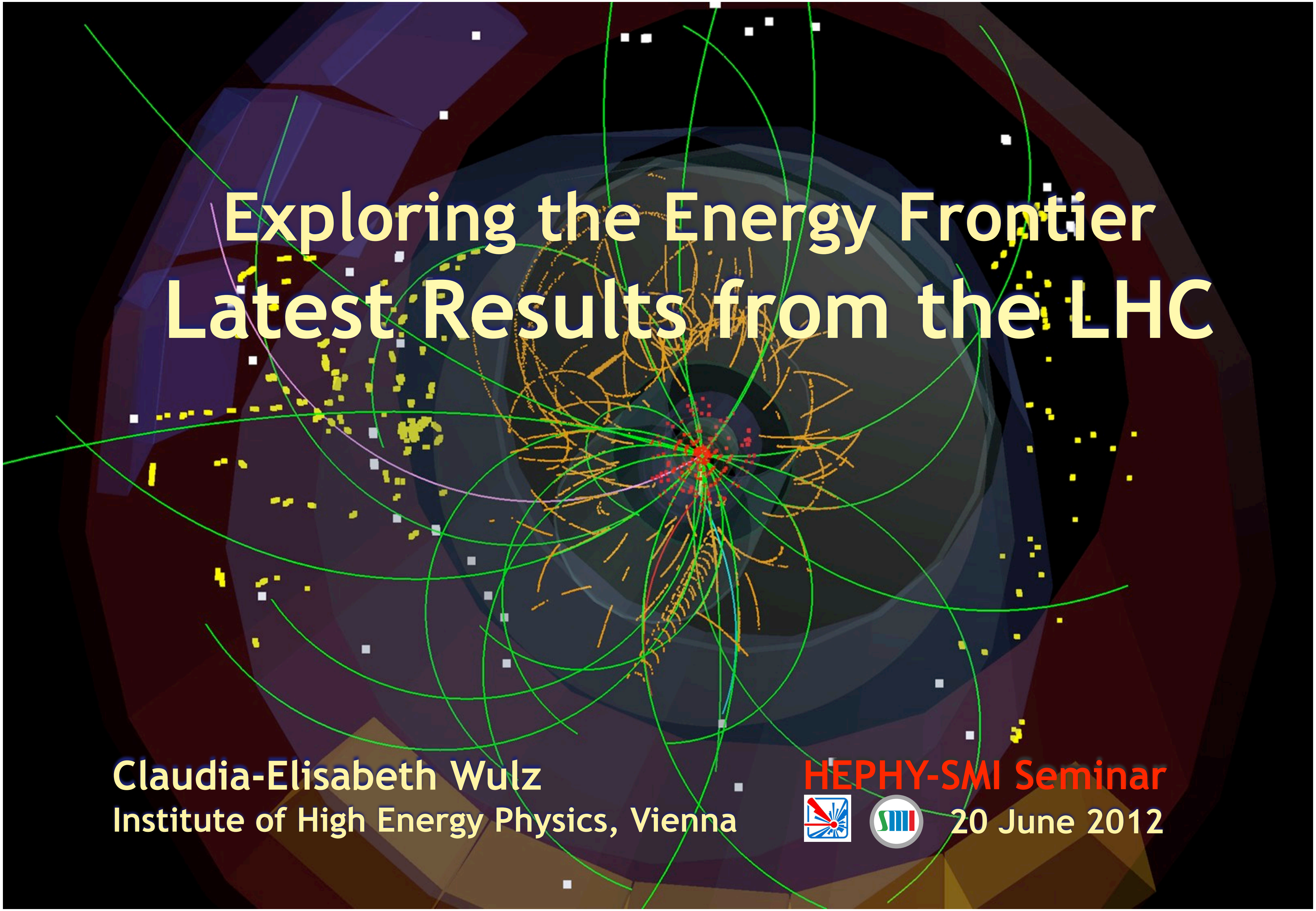


Exploring the Energy Frontier
Latest Results from the LHC

Claudia-Elisabeth Wulz
Institute of High Energy Physics, Vienna

HEPHY-SMI Seminar

20 June 2012

Important open questions

What is the origin of electroweak symmetry breaking?

Is it the simplest Higgs mechanism?

How must the Standard Model be extended?

Supersymmetry, Grand Unified Theories, …

What are dark matter and dark energy?

What are the last secrets of neutrinos?

Can we unify all forces?

Can we include gravity?

Are there extra dimensions?

Are quarks and leptons fundamental particles?

Are there more than three generations?

Why is there asymmetry between matter and antimatter?

Do we understand dense and hot matter?

Quark-gluon plasma

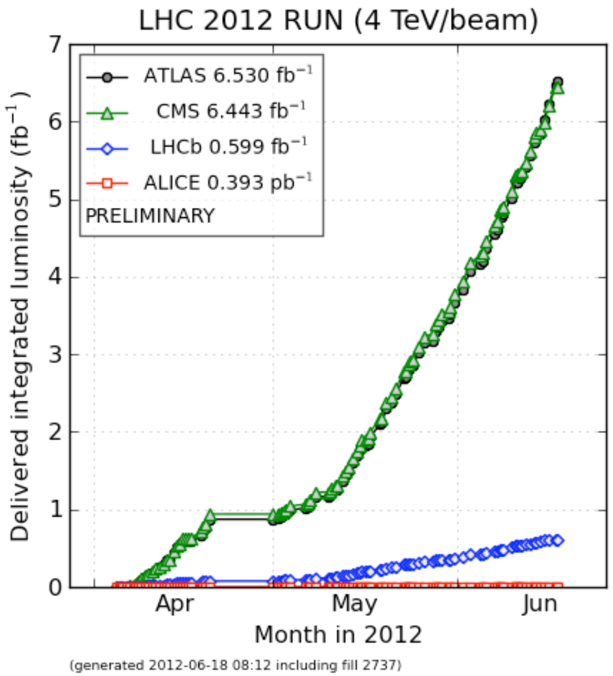
LHC and its experiments

LHC performance with protons

http://lpcc.web.cern.ch/LPCC/index.php?page=luminosity_charts

Integrated proton luminosities

- Almost 50 pb^{-1} delivered per experiment in 2010, $\sqrt{s}$ = 7 TeV
  (except ALICE: to keep pile-up in the TPC below 5%)
- More than 5 fb^{-1} each for ATLAS and CMS in 2011, $\sqrt{s}$ = 7 TeV
- More than 6 fb^{-1} recorded per experiment since 2012, $\sqrt{s}$ = 8 TeV
- Order of 15 fb^{-1} expected per experiment in 2012, $\sqrt{s}$ = 8 TeV



Peak luminosity

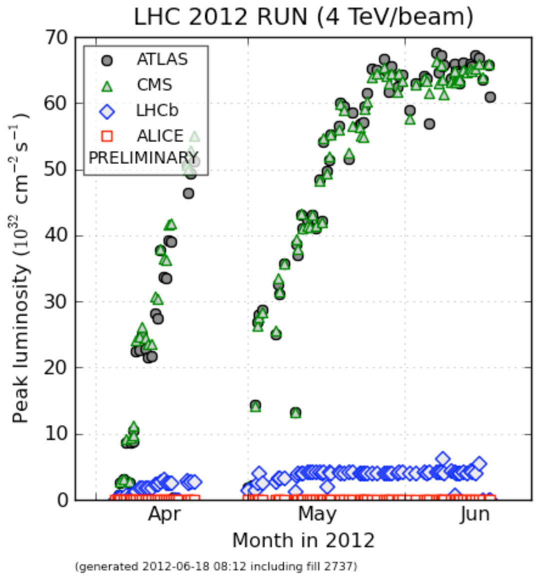
- 6.8×10^{33} $cm^{-2}s^{-1}$
  (nominal: 10^{34} $cm^{-2}s^{-1}$)

Bunch spacing

- 50 ns

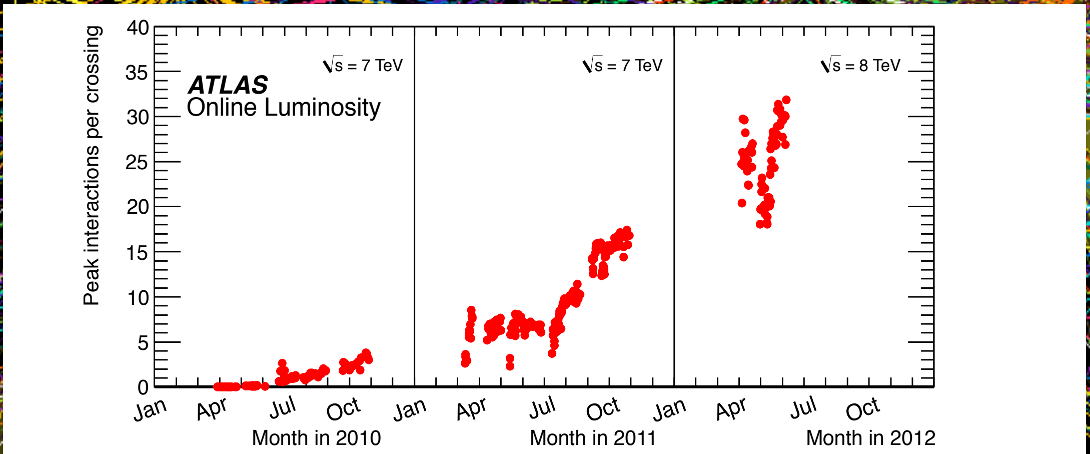
Number of bunches per beam

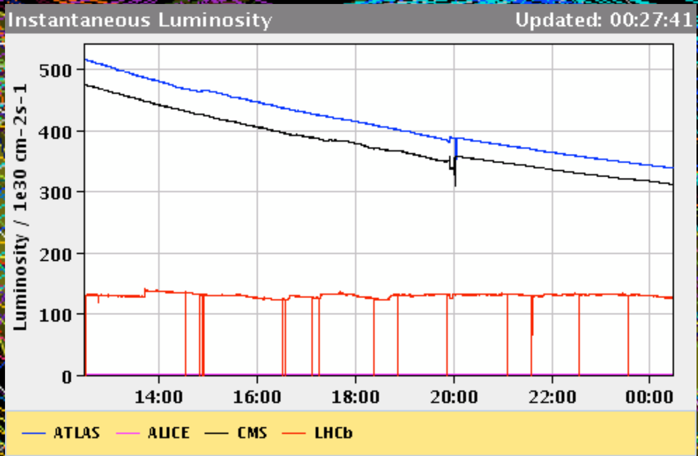
- 1380 (nominal 2808)



Challenge: in-time pileup

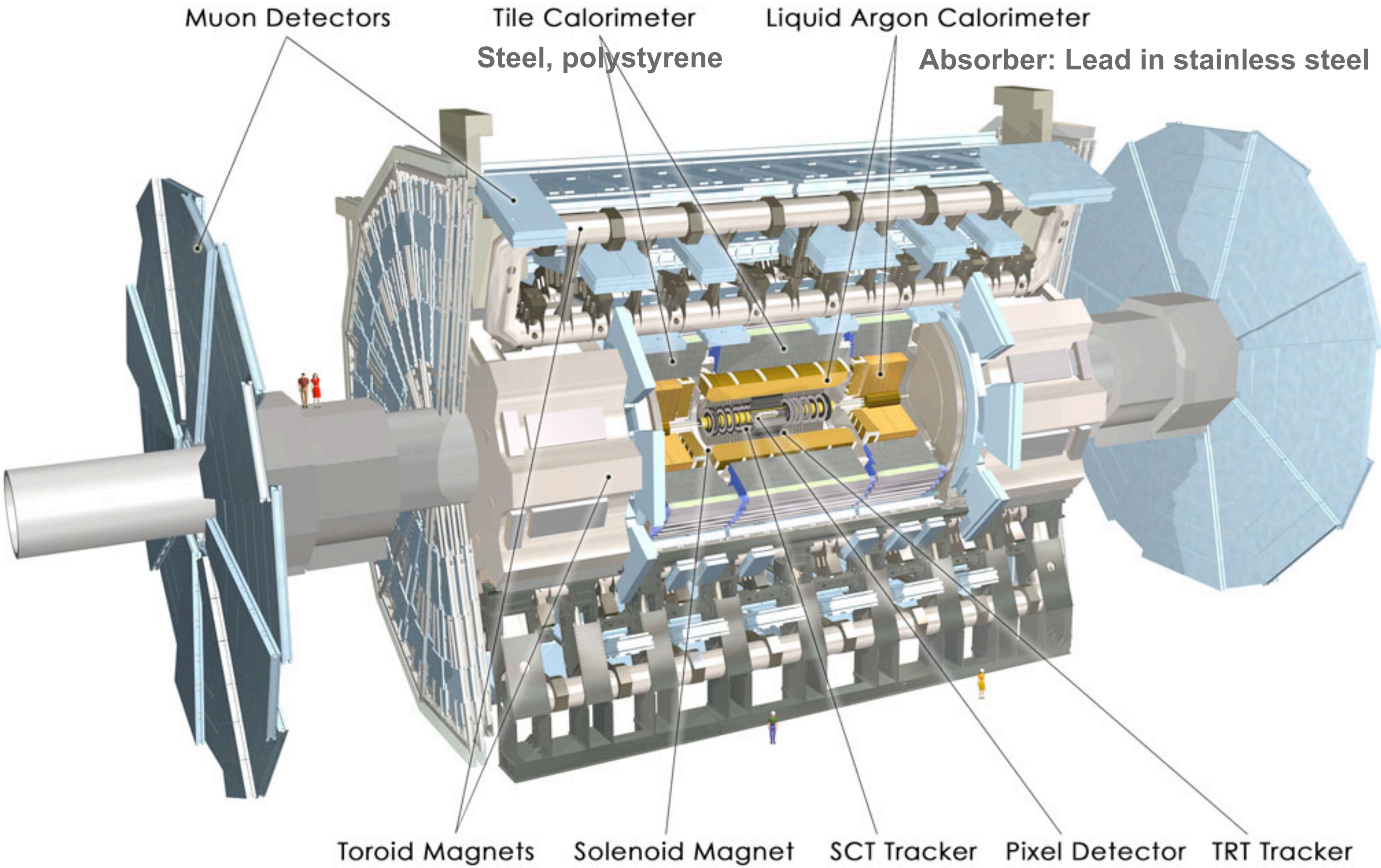
Multiple vertices, many tracks: <n>≈33 for highest luminosity in 2012
-> challenges to trigger and computing!
-> LHC explores luminosity leveling for ATLAS and CMS



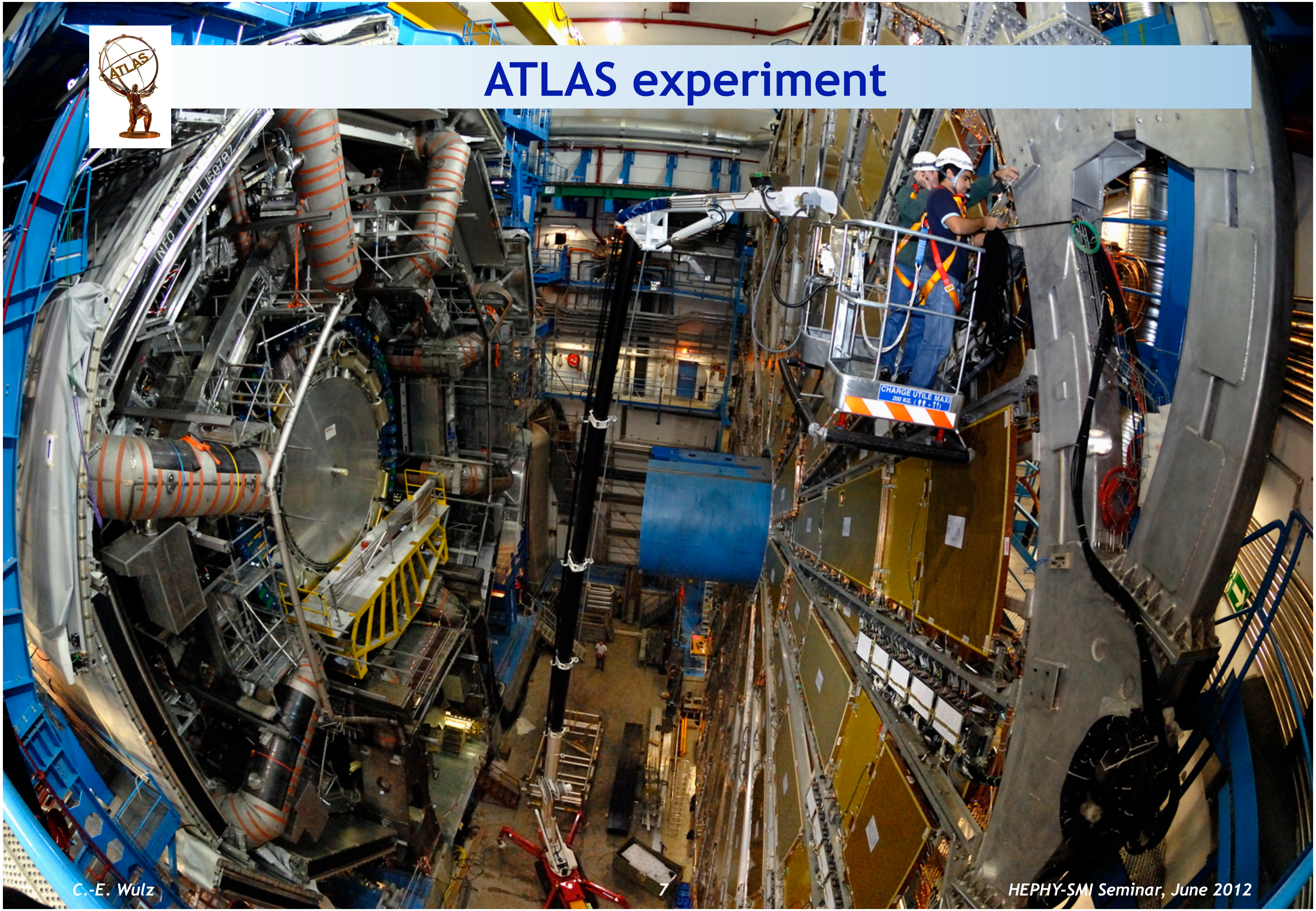


Vertex resolution better than ~200 μm, vertices a few cm apart, beam spot size 16 μm at collision point. Average number of interactions at nominal LHC luminosity and 25 ns bunch spacing: 23.

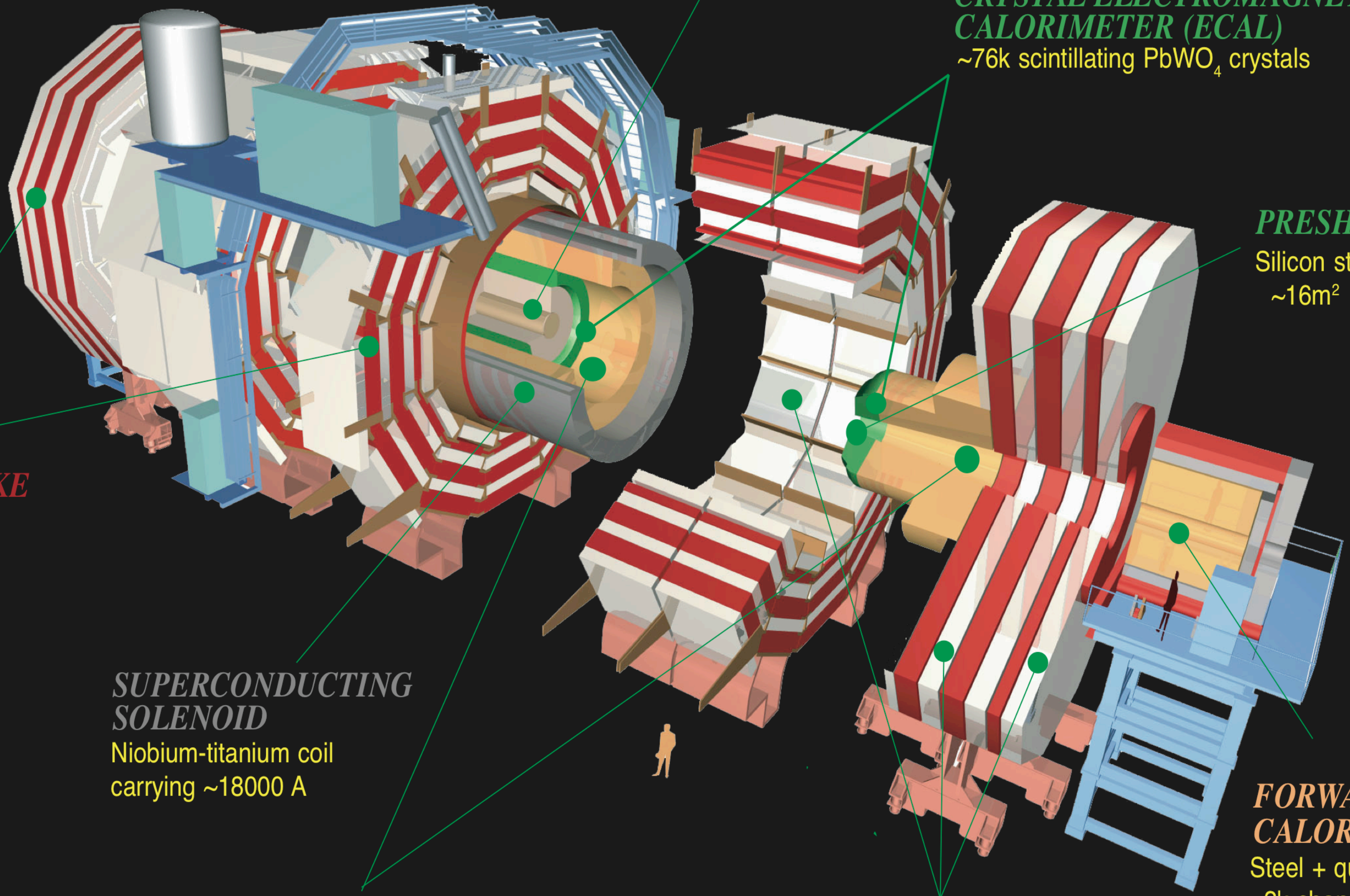
ATLAS experiment



ATLAS experiment

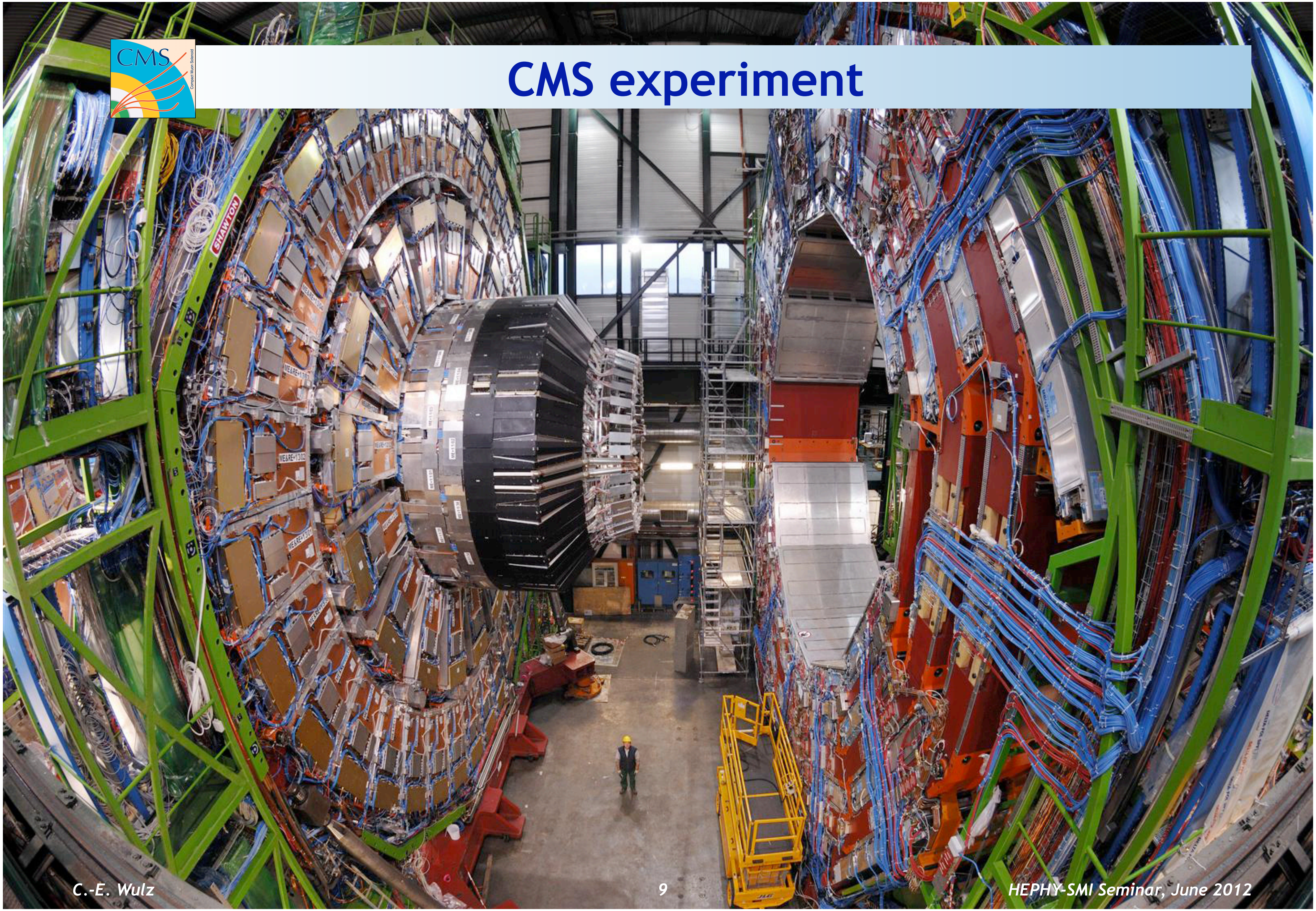


CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

CMS experiment



Physics outline

Cross-sections

- elastic, inelastic and total cross-sections

Standard Model physics

- particle production (soft physics, resonances, correlations)
- QCD and top physics
- electroweak physics (W, Z)
- Higgs boson search

Beyond the Standard Model physics

- fourth generation quarks
- leptoquarks, compositeness
- Supersymmetry, long-lived particles
- extra dimensions and heavy resonance states

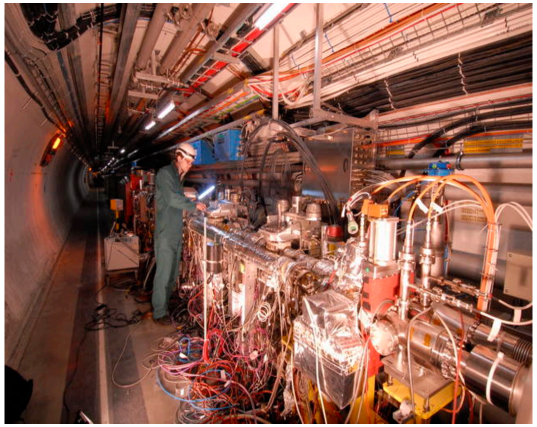
Remarks

Only selected results are presented. Heavy-ion physics is not covered in this talk.
More details:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

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

Cross-sections

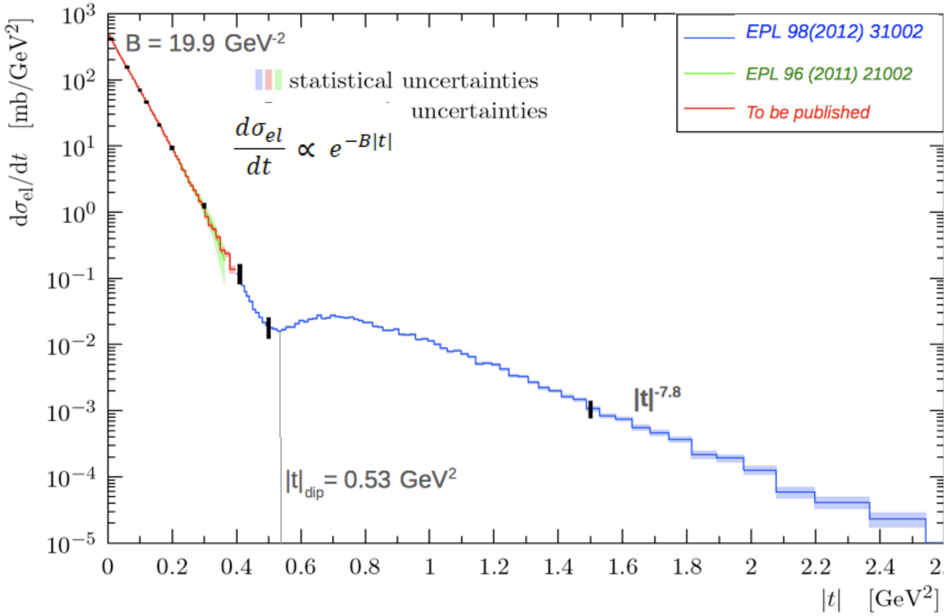


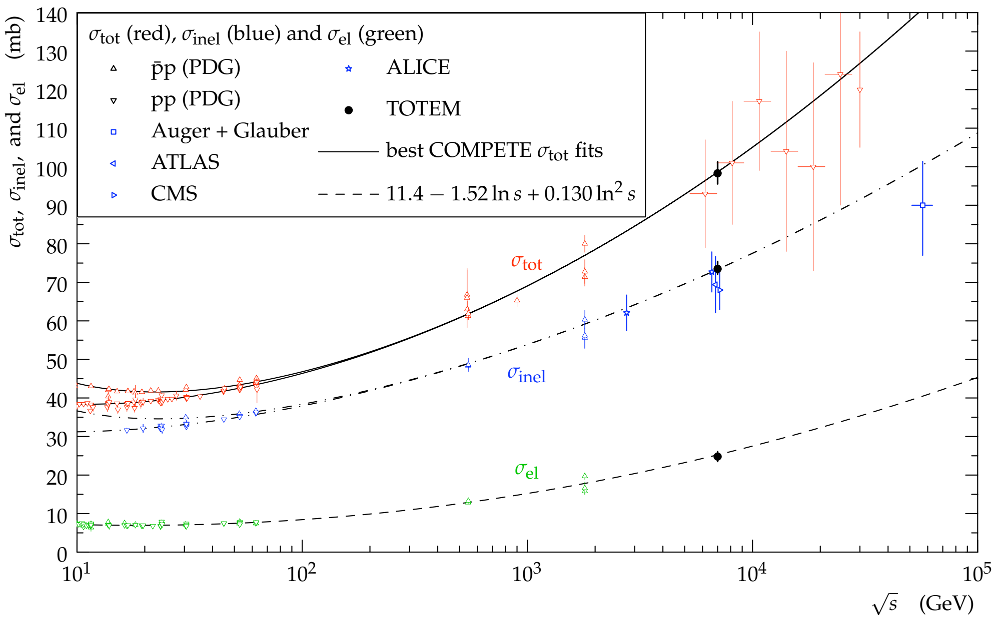
Elastic cross-section

measured by TOTEM (detectors up to ±220m from CMS centre)
as function of 4-momentum transfer squared |t|

Inelastic and total cross-sections

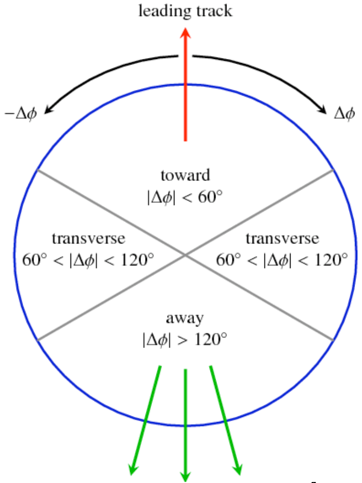
measured by particle and astrophysics experiments





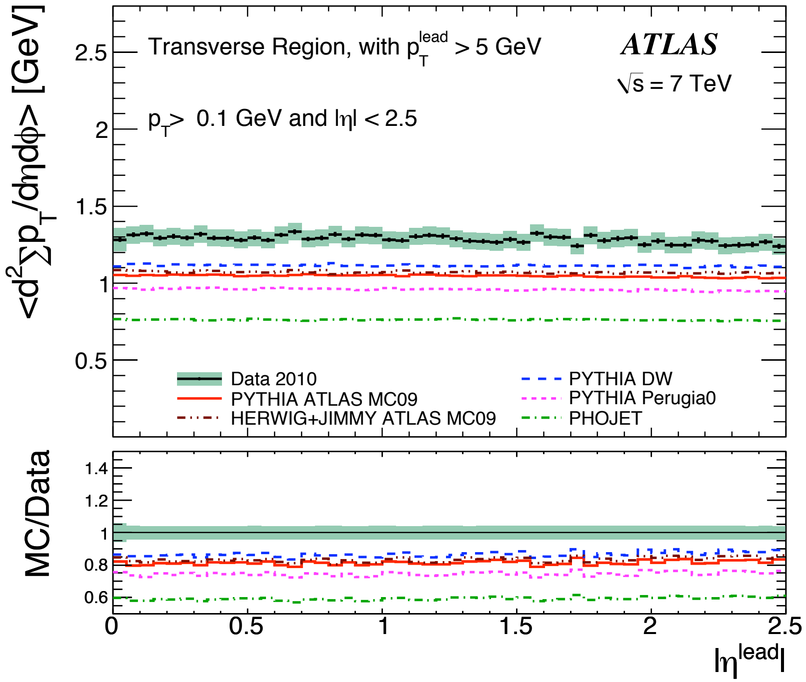
Underlying event characteristics

Study charged particle multiplicity, p_T density, $<p_T>$ in the transverse regions, which are most sensitive to the underlying event -> tune Monte Carlo models.

