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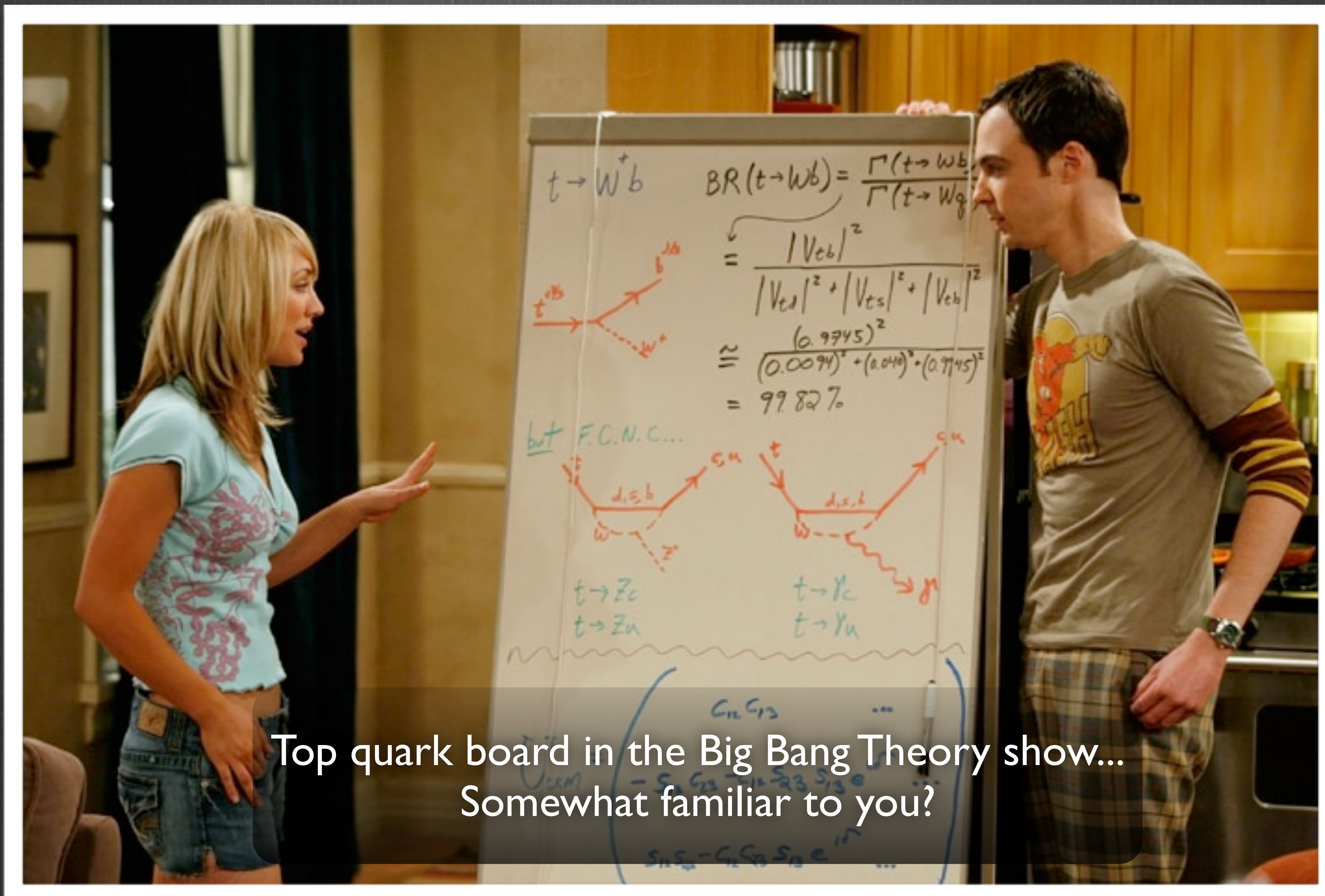
SPECIAL TOPICS IN EXPERIMENTAL PARTICLE PHYSICS

Lecture 5: The quark on the Top

THE TOP QUARK



Top quark board in the Big Bang Theory show...
Somewhat familiar to you?

THE TOP QUARK

- **Top quark is heavy**
  - The **heaviest** known point-like particle; ~36 times heavier than the bottom quark. *Any particular reason?*
  - Mass from Yukawa coupling in SM, strongly coupled with the Higgs boson. Play a significant role in the Higgs physics.
- **Top quark is short lived**
  - Lifetime is calculated to be very short, $\tau \sim 5 \times 10^{-25}$ sec.
  - It **decays before hadronization** — the only "free" quark — no bound states exist (ie. no mesons nor baryons with top).

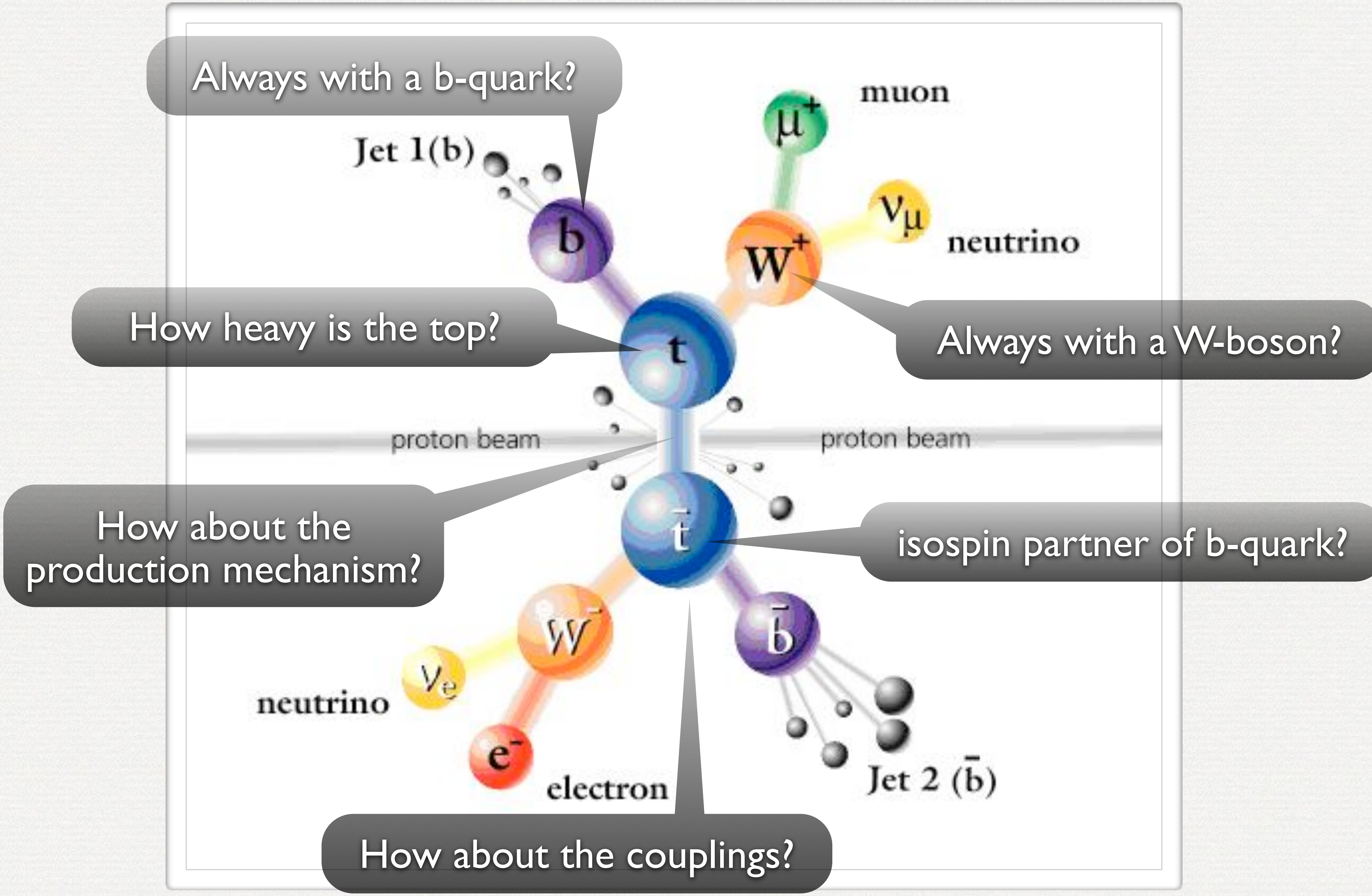
Decay to the final products without any dilution:
allow experimentalists to access to the quark properties directly!

TOP PHYSICS AT LHC

- **Precision measurement of top cross section.**
  - Top production rate at high center of mass energy.
- **Large top production rate at LHC — A TOP QUARK FACTORY**
  - Use top quark as a calibration source (e.g., a very clean source of b-jet).
  - High precision determination of top quark mass.
  - Test of spin/polarization, asymmetries, etc.
  - Probing electroweak couplings and top rare decays.
- **New physics heavier than the top quark**
  - Heavy new particles decay with (high-p_T) top in the final state.

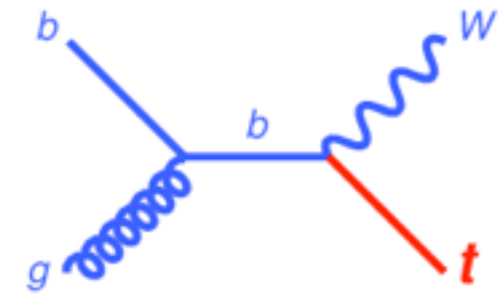
Total **>10 M** top quark pairs have been produced at ATLAS & CMS

