LHC Physics: SM processes

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Outline

- Studies and results within the Standard Model
  - QCD
  - Final states with W and Z bosons
  - Top physics

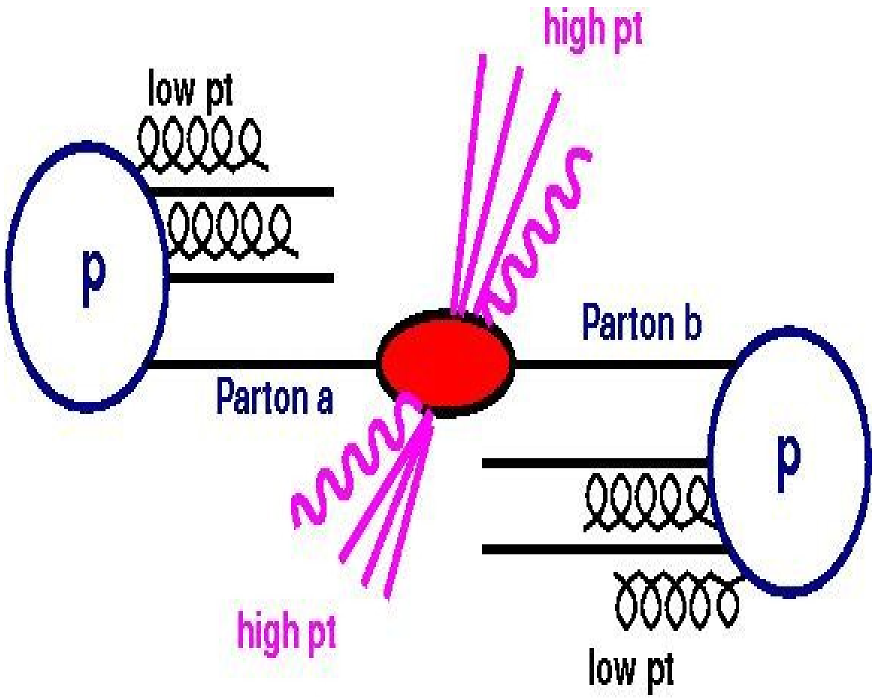
Couple of comments on SM processes

- Large cross sections in many cases ($\gtrsim$nb):
  - Their detailed study is an essential part of the LHC physics programme
- Their physics is interesting per-se:
  - Constraints on PDFs, precise measurement of fundamental parameters, search for tiny deviations from theory (vis cross sections, asymmetries, ratios, ...)
- They are the dominant background for many new physics signals:
  - Their understanding at the "percent" level is nevertheless a must in order to exploit the full potential of the LHC program
  - This is particularly important NOW in view of the next LHC phase of high-luminosity (HL-LHC)

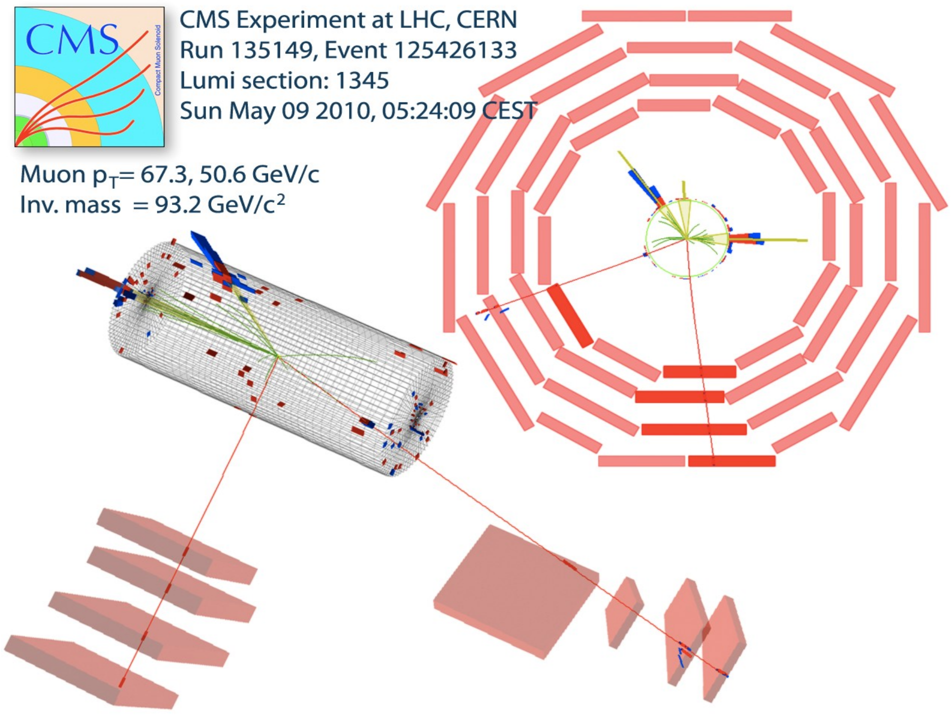
QCD

QCD at hadron colliders

- QCD is present in ALL processes of interest, since we are "colliding" quarks and gluons and they "QCD-radiate"



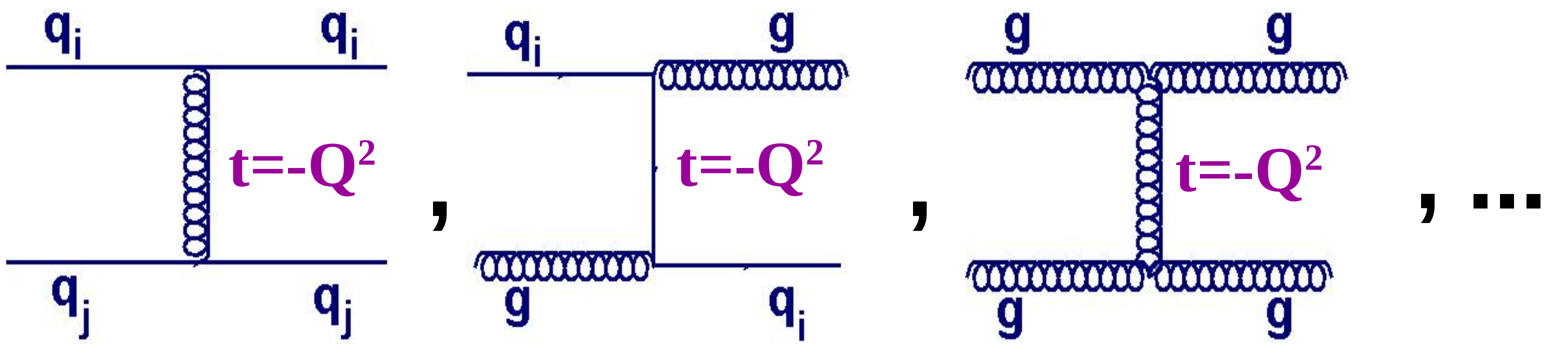
'hard interaction' 'Underlying event'



First Z+X event in CMS: two jets from hard 'QCD radiation'

QCD at hadron colliders

- Most of the events that we record at hadron colliders correspond to pure QCD processes. Cross sections are huge, dominated by t-channel diagrams, with QCD couplings $\alpha_S(Q^2)$ that increase substantially at low Q^2

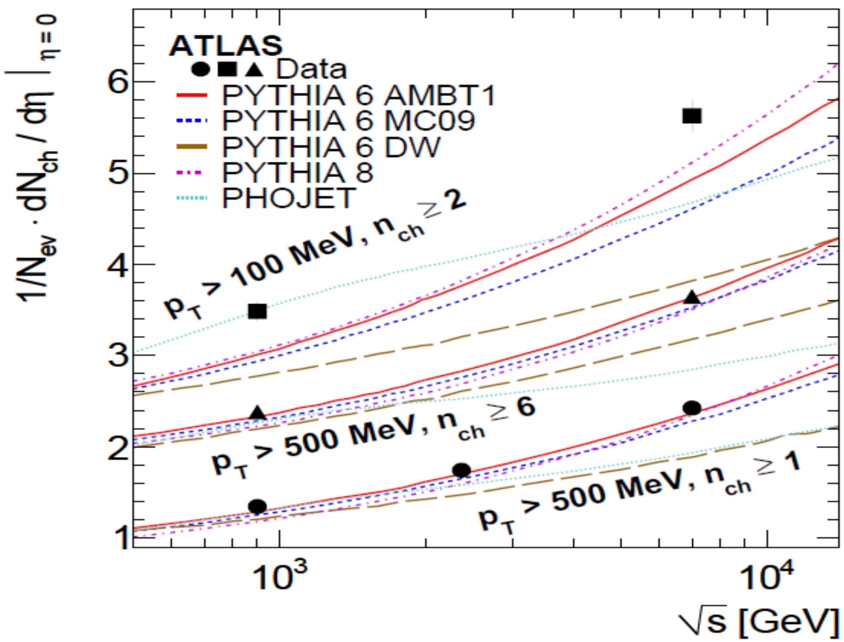


- Therefore we expect many (inelastic) interactions with hadrons in the final state, most of them with LOW p_T activity in the detector. This is what we usually identify with **MINIMUM BIAS EVENTS.** They are essentially events triggered by very loose activity (scintillators, calorimetry, tracks) in the detectors

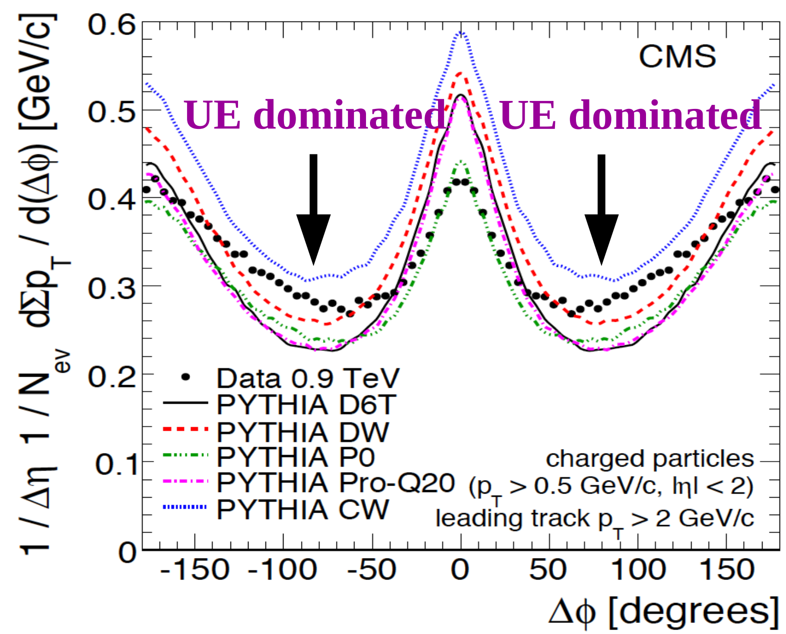
QCD at hadron colliders

• Obviously, total and low-p_T cross sections were the first ones to be measured at hadron colliders, as well as event multiplicities:

a) arxiv:1012.5104



b) arxiv:1006.2083



Some surprises with "non-perturbative" effects already at the beginning of the LHC:

a) evolution of the charged multiplicity per event (η=0) as a function of $\sqrt{s}$

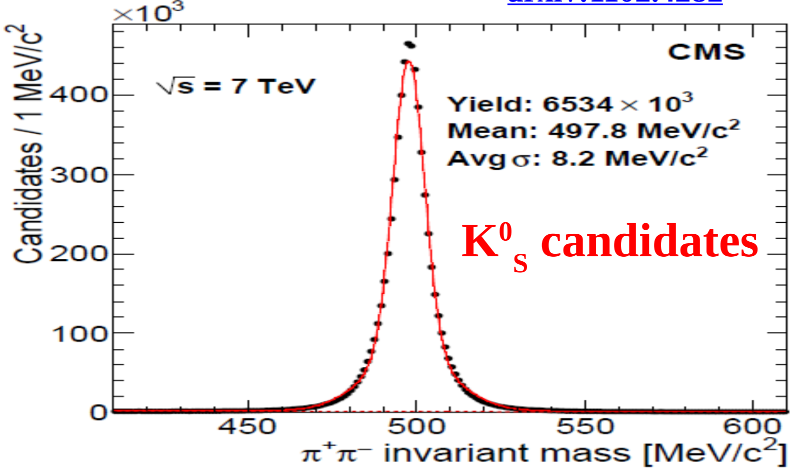
b) underlying event (UE) effects

- **Rise with energy more pronounced than predicted by initial models at the start of LHC → TUNING!**
- **Effect mostly seen as an excess of 'low p_T particles' (p_T< 1 GeV)**
- **Underlying event description not appropriate either → MORE TUNING!**

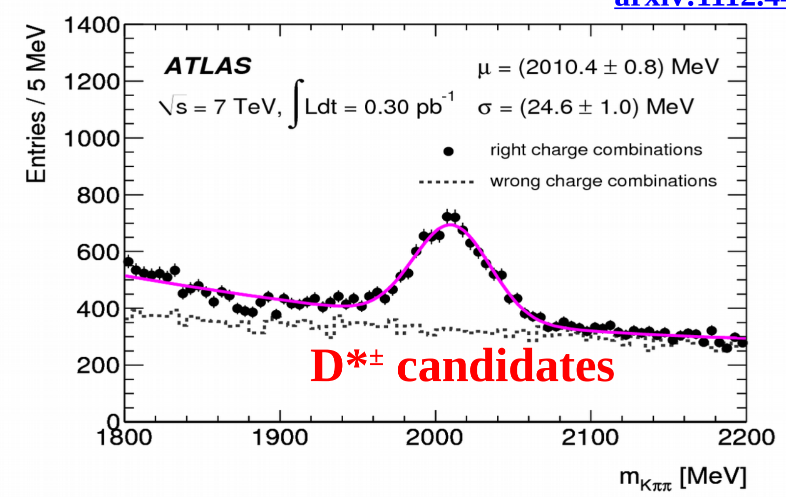
QCD at hadron colliders

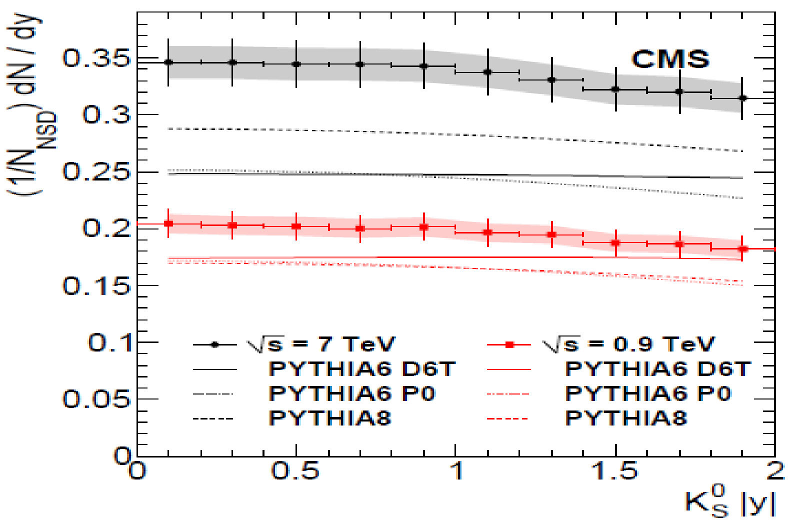
• Other 'surprise' at the LHC: production rate of strange and charmed particles larger than what is predicted by current LO MCs → more tuning needed

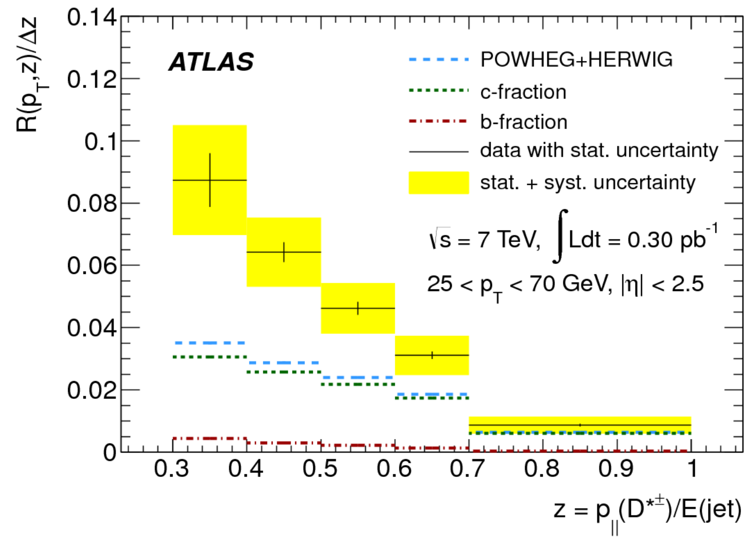
arxiv:1102.4282



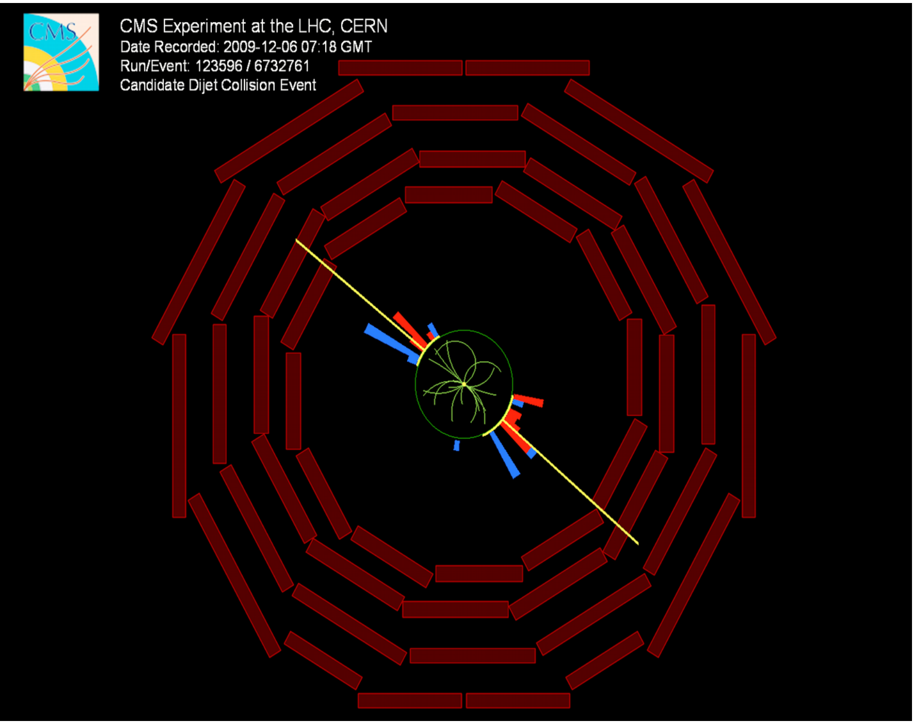
arxiv:1112.4432

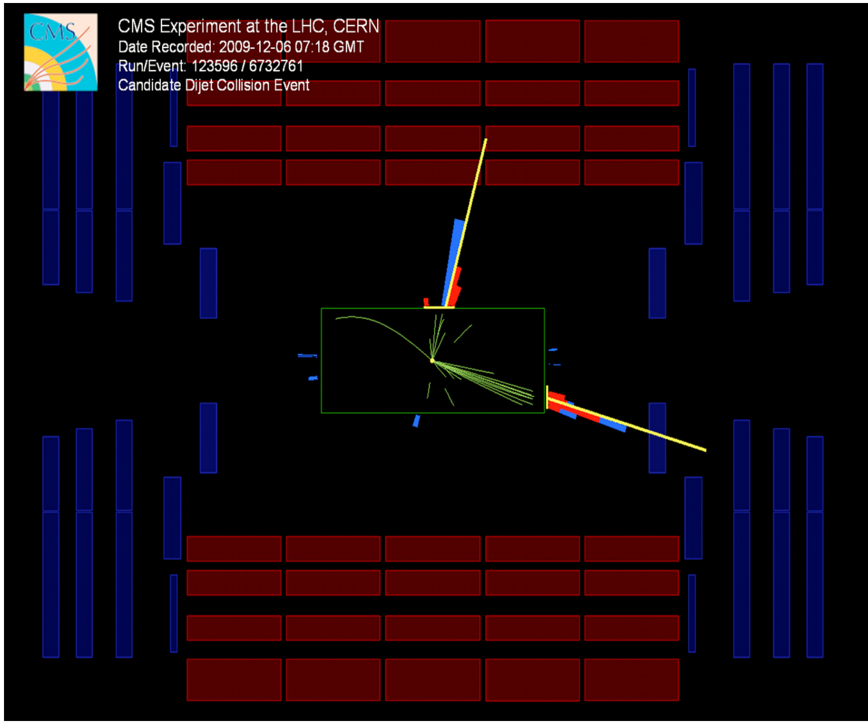






What about QCD at high p_T?





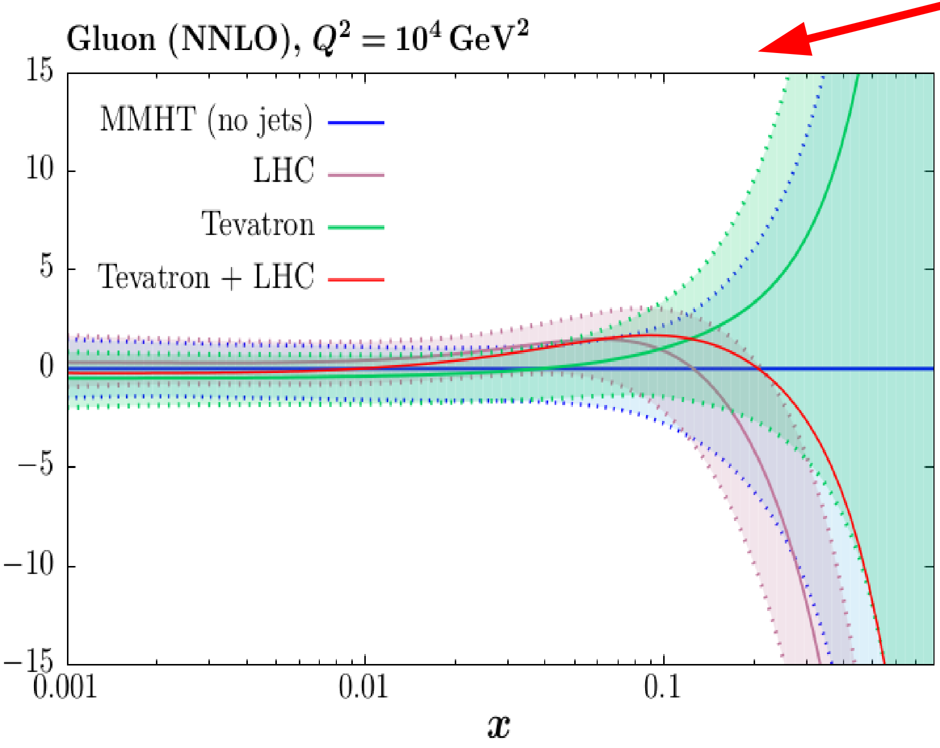
Transverse view **Longitudinal view**

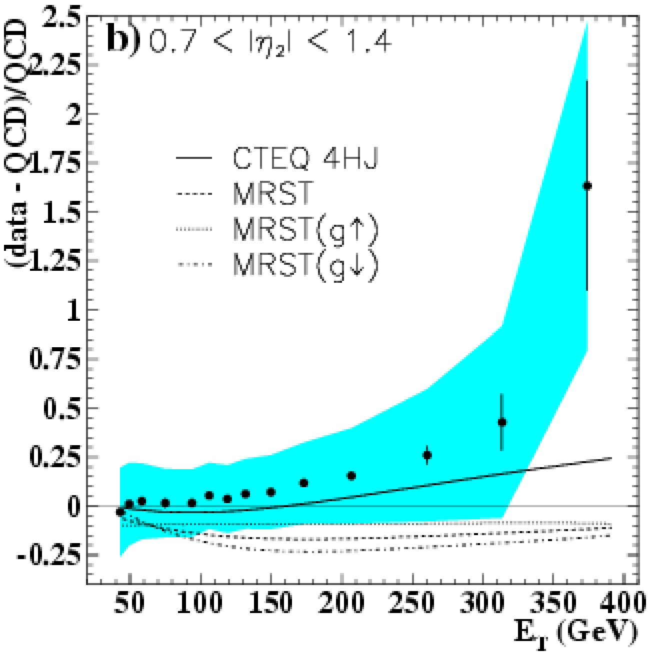
- Typical high-p_T di-jet events look like this at a hadron collider.

Energy is balanced only in the transverse plane

Jet production at high p_T is important

- It tests the validity of the Standard Model down to sizes of order $\hbar/p_T$.
- It also checks and constrains the parton density functions of the proton, and in particular of the gluon at high Q^2 and $x \gtrsim 0.1$



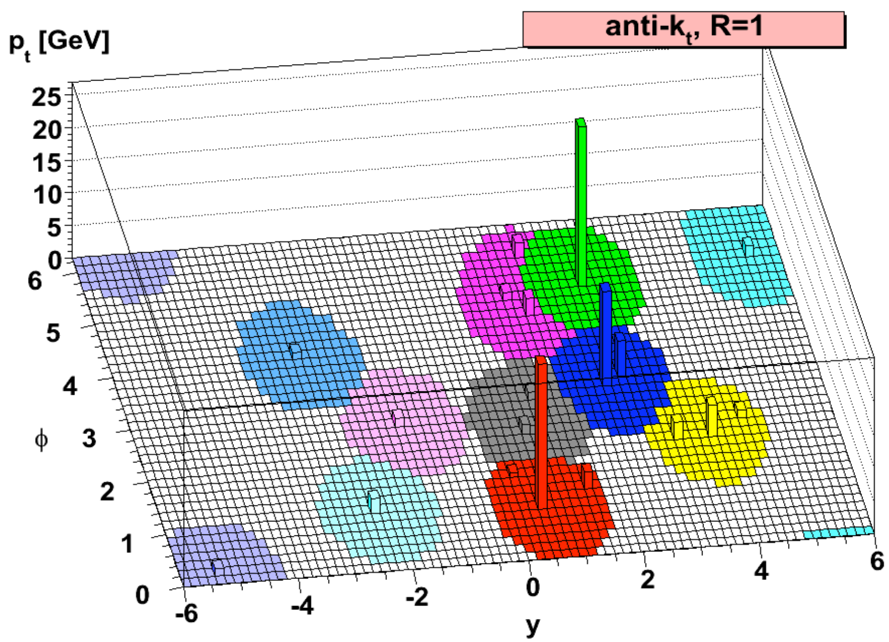


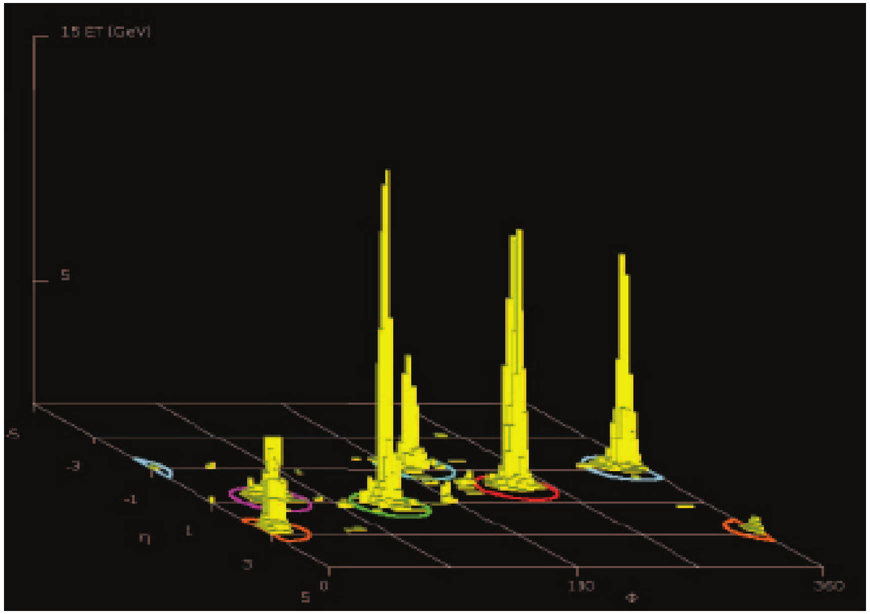
CDF comparisons of the dijet rate with theory in 2001, for (now old) NLO PDFs

THIS WAS NOT NEW PHYSICS!!

Jet production studies

- In ATLAS and CMS we reconstruct jets using the anti-kT algorithm, with a typical separation parameter $\Delta R \equiv [(\Delta\varphi)^2+(\Delta\eta)^2)]^{1/2} = 0.4$:
  - Infrared and collinear safe algorithm
  - It recombines less soft particles
  - It produces 'symmetric' areas in the Φ-η space

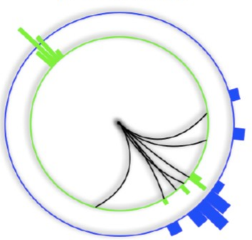


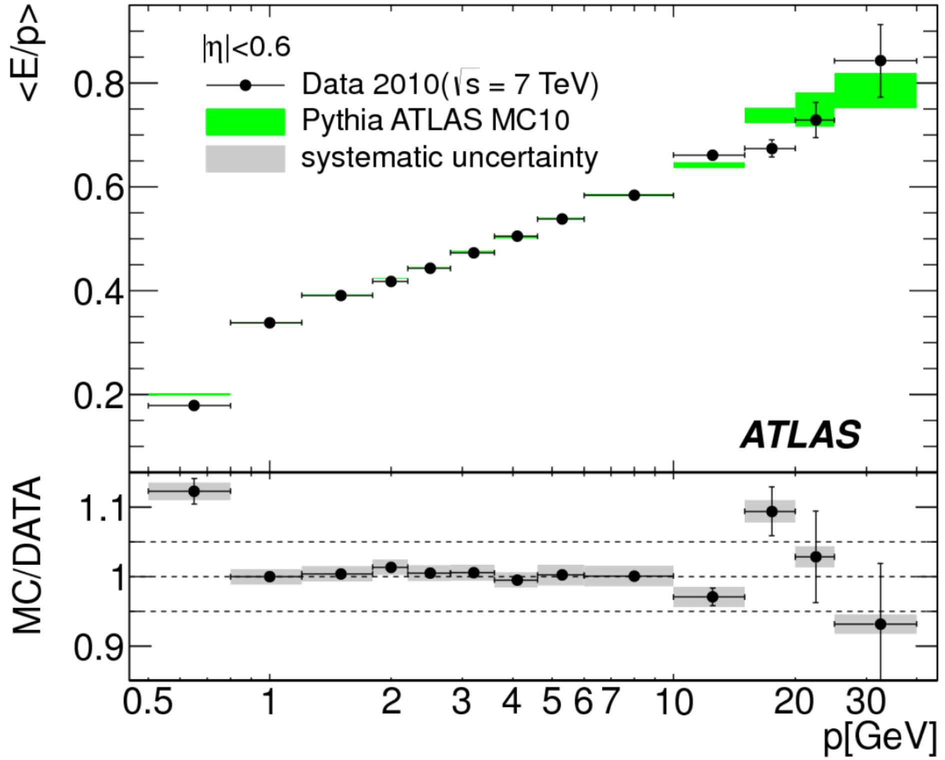


Real multijet event in ATLAS

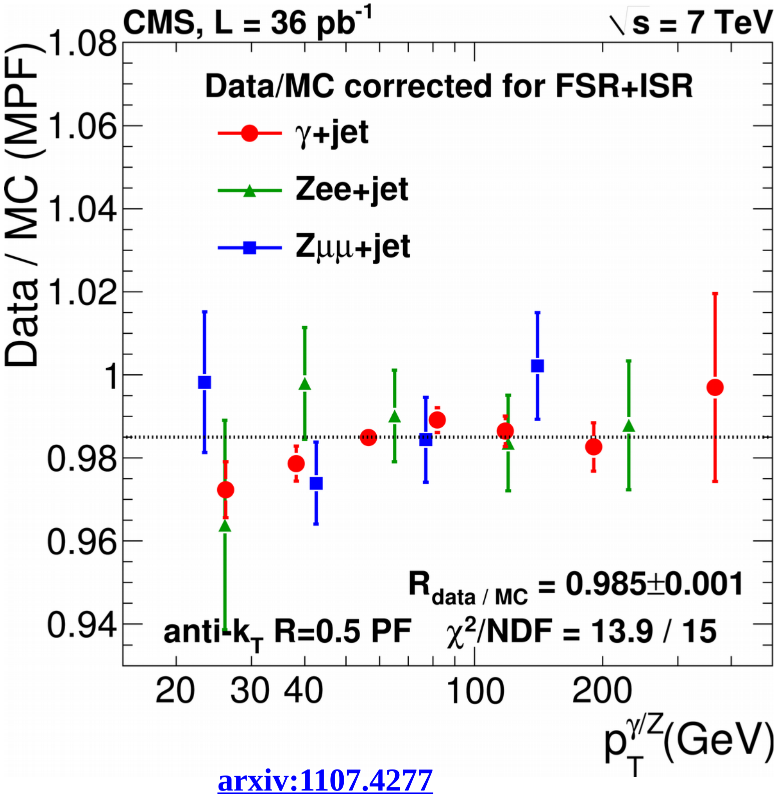
Jet production studies

- Historically, we have been building jets using electromagnetic+hadronic depositions. This is indeed mandatory at the trigger level 1, where there is not time to process tracking information (note: this will change in LHC Phase 2):
  - One needs to apply corrections to the deposited energy (which is particle-dependent): particularly sizeable in the calorimeters (up to factors of 2 or so)
  - Many methods are used: single particle response (E/p), γ+jet balance, ...





