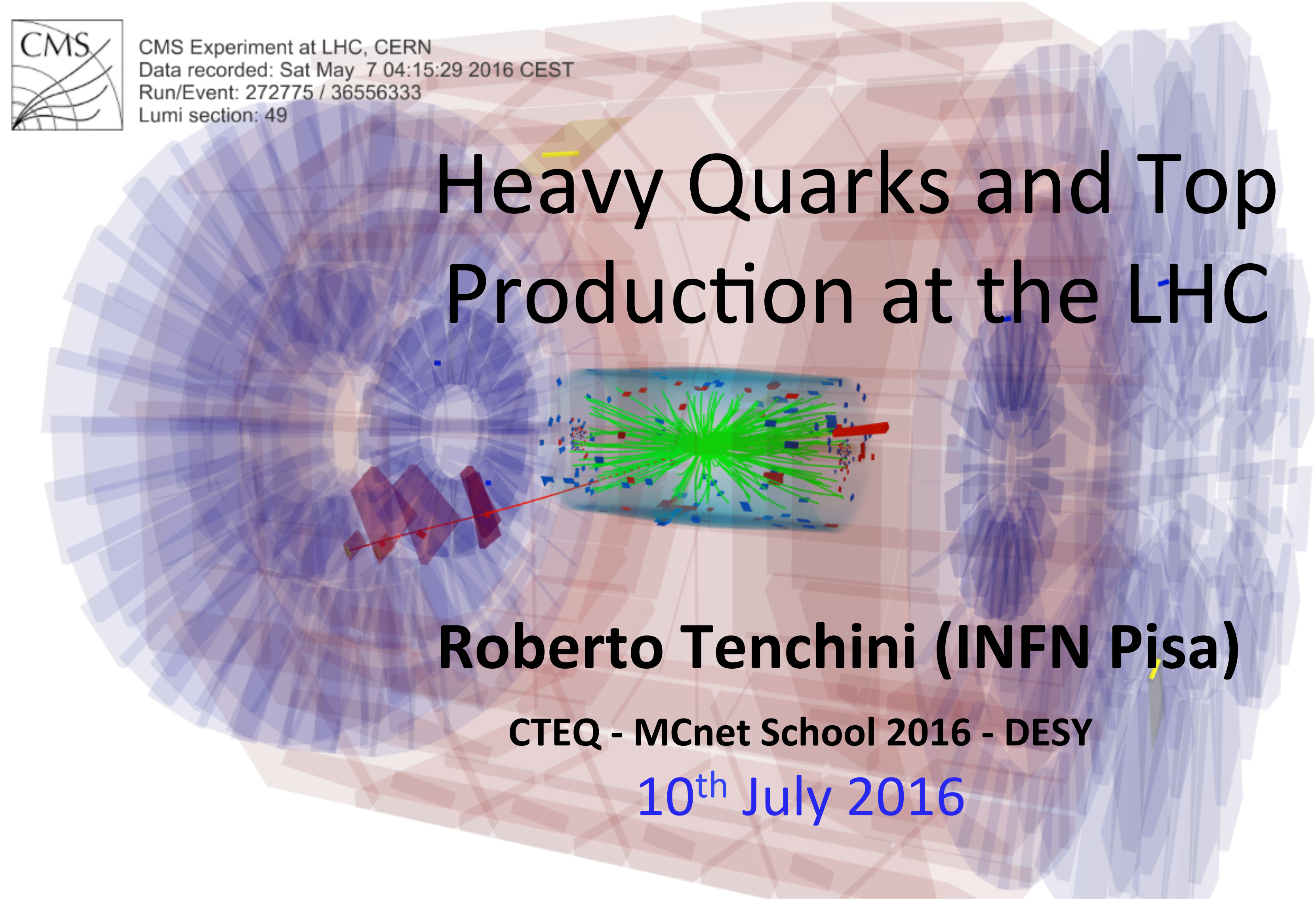


Heavy Quarks and Top Production at the LHC

Roberto Tenchini (INFN Pisa)

CTEQ - MCnet School 2016 - DESY

10th July 2016

Charm, bottom and top

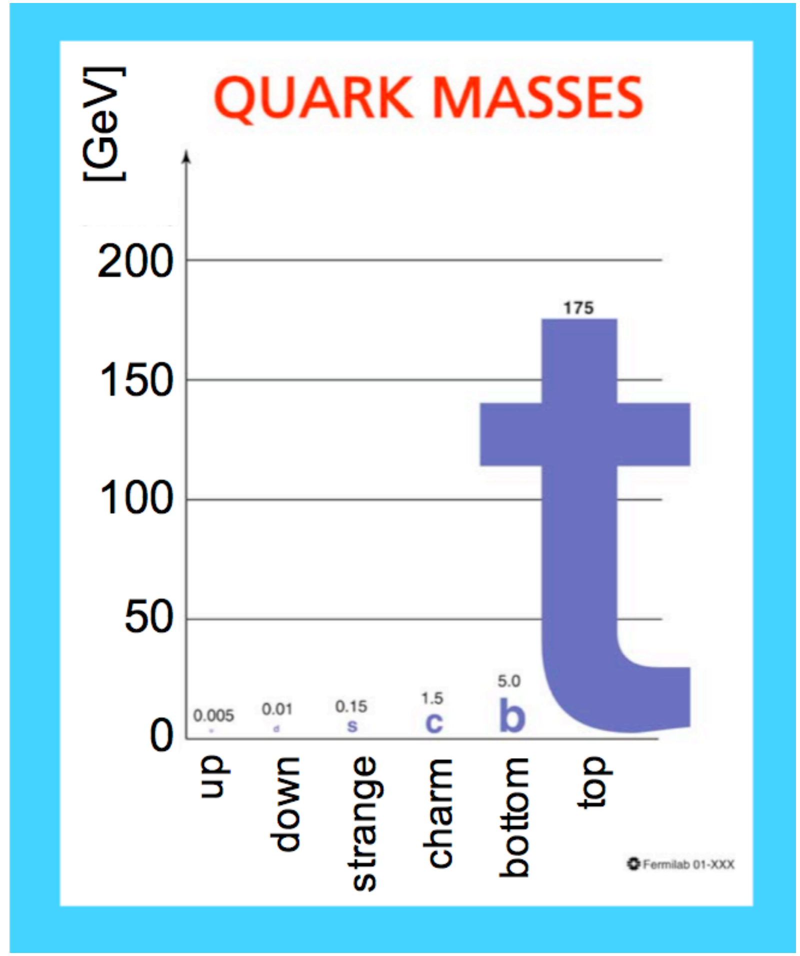
• Strong mass hierarchy: charm and bottom are called **heavy quarks**, but the heavier is top, with **a mass comparable to a tungsten atom** !

• Yukawa quark-Higgs couplings

$$Y=\sqrt{2}\,\frac{m}{\text{v.e.v.}(\sim 246\ \text{GeV})}$$

•top – Higgs Yukawa coupling is ≈1

•top is a window to electroweak symmetry breaking



The privilege of being heavy

- Experimentally, charm bottom top share several signatures
- **Secondary vertexes**
  - For c, b originating from long lived charm and beauty hadrons
  - For t from bW decay
- **Leptons**
  - For c, b from high semileptonic branching rations
  - For t from bW decay

The privilege of being even more heavy

- Experimentally, charm & bottom are very different from top
- **Exclusive states** are **key signatures** for c and b
  - quarkonia, D and B mesons
- **Exclusive states** are **not formed** for top
  - Very short lifetime: bound states are not formed, opportunity to study a free quark

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times 10^{-24} s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times 10^{-21} s << \tau_b \sim 10^{-12} s$$

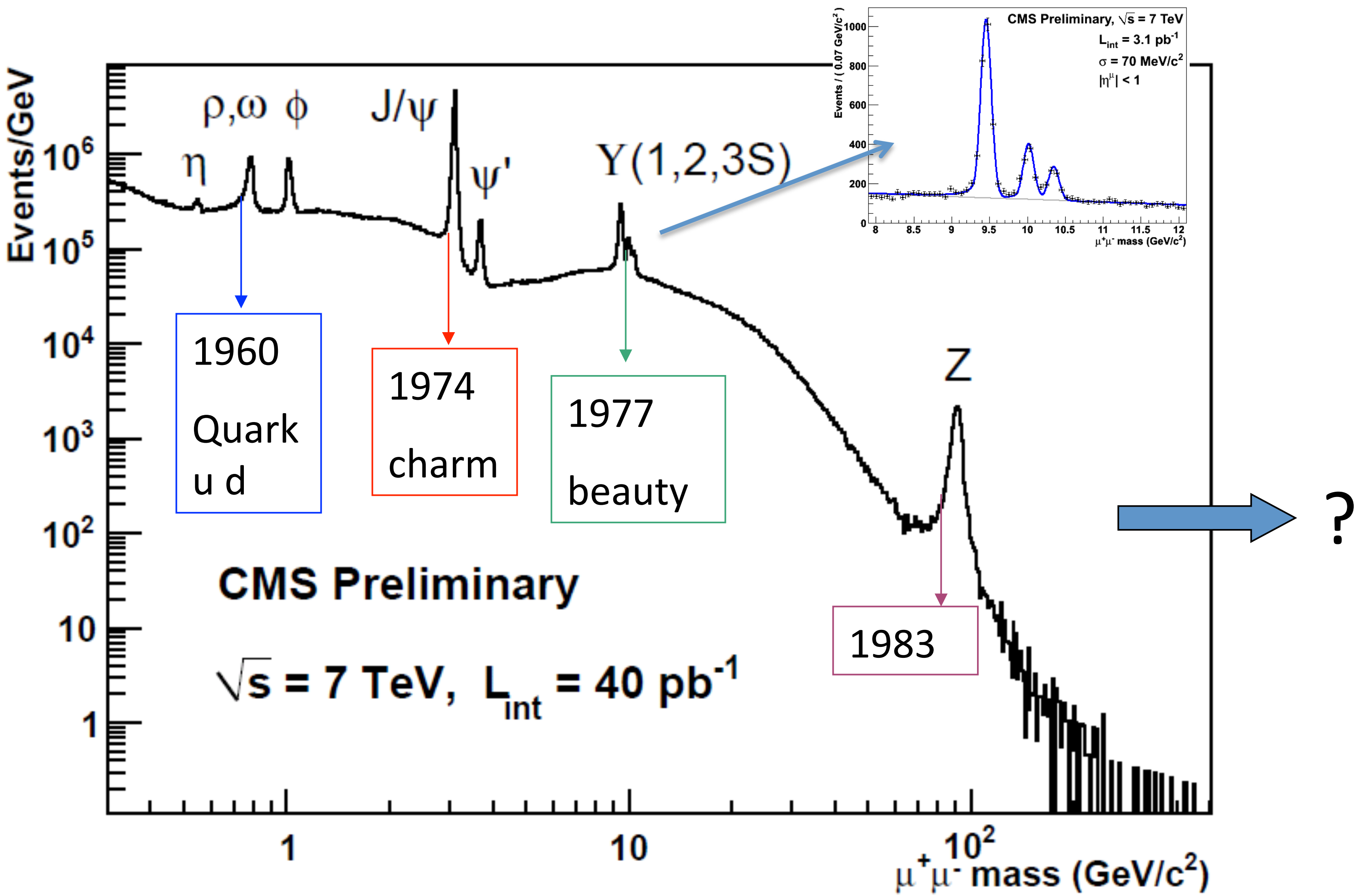
$$\tau_t < \tau(hadronization) < \tau(spin-decorrelation) << \tau_b$$

Basic ingredients of cross section measurements (example with leptons)

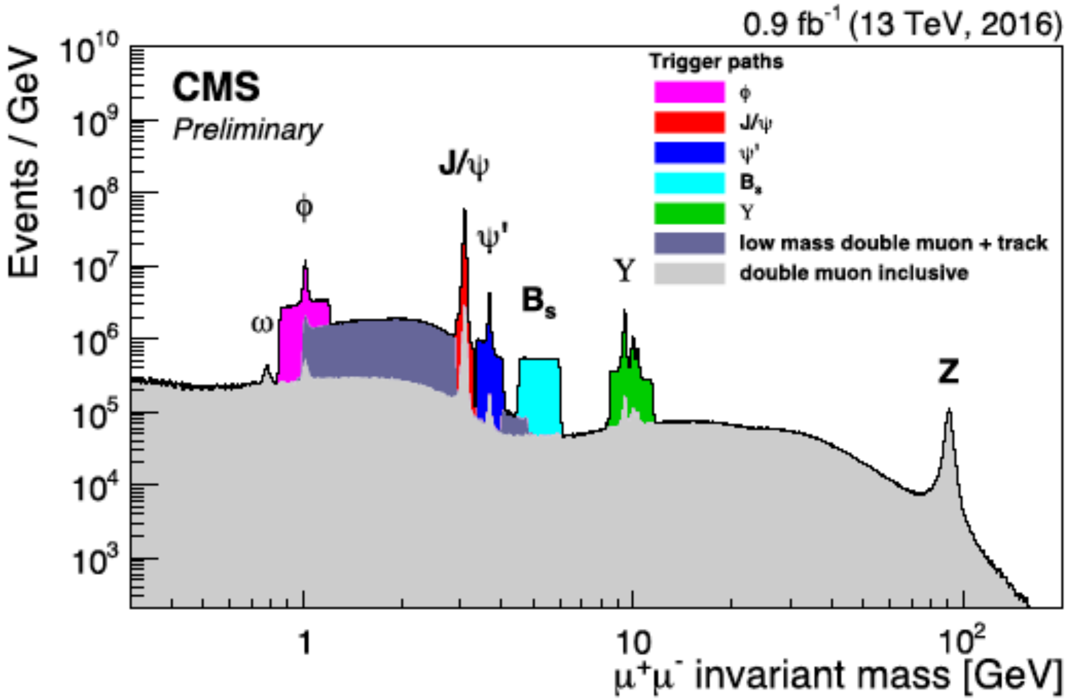
σ=(**Nsignal**-**Nbackground**)/(**efficiency** x **luminosity**)

- Trigger on leptons **(e,μ,τ)→p_t**, **isolation cuts if applicable**
- Offline lepton selection → cuts with improved reconstruction, define acceptance in fiducial region
  - **need to measure efficiencies from data !**
- Suppress background (e.g. suppress jet production with transverse mass cut)
  - **need to measure background from data !**
  - (typical bkg: leptons from b,c decays, decay in flights of π, K, conversions $\gamma \rightarrow e^+e^-$,etc.)
- **Need information on accelerator luminosity**

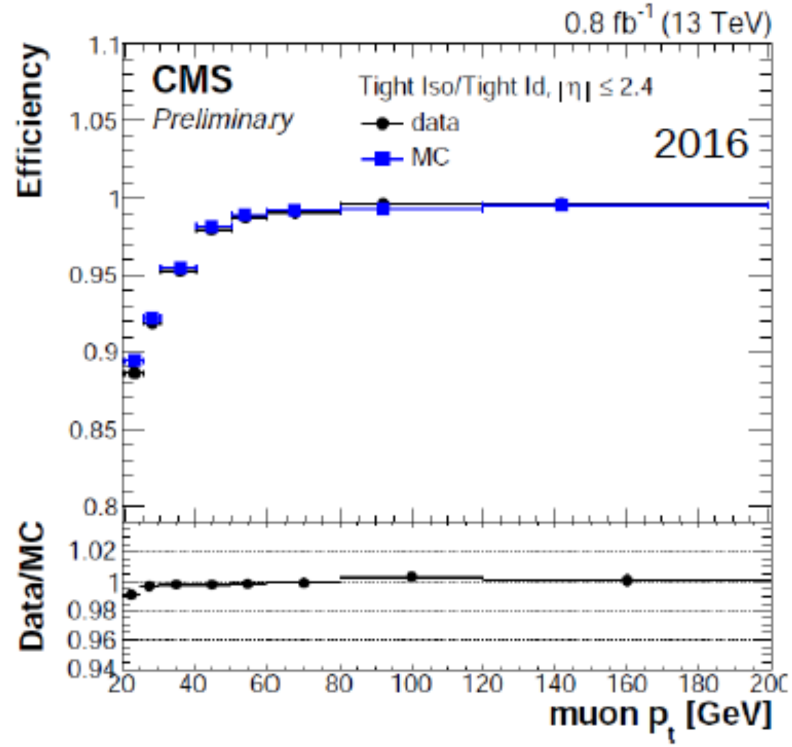
example from 2010: μ+μ- inv mass spectrum, after **trigger** selection (very low trigger thresholds !)



Need dedicated trigger streams at LHC Run II



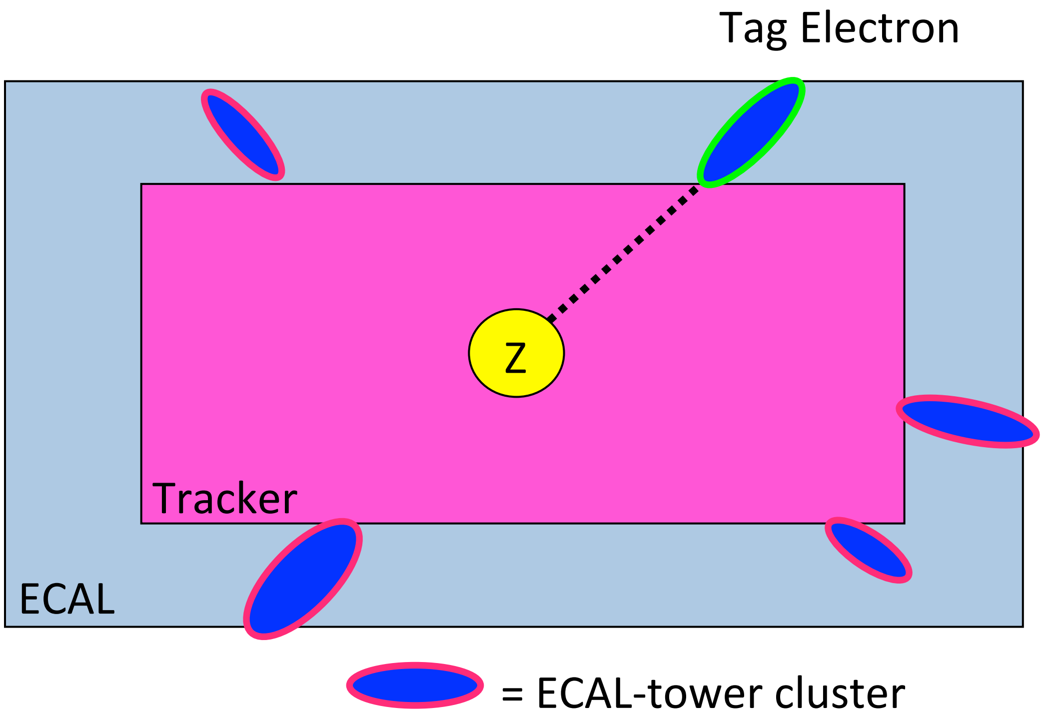
Dimuon mass distribution collected with various dimuon triggers.



Efficiency for tight muons to pass the isolation cut. Agreement between data and MC is very good.

