Experimental Conference Summary

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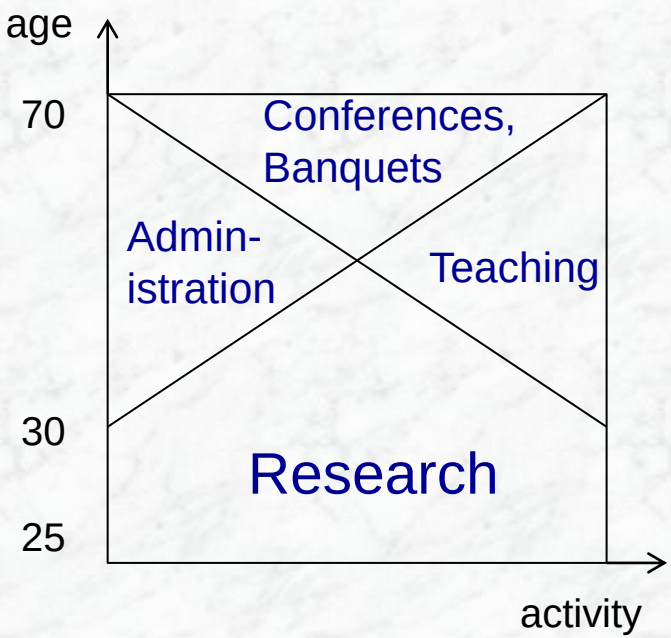
- At this conference more than 70 experimental talks were given

- I do not attempt to summarize all results in detail and I had to make a selection; I would in no way be capable of giving justice and fair credit to the fantastic amount of work presented during this week
  (I will also not quote any names of speakers)

- My apologies to those speakers whose results I have omitted
  It is not intended as a reflection of the relative importance !



The role of the LHC

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?
  Does the Higgs boson exist?

- Search for physics Beyond the Standard Model
  (Low energy supersymmetry, other scenarios…,)

Look for the "expected", but we need to be open for surprises

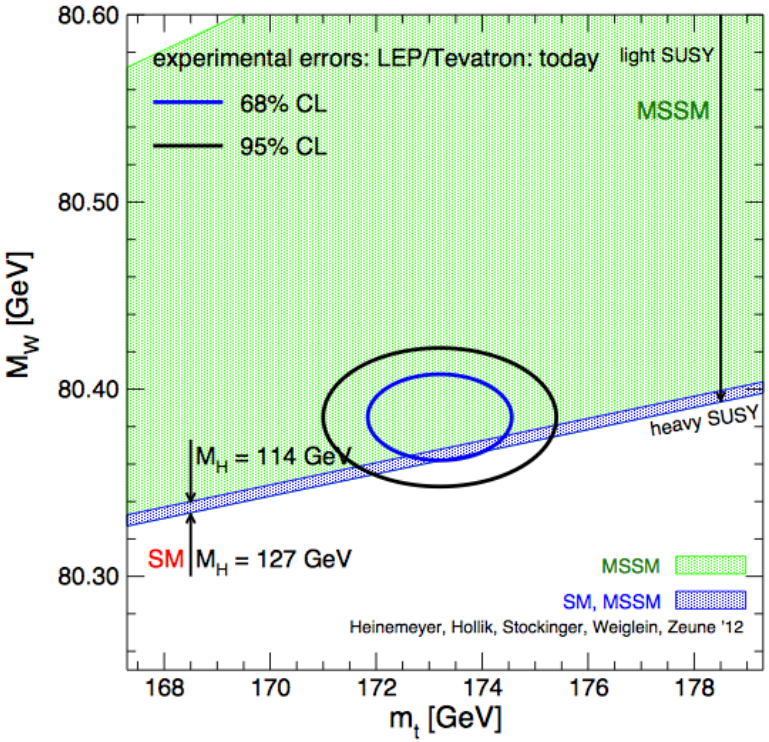
→ perform as many searches (inclusive, exclusive…) for as many final states as possible

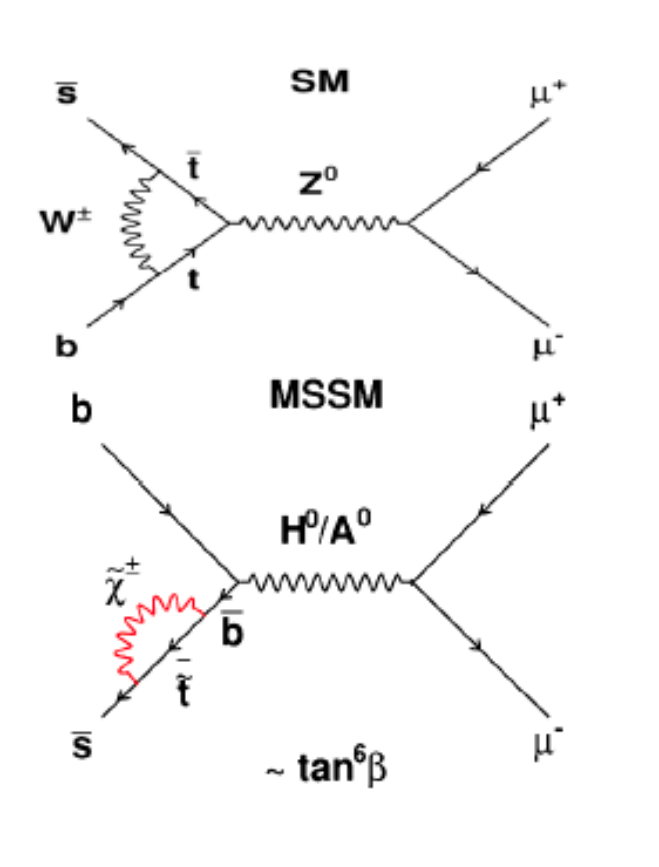
2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area (loop-induced effects, probe energy scales far beyond direct reach)
  → precise measurements, search for rare processes

Two important examples:

2012





Ultimate test of the Standard Model:

compare direct prediction of the Higgs boson mass with direct observation

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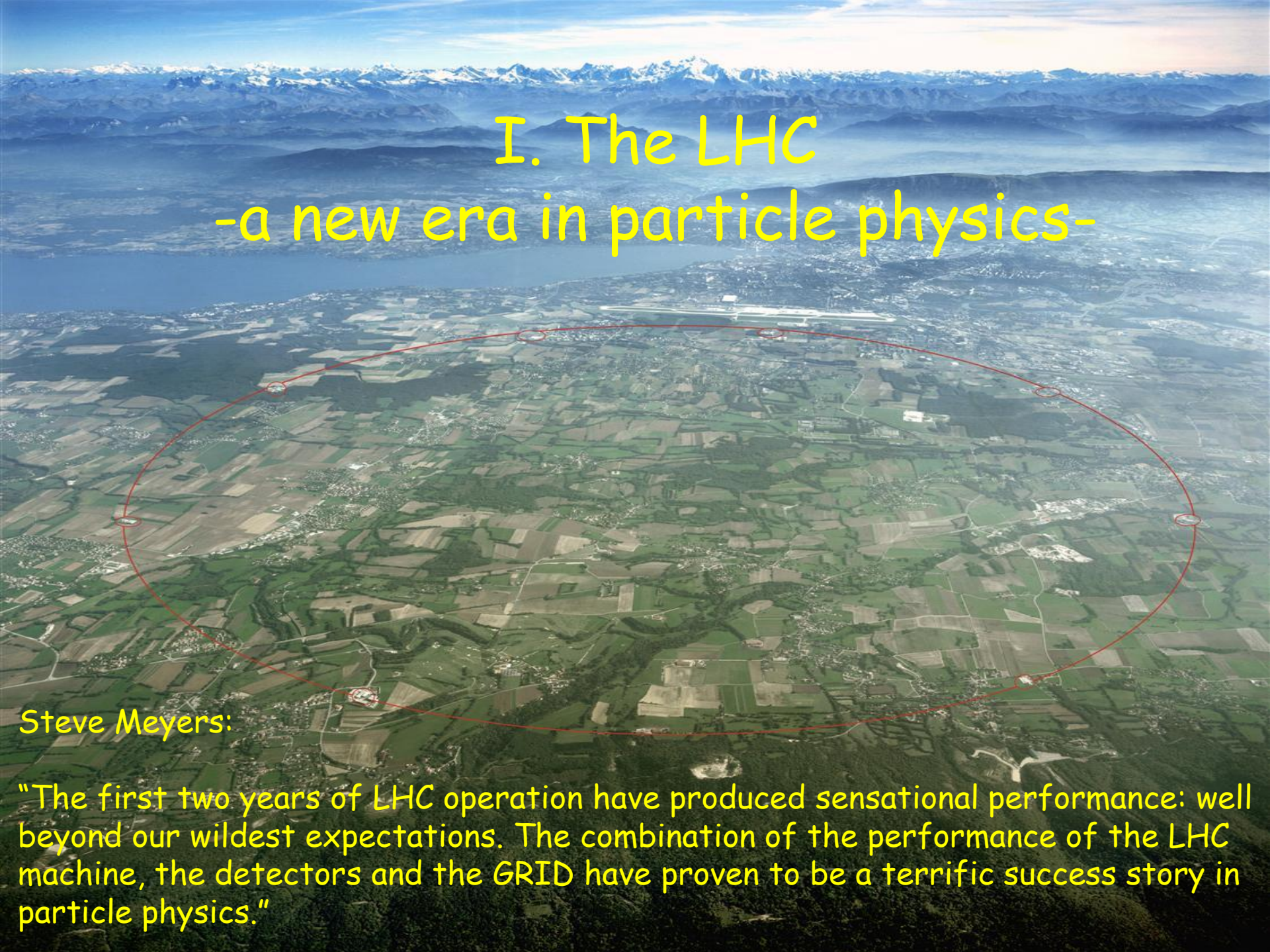
2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area (loop-induced effects, probe energy scales far beyond direct reach)
  → precise measurements, search for rare processes

→ Guidance to theory and Future Experiments

Many theoretical models for physics Beyond the Standard Model

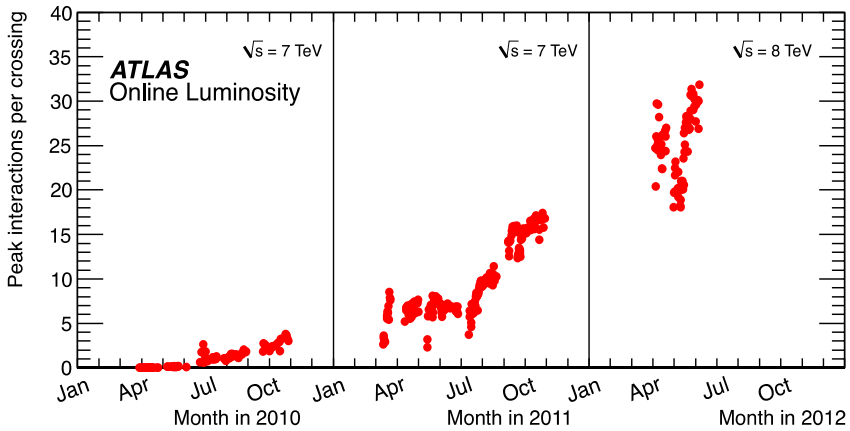
I. The LHC
-a new era in particle physics-



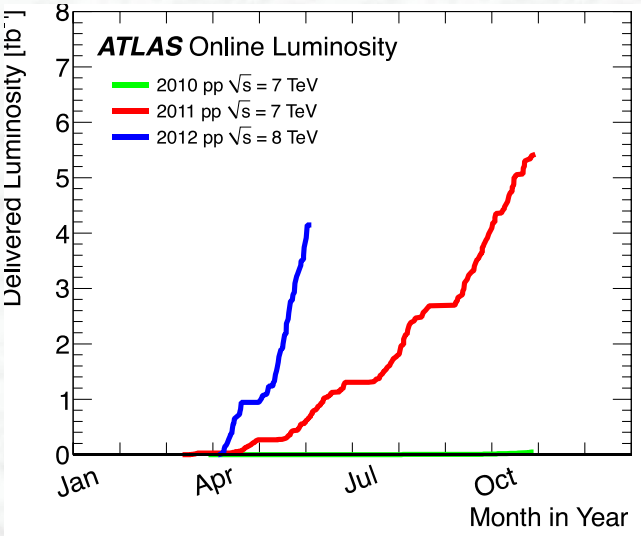
Steve Meyers:

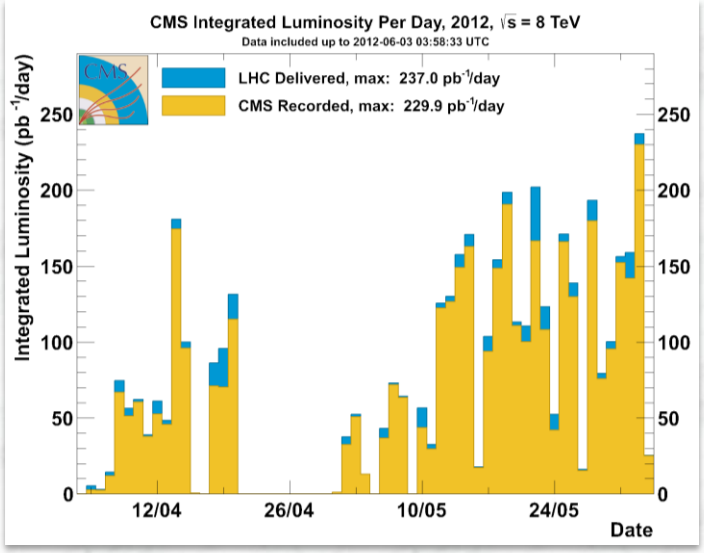
"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

A few facts to back this up:



- World record on instantaneous luminosity on 22. April 2011: $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$ (Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$)
- 2011: collect per day as much int. luminosity as in 2010
- 2012: now regularly above $6\ 10^{33}\ cm^{-2}s^{-1}$, record ~$6.6\ 10^{33}\ cm^{-2}s^{-1}$





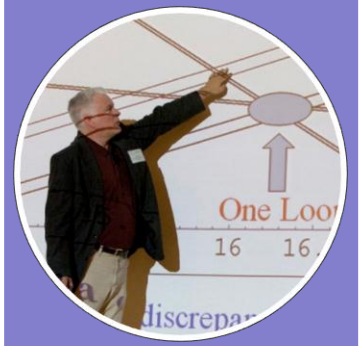
- Very rapid rise in luminosity
- + good machine stability → high integrated luminosities

Completion of an era: Tevatron

Accelerator Innovations

- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

and developing
- GRID pioneers



Major Discoveries

- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

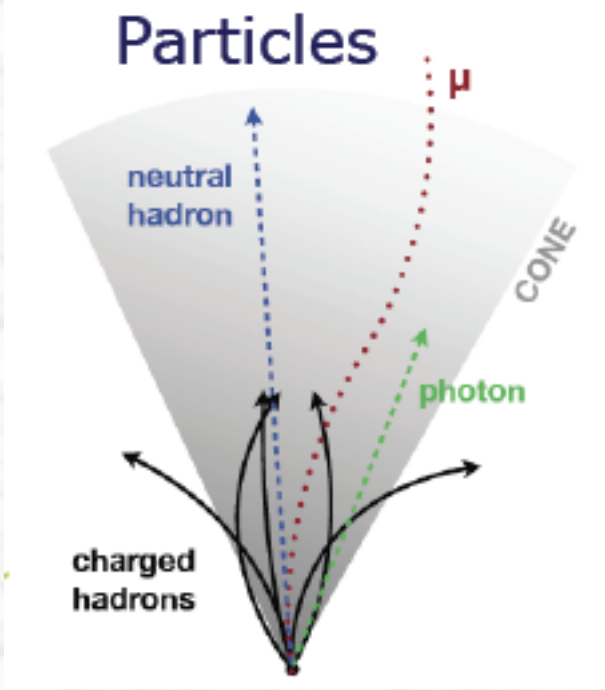
The next generation

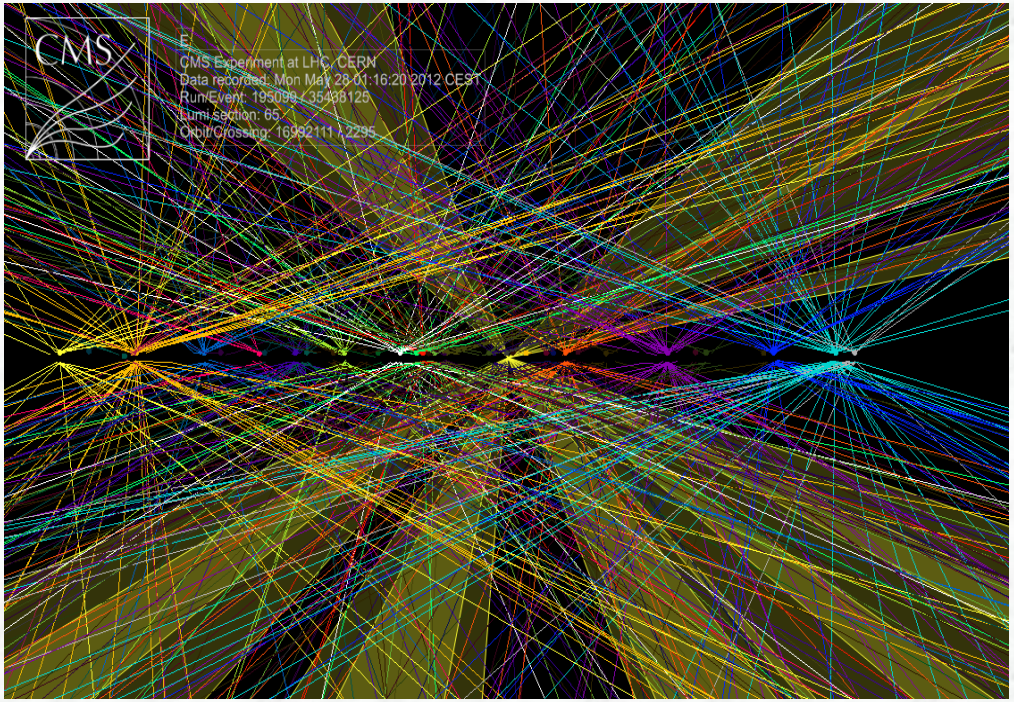
- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

But Tevatron is still in the game:

- W mass
- H → bb
- B physics
- …

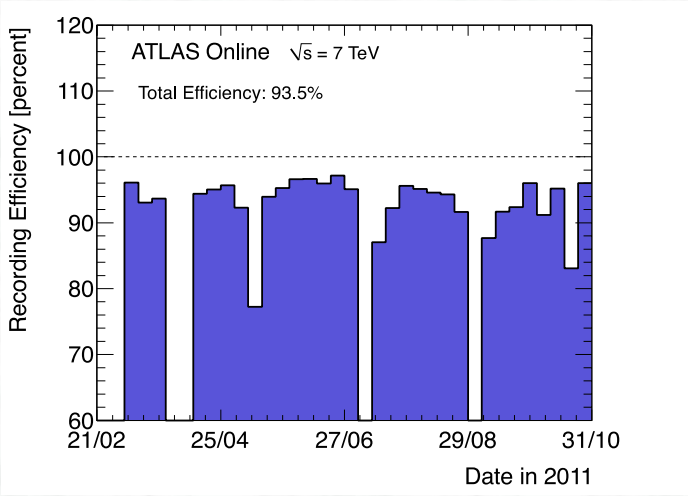
II. Detector Performance



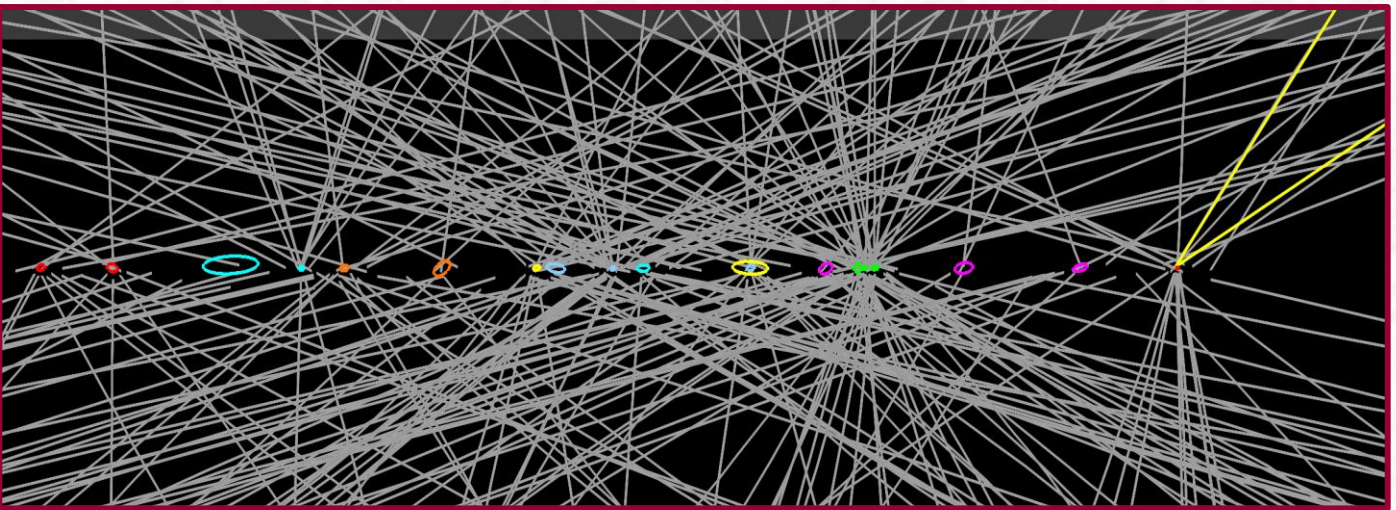


Detector performance is impressive:

- Very high number of working channels (> 99% for many sub-systems) in all experiments;
- Data taking efficiency is high (> 94%)
- Impressive reconstruction capabilities for physics objects (e, γ, μ, τ, jets, b-tagging, E_T^{miss})



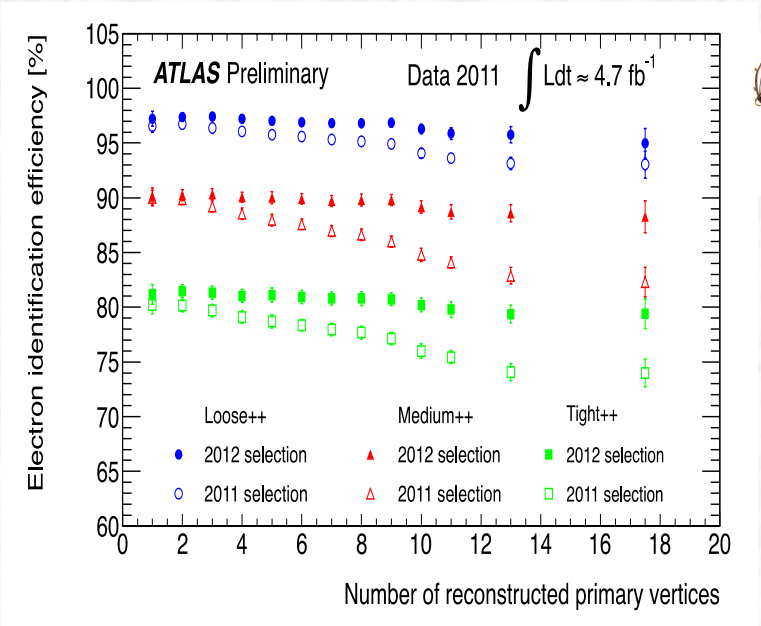
Have been optimized to cope with the ever increasing number of pile-up interactions (impressive examples shown here)



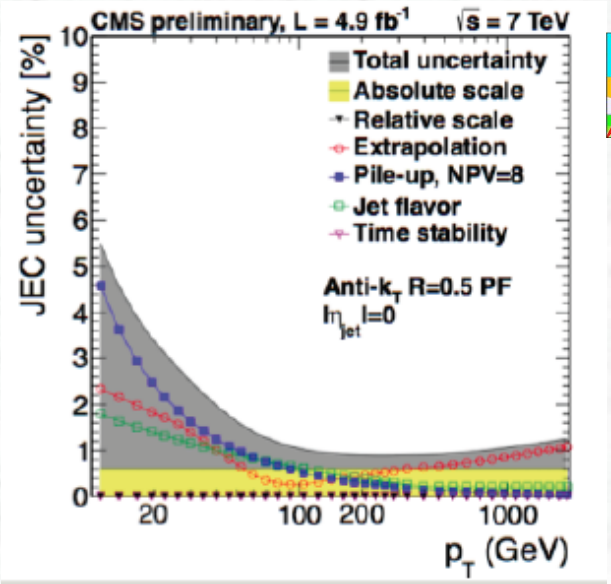
An event with 20 reconstructed vertices

(error ellipses are scaled up by a factor of 20 for visibility reasons)

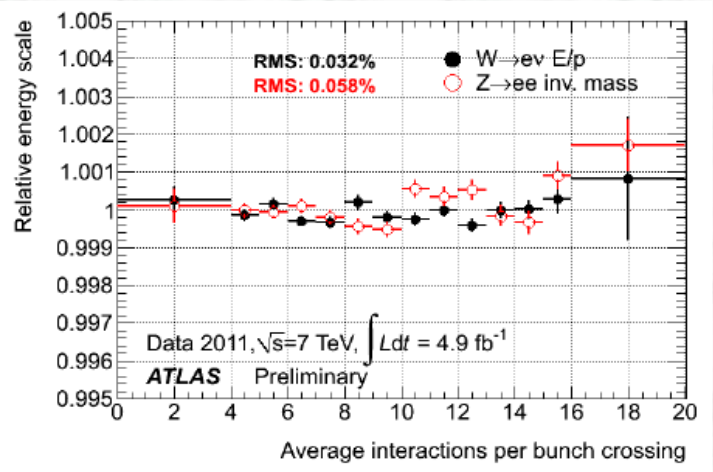
Some performance figures from 2011 data:

