Highlights of CMS Physics Results at 7 TeV

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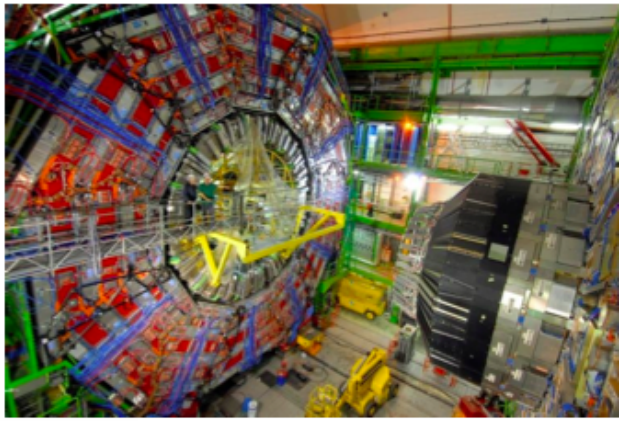
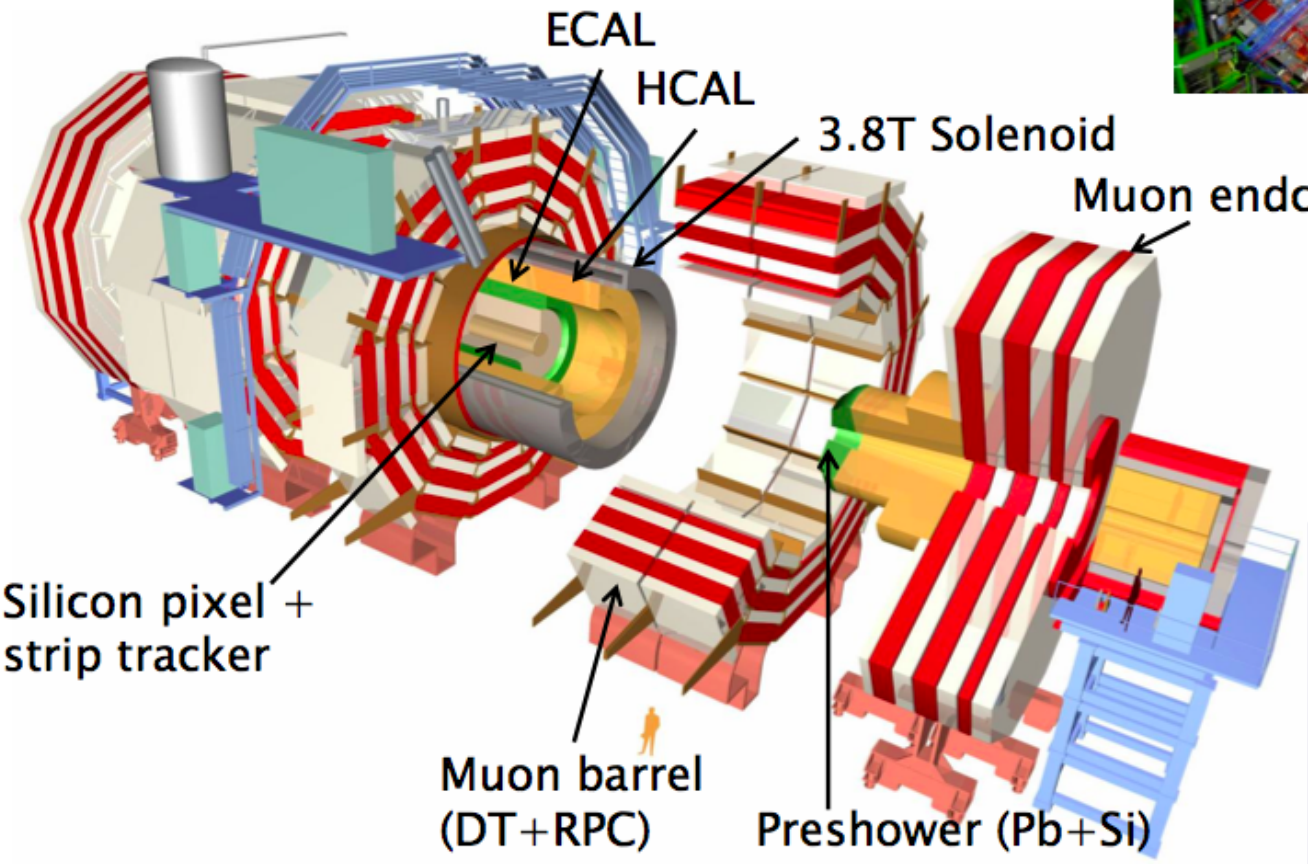
DESY

LHC Forum, DESY, 13 December 2011

The Compact Muon Solenoid detector

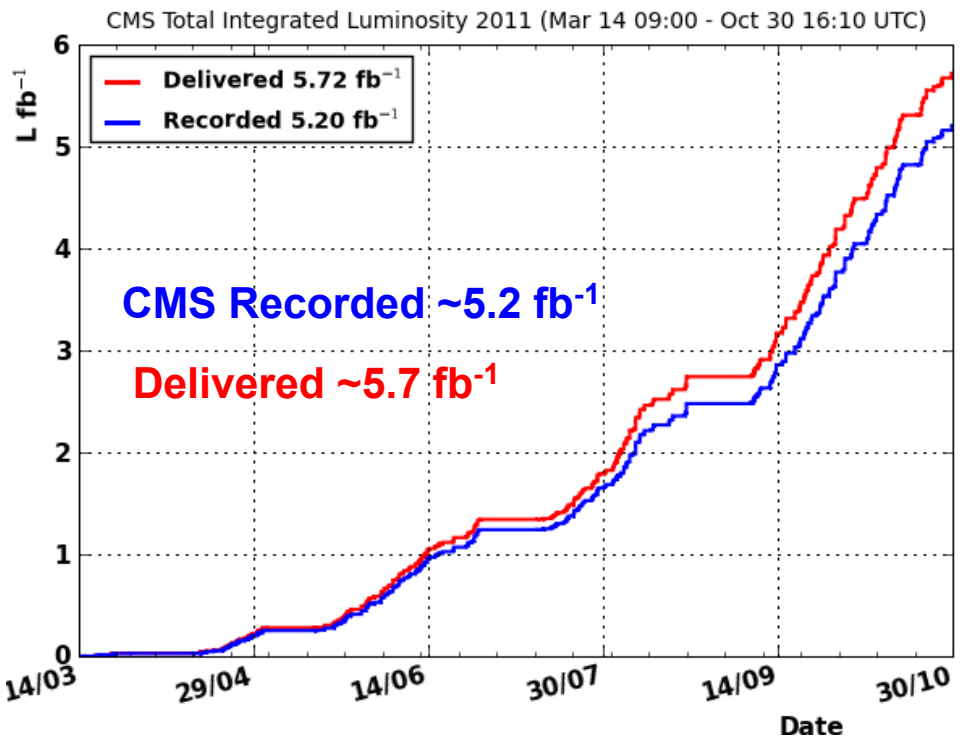


- 21m long, 15m in diameter
- 14000 tons



CMS Collaboration:
- *~2500 scientists + engineers*
- *~850 students*
- *173 institutes*
- *40 countries*

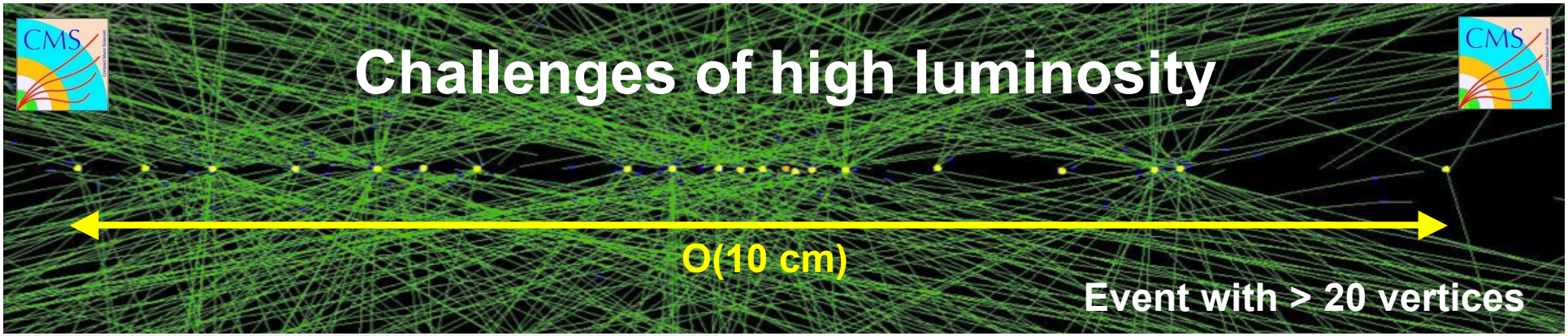
Welcome to the inverse femtobarn era!

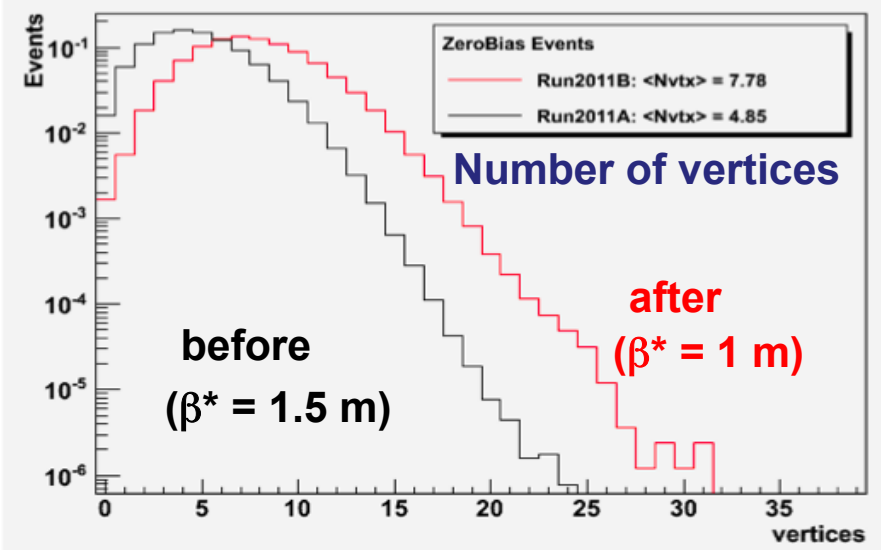


- Recorded 5.2 fb^{-1} of 5.7 fb^{-1} delivered with > 90% data-taking efficiency
- More than factor of 100 improvement over the 2010 statistics
- Max. inst. $\mathcal{L} \approx 3.54 \times 10^{33}\,cm^{-2}s^{-1}$
- Data certification for physics analysis:
  - 85% for all systems perfect
  - 90% for muon analysis (w/o calorimeters)
- Luminosity uncertainty is 4.5%
- All subdetector components operation at the level > 98.5%

Excellent performance of the CMS detector in 2011

Challenges of high luminosity





- High multiplicity of interactions in a single collision of two proton bunches (pile-up)
- Number of reconstructed vertices after the August Stop increased by factor 1.5
  - Fills start with ~15 pile-up interactions
  - CMS can deal with this: high granularity → relatively low occupancies

- Good tracker & vertexing performance: able to efficiently reconstruct vertices separated in z by less than 1mm
- Triggers able to cope with this challenging data-taking conditions
- Offline algorithms subtract activity not coming from event primary vertex
  - Protects performance of physics objects like jets, missing energy, and isolated leptons

Physics Results

The latest results are available here:

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

DESY-UHH contribution to physics analysis

Analysis:

Multiparton interactions/UE

MC tuning

Forward energy flow, hard forward/central jets

Drell-Yan and Zbb cross sections

Top-pair (differential) cross sections in (l+jets, dileptons), all hadronic channels

Cross section ratio $\sigma(t\bar{t})/\sigma(Z)$

Simultaneous top mass and JES measurement in l+jets

Top mass determination from cross section

SUSY searches in single photon, all hadronic, single tau

SUSY searches in SS and OS dileptons, single leptons with b-tag

SM and MSSM Higgs searches: $H(A)\to\tau\tau\to ll$, $bbH(A)\to bbbb$

Predictions based on HERAPDF, PDF fits using CMS data

Tools for analysis:

DQM / data certification

Alignment

Btagging

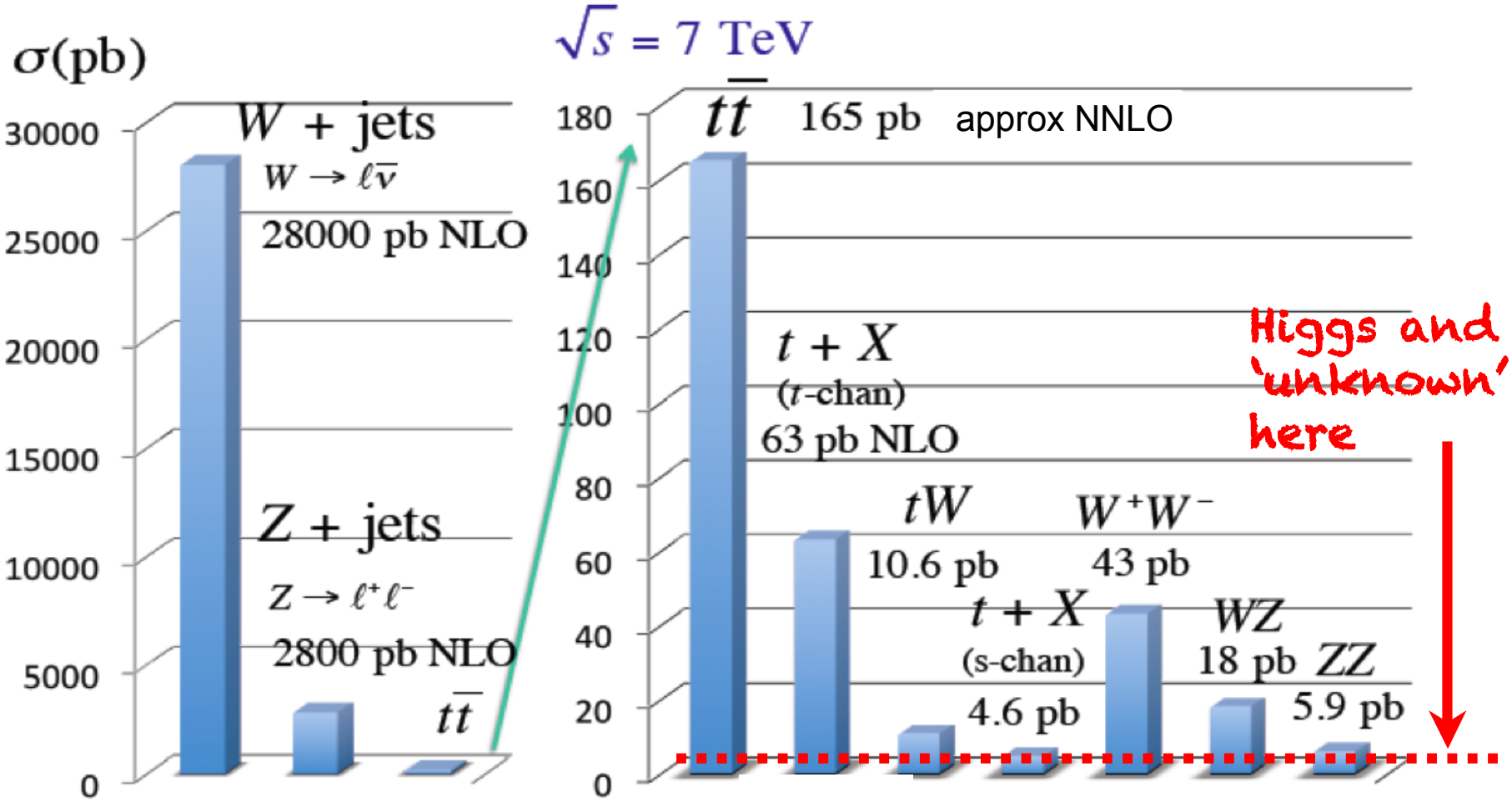
Trigger development

Jet energy calibrations

HERAFitter development

From the Standard Model to the unknown

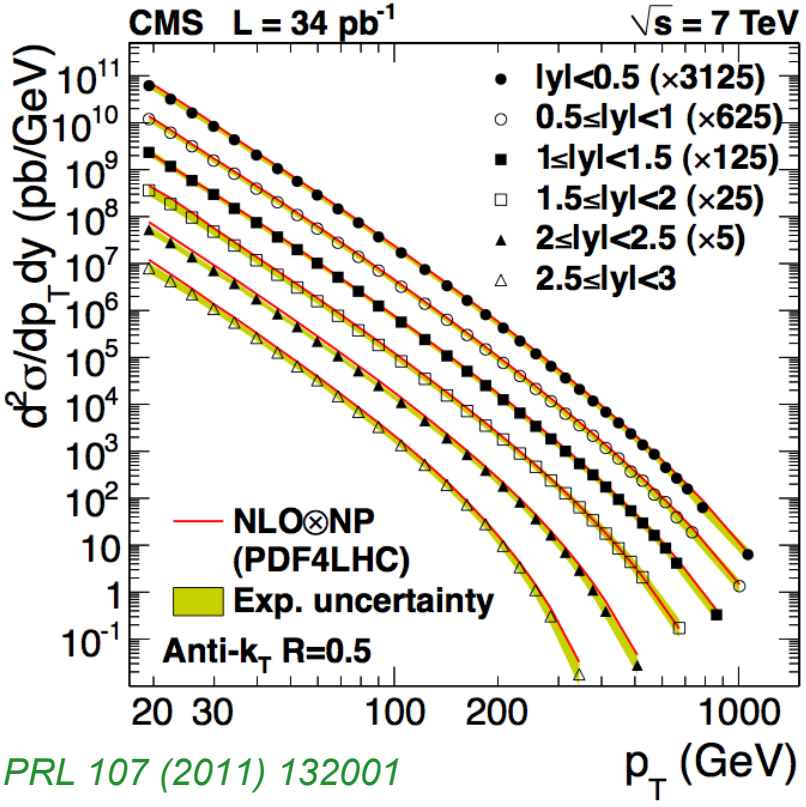
Cross sections for key Standard Model background processess



Deep understanding of SM processes necessary to investigate Higgs/New Physics processes

Jet cross-section measurement

Inclusive jet production rate

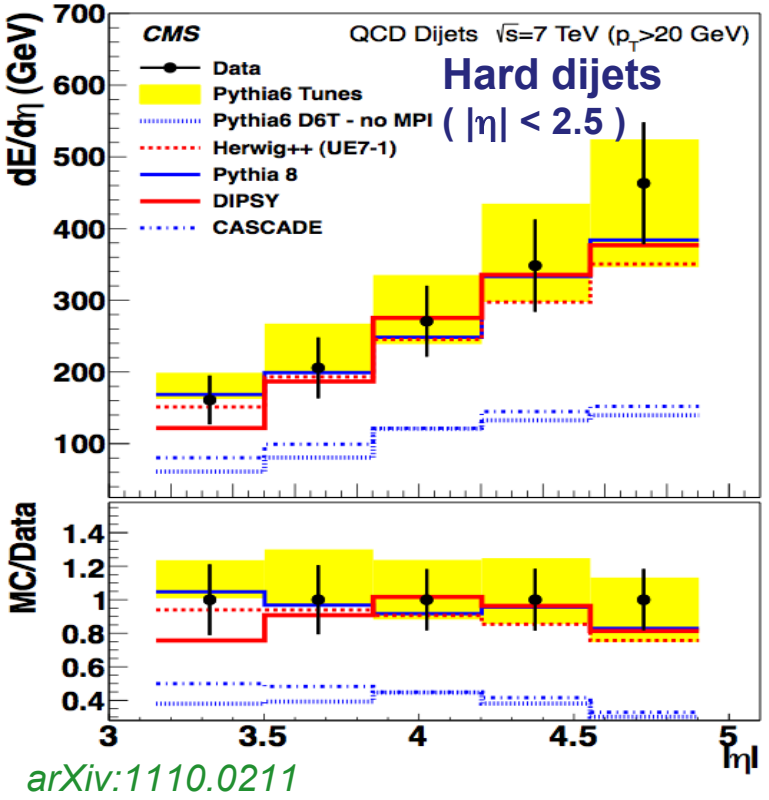


PRL 107 (2011) 132001

- Jets with p_T up to 1100 GeV and $|\eta| < 3$
- Good agreement, within uncertainties, with NLO QCD predictions and up-to-date PDFs in over 10 orders of magnitude!

