In Search of the Standard Model at CMS

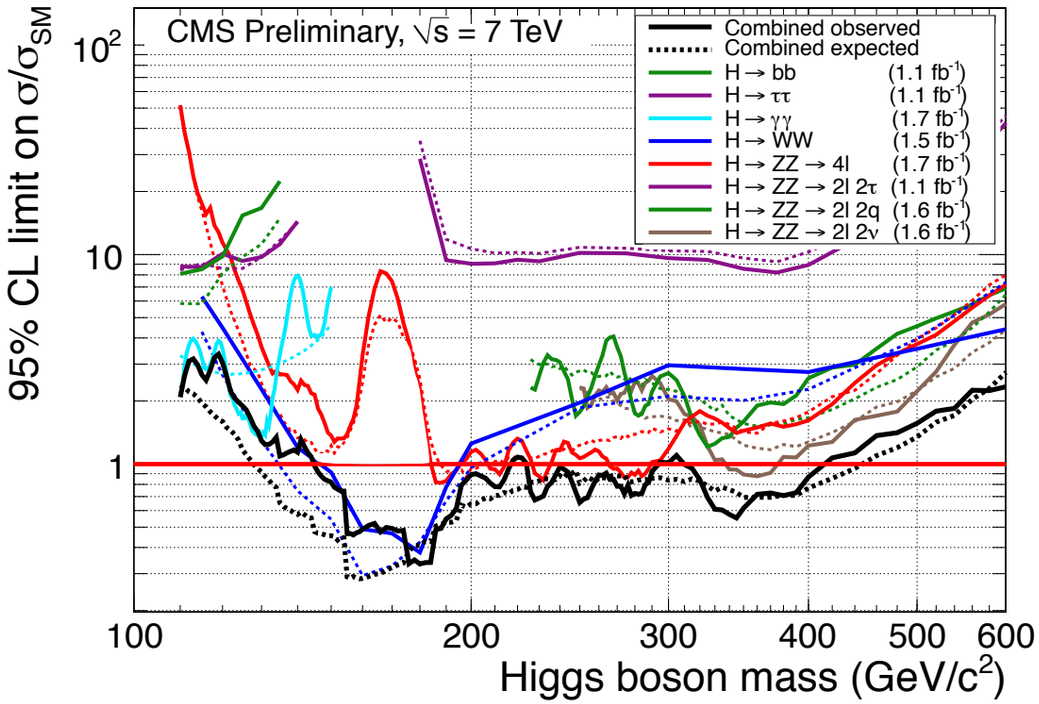
Ken Bloom for the CMS Collaboration

FNAL Joint Experimental-Theoretical Seminar

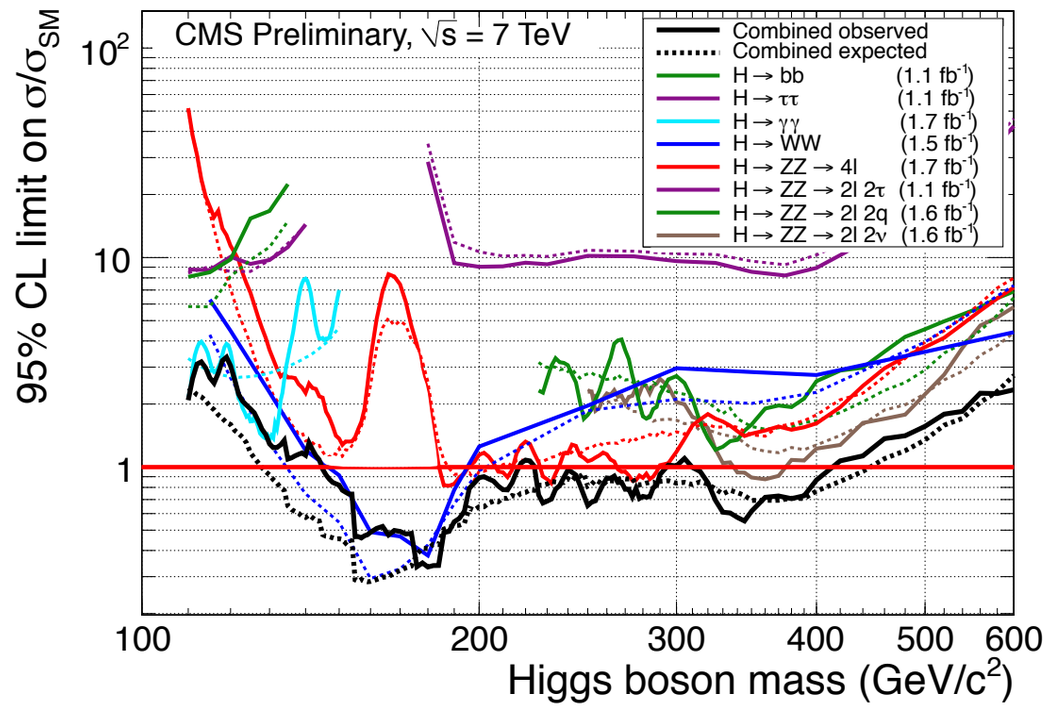
November 4, 2011

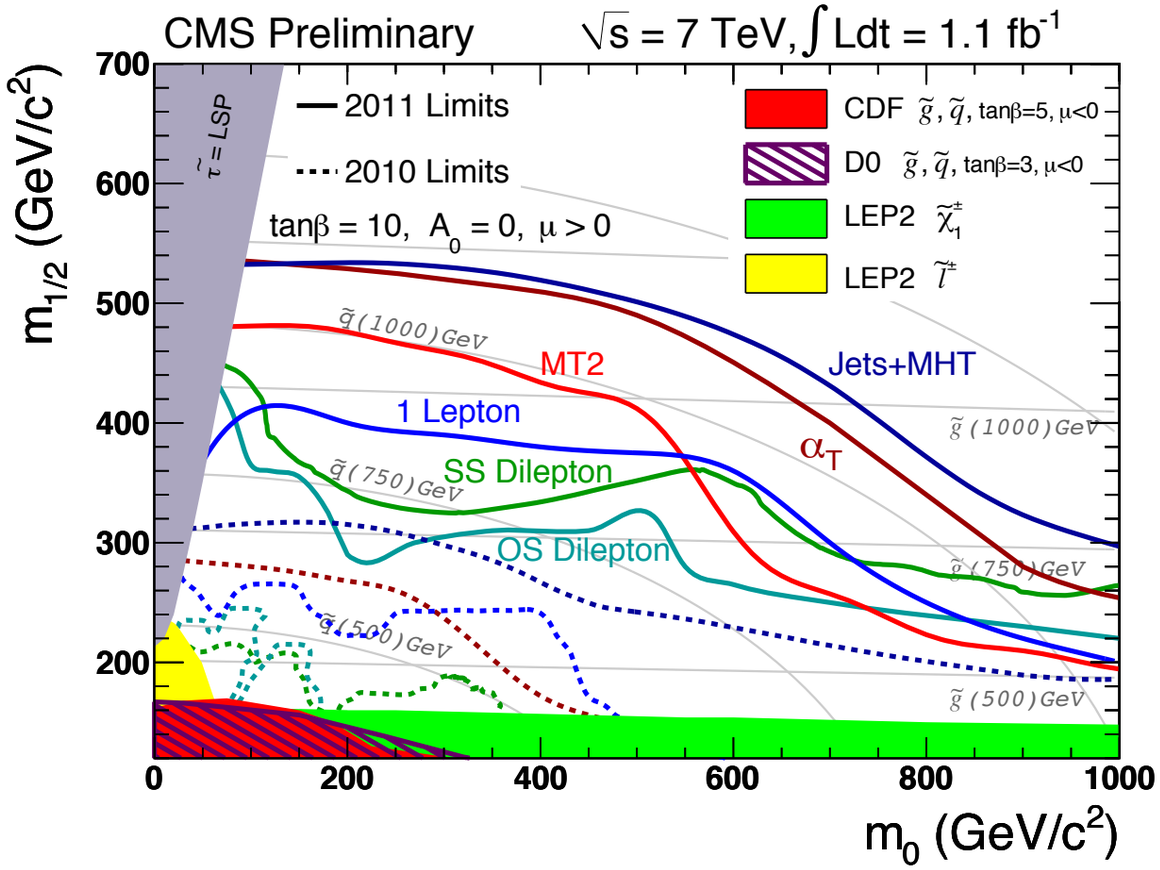
Searches at CMS

Searches at CMS

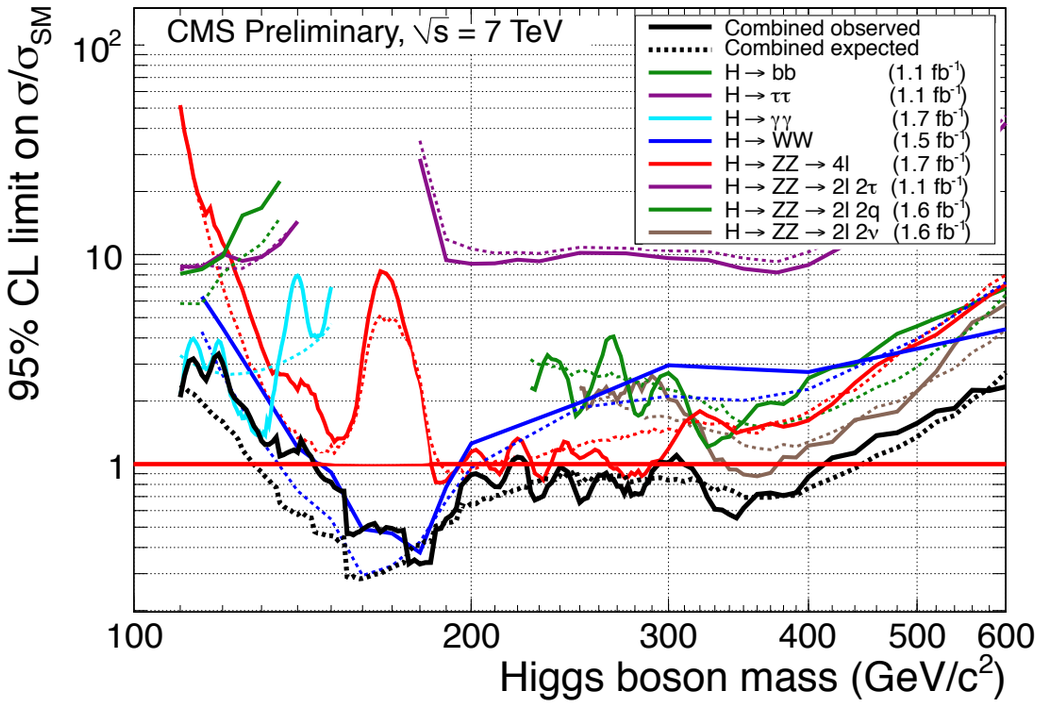


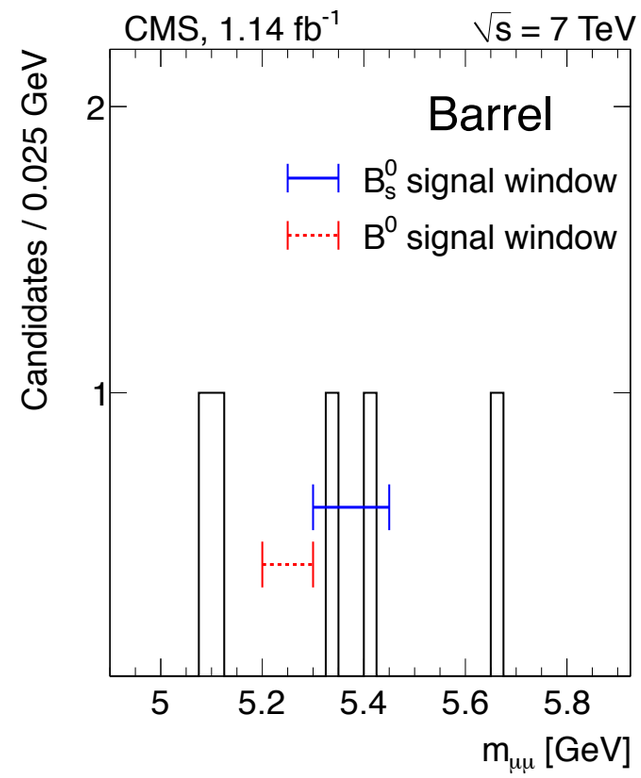
Searches at CMS

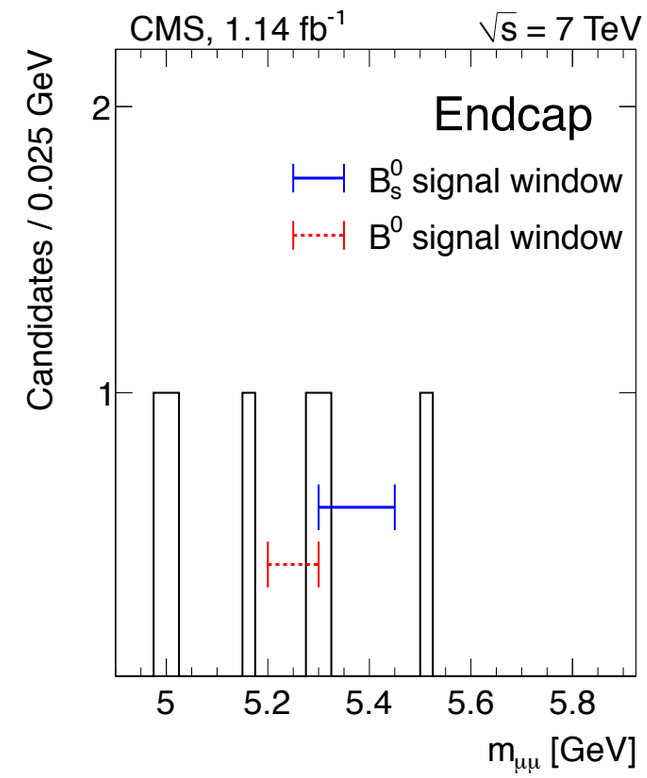


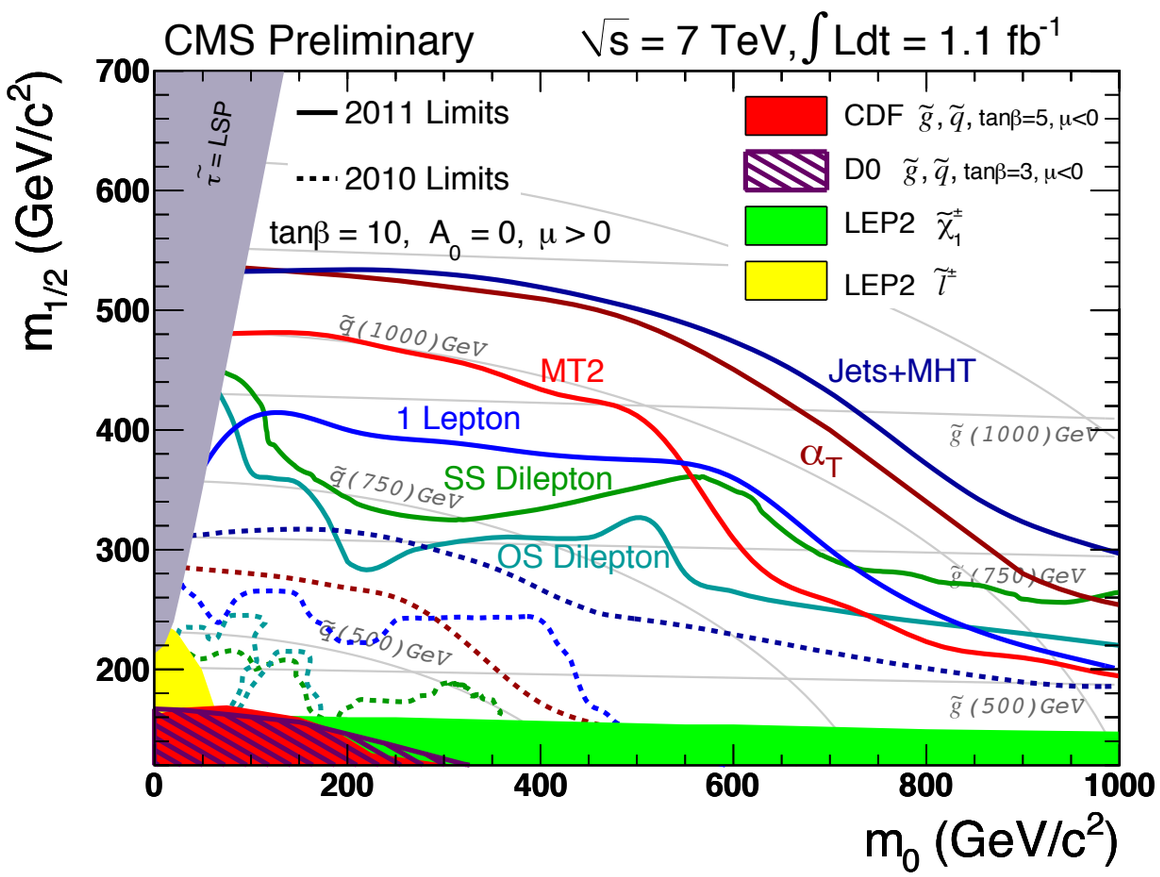


Searches at CMS

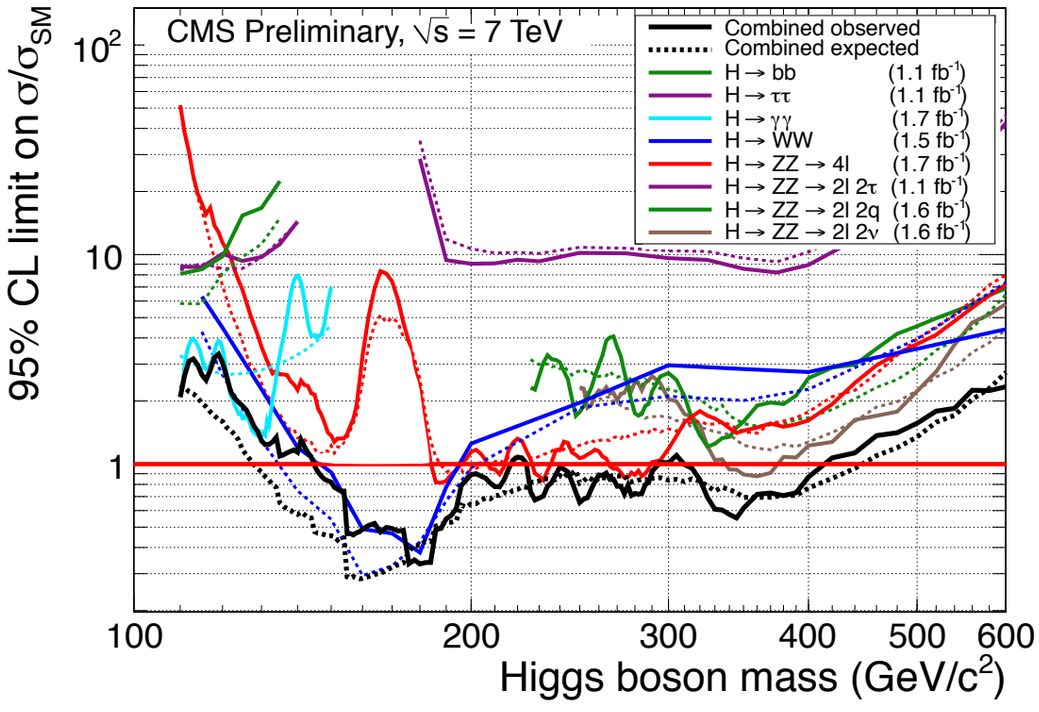


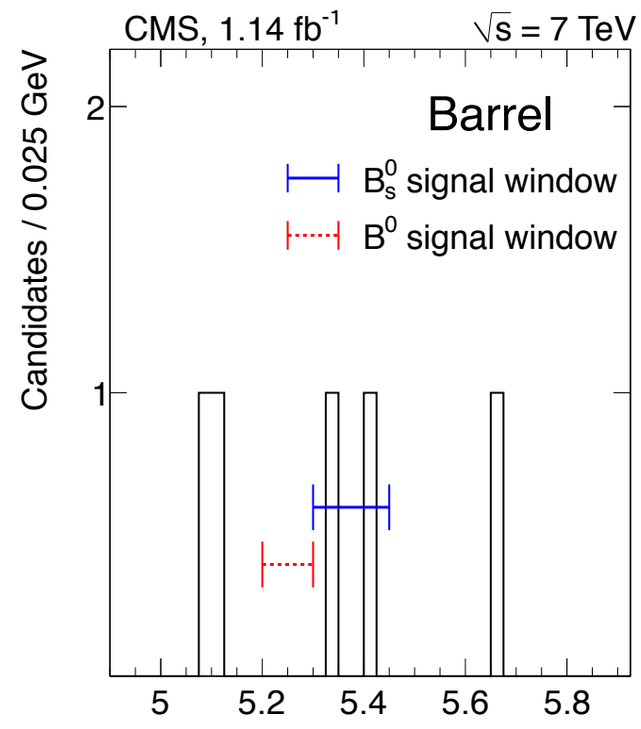


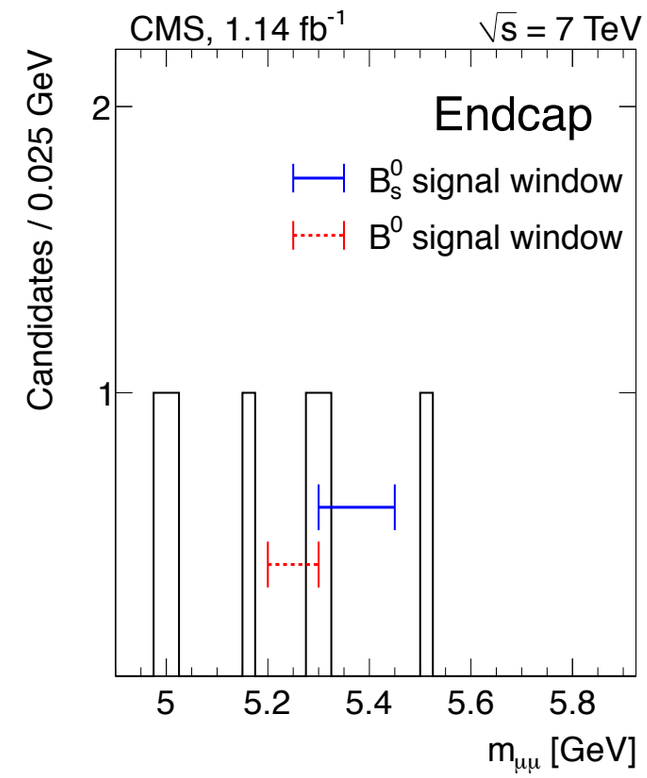


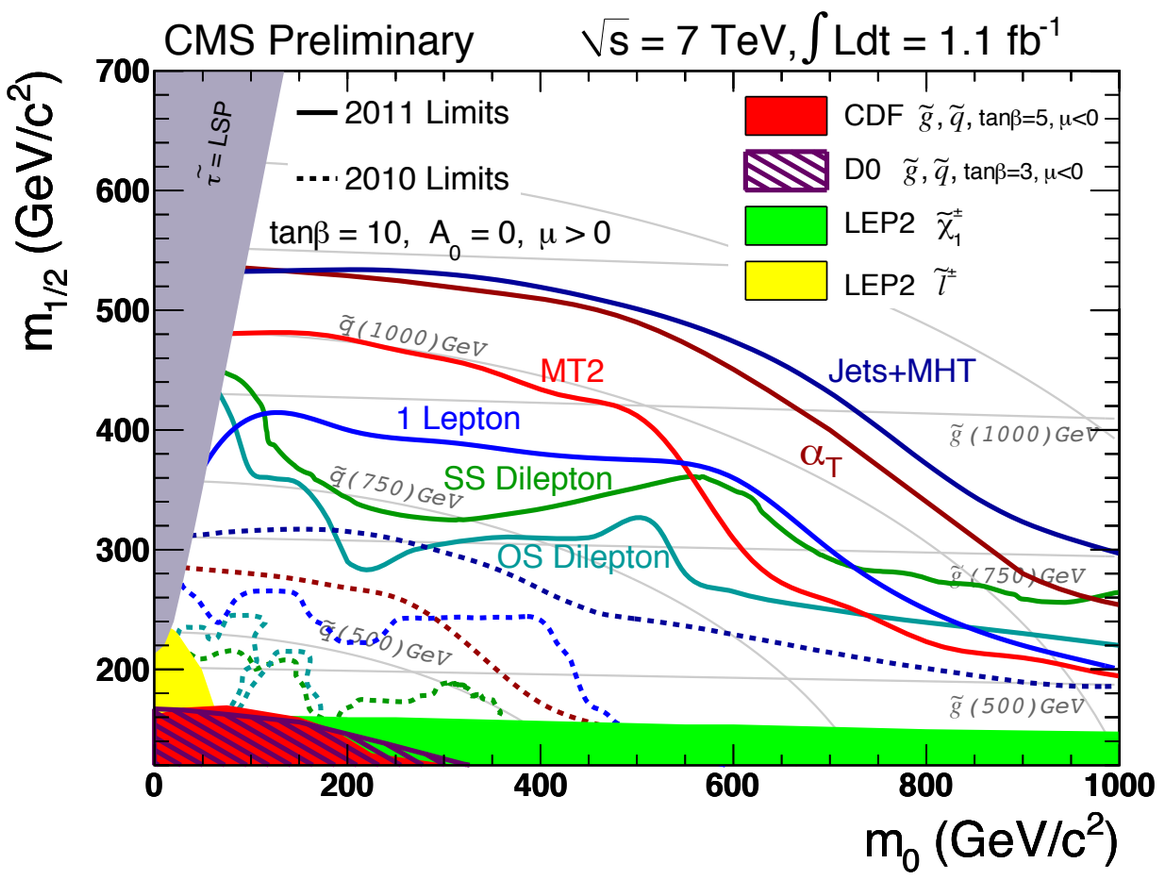


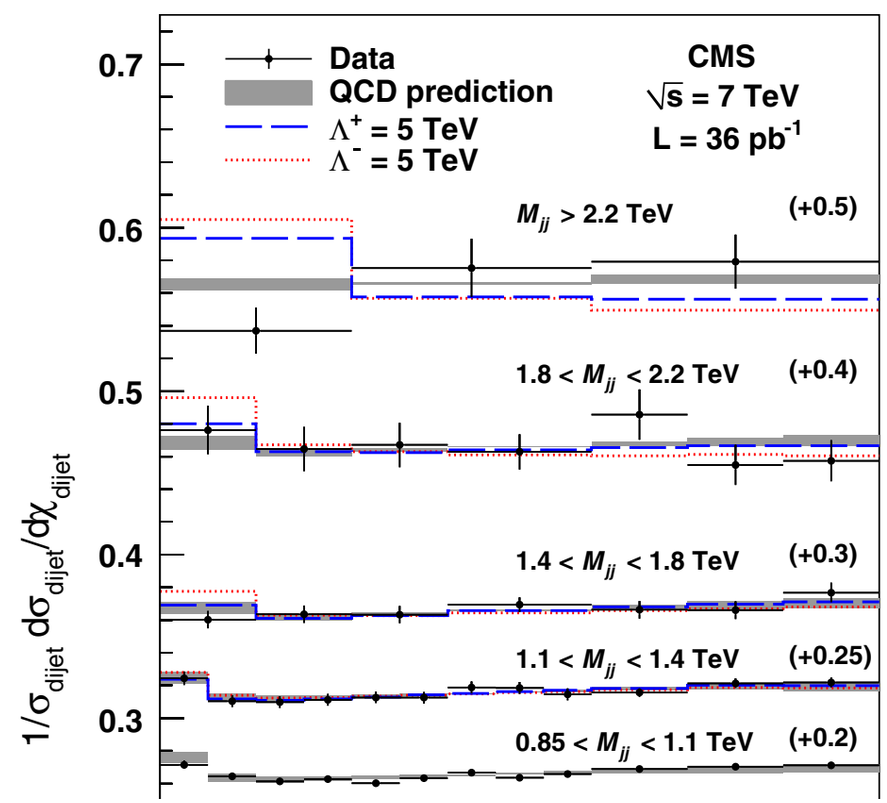
Searches at CMS



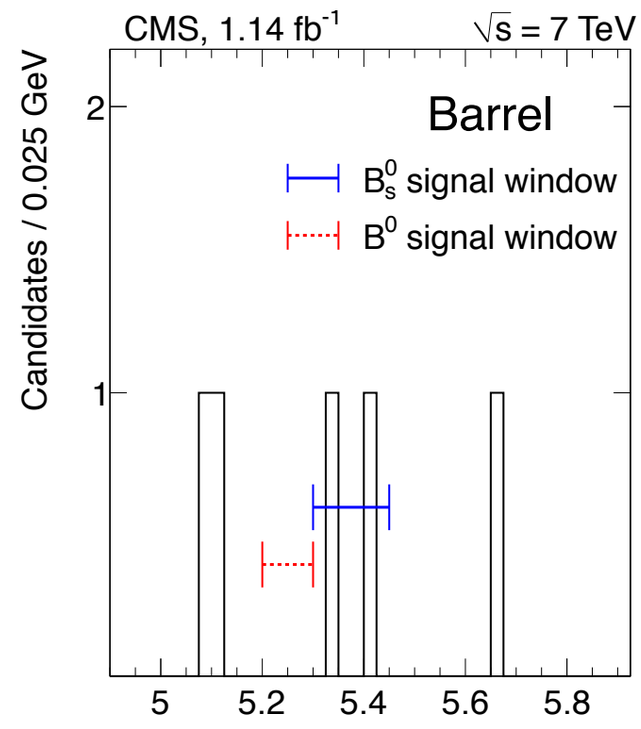