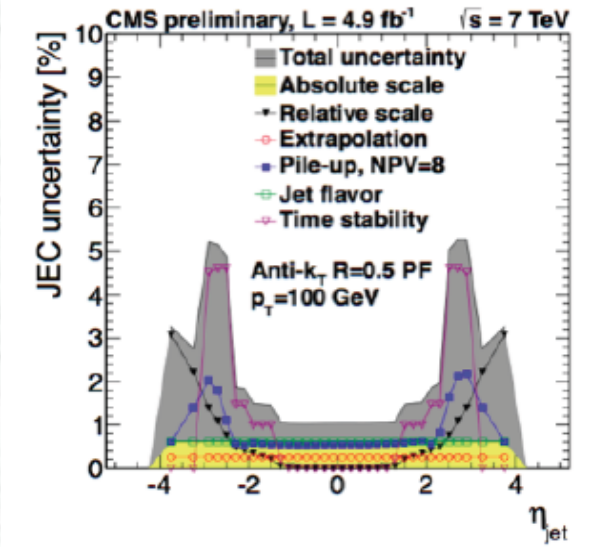


Electron ID efficiency in ATLAS

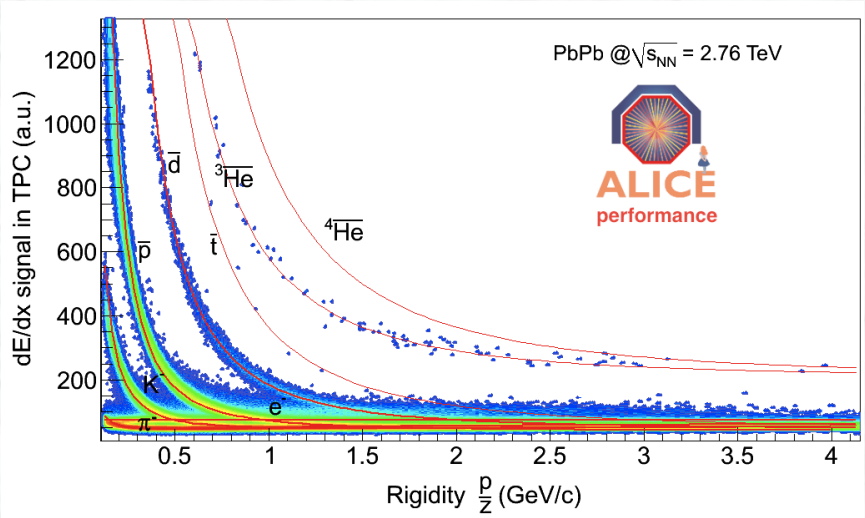


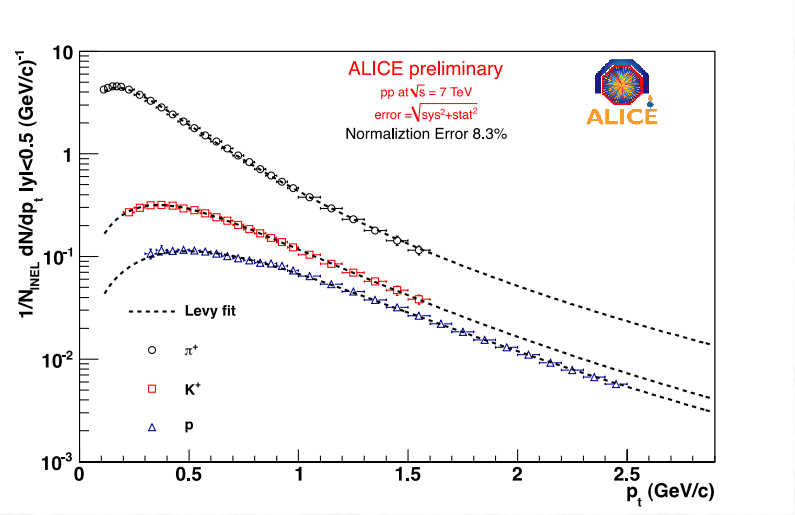
Jet energy scale, E-flow in CMS



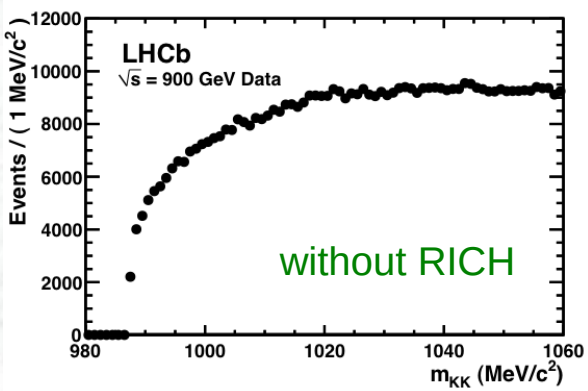


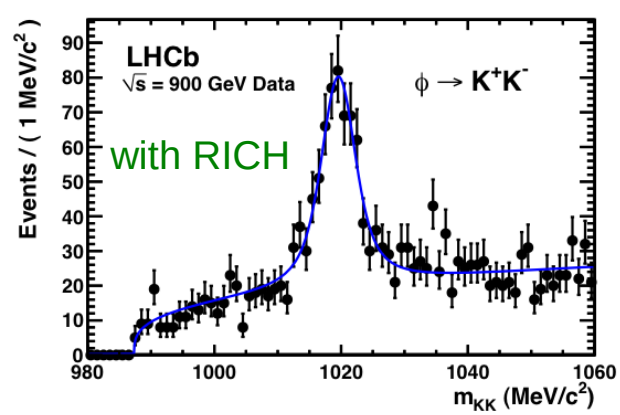
Particle Identification in ALICE and LHCb:

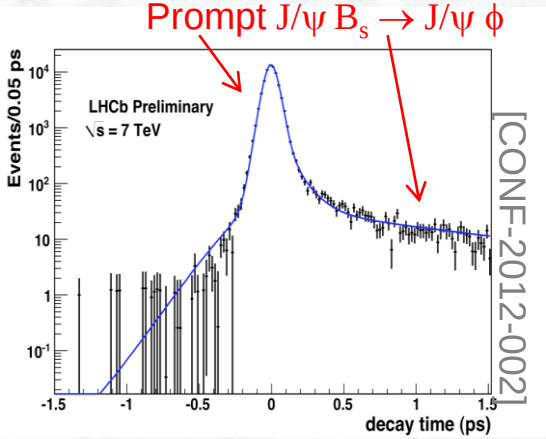




LHCb: Search for $\phi \rightarrow K^+K^-$

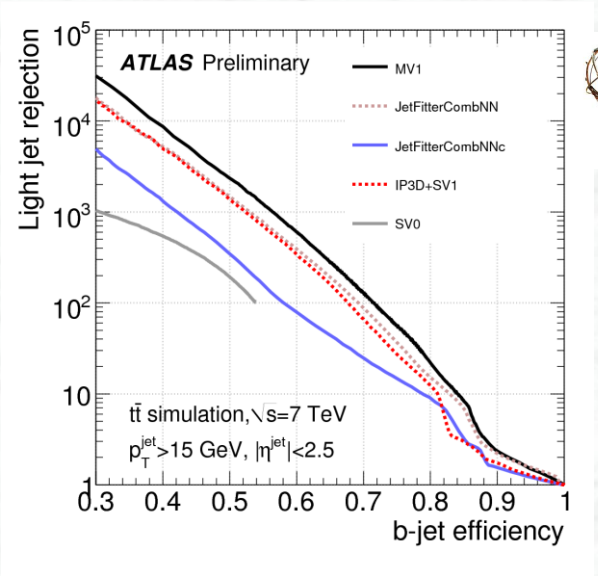


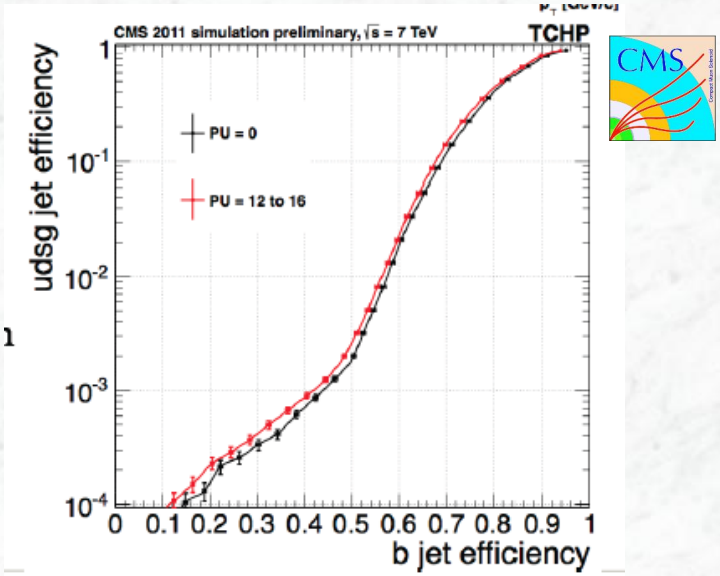


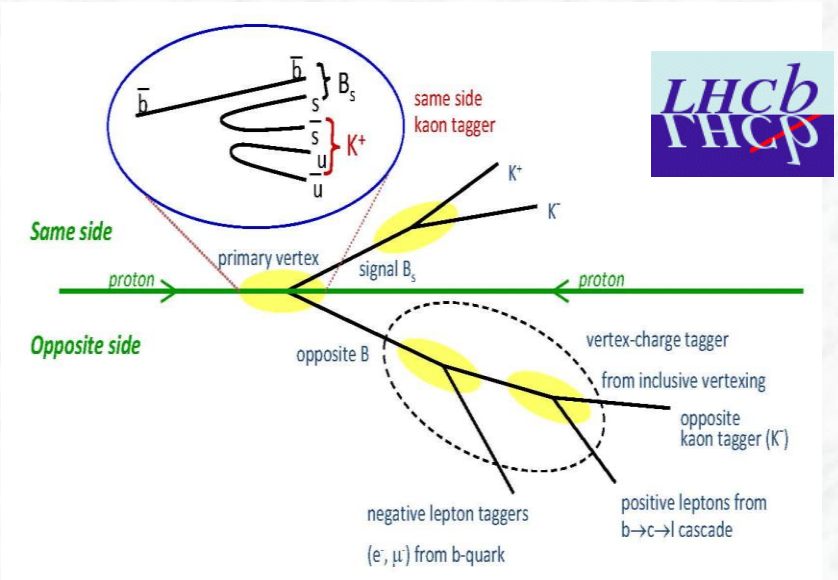


Proper time resolution: 45 fs

b-tagging performances in ATLAS and CMS:
extremely important for many physics analyses (Higgs, SUSY, SM, ….)





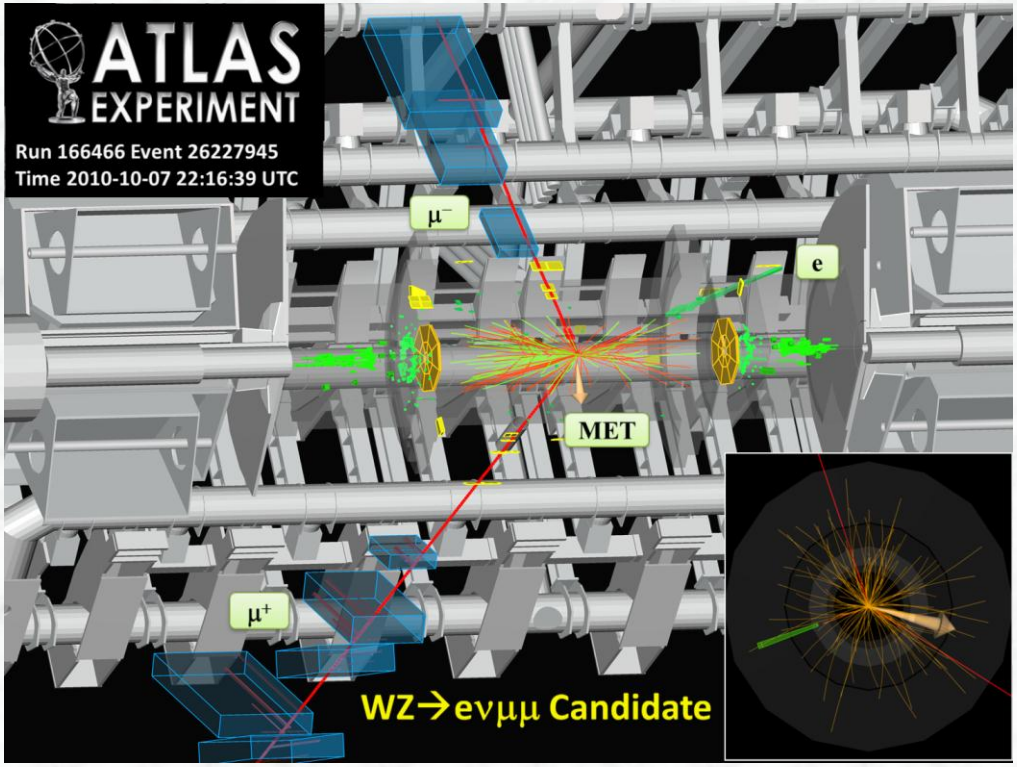


- Reconstruction of the original flavour (B, Bbar) of the reconstructed B meson (important for mixing and CP analyses)

- Performance calibrated from control channels, e.g.

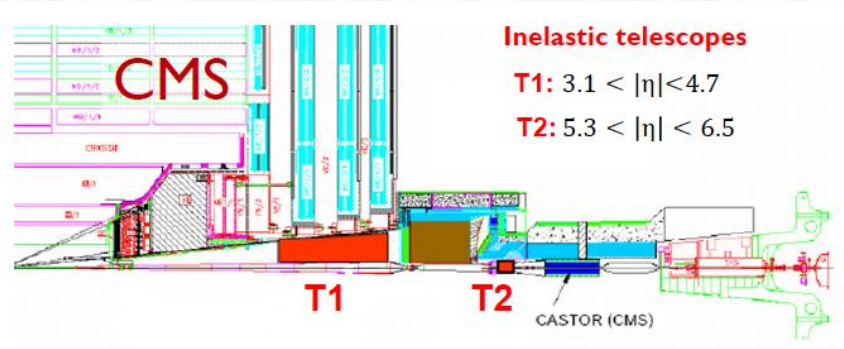
- Effective efficiencies 2.1-3.5% (opp. side) and 0.7% – 1.3% (same side) dep. on analysis

Physics Results



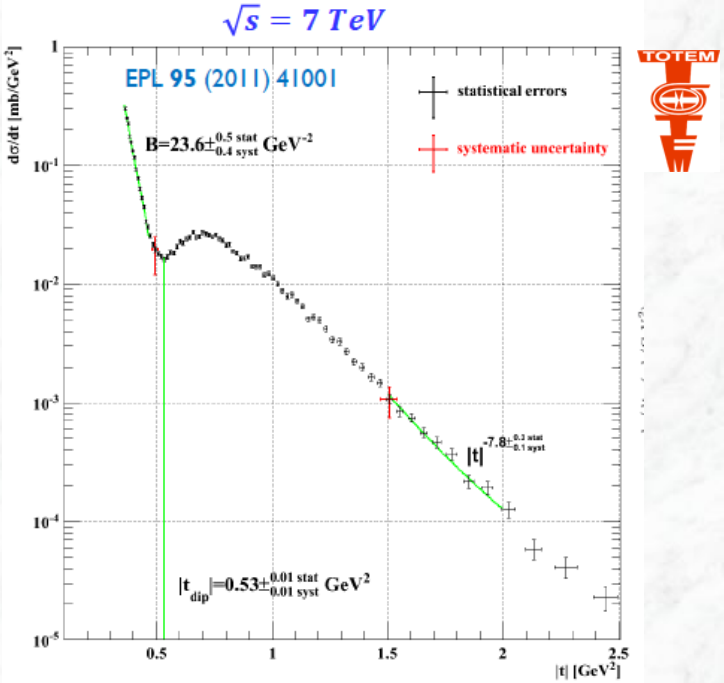
Total, elastic and inelastic pp cross sections at 7 TeV

- Domain of the TOTEM experiment
  Detectors in the CMS forward regions



Elastic scattering: $d\sigma_{el}/dt$

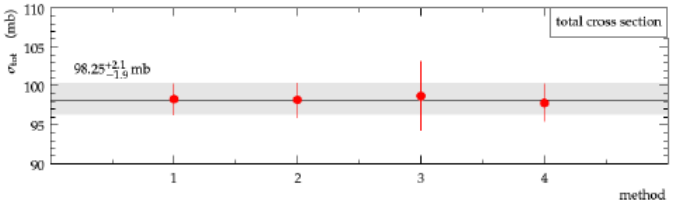
$0.36<|t|<2.5\ GeV^2$



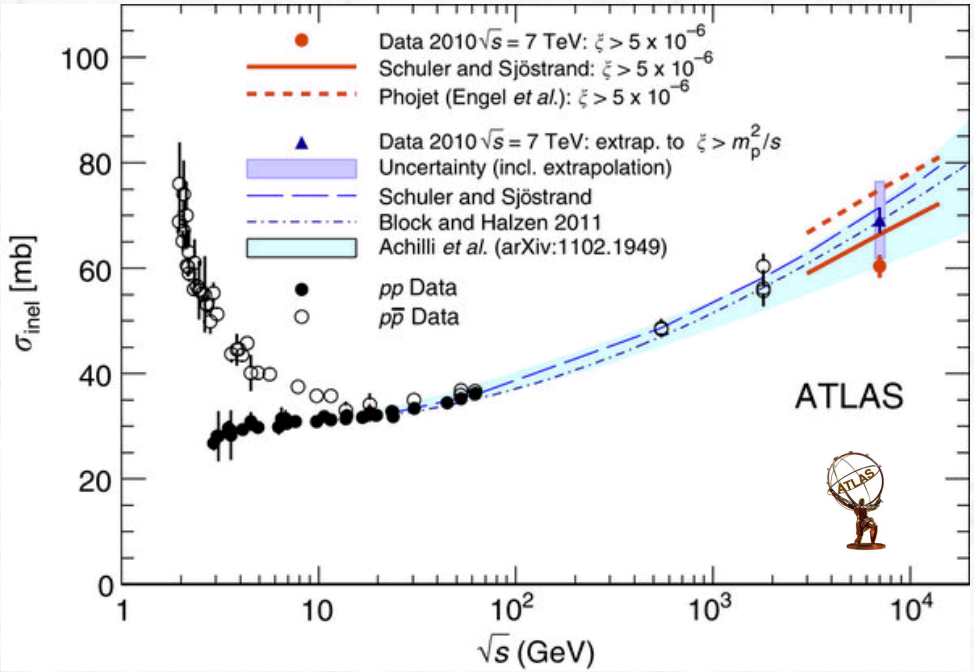
$$\frac{d\sigma_{el}}{dt} \propto e^{-B|t|}$$

Total cross section
(four methods give consistent results)

1. (*low*) Luminosity + Elastic scattering + Optical theorem
   $\sigma_{tot} = 98.3 \pm^{2.2}_{2.0}\ mb$
2. (*high*) Luminosity + Elastic scattering + Optical theorem
   $\sigma_{tot} = 98.2 \pm^{2.4}_{2.2}\ mb$
3. (*high*) Luminosity + Elastic scattering + Inelastic scattering
   $\sigma_{tot} = 98.7 \pm 4.4\ mb$
4. Elastic scattering + Inelastic scattering + Optical theorem
   $\sigma_{tot} = 97.8 \pm^{2.9}_{2.4}\ mb$



Inelastic pp cross section at 7 TeV:



ALICE:
σ_{inel} = (72.7 ± 1.1 (stat) ± 5.1 (model)) mb

ATLAS:
σ_{inel} = (69.1 ± 2.4 (stat) ± 6.9 (model)) mb

CMS:
σ_{inel} = (64.5 ±1.1 (stat) ± 3.0 (model)) mb

TOTEM:
σ_{inel} = (73.5 ± 0.5 (stat) $\pm^{1.8}_{-1.3}$ (syst)) mb

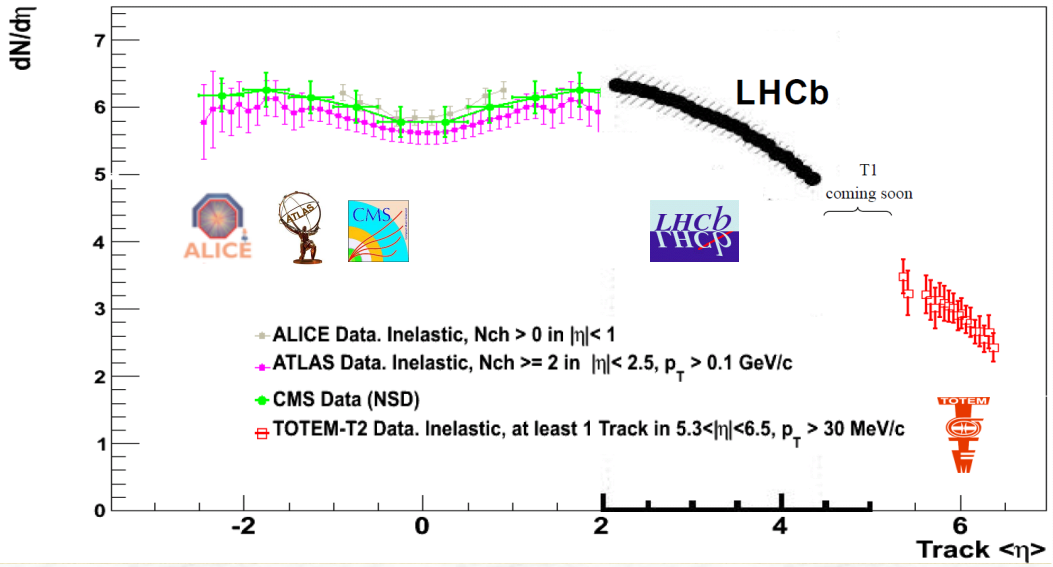
- The inelastic cross section was also measured by ALICE, ATLAS and CMS; Good agreement among the experiments, within systematic uncertainties

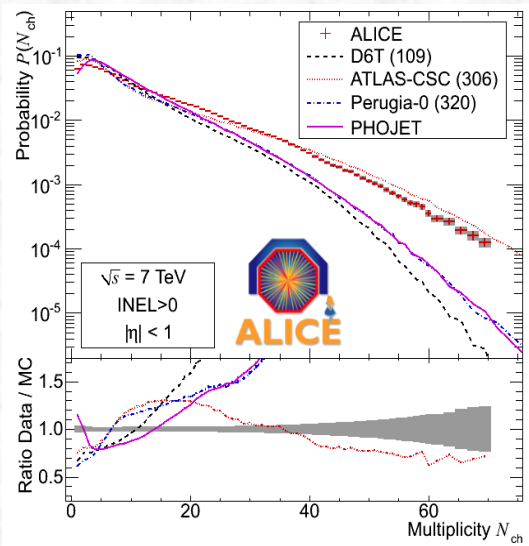
- Measurement require the subtraction of diffractive components and acceptance extrapolations;
  The associated model dependence (e.g. Donnachie-Landshoff) constitutes the largest systematic uncertainty

Soft Physics and diffraction

- Measurements of soft inelastic collisions and diffractive processes are important for any modeling of the underlying event or pile-up processes

- LHCb and Totem experiments extend the measurements far into the forward region

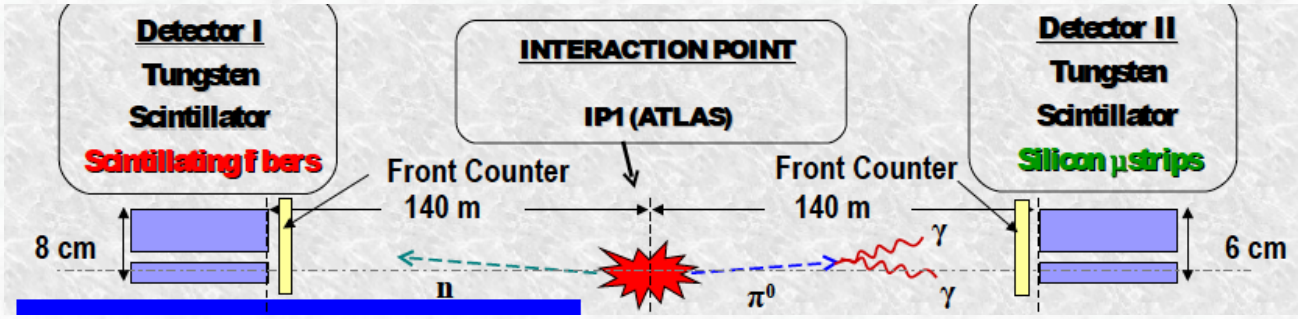




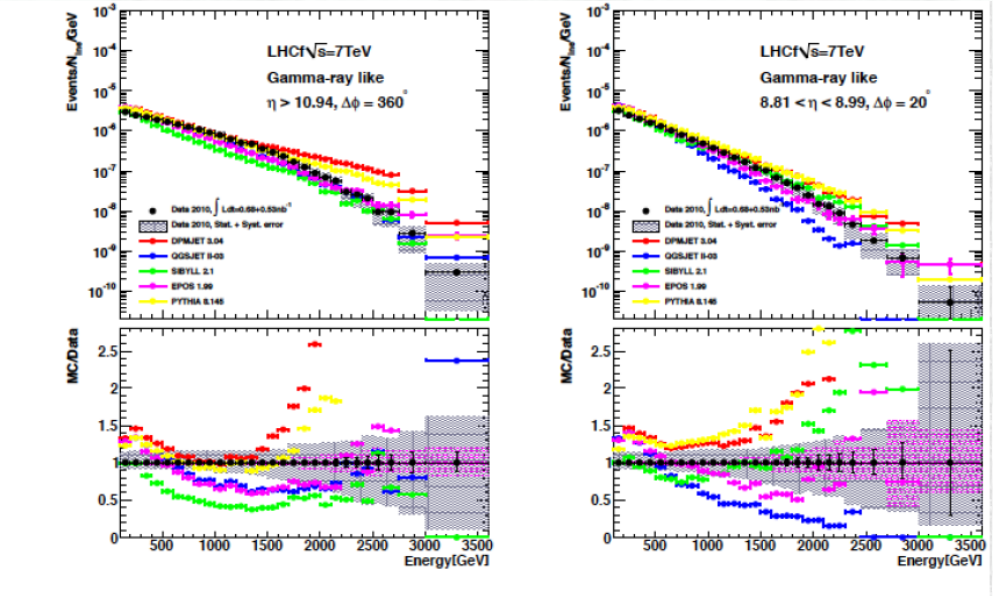
- General behaviour: experiments agree well among each other, however, Monte Carlo models underestimated inclusive particle production;

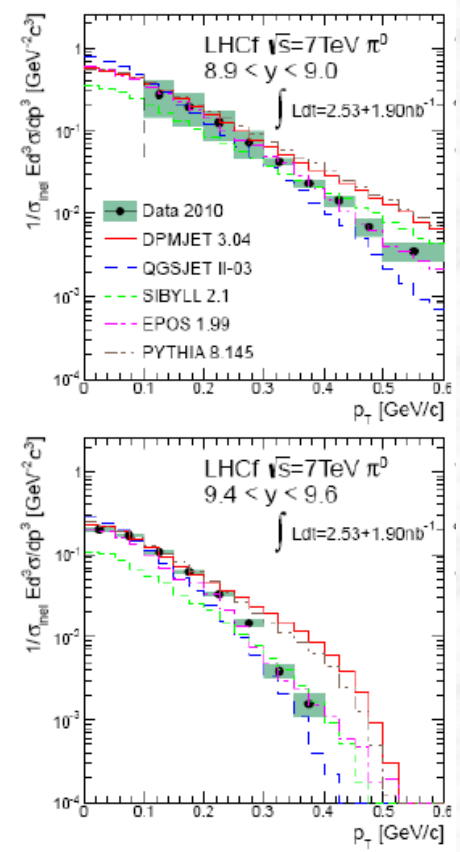
A Monte Carlo tuning that describes simultaneously all observables is still missing

Particle production in the extreme forward region



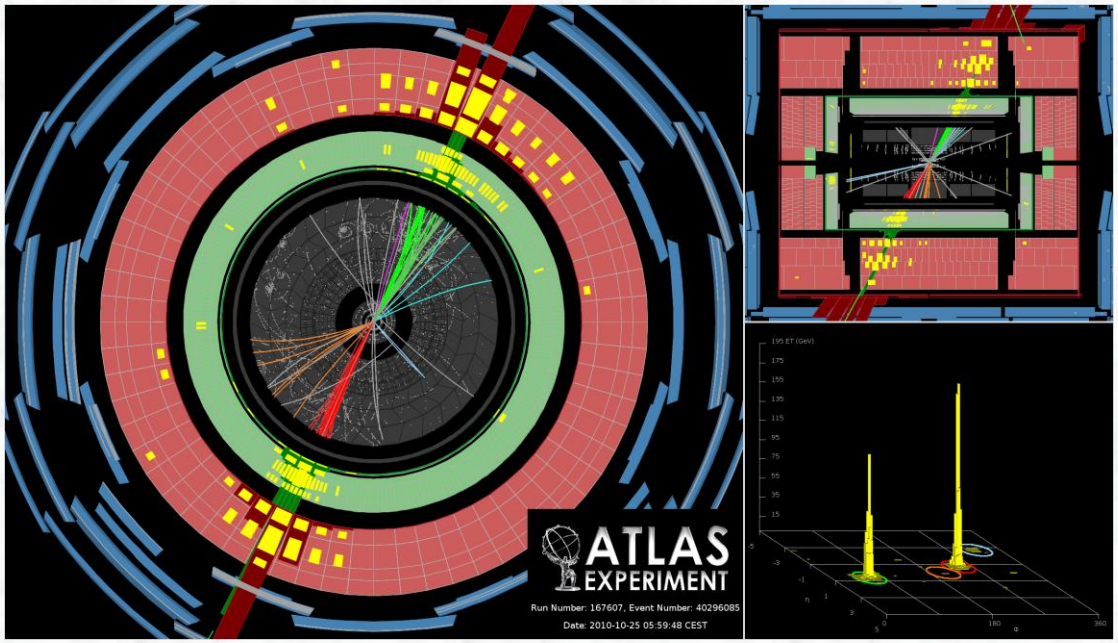
- Single photon and π^0 spectra, compared to models:





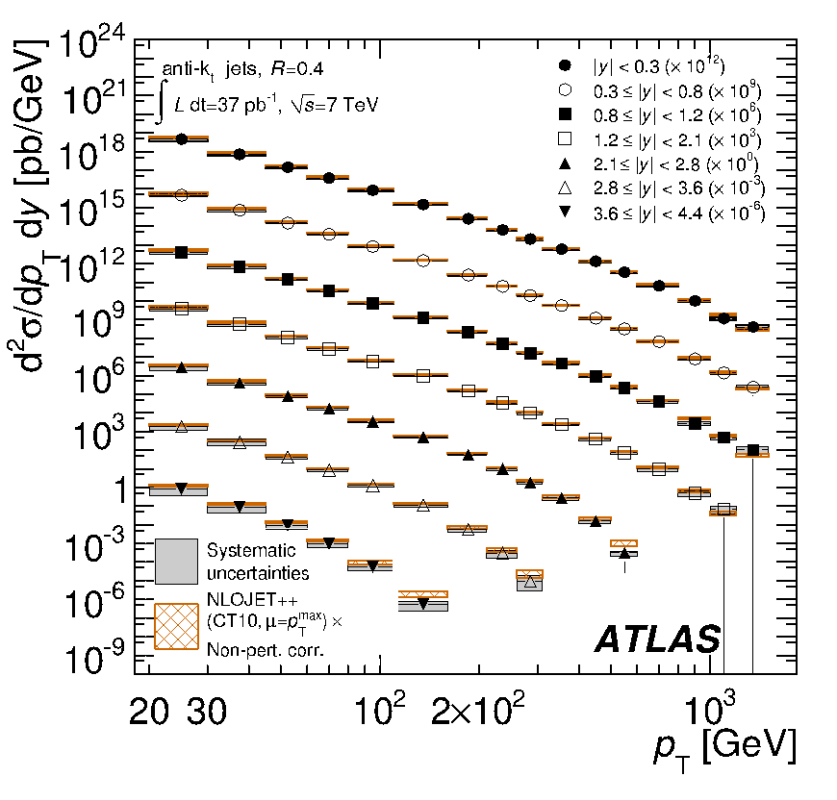
- Important input for astro-particle physics experiments

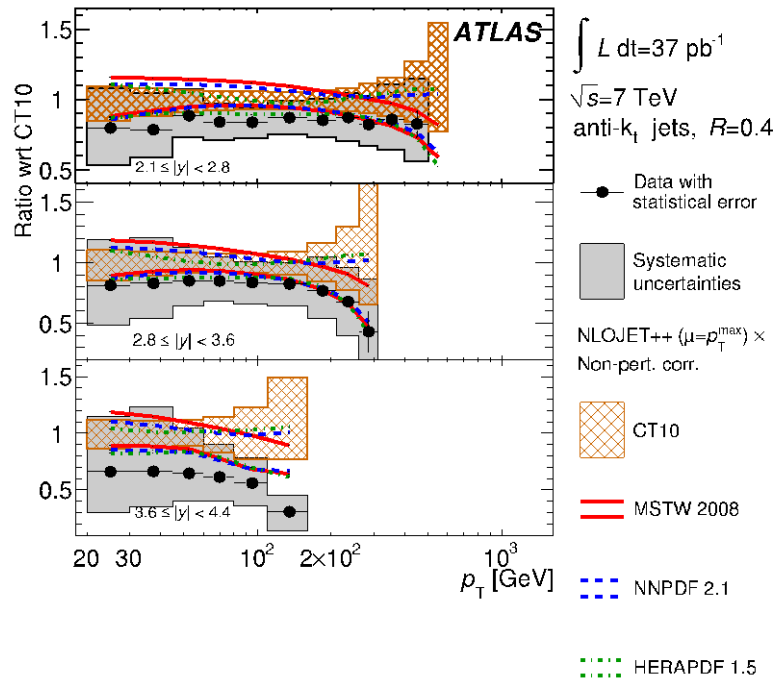
Hard processes:
Tests of perturbative QCD



- Jet production
- W/Z production
- Production of Top quarks
- Heavy hadrons
  (Onia and B hadrons)
- Quark-gluon plasma

Double differential cross sections, as function of p_T and rapidity y (full 2010 data set)

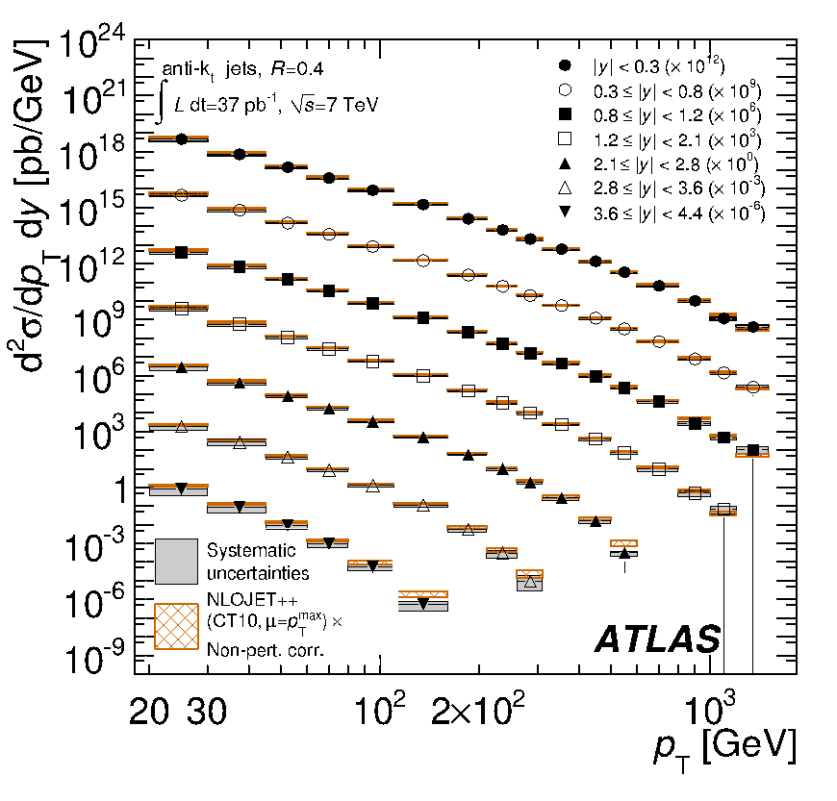


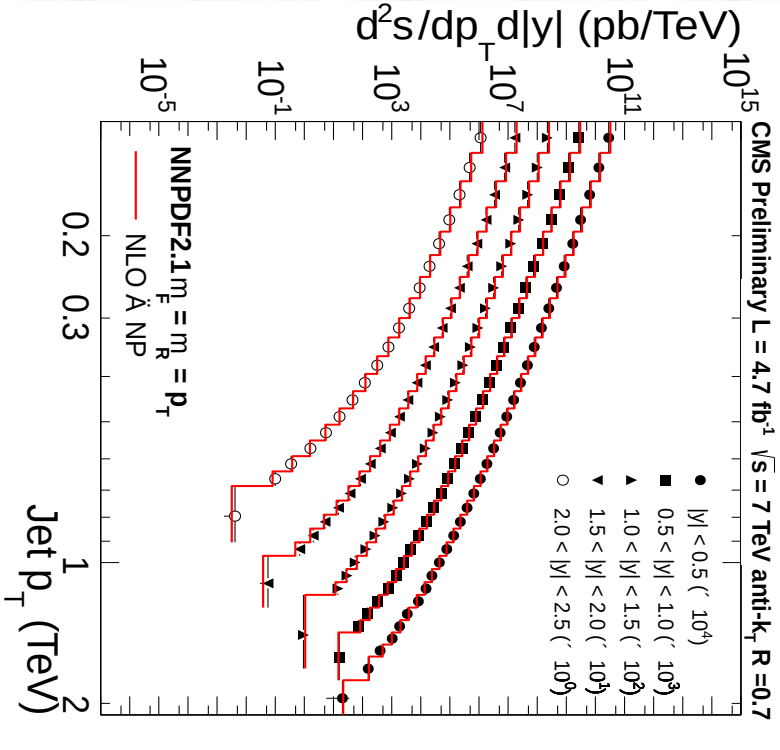


somewhat larger deviations in the forward region

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, α_s, …, uncertainties from non-perturbative effects

Double differential cross sections, as function of p_T and rapidity y: (full 2010 data set)

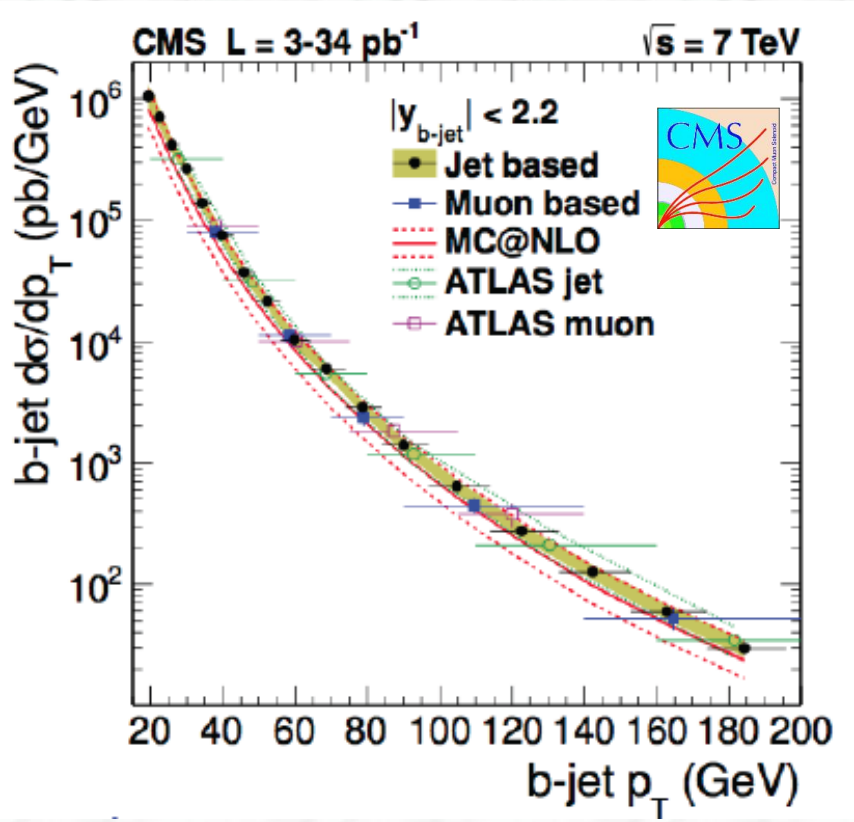




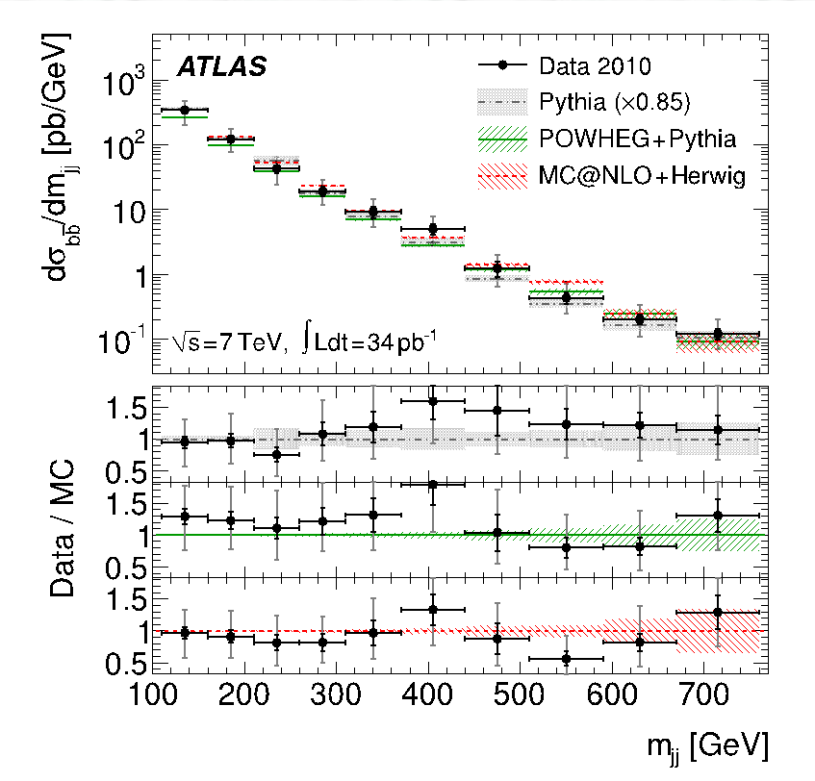
CMS: include full 2011 data set;
comparison up to 2 TeV (central rapidities)

- Data are well described by NLO pert. QCD calculations (NLOJet++)
- Experimental systematic uncertainty is dominated by jet energy scale uncertainty
- Theoretical uncertainties: renormalization/ factorization scale, pdfs, α_s, …, uncertainties from non-perturbative effects

Inclusive b and bb-cross sections



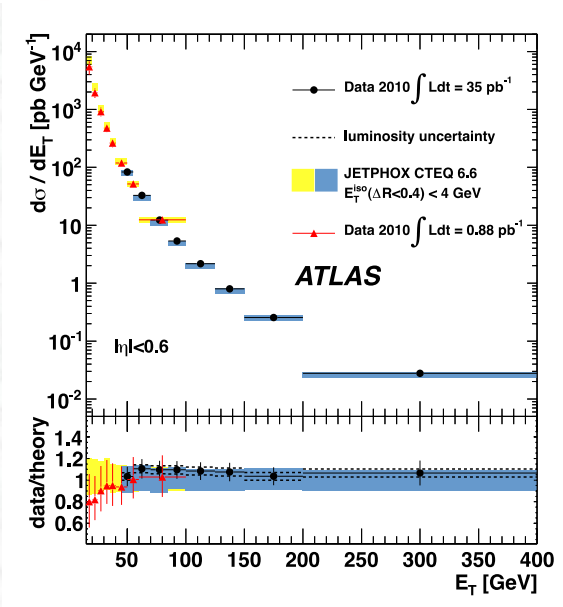
inclusive b-jet production

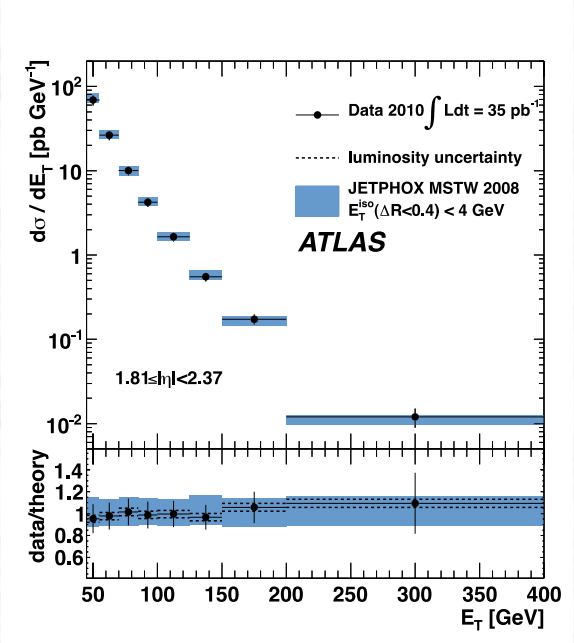


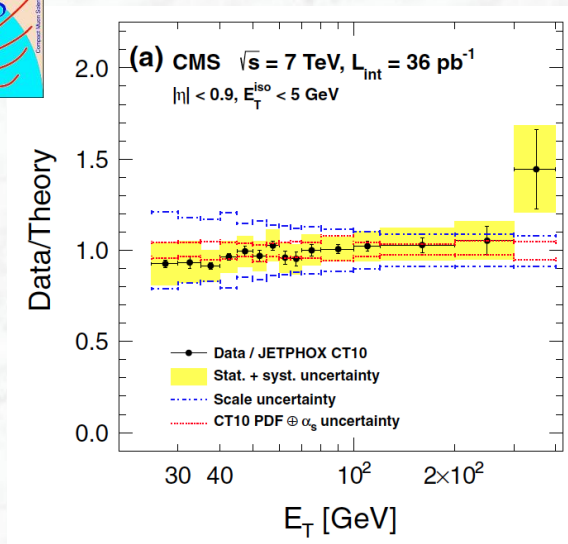
bb di-jet cross section as function of mass

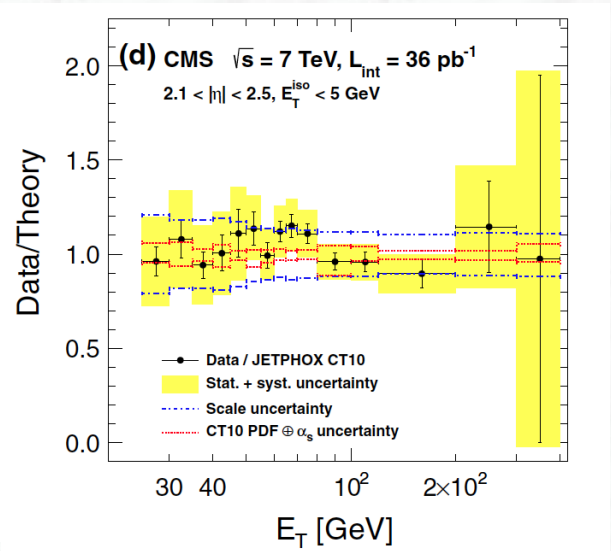
Also good agreement found for the more challenging inclusive b and bb di-jet cross sections (limited to central region, tracker acceptance)

Direct γ production (γ + jet)







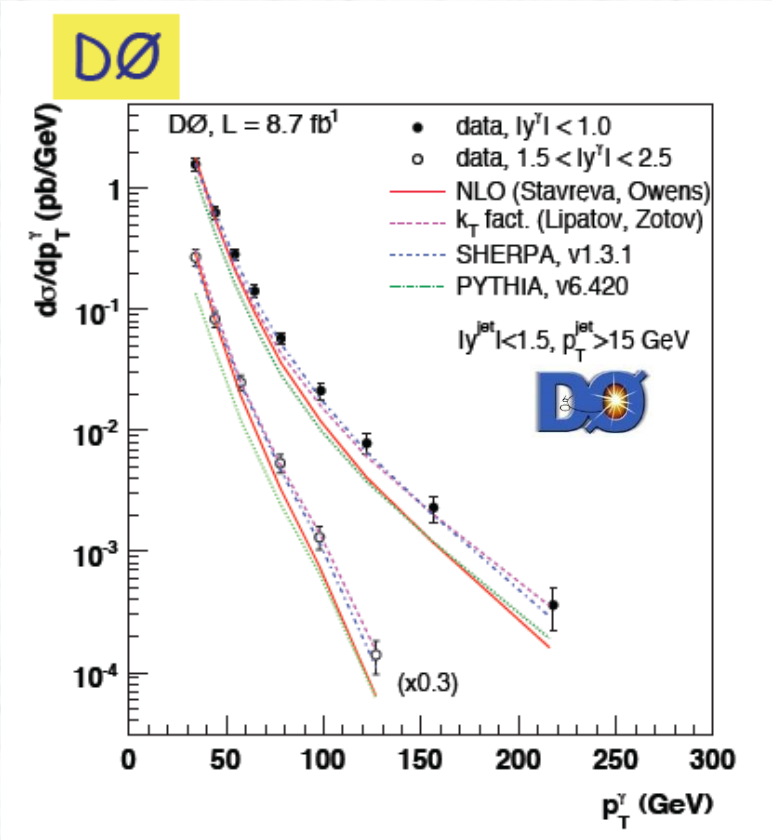


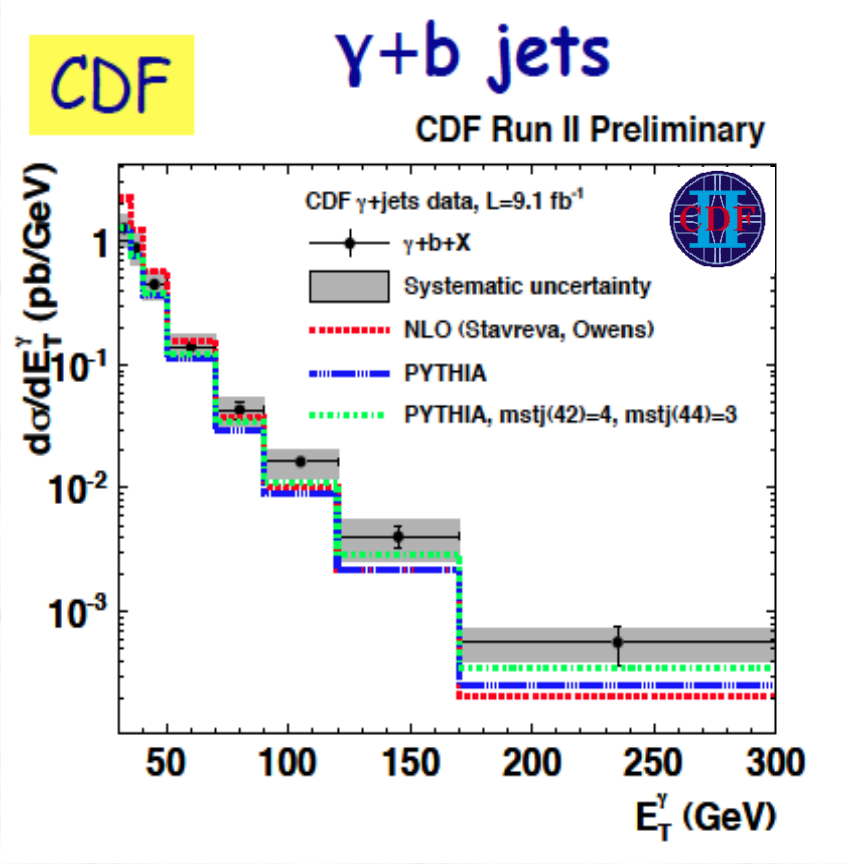
In general good agreement, (within uncertainties, dominated by systematics, e.g. π^0 background, contributions from fragmentation, pdfs, …)

Similar ratios (data / theory) found as function of pseudorapidity in ATLAS and CMS

S. Wolbers

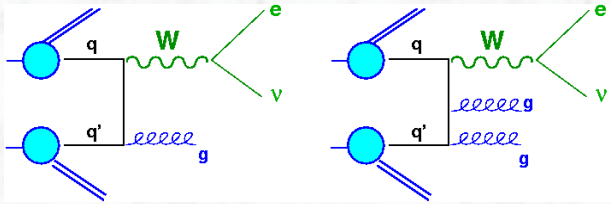
γ + b jet production at the Tevatron



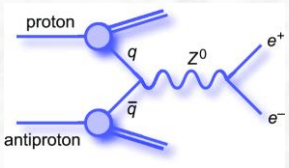


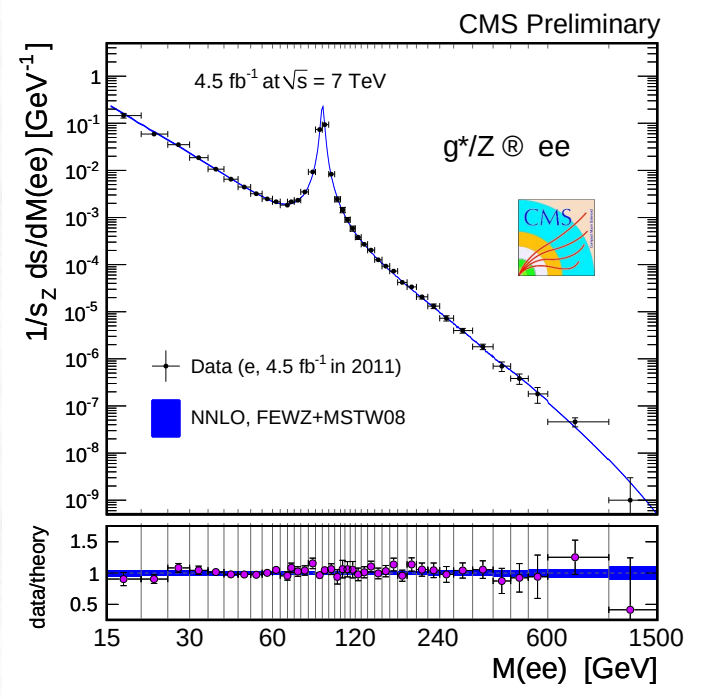
- NLO calculation describe data well in low p_T region
- Larger deviations at high p_T (large NNLO contributions ??)

