Cosa c'è ancora di interessante nel Modello Standard? Quali prospettive con energia o statistica più elevate?

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Preamble

LHC up to now:

- Most SM processes have been investigated: jets, W/Z (with jets), $t\bar{t}$, single t, W/Z pairs, prompt γ, heavy flavours
- LHC has benefited from the SppS and Tevatron experience: higher quality of the experiments and the analysis. Also, higher quality of the theoretical tools for calculations and simulation:
  - Finally IR-safe definition of jets are used. Jet algorithms for boosted objects are being explored
  - Most generators used are either ME+PS or NLO+PS (while previously there was a large dominance of general purpose Parton Shower generators.)
  - Comparing to different generators and calculations has become the standard at the LHC

SM a LHC

LHC ha trovato l'Higgs; non c'è indizio (per ora) di nuova fisica;
Gli scenari preferiti per la nuova fisica stanno perdendo forza;
La possibilità di un Modello Standard con 1 Higgs valido a grandi scale diventa realistica, così come la possibilità di nuova fisica di natura inaspettata.

Abbiamo l'opportunità di compiere un salto qualitativo nella precisione della fisica dei collisori adronici, grazie a due elementi:

- Massicci progressi teorici nel calcolo di sezioni d'urto adroniche, a LO, NLO e NNLO, negli algoritmi di Shower (i.e. nella descrizione esclusiva dei processi adronici) e nei calcoli di sezioni d'urto elettrodeboli
- Abbiamo un acceleratore e dei rivelatori eccellenti.

Se cogliamo quest'opportunità, riduciamo la probabilità di mancare segnali di nuova fisica non attesi, e raffiniamo enormemente la nostra capacitá di progettare esperimenti con collisori adronici.

At the horizon now:

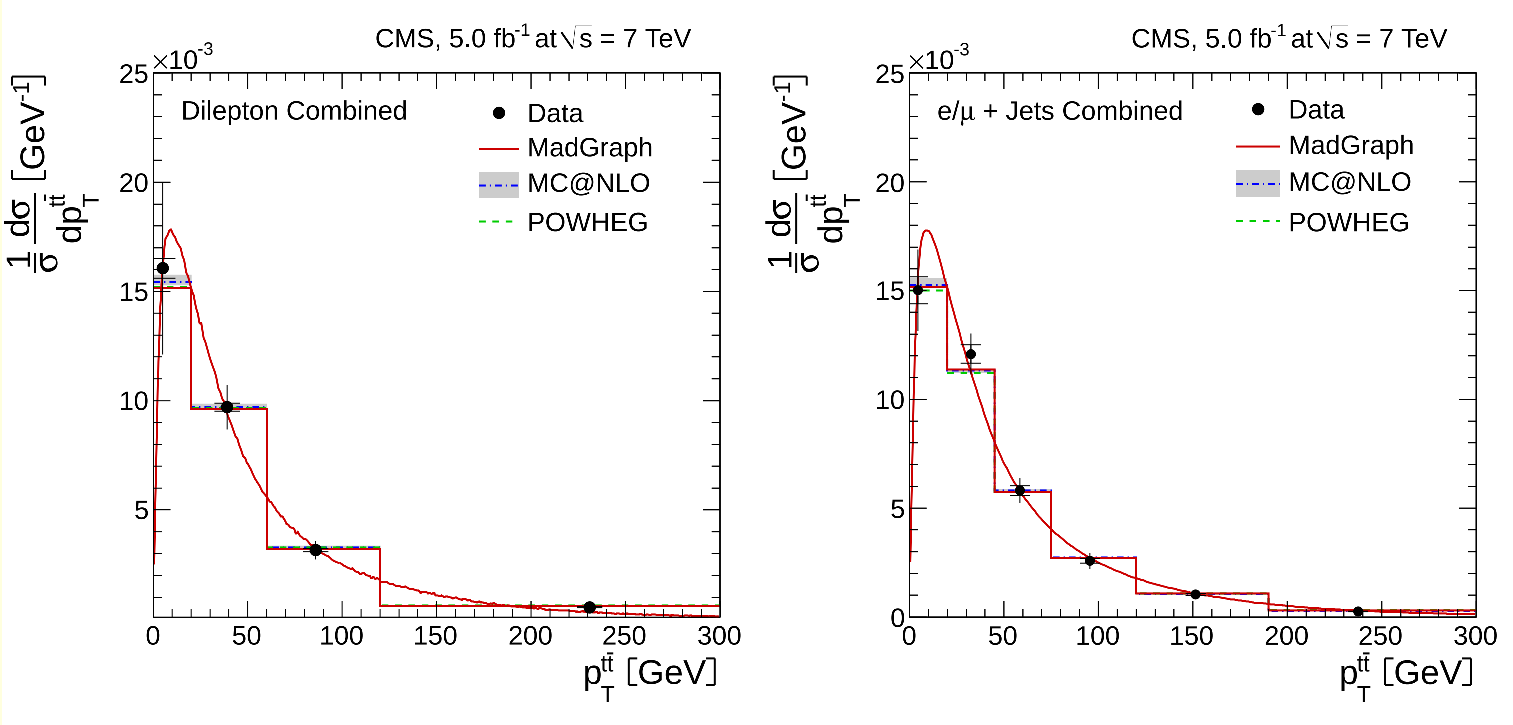
- Qualitative change in PRECISION
- Important constraints on the Parton Density Functions already becoming available at the LHC. With higher luminosity and energy, processe with lower cross sections but cleaner impact will become useful.
- NNLO calculations are becoming available for several processes:
  $t\bar{t}$ (Czakon,Fiedler,Mitov 2013),
  $H + \mathrm{jet}$ (Boughezal,Caola,Melnikov,Petriello,Schulze,2013),
  dijets (Gehrmann-DeRidder,Gehrmann,Glover,Pires, 2013).
  More will become available in the coming years
- It will become mandatory to include EW and photon induced corrections to many hadronic cross section

Outline

- Validating theory and generators for hard collisions at the LHC
  - $t\bar{t}$ production
  - jets
- PDF measurement
  - Direct photon
  - Top production
  - PDF at NNLO
- The top mass
- Standard model precision observables
- VBF processes

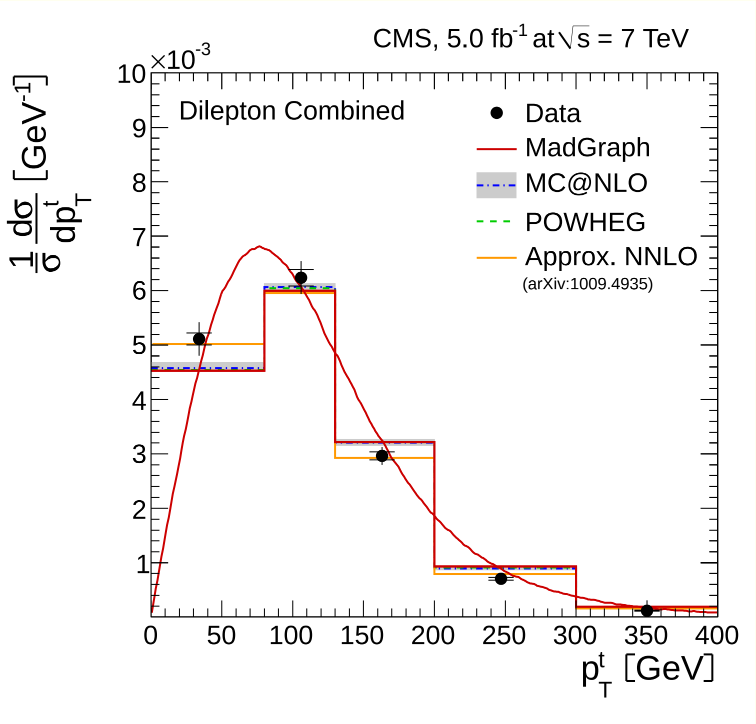
Validating theory and generators: $t\bar{t}$ transverse momentum spectrum

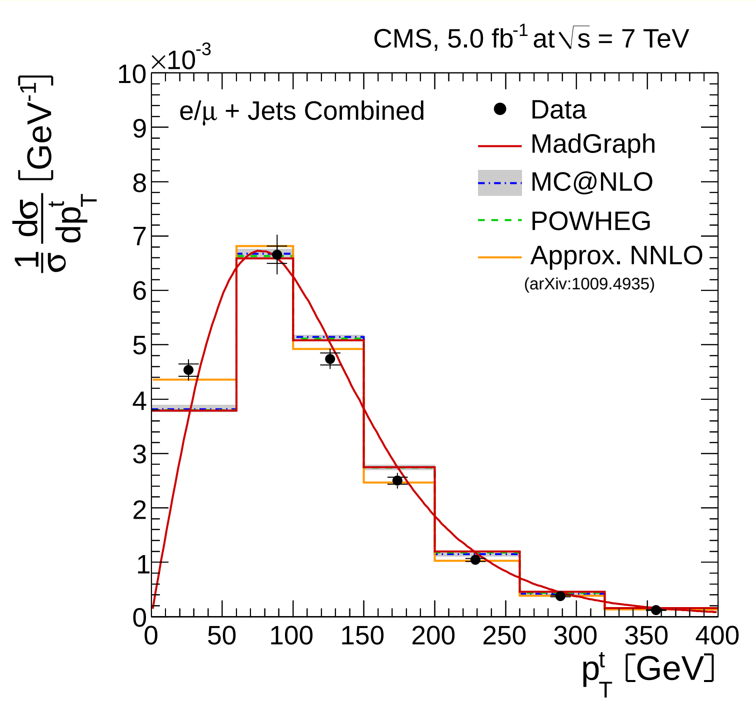
This is the ONLY example when the transverse momentum distribution in a process dominated by $gg \to X$ is measured (CMS, arXiv:1211.2220)



Its modelling relies on soft gluon resummation (similar to $W/Z\ p_T$, but for gg)
Comparison with generators is good (but will it resist refining? Higgs transverse momentum in $gg \to H$ relies upon this).

Notice: for a less delicate observable, the top p_T spectrum, not very good agreement:





The agreement with NLO PS+SHOWER generators is very good, but outside the theoretical uncertainty band.
An approximate NNLO calculation (Kidonakis,2010) claims better agreement.
Data begins to challenge NLO results ...

More on $t\bar{t}$ kinematics

Recent top studies:

- W helicity in top decays: t — W — b
  In W rest frame: incoming t, outgoing b with the same 3-momentum.
  If (SM) the b is left handed, t can have positive or negative helicity, the W longitudinal spin component is the difference of the t and b spin, thus 0 or 1 (no -1 in the standard model). Decay distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta^*} \propto 2(1-\cos^2\theta^*)\overbrace{F_0}^{0.311} + (1-\cos\theta^*)^2\overbrace{F_L}^{0.687} + (1+\cos\theta^*)^2\overbrace{F_R}^{0}$$

  Measured by ATLAS and CMS, also in single top production.

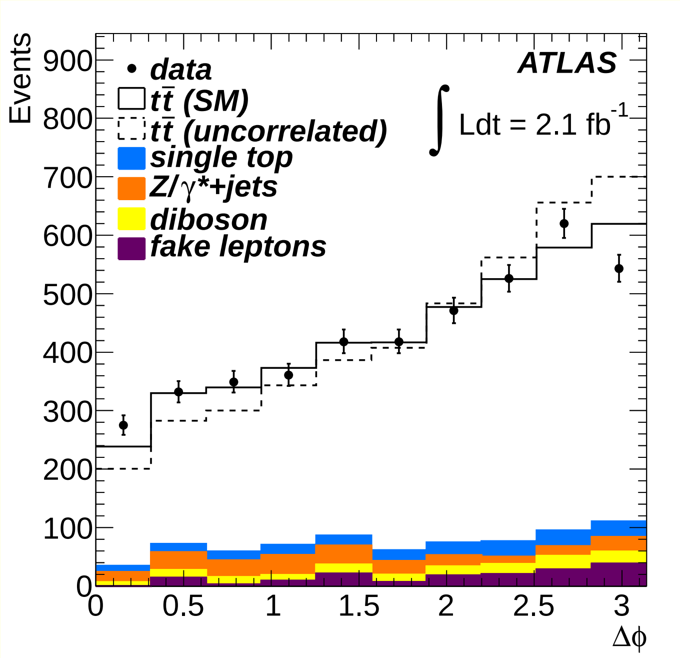
- Charge asymmetry: Heritage from Tevatron. With high statistics LHC can reach similar sensitivities.

