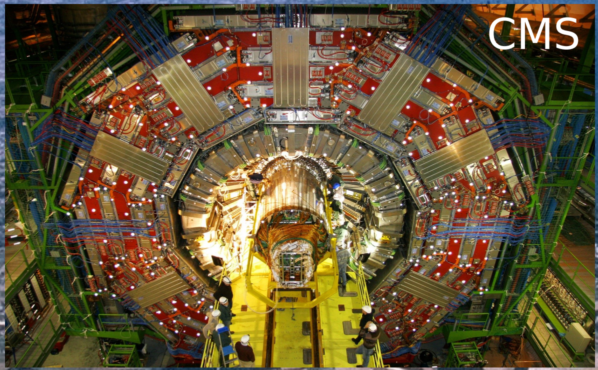


Highlights of CMS physics during the LHC Run-1

53rd Intl Winter on Nuclear Physics
Bormio 2015
28th January 2015

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:

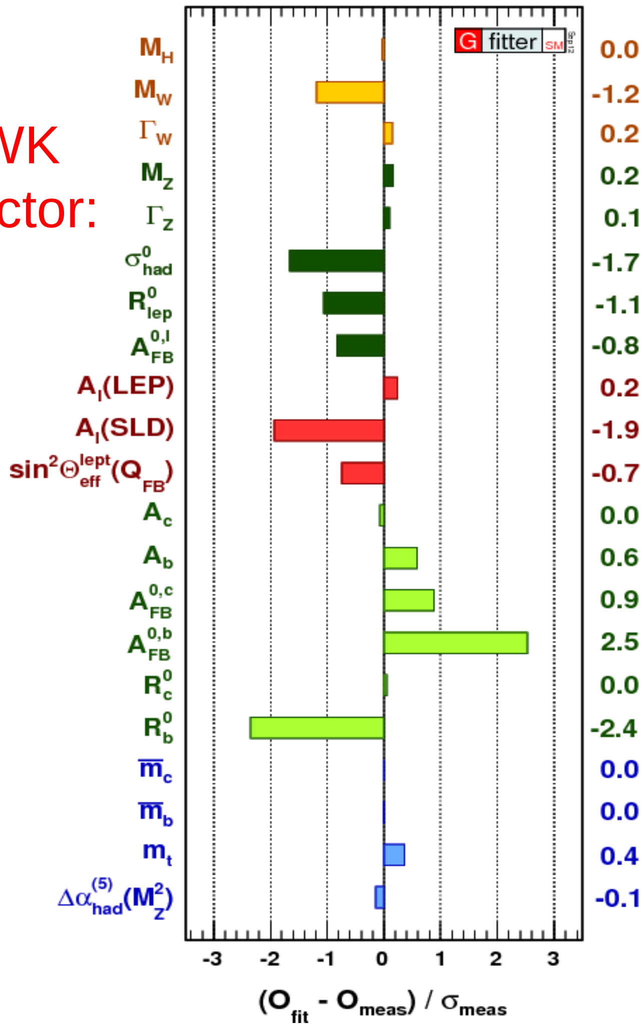
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu + ig_2(\mathbf{W}_\mu \mathbf{W}_\nu - \mathbf{W}_\nu \mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu \mathbf{G}_\nu - \partial_\nu \mathbf{G}_\mu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

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

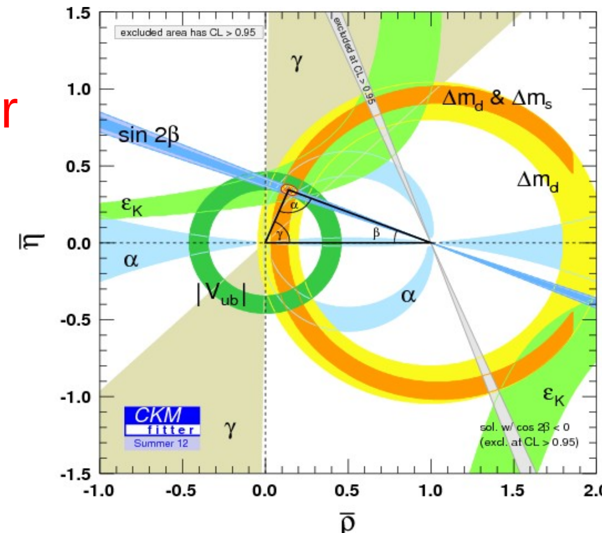
Standard Model of particles & interactions

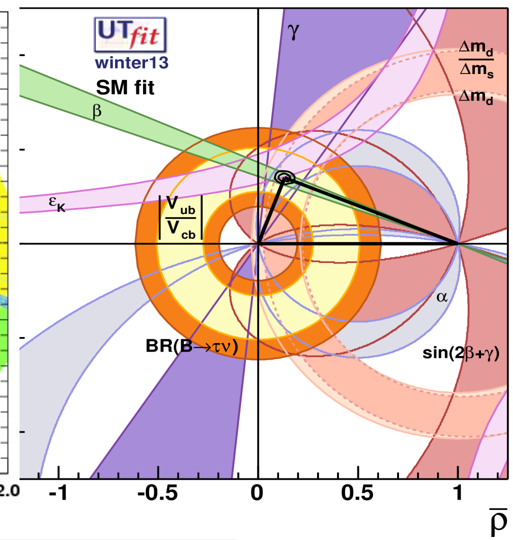
- SM: Renormalizable QFT whose internal consistence & predictive power have been experimentally confirmed to great precision:

EWK sector:

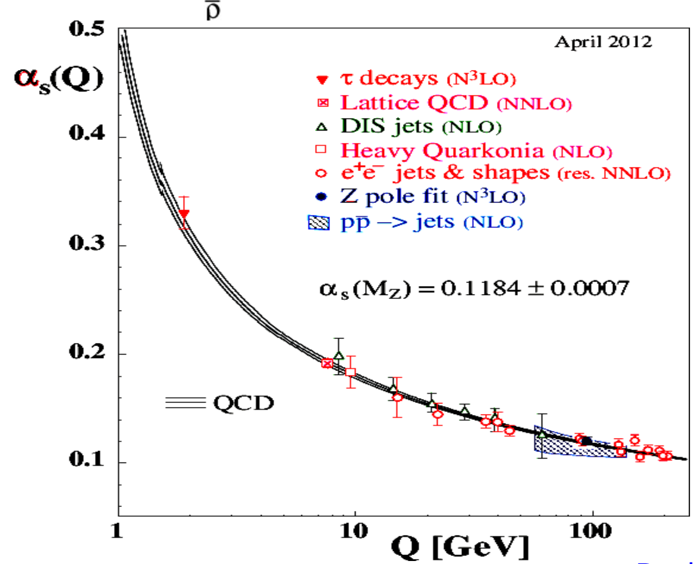


Flavour sector:





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]

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

✘ Higgs: Generation of masses* via BEH mechanism not confirmed (up to 2012)
(*) Plus unitarization of WW scattering at high energies

“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]

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

[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]

- ✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)
- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance

"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 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: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

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

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

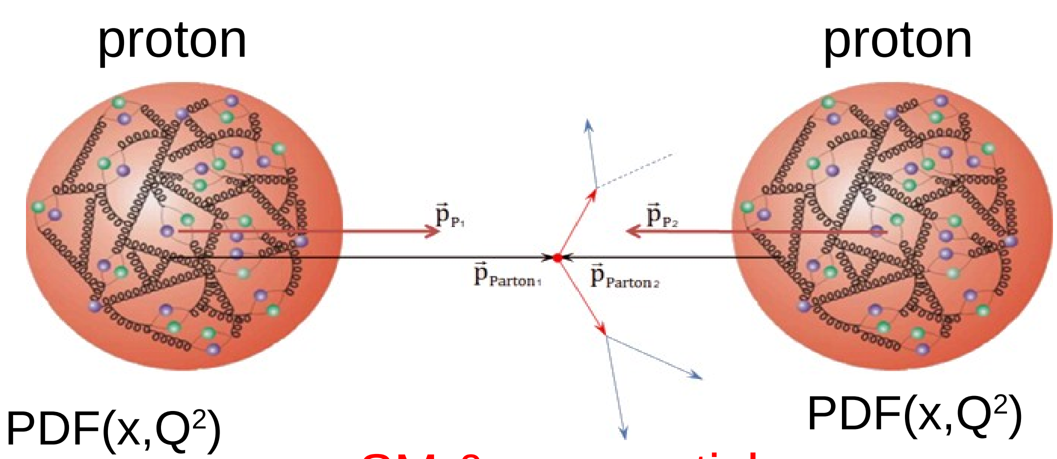
$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$
[Quark masses]

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

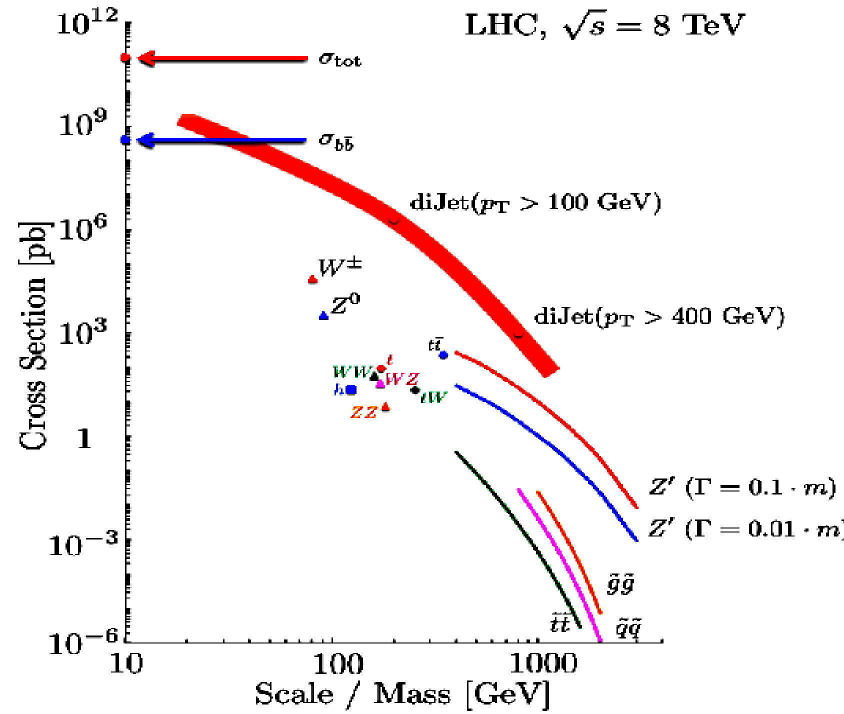
+ new particles/symmetries ?

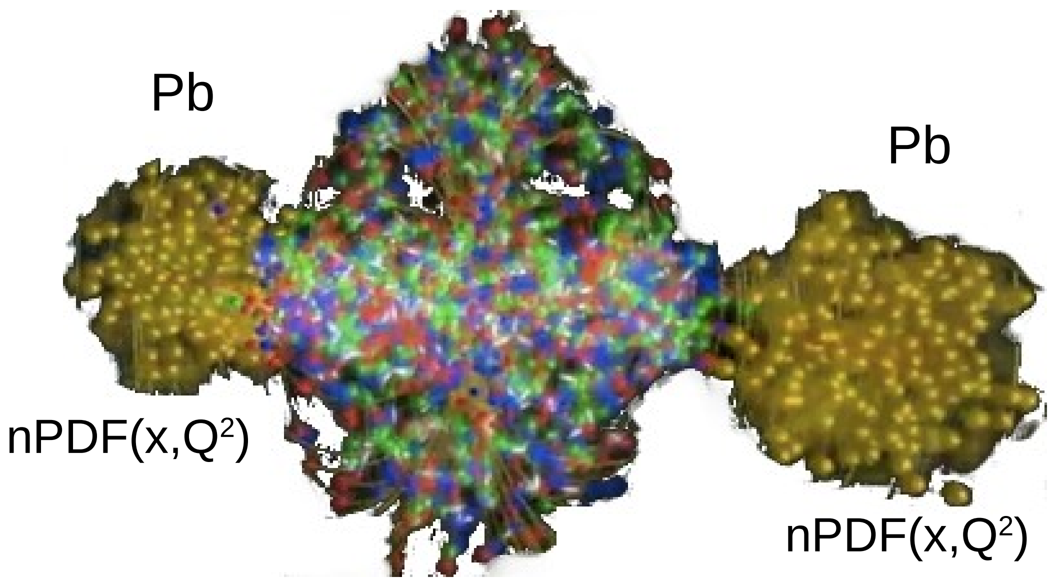
- ✘ Higgs: Generation of masses via BEH mechanism not confirmed (up to 2012)
- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✘ Fine-tuning: Higgs mass virtual corrections «uncontrolled» up to Planck scale
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)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

Tools: high-energy proton & ion collisions

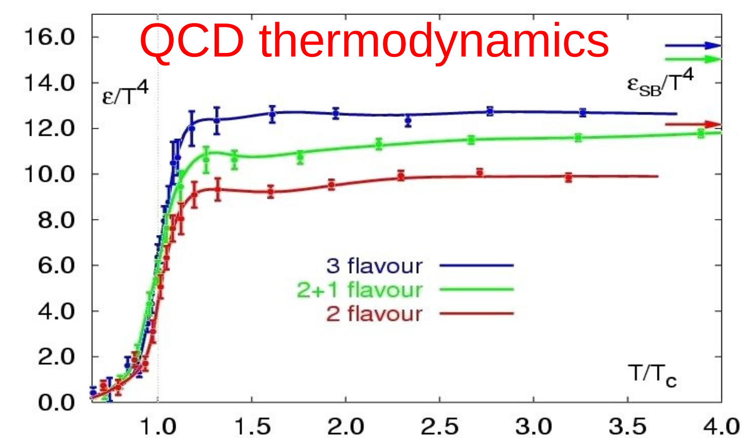


SM & new particles





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

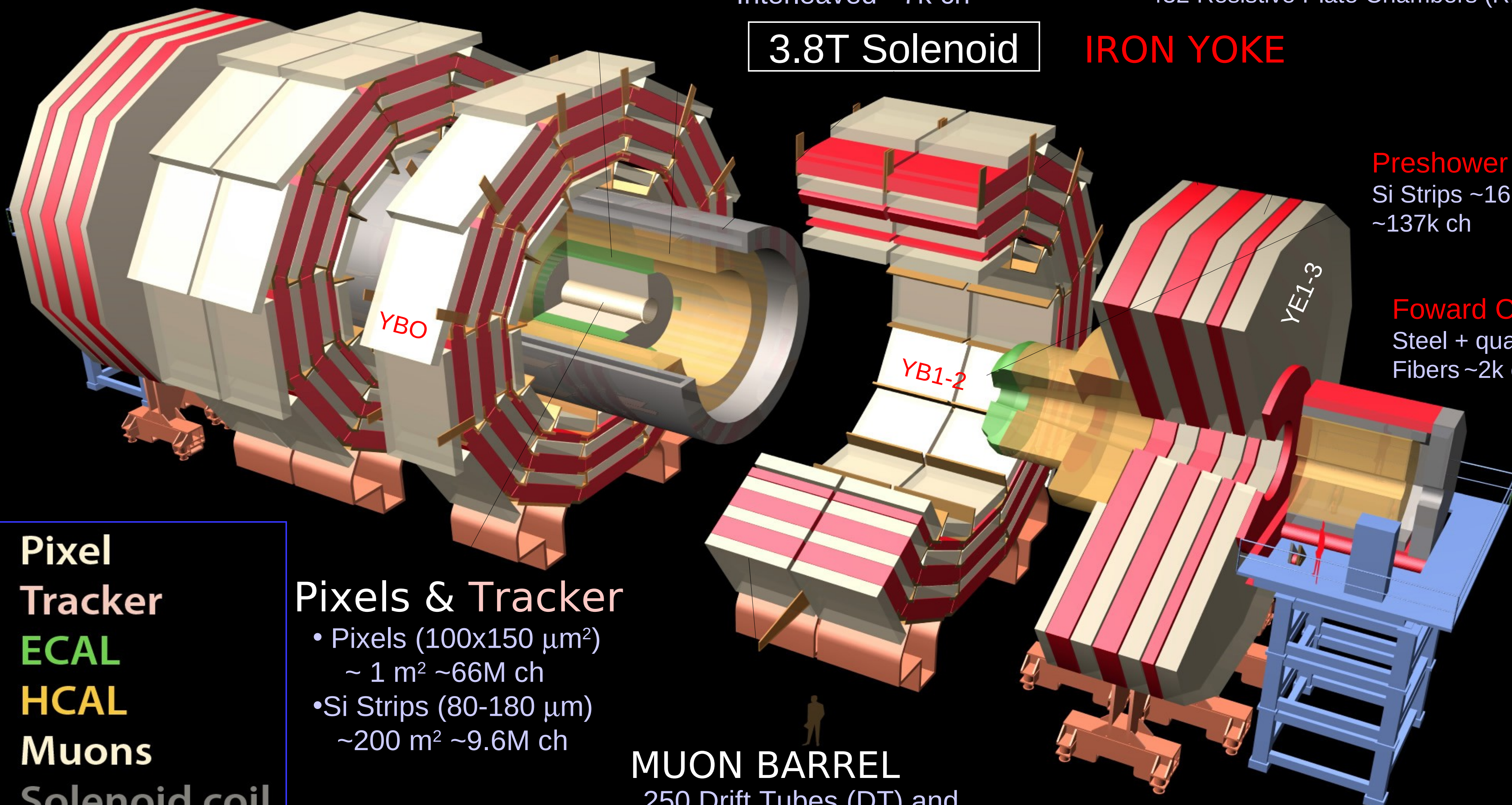
3.8T Solenoid

IRON YOKE

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

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

Foward Cal
Steel + quartz
Fibers ~2k ch



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

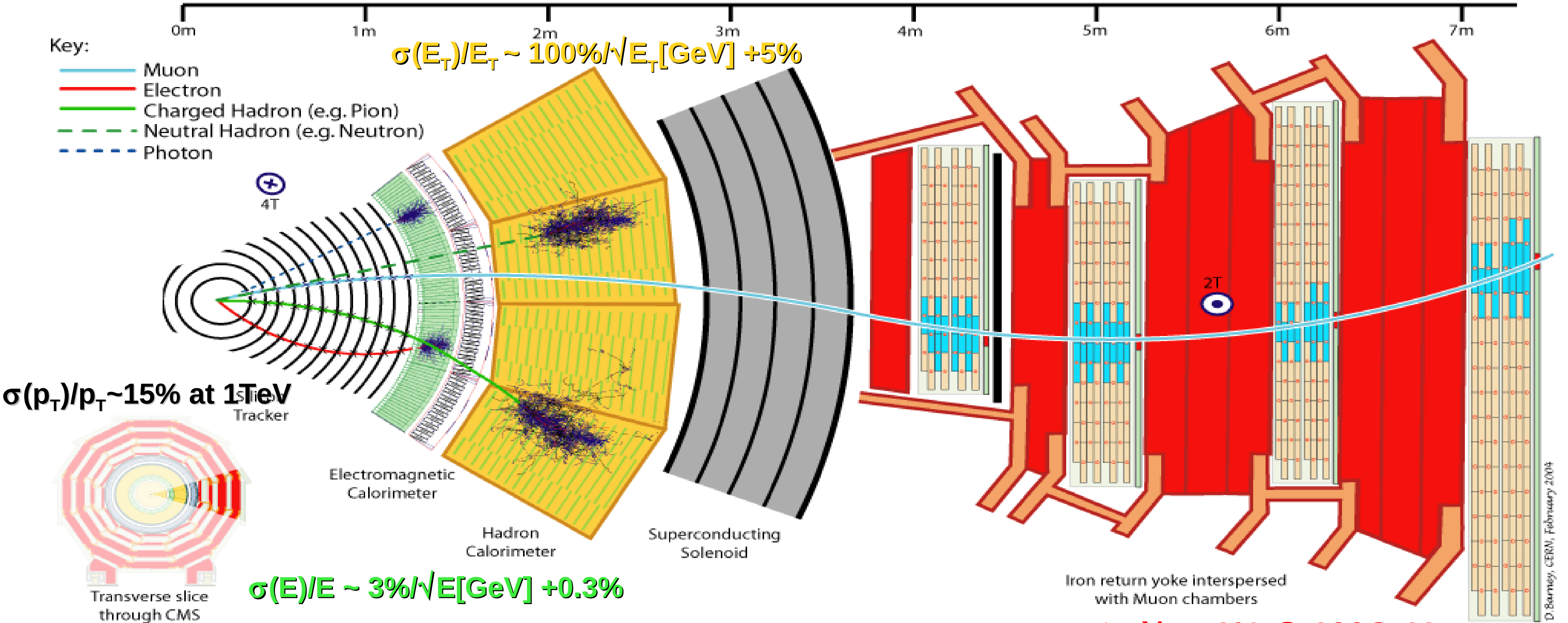
Pixels & Tracker
- Pixels (100x150 μm^2) ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm) ~200 m^2 ~9.6M ch

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



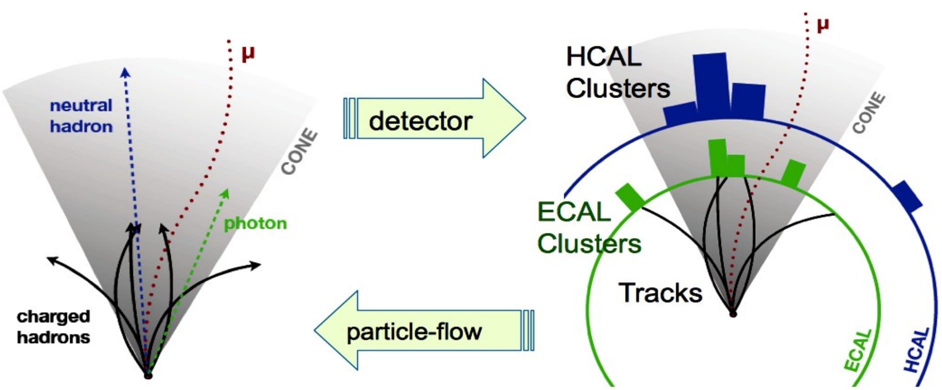
$\sigma(E_T)/E_T \sim 100\%/\sqrt{E_T[GeV]} + 5\%$

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

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

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

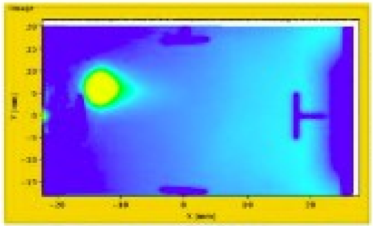
$\sigma(p_T)/p_T < 10\%$ @1 TeV



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

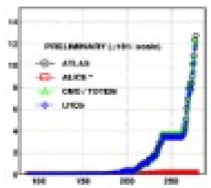
August 2008
First injection test



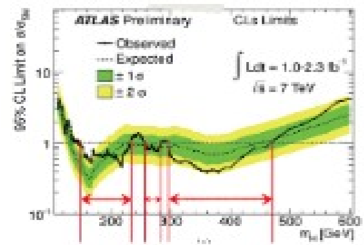
Sept. 10, 2008
First beams around

November 29, 2009
Beam back

Repair and Consolidation



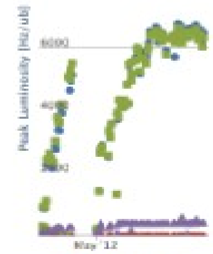
October 14, 2010
L= 1x10^{+32}
248 bunches



October, 2011
3.5x10^{+33}, 5.7 fb^{-1}

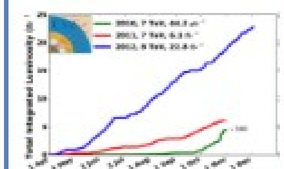
First Hints!!

