Standard Model Results (excl. top) from CMS at 13 TeV

Universidad de
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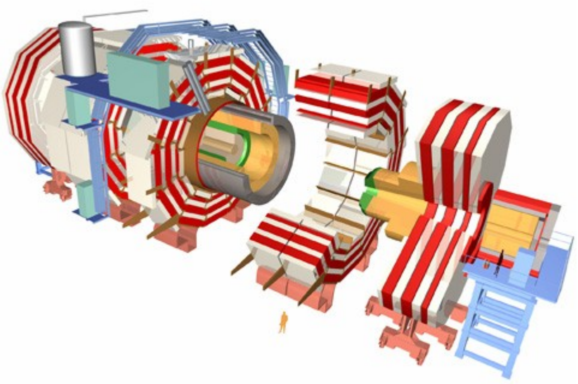
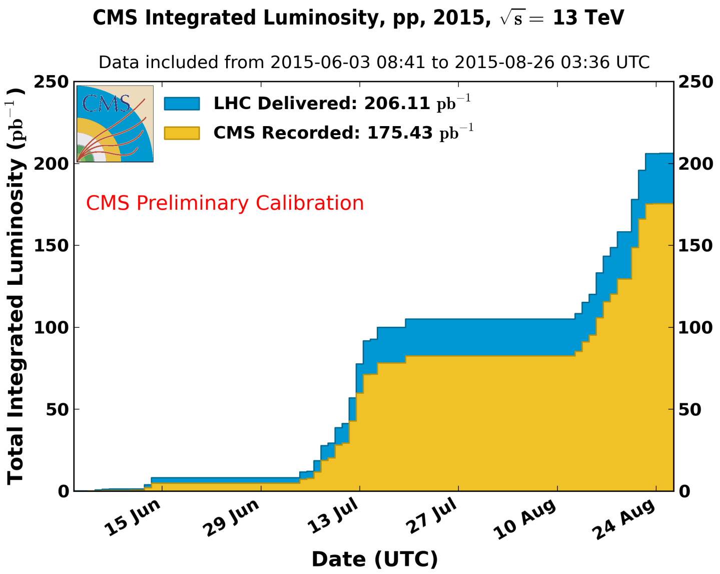
TOP2015: 8th International Workshop on Top Quark Physics
13 – 18 September, 2015
Ischia (Italy)

Outline

- This talk covers main aspects of the CMS Physics program, with **special emphasis on the first 13 TeV results**

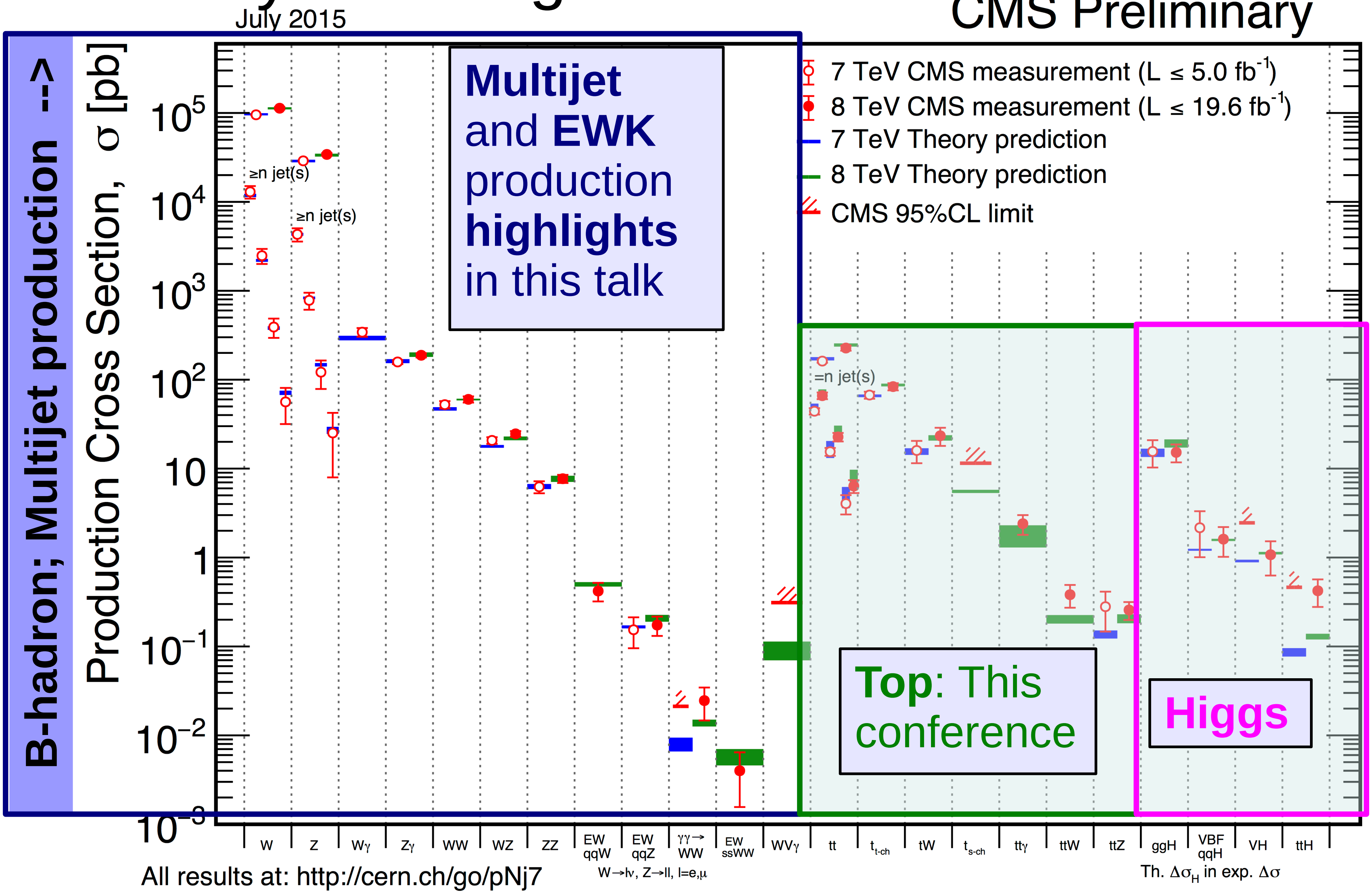




- Soft QCD
  - $dN_{ch}/d\eta$ first CMS paper at 13 TeV
- B Physics
  - First resonances at 13 TeV
- QCD and EWK
  - Highlights from Run 1
  - Z resonance at 13 TeV
  - **First 13 TeV analyses will arrive soon**

- Later in the program **@13 TeV**
  - First results from **CMS searches** → J. Andrea later in this session
  - Impressive set of results from top-quark physics → Many talks to come in the following days

LHC Physics Program

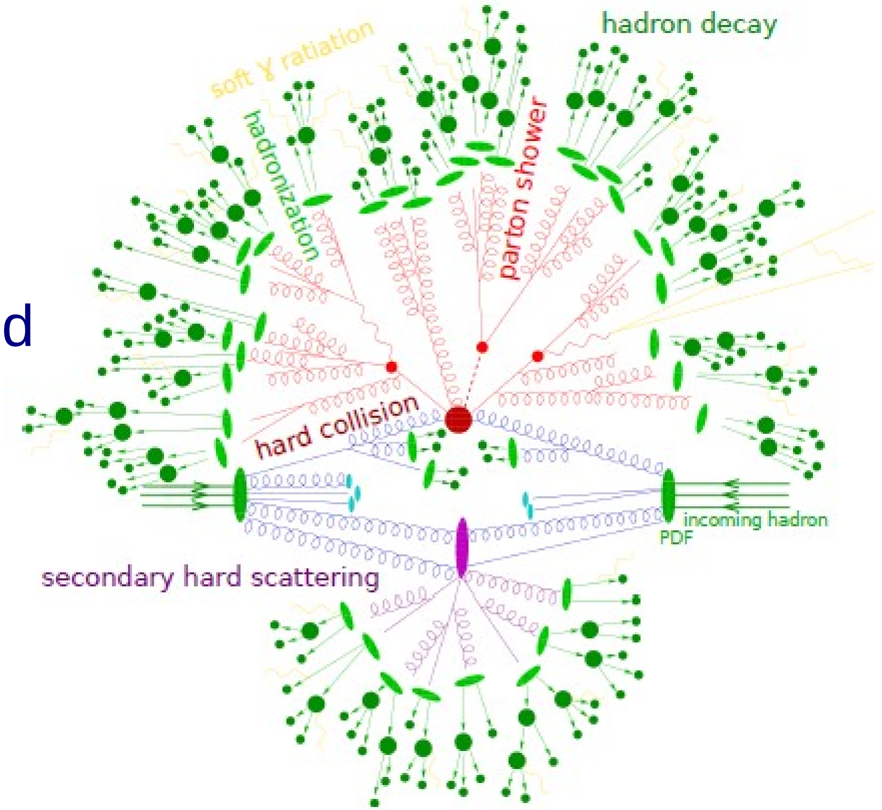


- **SM probed in Run 1 over vasts orders of magnitude**

Soft QCD in CMS

- The understanding and modeling of QCD interactions impacts directly potential for precision measurements and searches for new physics
- Soft particle production cannot be calculated reliably using pQCD and is generally described by phenomenological models → **MC tunes**
  - Minimum bias, underlying event, multiple interactions
- Study of soft QCD processes suitable for CMS due to high granularity and precision over a wide energy range
  - First CMS paper at 13 TeV submitted to PLB:

    Pseudorapidity distribution of charged hadrons in proton-proton collisions at √s = 13 TeV

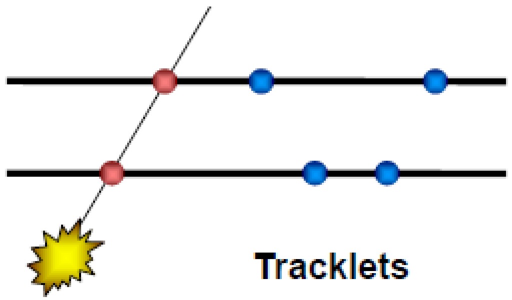


credit: sherpa-and-open-science-grid-predicting-emergence-jets

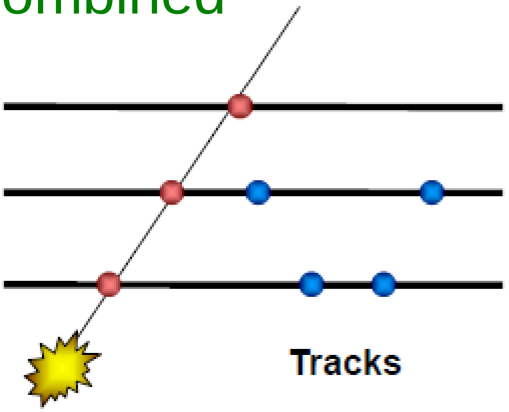
CMS-PAS-FSQ-15-001
Submitted to PLB
arXiv.1507.05915

$dN_{ch}/d\eta$ at 13 TeV: Analysis Overview

- Motivation: $dN_{ch}/d\eta$ gives a handle on the relative weight of soft and hard scattering contributions
  - Important for precise modeling of pile-up collisions
- Collect minimum bias data in low PU runs
  - Using Zero bias trigger
  - Data taken on June 7, <PU> ~0.2-5%, B=0 (straight tracks)
- Strategy: Use different techniques with different sensitivities to misalignment, cluster splitting, background contamination
  - pixel counting → cross check
  - tracking, tracklets → main result: combined