DESY

Forward energy flow



arXiv:1110.0211

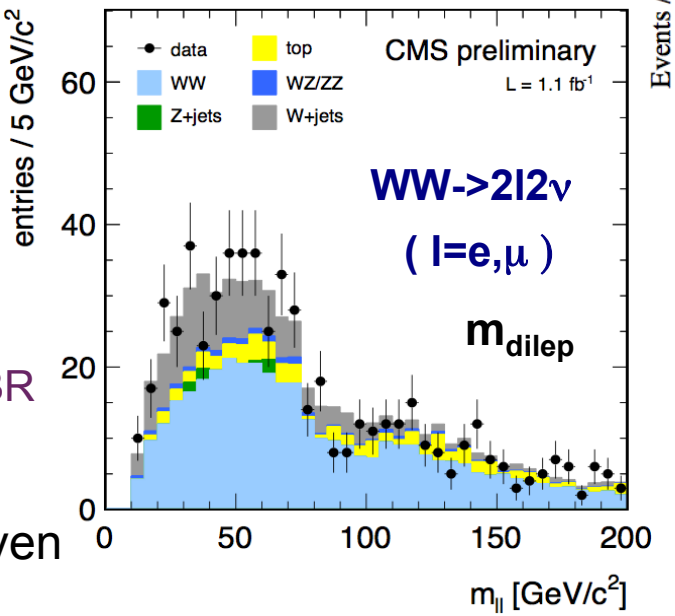
- Minimum bias and hard dijets at 0.9, 7 TeV in $3 < |\eta| < 5$
- Sensitive to multiparton interaction modelling
- No model describes data at all energies

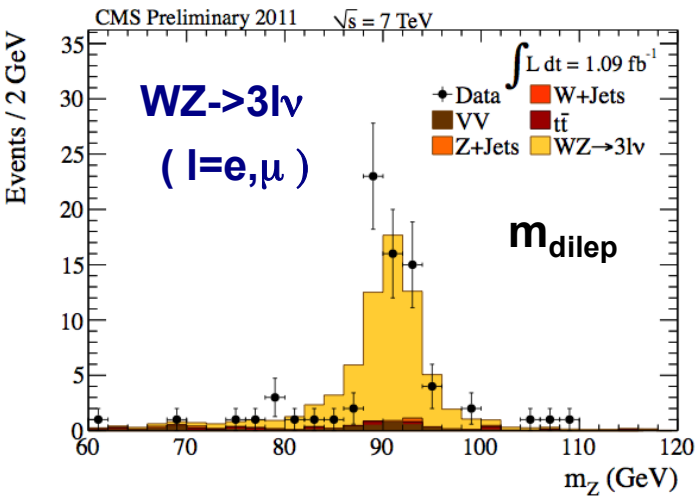
➔ Valuable input for tuning of MC generators

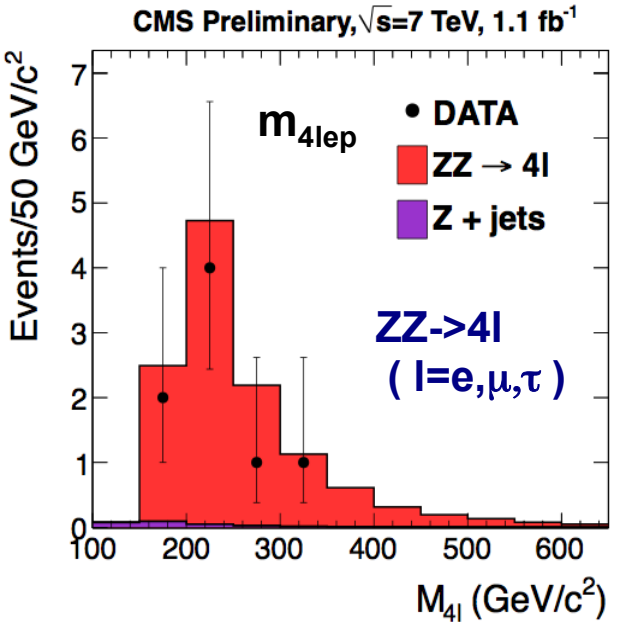
Electroweak: diboson cross sections (1.1 fb^{-1})

Test trilinear gauge couplings, indirect probe for NP, background for searches

- First measurements of WZ, ZZ cross section at 7 TeV !
- Use different leptonic decay modes
  - clean signature, but low BR
- Main backgrounds are estimated using data-driven methods
- Consistent with SM predictions:



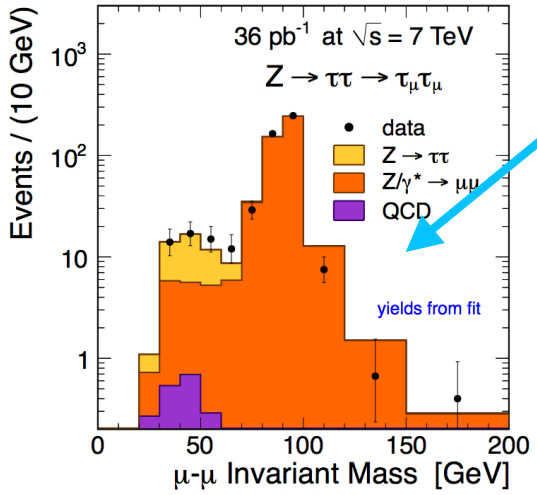




	Candidates	Background	σ (pb)	SM pred (pb)
WW	626	~202	55.3 ± 8.3	43.0 ± 2.0
WZ	75	~8	17.0 ± 2.8	19.8 ± 0.1
ZZ	9	~1	3.8 ±1.5	6.4 ± 0.6

CMS-PAS EWK-11-010

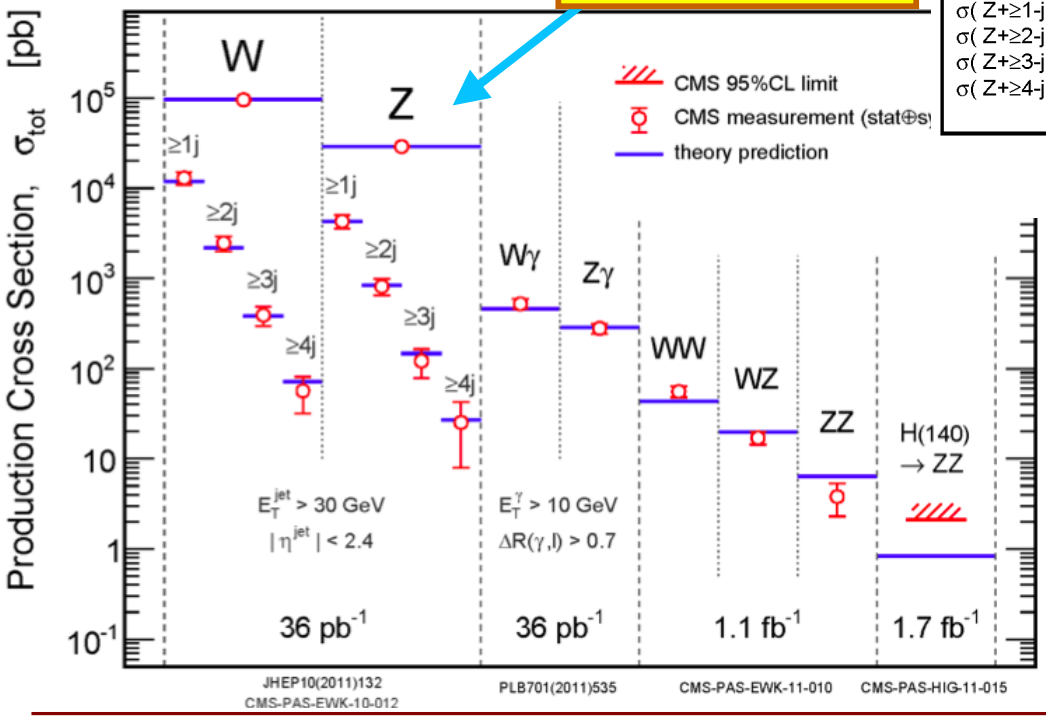
Summary of electroweak measurements

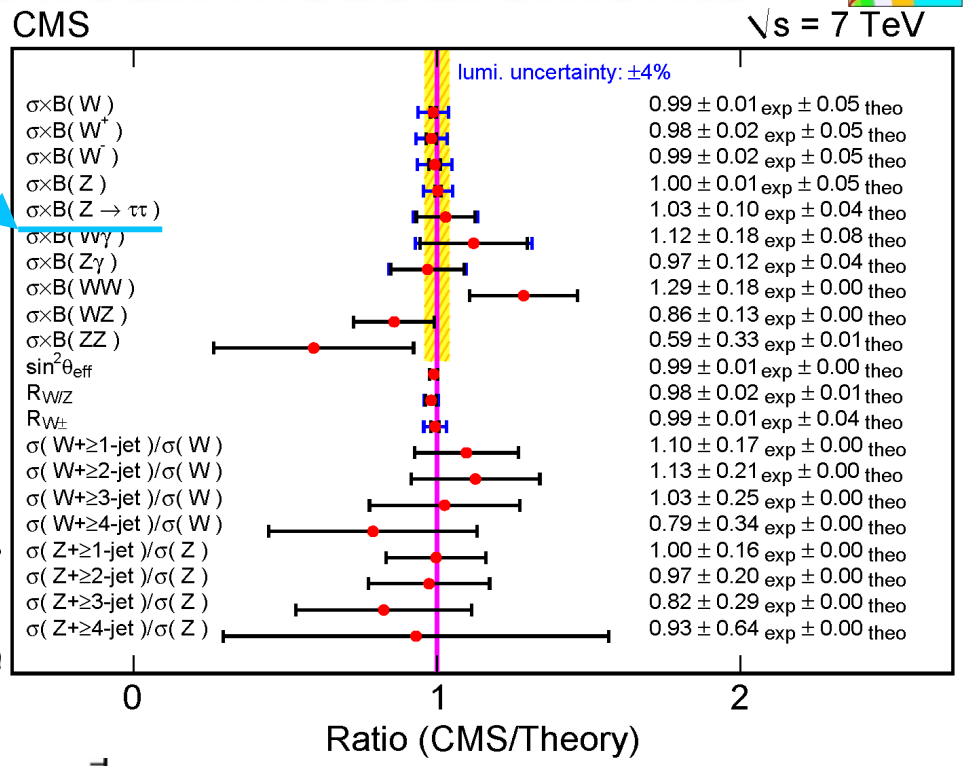


DESY:
Z->ττ->μμ,
JHEP 08 (2011) 117

DESY:
Z+b xsec paper

coming up soon!

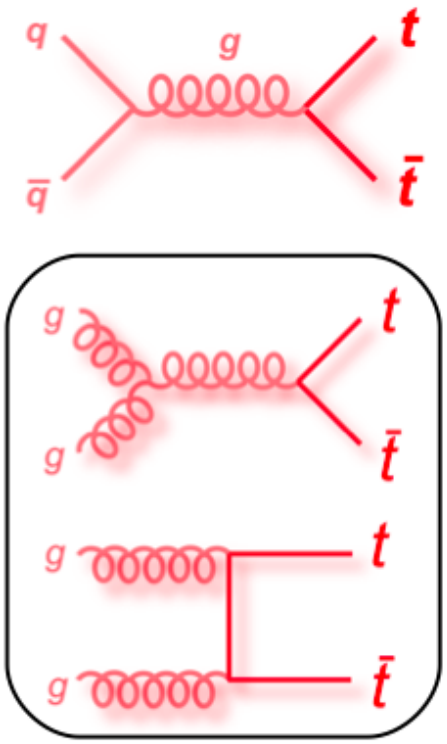




So far, very good agreement with predictions

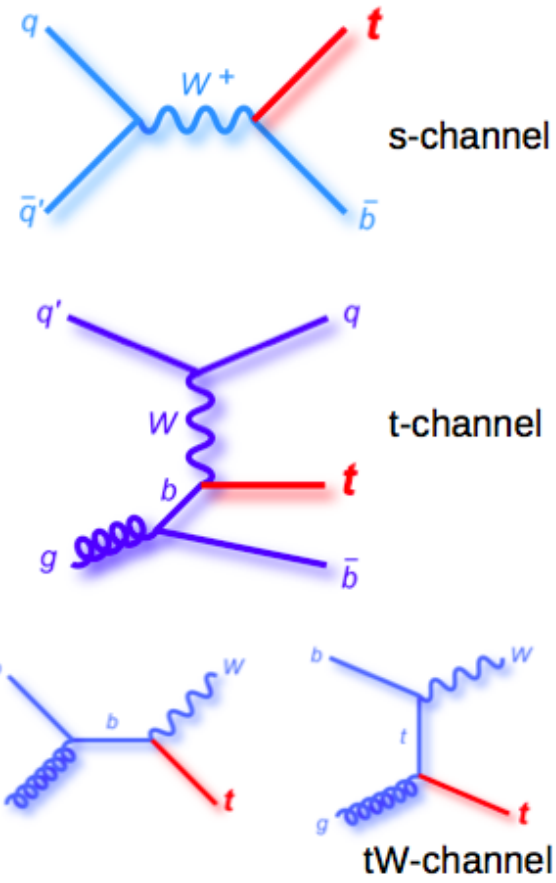
Top quark physics

Pairwise production of top and antitop via $q\bar{q}$ annihilation or gluon fusion

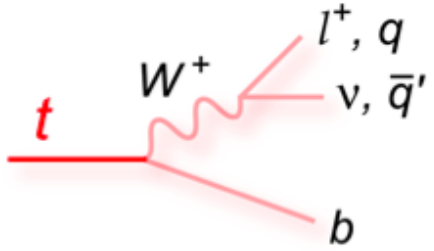


Dominant process at LHC

Production of single top quarks via electroweak force



Top quark decays into b quark and W boson



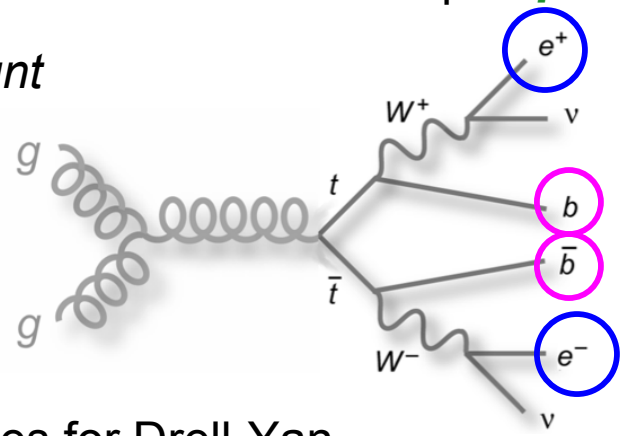
Event-classification depending on W-decay:
- dilepton
- lepton+jets
- allhadronic

Top-pair cross section measurements

Dilepton channel (1.14 fb^{-1}): DESY

UHH: tt->l+jets; also 36 pb^{-1} result: *EPJ C71 (2011) 1721*

- Update of published 2010 result with 36 pb^{-1} *[JHEP 07 (2011) 049]*
- Robust *cut-and-count* experiment in the **ee, μμ, με** channels



- Data-driven estimates for Drell-Yan, W+jets, QCD backgrounds
- Combined cross section:

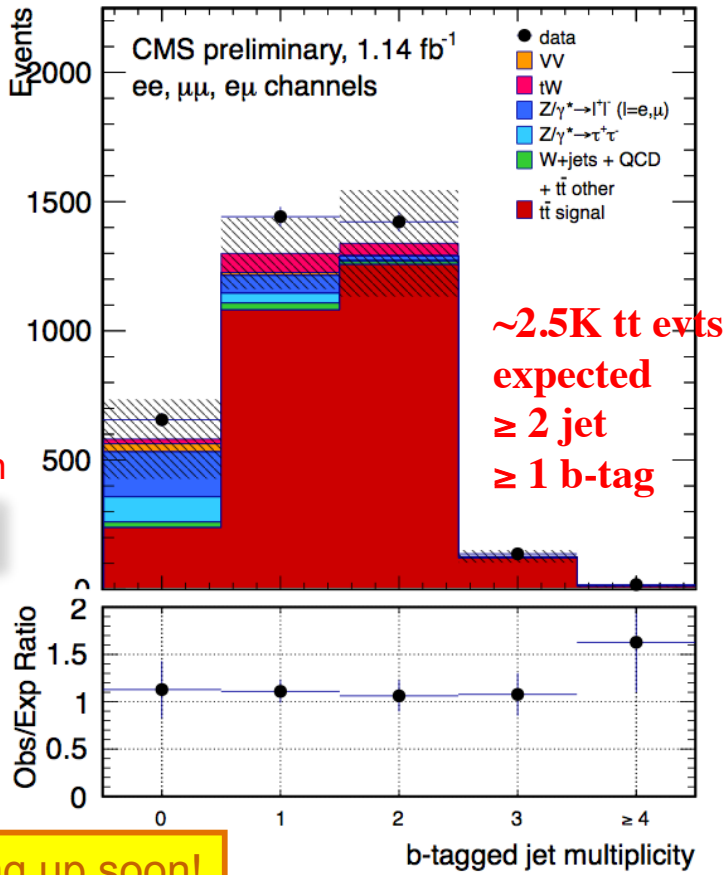
10.8% precision

$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

(2010 result: σ_{tt} = 168 ± 18(stat) ± 14(syst) ± 7(lumi) pb, 14% prec.)