QCD in W/Z (+ jet) production

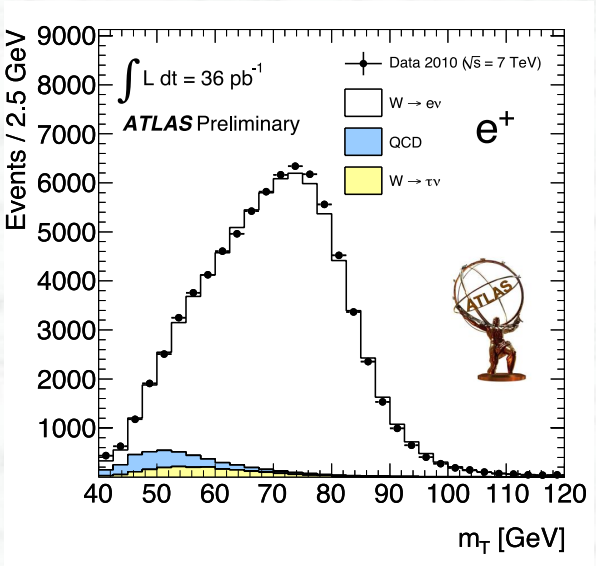


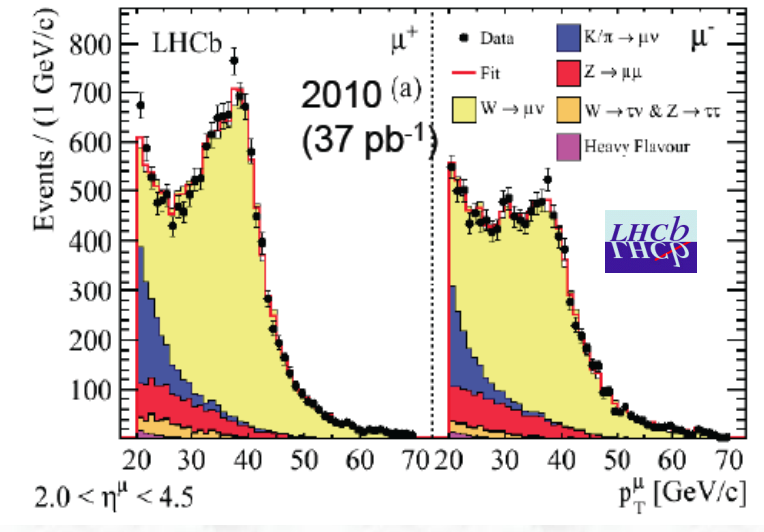
QCD at work



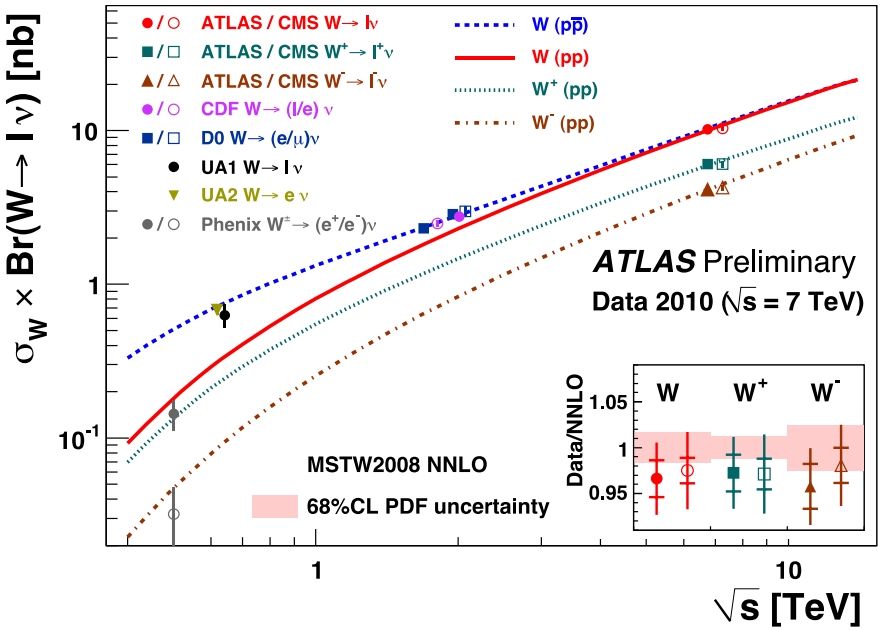


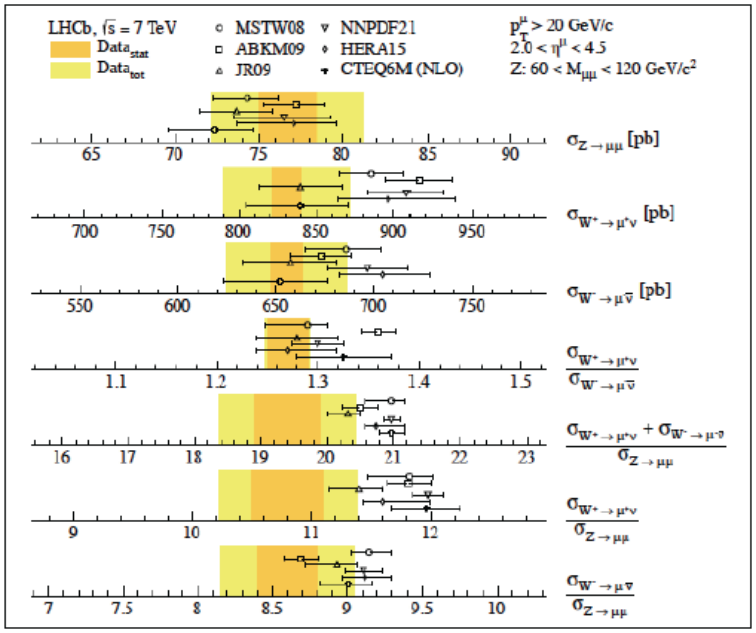
- Drell-Yan pair production measured over large mass range (normalized to Z peak)
- Clear signals, measurements extend into the forward rapidity region by LHCb





W cross sections at the LHC



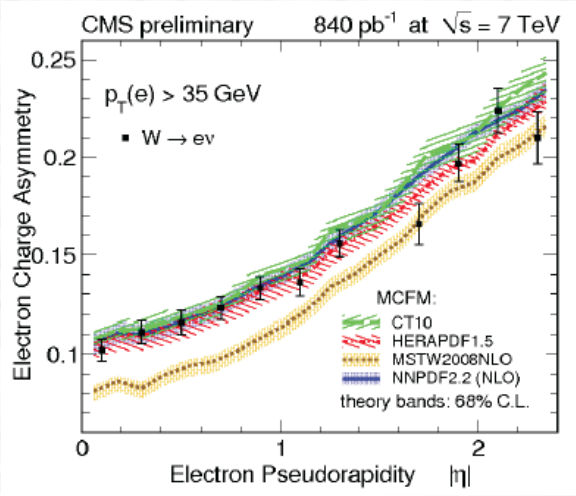


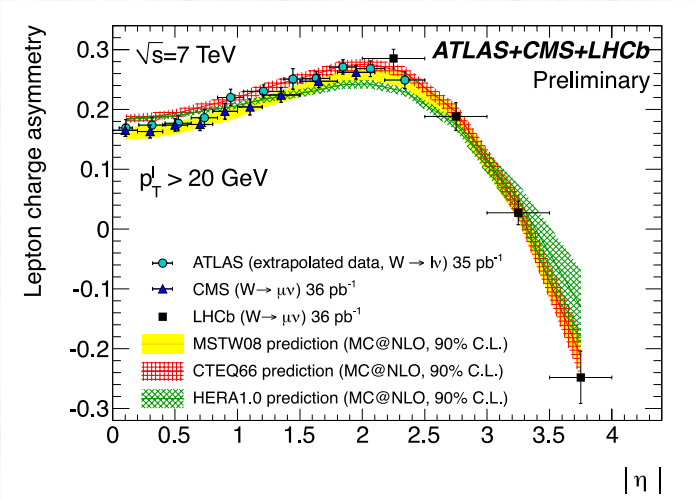
also in the forward region

- Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)
- Precision is already dominated by systematic uncertainties
- Good agreement as well between experiments

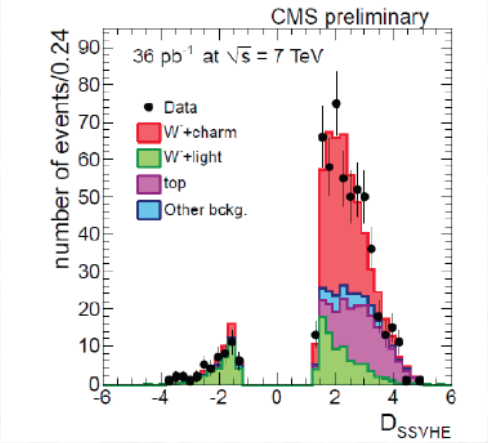
Differential measurements start to constrain pdfs

(i) Lepton charge asymmetries



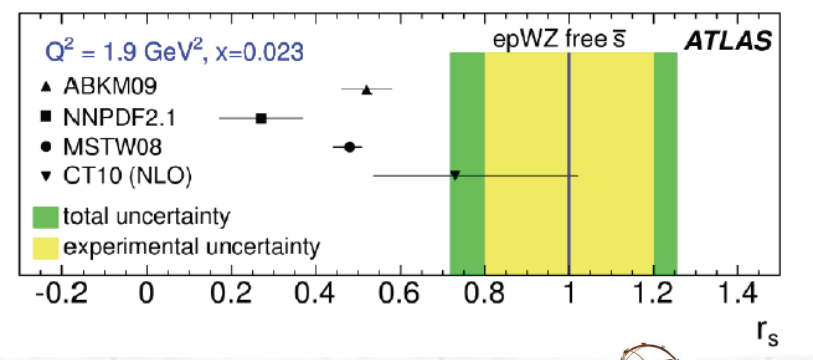


(ii) Flavour separated W+jet production



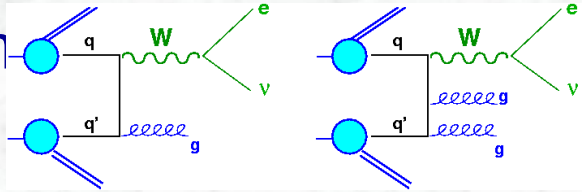
e.g. W+c production

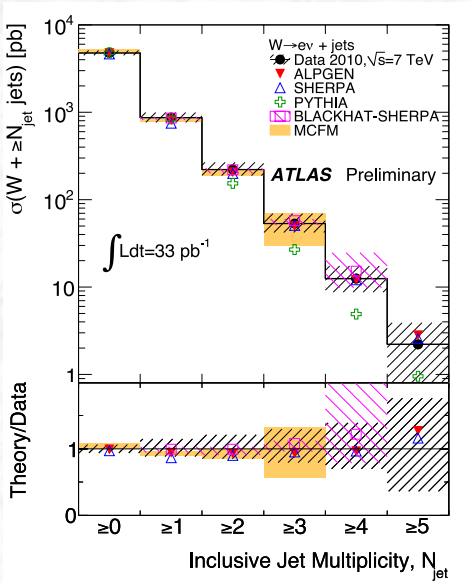
(iii) Extraction of s/sbar from global fit to ATLAS W/Z differential measurements

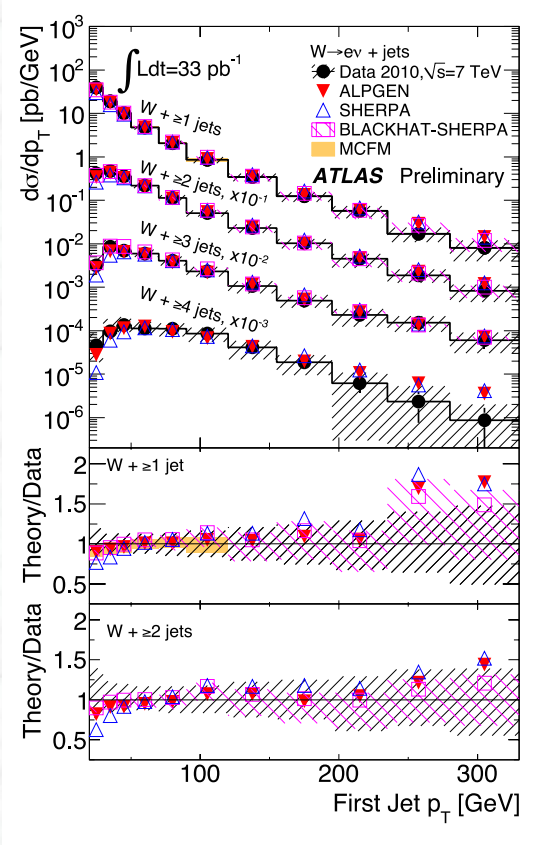


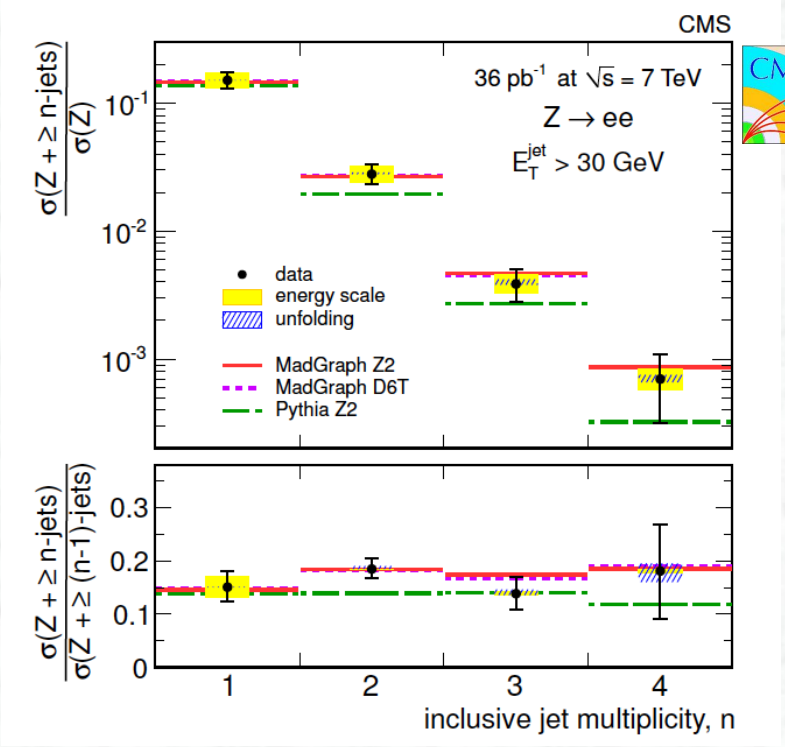
r_s = 0.5 (s + sbar) / dbar

W/Z + jet cross section measurem









Jet multiplicities
in W+jet production

p_T spectrum of
leading jet

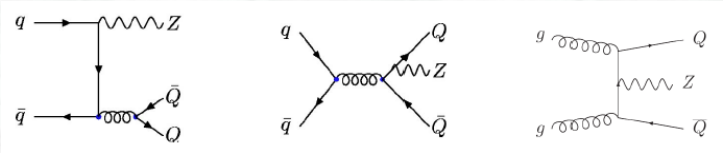
- Impressive description of jet multiplicities and kinematic properties up to high jet multiplicities

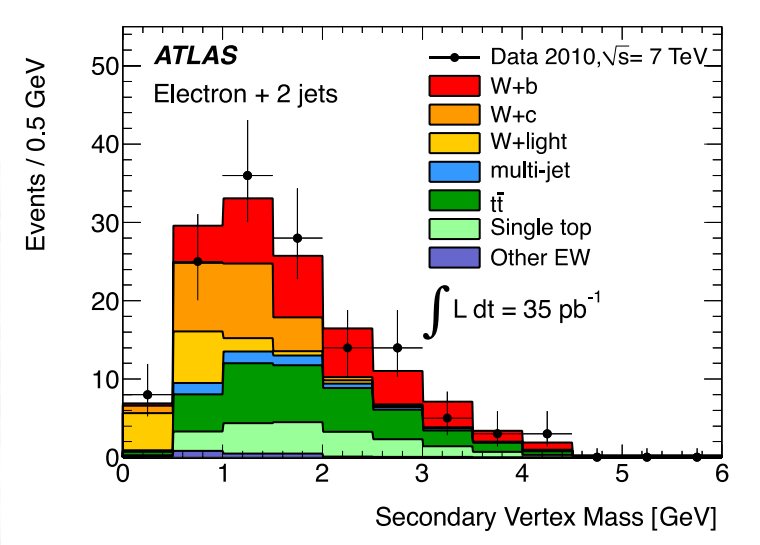
- Impressive progress on NLO calculations for higher jet multiplicity (NLO W+5 jet in reach)

W + b jets

- Important background for many studies (Higgs, SUSY, top)
- Measurements at the Tevatron exceed NLO prediction

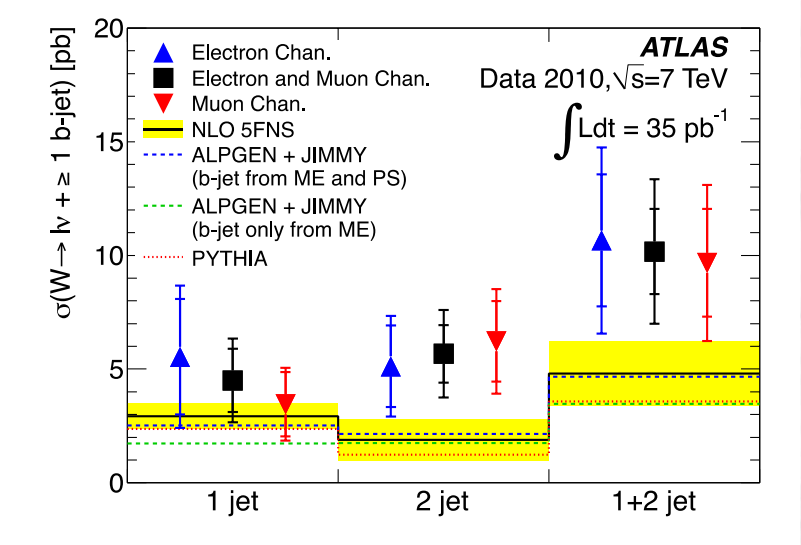
- Measured by ATLAS using 2010 data sample
  - studied W + 1 jet and W + 2 jets
  - require at least one b-tagged jet





W→ e ν + 2 jets

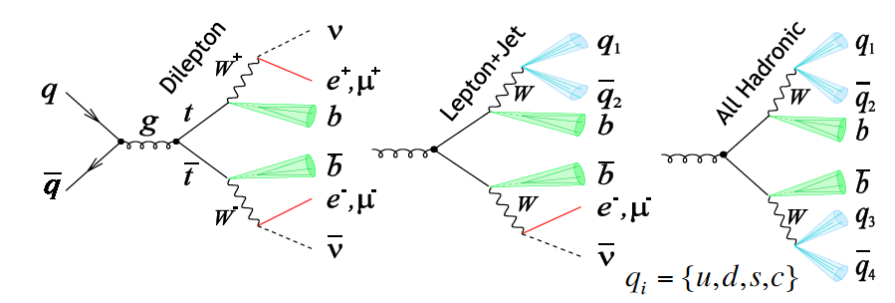
Distribution of the mass of the particles associated to the secondary vertex for b-tagged jets

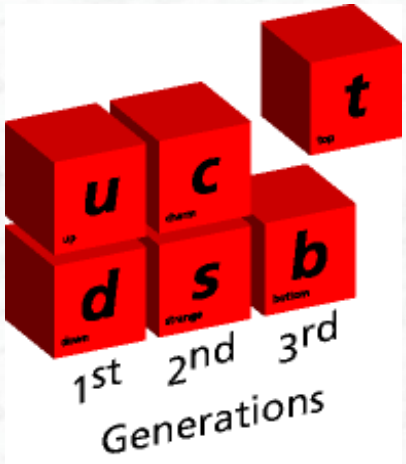


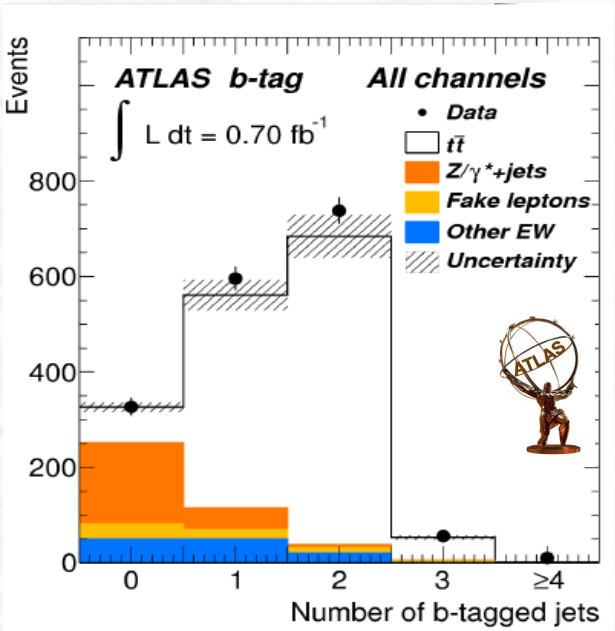
Results from e and μ combined. Measurements ~1.5σ above NLO prediction, but still consistent within uncertainties

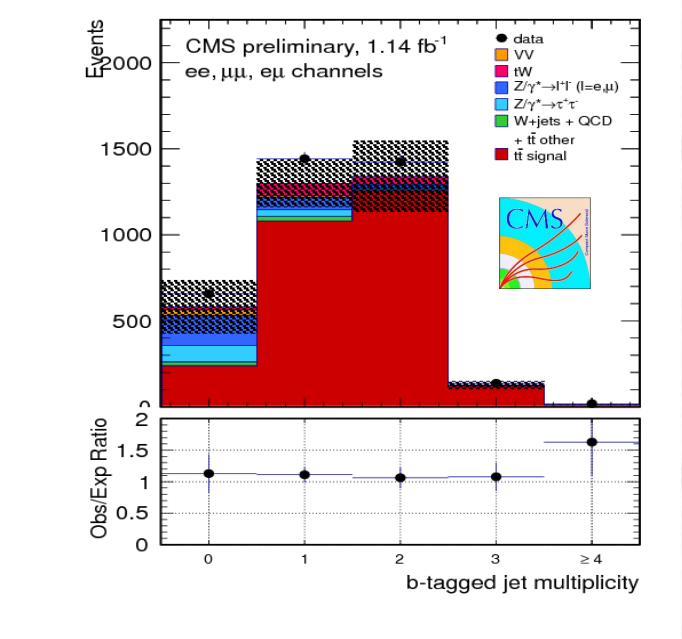
Top Quark pair production

Pair production: qq and gg-fusion



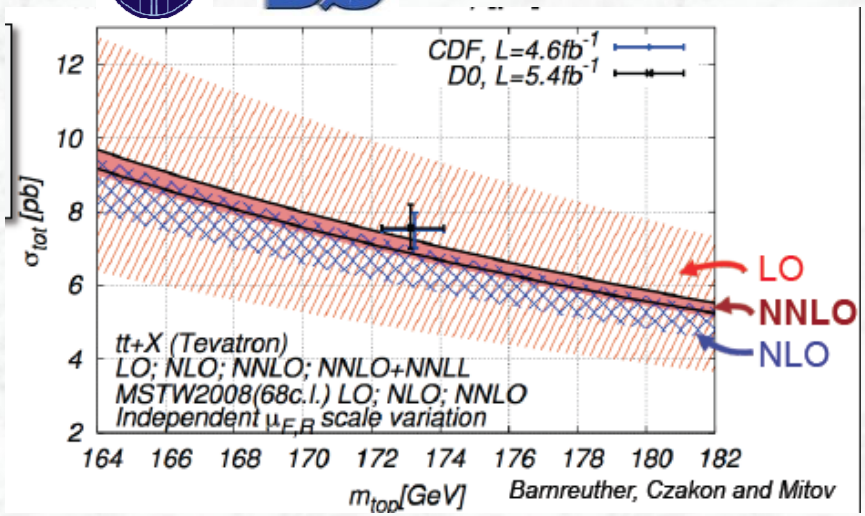


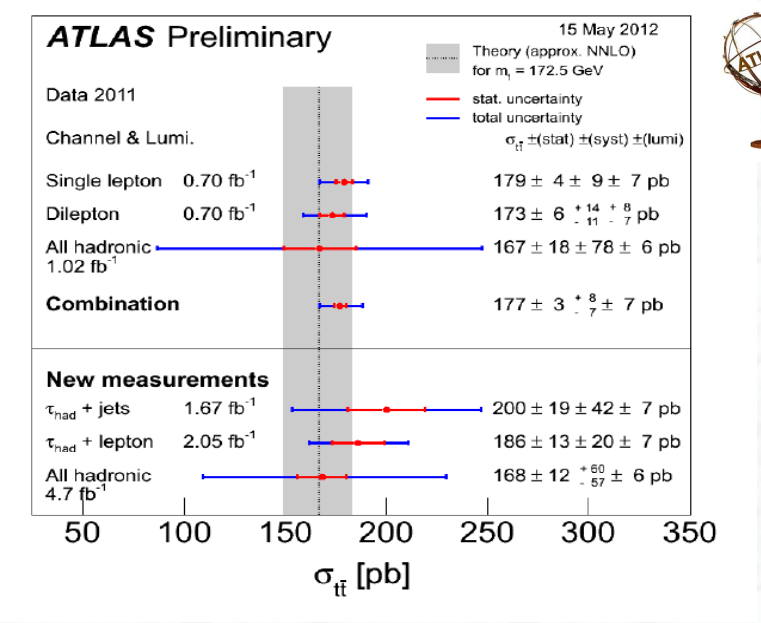


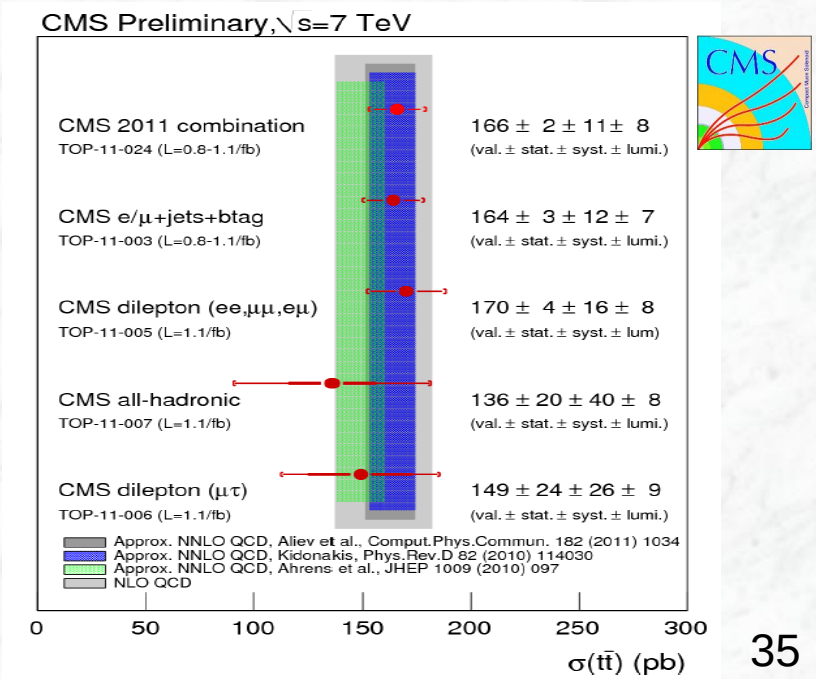


b-tag multiplicity in l-jet events ...and.. in di-lepton events

Top cross section measurements



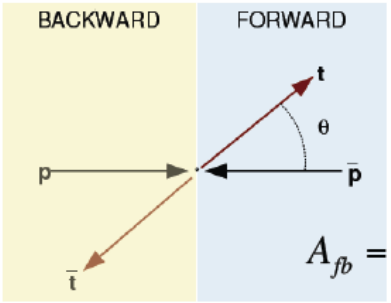


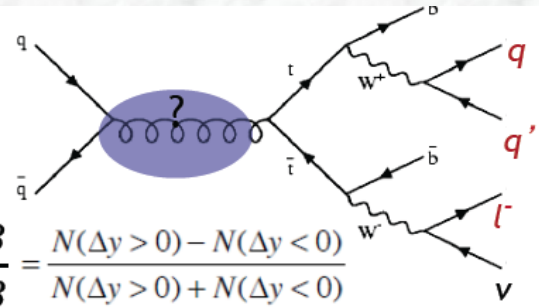


- Measurements at the Tevatron and at the LHC are well described by approx. NNLO calculations
- Precision reached at the Tevatron: 6.4%
- LHC experiments have already reached a comparable precision (6.2%)

  (large dataset, still potential to reduce the already dominant systematic uncertainties)

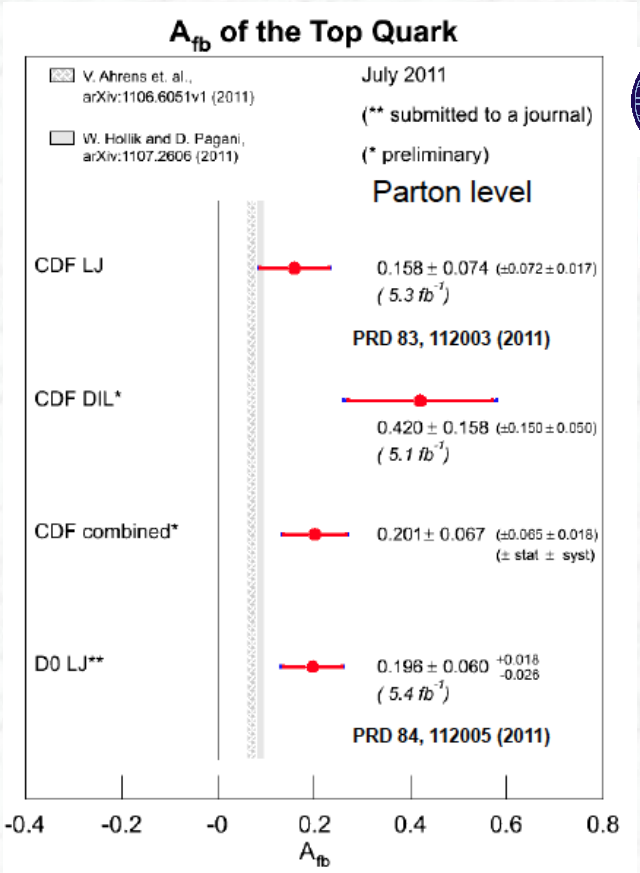
Top properties according to expectations, except maybe A_{FB} (Tevatron)





$$\Delta y = y_t - y_{\bar{t}}$$

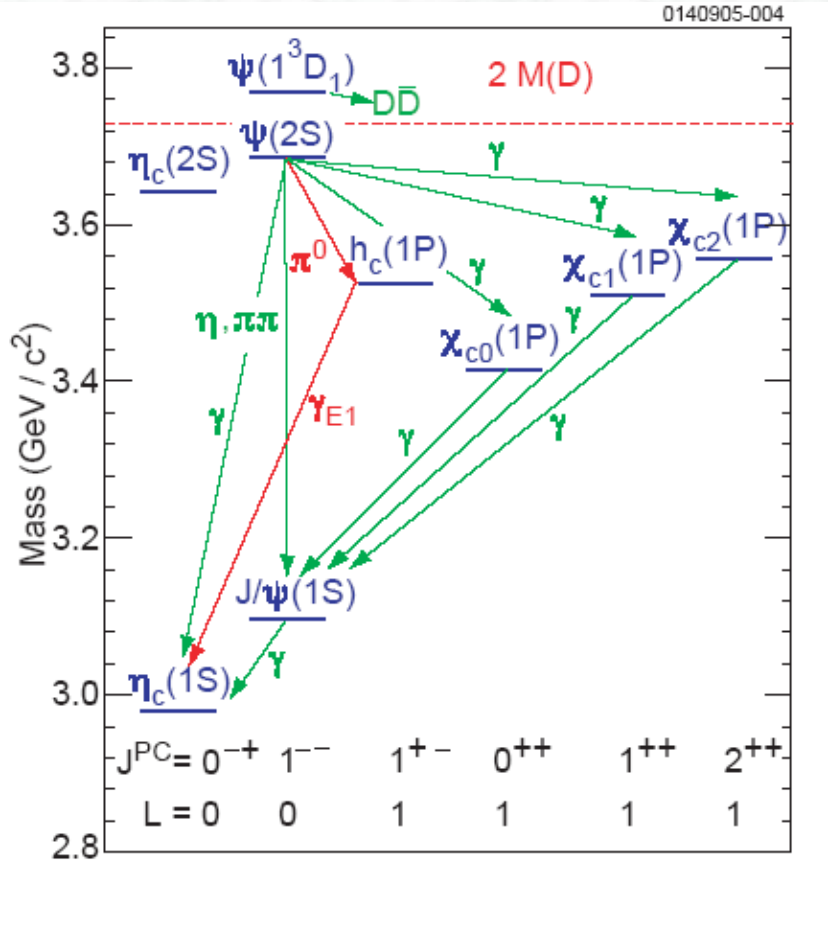
$$A_{fb} = \frac{F - B}{F + B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



Needs clarification:

More data, improved theoretical calculations

Charmonium and Bottomonium states



Is this for the LHC ?

