}$

$V \; : \; \kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

Why it is not THE Higgs Boson (of the SM) (1)

- Gravity is not included in the SM.
- The SM suffers from the hierarchy problem.
- Dark matter is not included in the SM.
- Neutrino masses are not included in the SM.
- There are known deviations in $a_\mu \equiv \frac{g_\mu - 2}{2}$ from the SM expectation (3.6σ unresolved).



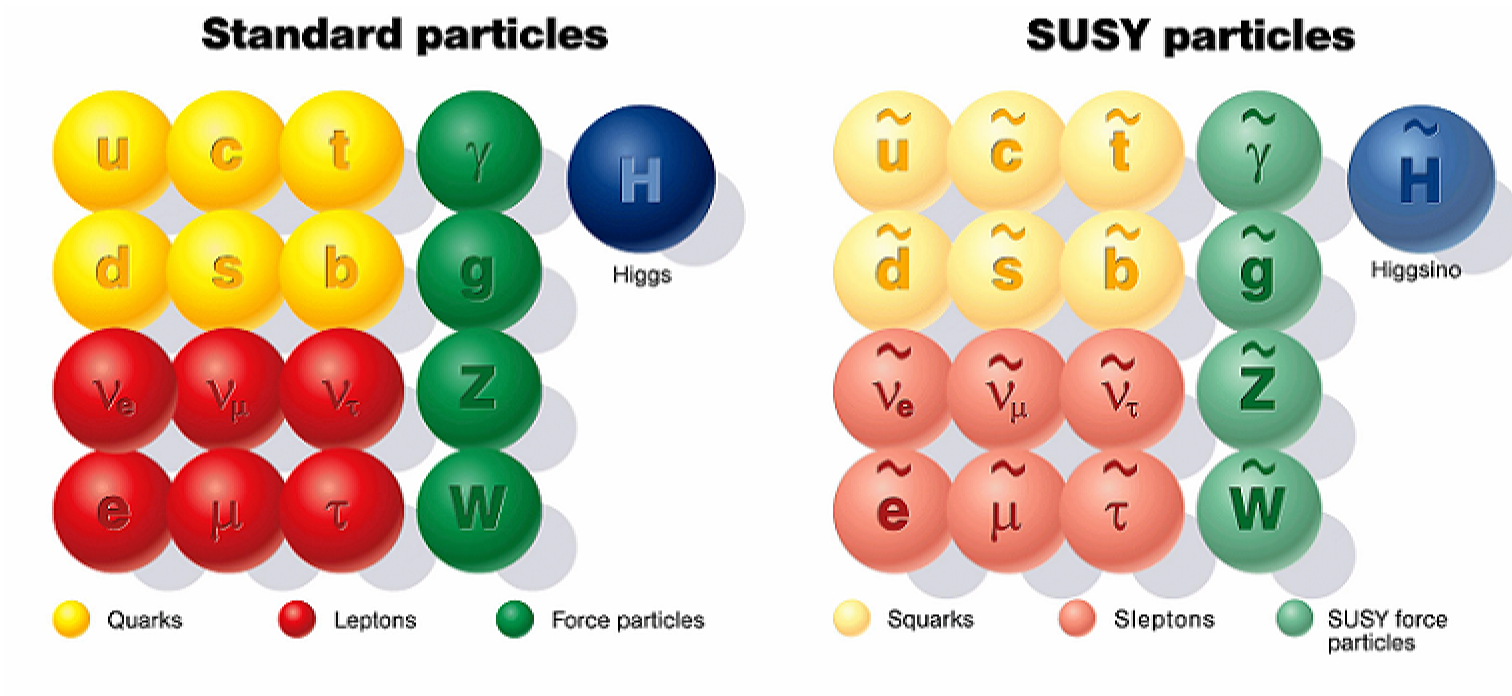


- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

(1) Arguments stolen from S. Heinemeyer (HH Higgs workshop 2014)

SUSY Extension of the SM

- Extension of SM by a last remaining, non-trivial, symmetry operation (boson ↔ fermion), SUSY, can cure many shortcomings of SM:



- E.g. lightest SUSY particle (LSP) perfect candidate for DM .

- **Problem:** SUSY itself is broken!

Higgs Sector in the MSSM

- Five neutral Higgs bosons predicted:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad Y_{H_1} = -1, \quad \mathrm{v}_1 : \mathrm{VEV}_1$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad Y_{H_2} = +1, \quad \mathrm{v}_2 : \mathrm{VEV}_2$$

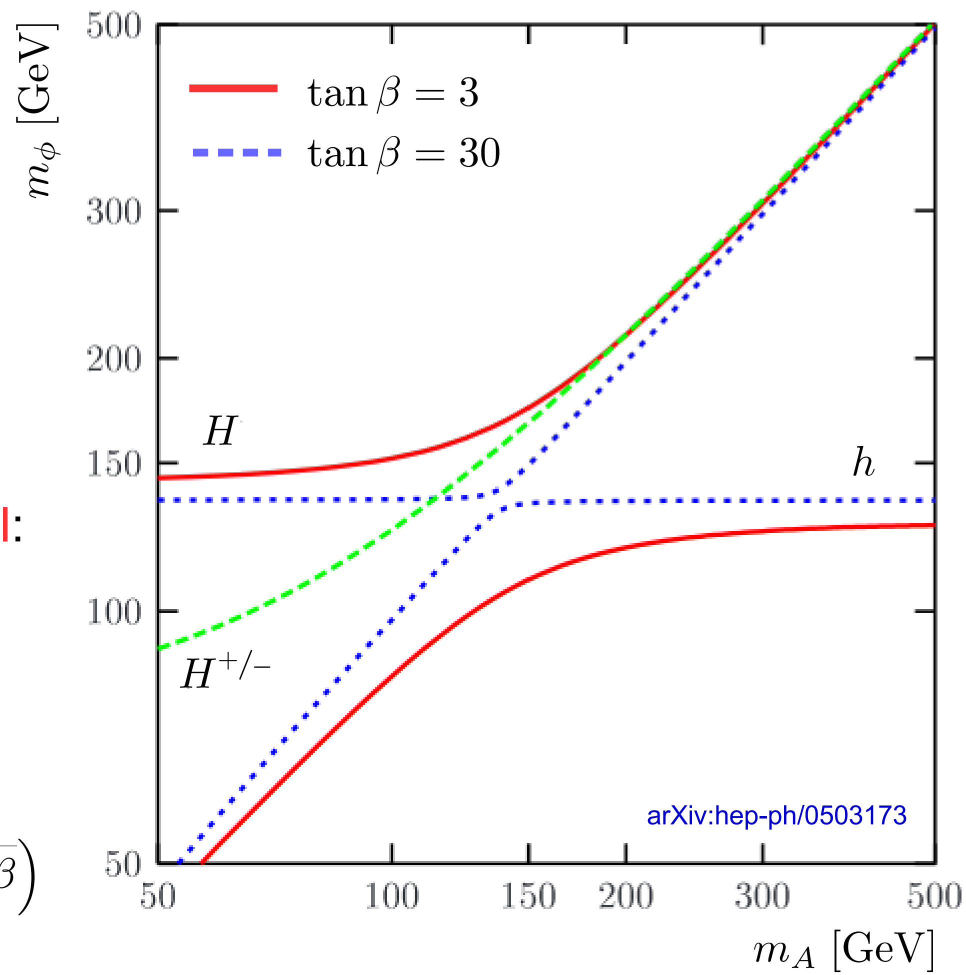
$$N_{\mathrm{ndof}} = 8 - \underbrace{3}_{W,\ Z} = \underbrace{5}_{H^{+/-},\ H,\ h,\ A}$$