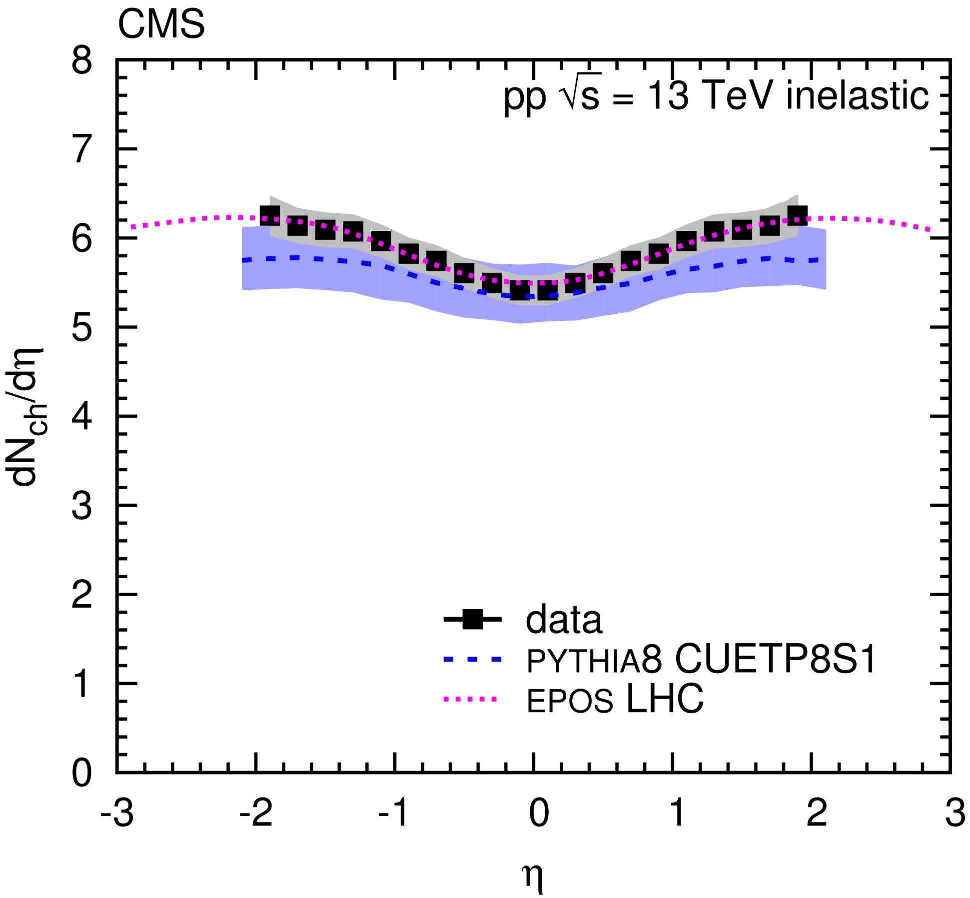


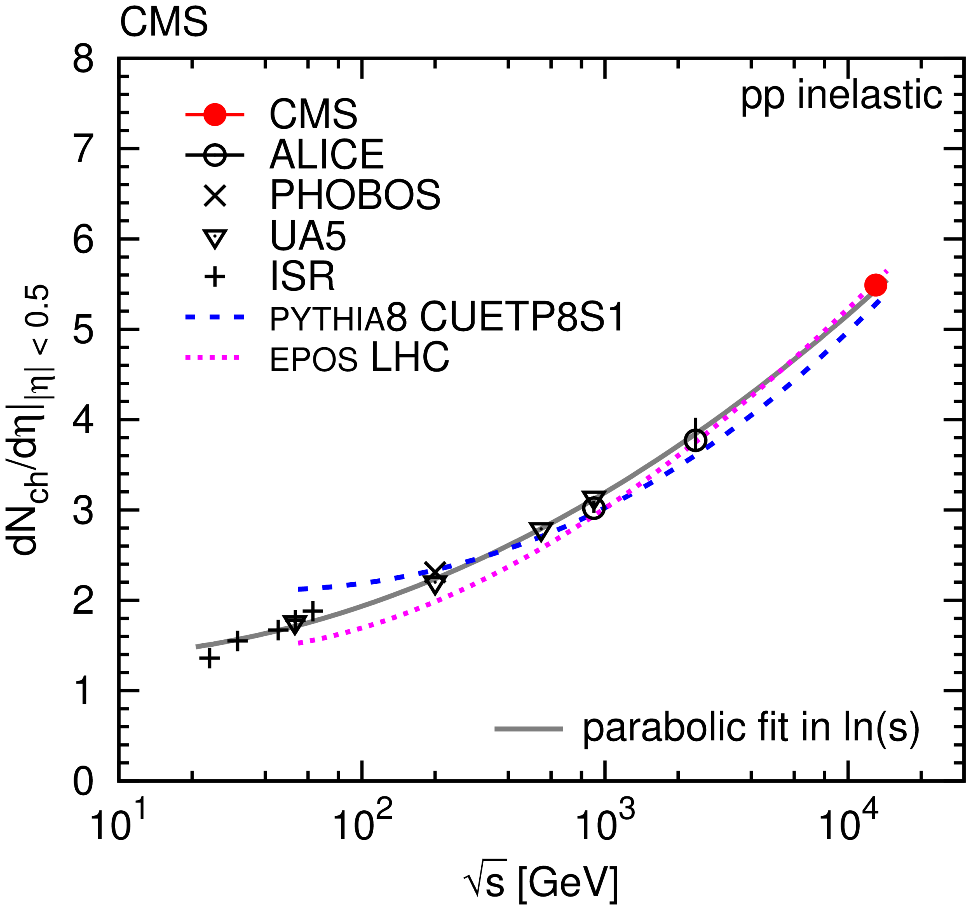
- Uses hit pairs
- Background subtraction based on data control samples



- Uses hit triplets
- Additional hit minimizes background contributions

$dN_{ch}/d\eta$ at 13 TeV: Results



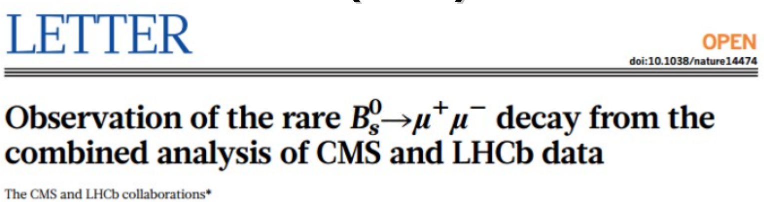


- Midrapidity ($|\eta|<0.5$)
  $dN_{ch}/d\eta = 5.49 \pm 0.01$ (stat) ± 0.17 (sys)
  - Both Pythia8 CUETP8S1 and EPOS LHC consistent with data
  - Pseudorapidity dependence better described by EPOS LHC
- Both Pythia8 and EPOS LHC globally reproduce the collisions-energy dependence

B-Physics in CMS

- Flavor physics provides particularly sensitive probes for BSM physics
  - ◊ Multitude of measurable processes, precise SM predictions, potentially sensitive above the direct reach of LHC
- CMS is a general purpose detector, but it presents excellent capabilities for B-physics
  - ◊ Good vertex reconstruction, p_T resolution muon system and tracker, and very flexible HLT
- Main Run 1 result: B-rare decays
  - ◊ **Observation** (with LHCb) of $\mathbf{B^0_s \to \mu^+\mu^-}$ and **evidence for** $\mathbf{B^0 \to \mu^+\mu^-}$

Nature 522 (2015) 68


LETTER

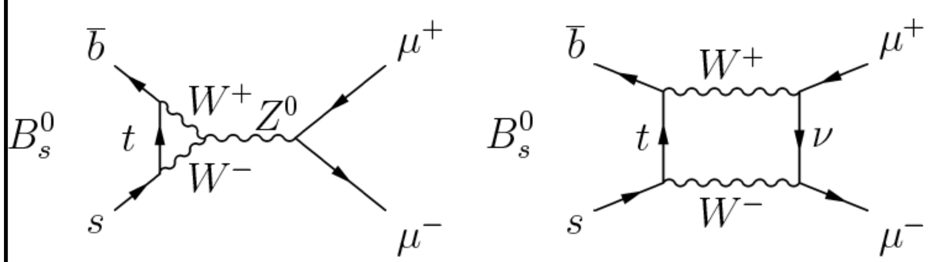
OPEN

doi:10.1038/nature14474

Observation of the rare $B^0_s \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

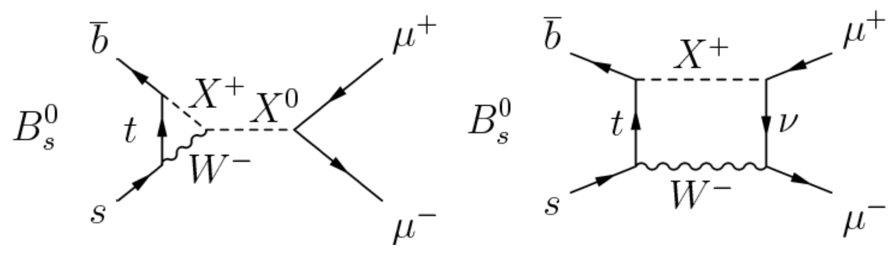
The CMS and LHCb collaborations*

- ◊ **SM predicts small BR** for those processes



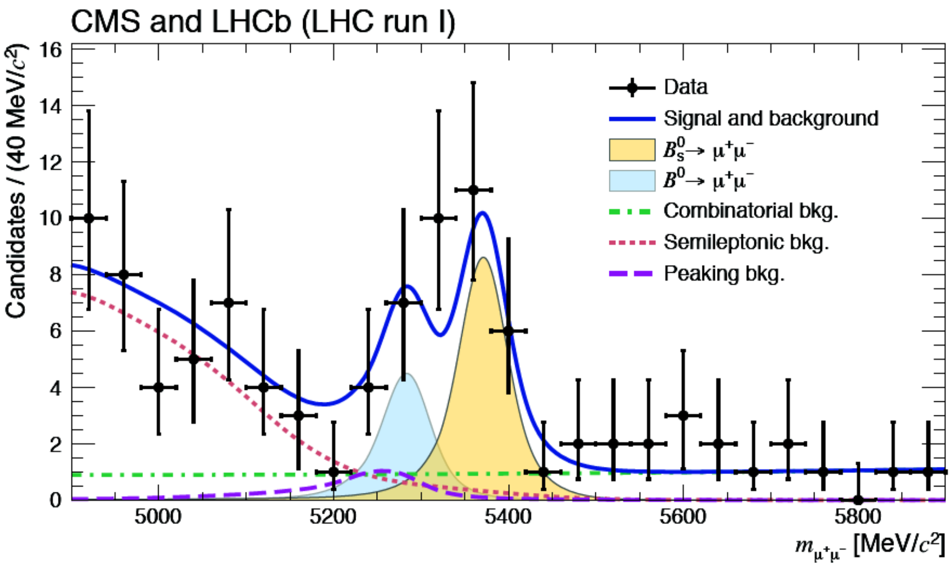
$B^0_s \to \mu^+\mu^-$

- ◊ Theories beyond SM predict larger BR

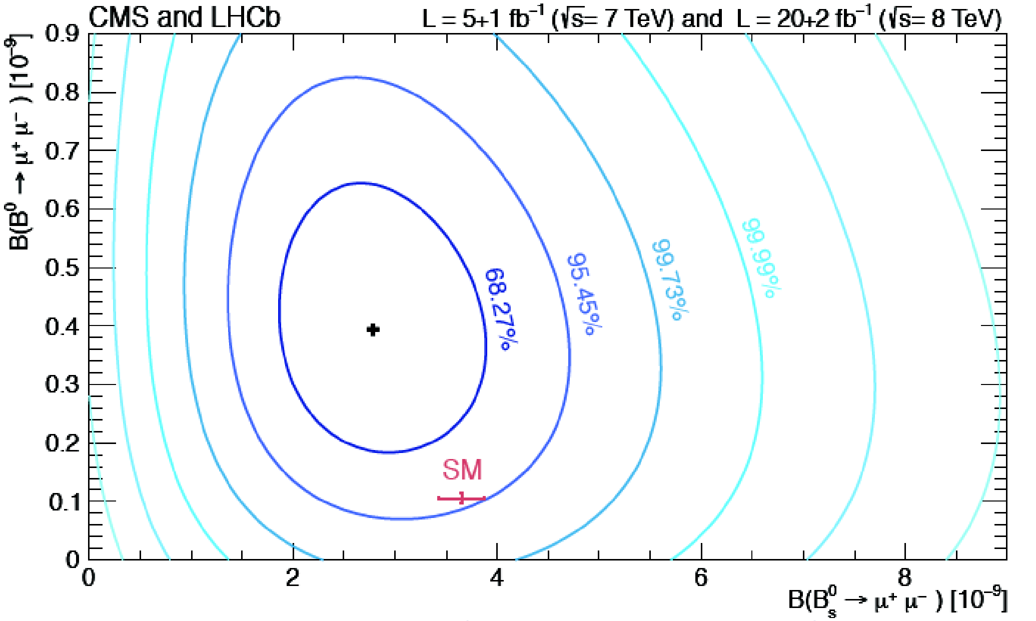


$B^0_s \to \mu^+\mu^-$

B-Physics in Run 1: $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ (CMS & LHCb)