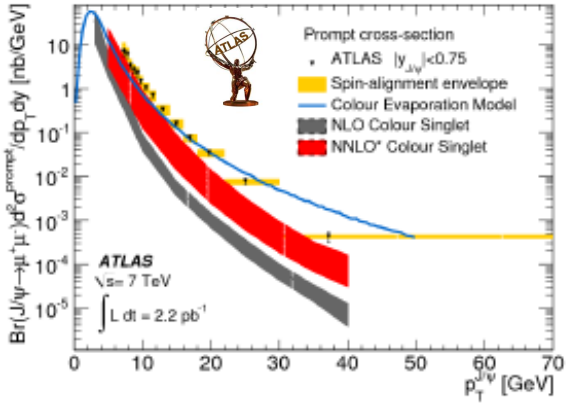
-except for ALICE and LHCb-

Yes, all experiments at the Tevatron and LHC have observed these states, measured production cross sections and have even discovered new ones

use $\mu\mu$ decays and γ-signatures

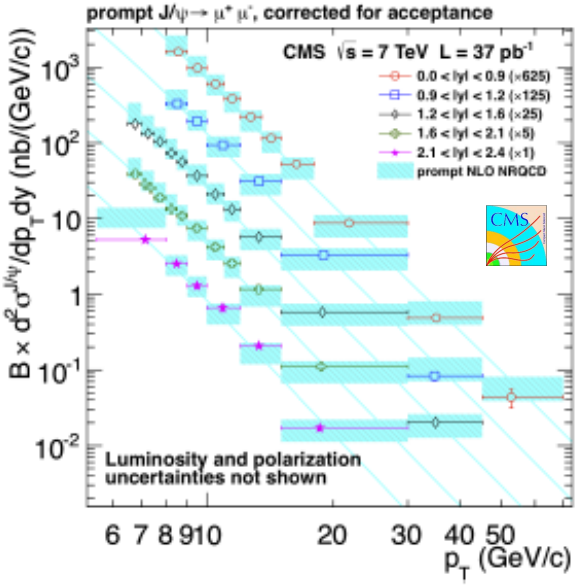
Charmonium production:

ATLAS data vs. CS



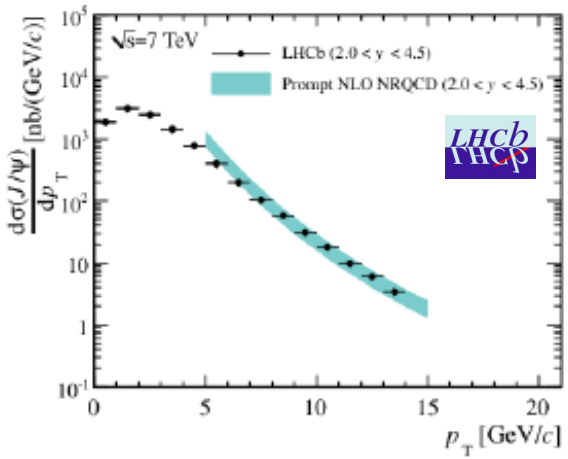
Nucl. Phys. B 850 (2011) 387-444

CMS data vs. CS+CO



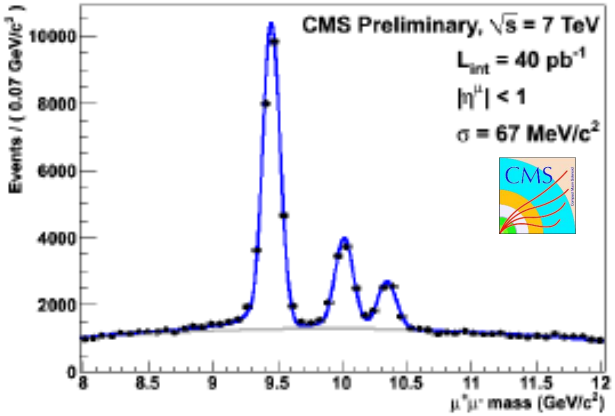
JHEP 02 (2012) 011

LHCb data (5.2 pb^{-1}) vs. CS+CO



EPJC 71(2011)1645

- Production reasonably well described by NLO QCD calculations
- Simple colour singlet model not adequate
- Similar conclusions for bottomonium states
- Polarization is still not understood, further measurements needed

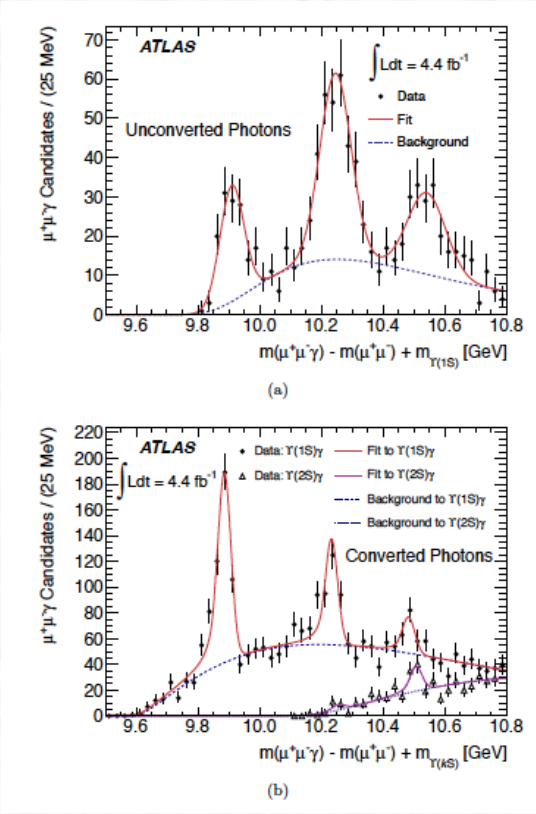


PRD 83 112004 (2011)

New heavy meson or baryon states

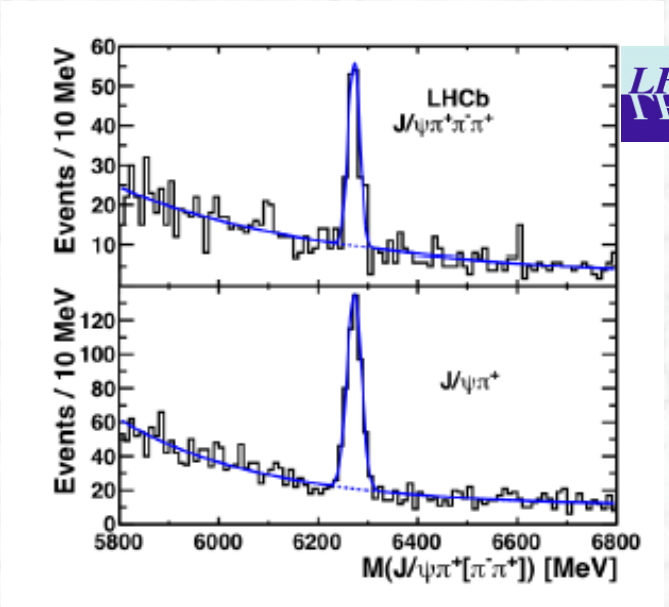
χ_b (3P)

- First observation by ATLAS:
  χ_b (3P) → Υ(1S)+ γ
  and Υ(2S)+ γ



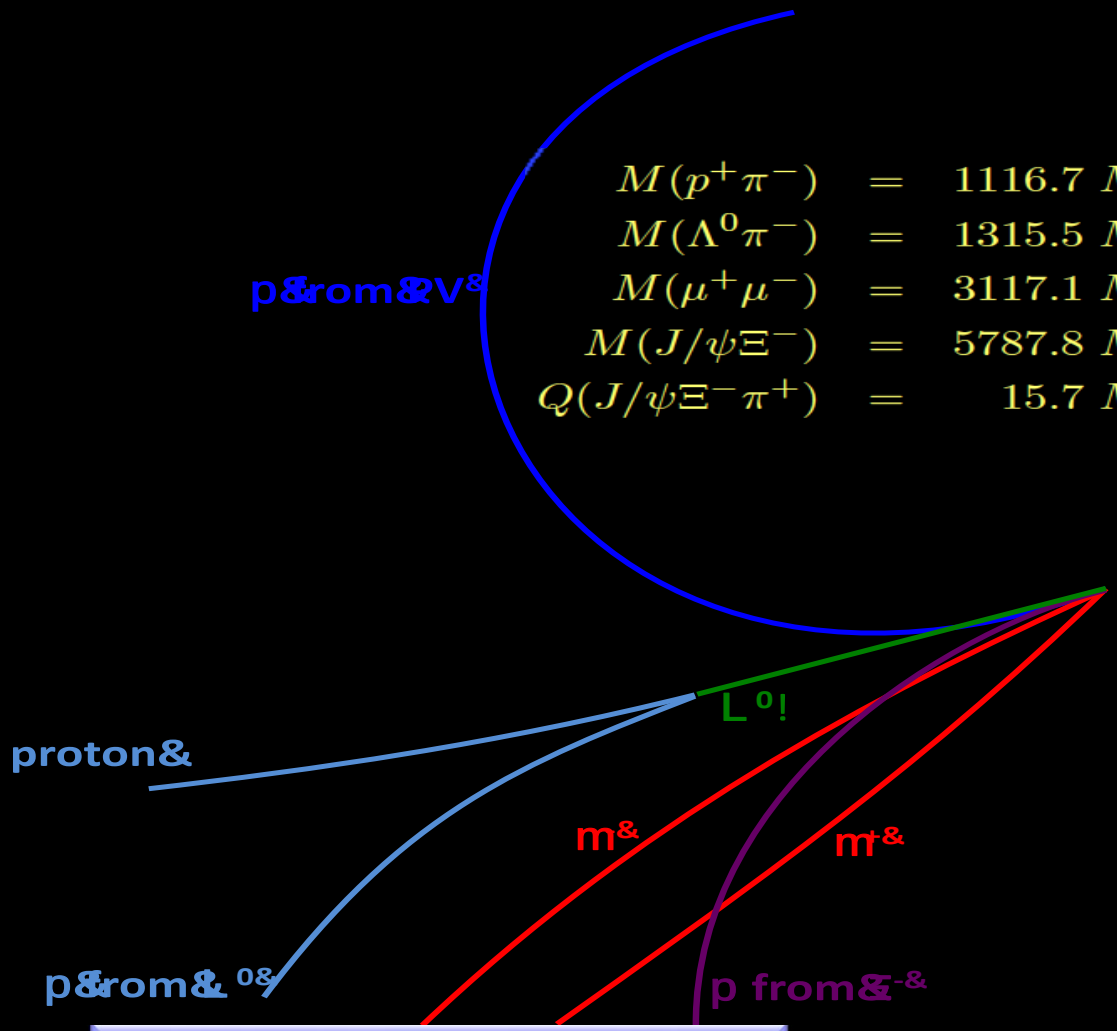
B^+_c

- First observed by CDF in B^+_c → J/ψ lν
- Observed in B^+_c → J/ψ π (LHCb, ATLAS) and J/ψ πππ (LHCb)

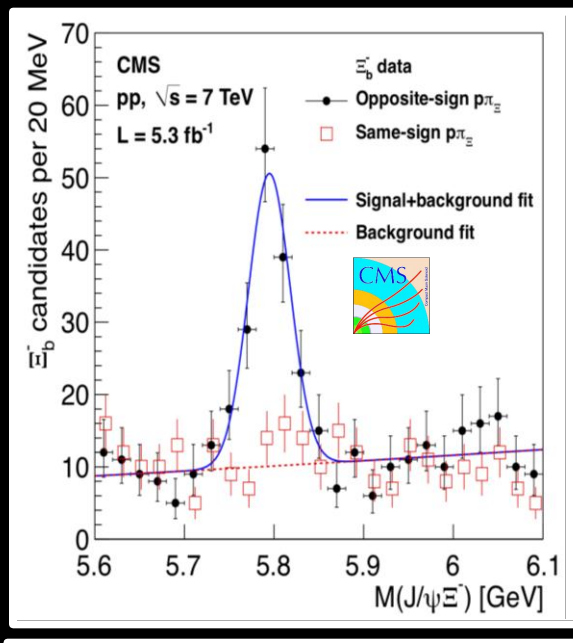


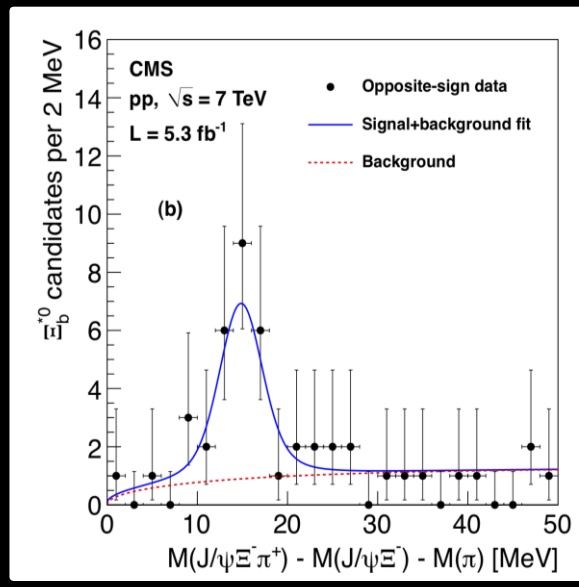
- Many other states by LHCb (B_s^{**}, Λ_b^{0*}, …)

$\Xi_b^{*0} \to \Xi_b^- \pi^+ \to \Xi^- J/\psi\, \pi^+ \to \Lambda \pi^- \mu^+ \mu^- \pi^+ \to p^+ \pi^- \pi^- \mu^+ \mu^- \pi^+$



$$
\begin{aligned}
M(p^+\pi^-) &= 1116.7\ MeV \\
M(\Lambda^0\pi^-) &= 1315.5\ MeV \\
M(\mu^+\mu^-) &= 3117.1\ MeV \\
M(J/\psi\Xi^-) &= 5787.8\ MeV \\
Q(J/\psi\Xi^-\pi^+) &= 15.7\ MeV
\end{aligned}
$$





Candidate Ξ_b^{*0} event with 3 secondary and ~10 primary vertices

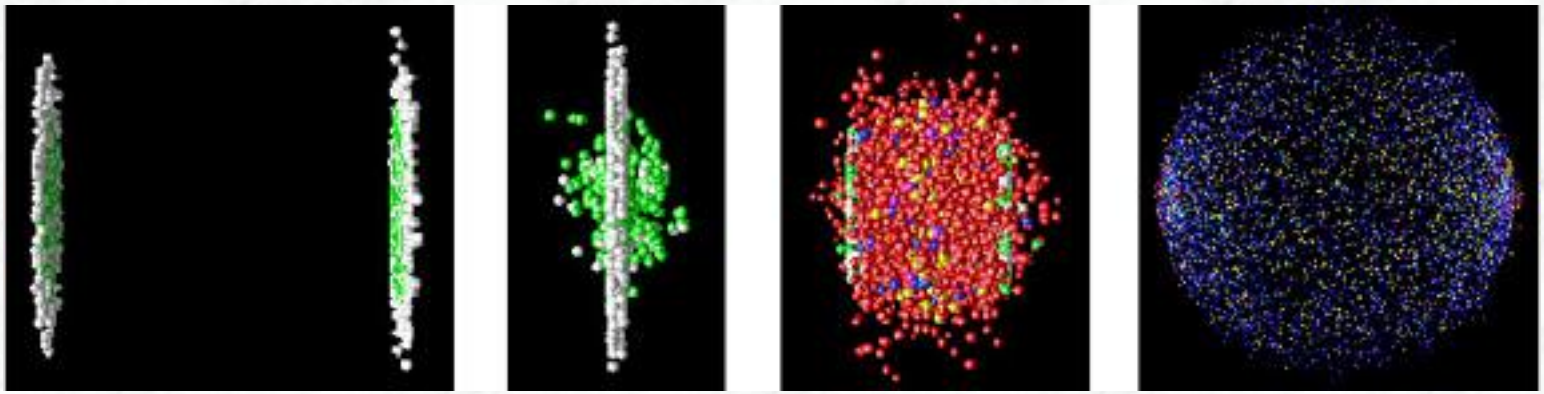
Heavy Ions

- Experiments at the RHIC collider have established a “New State of Matter“

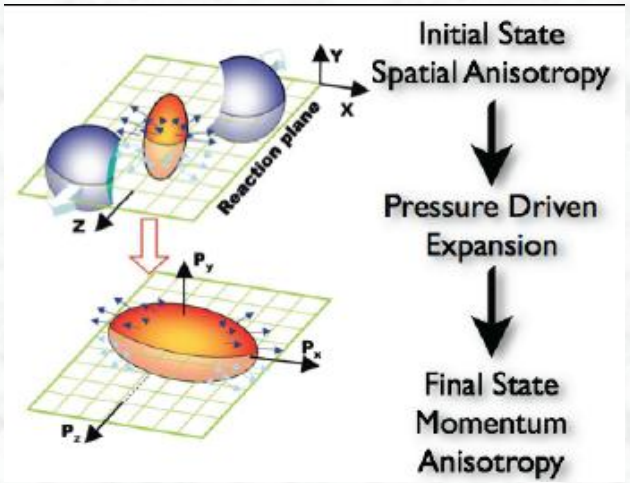
- The matter
  - shows a hydro-dynamical behaviour (like a nearly ideal fluid)
  - opaque to coloured partons,
  - transparent to el.magnetic and weakly interacting particles

- The LHC experiments ALICE, ATLAS and CMS have impressively confirmed the properties seen at RHIC in the first heavy ion runs in 2010/11;

  Impressive results on “jet quenching” right after first collisions

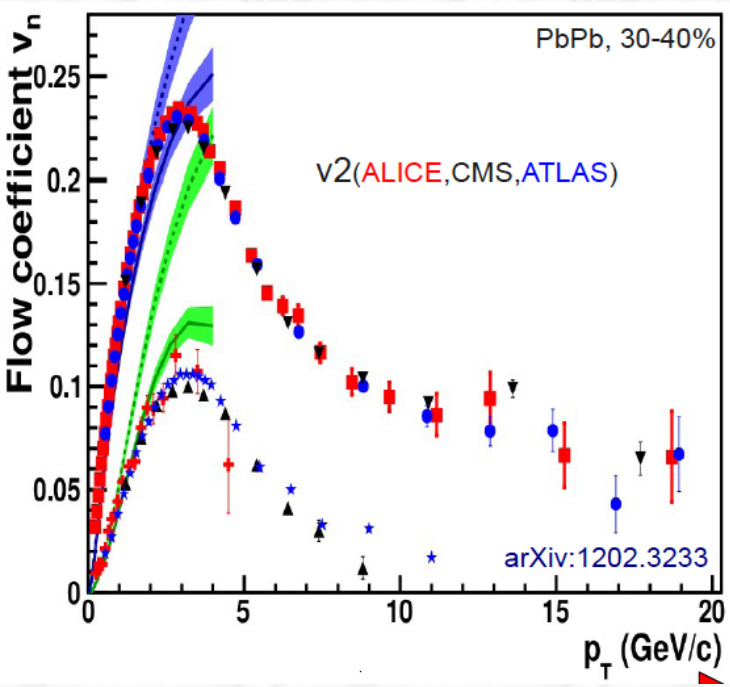


Flow Measurements:



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\varphi-\Psi_R\right)\right]\right)$$

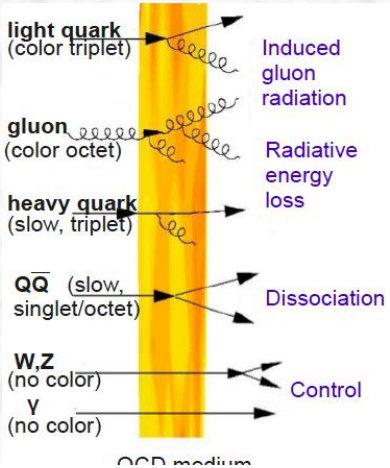
Ψ_R : angle of reaction plane
v_2 : known as elliptic flow

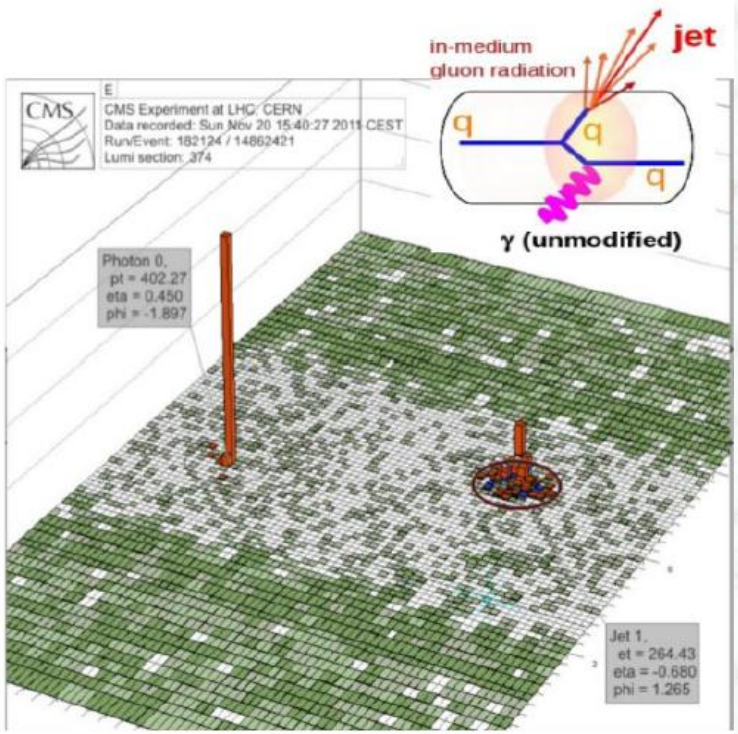


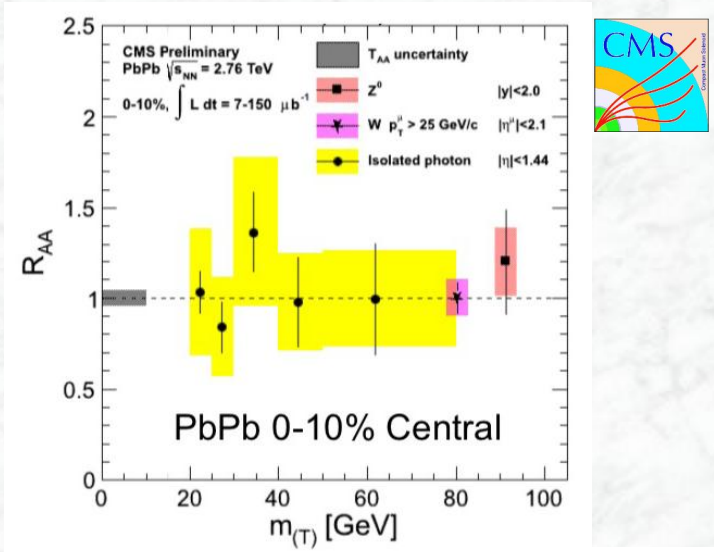
- LHC measurements confirm the hydro-dynamical behaviour;
  $v_2\,(p_T)_{LHC} \approx v_2\,(p_T)_{RHIC}$
- Low viscosity, nearly a perfect liquid
- Measurements extended to high p_T
- Flow measured for identified hadrons, including D mesons

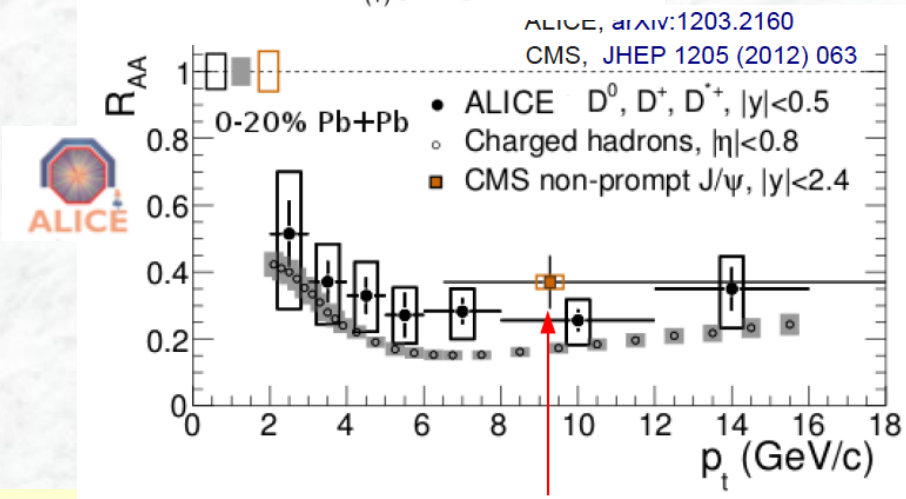
Matter effects, jet quenching:

$$R_{AA}(,p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}}$$



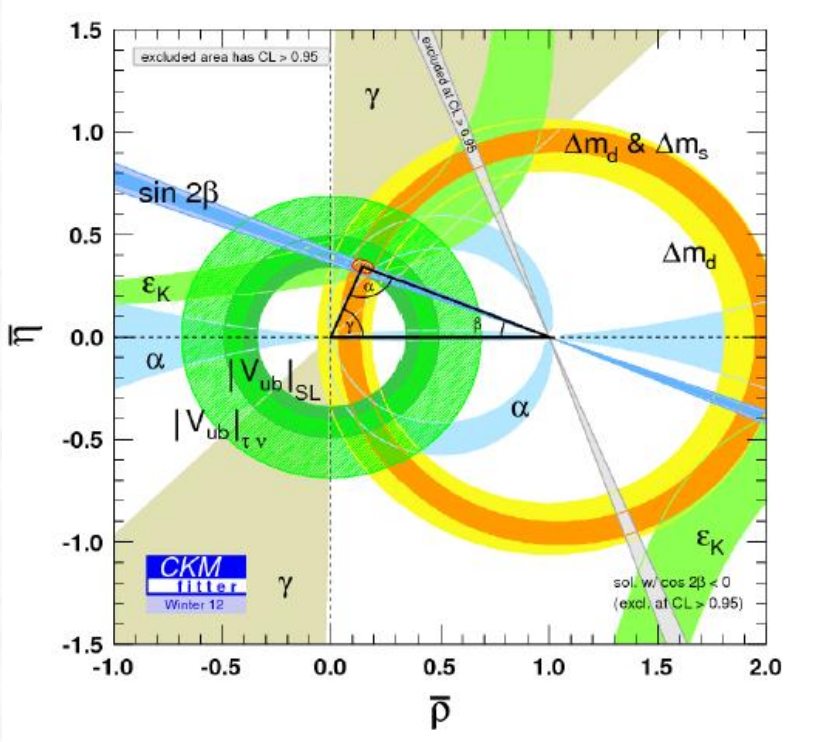






- Expected behaviour seen (hadrons, jets, photons, W and Z particles)
- Heavy mesons/quarks are less suppressed

