The 2013 CERN-Latin-American School of High-Energy Physics

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LHC Results Highlights

(Lecture II: Results on Goals of the LHC Experiments)

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(Results on Goals of the LHC Experiments)

- **Results from Heavy-Ion Physics**
  - ⇒ Motivation: a new era for Heavy-Ion Physics?
  - ⇒ Particle Yields and elliptic flow
  - ⇒ Results with hard probes and EWK bosons
  - ⇒ Results from heavy-flavour probes
- **Studies on top-quark properties**
  - ⇒ Motivation: The LHC as a top factories
  - ⇒ Cross sections production
  - ⇒ Top-quark properties: mass, width, helicities, charge...
  - ⇒ Single Top production
  - ⇒ Production of Top+X
- **Searches of Supersymmetric particles**
  - ⇒ Inclusive searches of SUSY particles
  - ⇒ Searches of third-generation

Results From Heavy-Ion Collisions

Motivation and goals of the Heavy Ion Program

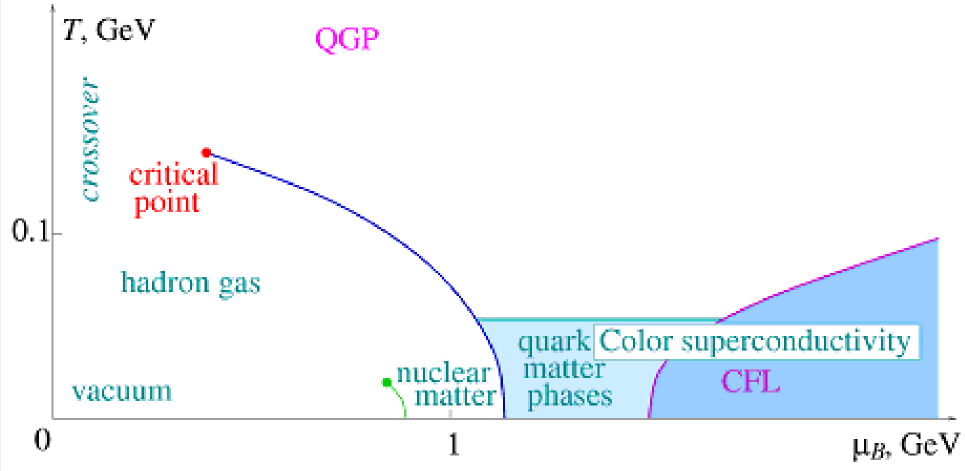
From "usual" HEP:

- **QCD is not fully proven: only well tested for low-range (parton) collisions.**
- **Concepts as confinement of free-parton behaviour are defined in practical terms, not actual dynamical properties of matter.**

The motivation to study the collisions of Heavy-Ions is to produce hot and dense QCD matter, yielding the possibility of studying matter with colour interaction.

The information from the studies allows to

- **complete the understanding of QCD: confinement, chiral symmetry,. . .**
- **get access to macroscopic/thermal phenomena from QCD**
- **get information about the early universe (∼ 10μs after Big Bang)**

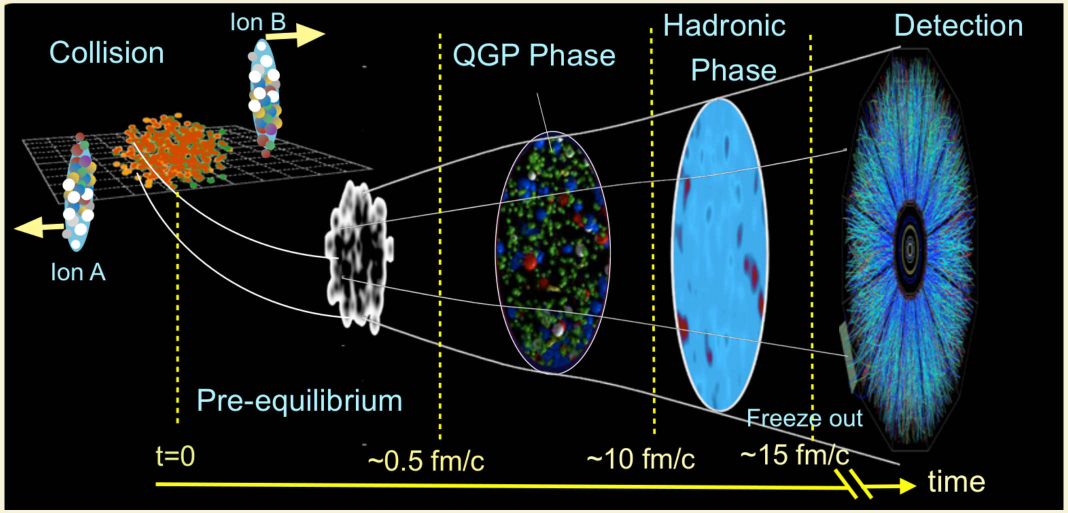


RHIC was the discovery machine: Evidences of strongly-interacting "perfect fluid"

The LHC will represent a huge step forward regarding Heavy-Ion physics due to the reach in energy and statistics: confirming RHIC results and increasing precision.

The “little bang” of Heavy-ion collisions

Heavy-Ion collisions try to get as close as possible to the Big-Bang



- Highest temperatures, density, magnetic fields, . . . ever produced
- All of it during a time of $\sim 10^{-23}$ s and a size of 10^{-14} m
- The main limitation is that the access is reduced to the detectable particles (tens of thousand).

⇒ The use of probes (specially without colour charge) produced in the very early stage of the collision helps to interpret the result.

⇒ If the main disadvantage of pp collision is how messy the initial state is, one can figure it out that Heavy-Ion collisions are even more difficult to handle.

⇒ It is very common to use pp collisions at the same effective energy to normalize.

Therefore, important to use concepts as:

– The energy per nucleon: $E_{LHC} \cdot Z/A = 2.76$ TeV for Lead @ 7 TeV

– The Nuclear Modification Factor: $R_{AA} = X/\langle N \rangle$

where X is an observable (e.g. yields), and $/\langle N \rangle$ the average number of binary collisions.

Studies based on low-p_T probes: elliptic flow

The elliptic flow is defined as **the second momentum of the azimuthal distribution of the produced hadrons.**

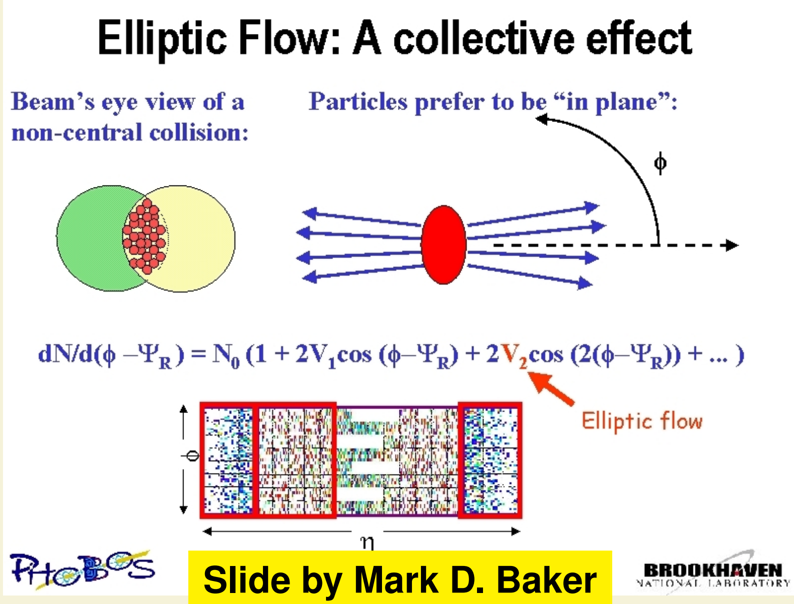
Large values of this quantity suggests **the presence of viscosity in the medium at the early times of the collision.**

These were observed at RHIC. . . and predicted (by models reasonably describing the measurements) to get larger at the LHC.

Results of the measurements with inclusive particles are:

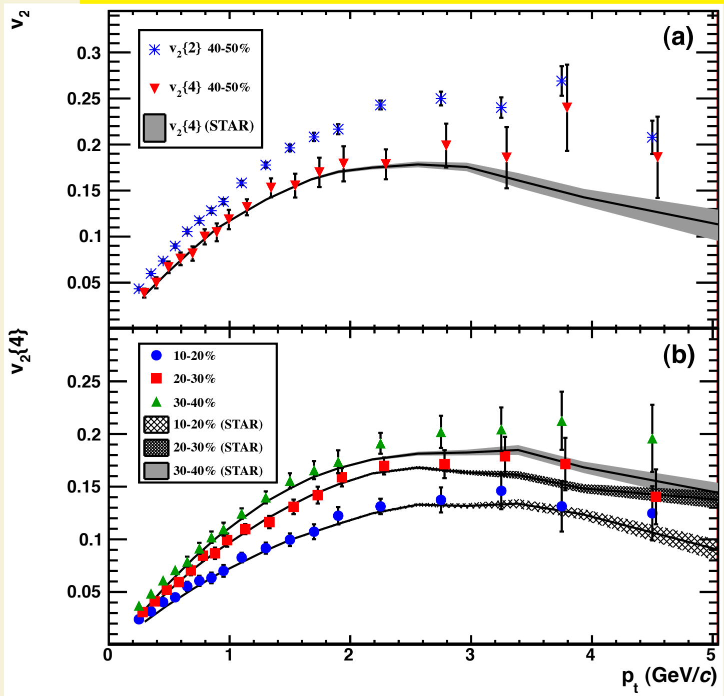
- similar to measurements at RHIC (at low p_T)
- in agreement with hydrodynamic models.

These are completed with many other elliptic-flow measurements for several species and high-p_T particles.



Slide by Mark D. Baker

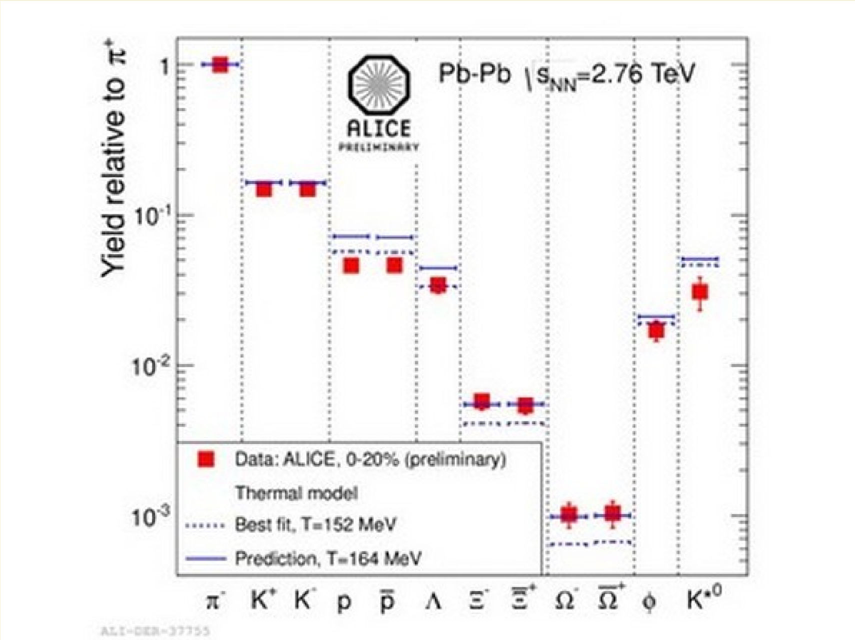
ALICE: PRL 105 (2010) 252302

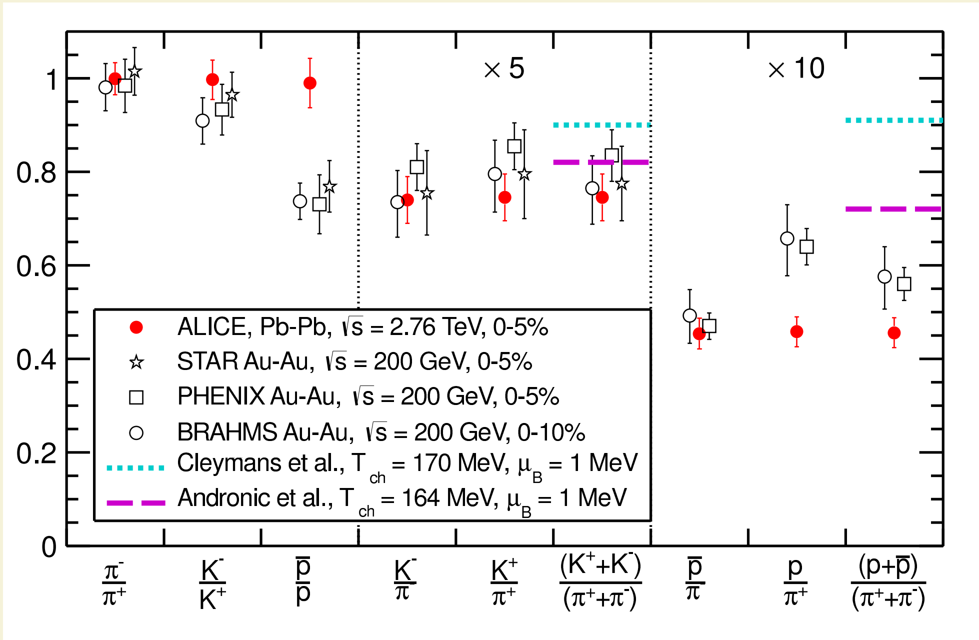


Hadron yields and ratios in Pb-Pb

Impressive set of accurate measurements for many types of particles by ALICE.

These yields are sensitive to the temperature of the medium, predicted to be 164 MeV, but measured to be better fitted with $T = 152$ MeV.





⇒ Observed a smaller ratio of p/π and Λ/π than predicted, and also confirmed when compared to measurements at RHIC.

⇒ Kaons are in very good agreement.

This factor 1.5 is a bit puzzling, perhaps due to hadronic rescattering?

ALICE also measured the elliptic flow of identified particles, which is very sensitive to the partonic degrees of freedom at early time of the collision.

Collective effects and correlations

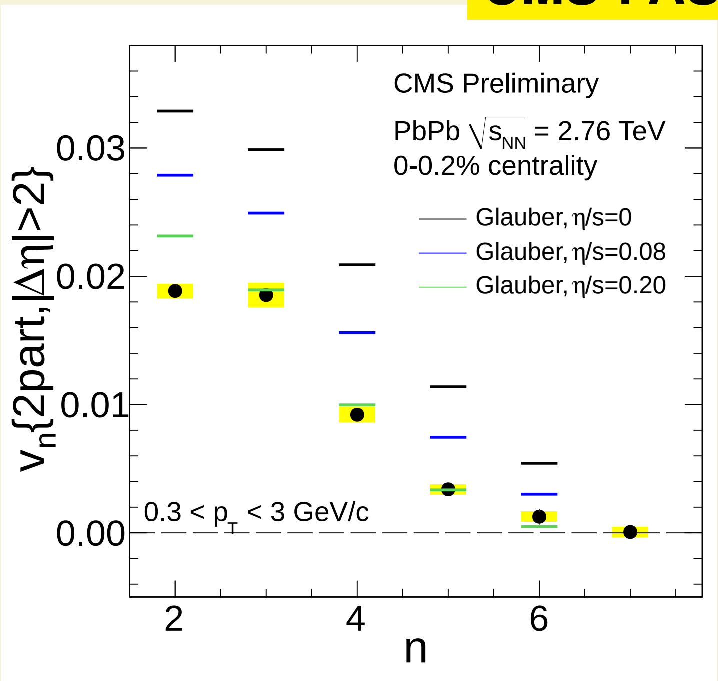
The study of the higher-order flow harmonics allows to study more detailed effects of the collective motion of the medium at the early stages.

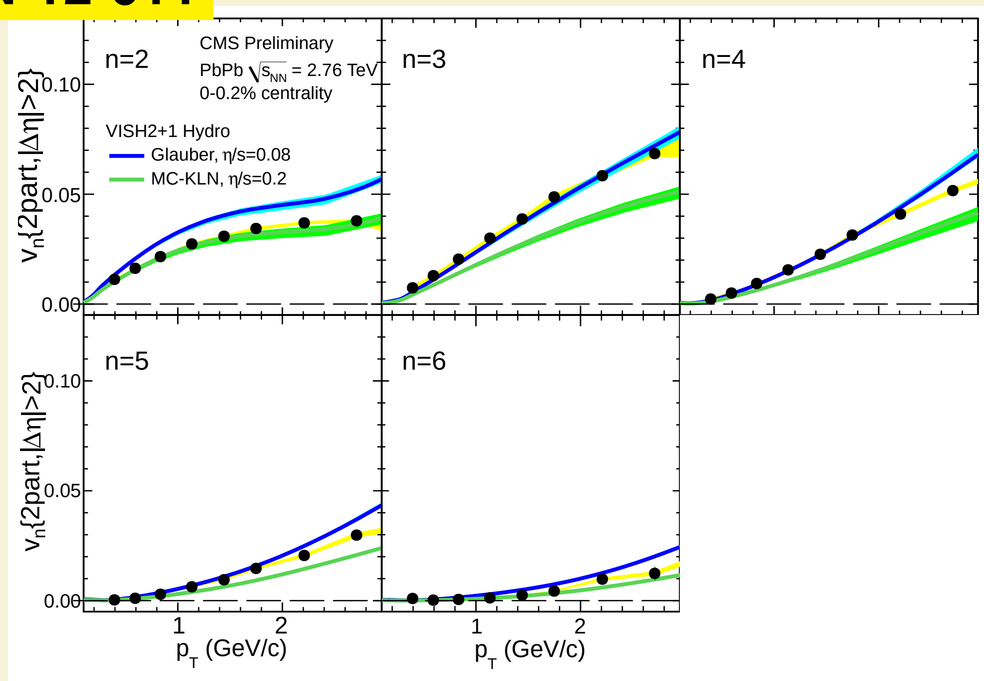
It provides strong constraints on the modeling of the medium.

CMS has meaured these harmonics in ultra-central Pb+Pb collisions (0-0.2%) using long-range dihadron correlations

- ⇒ **Use central: reduce theoretical uncertainties on initial anisotropy**
- ⇒ **Results constrains transport properties of the medium**
- ⇒ **Also ratio of sheer viscosity to entropy density**

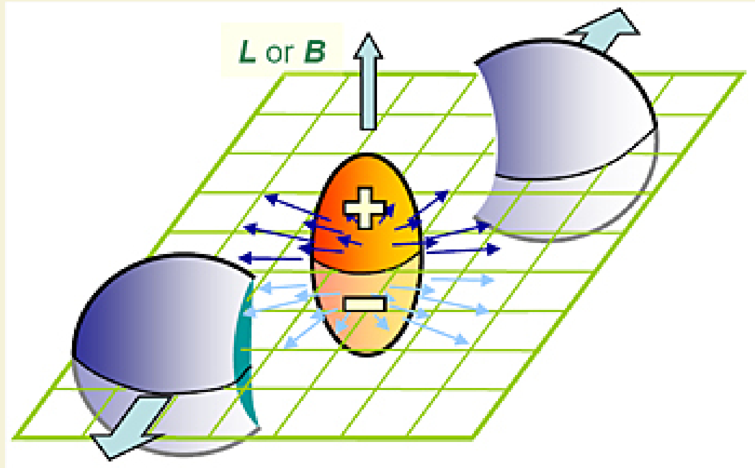
CMS-PAS-HIN-12-011





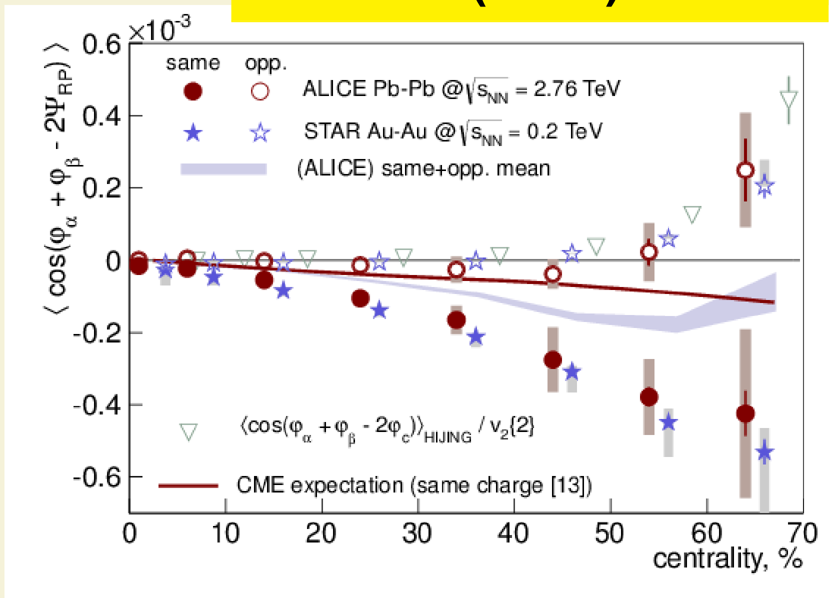
Correlations and the Chiral Magnetic Effect

Studies of the 2-particle correlations for same and opposite sign charge provide information of the Chiral Magnetic Effect (CME):



- **Induced by the magnetic field in the collision perpendicular to the reaction plane**
- **charges are separated and therefore we expect differences on correlations between same sign and opposite sign pairs.**
- **sensitive to the local parity violation in QCD: quest for the Strong CP Problem!**

PRL 110 (2013) 012301



ALICE confirms the results by STAR regarding larger correlation. Effect getting larger for less central collisions.

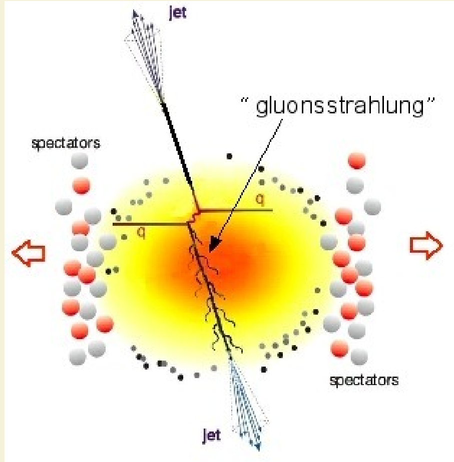
For those the event plane is better defined.

Interpretation of the results are still open due to the difficulties to get quantitative predictions.

But qualitative behaviour in agreement with CME

Due to the higher energies, the LHC offers unprecedented opportunities to study the collisions by using hard probes.

They are tomographic probes of the medium. As shown by RHIC the produced medium is opaque to the propagation of coloured particles (but transparent to colourless ones)

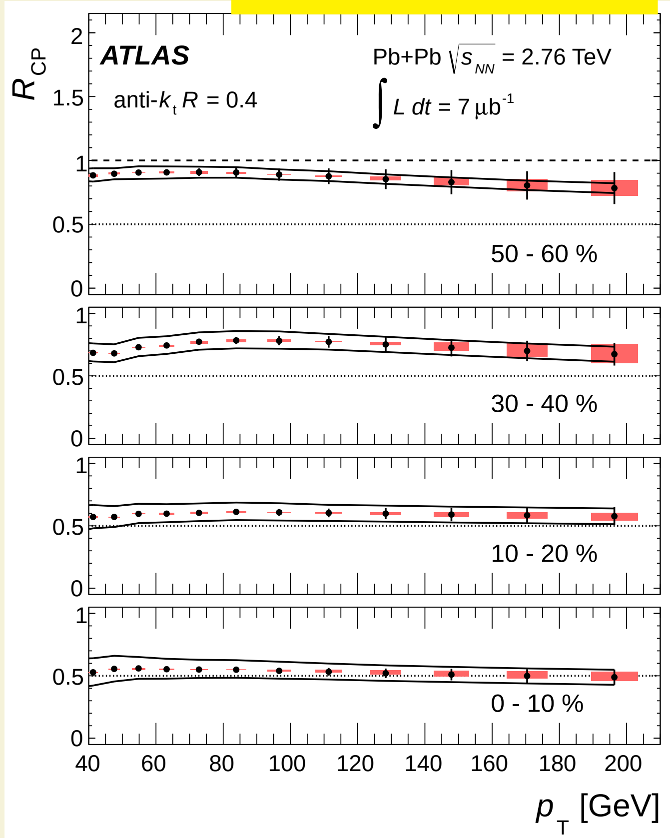


What to expect: events in which one leading jet is observed, but the other is suppressed due to assymetric propagation in the medium.

ATLAS presented the first LHC result on the topic, quantifying suppression with the central to peripheral ratio (centrality 60/80% is reference):

- Factor ~ 2 suppresion in most central collisions.
- They also observed the relative suppresion is pretty independent of the jet p_T.
- Measurement done for several R_{jet} (similar results).

arXiv:1208.1967

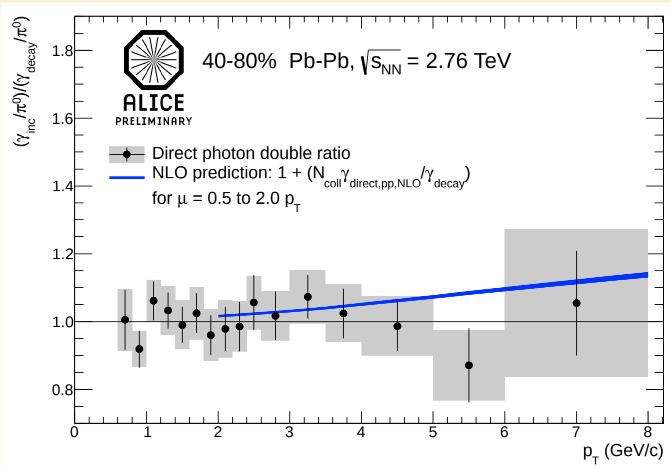


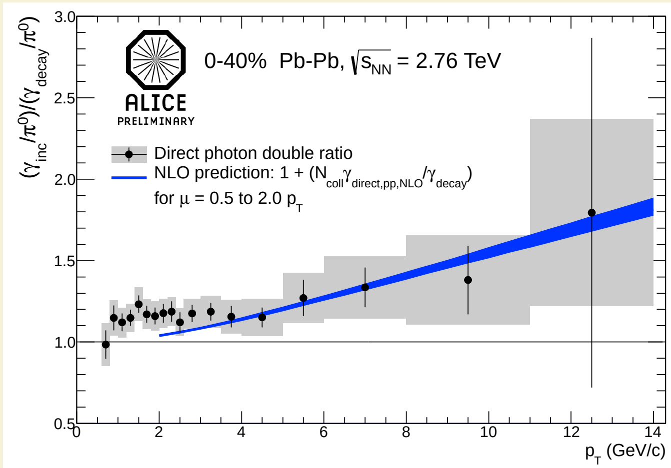
Photons as colourless probes

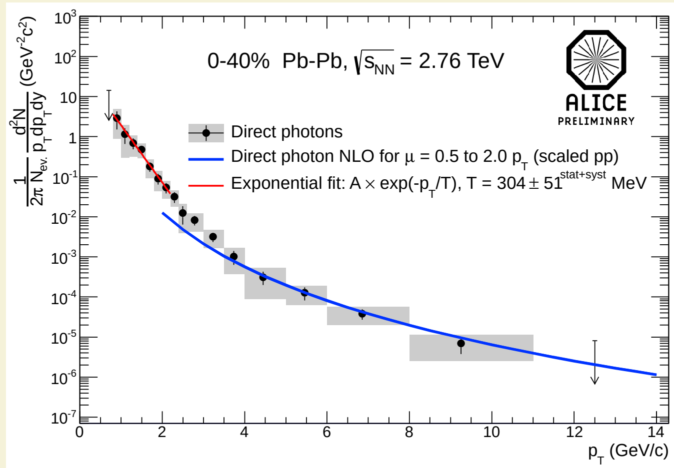
- Although the partons (jet production) gets affected by the medium, this is not the case for particles that are not affected by the strong interaction.

- Therefore we expect that colourless probes are able to cleanly cross the medium

- Photons is the most common probe, and it should be easy to identify in the detectors by means of conversions: main issue is the distinction from hadronic decays.







⇒ Low p_T region contain a large fraction of radiated photons, which seem to be produced in the thermalized medium (excess in more central collisions).

