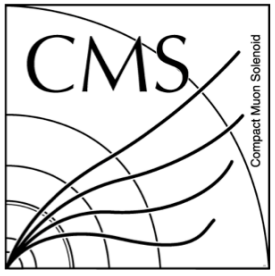
Results on Standard Model & Flavour Physics with the CMS detector at LHC



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The Cracow Epiphany Conference

7-9 January 2013

Outline

- CMS performance in 2010-2012
- Selected results:
  - QCD jets
  - Vector bosons
  - Top quarks
  - Heavy flavours
- Summary

CMS performance

- **Good detector coverage**

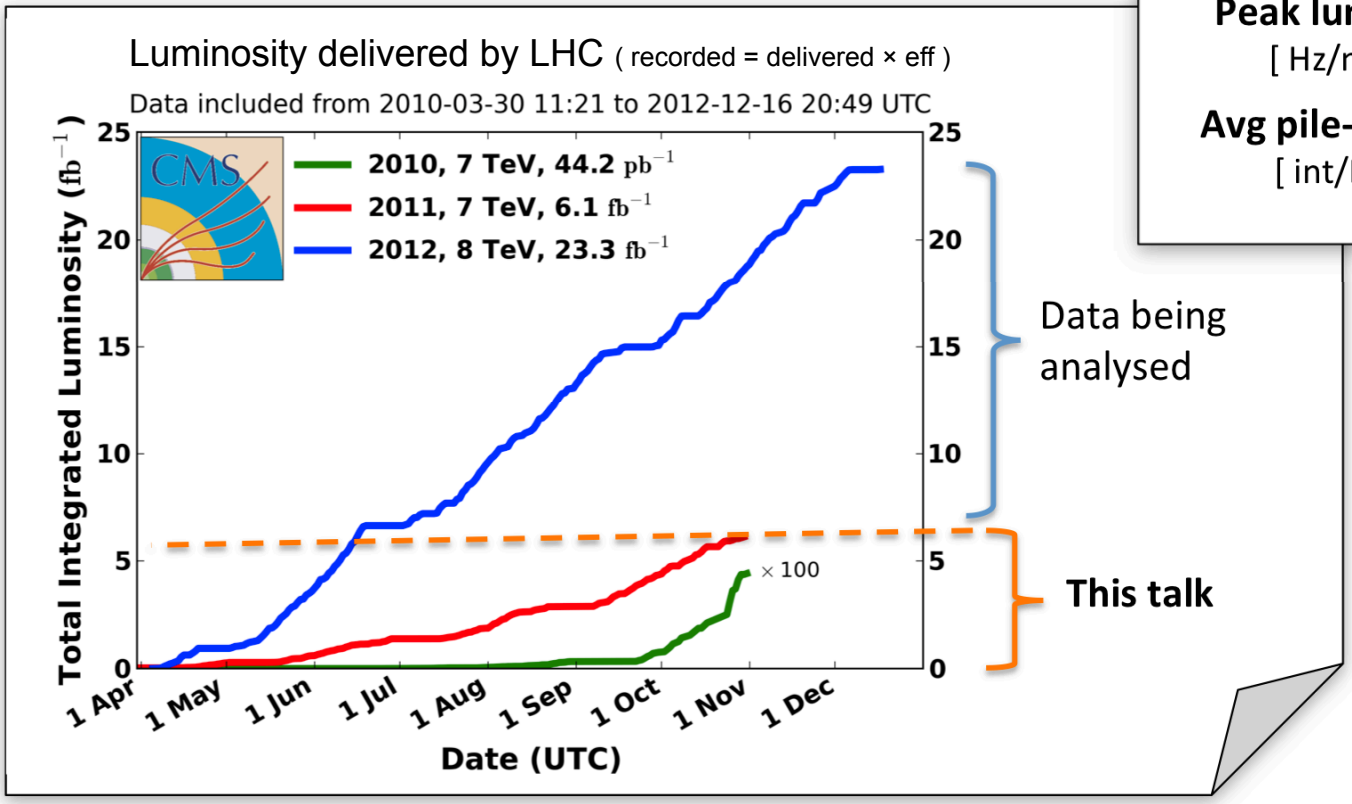
  Tracking : $|\eta| < 2.4$, Calorimetry : $|\eta| < 5$

- **High data taking efficiency**

  ~93% in 2012

	2011 7 TeV	2012 8 TeV
Recorded [1/fb]	*5.5*	*21.8*
Peak lumi. [Hz/nb]	*4.0*	*7.7*
Avg pile-up [int/BX]	*9*	*21*

8 TeV analyses more challenging due to pileup



Jets @ LHC

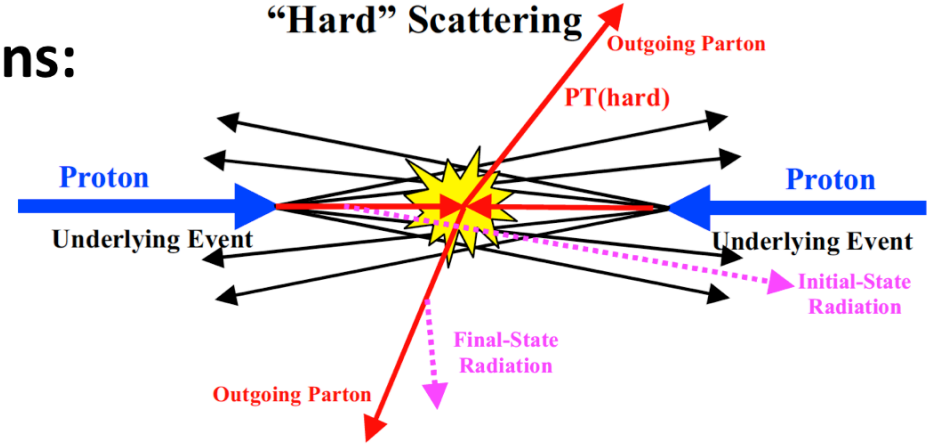
- **LHC : collisions of quarks & gluons:**
  - Gluon exchange dominates ⇒ high p_T quarks and gluons
  - FSR, confinement ⇒ measured jets of hadrons (or prompt γ)

- $\sigma \propto f_a(x_a,\mu_F) f_b(x_b,\mu_F) \otimes \hat{\sigma}(x_a,x_b,\mu_F,\mu_R,\alpha_S(\mu_R))$:
  - X-sec sensitive to: strong coupling constant $\alpha_S(Q)$, proton **PDFs**
  - Differential x-sec: QCD radiation, high order matrix elements, resummation techniques

- **Comparison with SM predictions:**
  - QCD calculations up to NLO
  - Different PDF sets

    MSTW, NNPDF, CT, ABKM, HERAPDF
  - Different hadronisation models

    HERWIG, PYTHIA



QCD analyses

>35 **QCD-related** analyses @ √s = **0.9 / 2.36 / 7 TeV** (up to ~5 fb^{-1})

- Inclusive jet and dijet double-differential x-sec
- Ratio $\sigma(3\text{-}jet)/\sigma(2\text{-}jet)$ and $\alpha_S(M_Z)$
- Jet mass in dijet and V+jet events
- Jet shapes, subjet multiplicity
- Dijet φ decorellations
- Differential $\sigma(b\text{-}jet)$
- Forward jets and small-x QCD studies
- Multi-parton interactions (MPI), underlying event (UE) and soft QCD studies

Jet Reconstruction:

- Particle Flow technique:

  info from several sub detectors, reconstructs all stable particles
- Anti-k_T clustering algorithm
- For inclusive jet measurements:

  $p_T^{jet\text{-}1} > 20$ GeV (2010)

  $p_T^{jet\text{-}1} > 100$ GeV (2011, pileup!)

Cross section uncertainty:

- Jet energy scale : 10-30 %
- Luminosity : 4 %
- Jet energy resolution : 1-3 %

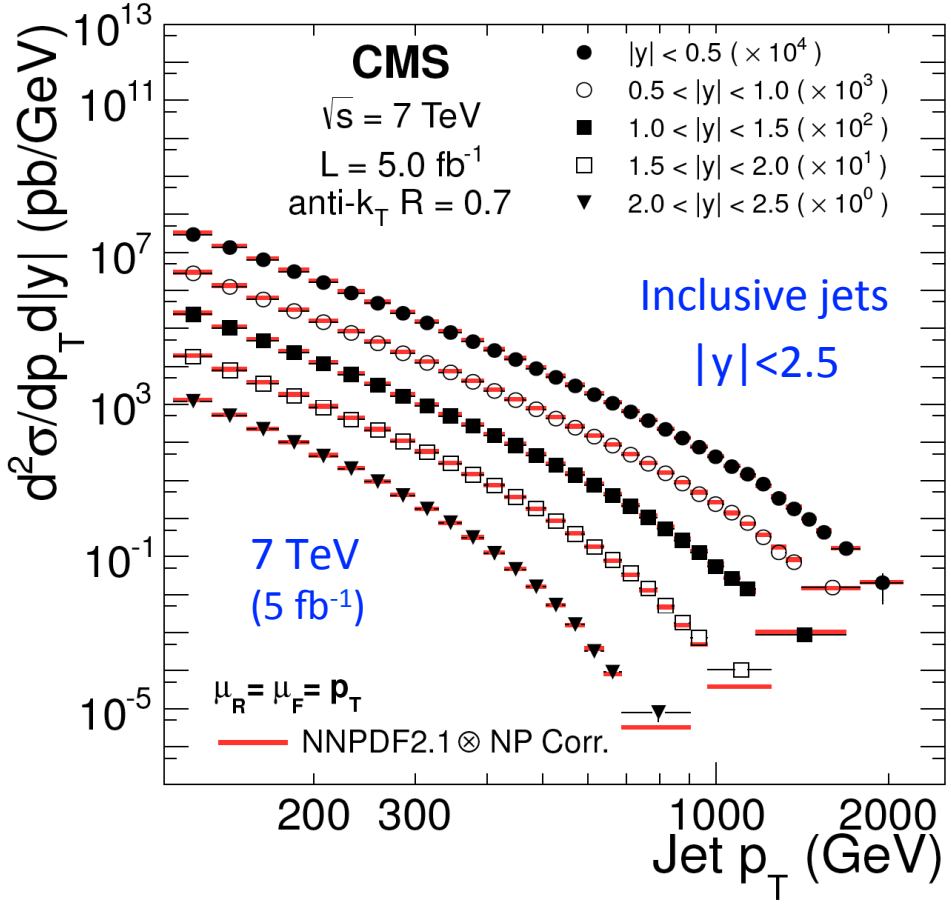
→ *see also talk by M.Misiura on Wednesday:*