- MSSM mass requirements at tree level:

two free parameters: m_A, $\tan\beta = \mathrm{v}_1/\mathrm{v}_2$

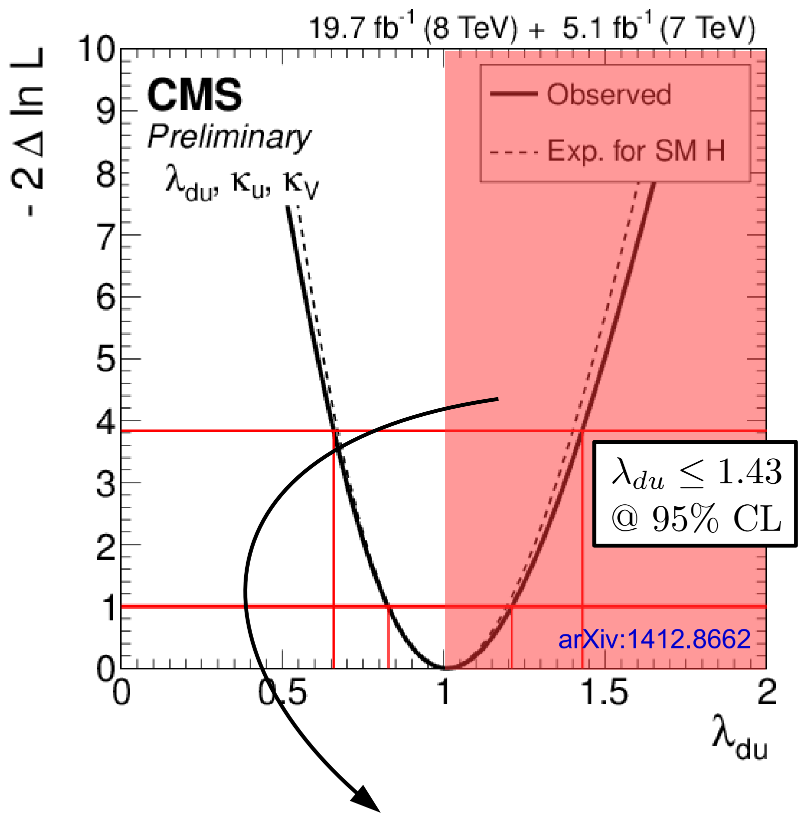
$$m^2_{H^{+/-}} = m_A^2 + m_W^2$$

$$m^2_{H,\,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 \pm 4_A^2 m_Z^2 \cos^2 2\beta}\right)$$



Enhancement of down-type Couplings

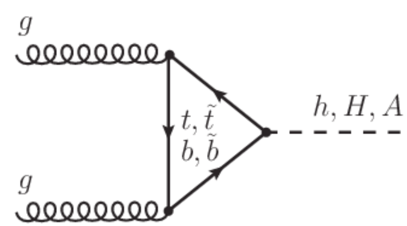
- In MSSM coupling to down-type fermions enhanced for $\tan\beta \gg 1$.



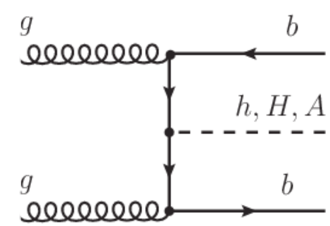
expect MSSM here!

- Interesting decay channels:
  - $H \rightarrow \tau\tau$ $\quad (\hat{\kappa}_\tau = 0.84\pm^{0.19}_{0.18})$
  - $H \rightarrow bb$ $\quad (\hat{\kappa}_b = 0.74\pm^{0.33}_{0.29})$

- Interesting production modes:



$gg \rightarrow H$ (“$gg\phi$”)

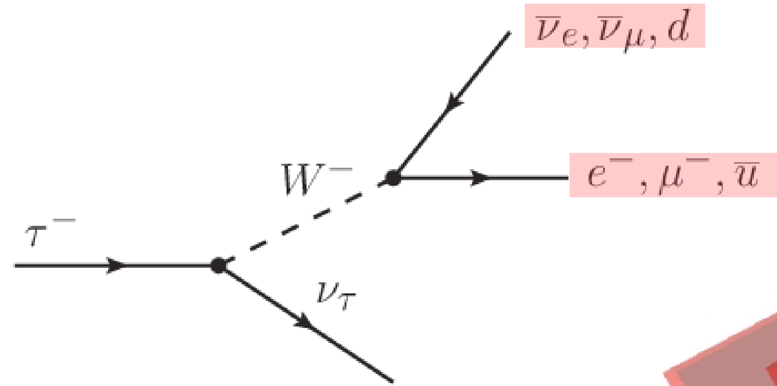


$gg \rightarrow Hb\bar{b}$ (“$bb\phi$”)

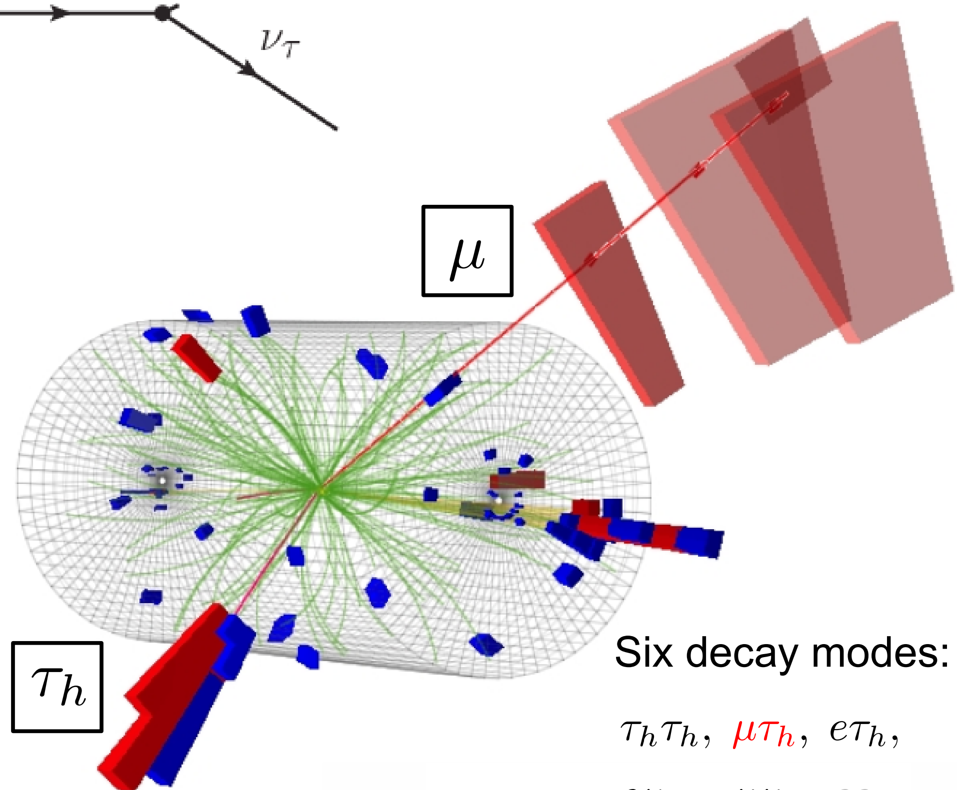
Search for $A/H/h \to \tau\tau$

Decay Mode	BR
$\tau \to e\nu_e\nu_\tau$	17.83%
$\tau \to \mu\nu_\mu\nu_\tau$	17.41%
$\tau \to$ 1-prong ν_τ	37.10%
$\tau \to$ 3-prong ν_τ	15.20%

$> 50\%$ of all decay modes.



