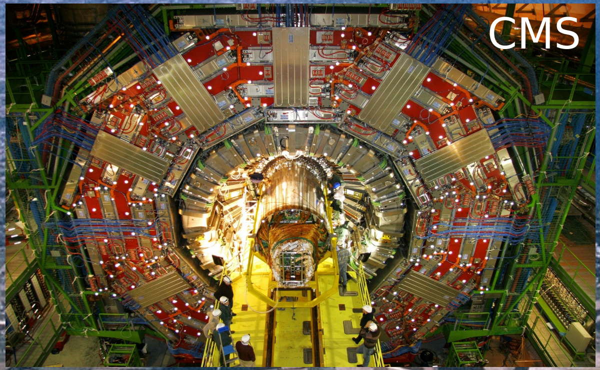


LHC Run-1 [2010–2013]: 3 years of physics with CMS

Seminari IFAE, Univ. Autònoma Barcelona

3rd March 2014

David d'Enterria (CERN)

Standard Model of particles & interactions

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$ [Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$$ [Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$ [Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$$ [Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ [Higgs dynamics & mass]

- Gauge-fermion dynamics via covariant derivatives:

$$D_\mu\begin{pmatrix}\nu_L \\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L \\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L \\ d_L\end{pmatrix},$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

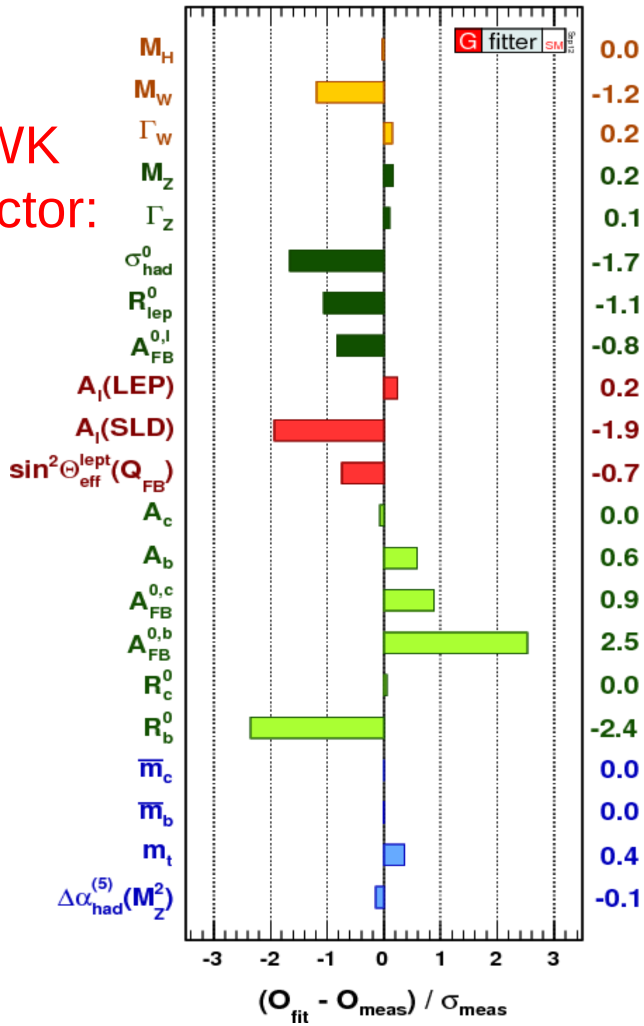
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

O(20) parameters: gauge couplings, H mass&vev, H-f Yukawa coupl., CKM mix., CP phases

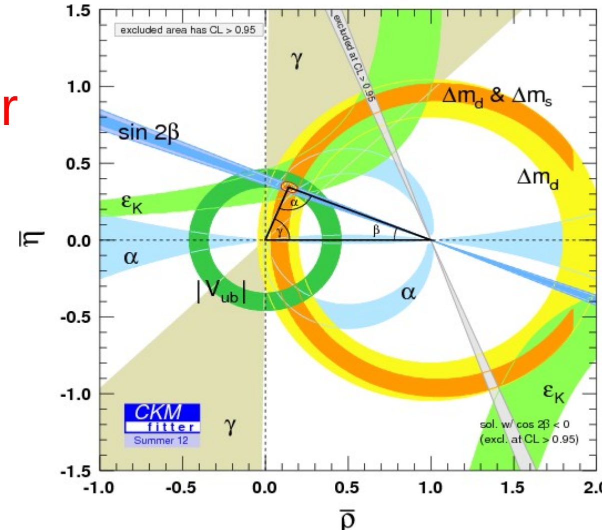
Standard Model of particles & interactions

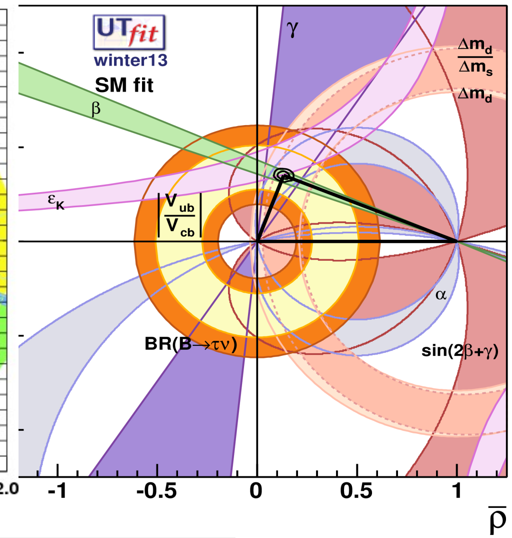
- SM: Renormalizable QFT whose internal consistence & predictive power have been experimentally confirmed to great precision:

EWK sector:

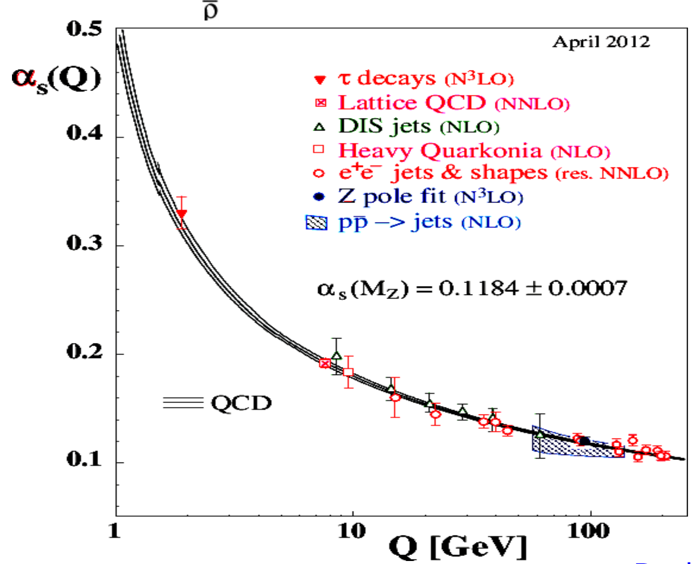


Flavour sector:





QCD sector:



"Issues" with the Standard Model (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$ [Lepton dynamics]

$$\boxed{-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]}$$ [Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$ [Quark dynamics]

$$\boxed{-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]}$$ [Quark masses]

$$\boxed{+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.}$$ [Higgs dynamics & mass]

✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)

“Issues” with the Standard Model (2)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

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[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[\boxed{(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}}\right] - \frac{\sqrt{2}}{v}\left[\boxed{(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\mathrm{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[\boxed{(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}}\right] - \frac{\sqrt{2}}{v}\left[\boxed{(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dynamics & mass]

- ✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)
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“Issues” with the Standard Model (3)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu i D_\mu e_R + \bar{\nu}_R \sigma^\mu i D_\mu \nu_R + (\text{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dyn. & mass]

+ new particles/symmetries ?

- ✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)
- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✘ Fine-tuning: Higgs mass virtual corrections «uncontrolled» up to Planck scale

“Issues” with the Standard Model (4)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$ [Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$ [Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$ [Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$ [Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ [Higgs dyn. & mass]

+ new particles/symmetries ?

- ✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)
- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✘ Fine-tuning: Higgs mass virtual corrections «uncontrolled» up to Planck scale
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✘ Others: ν's masses, gauge-gravity unification, cosmological constant, dark energy,...

Goals of the Large Hadron Collider

- Solve 6 basic open questions in HEP with 7 experiments:

1. Mass generation problem: What is the origin of the SM elementary particle masses ? Higgs boson ? other mechanism ?

2. Hierarchy / fine-tuning problem: What stabilizes m_{Higgs} up to m_{Planck} (10^{16} orders-of-magnitude!?) ? SUSY ? extra-D ? ... ?

3. Dark matter problem: ~1/4 universe = invisible matter. SUSY ? Other particles ?

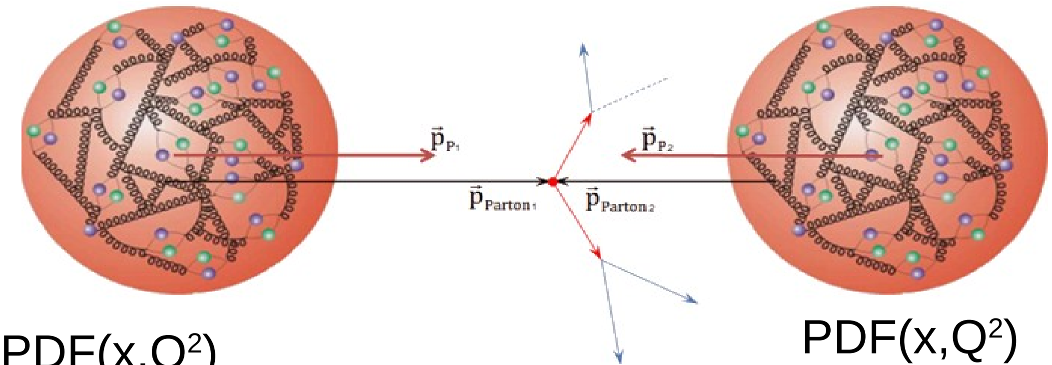
4. Flavour problem: Origin of matter-antimatter asymmetry in the Universe ? Why so many types of matter particles ?

5. QCD in non-perturbative regime: Why quark confinement ? Total hadronic x-sections ? Gauge-String duality (AdS/CFT) ?

6. Highest-energy cosmic-rays: Nature of CRs at 10^{20} eV ?

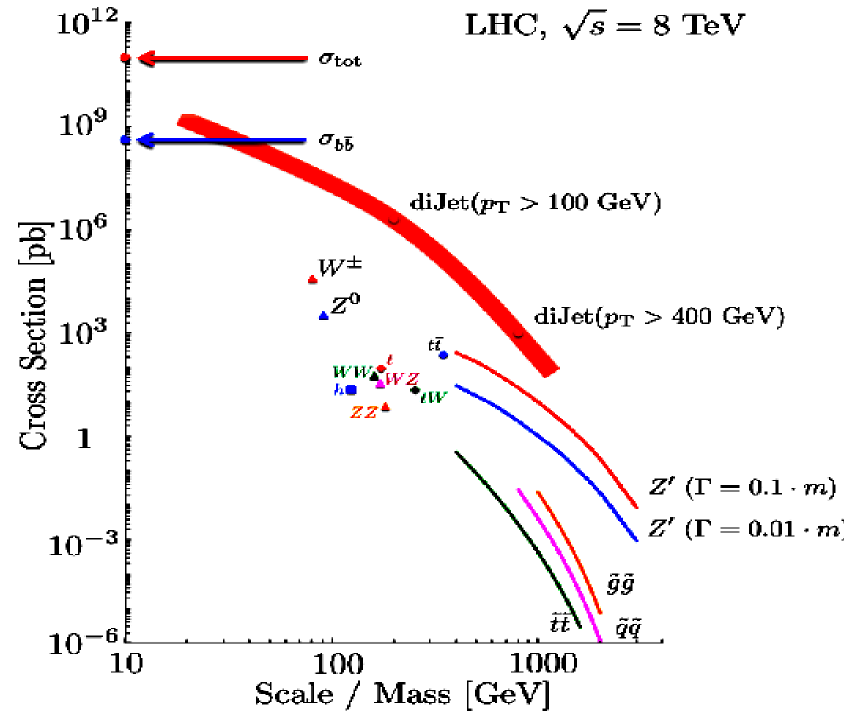
Tools: high-energy proton & ion collisions

proton proton

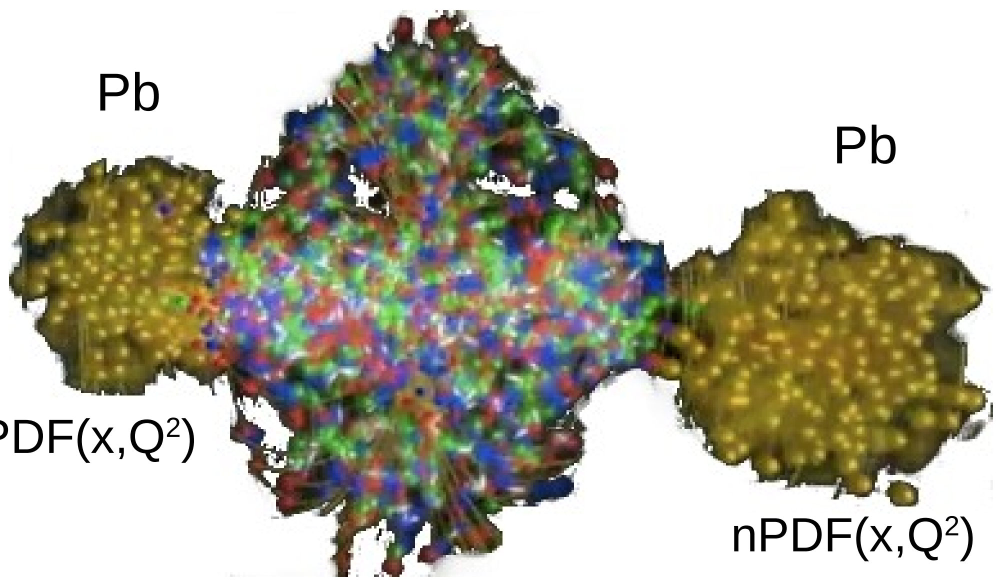


PDF(x,Q²) PDF(x,Q²)

SM & new particles

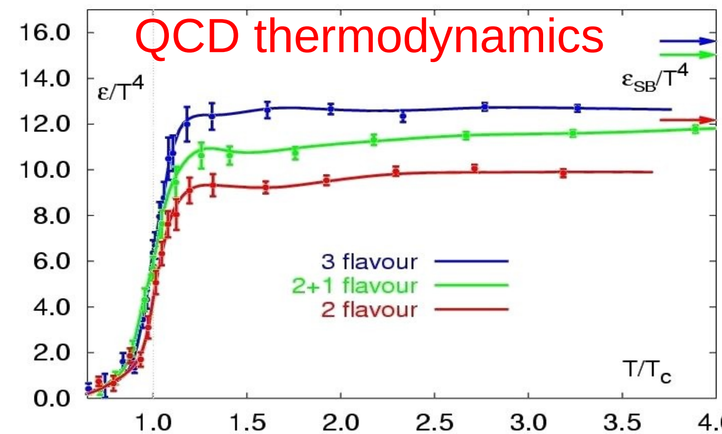


Pb Pb



nPDF(x,Q²) nPDF(x,Q²)

Quark-gluon plasma



CMS: the detector

Total weight 14000 t
Diameter 15 m
Length 28.7 m

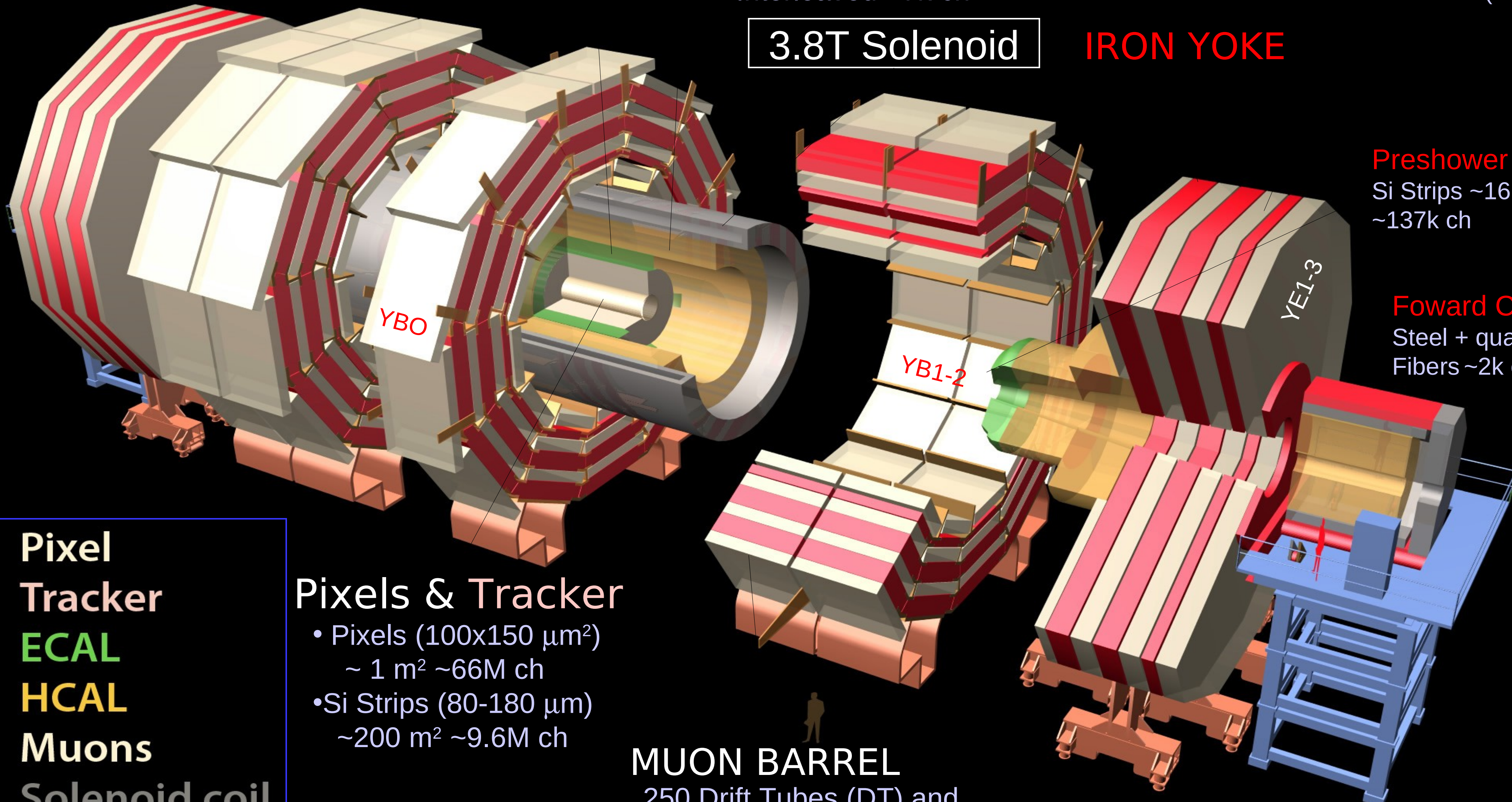
ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE



Preshower
Si Strips ~16 m^2
~137k ch

Foward Cal
Steel + quartz
Fibers ~2k ch

- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

Pixels & Tracker

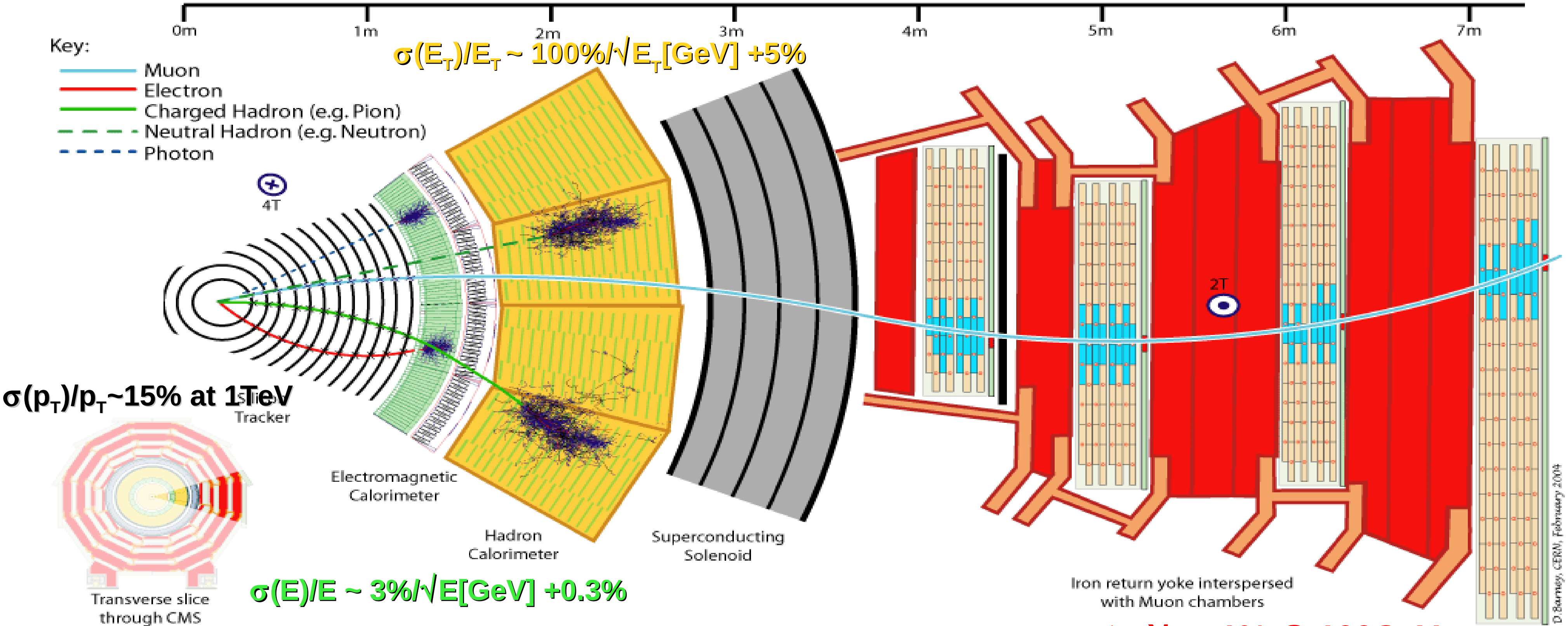
- Pixels (100x150 μm^2) ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm) ~200 m^2 ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CMS: the people

~3300 scientists & engineers (including ~900 students)
from 193 institutes in 40 countries

CMS: the physics objects



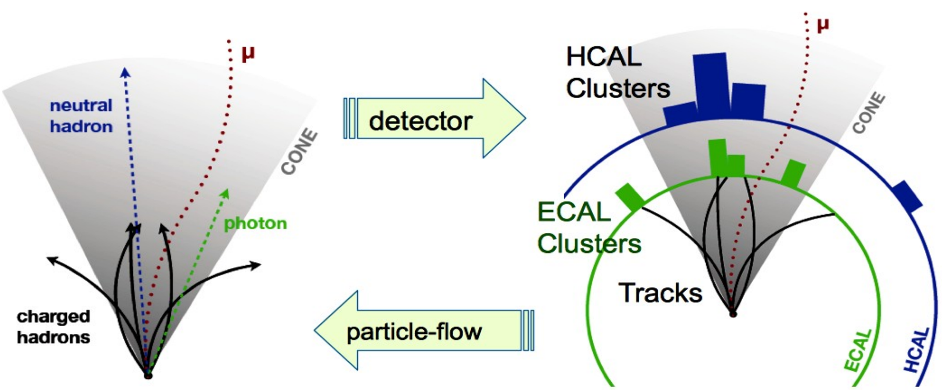
$\sigma(E_T)/E_T \sim 100\%/\sqrt{E_T[\mathrm{GeV}]} + 5\%$

$\sigma(p_T)/p_T \sim 15\%$ at 1TeV

$\sigma(E)/E \sim 3\%/\sqrt{E[\mathrm{GeV}]} + 0.3\%$

$\sigma(p_T)/p_T < 1\%$ @ 100GeV

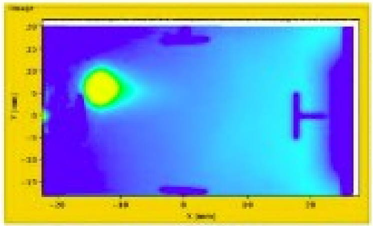
$\sigma(p_T)/p_T < 10\%$ @1 TeV



Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for:
jets, b-jets, taus, ν (miss. E_T), isolation

LHC Run-1: March 2010 – Feb. 2013

August 2008
First injection test



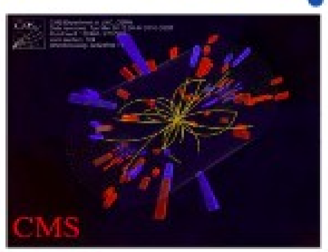
Sept. 10, 2008
First beams around

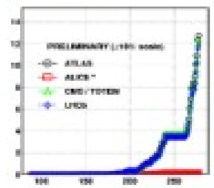
Sept. 19, 2008
Incident

Repair and Consolidation

November 29, 2009
Beam back

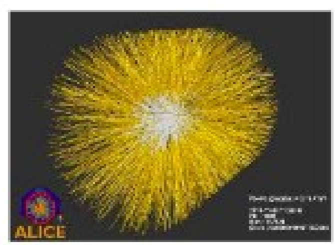
March 30, 2010
First collisions at 3.5 TeV



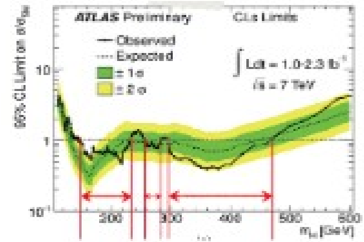


October 14, 2010
L= $1\times10^{+32}$
248 bunches

November 2010
Pb^{82+} Ions



June 28 2011
1380 bunches

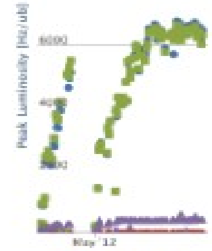


October, 2011
$3.5\times10^{+33}$, 5.7 fb^{-1}

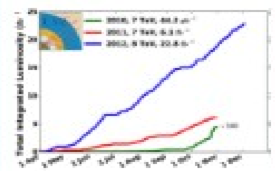
First Hints!!