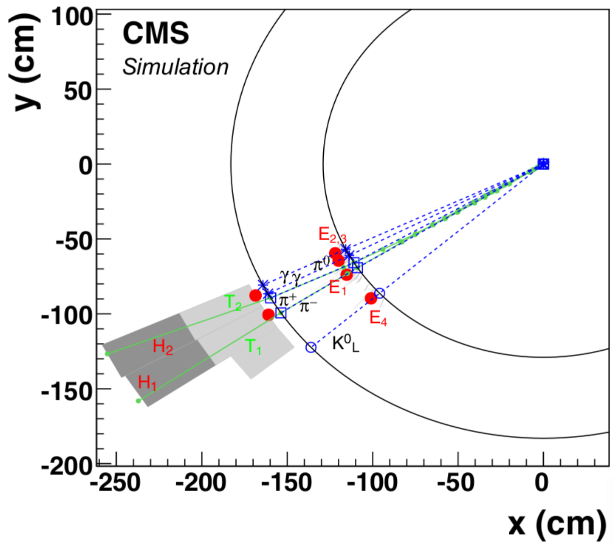
arxiv:1203.1302



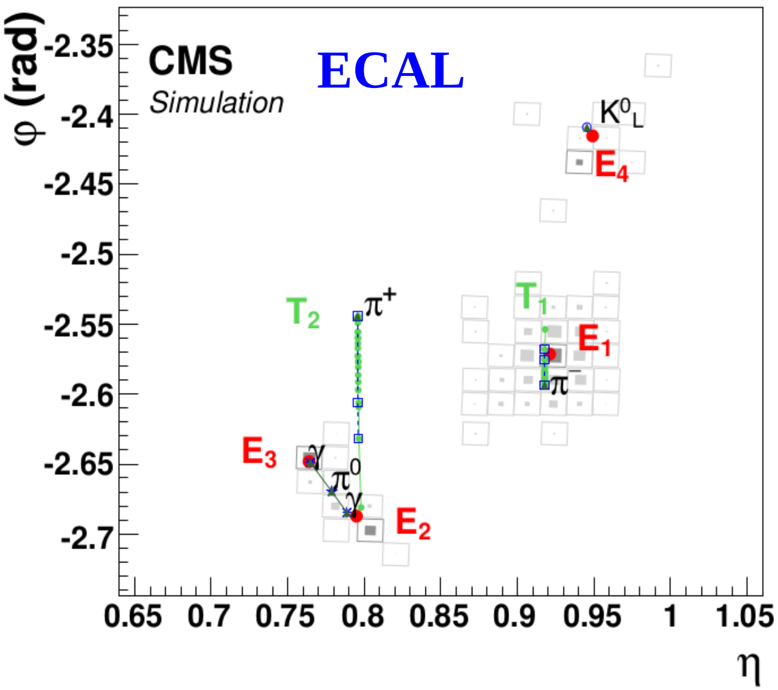
arxiv:1107.4277

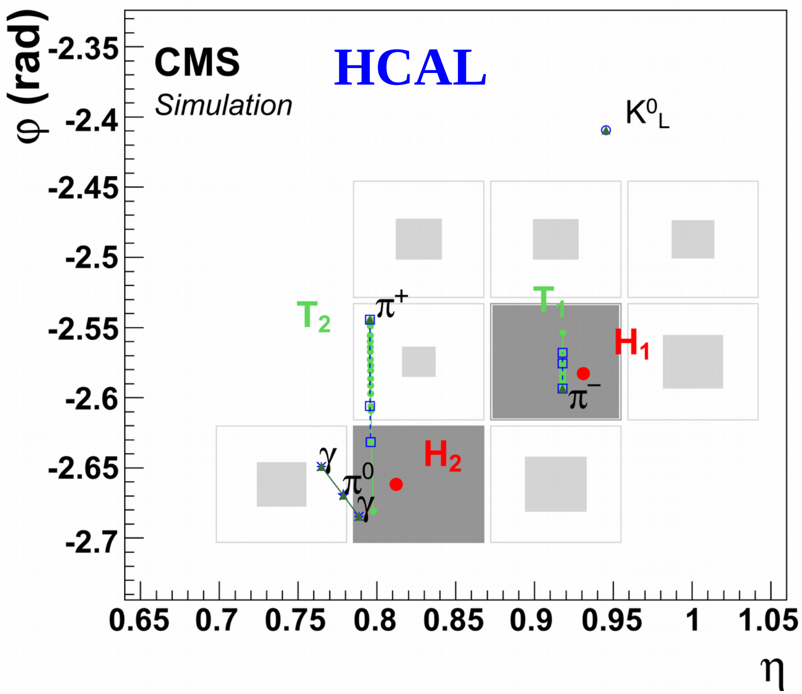
Jet production studies

arxiv:1706.04965
arxiv:1703.10485



- The state of the art today imposes the use of particle-flow reconstruction techniques:
- Global reconstruction using all subdetectors + particle identification => improved resolution
- **Example:**

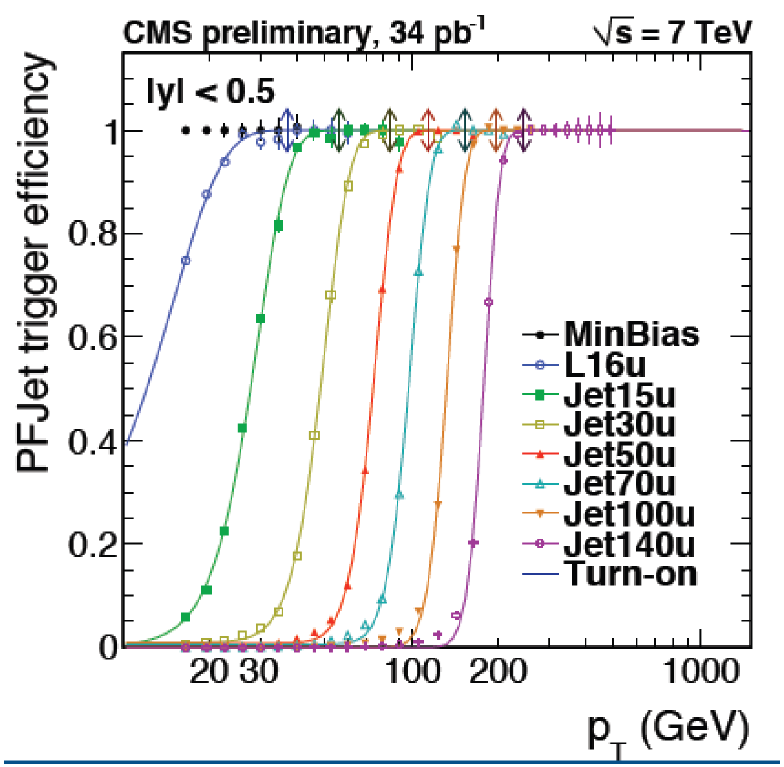


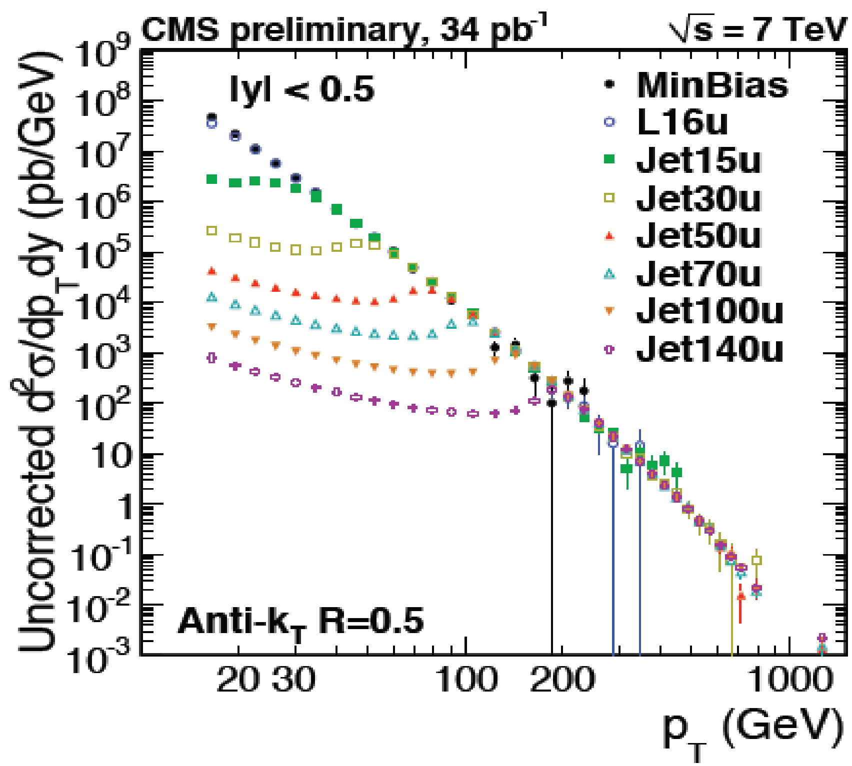


The 'real' analysis world

Sample	Prescale
Jet30U	111
Jet50U	10.9
Jet70U	4.1
Jet100U	1.9
Jet140U	1

- Main cut: events with two jets found with p_T>20-30 GeV
- First experimental difficulty: we do not record all events. We PRE-SCALE events differently depending on TRIGGER jet thresholds. CMS example from early analyses (√s=7 TeV)

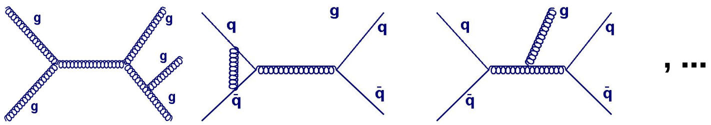




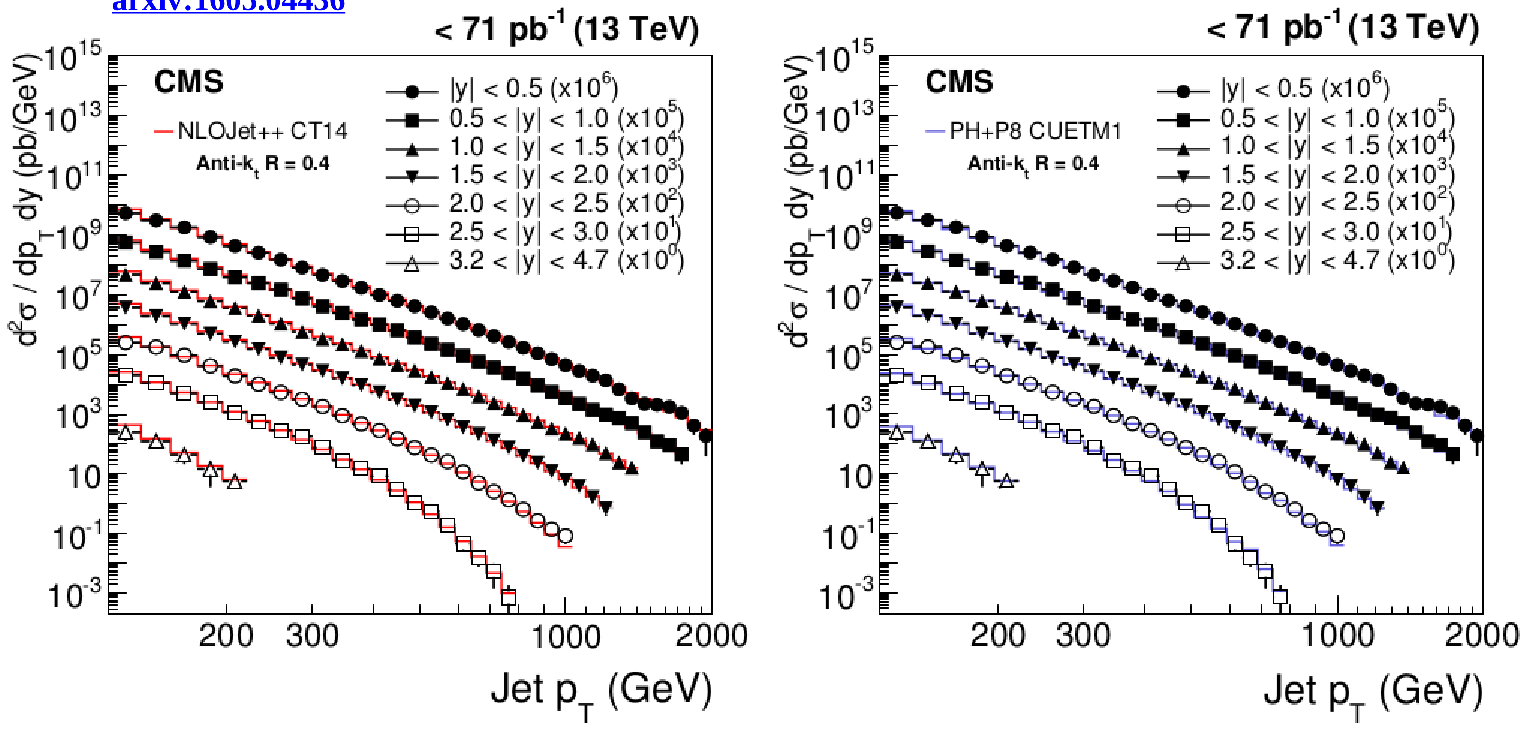
Used in arxiv:1104.1693

The 'real' analysis world

- State of the art TODAY: NLO calculations (perturbative: NLOJet++) and NLO+parton shower generators are available (POWHEG+Pythia,...). Two approaches:
  - Correct non-perturbative and EWK effects and then compare with NLO calculations
  - Direct comparison with NLO simulations



arxiv:1605.04436

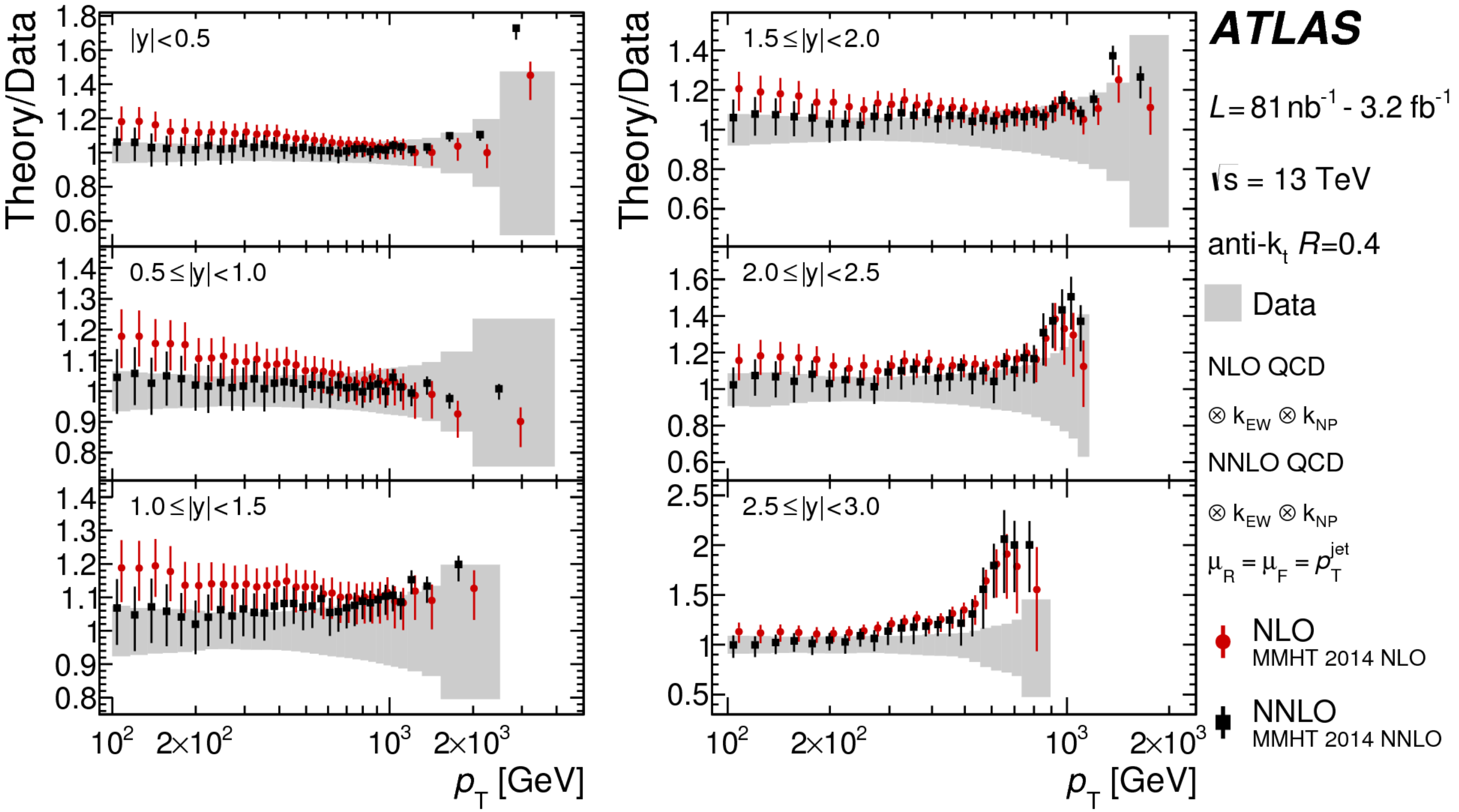


Good agreement with NLO predictions over >10 orders of magnitude

Jet production at the LHC

•Looking at it in more detail, the agreement is good but not perfect. Data show some tiny differences with respect to the predictions, even if things are consistent within uncertainties

arxiv:1711.02692

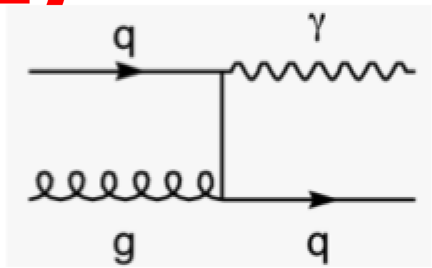


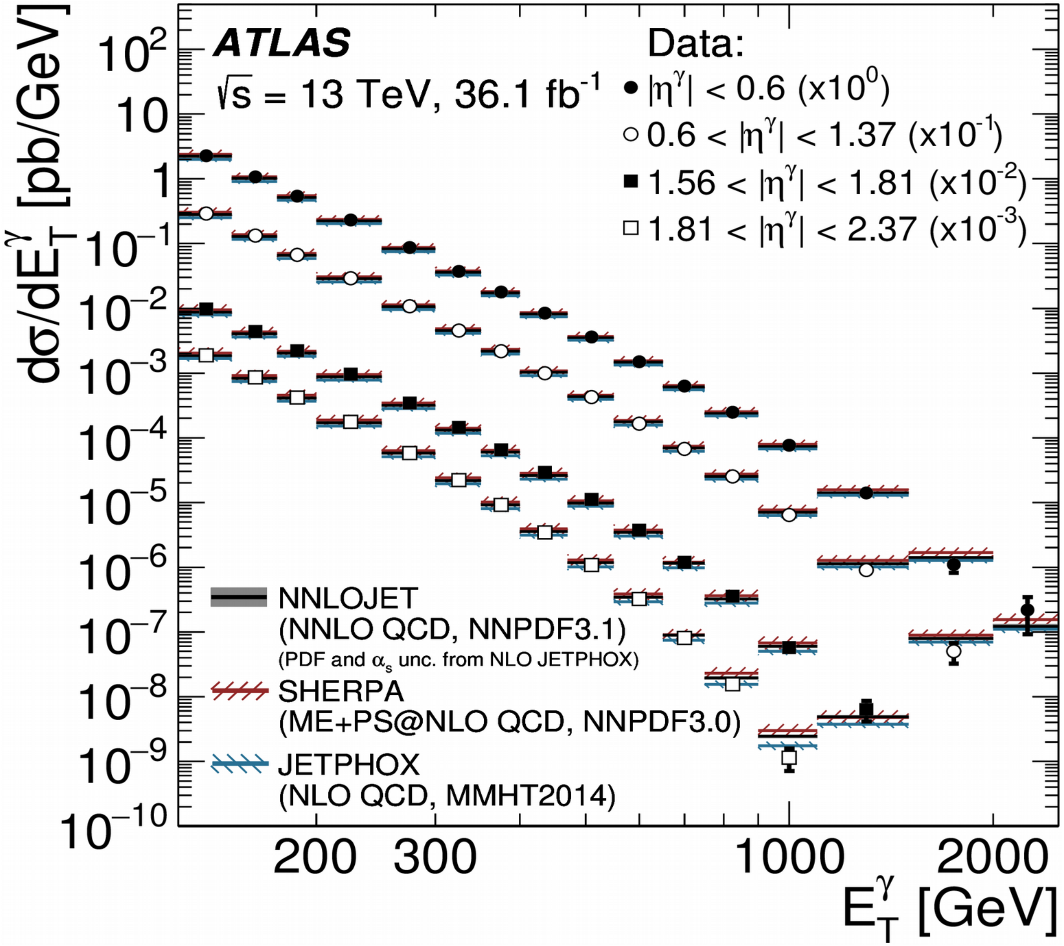
• **Experimental cross section are on the low side, in particular in some large rapidity regions compared with theory**

• **Note however that the (dominant) uncertainties from scales are “educated guesses”**

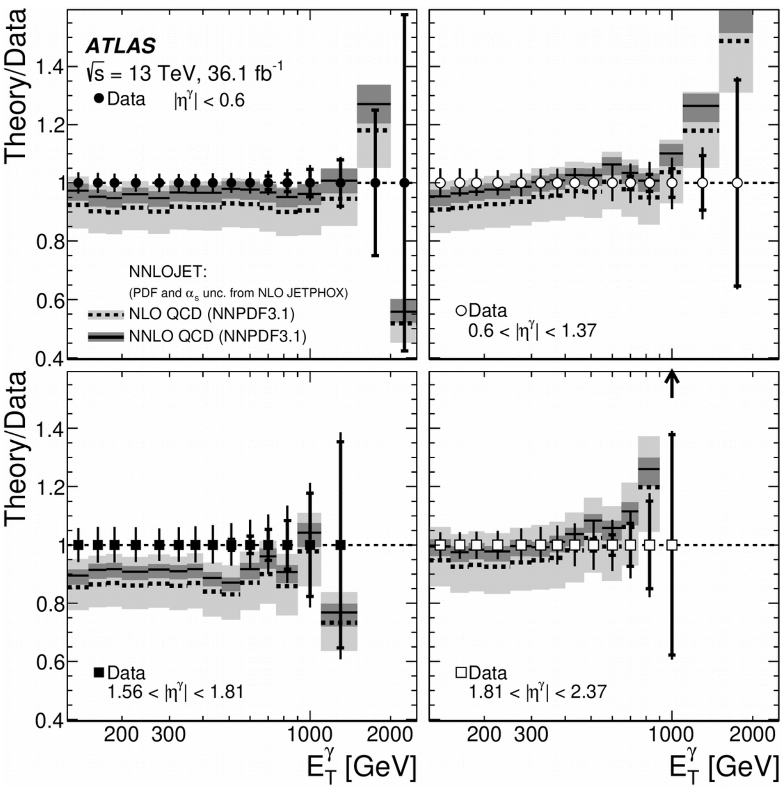
Photon+jet (Run2)

- Extremely sensitive to gluon PDFs
- Good agreement with NNLO predictions
  - Agreement data-theory far from satisfactory in the past



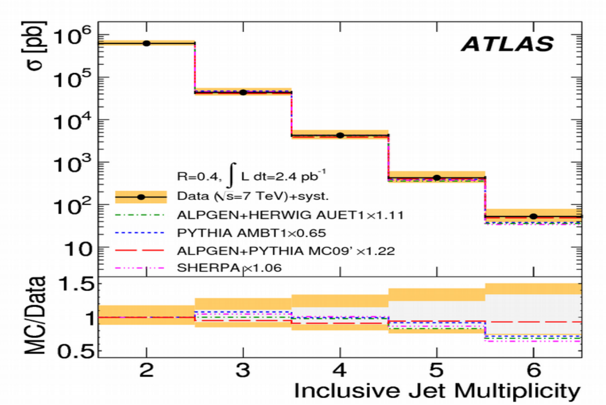


arxiv:1908.02746

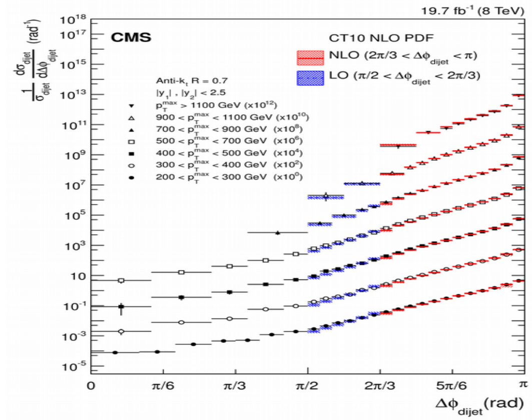


Many more QCD results at LHC...

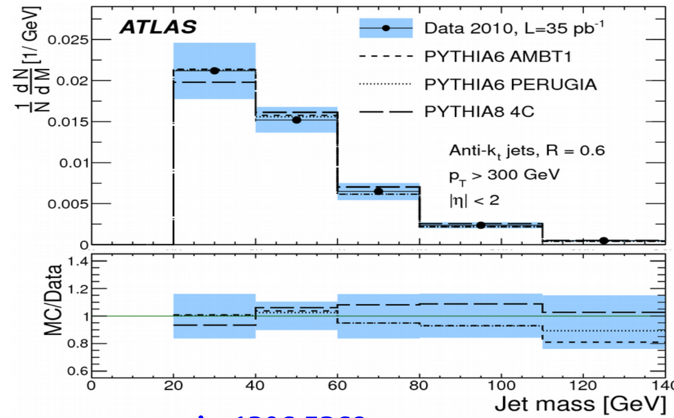
- But no time to go over them: multi-jet production, dijet angular (de-)correlations, di-jet mass mass distributions, distributions shape variables, measurement of α_s, jet substructure, ...



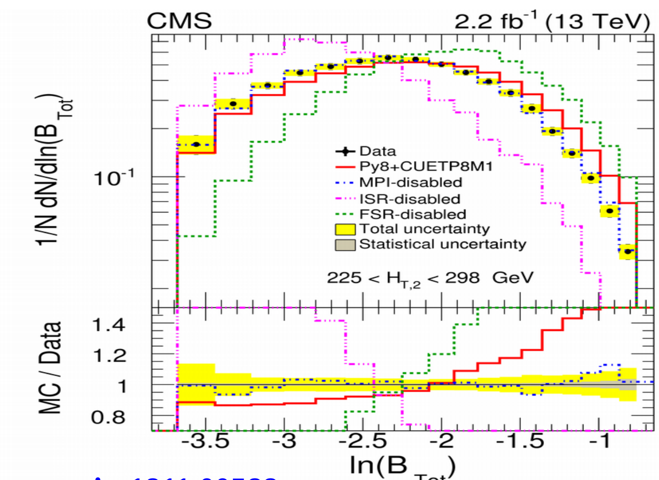
[arxiv:1107.2092](https://arxiv.org/abs/1107.2092)



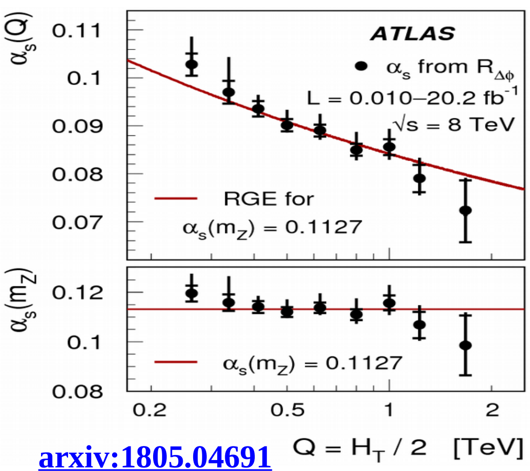
[arxiv:1602.04384](https://arxiv.org/abs/1602.04384)



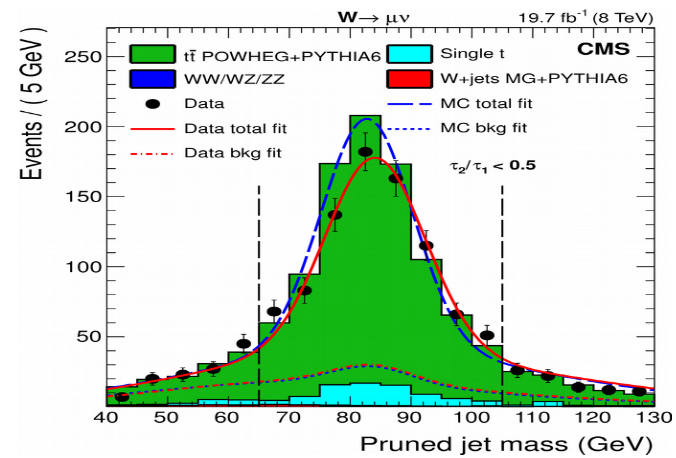
[arxiv:1206.5369](https://arxiv.org/abs/1206.5369)



[arxiv:1811.00588](https://arxiv.org/abs/1811.00588)



[arxiv:1805.04691](https://arxiv.org/abs/1805.04691)



[arxiv:1410.4227](https://arxiv.org/abs/1410.4227)

- **Many of these studies are important for particle searches in final states with jets**

W and Z production

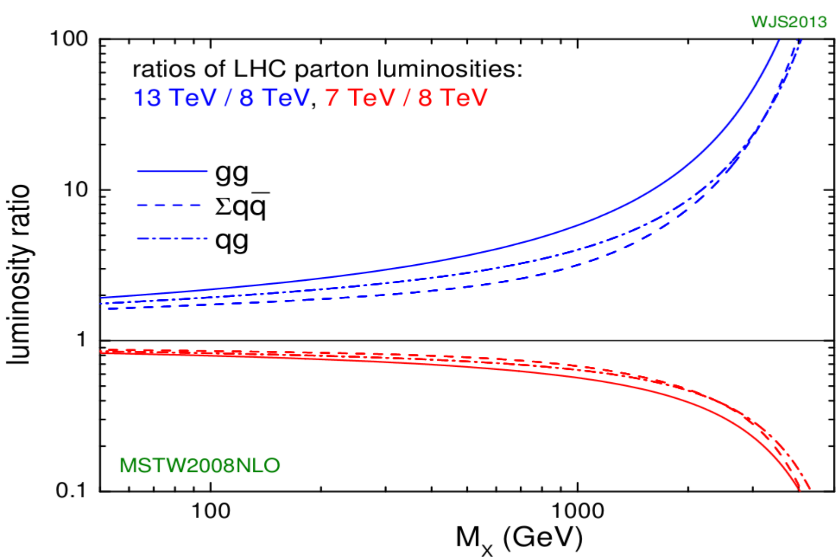
W and Z production at LHC

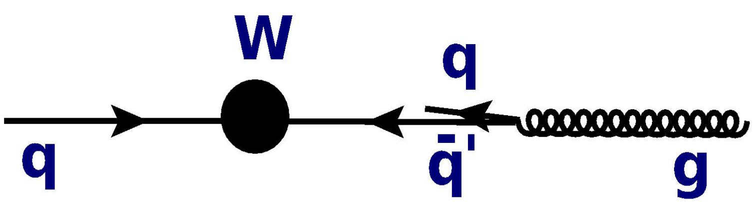
- We use leptonic decays (W→l+ν,Z→ll) for most analyses (clean, precise)
- W and Z production at LHC proceeds at the hard scattering level and leading order (LO) mostly via a valence quark (u,d) and a sea quark:

$$u+\bar{d}(\bar{s})\rightarrow W^{+}\rightarrow l^{+}\nu \qquad u+\bar{u}\rightarrow Z\rightarrow l^{+}l^{-}$$

$$d+\bar{u}(\bar{c})\rightarrow W^{-}\rightarrow l^{-}\bar{\nu} \qquad d+\bar{d}\rightarrow Z\rightarrow l^{+}l^{-}$$

- u quarks than More W+ than W- produced (more u quarks than u quarks, equal number of $\bar{u}$ and $\bar{d}$)
- Cross sections at LHC increase significantly with √s (factor of 2 between √s=8 TeV and √s=13 TeV





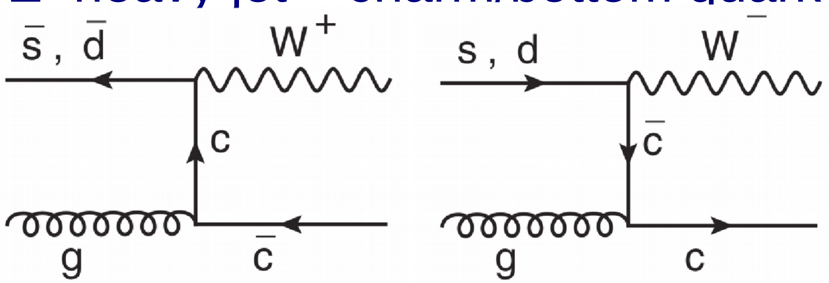
qq̄ enhancement via QCD evolution of PDFs with x,Q^2

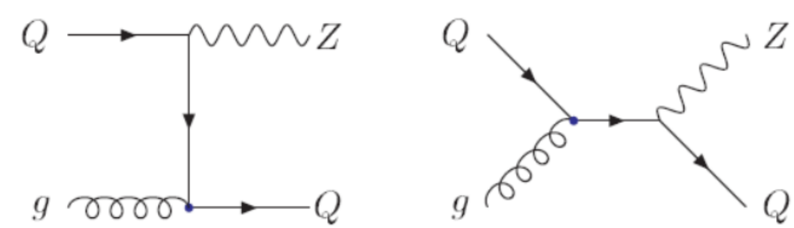
W,Z at LHC: PDF studies

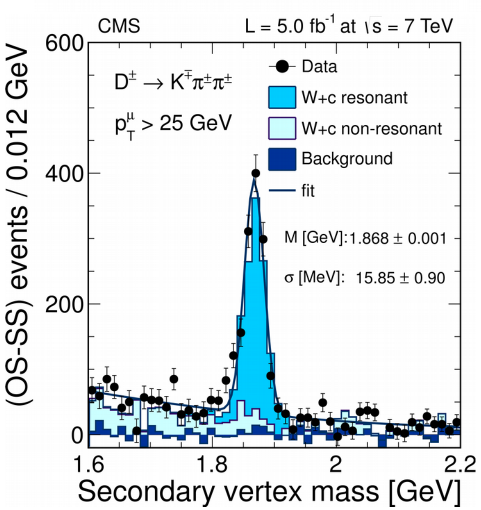
- W, Z inclusive production ⇒ directly sensitive to the PDFs of light quarks

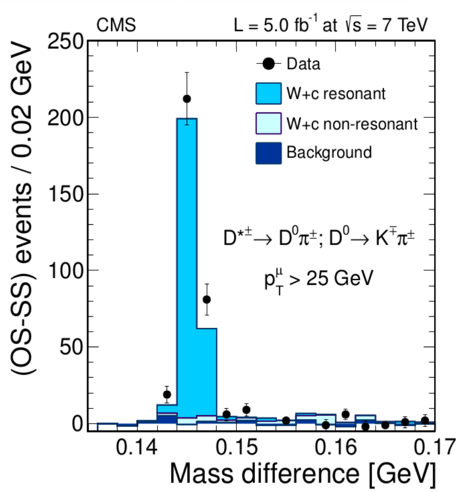
$$u+\bar{d}\,(\bar{s}) \rightarrow W^{+} \qquad\qquad u+\bar{u} \rightarrow Z$$
$$d+\bar{u}\,(\bar{c}) \rightarrow W^{-} \qquad\qquad d+\bar{d} \rightarrow Z$$

- V+light jet ⇒ also sensitive to gluon PDFs: **g u → Z u, g u → d W⁺**
- W+charm ⇒ probing the strange quark content of the proton: **g s → c W⁻**
- Z+heavy jet⇒ charm/bottom quark content of the proton: **Q g → Q Z**



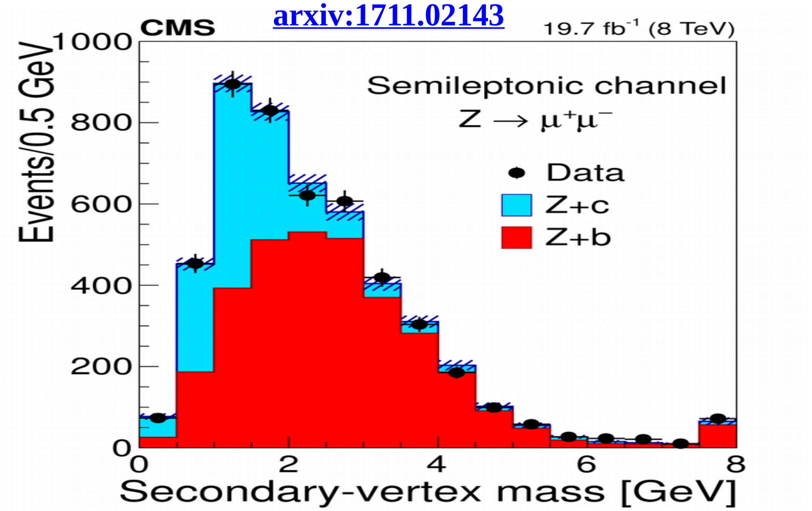






arxiv:1310.1138

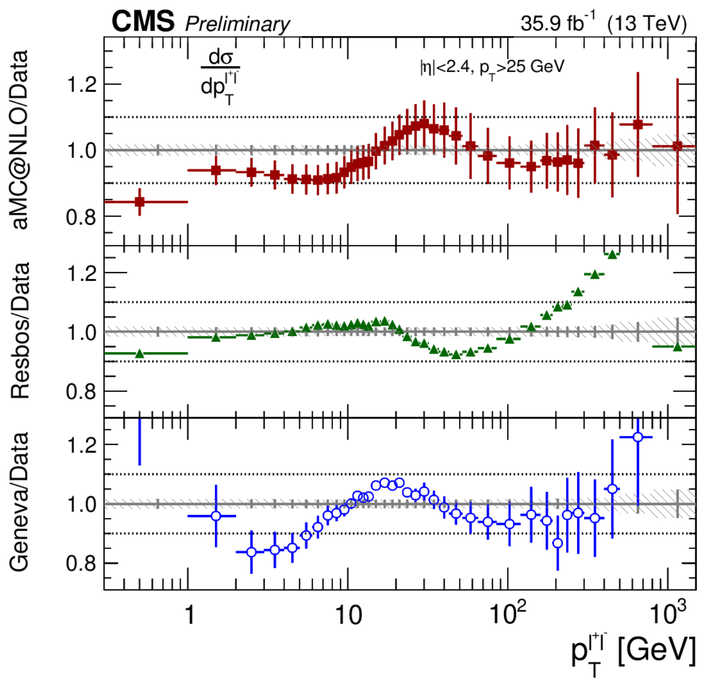
arxiv:1711.02143

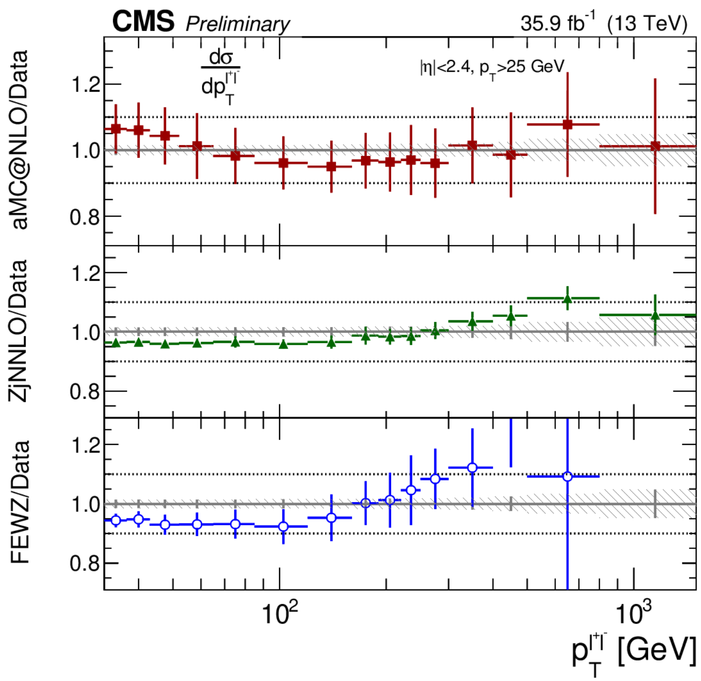


W, Z at LHC: QCD studies

- We can really do high precision studies on W and Z production:
  - Experimentally the W → l$\bar{\nu}$ and Z → l$\bar{l}$ channels are among the cleanest final states that we can measure at hadron colliders
  - We have now accurate theoretical tools now at our disposal: NLO MC generators (aMC@NLO, POWHEG, ...). These generators reproduce much better the kinematics of the process (both at high-PT and at low-PT after some remnant tuning)
  - We even have NNLO theoretical predictions for the total cross sections (FEWZ, DYNNLO, ...)