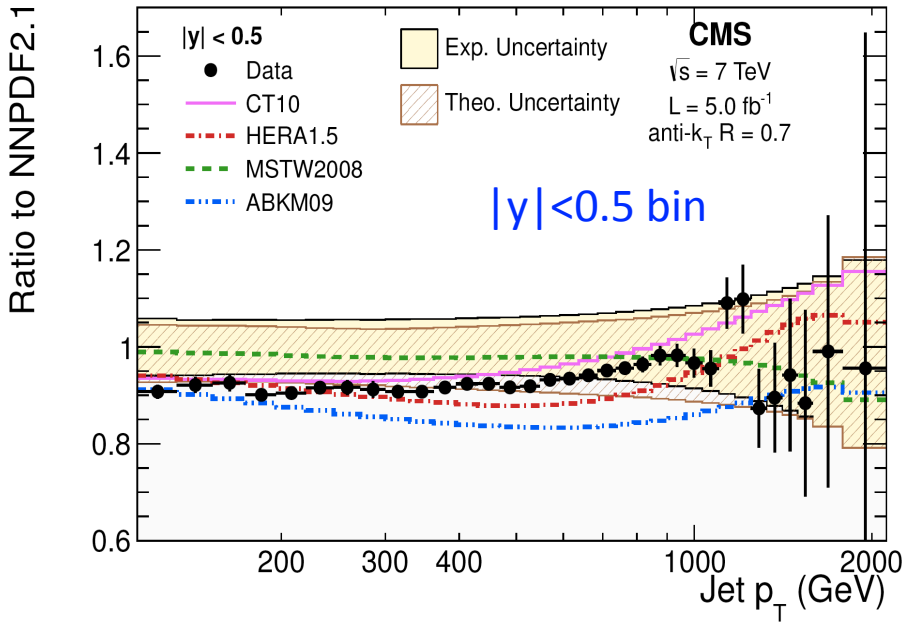
forward jets, small-x QCD

CMS-QCD-11-004
arxiv:1212.6660

Jet rates

- **Jet p_T probed up to 2 TeV**
- Dijet invariant mass M_{jj} up to 5 TeV





- Theory: NLOJet++ ⊗ Non-pert. correction:

  tested 5 PDFs: NNPDF2.1, CT10, MSTW2008, HERAPDF1.5, ABKM09

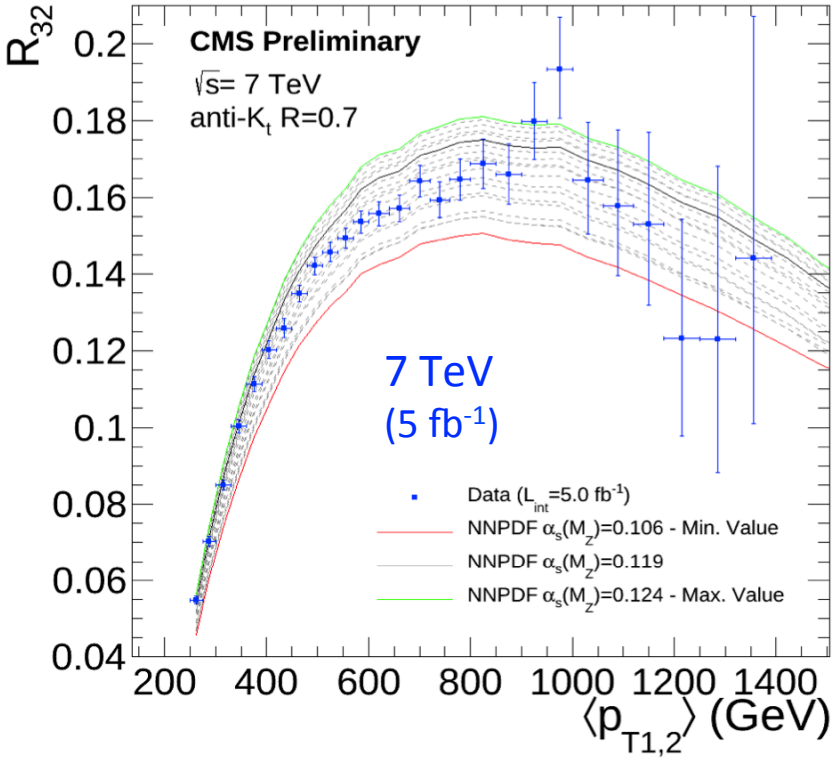
  MPI and hadronisation: PYTHIA6 vs HERWIG++

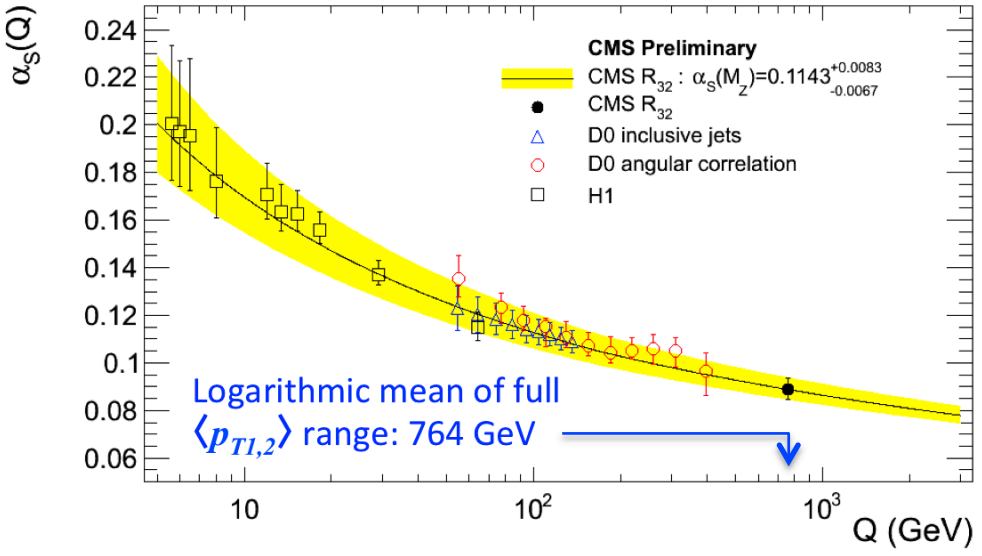
- **Good agreement with NLO predictions**

  differences ≈10% in some rapidity bins

Trijet/dijet ratio

- **Inclusive 3-jet to 2-jet x-sec ratio as a function of average p_T of 2 leading jets** $(R_{32} \propto \alpha_S)$
- Strong coupling α_S determined from best fit for $\langle p_{T1,2} \rangle \in$ [0.4, 1.4] TeV sub-range





- **Fit result with NNPDF2.1:**

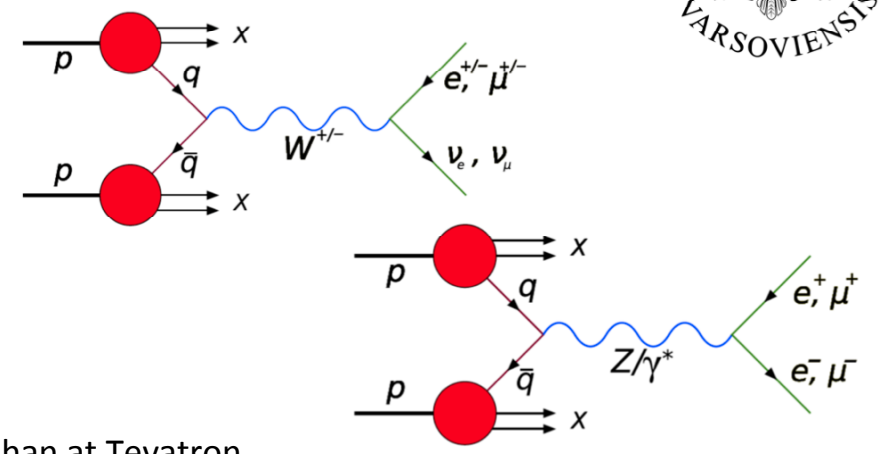
$$\alpha_S(M_Z) = 0.1143\ ^{+0.0083}_{-0.0067}$$

results for CT10, MSTW2008 are compatible

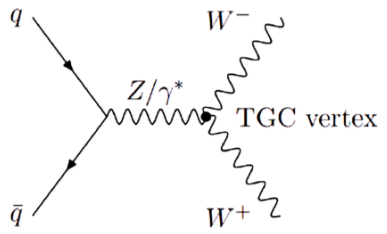
- **Differential ratio R_{32} agree with NLO theory**
  - tested **4 PDFs:** NNPDF2.1, CT10, MSTW2008, ABM11 (some tension for ABM11 below 600 GeV)

Vector Bosons @ LHC

- **Electroweak $W^{\pm}/Z^0/\gamma$ production:**
  - Well established theoretically
  - Clean final states



- **Important for:**
  - Testing SM at TeV scale : larger cross sections than at Tevatron
  - Performance measurements : detector alignment/calibration
  - Proton PDFs : probing $0.001<x<0.1$, sea quarks are important
  - Backgrounds for SM & BSM searches



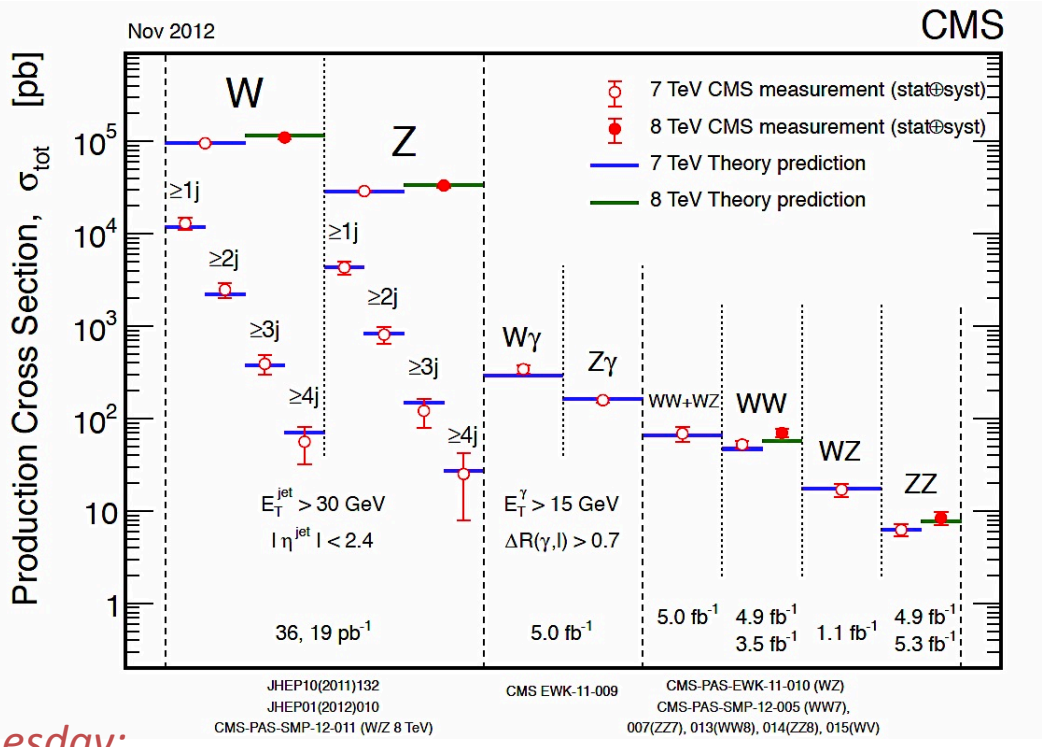
WWZ, $WW\gamma$ – allowed
ZZZ, $ZZ\gamma$, $Z\gamma\gamma$ – forbidden