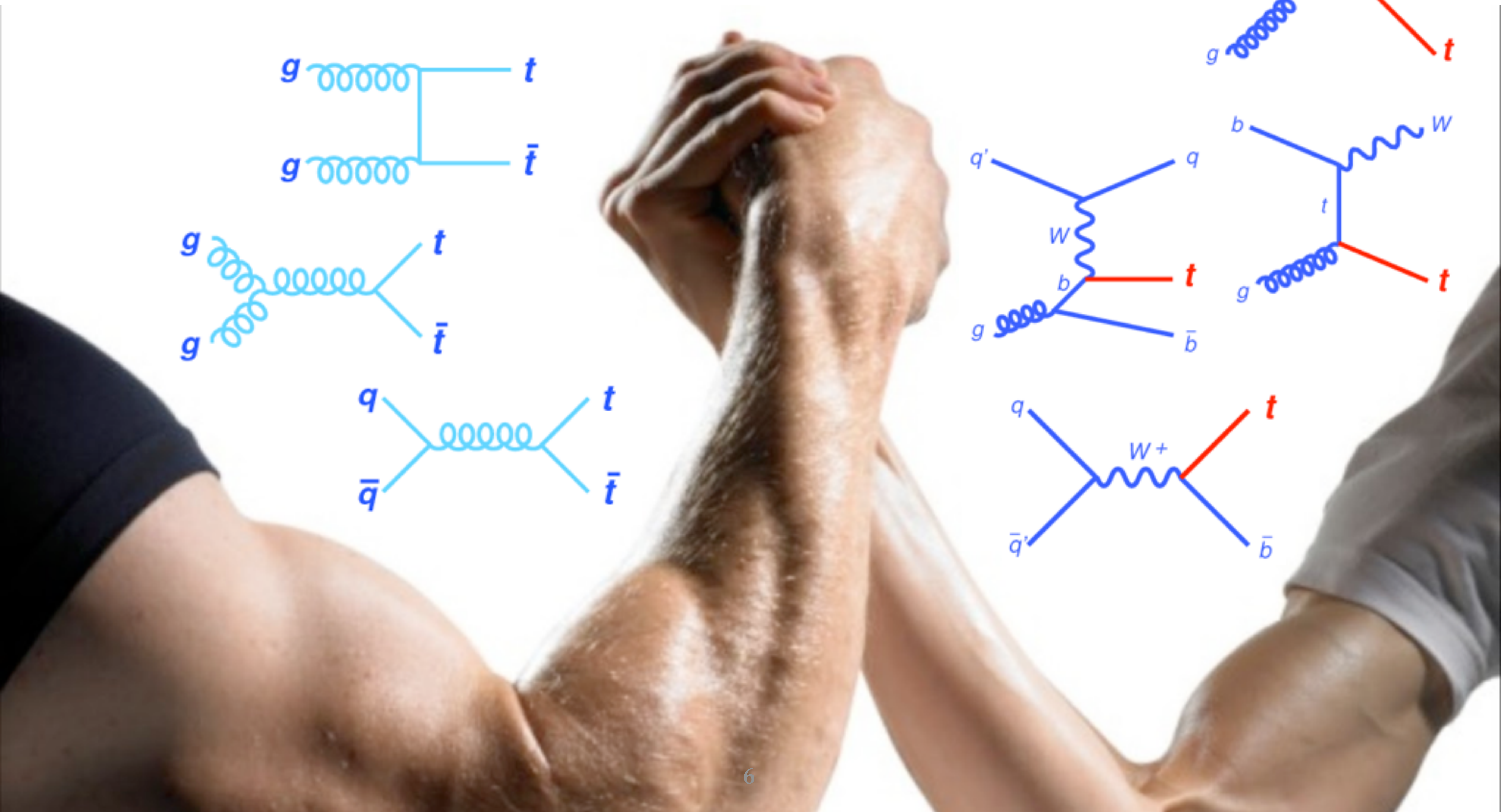
TOP PHYSICS AT LHC



TOP PRODUCTIONS

Either **STRONG** or **ELECTROWEAK**

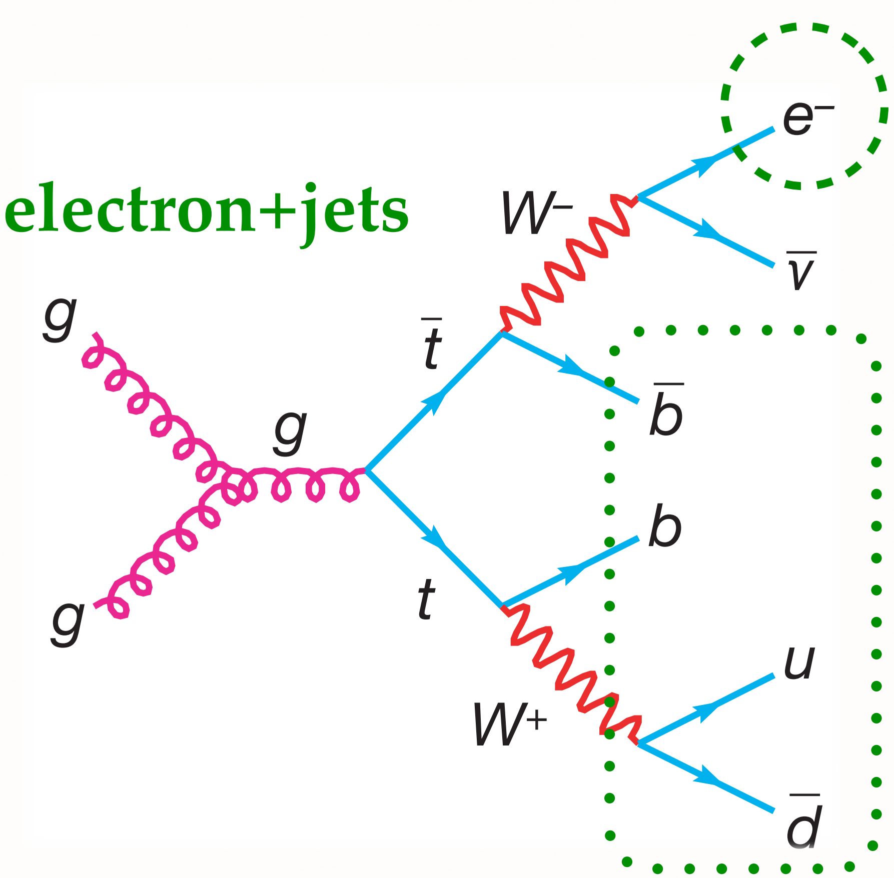


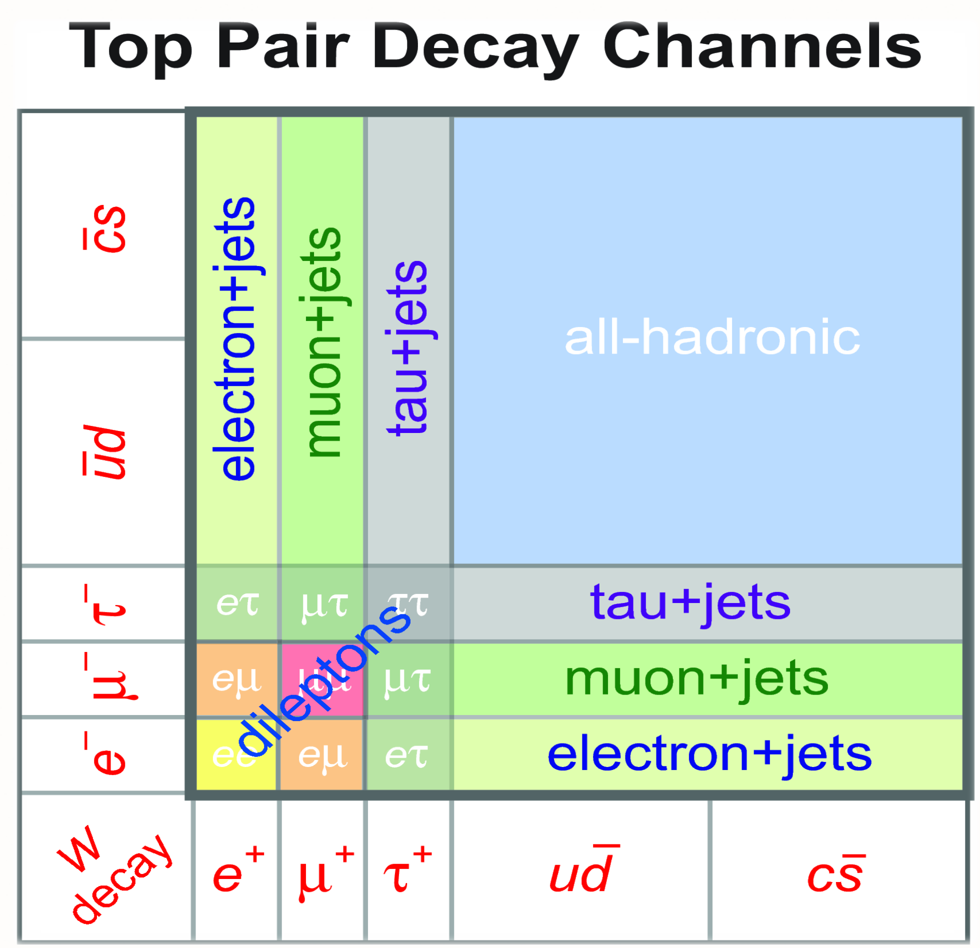


TOP PAIR PRODUCTIONS

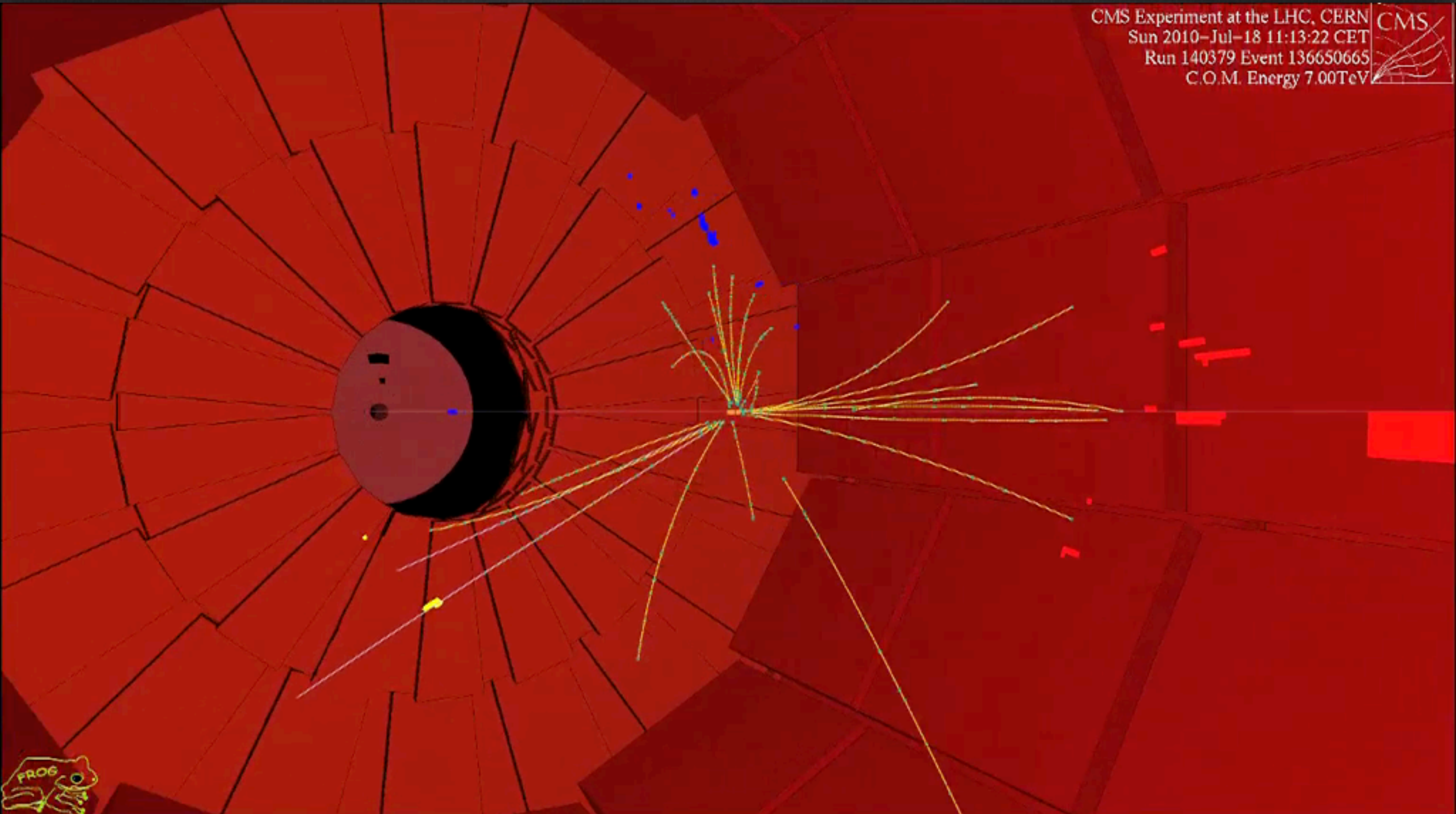
- **Top quark pairs are produced *strongly* with quark-antiquark annihilation or gluon-gluon fusion.**
  - Final states are categorized by W decay products: **dilepton / lepton+jets / all-hadronic jets**

e.g. **electron+jets**





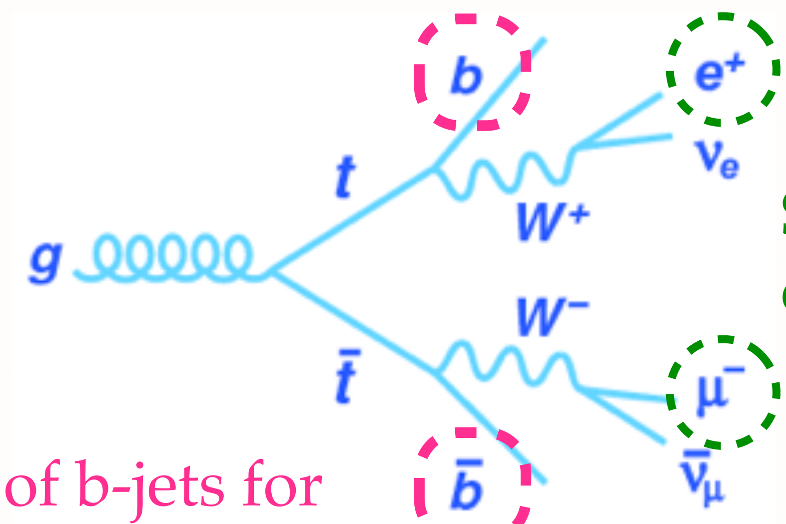
A TOP PAIR CANDIDATE
(FROM CMS)



TOP-PAIR PRODUCTION CROSS SECTIONS

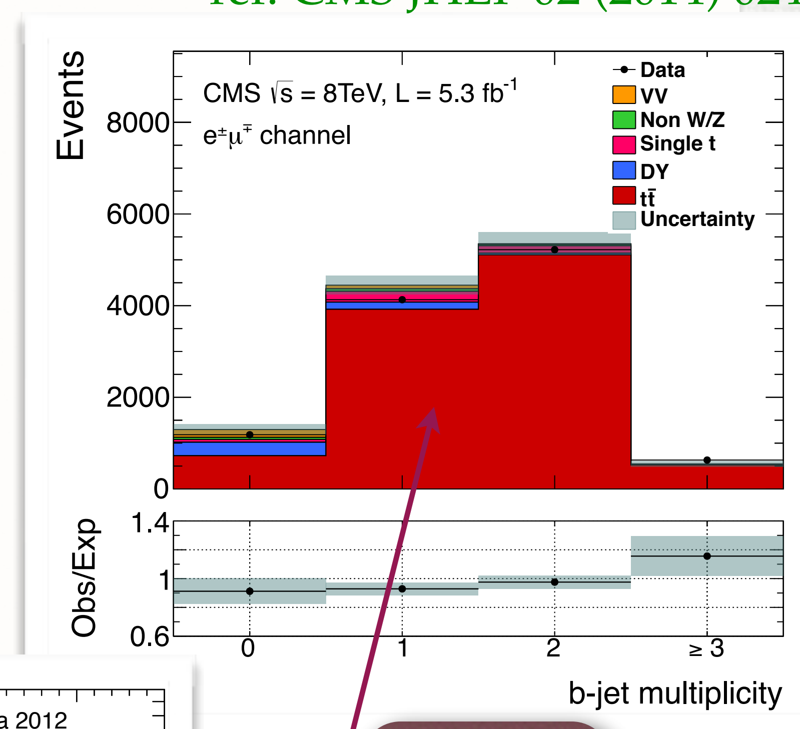
ref. CMS JHEP 02 (2014) 024

- The cleanest channel is **eμ+b-jets**, which suppresses the contributions from Z+jets events.

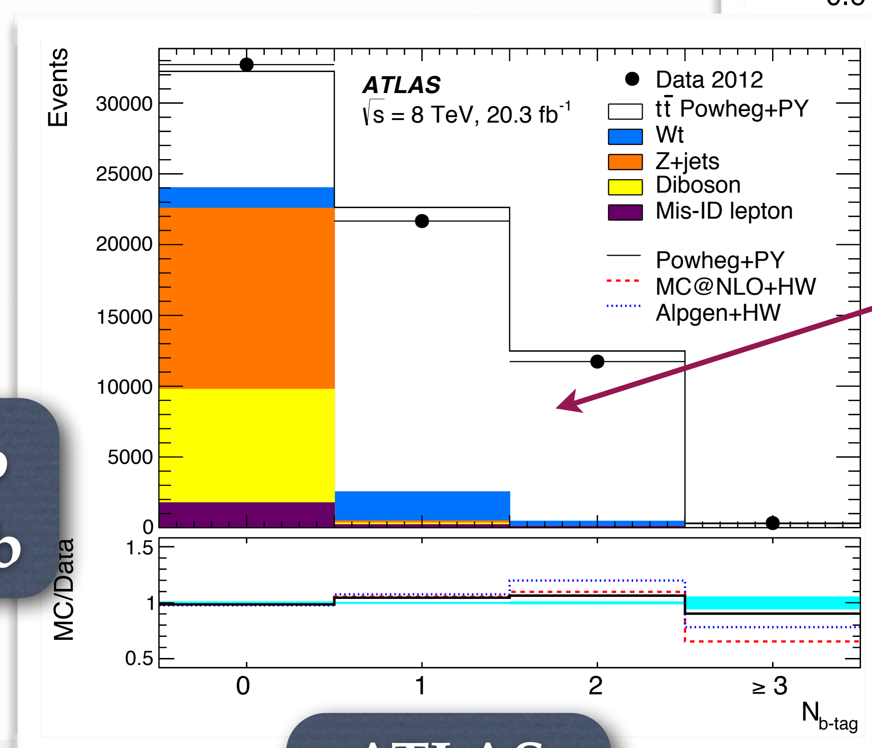


Selecting clean / isolated electrons and muons

Count # of b-jets for measuring the inclusive top cross sections.



CMS



ATLAS

Super clean top-pair events!

ref. ATLAS arXiv:1406.5375

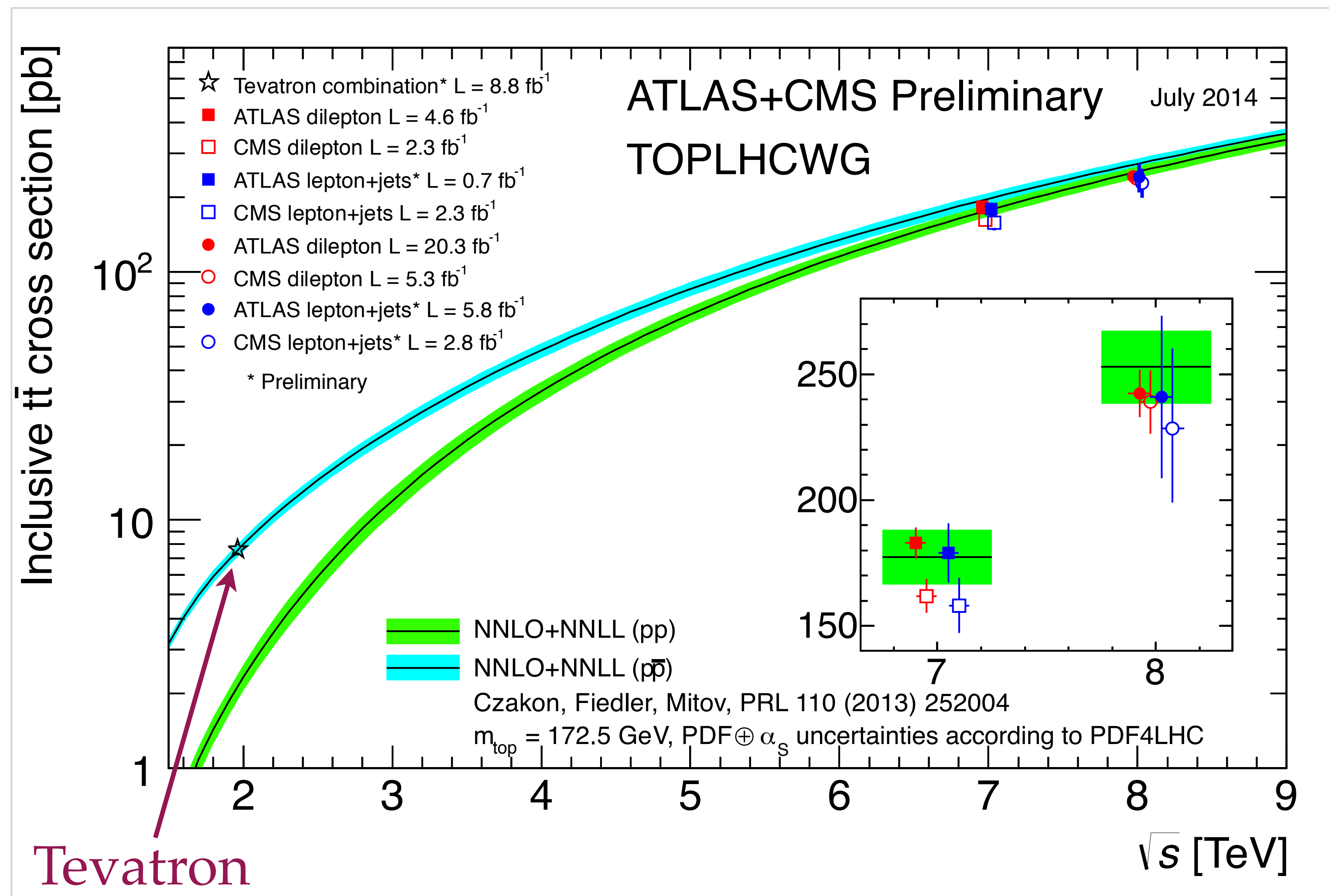
σ(7 TeV) = 182.9 ±3.1(stat.) ±6.4(syst.) pb
σ(8 TeV) = 242.4 ±1.7(stat.) ±10.2(syst.) pb

Precision 3.5~4.0%

TOP-PAIR PRODUCTION CROSS SECTIONS

Experimental precisions already reach ~4%, comparable to the precision of NNLO+NNLL theoretical calculations ~5%

LHC measurements achieved better precision than Tevatron; already dominated by systematic uncertainties!