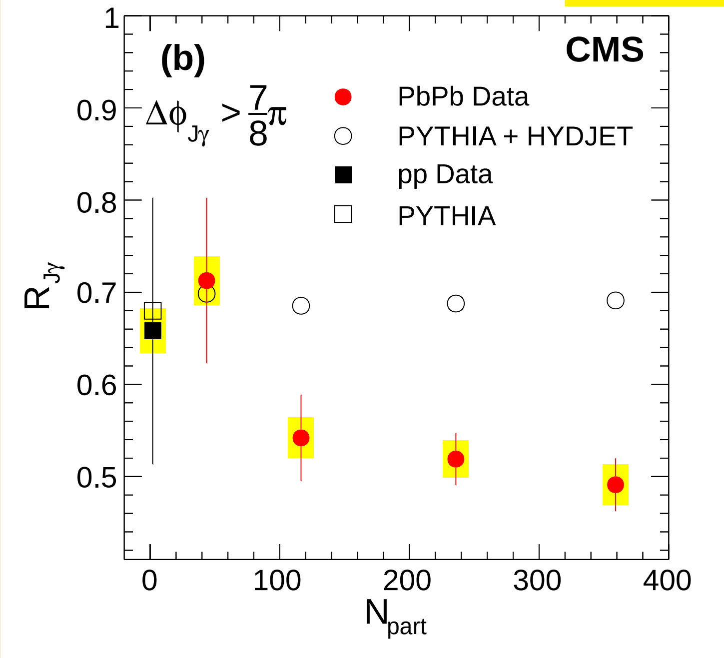
⇒ Fit to that region indicates $T = (304 \pm 51)$ MeV

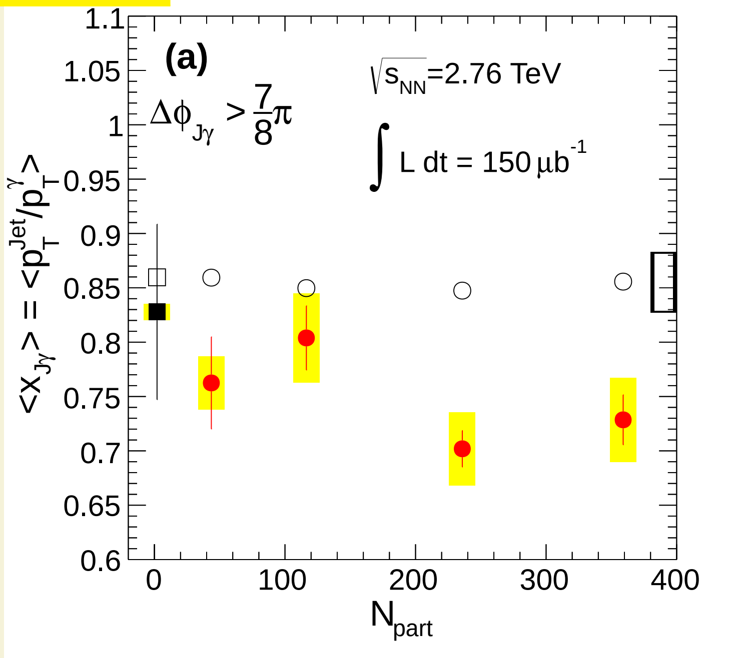
⇒ Hig- p_T region well described by binary scaling: independent of the medium!

γ+jet as probe of quenching

- Since high-p_T photons are transparent to the medium, they are perfect probes to identify jet quenching.
- Selecting events with photons ($p_T > 60$ GeV) and looking for fraction of events having a jet ($p_T > 30$ GeV) which are back-to-back with the photon.
- Also the ratio of transverse momenta.

PLB 718 (2013) 773



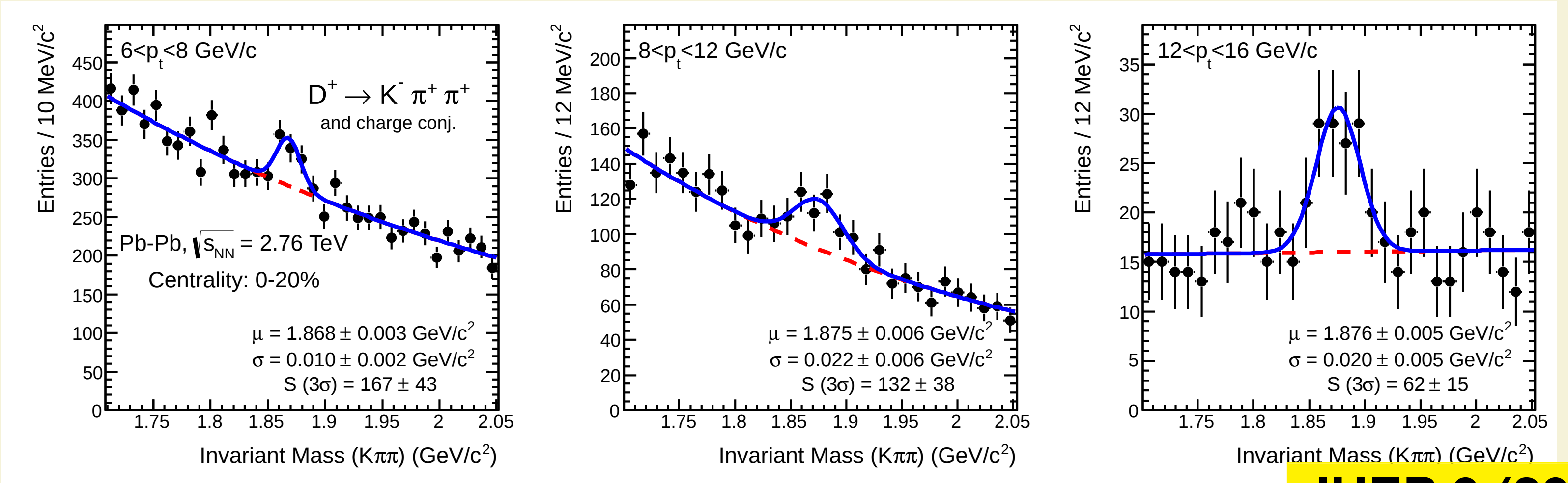


⇒ Values described by PYTHIA (with Underlying Event) for peripheral collisions.

⇒ Observed a decrease of the ratios as collisions become more central. Predictions by PYTHIA (not including parton energy loss) do not follow the trend.

Open Heavy-flavour production

- The possibility to identify heavy-flavour hadrons in the final state of Heavy-Ion collisions is also used to perform dedicated studies
- One nice demostration of the great performance of the detectors is the identification of open charm mesons (e.g. $D^{\pm}$ in ALICE).

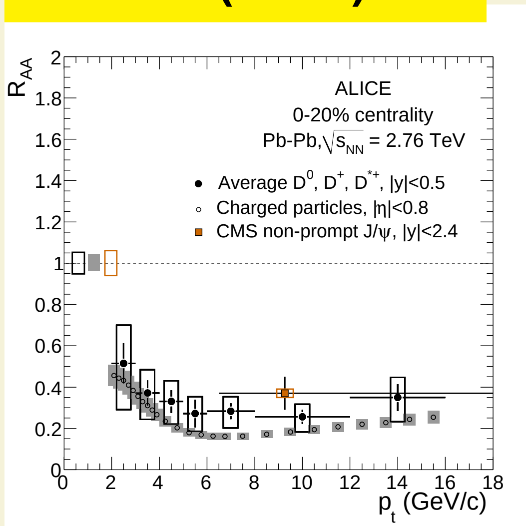


JHEP 9 (2012) 112

The open-charm mesons were used to compute the values of the scaled yield (by measuring R_{AA}) and provide a nice confirmation of the suppresion in central collisions.

In good agreement with other measurements.

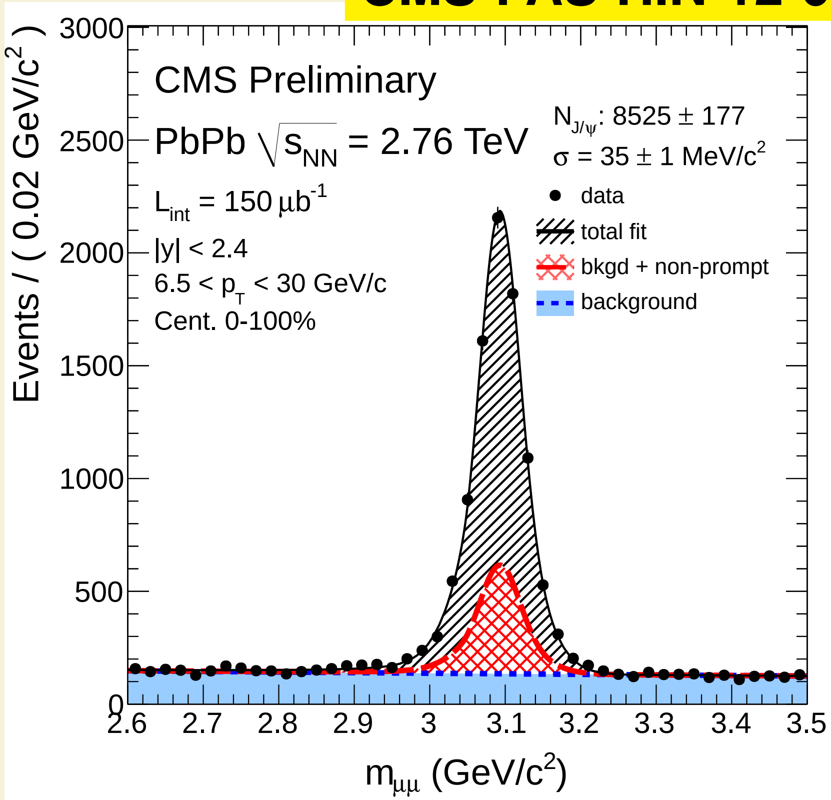
The goal is to quantify a different energy loss between (heavy/light) quarks and gluons.



Studies based on quarkonia resonances

- The possibility to reconstruct heavy-flavour mesons **extend to dilepton resonances: quarkonia states.**

CMS-PAS-HIN-12-014



- Easy to identify in dimuon decays.

- Very clean probes that are sensitive to the medium.

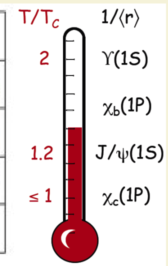
Although they are colourless, they rely on the strong force to keep the two quarks in a bound state:

⇒ Study the formation in a strongly interacting medium

⇒ Melting in the medium due to colour screening

- Since it is a screening efect, it is larger as the states are less bound.

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39



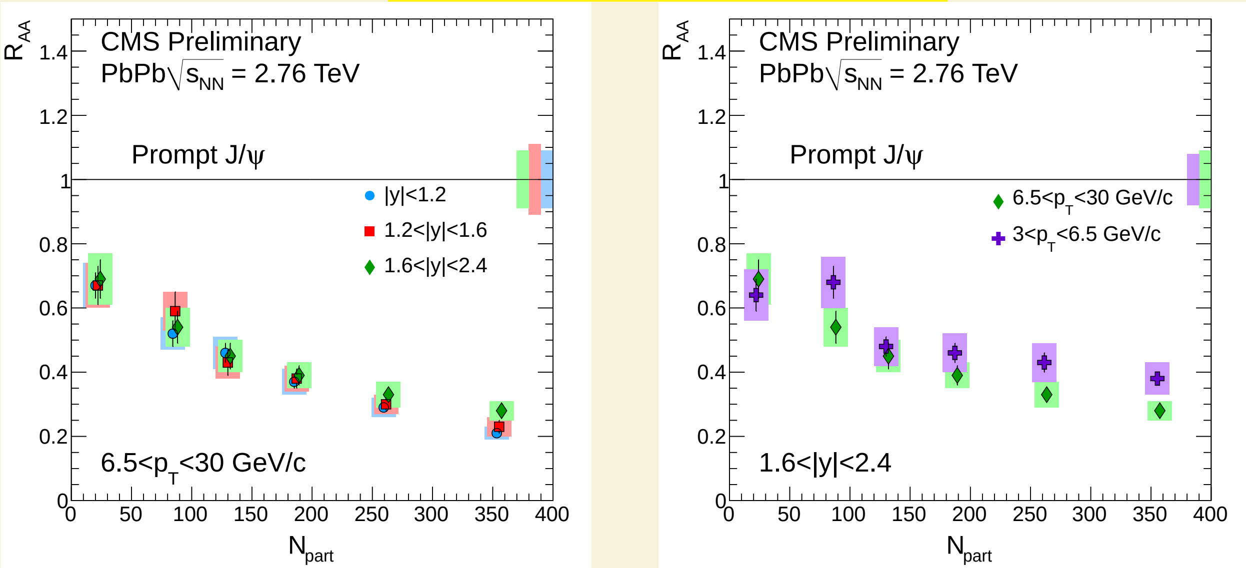
Quarkonia states serve as a Quark-Gluon-Plasma thermometer

J/ψ Suppression in Heavy-Ion collisions

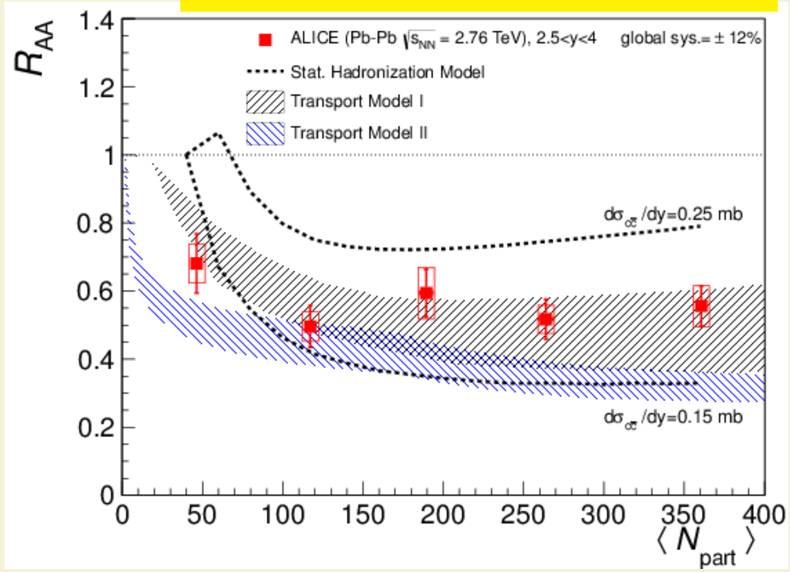
- **Collaborations looking at the quarkonia states and measuring their properties.**

- **J/ψ suppression (quantified by R_{AA}) measured in the central and forward rapidities: nice complementarity.**

CMS-PAS-HIN-12-014



PRL 109 (2012) 072301

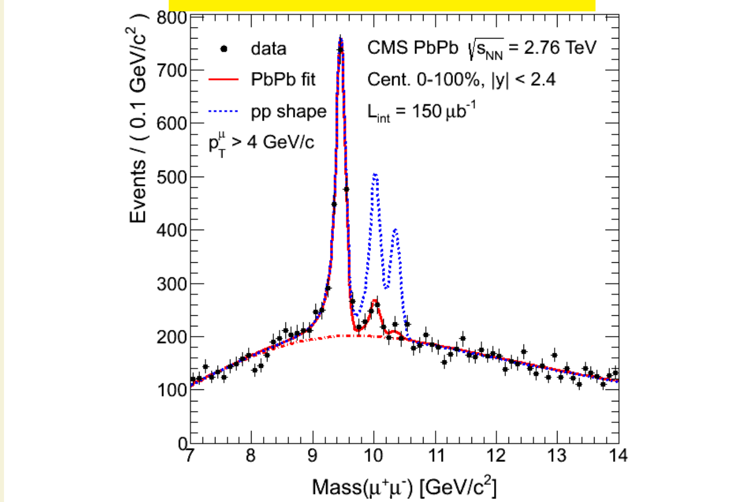


CMS observes a very dramatic suppression in central collisions. ALICE also in the forward region.

In a similar analysis, CMS observed that $\psi(2S)$ is less suppressed than J/ψ for $p_T > 3$ GeV (2σ significance). Not confirmed by ALICE.

Sequential Upsilon suppression at CMS

arXiv:1208.2826



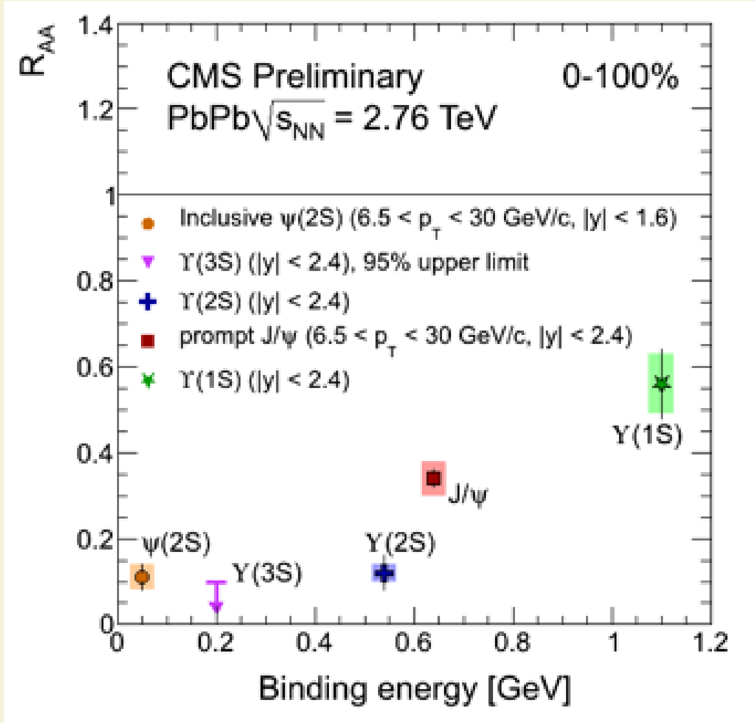
- **Additionally the suppression study is translated into the Upsilon family.**
- **Measurement shows a mass-dependent suppression of the family when comparing the Pb-Pb results with the pp at the same energy.**
- **Quantitative suppression in R_{AA}:**

  $\Rightarrow$ **Υ(1S):** 0.56 ± 0.08**(stat)** ± 0.07**(stat)**
  $\Rightarrow$ **Υ(2S):** 0.12 ± 0.04**(stat)** ± 0.02**(stat)**
  $\Rightarrow$ **Υ(3S):** < 0.1 **@ 95% CL**

- **We clearly observe the expected suppression.**

Confirmation of the sequential melting!

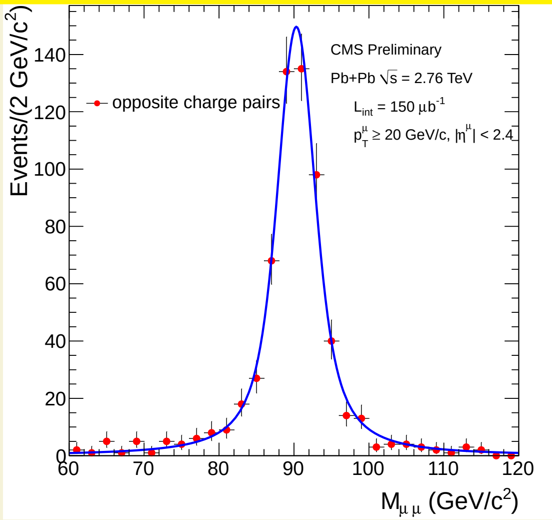
- **The qualitative picture is there and it seems to match quantitatively, but there are details which do not fully fit (yet?).**



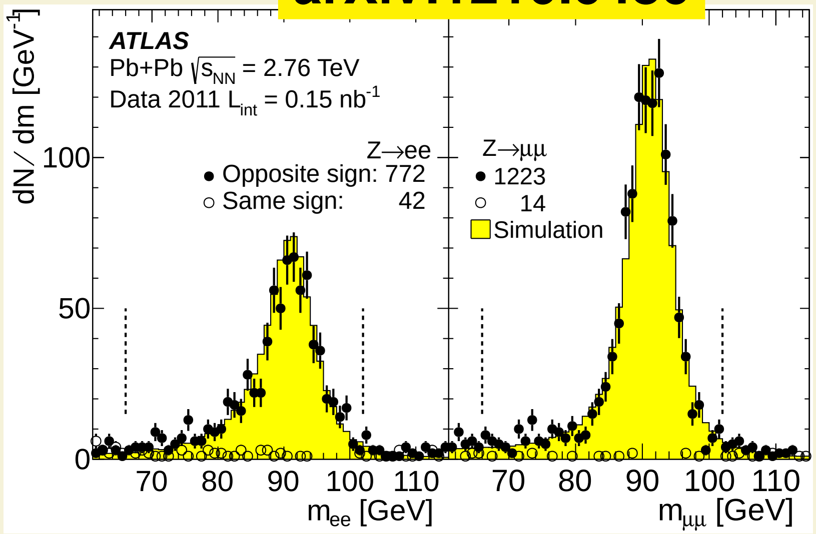
EWK-boson physics in Heavy-Ion Collisions

- **EWK bosons observed in Heavy-Ion collisions at the LHC for the first time.**
- **Very clean leptonic Z signals from ATLAS and CMS, which have already allowed first differential (in Z+jet) measurements**

CMS-PAS-HIN-2012-008



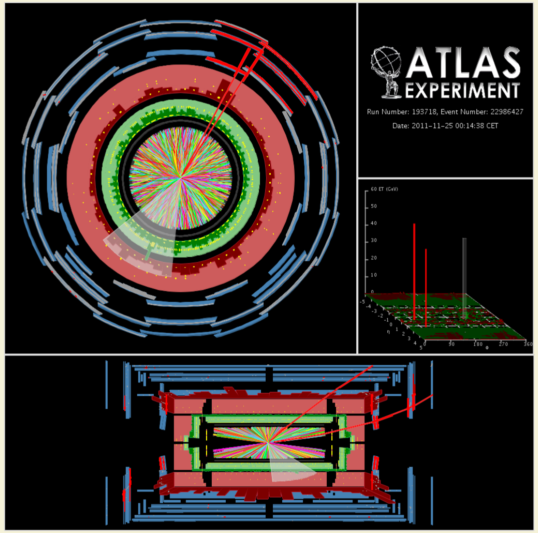
arXiv:1210.6486



- **The Z boson is a clean probe compared to photons and it is also blind to the medium.**
- **Very small effects from initial state or hadronization.**

IDEAL PROBE!

- **Looking forward to perform Z+jet precision physics in Heavy-Ion Collisions.**



$W \rightarrow \mu\nu$ production in Heavy-Ion Collisions

- Similarly, CMS has been able to isolate a sample of $W(\mu\nu)$ produced in the first data, collected in 2010.
- Selected by requiring a muon, specially with a high-p_T cut.
- Topology nicely consistent with the presence of a high-p_T neutrino.

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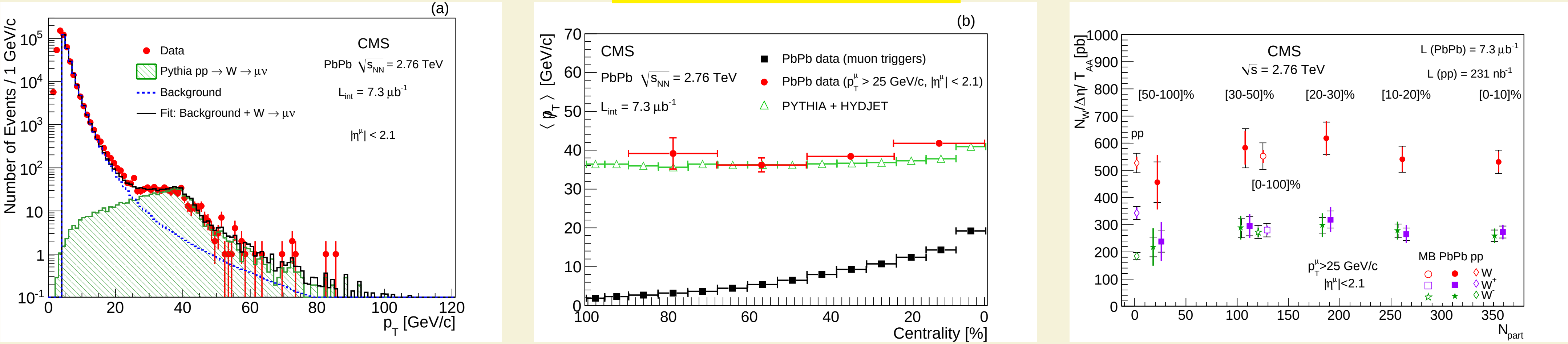
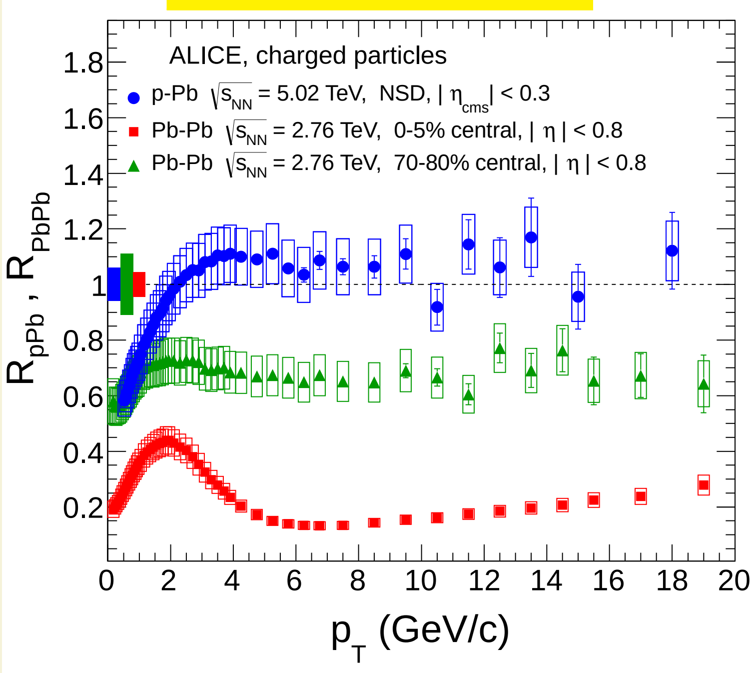


- First measurement of yields versus centralities and comparison to pp reference.
- Studies of the Isospin Effect (charge asymmetry reduced wrt pp collisions)
- $R_{AA}(W^+ + W^-) = 1.04 \pm 0.07(\text{stat}) \pm 0.12(\text{syst})$ (consistent with binary scaling)

Plans and perspectives for Heavy-Ion Physics

- Not covered the results from the run of p+pB collisions (at $\sqrt{s_{NN}} = 5.02$ TeV)
- Collected ~ 30 nb^{-1}

arXiv:1210.4520



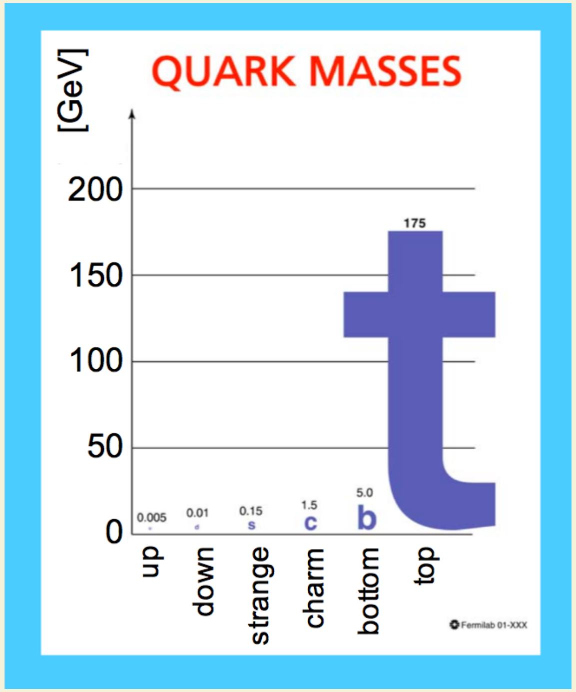
- p-Pb results are crucial to distinguish between initial (cold nuclear matter) and final (hot matter/QGP) effects.
- Very sensitive to small-x effects (QCD at high density): parton shadowing, gluon saturation,. . .
- First results (from test run) presented at HCP
- R_{pPb} ($\sim$ 1) indicates that Pb-Pb suppression (central collisions) is a QGP effect.
- The other collaborations are also presenting their results (e.g. observation of the rigdge at CMS also in p-Pb: arXiv:1210.5482).
- Preparing final results and waiting for the new data to come
- The long-term (LHC timescales) plan is well defined (discussed in third lecture)

The final goal: detailed characterization of QCD thermal matter

Results From Top Physics

The last of the quarks

- The top quark was discovered at the Tevatron Run I by CDF and DØ in 1995.

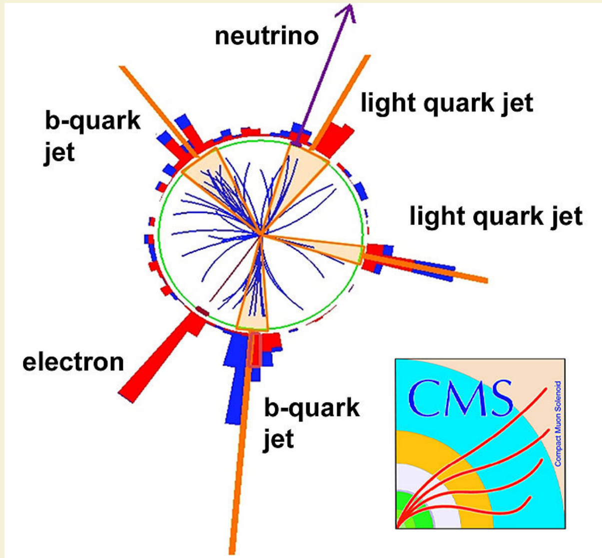


- Its big mass (173 GeV) leads to very relevant differences with respect to any other quark:
  - ⇒ It does not hadronize: it decays before that.
  - ⇒ Decay to a real W and a bottom quark 100%.
  - ⇒ Properties accesible before hadronization.

- And it also makes it the most interesting SM particle after the Higgs:
  - ⇒ Most massive fundamental object observed.
  - ⇒ Related to the hierarchy problem... and solution?

(closely attached to the Higgs mass-related issues, as fine-tuning)

  - ⇒ More sensitive to possible New Physics?
  - ⇒ Less studied charged fermion/quark



- The top quark may lead the path to Physics beyond SM at collider physics.