Main systematics from b-tagging (~5%), lepton selection (~4%), pileup (~4%)

CMS-PAS TOP-11-005



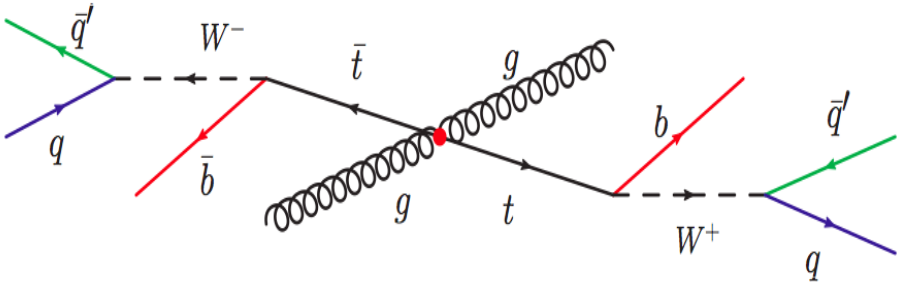
Differential cross sections in dileptons and l+jets coming up soon!

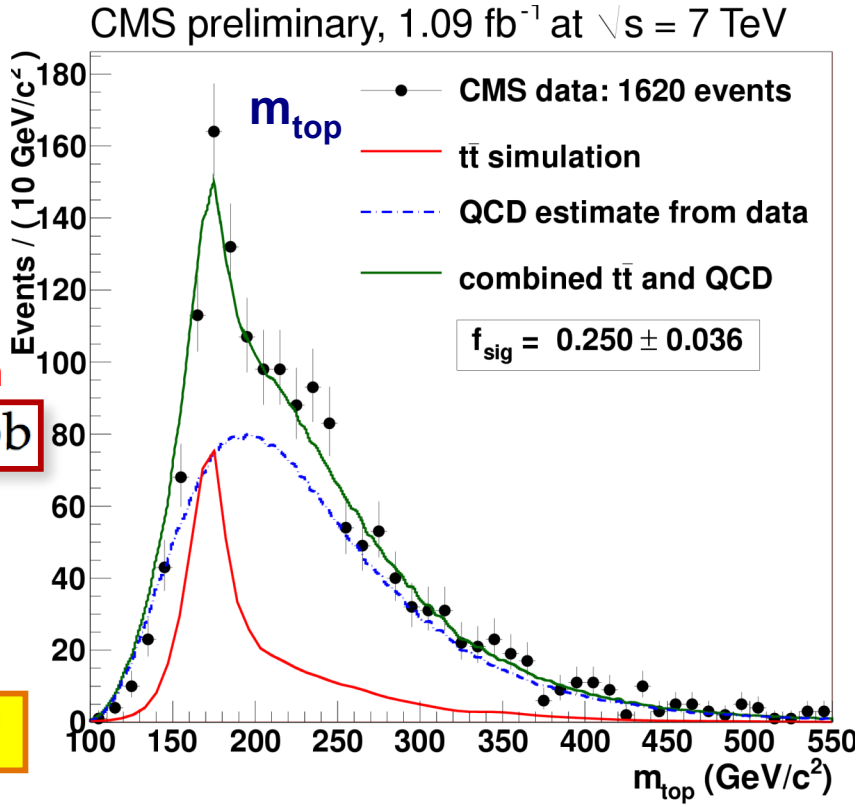
Top-pair cross section measurement

All hadronic channel (1.09 fb^{-1}): UHH

CMS-PAS TOP-11-007

- Large branching ratio (~ 45%), but suffers from large multijet background
- Selection: ≥ 6 high-p_T jets, 2 b-tags
- Cross section from unbinned maximum likelihood fit to reconstructed top mass distribution
- QCD background shape from sideband region in data (zero b-tag)





33% precision

$$\sigma_{t\bar{t}} = 136 \pm 20\,(\text{stat.}) \pm 40\,(\text{sys.}) \pm 8\,(\text{lumi.})\ \text{pb}$$

Main systematics from b-tagging (~16%), jet energy scale (JES) (~14%), background (~12%)

Paper coming up soon!

Top-pair cross sections summary 2011

CMS combined 2011: 8% precision

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb}$$

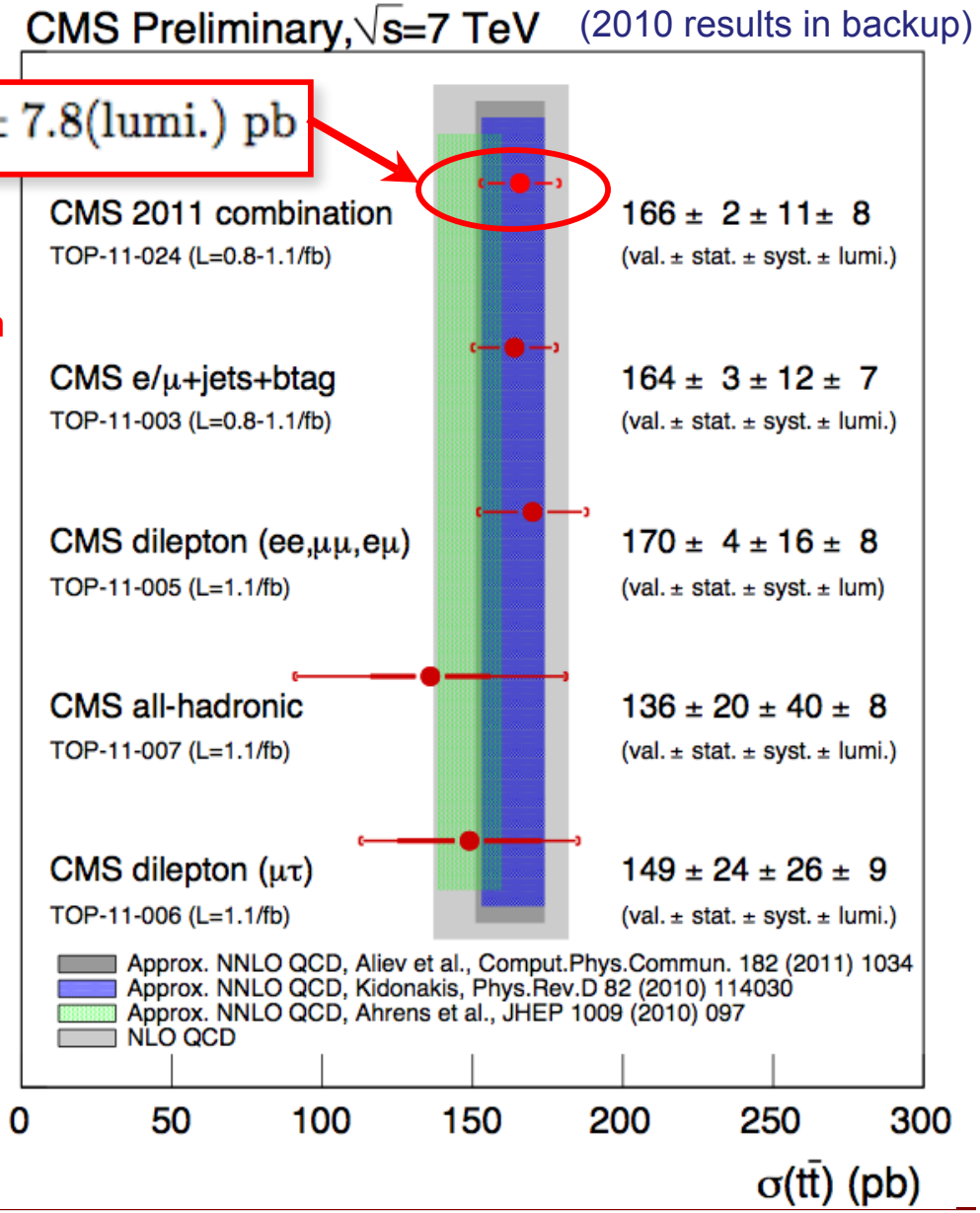
CMS combined 2010 (36 pb^{-1}):

$$\sigma_{t\bar{t}}(\text{CMS}) = 158 \pm 19\ \text{pb.}$$

12% precision

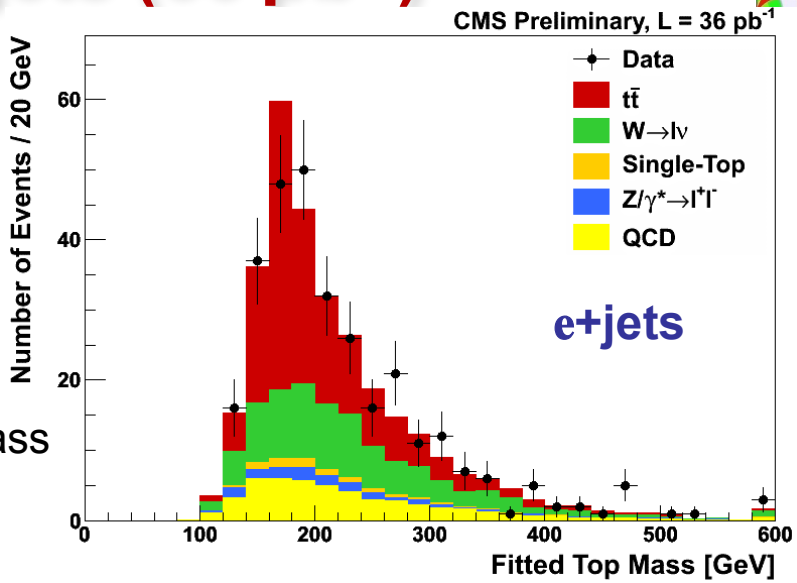
- Measured cross sections in agreement with each other and with SM predictions
- All measurements are now systematics limited by far

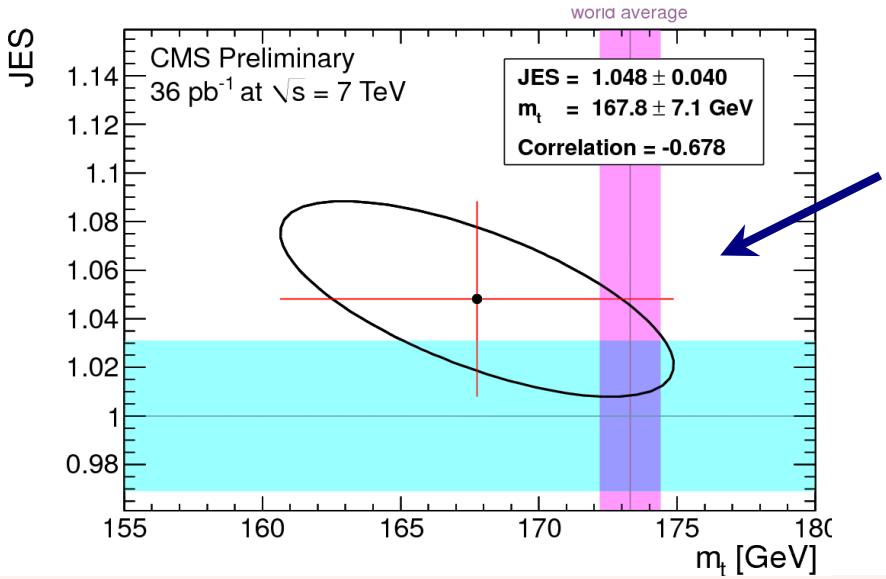
Start to become sensitive to differences between various approximations to NNLO theory !



Top quark mass in l+jets (36 pb^{-1}) UHH

- Select semileptonic ttbar events, requiring 1 isolated μ/e, ≥ 4 jets
- Kinematic fit to reconstruct top mass for each event and each jets combination
- Event likelihood as a function of the top mass hypothesis
- Joint likelihood fit over all events to extract top mass





- **Cross check**: simultaneous top mass and JES measurement in μ+jets:
  - Template fit of the top mass and the jet energy scale (JES) using 3-jet and 2-jet reconstructed mass, requiring 2-btagged jets
  - Consistent with main result

CMS-PAS TOP-10-009

- Combined e+jets & μ+jets: $m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst})$ GeV. Main syst: JES (2.3 %)
- Combined CMS result (with dilepton): $m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})$ GeV. **2% prec.**

t-tbar mass difference in μ+jets (1.09 fb^{-1})

Test of CPT invariance: particle and antiparticle must have the same mass

2σ deviation reported by CDF *[PRL 106, 152001 (2011)]*

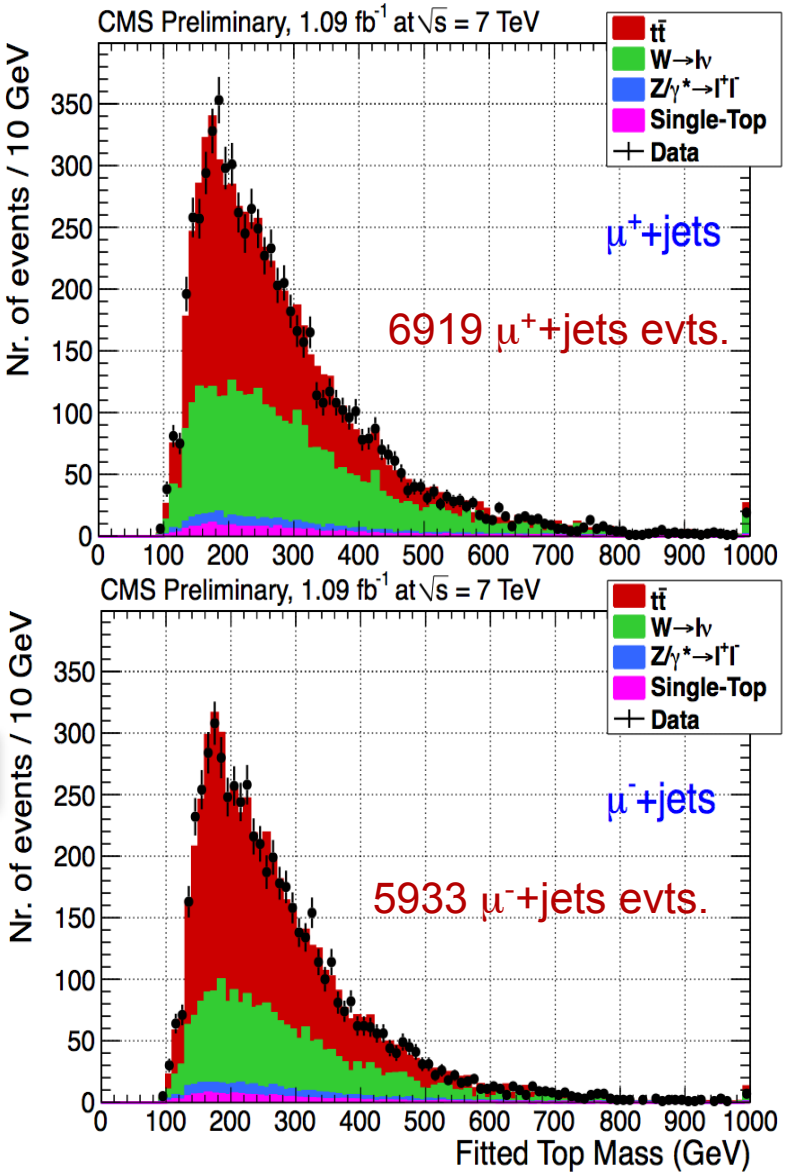
- Use μ+jets ttbar events (positive/negative μ)
  - 1 isolated high-p_T μ, ≥ 4 jets
- Mass reconstructed from hadronic t, tbar decay
  - Kinematic fit from the jet combination with lowest χ^2
- World's best measurement so far!