- Search for 2 isolated high p_T leptons (e , μ , τ_h).
- Reduce obvious backgrounds (use on $\not{E}_T$) & reconstruct $m_{\tau\tau}$.
- Exploit characteristics of production mode to increase sensitivity.



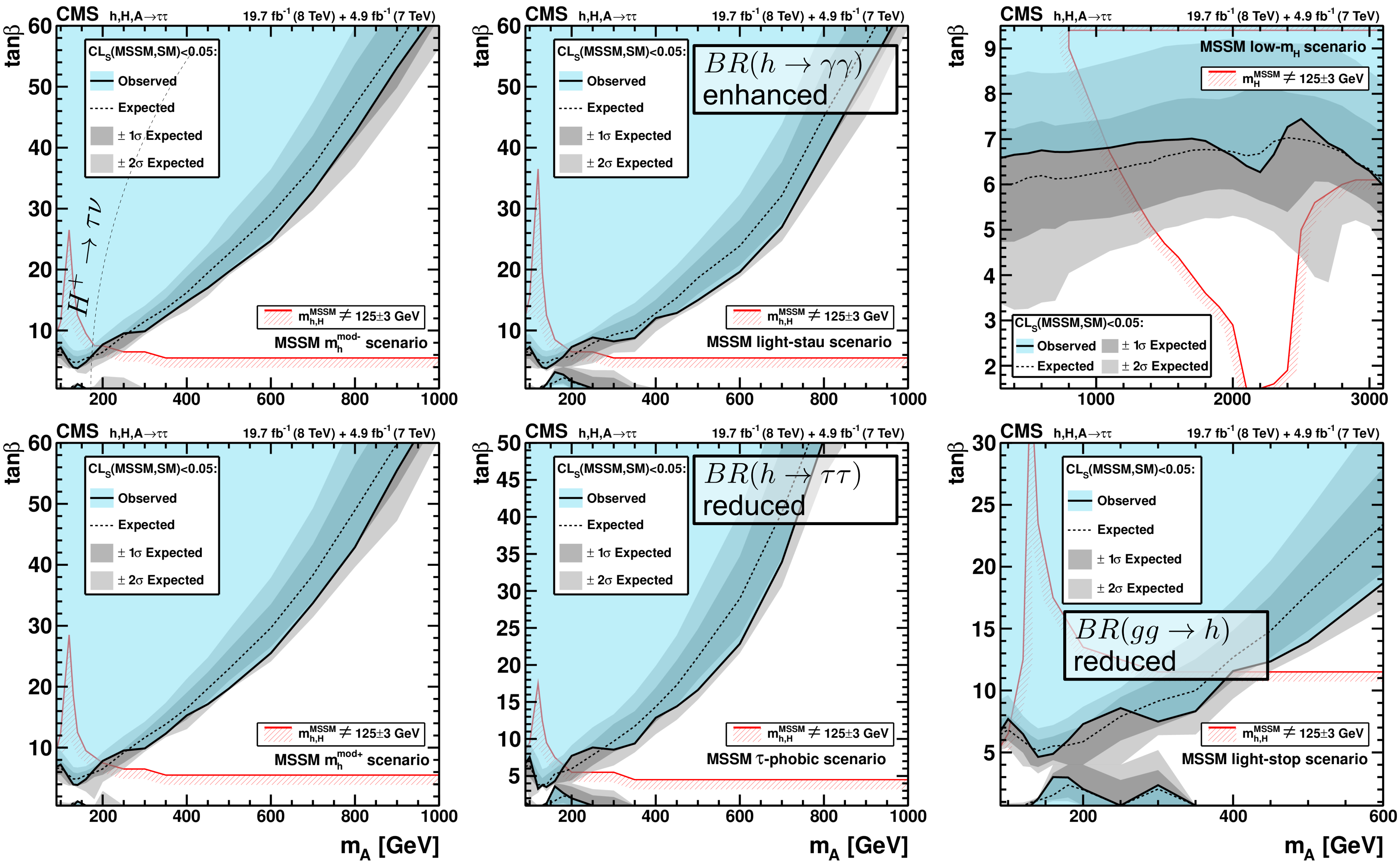
arXiv:1408.3316

Six decay modes:

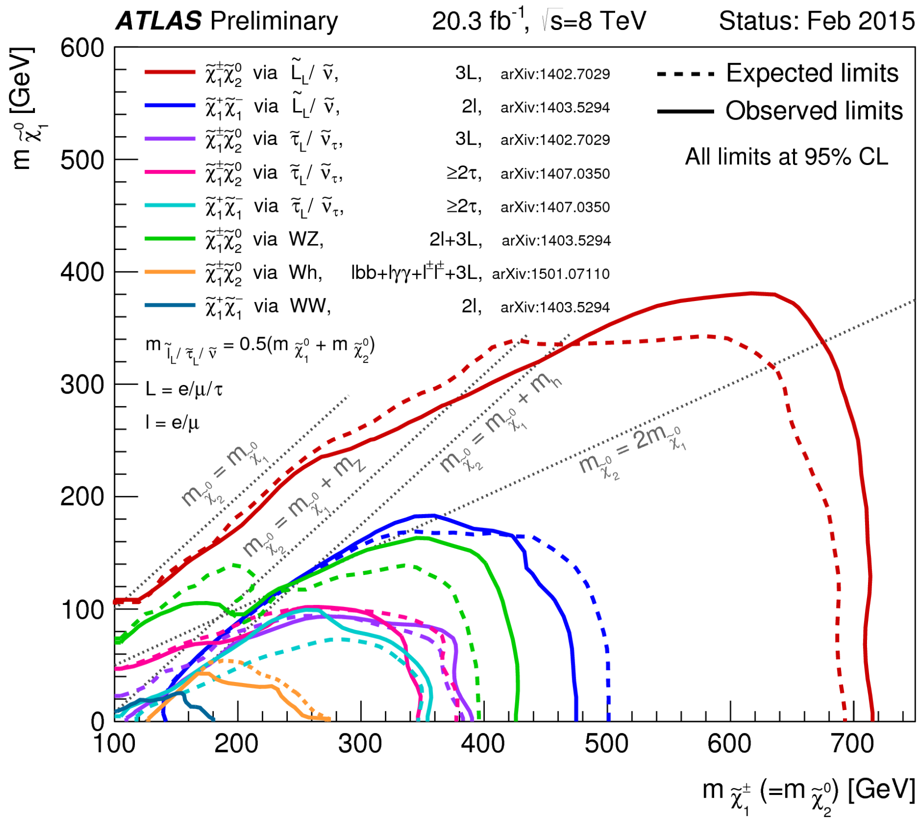
$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,
$e\mu$, $\mu\mu$, ee