Measure efficiency from data (Tag and Probe)

(example of a common technique)



Compute ECAL-tracker matching efficiency

$$eff = \frac{\text{number of matched probes}}{\text{number of probes}}$$

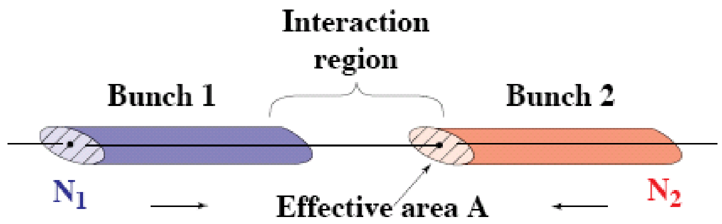
1. Find a good electron in a Z→ee event that meets Tag criteria
2. Loop over ECAL-tower clusters in the event with transverse energy above, e.g., 15 GeV and calculate the cluster-Tag invariant mass (M)
3. The cluster satisfying, e.g. : 82<M<100 GeV is a Probe

Luminosity determination

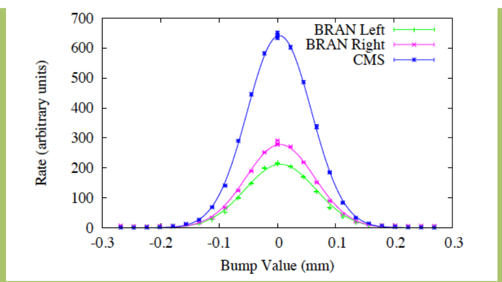
$\text{Rate}=\sigma L$

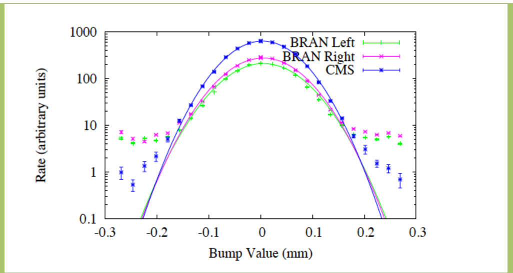
- The method is known as "Van Der Meer scan"

$$\mathcal{L} = \frac{N_1 \, N_2 \, f}{A_{\text{eff}}}$$



Beam intensities and crossing frequency are known with good accuracy
The effective overlap area A can be determined by scans in separation





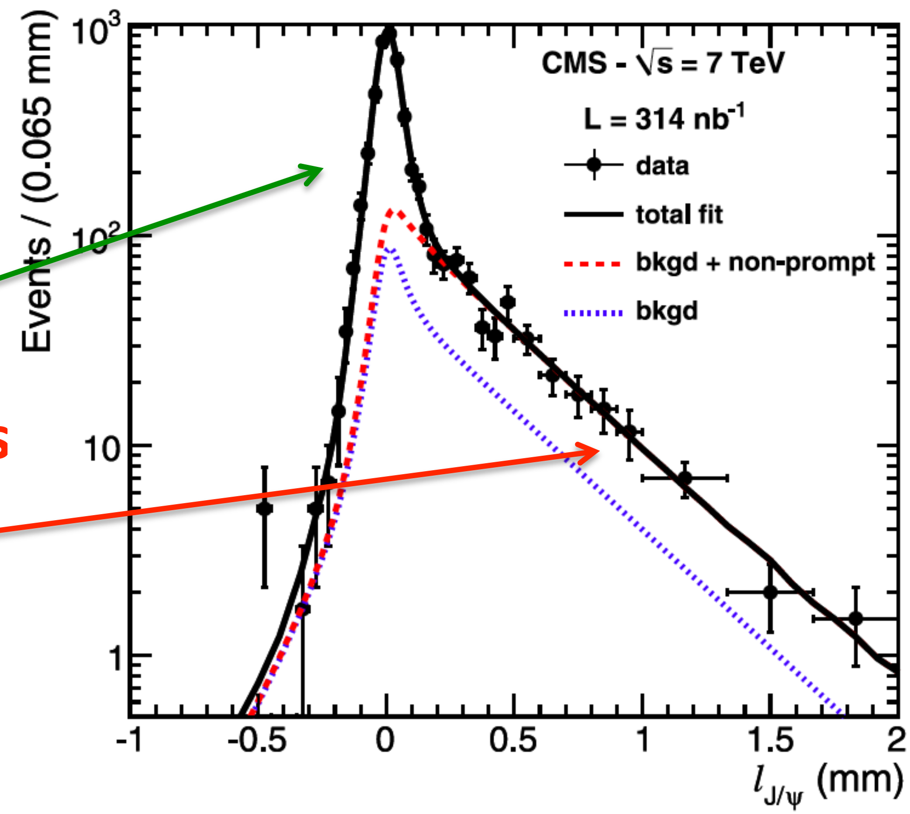
Details : LHC Report 1019 by Grafstrøm Burkhardt http://cdsweb.cern.ch/record/1056691

CHARM AND BOTTOM PRODUCTION (SOME RELEVANT EXAMPLES)

J/psi as a window to c and b

- Separate J/psi→$\mu^+\mu^-$ by means of decay length (L_{xy}) using **pseudo-proper lifetime, $\tau=L_{xy}(m/p_T)$**
- **Prompt J/psi from charm** show peak at production point
- **J/psi from B→J/psi X decays** show exponential behaviour from B lifetime
- Both component are smeared by detector resolution

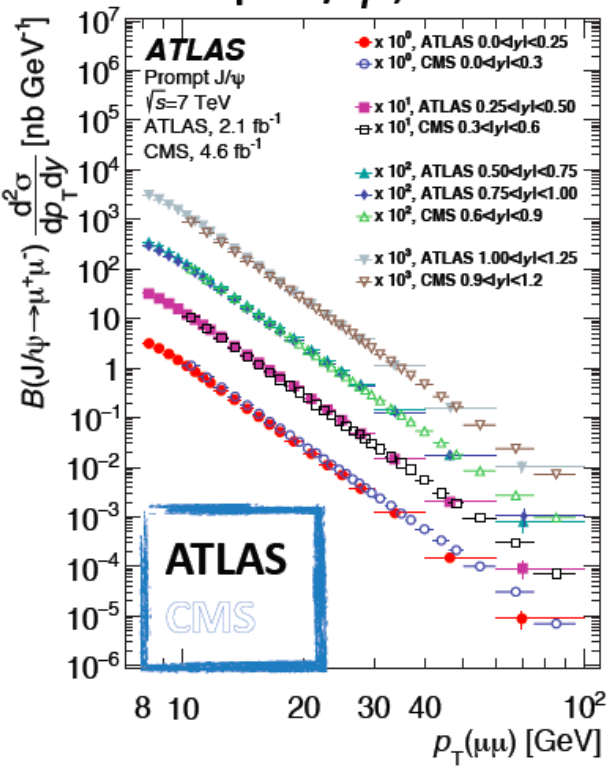
Eur. Phys. J. C (2011) 71: 1575



J/Psi and ψ(2s) prompt cross sections

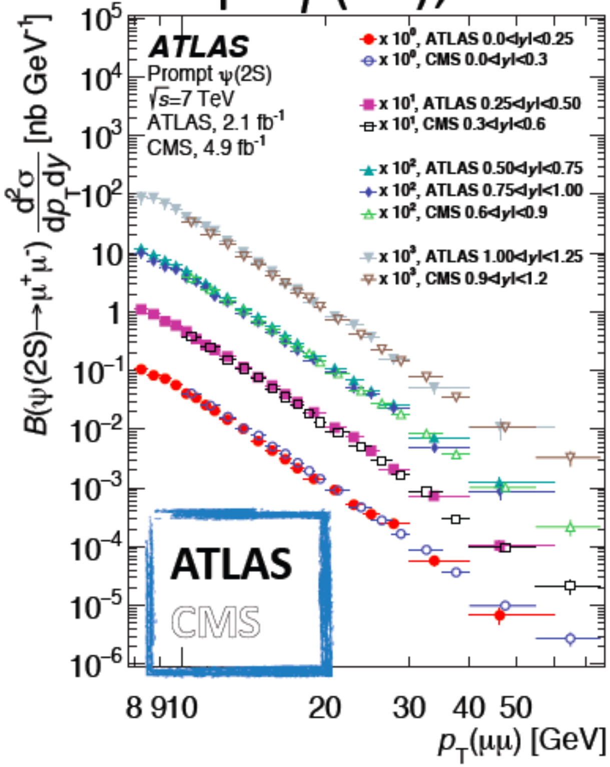
Data available at a wide pT and rapidity range

Prompt J/ψ, 7 TeV

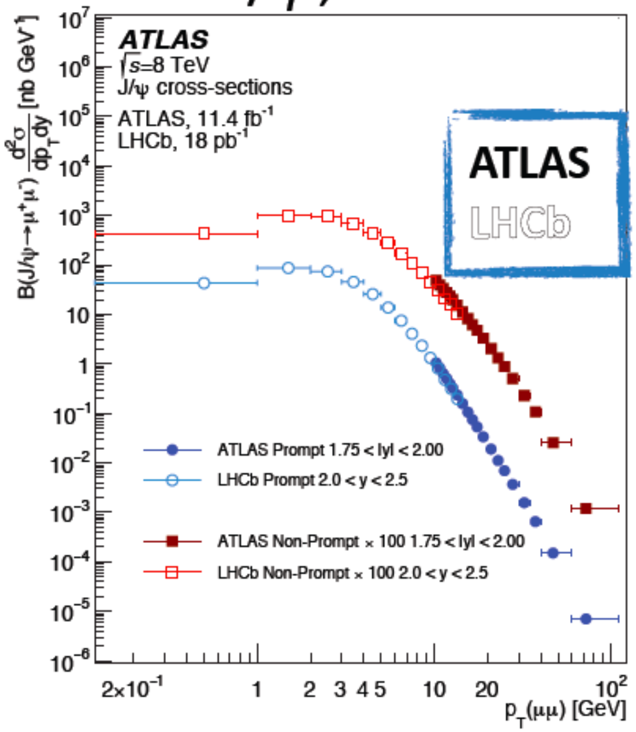


CMS: Phys. Rev. Lett. 114.19 (2015) 191802,

Prompt ψ(2S), 7 TeV



J/ψ, 8 TeV

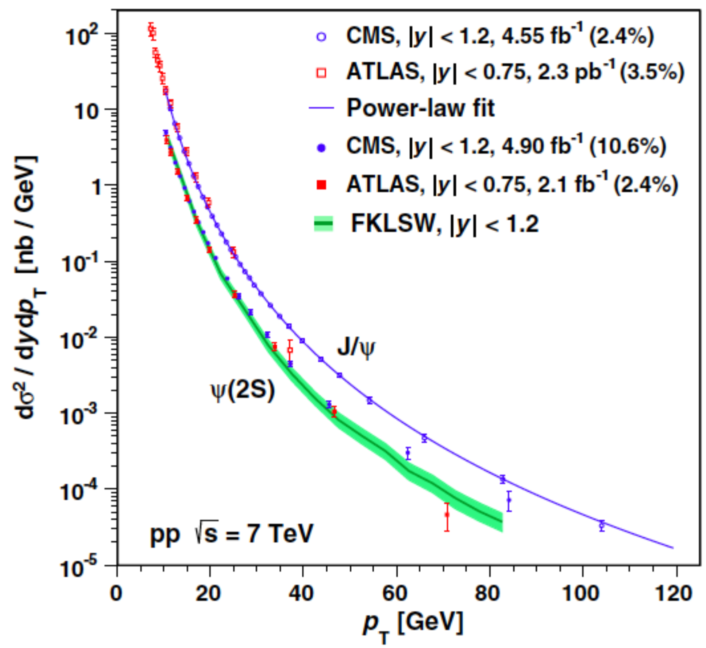


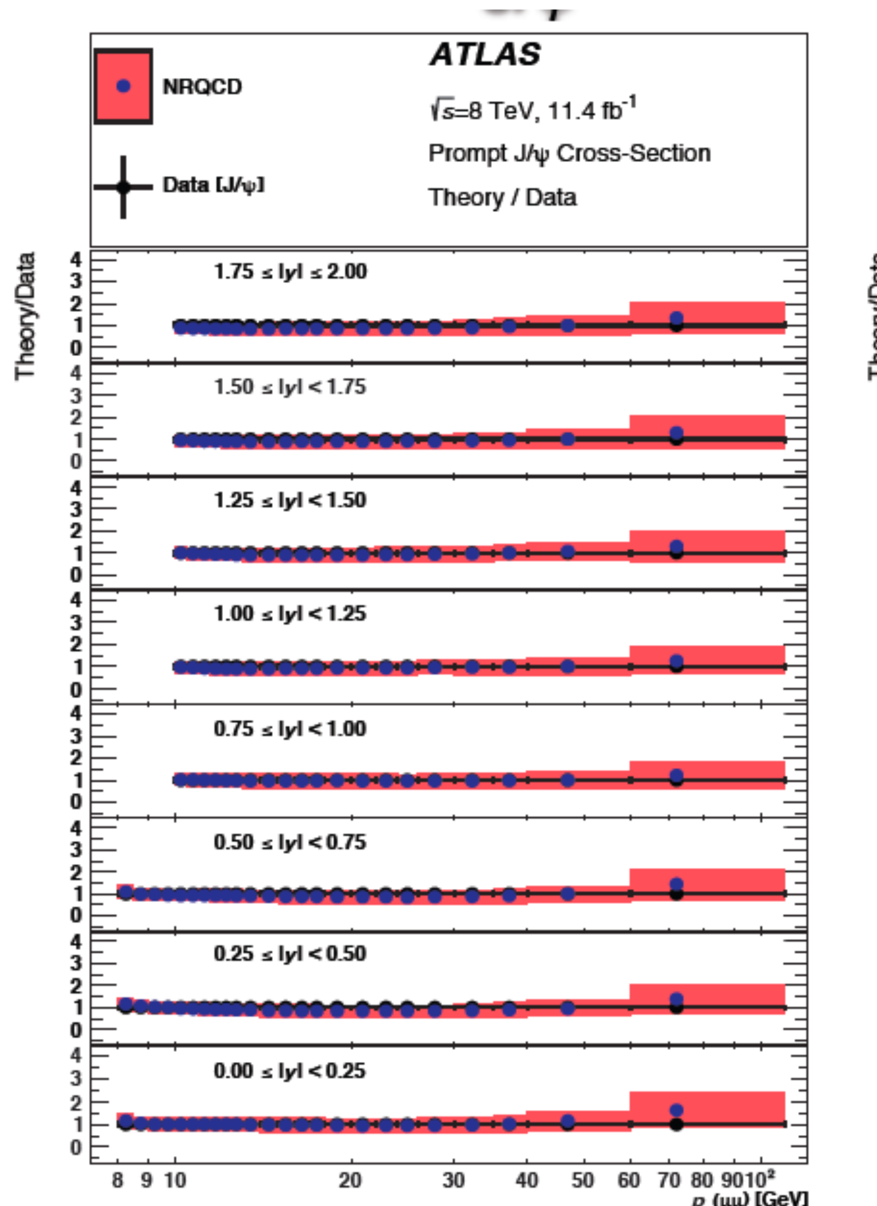
(LHCb) JHEP 1306 (2013) 064,

From J. Walder, BEAUTY 2016

Prompt J/psi and NRQCD

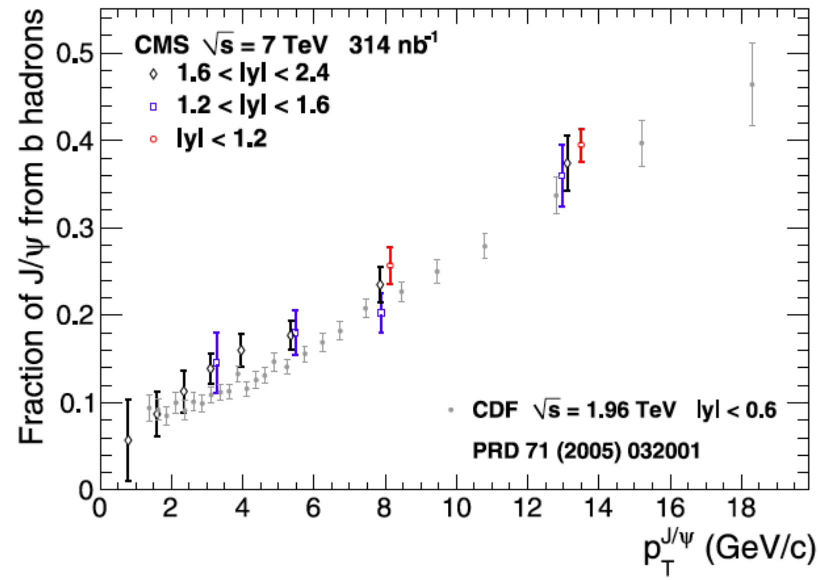
- Long standing disagreement in quarkonia production with theory until realized octet production had to be taken into account
- Requires input from Long Distance ME (growing evidence of universality)

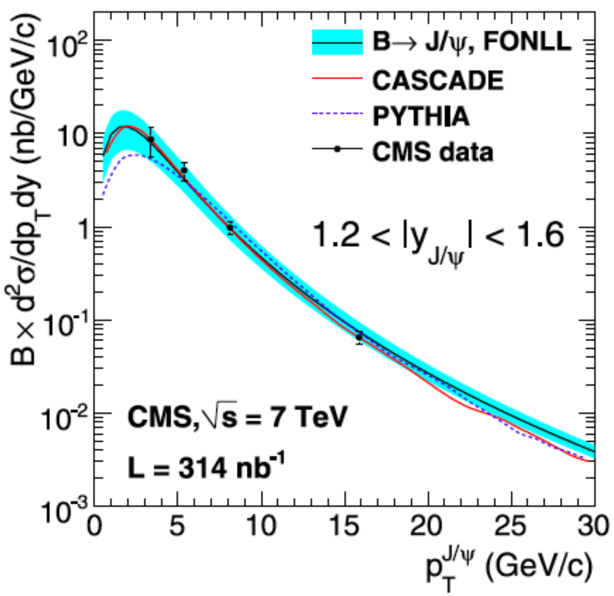


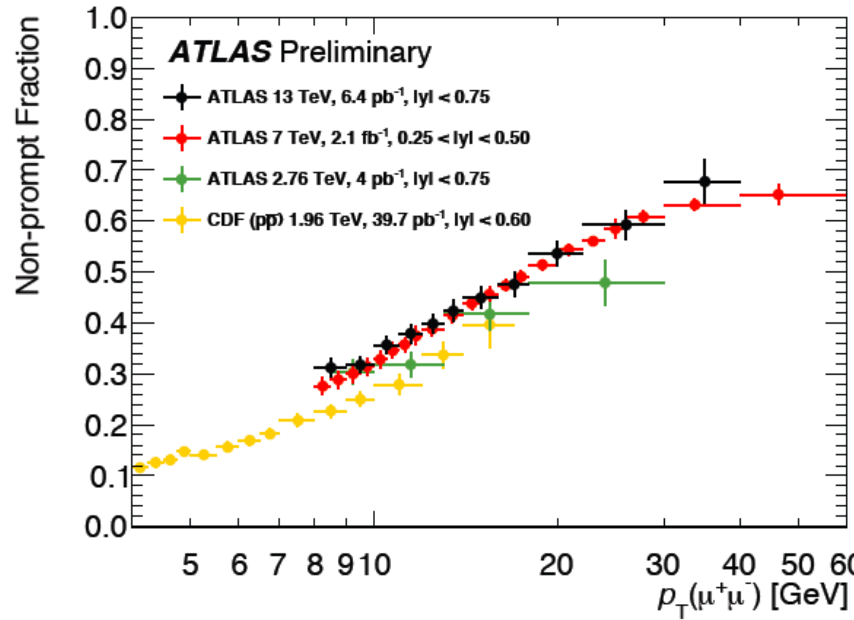


Non prompt fraction

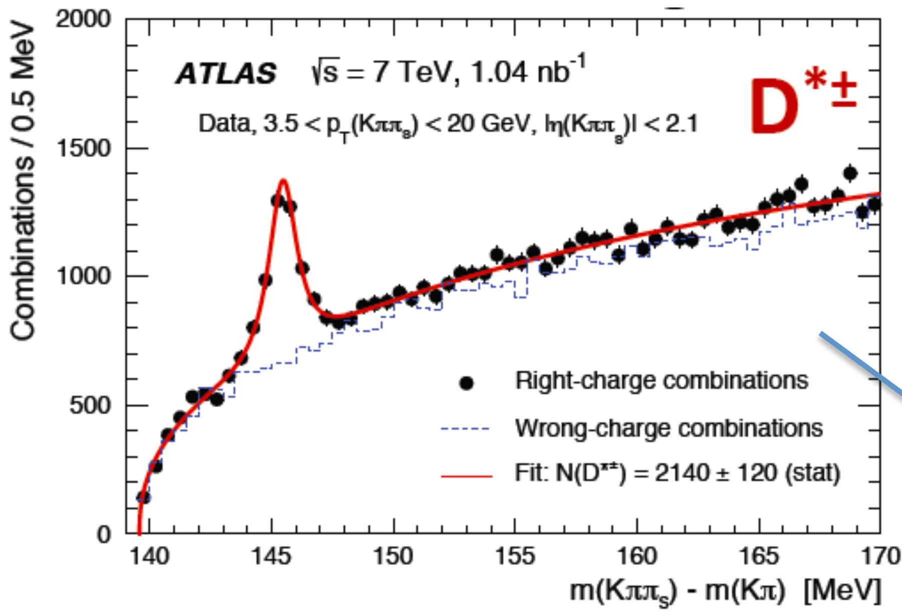
- Strong fraction dependence from pT
- Reasonably well described from current simulations