November 2011
Second Ion Run

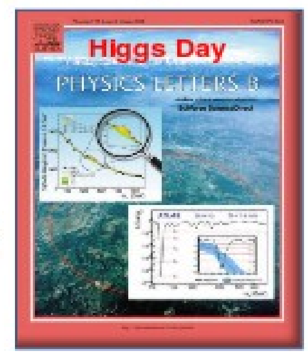
March 14th 2012
Restart
with Beam

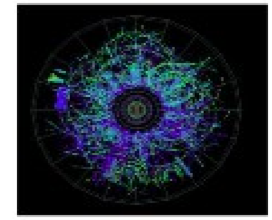


May 2012
Ramping
Performance



Nov. 2012
End of p^+ Run 1



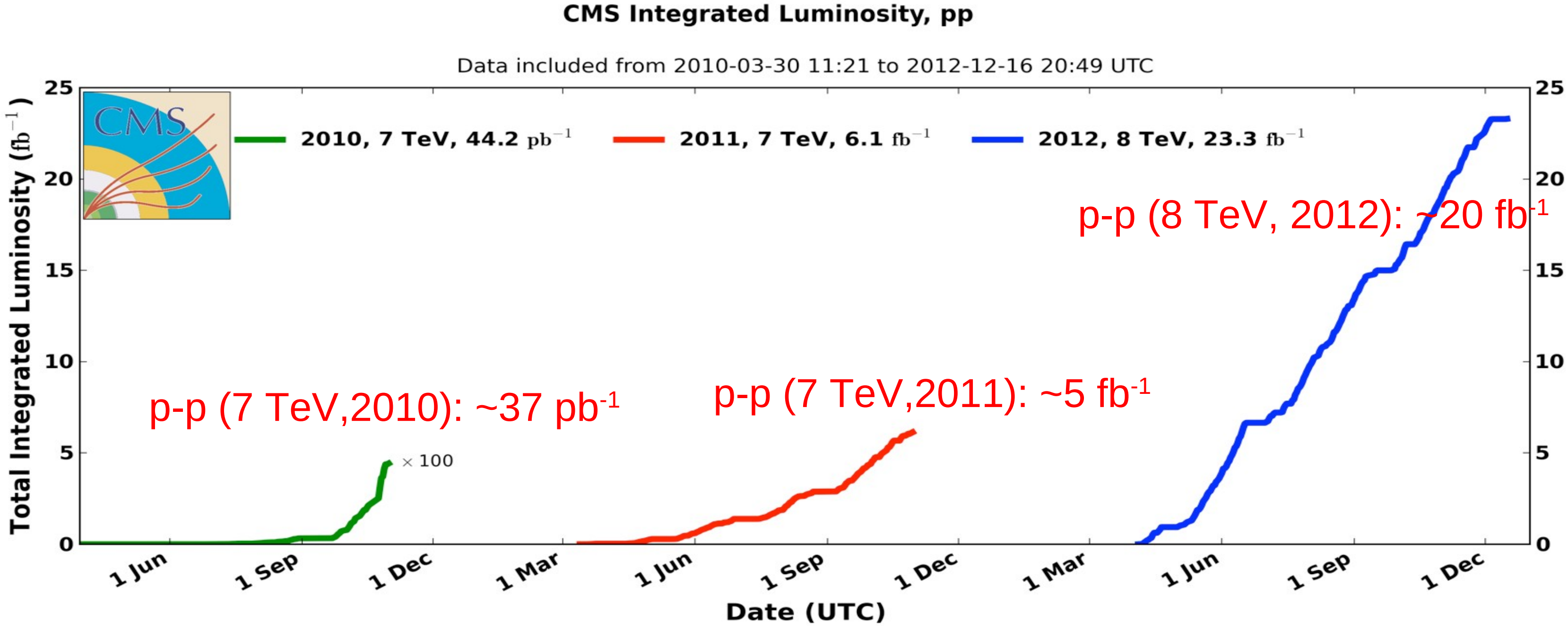


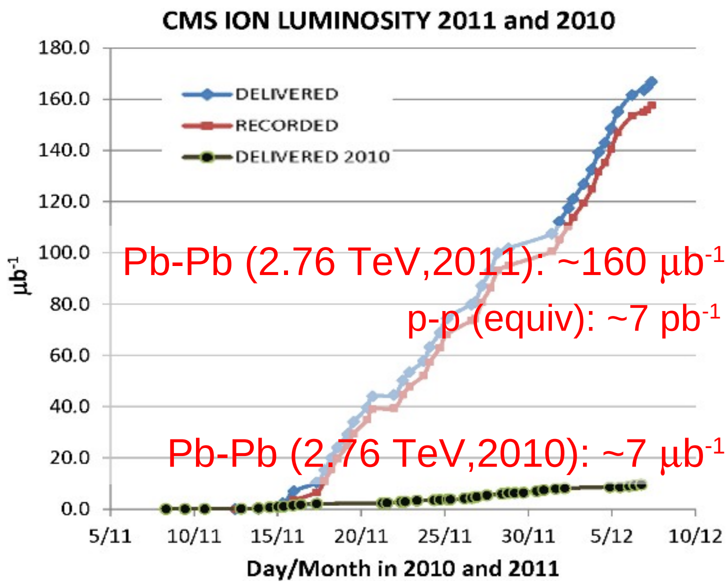
Feb. 2013
$p\text{-}Pb^{82+}$
New Operation
Mode

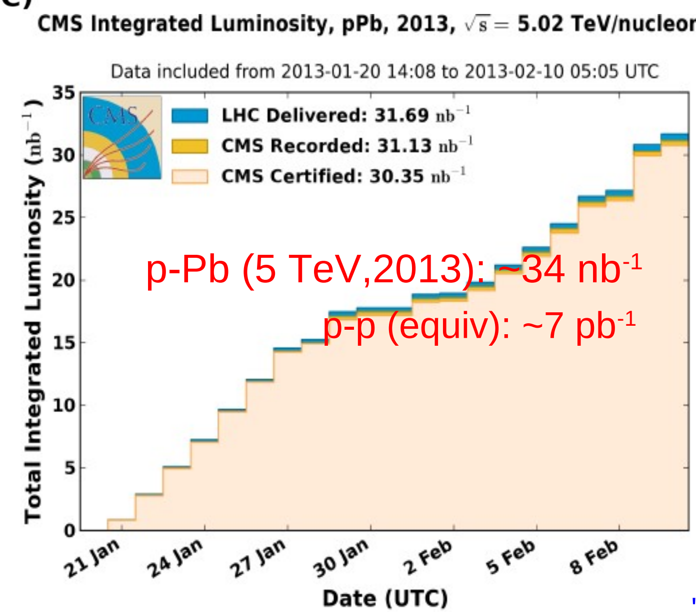
LS1

2008 | 2009 | 2010 | 2011 | 2012 | 2013

CMS: integrated luminosities (2010-13)

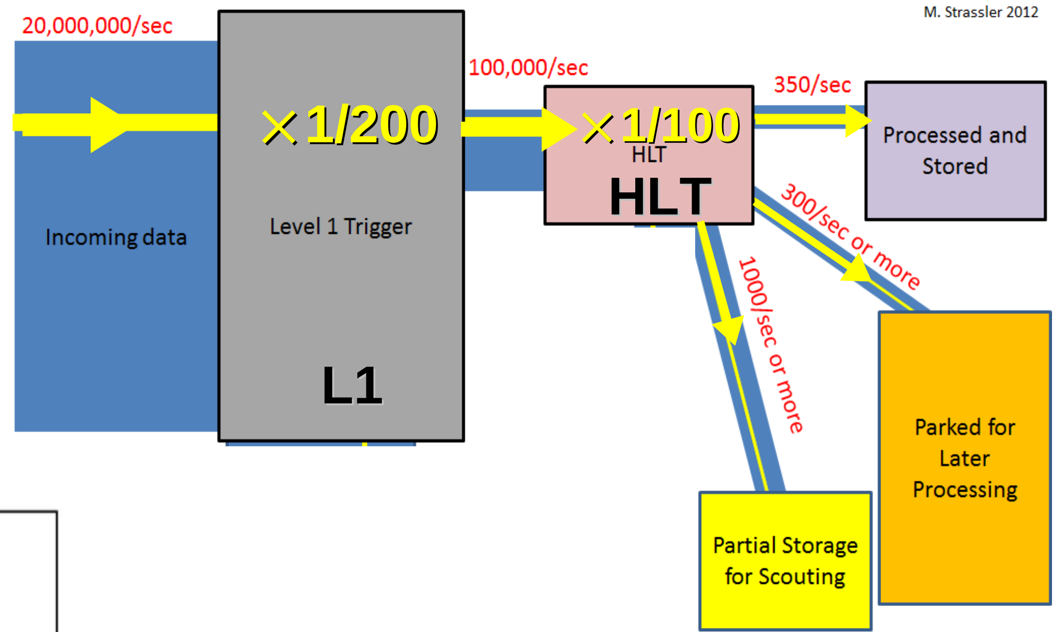


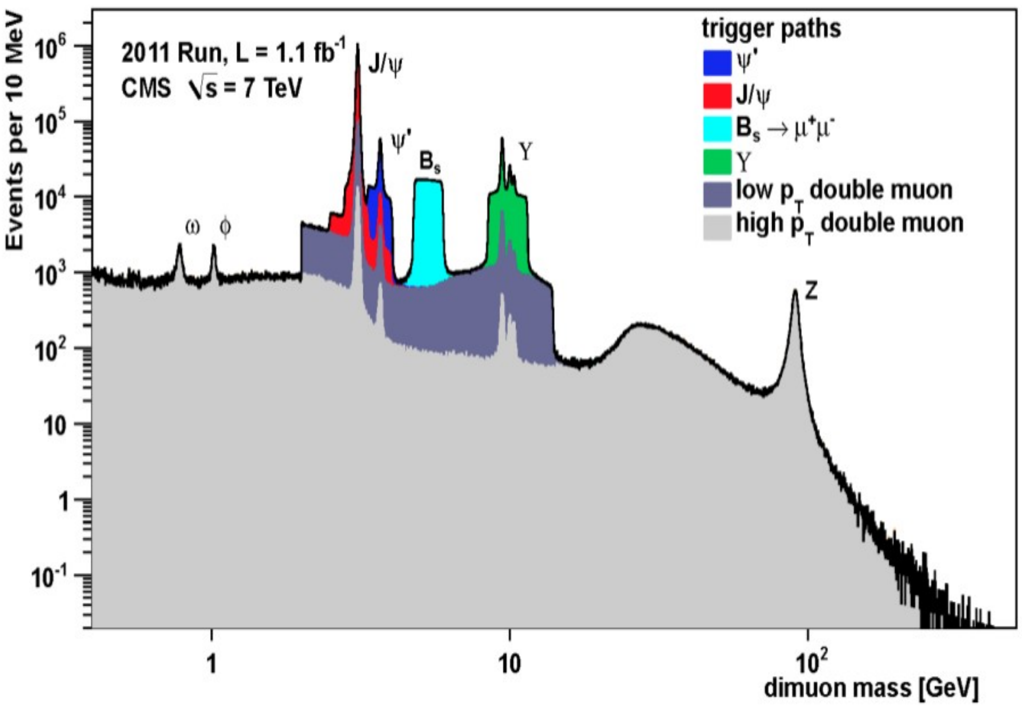




CMS: L1 & high-level triggers

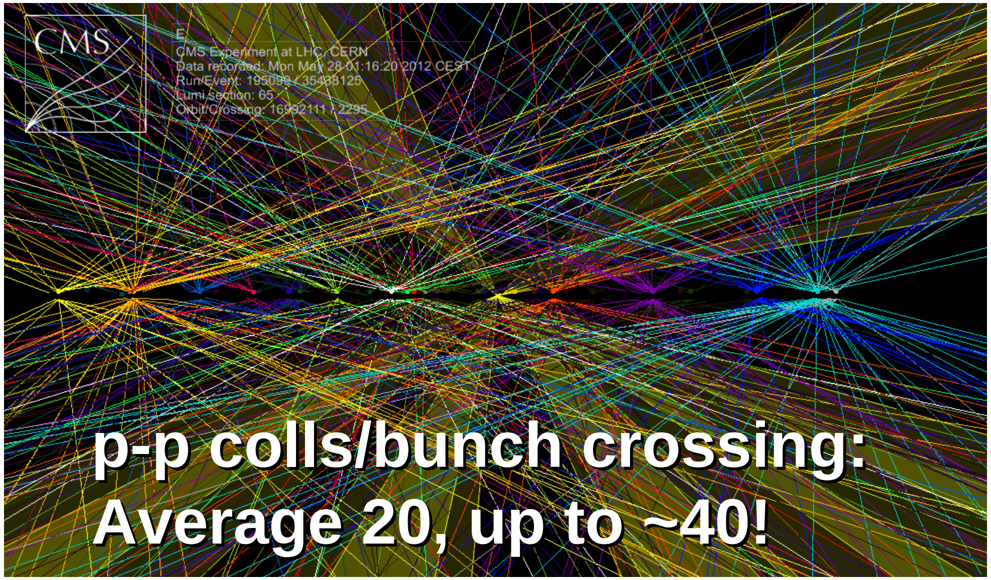
- Level-1 & HLT menus reduce # of p-p interactions from: $2{\cdot}10^7$ Hz (input) down to ~350 Hz (recorded), ~300 Hz ("parked" for later analysis)

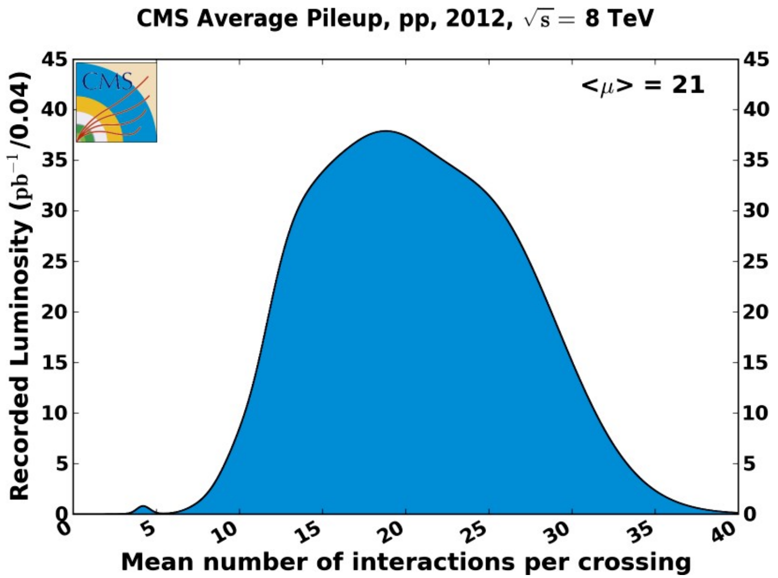




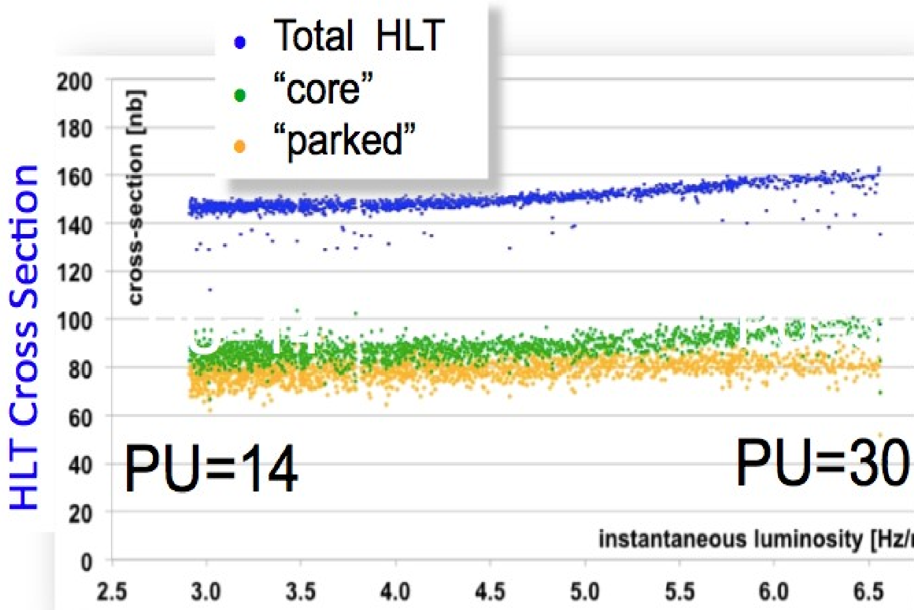
- Example: dimuon mass distribution from several double-μ trigger paths: calibration, $B_s(\mu\mu)$, quarkonia, DY/Z

CMS: p-p pileup & triggering



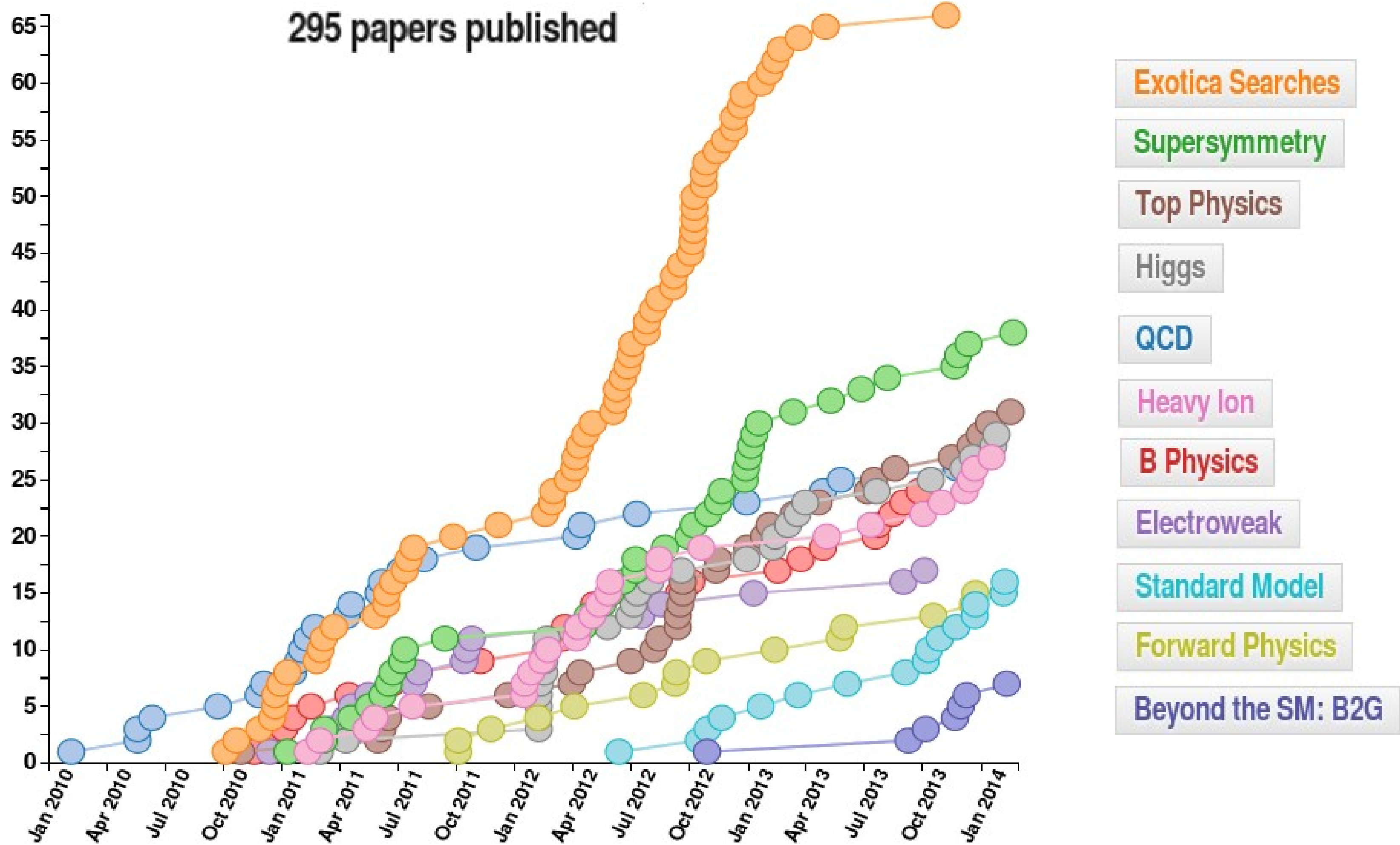


- Highly-flexible HLT system allows CMS to keep a constant-rate cross section with varying pile-up conditions without sacrificing physics:



CMS: publications & preliminary results

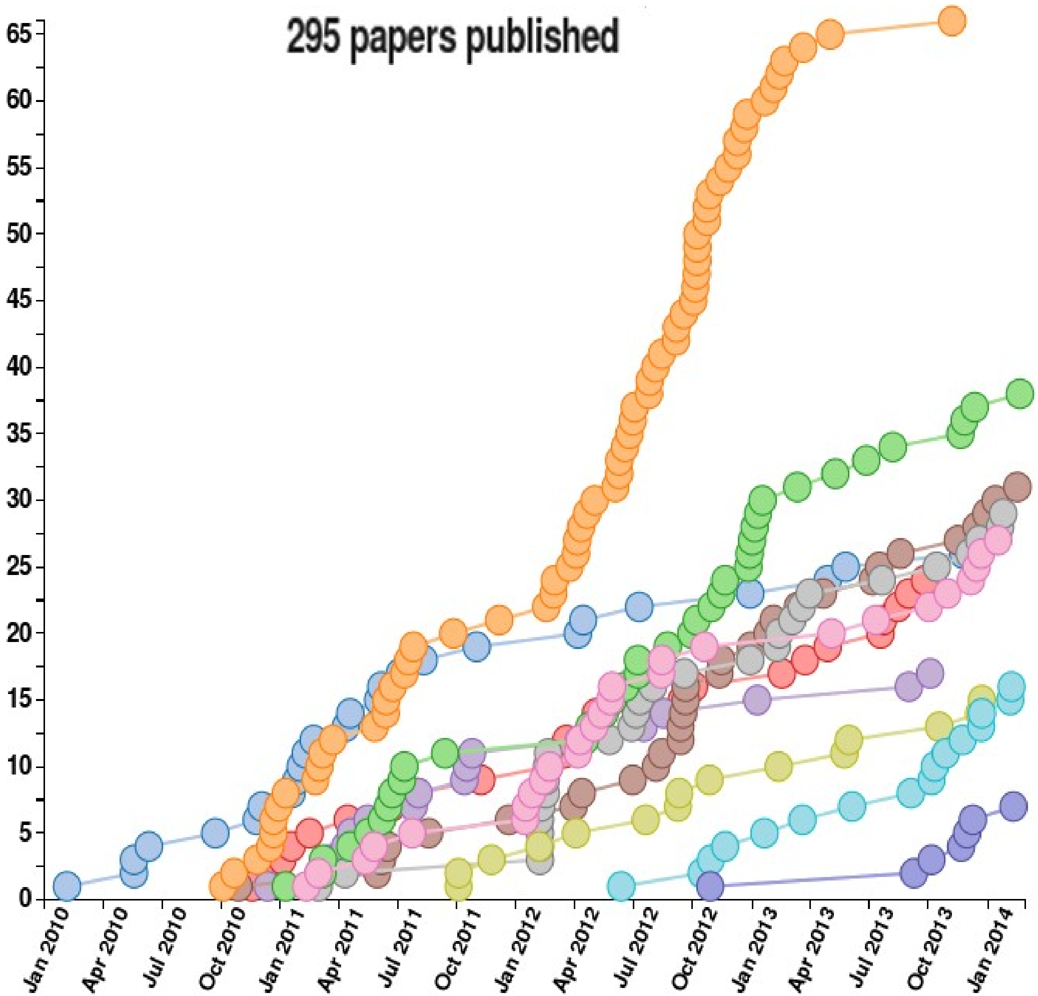
295 papers published + few hundreds preliminary notes as of Feb'14



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

CMS: publications & preliminary results

295 papers published + few hundreds preliminary notes as of Feb'14



Personal selection of «first-ever» observations & «best-ever» constraints:

- QCD: σ_{inel}, «ridge», α_s(TeV)
- QGP: Υ suppression
- EW: $\gamma\gamma\rightarrow$WW, VBF Z
- Top: most-precise m_{top}
- Higgs: m_H, spin, couplings
- Flavour: $B_s(\mu\mu)$
- SUSY: $m_{spartners}$ > O(TeV)
- DM: $\sigma_{\chi N}<10^{-39}$ for m_χ~1 – 10 GeV
- BSM: $m_{new\text{-}particles}$ > O(TeV)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Quantum Chromodynamics

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$$

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$$

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

- Gauge-fermion dynamics via covariant derivatives:

$$D_\mu\begin{pmatrix}\nu_L \\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L \\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L \\ d_L\end{pmatrix},$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

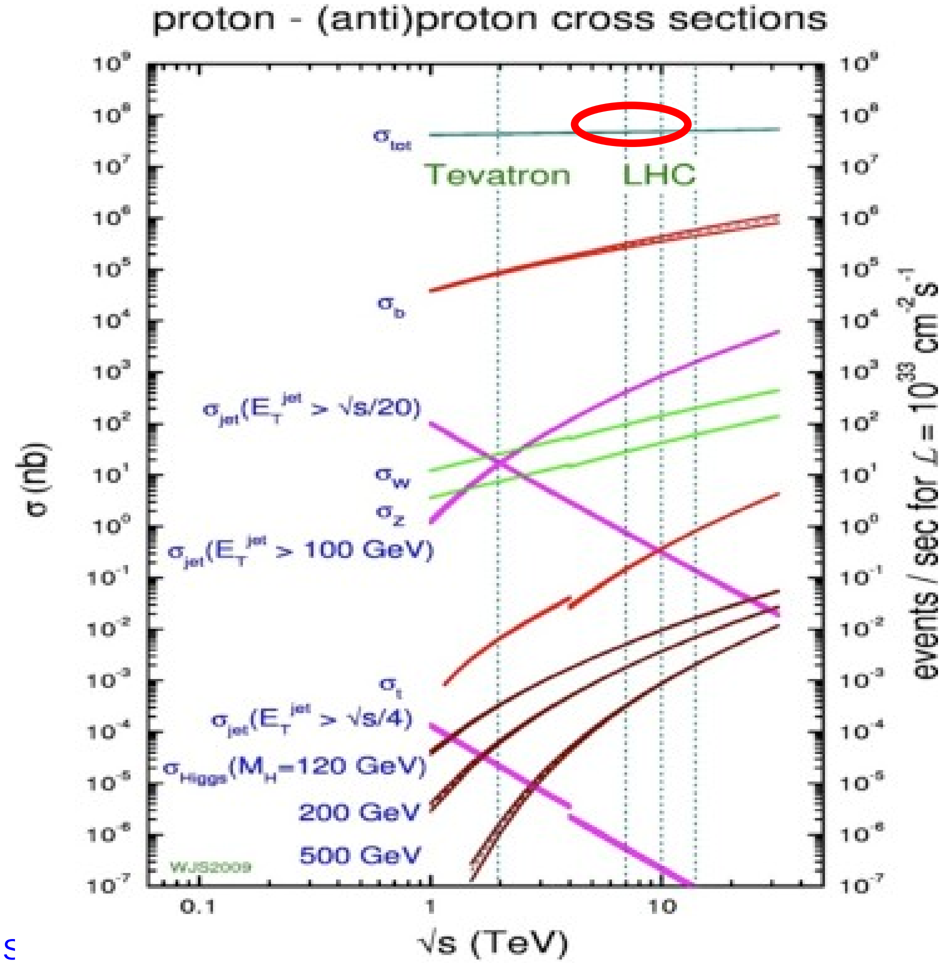
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

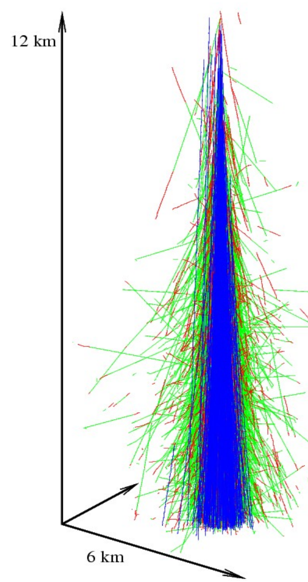
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

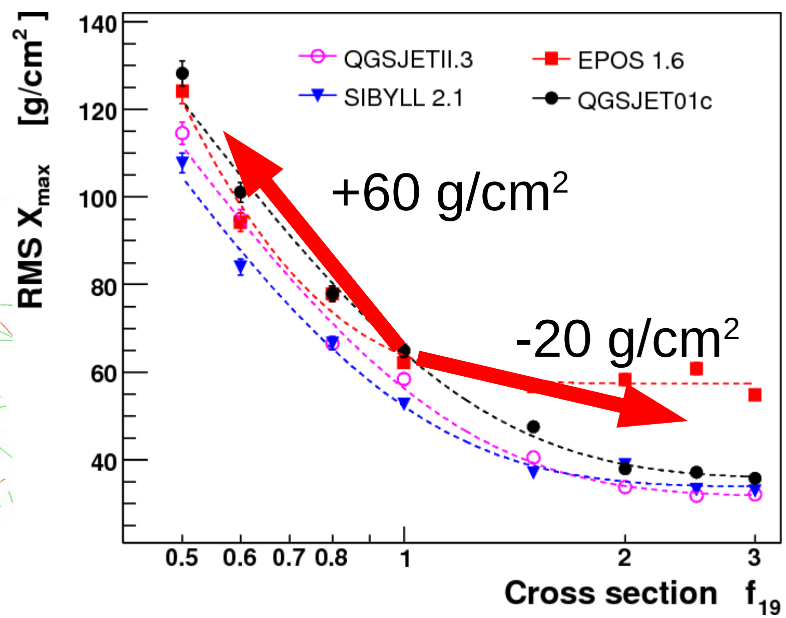
QCD: Inelastic p-p cross section

- Only ~60% of total p-p x-section at LHC directly connected to QCD Lagrangian (perturbative parton scatterings) ...
- Diffractive (15%) +elastic (25%) x-sections require: Data + Regge-Gribov approaches (QM constraints: Froissart bound, optical th., dispersion relations)



- Impact on cosmic-ray MCs at E_{lab}~10^{19} eV Uncertainties of σ_{inel} change by factor of ~2 the air-shower maximum fluctuations:

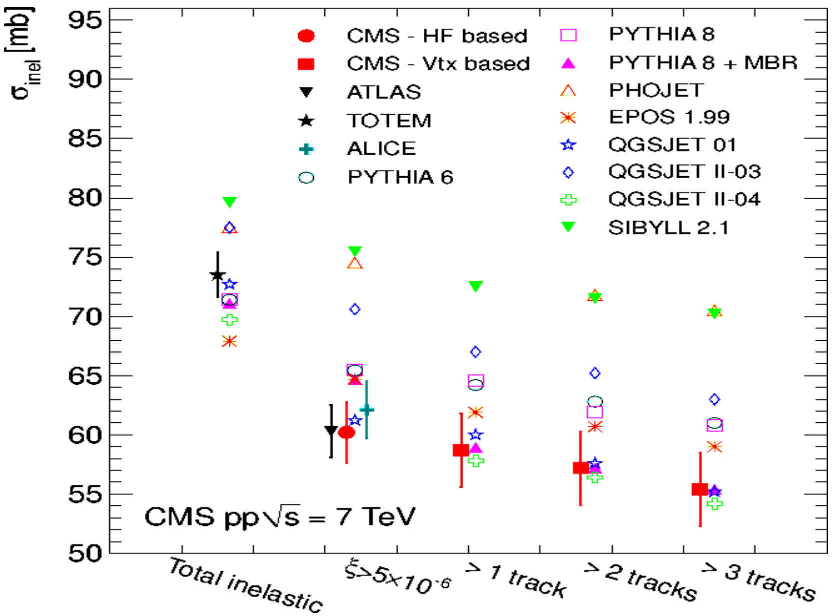




Ulrich-Engel-Unger, PRD83 (2011) 05426

QCD: Inelastic p-p cross section

PLB 722 (2013) 5



- Total inel. x-section σ_{CMS}~ 73 mb

Visible inel. x-section σ_{CMS}~ 60 mb

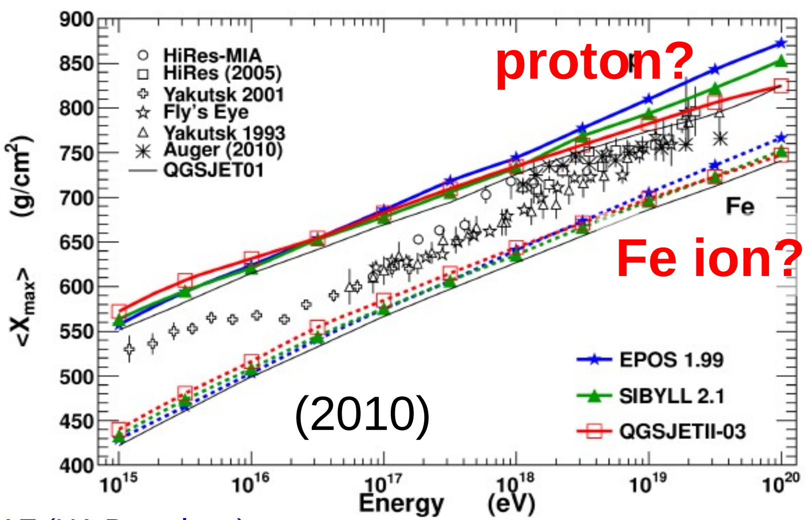
measured in CMS via:

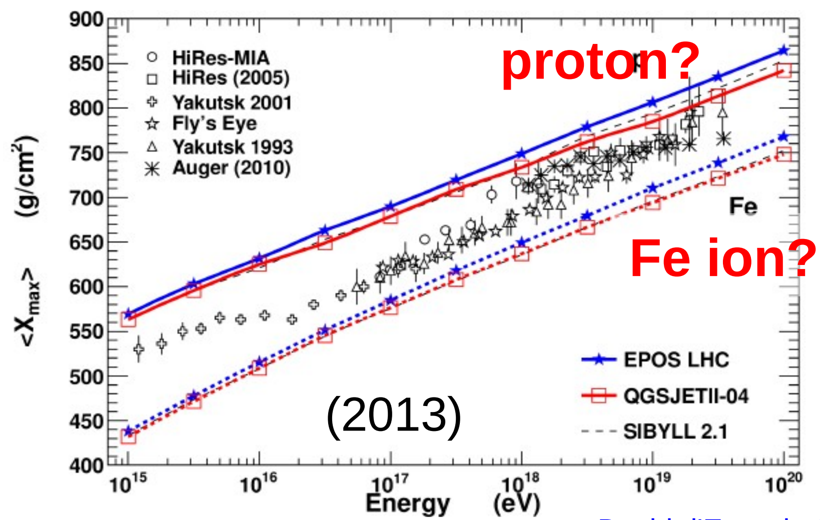
(i) pileup-events counting,

(ii) hadronic activity in single-sided triggers

Most hadronic models over(under)-estimate high(low)-mass diffraction.

- Mixed p-Fe UHECRs at GZK-cutoff after including LHC data (E_{lab} ~ 10^{17} eV):



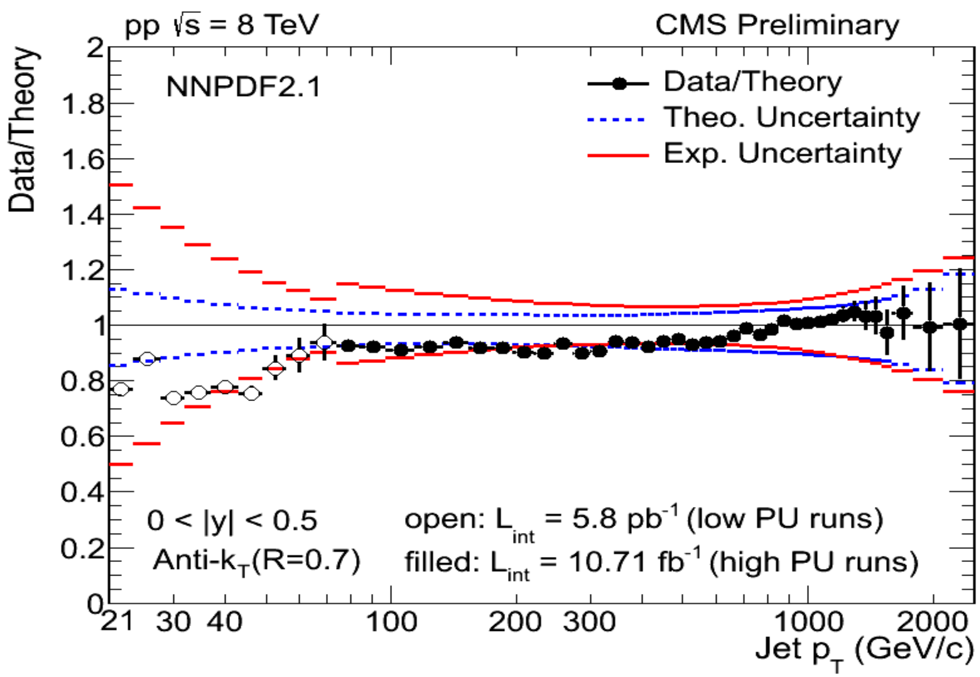


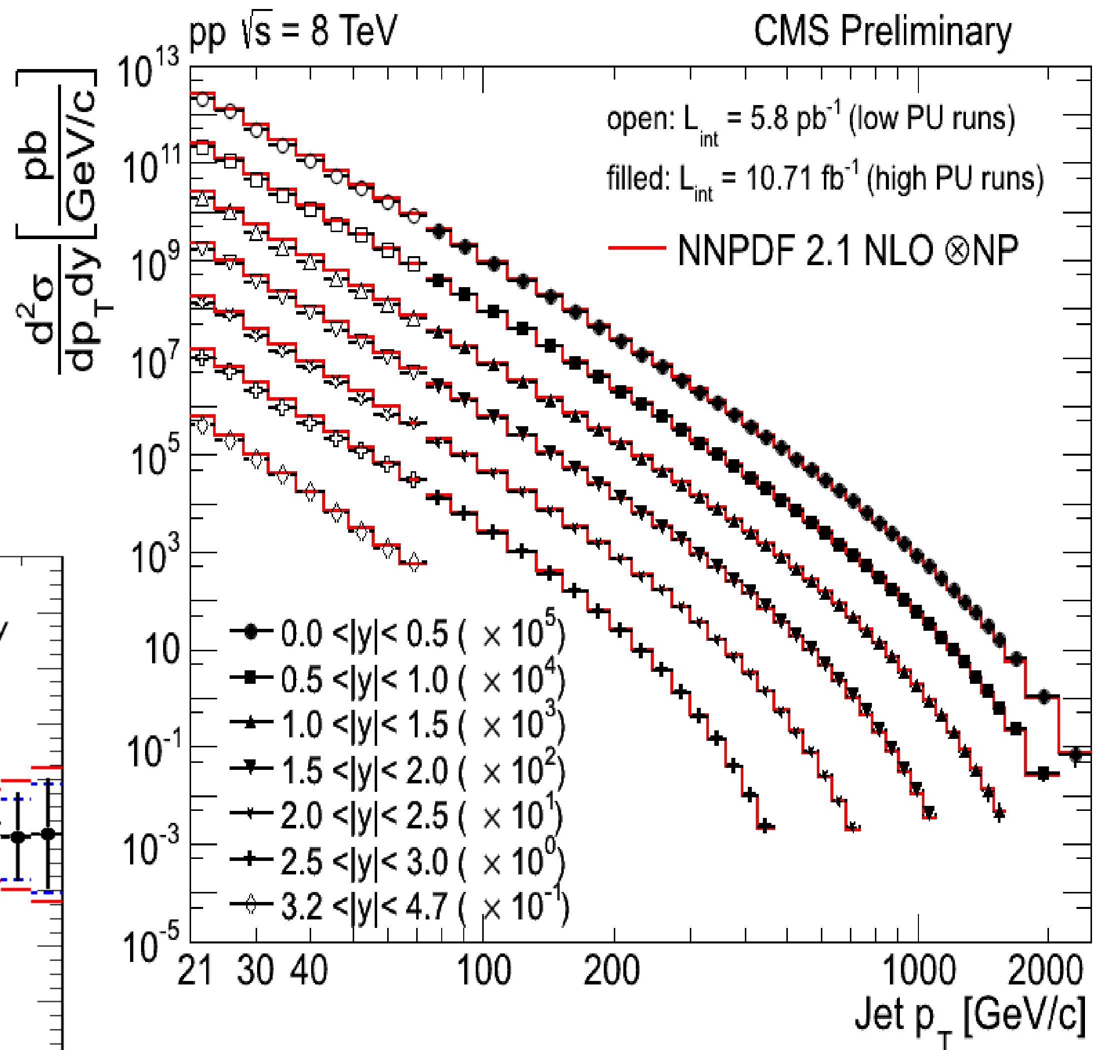
QCD: x-sections of light-quark & gluons jets

CMS-FSQ-12-031

- Inclusive jet p_T spectra:
  20 GeV up to 2-3 TeV
  (2-4% JES)

- NLO pQCD describes data over 14 orders-magnitude.
  Gluon PDF constraints.

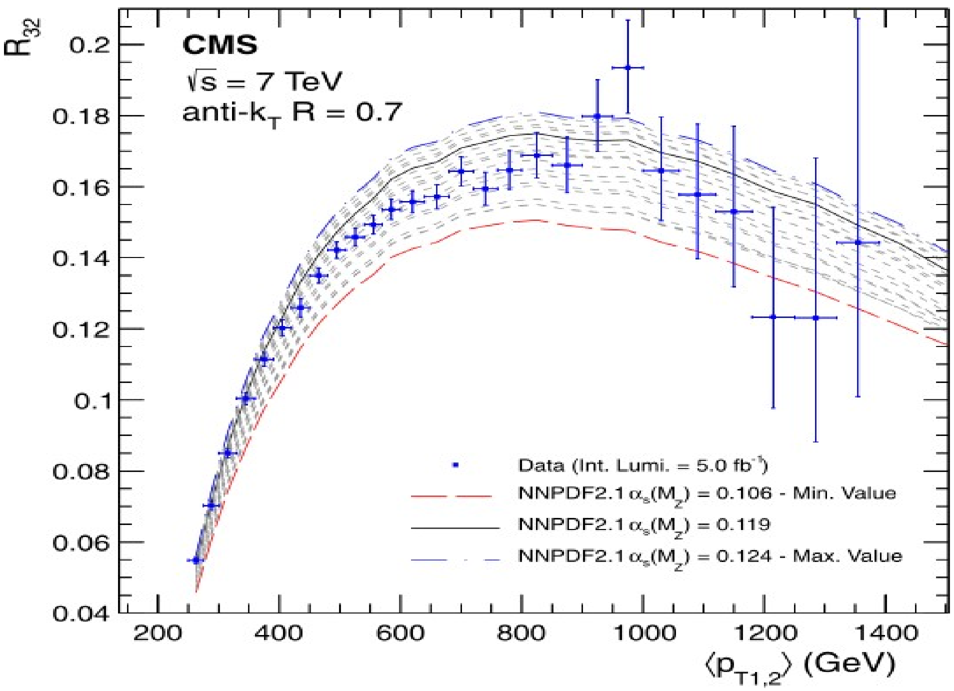


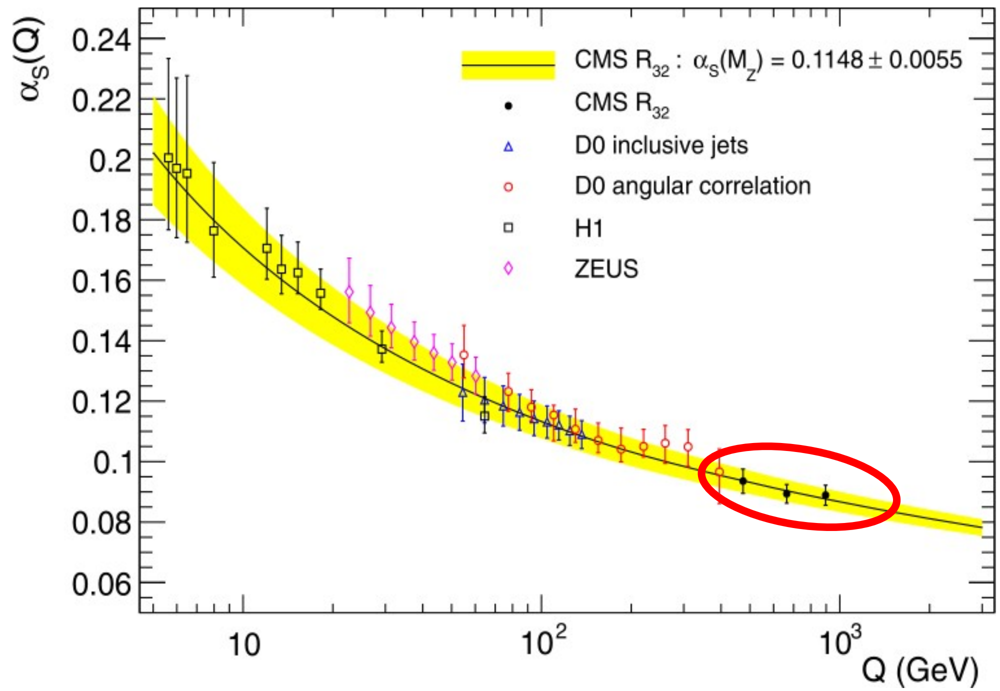


QCD: Strong coupling from jets x-sections

- Ratio of 3-jets of 2-jets & 3-jet mass x-sections constrain α_s at so-far unprobed scales up to Q ~ 1.4 TeV:

EPJC73 (2013) 2604





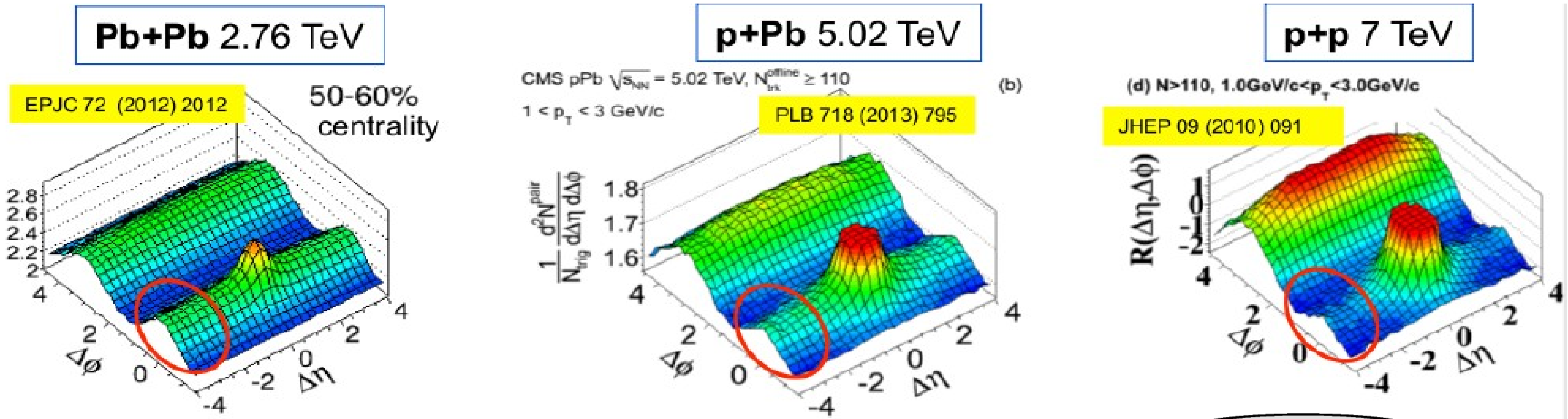
NNPDF21: $\alpha_s(M_Z) = 0.1148 \pm 0.0014$
CT10: $\alpha_s(M_Z) = 0.1135 \pm 0.0019$
MSTW2008: $\alpha_s(M_Z) = 0.1141 \pm 0.0022$
(ABM11: $\alpha_s(M_Z) = 0.1214 \pm 0.0020$**)**

Measurement dominated by TH uncertainty: PDF & (asymmetric) scale uncertainty

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

"Collective" QCD: "ridge" of correlated hadrons

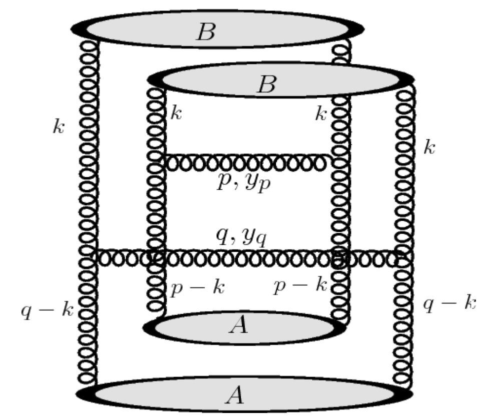
- Observation of long-range (over $\Delta\eta\sim 8$!) near-side hadron correlations "ridge" in "central" (high multiplicity) collisions:



- Initial-state ? Correlated gluons around Q_{sat} ?

$$|\mathbf{k}_\perp| \sim |\mathbf{p}_\perp - \mathbf{k}_\perp| \sim |\mathbf{q}_\perp \pm \mathbf{k}_\perp| \sim Q_s$$

Multiparton interactions enhance the near-side diagrams



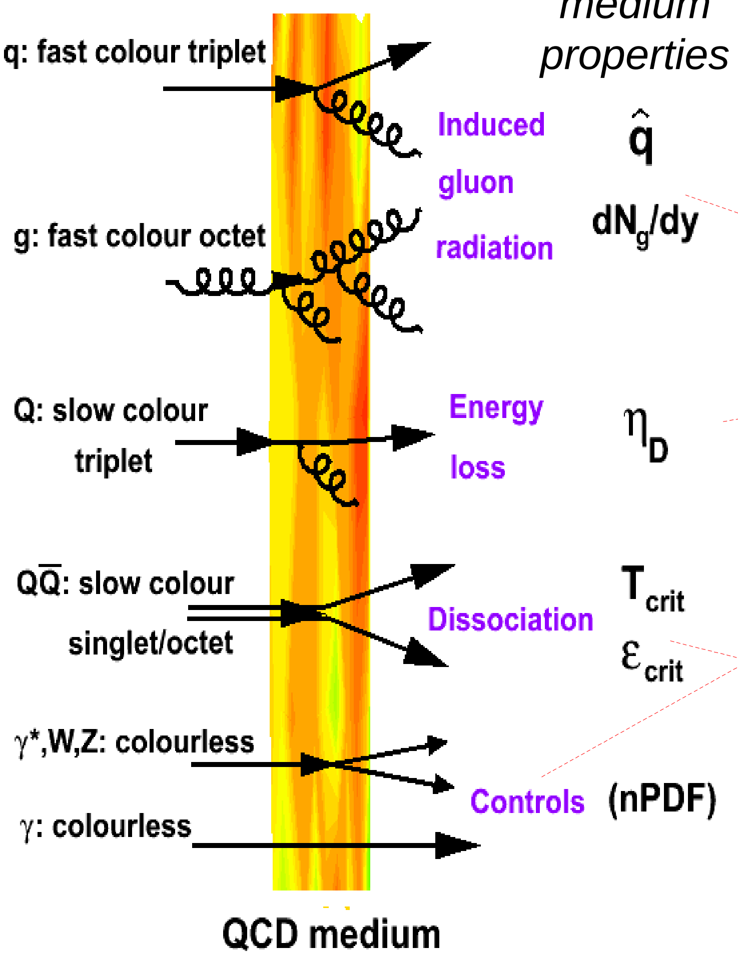
- Final-state ? Collective parton-flow ?

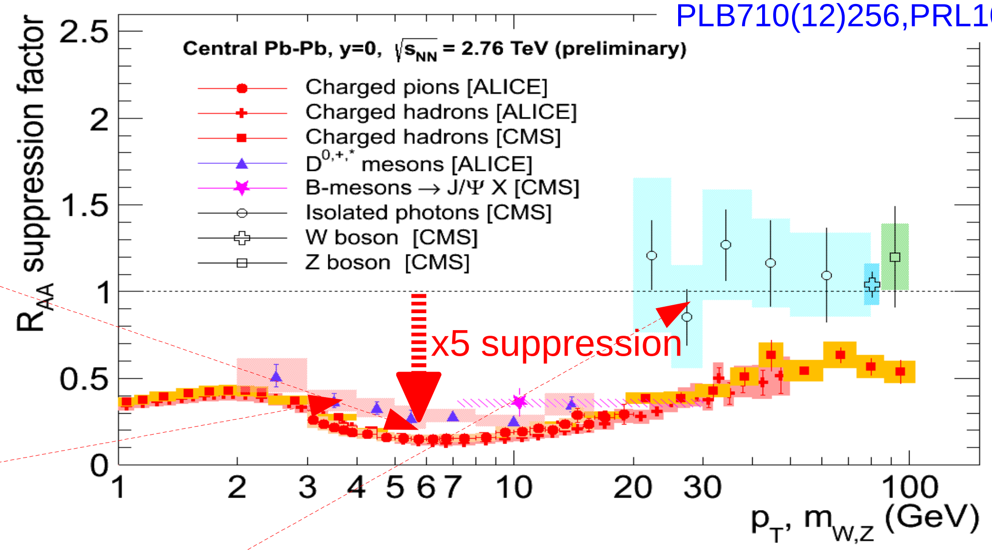
PYTHIA(pp) + $\beta_T \sim 0.5$ generates such structure

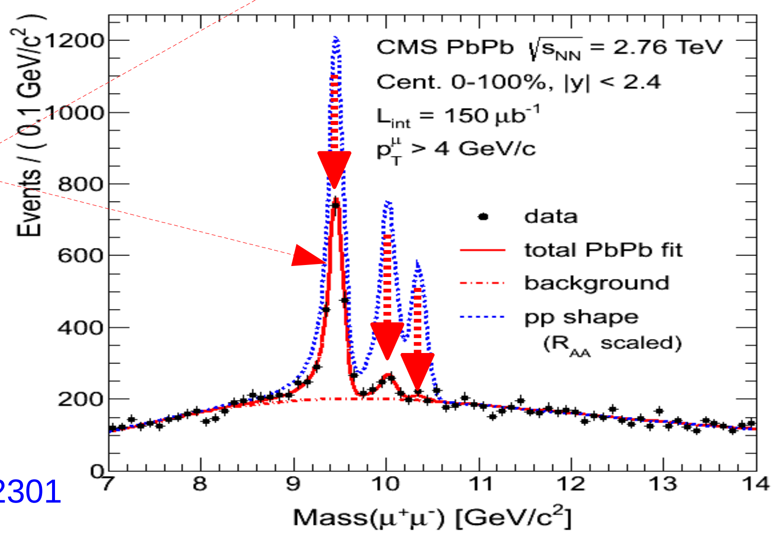
QCD plasma: q,g,$Q\bar{Q}$ suppression in Pb-Pb

- Yields of strongly-interacting particles suppressed in Pb-Pb compared to p-p. Weakly probes (γ,W,Z) unmodified by medium:

PLB715(12)66, EPJC 72(12)1945
PLB710(12)256,PRL106(11) 212301







PRL109(12)222301

Y(1S,2S,3S) yields suppressed as expected by seq. «melting» of b-bbar resonances in QGP

Electroweak sector (LHC)

$$\mathcal{L} = \boxed{-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu})} - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U_Y(1)$, $SU_L(2)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$$

$$\boxed{+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R} + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$$

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

- Gauge-fermion dynamics via covariant derivatives:

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$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu \boxed{+\frac{i2g_1}{3}B_\mu} + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu \boxed{-\frac{ig_1}{3}B_\mu} + ig\mathbf{G}_\mu\right]d_R,$$

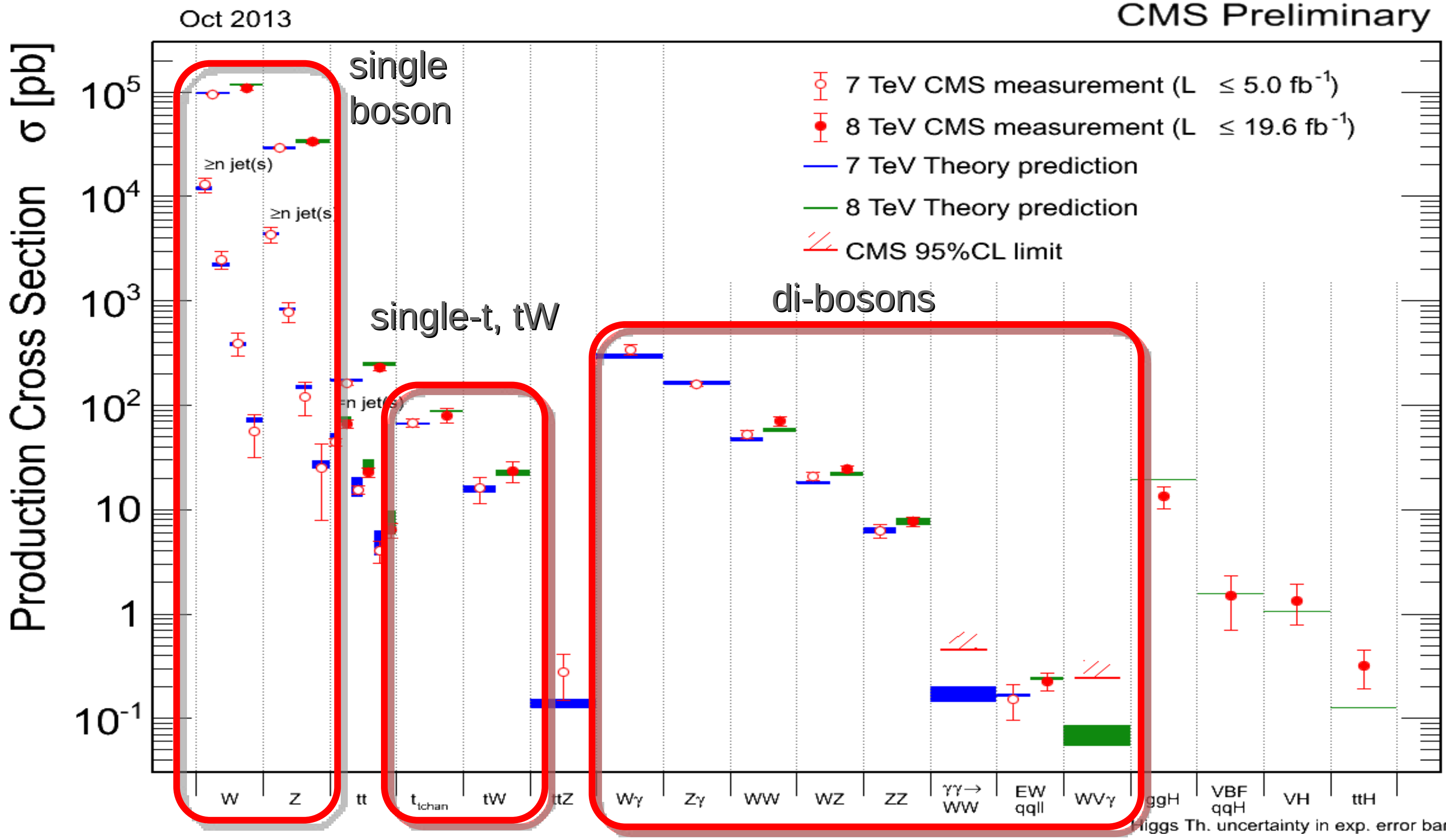
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

$$\boxed{B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2,} \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

