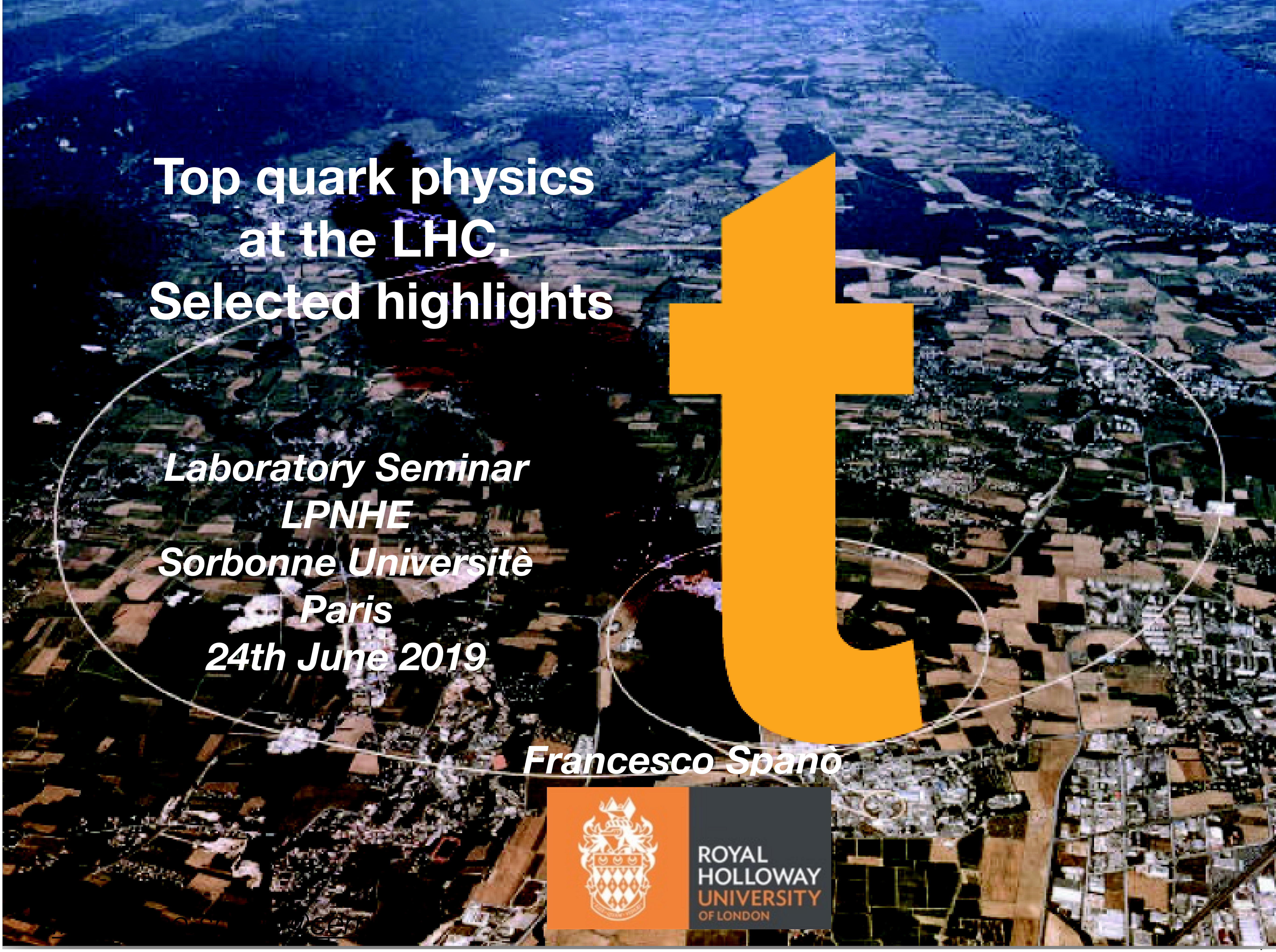


Top quark physics at the LHC. Selected highlights

Laboratory Seminar
LPNHE
Sorbonne Universitè
Paris
24th June 2019

Francesco Spanò

ROYAL
HOLLOWAY
UNIVERSITY
OF LONDON

Outline

- Why top quarks?
  - *Special, standard and “beyond” reasons*

- Top quark production @ LHC - *standard*
  - inclusive
  - differential

- Measuring the top quark mass - *special*

- Top quark and Higgs: Yukawa coupling - *special*

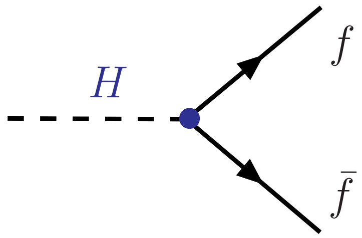
- Top quark and new physics - *“beyond”*
  - search for resonances
  - the quest for an effective field theory

- Conclusions & Outlook

Why study the top quark ?

“Special” reasons

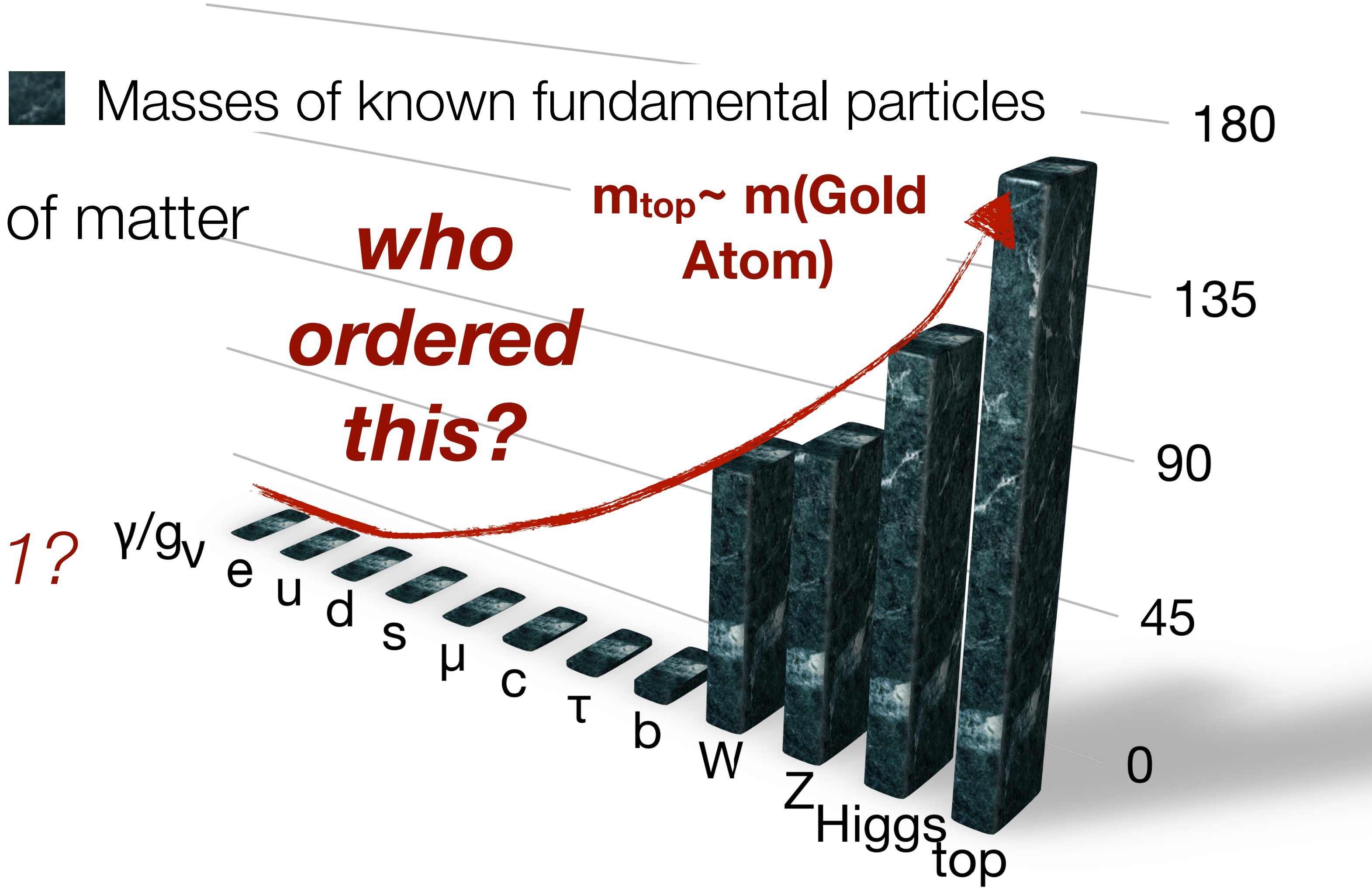
most massive known **constituent** of matter



$m_{top} = y_t \mathbf{v}/\sqrt{2}$

largest coupling y_t to Higgs boson

Is y_t~1?

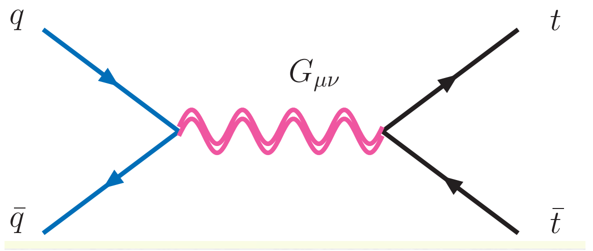


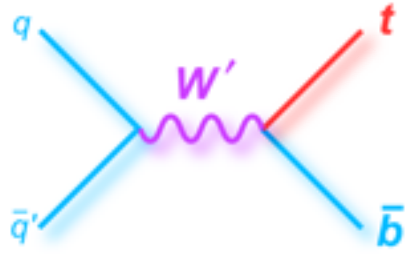
who ordered this?

m_{top}~ m(Gold Atom)

“Beyond” reason(s)

Various scenarios with **new particles prefer decay to/ like top (top partners)**





Ubiquitous background to new phys searches (SUSY, exotica..)

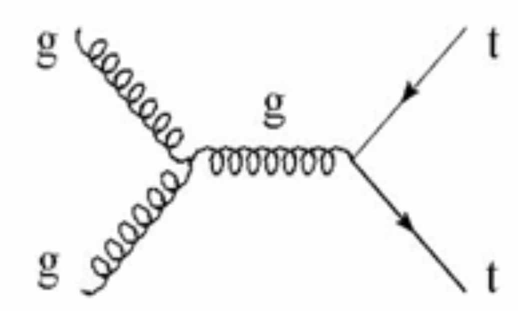
Why study the top quark ?

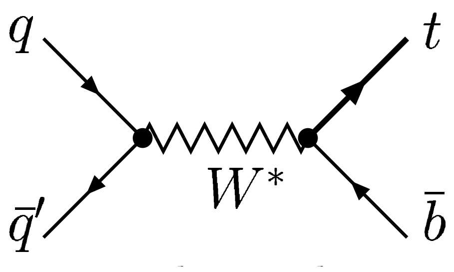
Standard reason(s)

interacts EM, strongly, weakly(NC), Higgs:t → t +g/γ/Z/H

test standard model interactions

Produced in pairs (strong) and singly (weak)



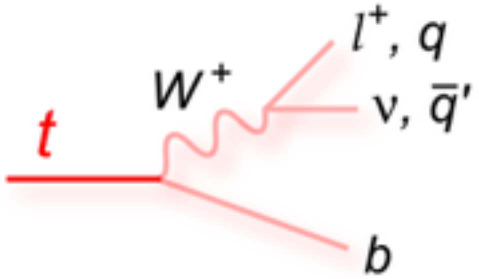


pp → tt: first time gluon-gluon dominates

√s(TeV)	***tt*** *(**t**) frequency at L= 10^{34} cm^{-2} s^{-1}*
13	**~8.3 (~3.0) Hz**

LHC (pp) is a "TOP FACTORY"

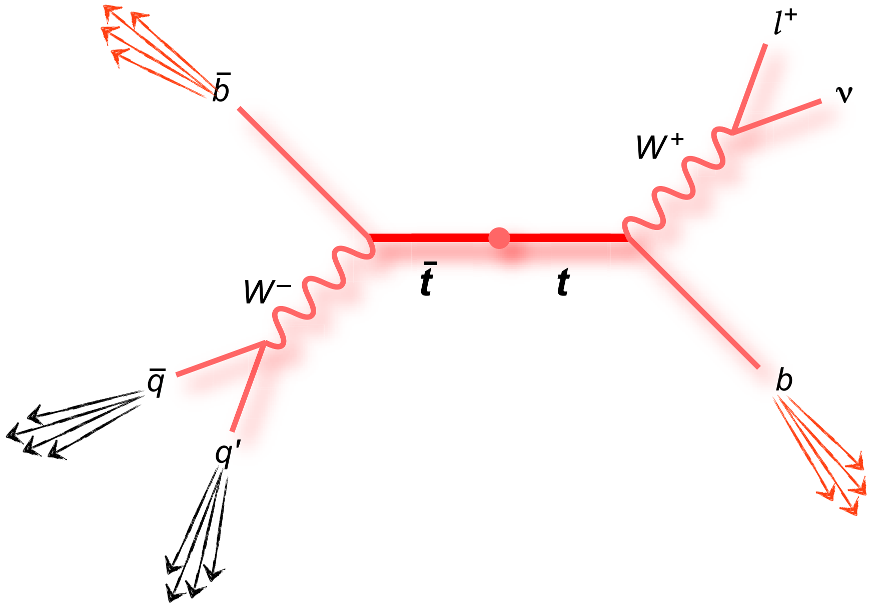
tool for calibration



- **Decays weakly**
  - **t→Wb~BR(99%)**
  - **Γ_{top} ~1.32 GeV**

$1/m_{top}$ ≪	$1/\Gamma_{top}$ ≪	$1/\Lambda_{QCD}$ ≪	m_{top}/Λ_{QCD}
Production time	Lifetime	Hadronization time	Spin decorrelation time

no tt meson observed, **spin info preserved** in decay



What to measure about the top quark

Special reasons

Mass

Coupling to Higgs boson

top-antitop mass difference

today

Standard reasons

Production cross section for double and single top quarks

inclusive & differential

Charge

Width/Lifetime

Branching Fractions

Spin: angular properties in production & decay (tt spin correlation top polarization, W helicity)

Couplings to other force mediators i.e. bosons (W, Z, photon, gluon)

“Beyond” reasons

Deviations from SM predictions

Resonant production & New Physics

LHC : a *Top* producer i.e. providing the luminosity

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm} or $\sqrt{s}$ = 7,8, 13 TeV in 27 Km tunnel

LHC Machine Coordination Twiki

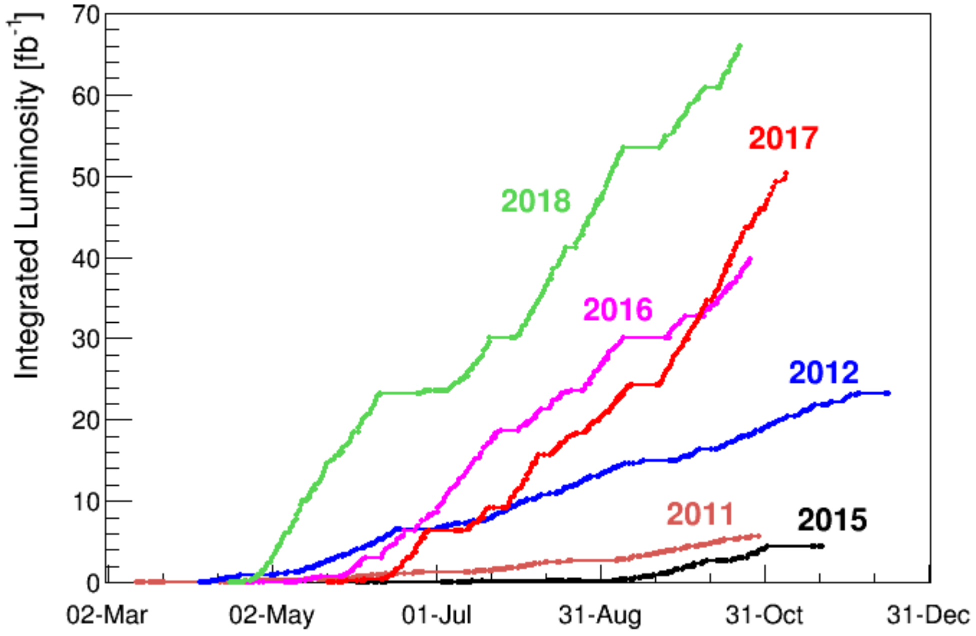
$$\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$$

Key parameters:

N_i = bunch intensity
n_b = number of bunches
σ = colliding beam size

$N_{events}(\Delta t) = \int \mathcal{L} dt$ * cross section

F. Bordry, LHC Status and PLans, Moriond QCD 2019

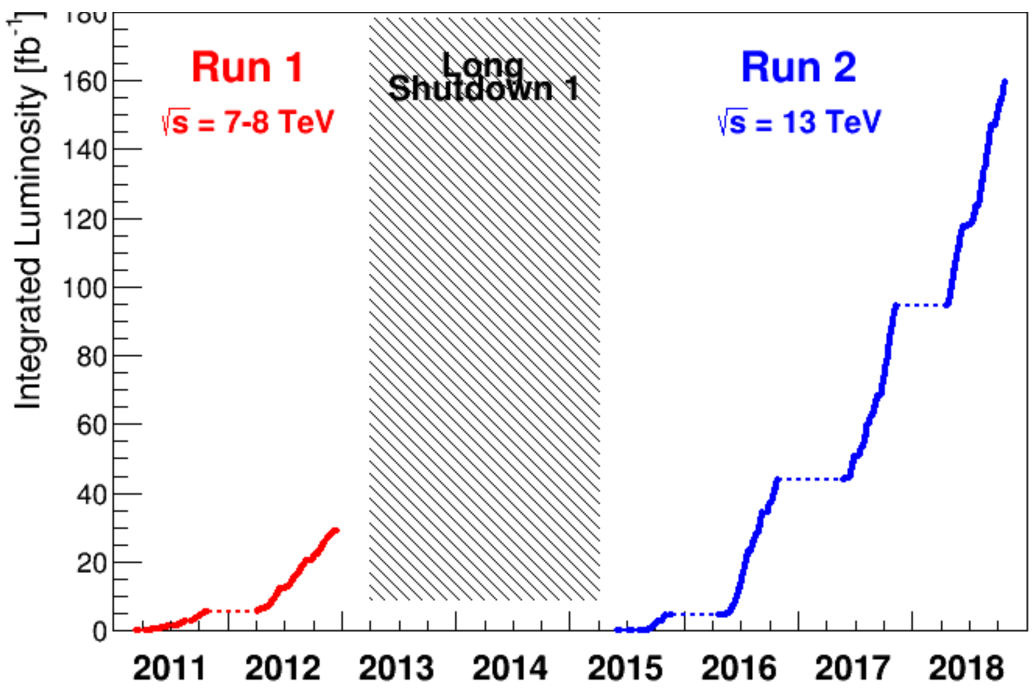


design:

E_{CM}=14TeV ,

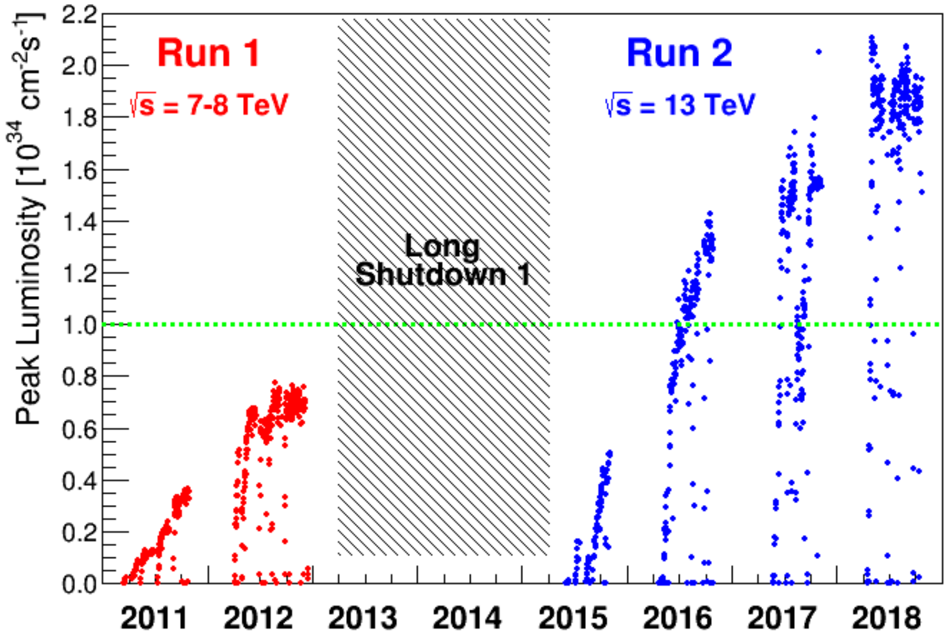
lumi ***10^{34}cm^{-2} s^{-1}***

(~30 times Tevatron pp collider)



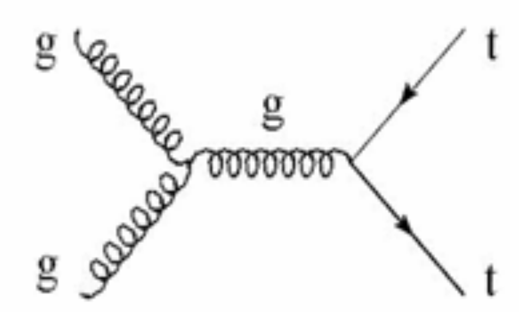
Period	**Integrated Luminosity [fb^{-1}]**
Run 1	**29.2**
Run 2: 2015	**4.2**
Run 2: 2016	**39.7**
Run 2: 2017	**50.2**
Run 2: 2018	**66.0**
Total Run1 + Run 2	**189.3**

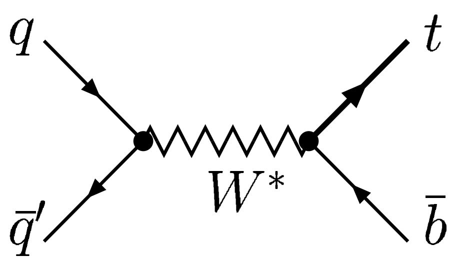
Run 2 at 13 TeV
160.1 fb^{-1}



Top quark @ LHC: top quark manifestation

- **Produced in pairs (strong) and singly (weak)**





√s(TeV)	*tt (t) frequency at L= 10^{34} cm^{-2} s^{-1}*
7	**~1.7 (~0.8) Hz**
8	**~2.4 (~1.2) Hz**
13	**~8.3 (~3.0) Hz**