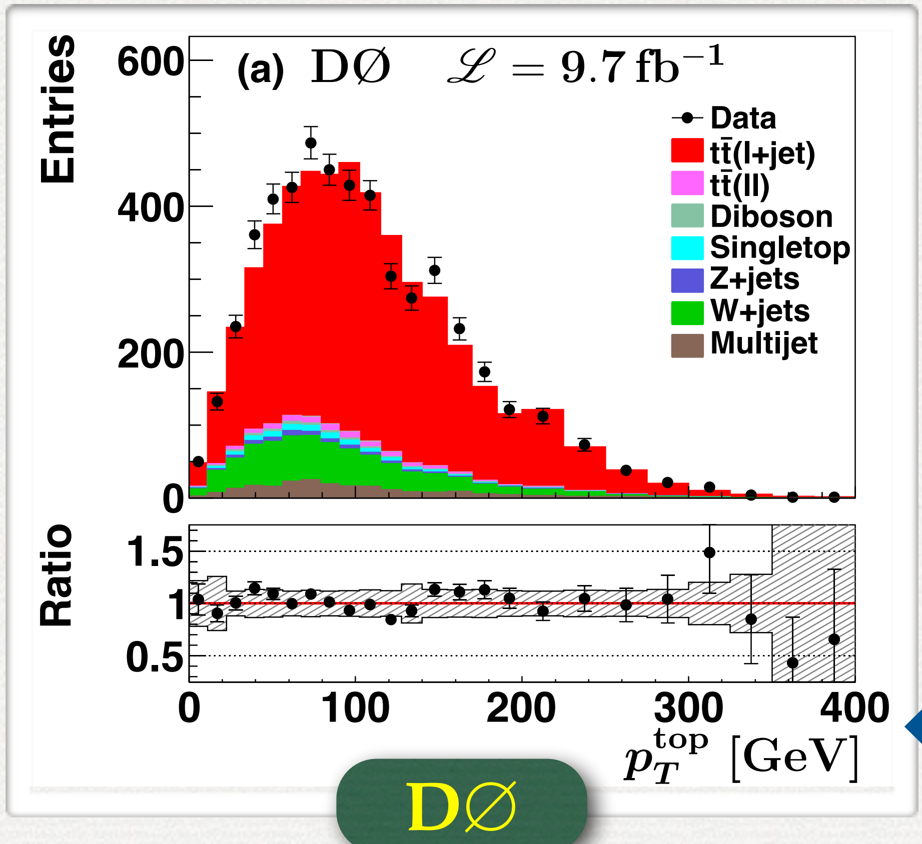
Excellent agreement for theoretical predictions and experimental measurements

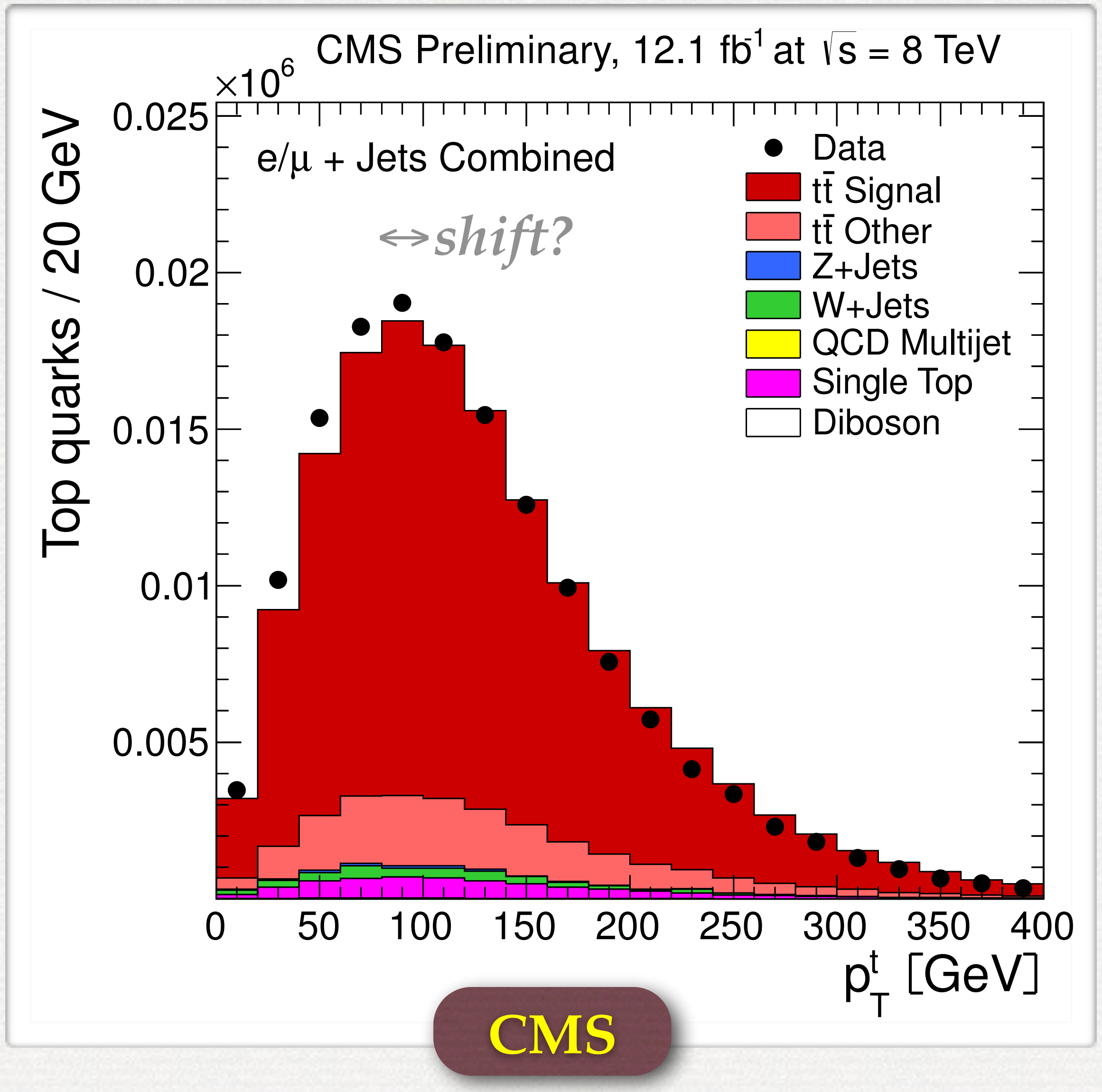
DIFFERENTIAL KINEMATIC DISTRIBUTIONS

ref. CMS-PAS-TOP-12-027

Although the cross sections are in good agreement, but there is some *shift* between data and Monte Carlo observed in the p_T distribution found:

ref. D0 FERMILAB-PUB-14-012-E





← Not so obvious from the Tevatron data (although CMS has >30 times statistics)

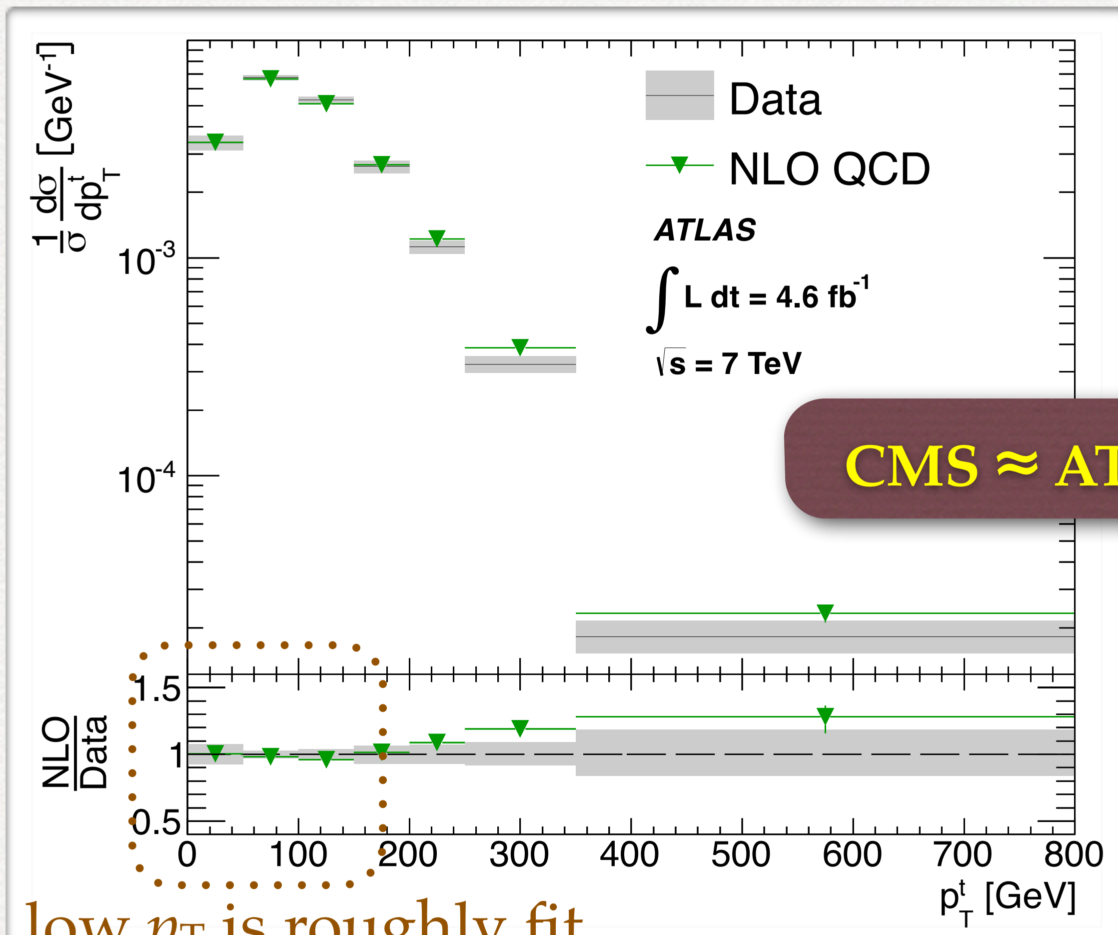
DIFFERENTIAL KINEMATIC DISTRIBUTIONS

This data⇔TH inconsistency at higher p_T has been observed by both CMS and ATLAS.

ref. ATLAS arXiv:1407.0371

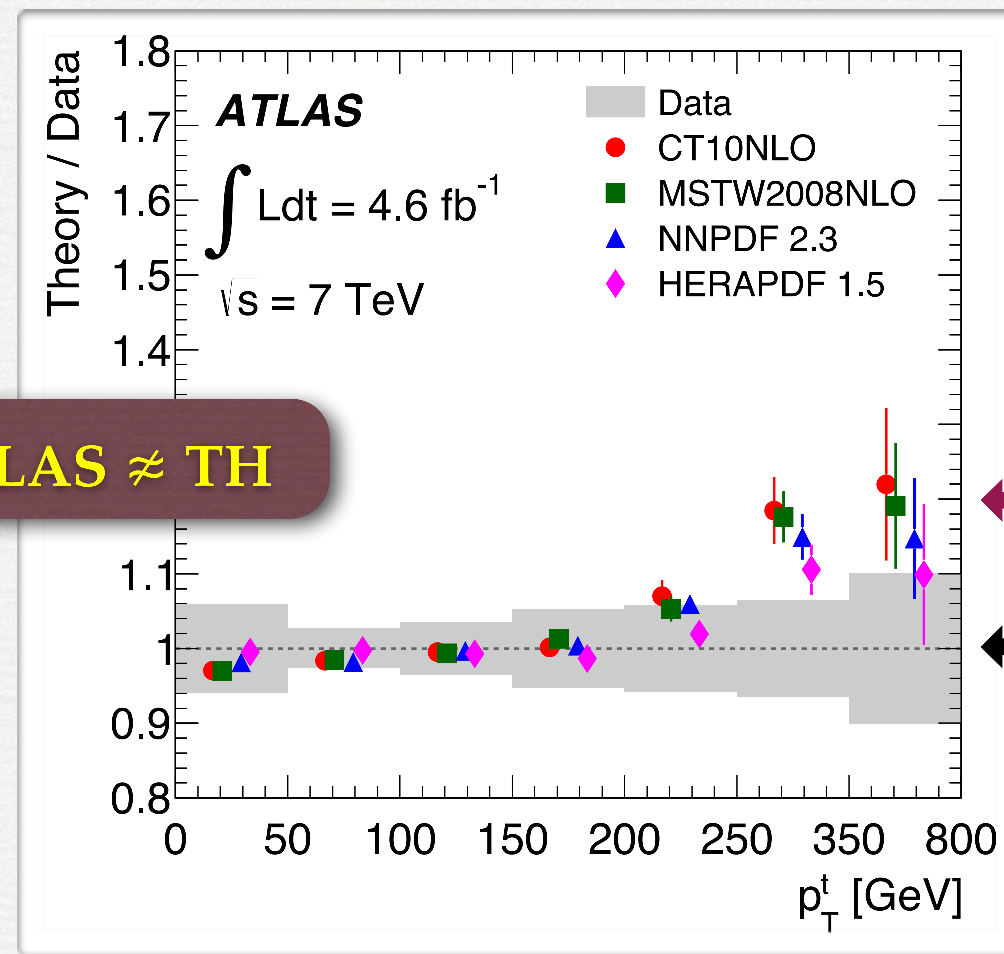
Possible explanations/issues:

- *Gluon density at large-x?*
- *Electroweak corrections?*
- *Other higher order effects?*
- *Hadronization?*



low p_T is roughly fit.