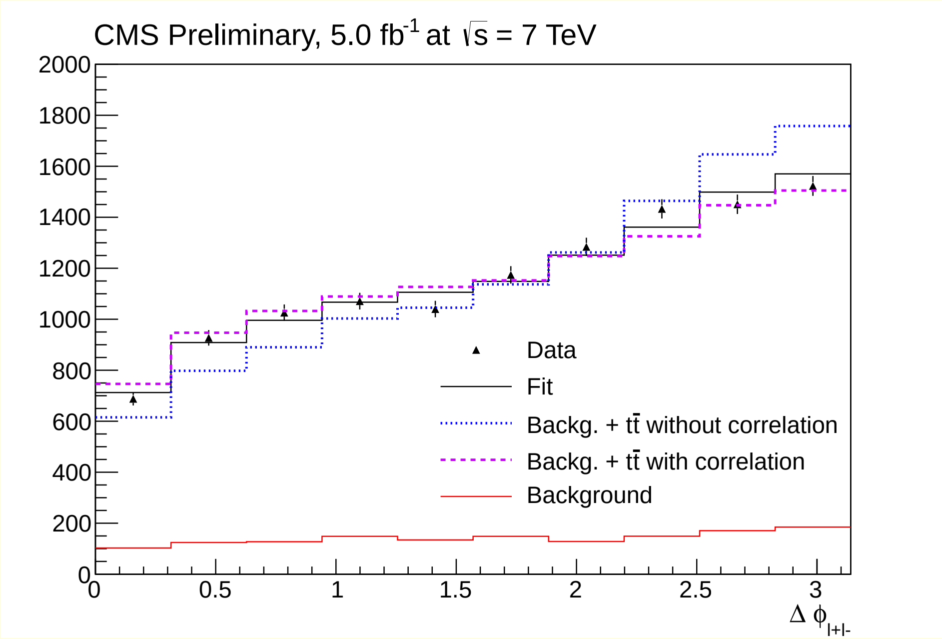
- Spin correlation in $t\bar{t}$ decays (in dilepton events) are predicted in the standard model, and now observed; with high statistic, can become a high precision tool to investigate the nature of possible new physics

Spin correlation in $t\bar{t}$ events

Top spin induces correlations among the $t\bar{t}$ decay products. For example, $\Delta\phi_{ll}$ in leptonic decay is different if we assume that the top decays isotropically.

ATLAS, prl 108(2012) CMS top-2012-004





New handle to study top production, will benefit from increased statistics.

Pseudotop

- t measurements imply event selection based on the top quark final states as measurable in the experiment (i.e. after hadronisation and decay of the top quark decay products)
- The extrapolation from the measured (particle-level) observables back to the t (parton-level) is then inherently model and scheme dependent.
- Goal of ATLAS and CMS (through TOPLHCWG): introduce a common particle-level definition of "top" to provide coherent measurement of particle-level differential cross sections
  - Facilitate comparisons with theory with a common language
  - Make ATLAS-CMS combination easier
  - measure top-quark distributions for which model dependencies are minimized.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PasTop12028AdditionalMaterial,
http://cds.cern.ch/record/1493494/files/ATLAS-CONF-2012-155.pdf

Jets

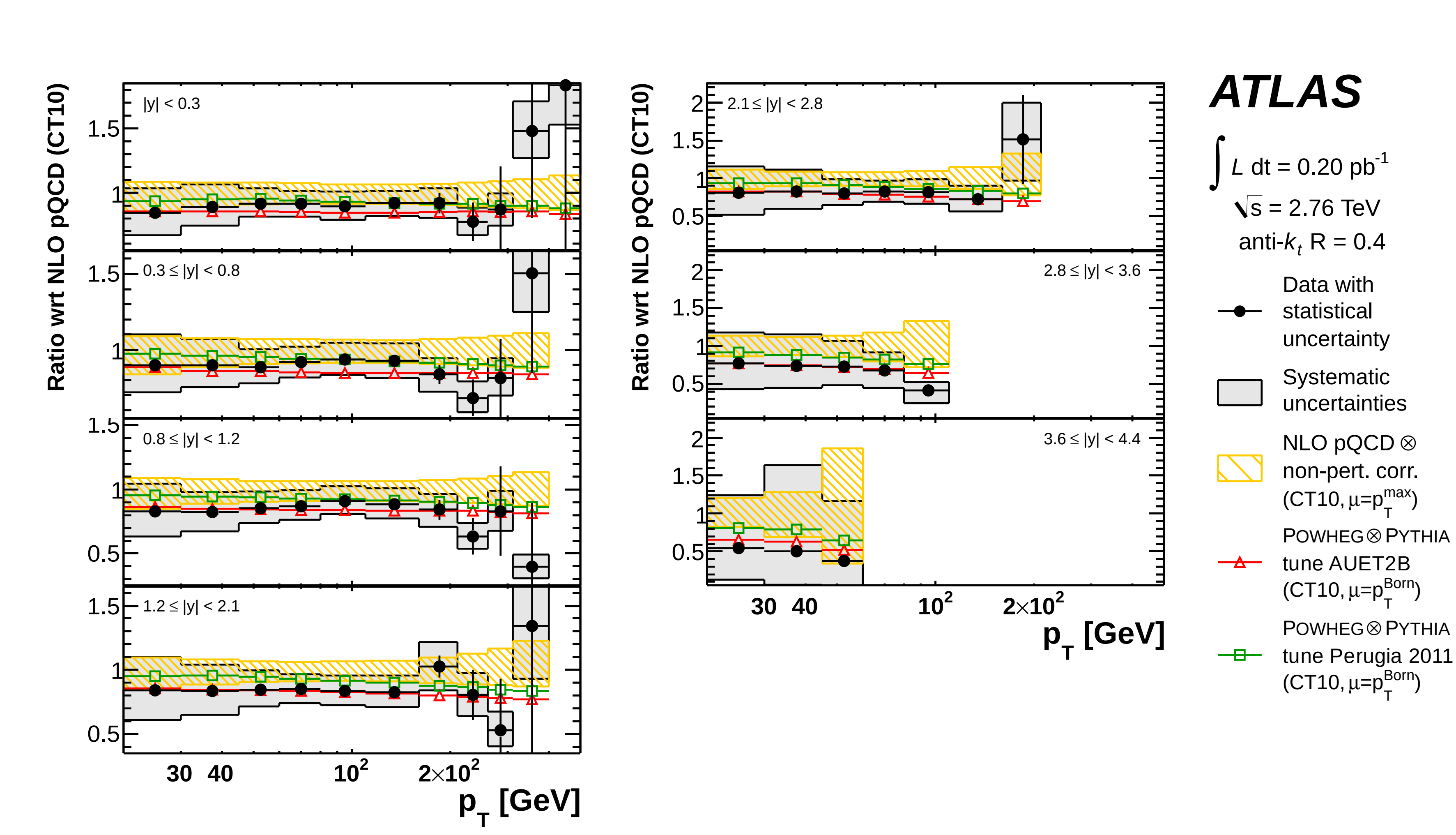
Jets are the objects that correspond to final state quarks in elementary reactions.
We must understand jets in order to do LHC physics.
Most elementary process: dijet production.
Several ATLAS and CMS studies on dijets. In which direction do we want to go?

Current studies:

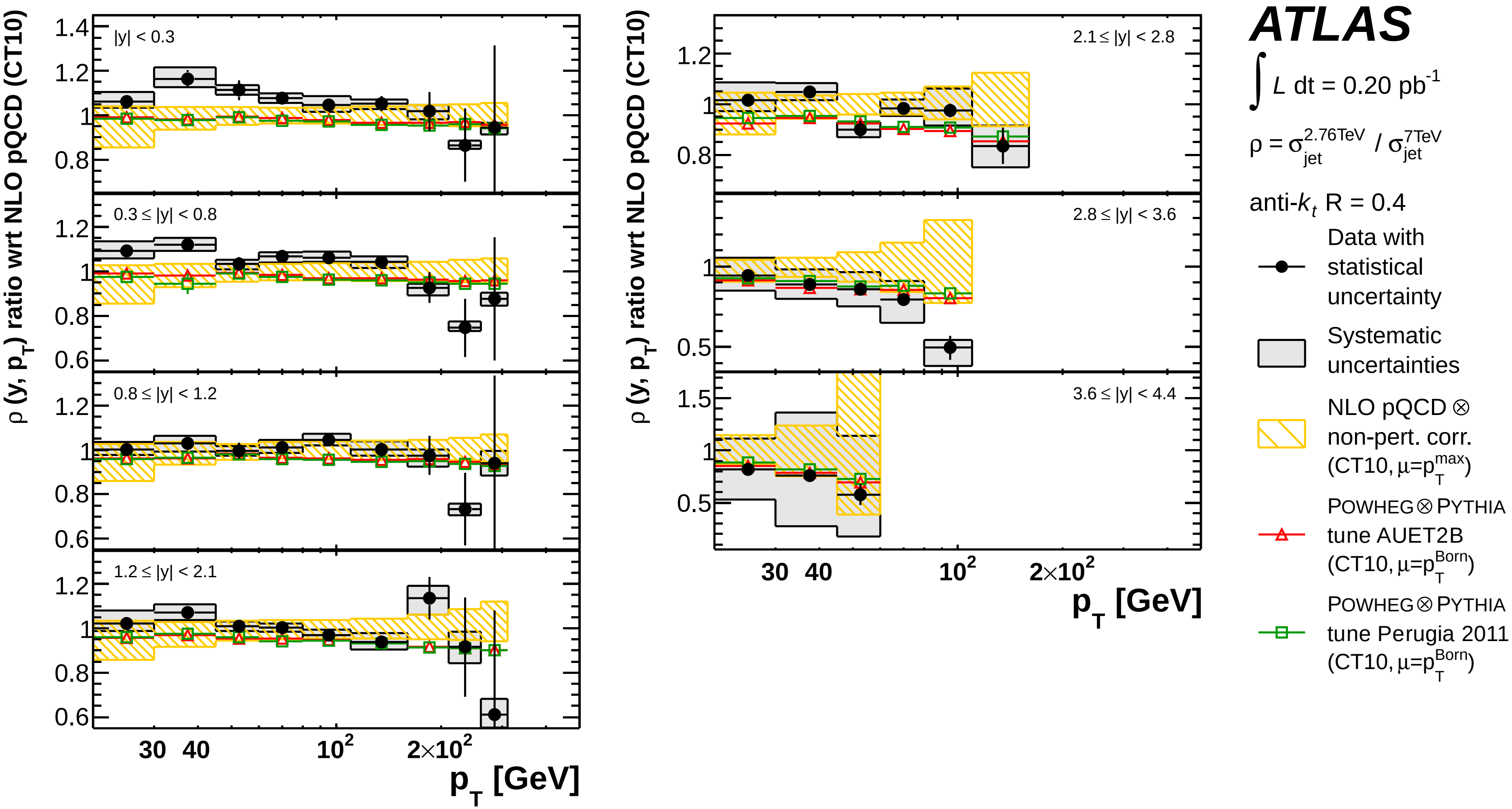
- Focus upon very inclusive quantities.
  Typically: p_T/y distribution of ALL jets in the final state
- Jet definition: anti-k_{T} (Cacciari, Salam, Soyez 2008)
- Compare to theory: fixed order NLO calculations $\times$ hadronization effects

$$\mathrm{Had\,effects} = \frac{\mathrm{d}\sigma(\mathrm{SMC})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}\sigma(\mathrm{SMC},\mathrm{no\,had.})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