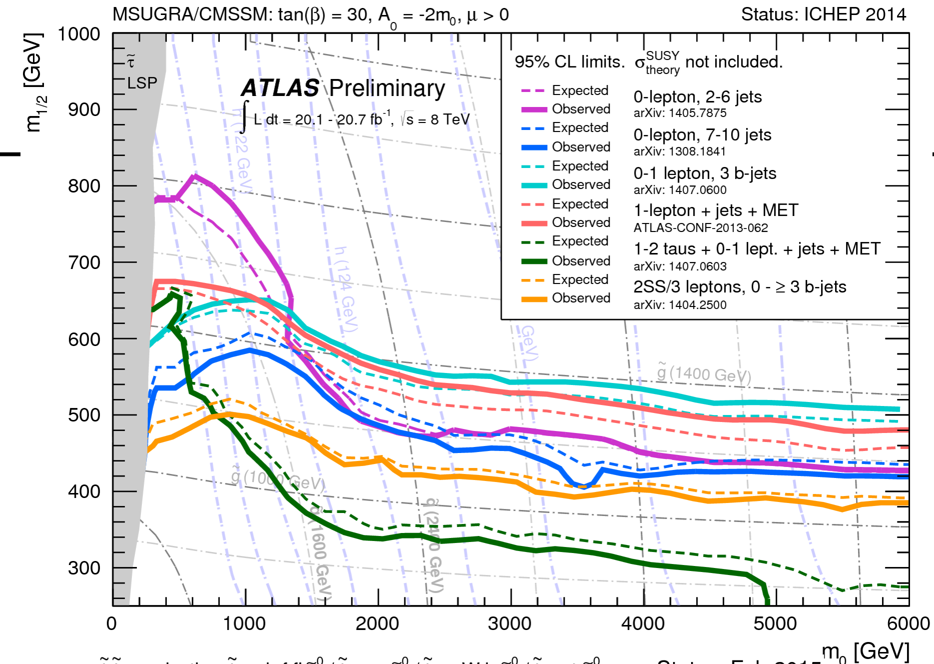
Complete Set of Benchmark Scenarios

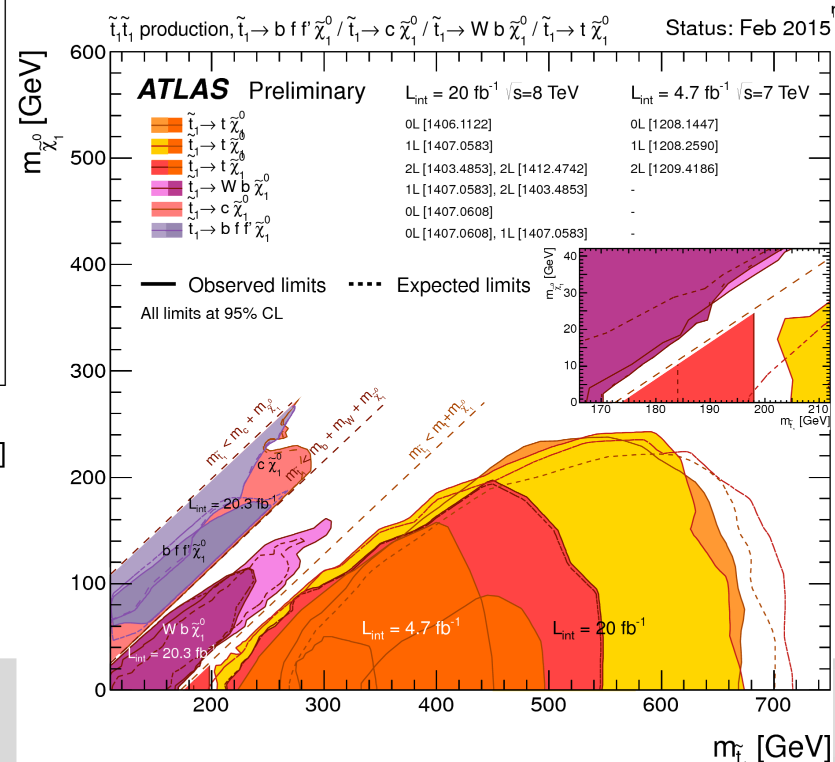
arXiv:1302.7033



More Searches for SUSY...







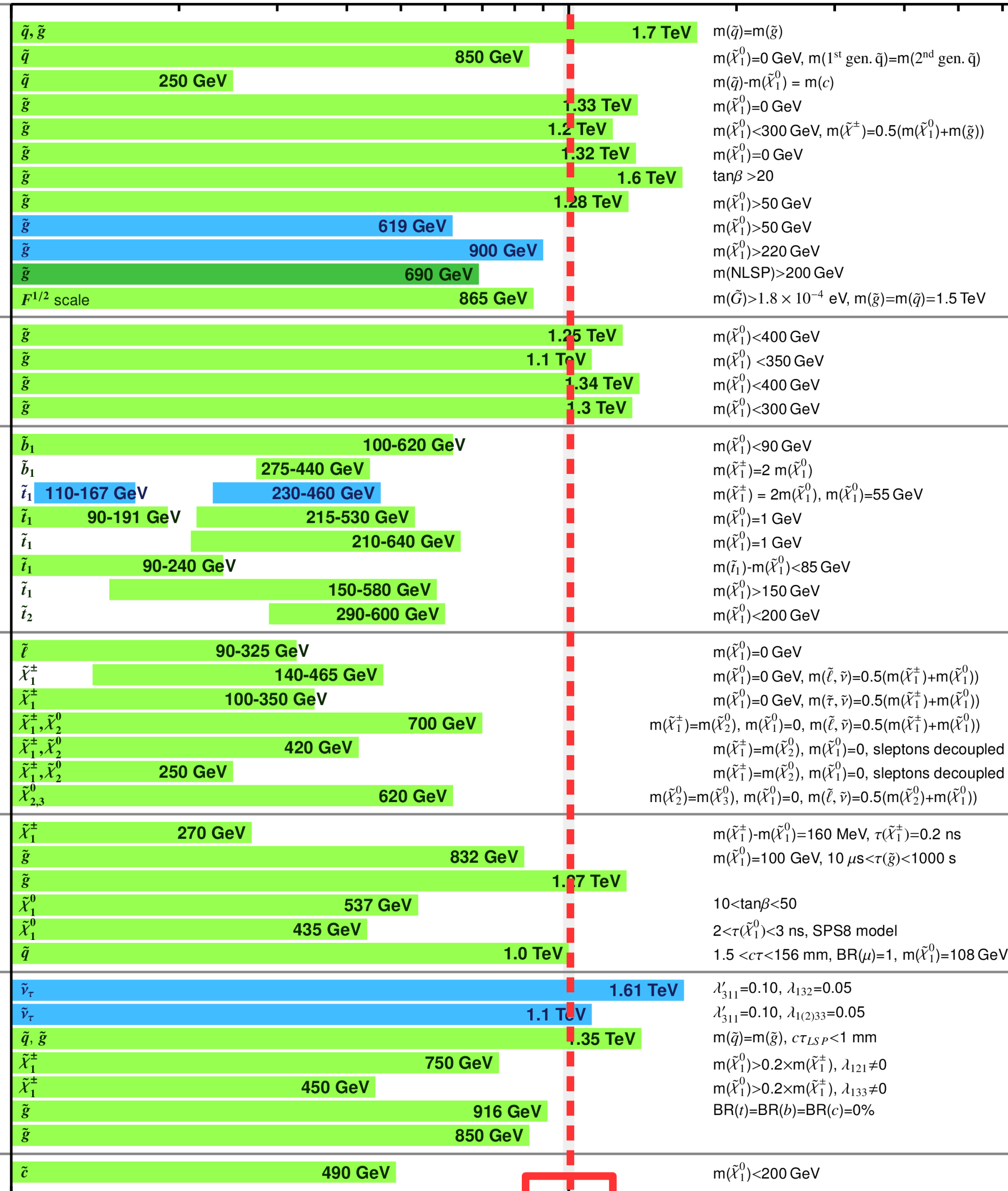
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