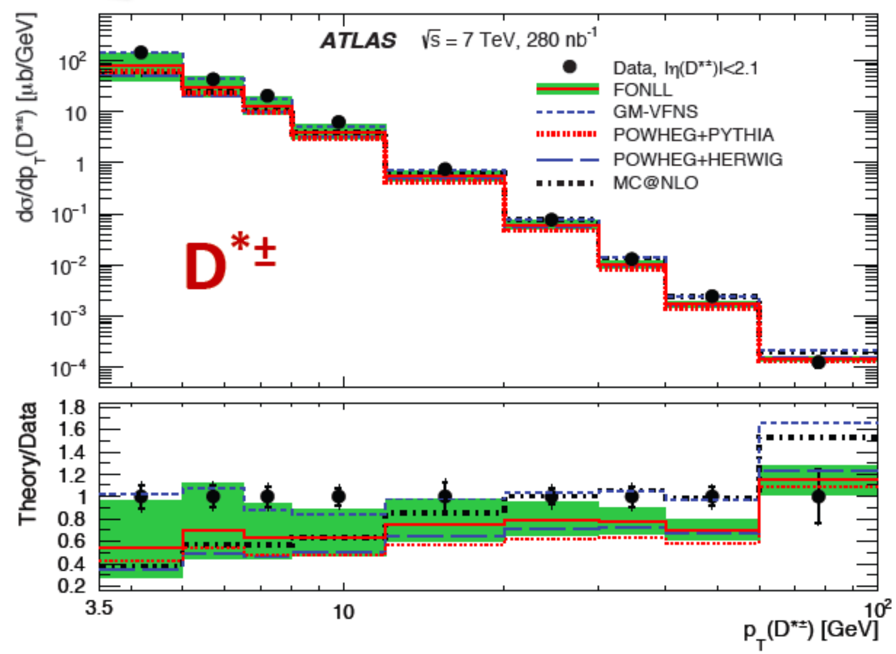


Charm production from exclusive states



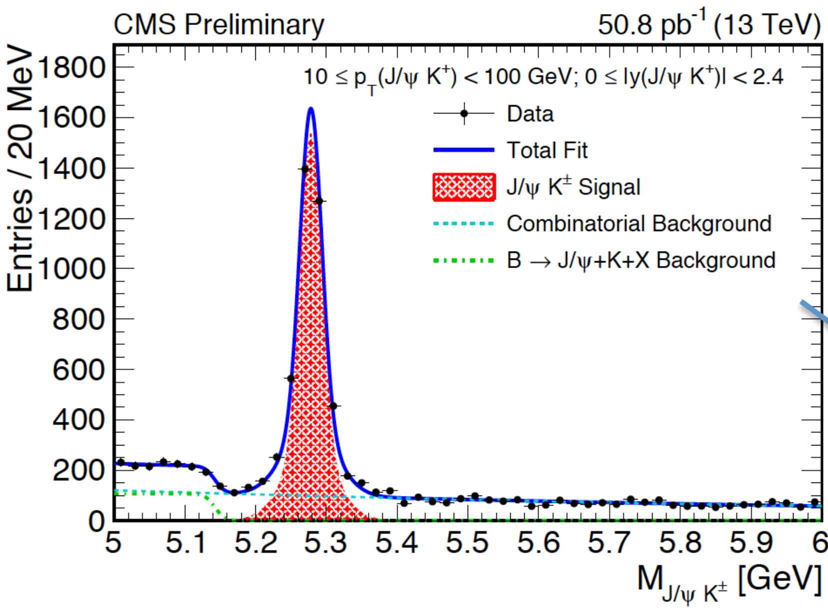
Example from

$$D^{*\pm} \rightarrow D^0 \pi_s^\pm$$
$$D^0 \rightarrow K^- \pi^+$$



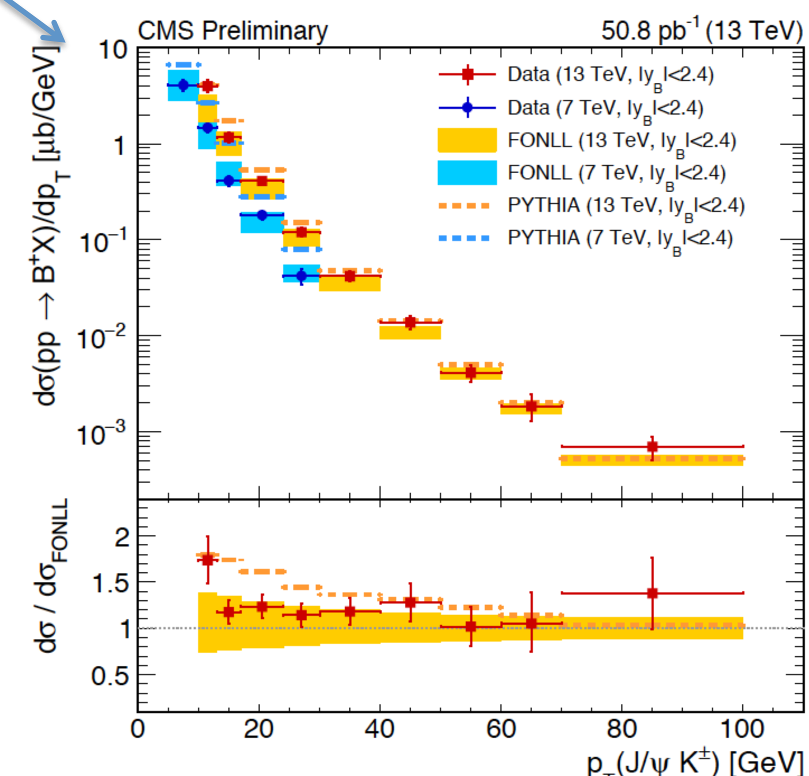
Important inputs to simulations
General description OK
Discrepancies appears in detailed trends and normalization

B production from exclusive states



Example from

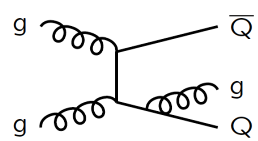
$$B^+ \to J/\psi\, K^+$$



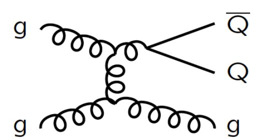
Important inputs to simulations
General description OK, especially for NLL-based calculations

Differential cross sections: example from BB angular correlations

- Provide information about the underling production subprocess, e.g.
  - flavour creation
  - flavour excitation
  - gluon splitting

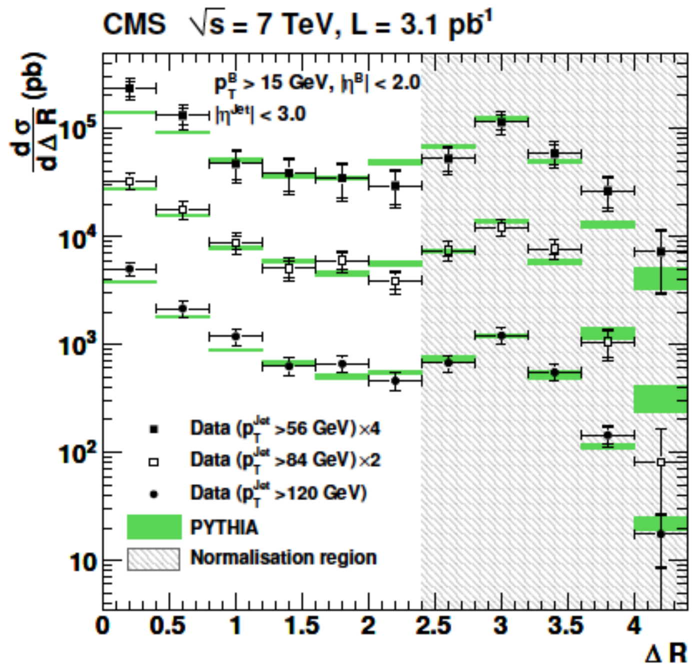


Pair creation



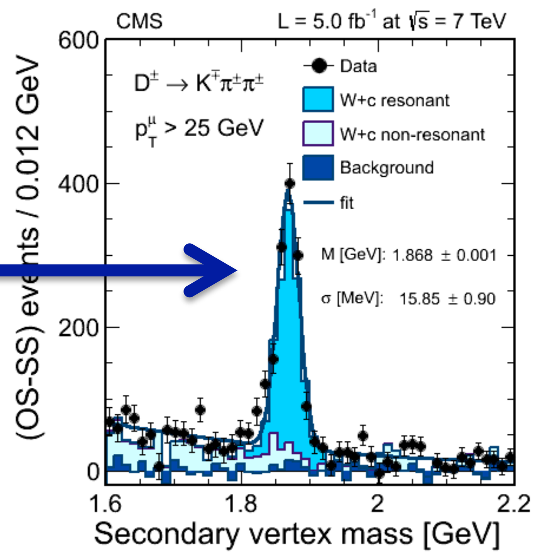
Gluon splitting

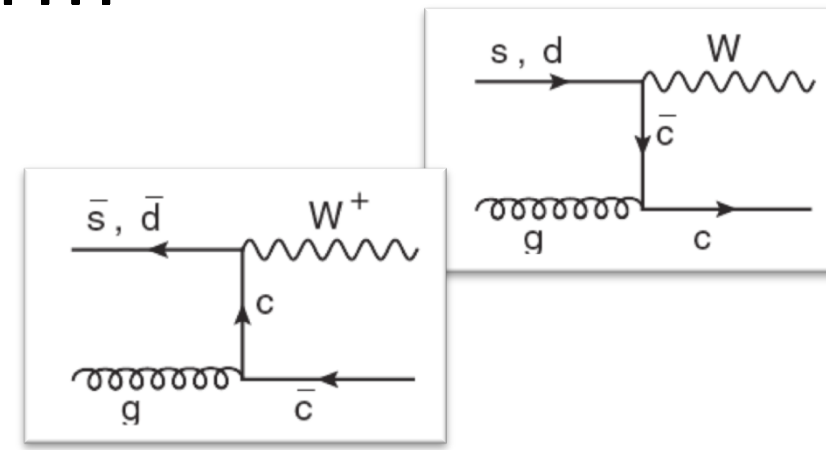
- sensitive test of pQCD leading-order (LO) and next-to-leading order (NLO) cross sections and their evolution with event energy scales



Associate production, an example: W+charm

High pT isolated lepton +

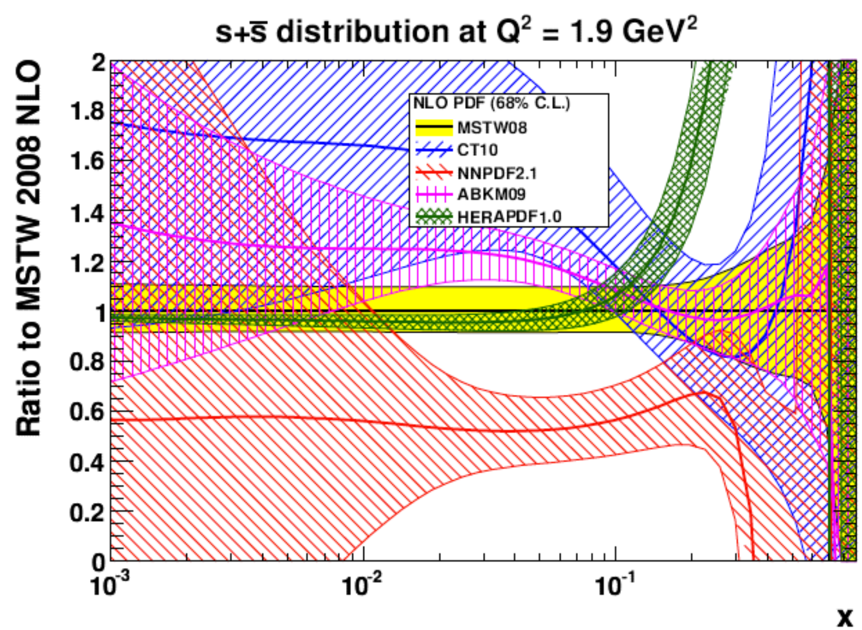




Probes the strange content of the proton

- contribution from d quark about ~10% (Cabibbo suppressed)

- Different PDFs assume different level of suppression of s-quark w.r. to d-quark sea.

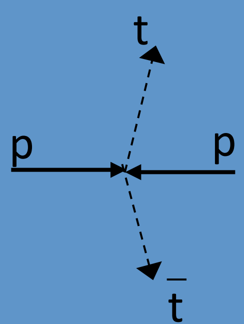


JHEP 05 (2014) 068 JHEP 02(2014)013

TOP PAIR PRODUCTION (AGAIN, SELECTED TOPICS, THIS IS NOT A REVIEW)

Top Quark Production at the LHC

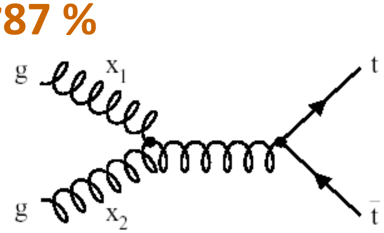
top pairs

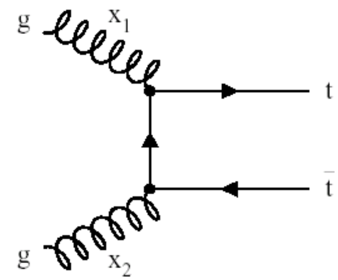


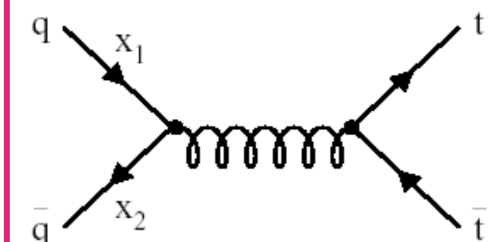
10 $t\bar{t}$ pairs per day @ Tevatron → 1 $t\bar{t}$ pair per second @ LHC

$q\bar{q} \rightarrow t\bar{t}$: 85% *$gg \rightarrow t\bar{t}$: 87%*

~87 %



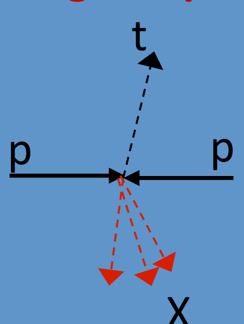




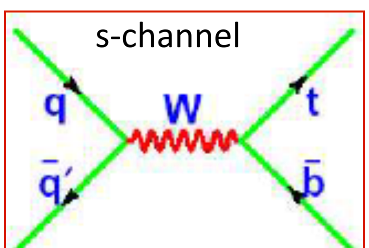
- NLO cross-section σ^{NLO} = **232** pb at 8 TeV ? ~2 M events/10fb^{-1}
- NNLO calculations now available, Czakon, Mitov (2013) arXiv:1303.6254

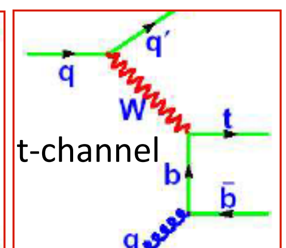
Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer et al. Phys.Rev. D56 (1997) 5919, M.C.Smith and S.Willenbrock Phys.Rev. D54 (1996) 6696, T.M.Tait Phys.Rev. D61 (2000) 034001

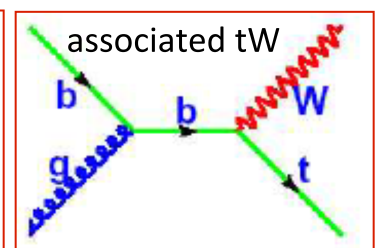
single-top



? 30 single-tops per minute @ LHC







σ_{top} & $\sigma_{anti\text{-}top}$ not equal

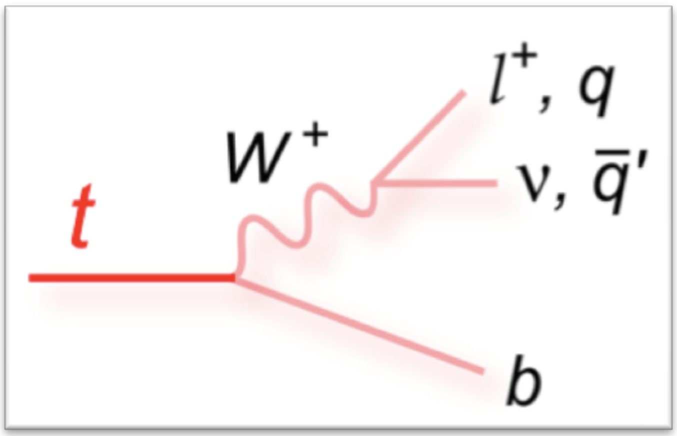
σ^{NLO}(total) 8 TeV = **112** pb

~1 M events/10fb^{-1}

s-channel	t-channel	associated tW	
σ^{NLO} = 3.4 pb	σ^{NLO} = 53 pb	σ^{NLO} = 11 pb	→ top production
σ^{NLO} = 2.1 pb	σ^{NLO} = 30 pb	σ^{NLO} = 11 pb	→ anti-top production

Top Quark decays

It decays almost excusively to Wb, from CKM elements V_{tu}, V_{ts}, V_{tb} :



$$\frac{BR(t \to Wb)}{BR(t \to Wq)} \approx 0.99825 \pm 0.00005$$

$$BR(t \to cZ, c\gamma, cg) \approx O(10^{-33})$$

W decays are used to classify top final states

Decay topologies for ttbar :

- Dileptonic
- Lepton+jets
- Fully hadronic

For single top measurements only W leptonic decays are used

ttbar topologies

Lepton + jets ≈ 34%

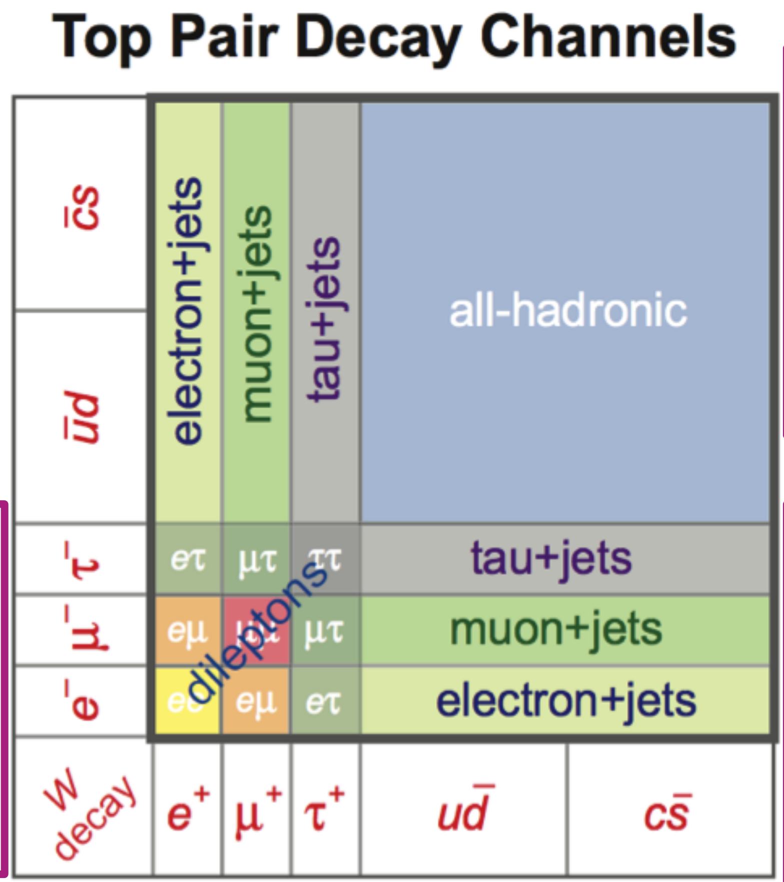
Low background

Main background:
W + jet

Dileptonic ≈ 6%

Very low background

main background:
Drell-Yan



Fully hadronic ≈ 46%

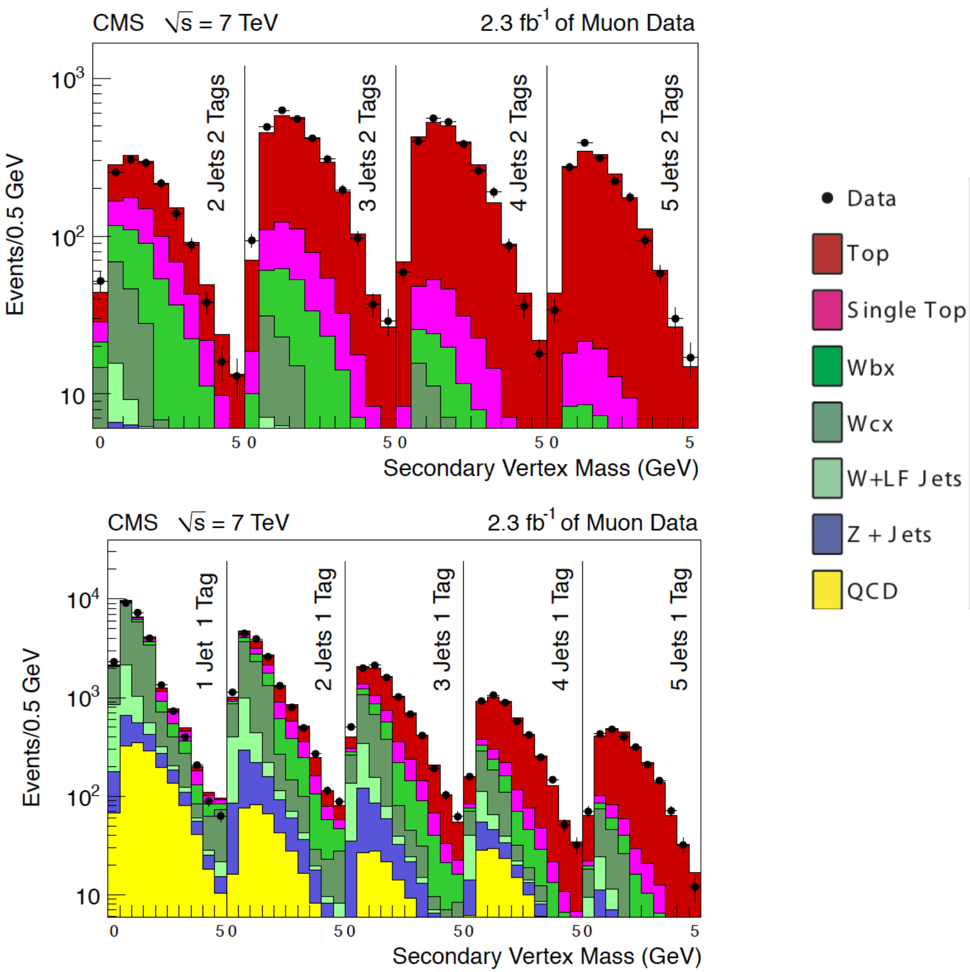
important background from QCD multijet events

