



Taller de Altas Energías
Bilbao 2011

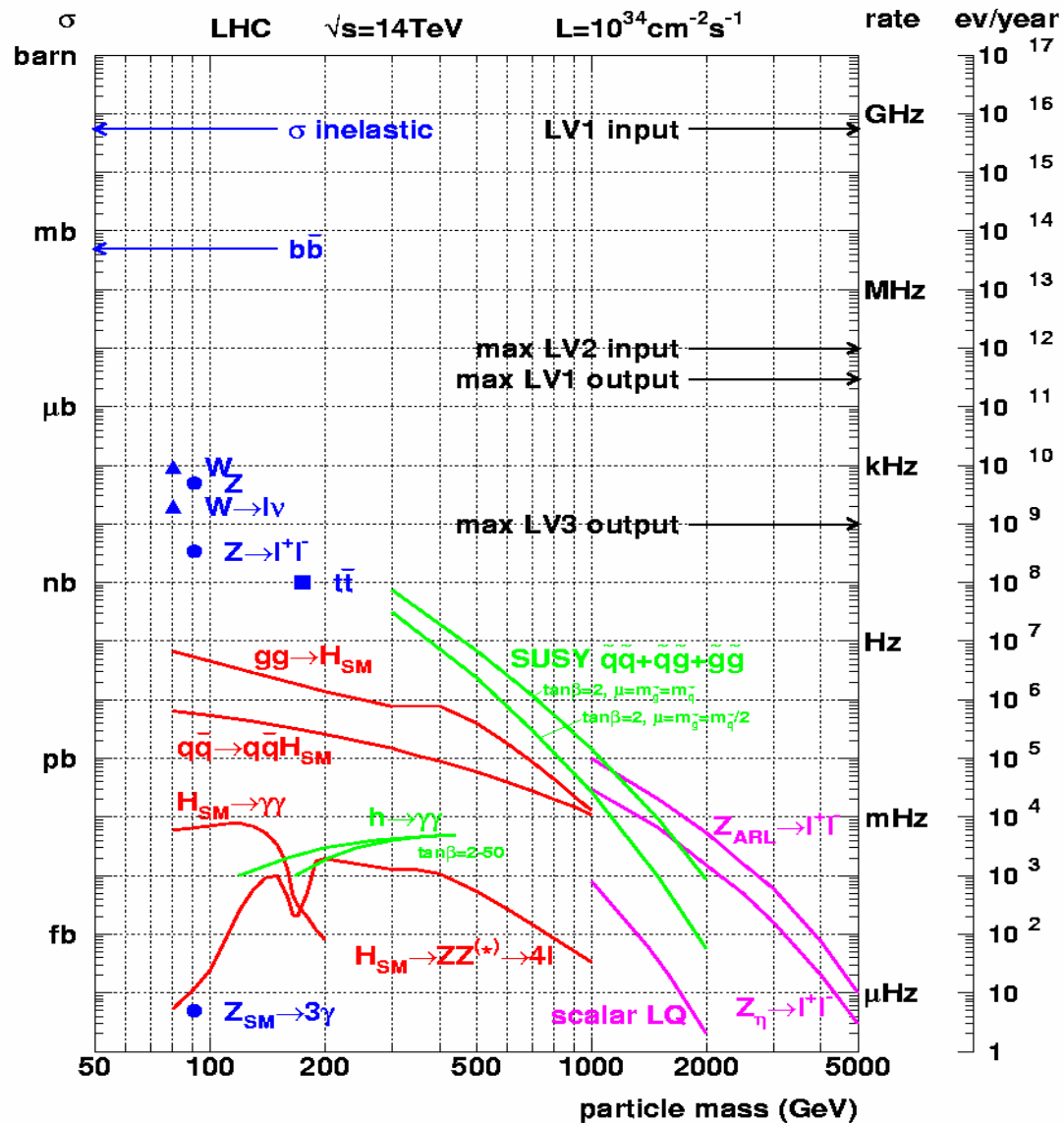


PHYSICS WITH CMS - PART II

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Universidad Autónoma de Madrid

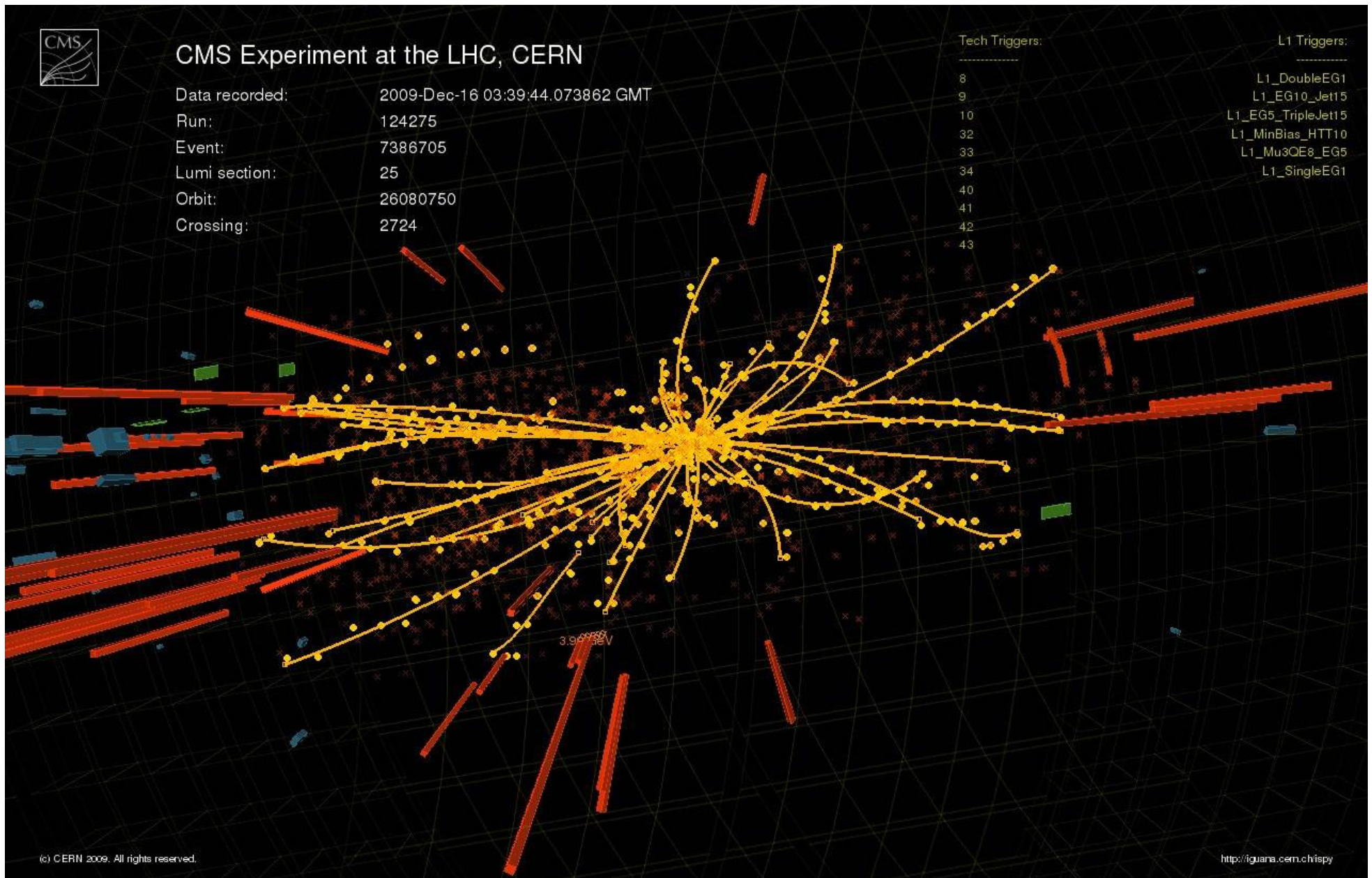
CMS PHYSICS RESULTS

LHC Cross Sections



1. SOFT AND HARD QCD

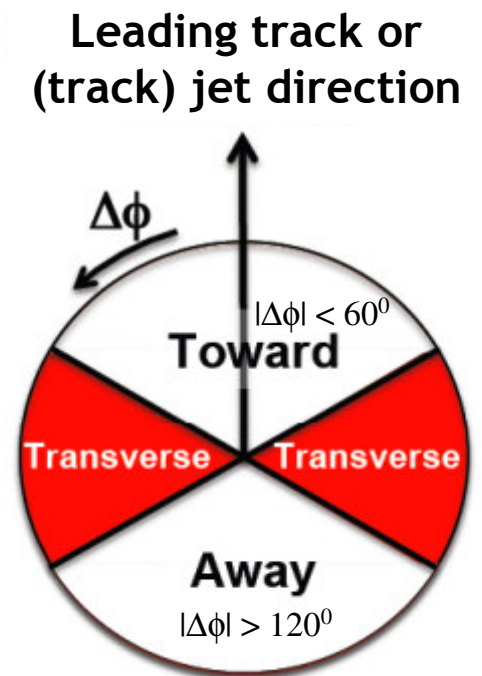
Soft Hadron-Hadron Collisions



Soft Hadron-Hadron Collisions

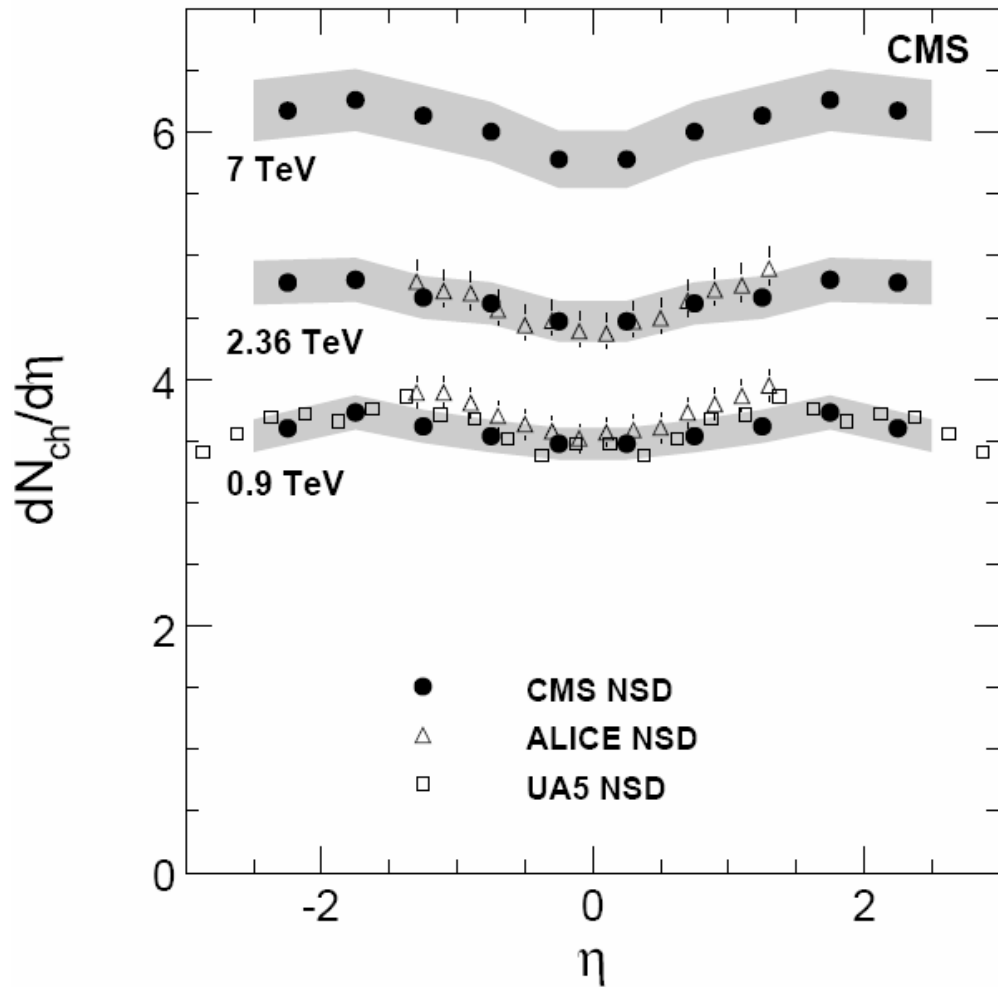
Minimum Bias events are those recorded with a totally inclusive trigger. The exact definition depends on the experiment, in particular the trigger. Usually Minimum Bias only refers to non-single diffractive (NSD) events.

Underlying event comprises all particles except the (hard) process of interest. It has components from multiple semi-hard parton scattering processes and soft components from beam-beam remnants. The region **transverse** to the dominant momentum flow is most sensitive to the underlying event.

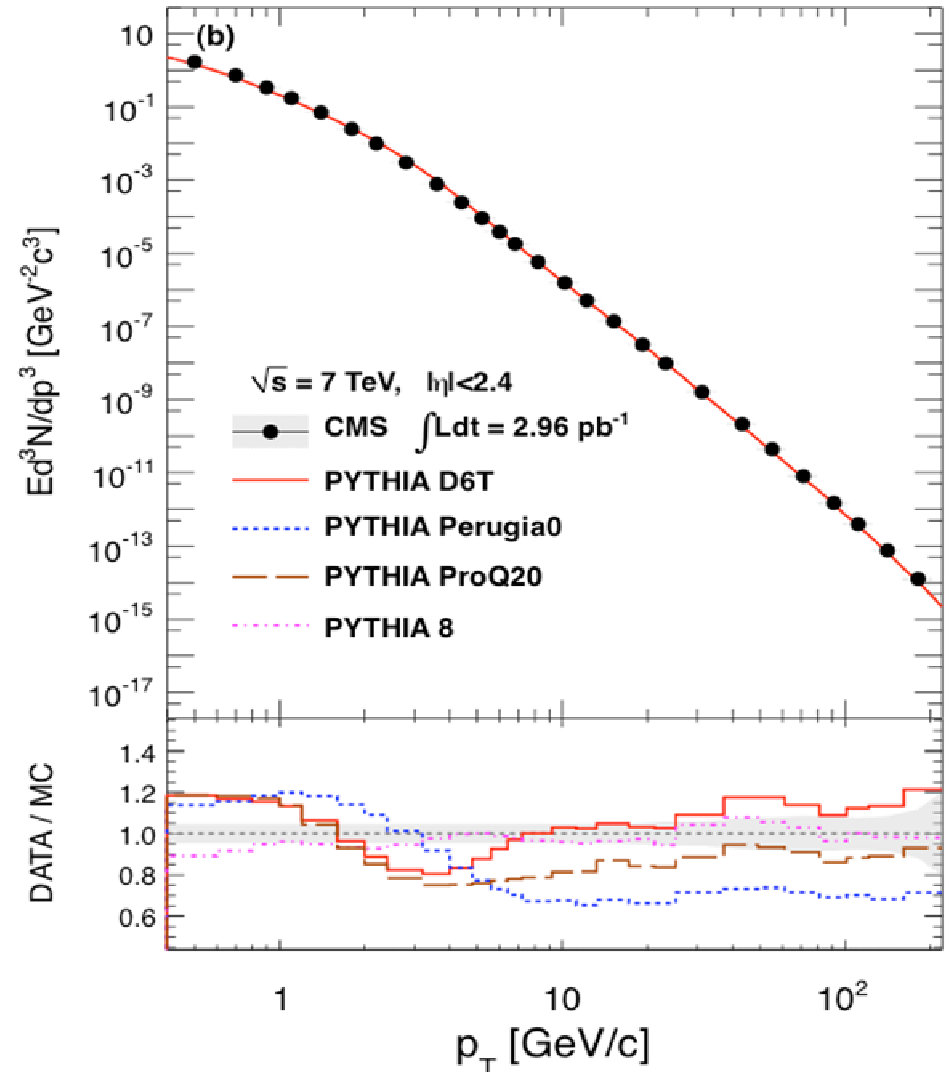


Minimum Bias

Inclusive charged particle production

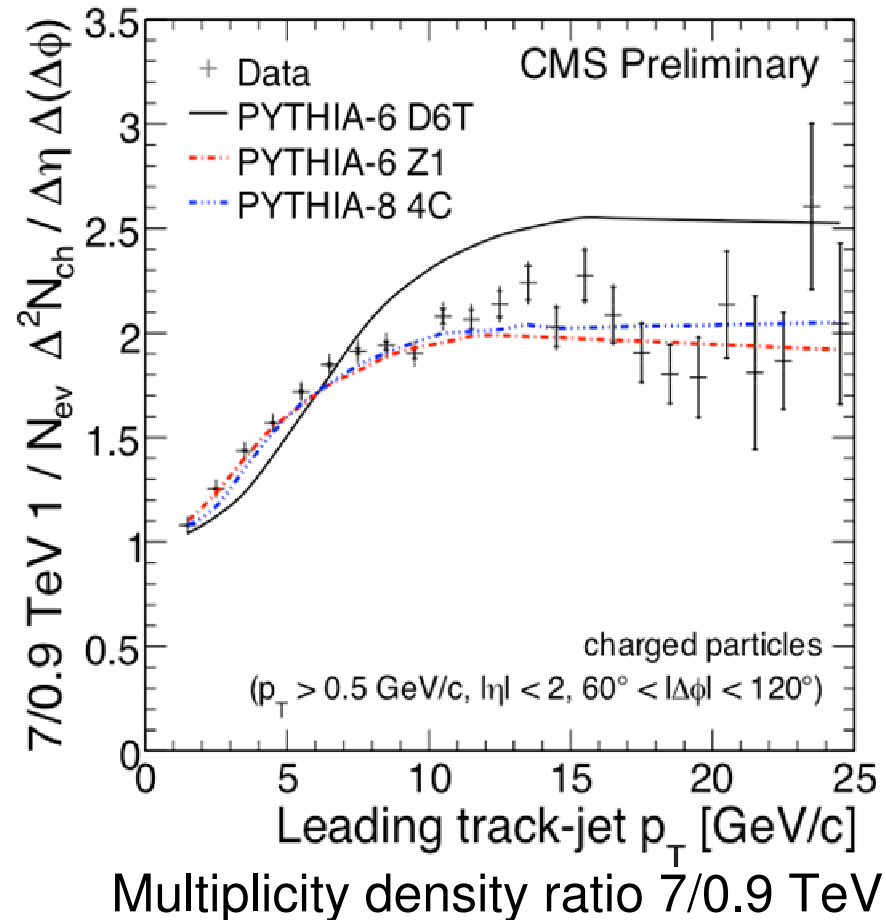
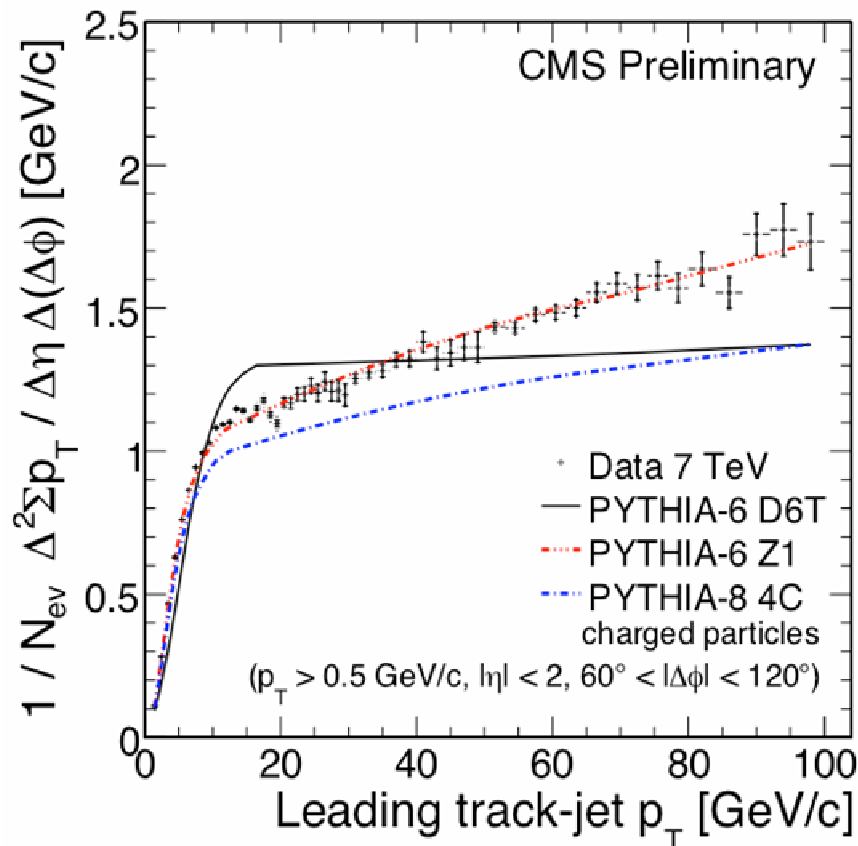


Pseudorapidity



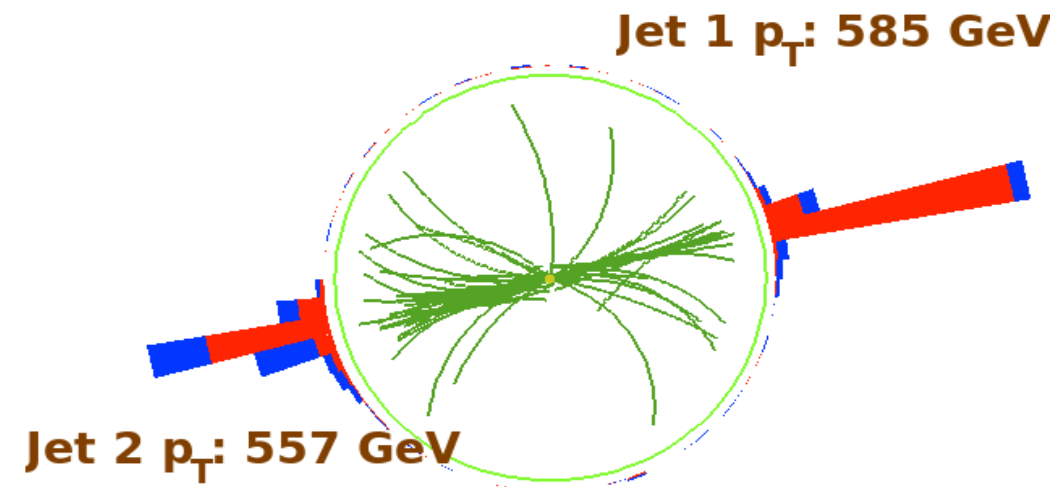
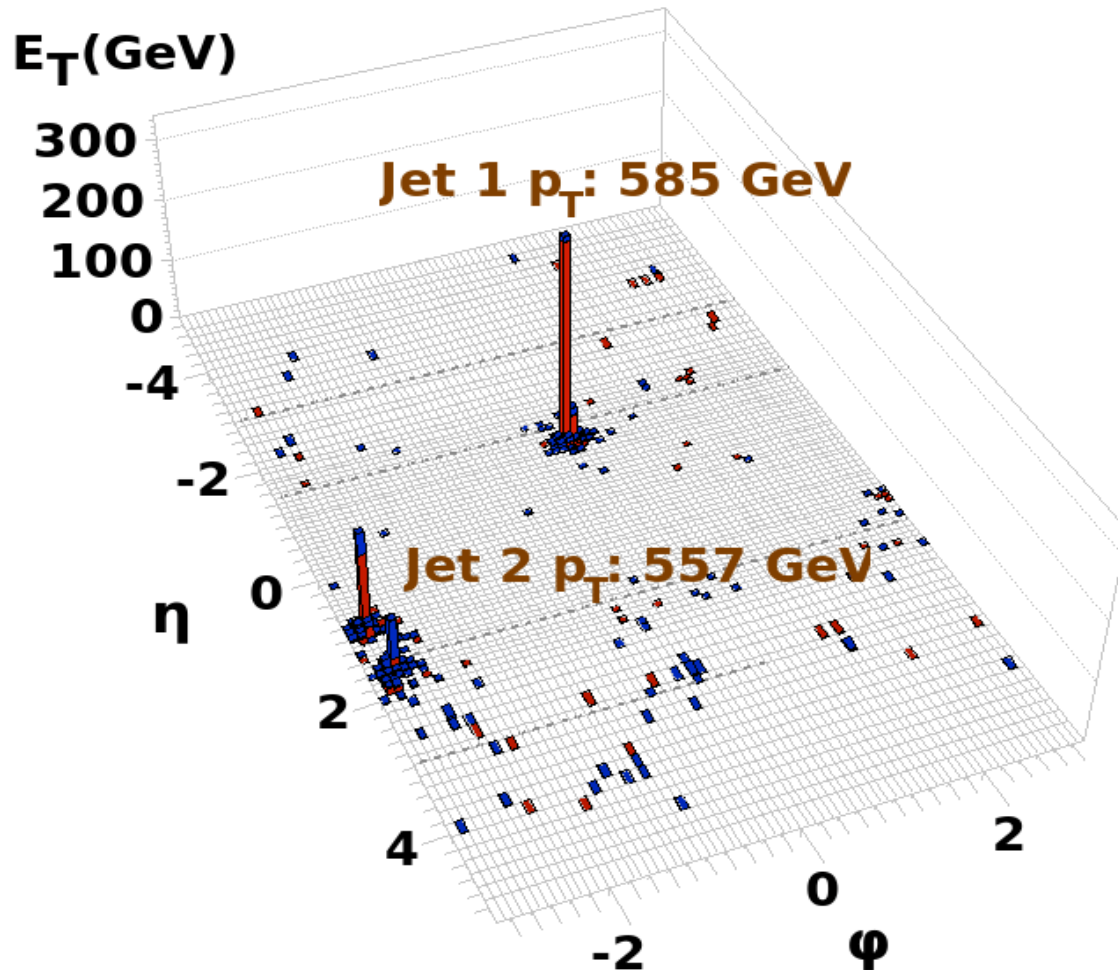
Transverse Momentum

Underlying Event

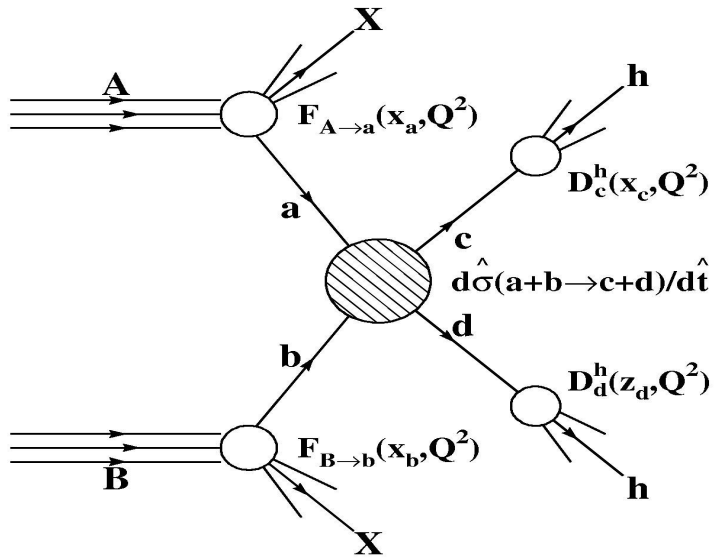


Strong growth of underlying event activity with \sqrt{s} . PYTHIA Tune Z1 describes the distributions and the \sqrt{s} dependence well.

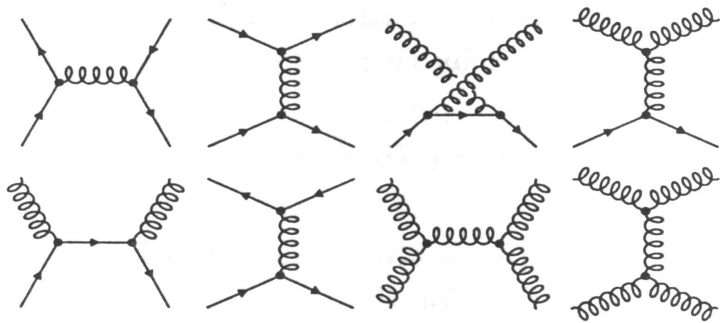
Hard QCD: Jets



Hard QCD: Jets

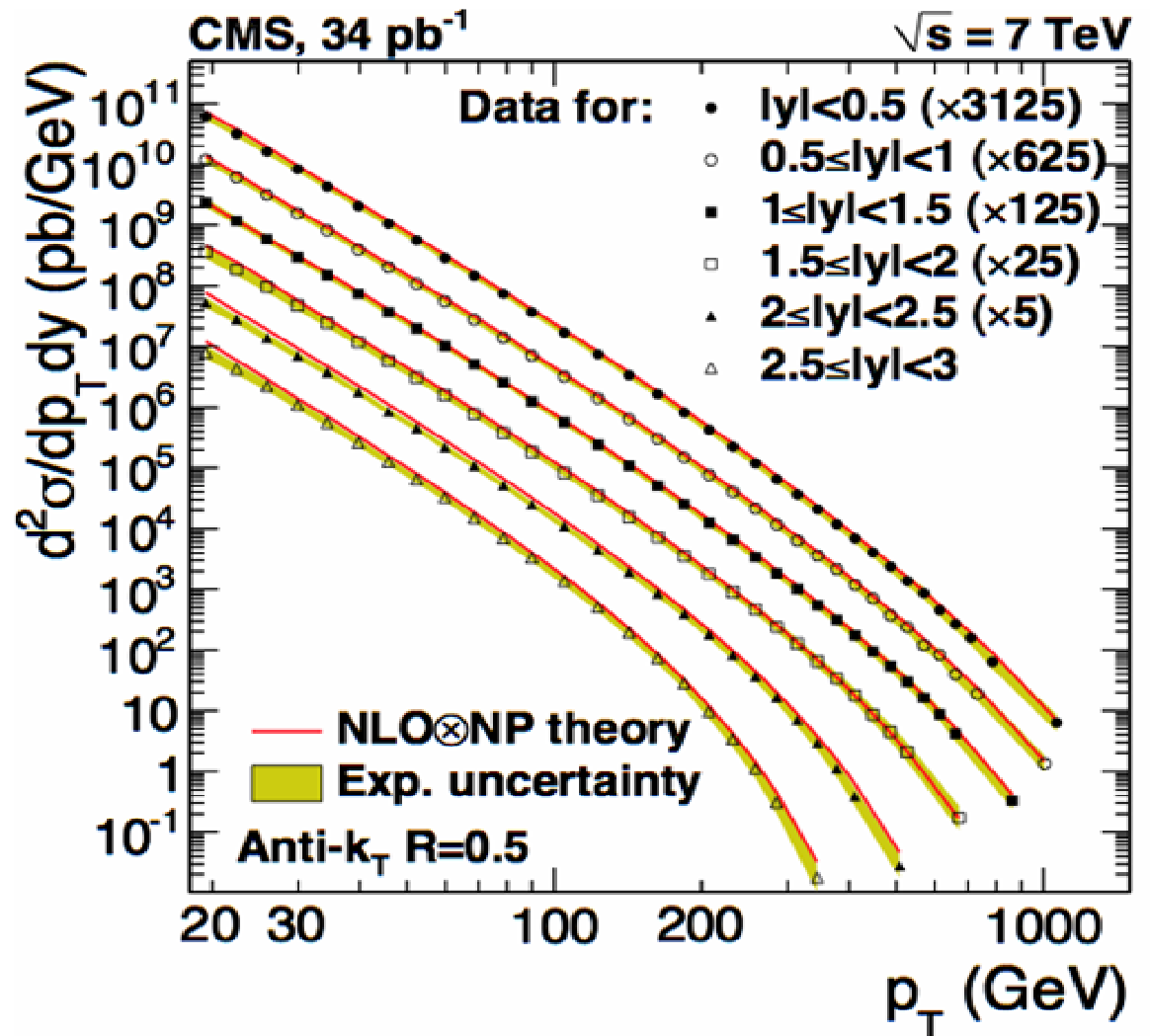


- ❑ Hard scattering processes are dominated by QCD jet production.
- ❑ Originating from quark-quark, quark-gluon and gluon-gluon scattering.
- ❑ Due to fragmentation of quarks and gluons in final state hadrons → Jets with large transverse momentum p_T in the detector.
- ❑ Cross sections can be calculated in pQCD (perturbation theory).
- ❑ Comparison between experimental data and theoretical predictions constitutes an important test of the theory.
- ❑ Deviations? Problem in the experiment? Problem in the theory (QCD)? New Physics, e.g. quark substructure?



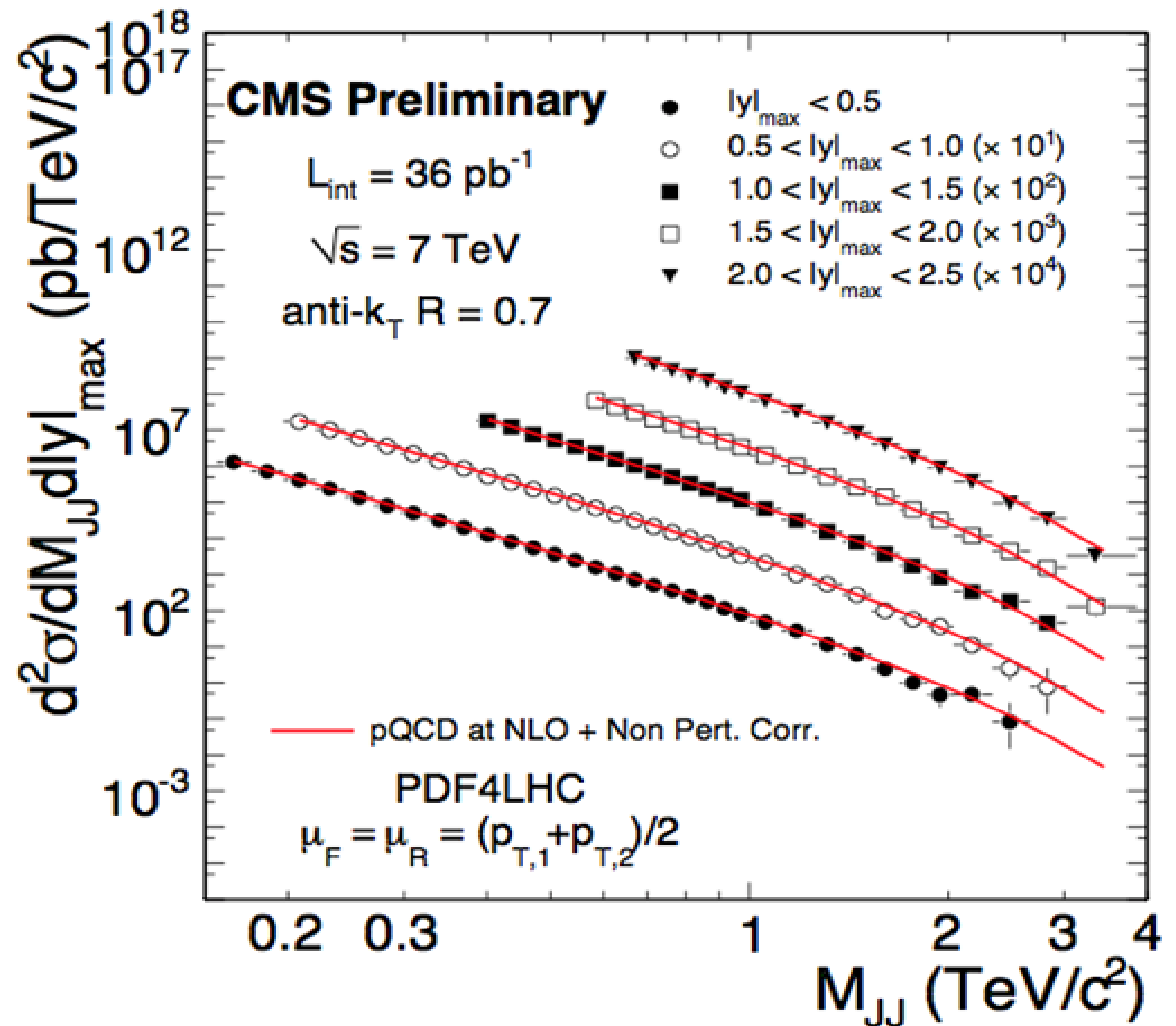
Inclusive Jet Cross Section

- Benchmark test of pQCD.
- Extended Tevatron results at high p_T .
- Accessing low p_T part with Particle Flow jet reconstruction.
 - From 18 GeV to 1.1 TeV
- Six rapidity bins, up to $|y| = 3$.
- Data unfolded with resolution.
- Good agreement with NLO QCD over 10 orders of magnitude.

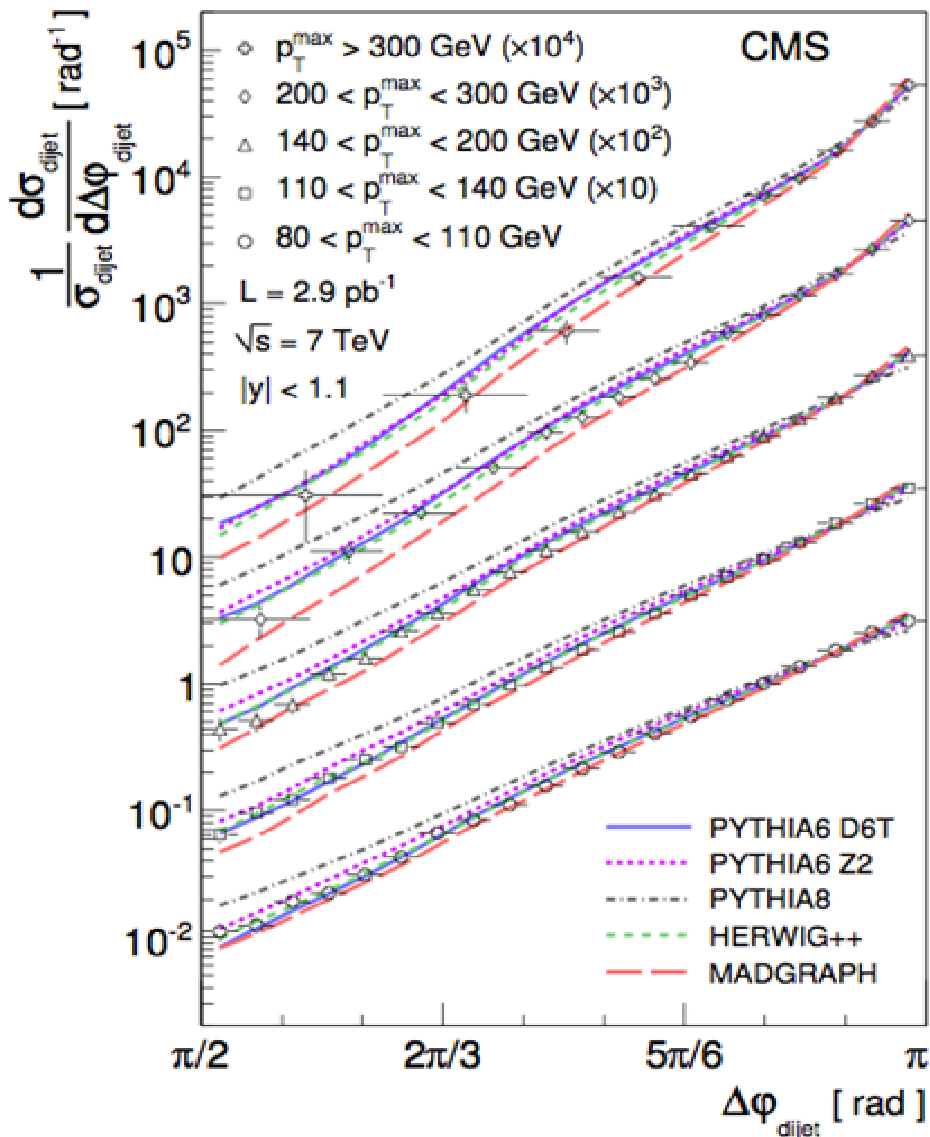


DiJet Mass Cross Section

- Additional test of pQCD.
- Up to $M_{JJ} = 3.5 \text{ TeV}/c^2$.
- Data/theory compatible with inclusive jet measurement.
- Background for 'bump hunting'.
- Agreement data vs. NLO QCD excludes a variety of models with narrow dijet resonances in the 1-2 TeV/c^2 mass region.



DiJet Azimuthal Decorrelations



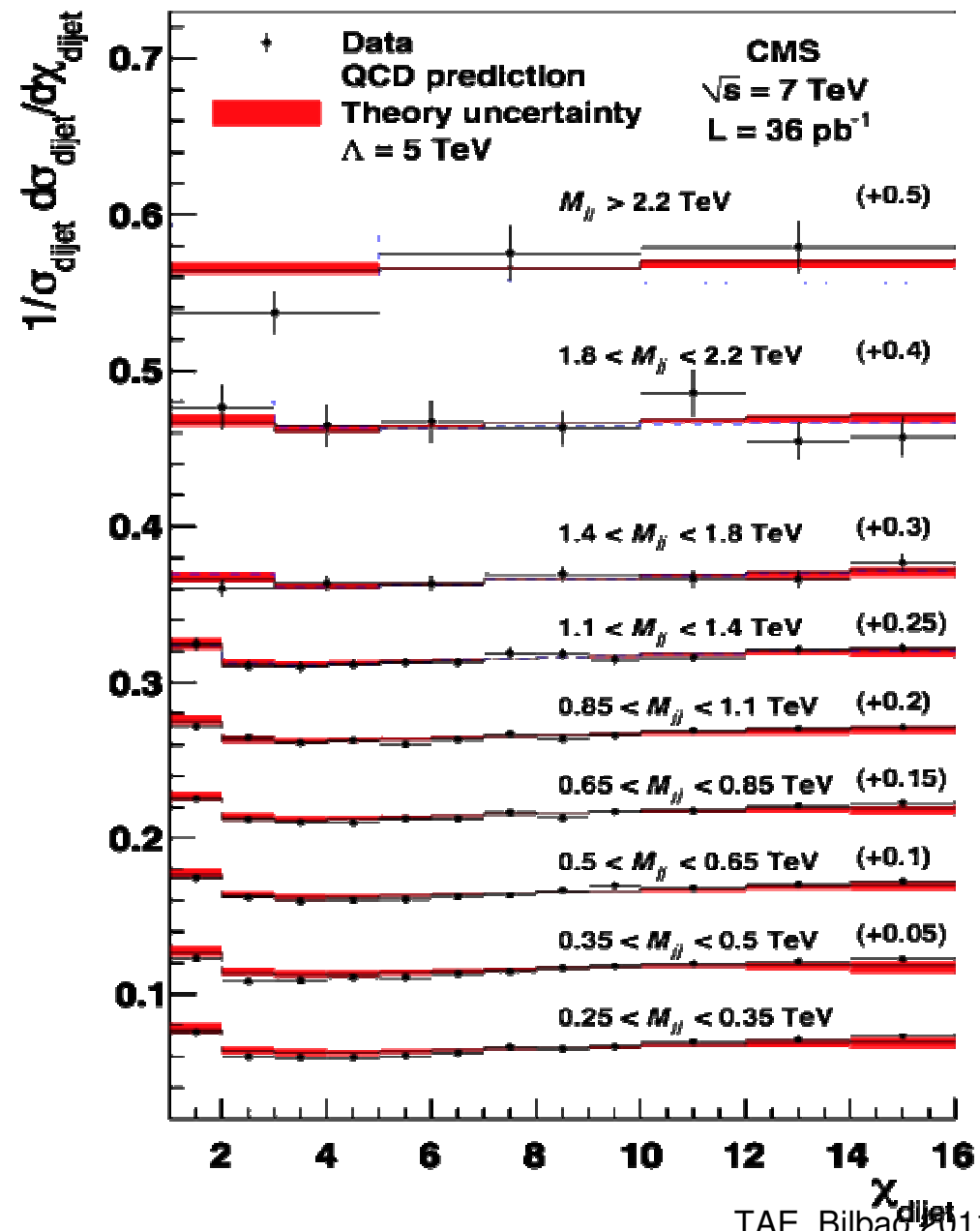
- Sensitive to high-order QCD radiation.
 - ❑ Probes high jet multiplicities without measuring all jets.
- Important test of MC description of multiple parton radiation.
 - ❑ Fundamental in precision measurements and search for new physics.
- Best description of the data: Pythia6 and Herwig++.

Search for Compositeness

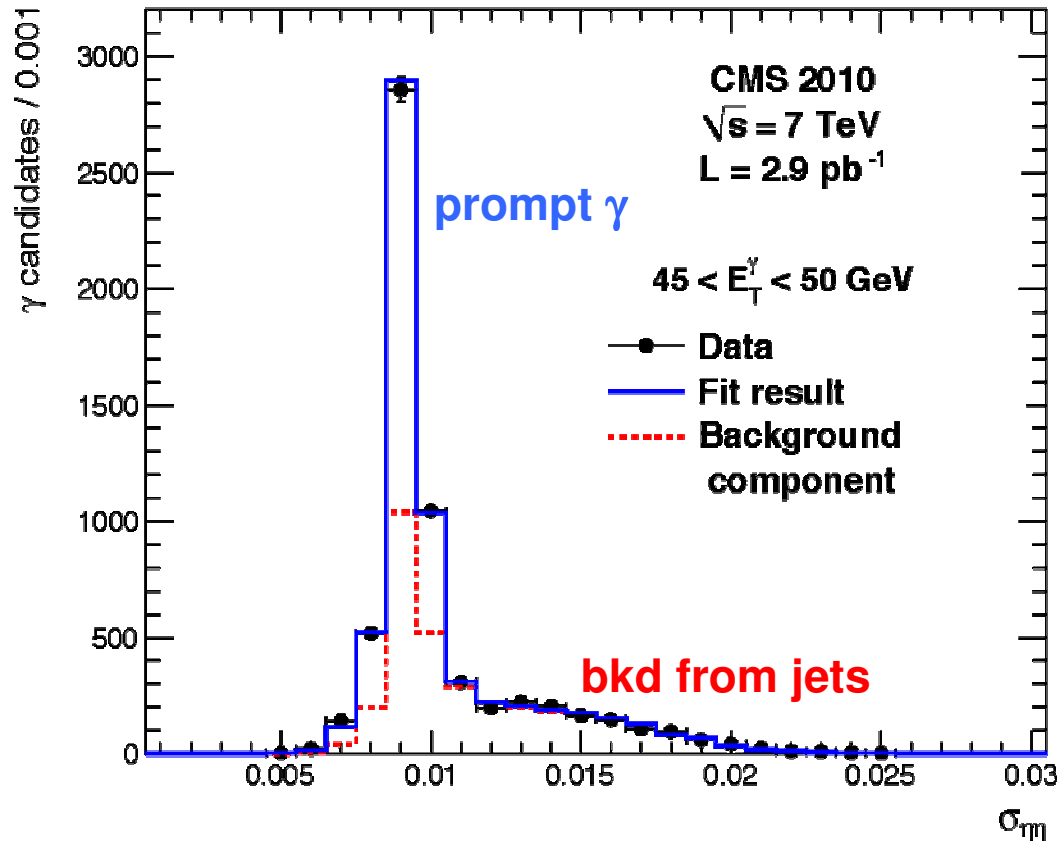
- Dijet angular analysis: exponential of the difference of jet rapidity gap:

$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

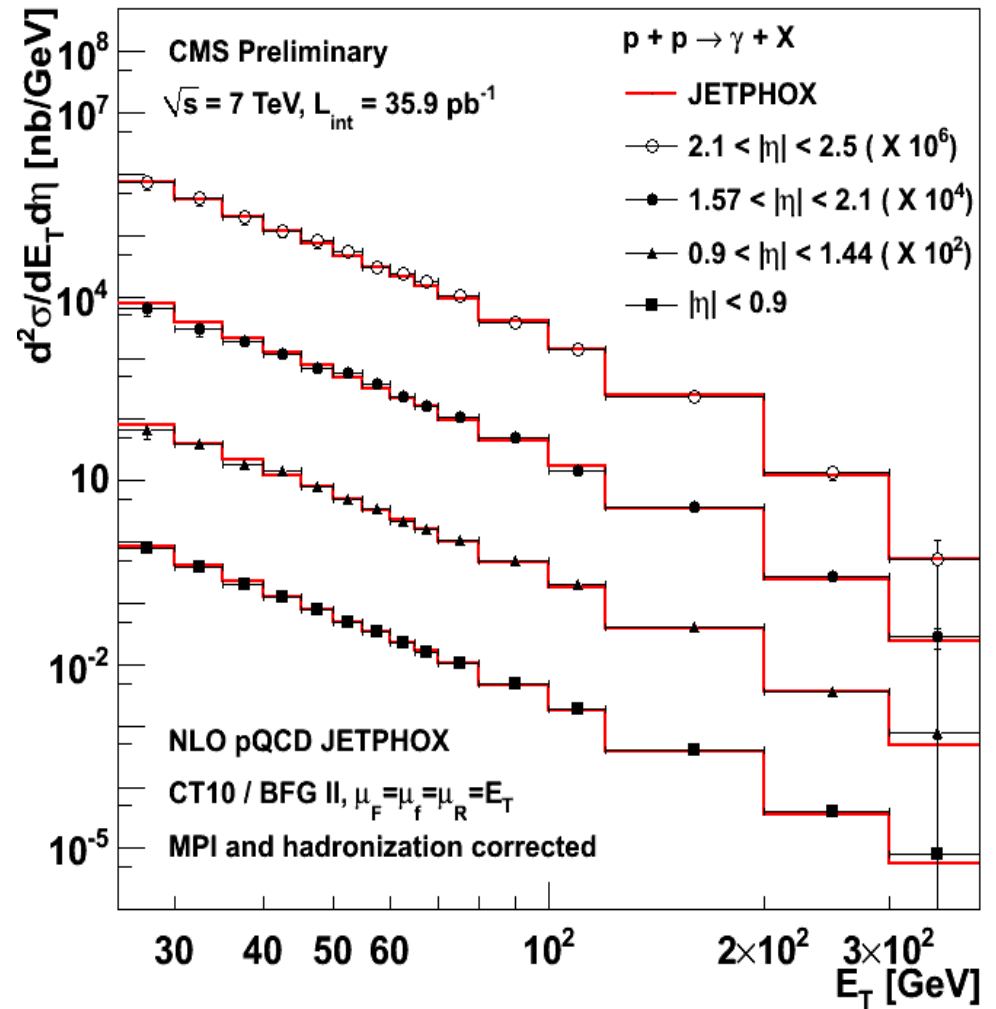
- Low dijet mass: stringent test of pQCD.
- High mass: search for quark compositeness.
 - ❑ Contact interactions (CI) enhance central dijet production ($\chi_{\text{dijet}} \sim 1$).
- Data well described by QCD prediction.
 - ❑ Excluding CI with $\Lambda < 5.6$ TeV.