CMS ≈ ATLAS ≉ TH



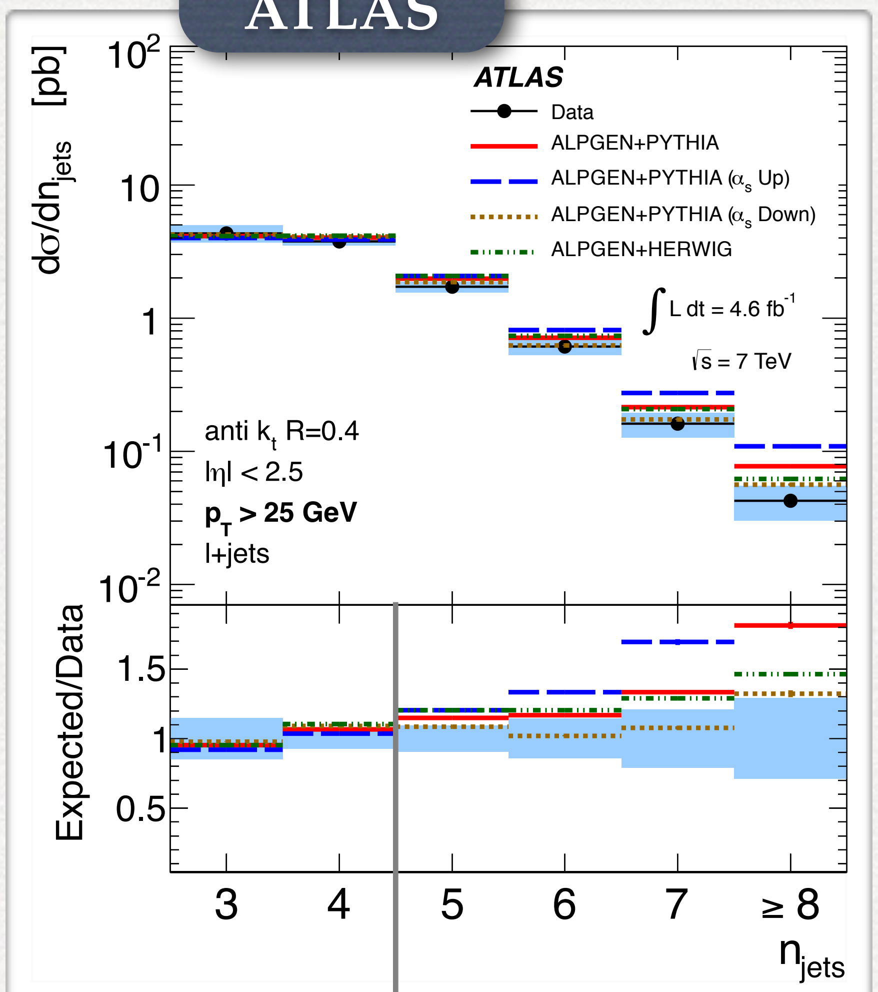
Predictions

Data

JET MULTIPLICITY

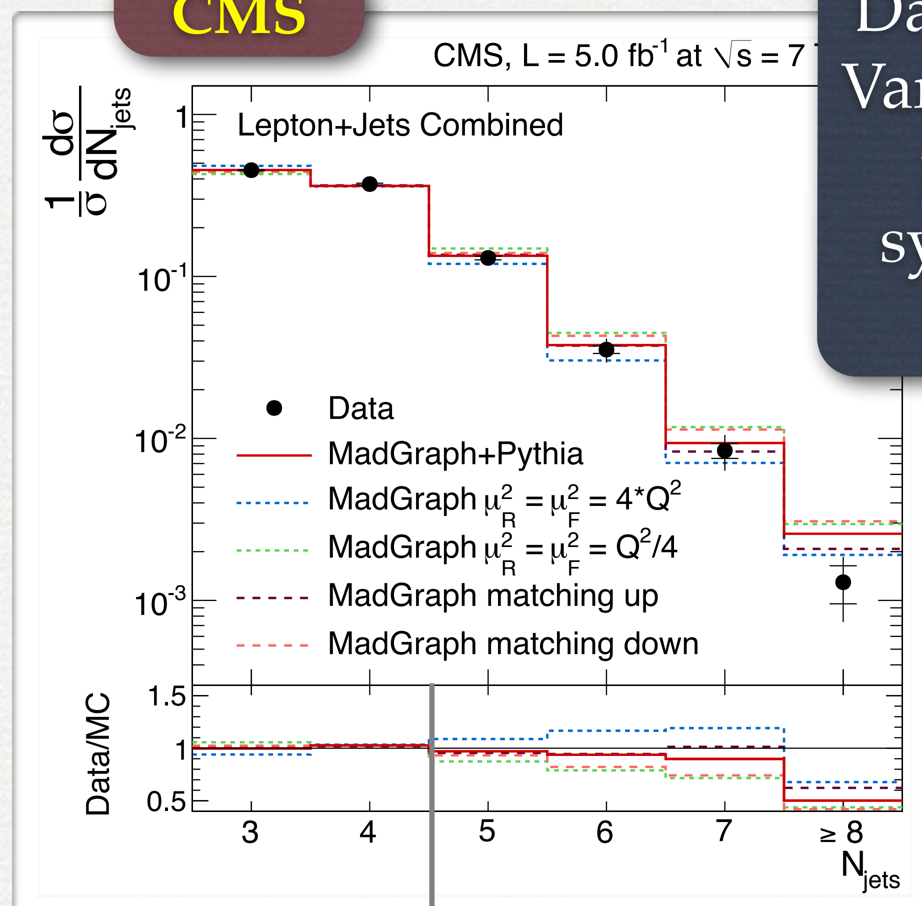
- Measuring additional jets multiplicity and other parameters can be used in the tuning of parton radiations used in the generator:
  - Renormalisation and factorization scale.
  - Jet matching (ME-PS matching) threshold in MadGraph.

ATLAS



additional jets

CMS



additional jets

Data is well-described – Variations on MadGraph parameters used as systematics for parton radiations.

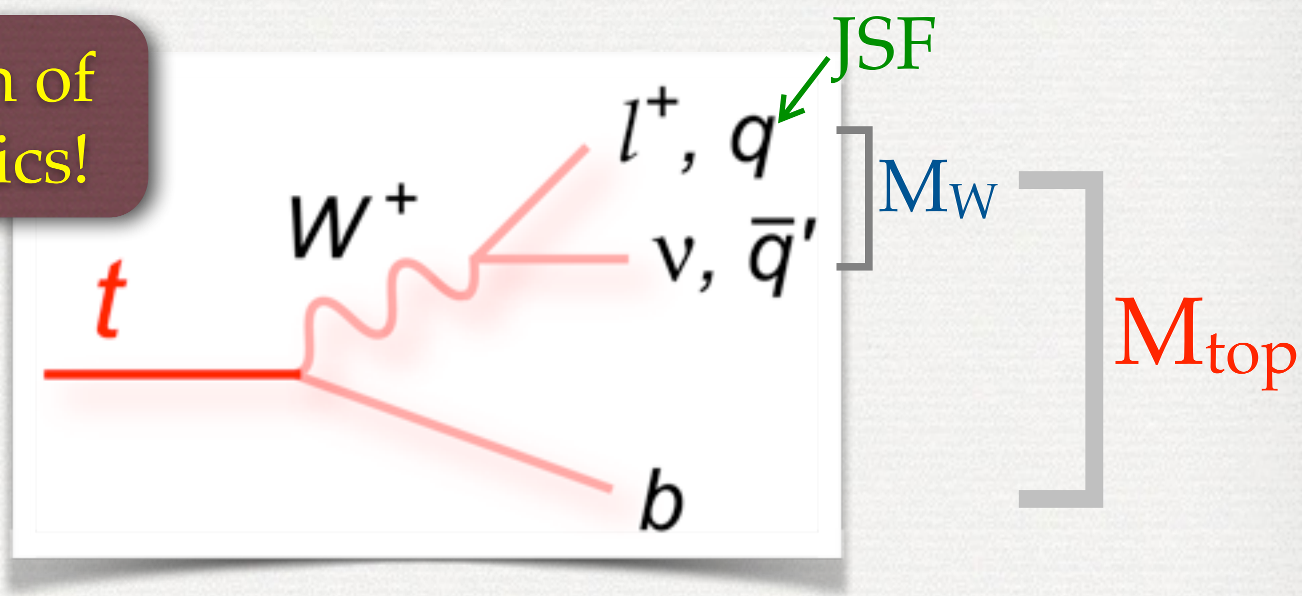
ref.
CMS arXiv:1404.3171
ATLAS arXiv:1407.0891

MEASURING TOP MASS

- Top quark decays before its hadronization; one can measure the invariant mass of decay products, reflecting the narrow resonance of top itself.
- Methods:
  - **Full reconstruction** of invariant mass – the most powerful method.
  - **Partial reconstruction** by fitting variables which are correlated to M_{top} (eg. lepton p_T end-point) – less powerful, but with different systematics.
  - **Indirect probing**, e.g. through the cross-section, B-hadron lifetime, etc.

MEASURING TOP MASS

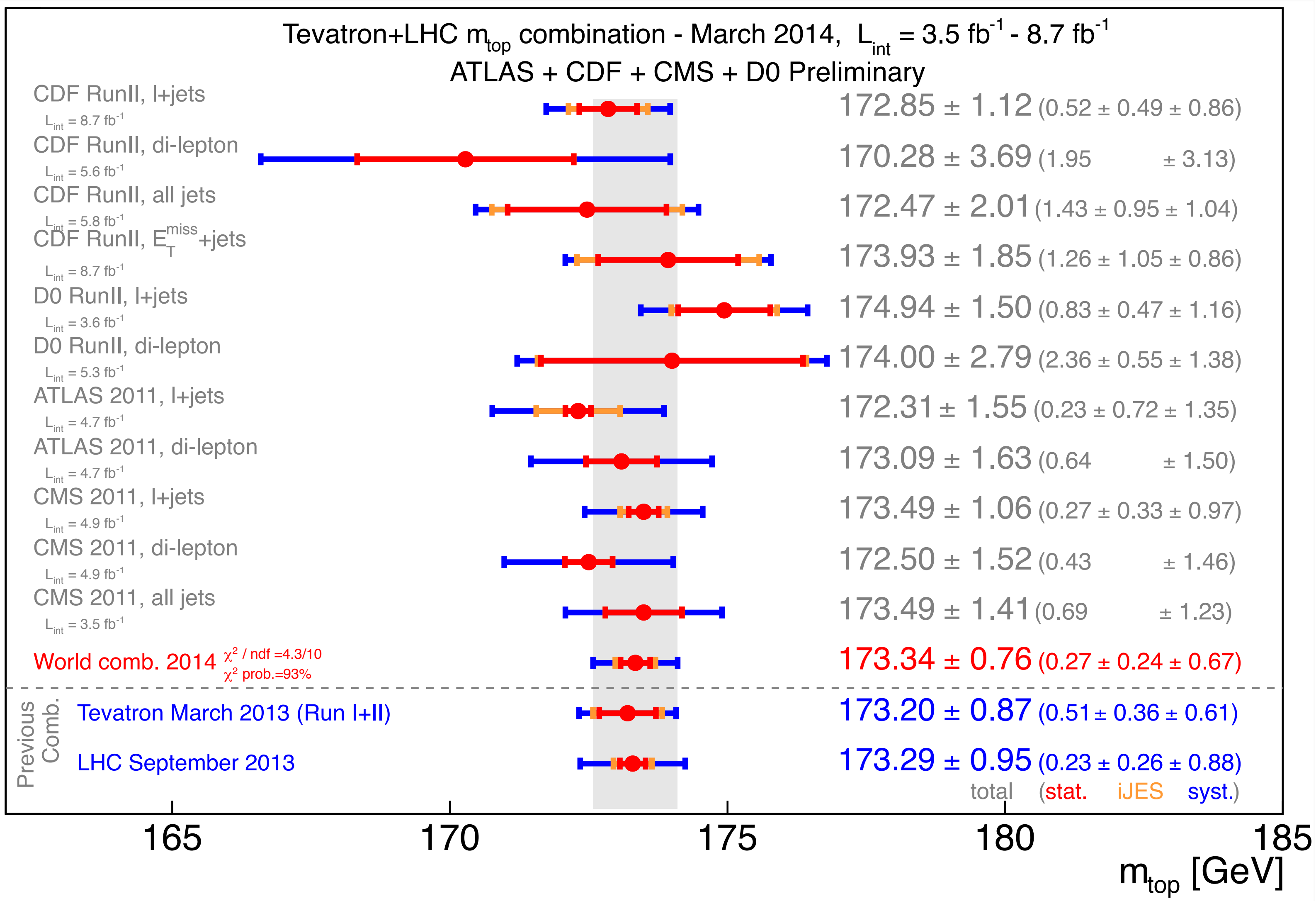
Full reconstruction of the event kinematics!

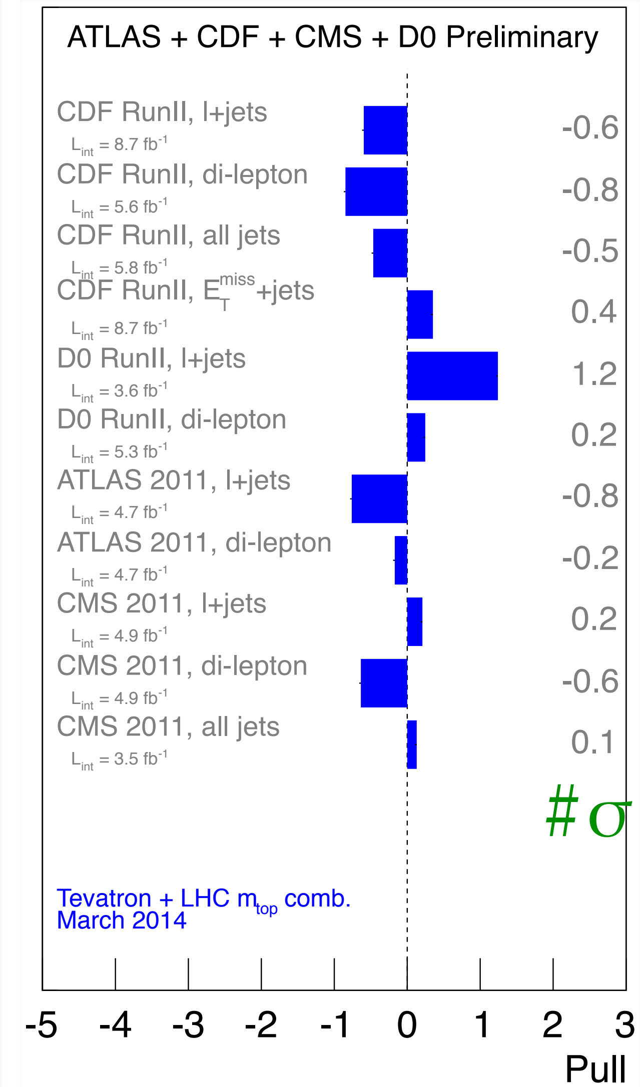


- **Matrix element** (DØ):
  leading order matrix element to calculate event probability density.
- **Ideogram** (CMS): kinematic fit to reconstruct M_{top}; likelihood function is used to test compatibility of kinematics with top decay hypothesis with every good permutation:
  - Adopt a 2D fit to M_{top} and jet energy scaling factor (JSF) with W-mass constraint.
- **Template method** (ATLAS): Use MC template with different M_{top} input and maximize the consistency of data:
  - 2D fit to extract M_{top}, JSF with M_W constraint.
  - 3D fit to extract M_{top}, JSF and b-jet scaling factor.

WORLD AVERAGE 2014

ref. ATLAS, CDF, CMS, D0, arXiv:1403.4427





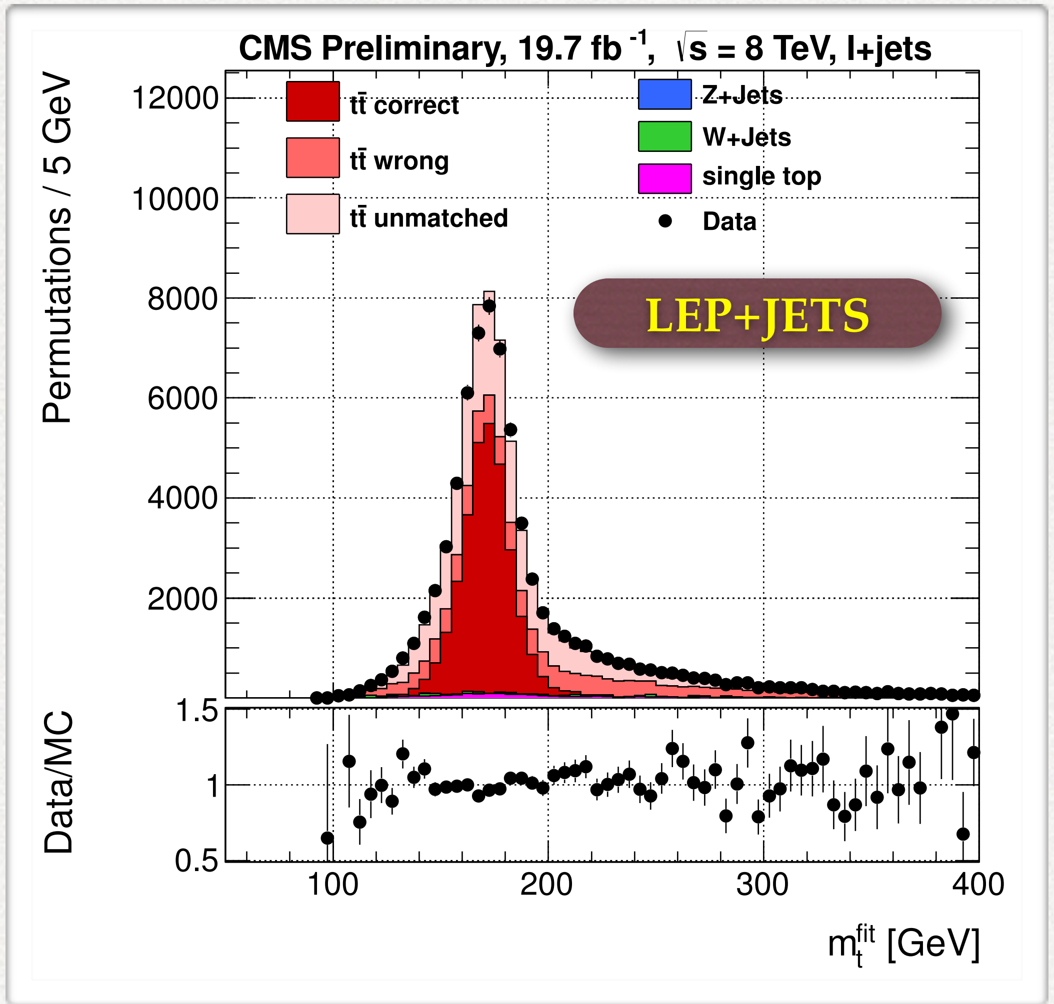
M_{top} = 173.34 ± 0.27 (stat.) ± 0.71 (syst.)