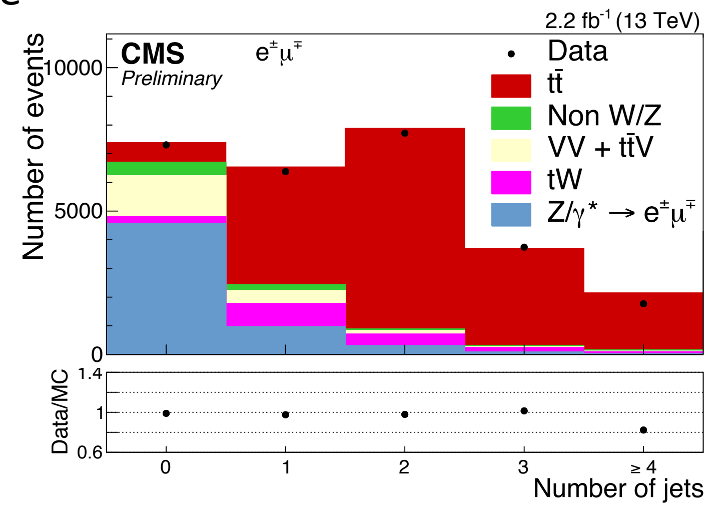
Tau channels ≈ 14%

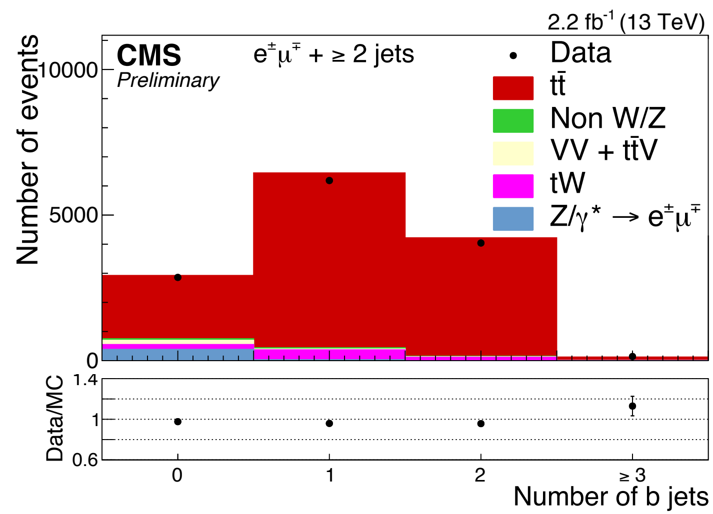
Important background from W + jet, QCD, other ttbar decays

Inclusive cross section from leptons+jets and dileptons (e, μ)

- Excellent background control thanks to jet categorization, b tagging and in situ measurement of jet-energy scale

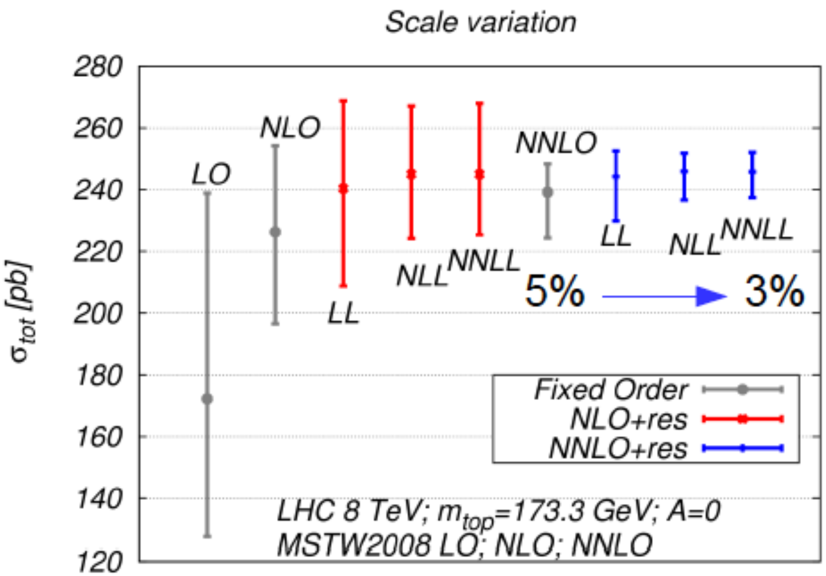


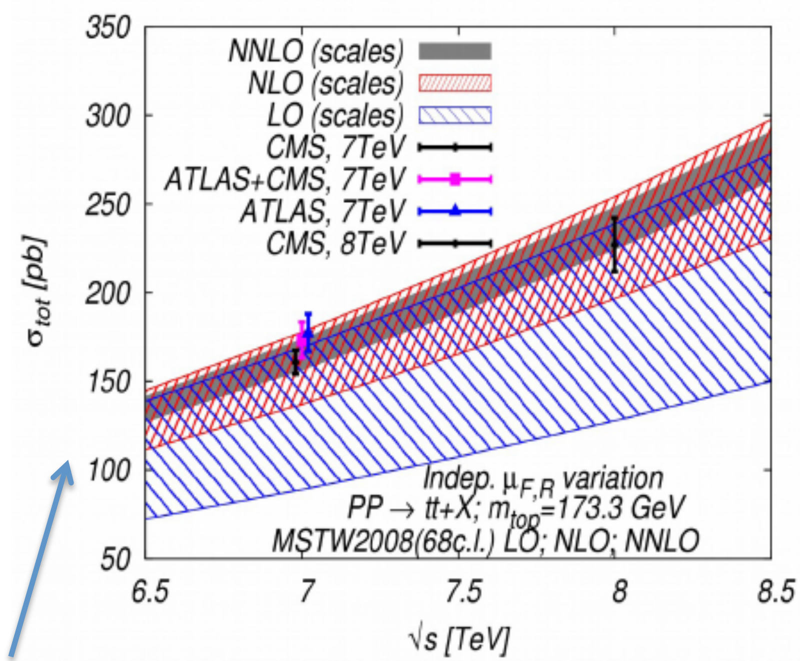




Inclusive cross section computed at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]



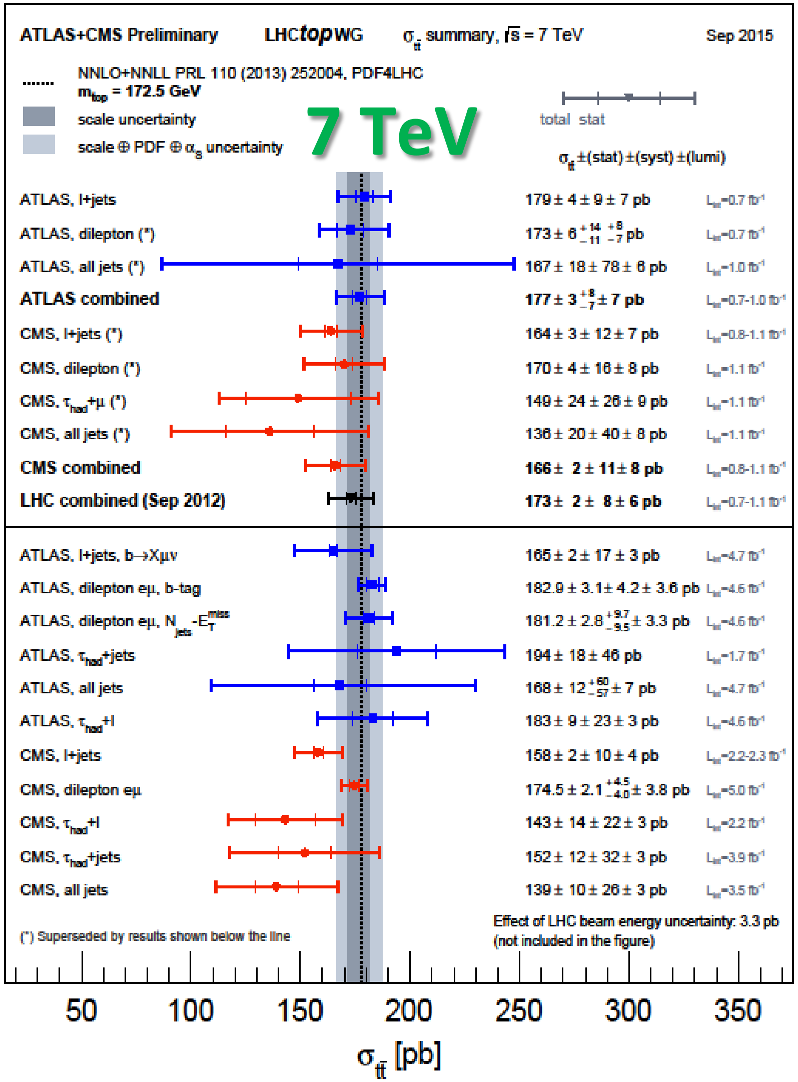


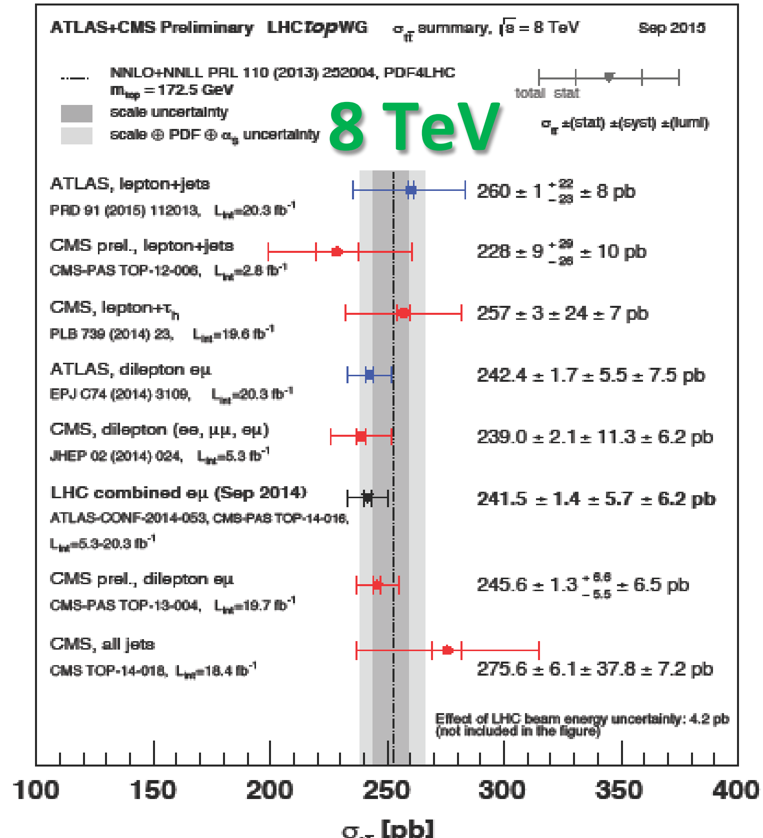
good perturbative convergence

- Uncertainties
  - Scales: ~ 3 %
  - PDF (68% cl): ~ 2 – 3 %
  - Top – mass: ~ 3 %
  - Coupling: ~ 1.5 %

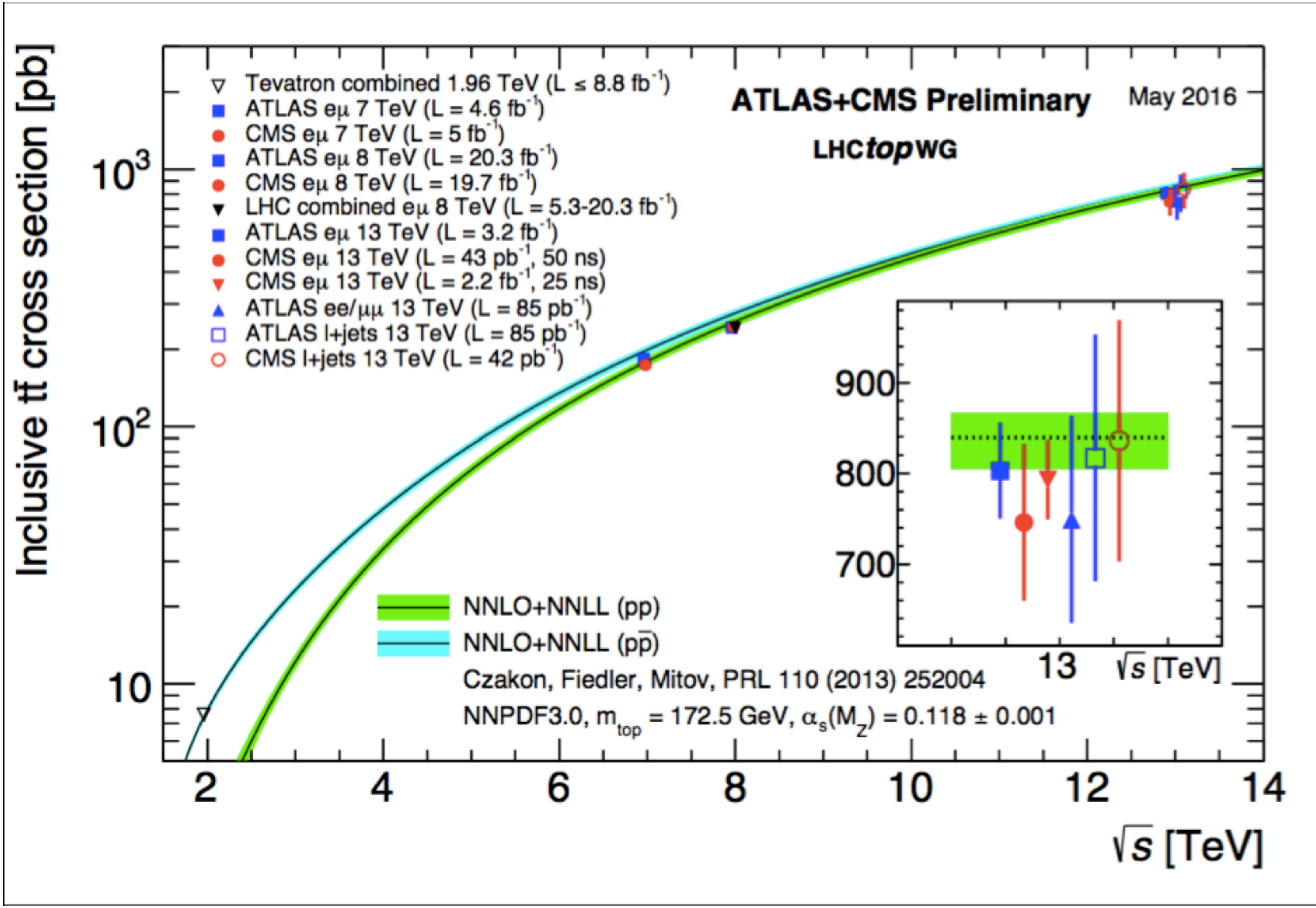
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

Inclusive top pair cross-sections



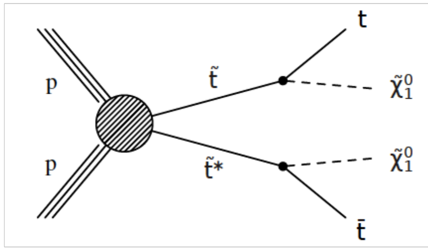


- All channels covered and consistent with SM
- Good agreement with NNLO+NNLL
- Precision of ~4% (di-lepton channel), similar to theoretical prediction



ATLAS+CMS Preliminary
May 2016
LHCtopWG
Tevatron combined 1.96 TeV (L ≤ 8.8 fb-1)
ATLAS eμ 7 TeV (L = 4.6 fb-1)
CMS eμ 7 TeV (L = 5 fb-1)
ATLAS eμ 8 TeV (L = 20.3 fb-1)
CMS eμ 8 TeV (L = 19.7 fb-1)
LHC combined eμ 8 TeV (L = 5.3-20.3 fb-1)
ATLAS eμ 13 TeV (L = 3.2 fb-1)
CMS eμ 13 TeV (L = 43 pb-1, 50 ns)
CMS eμ 13 TeV (L = 2.2 fb-1, 25 ns)
ATLAS ee/μμ 13 TeV (L = 85 pb-1)
ATLAS l+jets 13 TeV (L = 85 pb-1)
CMS l+jets 13 TeV (L = 42 pb-1)
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_top = 172.5 GeV, α_s(M_Z) = 0.118 ± 0.001
Inclusive tt̄ cross section [pb]
√s [TeV]

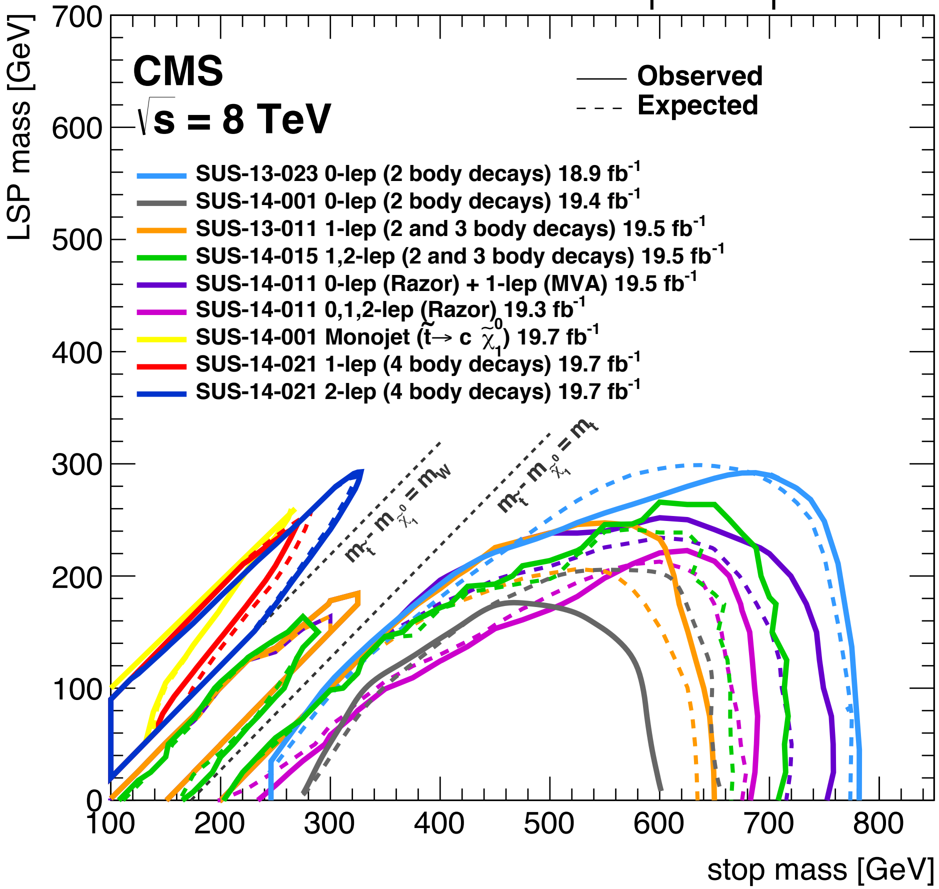
Inclusive ttbar cross section and bounds on stop



$m(\tilde{t}) \approx m(\tilde{\chi}_1^0) + m_t \rightarrow \sigma_{t\bar{t}}$ (and ttbar spin correlations)

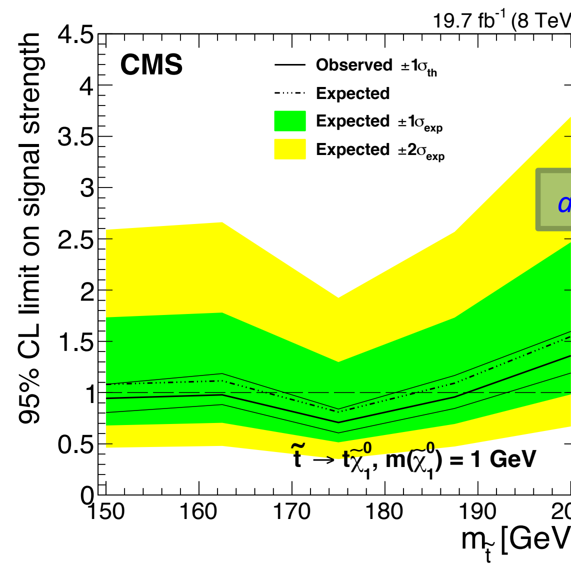
more sensitive than standard SUSY searches for low $m(\tilde{\chi}_1^0)$ and $m(\tilde{t}) \approx m_t$

$\tilde{t}$-$\tilde{t}$ production, $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$ / $c\,\tilde{\chi}_1^0$