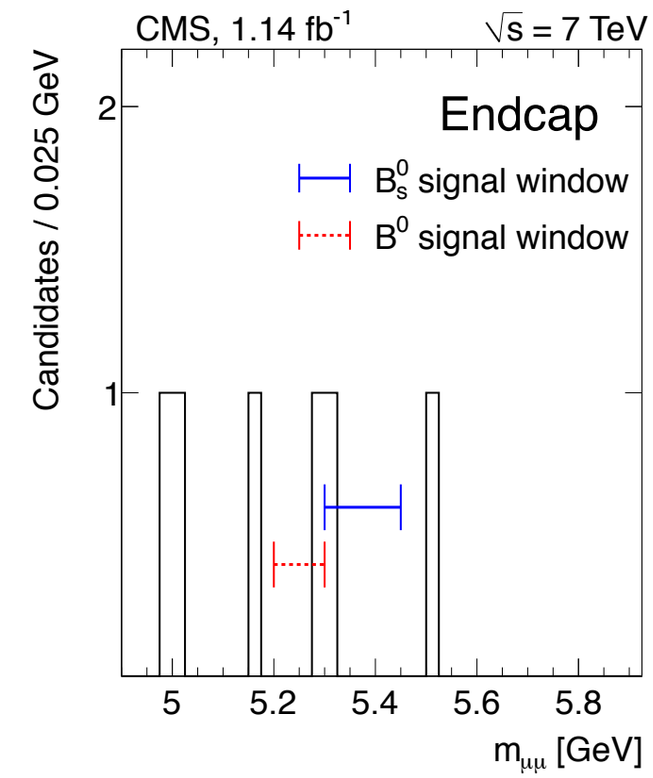


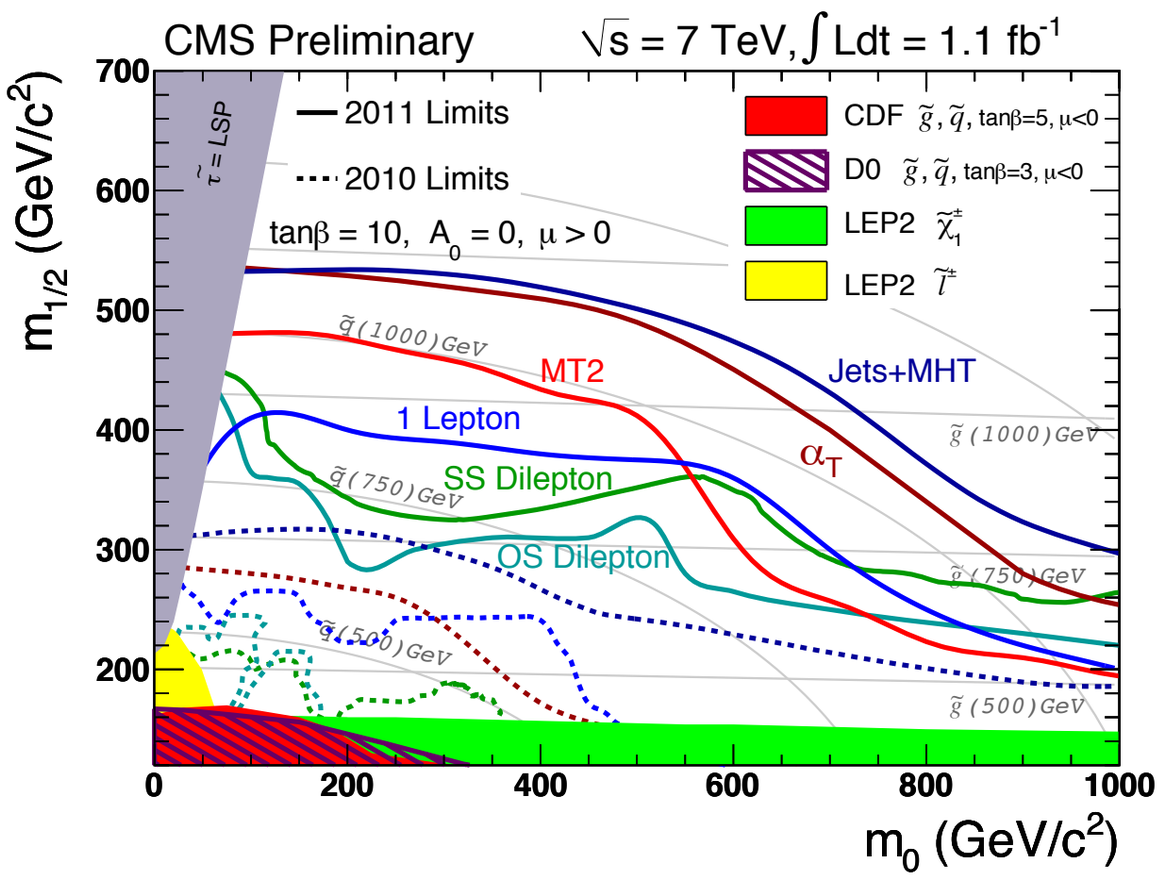


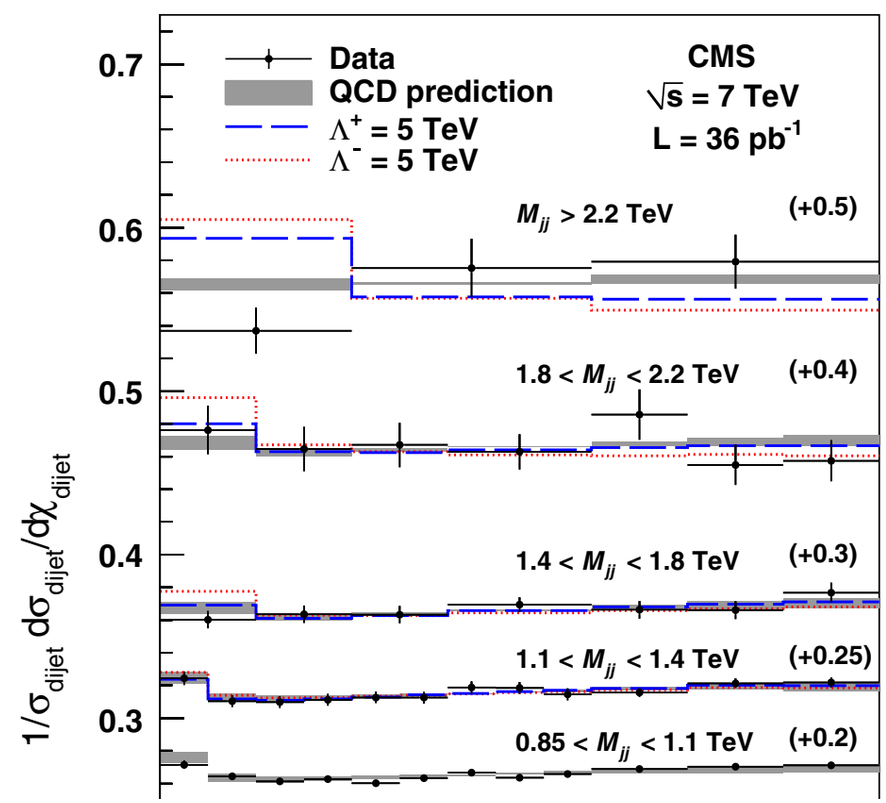


Searches at CMS



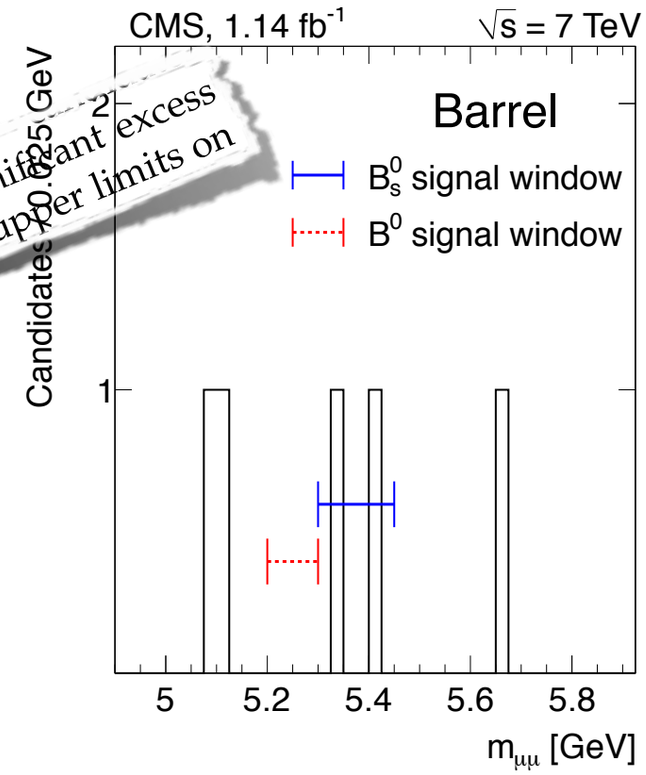


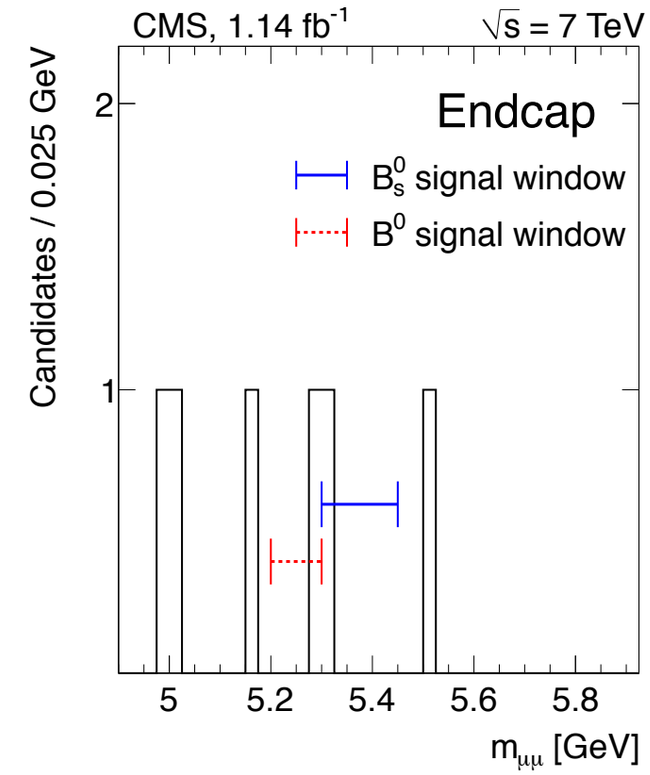


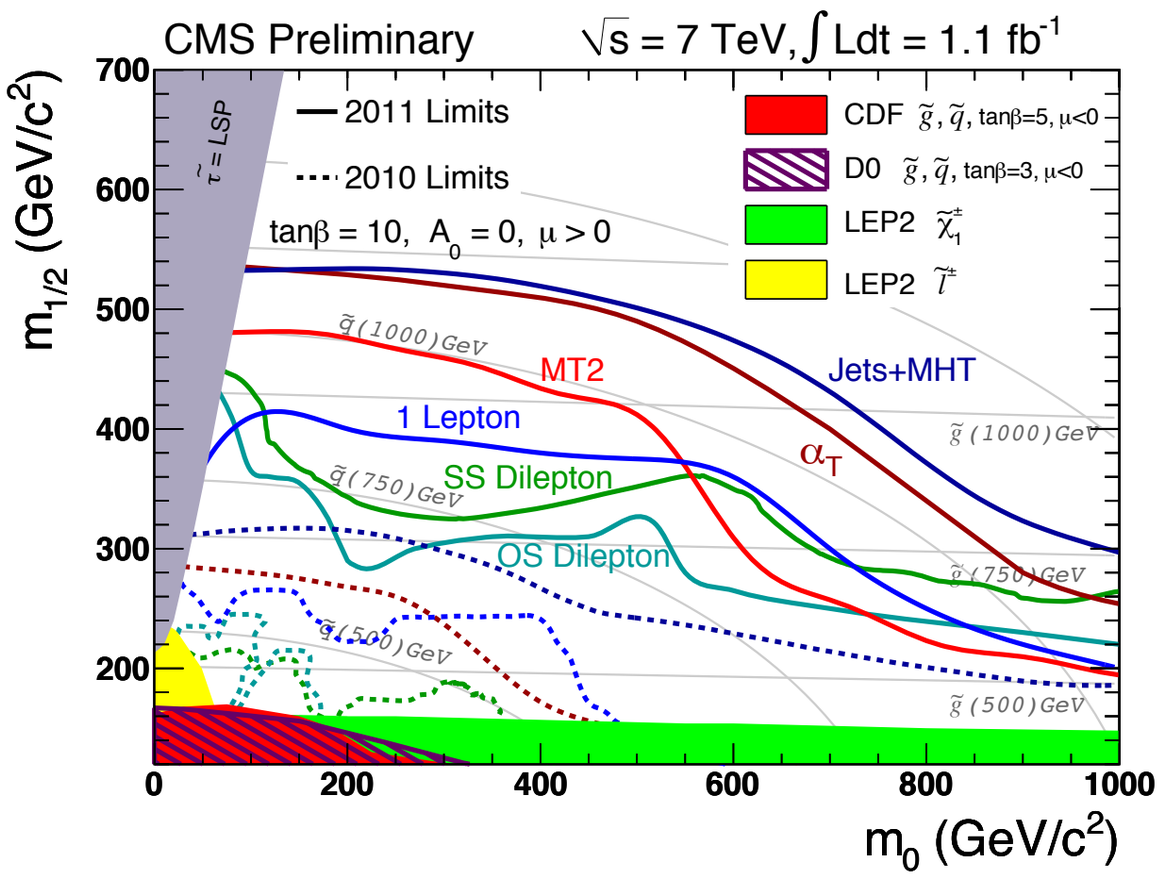


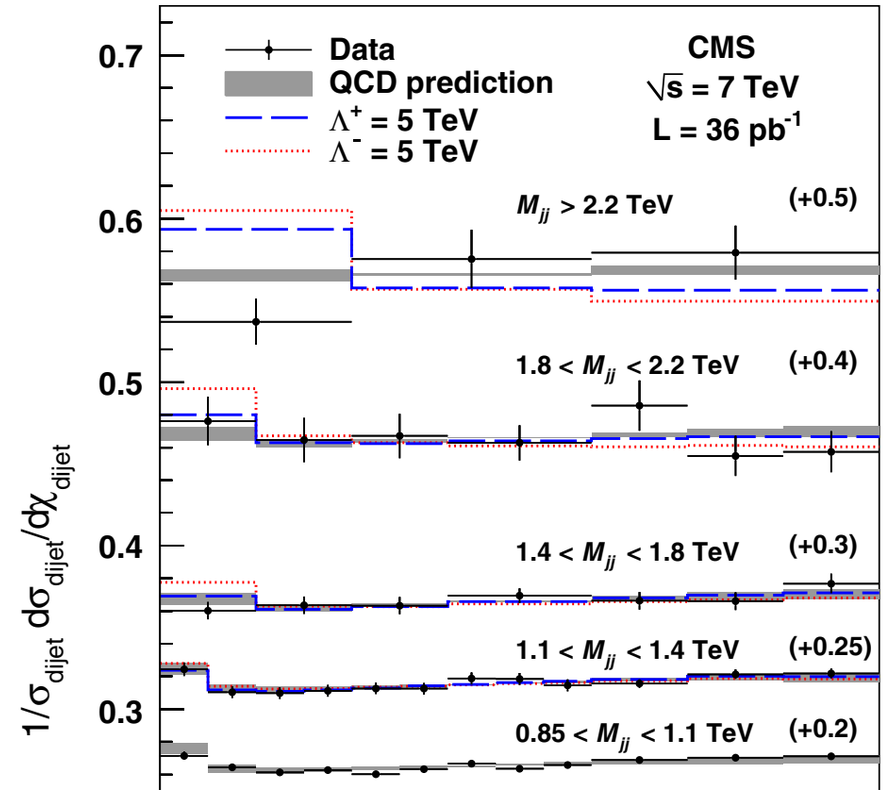
Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on



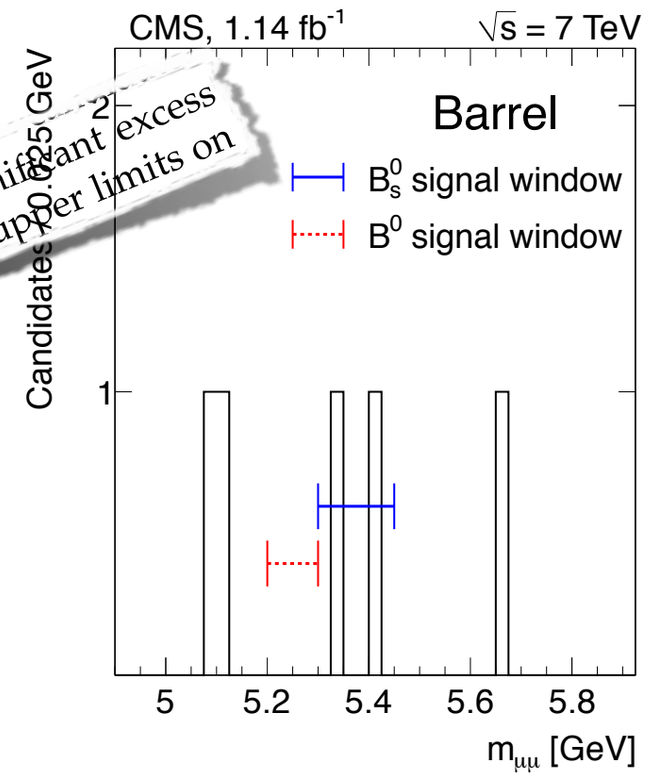


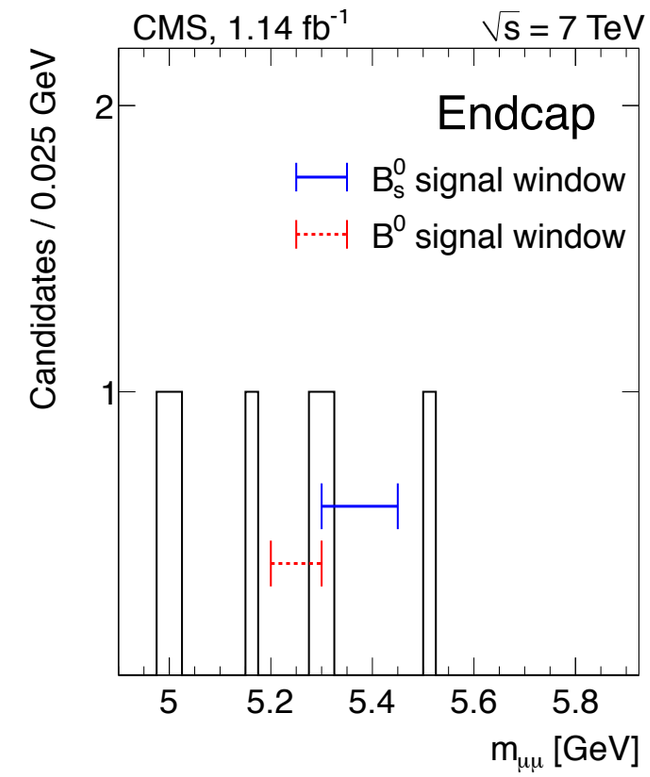


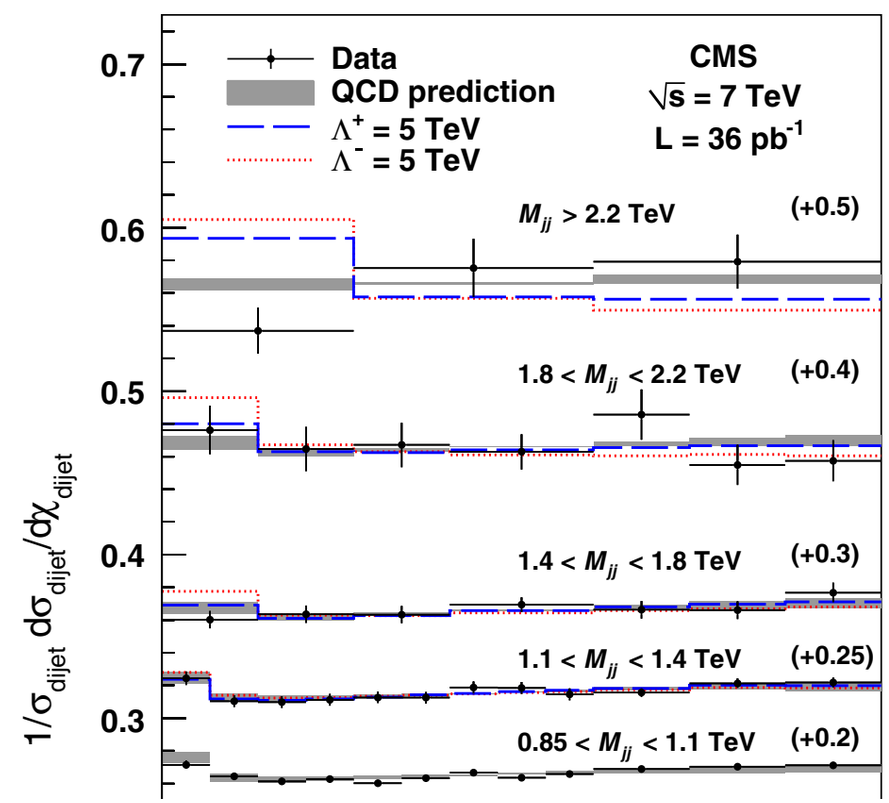


Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on

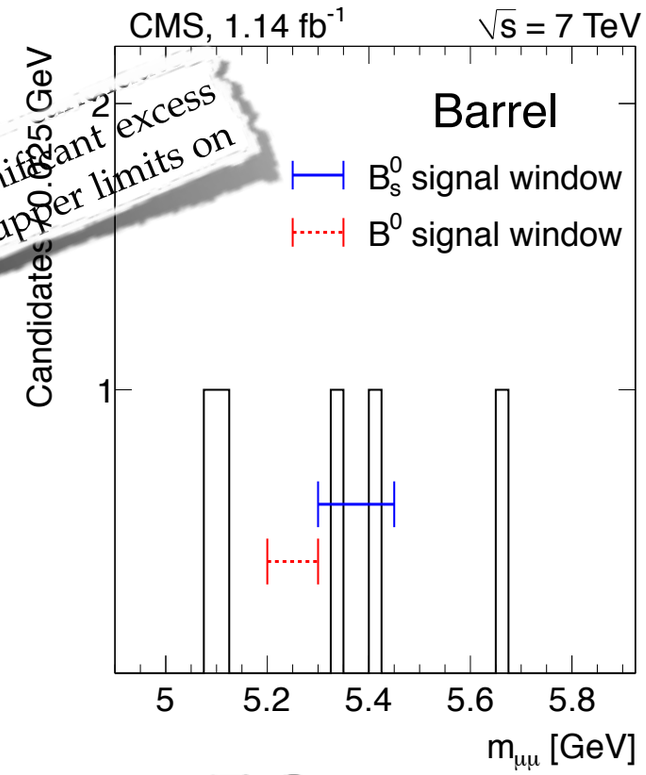


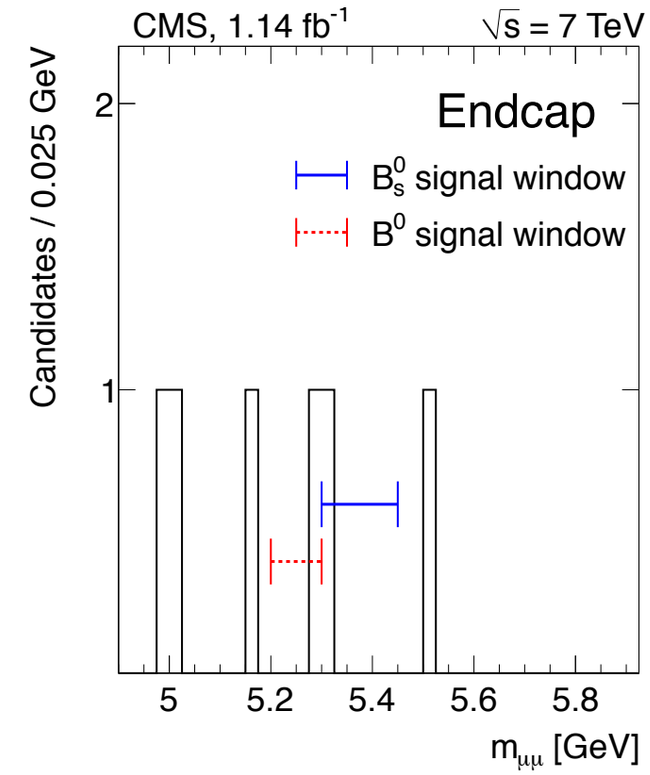




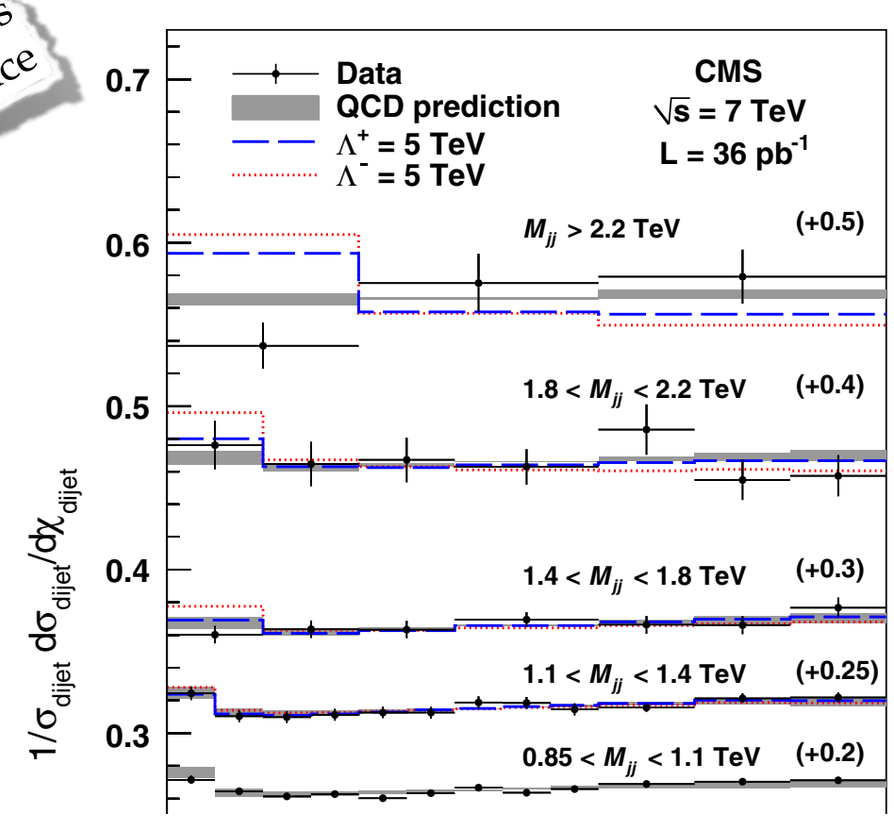
Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on