June 28 2011
1380 bunches

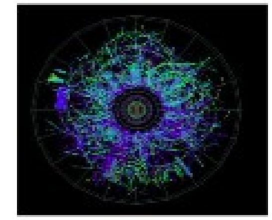


May 2012
Ramping
Performance

March 14th 2012
Restart
with Beam



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

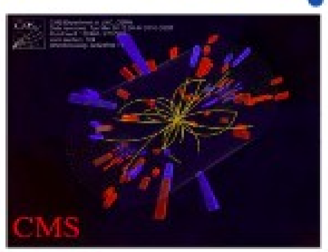


Nov. 2012
End of p^{+} Run 1

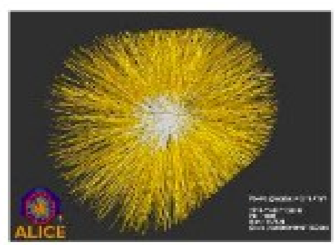
2008	2009	2010	2011	2012	2013

Sept. 19, 2008
Incident

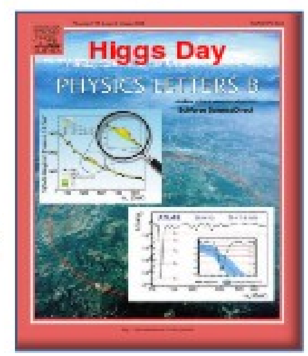
March 30, 2010
First collisions at 3.5 TeV



November 2010
Pb^{82+} Ions

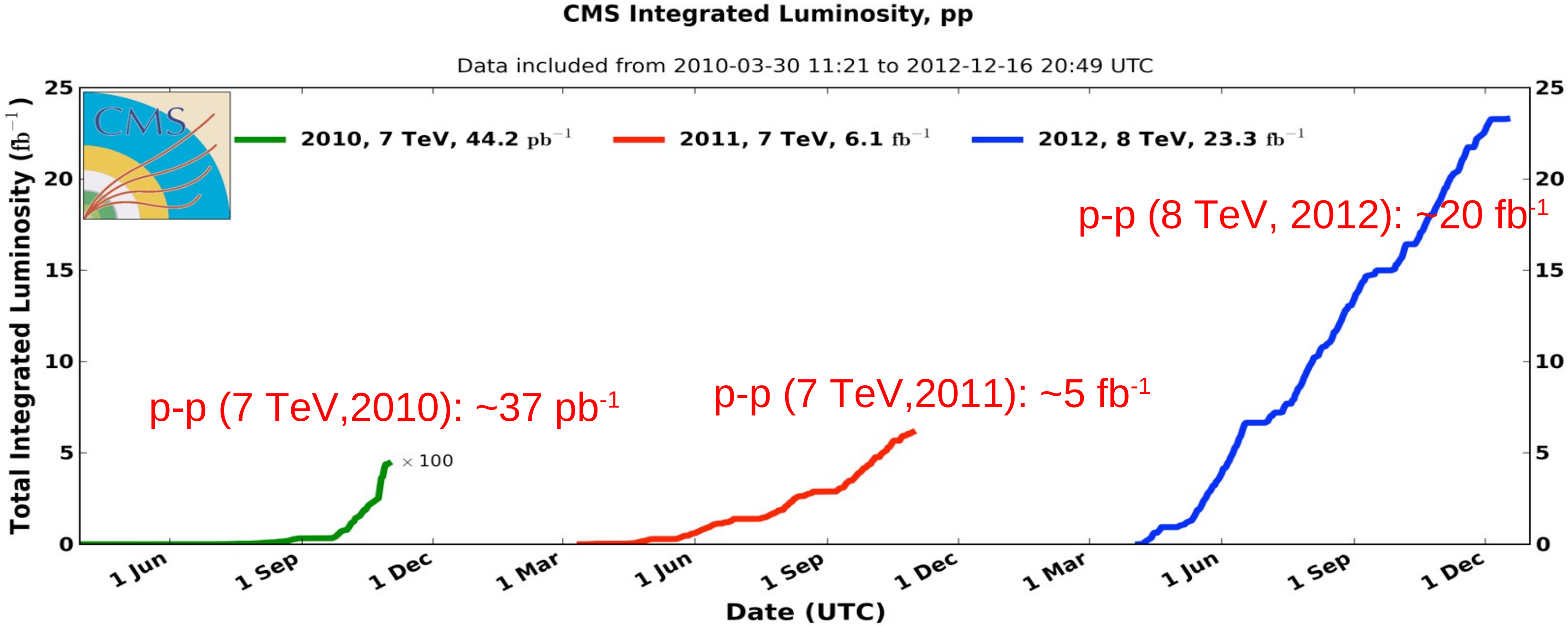


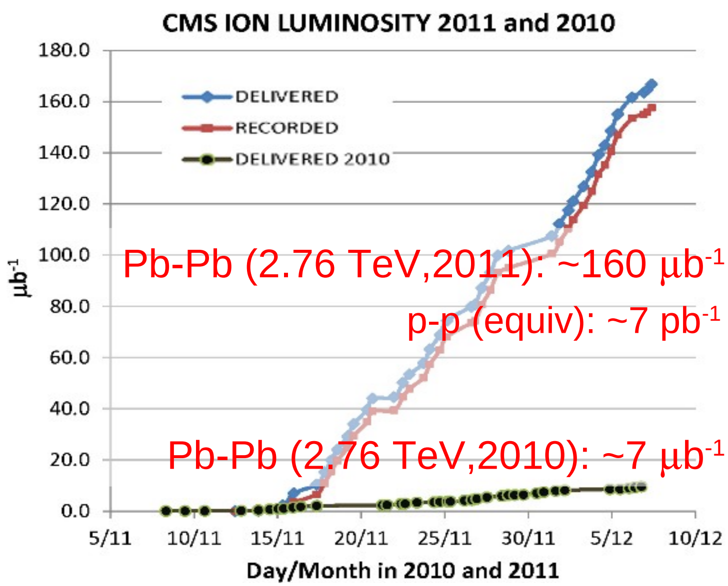
November 2011
Second Ion Run

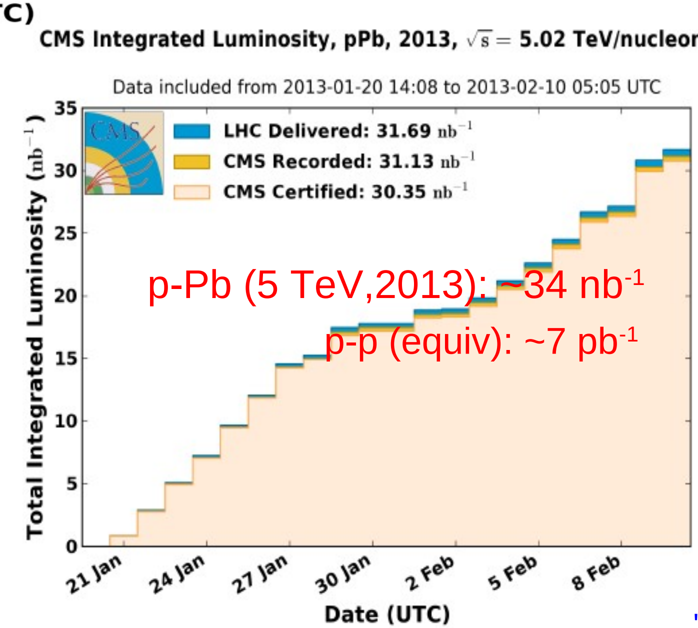


LS1

CMS: integrated luminosities (2010-13)

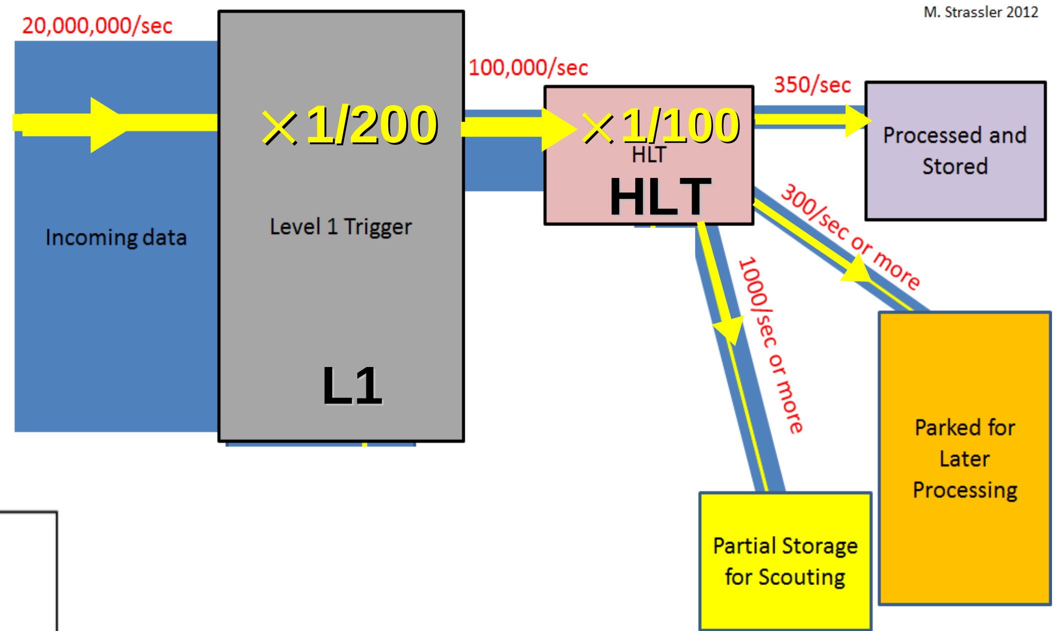


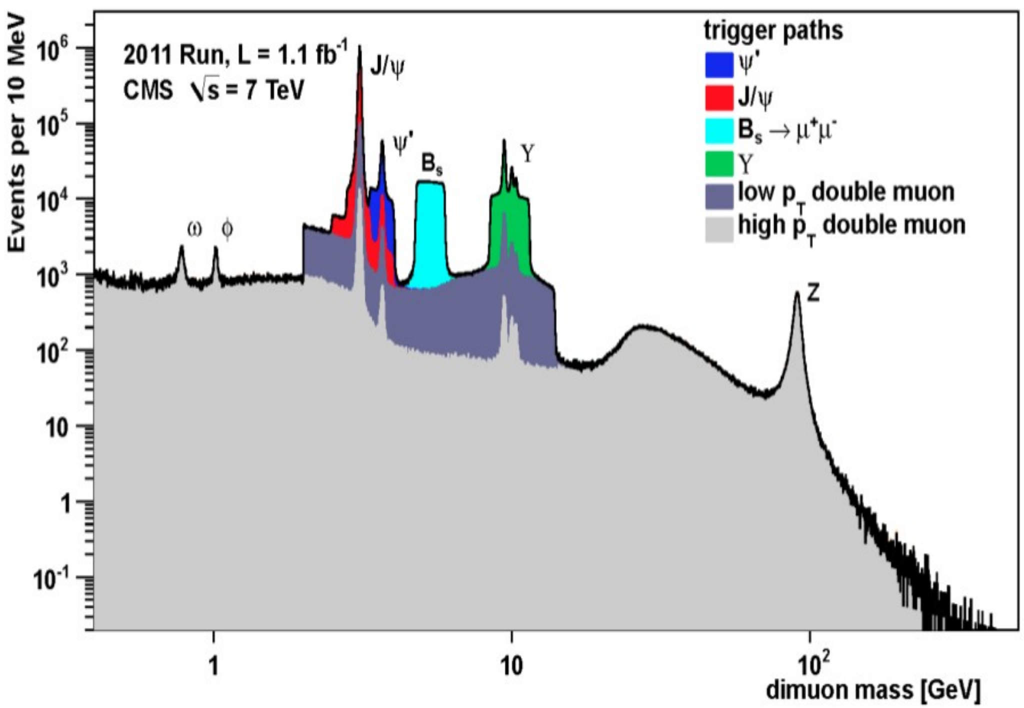




CMS: L1 & high-level triggers

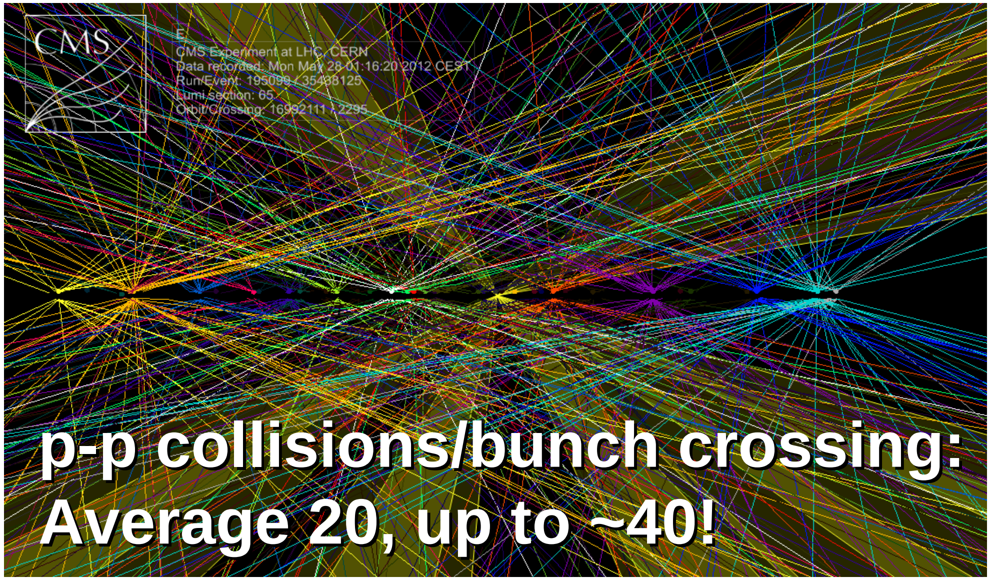
- Level-1 & HLT menus reduce # of p-p interactions from: $2{\cdot}10^{7}$ Hz (input) down to ~350 Hz (recorded), ~300 Hz (“parked” for later analysis)

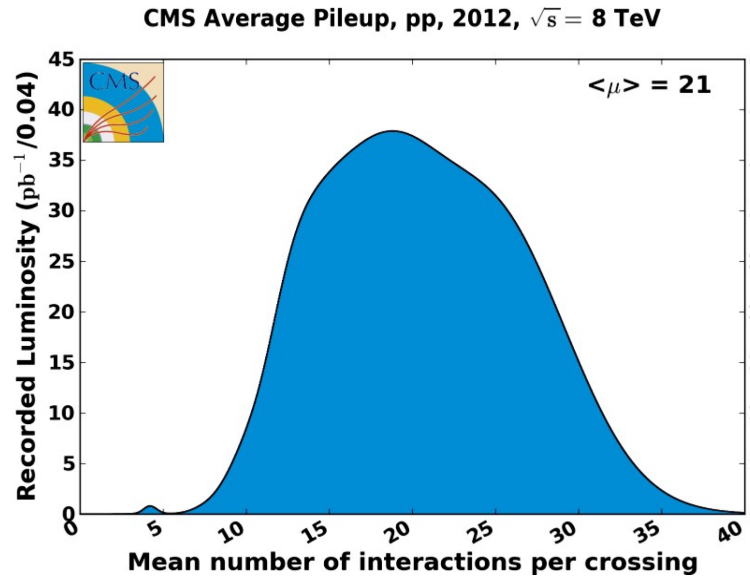




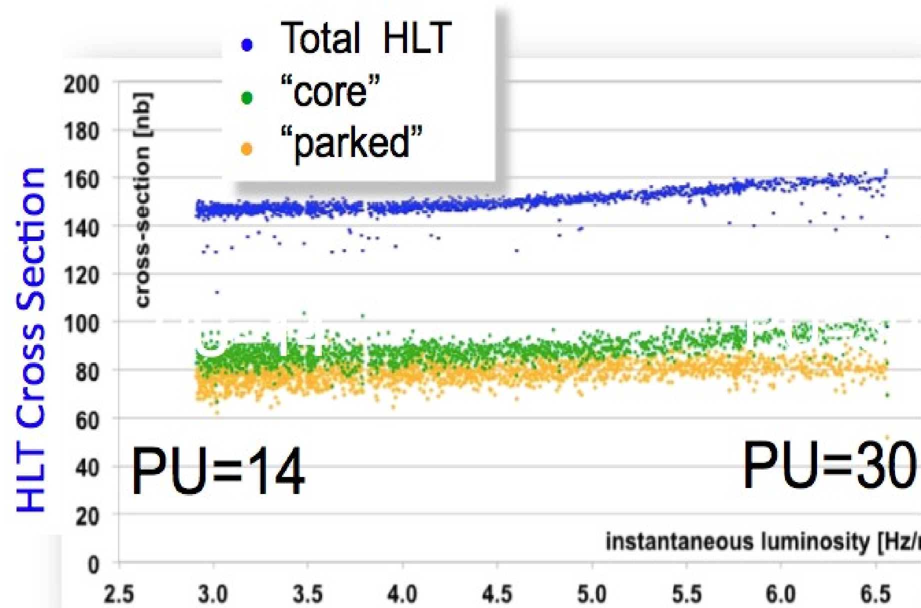
- Example: dimuon mass distribution from several double-μ trigger paths: calibration, $B_s(\mu\mu)$, quarkonia, DY/Z

CMS: p-p pileup & triggering



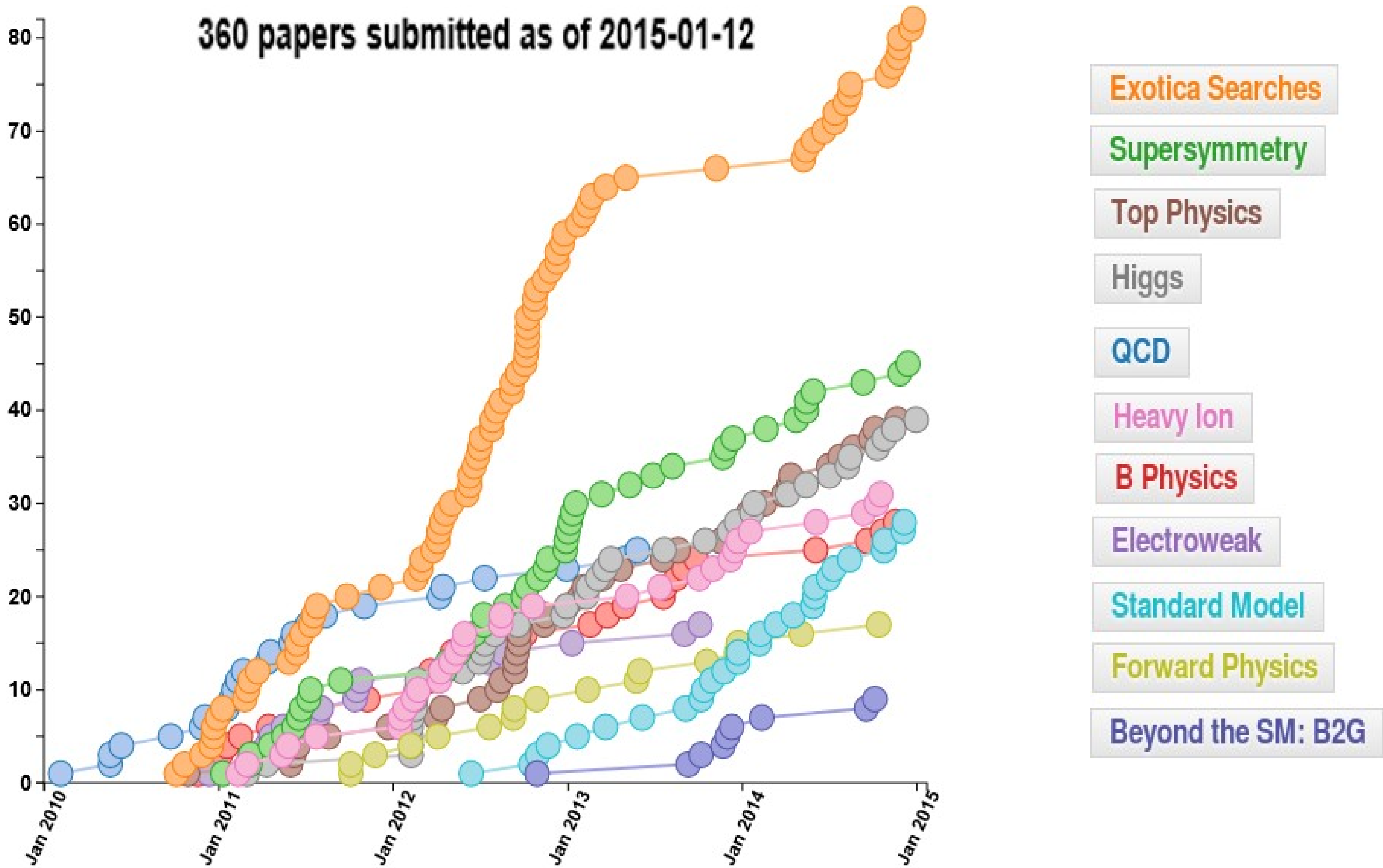


- Highly-flexible HLT system allows CMS to keep a constant-rate cross section with varying pile-up conditions without sacrificing physics:



CMS: publications & preliminary results

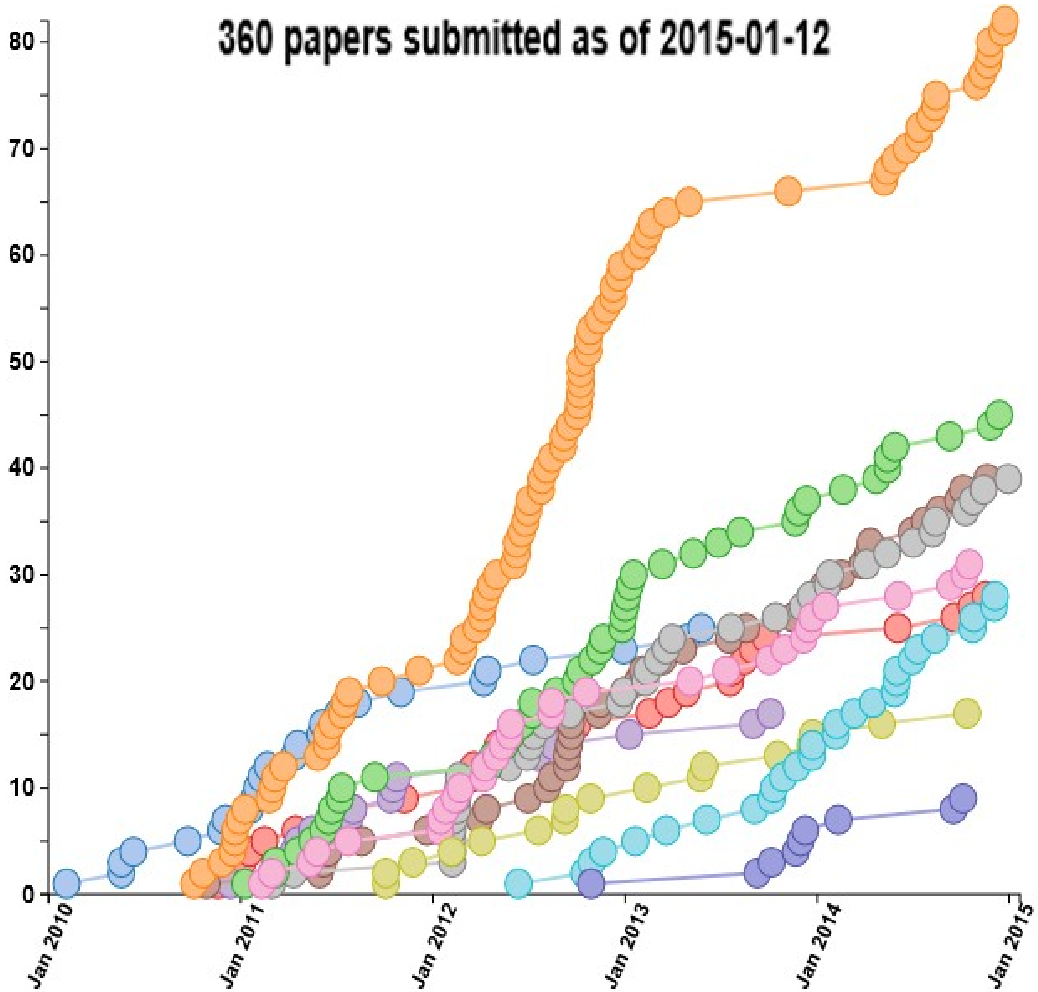
360 papers submitted + few hundreds preliminary notes as of Jan'15



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

CMS: publications & preliminary results

360 papers submitted + few hundreds preliminary notes as of Jan'15



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

QCD: σ_{inel},«ridge», α_s(TeV)

QGP: Υ suppression

EW: W,Z prod., $\gamma\gamma\rightarrow$WW

Top: most-precise m_{top}

Higgs: m_H, properties

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:

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

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

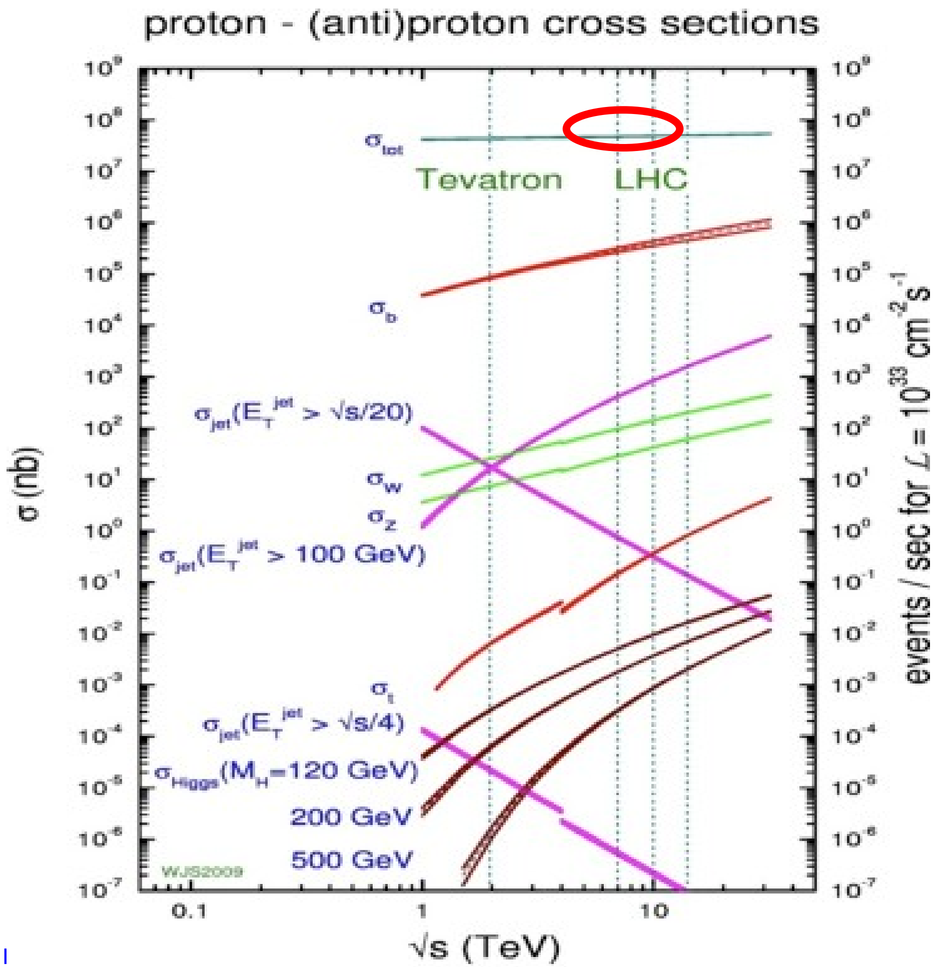
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

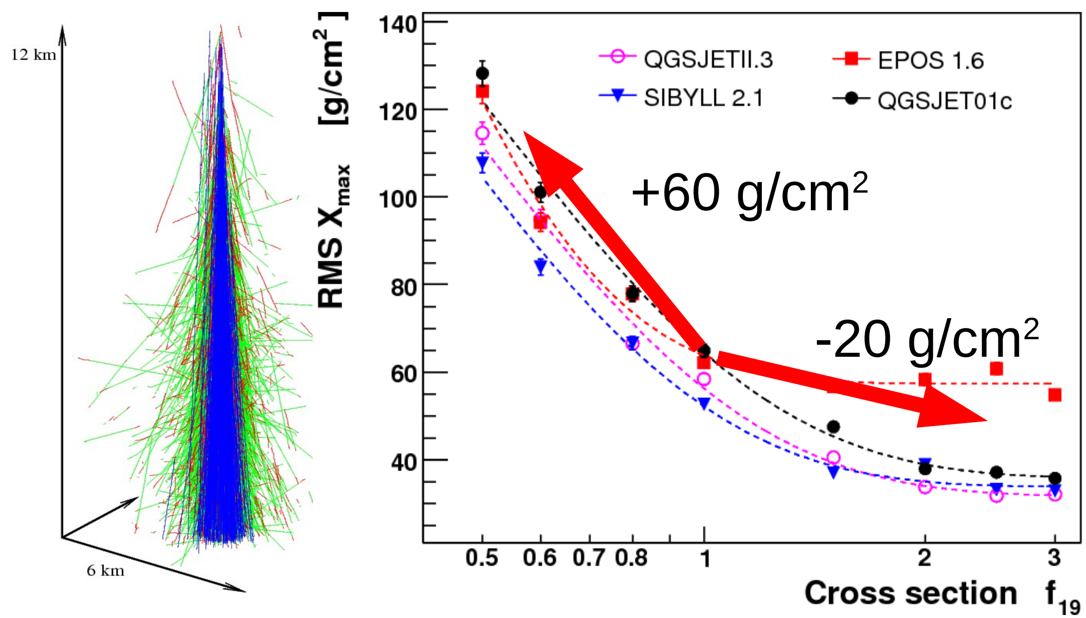
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu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