Simplified model with two parameters:

$$m(\tilde{t}), m(\tilde{\chi}_1^0)$$



arXiv:1603.02303

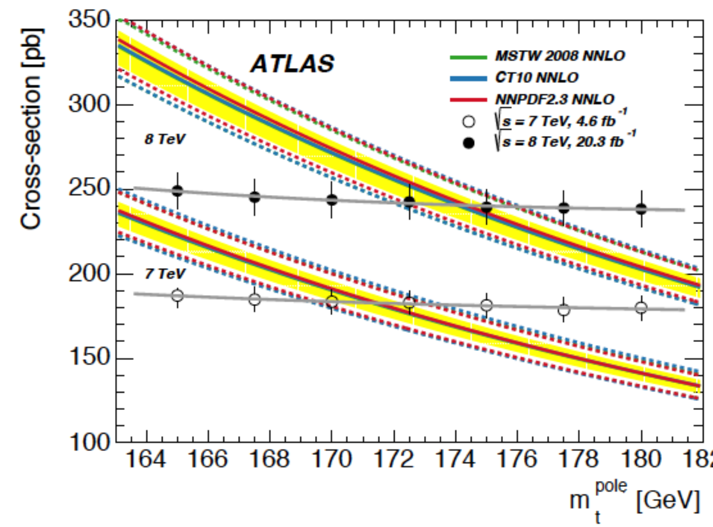
$$m(\tilde{t}; \tilde{\chi}_1^0 = 1\ GeV) > 189\ GeV$$

$$m(\tilde{t}; \tilde{\chi}_1^0) \notin 185-189\ GeV$$

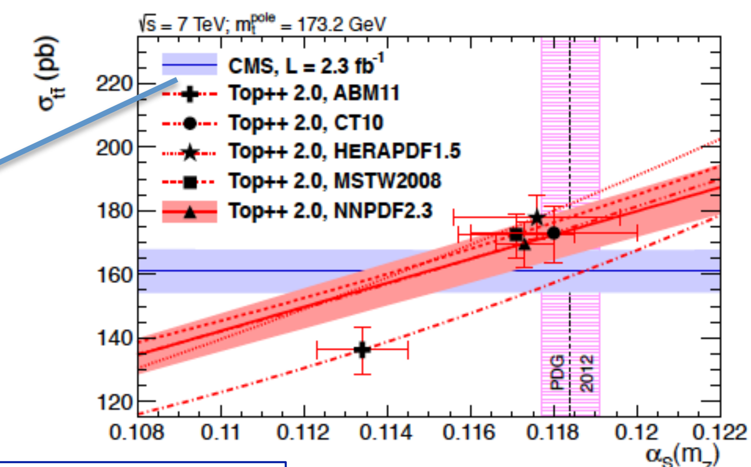
use ttbar cross section for top mass and α_s

[arXiv:1307.1908, arXiv:1406.5375]

- Measure cross section in the most precise channel: dilepton eμ
- Use recent NNLO calculation (*) of top pair cross section to extract m_t
- Provides also a measurement of α_s
- The method takes advantage of the excellent luminosity knowledge at LHC (~2%), which is also the long-term experimental limitation, together with the knowledge of the LHC beam energy

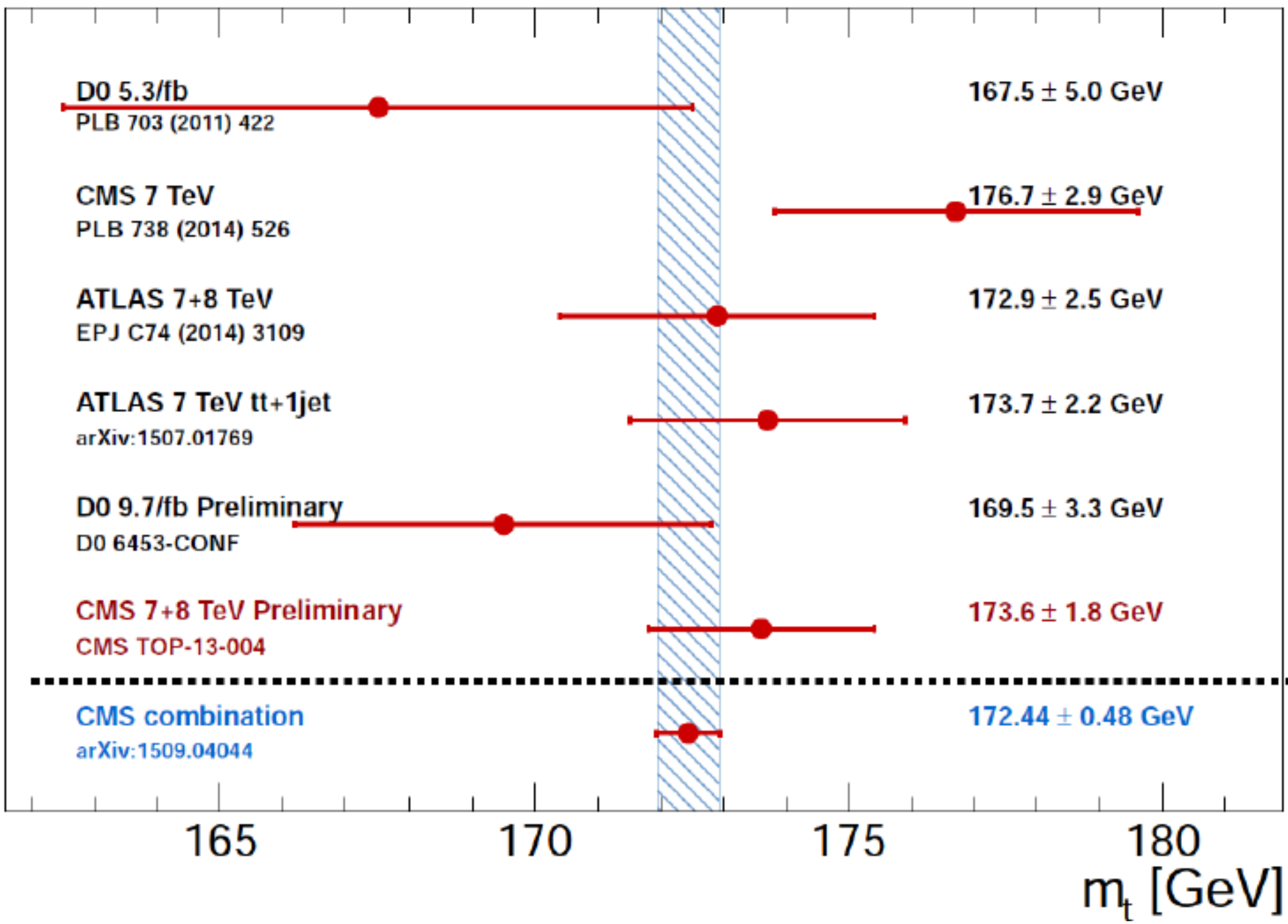


$$m_t = 176.7^{+3.0}_{-2.8}\ \text{GeV}$$
$$\alpha_s = 0.1151^{+0.0028}_{-0.0027}$$

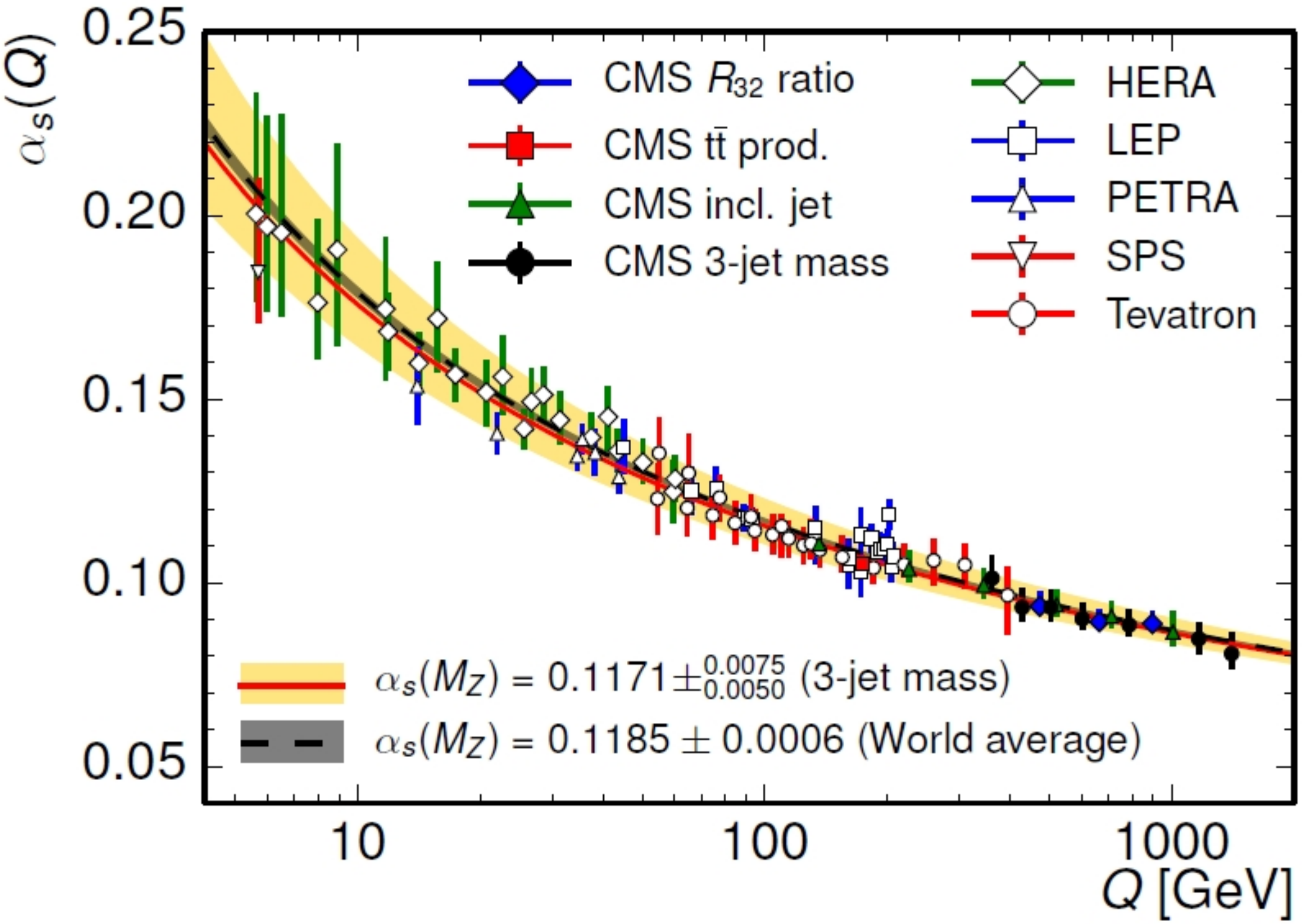


(*) Czakon, Fiedler, Mitov, (2013) arxiv:1303.6254, PRL 110.252004

Top mass extraction from cross section measurements

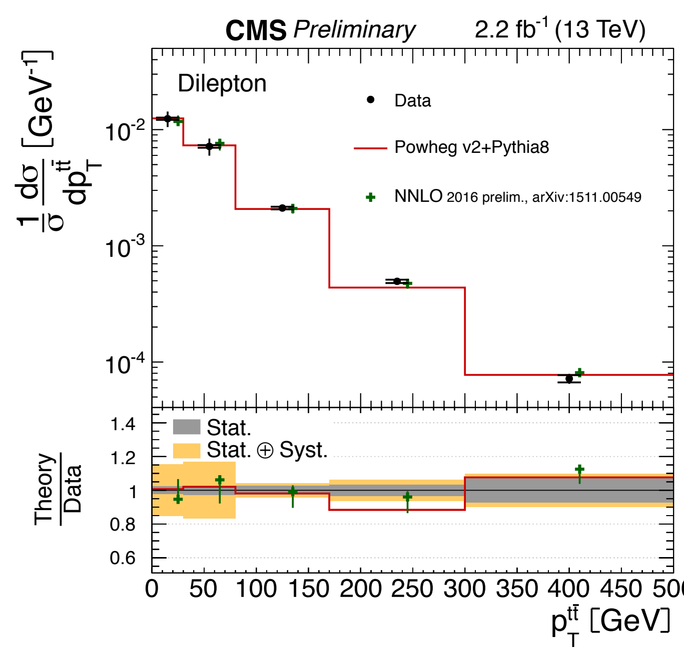


Running of α_s
- a very precise point from ttbar -

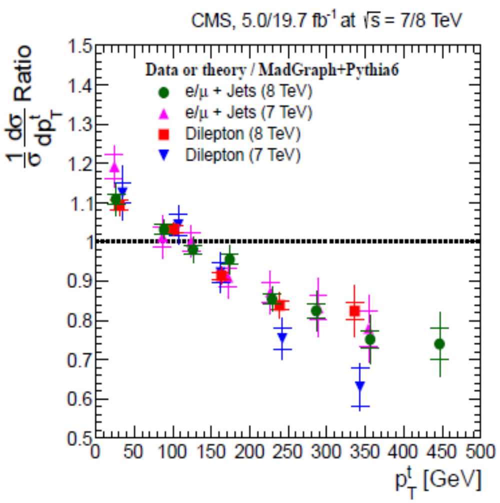


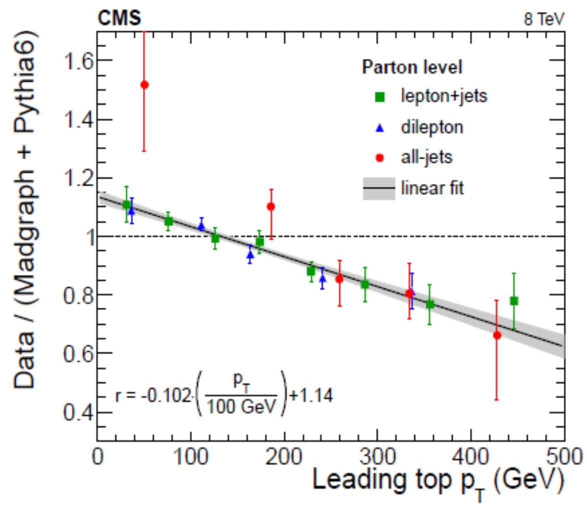
Differential cross sections

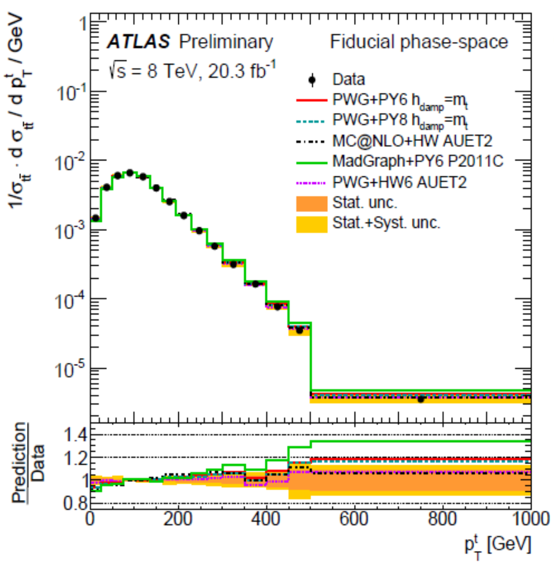
- Important measurements, they will play an important role for
  - i) investigate limitations of present MC (which QCD predictions and models describe our data best, in the search areas like high m(tt) and high multiplicities)
  - ii) provide independent interpretations (e.g. mass AND alpha_s from cross section)
  - Iii) sensitivity to high-x gluon (y(tt))

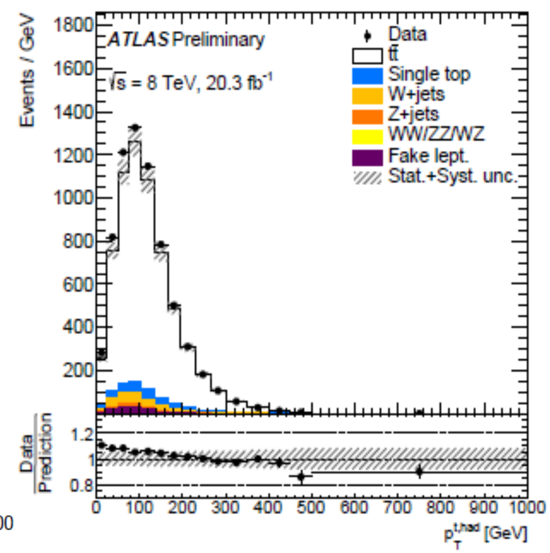


top p_T differential distribution

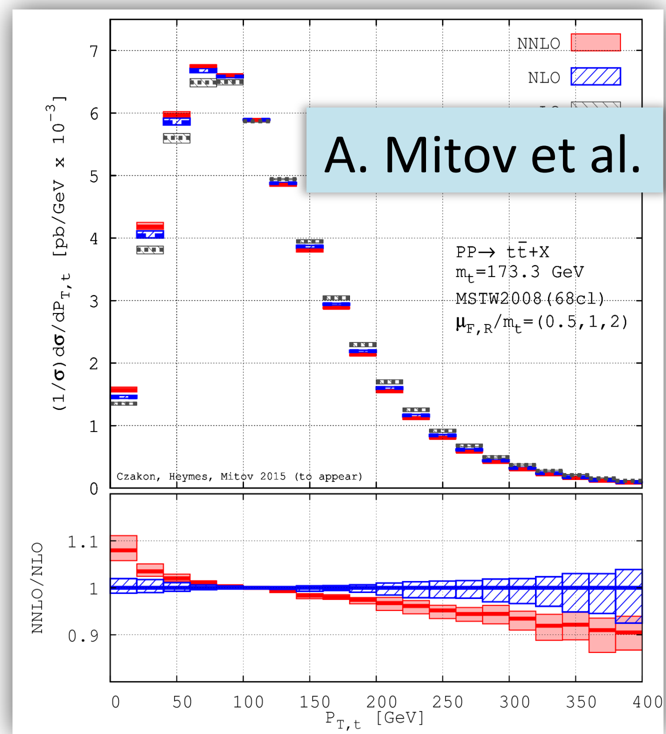








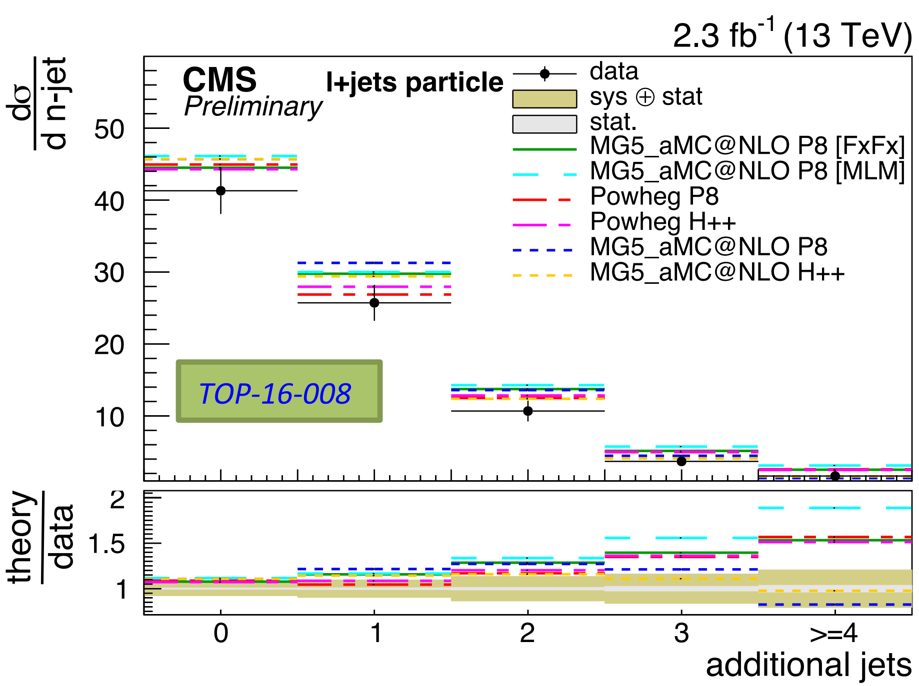
- full NNLO calculation seem confirm observed slope, in direction closer to the data

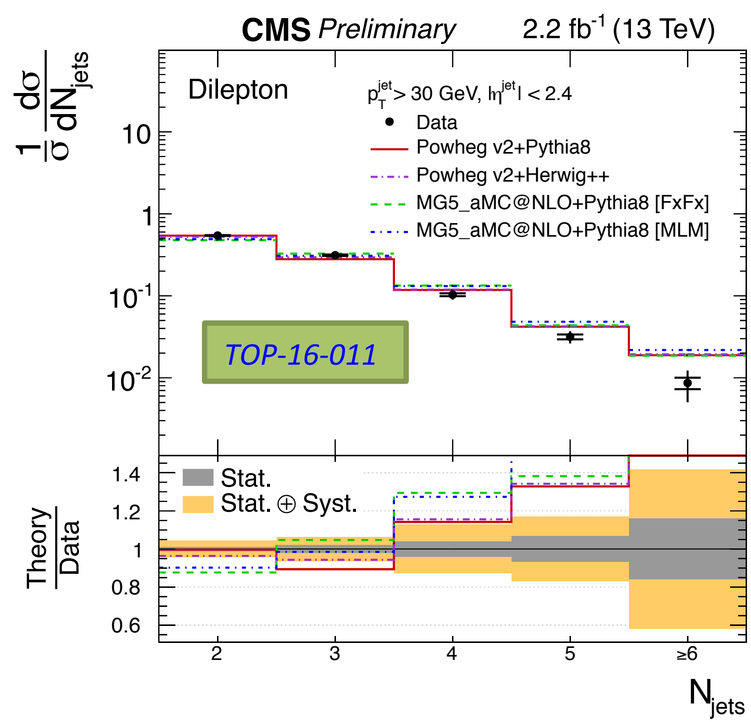


A. Mitov et al.

Jet Multiplicity at √s = 13 TeV

- Low jet multiplicities → Sensitive to Matrix element and matching to parton shower.
- High jet multiplicities → parton shower
- tt+jets important background to ttH.