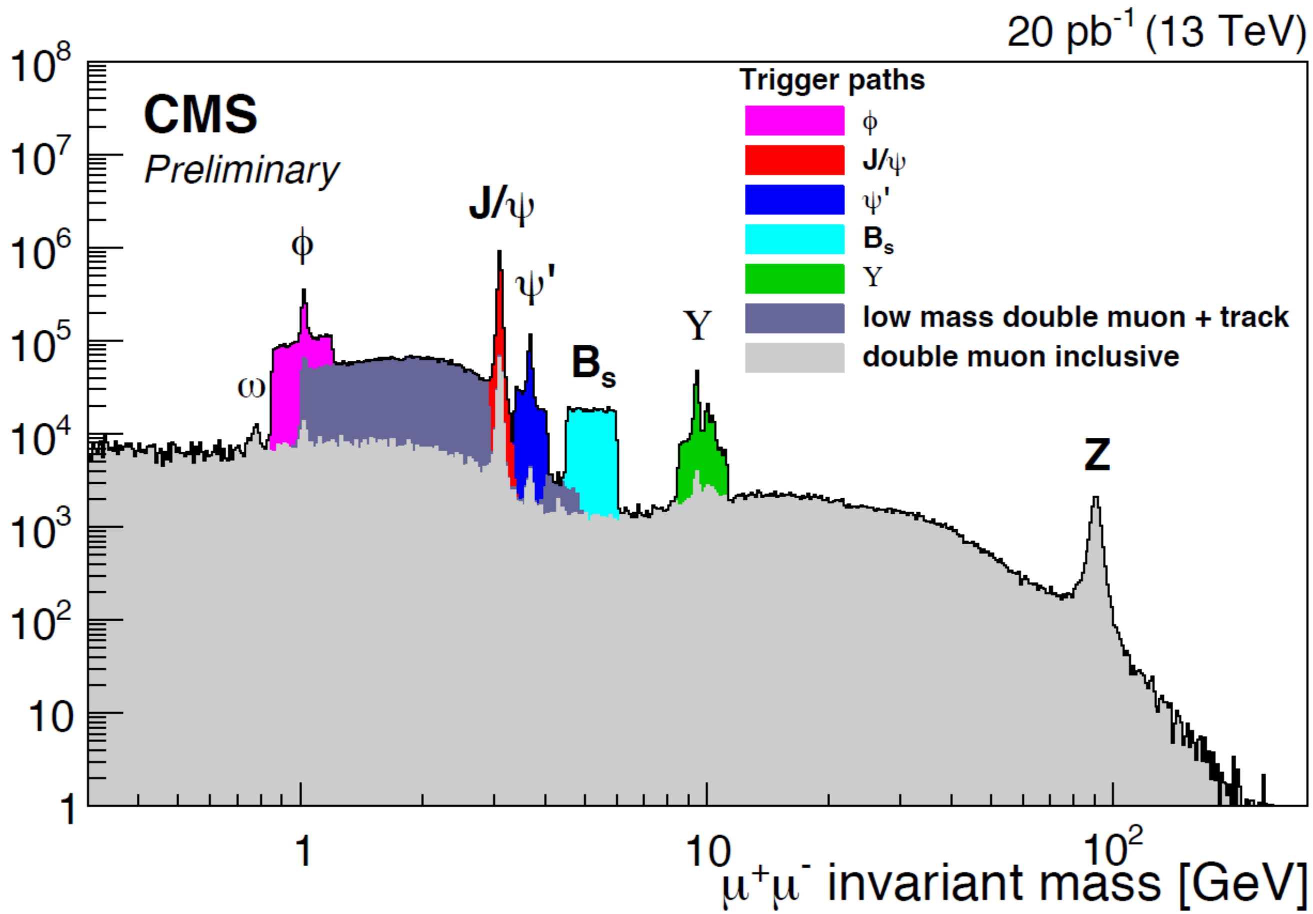
- Weighted distribution of dimuon mass spectrum, superimposed in a combined fit
  - **Observation** of $B^0_s \rightarrow \mu^+\mu^-$ (**6.2σ**) and **evidence** for $B^0 \rightarrow \mu^+\mu^-$ (**3.2σ**)



- Likelihood in $B^0_s \rightarrow \mu^+\mu^-$ vs $B^0 \rightarrow \mu^+\mu^-$ BR plane
  - $BR(B^0_s \rightarrow \mu^+\mu^-)=2.8^{+0.7}_{-0.6}$ X10^{-9}
    - Relative to SM: $\mathbf{0.76^{+0.20}_{-0.18}}$
  - $BR(B^0 \rightarrow \mu^+\mu^-)=3.9^{+1.6}_{-1.4}$ X10^{-10}
    - Relative to SM: $\mathbf{3.7^{+1.6}_{-1.4}}$
- Results in reduced phase space for searches
- Interest moving toward observation of B^0 for Run 2 and HL-LHC

B-Physics in Run 2 (13 TeV)

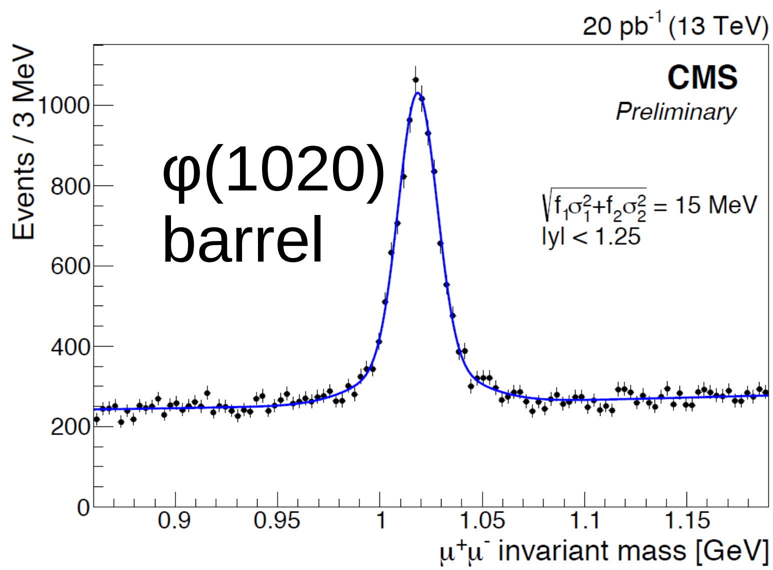
- Higher energy, luminosity and pileup represents both challenges and new possibilities for B-Physics
  - Newer kinematic regime, access higher p_T
  - Decreased tracker material budget, improved trigger system

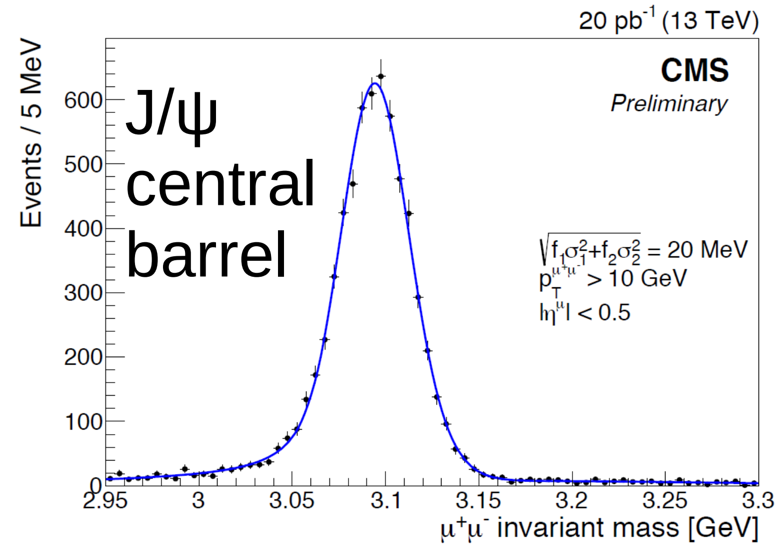


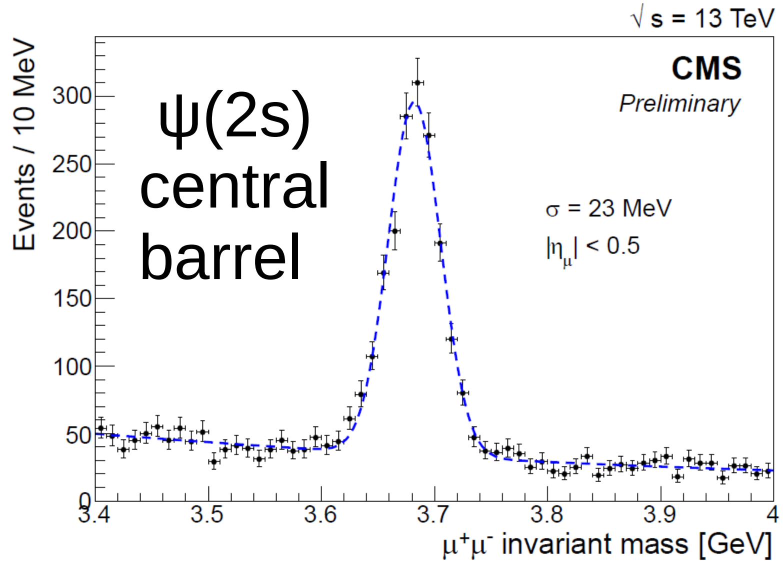
CMS-DP-2015-018

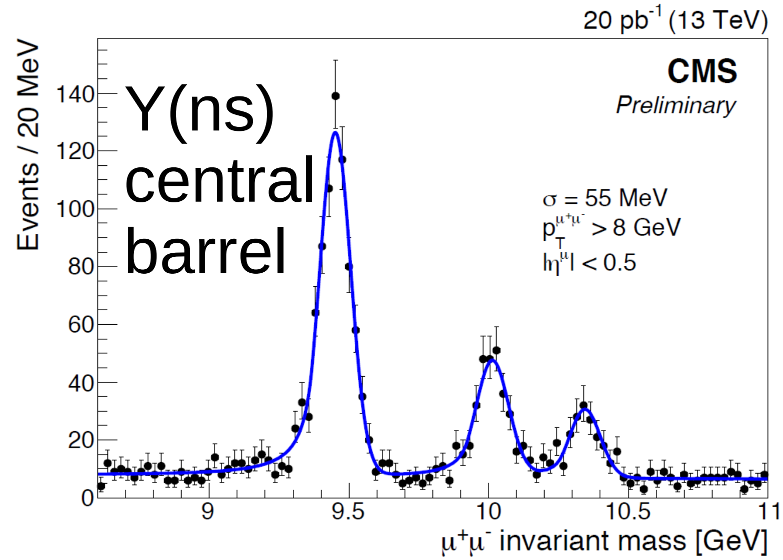
- CMS has already observed many standard candles
- Dimuon mass spectrum
  - Special triggers in certain mass regions with different pT cuts