$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

- Still statistically limited

JES uncertainty largely cancelled in the mass difference

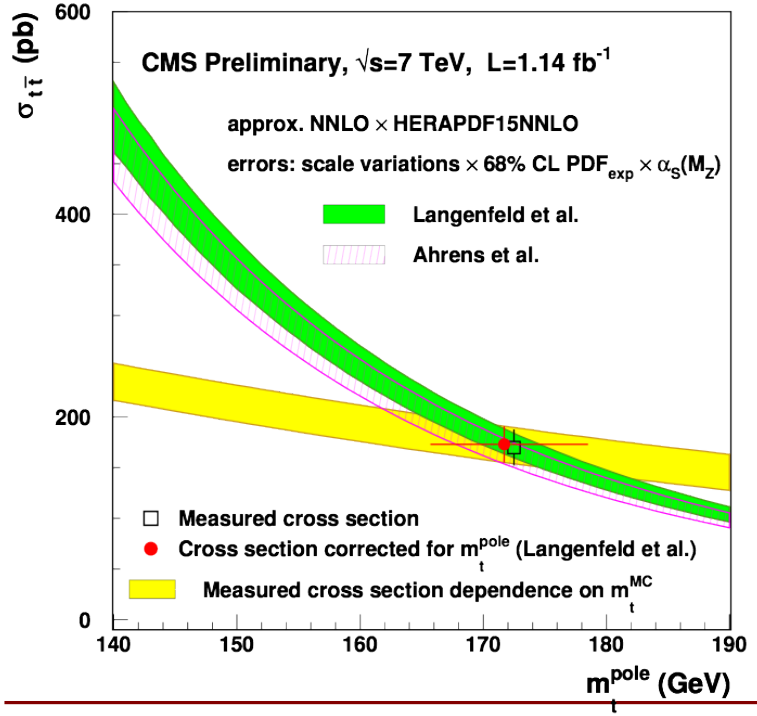
CMS-PAS TOP-11-019



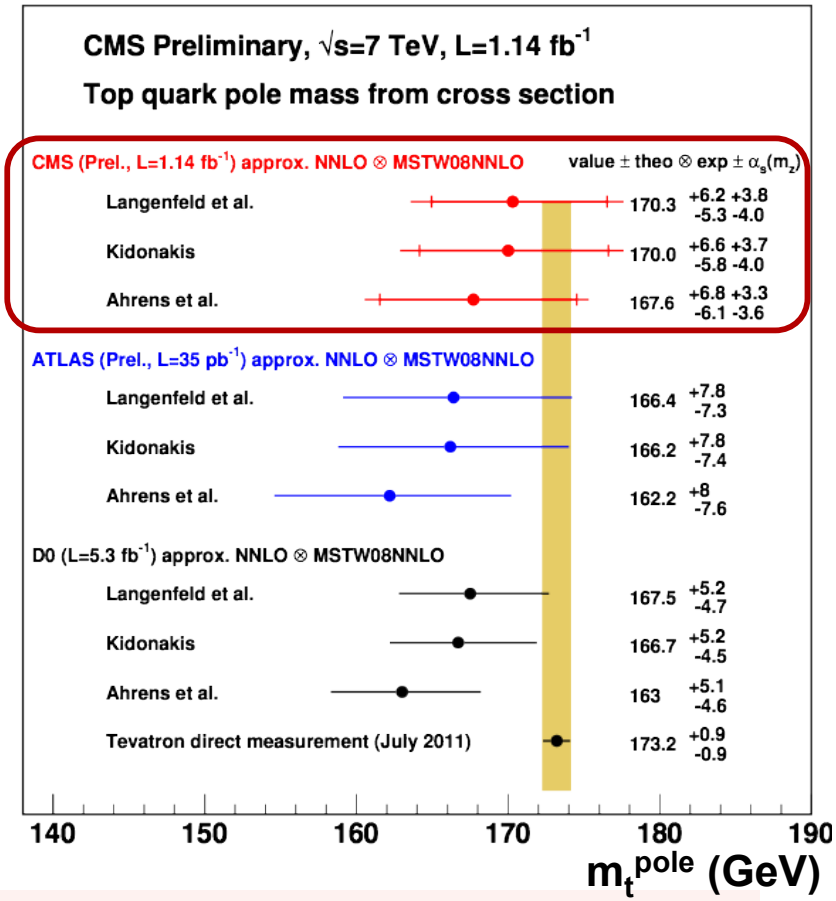
Top mass from cross section (1.14 fb^{-1})

DESY

- Extract the top quark mass, **pole** and **msbar mass**, from the inclusive dilepton cross section:
  - provides top quark mass value in an exact definition
  - important cross-check, complementary to direct top mass measurements
- Maximize a joint likelihood of measured and predicted cross section to extract the top mass



CMS-PAS TOP-11-008

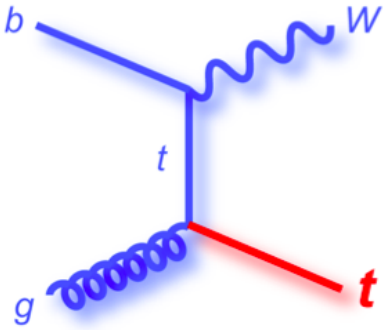


Good agreement between different calculations
Results consistent also with other experiments

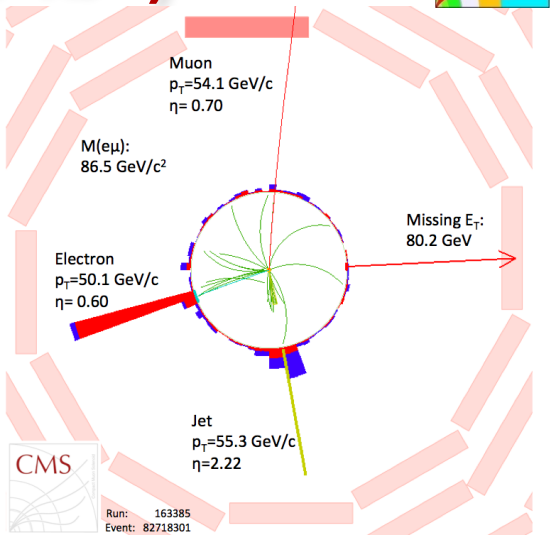
Precision limitations:
- systematic uncertainty of the measurement
- PDF uncertainty + α_S uncertainty in the PDF

Single top in tW mode (2.1 fb^{-1})

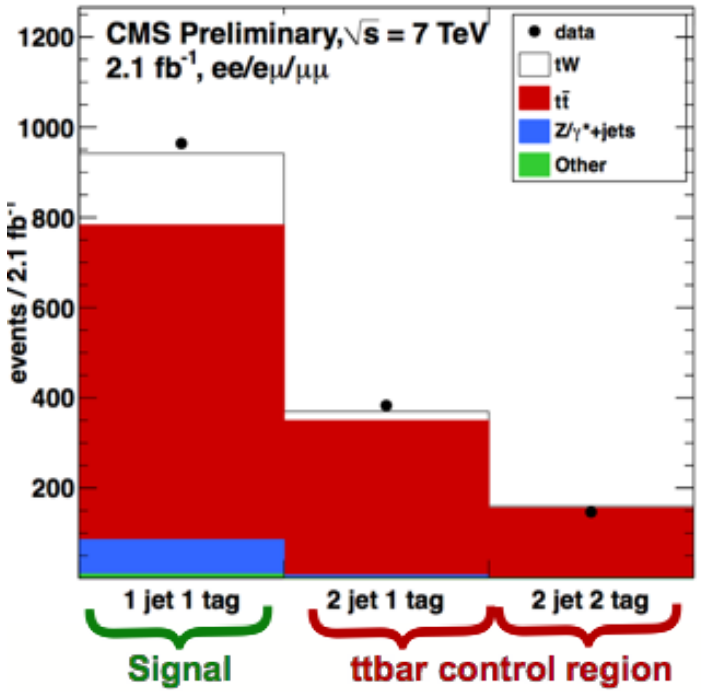
Test unitarity of CKM matrix ($\sigma \propto |V_{tb}|^2$), background for Higgs searches



NNLO approx. σ = 15.6 ± 1.3 pb
(Tevatron: 0.25 ± 0.03 pb)



- Good/bad news: looks like ttbar; easy to observe, but much ttbar background
- Select dilepton events with exclusively one b-tagged jet, Z veto, veto evts. with add. loose jets (tagged)
- Use two ttbar-enriched sidebands to constrain ttbar contribution and b-tagging efficiency (main syst uncert)
- Drell-Yan bg also determined from data

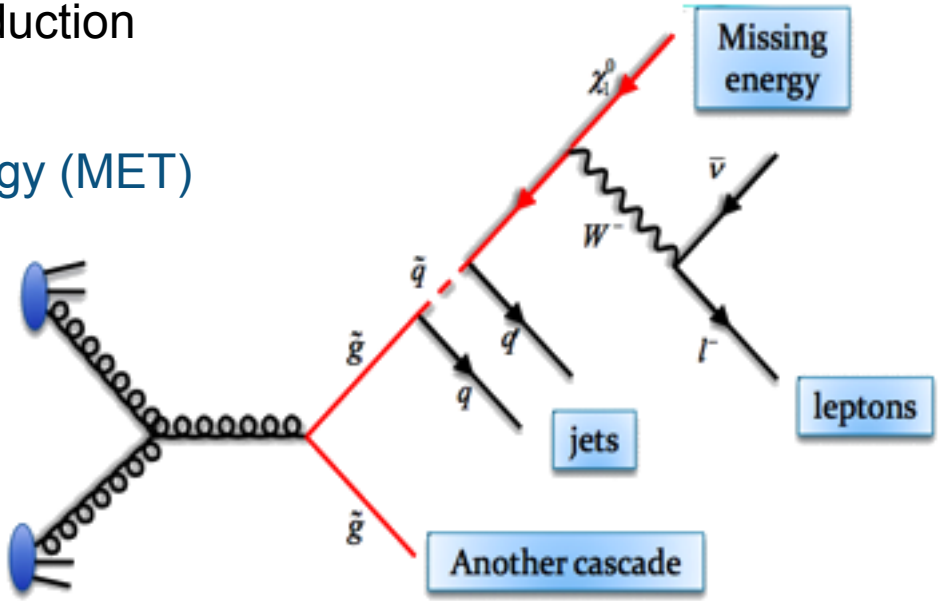


- Observed significance: **2.7σ** (1.8σ expected)
- Observed cross section:

$$22^{+9}_{-7}\ (\text{stat} \oplus \text{syst})\ \text{pb}$$

Searches for Supersymmetry

- Potential discovery due to strong production of squarks and gluinos:
  - Large total energy and missing energy (MET)
  - Long decay chains possible



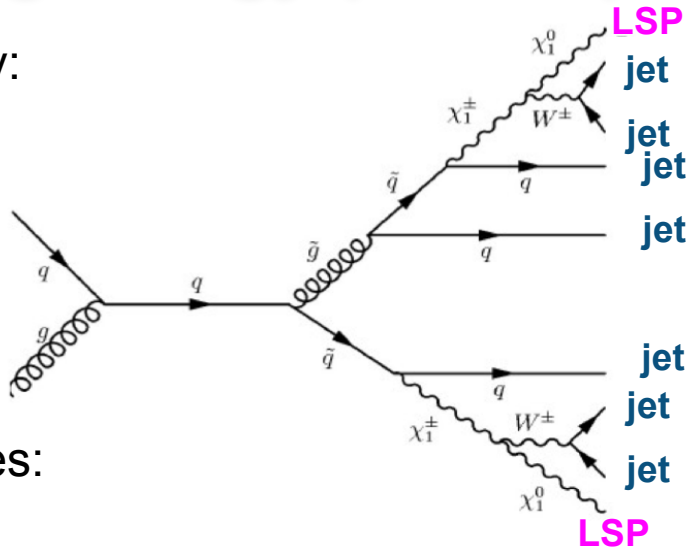
- Topology-based searches, not optimized for any particular model
- Generic MET signatures
  - Categorized by number of leptons, photons or jets
- Look for excess production of these signatures wrt SM prediction
- No excess found? → set limits

All-hadronic + missing energy (1.1 fb^{-1})

UHH

- Select events with large hadronic activity:

$$H_T = \sum_{jets} |\vec{p}_T| \qquad MH_T = \left| \sum_{jets} -\vec{p}_T \right|$$

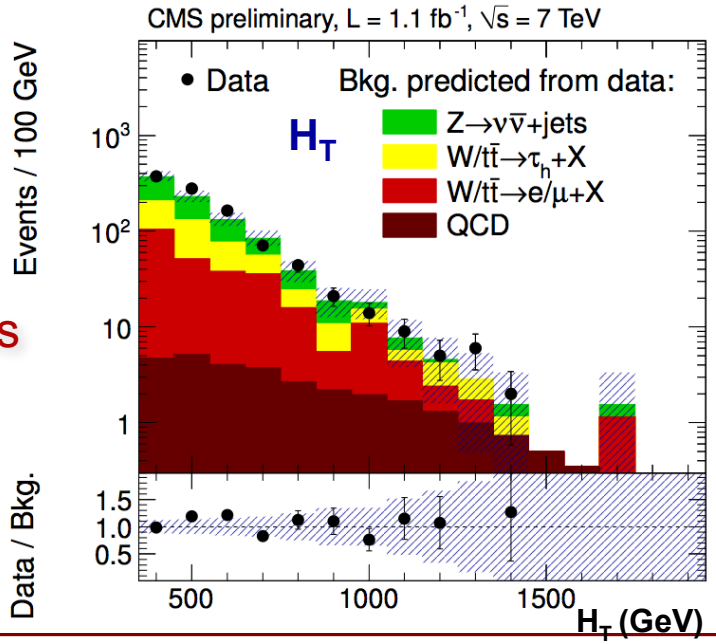


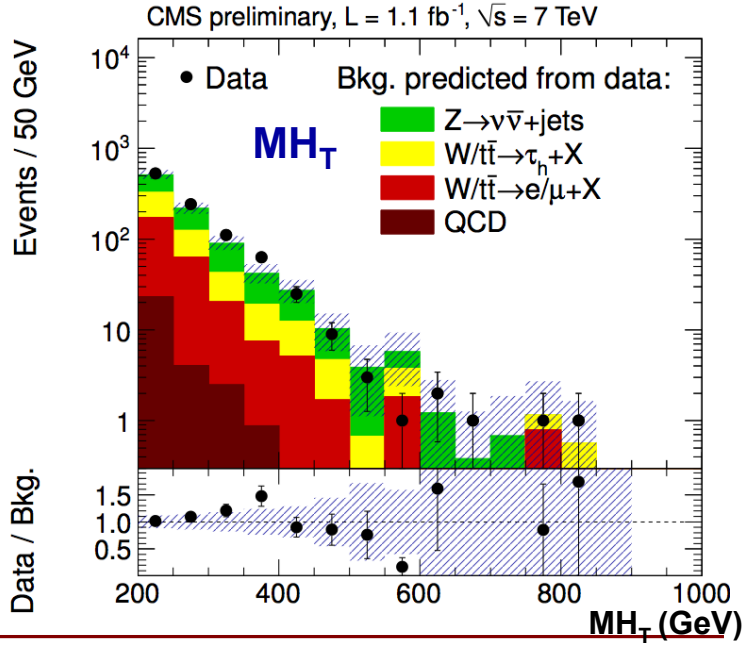
- Search in 3 (H_T, MH_T) regions
- Backgrounds from data-driven techniques:
  Z->νν+jets, QCD, W+jets, ttbar

CMS-PAS SUS-11-004

- Expect SUSY to show up in the tails of the distributions

So far, no excess of events observed

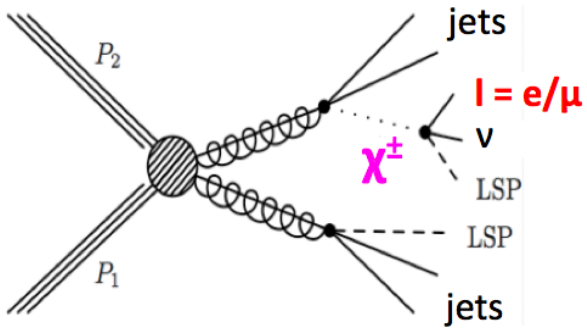




Single Lepton + jets + E_T^{miss} (1.14 fb^{-1})

DESY: SL w btag

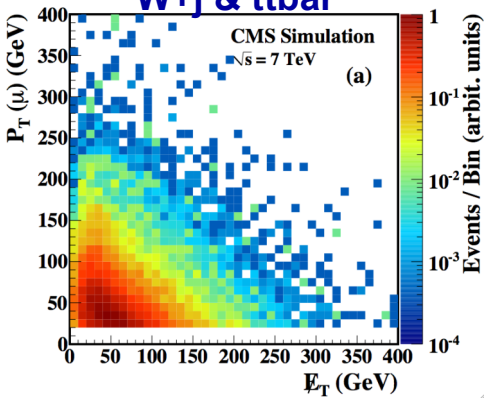
Paper coming up soon!