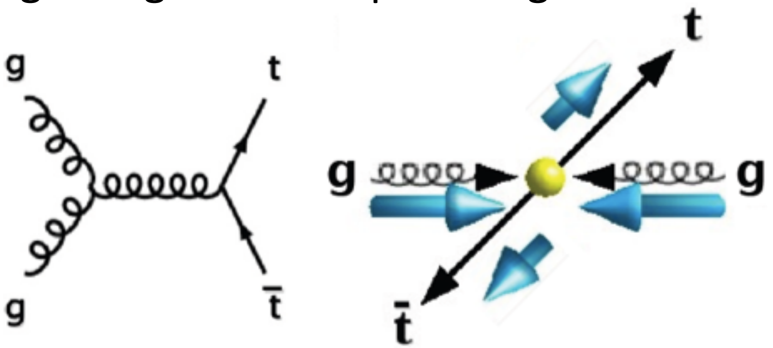


- New ME generator + PS codes in Run II
- Predictions overshoot the data for jet large multiplicities when out of the box parameters are used

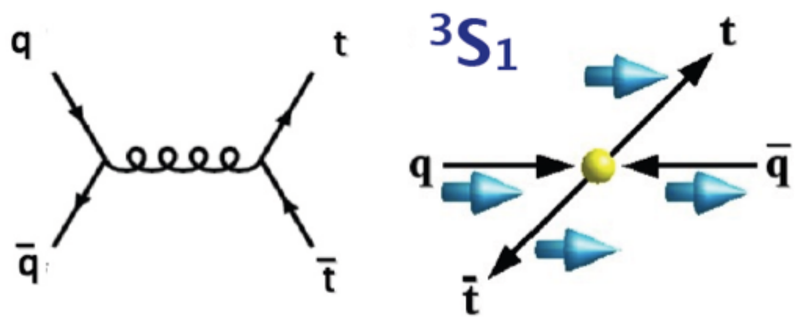
Spin correlations in ttbar

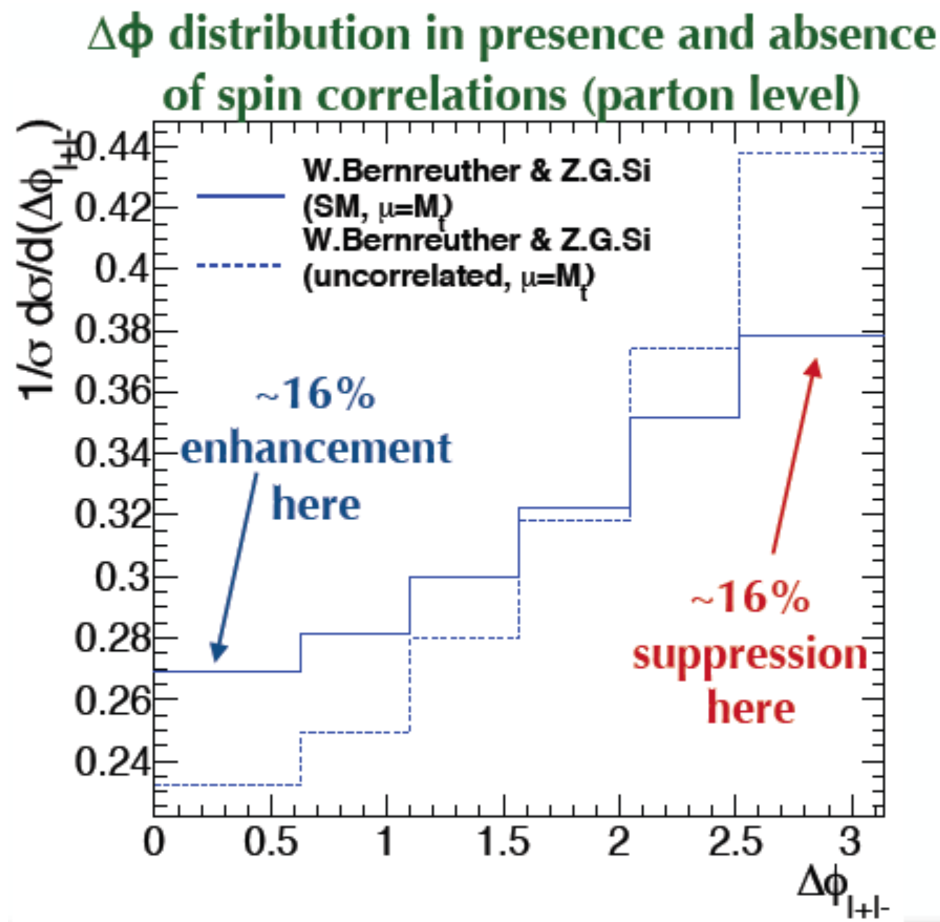
Another tool to investigate the production mechanism, possible only for the top quark
Investigating it now, but will become a precision tool with high statistics

gluon-gluon example at high boost



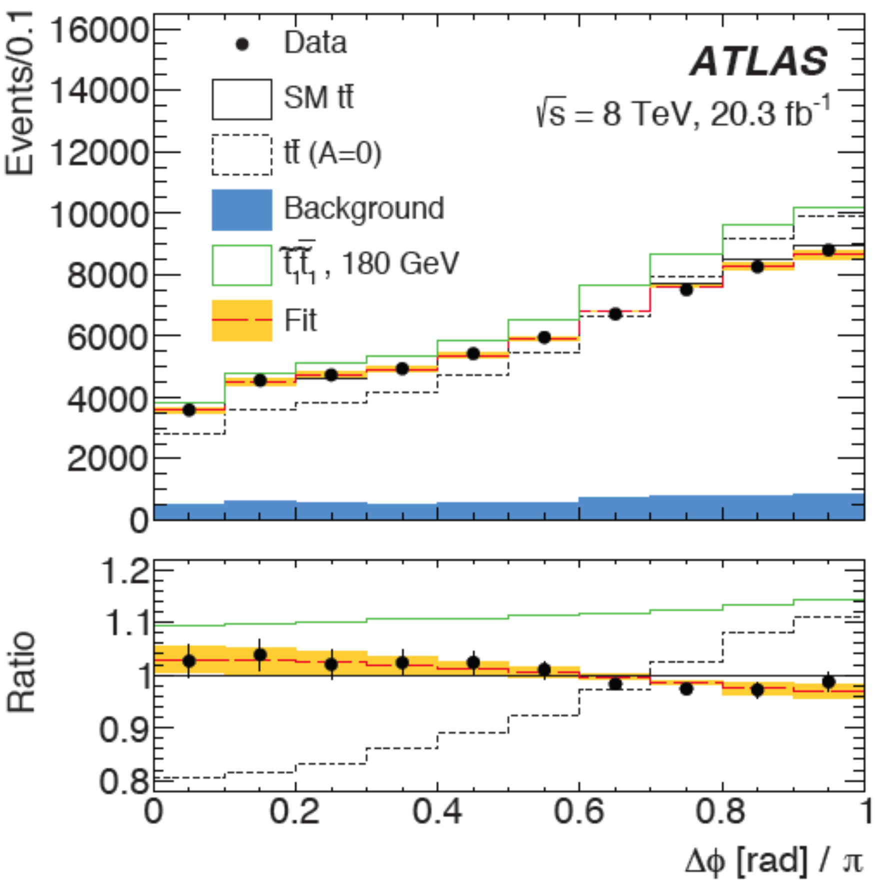
qqbar example at threshold

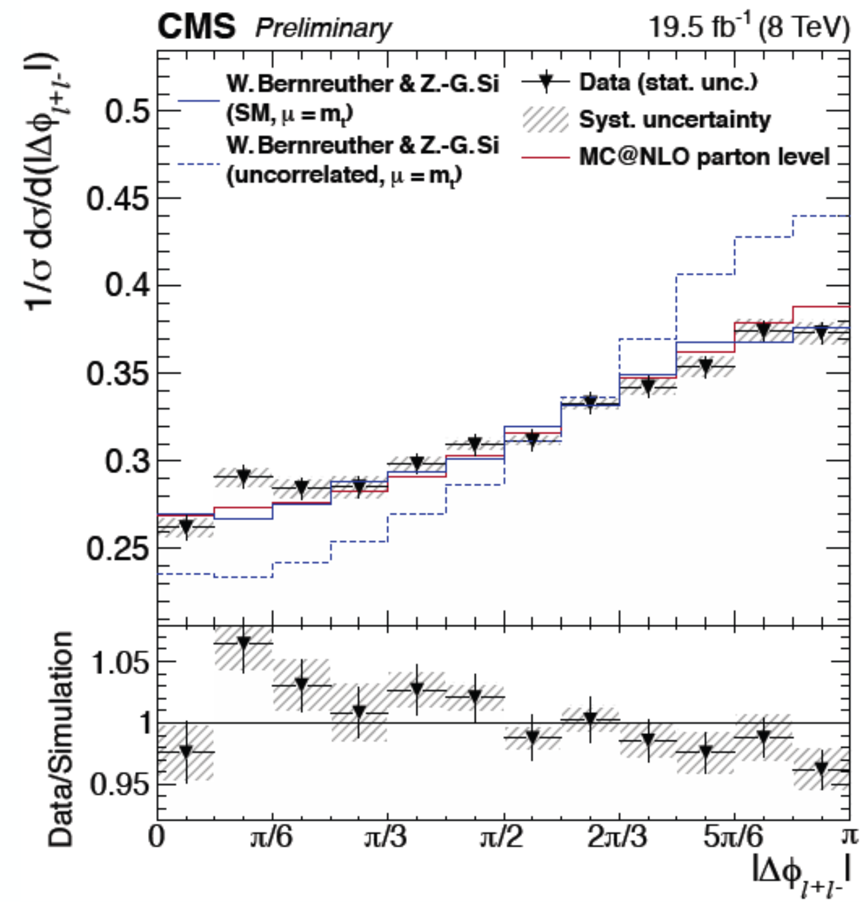




Δφ results from ATLAS and CMS

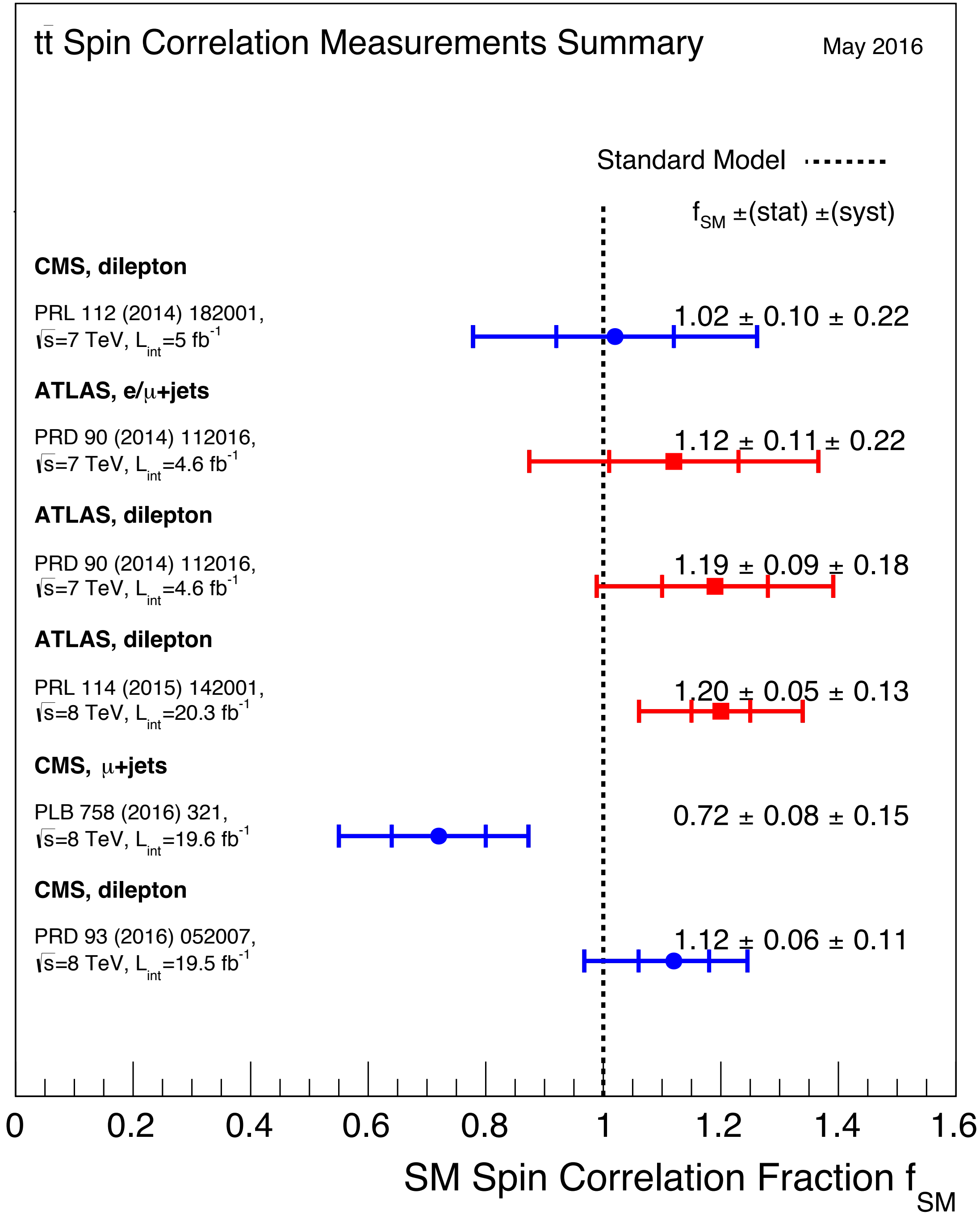
[PRL 114, 142001 (2015)](#) [CMS TOP-14-023](#)





can extract limits to chromomagnetic dipole moments or to probe SUSY (stop)

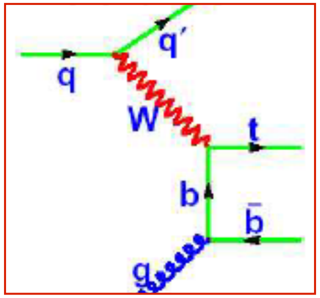
$-0.050 < \mathrm{Re}(\hat{\mu}_t) < 0.076$ **(95% CL)** [(CMS TOP-14-023)](#)

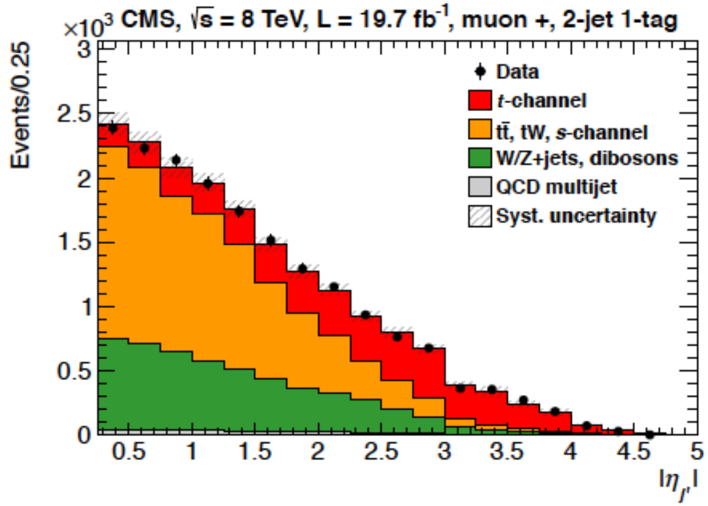


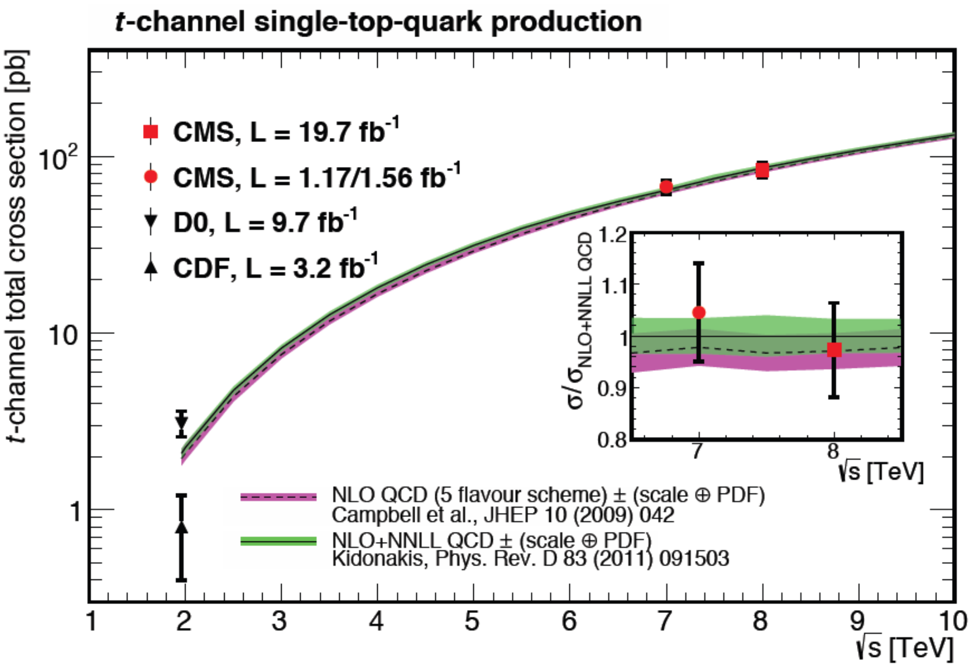
$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$

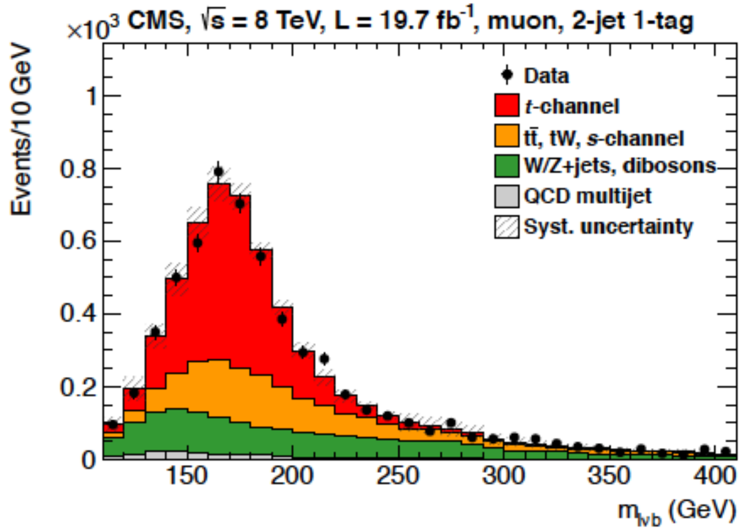
SINGLE TOP

Single top t-channel



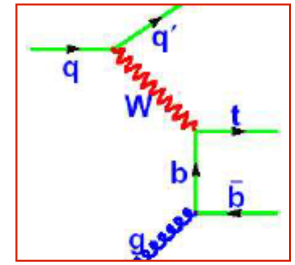


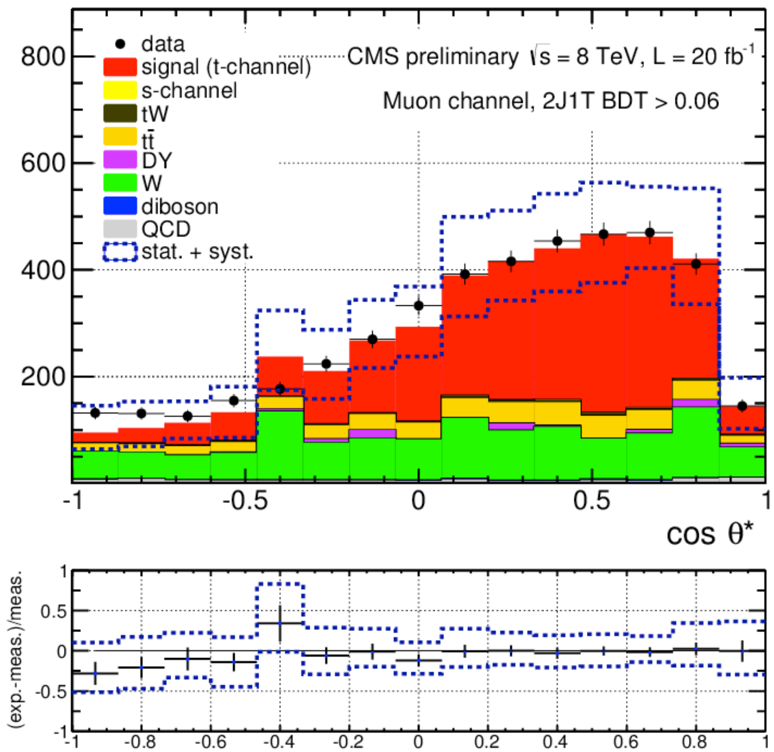


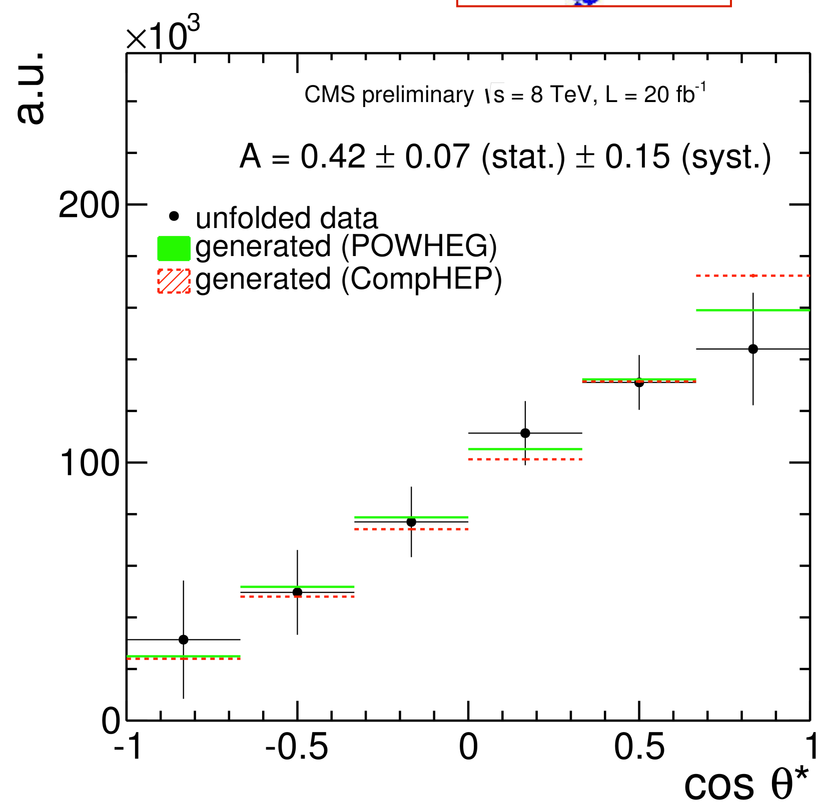


single top polarization in t-channel

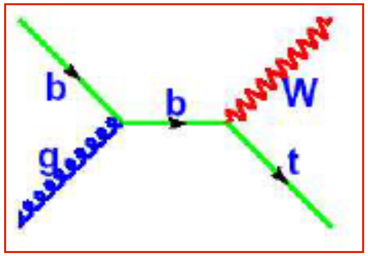
- V-A current, top 100% polarized !