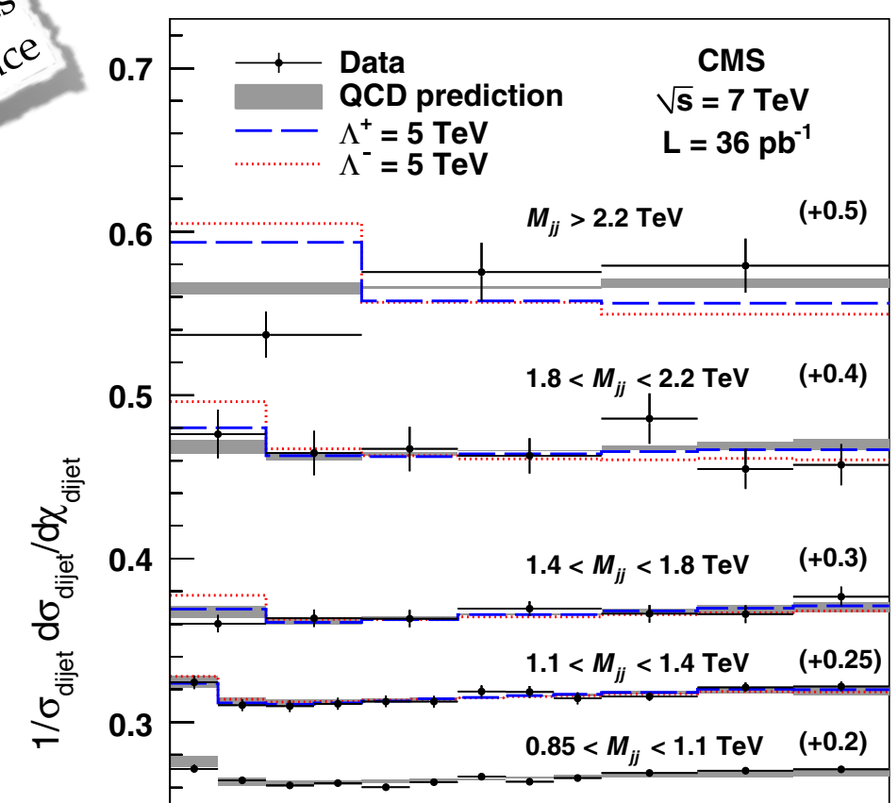
with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space



Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on

with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space

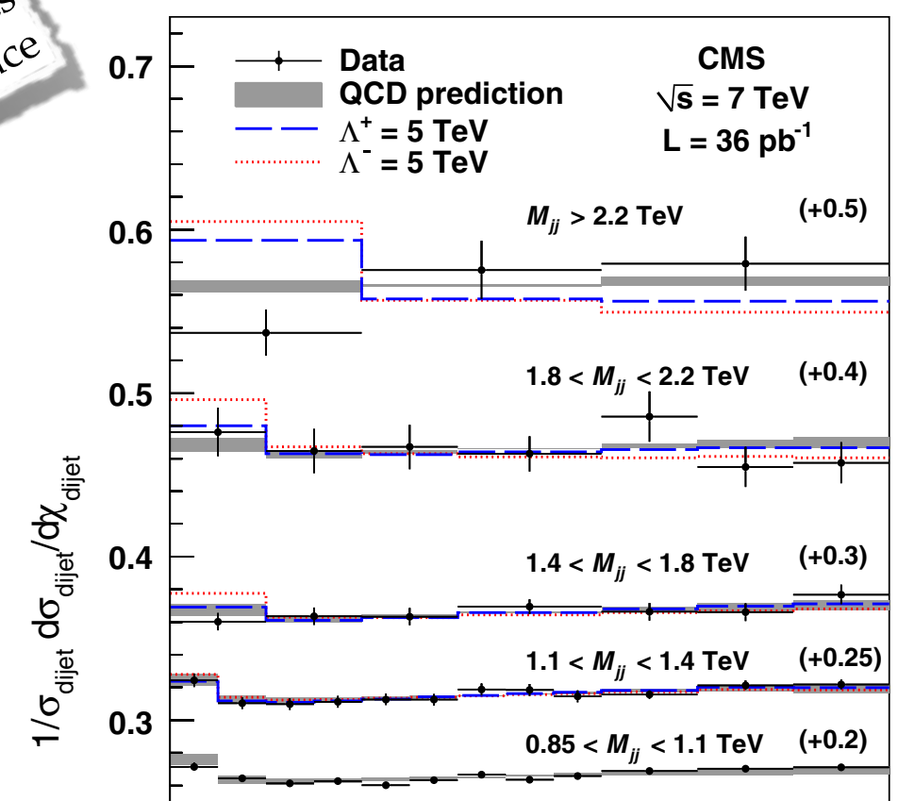


Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on

on a data sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of $1.14\,\mathrm{fb}^{-1}$. The observed event yields are consistent with those expected adding background and SM signals. Upper limits on the branching fractions have been determined at 90% and

with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space



Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on

on a data sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of $1.14\,\mathrm{fb}^{-1}$. The observed event yields are consistent with those expected adding background and SM signals. Upper limits on the branching fractions have been determined at 90% and

with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space

Searches at CMS

are selected in events with two leptons, electrons or muons. No significant excess above the Standard Model background expectation is observed, and upper limits on

on a data sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of $1.14\,\mathrm{fb}^{-1}$. The observed event yields are consistent with those expected adding background and SM signals. Upper limits on the branching fractions have been determined at 90% and

with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space

χ_{dijet} distributions are found to be in good agreement with NLO pQCD predictions, and are used to exclude a range of a color- and isospin-singlet contact interaction scale Λ for

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

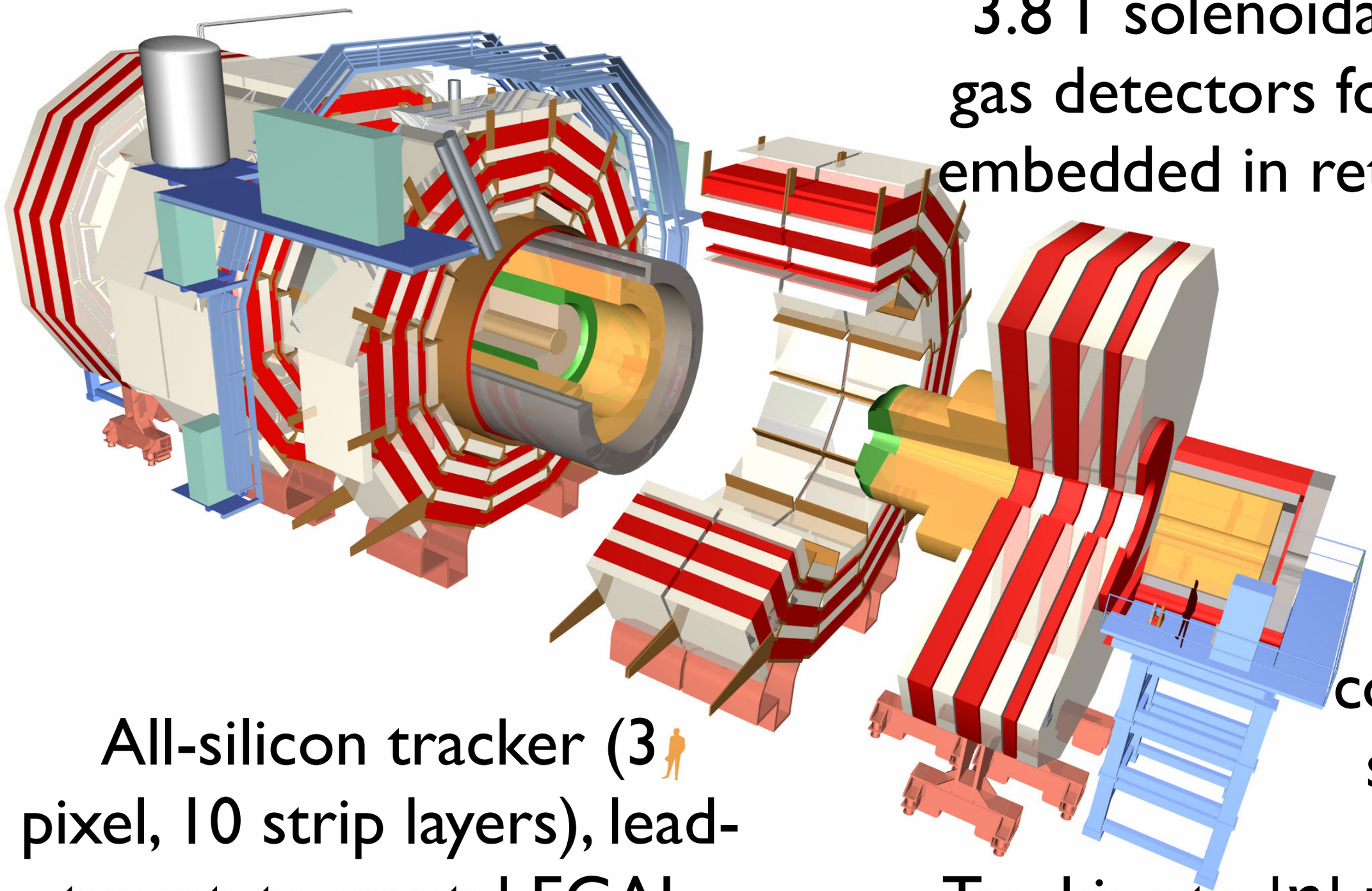
Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

Testing the standard model at CMS

- All of our measurements are tests of the current theory, the SM
- Searches for new-physics signatures test the SM in very particular corners of phase space
- Standard-model measurements test the SM through other, broader lines of attack
  - Test SM in already-explored regimes, but more stringently
  - Test SM in new regimes that are now accessible at the LHC
  - Develop and verify new tools for testing SM in regimes that will be accessible shortly

CMS detector



3.8 T solenoidal B field, gas detectors for muons embedded in return yoke

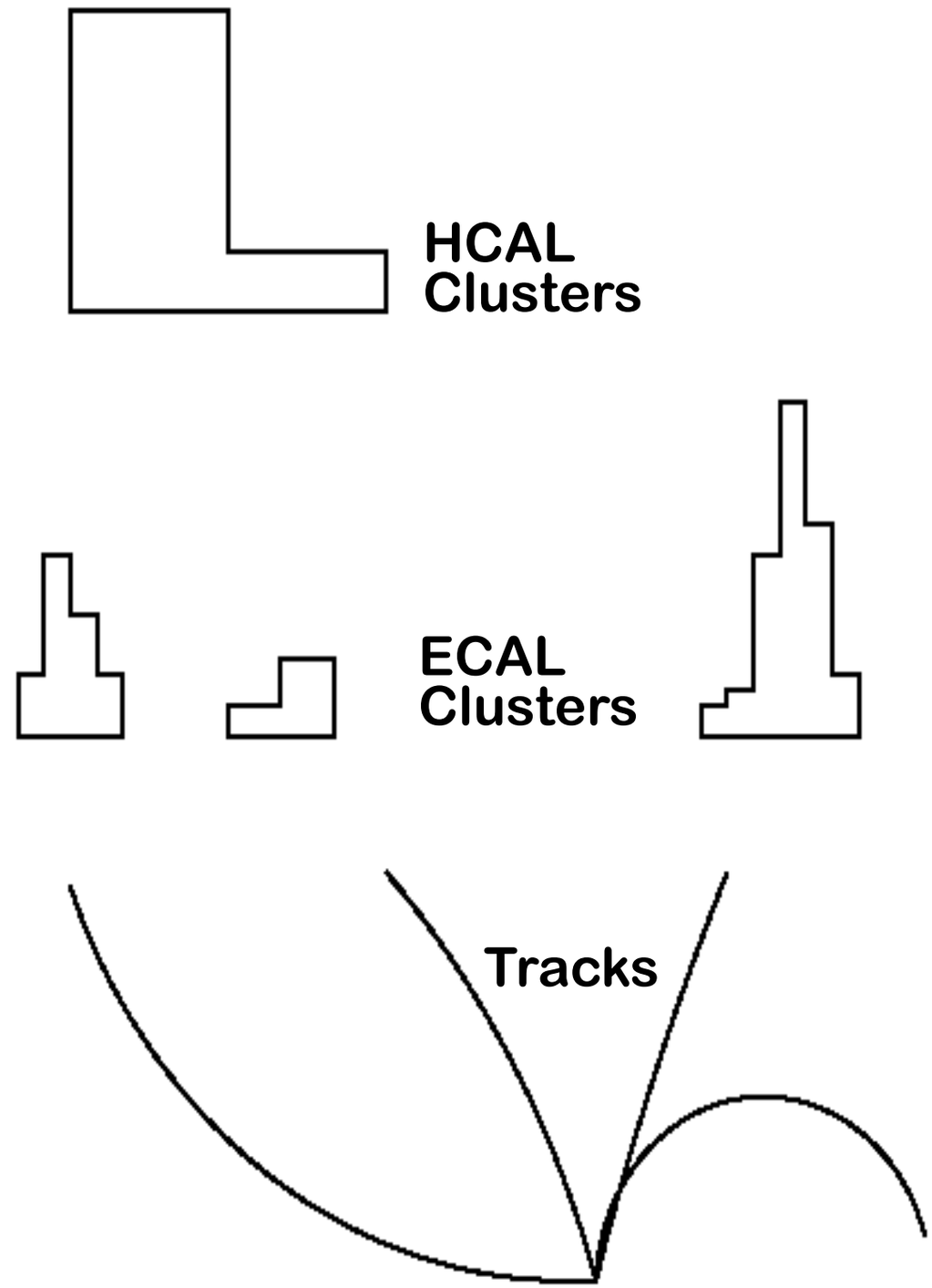
Not shown: DAQ/ trigger, computers, software

All-silicon tracker (3 pixel, 10 strip layers), lead-tungstate crystal ECAL, brass/scintillator HCAL

Tracking to $|\eta| = 2.5$, calorimetry to $|\eta| = 5$

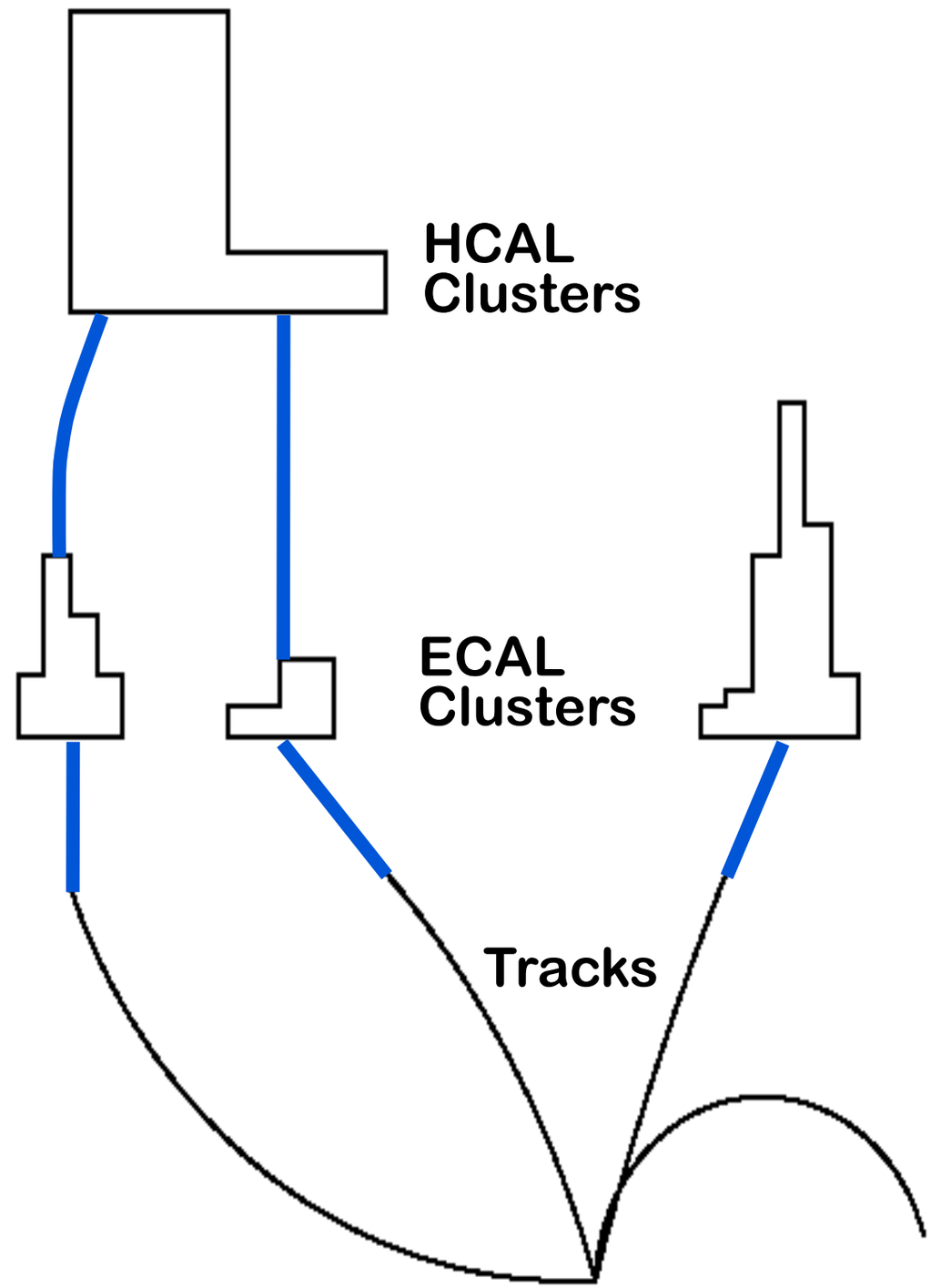
Precision reconstruction

- 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.



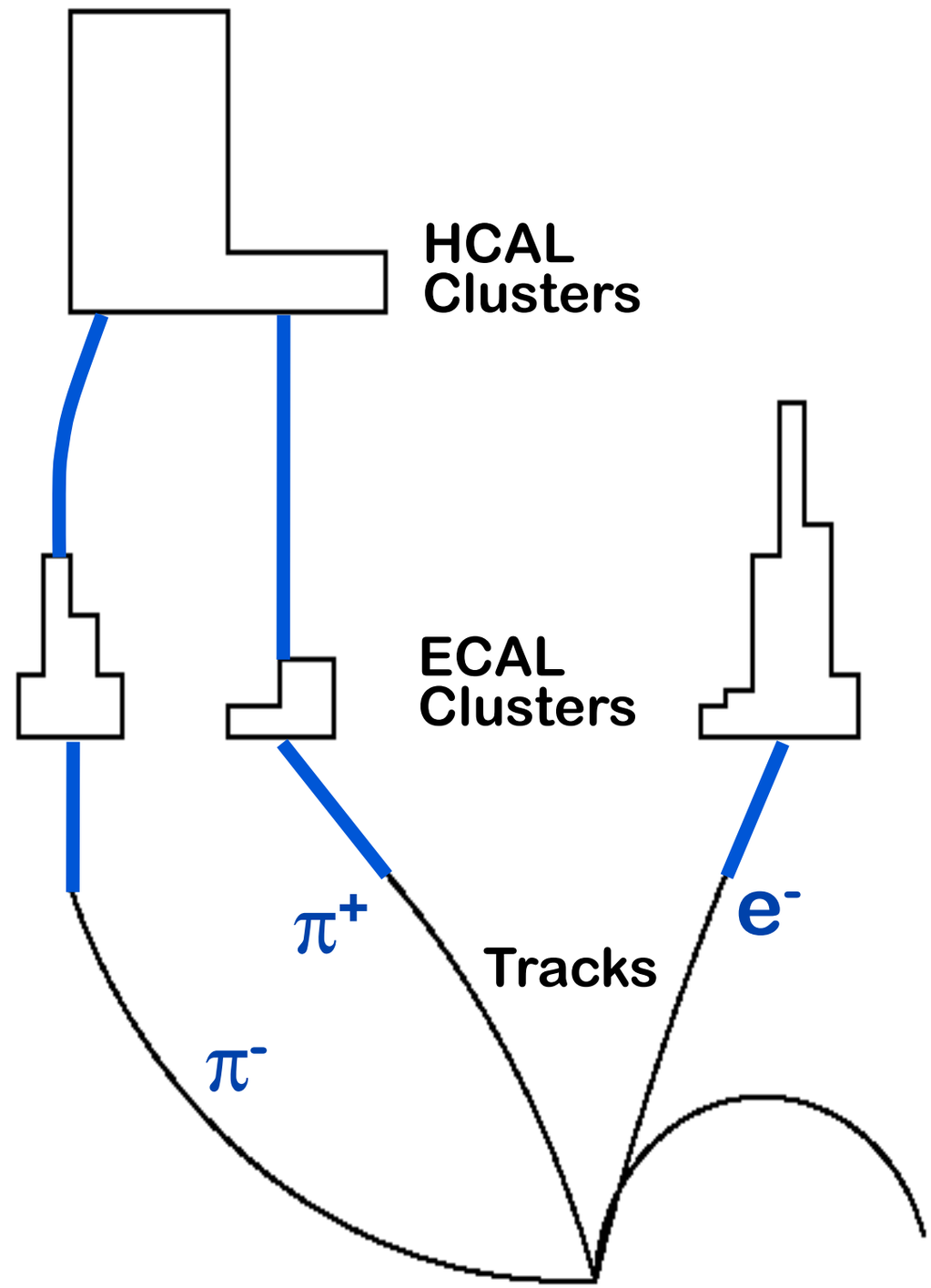
Precision reconstruction

- 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.



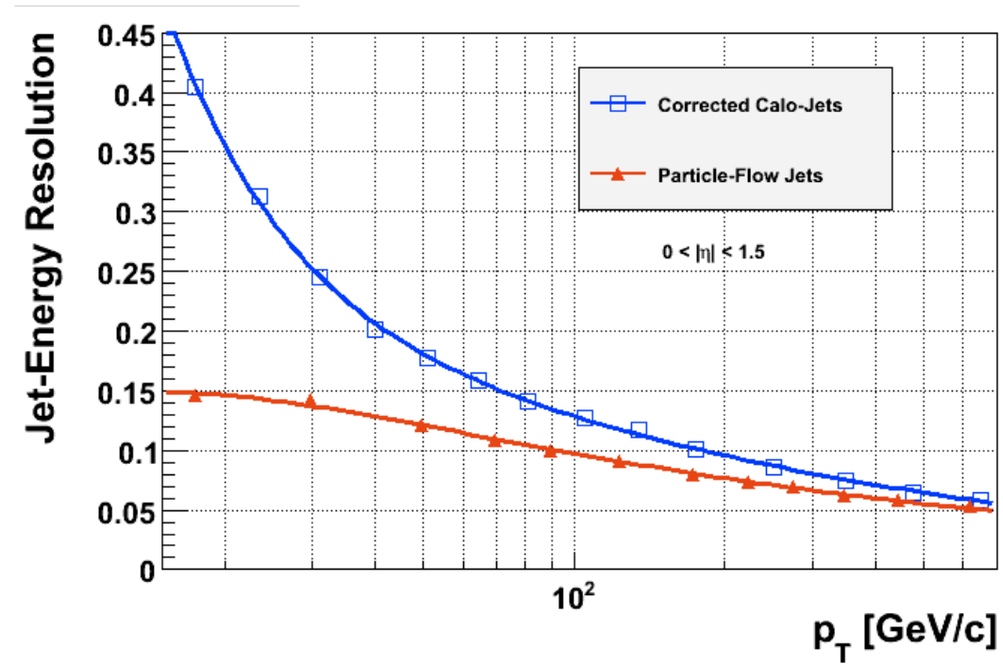
Precision reconstruction

- 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.

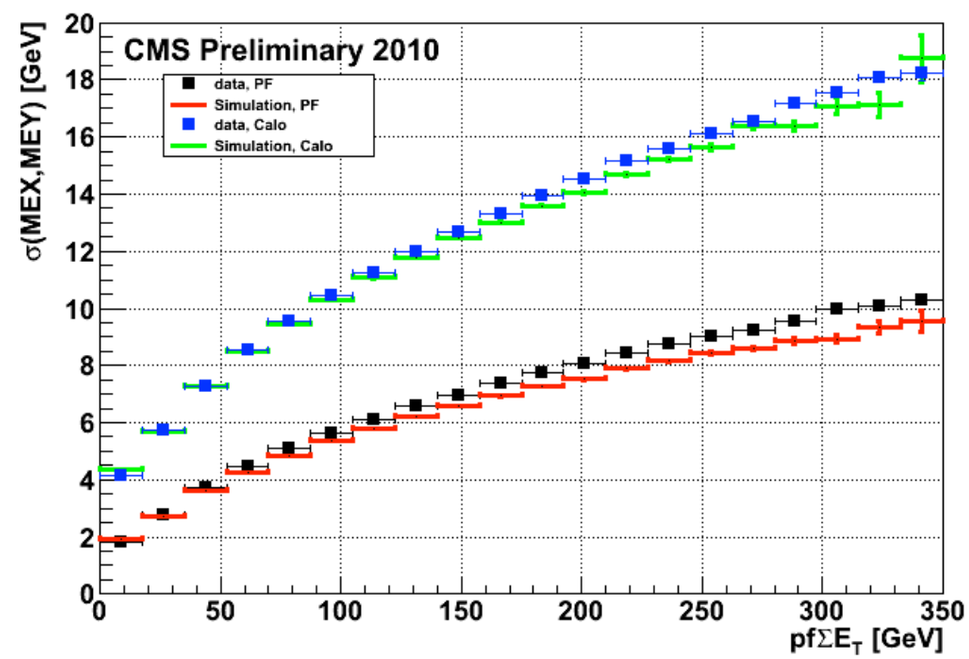


Precision reconstruction

- 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.

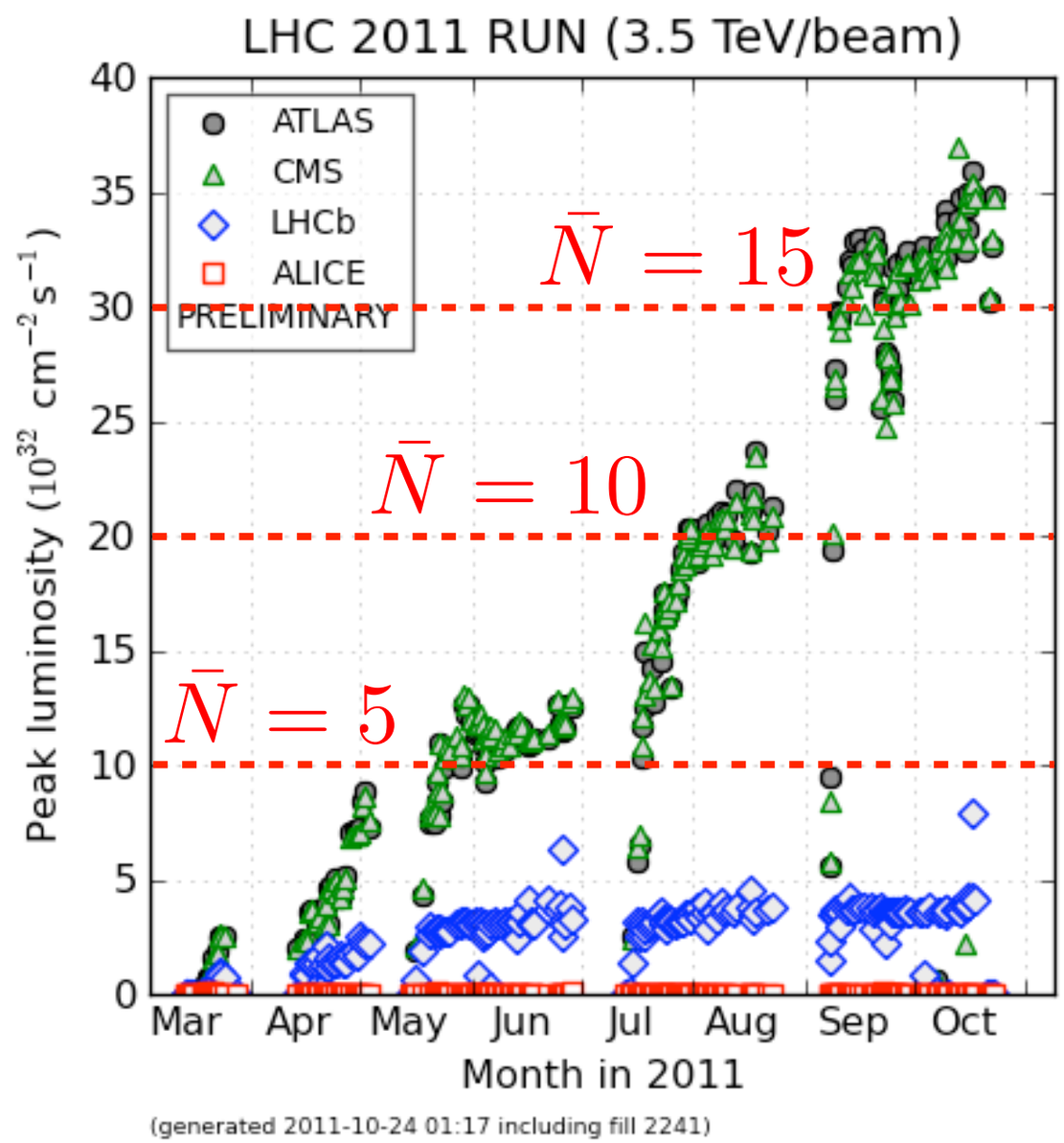


- Jet energies, missing energies computed from individual particles
  - Leads to relatively small corrections and thus small uncertainties on jet-energy scale (JES), good resolution on jet and missing energy.