Isolated Photons

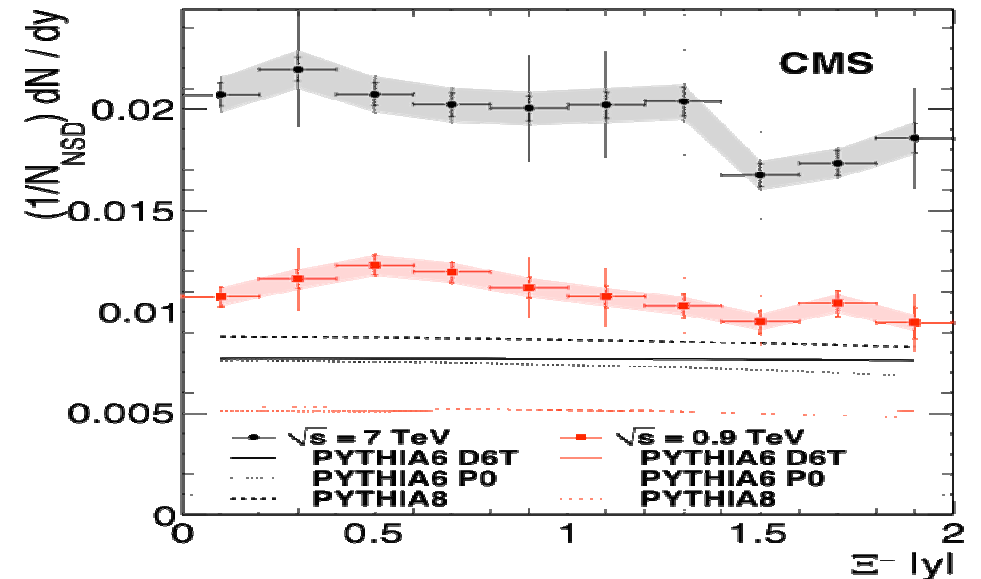
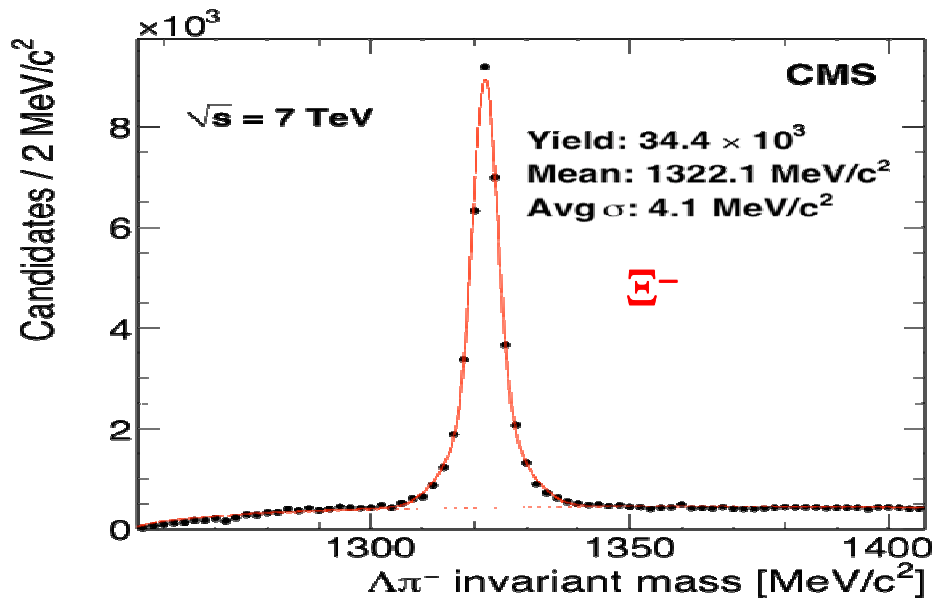
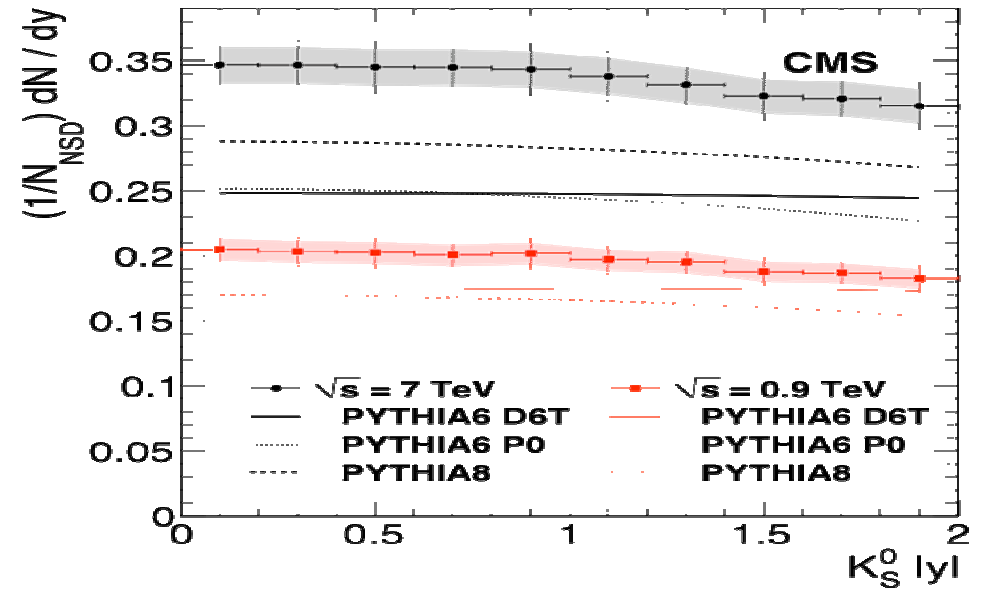
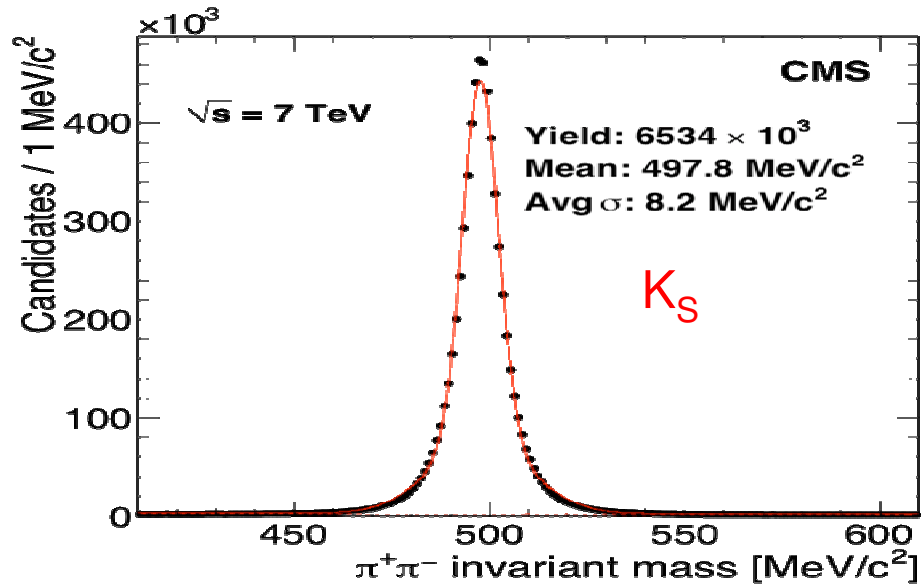


Transverse η profile of EM showers used to separate high energy isolated γ from π^0 enriched jets.



2. FLAVOUR PHYSICS

Strangeness Production

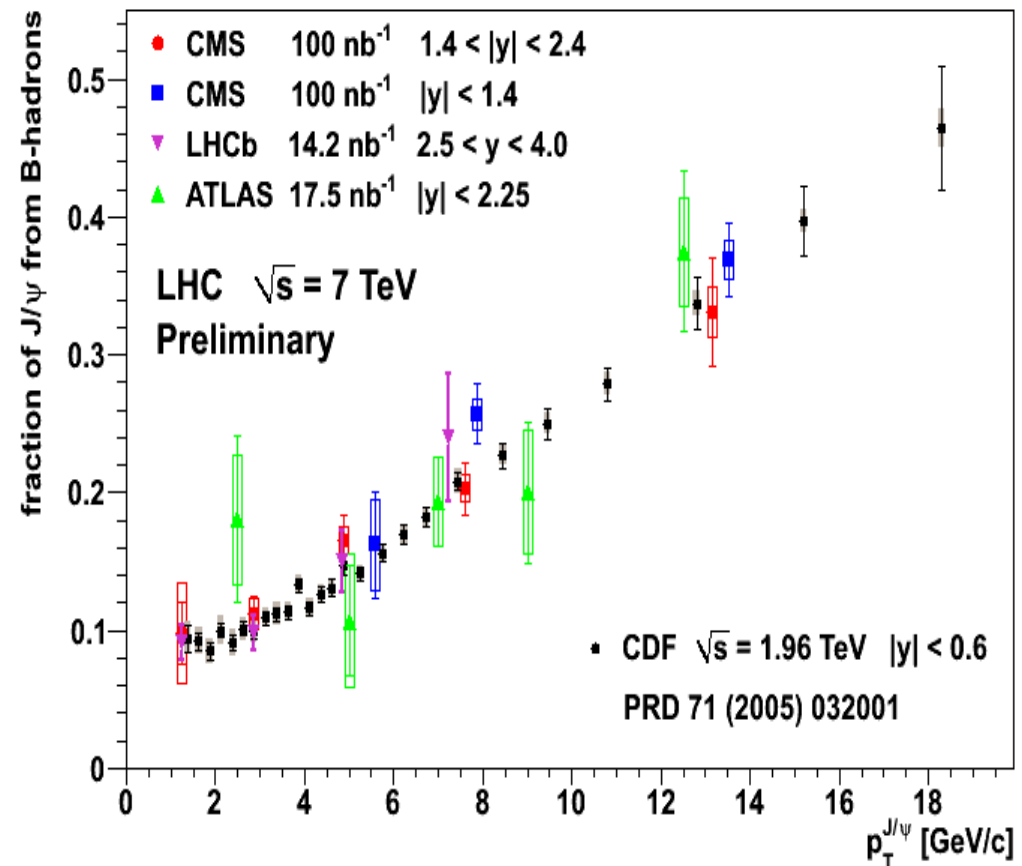
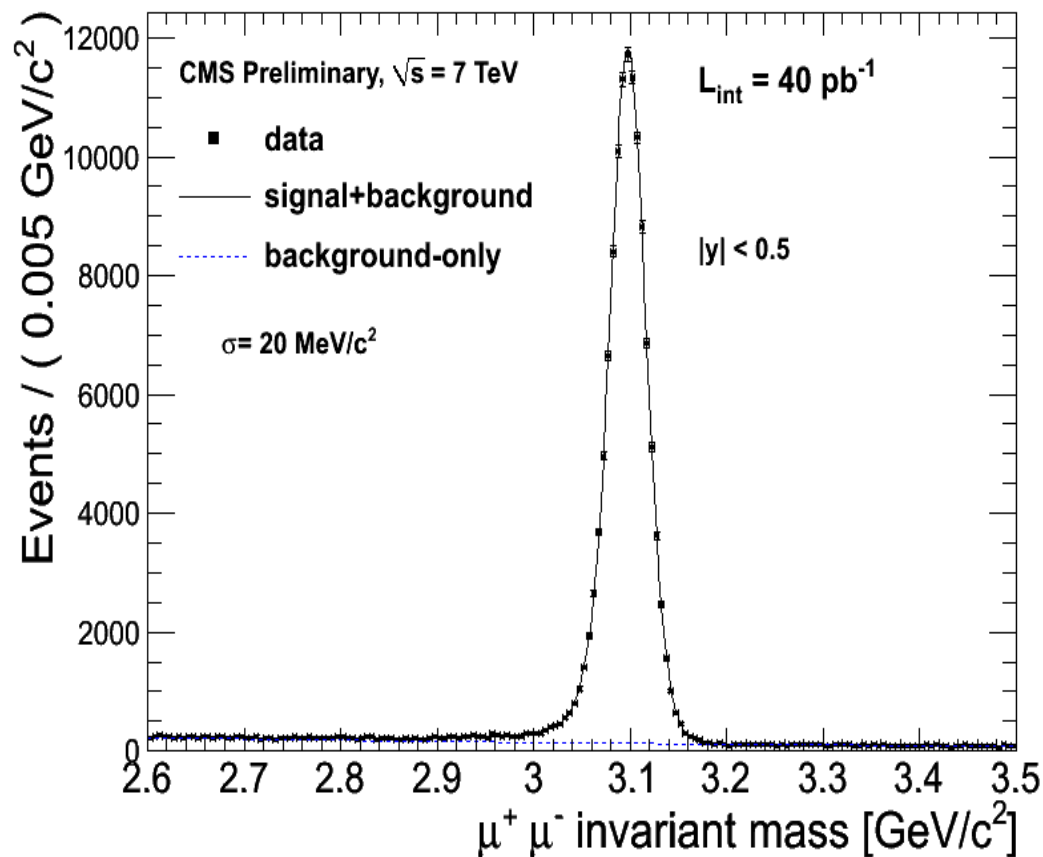


J/ψ Production

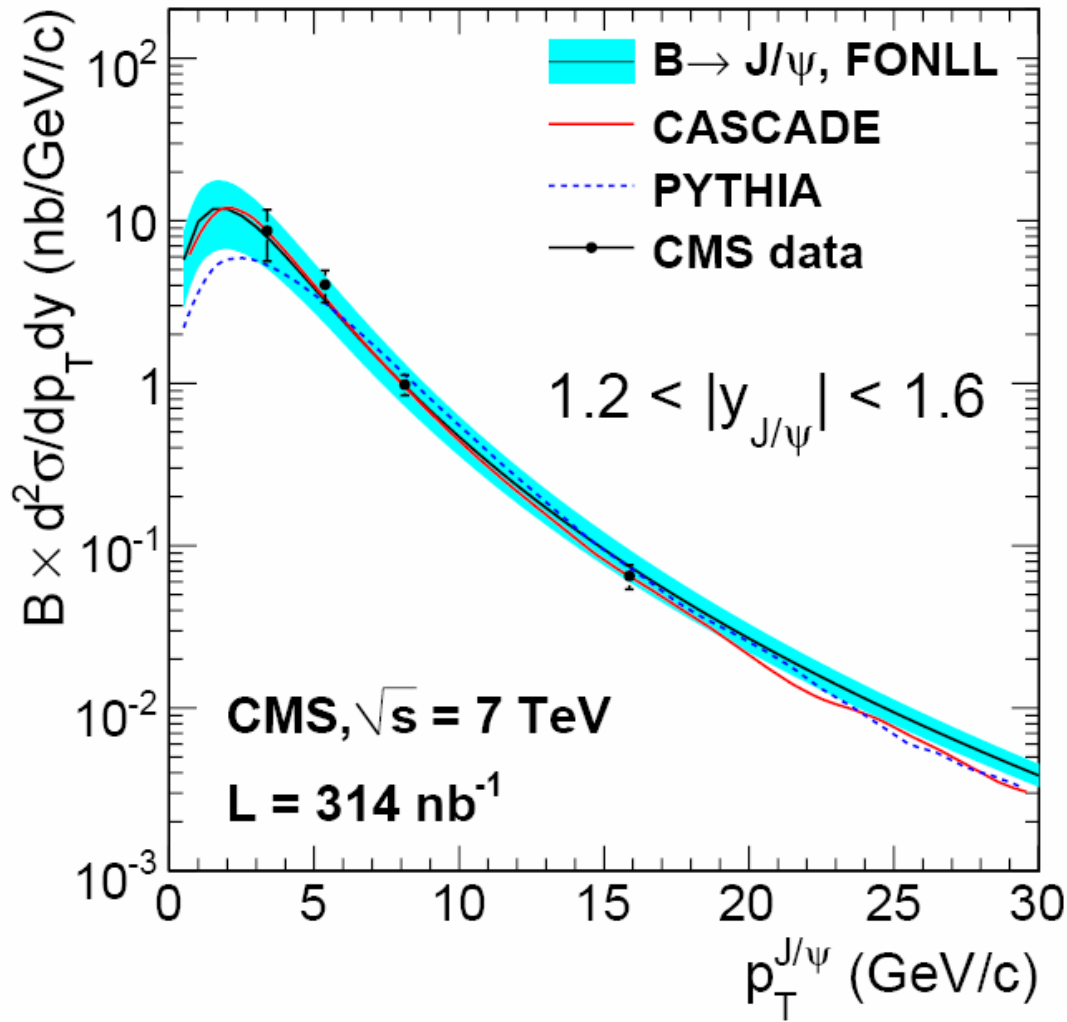
Sample of about 2M $J/\psi \rightarrow \mu\mu$.

❑ Available for studies of production properties, polarization.

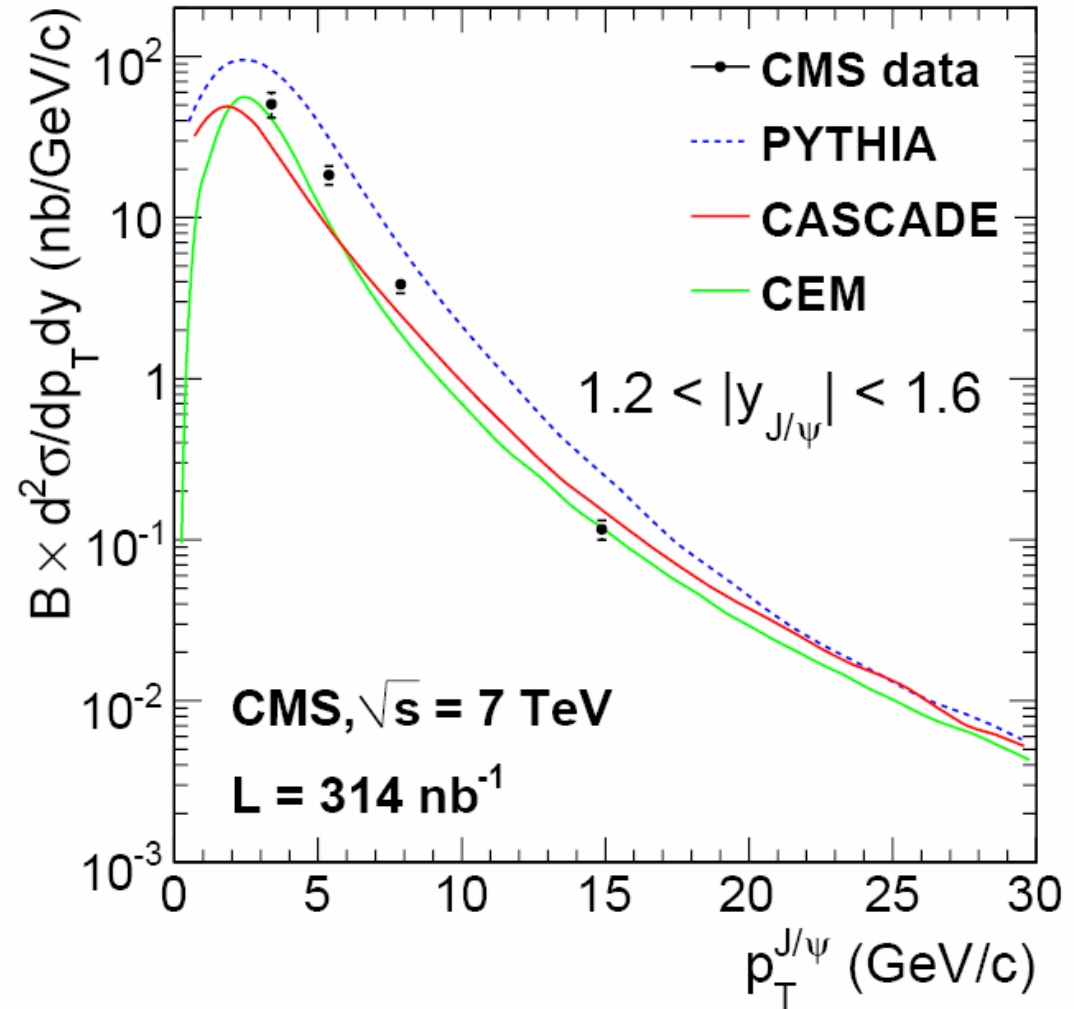
❑ Also for detector calibration (momentum scale, tag-and-probe efficiencies).



J/ψ Transverse Momentum Spectra

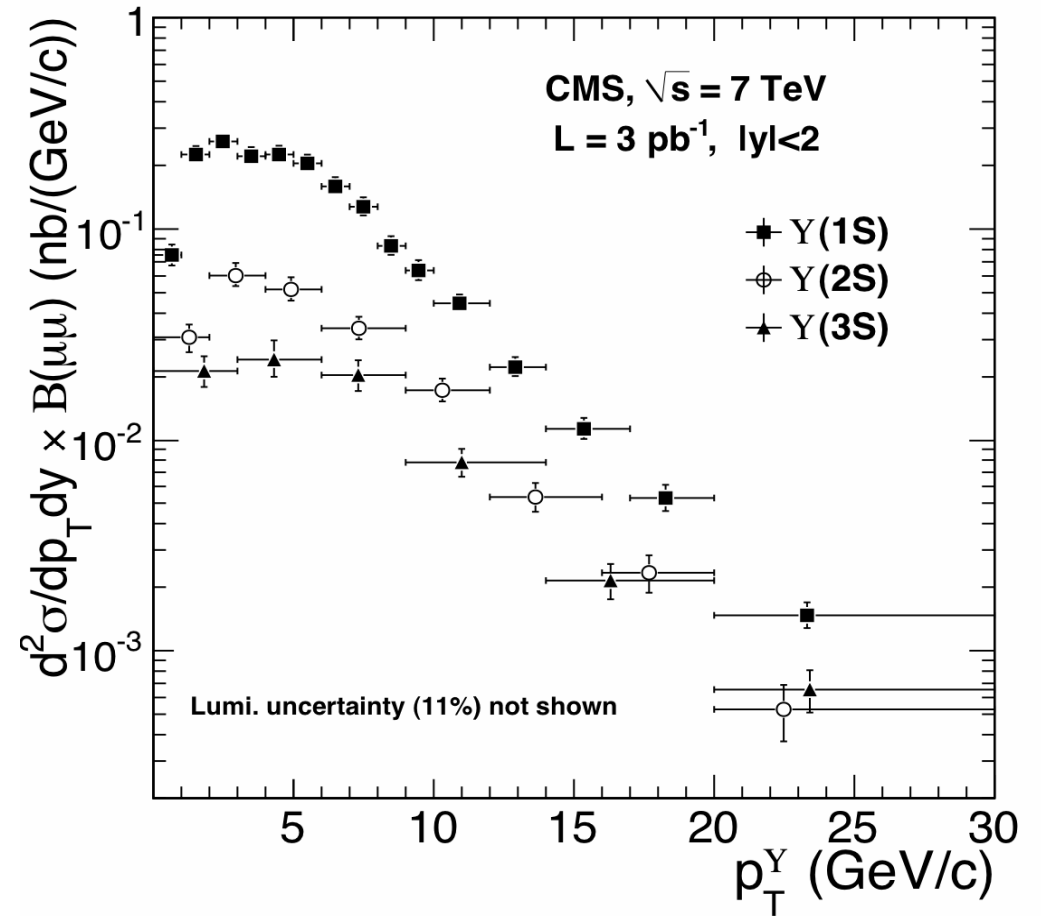
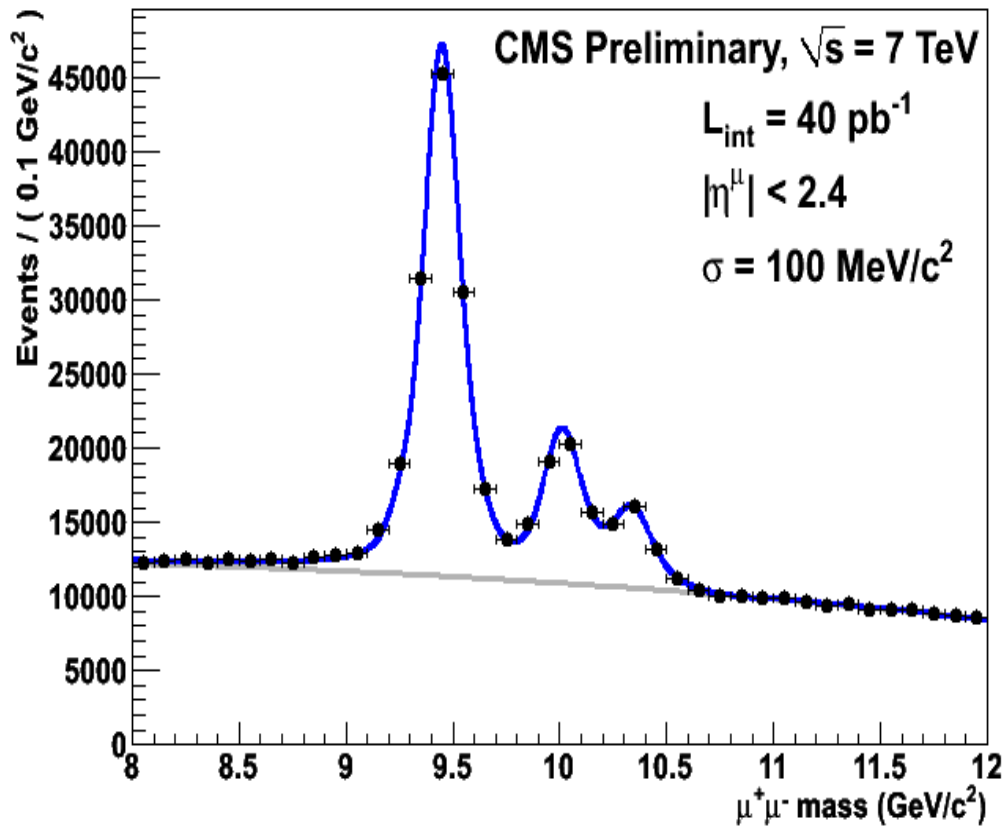


From B-hadron decays



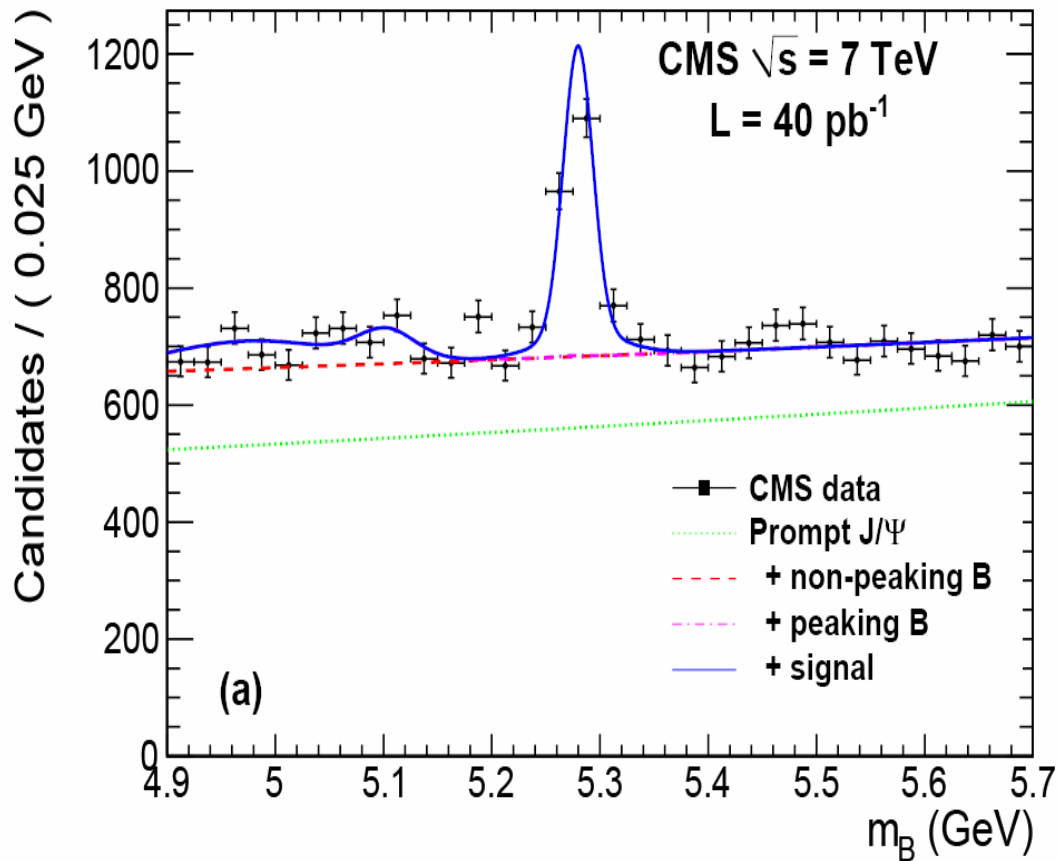
Prompt production

Y(1S, 2S, 3S) Production

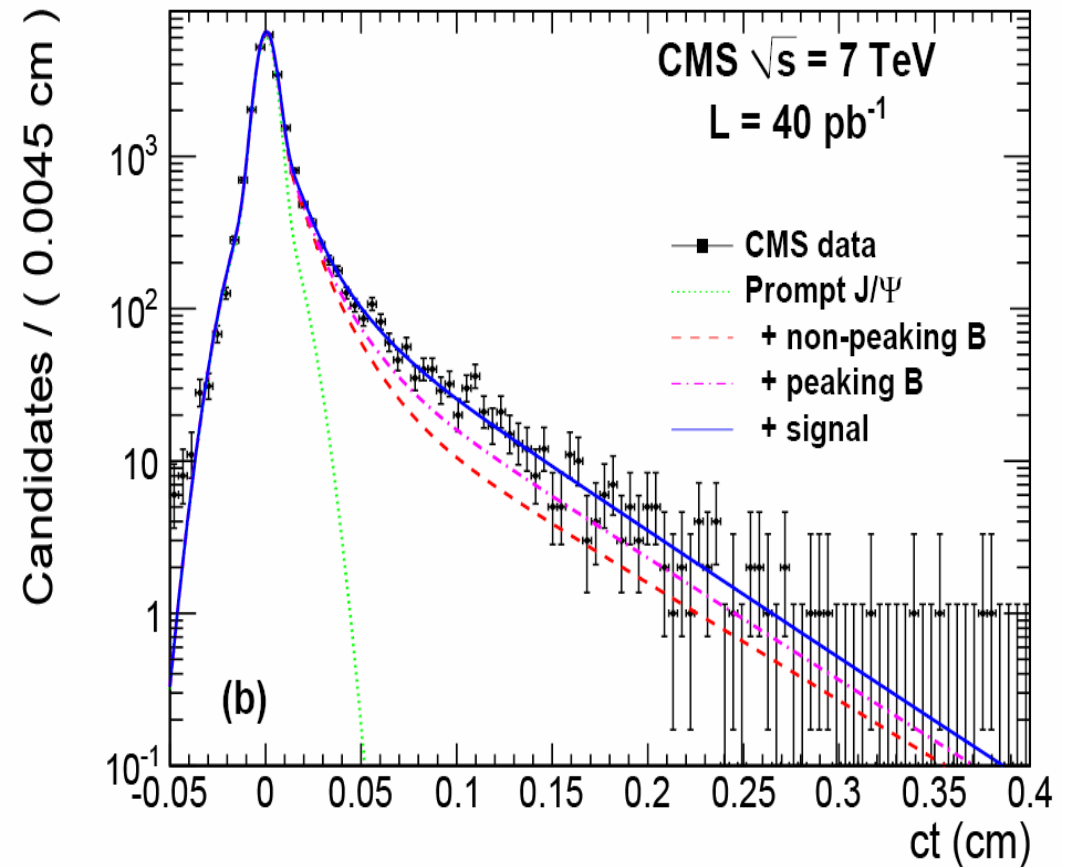


Exclusive B-hadron Production

Example: $B^0 \rightarrow J/\psi K_S$; similar for $B^+ \rightarrow J/\psi K^+$ and $B_s \rightarrow J/\psi \Phi$.



Resolution: 20 MeV

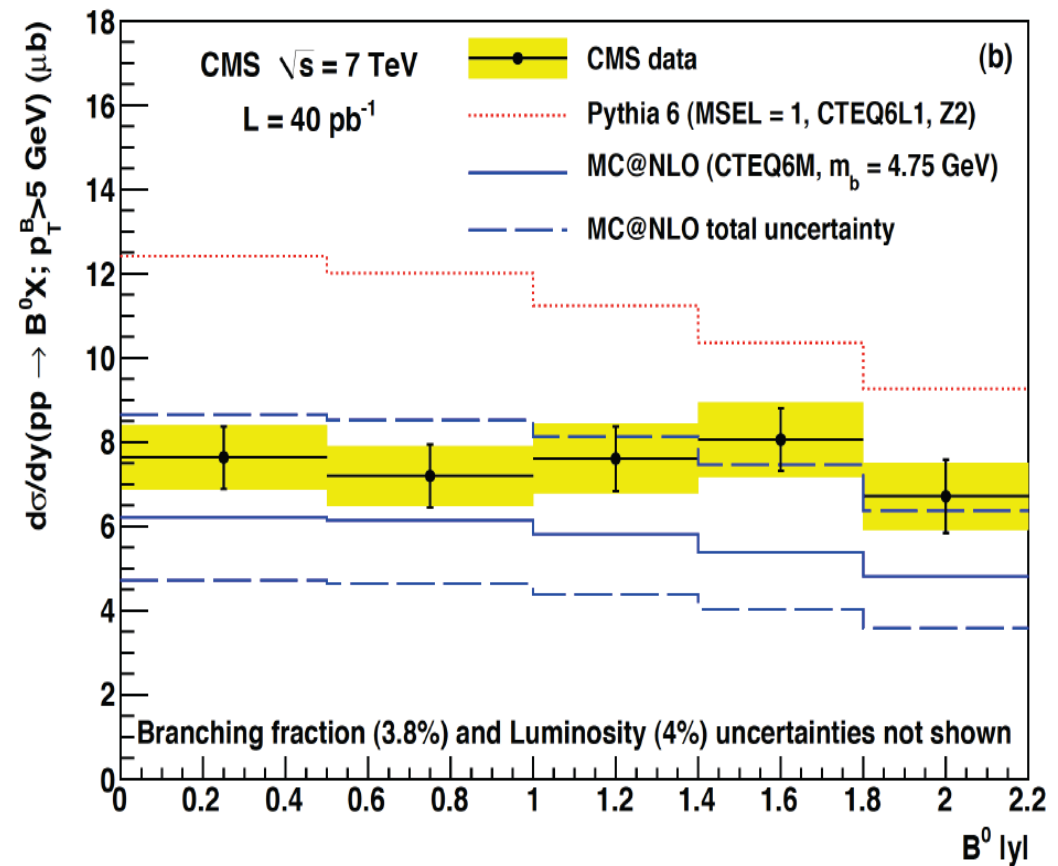
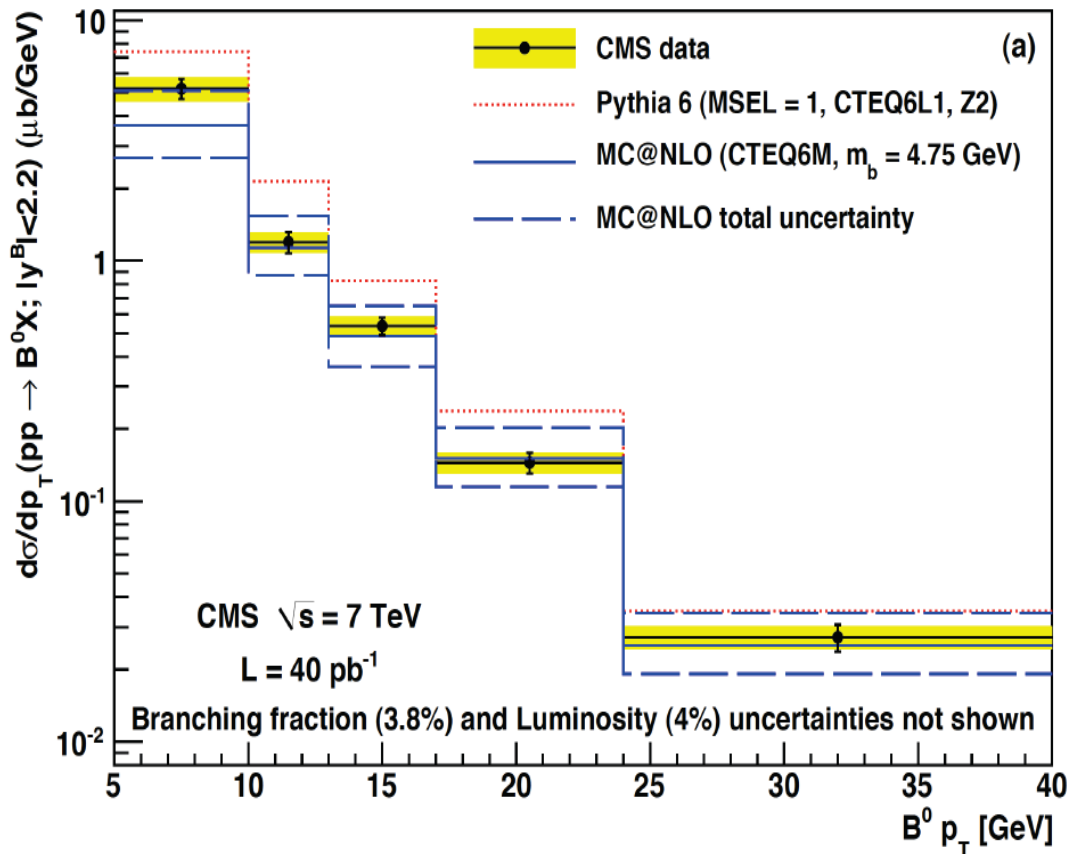


Lifetime: $479 \pm 22 \mu\text{m}$

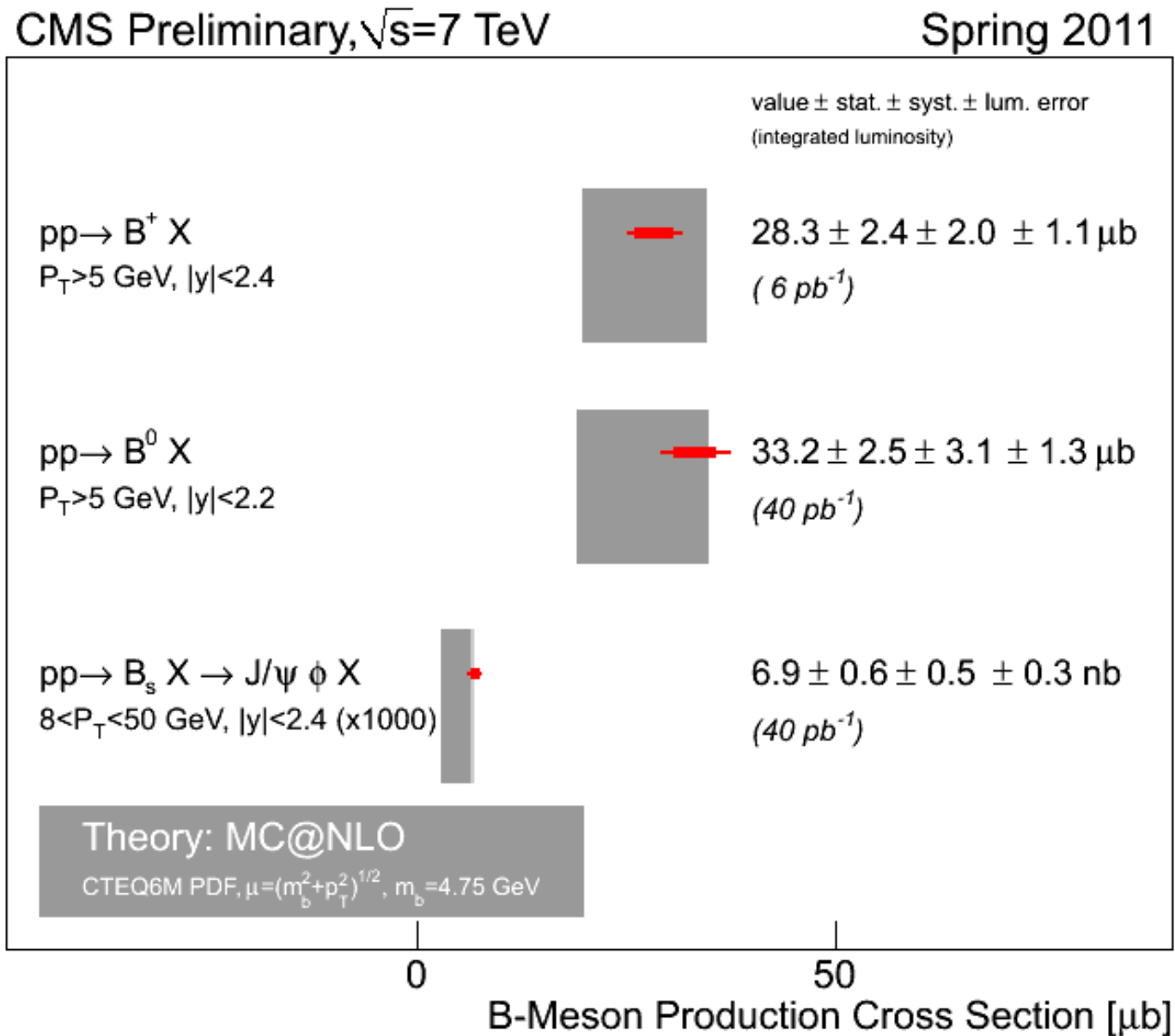
Exclusive B-hadron Production

Consistent picture in all channels:

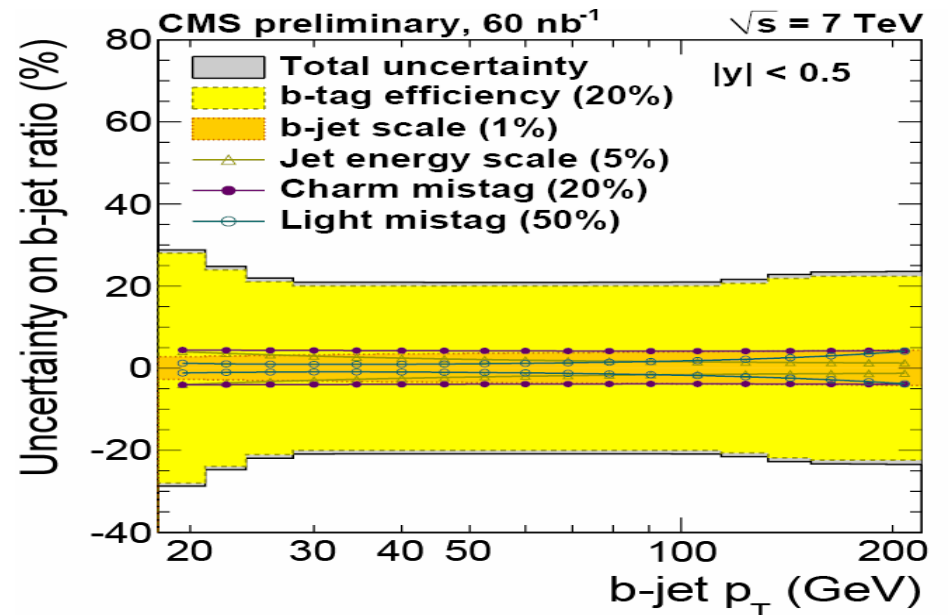
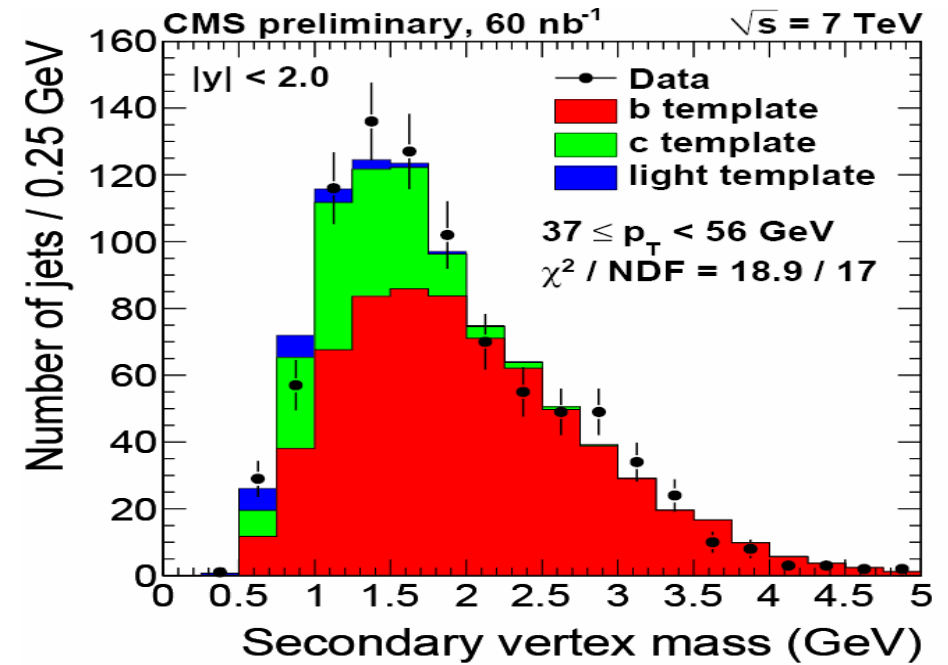
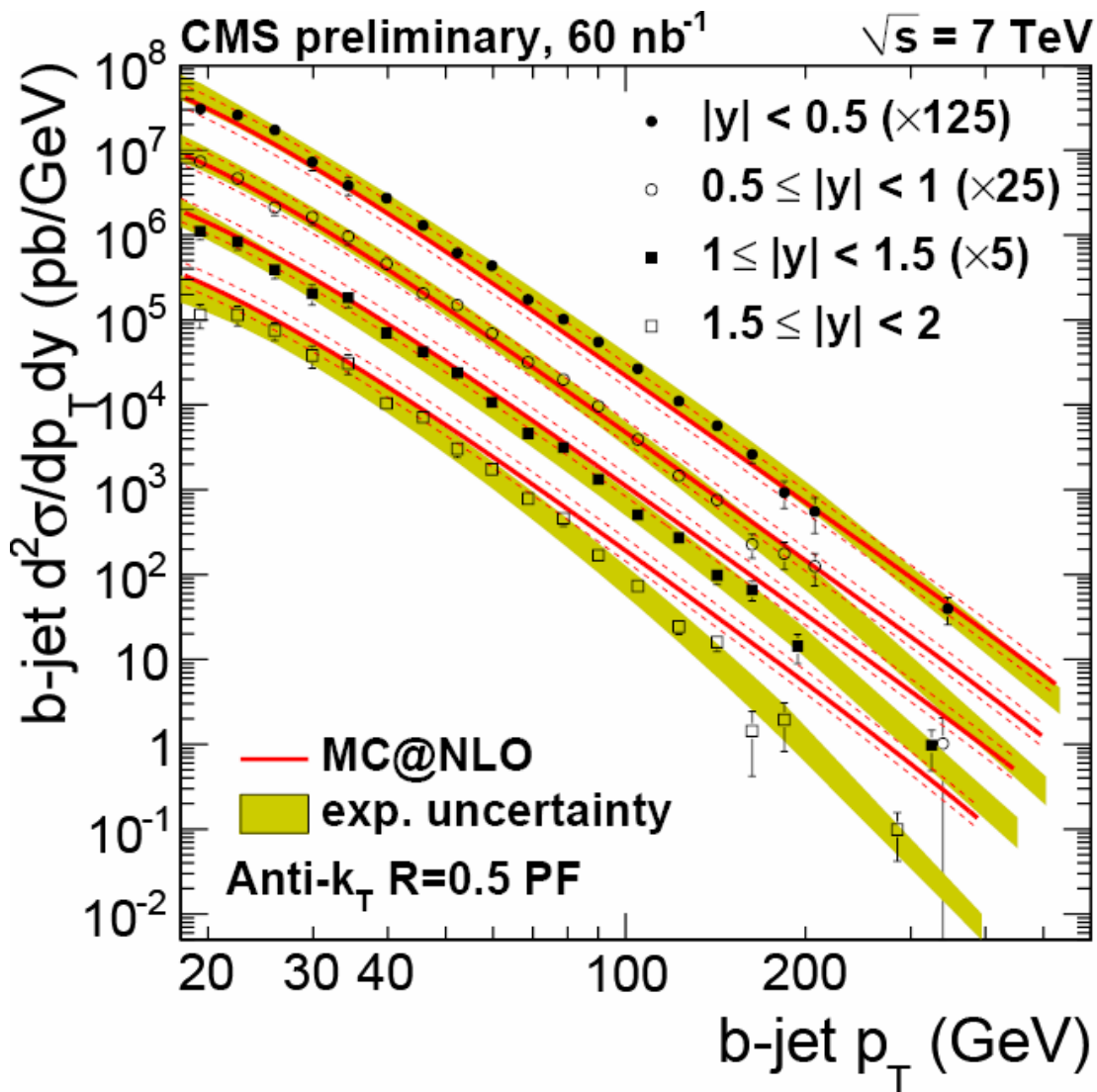
- Data is between the predictions of Pythia and compatible with NLO.
- Some shape differences in p_T and η distributions.