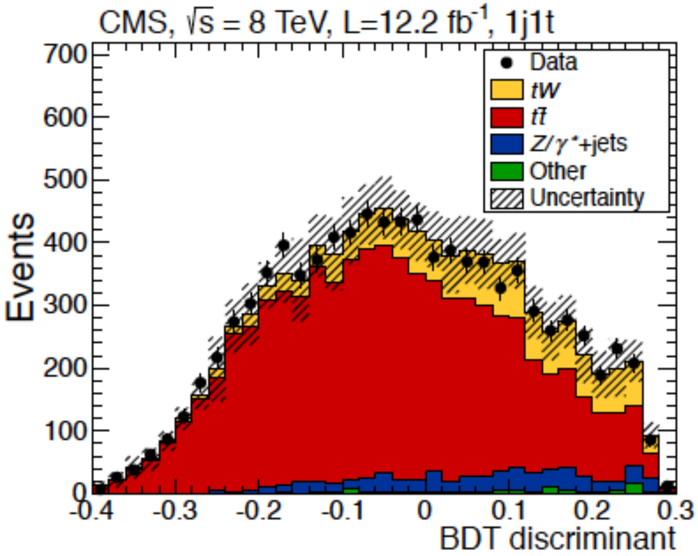


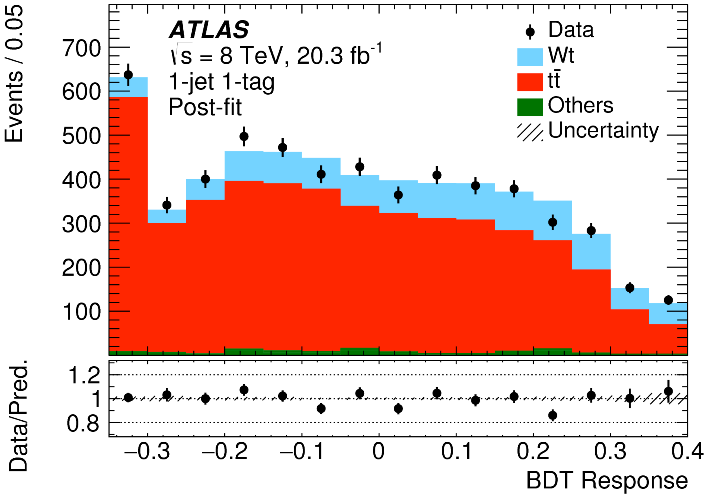


single top tW channel

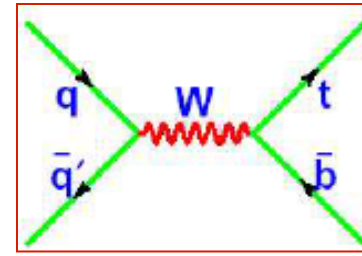


- Final state similar to top pair production
    - just miss one b in 5 flavour scheme
- At higher order interference with top pair
    - requires operative definition of cross section
- Experimentally not easy to separate from top pairs





Single top s-channel



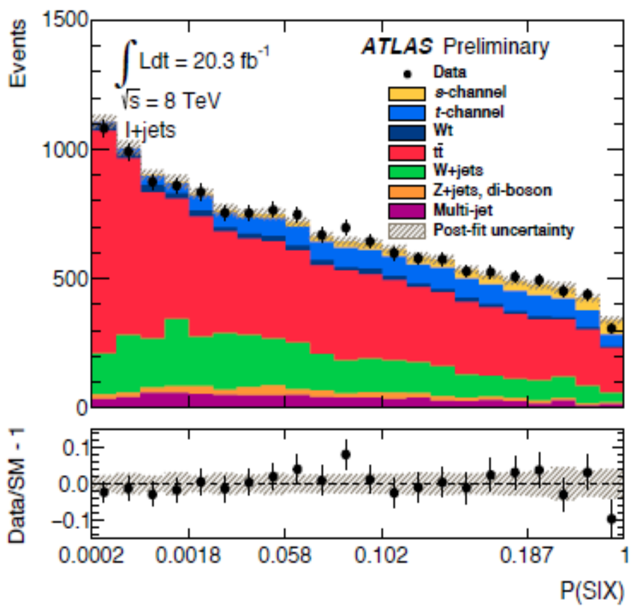
$\sigma_s = 4.8 \pm 1.1\,(\text{stat.})^{+2.2}_{-2.0}\,(\text{syst.})\text{pb}$

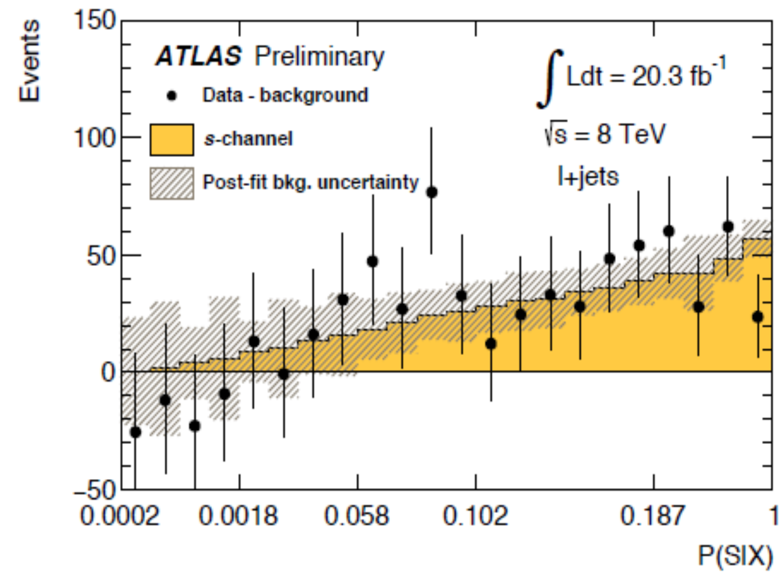
Significance: 3.2σ (exp. 3.9σ)

→ Consistent with SM expectation:
$\sigma^{theory}_{s-ch.} = 5.61 \pm 0.22$ pb

Uses the Matrix Element method to squeeze out optimal sensitivity…

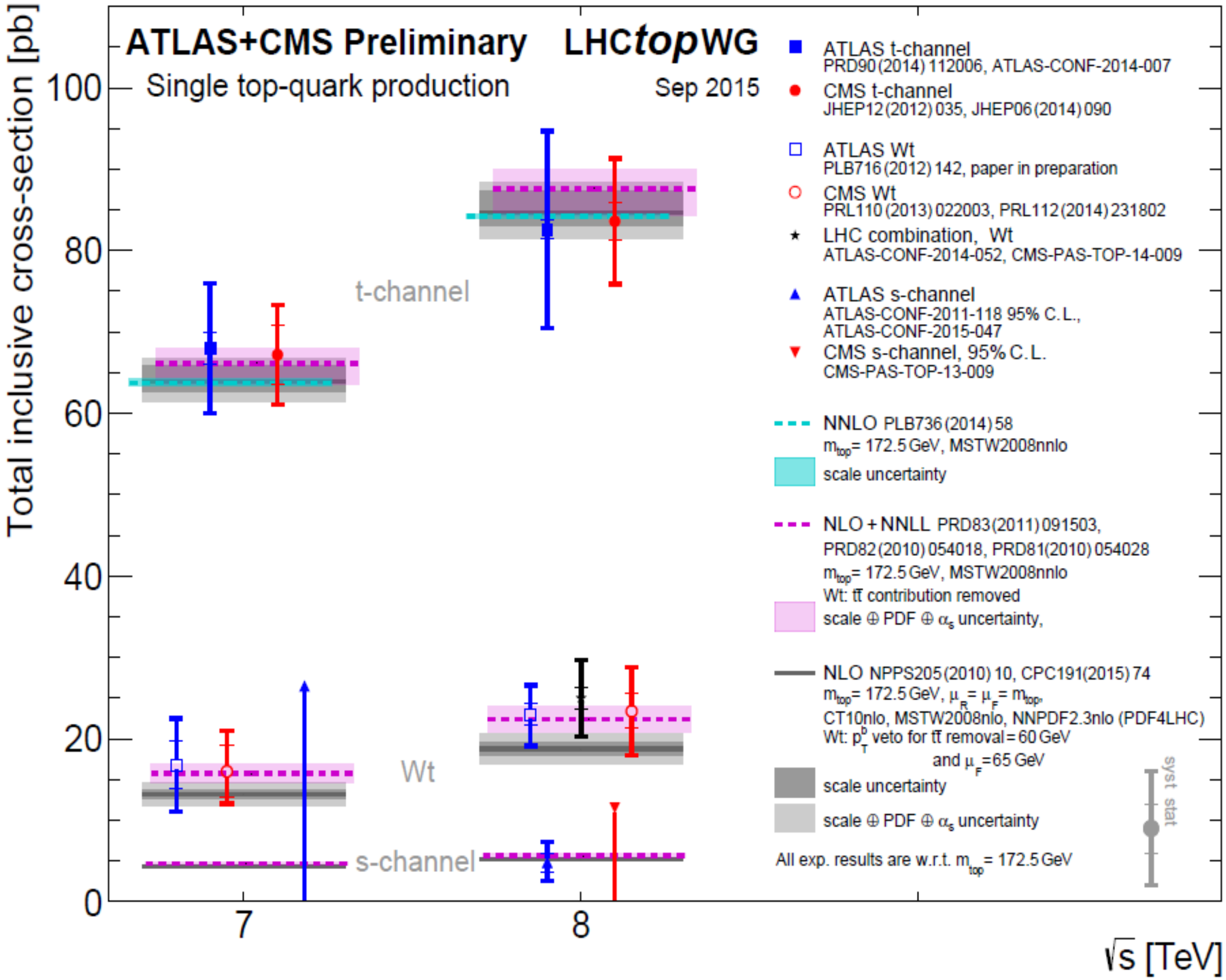
2-jet 2-tag (~ 4.3% of *s*-channel)



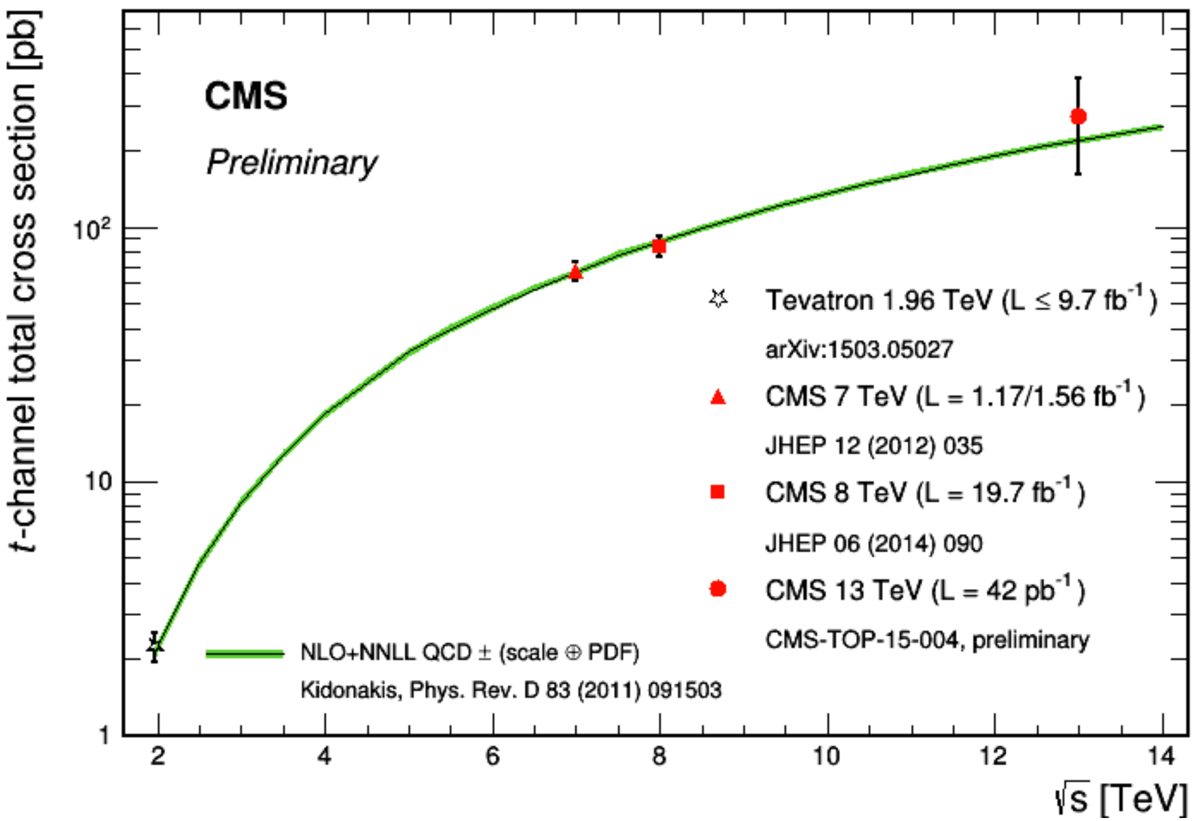


First EVIDENCE
of the *s*-channel production at LHC

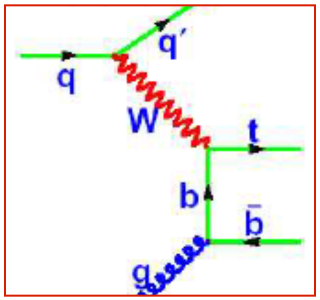
Single Top: the complete picture

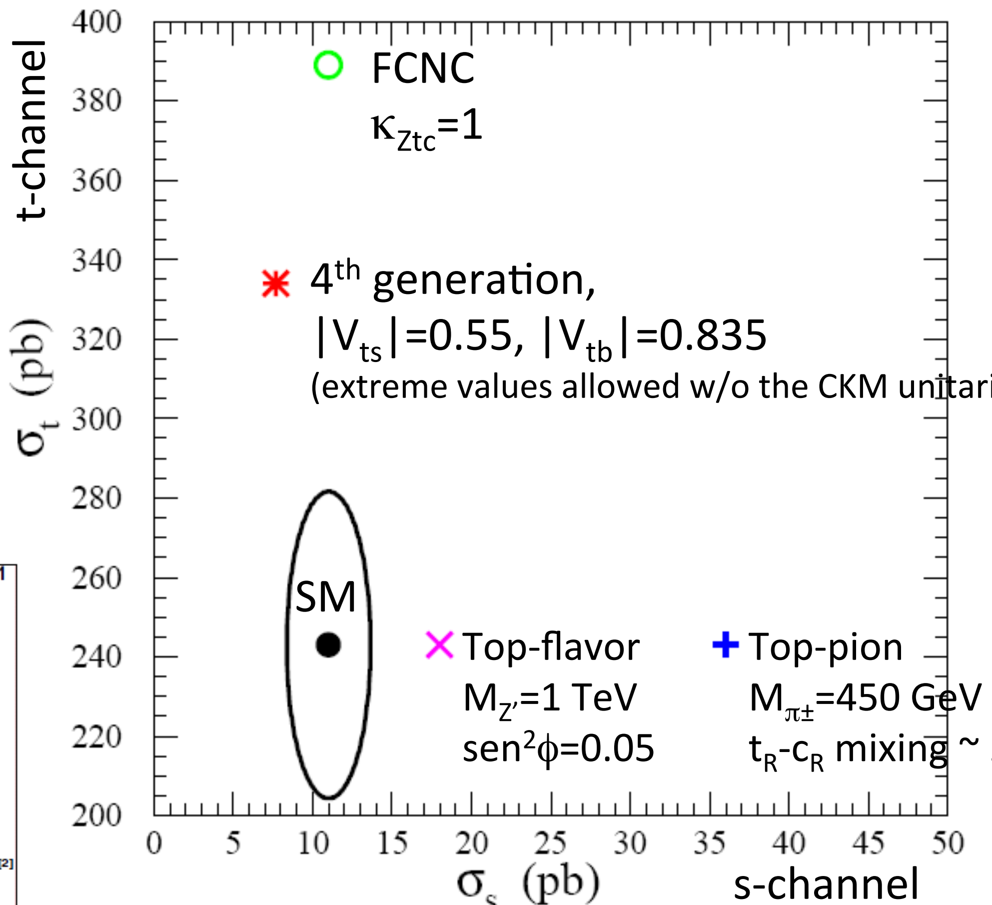


single top cross section vs sqrt(s)

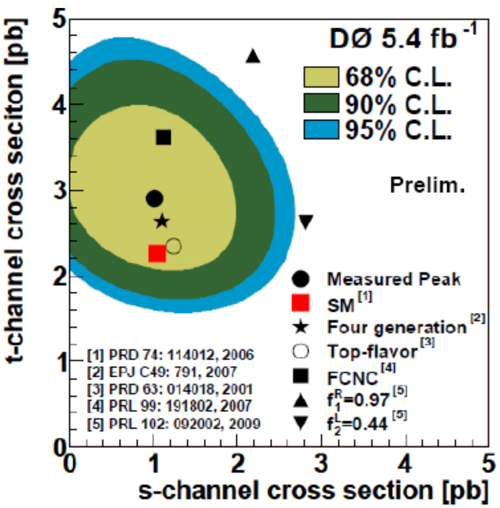


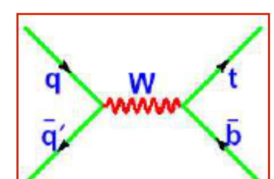
Single top in t and s channel sensitive to different aspects of New Physics (tW, too !)