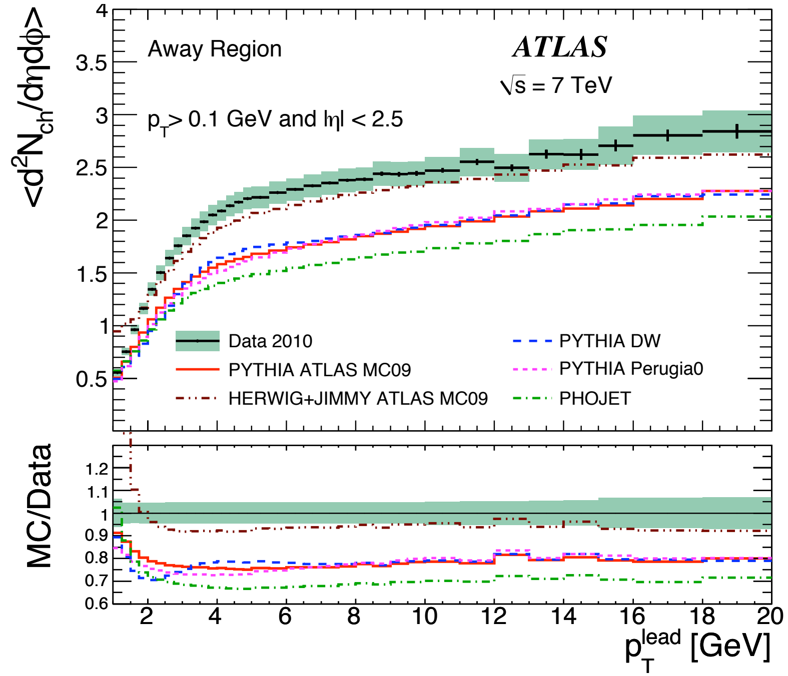


Data show higher underlying event activity than Monte Carlo data!

Scalar Σp_T density



Charged particle density



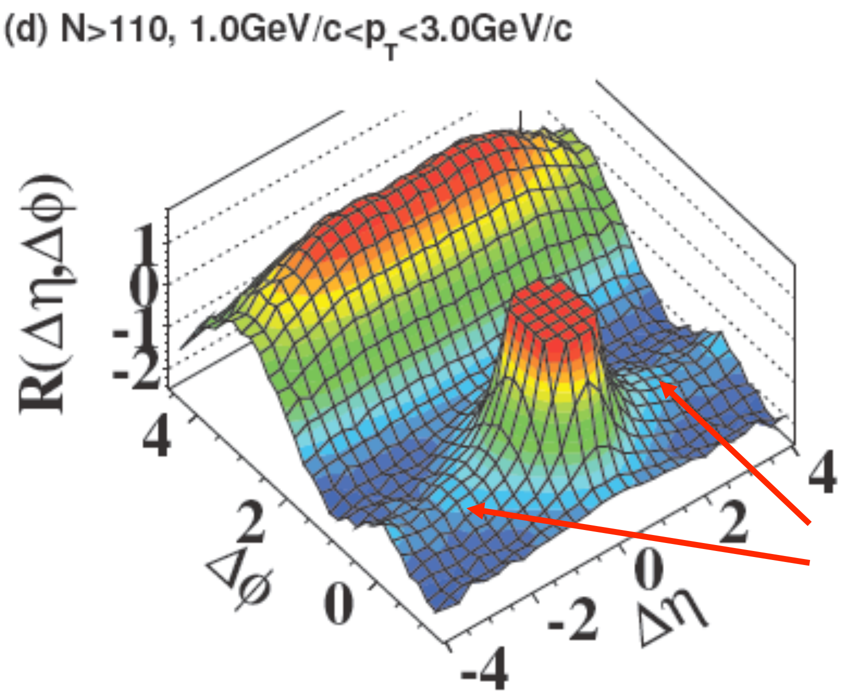
hep-ex 1012.0791, PRD 83 (2011) 112001

Near-side long-range correlations

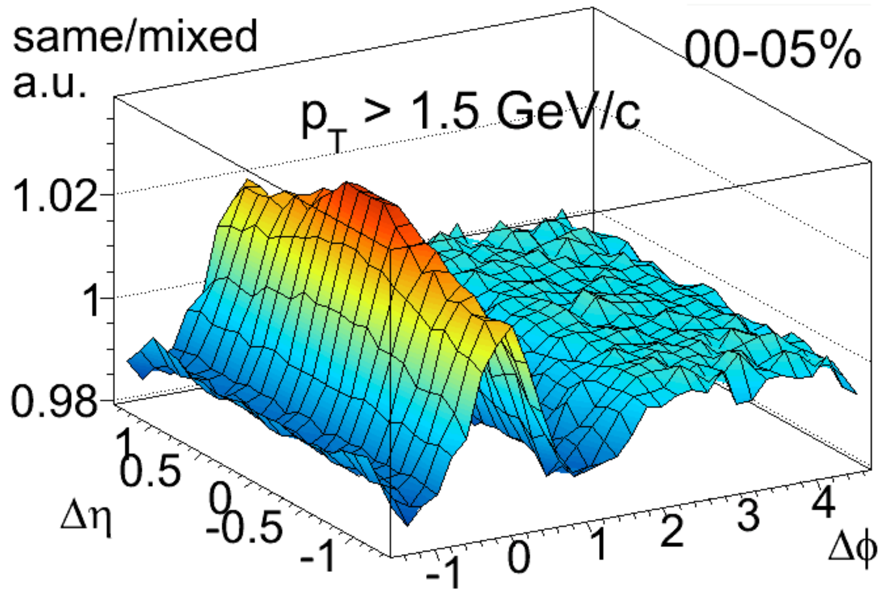
hep-ex 1009.4122, JHEP 09 (2010) 091

First surprise in LHC data!

CMS pp 7 TeV

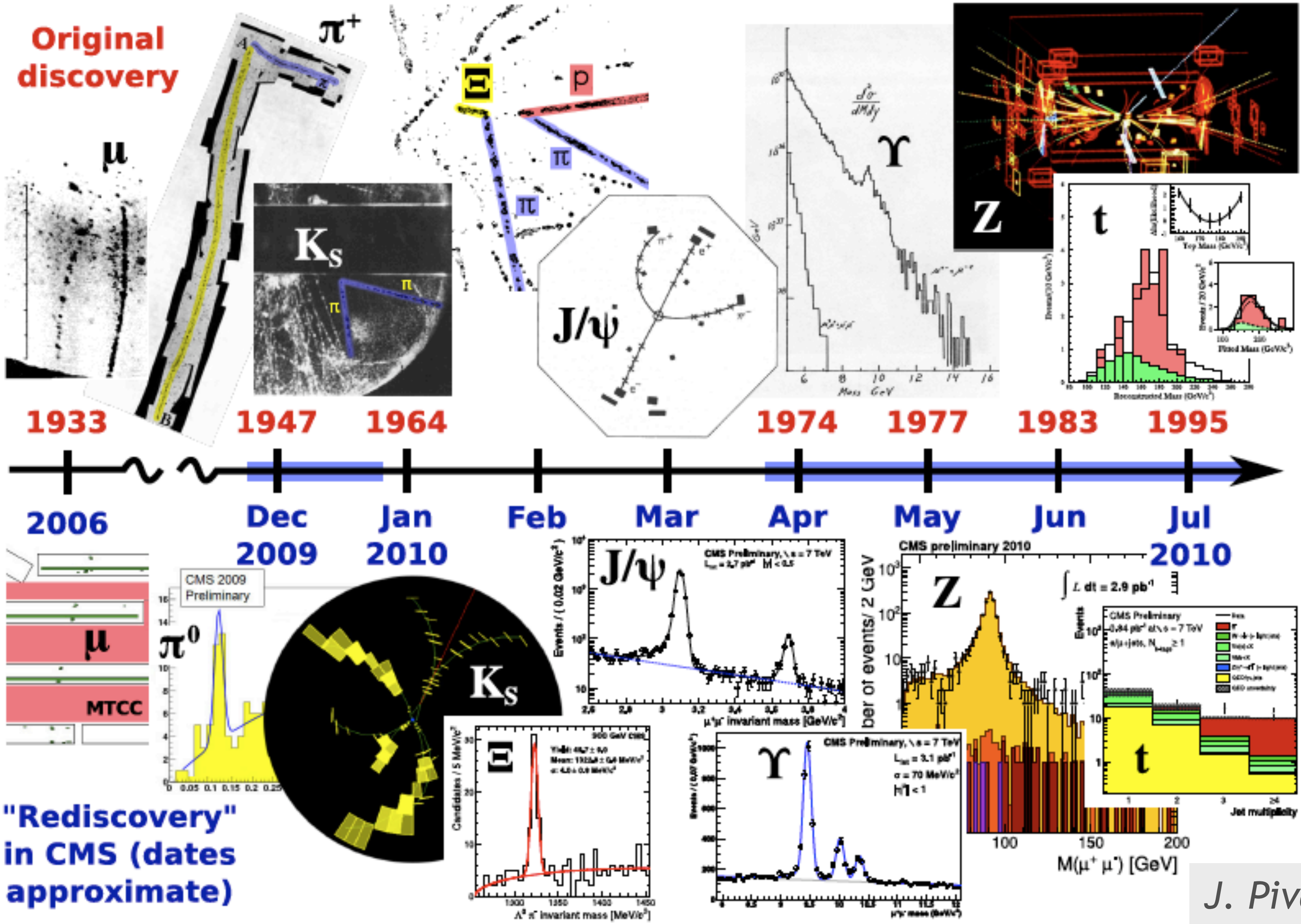


ALICE 2.76 TeV/nn
Central Pb-Pb collisions



Pronounced structure (ridge) in high-multiplicity events for $2.0 < |\Delta\eta| < 4.8$ and $\Delta\phi \approx 0$

Rediscovery of the Standard Model



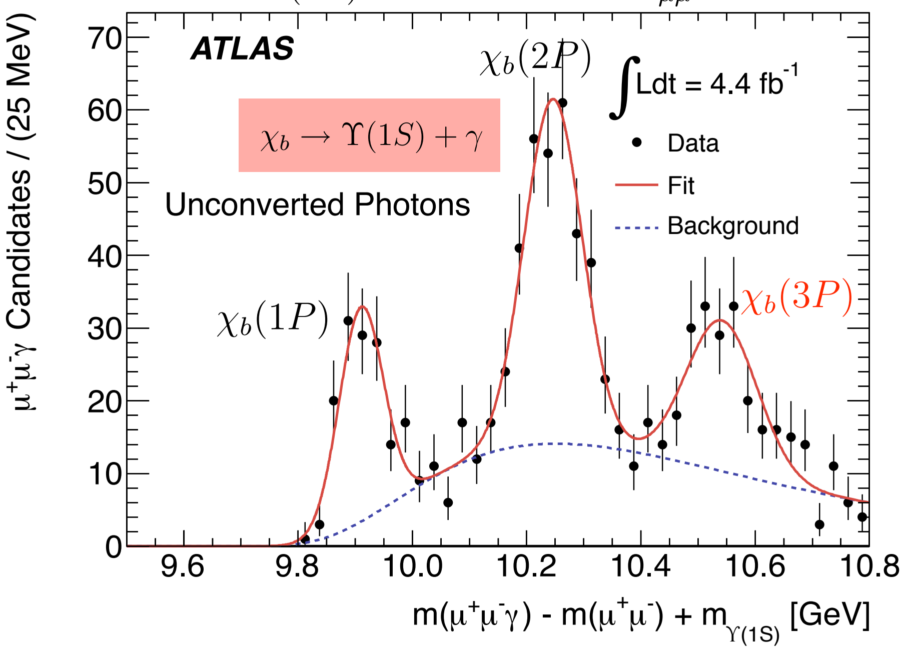
J. Pivarski

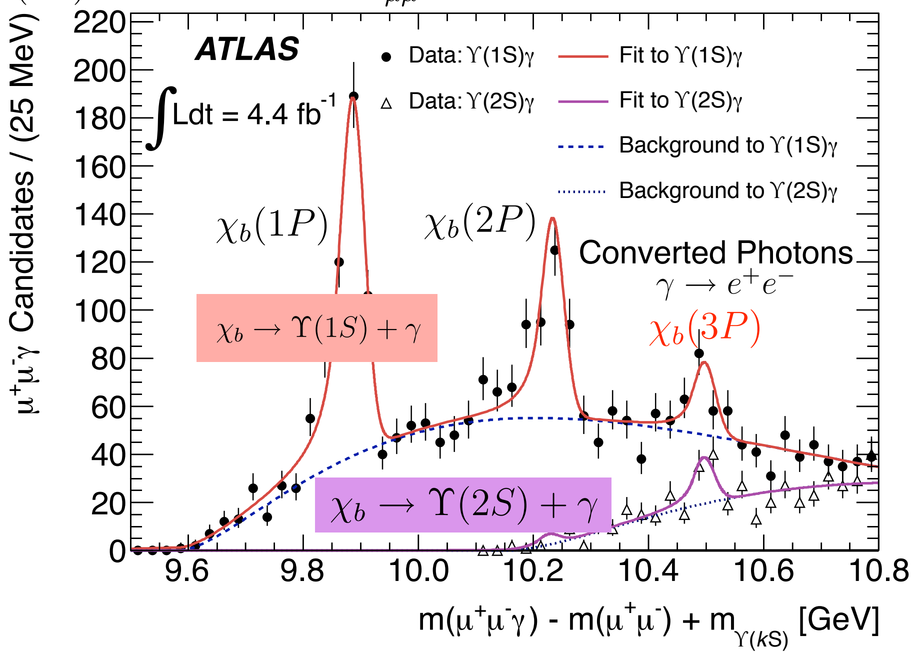
χ_b(3P)

Bound state of b$\bar{\text{b}}$, a QCD analogue of the hydrogen atom.
Transitions are observed through the emission of a photon.

$$\chi_b(3P) \rightarrow \Upsilon(1S, 2S) + \gamma, \qquad \Upsilon \rightarrow \mu^+\mu^-$$

$\Upsilon(1S):\ 9.25\ \text{GeV} < m_{\mu\mu} < 9.65\ \text{GeV}$ $\Upsilon(2S):\ 9.80\ \text{GeV} < m_{\mu\mu} < 10.10\ \text{GeV}$



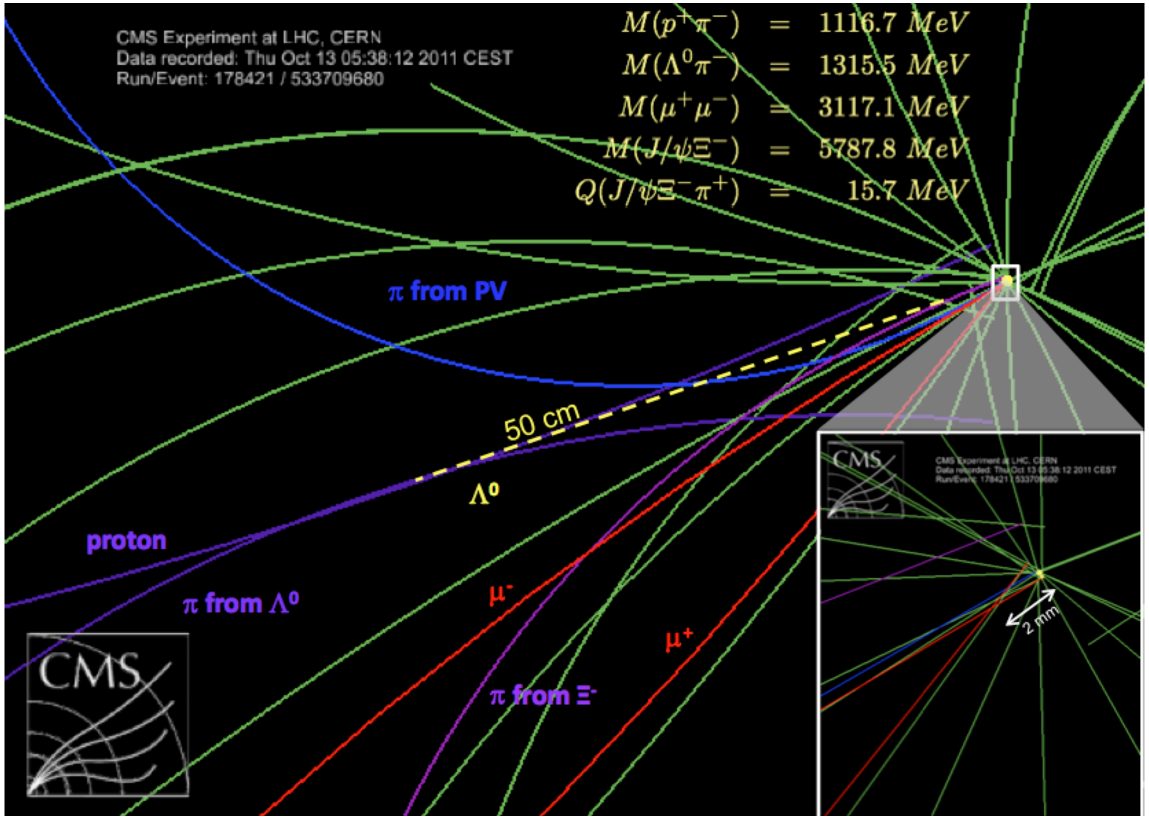


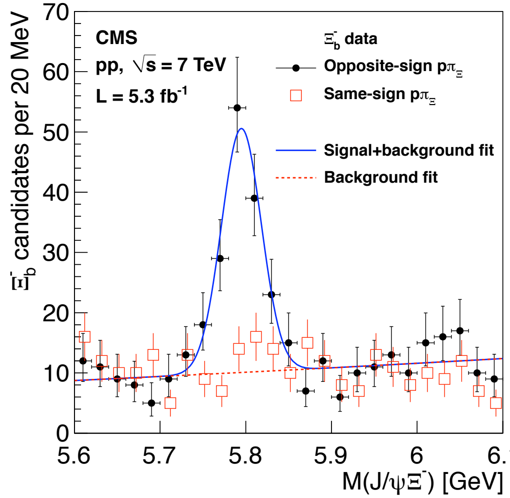
Mass slightly larger than predicted: 10.539 ± 0.004 (stat.) ± 0.008 (syst.) GeV

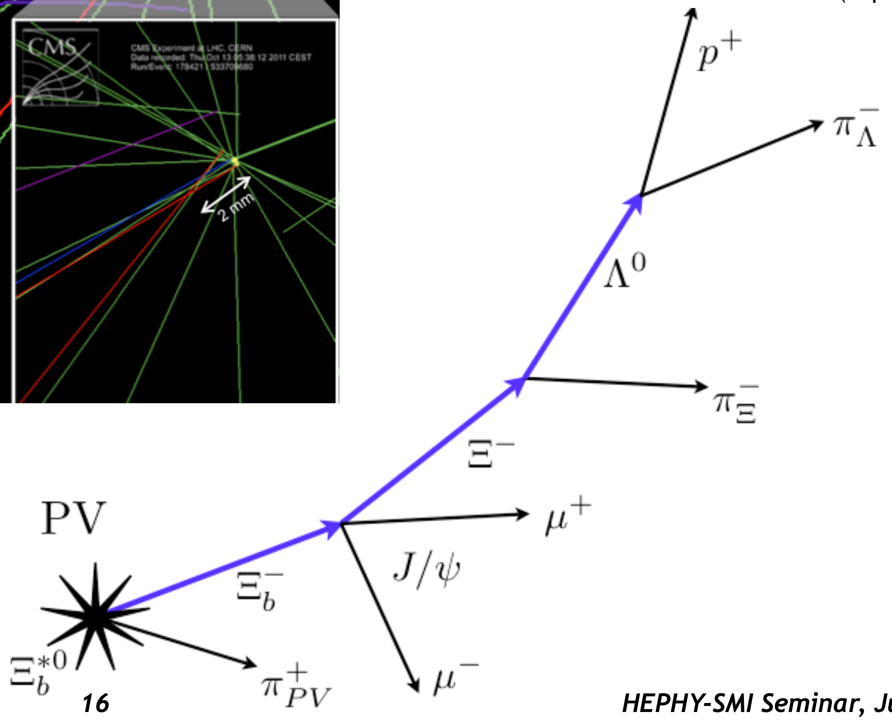
hep-ex 1112.5154, PRL 108 (2012) 152001

Ξ_b^{*0}

Excited b baryon



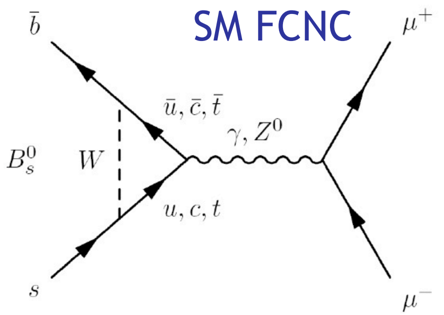


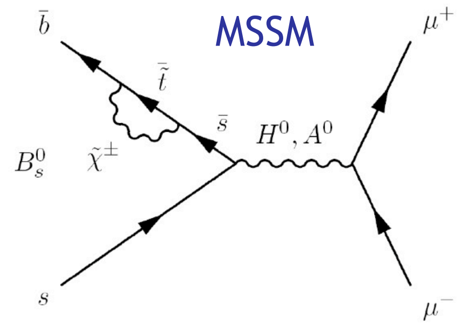


hep-ex 1204.5955
submitted to PRL

ATLAS/CMS/LHCb combination for BR($B_s \to \mu\mu$)

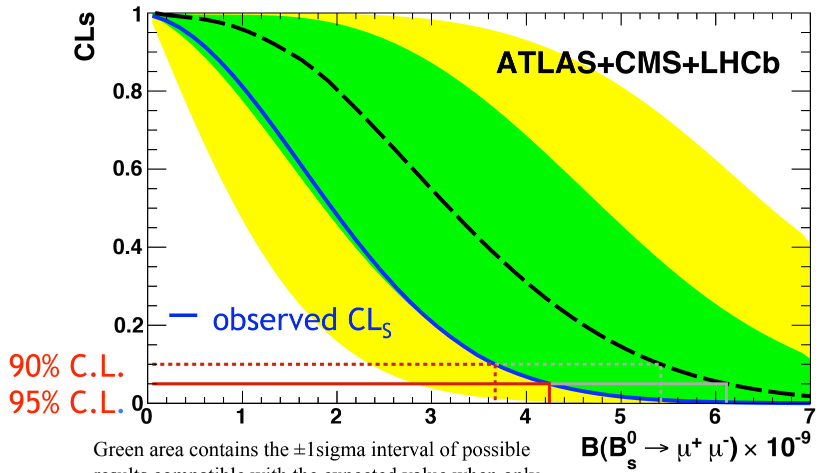
Standard Model value: $BR\,(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$





CDF value: *hep-ex 1107.2304, PRL 107 (2011) 191801*

$$BR\,(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$$
$$BR\,(B_s^0 \to \mu^+\mu^-) < 4.3 \times 10^{-8} \text{ at } 95\%\text{C.L.}$$



Green area contains the ±1sigma interval of possible results compatible with the expected value when only (background+SM is observed.

ATLAS/CMS/LHCb combined value:

$$BR\,(B_s^0 \to \mu^+\mu^-) < 4.2 \times 10^{-9} \text{ at } 95\%\text{C.L.}$$
$$BR\,(B_s^0 \to \mu^+\mu^-) < 3.7 \times 10^{-9} \text{ at } 90\%\text{C.L.}$$

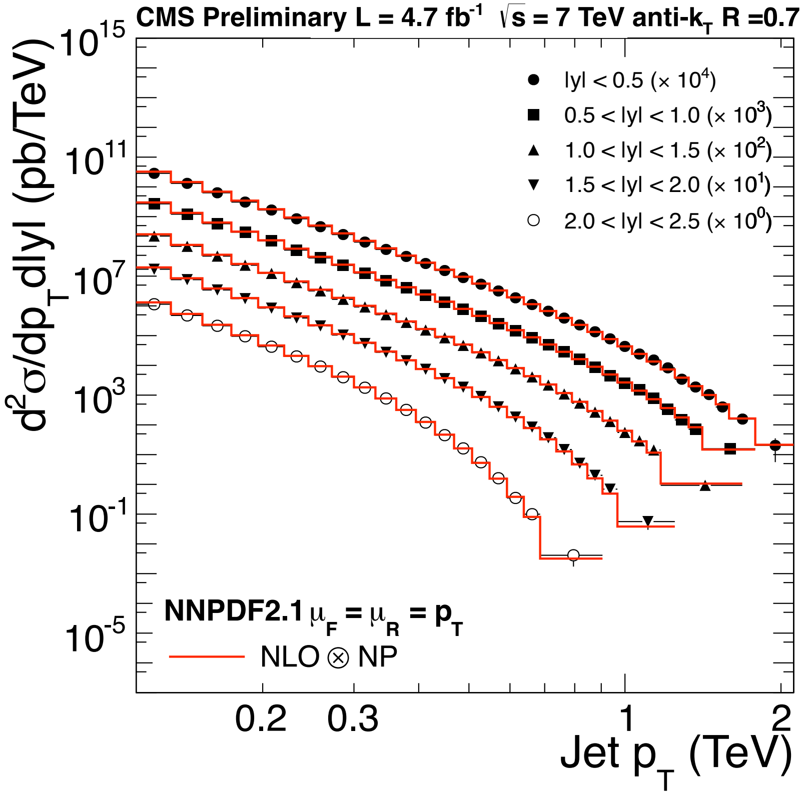
The excess over background is at the level of 2σ. Compatibility with the SM is within 1σ. But there is still room for new physics!