EW: Cross sections summary

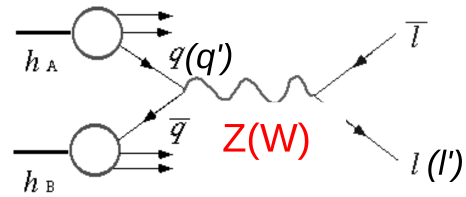
- Stringent tests of EWK (+QCD) sectors at TeV scale:

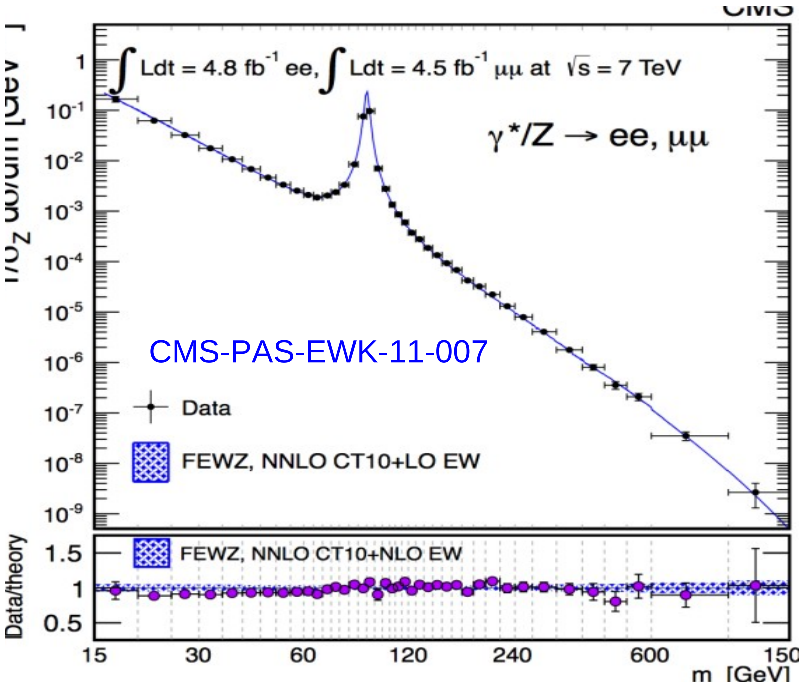


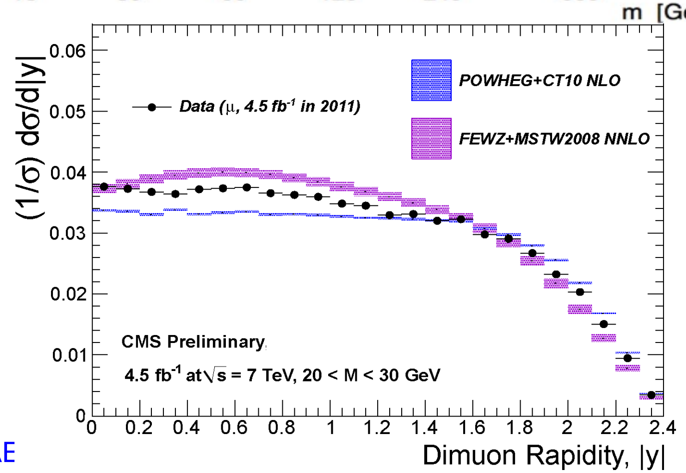
- Very good agreement with NLO (or approx. NNLO) predictions at 7,8 TeV
- First-ever measured: t-W, tt-Z, $\gamma\gamma \rightarrow$ WW, vector-boson-fusion Z

EW: W,Z ("standard candles") production

- Differential DY+Z x-section in agreement with NNLO at 7,8 TeV. PDF constraints at low m_{ll}

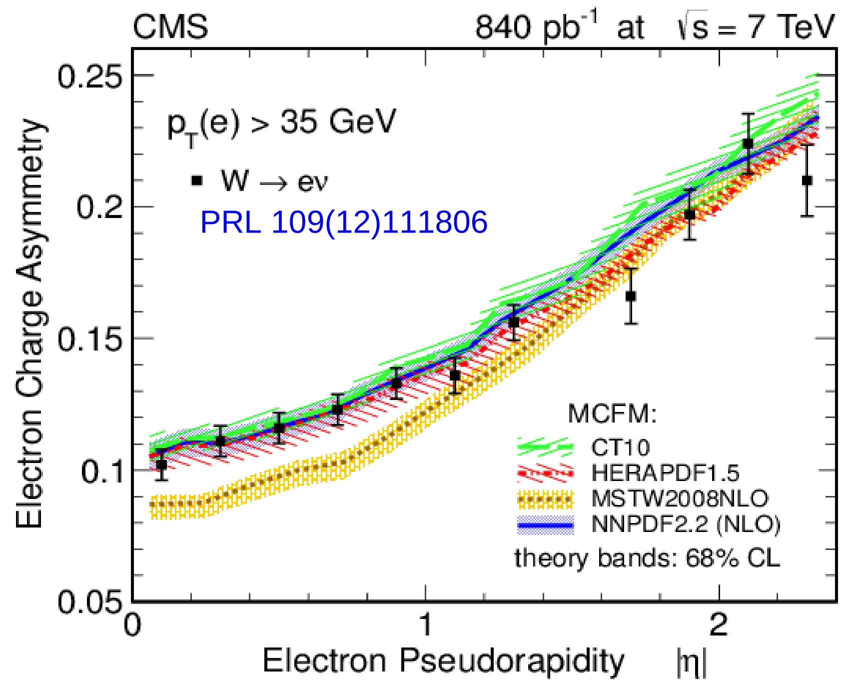




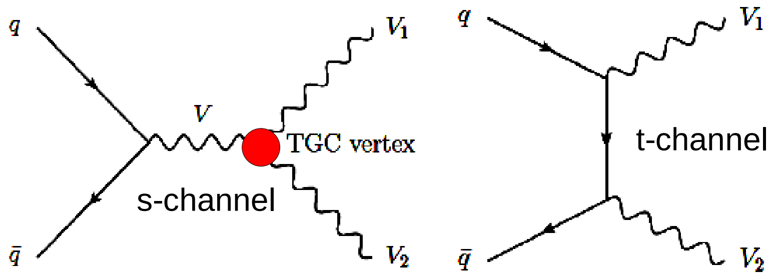


- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

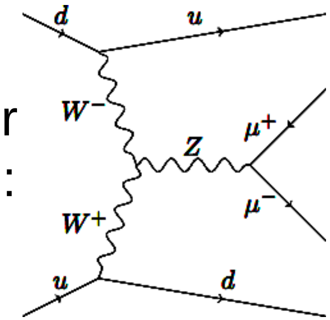
$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

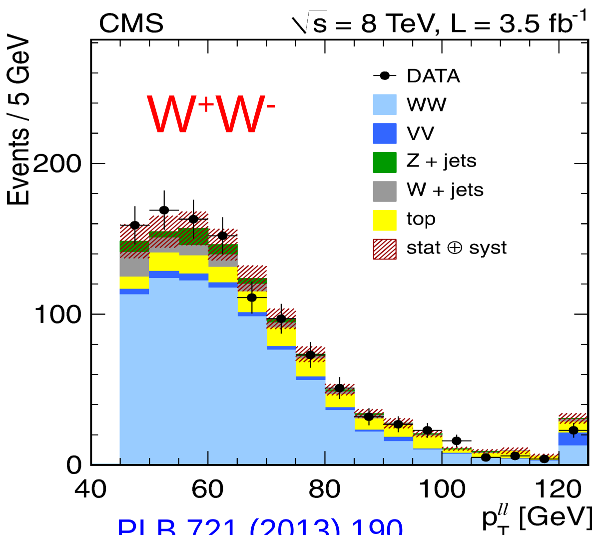


EW: WW, ZZ and VBF-Z production

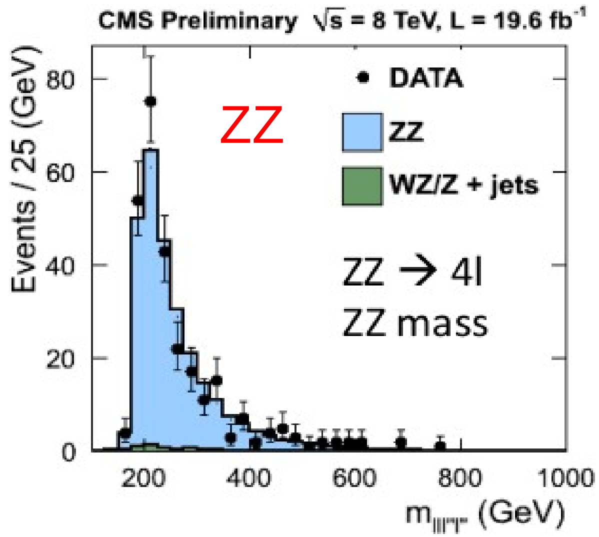


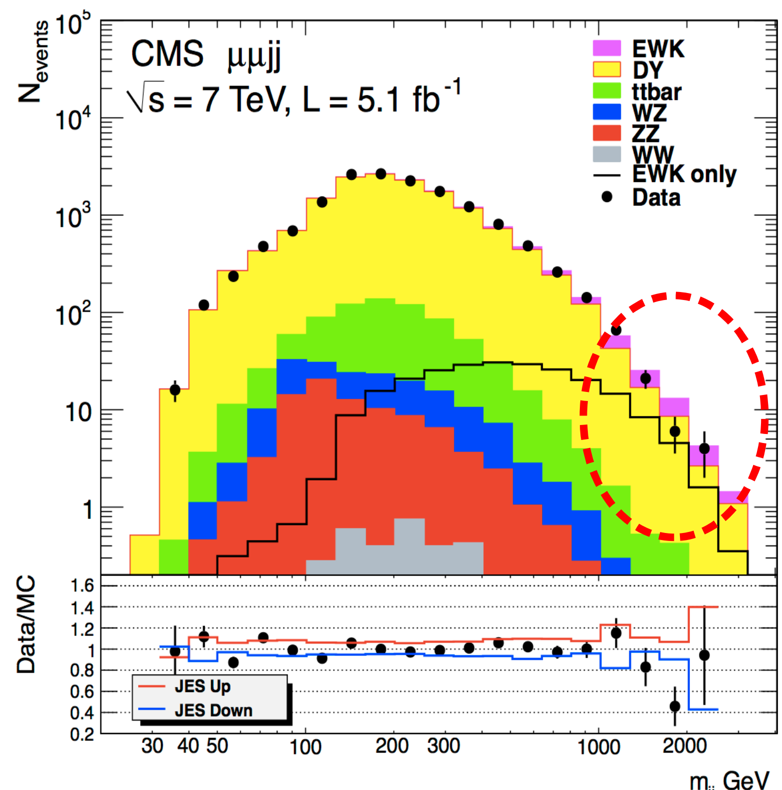
1^{st} evidence (~3sigma) for electroweak Z production:





PLB 721 (2013) 190





$$\sigma(pp \to W^+W^-) = 69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{lum.})\ \text{pb}$$

WW 10-20% above NLO prediction at 7,8 TeV

$$\sigma(pp \to ZZ) = 8.4 \pm 1.0\,(\text{stat.}) \pm 0.7\,(\text{syst.}) \pm 0.4\,(\text{lum.})\ \text{pb}$$

ZZ in agreement with NLO pQCD

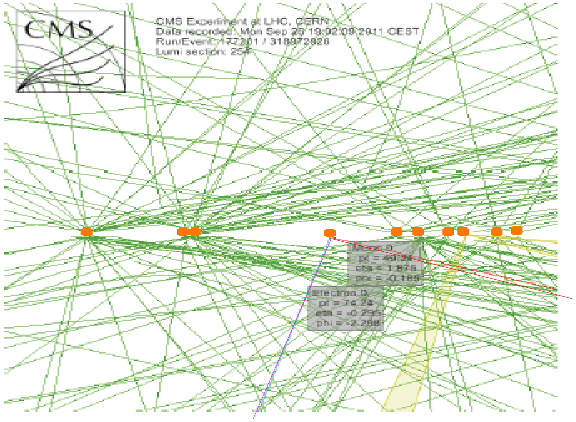
World's strongest constraints on neutral aTGCs (fZ ~ 3-5 10^{-3})

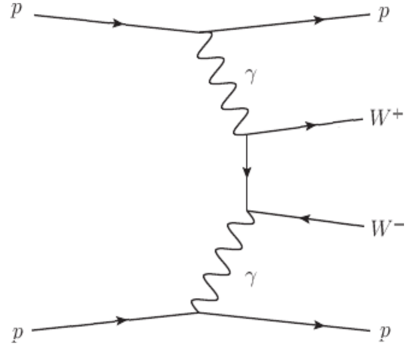
JHEP 1310 (2013) 101

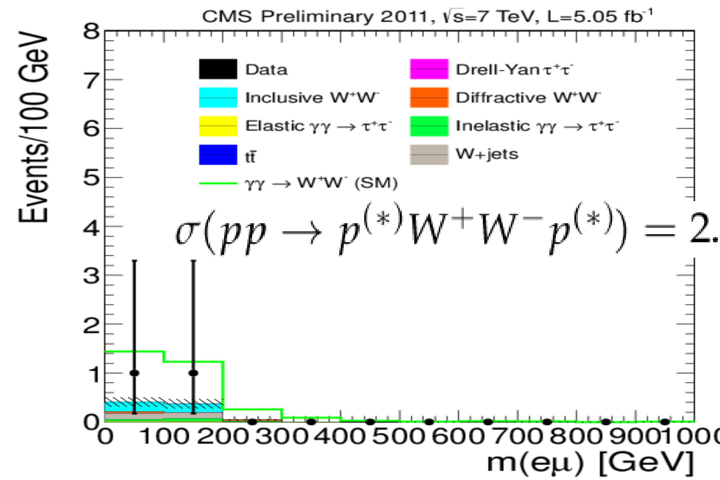
EW: $\gamma\gamma \rightarrow WW$ & anomalous QGCs

JHEP 07 (2013) 116

- Exclusive opposite-sign μ-e events: 2 evts in 5 fb^{-1} at 7 TeV:

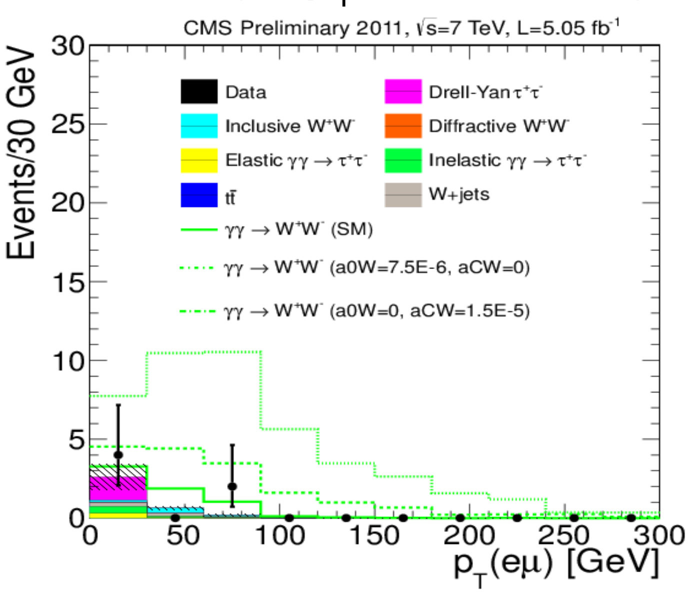




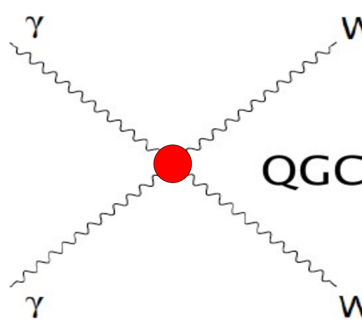


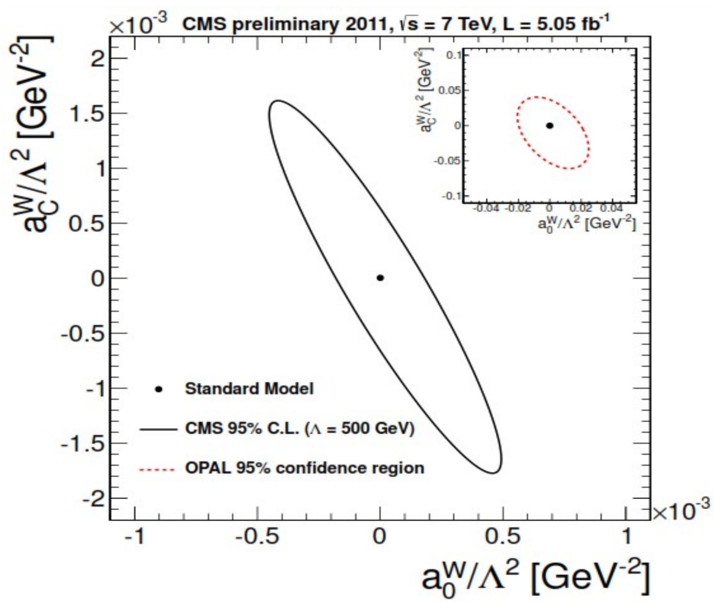
$$\sigma(pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb}$$

- No high-p_T evts: Strong constraints on anomalous quartic gauge couplings:



Limits ~100 times stronger than LEP:





Higgs sector

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dynamics & mass]

- Gauge-fermion dynamics via covariant derivatives:

$$D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix} u_L \\ d_L \end{pmatrix},$$

$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

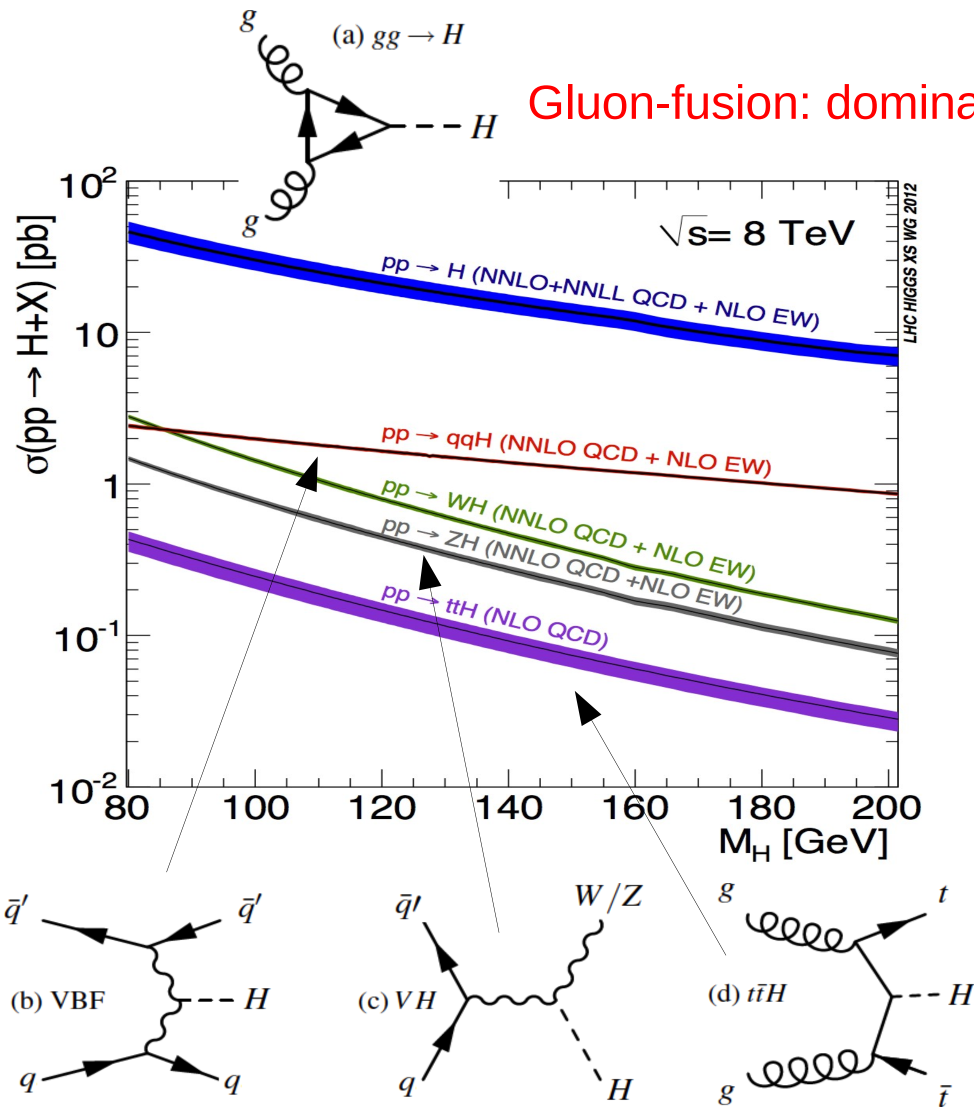
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

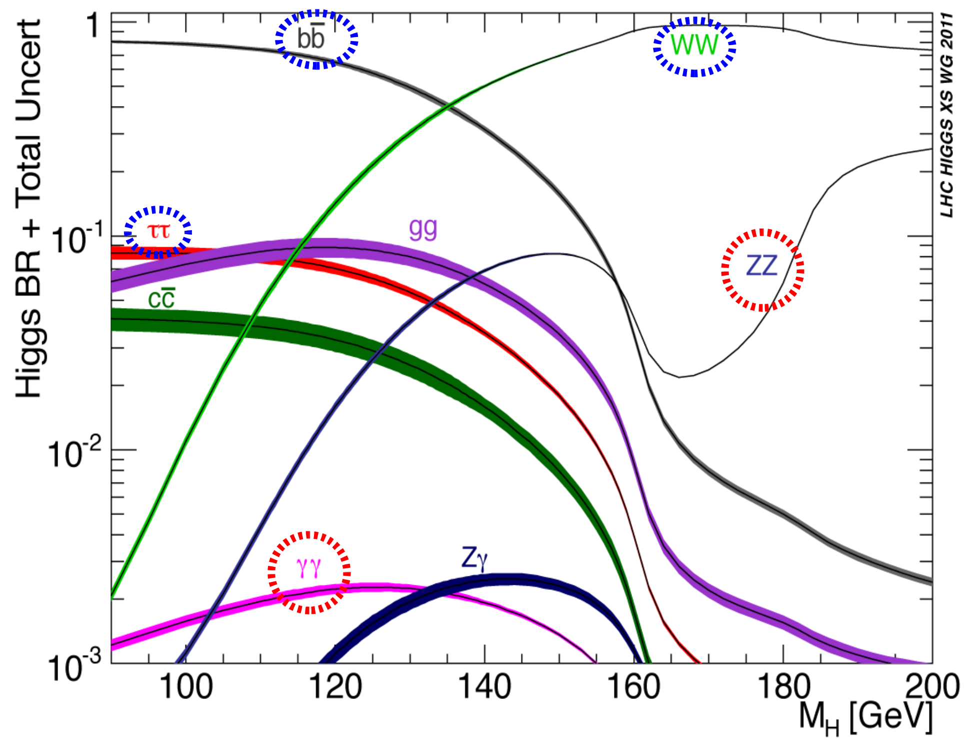
- Gauge-boson field strength tensors:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu \mathbf{G}_\nu - \partial_\nu \mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

SM Higgs boson: LHC production & decays

Gluon-fusion: dominant





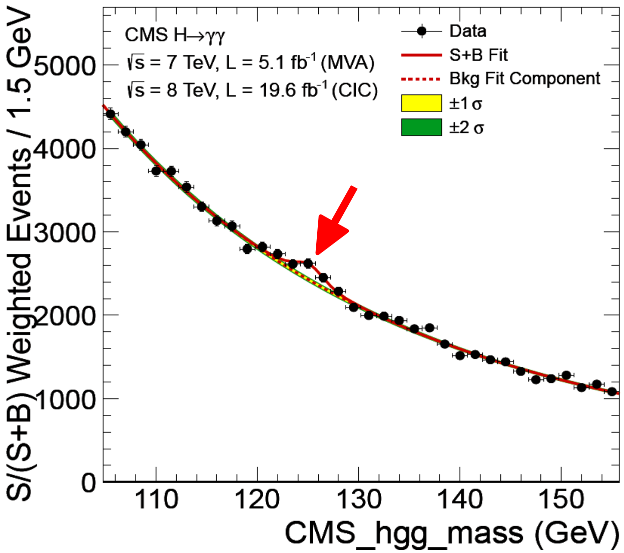
High-resolution channels: $H \to \gamma\gamma$, ZZ(4l)

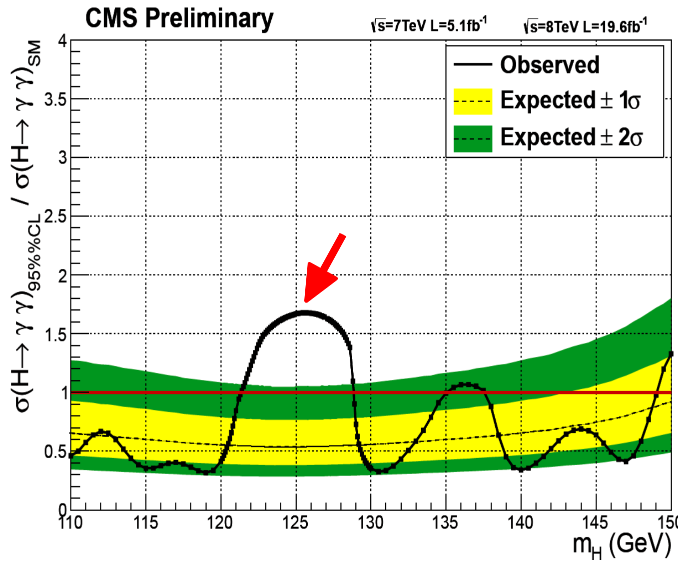
Large x-section channels: $H \to WW,\tau\tau,bb$

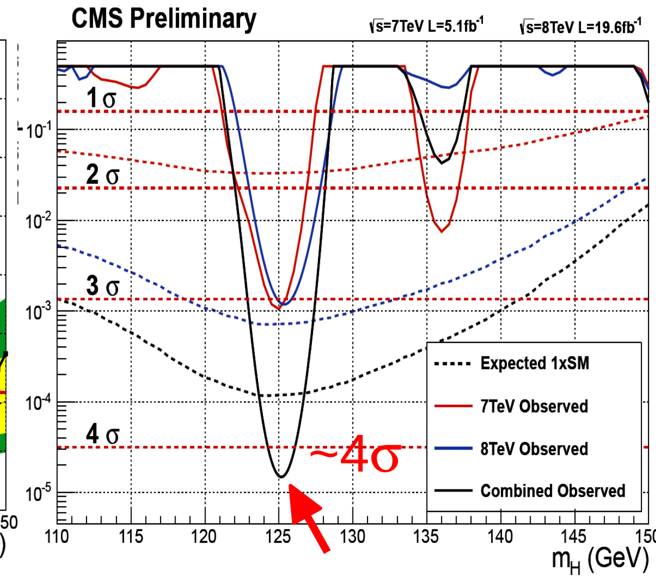
VBF & associated prod.: harder H, more jets