QCD: Inelastic p-p cross section

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

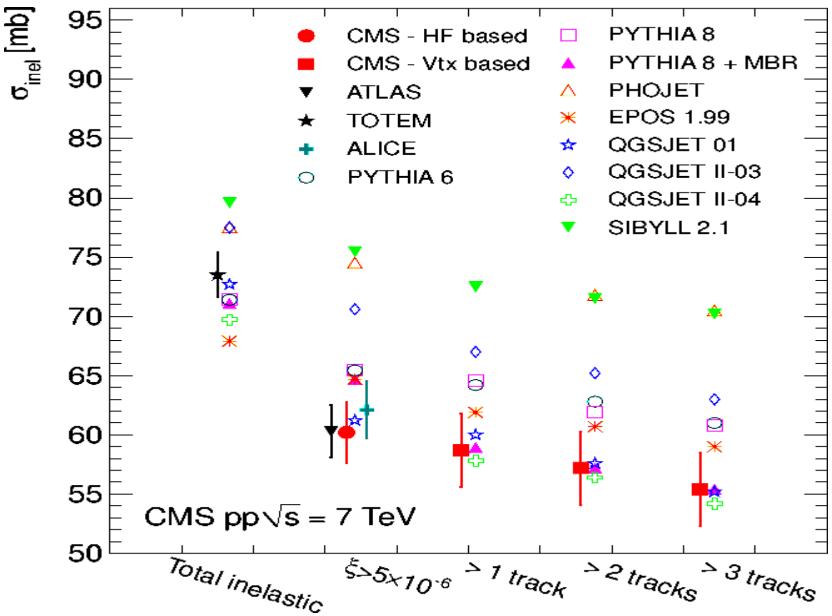


- Impact on cosmic-ray MCs at $E_{lab} \sim 10^{19}$ eV Uncertainties of σ_{inel} change by factor of ~2 the air-shower maximum fluctuations:



Ulrich-Engel-Unger, PRD83 (2011) 05426

QCD: Inelastic p-p cross section



PLB 722 (2013) 5

- Total inel. x-section $\sigma_{CMS} \sim 73$ mb

Visible inel. x-section $\sigma_{CMS} \sim 60$ mb

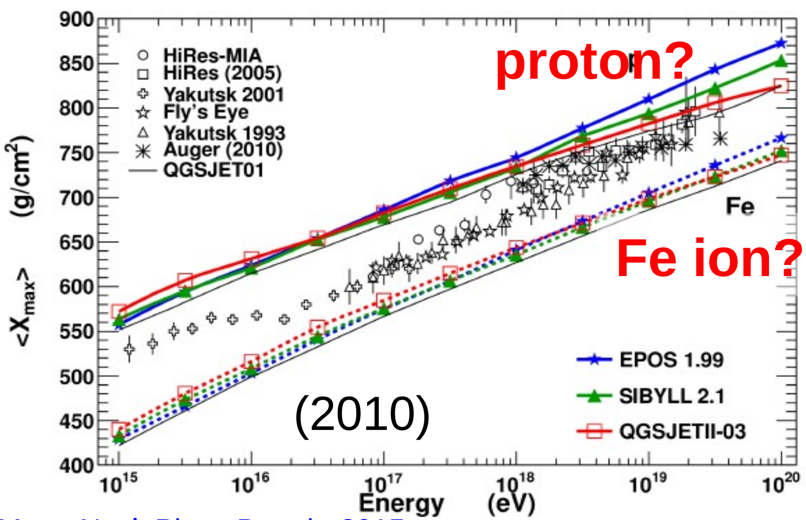
measured in CMS via:

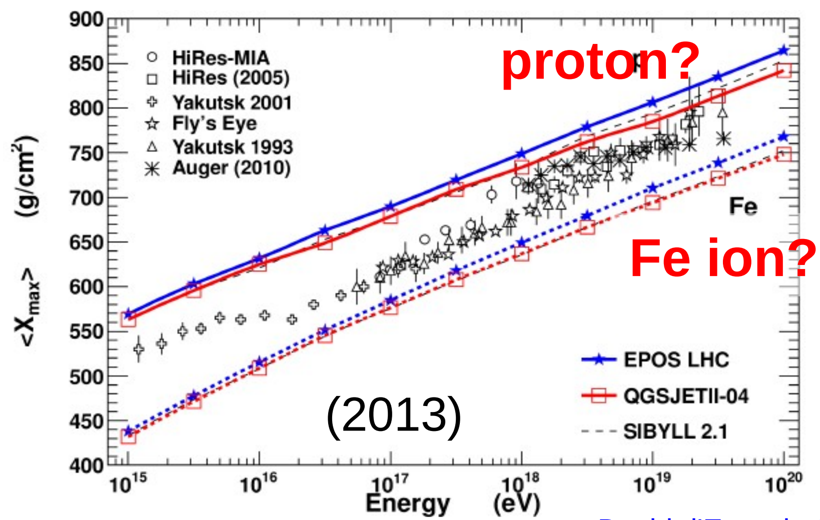
(i) pileup-events counting,

(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 ($E_{lab} \sim 10^{17}$ eV):



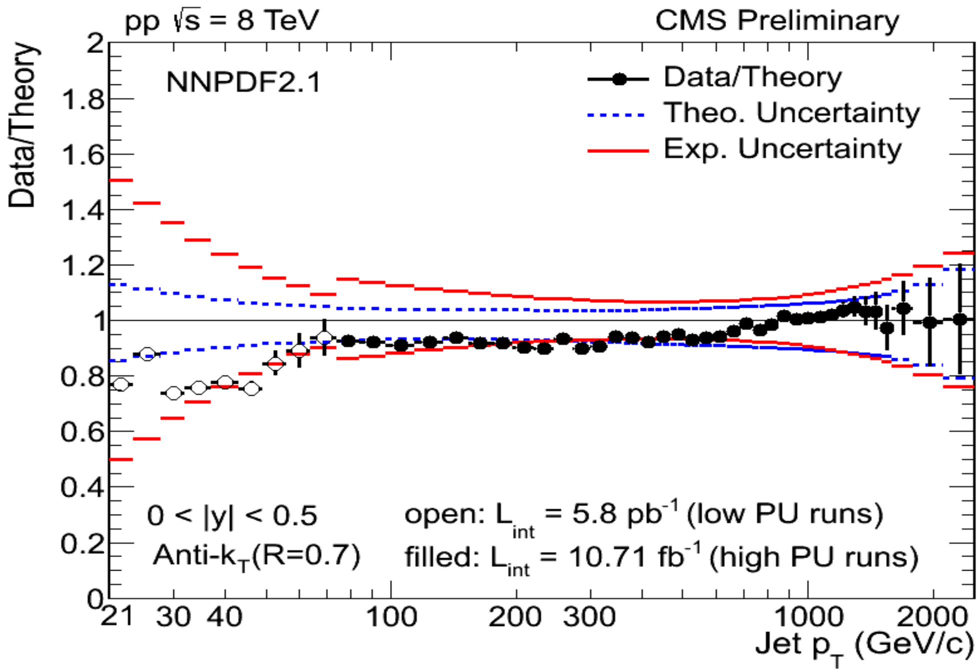


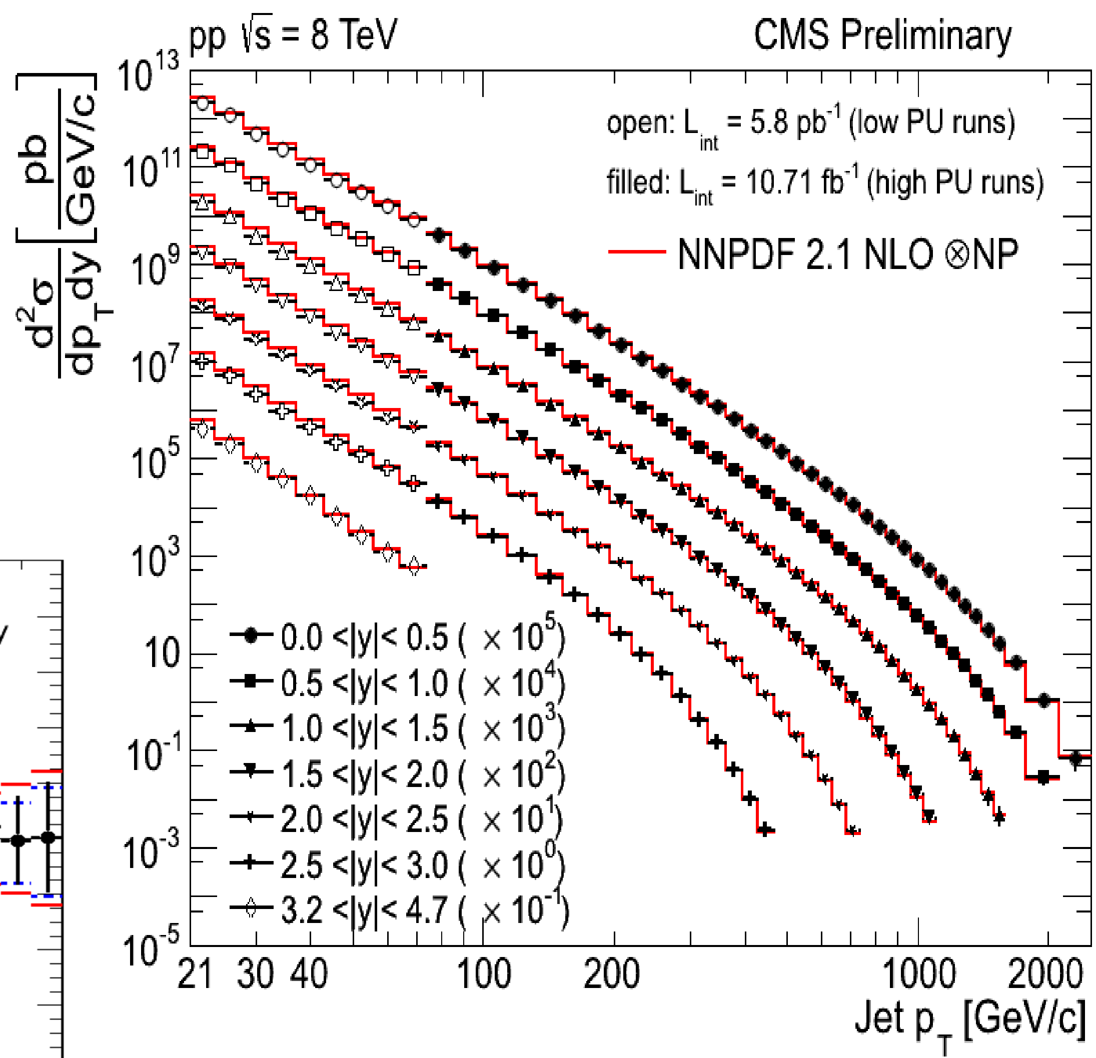
QCD: x-sections of light-quark & gluons jets

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.

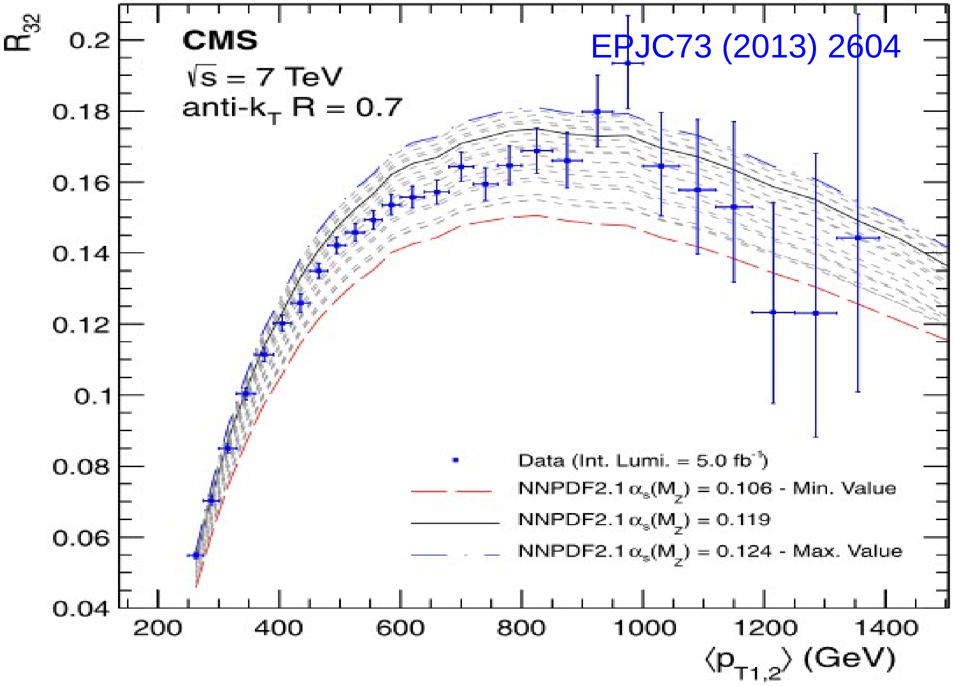


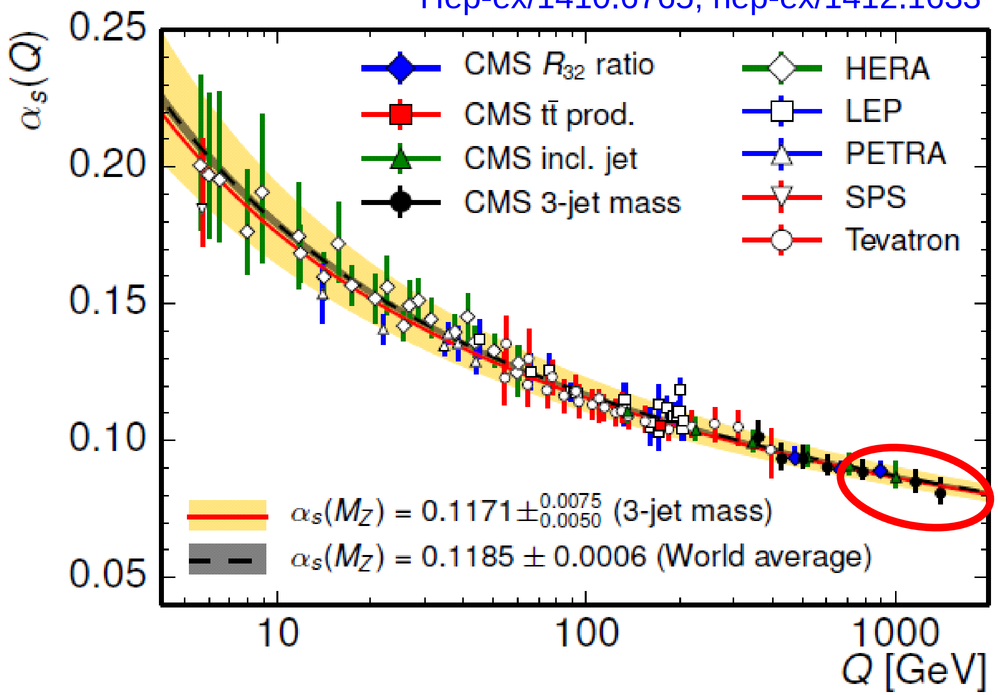


QCD: Strong coupling from jets x-sections

- Ratio of 3-jets of 2-jets, 3-jet mass, and incl.jets x-sections constrain α_s up to so-far unprobed scales Q ~ 1.4 TeV:

Hep-ex/1410.6765, hep-ex/1412.1633





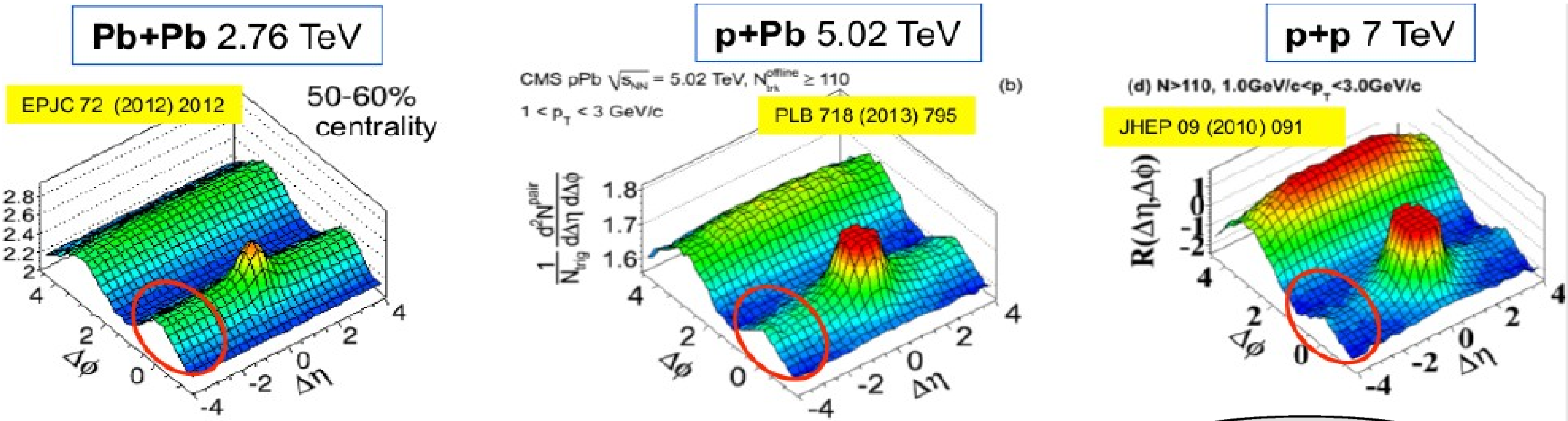
PDF set	$\alpha_S(M_Z)$	χ^2/n_{dof}
CT10-NLO	$0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0053}_{-0.0024}\,(\text{scale})$	104.1/132
NNPDF2.1-NLO	$0.1150 \pm 0.0015\,(\text{exp}) \pm 0.0024\,(\text{PDF}) \pm 0.0003\,(\text{NP})^{+0.0025}_{-0.0025}\,(\text{scale})$	103.5/132
MSTW2008-NLO	$0.1159 \pm 0.0012\,(\text{exp}) \pm 0.0014\,(\text{PDF}) \pm 0.0001\,(\text{NP})^{+0.0024}_{-0.0030}\,(\text{scale})$	107.9/132

Measurements dominated by TH uncertainty.
PDF & (asym,) scale uncertainty, e.g. incl. jets:

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp})\,^{+0.0060}_{-0.0037}\,(\text{theo})$$

"Collective" QCD: "ridge" of correlated hadrons

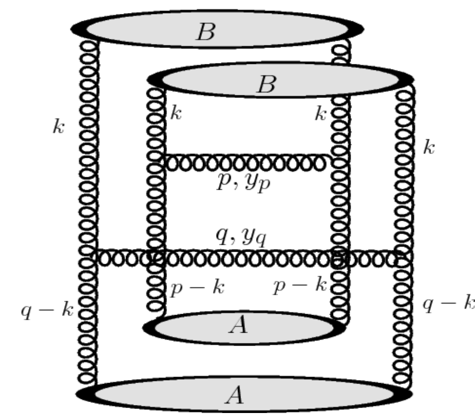
- Observation of long-range (over $\Delta\eta\sim 8$!) near-side hadron correlations "ridge" in "central" (high multiplicity) collisions:



- 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



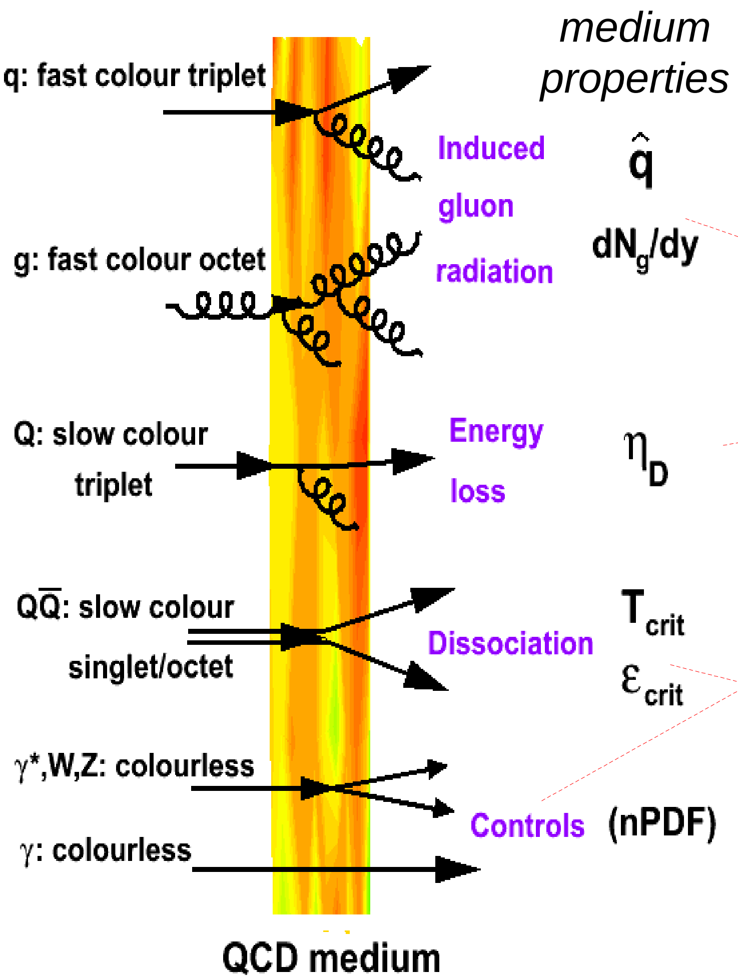
- Final-state ? Collective parton-flow ?

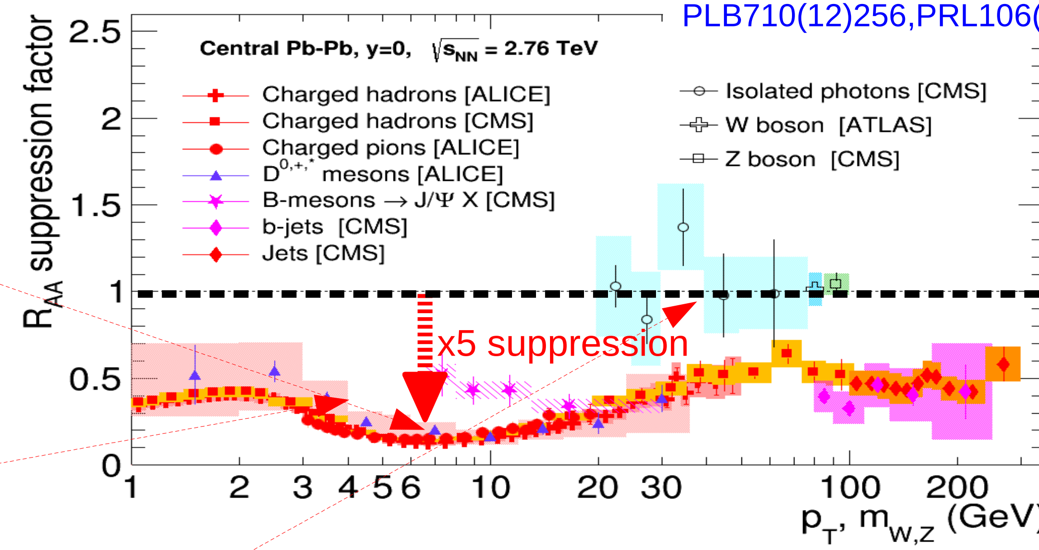
PYTHIA(pp) + $\beta_T \sim 0.5$ can generate such structure

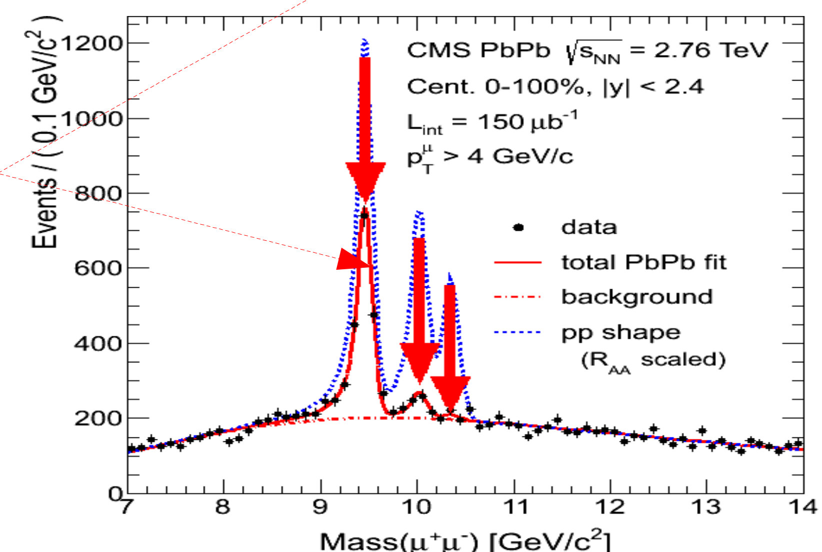
QCD plasma: q,g,$Q\bar{Q}$ suppression in Pb-Pb

- 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







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

PRL109(12)222301

Electroweak sector (LHC)

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

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

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

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

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

[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:

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

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

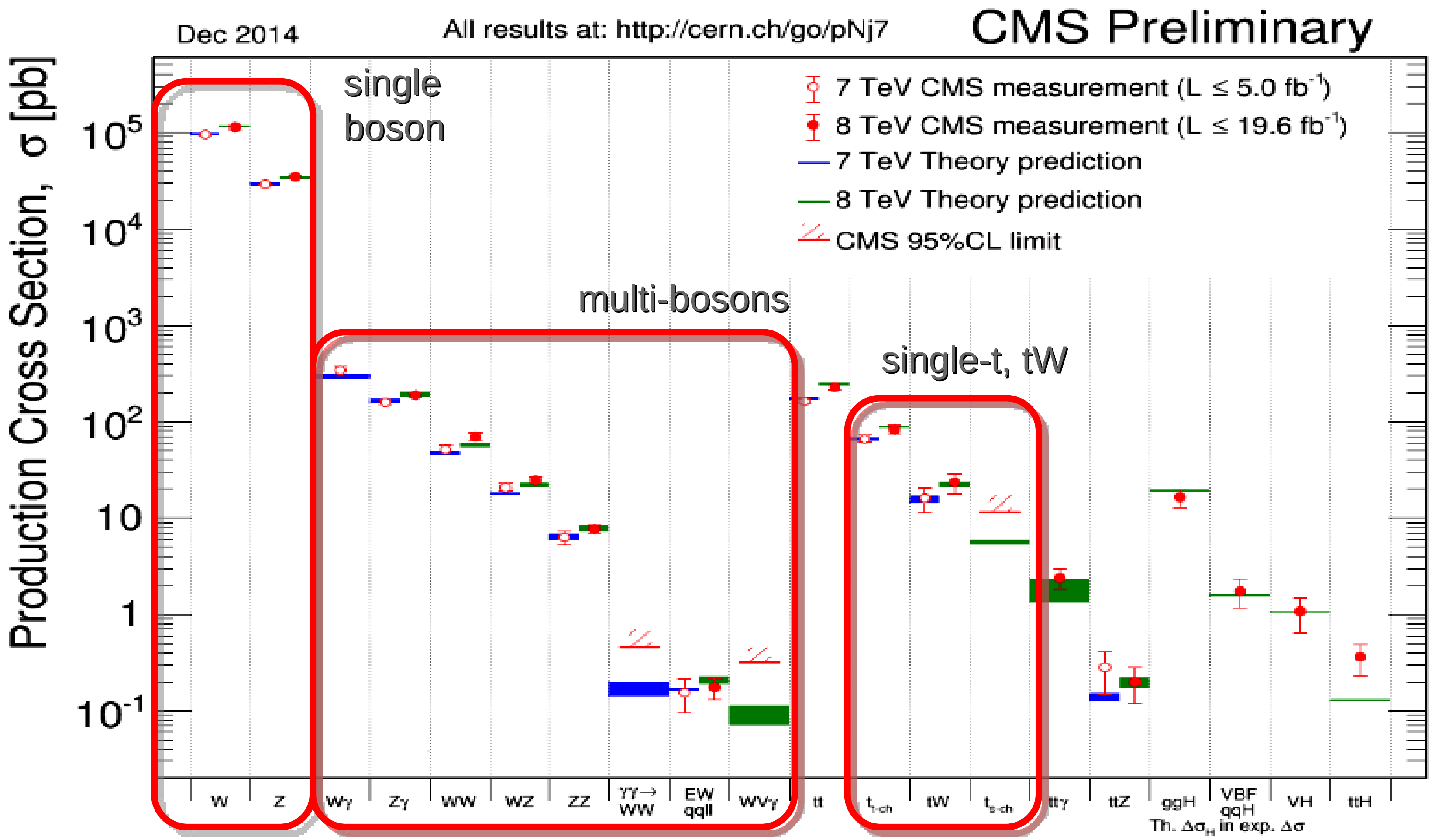
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