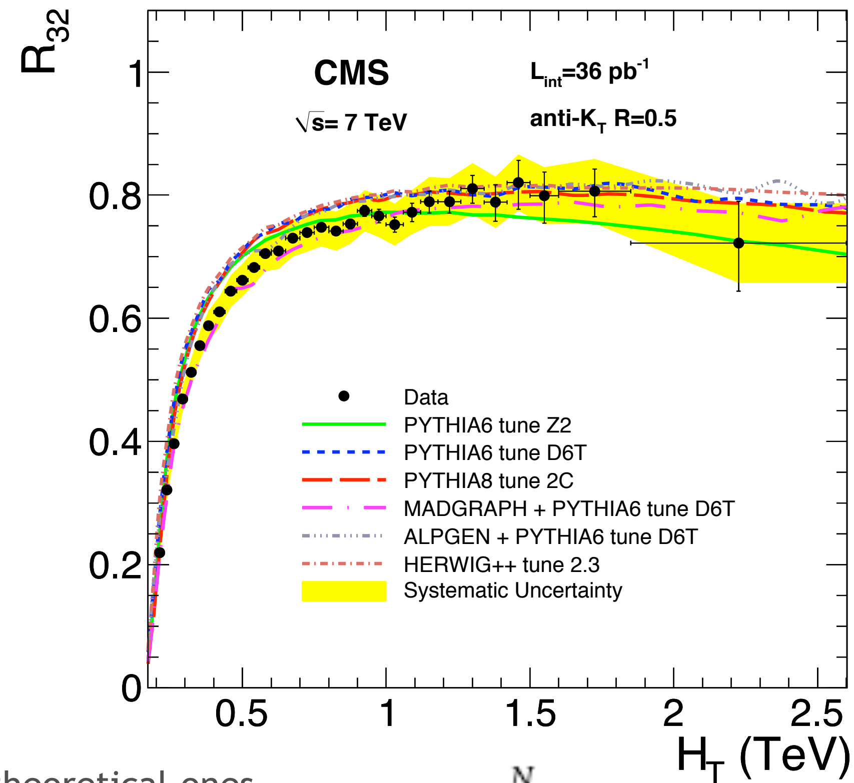
ATLAS CONF-2012-061
CMS-PAS-BPH-12-009
LHCb-CONF-2012-017

Inclusive jet cross-sections, 3-jet/2-jet ratio R_{32}

CMS-PAS-QCD-11-004

hep-ex 1106.0647, PLB 702 (2011) 336





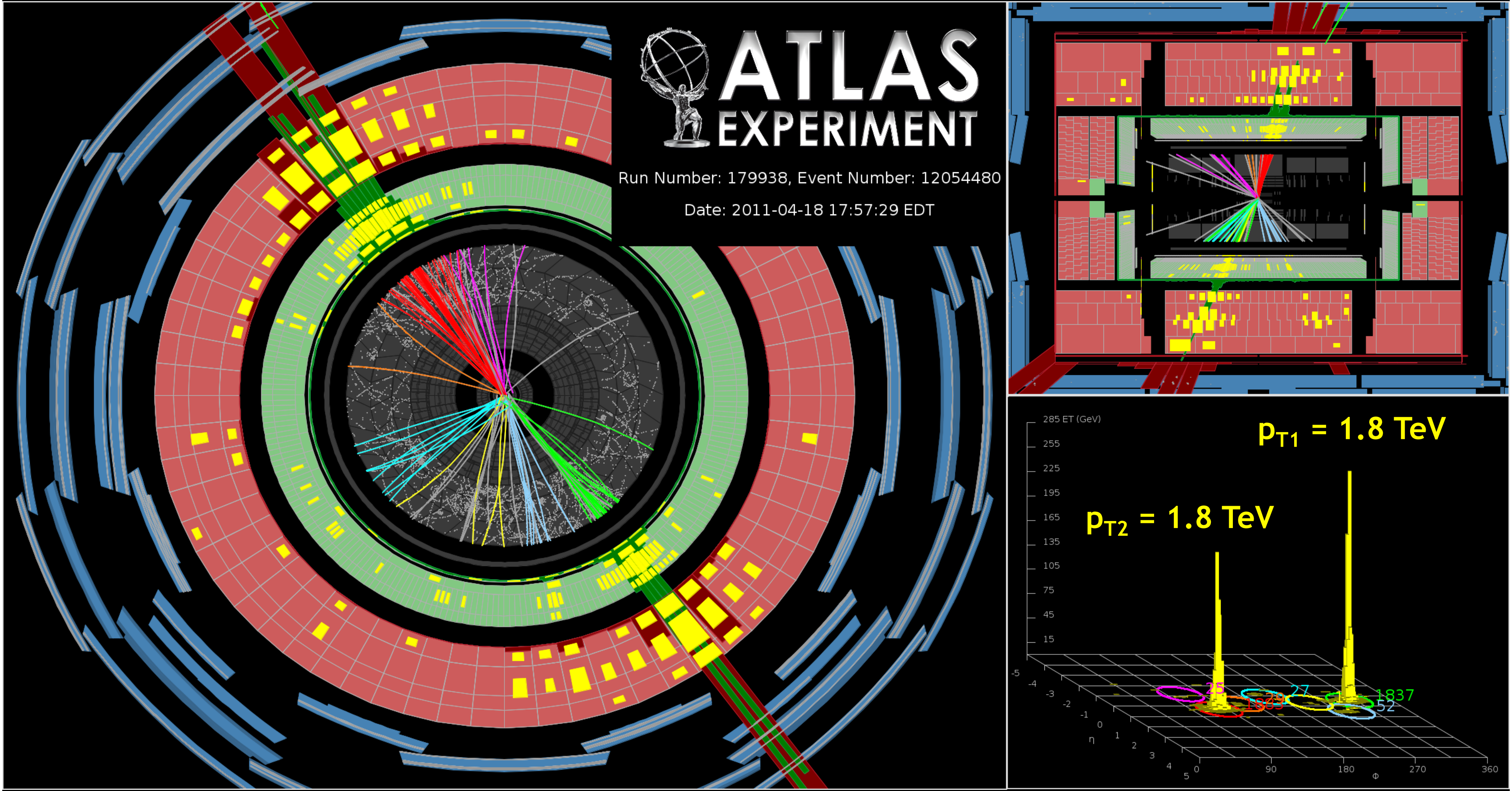
Experimental uncertainties are comparable to theoretical ones.
NP (non-pertubative): correction for multiparton interactions.

$$H_T = \sum_{i=1}^{N} p_{T_i}$$

Agreement with NLO pQCD cross-section predictions (with non-perturbative corrections) is good in general.

High-mass dijet events

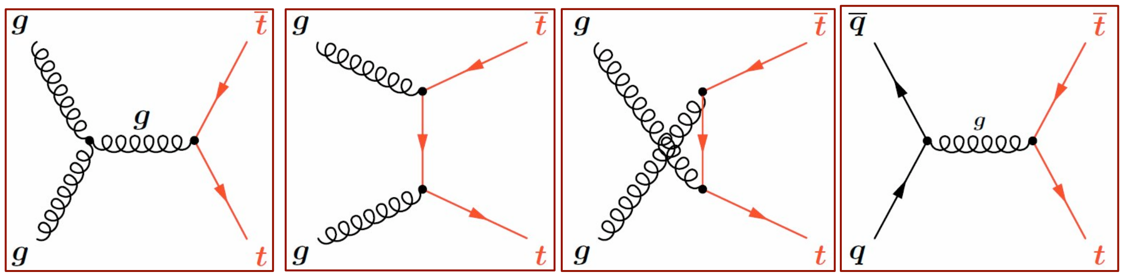
m_{JJ} = 4 TeV



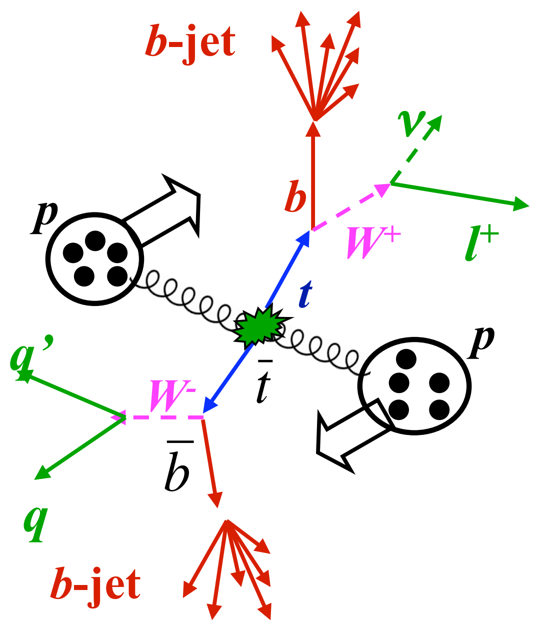
Top

"When top is measured, the experiment is ready for discovery phase"
P. Jenni, 2009

$t\bar{t}$ production at LHC stems from 87% gluon fusion, 13% $q\bar{q}$ annihilation
- Interesting in itself since t decays before hadronizing
- Decay products of new particles
- Background to new particle searches

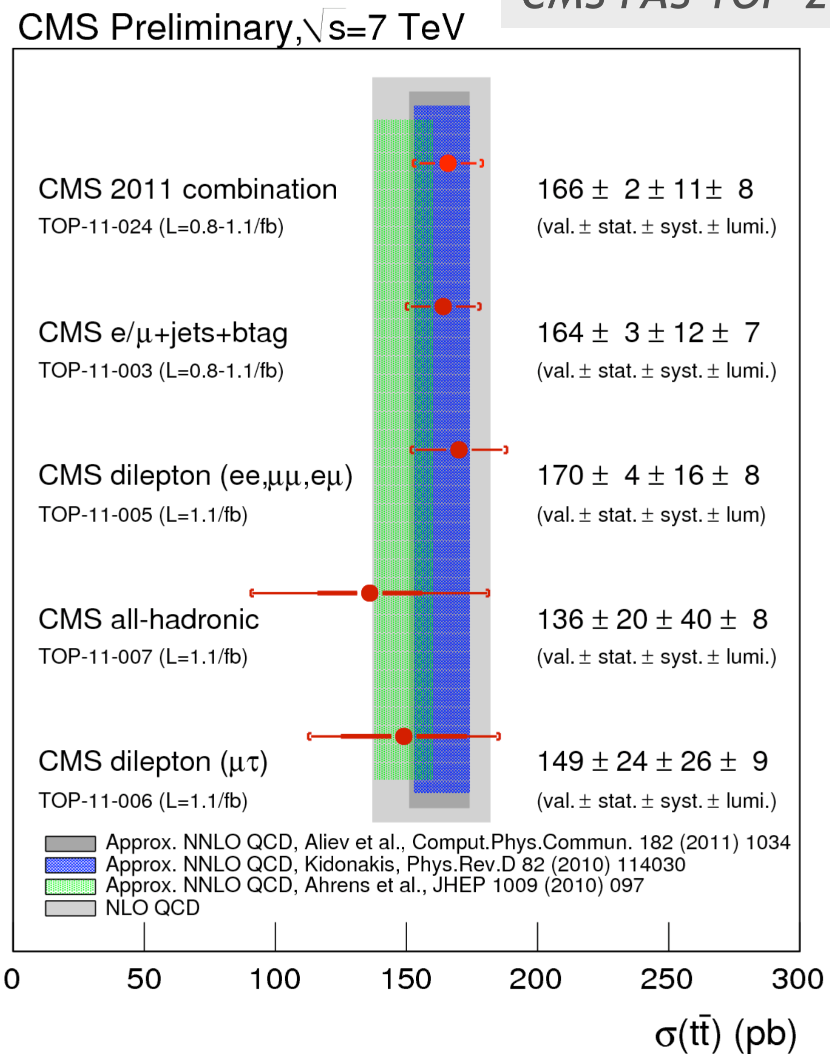


Top decays weakly as t -> Wb almost exclusively.
Event classes according to decay of W:
- All-hadronic
- lepton + jets
- dilepton (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)



$t\bar{t}$ cross section

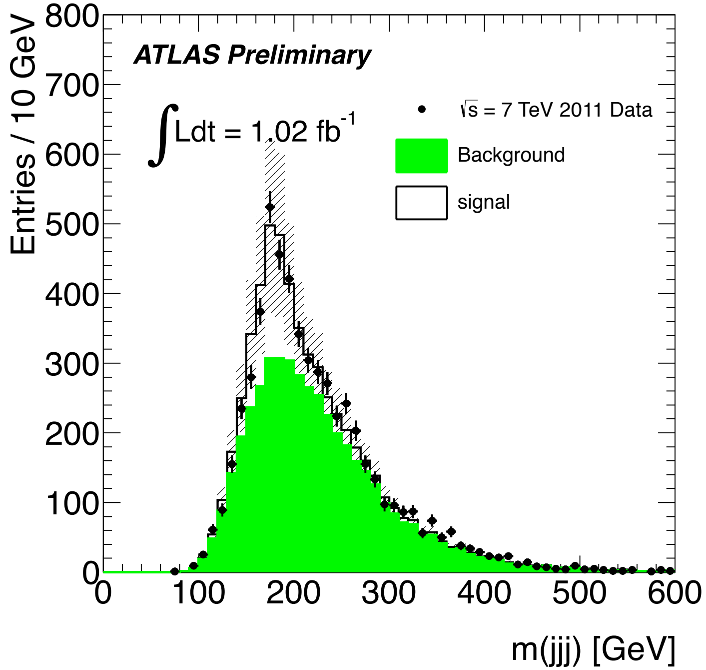
CMS PAS TOP-2011-024



Consistent with NLO SM predictions

ATLAS CONF-2011-140

All-hadronic channels:



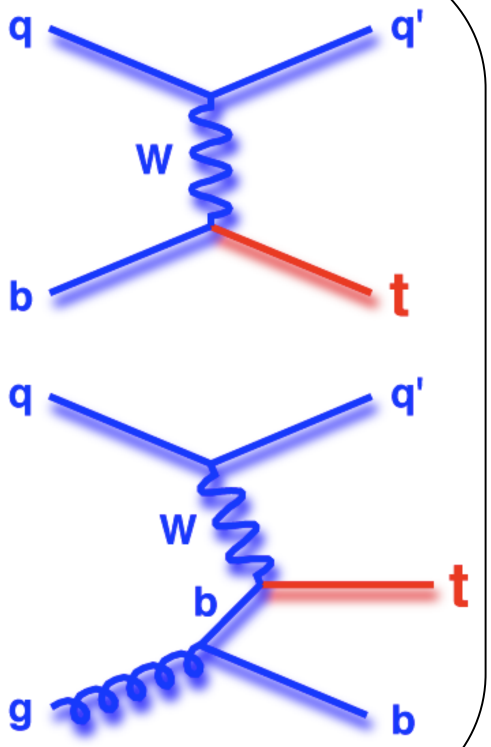
Measurements of charge, charge asymmetry and spin correlations are ongoing.

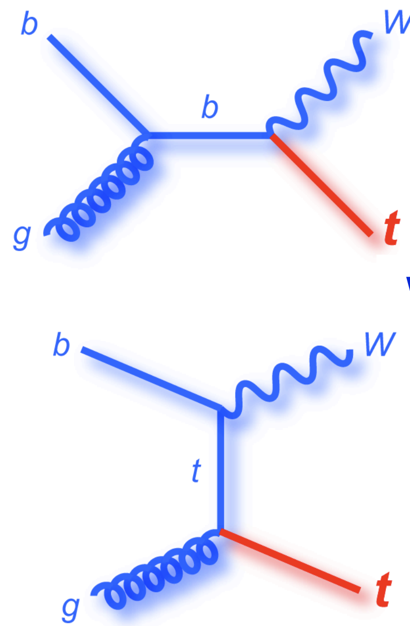
Single top

Electroweak production of single tops (announced 2009 at Tevatron, 2011 at LHC) occurs with smaller cross-sections compared to production of top pairs. Analysis is difficult, but cut-based procedures become viable in addition to the initially used multivariate techniques.

t-channel

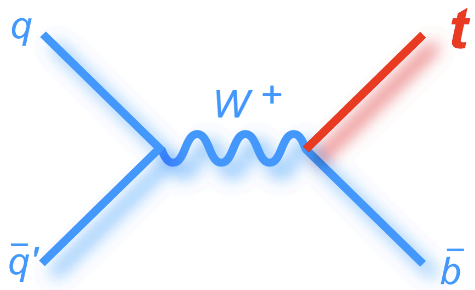
Dominant at Tevatron and LHC





Wt-channel

Small at Tevatron, significant at LHC



s-channel
Drell-Yan

Small at Tevatron and LHC

Single top results

t-channel — *ATLAS CONF-2011-101*

$\sigma_t = (90 + 32 - 22)$ pb

LHC prediction: $\sigma_t = (64.6 + 3.3 - 2.6)$ pb

Wt-channel — *CMS PAS TOP-2011-022*

$\sigma_{Wt} = (22 + 9 - 7)$ pb

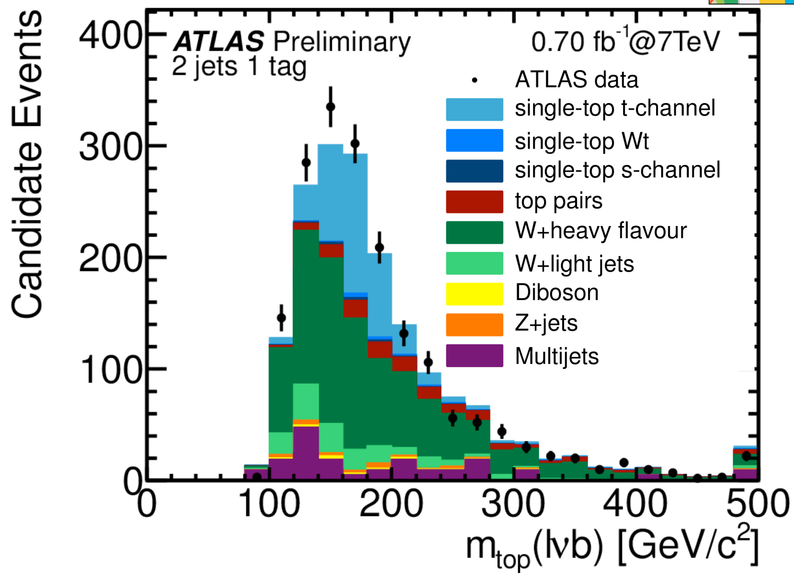
LHC prediction: $\sigma_t = (15.7 \pm 1.4)$ pb

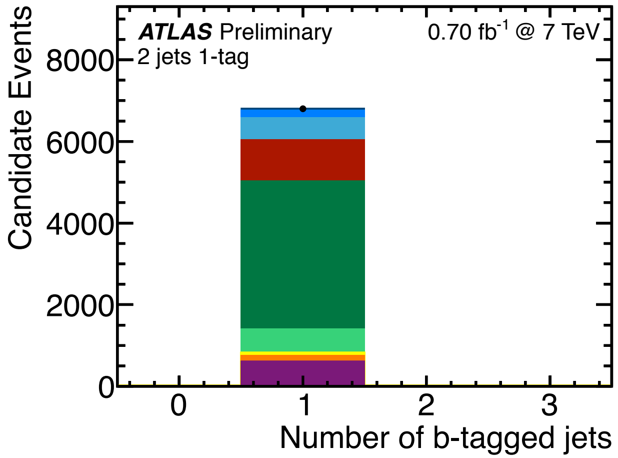
s-channel — *ATLAS CONF-2011-118*

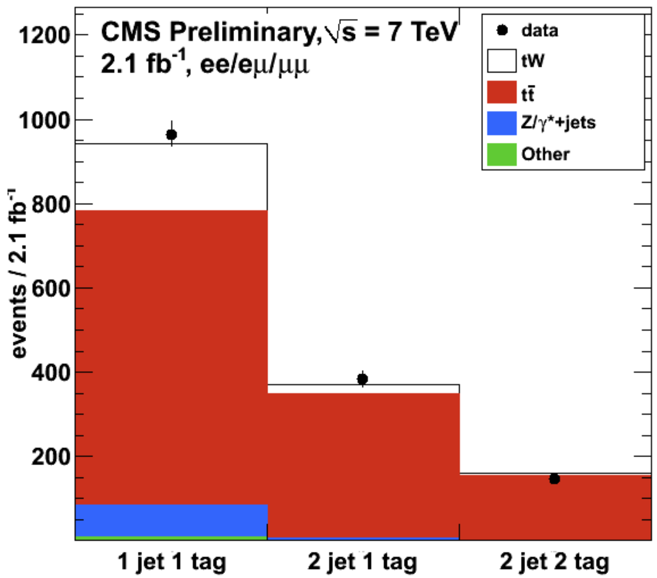
$\sigma_s < 26.5$ pb

LHC prediction:

$\sigma_t = (4.6 \pm 0.3)$ pb

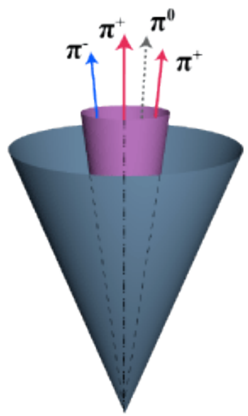




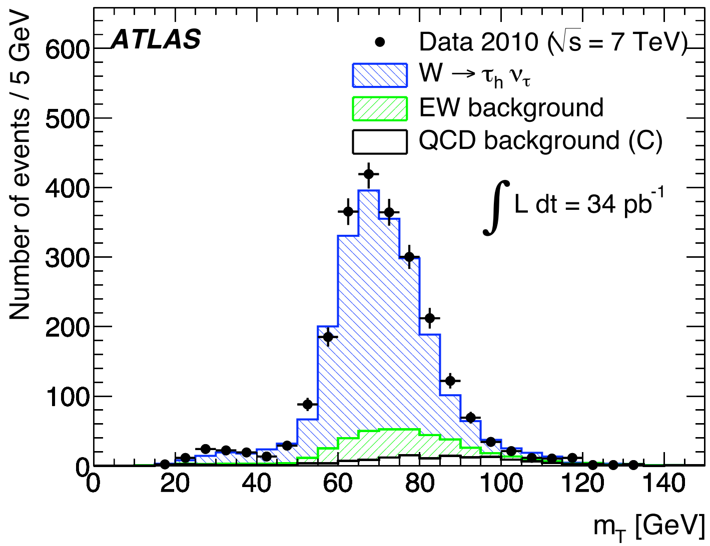


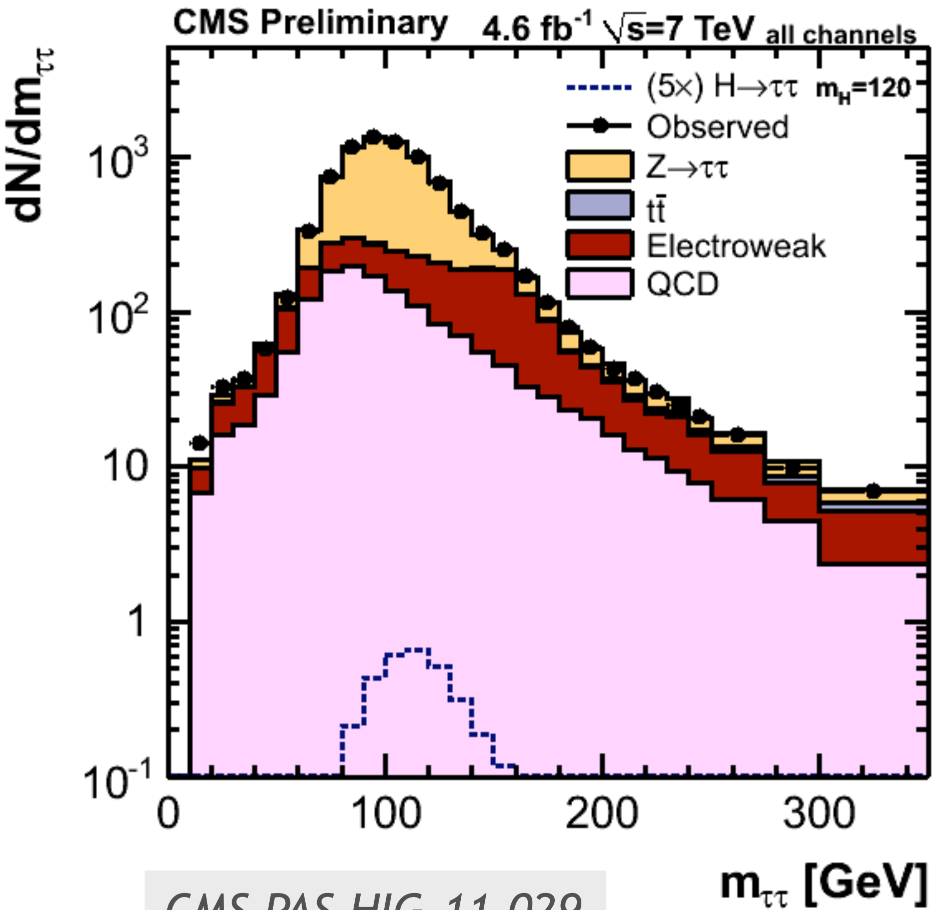
W and Z

Initial studies with electrons and muons, now also with taus.



hep-ex 1108.4101, PLB 706 (2011) 276





CMS PAS HIG-11-029

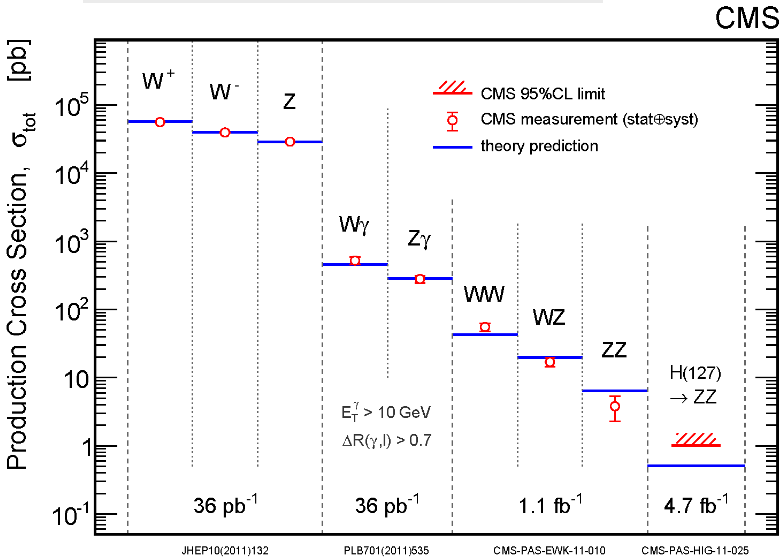
hep-ex 1104.1617, JHEP 08 (2011) 117

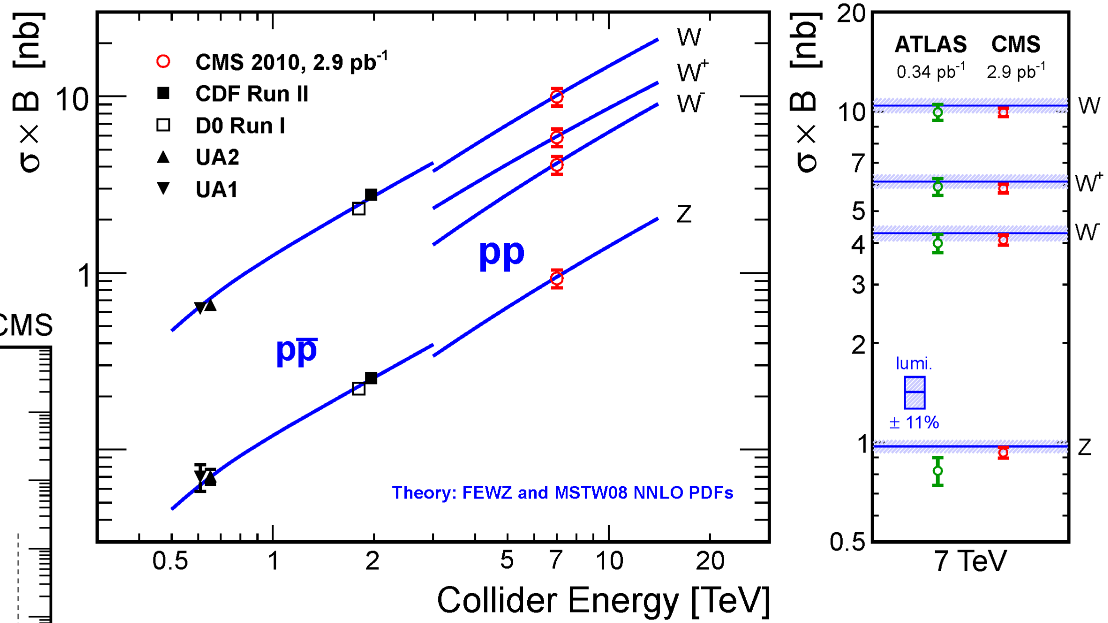
W and Z cross sections

- W and Z (e and μ channels) are the first electroweak processes measured at LHC
- Tests for perturbative QCD and PDF's (W charge asymmetry)
- Detector calibration with Z
- Luminosity measurement
- Background for new physics

hep-ex 1107.4789
JHEP 10 (2011) 132

CMS PAS SMP-12-005



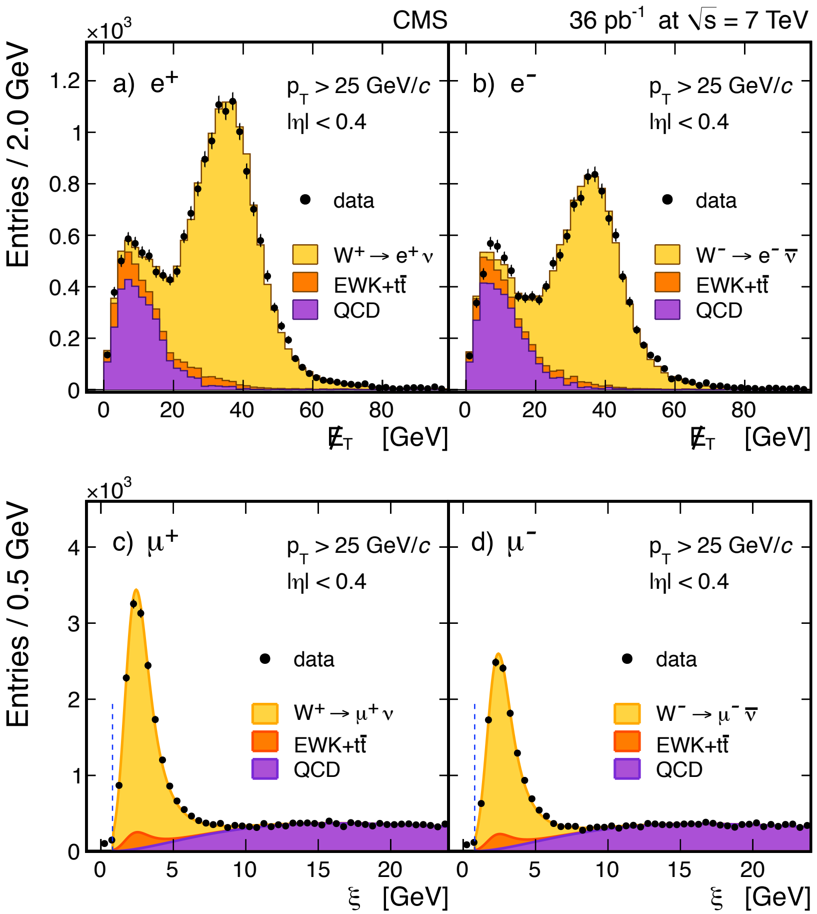


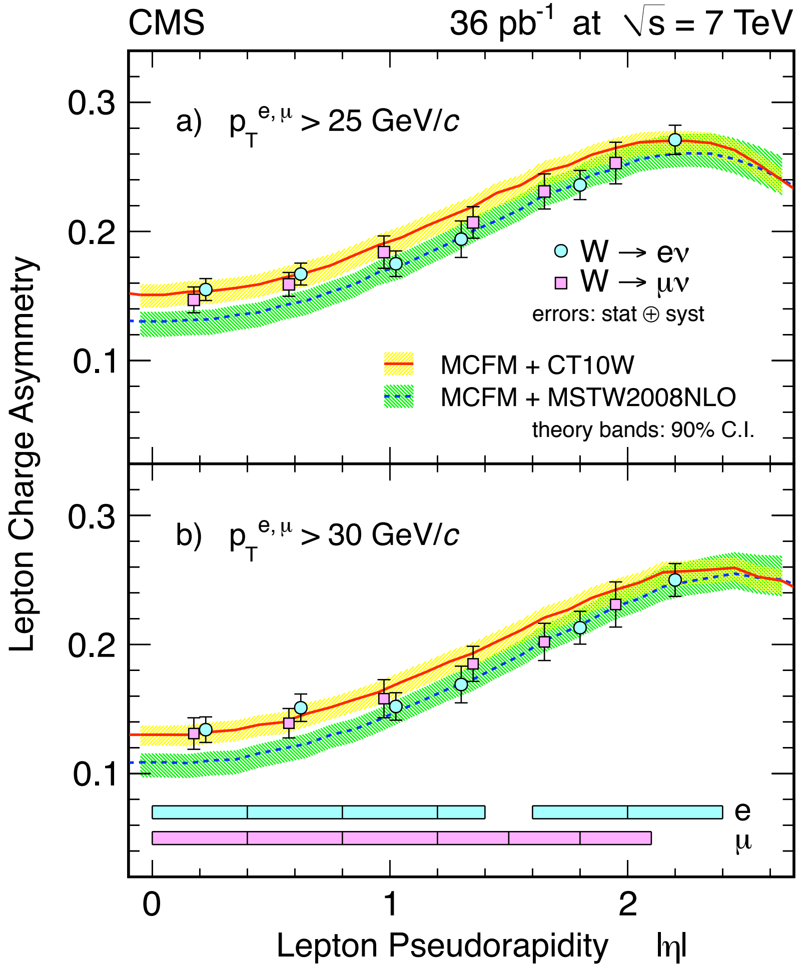
hep-ex 1012.2466, JHEP 01 (2011) 080

W^+/W^- charge asymmetry

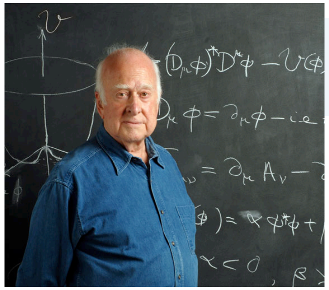
$$A(\eta) = \frac{d\sigma^+/d\eta_\ell - d\sigma^-/d\eta_\ell}{d\sigma^+/d\eta_\ell + d\sigma^-/d\eta_\ell}$$

Asymmetry is sensitive to valence quark PDF's.