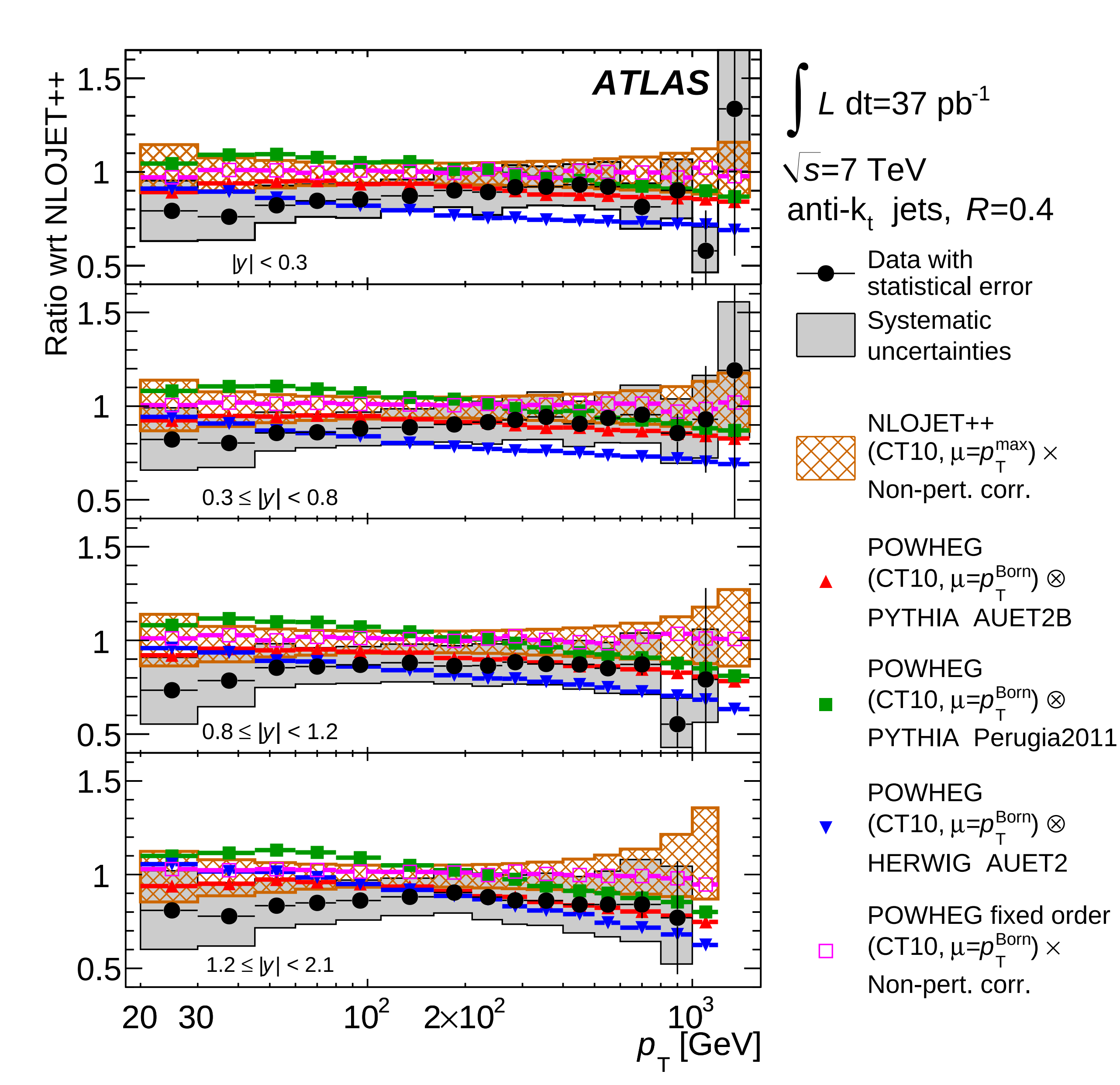
- Compare to theory: NLO interfaced to Shower MC (NLO+PS)
- Compare to theory, other: High Energy Jets (Hej), etc.



Good agreement with NLO, and with NLO+PS. At high rapidities, high p_T, NLO+PS seems to work better (improves near phase space restricted regions?)



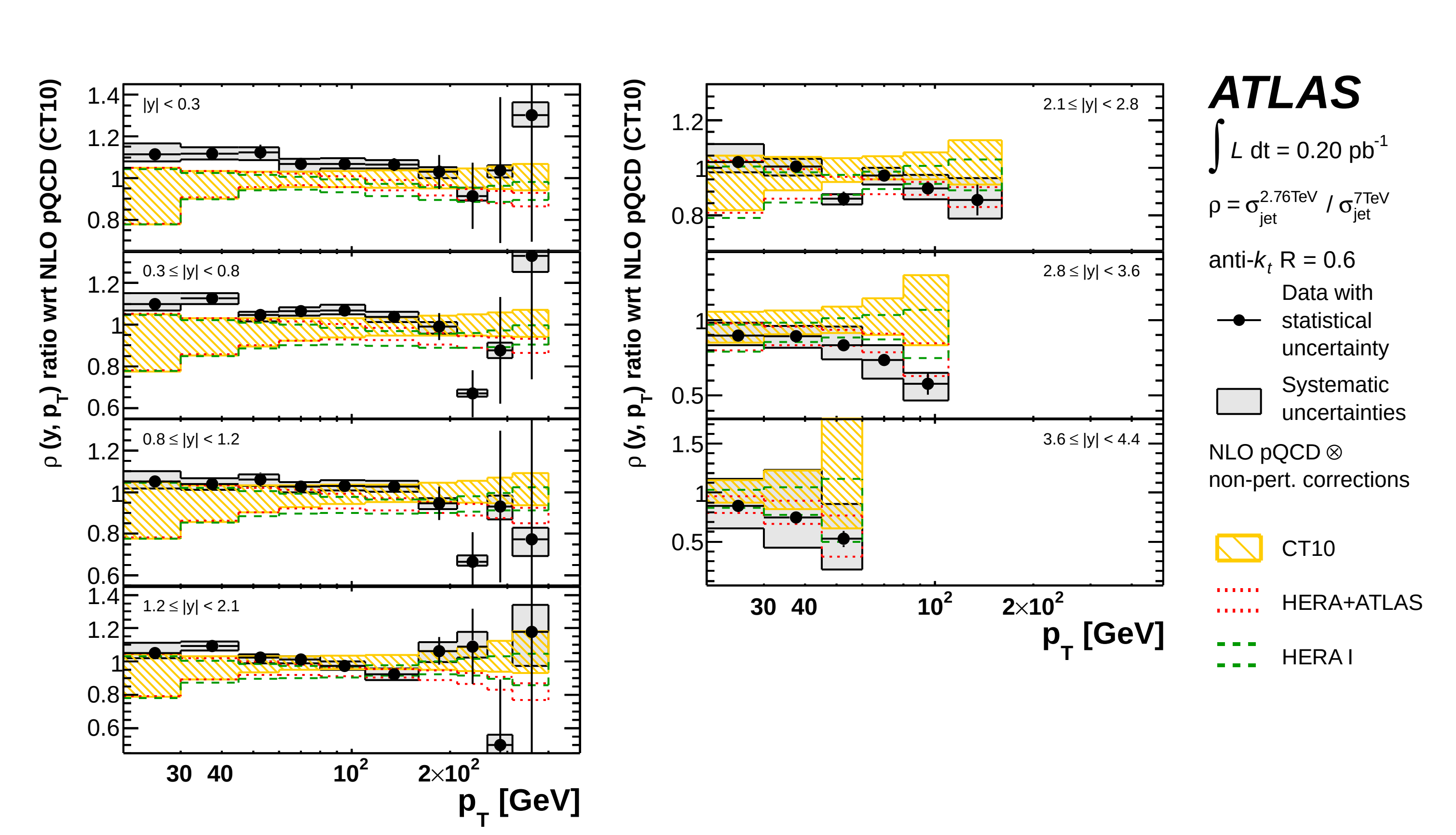
$\rho(y, p_T) = \frac{d\sigma/dy\,dp_T(2.76\text{ TeV})}{d\sigma/dy\,dp_T(7\text{ TeV})}$; NLO, NLO+PS, 20% high at 7 TeV for low p_T, central y;



arXiv:1112.6297
TH>Data, central low p_T.

Large differences when interfacing to HERWIG (>20%

Jets: open questions



Fitting data including ATLAS jet data improves agreement in ratio at large rapidity. Is this needed? Is NLO+PS already in better agreement?

Jets: open questions and prospects

- Does NLO+PS improve over NLO?
  Suggestion: look at other quantities: dijets with symmetric p_{T} cuts, hardest jet cross section, etc. (NLO results for dijets with symmetric cuts are out of control; does NLO+PS work?)
- Discrepancies: NNLO calculation for $gg \to gg$ available (Gehrmann-De Ridder,Gehrmann,Glover,Pires 2013) ; large positive effects (out of the scale variation NLO band) are found. Do they affect the low p_{T}, higher energy data? (more gg enters there).
- When constraining PDF's, should we use NLO or PS+NLO?

Some of these questions will be easier to understand when the full NNLO dijet calculation will become available. However: more extensive studies, involving new observables, are needed. Up to now, it has been shown that what was working before is also working now. Next, we need to expose what does not work, i.e. to what extent we understand jets.

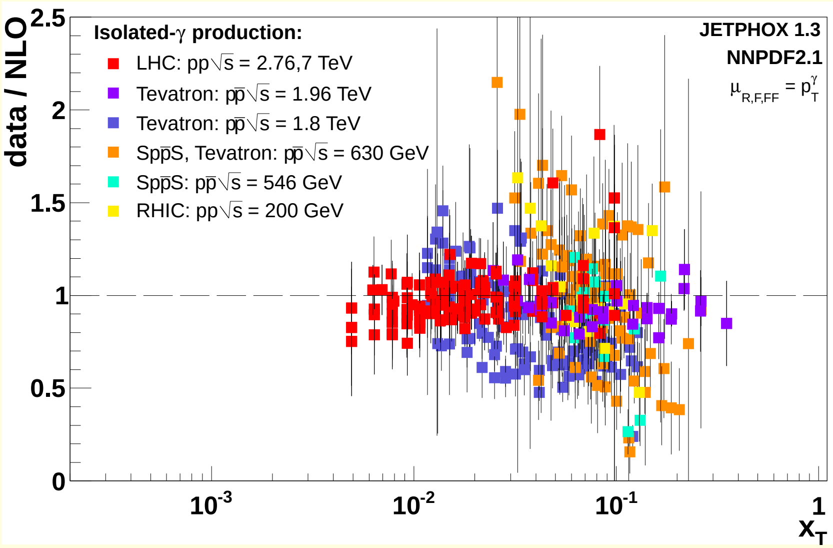
PDF's at the LHC

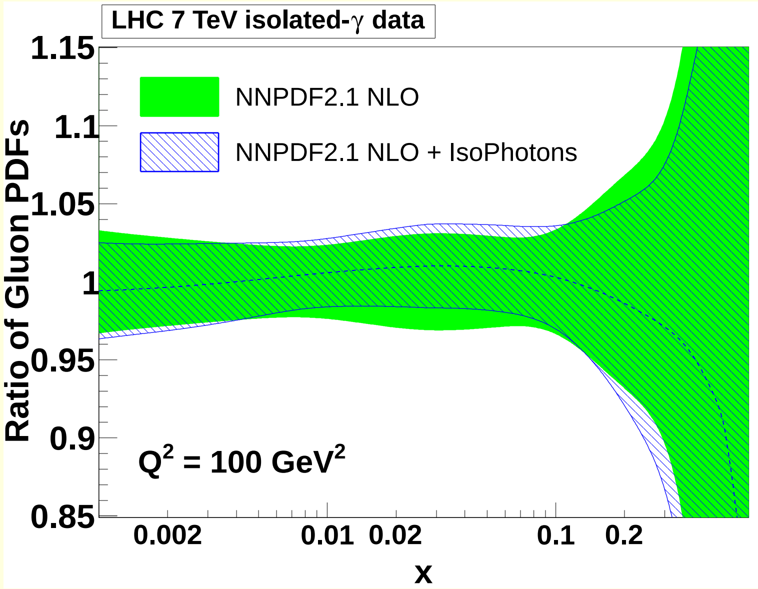
(J.Rojo,PDF4LHC. April 2013)

- Inclusive jets and dijets: large x quarks and gluons
- Inclusive W and Z prod. and asymmetries: flavour separation,strangeness
- Prompt γ, $\gamma + \mathrm{jets}$: medium x gluons
- $W + c$: strangeness density
- W and Z at high p_{T}: medium and small x gluons
- Off resonance Drell-Yan and highly virtual W: quarks at large x
- Low mass Drell-Yan: small x gluons
- Top cross section and distributions: large x gluon
- $Z + c$: intrinsic charm
- Single top: gluon and bottom PDF's
- Charmonium production: small x gluons
- Open heavy quark production: gluon and intrinsic heavy flavour

Direct photons

Used in early PDF fits to constrain the large x gluon PDF's, then abandoned due to poor data/theory agreement of some fixed-target data. Reanalysis of all collider data has shown consistency of all collider based studies (D'Enterria,Rojo,2012).