- Existing V+jets predictions:
  - LO matrix element + PS: ALPGEN / MADGRAPH / SHERPA
  - Fixed-order NLO: BLACKHAT+SHERPA (up to $Z + 5\ jets$) / ROCKET+MCFM / MCFM
  - Fixed-order NLO + PS: POWHEG+PYTHIA / MC@NLO / MENLOPS / MEPS@NLO
  - Approximate NNLO: LOOPSIM+MCFM
  - All order resummation: HEJ

EW analyses

>25 analyses on: **Vector Boson, V+jets, VV, VV'** @ √s = 7 or 8 TeV (up to ~5 fb^{-1})

- **Inclusive W and Z:**
  - $\sigma(W)$, $\sigma(Z)$, $\sigma(W\to\tau\nu)$, $\sigma(Z\to\tau\tau)$, $\sigma(Z\to 4\ell)$
  - Drell-Yan Z: differential x-sec, differential A_{FB}, weak mixing angle
  - W differential ℓ charge asymmetry A_C
  - W polarisation from $W\to\ell\nu$
  - Z rapidity and p_T spectra
- **V+jets:**
  - Differential $\sigma(W+jets)$, $\sigma(Z+jets)$
  - $\sigma(W+c)$, $\sigma(W)$, $\sigma(Z+b)$, $\sigma(Z+bb)$
- **Dibosons:**
  - $\sigma(WW)$, $\sigma(ZZ)$, $\sigma(WZ)$, $\sigma(W\gamma)$, $\sigma(Z\gamma)$
  - Isolated diphoton differential x-sec
- **BSM: limits on anomalous TGC**

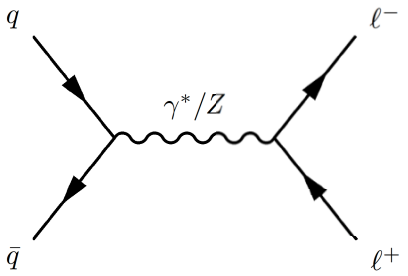


→ *see also talk by W.Wolszczak on Wednesday:*

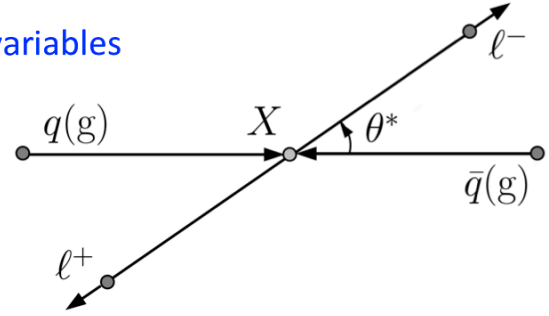
inclusive W/Z x-sec, differential DY x-sec, electron charge asymmetry in W production

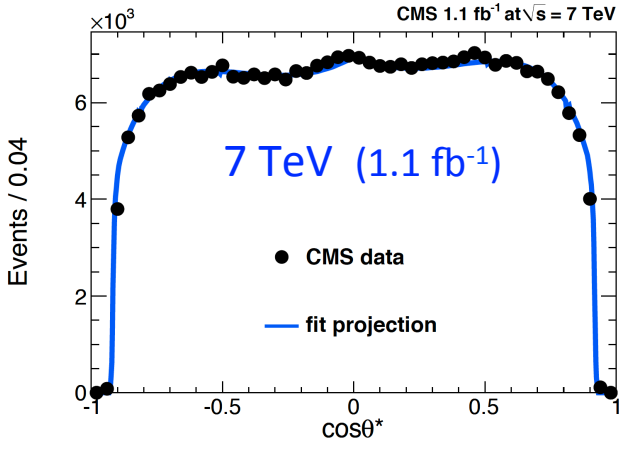
PRD 84 (2011) 112002

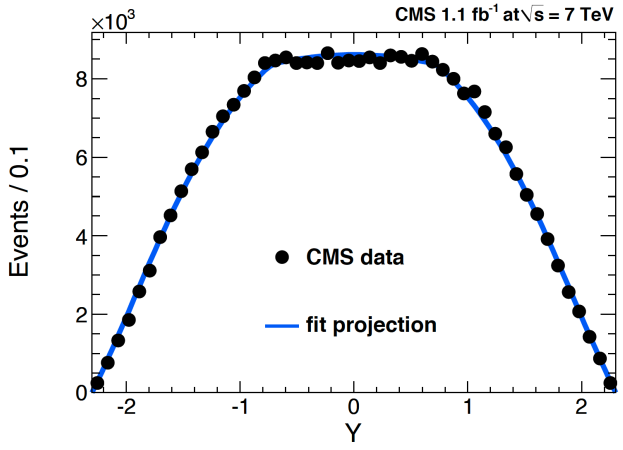
$\sin^2\theta_W^{\text{eff}}$



- **Forward-backward asymmetry in Drell-Yan Z^0/γ^* production:**
  - γ^* / Z^0 interference: asymmetric distribution of **quark-lepton θ* angle** in annihilating quarks' frame
  - Symmetric p-p collisions: valence quark direction more likely along dilepton boost direction
  - Electroweak mixing angle θ_W fitted from predicted shapes of 3 kinematic variables (dilepton rapidity, dilepton mass, decay angle θ^*) using $Z\to\mu\mu$ channel
  - Systematics: PDFs, FSR, effects beyond LO, tracker alignment







- $\sin^2\theta_{\text{eff}}$ **fit result:**

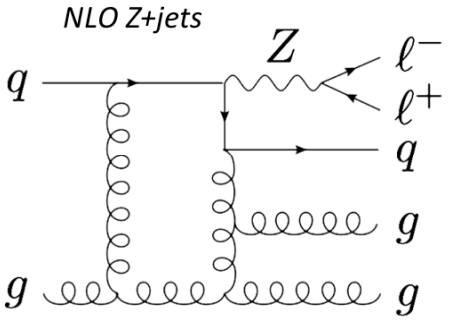
  0.2287

  ± 0.0020 (stat)

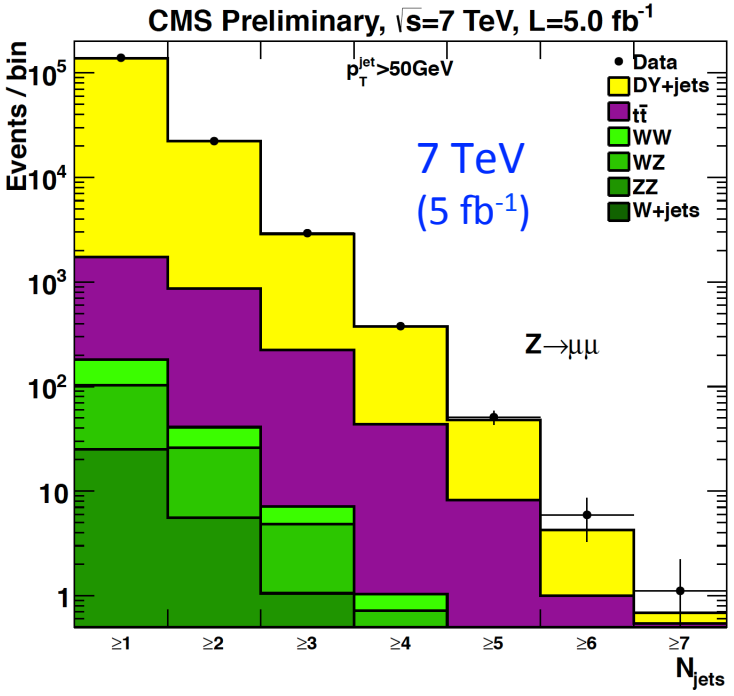
  ± 0.0025 (syst)

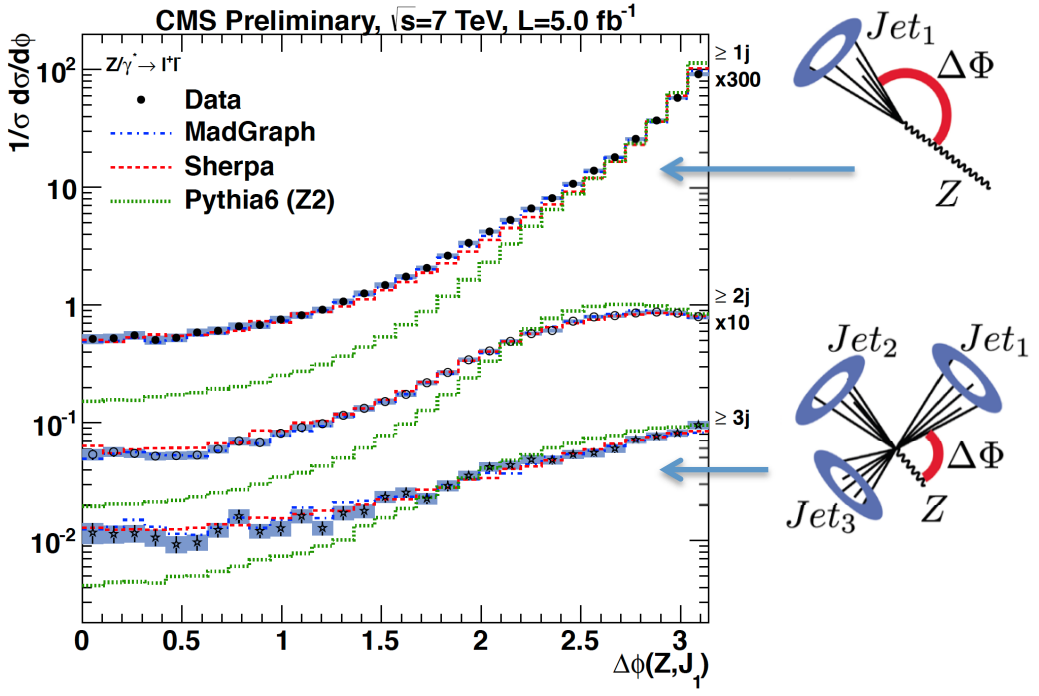
- **In agreement with other measurements**
  - Precision at 1% level with just 1fb^{-1}
  - Not as good as LEP (0.1%) or Tevatron (0.5%), comparable with NuTeV, H1 (1-2%)