B-Physics in Run 2: Dimuon resonances





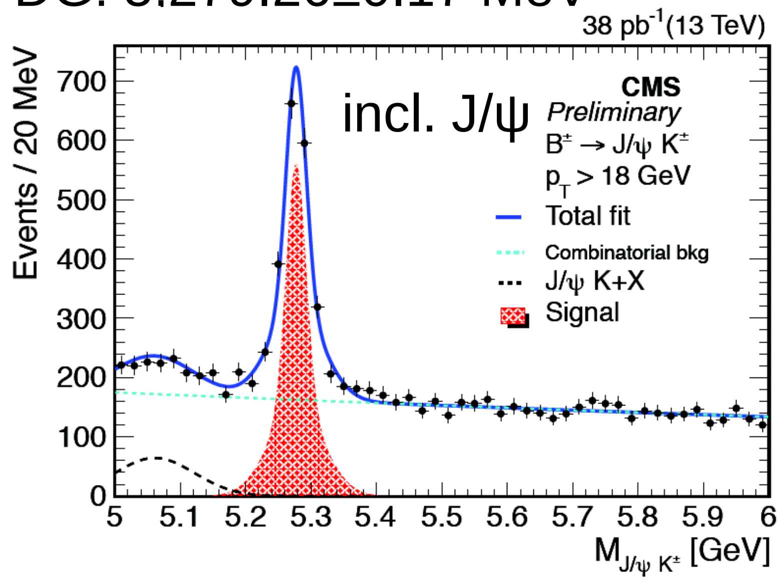


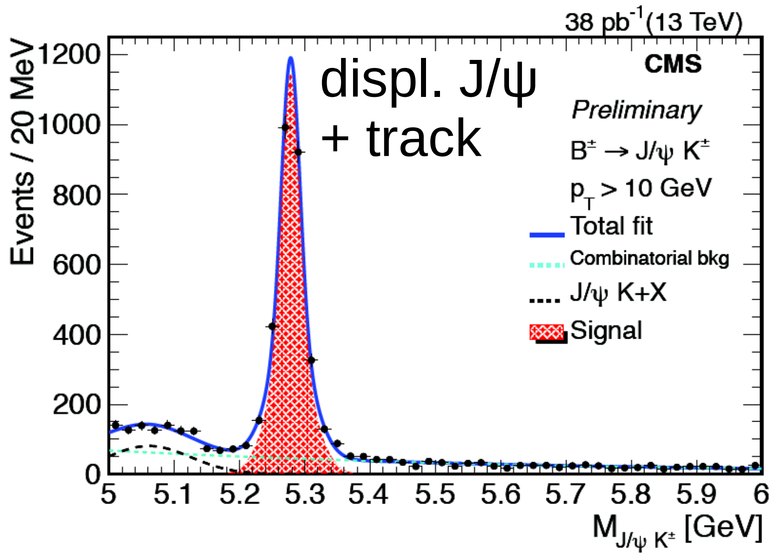


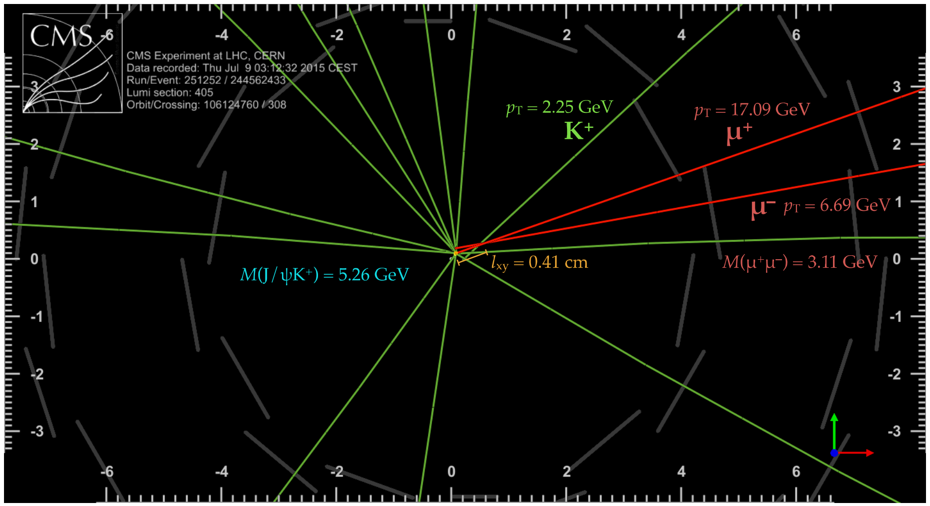
- Dimuon mass spectrum using trigger paths centered around φ(1020), J/ψ, ψ(2s), Υ(ns)

B-Physics in Run 2: $B^{\pm} \rightarrow J/\psi K^{\pm}$

- $B^{\pm} \rightarrow J/\psi K^{\pm}$ using inclusive J/ψ (left) and displaced J/ψ +track trigger (right)
  - Mass **inclusive**: 5.277±0.001(stat) GeV, **displaced**: 5.278±0.001(stat) GeV
    - PDG: 5.279.26±0.17 MeV

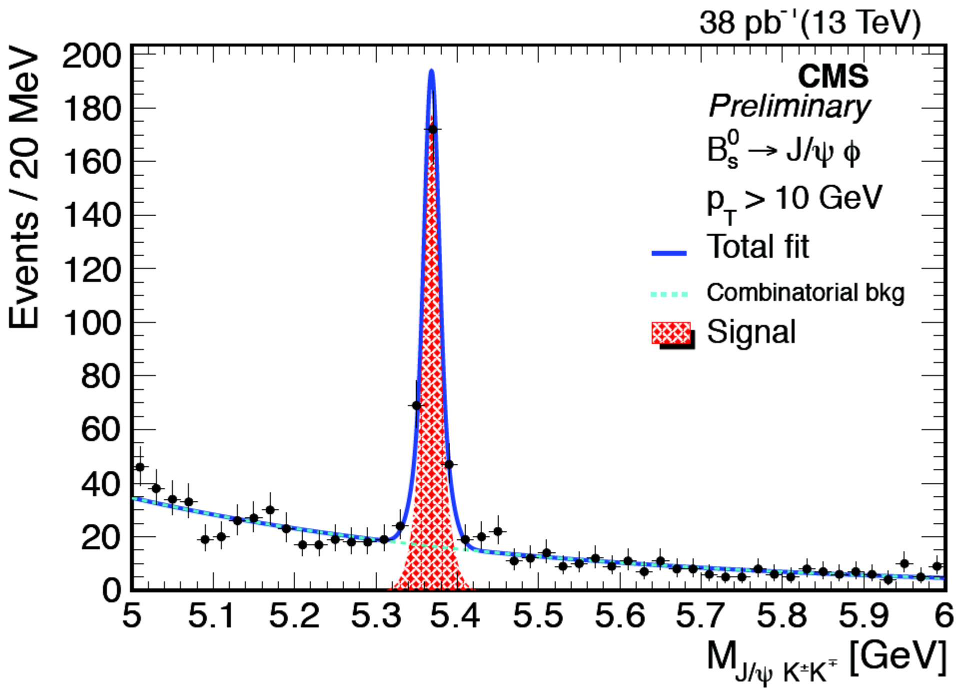


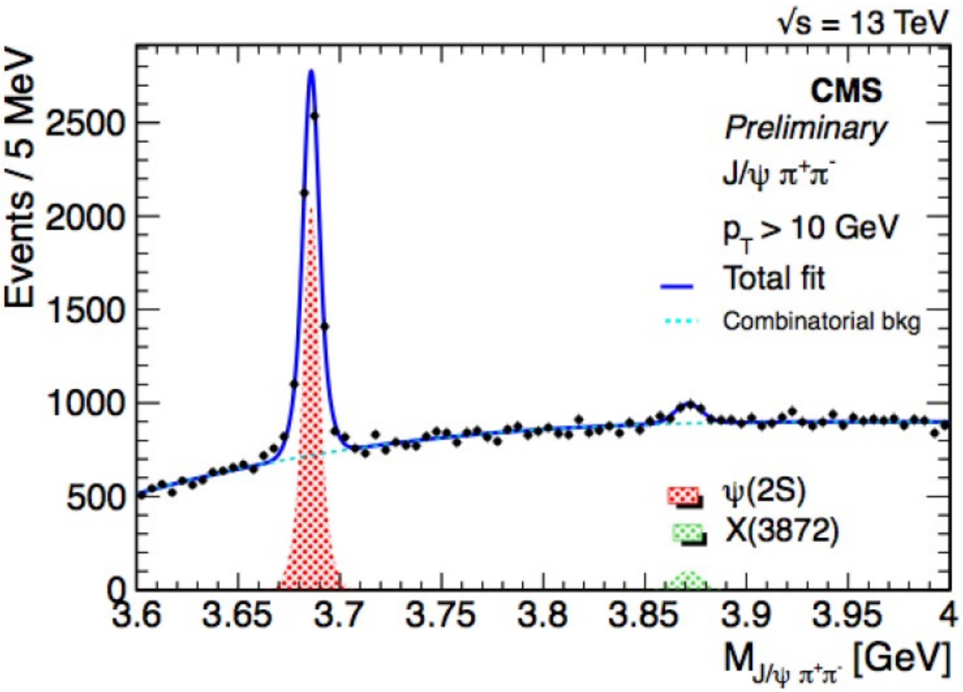




- Clean $B^{+} \rightarrow J/\psi K^{+}$ candidate with visible secondary vertex
  - l_{xy}=0.41cm
  - $M(J/\psi K^{+})$ = 5.26 GeV
  - $M(\mu^{+}\mu^{-})$ = 3.11 GeV

B-Physics in Run 2: $B^0_s \to J/\psi\ \varphi$; $J/\psi\ \pi^+\pi^-$





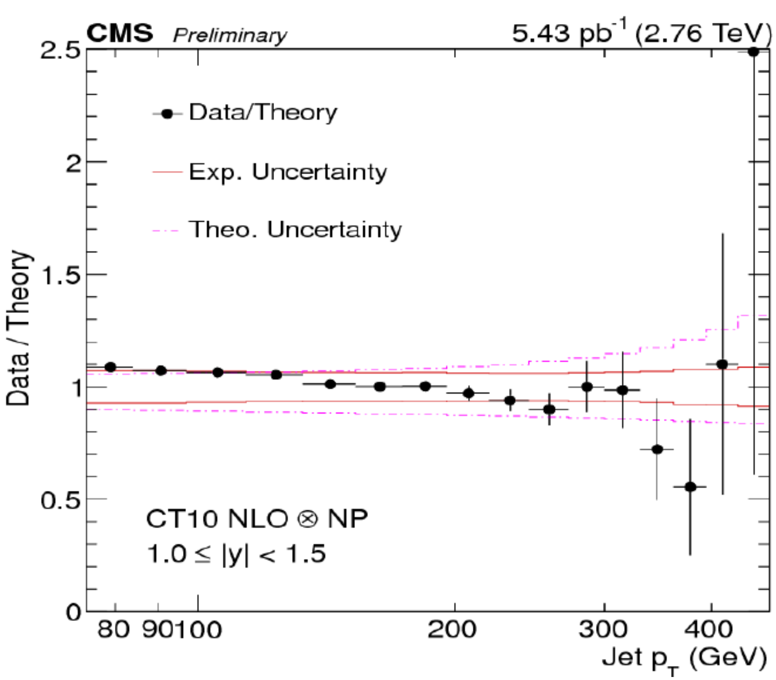
- $B^0_s \to J/\psi\ \varphi$ using displaced J/ψ + track trigger (right)
  - ◊ Mass: 5.369±0.001(stat) GeV
    - PDG: 5,366.7±0.4 MeV
- $J/\psi\ \pi^+\pi^-$
  - ◊ Mass ψ(2S): 3.686±0.001(stat) GeV
    - X(3872) also seen

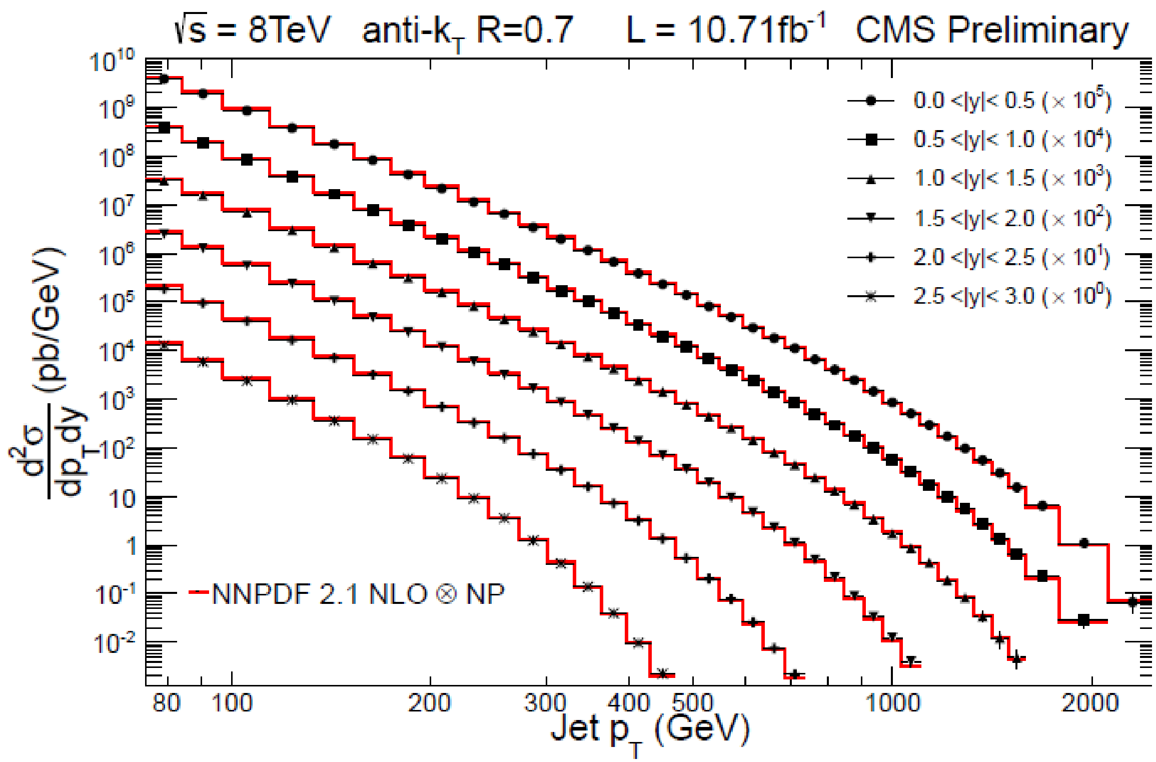
Run 1 Highlights: Inclusive jet cross section

7 TeV: **Phys. Rev. D 87 (2013) 112002**
8 TeV: **CMS-PAS-SMP-12-012**

- LHC is a jet factory
- Study of jet production presents a great interest
  - test pQCD over many orders of magnitude, and at different √s
  - sensitive to α_S
  - constraining PDF
  - MC tuning