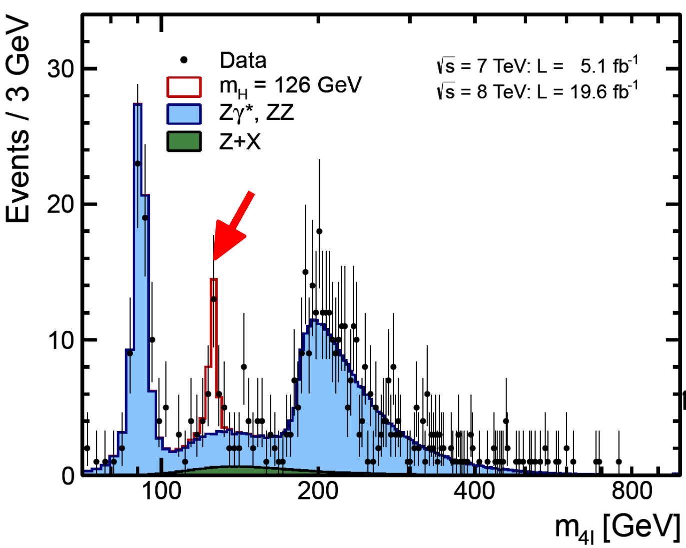
Discovery of Higgs boson: γγ, ZZ channels

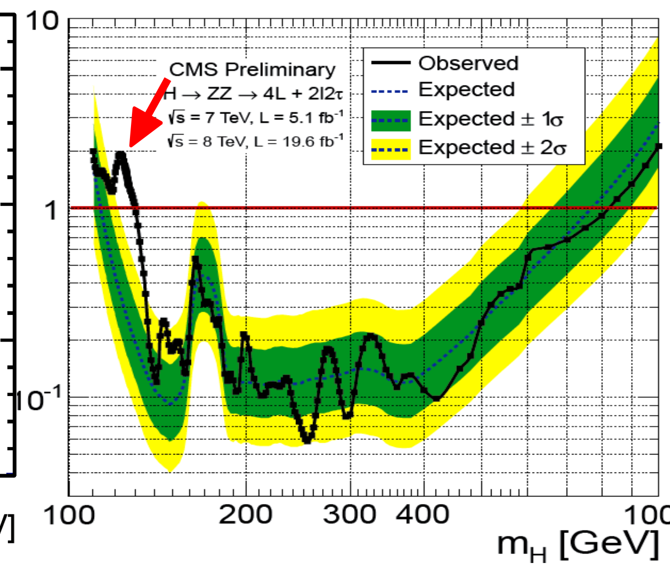
Invariant mass distributions: 95% CL-Limits on σ/σ(SM): Significance (local p-value):

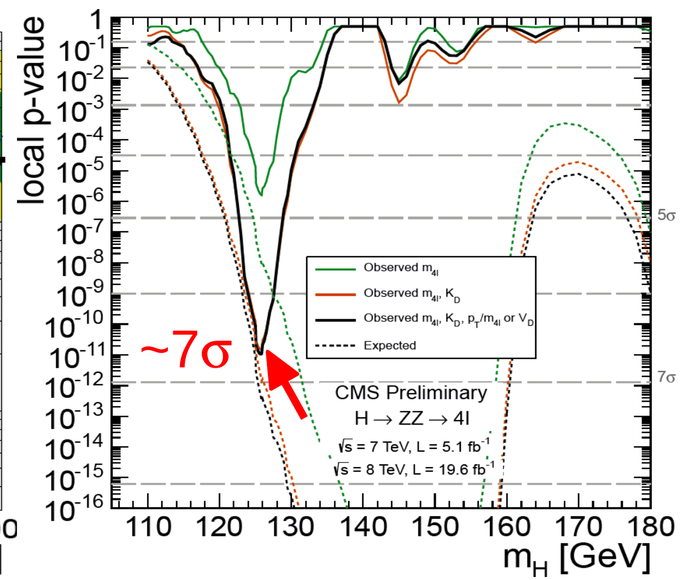






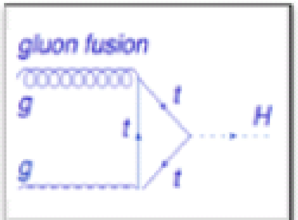


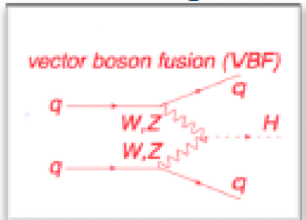


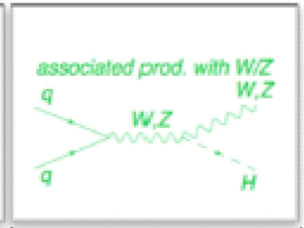


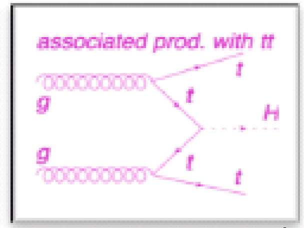
Higgs discovery/searches in other channels

- About 30 Higgs production-decay channels available:









Channel	ggF	VBF	VH	ttH	Dataset 7+8 TeV (fb^{-1})
$H \to \gamma\gamma$					5.1+19.6
$H \to ZZ \to 4l$					5.1+19.6
$H \to WW \to l\nu l\nu$					4.9+19.5
$H \to \tau\tau$					4.9+19.6
$H \to bb$					5.0+19.0
$H \to \mu\mu$					
$H \to$ invisible					5.0+19.6
$H \to Z\gamma$					

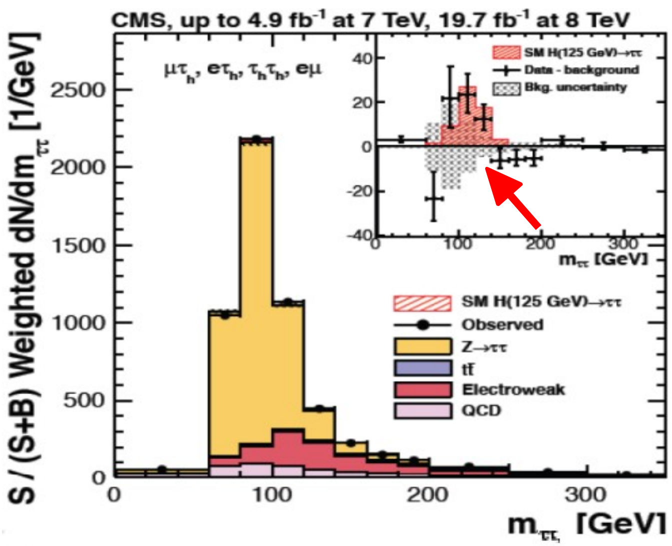
Released

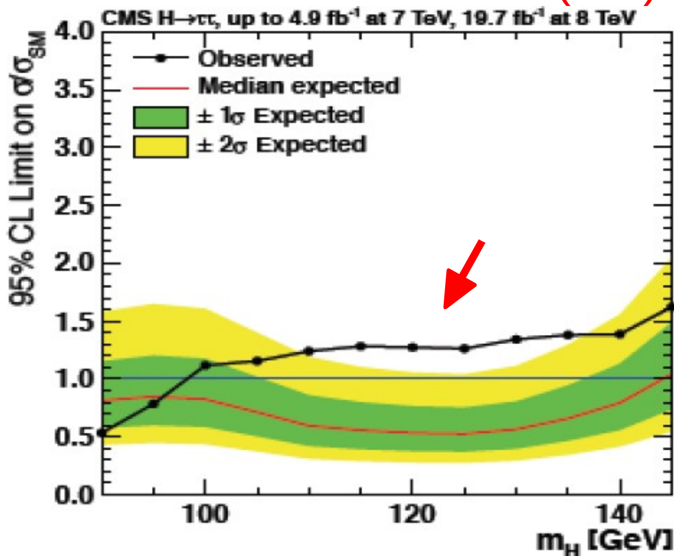
In progress

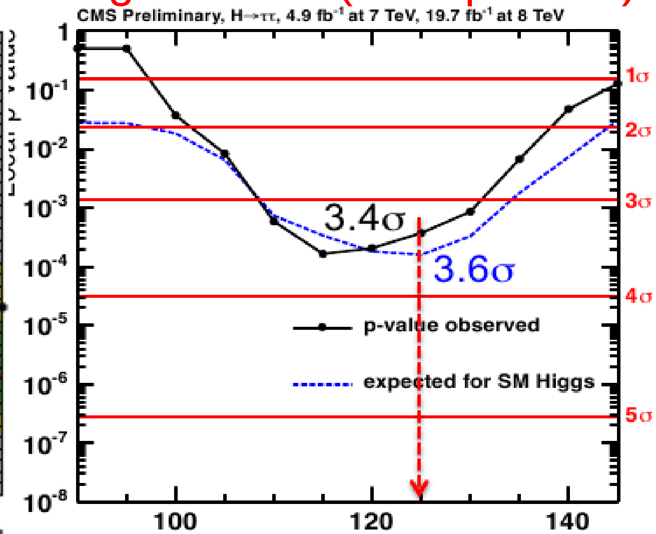
Discovery of Higgs boson: ττ, $b\bar{b}$ channels

- BEH mechanism proposed to give mass to W&Z bosons.
  Does it give mass to fermions? Does it couple to (down-type) fermions?

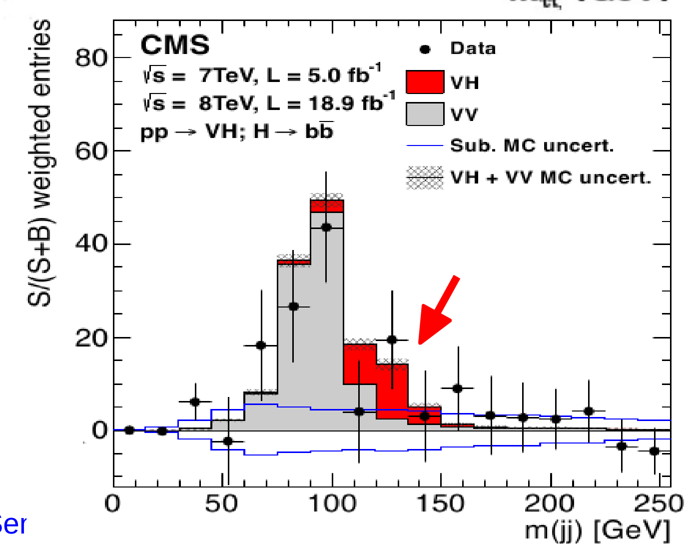
Invariant mass distributions: 95% CL-Limits on σ/σ(SM): Significance (local p-value):

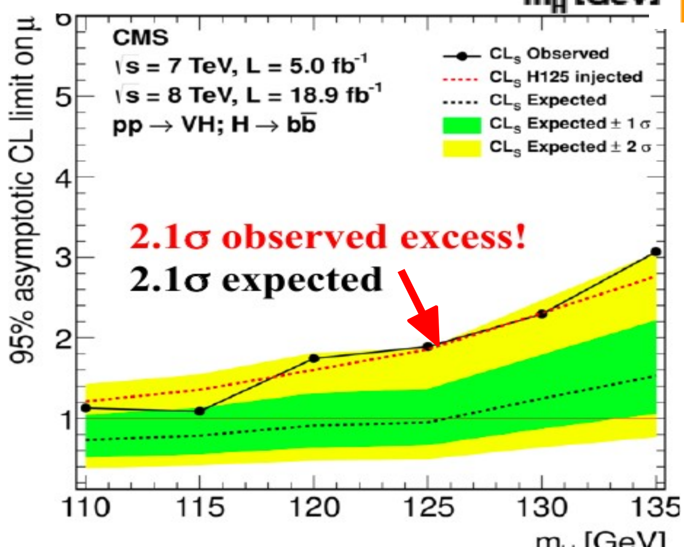


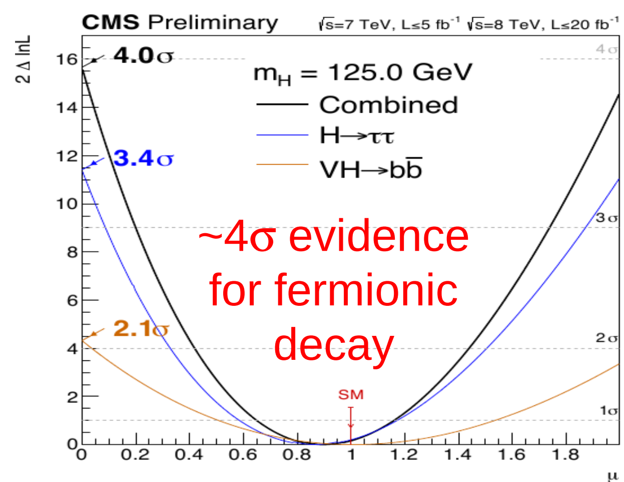




December 3, 2013



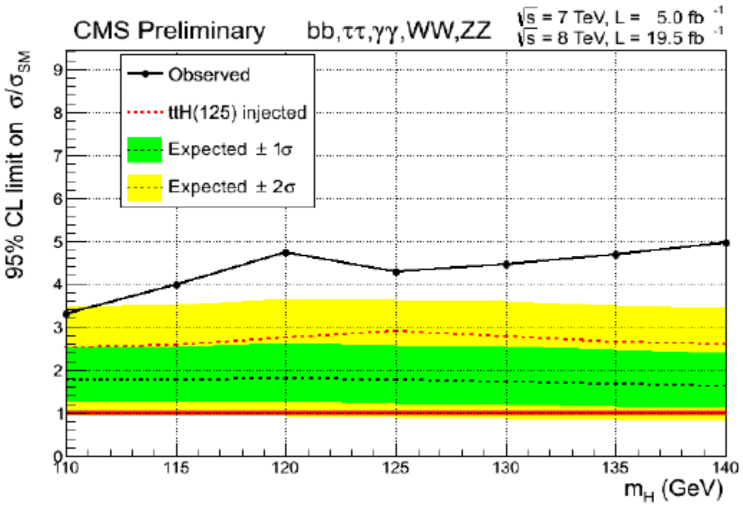




Higgs searches in other channels

- tt-H

$\gamma\gamma$, bb, $\tau\tau$, multi-lepton channels combined

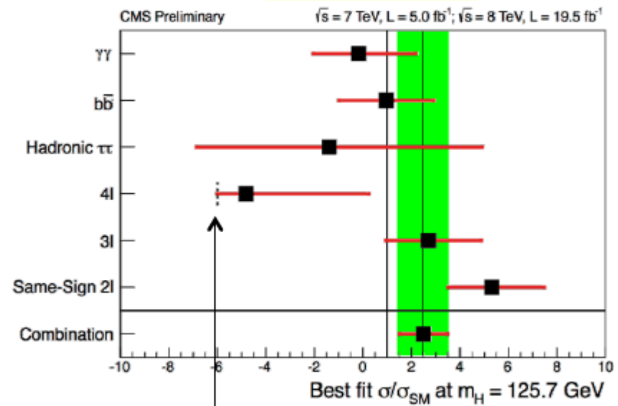


95% CL limit on μ at m_H= 125 GeV

Observed limit:	4.3
Expected limit:	2.9

Best fit of signal strength

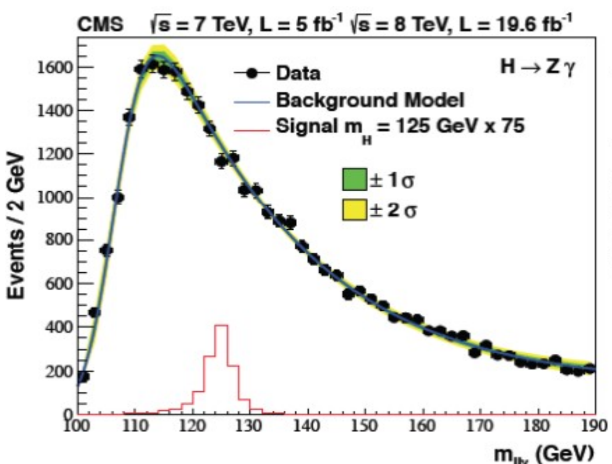
$$\mu = \frac{\sigma}{\sigma_{SM}} = 2.5^{+1.1}_{-1.0}$$

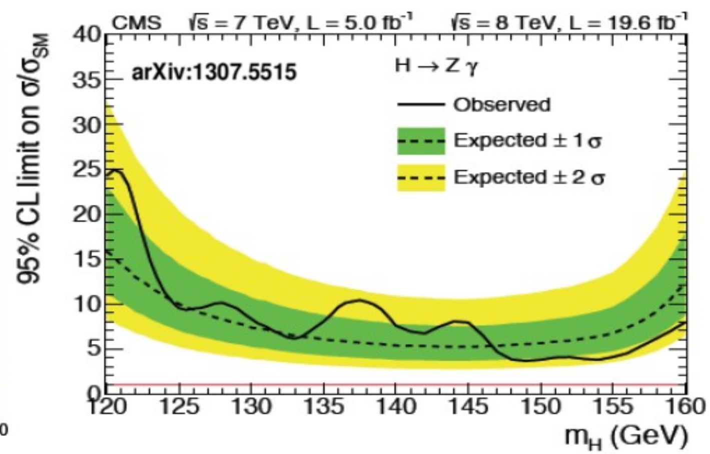


Expected signal-plus-background event yield must not be negative

Direct hint of H coupling to top

- H→Zγ

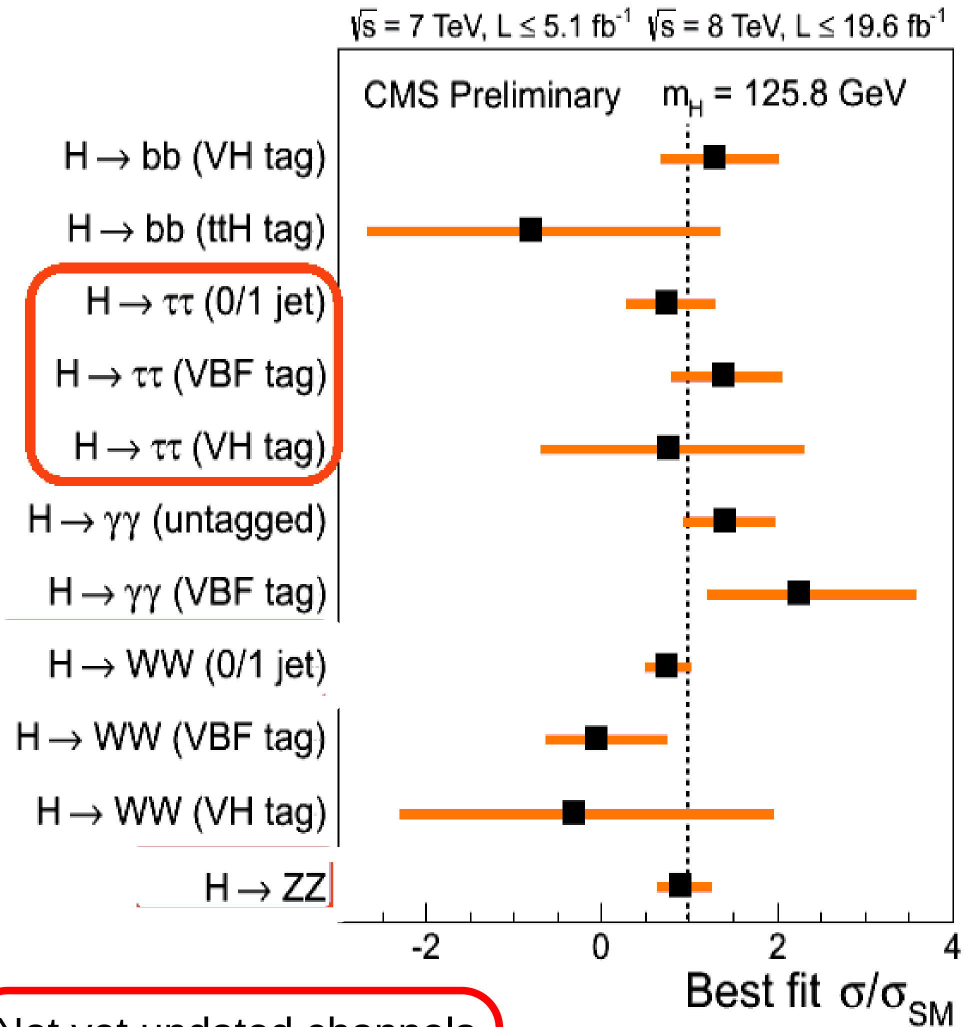




Similar BR to $\gamma\gamma$
High-resolution too
But small sensitivity
due to BR(Z→ll)

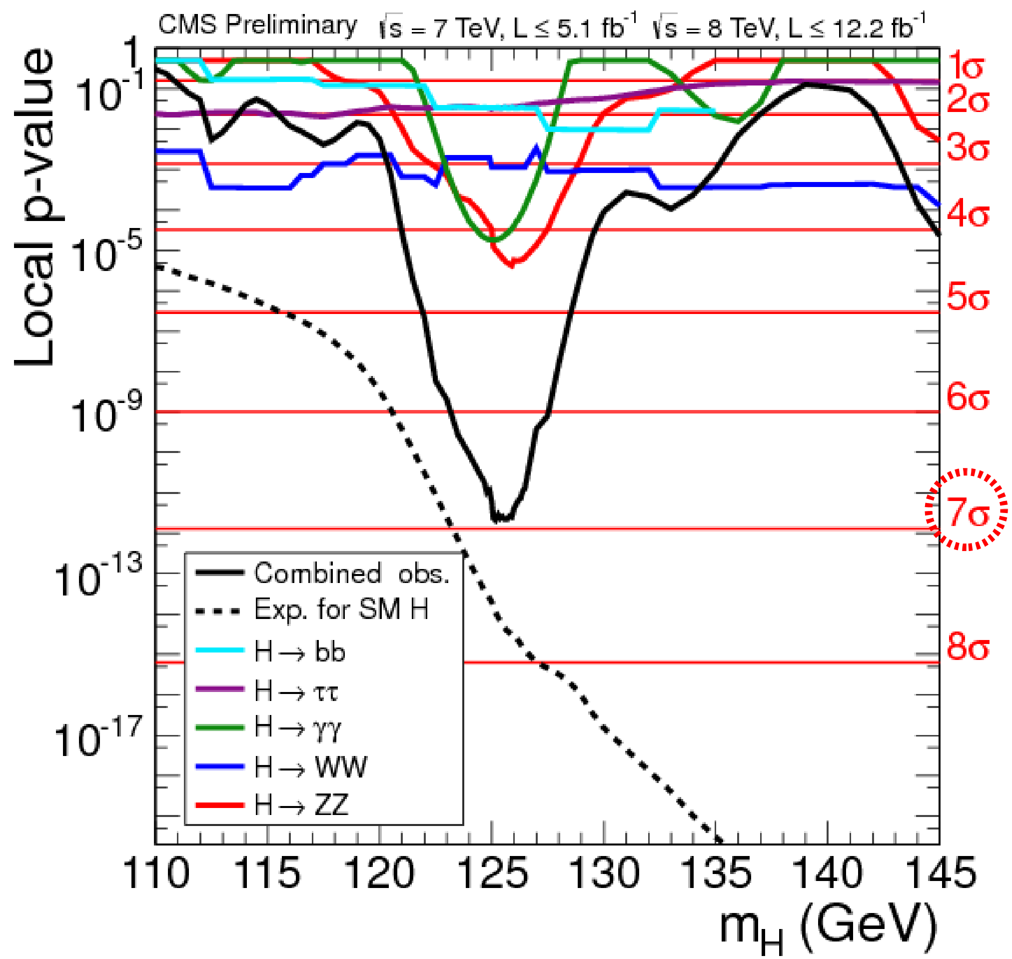
Discovery of Higgs boson: "all" channels

- Signal strength among channels & with respect to SM Higgs:



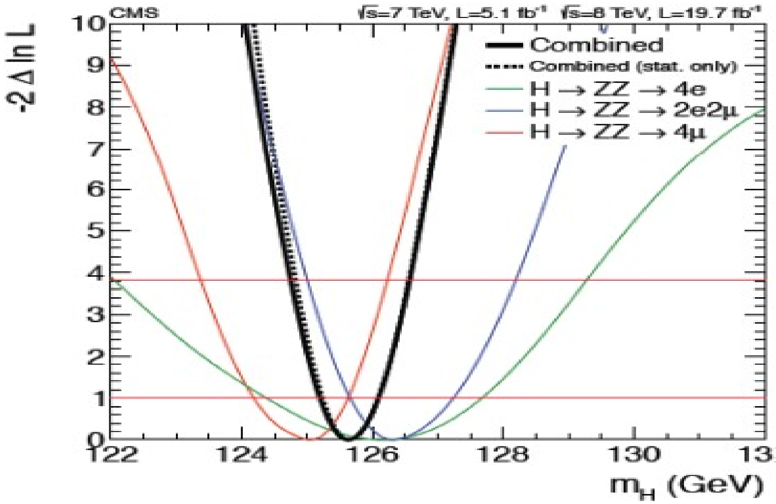
Not yet updated channels

Combined significance (local p-value):
(latest updates not included)

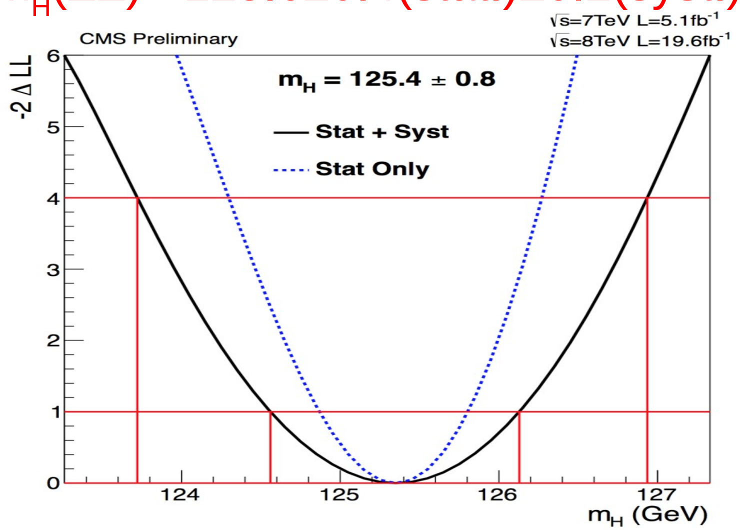


Discovery of Higgs boson: mas, spin-parity

- Mass peak position ($\gamma\gamma$,ZZ):

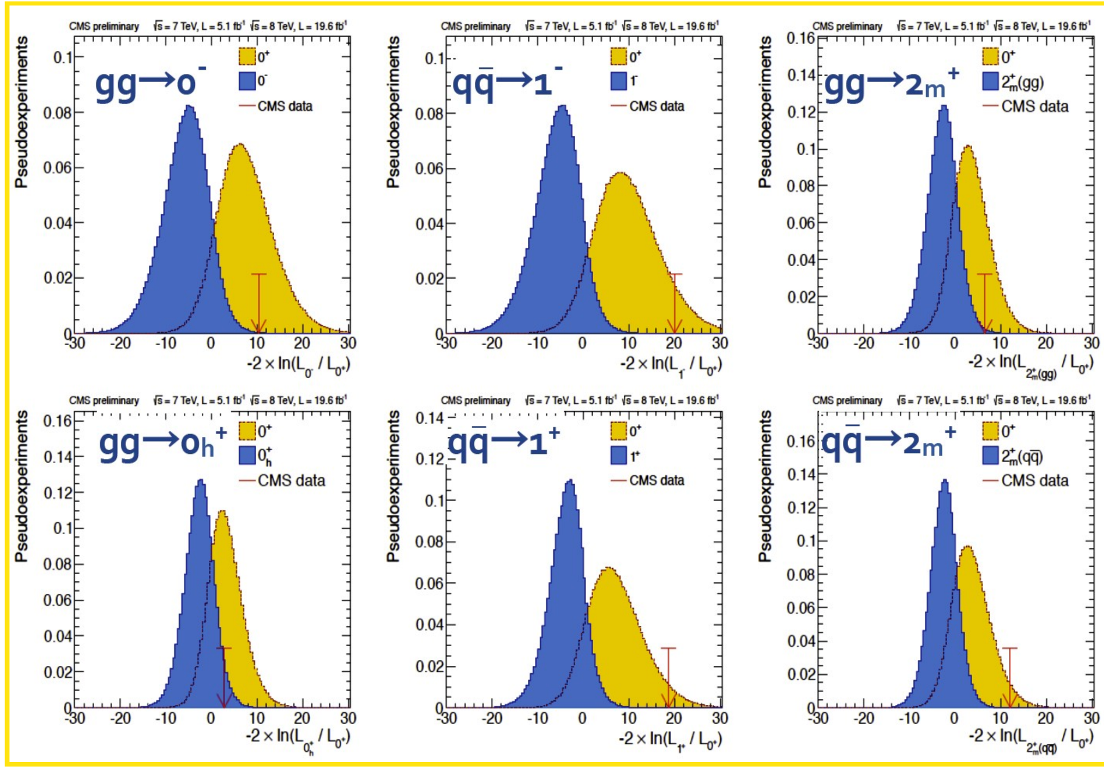


m_H(ZZ) =125.6±0.4(stat.)±0.2(syst.)