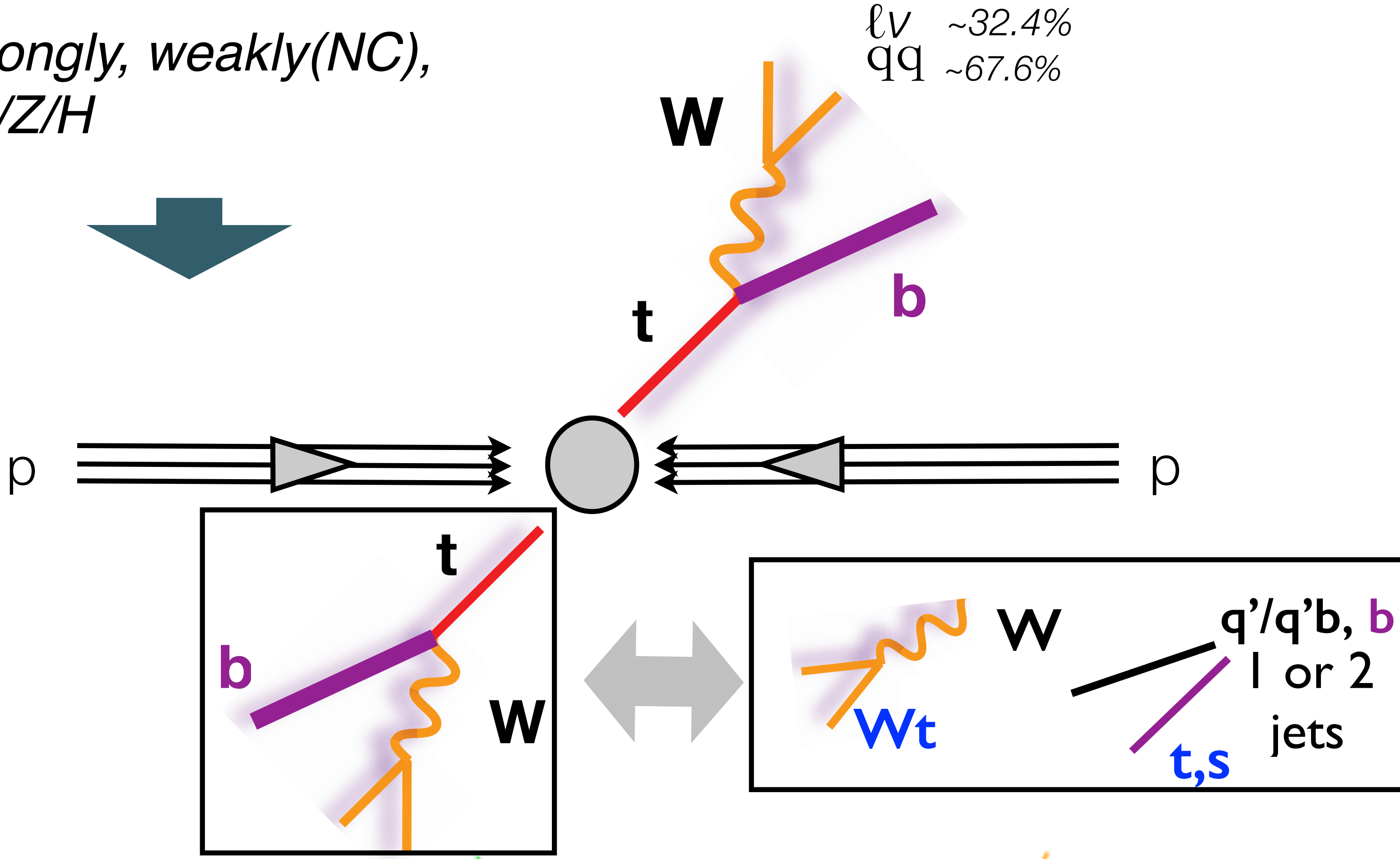
Run2 LHC peak lumi: 1.5·10^{34} cm^{-2} s^{-1}

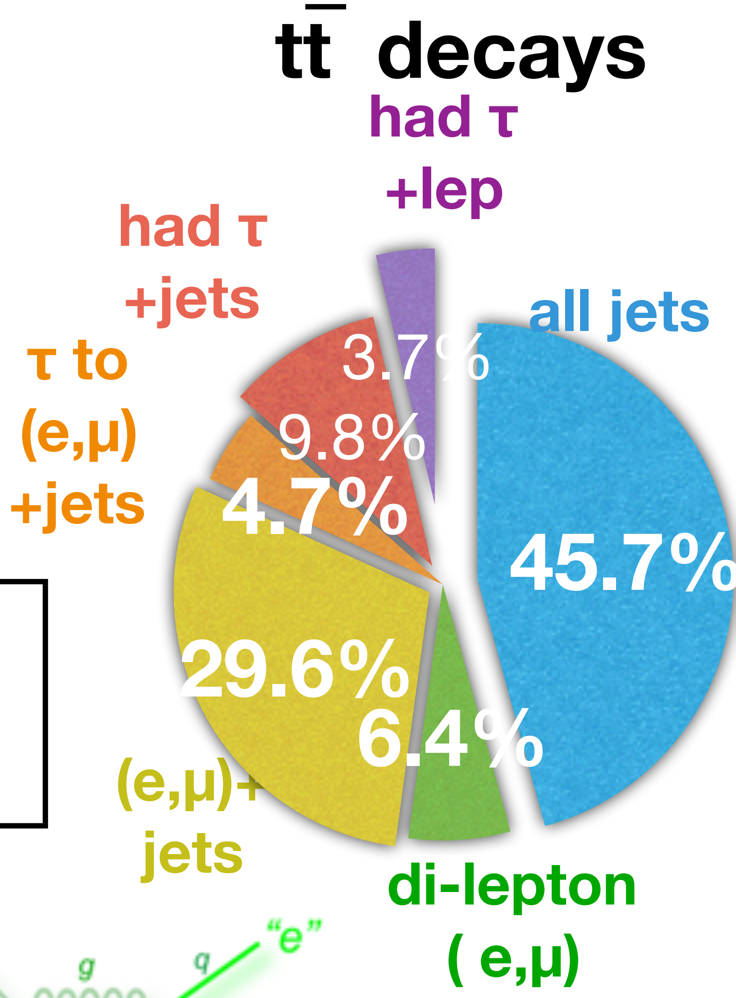
LHC (pp) is a “TOP FACTORY”

- **Decays weakly (CC): t→Wb~BR(99%)** Γ_{top} **~1.32 GeV**

interacts EM, strongly, weakly(NC),
Higgs:t →t +g/γ/Z/H

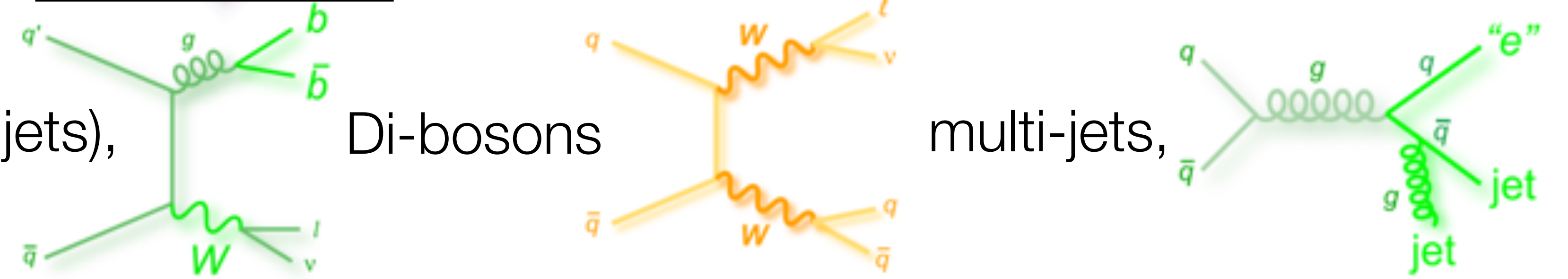
- **High P_T jets of hadrons**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**




$t\bar{t}$ decays

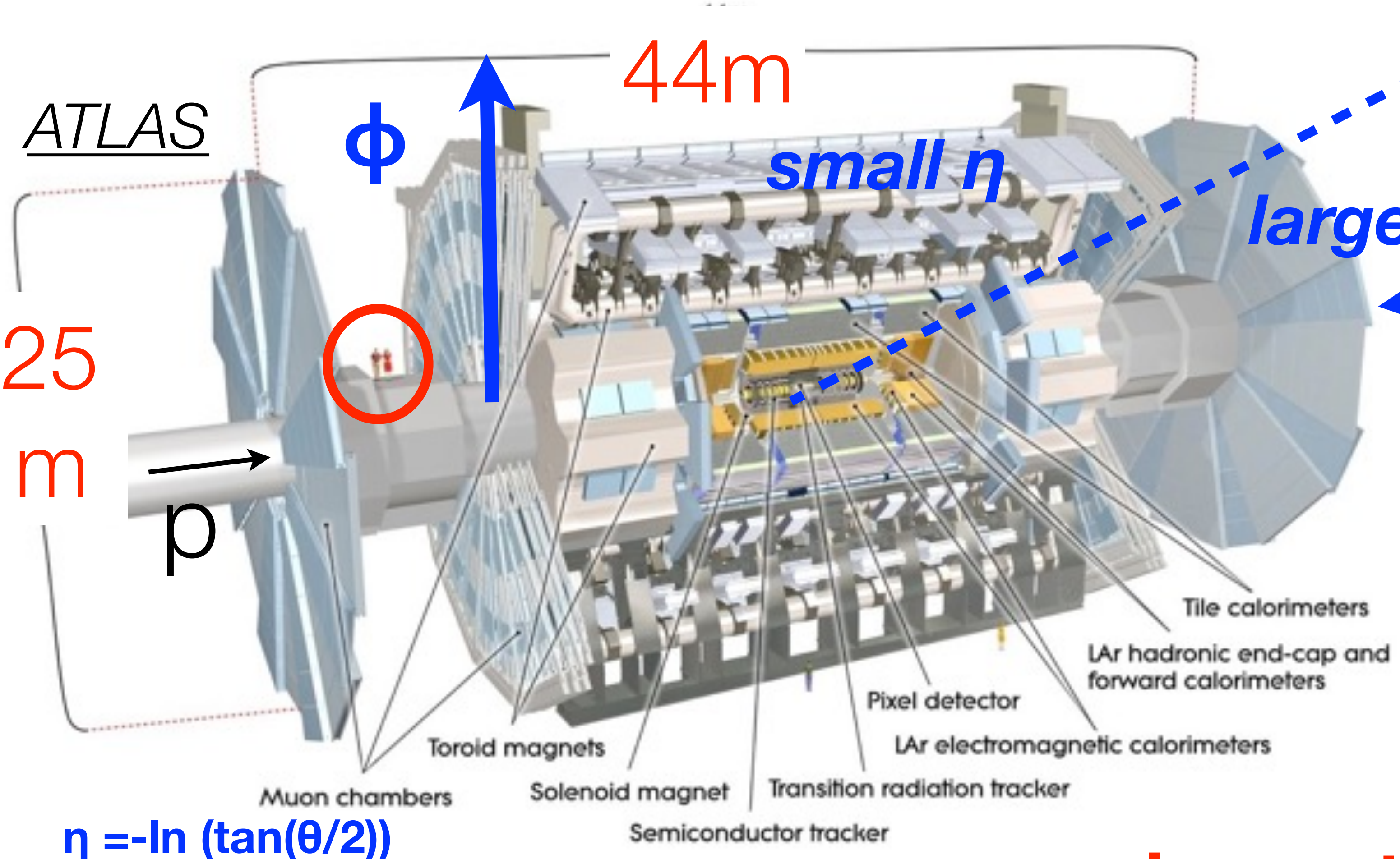
bkgs(tt): t+

bkgs(t): tt +

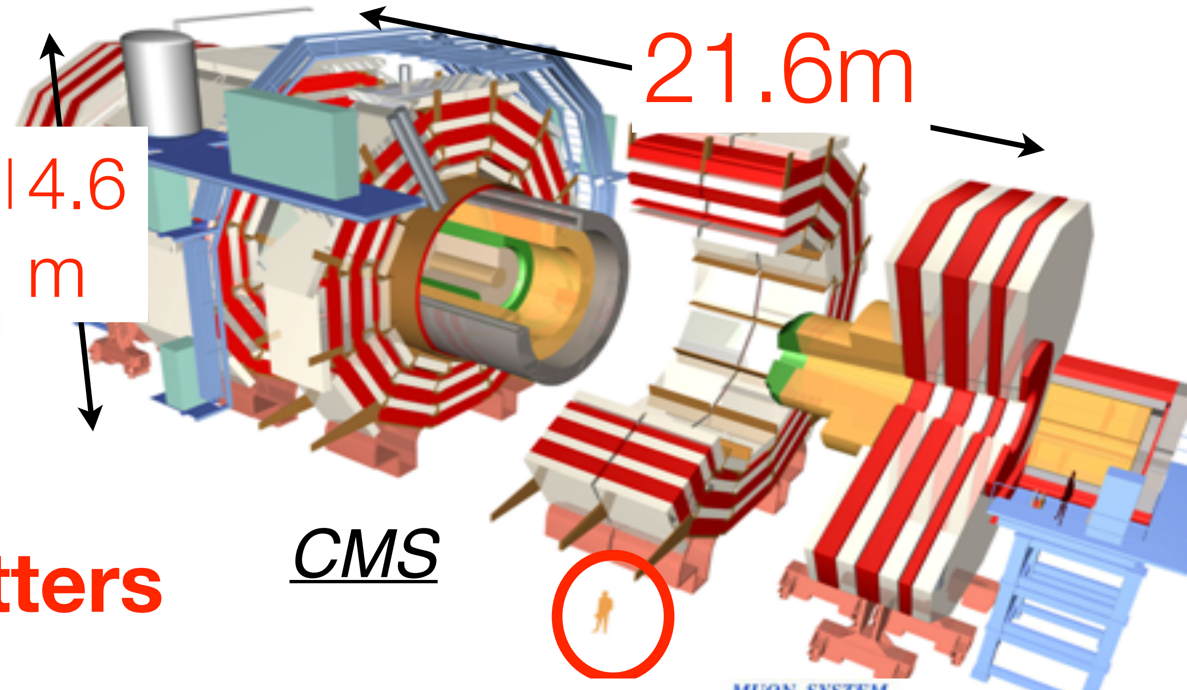


W/Z(+jets), Di-bosons multi-jets,

***Top* observers *ATLAS* & *CMS*:** @LHC(pp)

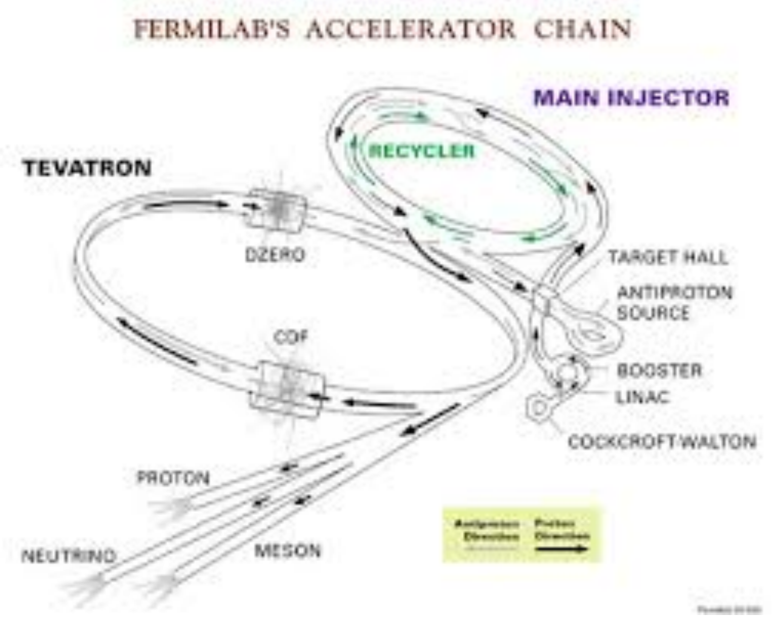


$\eta = -\ln(\tan(\theta/2))$

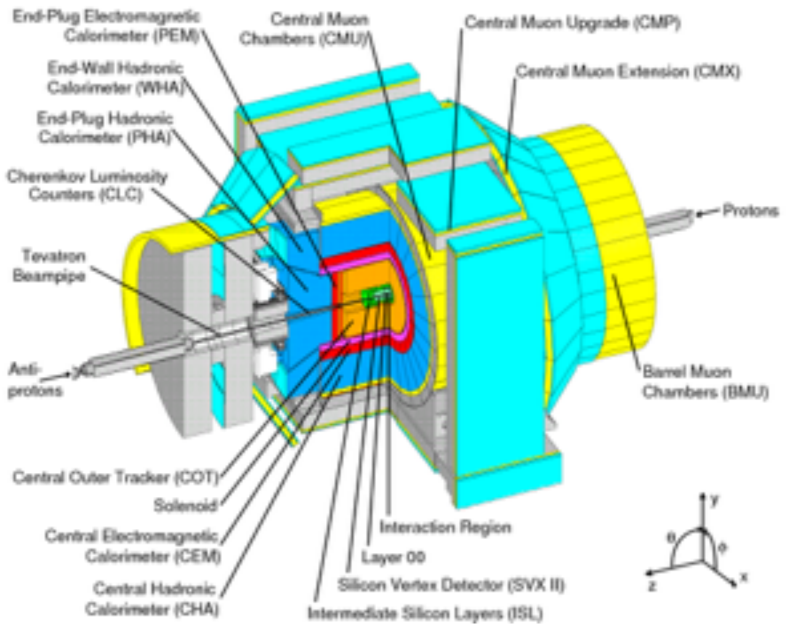


size matters

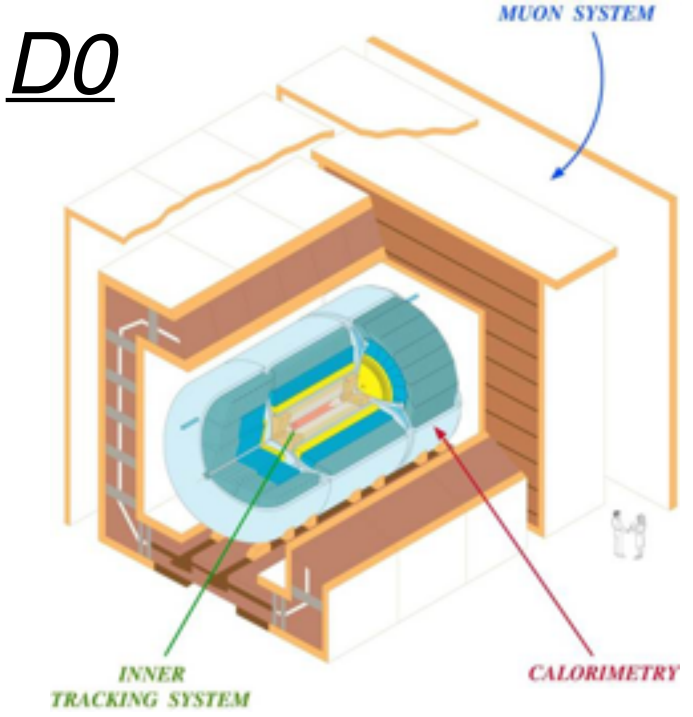
CDF & D0: @Tevatron (p$\bar{p}$)



CDF



D0



Measuring Top quark production @LHC

standard reasons

standard reasons: top quark production@ LHC

pp collisions

	Tevatron	LHC(8)	LHC(14)
gg	~10%	~86%	~90%
qq	~90%	~14%	~10%

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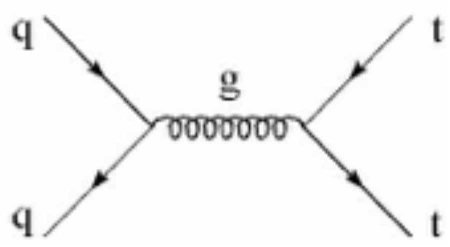
probing lower x than Tevatron → dominated by increasing gluon fusion

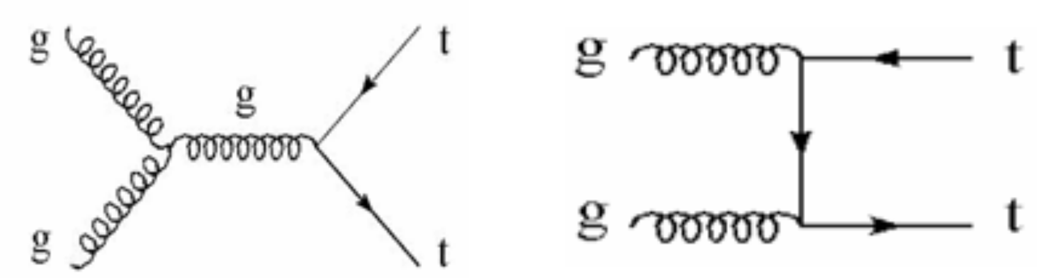
production cross section increases

top pairs: strong

qq annihilation



gluon fusion



At Tevatron

($\sqrt{s}$=1.96 TeV)

$\boxed{\sigma_{t\bar{t}} \sim 7\ pb}$

At LHC

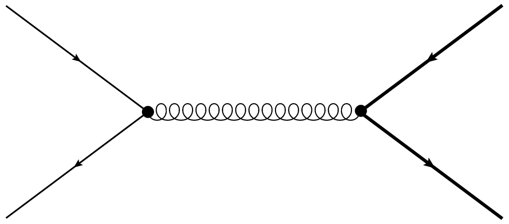
$\sqrt{s}$(TeV)	σ_{tt} (pb)	*nominal rate*
8	~245	~2.4 Hz
13	~830	~8.3 Hz

Measure

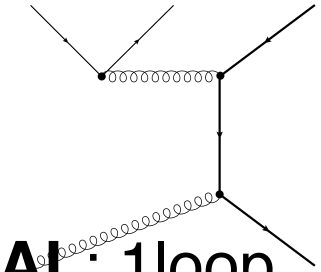
- **inclusively:high precision**
- **differentially: extreme regions**
- **explore rare decays (tt+X)**

Top quark predictions@ LHC- the NNLO revolution : tt

from LO



to NLO..