Datasets and conditions

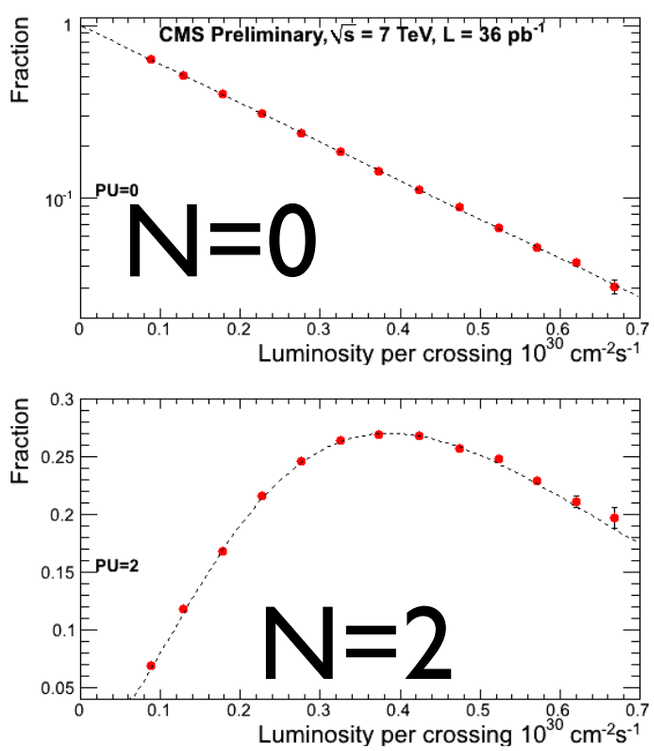
- Measurements largely come from two data-taking periods:
  - 2010 pp collision data, ~36 pb^{-1}
  - 2011 pp collisions up to July EPS conference, ~1.1 fb^{-1}
  - But some high-statistics analyses can be done with much less data
- Increasing luminosity leads to increasing "pileup"
  - Analyses shown here largely insensitive to pileup problems, thanks to good pileup subtraction algorithms, but a constant source of scrutiny going forward

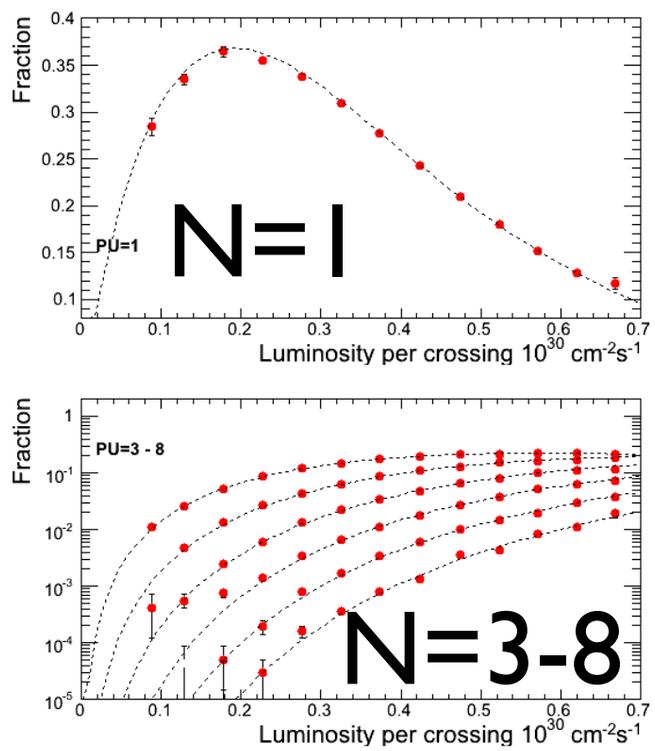


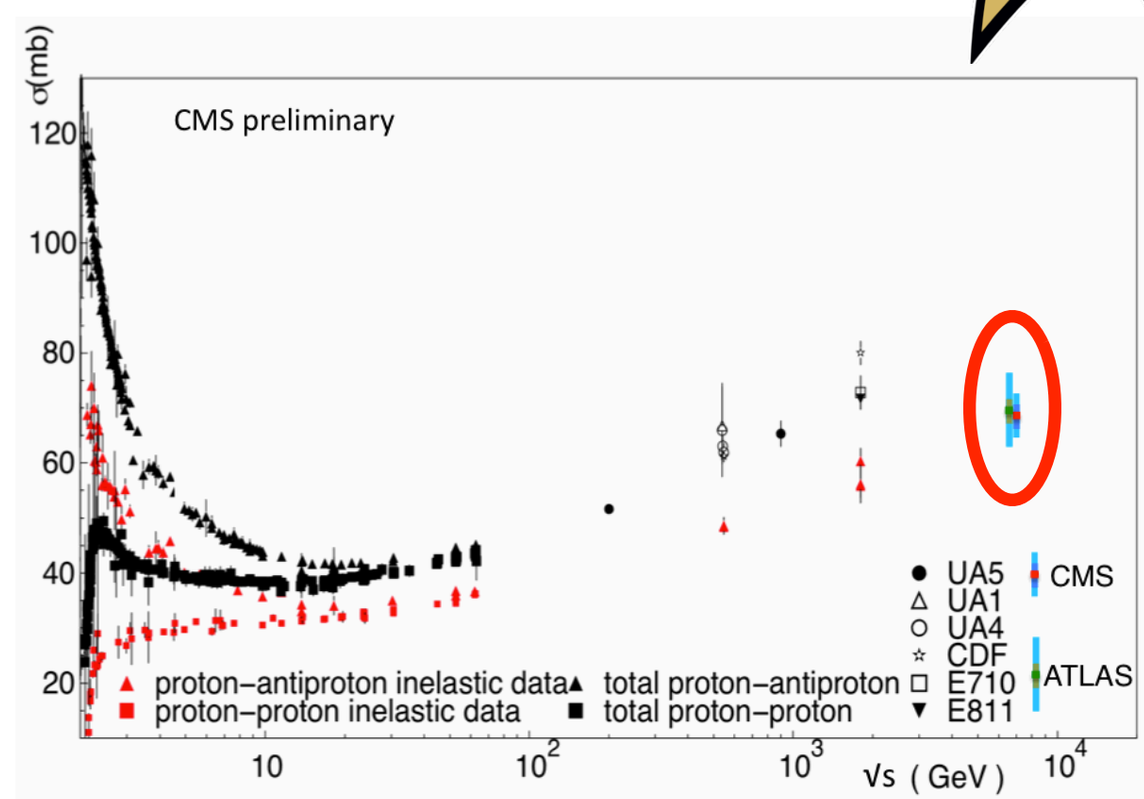
Total inelastic pp cross section

- Just count number of interaction vertices/event vs. luminosity
  - Small corrections for vertex inefficiencies, merging....
  - Get luminosity measurement from van der Meer scans
- Fit the results to Poisson distribution
- Dominant single uncertainty is 4% on luminosity normalization

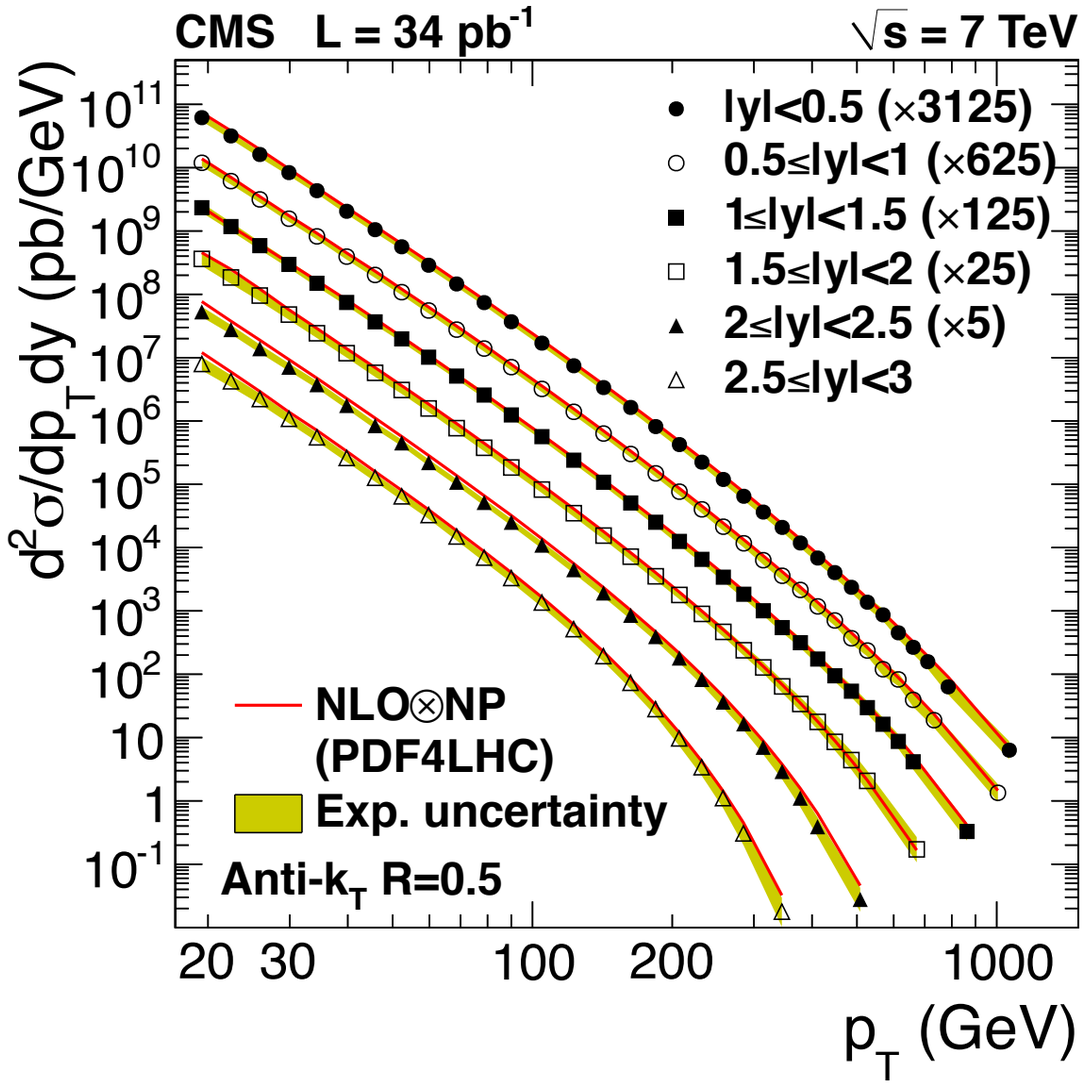
$$\sigma_{inel}(pp) = 68 \pm 2.0\,(\text{Syst}) \pm 2.4\,(\text{Lum}) \pm 4\,(\text{Ext.})\ \text{mb}$$



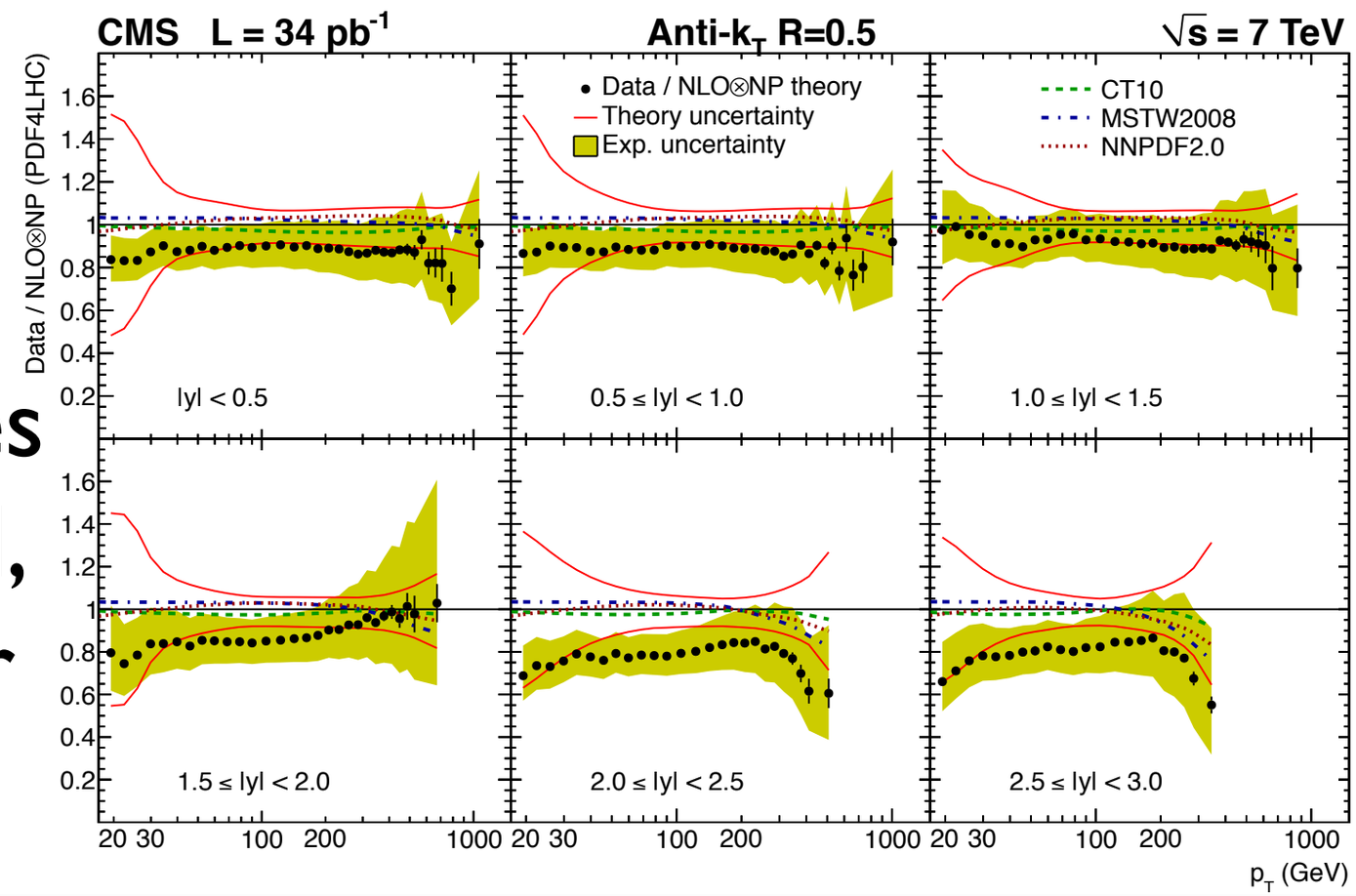




Inclusive jet cross section



Cross section falls over 10 orders of magnitude in rate!
Quality measurements to |y|=3!
Key element is JES precision, 3-4% over this range

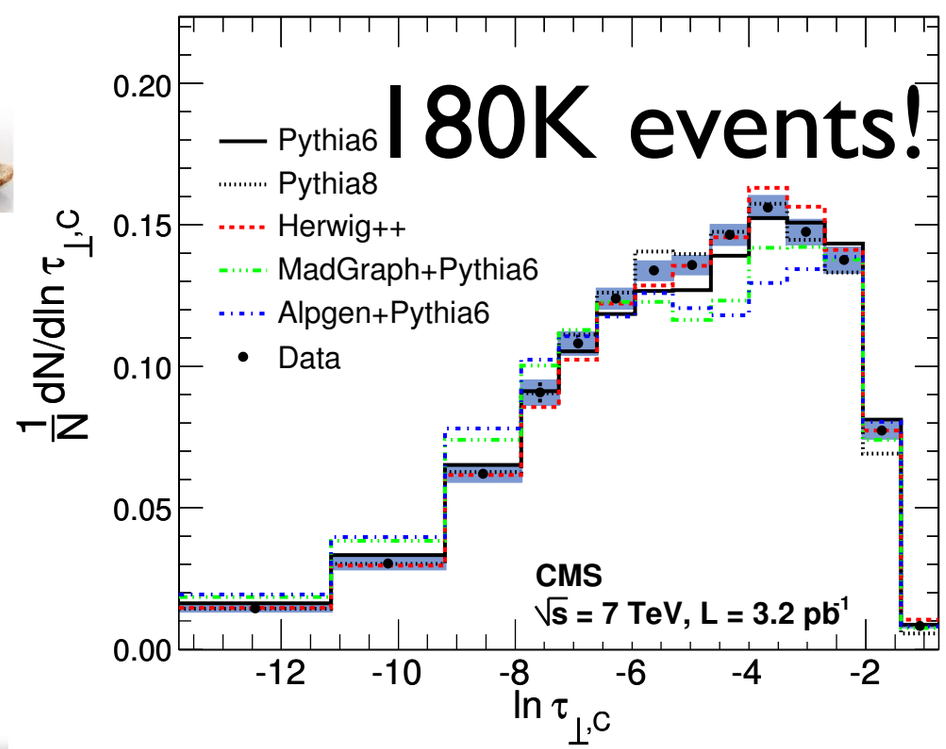


Experimental uncertainties similar size to theoretical, OK agreement but lower rates than predicted

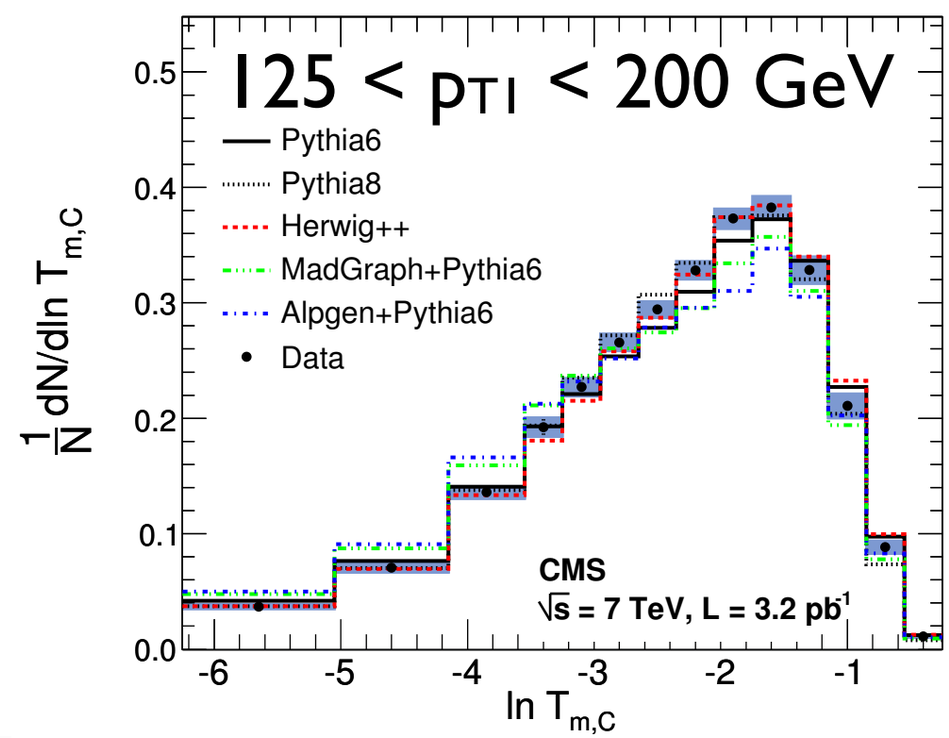
Hadronic event shapes

- Measure "central transverse thrust" = momentum carried by jets in plane defined by thrust and beam axes
- And "central thrust minor" = momentum out of plane
  - Both normalized to total p_T, minimize JES dependence
- Singular-variable decomposition for unfolding, < 5% uncertainty
- JES dominant uncertainty, but only affects jet thresholds

Transverse thrust

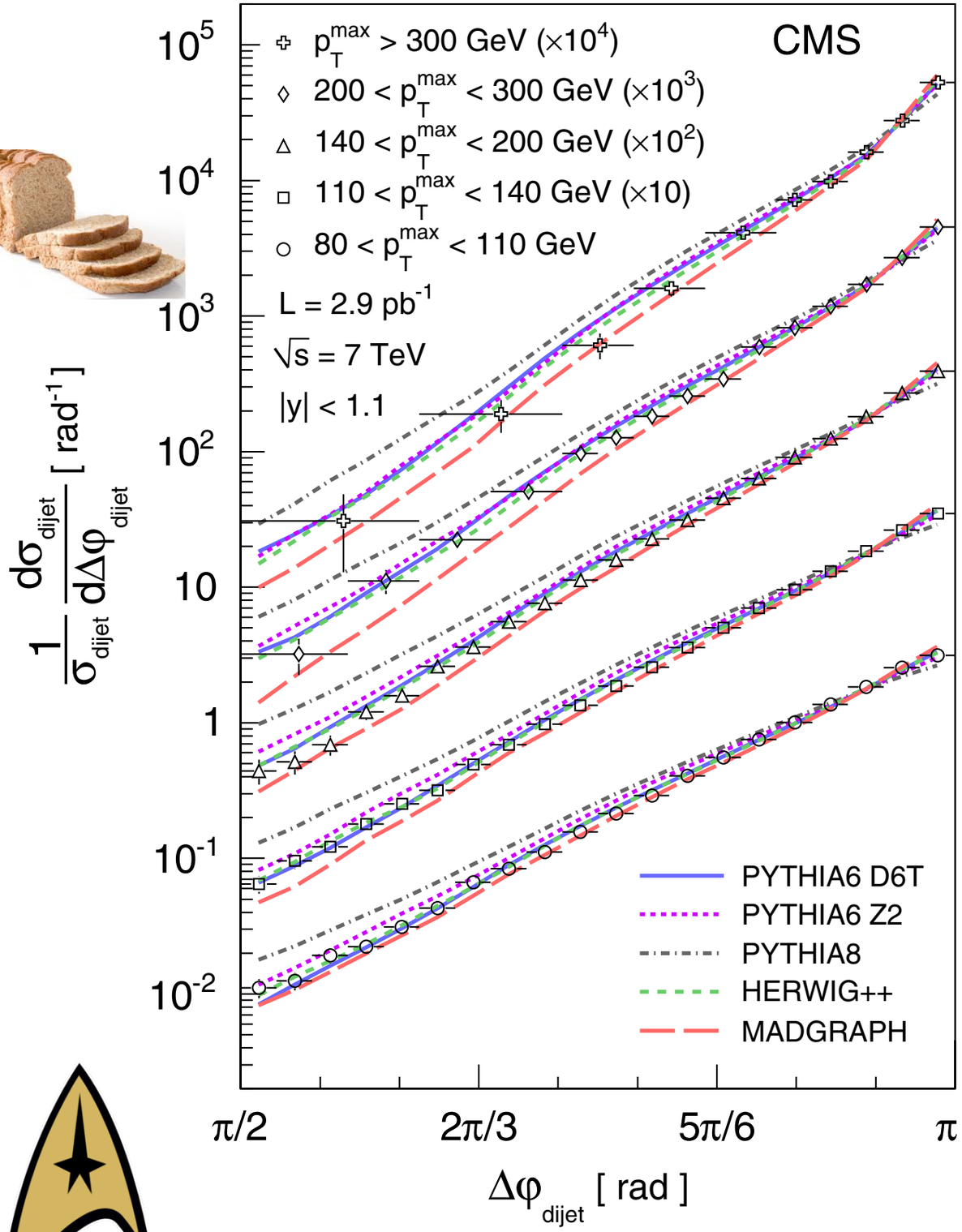


Thrust minor

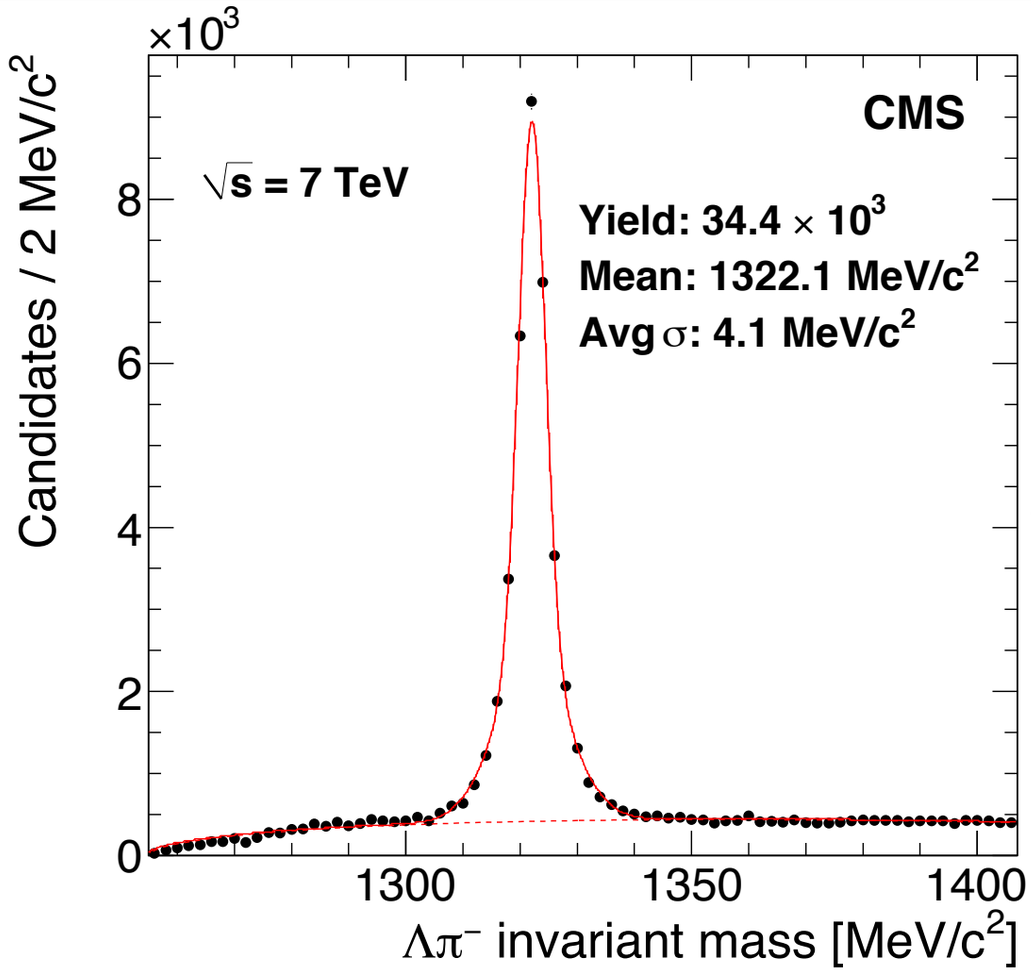


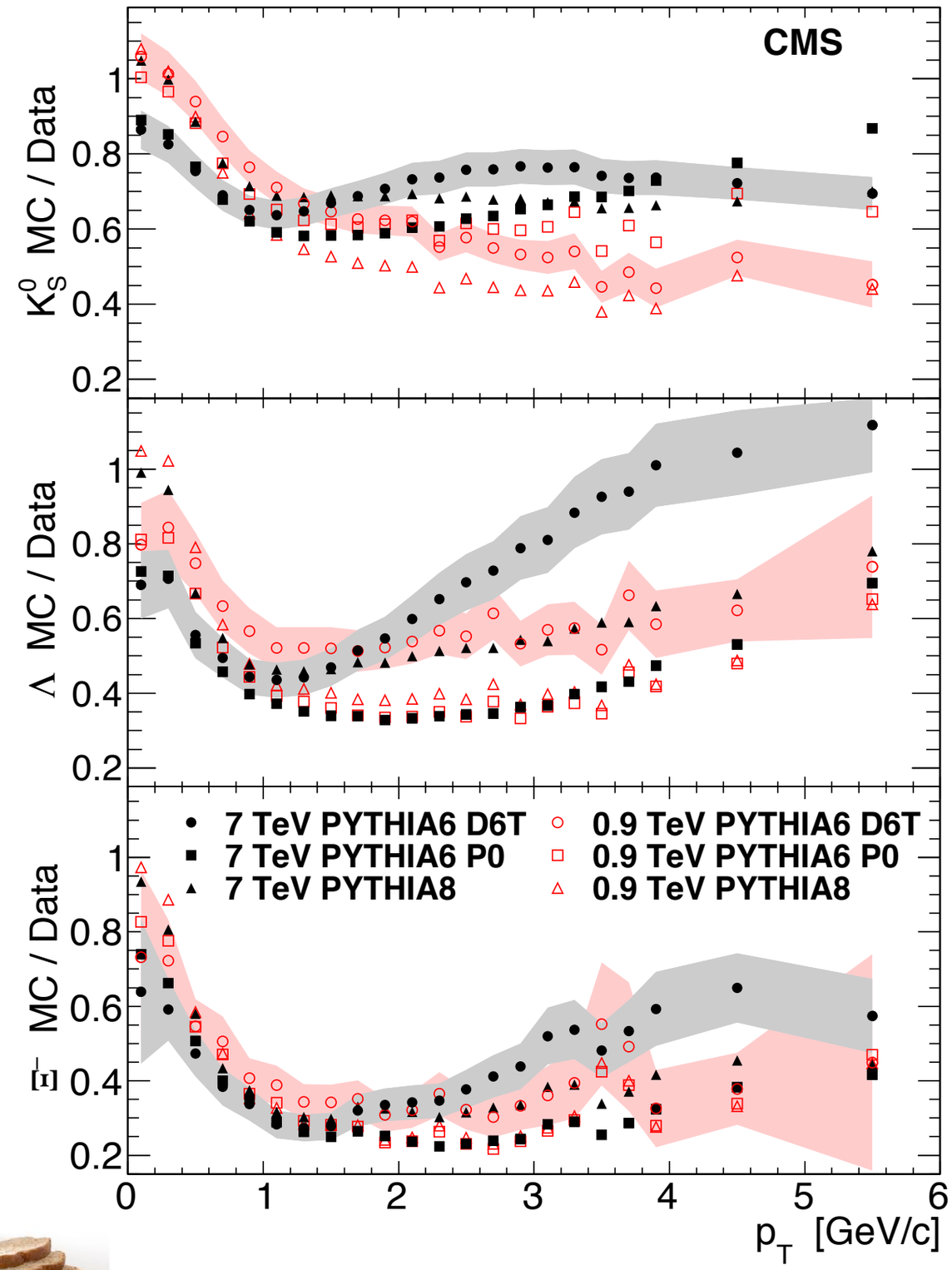
Dijet azimuthal decorrelations

- When there's extra radiation in a dijet event, the jets are less back-to-back. Just look at Δφ!
  - Sensitive to ISR, thus good for tuning that in generators
- Study as a function of lead jet pT
- Similar bin-migration issues; JES, JER and unfolding are leading systematics.
  - Total uncertainties 3-11%
- Detailed variation of generator parameters to explore uncertainties



Strange strange particle production

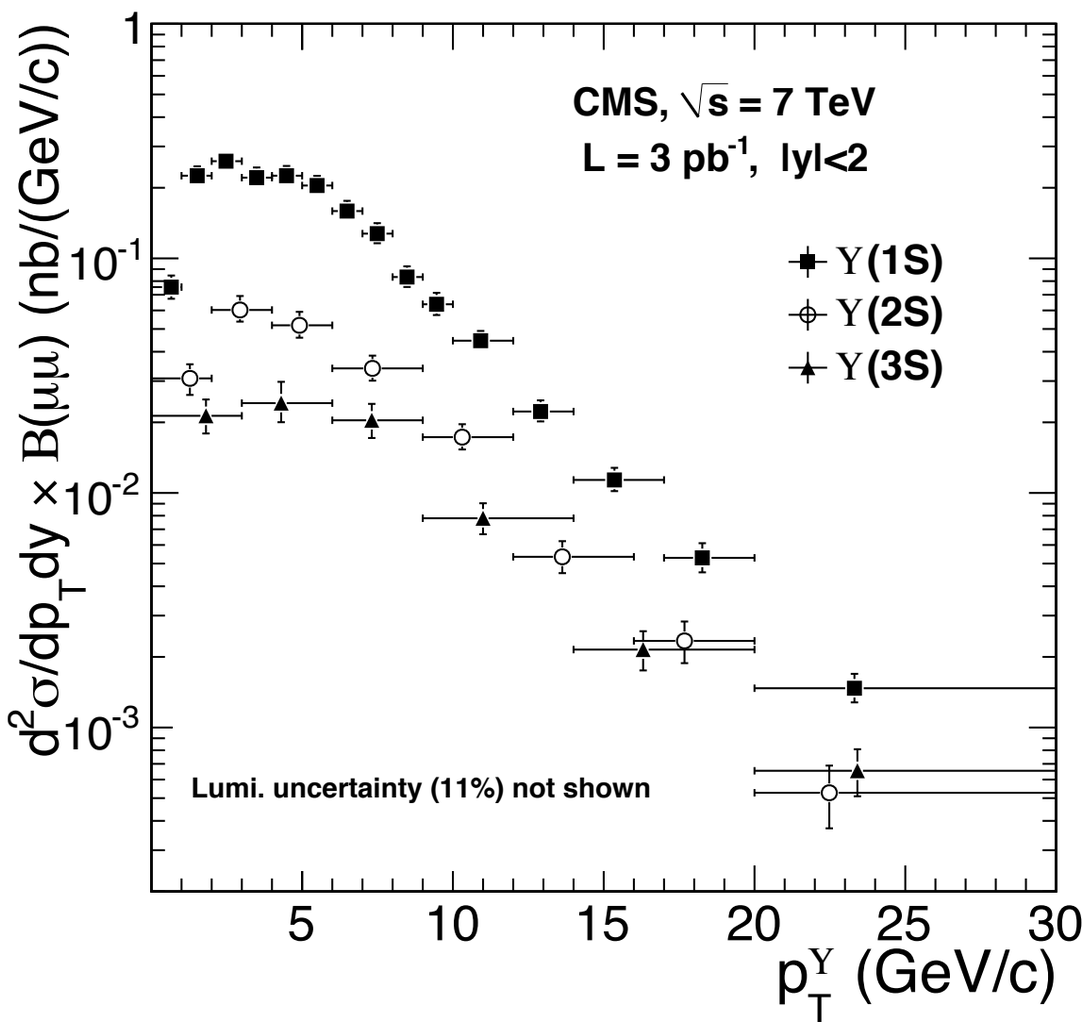


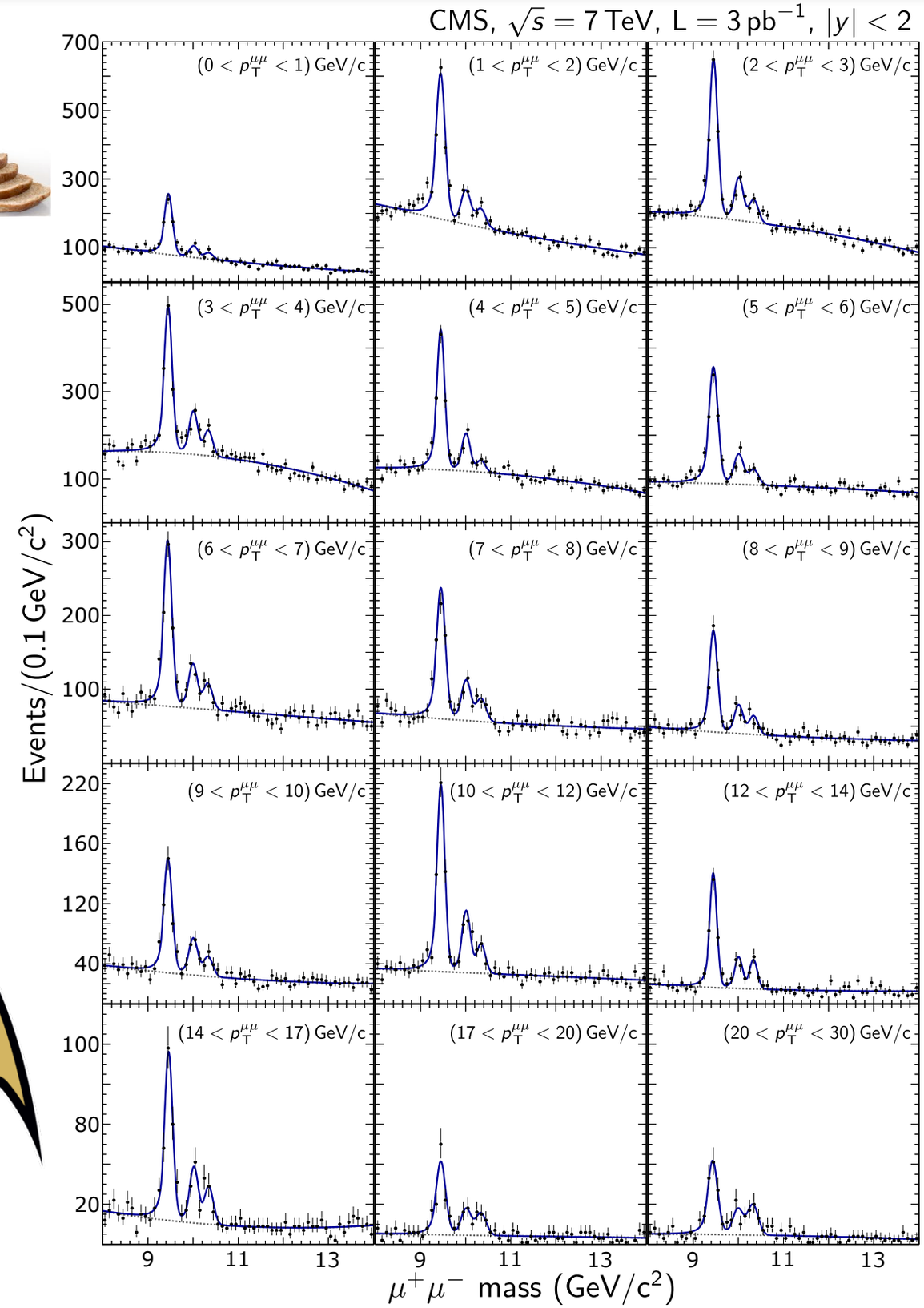


- Good low p_T tracking, can reconstruct resonances down to zero p_T
- PYTHIA doesn't model strange particle production rate or p_T spectrum very well??

Speaking of resonances...

Excellent resolution of tracker allows for good separation of ϒ resonances, even at large η, p_T(ϒ)

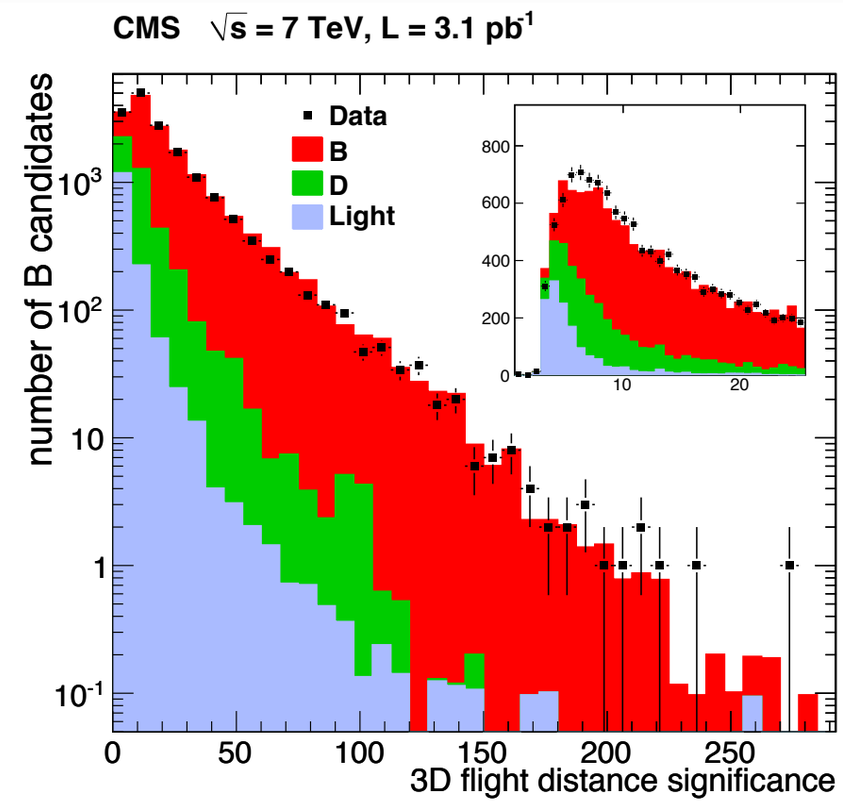


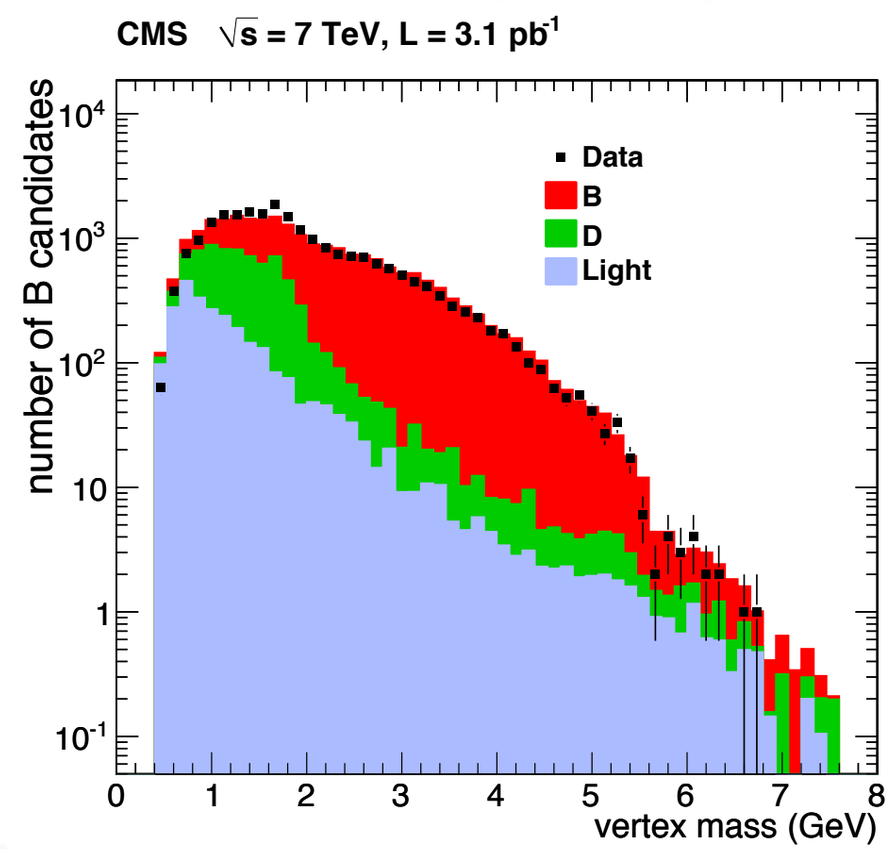


$B\bar{B}$ angular correlations

- Physics: test perturbative QCD
- Technology: test of resolving closely-spaced secondary vertices
  - Want to find two B-hadron vertices inside one jet

  - Need to separate sequential $B \rightarrow D$ from quasi-collinear B's!
- Use iterative secondary vertex finder, relies on good tracking
  - Can reconstruct B hadron mass
- Resolution on ΔR (0.02) much smaller than bin width (0.4)
- Biggest uncertainties are MC statistics, JES, B p_T spectrum

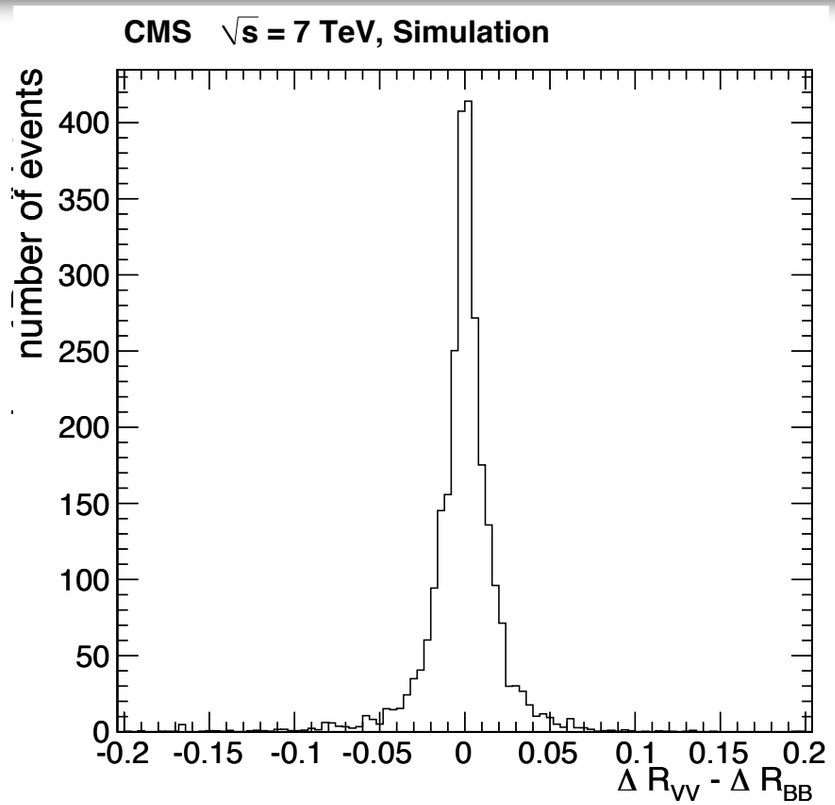


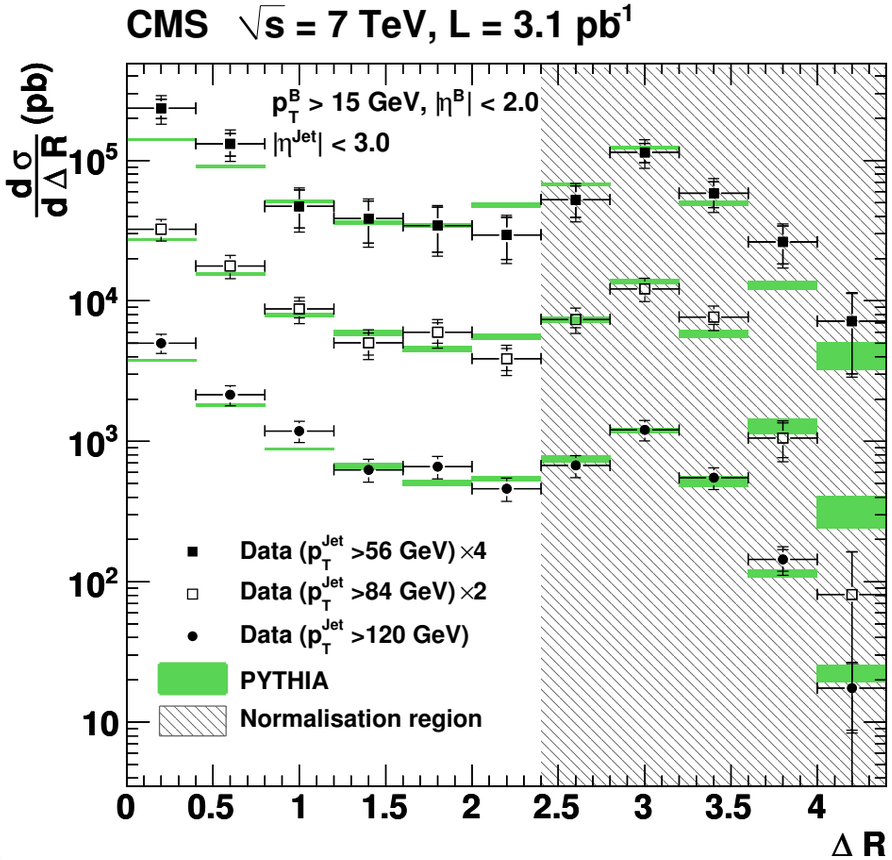


$B\bar{B}$ angular correlations

- Physics: test perturbative QCD
- Technology: test of resolving closely-spaced secondary vertices
  - Want to find two B-hadron vertices inside one jet

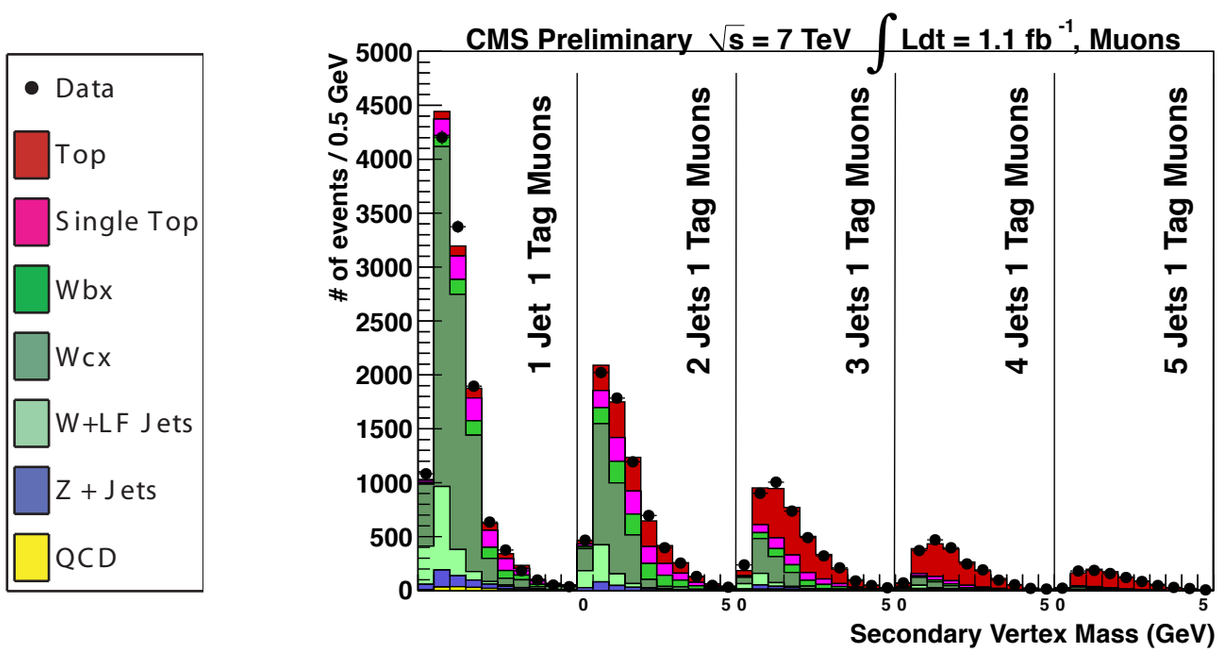
  - Need to separate sequential $B \rightarrow D$ from quasi-collinear B's!
- Use iterative secondary vertex finder, relies on good tracking
  - Can reconstruct B hadron mass
- Resolution on ΔR (0.02) much smaller than bin width (0.4)
- Biggest uncertainties are MC statistics, JES, B p_T spectrum

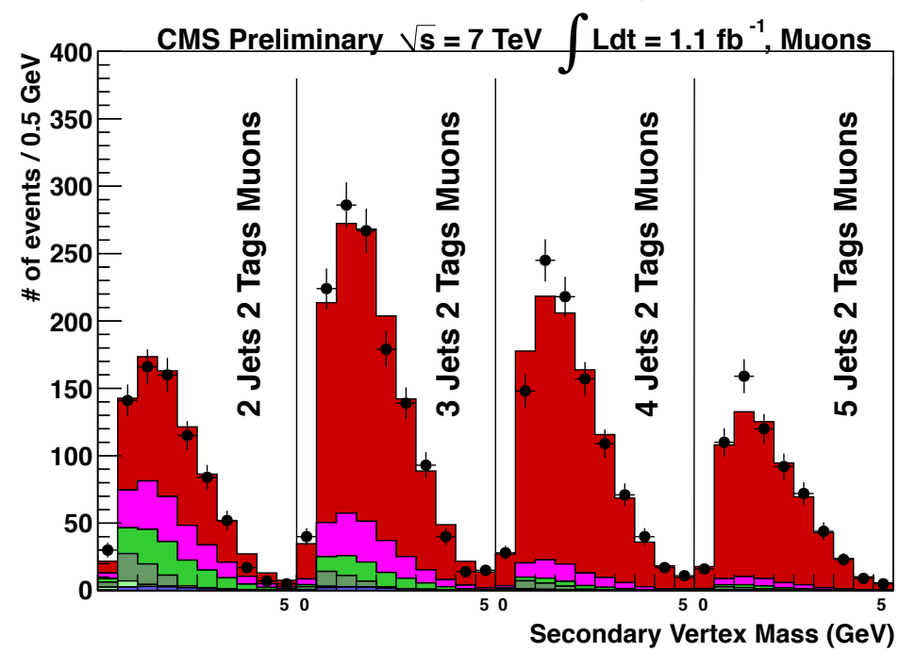




Precise $t\bar{t}$ cross sections

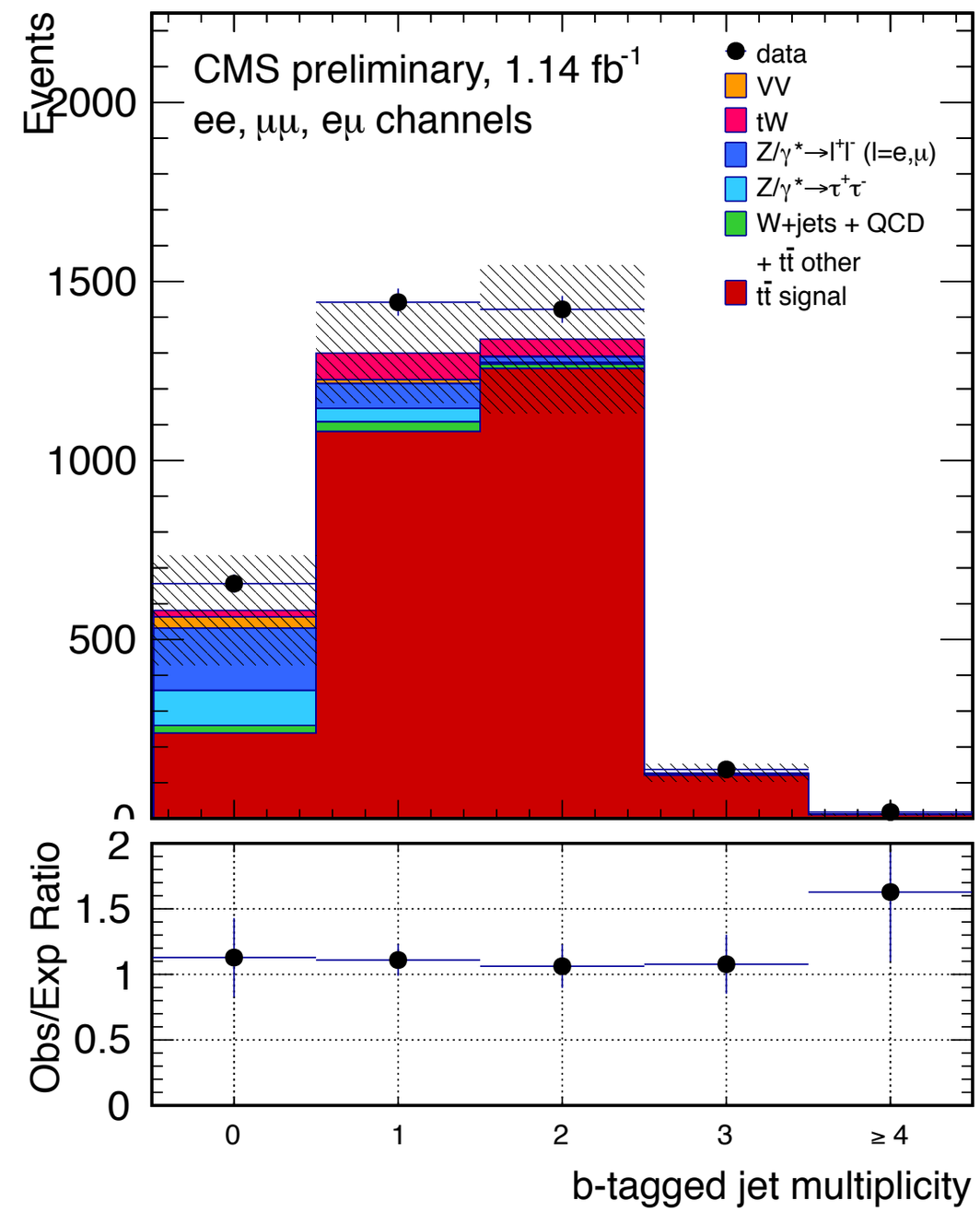
- Lepton plus jets mode: segregate events by number of jets and number of b-tagged jets, fit secondary vertex mass distribution.
  - $t\bar{t}$, W + heavy flavor have varying rates across the samples, different shapes in vertex mass
- Biggest systematic uncertainties are from JES and b-tag efficiency, but they float in fit, ameliorating the effects
- $\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lum.})\ \text{pb}$