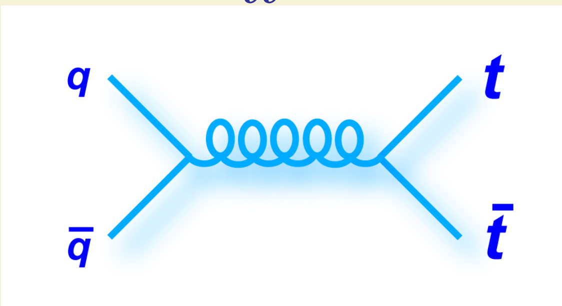
(as neutrinos are leading the path in non-collider results)

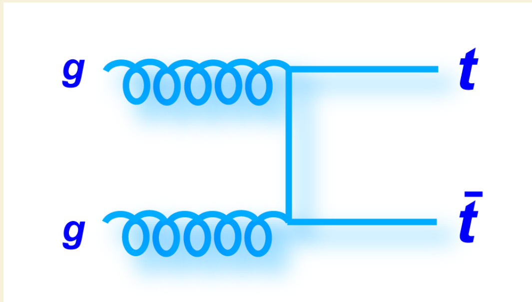
The top quark at the LHC

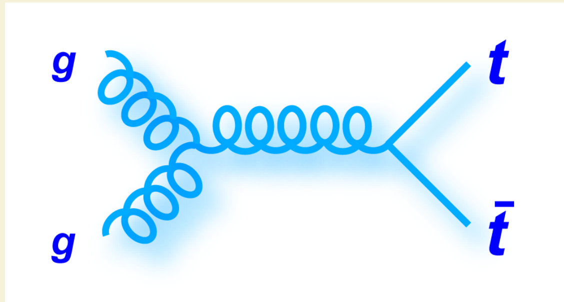
- Due to the large mass, the top quark could not be produced at any collider except the Tevatron and the LHC.

The LHC is in practice a top-factory and would allow very precise studies of the top-quark properties.

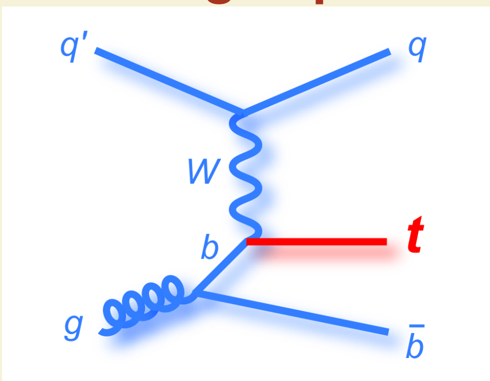
- In hadron colliders the dominant process to produce a top quark is QCD pair-production ($\sigma_{t\bar{t}} \sim 165$ pb at 7 TeV)



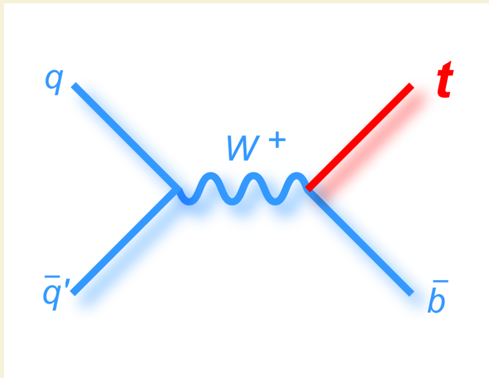




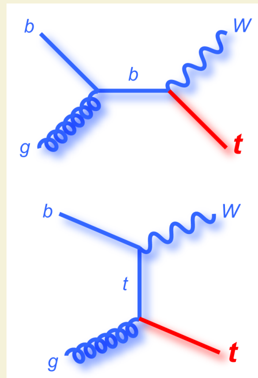
- However, single-top production is also available, but the need of weak-interation vertices has a big impact in the cross sections.



s-channel: 4.6 pb



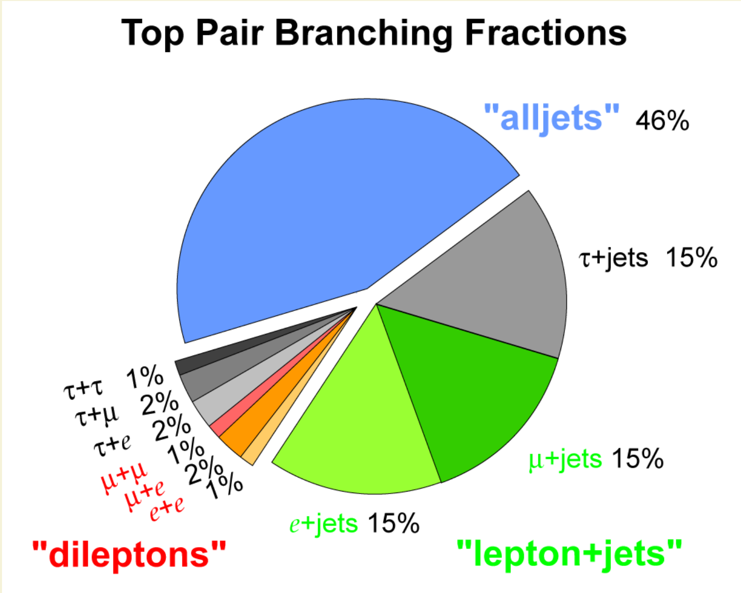
t-channel: 64.6 pb



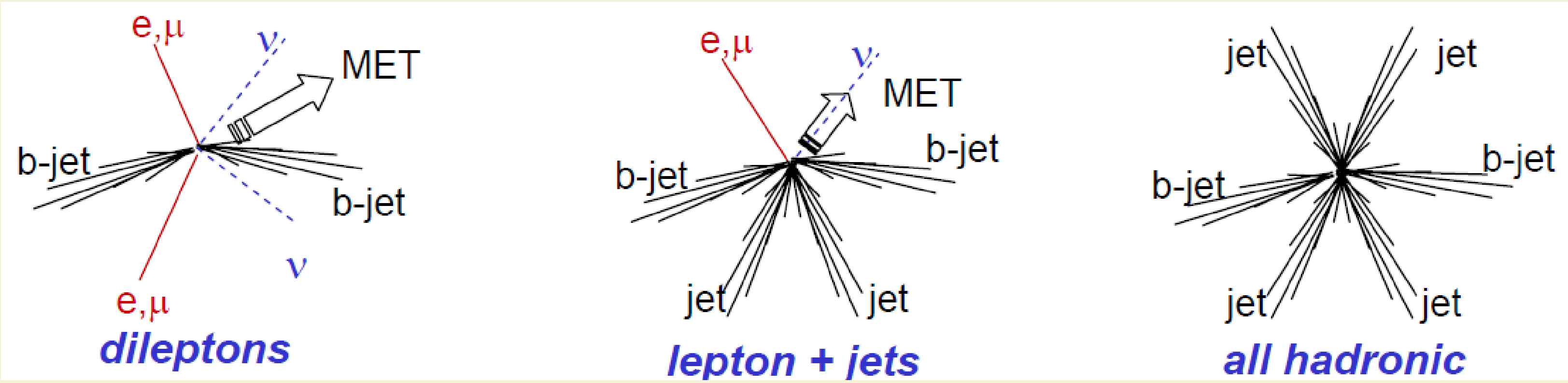
tW production: 15.7 pb

Top quark pair production at the LHC

- The cross section is so large that this is commonly one of the main backgrounds for studies of low-cross section processes (even not related to the top quark)
- So the understanding of this kind of event is needed by itself.
- Using top pair-production for general studies.



- Experimentally the studied signature is dictated by the decay of the W boson, which is well known.
- Due to trigger and selection, the number of leptons is the key characteristic.
- This yields to three kind of signatures:

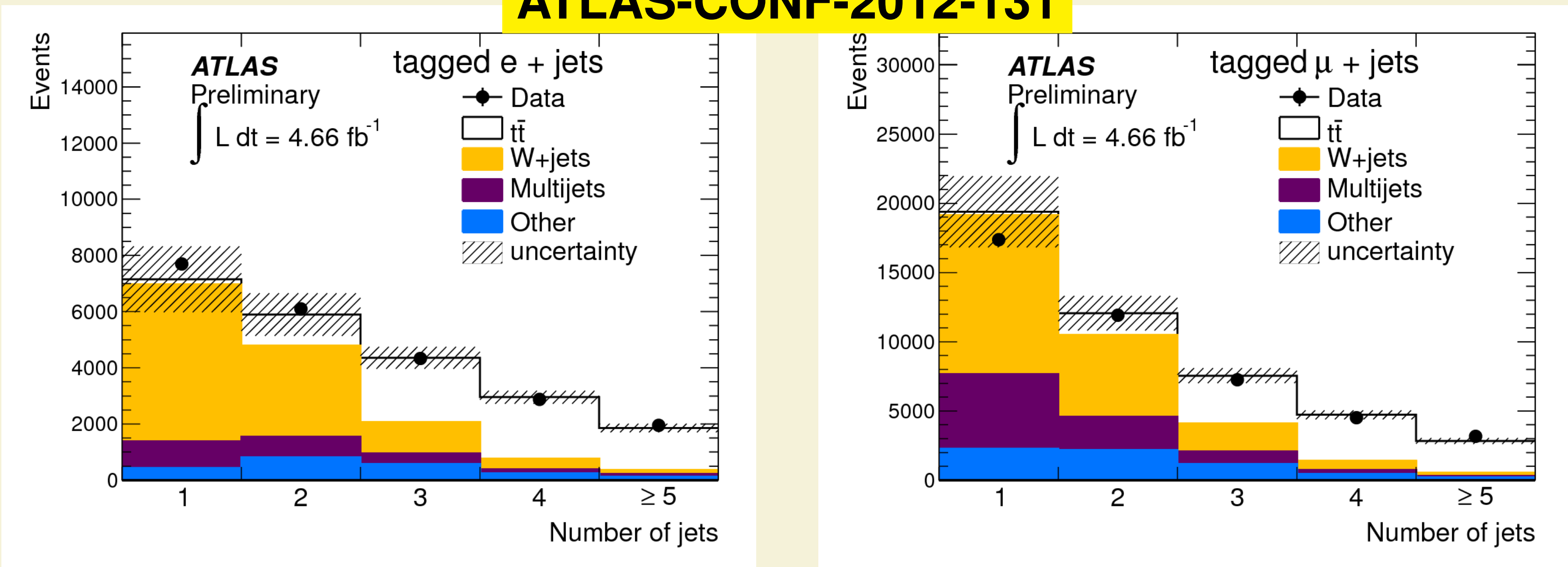


- Channels with τ are considered as a categoy by itself (and it refers to hadronic decays only).

Cross section in the semileptonic channel

- This is traditionally the most relevant channel since it
  - $\Rightarrow$ is clean enough: backgrounds are under control
  - $\Rightarrow$ has a relatively high yield.
- Note that there is the requirement of at least one b-tagged jet, in order to recude the $W + jets$ background.
- Measured in the electron and muon channels.
- Distribution of number of jets is in reasonable agreement.

ATLAS-CONF-2012-131



- Production cross section measured to be

$$\sigma_{t\bar{t}} = 165 \pm 2(\text{stat}) \pm 17(\text{syst}) \pm 3(\text{lumi})\ \text{pb}$$

τ+jets and all-hadronic channels

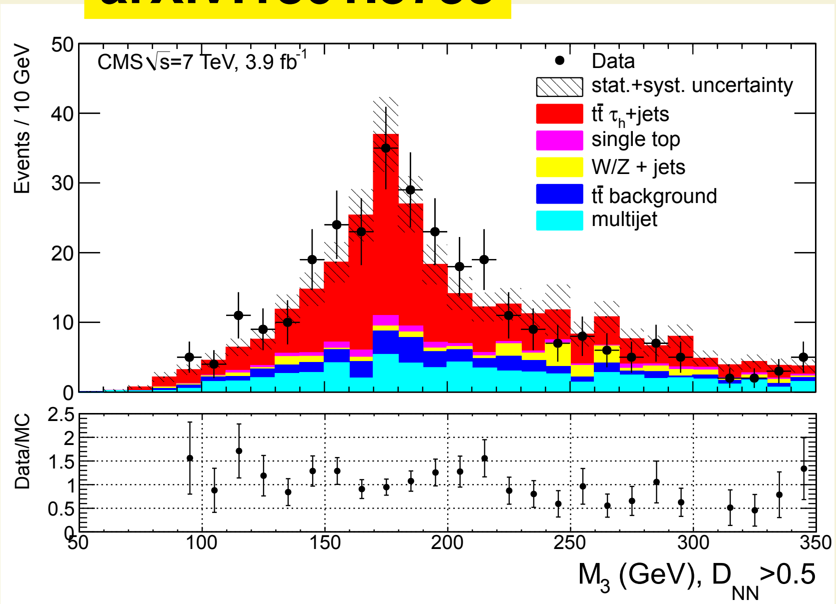
Difficult analyses and results are not precise. Not very useful for top-quark properties, but needed for getting the full picture.

τ-based channels are very important since could be the most sensitive to new physics (charged Higgs: $t \rightarrow bH^{+}(\tau\nu)$)

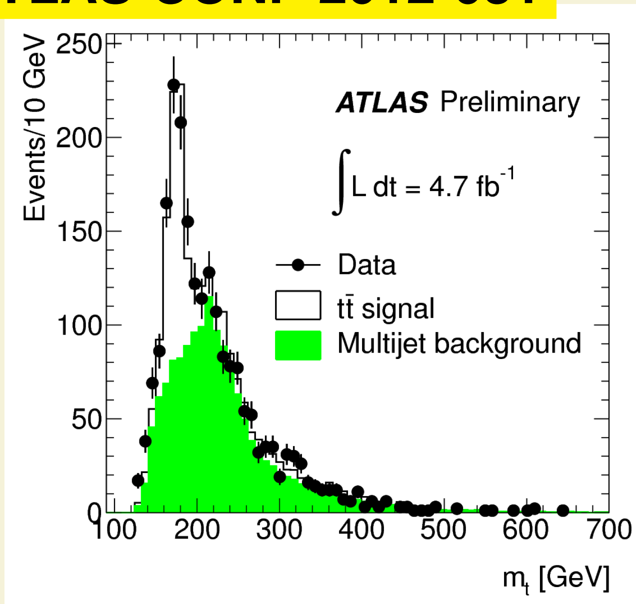
Usually completely swamped in the leptonic channels, hadronic tau is needed!

The all-hadronic channel is an important background for searches involving multi-jets (even with MET due to the semileptonic decays).

arXiv:1301.5755



ATLAS-CONF-2012-031



$\sigma_{t\bar{t}} = 152 \pm 2\text{(stat)} \pm 32\text{(syst)} \pm 3\text{(lumi) pb}$

$\sigma_{t\bar{t}} = 168 \pm 12\text{(stat)}^{+60}_{-57}\text{(syst)} \pm 7\text{(lumi) pb}$

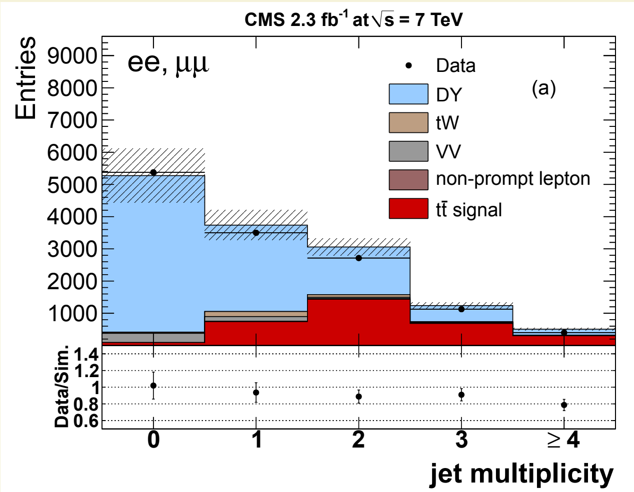
Cross section in the dilepton channel

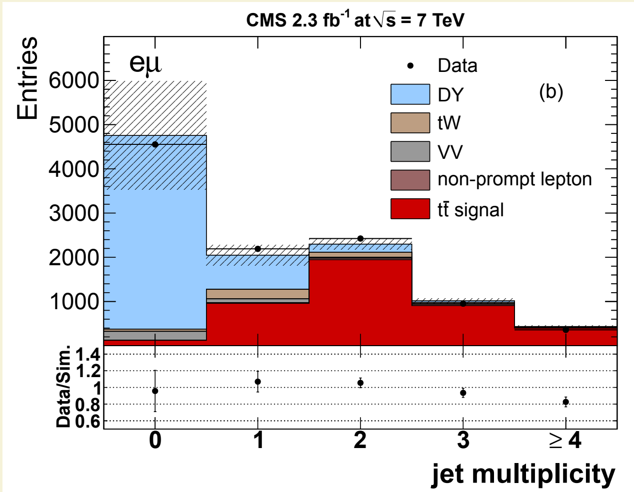
- At the Tevatron the dilepton channel suffered of the low statistics, which is no longer a problem since we have a top-quark factory in our hands.

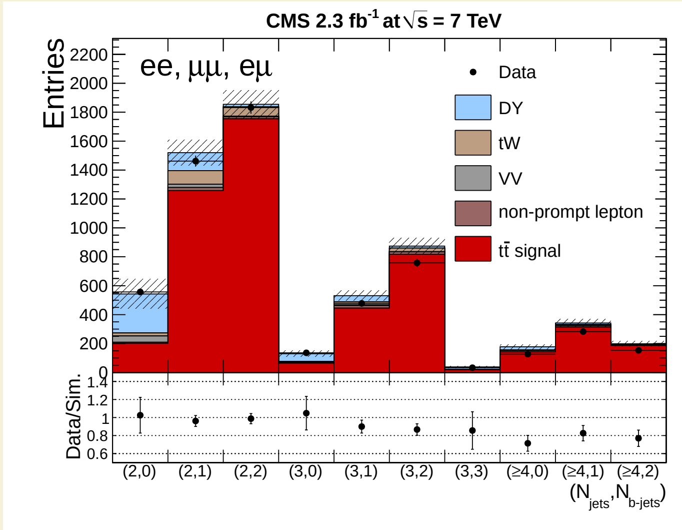
- Recent measurement by CMS using a profile likelihood method in several bins. Combining the three dilepton categories available.

- MET, jets and b-tagging requirements help to reduce the background.

arXiv:1208.2671







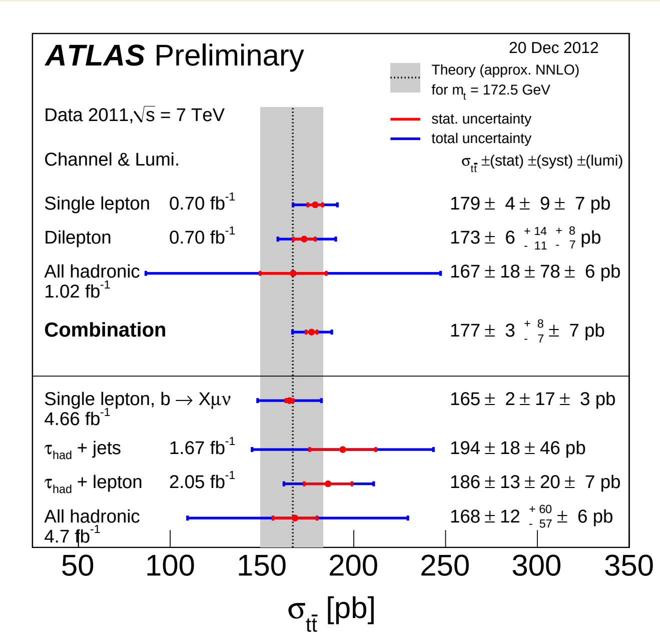
$$\sigma_{t\bar{t}} = 161.9 \pm 2.5\text{(stat)}^{+5.1}_{-5.0}\text{(syst)} \pm 3.6\text{(lumi) pb}$$

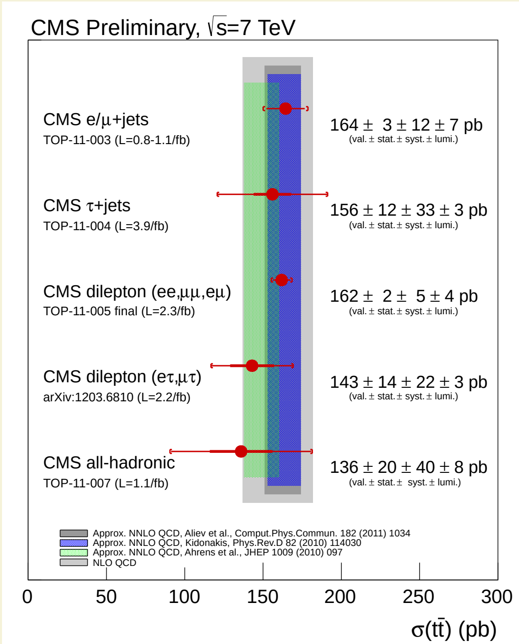
- The single most precise measurement of the cross section.

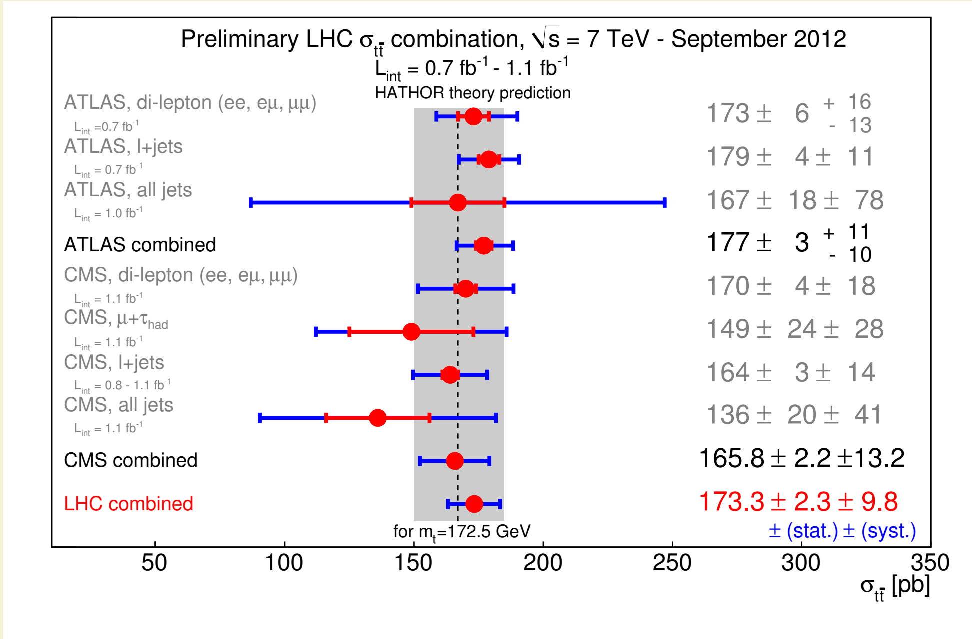
- In nice agreement with the SM prediction, for a top-quark mass of 172.5 GeV.

Cross section measurements (7 TeV)

- Several measurements in the two experiments for the cross section: combine for general usage.
- Summaries and combination of the two experiments already available for 7 TeV measurements.





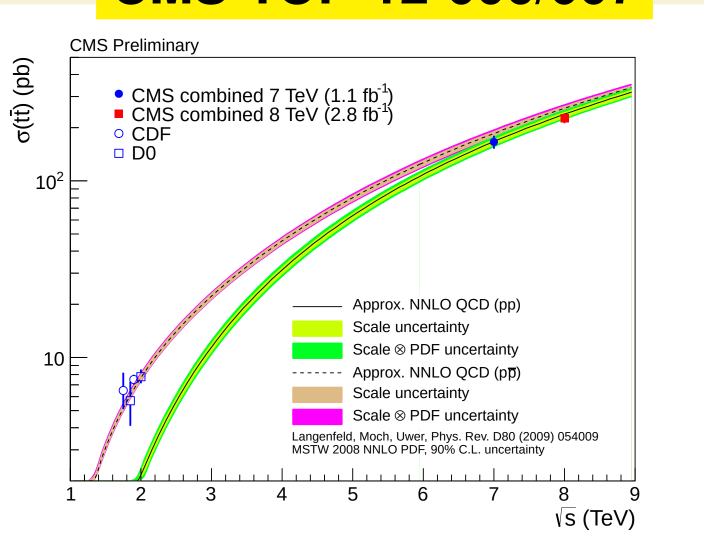


- The general picture looks ok: consistency among different channels.
- Currently working on getting similar coverage and precision with the 8 TeV dataset.
- Full combination and information about the used analysis documented in public documents **ATLAS-CONF-2012-134** and **CMS-PAS-12-003**

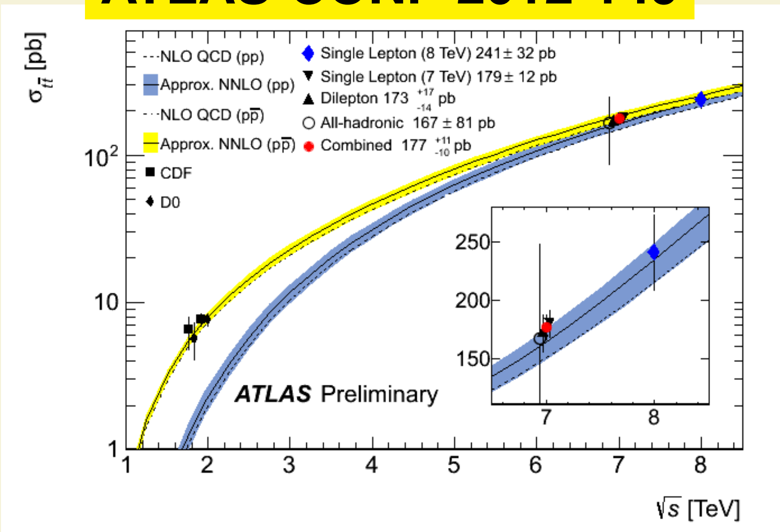
Pair production cross section at 8 TeV

- First measurements are already showing up...
- CMS has published an analysis using 2.8 fb^{-1} combining measurements in the lepton+jets and dilepton channels.
- ATLAS has a new result of lepton+3 jets using 5.8 fb^{-1} and a kinematical likelihood discriminant fit to enhace sensitivity to the signal events.

CMS-TOP-12-006/007



ATLAS-CONF-2012-149



Apart from the interest of the measurements at different energies, there is the plan to measure the ratios of cross-sections at different energies.

And even double ratios, by adding the Z production cross section as normalization.

These enhance the sensitivity to New Physics.

Measuring α_s from top-quark pair production

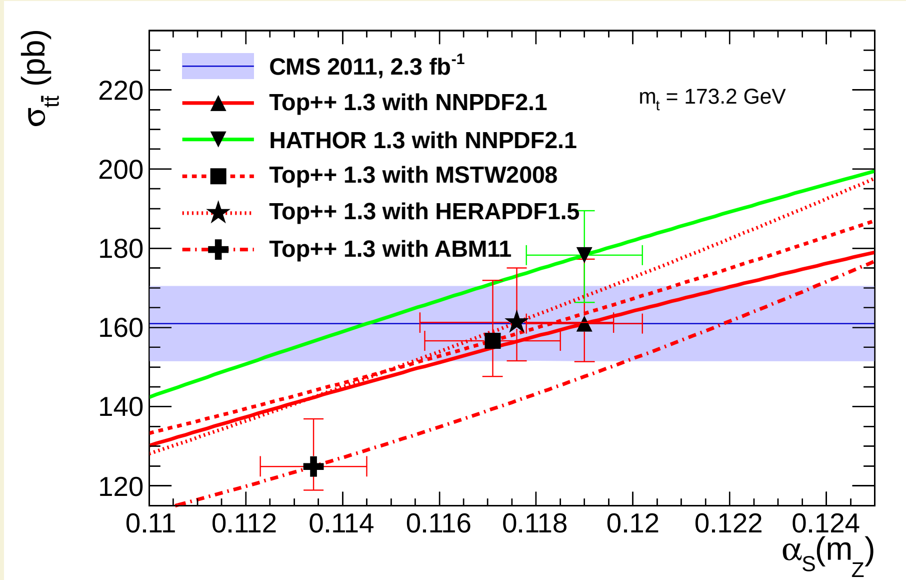
- **With part of the dataset taken at 7 TeV, CMS has performed a determination of α_s from the top-quark pair production.**

- **A proof that we are now in a different era for Top Physics: not only precision, but reference for SM measurements.**

- **Using approximated NNLO calculations**

- **CMS dilepton cross section at 7 TeV**

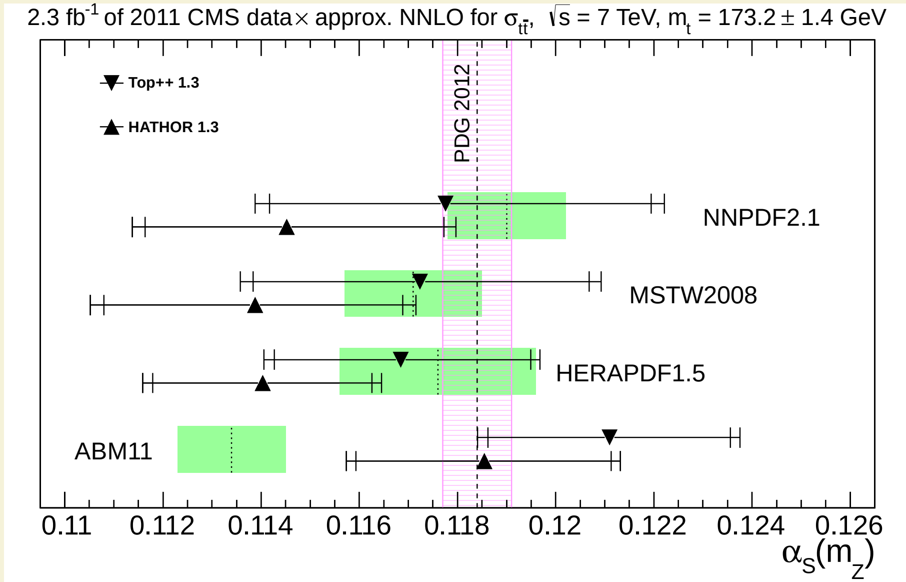
- **Taking $m(t)$ from the world average.**



Note that the calculation by HATHOR is systematically lower due to theory approximations (that predicts larger $\sigma_{t\bar{t}}$ for same mass).