$m_H(\gamma\gamma)$ =125.4±0.5(stat.)±0.6(syst.)

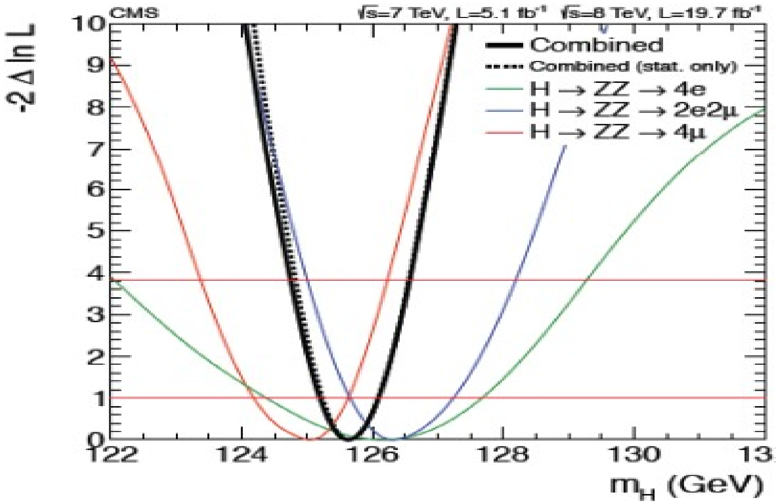
- ZZ leptons kinematics sensitive to resonance spin-parity (H prod. & decay):



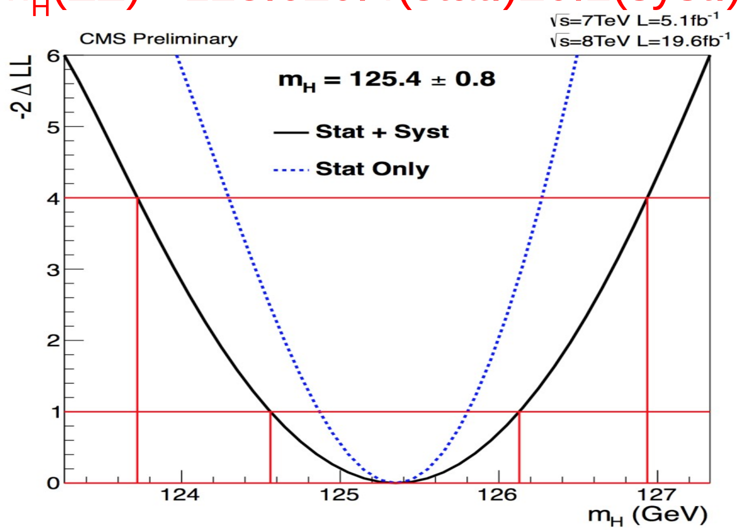
Studied pseudo-scalar, spin-1 and spin-2 models excluded at 95% CL or higher

Discovery of Higgs boson: properties

■ Mass peak position (γγ,ZZ):



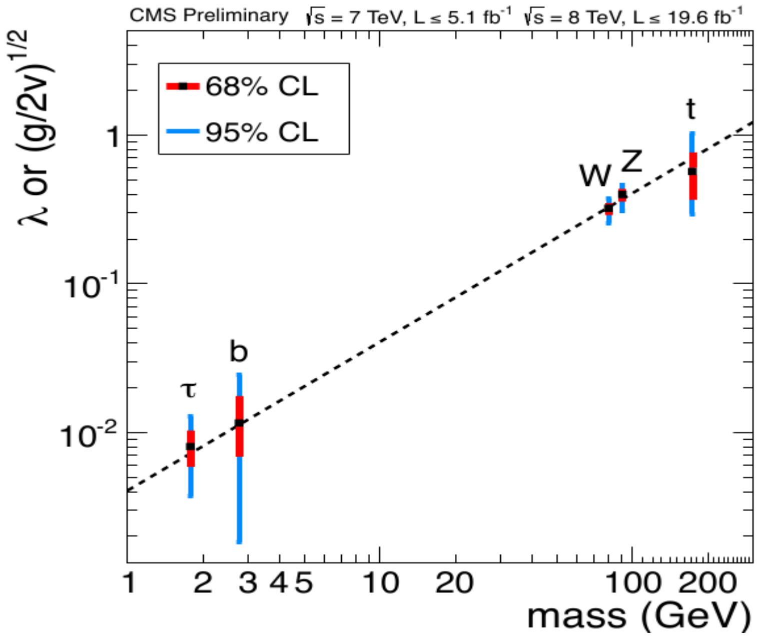
$m_H(ZZ)$ =125.6±0.4(stat.)±0.2(syst.)



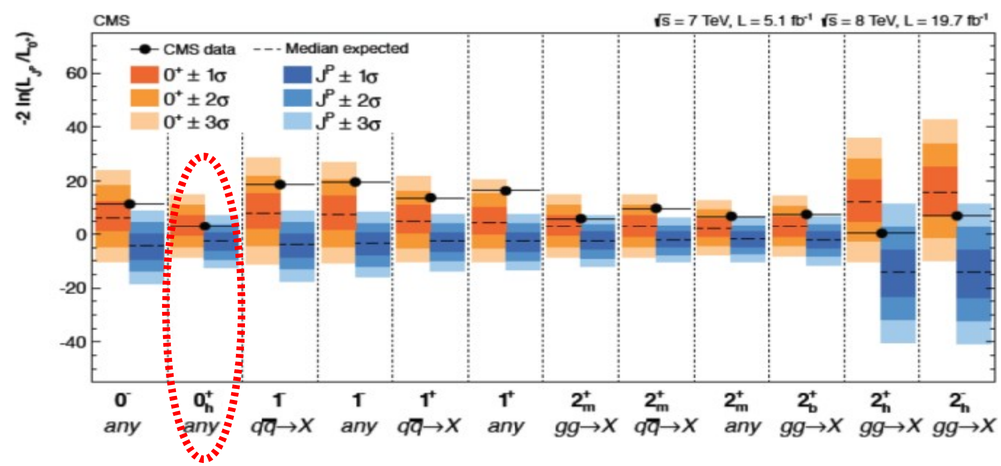
$m_H(\gamma\gamma)$ =125.4±0.5(stat.)±0.6(syst.)

■ Couplings:

Including all production & decay modes



■ Spin-parity:



Properties indicate <u>no deviation</u> from H(SM) so far

Higgs mass & top-quark mass

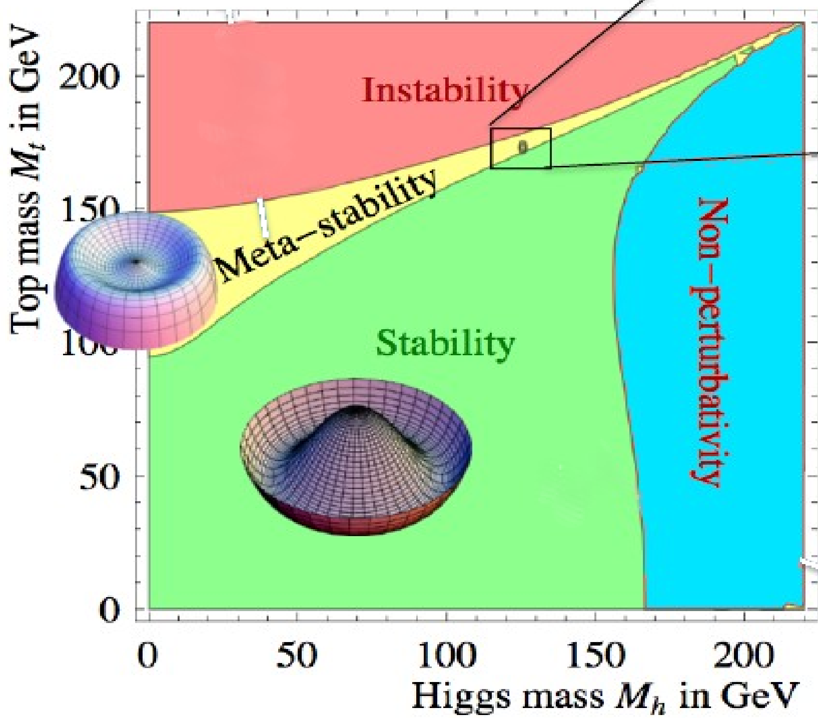
- Running of the Higgs self-coupling with energy:

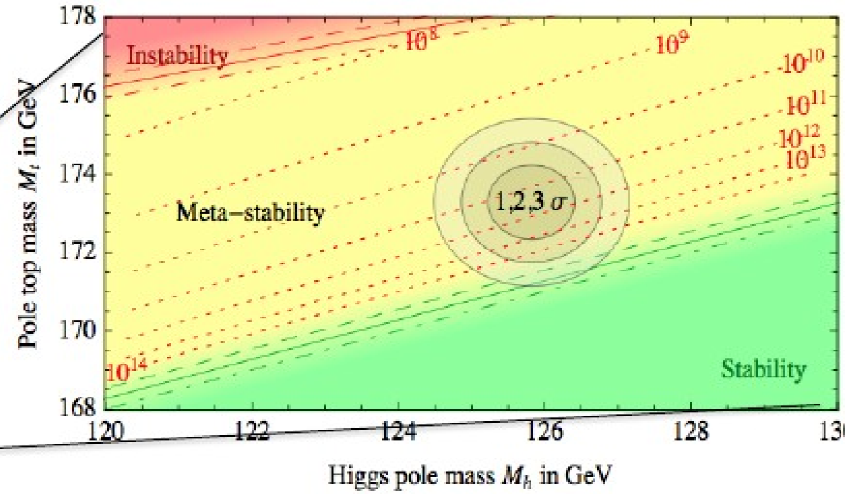
$$(4\pi)^2\frac{d\lambda}{d\ln\mu} = -6y_t^4+\frac{9}{8}g_2^4+\frac{27}{200}g_1^4+\frac{9}{20}g_2^2g_1^2+\lambda(12y_t^2-9g_2^2+\frac{9g_1^2}{5})+24\lambda^2+\text{higher loops}$$

If m_H too large: $\lambda \to$ non perturbative

If m_{top} too large: $\lambda \to$ negative

[Strumia, Moriond EWK'13]





$$M_h\ [\text{GeV}] > 129.8 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

$M_h = 125.8 \pm 0.4$ GeV (naive average of latest results)

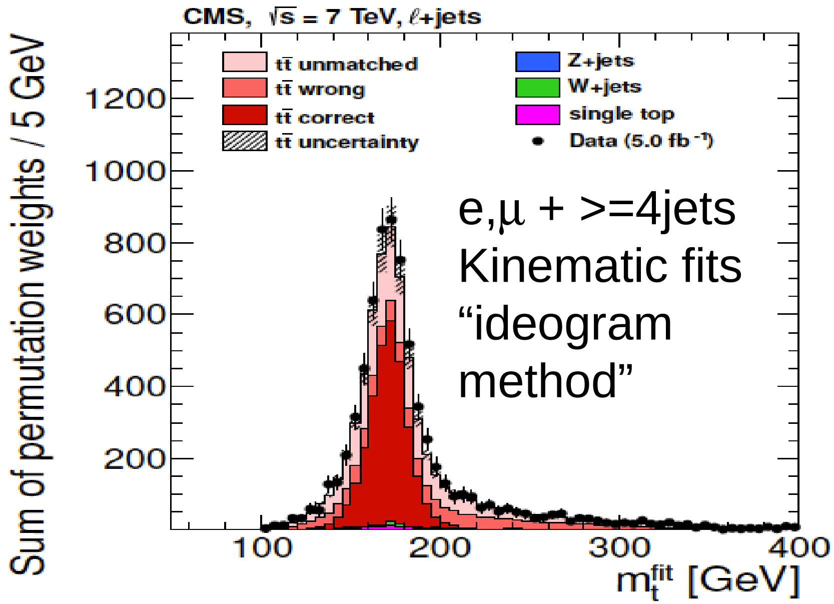
If m_{top}(pole)>171.2 GeV:

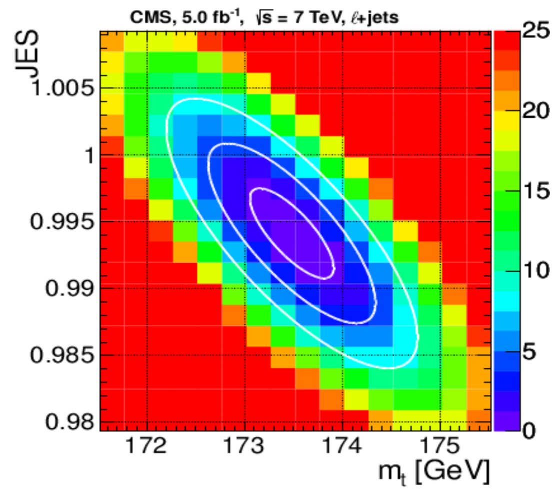
the universe is in a meta-stable state

(it will decay to true vacuum eventually)

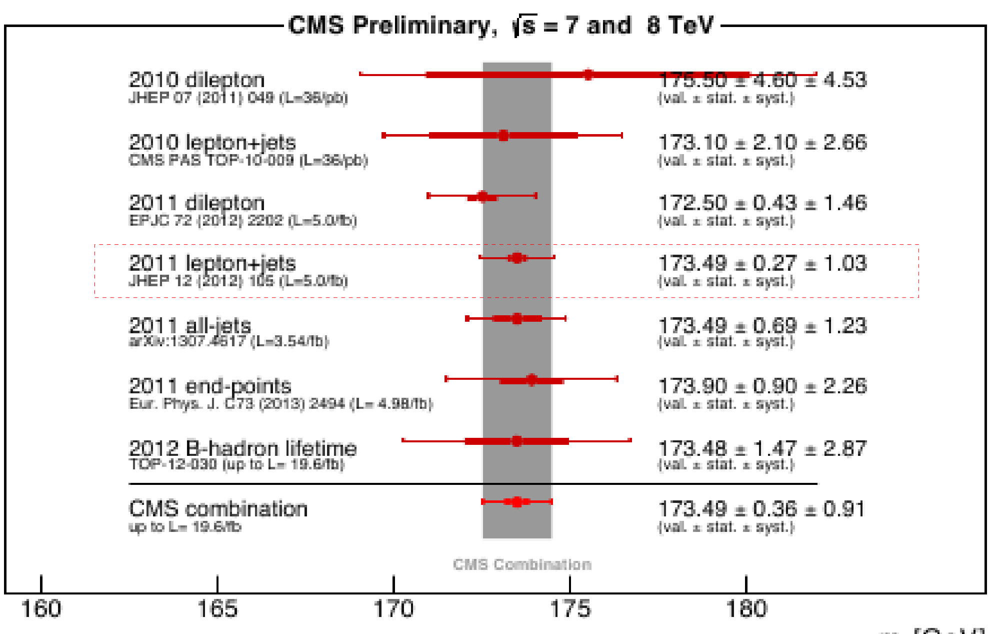
Top-quark mass

JHEP12(2012)105





Common likelihood fit to jet-energy-scale & m_{top}



- 7 different methods used at 7,8 TeV
  Good consistency among all:

CMS average:
m_{top} = 173.49 ± 0.36 ± 0.91 GeV

Dominant syst. uncertainties:
EXP: 0.36 GeV (JES)
TH: 0.45 GeV (color reconnection)

(Universe meta-stable at 2σ ?)

“Issues” with the Standard Model (2)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$ [Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[\boxed{(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}}\right] - \frac{\sqrt{2}}{v}\left[\boxed{(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}}\right]$$ [Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$ [Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[\boxed{(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}}\right] - \frac{\sqrt{2}}{v}\left[\boxed{(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}}\right]$$ [Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ [Higgs dynamics & mass]

✔ Higgs: Generation of masses via BEH mechanism now confirmed (2012!)

✘ Flavour: SM cannot generate observed matter-antimatter imbalance.

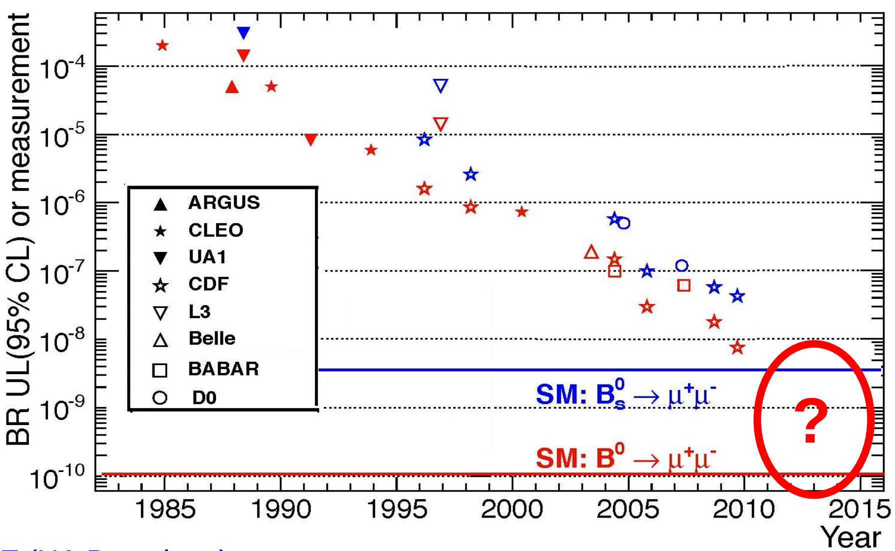
Origin of matter-antimatter asymmetry?

- Differences between particles-antiparticles (CP-violation in SM) way too small (10^{-16}) to explain matter-antimatter imbalance in Universe.

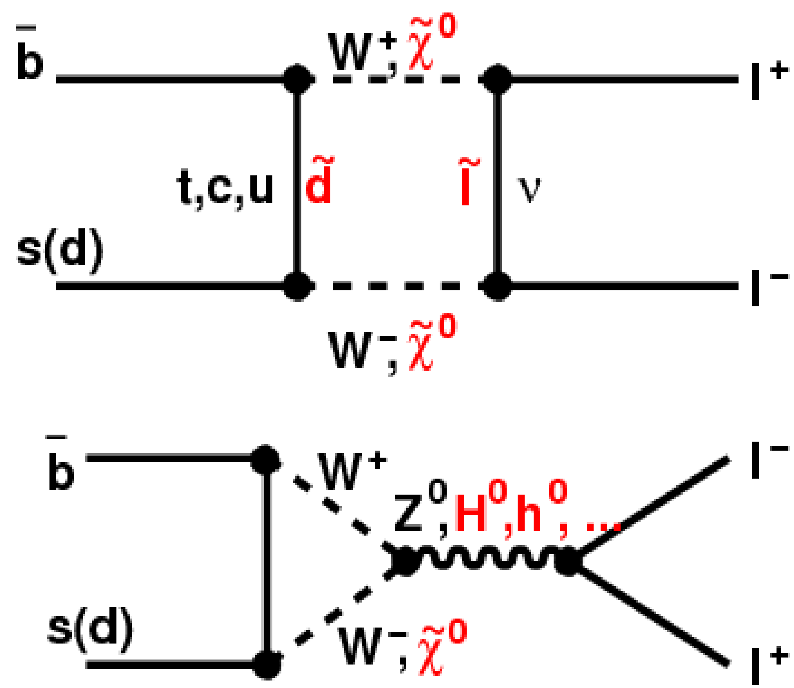
  ⇒ New particles/CP-phases needed to explain baryogenesis

- Indirect search of New Physics via virtual particles in loops:
  - Detailed B-mesons studies:

    - Rare decay rates
    - Branching ratios
    - Asymmetries in decays
    - Oscillation frequencies
    - Lifetimes

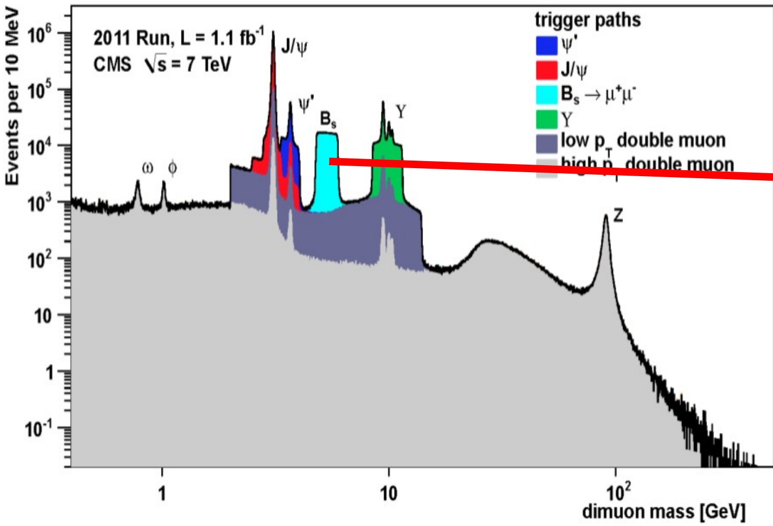


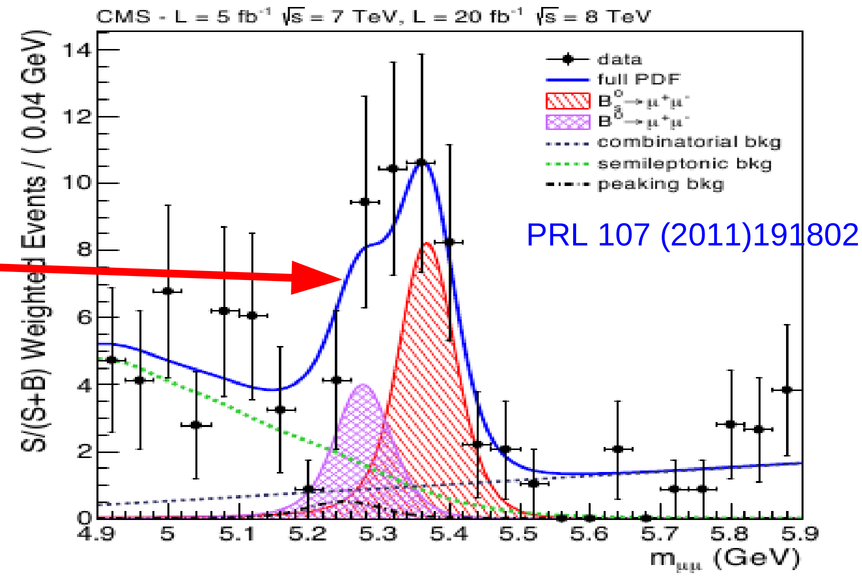
$BR(B_s, B_0 \to \mu\mu) \sim 4\cdot10^{-9}, 1\cdot10^{-10}$



Observation of $B_s \rightarrow \mu\mu$

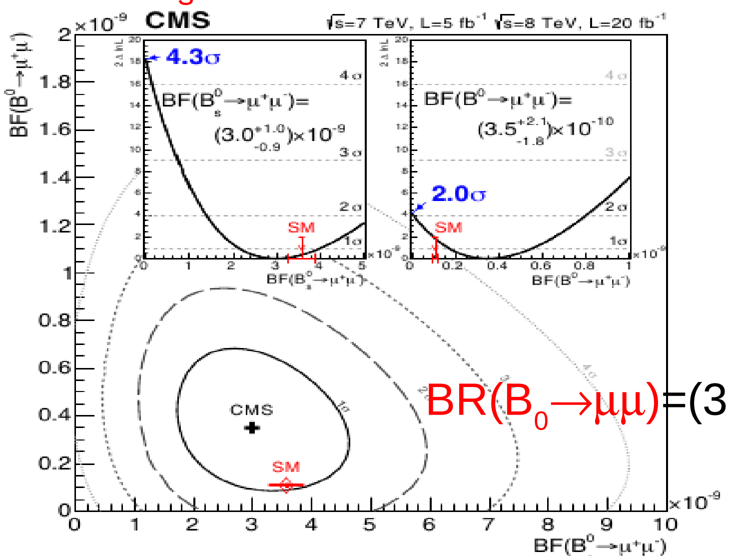
- High-stats trigger + MVA techniques:



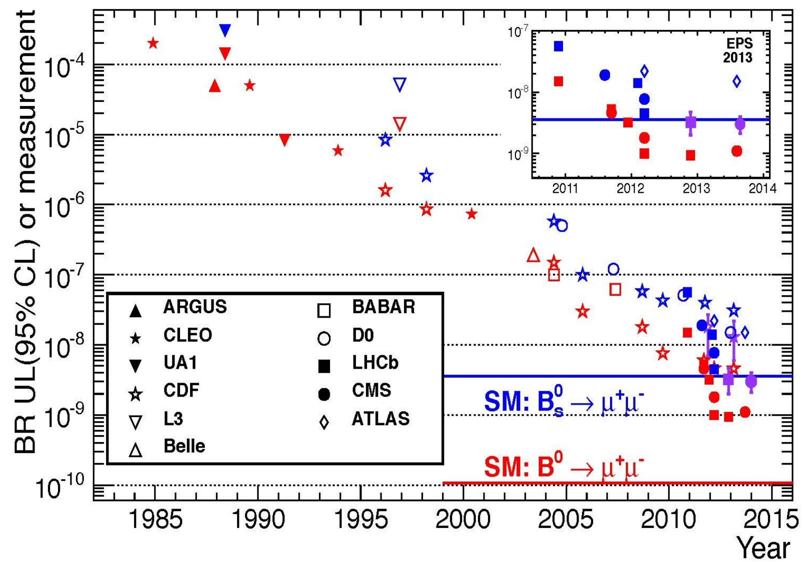


PRL 107 (2011)191802

- $BR(B_s \rightarrow \mu\mu)=(3.0\pm1.0)\cdot10^{-9}$,$(2.9\pm0.7)\cdot10^{-9}$ (CMS+LHCb)



$BR(B_0 \rightarrow \mu\mu)=(3.6\pm1.6)\cdot10^{-10}$ (2σ)



- No deviation wrt. SM (on to 5σ for B_0 at Run-2)

"Issues" with the Standard Model (3)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)}$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)}$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dyn. & mass]

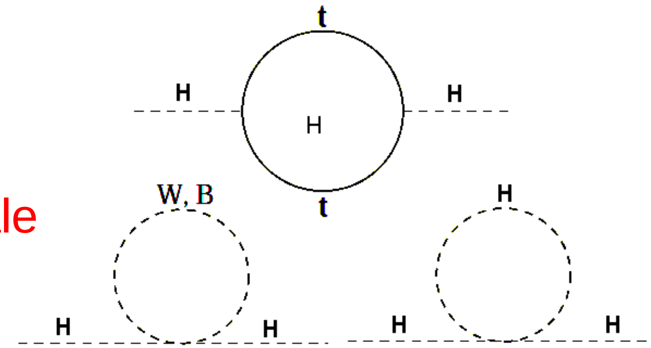
+ new particles/symmetries ?

✔ Higgs: Generation of masses via BEH mechanism now confirmed (2012!)

✘ Flavour: SM cannot generate observed matter-antimatter imbalance

✘ Fine-tuning: Higgs mass runs up «uncontrolled» up to Planck scale

BSM searches: SM fine-tuning problem

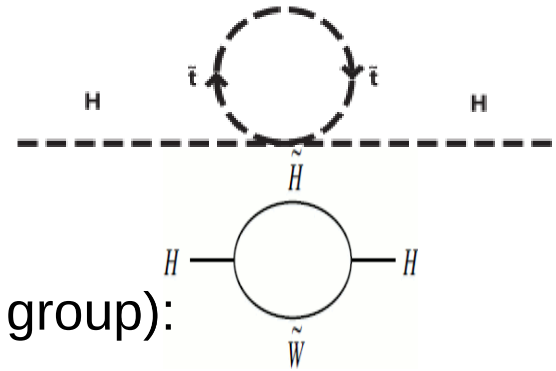


- Higgs boson is the only SM particle with mass:
  - m_H not "protected" by any internal symmetry
  - Scalar m_H has radiative corrections up to next phys. scale

$$m_h^2 = m_{tree}^2 + (\Delta m_H^2)_{top} + (\Delta m_H^2)_{gauge} + (\Delta m_H^2)_{higgs}$$

  - m_H from symmetry at Planck scale: fine-tuned to 10^{-16} !