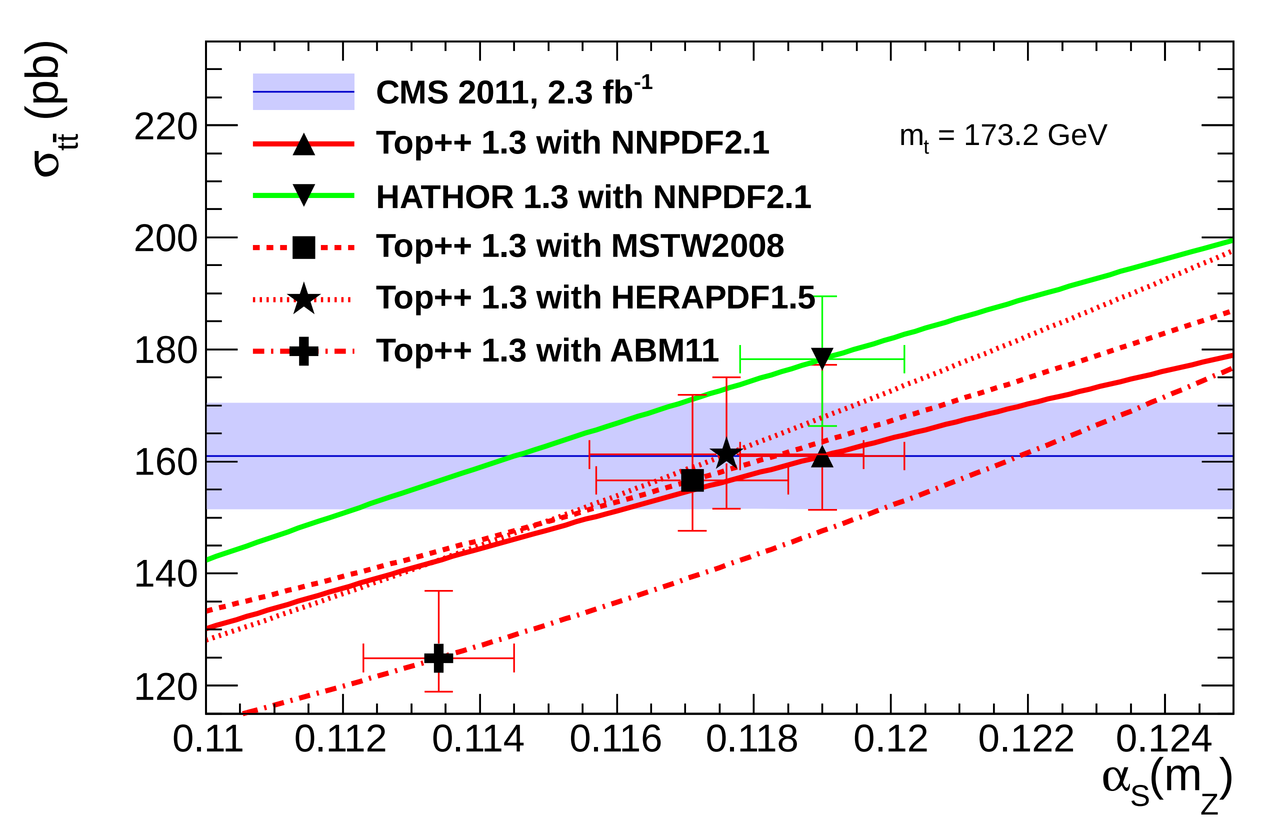




Addition of photons maintains consistency. It has been shown that future LHC data (Carminati etal, 2013) may indeed provide important constraints in PDF's determination.

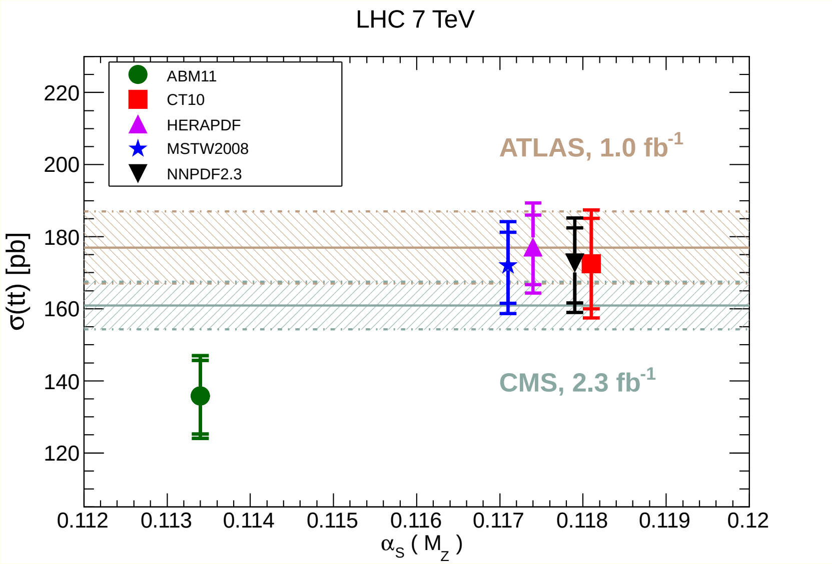
Top production

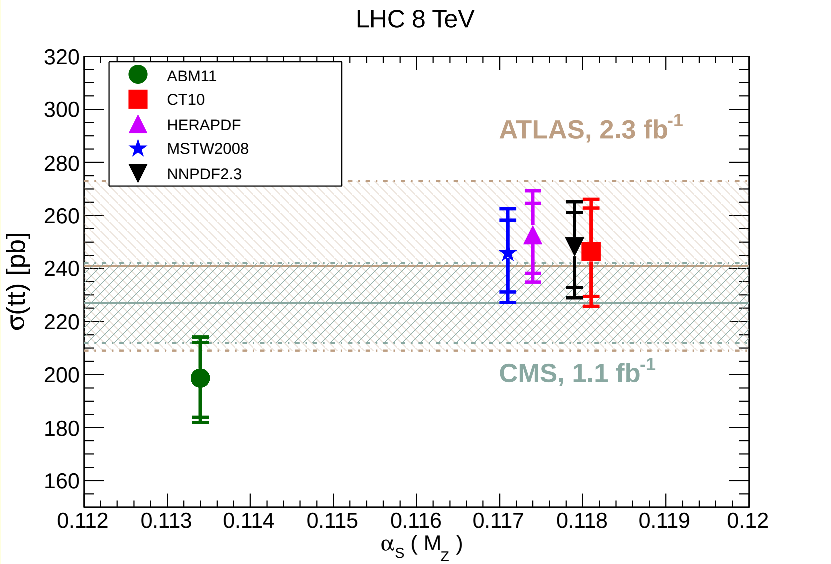
Already used for measurement of α_s:



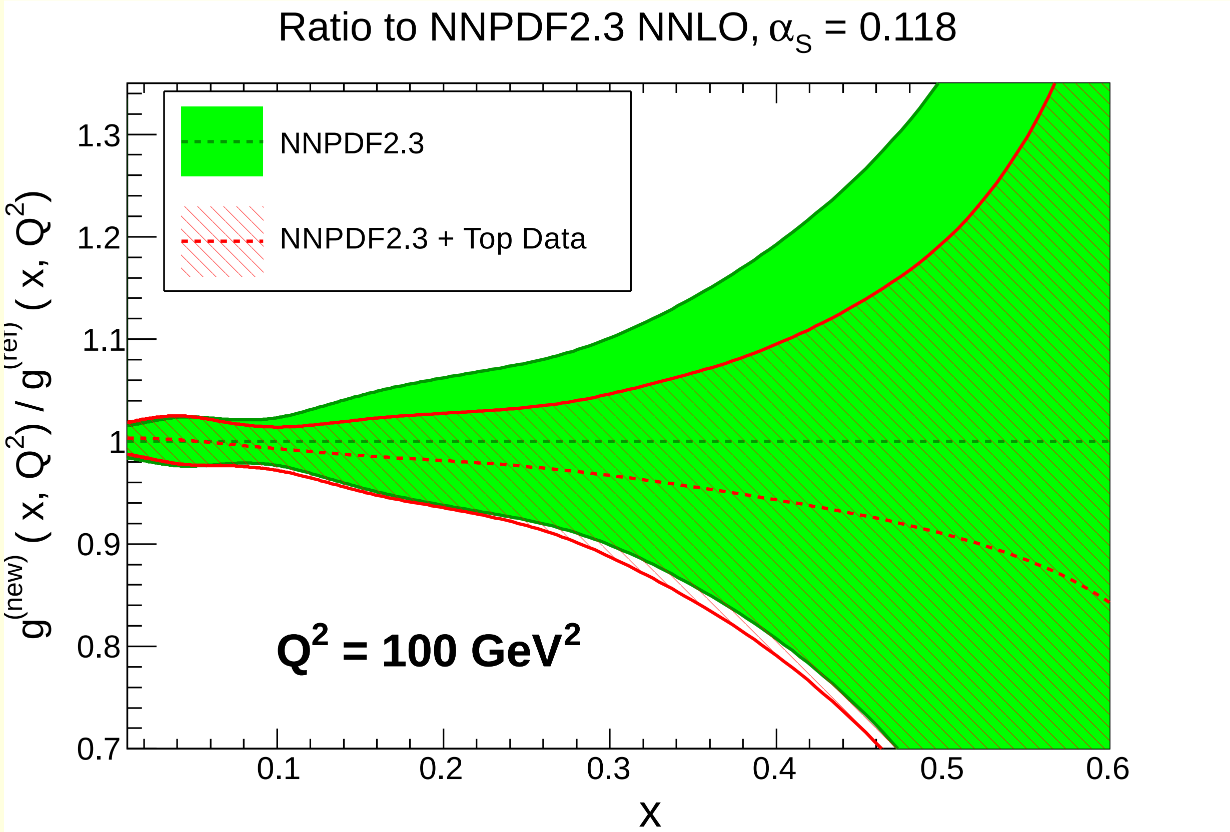
NNLO total cross section for $t\bar{t}$ now availoable, (Czakon,Fiedler,Mitov 2013), Can extended α_s determination to NNLO accuracy, and also constrain the gluon distribution at NNLO (Czakon,Mangano,Mitov,Rojo,2013).

Caveat: only the total cross section is known at NNLO; the measured cross section is a fraction of the total (large acceptance correction).





(On small α_s for ABM11, see PDF4LHC, 17 April)



Impact of the inclusion of the top data in the fit quite visible, but at high x. Relevant for BSM searches.
When NNLO calculation for differential $t\bar{t}$ cross section will become available, looking ad different rapidities will extend the x range.

PDF's at NNLO

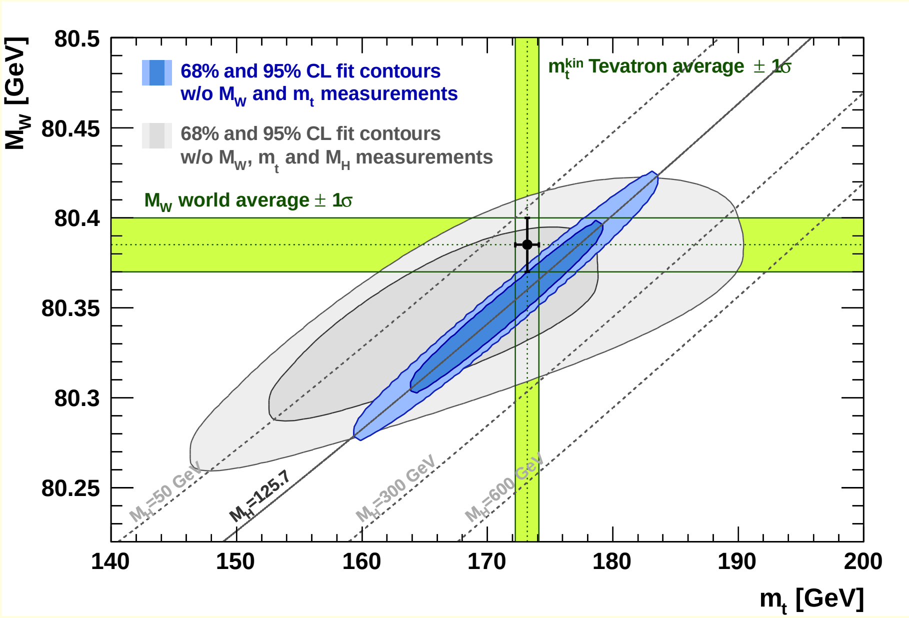
Uncertainty in Higgs production by gluon fusion is now 14%, 7% PDF+α_s. Need gluon at NNLO. What are the best processes?