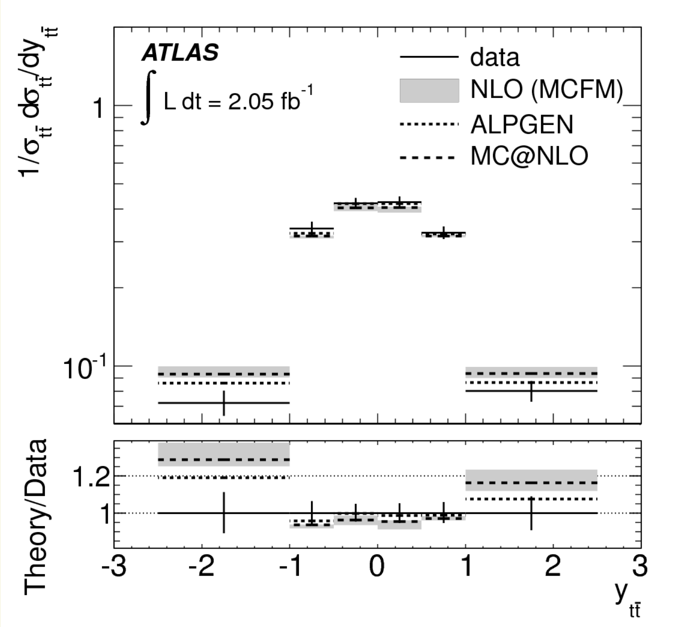
The obtained value is:

$$\alpha_s(m_Z) = 0.1178^{+0.0046}_{-0.0040}$$

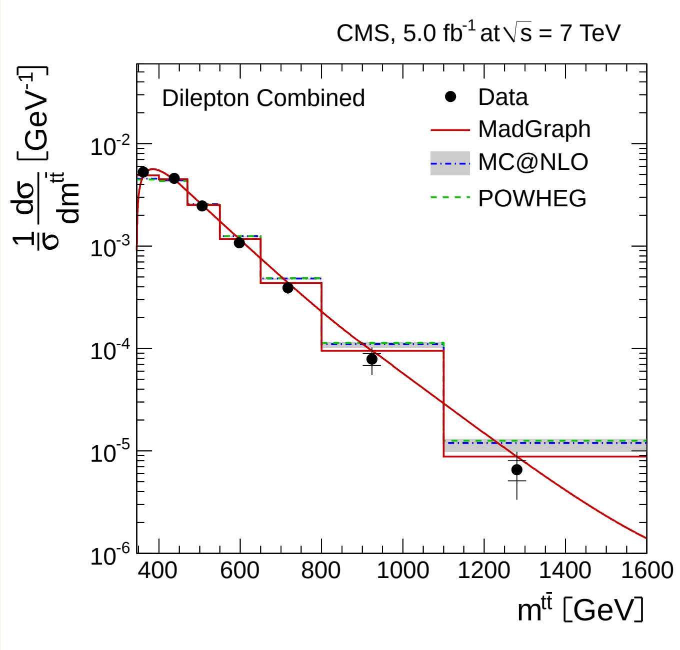


Competitive because it is determined from an energy regime that has been accessible to only a small number of measurements.

Differential cross sections (I)



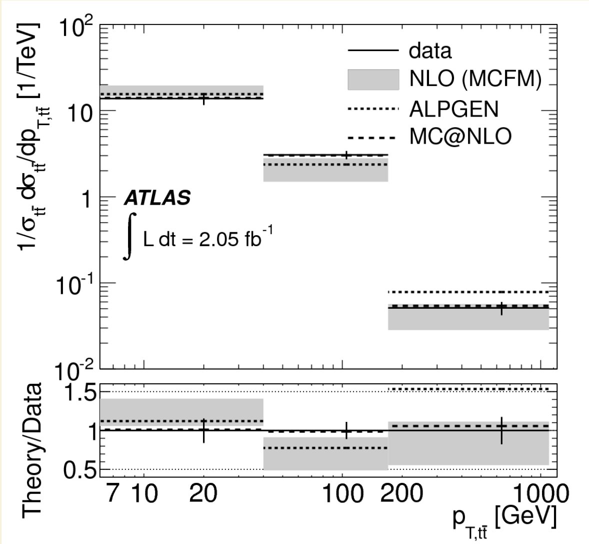
- The large sample of top-pair events allows to perform detailed studies of the production process.
- Specifically, it is possible to study the differential cross section distributions:
  - ⇒ More stringent test of theory and MC models
  - ⇒ Would allow to reduce systematics on modeling
  - ⇒ Improve background estimation in searches
- Measuring unfolded (parton or hadron) cross sections to simplify the comparison with theory and between experiments.
- Results described in **EPJC 73 (2013) 2261** for ATLAS and **arXiv:1211.2220** for CMS

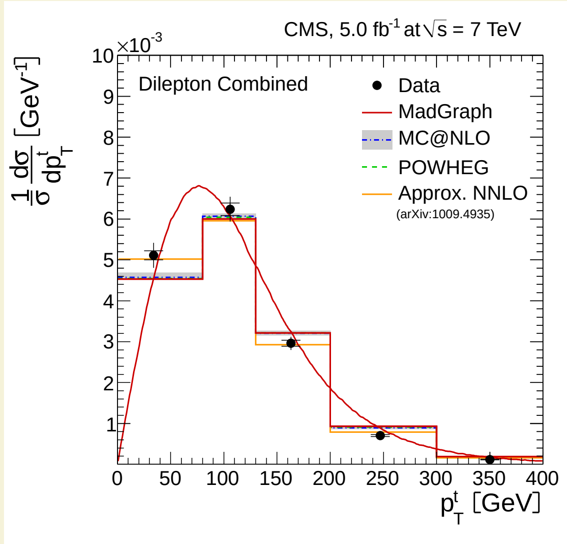


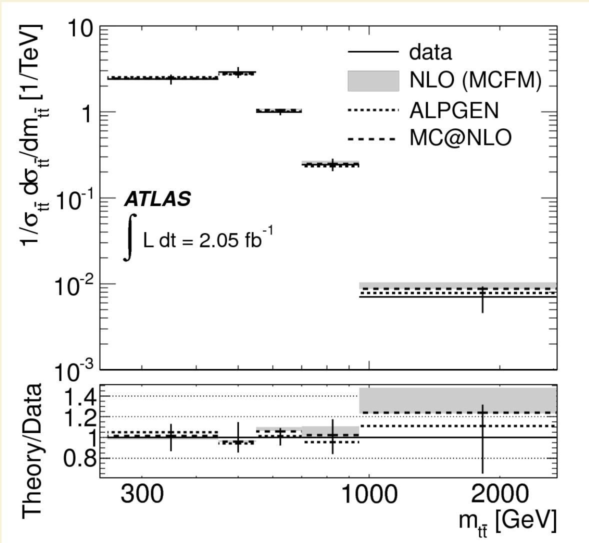
- One of the most interesting distributions is the invariant mass of the produced top-quark pair.
- Sensitive to the presence of resonance decaying into a top-quark pair.

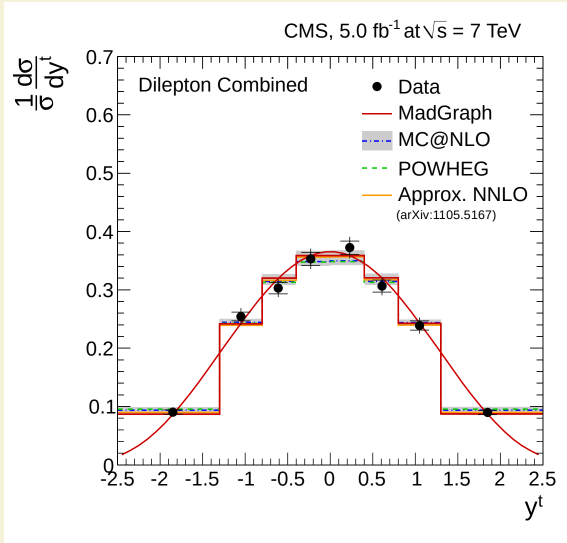
Differential cross sections (II)

- **More distributions from the same papers:**









⇒ Good agreement with the theory and MC-based predictions.

⇒ No significant deviation from SM and good work by MC.

Measurements of the top quark mass

- Since the discovery of the top quark, the measurement of its mass has been a complete priority: a key (and puzzling!) parameter of the SM.
- Several measurements already performed at the LHC, using different techniques and datasamples.

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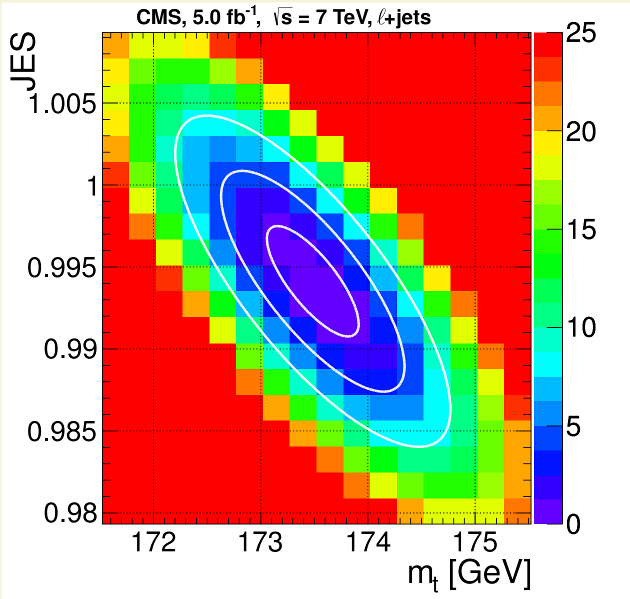
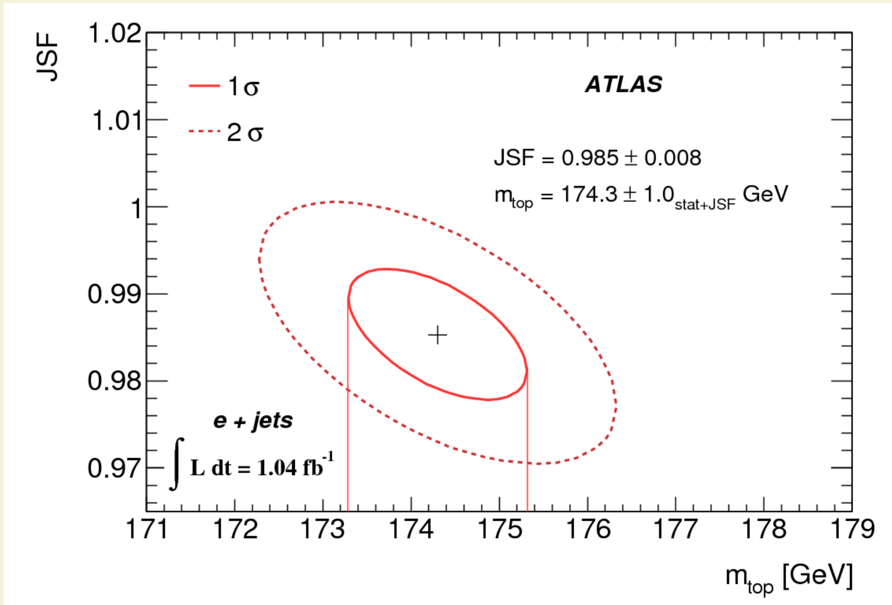
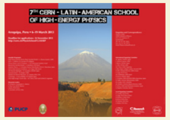


EPJC 72 (2012) 2046

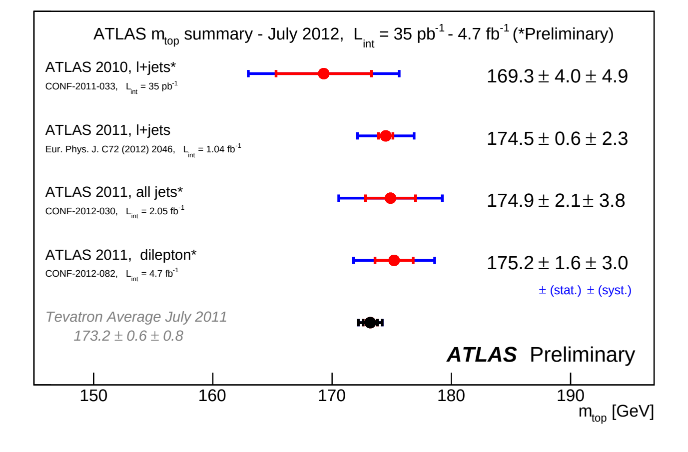


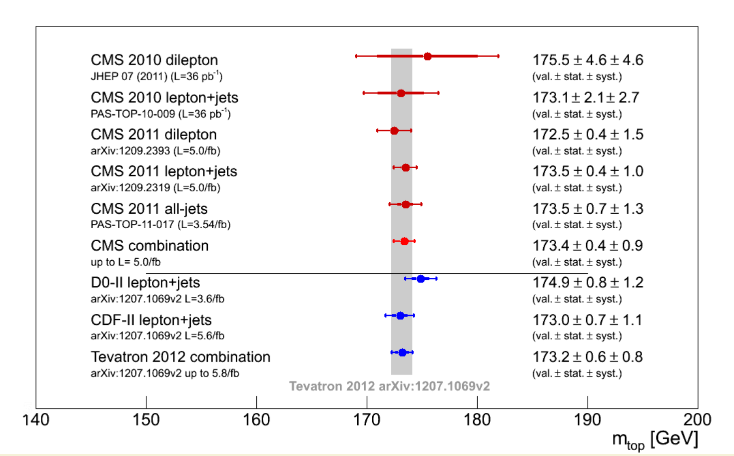
- CMS has measured the mass in lepton+jets and the JES in-situ obtaining the most precise single measurement.
- ATLAS measurement based on template fit in lepton+jets, again calibration jet scale in-situ.
- Both method were validated in MC.

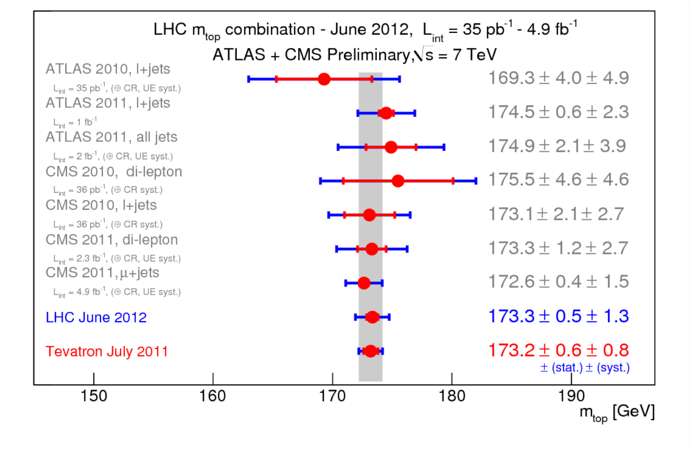
LHC Combination and plans



- Several measurements of the top-quark mass around. As with the cross section, the solution is to combine the results to improve the precision.
- The LHC combination is still missing most up to date results, but it was a very important achievement since it would be required to repeat it in the future.
- Information on the combined process and details of the inputs has been documented in public notes: **CONF-ATLAS-2012-095** and **CMS-PAS-TOP-12-001**







- It is expected that the top-quark mass will keep its relevance even if precision achieved is hard to improve.
- The available statistics of the 2012 dataset would allow to perform differential measurements of the mass (dM_t/dX), which provides additional theoretical constraints and sensitivity to new effects.

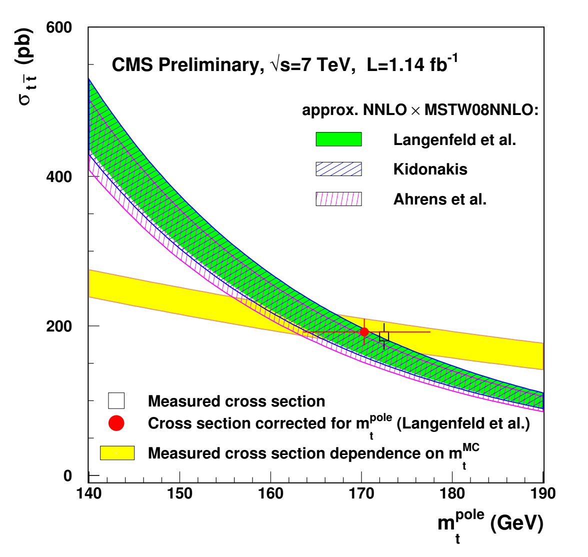
Mass from the production cross section

- **Apart from the direct measurments of the top-quark mass, indirect methods has been tried, mostly motivated for the precision achieved in top-quark related measurements.**

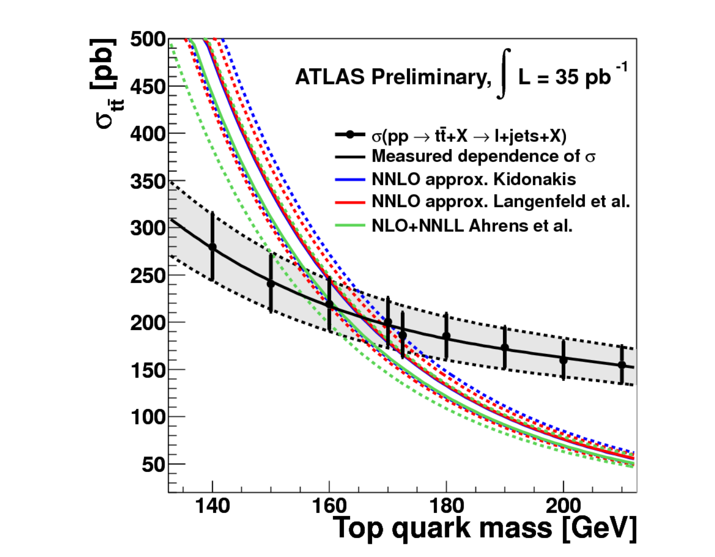
- **Specifically, the precision achieved in the cross section allows to use the comparison with the theory to determine the best value for the top-quark mass.**

- **Method tried at Tevatron (DØ) and by the two colaborations at the LHC. The mass is extracted using a joint-likelihood approach.**

CMS-PAS-TOP-11-008



ATLAS-CONF-2011-054

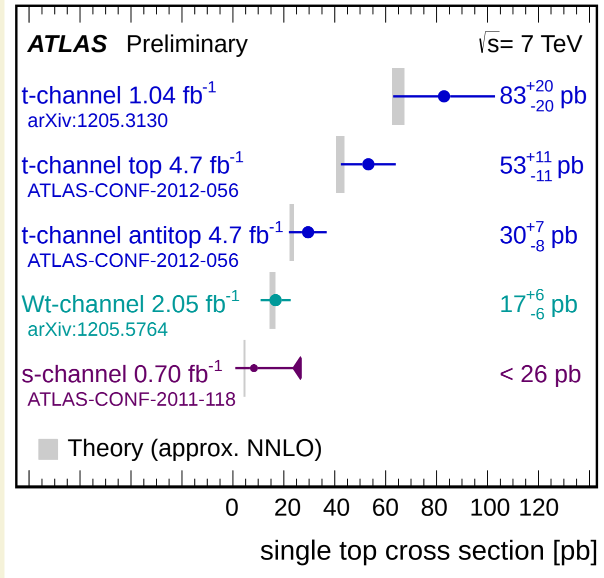


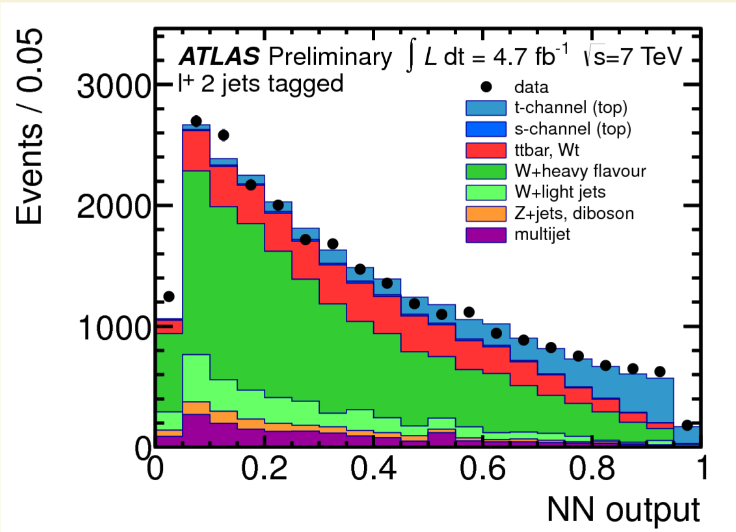
- **It should be noted that comparison of this result with the direct measurement provides a new handle to find effects beyond the SM. For now, good agreement. . .**

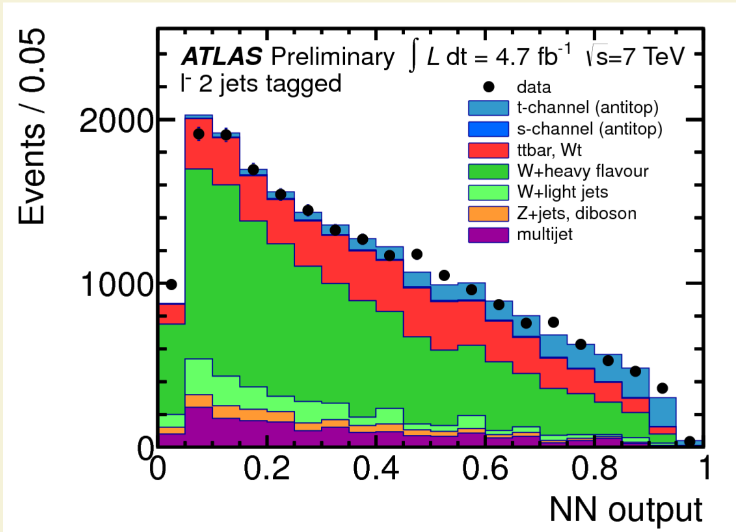
Single-top production

- The EWK production of top is dominated by the single-top production, that is usually classify in t-channel, s-channel and tW production.
- Measurements performed at 7 TeV, where it was shown that the t-channel is not as challenging as at the Tevatron:
  - $\Rightarrow$ Large increase in yield
  - $\Rightarrow$ Affordable hard cuts to reject backgrounds.

ATLAS-CONF-2012-056





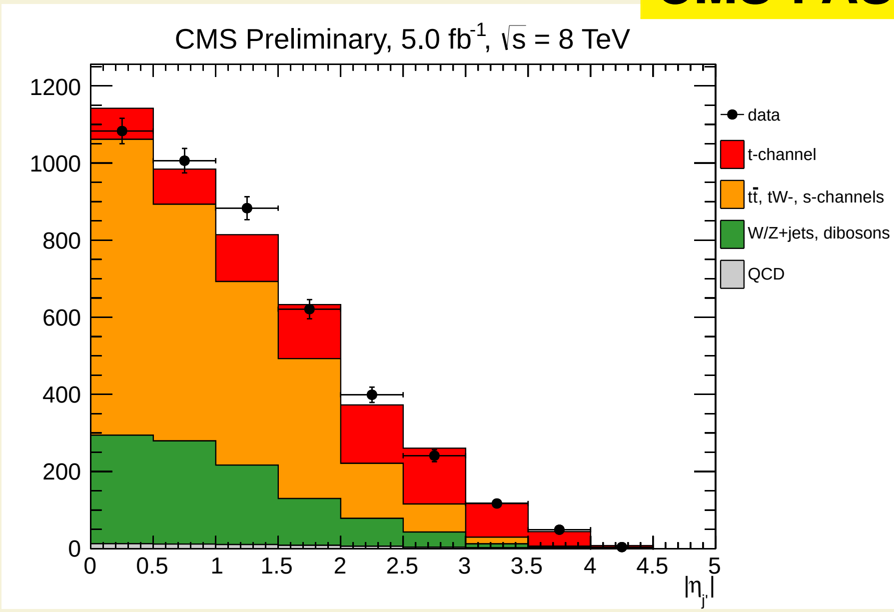


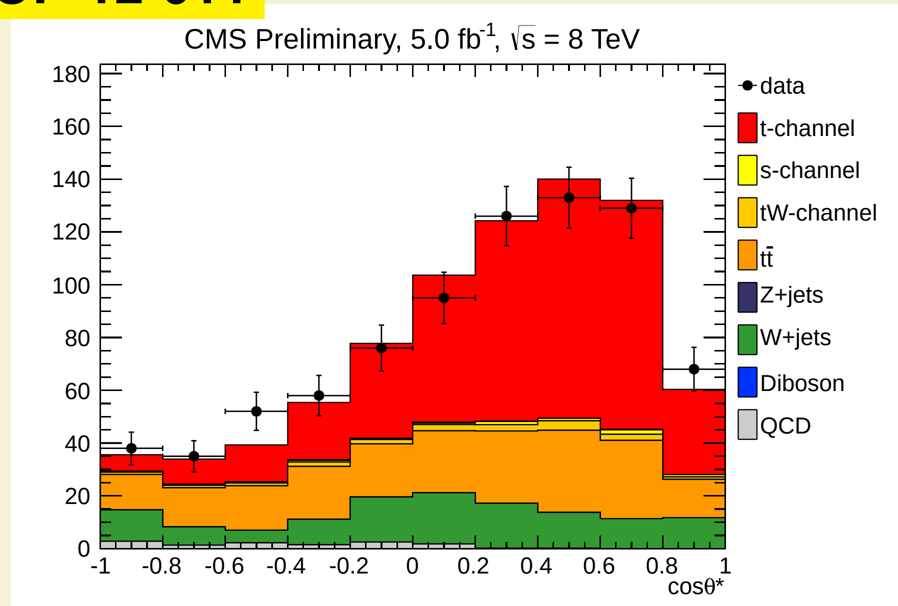
- The s-channel is very challening, specially due to the low cross section.
  - $\Rightarrow$ Also very large backgrounds (Wbb,$t\bar{t}$) hard to reduce.
  - $\Rightarrow$ Analysis by ATLAS set an upper limit on ~ 5 times the SM prediction.
  - $\Rightarrow$ More data is needed to be sensitive to the signal.

Measurement of the t-channel production

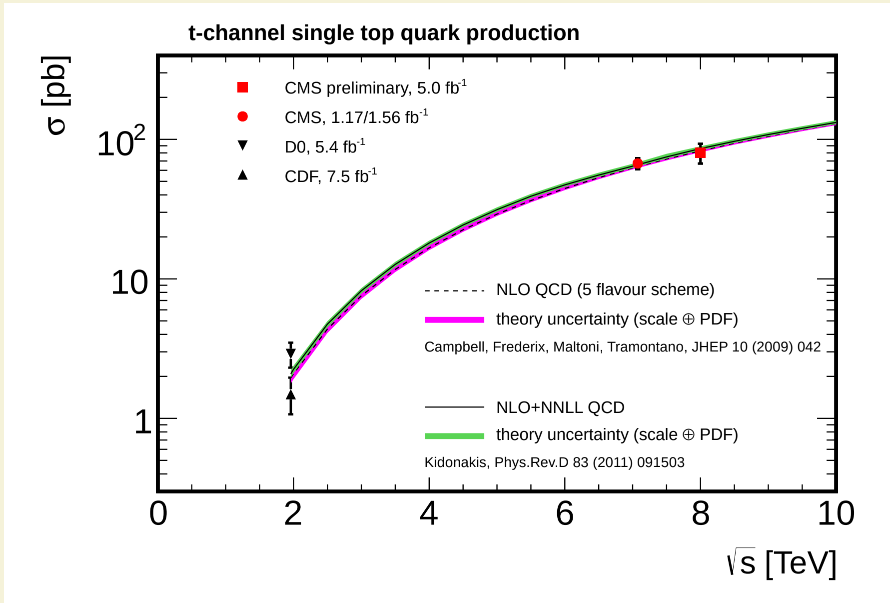
- Already measurements of single-top production at 8 TeV available.

CMS-PAS-TOP-12-011





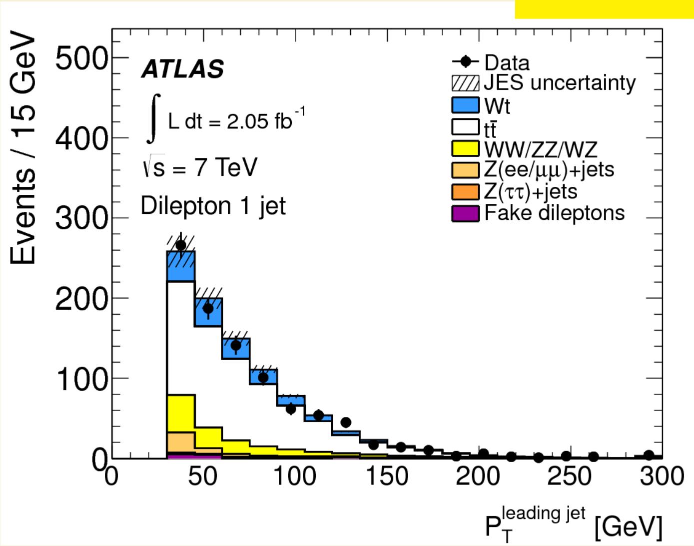
- Starting with the t-channel, due to practical purposes.
- Precision in cross section at 15-20%.
- Very good agreement with the expected cross section, using NNLO (approx).
- Sizes of samples are already allowing precision studies separating quark and antiquark production.