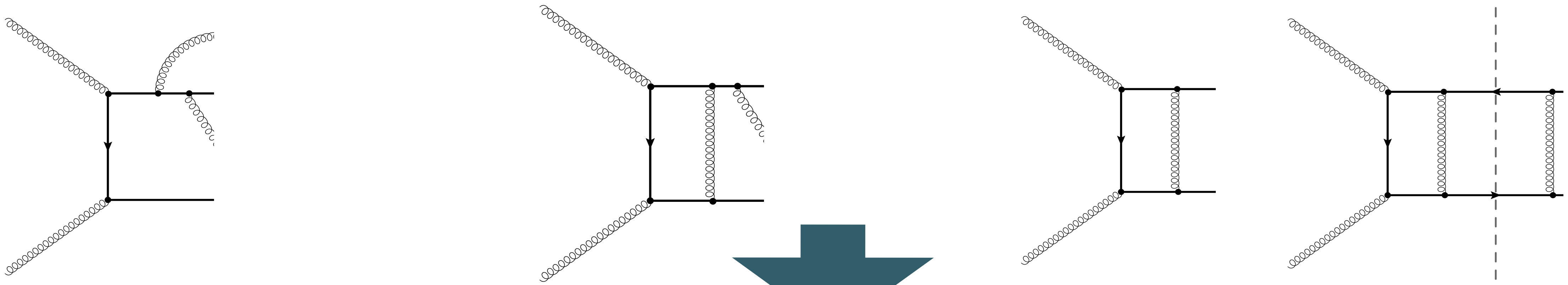


Double REAL: 2 extra emitted real partons at tree level

REAL-VIRTUAL:1 virtual loop+ 1 extra parton

Double VIRTUAL: 1loop squared + two virtual loops

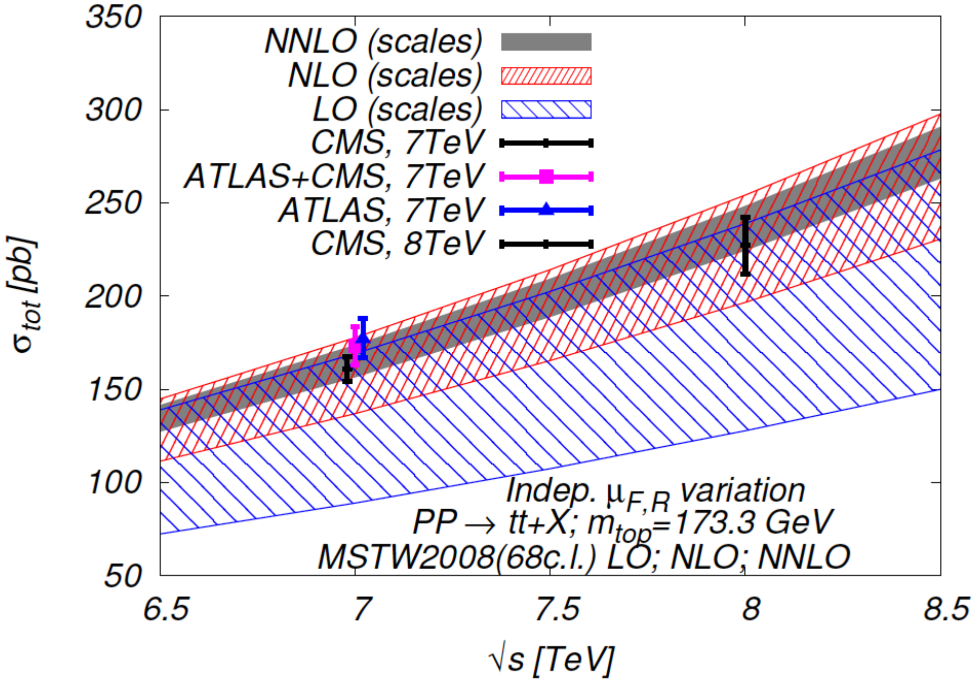
NNLO



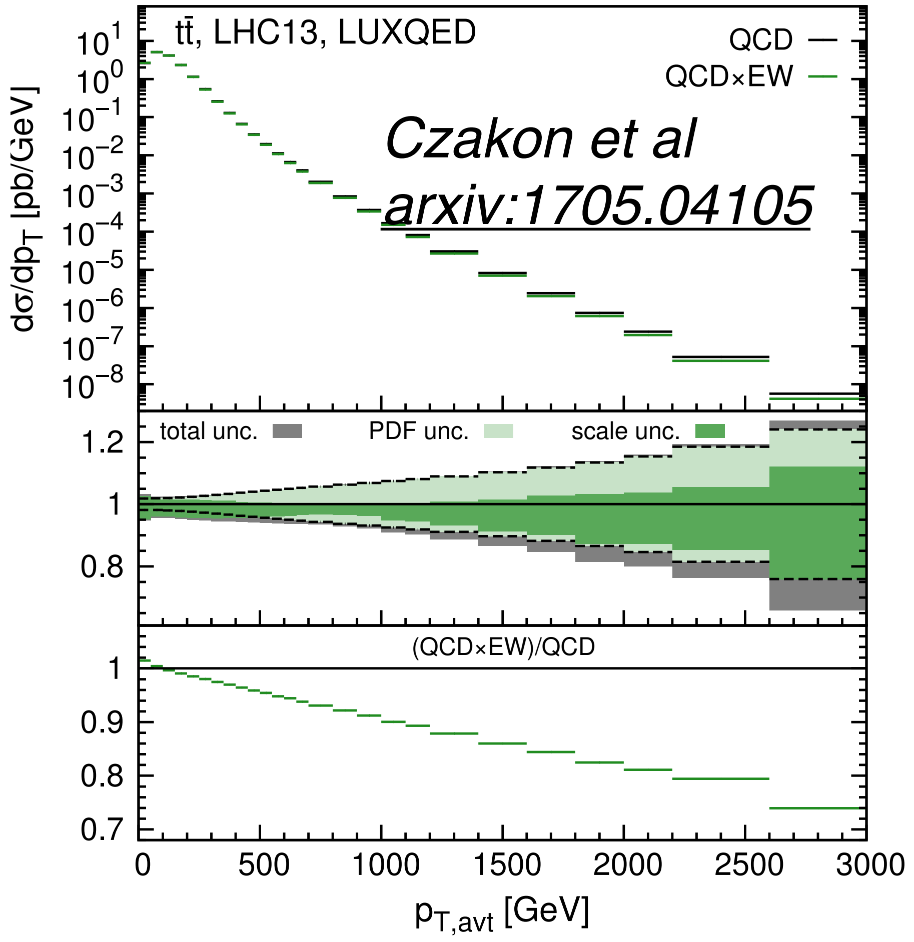
inclusive σ_{tt}

Czakon,Fedler,Mitov PRL 110.252004

Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_s (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%



$d\sigma_{tt}/dX$:NNLO+EWK



Czakon et al arxiv:1705.04105

Standard reasons: **top quark production @ LHC**

pp collisions

probing lower x than Tevatron → dominated by increasing gluon fusion

	Tevatron	LHC87	LHC(14)
gg	~10%	~86%	~90%
qq	~90%	~14%	~10%

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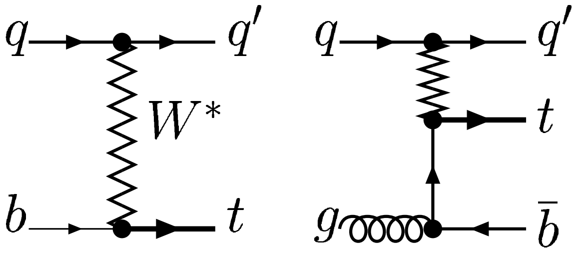
production cross section increases

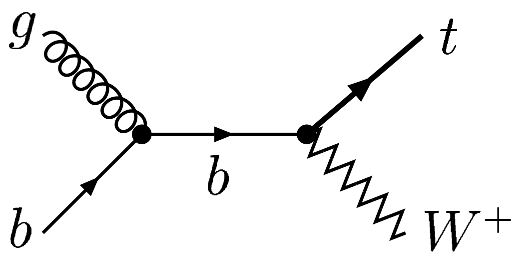
single top:
electroweak

t-chan



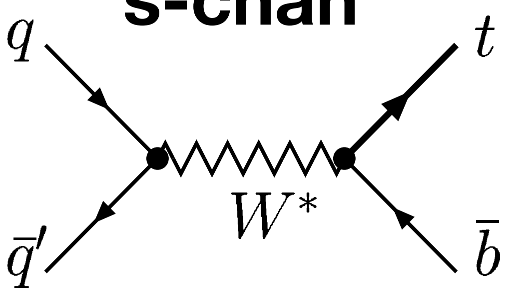
~76-72%

tW chan



~19-24%

s-chan



~5-4%

At Tevatron

(√s=1.96 TeV)

σ_t ~ 3.5 pb

At LHC

√s(TeV)	σ_t (pb)	*nominal rate*
8	~116	~1.2 Hz
13	~305	~3.0 Hz

Swamped by tt (2-3 x)

Measure

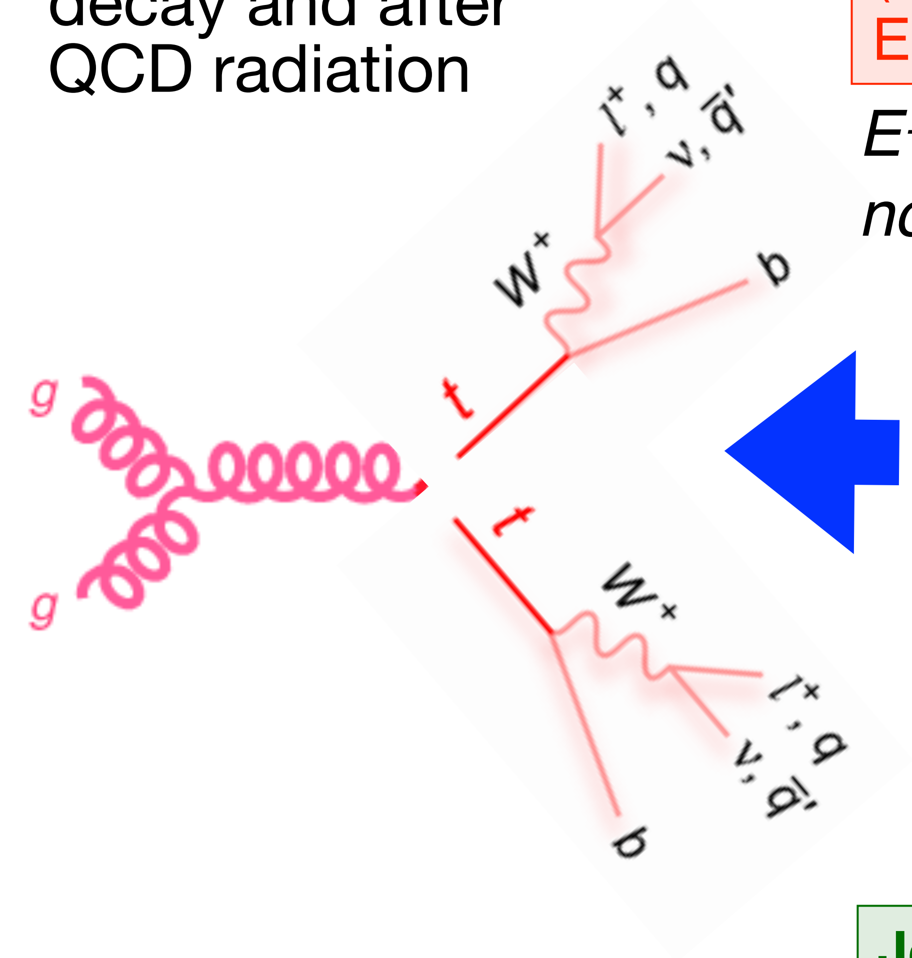
- **inclusively & differentially**
- **explore rare processes (t+X)**

Standard reasons: **measure top quark production**

$$\sigma^{total}_{tt,t} = \frac{\sigma^{fid}_{tt,t}}{BR \cdot \mathcal{A}}$$

- **Parton level,full phase space**

- generated quarks before decay and after QCD radiation



LHCtopWGParticleLevelDef

$$\sigma^{fid}_{tt,t} = \frac{N_{obs,events} - N_{background}}{\int L dt \cdot \mathcal{E}}$$

- **Particle level, fiducial phase space**
  - stable particles after rad & had; close to (detector-level) selection

Leptons: from W decay (not from hadron)+ “including” close-by EM radiation (photons not from hadrons)

E_T^{miss}=sum ν *not from had*

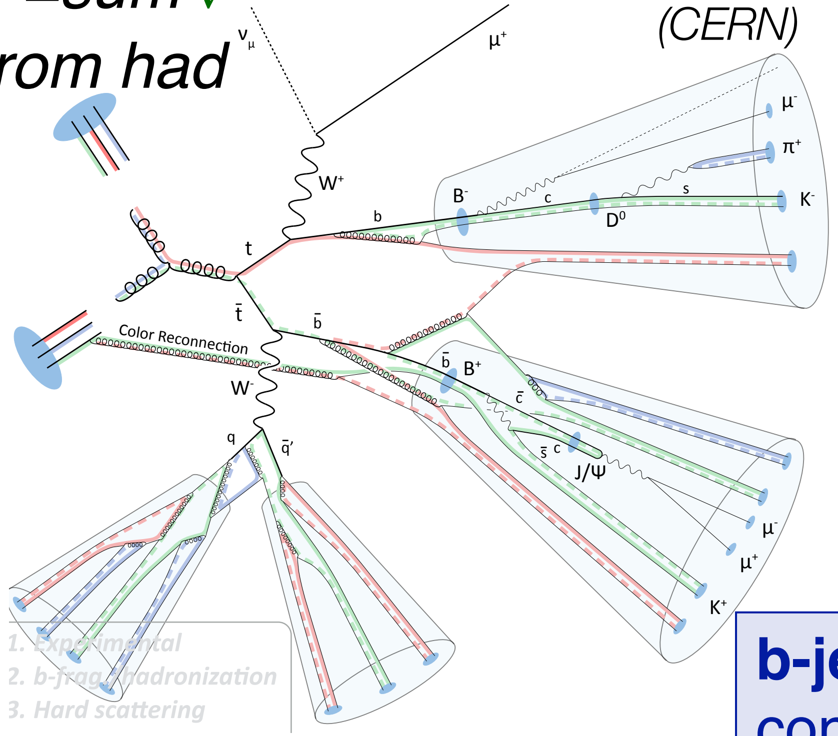
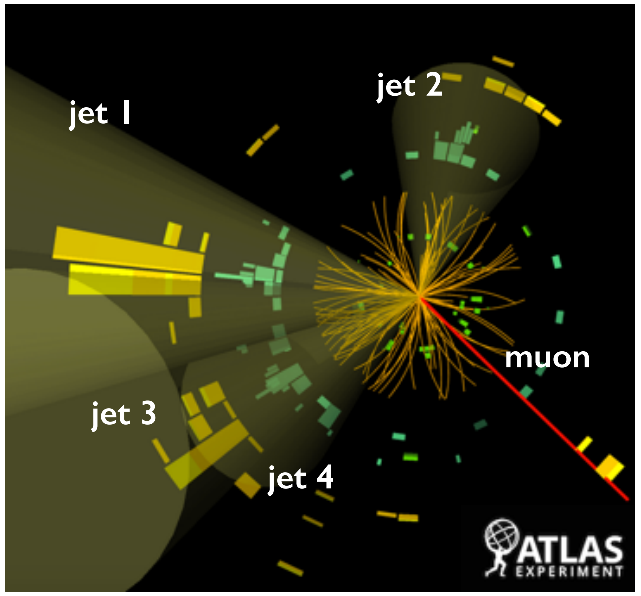


Figure by B Stieger (CERN)

Jets: anti-kT algorithm (as for reco jets), cluster all but prompt particles (i.e, ν, μ from hadron decays are inside jets)

b-jets: contains a B-hadron (in jet algo)

- **Select events**
- **Subtract estimates of bkg**
- **ϵ = correction for branching fraction, detection/ extrapolation efficiency, luminosity**



- **Detector level**

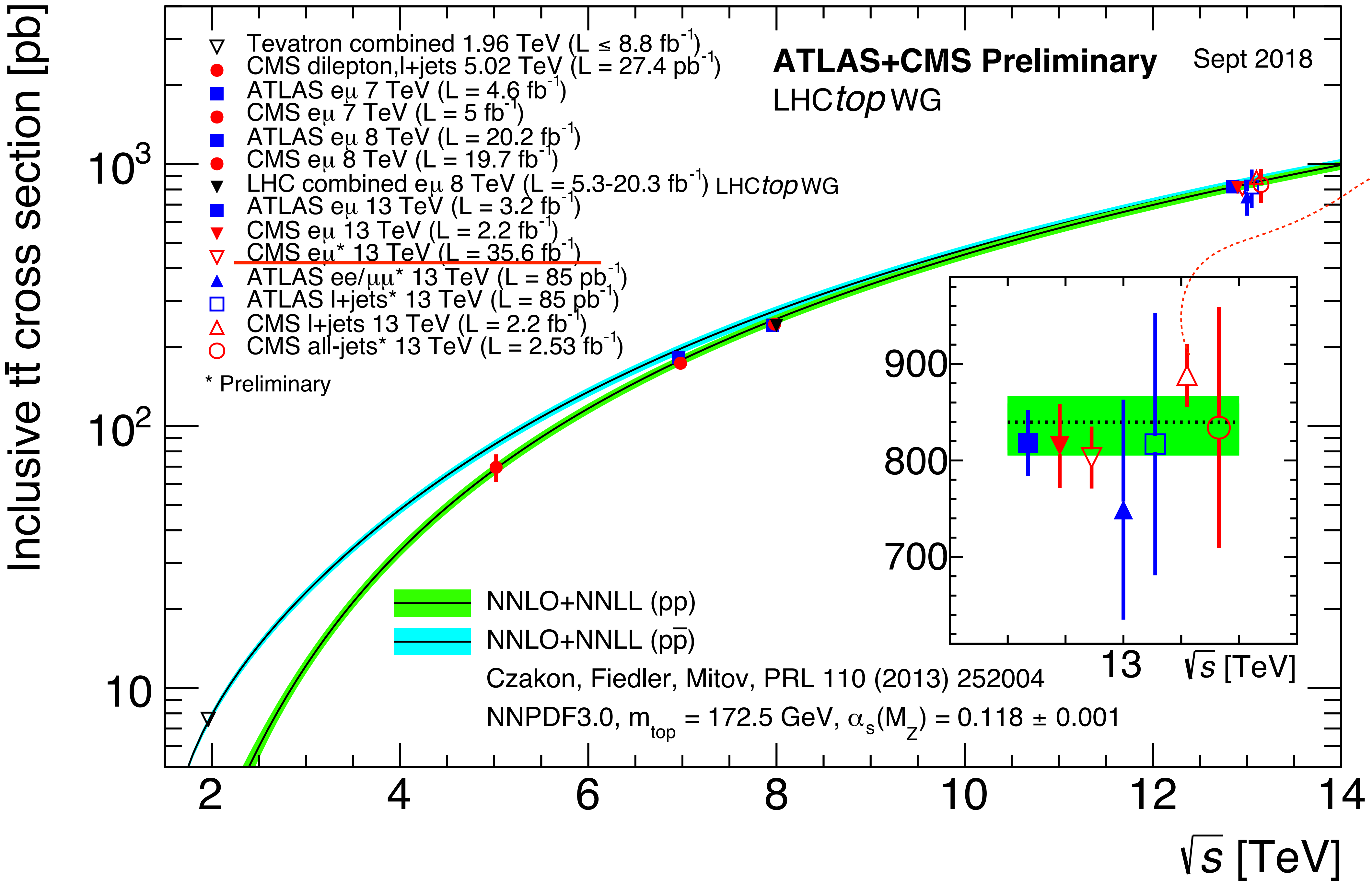
example uses tt valid for single top quark as well

Standard reasons: **measure inclusive σ_{tt} vs $\sqrt{s}$**

Systematics dominated in most precise results, comparable to theory uncertainty

all results consistent with NNLO+NNLL predictions over 2 orders of magnitude

LHCTopWGSummaryPlots



Published in Eur. Phys. J. C 79 (2019) 368

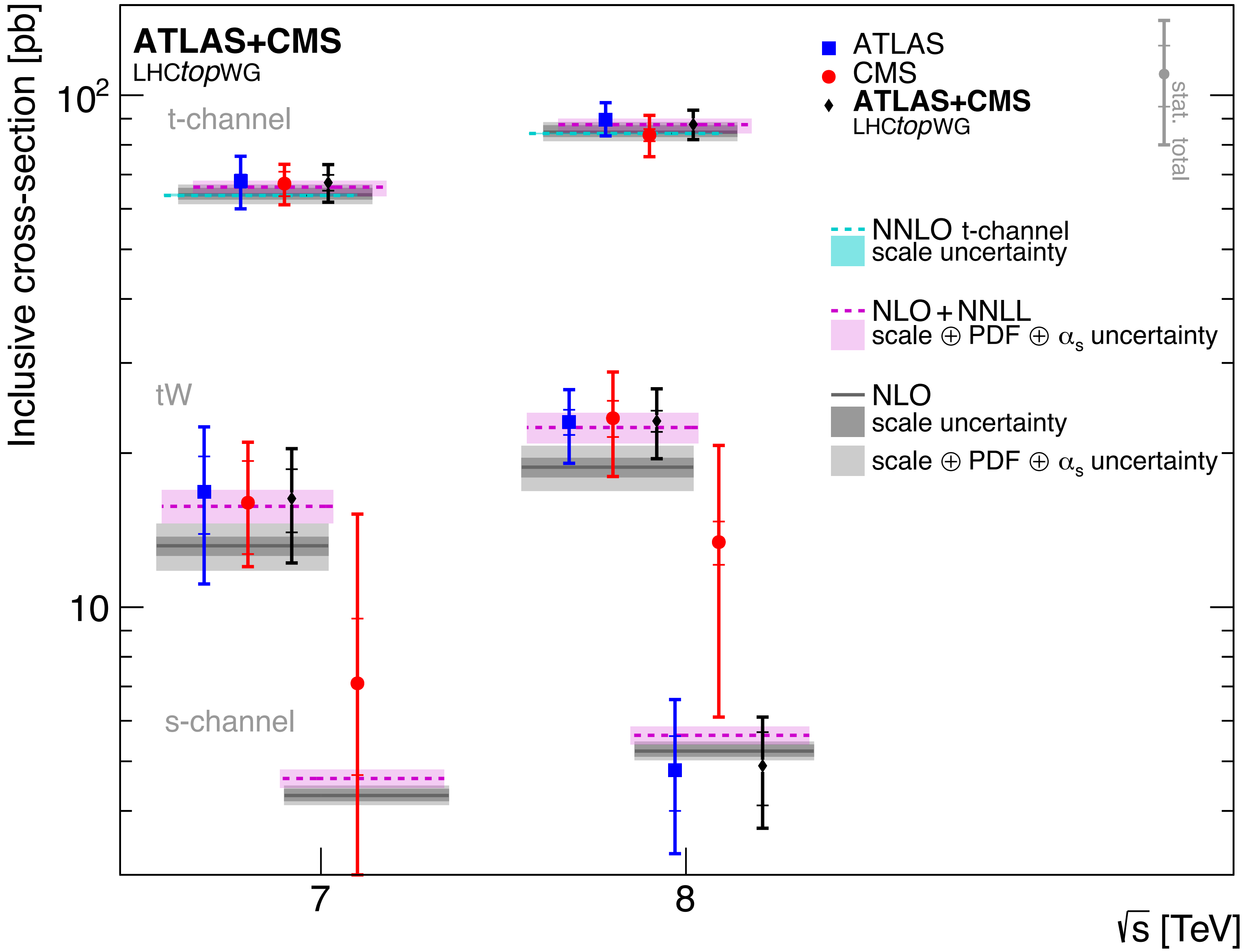
$\delta\sigma_{tt}/\sigma_{tt}$ ~4%

$\sqrt{s}$	most precise $\delta\sigma_{tt}/\sigma_{tt}$ (%)	
	ATLAS	CMS
7	3.9	3.6
8	4.2	3.7
13	4.4	3.9