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

EW: Cross sections summary

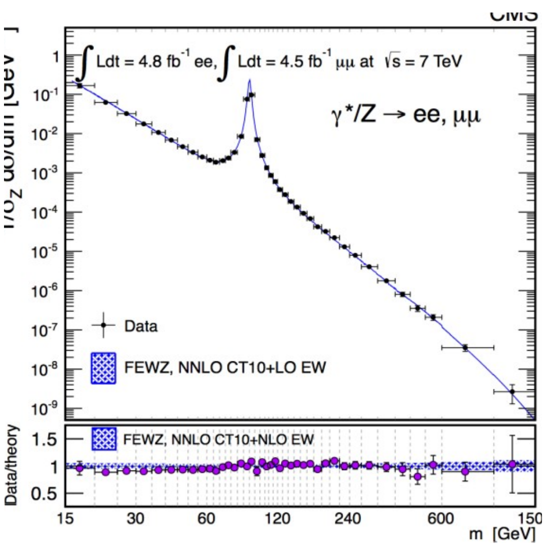
- Many stringent tests of EWK sector at the TeV scale:

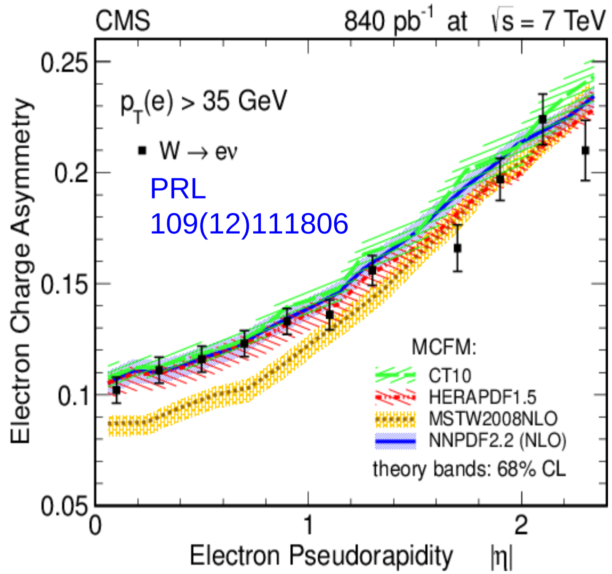


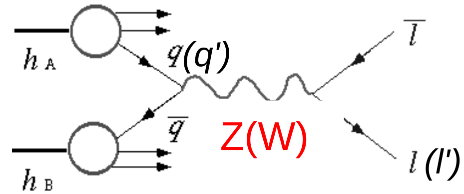
- Very good agreement with NLO (or approx. NNLO) predictions at 7,8 TeV
- First-ever measured: t-W, tt-Z, $\gamma\gamma \rightarrow$ WW, vector-boson-fusion Z

EW: W,Z "standard candles" for PDFs

- Differential Z,W x-sections in agreement w/ NNLO at 7,8 TeV: PDF constraints



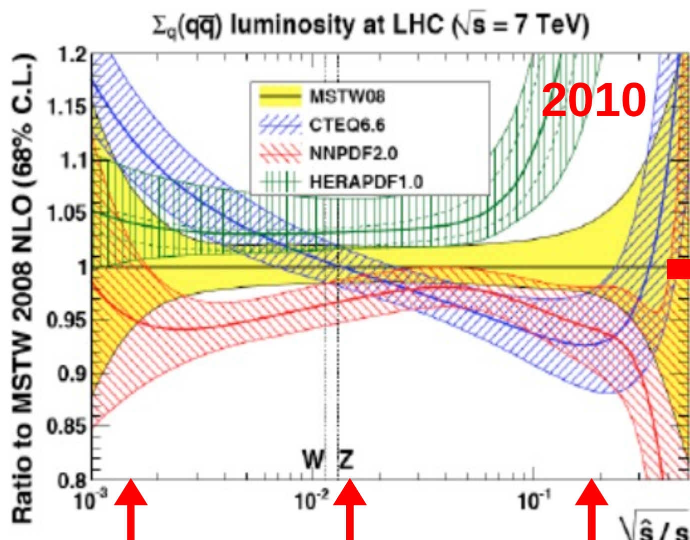


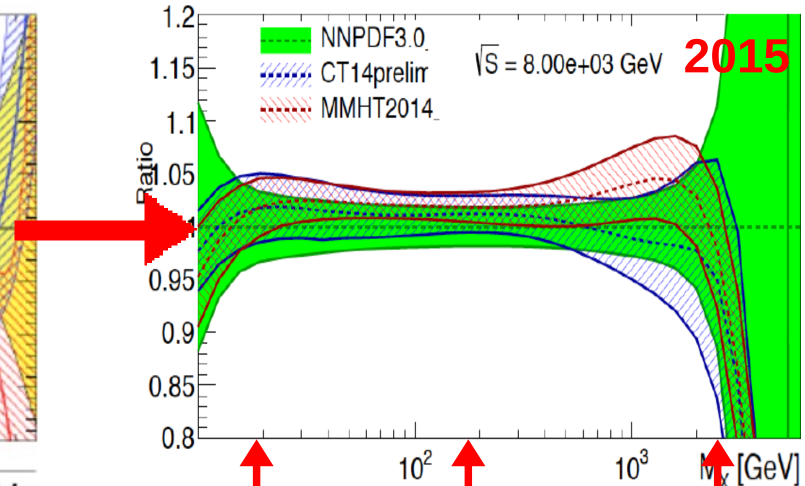


- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

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

- Reduced PDF uncertainties:





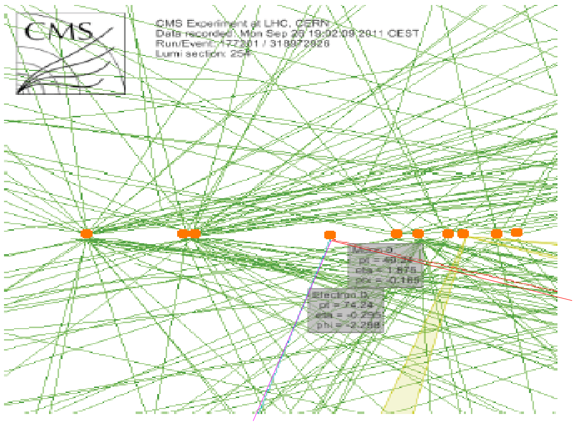
Small-x Precision phys. New phys.

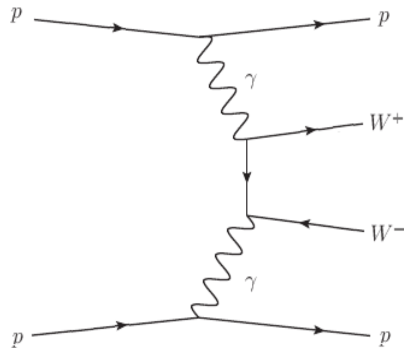
Small-x Precision phys. New phys.

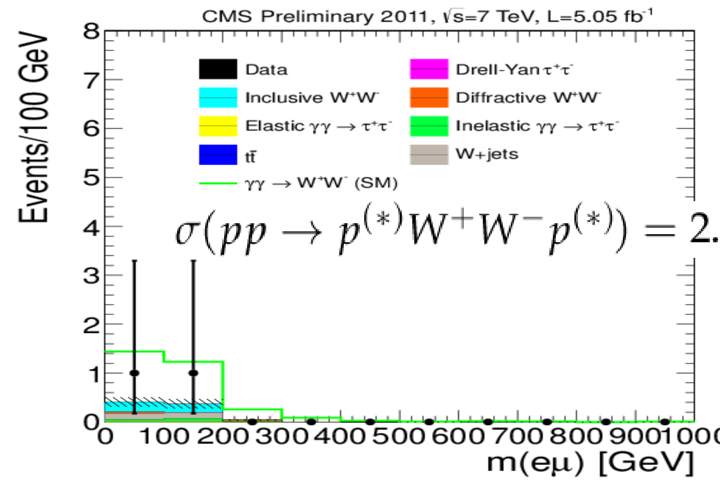
EW: γγ →WW & anomalous QGCs

JHEP 07 (2013) 116

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

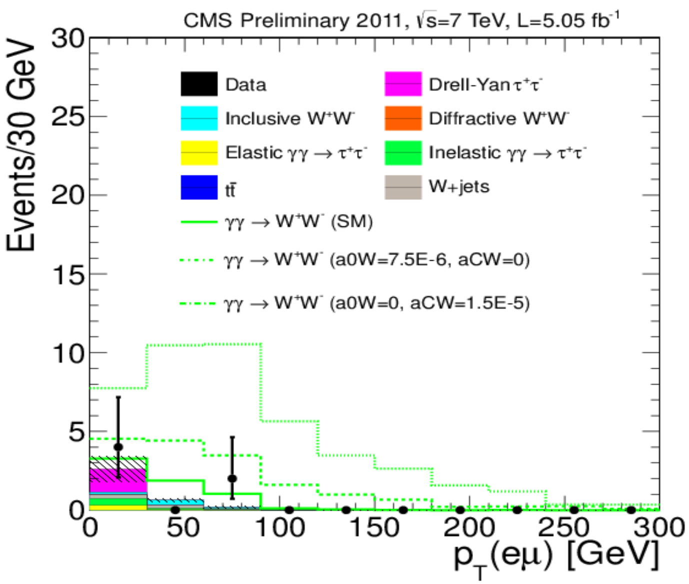




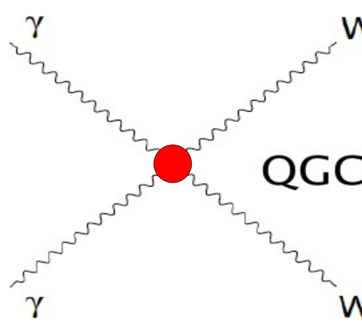


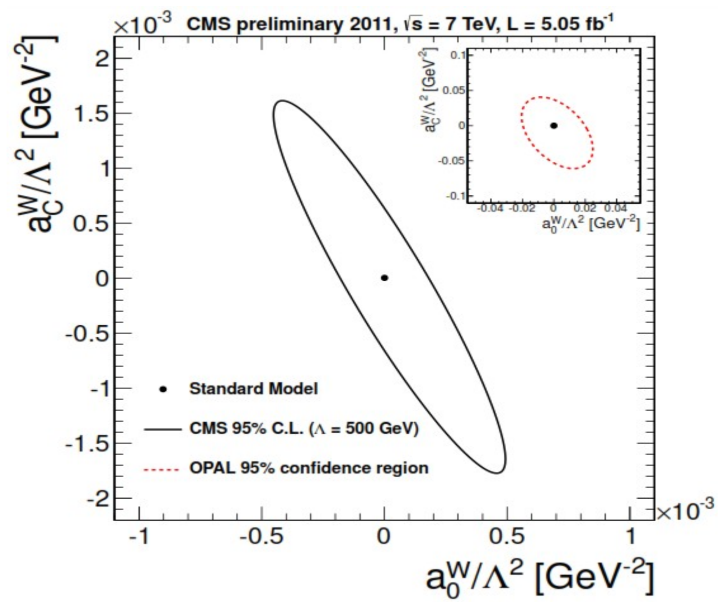
$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb}$$

- 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:

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

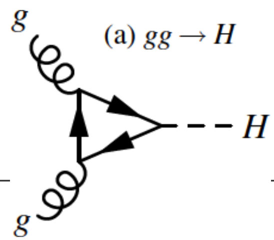
$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

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

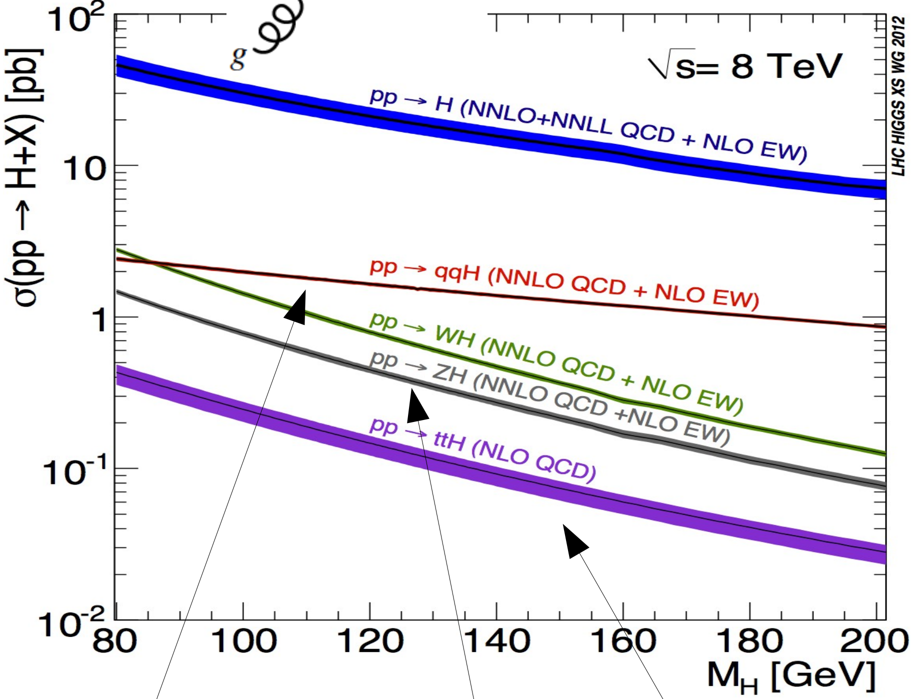
- Gauge-boson field strength tensors:

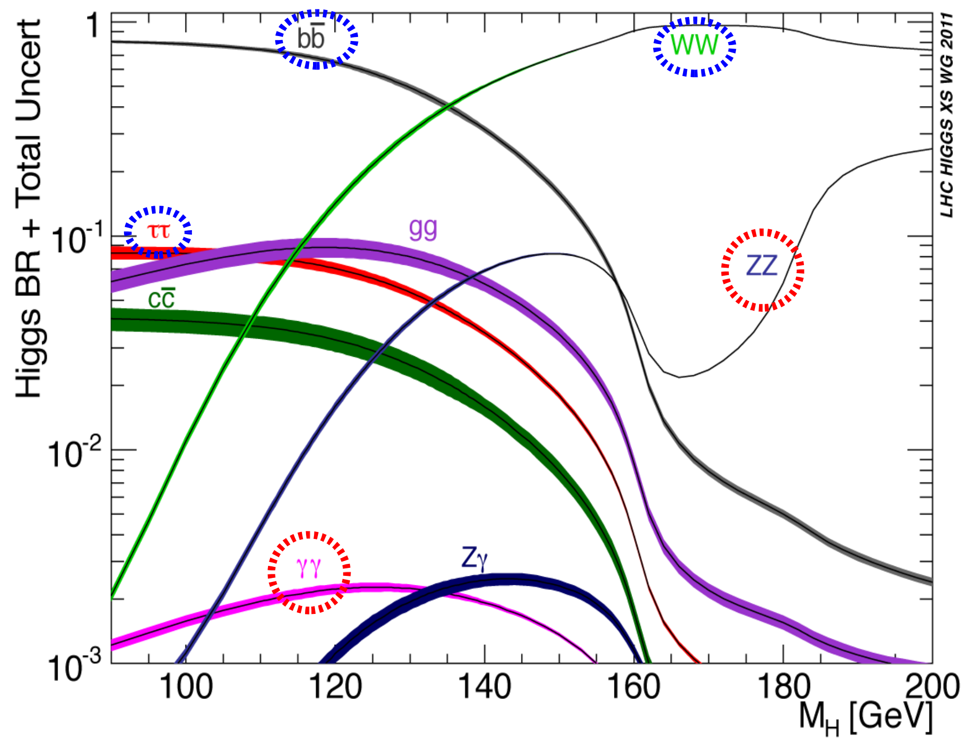
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu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

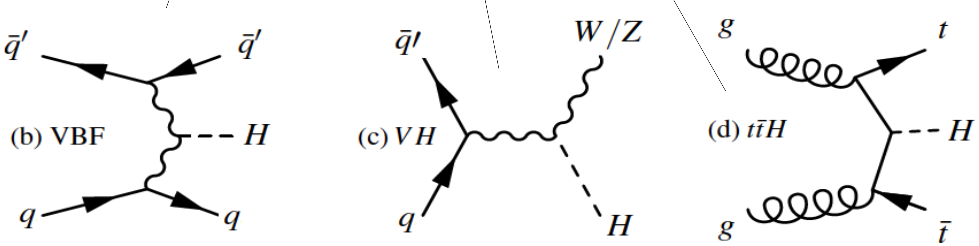
SM Higgs boson: LHC production & decays



Gluon-fusion: dominant







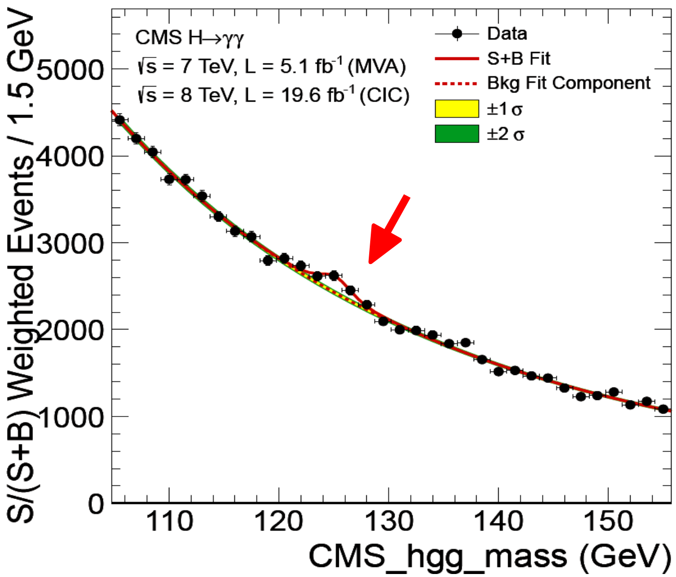
High-resolution channels: H → γγ, ZZ(4l)

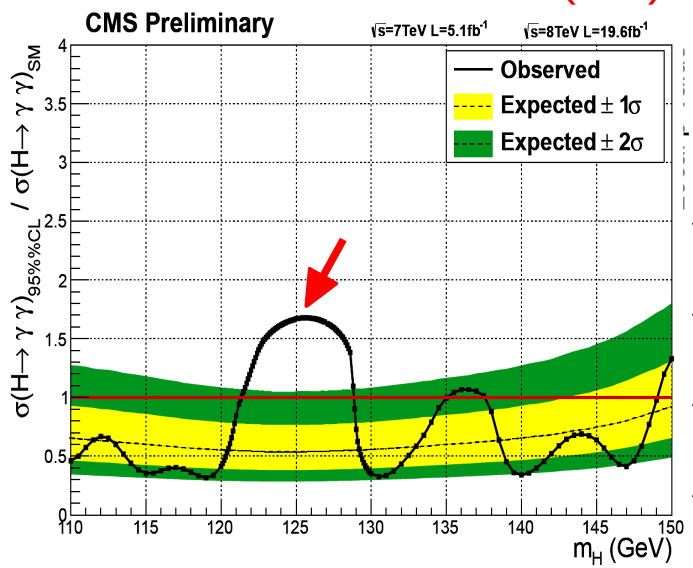
Large x-section channels: H → WW,ττ,bb

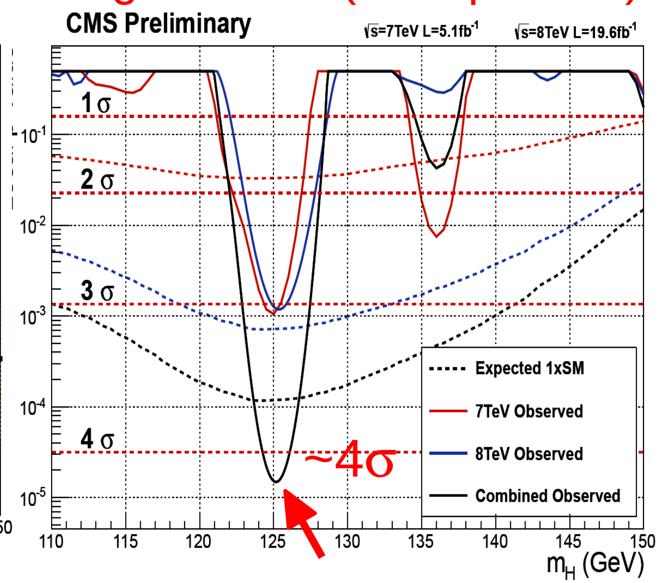
VBF & associated prod.: harder H, more jets

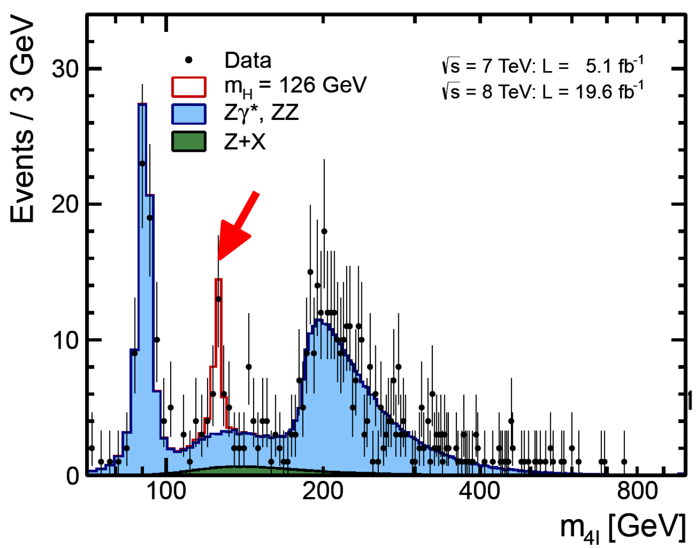
Discovery of Higgs boson: γγ, ZZ channels

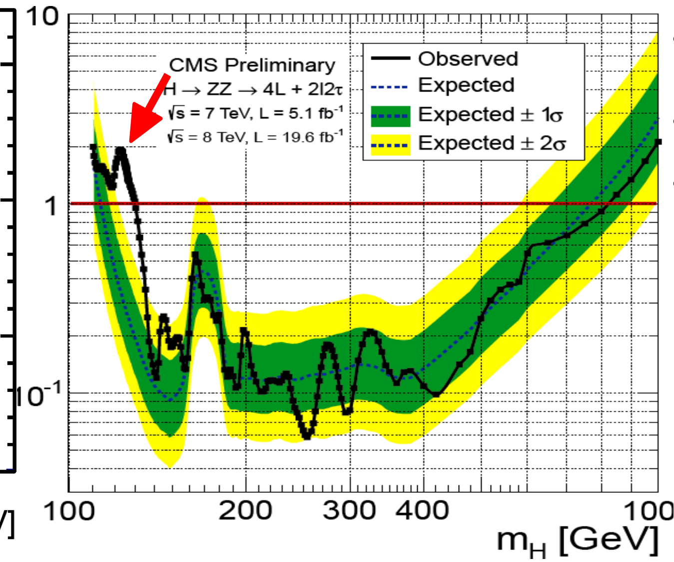
Invariant mass distributions: 95% CL-Limits on σ/σ(SM): Significance (local p-value):