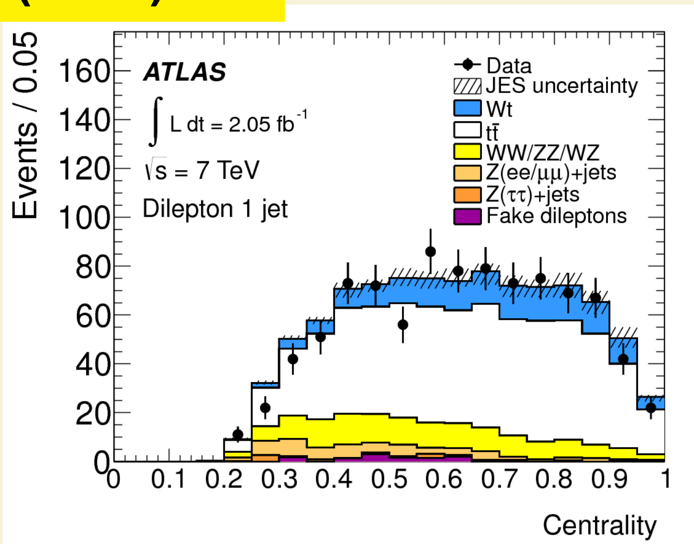


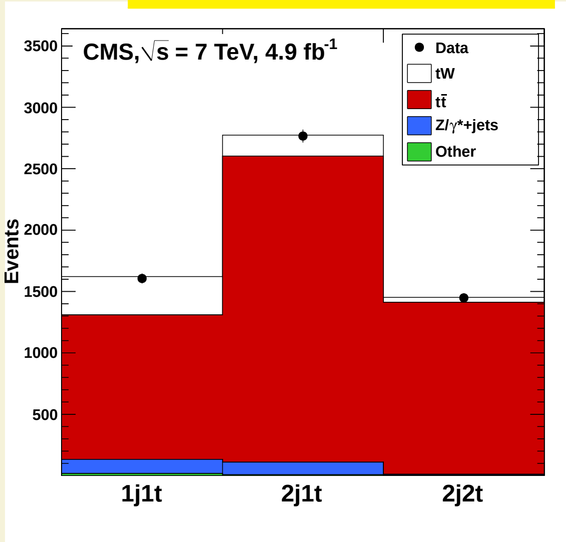
tW production

- The associated production of a top quark (or antiquark) with a W boson is another channel in which the final state contains just one top quark.
- Also sensitive to the EWK parameters of the top quark.
- The cross section at the Tevatron was too small for even considering the channel.
- It will be observed at the LHC. Already nice results in the dilepton channel.

PLB 716 (2012) 142 **arXiv:1209.3489**





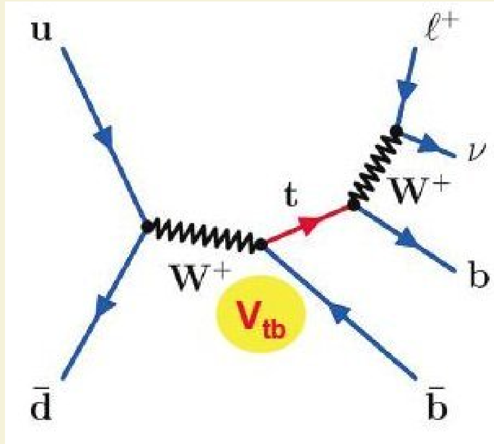


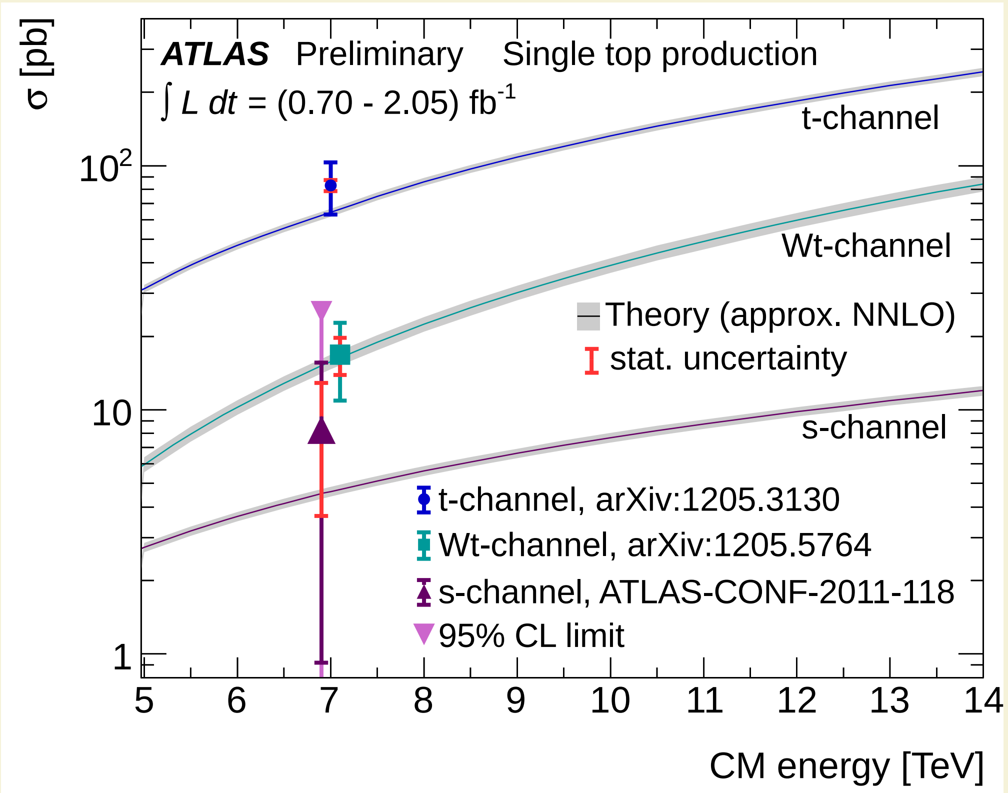
- The two experiments already reached the level to claim evidence: 3.3σ for ATLAS and 4σ for CMS.
- In good agreement with the SM predictions.
- Observation should be at hand in the 8 TeV data.
- Challenging analysis due to the tougher running conditions.

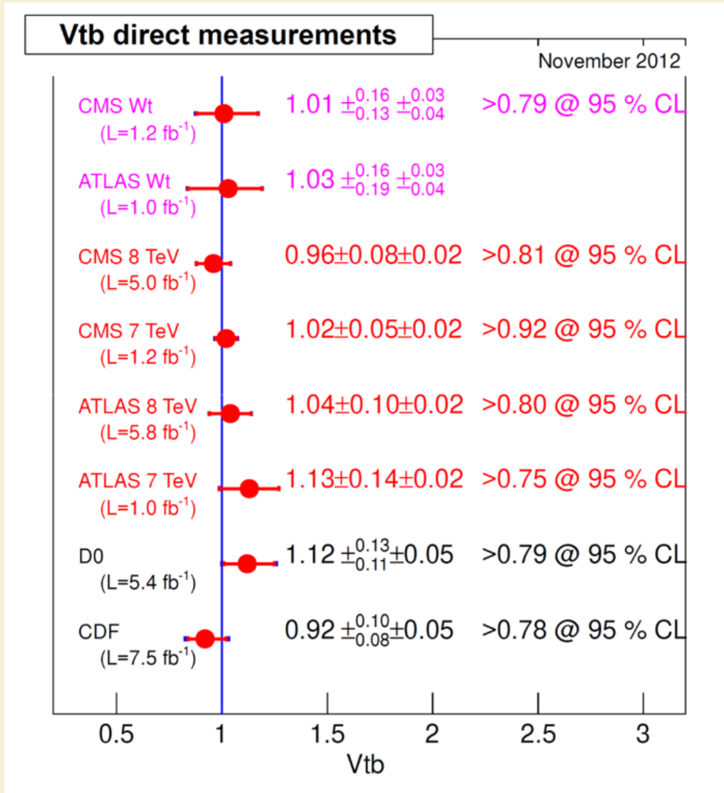
Summary and Vtb measurements

- **Several measurements from Tevatron and LHC are providing a detailed picture of the single top production.**

- **Sensitivity to the CKM element V_{tb}: measuring values.**



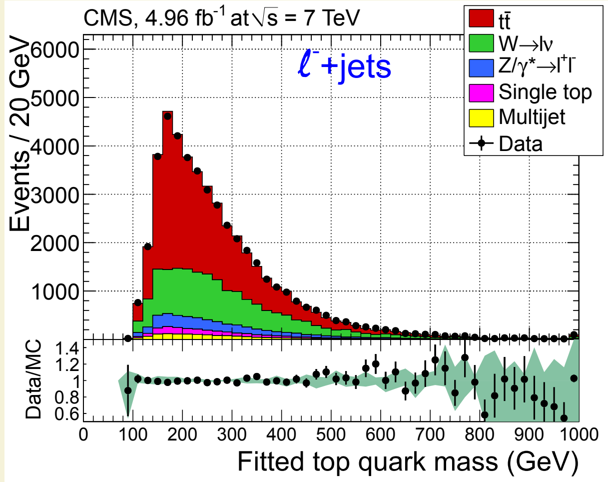


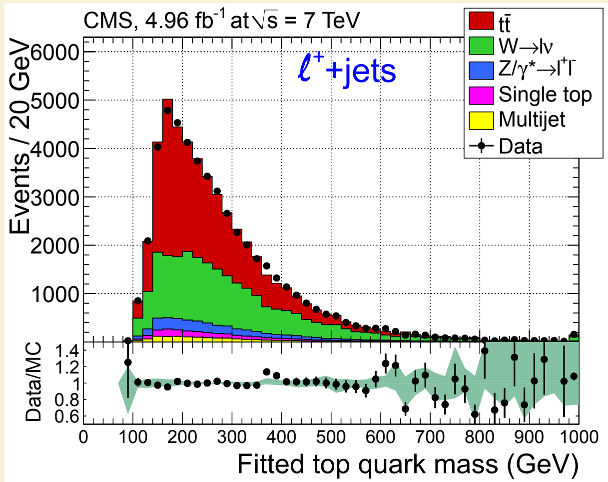


- **Very good compatibility with the SM expectations.**

Properties of the top quark

- As mentioned before, the top quark gives many possibilities about studying particle properties that are not accessible for the other quarks.
- One of the goals of the LHC is to actually measure these properties and confirm that the nature of the top quark is as expected for a fermion/quark in the SM.
- Many measurements already in place:
  - ⇒ Electric charge
  - ⇒ Spin behaviour and correlations
  - ⇒ Polarization of the top quark
  - ⇒ Helicity of the W in top decays
  - ⇒ Forward-backward asymmetry





- In addition to these measurements, other set of useful quantities to measure is to perform tests of the
- For example, CMS has measured the mass difference between the top quark and the antiquark.

The result is a stringent test of the CPT invariance:

$$\Delta m_T = -0.44 \pm 0.46\text{(stat)} \pm 0.27\text{(syst) GeV}$$

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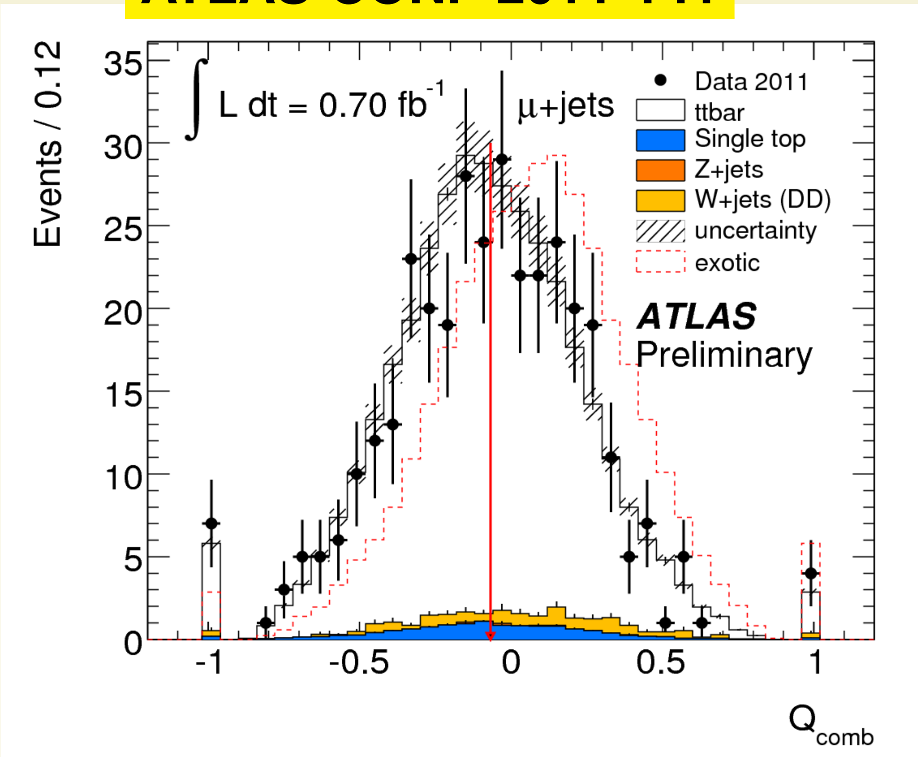
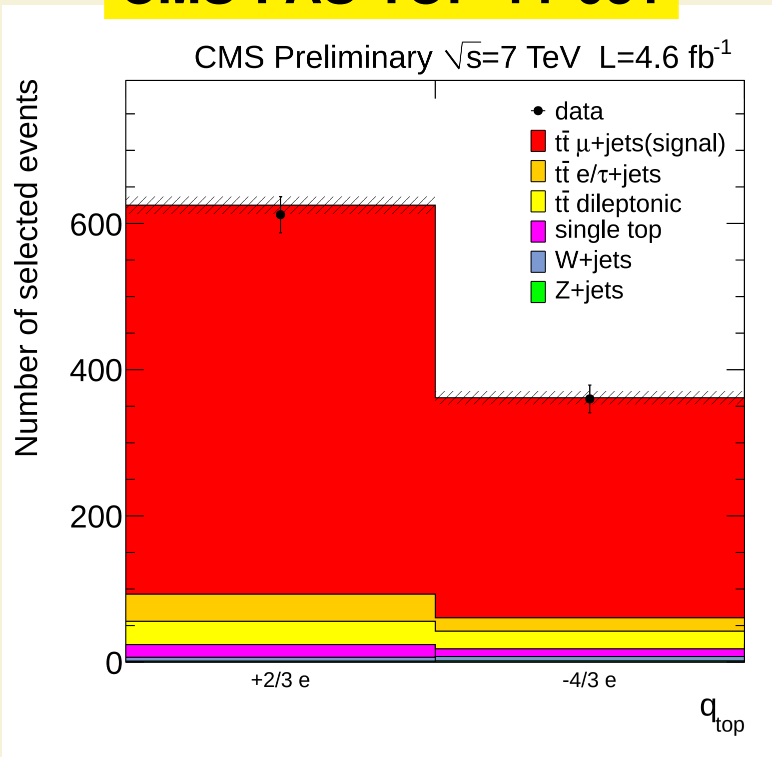
Electric charge of the top quark

- Although the SM predicts the top quark to have an electric charge of +2/3, there are some models predicting a charge of -4/3.
- In orden to discriminate the correct charge, the method uses:
  - ⇒ Determine the W charge using the lepton.
  - ⇒ Determine the b charge using soft muon or weighted charge within jet.
  - ⇒ Perform W+b pairing, using kinematic reconstruction.

ATLAS-CONF-2011-141



CMS-PAS-TOP-11-031

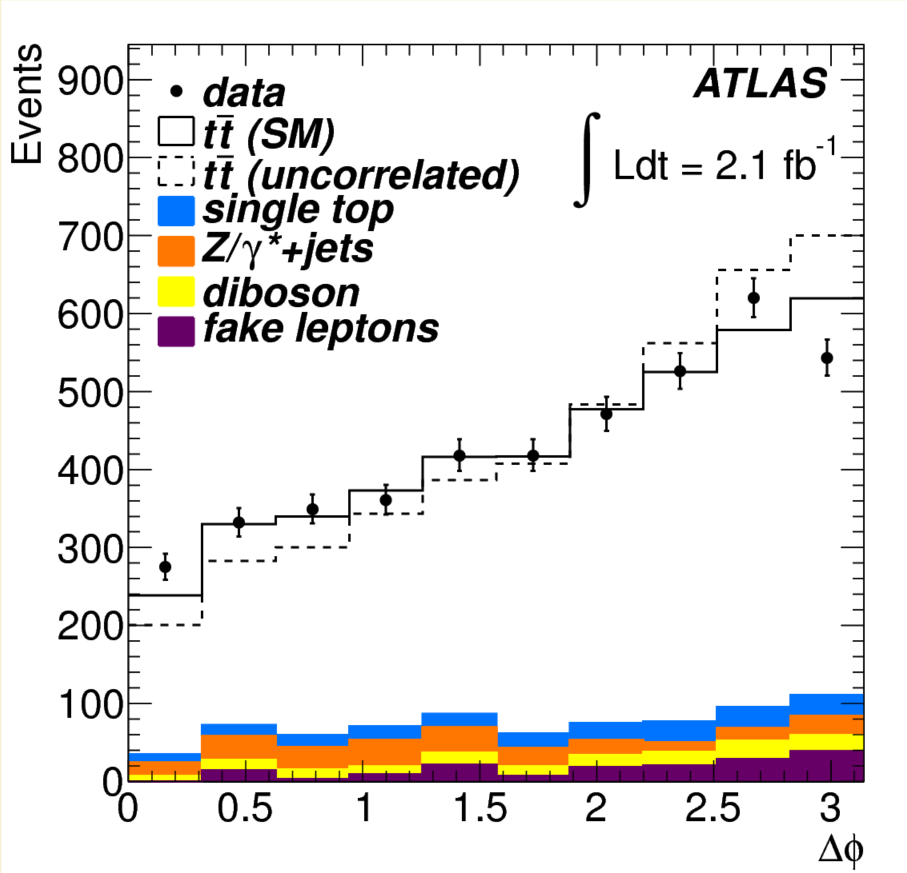


- Both analysis exclude the -4/3 value beyond any reasonable doubt.

Spin correlations

- Due to the short lifetime of the top quark, its decay happens before a change of the spin.
  - $\Rightarrow$ Spin information is propagated to the decay products.
  - $\Rightarrow$ Only quark whose polarization is accessible.
- In top-pair production the top is not polarized, but spin of the quark and antiquark are correlated.

PRL 108 (2012) 212001



- At the LHC the azimuthal angle between charged leptons in the laboratory frame is able to distinguish between the SM prediction and total uncorrelation.
- In helicity basis, the measured degree of correlation is $0.40^{+0.09}_{-0.08}$.
- Perfect agreement with NLO SM prediction.
- The zero spin correlation is excluded at 5σ

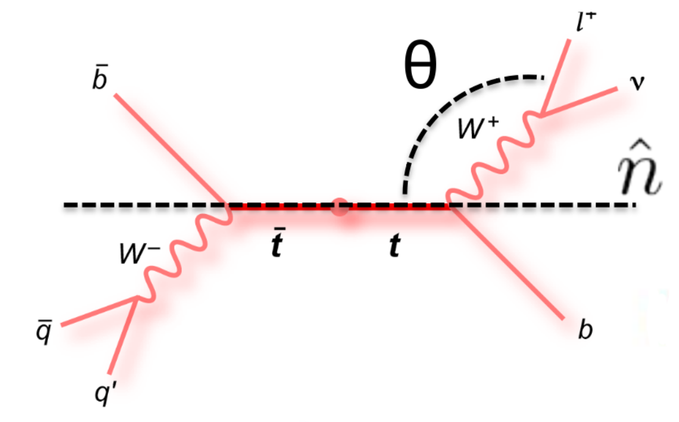
First observation of spin correlations

Polarization of the top quarks

- The polarization of the produced top quark is studied by using the angle between the quark and the lepton.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{l,n}} = \frac{1}{2}\left(1 + 2\alpha_l P_n \cos\theta_{l,n}\right)$$

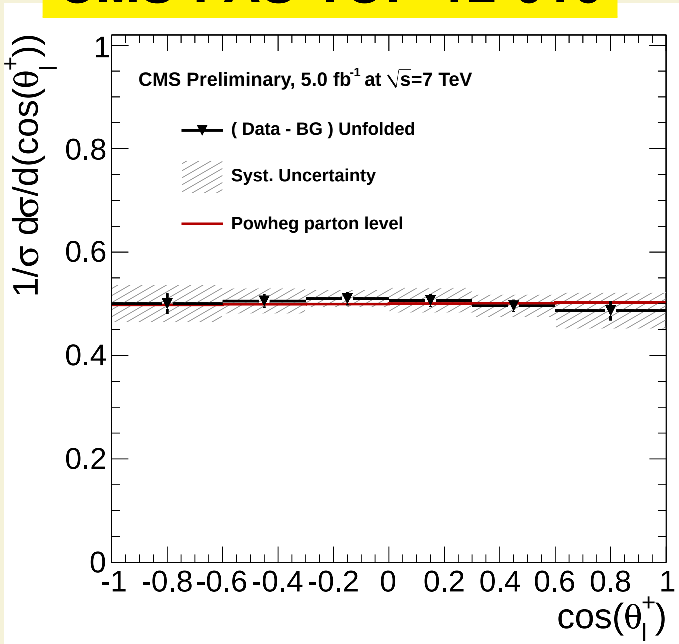
where P_n is the polarization relative to axis n.



- Measured by the two collaborations in different channels:

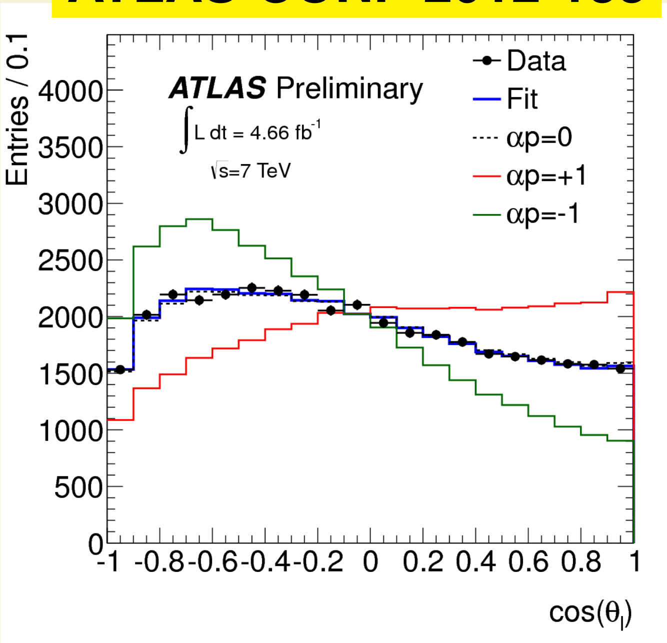
Dilepton channel (CMS)

CMS-PAS-TOP-12-016



l+jets channel (ATLAS)

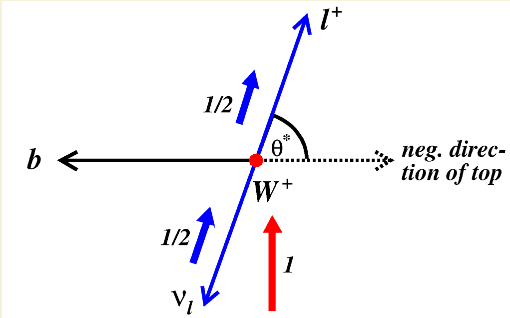
ATLAS-CONF-2012-133

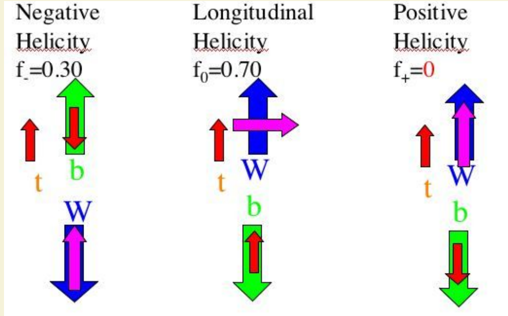


- Results perfectly in agreement with the SM prediction (no polarization).

Helicity of W from top decays

- Due to the properties of the W coupling to fermions and to the spins combinations, **the helicity of the W from top quark decays is determined:**

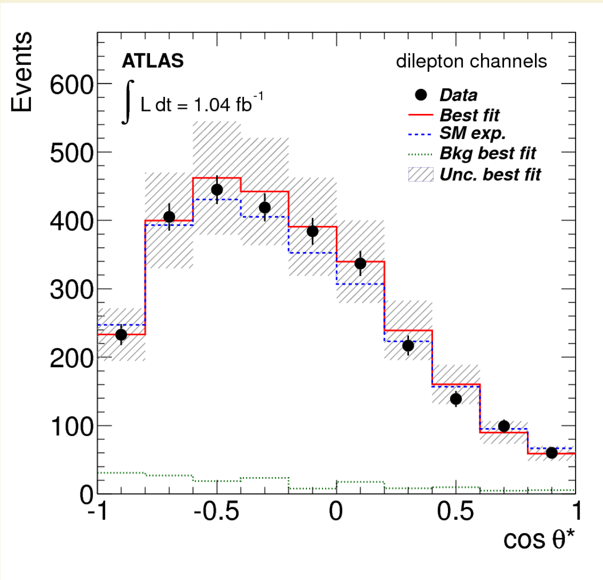




- The parameters are related to $\cos\theta^*$ with the equation:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_- + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_+$$

- Measurements by the two collaborations using the 7 TeV data:



ATLAS (combined)

- $F_0 = 0.67 \pm 0.03$(stat) ± 0.06(syst)
- $F_- = 0.32 \pm 0.02$(stat) ± 0.03(syst)
- $F_+ = 0.01 \pm 0.01$(stat) ± 0.04(syst)

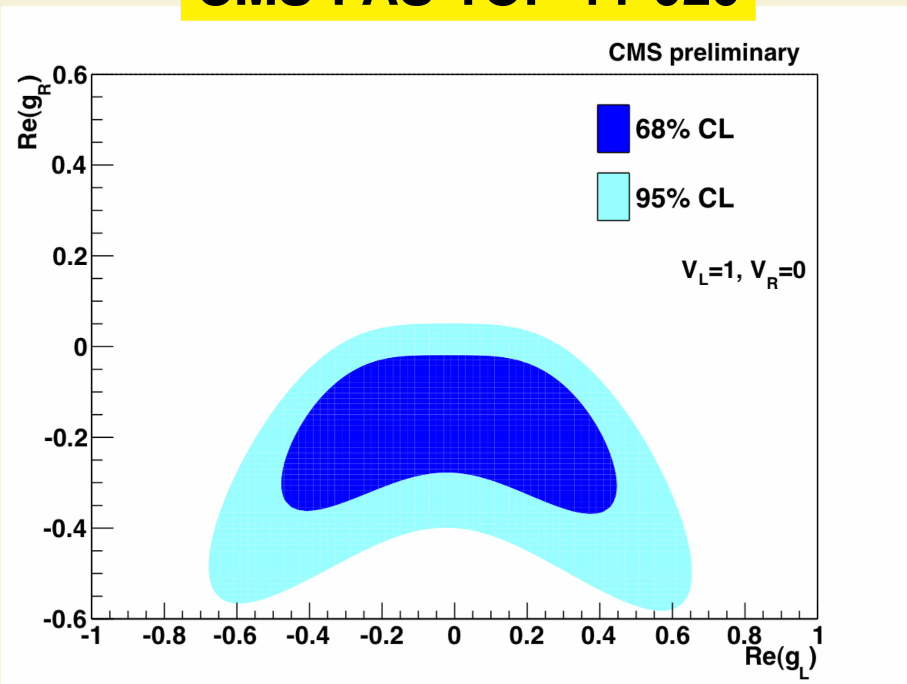
CMS (μ+jets)

- $F_0 = 0.567 \pm 0.074$(stat) ± 0.047(syst)
- $F_- = 0.393 \pm 0.045$(stat) ± 0.029(syst)
- $F_+ = 0.040 \pm 0.035$(stat) ± 0.044(syst)

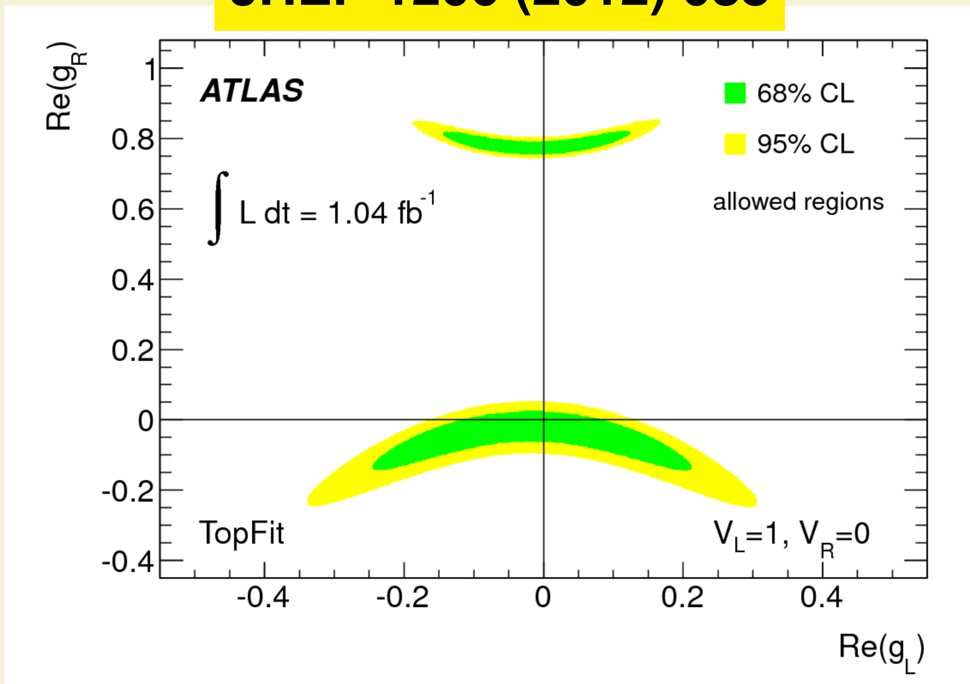
Limits on anomalous couplings

- The previous results on the W helicity are used to study the presence in Nature of anomalous couplings.
- Basically New Physics: we look for coupling violating the V-A structure of the W coupling to the top quark.
- The good agreement with the SM expectation leads to set limits on the allowed regions, around the (0,0) of the SM in the indicated plane.