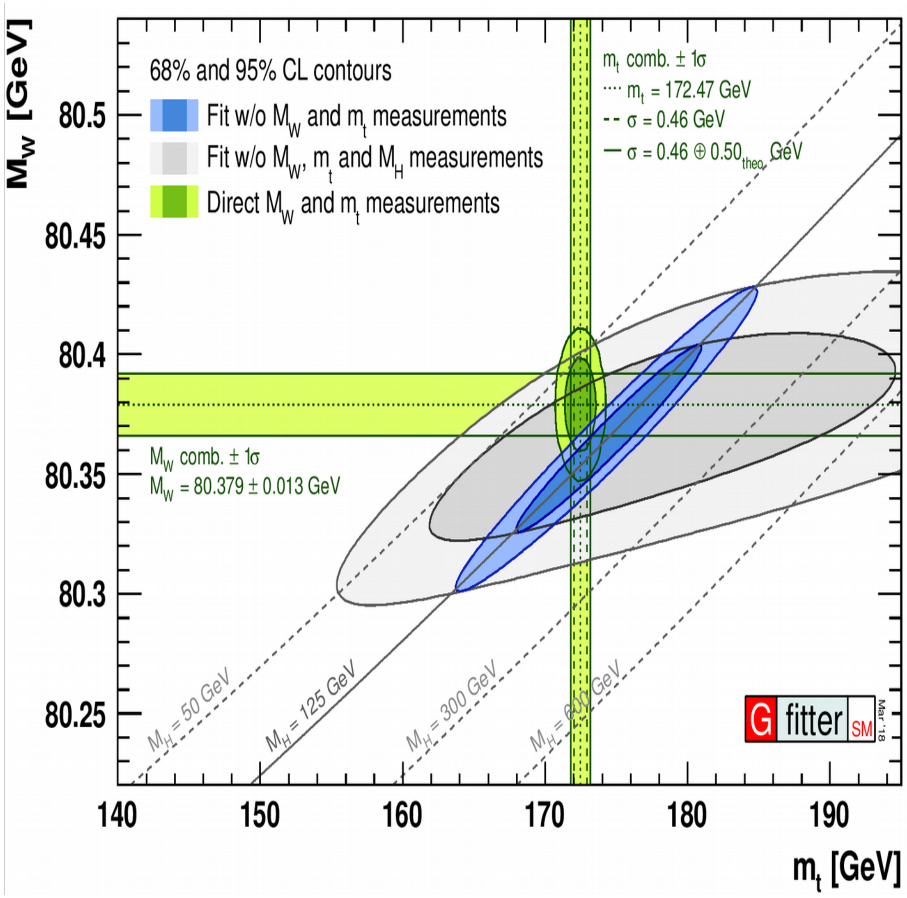
[CMS-PAS-SMP-17-010]

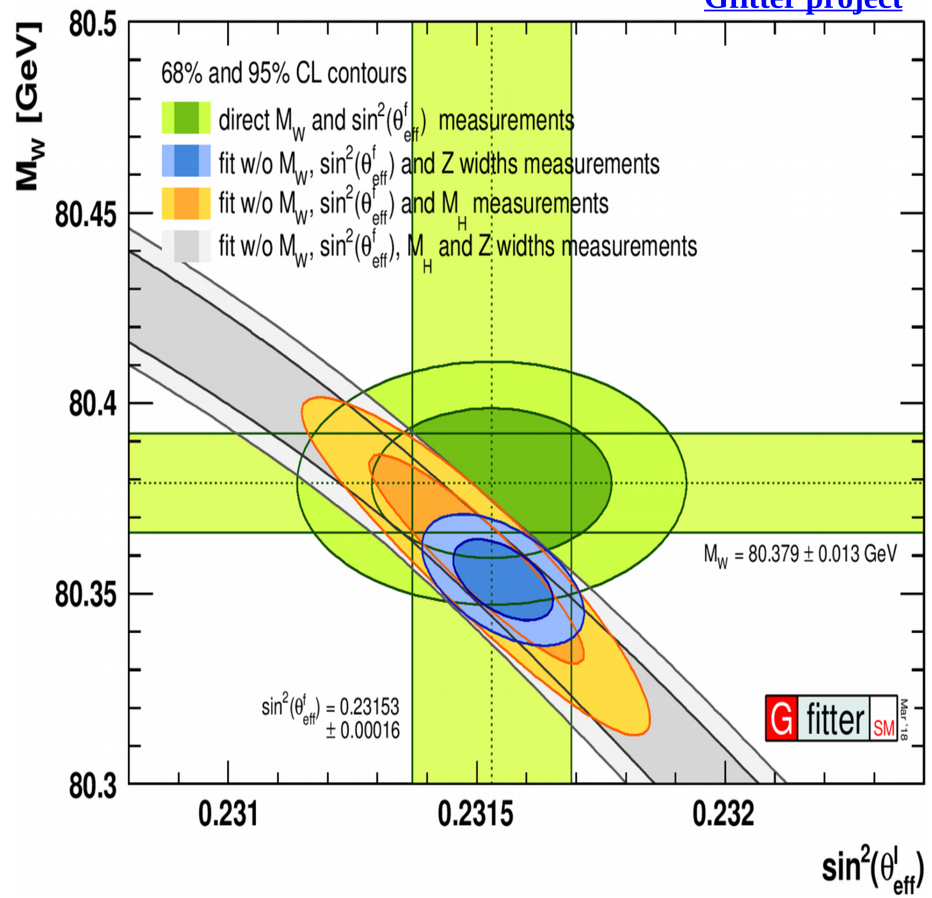




W,Z: EWK parameters at LHC

Gfitter project

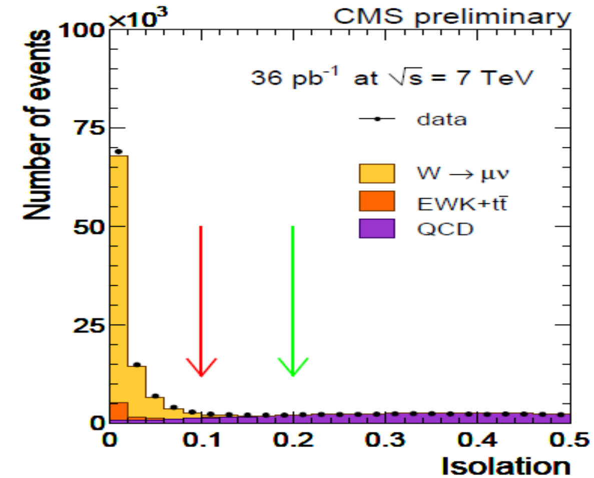




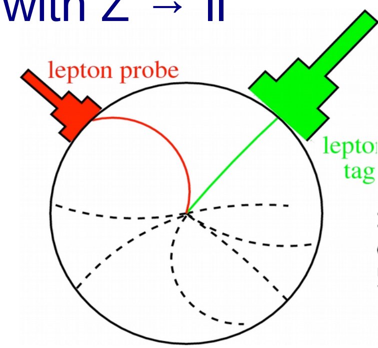
- m_W, m_t and $\sin^2\theta_{eff}$ are essential parameters of the SM. Deviations from the expected behavior may signal the presence of new physics.
- The LHC is well placed to improve the precision on these parameters. We discuss the measurements of m_W and $\sin^2\theta_{eff}$ in the following

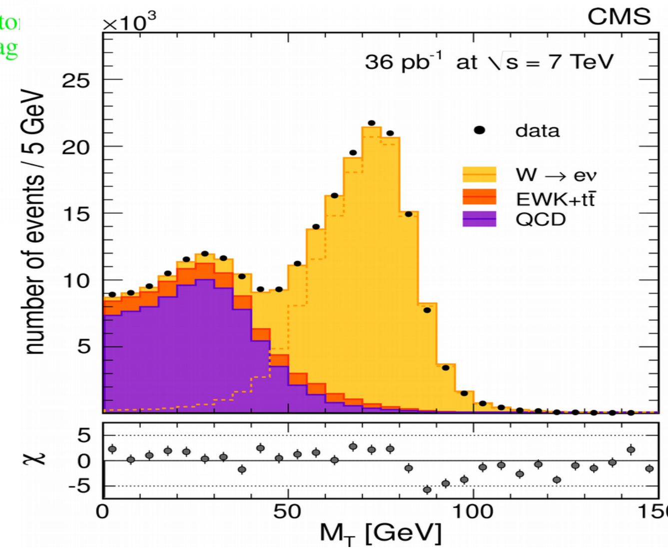
W selection: how?

- Select isolated leptons with $p_T \gtrsim 20$-25 GeV and some missing transverse energy, E^T(miss)



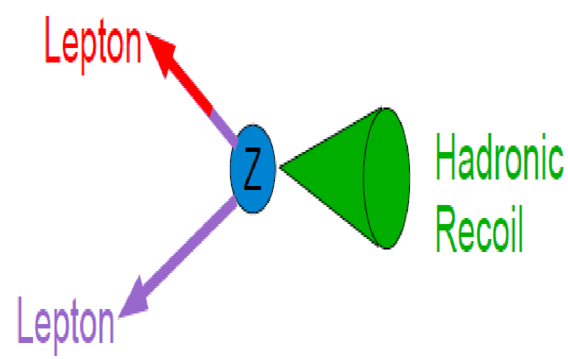
- Efficiencies: tag-and-probe methods with $Z \rightarrow l\bar{l}$ selected events
  - One lepton satisfying tight selection criteria. The second lepton is used to determine TRIGGER, ISOLATION and RECONSTRUCTION/ID efficiencies as a function of p_T and η





- The shape of the remaining QCD background is determined or parametrized from a data sample of non-isolated leptons. The overall QCD normalization is extracted from a fit to the E_T(miss) distributions

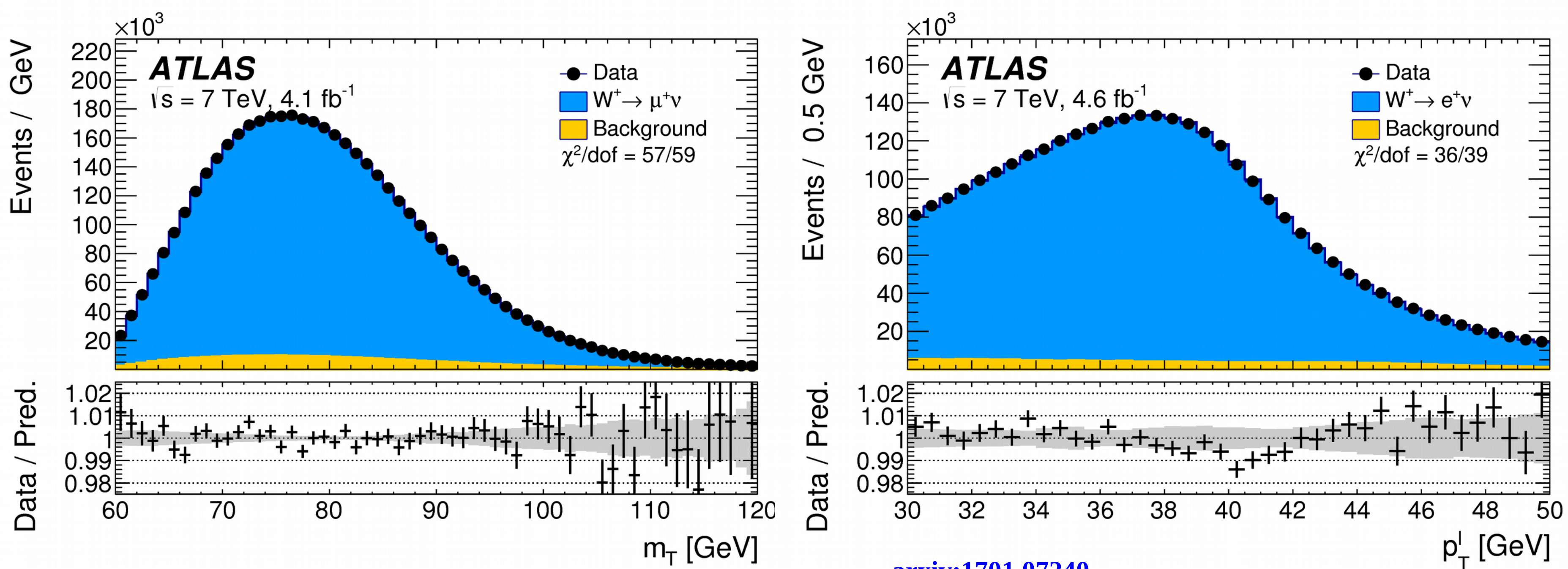
- The shape of the missing E_T for the signal is extracted from the recoil distribution of $Z \rightarrow l\bar{l}$ events by dropping one of the leptons



- $Z \rightarrow l\bar{l}$ events are also used to control momentum and energy resolution discrepancies data-MC

W mass at LHC: how?

- **Several distributions are sensitive to the W mass. Most popular:**
  - **Transverse mass of lepton+missing energy: $m_T \equiv [2p_{Tl}p_{T\nu}(1-\cos\varphi_{l\nu})]^{½}$**
    - **Better for theoretical uncertainties: similar to a mass measurement**
    - **Worse for experimental uncertainties: transverse momentum of ν requires measurement of all calorimetric depositions in the detector (missing $\not{E}_T$)**
  - **Lepton transverse momentum:**
    - **Better for experimental uncertainties: excellent lepton resolution (but note that one needs to keep systematics at the level of 20 MeV / m_W ≈ 0.25 ‰ !!)**
    - **Worse for theroretical uncertainites: affected by all QCD/EWK radiation effects**



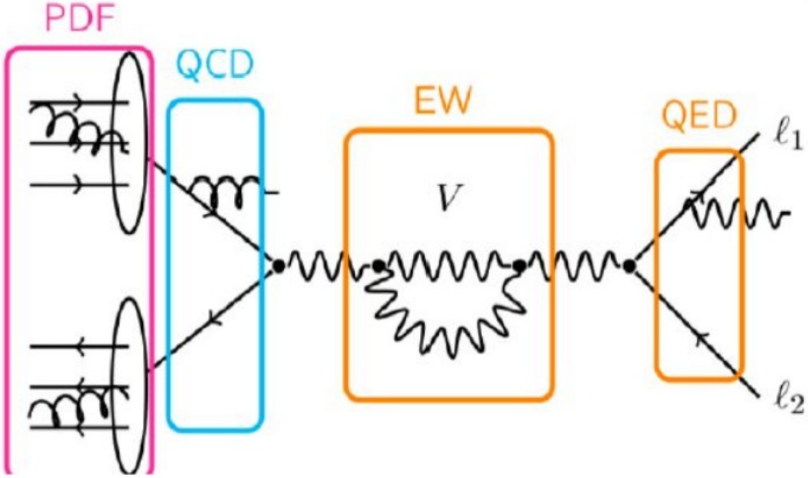
arxiv:1701.07240

W mass at LHC: theory uncertainties

High precision ($\Delta m_W \leq$ 20 MeV) => very complicated measurement

N. Andari, Moriond EW 2017

Physics modelling corrections



Electroweak corrections

- *QED FSR and ISR (included)*
- *missing higher order effects and FSR pair production (uncertainties)*

QCD corrections

- *pT distribution*
- *polarisation*
- *rapidity*

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

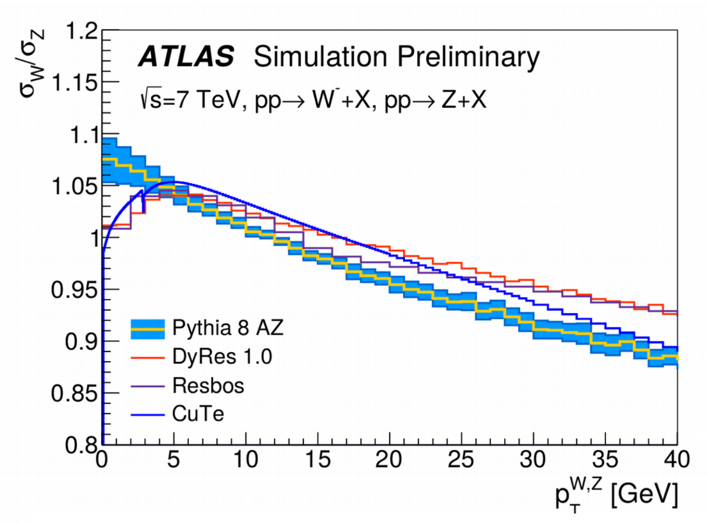
Breit-Wigner

NNLO pQCD

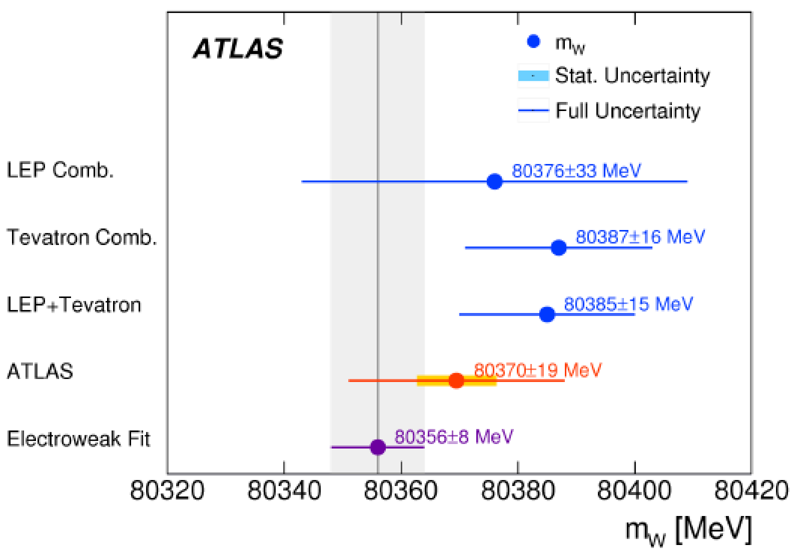
Parton Shower

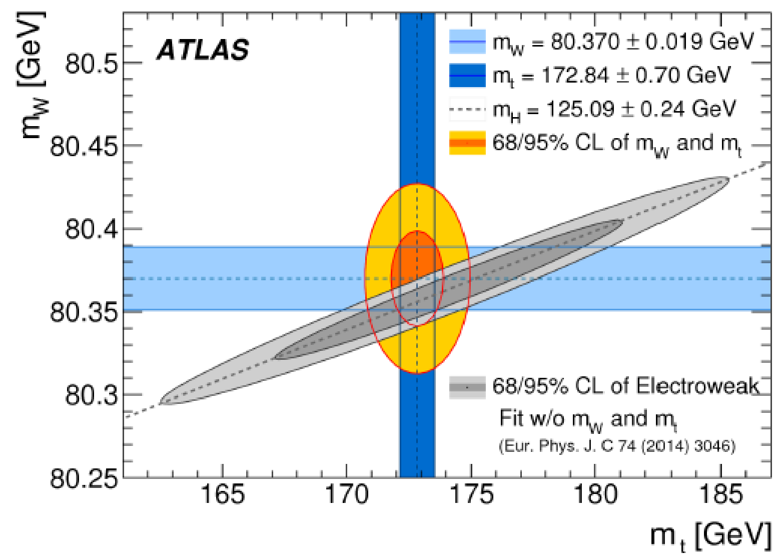
W mass at LHC

arxiv:1701.07240



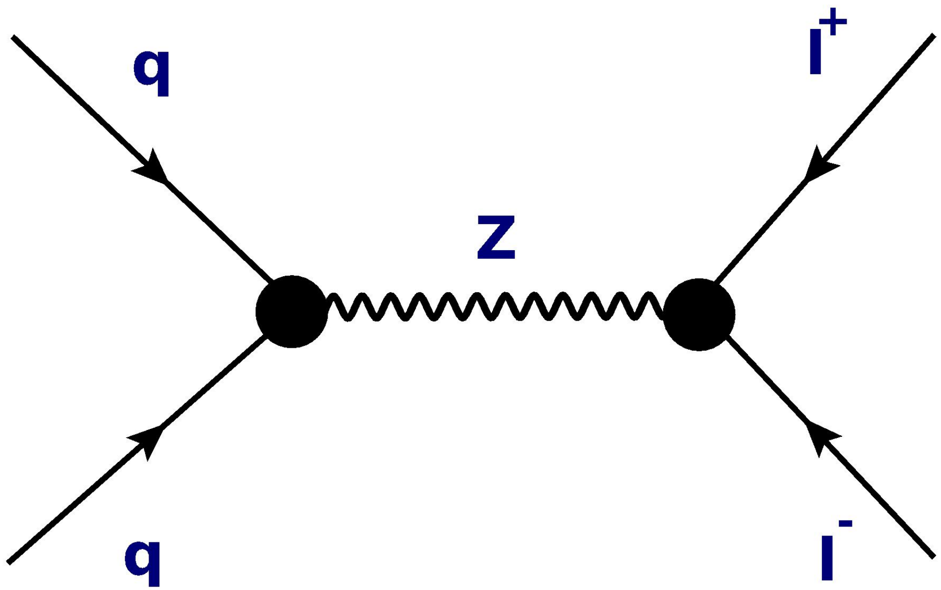
- Z p_T data distribution used to tune PYTHIA8
- Discrepancies between data and some NLO predictions
- Fit ranges : $32<p_T^l<45$ GeV; $66<m_T<99$ GeV, minimizing total expected measurement uncertainty
- Largest weight of p_T^l in the measurement





- **Still way to go in order to consolidate uncertainties, in particular those regarding modeling**

$\sin^2\theta_{eff}$ at LHC



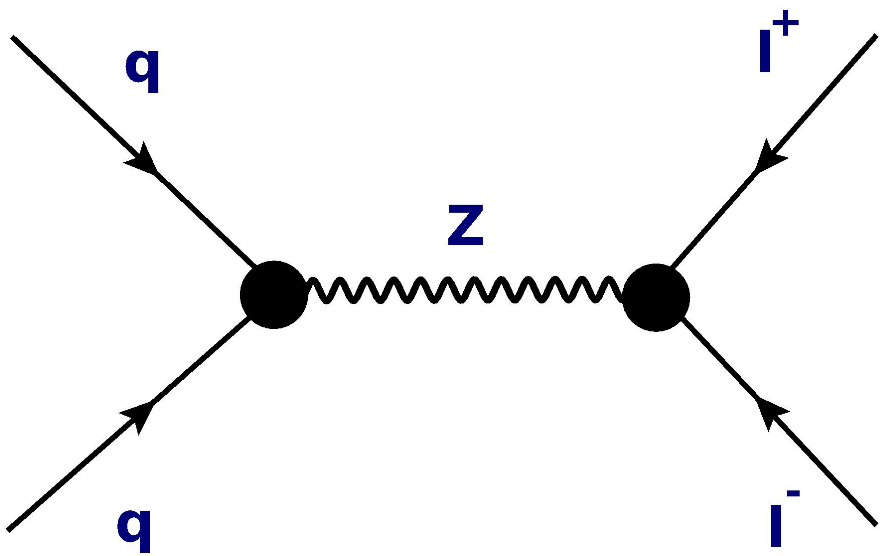
$g_{Vf} = T_{3f} - 2Q_f \sin^2\theta_{eff}$

$g_{Af} = T_{3f}$

(to a good approximation, 0.1% level)

with: $\sin^2\theta_{eff} = 0.2315$

$\sin^2\theta_{eff}$ at LHC



$$d\sigma/dz = \sigma_{total}\,[3/8\,(1+z^2) + A_{FB}\,z]; \quad (z=\cos\theta_{CM})$$

$$A_{FB} = (\sigma(z>0)-\sigma(z<0))/\sigma_{total}$$

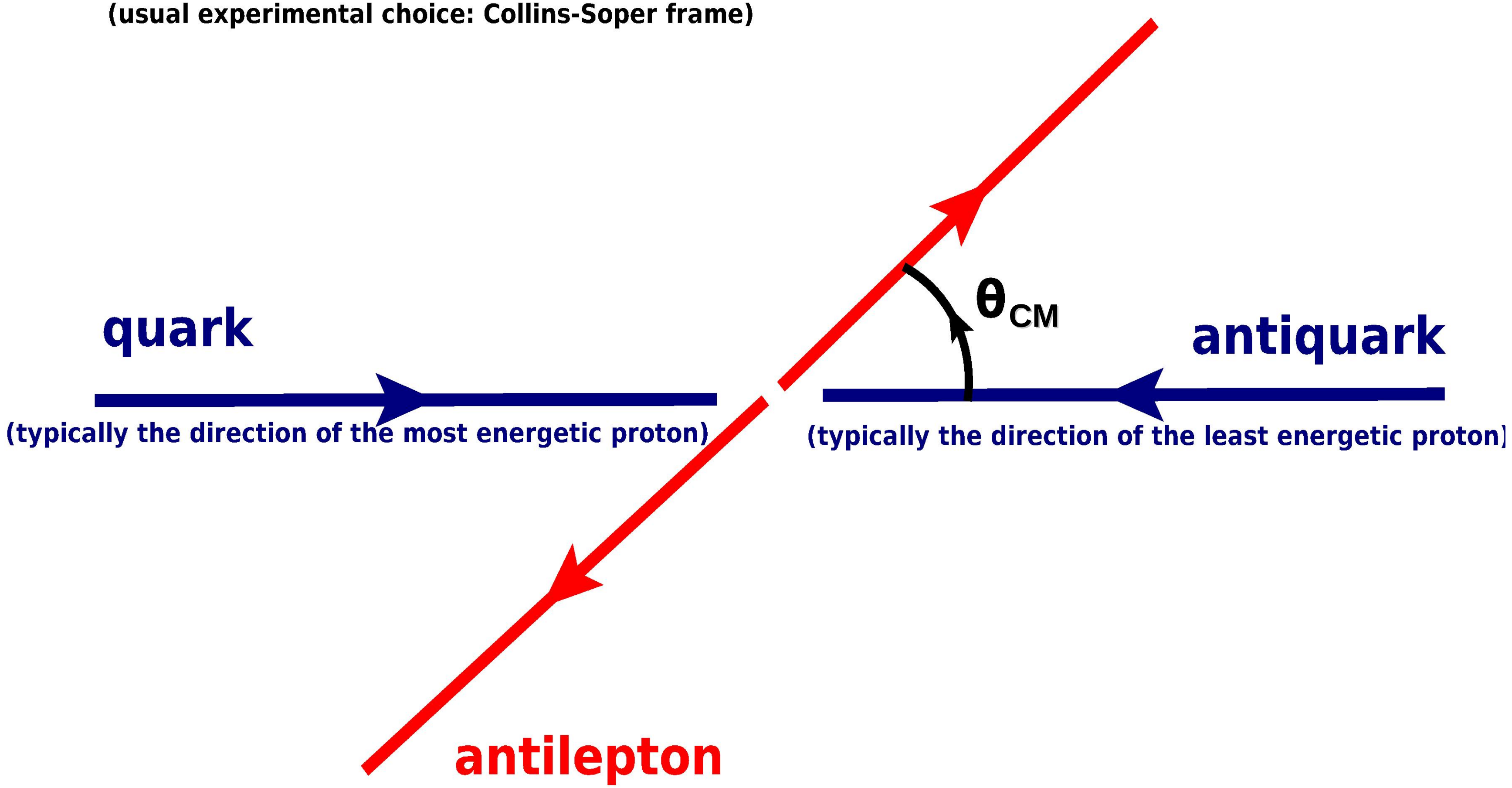
A_{FB} depends on $\sin^2\theta_{eff}$. At the Z pole:

$$A^0_{FB} = 3/4\,A_q\,A_l; \qquad A_f = 2\,[g_{Vf}g_{Af}/(g^2_{Vf}+g^2_{Af})]$$

$\sin^2\theta_{eff}$ at LHC

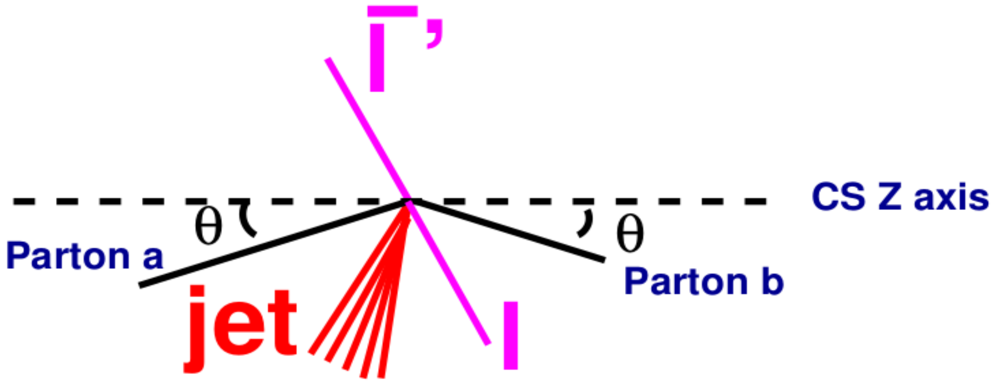
In the quark-antiquark CM frame:

(usual experimental choice: Collins-Soper frame)



Little halt: Collins-soper angle

Going to the CS reference frame via Lorentz boosts

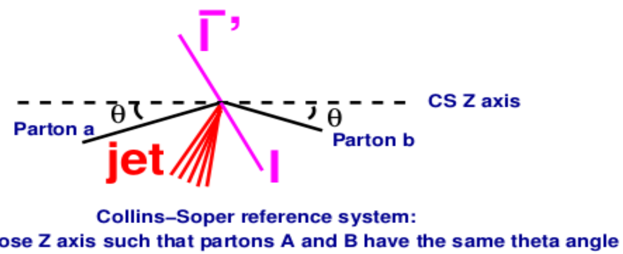


Collins–Soper reference system:
Choose Z axis such that partons A and B have the same theta angle

- My preferred procedure (operationally simpler):
  1. Boost the electroweak boson to the system where it has zero longitudinal momentum ($p_z^{new}(V) = 0$).
  2. Apply a second boost to the system where it has zero transverse momentum ($p_x^{new}(V) = 0$).

Little halt: Collins-soper angle

$$\Lambda(LAB \to CS) \equiv \Lambda_\perp(y_\perp)\ \Lambda_\parallel(y_V)$$



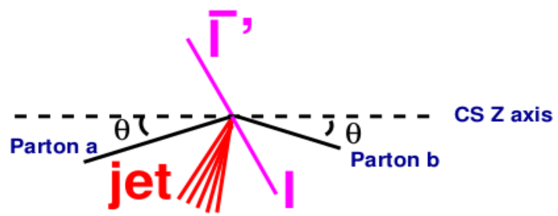
$$\Lambda_\parallel(y_V) = \begin{pmatrix} \cosh y_V & 0 & 0 & -\sinh y_V \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sinh y_V & 0 & 0 & \cosh y_V \end{pmatrix}$$

$$\Lambda_\perp(y_\perp) = \begin{pmatrix} \cosh y_\perp & -\sinh y_\perp & 0 & 0 \\ -\sinh y_\perp & \cosh y_\perp & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\sinh y_\perp = \frac{p_x^{LAB}(V)}{M_V} \equiv r; \qquad \sinh y_V = \frac{p_z^{LAB}(V)}{\sqrt{M_V^2 + p_x^{LAB}(V)^2}} \equiv \frac{r_z}{\sqrt{1+r^2}}$$

Little halt: Collins-soper angle

Transformations to the Collins-Soper frame

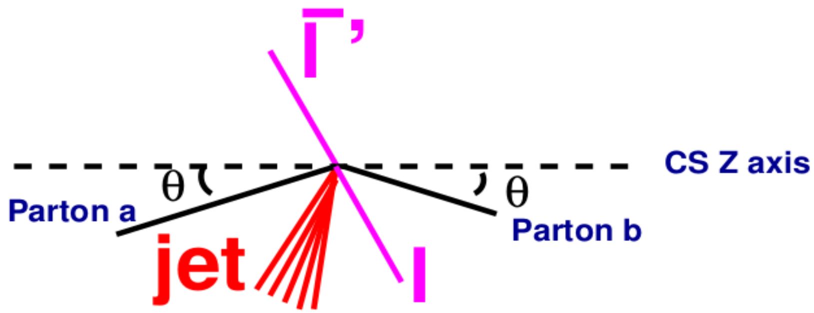


Collins–Soper reference system:
Choose Z axis such that partons A and B have the same theta angle

$$\Lambda(LAB \rightarrow CS) = \begin{pmatrix} \sqrt{1+r^2+r_z^2} & -r & 0 & -r_z \\ -\frac{r\,\sqrt{1+r^2+r_z^2}}{\sqrt{1+r^2}} & \sqrt{1+r^2} & 0 & \frac{r_z\,r}{\sqrt{1+r^2}} \\ 0 & 0 & 1 & 0 \\ -\frac{r_z}{\sqrt{1+r^2}} & 0 & 0 & \frac{\sqrt{1+r^2+r_z^2}}{\sqrt{1+r^2}} \end{pmatrix}$$

Little halt: Collins-soper angle

CS polar angle



- Using the transverse momenta of the leptons one can only determine $\sin\theta_{CS}$ (and therefore $|\cos\theta_{CS}|$). To determine the sign of $\cos\theta_{CS}$ one needs to estimate the longitudinal momenta of all leptons:

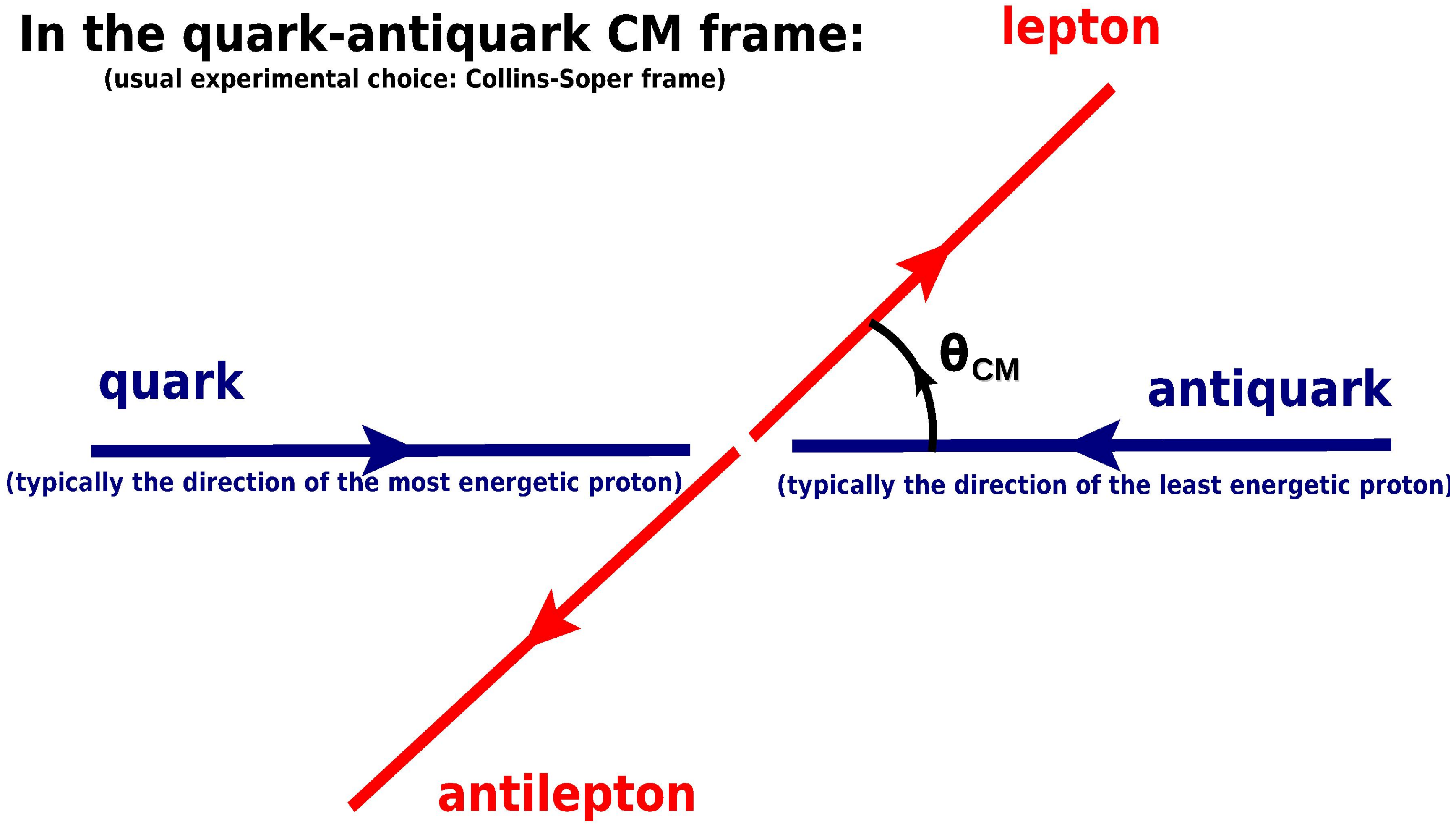
$$\sin\theta_{CS} = \frac{\sqrt{(p_x^{\ell} - p_x^{\bar{\ell}})^2/(1+r^2) + (p_y^{\ell} - p_y^{\bar{\ell}})^2}}{M_V}$$

$$\cos\theta_{CS} = \frac{2(p_z^{\ell} E^{\bar{\ell}} - p_z^{\bar{\ell}} E^{\ell})}{M_V^2\sqrt{1+r^2}}$$