Precision ~0.44%

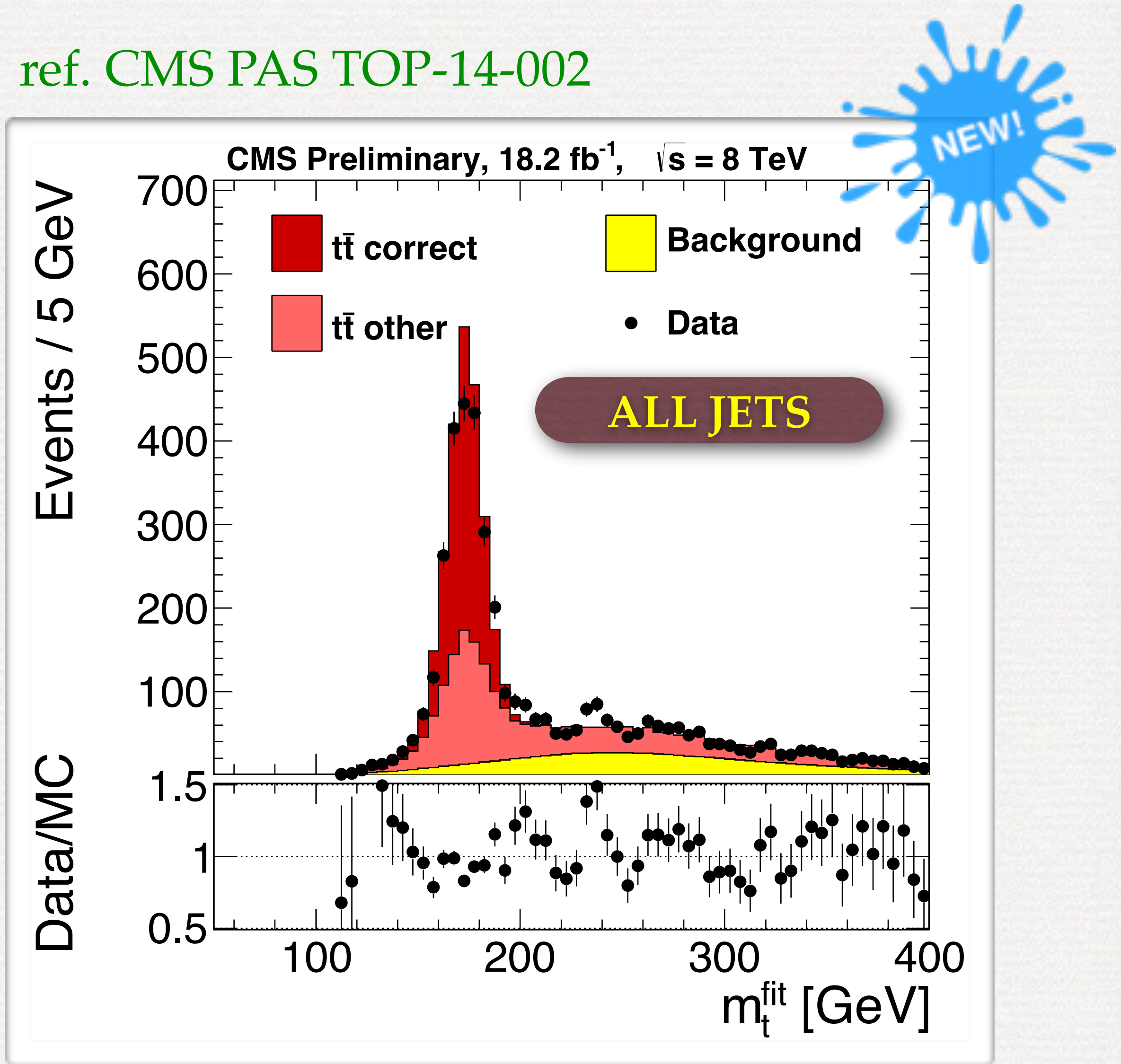
Consistency between measurements are excellent.

VERY RECENT TOP MASS RESULTS

ref. CMS PAS TOP-14-001



ref. CMS PAS TOP-14-002



M_{top} = 172.04 ±0.19(stat.) ±0.75(syst.)

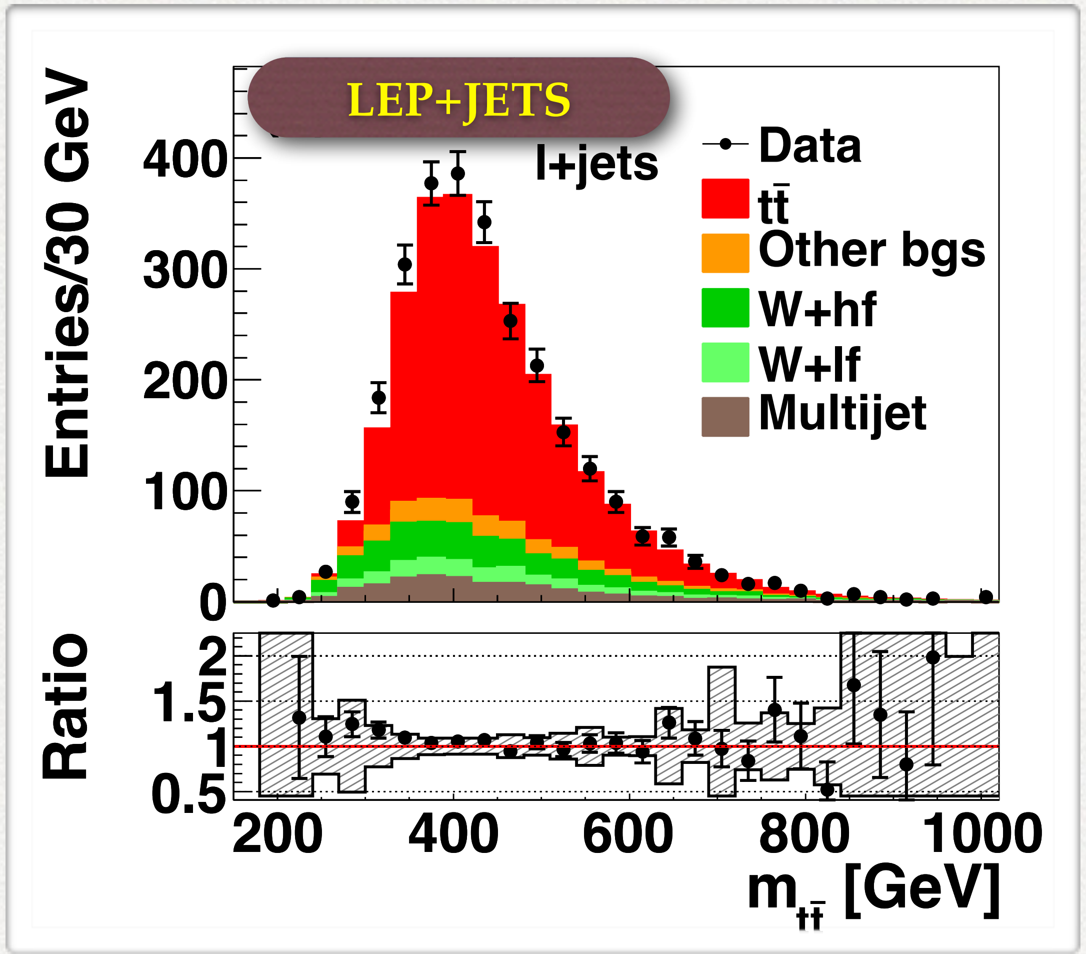
Precision ~0.45%

M_{top} = 172.08 ±0.36(stat.) ±0.83(syst.)

Precision ~0.53%

VERY RECENT TOP MASS RESULTS

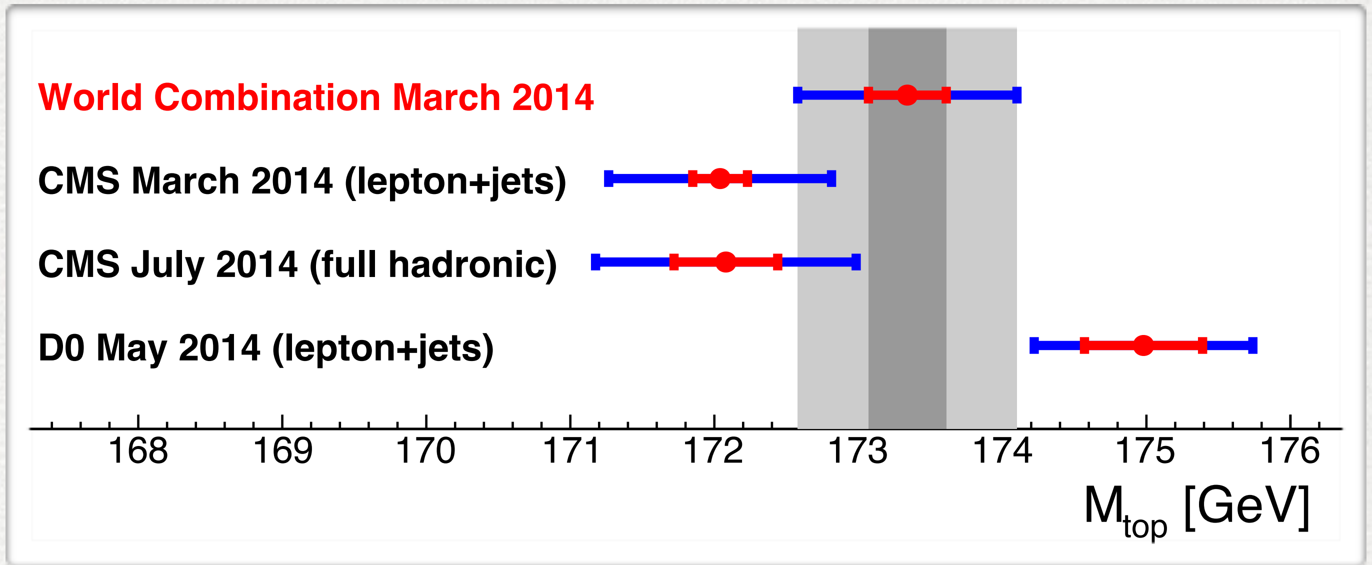
ref. D0 arXiv:1405.1756



M_{top} = 174.98 ±0.58(stat.) ±0.49(syst.)

Precision ~0.43%

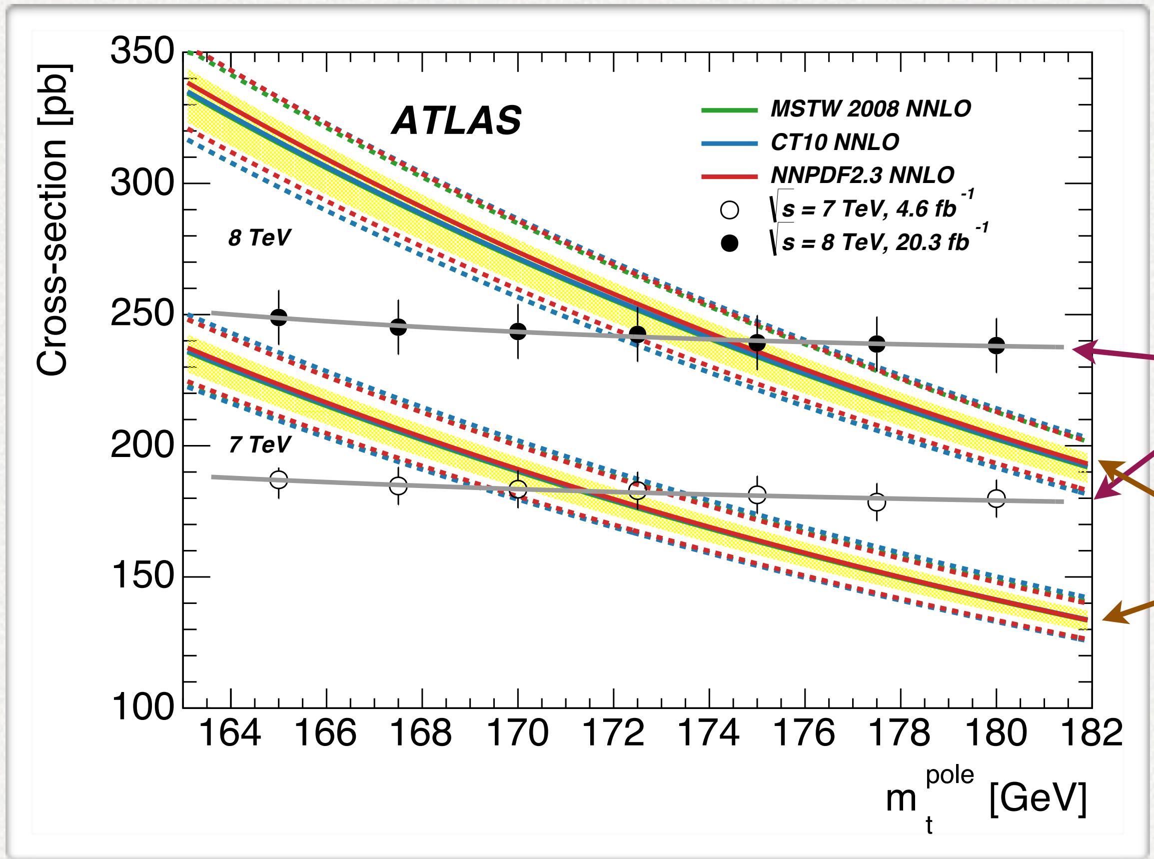
These recent measurements are almost at the same precision as the 2014 march average.



Some mild tensions (1.5~3.0σ) between the March 2014 world average and the most recent D∅ and CMS measurements, depending on systematic uncertainty treatments.