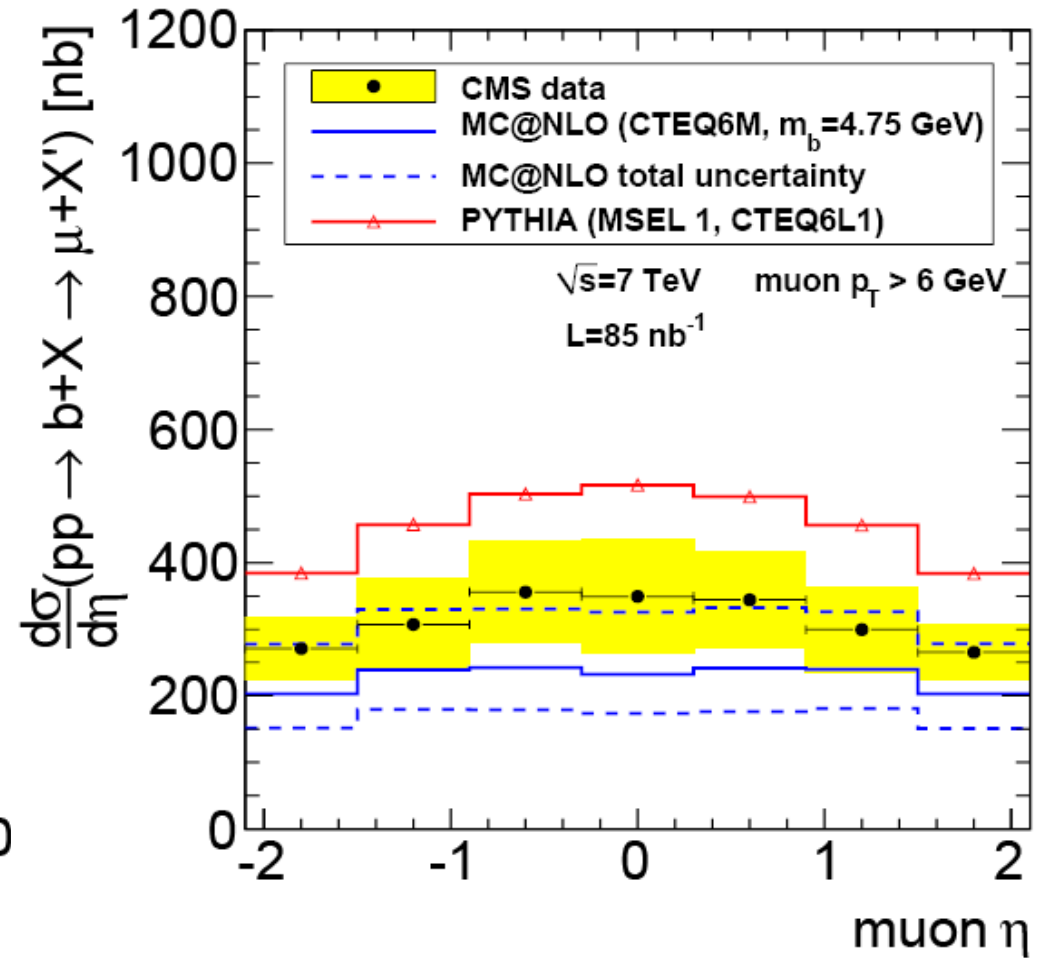
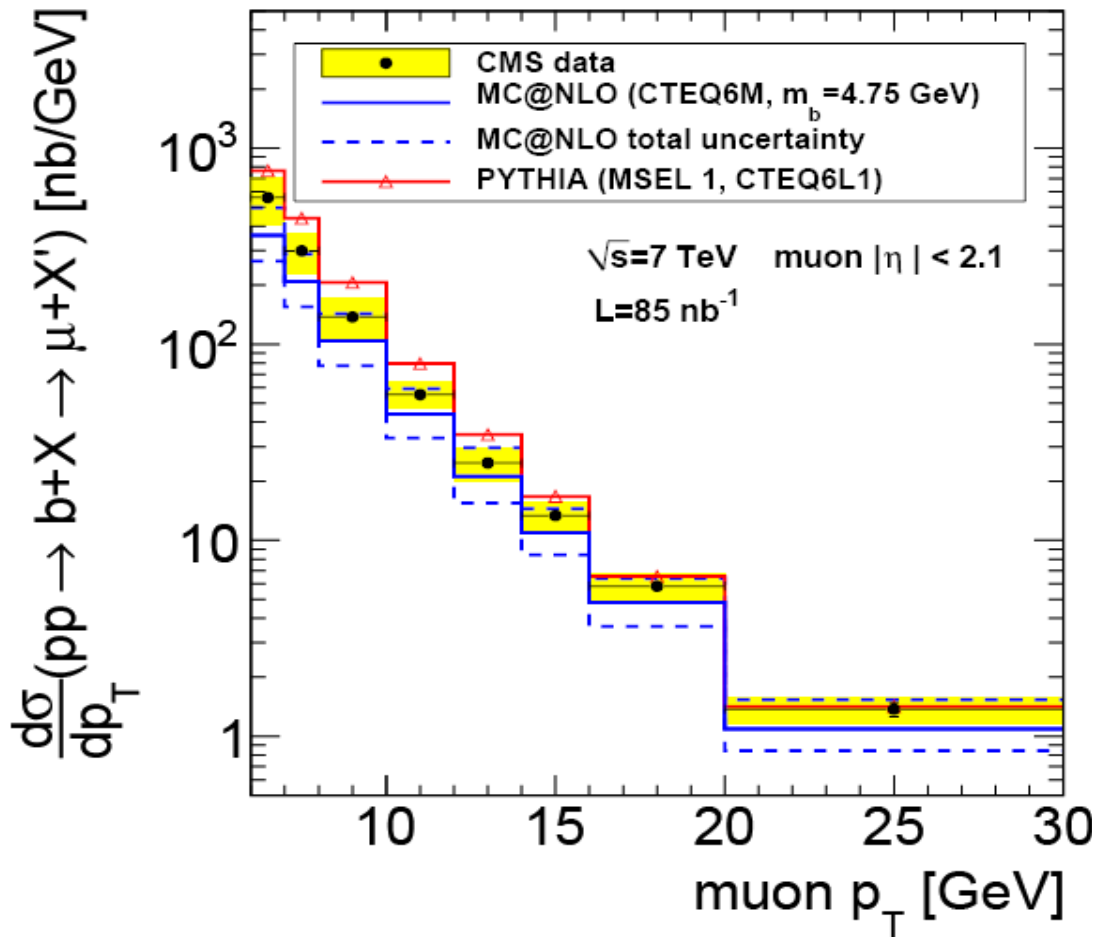
Exclusive B-hadron Production



Inclusive B-hadron Production: Vertex Tag

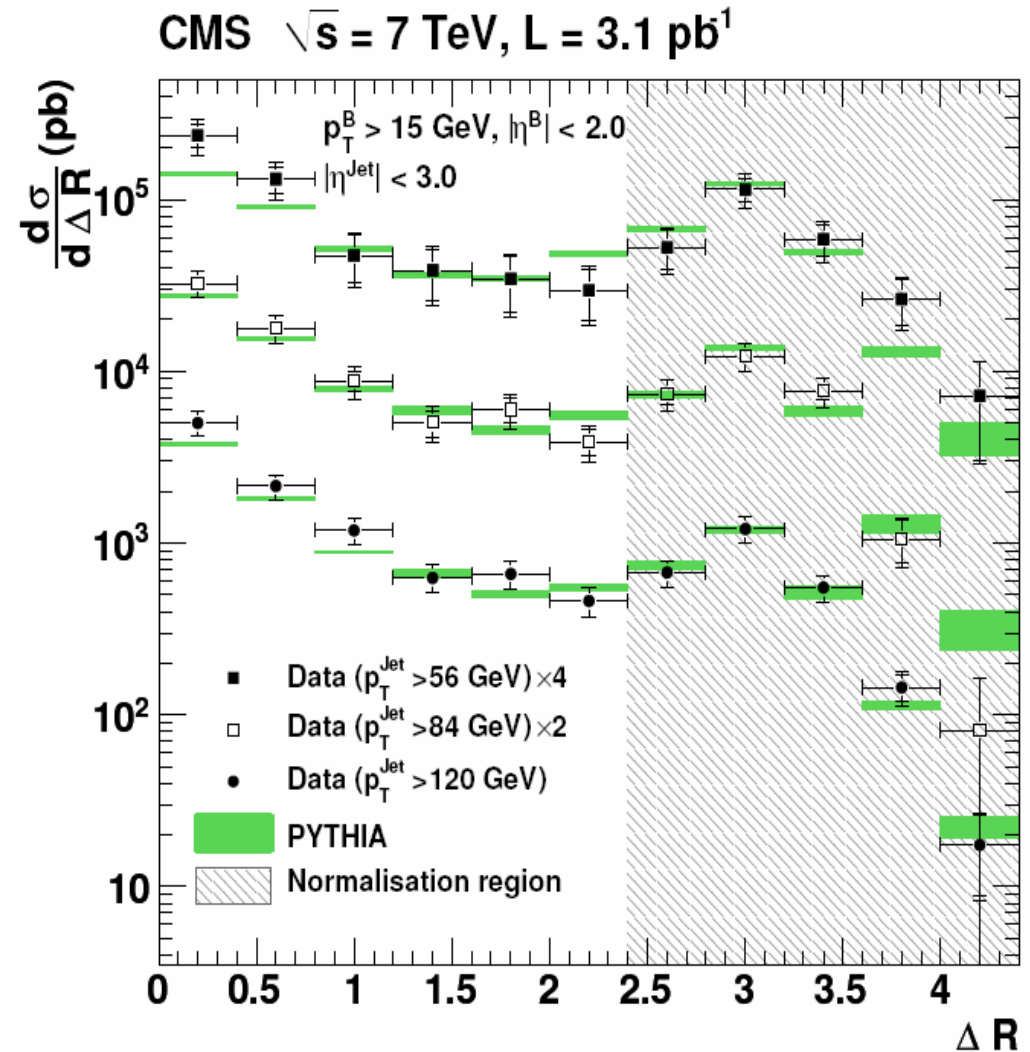


Inclusive B-hadron Production: μ Tag

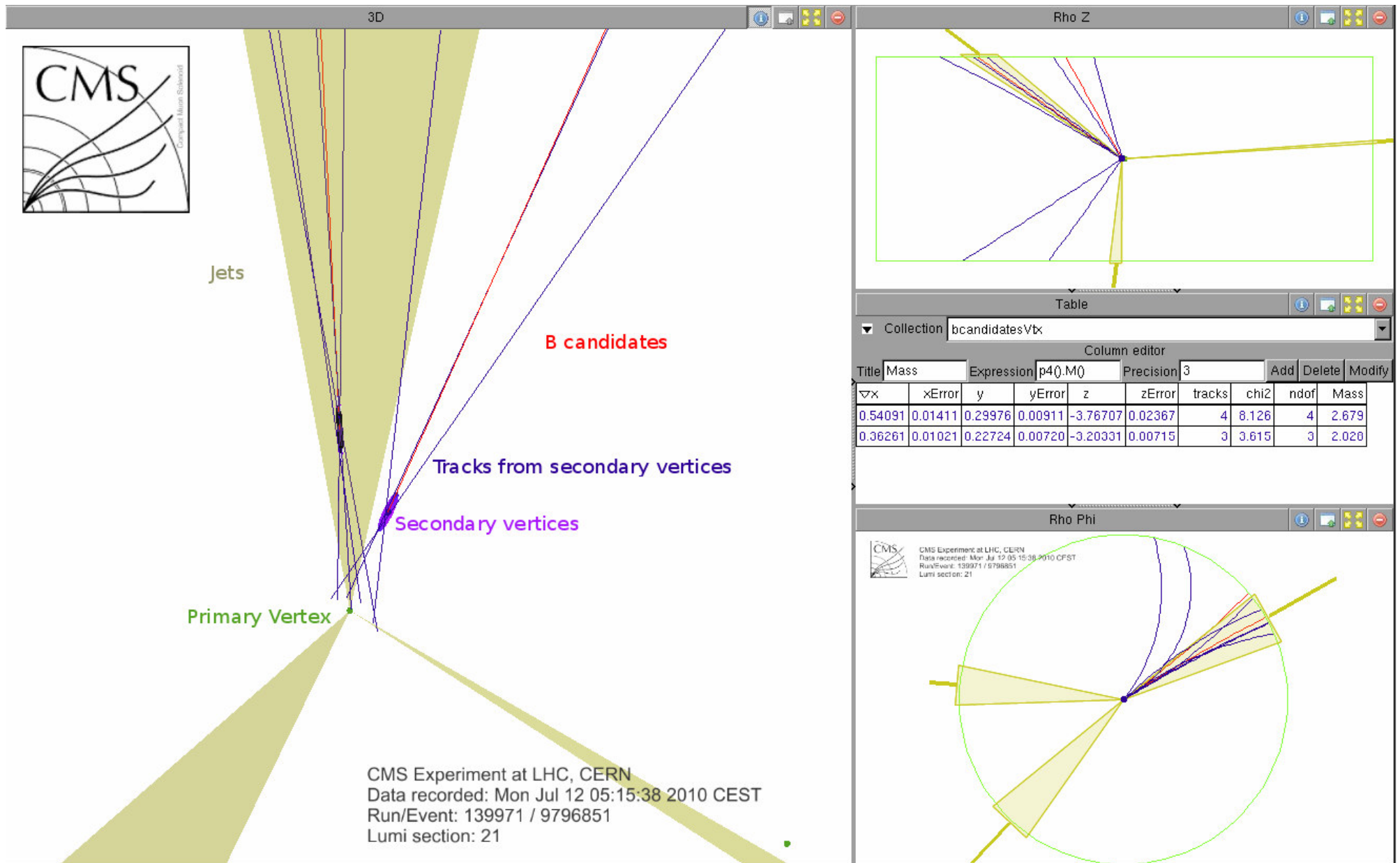


BB correlations

- Angular correlations in BB production.
- Use powerful Secondary Vertex reconstruction to probe the small angle region.
- ❑ Normalize to back-to-back production (LO).
- ❑ Look for two Bs inside single jet (gluon splitting).
- Very large differences in generator predictions.

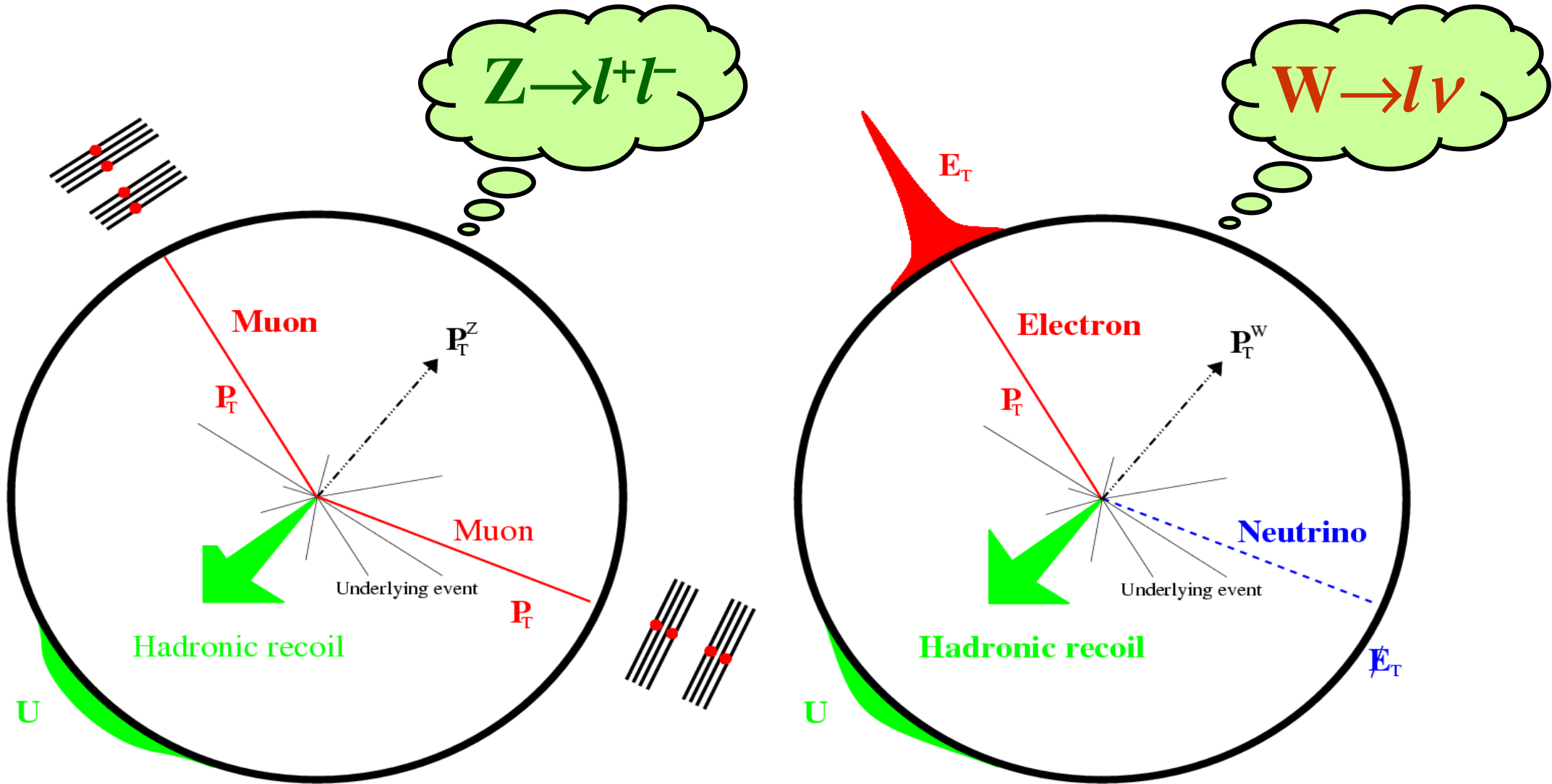


BB correlations



3. ELECTROWEAK PHYSICS

Signature of W/Z Decays

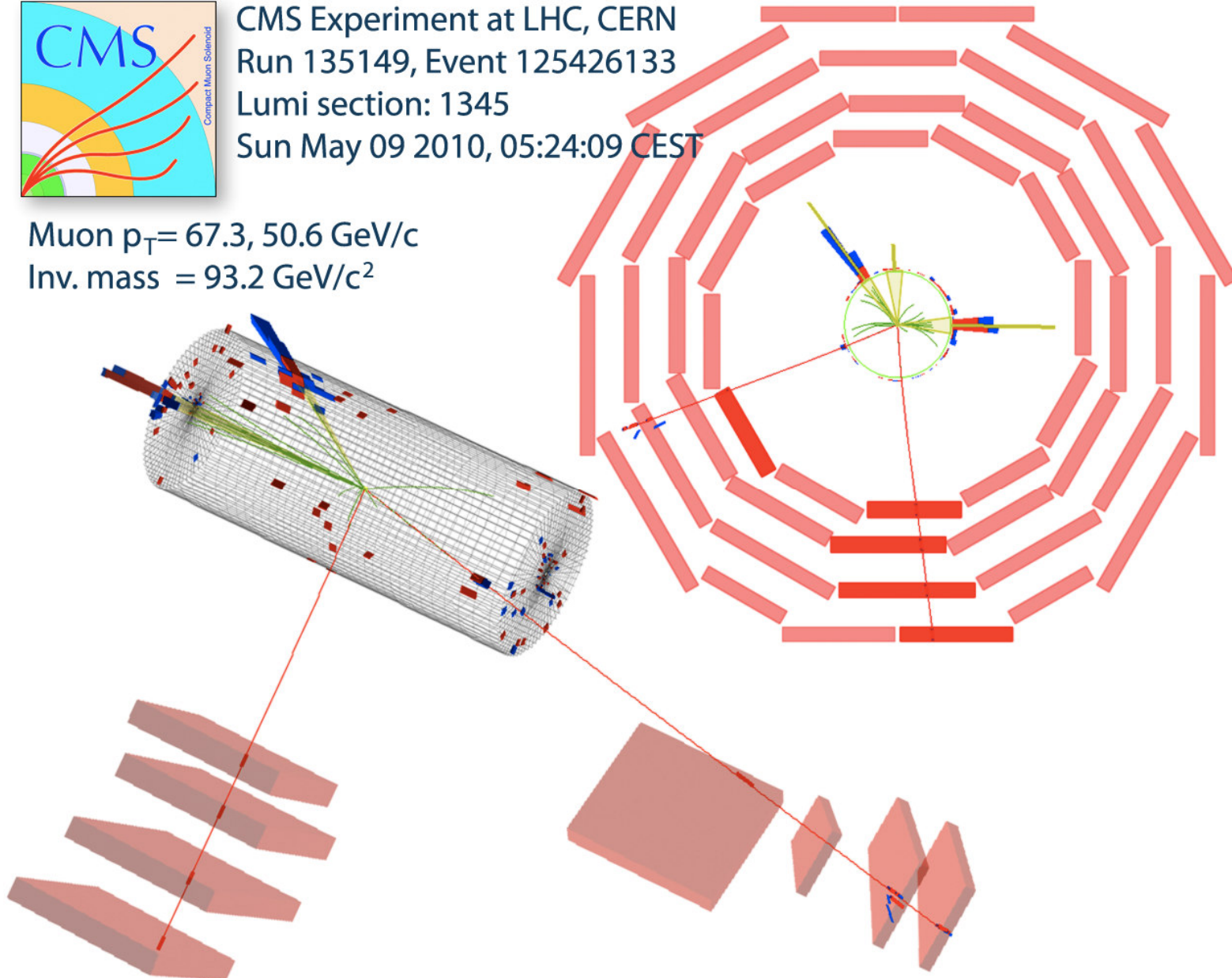


Signature of W/Z Decays



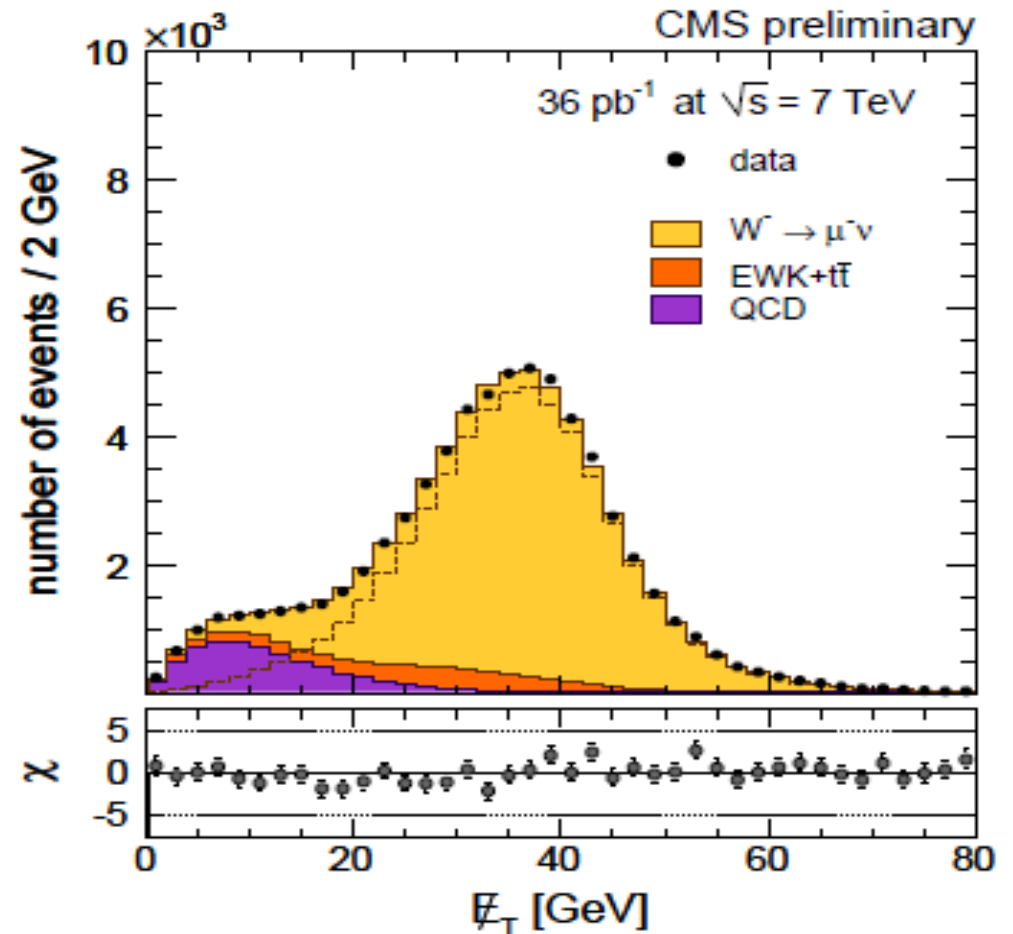
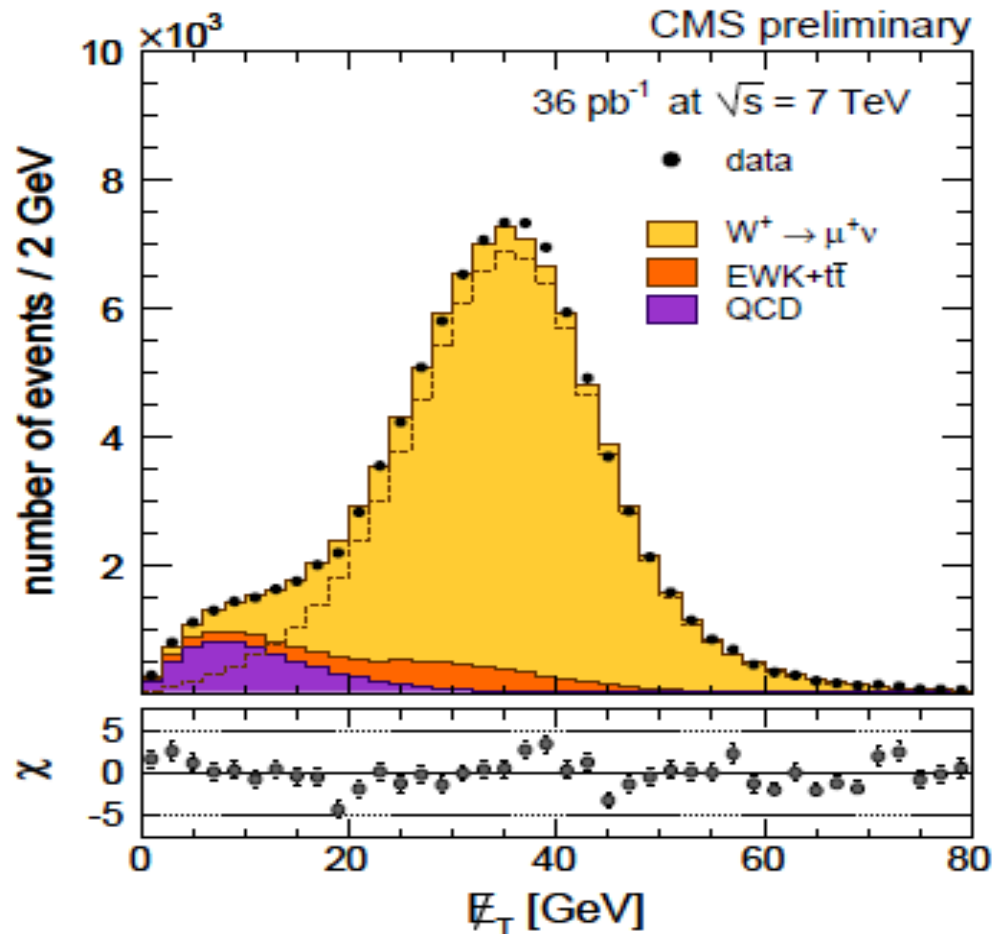
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

Muon $p_T = 67.3, 50.6$ GeV/c
Inv. mass = 93.2 GeV/c²



W Production

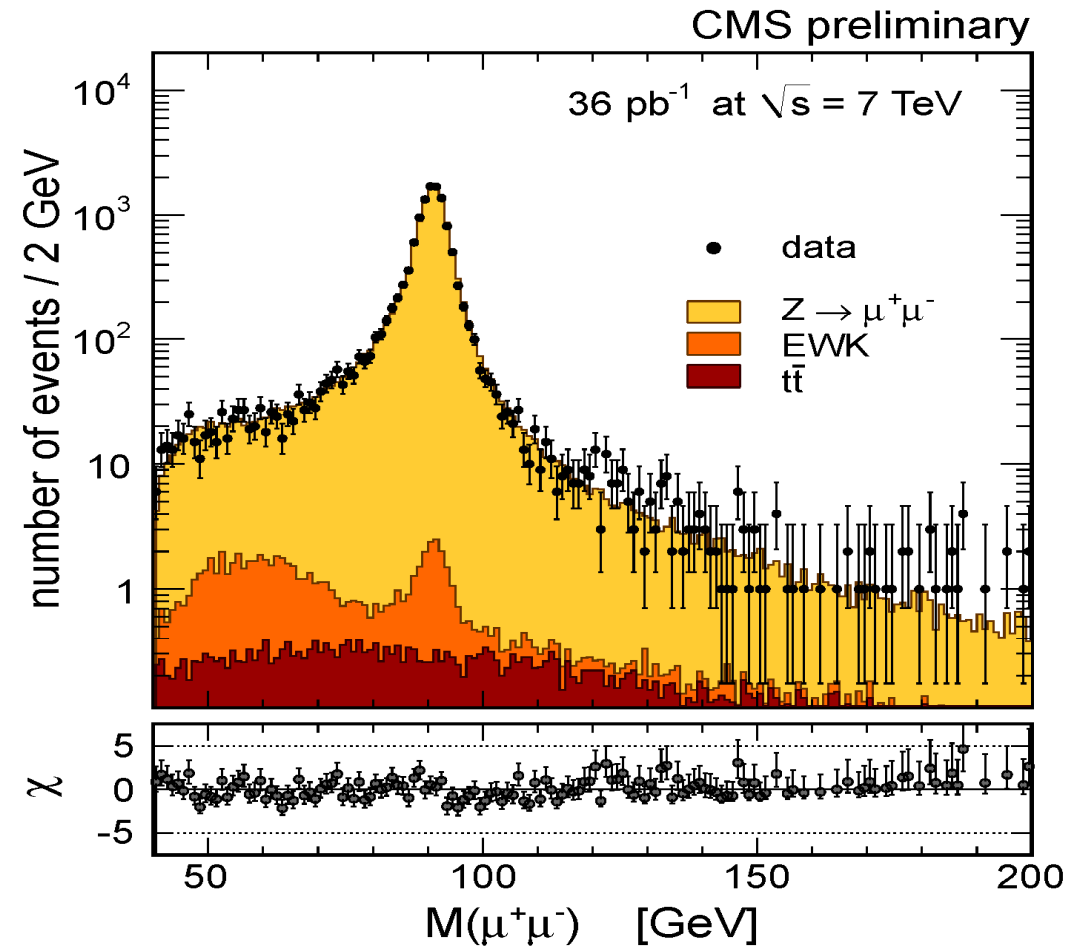
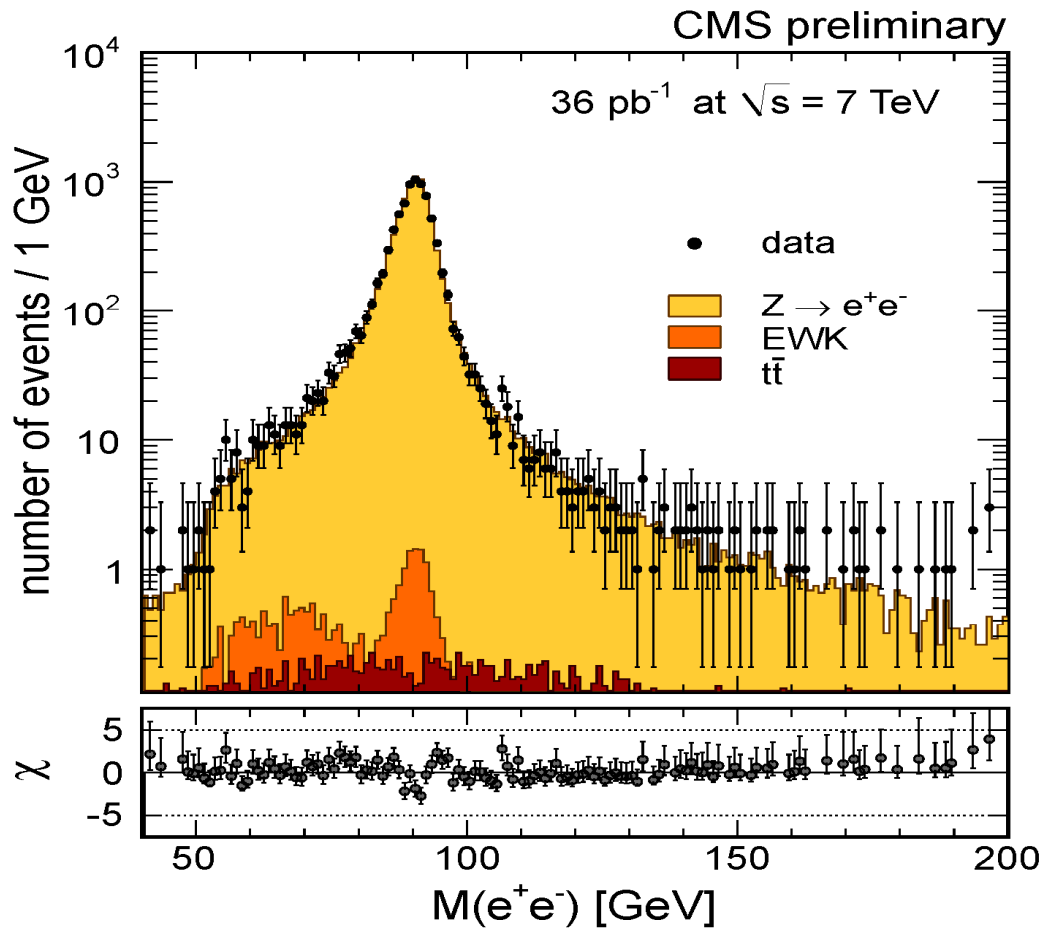
> 10^5 $W \rightarrow l\nu$ events in 2010 data.



Fit missing E_T distribution for W^+ and W^- separately.

Z Production

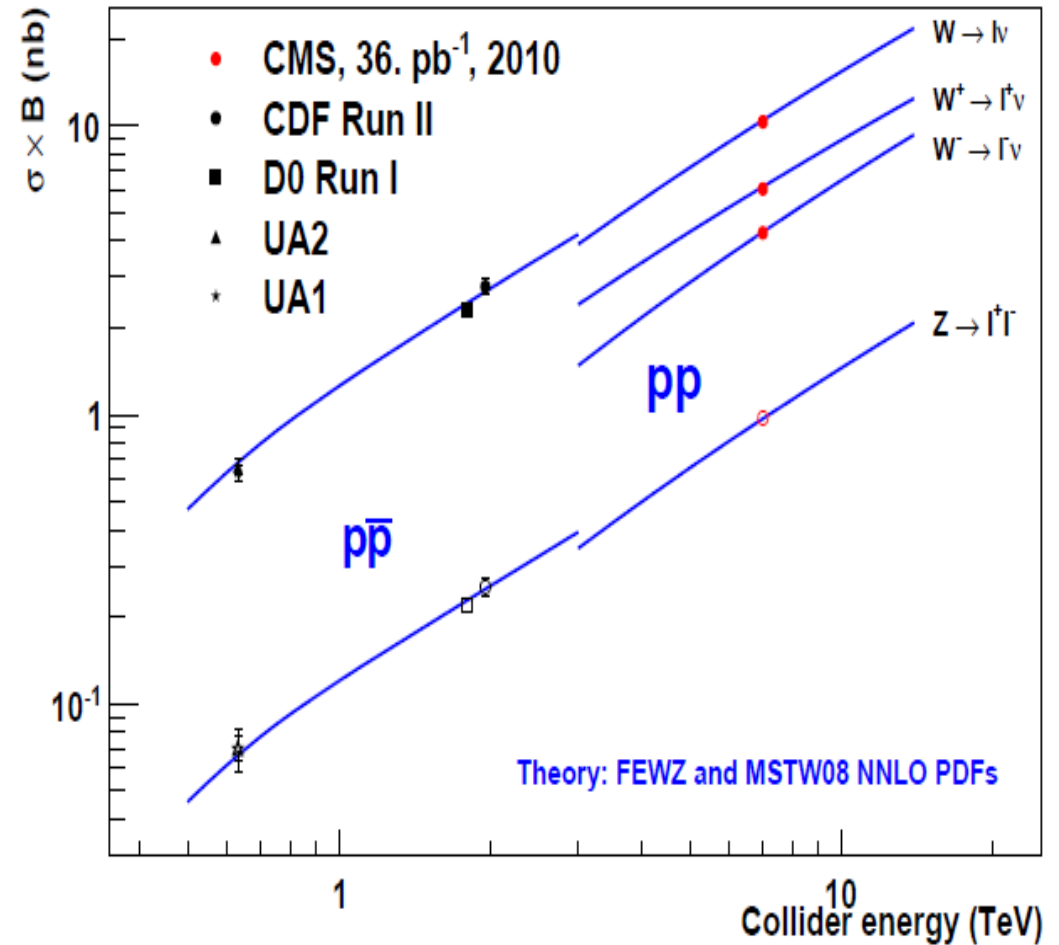
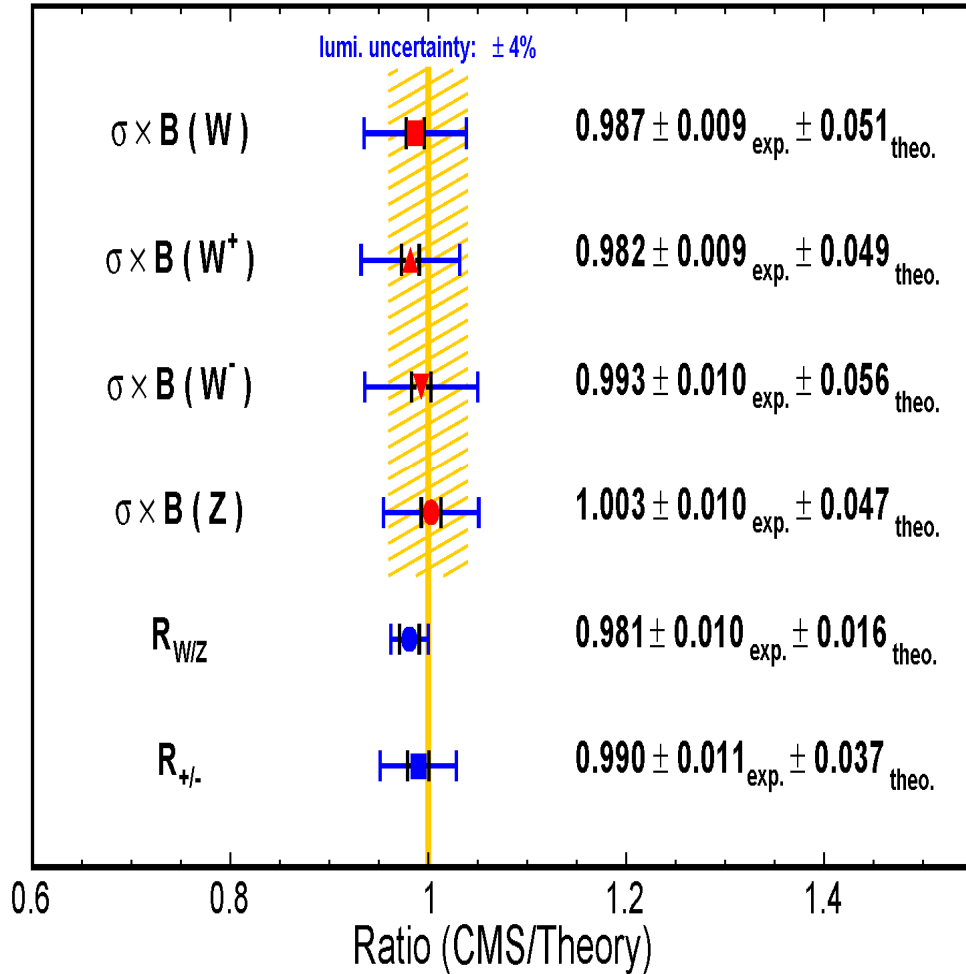
> 10^4 $Z \rightarrow l^+l^-$ events in 2010 data.



Fit M_{ll} distribution; almost background free analysis.

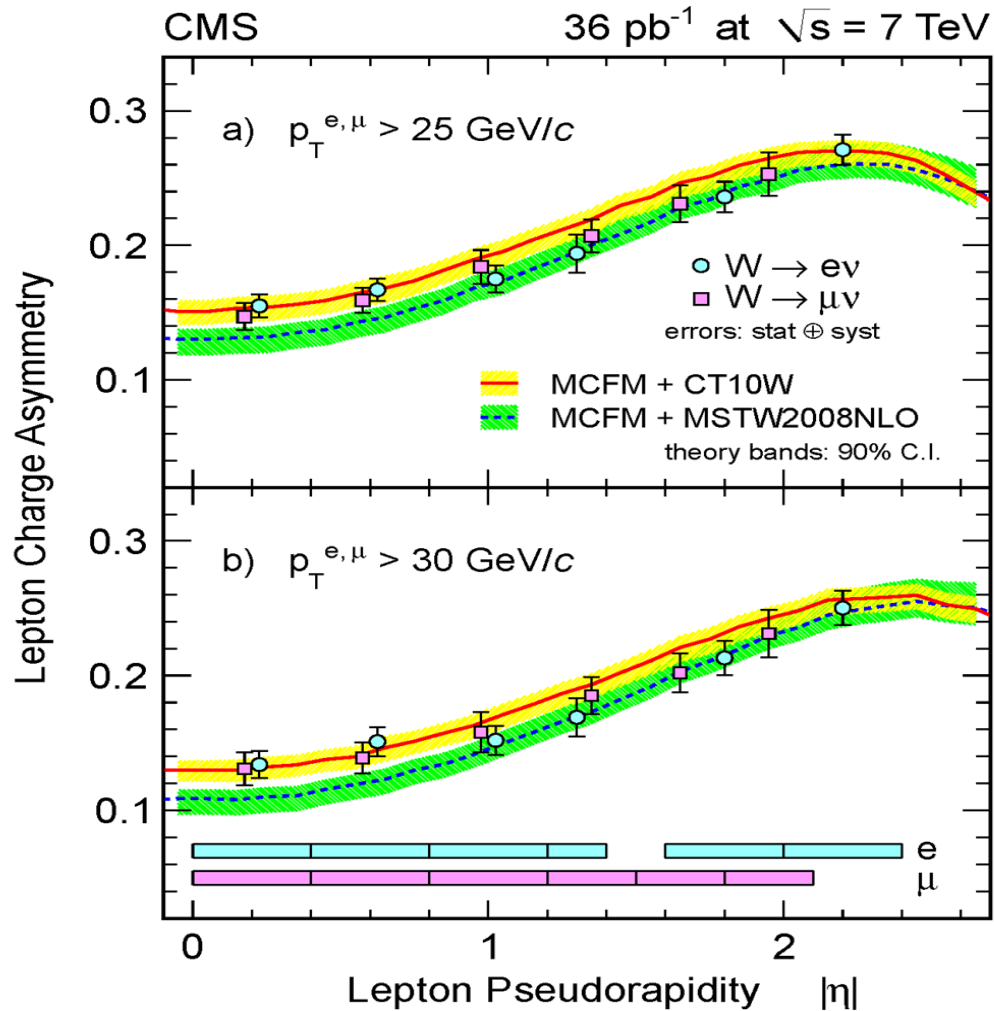
W/Z Cross Sections

CMS 36 pb⁻¹ at $\sqrt{s} = 7$ TeV

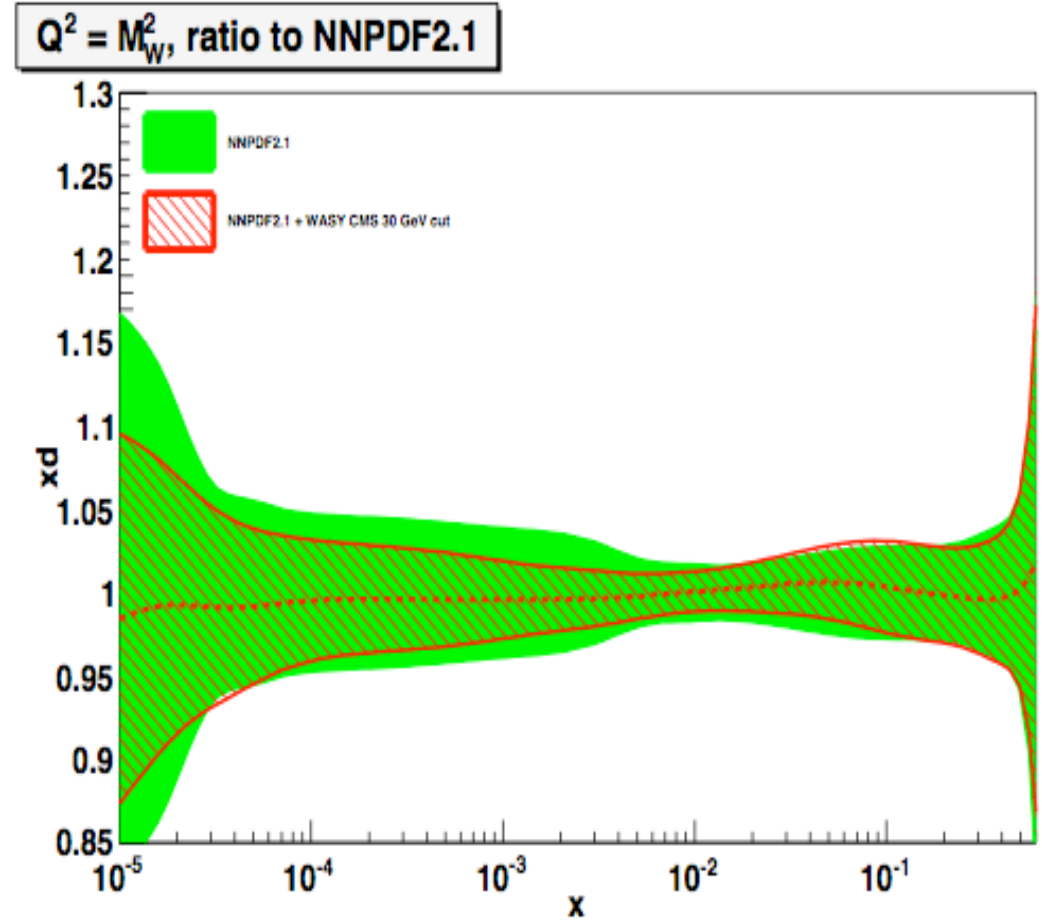


Good agreement with theoretical NNLO predictions.

W Lepton Charge Asymmetry

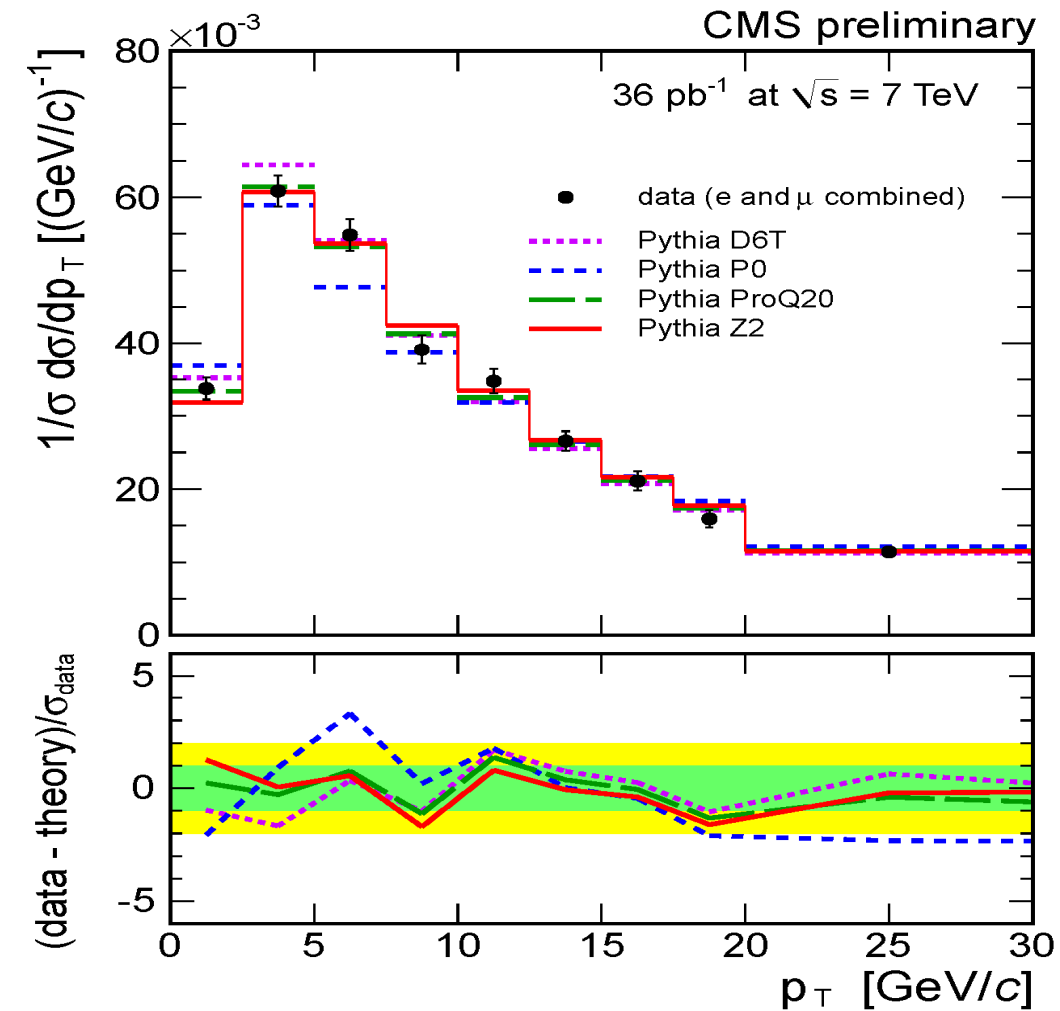


Sensitive to PDFs; complementary to other LHC experiments.

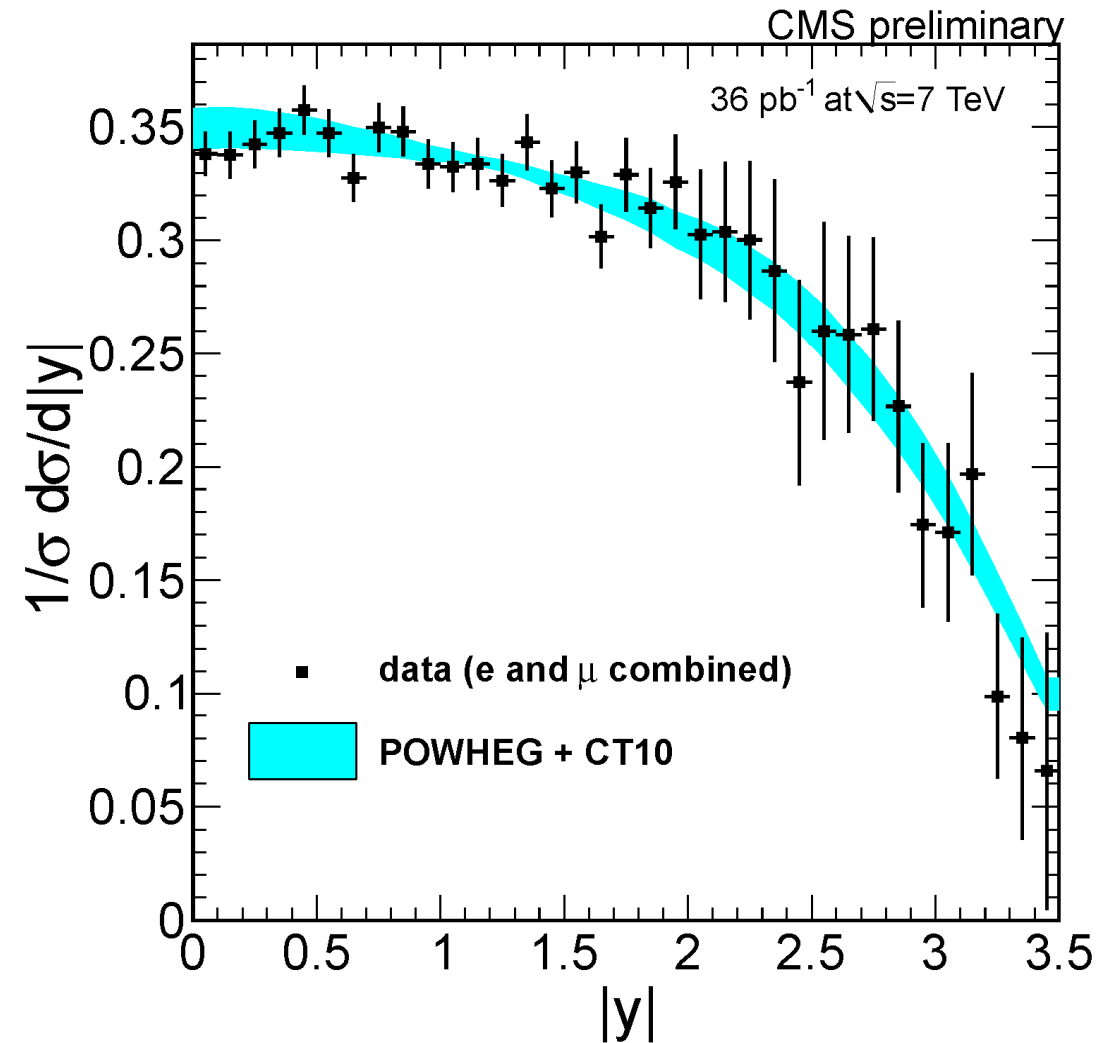


CMS results improve quark PDFs by $> 40\%$ in range $10^{-3} < x < 10^{-2}$.