Special reasons: measure inclusive σ_t vs $\sqrt{s}$

Systematics dominated, larger bkg than tt

JHEP 05 (2019) 088



All results consistent with approx NNLO/ NNLO predictions

dominant systematic uncertainties: theoretical modelling, jets

7 TeV

$$\sigma_{t\text{-chan.}} = 67.5 \pm 2.4\ (\text{stat.}) \pm 5.0\ (\text{syst.}) \pm 1.1\ (\text{lumi.})\ \text{pb} = 67.5 \pm 5.7\ \text{pb}.$$ **$\delta\sigma_t/\sigma_t$ ~8.4%**

$$\sigma_{tW} = 16.3 \pm 2.3\ (\text{stat.}) \pm 3.3\ (\text{syst.}) \pm 0.7\ (\text{lumi.})\ \text{pb} = 16.3 \pm 4.1\ \text{pb}.$$ **$\delta\sigma_t/\sigma_t$ ~4.1%**

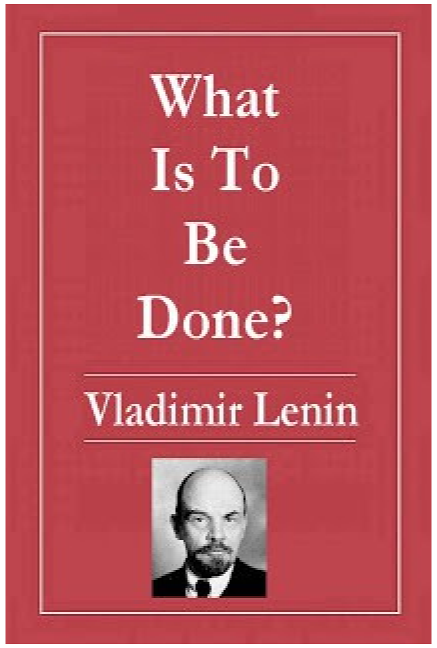
8 TeV

$$\sigma_{t\text{-chan.}} = 87.7 \pm 1.1\ (\text{stat.}) \pm 5.5\ (\text{syst.}) \pm 1.5\ (\text{lumi.})\ \text{pb} = 87.7 \pm 5.8\ \text{pb}.$$ **$\delta\sigma_t/\sigma_t$ ~6.7%**

$$\sigma_{tW} = 23.1 \pm 1.1\ (\text{stat.}) \pm 3.3\ (\text{syst.}) \pm 0.8\ (\text{lumi.})\ \text{pb} = 23.1 \pm 3.6\ \text{pb}.$$ **$\delta\sigma_t/\sigma_t$ ~3.6%**

francesco.spano@cern.ch

When you hit the systematics wall



General consideration: when syst >> stat, to maximize the utility of your data you can:

- Stop and think
  - (e.g., pin down the source of the problem, constrain it, then come back)
- Take ratios
- Go differential
- Any combination of the above

We had examples of all of those at TOP2017

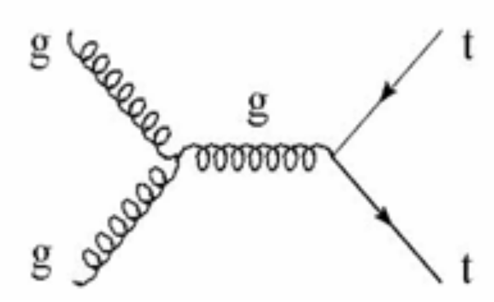
(A Giammanco, TOP20127)

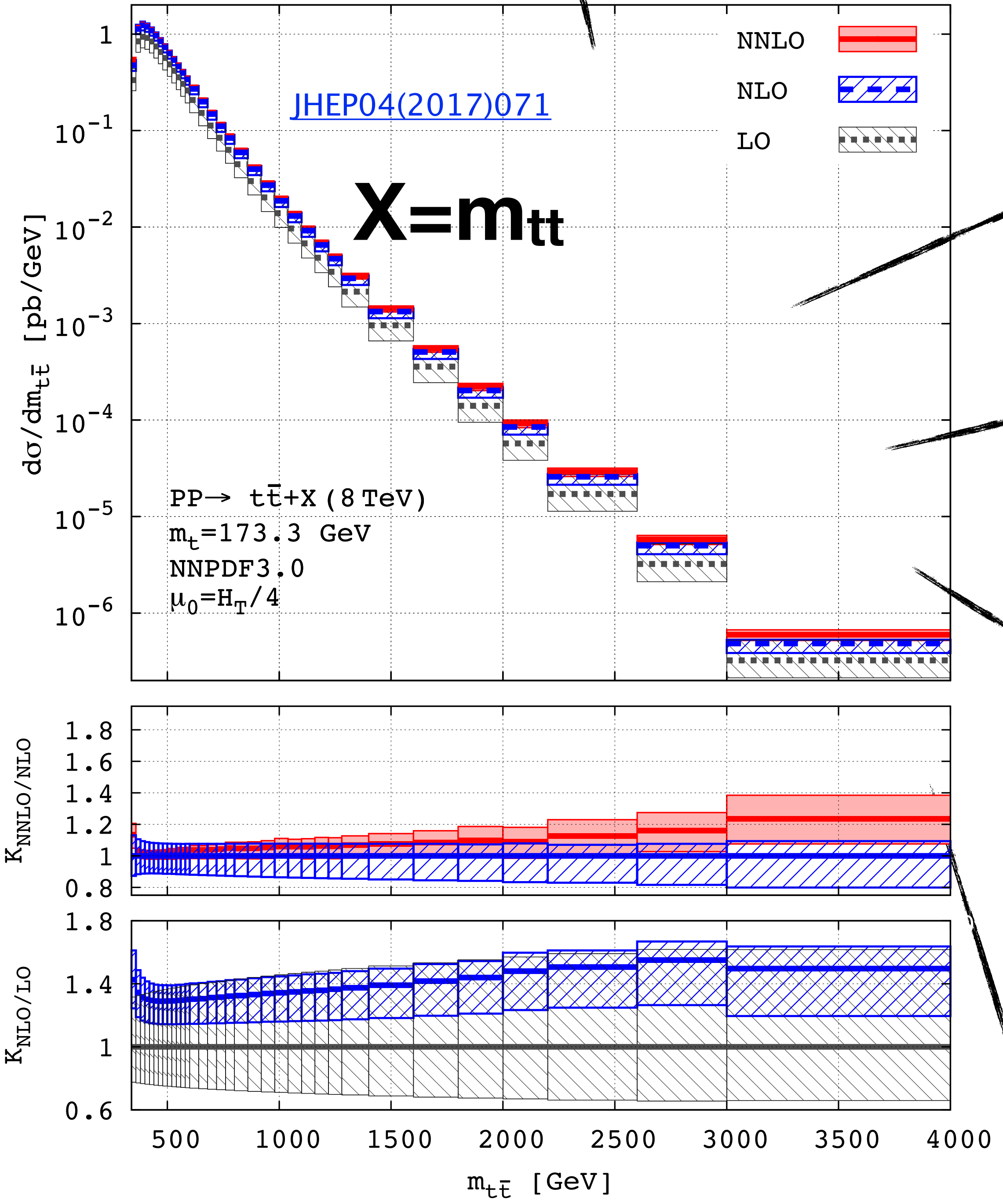
Standard reasons: On to measure d$\sigma_{tt,t}$/dX: why?

test SM predictions (NLO+PS,NNLO QCD) & extension (EFT)

complement new physics searches

- **LHC is a top factory**





measure kinematics→ **reduce t/tt modeling uncertainties**

extract SM parameters (m_{top},α_s)

Constrain gluon content of the proton at high x (PDF)

increasing precision!

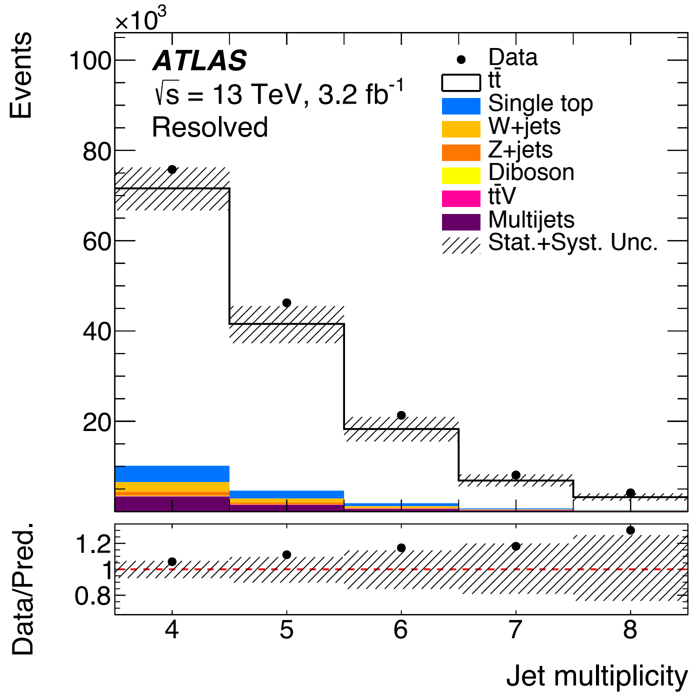
develop **new reconstruction/recognition techniques**

(high pile-up, very high p_T..) :

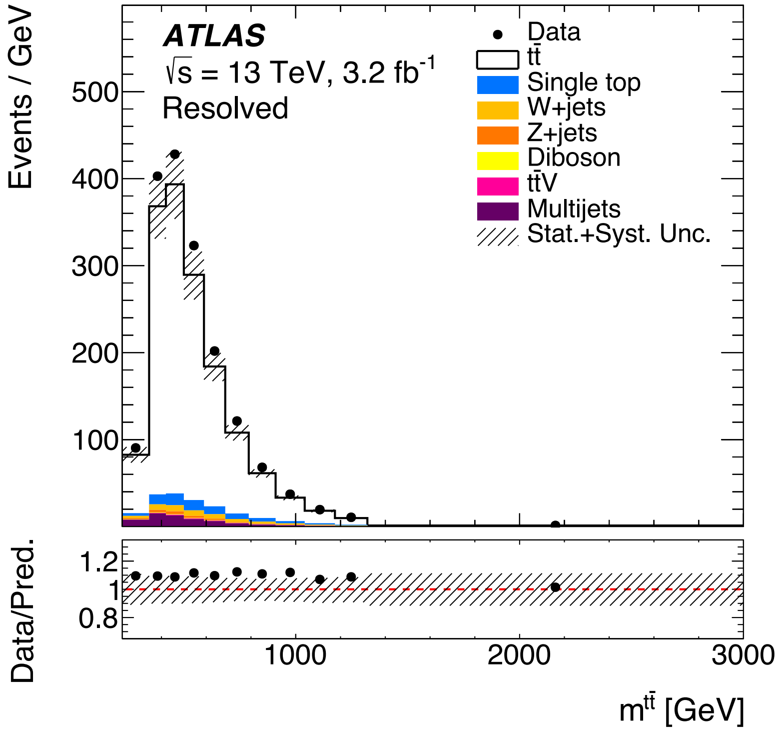
Standard reasons: **How?**

(thanks to Maria Aldaya (DESY))

(1) Select pure tt̄/t sample



(2) tt̄/t kinematic reconstruction

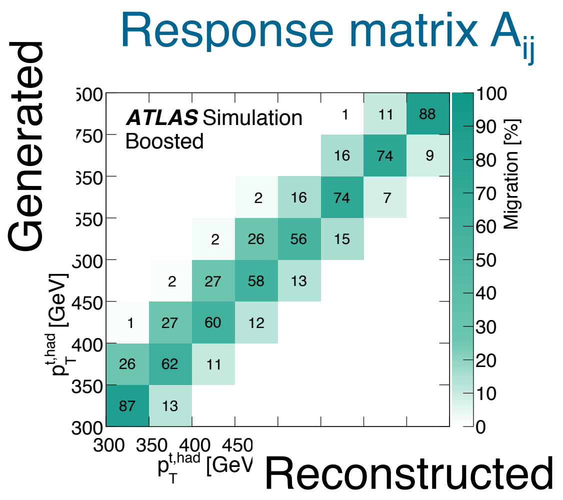


(3) Bin-wise cross section measurement

- Subtract background
- Correct for detector effects & acceptance → **unfolding**

Δ^i_X = bin width for variable X

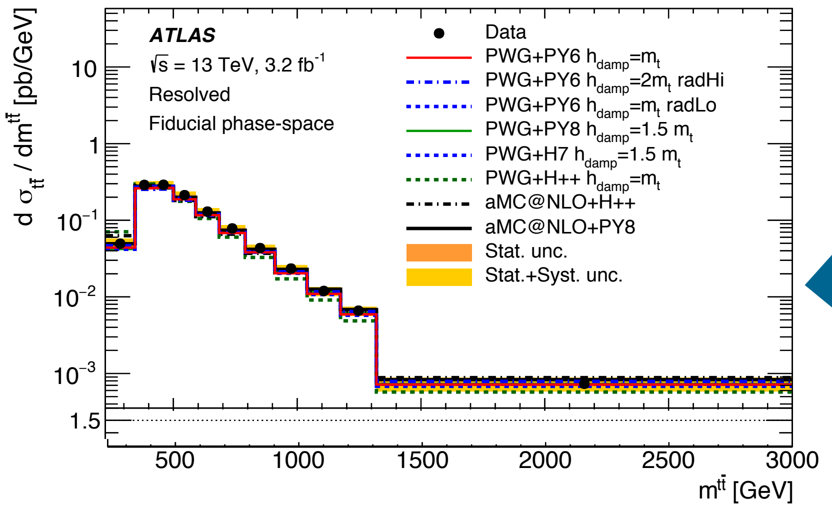
$$\frac{1}{\sigma}\frac{d\sigma}{dX_i} = \frac{1}{\sigma}\frac{\sum_j A^{-1}_{ij}\left[(N_{\mathrm{data,j}} - N_{\mathrm{BG,j}})\right]}{\Delta_{X_i} \cdot L}$$



(4) **Compare to Predictions with χ^2 & p values** using **Covariance** (stat,sys and correlation).

$$\chi^2 = (\mathbf{X} - \mathbf{P})^T \mathbf{C}^{-1} (\mathbf{X} - \mathbf{P})$$

- Parton or particle level
- Fiducial or extrapolated to full phase space
- Absolute or normalized to inclusive σ_{tt}