CMS-PAS-TOP-11-020



JHEP 1206 (2012) 088



- Upper region in ATLAS plot is disfavoured by the single top cross section

  (that of course depends strongly on the W-t coupling)

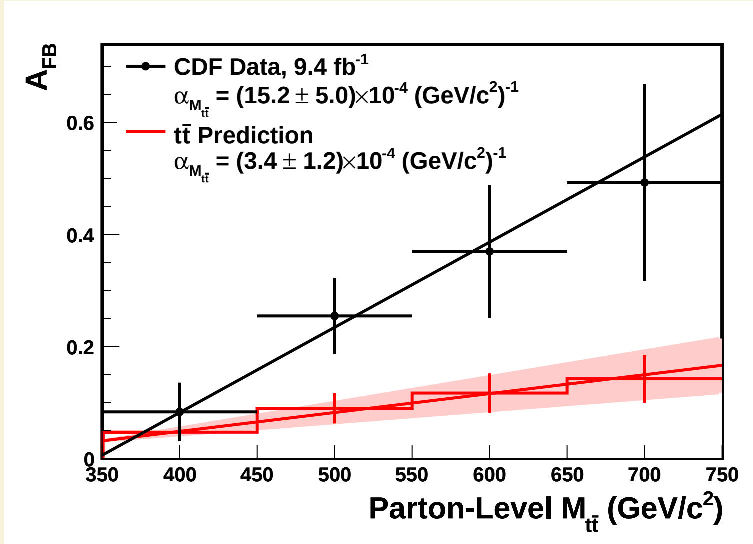
FB Asymmetry in top-pair production

- At Tevatron, striking asymmetry observed in the forward-backward position of the produced quarks:

  ⇒ Top quark is emitted preferentially in direction of the incoming quark

  ⇒ The antiquark the opposite.

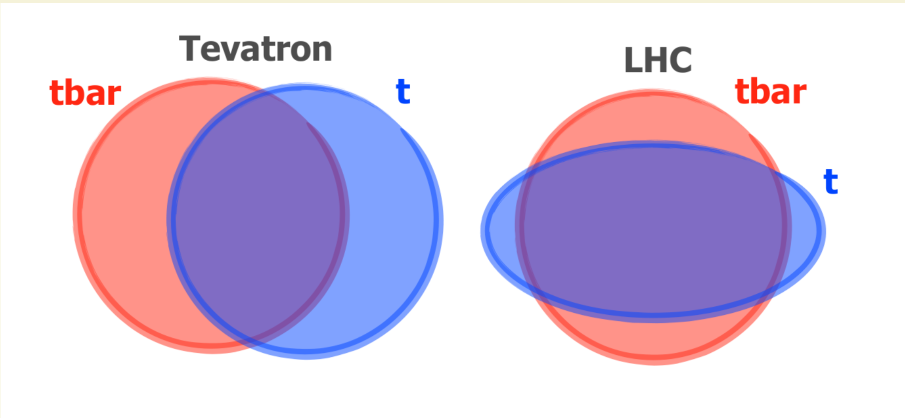
  ⇒ Observed value much larger than expectation by SM.



- The source of this discrepancy is not known. Theoretical QCD-based predictions may have large uncertainties. Improved calculations expected soon.

- The symmetric initial state at the LHC prevents to do the same measurement.
- However, there is a measurement that could spot the reason of the discrepancy:

At the LHC the top quark tends to be more aligned with the beam direction, while the antiquark is more central.



Something producing the asymmetry at Tevatron may also distort the expected distributions of rapidities at the LHC.

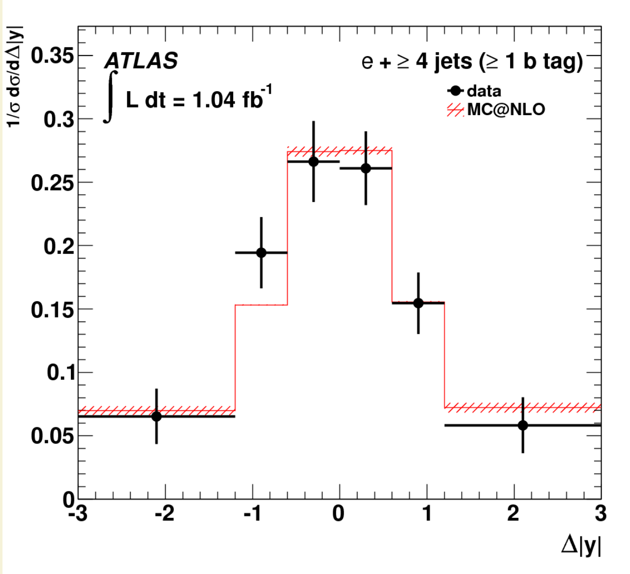
We measure then: $\Delta|y| = |y_t| - |y_{\bar{t}}|$

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

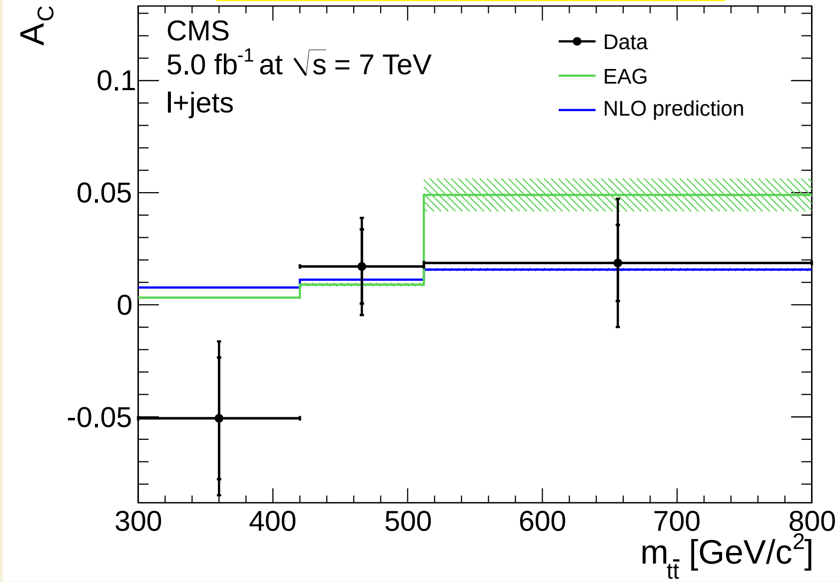
LHC Results on FB Asymmetry

- Measurements by ATLAS and CMS are in good agreement with expectations.
- In the lepton+jets and dilepton channels. More data needed to explore a smaller discrepancy.

EPJC 72 (2012) 2039



PLB 717 (2012) 129



- However, the result does not discard Tevatron result, since the measurement is not exactly the same: only a discrepancy might have been related.
- The problem is the lack of model to explain it. Most of them are ruled out by other searches and studies.
- The LHC result just exclude some models, not the possibility of New Physics.

Candidate to be one of the hot topics for next years

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Study of $t\bar{t} + X$ production

- **Since the pair production cross section is so large at the LHC, some additional studies have been designed to study the production of additional objects in $t\bar{t}$ events.**

- **They provide information about the SM and also they are useful to validate/tune the MC predictions**

Of special interest:

$\Rightarrow$ $t\bar{t}$+jets: QCD test

$\Rightarrow$ $t\bar{t} + \gamma$

$\Rightarrow$ $t\bar{t} + W/Z$: EWK test

$\Rightarrow$ $t\bar{t} + H$: in Higgs Physics

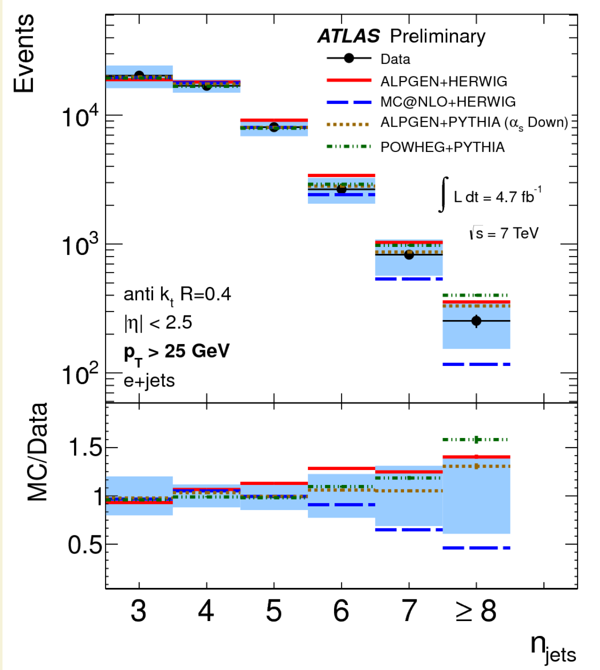
$\Rightarrow$ ...

Also relevant to compute ratios of these quantities (e.g. ratio of $t\bar{t} + bb$ to $t\bar{t} + jj$) to reduce uncertainties.

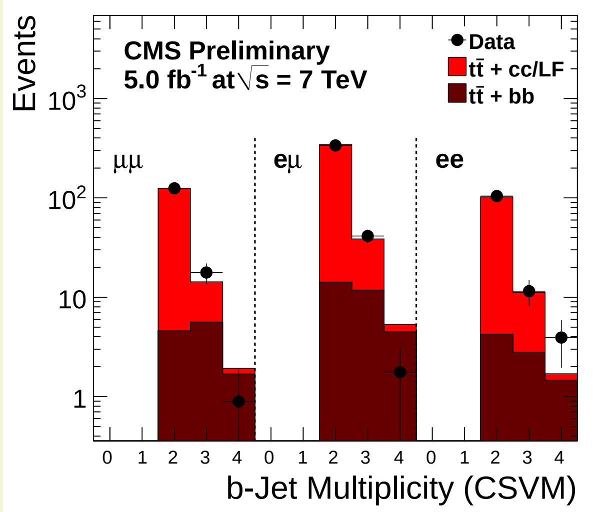
Most of these studies are still lacking events, but they will be primary goals when more data (at higher energy) are collected.

The era of precision physics with the Top Quark is here

ATLAS-CONF-2012-155

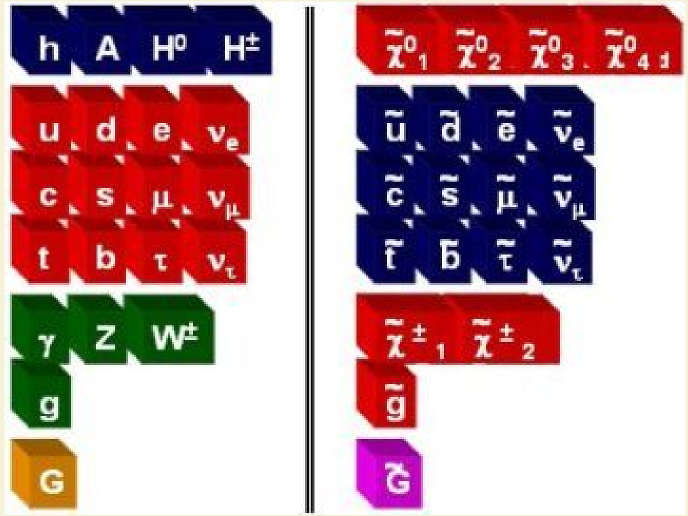


CMS-PAS-TOP-12-024



Search of Supersymmetric Partners

Motivation for Supersymmetry



- Supersymmetry (SUSY) makes Nature invariant for changing bosons and fermions.

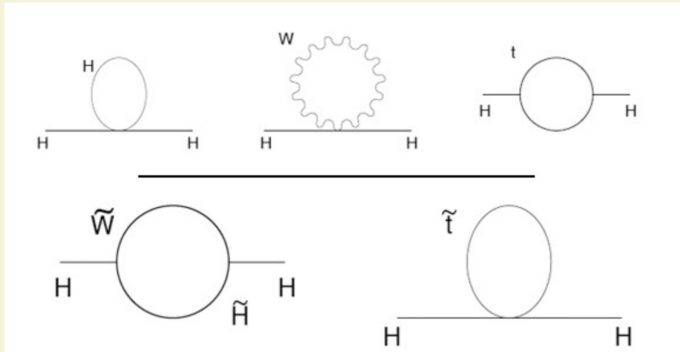
⇒ It is a broken symmetry: not realized at the lowest scales

⇒ It requires to at least duplicate the spectrum of particles

⇒ It usually introduces *R-parity* that if conserved it implies:

  – SUSY particles produced in pairs

  – Lightest SUSY Particle (LSP) is stable: dark matter?



- Theoretically is very strongly motivated since it solves some problems of the SM (Higgs mass fine-tuning) and may help with others (e.g. unification).

- And it opens nice possibilities about experimental hints beyond the SM.

Supersymmetry is such a good idea and helps theory that much that it is the "obvious" extension of the SM even without any experimental hint supporting it.

The fact that SM works so well seems to be the experimental hint.

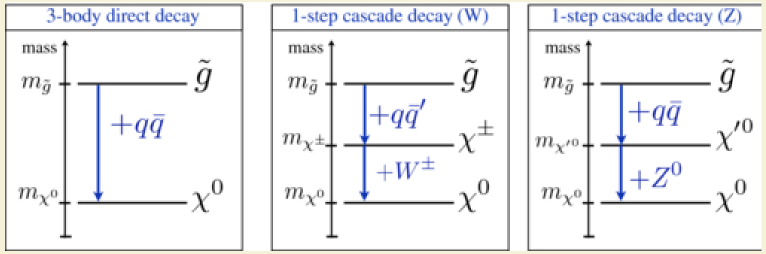
Experimental Context for Supersymmetry

- From the experimental point of view, SUSY is great since its rich phenomenology allows to cover basically any possible final state.

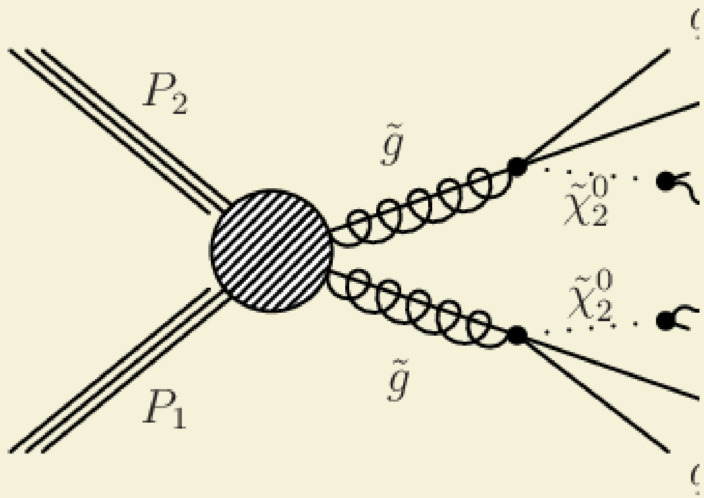
This is enough to set SUSY as the reference for searches of New Physics

However, it is now common to interpret the results in terms of simplified models:

- Focused on specific phenomelogy, but parameters may be adjusted to keep the wide range of final states, but with some interchannel connections.



- Instead of using models with broader predictivity power, with less parameters and more analysis-specific predictions: each analalysis depends on a few well-determined parameters.

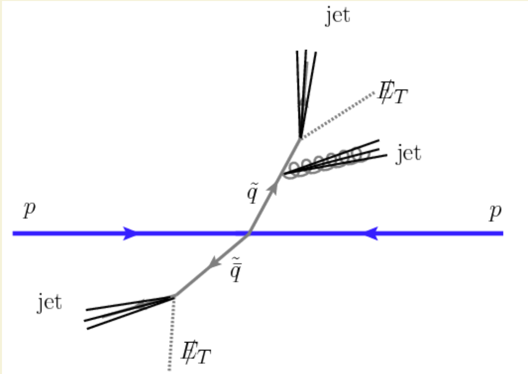


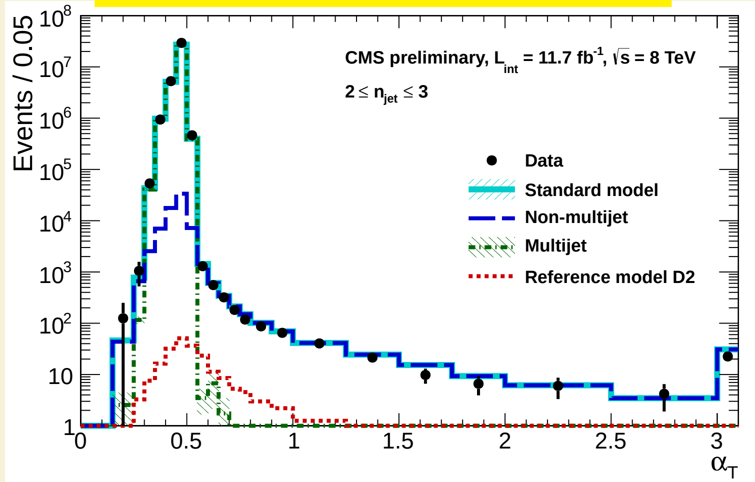
The simplified models are increasingly gaining importance, although traditional "full model" approach is still of general use, for easier comparison/combination of the data from different sources.

Search of squarks and gluinos

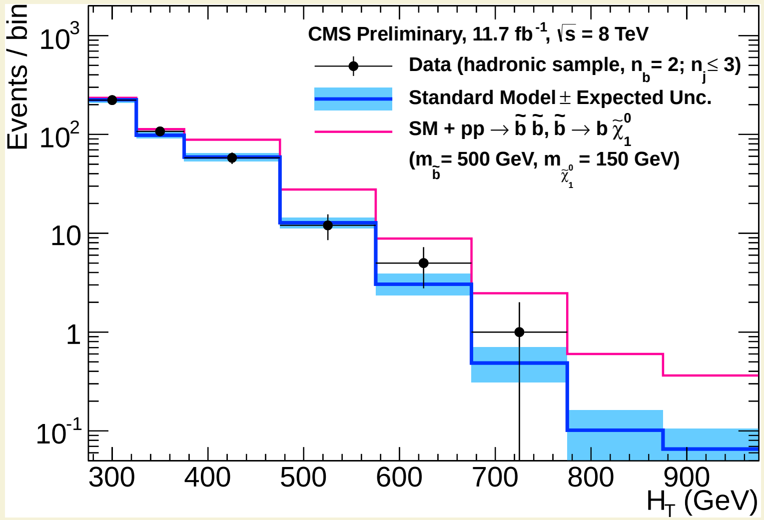
CMS-PAS-SUS-12-028

- The basic process producing SUSY partners is the production of squarks and gluons, yielding jets and MET.





- Need to minimize impact of mismeasured MET from normal multijet production.



- Use of special variables, e.g. $\alpha_T > 0.55$

$$\alpha_T = \frac{E_{T,j2}}{M_T} = (> 2 \text{ jets}) \frac{1-(\Delta H_T/H_T)}{2\sqrt{1-(MHT/H_T)^2}}$$

- Remaining background is dominated by SM backgrounds with real MET.

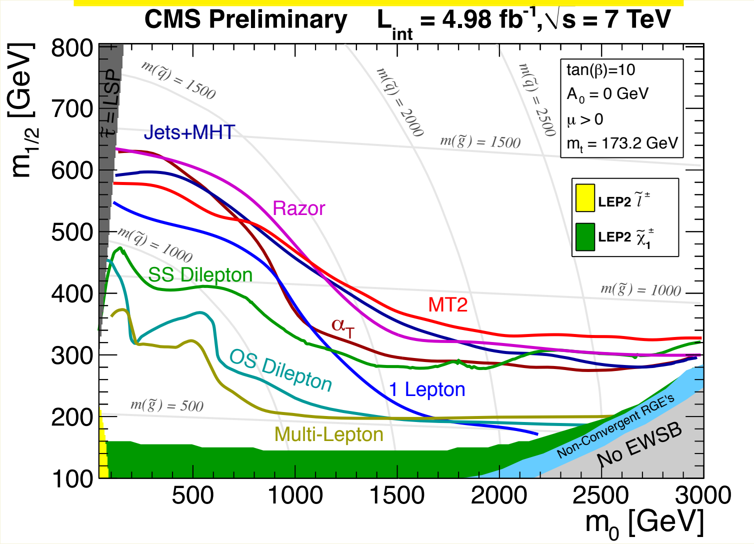
- Categories extensively used: hardness (MET, H_T), N_{jets}, $N_{b\text{-jets}}$

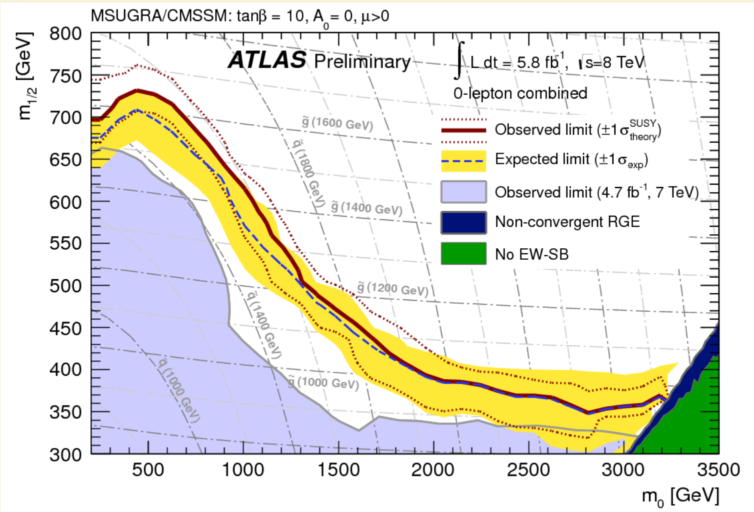
- Sensitivity to different processes: gluino pairs, squark pairs,. . .

Interpretation in CMSSW and particles masses

- Many searches performed to look for inclusive SUSY production.

ATLAS-CONF-2012-109





- Specially because many categories explored.
- No hint of discrepancies with respect to SM.
- Interpretation is done in the Constrained MSSM to reduce the parameter space to:

$$m_0,\ m_{1/2},\ \tan\beta,\ A_0 \text{ and } \mu \text{ (just the sign)}$$

- Although this model is losing interest, it is still the main reference for comparing results.

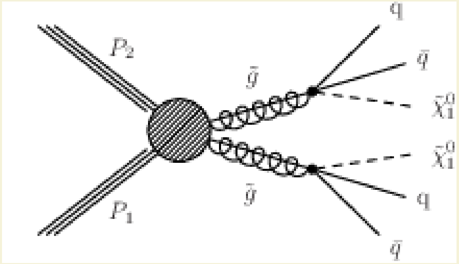
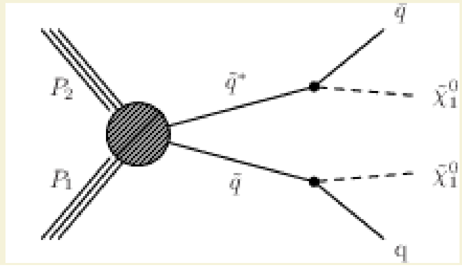
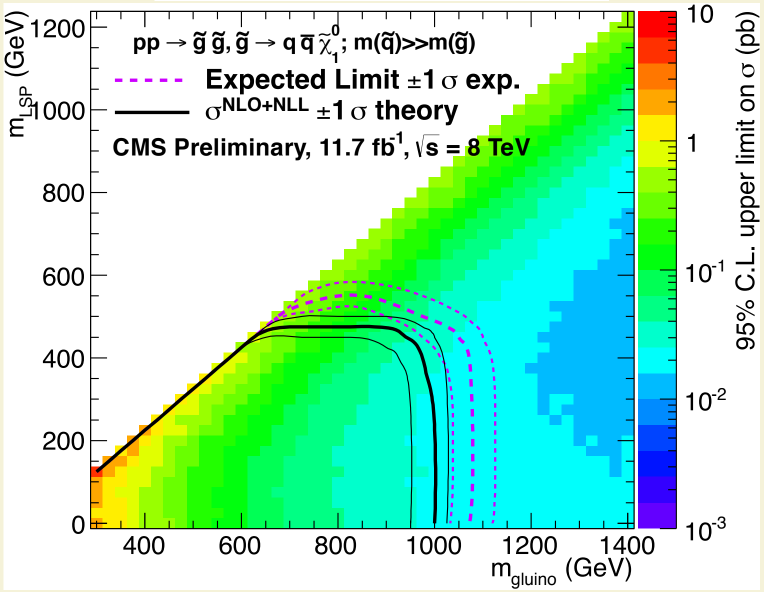
- Sometimes is also useful to set limits on the mass of the relevant particles, specially to set the scale for SUSY parameters:

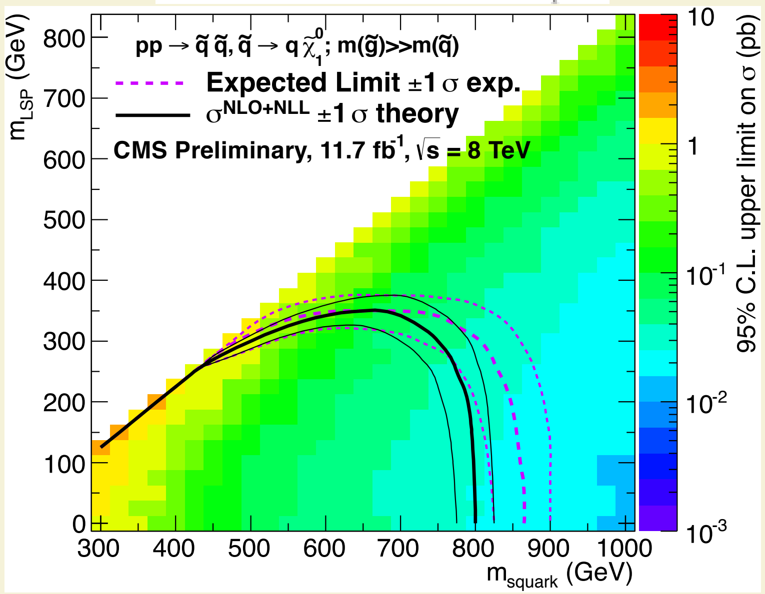
$$m(\tilde{q}) > 1400 \text{ GeV}$$
$$m(\tilde{g}) > 900 \text{ GeV}$$
$$m(\tilde{q}) \sim m(\tilde{g}) > 1400 \text{ GeV}$$

But these are still model-parameter dependent (better said, dependent on the asumptions done in the production and decay).

Interpretation in Simplified Models

- Interpretation of the results is **also performed in the context of simplified models.**
- Depending on the assumed model, **the same results are sensitive to different parameters.**
- Exclusion limits set on mass planes, for given cross sections.

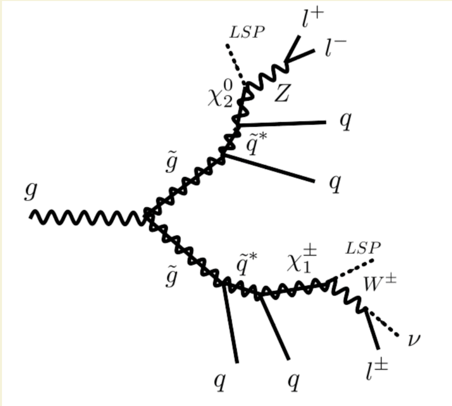






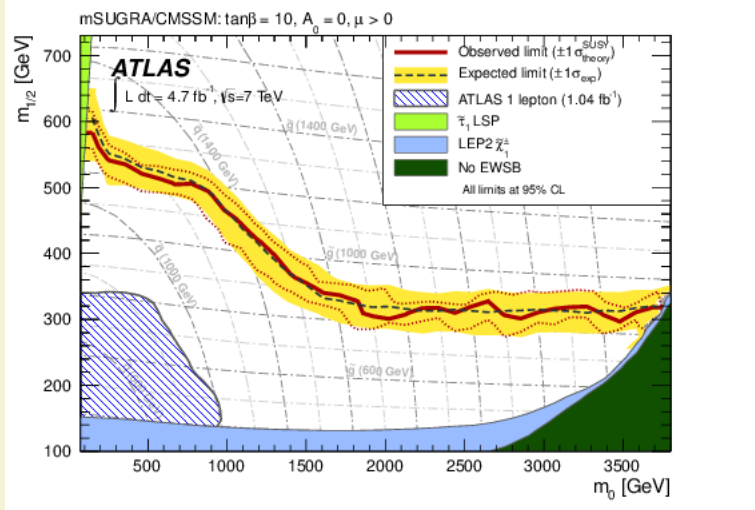
- It allows a **much simpler/faster interpretation of results: independent of SUSY-breaking model.**
- Qualitatively setting the SUSY energy scale.

Searches with leptons in the final state

- In gluino and squark production, cascade decays may give rise to the presence of gauginos, which leads to the presence of leptons in the final state.



arXiv:1208.4688



- Several analyses performed with this approach, due to simplified events with high-p_T leptons.