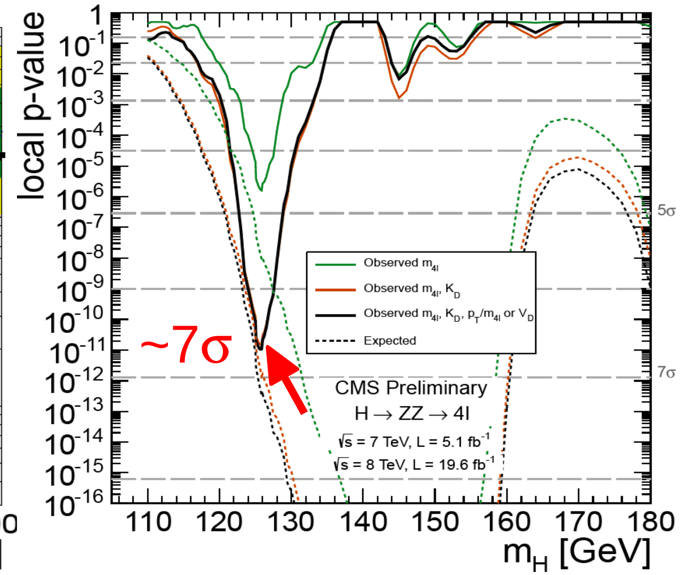






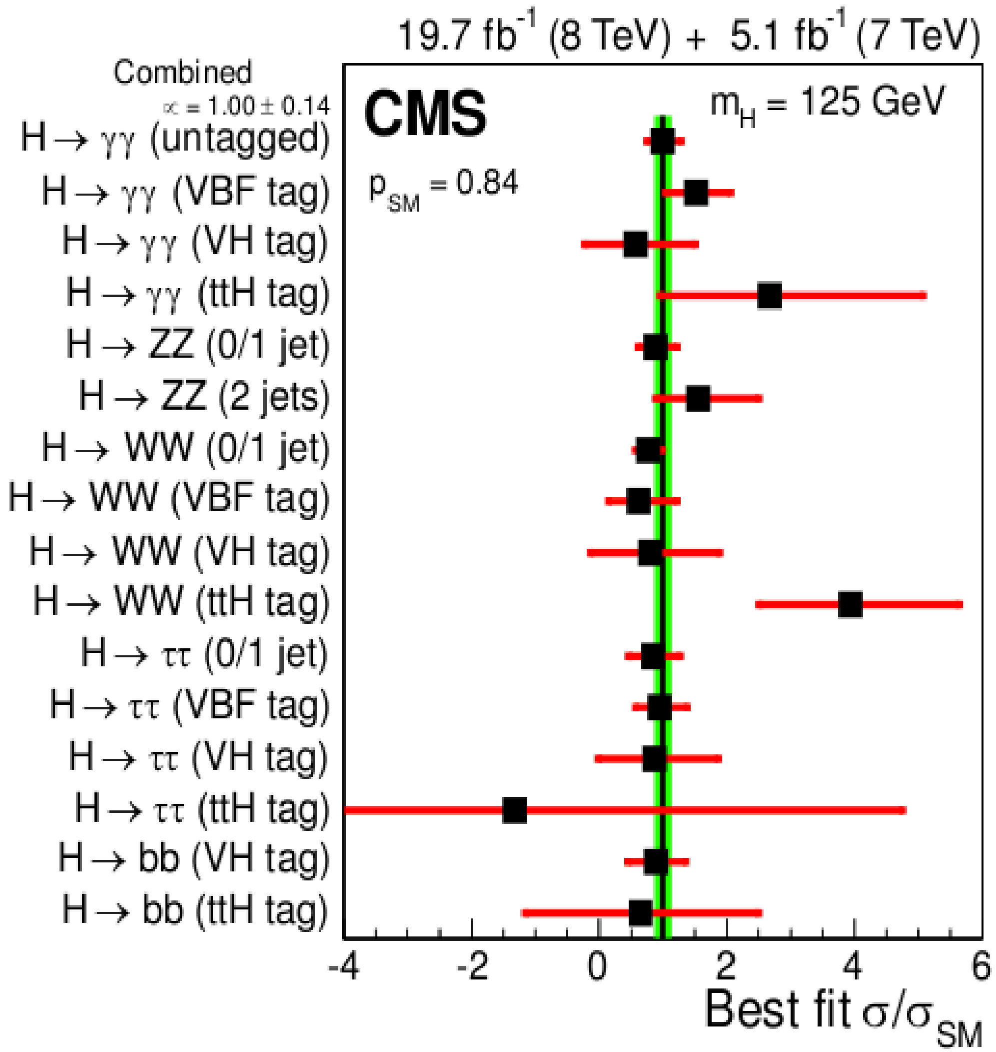




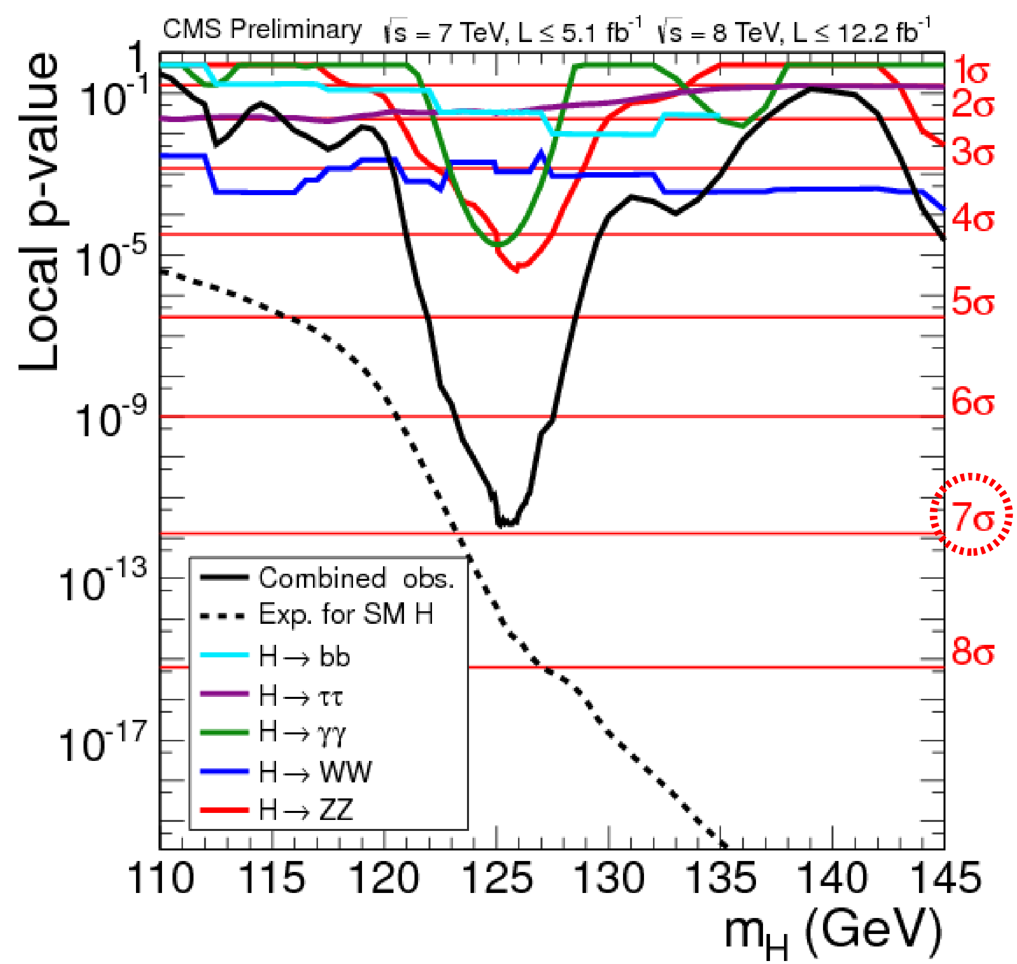


Discovery of Higgs boson: “all” channels

- Signal strength for all channels fully consistent with the SM Higgs:

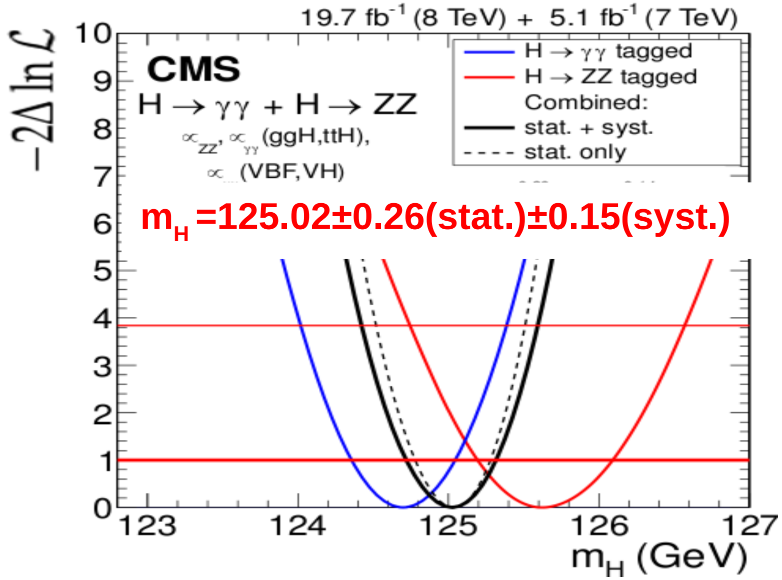


Combined significance (local p-value):
(latest updates not included)



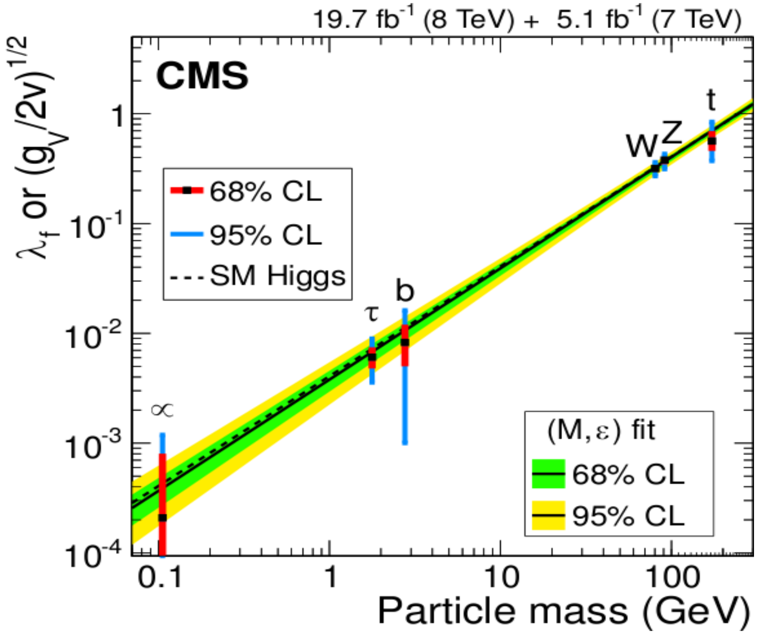
Properties of the Higgs boson

■ Mass peak position (γγ,ZZ):

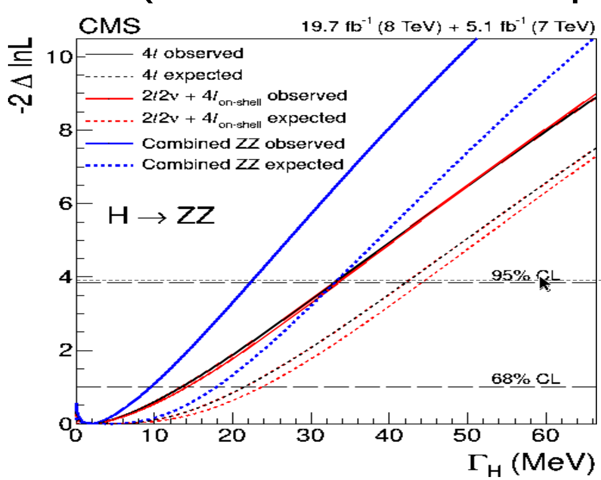


■ Couplings:

Including all production & decay modes

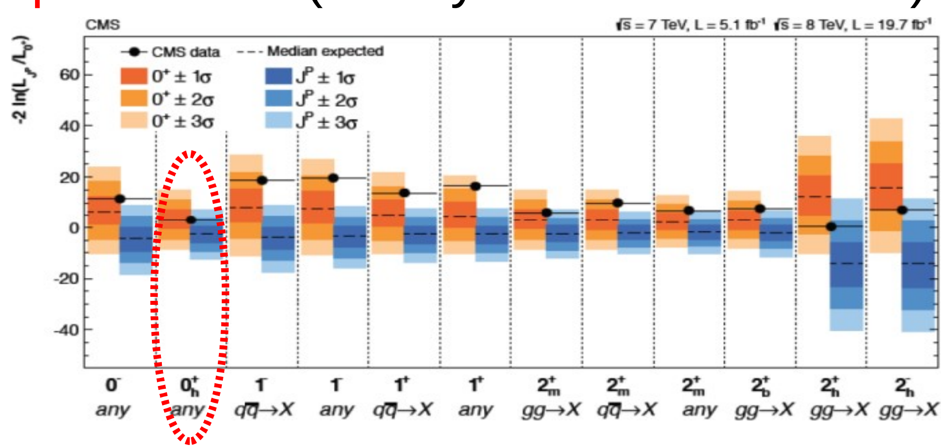


■ Width (via on/off-shell ZZ prod.):



$\Gamma[H] < 22$ MeV $= 5.4 \cdot \Gamma[H_{SM}]$ (95% C.L.)

■ Spin-PC: 0^{++} (mostly via ZZ kin. distrib.):



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

Higgs mass & top-quark mass

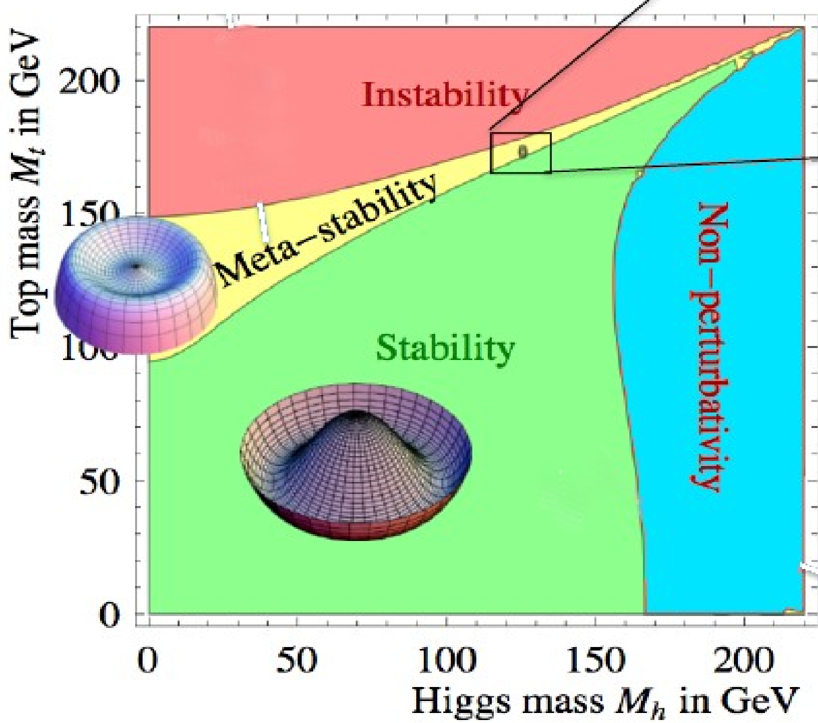
- Running of the Higgs self-coupling with energy:

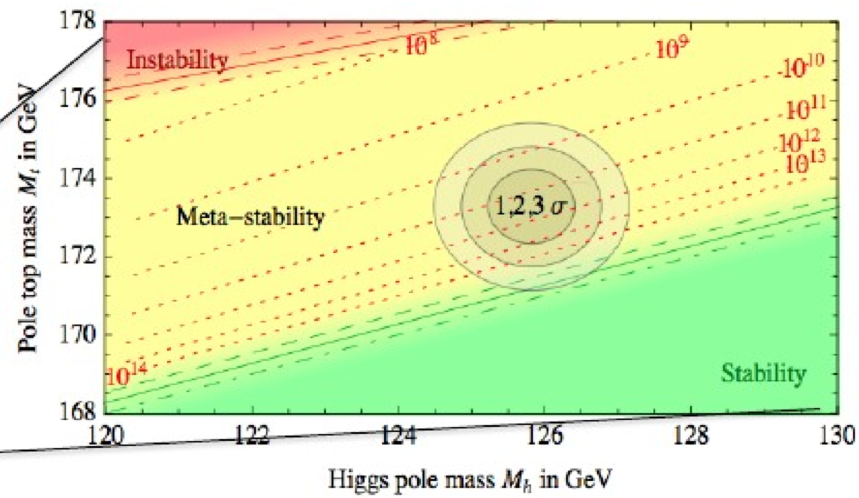
$$(4\pi)^2\frac{d\lambda}{d\ln\mu} = -6y_t^4+\frac{9}{8}g_2^4+\frac{27}{200}g_1^4+\frac{9}{20}g_2^2g_1^2+\lambda(12y_t^2-9g_2^2+\frac{9g_1^2}{5})+24\lambda^2+\text{higher loops}$$

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

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

[Strumia, Moriond EWK'13]





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

$$M_h = 125.8 \pm 0.4\,\text{GeV} \qquad \text{(naive average of latest results)}$$

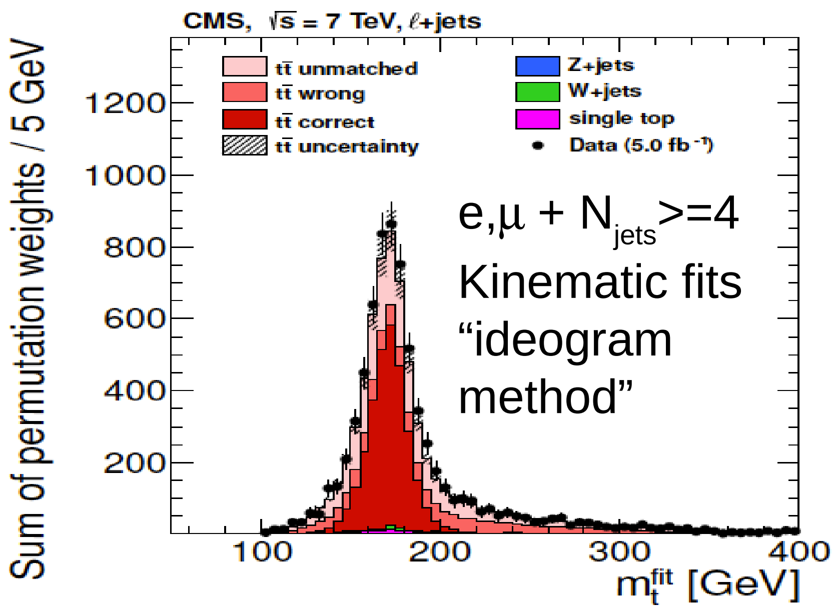
If m_{top}(pole)>171.2 GeV:

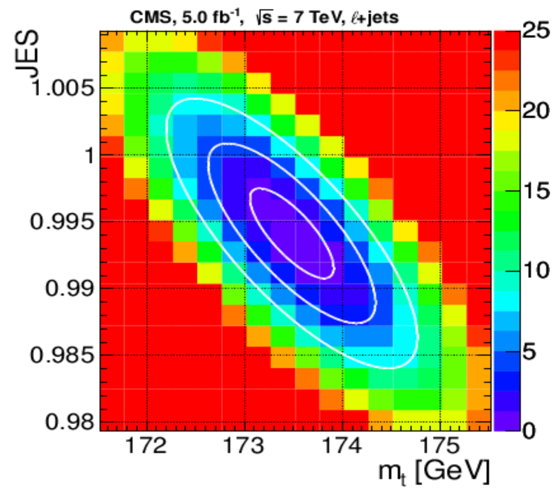
the universe is in a meta-stable state

(it will decay to true vacuum eventually)

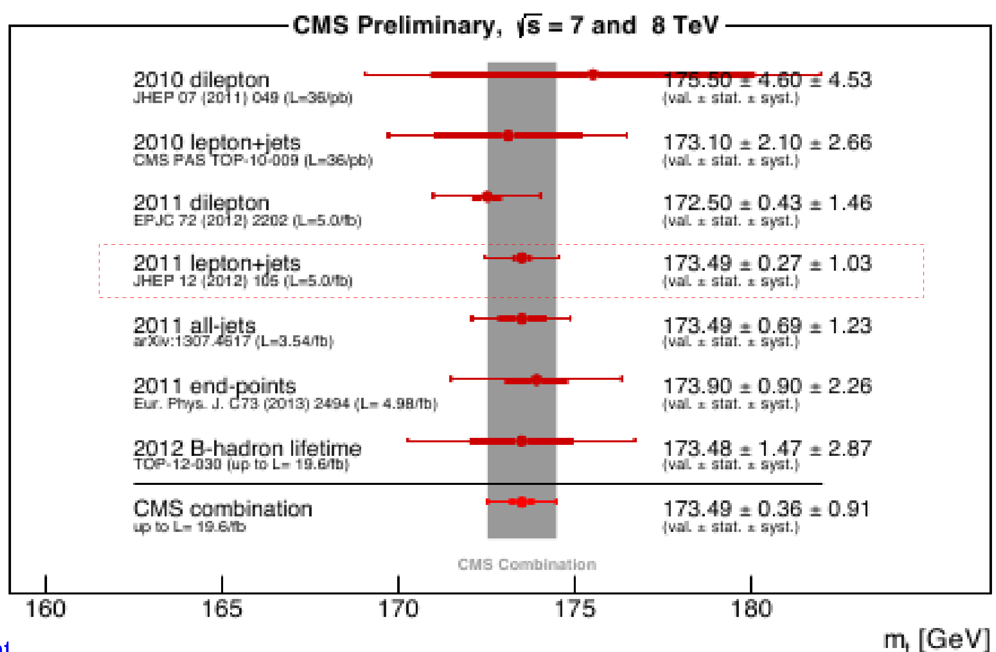
Top-quark mass

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

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

[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 dynamics & mass]

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

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

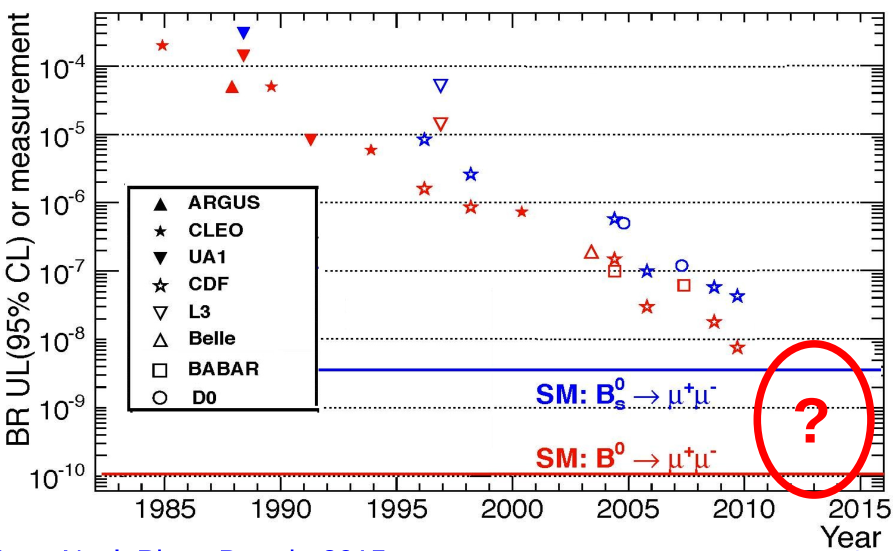
Origin of matter-antimatter asymmetry?

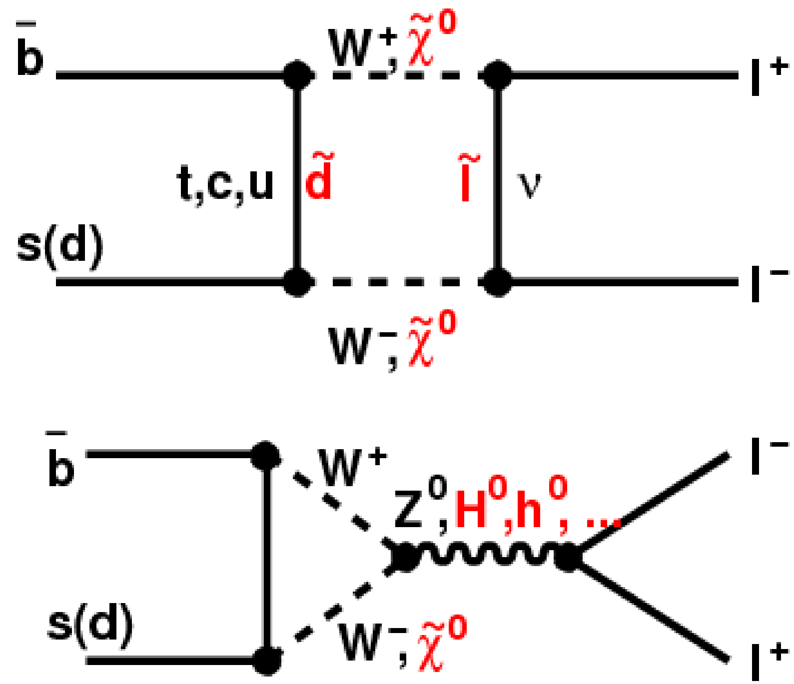
- Differences between particles-antiparticles (CP-violation in SM) way too small (10^{-16}) to explain matter-antimatter imbalance in Universe.