Z Differential Distributions

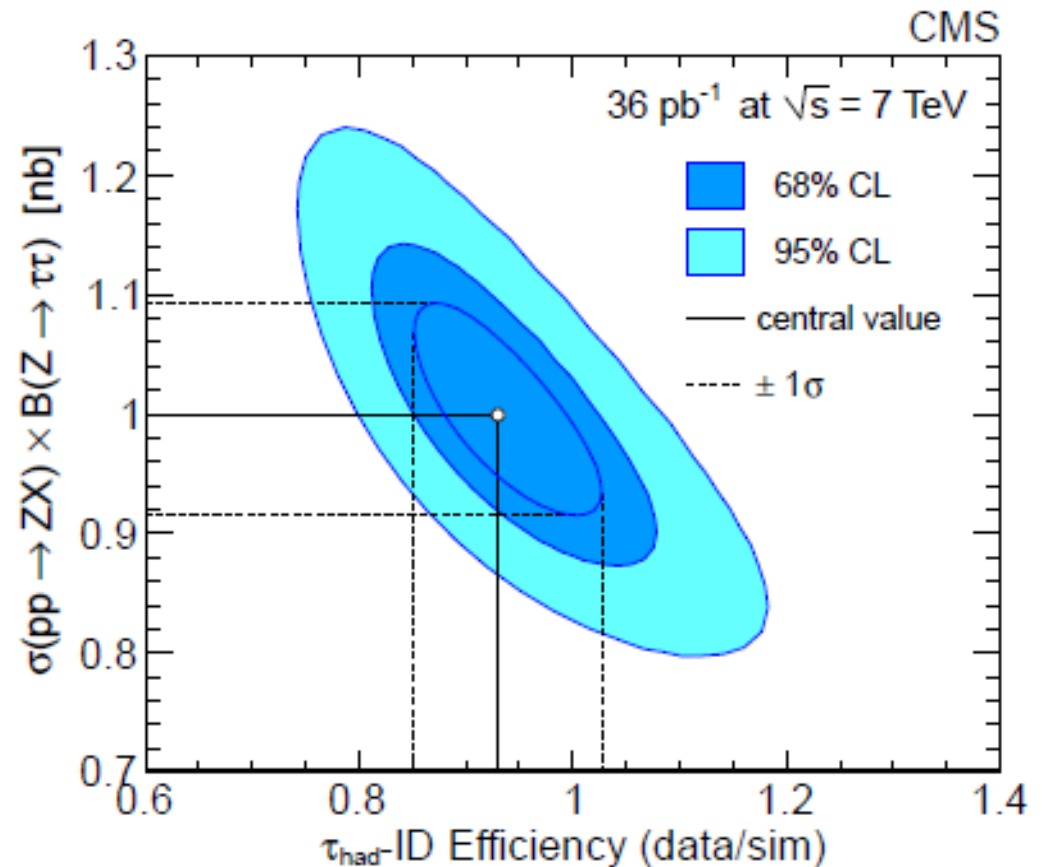
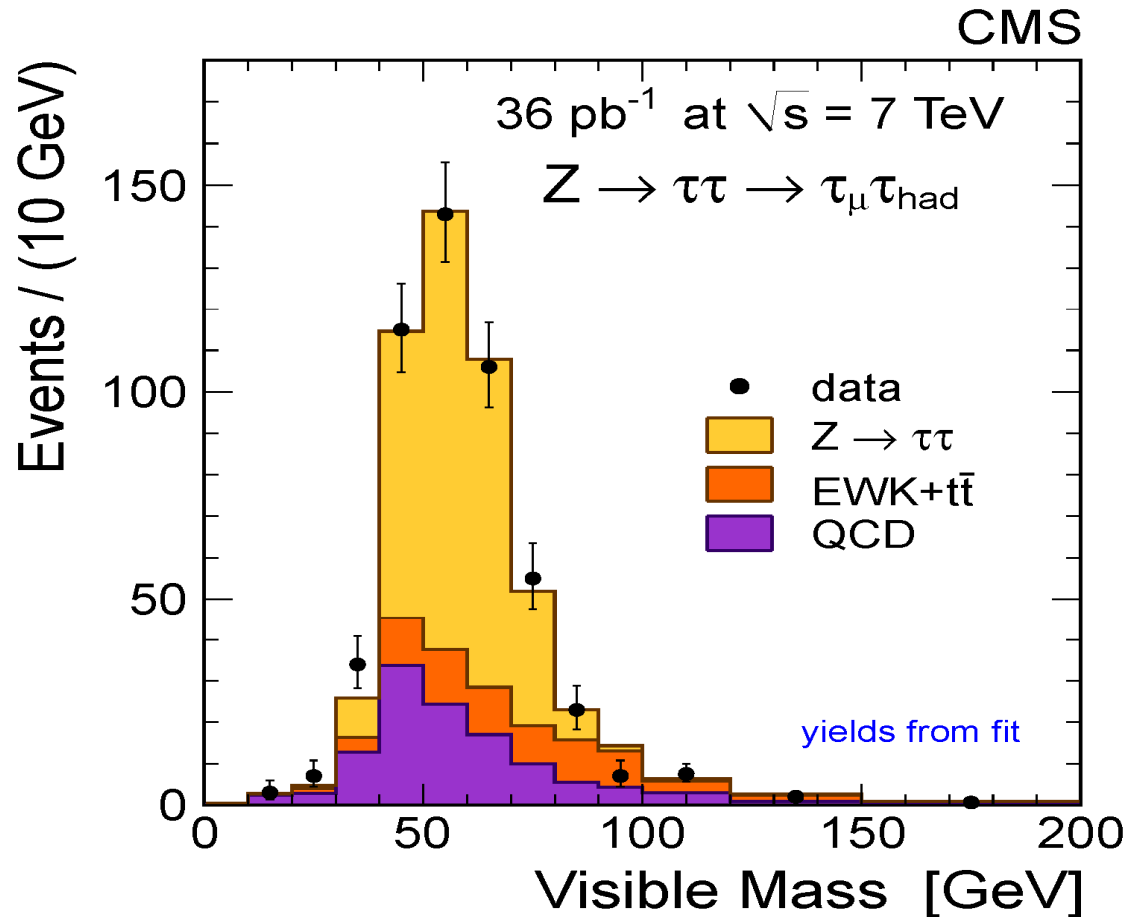


Z p_T well reproduced by latest PYTHIA predictions.



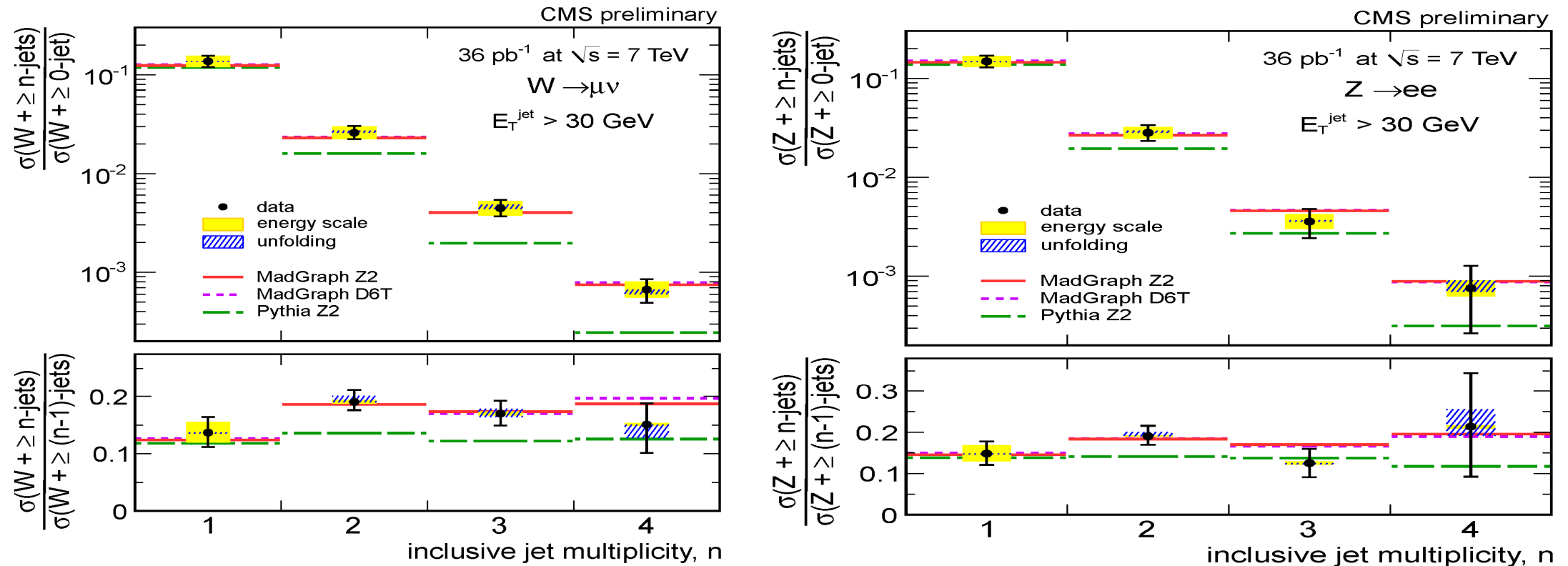
Z rapidity sensitive to PDFs.

$Z \rightarrow \tau\tau$ Production



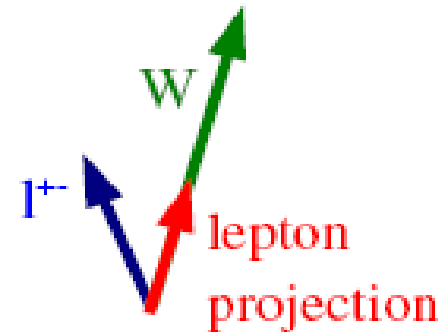
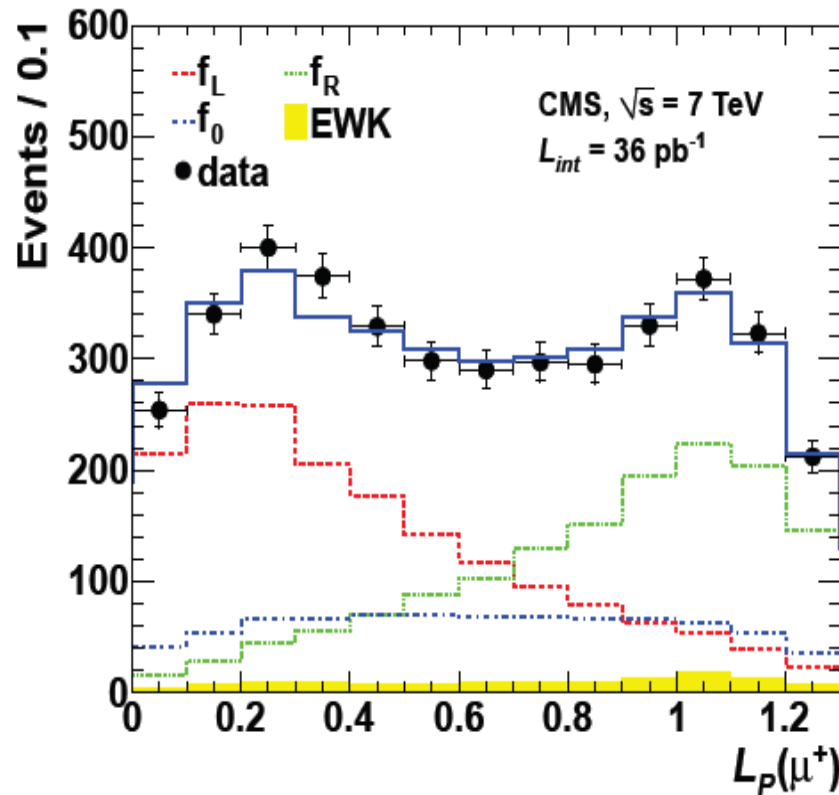
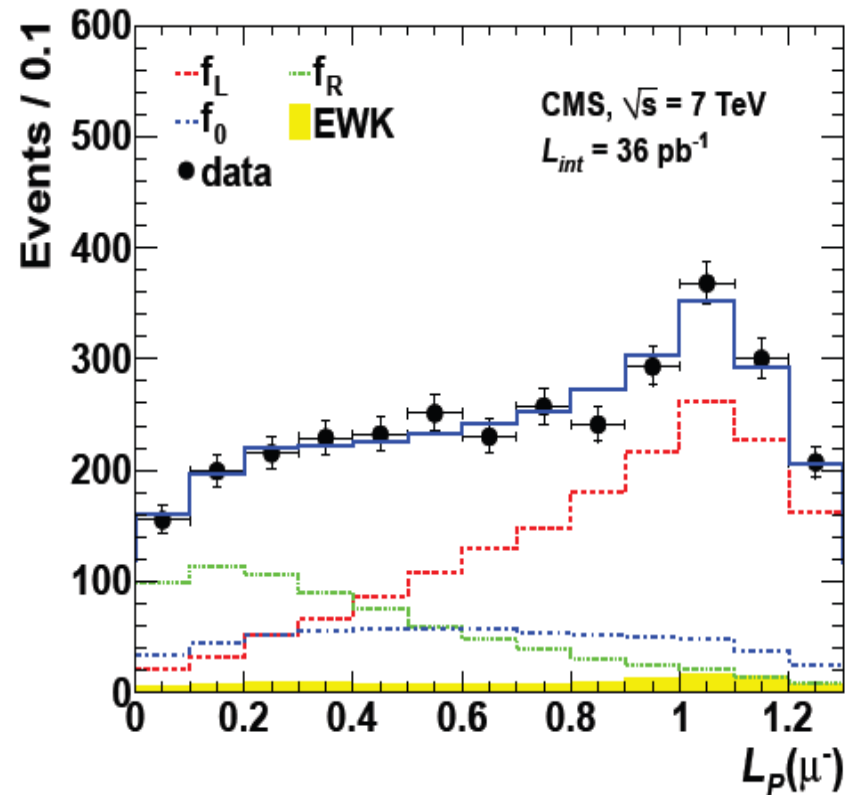
- ❑ Special effort to determine efficiencies and background using data-driven methods.
- ❑ Big improvement in τ -id with respect to PTDR expectations.

W/Z + Jets



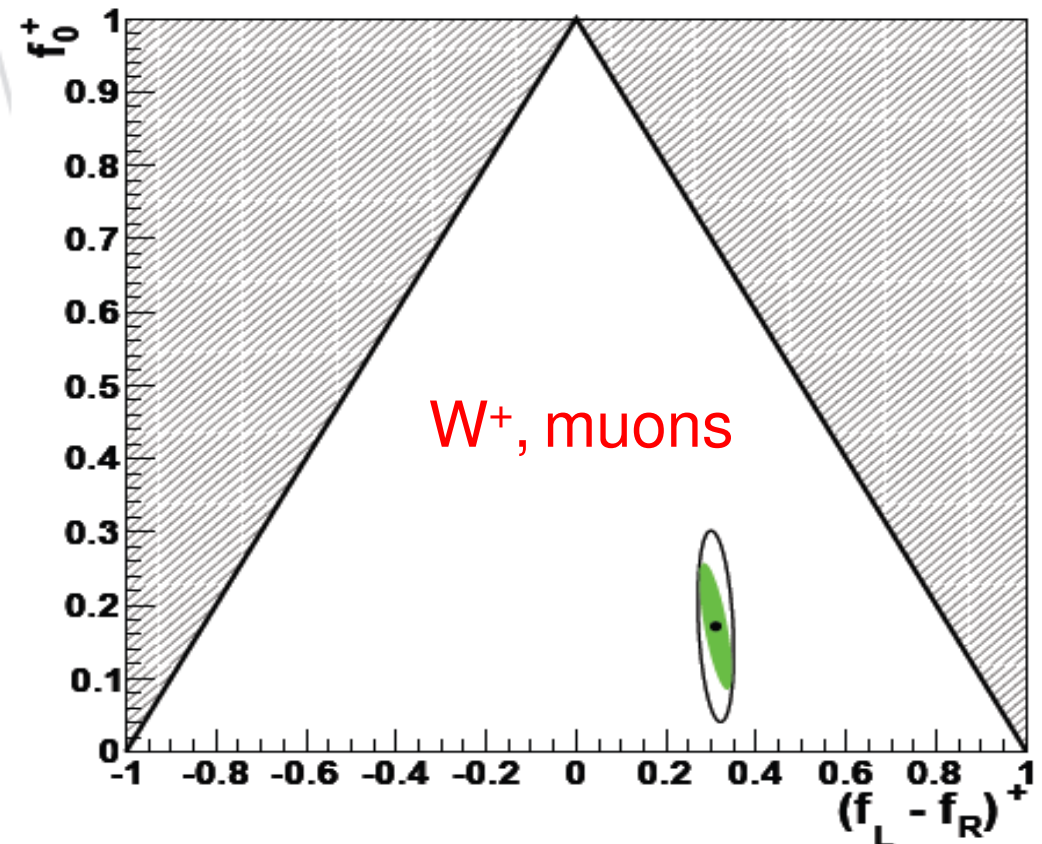
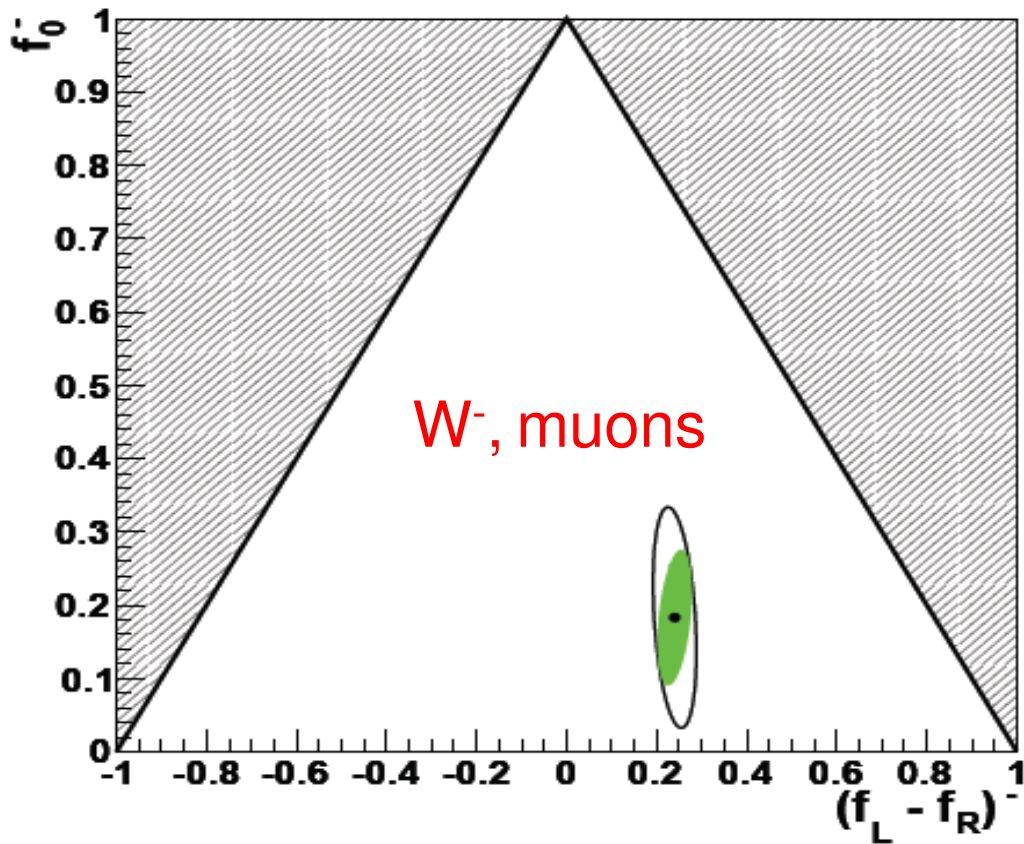
- ❑ Results agree with MADGRAPH prediction (LO for each jet multiplicity).
- ❑ PYTHIA doesn't reproduce the data (expected to describe up to 1 hard jet + radiation).

W Polarization



- At LHC, W bosons exhibit a significant polarization when produced in association with hard jets.
- Polarization depends on the proportions of $q\bar{q}$, gq and $g\bar{q}$ contributions.
- At high p_T no need to estimate the longitudinal momentum of the neutrino.

W Polarization

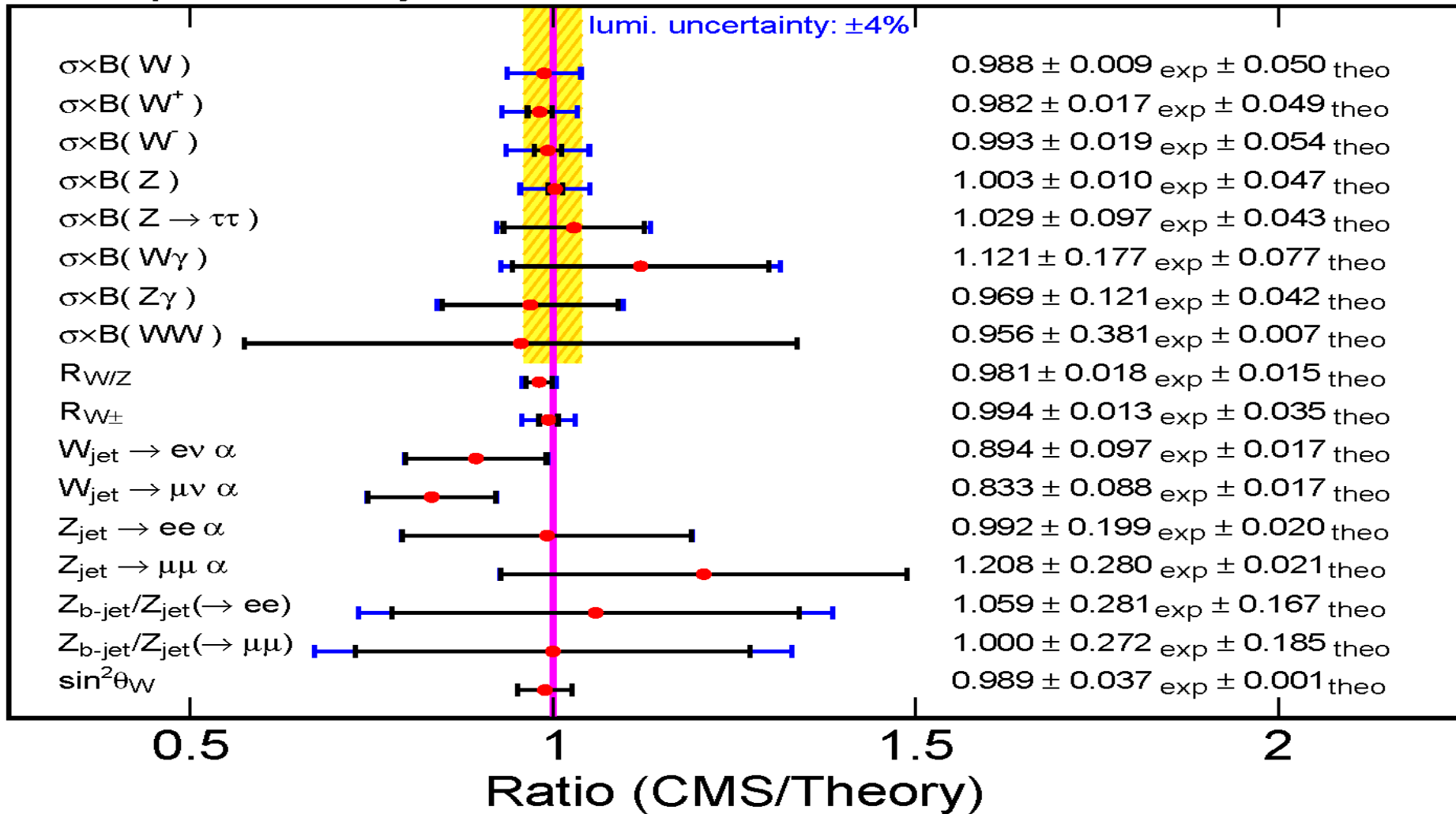


- ❑ Clear observation of W polarization at LHC.
- ❑ Potentially useful for new particle searches, where W polarization may differ significantly.

CMS EWK Results

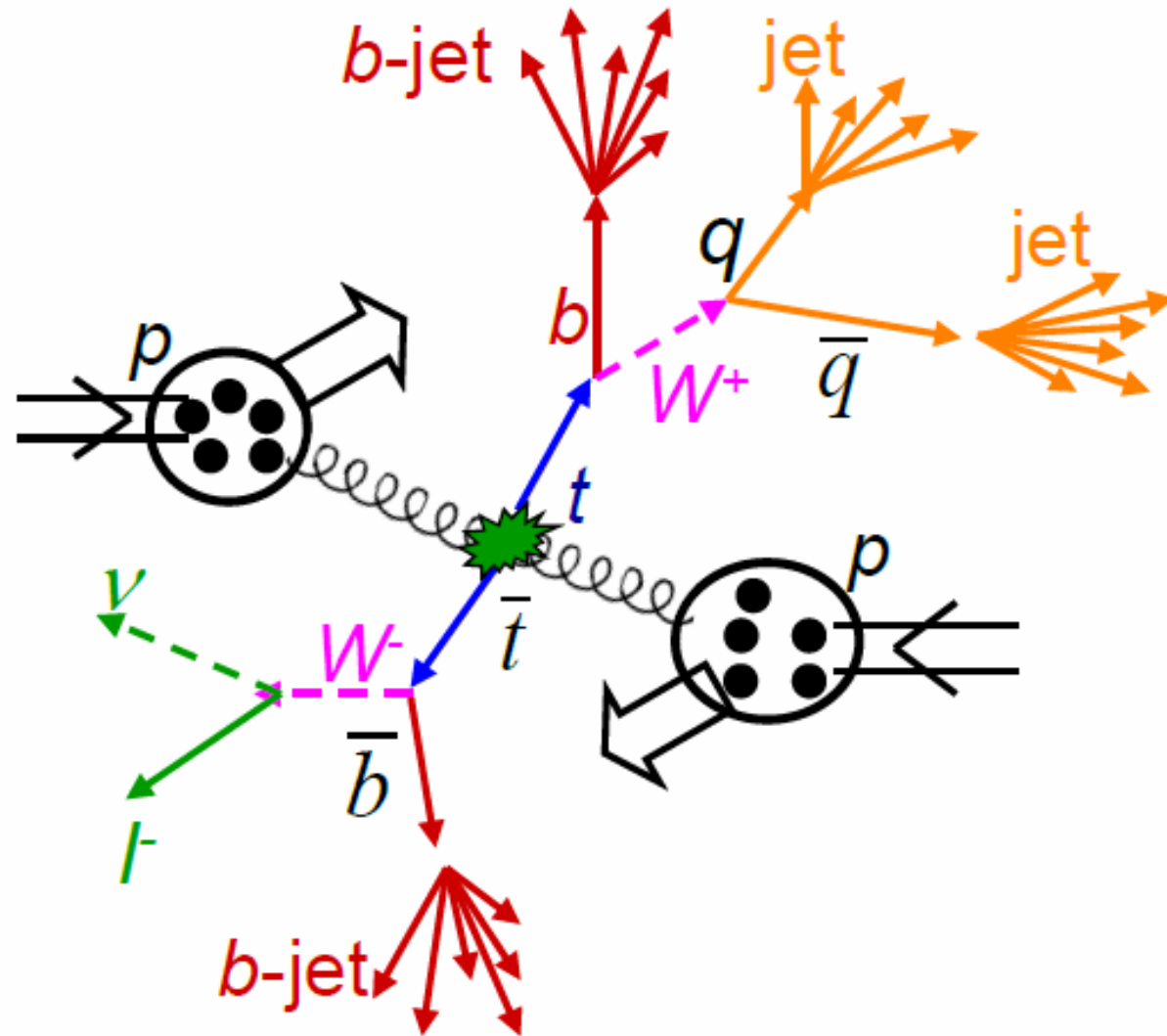
CMS preliminary

36 pb⁻¹ at $\sqrt{s} = 7$ TeV



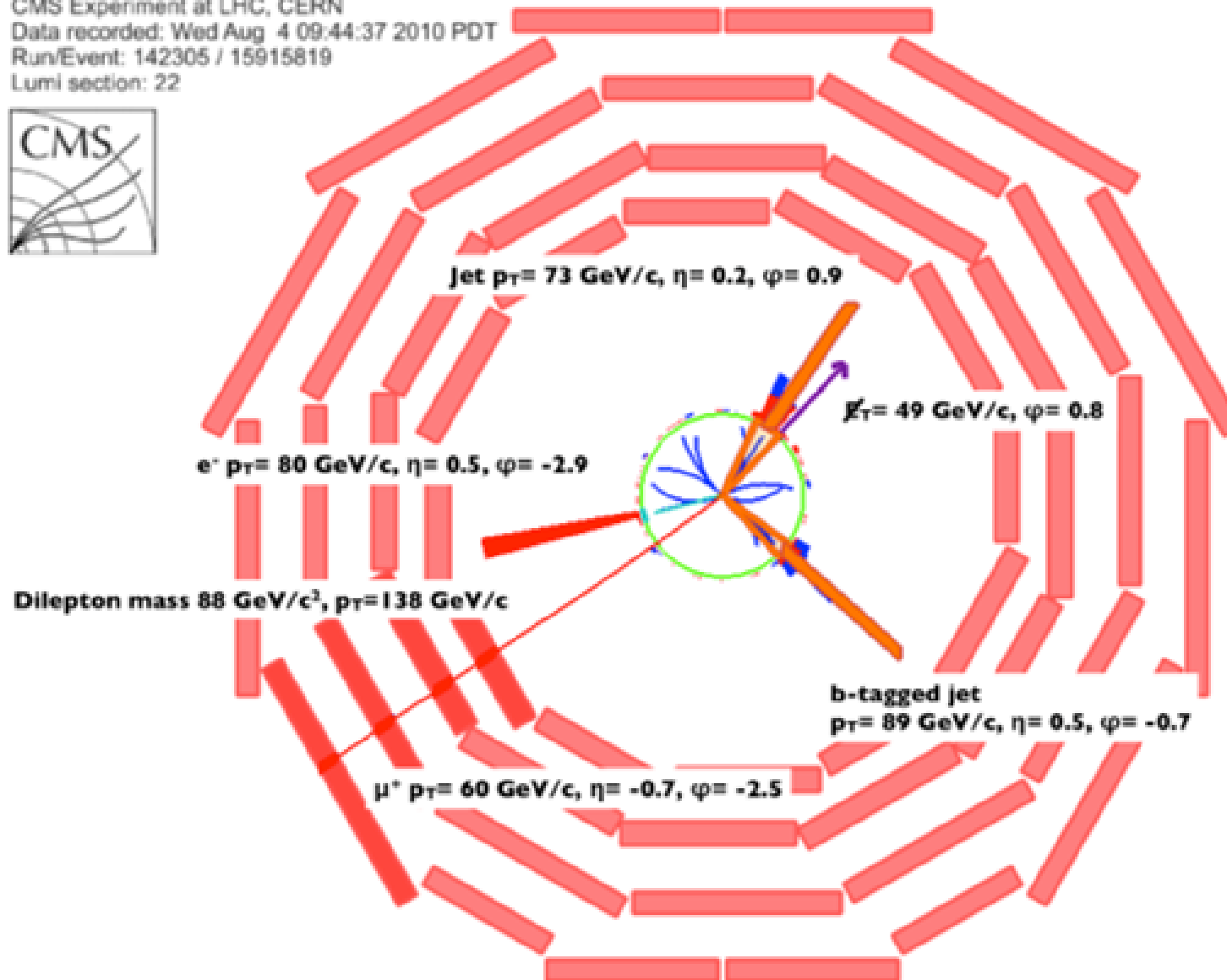
4. TOP PHYSICS

Top Production

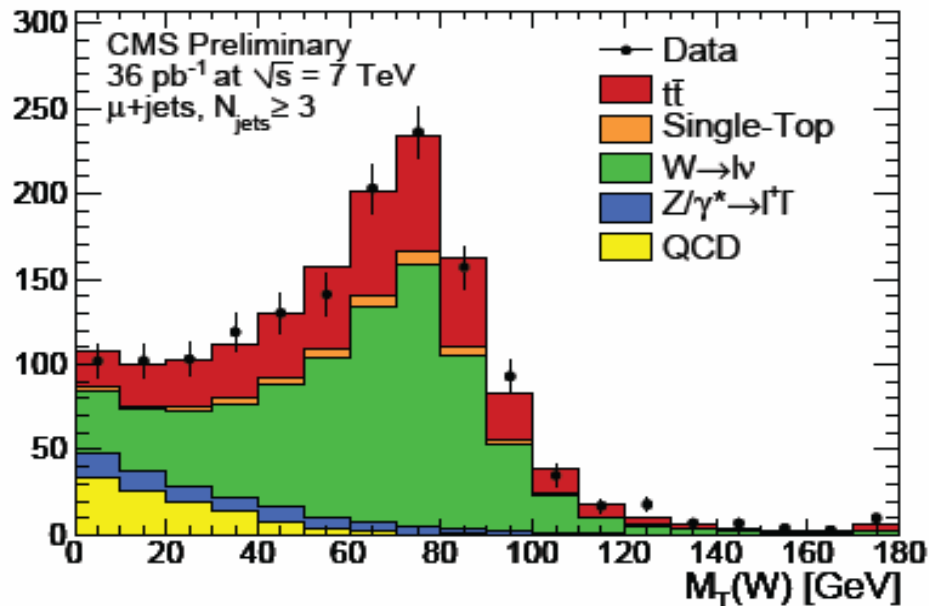
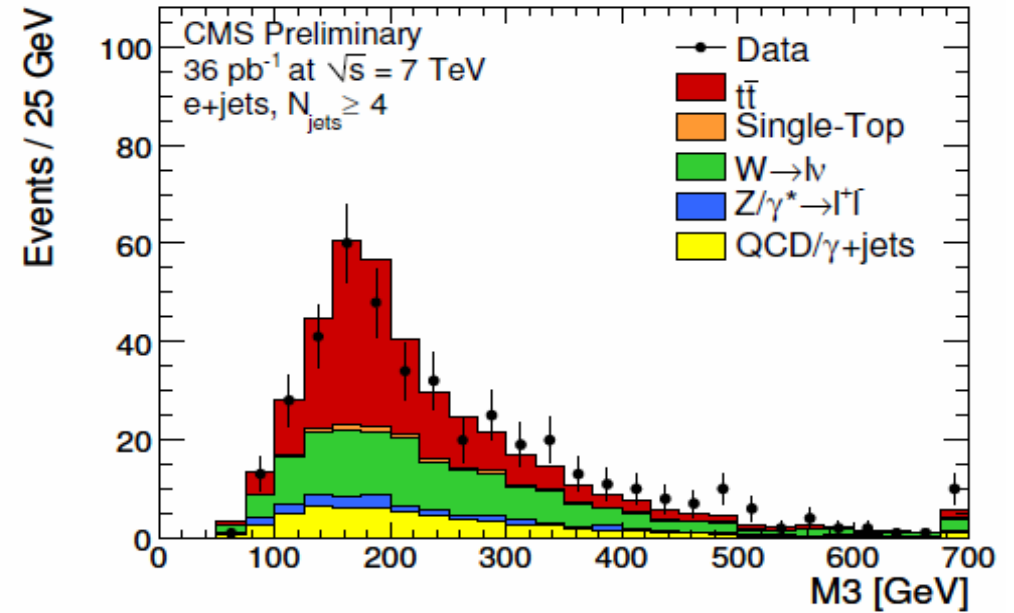
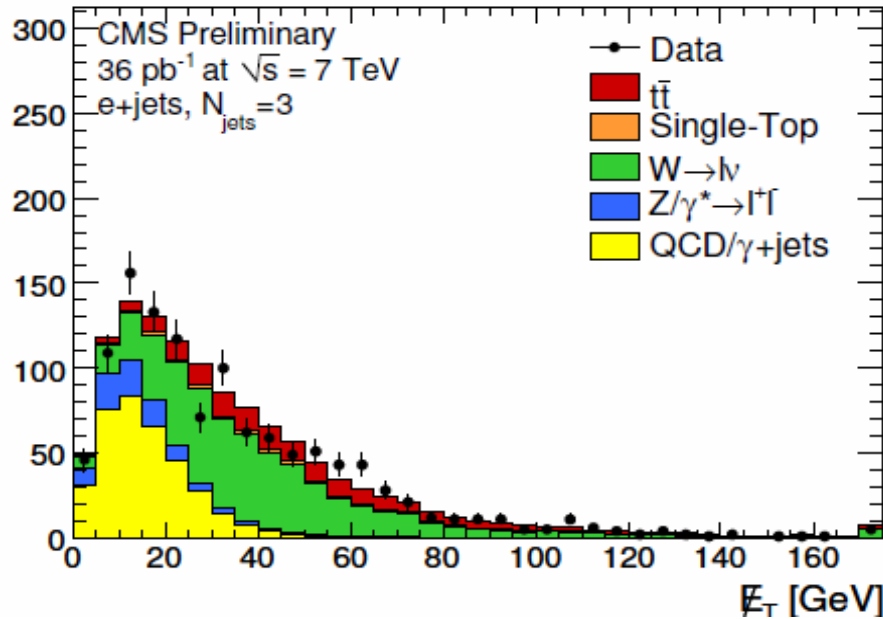


Top Production

CMS Experiment at LHC, CERN
Data recorded: Wed Aug 4 09:44:37 2010 PDT
Run/Event: 142305 / 15915819
Lumi section: 22

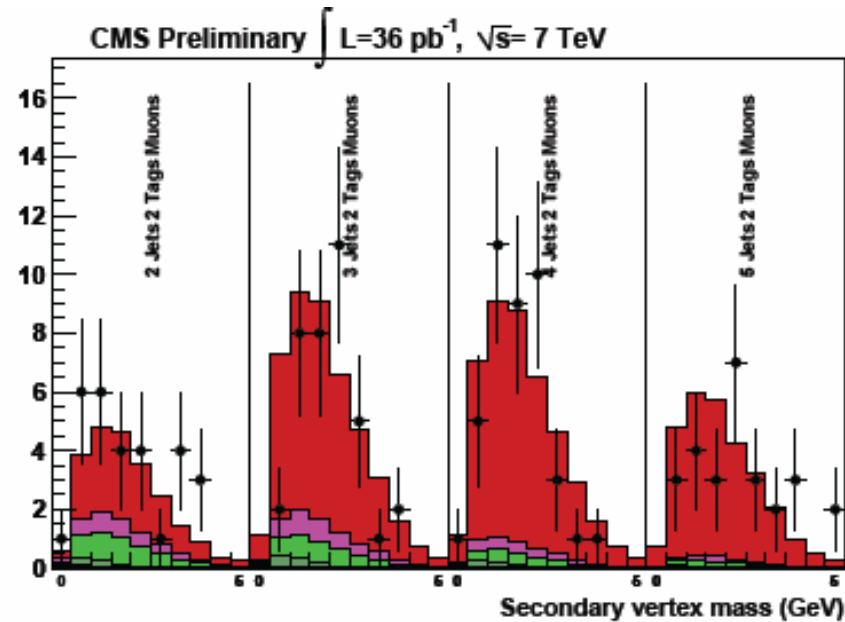
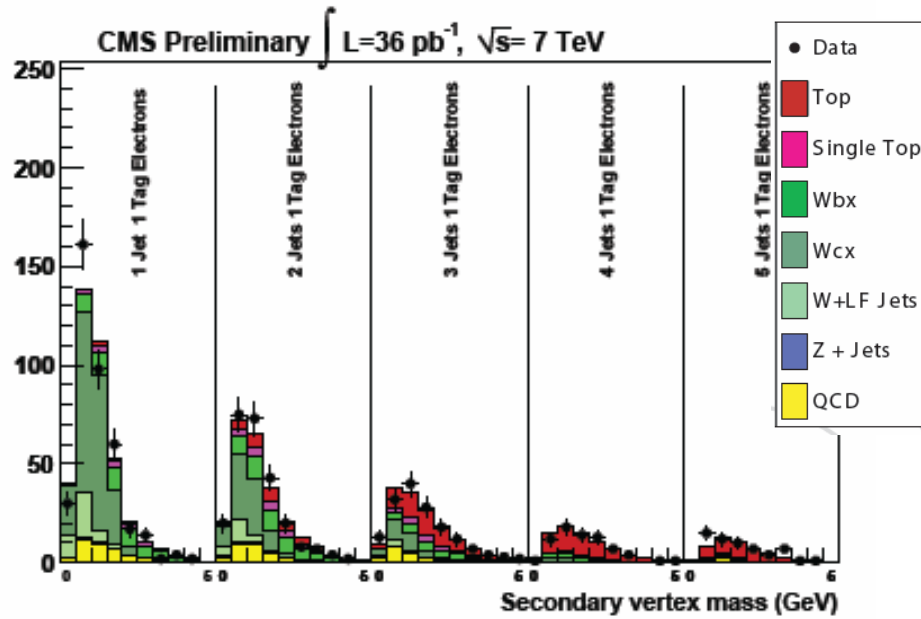


ttbar Cross Section in l+jets w/o B-tagging

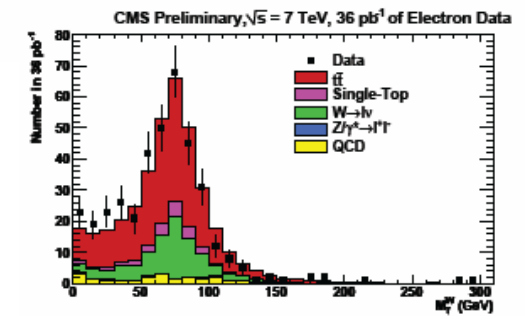
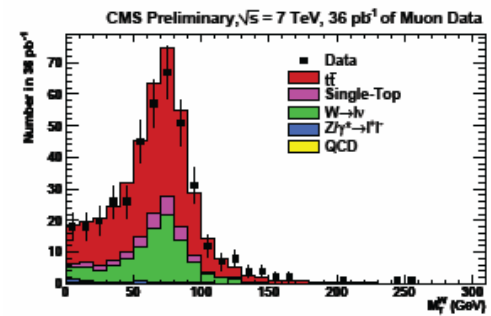
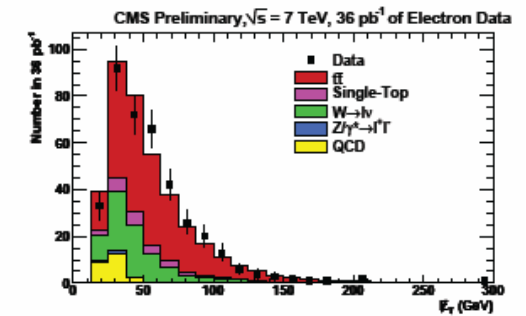
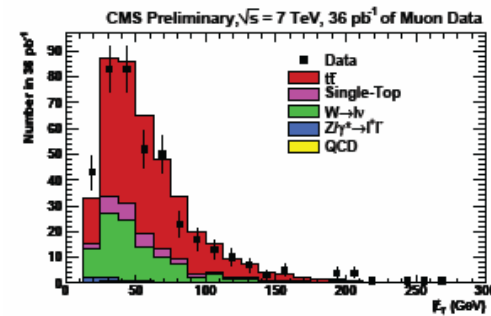
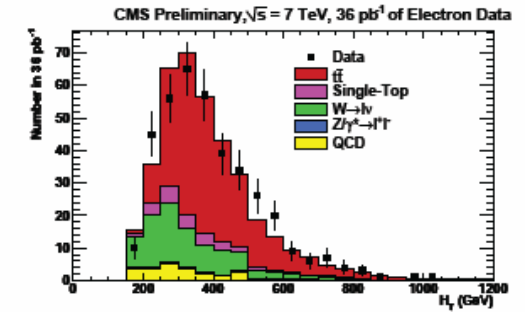
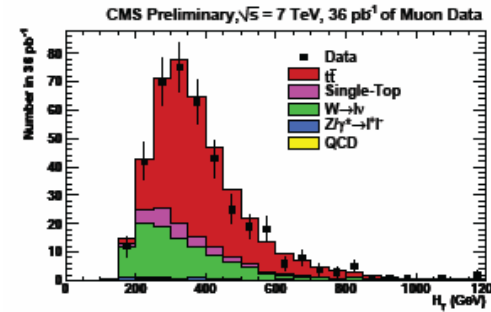


$$\sigma_{t\bar{t}} = 173_{-32}^{+39} (\text{stat} + \text{syst}) \pm 7 (\text{lumi}) \text{ pb}$$

ttbar Cross Section in l+jets w/ B-tagging

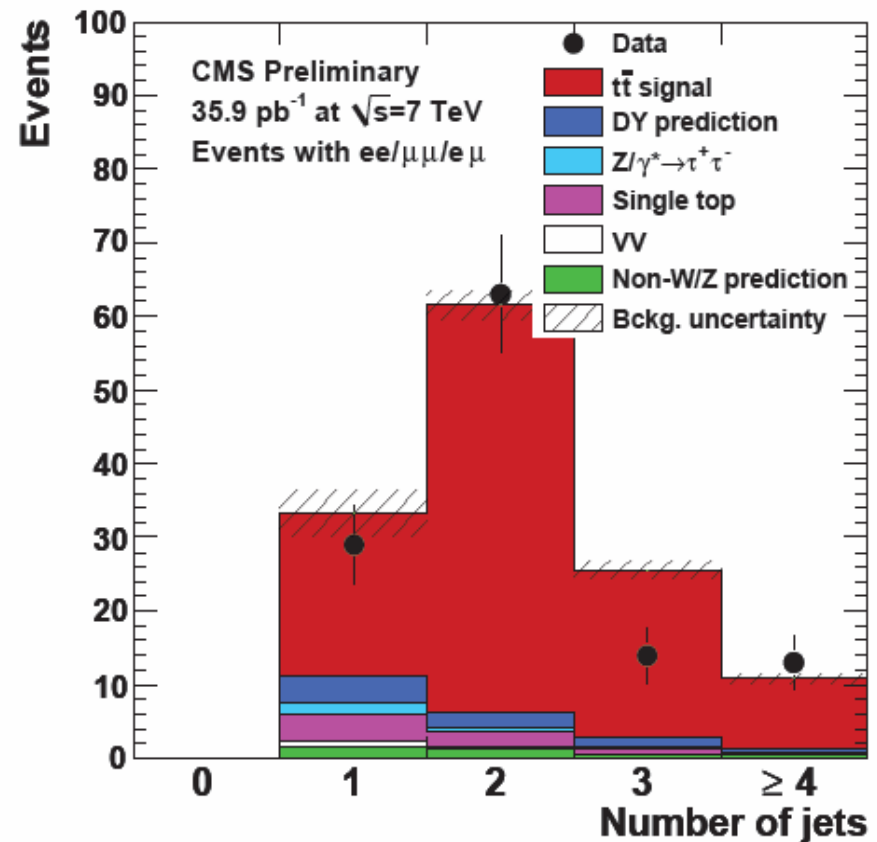
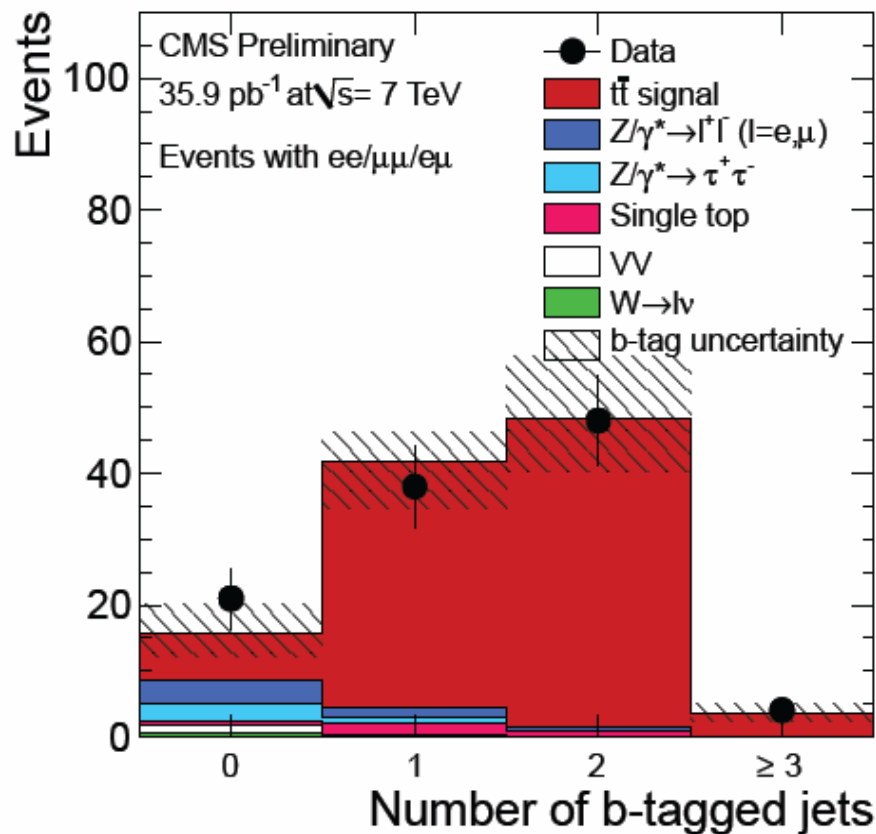


≥ 3 jets, ≥ 1 tag



$$\sigma_{t\bar{t}} = 150 \pm 9 \text{ (stat.)} \pm 17 \text{ (syst.)} \pm 6 \text{ (lum.) pb}$$