+



- 3 general theoretical solutions:

  (1) Supersymmetry - SUSY: ➔ SM superpartners

  Extra "svirtual" contributions stabilize Higgs potential.

  (2) Higgs not elementary (Golds. boson of new gauge group):

  Technicolor, composite-Higgs, ..., (little-Higgs), ...

  ➔ techni-mesons/baryons, heavy-ρ, ..., (heavy-top, Z'), ...

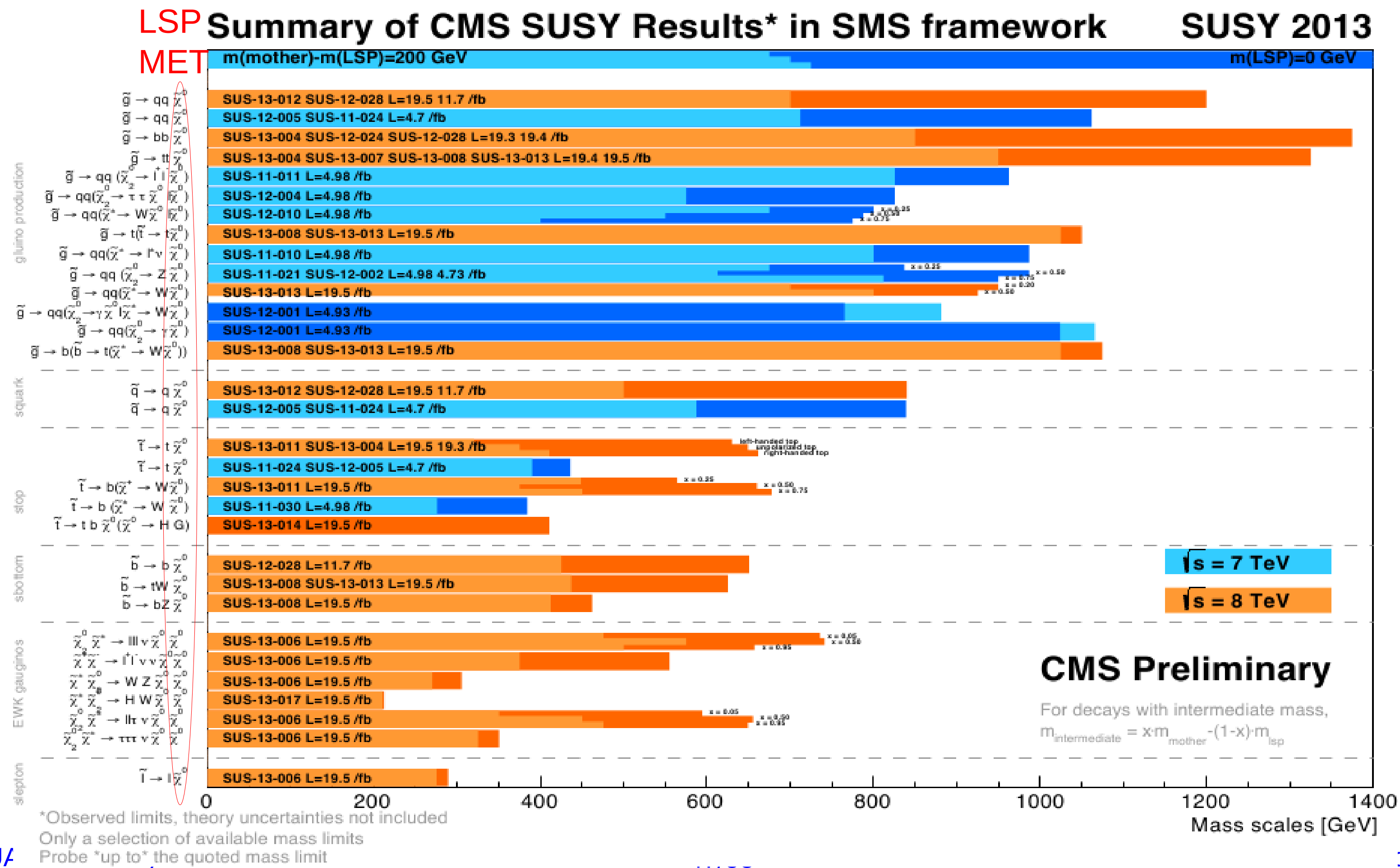
  (3) Quantum gravity sets in at ~TeV:

  Effects from hidden dims (0.1 mm to 10^{-19} m). ➔ KK-towers, radion, mini-BH, ...

- All solutions imply new particles at TeV scale

Constrained SUSY searches

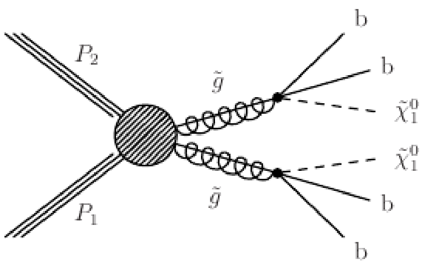
- cMSSM or mSUGRA = minimal SUSY SM extension with least # of params (m_0,$m_{1/2}$,tanβ,A,signμ), defined at GUT-scale & evolved down in energy.
- Many searches w/ multiple observables (mostly with MET). Spartner masses pushed to increasingly heavier masses. No signal of «simple» SUSY so far ...



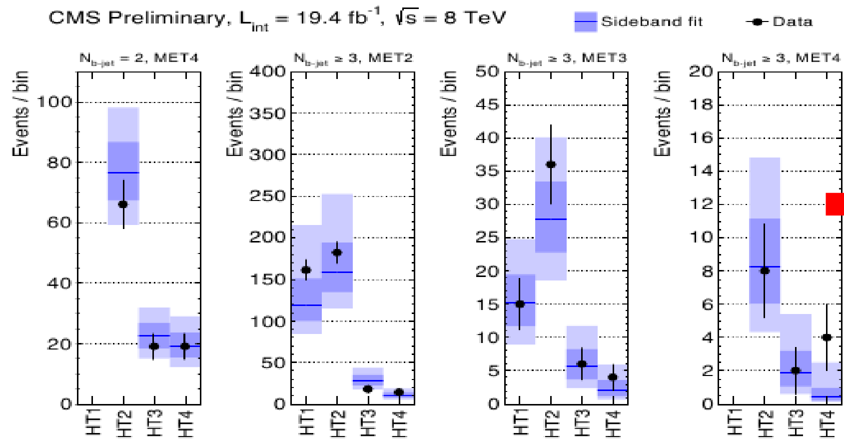
Less constrained searches: natural-SUSY

- Natural SUSY: m_H regularized by m_{stop}, squarks can be heavy, gluinos less.
- ~10% fine-tuning: squarks>TeV, stops<0.6 TeV, gluinos<1.4 TeV

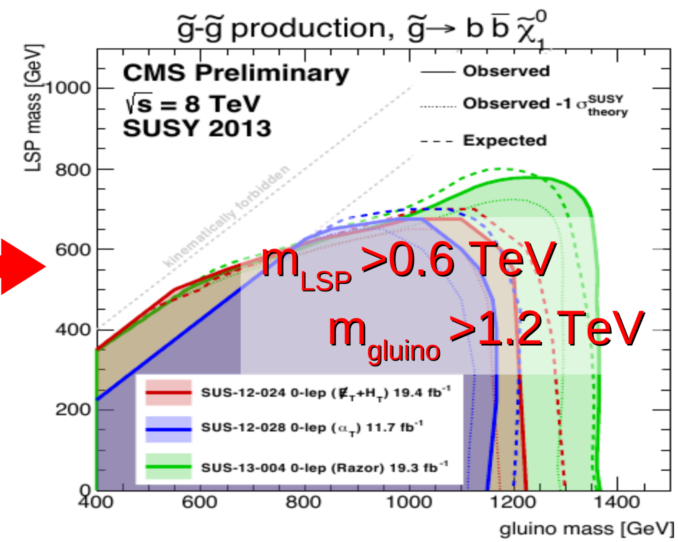
Gluinos decays into 3rd generation:

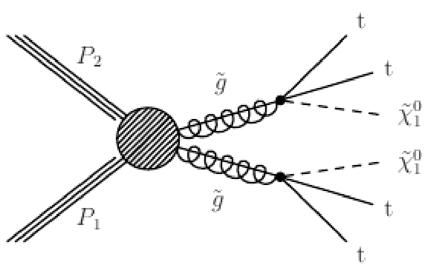


4 b-jets, MET



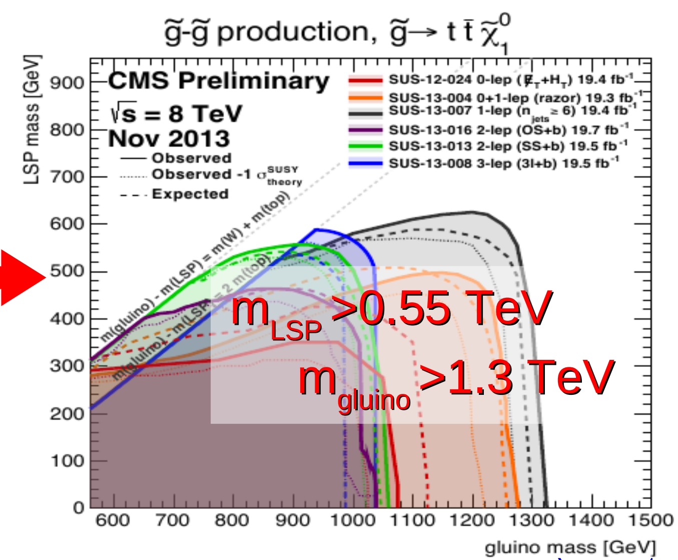
Increasing MET & N-jets --⟶





4 b-jets, 4W, MET

		S_T^{lep} [GeV]	control reg. data	prediction	observation
N_b=2	Muons	[250,350]	141	6.00 ± 2.40 (2.23)	9
		[350,450]	24	1.37 ± 1.19 (1.12)	2
		>450	9	0.0 ± 0.66 (0.66)	0
	Electr.	[250,350]	112	3.83 ± 1.84 (1.75)	9
		[350,450]	28	2.74 ± 2.02 (1.86)	2
		>450	9	0.0 ± 0.42 (0.42)	0
N_b ≥3	Muons	[250,350]	28	1.92 ± 0.95 (0.84)	0
		[350,450]	13	0.57 ± 0.58 (0.52)	0
		>450	2	0.0 ± 0.22 (0.22)	0
	Electr.	[250,350]	45	1.89 ± 1.03 (0.94)	4
		[350,450]	7	0.85 ± 0.80 (0.70)	0
		>450	0	0.0 ± 0.08 (0.08)	0



"Issues" with the Standard Model (4)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar\nu_L, \bar e_L)\,\tilde\sigma^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu\nu_R + (\text{h.c.})$$ [Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar\nu_L, \bar e_L)\,\phi M^e e_R + \bar e_R \bar M^e \bar\phi \begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar e_L, \bar\nu_L)\,\phi^* M^\nu \nu_R + \bar\nu_R \bar M^\nu \phi^T \begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$ [Lepton masses]

$$+(\bar u_L, \bar d_L)\,\tilde\sigma^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$ [Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar u_L, \bar d_L)\,\phi M^d d_R + \bar d_R \bar M^d \bar\phi \begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar d_L, \bar u_L)\,\phi^* M^u u_R + \bar u_R \bar M^u \phi^T \begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$ [Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2.$$ [Higgs dyn. & mass]

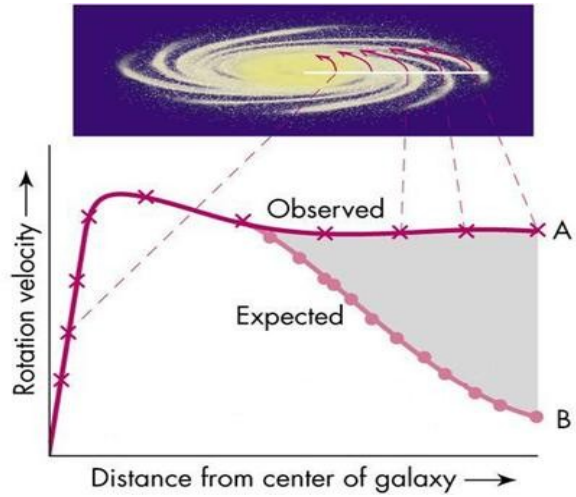
+ new particles/symmetries ?

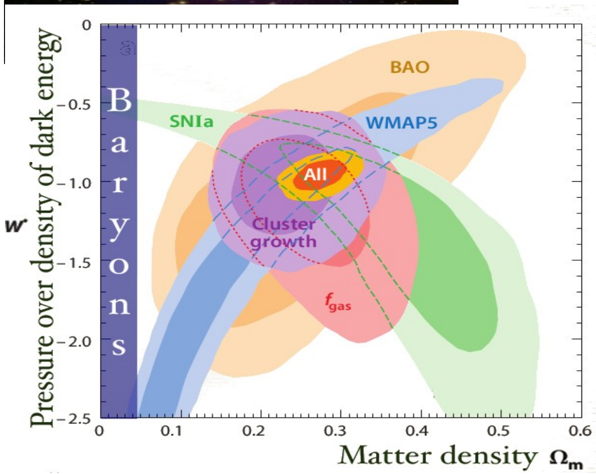
- ✔ Higgs: Generation of masses via BEH mechanism now confirmed (2012!)
- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✘ Fine-tuning: Higgs mass runs up «uncontrolled» up to Planck scale
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions-bosons)
- ✘ Others: ν's masses, gauge-gravity unification, cosmological const., dark energy,...

BSM searches: Dark matter = new heavy particle?

- Dark matter evidences:

  - Galactic rotation curves
  - Collision of cluster galaxies
  - CMB background T fluctuations
  - Large-scale structure universe





- Properties:

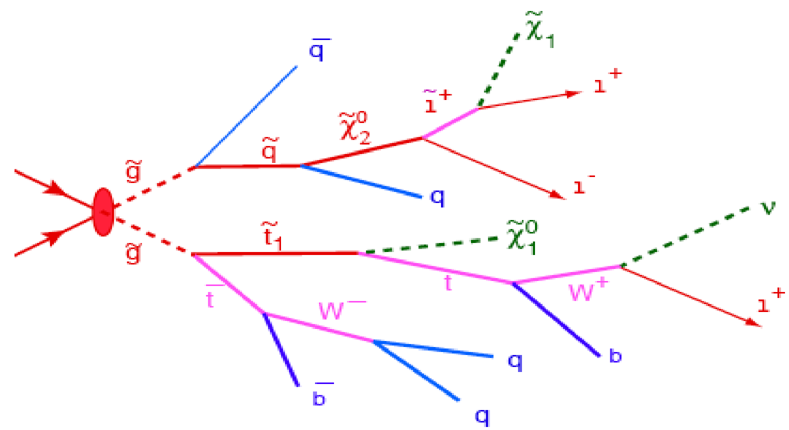
  - Sensitive to gravitation, stable, massive, early Universe relic

  $\rightarrow$ Weakly Interacting Massive Particle (WIMP) ?

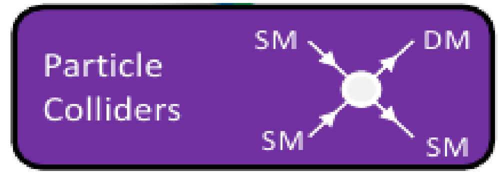
  $m_{DM} \sim$ 10 GeV – 1 TeV, $\sigma_{DM\text{-}SM} \sim \sigma_{weak}$, $\Omega_{DM} \sim O(10\%)$

- Beyond-SM candidate DM particles:

  - Lightest SUSY Particle (LSP): neutralino, ...
  - Extra-Dims: lightest Kaluza-Klein tower, ...
  - Heavy R-handed or sterile neutrinos.
  - Axions.
  - Unknown hidden sector.



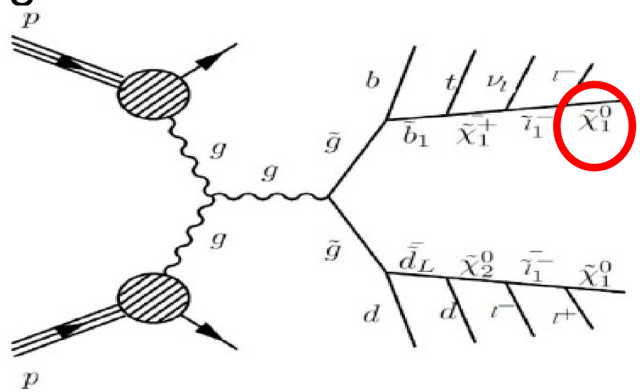
Dark matter: Collider searches



- DM produced in p-p final-state observable via:
  large missing transverse energy (MET) from:

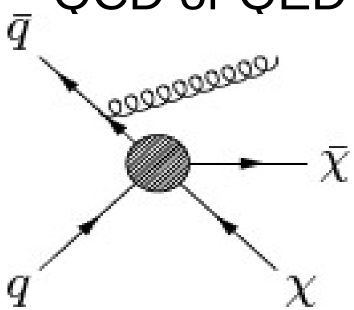
➔ Lightest Particle (χ^0) in RP-conserving SUSY:

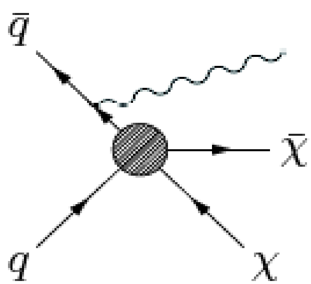
Prominent WIMP candidate.
Decay cascade with
large MET, many jets & leptons



➔ Generic DM-pair searches:

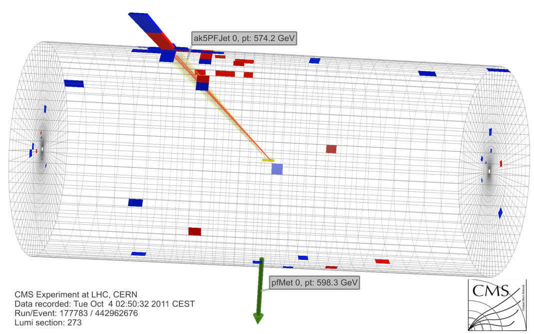
Large MET plus initial-state
QCD or QED radiation:





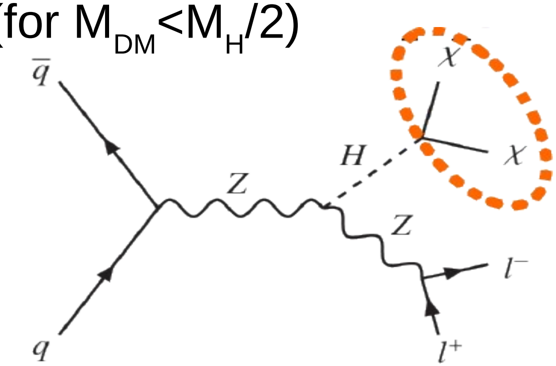
mono-jet mono-photon

(also mono-leptons)



➔ Higgs decay to DM-pair:

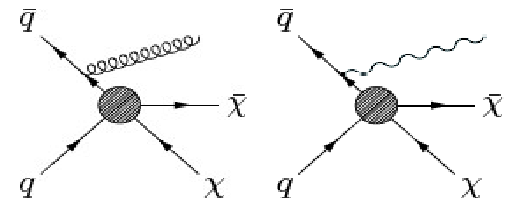
(for $M_{DM}<M_H/2$)



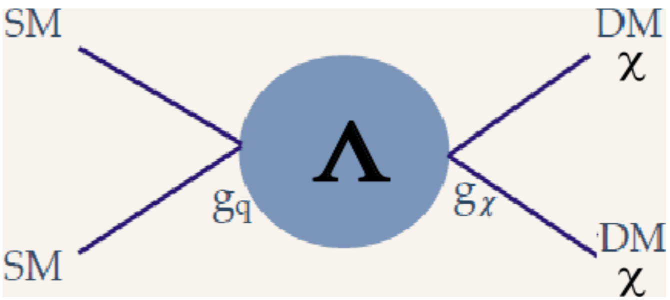
Dark matter: Collider searches (generic DM pair)

(1) Search mono-jet,mono-photon excess above SM background: $Z(\nu\nu)$+j,γ (~70%), $W(\nu l_{escape})$+j,γ (~30%).

Remove other EWK&QCD backgds: veto iso-leptons & $\Delta\phi$ cut



(2) Interpret (no) excess within generic effective field theory (EFT) for contact SM-DM interaction, characterized by 2 parameters:



$\Lambda = M_*/\sqrt{g_\chi g_q}$: Scale of effective interaction

M_χ : mass of DM particle (Dirac fermion)

for various types of DM-SM couplings, e.g.:

Name	Initial state	Type	Operator
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$

(spin-independent: SI)

(spin-dependent: SD)

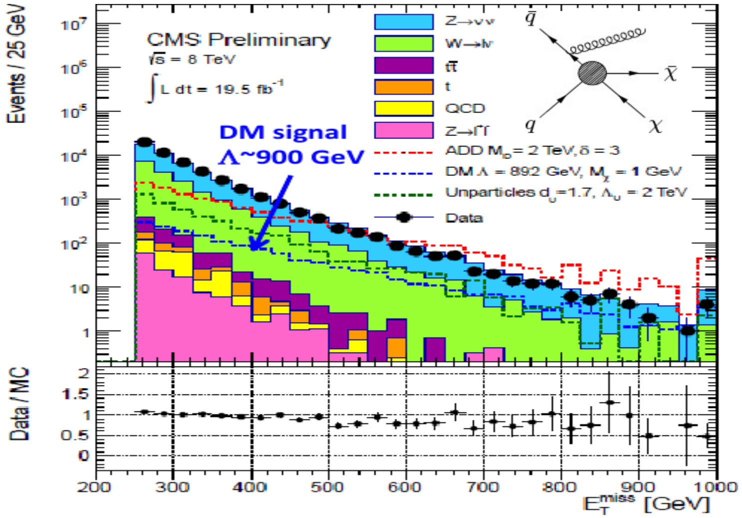
(3) Set limits in DM mass vs. interaction-strength for SI & SD couplings:

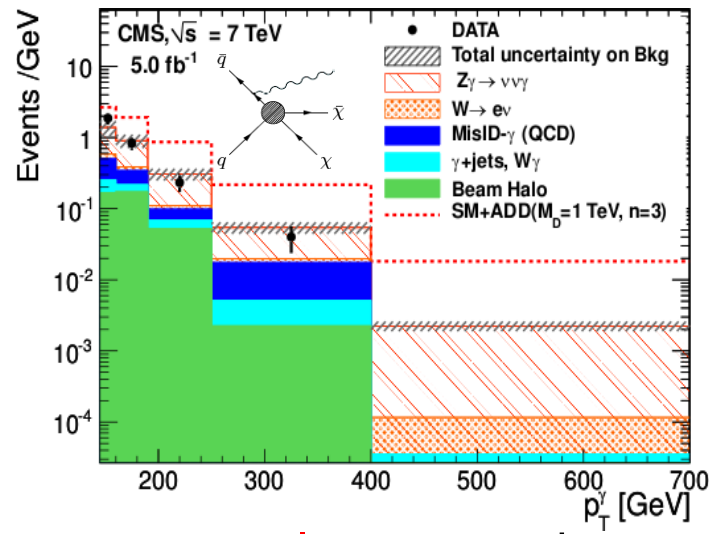
$$\sigma(\chi N \rightarrow \chi N) \sim \frac{g_q^2 g_\chi^2}{M_*^4}\mu_{\chi N}^2$$

$M_{\chi N}$ = reduced mass of DM-nucleon system

Dark matter searches: monojets/monophotons

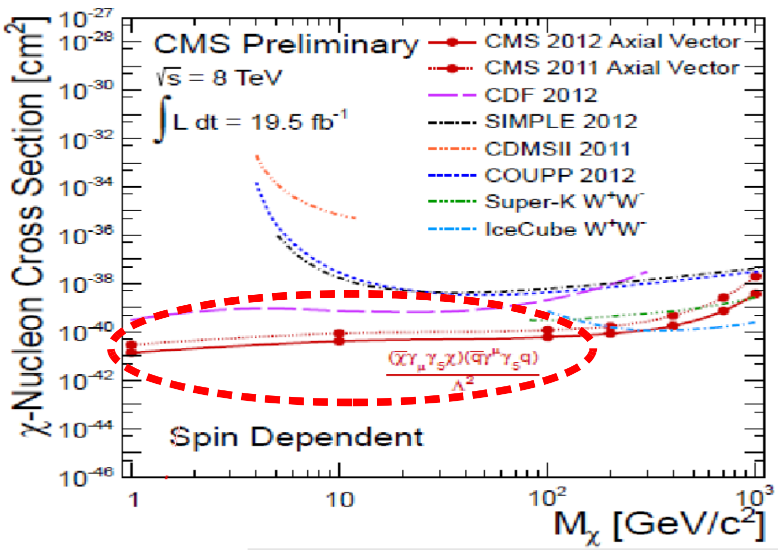
- MET, p_T^{γ} distributions after cuts for SM backgrounds & DM signal:

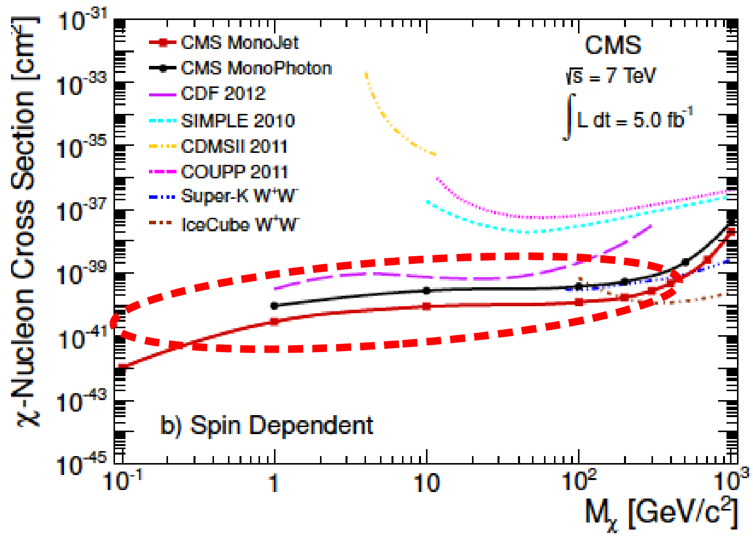




CMS-PAS-EXO-12-048
JHEP09(2012)094
PRL 108 (2012)261803

- No excess: Limits on DM mass & WIMP-nucleon x-sections:





Best limits for low DM mass!