Precise $t\bar{t}$ cross sections

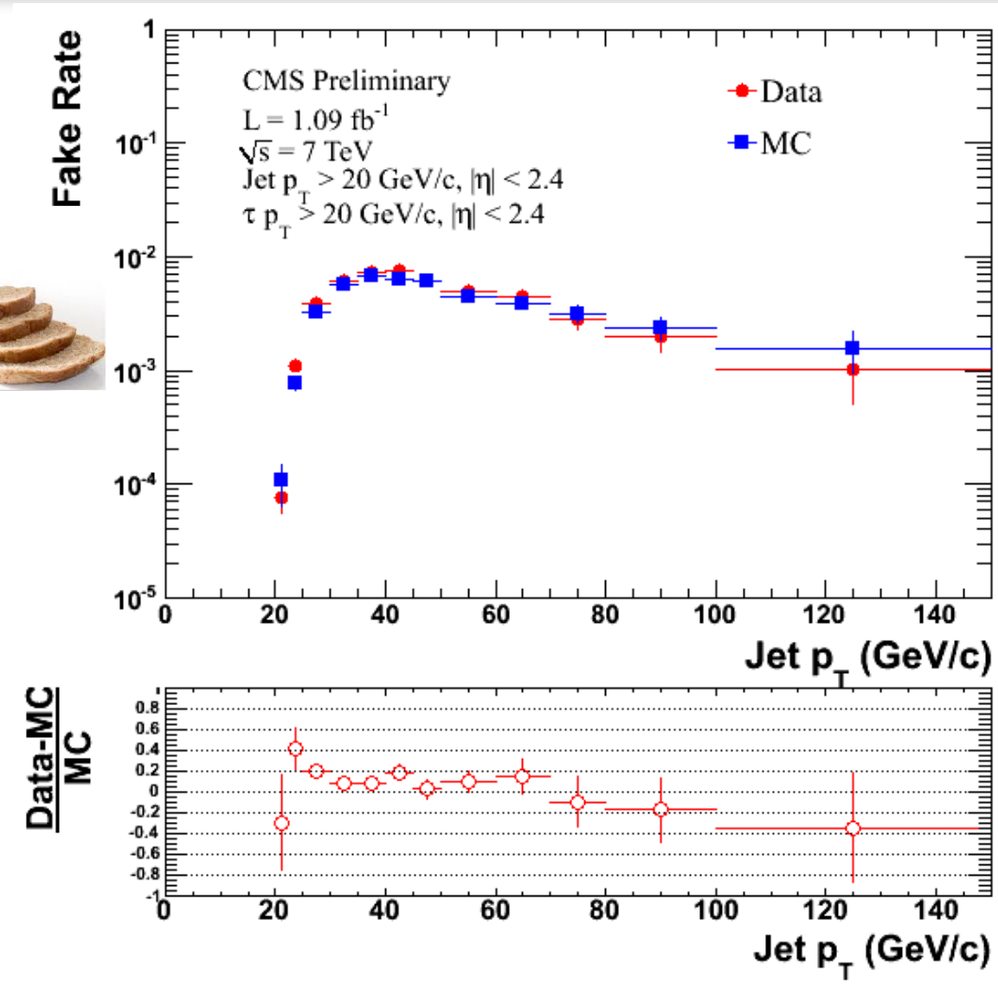
- Even dileptons have statistics to burn! Require that one jet be b-tagged, veto Z window for ee,μμ
- Drell-Yan to ll, QCD, W+jets backgrounds estimated from data
- Biggest uncertainties from efficiencies, b-tagging, pileup
- About 3000 dilepton candidates, about 90% pure samples

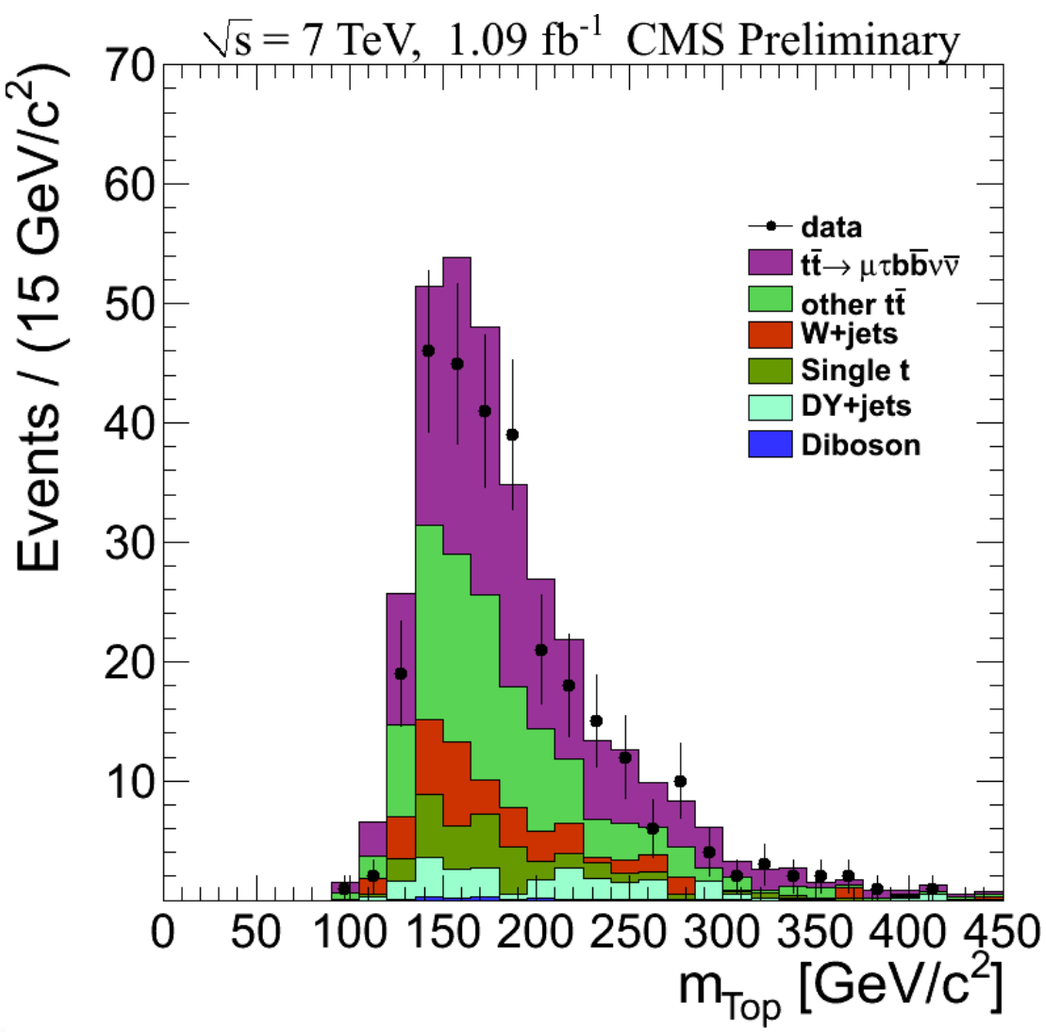


$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

Harder $t\bar{t}$ cross sections: μτ

τ reconstructed from individual hadrons, in both 1- and 3-prong modes. Require b tag, do kinematic fit to estimate top mass



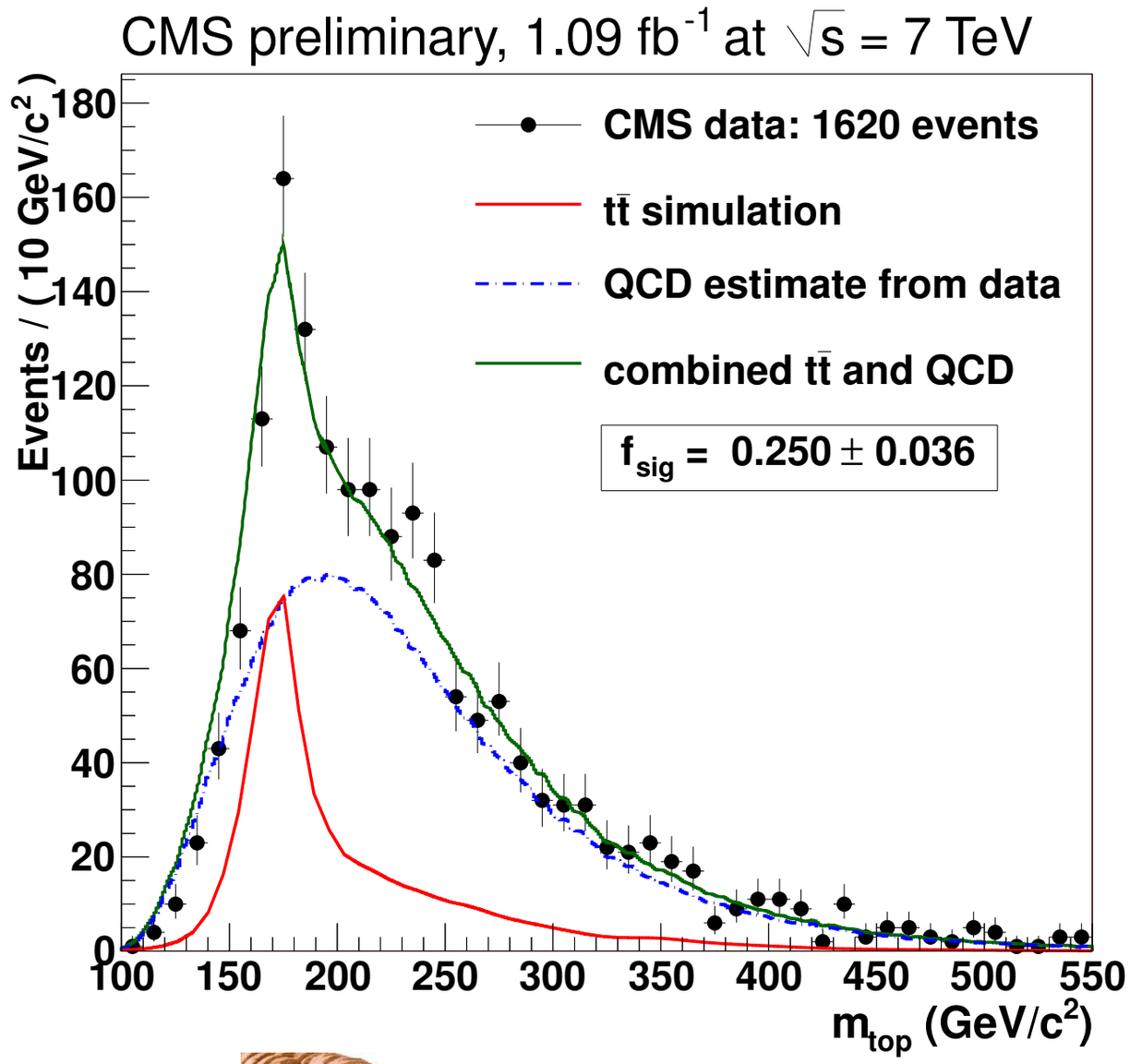


τ fake rates determined from data, matches up well with MC. Biggest systematics from fake rates and τ ID efficiency.

$$\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.})\ \text{pb}$$

Harder $t\bar{t}$ cross sections: hadronic

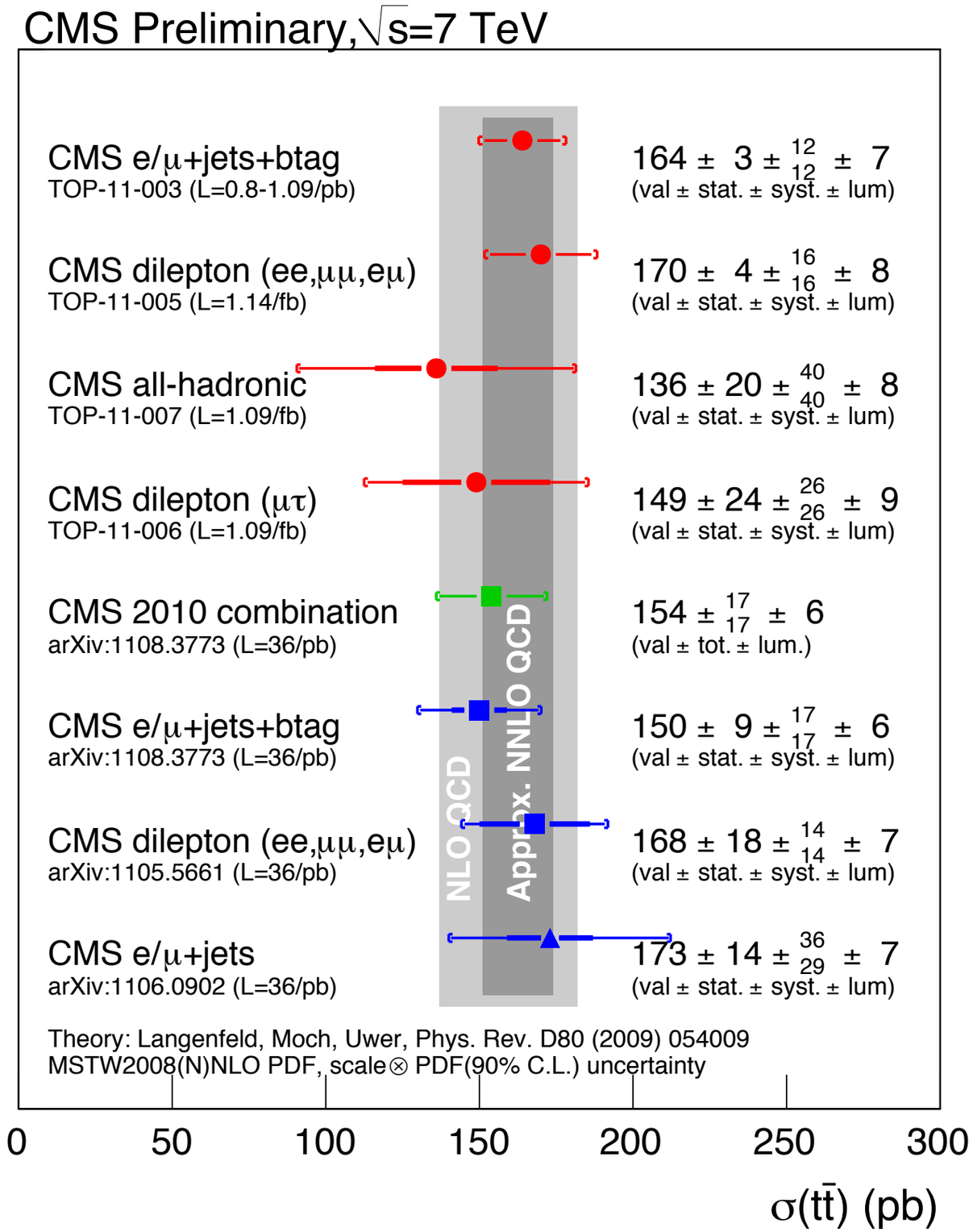
- Huge backgrounds to this 6-jet signal
  - Cut hard on jet p_T's, require two jets to be b-tagged
  - Do a kinematic fit to reconstruct top mass
- Use 0-tag events as background model, with suitable reweighting of kinematic distributions
- Biggest uncertainties from b tagging, JES, background model



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

$t\bar{t}$ cross section summary

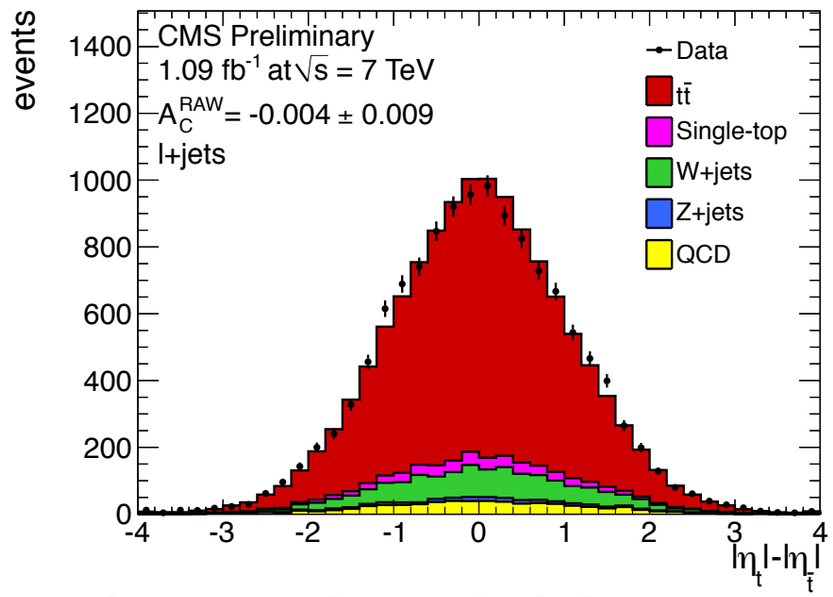
- Measured cross sections in agreement with each other and with QCD predictions
  - This cross section is only about 7 pb at the Tevatron!
- All measurements are now systematics limited by far
- Successful cross section measurements with pure samples are the first step towards examining top production and properties in detail

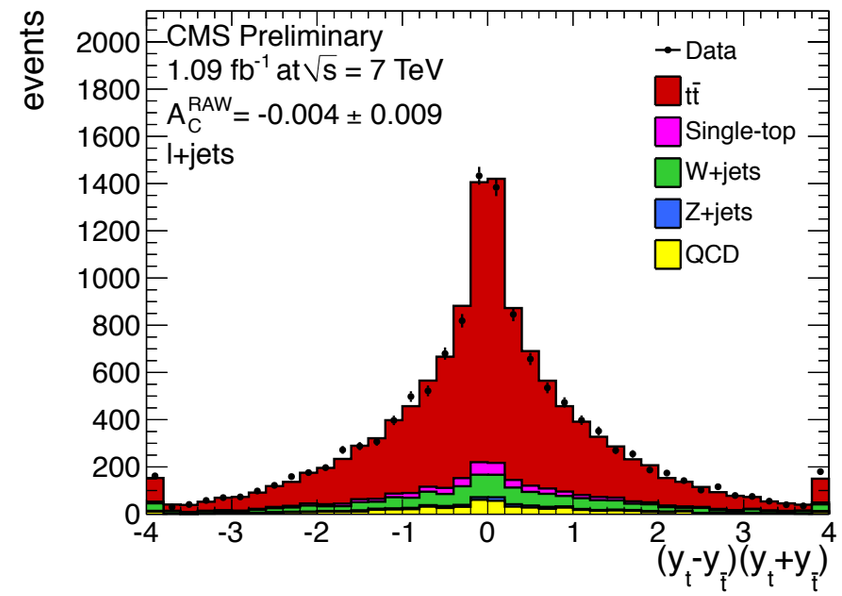


$t\bar{t}$ charge asymmetry

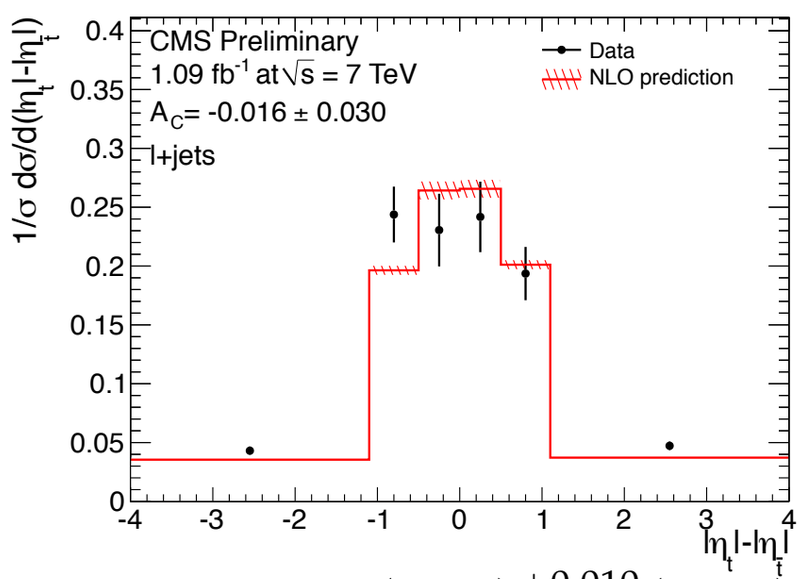
- Studied at Tevatron as forward-backward asymmetry in $q\bar{q} \rightarrow t\bar{t}$
  - Currently 3σ discrepancies from SM prediction
  - Unexpected asymmetries = near a production resonance?
- At the LHC, $q\bar{q} \rightarrow t\bar{t}$ produced by annihilation of valence quarks and sea antiquarks, which have different momentum distributions
  - Rapidity of top is broader than rapidity of antitop
  - Looking for an asymmetry in $\Delta(|\eta|) = |\eta_t| - |\eta_{\bar{t}}|$ or $\Delta(y^2) = (y_t - y_{\bar{t}}) \cdot (y_t + y_{\bar{t}})$
  - Expected value is tiny, ~(1.0 ± 0.1)%
- Use lepton + jets events with b-tag
  - Fit of kinematic variable with templates for signal content
  - Reconstruct top directions with kinematic fit, resolve neutrino ambiguities through a likelihood that picks most likely combination of jet-parton assignments

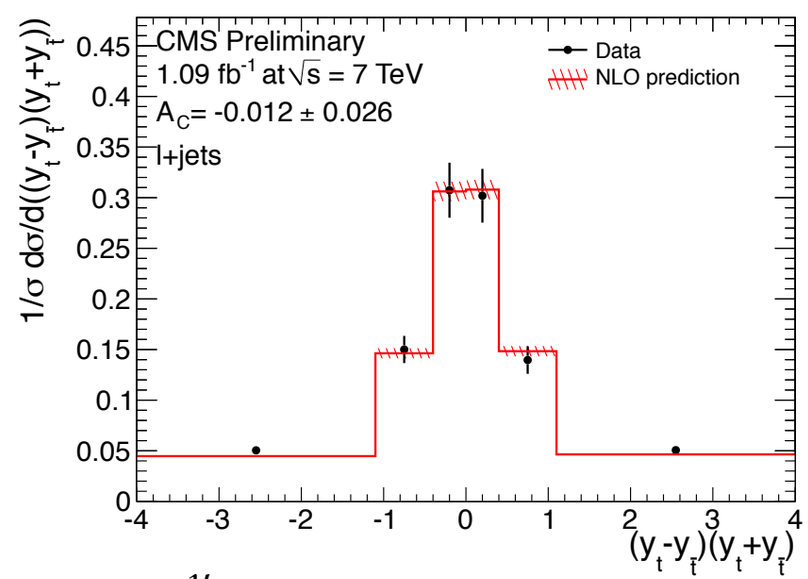
$t\bar{t}$ charge asymmetry





- Do a regularized unfolding to get true asymmetry
- Results consistent with expectations, large uncertainties
  - No dependence on $M_{t\bar{t}}$ expected or observed





$$A_C^{\eta} = -0.016 \pm 0.030\ (\text{stat.})^{+0.010}_{-0.019}(\text{syst.})$$

$$A_C^{y} = -0.013 \pm 0.026\ (\text{stat.})^{+0.026}_{-0.021}(\text{syst.})$$

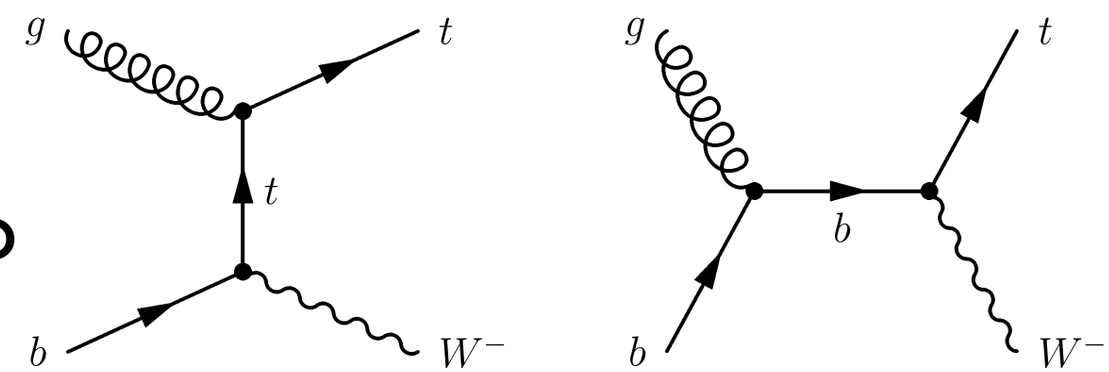
$t\bar{t}$ mass difference

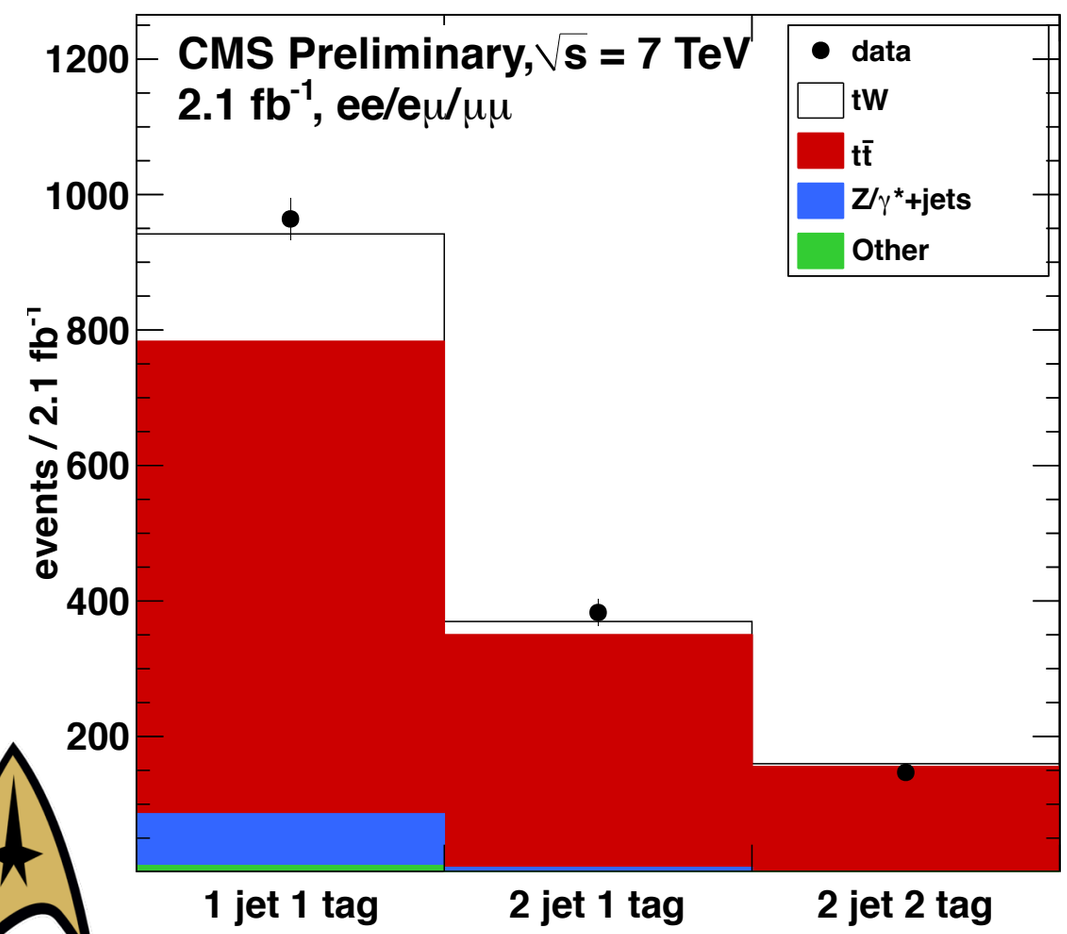
- Test of CPT symmetry with a bare quark
- Use the "ideogram" method:
  - Relatively loose selection of μ + jets events
  - Each event is kinematically reconstructed to determine top mass
  - Incorporate information on number of b-tagged jets, likelihood of correct jet-parton assignment to determine probability that the event is $t\bar{t}$, and to form a per-event likelihood as a function of mass
  - Do separately for μ^+ and μ^-
- Resulting mass difference is $\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$
- Most precise measurement of this quantity yet!