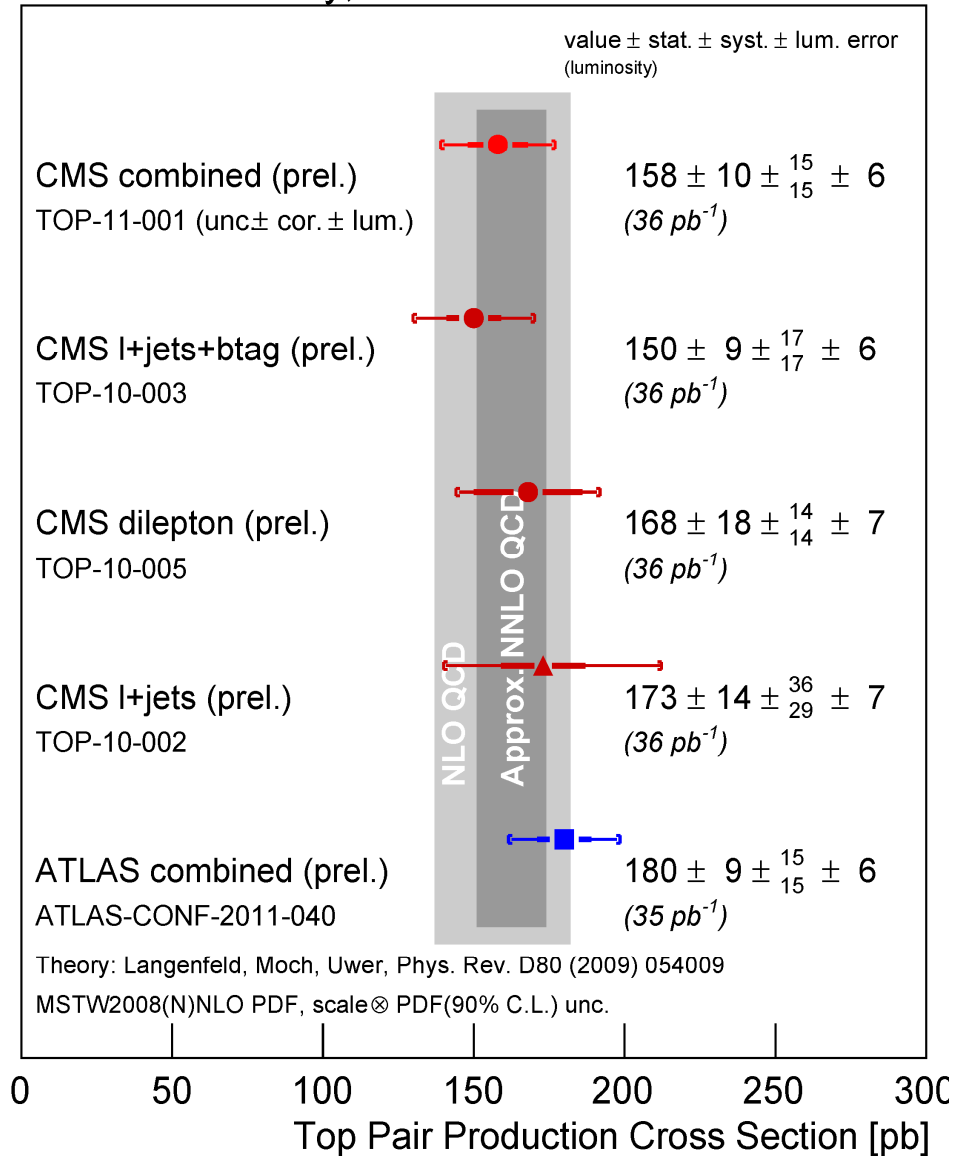
ttbar Cross Section in Dilepton Events



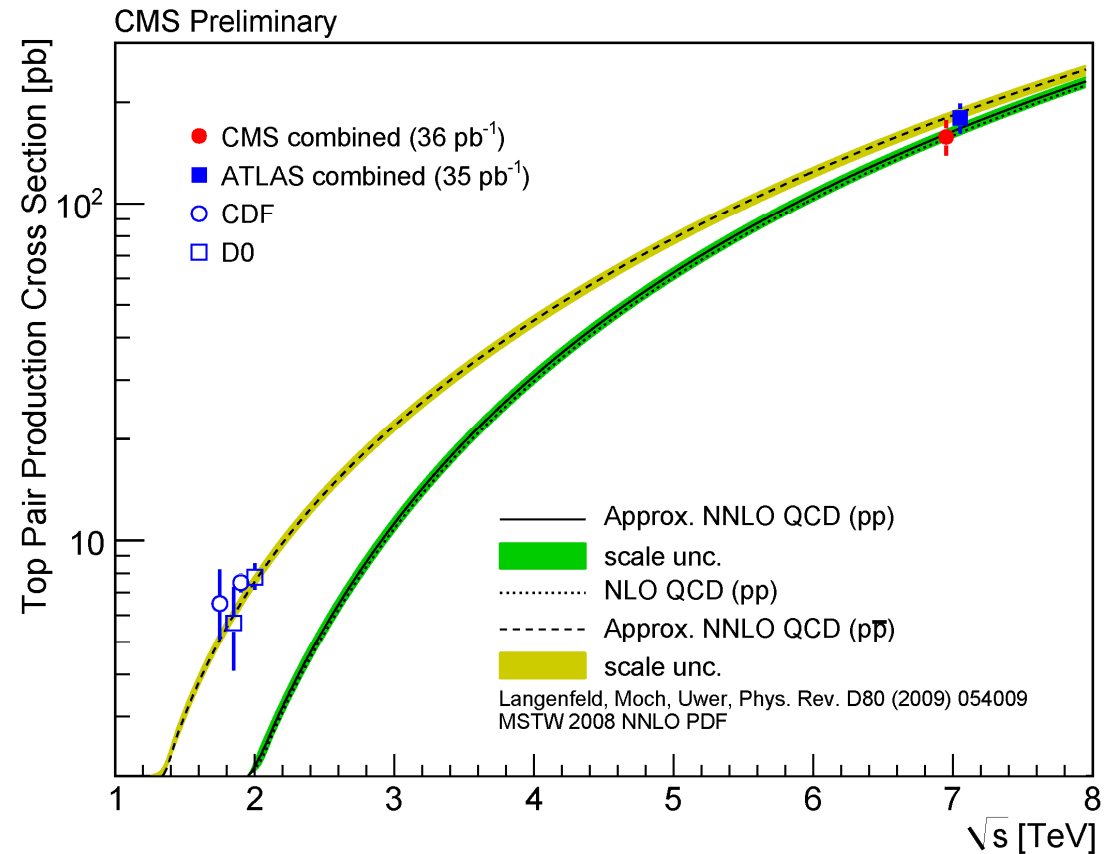
$$\sigma_{t\bar{t}} = 168 \pm 18(\text{stat}) \pm 14(\text{syst}) \pm 7(\text{lumi}) \text{ pb}$$

ttbar Cross Section

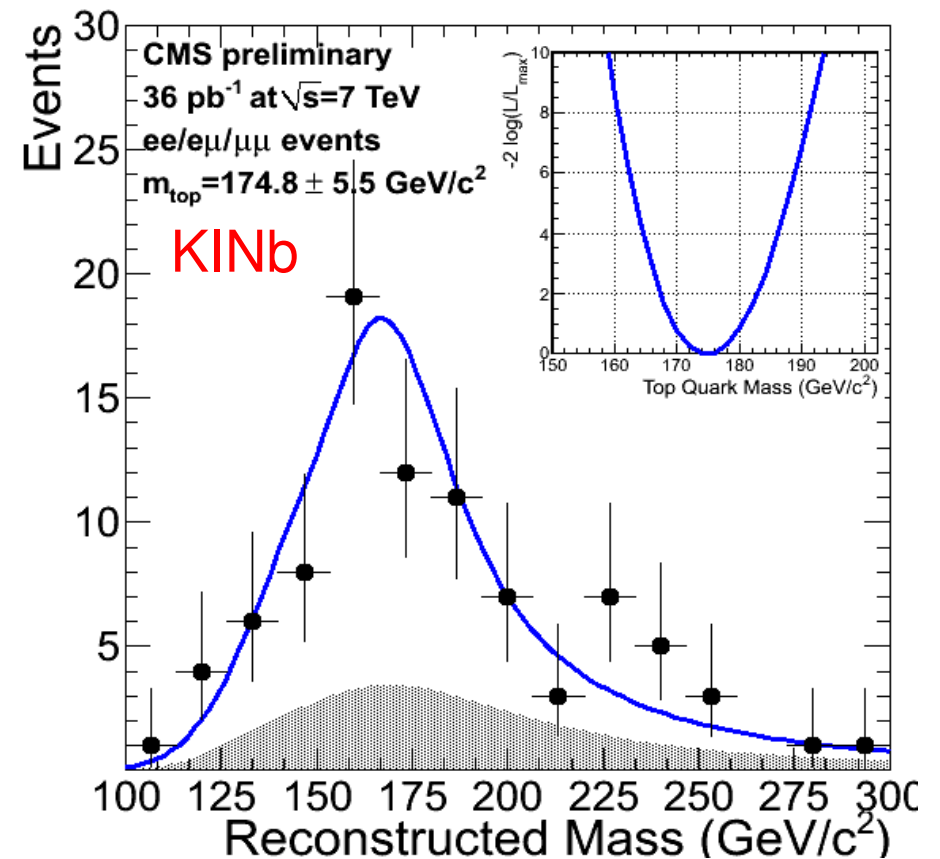
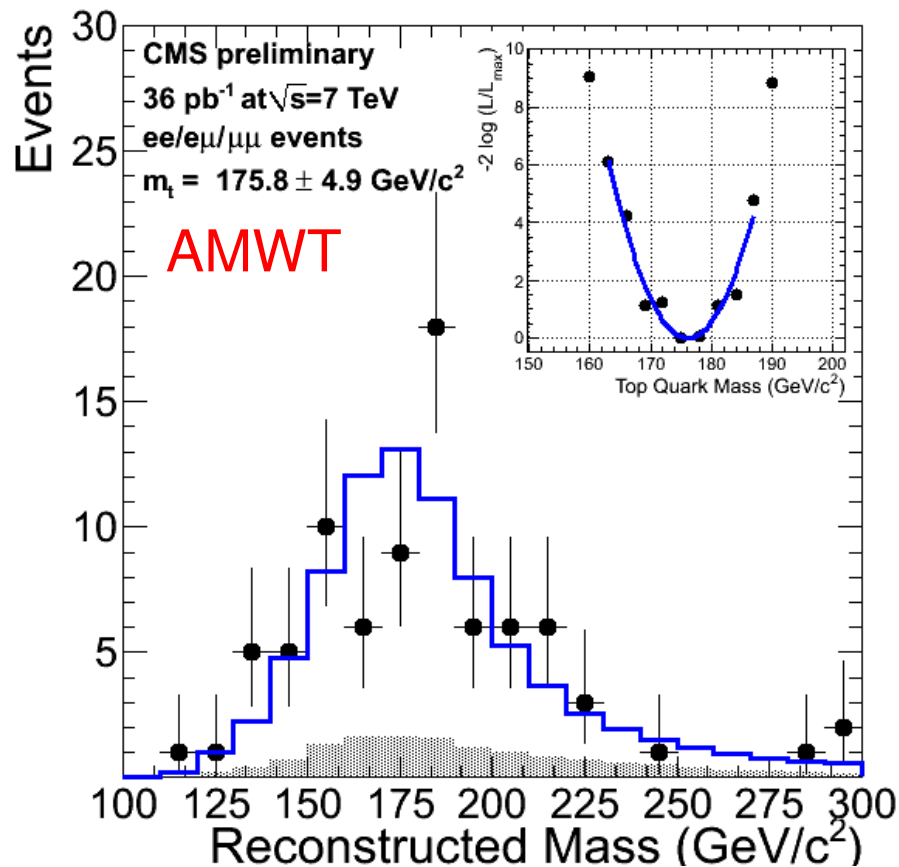
CMS Preliminary, $\sqrt{s}=7$ TeV



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

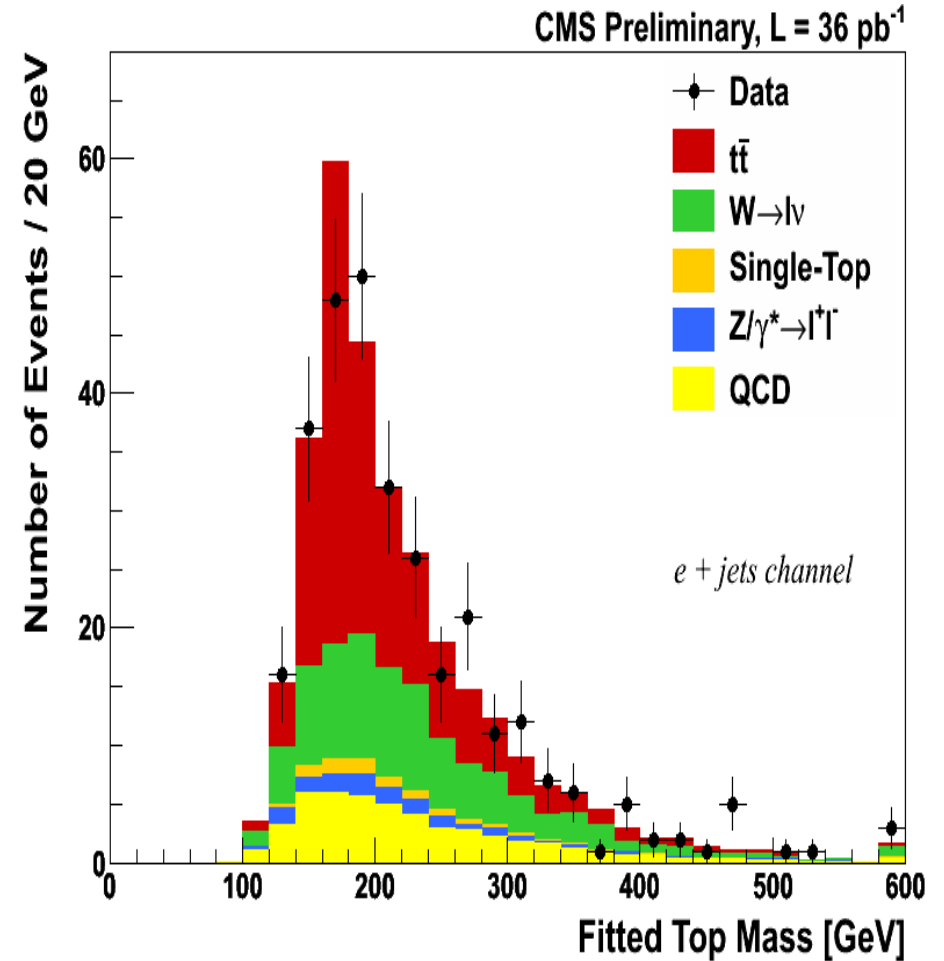
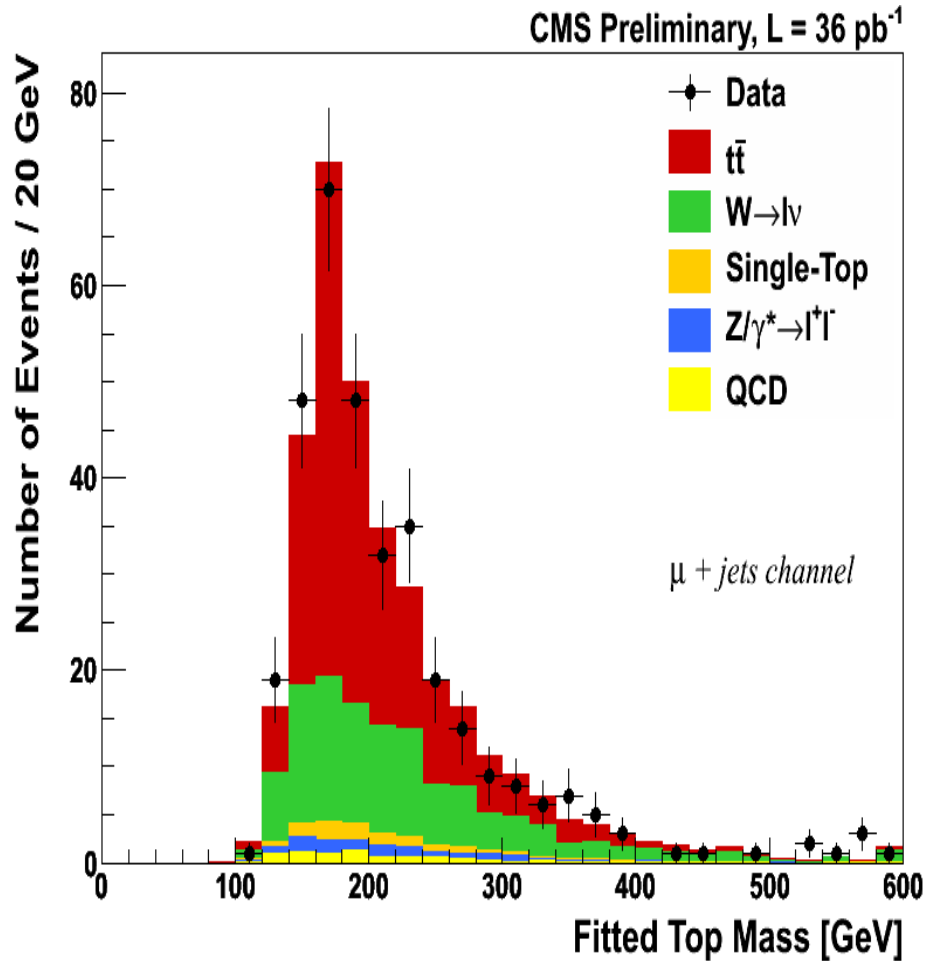


Top Mass in Dilepton Events



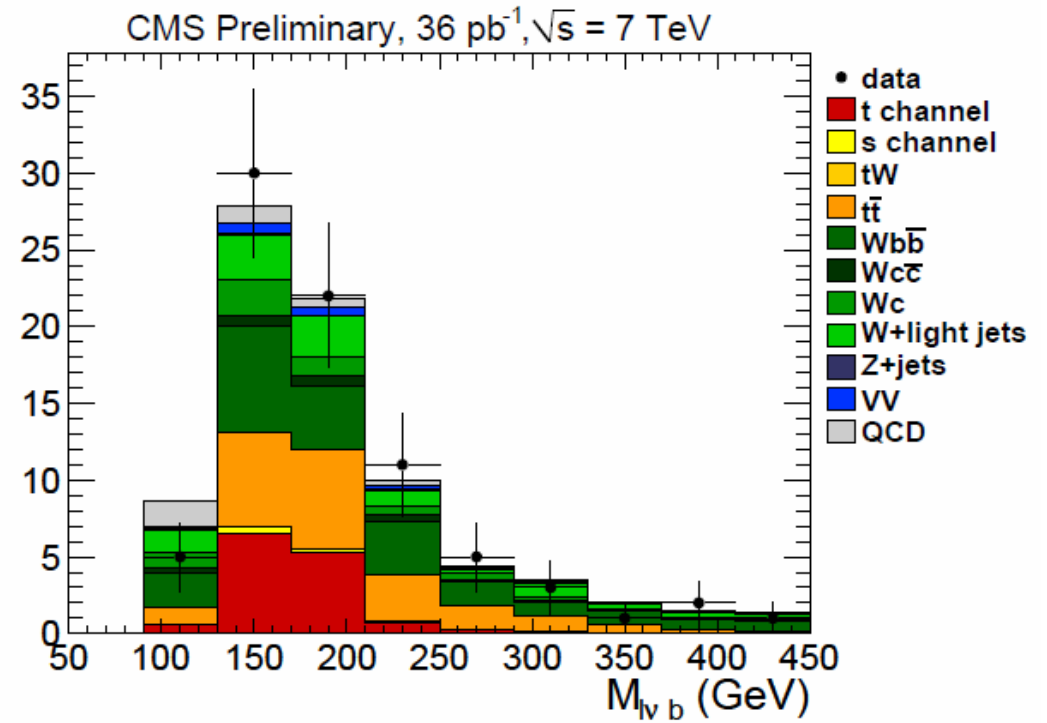
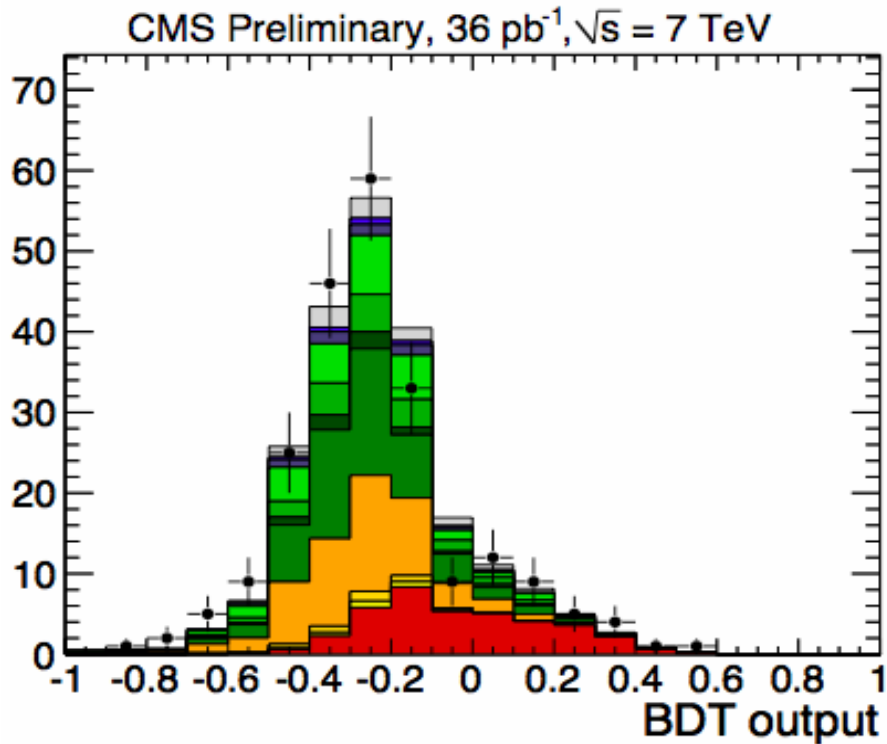
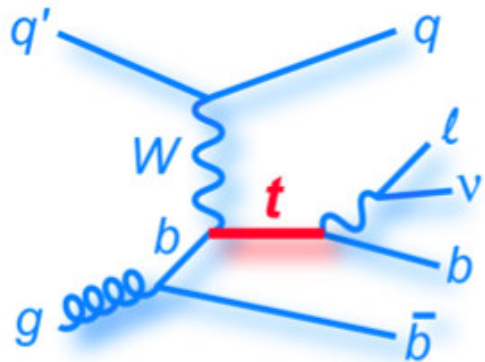
Method	Measured m_{top} (in GeV/c ²)
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$
KINb	$174.8 \pm 5.5(stat) \pm_{5.0}^{4.5}(syst)$
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$

Top Mass in l+jets



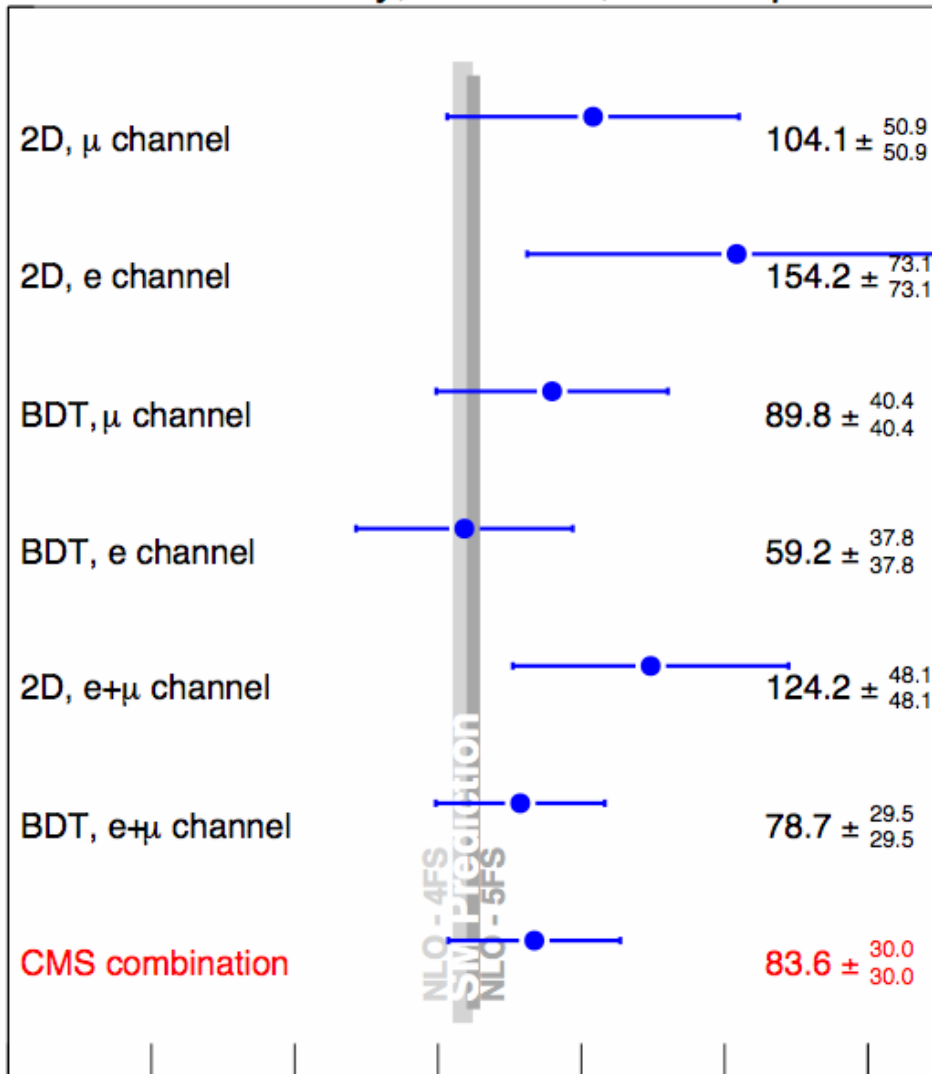
$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst}) \text{ GeV}$$

Single Top Production



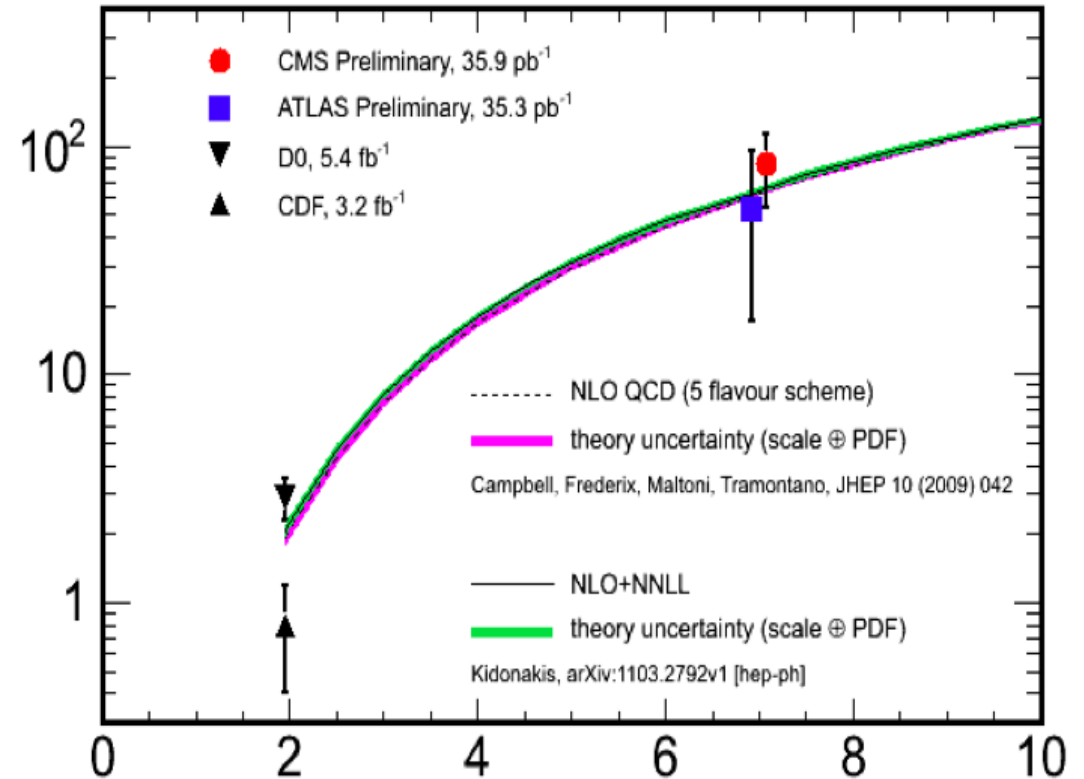
Single Top Cross Section

CMS Preliminary, $\sqrt{s}=7$ TeV, $L=35.9$ pb⁻¹



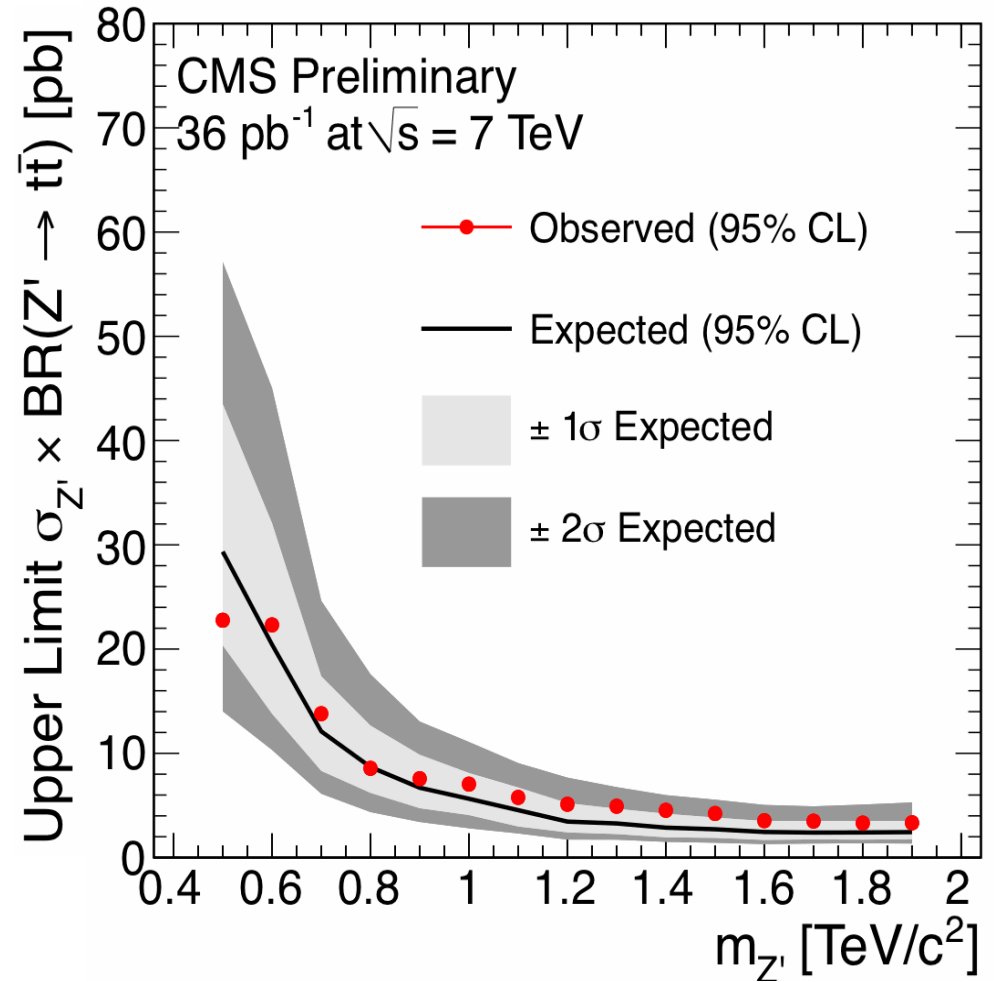
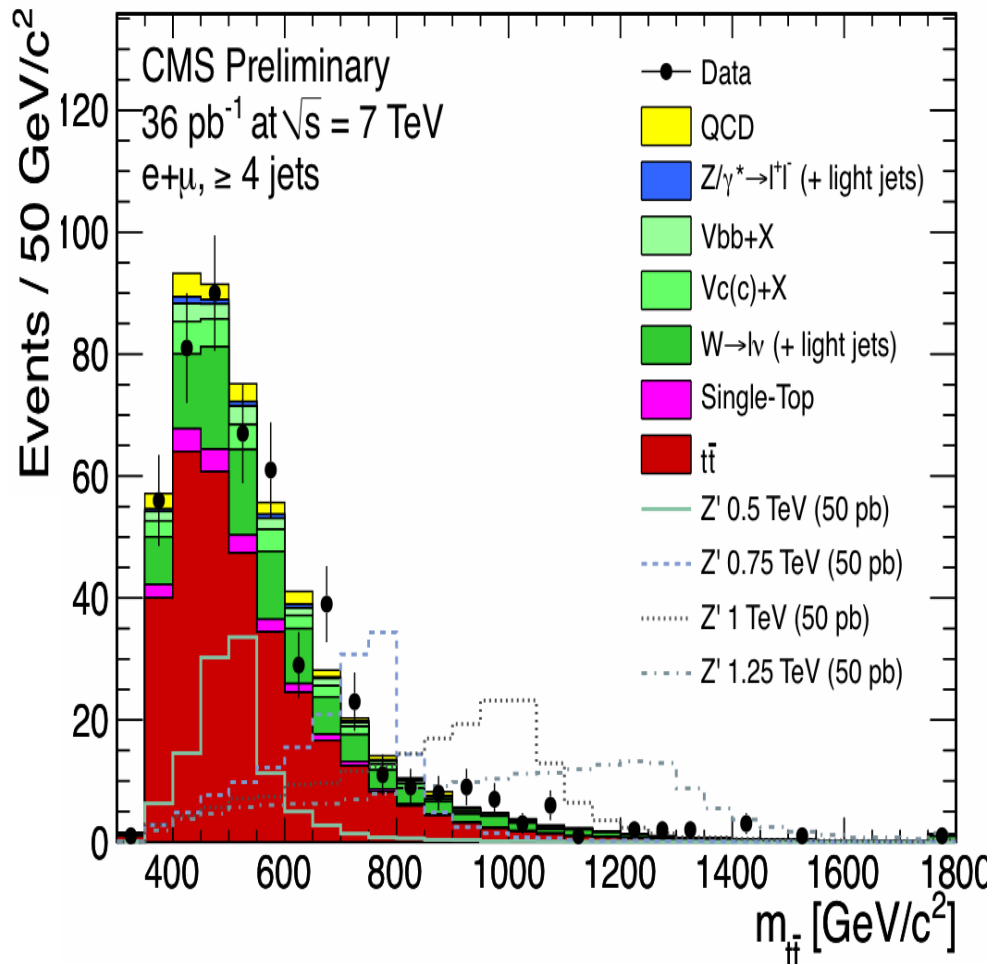
-100 -50 0 50 100 150 200
Single Top t-Channel Production Cross Section [pb]

t-channel single top quark production

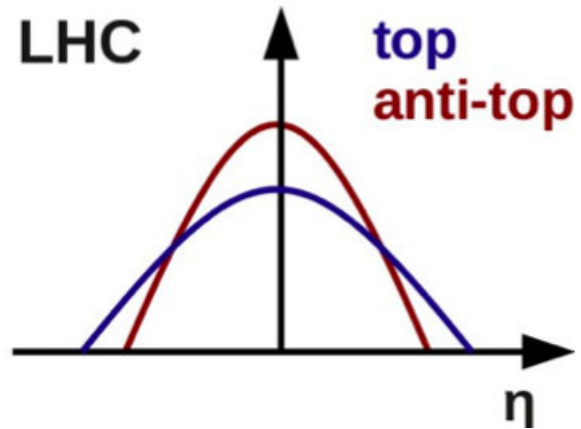
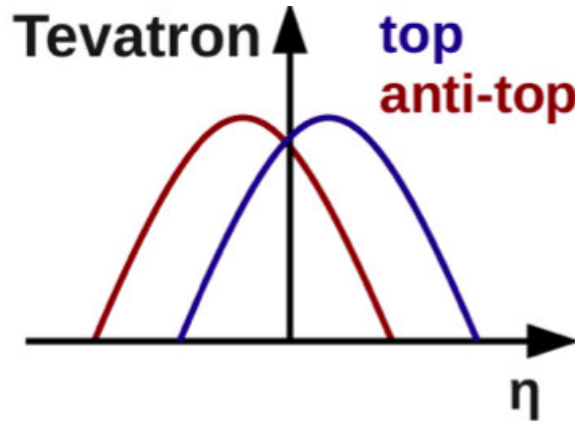


$83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.) pb$

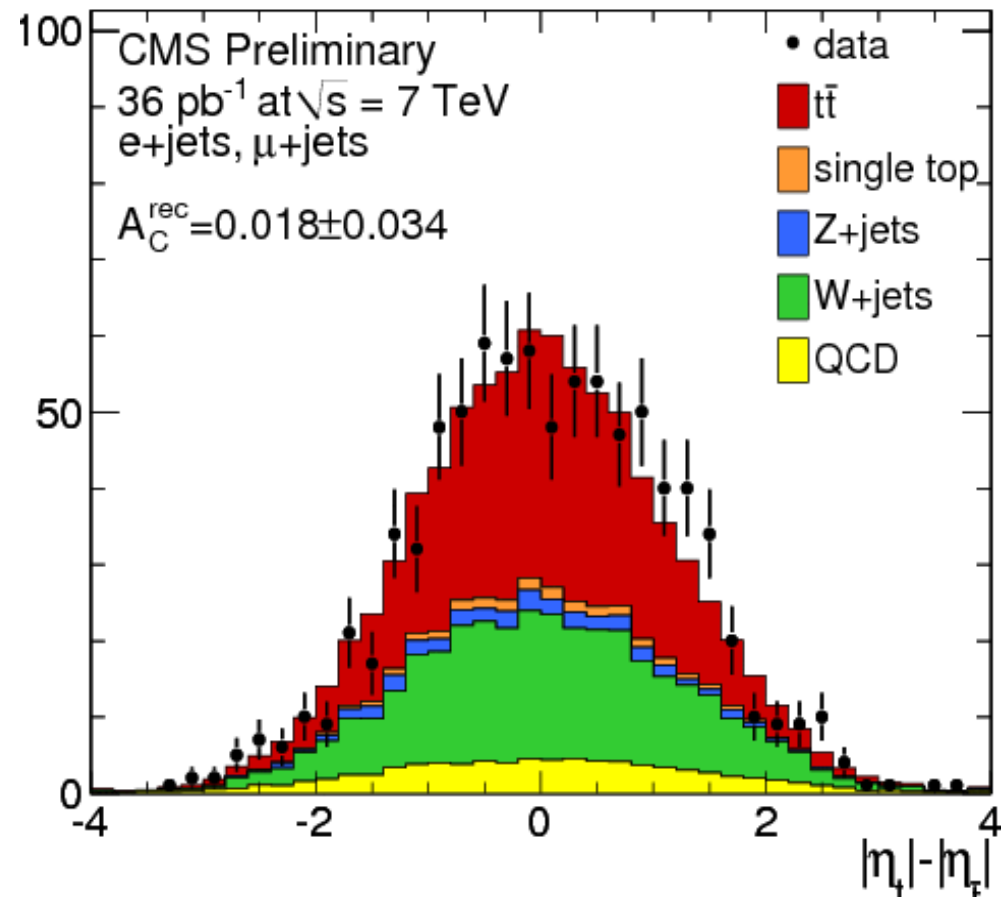
Top Pair Invariant Mass



Top Charge Asymmetry



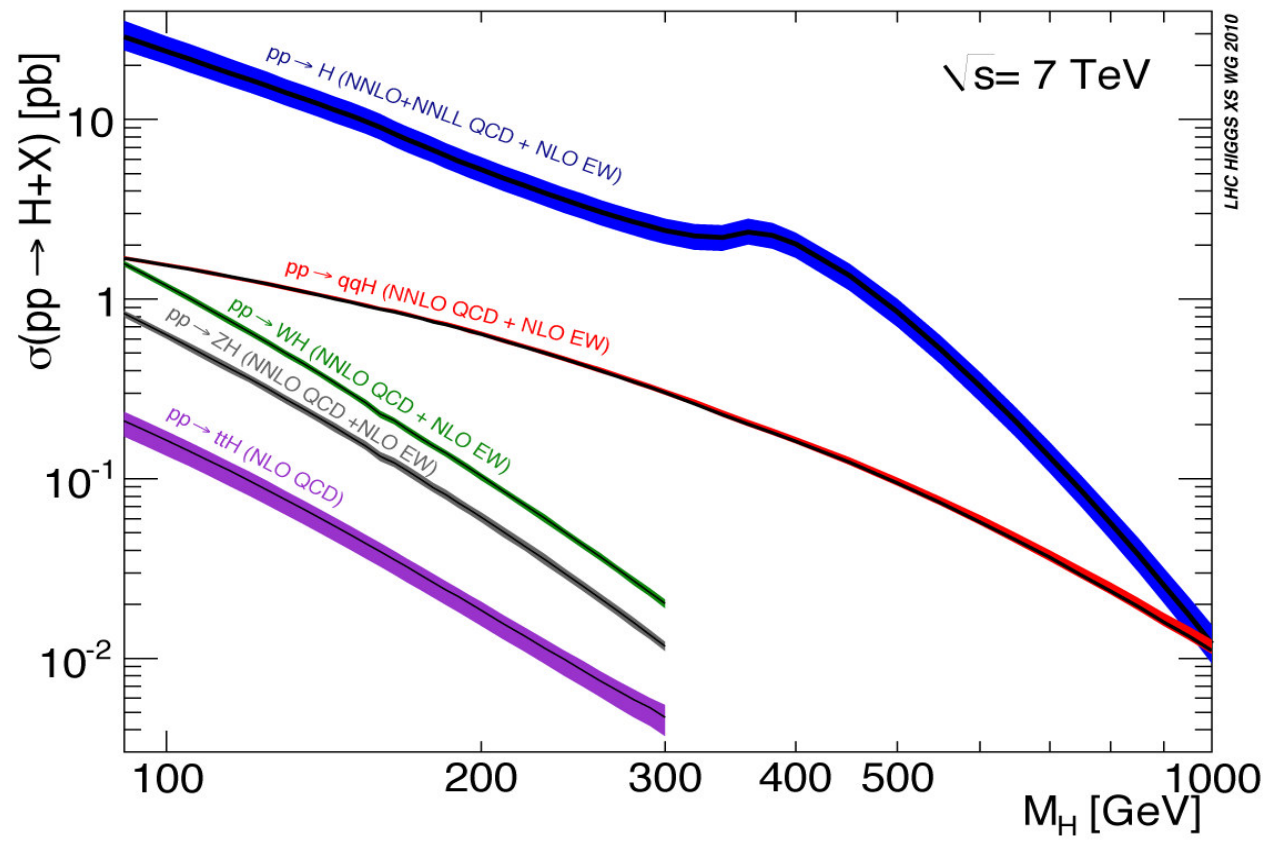
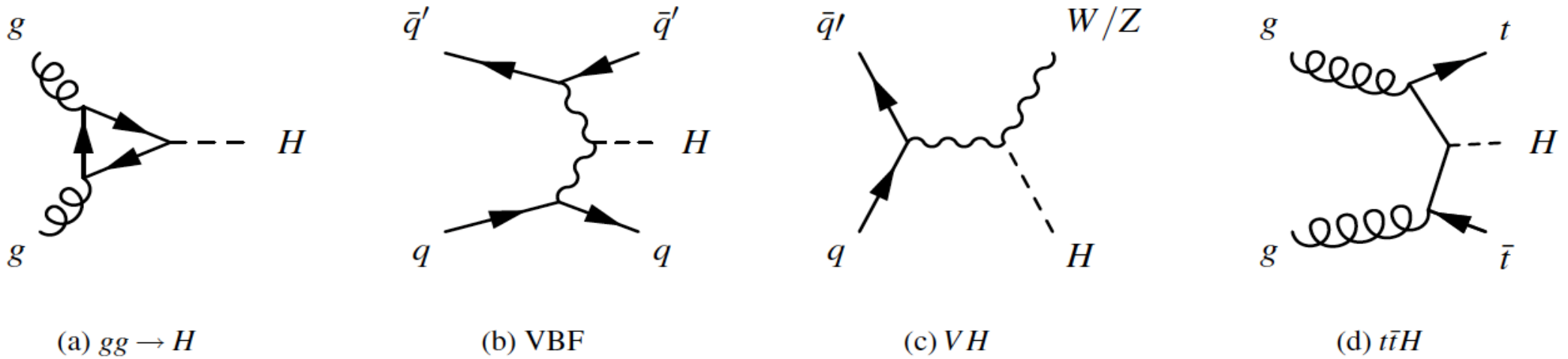
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$



$$A_C = 0.060 \pm 0.134(\text{stat.}) \pm 0.026(\text{syst.})$$

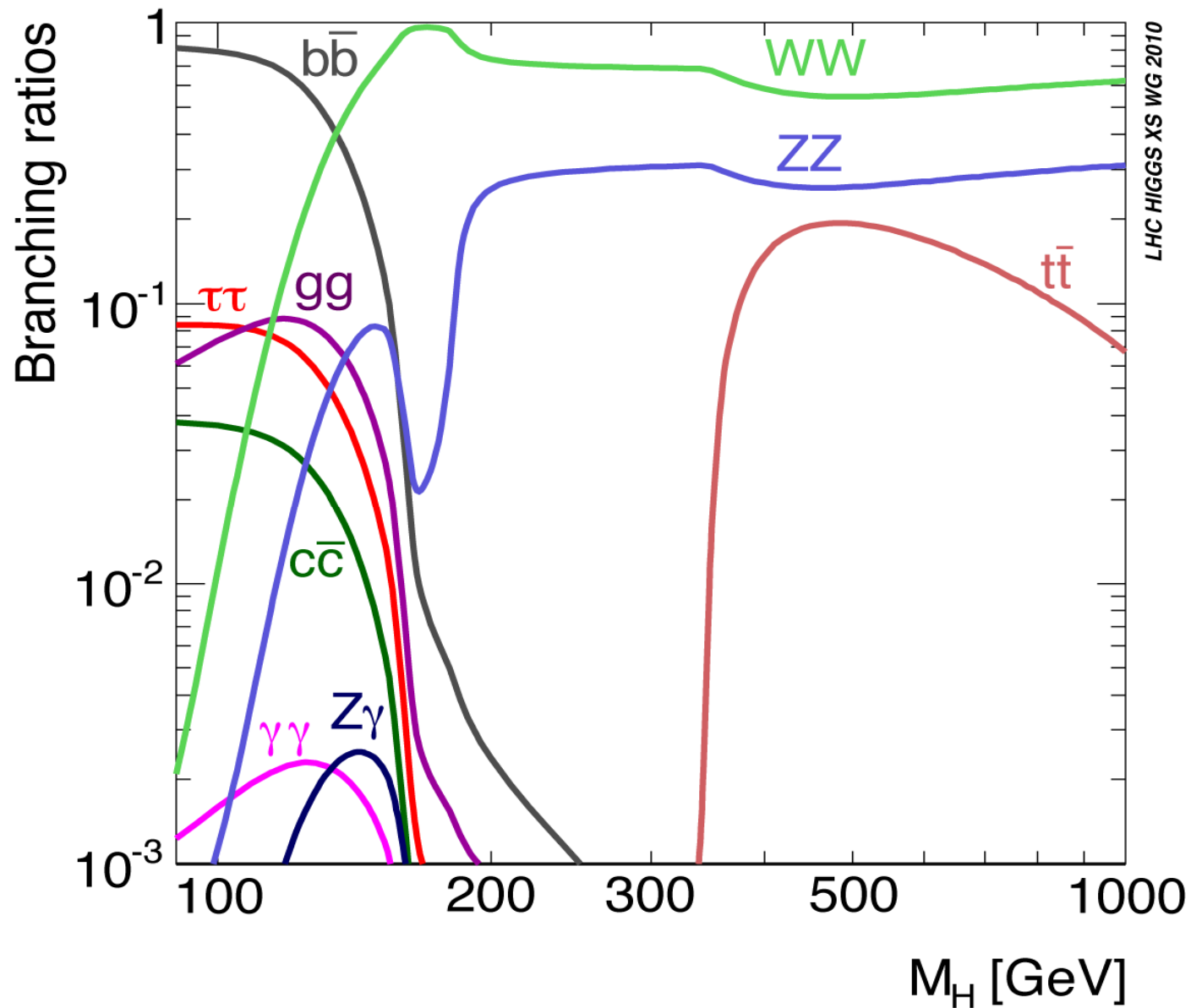
5. HIGGS PHYSICS

Higgs Production at LHC

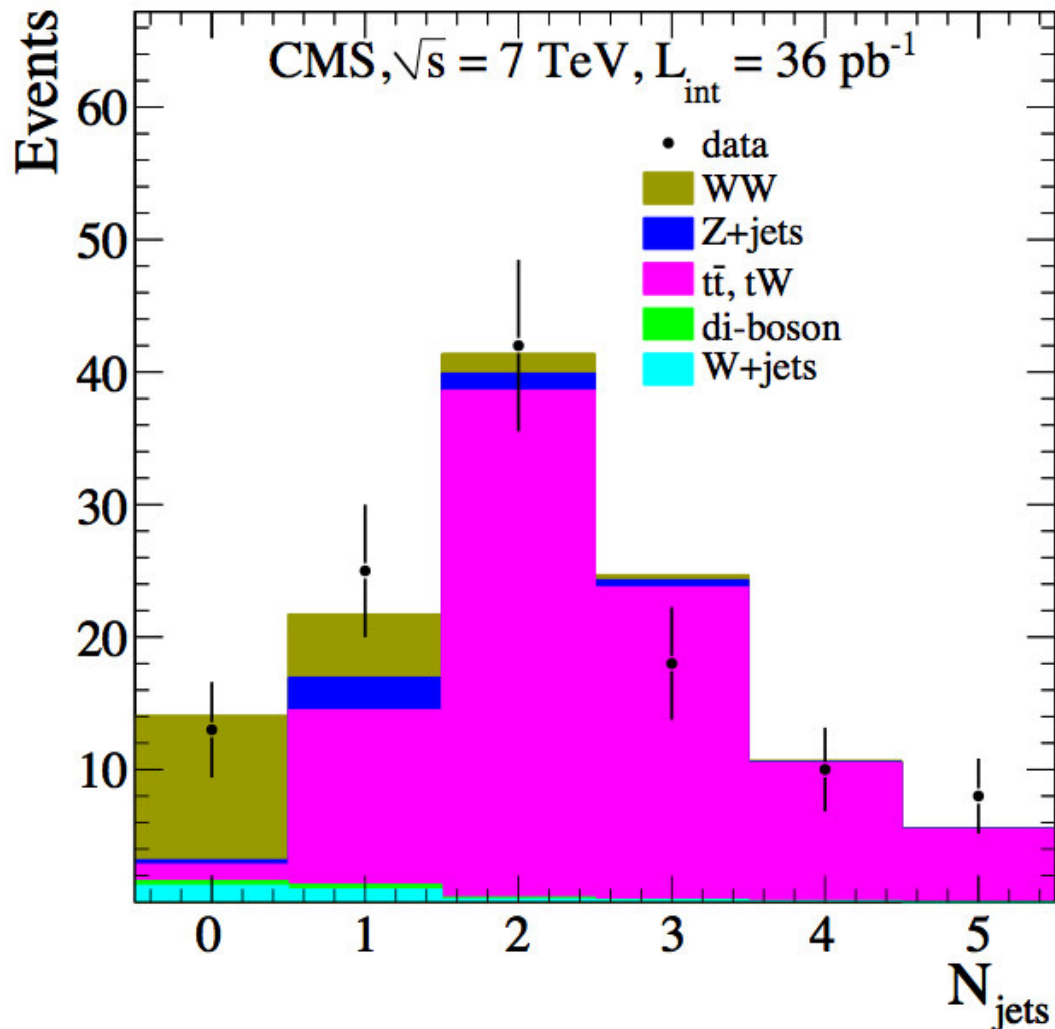


$gg \rightarrow H$ is the dominant production mechanism

Higgs Decay Channels



WW Production



13 events observed in 36 pb^{-1}

3.3 ± 1.2 background events expected.

$$\sigma_{W+W-} = 41.1 \pm 15.3 \text{ (stat)} \pm 5.8 \text{ (syst)} \pm 4.5 \text{ (lumi)} \text{ pb}$$

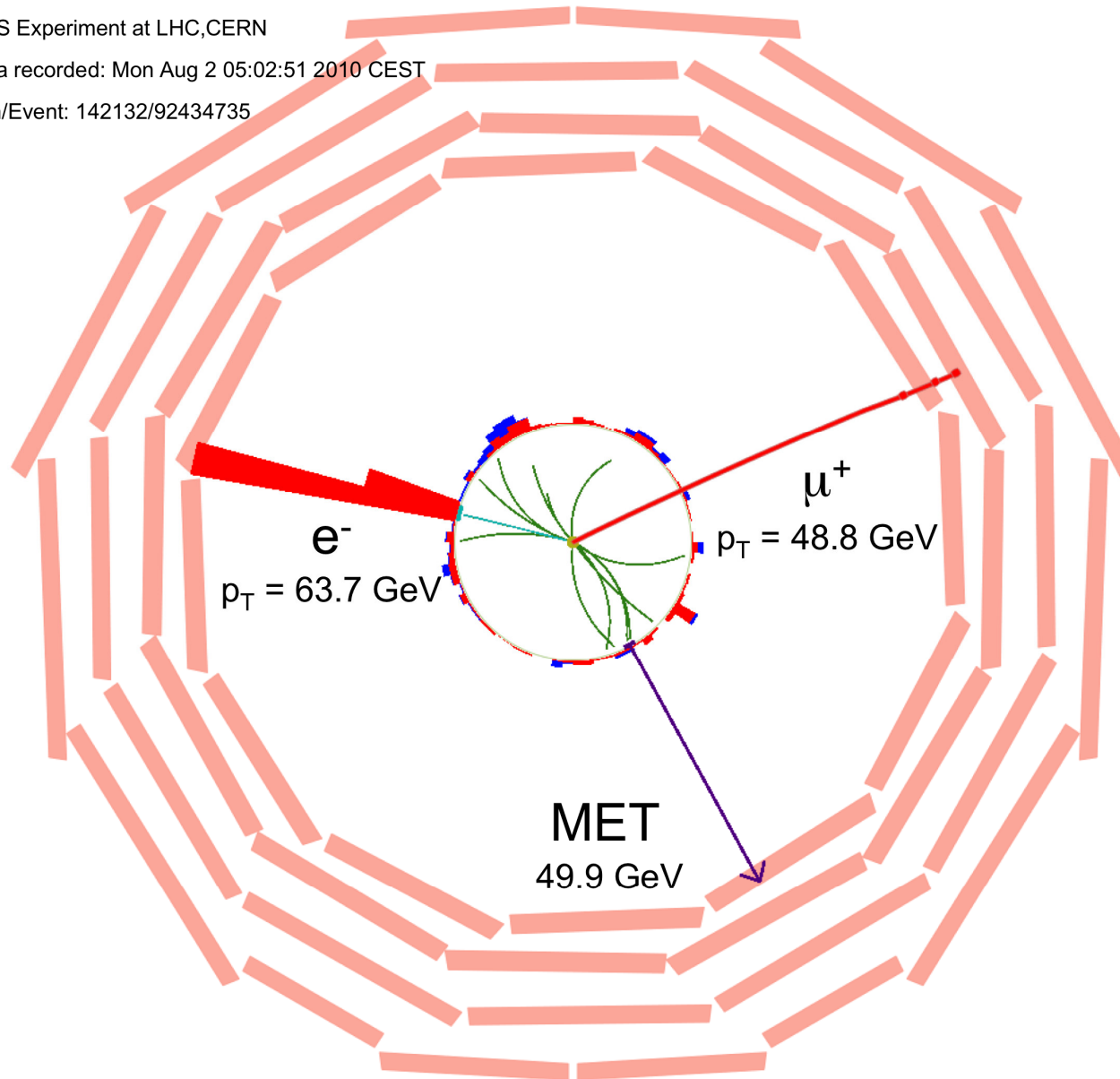
Good agreement with NLO prediction of $43.0 \pm 2.0 \text{ pb}$