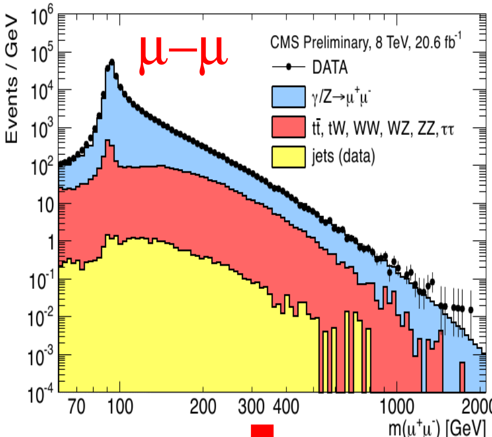
$M_\chi \sim 1 - 10$ GeV

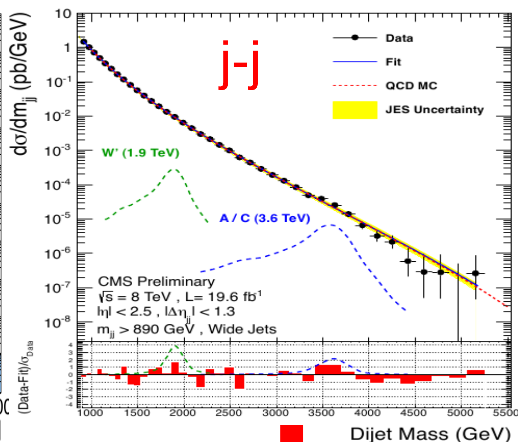
$\sigma_{\chi N} \sim 10^{-39}$ (SI)

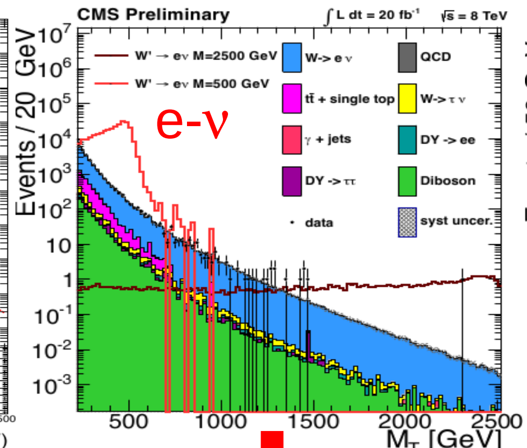
$\sigma_{\chi N} \sim 10^{-41}$ (SD)

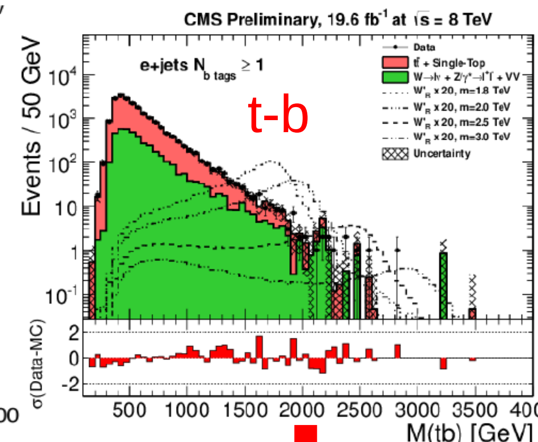
BSM searches: High-mass resonances

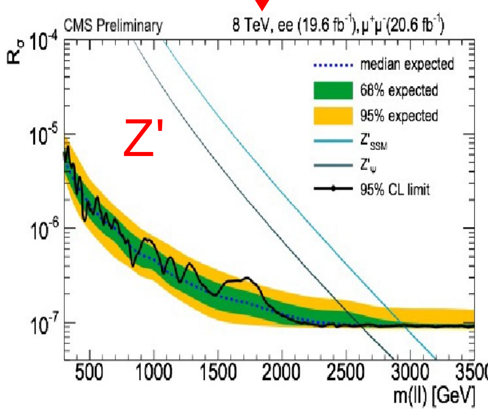
- «Simple» generic procedure:
  (i) Reconstruct pairs of high-p_T objects: jets, leptons, bosons, ...
  (ii) Look at inv. mass tails for deviations from smooth SM backgrounds.
  (iii) Interpret (lack of) excess within (simplified) BSM models: Set limits for NP

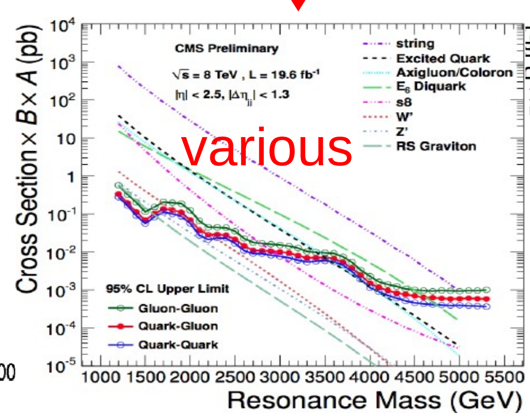


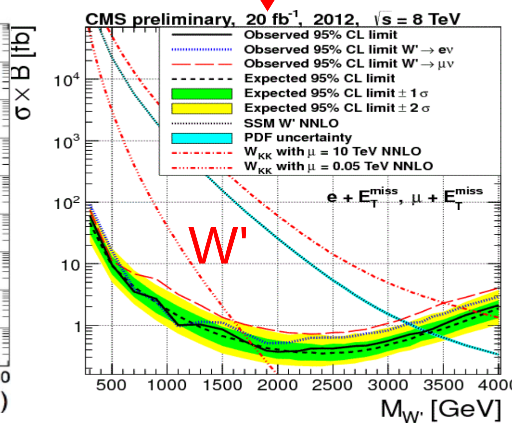


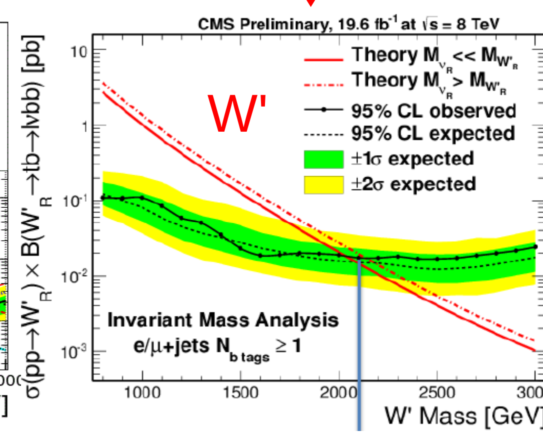








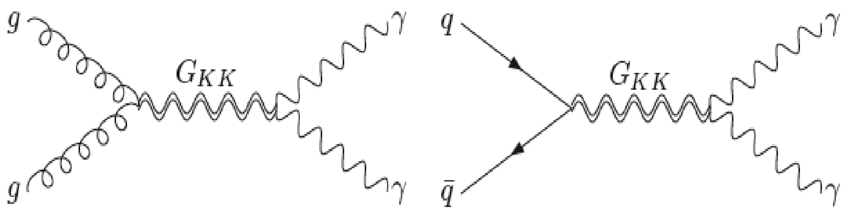




BSM searches: Extra-Dimensions via high-mass $\gamma\gamma$

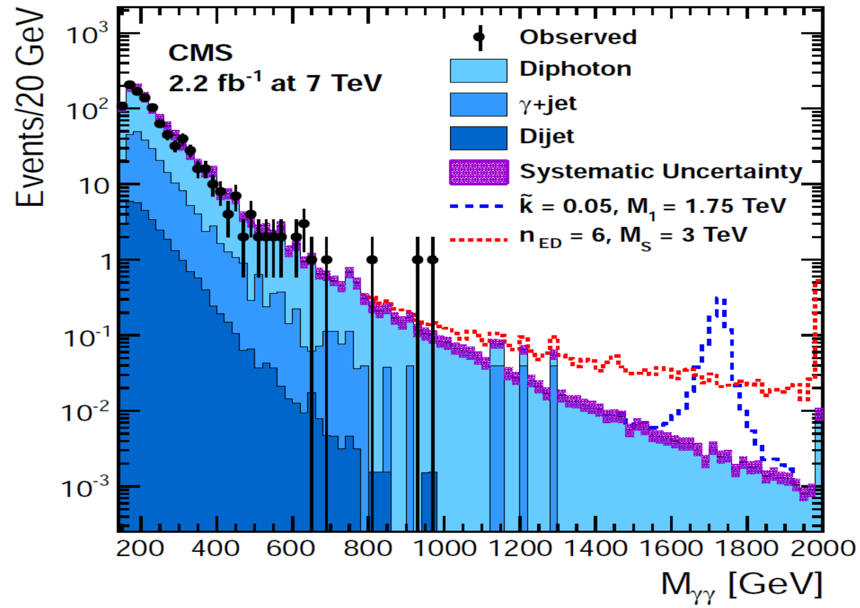
PRL108 (2012) 111801

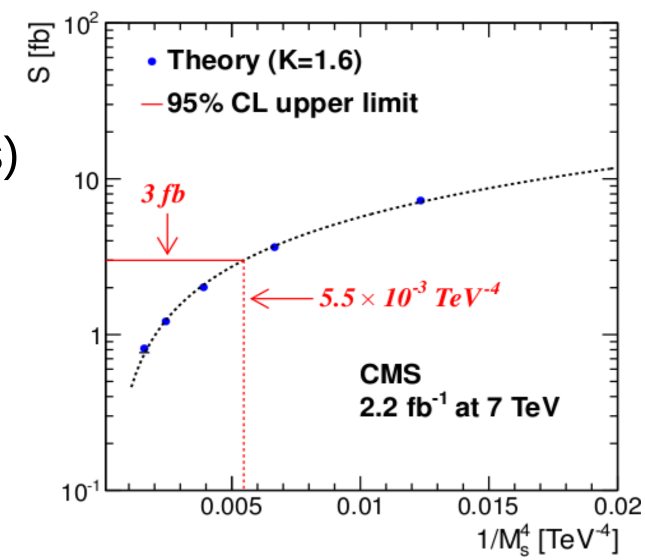
- Extra Dimensions (ED) signature: virtual Gravitons ($qq/gg \to G^* \to \gamma\gamma$):



(spin-2 G* s-wave decay into diphoton)

- Warped ED (RS):
  - G* resonance (Kaluza-Klein modes)
  - 2 parameters:
    M_1 (1^{st} excitation)
    k/M_{Pl} (dimensionless coupling to SM fields)
- Large ED (AAD):
  - Non-resonant enhancement at high $m_{\gamma\gamma}$
  - 2 parameters:
    n_{ED} (num. extra-dims),
    M_s (effective Planck scale)



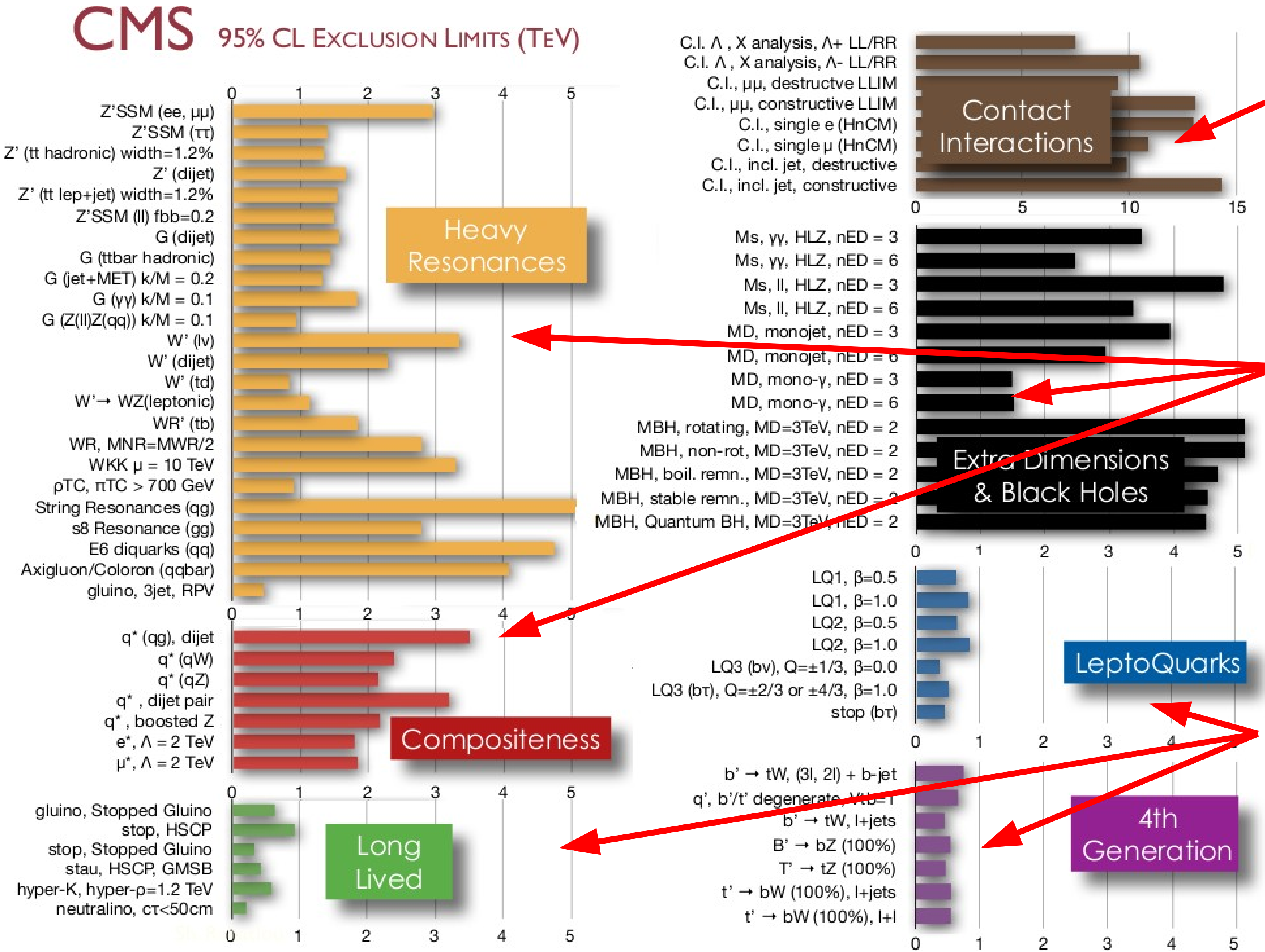


RS G* limits:

k/M_{Pl}	M_1(TeV)
0.01	0.86
0.1	1.84

ADD (non-reso):
M_S >2.3-3.8 TeV
(depends on n_{ED} & formalism)

Summary beyond-SM (non-SUSY) searches



(1) No contact interaction up to Λ~10 TeV

(2) Λ,m_X pushed above 1–5 TeV in many NP models:

- Extra-dim, BH
- Z',W',G reson.
- Compositeness

(3) m_X >0.5 TeV for

- long-lived
- leptoquarks
- 4^{th} gen. b',t'

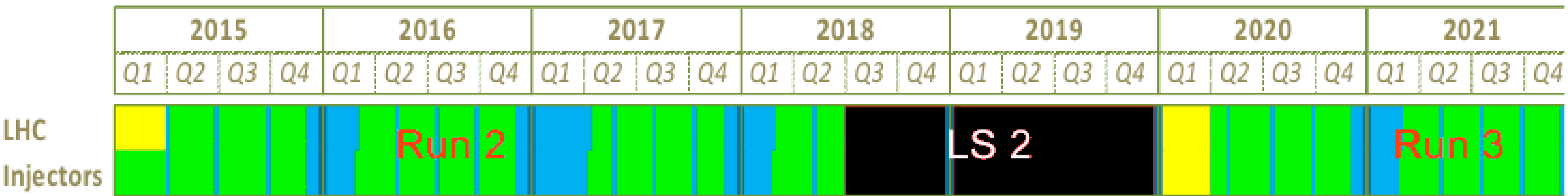
LHC Outlook

Run-2 [2015-2018]: p-p @ 13-14 TeV, L_{int} ~ 200 fb^{-1} (Pb-Pb@5-5.5 TeV, p-Pb@8-8.8 TeV)

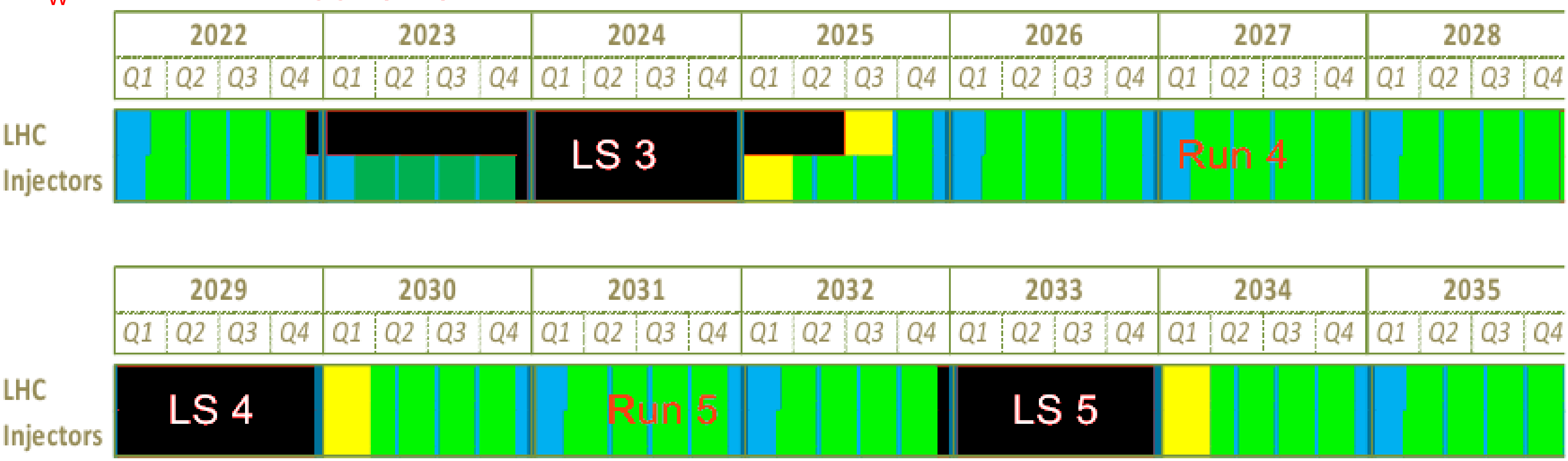
Run-3 [2020-2022]: p-p @ 14 TeV, L_{int} ~ 300 fb^{-1} (Pb-Pb @ 5.5 TeV, p-Pb @ 8.8 TeV)

Run-4 [2026-2028] High-luminosity LHC: p-p @ 14 TeV, L_{int}= 3000 fb^{-1}

LS2	starting in 2018 (July)		18 months + 3months BC (Beam Commissioning)
LS3	LHC: starting in 2023	=>	30 months + 3months BC (Beam Commissioning)
	injectors: in 2024	=>	13 months + 3months BC (Beam Commissioning)



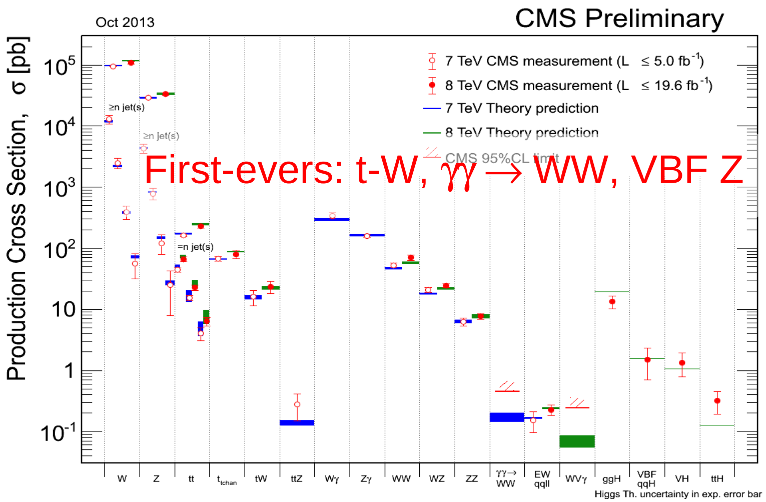
m_W, WW→WW, Higgs properties, SUSY/BSM searches,...



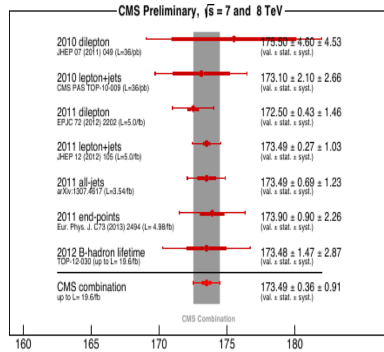
Summary

■ Precision (N)NLO QCD&EWK:

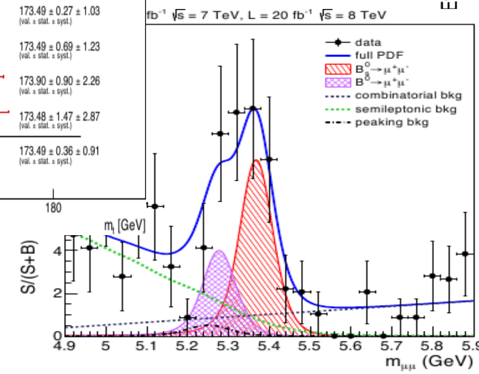
First-evers: t-W, $\gamma\gamma \to$ WW, VBF Z



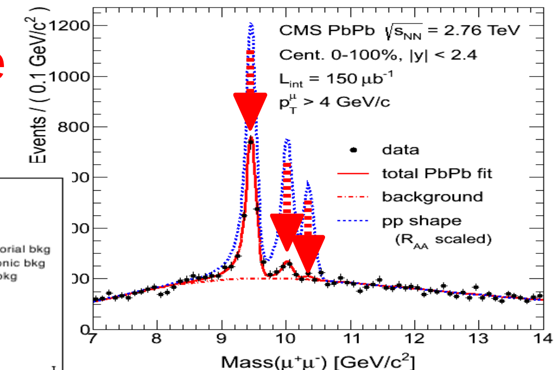
■ Precision fundamental SM parameters:

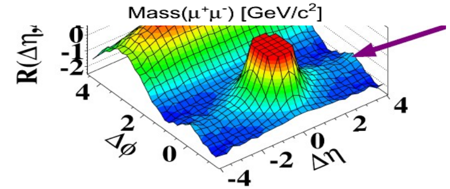


■ Very rare decays:

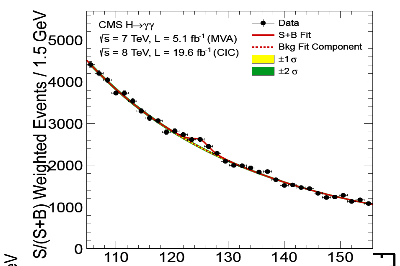


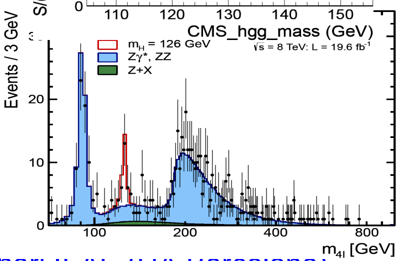
■ Intriguing dense QCD-matter data:

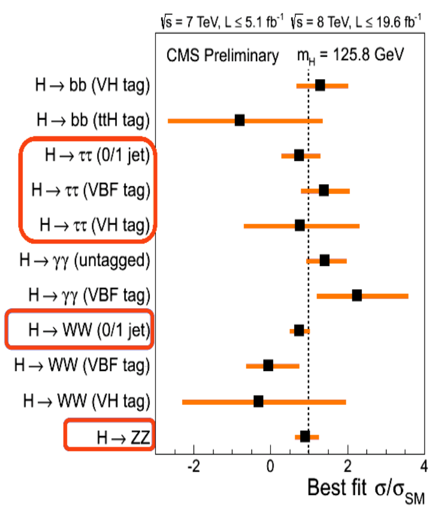




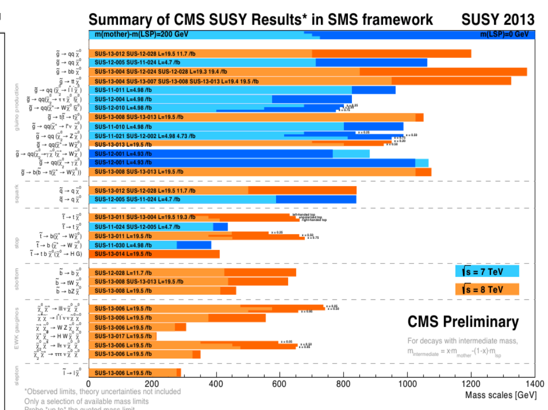
■ Discovery of Higgs boson w/ SM properties at m~125 GeV!

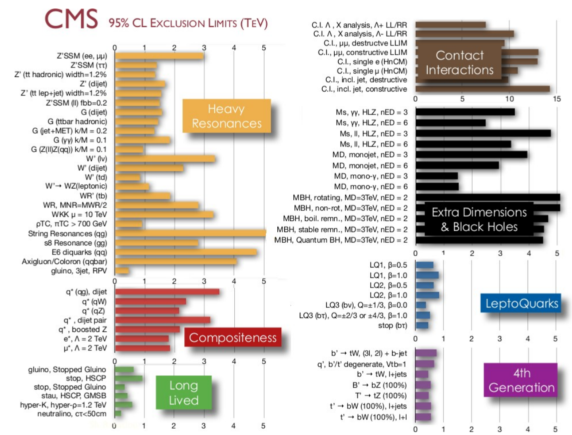






■ No (simple)SUSY/BSM signals yet at ~1 TeV



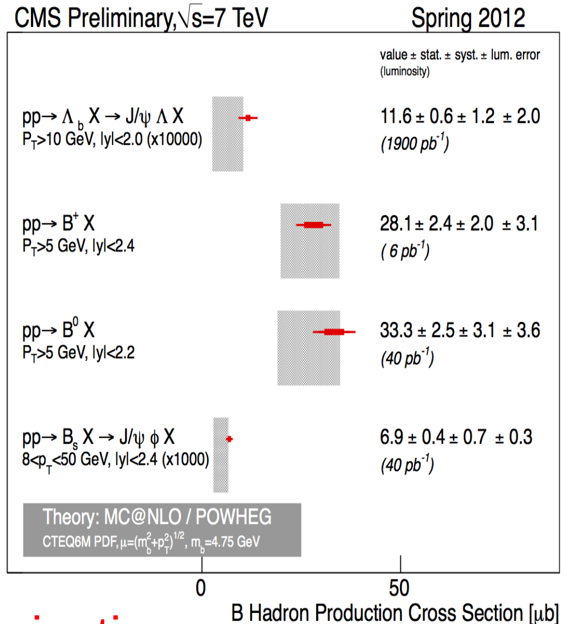


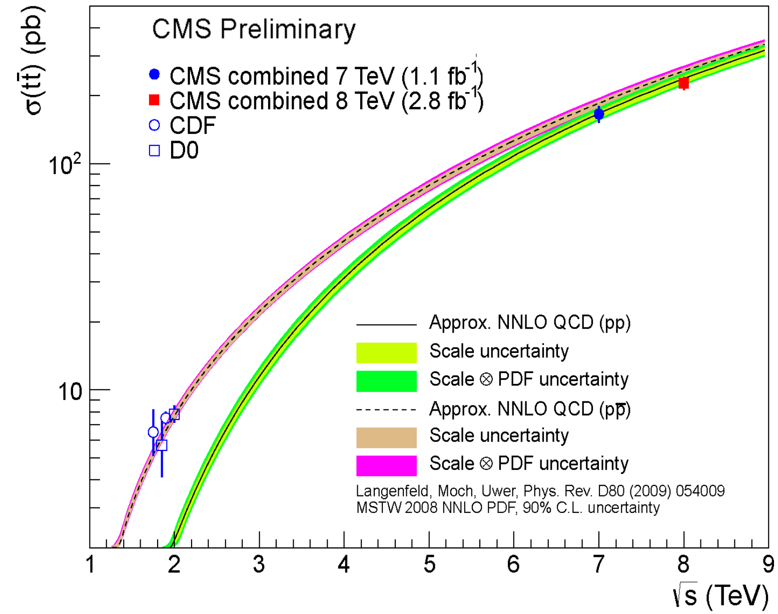
■ Back to discovery-mode starting Apr'15 !

Back up slides

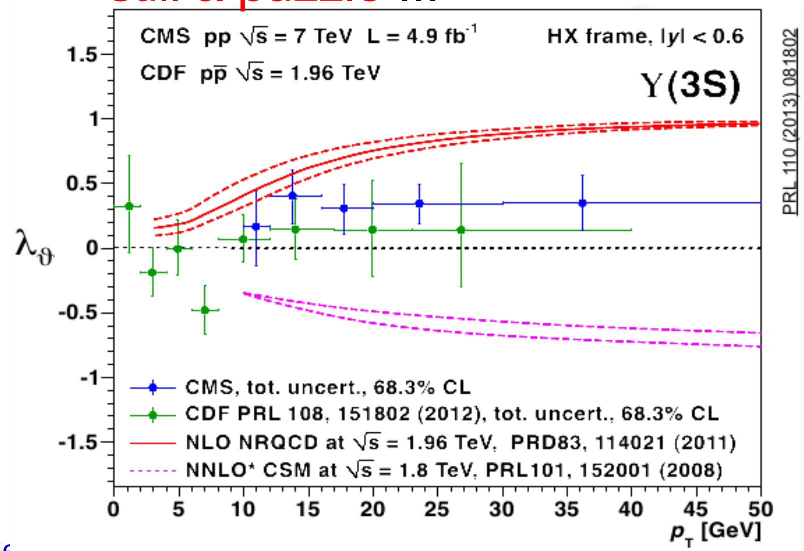
QCD: heavy-Q cross-sections (& $Q\bar{Q}$ polarization)

■ Bottom & top x-sections in good agreement with NLO (approx. NNLO) predictions:





■ Although quarkonia polarization still a puzzle ...



■ Quality of differential top x-sections can constrain gluon (N)NLO PDF: