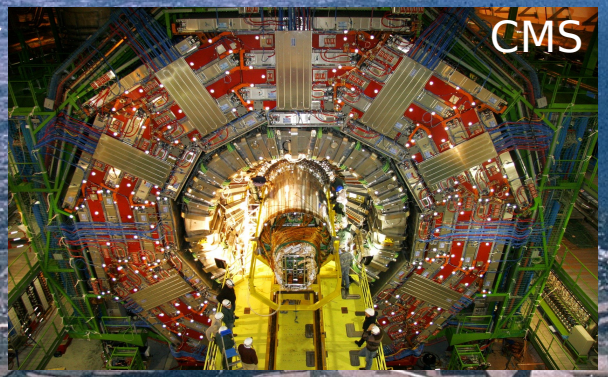

CMS physics overview

LISHEP-2013, March 18-22, Rio de Janeiro

David d'Enterria (CERN)
on behalf of the CMS Collaboration

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

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

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

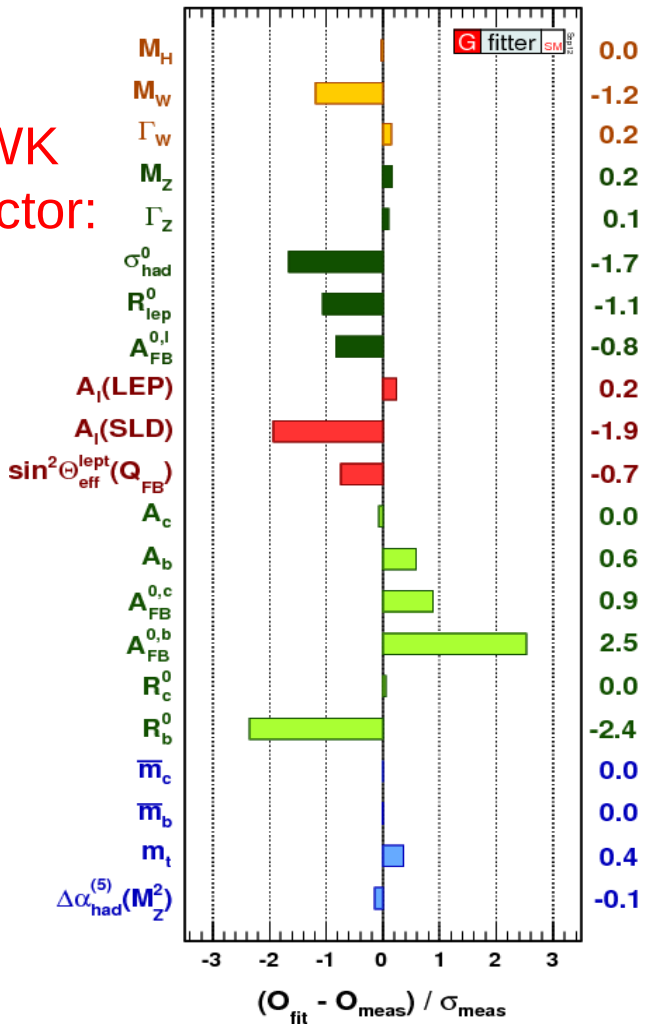
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu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

19 parameters: gauge couplings, H mass&vev, H-f Yukawa coupl., CKM mixings, CP phases

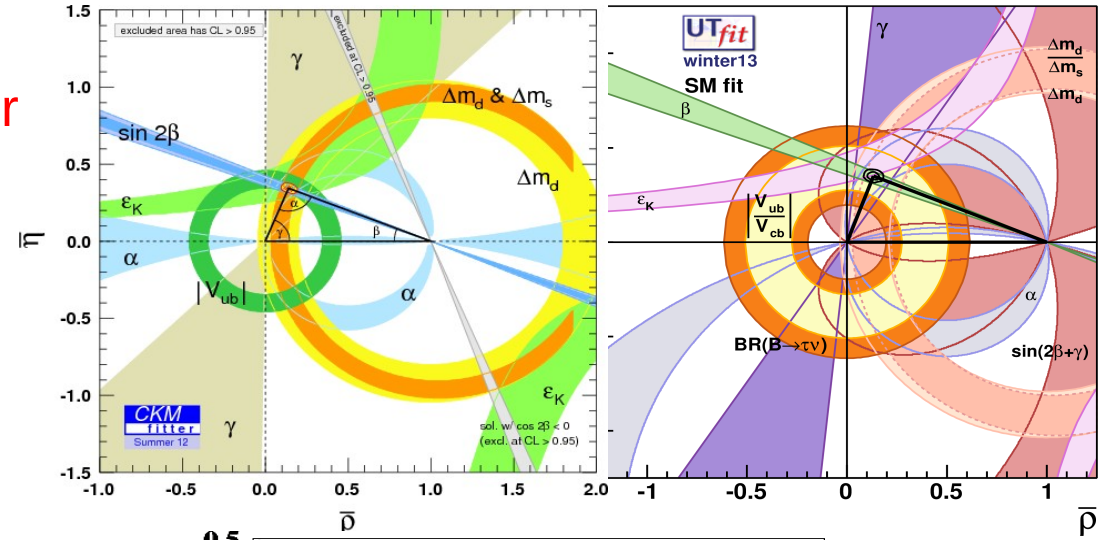
Standard Model of particles & interactions

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

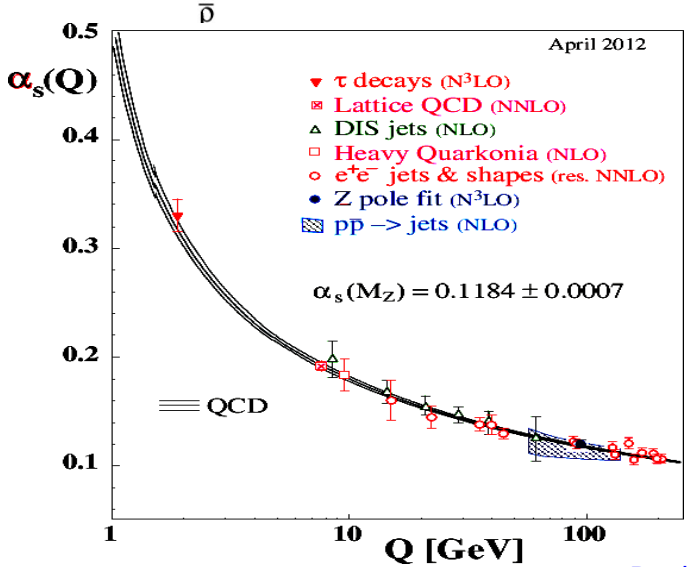
EWK sector:



Flavour sector:



QCD sector:



“Issues” with the Standard Model

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

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

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- Higgs: Generation of masses via BEH mechanism not confirmed (up to 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)
- neutrino masses, gauge-gravity unification, ...

Goals of the Large Hadron Collider

- Solve 6 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 ? ... ?

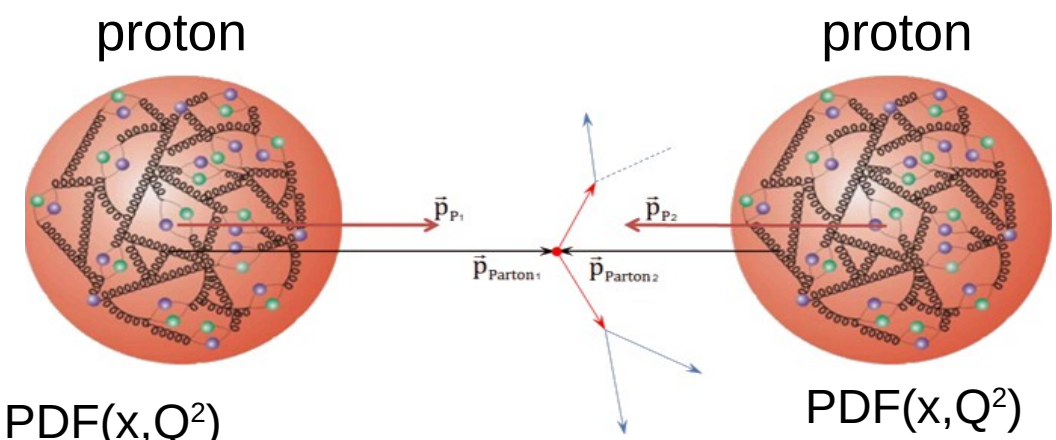
3. Dark matter problem: ~1/4 universe = invisible matter. SUSY ? Other particles ?

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) ?

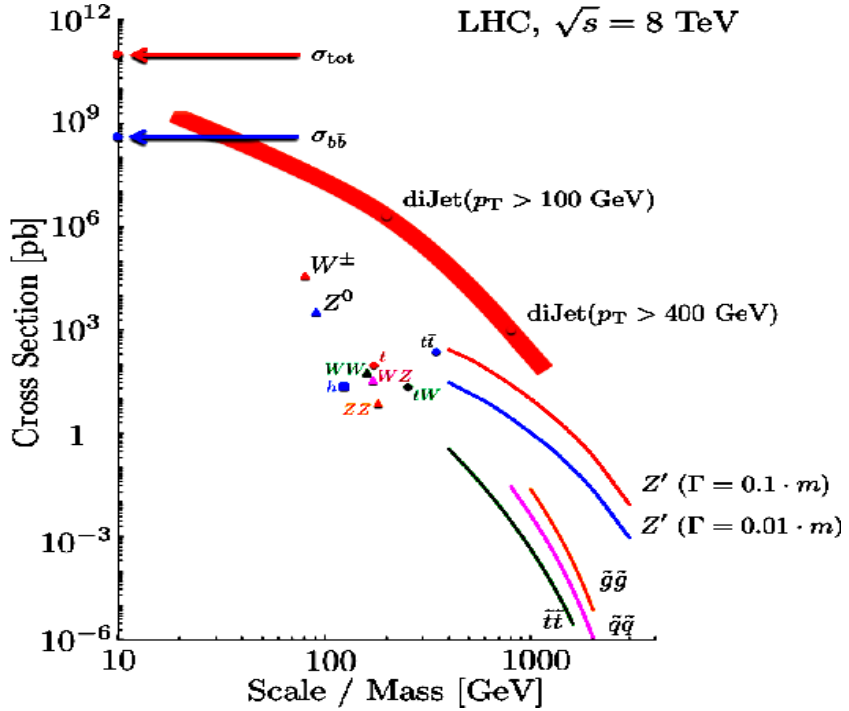
6. Highest-energy cosmic-rays: Nature of CRs at 10^{20} eV ?

Tools: high-energy proton & ion collisions

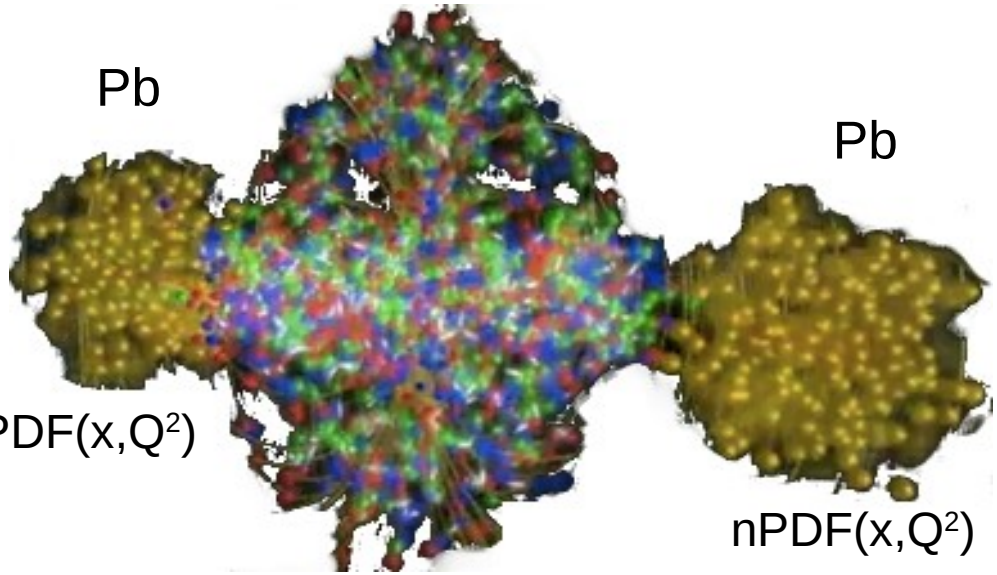


PDF(x,Q²) PDF(x,Q²)

SM & new particles

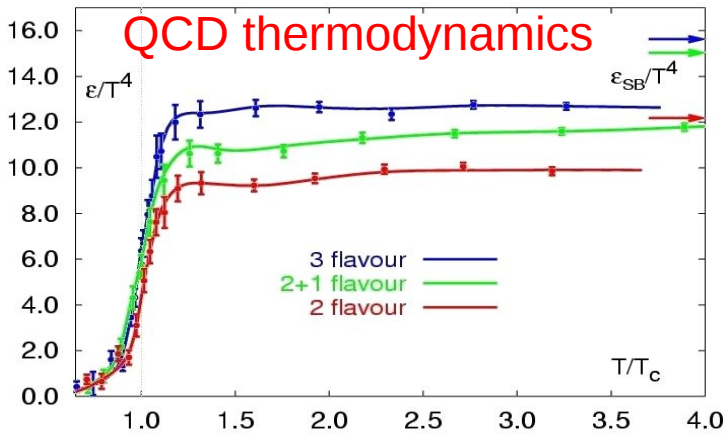


Pb Pb



nPDF(x,Q²) nPDF(x,Q²)

Quark-gluon plasma



CMS: the detector

Total weight
14000 t
Diameter 15 m
Length 28.7 m

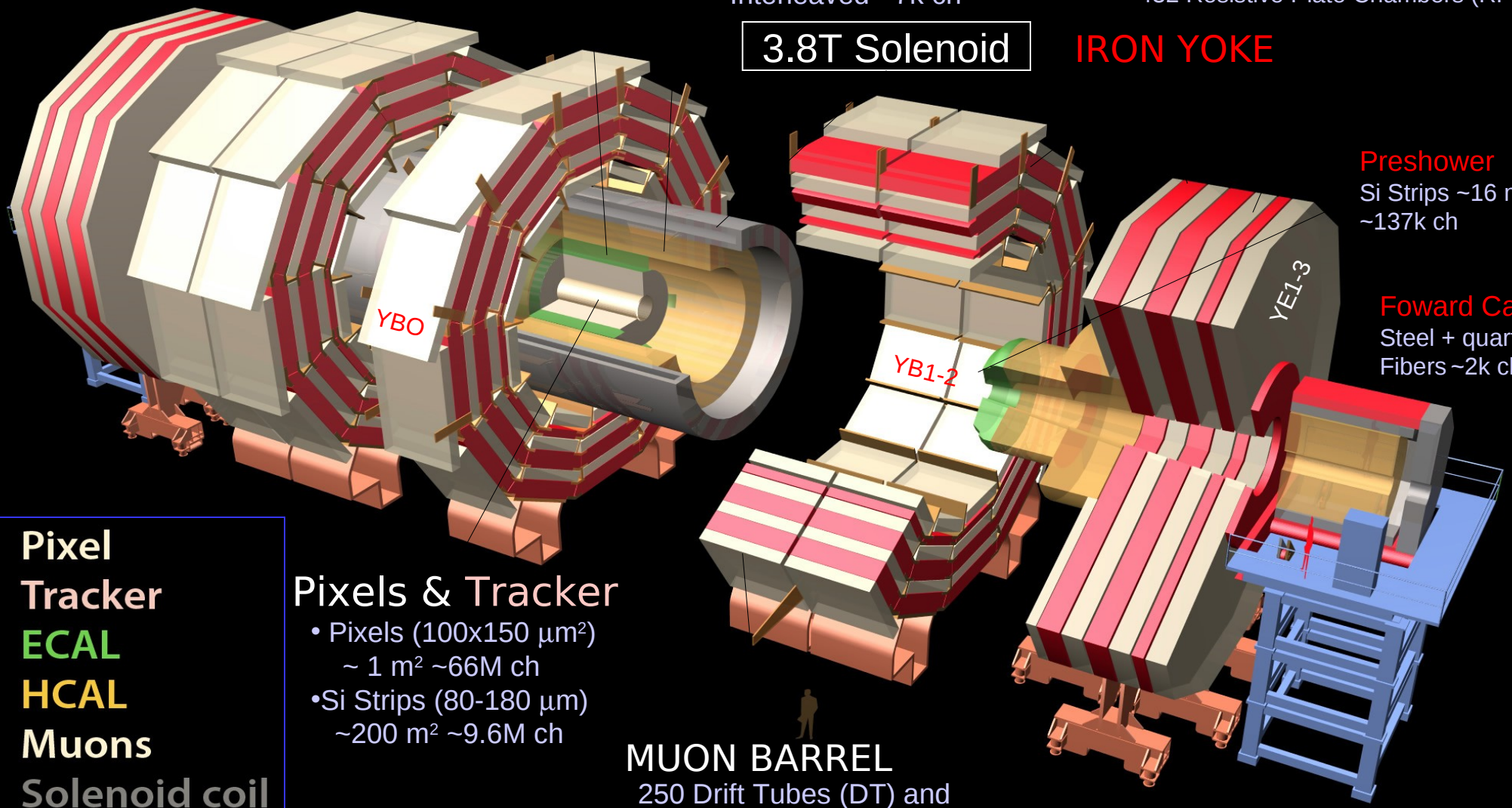
ECAL 76k scintillating $PbWO_4$ crystals

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 m²
~137k ch

Foward Cal
Steel + quartz
Fibers ~2k ch

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

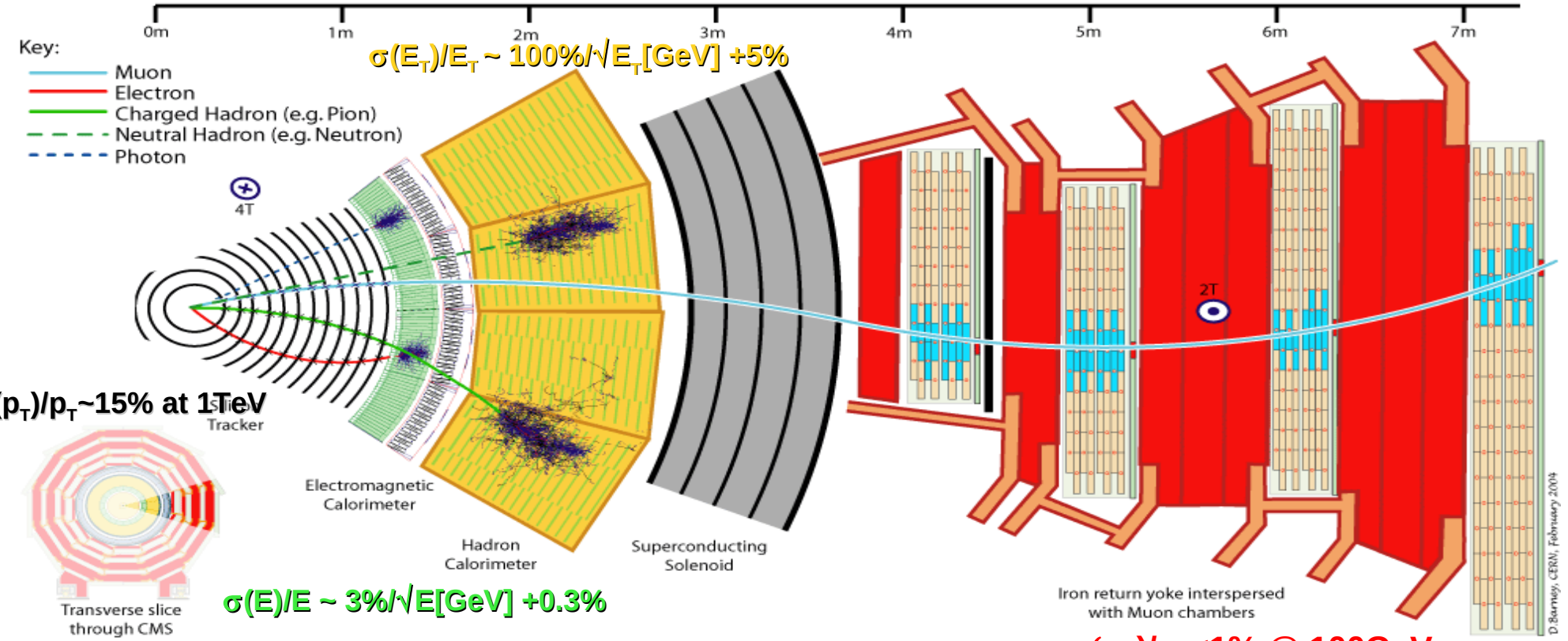
Pixels & Tracker
- Pixels (100x150 μm²)
  ~ 1 m² ~66M ch
- Si Strips (80-180 μm)
  ~200 m² ~9.6M ch

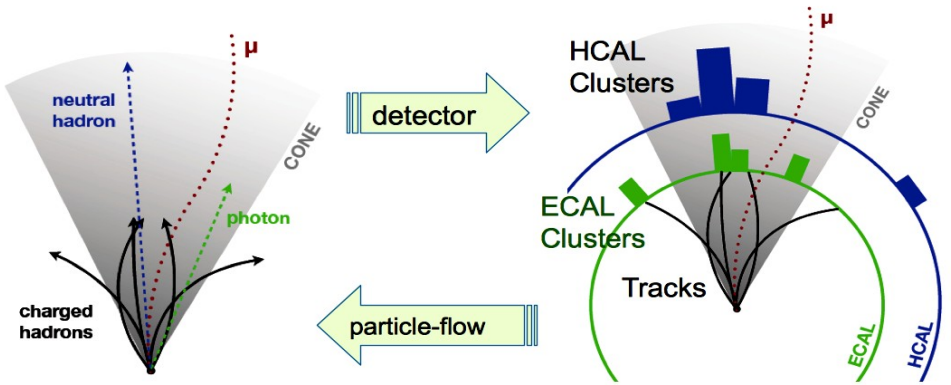
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CMS: the people

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

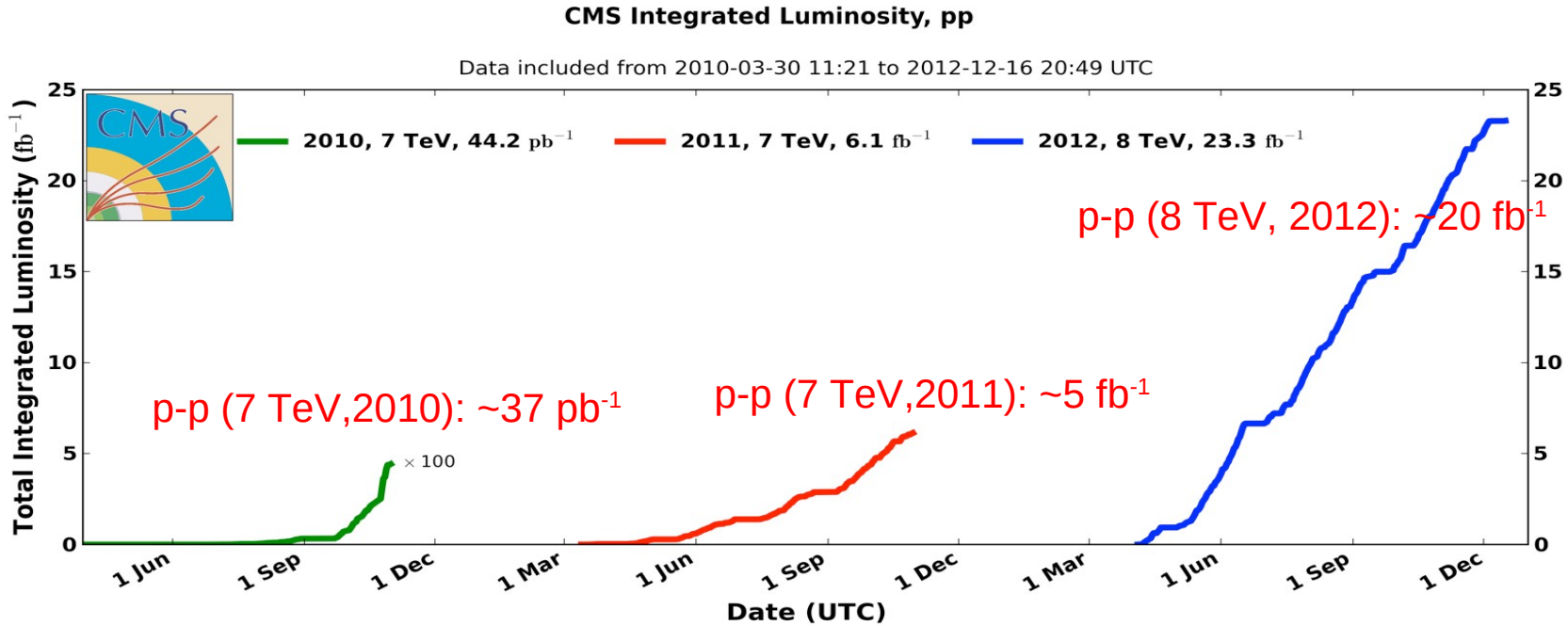
CMS: the physics objects

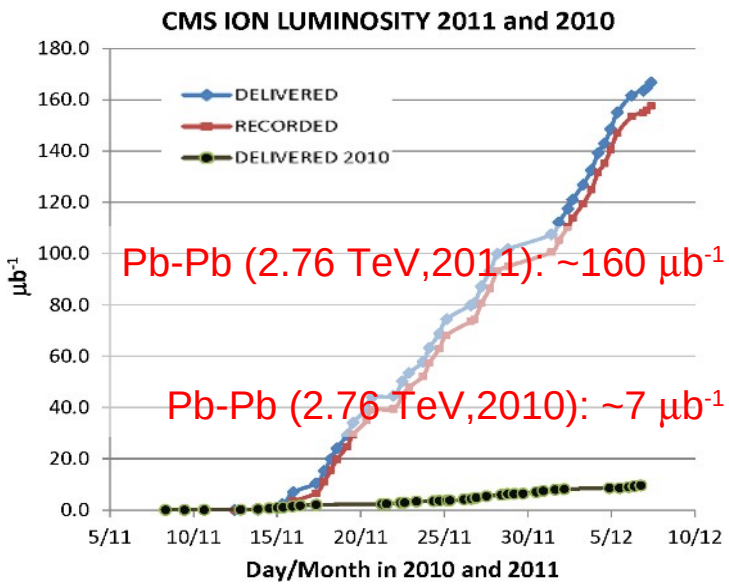


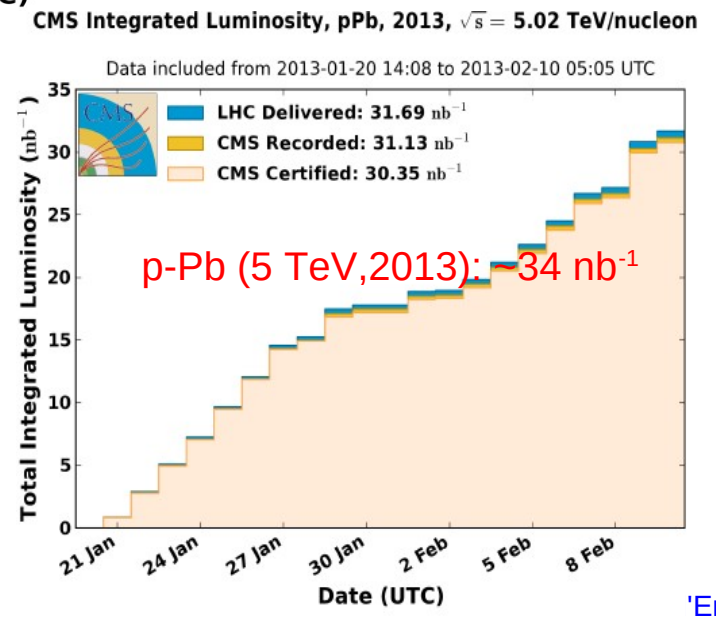


Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for:
jets, b-jets, taus, ν (miss. E_T), isolation

CMS: integrated luminosities (2010-13)

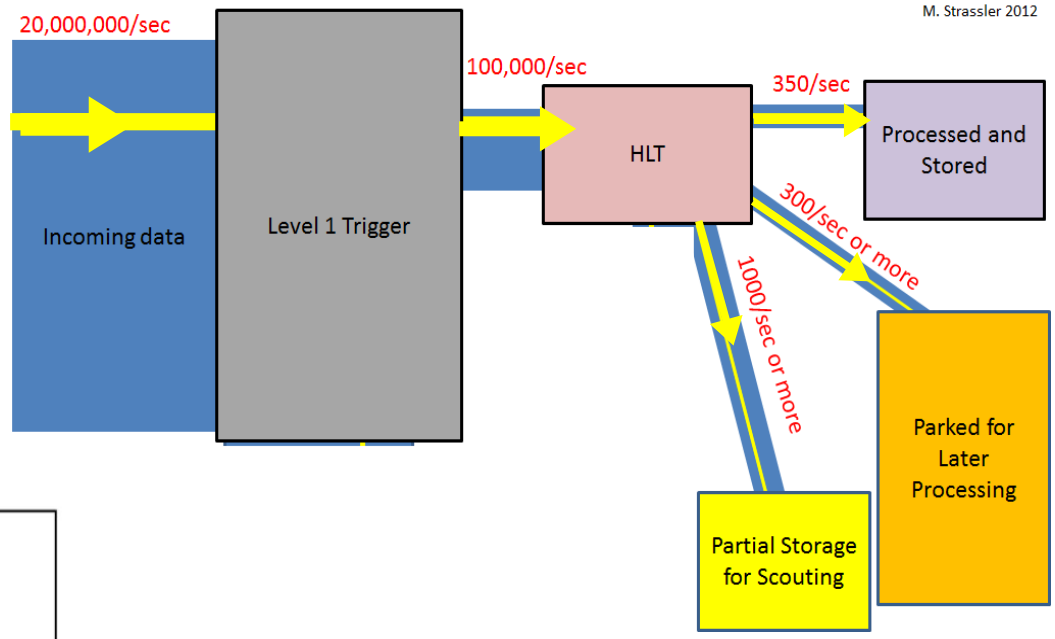


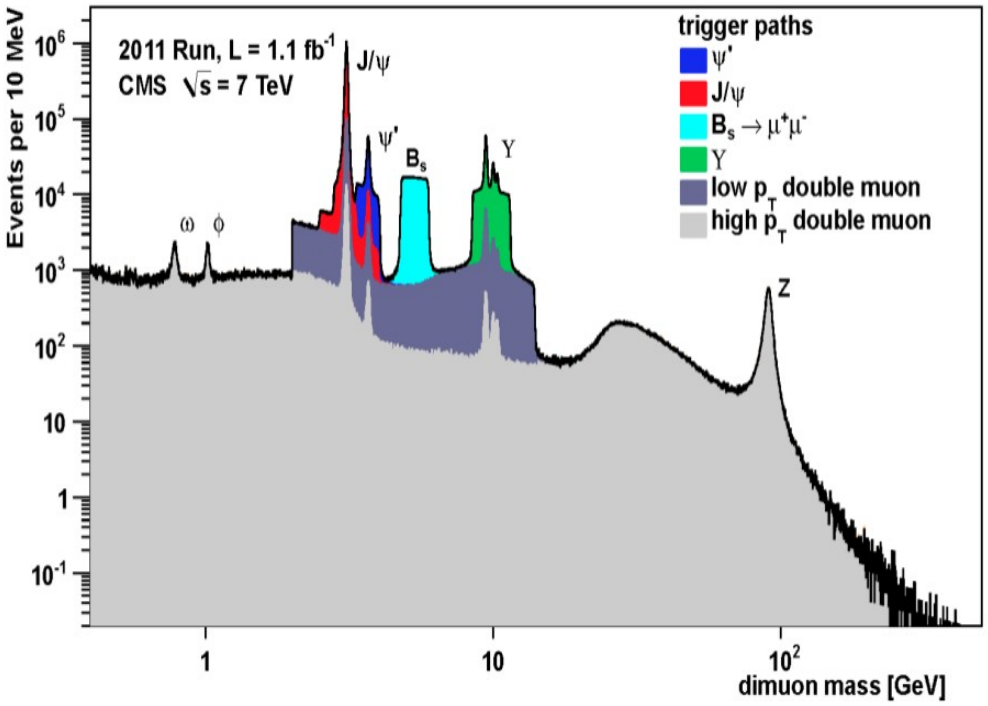




CMS: L1 & high-level triggers

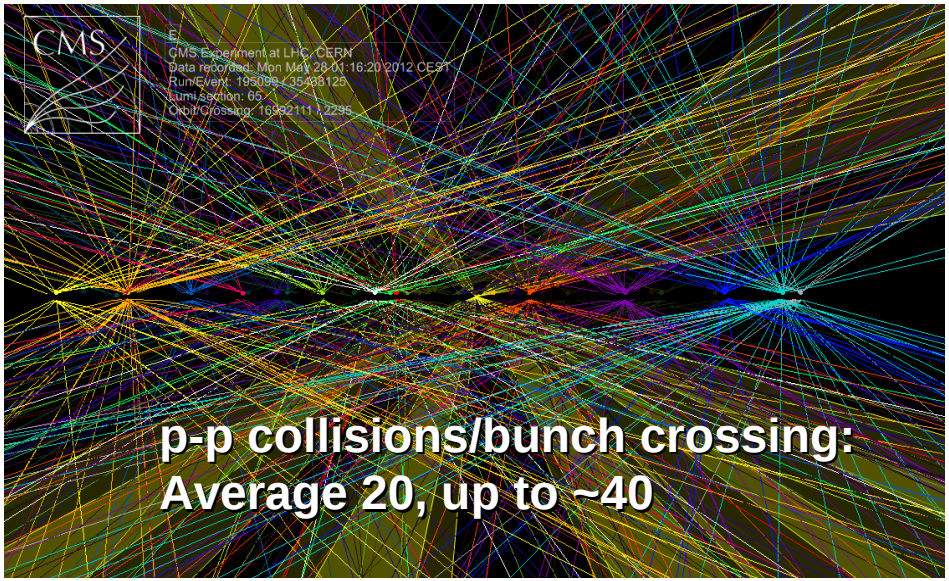
- Level-1 & HLT menus reduce # of p-p interactions from: $2 \cdot 10^7$ Hz (input) down to ~350 Hz (recorded), ~300 Hz ("parked" for later analysis)

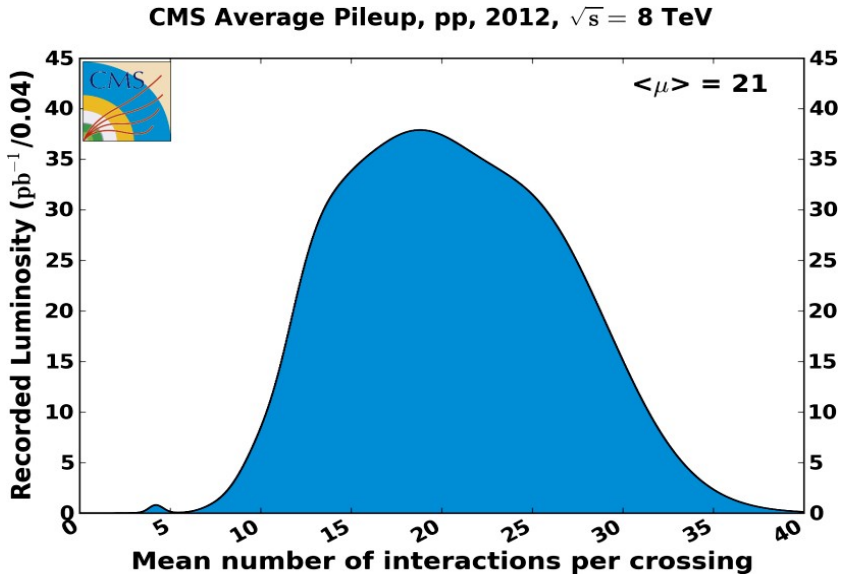




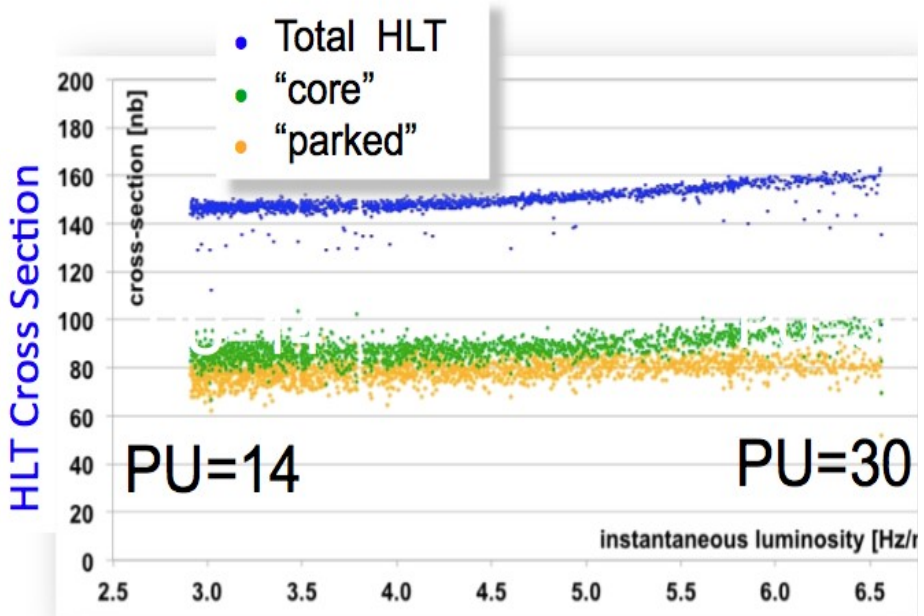
- Example: dimuon mass distribution from several double-μ trigger paths: calibration, $B_s(\mu\mu)$, quarkonia, DY+Z

CMS: p-p pileup & triggering



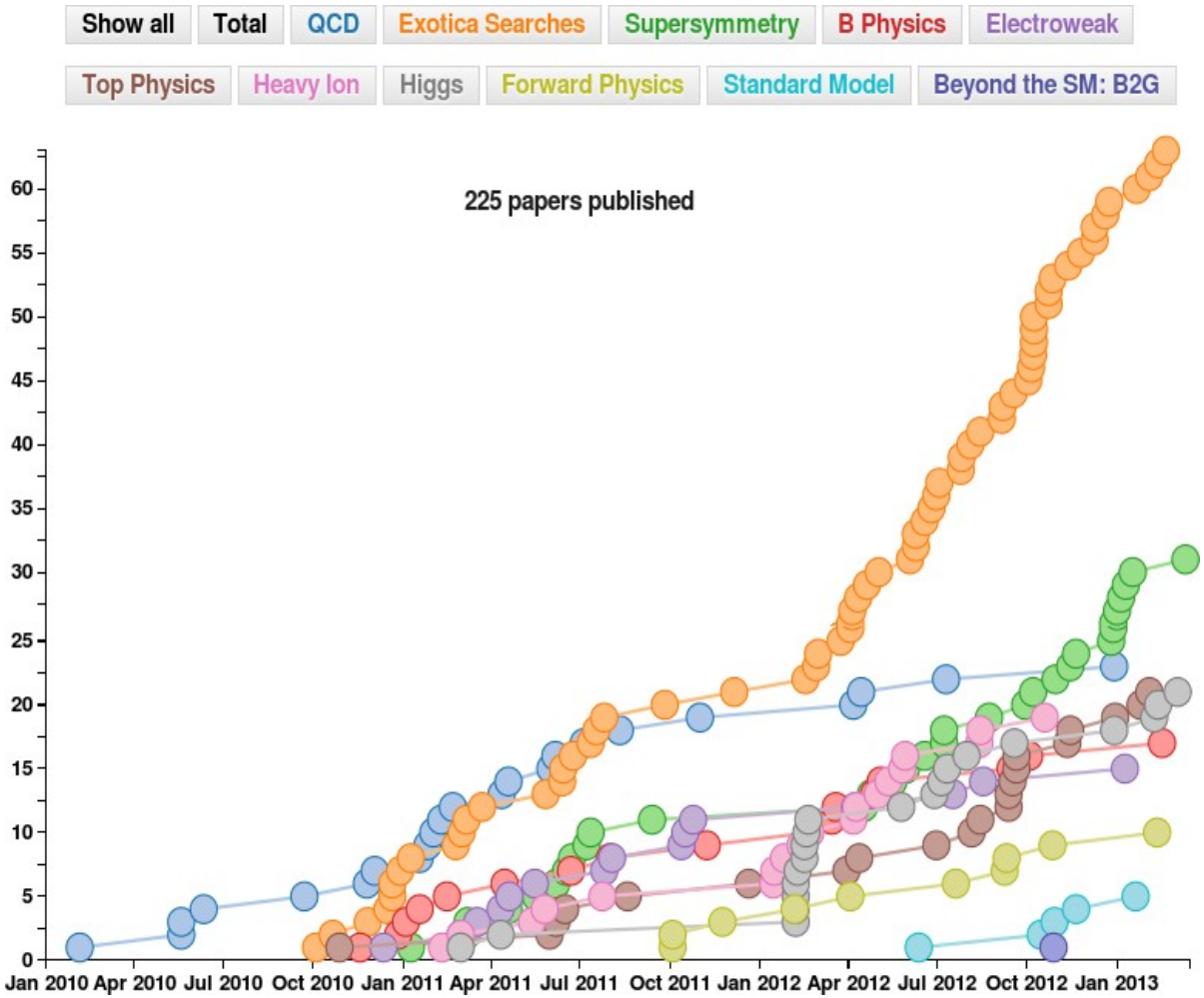


- Highly-flexible HLT system allows CMS to keep a constant-rate cross section with varying pile-up conditions without sacrificing physics:



CMS: publications & preliminary results

250 papers published/submitted + 350 preliminary notes as of March'13



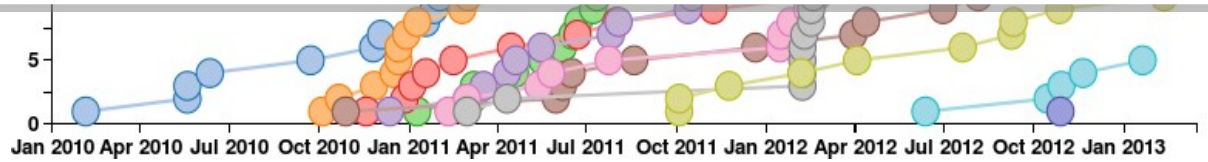
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

CMS: publications & preliminary results

250 papers published/submitted + 350 preliminary notes as of March'13

Only a reduced fraction of hundred CMS analyses presented here.
See CMS LISHEP'13 talks for more results & details:

QCD:	A. Vilela, N. Cartiglia, G. Brona
HI:	M. Malek, M. Murray
EWK:	M. Herndon
Higgs:	H. Newman, G. Mitselmakher, C. Palmer, R. Walsh
EXO/SUSY:	J. Mans



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

Quantum Chromodynamics

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[Gauge interactions: $SU_c(3)$]

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

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

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

[Quark dynamics]

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

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

- Gauge-fermion dynamics via covariant derivatives:

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

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

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

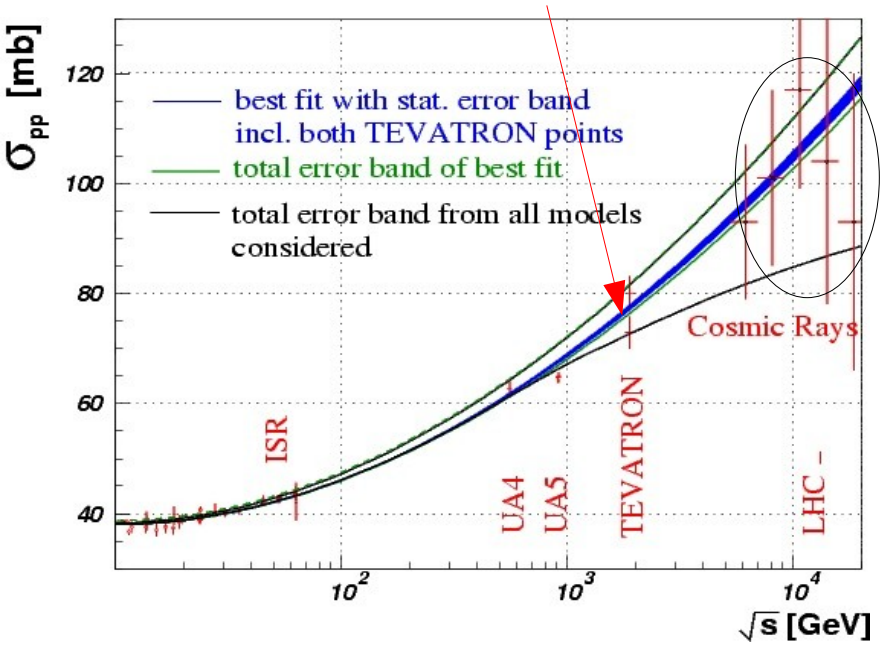
- Gauge-boson field strength tensors:

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

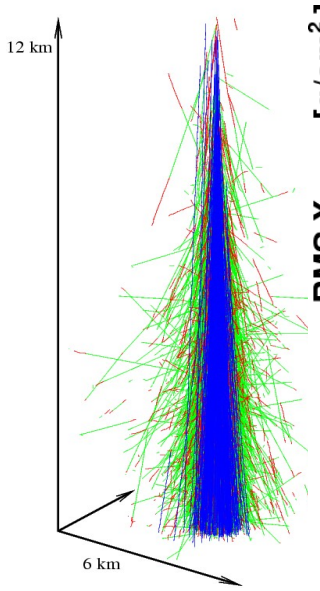
QCD: Inelastic p-p cross section

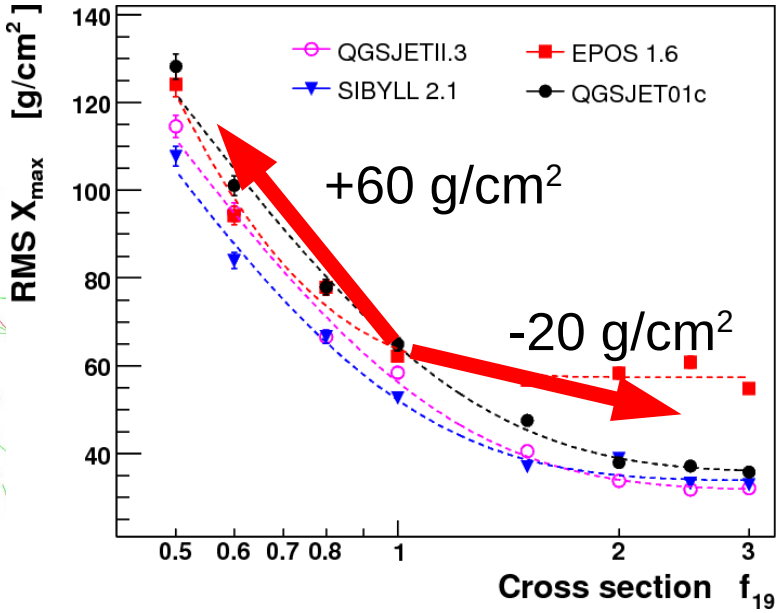
- Only ~60% of total p-p x-section at LHC computable from QCD Lagrangian (perturbative parton scatterings) ...
- Diffractive (15%) +elastic (25%) x-sections require: Data + Regge-Gribov approaches (QM constraints: Froissart bound, optical th., dispersion relations)

- Pre-LHC predictions uncertainties driven by E710–CDF σ_{tot} disagreement



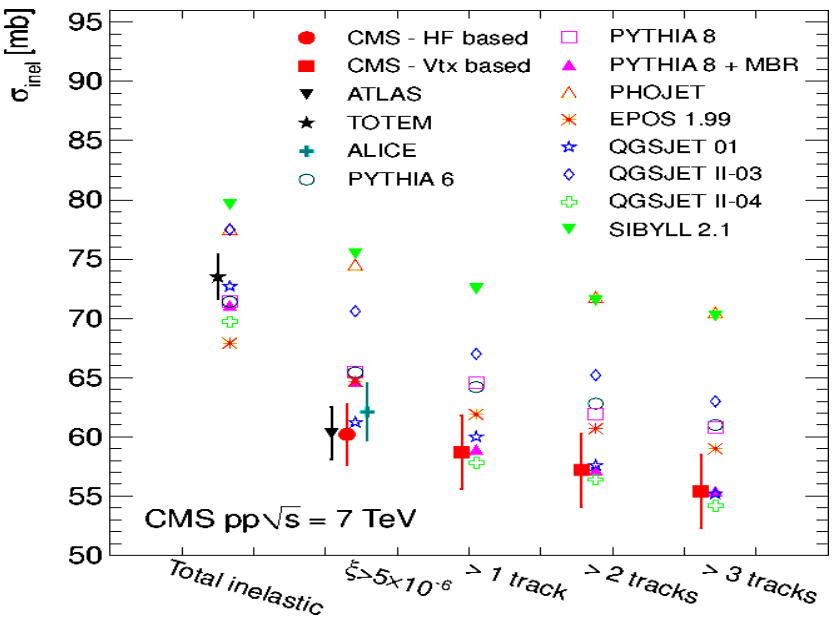
- Impact on cosmic-ray MCs at E_{lab}~10^{19} eV
  Uncertainties of σ_{inel} change by factor of ~2 the air-shower maximum fluctuations:





Ulrich-Engel-Unger, PRD83 (2011) 05426

QCD: Inelastic p-p cross section



CMS: arXiv:1210.6718. [See talk by N.Cartiglia]

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

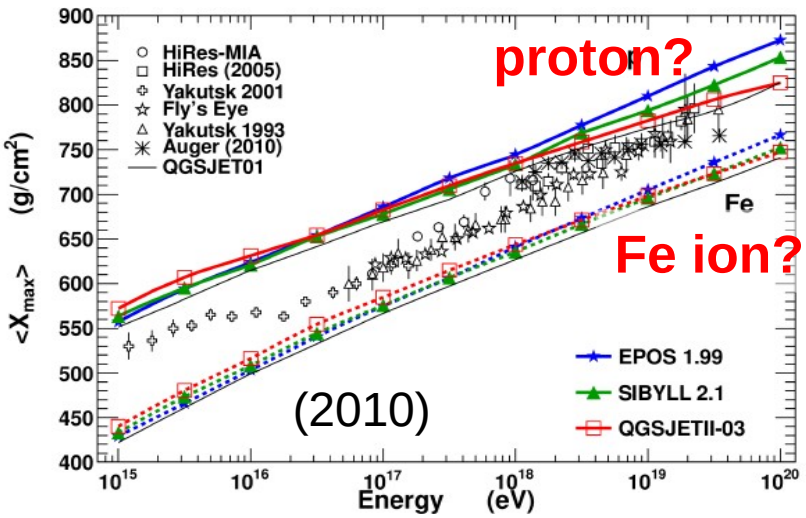
measured via:

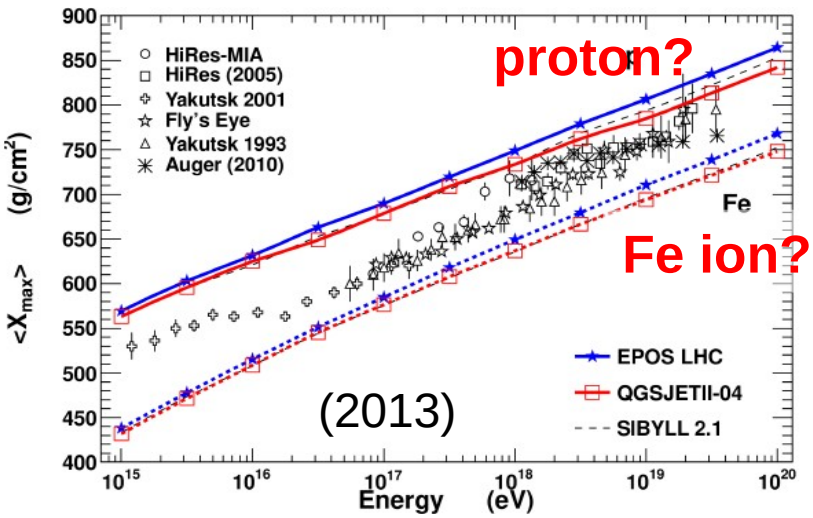
(i) pileup-evt counting,

(ii) hadronic activity in single-sided triggers

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

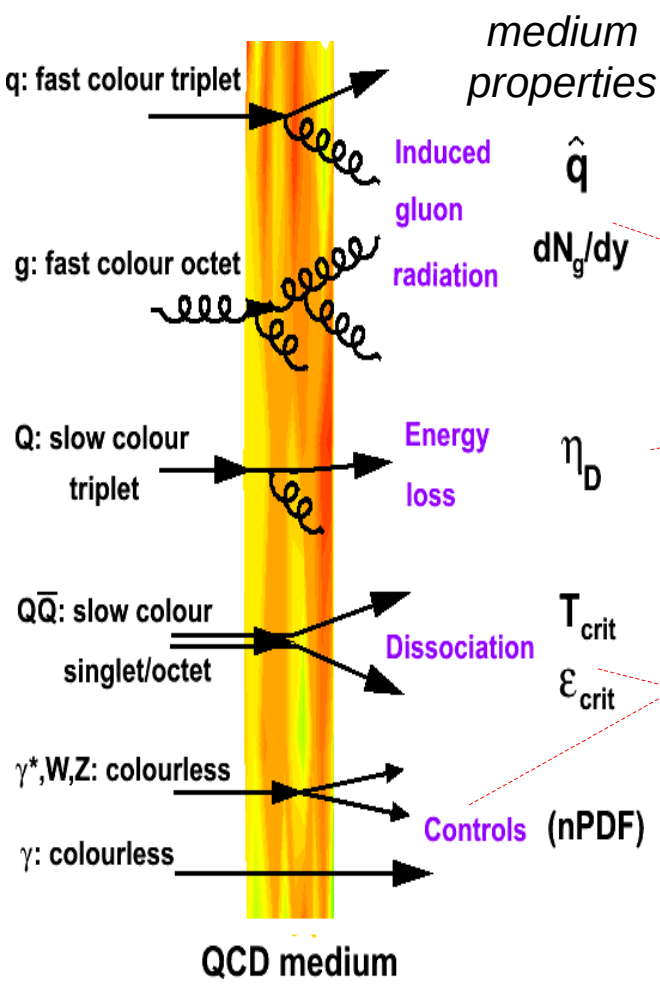
- CRs identity at GZK-cutoff before&after including LHC data (E_{lab} ~ 10^{17} eV):



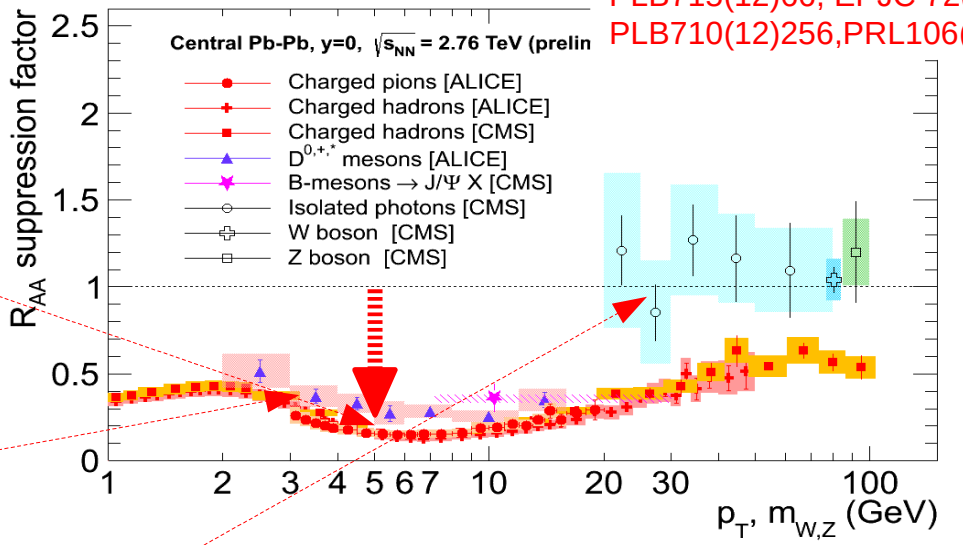


QCD thermodyn.: $Q\bar{Q}$,q,g suppression in Pb-Pb

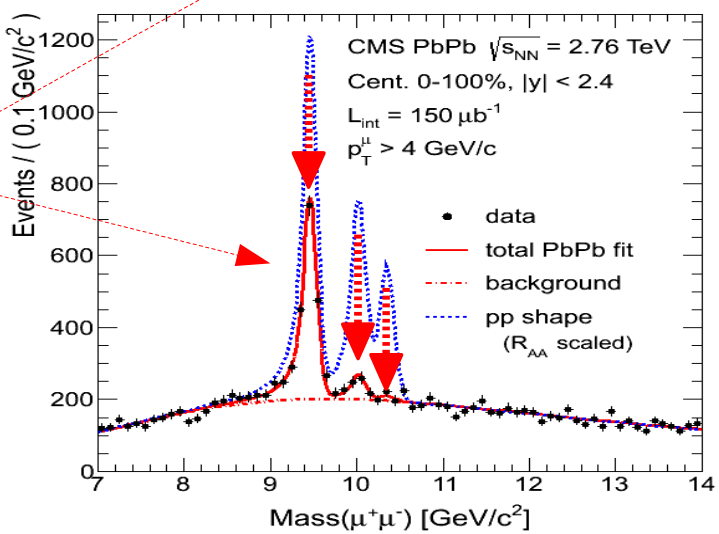
- Yields of strongly-interacting particles suppressed in Pb-Pb compared to p-p. Weakly probes (γ,W,Z) unmodified by medium:



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



PRL109(12)222301

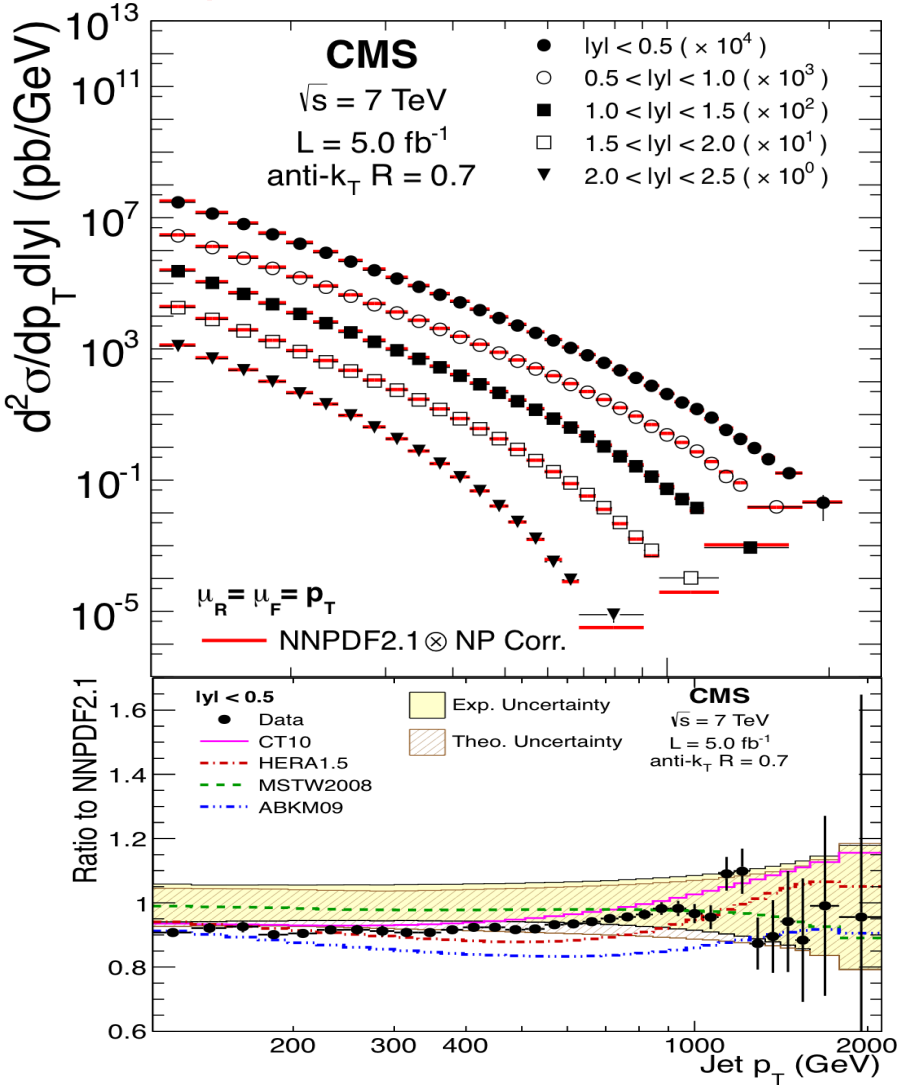


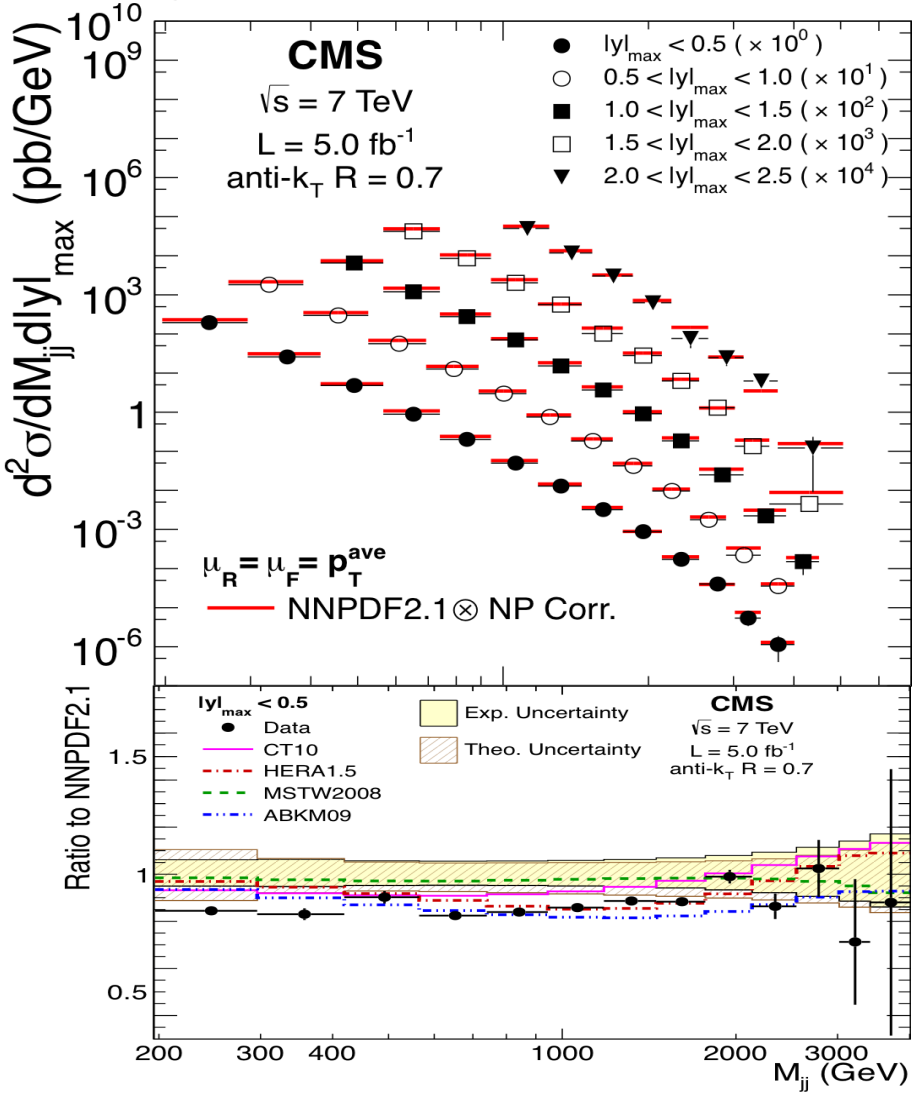
See talks by:
M. Malek,
M.Murray

QCD: light-q & gluons (jets) x-sections

- Inclusive jet & di-jets spectra up to 2-3 TeV (2-4% JES). NLO pQCD describes data over 9 orders-magnitude. Gluon PDF constraints.