Standard reasons: $\mathbf{d\sigma_{tt,t}/dX}$ **@ √s=8,13 TeV**

Absolute and normalised cross sections for

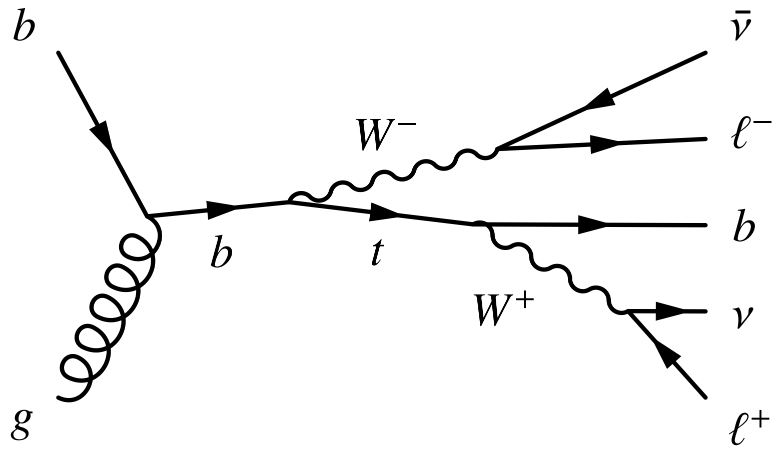
Final state kinematics

kinematic variables of leptons

mass, p_T and energy of dilepton system

energy, mass of system of leptons, b-jets and E_T^{miss}

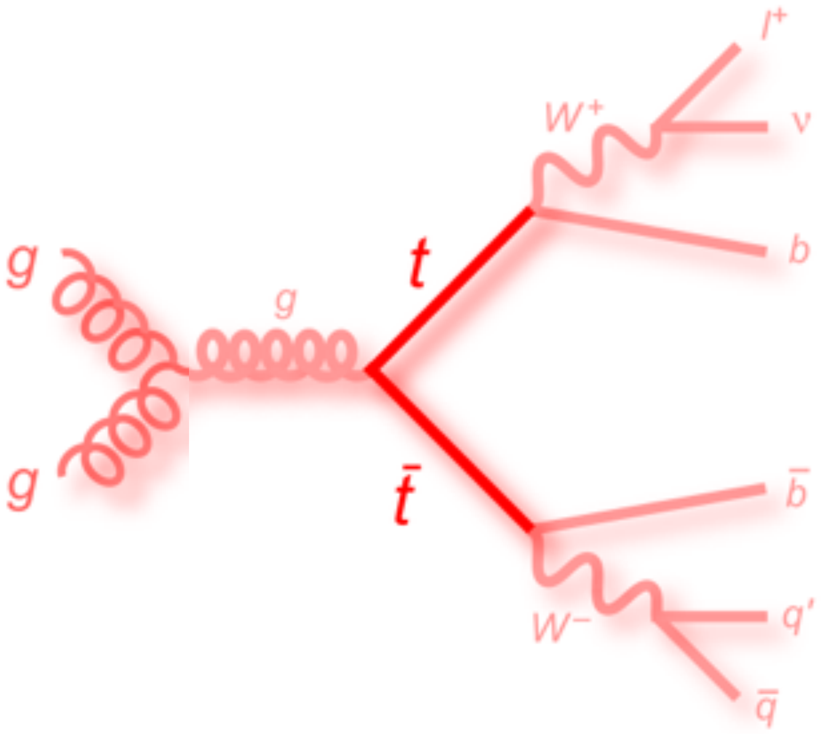
jet multiplicities



Individual top variables

p_T of leading, sub-leading top quarks

average p_T of top quarks



Standard tt kinematics

mass, rapidity and p_T of top-antitop system

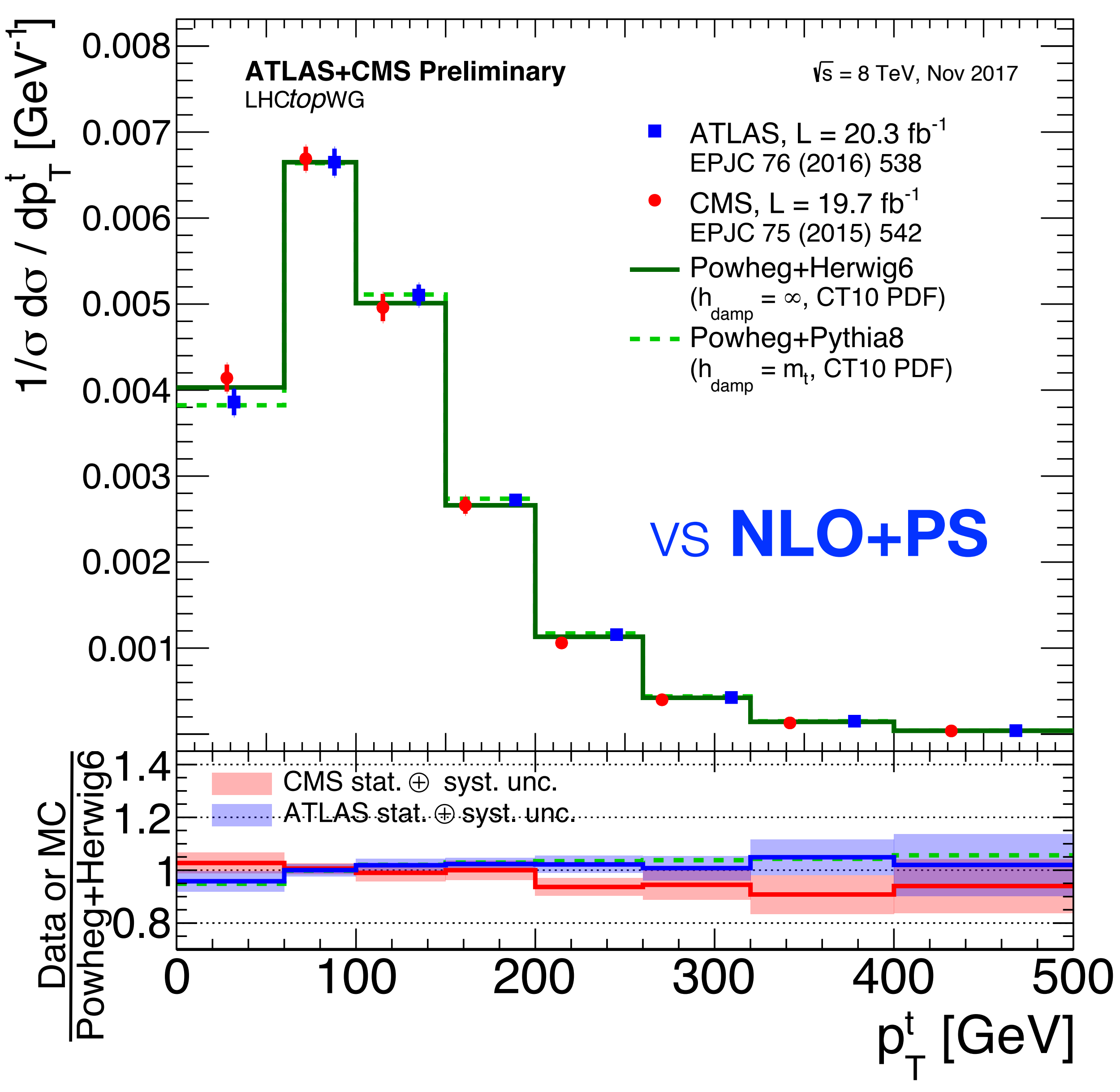
"QCD" tt kinematics

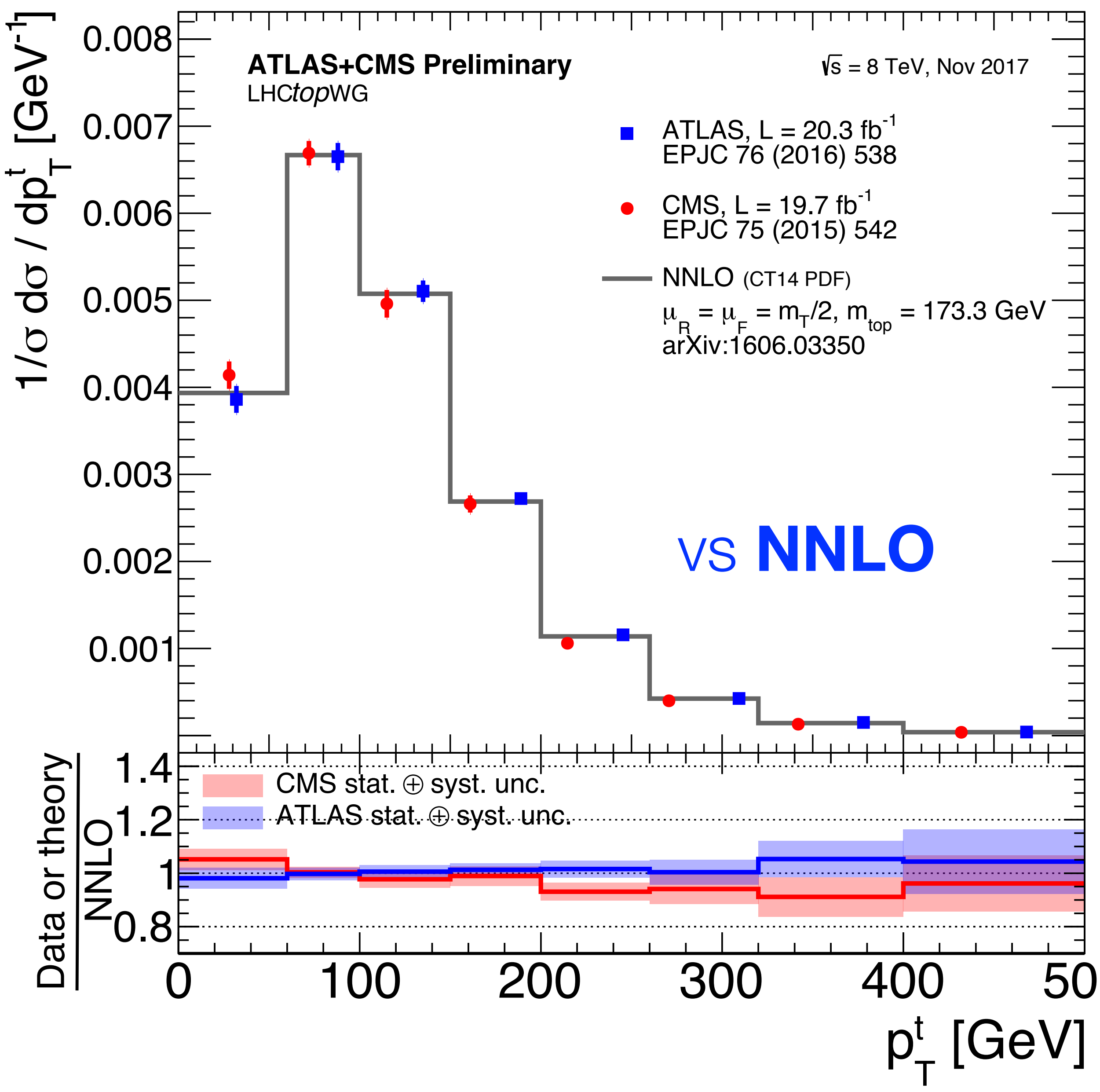
angular, p_T- and radiation- related variables

Standard reasons: **Extreme test of SM: $d\sigma_{tt}/dp_{T,top}$ “saga”**

Parton level vs NLO+PS & NNLO

√s=8 TeV





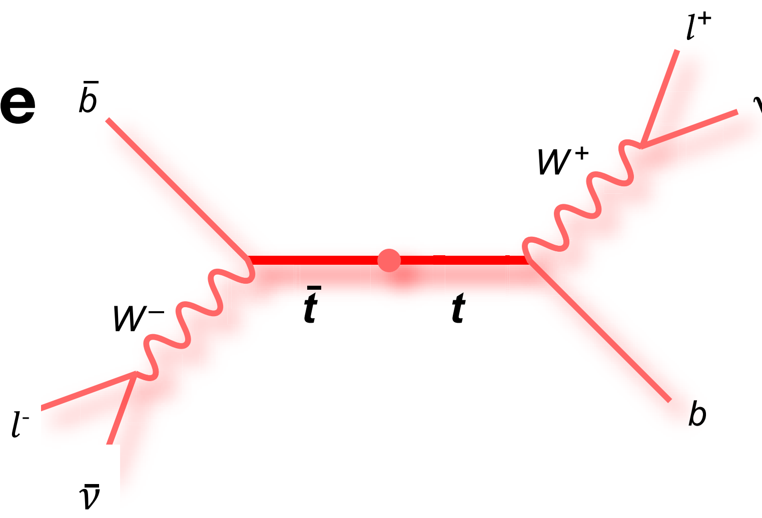
- **ATLAS & CMS measurements are generally consistent with each other**
  - CMS shows slight slope
- *Using latest predictions with dynamic factorisation & renormalization scale*

Qualitative statement,
no statistical test performed yet

Standard reasons: **Extreme test of SM: dσ_{tt}/dp_T "saga"- dilepton**

$\sqrt{s}$=13TeV `JHEP 02 (2019) 149

- Particle flow → individual particles using all CMS subdet→ **Require**
  - **2 opposite sign ℓ (e,μ), ≧2 jets, ≧1 b-tag**
  - **m(ℓ⁺ℓ⁻) > 20 GeV and ≠M_Z** *(15 GeV window),* **large p_T^{miss}** *(>40 GeV)*



- **Bkg:** data-driven Z+jets**, simulated tW,W/Z jets, other tt**

- **Reconstruct tt system: impose constraints from m_{top} , m_W , total p_T + weights from expected mass to**
  - **assign jets, leptons to quarks**
  - **reconstruct 2 separate neutrinos 3-momenta**

90% efficient on tt

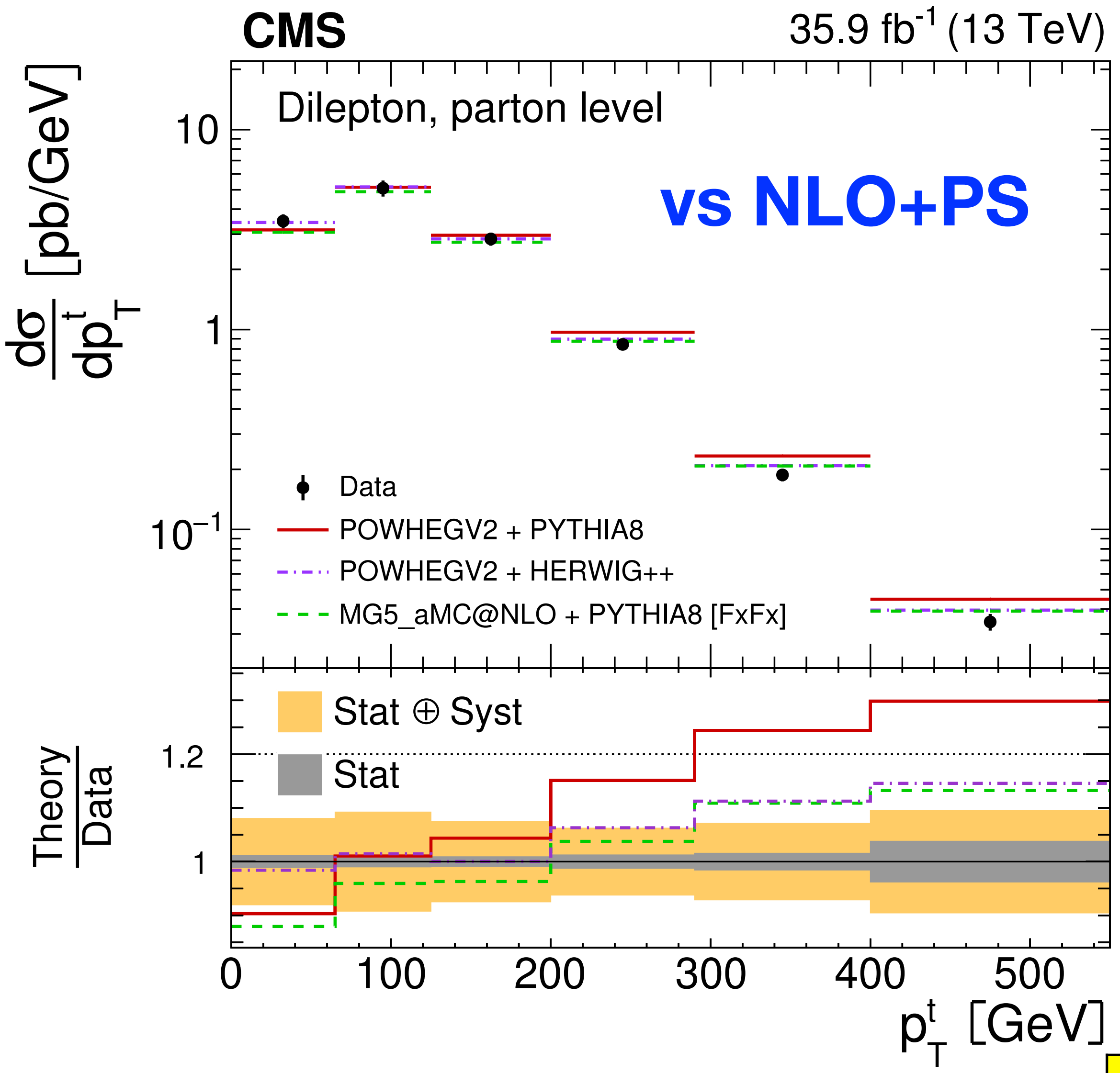
- **Bkg-subtract & Unfold to parton and particle level → dσ_{tt}/dX** ➡

Standard reasons: **Extreme test of SM: dσ_{tt}/dp_T “saga”- dilepton**

$\sqrt{s}$=13TeV

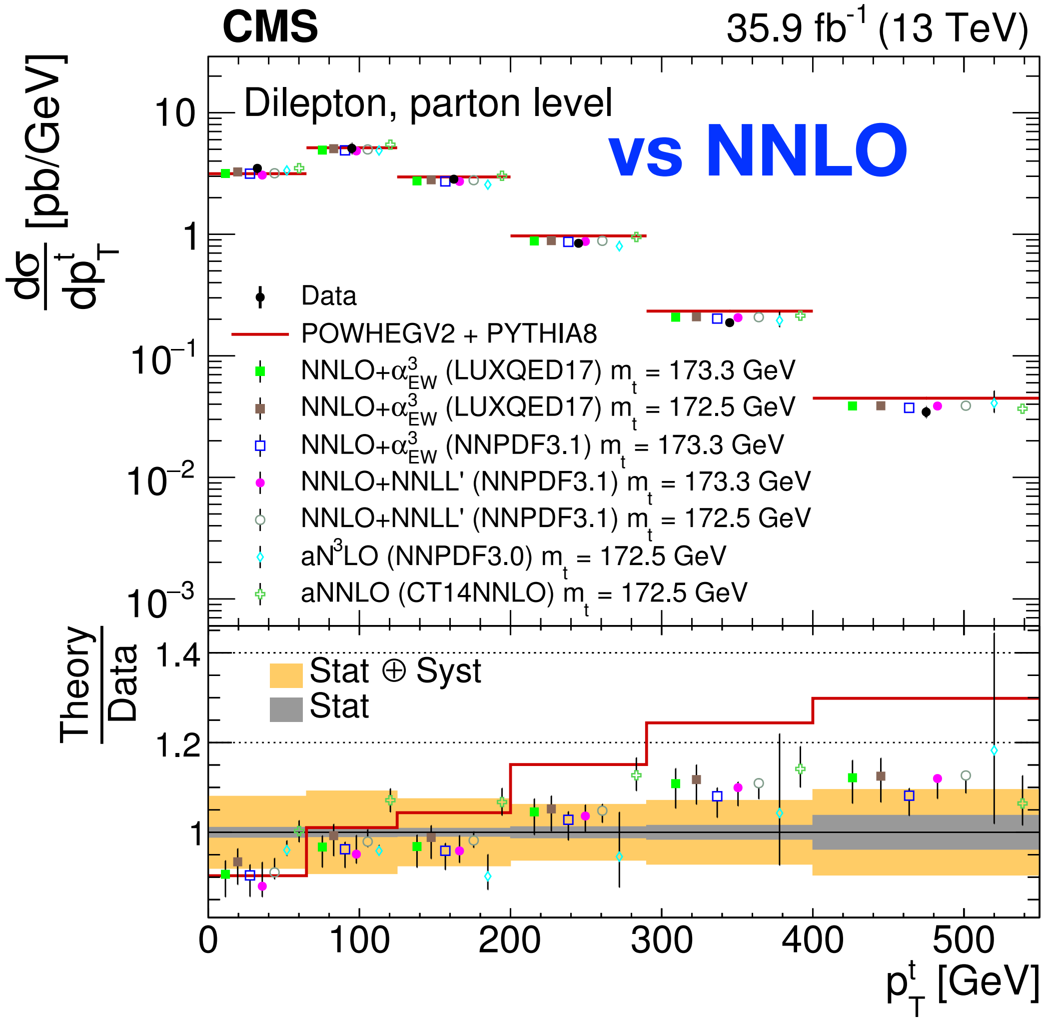
Parton level

`JHEP 02 (2019) 149



N_{dof} = 6

no theory uncertainties included in χ^2



N_{dof} =5 o 6	normalised		absolute	
NLO+PS	χ^2	p-val	χ^2	p-val
PW+PY8	43	$<10^{-3}$	51	$<10^{-3}$
PW+H++	6	0.269	8	0.239
MG5+PY8	21	$<10^{-3}$	18	0.007

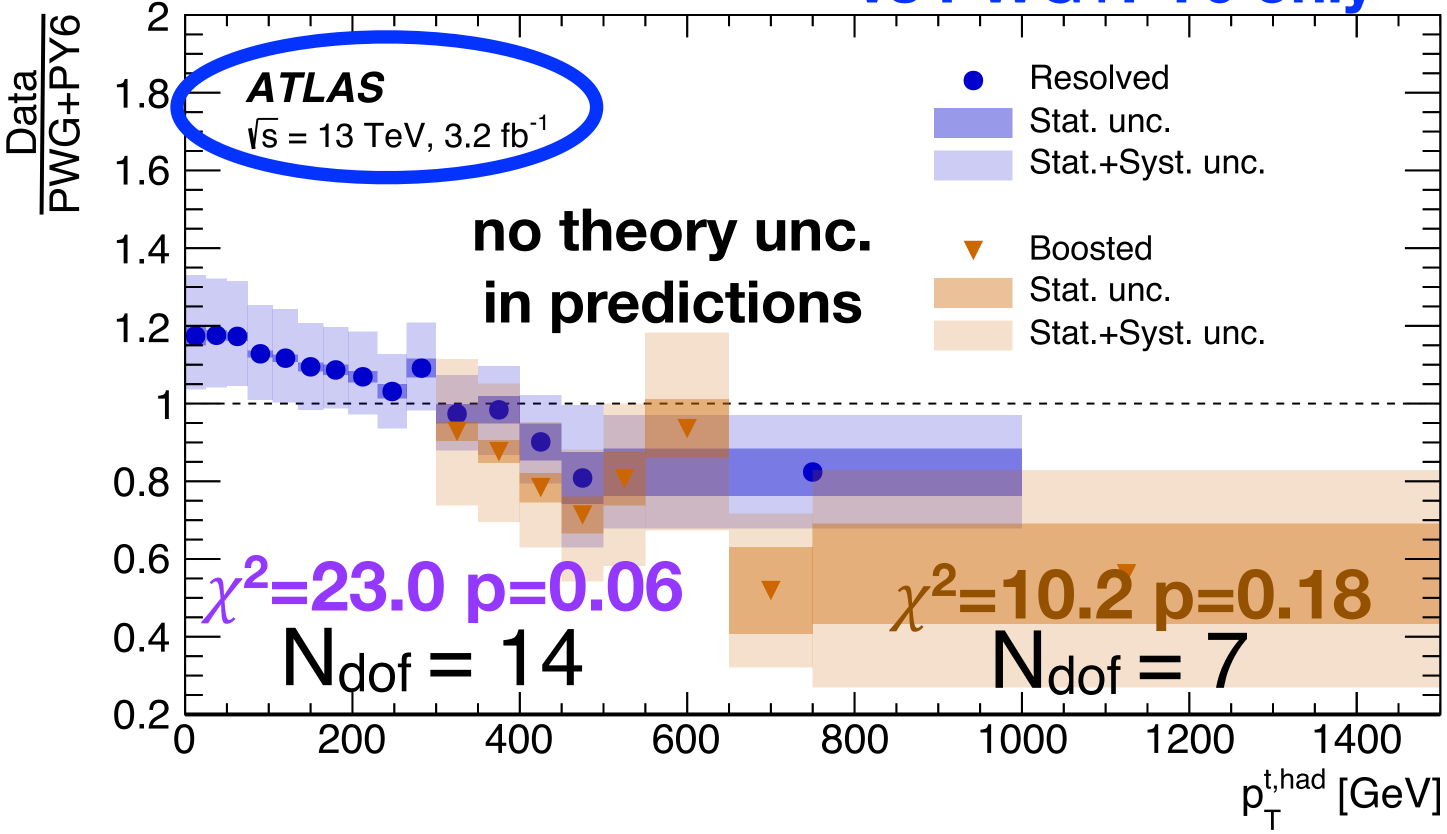
N_{dof} =5 or 6		normalised		absolute	
NNLO		χ^2	p-	χ^2	p-val
NNLO+EW	**LUXQED17 m_{top} = 173.3**	16	0.006	14	0.026
NNLO+EW	**LUXQED17 m_{top} = 172.5**	12	0.036	12	0.071
NNLO+EW	**NNPDF3.1 m_{top} = 173.3**	12	0.02	10	0.115
NNLO	**NNPDF3.1 m_{top} = 173.3**	20	0.001	17	0.01
NNLO	**NNPDF3.1 m_{top} = 172.5**	15	0.01	14	0.032

Standard reasons: **Extreme test of SM: dσ_{tt}/dp$_T$ "saga" - ℓ+jets**

Particle level vs NLO+PS √s=13TeV

JHEP 11 (2017) 191

vs PWG+PY6 only



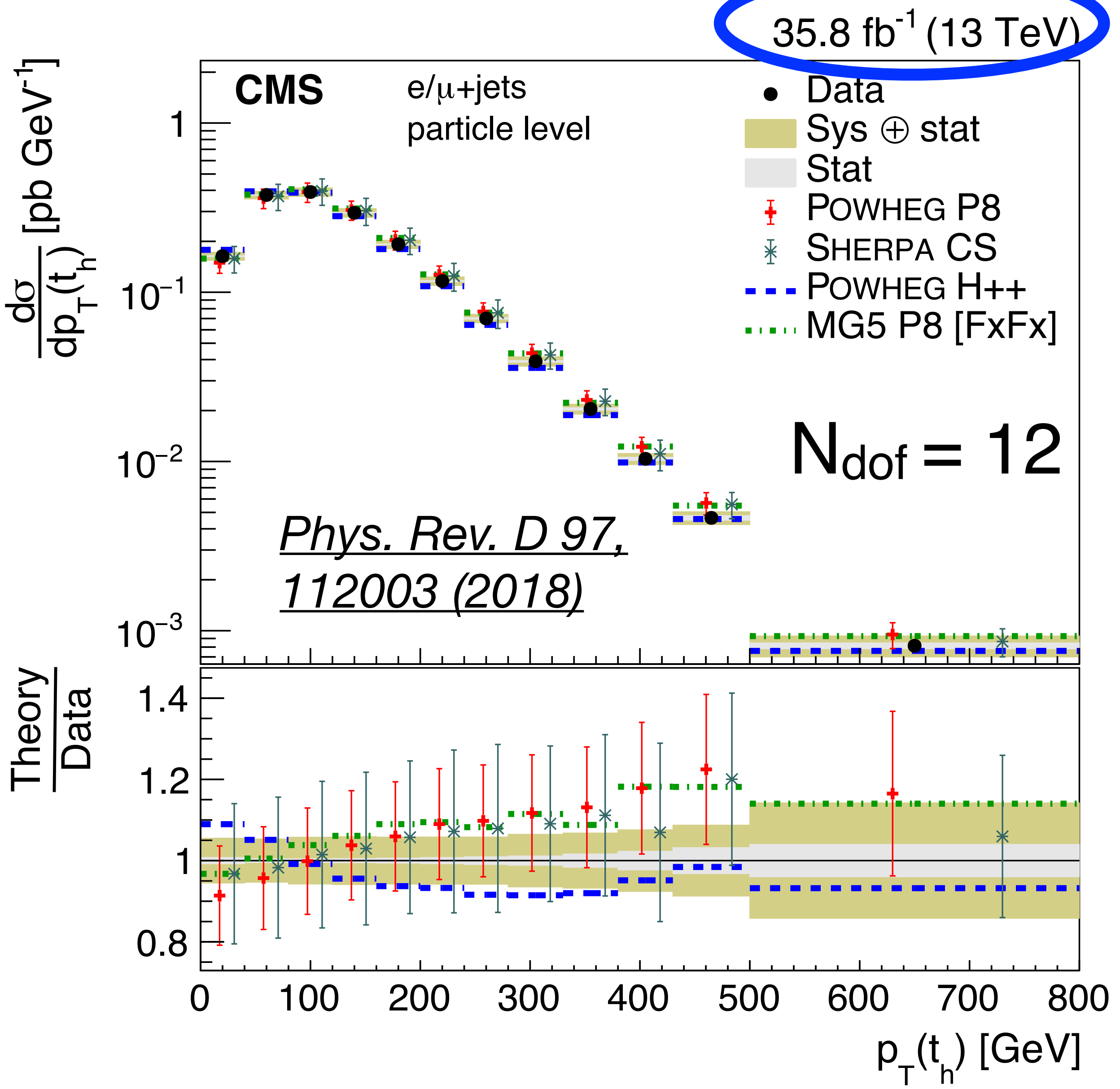
no theory unc. in predictions

χ^2=23.0 p=0.06

N$_{dof}$ = 14

χ^2=10.2 p=0.18

N$_{dof}$ = 7



N$_{dof}$ = 12

Phys. Rev. D 97, 112003 (2018)