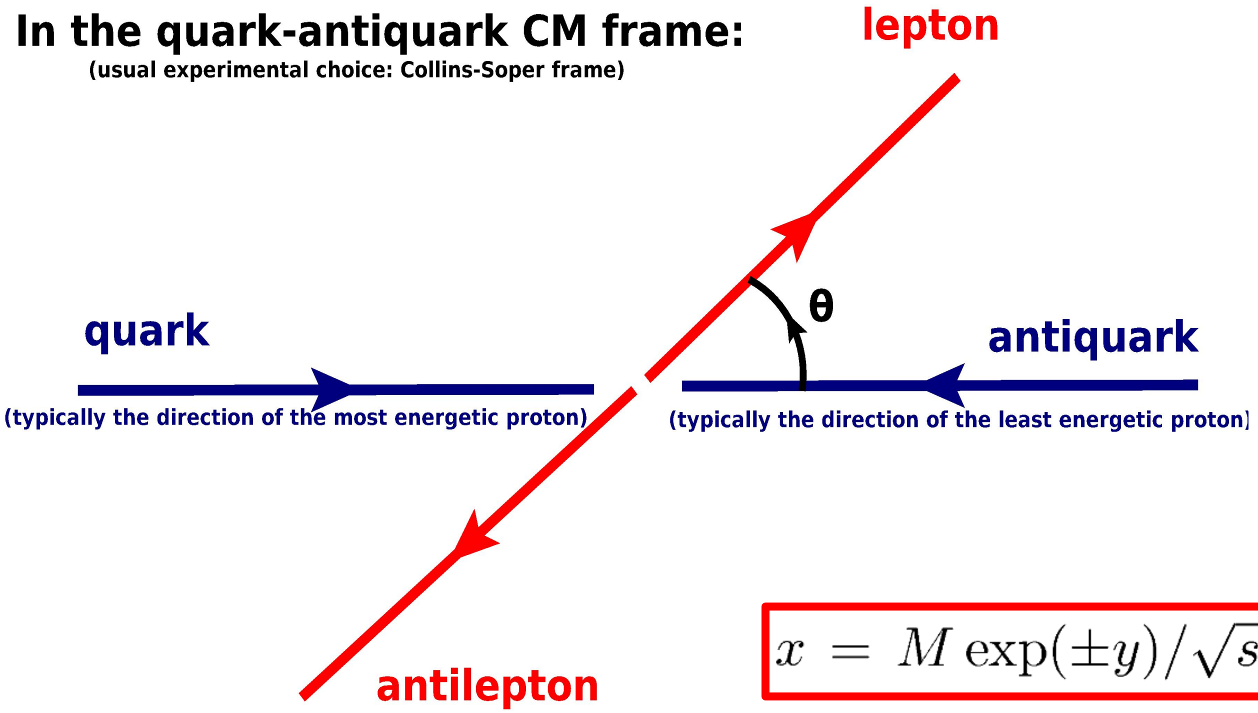
$\sin^2 \theta_{eff}$ at LHC

In the quark-antiquark CM frame:

(usual experimental choice: Collins-Soper frame)



$\sin^2\theta_{eff}$ at LHC: complications/features



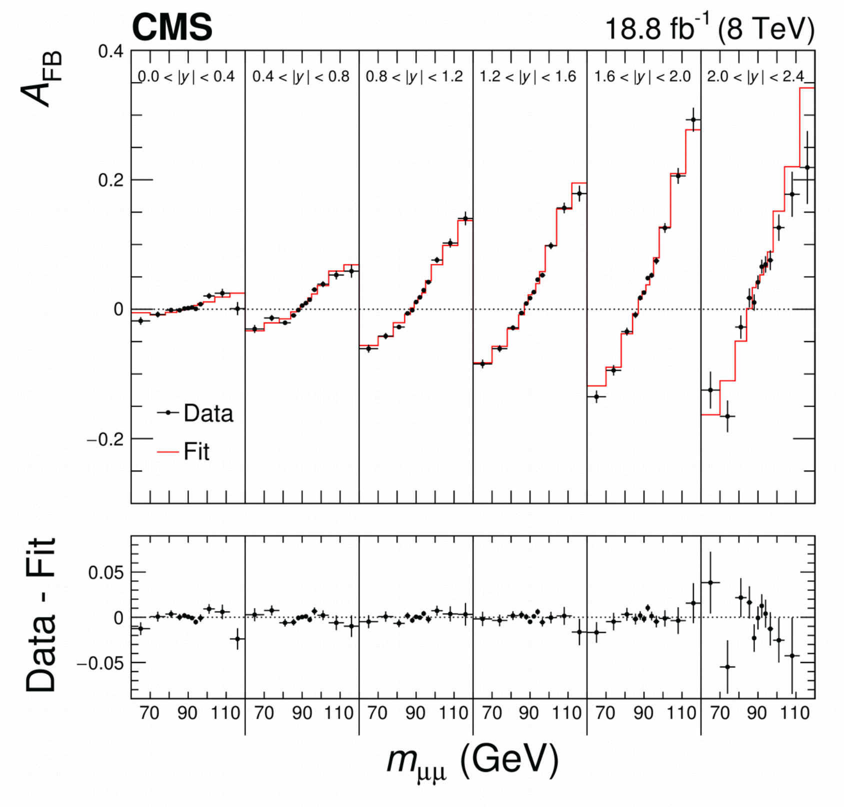
$$x = M\exp(\pm y)/\sqrt{s} \text{ and } Q = M$$

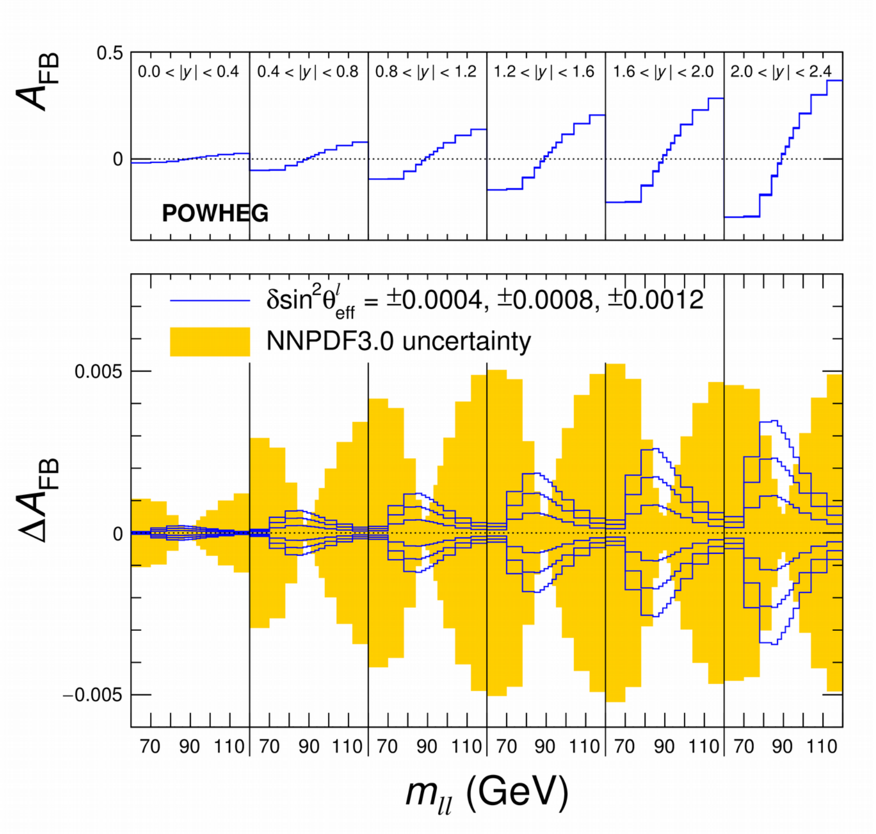
- The asymmetry depends on the <u>mass M</u> of the exchanged Z boson (dilepton mass), but it is always a function os $\sin^2\theta_{eff}$
- It can be also measured as a function of the <u>rapidity y</u> of the dimuon system. Each (M, y) bin fixes x_1, x_2 and Q^2 for the event (⇐ PDF ≡ PDF(x_i,Q^2)).
- For each bin the quark content/type is different ⇒ dependence/sensitivity of the analysis on PDFs
- Associating the most energetic proton to the direction of the quark is far from perfect: dilution of the asymmetry

$\sin^2\theta_{eff}$ at LHC

arxiv:1806.00863

ATLAS-CONF-2018-037

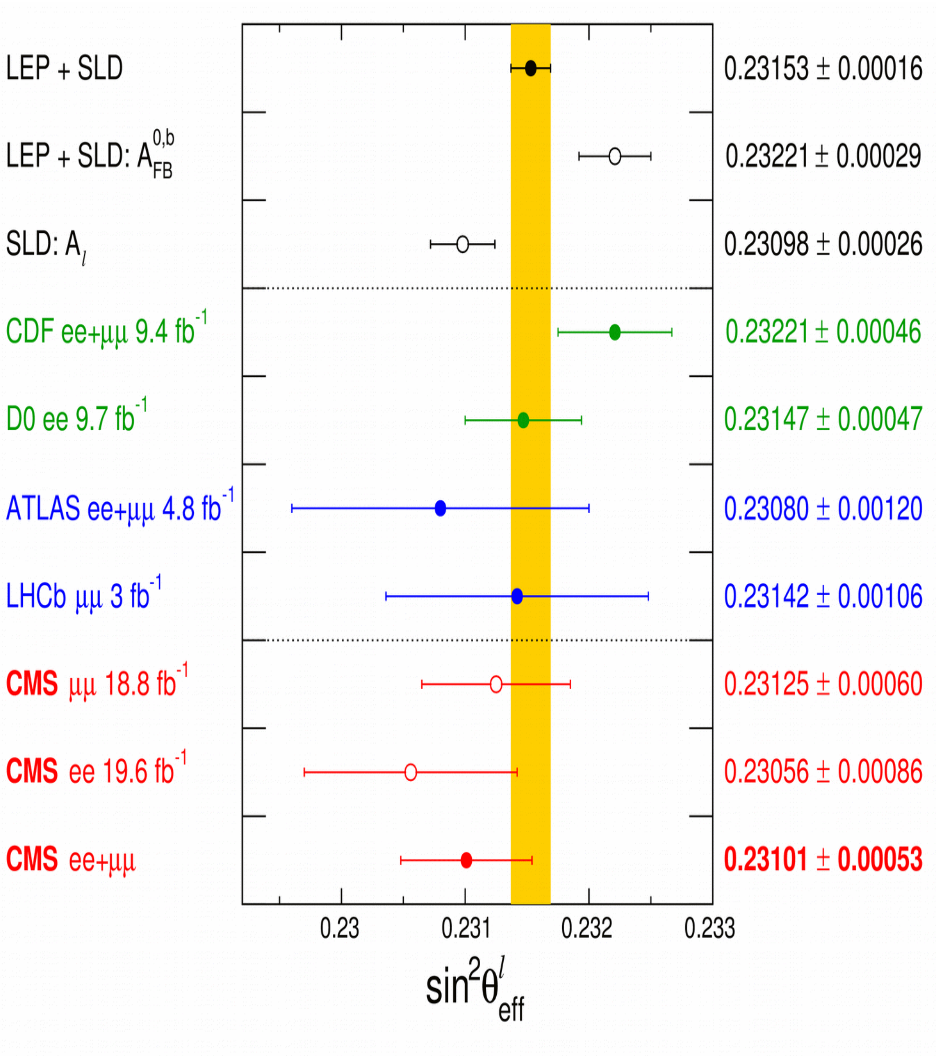




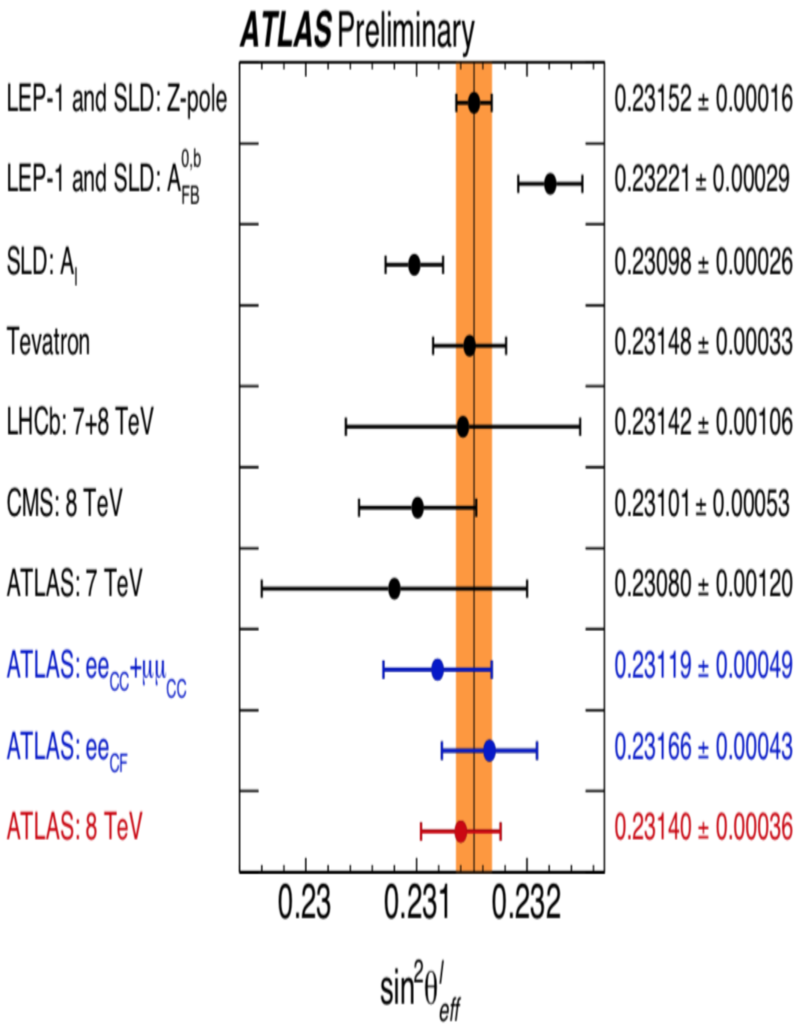
- Measurement of $\sin^2\theta_{eff}$ from the forward-backward asymmetry determined in many different bins of dilepton mass and rapidity
- Interplay with PDF uncertainties via consistency of the $\sin^2\theta_{eff}$ value in all bins. PDFs get also constrained in the fit within their uncertainties

$\sin^2\theta_{eff}$ at LHC

arxiv:1806.00863



ATLAS-CONF-2018-037



Top physics

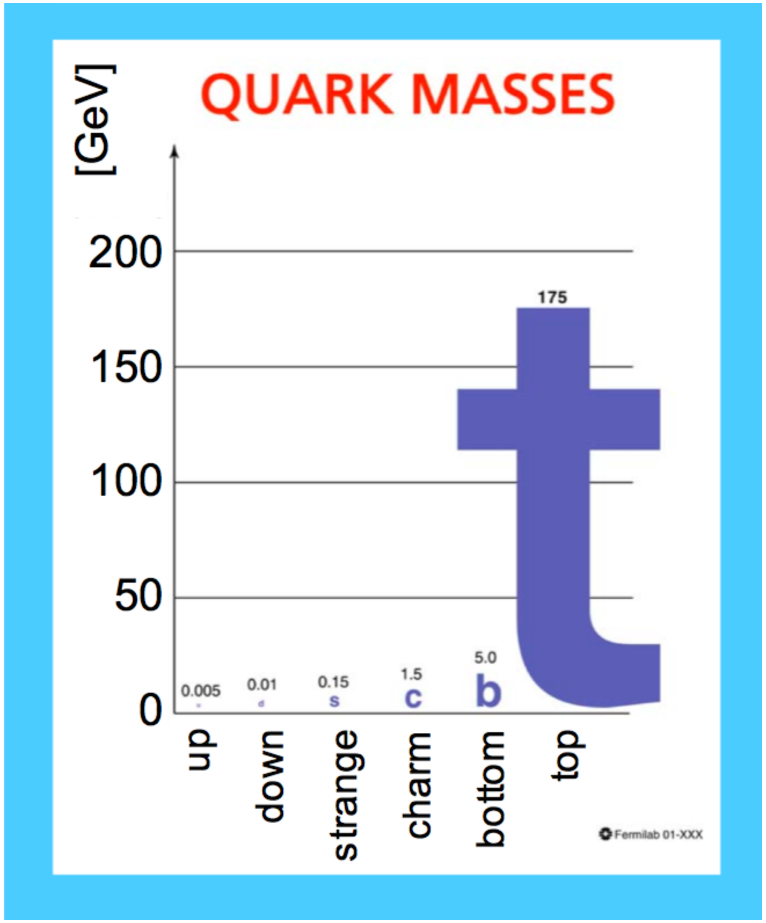
Top quark

- The most massive "elementary" particle known to date (m_t≈175 GeV)

- Large width too in the SM, Γ_t≈1.3 GeV:
  - dominated by the weak decay $t \to Wb$
  - $\tau=1/\Gamma_t=5\times10^{-25}$ s, one order of magnitude smaller than QCD decay times (≈10^{-24} s) ⇒ it does not feel hadronic interactions before decaying

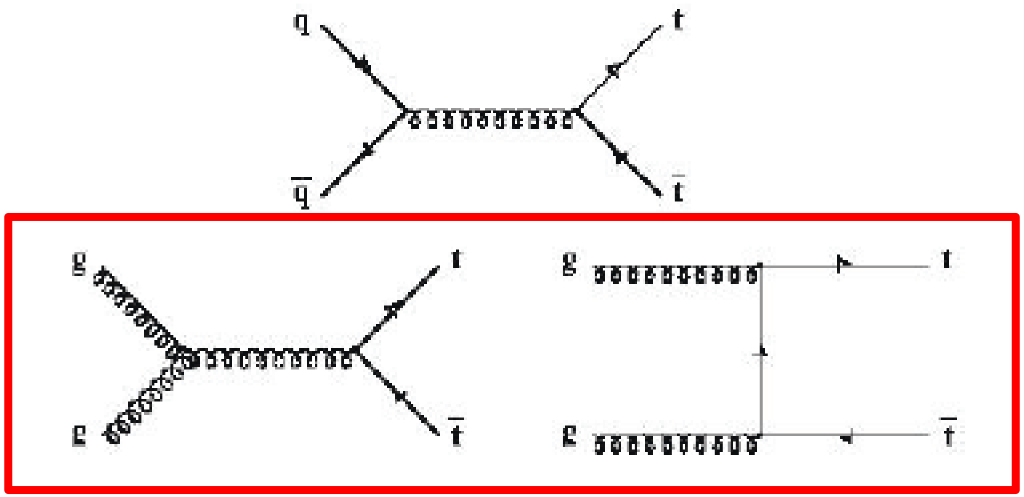
- A massive, 3rd generation quark ⇒ high potential to discover new physics

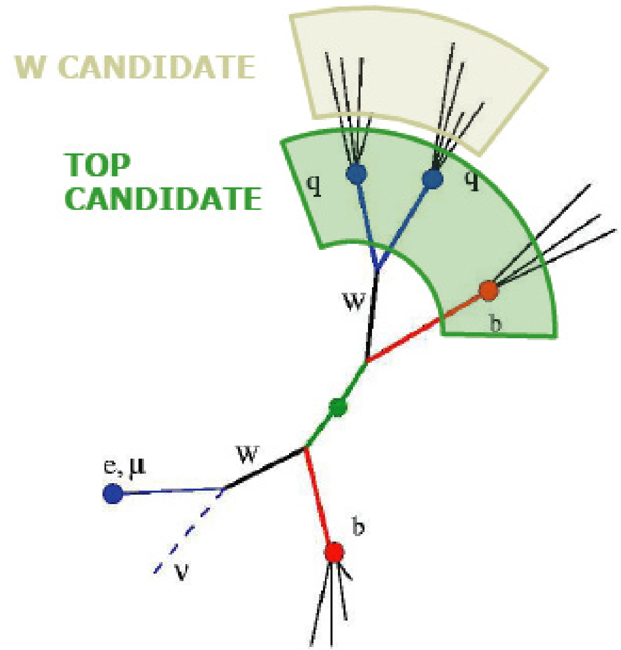
- Puzzling features (special connection with ElectroWeak Symmetry Breaking?):
  - Why is it so massive ?
  - The only fermion with a "natural" coupling (≈1) to the Higgs boson



Tops at LHC

- Top production is huge at the LHC: At √s=13 TeV:
  - Dominated by $t\bar{t}$ production
  - σ≈1 nb (≈10 $t\bar{t}$ pairs per second at nominal LHC luminosity)
  - Dominant process is gg->ttbar (≈90%)

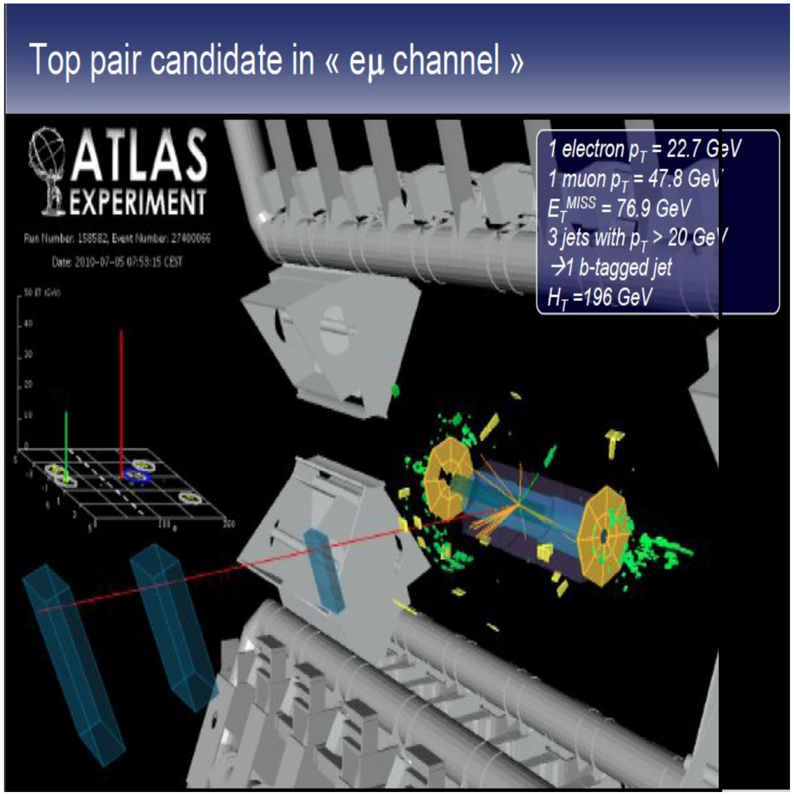


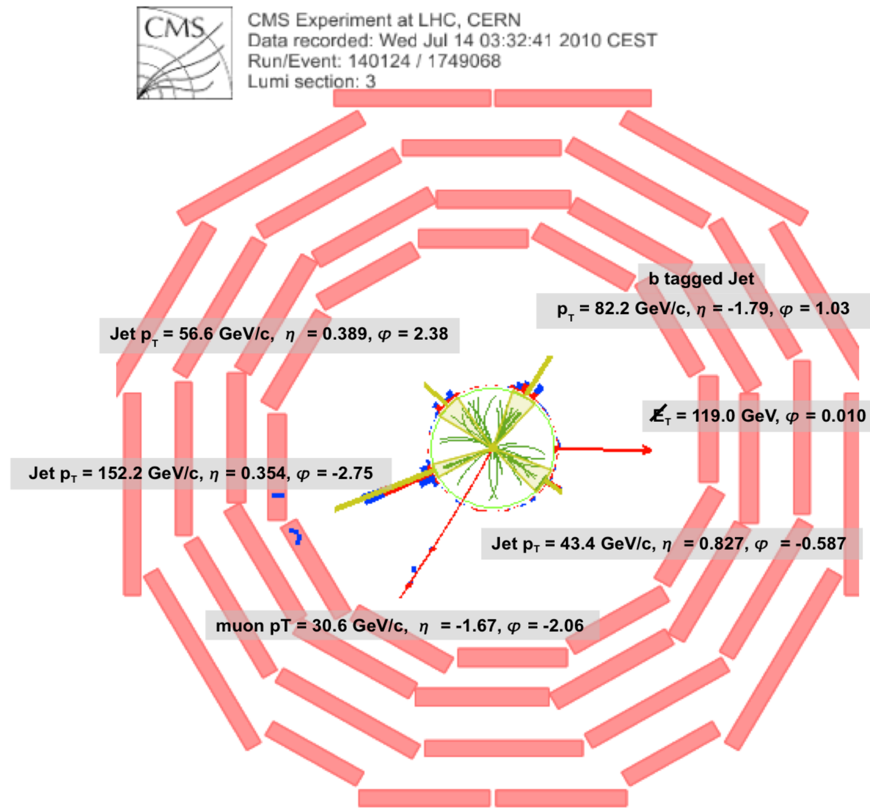


- Understanding top production ⇒
  - Understanding the whole detector: lepton identification, resolutions, isolation, jets, missing energy, b-tagging, ...
  - Spin-offs: jet scale calibration, b-tagging efficiencies, ...

$t\bar{t}$ production at LHC

- Two main clean topological configurations (lepton here ⇒ electron or muon):

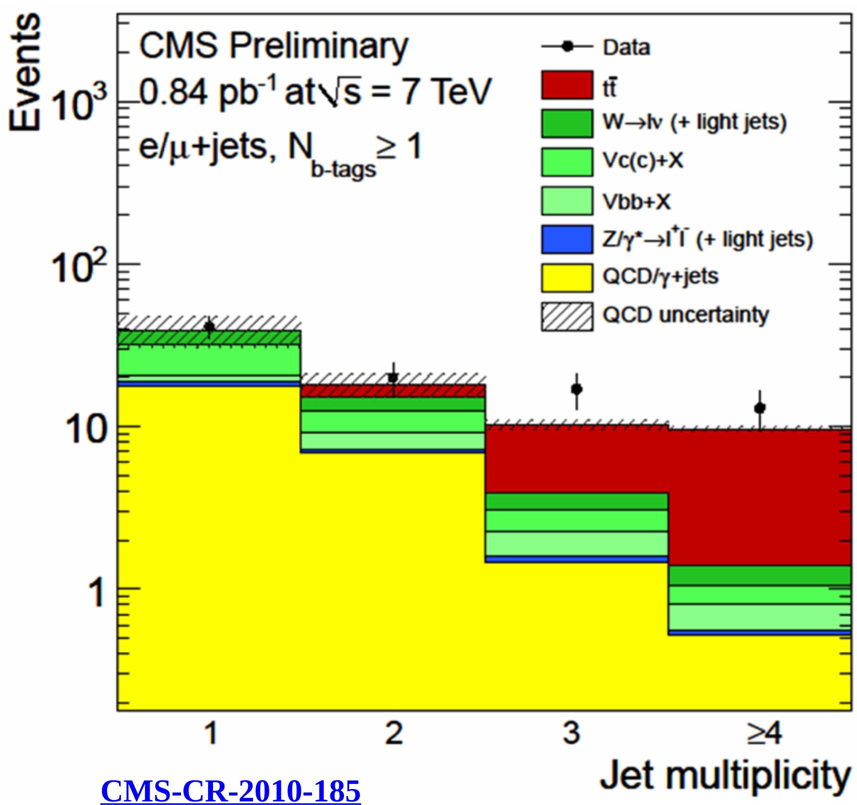




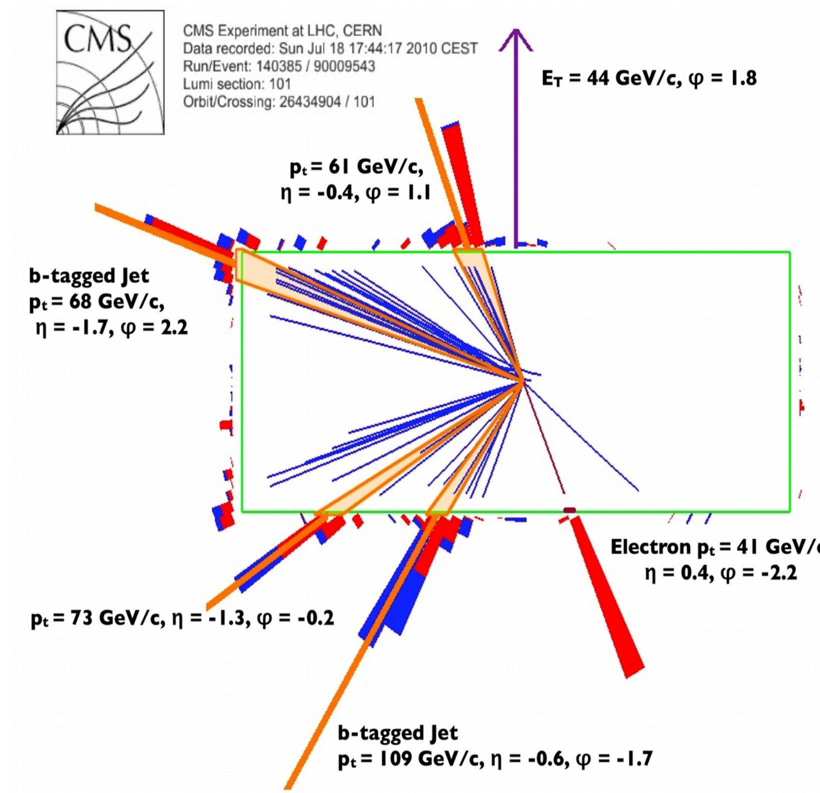
- 'Dilepton channel', $t\bar{t} \to bl\bar{\nu}\ \bar{b}l\nu$: clean but just ≈5% of total decays
- More difficult for kinematic studies (two neutrinos in the event)

- 'lepton+jets channel', $t\bar{t} \to bqq'\ \bar{b}l\nu$: less clean but more abundant (≈30%)
- Better for kinematic studies (just one neutrino in the event)

Selecting $t\bar{t}$ samples is easy



[CMS-CR-2010-185](CMS-CR-2010-185)

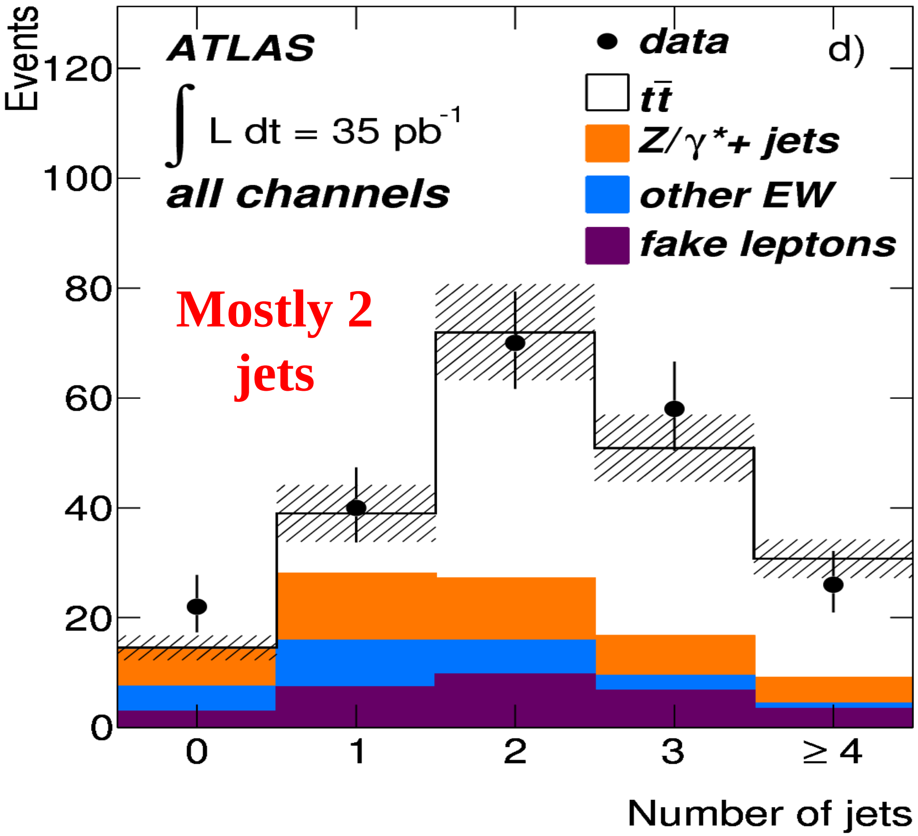


- **Initial CMS study of $t\bar{t} \rightarrow bq\bar{q}'\ \bar{b}l\nu$ at $\sqrt{s}$=7 TeV with < 1 pb^{-1} : just one high-pt, isolated lepton and at least one b-tagged jet. Then just look at the number of jets in the event**

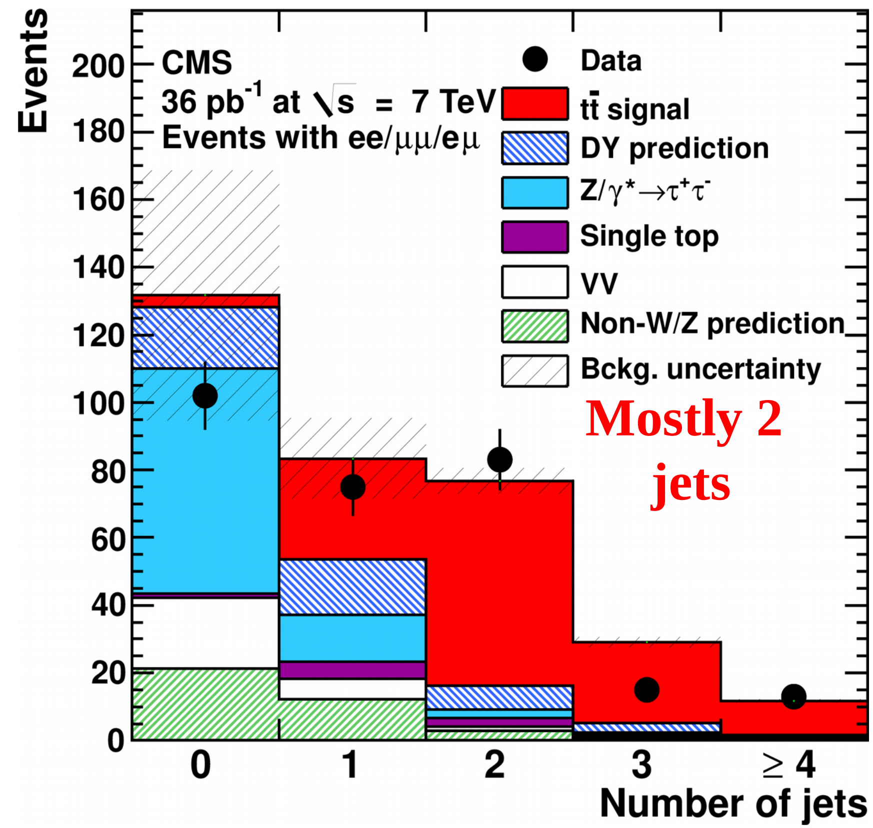
Clearly showing that LHC is indeed a top factory !