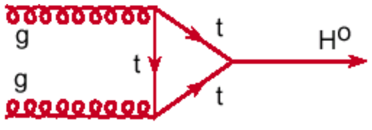




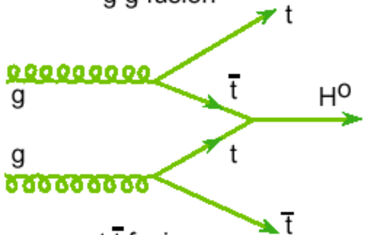
hep-ex 1103.3470, JHEP 04 (2011) 050



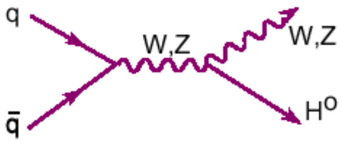
Higgs boson production



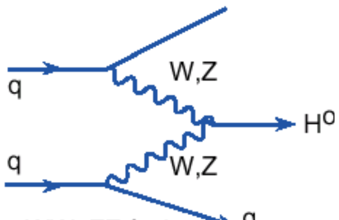
g g fusion



t t̄ fusion



W, Z bremsstrahlung



WW, ZZ fusion

Production modes:

gg → H

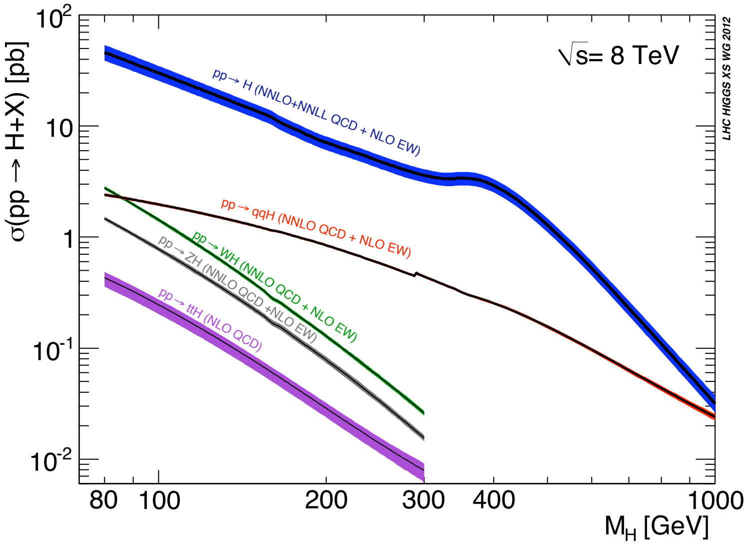
dominant, as at the Tevatron, but σ 10 times larger

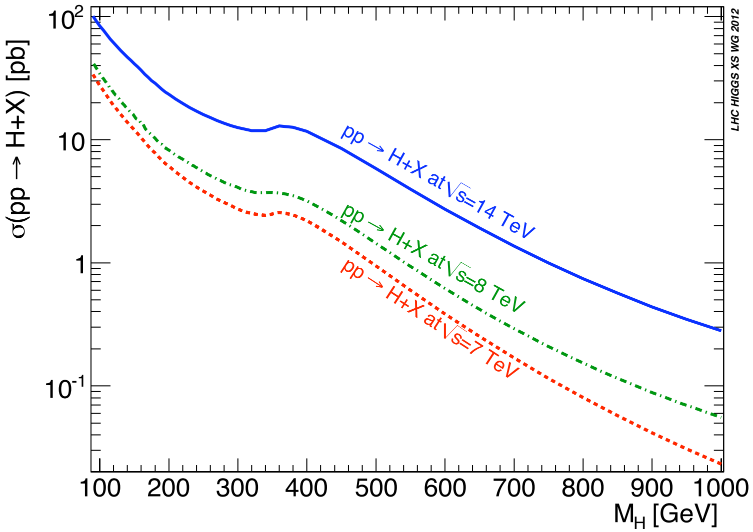
qq → Hqq

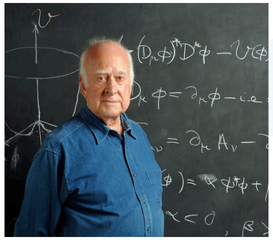
2nd most important mode at the LHC (vector boson fusion)

qq → HW, HZ

2nd most important mode at the Tevatron, but σ about 100 times larger at the LHC

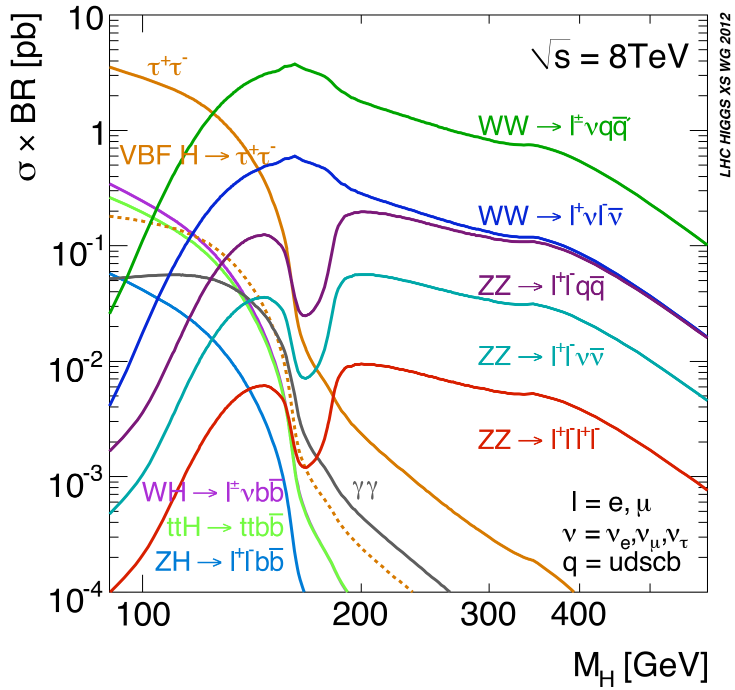






Higgs boson searches

Several search channels can be used, depending on branching fraction and background. The mass range up to about 600 GeV has been studied.



110 GeV < m_H < 150 GeV

H → γγ (BR ≈ 0.001-0.002)

H → bb (in association with W/Z due to QCD background, up to m_H ≈ 130 GeV)

H → ττ (QCD background → VBF production, needs high luminosity)

110 GeV < m_H < 600 GeV

H → ZZ → 4*l*

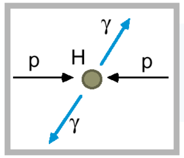
H → ZZ → 2*l*2*ν* (from m_H ≈ 200 GeV)

H → ZZ → 2*l*2*q* (from m_H ≈ 200 GeV)

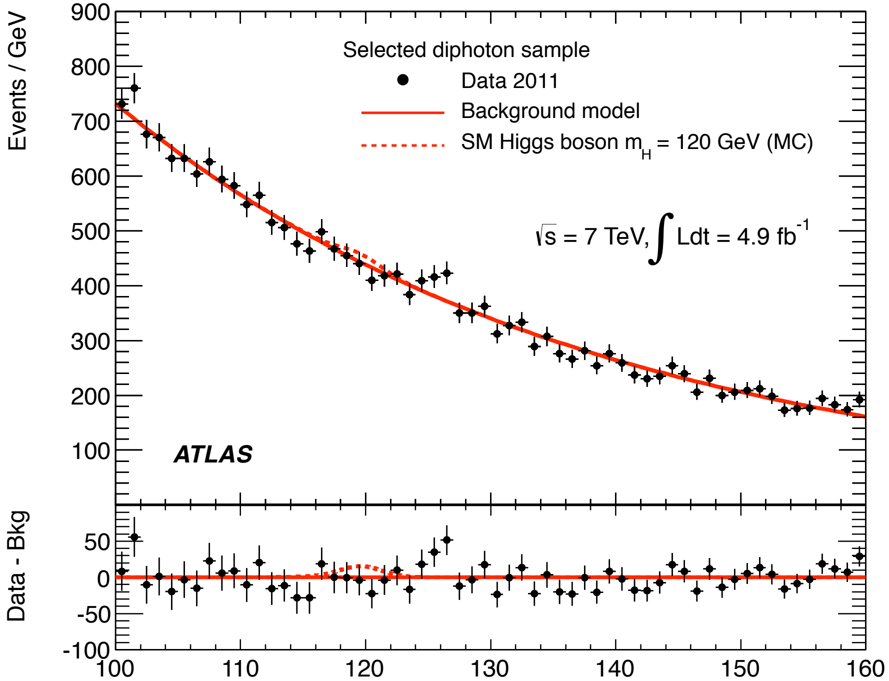
H → WW → 2*l*2*ν*

H → WW → $l\nu q\bar{q}'$ (from m_H ≈ 300 GeV)

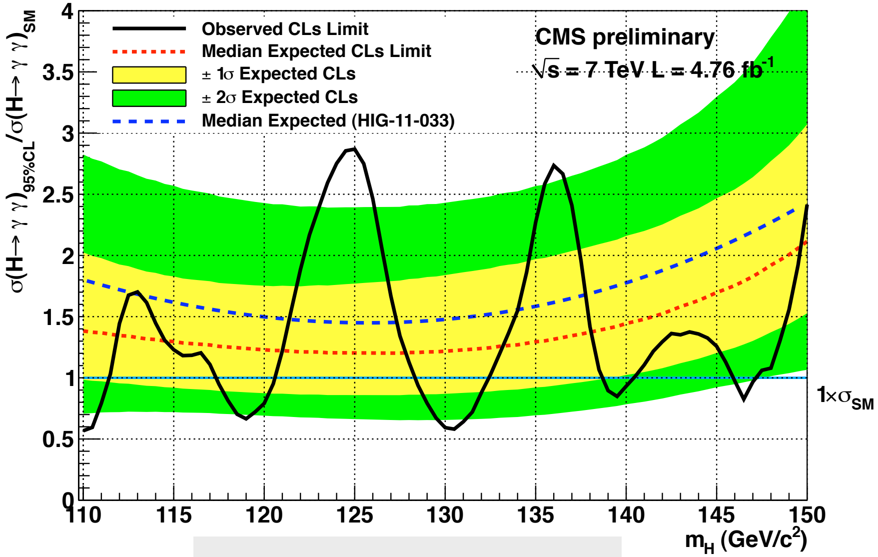
In high resolution channels (σ_{m_H} ≈ 1-2%) one searches for a narrow mass peak (γγ, ZZ → 4*l*), in others one looks for a broad excess (channels with neutrinos and jets).



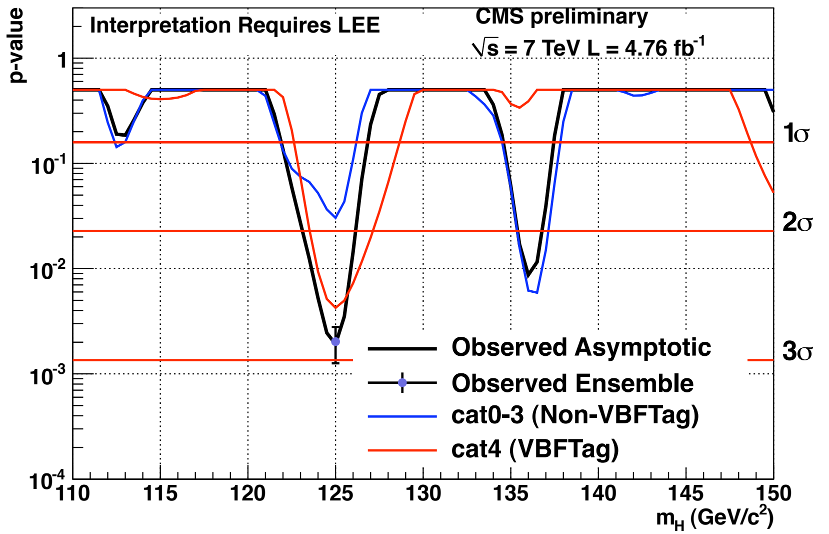
H → γγ



hep-ex 1202.1414, PRL 108 (2012) 111803



CMS-HIG-2012-001



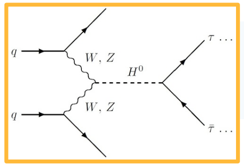
Largest excess: around 125 GeV

CMS significances (ATLAS similar):

Local significance: 2.9 σ

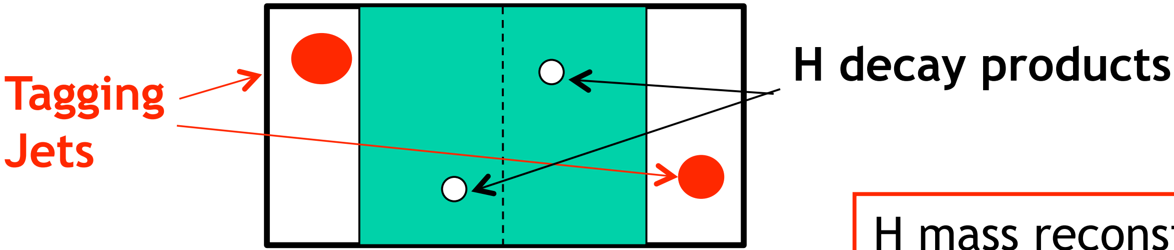
Global significance: 1.6 σ (LEE 100-150 GeV)

CMS has added a multivariate analysis method to the previous cut-based one.



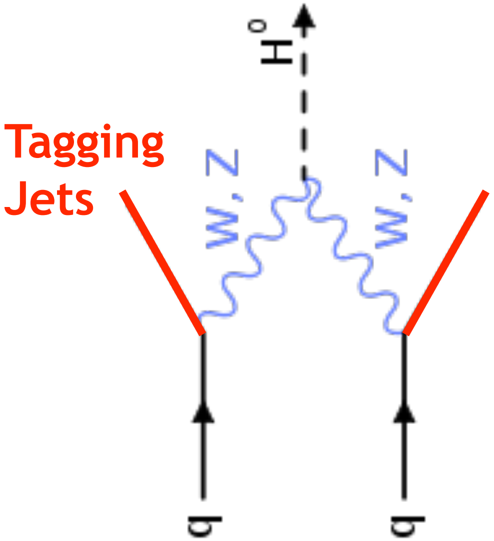
$H \to \tau\tau$

Production by vector boson fusion allows use of the rapidity gap between the "Tagging Jets" with high p_T in forward direction -> jet veto in central region:

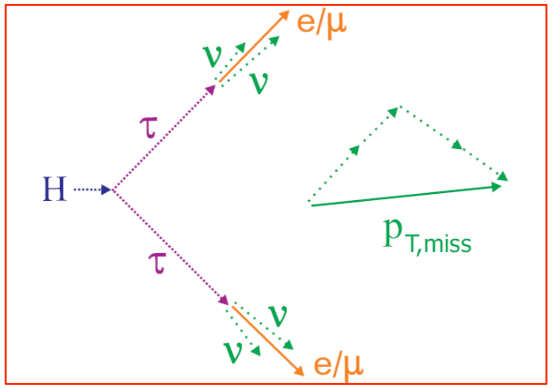


τ identification:

$\tau\tau \to ll, lh, hh$

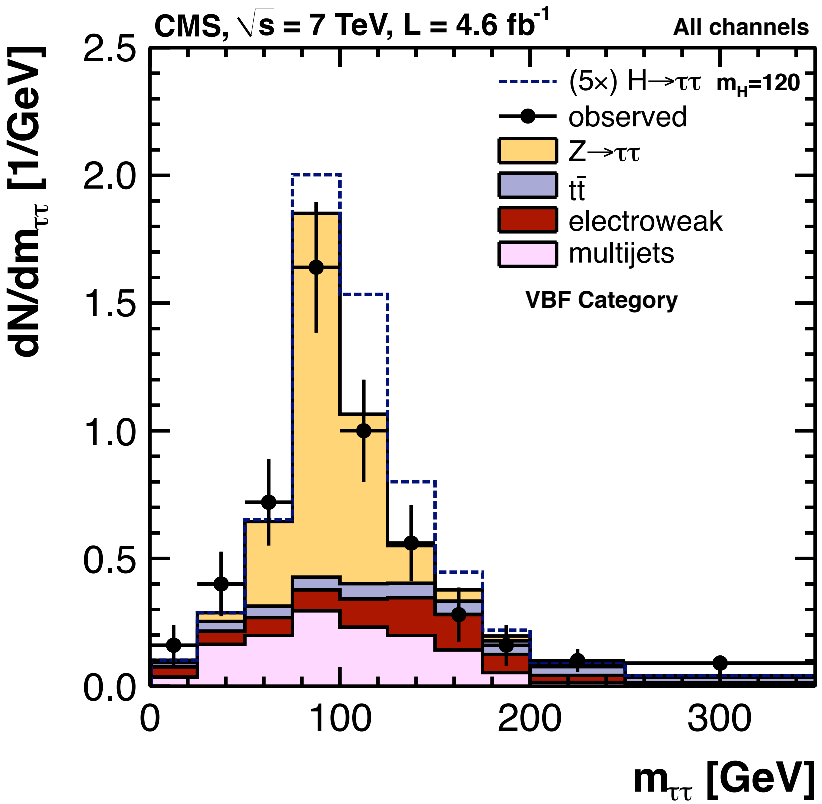


H mass reconstruction:
Make use of collinear approximation of l-ν (high mass results in strong boost along the original flight direction of the τ) and the angle between the two τ's



H → ττ

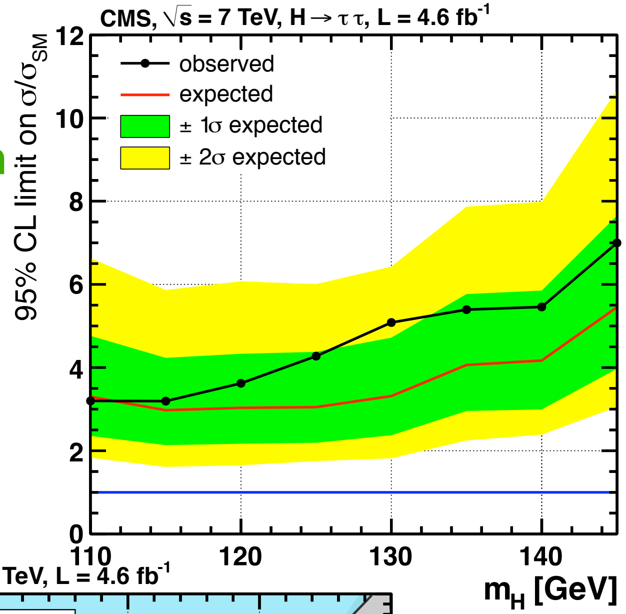
3 independent channels: $e\tau_h$, $\mu\tau_h$, $e\mu$

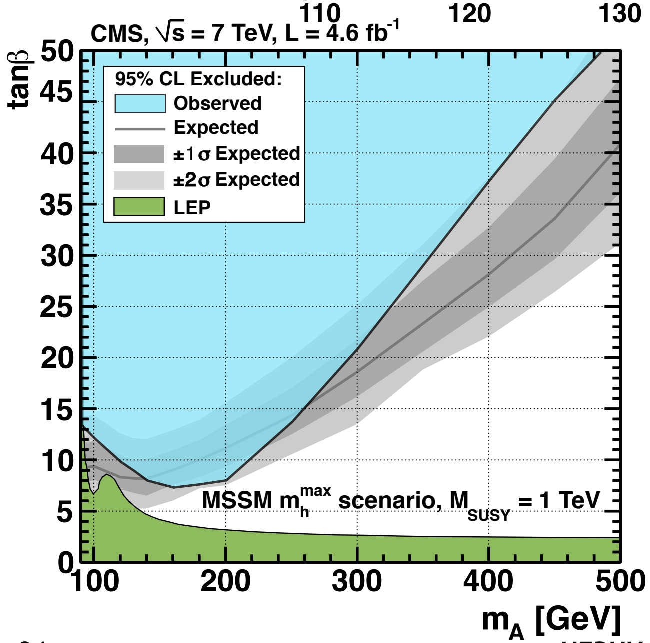


hep-ex 1202.4083, subm. to PLB

No excess seen yet.

SM search





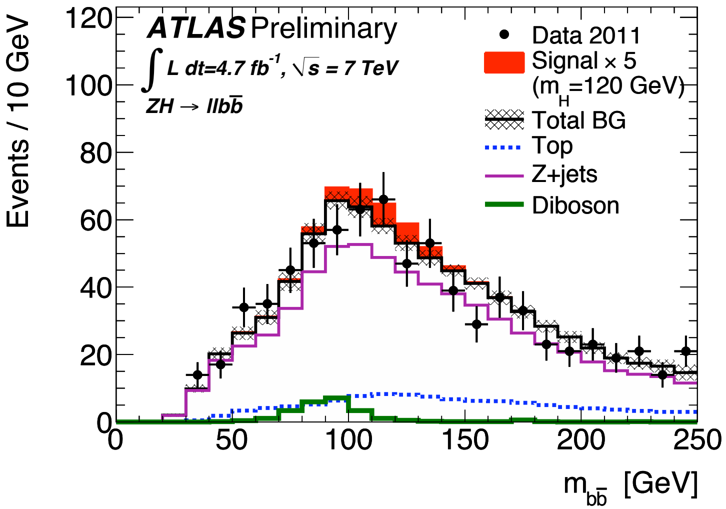
MSSM search

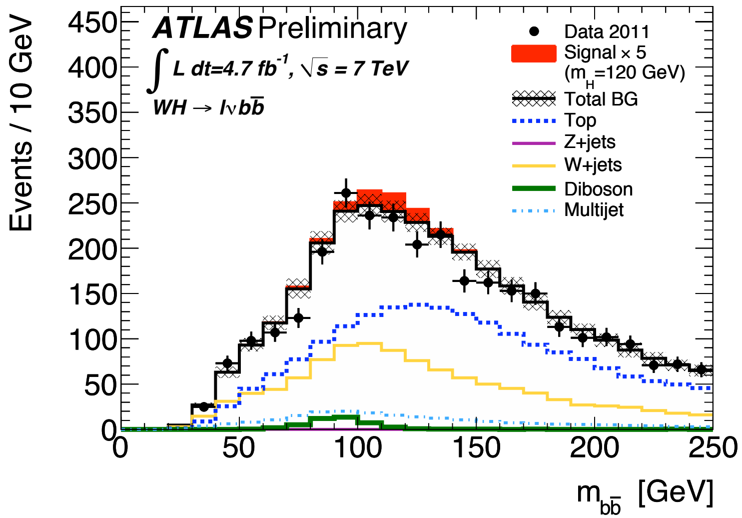
Significant probability that b-jet is produced in association with H

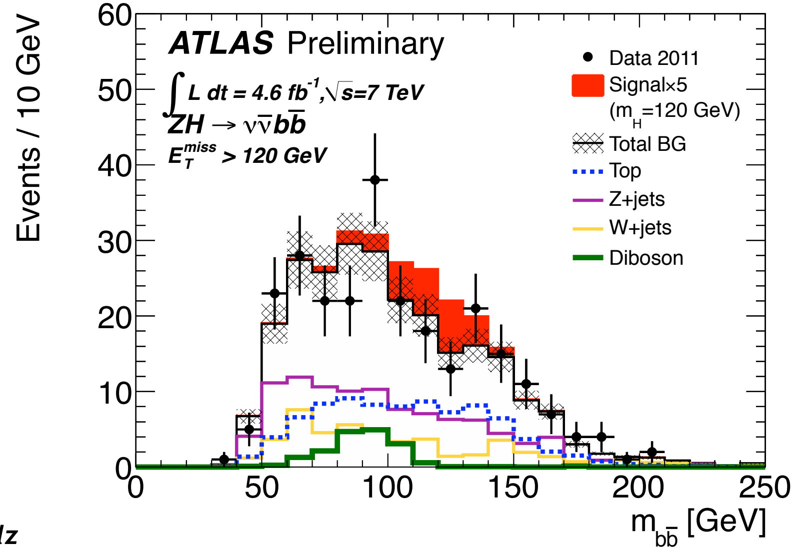
$H \rightarrow bb$

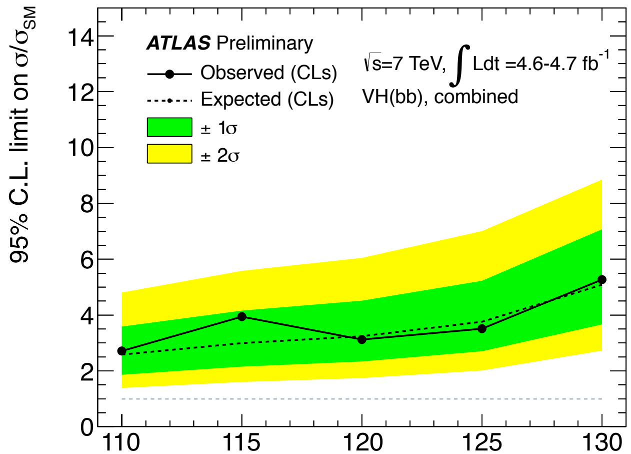
Select events with 2 b-tagged jets and either $Z \rightarrow ll$, $W \rightarrow l\nu$, or $Z \rightarrow \nu\nu$.

ATLAS-CONF-2012-015

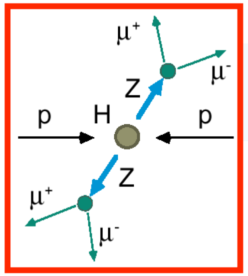








No excess seen.



$H \to ZZ^{(*)} \to 4$ leptons

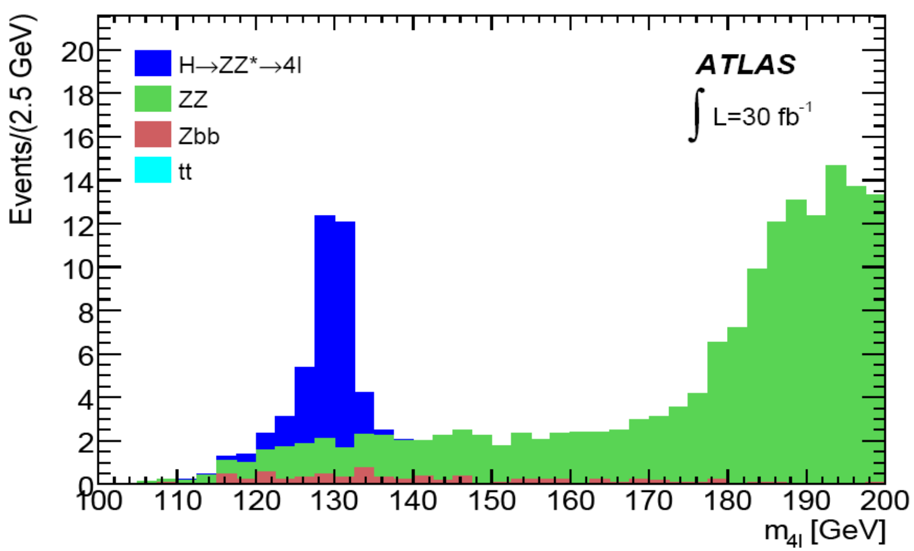
"Golden" channel! Need excellent tracker, electromagnetic calorimeter and muon system. High efficiency for all leptons is important, as four of them are involved. Efficient lepton reconstruction down to low p_T is also necessary.