CMS: arXiv:1212.6660.
See G. Brona talk

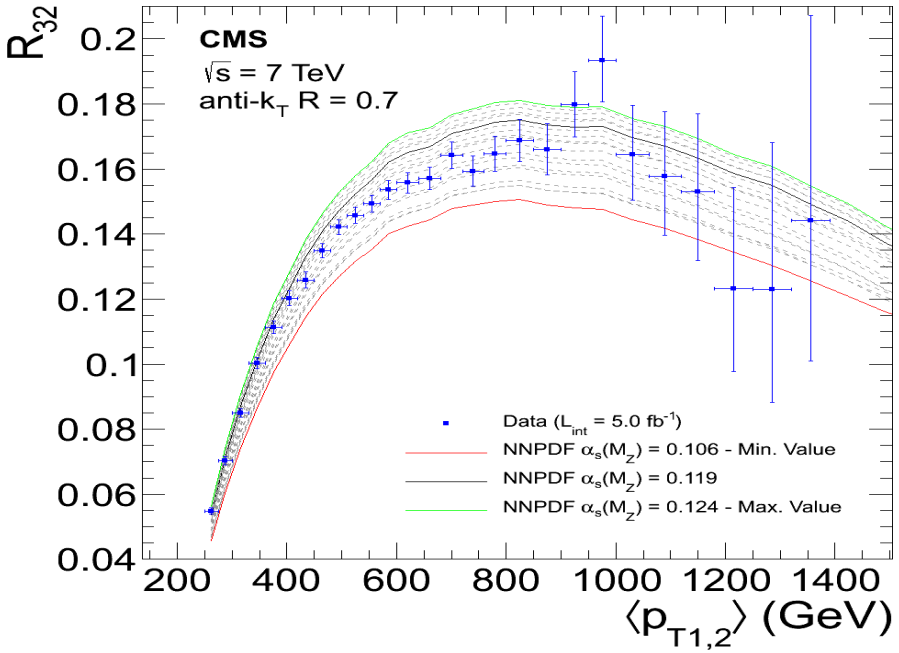


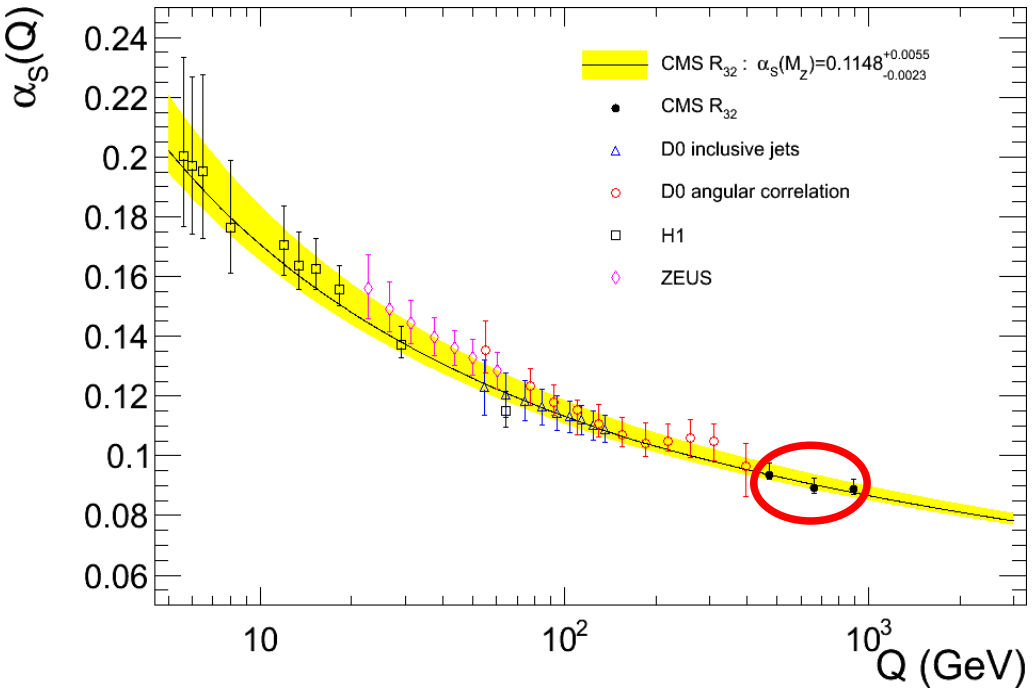


QCD: Strong coupling from jets x-sections

- Ratio of 3-jets of 2-jets differential x-sections constrains α_s at (so-far unprobed) scales Q ~ 0.5 – 0.9 TeV:

CMS-QCD-11-003





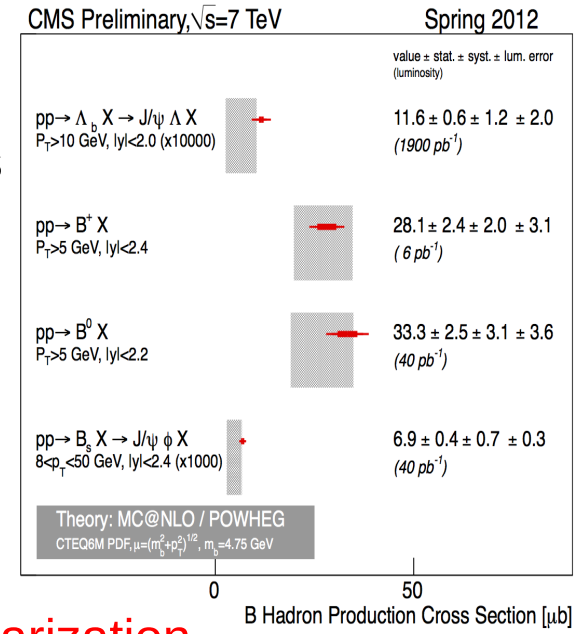
NNPDF21: $\alpha_s(M_Z) = 0.1148 \pm 0.0014$
CT10: $\alpha_s(M_Z) = 0.1135 \pm 0.0019$
MSTW2008: $\alpha_s(M_Z) = 0.1141 \pm 0.0022$
(ABM11: $\alpha_s(M_Z) = 0.1214 \pm 0.0020)$

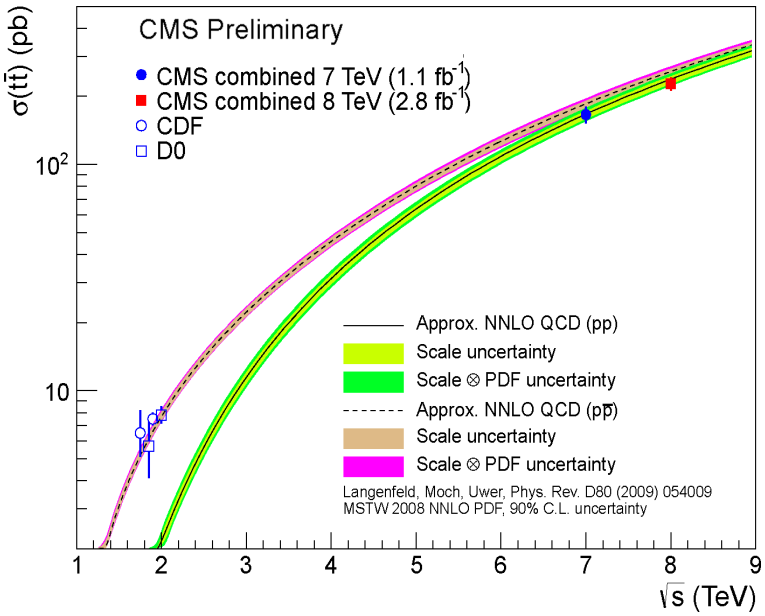
Measurement dominated by TH uncertainty:
PDF & (asymmetric) scale uncertainty

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

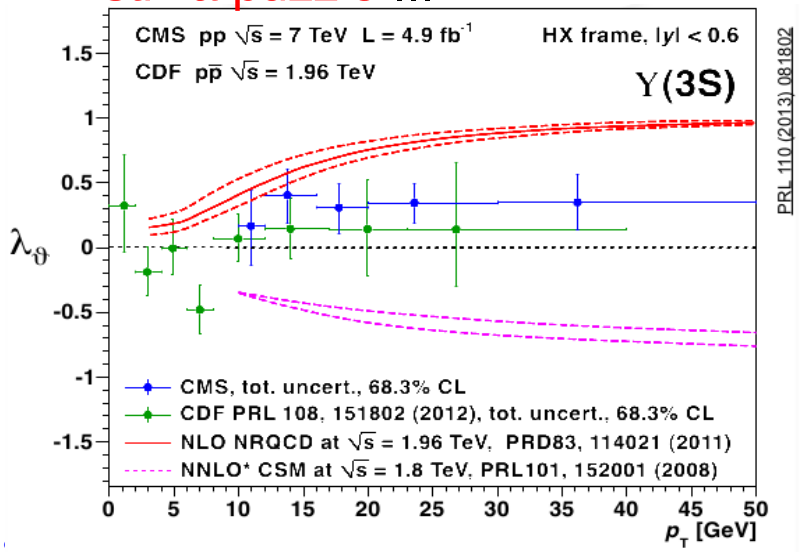
QCD: heavy-Q cross-sections (& $Q\bar{Q}$ polarization)

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

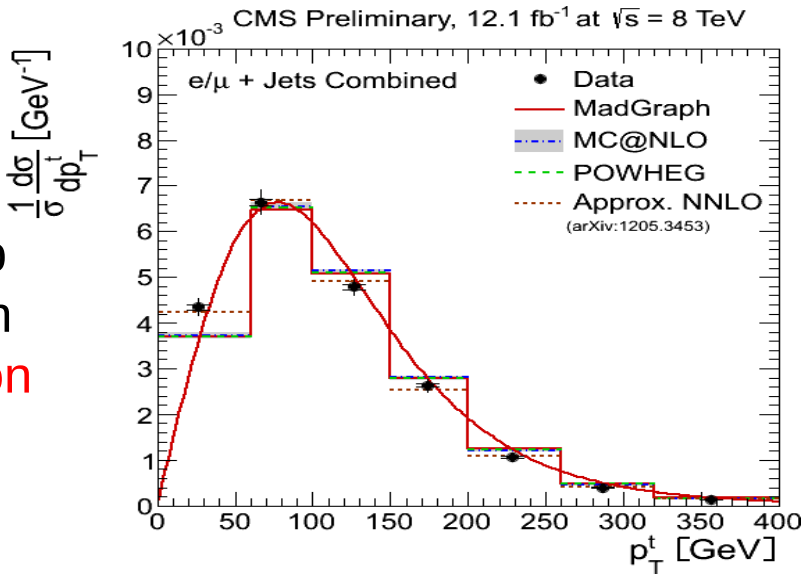




- Although quarkonia polarization still a puzzle ...



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



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

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

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

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

[Quark dynamics]

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

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

- Gauge-fermion dynamics via covariant derivatives:

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

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

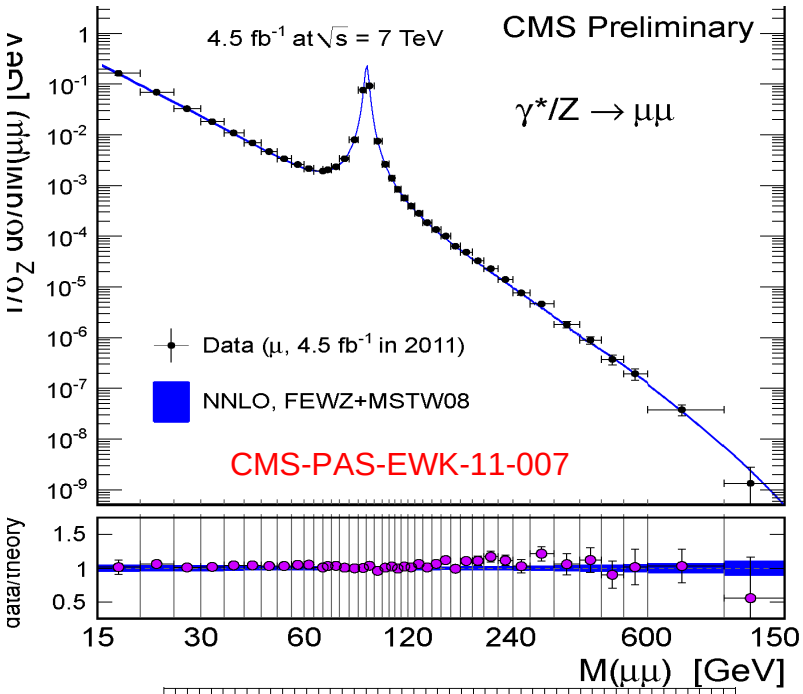
$$D_\mu \phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

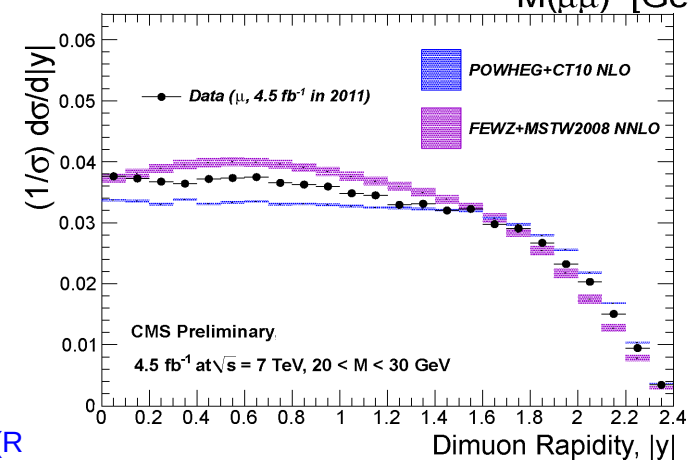
- Gauge-boson field strength tensors:

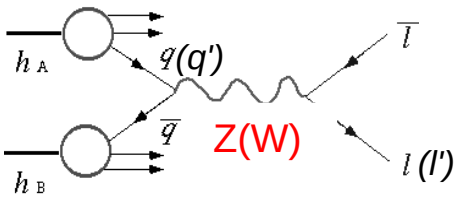
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu + ig_2(\mathbf{W}_\mu \mathbf{W}_\nu - \mathbf{W}_\nu \mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu \mathbf{G}_\nu - \partial_\nu \mathbf{G}_\mu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

Electroweak: W,Z boson production

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

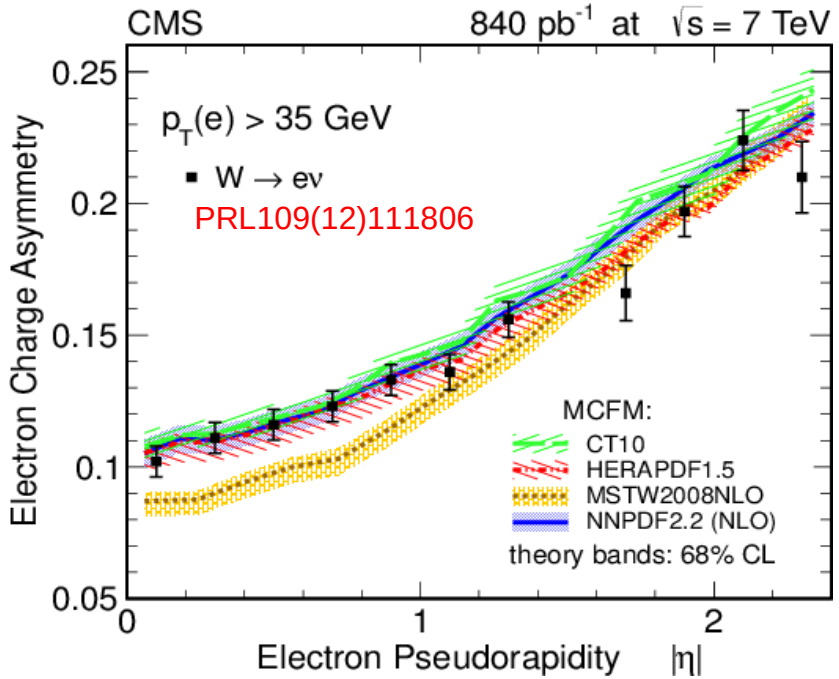




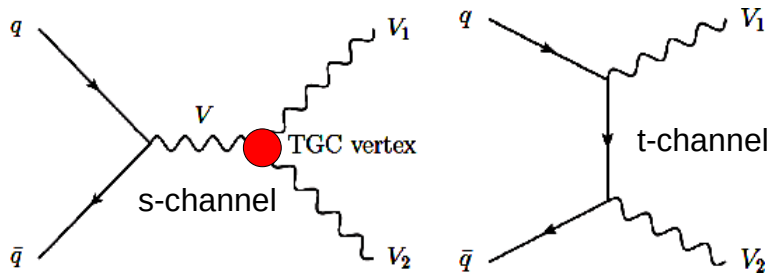


- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

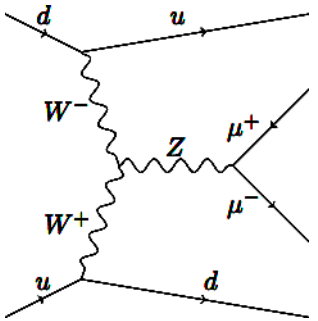
$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

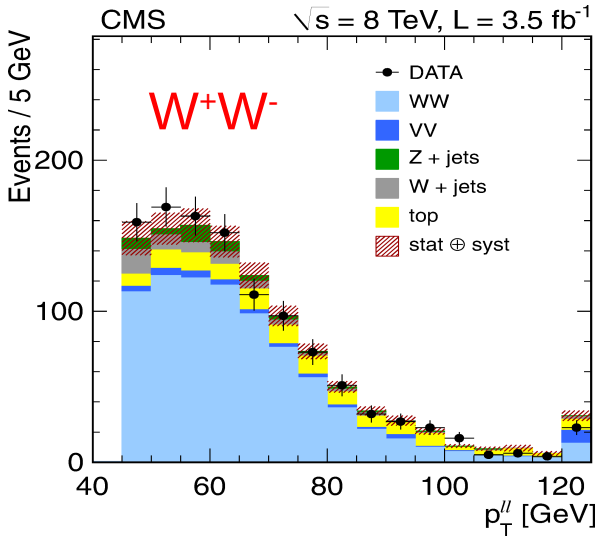


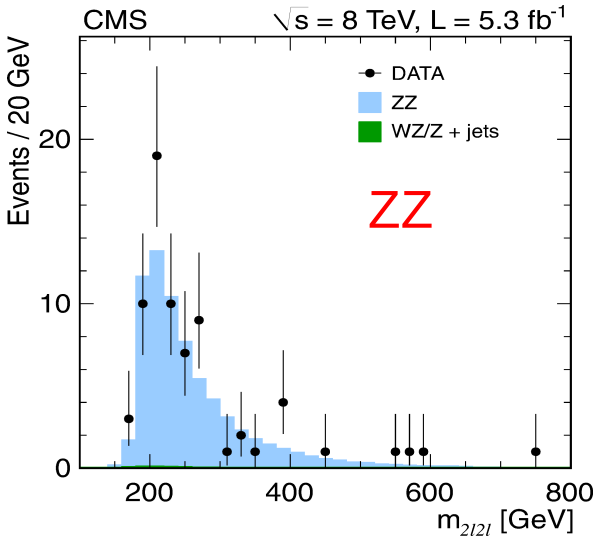
Electroweak: diboson production

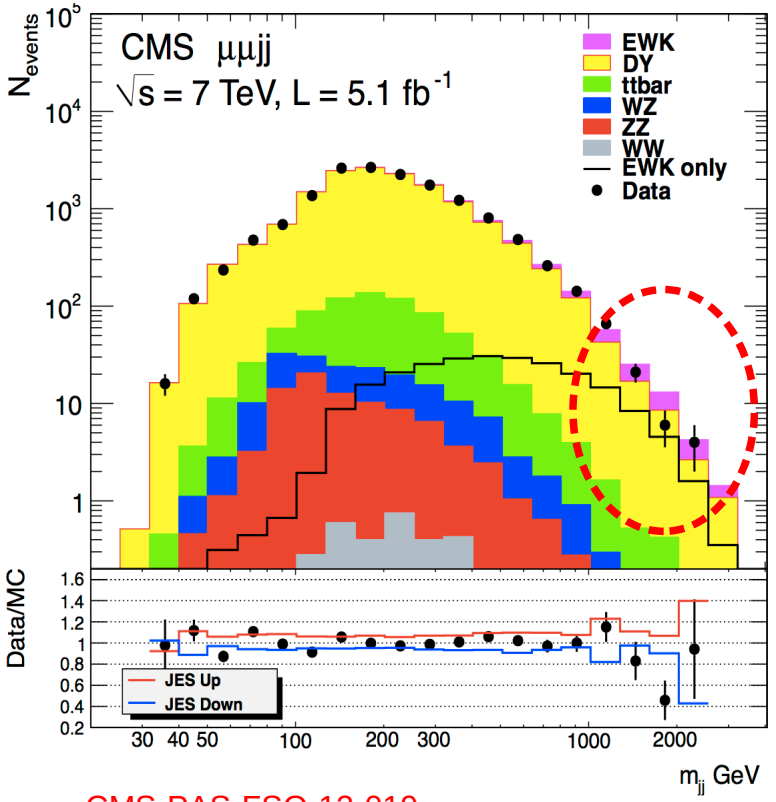


1st evidence (~3sigma) for electroweak Z production:









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

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

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

ZZ in agreement with NLO pQCD

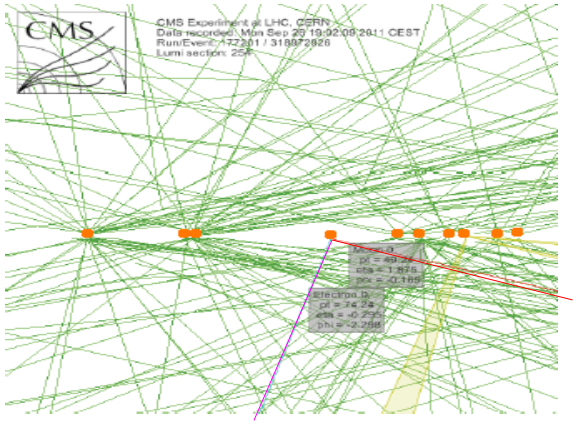
CMS: arXiv:1301.4698

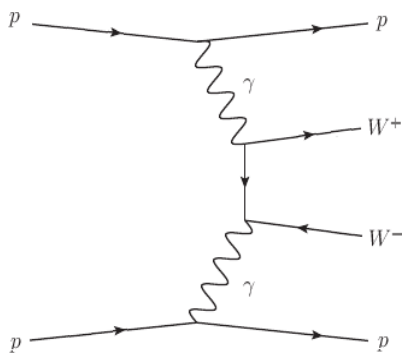
CMS-PAS-FSQ-12-019

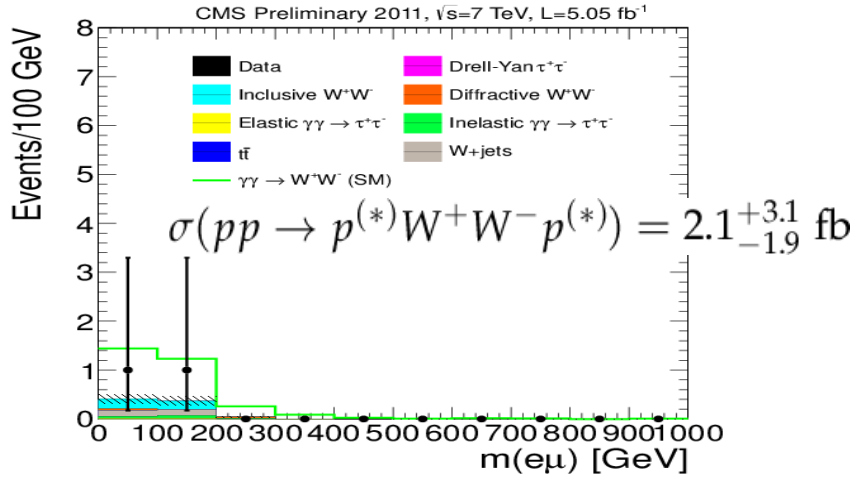
Electroweak: dibosons & gauge-couplings

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

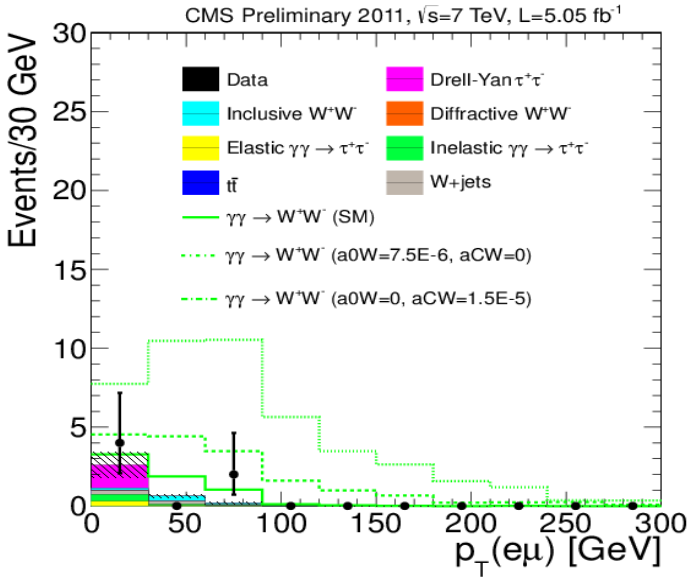
CMS PAS-FSQ-12-010
See A.Vilela's talk



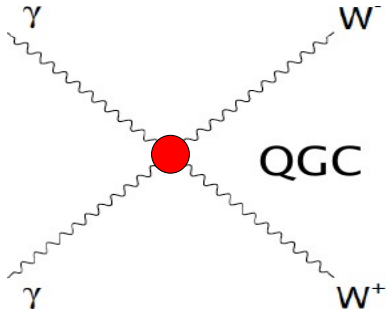


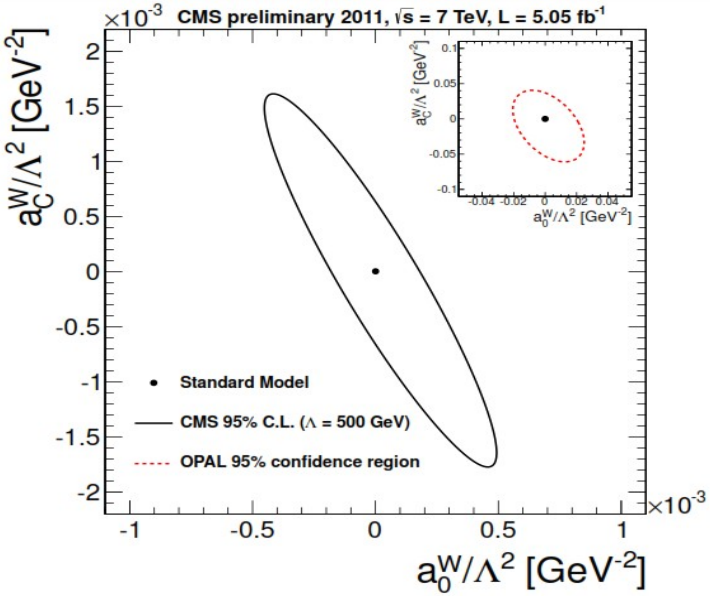


- No high-p_T evts: Strong constraints on anomalous quartic gauge couplings:



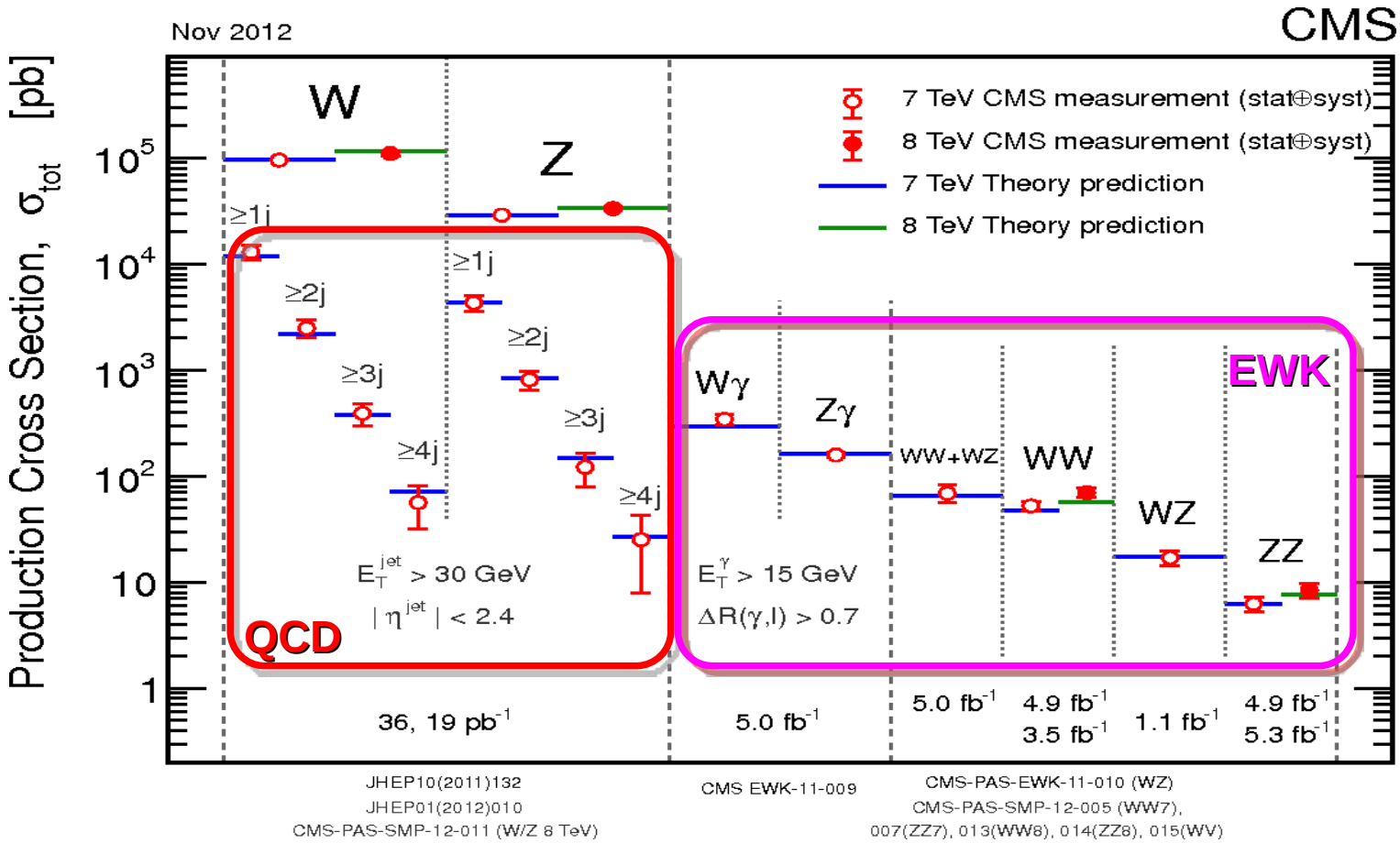
Limits ~100 times stronger than LEP:





Electroweak: x-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 constraints on triple- & quartic-gauge couplings.

Higgs sector

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

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

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

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

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

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

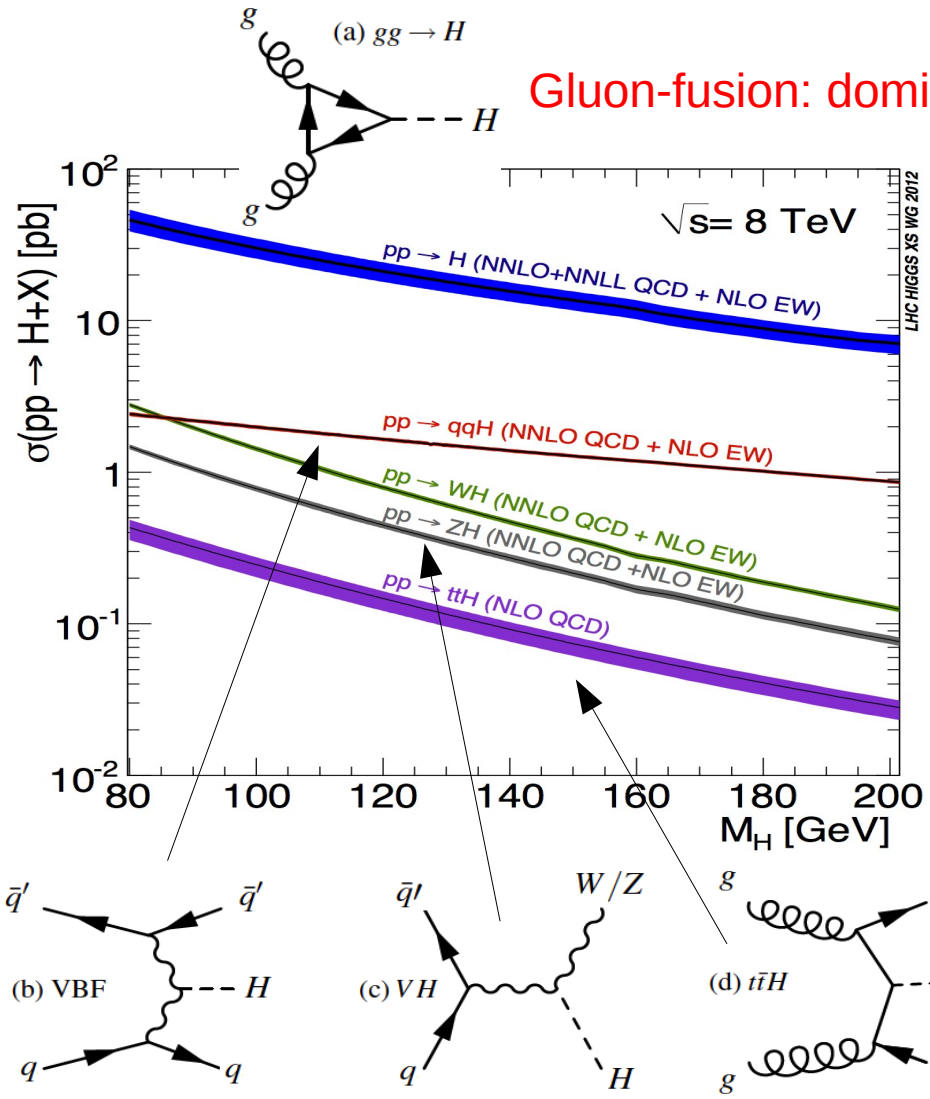
$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\, e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

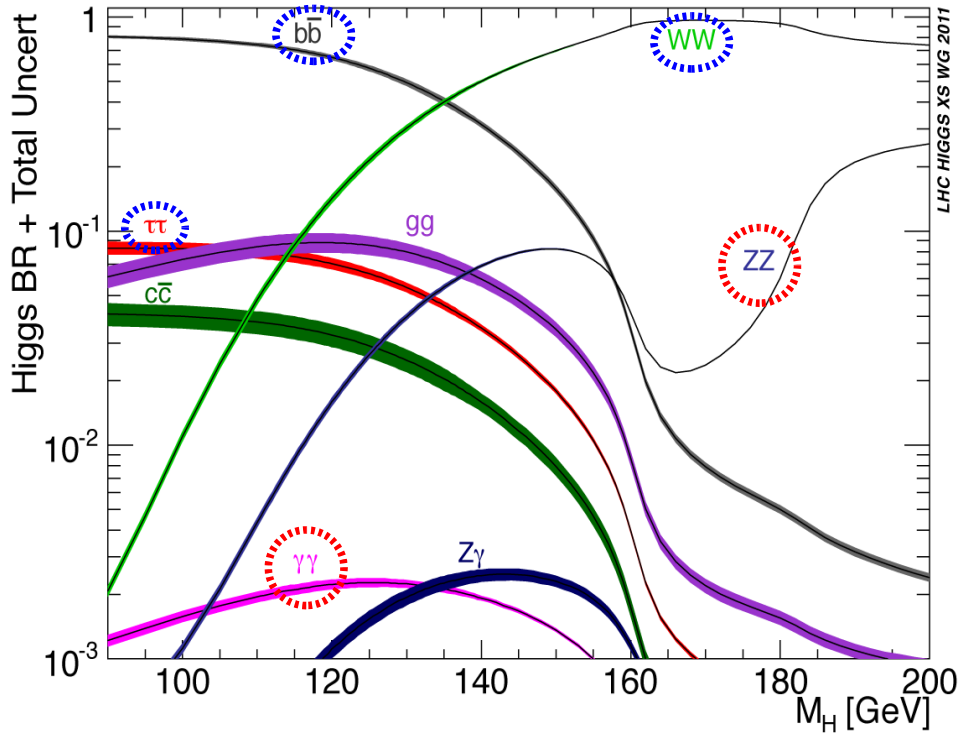
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- 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



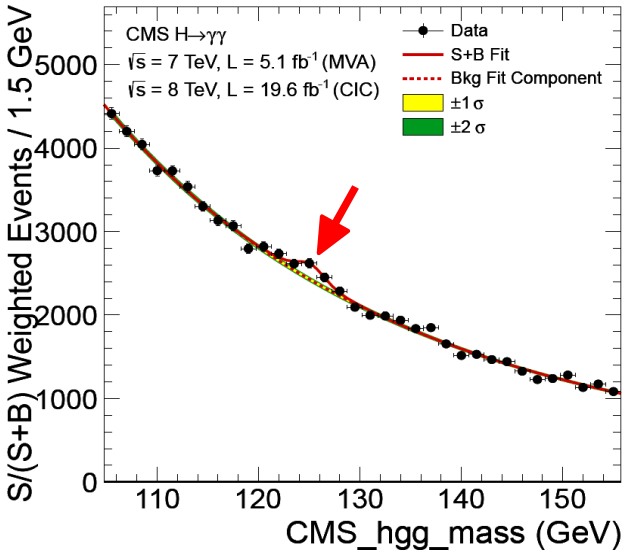


«Cleanest» channels: H → γ's, leptons

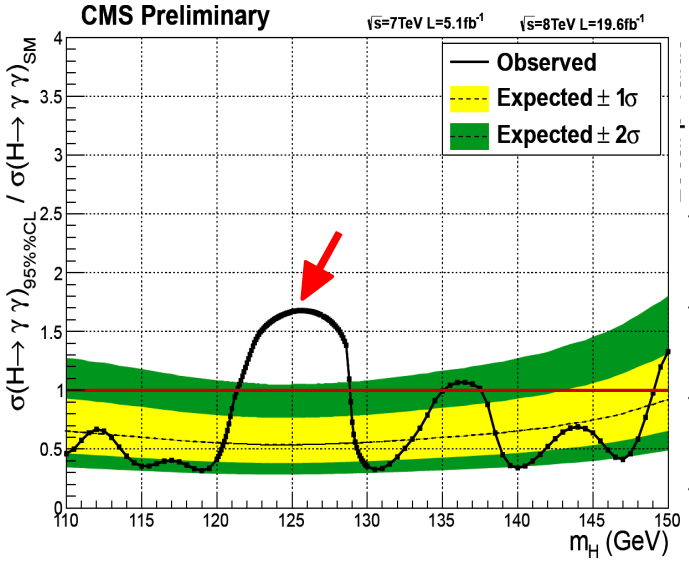
Large x-section channels: H → WW,ττ,bb

Discovery of Higgs-like boson: γγ, ZZ channels

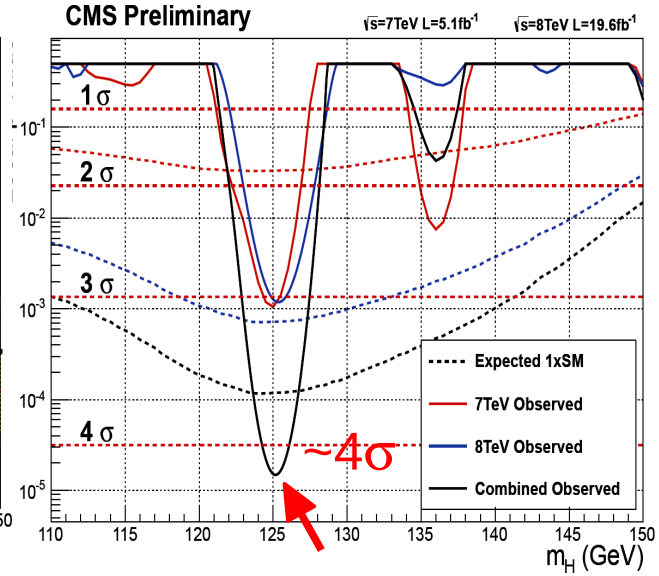
Invariant mass distribution:

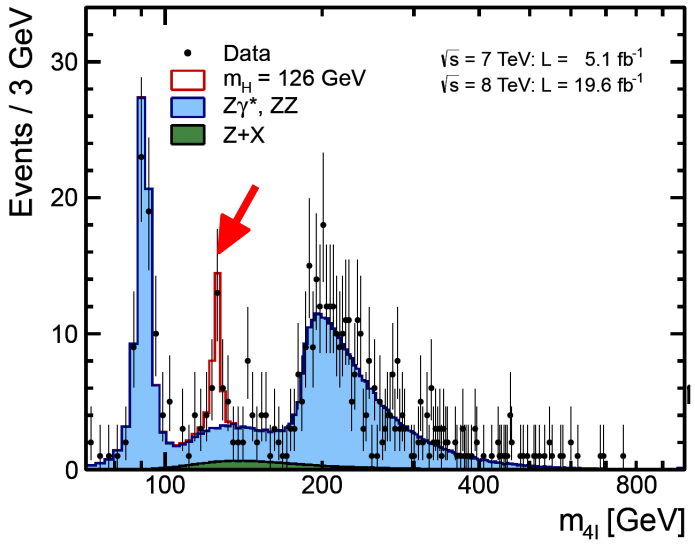


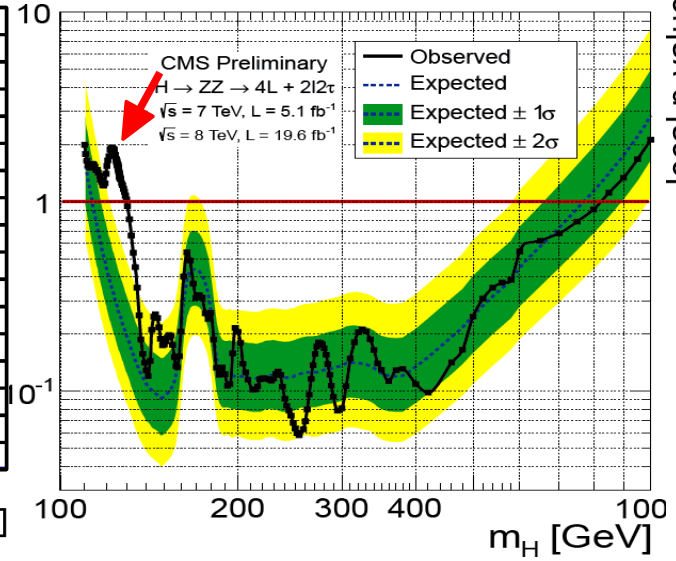
95% CL-Limits on σ/σ(SM):

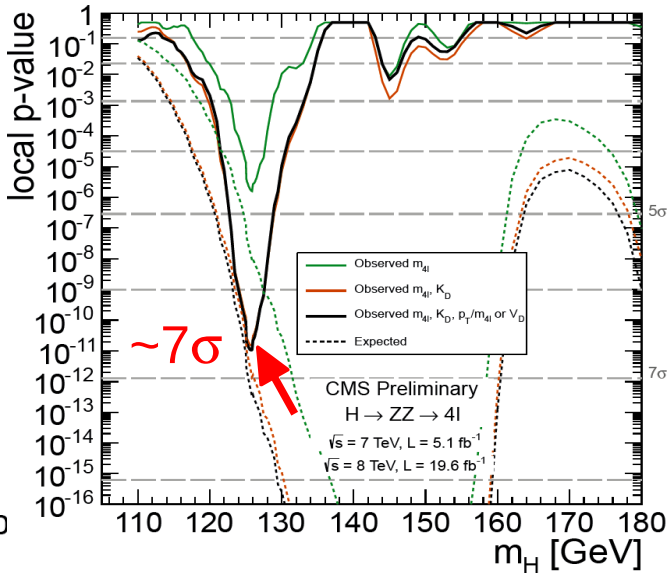


Significance (local p-value):





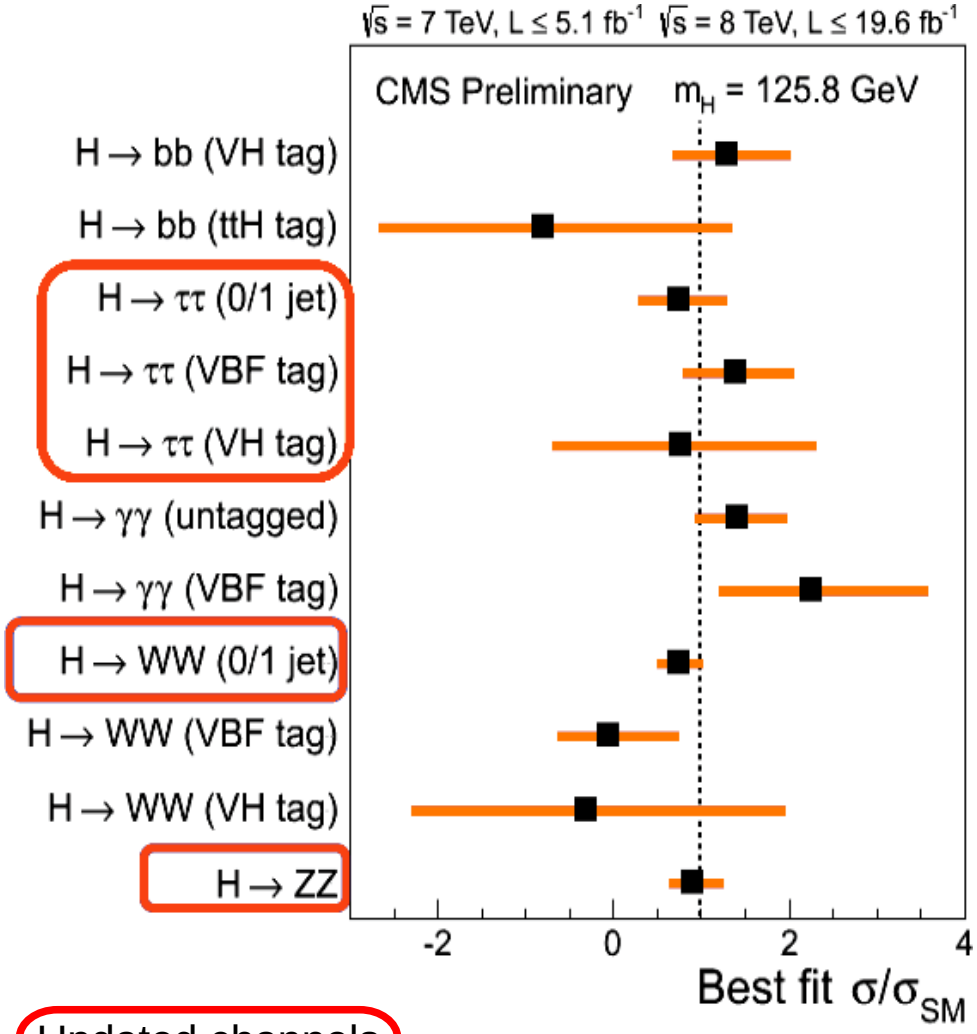




Discovery of Higgs-like boson: all channels

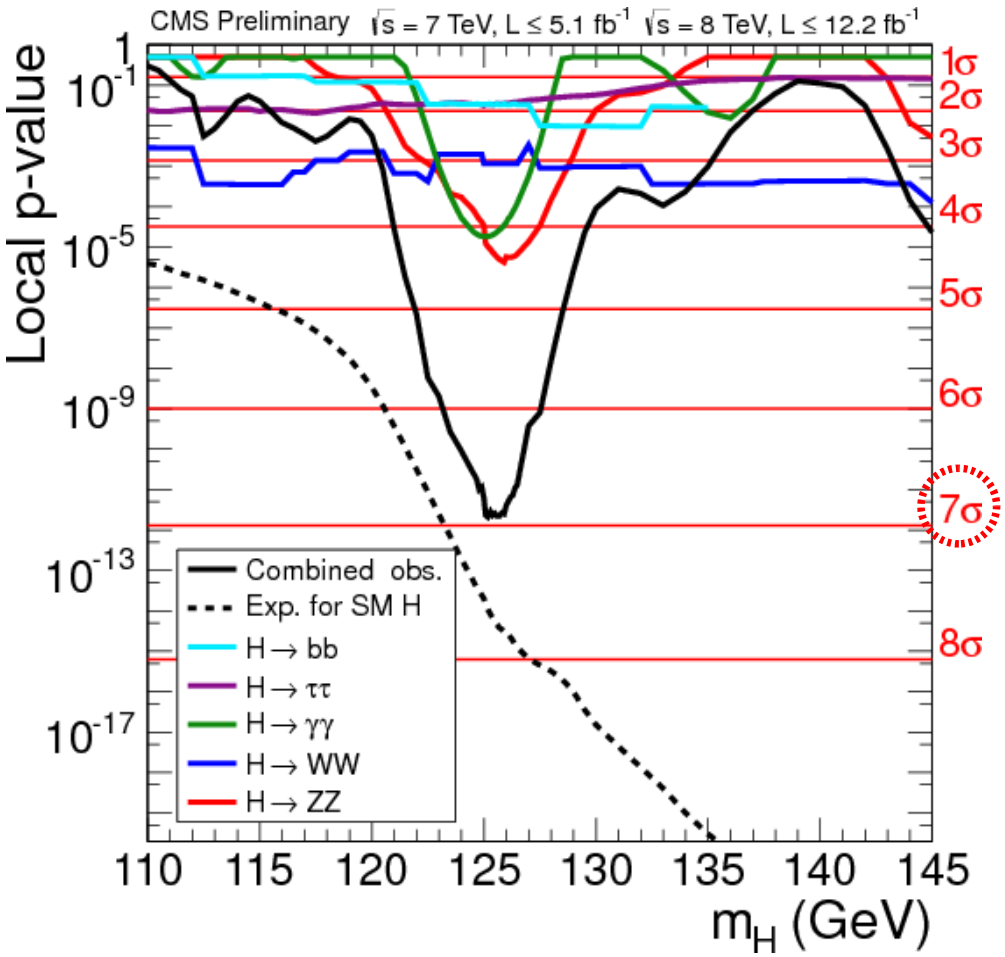
See talks by: H.Newman, C.Palmer, G.Mitselmakher, R.Walsh

Signal strength among channels & wrt SM Higgs:



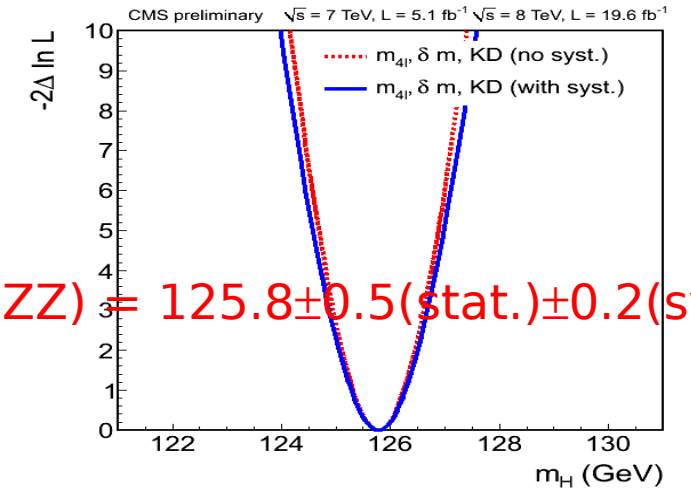
Updated channels

Combined significance (local p-value):



Discovery of Higgs-like boson: properties

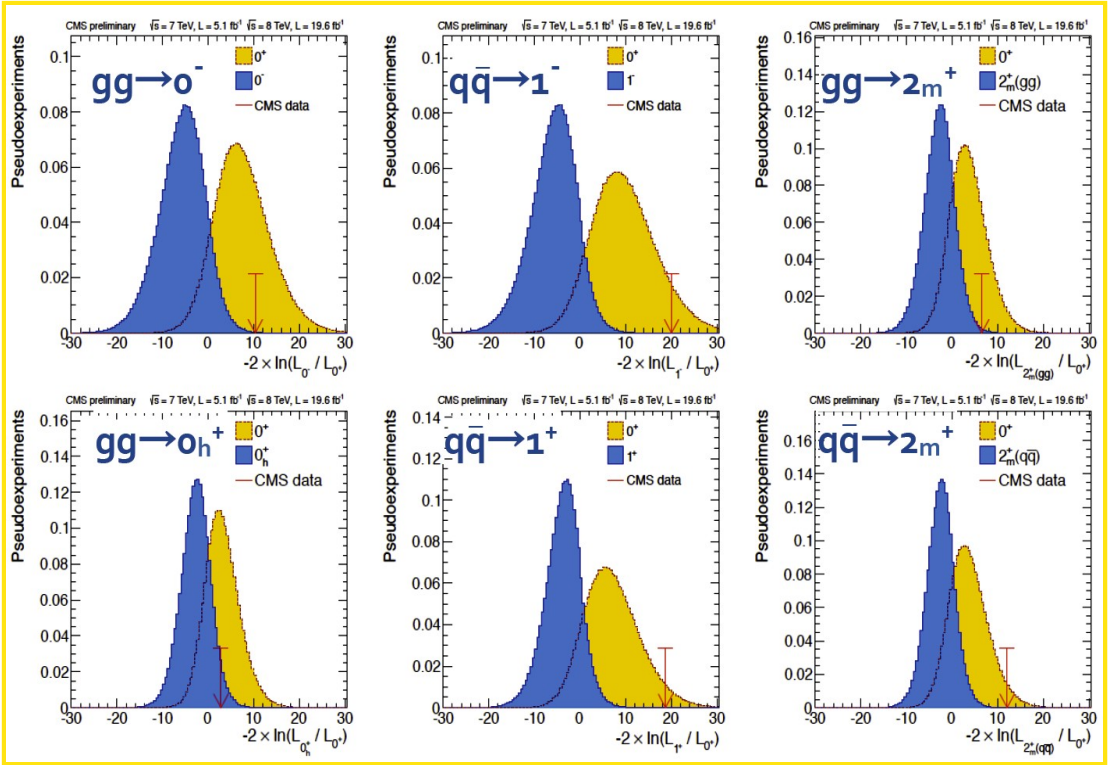
Mass peak position:



$m_H(ZZ) = 125.8 \pm 0.5(stat.) \pm 0.2(syst.)$

See talks by: H.Newman, C.Palmer, G.Mitselmakher, R.Walsh

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

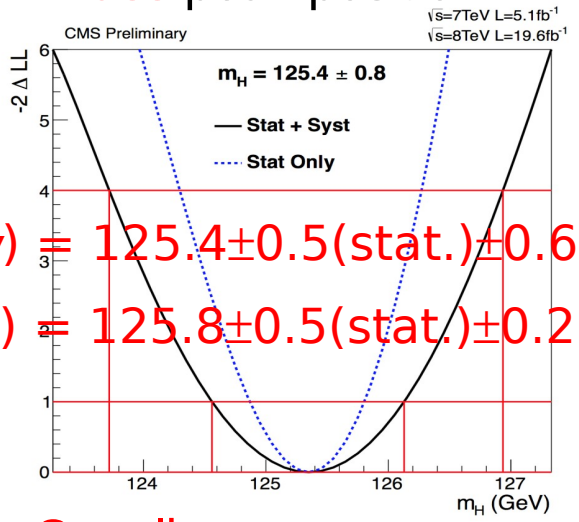


Studied pseudo-scalar, spin-1 and spin-2 models excluded at 95% CL or higher

Discovery of Higgs-like boson: properties

See talks by: H.Newman, C.Palmer, G.Mitselmakher, R.Walsh

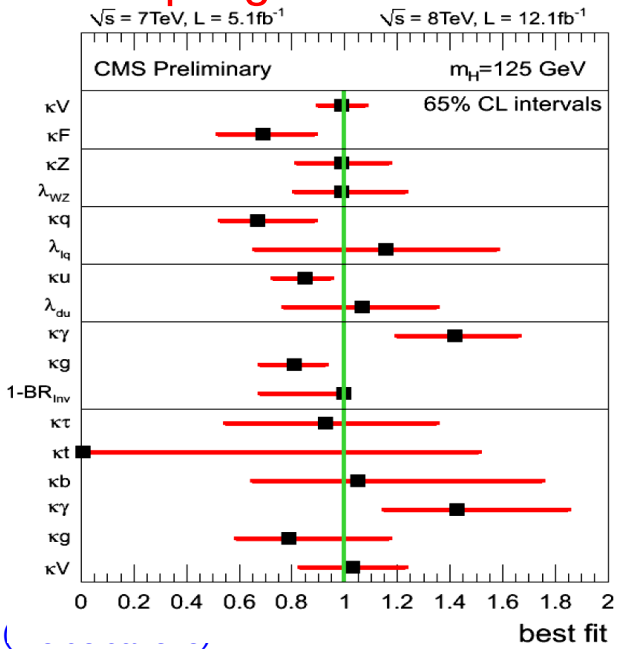
Mass peak position:



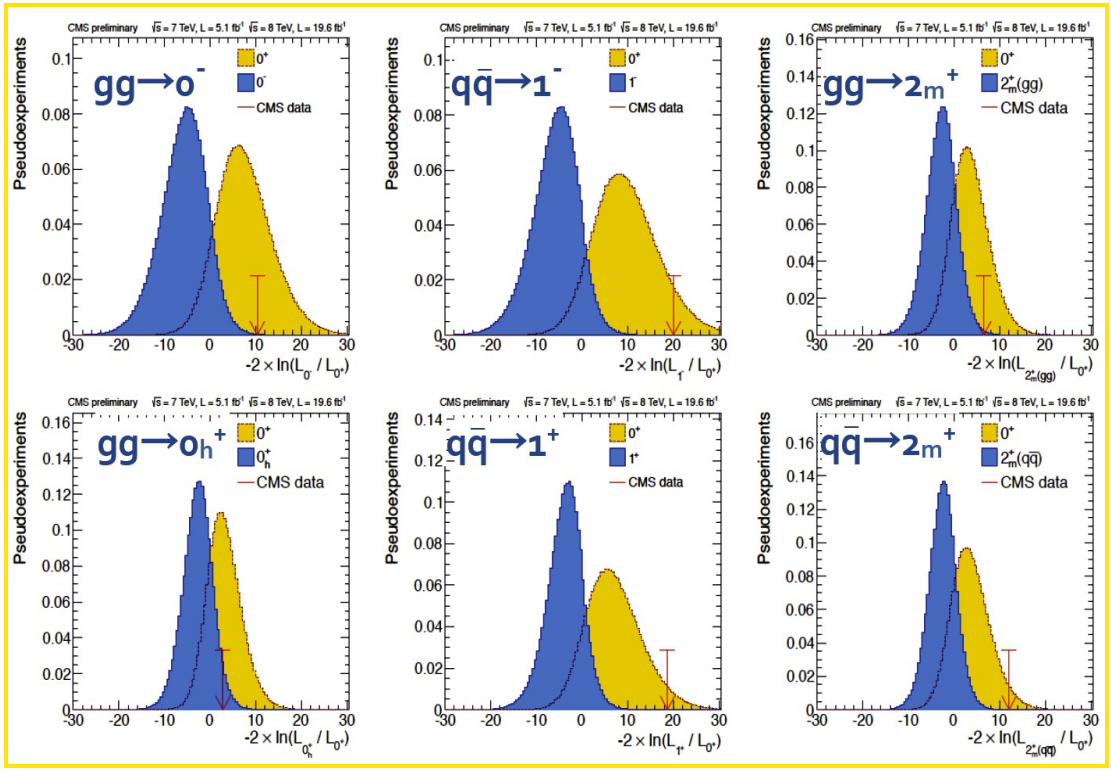
$m_H(\gamma\gamma) = 125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$

$m_H(ZZ) = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})$

Couplings:



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

Properties indicate no deviation from H(SM) so far

Higgs mass & top-quark mass

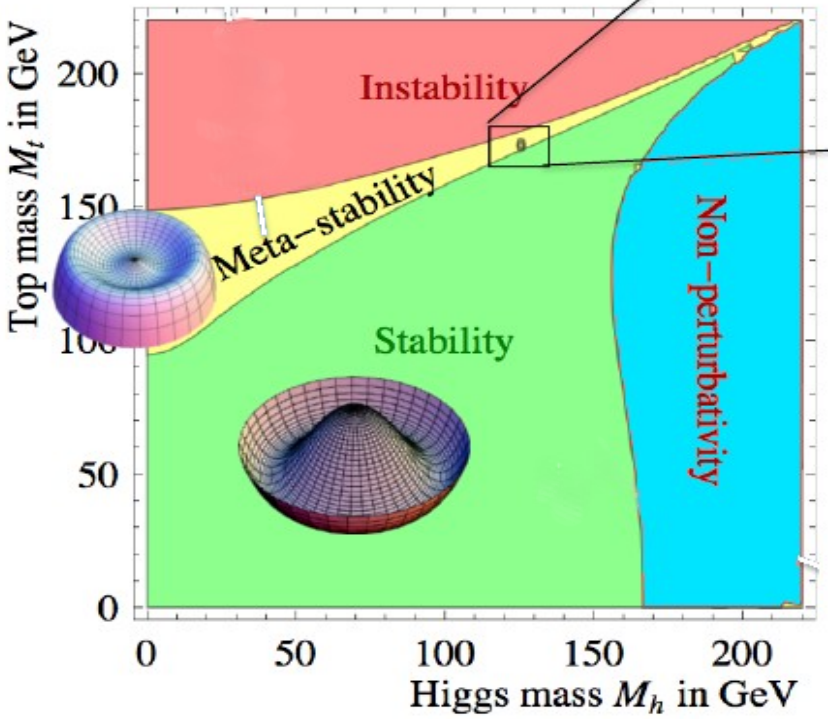
- Running of the Higgs self-coupling with energy:

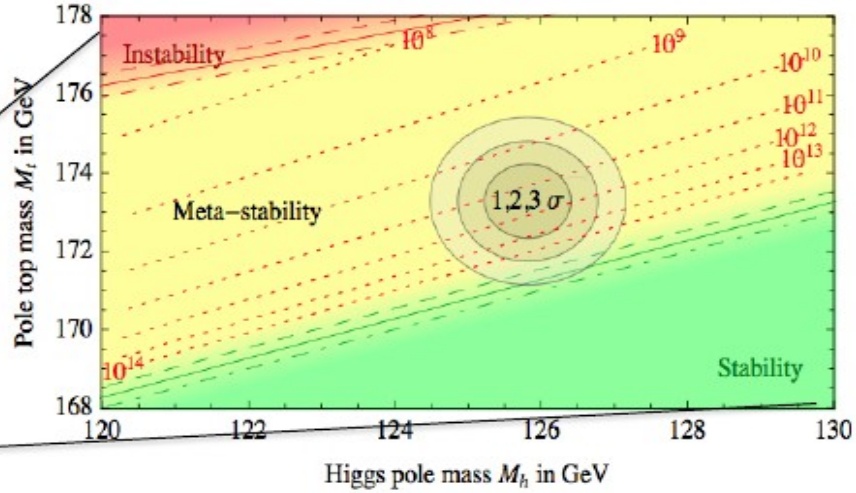
$$(4\pi)^2\frac{d\lambda}{d\ln\mu} = -6y_t^4+\frac{9}{8}g_2^4+\frac{27}{200}g_1^4+\frac{9}{20}g_2^2g_1^2+\lambda(12y_t^2-9g_2^2+\frac{9g_1^2}{5})+24\lambda^2+\text{higher loops}$$

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

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

[Strumia, Moriond EWK'13]





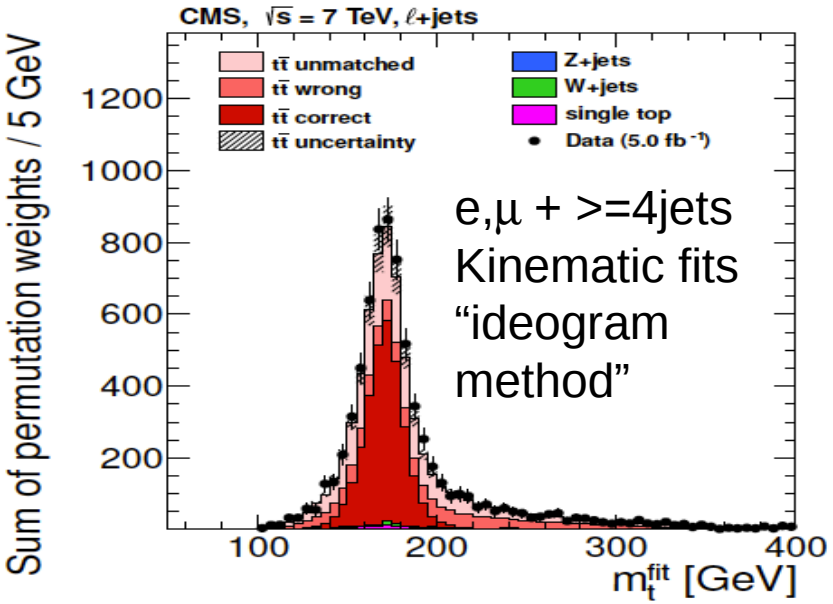
$$M_h\ [\text{GeV}] > 129.8 + 1.4\left(\frac{M_t\ [\text{GeV}]-173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z)-0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

$M_h = 125.8 \pm 0.4\,\text{GeV}$ (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



e,μ + >=4jets
Kinematic fits
"ideogram method"

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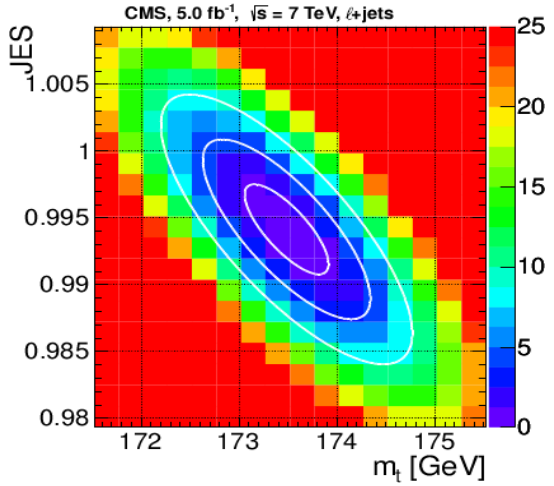
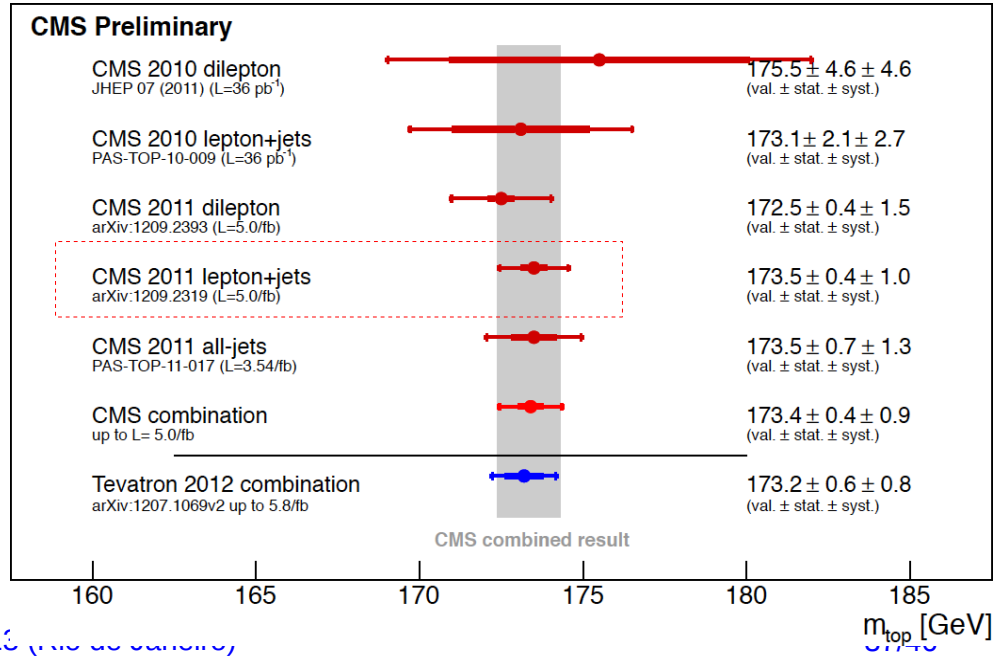


Common likelihood fit to JES & m_{top}



Good consistency among all measurements at 7,8 TeV !