  $\Rightarrow$ 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

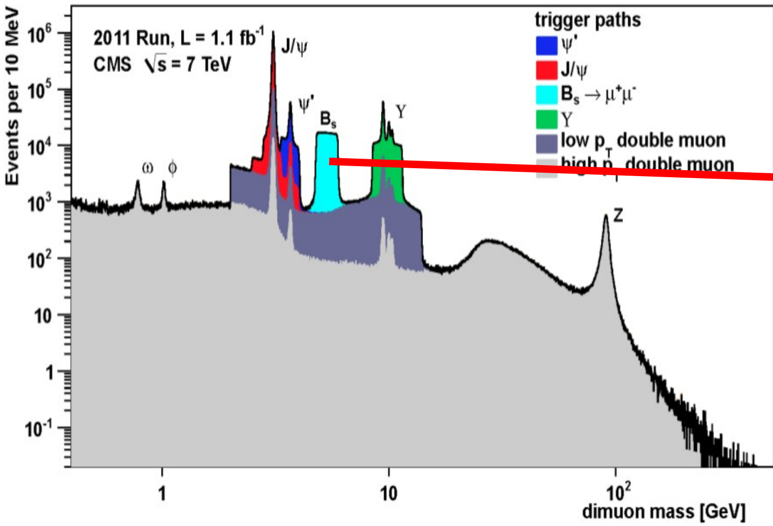
$BR(B_s,B_0 \to \mu\mu) \sim 4\cdot10^{-9}, 1\cdot10^{-10}$

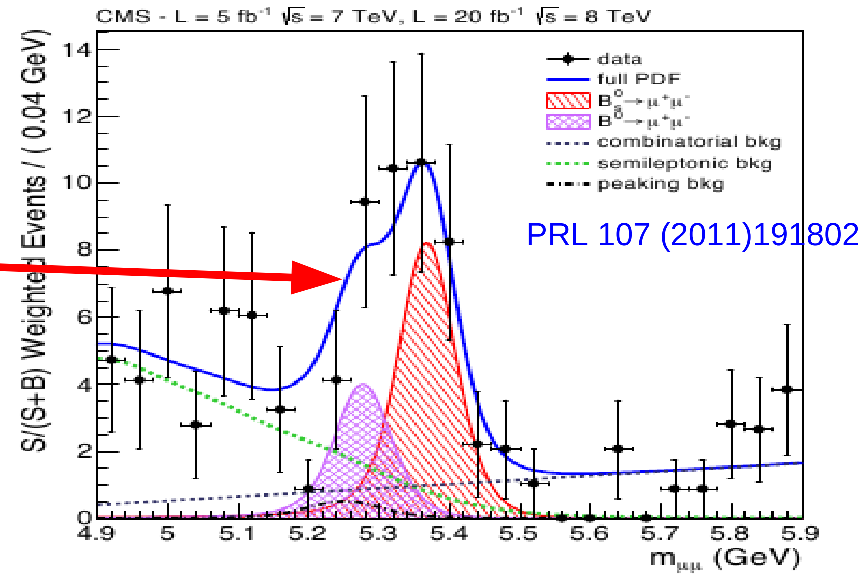




Observation of $B_s \to \mu\mu$

- High-stats trigger + MVA techniques:



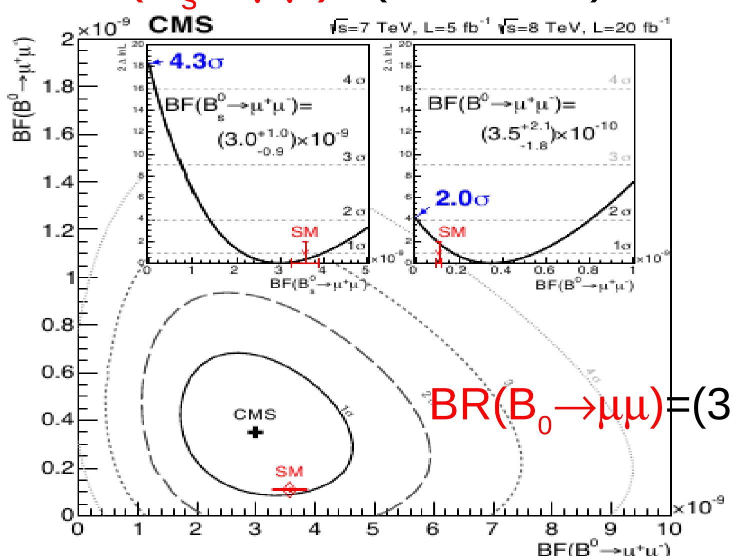


PRL 107 (2011)191802

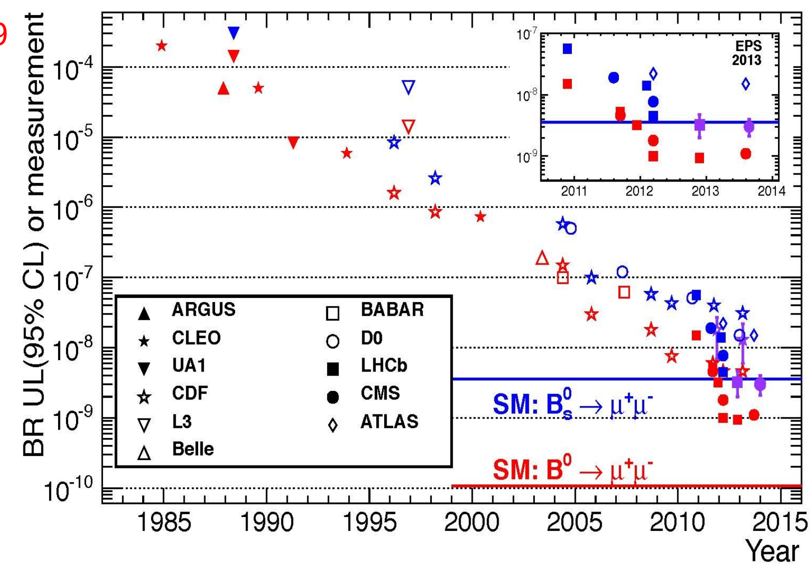
- $BR(B_s \to \mu\mu) = (3.0 \pm 1.0) \cdot 10^{-9}$, $(2.9 \pm 0.7) \cdot 10^{-9}$

(CMS+LHCb)

arXiv:1411.4413



$BR(B_0 \to \mu\mu) = (3.6 \pm 1.6) \cdot 10^{-10}$ (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

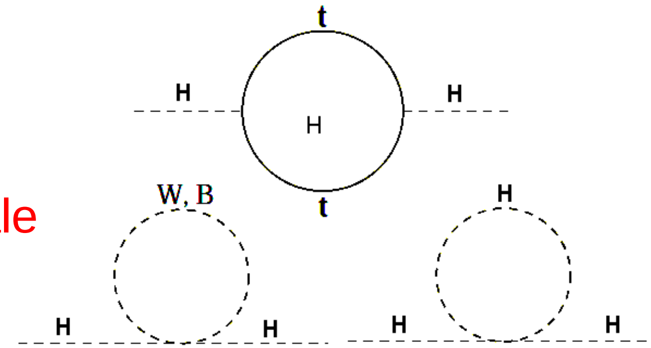
BSM searches: SM fine-tuning problem

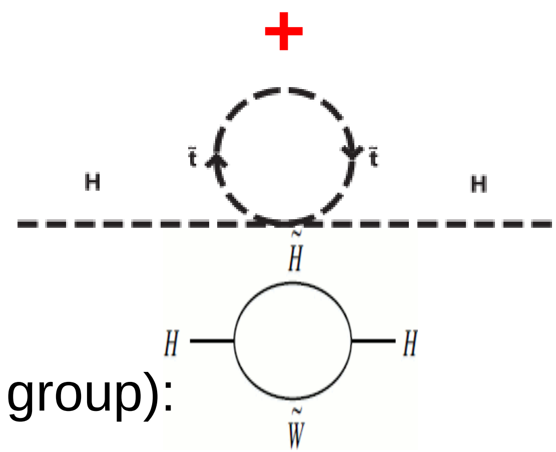
■ Higgs boson is the only SM particle with mass:

- 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'), ...

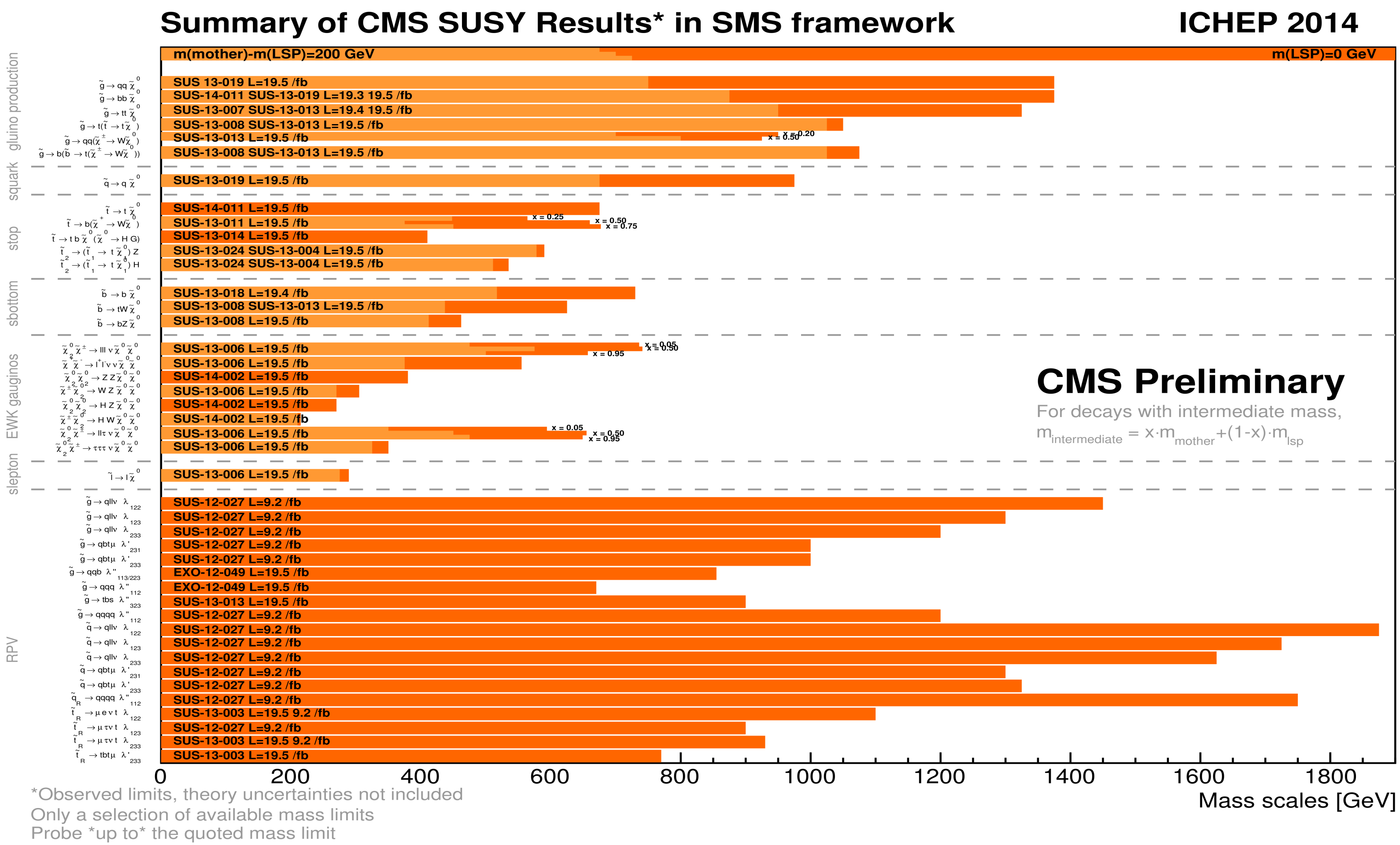
(3) Quantum gravity sets in at ~TeV:

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 ...



"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]

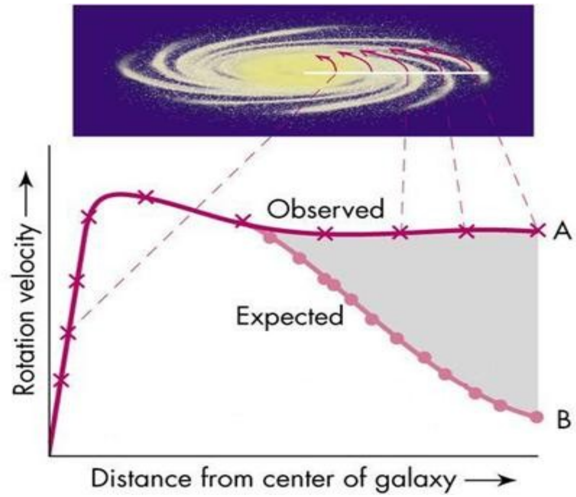
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ [Higgs dyn. & mass]

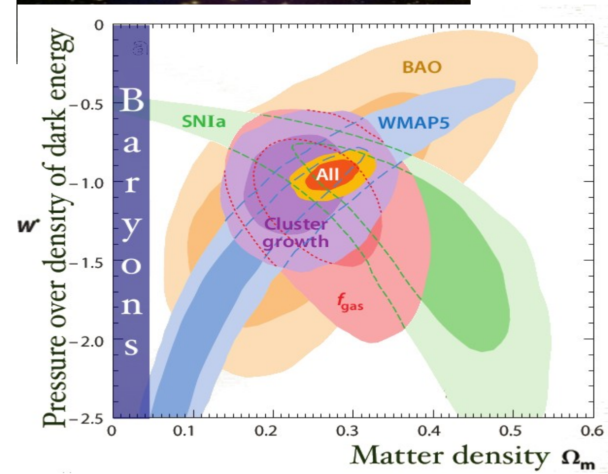
+ new particles/symmetries ?

- ✔ 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



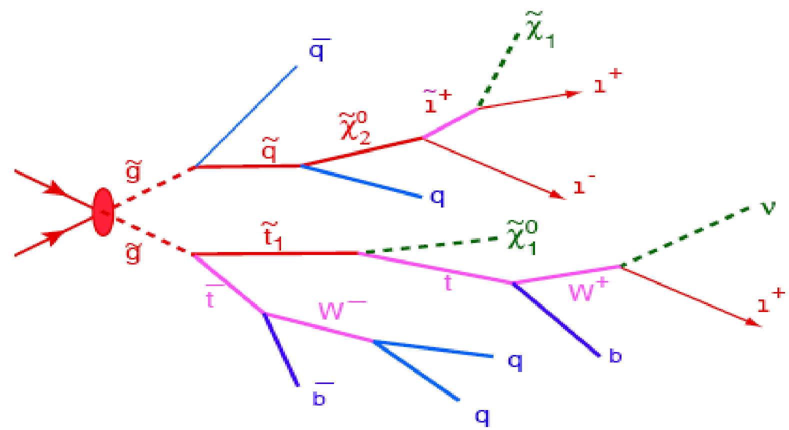


- Properties:
  - Sensitive to gravitation, stable, massive, early Universe relic

  → 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.
  - ...

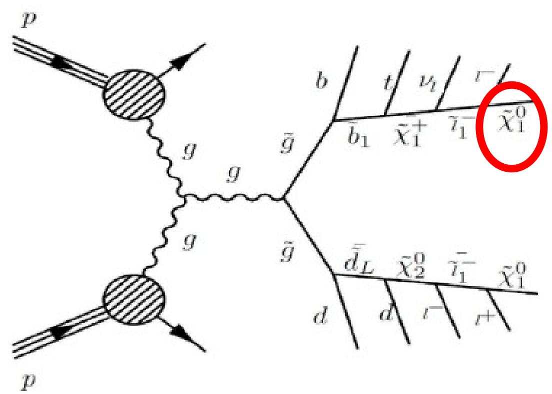


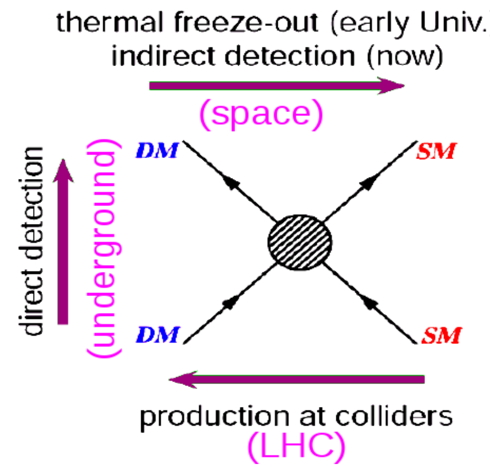
Dark matter: Collider searches

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

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

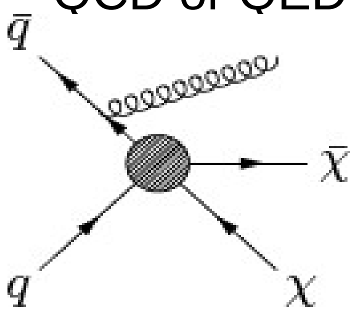
Prominent WIMP candidate.
Decay cascade with large MET, many jets & leptons

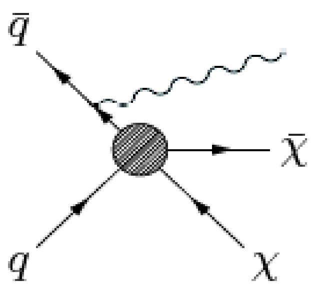




➔ Generic DM-pair searches:

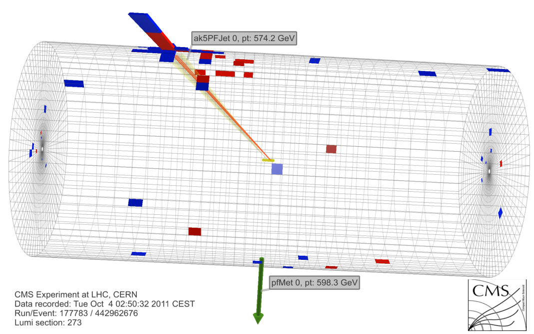
Large MET plus initial-state QCD or QED radiation:





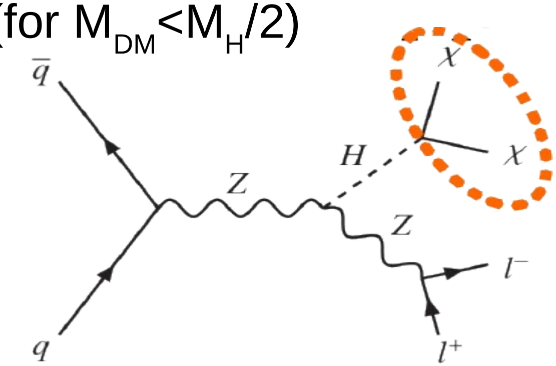
mono-jet mono-photon

(also mono-leptons)

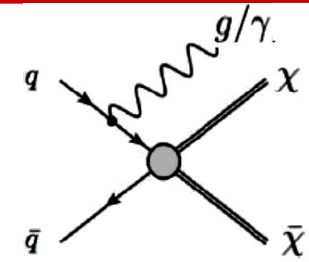


➔ Higgs decay to DM-pair:

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

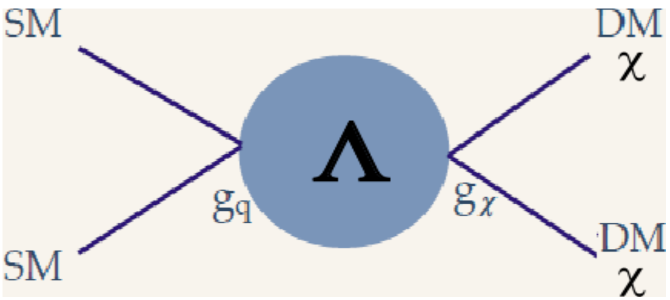


Dark matter: Collider searches (generic DM pair)



(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	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	(spin-independent: SI)
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	(spin-dependent: SD)

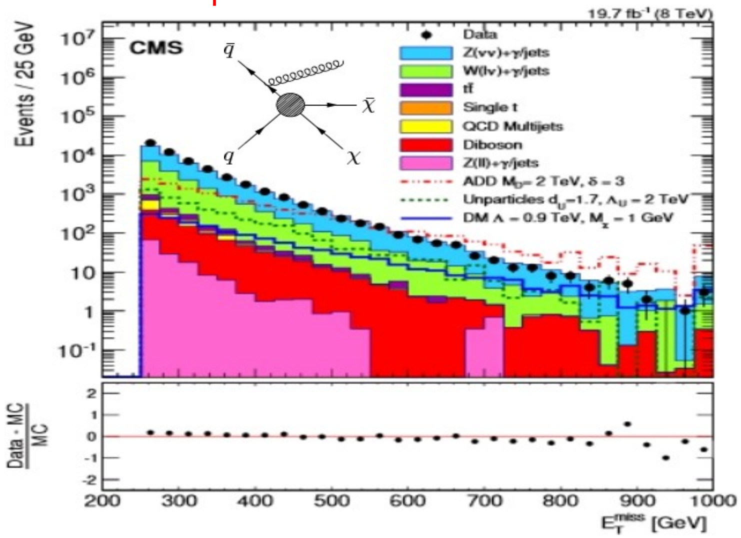
(3) Set limits in DM mass vs. interaction-strength for SI & SD couplings:

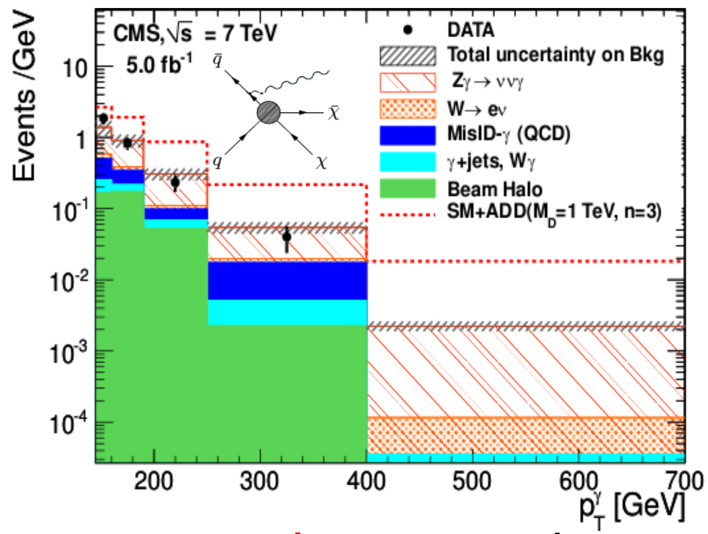
$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M_*^4}\mu_{\chi N}^2$$

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

Dark matter searches: monojets/monophotons

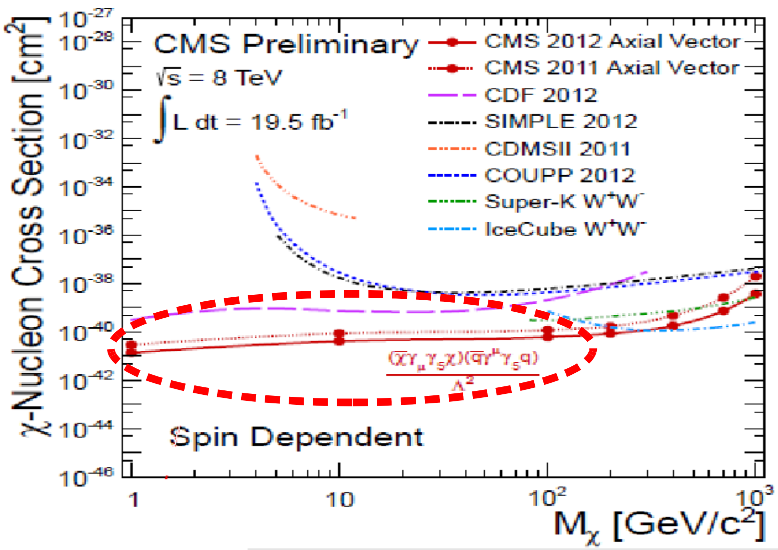
- MET, p_T^γ distributions after cuts for SM backgrounds & DM signal:

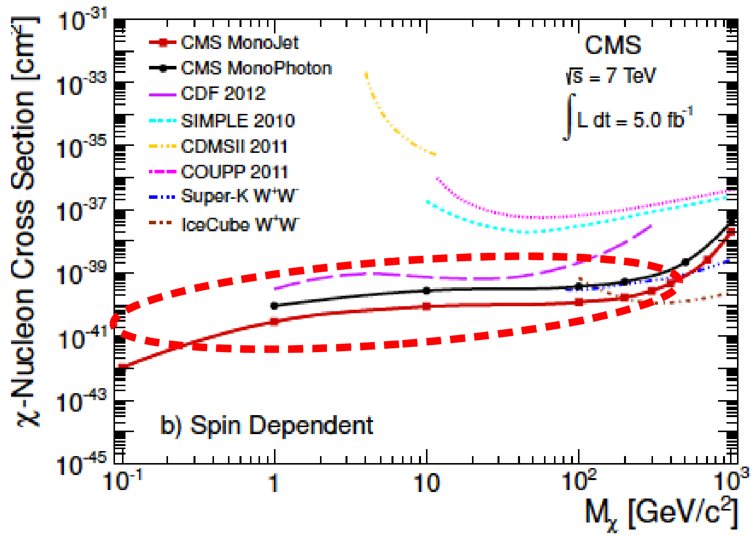




CMS-PAS-EXO-12-048
JHEP09(2012)094
PRL 108 (2012)261803

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





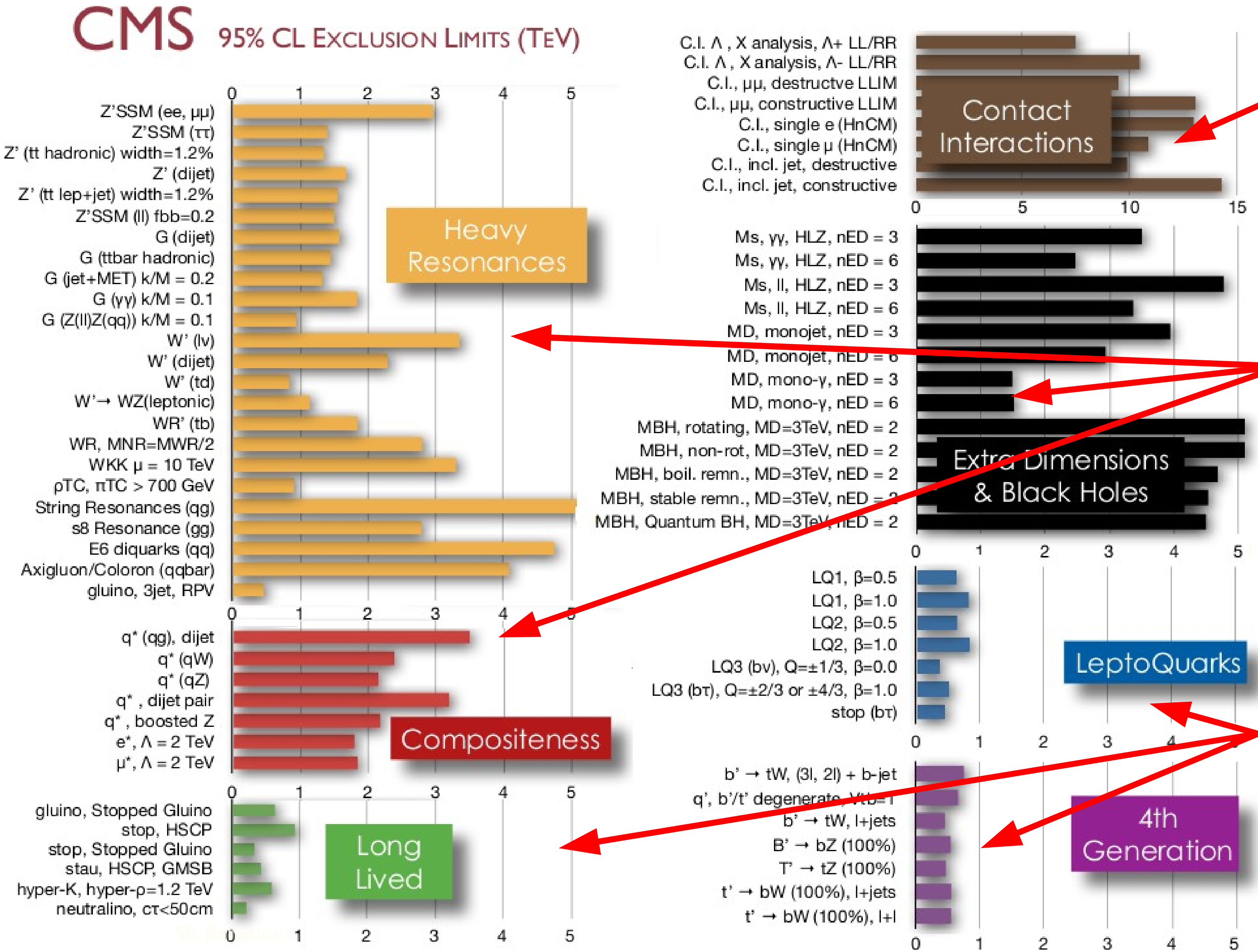
Best limits for low DM mass!