OTHER APPROACHES

- Extract the pole mass from inclusive production cross section.
- Fit to the kinematic distribution and extract the mass from end-point
  - Different systematics, no Monte Carlo calibration used.
- B-hadron lifetime from top events, which is linear dependent on M_{top}:
  - No jet reconstruction; but limited by top p_T model.



ref. ATLAS arXiv:1406.5375

Extract *well-defined* pole mass:

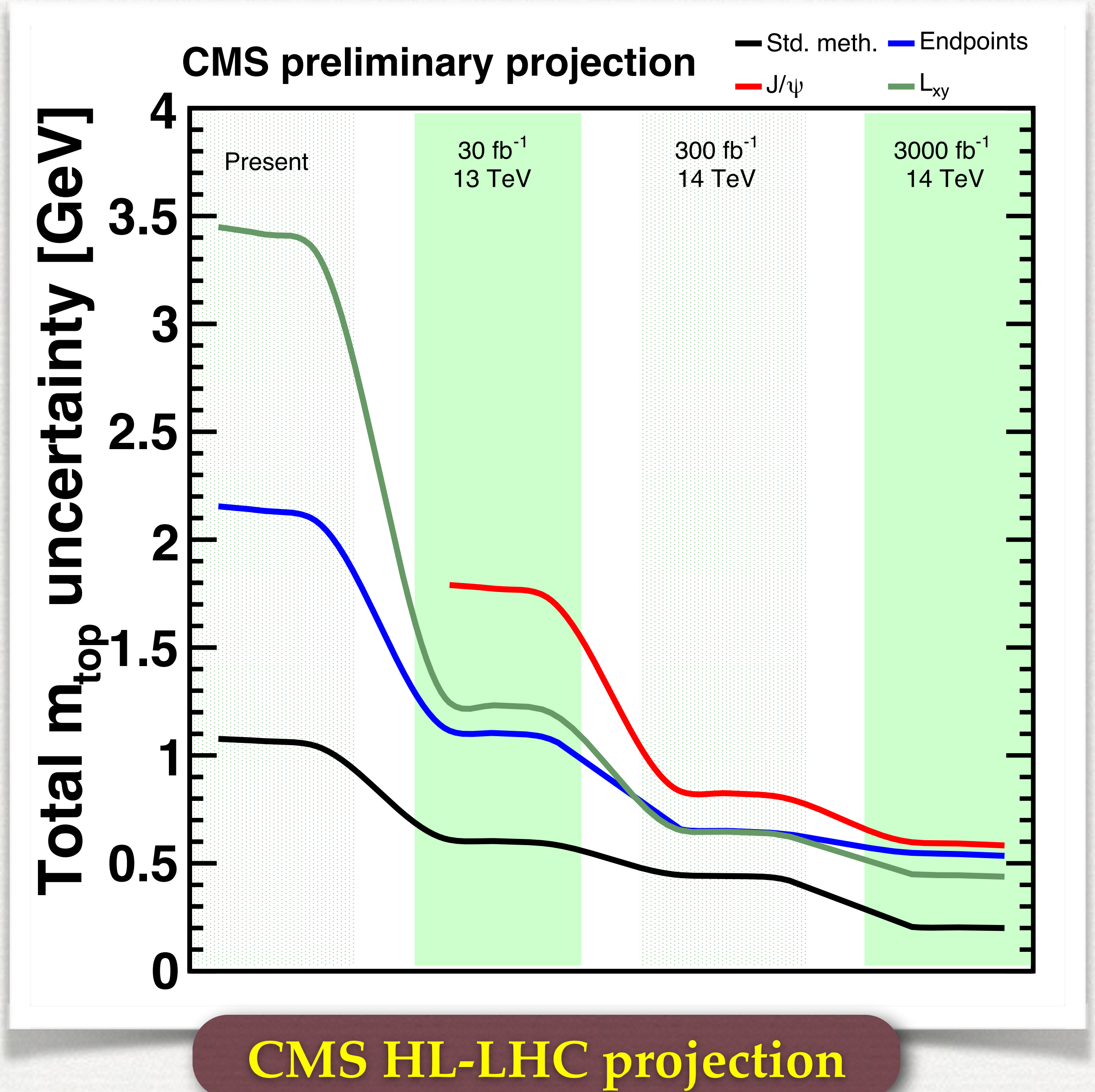
M_{top} dependence (–0.28% / GeV) of the cross section measurement

NNLO+NNLL predictions for various PDFs

M_t (7 TeV) = 171.4 ± 2.6 GeV
M_t (8 TeV) = 174.1 ± 2.6 GeV

TOWARD THE FUTURE

ref. CMS-PAS-FTR-13-017



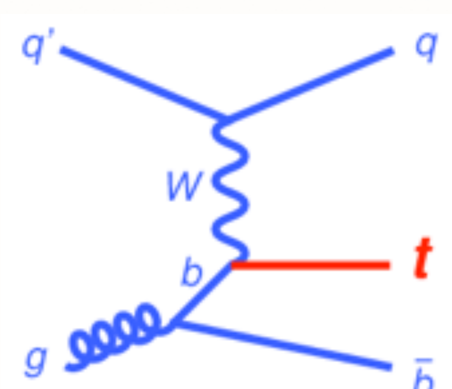
- Standard (full reconstruction) method may reach ~0.2 GeV experimental precision, if the understanding of radiation, jet fragmentation, non-perturbative QCD effects, etc. can be improved.
- Alternative methods may already reach sub-GeV precision with 300 fb^{-1}.

Expected precision on top mass (GeV)

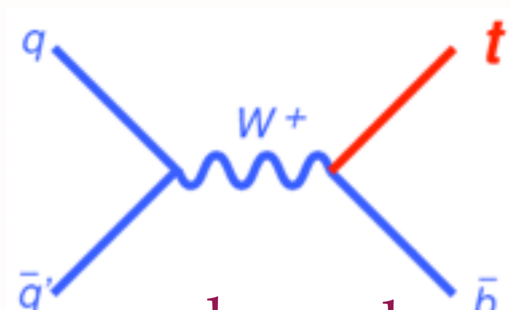
	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Standard met.	0.62	0.44	0.2
end-point met.	1.1	0.6	0.5
J/ψ method	1.8	0.8	0.6
L_{xy} method	1.3	0.6	0.4

SINGLE TOP PRODUCTIONS

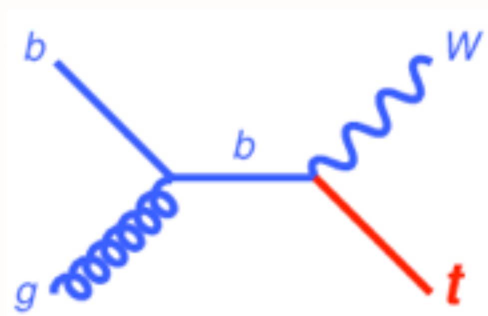
- Single top-quark production via *electroweak charged current* processes. Many measurements can be carried out:
  - Cross sections, polarization, V_{tb}, etc.
  - Sensitive to many new physics models, e.g. W', charged Higgs.
- Background to many searches (SUSY, etc.)



t-channel



s-channel



tW-channel

Production cross sections (pb)

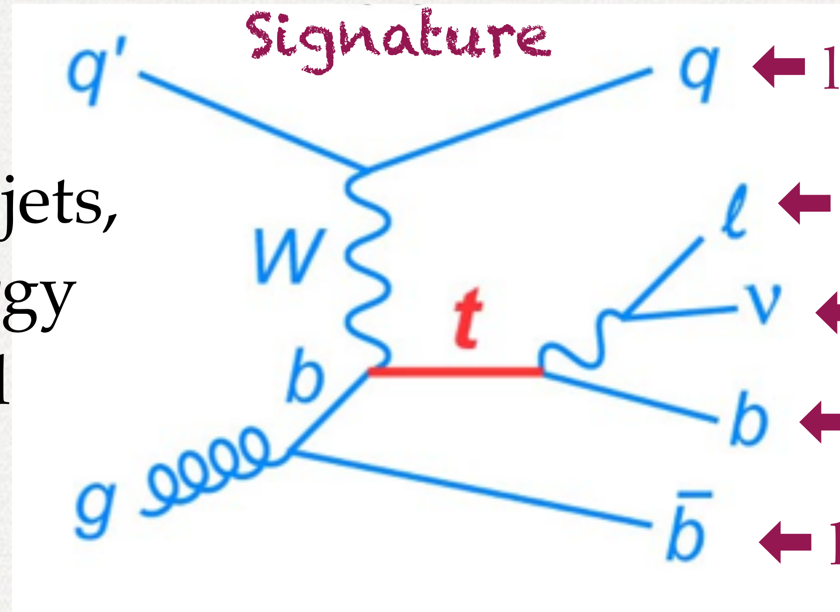
	t-ch.	tW-ch.	s-ch.	ttbar
Tevatron	2.08	0.25	1.05	7.08
LHC 7 TeV	64.6	15.6	4.59	172
LHC 8 TeV	87.2	22.2	5.55	249

t-channel is the dominant process;
At LHC tW-channel is favored,
but s-channel is challenge.

T-CHANNEL SINGLE TOP

Event Signature

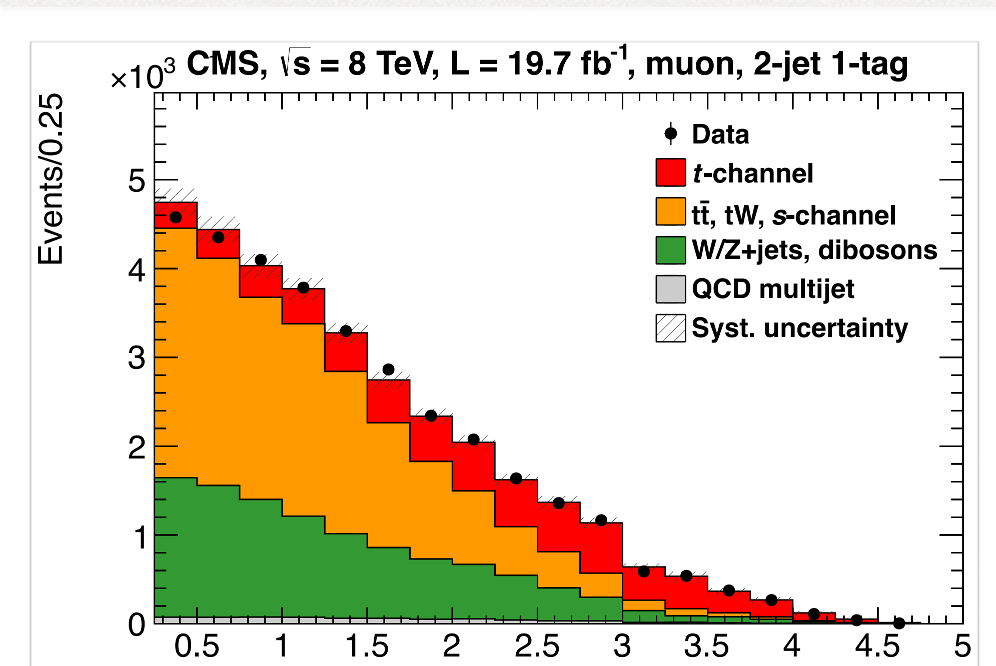
Select e/μ+2jets, missing energy one b-tagged



- light-quark jet (forward) ← η_f
- isolated charged lepton (e & μ)
- missing energy
- high p_T b-jet (central)
- low p_T b-jet, not always visible.

] M_W] M_{top}

Fit to forward jet η distribution:



ref. CMS arXiv:1403.7366

Inclusive single top @ LHC 8 TeV by CMS:

$\sigma_{t\text{-}ch}$ = 83.6 ± 2.3 (stat.) ± 7.4 (syst.) pb

Precision ~9.3%

top & anti-top (*which are different at LHC!*):

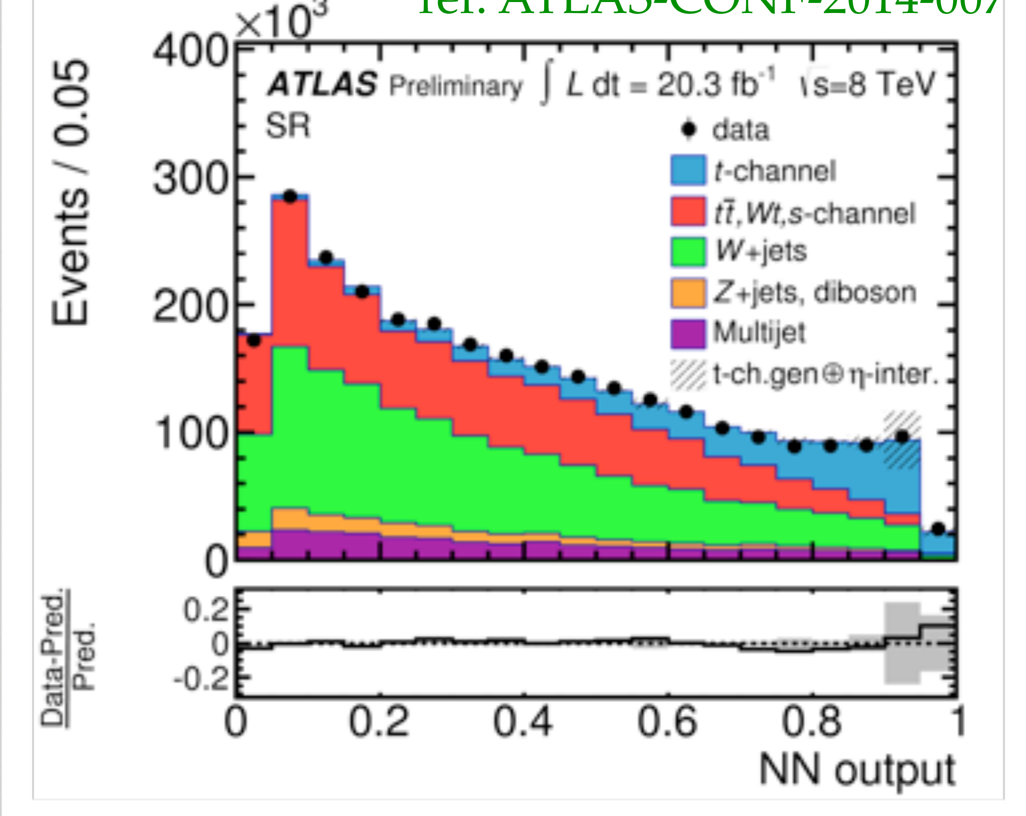
$\sigma_{t\text{-}ch}$(top) = 53.8 ± 1.5 (stat.) ± 4.4 (syst.) pb
$\sigma_{t\text{-}ch}$(anti-top) = 27.6 ± 1.3 (stat.) ± 3.7 (syst.) pb

⇒ $R_{t\text{-}ch}$ = 1.95 ± 0.10 (stat.) ± 0.19 (syst.)

T-CHANNEL SINGLE TOP

- ATLAS performed a **"fiducial"** cross section measurement, which measures the cross section only in the visible phase space, minimize dependence on theoretical models.
- Single extraction via a likelihood fit to a neural network (NN) discriminant based on kinematic variables.

ref. ATLAS-CONF-2014-007



$$\sigma = \frac{1}{\epsilon_{\text{fid}}}\sigma_{\text{fid}} = \frac{1}{\epsilon_{\text{fid}}}\left(\frac{\epsilon^{\text{sel}}_{\text{corr}}}{\epsilon^{\text{fid}}_{\text{corr}}}\frac{N_{\text{sig}}}{\mathcal{L}}\right)$$

fiducial cross section

Can be corrected with different MC model afterwards.

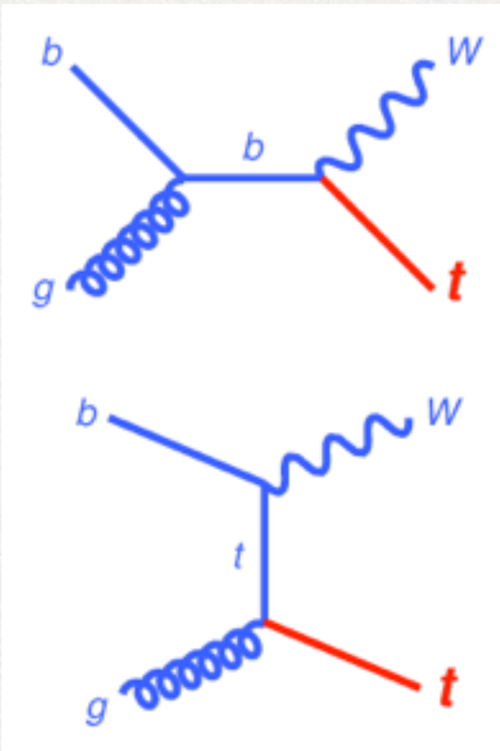
σ_{fid} = 3.37±0.05(stat.)±0.47(syst.)±0.09(lumi.) pb