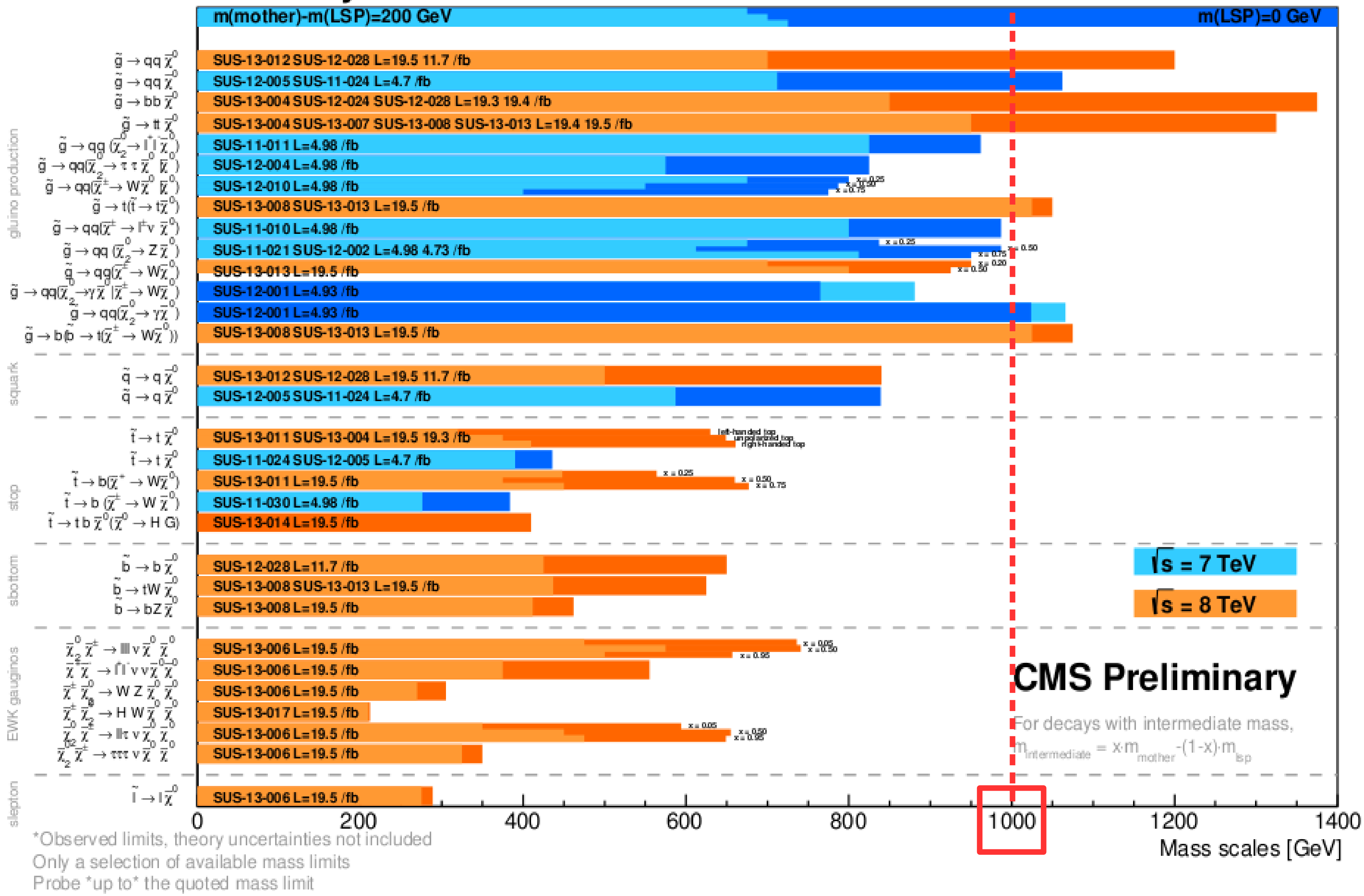
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV; 230-460 GeV	$m(\tilde{\chi}_1^\pm)$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV; 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu s<\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

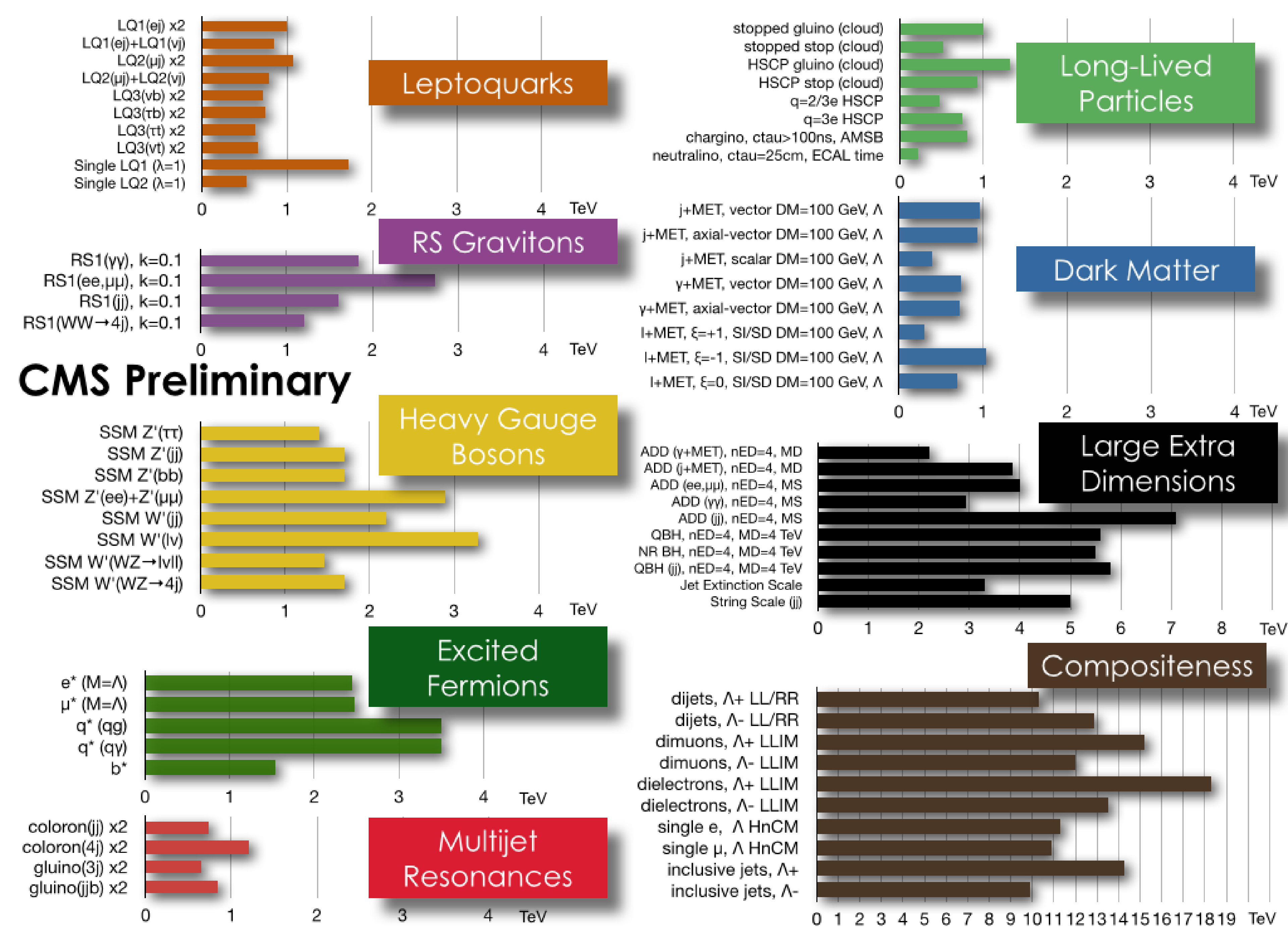


$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Summary of CMS SUSY Results* in SMS framework SUSY 2013