CMS average:
m_{top} = 173.4 ± 0.4 ± 0.9 GeV

Dominant syst. uncertainties:
EXP: 0.55 GeV (JES)
TH: 0.45 GeV (color reconnection)

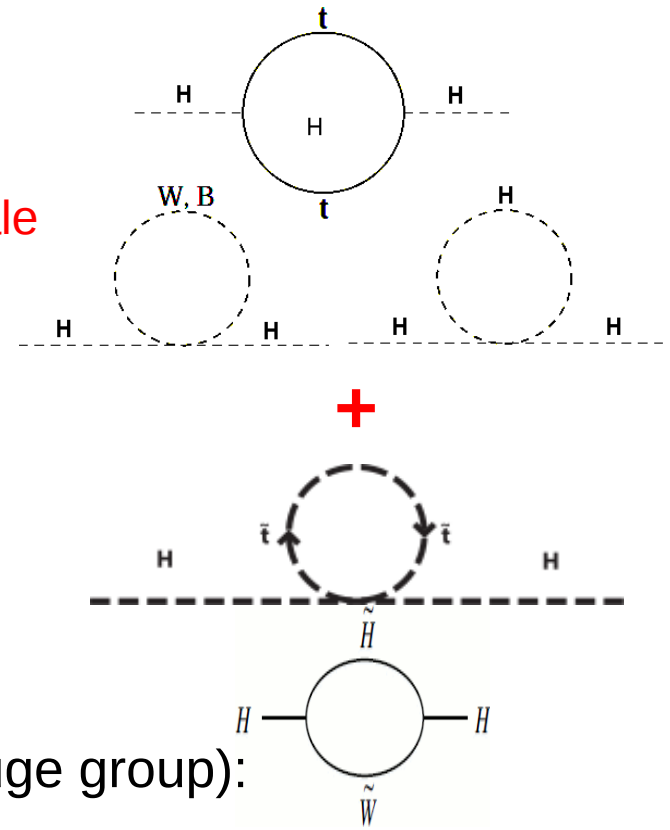
(Universe meta-stable at 2σ ?)

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:

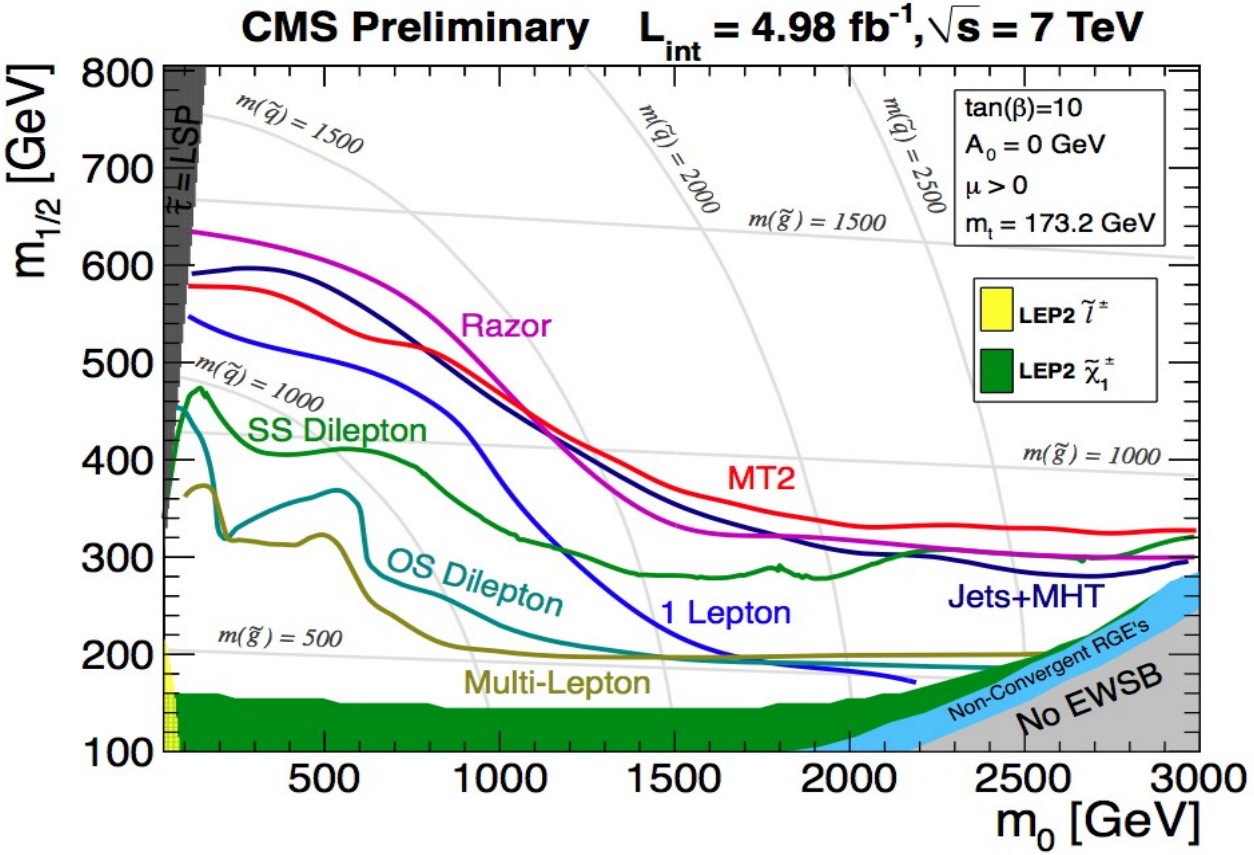
  Effects from hidden dims (0.1 mm to 10^{-19} m). ➔ KK-towers, radion, mini-BH, ...

- All solutions imply new particles at TeV scale !

Constrained SUSY searches (7 TeV)

See talk by: J. Mans

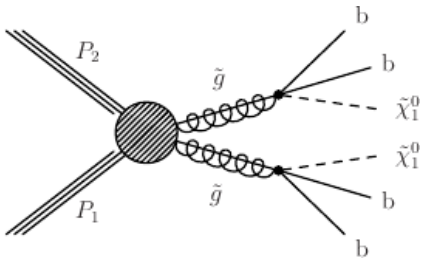
- cMSSM or mSUGRA = minimal SUSY SM extension with least # of params (m_0,$m_{1/2}$,tanβ,A,signμ), defined at GUT-scale & evolved down in energy.
- Many searches with multiple observables: Spartner masses pushed to increasingly heavier (TeV) masses. No «simple» SUSY so far ...



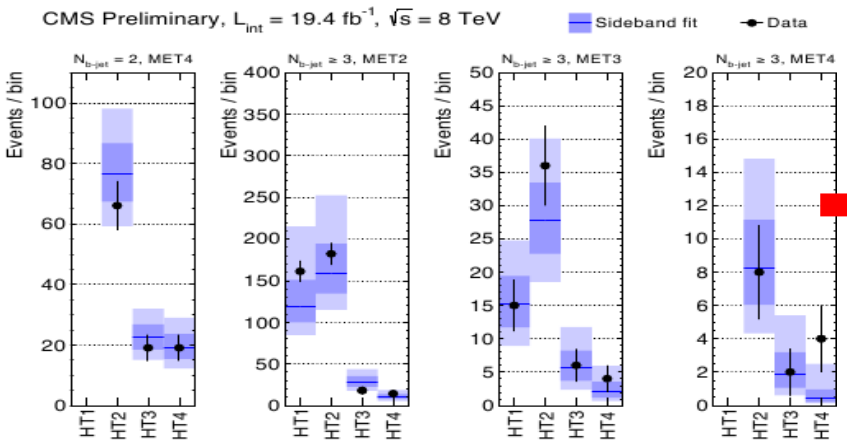
Typical Natural-SUSY searches (8 TeV)

See talk by: J. Mans

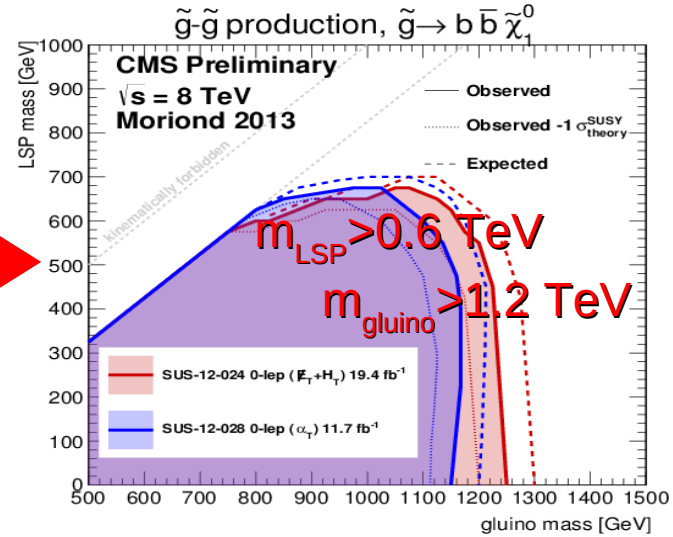
- ~10% fine-tuning: squarks>TeV, stops<0.6 TeV, gluinos<1.4 TeV
  Gluinos decays into 3rd generation:

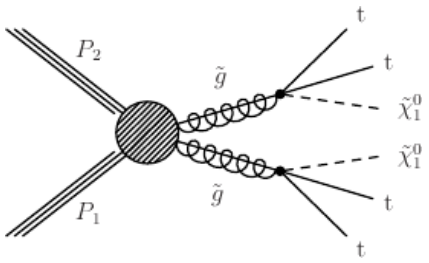


4 b-jets, MET



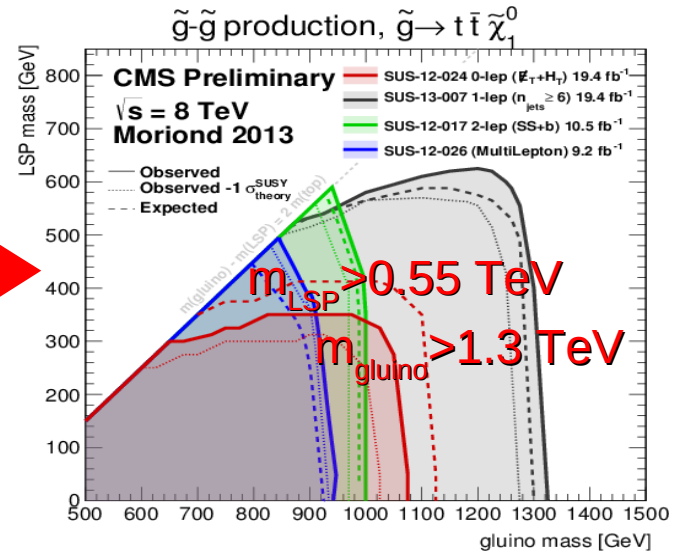
Increasing MET & N-jets --→





4 b-jets, 4W, MET

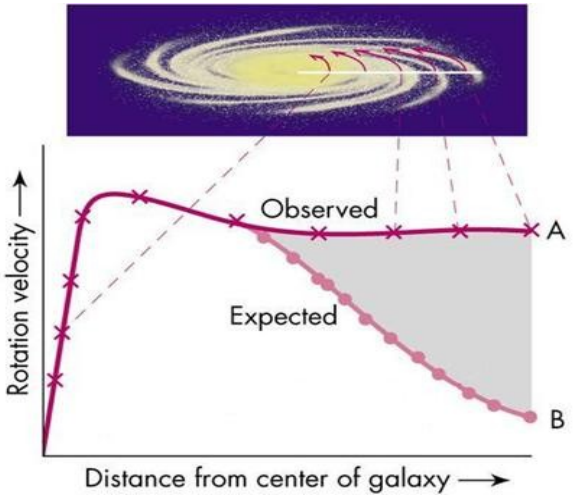
		S_T^{lep} [GeV]	control reg. data	prediction	observation
N_b=2	Muons	[250,350]	141	6.00 ± 2.40 (2.23)	9
		[350,450]	24	1.37 ± 1.19 (1.12)	2
		>450	9	0.0 ± 0.66 (0.66)	0
	Electr.	[250,350]	112	3.83 ± 1.84 (1.75)	9
		[350,450]	28	2.74 ± 2.02 (1.86)	2
		>450	9	0.0 ± 0.42 (0.42)	0
$N_b \geq 3$	Muons	[250,350]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

- Dark matter evidences:

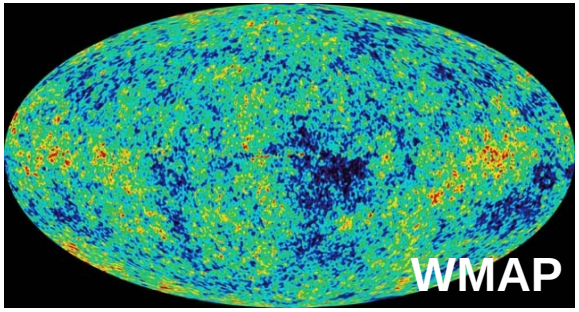
  - Galactic rotation curves.
  - Collision of cluster galaxies.
  - CMB background T fluctuations.



- Properties:

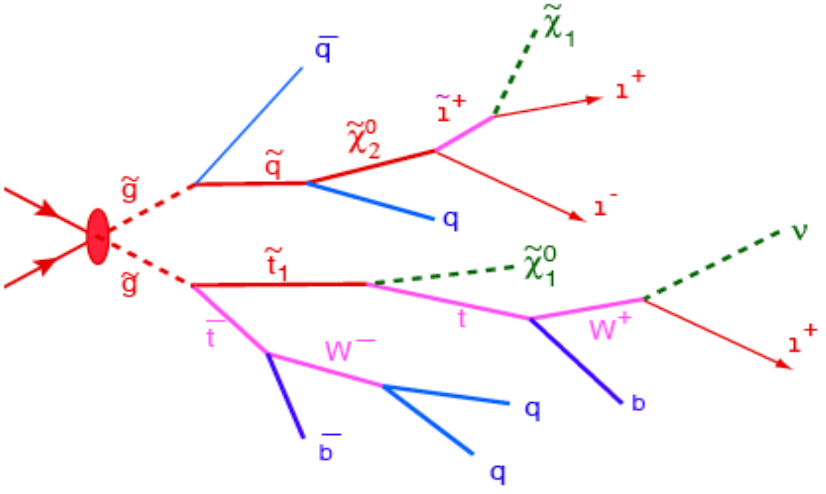
  - Sensitive to weak-interaction & gravitation
  - Stable, massive, early Universe relic.

  → Weakly Interacting Massive Particle (WIMP)



- Possible BSM candidates:

  - Lightest SUSY Particle (LSP): neutralino, ...
  - Technicolor: lightest technibaryon
  - Extra-Dims: lightest Kaluza-Klein tower, gravitons (from adjacent branes), ...
  - Heavy R-handed (sterile) neutrinos.
  - Axions
  - ...

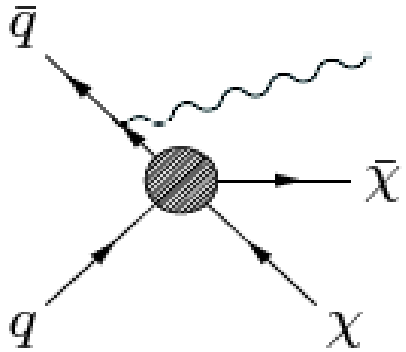


BSM searches: generic dark-matter

See talk by: J. Mans

- Dark matter via monophotons + MET:

f-fbar (+ISR) → X+Xbar



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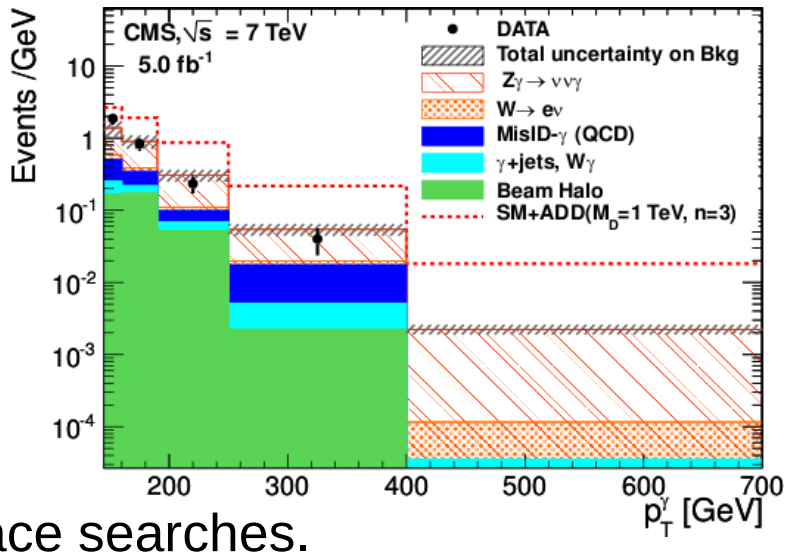
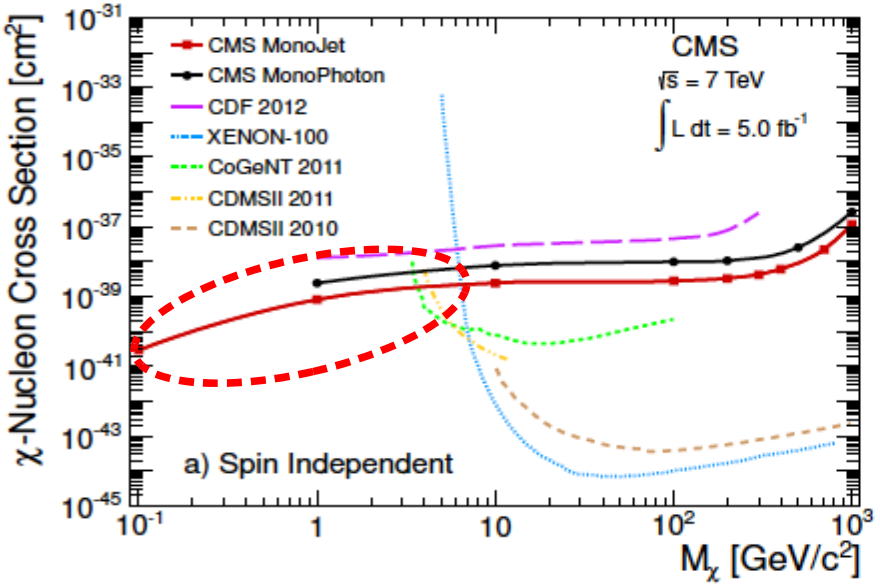
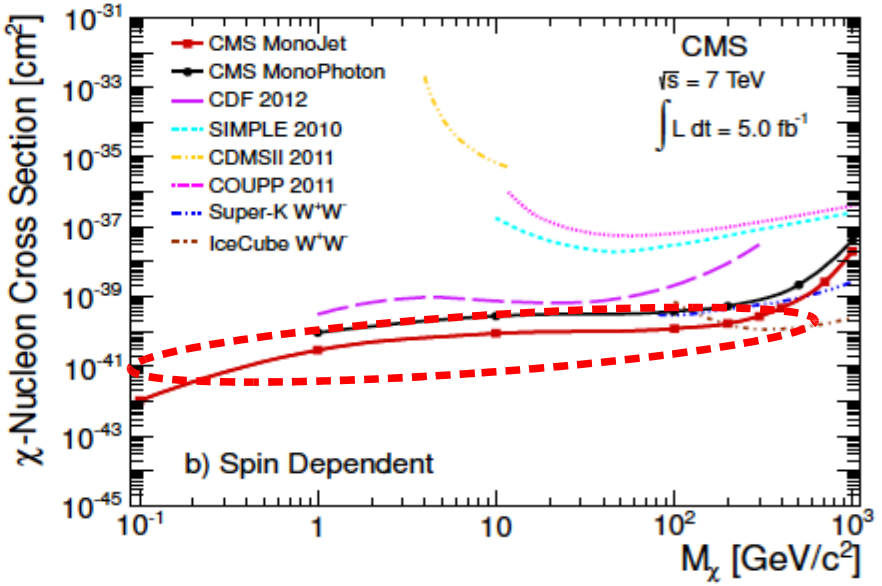
PRL 108 (2012) 261803



- Complementary to direct underground/space searches.
  Best χ-nucleon (spin-indep) x-section limits for m_χ ~ 0.1-10 GeV:





BSM searches: High-mass resonances

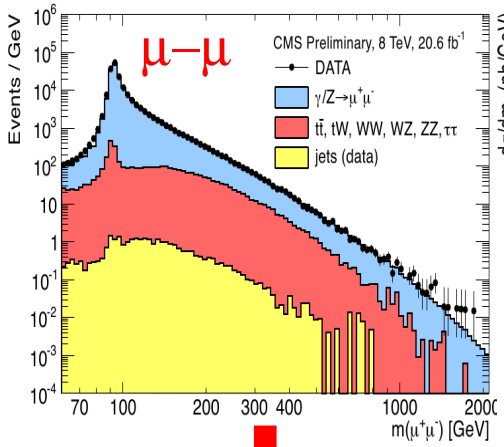
- «Simple» procedure:

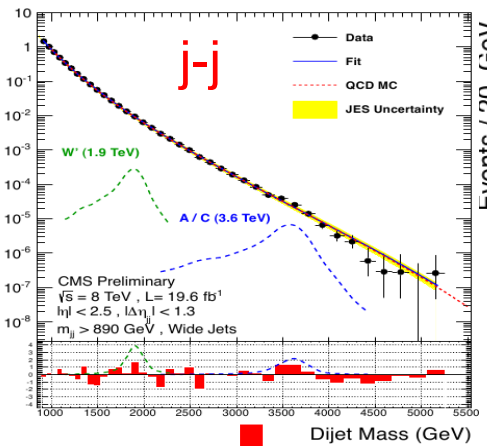
  (i) Reconstruct pairs of high-p_T objects: jets, leptons, bosons, ...