Z+jets



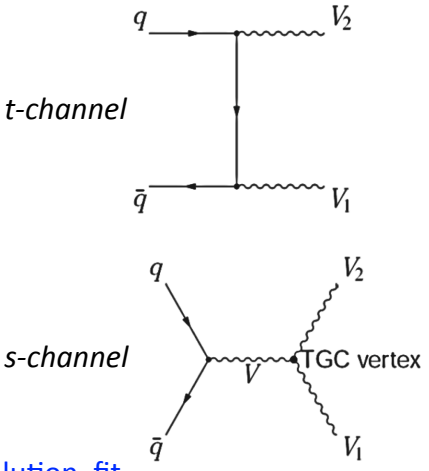
- **Jet multiplicities** and **azimuthal correlations $\Delta\Phi$ (Z, Leading Jet):**
  - Selection: ≥1 jet, 2 high p_T leptons, Z-mass requirement
  - Distributions unfolded back to particle level



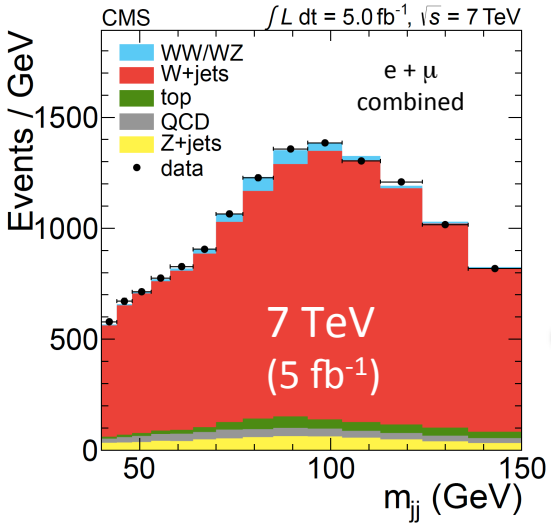


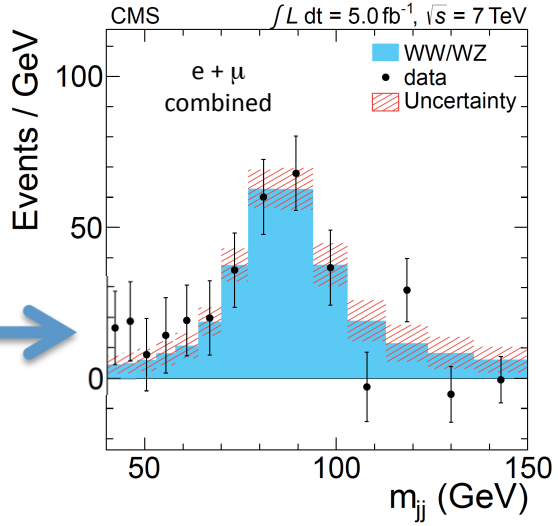
- **MADGRAPH, SHERPA describe data well**
  - Also true for other observables: $\Delta\Phi(jet, jet)$, $\Delta\Phi(Z, jet_2)$, transverse event thrust @ two $p_T(Z)$ regions
  - PYTHIA does not agree with data

WW / WZ → ℓνjj



- **Diboson *WW + WZ* production** from ***W + 2 jets*** channel:
  - Dijet invariant mass m_{jj} distributions for 2 channels (high BR, low purity): ***evjj*** and ***μνjj*** , where ***j*** = non-***b*** jet
  - Unbinned maximum likelihood fit to m_{jj} spectra in [40, 150] GeV window
  - Systematics: acceptance (4%$|_{theory}$), lumi.(2%), lepton reco/selection (2%), trigger, JES, MET resolution, fit





- **Result @ 7 TeV:**

$$\sigma(pp \to WW + WZ) =$$

68.9 ± 8.7 (stat)
± 9.7 (syst) ± 1.5 (lumi) **pb**

- From dijet p_T distribution shapes set 95% CL limits on anomalous WWγ triple gauge couplings (λ_γ and $\Delta\kappa_\gamma$)

- **Data agree with NLO prediction: 65.6 ± 2.2 pb**
  - No sign of anomalous TGCs
  - Limits on aTGC from LHC data are already competitive with LEP and Tevatron

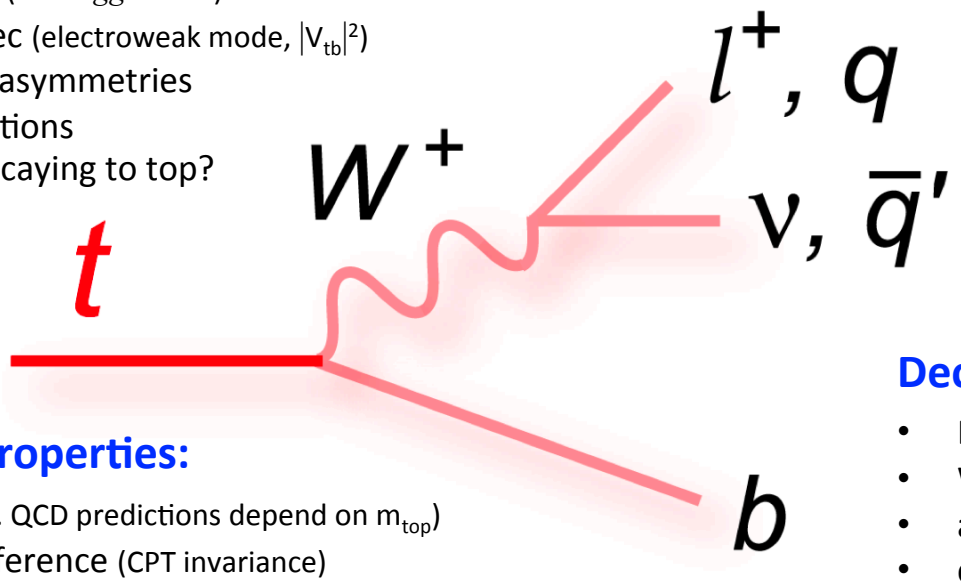
TOP quarks @ LHC

- LHC delivered **~1M (~5M)** top quark pairs in **2011 (2012)**
  per ATLAS/CMS experiment $(\int L\,dt \times \sigma)$

- **Top physics:**

Production modes:

- top-pair x-sec (~80% *gg* fusion)
- single top x-sec (electroweak mode, $|V_{tb}|^2$)
- tt production asymmetries
- tt spin correlations
- new states decaying to top?



Particle properties:

- mass (eg. QCD predictions depend on m_{top})
- mass difference (CPT invariance)
- width, lifetime (decaying before hadronisation)
- charge (+2/3e)
- radiation of bosons

Decays:

- BR(t→Wb) almost 100%
- W helicity measurement
- anomalous Wtb couplings?
- charged H^+ from top decays?
- FCNC top decays? (penguin t→cZ)

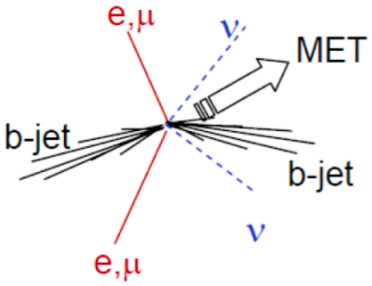
TOP quark analyses

>40 analyses on: **Top Pair**, **Single Top** @ √s = 7 or 8 TeV (up to ~5 fb^{-1})

- **Top-antitop production:**
  - Cross section (channels: *ee*, *eμ*, *eτ*, *μμ*, *μτ*, *e/μ/τ +jet*, *all hadronic*)
  - Top mass (channels: *ee*, *eμ*, *μμ*, *e/μ+jet*, *all hadronic*; also: σ(*tt*), kinematic endpoints)
  - Top charge, Top charge asymmetry, $\alpha_S(M_Z)$ from σ(*tt*)
  - Mass difference $\Delta m_t = m_t - m_{\bar{t}}$
  - Pert. QCD tests (N_{jets}, p_T^{top}, y^{top} ...)
  - σ(*tt +jets*), σ(*tt +V*)
  - Ratios: σ(*ttbb*)/σ(*ttjj*), BR(*t*→*Wb*)/BR(*t*→*Wq*)
  - Rare FCNC top decays (*t*→*qZ*)
  - Top spin correlations
  - *t* and *W* polarisations
- **Single top production:**
  - Cross section (channels: **t**, *tW*, **s**)
  - Rare FCNC production (*qg*→*t*)
- BSM: 4th generation quarks, $t\bar{t} + \not{E}_T$

$t\bar{t}$ signatures:

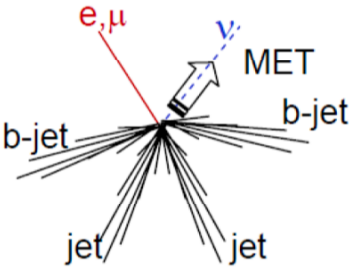
according to W decays



dileptons

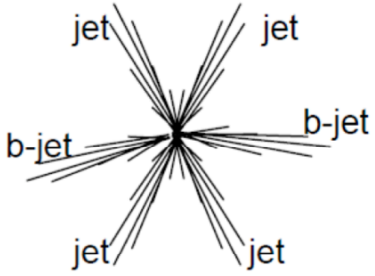
9%

e + μ + τ



lepton + jets

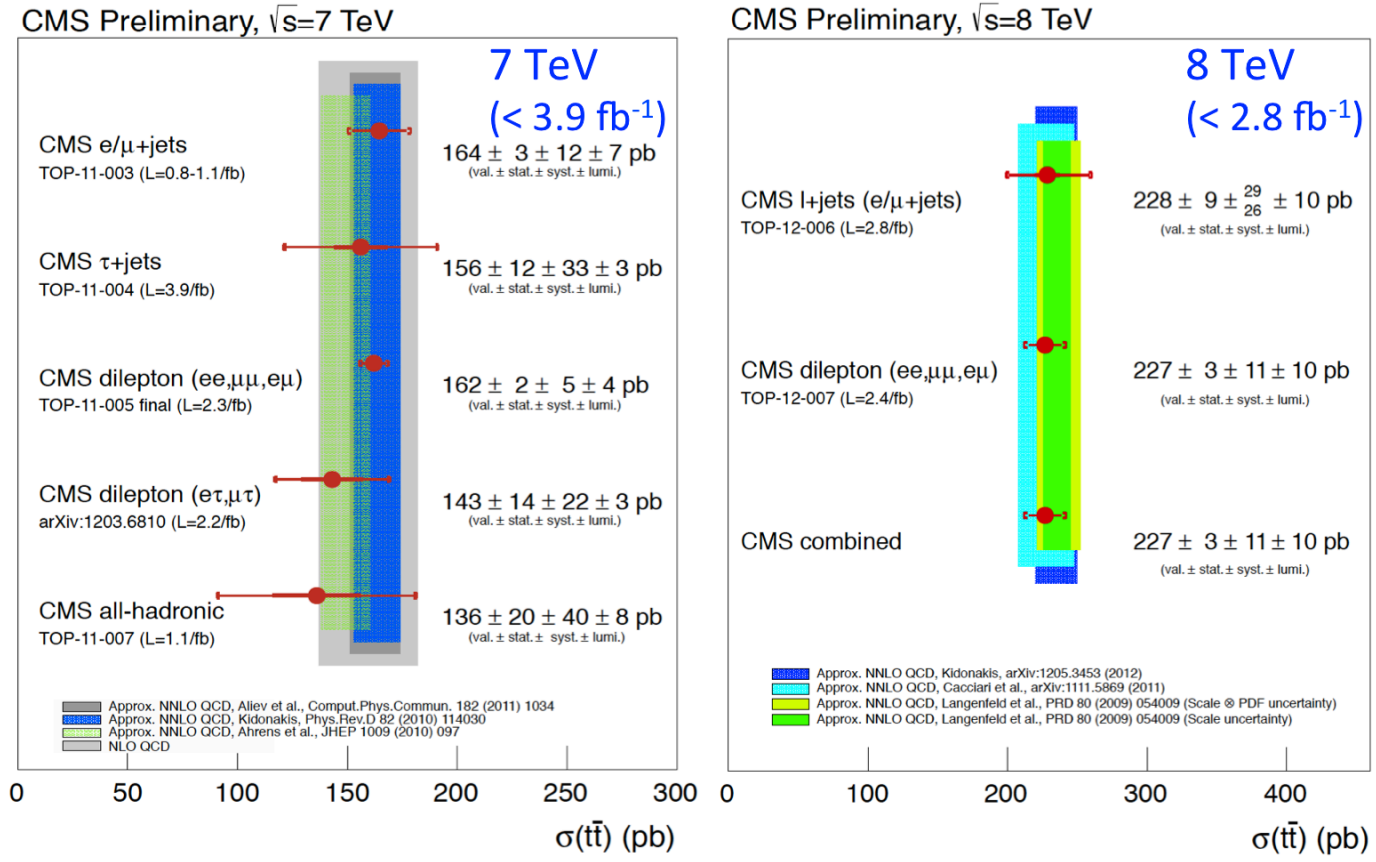
45%



all hadronic

46%

Top-antitop production



- Dilepton channel most precise
- **Data agree with Approx. NNLO**

- **Combined results @7 TeV:**

CMS : **165.8** ± 2.2 (stat) ± 10.6 (syst) ± 7.8 (lumi) pb

LHC : **173.3** ± 2.3 (stat) ± 9.8 (syst) pb

CMS-PAS-TOP-12-003 with < 1.1 fb^{-1}

@8 TeV:

CMS : **227** ± 3 (stat) ± 11 (syst) ± 10 (lumi) pb

CMS-PAS-TOP-12-007 with < 2.8 fb^{-1}

Top mass

- **Methods:**
  - Jet Energy Scale in-situ calibration:

    Use invariant mass of 2 light jets from W decay to constrain the JES
  - Template:

    Data-MC comparison of variables sensitive to m_{top}
  - Analytical Matrix Element Weighting:

    Compute event probability density that the event with certain input m_{top} would lead to variables observed in the detector
  - Ideogram:

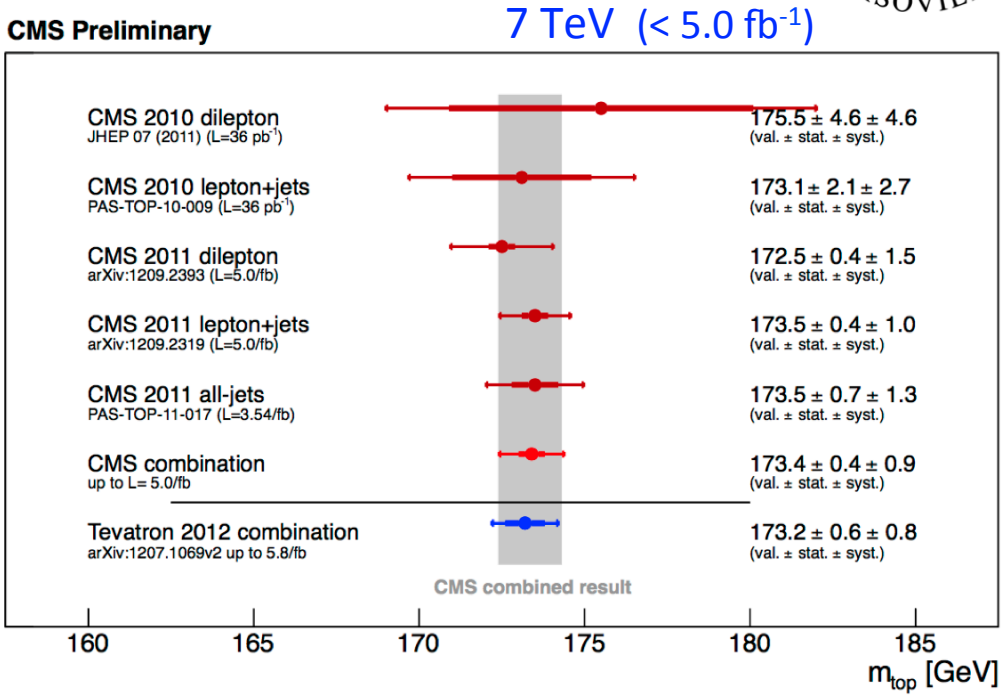
    Calculate event-by-event 2D Likelihood(m_{top}, JES), consider all permutations of jet assignments to ***t*** decays
  - From kinematic endpoints:

    Explore variables suited to analyse events with symmetric 3 body decay
  - (Indirect) from cross section:

    Parameterise dependence of the measured- and the predicted cross sections on m_{top}

- **Systematics:**

  JES, b-JES, colour reconnection, MC generator



- **Combined results @7 TeV:**

  CMS : **173.4** ± 0.4 (stat) ± 0.9 (syst) GeV Sept 2012

  CMS-PAS-TOP-11-018 with < 5.0 fb^{-1}

  LHC : **173.3** ± 0.5 (stat) ± 1.3 (syst) GeV July 2012

  CMS-PAS-TOP-12-001 with < 4.9 fb^{-1}

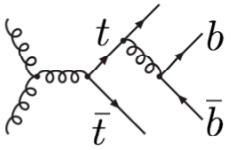
7 TeV
(5 fb^{-1})

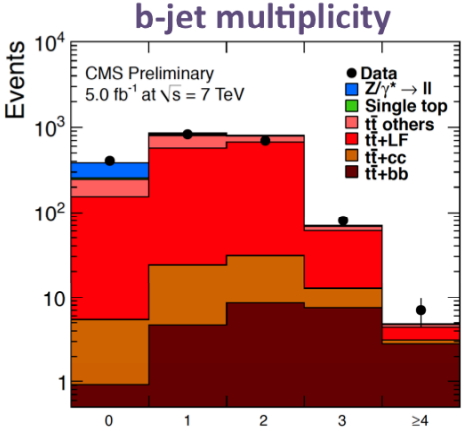
Top properties

- **First measurement of ratio $\sigma(t\bar{t}\,b\bar{b})/\sigma(t\bar{t}\,jj)$:**

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

  - tt+jets in dilepton mode : ≥4 jets (including ≥2 b-tagged jets)
  - **Data compatible with: MADGRAPH (1.2%) and POWHEG (1.3%)**
  - ttbb is important background for ttH



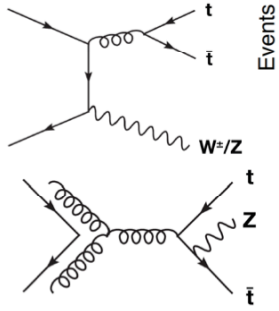


CMS-PAS-TOP-12-024

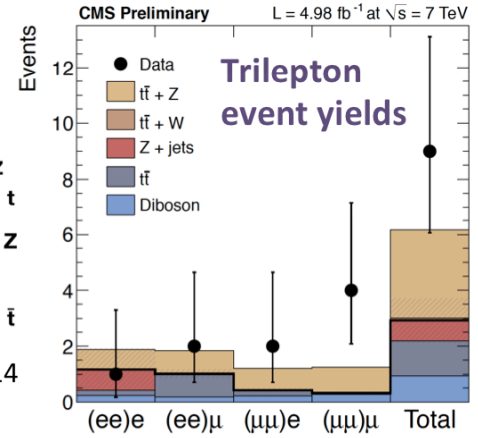
- **Evidence for associated $t\bar{t}\,W$ and $t\bar{t}\,Z$ production :**

$$\sigma_{ttV} = 0.51\ ^{+0.15}_{-0.13}\ (\text{stat})\ ^{+0.05}_{-0.04}\ (\text{syst})\ \text{pb}$$

  - Same-sign dileptons (tt+W/Z) or trileptons (tt+Z)
  - **Data compatible with SM NLO : 0.308 pb, 4.6 σ evidence**



CMS-PAS-TOP-12-014



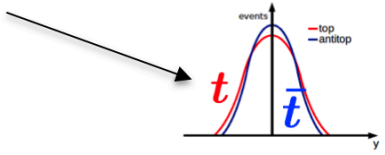
- **Top charge asymmetry A_C:**

SM predicts charge asymm. in $t\bar{t}$ prod. from interference of QCD/QED/weak diagrams