  - Still statistics limited
  - JES uncertainties largely cancel in the mass difference, but be sure no charge-dependent detector response or efficiencies

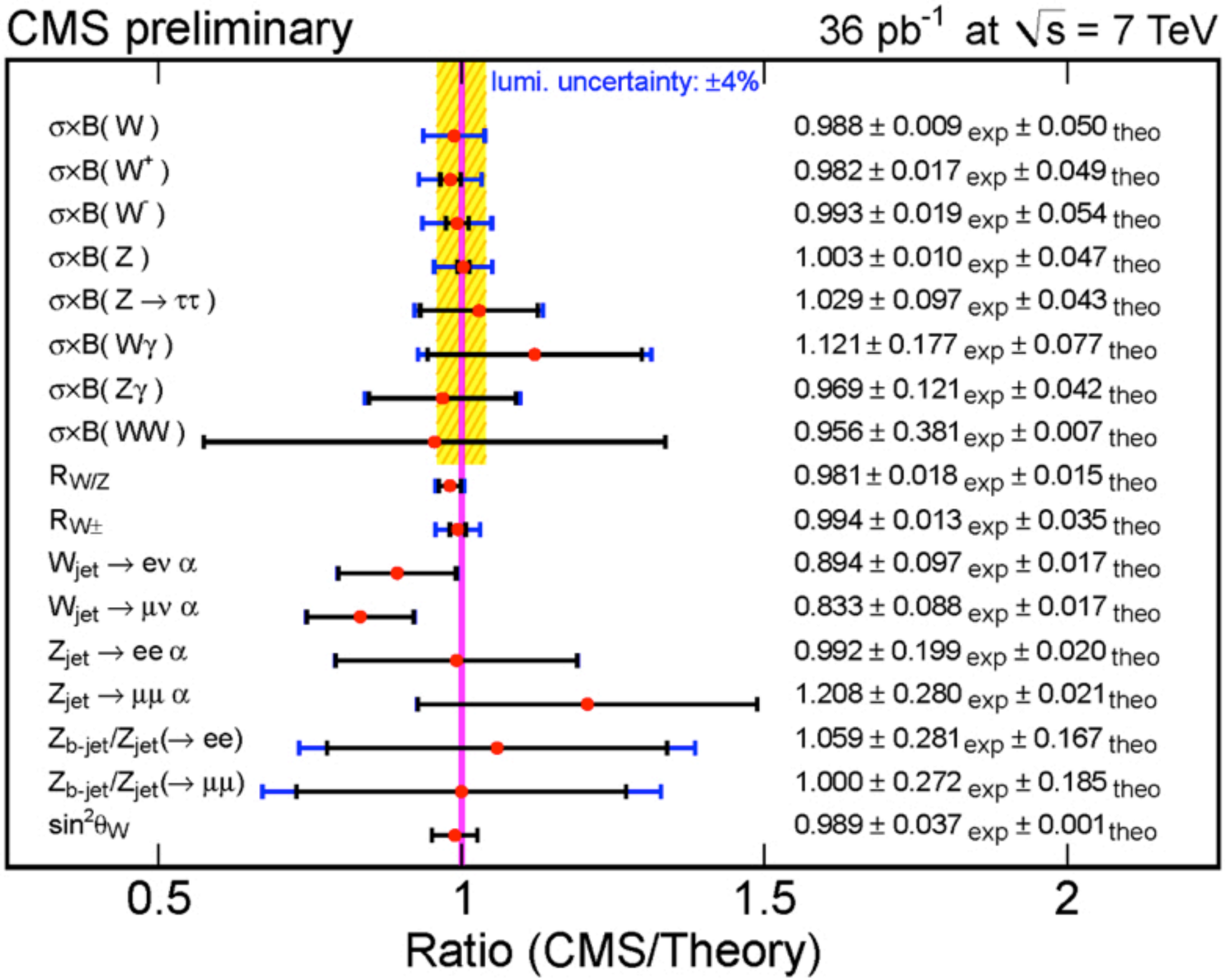
Single top in tW mode

- tW mode is rare at Tevatron, but dominant over s channel at LHC
- Good/bad news: looks like $t\bar{t}$; easy to observe, but much $t\bar{t}$ background
- Look in dileptons with exactly one tagged jet, constrain $t\bar{t}$ there by extrapolating from $t\bar{t}$-dominated control regions.
- Expect to observe signal with 1.8 ± 0.9 σ significance; actually observe 2.7 σ significance
  - Measured cross section higher than but consistent with SM prediction



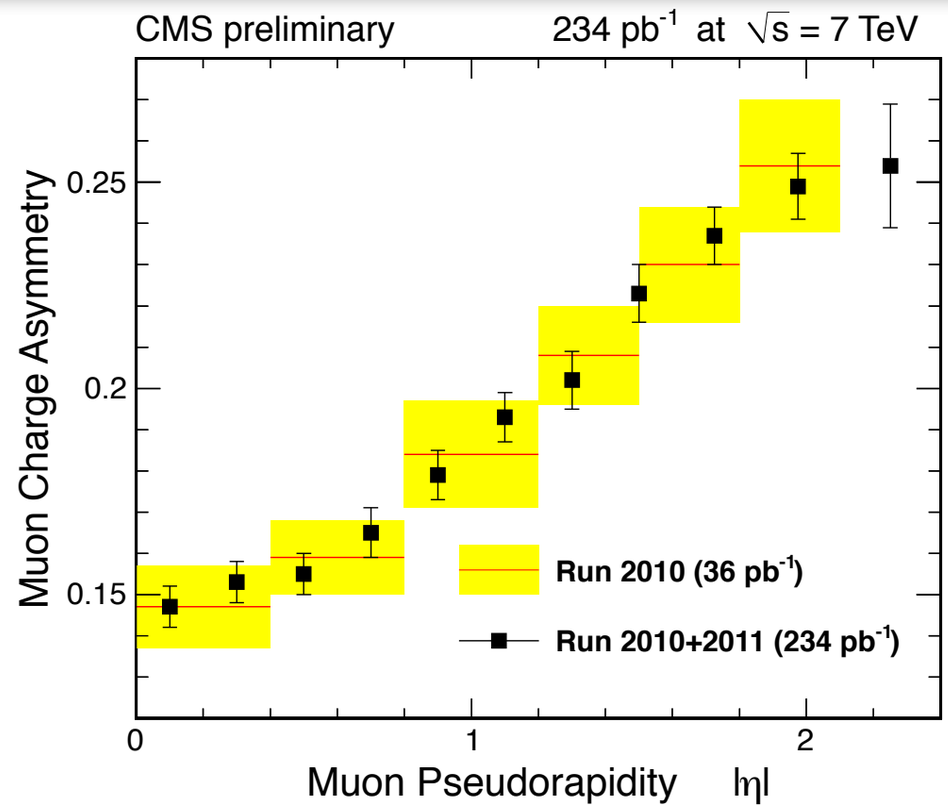


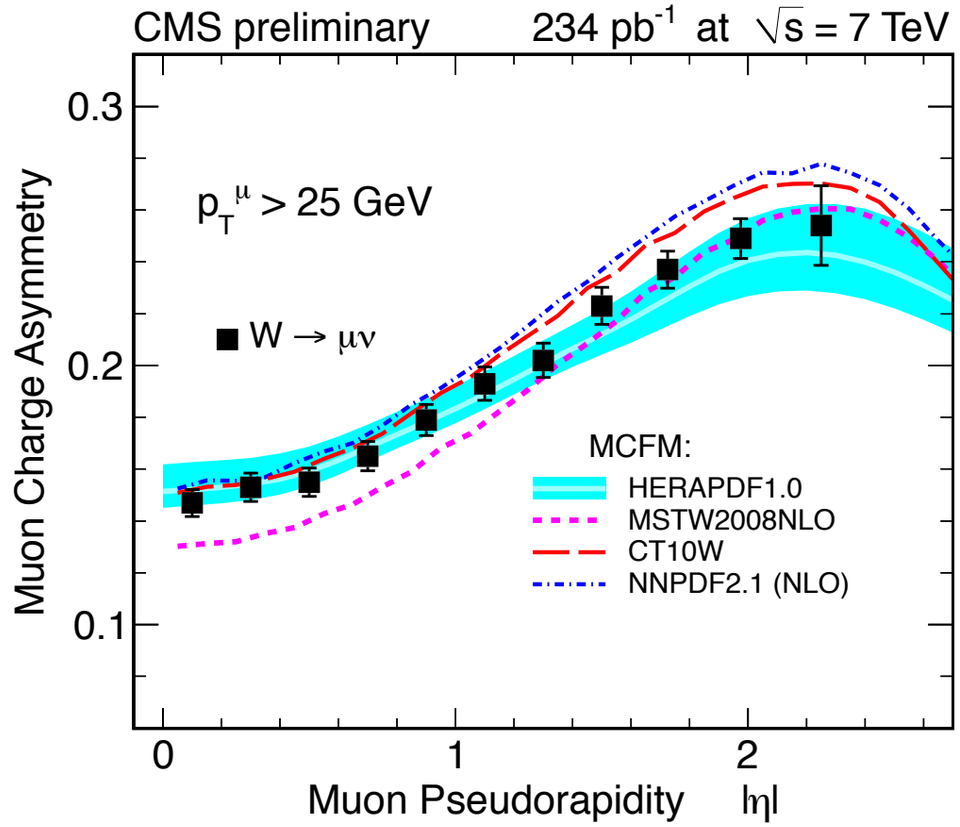
Inclusive cross sections are passe?



W charge asymmetry

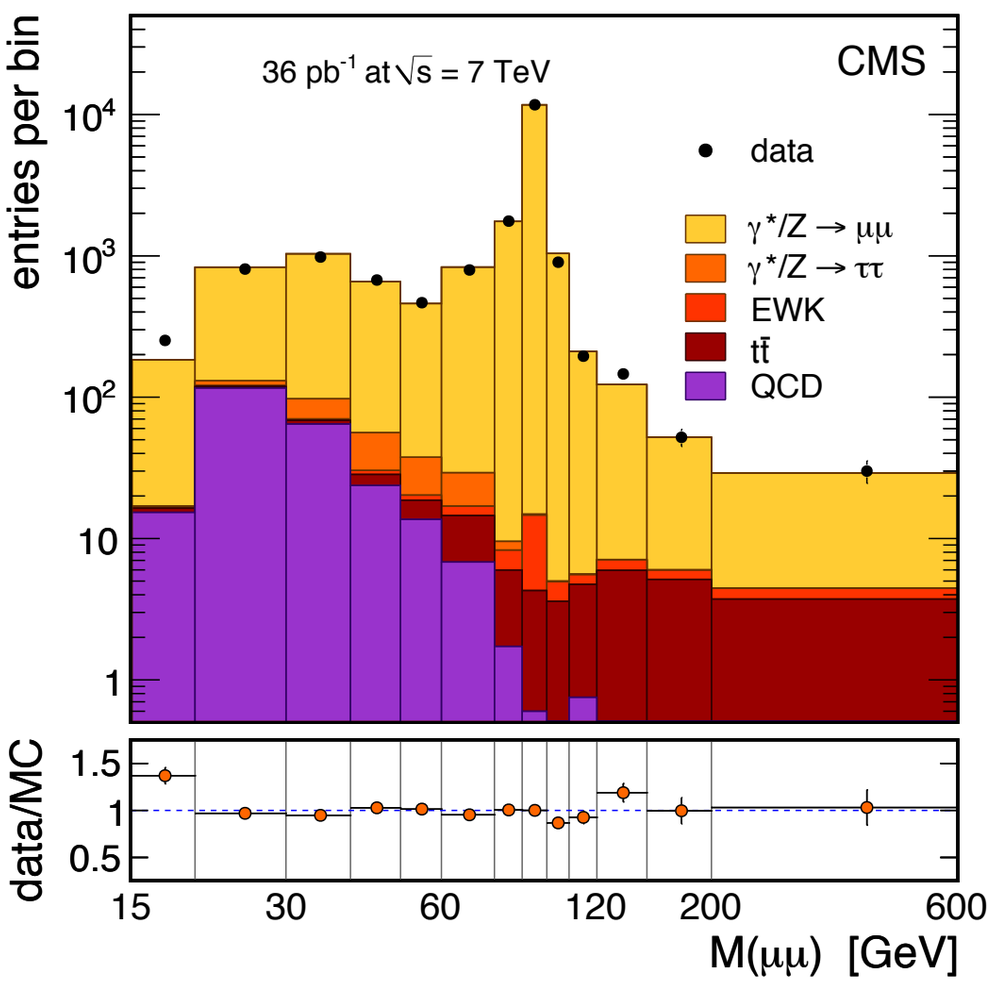
- More W^+ than W^- because 2 valence u quarks, 1 valence d quark in proton
- Charge asymmetry as function of rapidity constrains PDFs at small x
- Be careful about biases in efficiencies, momentum scale between charges
- Improved over previous result by more data, better tracker alignment
- Main systematics from signal and background estimate, efficiency ratio
- Precise enough to discriminate between PDF sets

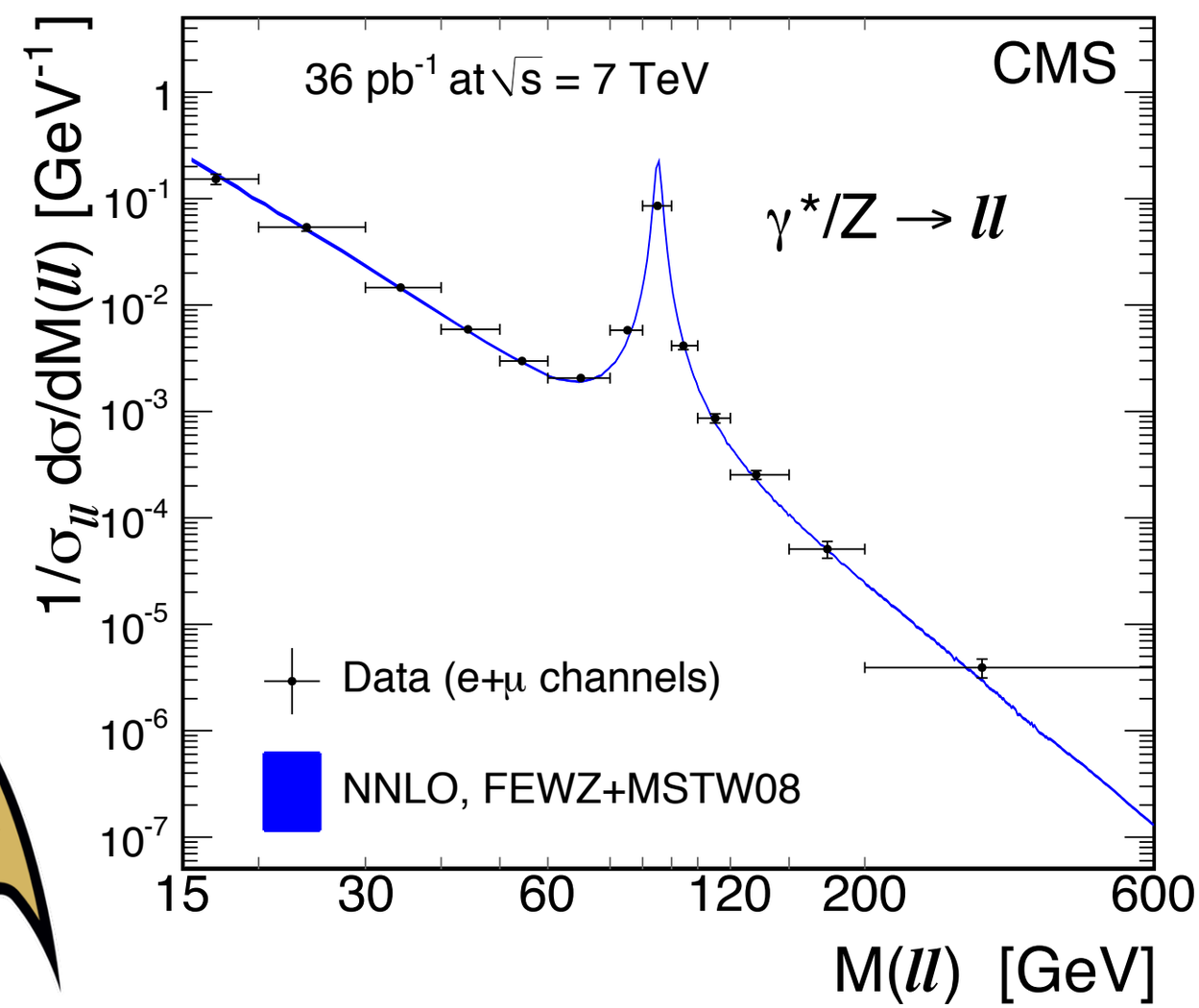




Drell-Yan differential cross section

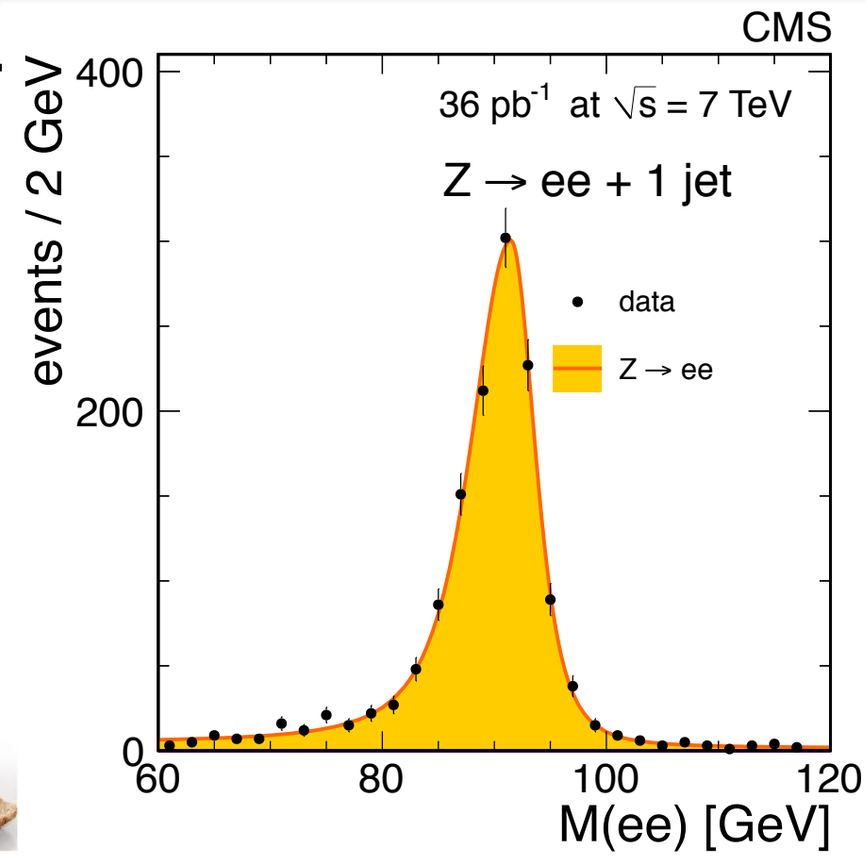
- Cross sections over $15 < M_{ll} < 600$ GeV, or $0.0003 < x < 0.633$
- Normalize measurement to cross section in Z region to reduce lumi, other uncertainties
- Modeling at NNLO required for lowest masses
- Careful attention to FSR effects



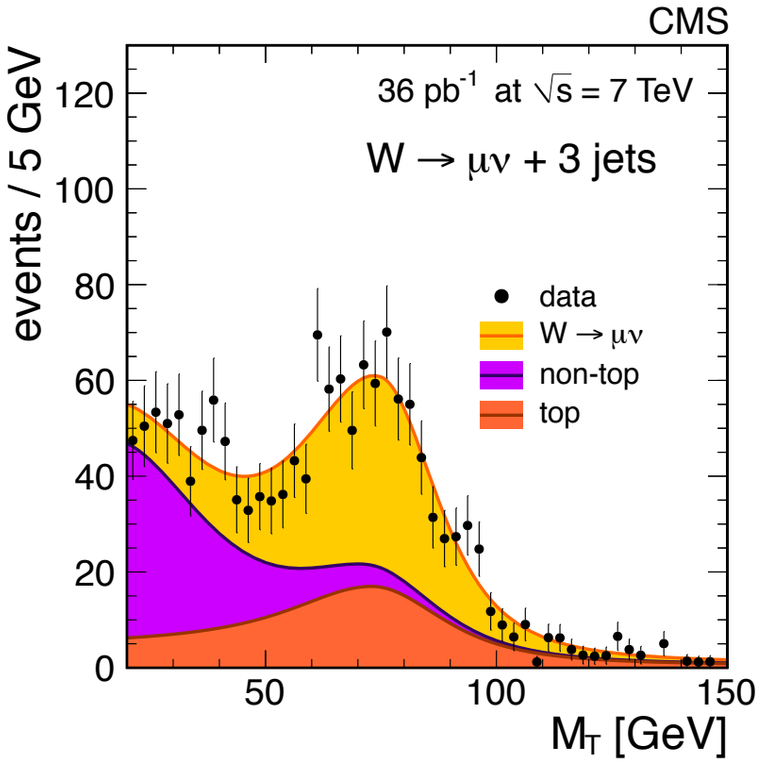


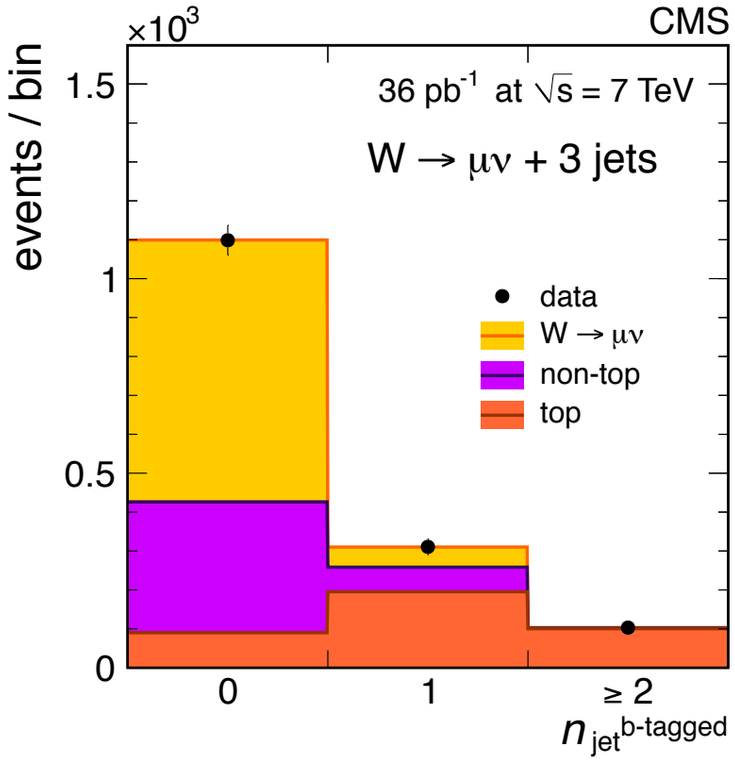
W/Z + jets

- Jets are anti-k_T, R = 0.5, E_T > 30, |η| < 2.4
  - Quote results within this acceptance
  - Pileup, JES uncertainties can lead to promotion of jets, changing multiplicity
- In each multiplicity bin, do template fits to extract boson yields
- Z is essentially background-free



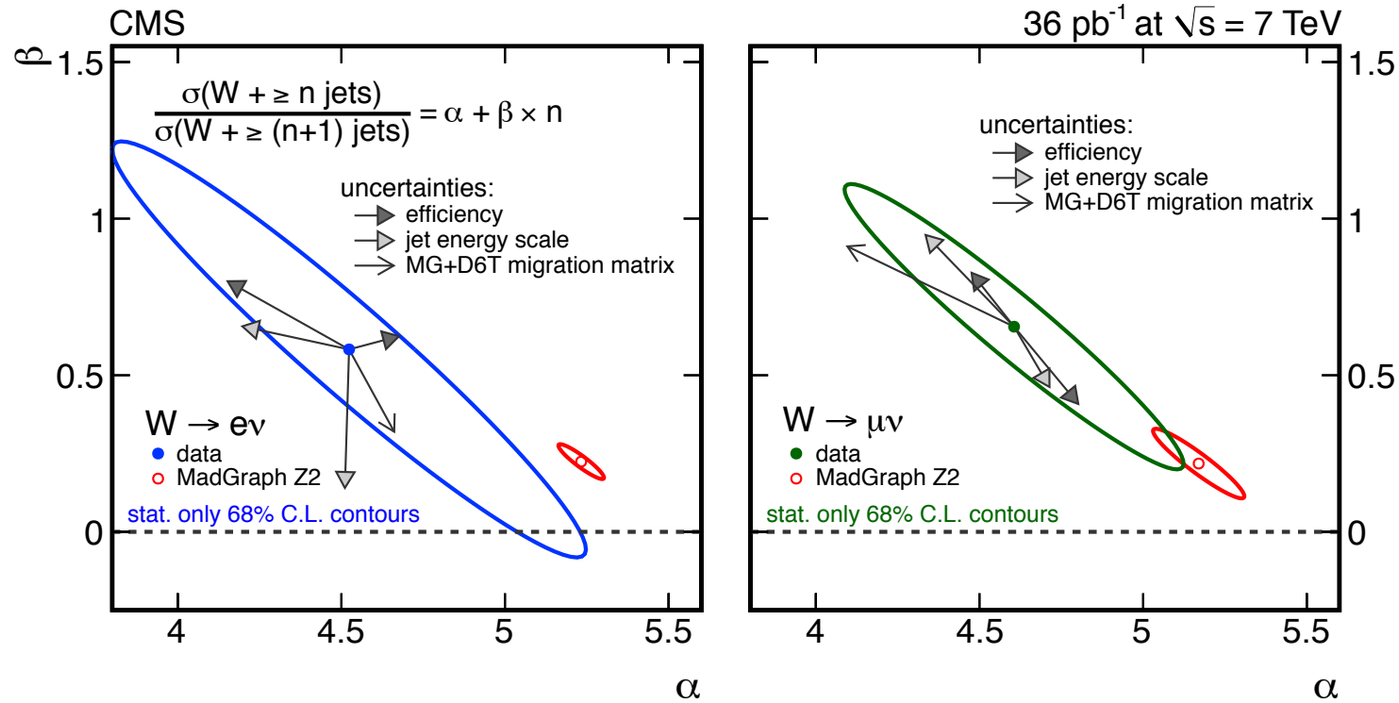
- For W, handle top background by simultaneous fit with b-tag multiplicity distribution
- Unfold via singular value decomposition

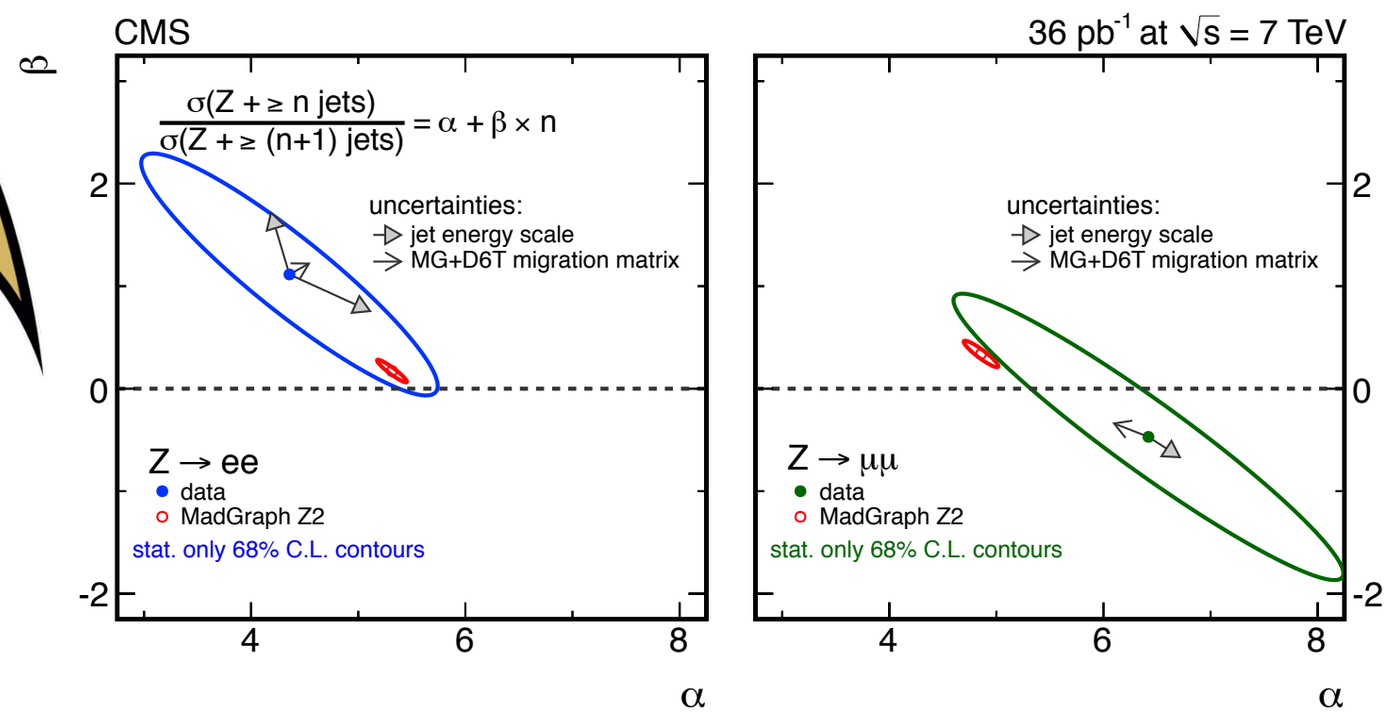




W/Z + jets

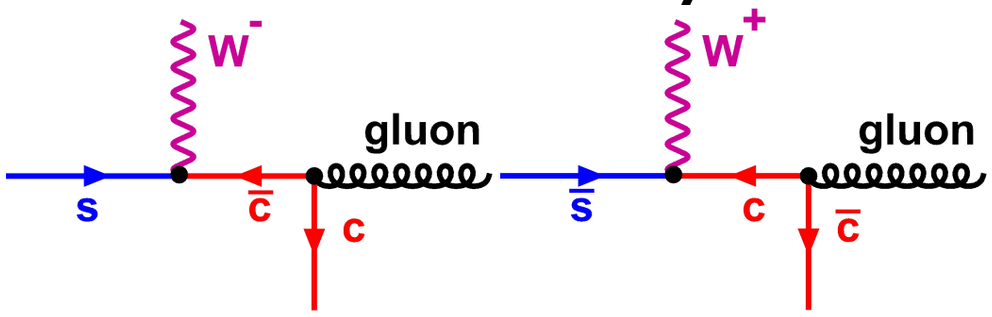
- W yield statistics limited at 4 jets, Z yield at 3 jets
- JES dominates systematics, and lepton ID at large n
- Lots to measure!
  - σ(V+≥n jets)/σ(V)
  - W+n jets charge asymmetry
  - Berends-Giele scaling
- Results consistent with matrix-element calculations, not so much with parton showers only