- Jets; NNLO possible (now only gluons); measuring jets is difficult;
- Direct photon; no NNLO yet, but possible; cleaner than jets (needs good understnanding of isolation-fragmentation issues)
- $t\bar{t}$, NNLO available for total; soon (1 year?) differential distributions, that can be used to explore wider x range for the gluon density.
- High $p_{\rm T}$ vector bosons: Z (at large $p_{\rm T}$) very clean; gluon contribution similar to prompt γ case. NNLO not available. However:
  $H + \text{jet}$ at NNLO, Boughezal,Caola,Melnikov,Petriello,Schulze, 2013.
  $Z + \text{jets}$ not much more difficult than this!
  $W/Z + \text{jet}$ and their ratios (W^+, W^- and Z) (Malik and Watt, 2013) can also yield PDF constraints on d/u ratio at large x.

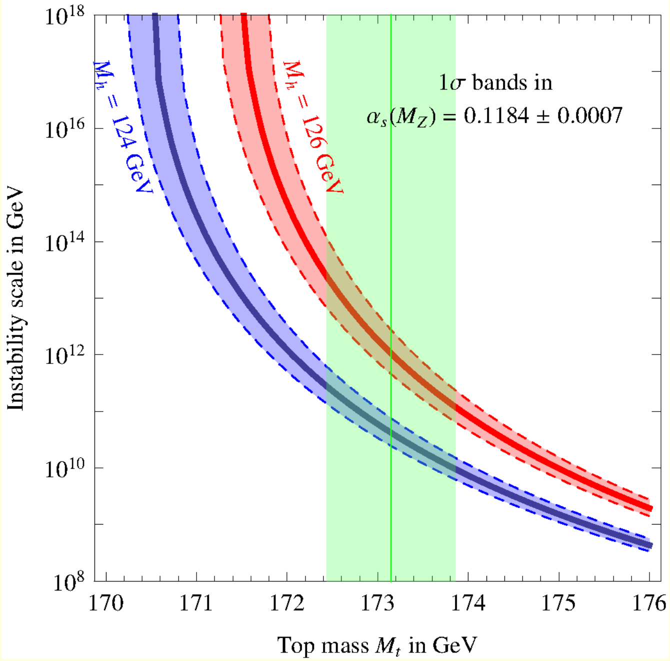
Off shell Drell-Yan; $\mathrm{d}\sigma/\mathrm{d}M\mathrm{d}y$ can be used to constrain PDF's at very large x. Known at NNLO. Electroweak NLO effects and γ induced effects must be accounted for (photon PDF's may be needed).

Top mass: the error is small; but where is the central value?

Fundamental standard model parameter:



Gfitter coll., Baak etal, 2012



De Grassi etal, 2012

Error on top now seems small enough ... But do we know the central value?
What is the measured top mass? The pole mass? The "Monte Carlo" mass?

Some reassuring thoughts:

- If we measure the mass from observables that are correlated to the mass of the top decay products, we measure some kind of pole mass.
- If we measure the mass from other (calculable) observables, like, for example, the total cross section, we are measuring the mass parameter used in the calculation (pole mass, $\overline{\mathrm{MS}}$ mass, etc.)

"Monte Carlo" dependence is in modeling production and decay (to which an appropriate error is associated).

Problem: the top is a coloured parton, its decay products are neutral.
Must pick up (or loose) a coloured parton to form a neutral system.

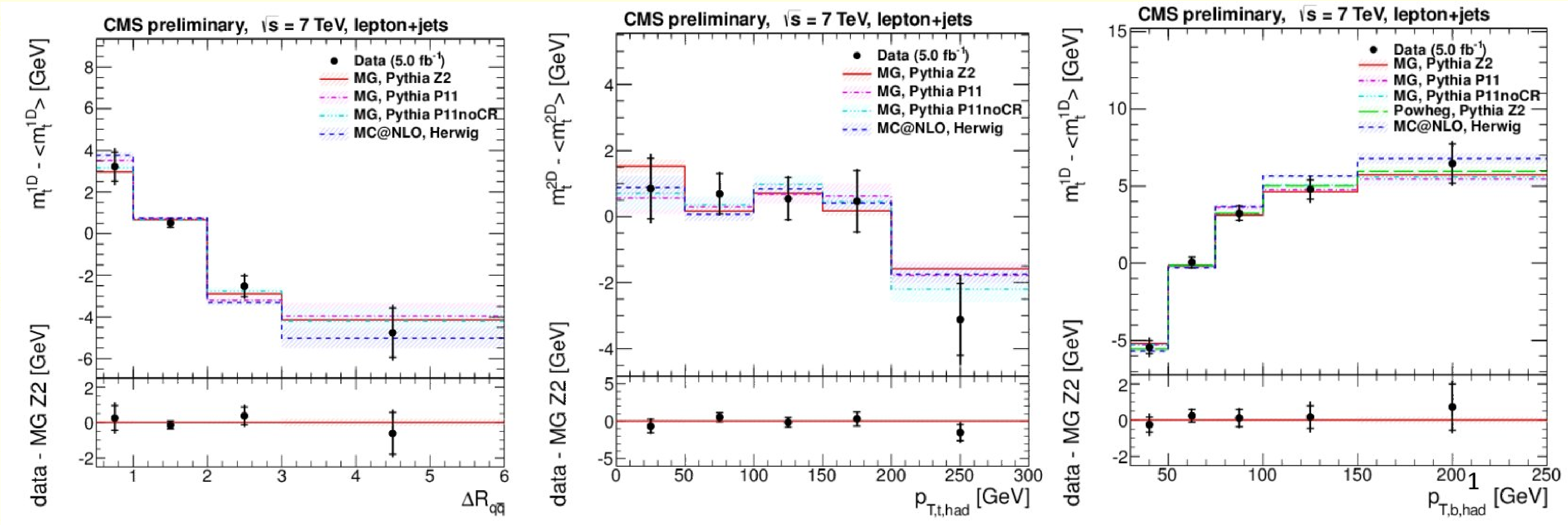
This effect can be modelled, but not computed!
Yields an error on the top mass of the order of a typical hadronic scale (few hundred MeV? 1 GeV? 1.5 GeV?)

Measuring the top mass in several different ways may help to reassure us about the placement of its central value

CMS: top mass in different kinematic bins

Identify observables that are sensitive to sources of error:

- Color reconnection: $\Delta R_{q\bar{q}}, \Delta\phi_{q\bar{q}}, p_{\mathrm{T},t,\mathrm{had}}, |\eta_{t,\mathrm{had}}|$
- ISR/FSR: $H_{\mathrm{T}}, m_{t\bar{t}}, p_{\mathrm{T},t\bar{t}}, \mathrm{Jet\,multiplicity}$
- b-quark kinematics: $p_{\mathrm{T},b,\mathrm{had}}, |\eta_{b,\mathrm{had}}|, \Delta R_{b\bar{b}}, \Delta\phi_{b\bar{b}}$



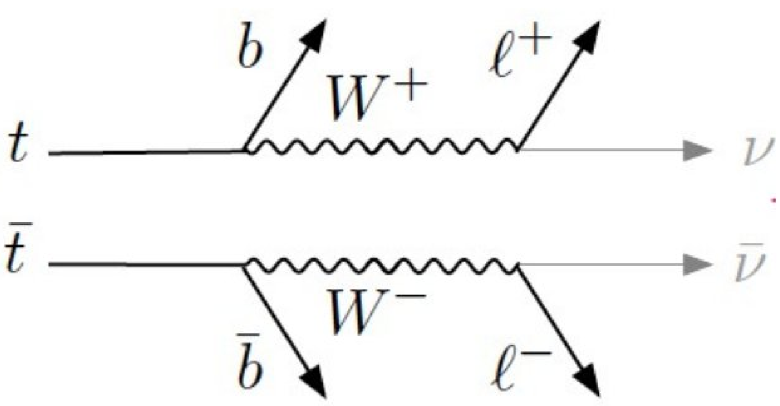
With the current precision: no mismodeling found due to Color reconnection, ISR/FSR modeling, b-quark kinematics.

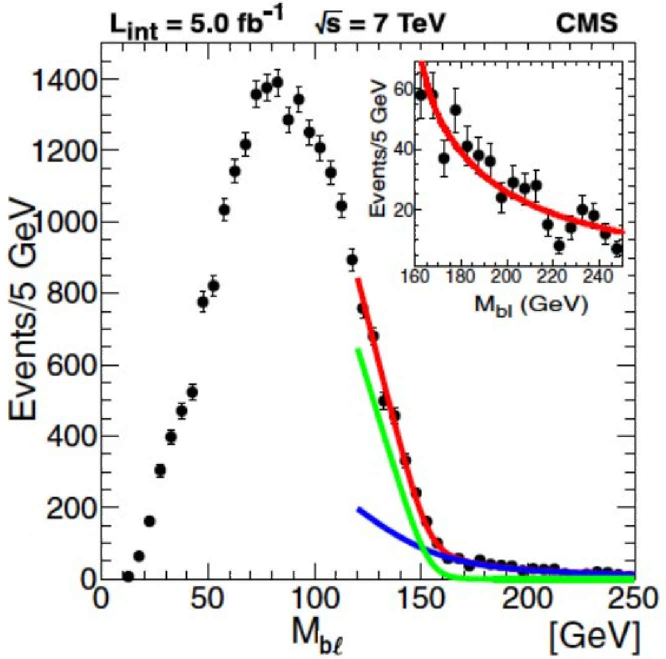
Top mass from alternative techniques

- Standard methods: based upon the invariant mass of decay products associated to the reconstructed top in a given channel (lepton+jets, dilepton,fully hadronic channels).
- Given the issues related to the top mass interpretation, important to explore alternative techniques, e.g.
  - $\rightarrow$ Measure the decay length (the boost) of b hadrons produced in top decays, the boost is related to the original top mass
  - $\rightarrow$ Measure the endpoint of the lepton spectrum or other quantities in top decays
  - $\rightarrow$ Select specific channels, for example top with $W \rightarrow l\nu$ and $B \rightarrow \Psi + X$ decays and measure the three-lepton invariant mass
- Alternative methods have typically larger statistical uncertainties; however at LHC we have large $t\bar{t}$ samples.
- Systematic uncertainties can be controlled with data (large samples help).