$t\bar{t}$ production: dilepton channels

arxiv:1108.3699



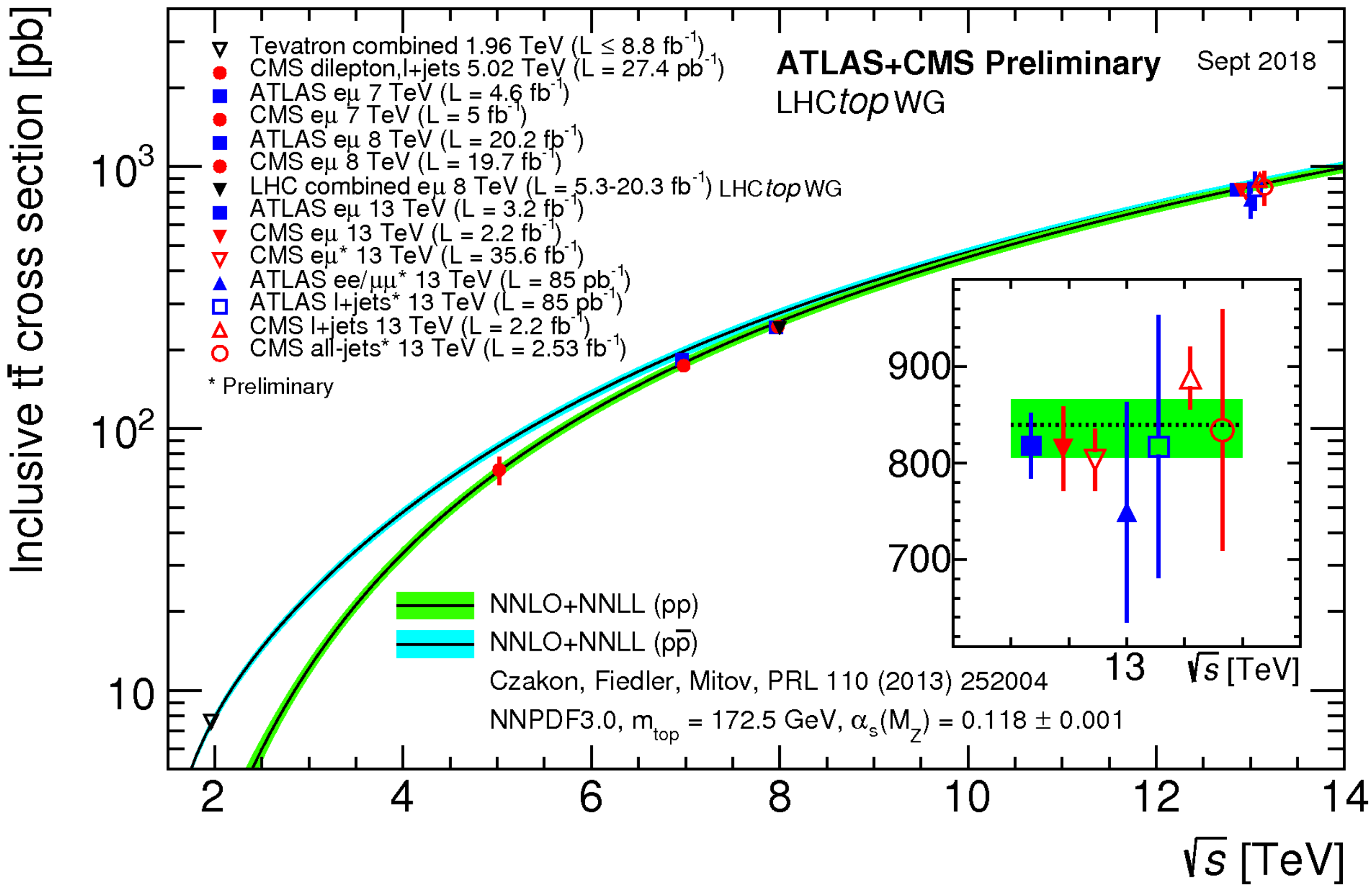
arxiv:1105.5661



- Typical selection in initial studies at LHC:
  - two isolated high-p_T leptons (electrons or muons)
  - missing E_T (>20-40 GeV, depending on channel/experiment)
  - veto $Z \rightarrow ee,\mu\mu$ and low mass hadronic resonances (<20 GeV)
  - No b-tagging required on jets !!

$t\bar{t}$ cross section results at LHC

LPCC Top Working Group



Stringent test of NNLO predictions (NLO→NNLO effects ≈ 10%) !!

$t\bar{t}$ cross section results at LHC

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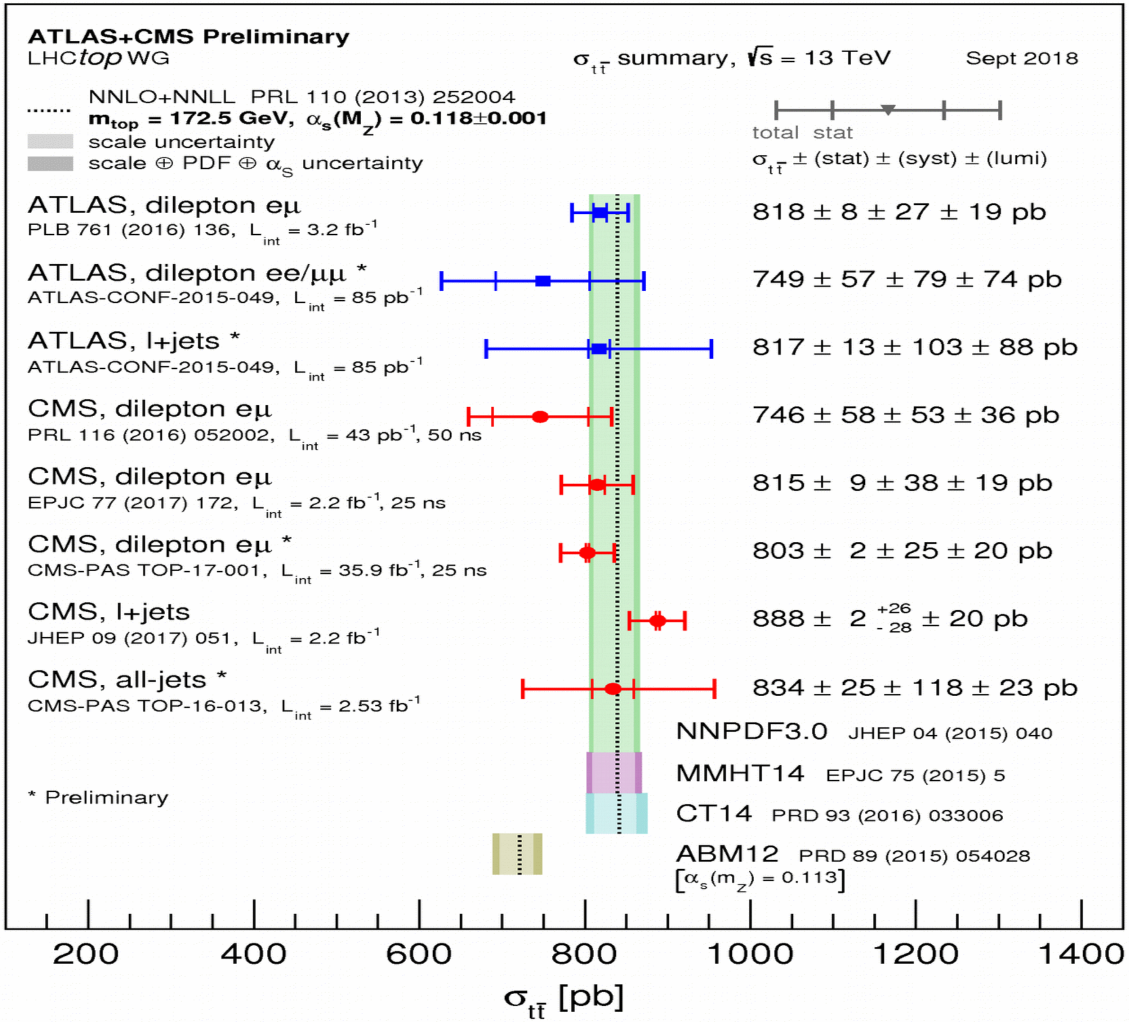
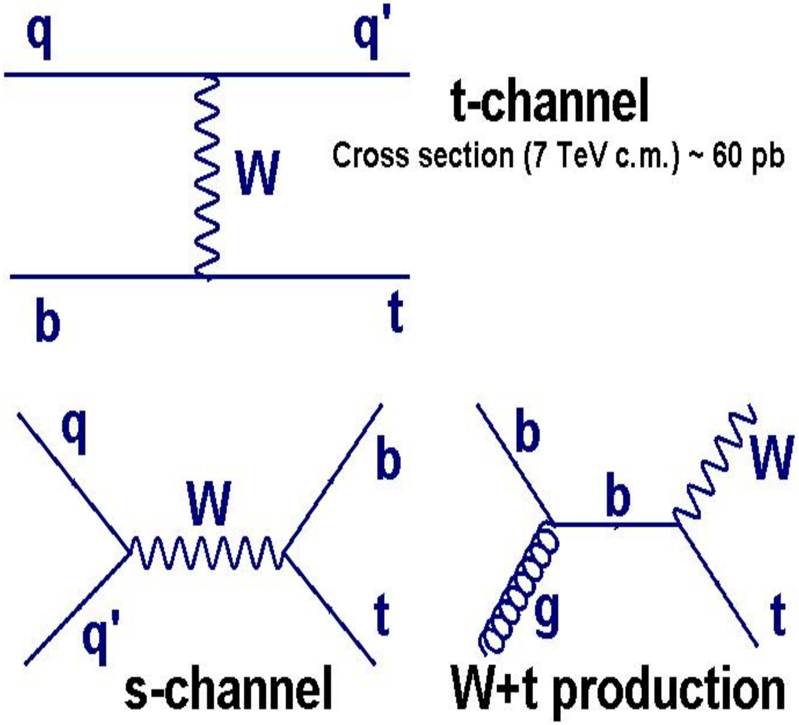
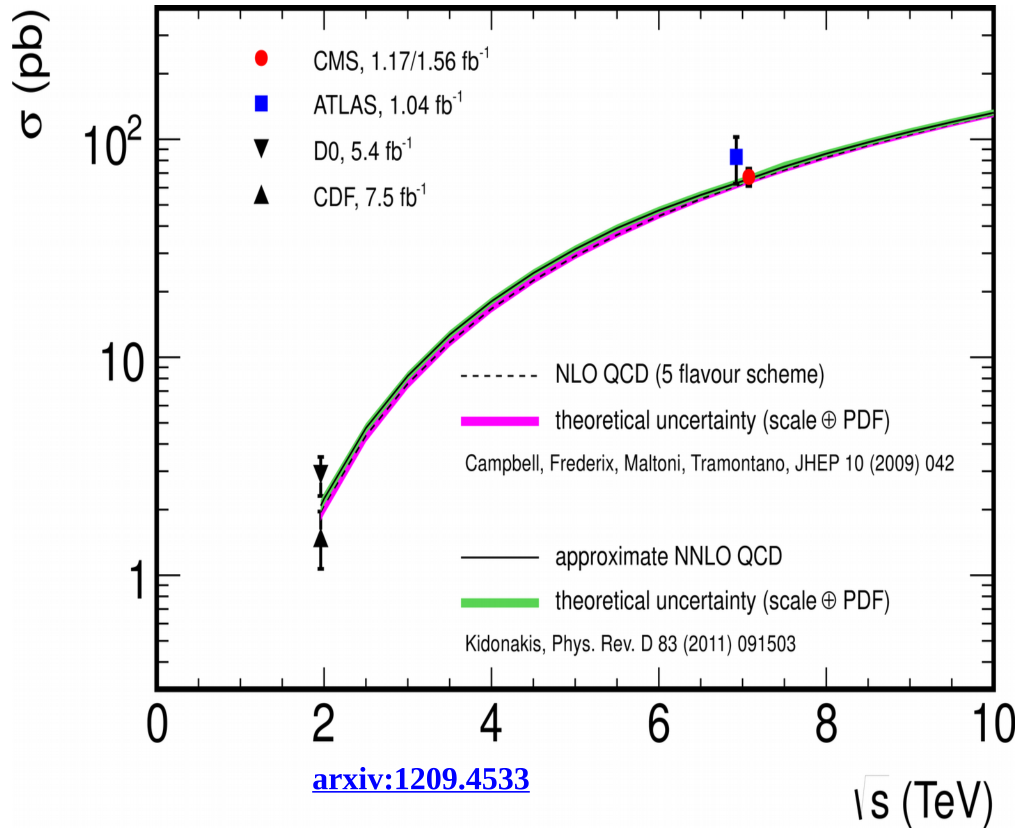


Analyses typically dominated by systematic uncertainties (typical largest individual source of systematics is luminosity!)

Single-top production at LHC



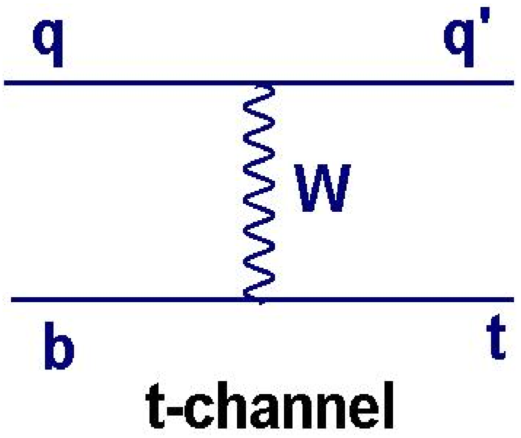


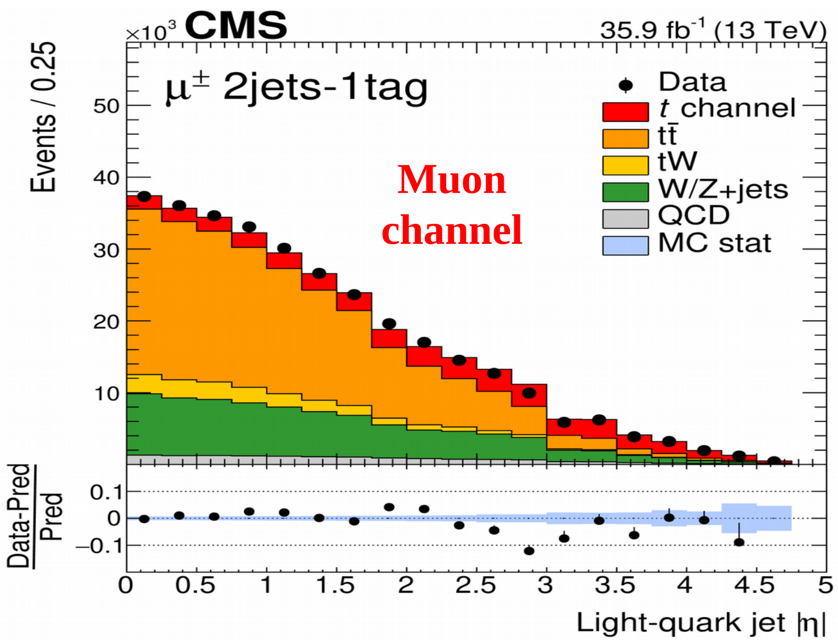
arxiv:1209.4533

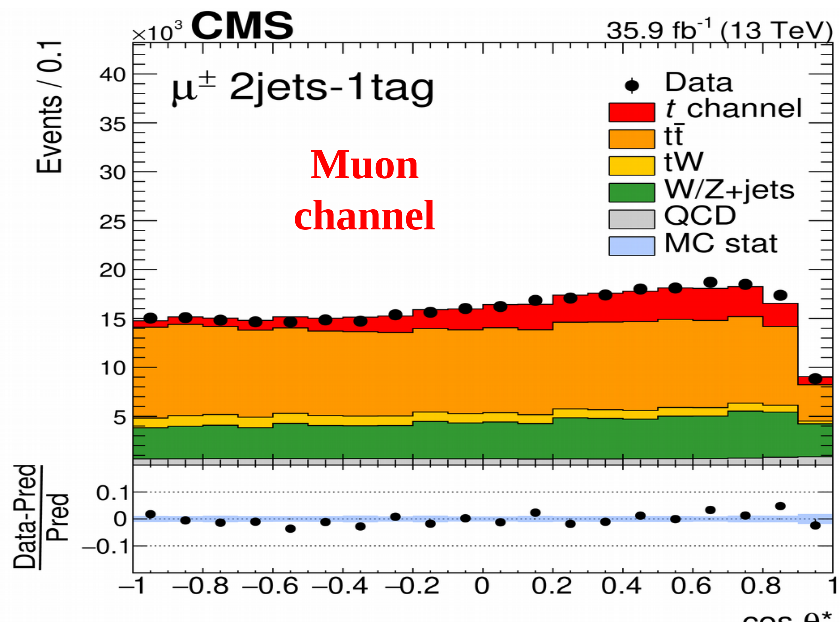
- Cross section directly sensitive to the V_{tb} coupling and the structure of top couplings
- This was a very difficult measurement at Tevatron due to the extremely low cross section (complicated multivariate methods necessary to get a minimal significance)
- Single-top cross section is large at the LHC ⇒ simpler to select
- Note that single-top (≈ub→dt) and single-antitop (≈$d\bar{b}\rightarrow u\bar{t}$) contributions have different cross sections due to the different u/d content of the proton !!

Single-top selection at LHC (t-channel)

- Two different analyses in CMS in the top→bW→blν channel. One of them is relatively simple (multivariate approaches are not necessary), using just:
  a) Selection of W→lν final states and b-tagging requirements for one of the jets in the event. This identifies the top system
  b) Pseudo-rapidity of the light-quark jet (it tends to go to low angles compared to backgrounds → high rapidity)
  c) Angle between lepton and top direction in the top center-of-mass frame (V-A coupling to W constrains angular distributions: top is left-handed polarized)



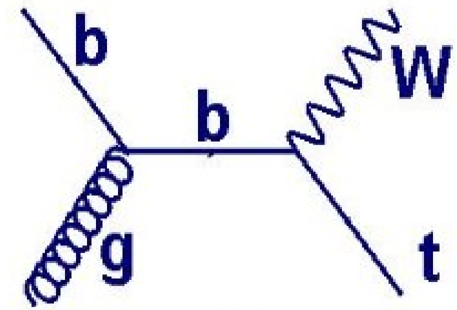




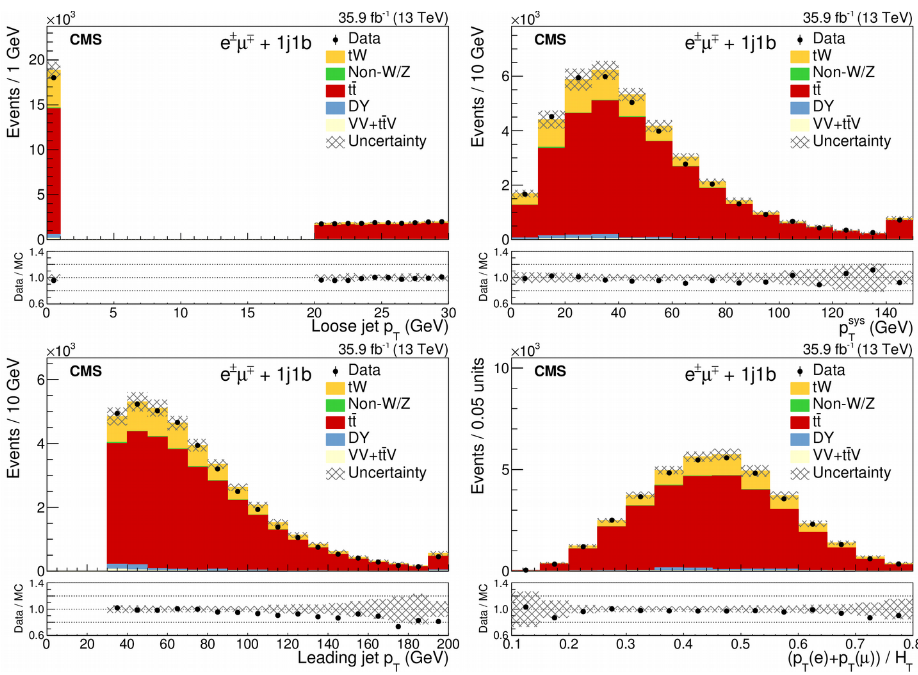
arxiv:1812.10514

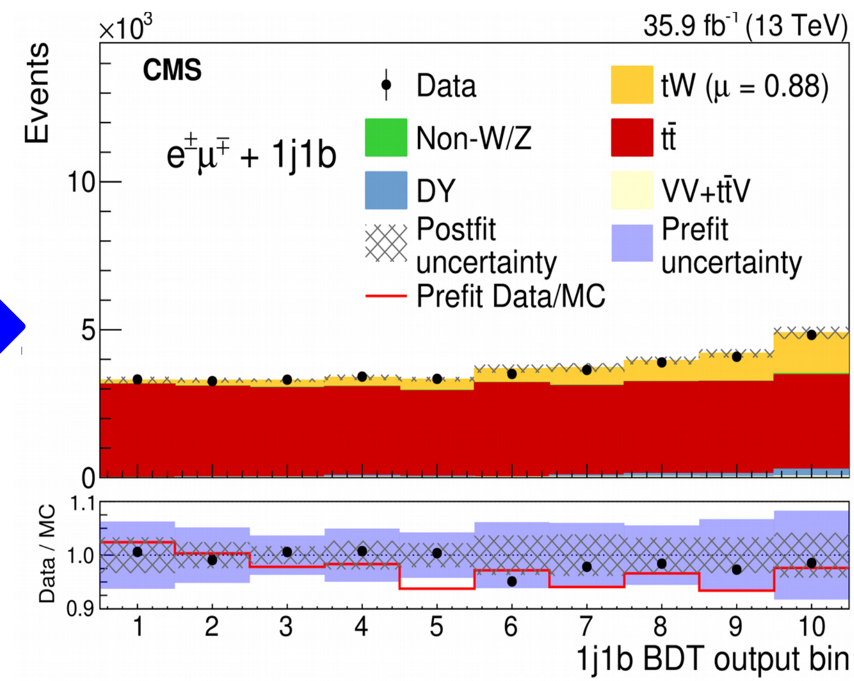
Single-top selection at LHC (Wt channel)

- State-of-the-art: include the most sensitive variables (+others) in a multidimensional analysis (Neural Nets (NN), Bayesian Decision Trees (BDT), ...) in order to increase the sensitivity even more
- This kind of methods are almost mandatory to get sensitivity to the Wt single-top production mechanism (≈20-30% of t-channel production, huge top-pair background)



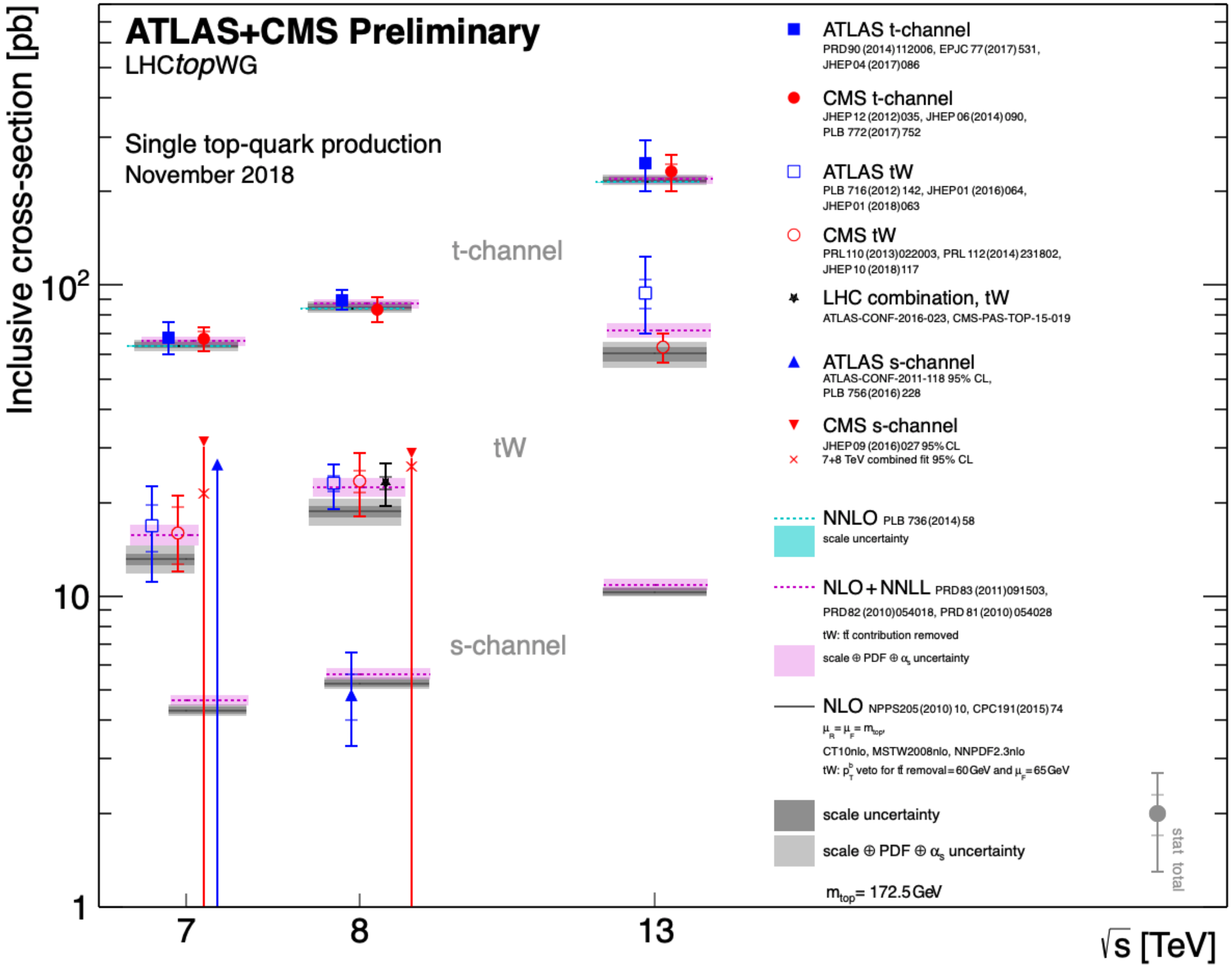
W+t production





arxiv:1805.07399

Single-top cross section measurements



[LPCC Top Working Group]

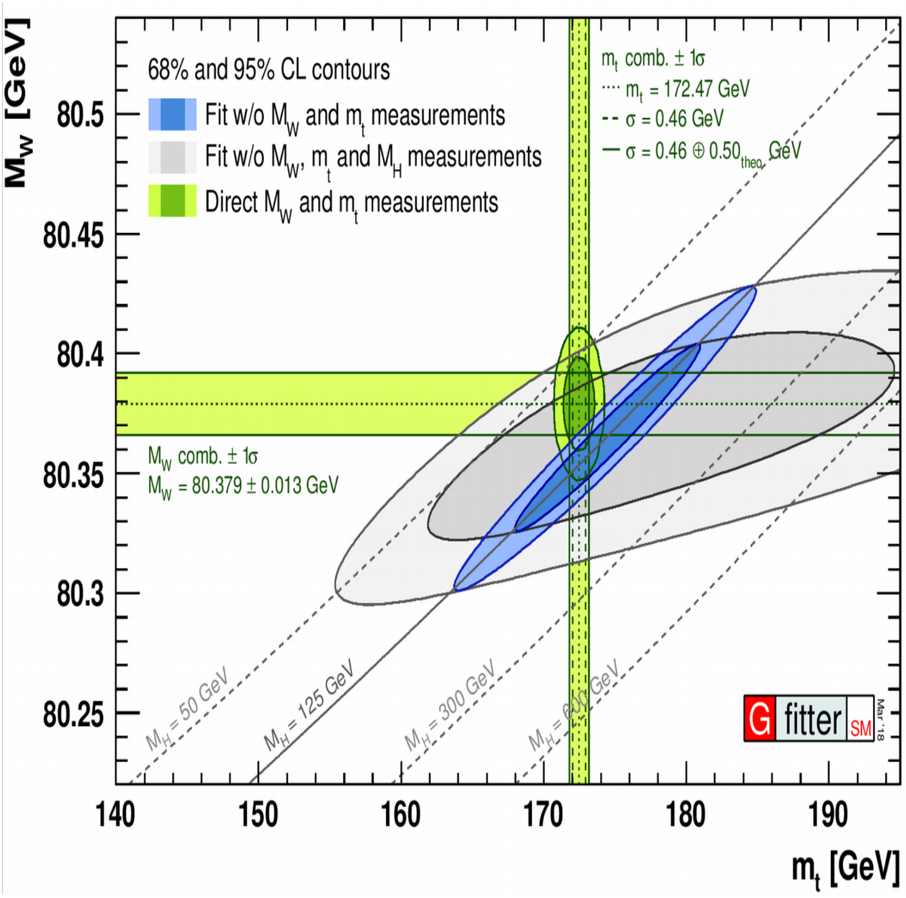
- **Good agreement with SM, large systematic uncertainties**
- **Experimental measurements slowly approaching theoretical precision**

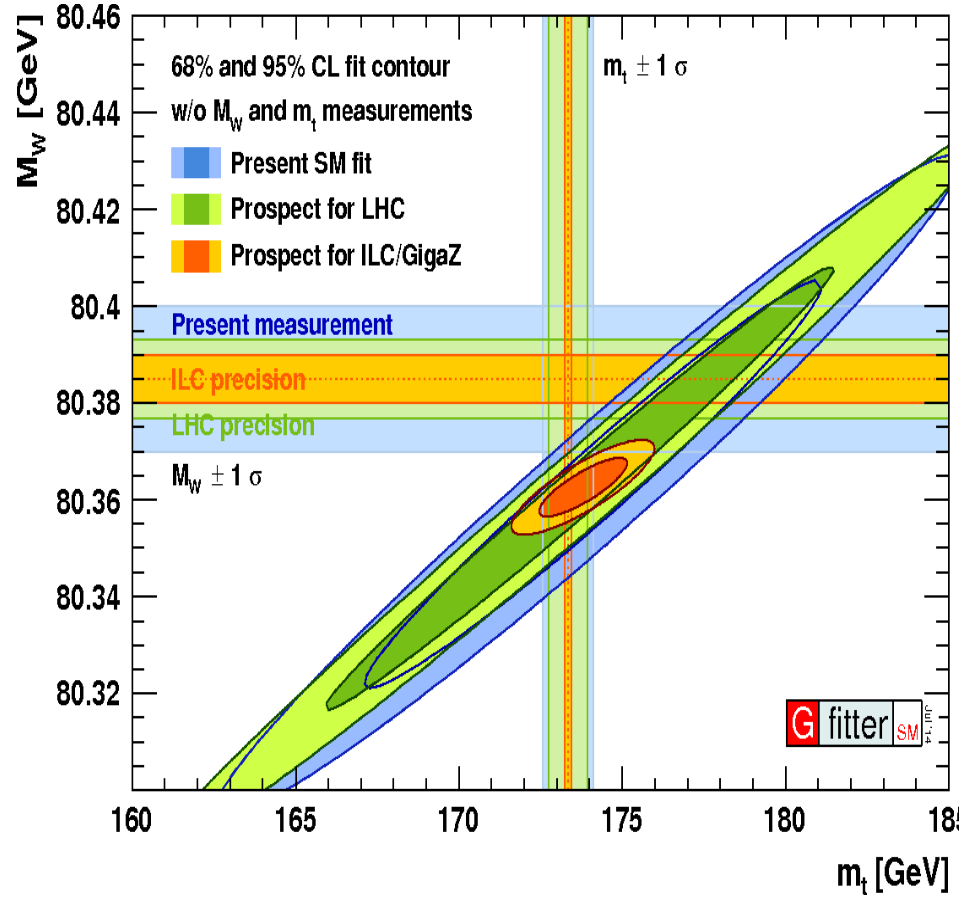
Top Physics at LHC: a vast field

- An LHC top factory is particularly well suited to study possible deviations from the standard model via intrinsic properties related with production and decay. Some examples:
  - Top mass, top width
  - $q\bar{q} \to t\bar{t}$ forward-backward asymmetries (very small in the SM)
  - Top polarization (SM expectations: 0 in $t\bar{t}$, very large in single-top production)
  - Spin correlations between top and antitop in top-pair events: sign of any additional contributions beyond the SM ?
  - Differential analysis of single-top production
  - Wtb vertex structure: any anomalies ?
  - Associated production: $t\bar{t}+\gamma$ (sensitive to QED charge), $t\bar{t}$+Z, $tt\bar{t}\bar{t}$, $t\bar{t}b\bar{b}$, … → critical background to many new physics searches, sensitive to new physics by themselves
  - Rare decays: Flavor Changing Neutral Currents (FCNC), which are extremely suppresses in the SM ($t\to Z+c$, $t\to Z+u$, $t\to \gamma+c$, $t\to \gamma+u$, …), …
- We can not cover everything here. Focus on some general aspects that could be useful for analyses containing top quarks (as signal or background):
  - Top-pair production: selection, production cross sections, spin correlations
  - Single-top production: general features, selection, production cross sections
  - **Measurement of the top mass**
  - **Top decay: decay/spin features, search for anomalous couplings**

Relevance of top mass measurements

Gfitter project



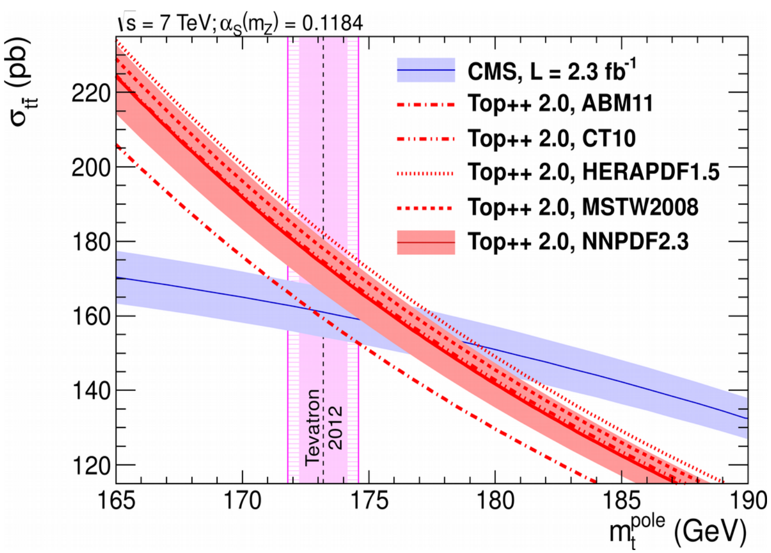


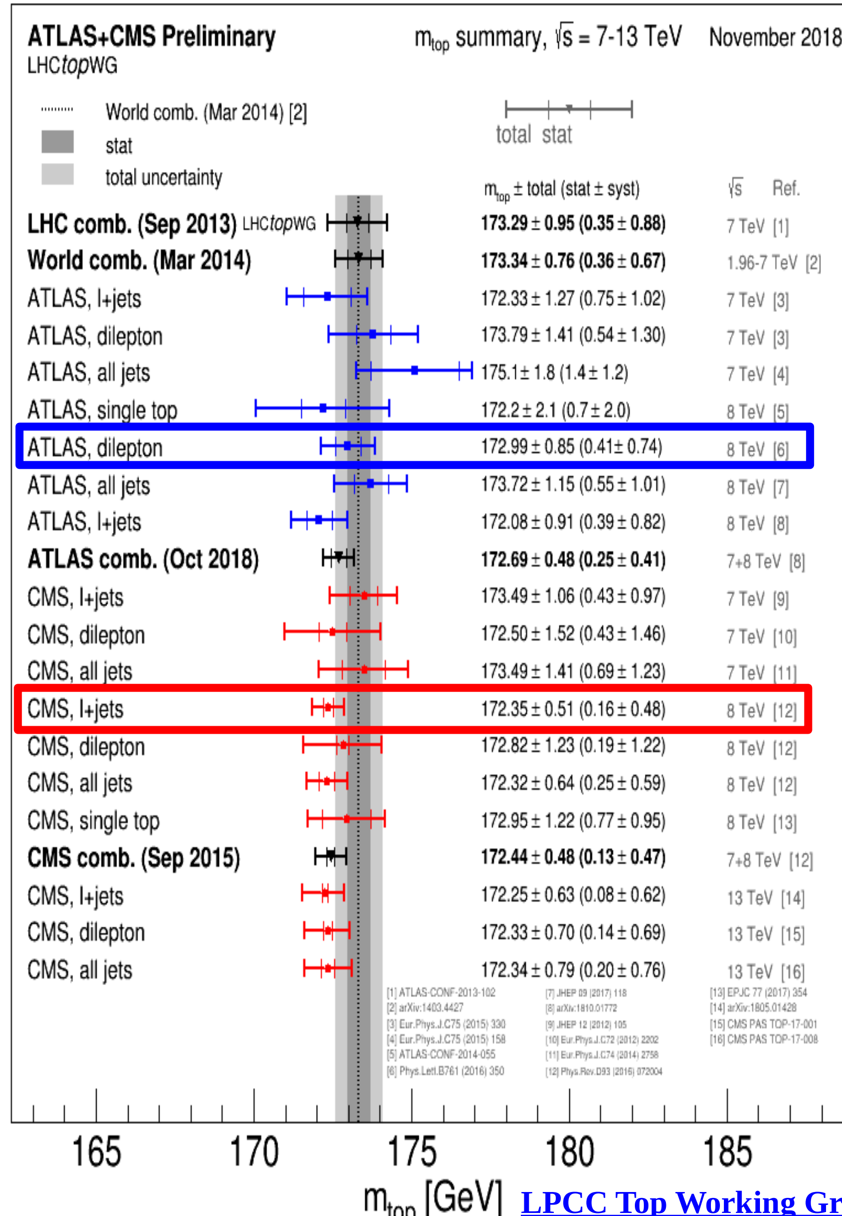
- Together with recent measurements of M_W and the Higgs mass, a precise measurement of m_t helps to severely constrain (or instead discover) deviations from the SM.