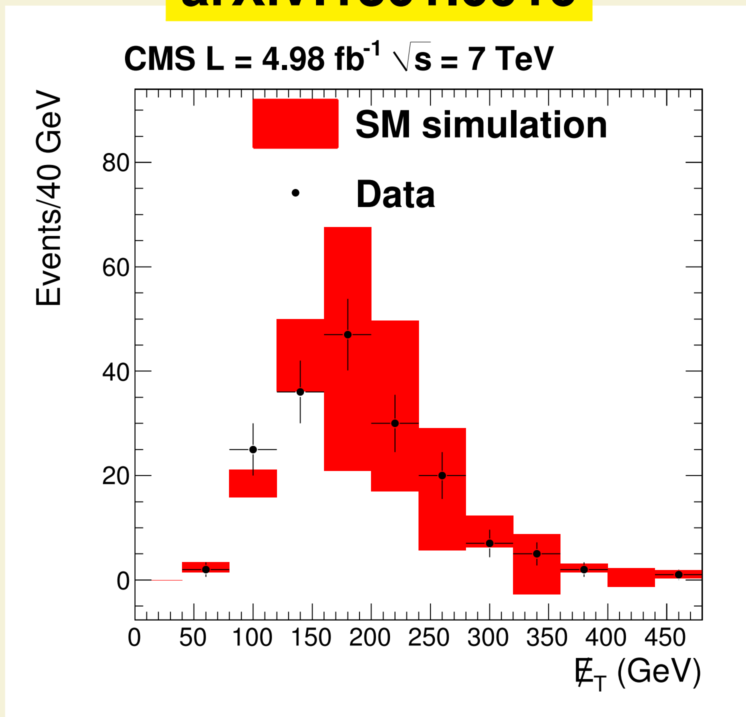
⇒ ATLAS looked at lepton+jets+MET events:

  – Using events with leptons.
  – Classify events in categories.
  – Combination of 10 regions to get CMSSM limit.

⇒ CMS has a dilepton analysis using an ANN:

  – Good agreement with SM backgrounds.
  – Limits set in CMSSM and simplified models.

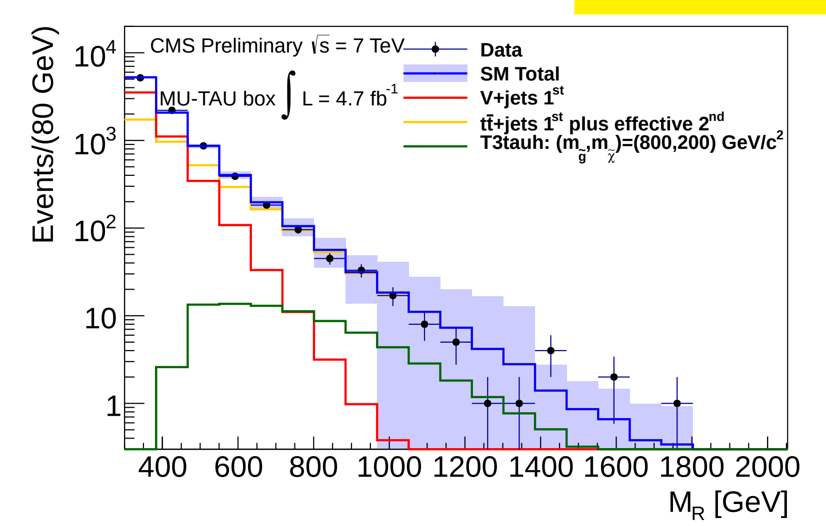
arXiv:1301.0916

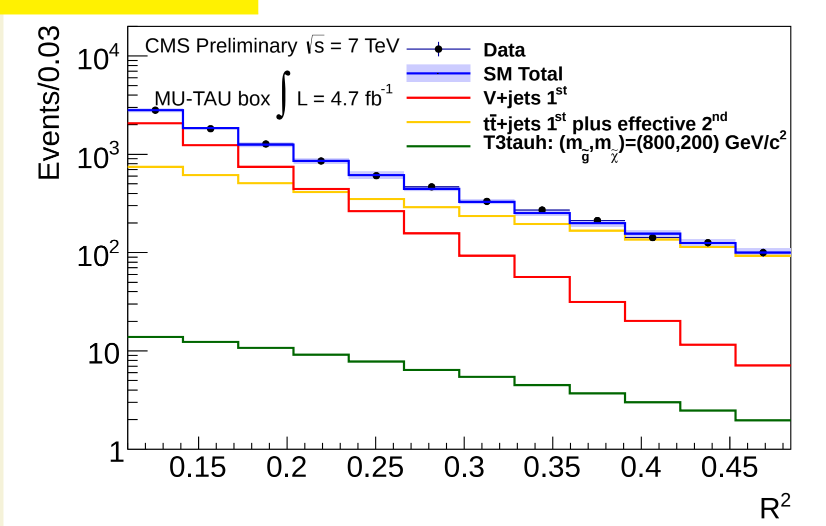


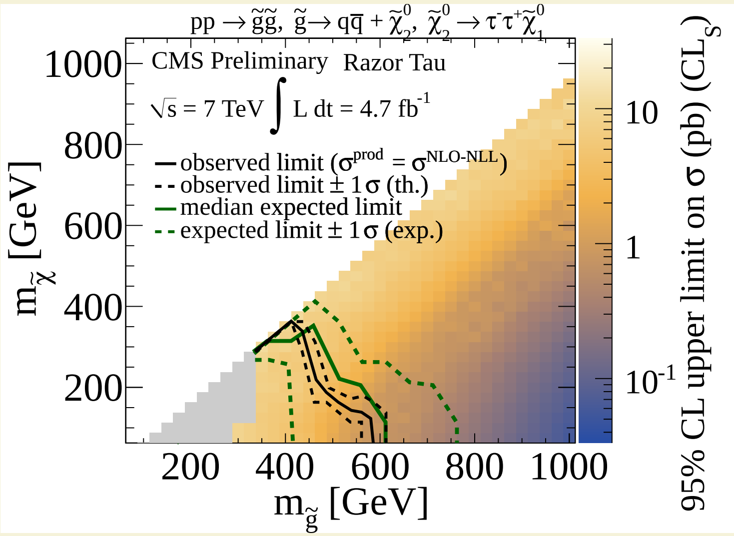
Search of SUSY with τ's in the final state

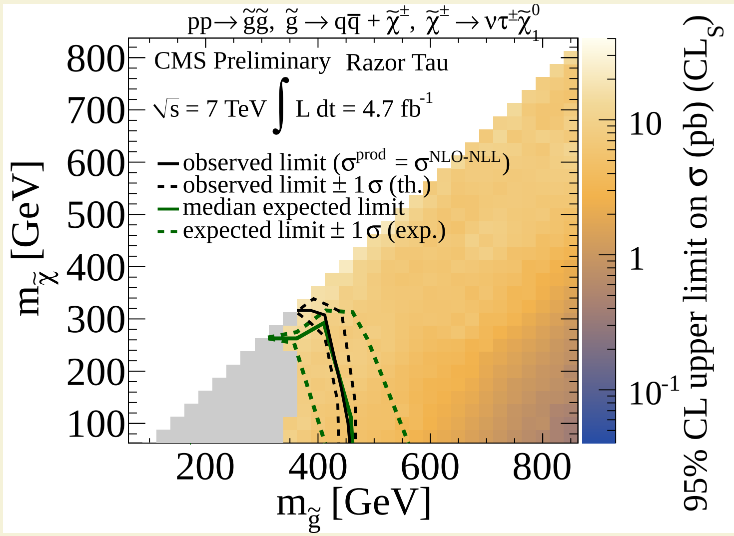
- As part of the final states containing leptons, **special interest in τ.**
- Increased sensitivity in the case of Higgsino-like gauginos.

CMS-PAS-SUS-11-029



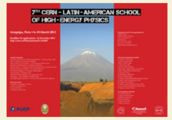




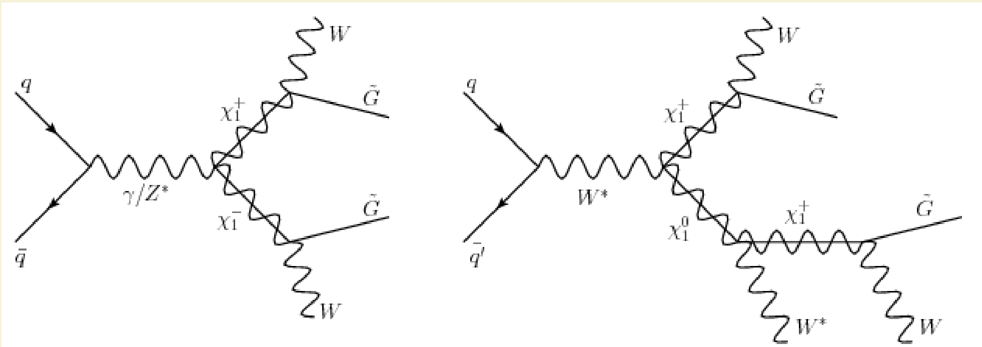


⇒ **Data well reproduced: limits on masses of particles (also in simplified models).**

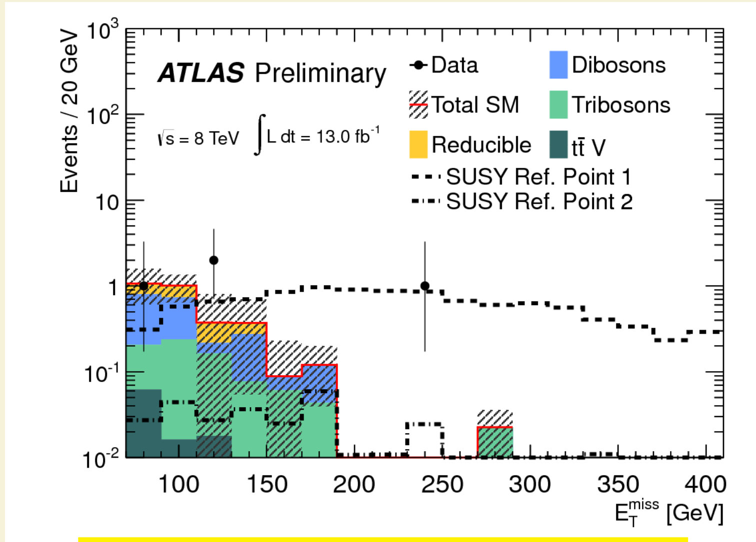
Multilepton+MET searches (I)



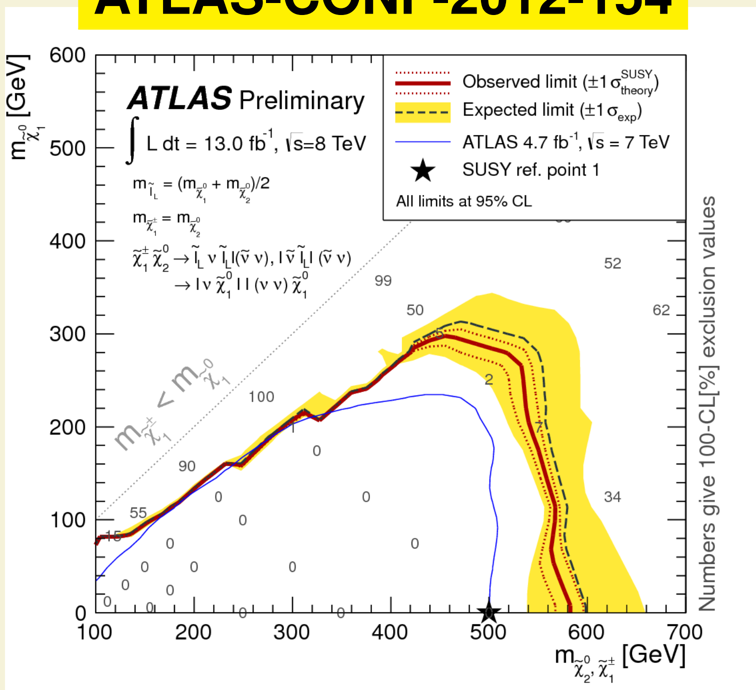
- The production of gauginos is a very clean probe of SUSY, due to the lower backgroundand reasobly high cross section.
- Channels containing multileptons+MET.
- Specially attractive for chargino-neutralino production.



- That was much more important at the Tevatron, where cascades decays where not that simple.
- Background dominated by diboson production.
- Using data-driven estimations (if available).



ATLAS-CONF-2012-154

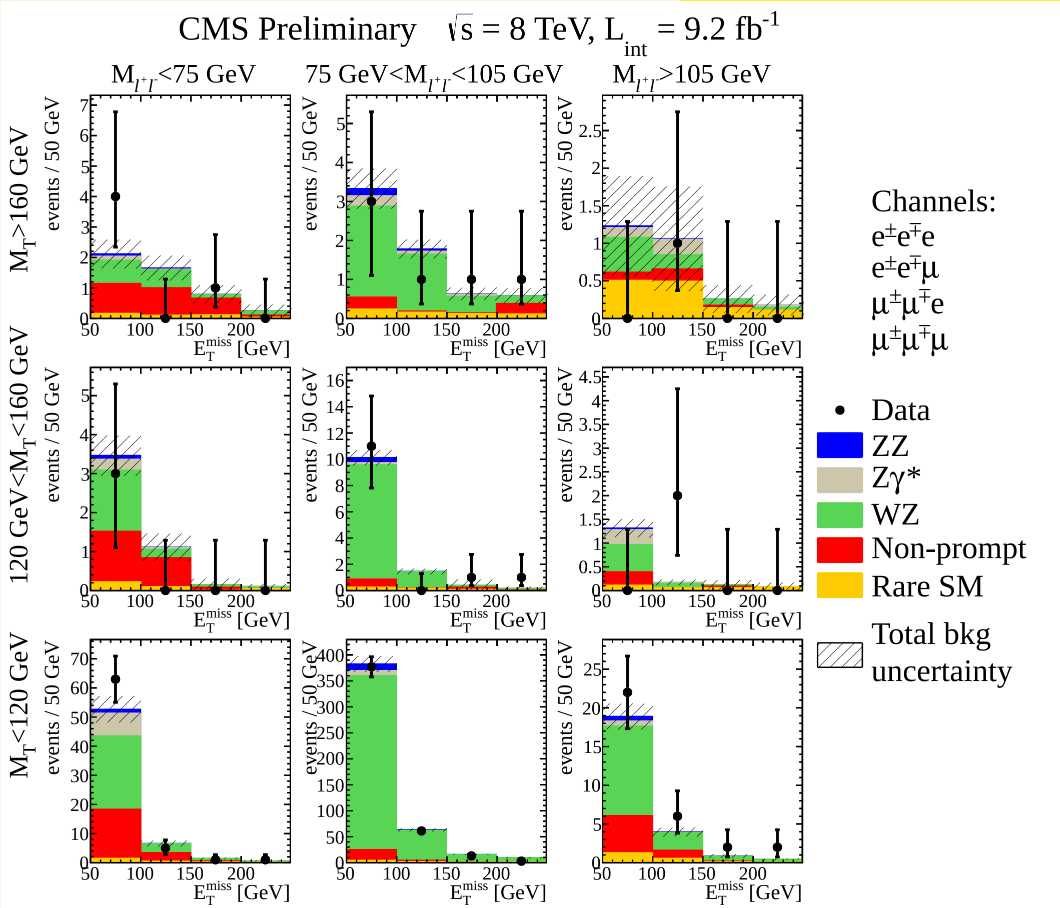


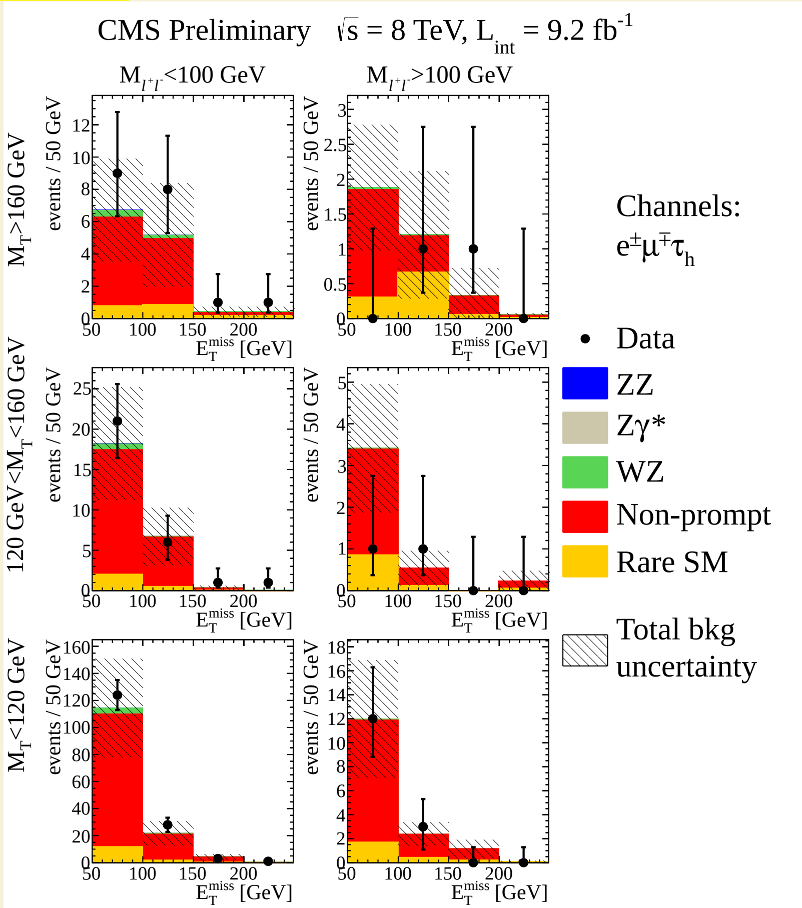
- No significant excess: setting limits on particle production.

Multilepton+MET searches (II)

- Trileptons in CMS: covering many final states, including τ that give sensitivity in certain areas of the parameter space.

CMS-PAS-SUS-12-022





⇒ Good agreement with the SM backgrounds in distributions.

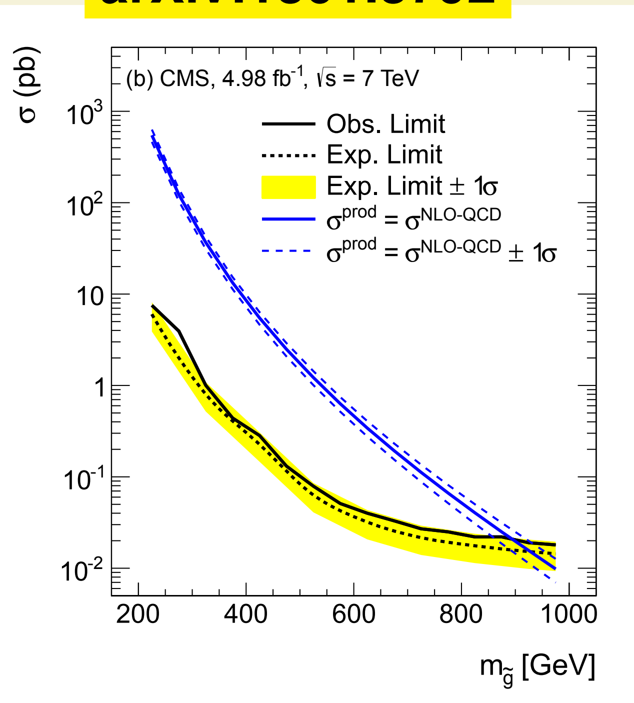
⇒ Set limits on the direct production of charginos, neutralinos, and sleptons.

Gauge-mediated Supersymmetry breaking

- In certain models, SUSYS is broken in a hidden sector and communicated via gauge interations: LSP is a light gravitino, and phenomenology given by NLSP.
- Specially relevant in the cases where ths NLSP is a slepton, and specifically the case of $\tilde{\tau}$ is a well motivated case.
- Searches by the two collaborations to set limits on this kind of models.

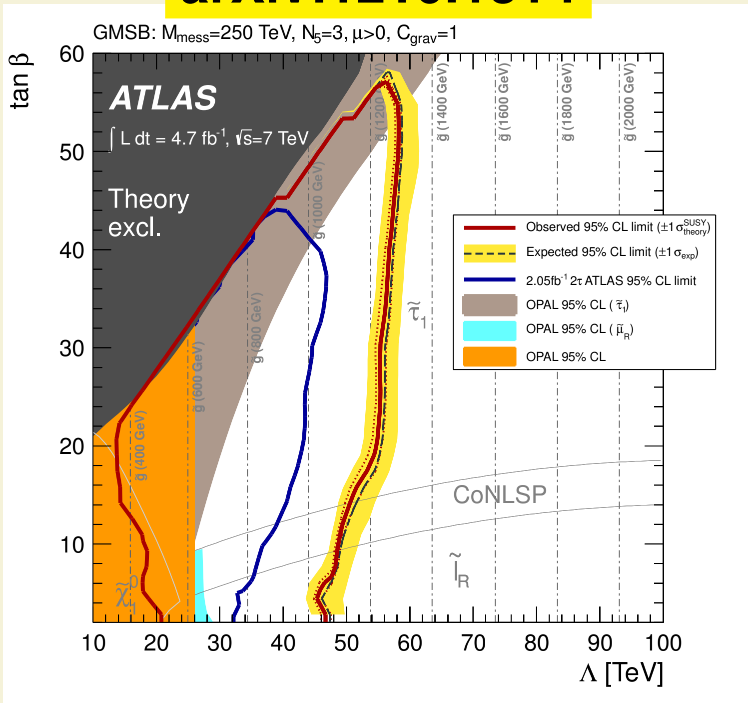
CMS: 2τ+jets+MET

arXiv:1301.3792



ATLAS: jets+MET+$\geq 1\tau$

arXiv:1210.1314

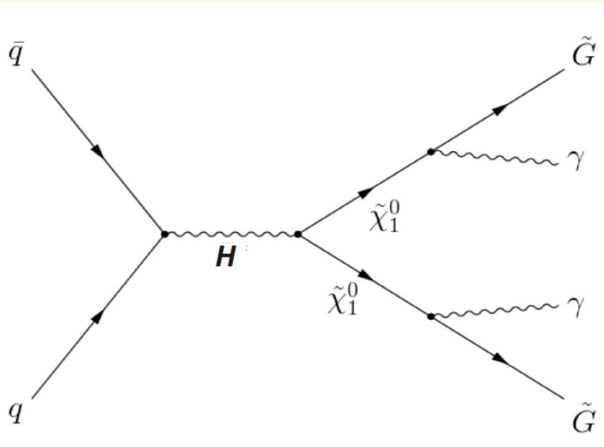


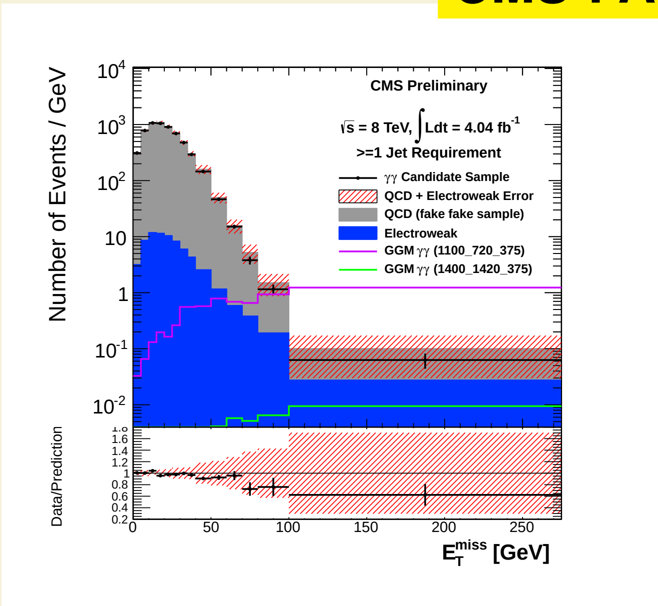
- In adittion: the production of squark+gravitino brings a monojet topology that allows to set limits on the gravitino mass (discussed in Lecture III).

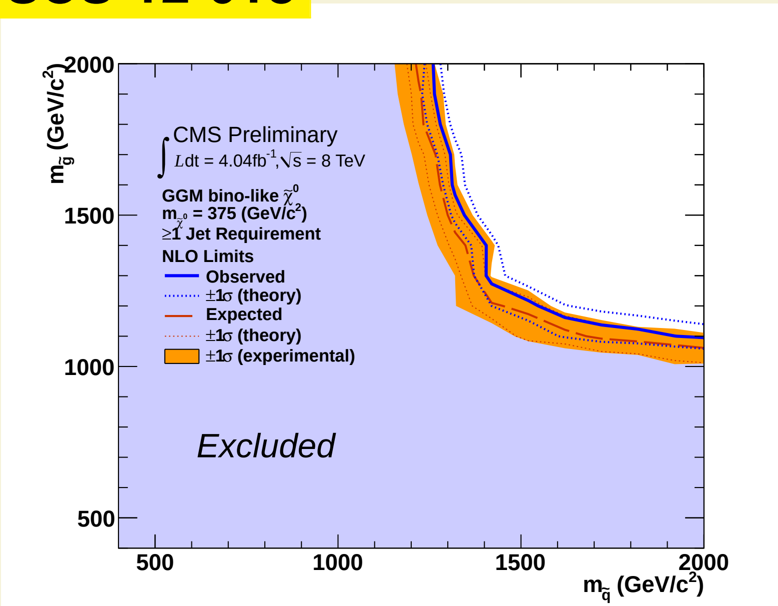
Search of SUSY with photons and MET

- Other relevant case in GMSB is when the NLSP is a neutralino, since the final state contains gauge bosons, specifically photons.
- Signature with $\gamma\gamma$+MET has become a reference for GMSB searches.
- At the LHC more inclusive signatures since neutralinos may appear in cascades.

CMS-PAS-SUS-12-018







⇒ Good agreement in the spectrum: good job by the SM!

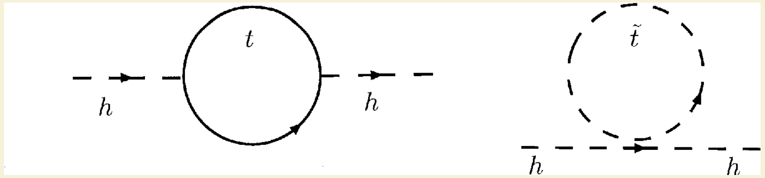
⇒ Limits sets on the parameters translated to masses of $\tilde{g}$ and $\tilde{q}$.

⇒ As with MSSM-inspired searches, GMSB discovery will have to wait a bit more.

Third-generation sfermions

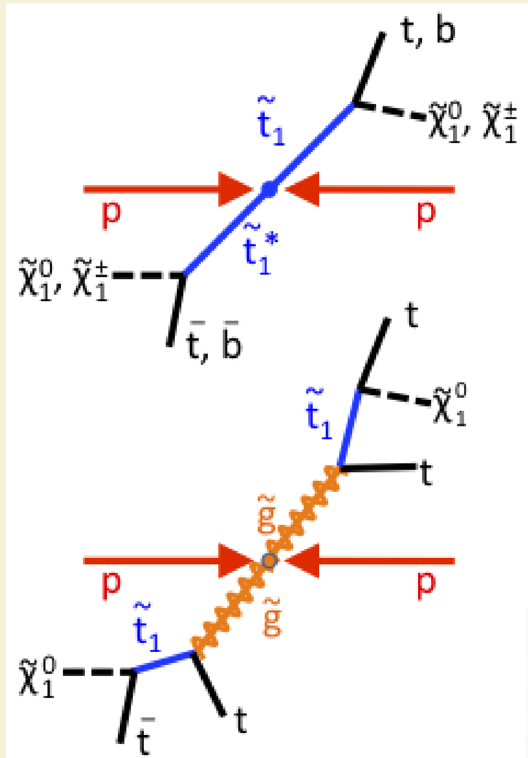
- Although "basic" supersymmetric particles do not seem to be at a close scale, we may still enforce SUSY to be the solution and explain the low mass of the Higgs boson, and we are left with:

  $\Rightarrow$ a reasonably low scalar top to compensate top-corrections.



Need $m(\tilde{t}) \lesssim 400$ GeV

  $\Rightarrow$ not very high gluino mass ($m(\tilde{g}) \lesssim 1 - 2$ TeV) to avoid 2$^{\text{nd}}$-order effects



- Depending on the models, the $\tilde{\tau}$ and the sbottom may also be light and introduce a way to avoid the inclusive limits.

- Searches with $\tilde{\tau}$ were discussed in the lepton part.

- For the others, dedicated searches exploting the identification of b-tags or because of the presence of leptons (W's in final state from top).

- Even if these models have a limited set of particles ($\tilde{t}$, $\tilde{b}$, $\tilde{g}$), they provide very complex phenomenologies.