Alternative mass-sensitive observables: Endpoint method (CMS):

$$M_t = 173.9 \pm 0.9(\mathrm{stat})^{+1.6}_{-2.0}(\mathrm{syst.})\ \mathrm{GeV}$$

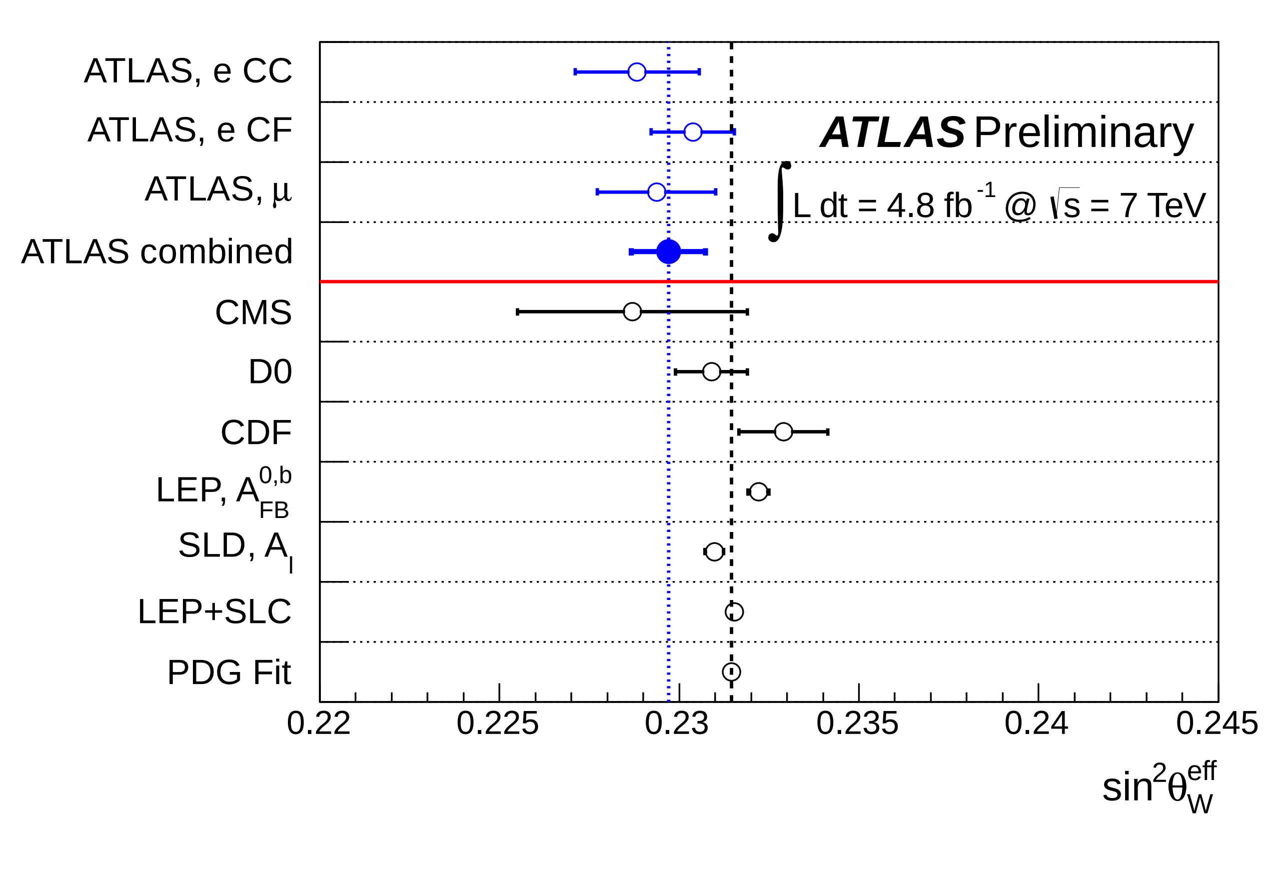




Must insist with this and other observables!

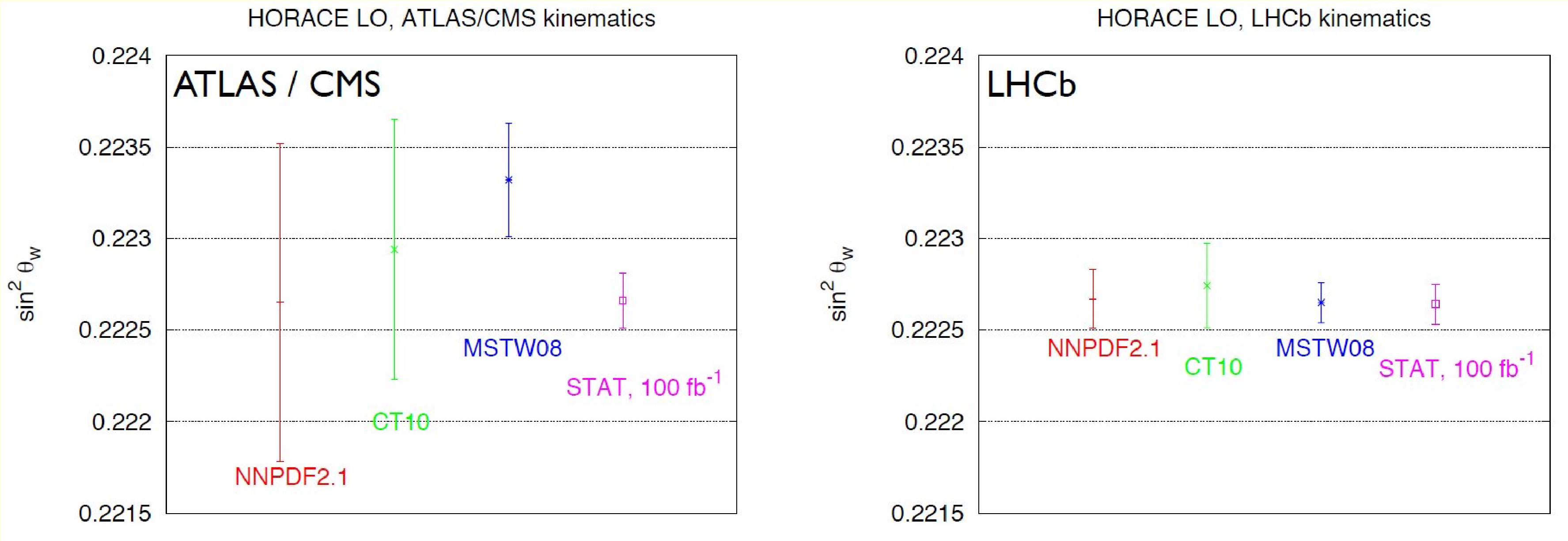
Precision EWK measurements: $\sin^2\theta_W^{\rm eff}$

- Current status from LEP-SLD, $\sim 3\sigma$ discrepancy in $A_{\rm FB}^{0,b}$, A_l
- LHC measurements from $Z\,A_{\rm FB}$ dominated by PDF uncertainty



LHCB has an advantage?

G.Bozzi, PDF4LHC, April 17

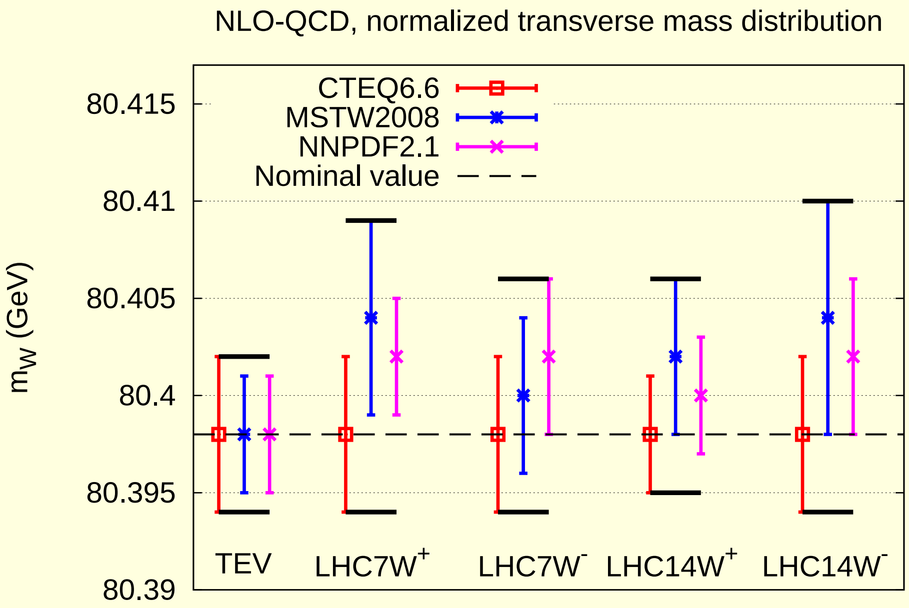


It seems so from the point of view of the PDF errors alone ...

ATLAS, CMS: $|\eta_l| < 2.5$, LHCb: $2 < |\eta_l| < 4.5$; pdf's at large and small x better known ... Can one limit $|\eta_l| > 1.5, 2$ in ATLAS and CMS?

Prospects for M_W measurement

Stat. precision: 2MeV/channel; experimental precision target: $\leqslant 10\,\mathrm{MeV}$. But:

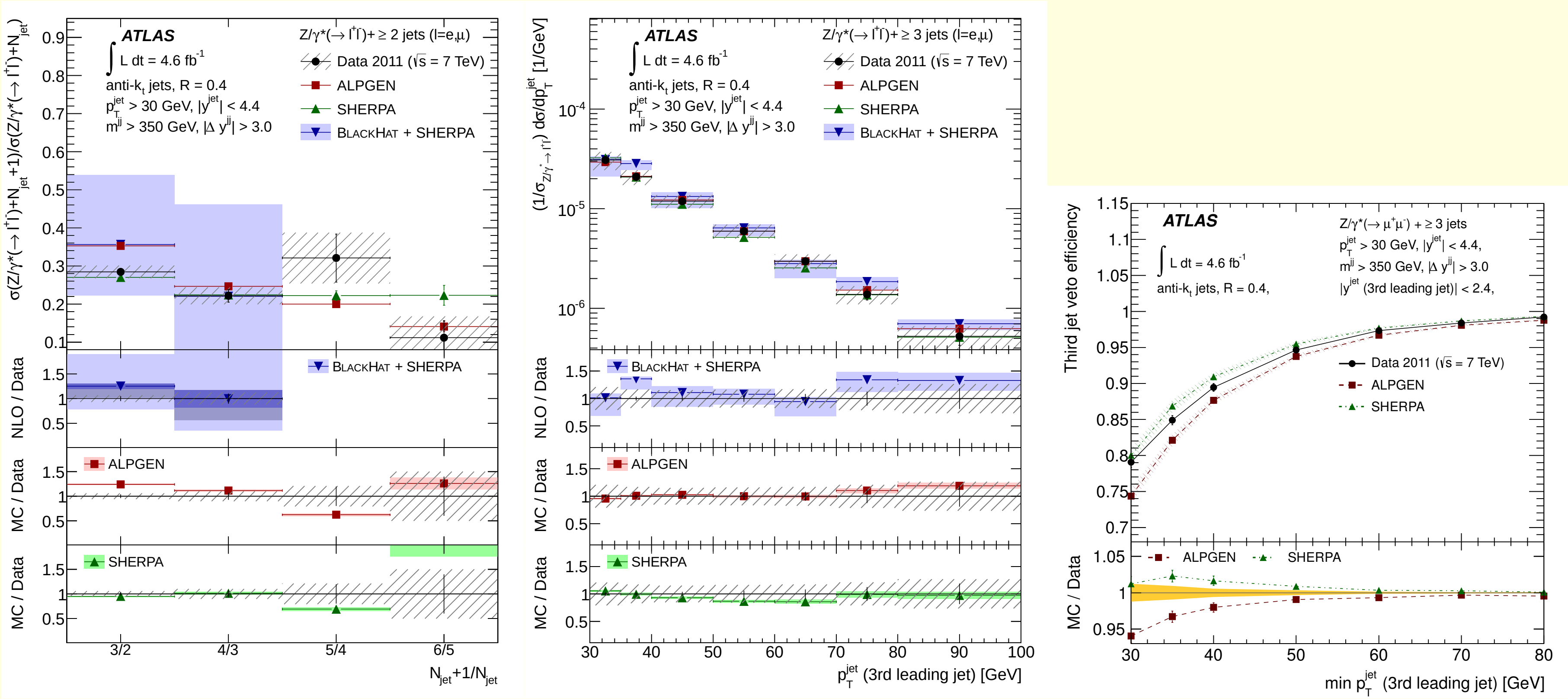


PDF error larger at LHC. (Will it improve with further LHC PDF constraints?)

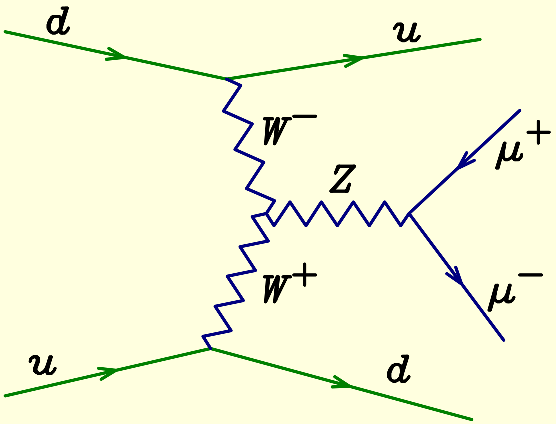
- @Tevatron : measure $Z\ p_{\mathrm{T}}$ and extrapolate to W using Resbos
- @LHC: W^+ and W^- are produced with different rates and kinematics. Larger E_{CM} implies smaller x, thus more s, c component, and more uncertainties. Cannot rely upon $Z\ p_{\mathrm{T}}$ alone. Need to measure $W^{\pm}\ p_{\mathrm{T}}$.
  - Use real data zero bias trigger overlayed with MC W events to control hadronic resolution in data?
  - Better understanding of angular coefficients in W and Z cross sections (CDF, arXiv:1103.5699, 2011)
  - What about a low pileup run for the measurement of M_W?