W+charm production

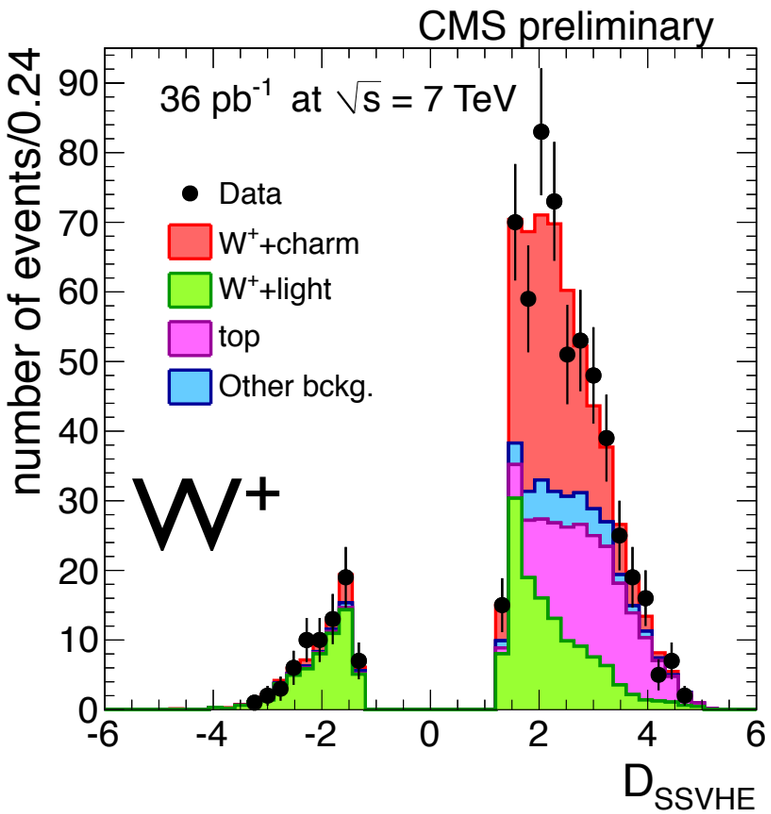
- Wc production is mostly from

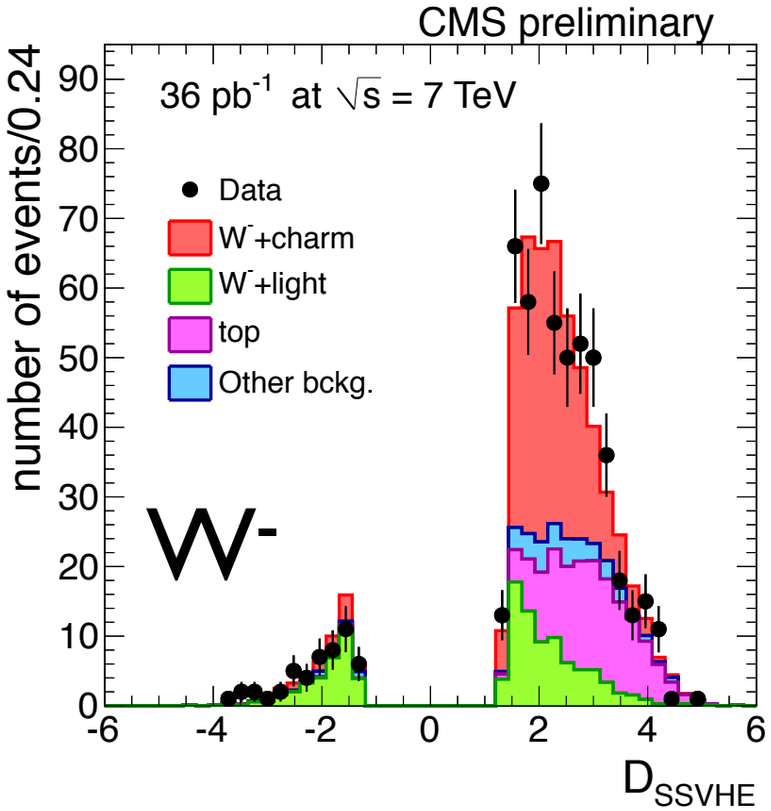


- Wb is largely suppressed, so charm jets can be identified with secondary vertices
- Fit tag discriminant with MC templates for processes; top verified in control samples
- Measure W^+c/W^-c and Wc/W+jets
  - Many systematics cancel in ratios, vertex reconstruction efficiency dominates latter

$$R_c^{\pm} = 0.92 \pm 0.19\ (stat.) \pm 0.04\ (syst.)$$
$$R_c = 0.143 \pm 0.015\ (stat.) \pm 0.024\ (syst.)$$

- Consistent with predictions





WW, WZ, ZZ

- Test trilinear gauge couplings, backgrounds for searches
- Measure in multiple multi-lepton modes:
  - WW: ee, μμ, eμ
  - WZ: eee, eeμ, μμe, μμμ
  - ZZ: ee, μμ, ττ
  - Analyses emphasize data-driven background estimates, including using orthogonal control samples to normalize top contribution

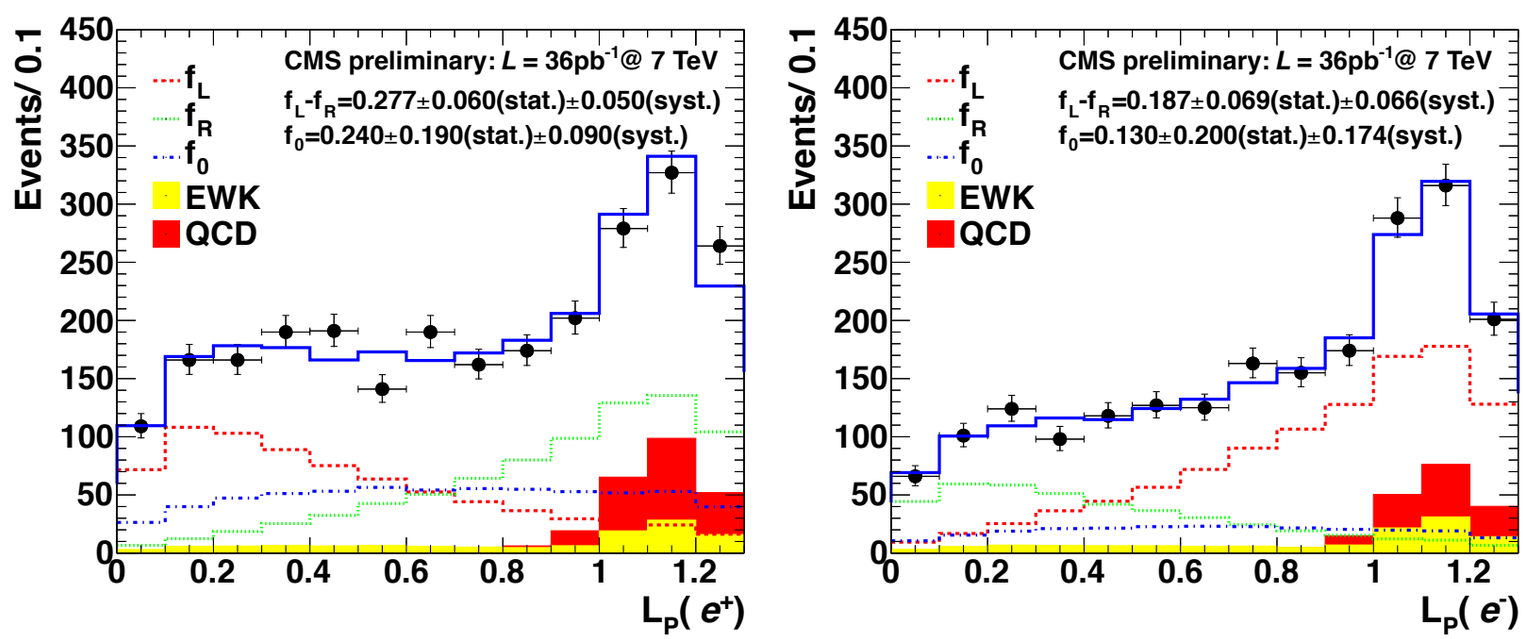
	Candidates	Background	σ (pb)	SM pred (pb)
WW	626	~202	55.3 ± 8.3	43.0 ± 2.0
WZ	75	~8	17.0 ± 2.8	19.8 ± 0.1
ZZ	9	~1	3.8 ±1.5	6.4 ± 0.6

High-p_T W polarization

- Dominance of quark-gluon initial states plus V-A leads to significant transverse polarization of high-p_T W's
- Reflected in helicity angle (cos θ*) distribution
- Can't determine p(W) precisely due to ambiguity of neutrino direction, so measure the correlated

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

- Require $p_T(W) > 50$ GeV to optimize correlation and statistics
- Biggest uncertainties from recoil energy scale, resolution

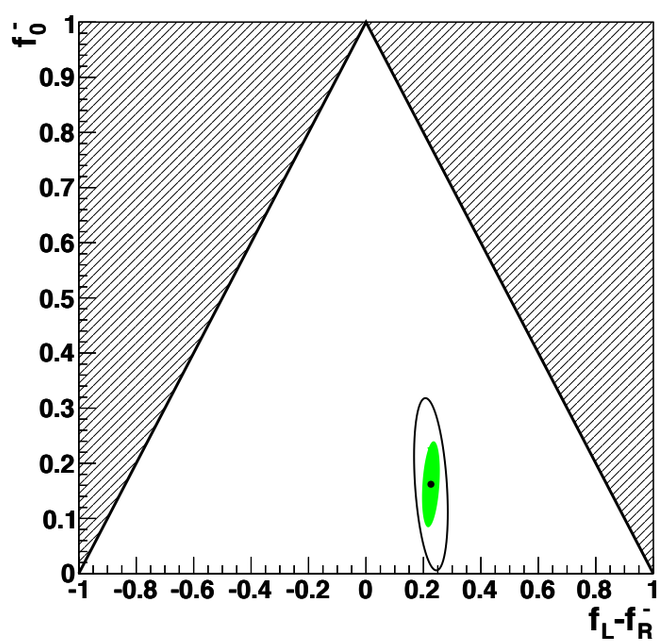


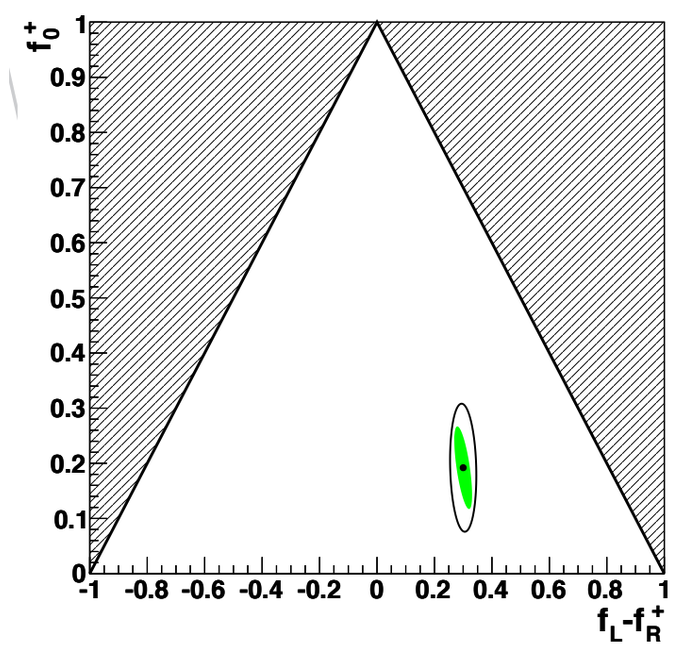
High-p_T W polarization

- Dominance of quark-gluon initial states plus V-A leads to significant transverse polarization of high-p_T W's
- Reflected in helicity angle (cos θ*) distribution
- Can't determine p(W) precisely due to ambiguity of neutrino direction, so measure the correlated

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

- Require $p_T(W) > 50$ GeV to optimize correlation and statistics
- Biggest uncertainties from recoil energy scale, resolution





$\sin^2\theta_W$ in Drell-Yan

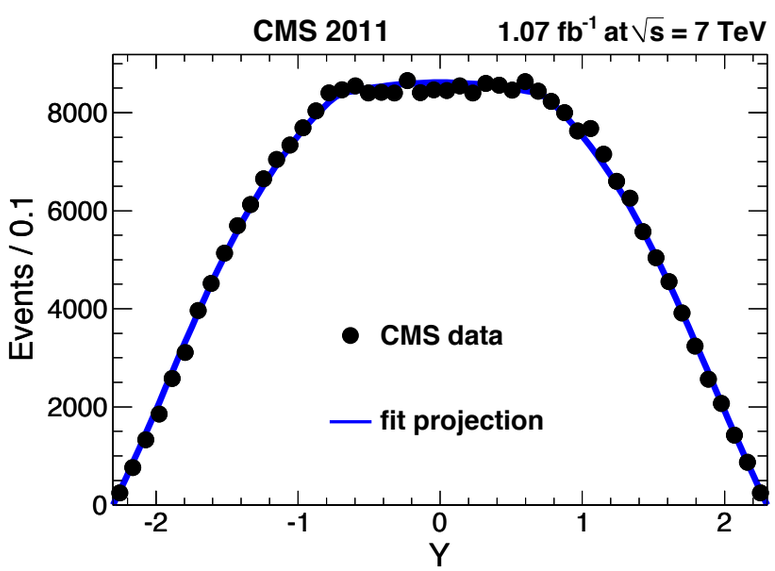
- $\sin^2\theta_W$ measured to 0.1% at Z factories, 0.23116 ± 0.00013
- Usually measure through forward-backward asymmetry of leptons with respect to production axis
  - But in pp collisions, hard to know production axis
  - Only on a statistical basis, based on boost of lepton pair
- Use a per-event likelihood -- a matrix-element approach
  - Write cross section in terms of fundamental interaction, incorporate factors for PDFs and detector effects
  - Each event has a likelihood as a function of $\sin^2\theta_W$
    - Only free physical parameter, but could expand to fermion couplings, PDF parameters, etc.
  - Some parameters of detector resolution also float in maximum likelihood fit, allowing data to determine energy scale
- Measure in $Z \rightarrow \mu\mu$ sample, 297364 events, 0.05% background (!)

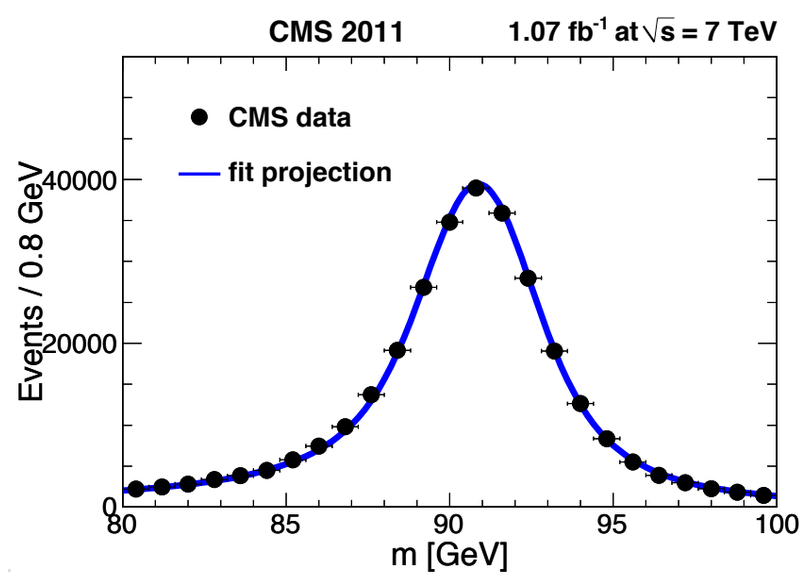
$\sin^2\theta_W$ in Drell-Yan

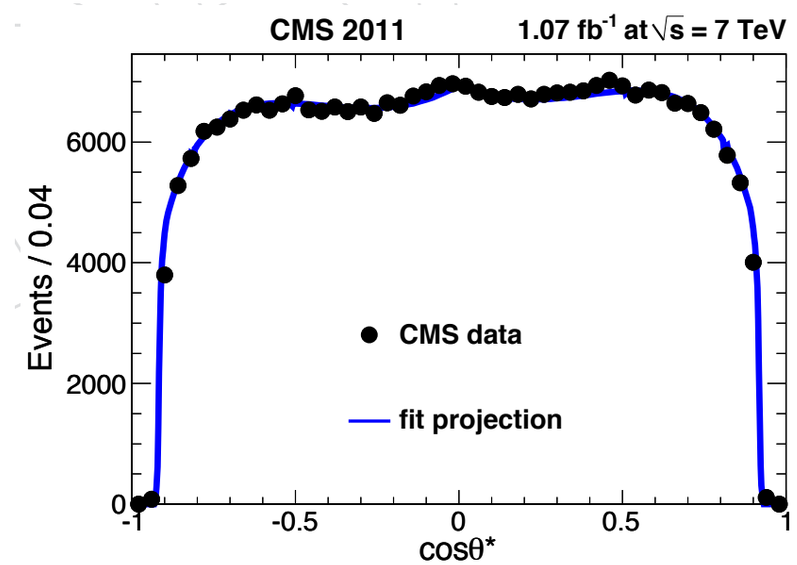
- Simultaneous fit of rapidity, pair mass and decay angle
- Improvements could come with better PDF's, NLO models
- Alignment in good shape
- Great potential for this technique in other contexts

source	correction	uncertainty
PDF	–	±0.0013
FSR	–	±0.0011
LO model (EWK)	–	±0.0002
LO model (QCD)	+0.0012	±0.0012
resolution and alignment	+0.0007	±0.0013
efficiency and acceptance	–	±0.0003
background	–	±0.0001
total	+0.0019	±0.0025

$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0020(\text{stat.}) \pm 0.0025(\text{syst.})$$





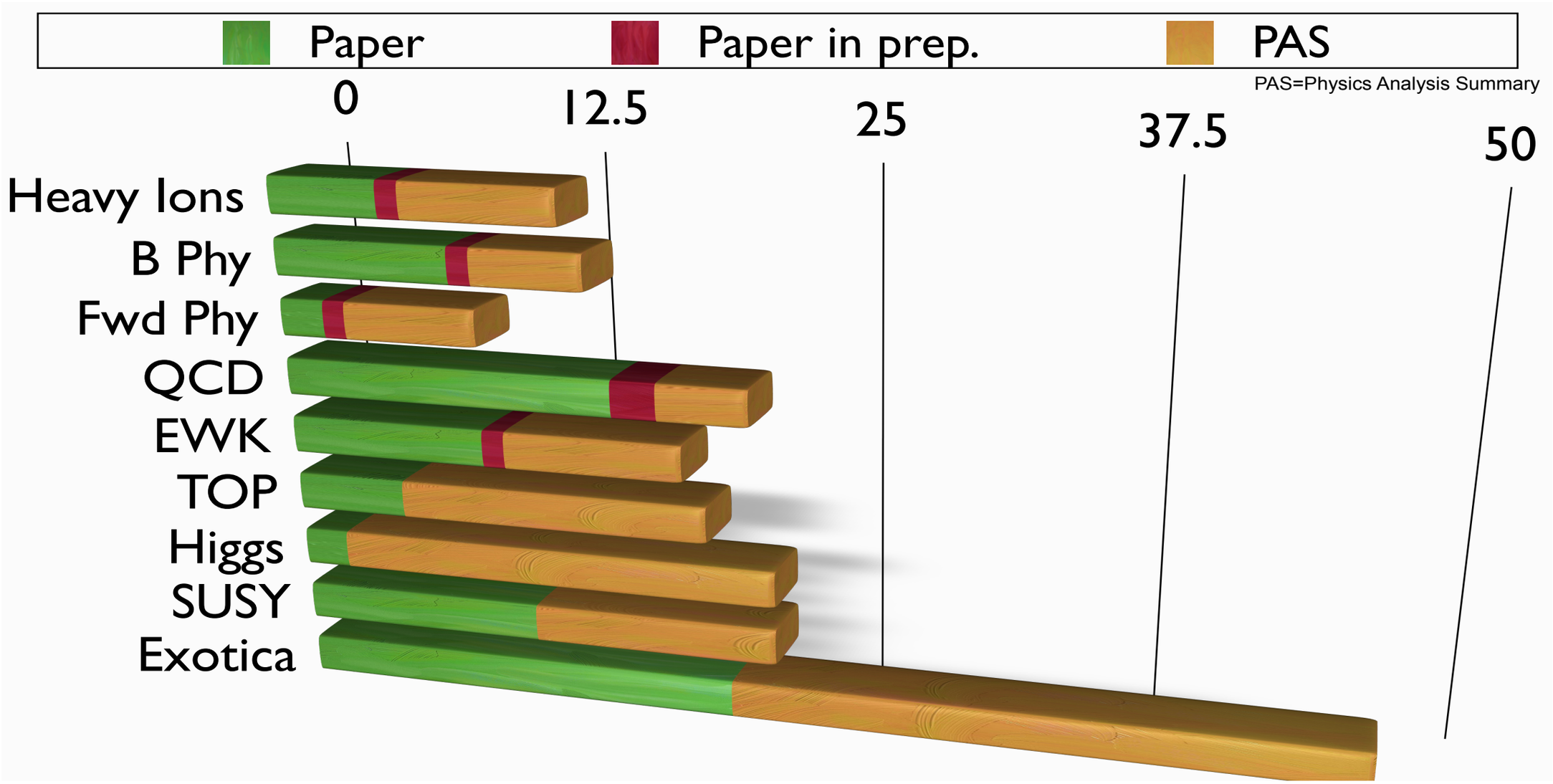


Scorecard

1 14 14

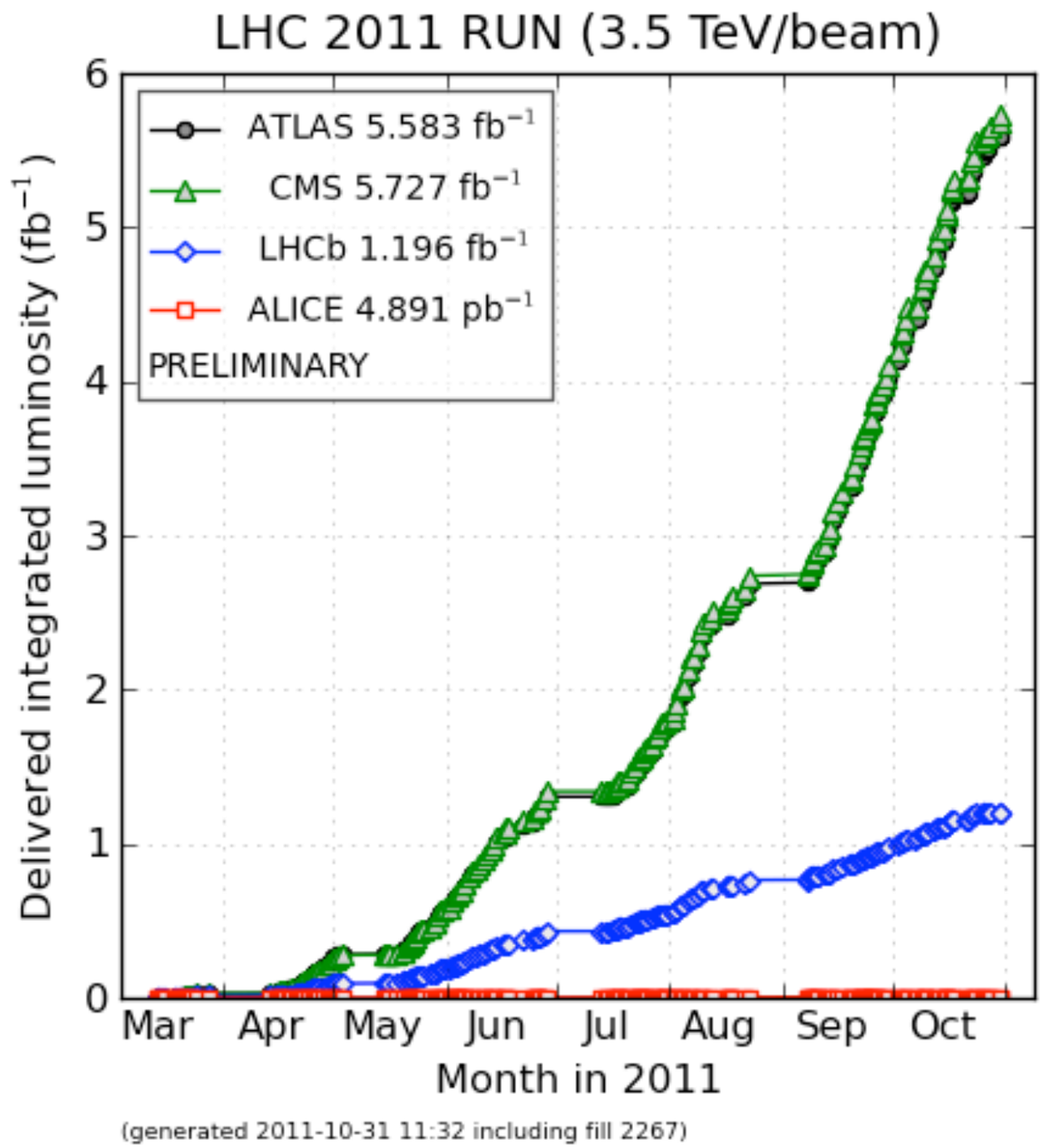
CMS scorecard

- Many standard-model results now in public domain
  - Obviously cannot discuss all in one seminar....
- Many SM measurements do not require lots of data, but are often limited by systematics that require time for proper evaluation



Prospects

- The 2011 proton run ended on Sunday afternoon!
  - LHC delivered 5.74 fb^{-1}
  - CMS recorded 5.21 fb^{-1}
- All analyses shown here will be able to incorporate about four times as much data during the next few months.



Prospects

- Many SM measurements are already systematics limited, but paths towards improvement in many sectors:
  - JES -- hope to improve to the ~1% level, much of current uncertainty due to low statistics in various samples
  - b-tagging -- currently 10% efficiency uncertainty, will be greatly improved through calibration in $t\bar{t}$ events
  - Luminosity -- at 4%, won't get much better
  - PDFs will continue to be constrained with more data
  - Theory calculations at higher order possible?
- However, experimental conditions will become more challenging:
  - LHC might remain at 50 ns spacing next year while reducing β^* and increasing currents: 25 interactions/crossing
  - Will require even more cleverness in event reconstruction, cleaning

The search continues....

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:
  - Many are exploring the new world of 7 TeV pp collisions

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:
  - Many are exploring the new world of 7 TeV pp collisions
  - Some have already reached impressive levels of precision

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:
  - Many are exploring the new world of 7 TeV pp collisions
  - Some have already reached impressive levels of precision
  - And many have established powerful measurement techniques that are effective in the hadron collider environment and can be carried through into searches for new physics

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:
  - Many are exploring the new world of 7 TeV pp collisions
  - Some have already reached impressive levels of precision
  - And many have established powerful measurement techniques that are effective in the hadron collider environment and can be carried through into searches for new physics
- So far, no significant deviations from the SM that we know anywhere within the body of CMS measurements

The search continues....

- CMS has completed a great variety of measurements that test the predictions of the standard model:
  - Many are exploring the new world of 7 TeV pp collisions
  - Some have already reached impressive levels of precision
  - And many have established powerful measurement techniques that are effective in the hadron collider environment and can be carried through into searches for new physics
- So far, no significant deviations from the SM that we know anywhere within the body of CMS measurements
- The search for the standard model will continue -- not until it is found, but until it is lost....

Bibliography

- CMS-FWD-11-001: Inelastic pp cross section
- CMS-QCD-10-011: Inclusive jet cross section
- CMS-QCD-10-013: Hadronic event shapes
- CMS-QCD-10-026: Dijet azimuthal decorrelations
- CMS-QCD-10-007: Strange particle production
- CMS-BPH-10-003: Upsilon production cross section
- CMS-TOP-11-003: Top cross section in lepton plus jets
- CMS-TOP-11-005: Top cross section in dileptons
- CMS-TOP-11-006: Top cross section in muon+tau
- CMS-TOP-11-007: Top cross section in all-hadronic
- CMS-TOP-11-014: Top-antitop charge asymmetry
- CMS-TOP-11-019: Top-antitop mass difference
- CMS-TOP-11-022: Single top in tW channel
- CMS-EWK-11-005: W charge asymmetry
- CMS-EWK-10-007: Drell-Yan cross section
- CMS-EWK-10-012: W/Z + jets
- CMS-EWK-10-013: W + charm
- CMS-EWK-11-010: WW, WZ, ZZ
- CMS-EWK-10-014: W polarization
- CMS-EWK-11-003: Weak mixing angle