WW Production

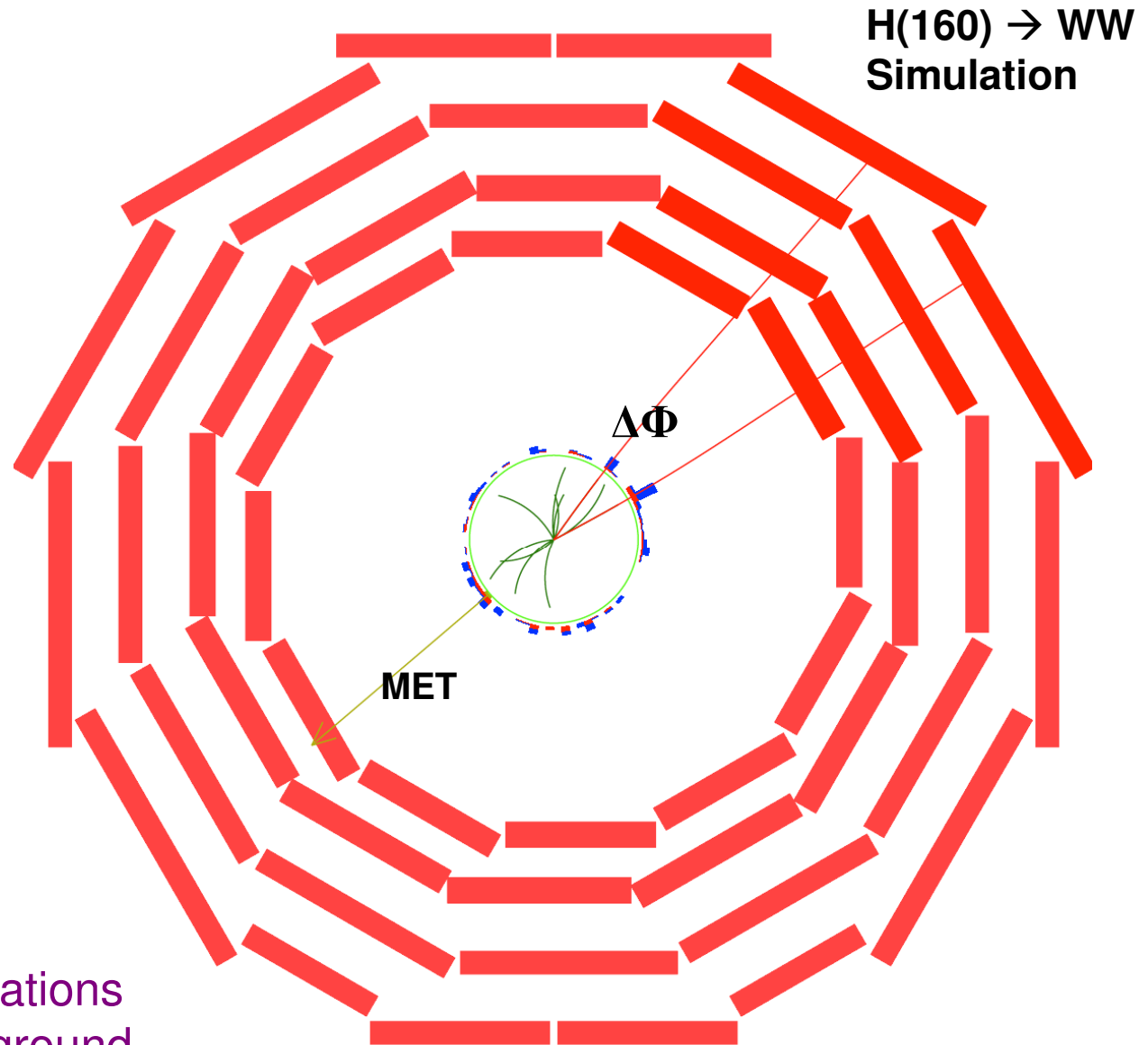
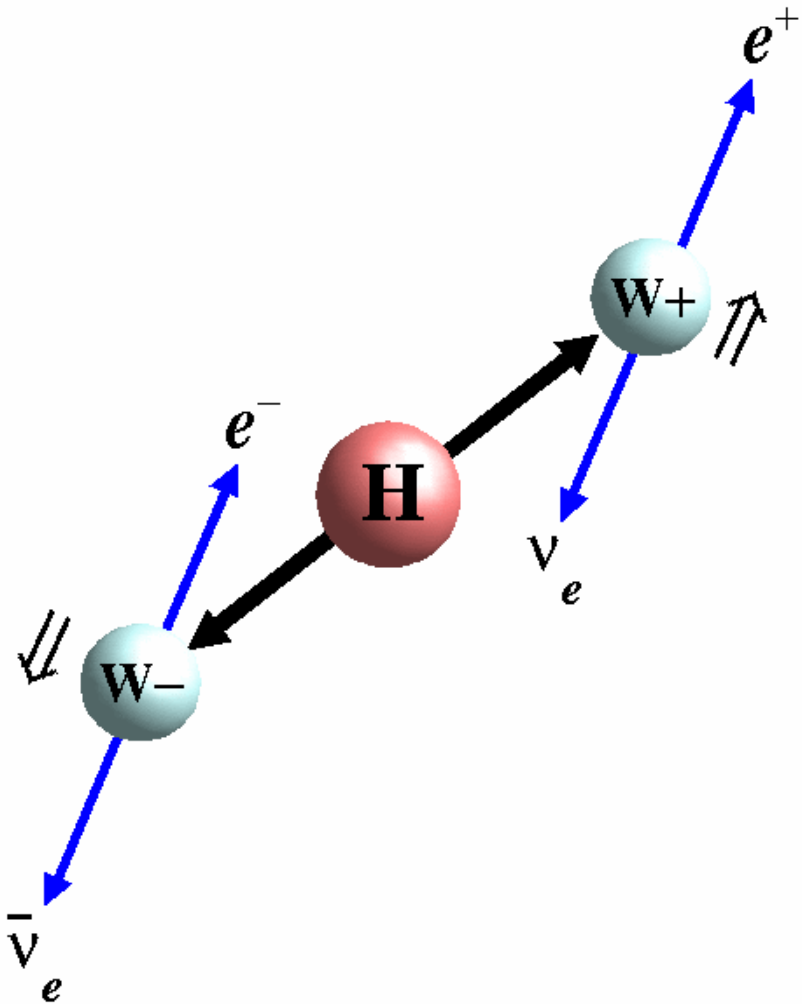
CMS Experiment at LHC,CERN

Data recorded: Mon Aug 2 05:02:51 2010 CEST

Run/Event: 142132/92434735



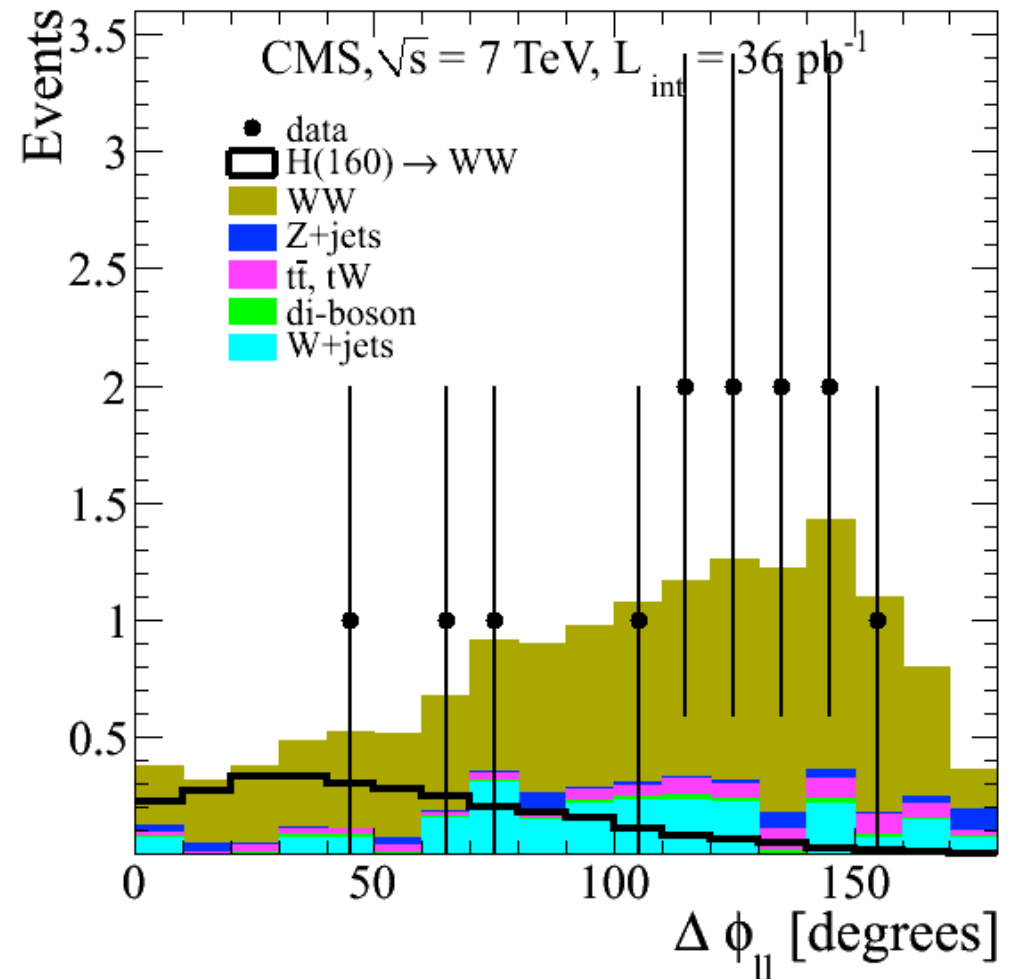
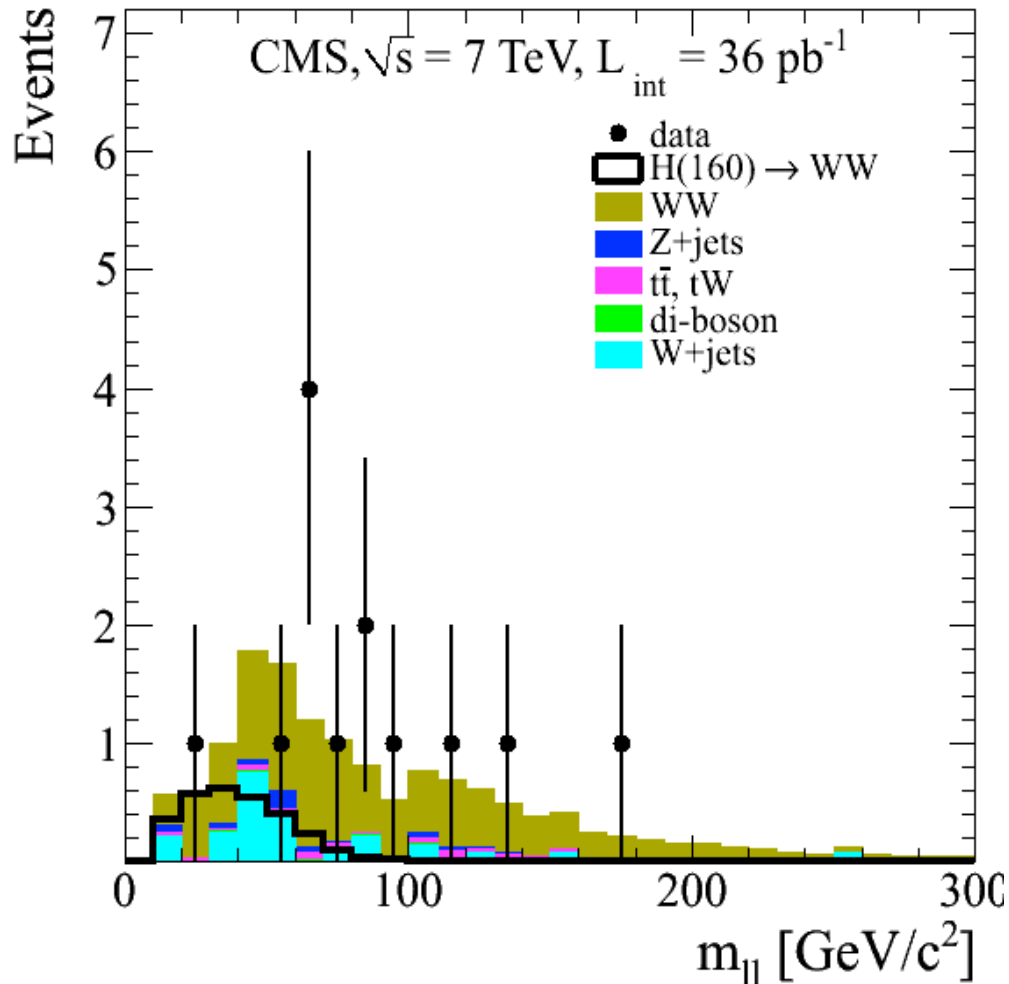
$H \rightarrow WW \rightarrow l\nu l\nu$



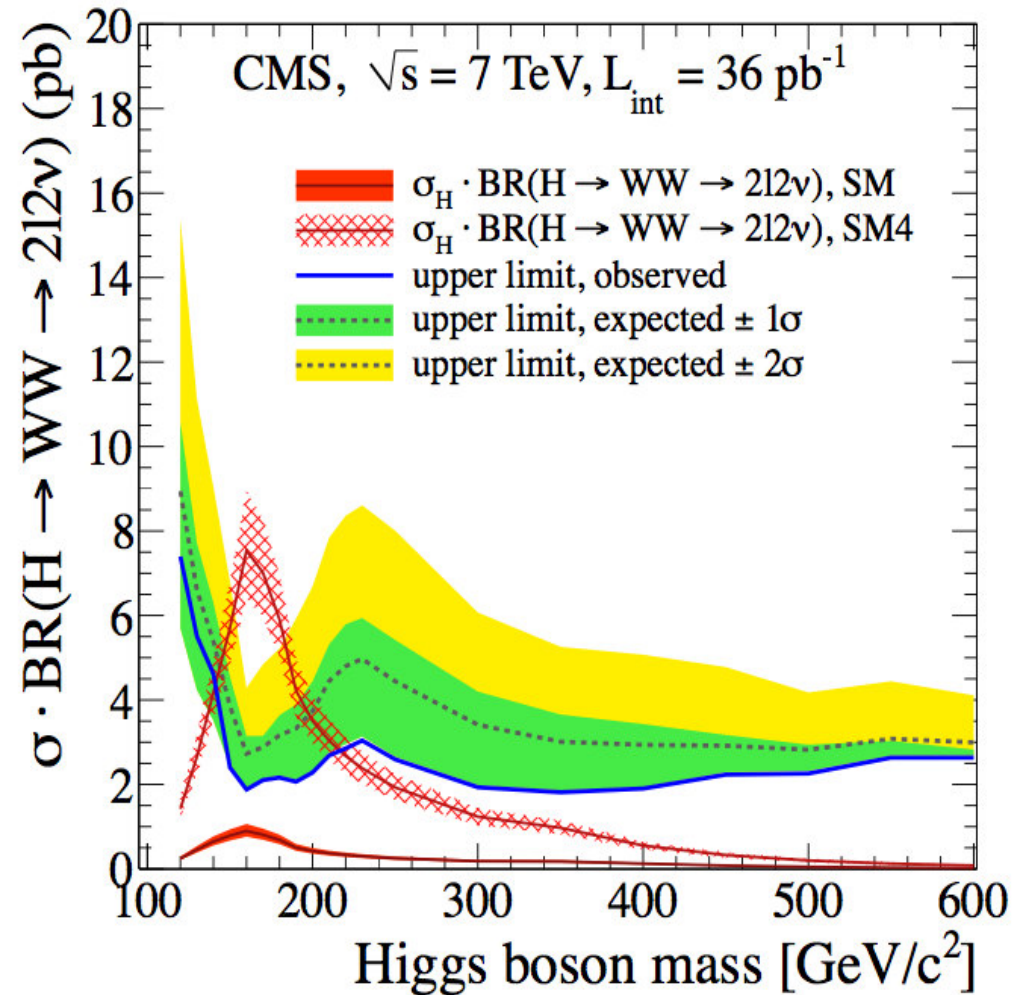
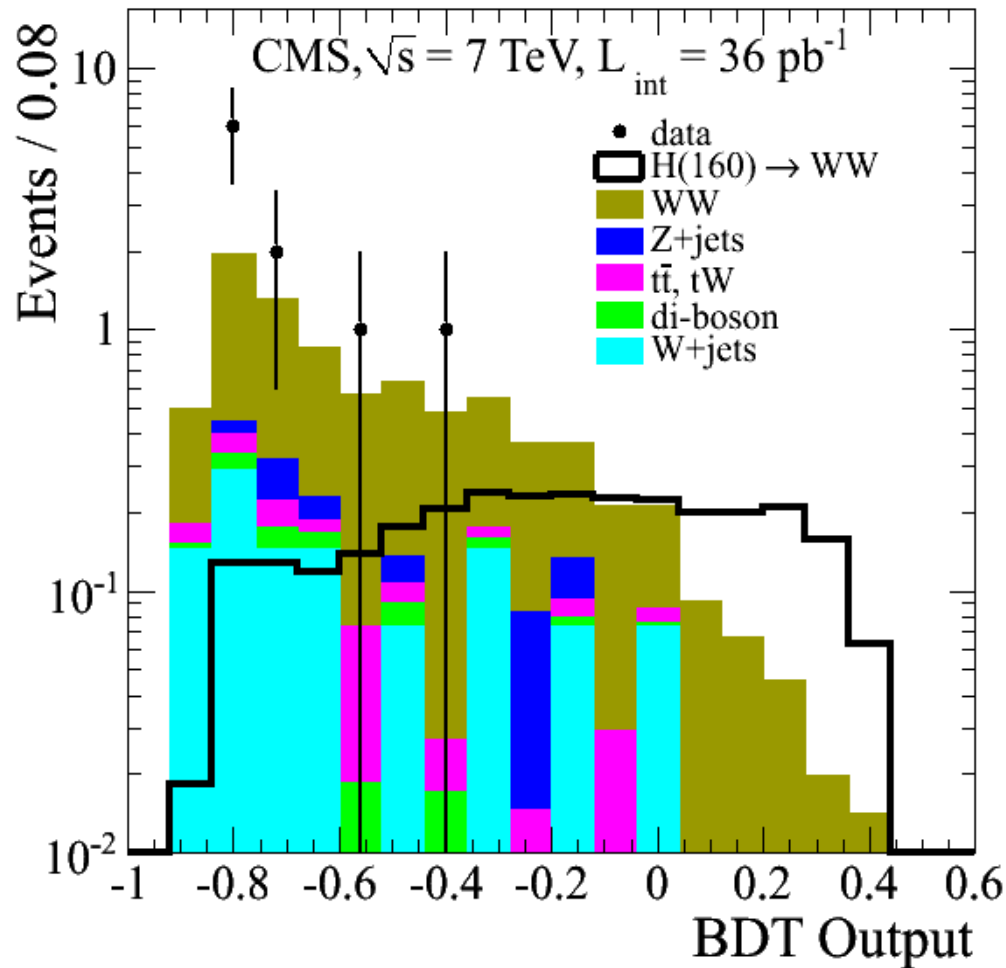
Small opening angle due to spin correlations
→ Can be used to suppress WW background

$H \rightarrow WW \rightarrow l\nu l\nu$

Comparison of key kinematical observables after WW selection.



$H \rightarrow WW \rightarrow l\nu l\nu$



❑ Not yet sensitive to SM Higgs.

❑ In SM extension with a 4th family, $144 < m_H < 207 \text{ GeV}/c^2$ is excluded.

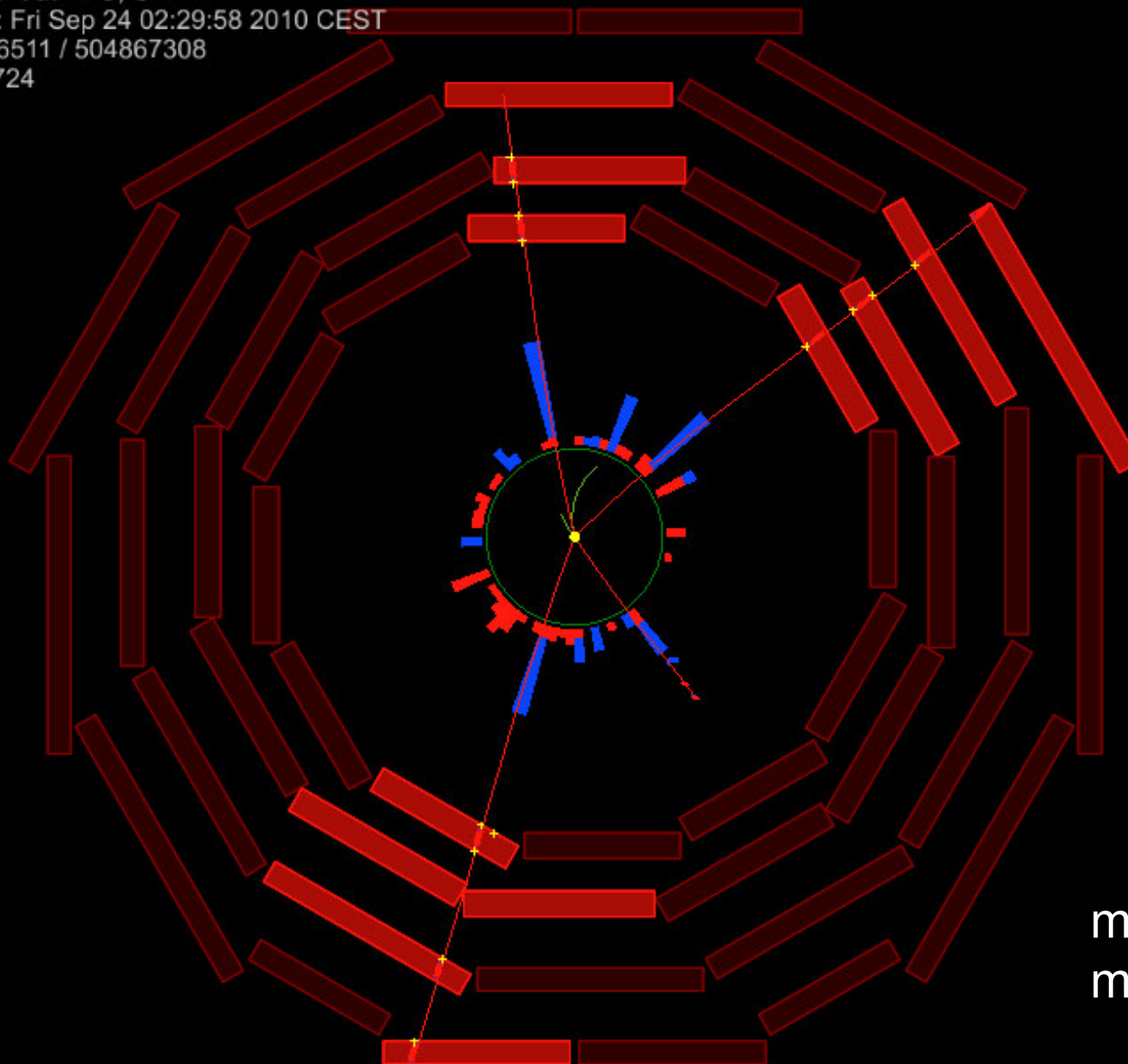
$H \rightarrow ZZ \rightarrow 4l$

CMS Experiment at LHC, CERN

Data recorded: Fri Sep 24 02:29:58 2010 CEST

Run/Event: 146511 / 504867308

Lumi section: 724

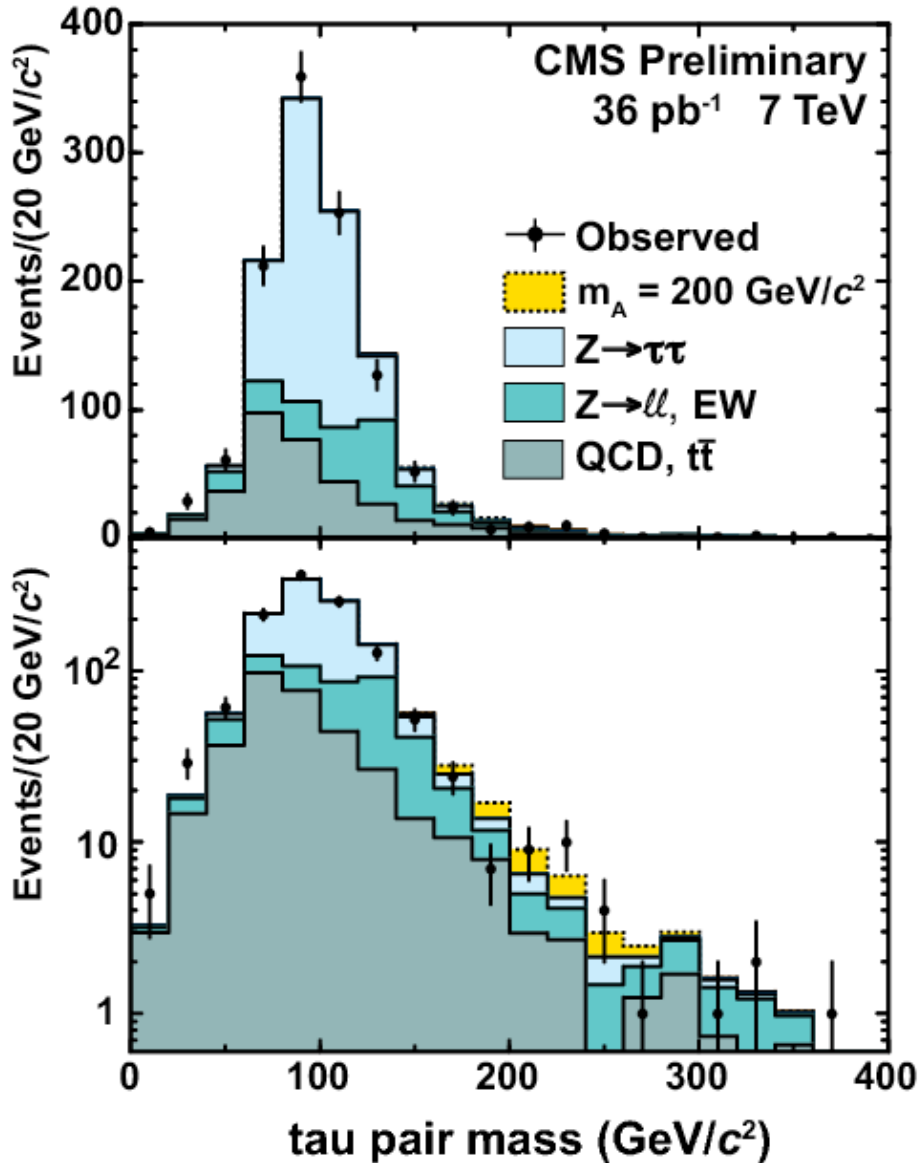


$m_{\mu_1\mu_2} = 92.15 \text{ GeV}$

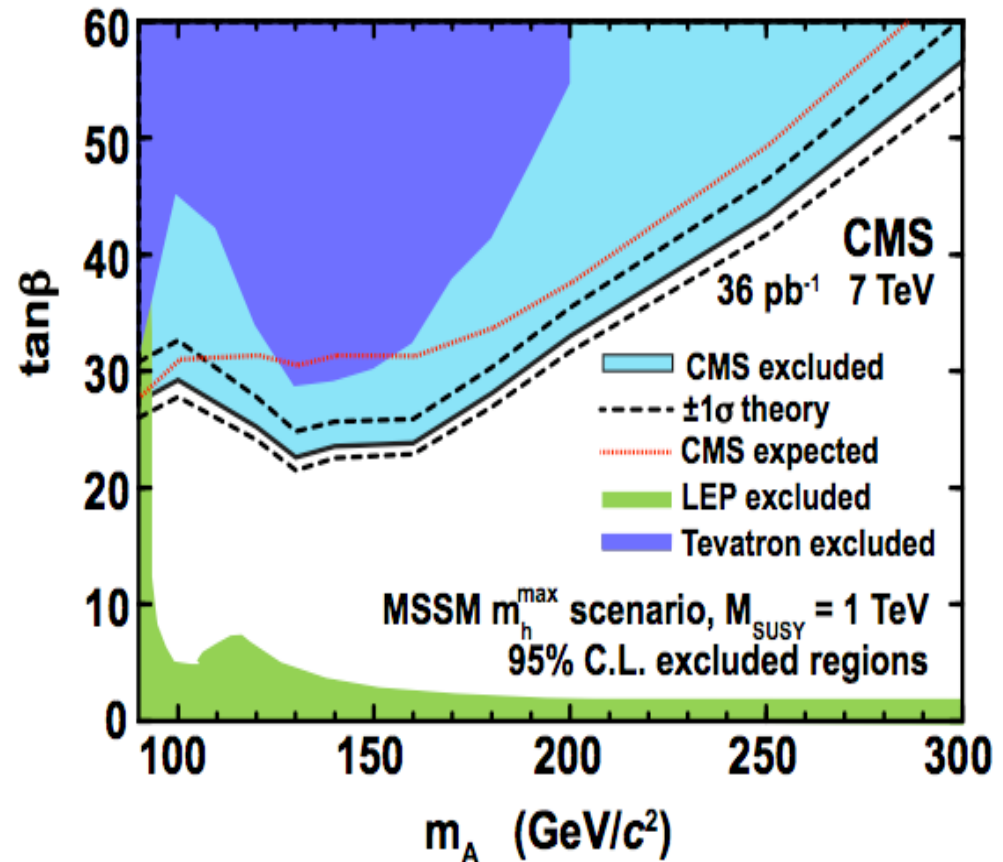
$m_{\mu_3\mu_4} = 92.24 \text{ GeV}$

$m_{4\mu} = 201 \text{ GeV}$

MSSM Higgs: $H, A \rightarrow \tau^+\tau^-$

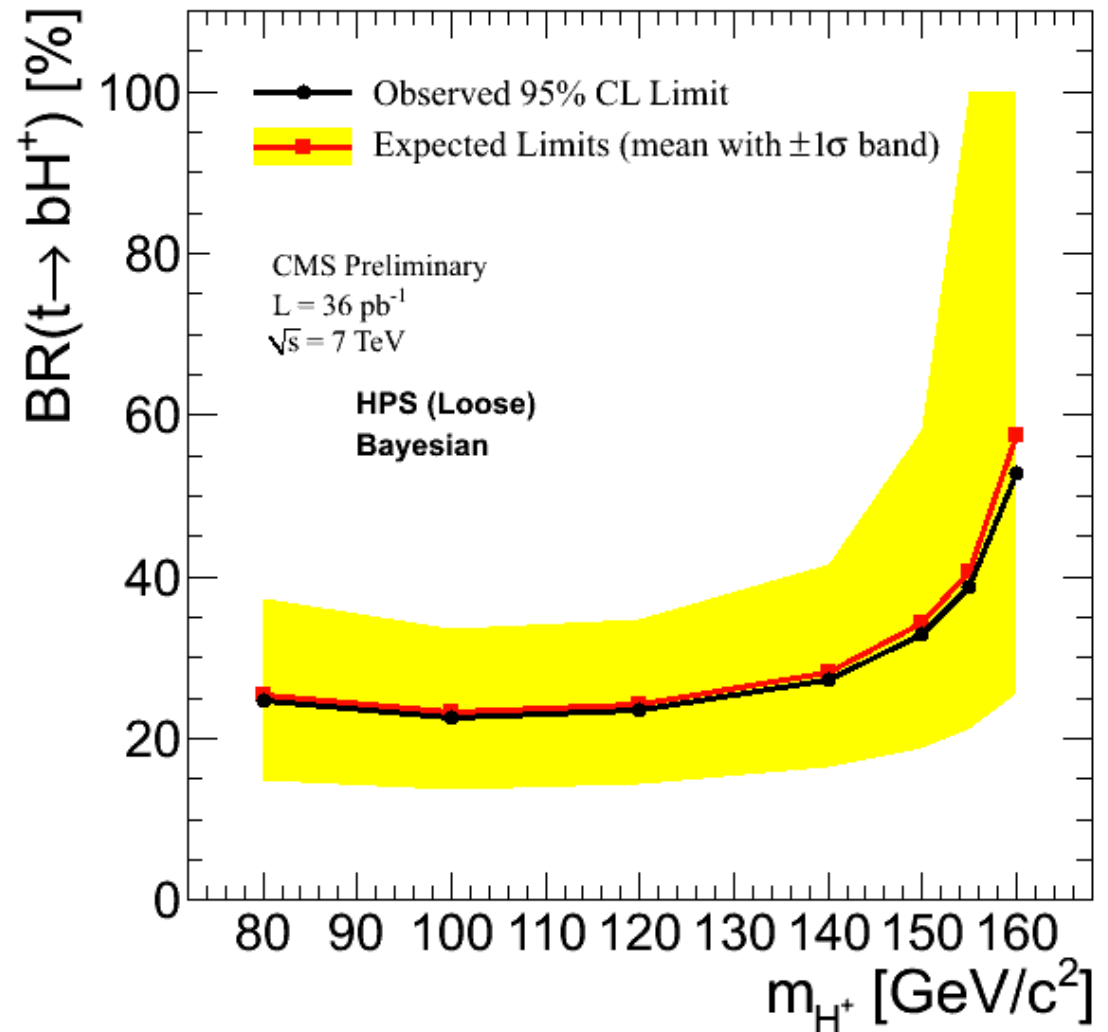
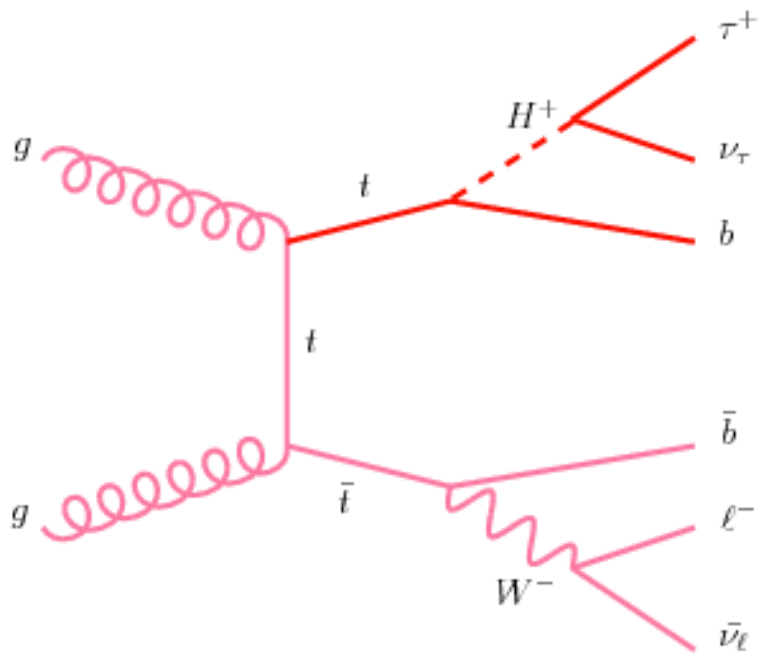


- $\tau_\mu + \tau_{\text{had}}, \tau_\mu + \tau_e$ and $\tau_e + \tau_{\text{had}}$ studied.
- Limits on cross section and MSSM $[\tan\beta, m_A]$ exclusion region.



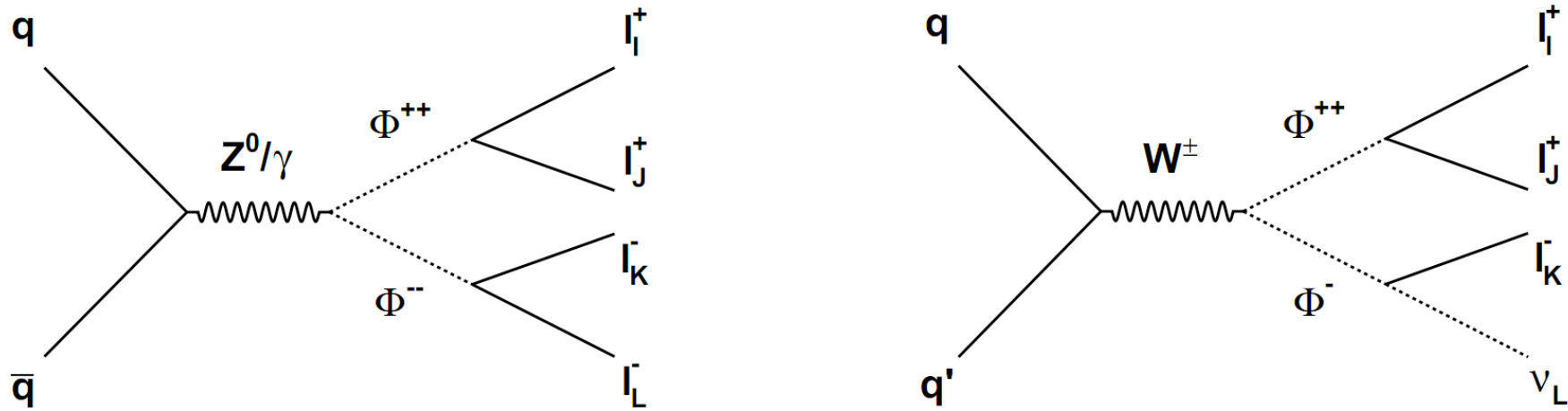
Charged Higgs in Top Decays: $H^+ \rightarrow \tau^+\nu$

Limits assume $B(H^+ \rightarrow \tau^+\nu) = 100\%$.



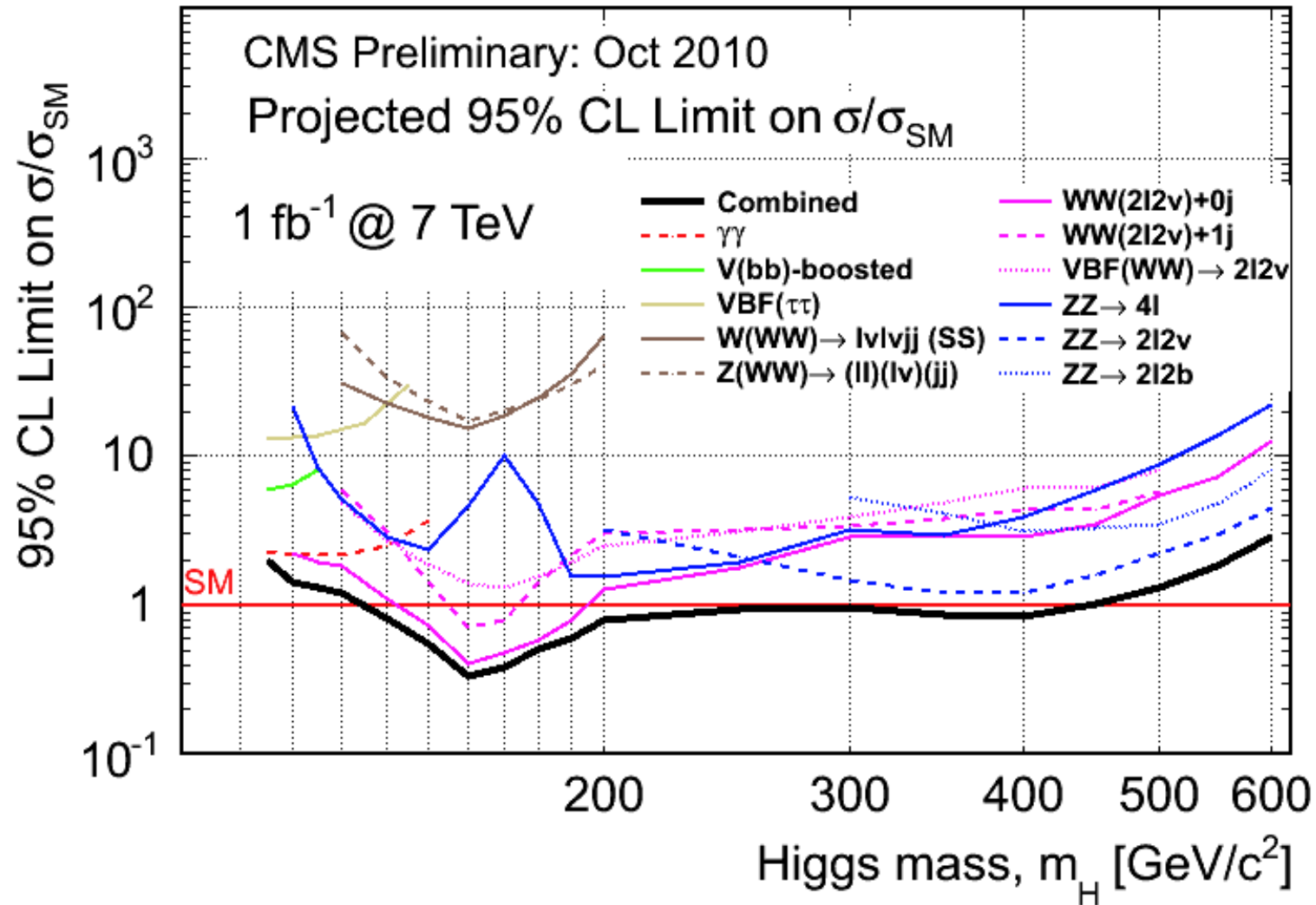
Exotic Higgs: $\Phi^{++} \rightarrow l^+l^+$

Search on 3 or 4 lepton final state, using all lepton flavours.



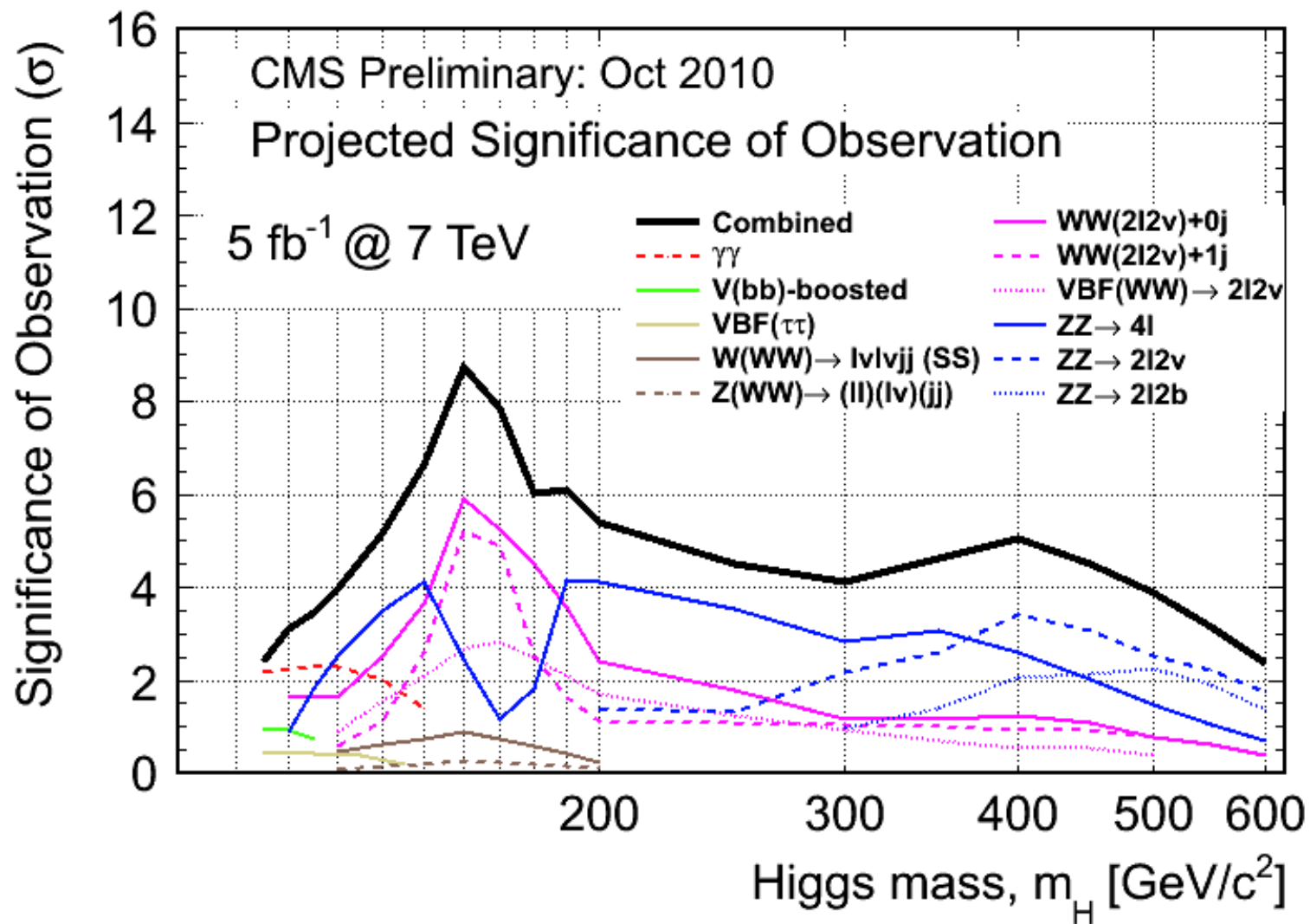
Benchmark point	Former limit	New result
$BR(\Phi^{++} \rightarrow e^\pm e^\pm) = 100\%$	133 GeV [31]	144 GeV
$BR(\Phi^{++} \rightarrow e^\pm \mu^\pm) = 100\%$	115 GeV [31]	154 GeV
$BR(\Phi^{++} \rightarrow e^\pm \tau^\pm) = 100\%$	112 GeV [32]	106 GeV
$BR(\Phi^{++} \rightarrow \mu^\pm \mu^\pm) = 100\%$	150 GeV [33]	156 GeV
$BR(\Phi^{++} \rightarrow \mu^\pm \tau^\pm) = 100\%$	114 GeV [32]	106 GeV

Higgs Projected Exclusion with 1 fb⁻¹



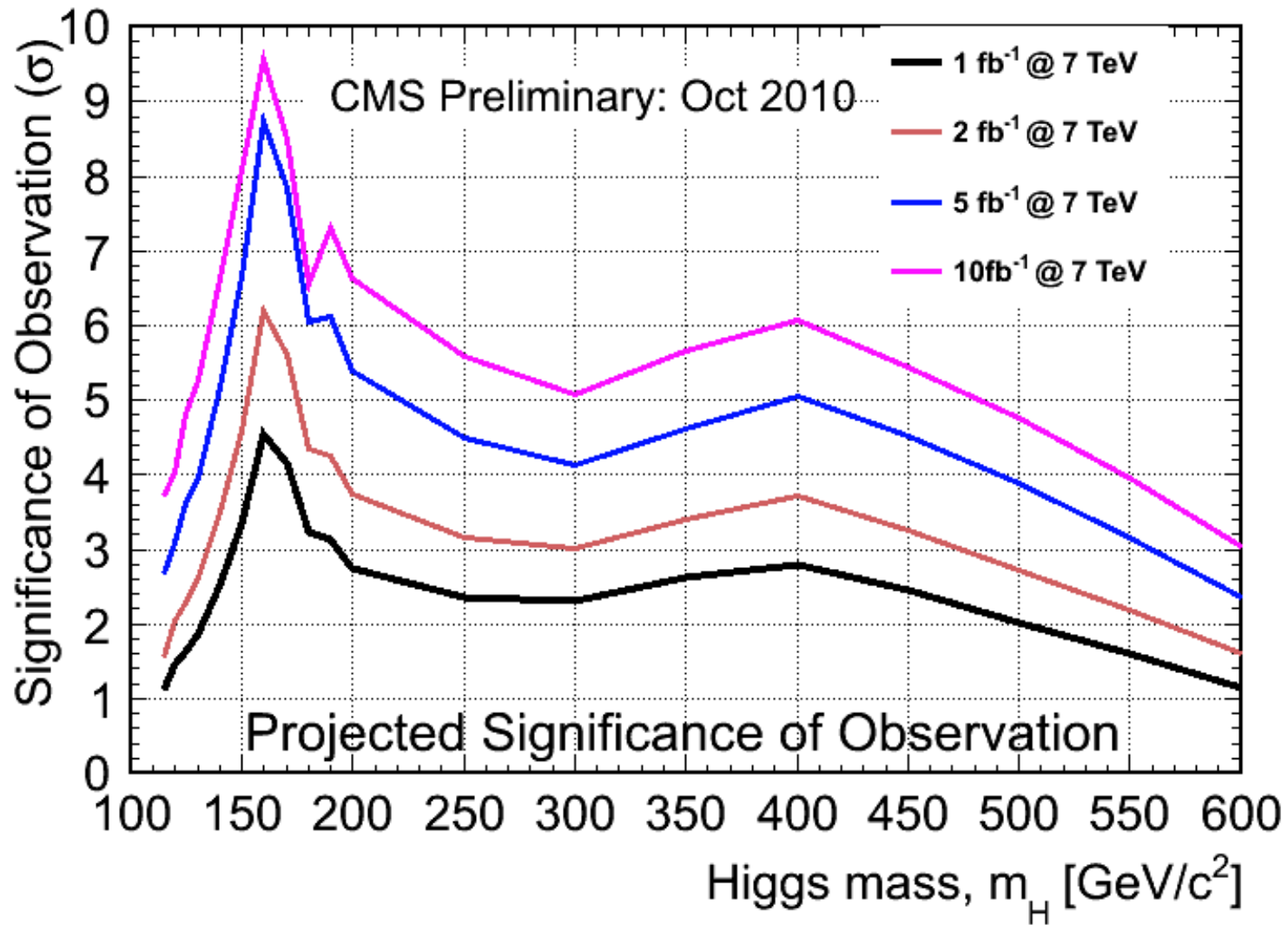
With 1 fb⁻¹, exclude m_H in the range 135-450 GeV/c²

Higgs Projected Sensitivity with 5 fb⁻¹



With 5 fb⁻¹, 4 σ sensitivity for m_H in the range 130-500 GeV/c²

Higgs Sensitivity with 1–10 fb⁻¹



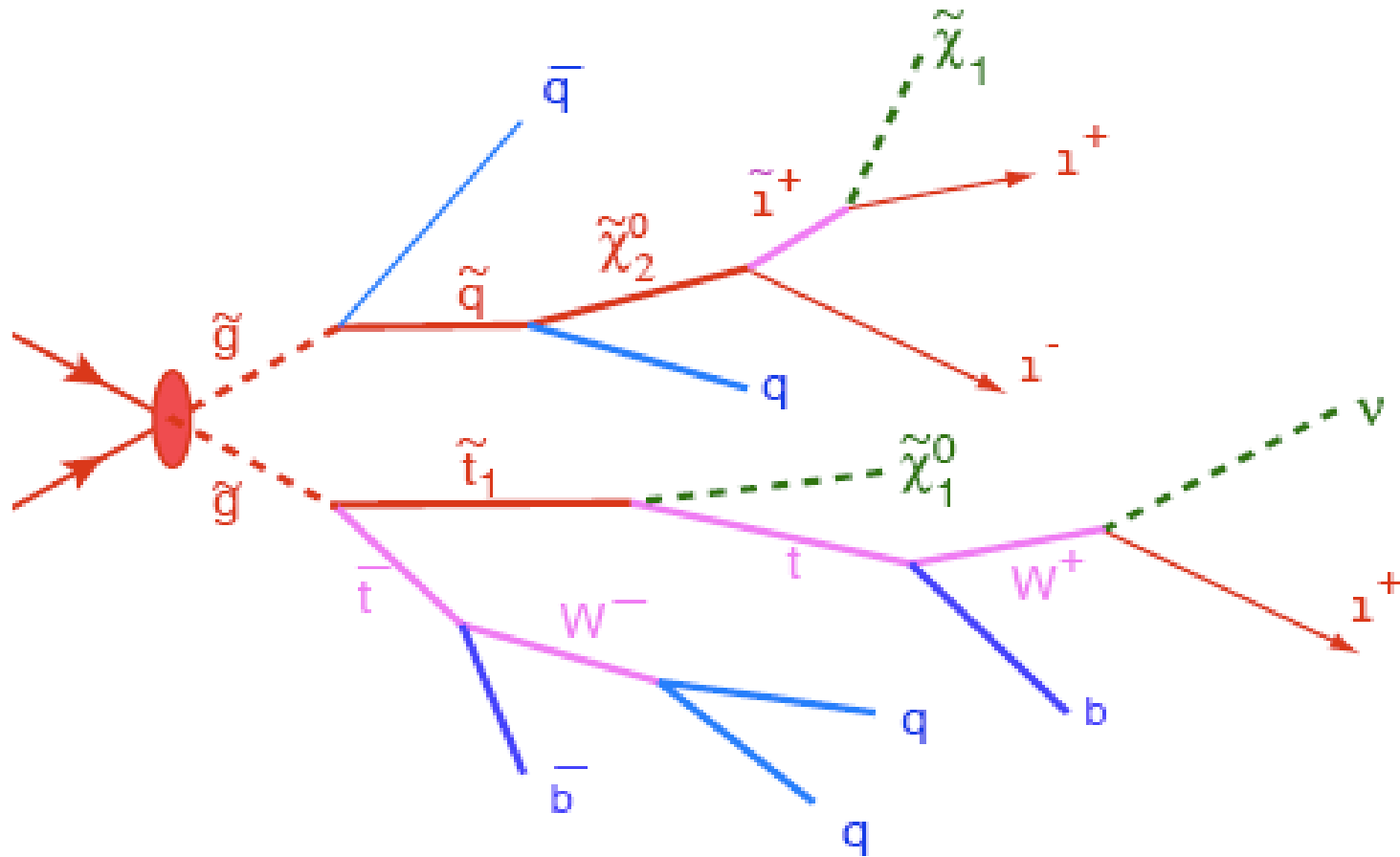
Combining CMS+ATLAS,
with 1 fb⁻¹, 3 σ sensitivity 135-475 GeV/c²

Summary of Sensitivity to SM Higgs

ATLAS + CMS $\approx 2 \times \text{CMS}$	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

6. SUSY AND EXOTICA

SUSY Production and Decay



SUSY Search Strategy

➤ Production

- ❑ Squark and gluino expected to dominate.
- ❑ Strong production, so high cross section.
- ❑ Cross section depends only on masses.
- ❑ Approx. independent of SUSY model.

➤ Decay

- ❑ Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc).
- ❑ Assume R_P conserved → decay to lightest SUSY particle (LSP).
- ❑ Assume squarks and gluinos are heavy → long decay chains.

➤ Signatures

- ❑ MET from LSPs, high- E_T jets and leptons from long decay chain.

➤ Focus on simple signatures

- ❑ Common to wide variety of models.
- ❑ Let Standard Model background and detector performance define searches not models.

SUSY Search Strategy

0-leptons	1-lepton	OSDL	SSDL	≥ 3 leptons	2-photons	γ +lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Generic missing energy signatures.
- Categorised by numbers of leptons and photons.
- Many include jet requirement → strong production.
- All counting experiments at this point.

The Key: Backgrounds

➤ Physics

- ❑ Standard Model processes that give the same signatures as SUSY.
- ❑ Cannot (yet?) rely on Monte Carlo predictions → measure in data.

➤ Detector effects

- ❑ Detector noise, mis-measurements etc. that generate MET or extra jets.
- ❑ Commissioning and calibration → good performance shown earlier.

➤ Other

- ❑ Beam-halo muons and cosmic-ray muons, beam-gas events.
- ❑ Data and simulation already → measure in situ too.

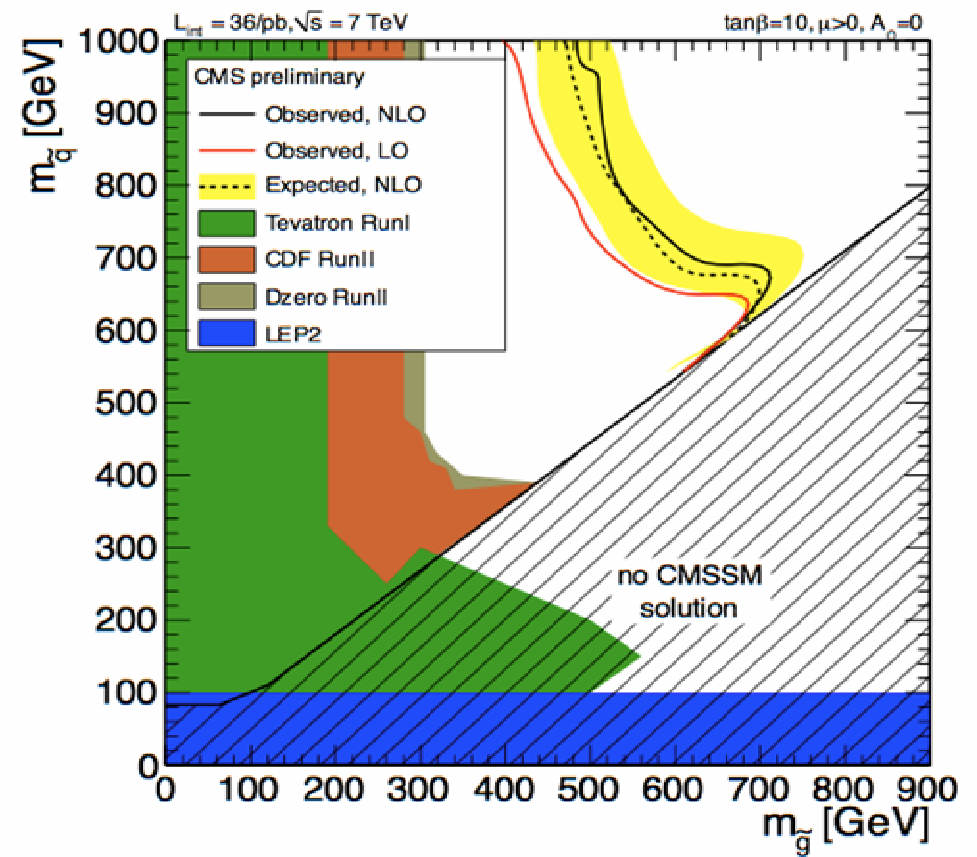
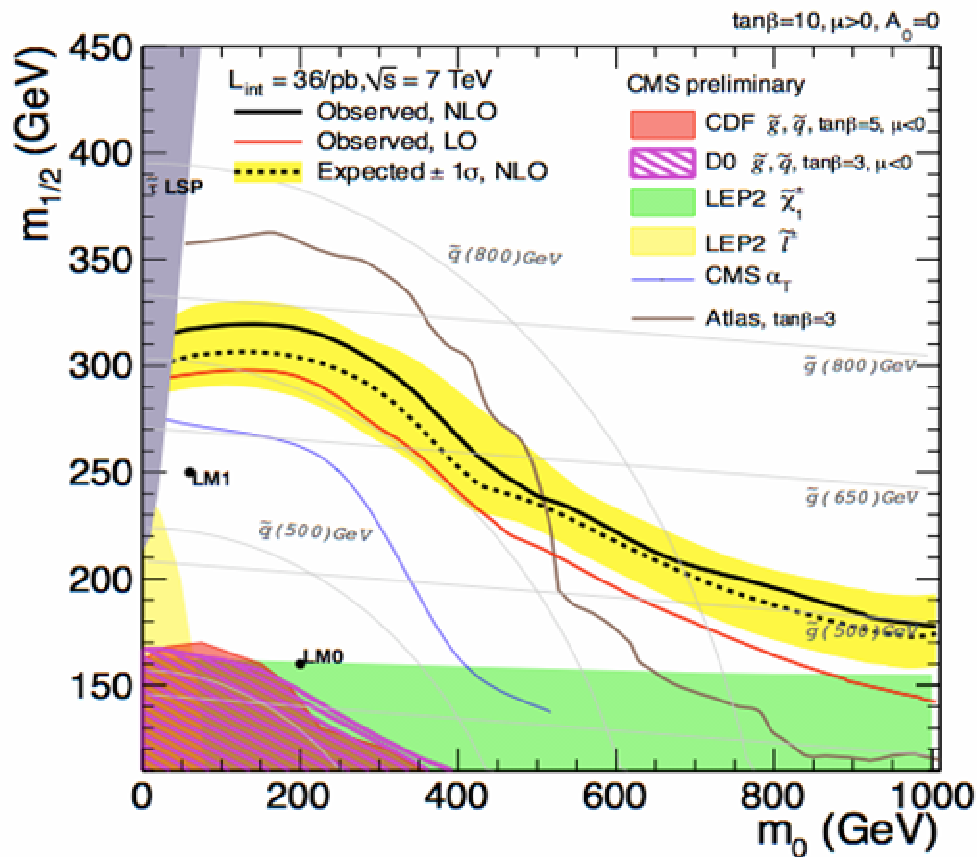
SUSY Searches in 2010

Signature	ATLAS	CMS
		CMS-PAS-SUS-10-005 (MHT v MET) CMS-PAS-SUS-11-001 (αT) CMS-PAS-SUS-10-009 "Razor"
jet+MET	arxiv:1102.5290	PLB 698 (2011) 196 (αT)
lepton+jets+MET	PRL 106, 131802	SUS10006
bjets+(lepton)+MET	arxiv:1103.4344	CMS-PAS-SUS-10-011
	arXiv:1103.6214 (OS+SS)	arXiv:1103.1348 (OS)
2lepton+(jets)+MET	arXiv:1103.6208 (FS)	arXiv:1104.3168 (SS)
multileptons+jets+MET	ATLAS-CONF-2011-039	SUS10008
diphoton+MET	arXiv:1012.4272 (3.1pb ⁻¹)	arXiv:1103.0953
lepton+photon+MET		arXiv:1105.3152
Z+jets+MET		CMS-PAS-SUS-10-010

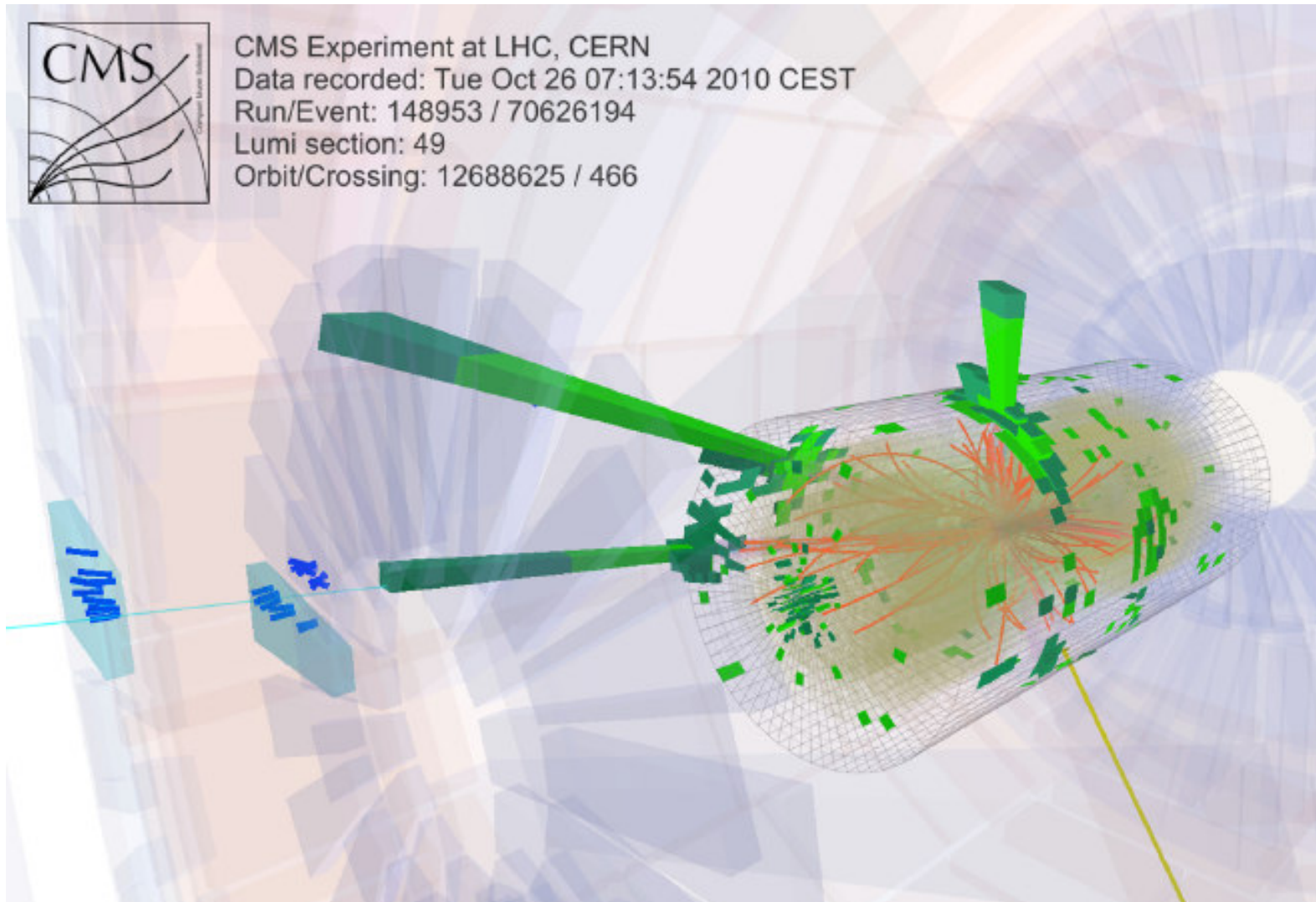
Hadronic Search with MET

	Predicted	Observed
$MH_T > 250 \text{ GeV}$	18.8 ± 3.5	15

	Predicted	Observed
$H_T > 500 \text{ GeV}$	43.8 ± 9.2	40

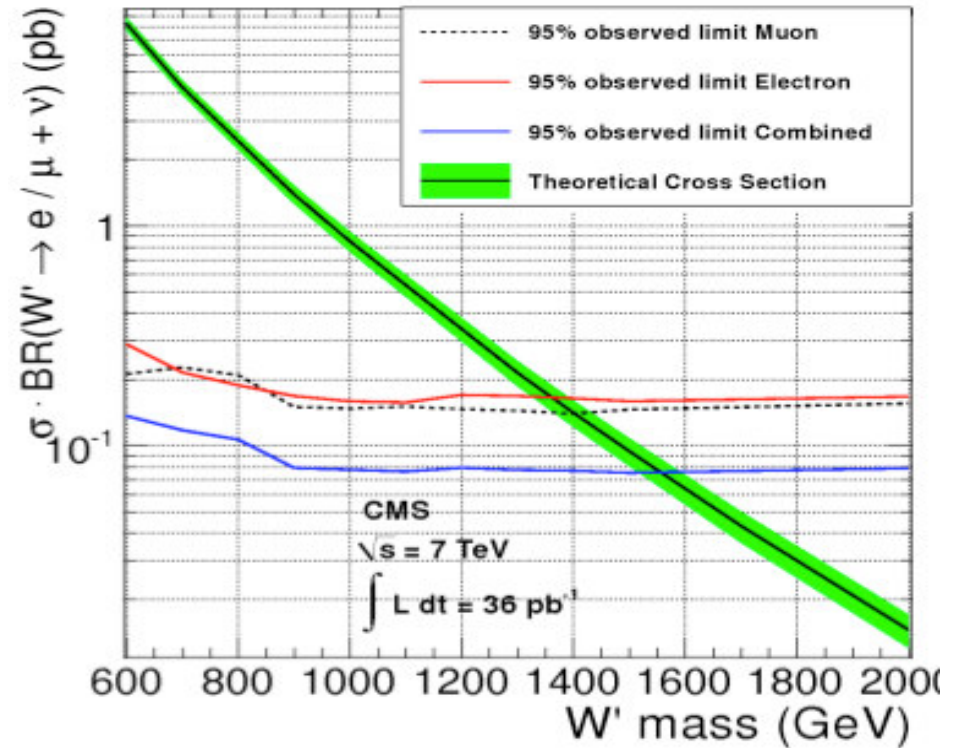
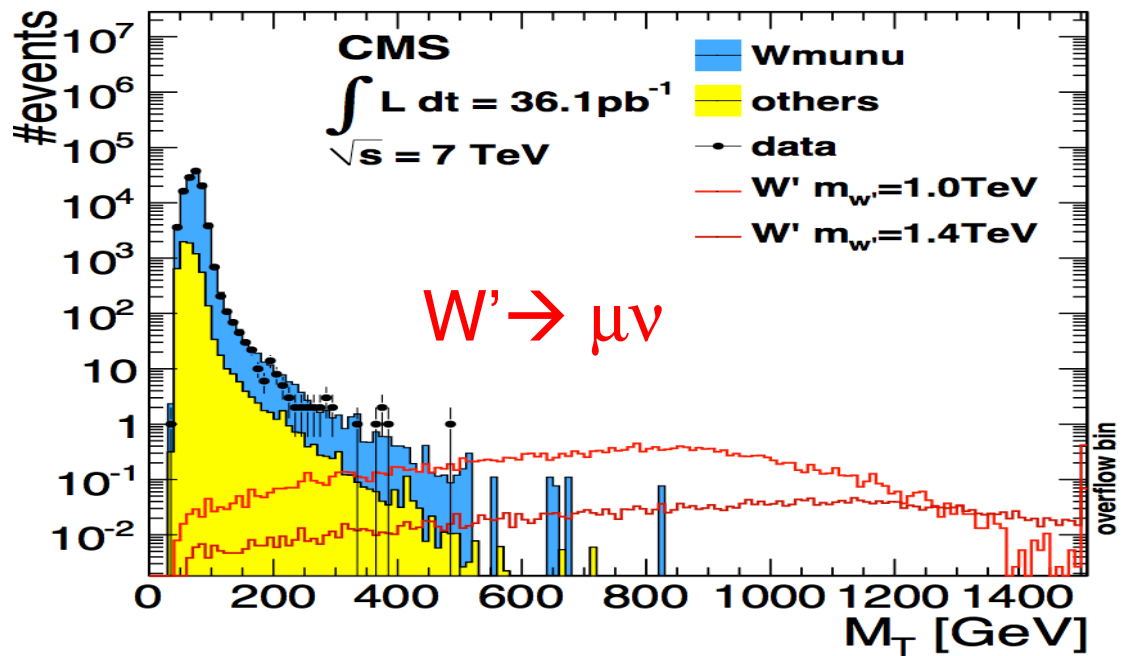
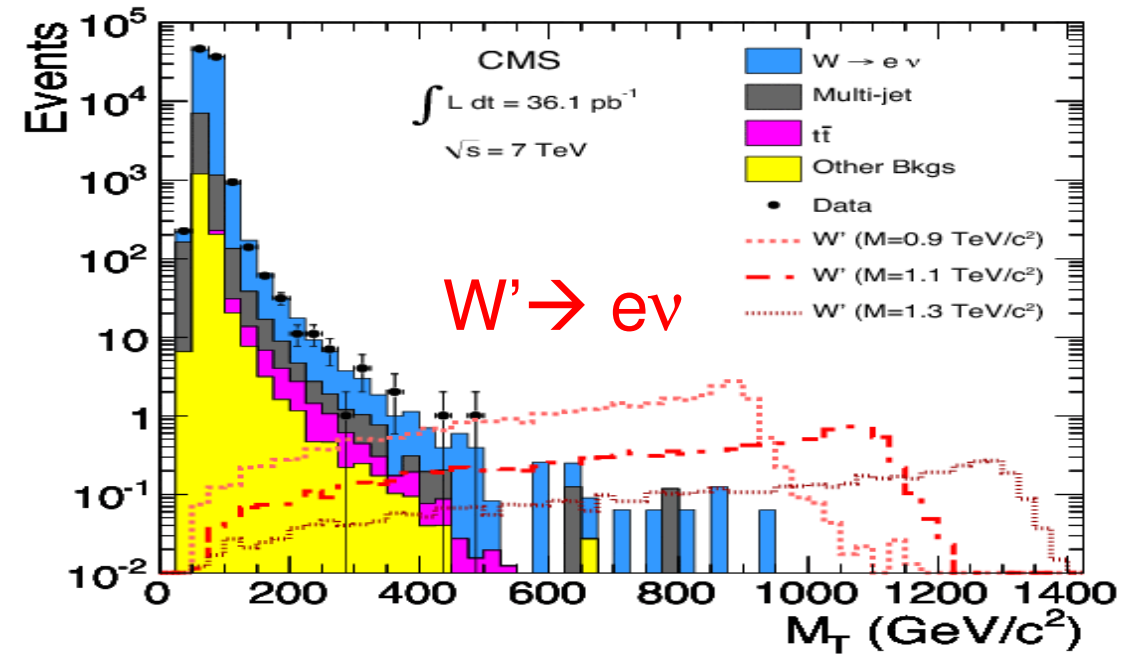


Jets + MET Candidate Event



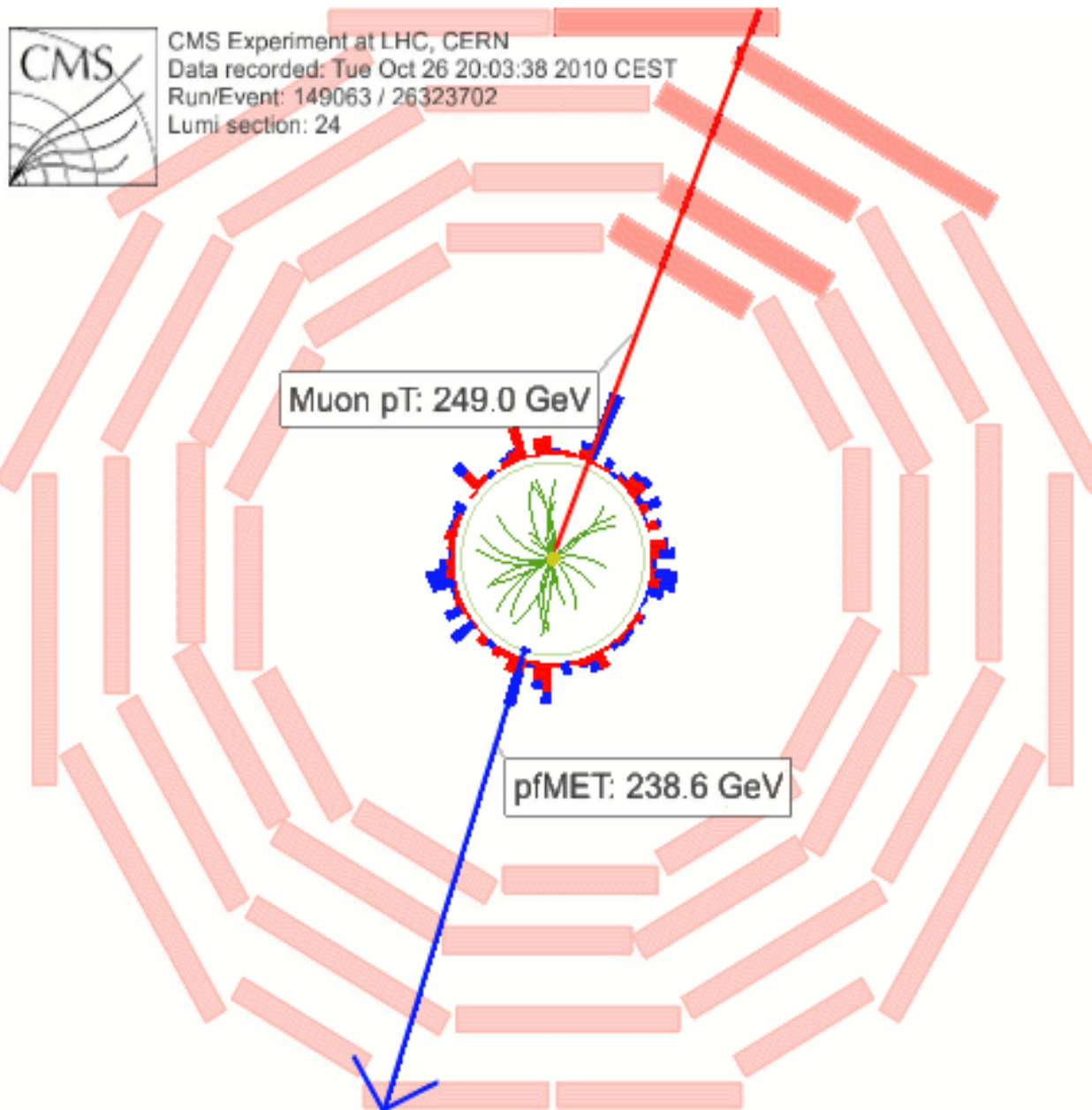
Five jets; total sum of transverse momentum $H_T = 1132 \text{ GeV}$;
missing transverse energy $MH_T = 693 \text{ GeV}$

Search for W'

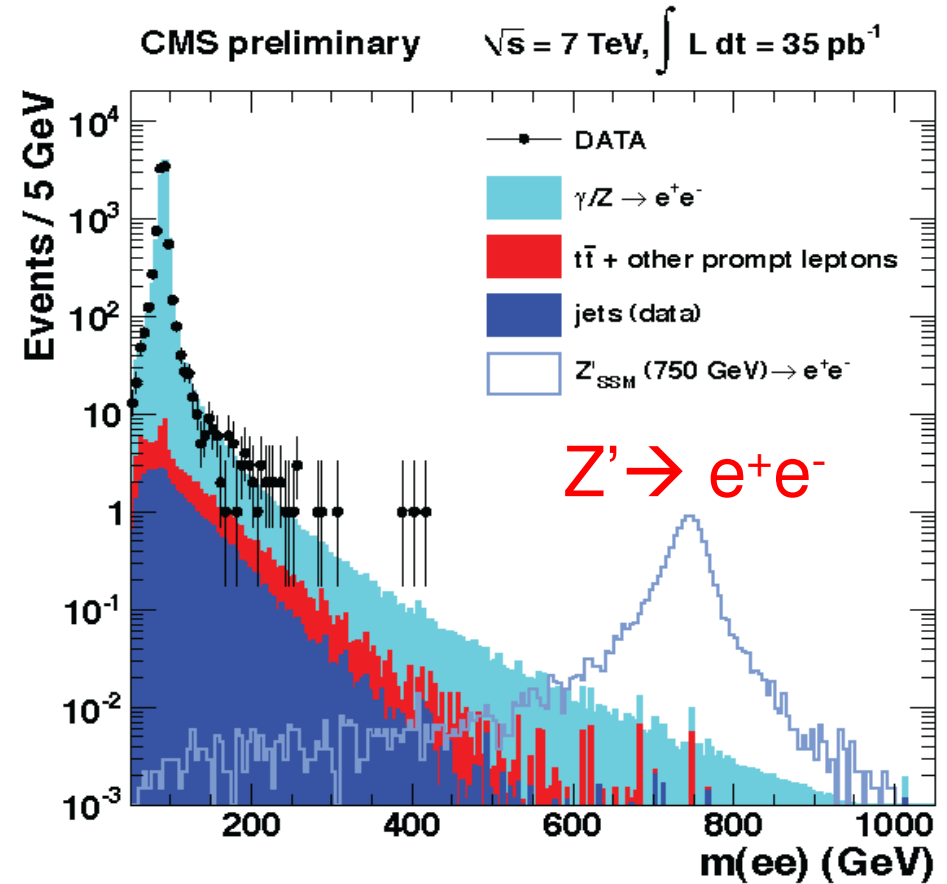
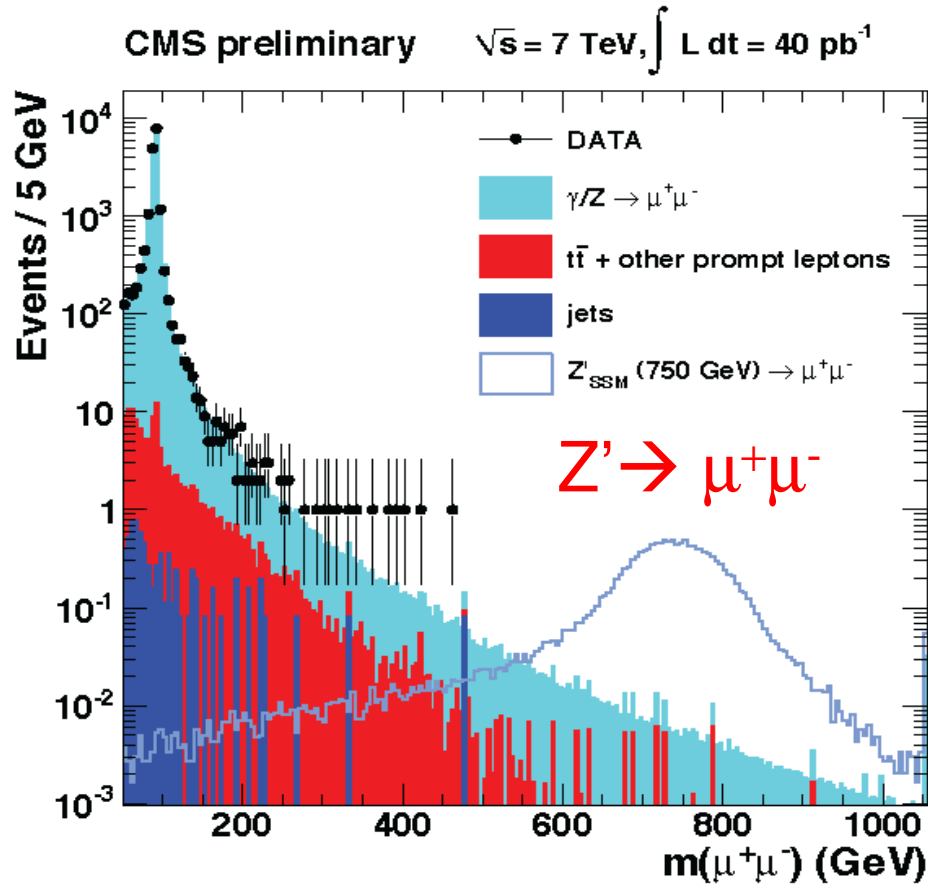


Assuming SM-like couplings and branching fractions a W' with mass $< 1.58 \text{ TeV}$ is excluded at 95%CL.

W' Candidate Event



Search for Z'

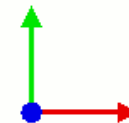
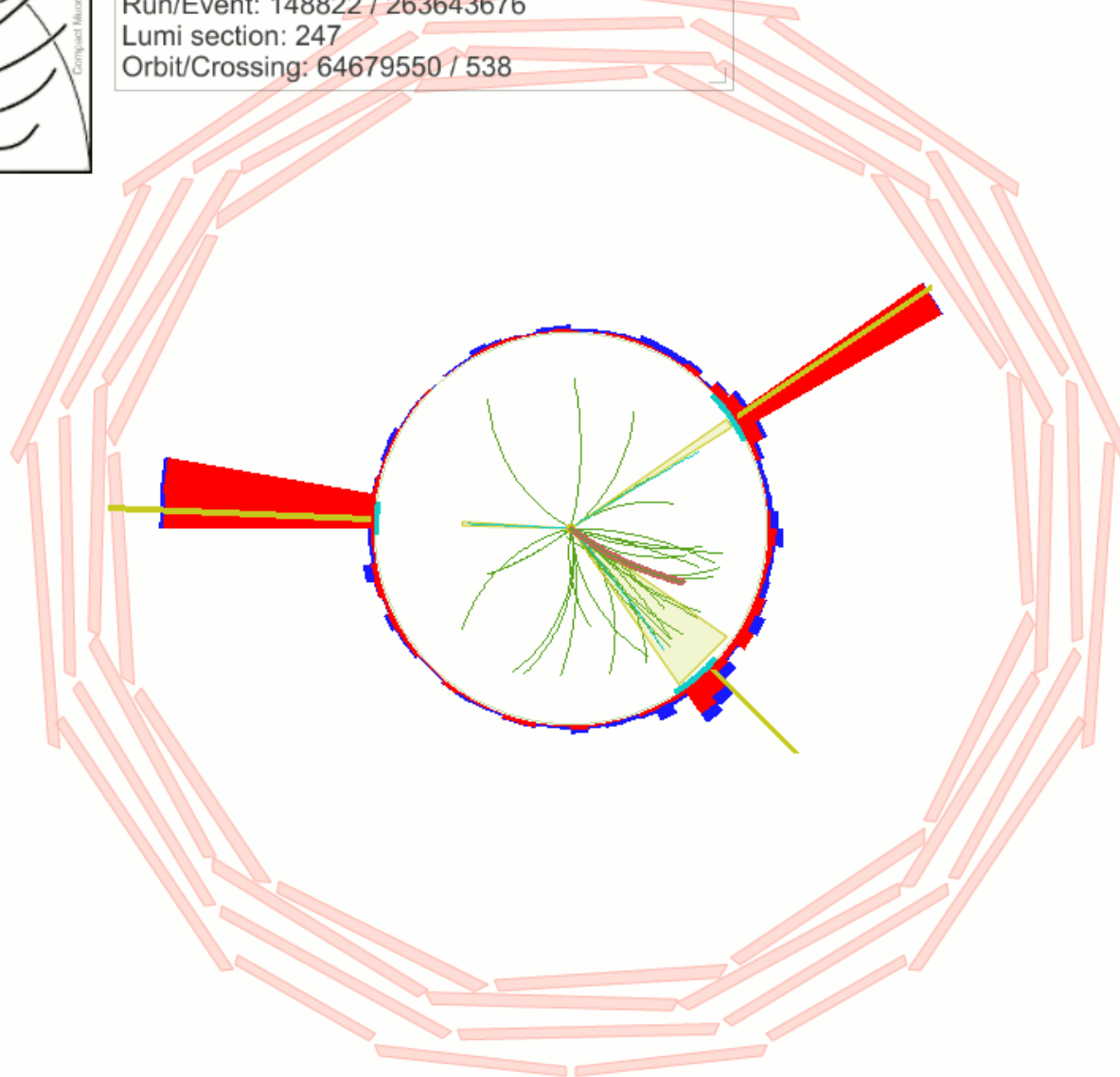


The following Z' 95% C.L. are obtained: **1140 GeV** for the Sequential Standard Model; **887 GeV** for Super-String inspired models; **885-1079 GeV** for RS Kaluza-Klein Gravitons with couplings (k/M_{Pl}) 0.05-0.1.

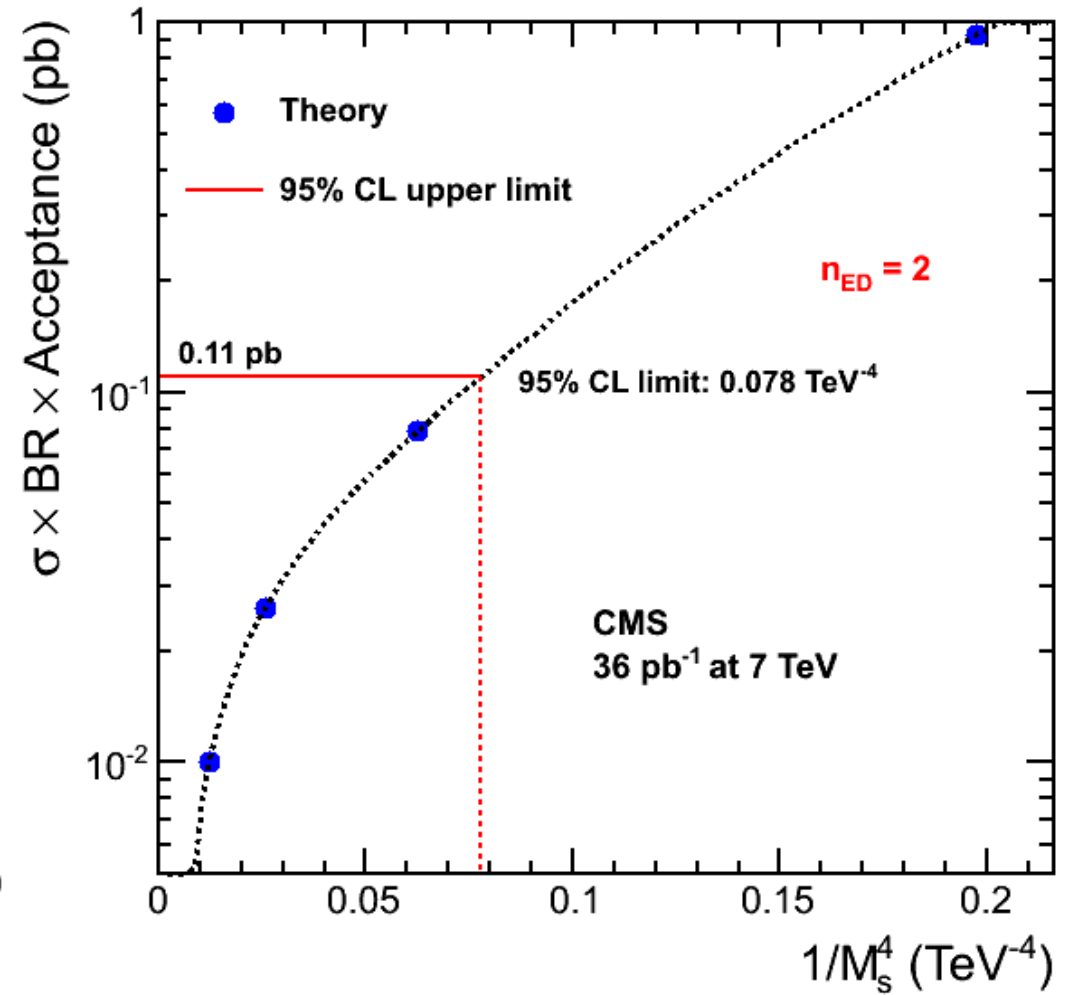
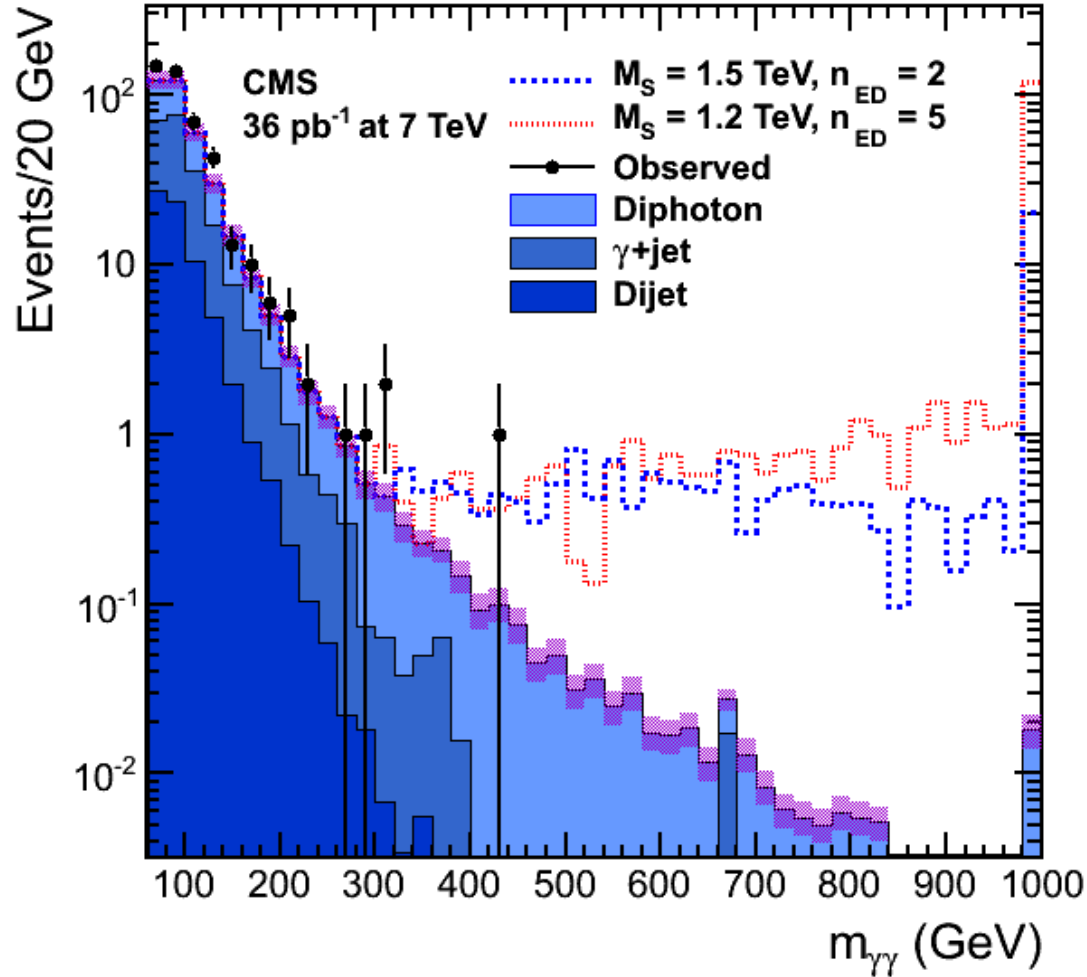
Z' Candidate Event



CMS Experiment at LHC, CERN
Data recorded: Sun Oct 24 15:44:03 2010 CEST
Run/Event: 148822 / 263643676
Lumi section: 247
Orbit/Crossing: 64679550 / 538



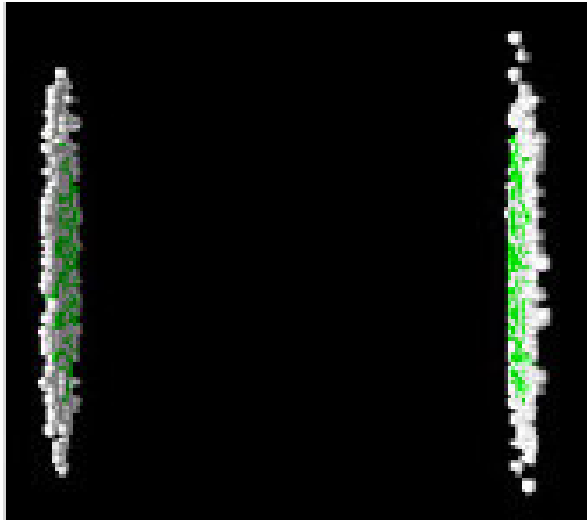
Search for Large Extra Dimensions



... and many other searches

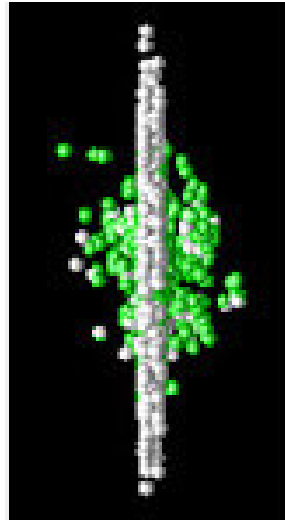
7. HEAVY ION COLLISIONS

Relativistic Heavy Ion Collisions

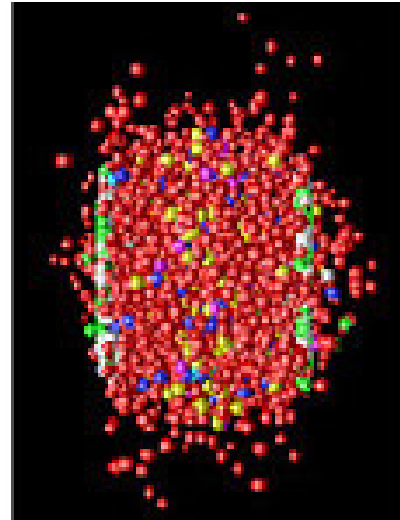


Ions at relativistic energies

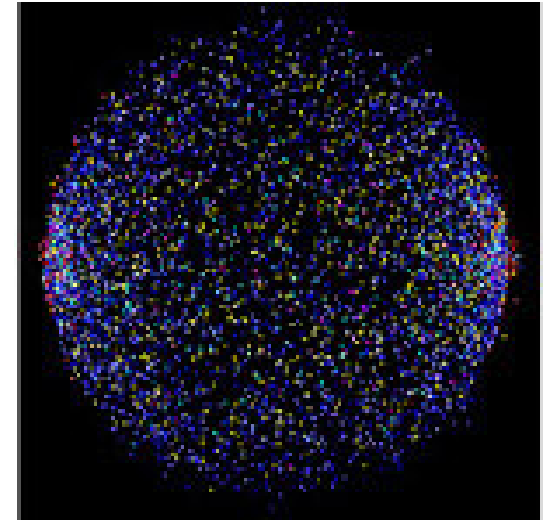
Accelerate



High density of gluons and quarks



Interacting partons



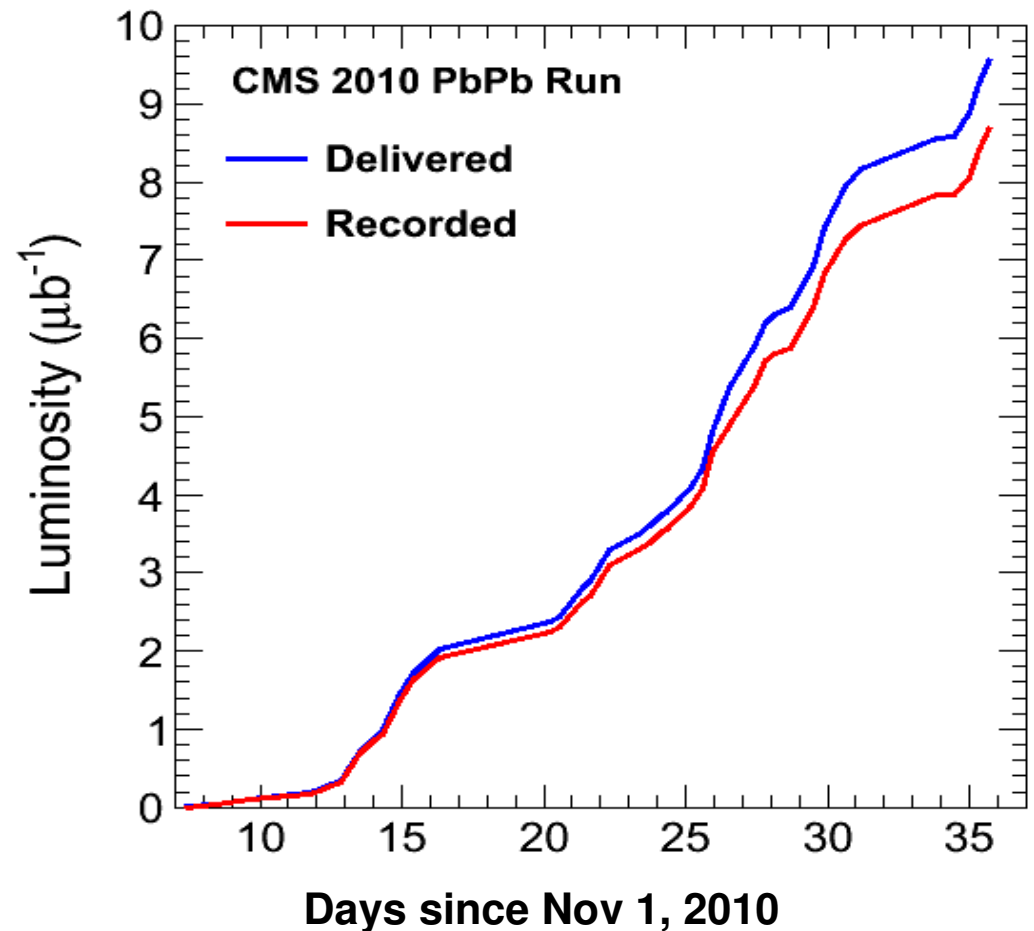
Frozen final state particles

Detect

High Density QCD Physics

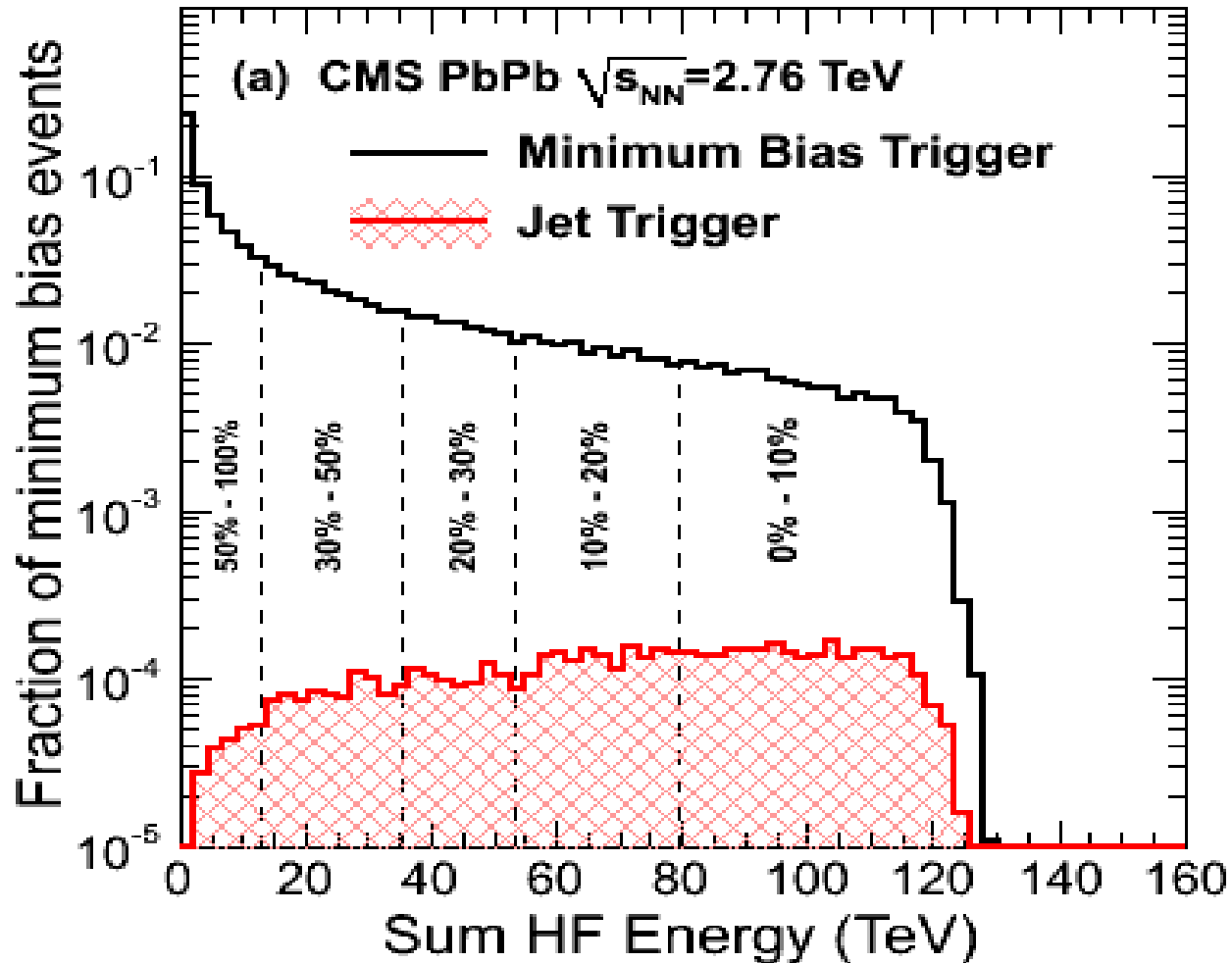
Data Taking during 2010 PbPb Run

- CMS configured in a dedicated mode for heavy ions
 - ❑ Turn off zero suppression
 - ❑ Taking data at up to 220 Hz
 - ❑ 12 MB event size
- Triggering on minimum bias, jets, muons and photons
 - ❑ ALL rare probes written to tape
 - ❑ ~half of minimum bias written
- Recorded luminosity PbPb: 8.7 mb^{-1}
- Recorded luminosity pp@2.76 TeV: 241 nb^{-1}