B physics

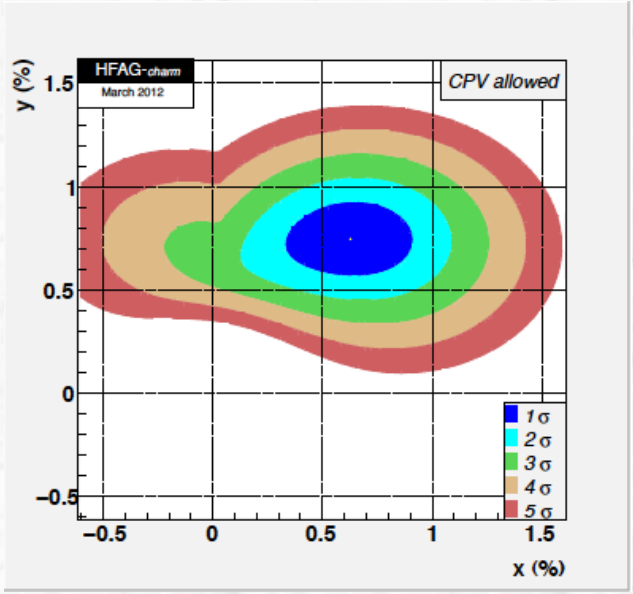


"Early hints of news from "Beyond the Standard Model" physics may come from "beautiful" flavour physics
(P. Jenni, PLHC Summary DESY-2010)

Highlights from LHCb and other Flavour Experiments:

Lot of impressive results

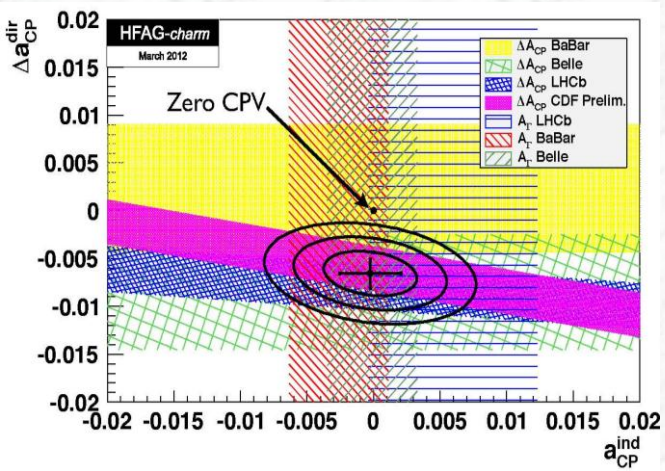
- Charm mixing has been well established (combination of many experiments)
- Large CP violation effects emerge in the charm system (lager than expected)



LHCb measures difference in CP asymmetry for $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$

Zero CP violation is excluded at the 3.5σ level (LHCb only)

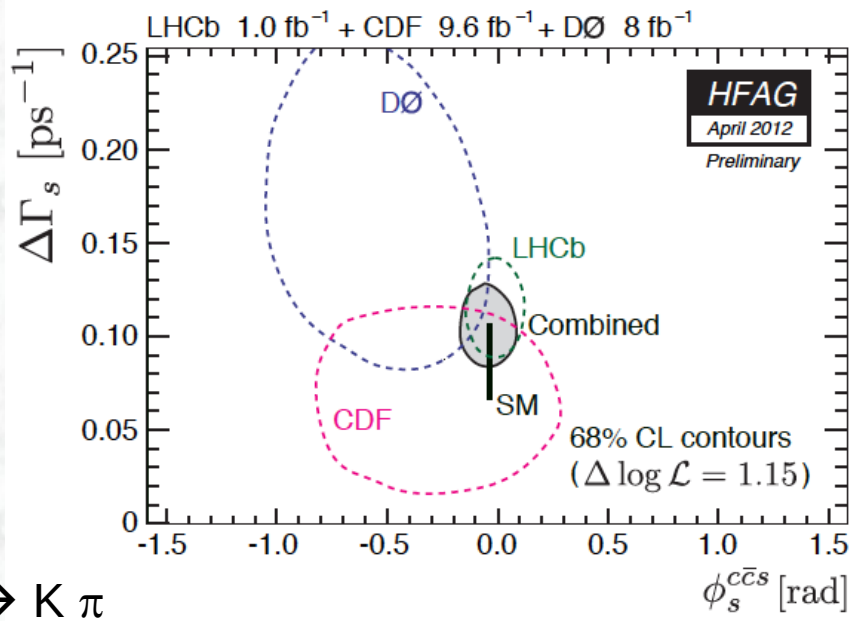
Theoretical work needed and ongoing to disentangle possible new physics effects from SM hadronic effects.



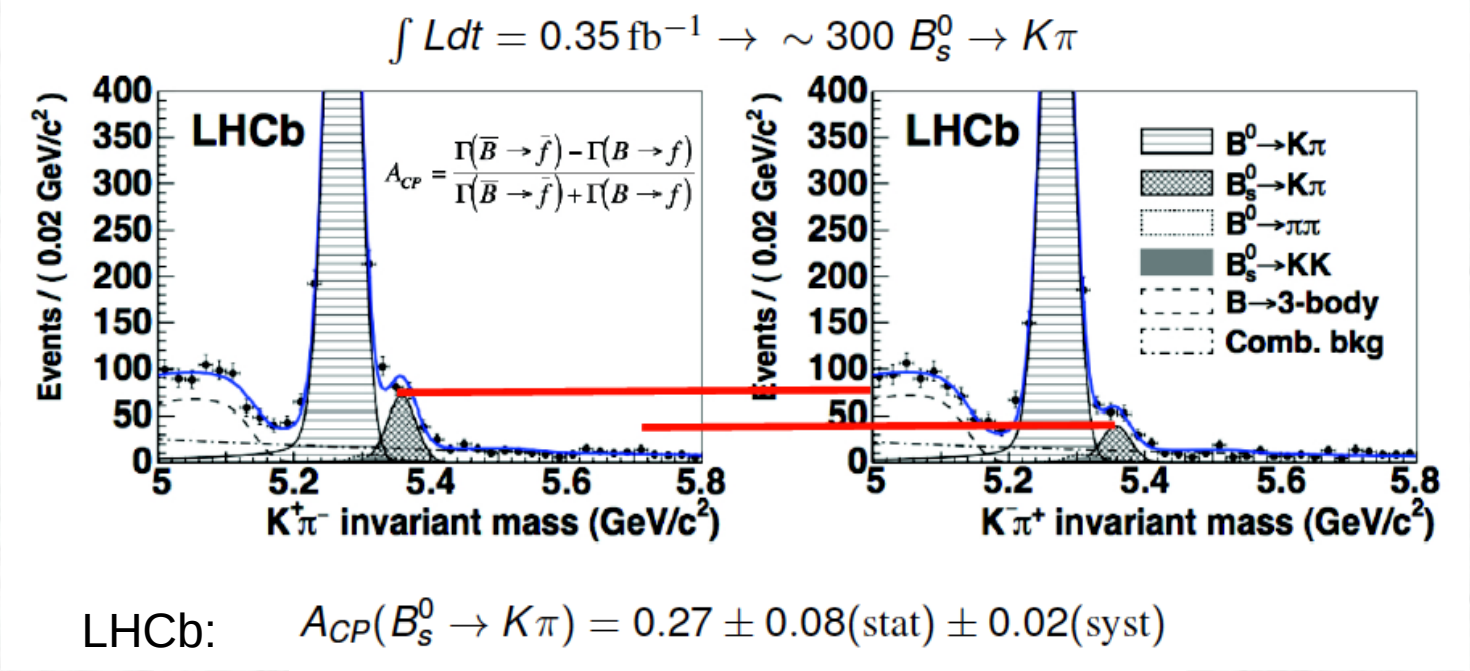
CP violation in B decays

- Precise measurement of CP phase ϕ_s :
  LHCb result consistent with Standard Model

- First significant direct measurement of
  $\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\ ps^{-1}$



- First evidence for direct CP violation in $B_0^s \rightarrow K\pi$

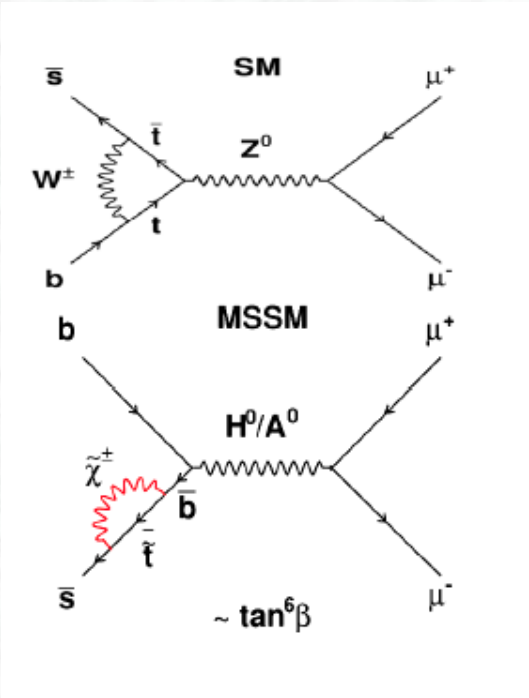


LHCb: $A_{CP}(B_s^0 \rightarrow K\pi) = 0.27 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{syst})$

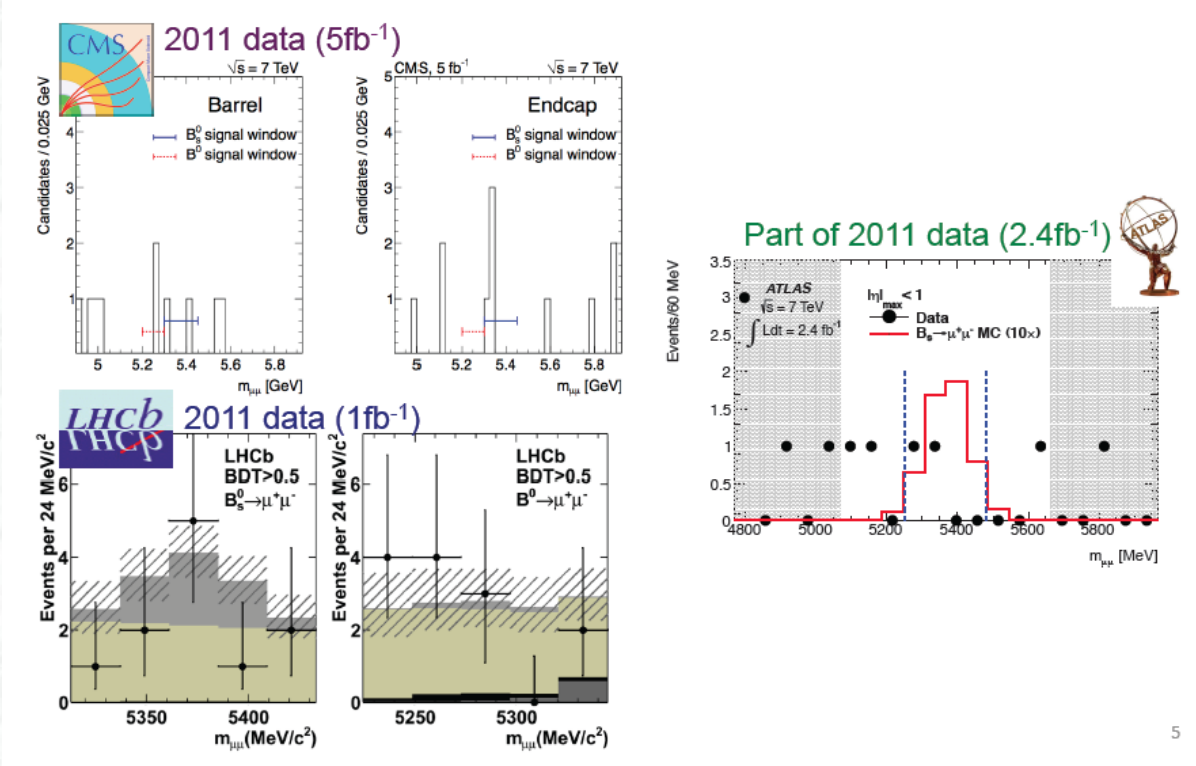
CDF: $A_{CP}(B_s^0 \rightarrow K\pi) = 0.39 \pm 0.15(\mathrm{stat}) \pm 0.08(\mathrm{syst})$

Search for the decays $B_0 \rightarrow \mu^+\mu^-$ and $B_o^s \rightarrow \mu^+\mu^-$

The motivation:

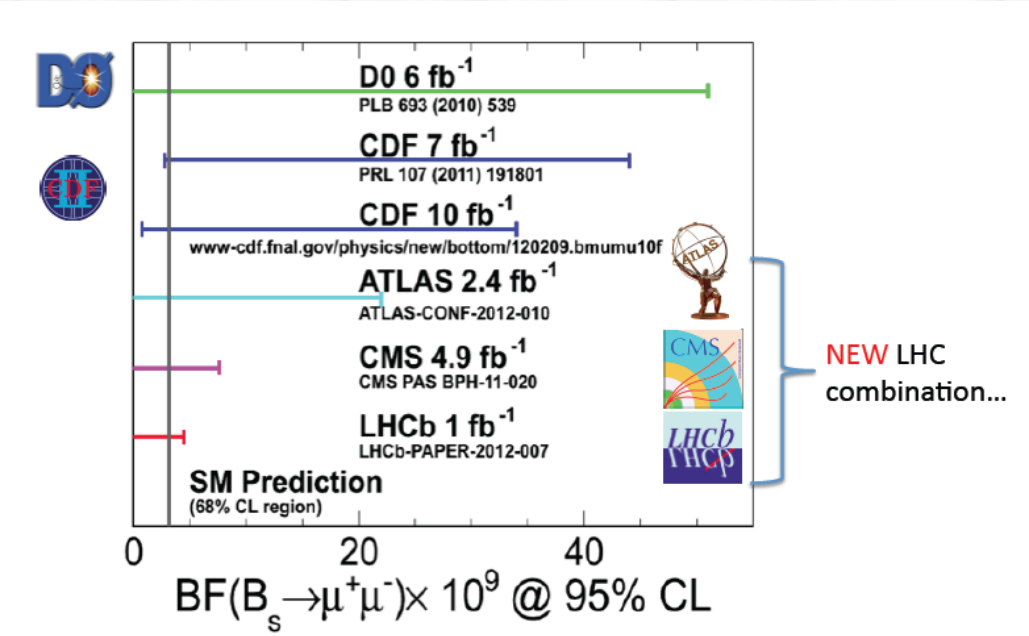


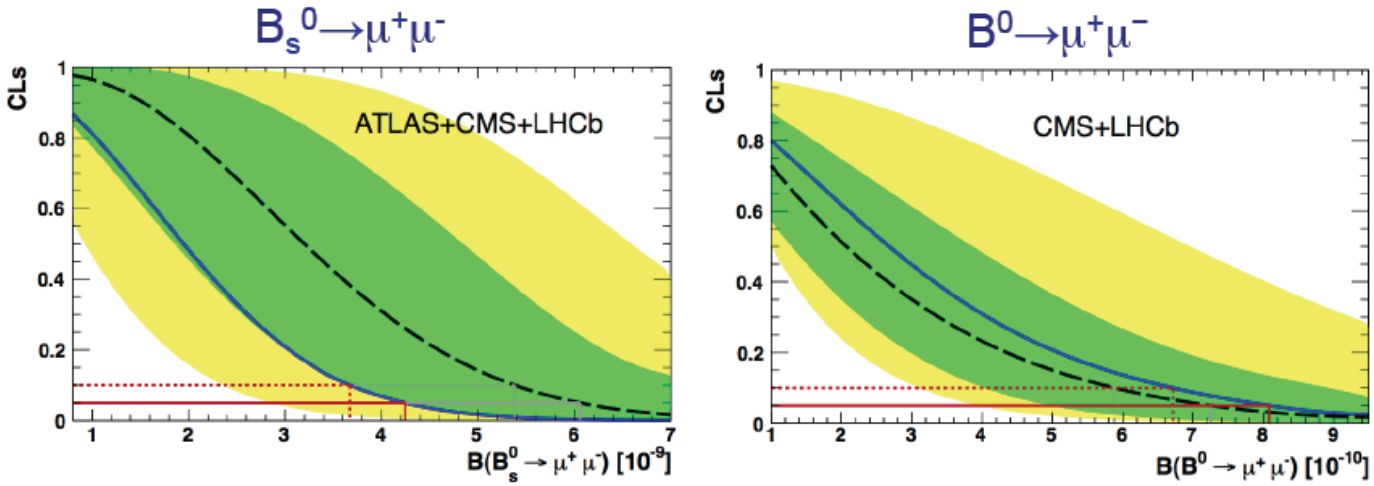
The data:



$B(B_s^0 \rightarrow \mu^+\mu^-) = 1.1\times(3.2\pm0.2)\times10^{-9}$

The limits:





$B(B_s^0 \to \mu\mu) < (3.7\ (4.2)) \times 10^{-9}$ at 90(95) % C.L.

- Excess over background at ~2σ level (1-CL_b (p-value)=5%)
- Compatible with SM at 1σ (1-CL_{s+b}=84%)

$B(B^0 \to \mu\mu) < (0.67\ (0.81)) \times 10^{-9}$ at 90(95) % C.L.

My summary on B physics

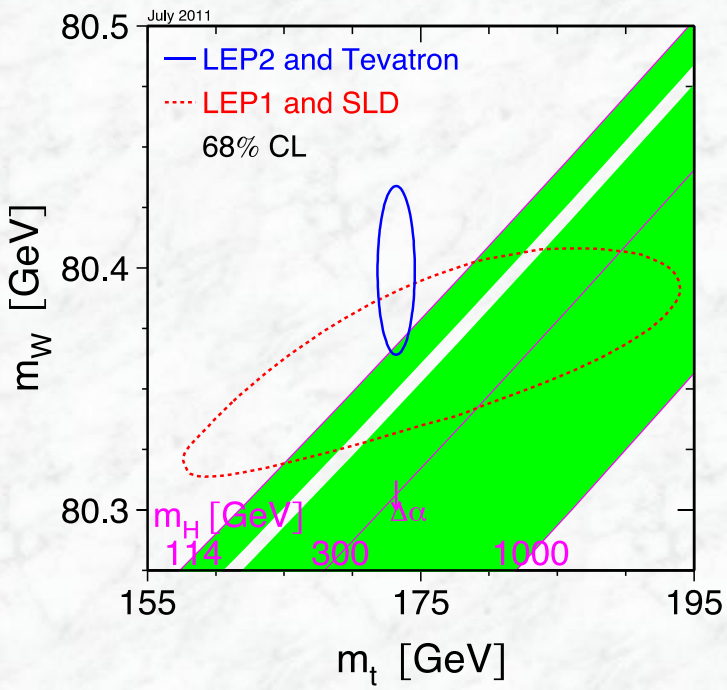
- Beautiful results are coming out !
- LHCb has taken a leading role in many areas, but Tevatron is still nicely in the game
- e^+e^- machines complementary (τ decays)
- LHCb appears as an "Anomaly terminator" (ϕ_s, BR ($B_s \rightarrow \mu\,\mu$) approaching Standard Model prediction)

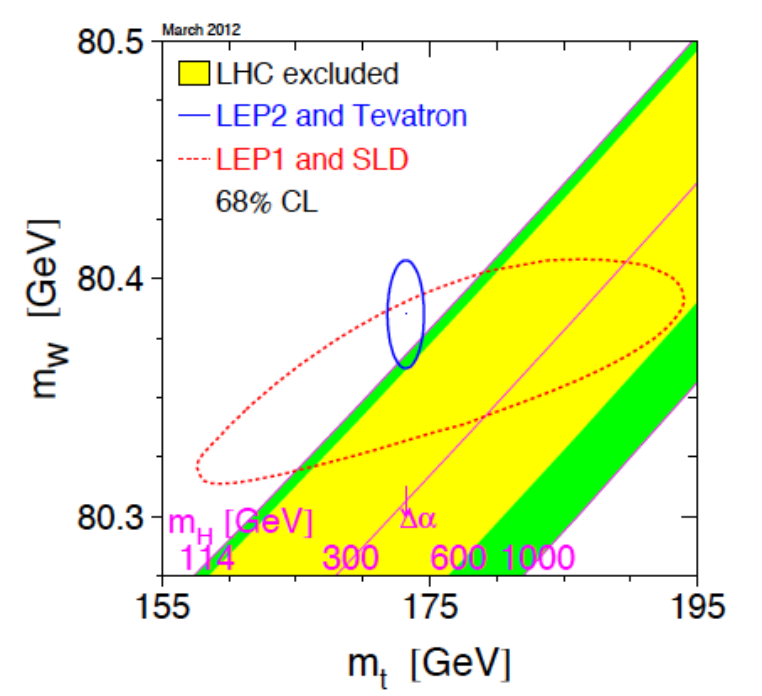
G. Dissertori, Moriond

- Some remaining "tensions":

  - large CP violation in charm → LHCb, Theory
  - sin 2β vs. BR ($B \rightarrow \tau\,\nu$) → BELLE
  - Asymmetry in semileptonic B decays from D0 → CDF, D0

V. Electroweak parameter



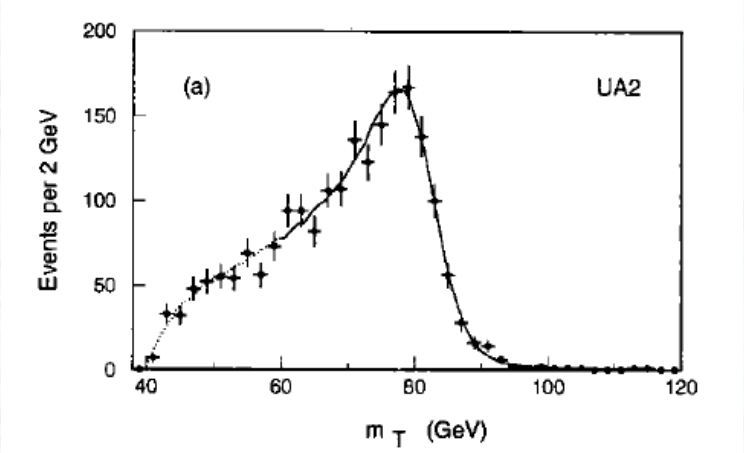


July 2011

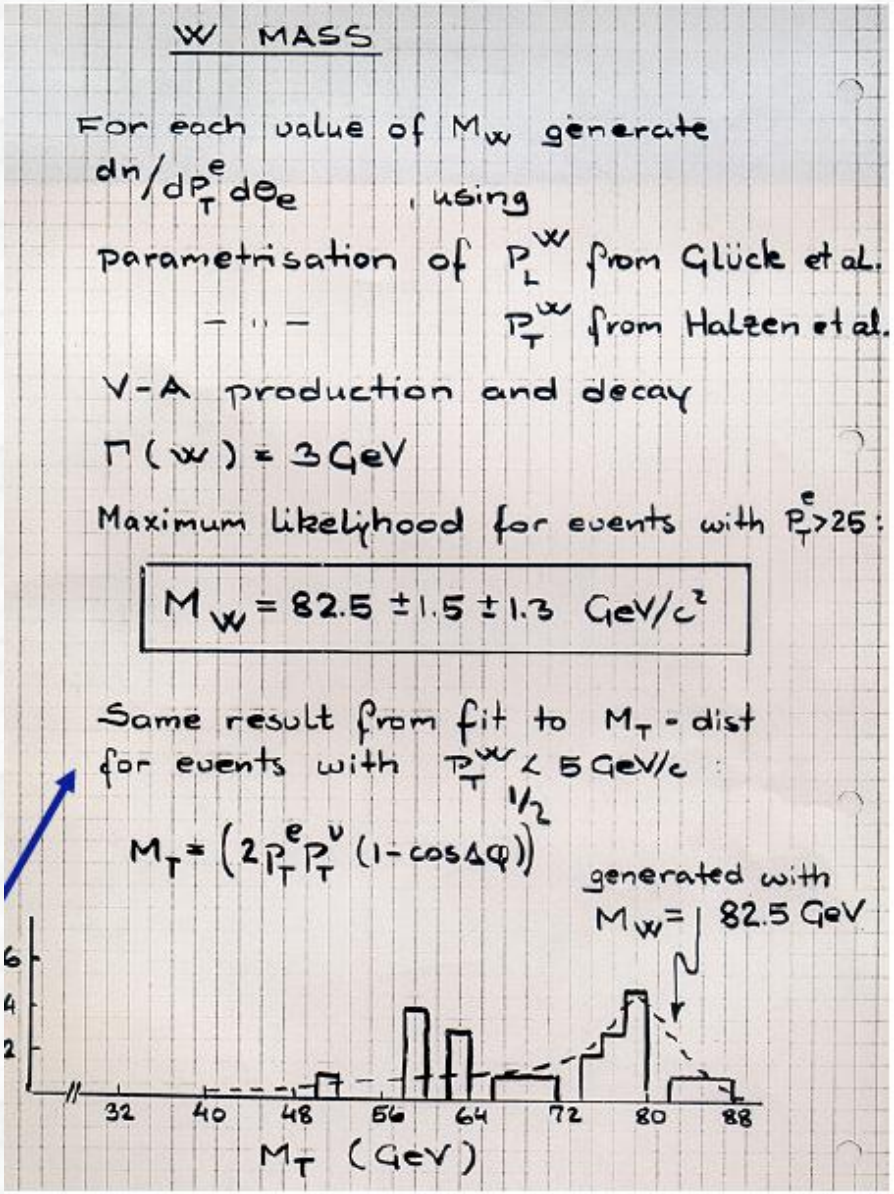
today

W mass measurements

The beginning



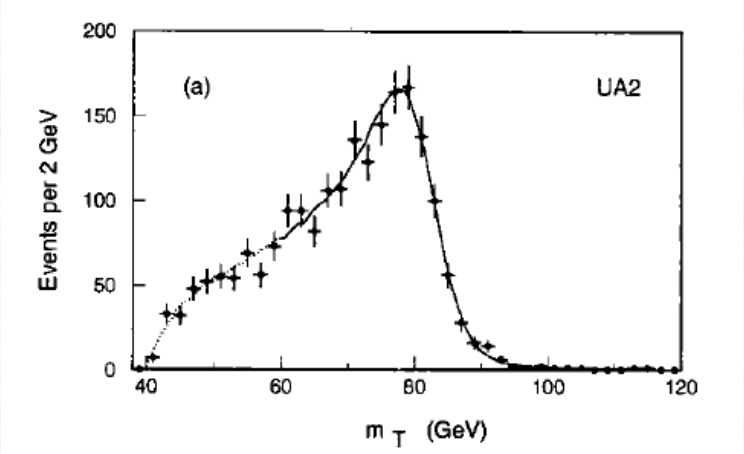
$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$