CMS-PAS-SMP-14-017



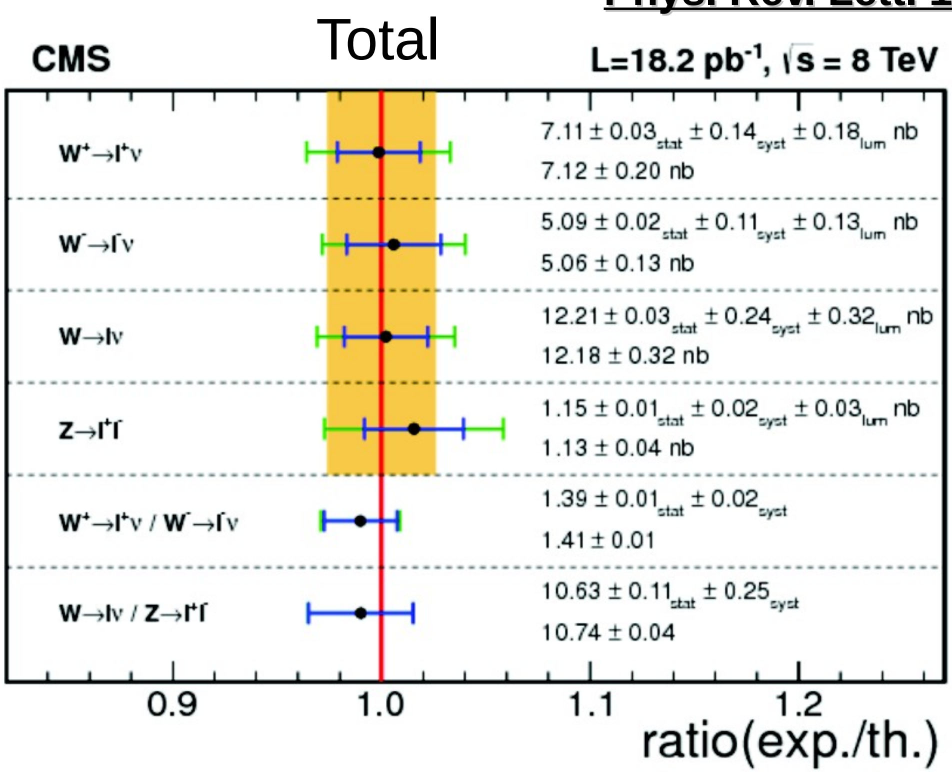


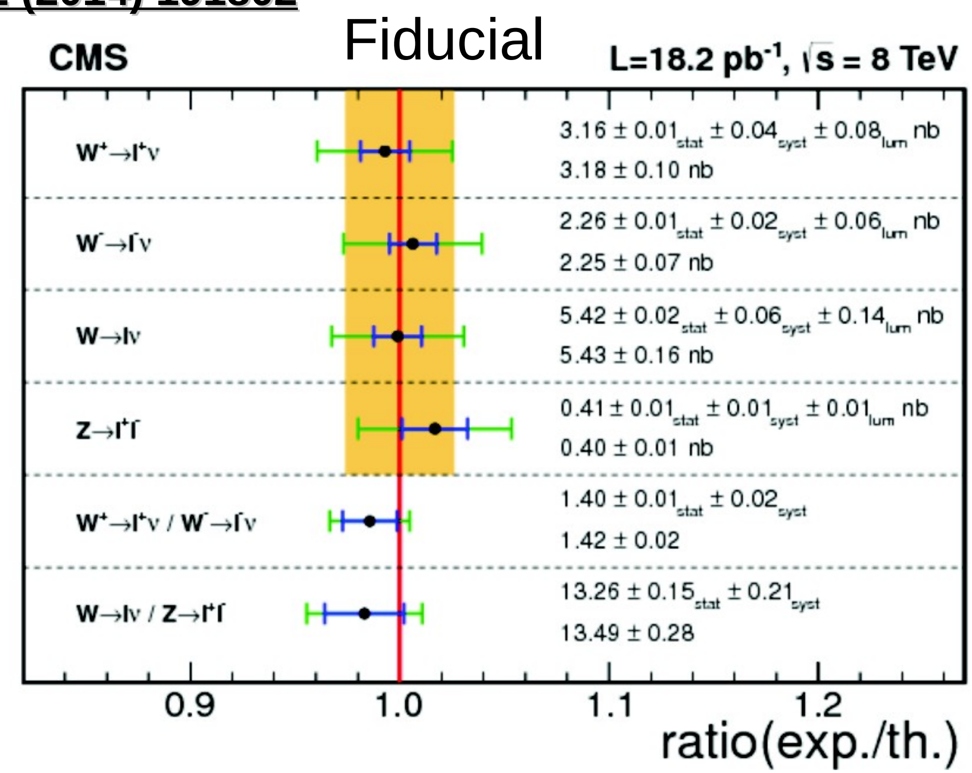
- **New:** Also measured for 2.76 TeV pp collisions

Run 1 Highlights: W/Z physics

- Theoretical predictions available to NNLO → **precision tests of the SM**
- Useful to **constrain PDF uncertainties**

Phys. Rev. Lett. 112 (2014) 191802





luminosity, **experimental**, and **theoretical** uncertainties

- Total and fiducial W/Z cross section agree with theory within theoretical uncertainties

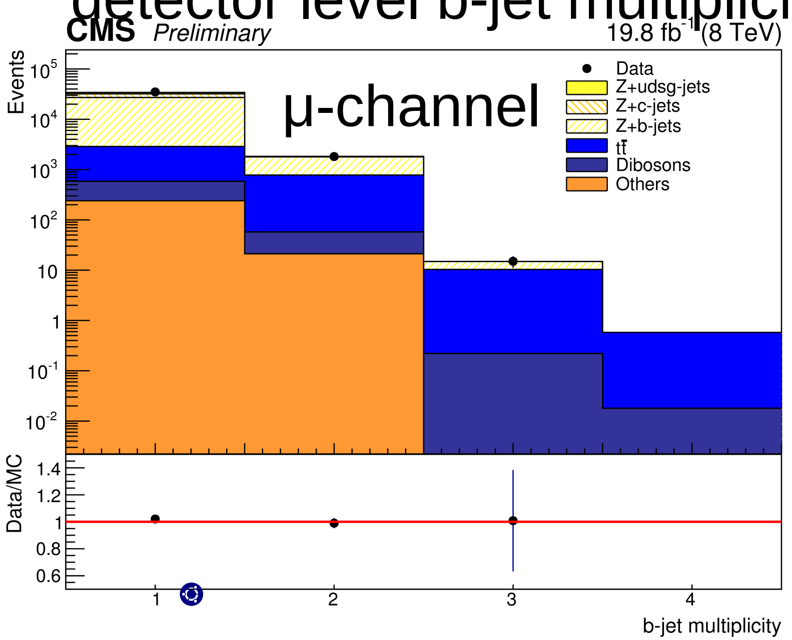
Run 1 Highlights: V+jets; Zb, Zbb results

- Extensive studies of W/Z production in association with jets and heavy flavor quarks in CMS
  - W + up to >=6 j, W + c, W + 2b, Z + >= 4j, **Z + >= 1b, Z + >=2b**
  - **Excellent overall agreement with SM**
  - QCD phenomenology and important background for many searches (and top physics)

CMS-PAS-SMP-14-010

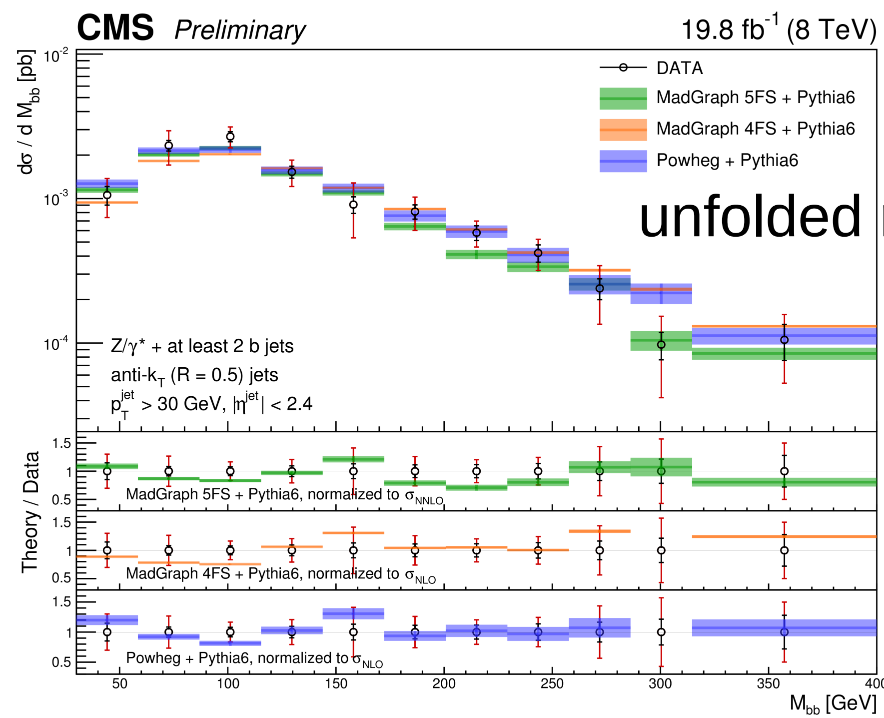
- New: **Z + >= 1b, Z + >=2b** at 8 TeV
  - **main background for tt production**

detector level b-jet multiplicity



  - very good agreement

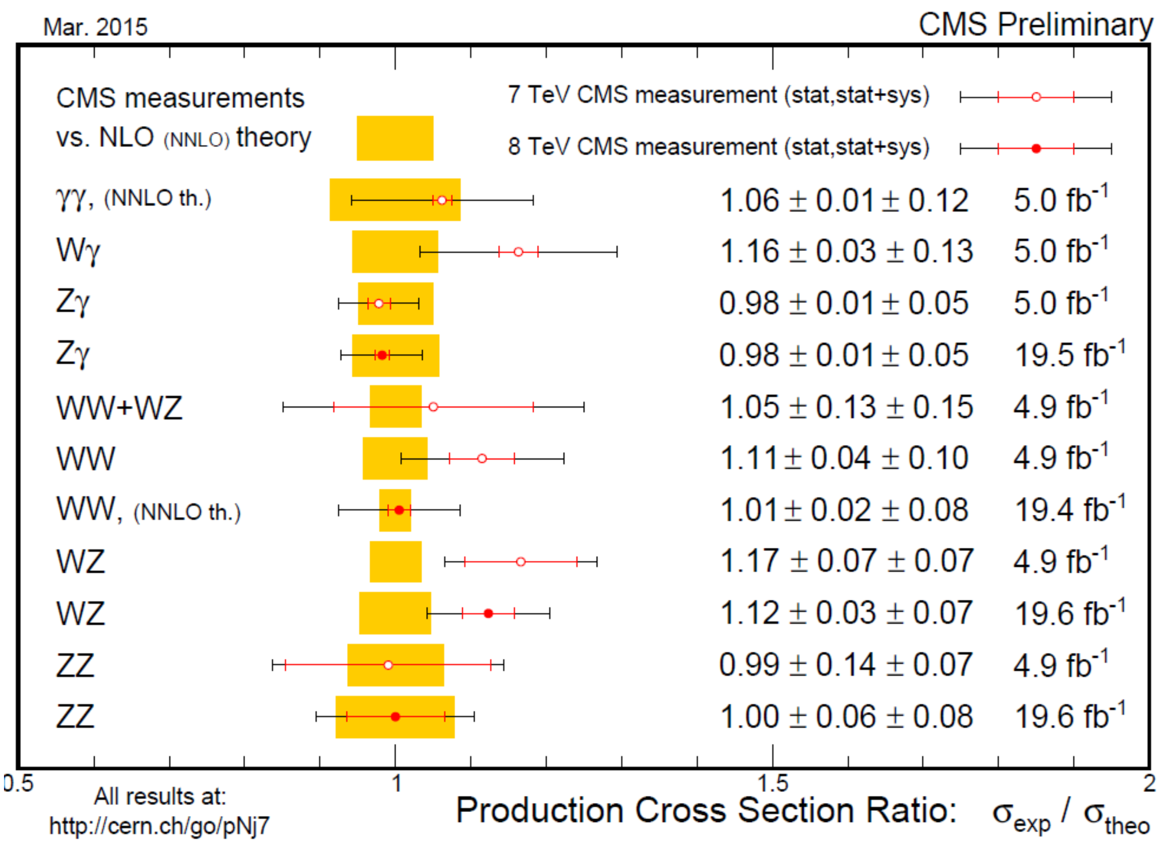
unfolded mbb



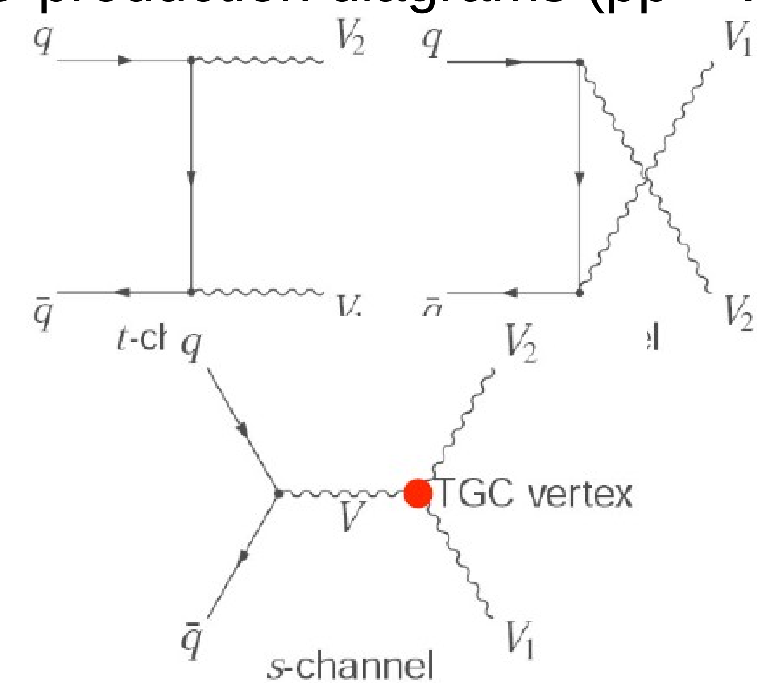
- Comparison with MadGraph5 (LO) 4FS, 5FS and Powheg (NLO for 1jet) for different observables