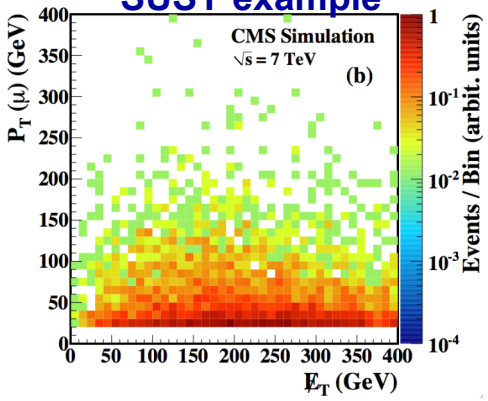
- Exactly 1 isolated μ/e
- ≥ 3-4 jets
- large H_T, large E_T^{miss}

- Main bg: W+jets, ttbar+jets
  - Single lepton (dominant):
    - Exploit the fact that in W+jets events l and ν have similar p_T spectra
    - Use μ spectrum to predict shape and normalization of E_T^{miss}
  - Dilepton, lepton from τ decays

W+j & ttbar

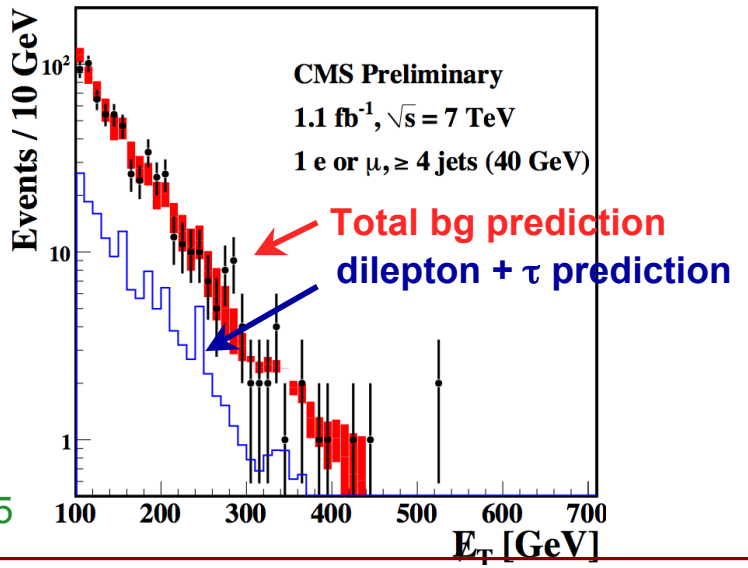


SUSY example



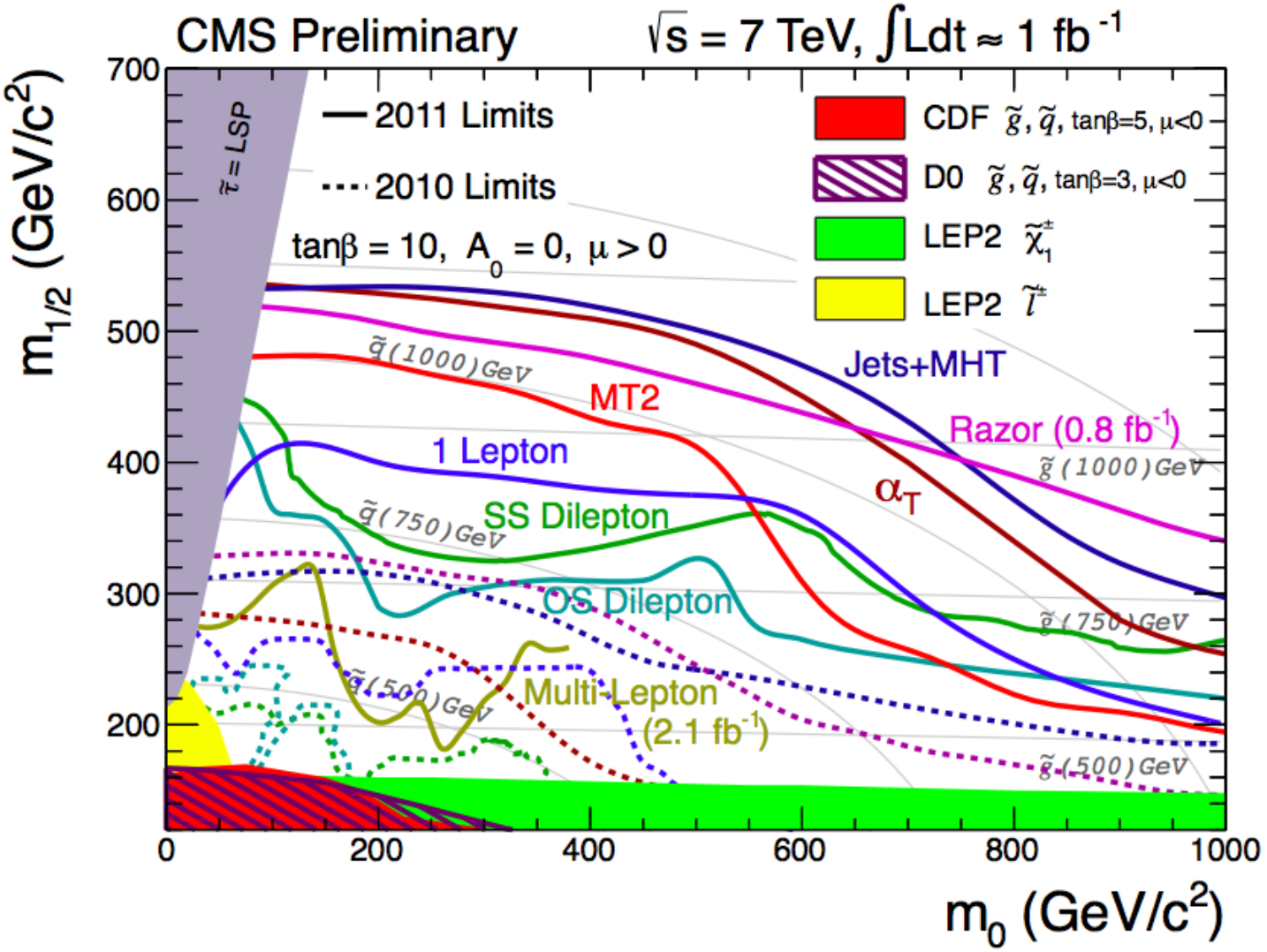
- E_T^{miss} distribution agrees well with prediction

No evidence of new physics



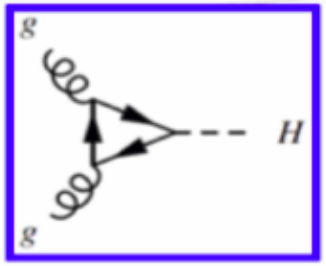
CMS-PAS SUS-11-015

Limits on CMSSM

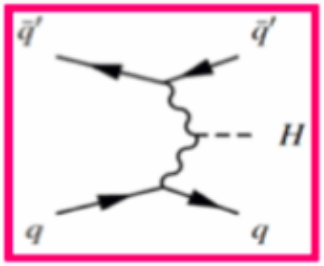


Within the constrained SUSY models we have crossed the boundary of disfavouring gluinos and squarks with masses up to 1 TeV

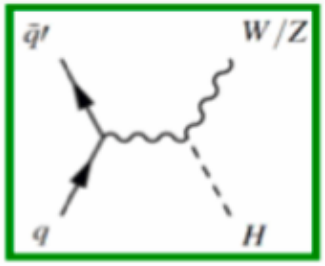
Searches for the SM Higgs



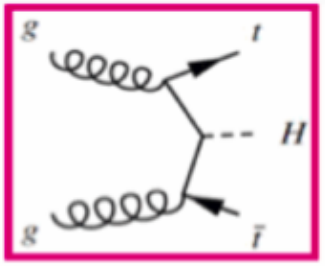
Gluon Fusion



Vector-Boson Fusion

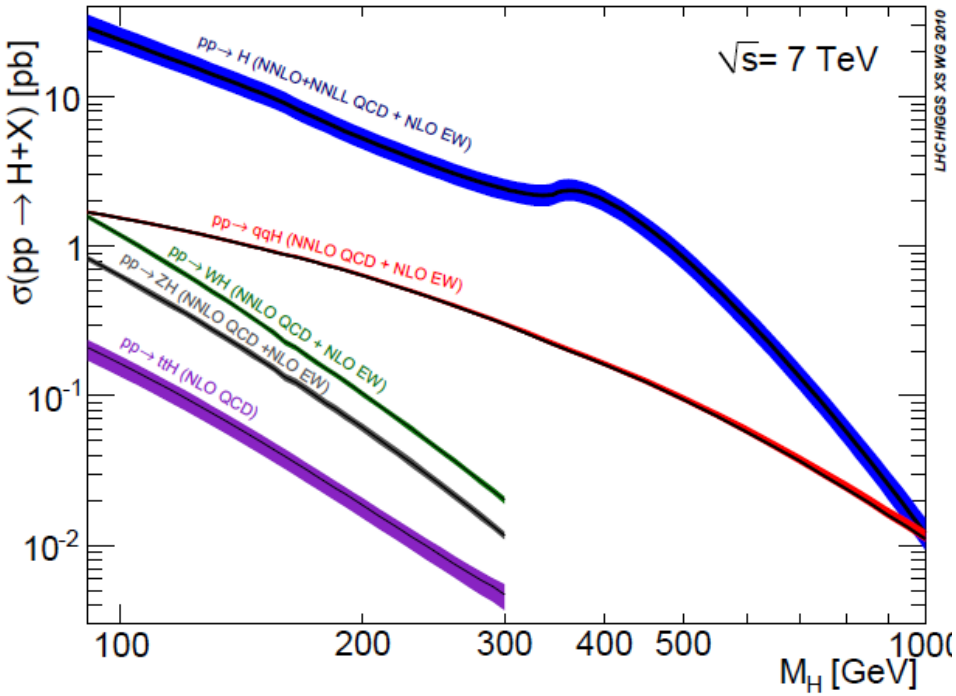


Higgs-strahlung

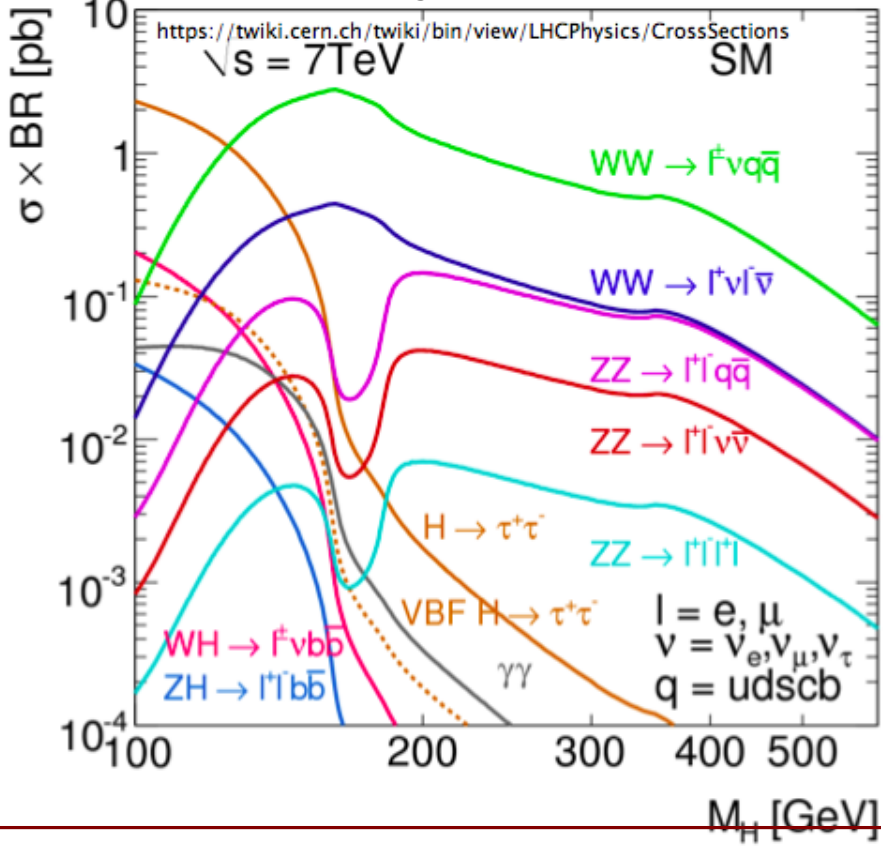


Assoc. Prod. ($t\bar{t}H$)

Higgs boson production…



… and decay



Hot from the press !!

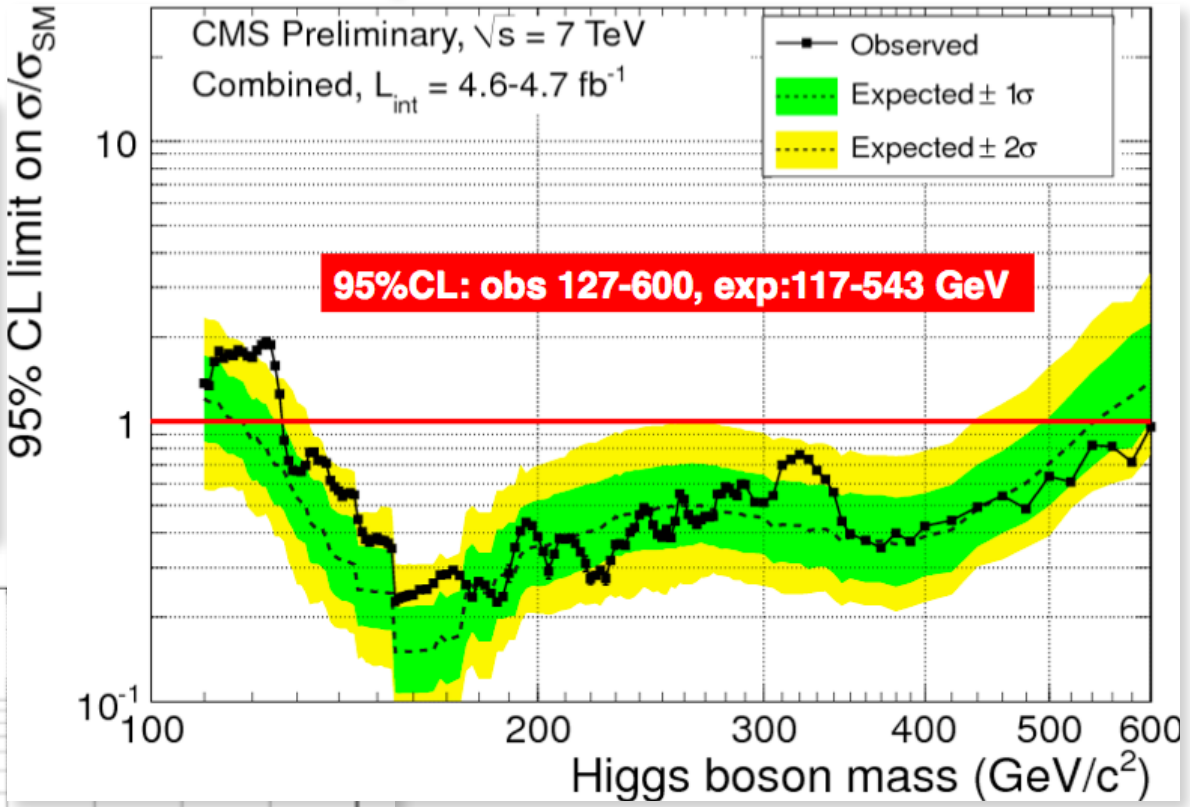
Using full 2011 statistics:

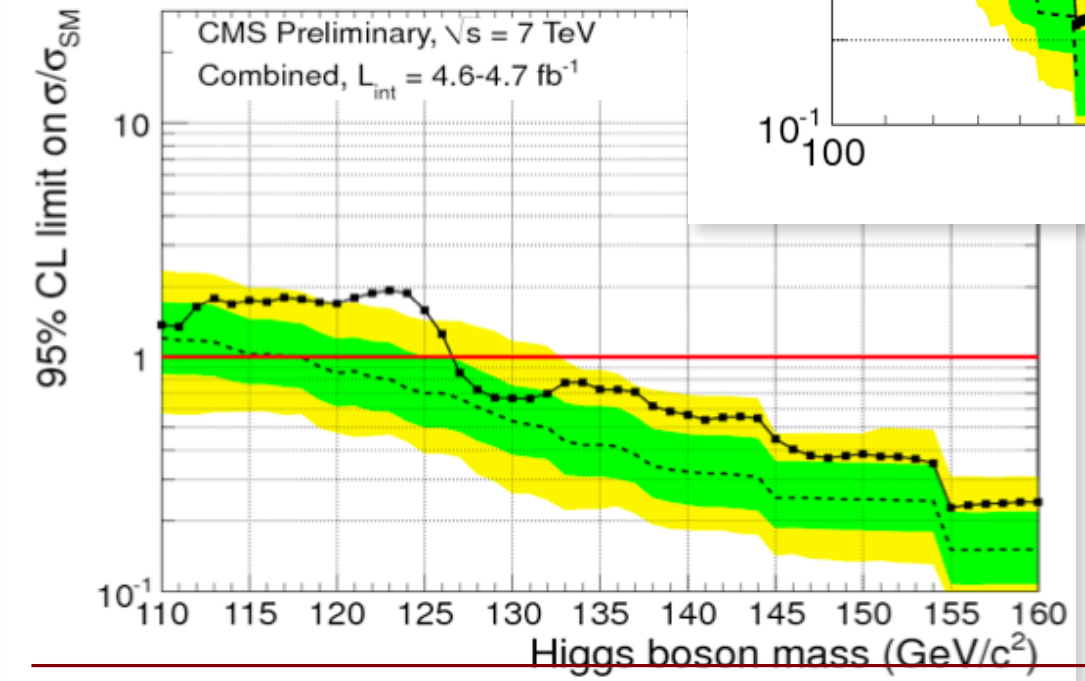
- The SM Higgs boson is disfavoured at 95% C.L.:

[127 - 600] GeV

- The expected exclusion in the absence of a signal is

[117 - 543] GeV





Modest, broad excess between 115 and 127 GeV, visible in 5 channels

Significance < 2σ

More statistics needed !

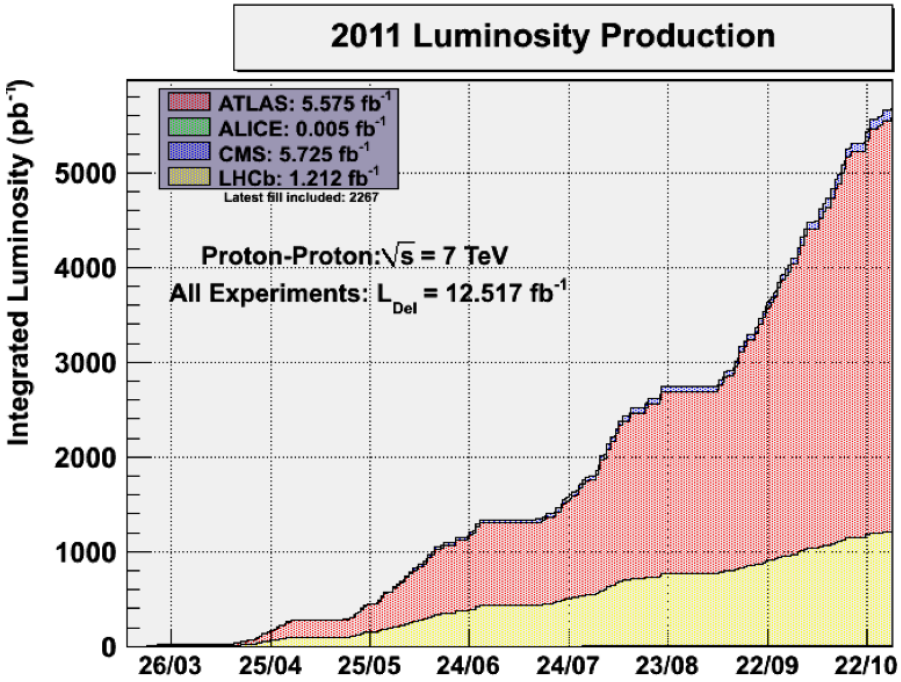
Summary

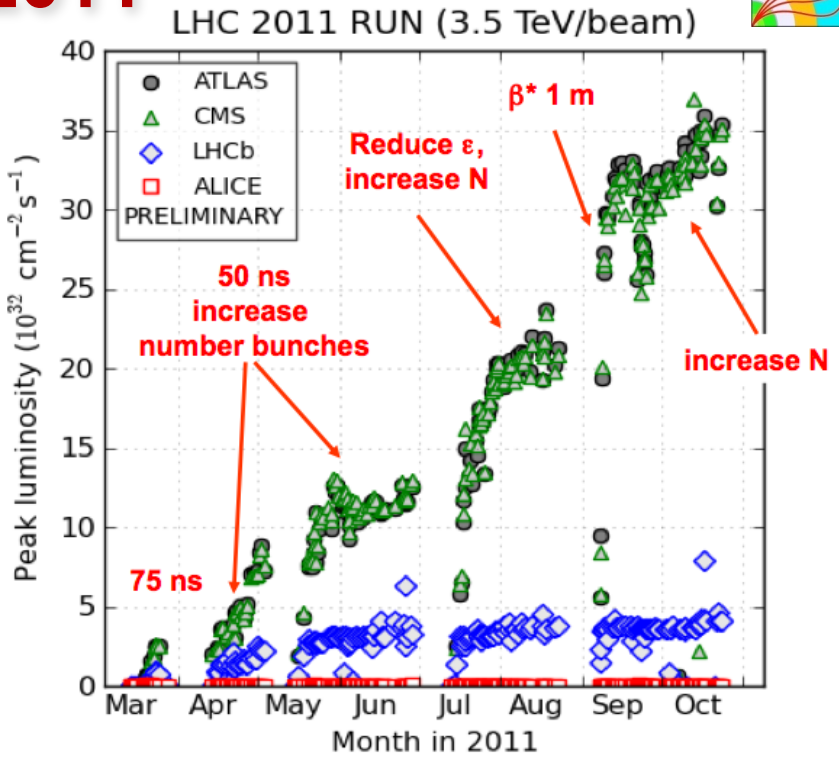
- The LHC is performing very well
  - Entered the 1/fb era and accumulating data fast
- The CMS detector is in excellent shape
  - Operation, performance, detector understanding, analysis tools
- CMS has completed a comprehensive set of SM measurements at 7 TeV
  - Some have already reached impressive levels of precision
- So far, good agreement with SM predictions
- SUSY searches with sensitivity to squark/gluino masses in the range 0.5 - 1 TeV
- Higgs prospects very promising for 2012
  - SM Higgs will either be discovered or ruled out soon

More exciting results to come in 2012, stay tuned !