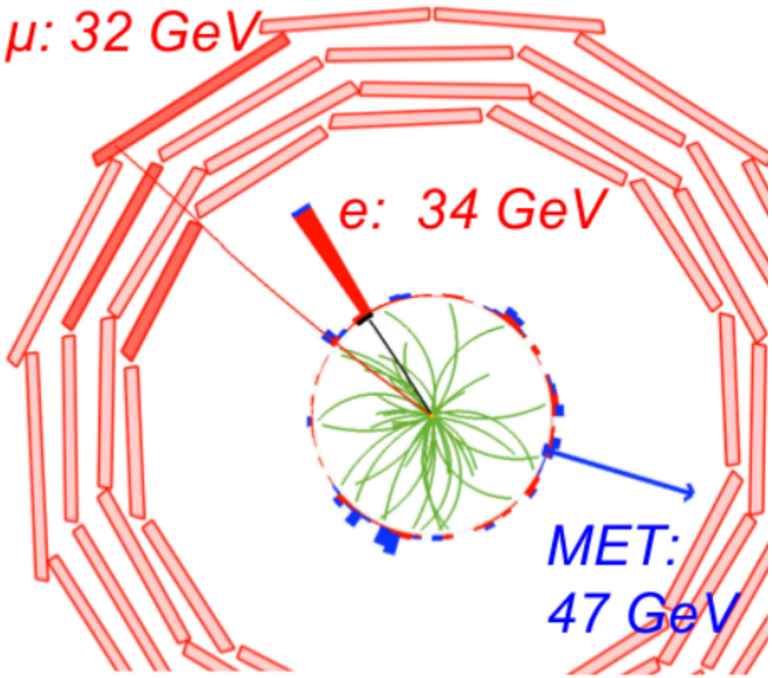

CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
0 1 2 3 4 TeV
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 TeV
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 1 2 3 4 5 6 7 8 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV

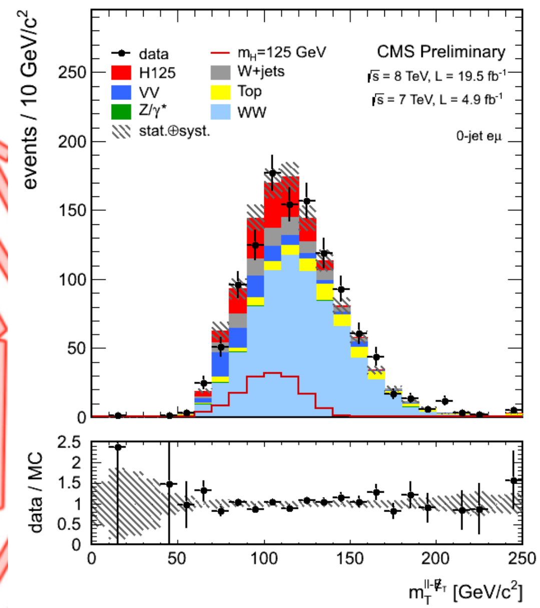
Conclusions

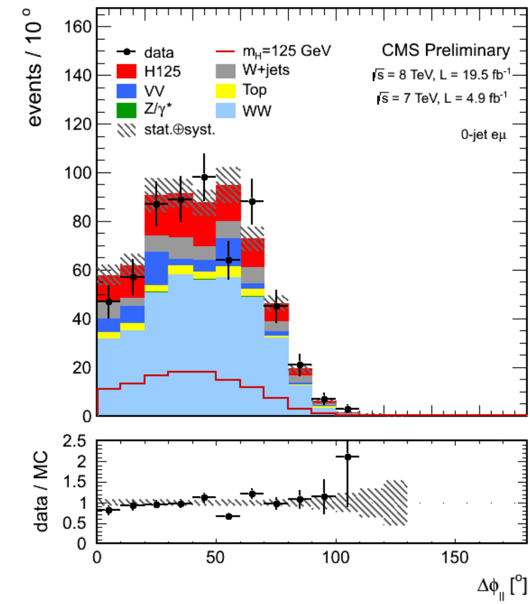
- The SM is one of the **best theories that mankind has ever come up with** so far.
- The LHC has widely **opened the door to the Terascale**. This is where we expect the new physics to set in!
- It has brought the **discovery of a Higgs boson thus the completion the SM**! Spontaneous symmetry breaking is not a trick nor a back door solution, it is reality!
- It is clear that **we have to account for physics beyond the SM**. Where is it? Good arguments that LHC run-II has a good chance to bring it.
- If so the LHC will bring us the **best times ever for particle physics!**