Top mass measurement at the LHC

- Statistics is very high, so measurements will be dominated by systematic uncertainties (theoretical and experimental)
- Many different methods employed, focusing on different systematic sources. Three main paths can be highlighted:
  - Most precise (today): lepton+jets channel
  - Experimentally cleanest: dilepton channel
  - Theoretically cleanest: $t\bar{t}$ or $t\bar{t}$+jet cross sections

arxiv:1307.1907



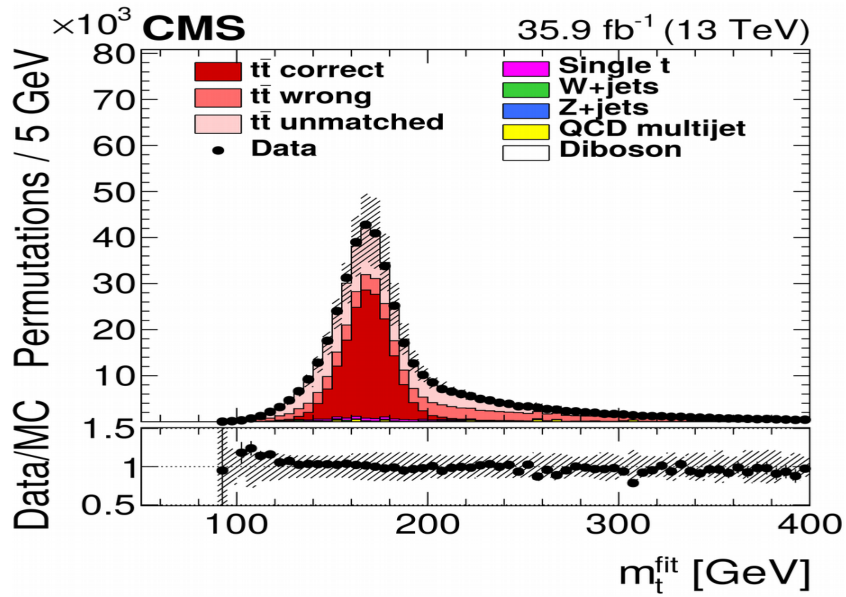


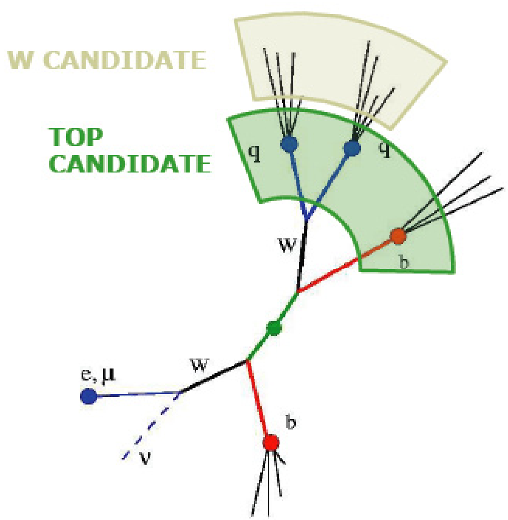
LPCC Top Working Group

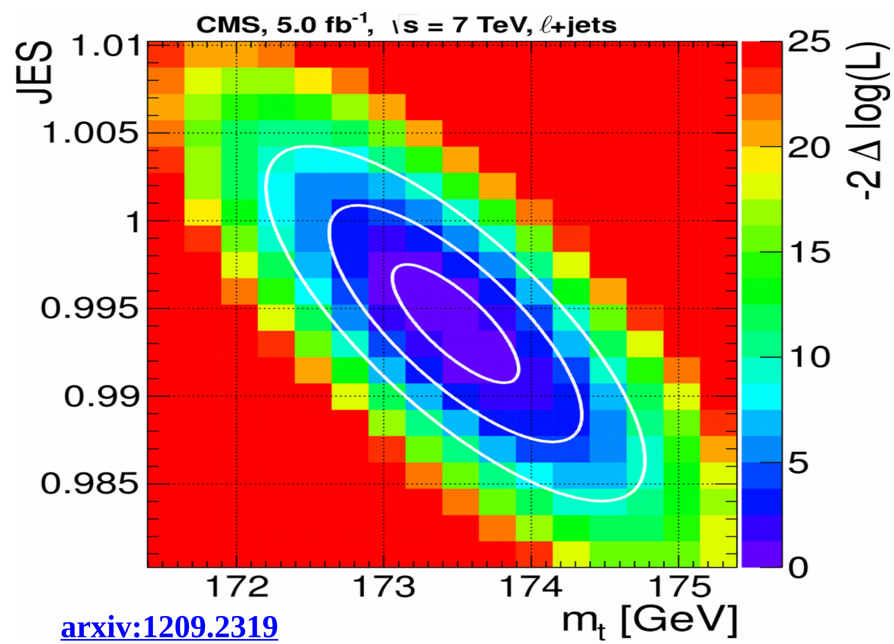
Top mass measurement at the LHC

- **Lepton+jet measurement:**
  - Basically, it implies a full kinematic reconstruction of the two tops in the event, where m_t is a free parameter in the game
  - An additional parameter is the energy scale factor for the jets in the event, which is partially constrained by the mass of the two light jets in the event (from the hadronic W)
  - Different versions for the final strategy: ideograms, templates, ...

arxiv:1805.01428







arxiv:1209.2319

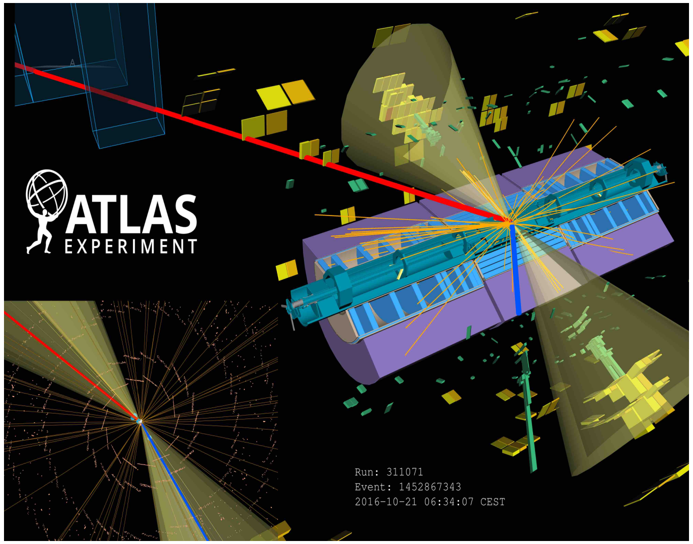
Top mass measurement at the LHC

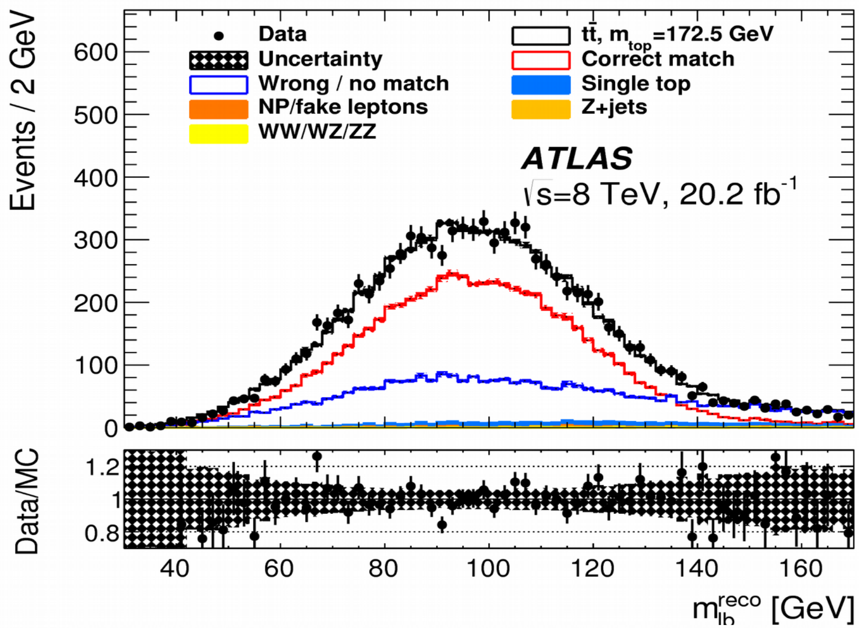
arxiv:1606.02179

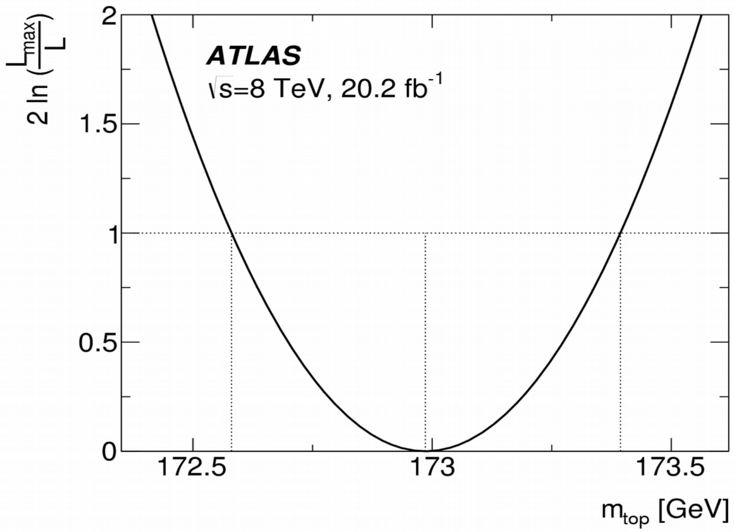
- **Dilepton measurement:**
  - Basically, it gets its sensitivity from the bl invariant mass distribution (no need to get the kinematics of the neutrinos)
  - It just assumes that there are no deviations in the Wtb vertex structure (i.e. no anomalous couplings):

$$M_{bl} = \sqrt{m_t^2 - m_W^2}\ \cos\left(\frac{\theta^*_{Wl}}{2}\right); \qquad (m_b \to 0)$$

  - Still directly dependent on b-jet energy scale uncertainties

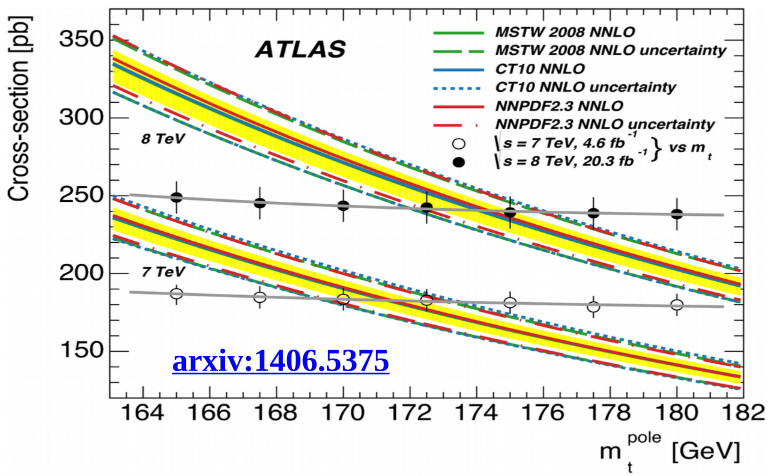




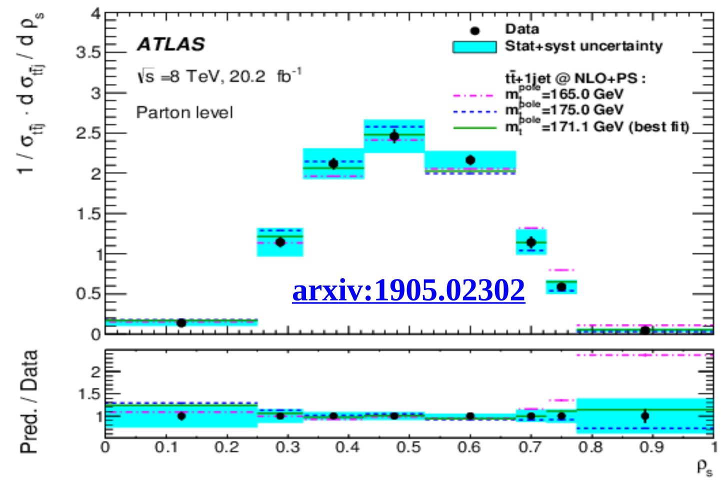


Top mass measurement at the LHC

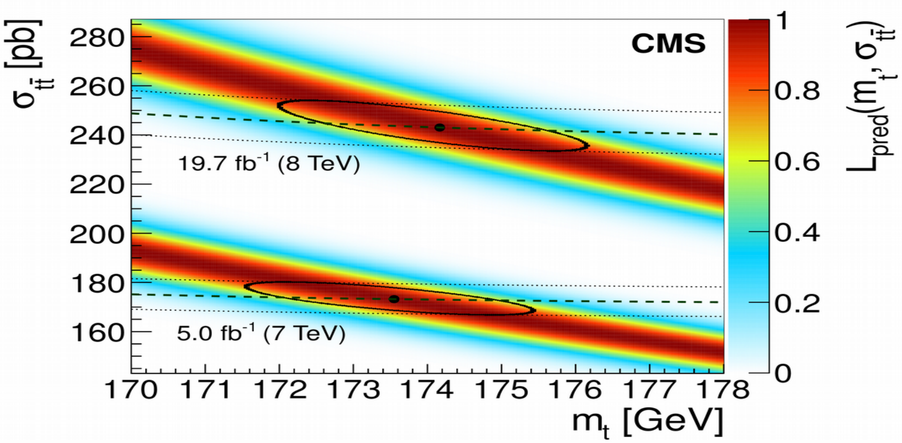
- $t\bar{t}$ cross section measurements in general:
  - Reduce theoretical uncertainties: m_t (pole) is well defined in this context
  - Interesting interplay with theory uncertainties: PDFs, α_s, … → not so negligible !!
- New wave: differential cross sections as a function of different kinematic variables
  - ρ_s=340 GeV/mass($t\bar{t}$+1jet) (ATLAS)
  - N_{jet}, M($t\bar{t}$), y($t\bar{t}$) (CMS)

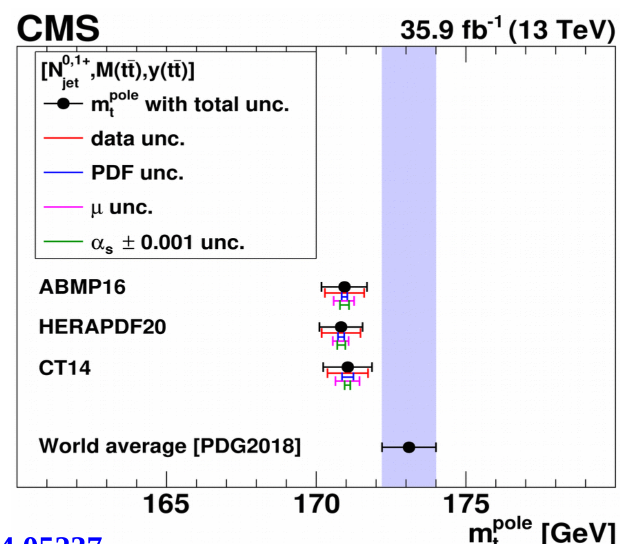


arxiv:1406.5375



arxiv:1905.02302

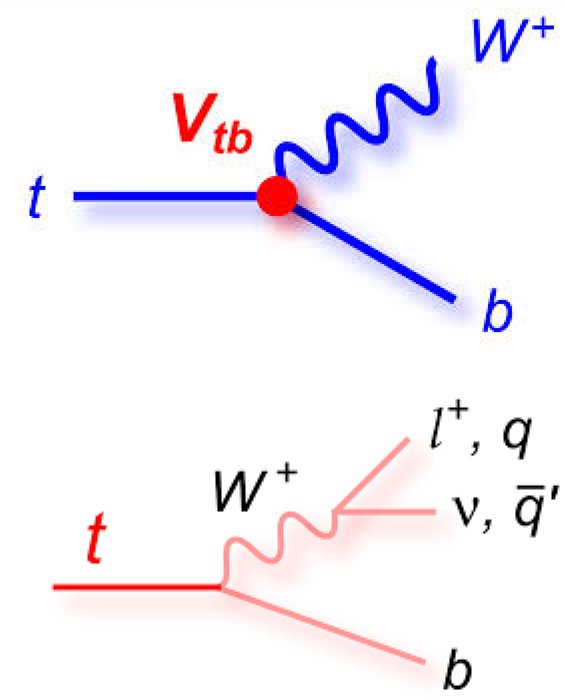


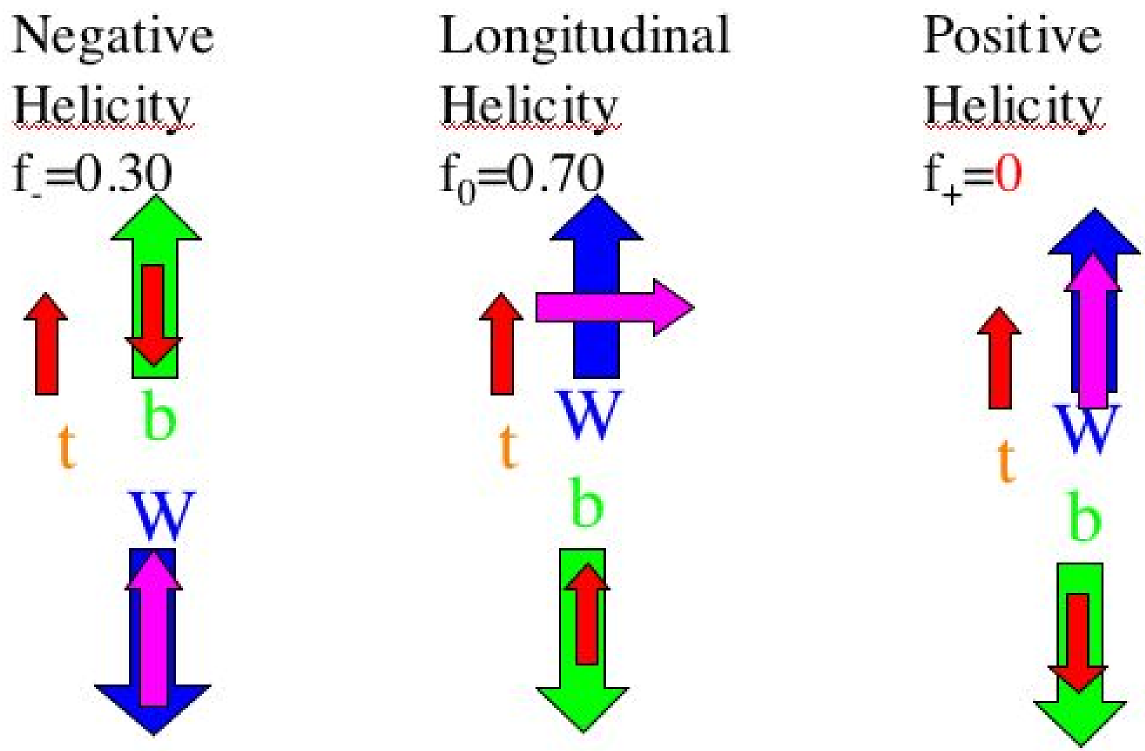


arxiv:1603.02303

arxiv:1904.05237

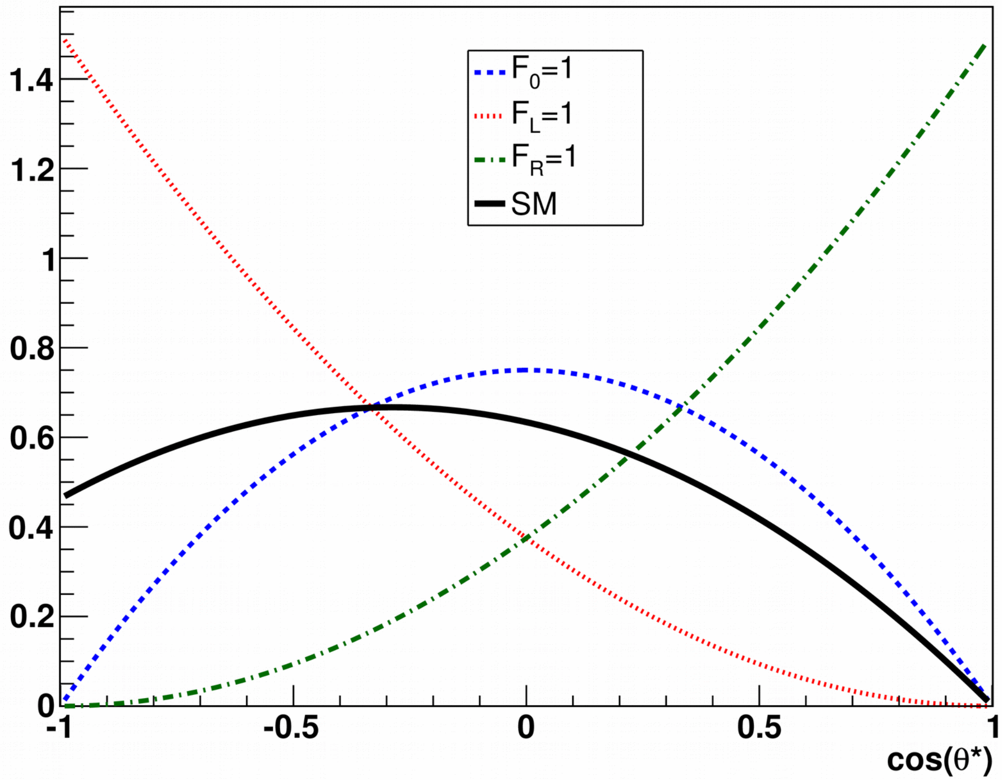
Top decay properties





- Easy features to deduce without any calculation:
  - V-A ("left-handed") nature of the charged weak current: massless particles are always left-handed (negative helicity), massless antiparticles are always right-handed (positive hel.)
  - b quark in final state is left-handed ⇒ W spin must compensate to match the top spin
  - In the top center-of-mass frame the W can not be "right-handed" ($f_+=0$), independently of the top spin direction; strictly speaking, its size is $\leq O(m_b^2/m_W^2)$
- The sharing of amplitudes requires the calculation of the amplitudes via Feynman diagrams

Angular distributions in W rest frame



$$\frac{1}{\sigma}\ \frac{d\sigma}{dc} = \frac{3}{8}\ \left[f_{-}(1-c)^2 + f_{+}(1+c)^2 + 2 f_0 (1-c^2) \right]$$

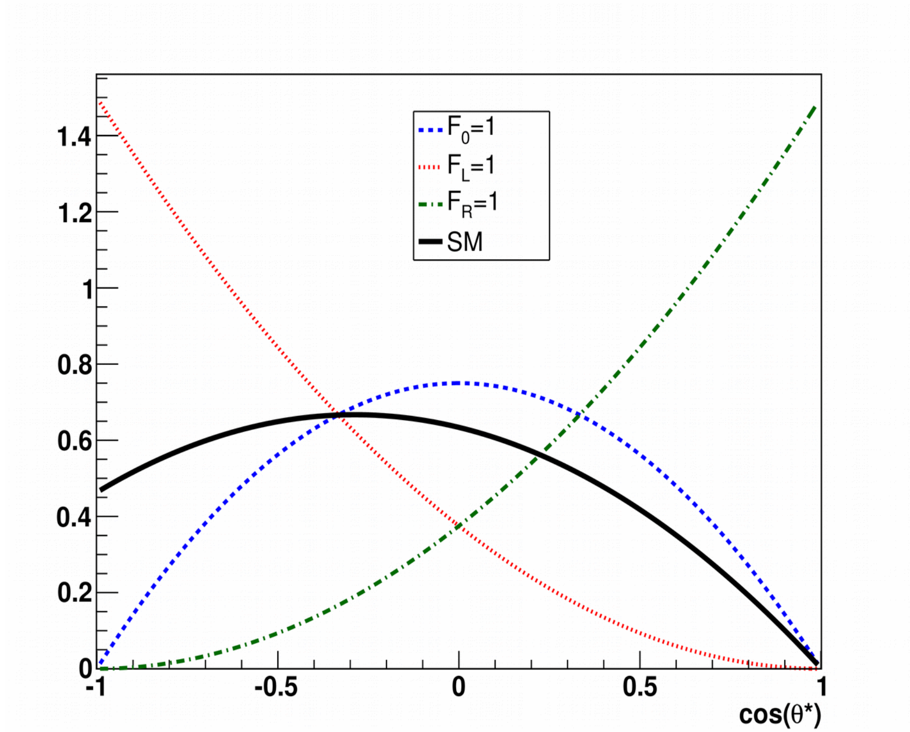
$$c \equiv \cos(\theta^*); \qquad f_{-} \approx 0.3;\ \ f_0 \approx 0.7;\ \ f_{+} \approx 0$$

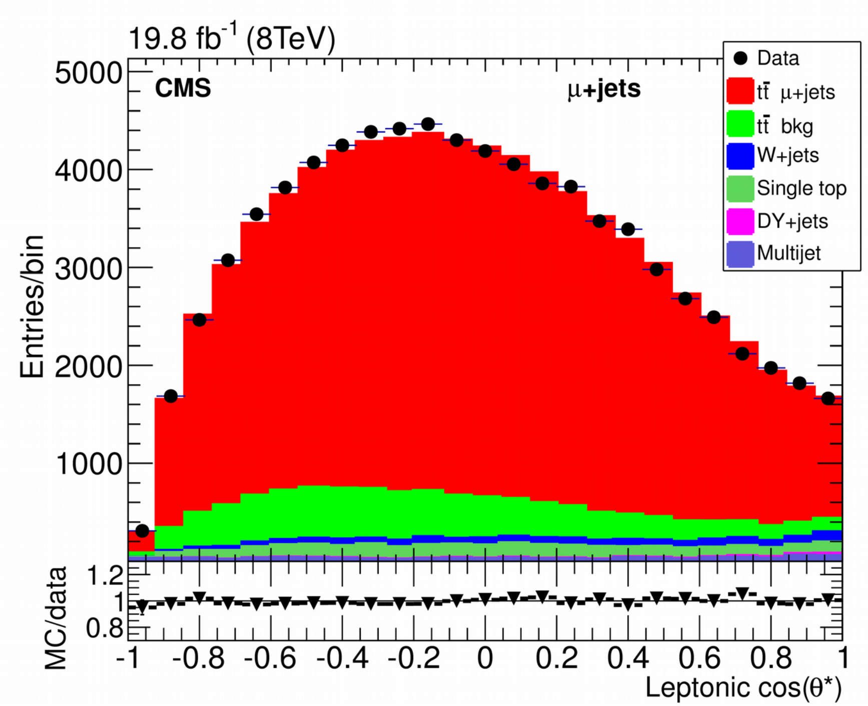
- θ* is the polar angle of the down-type fermion in the W decay rest frame(*)
  - (*) Technically: 1) boost to top rest frame, 2) Z axis ≡ W flight direction, 3) boost to W rest frame

Measurement of W helicity fractions

$$\frac{1}{\sigma}\frac{d\sigma}{dc}=\frac{3}{8}\left[f_-(1-c)^2+f_+(1+c)^2+2f_0(1-c^2)\right]$$

$$c\equiv\cos(\theta^*);\qquad f_-\approx 0.3;\ f_0\approx 0.7;\ f_+\approx 0$$

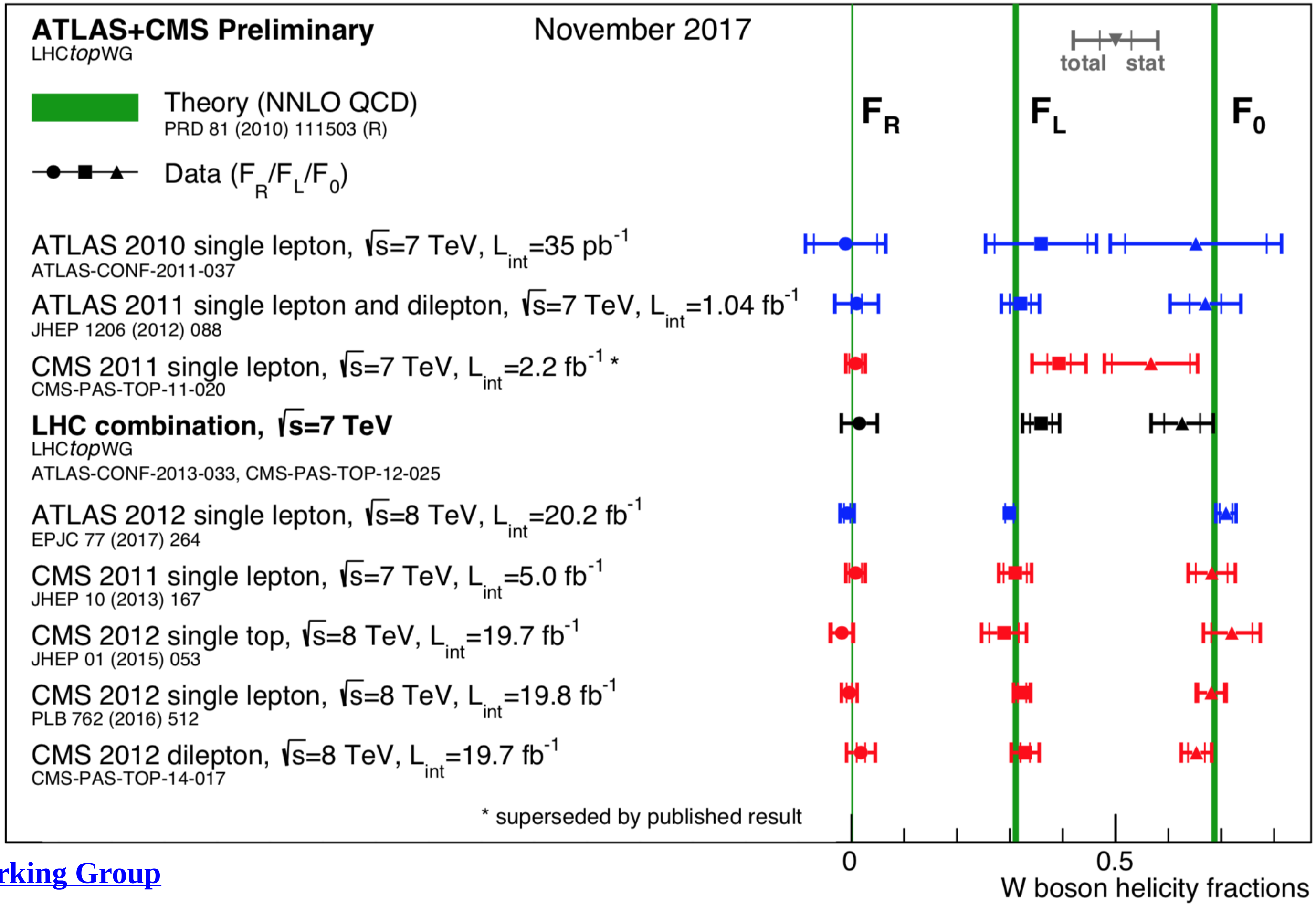




arxiv:1605.09047

- cos(θ*) distribution is the optimal observable for the measurement of the W polarization fractions in top decays.
- Affected by intrinsic theoretical uncertainties (top mass, scales, …) and experimental distortions: jet resolutions, b-tagging, lepton isolation, kinematic fitting for the ν, ...

Angular distributions in W rest frame

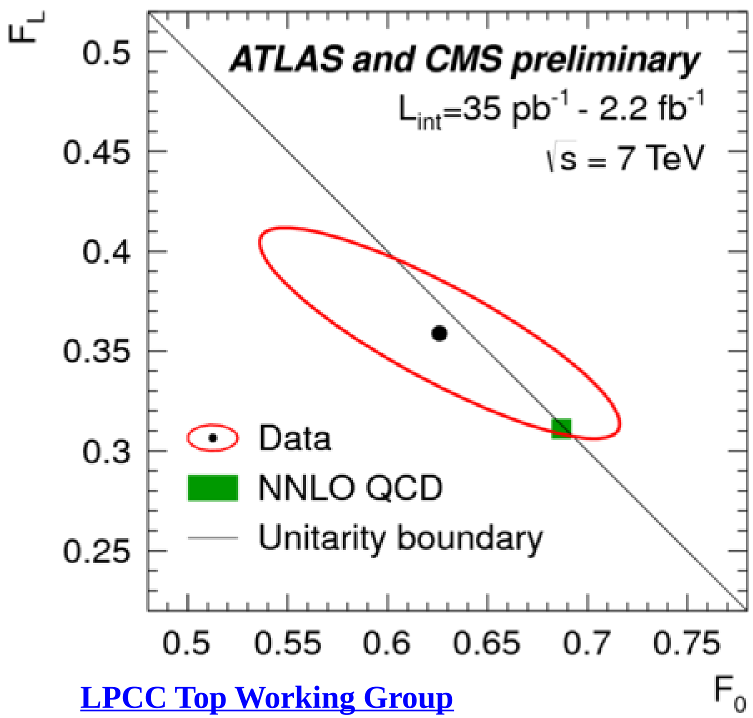


[LPCC Top Working Group]

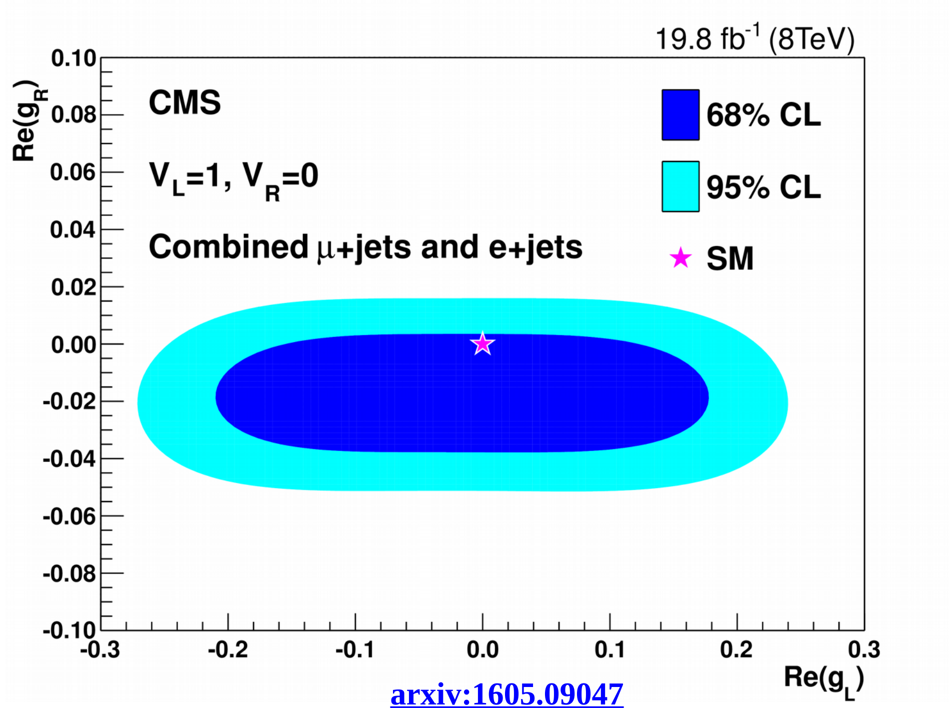
Wtb anomalous couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

- **In the SM:**
  - **V_L=1**
  - **V_R=g_L=g_R=0**



LPCC Top Working Group

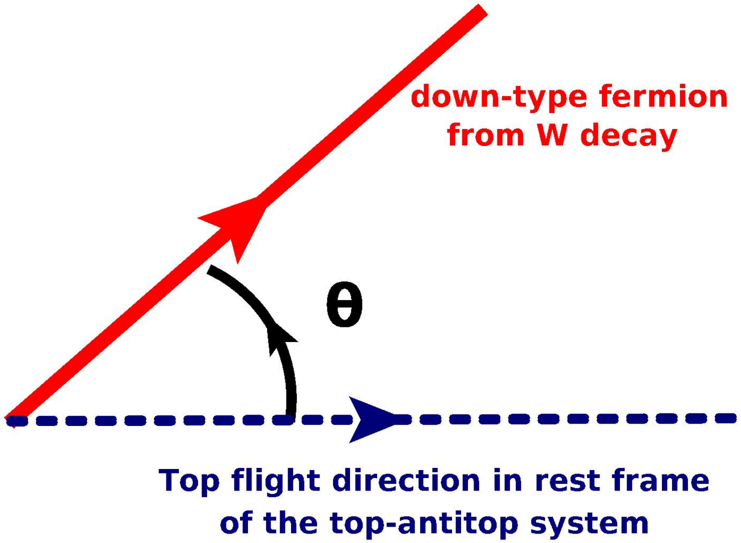


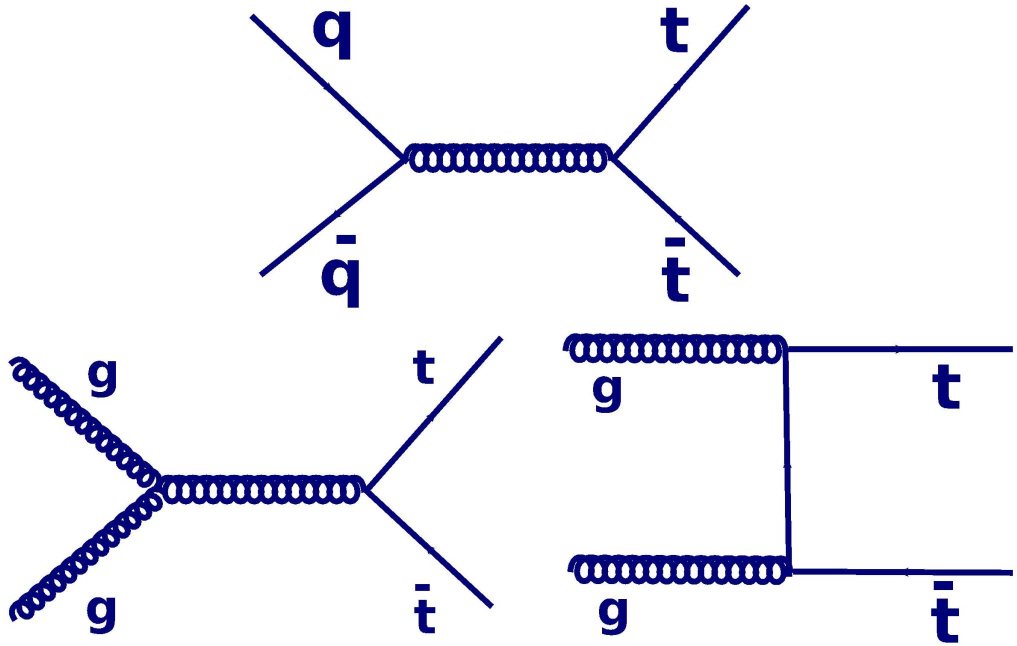
arxiv:1605.09047

- **Currently studied via W helicity fractions, but should be studied in the future in more detail via angular distributions / spin properties in 3D**