Additional information

LHC in 2011



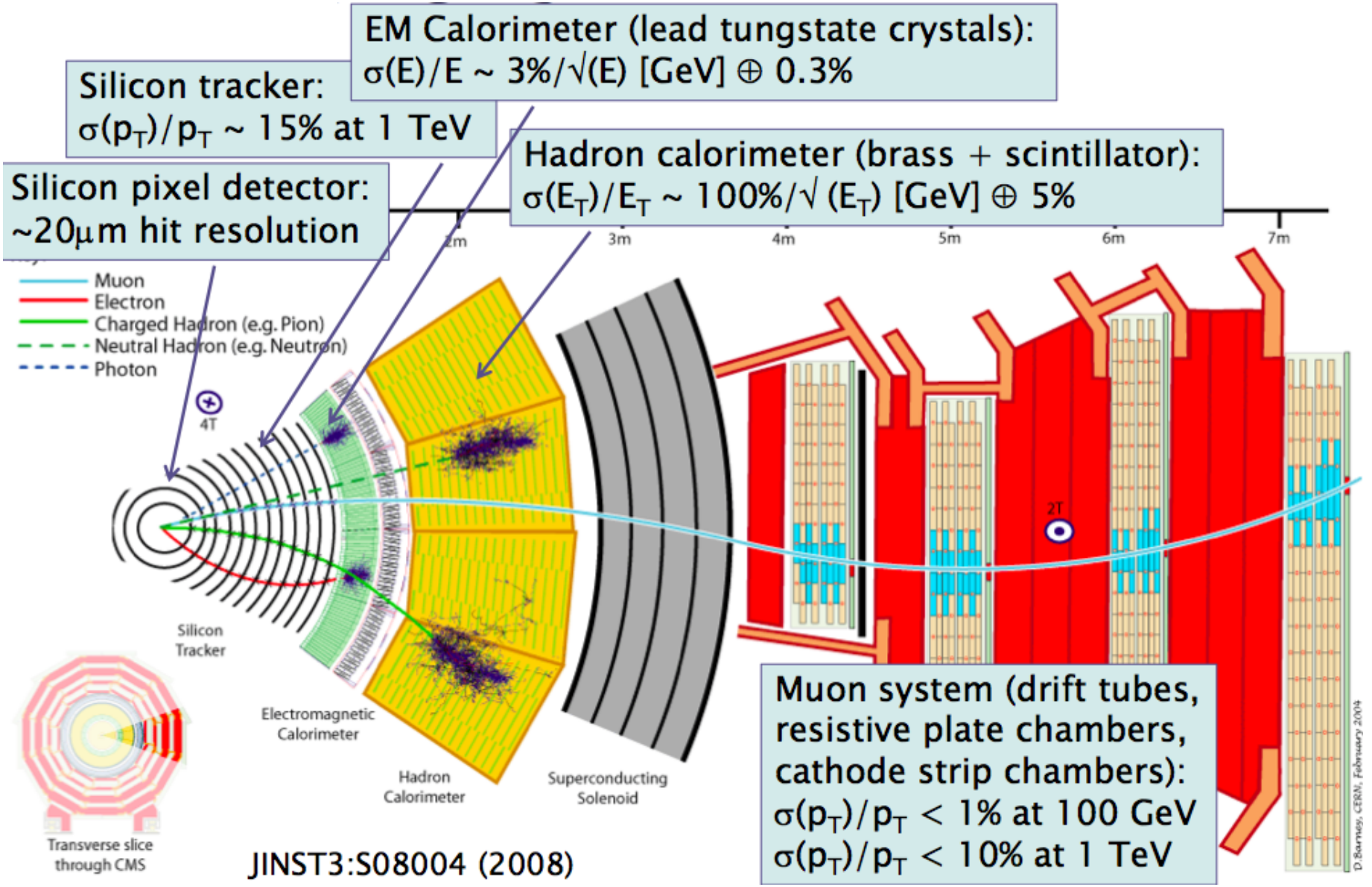


- Around 5.5 fb^{-1} delivered to ATLAS & CMS
- Peak luminosity increased from 1.2×10^{33} to 3.7×10^{33} cm^{-2} s^{-1}
- Record weekly luminosity of 550 pb^{-1}
- Collected per (good) day more data than 4 x entire 2010 run

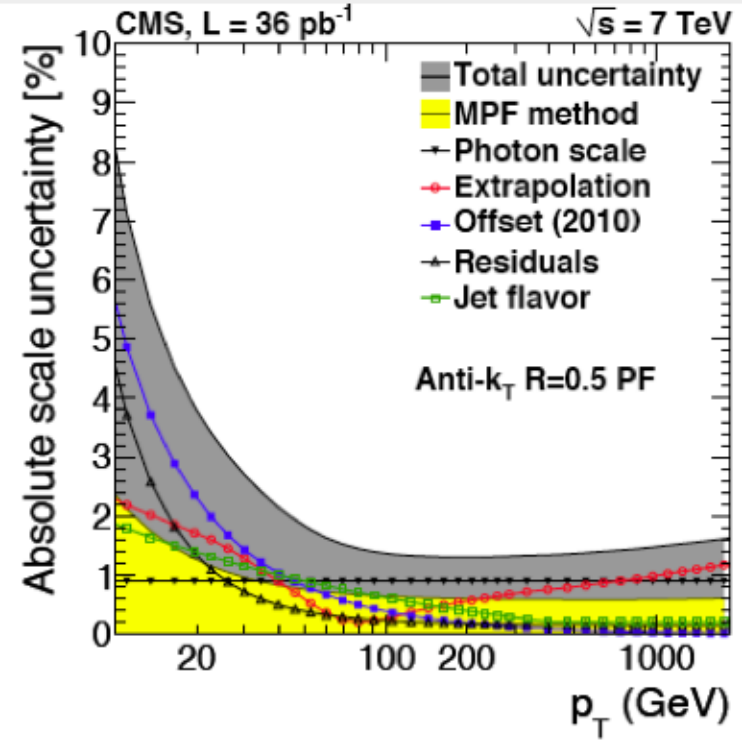
Improvements in 2011:

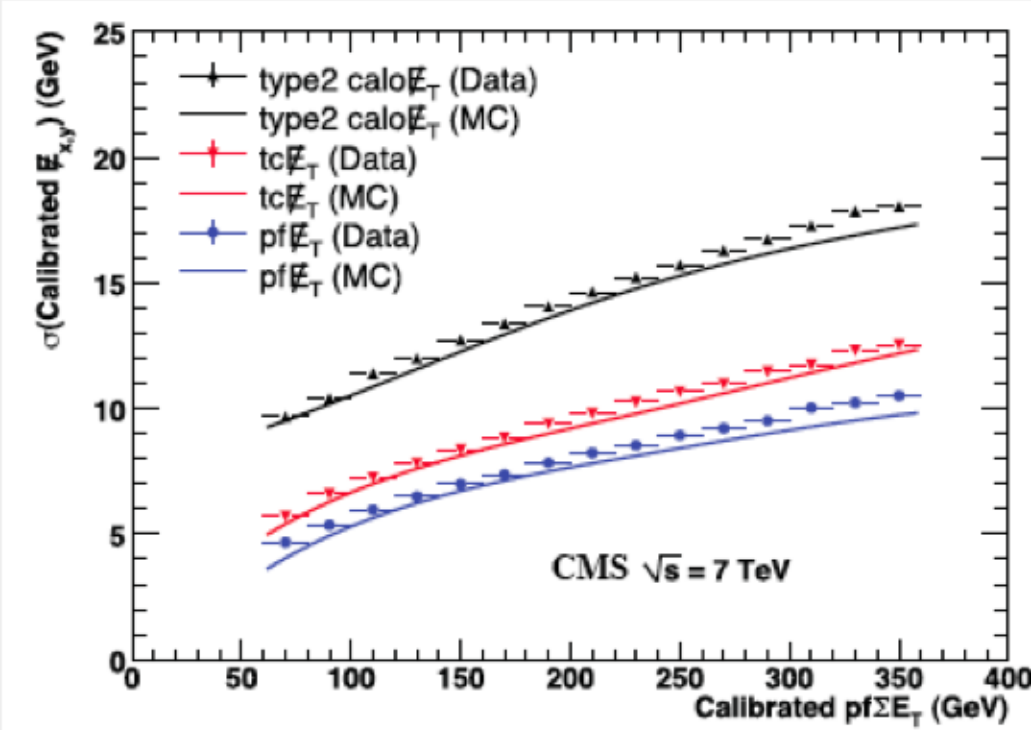
- 50 ns bunch spacing (started with 75 ns)
- Increase bunch charge up to $N = 1.45 \times 10^{11}$ protons per bunch
- Increase focusing to $\beta^* = 1$m
- Reduction of emmittance ε, to ~ 2μm
- Max. number of bunches = 1380 at 50 ns

A slice of CMS



JES, JER, MET



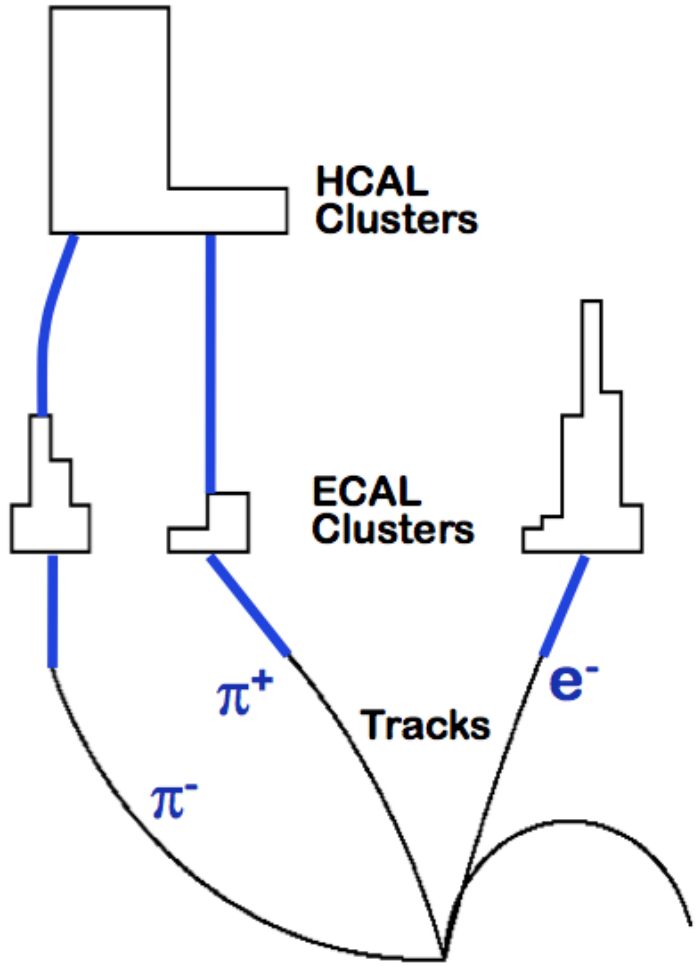


Jet energy scale known to few %
Jet resolution 10-15%

Missing energy resolution improvement with Particle Flow

Precise object reconstruction

- Detector is sufficiently granular to reconstruct and identify individual particles using best combination of all subdetector information
  - "Particle flow" technique
  - Redundant information gives better calibration, resolution, etc.
- Jet energies, missing energies computed from individual particles
  - Leads to relatively small corrections and thus small uncertainties on jet-energy scale (JES), good resolution on jet and missing energy.



Electroweak: access to proton PDFs

W->μν charge asymmetry: CMS-PAS EWK-11-005

- More W^+ than W^- due to excess of u quarks over valence d quarks in pp collisions

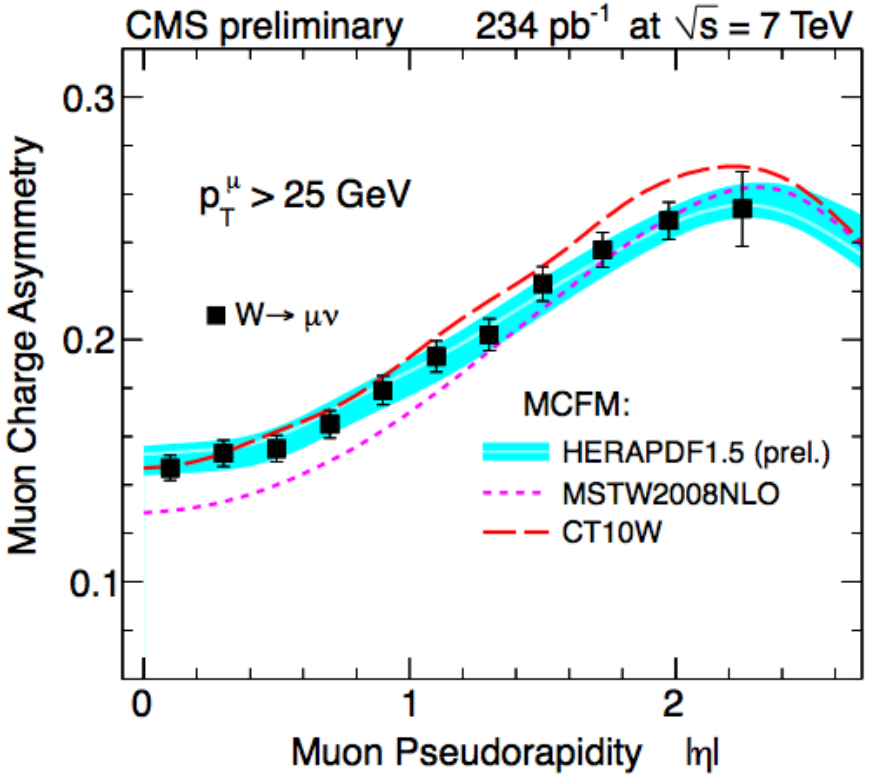
- Asymmetry = f(η), since u carries higher fraction of proton momentum

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

- In terms of valence quarks:

$$A \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

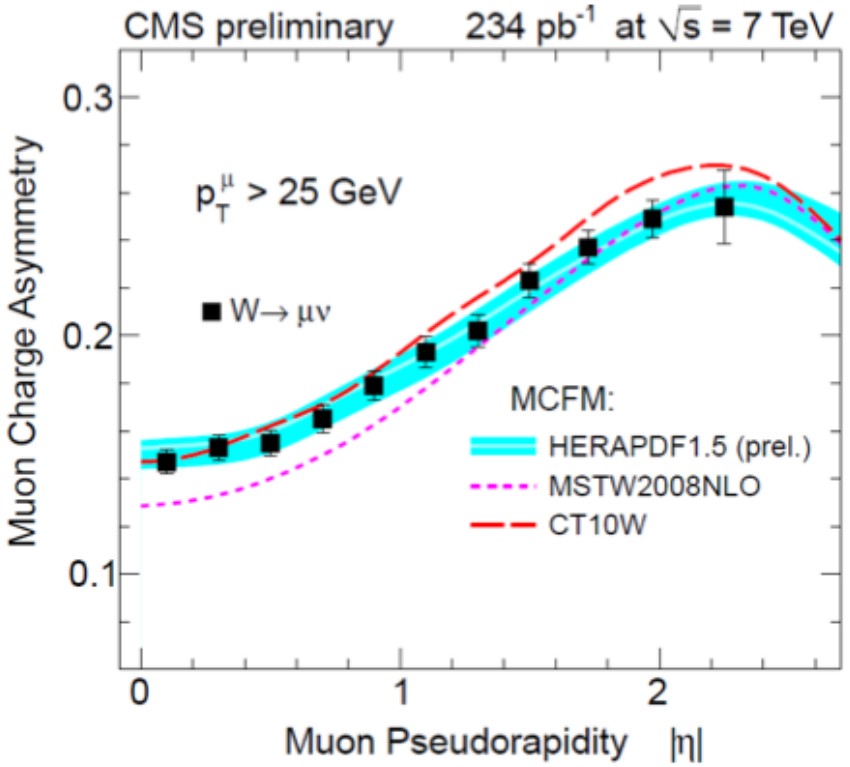
- Very sensitive to PDFs



Precision of the measurement good enough to provide new input to the PDF global fits