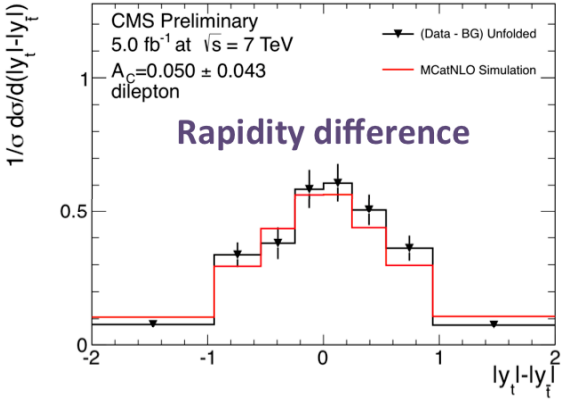
At LHC width of $|y|$ distribution for t is broader than for $\bar{t}$

$\Delta|y| = |y_t| - |y_{\bar{t}}|$ is sensitive to charge asymmetry

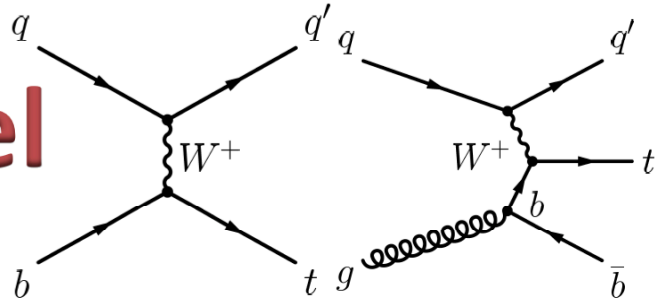
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$



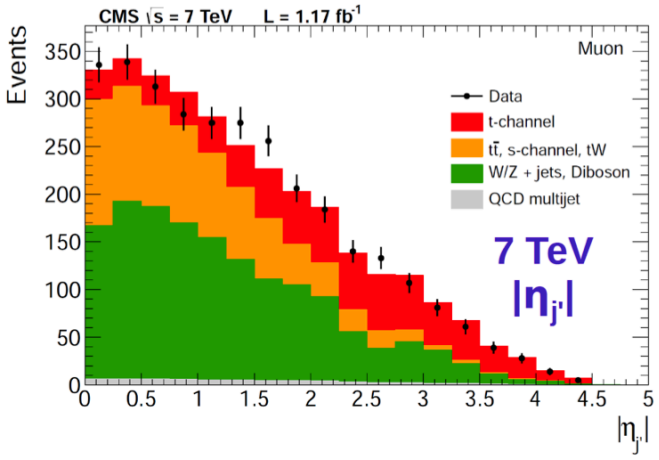
  - Dileptons : $0.050 \pm 0.043\,(\text{stat})\ ^{+0.010}_{-0.039}\,(\text{syst})$ CMS-PAS-TOP-12-010
  - ℓ+jets : $0.004 \pm 0.010\,(\text{stat}) \pm 0.012\,(\text{syst})$ CMS-PAS-TOP-11-030
  - **Data agree with SM : 0.0115 ± 0.0006**



Single top : *t*-channel

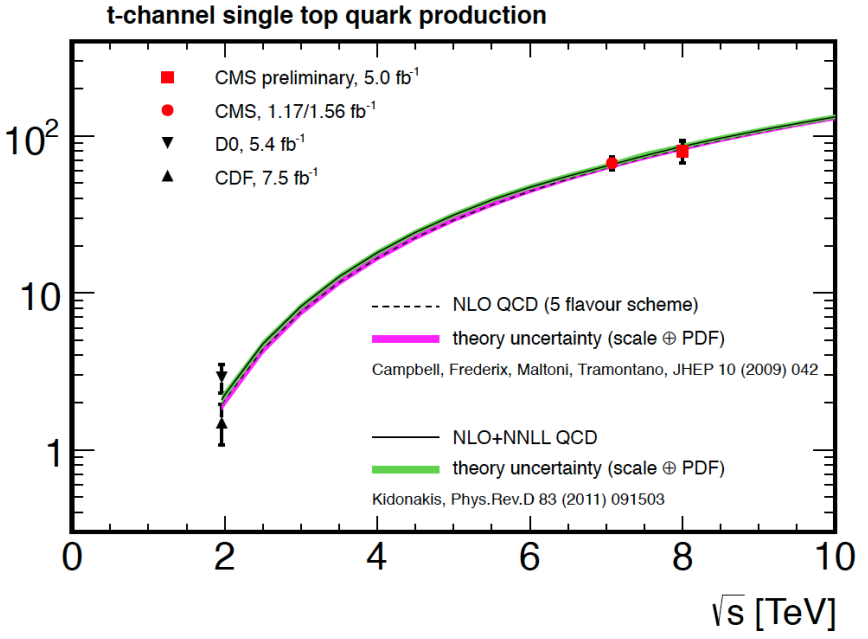


- **Methods:**
  - $|\eta_{j'}|$: light jet recoiling against ***t*** @7, 8 TeV
  - Multivariate Analyses : BDT, NN @7 TeV



Selection:
- 1 isolated lepton
- MET
- 2 jets (≥1 b-jet)

Systematics:
- W+jets modelling
- b-tagging
- Theory (tt, single top)



- **Results on cross sections:**

  67.2 ± 3.7 (stat) ± 3.0 (syst) ± 3.5 (theor) ± 1.5 (lumi) pb @7 TeV (< 1.6 fb^{-1}) CMS-PAS-TOP-11-022

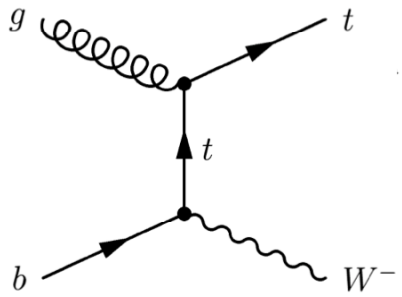
  80.1 ± 5.7 (stat) ± 11.0 (syst) ± 4.0 (lumi) pb @8 TeV (5 fb^{-1}) CMS-PAS-TOP-12-011

  - **Data consistent with NLO+NNLL predictions**, exp. uncert. @7 TeV is < 10%

- **Measurement of $|V_{tb}|$:** $|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{th}_{t\text{-ch.}}}} =$ **1.020** ± 0.046 (exp) ± 0.017 (theor) from 7 TeV x-sec

  $0.92 < |V_{tb}| \leq 1$ @ 95% C.L. assuming $|V_{tb}| \leq 1$ and $f_{LV} = 1$

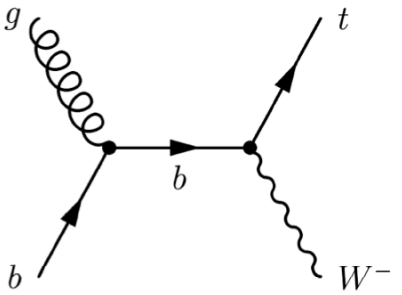
Single top : *tW*-channel



- **Methods**:
  - Cut-based : signal region (1j1t) and tt control region
  - BDT : with 4 variables

Selection:
- 2 isolated leptons
- 1 b-tagged jet
- MET

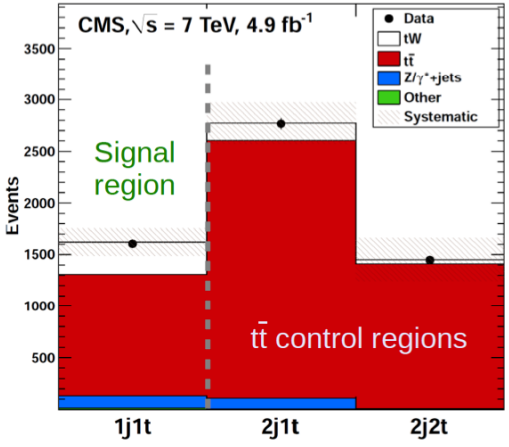
Systematics:
- JES
- Theory (tt, tW)

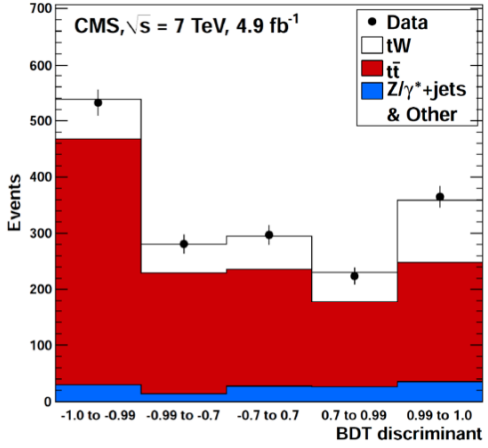


- **Evidence on associated *t+W* EWK production:**

Cut-based: 3.5 σ — 15 ± 5 pb

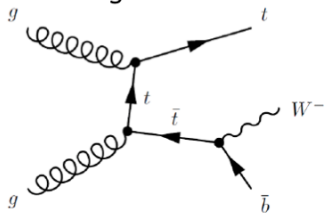
BDT: 4.0 σ — 16^{+5}_{-6} pb





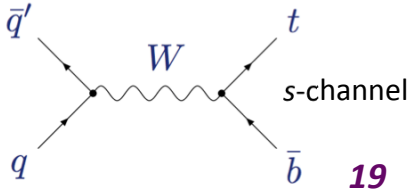
7 TeV
(< 4.9 fb^{-1})

Doubly resonant NLO diagrams not included in tW signal:



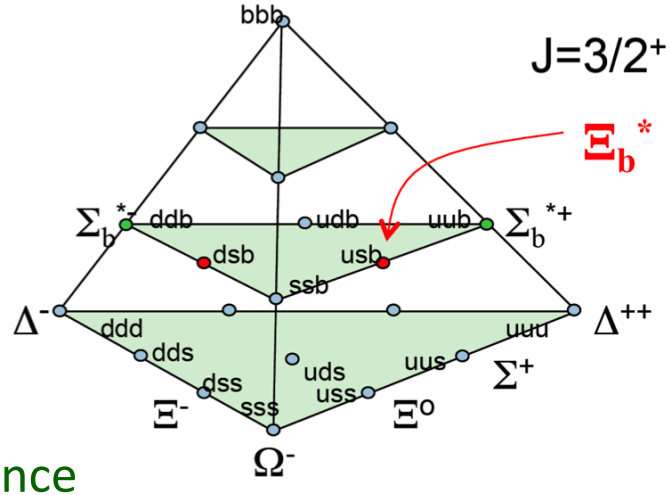
- **Data consistent with SM Approx. NNLO: 15.6 pb** N.Kidonakis, PRD 82 (2010) 054018
  - *tW*-channel has not been observed at Tevatron (SM : 0.3 pb)