Backup

$H \to WW$ Decay Channel

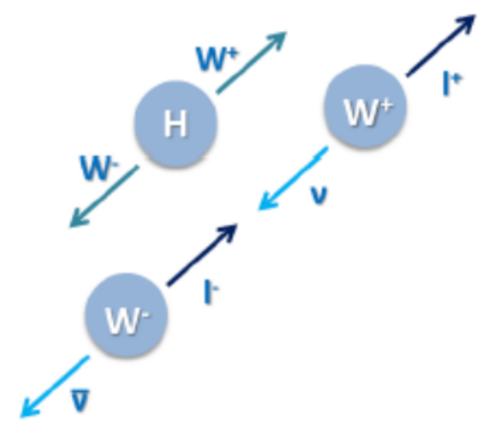




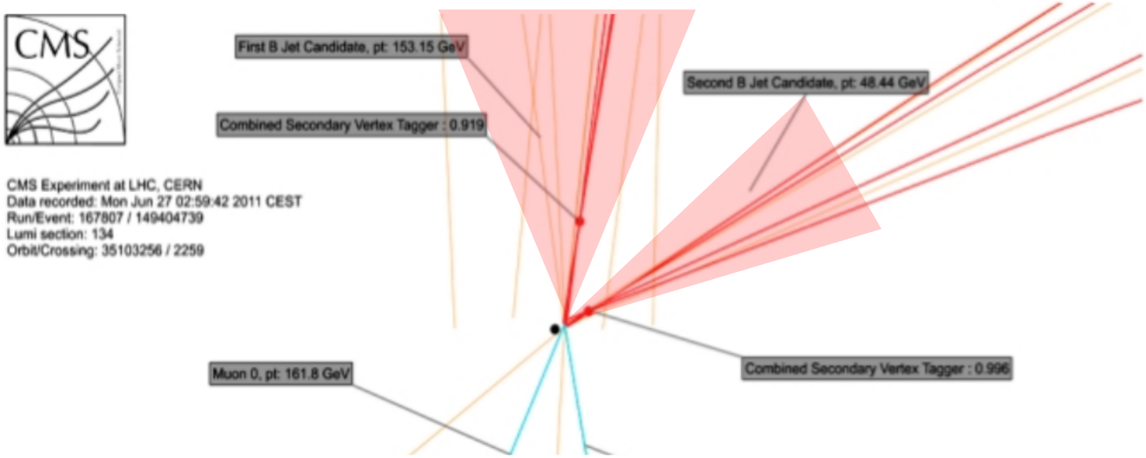


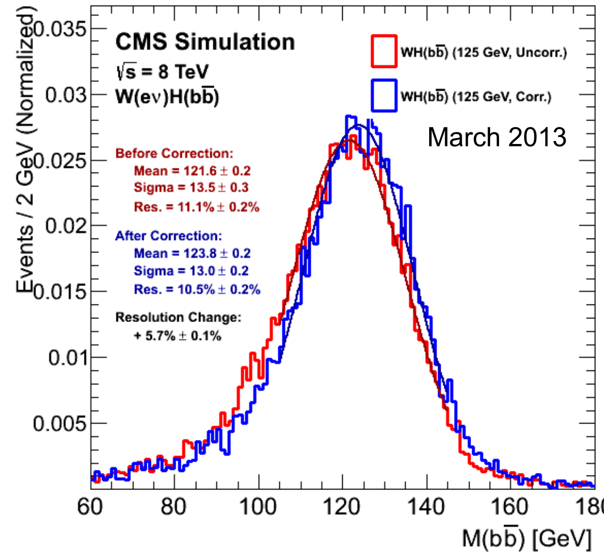
- High discovery potential, but bad mass resolution.

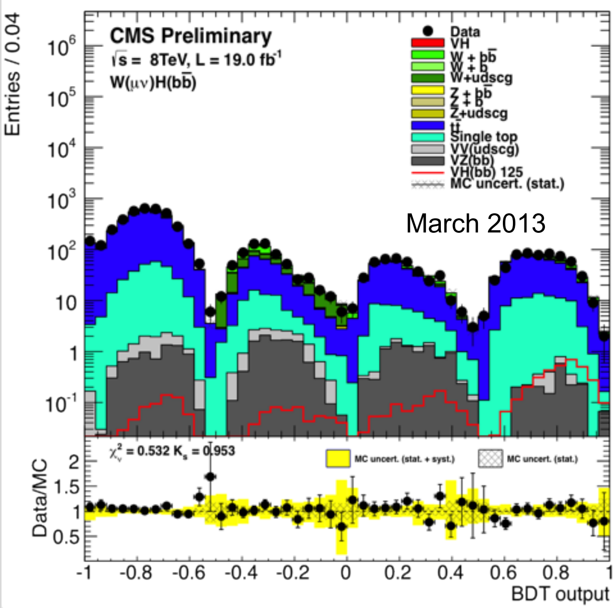
ff	0-jet	1-jet	2-jet(VBF)
ff'	0-jet	1-jet	2-jet(VBF)