Run 1 Highlights: Multibosons

- Important test of the SM, sensitive to theoretical calculations
- Precision study of V self coupling
- Sensitive to new physics
  - ◊ Important background in direct searches, study of anomalies in vector boson couplings



LO production diagrams (pp→VV)



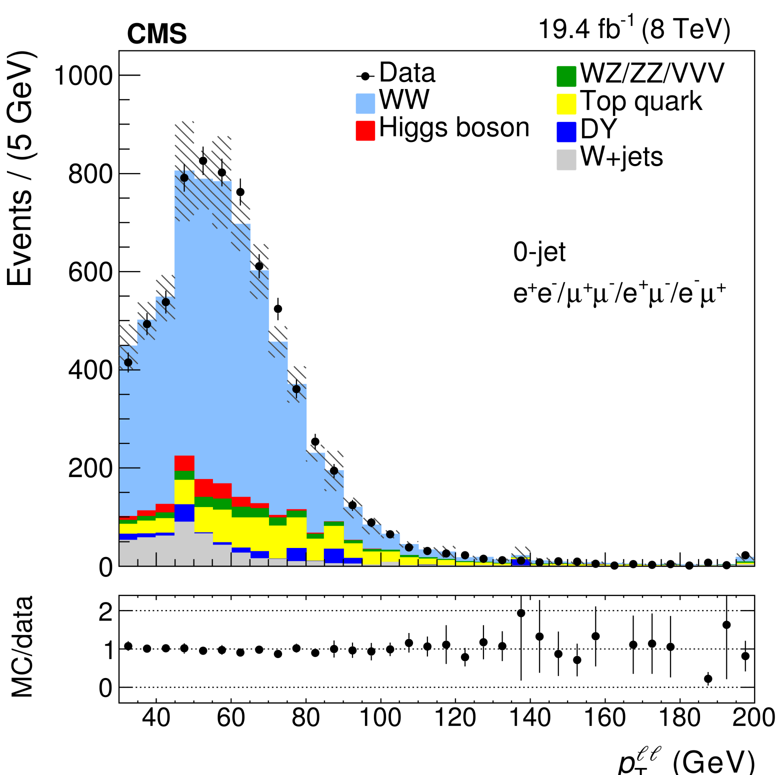
- Diboson (W/Z/γ) production measured in **all possible final states in CMS**

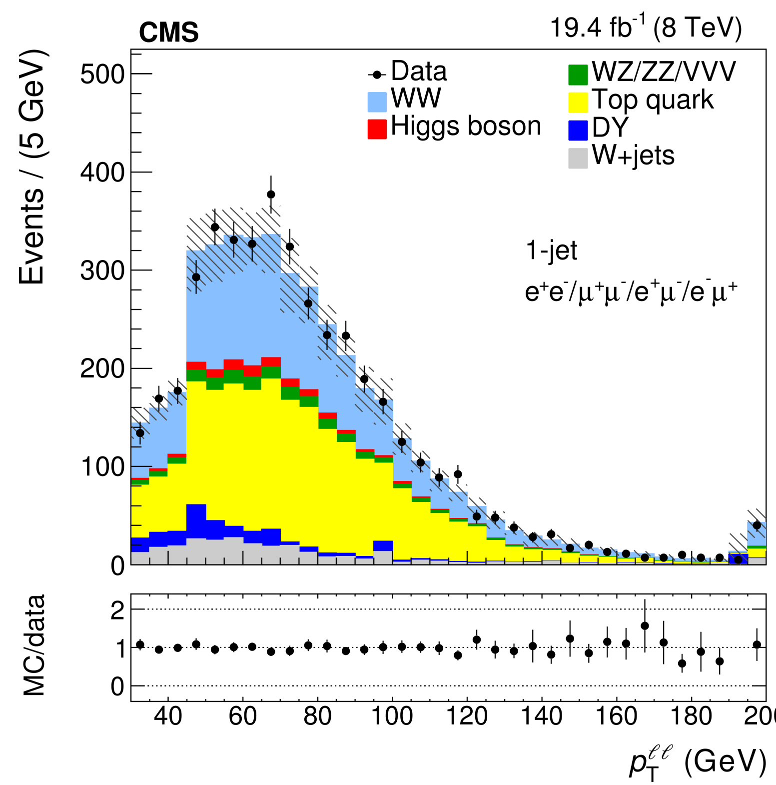
Run 1 Highlights: WW → 2l2ν at 8 TeV

- New: including full 8 TeV dataset

CMS-PAS-SMP-14-016
Submitted to Eur. Phys. J. C
arXiv.1507.03268

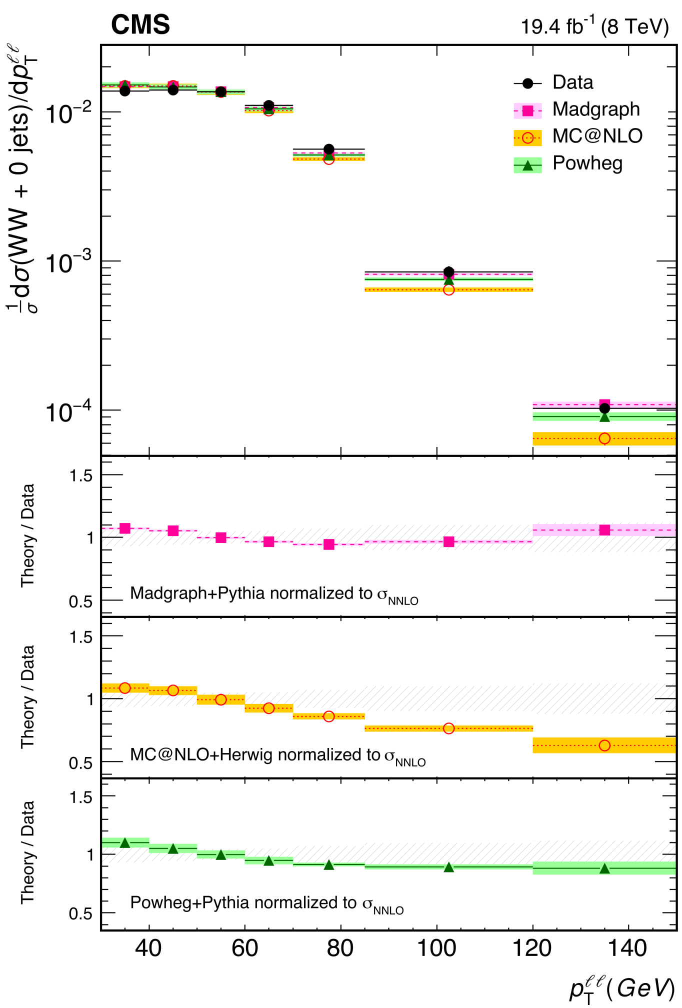
- Basic signature: 2 isolated leptons + E_T^{miss}
- Relatively large cross section but large backgrounds
  - W+jets → tight lepton selection
  - Top → anti b-tagging and >1j veto
  - DY → Z mass veto and E_T^{miss}
  - WZ/ZZ → third lepton veto
- Background estimations mostly from data
  - W+jets → fake rate
  - Top → inverted top veto
  - DY → normalized to data
  - Z → ττ → embedded data



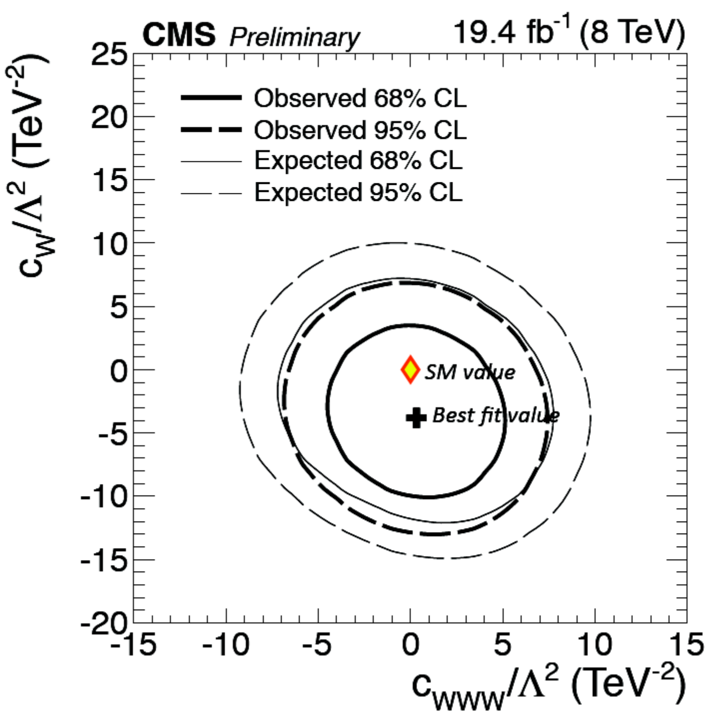


Run 1 Highlights: WW → 2l2ν at 8 TeV results

- total **σ=60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1 (th) ± 1.6 (lumi) pb**
  - In agreement with theory (NNLO): **$59.8^{+1.3}_{-1.1}$ pb**
- Differential cross sections and aTGC measurements (0 jets)



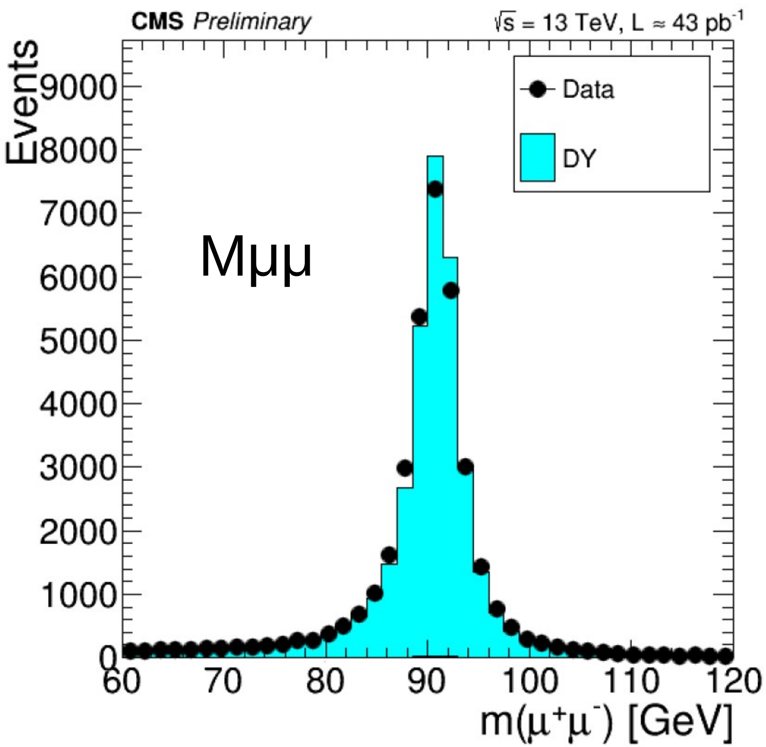
- Good agreement between data and theory (few differences depending on variable and generator