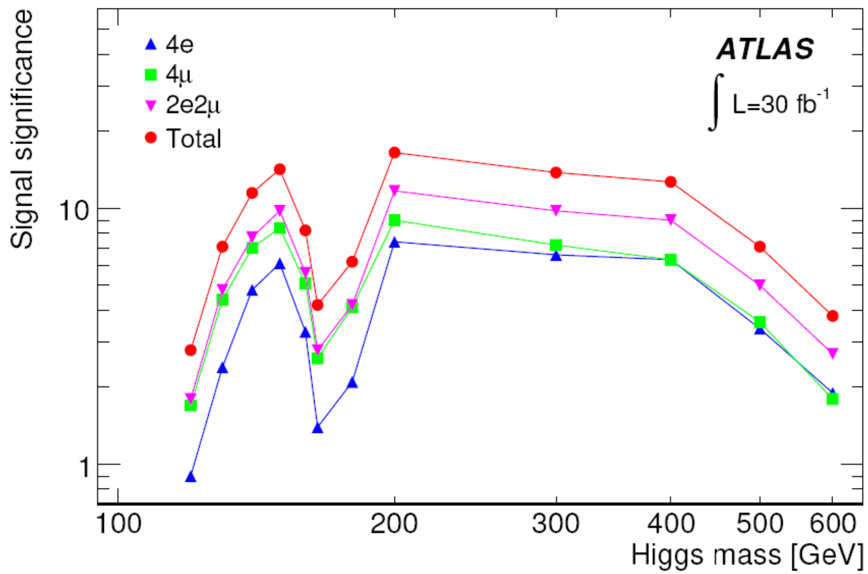
Background:

Irreducible: *ZZ*

Reducible: *tt*, *Zbb*

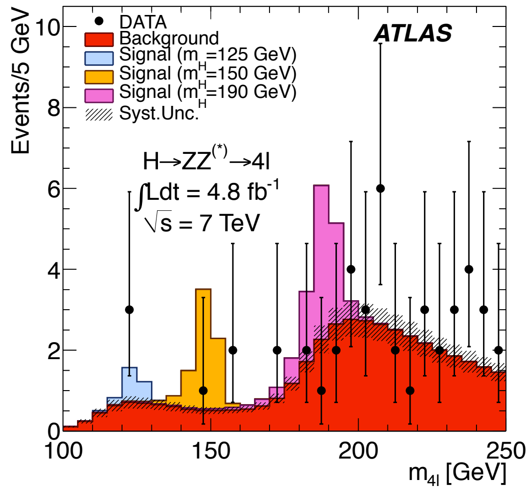
Suppression mainly through lepton isolation and b-tagging (impact parameter)





$H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons

Event selection: pair of leptons close to Z mass

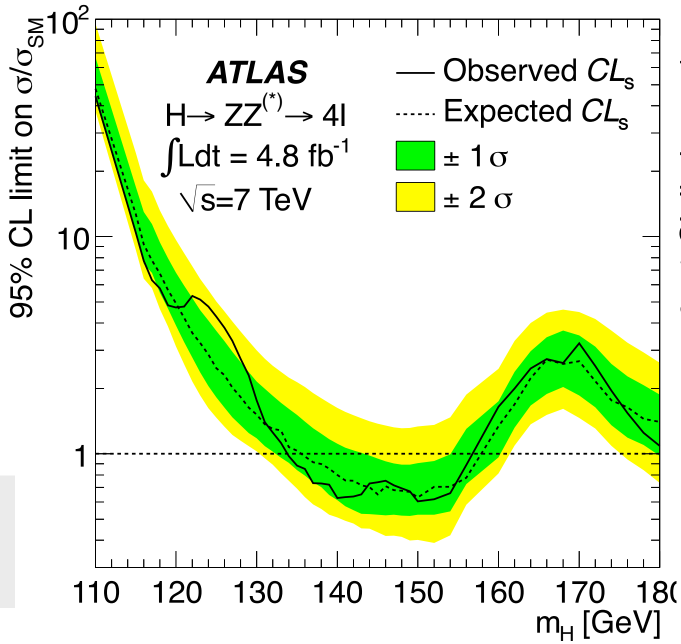


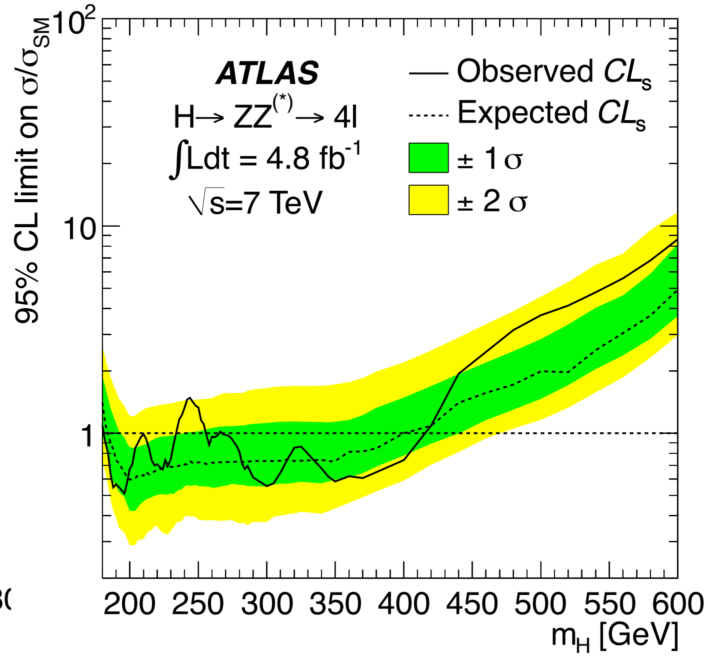
SM Higgs boson is excluded at 95% CL in the mass ranges 134–156 GeV, 182–233 GeV, 256–265 GeV and 268–415 GeV. The largest upward deviations from the background-only hypothesis are observed for m_H = 125 GeV, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 standard deviations, respectively. Once the look-elsewhere effect is considered, none of these excesses are significant.

3 events near 125 GeV:
2 with 2e2μ
1 with 4μ

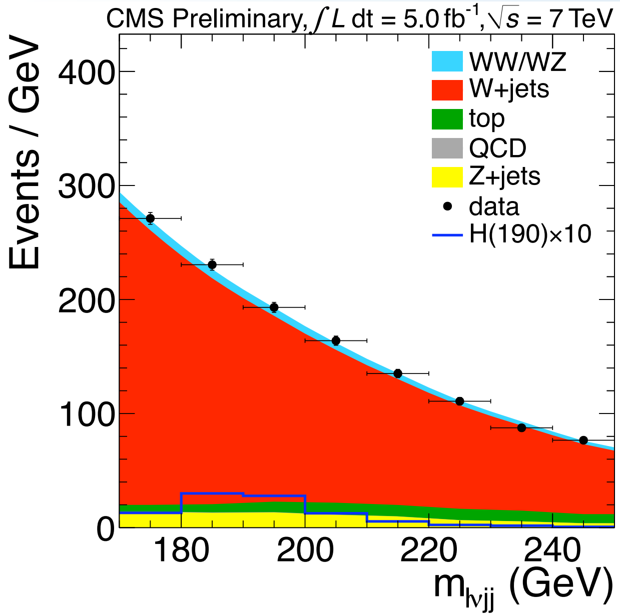
In total: 71 events
62±9 background

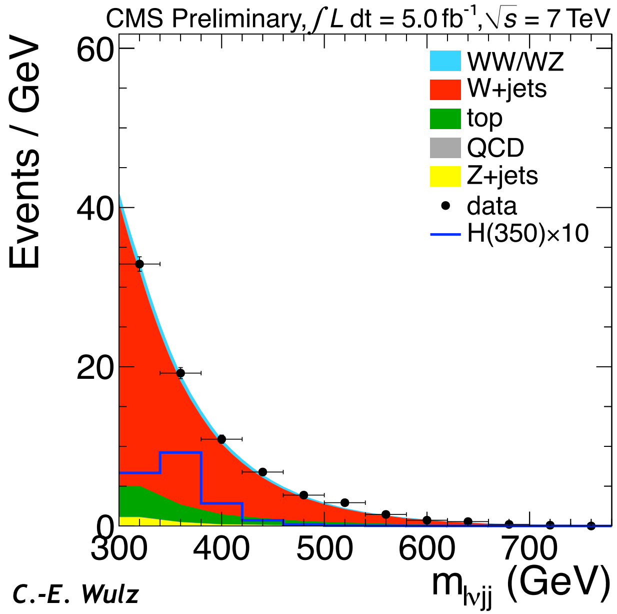
hep-ex 1202.1415
PLB 710 (2012) 383





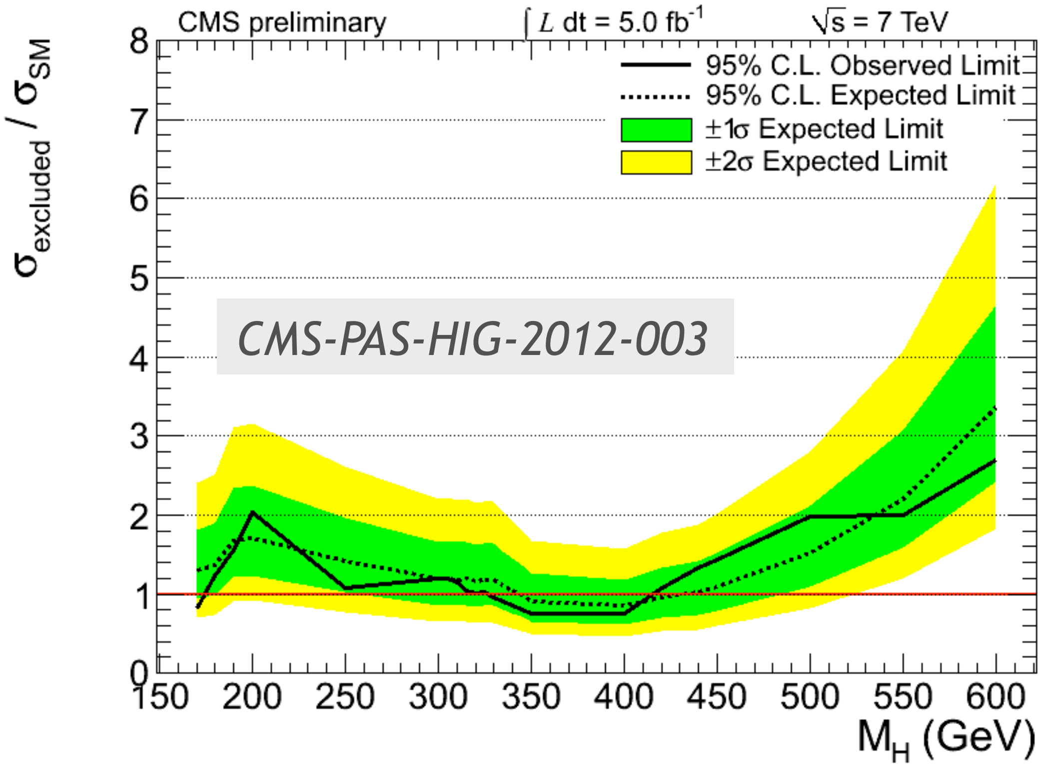
H → WW → $l\nu$ qq'



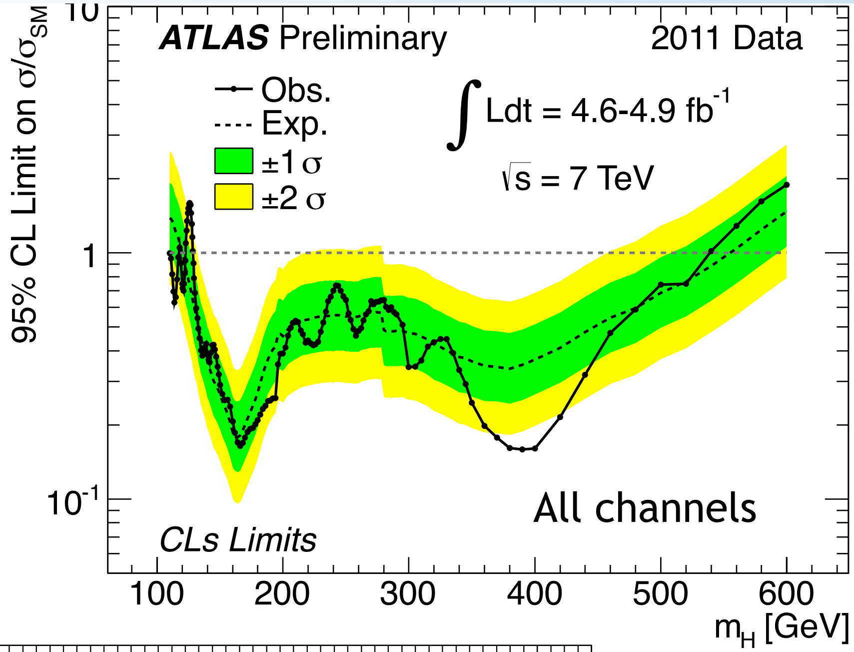


Event selection: Selections to discriminate between the signal and background events are based on kinematic and topological quantities including the angular spin correlations of the decay products.

No evidence for the Higgs boson is found, and at 95% confidence level the SM Higgs boson production in the mass range 327-415 GeV is excluded.



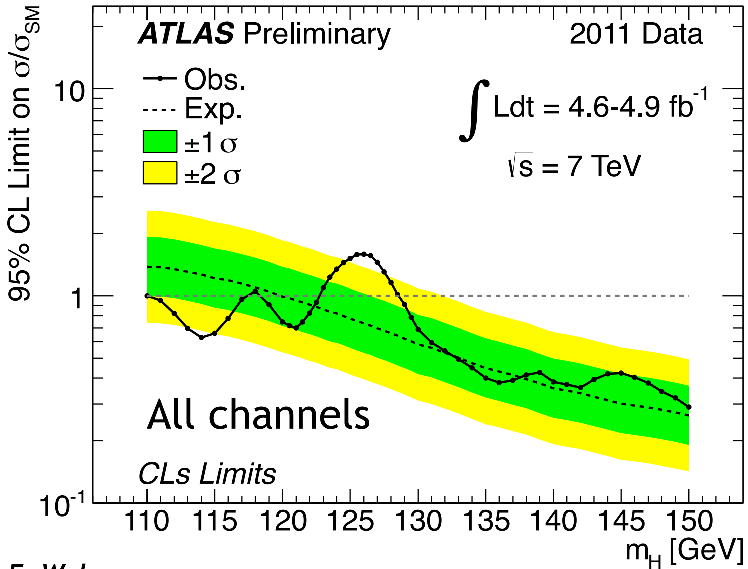
Standard Model Higgs combination in ATLAS

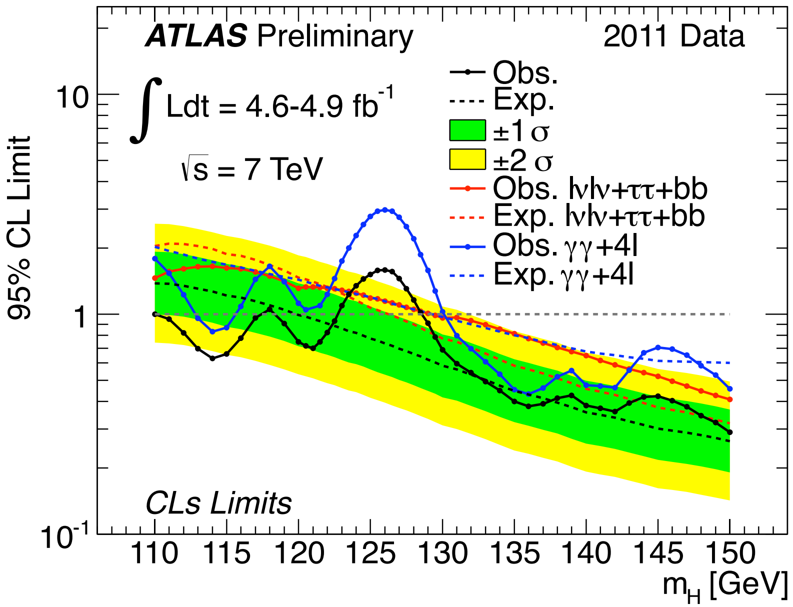


H → γγ, bb, ττ, WW, ZZ

ATLAS-CONF-2012-019

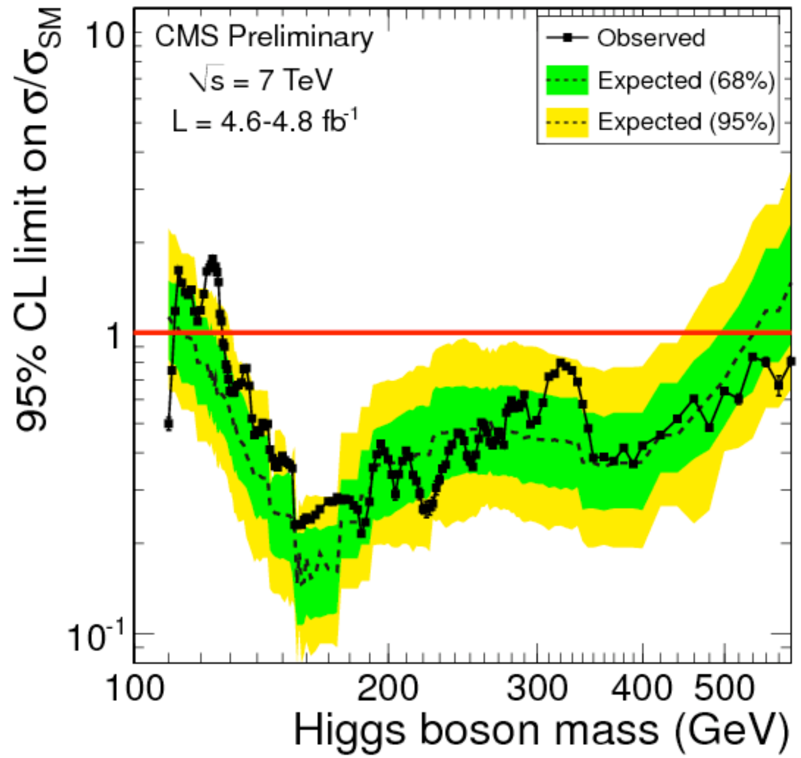
High mass resolution channels (blue)
Low mass resolution channels (red)

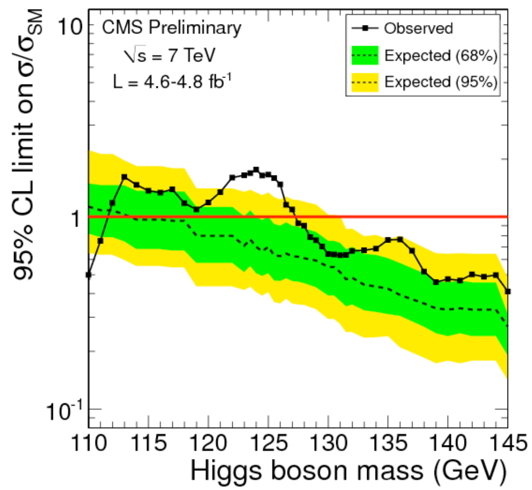


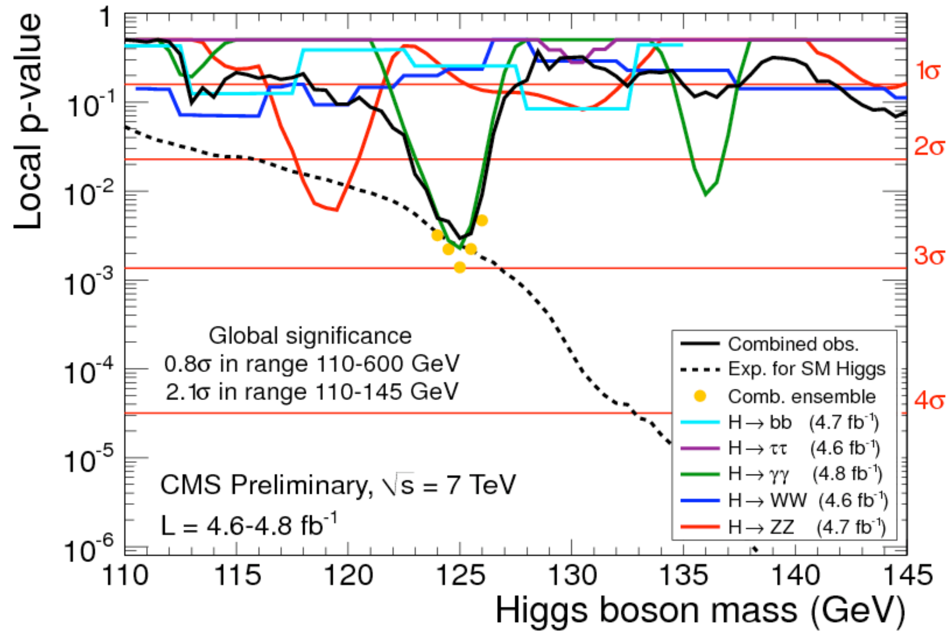


Standard Model Higgs combination in CMS

H → γγ, bb, ττ, WW, ZZ





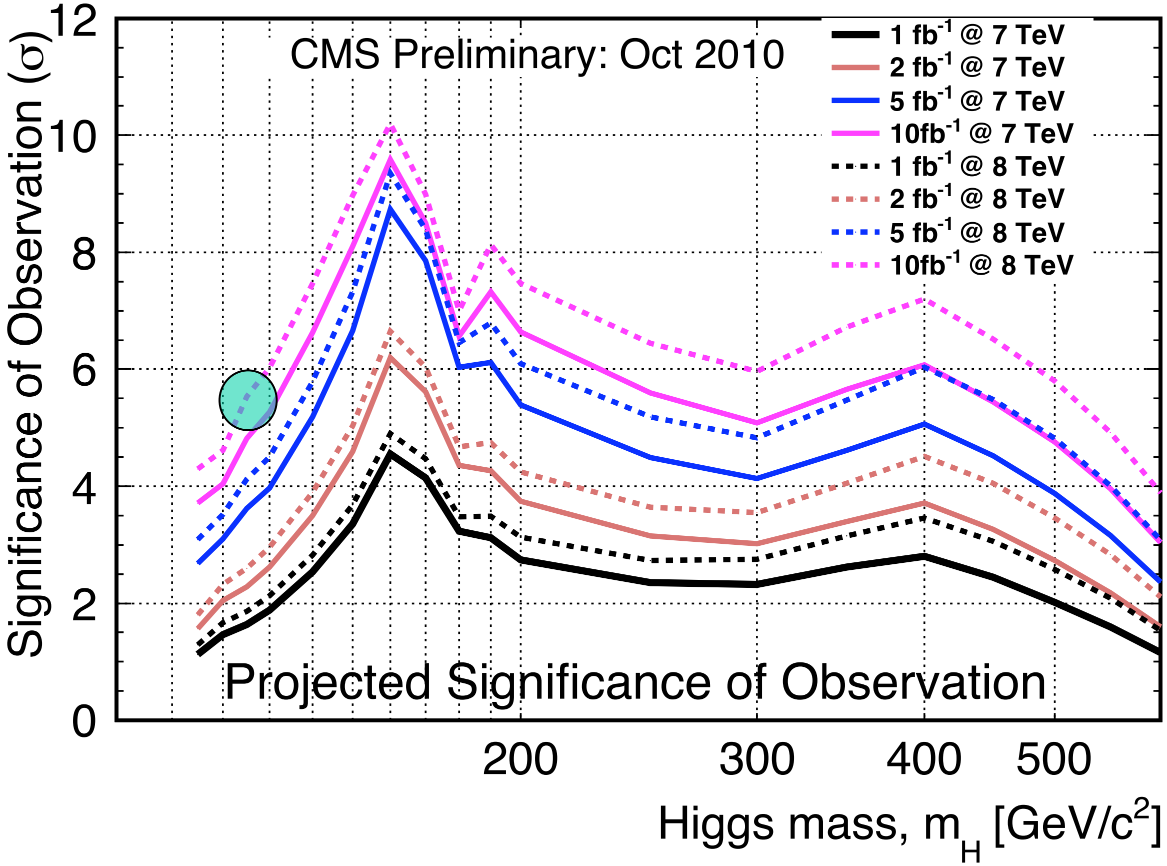


CMS-PAS-HIG-2012-008

Higgs boson discovery prospects

CMS-NOTE-2010-008

What's your bet?

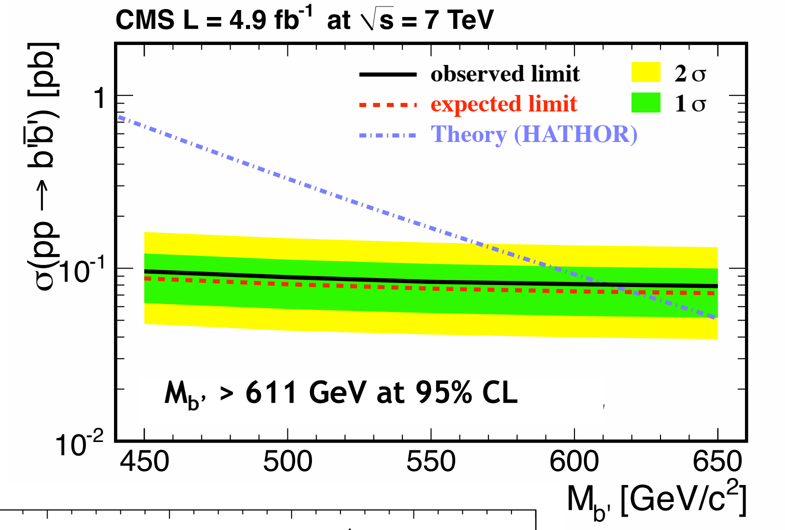


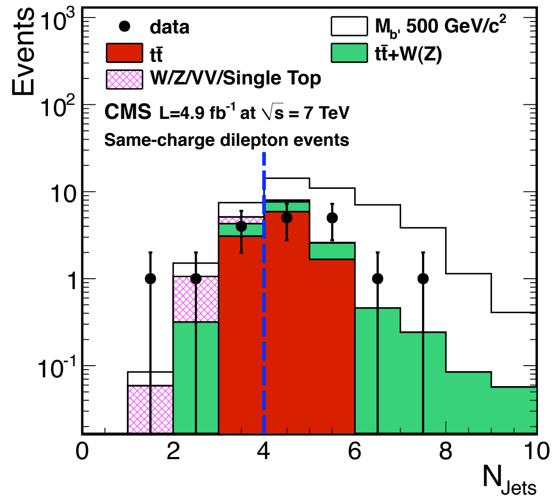
8 TeV instead of 7 TeV centre-of-mass energy saves about 25% of the data taking time.

Fourth generation quarks

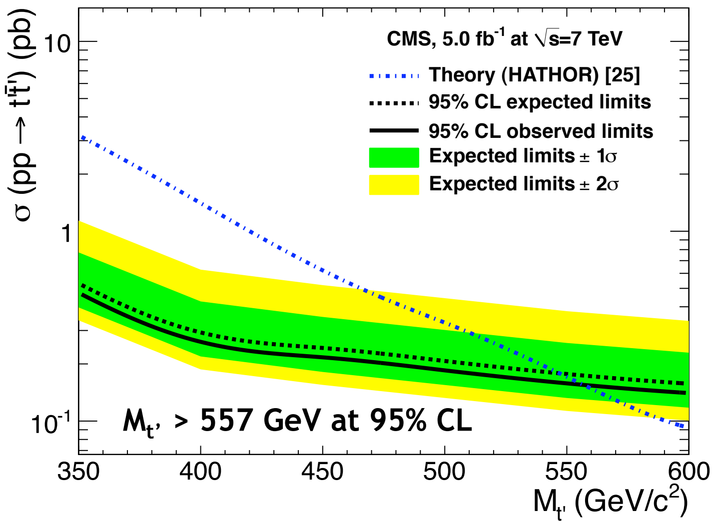
Top- and bottom-like quarks: b′, t′ -> tW
Signatures for b′: trileptons or same-sign dileptons plus at least one b-jet
Signatures for t′: opposite-sign dileptons

hep-ex 1204.1088

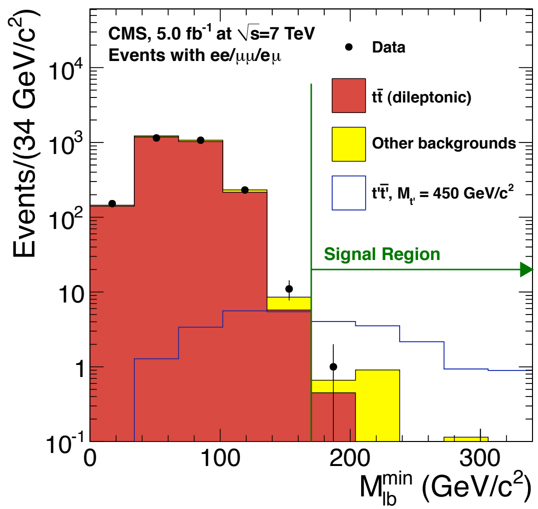




hep-ex 1203.5410



Minimum value of four possible M_{lb} combinations



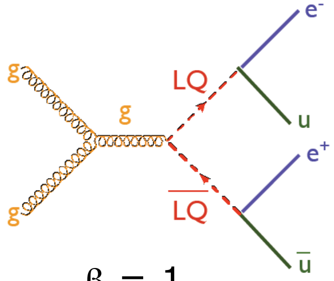
Leptoquarks

Leptoquarks are color-triplet bosons with fractional charge arising e.g. in GUT theories.
Assumption: LQ couple only to quarks and leptons of the same SM generation.