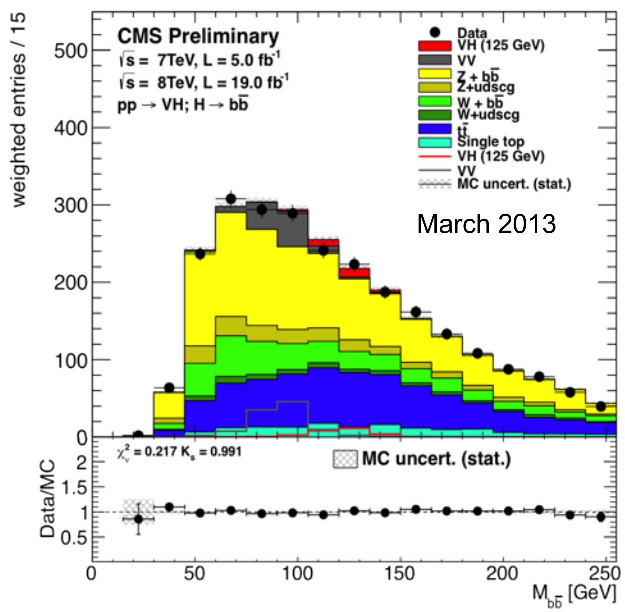


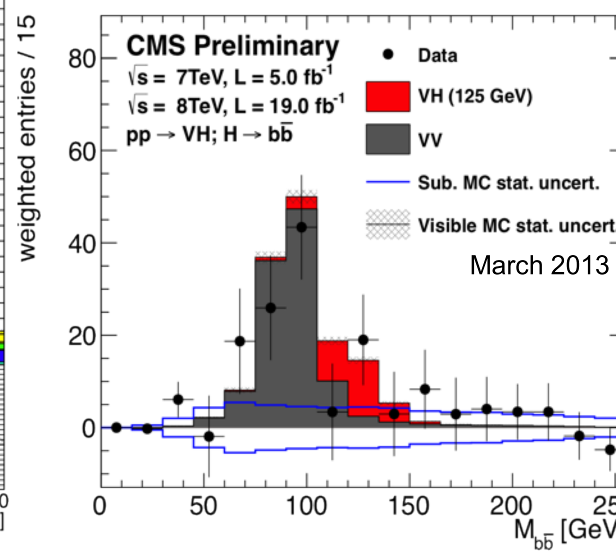
$H \to bb$ Decay Channel



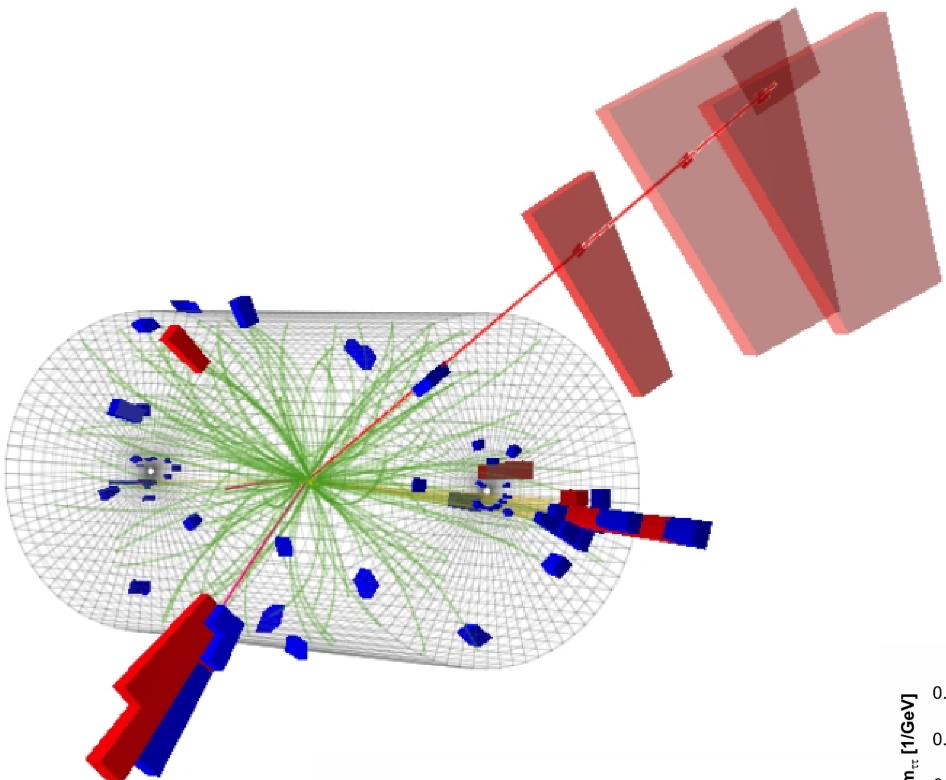


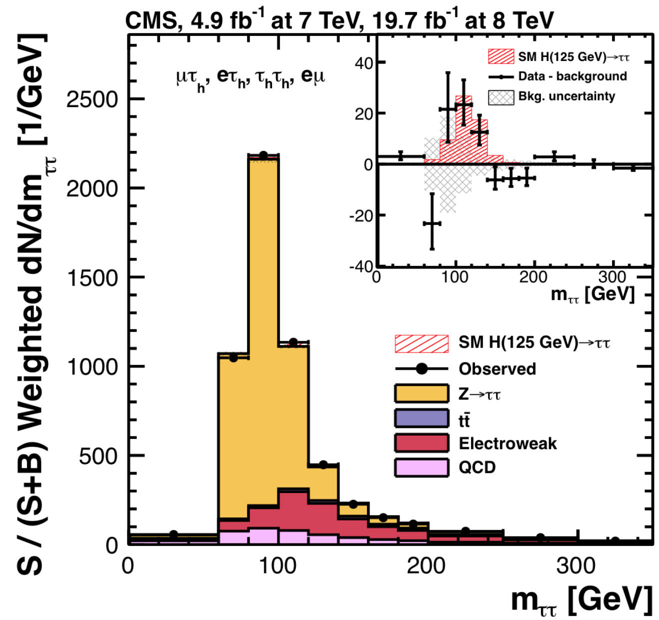




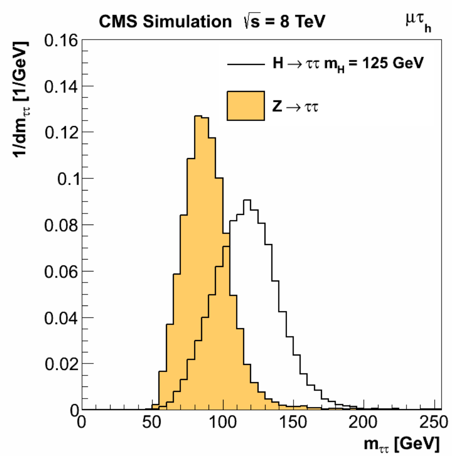


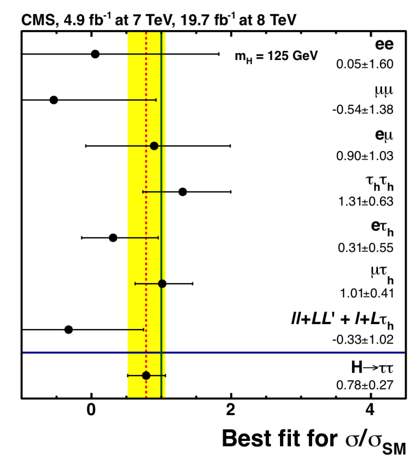
$H \to \tau\tau$ Decay Channel





- $m_{\tau\tau}$ as main discriminating variable.
- Separation between irreducible $Z \to \tau\tau$ background and $H \to \tau\tau$ signal.

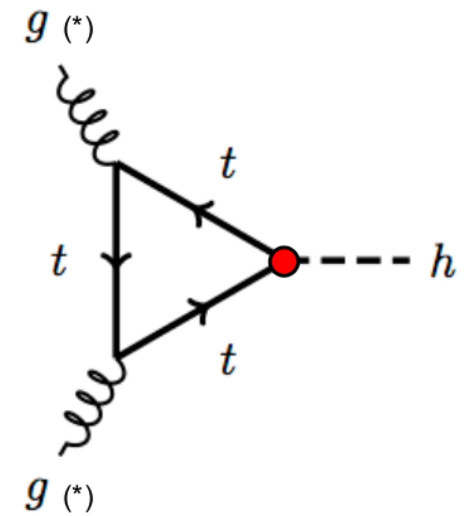




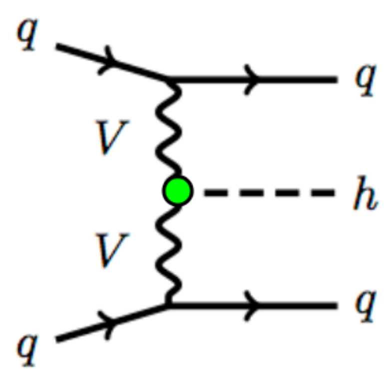
Coupling Estimates

- Determine couplings from production mode and decay channel:

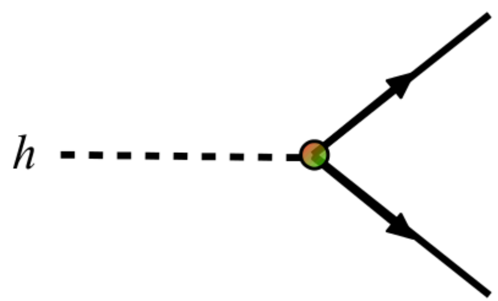
$gg \to H$ production:



$qq \to qqH$ production:



Decay to f or V:



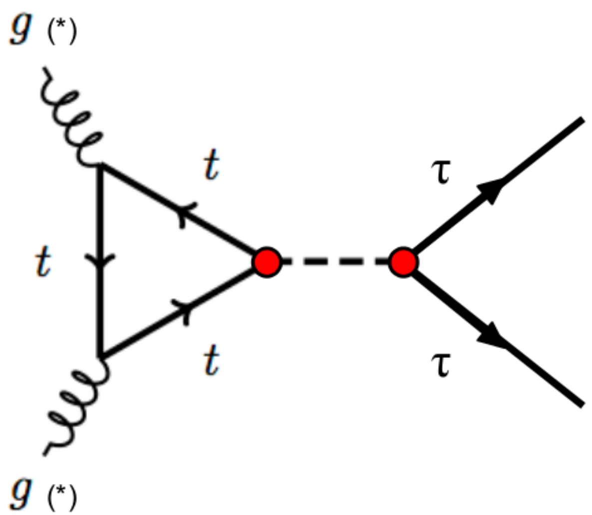
- (red) f : $\kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}}$
- (green) V : $\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

- Coupling to gluon can be f or effective (*).
- Coupling to γ can be effective or a mixture of $f + V$.

- Direct measurement not possible since κ_i appear in nominator and denominator of $\mathrm{BR}_i = \frac{\kappa_i}{\Gamma_h} = \frac{\kappa_i}{\sum \kappa}$

Narrow Width Approximation

- Assume $\Gamma_H \ll m_H$, which is well justified by $\Gamma_H = 4.04\ \mathrm{MeV}$ and $m_H = 125\ \mathrm{GeV}$.
- Propagator: $\frac{1}{(q^2 - m^2 + m^2\Gamma^2)} \rightarrow \frac{\pi}{m\Gamma}\delta(q^2 - m^2)$ for $\Gamma \rightarrow 0$.



- i.e. put propagating particle on shell.
- Calculate cross section as $\sigma \times \mathrm{BR}$.
- $\mathrm{BR}_X = \frac{\Gamma_X}{\Gamma_H}, \quad \Gamma_H = \sum_i \Gamma_i$.
- $\sigma \propto (\kappa_t \kappa_\tau)^2 \propto (\kappa_u \kappa_d)^2 \propto (\kappa_q \kappa_f)^2 \propto (\kappa_g \kappa_f)^2$.

- For each production mode and decay channel collect κ_i and express Γ_H as sum of individual κ_i .