D. Froidevaux, Blois 2012

W mass measurements

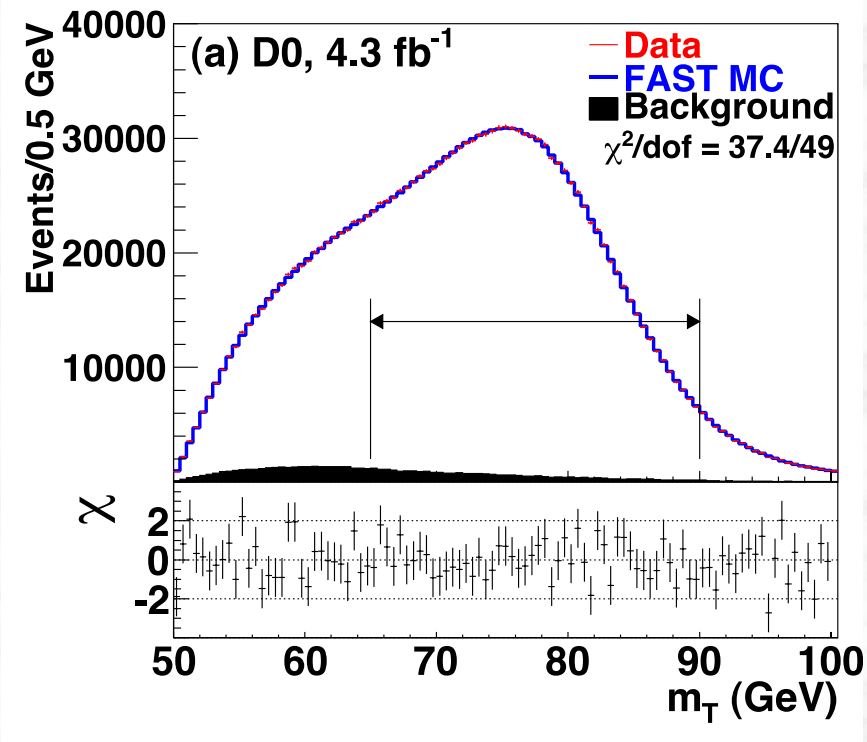
The beginning



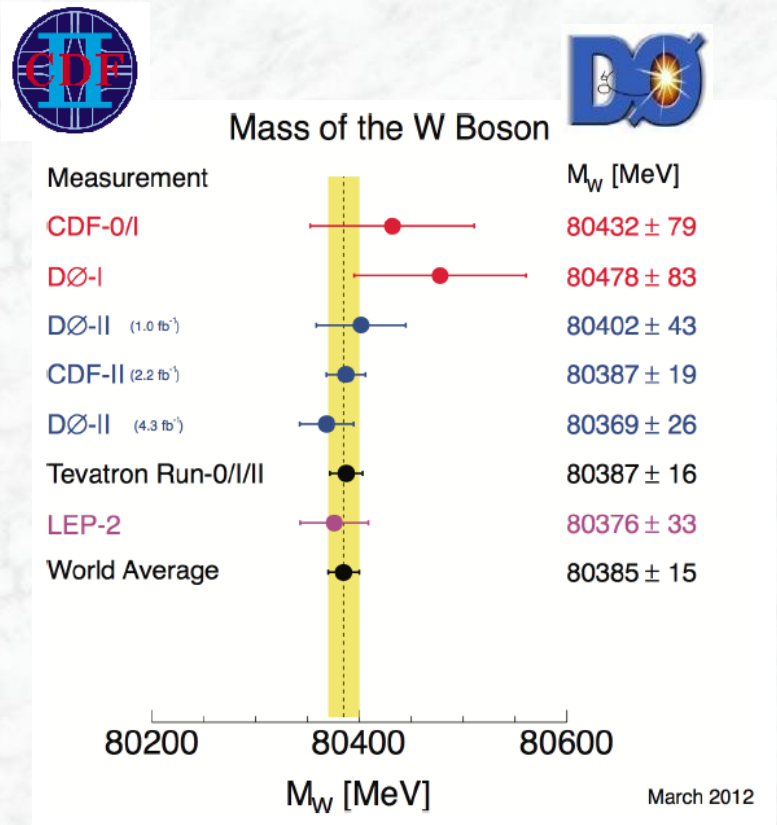
$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

State of the art, today

1.68 M events, electrons $|\eta| < 1.05$



$m_W = 80.371 \pm 0.013$ (stat.) GeV



Systematic uncertainties:

New CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

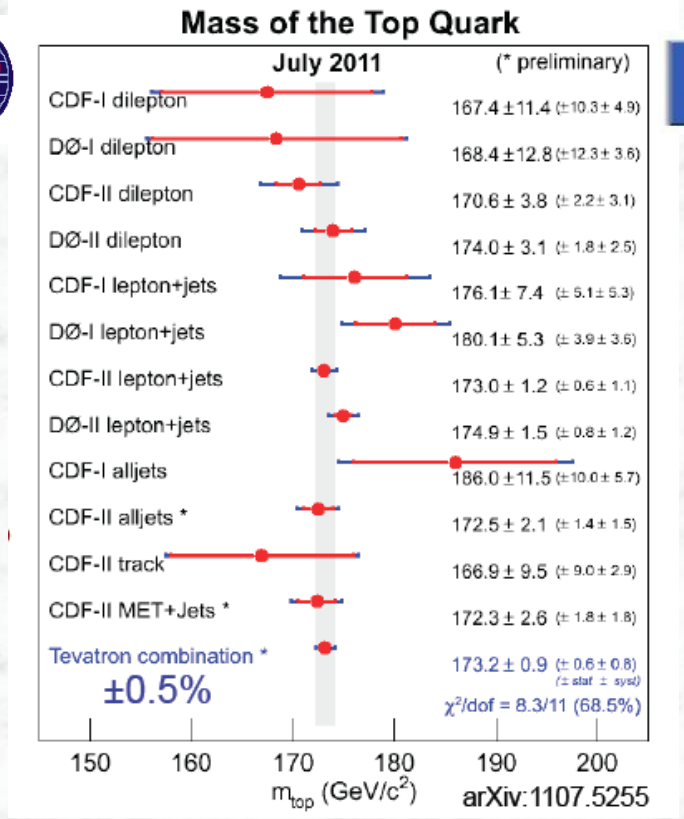
Can the LHC improve on this?

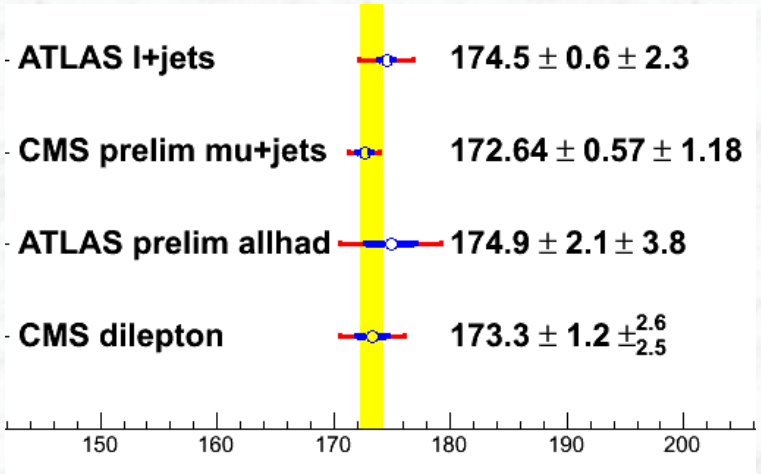
In principle yes, but probably not soon .and. not with 30 pileup events

- Very challenging (e-scale, hadronic recoil, p_T (W),..)

- However there is potential for reduction of uncertainties
  - statistics
  - statistically limited systematic uncertainties (marked in green above)
  - pdfs, energy scale, …., recoil(?)

Top quark mass



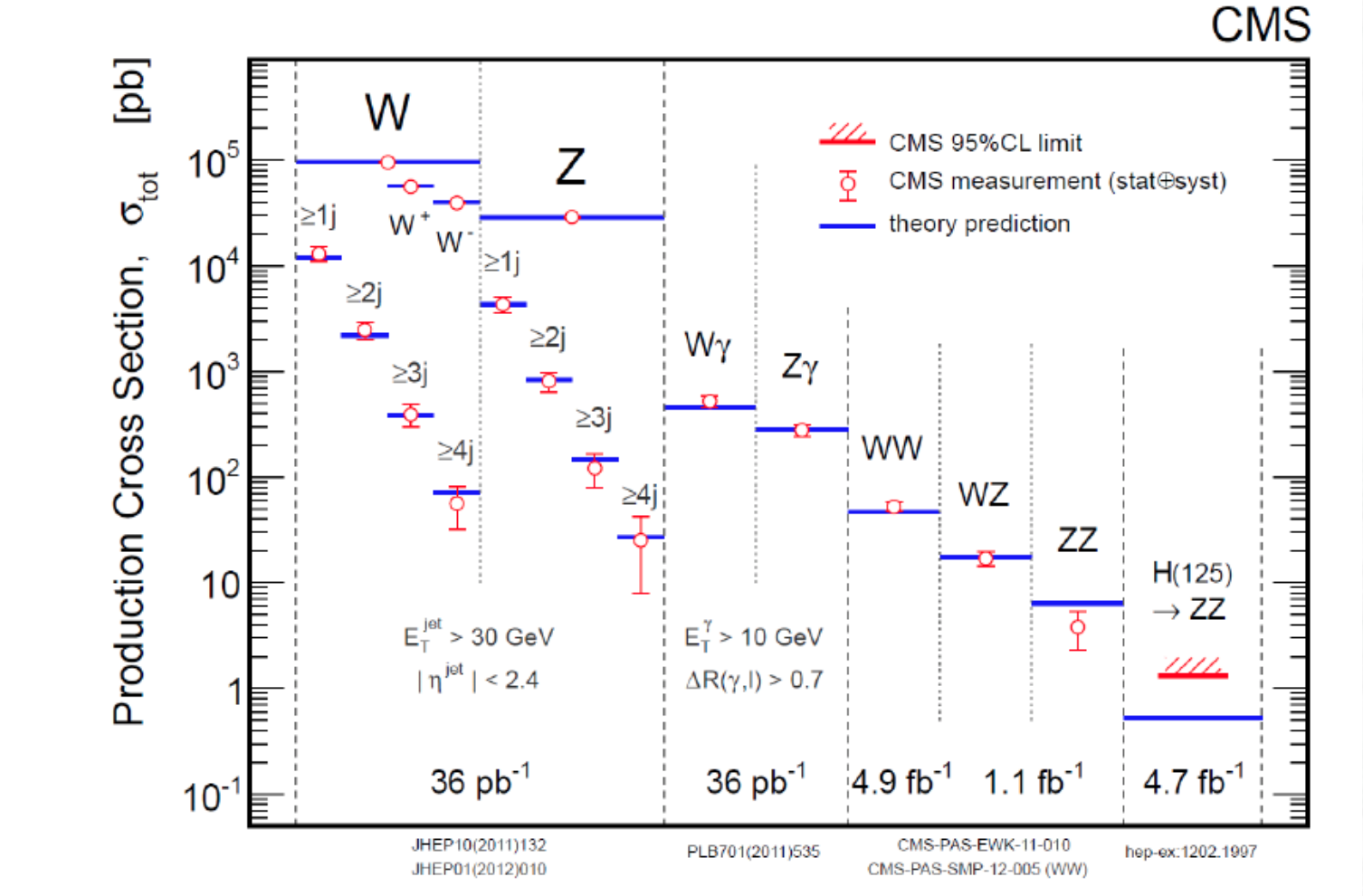


without uncertainties due to
underlying event and colour reconnection

- Still dominated by the Tevatron experiments
- However, first competitive LHC results appear;
  CMS measurement in (l-jet)-channel claims a precision of 1.2 GeV;

  Uncertainties need to be analyzed / understood

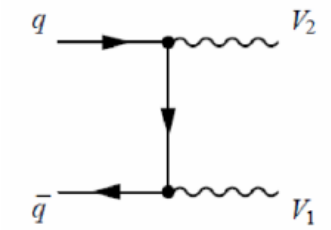
Di-boson production: Wγ, WW, WZ, ZZ

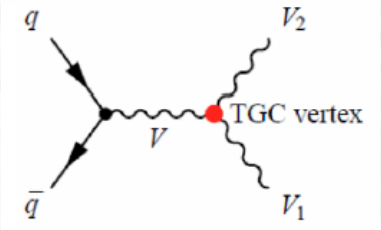


- All di-boson processes have been measured by both ATLAS and CMS
- Good agreement with expected Standard Model cross sections

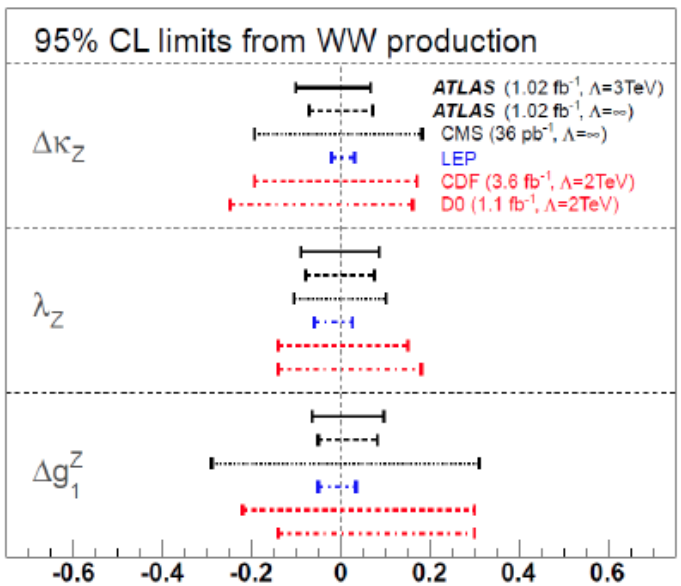
→ Constraints on anomalous Triple Gauge Couplings

Coupling	Parameters	Channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
ZZZ	f_{40}^Z, f_{50}^Z	ZZ
$Z\gamma Z$	f_{40}^γ, f_{50}^γ	ZZ

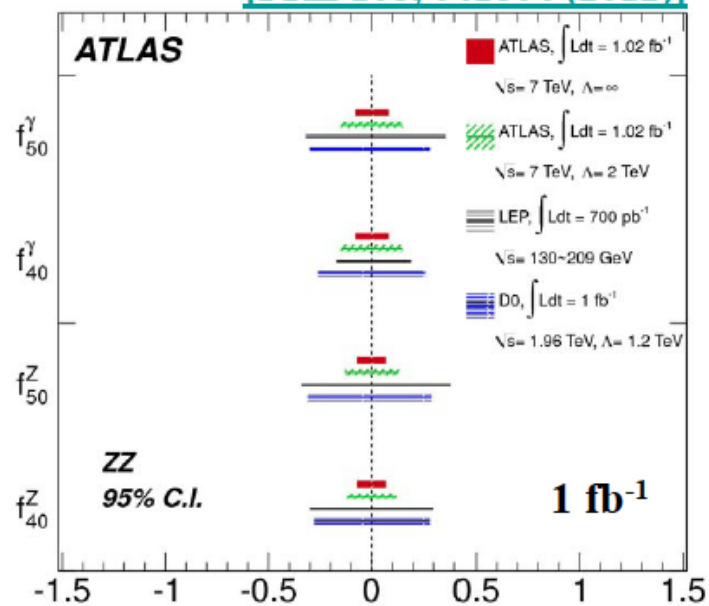




- Anomalous coupling modify production rates (cross sections) and kinematics
- So far, limits extracted from production cross sections
- Start to be competitive with limits from LEP and Tevatron (process dependent)



[PRL 108, 041804 (2012)]



Some numerology:

Frequently mentioned numbers at this conference ?

125

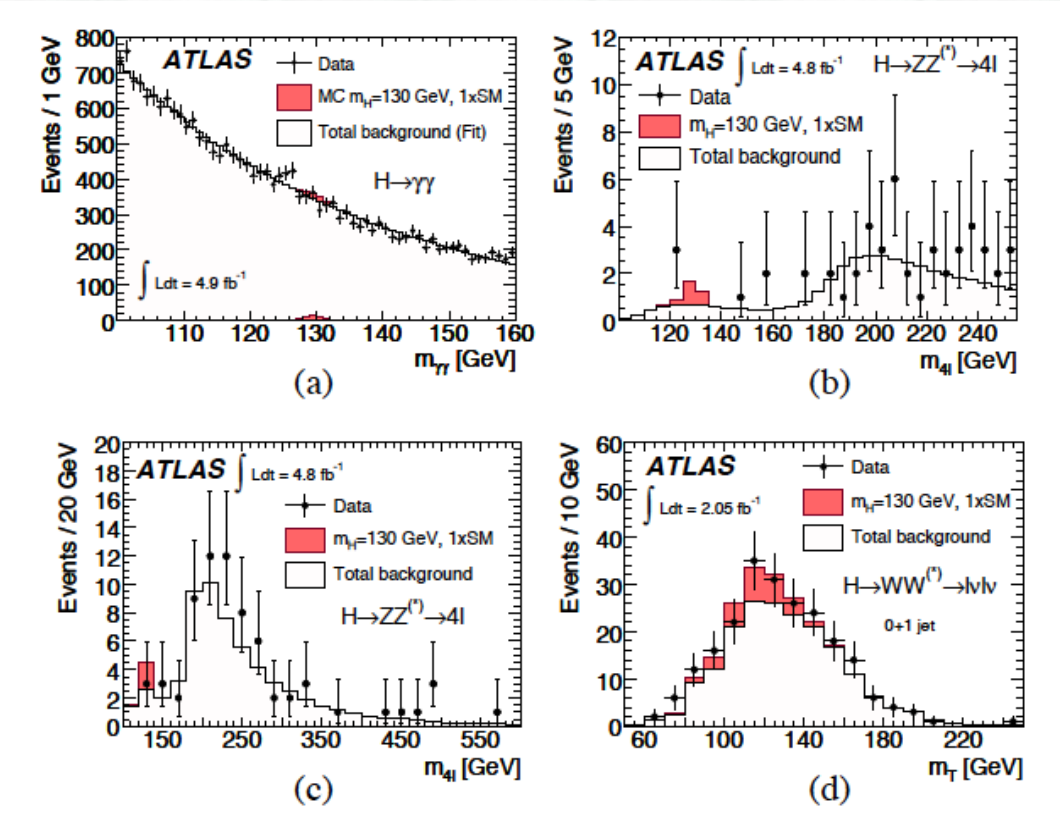
95

$3\ 10^{-9}$

Where is the Higgs boson ?

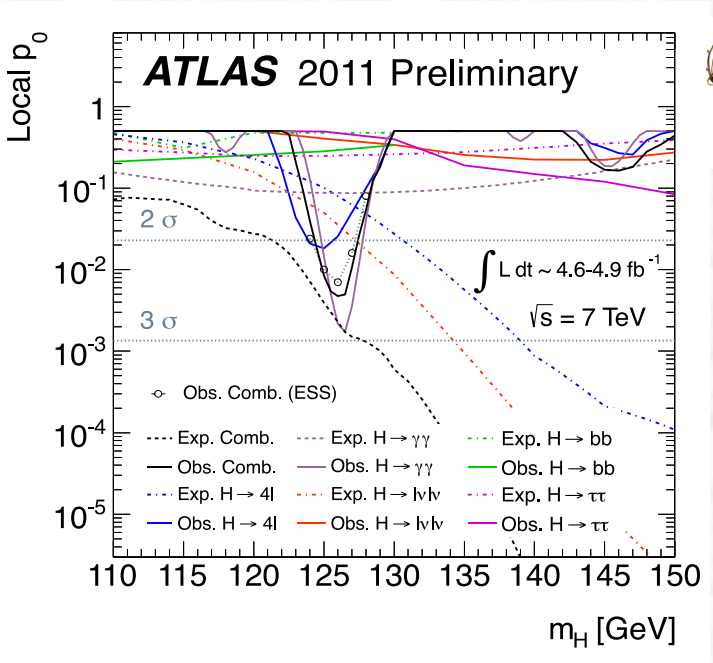
- The Higgs boson has been searched for in both experiments, ATLAS and CMS, in a large mass range and in many channels

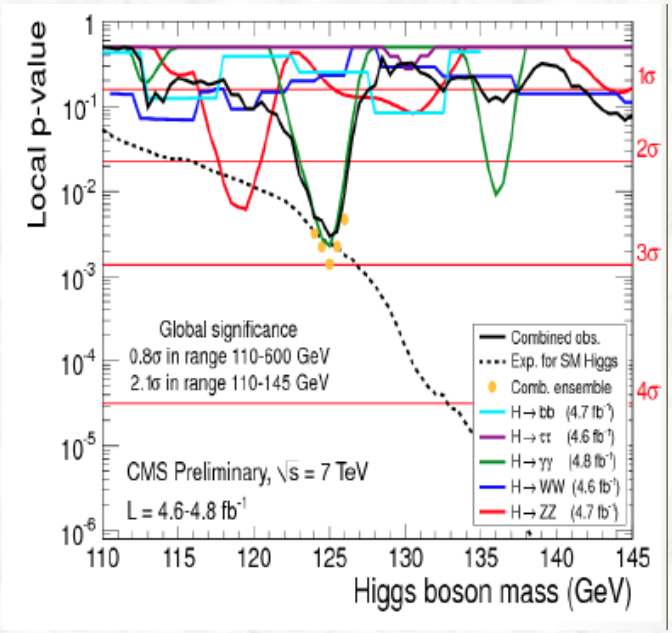
- Example: Some ATLAS search channels



- Data are largely consistent with the expectations from Standard Model background processes …
  use statistical methods to quantify this statement

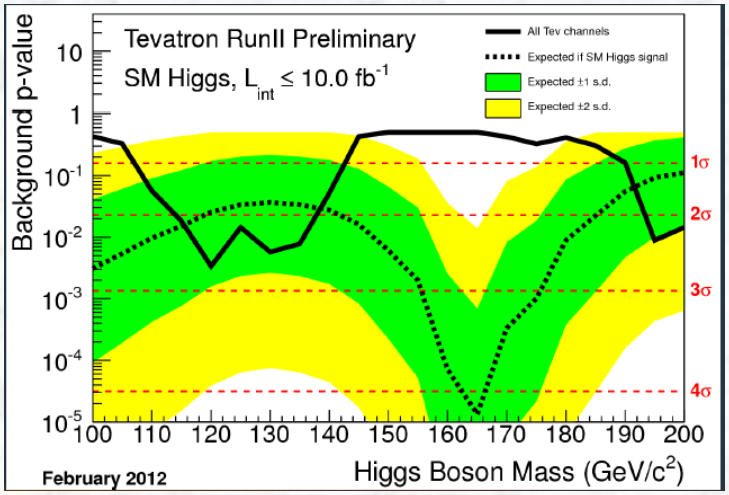
Compatibility with the background-only hypothesis



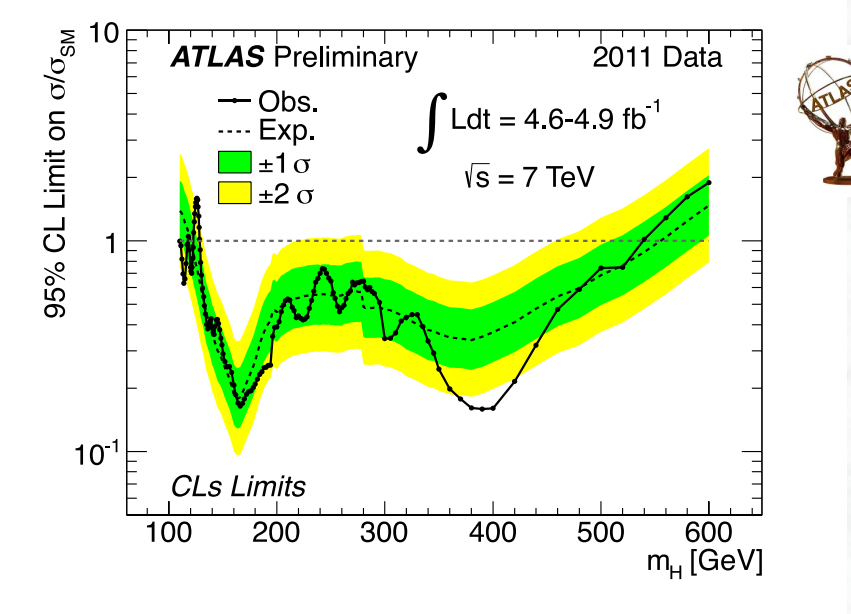


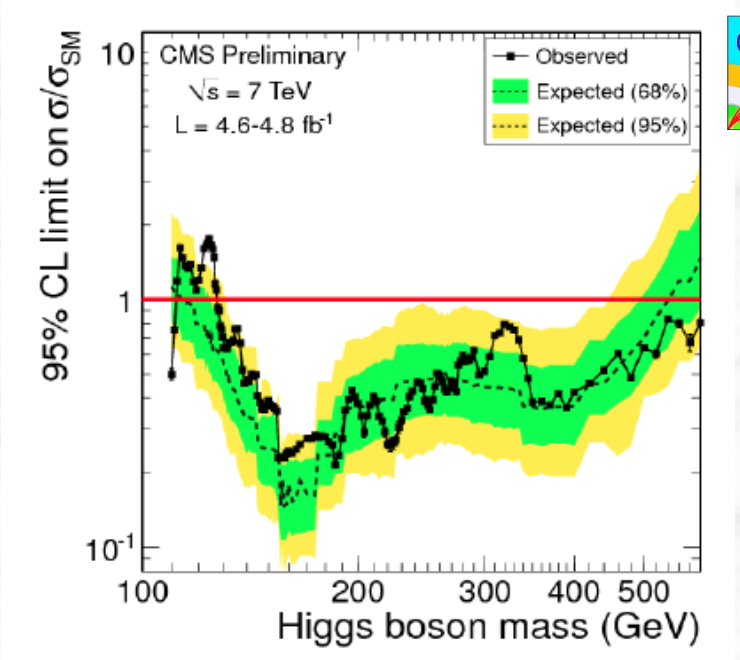
Comments:

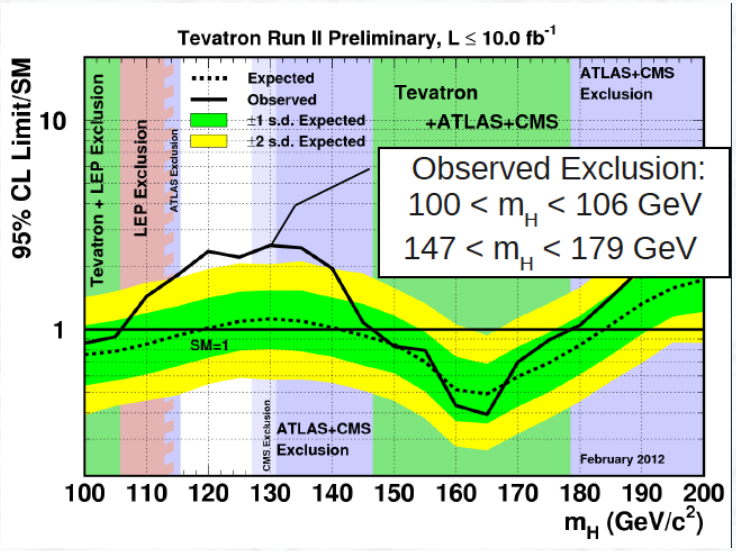
- ATLAS: low p_0 value around 126 GeV driven by γγ and ZZ channels
- CMS: γγ channel is dominant
- WW → lν lν contributes little in both experiments



Exclusion limits on Higgs boson cross sections







My personal comments:

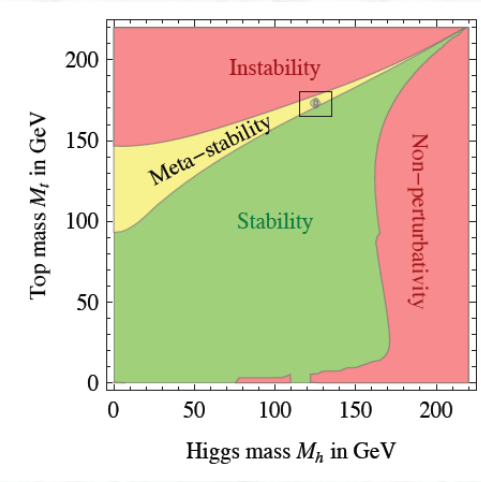
- It is impressive to see what Higgs boson mass range the LHC experiments were able to explore after just two years of running !!

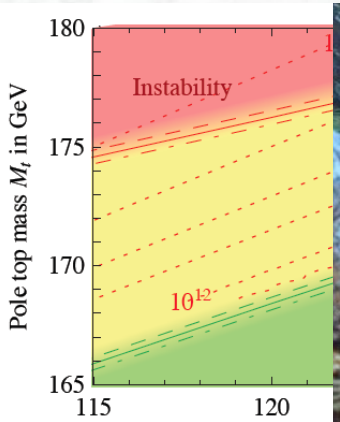
  Many beloved plots (blue-band, m_W vs. m_t) have drastically changed

- But: the Higgs boson has not yet been discovered !