Scaled with aMC@NLO+Herwig

$\sigma_{\text{t-ch}}$ = 82.6±1.2(stat.)±11.4(syst.)±2.3(lumi.)±3.1(PDF) pb

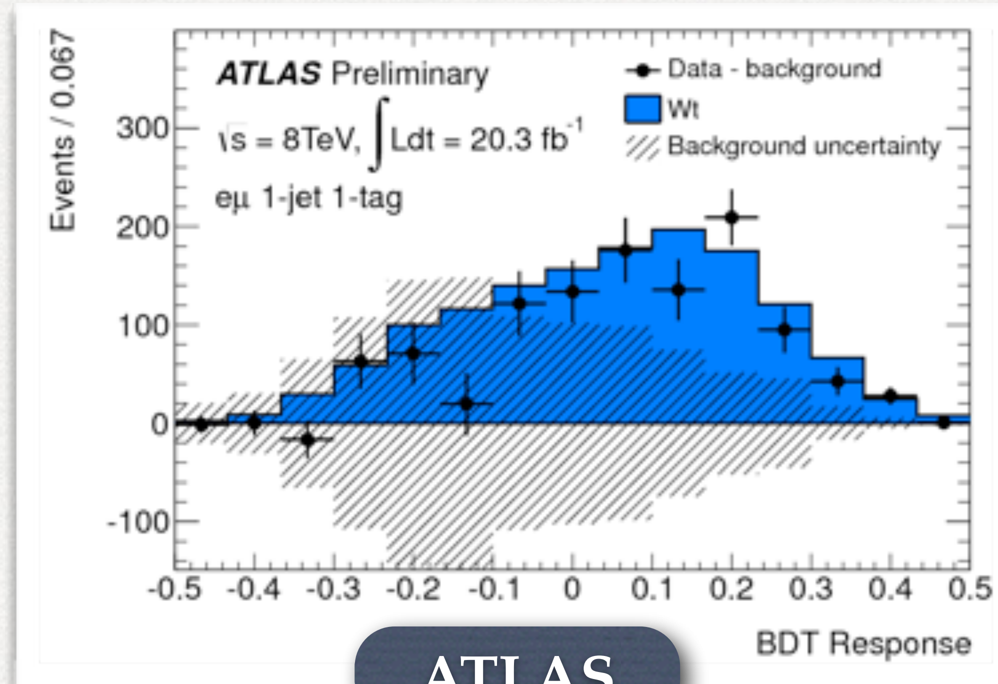
Precision ~14%

W-ASSOCIATED PRODUCTION



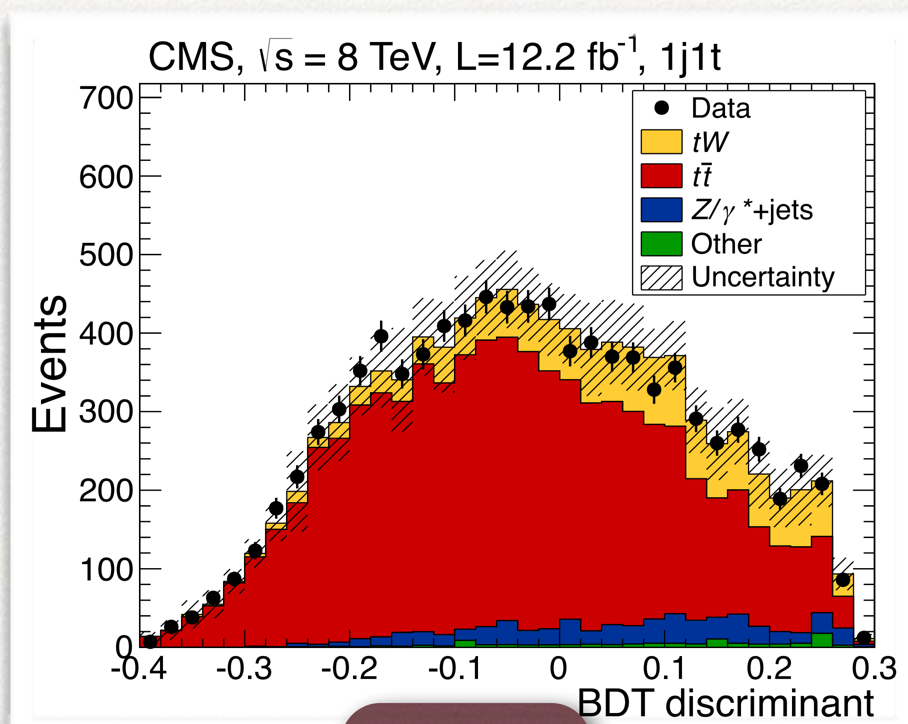
The cross section is negligibly small at Tevatron. Signature: almost top-pair with 1 b-jet missing. Large background from top pair.

ref. ATLAS-CONF-2013-100



ATLAS

ref. CMS PRL 112, 231802 (2014)



CMS

Analyses are carried out with dilepton final state + boosted decision tree (BDT) for background suppression.

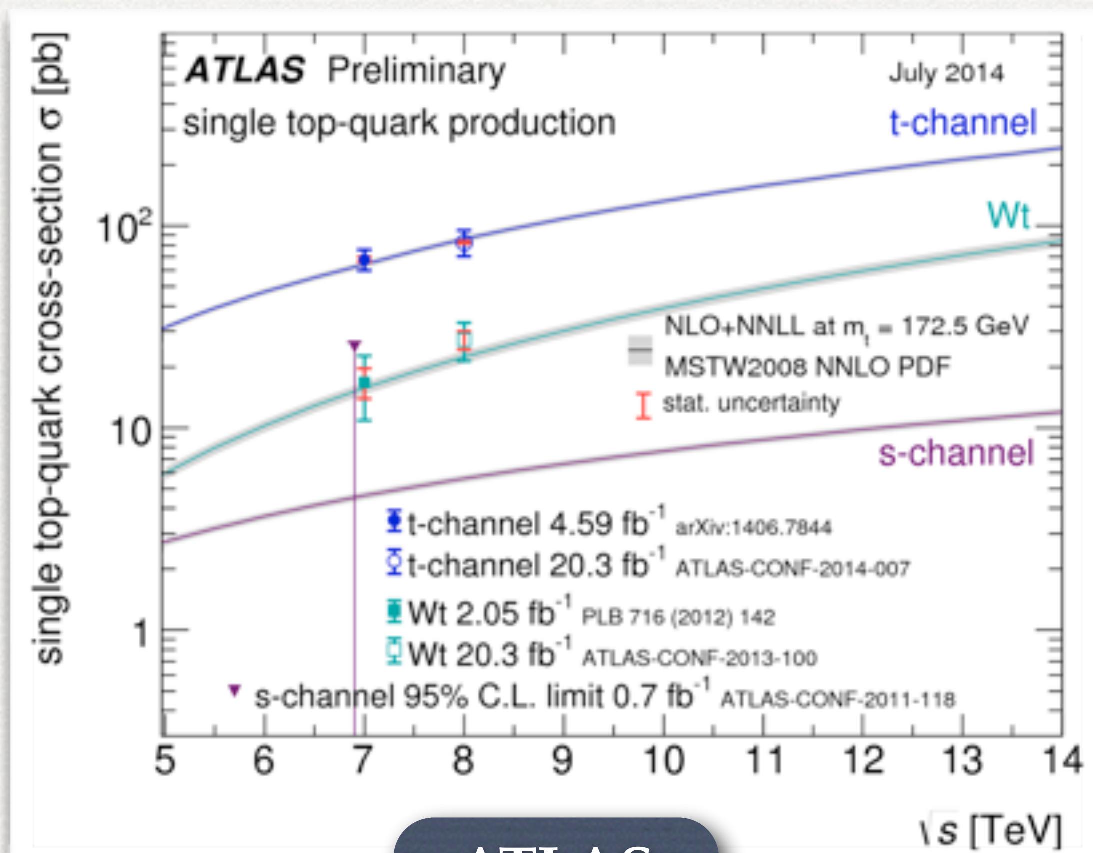
First observation (>5σ) with 8 TeV data:

CMS 8 TeV: $\sigma_{tW} = 23.4 \pm 5.5$ pb [6.1σ]

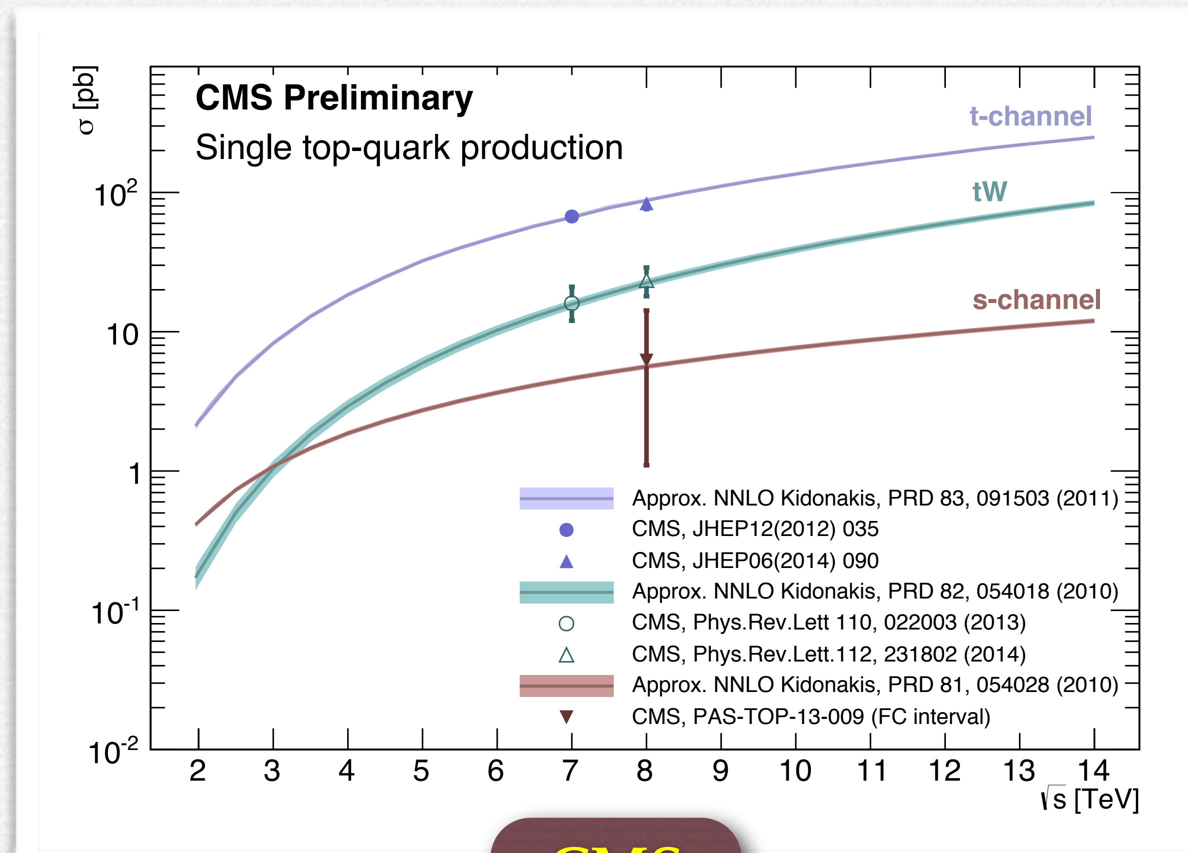
ATLAS 8 TeV: $\sigma_{tW} = 27.2 \pm 2.8 \pm 5.4$ pb [4.2σ]

SUMMARY OF SINGLE TOP

- t- and tW-channel have been observed and the measured cross sections are in good agreement with TH predictions.
- The upper limits for s-channel have been evaluated.
- The charge asymmetry (top and anti-top) has been measured, can be used to constrain the PDF models.
- Determination of $|V_{tb}|$ $\Rightarrow$ *next slide.*

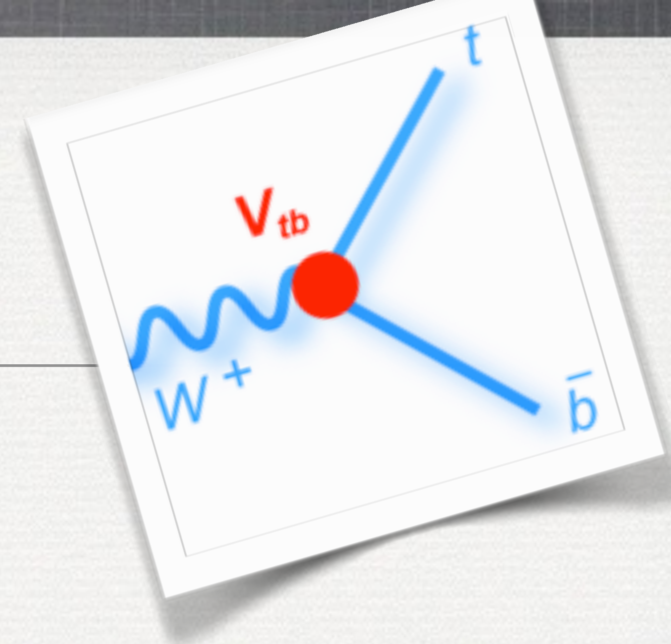


ATLAS

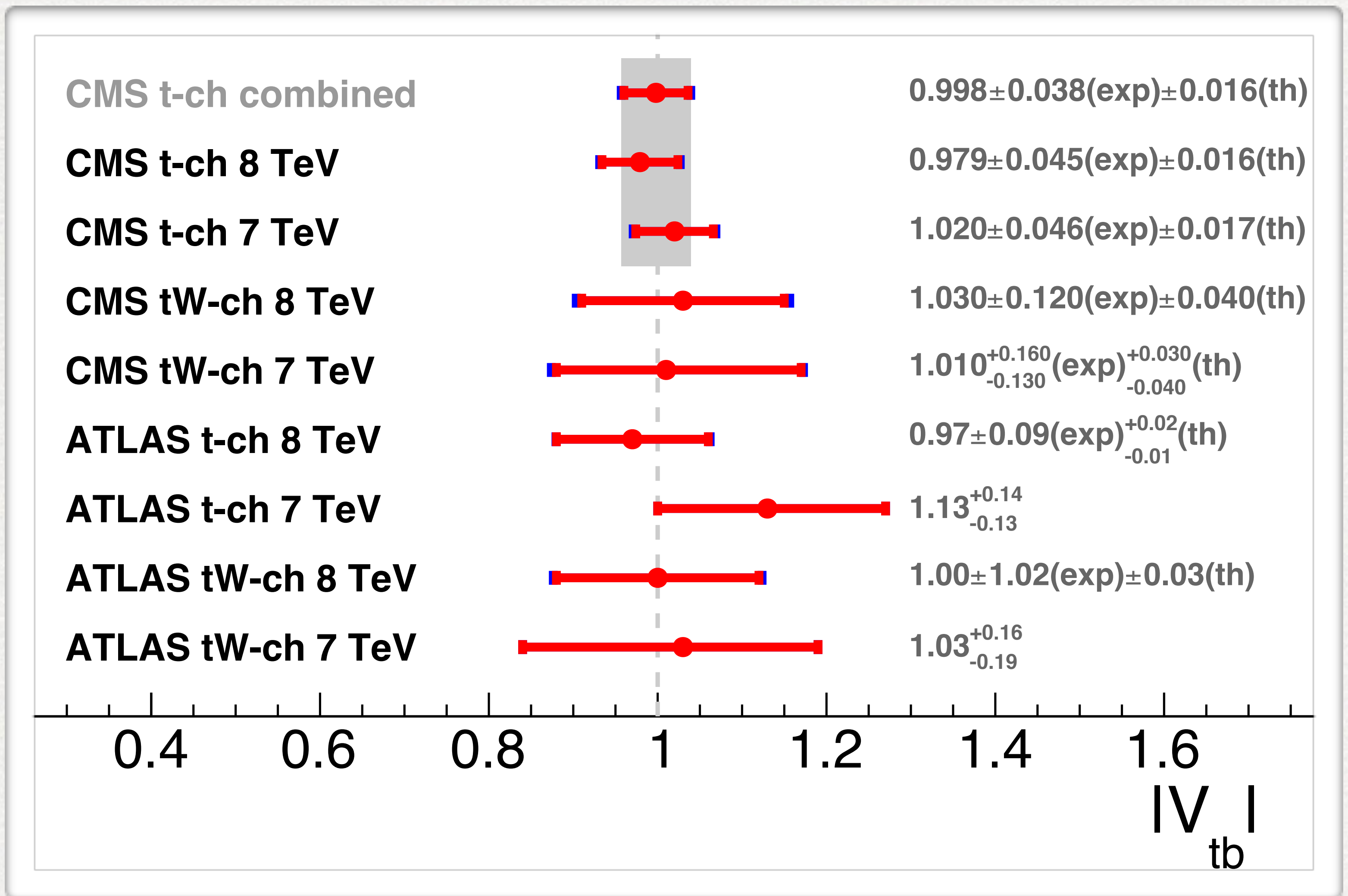


CMS

PROBING V_{tb}



- The absolute value of the CKM element $|V_{tb}|$ can be determined with single top cross sections if
  - $|V_{tb}| >> |V_{td}|, |V_{ts}|$
  - Anomalous form factor $f_{LV} = 1$ (sure SM)



$|f_{LV} \cdot V_{tb}|^2 = \sigma^{exp}/\sigma^{th}$
where σ^{th} is the prediction with $|V_{tb}|=1$.

Precision reaches 4~5%!

Dominated by experimental uncertainty at this moment! Expecting to be improved in the future.