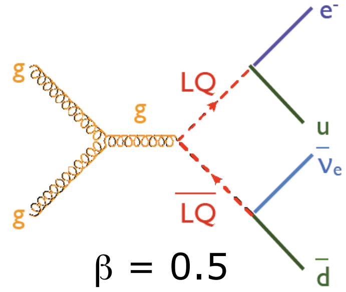
β = B(LQ -> eq)

2 scenarii for first generation:

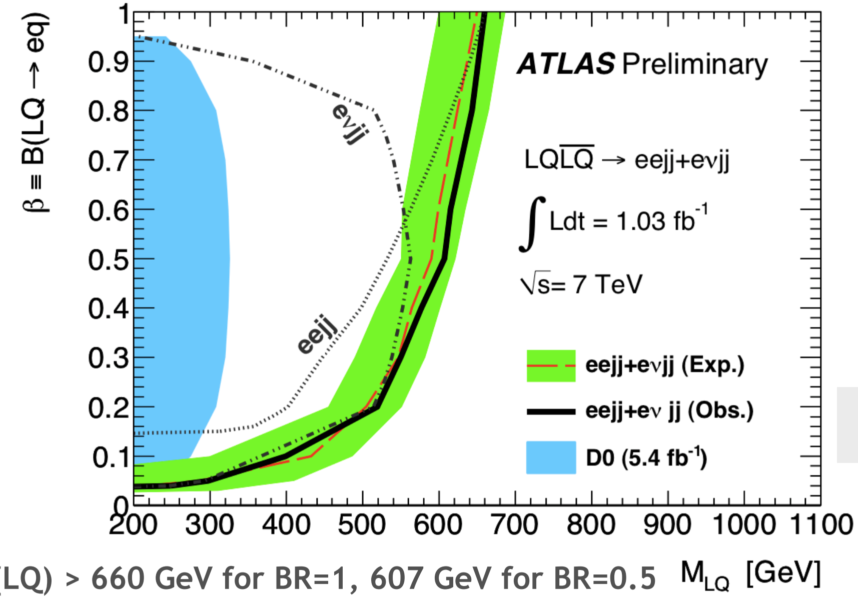
hep-ex 1112.4828,
PLB 709 (2012) 158



β = 1
2e + 2jets

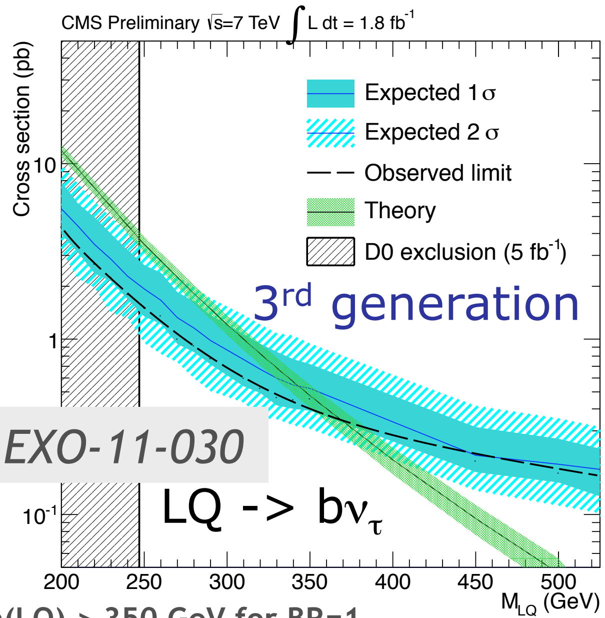


β = 0.5
1e + 2jets + E_T^{miss}



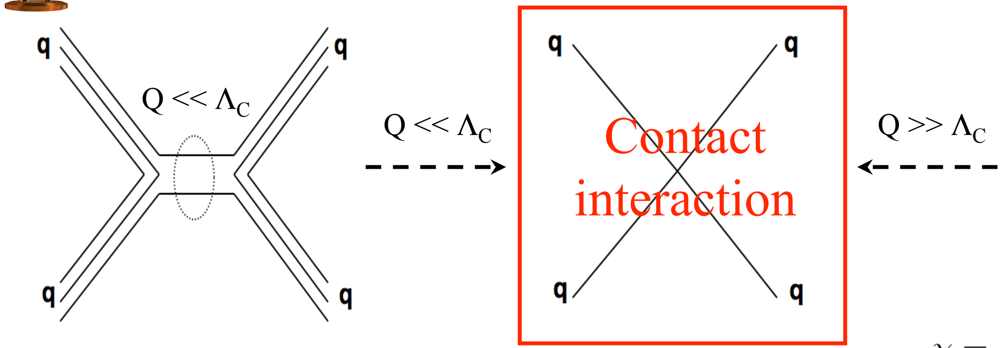
m(LQ) > 660 GeV for BR=1, 607 GeV for BR=0.5

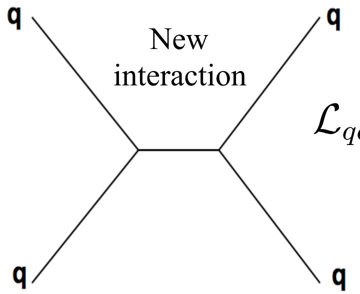
CMS-PAS EXO-11-030



m(LQ) > 350 GeV for BR=1

Compositeness, contact interactions



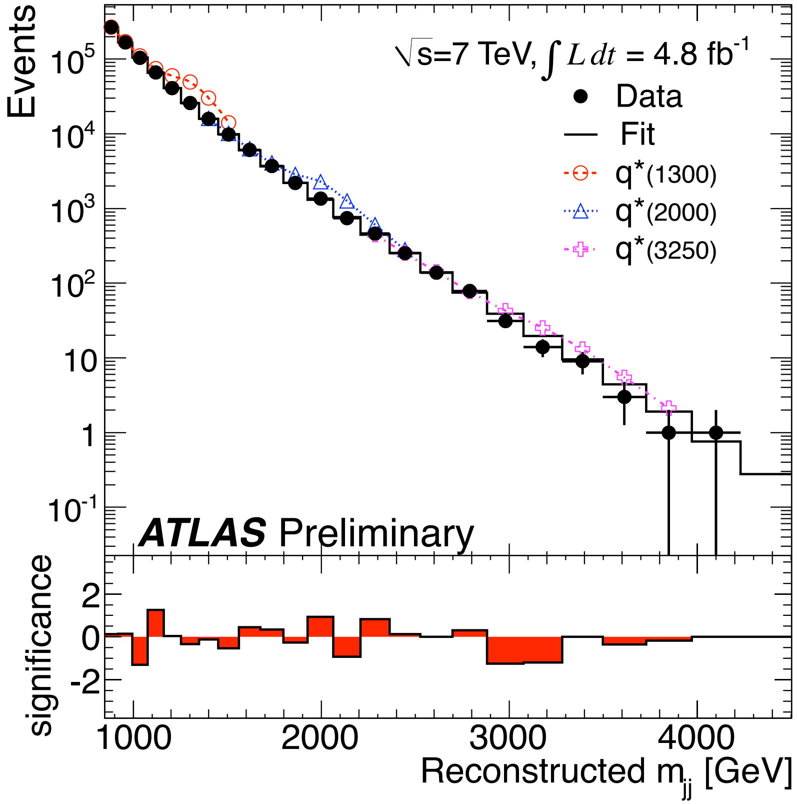


$$\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{qqqq}$$

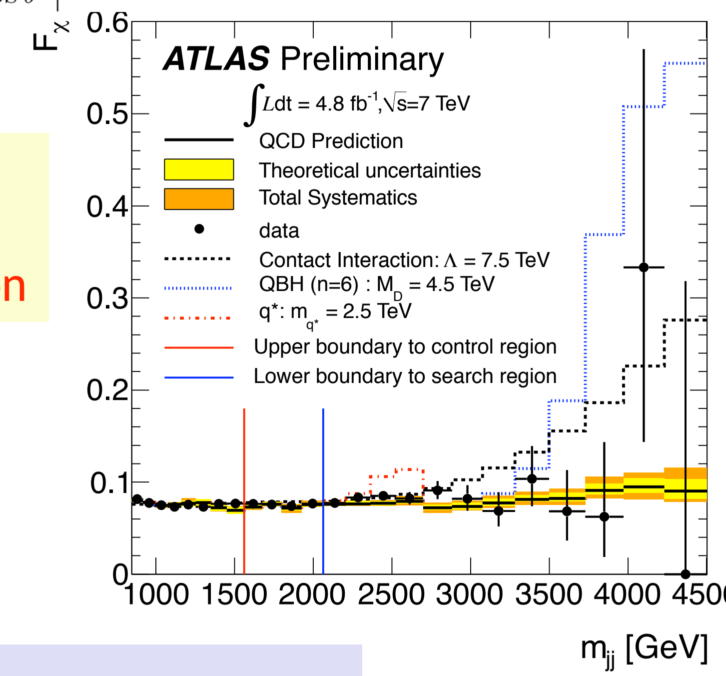
$$\mathcal{L}_{qqqq} = \frac{\eta g^2}{2\Lambda_C^2} \overline{\Psi_q^L}\gamma_\mu\Psi_q^L\overline{\Psi_q^L}\gamma^\mu\Psi_q^L$$

$$\chi = \frac{1+|\cos\theta^\star|}{1-|\cos\theta^\star|} = \exp(|\Delta\eta|)$$

ATLAS-CONF-2012-038



Dijet angular distribution



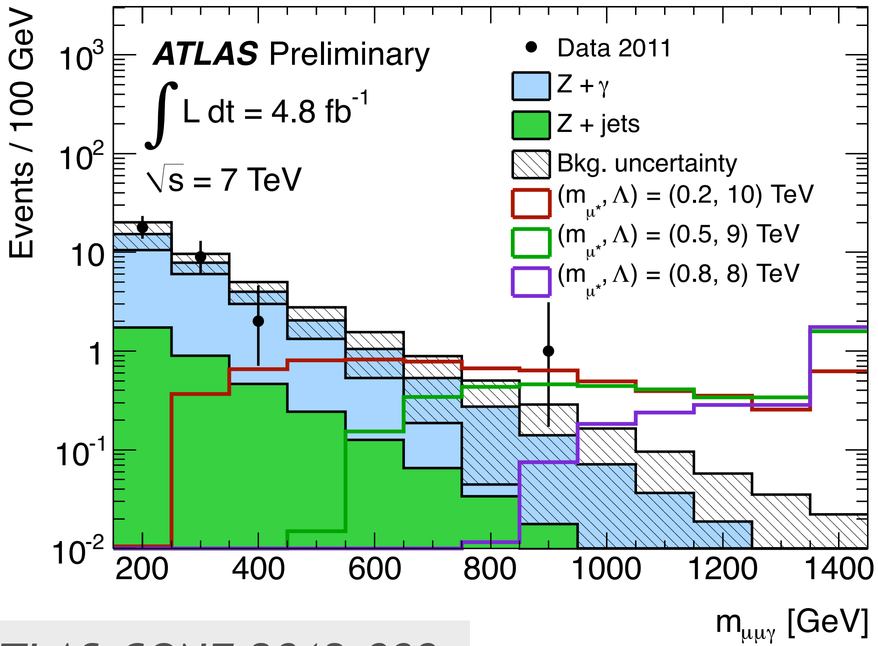
Λ_C > 7.6 TeV (95% CL)

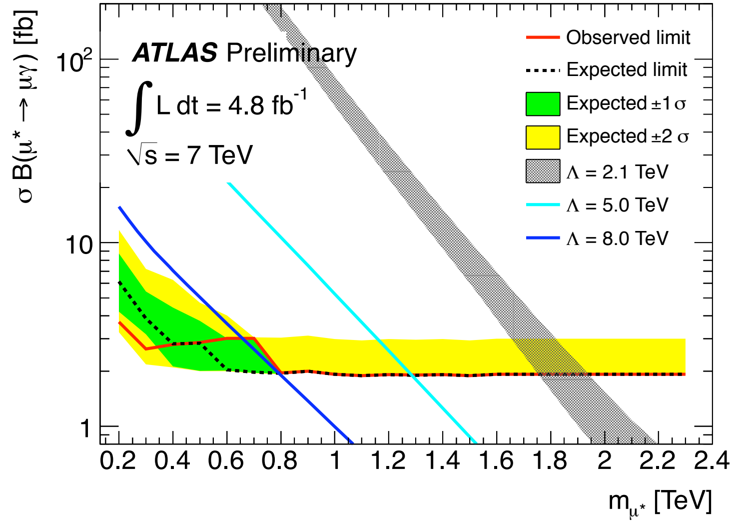
$l^* \to l\gamma$ Excited leptons

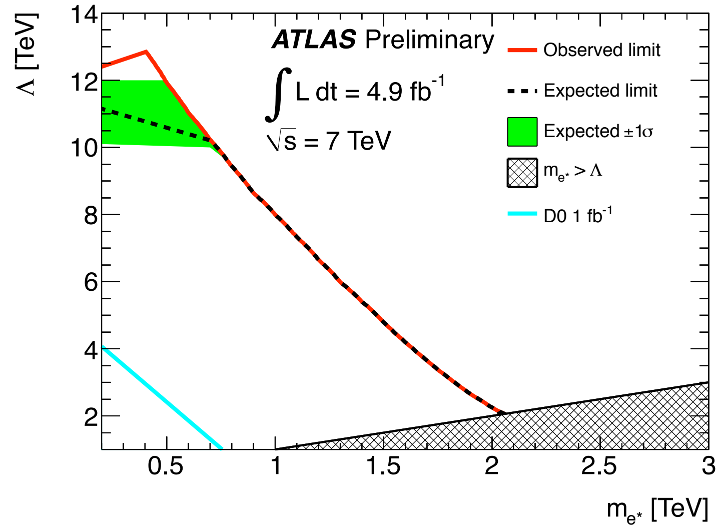
Excited lepton production via 4-fermion contact interactions can be described by an effective Lagrangian:

$$\mathcal{L}_{contact} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu$$

Clean final state: $\ell\,\ell\,\gamma$

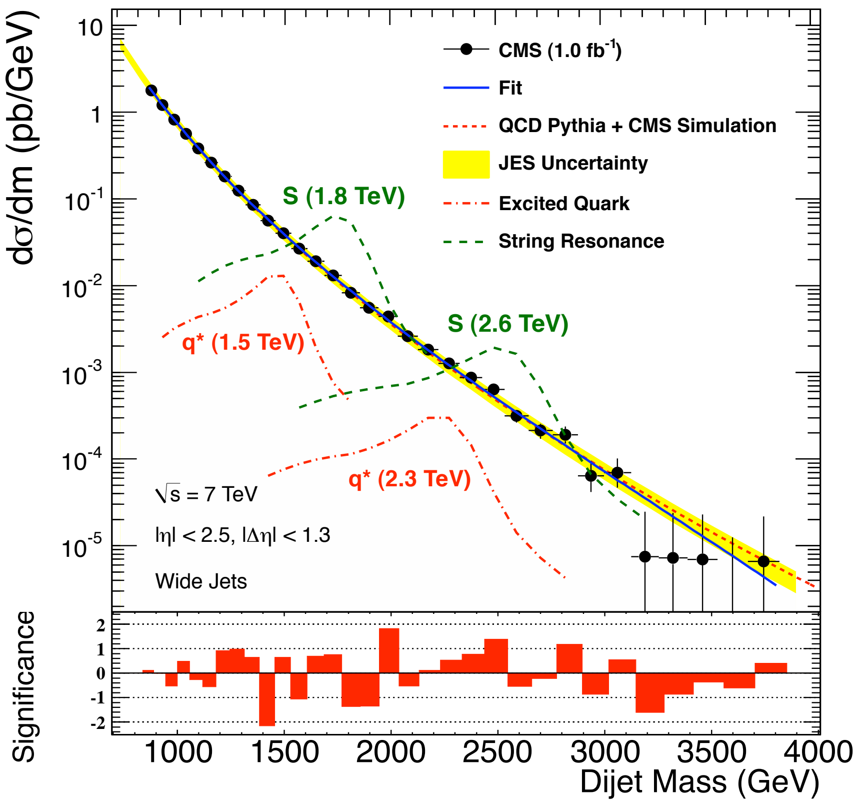




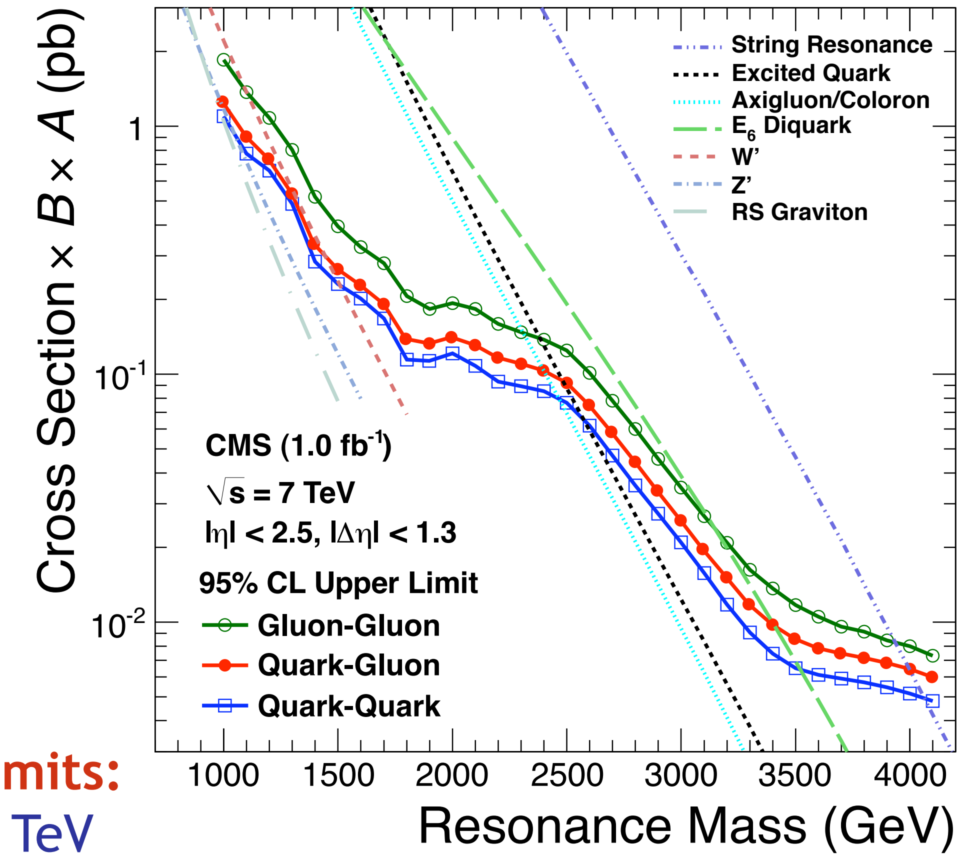


ATLAS-CONF-2012-008

Dijet resonances



Observed 95% CL upper limit of
σ x branching fraction x acceptance



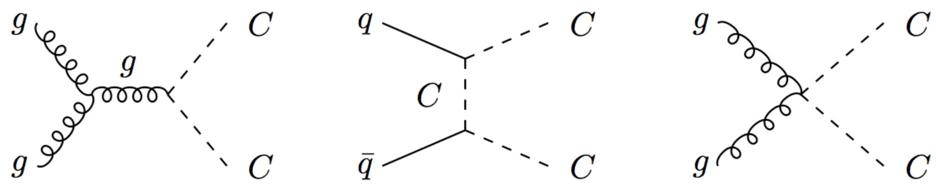
Highest JJ mass event:
m_{JJ} = 3.8 TeV

Exclusion limits:
String: 4.00 TeV
Excited quarks: 2.49 TeV

hep-ex 1107.4771, PLB 704 (2011) 123

Search for new physics with pairs of dijets

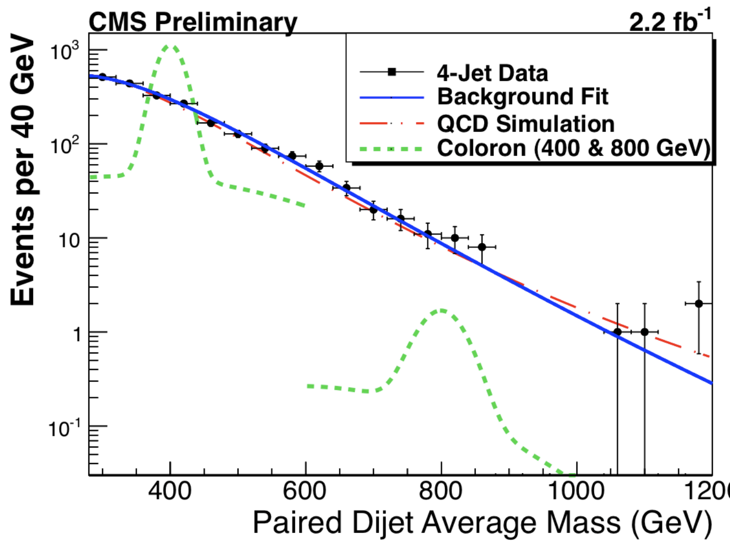
Pair production of narrow dijet resonances, for example colorons.



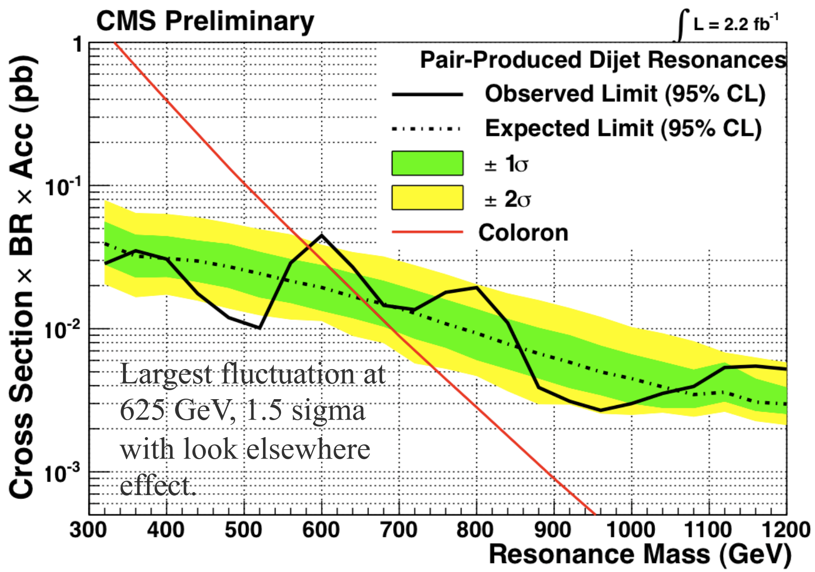
$$CC \to q\bar{q}q\bar{q}$$

CMS PAS EXO-11-016

Colorons: color octet scalars or vectors



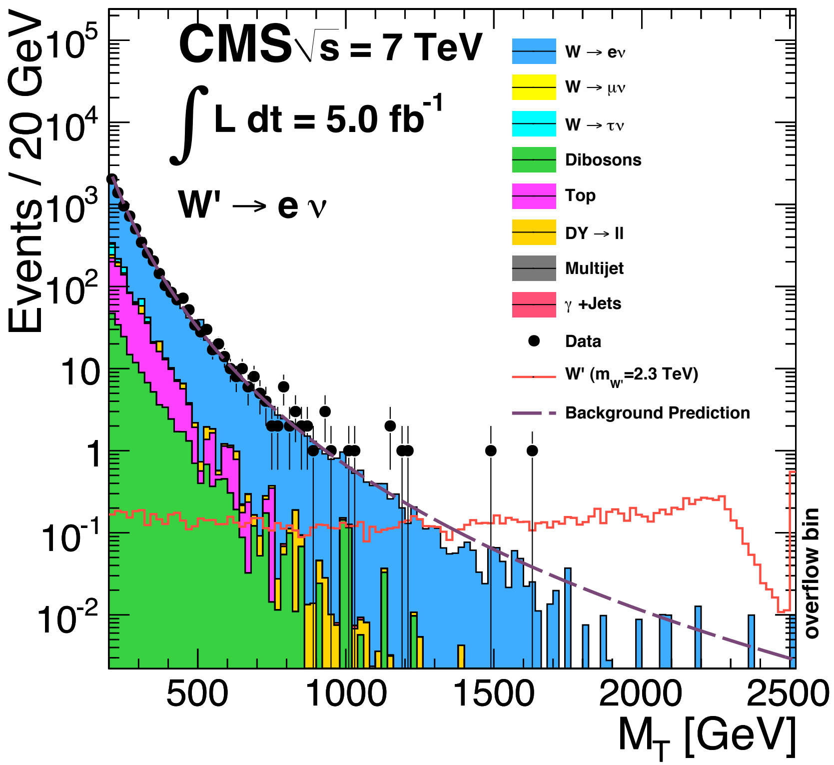
Event selection: at least 4 jets, jet pairs with equal mass

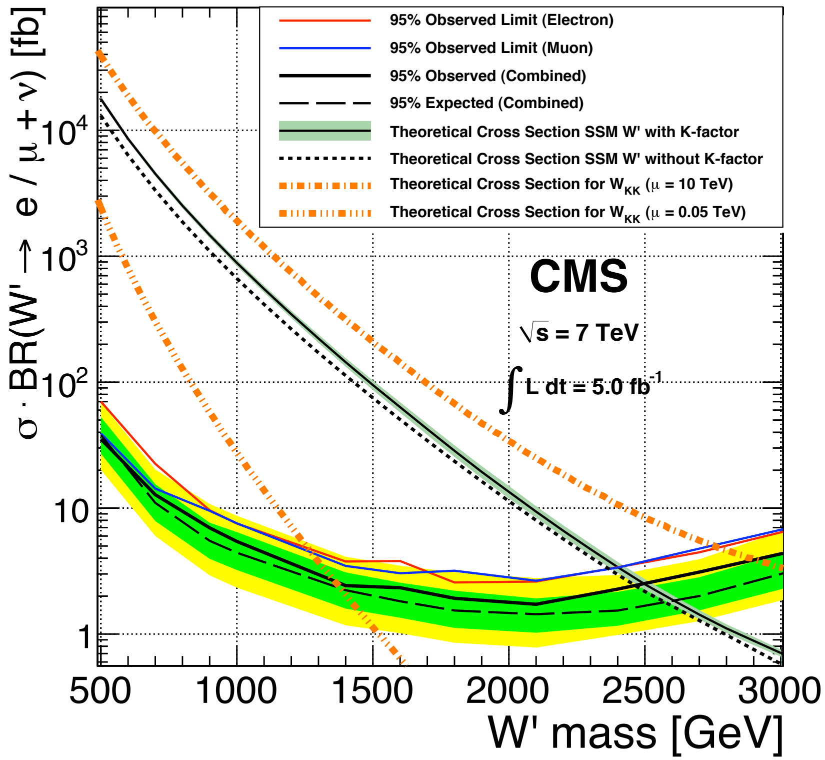


Pair production of colorons is excluded for:
320 GeV < m(C) < 580 GeV

W' → $l\nu$

Exclusion limits for several W' models have been derived:
- left-handed W' with Standard Model couplings
- right-handed W_R' with W-W' interference
- Kaluza-Klein W_{KK}' states in split universal extra dimensions framework



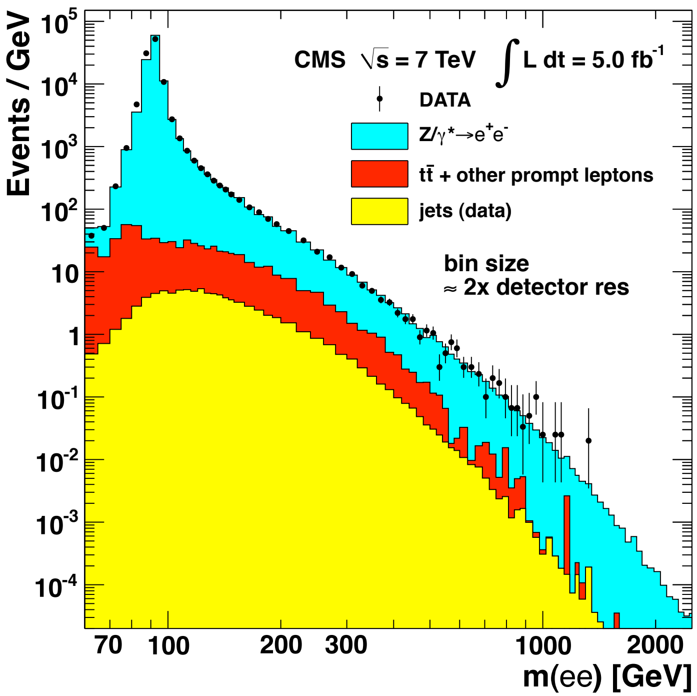


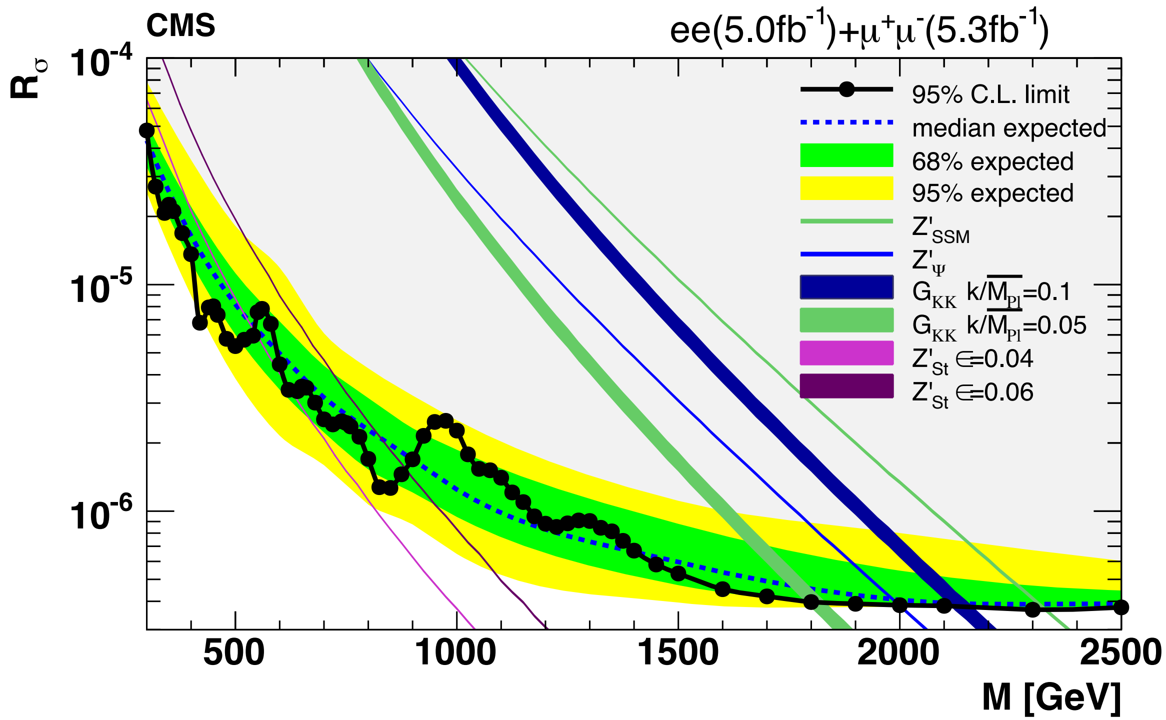
hep-ex 1204.4764, submitted to JHEP

$Z' \rightarrow l^+l^-$

Several Z' models have been studied:
- sequential Standard Model
- Z'_ψ model (superstring inspired E_6 model)
- Z'_{st} Stückelberg extension

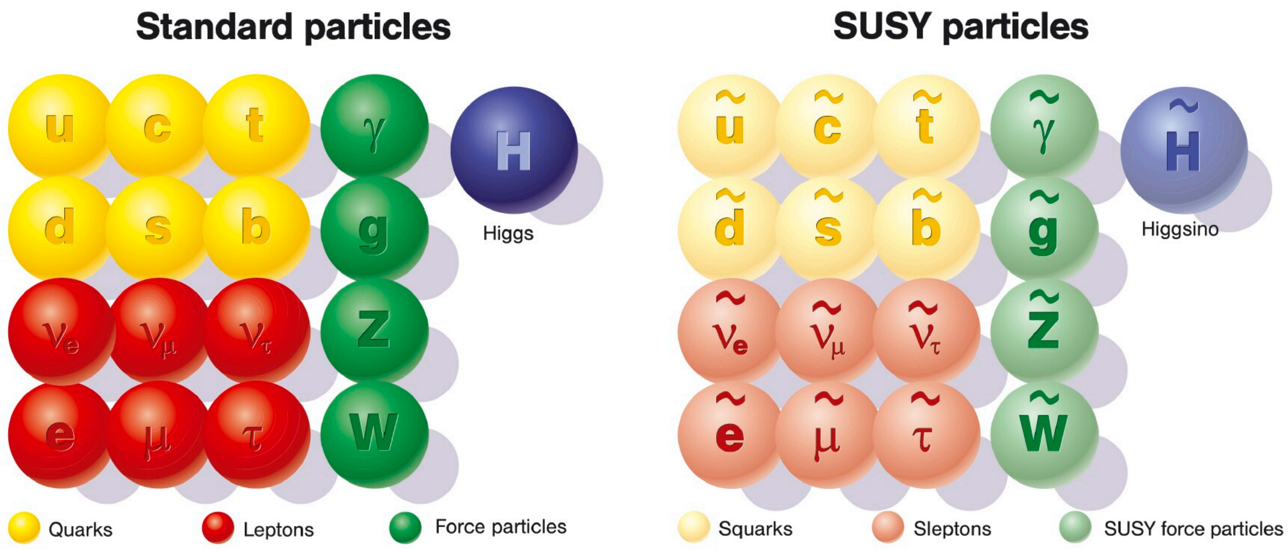
Kaluza-Klein Graviton G_{KK} search is also possible in this channel.





hep-ex 1206.1849, submitted to PLB

Supersymmetry



For each fermion of the Standard Model there is a supersymmetric boson partner and vice versa.
-> stability of Higgs mass
-> unification of forces
-> candidate for dark matter

Up to now no SUSY partners with the same mass as SM particles have been found, therefore SUSY must be broken:

$$m \neq \tilde{m}$$

Exploration of SUSY models

SUSY is not a single theory, but a framework of models.
The minimal supersymmetric Standard Model (MSSM) has 105 parameters -> difficult to explore.
We can study benchmark MSSM models with fewer parameters, and NMSSM's as well as R-parity [$R = (-1)^{2S+L+3B}$] violating scenarios. New and sometimes more unusual experimental signatures will arise.