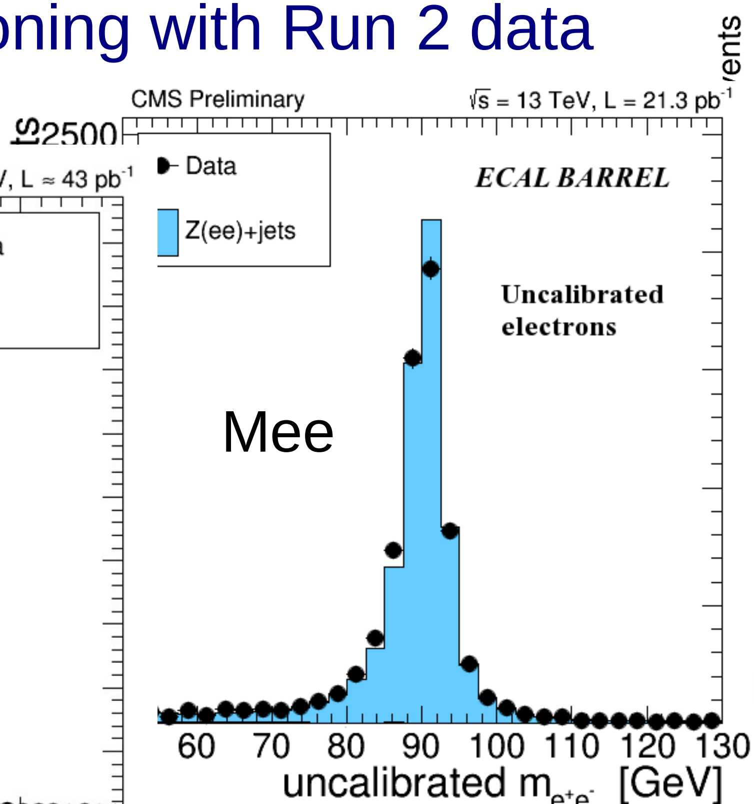


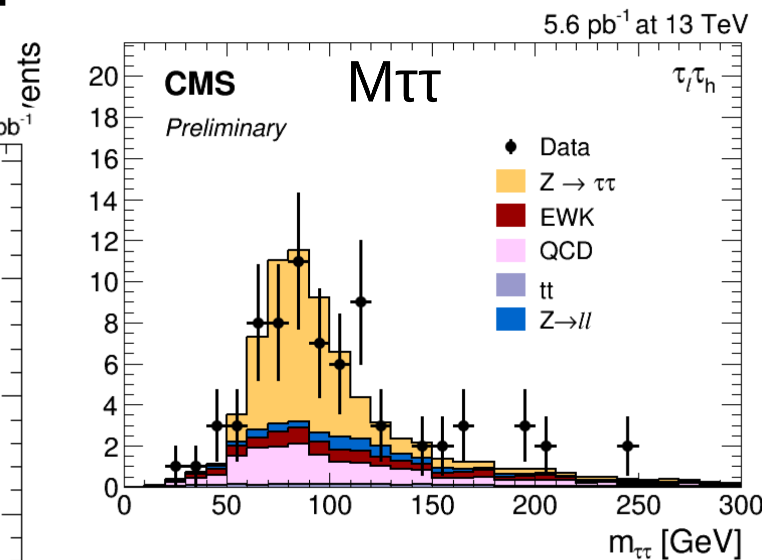
- Effective field theory parametrization (Phys. Rev. D48 (1993) 2182)
- Limits on aTGC comparable to current world average)

QCD and EWK in the Run 2: present

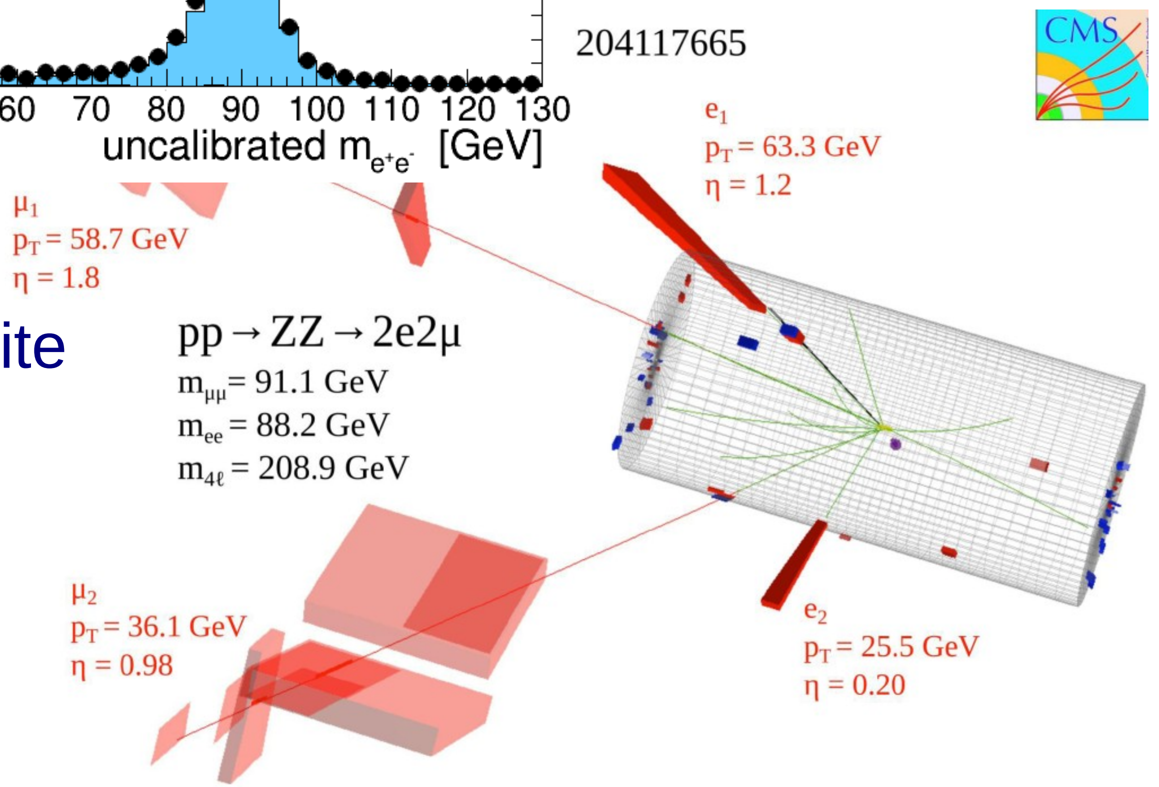
- CMS commissioning with Run 2 data







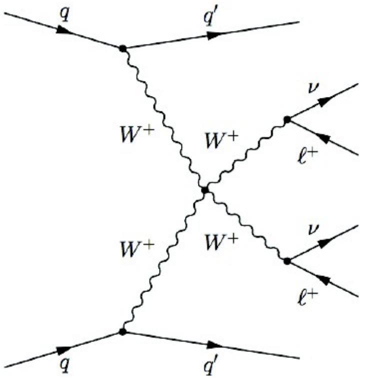
ZZ → 2e2μ candidate



- Detectors and objects quite well understood, basic candles observed

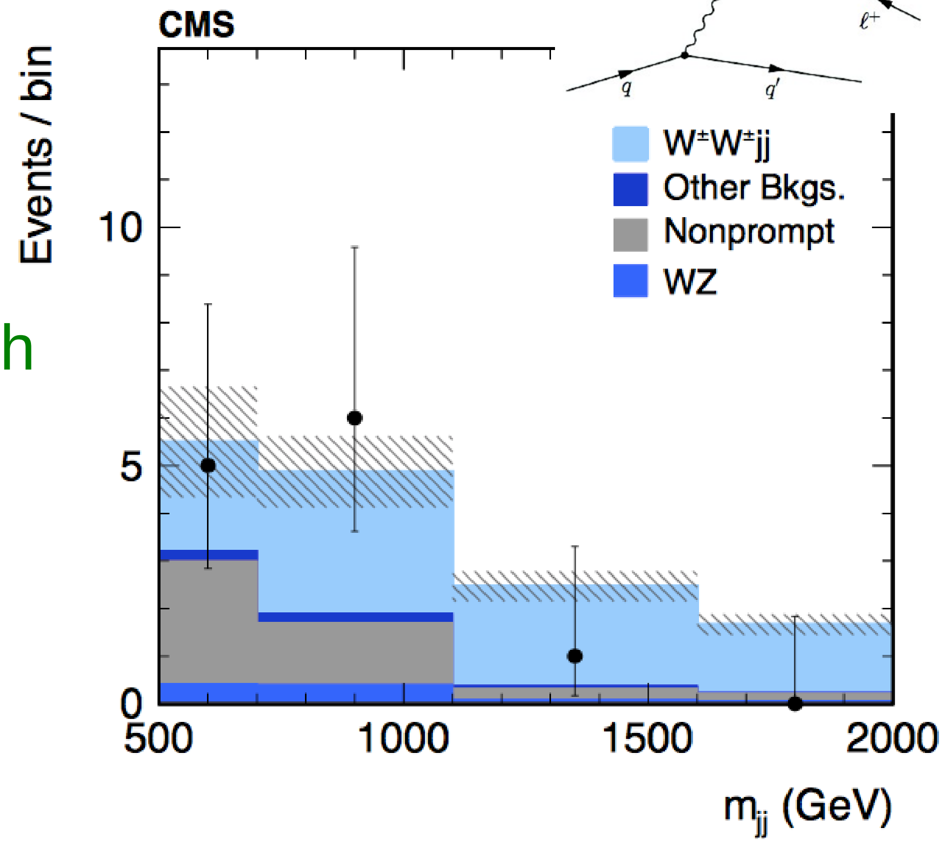
QCD and EWK in the Run 2: future

- 13 TeV run allow to **go beyond precision achieved during Run 1**
- Example: EWK scattering with same-sign dileptons + jj
  - Key process to **probe nature of Higgs boson**



- Run 1 result: **2.0 σ significance** with 20 fb^{-1} at 8 TeV
  - 3.0 σ expected significance
  - background mostly reducible
  - a handful of events selected
- Run 2 projections
  - **~5.0 σ expected significance** with **50fb^{-1} @13TeV** from rough theoretical extrapolations (**cern.ch/collider-reach**)
- Beyond Run 2
  - **~5%** precision on cross section after **3ab^{-1} of HL-LHC** (Technical Proposal for the Phase II Upgrade of the Compact Muon Solenoid: **CERN-LHCC-2015-010**)

PRL 114, 051801 (2015)



Summary

- Very successful Run 1 of the LHC, with multitude of CMS measurements in many different areas: QCD and EWK production, B-physics, ...
  - Legacy Run 1 analyses still ongoing, with new precision results

- The SM will be tested with an unprecedented level of precision in new unexplored territories, setting as well the ground for new physics searches
  - Not only objects: SM candles, resonances, but also methods and strategies in place.
  - First results have already arrived, many more will appear soon

Stay tuned!

BACK-UP SLIDES

BPH

Dimuon mass distribution collected with various dimuon triggers

The light gray continuous distribution represents events collected with inclusive dimuon triggers with high p_T thresholds

The dark gray band is collected by a trigger with low-mass non-resonant dimuon plus a track

The other colored spectra are acquired using specialized triggers which require a pair of muons with opposite charge, a vertex-fit probability greater than 0.5%, and specific dimuon invariant mass and p_T regions:

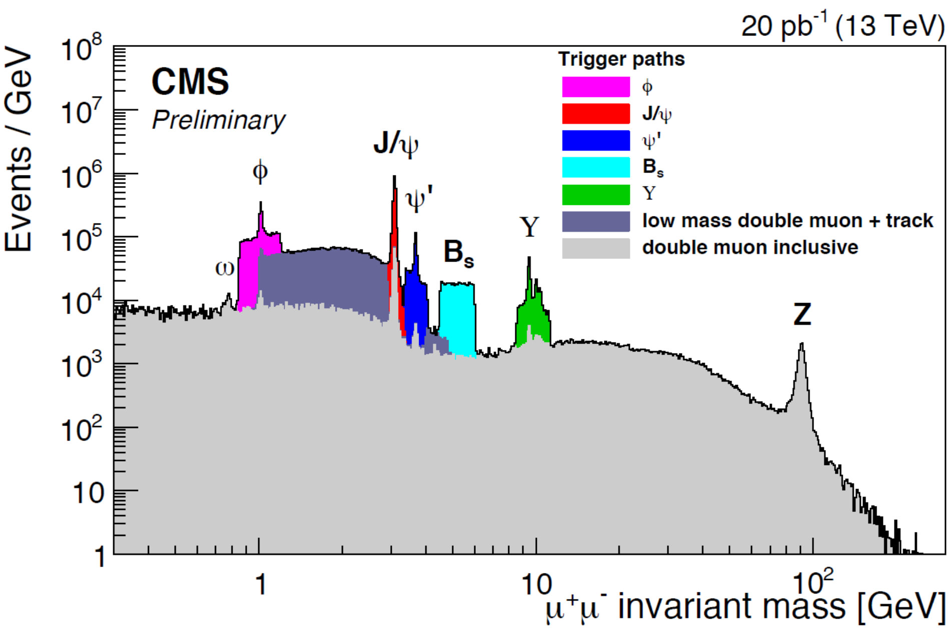
Magenta: dimuon mass within (0.85, 1.2) GeV, dimuon $p_T > 0$ GeV, dimuon |y| < 1.25