W lepton charge asymmetry

W lepton asymmetry: $A_W = \frac{W^+ - W^-}{W^+ + W^-}$



$$\frac{d\sigma_{W^+}}{dy} \approx u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)$$

$$\frac{d\sigma_{W^-}}{dy} \approx d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)$$

in terms of valence quarks:

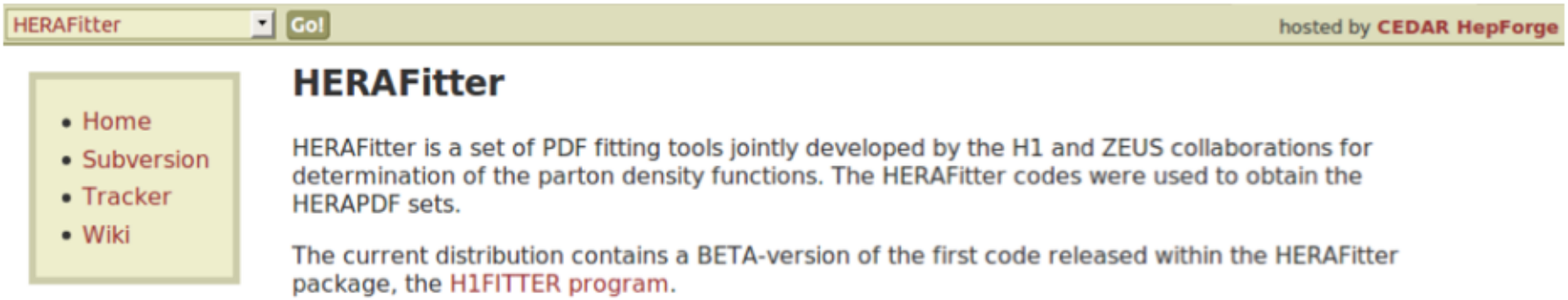
$$A_W \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

A_W sensitive to *u* and *d* quarks

Differences in predictions are related to not well known valence quarks at low x → LHC data help to constrain PDFs

HERAFitter project

HERAFitter: a set of PDF fitting tools jointly developed by the H1 and ZEUS collaborations for determination of the parton density functions



Out of the box:

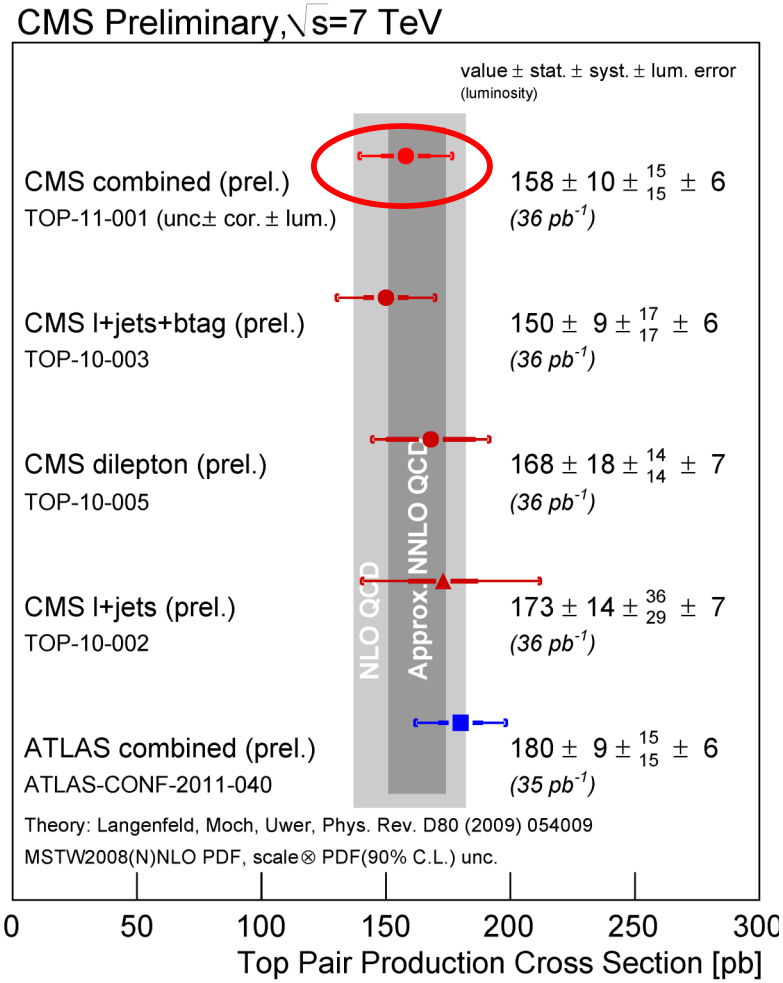
- H1Fitter produces the central fit for HERAPDF1.0
- DY and jet packages can be used to fit pp, ppbar data

→ Can be used to study the direct impact of CMS data (jet, DY, W asymmetry, top) with minimal necessary input from HERA

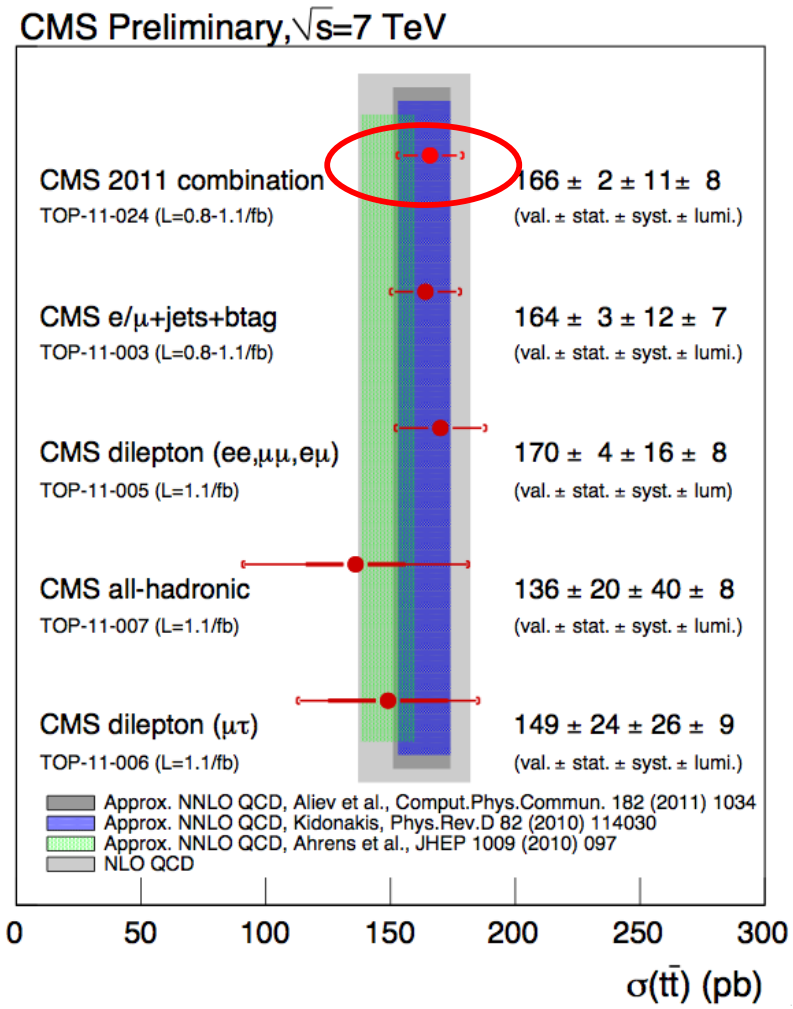
HERAFitter package available online at http://projects.hepforge.org/herafitter/

Top-pair cross section comparison 2010-2011

2010 Results



2011 Results



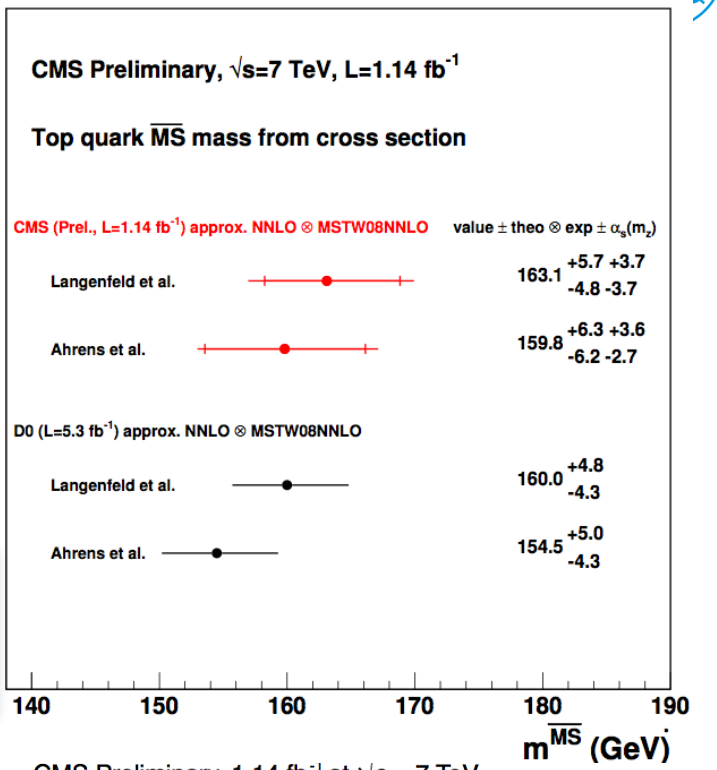
Cross section ratio ttbar/Z (36 pb^{-1})

$$\frac{\sigma(pp \to t\bar{t})}{\sigma(pp \to Z/\gamma^{\star} \to e^{+}e^{-}/\mu^{+}\mu^{-})} = 0.175 \pm 0.018\,(stat.) \pm 0.015\,(syst.)$$

Top mass from cross section

Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

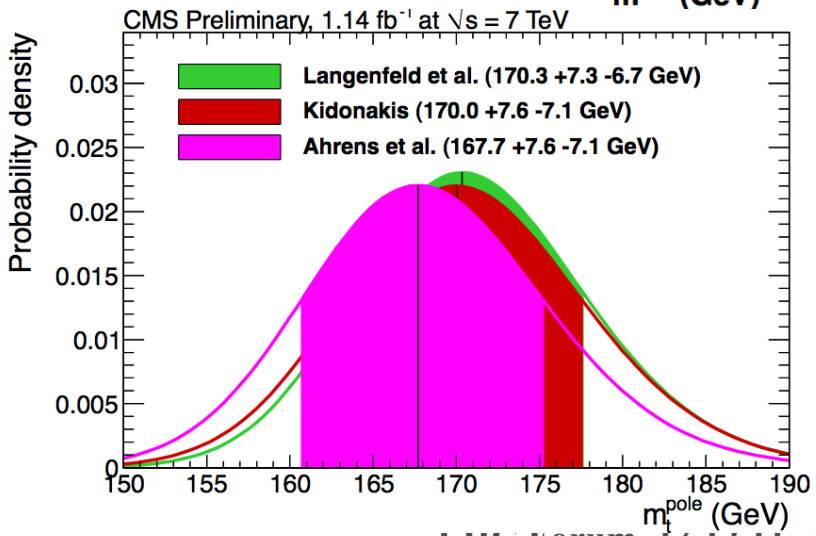
Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$



CMS direct (dilepton & l+jets combined)

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst}) \text{ GeV}$$

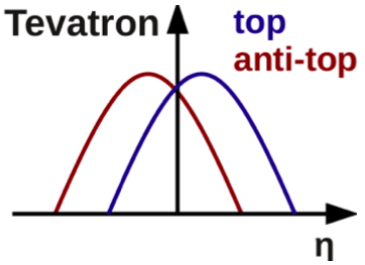
2% prec.



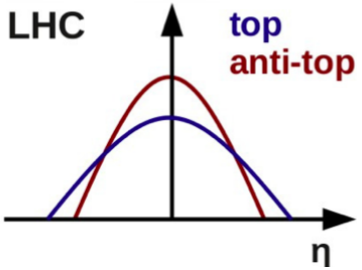
ttbar charge asymmetry in l+jets (1.09 fb^{-1})

May indicate BSM top production interfering with SM production

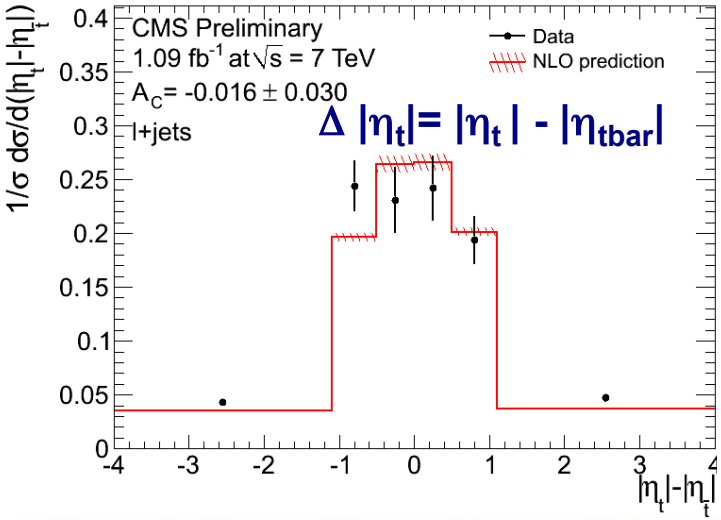
- Tevatron (p-pbar collider): Valence (anti)quarks from certain direction
  → Forward-backward asymmetry
  CDF: 3σ excess in A_{FB} for m_{ttbar} > 450 GeV

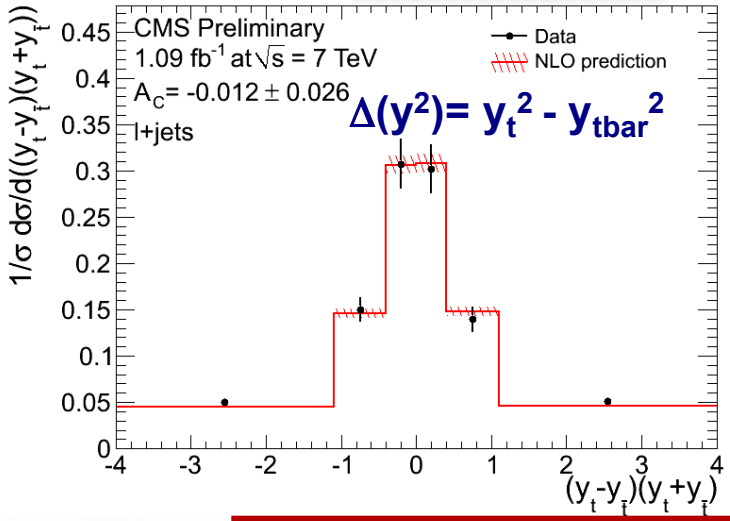


- LHC (p-p collider): gg symmetric → SM asymmetries more diluted
  • No valence antiquarks, quarks have higher x on average
  → Asymmetry in (pseudo)rapidity



$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$





$A_C^{\eta}(\text{theory}) = 1.3\ \%$
$A_C^{y}(\text{theory}) = 0.6\ \%$

Consistent with SM

Observable	Raw A_C	BG-subtracted A_C	Unfolded (and corrected) A_C
$\Delta\lvert\eta\rvert$	-0.004 ± 0.009	-0.009 ± 0.010	$-0.016 \pm 0.030^{+0.010}_{-0.019}$
$\Delta(y^2)$	-0.004 ± 0.009	-0.007 ± 0.010	$-0.013 \pm 0.026^{+0.026}_{-0.021}$

CMS-PAS TOP-11-014

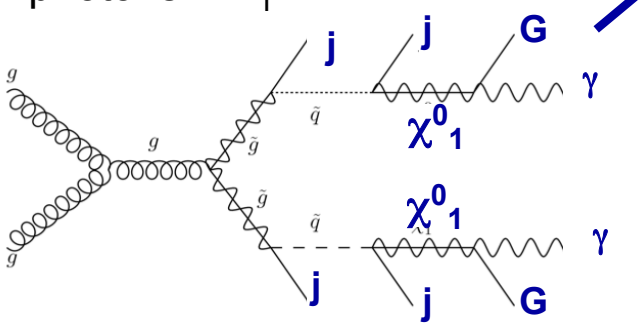
SUSY with photon(s) (1.14 fb^{-1})

UHH

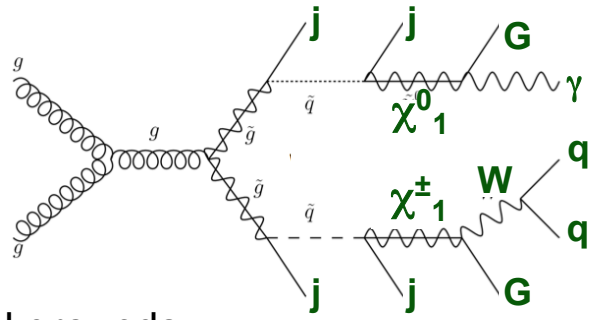
- General Gauge Mediated SUSY breaking (GGM):
  - LSP is Gravitino (LSP)
  - Decay chain depends on the Neutralino NLSP, mixture of Bino, Wino, Higgsino