- *s*-channel measured at Tevatron (SM : 1 pb)
  ...but **not yet at LHC** (SM : 5 pb @7TeV / 6 pb @8TeV)



Heavy Flavours @ LHC

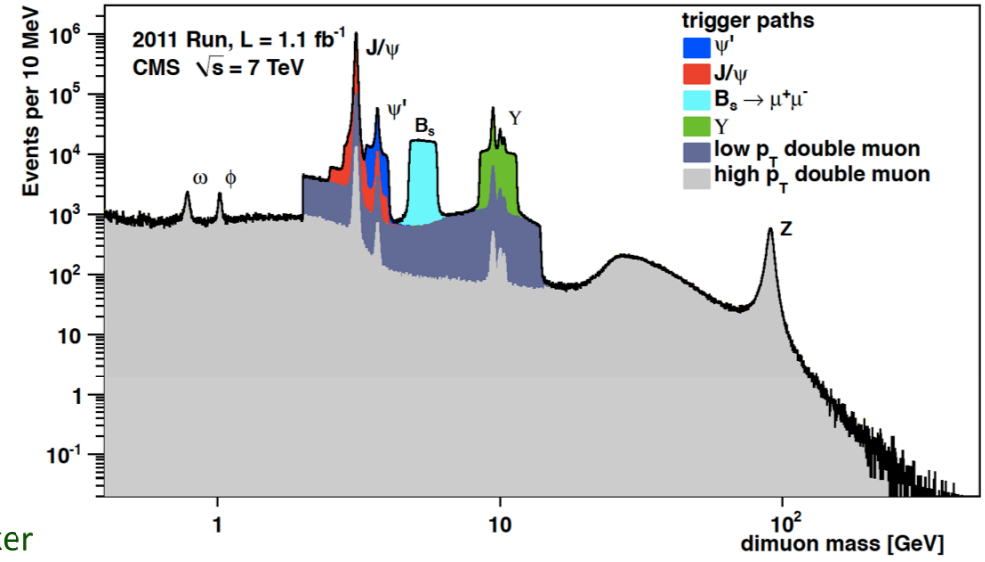
- **Quarkonia and Charm/Bottom-hadron production:**
  - LHC pp: high centre-of-mass energies, wide momentum and rapidity range
  - J/ψ and Υ differential cross sections and polarisations still not well understood theoretically
- **HF spectroscopy:**
  - Verification of: lattice QCD (LQCD), non-relativistic QCD (NRQCD) techniques
- **B and D meson decays:**
  - CPV tests: direct, in mixing and their interference
  - Alternative way to look for NP (asymmetries, BRs)



Heavy Flavour analyses

>30 analyses on **HF-hadrons**: @ √s = 7 TeV (up to 5.3 fb^{-1})

- Heavy hadron production: J/ψ, $\psi(2S)$, $X(3872)$, χ_{c1}, χ_{c2}, $\Upsilon(nS)$, B^0, B_s^0, B^+, B_c^+, Λ_b, Ξ_b^{*0}
- Decays: $B^+ \to J/\psi\, \phi\, K^+$, $B_s^0 \to J/\psi\, \phi$, $B_c^+ \to J/\psi\, \pi^+(\pi^+\pi^-)$
- Rare decay searches: $B^0_{(s)} \to \mu^+\mu^-$, $D^0 \to \mu^+\mu^-$
- Lifetimes: B_s^0, Λ_b
- $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ polarisation
- B – anti-B angular correlations
- Inclusive b-hadron production
- Inclusive muons from Heavy Flavours



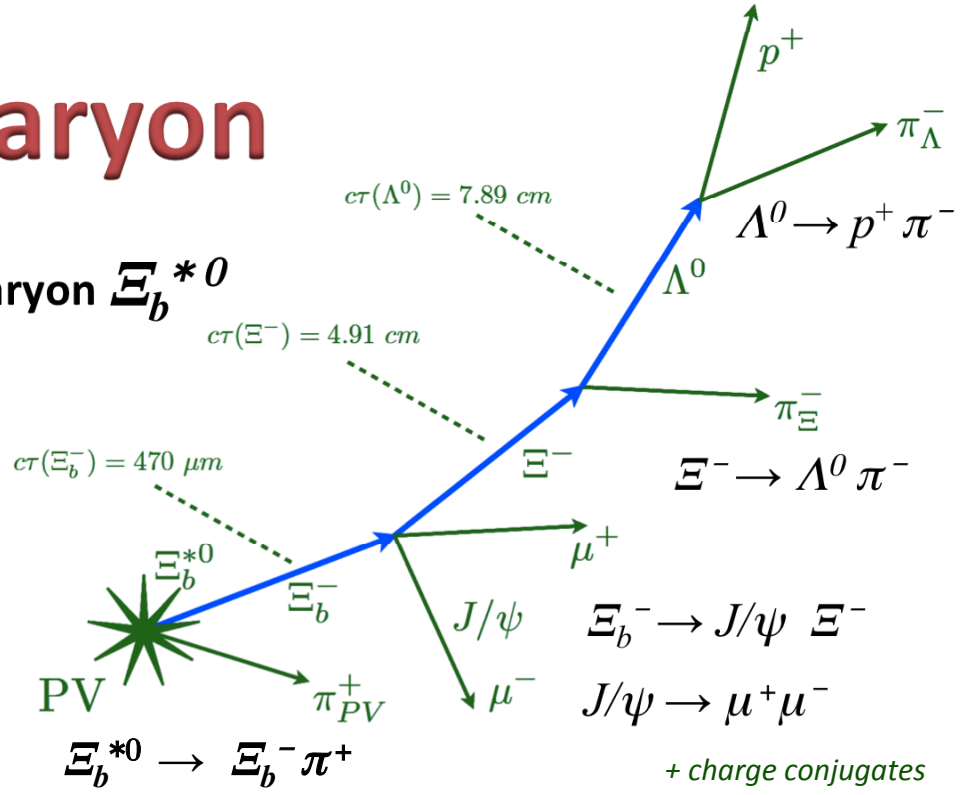
Triggering & reconstruction:

- Good track p_T and vtx position resolution from tracker
- Good dimuon mass resolution ($\sigma_{\mu\mu}$ ~40 MeV in barrel)
- High μ reconstruction efficiency for $|\eta|$<2.4 & p_T>3 GeV
- High purity, fake μ rate: ~0.1% for K,π and ~0.05% for p
- B-hadron and quarkonium triggers from dimuons (PU rejected by DCA and vtx prob. cuts, require 3σ separation from beam line for B-hadrons)

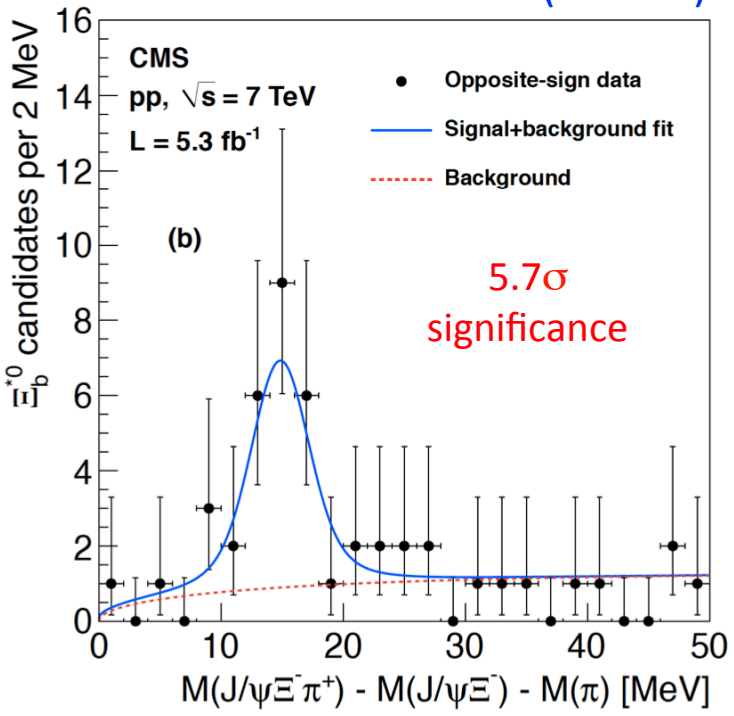
PRL 108 (2012) 252002

New B-baryon

- **Discovery of (SM predicted) excited B-baryon Ξ_b^{*0}**
  - Primary vertex + 3 displaced vertices
  - Ξ_b^- candidates combined with pion tracks



7 TeV (5.3 fb^{-1})



- **Mass and width:**

  $M(\Xi_b^{*0})$ = **5945.0** ± 0.7 (stat) ± 0.3 (syst) ± 2.7 (PDG) MeV

  $\Gamma(\Xi_b^{*0})$ = **2.1** ± 1.7 (stat) MeV

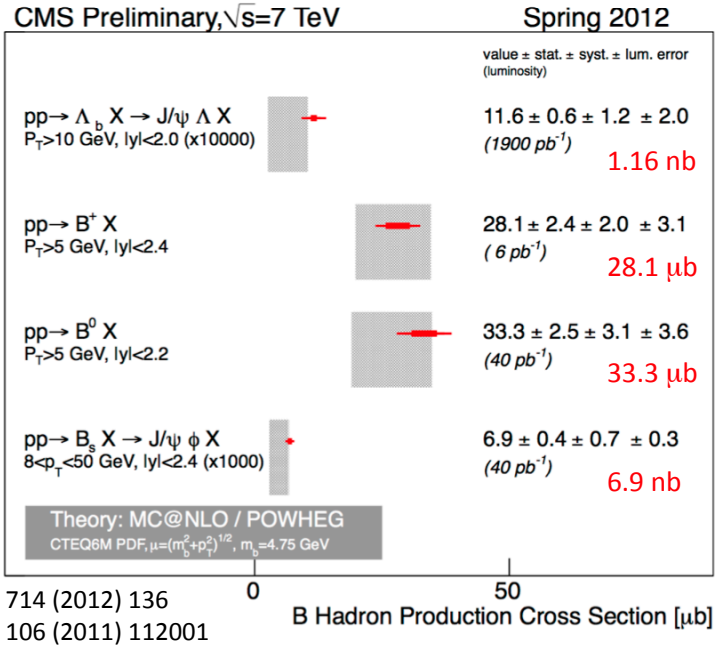
- **Data compatible with predictions** (lattice QCD, Regge trajectories)