Top polarization at LHC

top rest frame





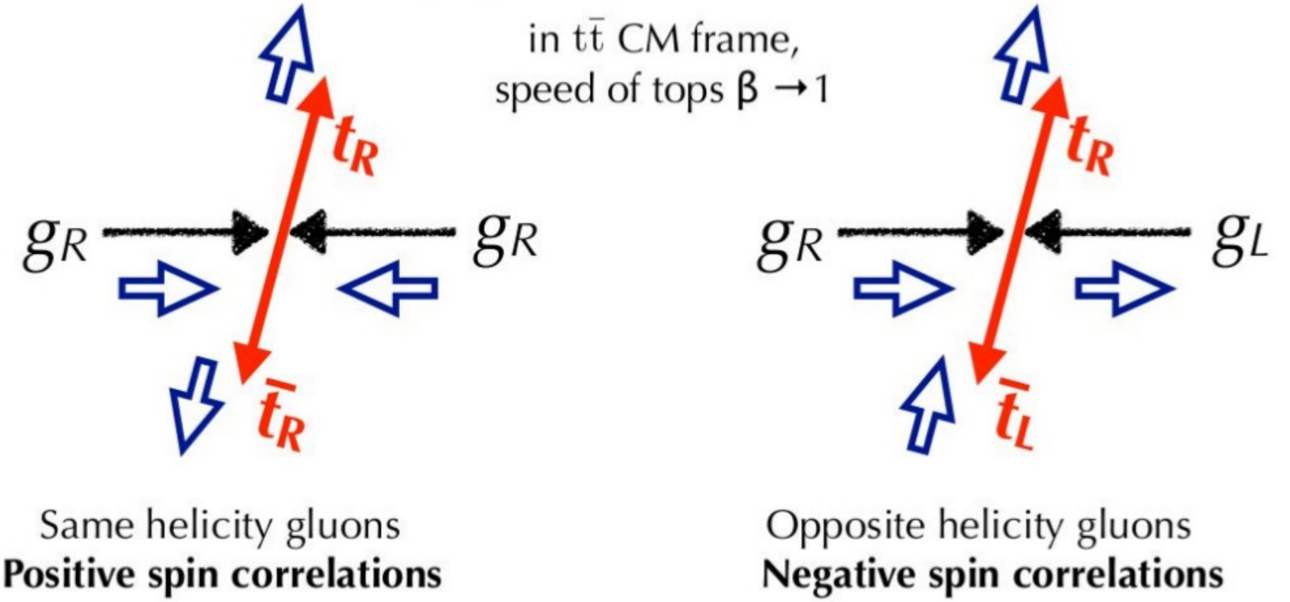
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}=\frac{1}{2}\left[1 + \left[\overline{P}\right]\ \alpha_f \cos\theta\right]$$

$$\alpha_f = +1 \textit{ for down-type fermions}$$

- The best top (or antitop) polarization analyzer is the angle of the down-type fermion from W the decay (the charged lepton in semileptonic decays), measured in the top (or antitop) rest frame
- No top polarization on average in $t\bar{t}$ production at LHC:
  - The process is fully dominated by QCD interactions, and QCD has no net preference for any given “handedness” of the top quark

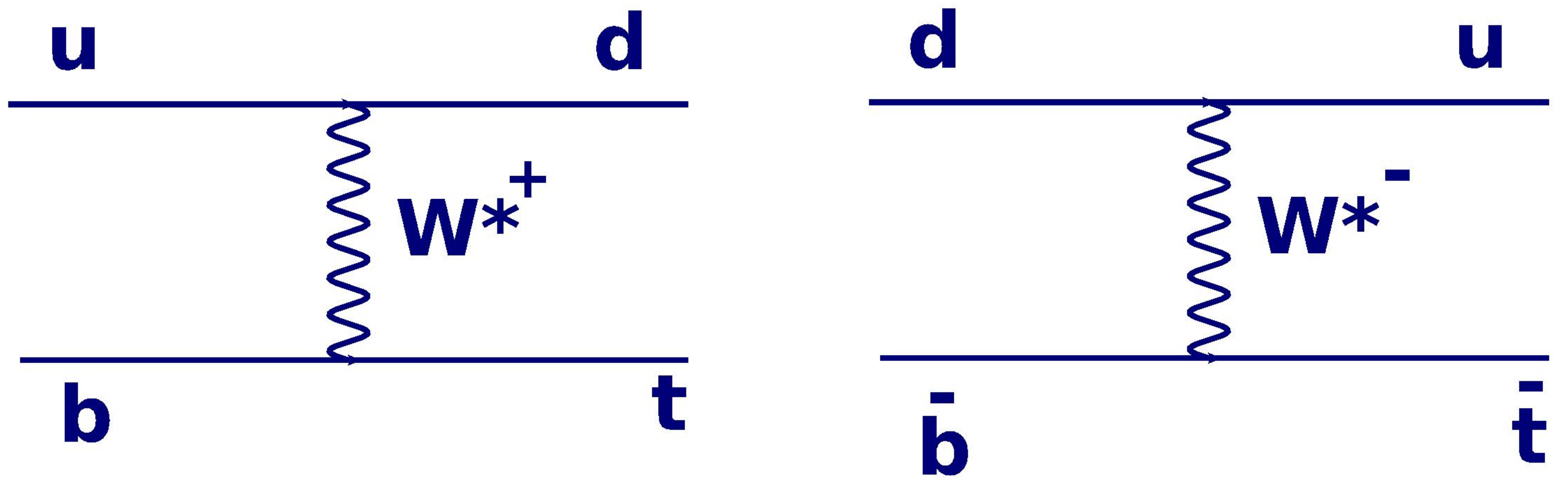
Top spin correlations at LHC

- **Same** and **opposite** helicity gluon fusion contributions **impart different spin correlations to the top quark pairs**



- **Same helicity** contribution is **dominant near threshold**
- Opposite helicity dominant when $E_t >> m_t$ (helicity conservation)
- Expected net spin correlation strength of about **+30%** at the LHC
  - **modified in many new physics scenarios**

Top polarization in single-top production



Single-top, dominant t-channel diagrams

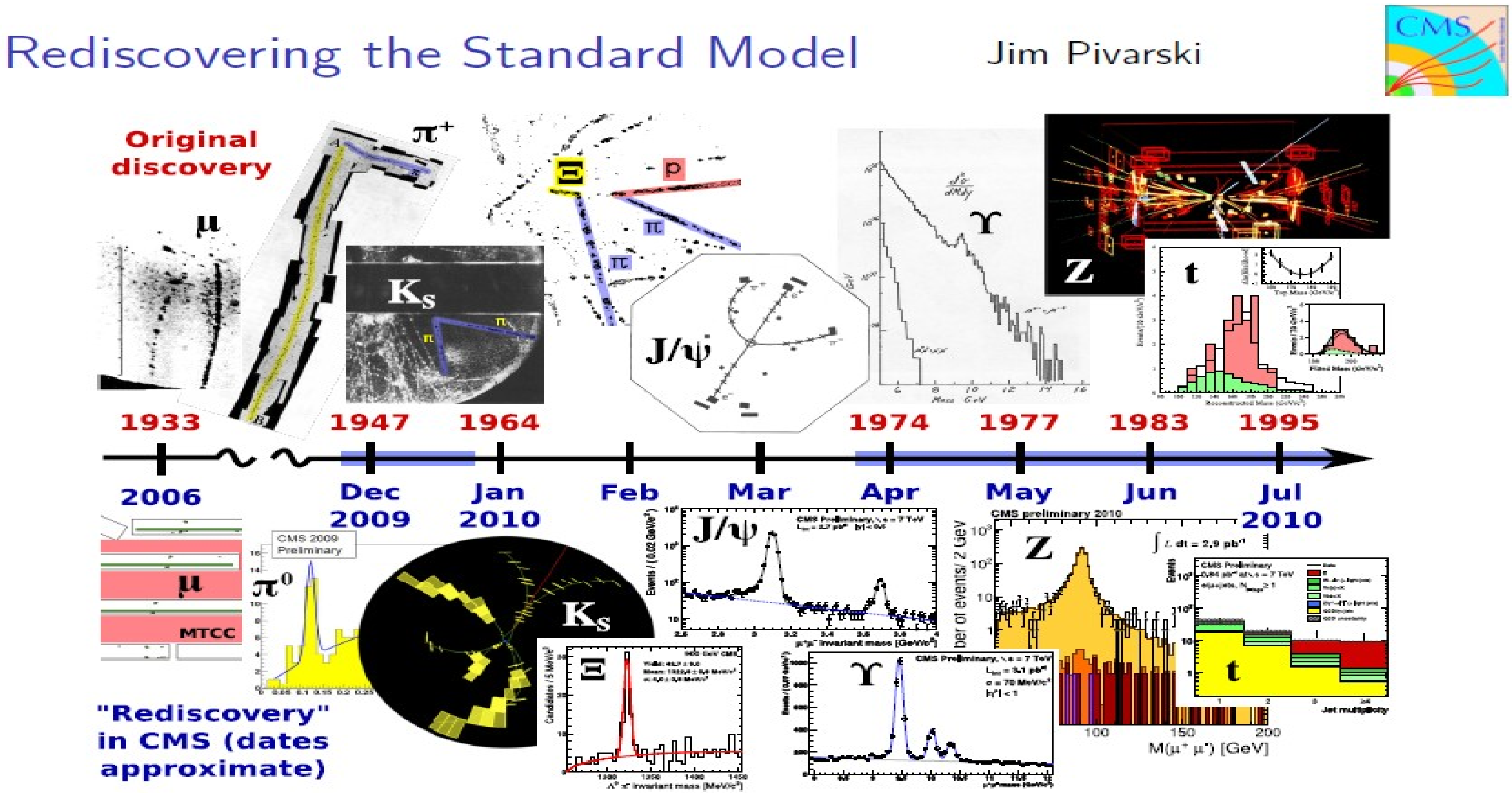
- Easy features to deduce without any calculation:
  - For top: u, b are left handed, so total spin is zero, d is also left-handed ⇒ top has +100% polarization along the flight direction of the spectator quark (the d quark)
  - For antitop: d is left-handed, anti-b is right-handed, so 3rd component of spin is -1 along the d quark direction ⇒ the antitop has -100% polarization in the limit in which the u quark is very close to the direction of the initial d quark

Outlook

- SM studies at the LHC are extremely important
  - It is the baseline to do any other analyses, like Higgs studies or searches for new particles
    - Final state particles in these studies include W,Z,tops,jets, and they are triggered/selected in similar ways
    - SM W/Z/top production is the main background for new particle searches
  - First class / unique results on QCD, W/Z, top physics, including the measurement of fundamental SM parameters like m_W, m_t, $\sin^2\theta_{eff}$
- Still large margin for improvement in future runs of the LHC (see next talks)

Backup

Rediscovery of SM



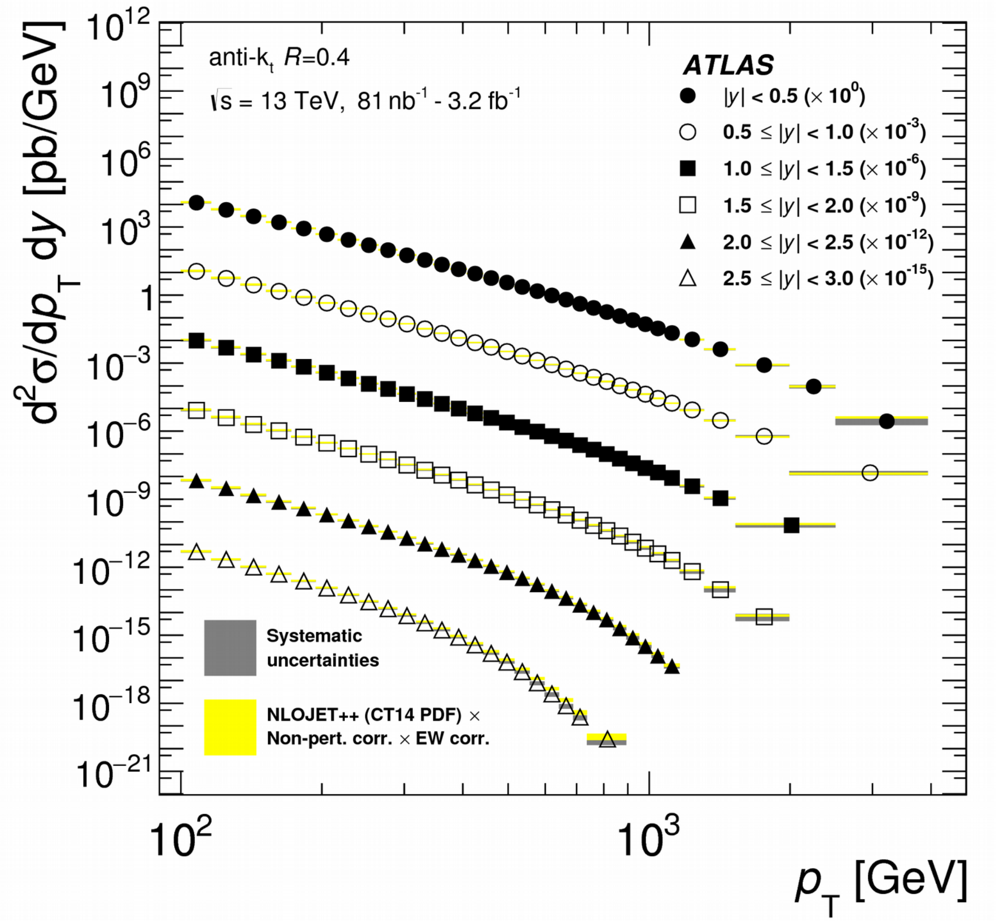
Jet production studies

• What we want to measure in this example is the differential cross section of jet production as a function of jet p_T and rapidity:

$$\frac{d^2\sigma}{dp_T\, dy} = \frac{\dfrac{d^2 N}{dp_T\, dy}}{Lum. \otimes Effic.(p_T, y)}$$

• This is one of the most basic measurements one can think of for a hadron collider

arxiv:1711.02692

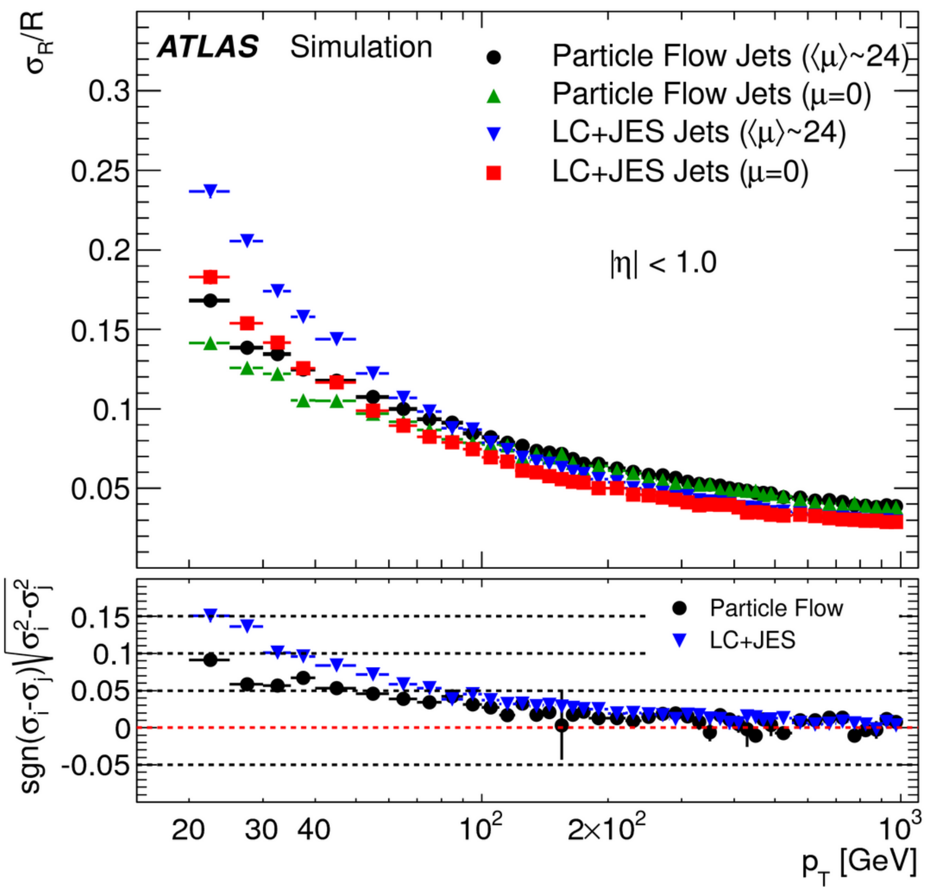


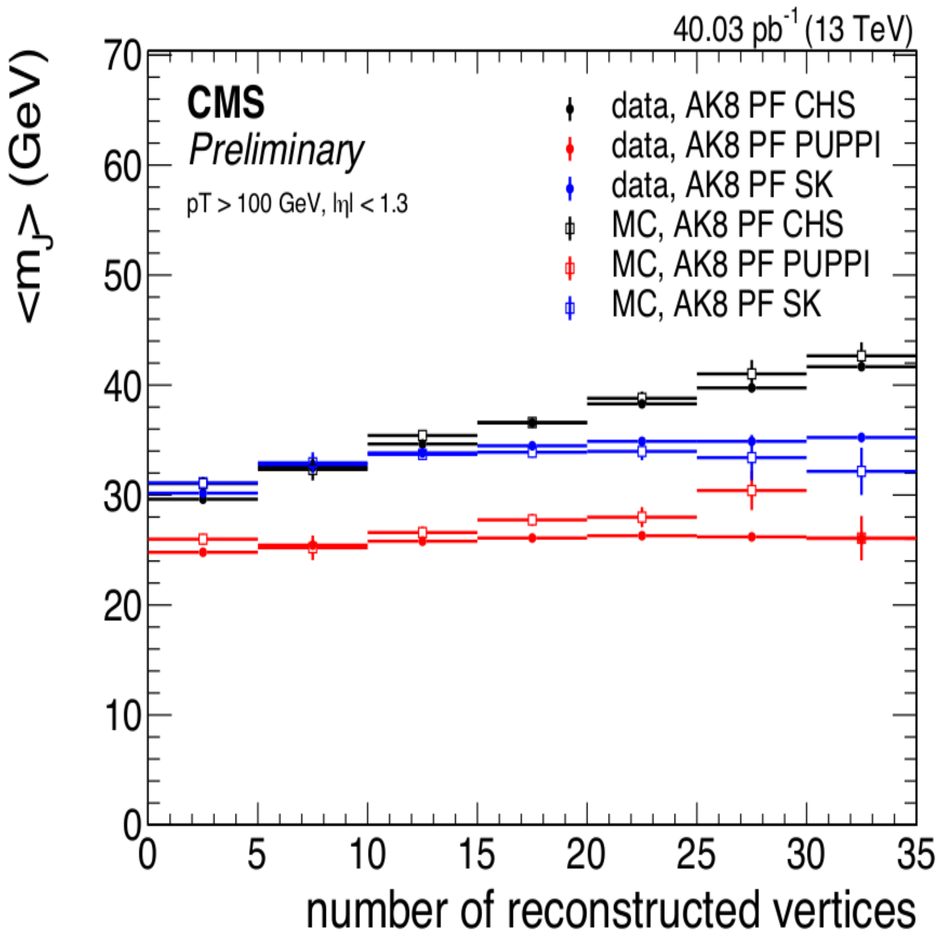
Impressive agreement with (NLO) theoretical predictions over several orders of magnitude !!

Particle flow, pileup subtraction

arxiv:1703.10485

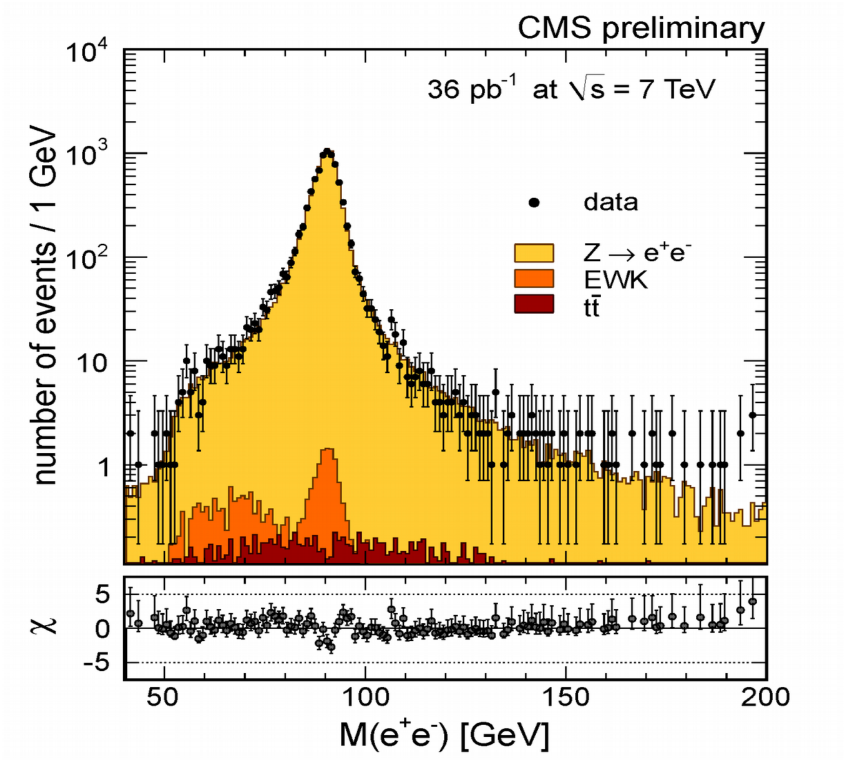
CMS-DP-2015-034

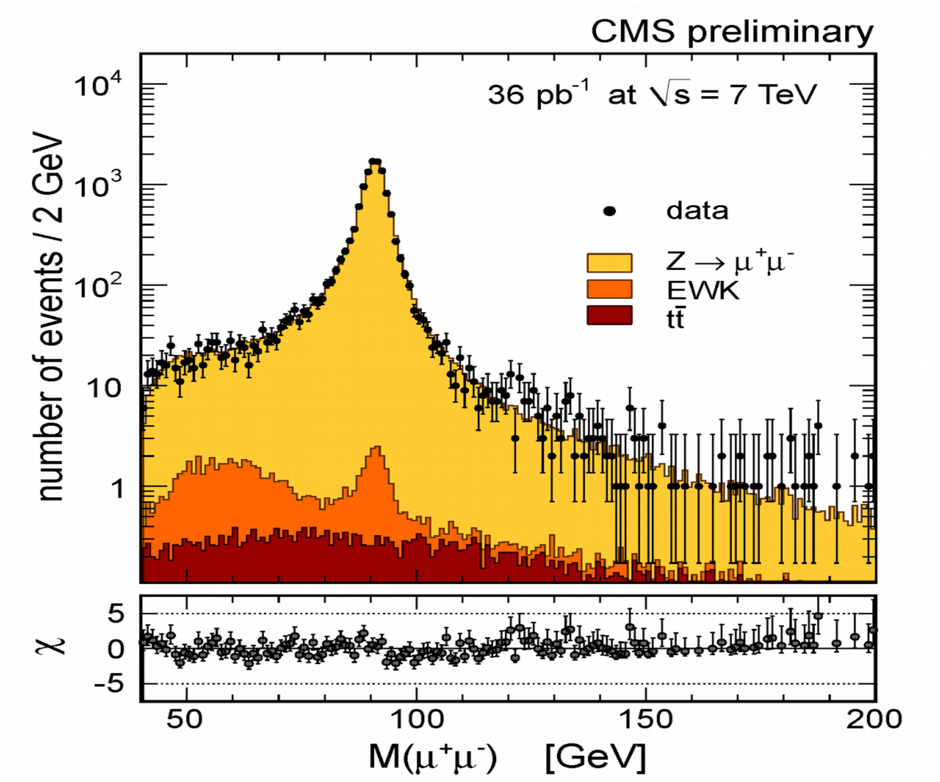




Z production

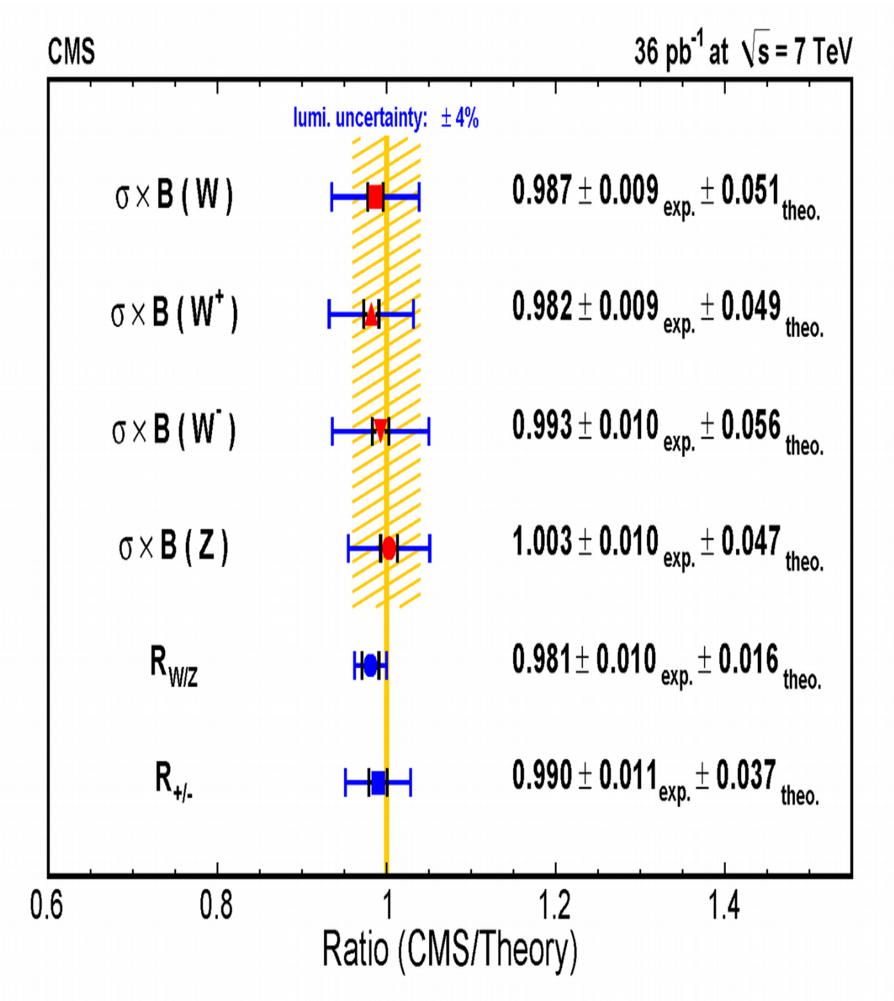
- How do we select Z → μμ and Z → ee events?
  - This is rather simple: just plot the reconstructed invariant mass of isolated dimuon and dielectron candidates with high-p_T: (p_T^{lepton} > 20-25 GeV)

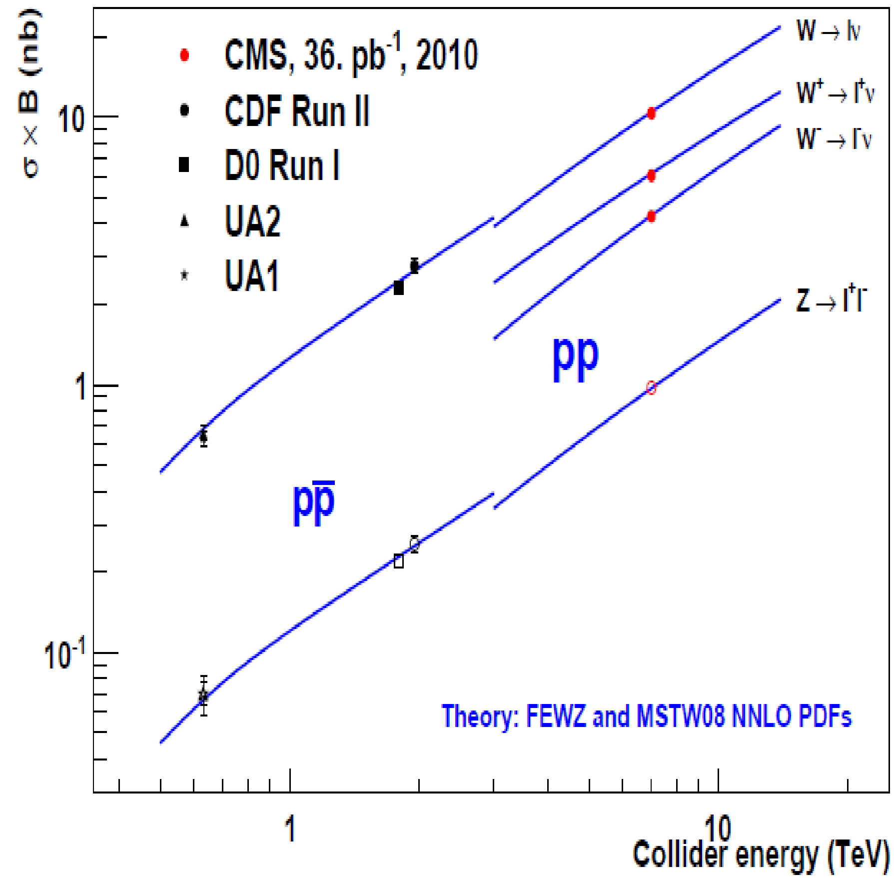




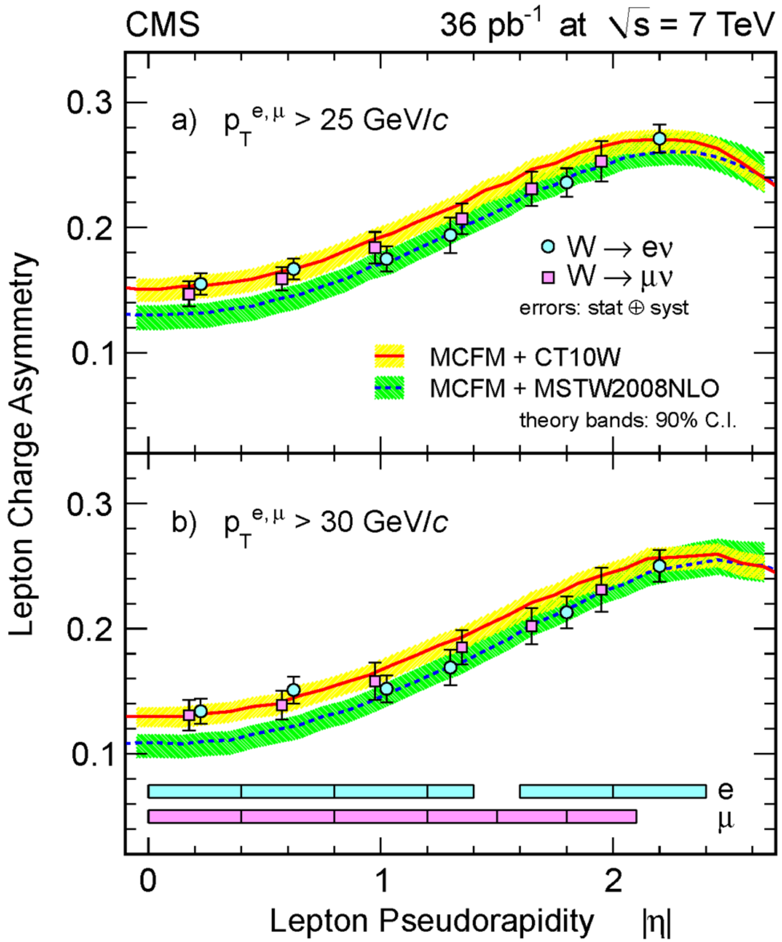
- Note that backgrounds are extremely small (these are logarithmic plots)

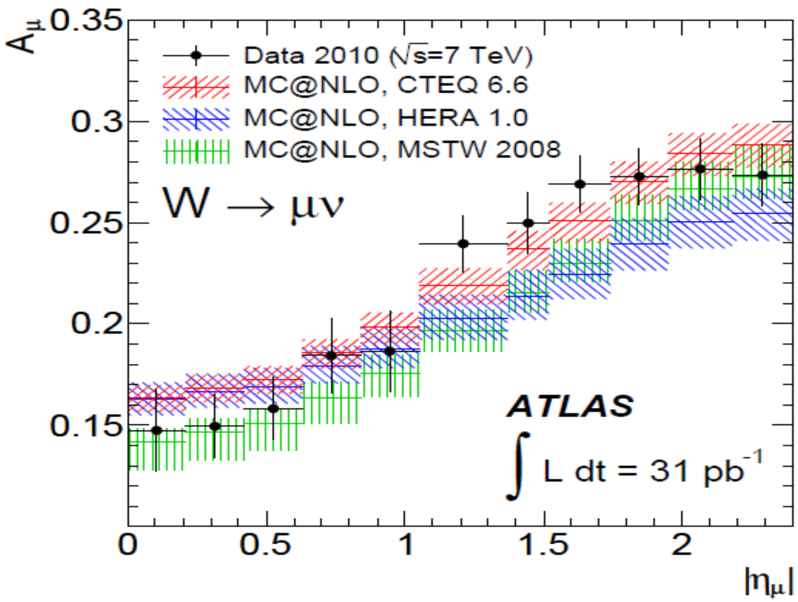
Early CMS W/Z inclusive results





Early EWK results (W asymetries)



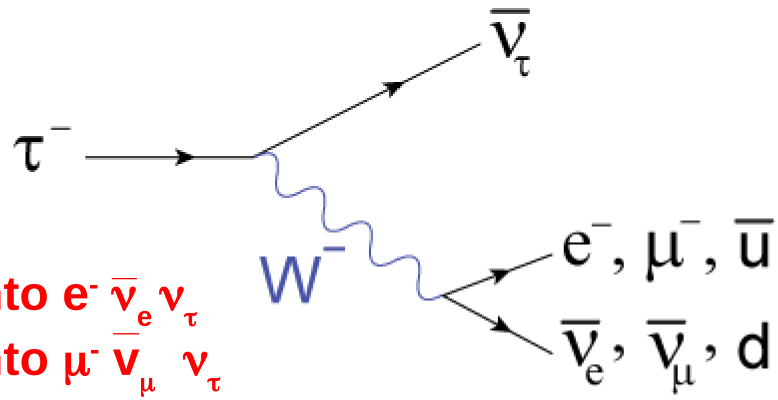


$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

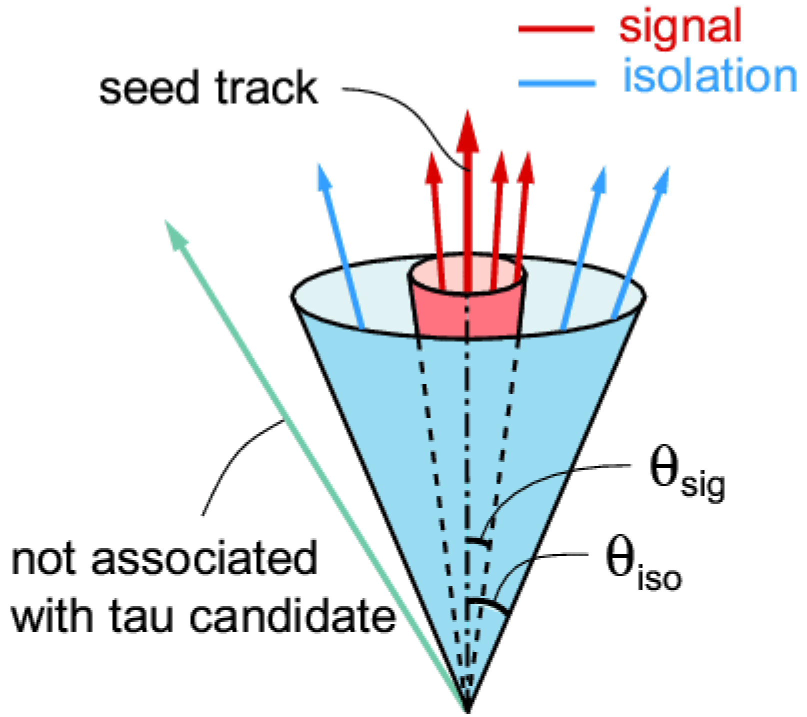
- W charge asymmetry: directly sensitive to PDFs. Selections follow from inclusive measurements, but most systematics cancel in the ratio