→ Signatures with photons + E_T^{miss}

- Topology 1:
  - ≥ 2 isolated γ
  - ≥ 1 jet
  - E_T^{miss}

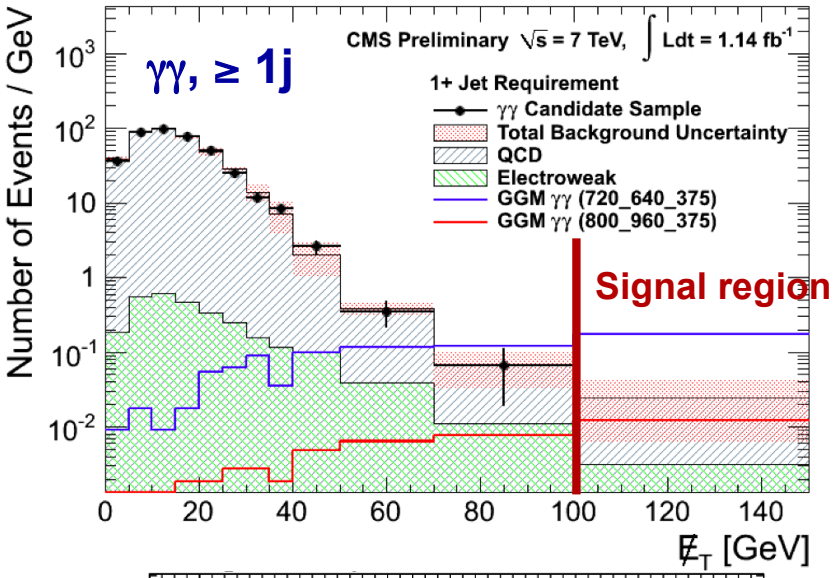


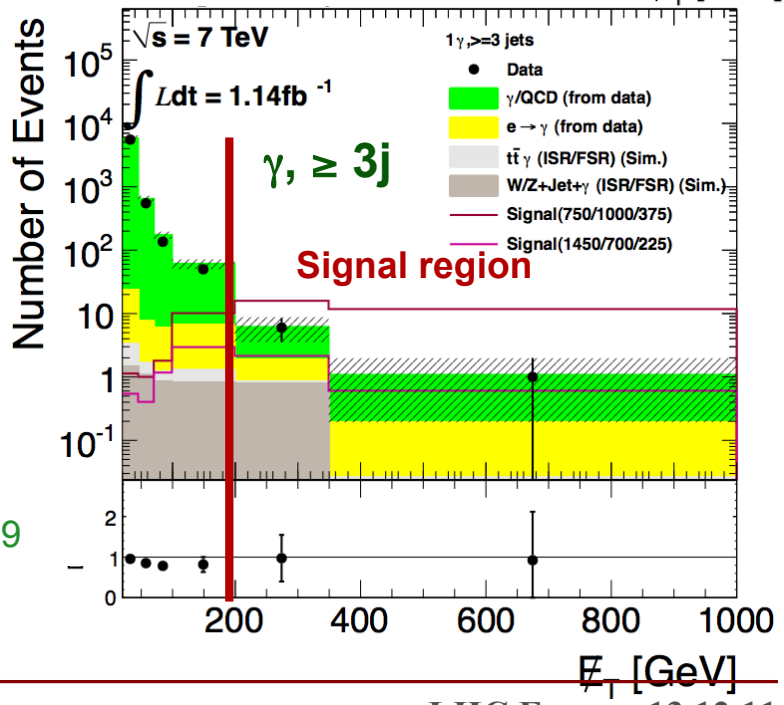
- Topology 2:
  - 1 isolated γ
  - ≥ 3 jets
  - E_T^{miss}



- Data-driven backgrounds:
  - QCD dominant
  - W->eν+jets, with e misidentified as γ

CMS-PAS SUS-11-009



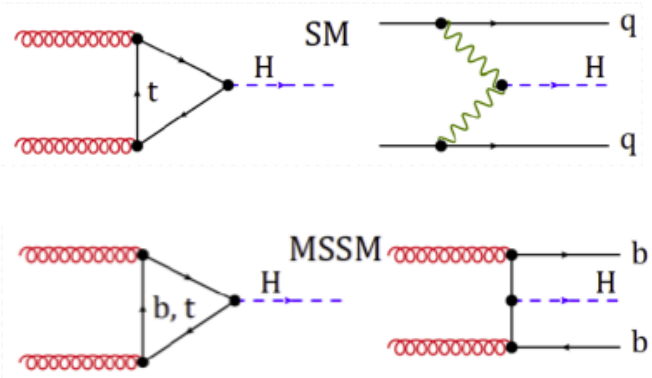


So far, no excess of events observed

H/ϕ->ττ->μμ (1.1 fb^{-1})

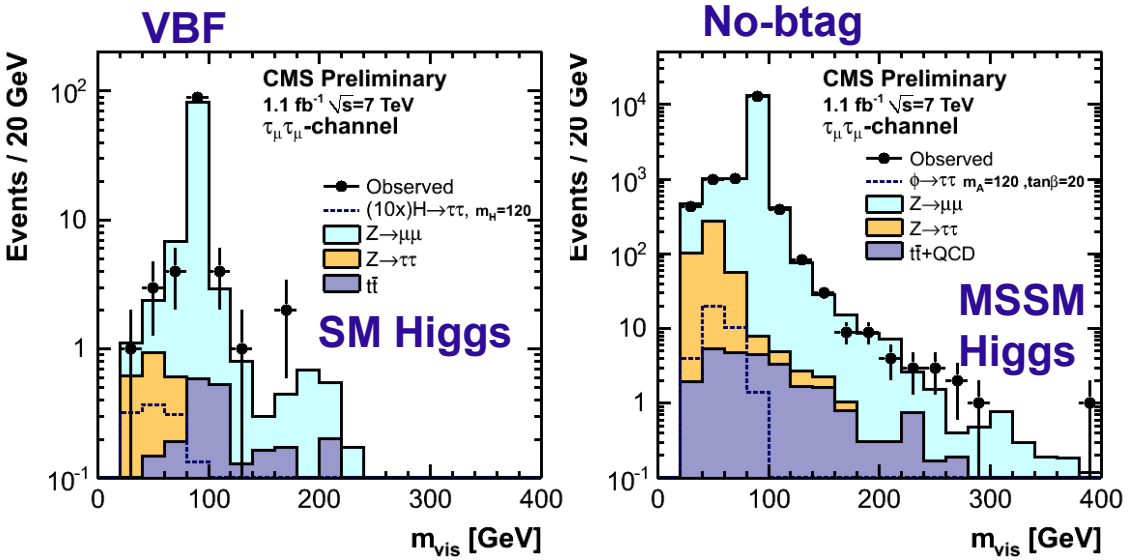
DESY

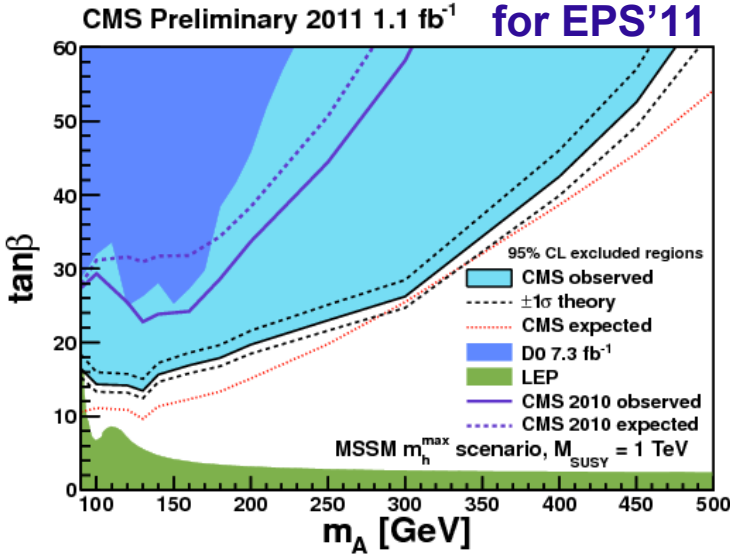
- Require 2 OS muons, E_T^{miss}
- Separate jet categories to exploit characteristics of production mode:
  - SM: 2 jets (VBF) or not
  - MSSM: at most 1 b-jet or at most 1 jet (untagged)



- Likelihood fit to $m_{\tau\tau}$ visible mass distribution

Channels used: $\tau_\mu\tau_h+\tau_e\tau_h+\tau_e\tau_\mu+\tau_\mu\tau_\mu$

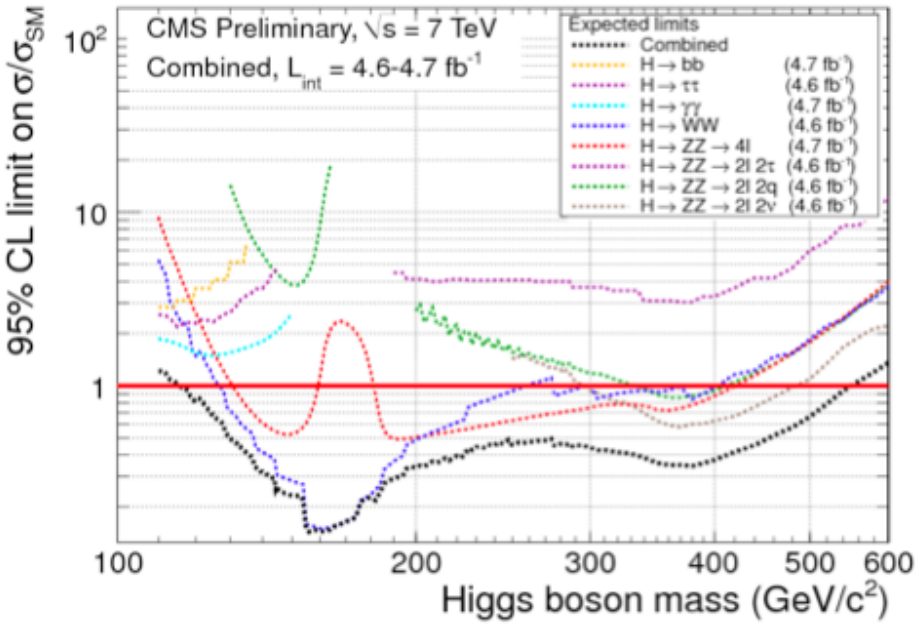


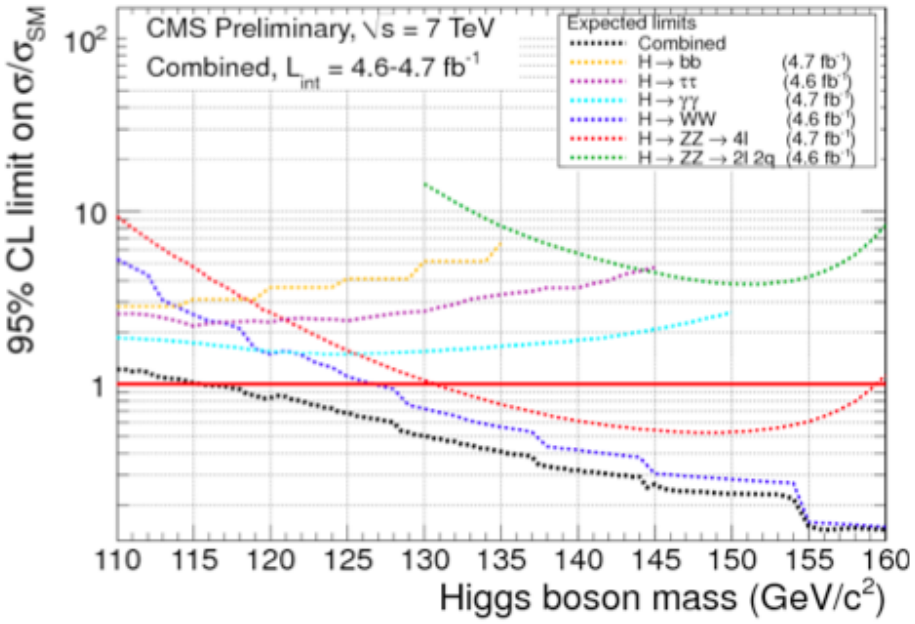


No evidence of any signal is observed

CMS-PAS HIG-11-009

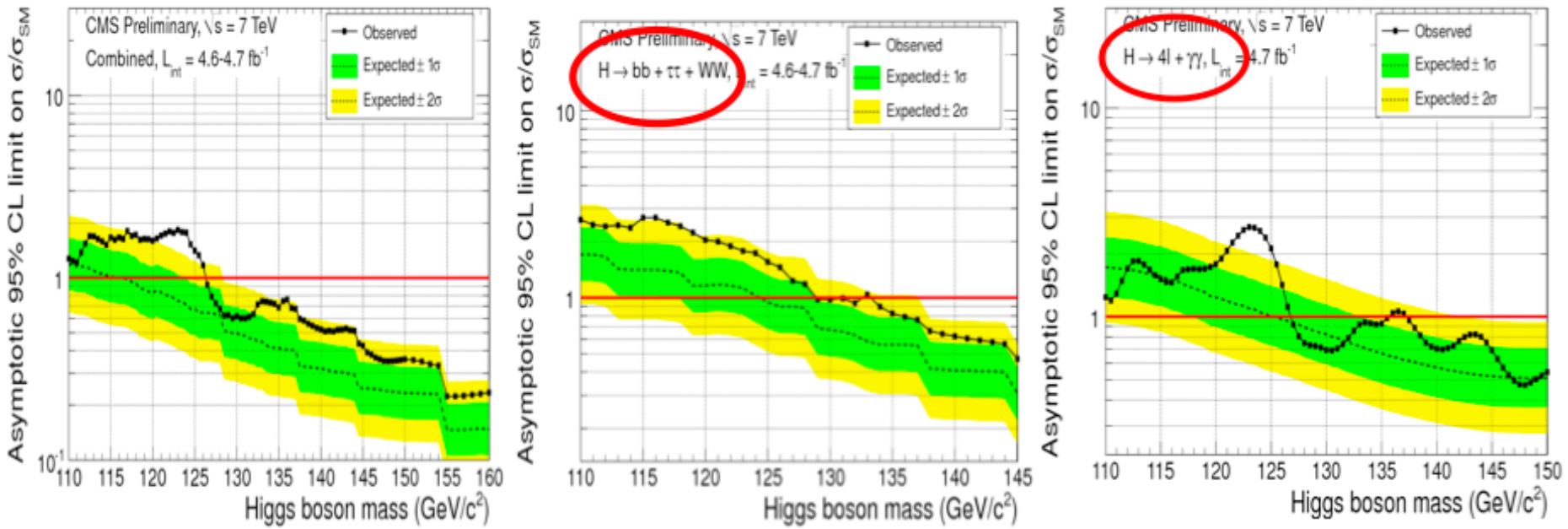
Combination and sensitivity @ 4.7fb^{-1}





Very close or better than 1xSM in the full mass range.
Optimization of some analyses still ongoing.
Additional sub-channels under study.

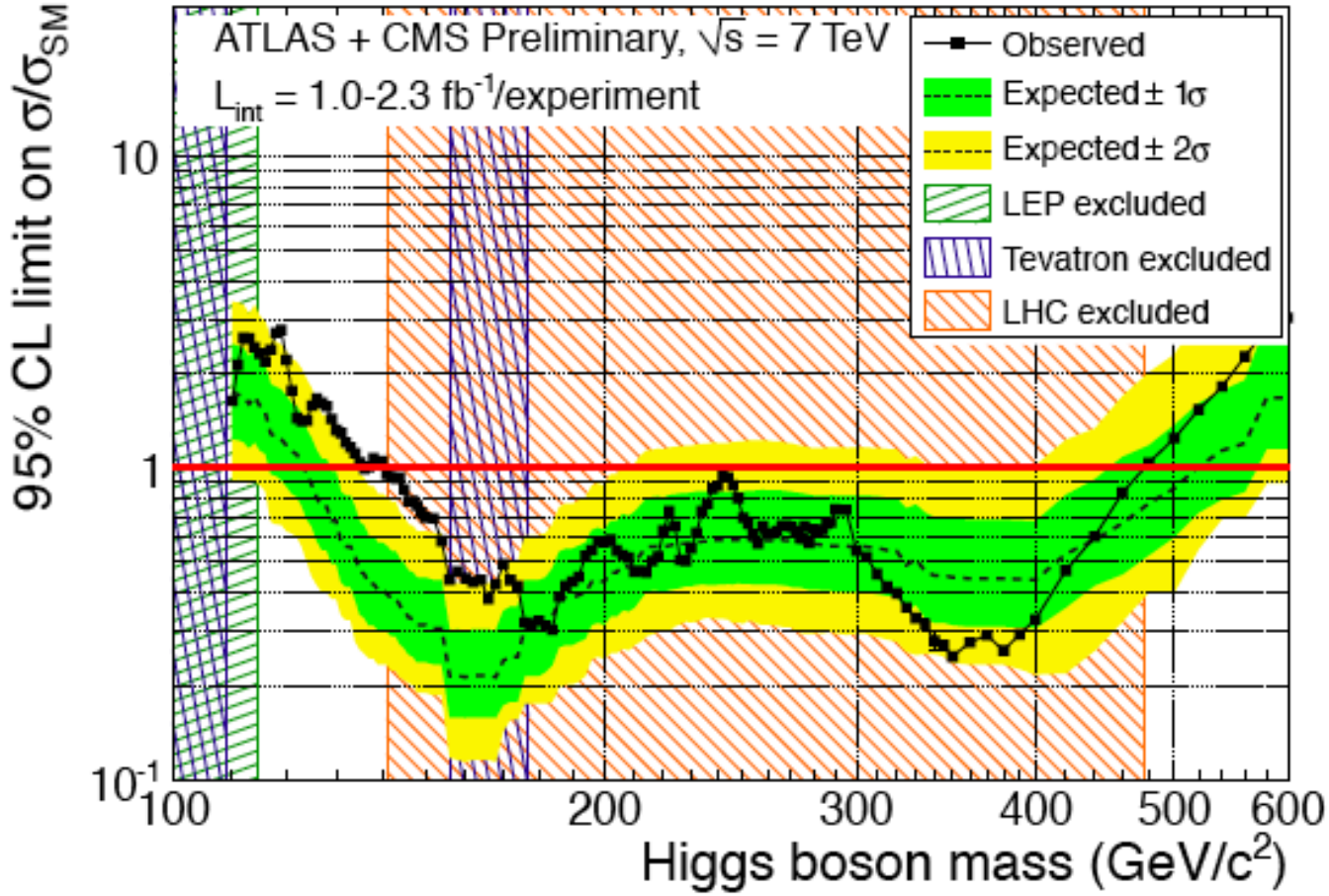
Hot from the press !!



We cannot exclude the presence of the SM Higgs boson below 127GeV because of a modest excess of events interesting the region between 115 and 127 GeV

The excess at low mass is produced by a broad excess driven by the low resolution channels (H2$\tau\tau$, H2WW, H2bb, center), modulated by the localized excesses seen by the high resolution channels (H2$\gamma\gamma$ and H2ZZ, right)

LHC SM Higgs combination (1-2.3 fb^{-1})



HCP2011

Observed disfavoured mass range at 95% CL: 141-476 GeV
Observed disfavoured at 99% CL: 146-443 GeV
except 3 small regions between 220-320 GeV
Expected disfavoured mass range at 95% CL: 124 – 520 GeV