Red: dimuon mass within (2.95, 3.3) GeV, dimuon $p_T > 16$ GeV; or dimuon mass within (2.95, 3.3) GeV, dimuon $p_T > 10$ GeV, dimuon |y| < 1.25

Blue: dimuon mass within (3.4, 4) GeV, dimuon $p_T > 13$ GeV; or dimuon mass within (3.4, 4) GeV, dimuon $p_T > 8$ GeV, dimuon |y| < 1.25

Cyan: dimuon mass within (4.5, 6) GeV, the leading muon $p_T > 4$ GeV and the sub-leading muon $p_T > 3$ GeV

Green: dimuon mass within (8.5, 11) GeV, dimuon $p_T > 13$ GeV; or dimuon mass within (8.5, 11) GeV, dimuon $p_T > 8$ GeV, dimuon |y| < 1.25



BPH

Dimuon invariant mass in vicinity of ϕ(1020), detector barrel region

- Trigger Conditions: opposite-sign muon pair with invariant mass in range 0.85-1.2 GeV, $p_T > 0$ GeV, $|y| < 1.25$, and vertex-fit probability greater than 0.5%
- Offline, each muon has soft identification requirement
- Fit Method: unbinned extended maximum likelihood
  - Mass PDF: double Gaussian with common mean
  - Background PDF: Chebychev polynomial series of order 2
- Quoted resolution: weighted quadrature sum of the two Gaussian sigmas

Dimuon invariant mass in vicinity of ψ(2S), detector barrel region

- Trigger Conditions: opposite-sign muon pair with invariant mass in range 3.4-4.0 GeV, $p_T > 8$ GeV, $|y| < 1.25$, and vertex-fit probability greater than 0.5%
- Offline, each muon has soft identification
- Fit Method: unbinned extended maximum likelihood
  - Mass PDF: single Gaussian
  - Background PDF: Chebychev polynomial series of order 2
- Quoted resolution: sigma of Gaussian

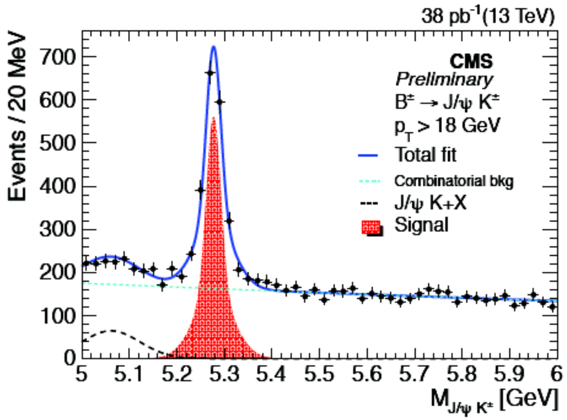
Dimuon invariant mass in the J/ψ mass region, detector central barrel region

- Trigger Conditions: opposite-sign muon pair with invariant mass in range 2.95-3.3 GeV, $p_T >$ 10 GeV, $|y| < 1.25$, and vertex-fit probability greater than 0.5%
- Offline, each muon has soft identification and each muon has $|\eta| < 0.5$
- Fit Method: unbinned extended maximum likelihood
  - Mass PDF: double Crystal Ball with common mean, n and alpha parameters
  - Background PDF: Chebychev polynomial series of order 2
- Quoted resolution: weighted quadrature sum of the two CB sigmas

- Trigger Conditions: opposite-sign dimuon pair with invariant mass in range 8.5-11.0 GeV, $p_T >$ 8 GeV, $|y| < 1.25$, and vertex-fit probability greater than 0.5%
- Offline, each muon has soft identification and each muon has $|\eta| < 0.5$
- Fit Method: unbinned extended maximum likelihood
  - Mass PDF: single Crystal Ball. The mean of each peak is fixed to the PDG Υ(nS) mass multiplied by a floating scale factor. This scale factor is common for the three mass peaks. The widths are common to the three mass peaks but scaled by the ratio of the PDG masses, giving a total of four free parameters
  - Background PDF: Chebychev polynomial series of order 1
- Quoted resolution: weighted quadrature sum of the two CB sigmas

BPH

Inclusive J/ψ trigger with p_T > 16 GeV



$B^{\pm} \to J/\psi K^{\pm}$

2D (mass, proper time) fitting method: mass projection

Quality cuts:

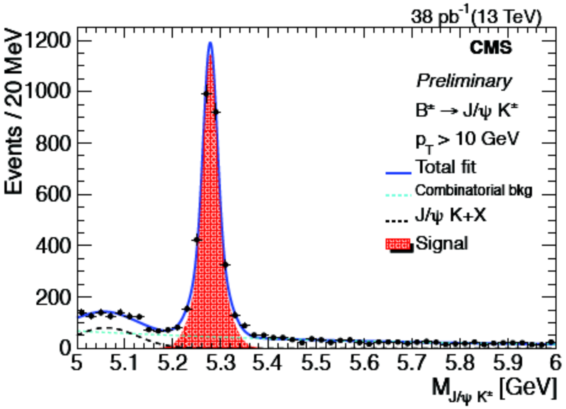
- $p_T(K^{\pm})$ > 2.0 GeV
- Vertex probability > 15%
- p_T (J/ψ) > 16 GeV

PDF shape:

- Signal: double Gaussian
- Combinatorial background: exponential
- J/ψ K+X: Gaussian

Mass: 5.277 ± 0.001(stat.) GeV

Displaced J/ψ + track trigger



$B^{\pm} \to J/\psi K^{\pm}$

1D fitting method

Quality cuts:

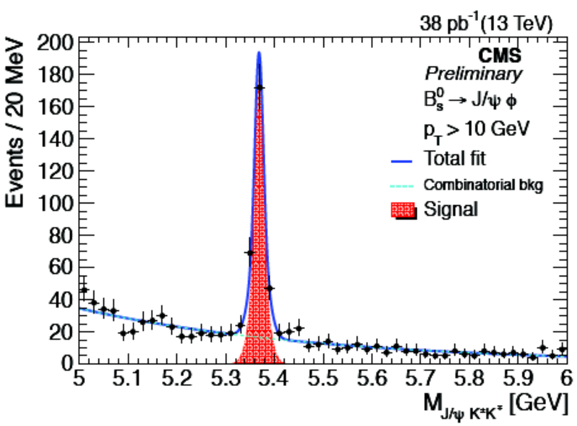
- cos α > 0.99
- $l_{xy}/\sigma(l_{xy})$ > 3.0
- Vertex probability > 10%
- p_T (J/ψ) > 8 GeV
- p_T (K) > 1.6 GeV
- |η (K)| < 2.4

PDF shape:

- Signal: double Gaussian
- Combinatorial background: exponential
- J/ψ K+X: Gaussian

Mass: 5.278 ± 0.001(stat.) GeV

Displaced J/ψ + track trigger



$B^0_s \to J/\psi \phi$

1D fitting method

Quality cuts:

- cos α > 0.99
- $l_{xy}/\sigma(l_{xy})$ > 3.0
- Vertex probability > 10%
- p_T (J/ψ) > 8 GeV
- p_T (K,π) > 0.7 GeV
- |η (K,π)| < 2.4

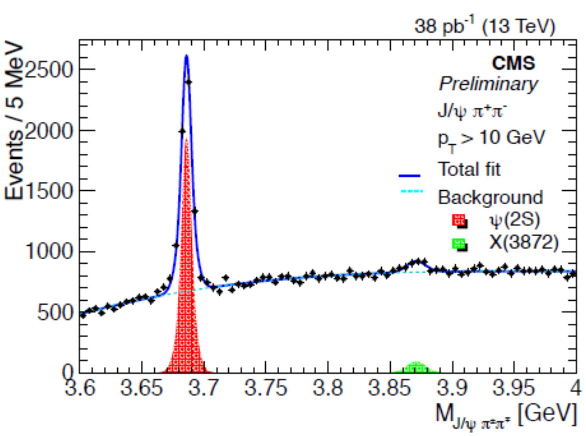
$$|M(KK) - M(\phi)| < 10MeV$$

PDF shape:

- Signal: double Gaussian
- Combinatorial background: exponential

Mass: 5.369 ± 0.001(stat.) GeV

J/ψ $\pi^{\pm} \pi^{\mp}$ invariant mass



1D fitting method

Quality cuts:

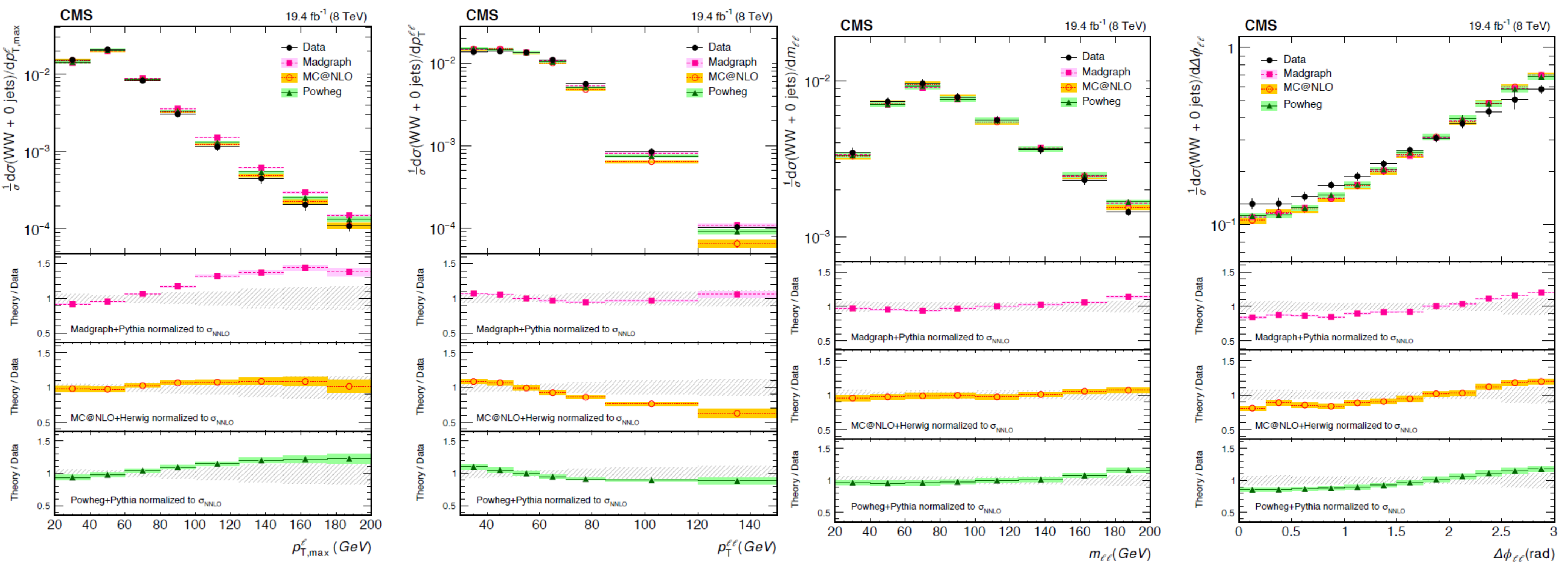
- p_T (J/ψ) > 8 GeV
- p_T (π) > 0.7 GeV
- |η (π)| < 2.4

PDF shape:

- Signal: double Gaussian
- Background: 3[rd] order polynomial

Mass: 3.686 ± 0.001(stat.) GeV

WW → 2l2ν



Source	Uncertainty (%)
Statistical uncertainty	1.5
Lepton efficiency	3.8
Lepton momentum scale	0.5
Jet energy scale	1.7
E_T^{miss} resolution	0.7
$t\bar{t}$+tW normalization	2.2
W+jets normalization	1.3
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \to W^+W^-$ normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistical uncertainty	0.9
Integrated luminosity	2.6
Total uncertainty	7.9

WW → 2l2ν

$$\frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}],$$

$$\frac{c_W}{\Lambda^2}\mathcal{O}_W = \frac{c_W}{\Lambda^2}(D^\mu\Phi)^\dagger W_{\mu\nu}(D^\nu\Phi),$$

$$\frac{c_B}{\Lambda^2}\mathcal{O}_B = \frac{c_B}{\Lambda^2}(D^\mu\Phi)^\dagger B_{\mu\nu}(D^\nu\Phi).$$

- Effective field theory parametrization (Phys. Rev. D48 (1993) 2182)