Examples:

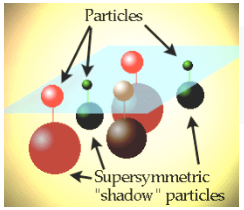
CMSSM (constrained MSSM): $m_{1/2}$, m_0, A_0, $\tan\beta$, $\mathrm{sign}(\mu)$

mSUGRA (minimal supergravity model): $m_{1/2}$, m_0, A_0, $\mathrm{sign}(\mu)$

NUHM (non-universal Higgs mass models; Higgs mass not unified with sfermion mass):
$m_{1/2}$, m_0, m_H (or m_{Hu}, m_{Hd}), A_0, $\tan\beta$, $\mathrm{sign}(\mu)$

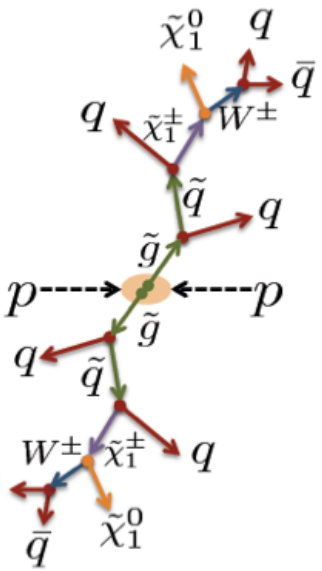
mGMSB (minimal gauge-mediated SUSY breaking):
$M_{messenger}$, Λ (visible sector soft SUSY breaking scale), $\tan\beta$, $c_{gravitino}$, $N_{messenger}$

RPV MSSM (R-parity violating): $m_{1/2}$, m_0, A_0, $\tan\beta$, $\mathrm{sign}(\mu)$, Λ

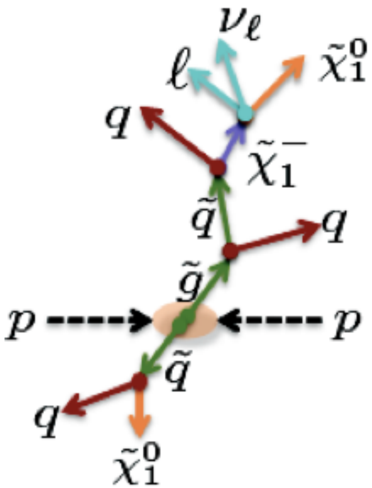


SUSY searches

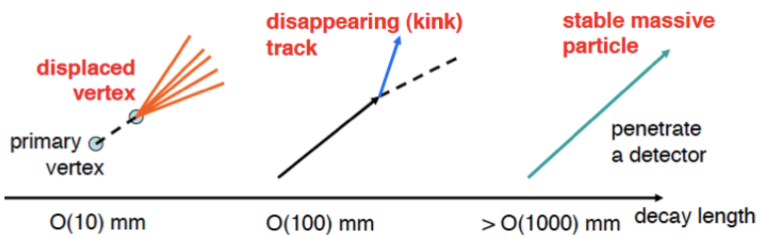
Examples



multijets + E_T^{miss}



1 lepton,
jets + E_T^{miss}



Initial generic searches are performed with a number of inclusive final states. Signatures can contain (b)-jets, missing transverse energy, leptons or photons. Specific searches have begun, for example for third generation squarks.

Interpretations can be made either through constrained (e.g. mSUGRA, GMSB) or simplified models (phenomenological, defined by an effective Lagrangian describing interactions of a small number of new particles).

New signatures are starting to be exploited (e.g. long-lived particles).

Examples of new signatures

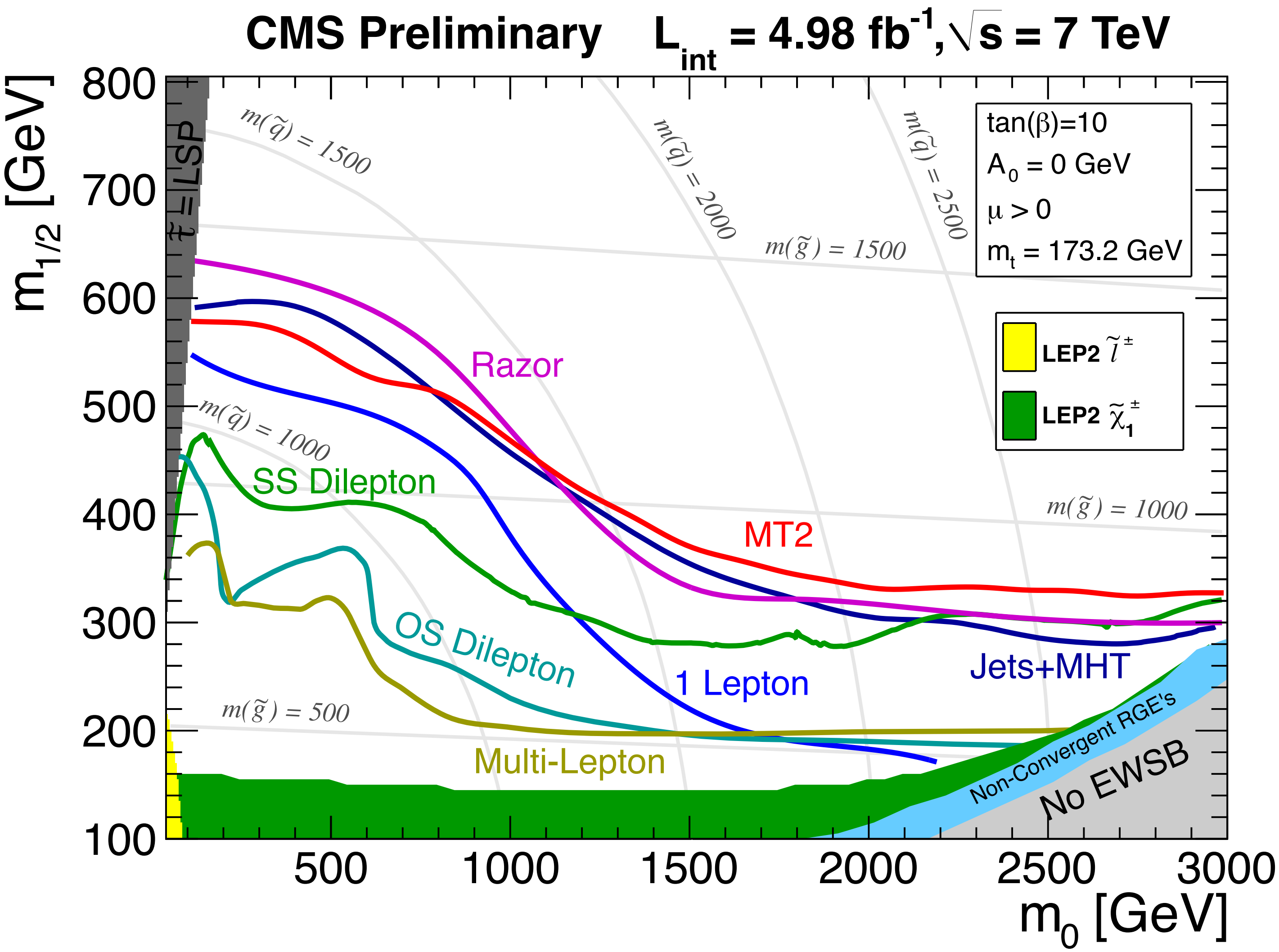
mGMSB:

The NLSP plays an important role since cascade decay chains of sparticles typically end in the NLSP. This is often a stau, which decays to tau and gravitino or neutralino, which can decay to a photon and a gravitino (missing energy in the detector).

RPV MSSM:

Lepton number violation or baryon number violation is allowed, the proton is still stable. The LSP (not necessarily a neutralino) decays to Standard Model particles. For a neutralino LSP the signatures are the same as for R-parity conserving models, except that there is no missing energy. If the RPV coupling is very small, decays are delayed, leading to displaced vertices. For stau LSP there are taus in the final state.

CMSSM limits



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

MSSM direct sbottom pair production

In the MSSM $\tilde{q}_R$ and $\tilde{q}_L$ can mix to form 2 mass eigenstates. Mixing is proportional to the mass of the corresponding SM fermion, therefore it is important for the 3rd generation. Large mixing can yield sbottom and stop mass eigenstates that are much lighter than other squarks.

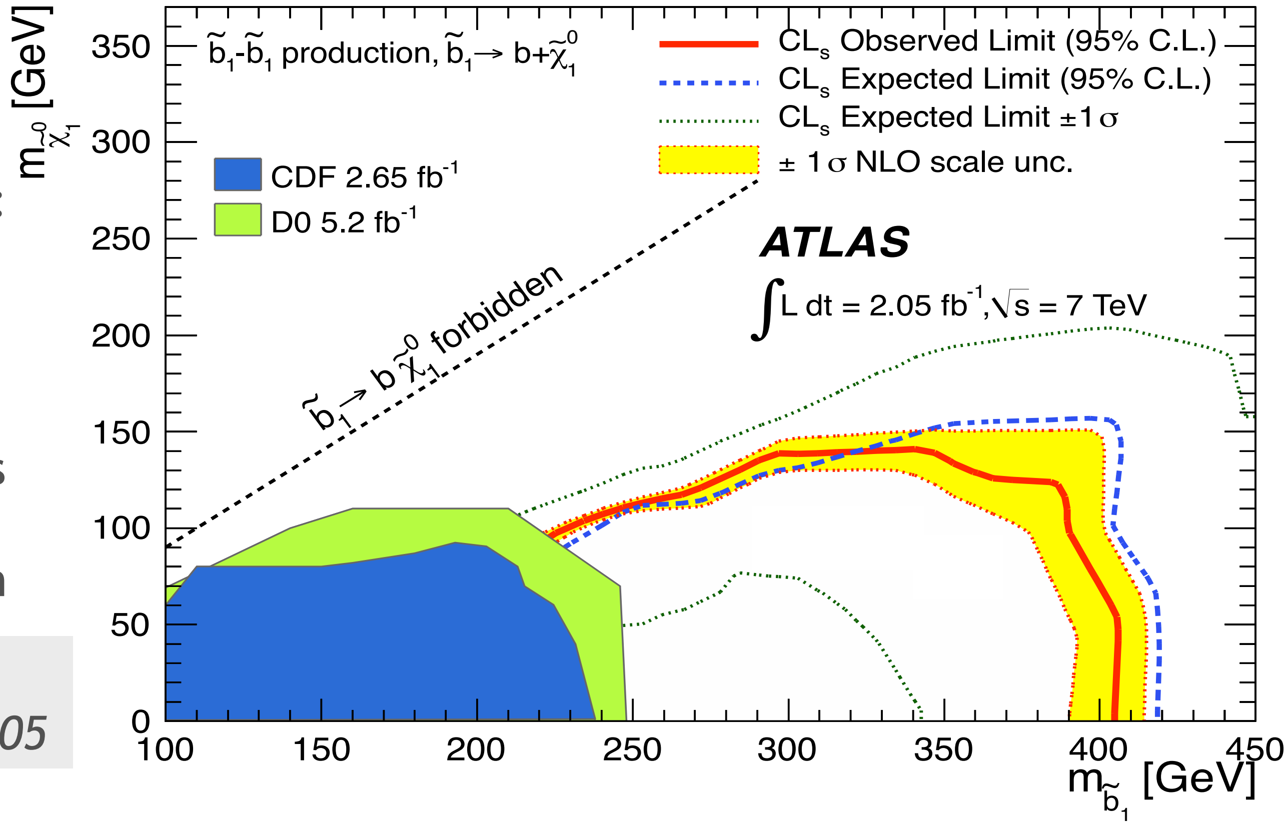
Exclusive decay mode:

$$\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$$

Event selection:
Large E_T^{miss} + 2 b-jets

R-parity conservation

hep-ex 1112.3832, PRL 108 (2012) 041805

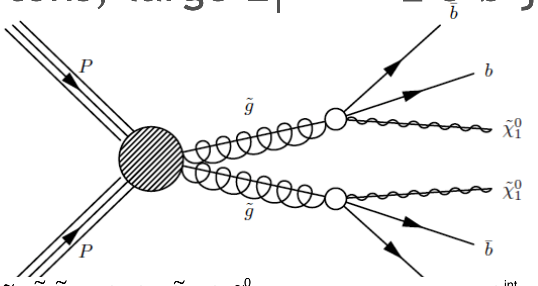


Sbottom masses are excluded below 390 GeV for neutralino masses below 60 GeV.

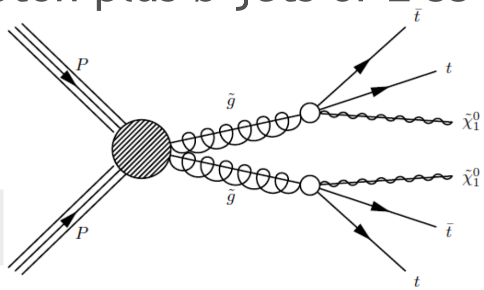
Sbottom and stop production from gluinos

Event selection:

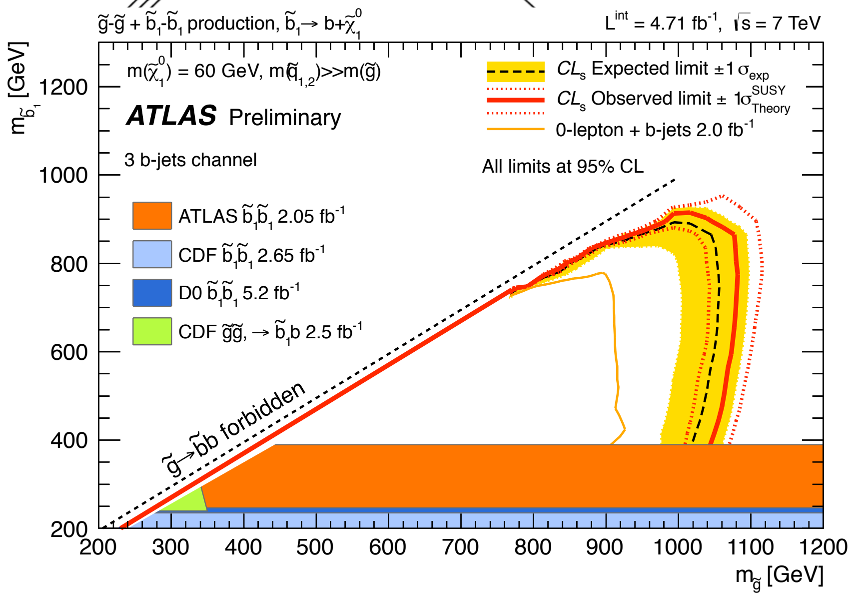
no leptons, large E_T^{miss} + ≥ 3 b-jets



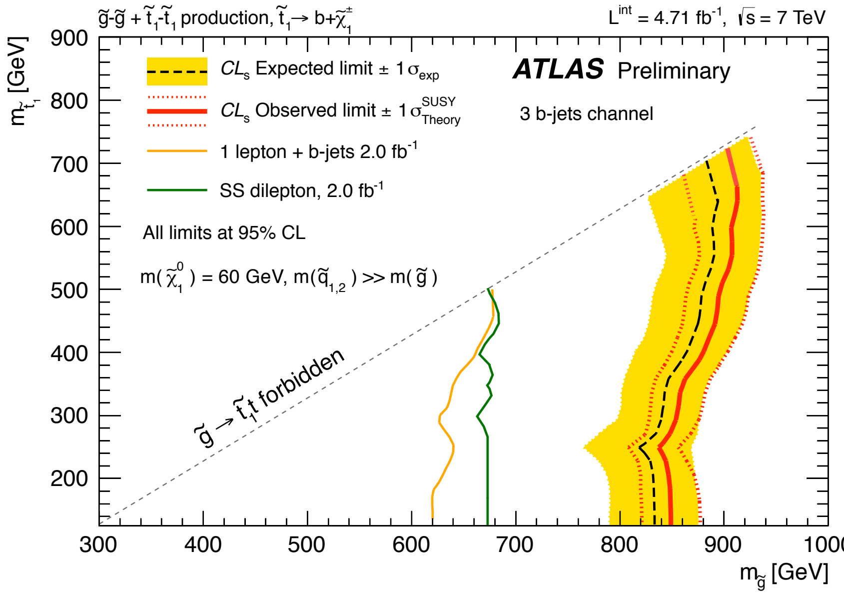
1 lepton plus b-jets or 2 SS leptons



ATLAS-CONF-2012-058



Gluino-sbottom model



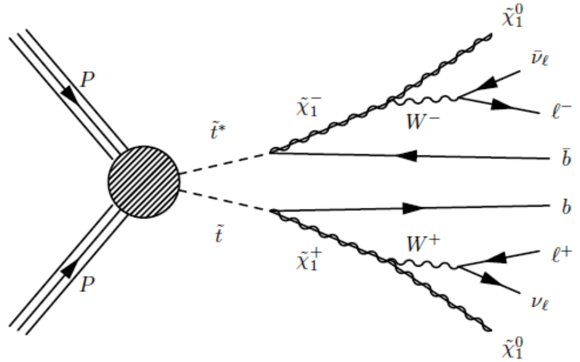
Gluino-stop model

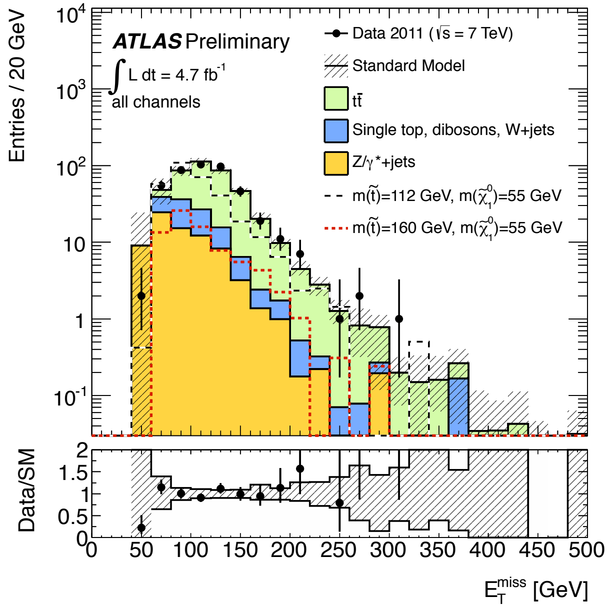
A gluino mass below 1 TeV is excluded for sbottom masses up to 870 GeV.

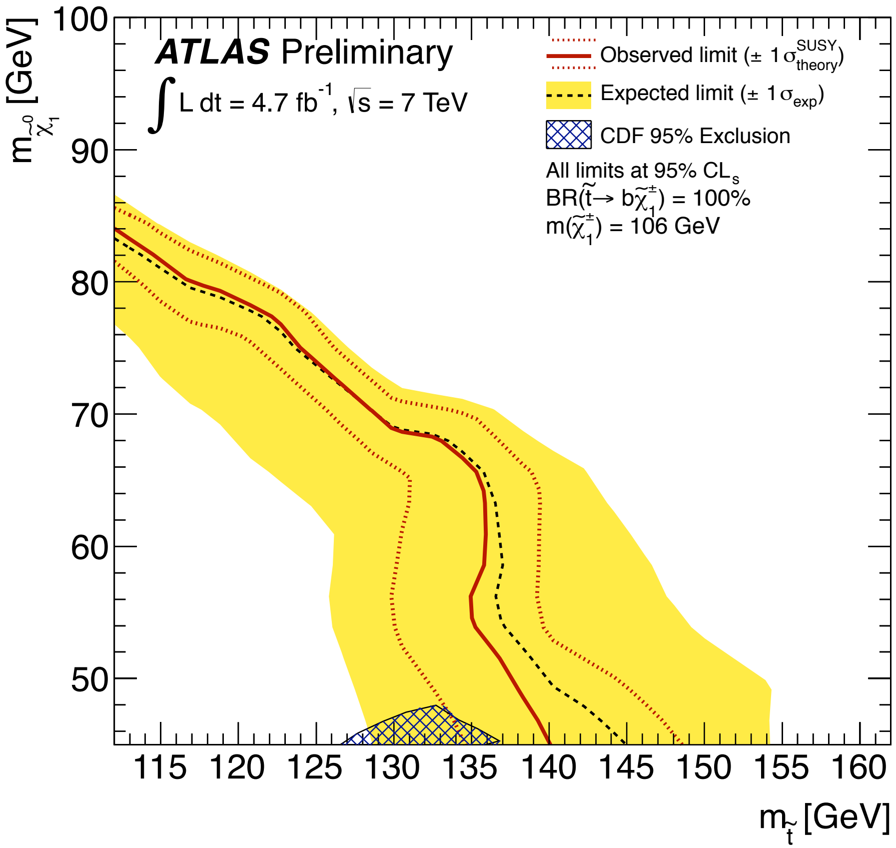
A gluino mass below 820 GeV is excluded for stop masses up to 640 GeV.

Search for a very light scalar top

Event selection: 2 opposite-sign leptons, large E_T^{miss} + ≥ 1 jet







ATLAS-CONF-2012-059

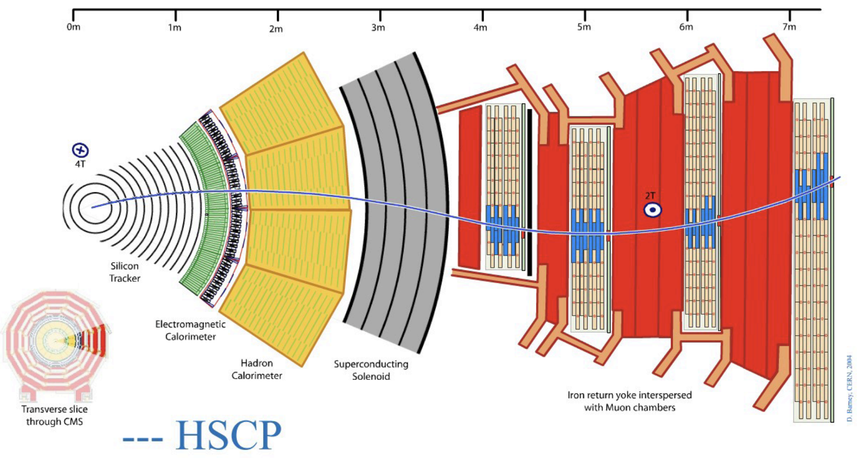
Stop masses are excluded up to at least 130 GeV for neutralino 1 masses up to 65 GeV.

Heavy "stable" charged particles

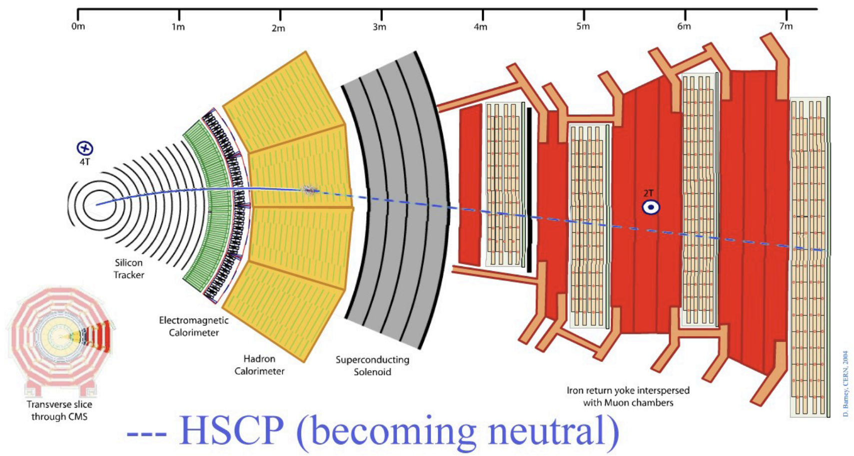
HSCP may be a long-lived NLSP, e.g. in Split-SUSY or GMSB.

If mass greater than about 100 GeV: $\beta = v/c < 0.9$.

Nuclear interactions may lead to charge exchange.
Signature: high-momentum particle with anomalously large energy loss dE/dx through ionization and an anomalously long time-of-flight.



Tracker (high dE/dx) + μ system (long TOF)

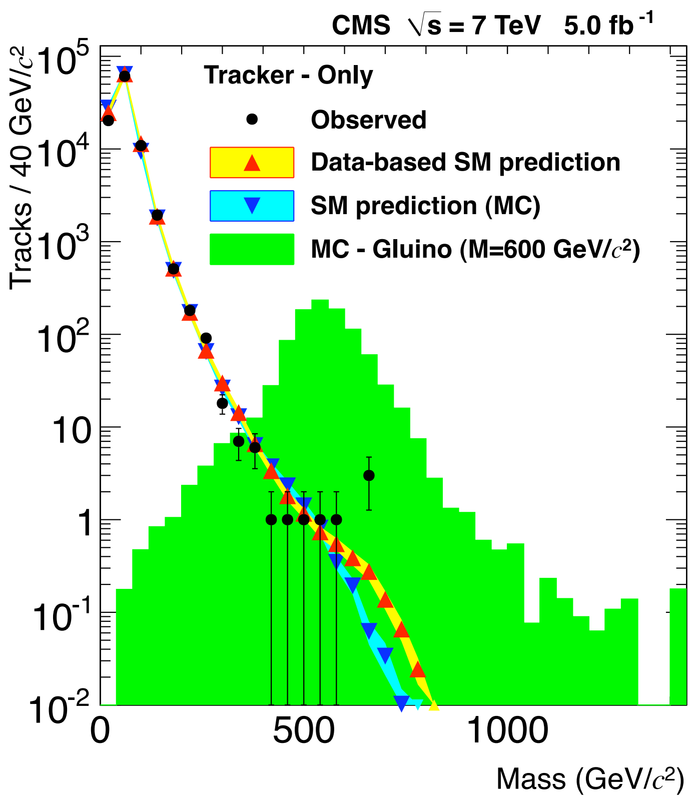


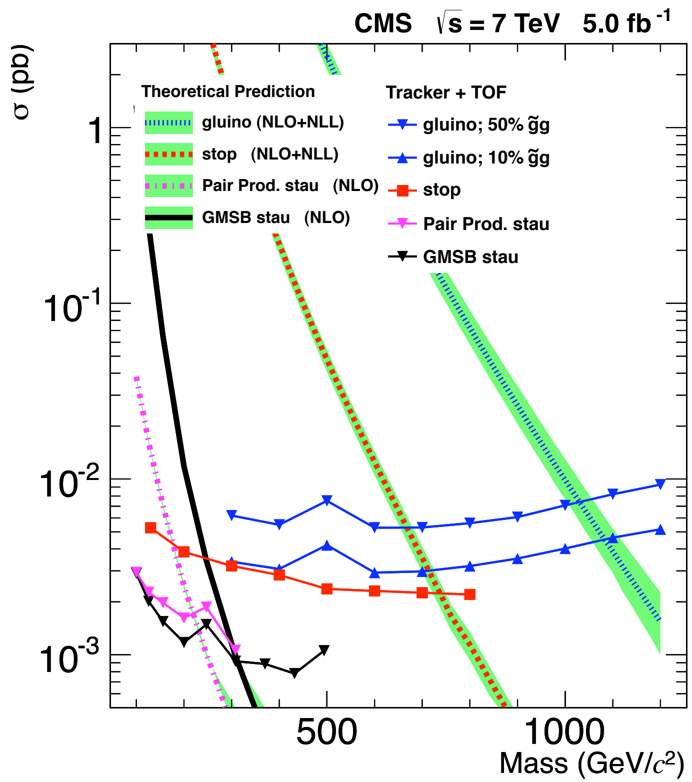
Tracker only (charge exchange)

Heavy long-lived charged particles

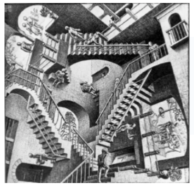
Data are consistent with background, estimated from data.