- **No slope in all had @ particle**
- ℓ+jets measurements @ particle **show slope up to ~700-800 GeV** (similar in dilepton @ particle & parton)
- **Still at the edge of consistency for ATLAS, CMS: consistent if theory unc. included.**

ATLAS new result with 36/fb is in preparation

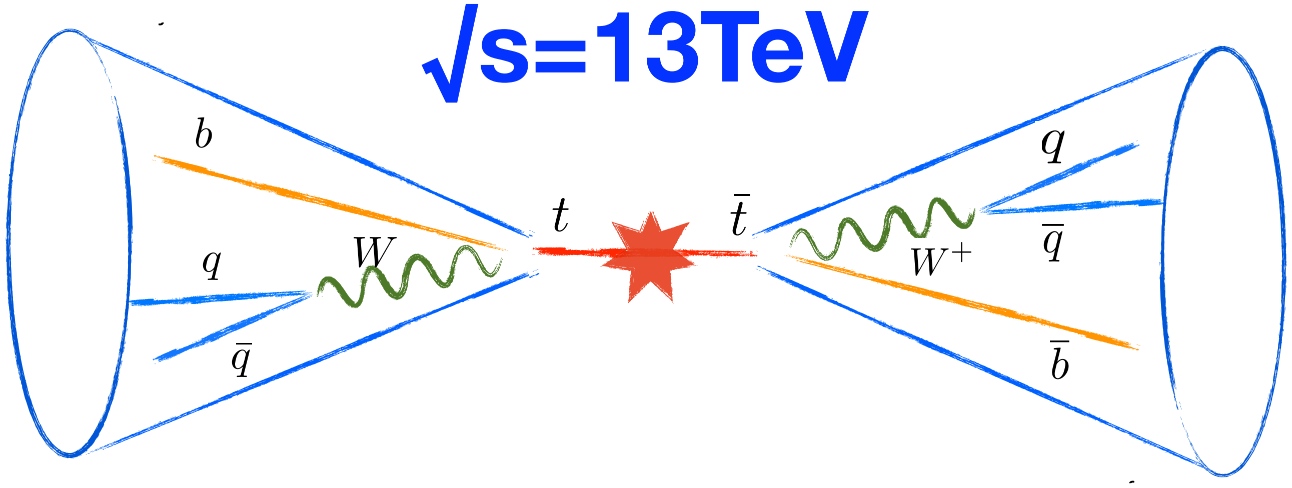
Revisit with theory unc. & larger dataset (full Run2 and beyond)!

N$_{dof}$ = 12	no theory unc.		with theory unc.	
NLO+PS	χ^2	p-val	χ^2	p-val
PW+PY8	**29.5**	**<0.01**	**15.9**	**0.197**
SHERPA	**13.5**	**0.335**	**7.21**	**0.844**
PW+H++	**31.1**	**<0.01**		
MG5+PY8	**17.4**	**0.137**		

Standard reasons: **Extreme test of SM: first "all had boosted" $d\sigma_{tt}/dX$**

Di-top-jet kinematics

$\sqrt{s}$=13TeV

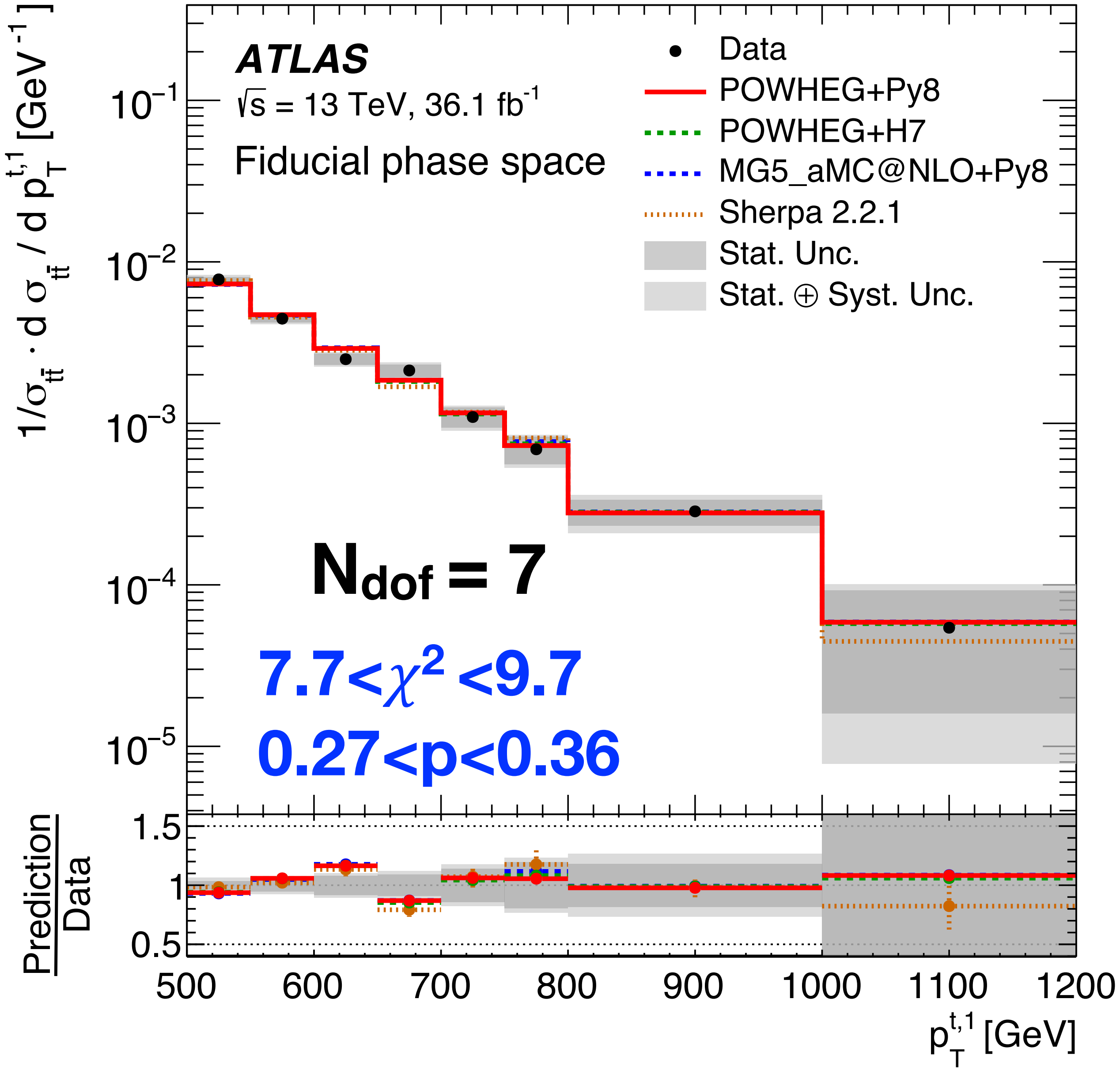


- **recognise high p_T 2 top-jets using jet mass & jet substructure**
- **estimate large multi-jet bkg from data**

Reconstruct

X= ***$p_{T,top1\ \&\ 2}$, $y_{top1\ \&2,}$ m_{tt} , y_{tt} , $p_{T,tt}$ angles (t,anti-t), global energy variables***

Phys. Rev. D 98, 012003 (2018)



N_{dof} = 7

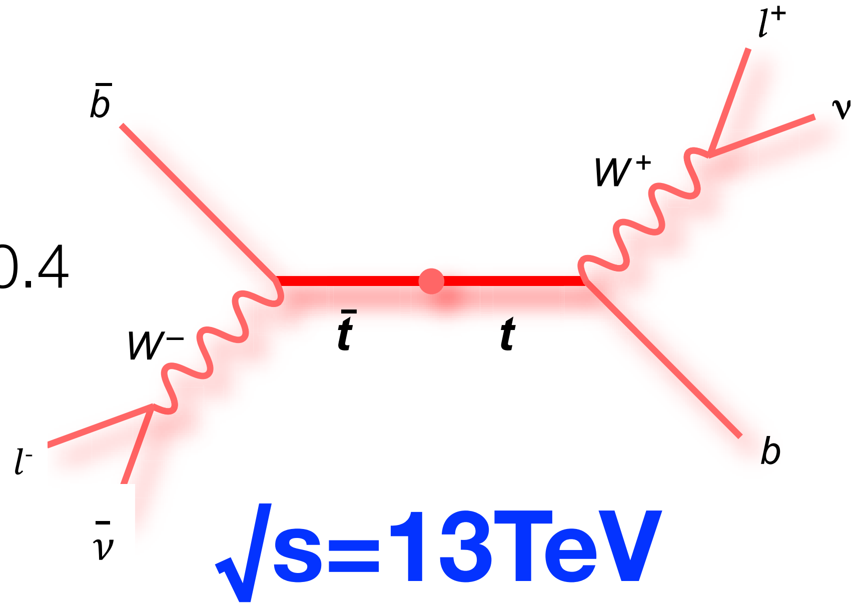
$7.7<\chi^2<9.7$

$0.27<p<0.36$

No SM deviations up to m_{tt} ~ 3TeV, $p_{T,top}$ ~1.2 TeV,
significant stat uncertainties

Extreme test of SM: double and triple diffxsec - dilepton+jets

CMS-TOP-18-004, submitted to Eur. Phys J. C



√s=13TeV

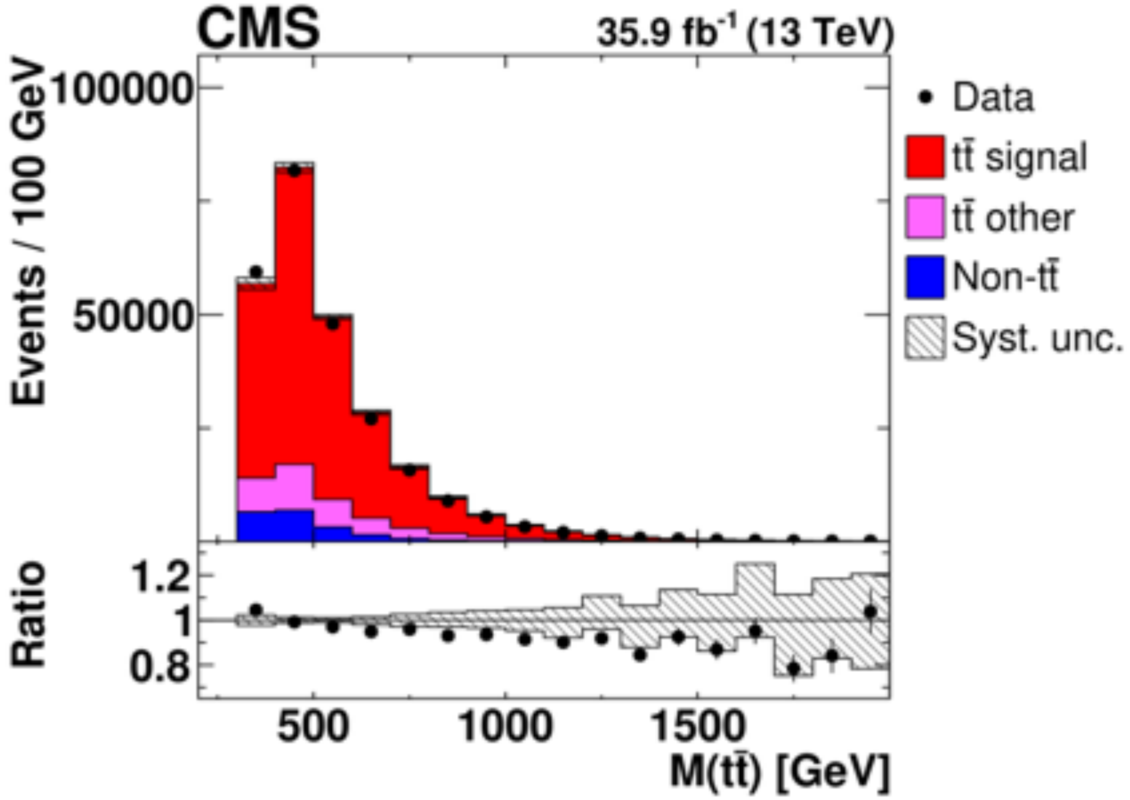
- 13 TeV Dilepton selection as *JHEP 02 (2019) 149*
- **Extra jets**: central, high p_T jets with ΔR(e-jet,lep)=ΔR(e-jet,b-jet) > 0.4
- **Bkg:** data-driven Z+jets, **simulated tW,W/Z jets, other tt**
- **Reconstruct tt system with dilepton kinematic reco**

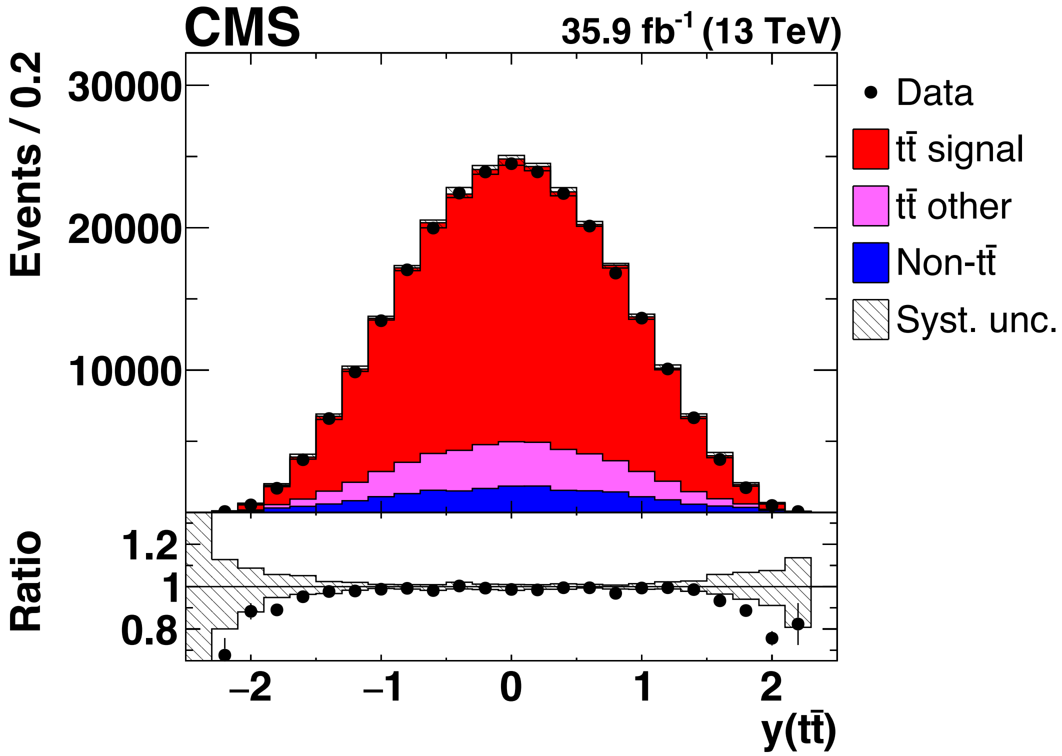
standard for 2d distributions

- M_{tt} vs {$p_{T,top}$ $|y_{top}|$ $|y_{tt}|$ $\Delta\eta(t,t)$, $\Delta\varphi(t,t)$, $p_{T,tt}$}
- [$|y_{top}|$, $p_{T,top}$]

loose: for 3d distributions

- reconstruct **2 ν system (no separate ν)**
- keep (ℓ,jet) assignment with maximum p_T jets
- [M_{tt} ,y_{tt}, $N_{extra\ jets}$] 2 bins (0,1) and 3 bins (0,1,2)



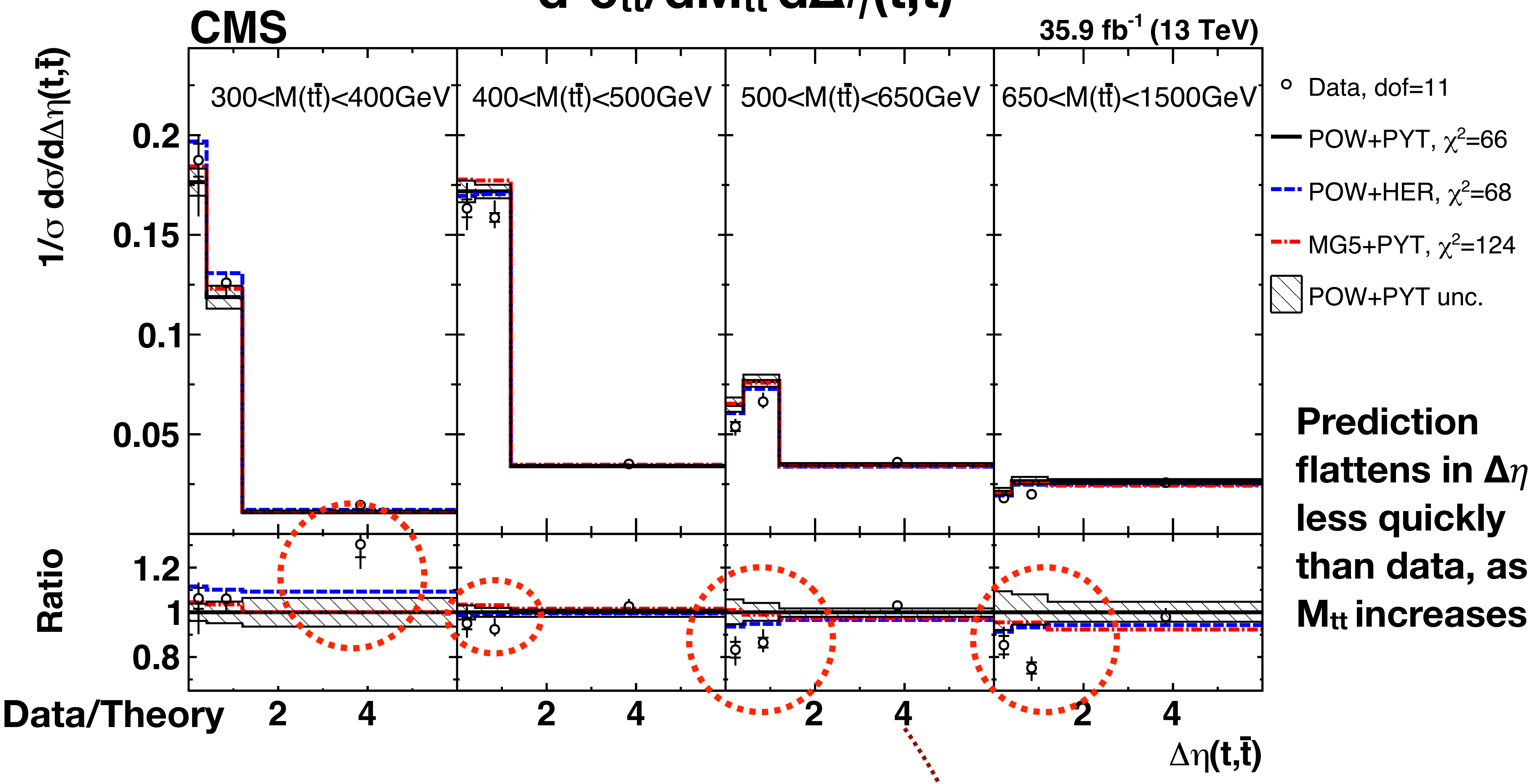


Extreme test of SM: double and triple diffxsec - dilepton+jets

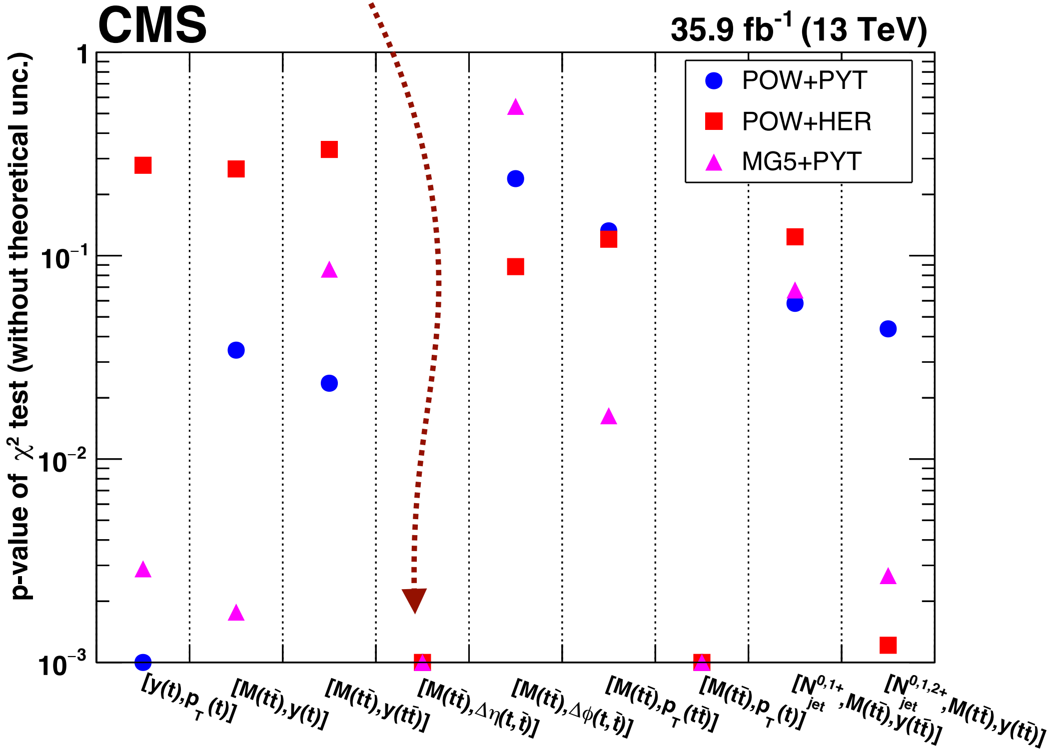
CMS-TOP-18-004, submitted to Eur. Phys J. C

$d^2\sigma_{t\bar{t}}/dM_{t\bar{t}}\, d\Delta\eta(t,\bar{t})$

- **Bkg-subtract & Unfold to parton level → $d^2\sigma_{tt}/dXdYdZ$ and $d^3\sigma_{tt}/dXdYdZ$**
- **Compare with different NLO+PS predictions**
  - PS+HAD: p_T -ordered+string vs angular-ordered +cluster
  - NLO ME :inclusive vs tt+2 extra parton



Prediction flattens in $\Delta\eta$ less quickly than data, as M_{tt} increases



- **No prediction describes all distributions**
- $[M_{tt},\Delta\eta(t,t)],[M_{tt},p_{T,tt}]$: discrepant for all
- most consistent with data : PW+HW (for p_T PW+PY (for N_{jet} and radiation)

Measuring Top quark mass @LHC

special reasons

Special reasons:measure the top quark mass
What is the top mass?