$V + \mathrm{jets}$ in extreme kinematics regions

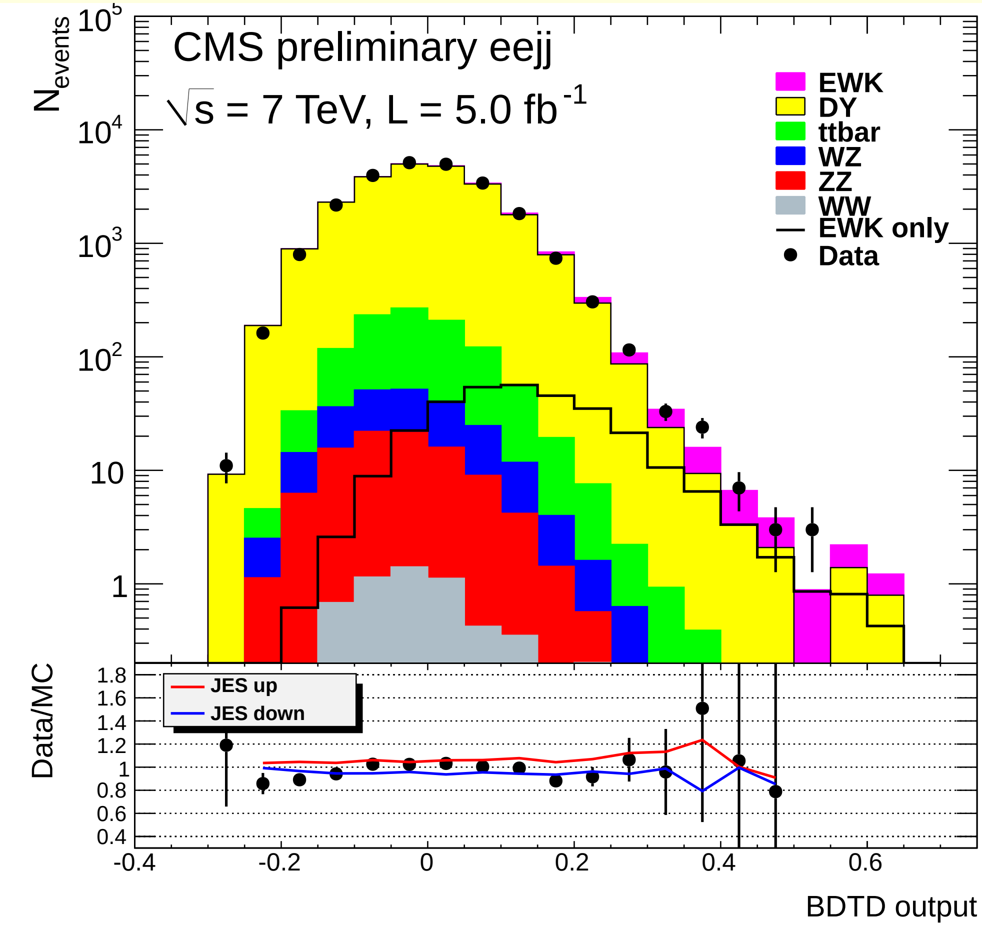
Approach the VBF region;
ATLAS: $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|y| < 4.4$, $m_{jj} > 350\,\mathrm{GeV}$, $\Delta y_{jj} > 3$ for leading jets:



CMS: extraction of VBF component from $Z + 2\,\mathrm{jets}$



- $M_{ll} > 50\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$, $|\eta_{\mathrm{jet}}| < 4$, $m_{jj} > 120\,\mathrm{GeV}$
- Measured cross section: $154 \pm 24(\mathrm{stat}) \pm 46(\mathrm{syst})$ $\pm 27(\mathrm{th}) \pm 3(\mathrm{lumi})\,\mathrm{fb}$
- NLO prediction from `VBFNLO`: $166\,\mathrm{fb}$



Understanding VBF

- We are just at the beginning! EW Z production is very similar to VBF Higgs production. Can help to understand jet tagging and veto efficiencies.

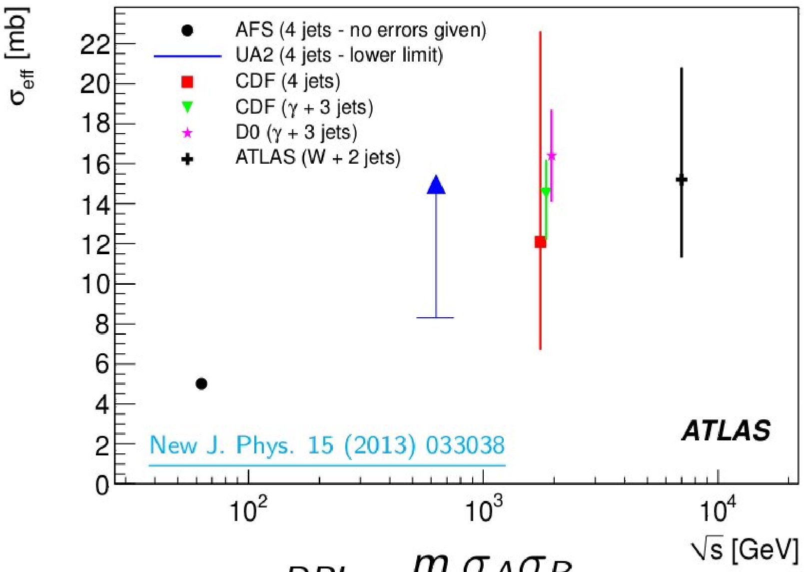
- Long term goal: study vector boson scattering.

Points for discussion

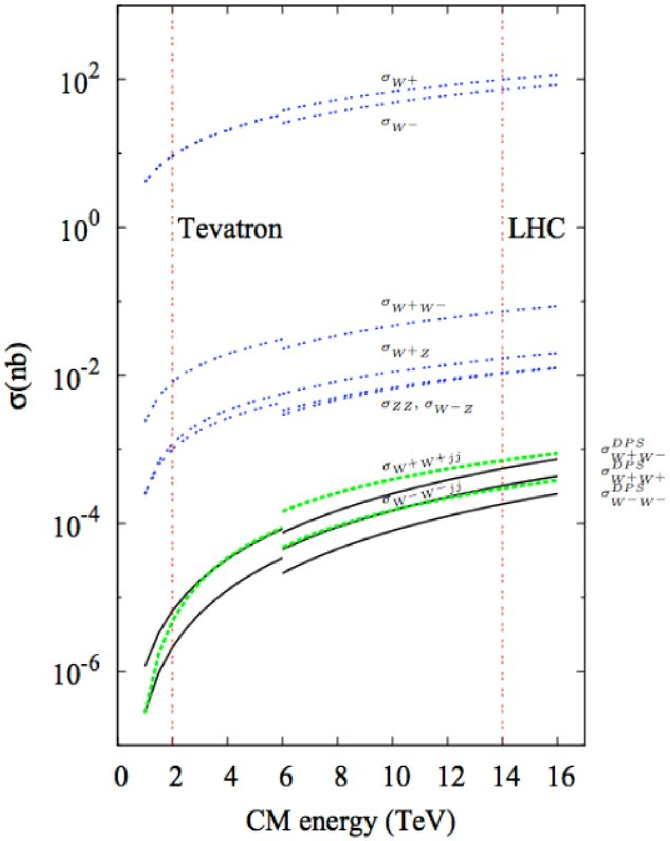
- Broad: SM physics goals for the LHC
- Modeling of SM processe at hadron colliders
- NNLO goals, PDF's and the like
- Top mass
- Precision EW physics
- VBF processes

Backup slides

- ⋆ LHC higher $\sqrt{s}$ leads to enhanced PDFs and so to a larger impact of MPI effect on a multitude of physics signatures
- ⋆ MPI impacts on the underlying-event at small p_T and contributes with double parton scatterings to high p_T processes

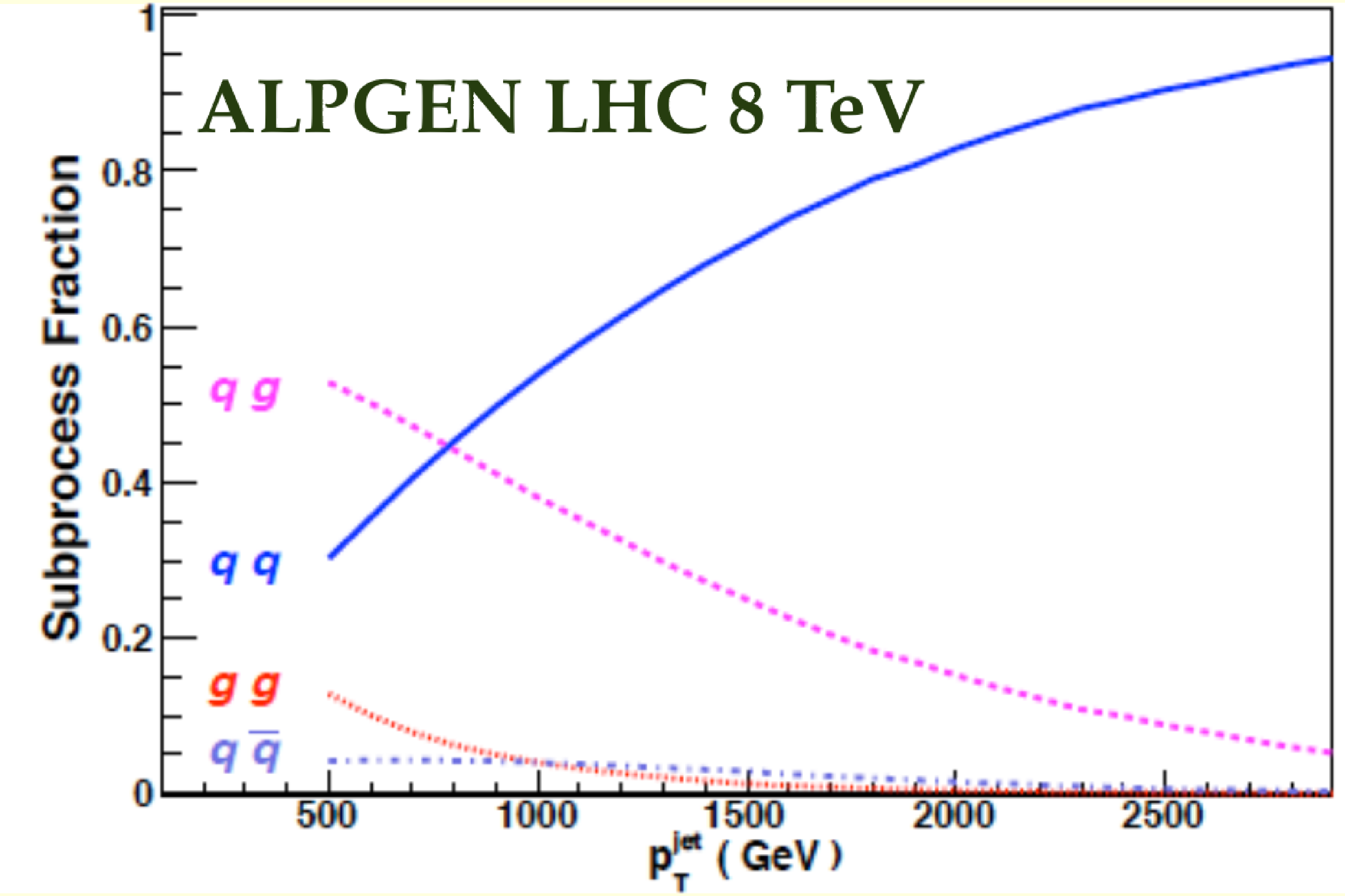


$$\sigma_{AB}^{DPI} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

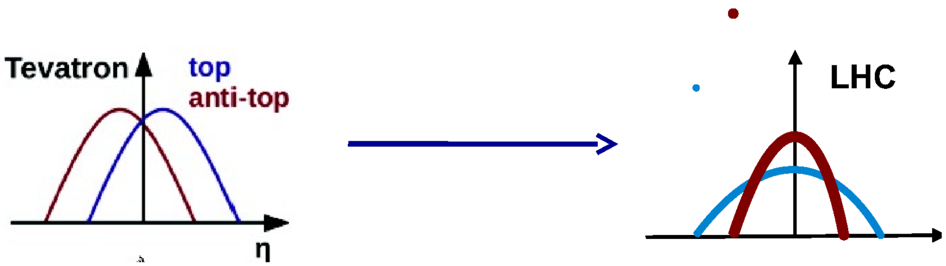


- ⋆ σ_{eff} measured at LHC in $W + 2jet$ events
- ⋆ Sizeable contribution to $W^{\pm}W^{\pm}$ prod.