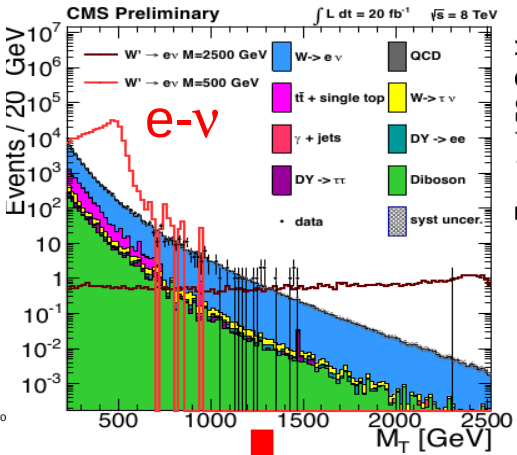
  (ii) Look at inv. mass tails for deviations from smooth SM backgrounds.

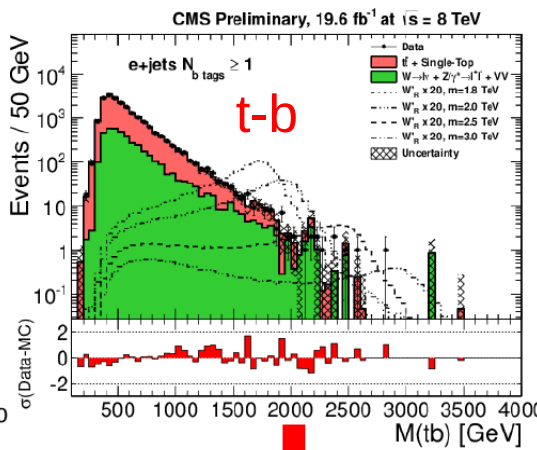
  (iii) Interpret (lack of) excess within (simplified) BSM models: Set limits for NP

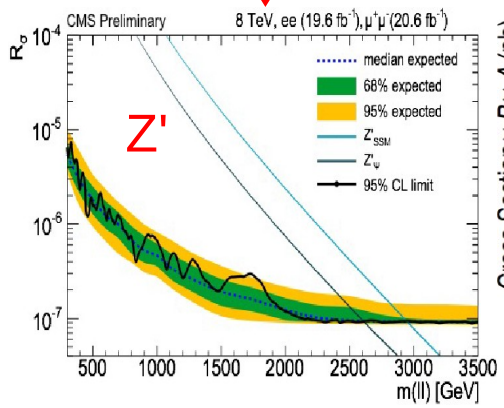
See talk by: J. Mans

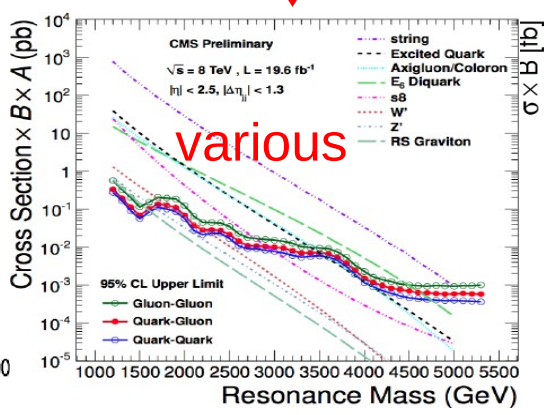


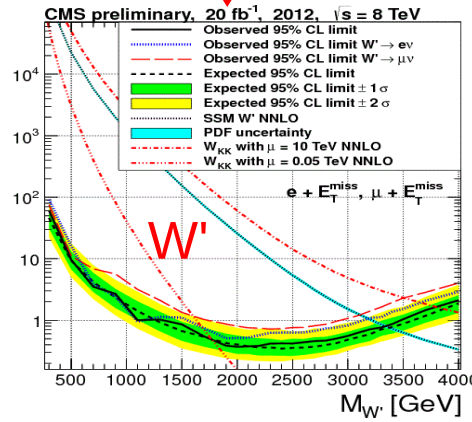


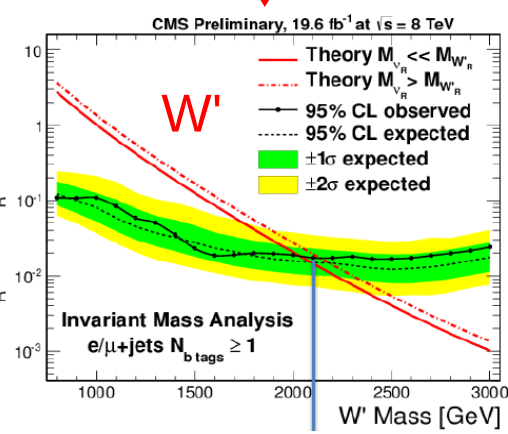






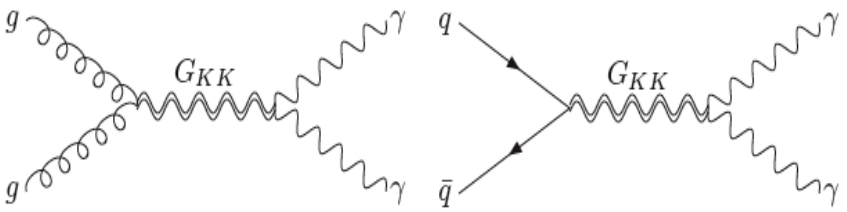






BSM searches: Extra-Dimensions

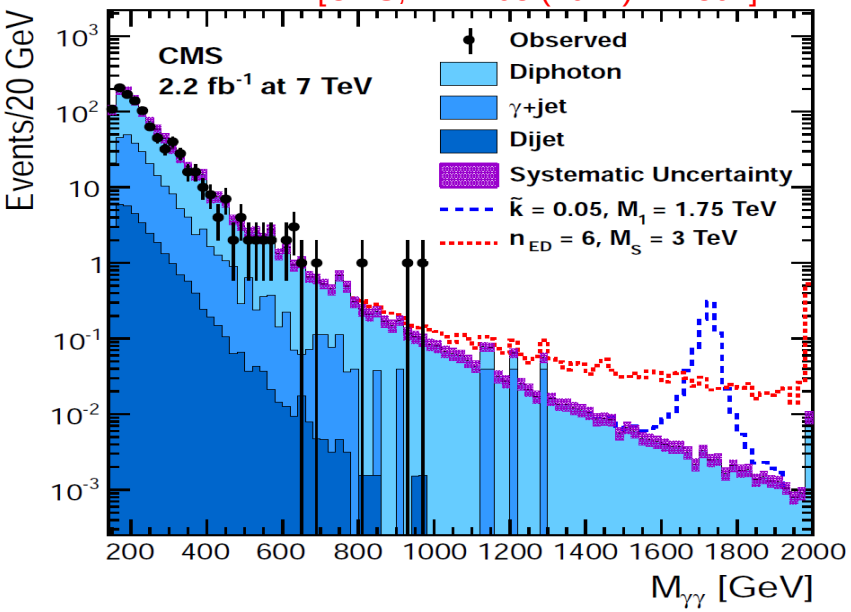
- Extra Dimensions (ED) signature: virtual Gravitons ($qq/gg \rightarrow G^* \rightarrow \gamma\gamma$):

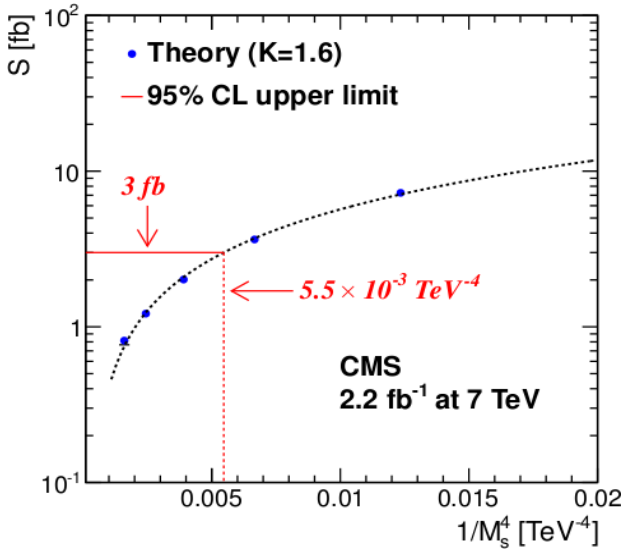


(spin-2 G* decay into diphoton in the s-wave)

- Warped ED (RS):
  - G* resonance (Kaluza-Klein modes)
  - 2 parameters:
    M_1 (1st 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)

[CMS, PRL108 (2012) 111801]



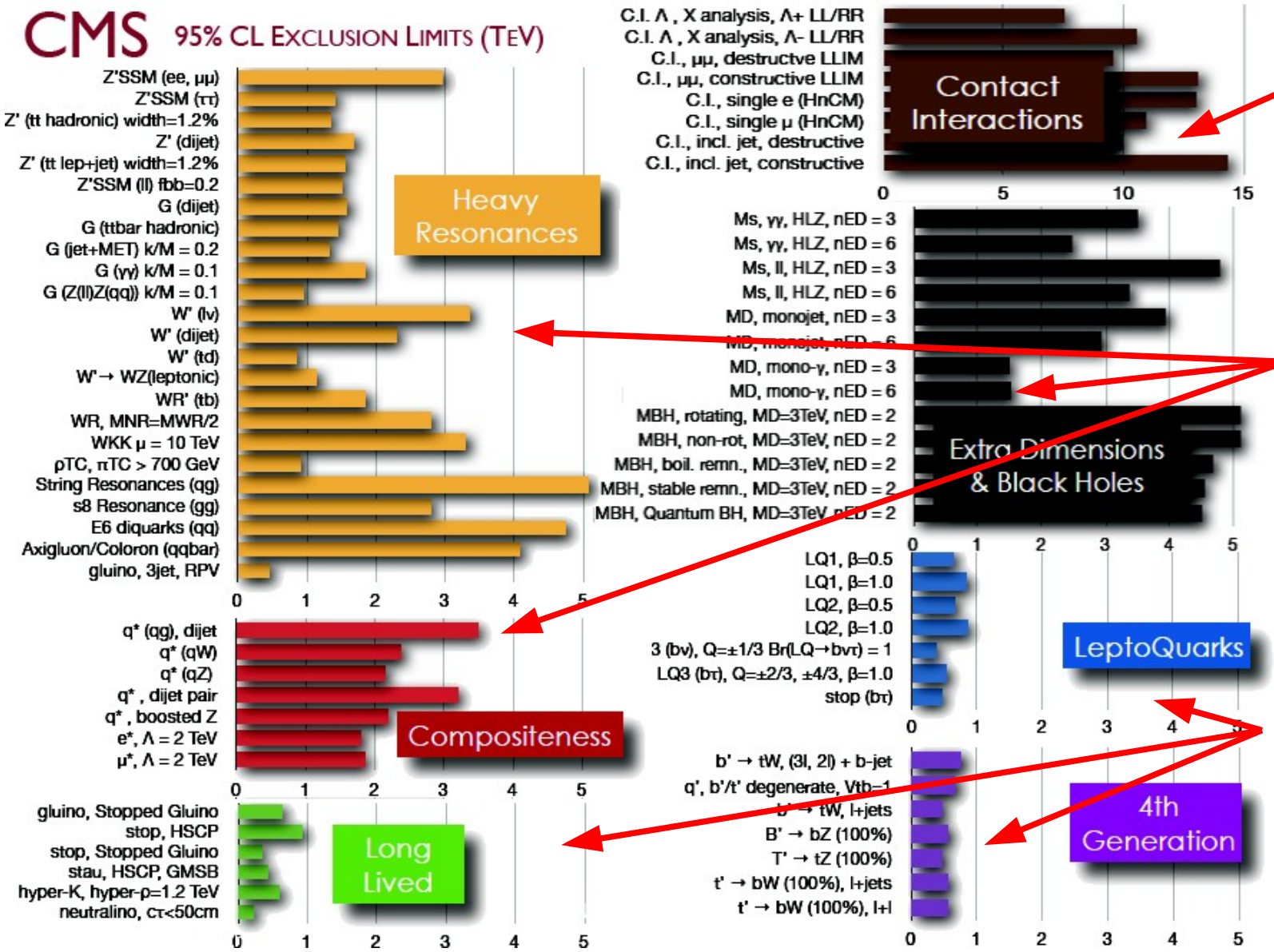


RS G* limits:

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:

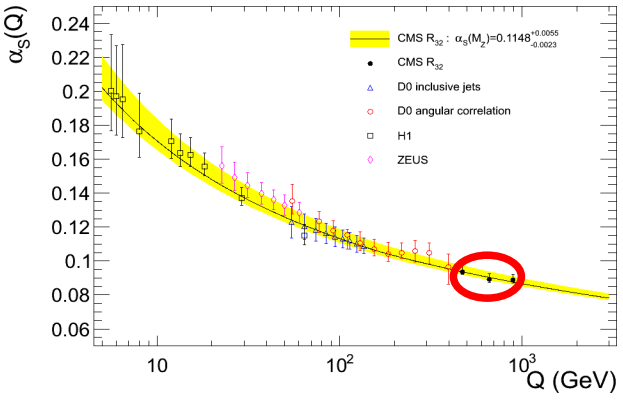
- Extra-dim, BH
- Z',W',G reson.
- Compositeness

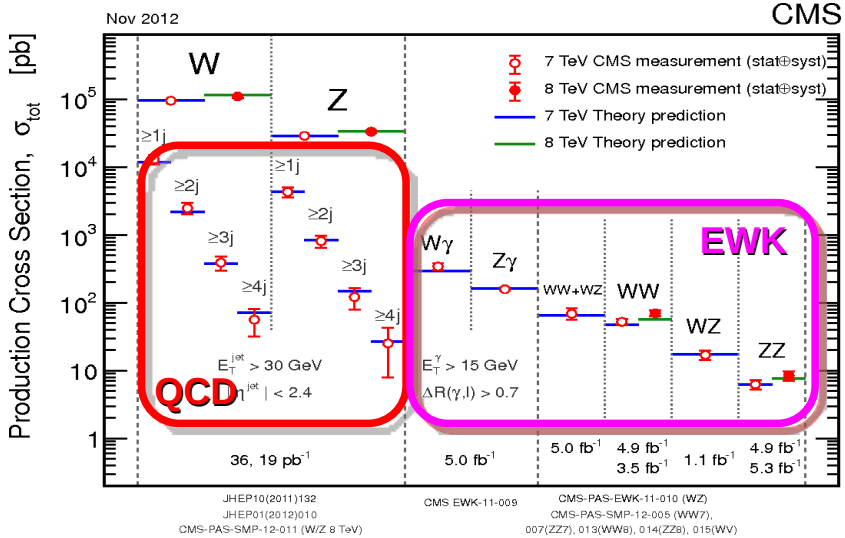
(3) m_X >0.5 TeV for

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

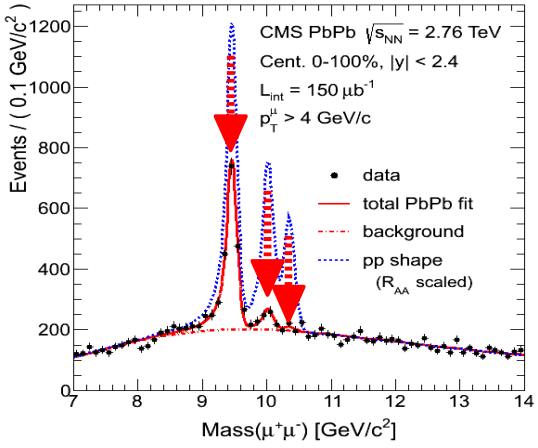
Summary

- Precision (N)NLO QCD&EWK studies at 7, 8 TeV:

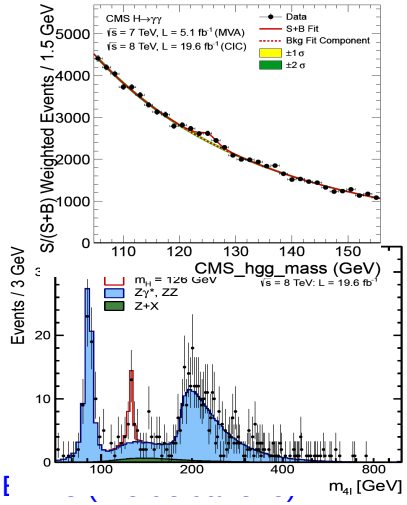


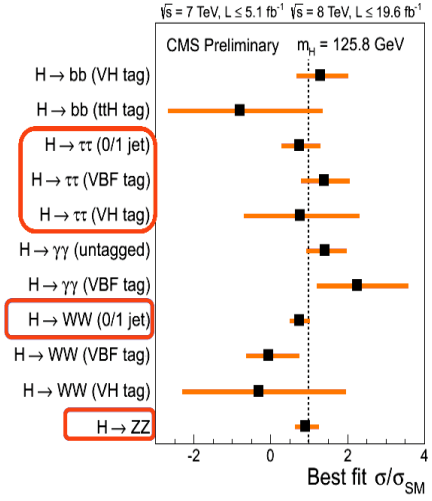


- Interesting dense QCD-matter data:

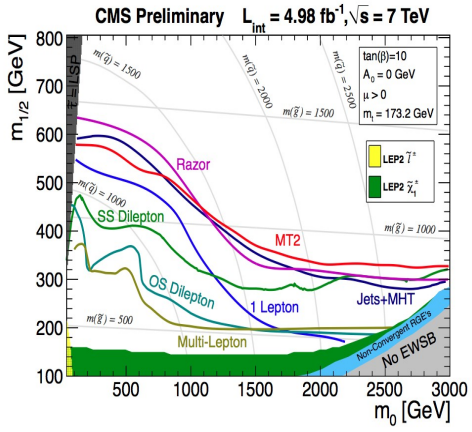


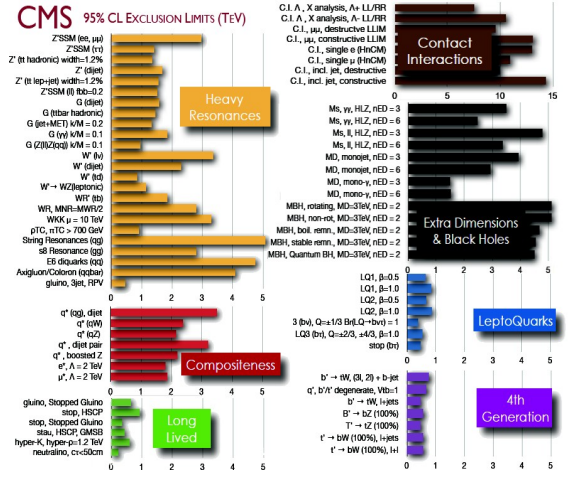
- Discovery of SM-like Higgs boson at m~125.5 GeV !





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





Back up slides