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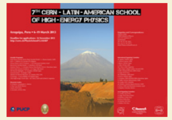
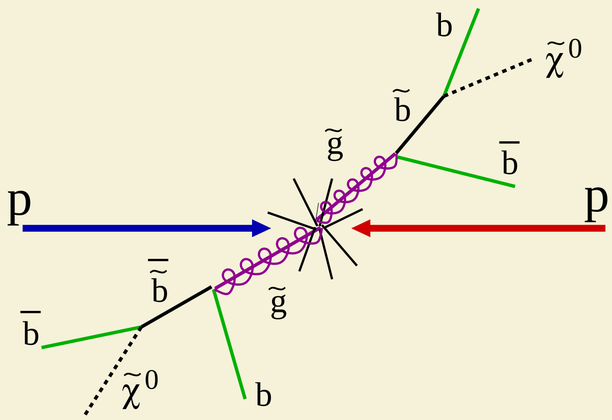
Gluino pair-production: b-jets



- Since we think the gluino is not that high, **we use it as the production mechanism of third generation squarks due to the larger cross section.**
- With the sbottom, we expect many b-jets. **Tagging 3 of them reduces the background to small levels.**
- **With the MET requirement, the signature is very clean.**



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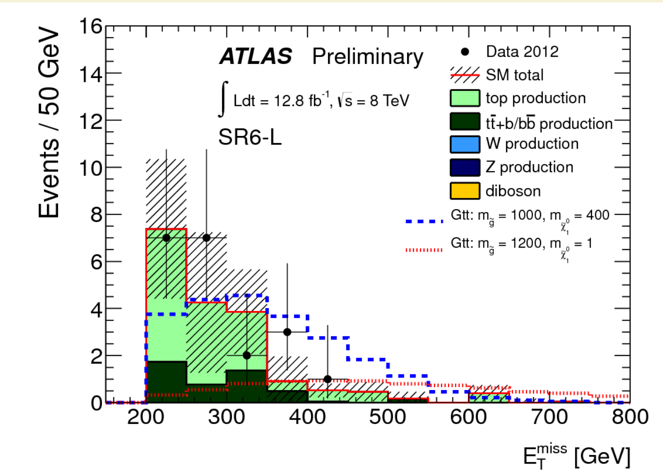
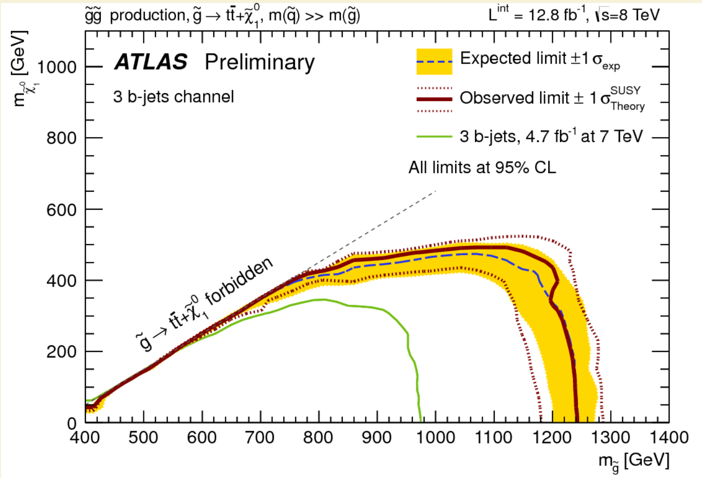
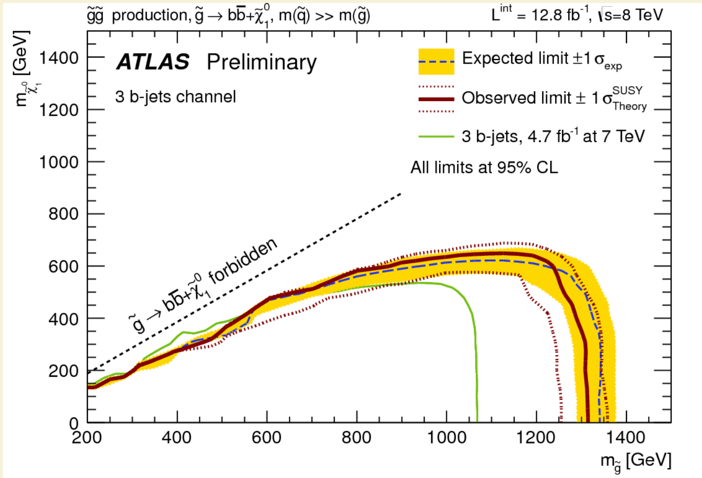






$\Rightarrow$ **Good agreement with SM backgrounds, no hint of SUSY (or other New Physics).**

$\Rightarrow$ **Also sensitivity to scalar tops, since the 4 tops decay into 4 b-jets.**

$\Rightarrow$ **Very competitive limits.**

Gluino-mediated stop production (I)

ATLAS-CONF-2012-151

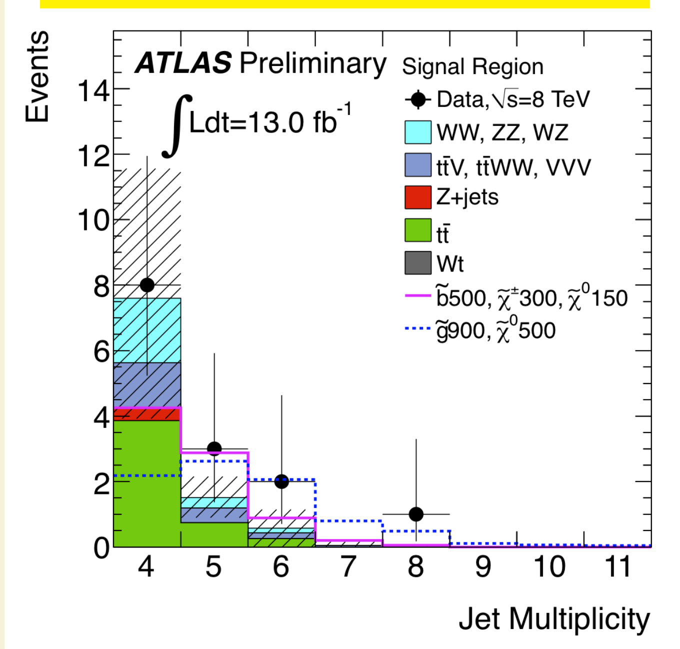
- The production of stops by gluinos provides a very rich signature that contains many kind of many different objects.

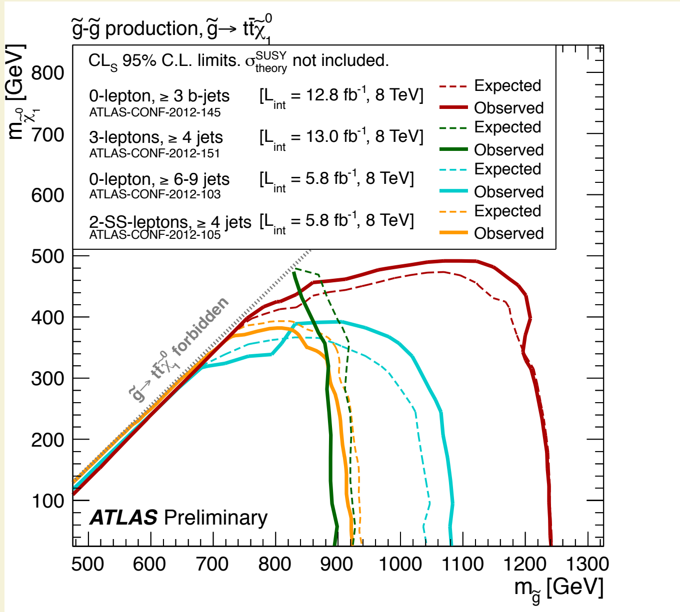
- Exploited in several signatures sensitive to this process:

  ⇒ Multi (b-)jets

  ⇒ Multileptons (from the W's)

  ⇒ Same-sign leptons





- Analyses covering the several options, specially since these are striking signatures by themselves.

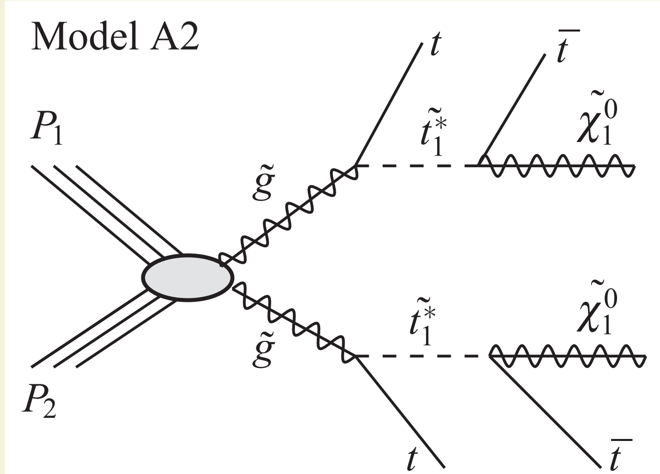
- Good agreement observed in the signal regions.

- The SM predictions at its best:

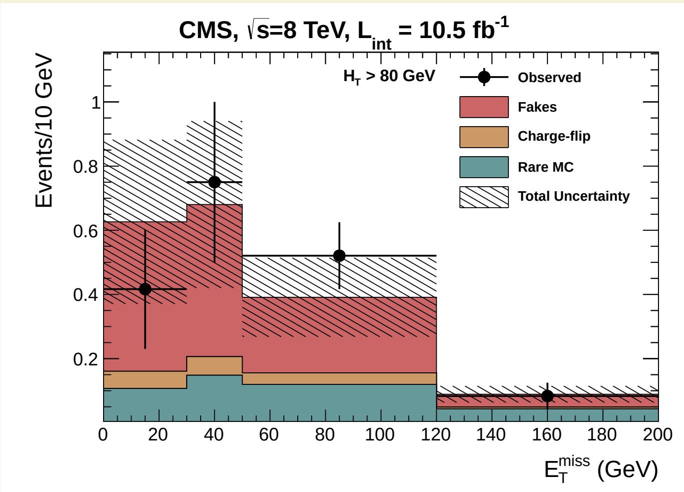
really challenging final states

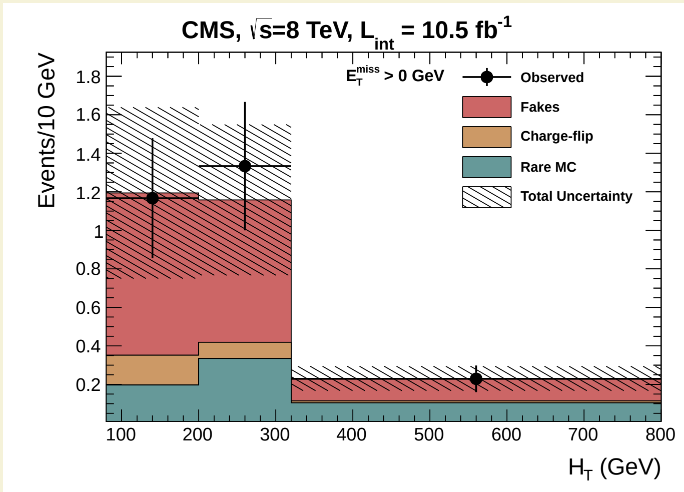
Gluino-mediated stop production (II)

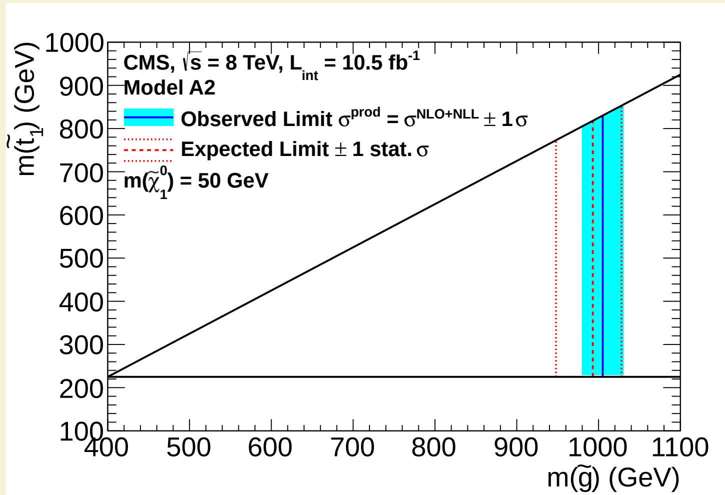
- It should be remarked that **these searches are valid even with virtual stops.**
- Although sensitivity may be a bit lowered due to softer objects.
- Sometimes specificselections are found for those cases: **looser cuts, veto on hardness against top-pair production.**



arXiv:1212.6194





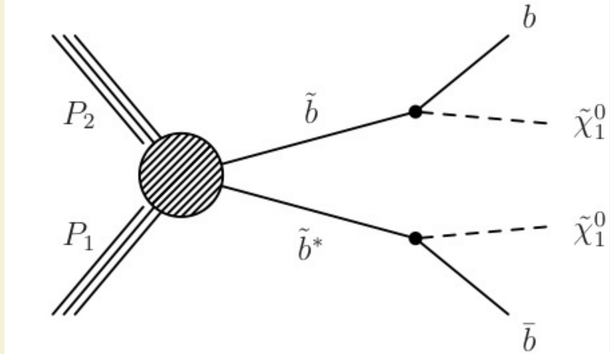


⇒ Good agreement in the same-sign dileptons at CMS.

⇒ Limits..., also in the ATLAS analysis (see previous slide).

Direct sbottom production

- When using gluino-mediated production, signatures are striking.
- but we are ignoring that the gluino may be too high to be produced.
- Looking at direct production of sbottoms, less striking signature, but still competitive.



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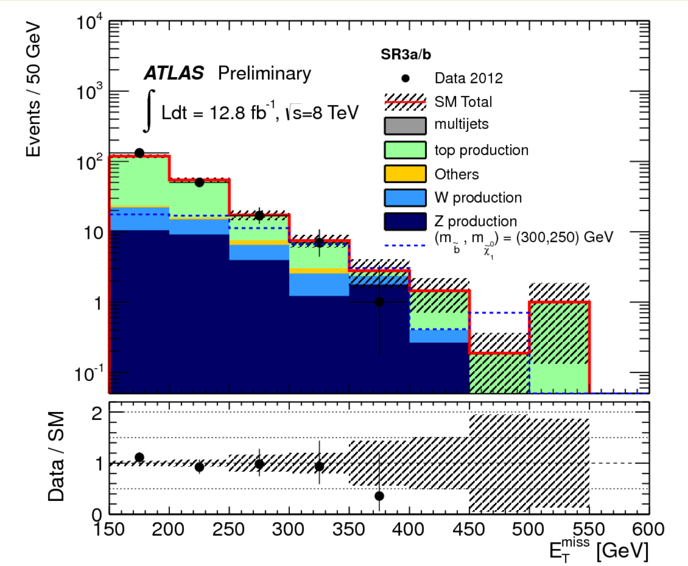
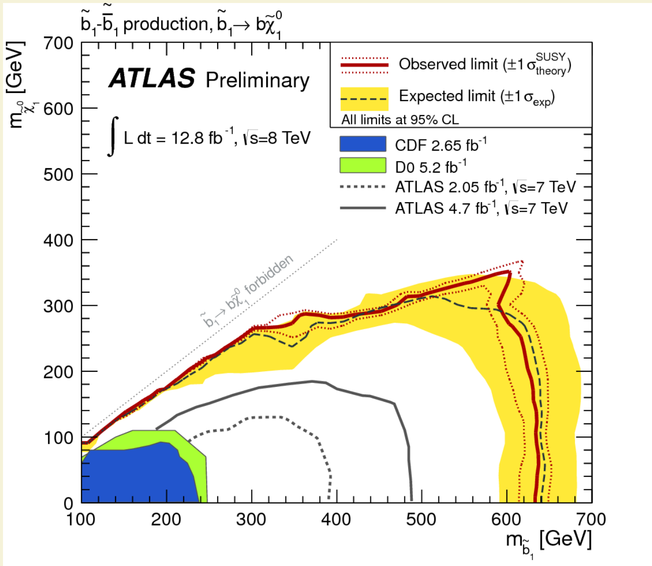
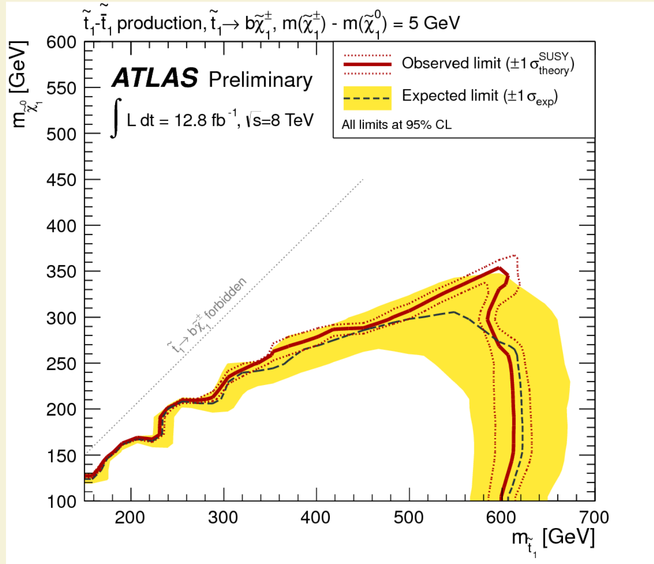




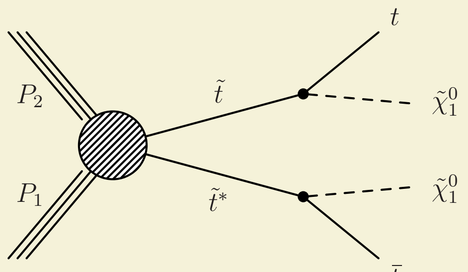
ATLAS-CONF-2013-001



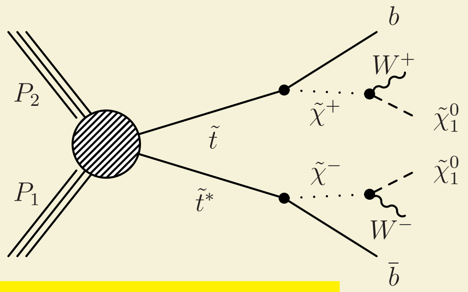
- Same final state also interpreted as stop search, where $\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW^{(*)}\tilde{\chi}_1^0$
- Competitive limits in both cases.

Direct stop production (I)

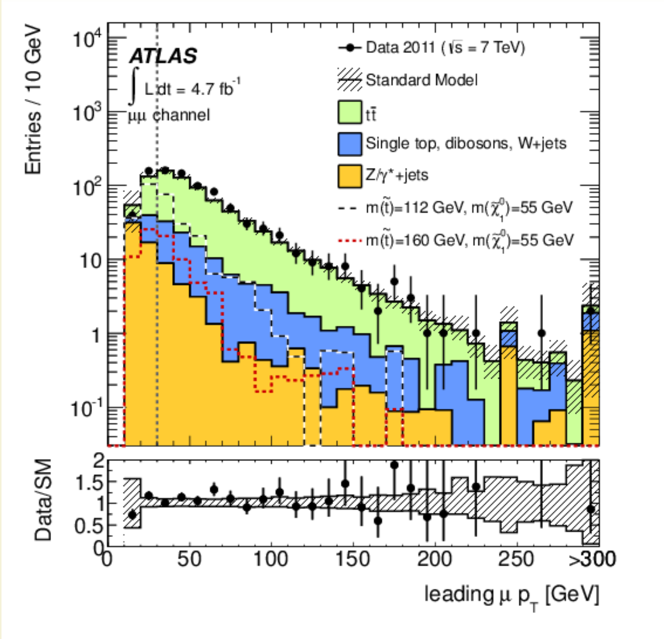
- In the case of the stop, the obvious channel is $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ where the chargino may be virtual.

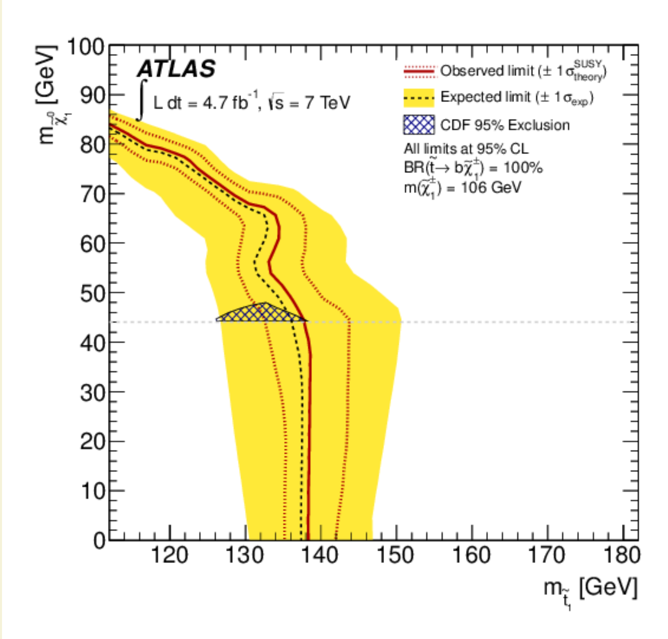


- Specific analysis for each case, due to different kinematics.
- Looking at leptonic channels (less background).

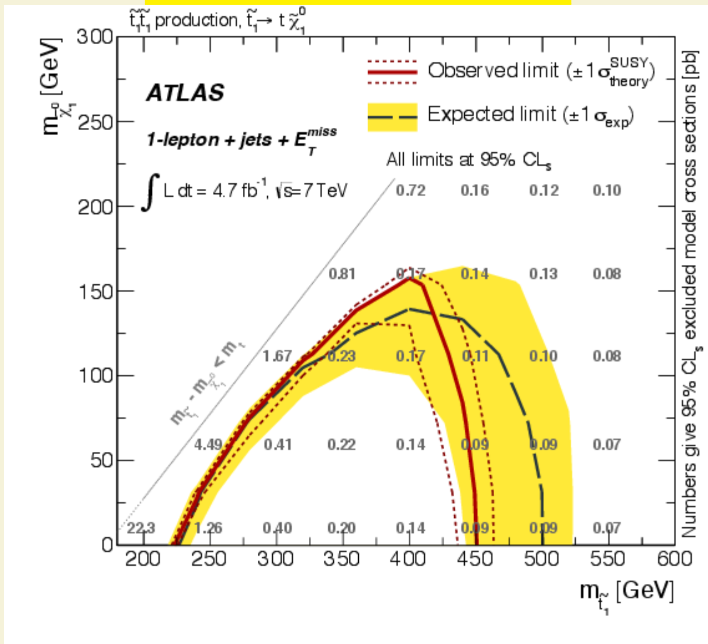


arXiv:1208.4305





arXiv:1208.2590

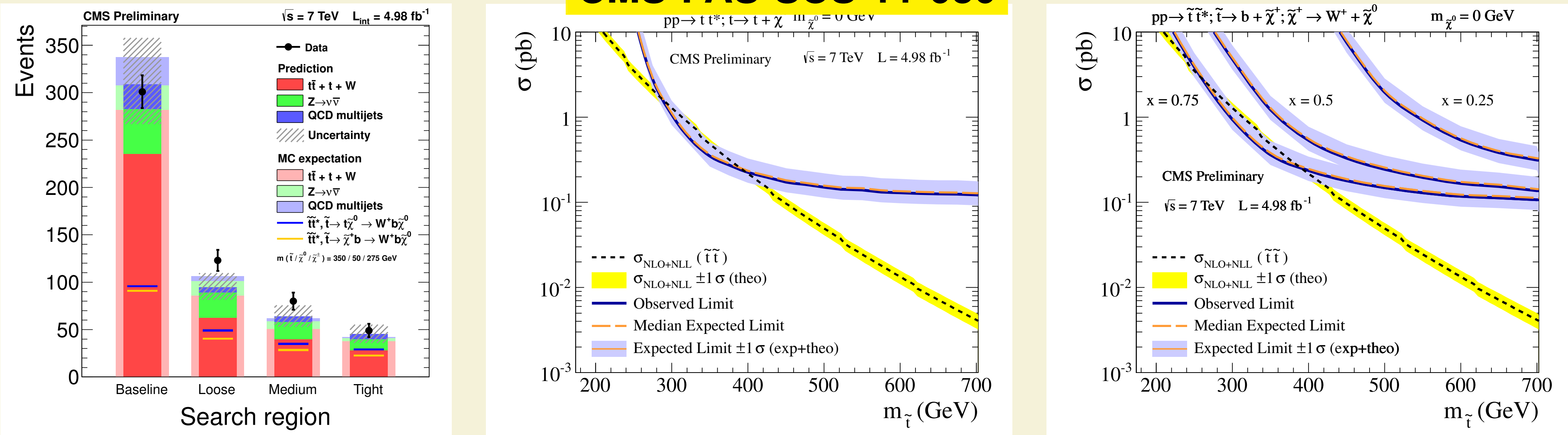


- Excluding big areas in the parameter space. **Degeneracy region not excluded.**

Direct stop production (II)

- Similar signature by CMS, but **now looking also at the hadronic decays.**
- Still with MET due to LSP in the final state.
- Same final state as usual $\tilde{t} \rightarrow t\tilde{\chi}^0_1$. **Sensitivity to both channels possible due to lack of top tagging tools.**

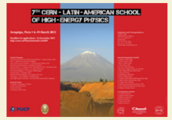
CMS-PAS-SUS-11-030



⇒ Dominant background $t \rightarrow bW(\tau_h \nu)$ estimated with τ-embedding.

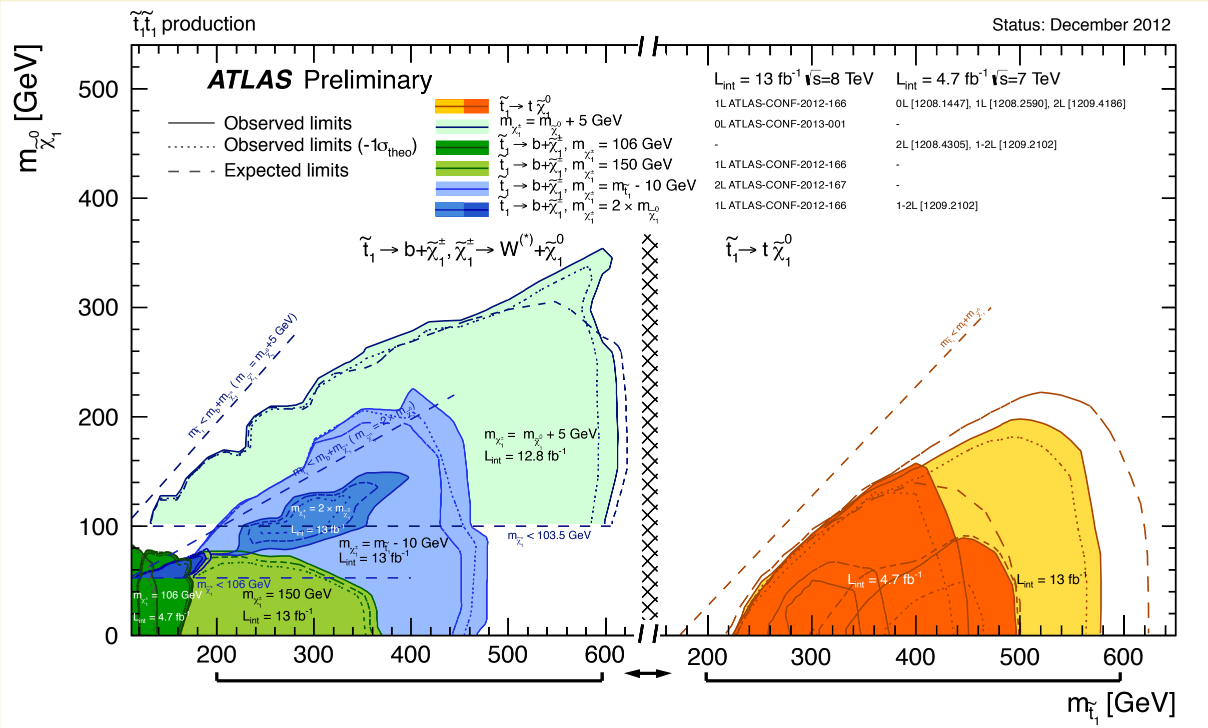
⇒ Nice agreeement, limits in the two possible decay chains.

Where are all these guys hiding?



- Despite of the strong motivation, **"obvious" Supersymmetric partners are not as close to the EWK scale as thought.**

- **Studies performed in many signatures and methods, in searches that are more inclusive or more topology dependent: measurements well reproduced by SM.**



⇒ Limits set in many parameters and models.

⇒ No obvious hint on where to keep looking…

look everywhere, as always!

⇒ Perhaps higher energy: waiting for 13-14 TeV!

- **Still more data to go, even from the last year: perhaps news to come soon.**

- **But perhaps it is the time to consider other posibilites, even those still that include SUSY: long-lived states, R-parity violating SUSY, … Covered in the third lecture!**

Overview and Conclusions

- The LHC program is at full speed now.
- Results available in record time in most of the topics.

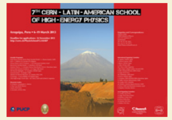
⇒ Heavy-Ion Physics:

- LHC has passed previous frontiers in the field.
- A step forward in energy and statistics.
- The era of discovery/Preliminary studies: moving towards precision physics!

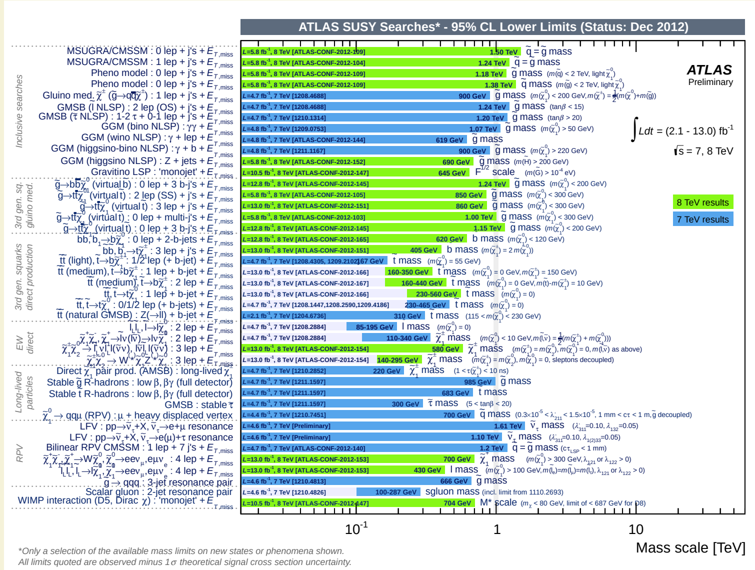
⇒ Studies of the properties of the top quark:

- Very precise measurements of properties.
- Even differential cross sections.
- Constraining SM parameters: new era for top physics.
- Sensitivity to New Physics in the top sector has exploded.

Overview and Conclusions (cont'd)



⇒ **Searches of Supersymmetric particles:**



– No evidence of superparticles.

– Experiments covering all possibilities at reach.

– SUSY may be there, hiding under unlucky cancellations or degeneracies.

– Tons of results and limits… experiments doing summary plots.

– Already expecting the 14 TeV run!

• The good understanding of the detectors and analysis tools (described in first lecture) already yields impressive achievements in goals.

• This will improve with further data and better analyses.

• In addition, the feedback from these measurements are fundamental pieces for discoveries at the LHC, covered in the third lecture…)