Subprocess fraction for jets



AFB a LHC – charge asymmetry



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

$$\Delta|y| = |y(t)| - |y(\bar{t})|$$

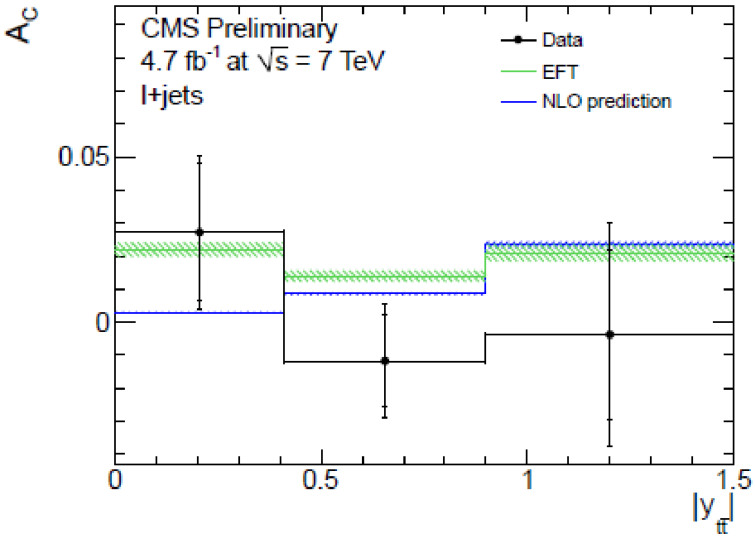
- top / anti-top rapidity asymmetry at LHC from quark-antiquark annihilation, gluon-gluon fusion, dominant process, intrinsically symmetric $\quad 14\ \mathrm{TeV}\ gg \to t\bar{t}\ (90\%),\ q\bar{q} \to t\bar{t}\ (10\%)$

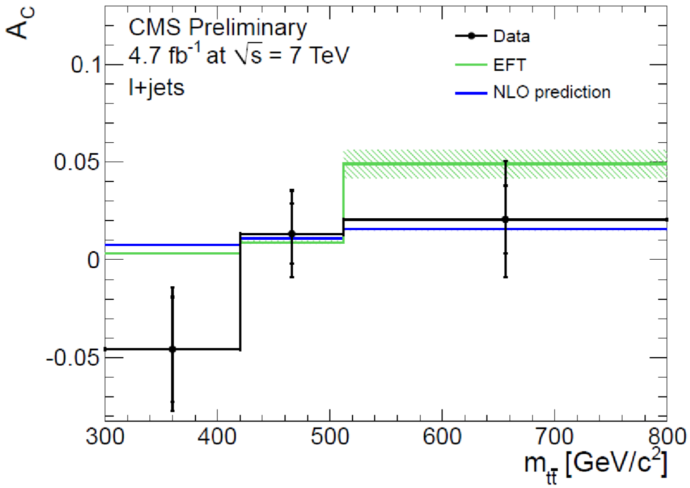
- **Important at LHC to study differential asymmetries**, to enhance new physics
  - **Sum of t and tbar rapidity to separate quark-antiquark and gluon-gluon fusion**
  - **ttbar invariant mass sensitive to new heavy states**
  - **Transverse momentum of the ttbar system sensitive to interference due to ISR**

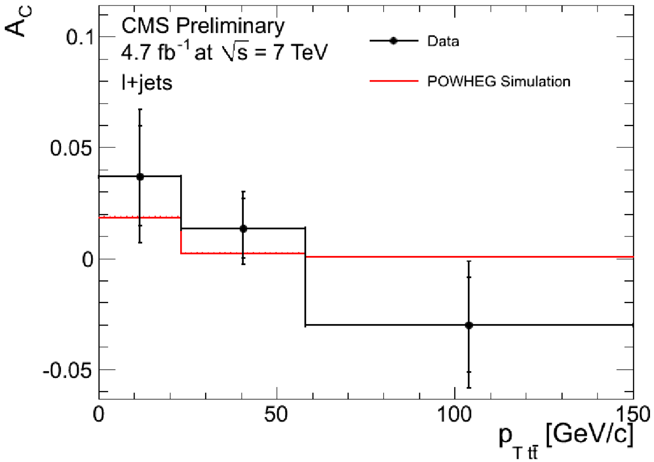
CMS PAS TOP-11-030

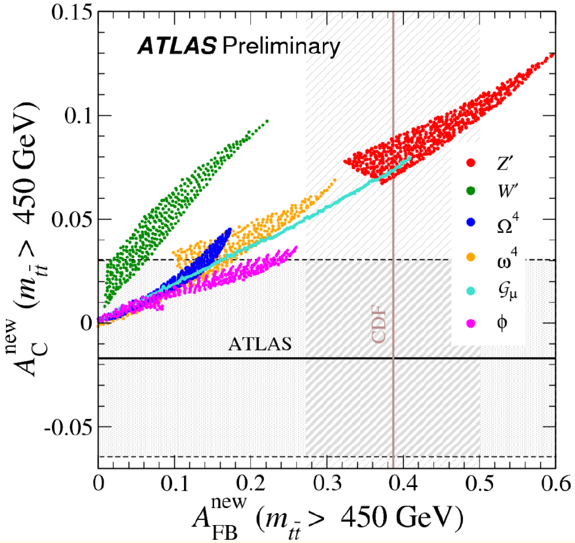
ATLAS CONF-2011-106

Charge asymmetry a LHC

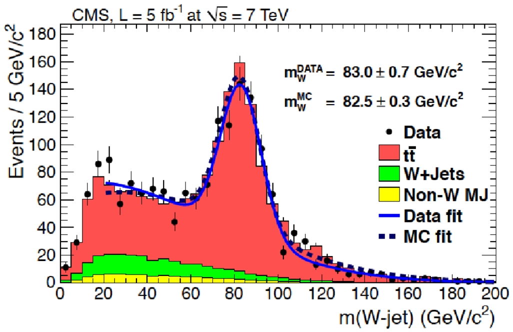


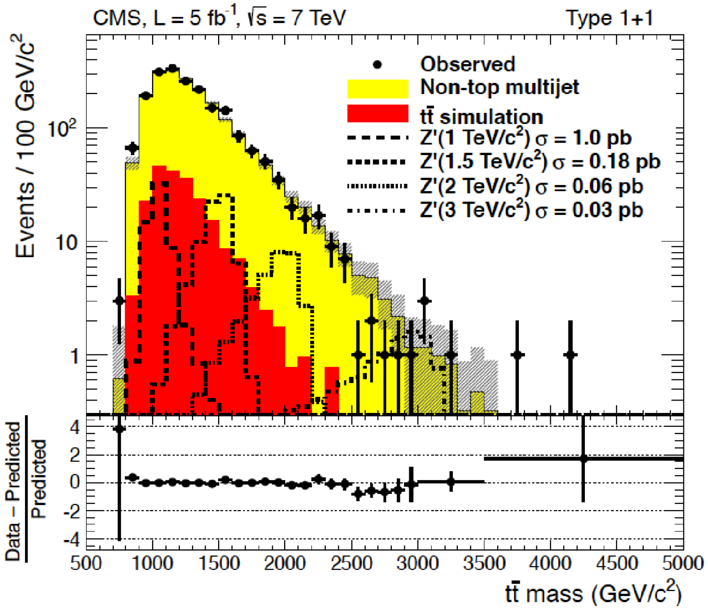




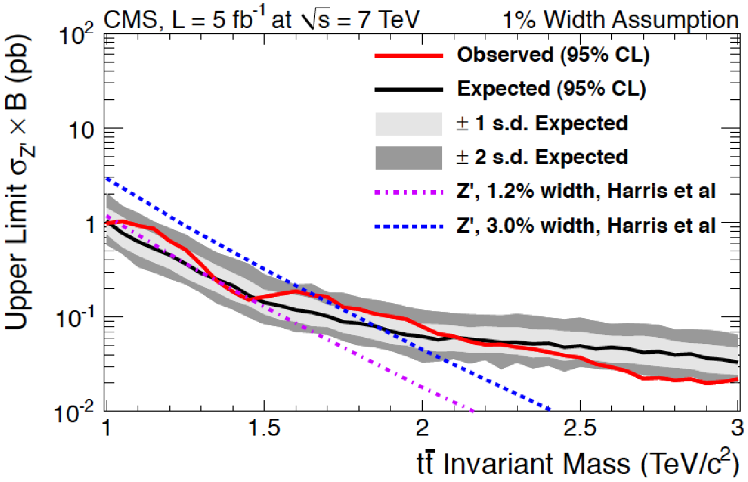


Jet pruning: Substructures and Boosted top



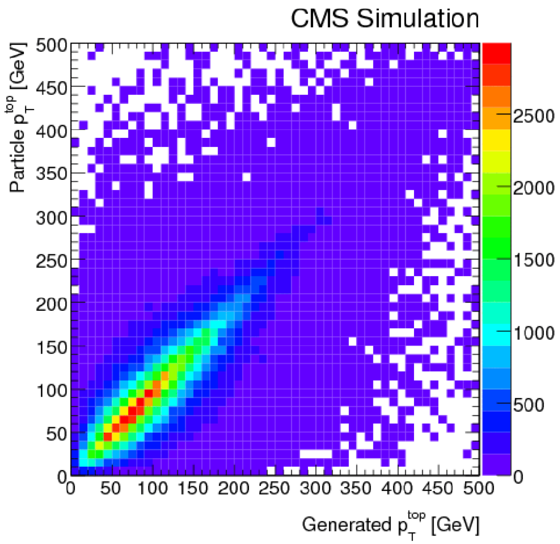


CMS arXiv1204.2488



Low background at high m(ttbar) a resonance would eventually stand up with enough luminosity

Differential distributions and pseudo-top



unfoldi
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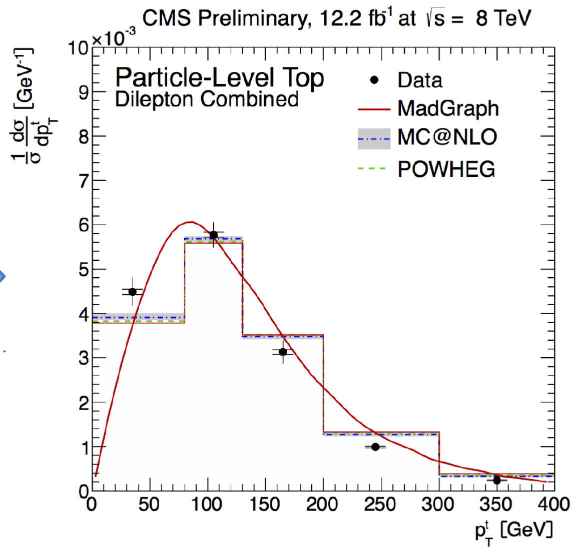
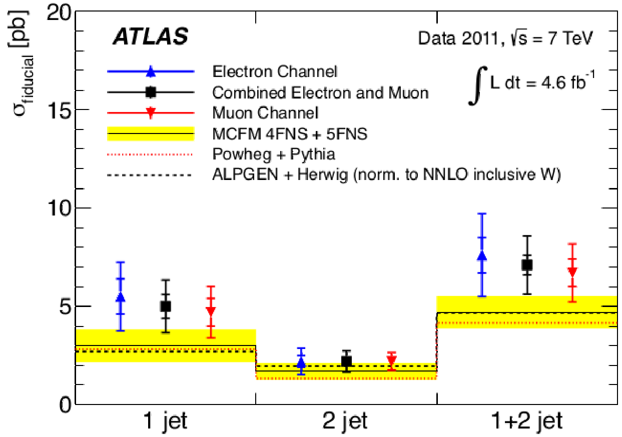


Measurements of V + h.f. cross sections

- ★ 7 TeV LHC data ⇒ first differential measurement of $W + b$ cross-section
- ★ More measurements still to come ($Z + b$, $W + c$, $Z + c$)
- ★ 8 TeV dataset and next run will allow for more differential results



ATLAS $W + b - jets$, arXiv:1302.2929