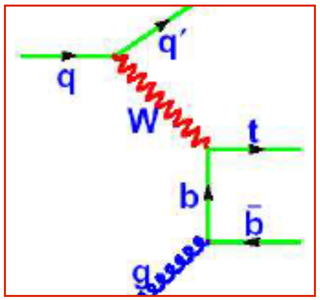
(plot for 14 TeV)

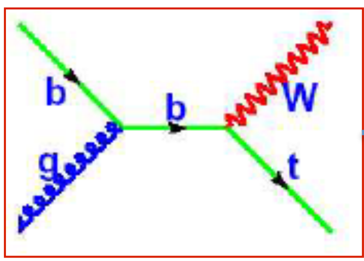


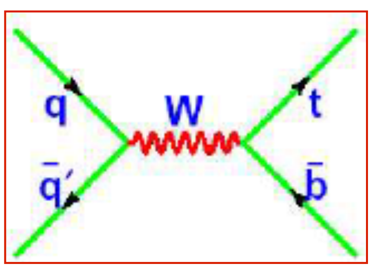


T.Tait, C.-P.Yuan, Phys.Rev. D63 (2001) 0140018

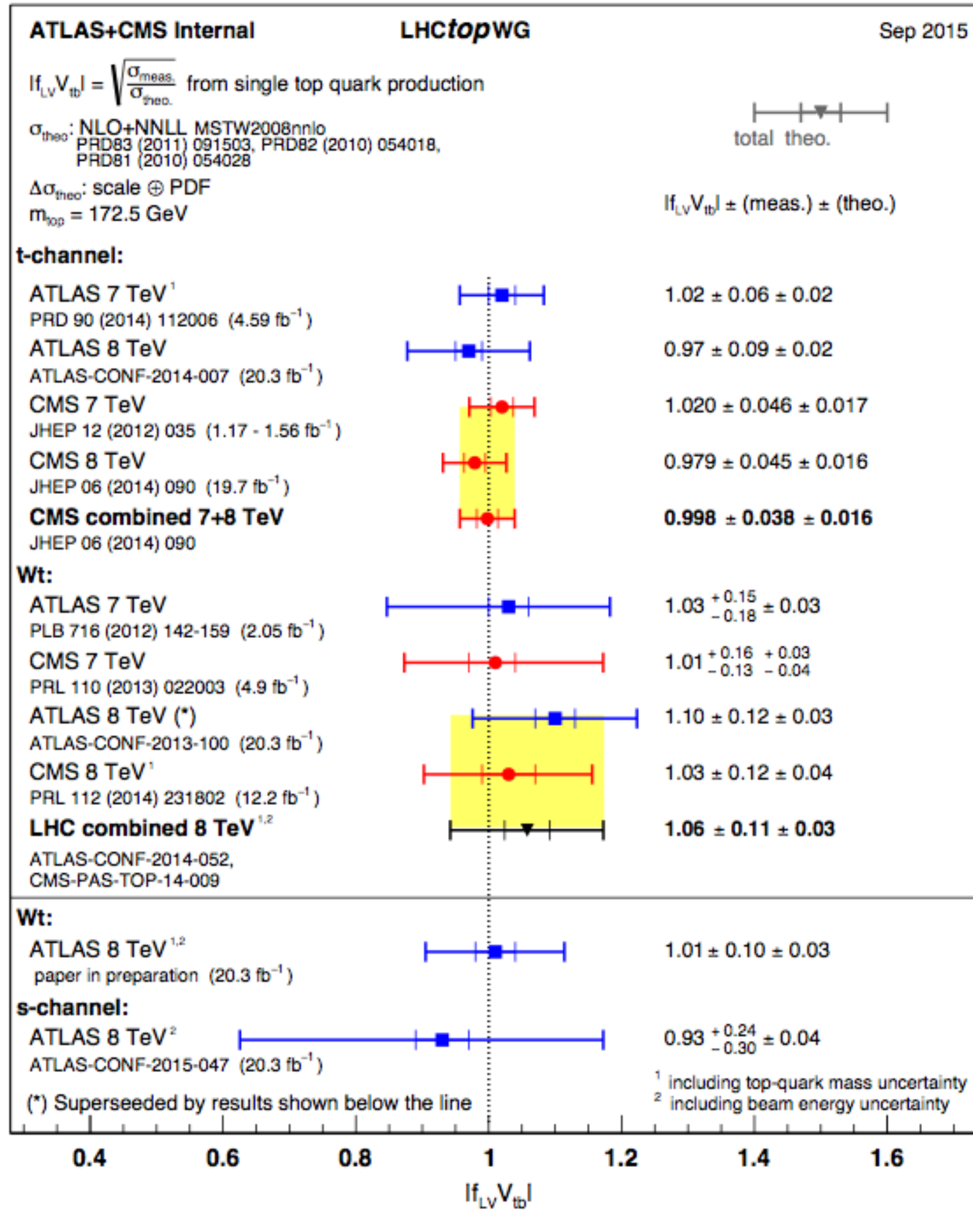
Single top and $|V_{tb}|$





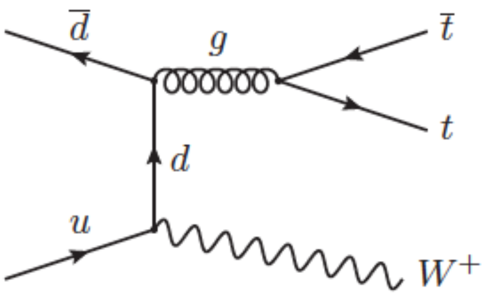


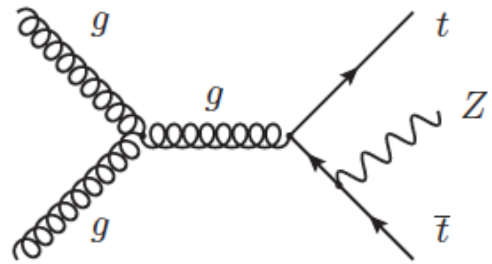
$$\sigma \propto |V_{tb}|^2$$



ASSOCIATED PRODUCTION OF TOP AND BOSONS (AND MORE ...)

Associated production of top pair and **vector** boson





CMS TOP-14-021

ATLAS arXiv:1509.05276

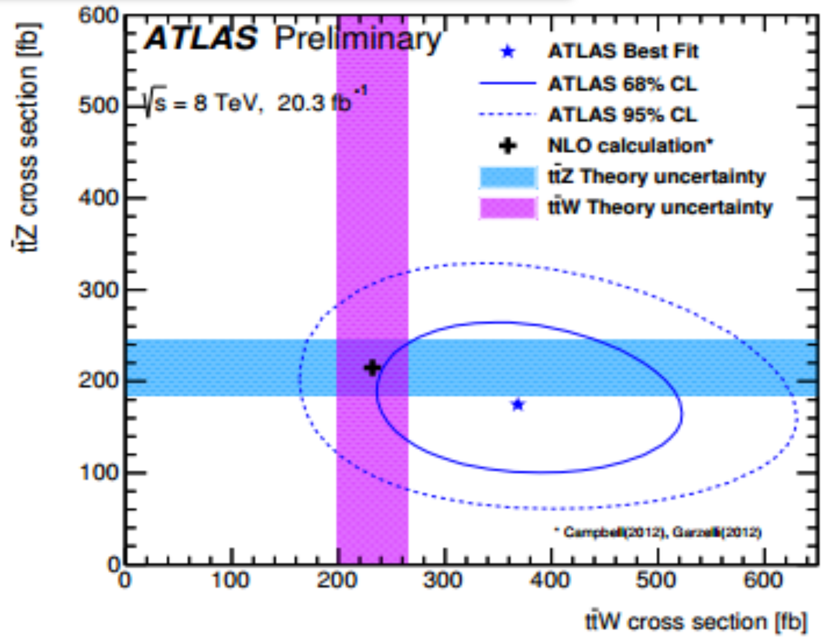
- The ttZ process provides direct access to Z-top couplings
- Both ttW and ttZ processes can be altered by BSM physics
- Measured **ttW** and **ttZ** cross sections with 19.5 fb^{-1} of data collected at 8 TeV
- Measurement performed in multilepton (e or μ) final states
  - **ttZ measured in channels with two, three, or four leptons, with exactly one pair of same-flavor opposite-sign (OS) leptons close to the Z mass**.
  - **ttW measured in in channels with two same-sign (SS) leptons or three leptons, where no lepton pair is consistent with coming from a Z boson decay.**
  - **full or partial reconstruction of the ttW or ttZ system with a linear discriminant that matches leptons and jets to their parent particles using mass, charge, and b tagging information.**

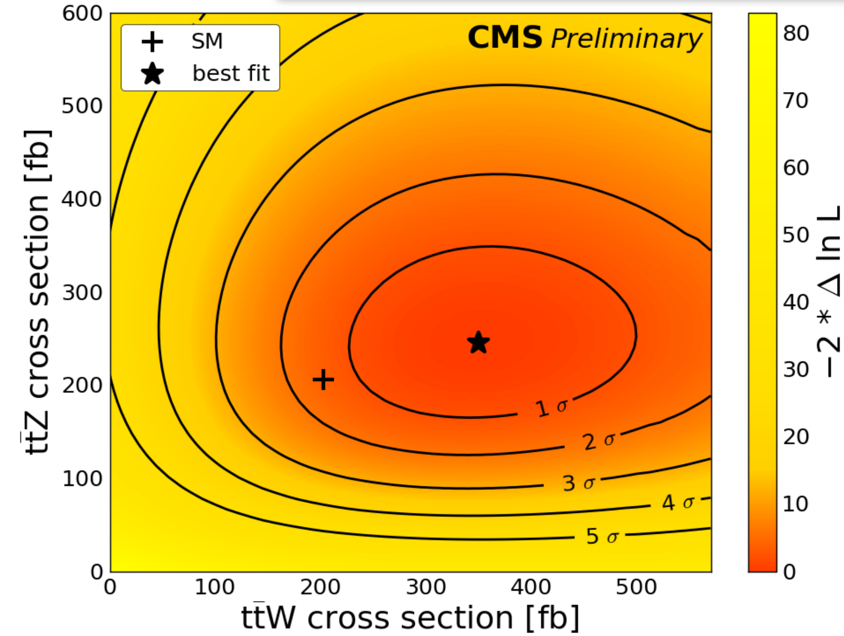
ttV: Observation !

ttW: 3.2 σ (exp) 5.0 σ (obs)
ttZ: 4.5 σ (exp) 4.2 σ (obs)

TOP 2015

ttW: 3.8 σ (exp) 4.8 σ (obs)
ttZ: 5.7 σ (exp) 6.4 σ (obs)



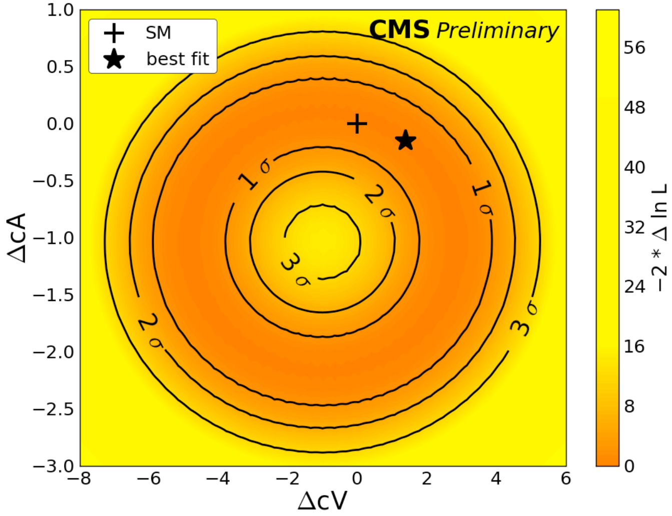


arXiv:1509.05276

+ limits on 6D EFT operators

CMS TOP-14-021

ttZ couplings



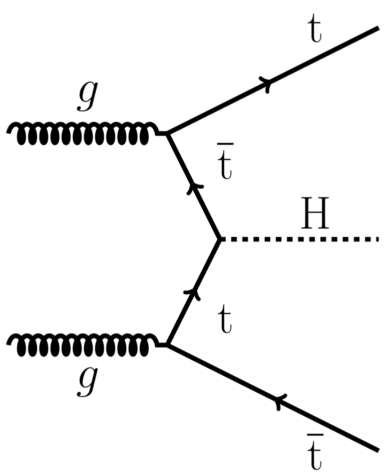
Constraints on vector and axial couplings

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{1}{\Lambda^2}\mathcal{L}_2 + \cdots$$
$$= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i (c_i \mathcal{O}_i + \text{h.c.}) + \frac{1}{\Lambda^2}\sum_i (c_i \mathcal{O}_i + \text{h.c.}) + \cdots$$

Constraints on dimension-6 operators

operator	best fit point(s)	1σ CL	2σ CL
$\bar{c}_{uB}$	-0.07 and 0.07	{-0.11, 0.11}	{-0.14, 0.14}
$\bar{c}'_{HQ}$	0.12	{-0.07, 0.18}	{-0.33, -0.24} and {-0.02, 0.23}
$\bar{c}_{HQ}$	-0.09 and 0.41	{-0.22, 0.08} and {0.24, 0.54}	{-0.31, 0.63}
$\bar{c}_{Hu}$	-0.47 and 0.13	{-0.60, -0.23} and {-0.11, 0.26}	{-0.71, 0.37}
$\bar{c}_{3W}$	-0.28 and 0.28	{-0.36, -0.18} and {0.18, 0.36}	{-0.43, 0.43}

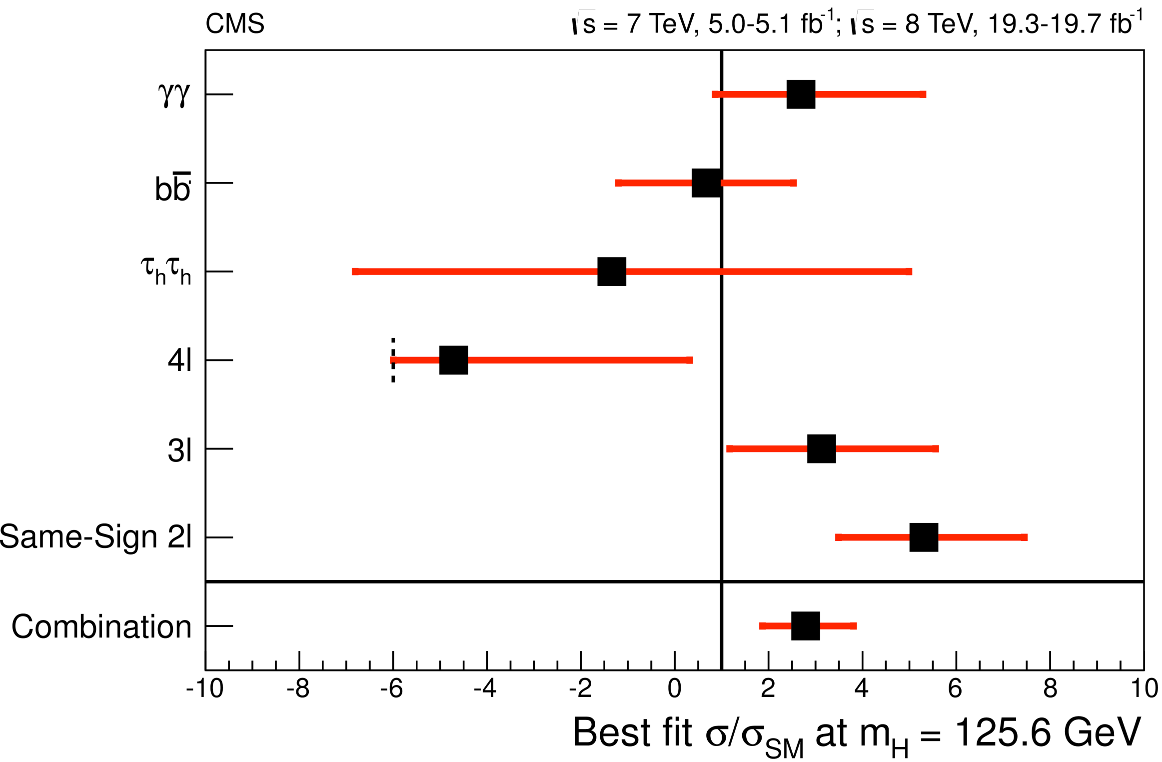
Associated production of top pair and **scalar** boson



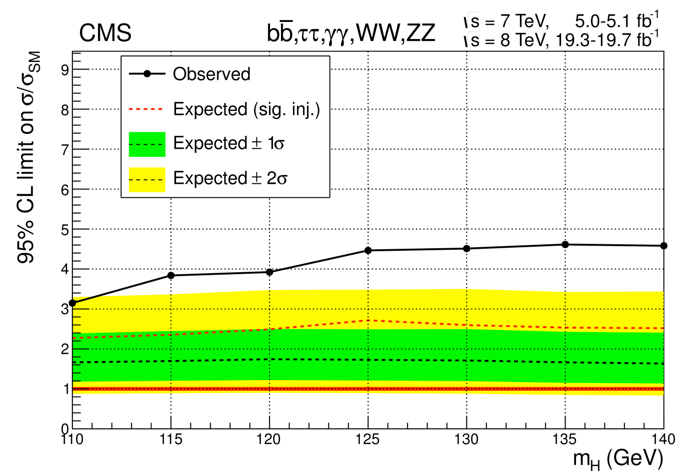
CMS HIG-14-021

- The ttH process gives direct access to the top-Higgs Yukawa coupling.
- The process can be altered by BSM physics
- Searched with 5.1 fb^{-1} at 7 TeV and 19.7 fb^{-1} of at 8 TeV
- Measurement performed in several final states
  - top pair all hadronic, lepton+jets, dilepton
  - with H→hadrons, H→ leptons, H→ γγ
  - categorization includes H→bb and H→ ττ

Results for ttH search



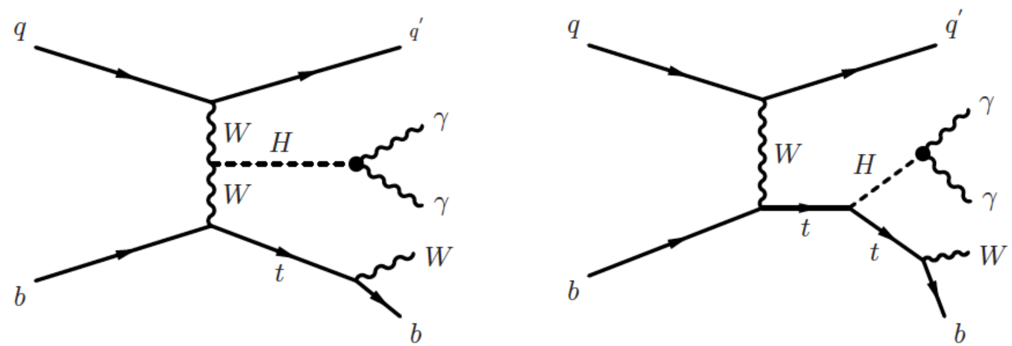
CMS HIG-14-021
JHEP 09 (2014) 087



μ=2.8±1.0 for an Higgs boson mass of 125.6 GeV

Associated production of single top and Higgs boson

CMS HIG-14-001

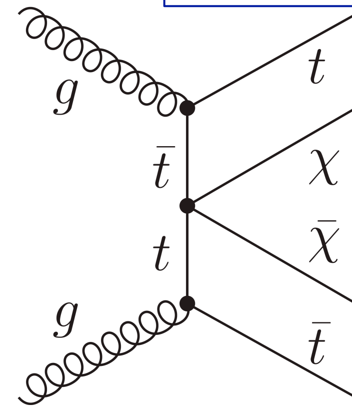


- Potentially gives the relative sign of the top-Higgs Yukawa coupling with respect to the Higgs-W coupling
- The two diagrams interfere destructively in the SM (σ=18 fb), but with flipped sign cross section increases by a factor 15
- Analysis performed in the H→γγ channel, zero events found, upper limit at 4.1 times the flipped sign case

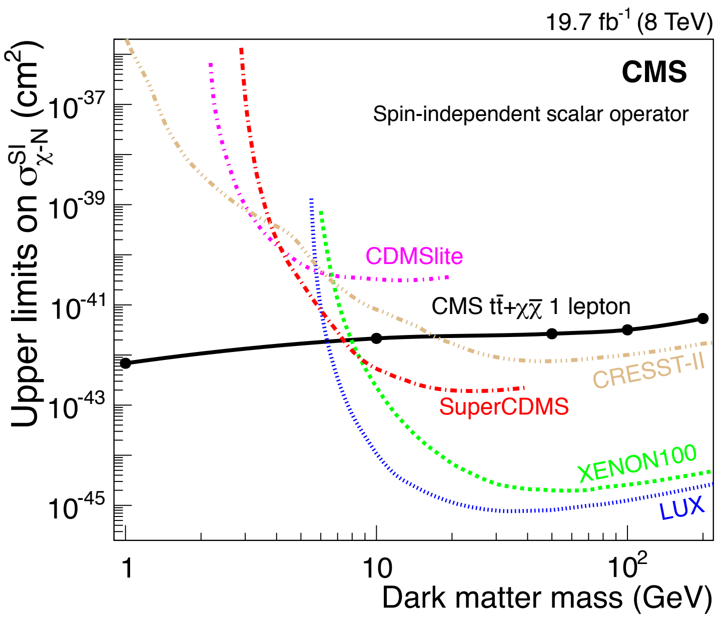
$$\mathrm{tHq} \to (\mathrm{t} \to \mathrm{b}\ell\nu)(\mathrm{H} \to \gamma\gamma)q \quad \text{with } \ell = \mathrm{e}, \mu$$

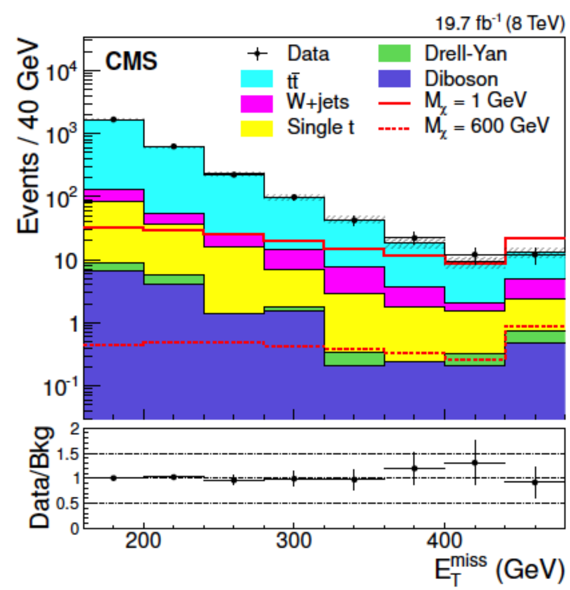
Search for Dark Matter produced in association with top pairs

JHEP 06 (2015) 221



- Dark matter could couple to heavy fermions through contact interactions
- Search requires the presence of one lepton, multiple jets, and large missing transverse energy.





Conclusions

- Charm and Bottom production measurements at LHC an important playground for QCD and MC tuning
  - Considerable improvements in understanding of quarkonium production
- Top production (in pair or singly) provides key information to many aspects (QCD, searches) and represents an important sector of electroweak-symmetry-breaking studies
  - A complement to direct Higgs measurements
- After first three years at 7, 8 TeV (Run 1) **LHC** now entered a new phase (Run 2) at higher c.m. energy, 13 TeV, and at design luminosity (recently surpassed **$10^{34}cm^{-2}s^{-1}$**)

- **Entering uncharted territory in terms of (statistical) precision: will use statistics as a tool to reduce systematic uncertainties**