$M_\chi \sim 1 - 10$ GeV

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

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

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'

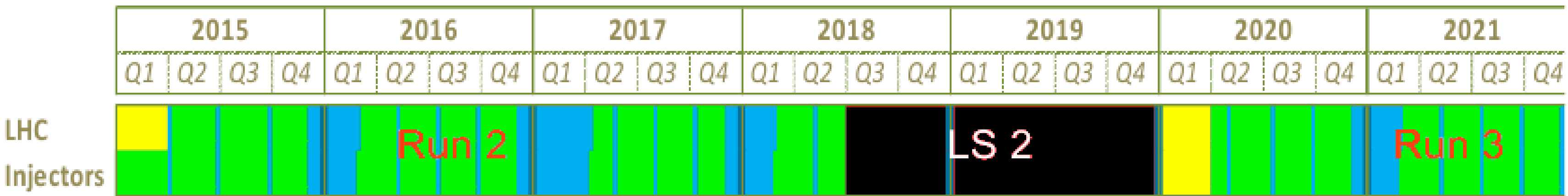
LHC Outlook

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)

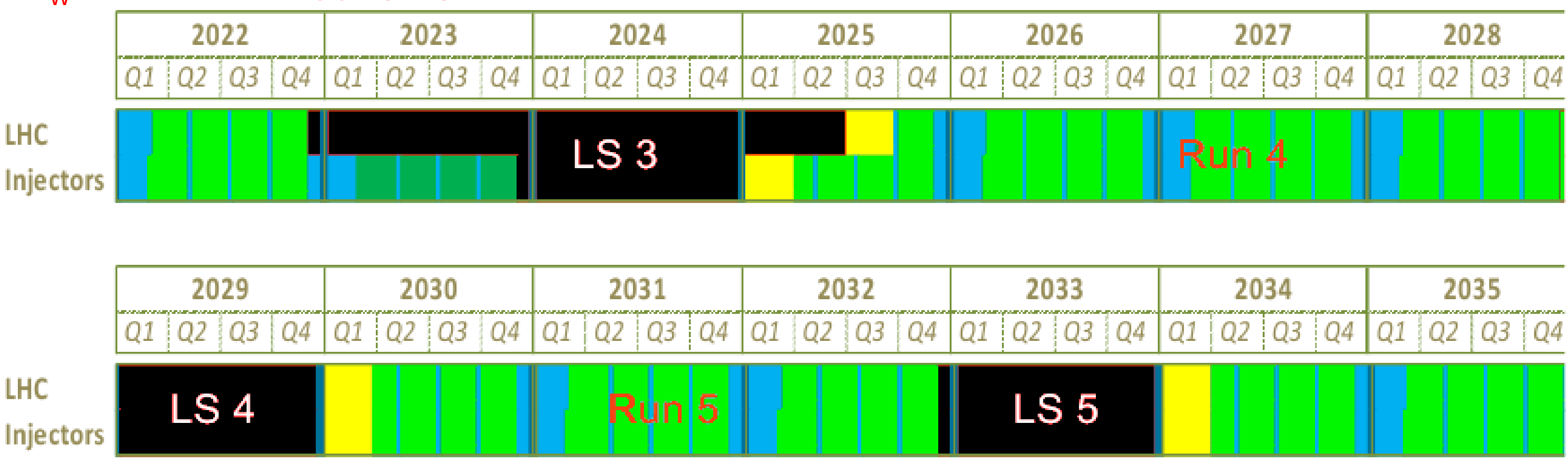
Run-3 [2020-2022]: p-p @ 14 TeV, L_{int} ~ 300 fb^{-1} (Pb-Pb @ 5.5 TeV, p-Pb @ 8.8 TeV)

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)

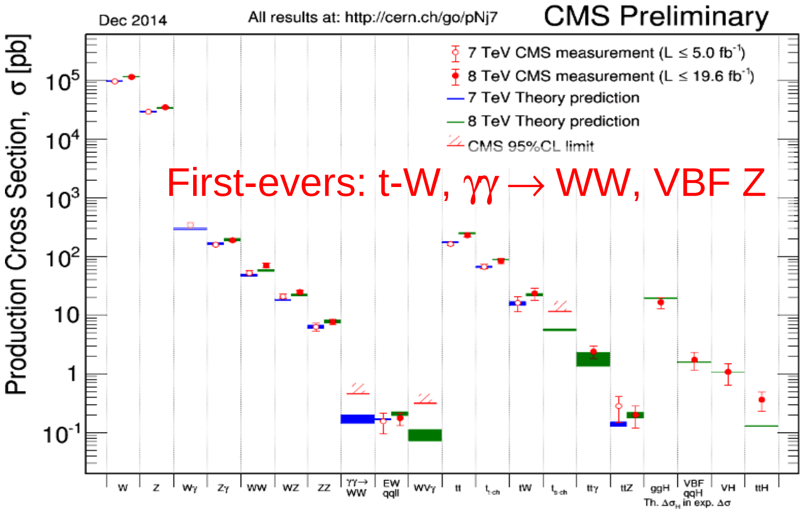


m_W, WW→WW, Higgs properties, SUSY/BSM searches,...

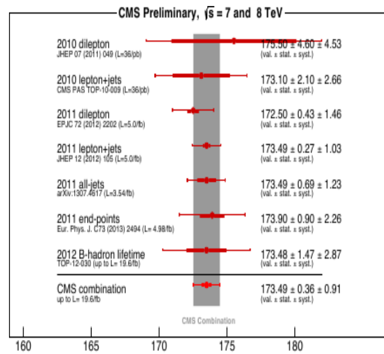


Summary

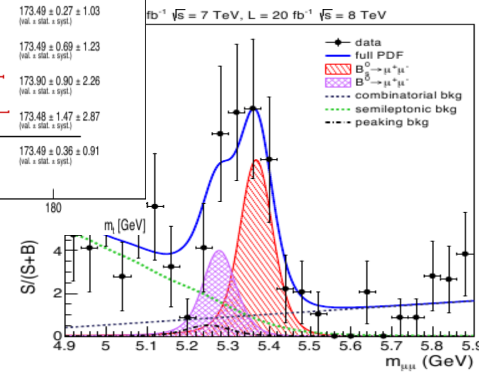
- Precision (N)NLO QCD&EWK:



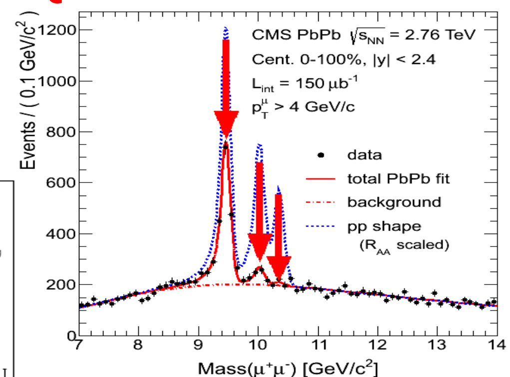
- Precision fundamental SM parameters:

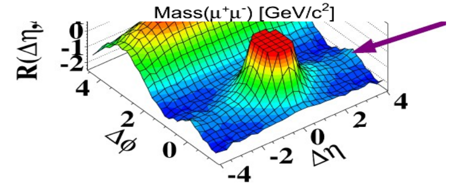


- Very rare decays:

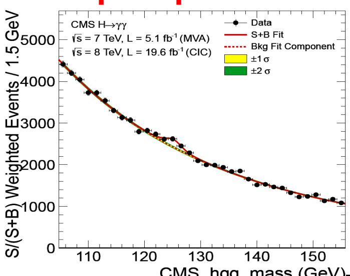


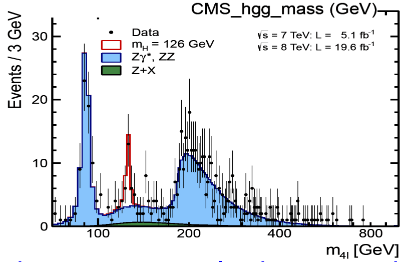
- Intriguing dense QCD-matter data:

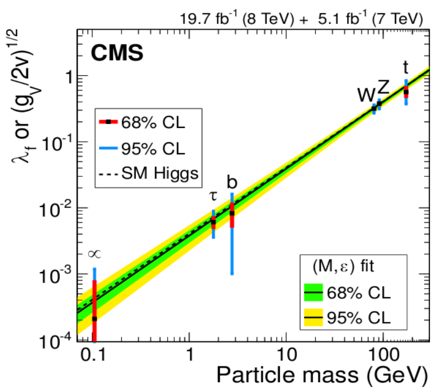




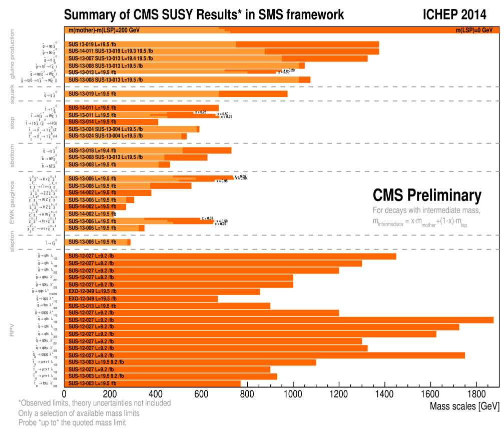
- Discovery of Higgs boson with SM properties at m~125 GeV!

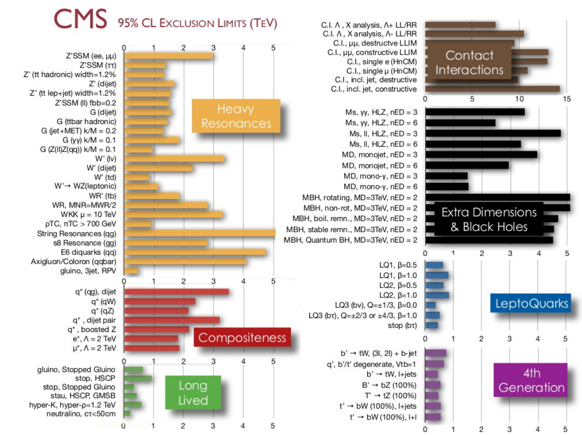






- No (simple)SUSY/BSM signals yet at ~1 TeV





- Back to discovery-mode starting Apr'15 !

Back up slides

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 ?

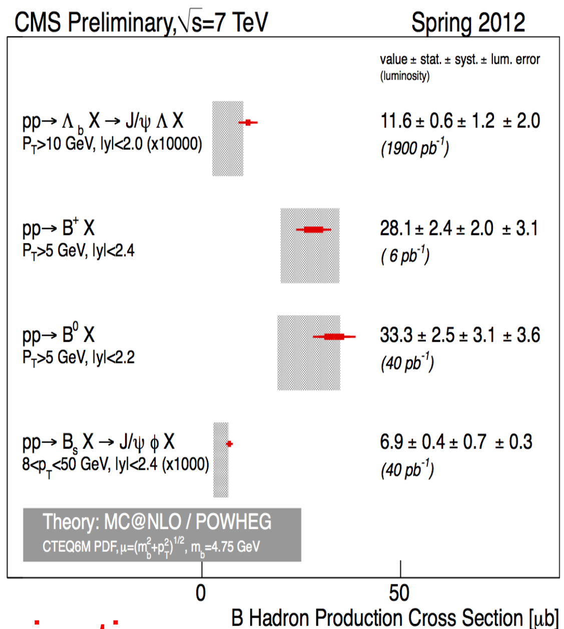
4. Flavour problem: Origin of matter-antimatter asymmetry in the Universe ? Why so many types of matter particles ?

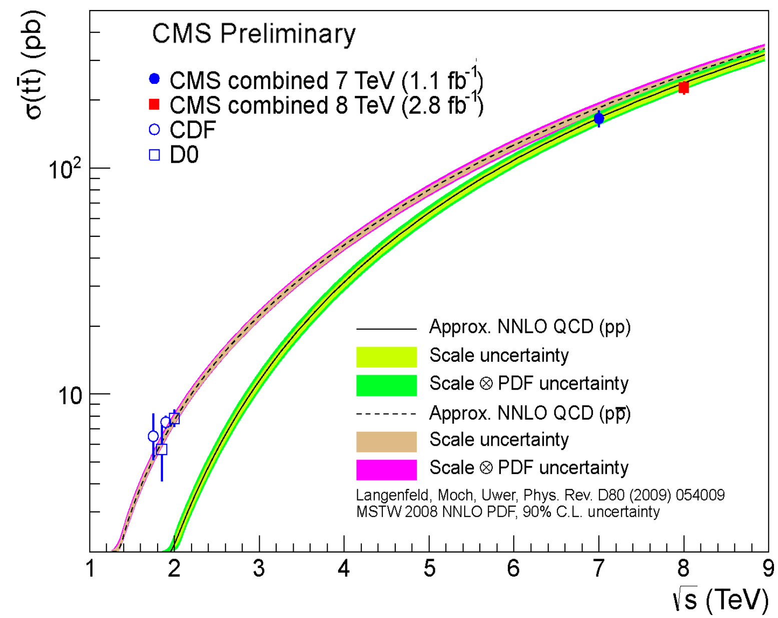
5. QCD in non-perturbative regime: Why quark confinement ? Total hadronic x-sections ? Gauge-String duality (AdS/CFT) ?

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

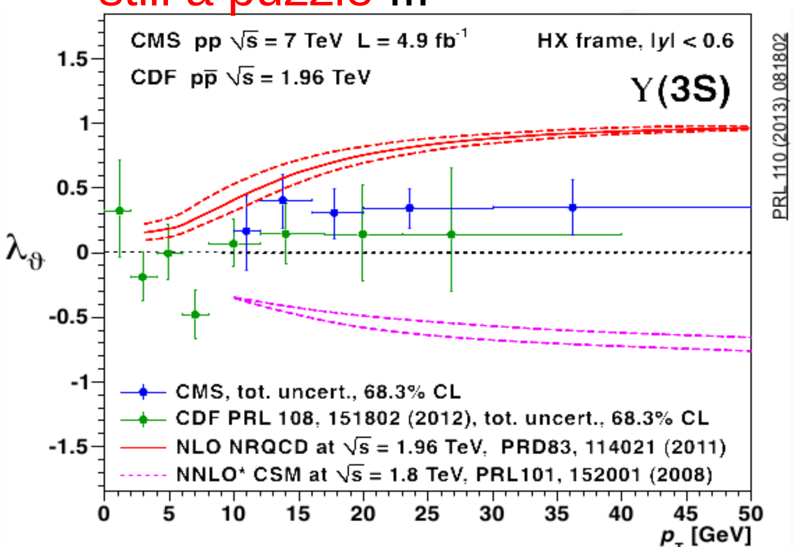
QCD: heavy-Q cross-sections (& $Q\bar{Q}$ polarization)

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

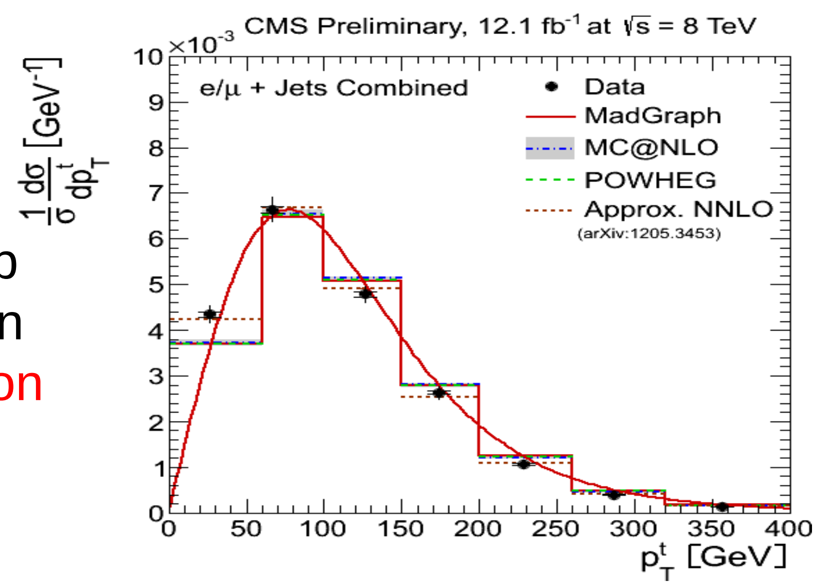




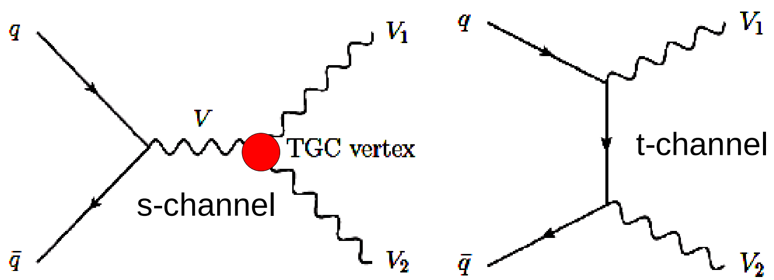
- Although quarkonia polarization still a puzzle ...



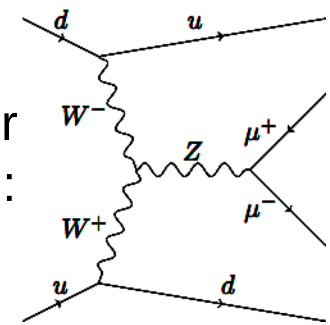
- Quality of differential top x-sections can constrain gluon (N)NLO PDF:

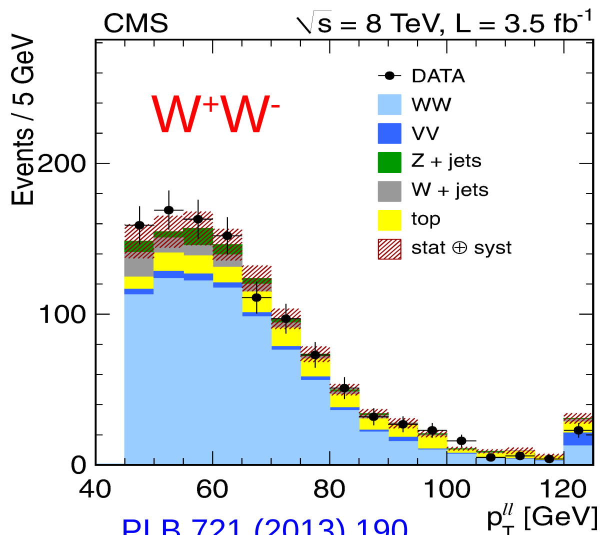


EW: WW, ZZ and VBF-Z production

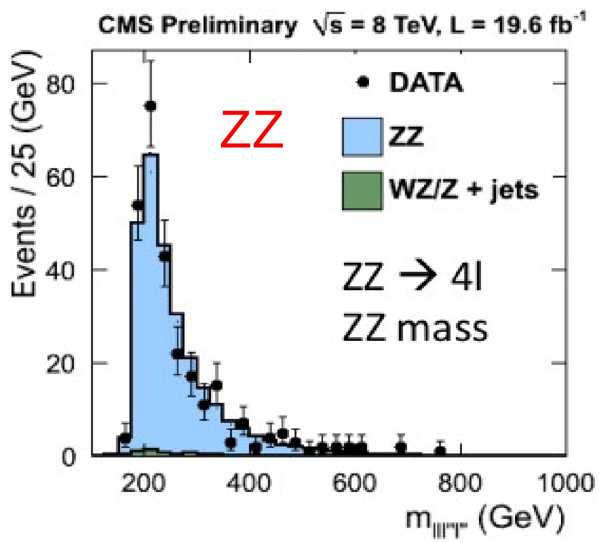


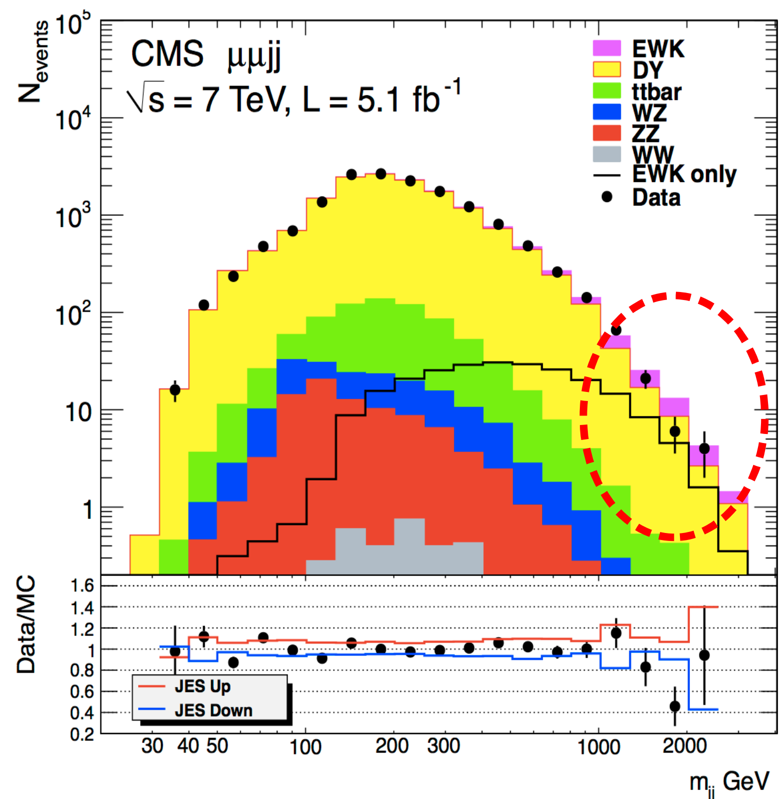
1[st] evidence (~3sigma) for electroweak Z production:





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

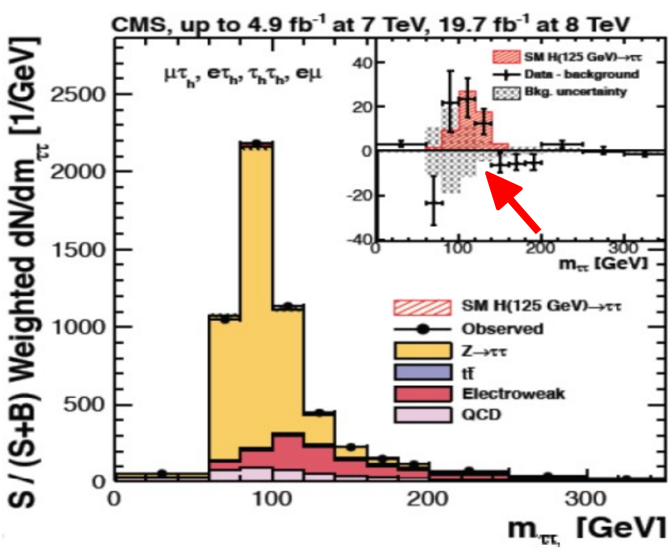
World's strongest constraints on neutral aTGCs (fZ ~ 3-5 10^{-3})

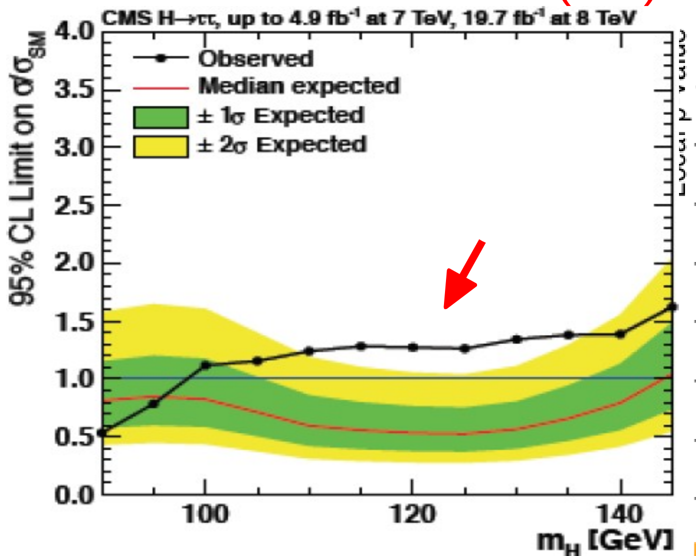
JHEP 1310 (2013) 101

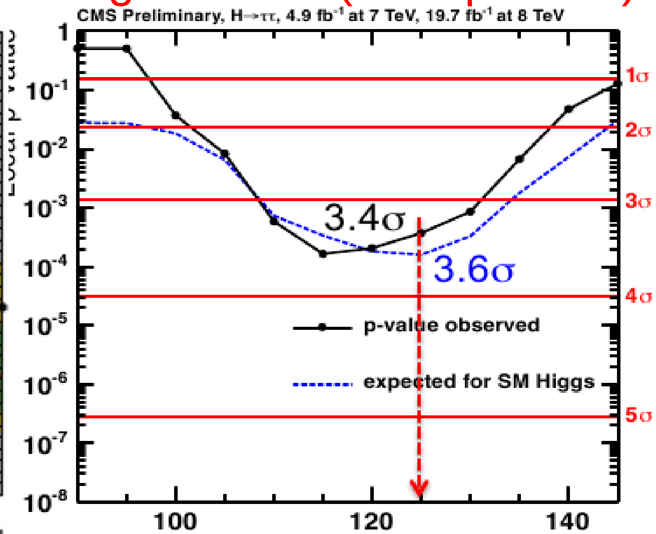
Discovery of Higgs boson: ττ, $b\bar{b}$ channels

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

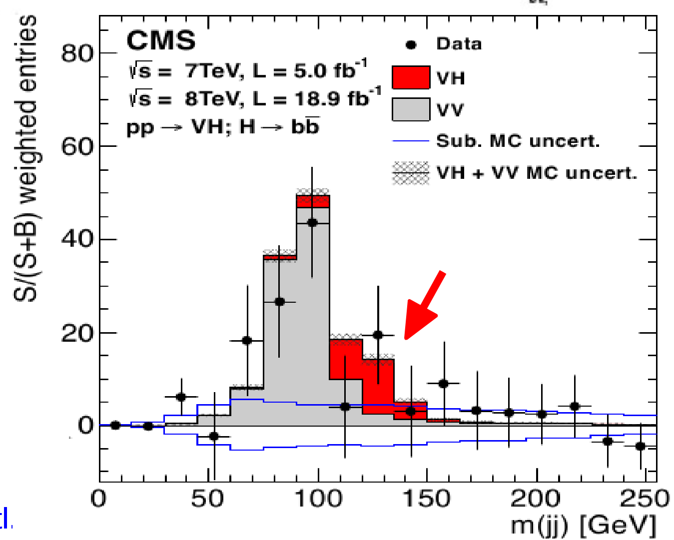
Invariant mass distributions: 95% CL-Limits on σ/σ(SM): Significance (local p-value):