  $Q = M(\Xi_b^{*0}) - M(\Xi_b^-) - M(\pi^+)$ ~ **11-29 MeV**

  Γ < 1 MeV

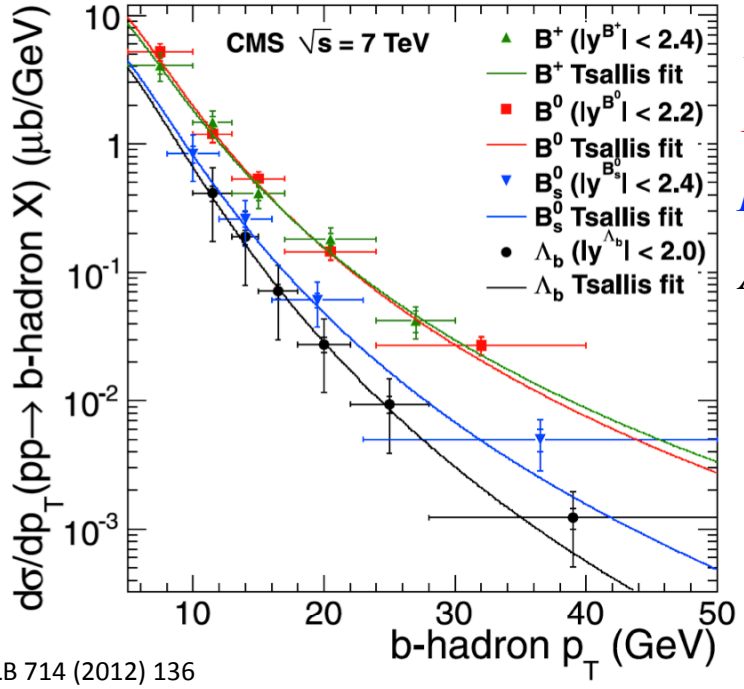
  Most likely (u-s-b) excited state Ξ_b^{*0} with **$J^P = 3/2^+$**

B-hadron production



Λ_b B^+ B^0 B_s^0

PLB 714 (2012) 136
PRL 106 (2011) 112001
PRL 106 (2011) 252001
PRD 84 (2011) 052008



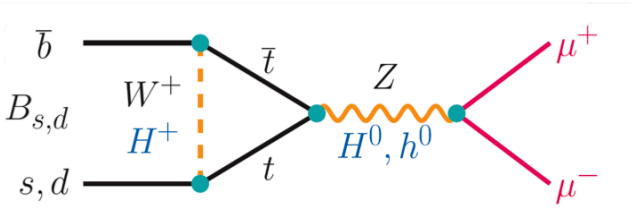
B^+ B^0 B_s^0 Λ_b

PLB 714 (2012) 136

- **B-hadron exclusive production cross sections agree with NLO predictions**
  - Data slightly above theory
- **Λ_b baryon exhibits steeper p_T distribution than B-mesons**
  - 4σ effect

7 TeV
(< 1.9 fb^{-1})

Rare B decays

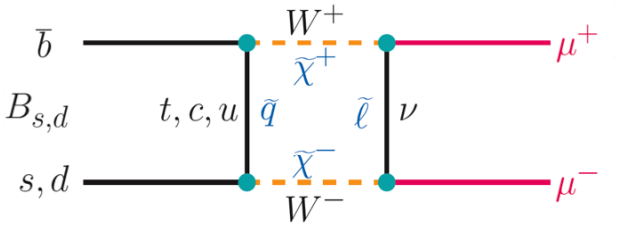


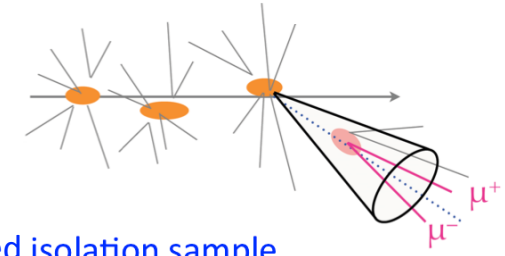
- $B_{s,d} \to \mu^+\mu^-$ **decays highly suppressed in SM:**
  - FCNC through Z-penguin & box diagrams
  - Cabbibo suppressed, helicity suppressed

$$BR(B_s^0 \to \mu^+\mu^-) = (3.23 \pm 0.27) \cdot 10^{-9}$$

$$BR(B_d^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \cdot 10^{-10}$$

  - BSM: sensitive to extended Higgs sectors





- **Cut-based method**:
  - **Purity :** relative $\mu\mu$ isolation, good secondary vertex separation
  - **Bias checks :** normalization channel $B^+ \to J/\psi\, K^+$, pileup dependence, inverted isolation sample
  - **Blind analysis :** hiding signal region **5.20 < M($\mu\mu$) < 5.45 GeV** while optimising cuts, evaluating systematics
  - **Systematics :** acceptance, muon ID, trigger efficiency, normalisation channels, B-hadronisation composition

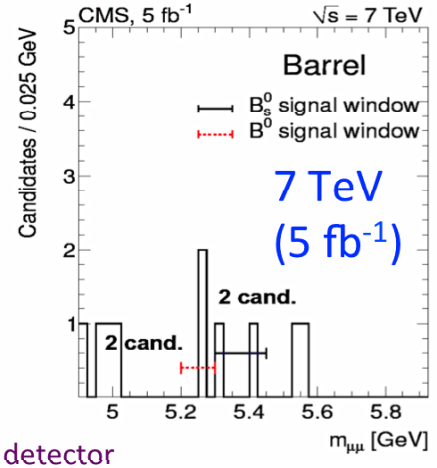
- No events excess w.r.t. background, set **95 % CL** limits:

$$BR(B_s^0 \to \mu^+\mu^-) < 7.7 \cdot 10^{-9} \quad \text{: CMS}$$

$$< 4.2 \cdot 10^{-9} \quad \text{: ATLAS+CMS+LHCb}$$

$$BR(B_d^0 \to \mu^+\mu^-) < 18 \cdot 10^{-10} \quad \text{: CMS}$$

$$< 8.1 \cdot 10^{-10} \quad \text{: CMS+LHCb}$$



JHEP 1204 (2012) 033
CMS-PAS-BPH-12-009 June 2012

Summary

- Presented selected results on: Jets, VBs, Top and HFs production at CMS:
  - 7 TeV analyses still being updated
  - first 8 TeV are results available
- Data agree well with Standard Model predictions:
  - **Jets :** probed up to p_T of 2 TeV
  - **Vector bosons :** calibration tool and pQCD tests, no signs of anomalous TGCs
  - **Top :** precision of Tevatron reached, single-top *s-channel* still challenging
  - **Heavy Flavours :** new spectroscopy measurements, improving limits on rare meson decays
  - many differential observables now available, some tensions between models
- *Looking forward to...*
  - *CMS analyses with full 7 TeV + 8 TeV datasets*
  - *updated combinations between LHC experiments*

Public CMS results

- SM Vector Bosons & Jets:

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

- Forward jets & small-x QCD:

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

- Top physics:

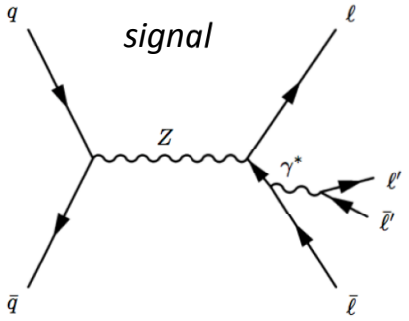
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

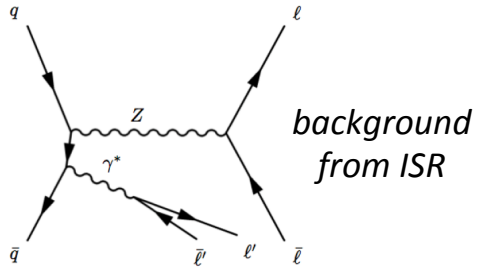
- B-physics, Quarkonia:

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

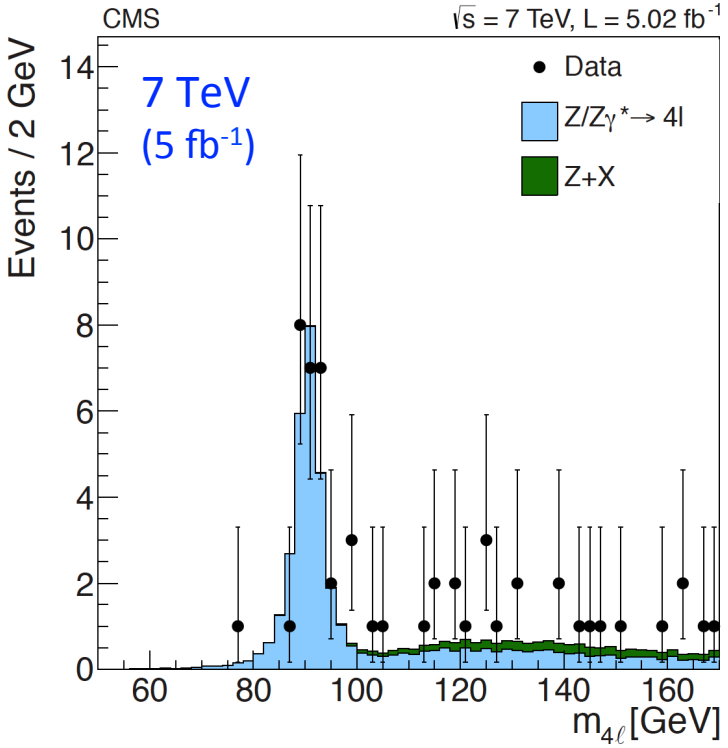
BACKUP slides

Observation of Z→4ℓ





- **Observation of $Z \to 4\ell$ decay:**
  - Calibration channel for $pp \to H \to 4\ell$: 4-muon mass scale, resolution
  - Resonant peak in 4-lepton invariant mass distribution at m_Z
  - 3 channels: $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
  - Selection: $80 < m_{4l} < 100$ GeV and $m_{2l} > 4$ GeV



- **Cross section and branching ratio:**

$$\sigma(pp \to Z) \times BR(Z \to 4\ell) =$$

$$= 112^{+23}_{-20}\,(\text{stat})\,^{+7}_{-5}\,(\text{syst})\,^{+3}_{-2}\,(\text{lumi})\,\text{fb}$$

$$BR(Z \to 4\ell) =$$

$$= (\,4.2\,^{+0.9}_{-0.8}\,(\text{stat}) \pm 0.2\,(\text{syst})\,) \times 10^{-6}$$

  - Significance **9.7σ**, observed 20 events

- **Data agree with SM predictions:**
  120 ± 5 fb and **4.45 × 10⁻⁶**
  - Z/γ* background: POWHEG (NLO)
  - Z decay widths: CALCHEP (LO, interference)