- **Parameter in SM Lagrangian describing Higgs-quark interaction**

- **At Leading Order (LO), m_{top} = m_t (“bare”)**
- **Beyond LO, resum higher order corrections**

m_{top} depends on renormalisation scheme to absorb divergences

Examples (non exhaustive)

long distance scheme: pole mass

- **mass = rest energy of free particle at infinity**
- impossible in QCD: no isolated stable coloured particles → only bound states → m(bound) ≠ m(pole) : 70 MeV ambiguity

short distance scheme: minimal subtraction mass

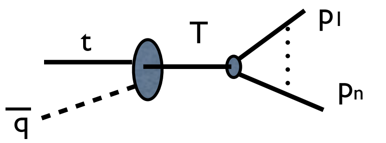
- **running mass at scale μ of the interaction (like $\alpha_s(\mu)$)**

Difference between long and short is calculable

Monte Carlo “scheme”: NLO+PS

Definition of m_{top} from top decays
(M. Mangano @ TOP2013)

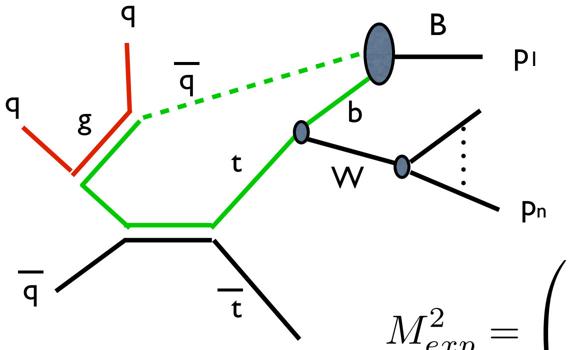
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i\right)^2$$

$m_t = F_{\text{lattice/potential models}}(m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i\right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top})$~ 1 GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

present estimate: difference from pole mass ~ 0.5 to 1 GeV

Special Reasons: **top mass tests SM & vacuum stability**

EWSB

$\mathcal{L}_{top} = m_t t_L \bar{t}_R + y_t H t_L \bar{t}_R / \sqrt{2}$

mass term

interaction term

$\mathcal{L}_{Higgs} = (\partial^\mu H)^2 + (1/2)\lambda v^2 H^2 - \lambda v H^3 - (1/4)\lambda H^4$

$m_{top} = y_t v/\sqrt{2}$

$\lambda = m_H^2 / \sqrt{2} v^2$

$$v = \frac{1}{(\sqrt{2}G_\mu)^{1/2}}$$

~246 GeV

RENORMALISATION

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

$\Delta r = \Delta r(m_W, m_H, m_{top})$

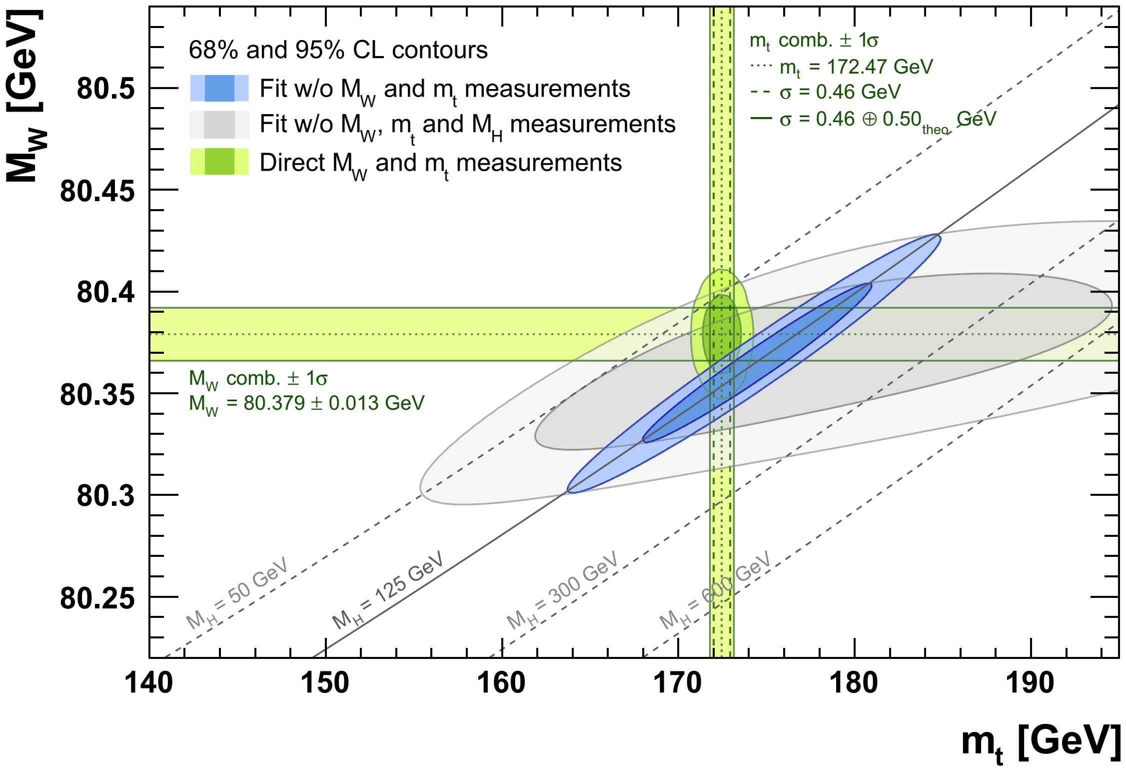
$\lambda(\mu) = m_H^2 / \sqrt{2} v^2 + \Delta\lambda(\mu, m_{top}, m_W, m_Z, m_H)$

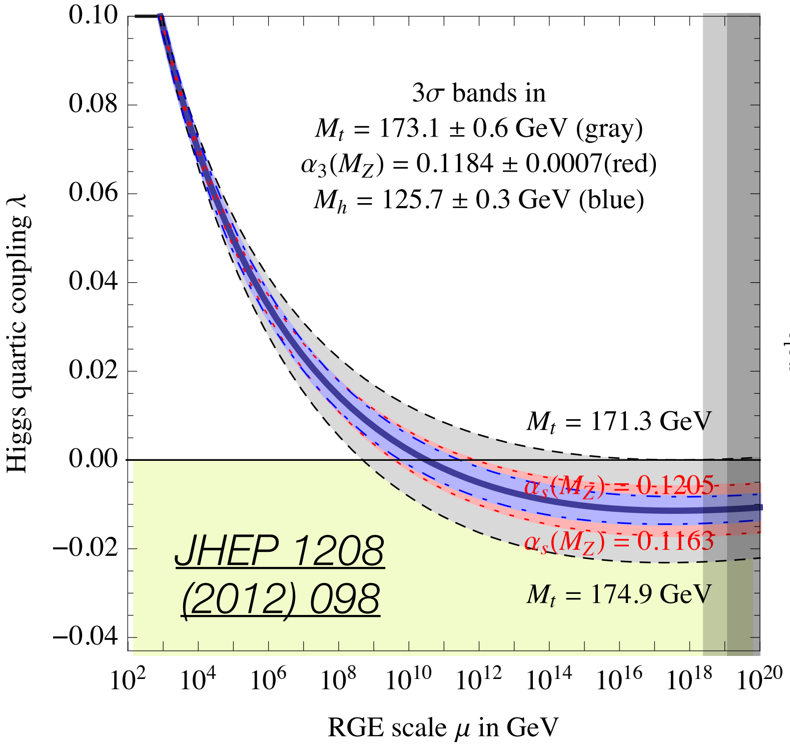
If SM is valid up to the Planck scale
(no quantum gravity, no new phys)

*as $\mu \rightarrow E_{Planck}$, $\lambda \rightarrow$ **0 or <0***
depending on m_{top}

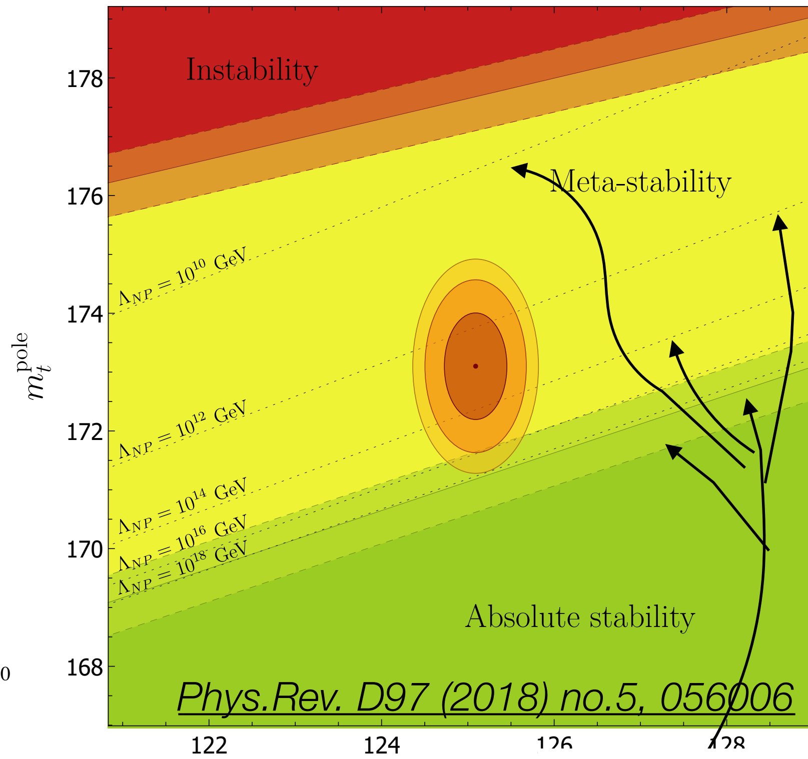
λ<0 → *Higgs potential has more minima (meta-stable) or none (unstable)*

Eur. Phys. J. C (2018) 78: 675





JHEP 1208 (2012) 098



Phys.Rev. D97 (2018) no.5, 056006

new stability lines

Test consistency of SM

$$10^{65} < \frac{\tau_{SM}}{\text{years}} < 10^{1383}$$

Lifetime of vacuum is >> life of universe

New physics can stabilize or destabilize vacúum

Special reasons: measure the top quark mass: HOW?

1 Select tt/t events

2 Construct observable that is "sensitive to top mass i.e that varies with top mass

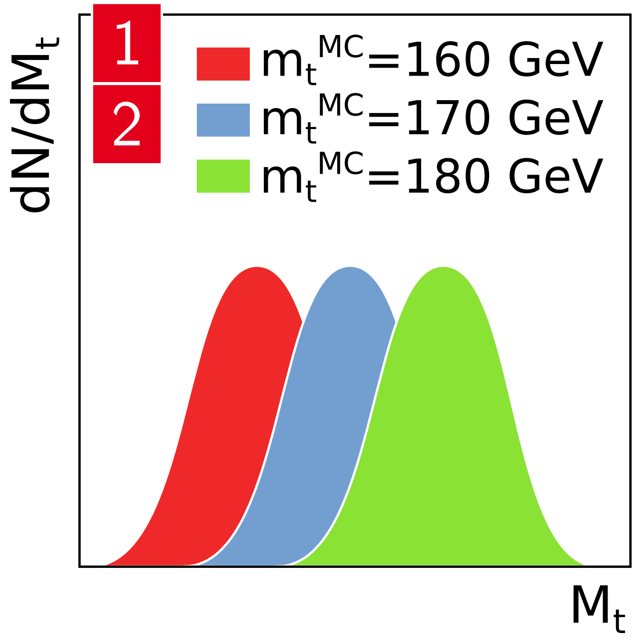
3 Calibrate observable

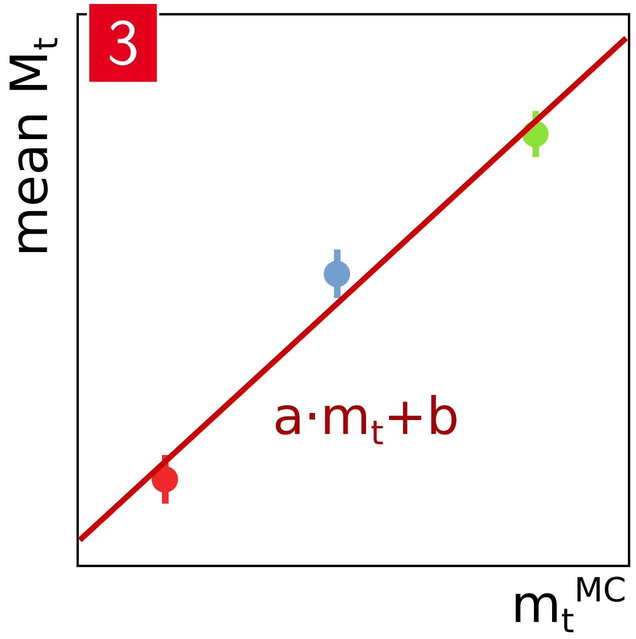
Extract/Parametrize dependence of observable as a function of top mass observable as a function of top mass

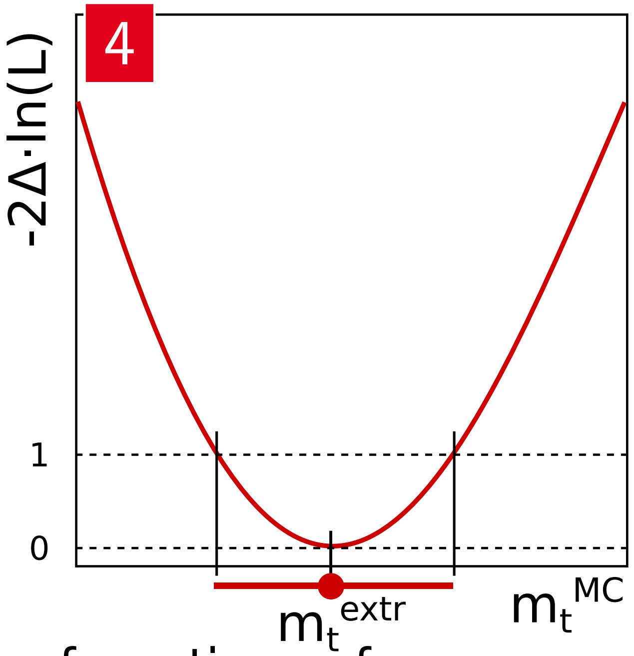
4 Extract the mass

Compare observable measured distribution with predicted as a function of m_{top} ⇒ ***Max Likelihood fit***

(images by B Stieger (CERN))







Different (ways to find)/(format for) the likelihood as function of m_{top}

- measured **top mass is the mass used in the prediction !**

Uncertainties

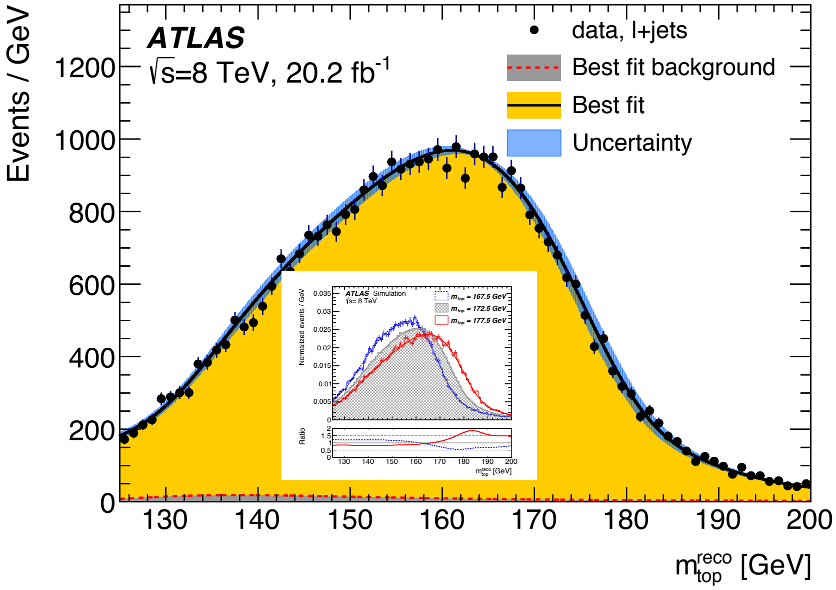
- Most precise methods **need full event reconstruction**: what jets to use and assign to quark, missing energy due to neutrinos in final state
- Precision measurement dominated by systematic uncertainties: mostly jet & theory related. **Develop techniques to constrain uncertainties from data or make analysis less sensitive or insensitive.**

Special reasons: direct measurement of top quark mass

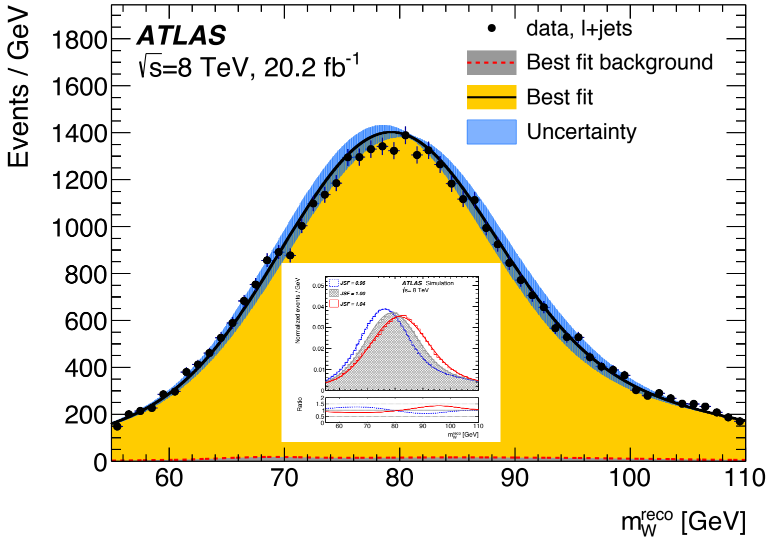
most recent ATLAS result from all data @ √s=8 TeV *Eur. Phys. J. C79 (2019) 290*

- **Select ℓ+≥ 4jets events** *(subtract data-driven W +jets, fakes & stimulated dibosons &single top),* ***require 2 b-jets***
- Likelihood-based **kinematic fit** (m_W & m_{top} constr) → assign jets/ leptons to tt decay products
- Kine variables→ **Boosted Decision Tree→discriminant** to enrich sample with events with correct jet/lepton assignment.
- **Likelihood-fit 3 m_{top} sensitive variables to data**
- **m_{top} + 2 scale factors: jet and b-jet-to-light-jet energy** → *reduce dominant jet & b-jet uncertainties*

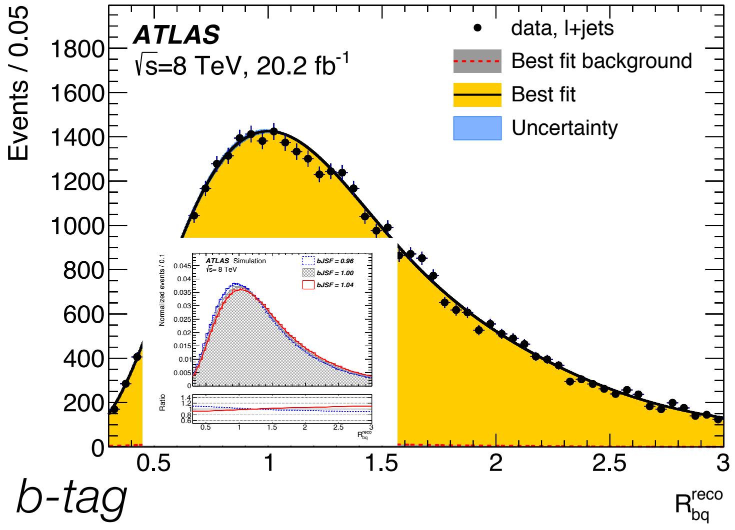
- **m_{top}^{reco}** sensitive to **m_{top} , JSF, bJSF**