  [For many many theorists it seems obvious that m_H = 125 GeV]

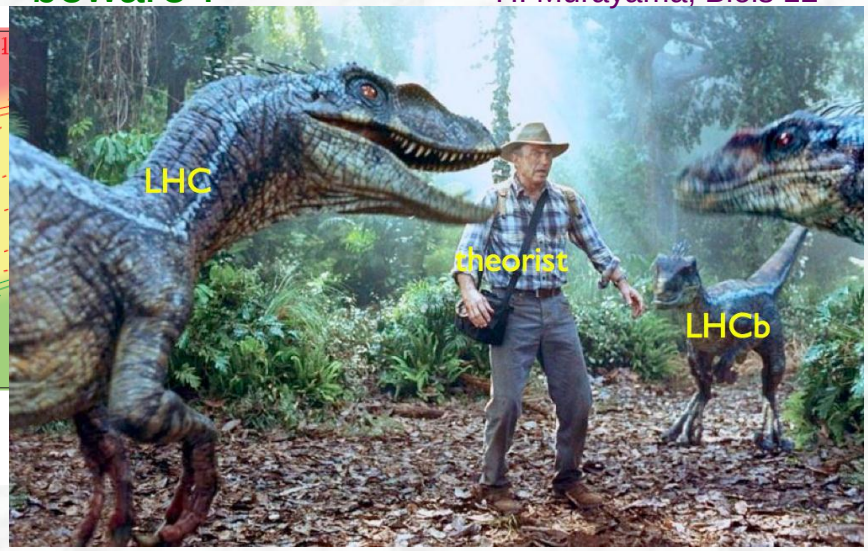
  Due to m_H = 125 the fate of the universe now seems to depend critically on the top mass and 1 GeV can make an enourmous difference





beware !

H. Murayama, Blois 12

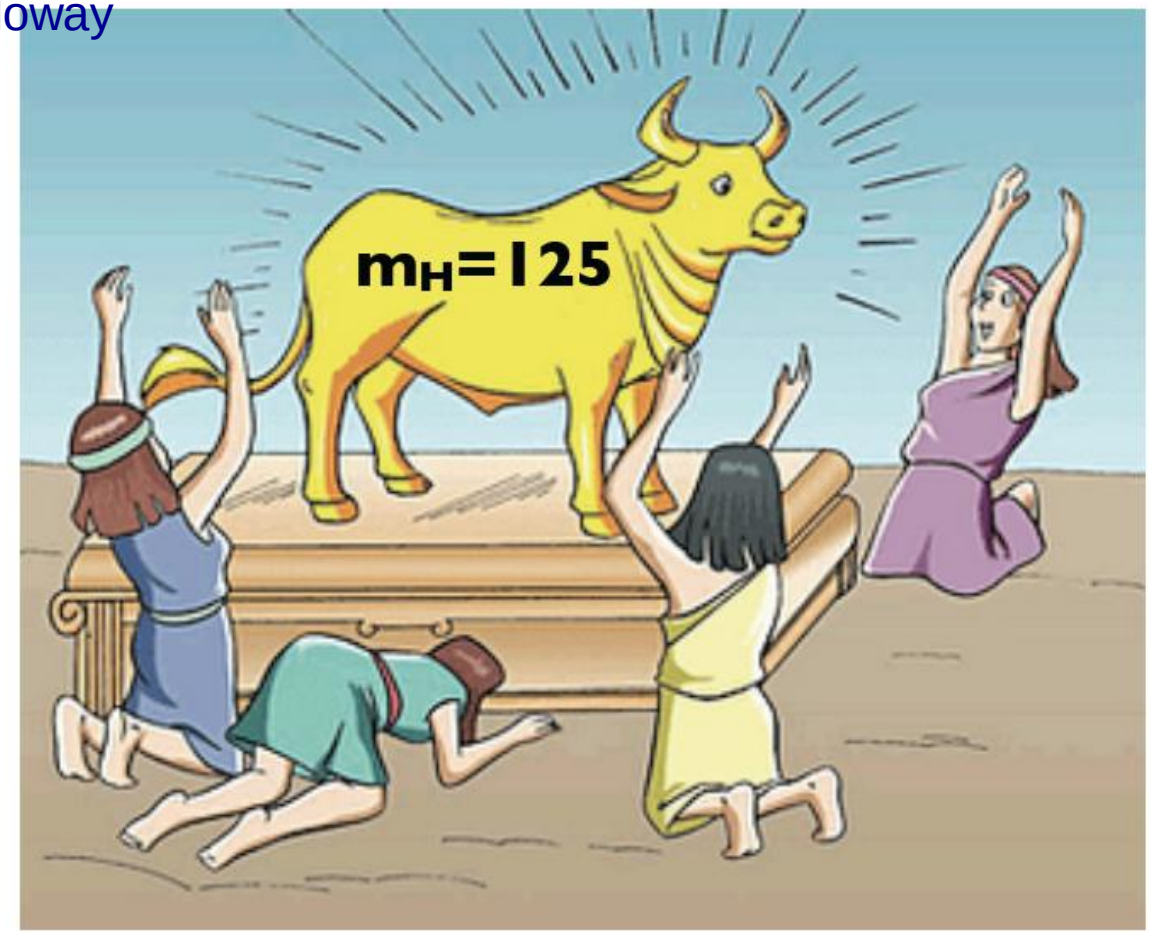


Picked up for you in the parallel sessions:

still early... lets not get carried away

J. Galloway

A. Martin



My personal comments (part II, more positive):

- The two experiments have sensitivity to exclude the existence of the SM Higgs boson over the entire mass range [114 – 600 GeV]

- But they don't ! …. and leave the same mass window open !

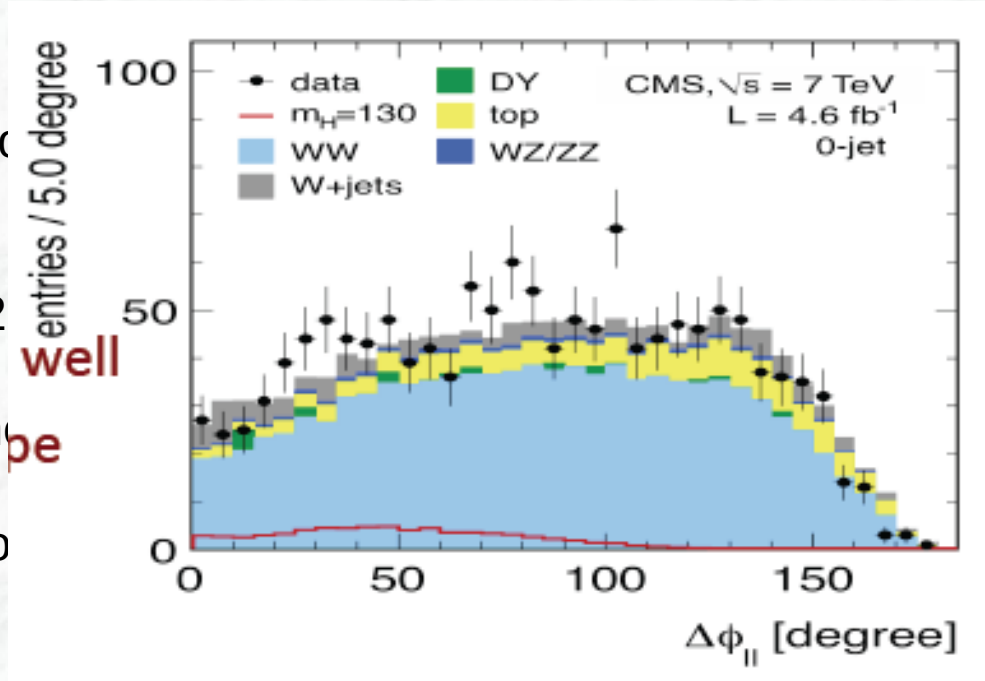
- There are interesting events in both experiments in the high resolution $\gamma\gamma$ and ZZ* channels;

  but the significances are low (in particular after correcting for the famous "look-elsewhere effect")

- The WW channel does not seem to co
  experiment
  But: - this is a challenging channel
  - this channel is not made for 12

- More data and careful analyses are n

- $\tau\tau$ and bb decay modes will come into
  (challenging as well)

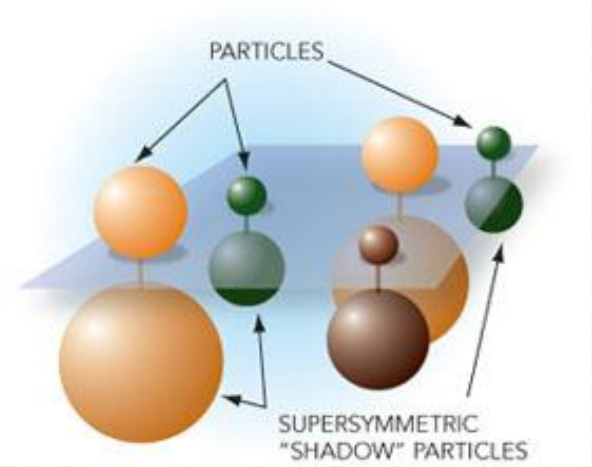


well

pe

Searches for

Physics Beyond the Standard Model



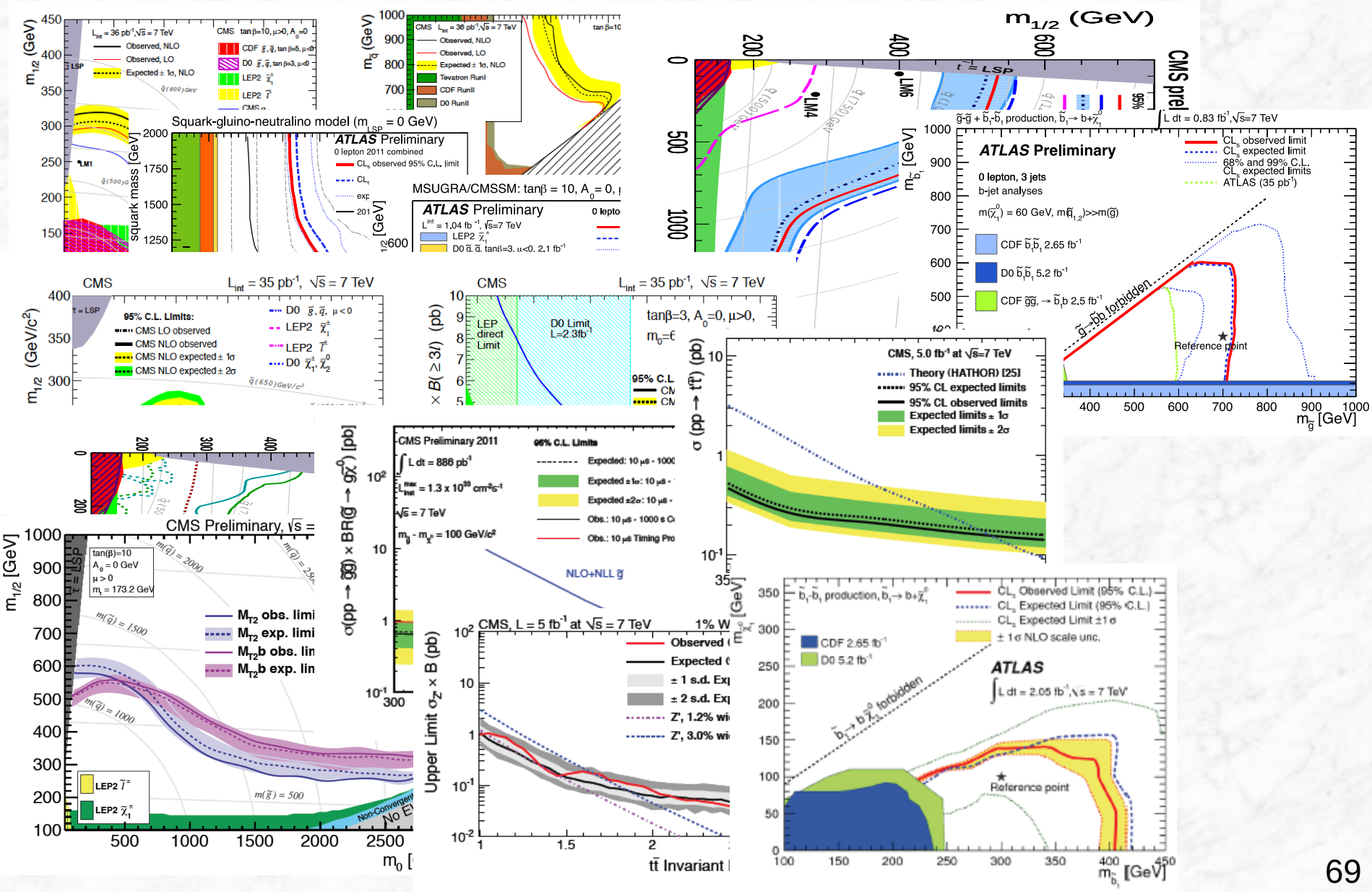
The story in short:

- Many searches, many papers,
  even more exclusion plots 95

- Nothing found …
  …. and frustration increased

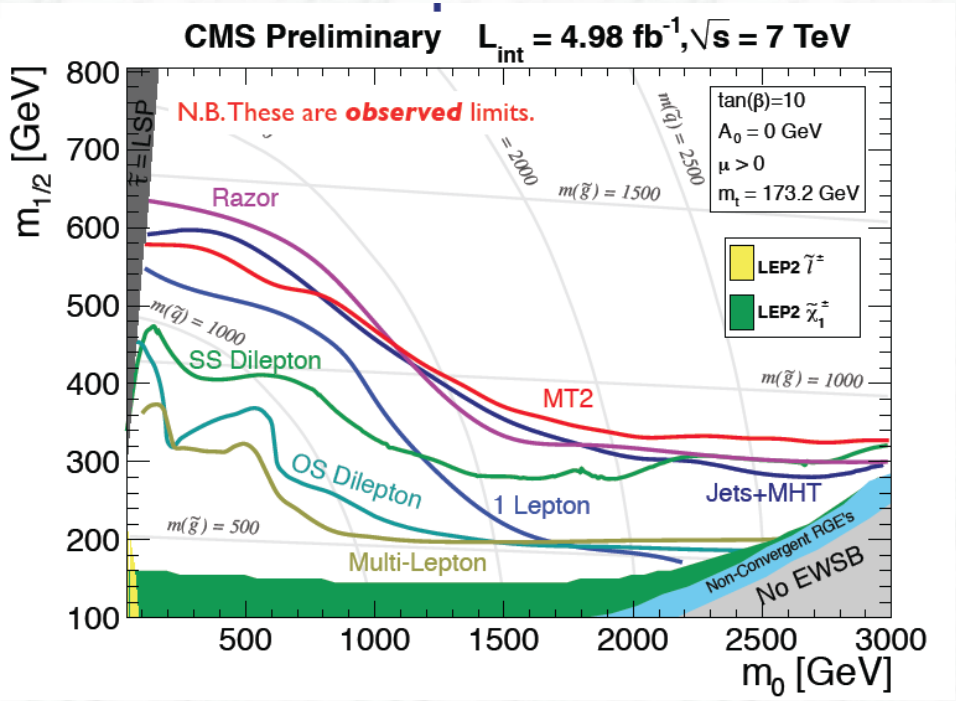
- There are not even the “Zoo” events that appeared at any collider so far

Some exclusion plots show at this conference



…. a few selected ones

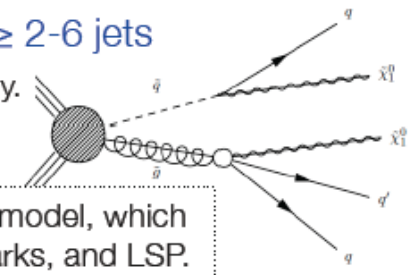
mSUGRA interpretation



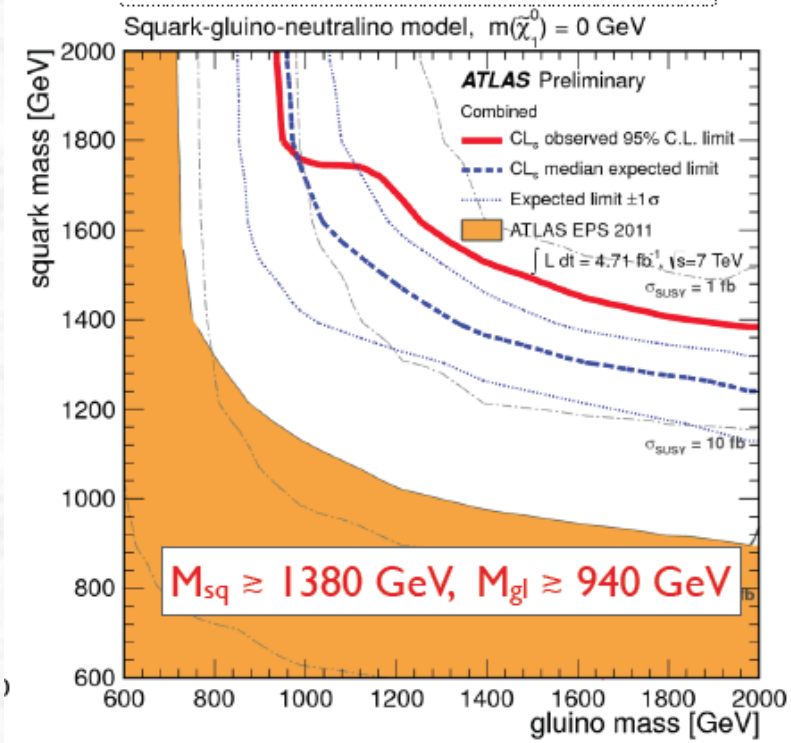
Search channels:

1. veto leptons + E_T^{miss} + ≥ 2-6 jets

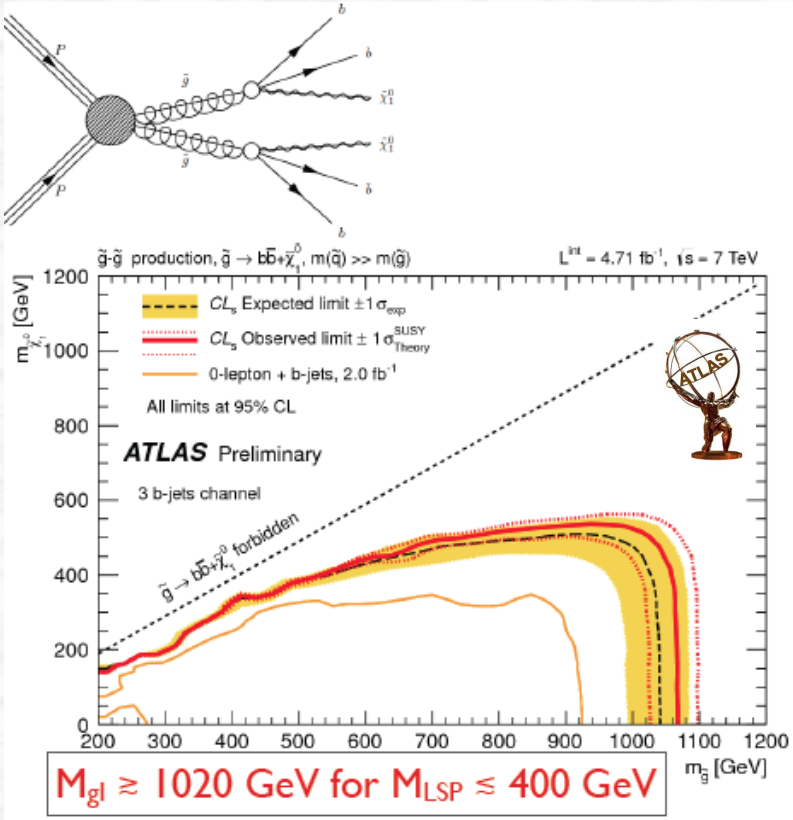
Results compatible with SM only.



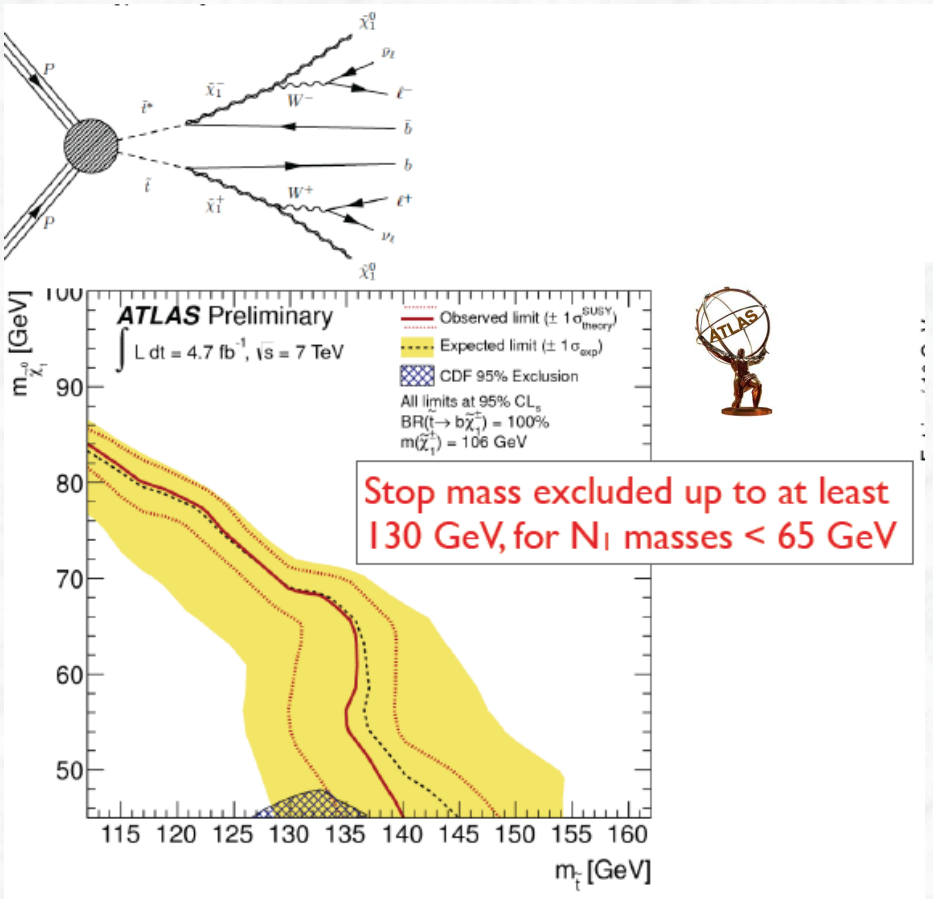
Interpretation in simplified model, which assumes only gluino, squarks, and LSP.



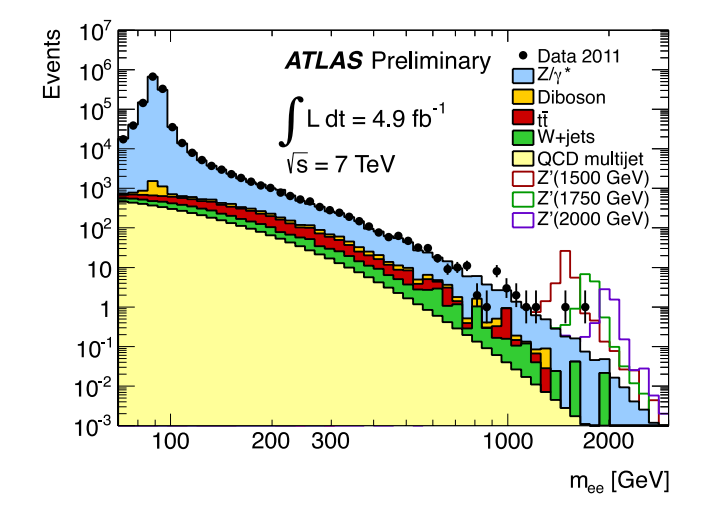
limits from 3rd generation squarks (gluon mediated sbottom production)

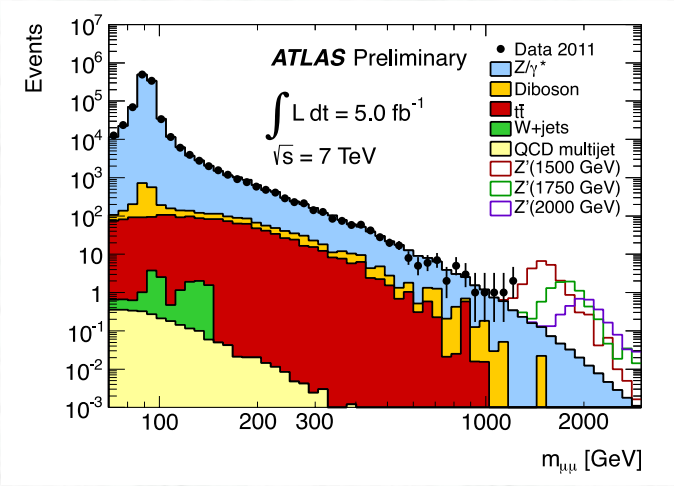


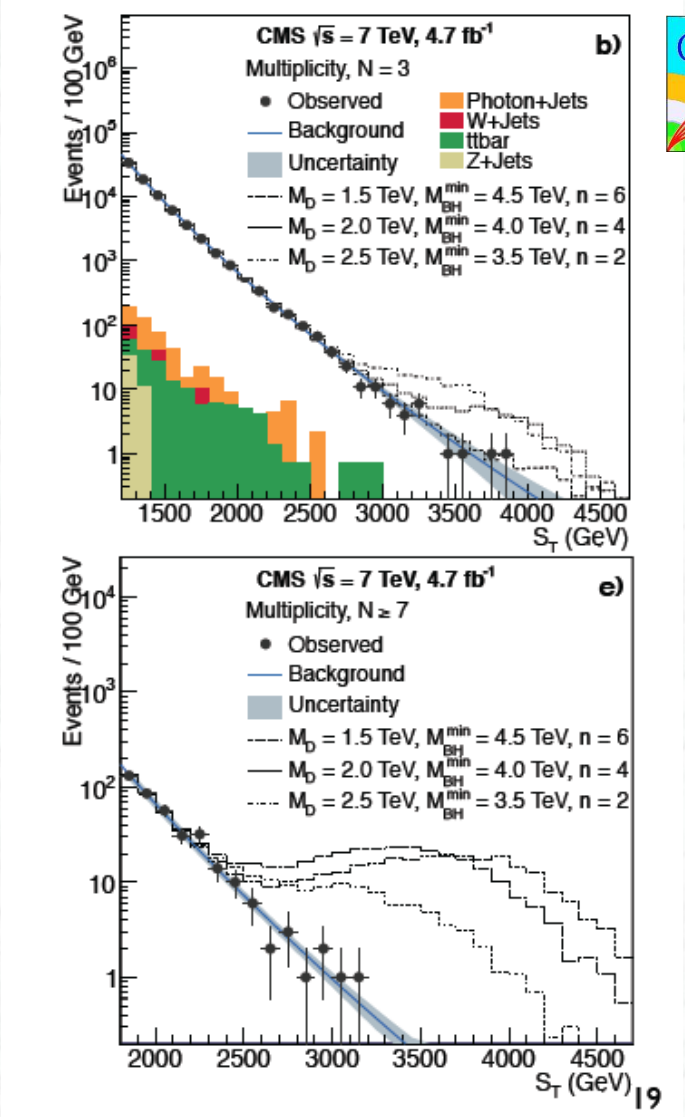
first limits on stop quarks from the LHC



… a few more selected ones (Exotics)







No Black holes (so far)

What are the main messages ?

- **“Low energy SUSY”** in its minimal version with E_T^{miss} signatures is in trouble
  - squark and gluino limits for sparticles of first two generations at TeV scale

- Limits do not hold for third generation squarks, in particular the light stop window is not yet closed

What are the main messages ?

- **"Low energy SUSY"** in its minimal version with E_T^{miss} signatures is in trouble
  - squark and gluino limits for sparticles of first two generations at TeV scale

- Limits do not hold for third generation squarks, in particular the light stop window is not yet closed

- There might be more complicated realizations of SUSY (R-parity violation, long-lived sparticles,…multileptons, …)

- Goto MMSSM, NMSSM, NNMSSM,……, NNNNNNNNNN

- We had an excellent talk on such "escape roads" by Csaba Csaki yesterday…

  and I am confident that Gian Giudice will come up with further ideas to keep the experimentalists' motivation for the search for BSM physics high

→ The experimentalists program: we will continue to study as many final state topologies as precisely as possible and confront the data to the predictions of the model that seem to survive all attacks (even those from LHCb)

2012/13 are exiting years for particle physics:

- Final word on the existence of the Standard Model Higgs boson ?
- There might be surprises in searches
  (more data, slightly higher energy, not yet looked in all corners …)
- LHCb will challenge the Standard Model at the precision frontier
- ALICE will measure more parameters of the Quark-Gluon-Plasma

THANKS to the Organizers of the Conference for the fantastic meeting !

… and to all Speakers for presenting such a wealth of interesting and exiting results !