Tau decay and signatures

- Reminder on tau decays:



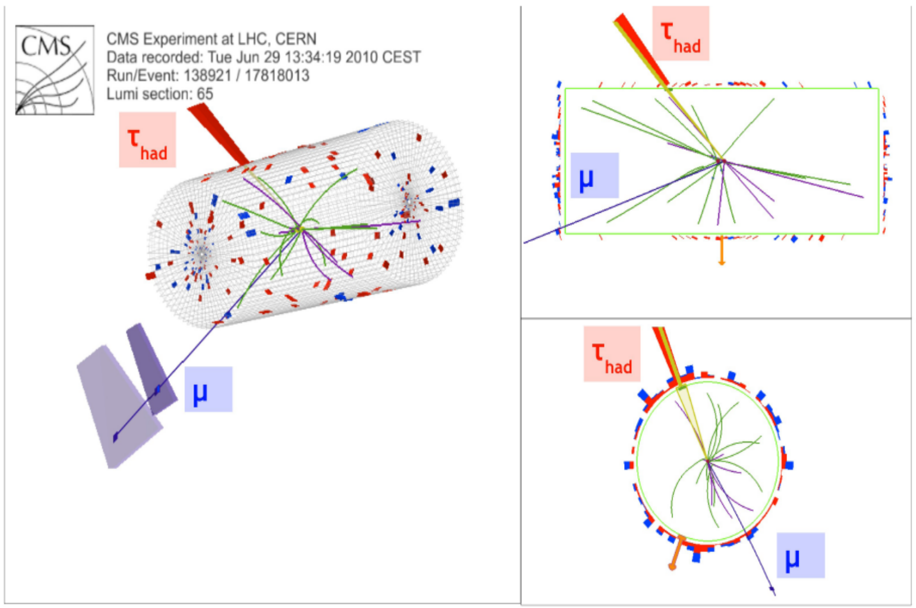
~17% into $e^- \bar{\nu}_e \nu_\tau$
~17% into $\mu^- \bar{\nu}_\mu \nu_\tau$
~25% into $\rho^- \nu_\tau$
~11% into $\pi^- \nu_\tau$
~85% into 1 charged particle + X (``one prong")
~15% into 3 charged particles + X (``three prong")



- **The signature of a ``hadronic tau" decay is the presence of a high-p_T and collimated jet with very low multiplicity (typically just one charged track, and at most three charged tracks), well isolated from other particles in the event**

Selecting taus

Z → tau tau → mu +tau_{had} (one prong+pi0 tau)

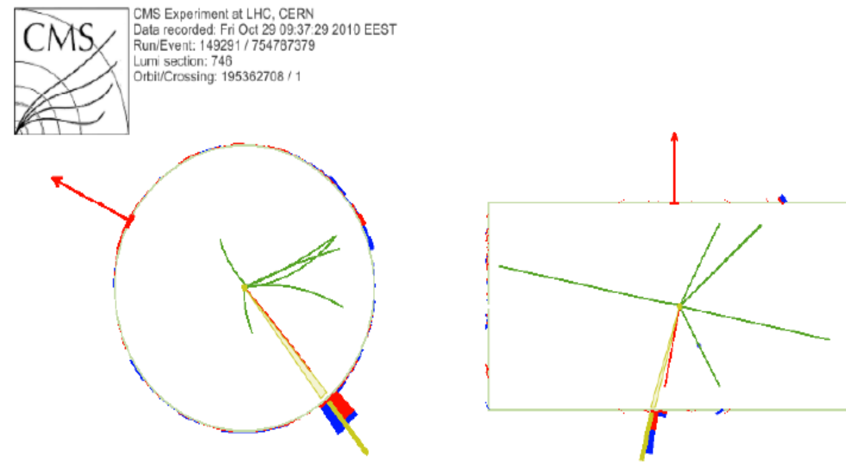


μ p_T = 22.8 GeV/c

T_{had} E_T = 32.9 GeV

Vis. Mass = 60.8 GeV/c^2
M_T(μ,MET) = 10.1 GeV

W → tau_{had} nu (one prong+pi0 tau)



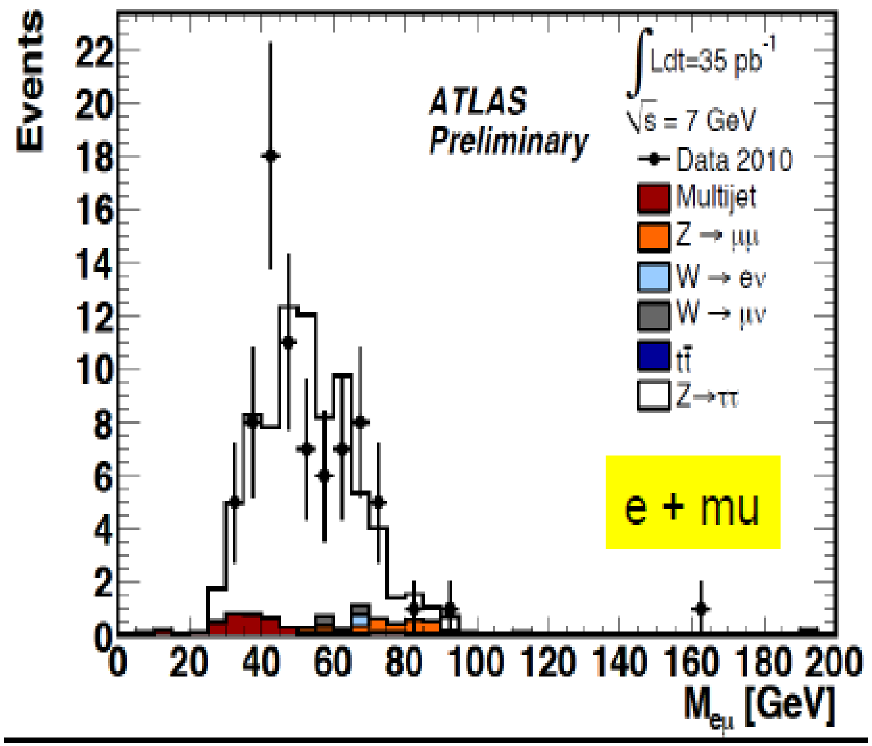
m_{vis} = 0.87 GeV

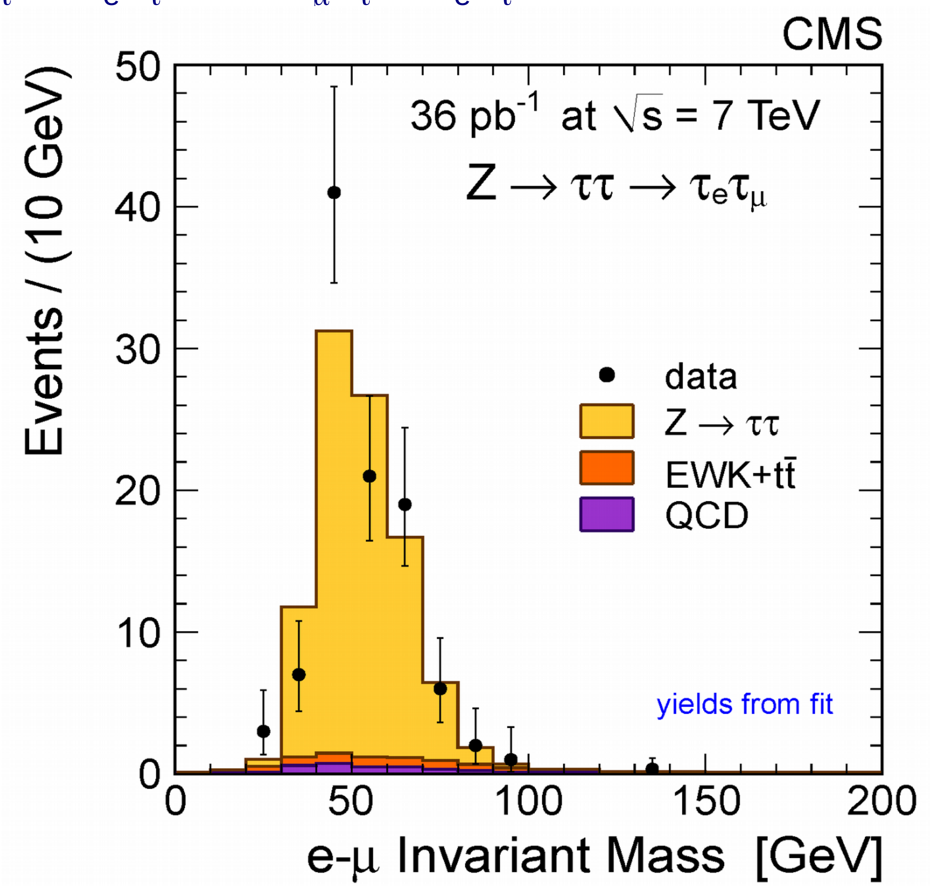
τ_{had} (1 prong, 1 π^0):
p_T = 33 GeV
η = -0.25
p_T(lead. track)= 21 GeV
E_T miss= 57 GeV
EM-fraction = 0.38
m_T(τ,υ) = 88 GeV

- These are examples of the power of particle-flow techniques
- Visible tau signal in Z-> tau tau production with just 1.7 pb^{-1} of data !!
- These are important benchmark measurement for key new particle searches like H-> tau tau, for instance!

Selecting taus

- Cleanest channel: $Z \to \tau\bar{\tau} \to \mu^- \bar{\nu}_\mu \nu_\tau \; e^+ \nu_e \bar{\nu}_\tau$, $\mu^+ \nu_\mu \bar{\nu}_\tau \; e^- \bar{\nu}_e \nu_\tau$

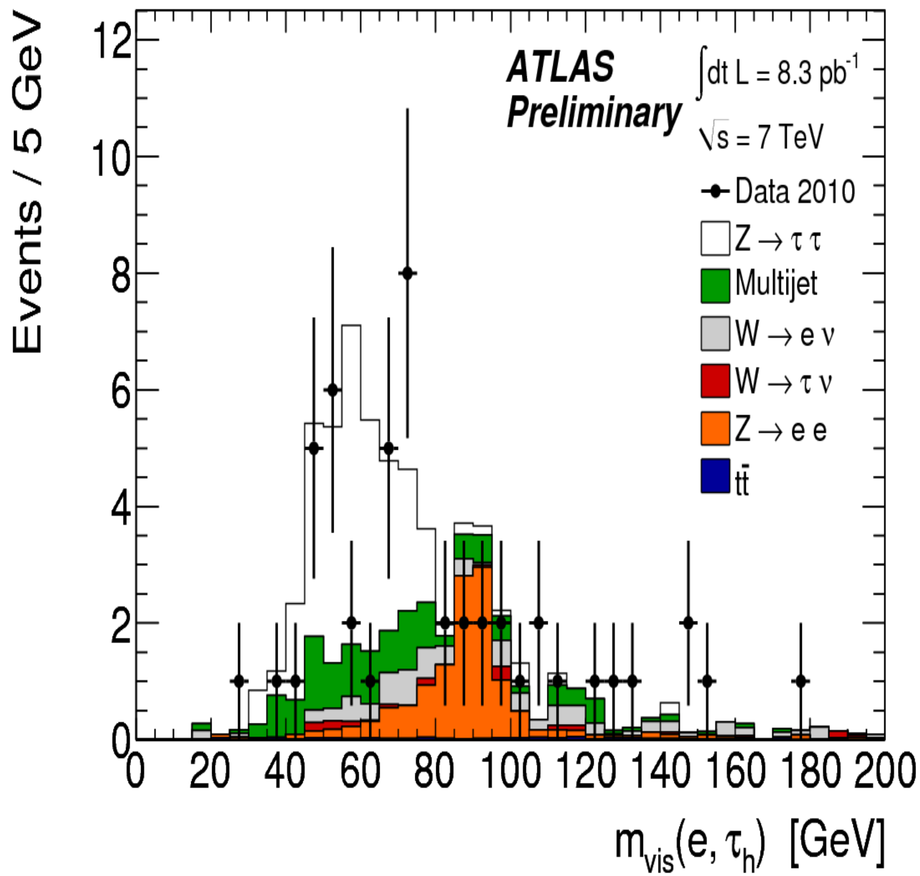


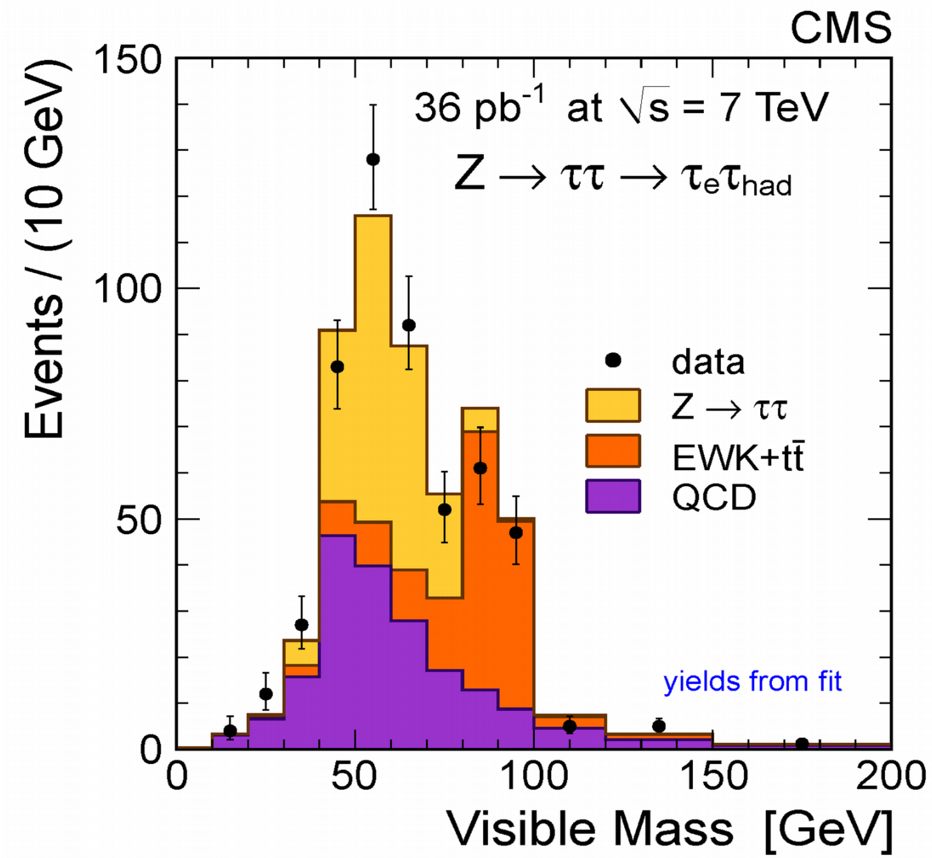


Minimal QCD backgrounds and no $Z \to ee$, $\mu\mu$ contributions

Selecting taus

- Third cleanest channel: $Z \to \tau\bar{\tau} \to e^-\bar{\nu}_e\nu_\tau\ \text{had}^+\bar{\nu}_\tau\ ,\ e^+\nu_e\bar{\nu}_\tau\ \text{had}^-\nu_\tau$

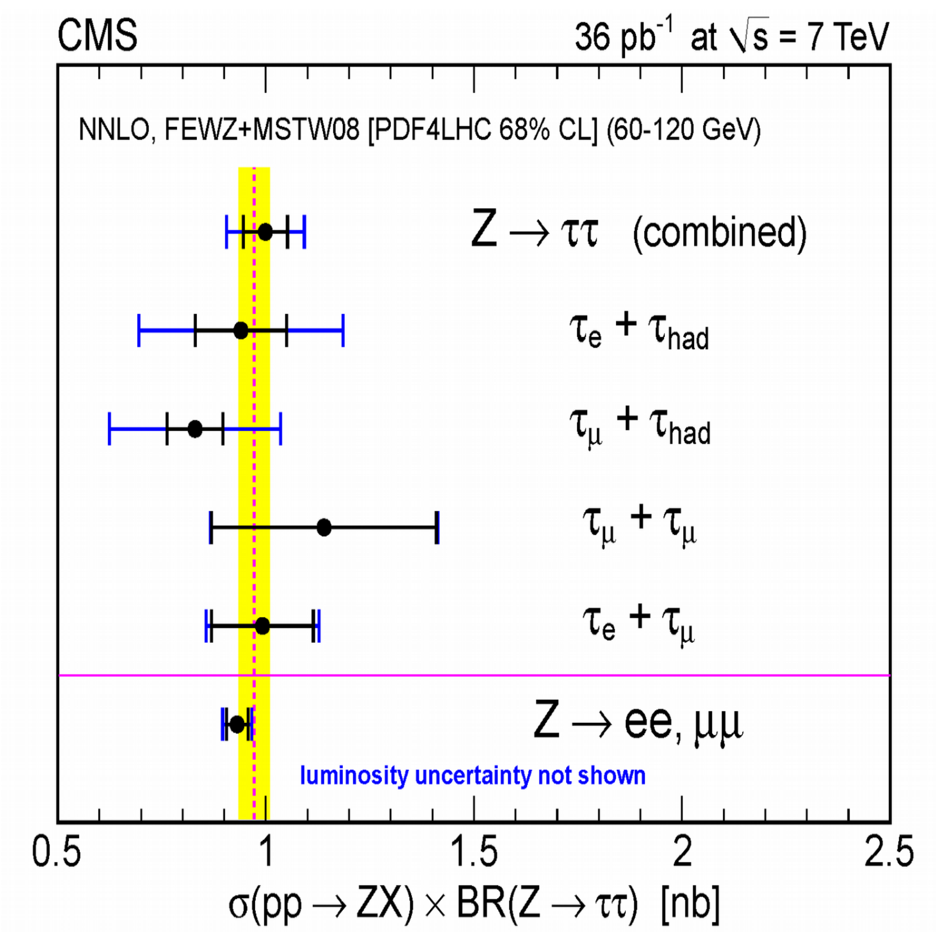


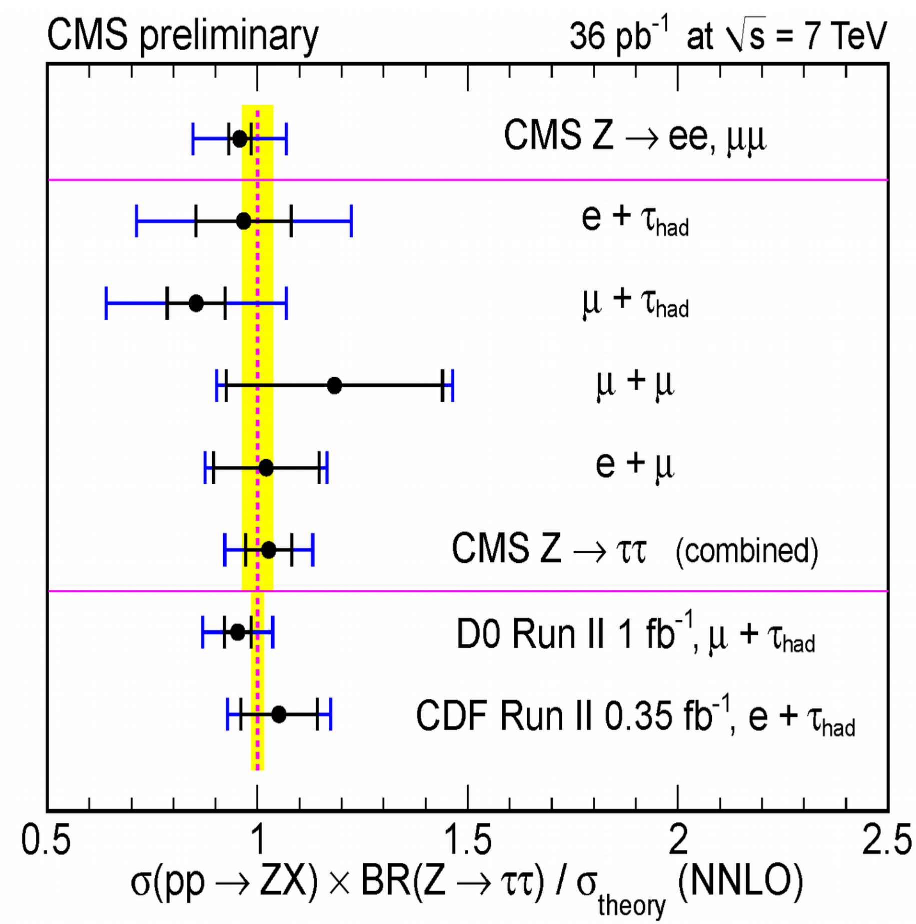


Note the presence of an almost irreducible $Z \to ee$ background (reduced via missing E_T cuts) and significant QCD contamination (fake electrons)

Early EWK physics results: Taus

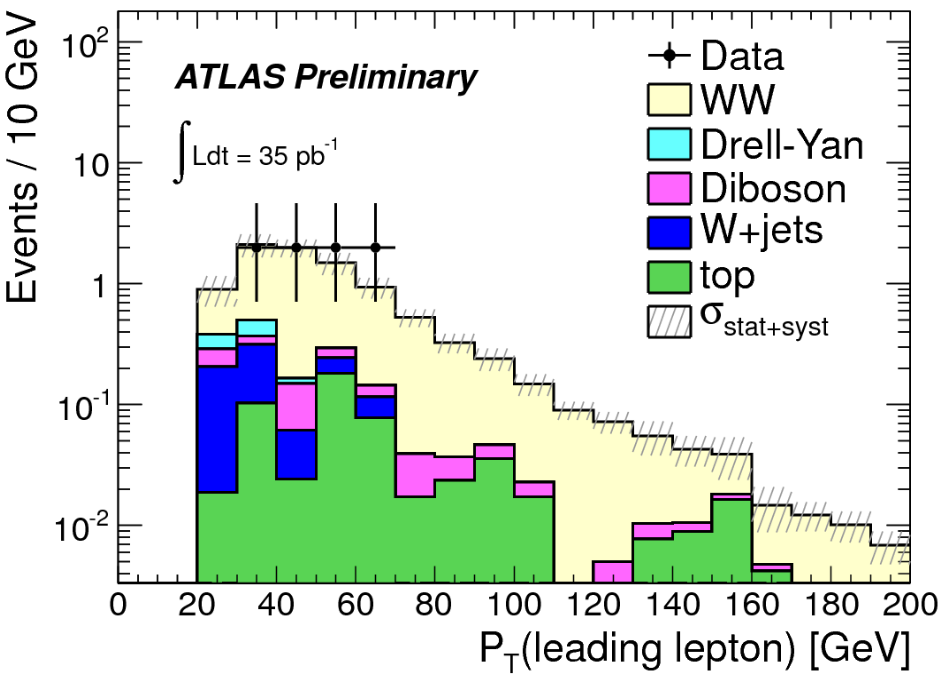
- CMS results: consistent with Z → ee, μμ. We reached the level of precision of the Tevatron with 36 only pb^{-1} at $\sqrt{s}$=7 TeV !!

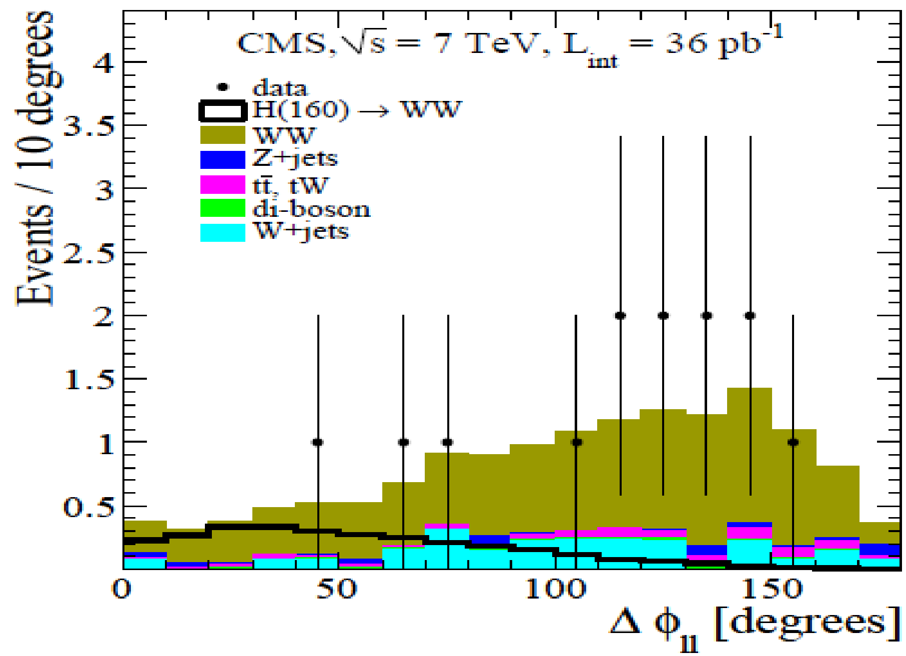




EWK physics results: WW production

- Main strategy: use W → e,μ decays, veto Drell-Yan->ee,μμ (no Z peak, require missing E_T), veto taus (no missing E_T along lepton axes), veto tops and W+jets (no jets, no extra leptons)



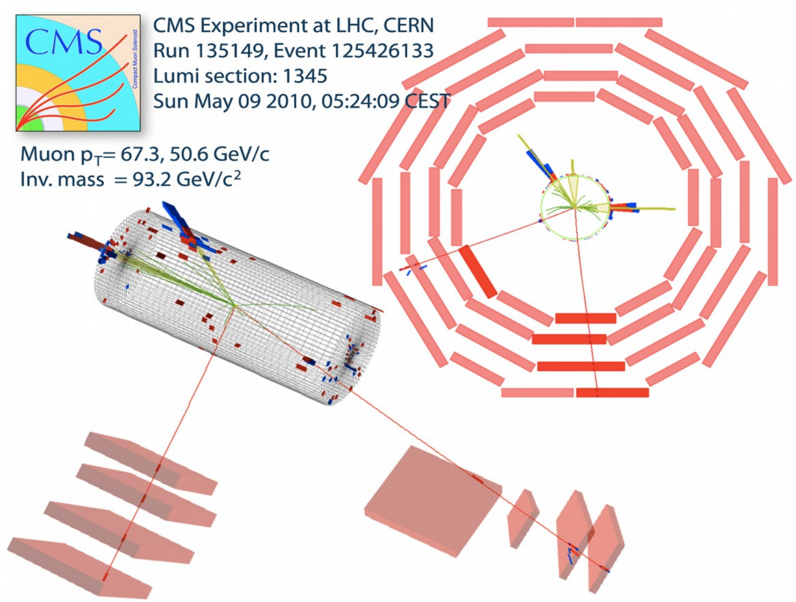


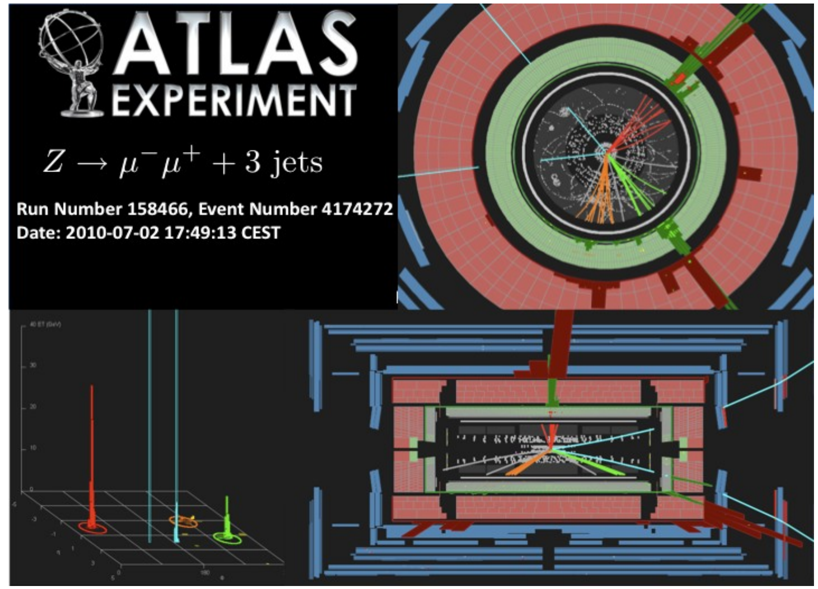
$$\sigma_{WW} = 40\,^{+20}_{-16}\,(stat) \pm 7\,(syst)\,pb$$

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

EWK physics results: W+jets, Z+jets

- This analysis is extremely important for new physics searches. Almost all the new physics studies at LHC (and Tevatron) deal with W,Z bosons plus jets in the final state, either as signal or as background

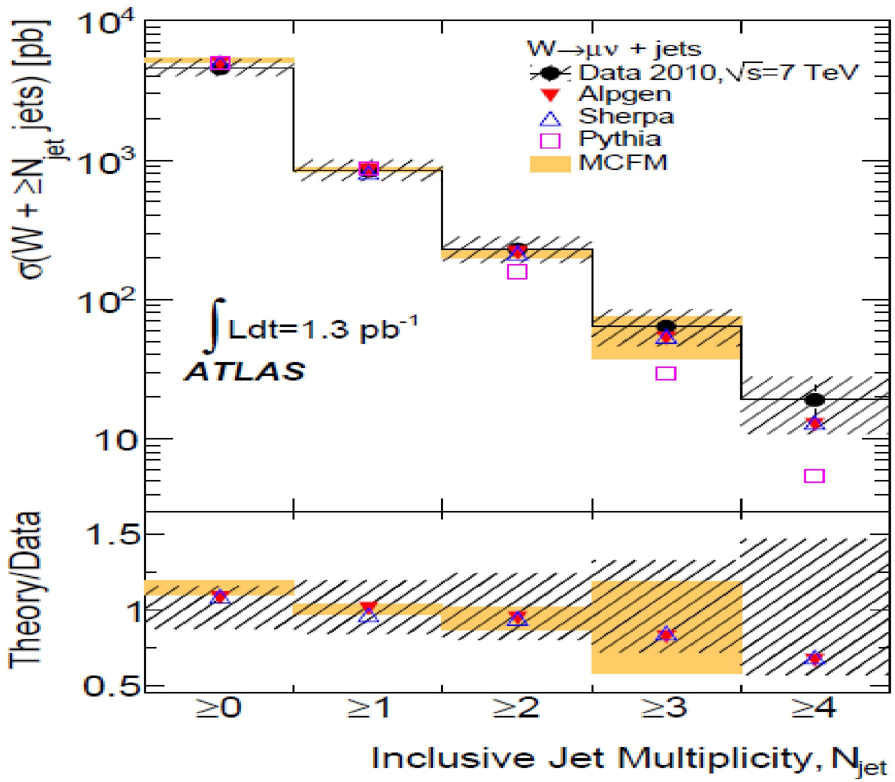


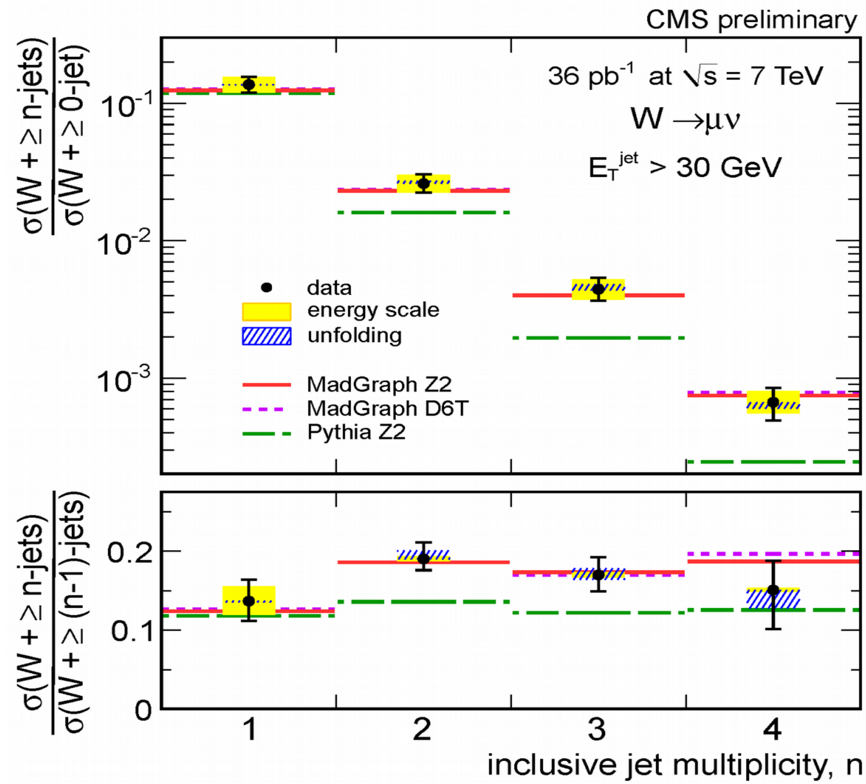


- We need different MC generators for these studies compared with inclusive measurements. A true W + 4 jet MC would be a **NNNLO generator** !!
- Until now we used LO generators for V+ N jets, and there are 'prescriptions' to merge them with parton shower generators (these prescriptions account for missing “virtual effects” in the calculation). MC names: ALPGEN, MADGRAPH, SHERPA
- Now NLO V+jets generatrs are available (POWHEG, aMC@NLO,…) and we will get (eventually) NNLO generators in the coming years

EWK physics results: W+jets, Z+jets

- The selection procedure follows closely what is done for inclusive measurements, adding the requirement of the presence of jets. Signal extraction is more difficult, due to larger backgrounds (QCD and top)

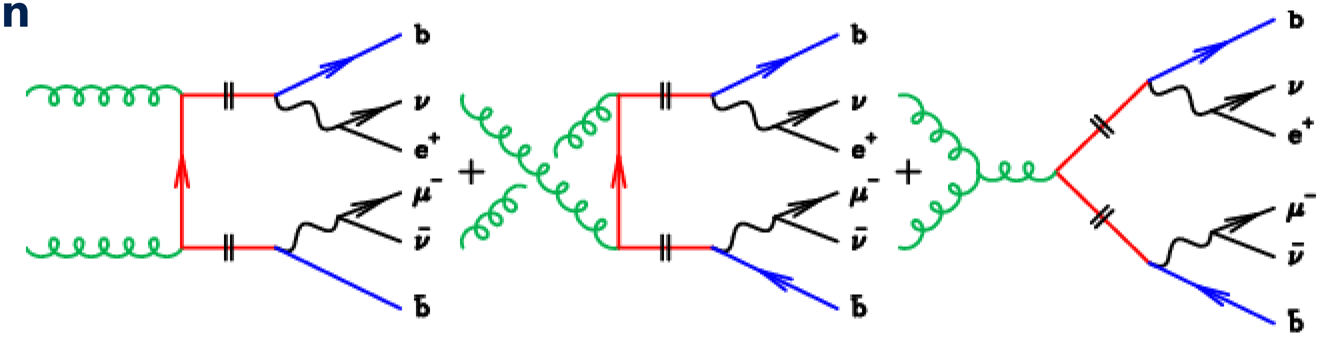




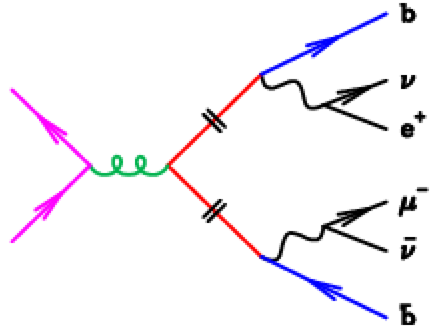
- Results agree with the expectations of the different MC predictions (ALPGEN, MADGRAPH, SHERPA), confirming the need of NNLO corrections and beyond
- PYTHIA reproduces accurately up to 1 hard jet + soft collinear jets (LO+ME reweighting)

Top spin correlations at LHC

- **Gluon gluon -> ttbar: ~90% of total at LHC (13 TeV), ~10% of total at Tevatron**



- **qqbar -> ttbar: ~10% of total at LHC (13 TeV), ~90% of total at Tevatron**



- **If we assume that the process is fully QCD-dominated (neglecting "weak" contributions), there is no preference for producing left-handed or right-handed tops => tops are not polarized on average.**

- **However there is an asymmetry in the number of tops produced with same helicities (+½,+½ or -½,-½) or opposite helicities (+½,-½ or -½,+½). This is what we call "spin correlations". At the LHC, the average "helicity" correlation is about +30%**

Top asymmetries and Tevatron at LHC startup

- Charge asymmetry in $t\bar{t}$ production. An excess with respect to SM could signal the presence of new physics. Excess seen at Tevatron. First results at the LHC, consistent with the SM