Mass limits for several models:
M(gluino) > 1091 GeV, M(stop) > 735 GeV, M(stau) > 232 GeV



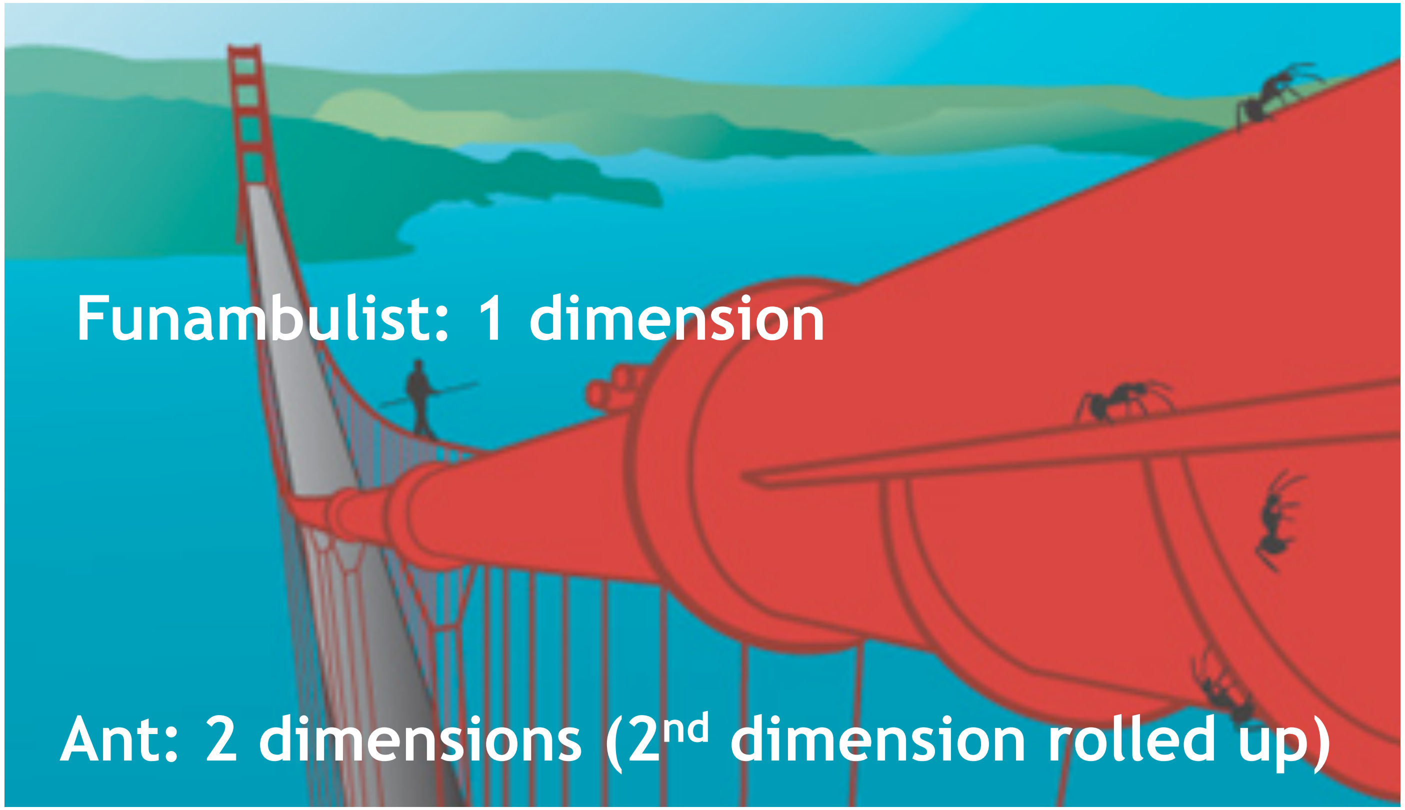


hep-ex 1205.0272, submitted to PLB



Extra dimensions

Our well known universe: 3 space dimensions + 1 time dimension
String theory: minimum 6 extra dimensions



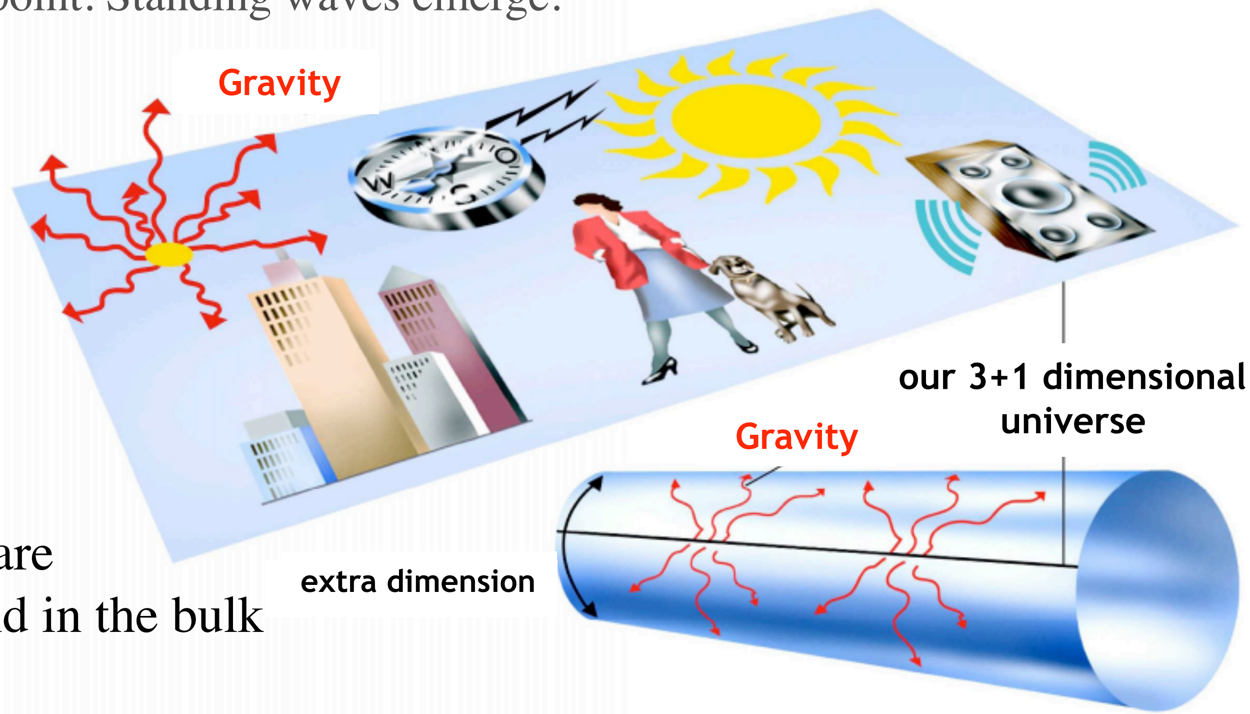
Gravity seems to be 10^{-38} times weaker than the strong interaction -> difficult to unify with other forces! A possible solutions of this hierarchy problems are extra dimensions.

Models with extra dimensions

There are several models, which have the following in common:

- There is a 3+1-dimensional (sub)space (brane, membrane)
- The brane is embedded in an 3+1+d dimensional space (bulk)
- The d extra dimensions have the same size *R*
- All particles and fields living in the bulk are replicated in Kaluza-Klein-towers.

O. Klein 1926: Extra dimensions are rolled up, i.e. a particle, which moves in these dimensions, comes back to the starting point. Standing waves emerge.



Differences between the models:

- Size and geometry of the bulk
- Kinds of particles that are allowed to move around in the bulk

ADD model - large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali *hep-ph 9803315, Phys. Lett. B 429, 263 (1998)*

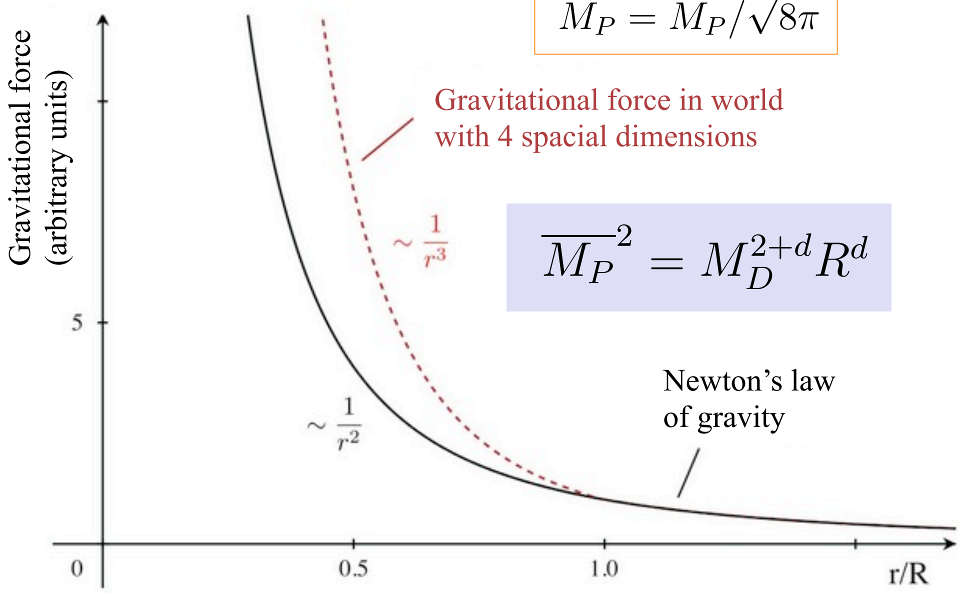
Not the effective 4-dim. Planck scale, but the quantum gravity scale of the higher-dimensional theory M_D is relevant. The only fundamental scale should be the electroweak scale $M_{EW} \approx M_D \approx 1$ TeV!

$$V(r) \sim \frac{m_1 m_2}{M_D^{d+2}} \frac{1}{r^{d+1}}, \quad r \ll R$$

$$V(r) \sim \frac{m_1 m_2}{M_D^{d+2} R^d} \frac{1}{r}, \quad r \gg R$$

$$\overline{M_P} = M_P/\sqrt{8\pi}$$

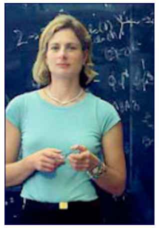
$$\overline{M_P}^2 = M_D^{2+d} R^d$$



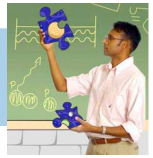
- Known particles live in the 3+1-dimensional brane
- The graviton can also move in the bulk
- There are d≥2 extra dimensions
- Extra dimensions are rolled up in a torus with compactification radius *R*
- $d = 2$: $R \approx 1$ mm, d = 3: R ≈ 1 nm

Newton's law of gravity is tested down to about 0.1 mm.

- The graviton corresponds to a KK-tower with 3+1 mass spectrum $M_l = l/R$ ($l = 0,1,2, \ldots$).



Randall-Sundrum Model (Warped ED)

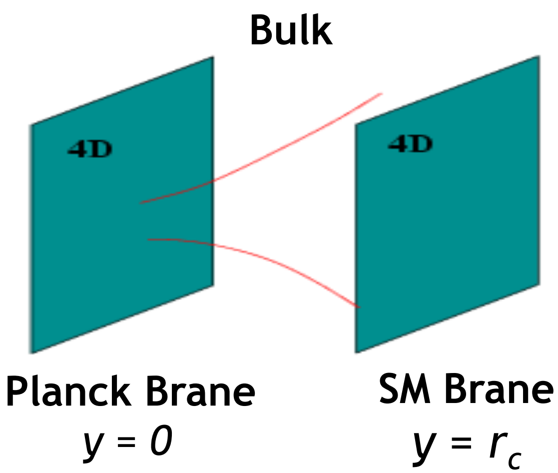


L. Randall, R. Sundrum, PRL ***83*** *(1999) 3370*

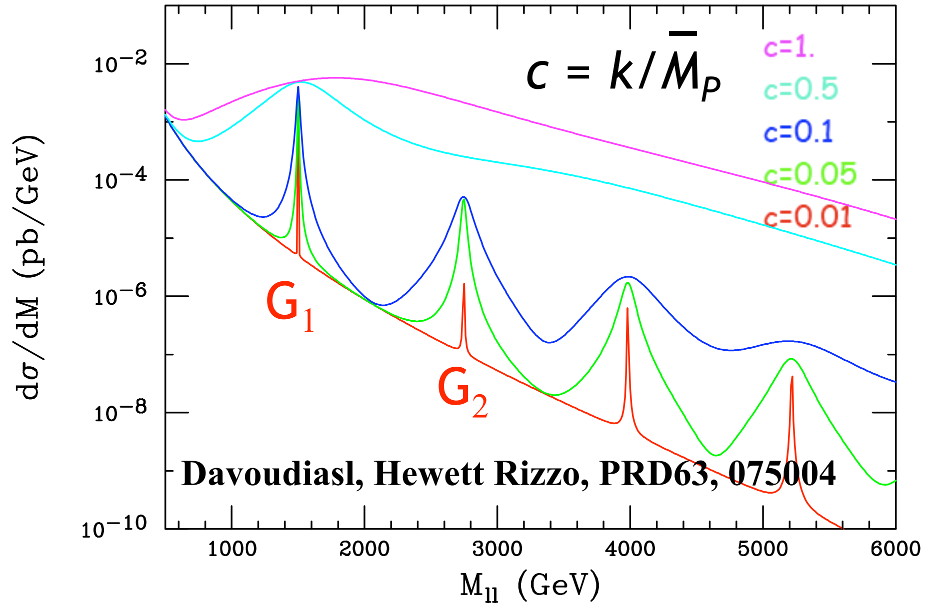
5D-model with warped metric:

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

$\eta_{\mu\nu}$ … graviton field
k …… curvature
r_c …. . distance between branes



Non-equidistant KK-towers

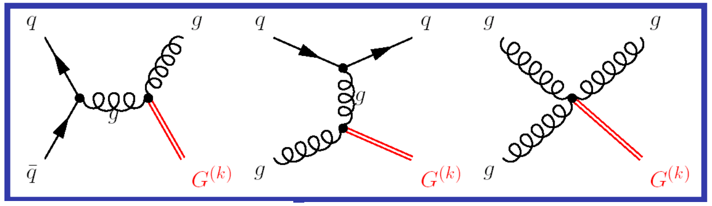


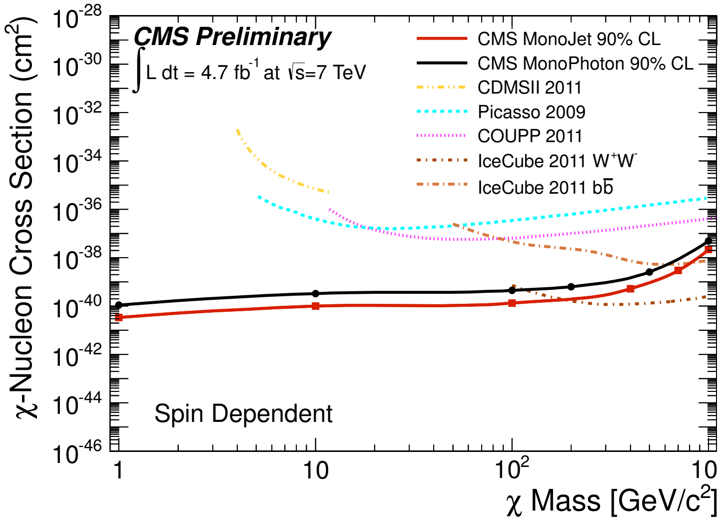
Signature (examples):
$G_1 \to \gamma\gamma,\ e^+e^-,\ \mu^+\mu^-$

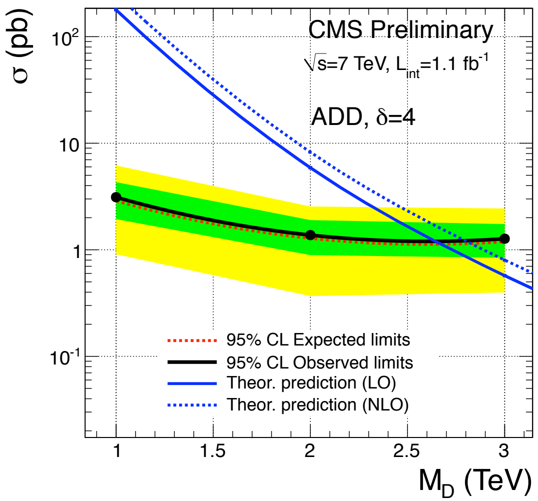
Direct search for large extra dimensions

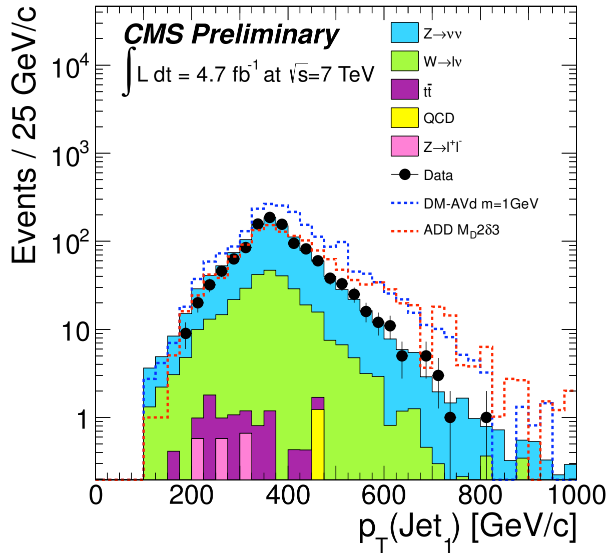
Direct search:

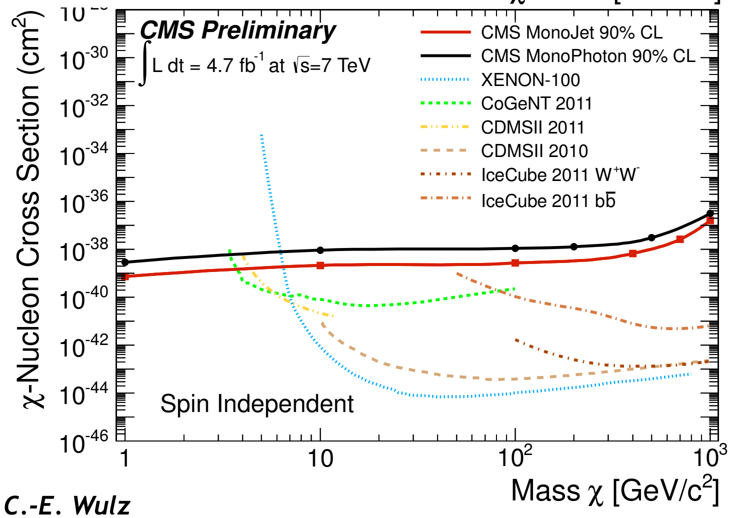
Signature (e.g.): monojet, E_T^{miss}

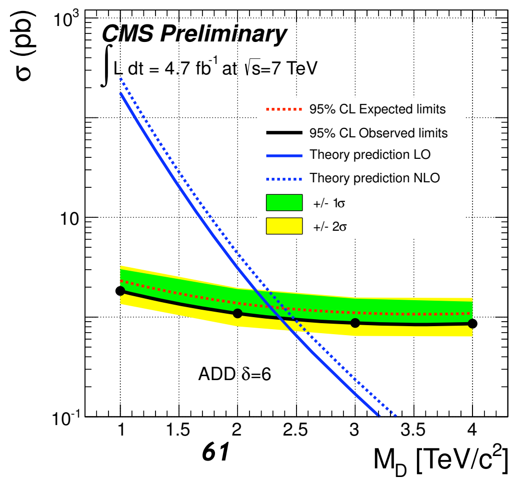












$M_D >$ 4.58 TeV (δ=2)

$M_D >$ 3.54 TeV (δ=3)

$M_D >$ 3.00 TeV (δ=4)

$M_D >$ 2.72 TeV (δ=5)

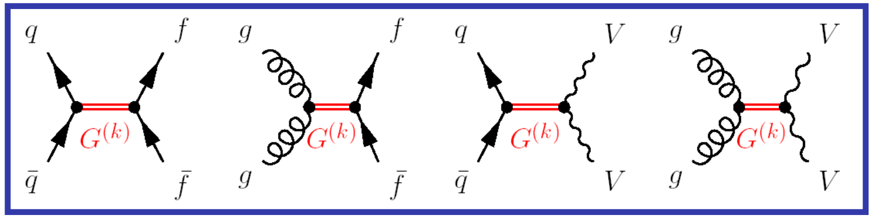
$M_D >$ 2.52 TeV (δ=6)

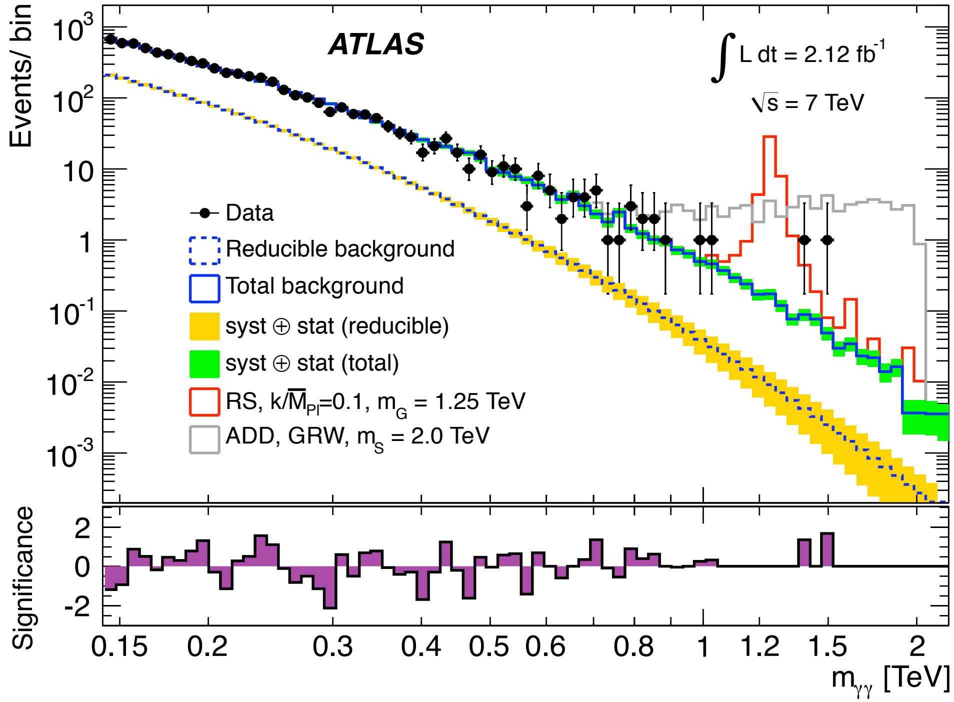
CMS PAS EXO-11-059

Search for large ED with diphotons and dileptons

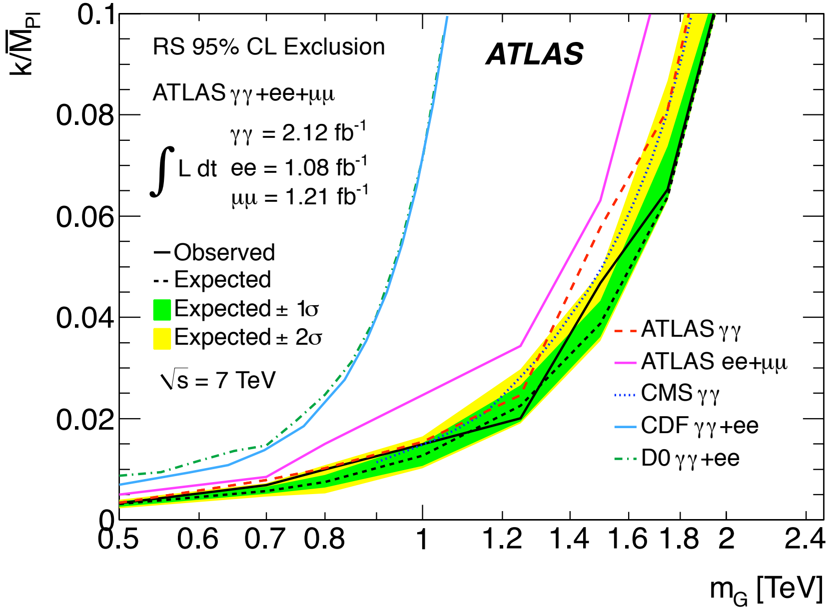
Indirect search:

Signature (e.g.) : enhancement of the Drell-Yan cross section





hep-ex 1112.2194, PLB 710 (2012) 538



2 models studied: ADD and RS

Black holes

Definition:

Object, whose gravitation is so strong that even light cannot escape from it. From the event horizon the escape velocity is larger than the speed of light.

The Schwarzschild radius defines the size of a black hole ($M_{BH} > M_P$):

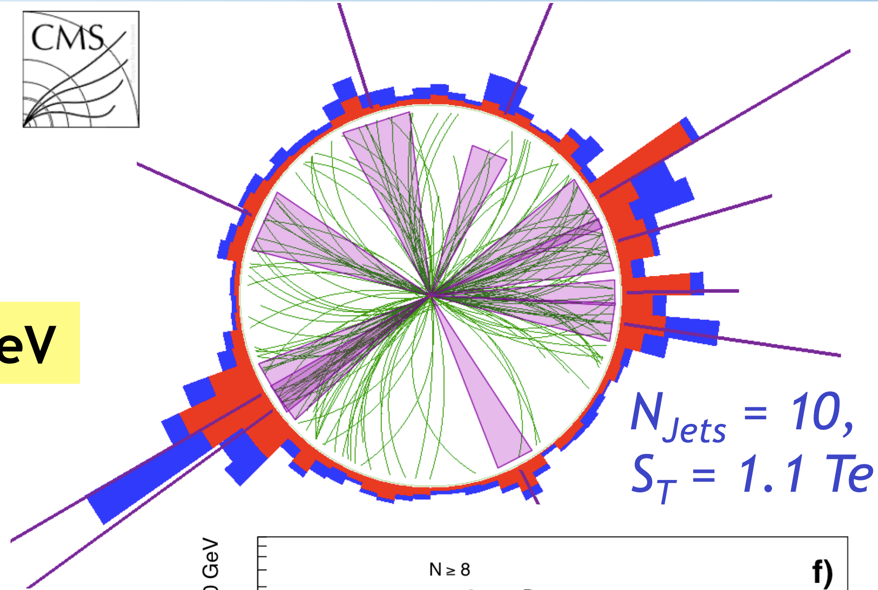
$$R_S = 2M_{BH}G_N/c^2$$

If gravity becomes strong at small distances through extra dimensions (M_P -> M_D), LHC could also produce microscopic black holes (Ø 10^{-18} m). The colliding partons must come closer than a distance of 2 R_S. The black holes should very quickly (~10^{-26} s) evaporate through Hawking radiation (T_H ~$1/M_{BH}$), producing all possible kinds of Standard Model particles. Signature at the LHC: many jets, leptons and photons with high p_T.

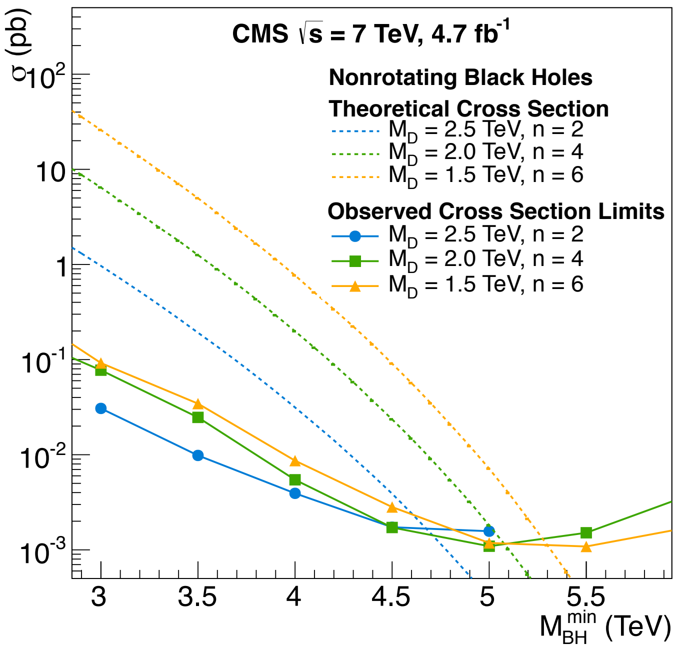
Black holes

Democratic and isotropic decay.
Signature: Events with large transverse energy sum S_T, high multiplicity of jets, leptons and photons.

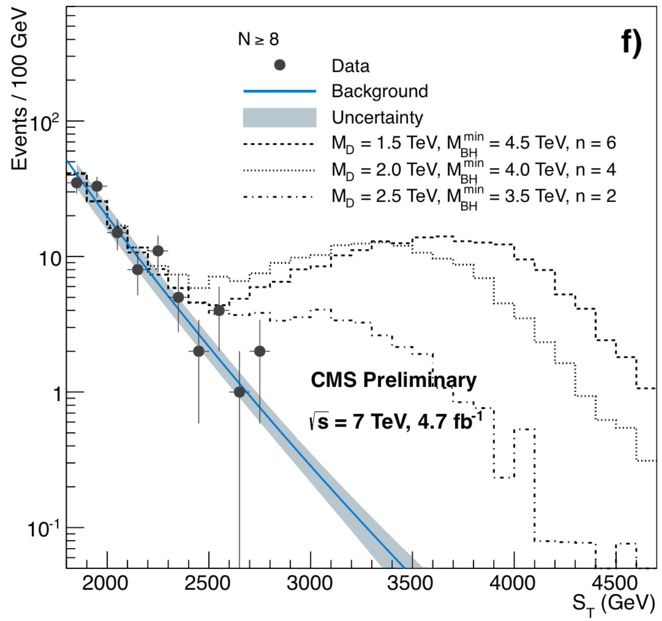
M_{BH} > 3.8 – 5.3 TeV



N_{Jets} = 10,
S_T = 1.1 TeV

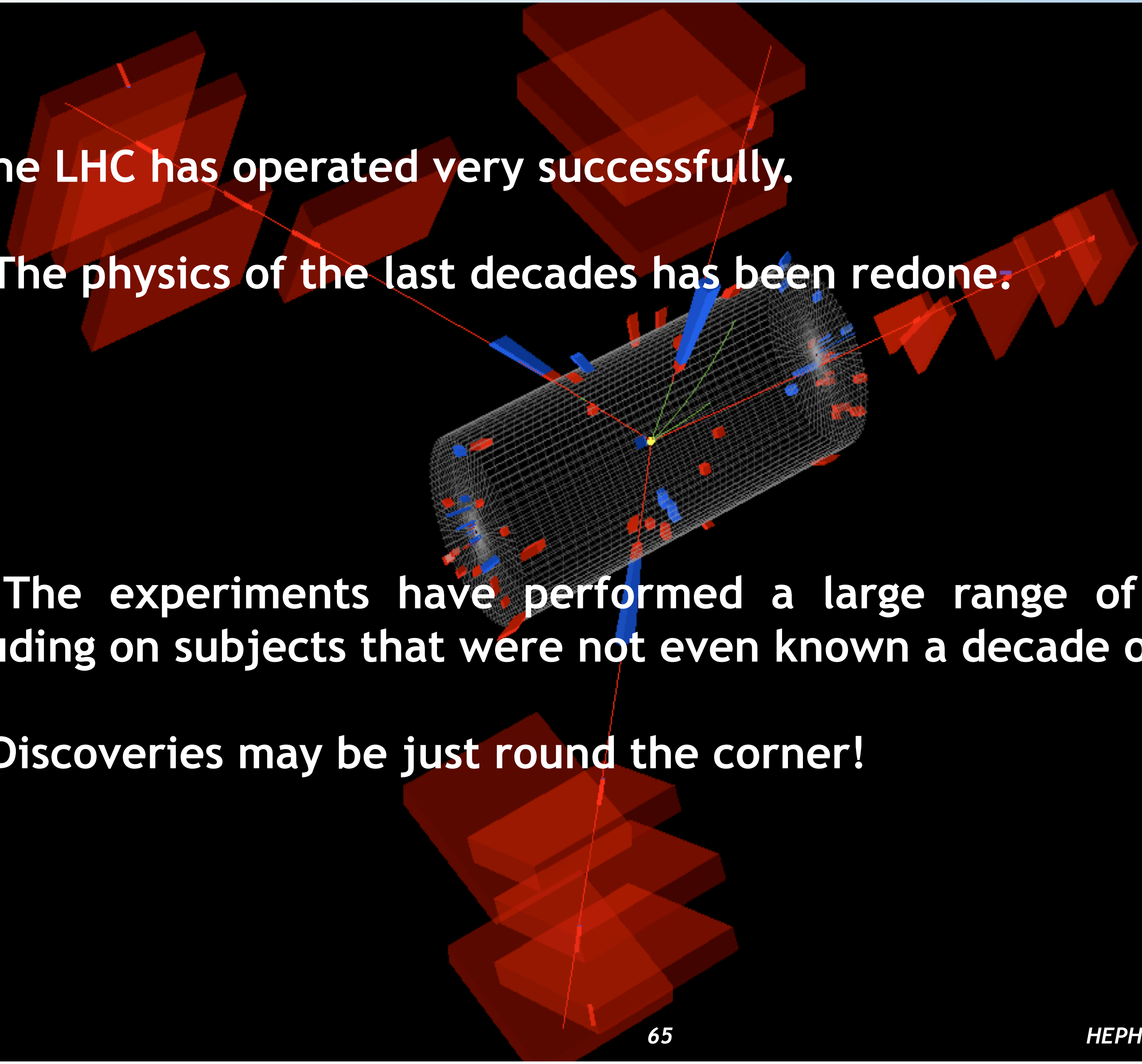


ADD model



hep-ex 1202.6396
JHEP 04 (2012) 061

Conclusions



- The LHC has operated very successfully.
- The physics of the last decades has been redone.
- The experiments have performed a large range of analyses, including on subjects that were not even known a decade or so ago.
- Discoveries may be just round the corner!