Centrality

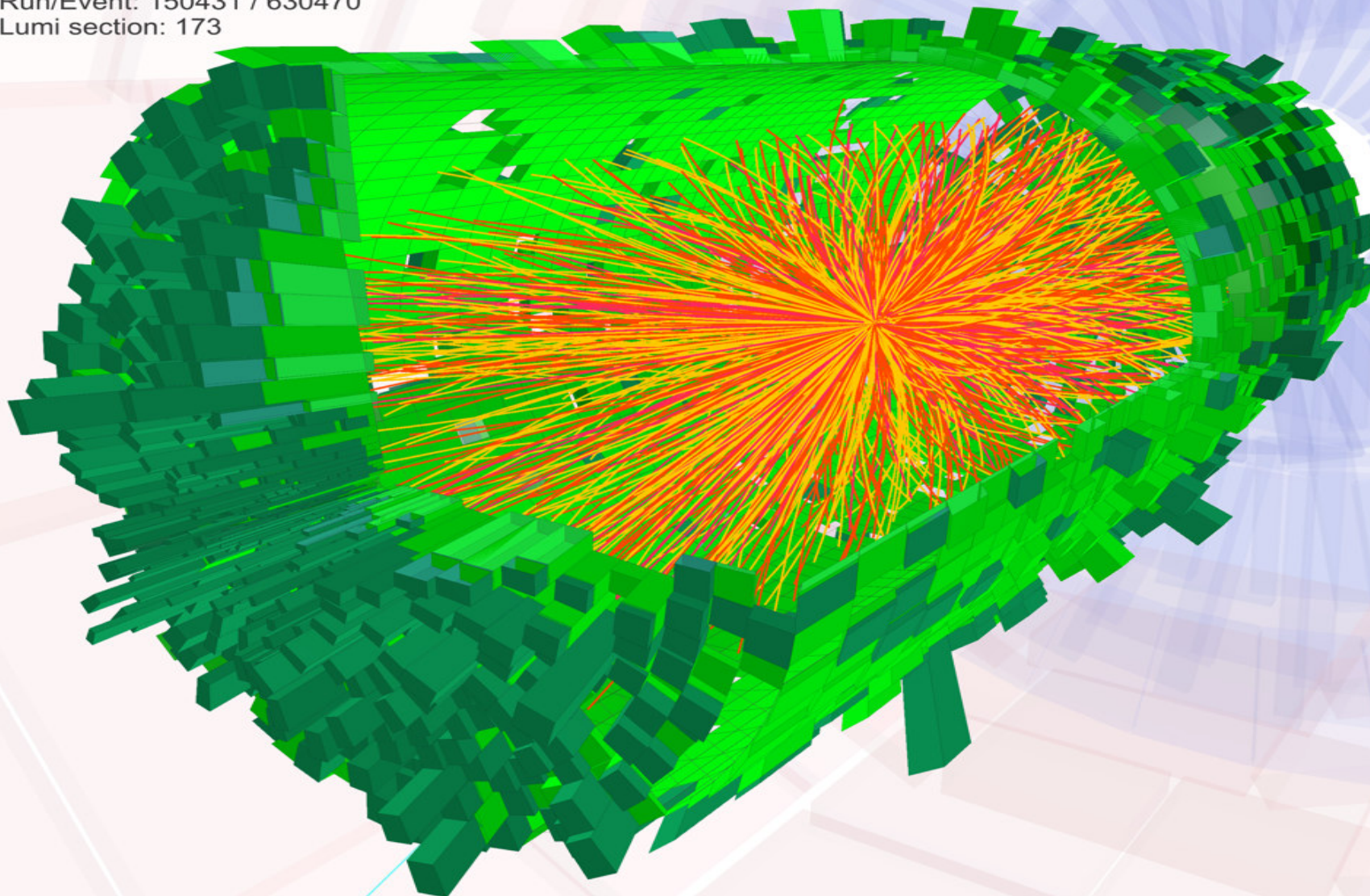
- Hadron-Forward (HF) calorimeter energy deposits in $3 < |h| < 5$



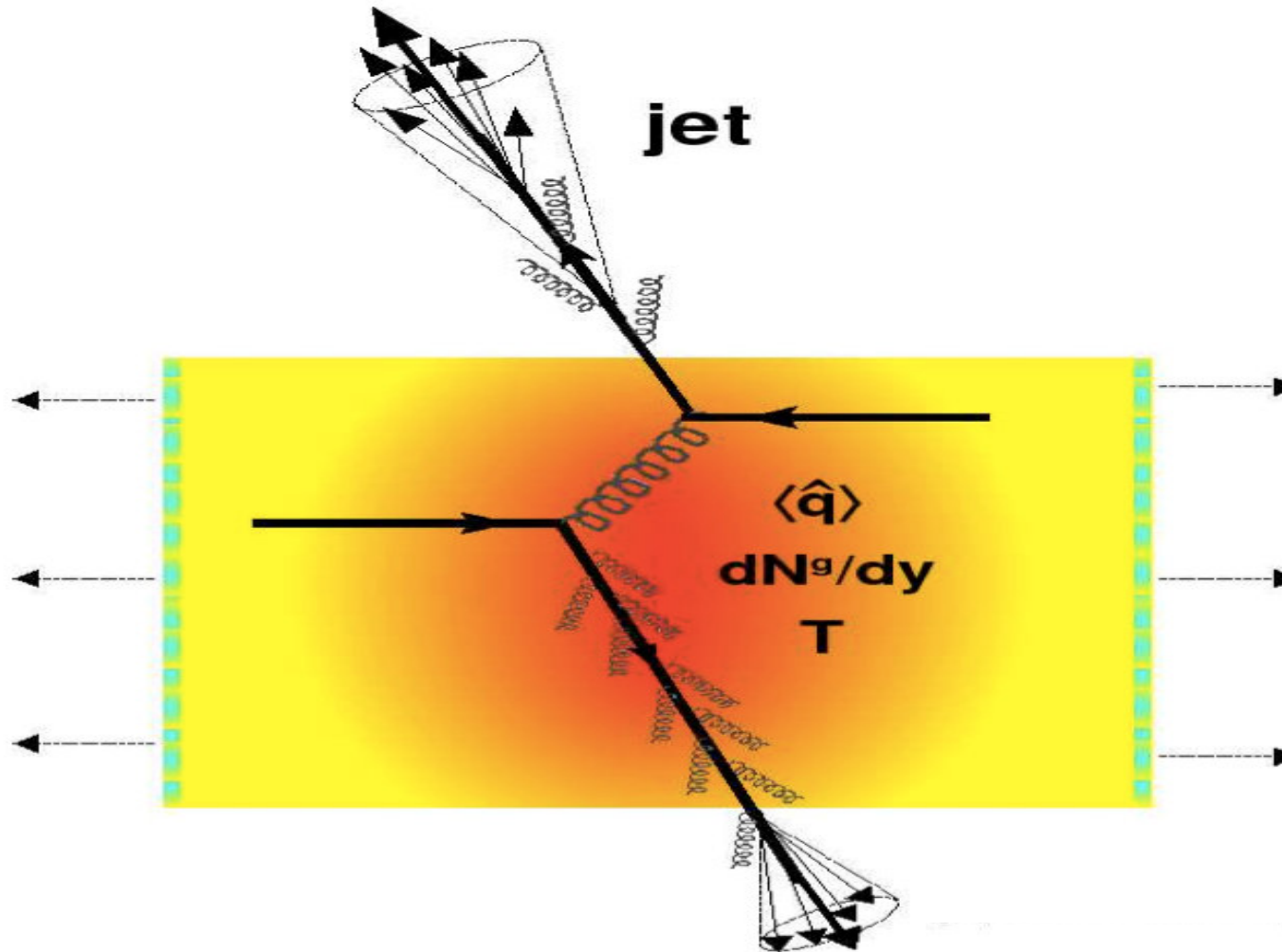
PbPb Collision



CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173



Jet “Quenching”

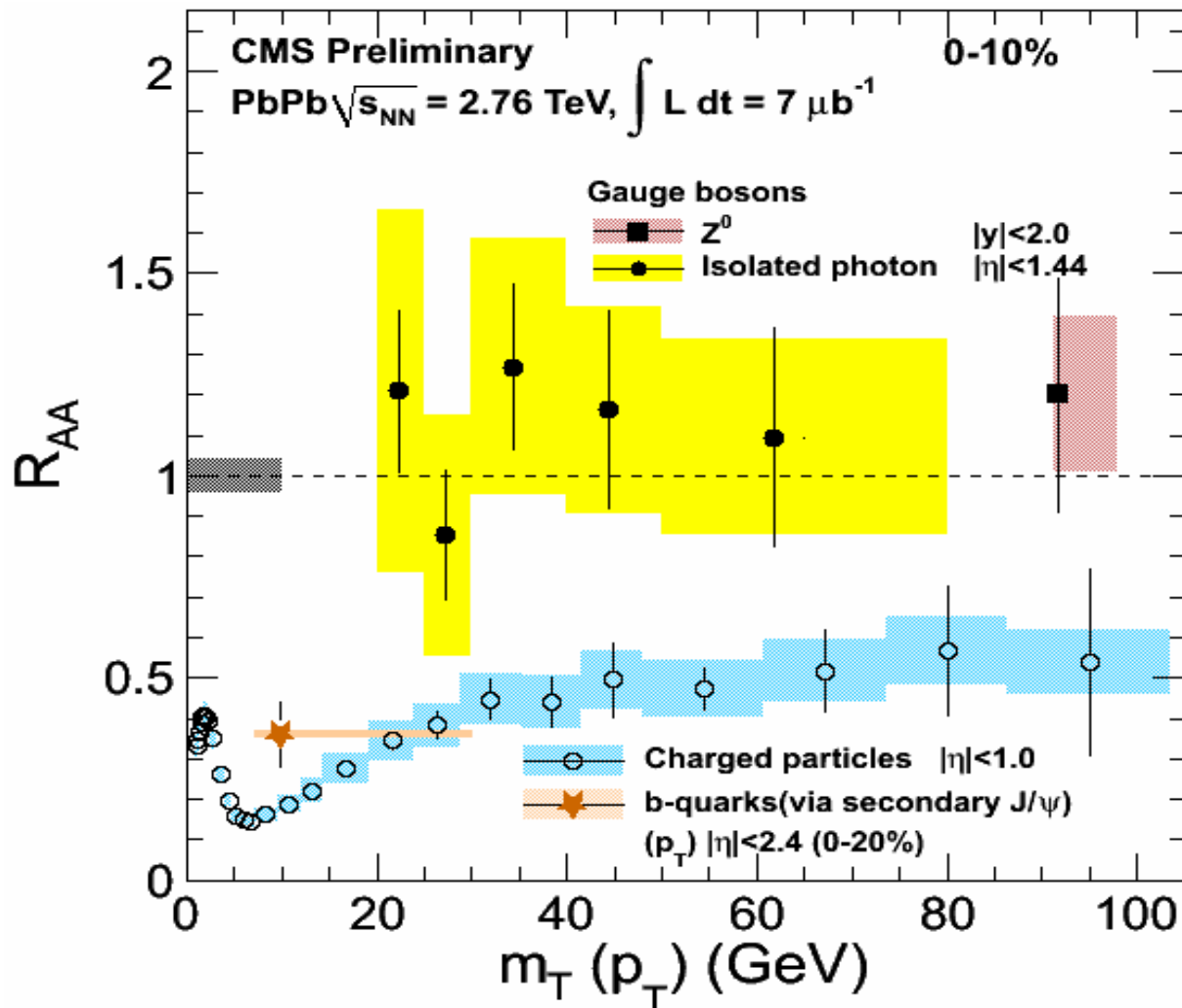


R_{AA} for Multiple Particle Types

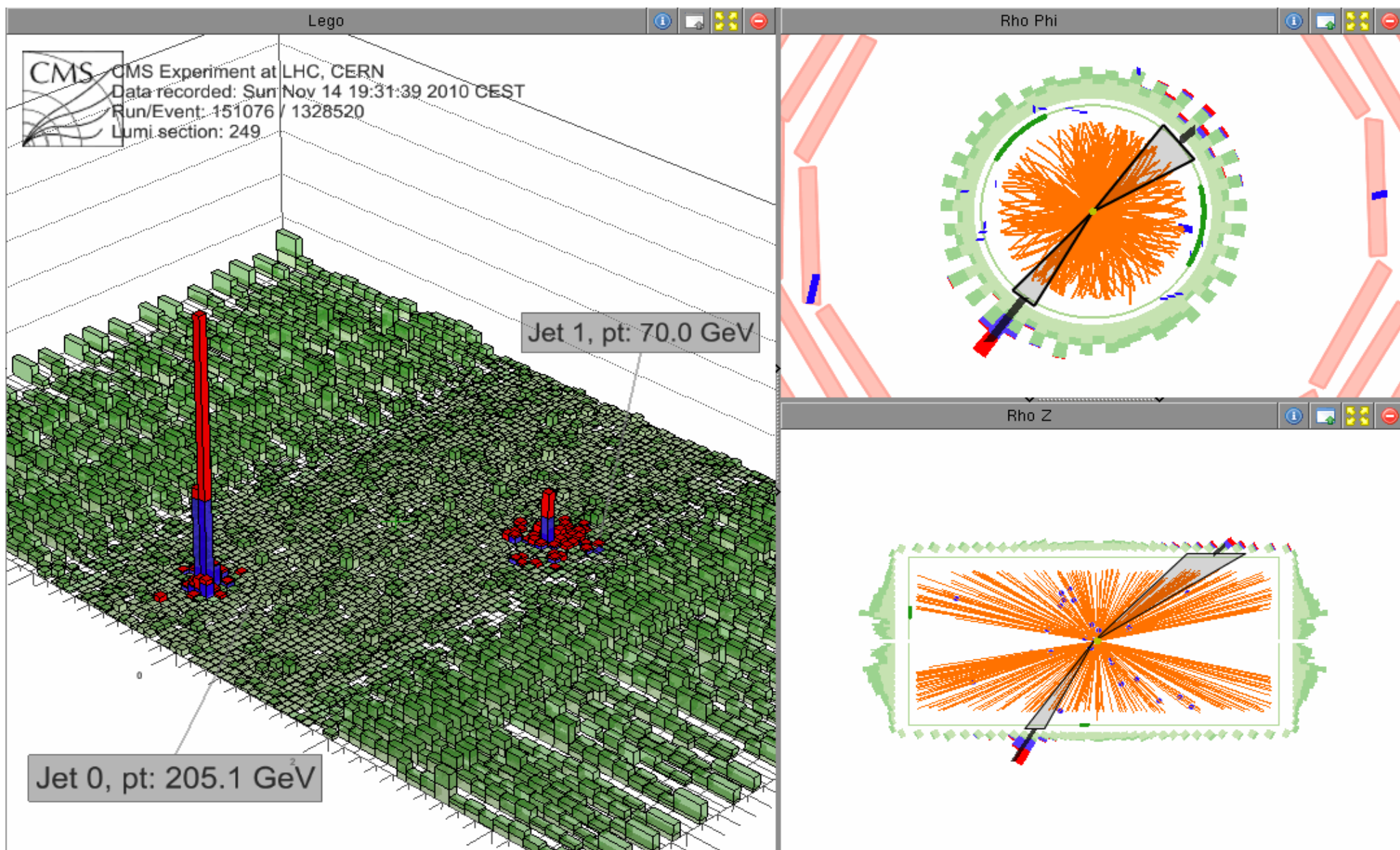
$$R_{AA} =$$

#(particles observed in AA collision per N-N (binary) collision)

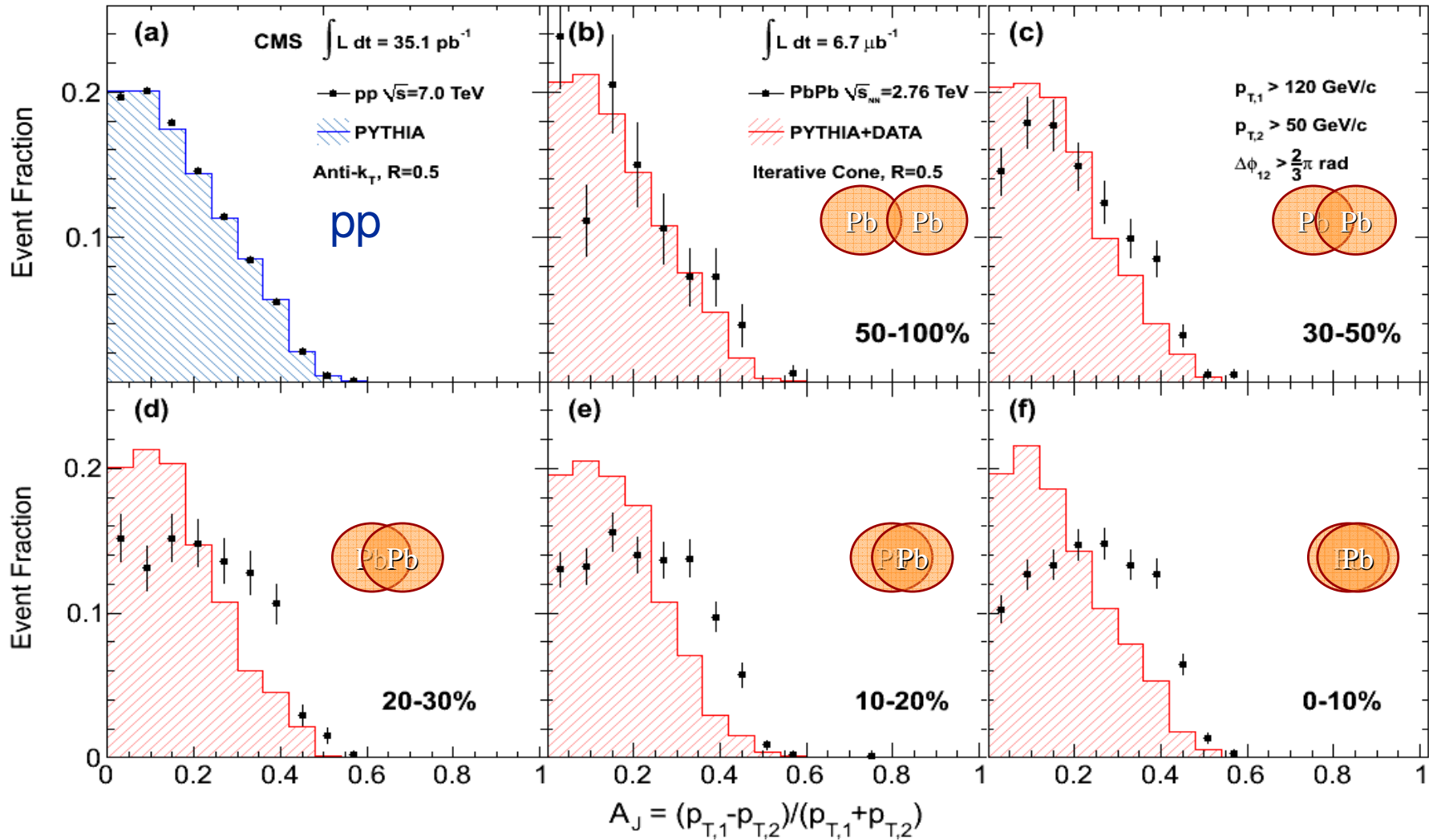
#(particles observed per p-p collision)



Jets in HI Collisions



Dijet Energy Imbalance

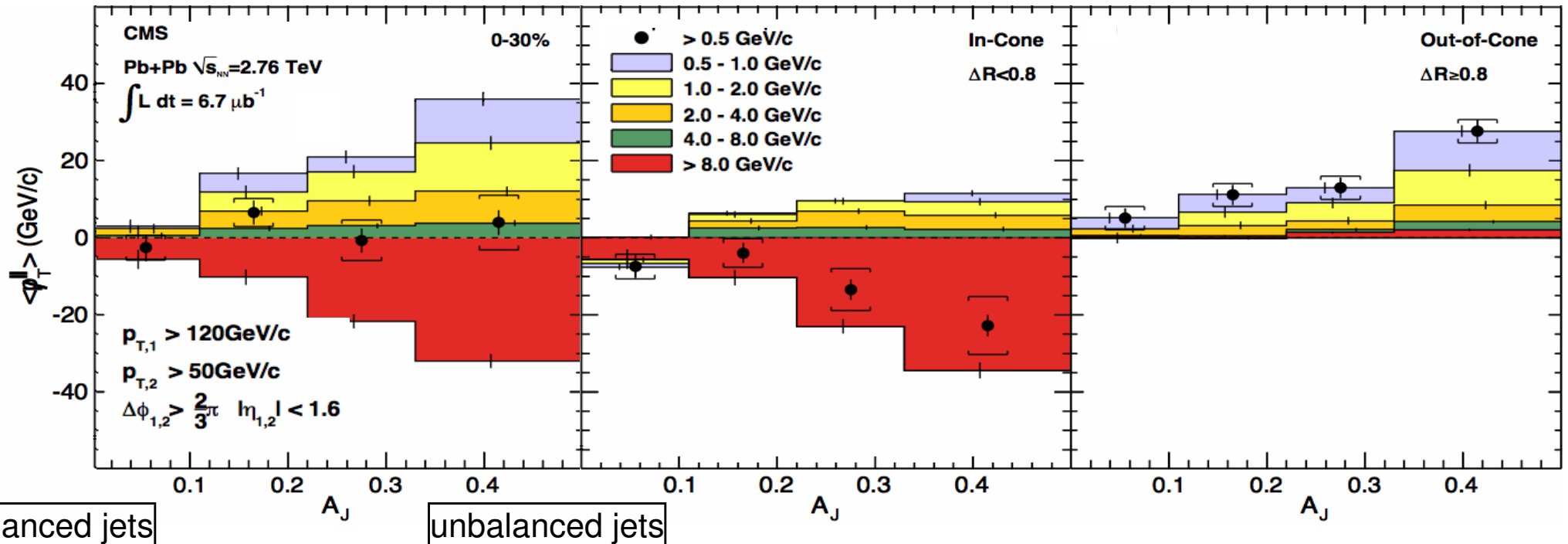
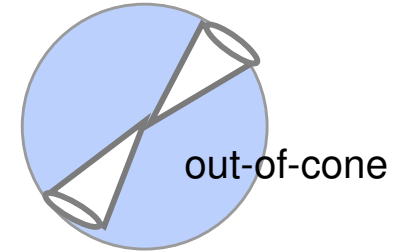
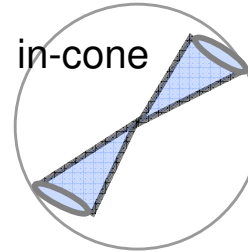


Parton energy loss is observed as a pronounced energy imbalance in central PbPb.

Where is the Energy?

$$\cancel{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$

0-30% Central PbPb

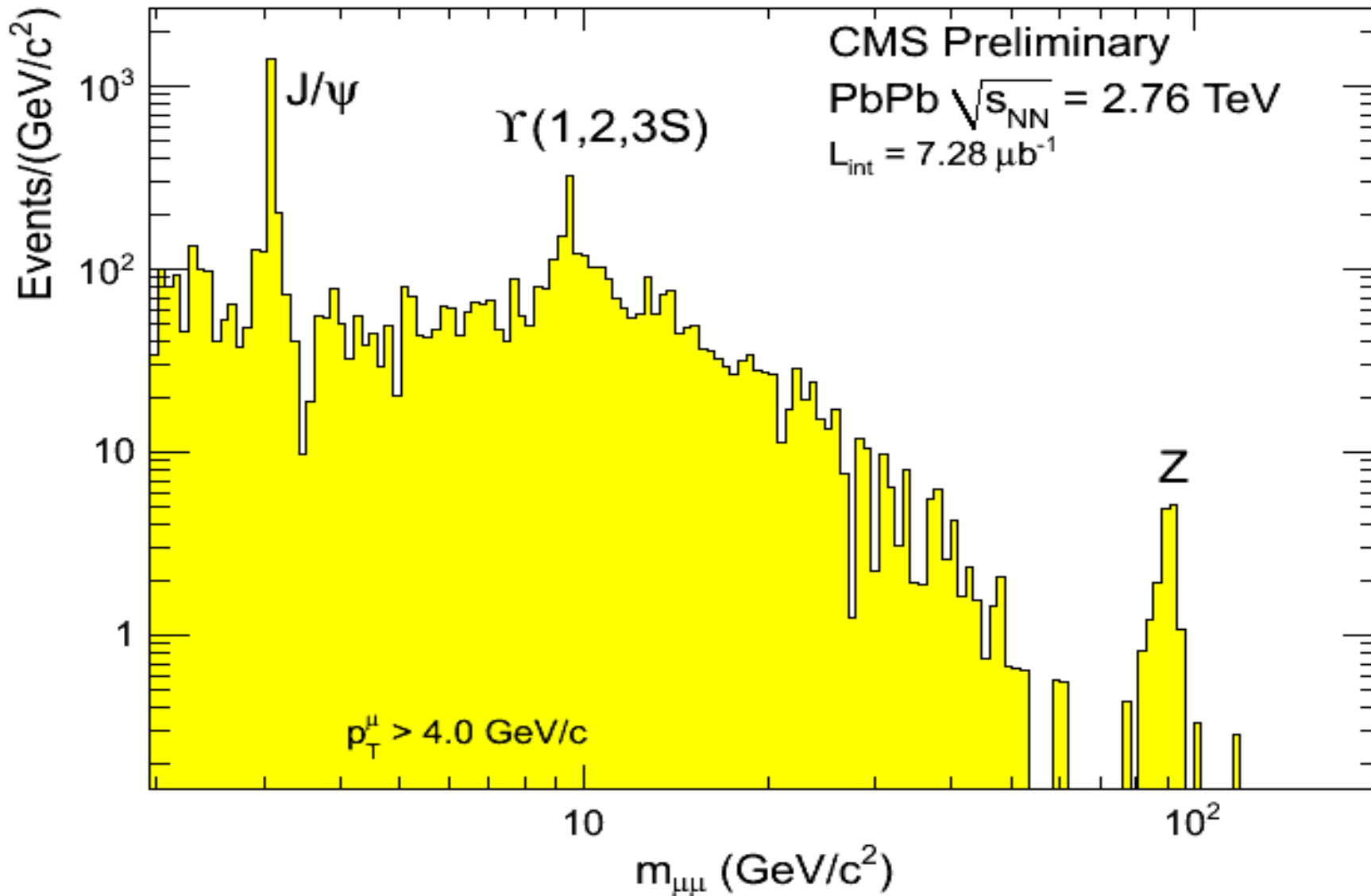


Low p_T , full acceptance
Momentum is balanced

In-cone large momentum
imbalance at high p_T
Consistent with calorimetry

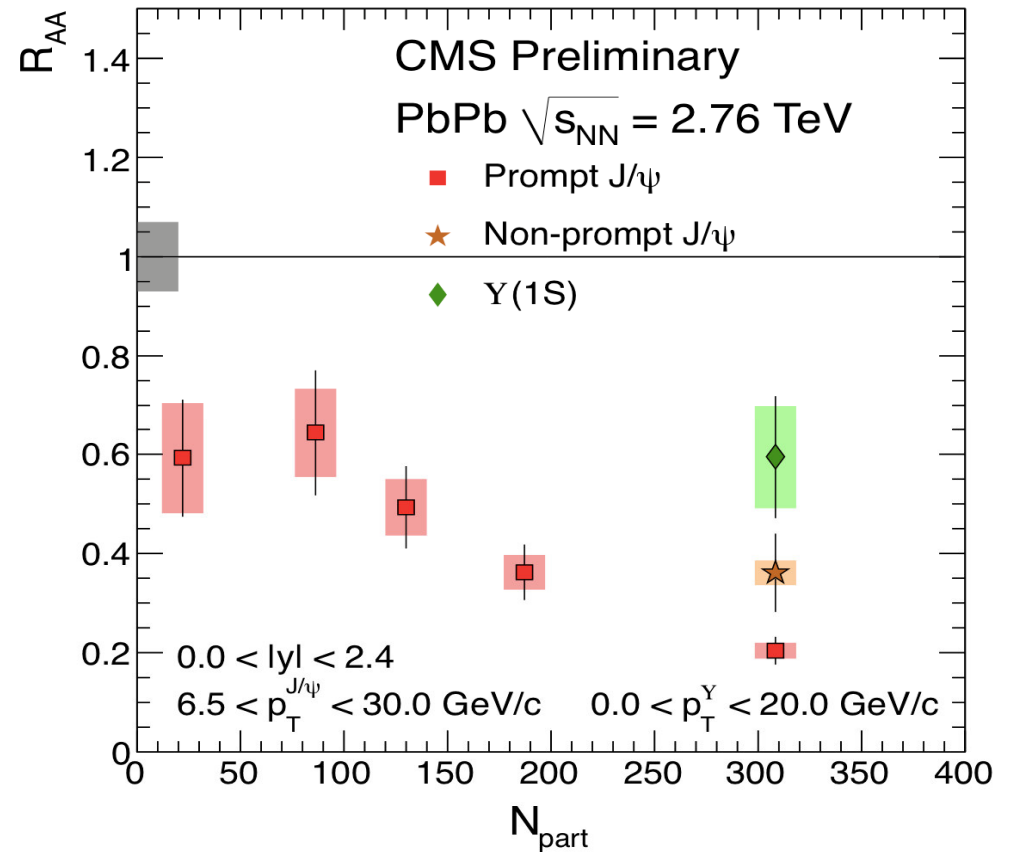
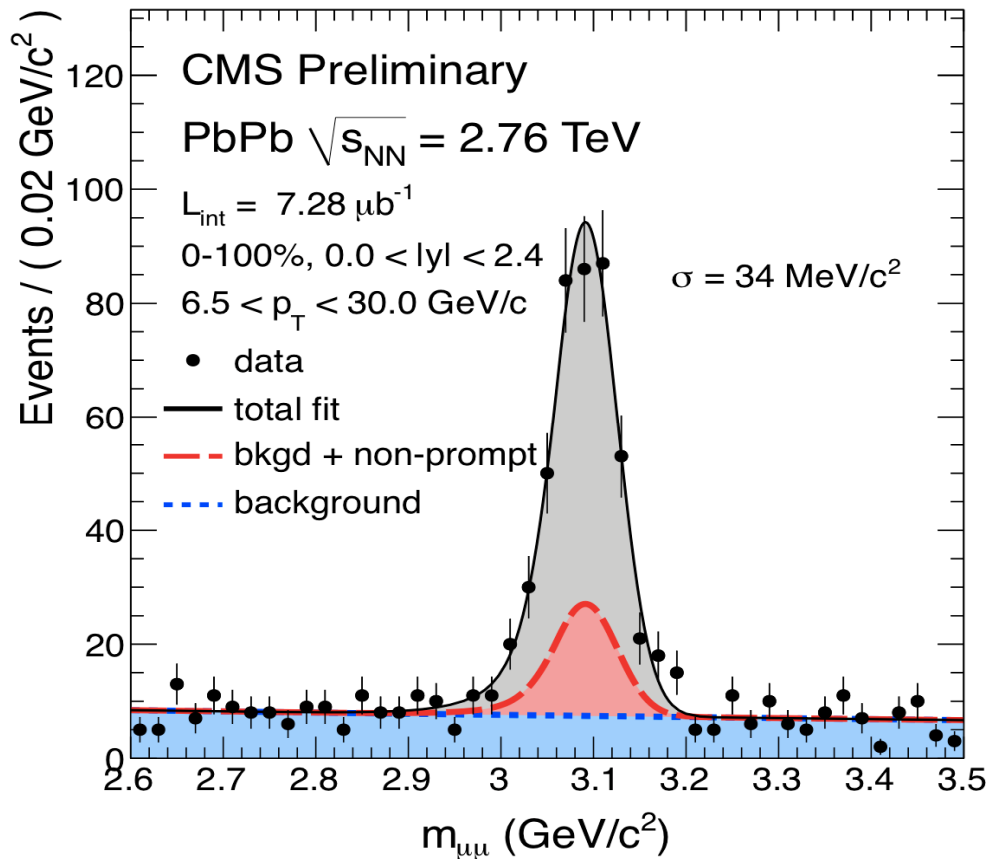
Out-of-cone low p_T particles
balance the complete event

Quarkonia Production

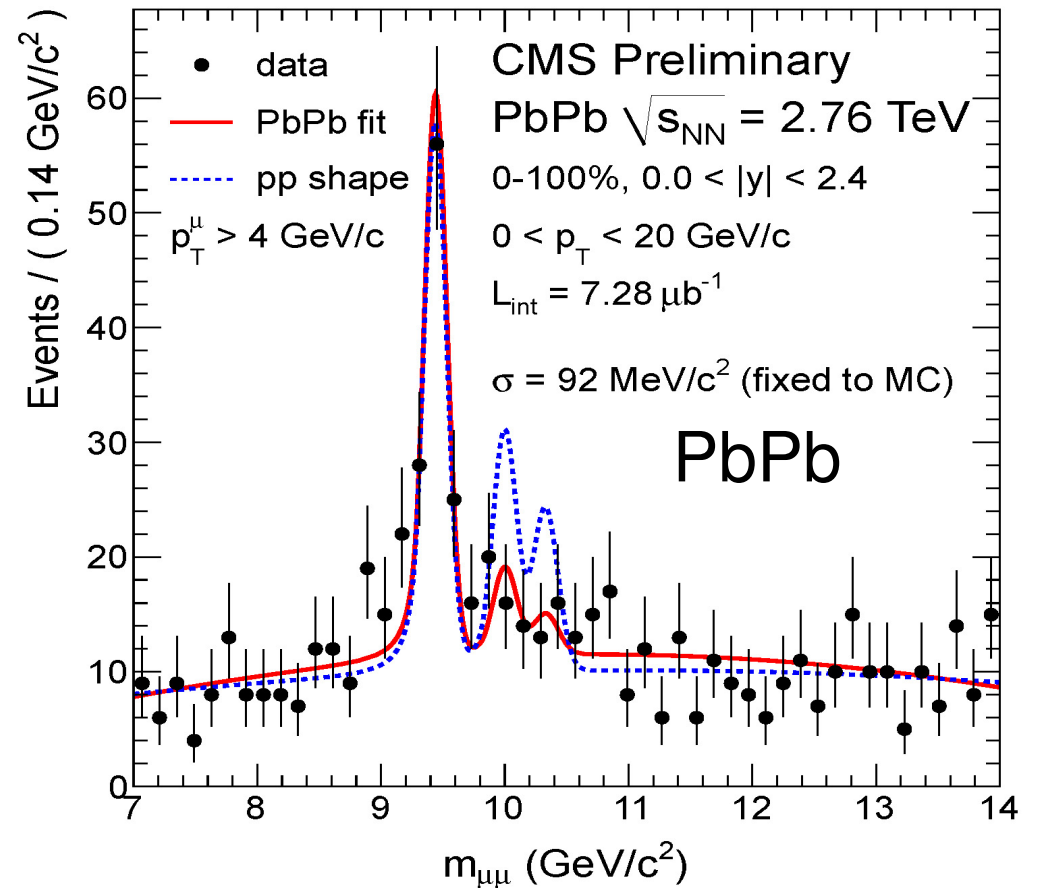
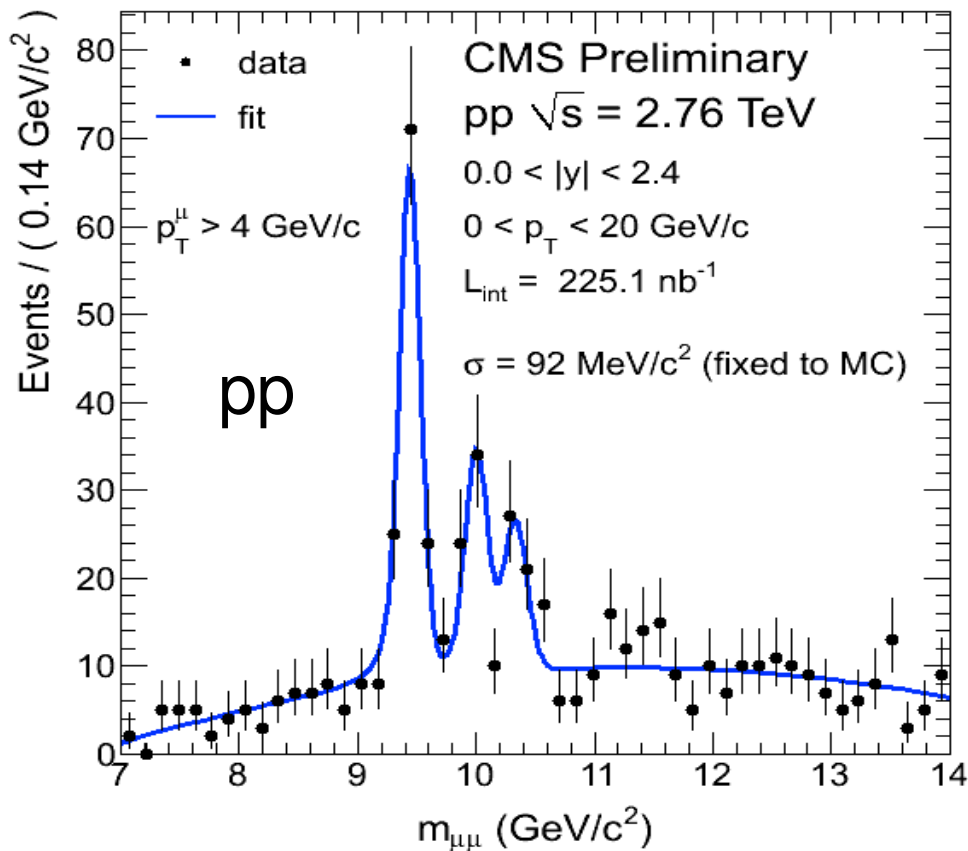


Quarkonia Suppression

- ❑ Non-prompt J/ψ suppression is a measure of b-quark quenching
- ❑ High p_T J/ψ is strongly suppressed at the LHC
- ❑ Inclusive $\Upsilon(1S)$ is suppressed



Suppression of Excited Υ States

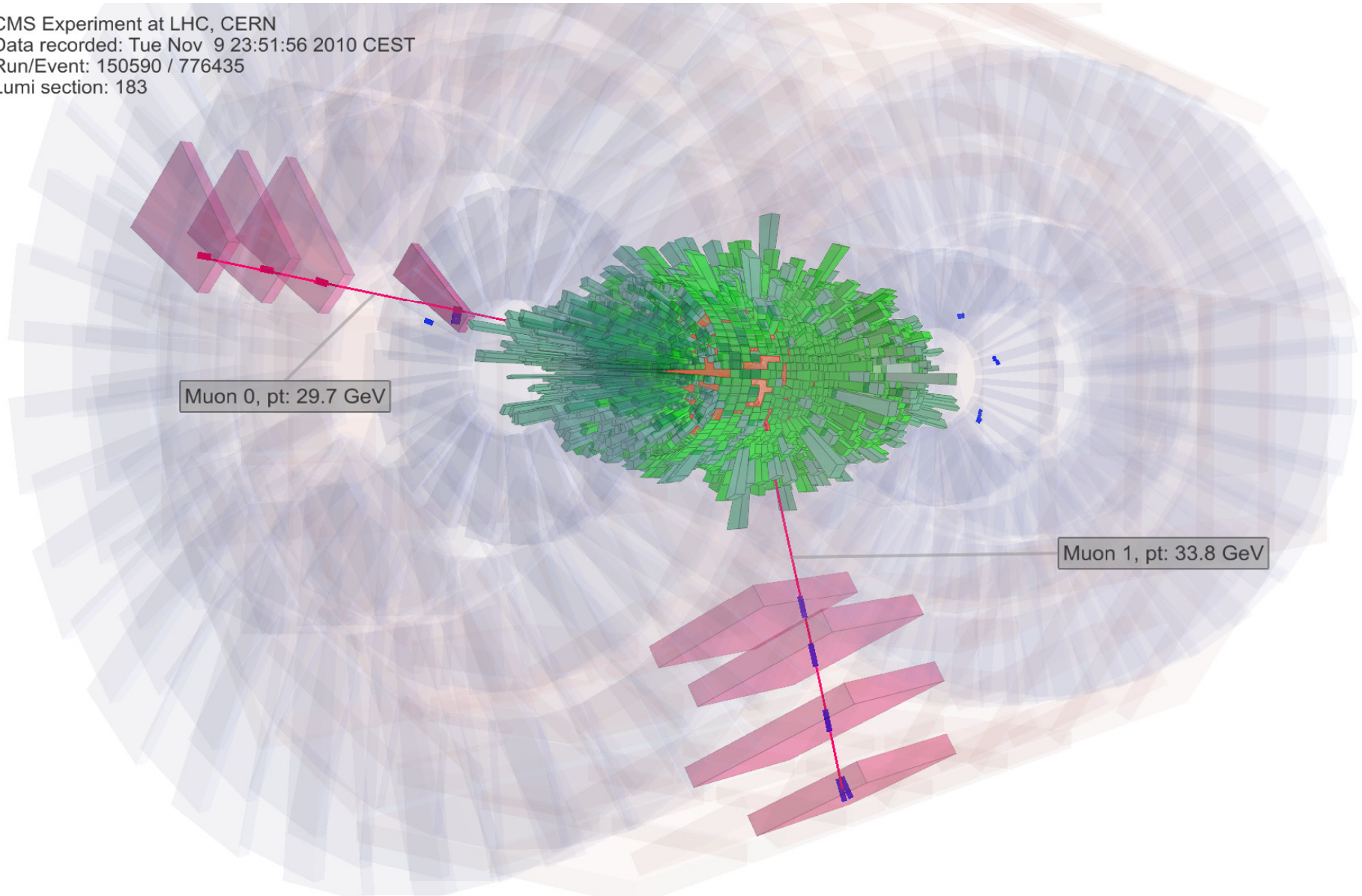


$$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S + 3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

First Z^0 Dimuon Candidate



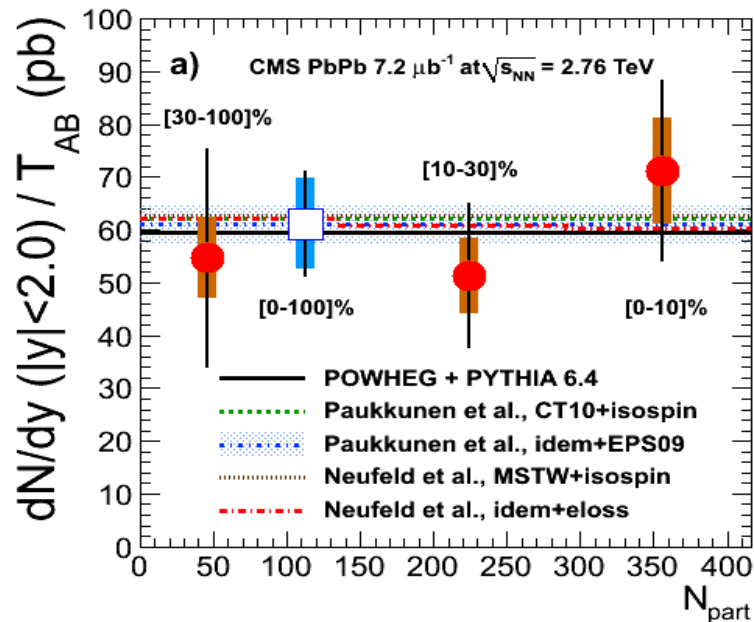
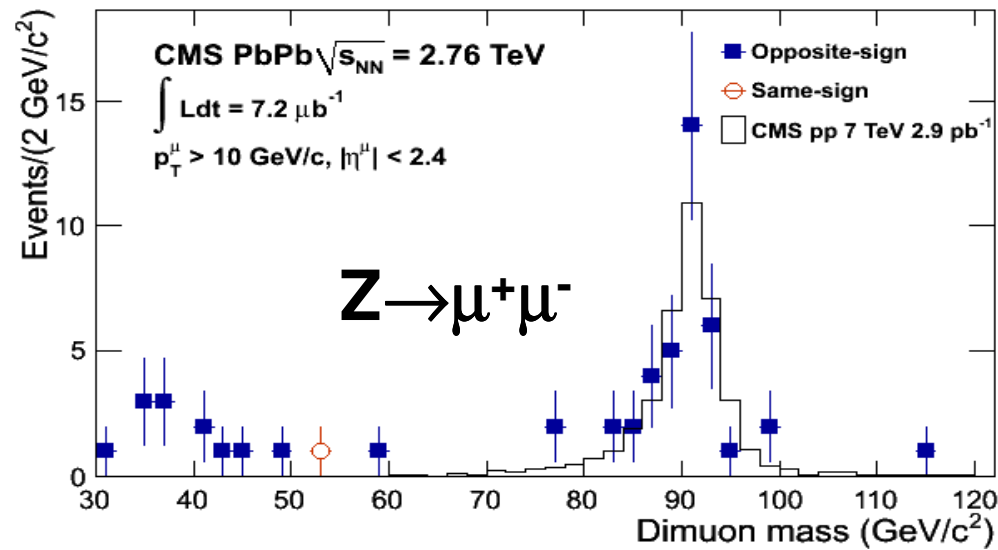
CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:51:56 2010 CEST
Run/Event: 150590 / 776435
Lumi section: 183



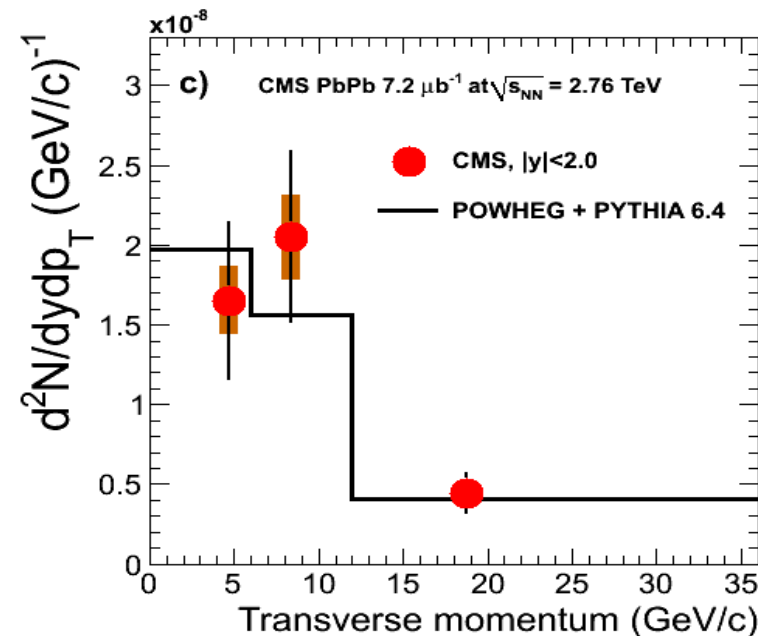
Muon 0, pt: 29.7 GeV

Muon 1, pt: 33.8 GeV

Z Bosons Scaling



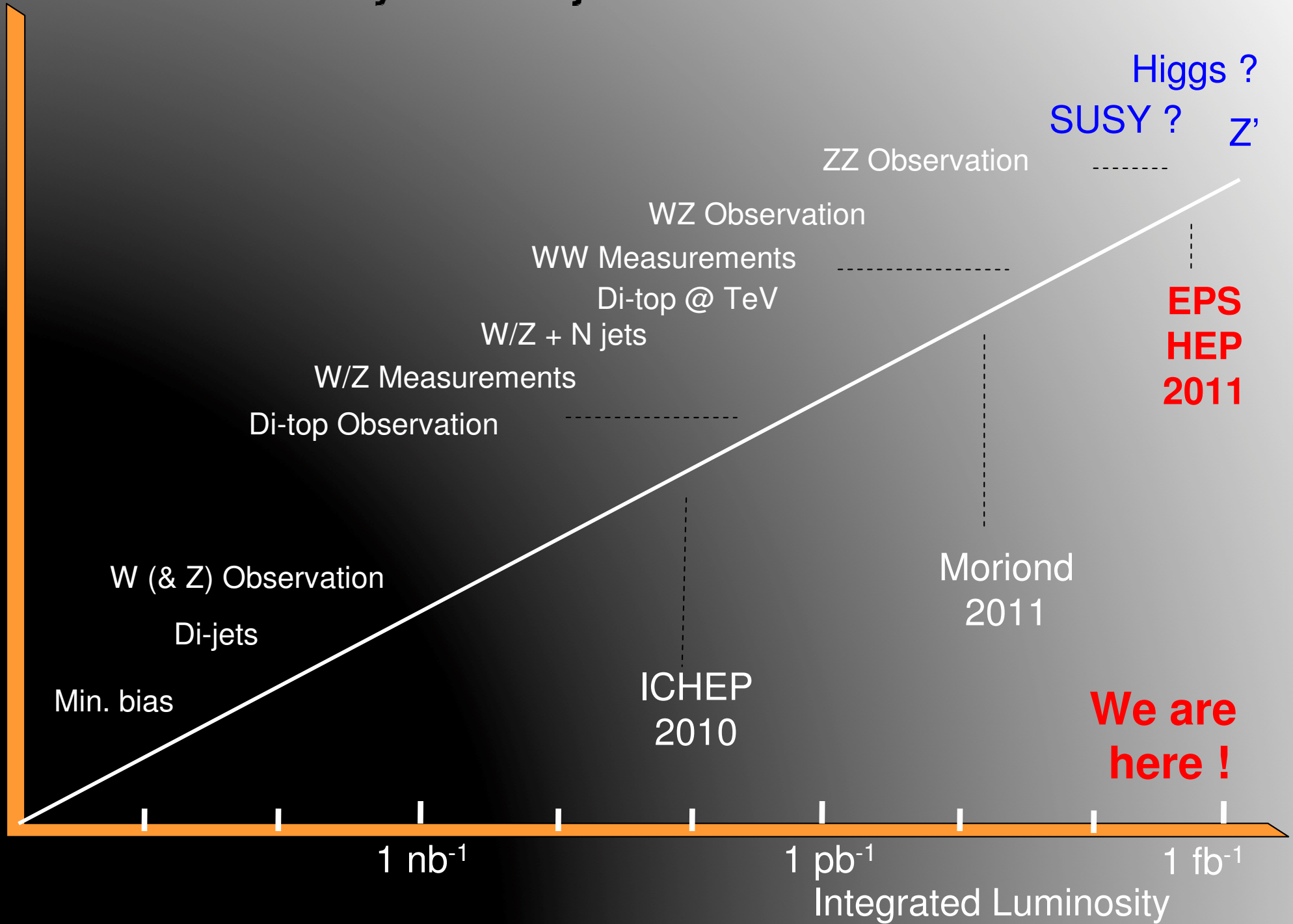
No significant dependence on centrality



p_T dependence consistent with pp

CMS Physics Objectives for LHC Run I

Physics=f(Time)



We are here !