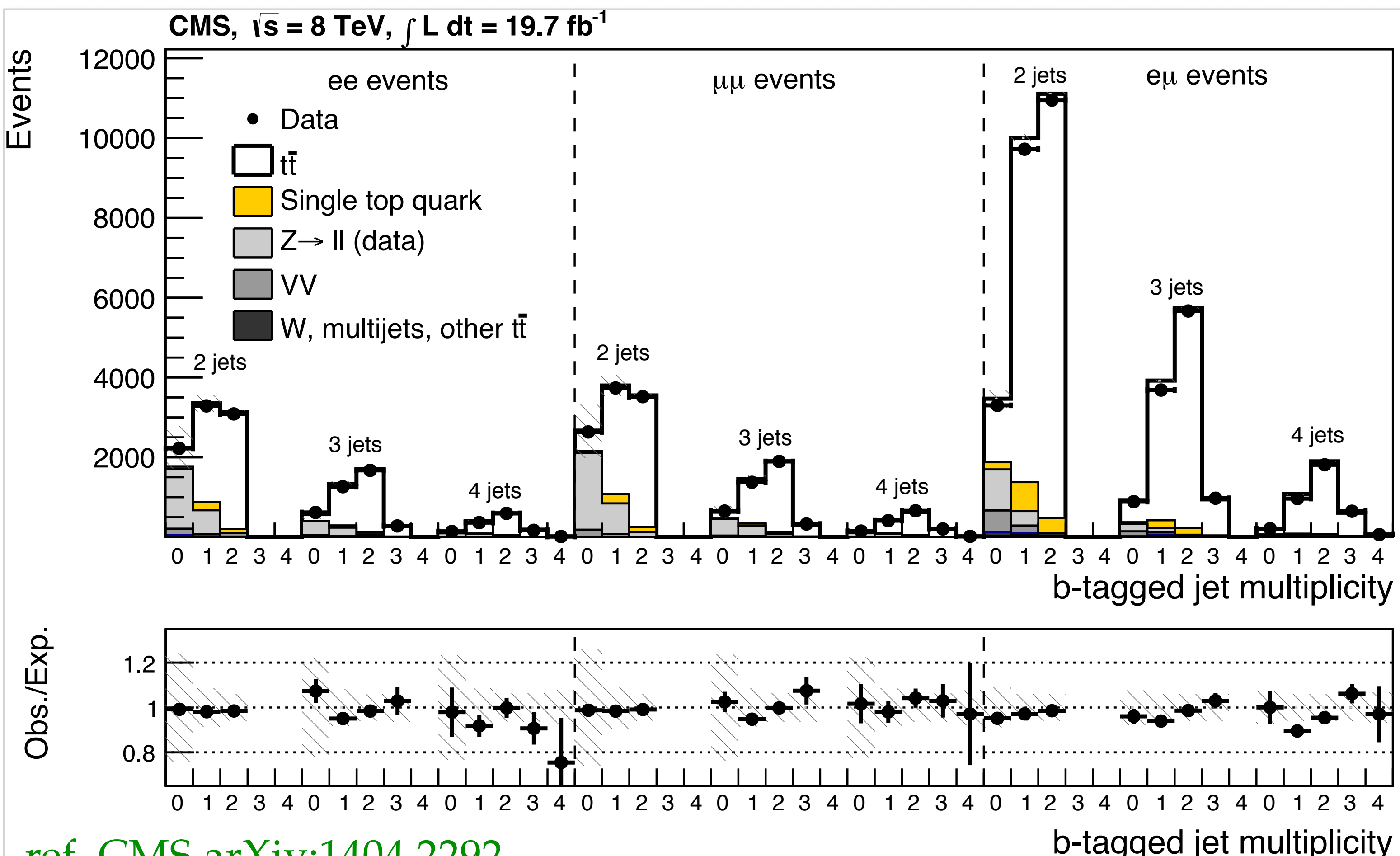
TOP QUARK DECAY

- Top branching fraction to **bW**:

$$R = \frac{\mathcal{B}(t \to bW)}{\mathcal{B}(t \to qW)} = \frac{|V_{\rm tb}|^2}{|V_{\rm tb}|^2 + |V_{\rm ts}|^2 + |V_{\rm td}|^2}$$

Approach V_{tb} with high precision!

can be measured by counting **# of b-jets** from the **top pair** events.

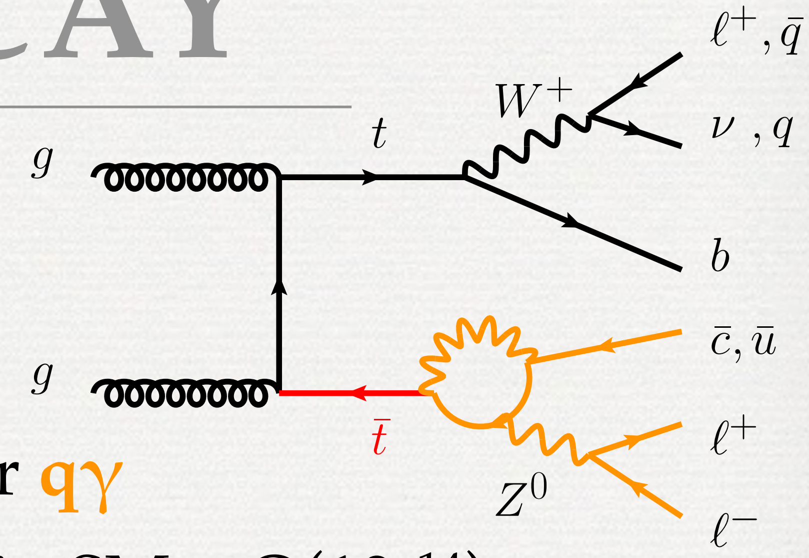


ref. CMS arXiv:1404.2292

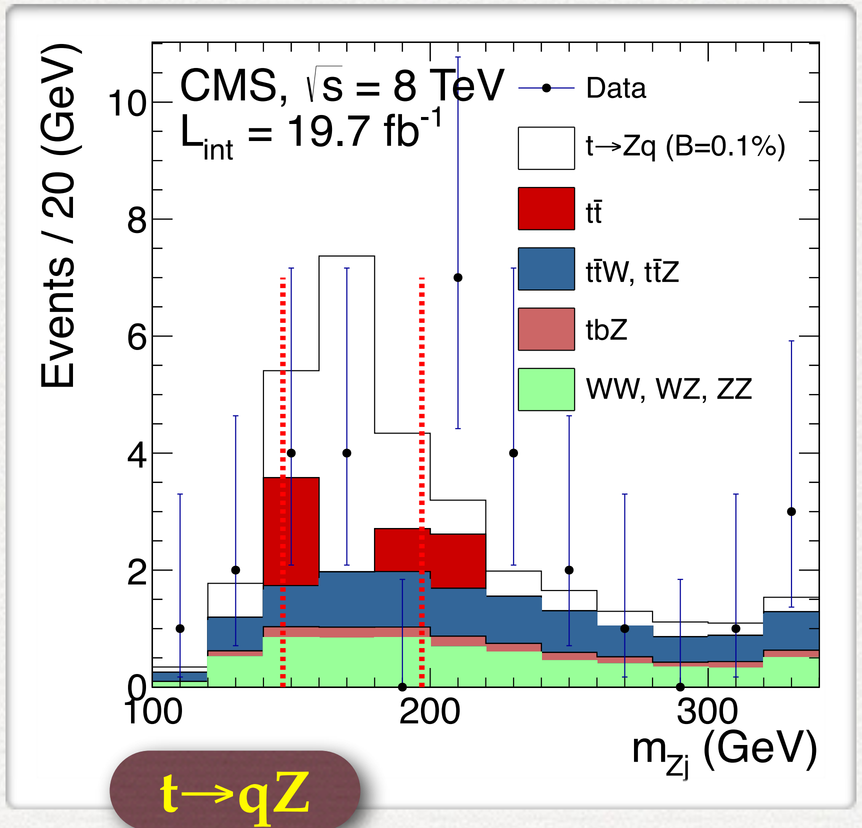
	R
D0	0.90 ± 0.04
CDF	0.871 ± 0.045 ± 0.058
CMS	1.014 ± 0.003 ± 0.032

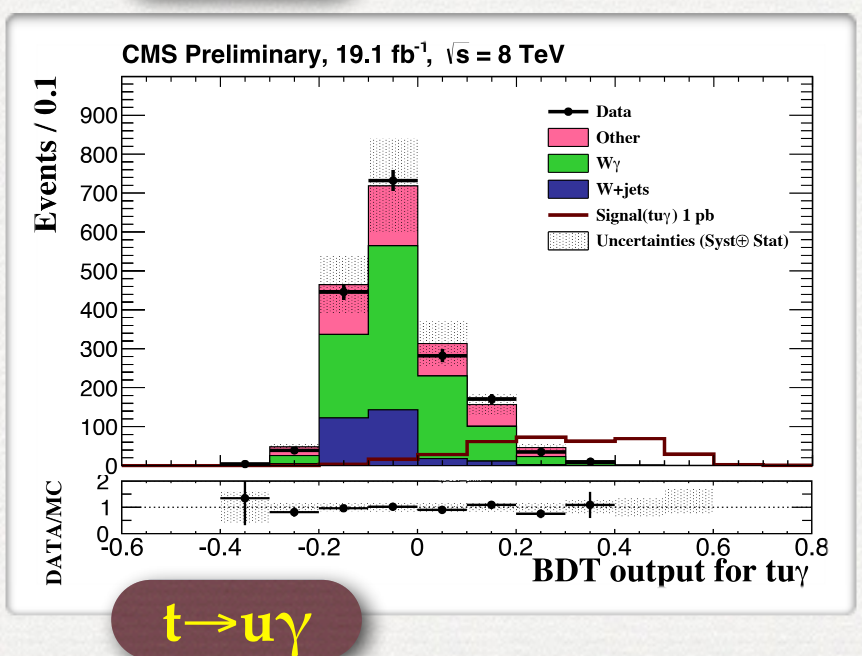
Tevatron measurements are on the lower side; recent CMS result is very close to 1.

TOP FCNC DECAY



- Top decaying to qZ or qγ is highly suppressed in SM: ~O(10^{-14}).
- New physics (e.g. SUSY, Technic color) might enter the loop and enlarge the rate to "detectable level".



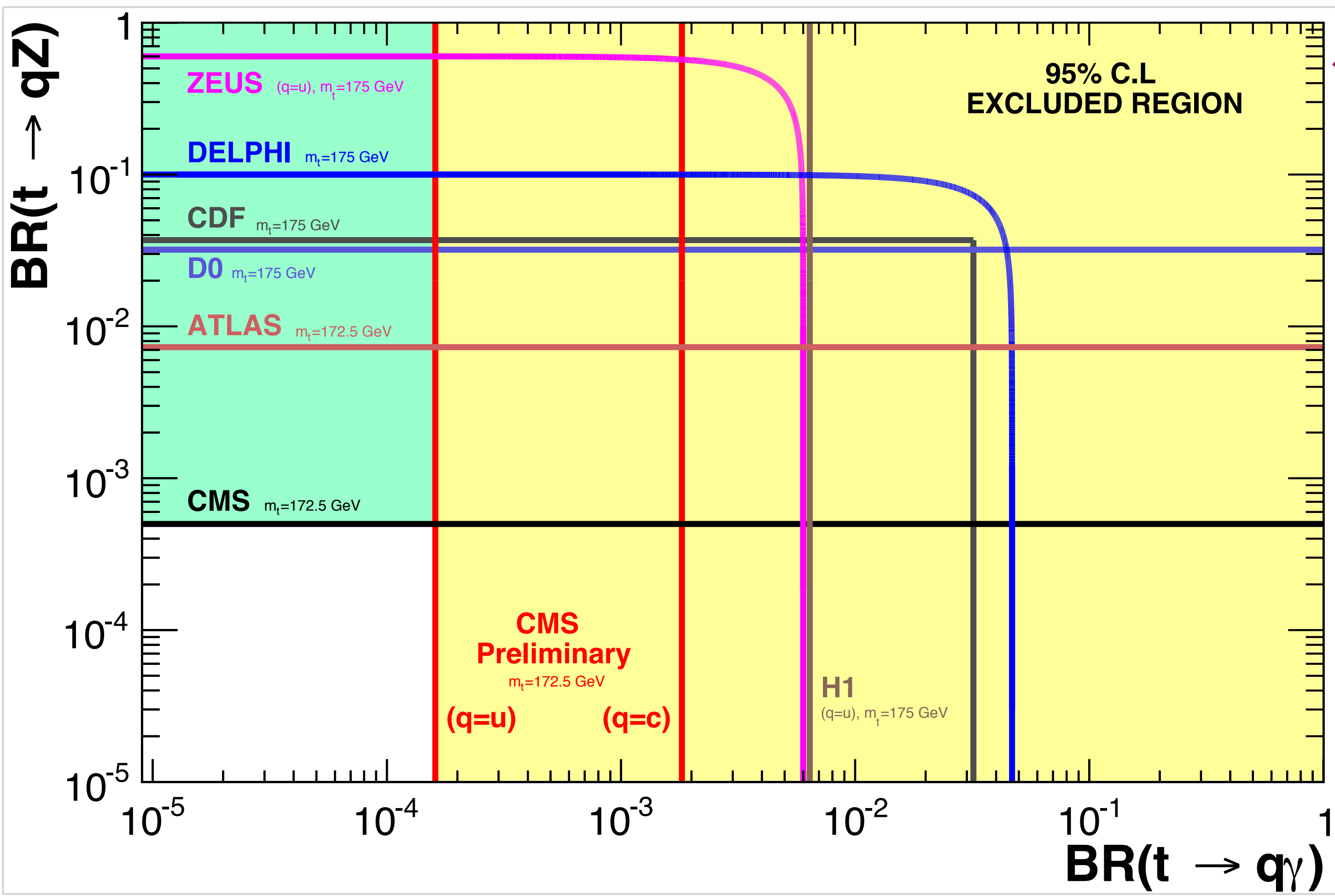


Best limit for each channel so for:

Channel	Best limit @ 95%
BR(t→ug)	< 0.0031% (ATLAS)
BR(t→cg)	< 0.016% (ATLAS)
BR(t→qZ)	<0.05% (CMS)
BR(t→uγ)	< 0.016% (CMS)
BR(t→cγ)	<0.18% (CMS)

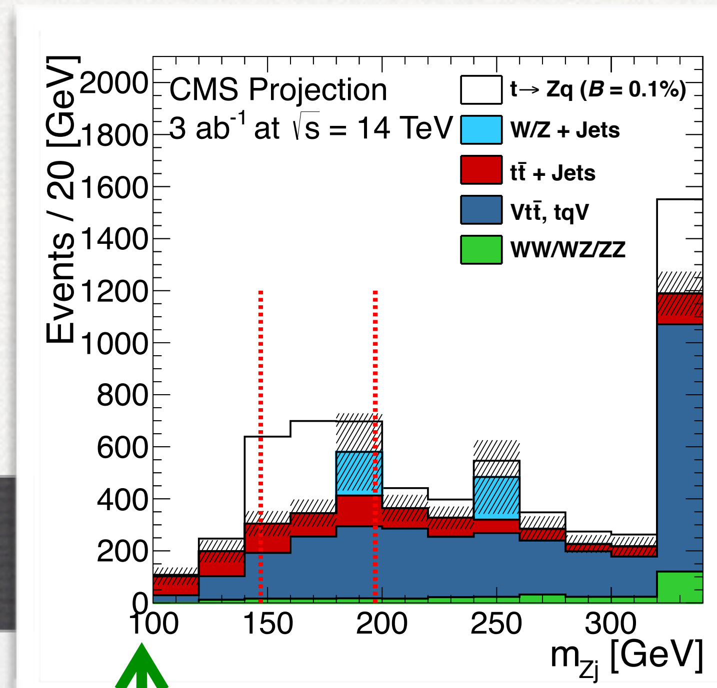
Ref.
CMS PRL 112 (2014) 171802
ATLAS JHEP 1209 (2012) 139
ATLAS PLB 712 (2012) 351
CMS TOP-14-003

TOP FCNC DECAY



Summary of all current FCNC measurements.

LHC improved the limit by 1-2 order of magnitudes already. Further improvement is expected for the future, e.g.:



	20 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	184	1841
Expected limit	< 0.10%	< 0.011%	< 0.007%

HL-HLC projection

Ref. CMS PAS FTR-13-016

SUMMARY

- Top quark physics has reached excellent precisions —
  - Top pair production cross sections have been well measured with all possible decay channel. The best precision from a single measurement already reaches ~4% uncertainty.
  - Some tension between data and TH calculation shows in the top momentum distribution at LHC. New some more investigation from theoretical side.
  - The mass of top is measured to very precision, ~0.5% precision, which provides a strong constraint in the SM.
  - Single top production processes have been all discovered, and the measurements already provide a good constraint on V_{tb}.

After 20 years of top discovery, now the top quark has been detailed measured/tested. How to improve the systematic uncertainties is the crucial work in the near future!

BACKUP SLIDES