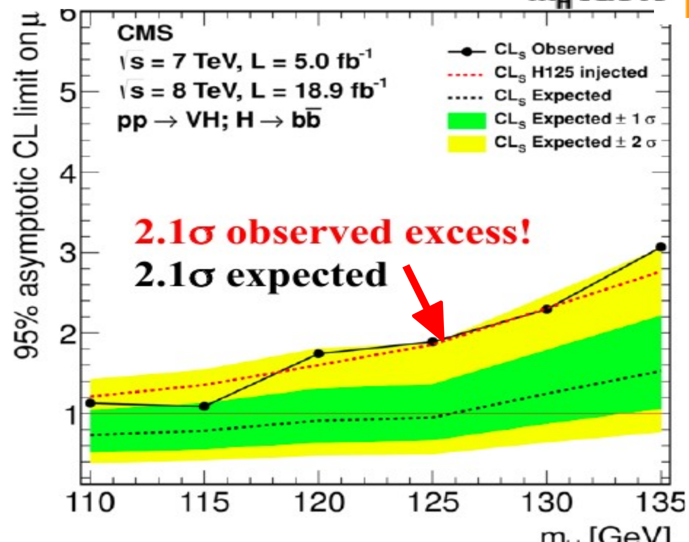


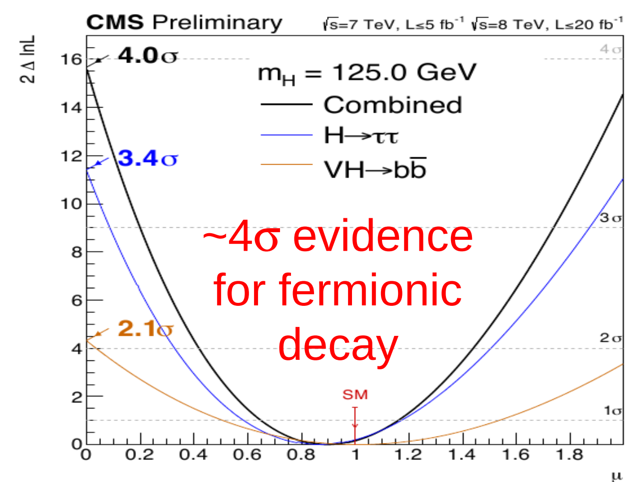




December 3, 2013



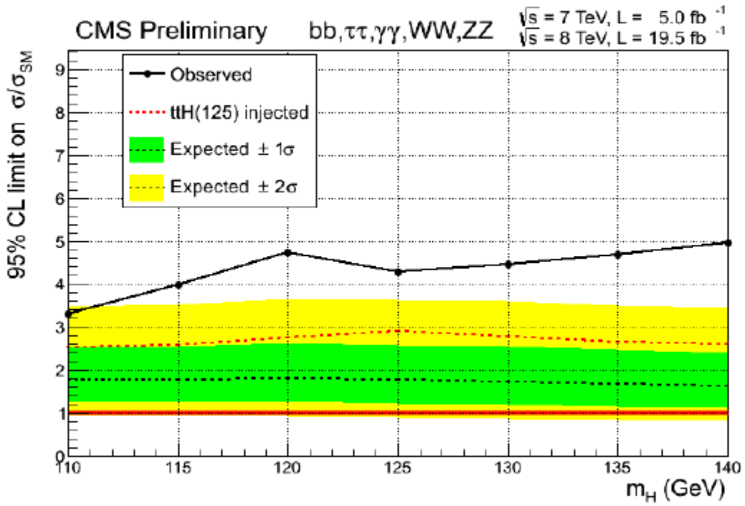




Higgs searches in other channels

- tt-H

γγ, bb, ττ, multi-lepton channels combined

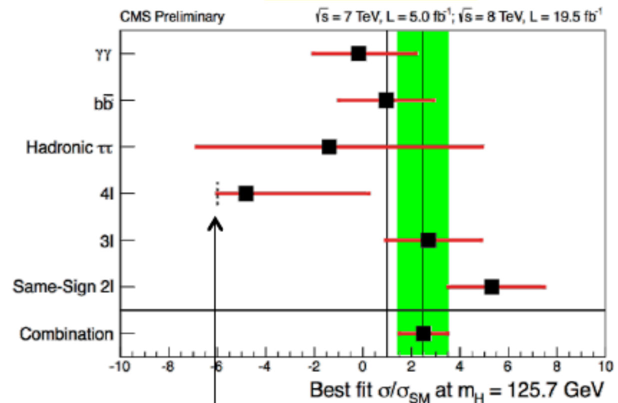


95% CL limit on μ
at m_H= 125 GeV

Observed limit: 4.3
Expected limit: 2.9

Best fit of signal strength

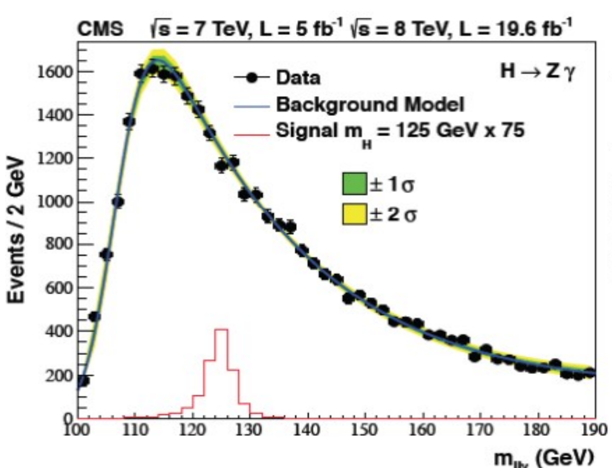
$$\mu = \frac{\sigma}{\sigma_{SM}} = 2.5^{+1.1}_{-1.0}$$

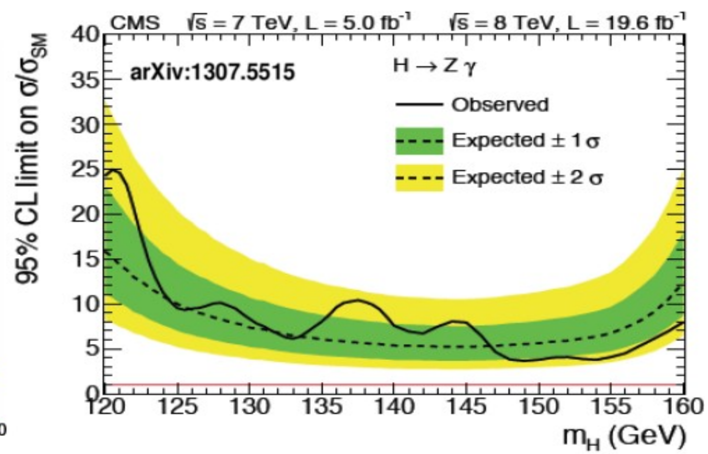


Expected signal-plus-background event yield must not be negative

Direct hint of H coupling to top

- H→Zγ

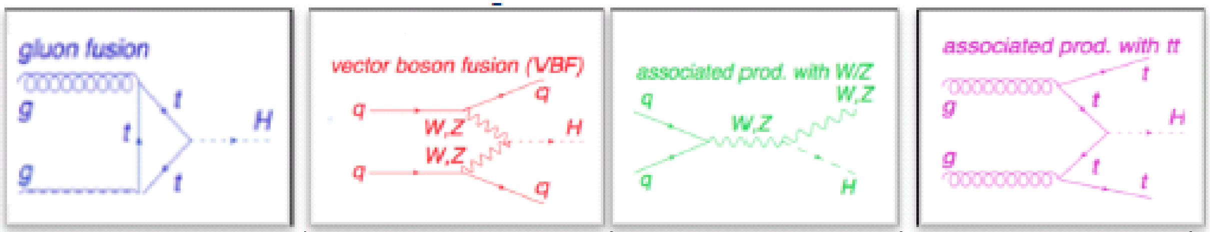




Similar BR to γγ
High-resolution too
But small sensitivity
due to BR(Z→ll)

Higgs discovery/searches in other channels

- About 30 Higgs production-decay channels available:

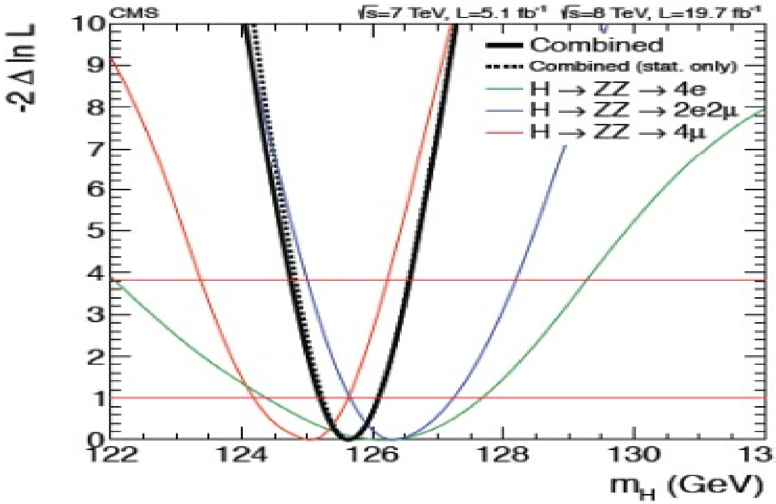


Channel	ggF	VBF	VH	ttH	Dataset 7+8 TeV (fb^{-1})
$H\rightarrow\gamma\gamma$	Released	Released	Released	Released	5.1+19.6
$H\rightarrow ZZ\rightarrow 4l$	Released	Released	Released	In progress	5.1+19.6
$H\rightarrow WW\rightarrow l\nu l\nu$	Released	Released	Released	Released	4.9+19.5
$H\rightarrow\tau\tau$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

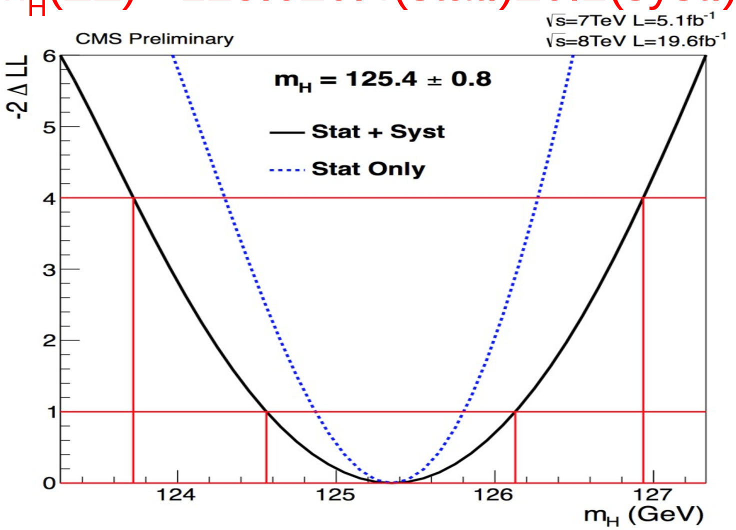
Released (green) In progress (yellow)

Discovery of Higgs boson: mass, spin-parity

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

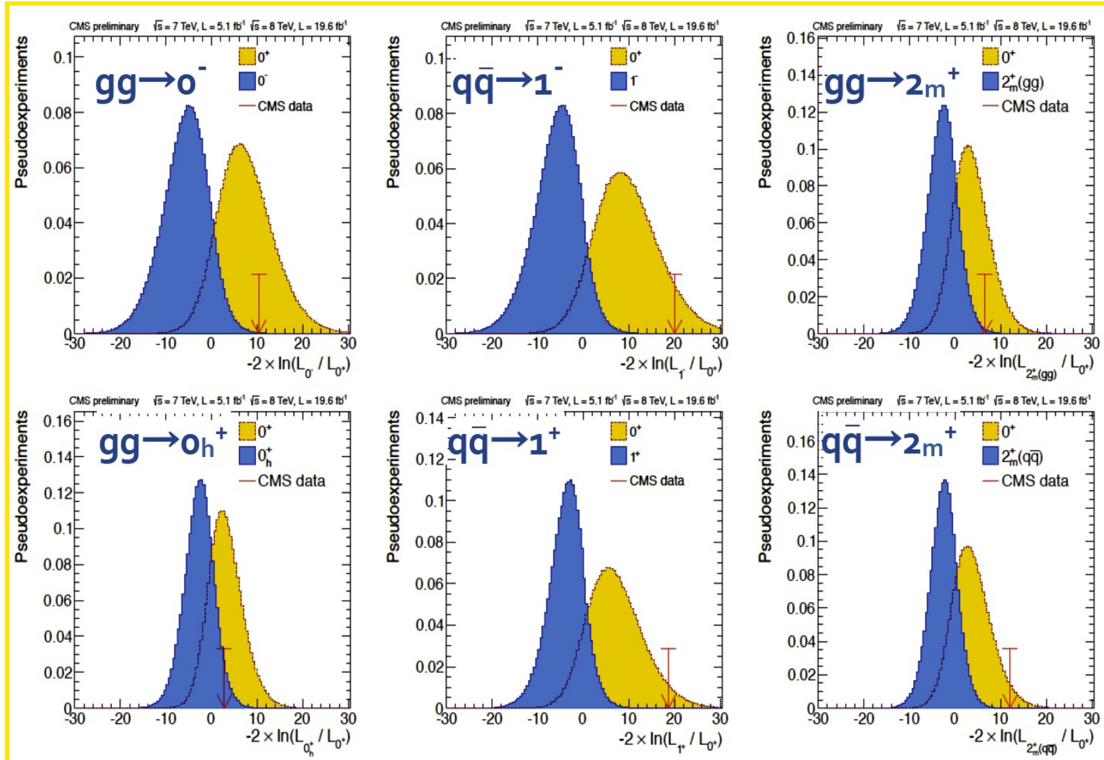


$m_H(ZZ) = 125.6 \pm 0.4(stat.) \pm 0.2(syst.)$



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

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

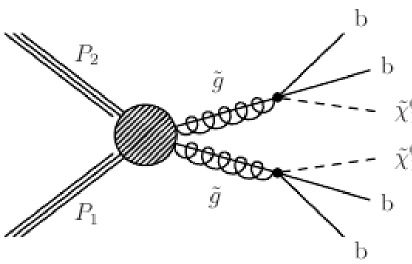


Studied pseudo-scalar, spin-1 and spin-2 models excluded at 95% CL or higher

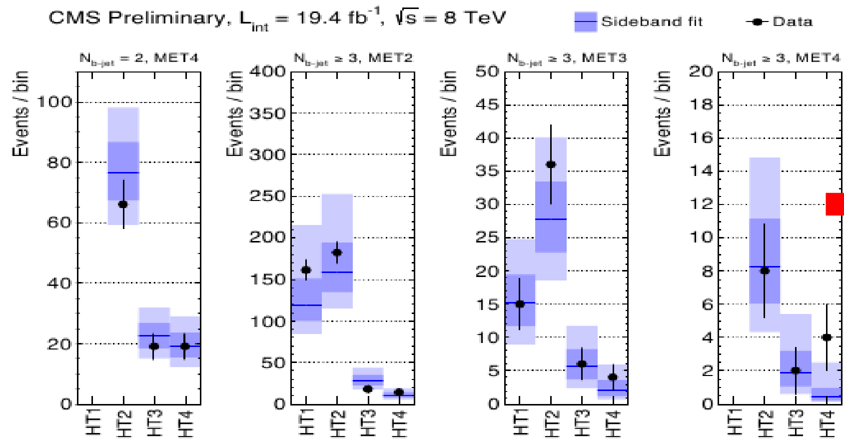
Less constrained searches: natural-SUSY

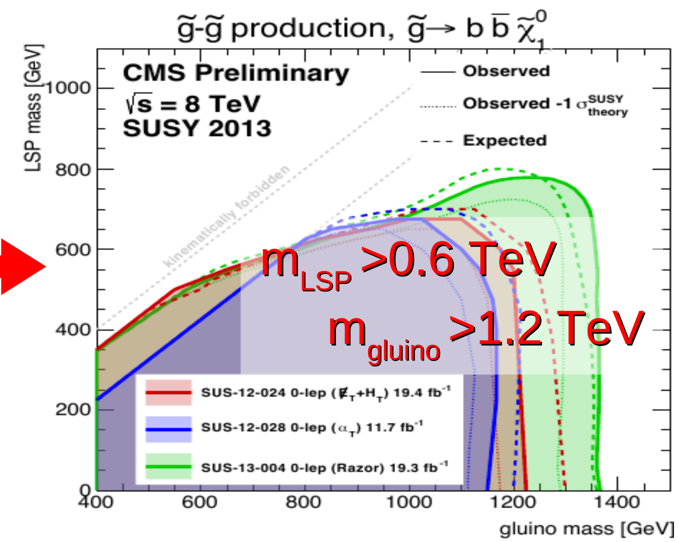
- Natural SUSY: m_H regularized by m_{stop}, squarks can be heavy, gluinos less.
- ~10% fine-tuning: squarks>TeV, stops<0.6 TeV, gluinos<1.4 TeV

Gluinos decays into 3rd generation:

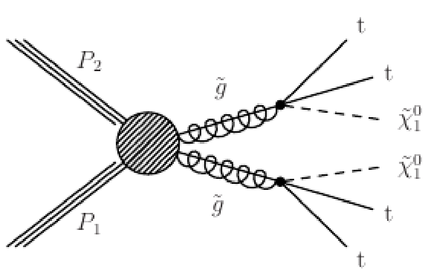


4 b-jets, MET



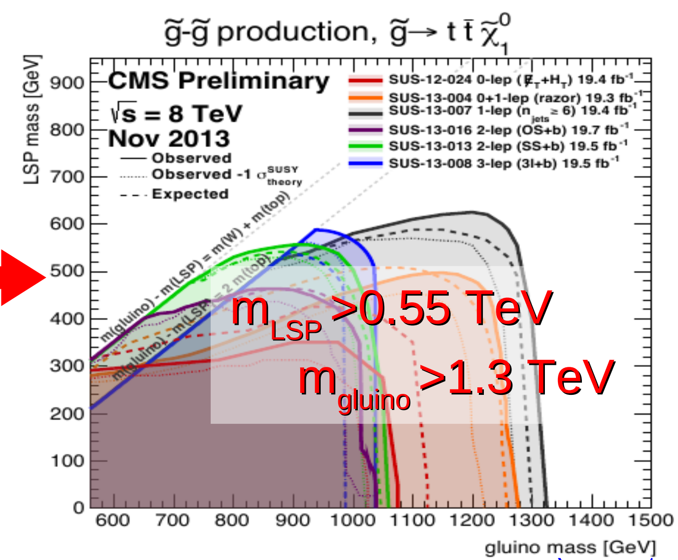


Increasing MET & N-jets --⟶



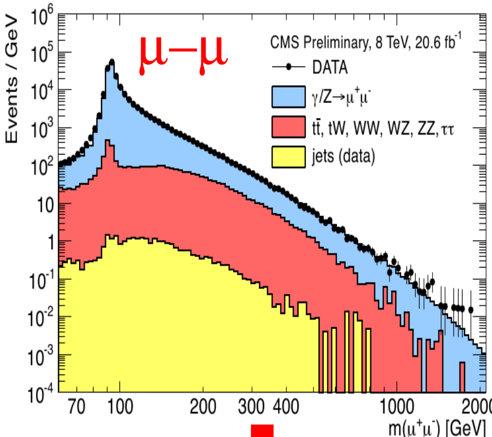
4 b-jets, 4W, MET

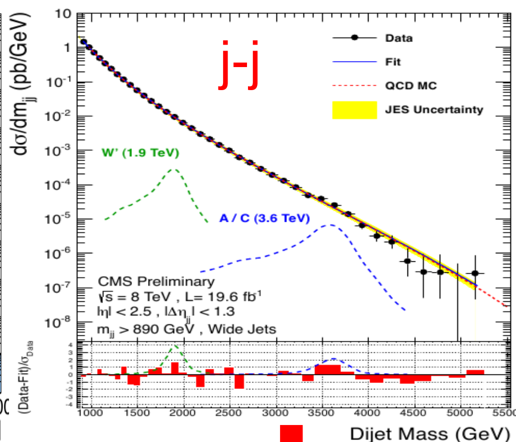
		S_T^{lep} [GeV]	control reg. data	prediction	observation
N_b=2	Muons	[250,350]	141	6.00 ± 2.40 (2.23)	9
		[350,450]	24	1.37 ± 1.19 (1.12)	2
		>450	9	0.0 ± 0.66 (0.66)	0
	Electr.	[250,350]	112	3.83 ± 1.84 (1.75)	9
		[350,450]	28	2.74 ± 2.02 (1.86)	2
		>450	9	0.0 ± 0.42 (0.42)	0
$N_b \geq 3$	Muons	[250,350]	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

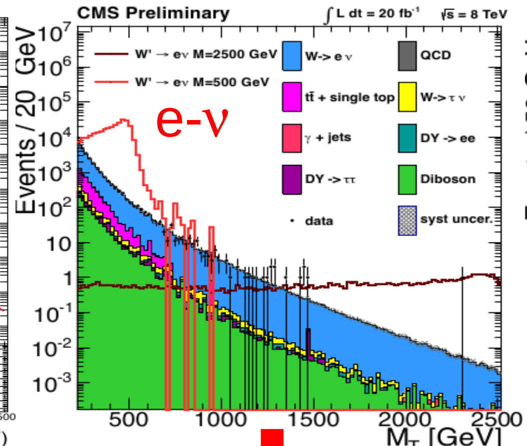


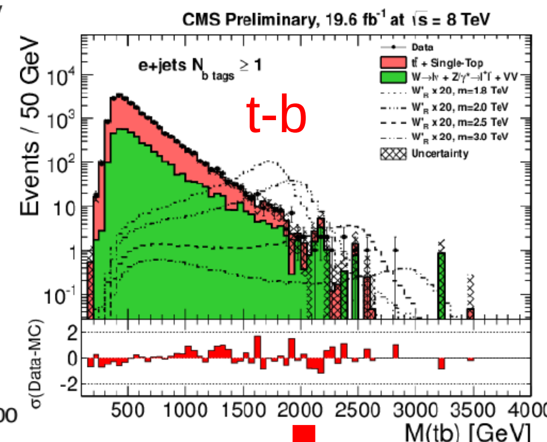
BSM searches: High-mass resonances

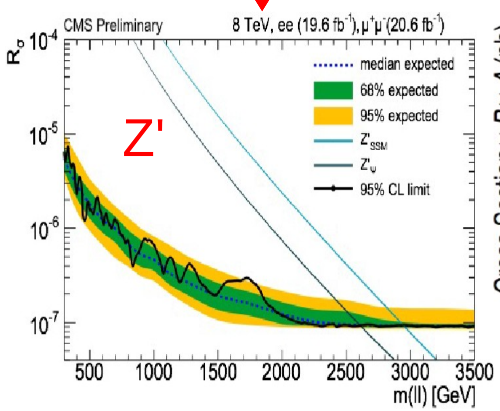
- «Simple» generic procedure:
  (i) Reconstruct pairs of high-p_T objects: jets, leptons, bosons, ...
  (ii) Look at inv. mass tails for deviations from smooth SM backgrounds.
  (iii) Interpret (lack of) excess within (simplified) BSM models: Set limits for NP

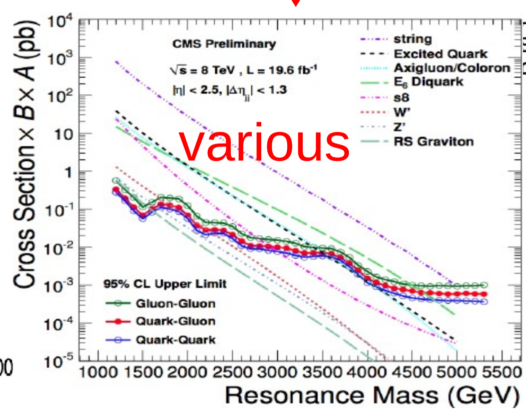


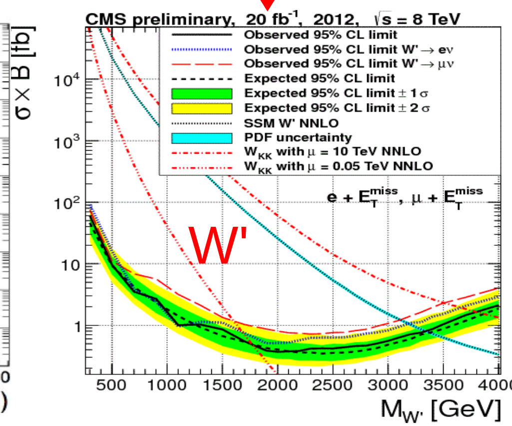


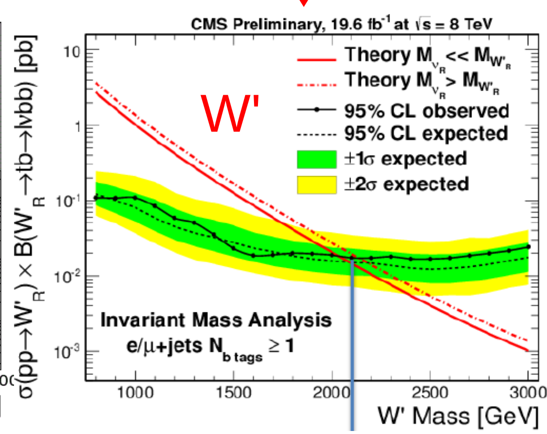








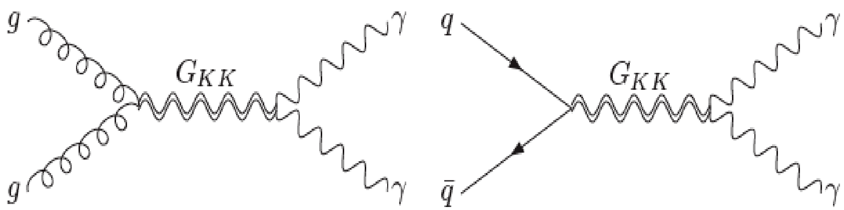




BSM searches: Extra-Dimensions via high-mass γγ

PRL108 (2012) 111801

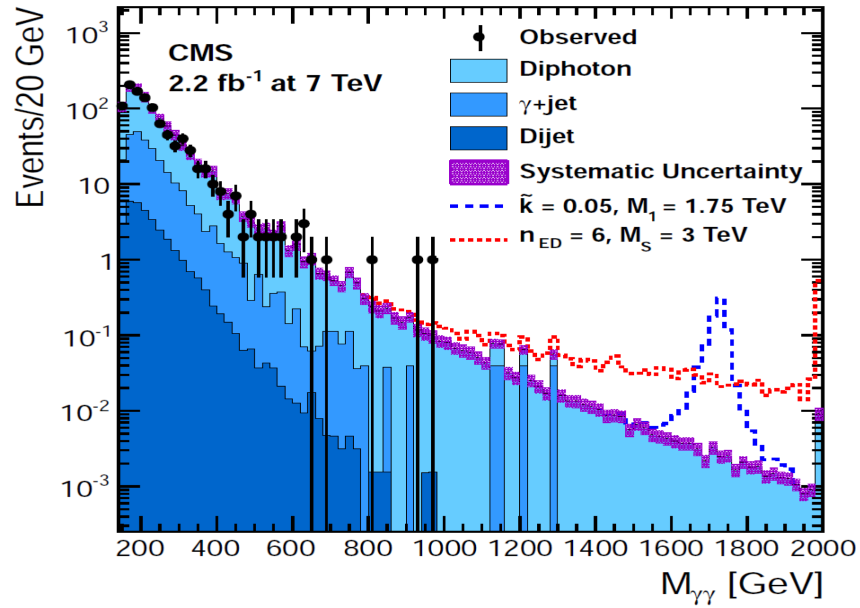
- Extra Dimensions (ED) signature: virtual Gravitons (qq/gg → G*→ γγ):

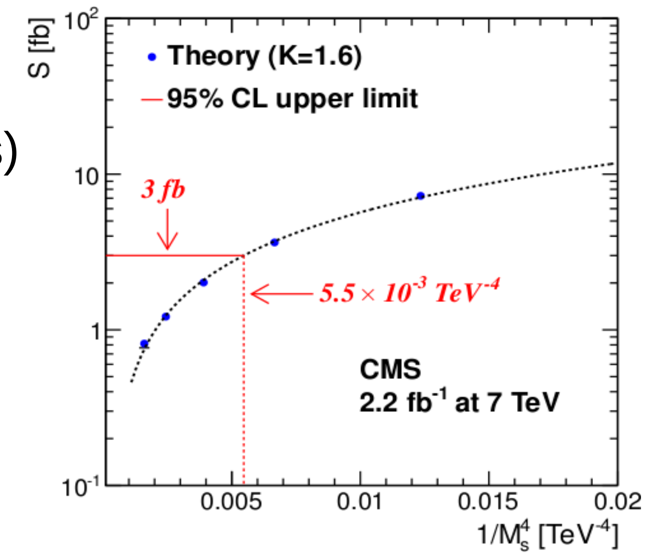


(spin-2 G* s-wave decay into diphoton)

- 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)