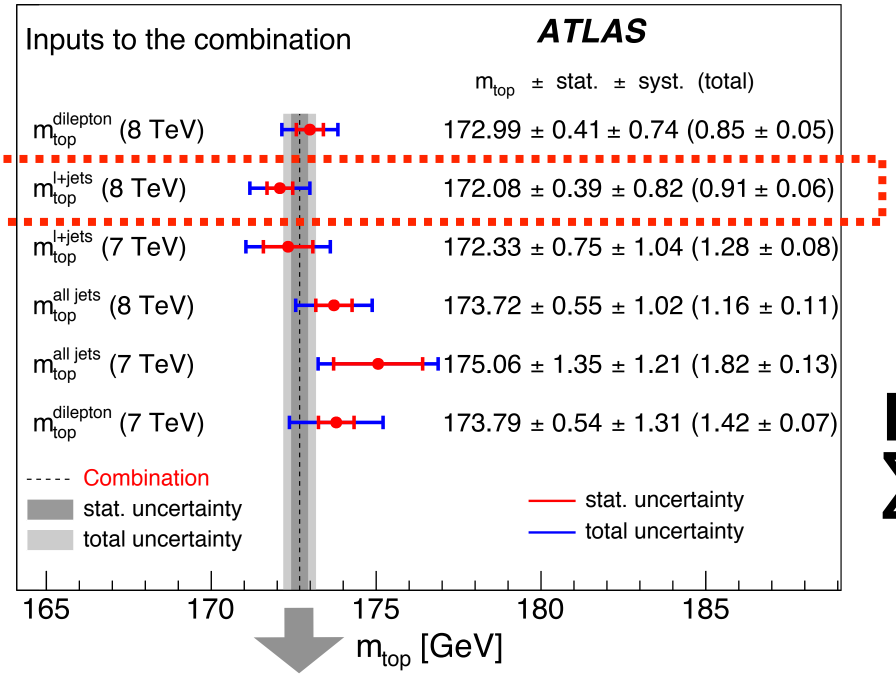
- **m_W^{reco}** sensitive to **JSF**



$R = \sum |p_{T,b\text{-}jets}| / \sum |p_{T,jets\_in\_W}|$ sensitive to **bJSF**



- ***Optimize w.rt. BDT: 19% improvement***
- ***Combine with dilepton and all jets result***



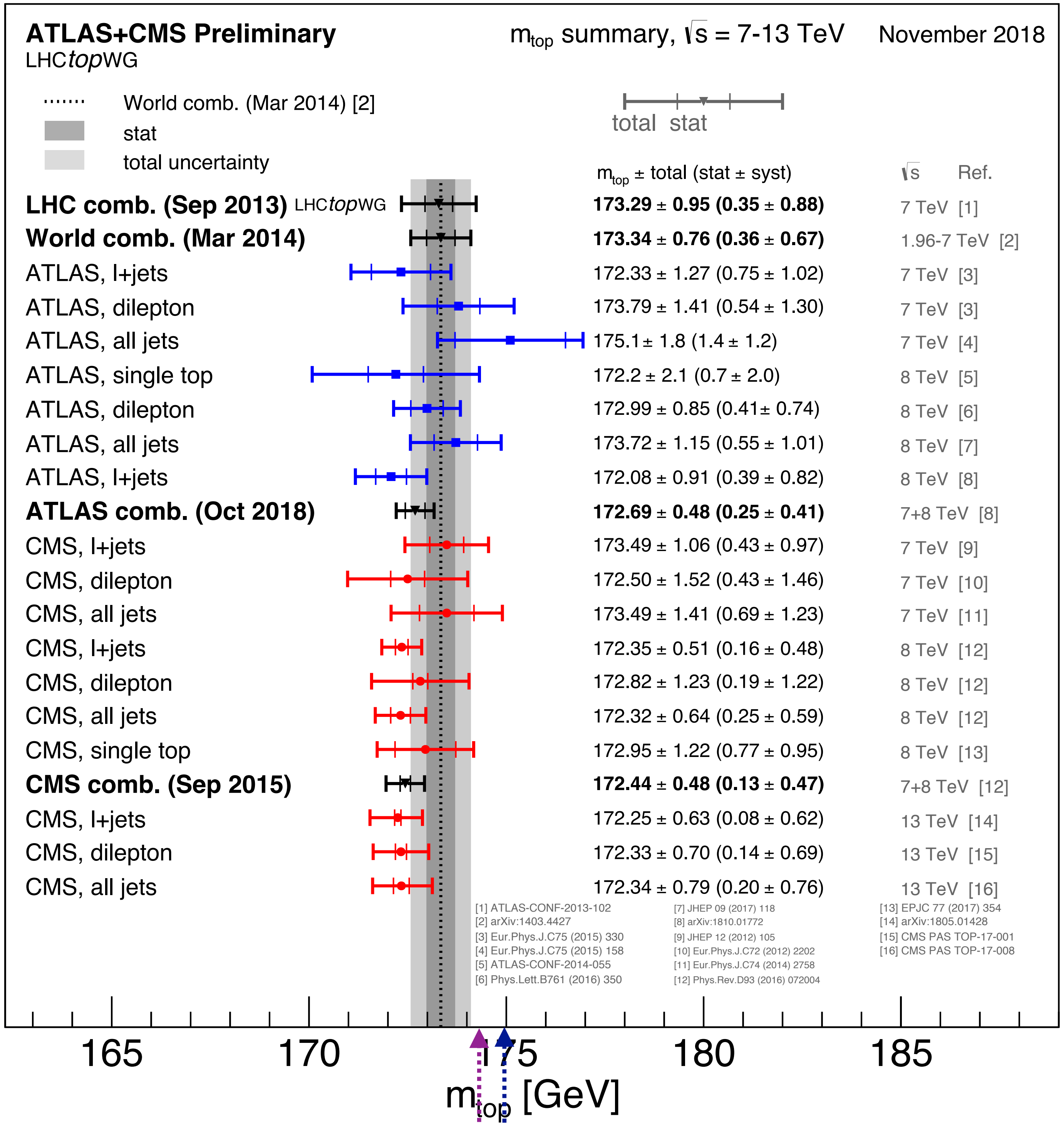
$\delta m_{top} / m_{top}$ ~0.28%

$$\boxed{172.69 \pm 0.25\,(\text{stat}) \pm 0.41\,(\text{syst})\ \text{GeV}}$$

dominant syst: JES, b-tag

Special reasons: **summary of direct measurements of m_{top}**

Global "standard" M_{top} picture (June 2019)



$\delta m_{top} / m_{top}$ ~0.44%

$\delta m_{top} / m_{top}$ ~0.54%

$\delta m_{top} / m_{top}$ ~0.28%

$\delta m_{top} / m_{top}$ ~0.28%

ATLAS Combination (Oct.2018)
D0 (June 2017)
ATLAS fully had & CMS l+jets (Mar 2017)
CMS Combination (Sep 2016)
Tevatron (July 2016),
ATLAS (June 2016)
CMS Combination (Sep 2015)
D0 (Jan 2015)
ATLAS Run1 (Mar 2015)
World (March 2014),
Tevatron (July 2014),
LHC (Sept 2013)

some tension between
LHC & Tevatron measurements

D0 latest (June 2017) $174.95 \pm 0.40\,(\mathrm{stat}) \pm 0.64\,(\mathrm{syst})\ \mathrm{GeV}$ **$\delta m_{top} / m_{top}$ ~0.43%**

Tevatron latest (July 2016) $174.30 \pm 0.35\,(\mathrm{stat}) \pm 0.54\,(\mathrm{syst})\ \mathrm{GeV}/c^2$ **$\delta m_{top} / m_{top}$ ~0.37%**

Indirect measurement of top quark mass: from 1d diffxsec

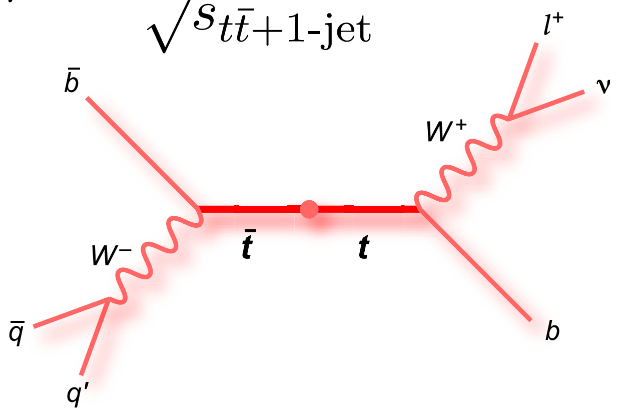
arXiv:1905.02302, submitted to EPJC

$$m_T^W = \sqrt{2p_{T,\ell} \cdot E_T^{miss}[1 - \cos(\phi_\ell - \phi_{E_T^{miss}})]}$$

Exploit m_t^{pole} **dependence of $d\sigma_{tt}/dX$** with X= **inverse of the invariant mass of the tt+1jet system**

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}} \quad m_0 = 170 \text{ GeV}$$

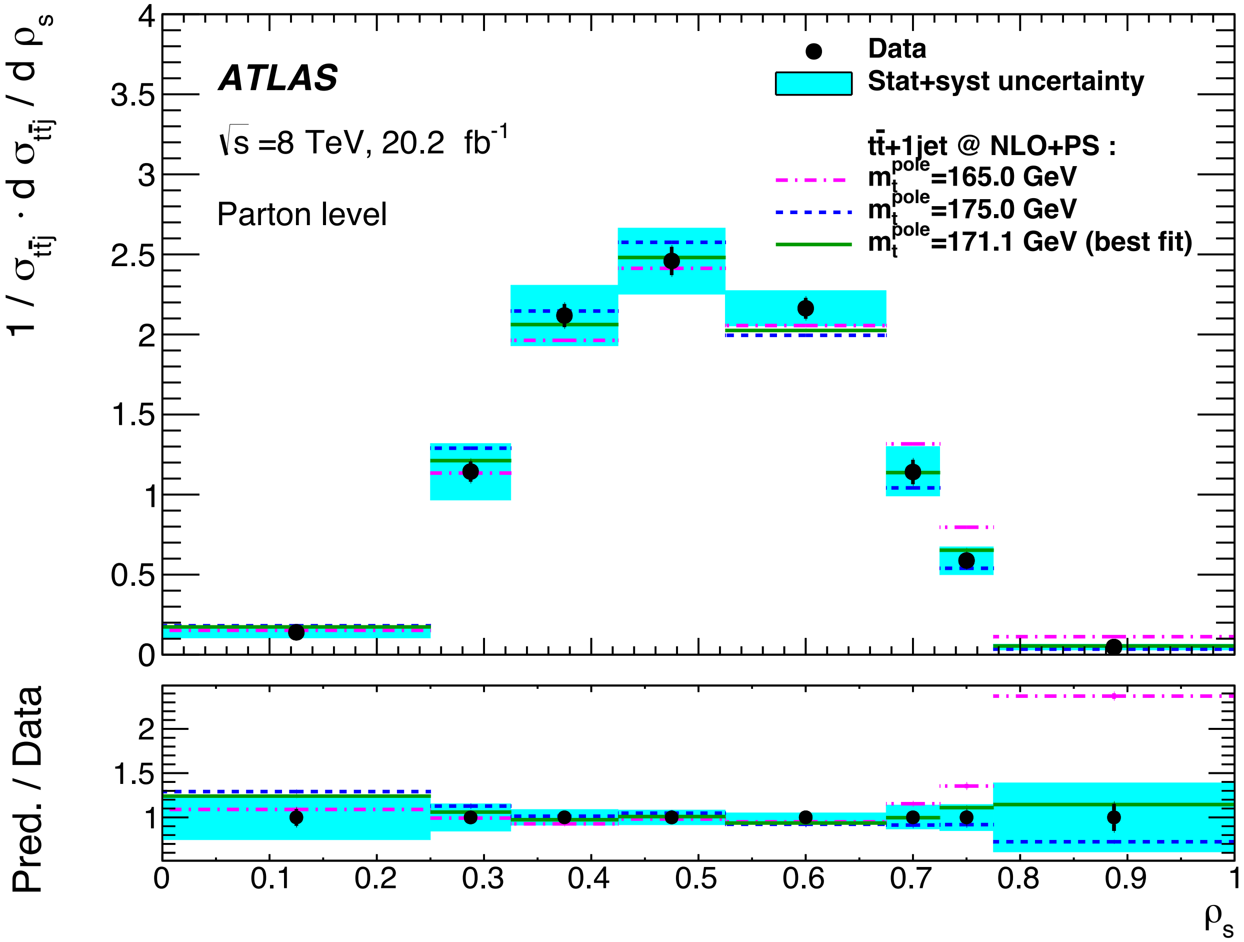


- Require 1 **ℓ, ≧5 jets, 2 b-tag(s),** large E_T^{miss} and m_T^W
- **Reconstruct ρ_s from tt system by**
  - **hadronic W: non-b jets pair** with m(jj) ~ m_W and min(p_{T1},p_{T2}) ΔR(i,j)<90 GeV
  - **leptonic W**: lepton+ neutrino from $\mathbf{E_T^{miss}}$ **and** m_W constraint
  - **top candidates:(W+b-jet) pair**←minimise $|m_{lep,top} - m_{had,top}|/|m_{lep,top} + m_{had,top}|$
  - **tt+jet = tt+leading-p_T jet unused in reco**
- ***Unfold R (regularized) to parton level* and fit to NLO+PS prediction**

$$\chi^2(m_t) = V^T(m_t) \times \boldsymbol{COV}(m_t)^{-1} \times V(m_t)$$

measured - predicted

stat+sys covariance through unfolding!



$$\boxed{m_t^{\text{pole}} = 171.1 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)} \, {}^{+0.7}_{-0.3} \text{ (theo) GeV}}$$

$\delta m_{top,pole}/m_{top,pole}$ ~0.70% ***uncertainty reduced by a factor 2 w.r.t 7 TeV result !***

Indirect measurement of top quark mass: from 3d diffxsec

CMS-TOP-18-004, submitted to Eur. Phys J. C

- **Fit normalised diffxsec [$N_{\text{extra jets}}^{0,1}$, M_{tt} ,y_{tt}] to NLO prediction for tt+1,2 jets, corrected from particle to parton level by POWHEG+PYTHIA, by minimising χ^2 as function of**
  - **$m_{t,pole}$, α_s with varying PDF sets (7 sets)→ $m_{t,pole}$, α_s (separately)**
  - **$m_{t,pole}$, α_s PDF parameters → $m_{t,pole}$, α_s , PDF par simultaneously (+ HERA data)**

$$\mathcal{C}_{\text{NP}} = \frac{\sigma^{\text{particle jets}}_{\text{isolated from t} \to \ell,\text{b}}}{\sigma^{\text{parton jets}}_{\text{no MPI, no had., no t}\bar{\text{t}}\text{ decays}}}.$$

- Caveat! Predictions miss
  - higher order gluon resummation relevant for production @mass threshold
  - electroweak corrections

- Uncertainties in **separate fit**
  - **Data**: all sources in diffxsec cov matrix → **by $\Delta\chi^2$ =1**
  - **Scale** : envelope of ren. and fact. scale variations varied independently by fact 2 → **repeat fit**
  - α_s : vary within 0.001 of 0.118→ **repeat fit**
  - **PDF**: variation within 68% CL uncertainty associated to each set→ **repeat fit**
  - **Modelling of C_{NP}**: vary hadronisation, PS, matrix element, underlying event tune

- Uncertainties in **simultaneous fit**
  - **Fit**: all sources in diffxsec cov matrix **by $\Delta\chi^2$ =1**
  - **Model**: vary mass of c-quark, strangeness fraction, Q^2→ **repeat fit**
  - **Parametrisation**: vary PDF parametrisation by adding or removing pars.→ **repeat fit**
  - **Scale & α_s**

- Separate fit validated by **repeating fit to single diffxsec** M_{tt} ,|y_{tt}|, Mtt, N_{jet} , **to alternative 3d diffxsec** [$N_{\text{extra jets}}^{0,2}$, M_{tt} ,y_{tt}] [$p_{T,tt}$, M_{tt} ,y_{tt}] **and using absolute diffxsec**

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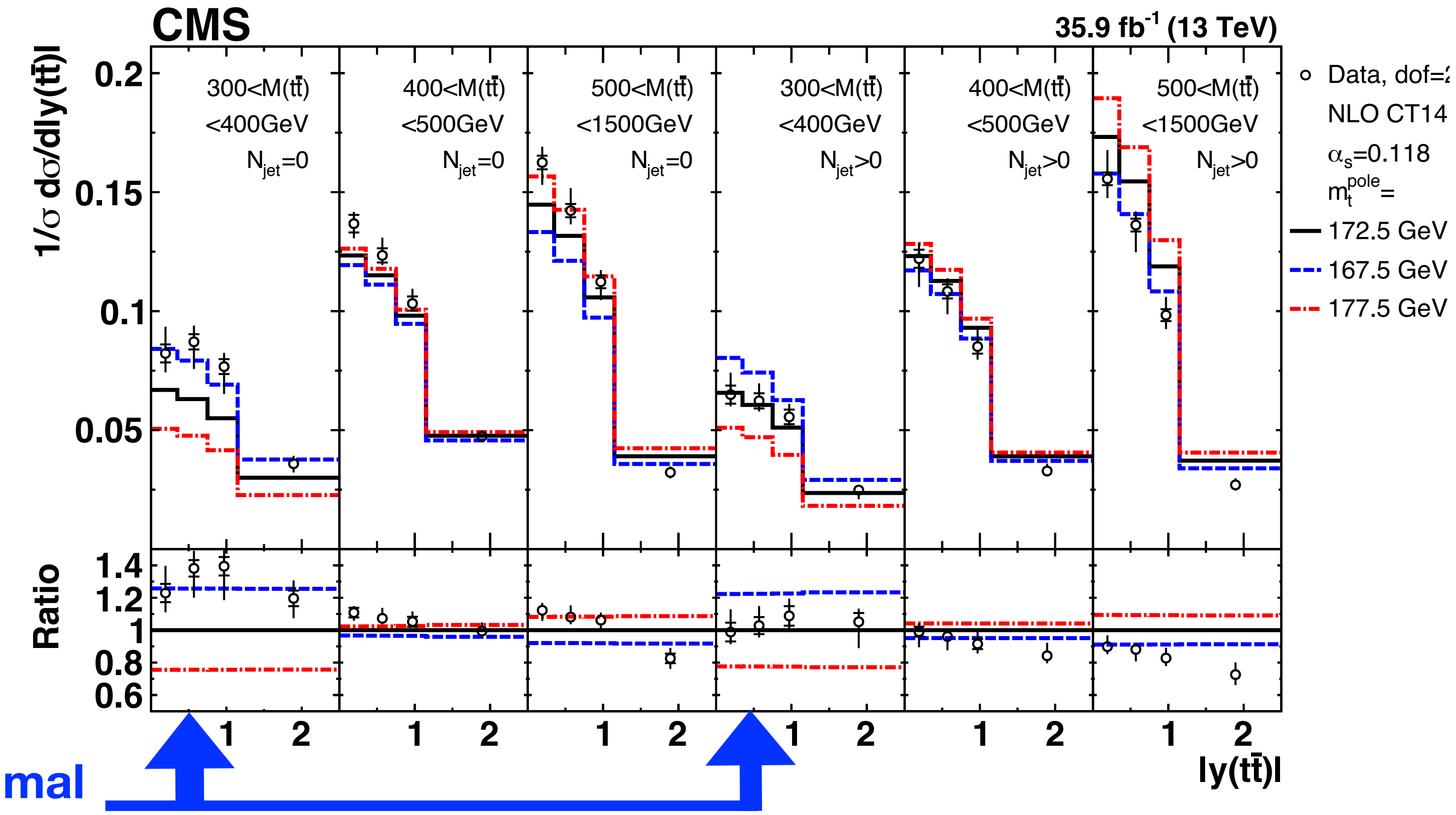
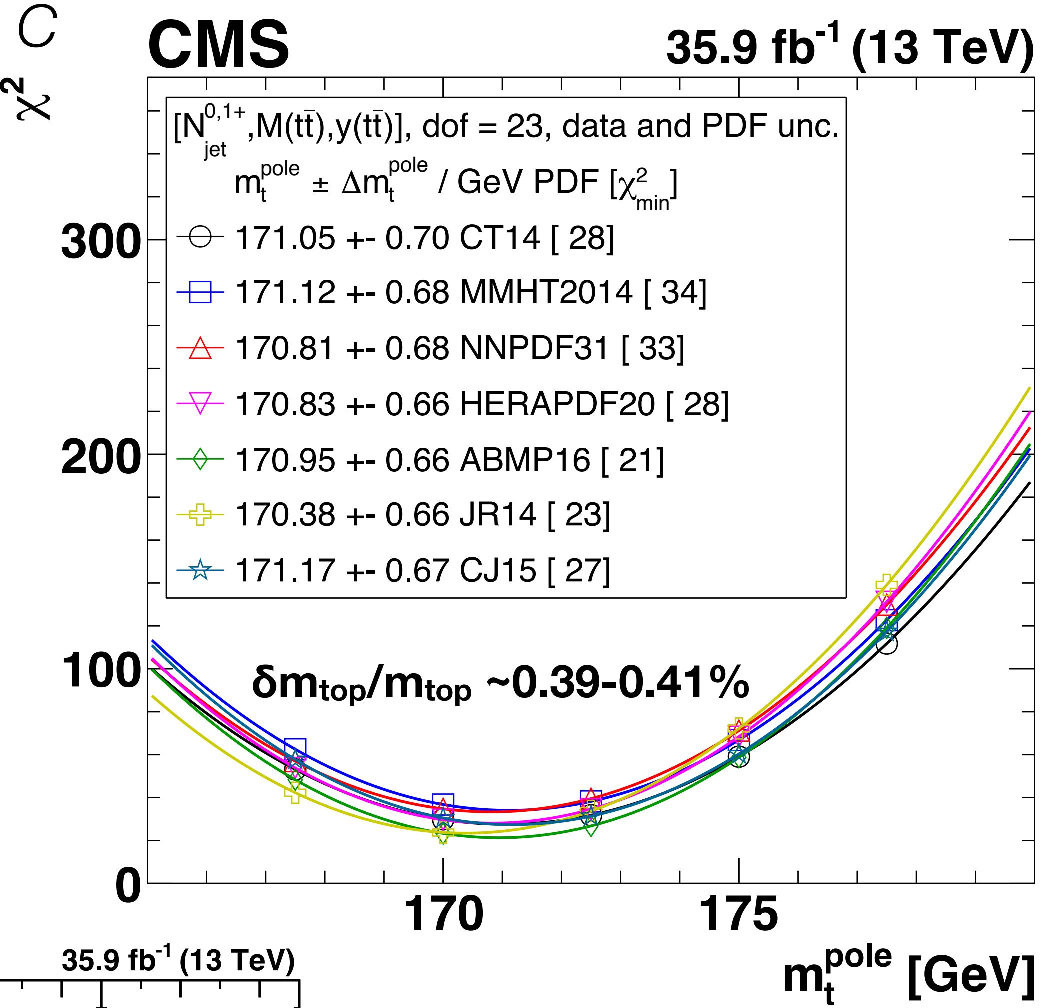
Separate fit

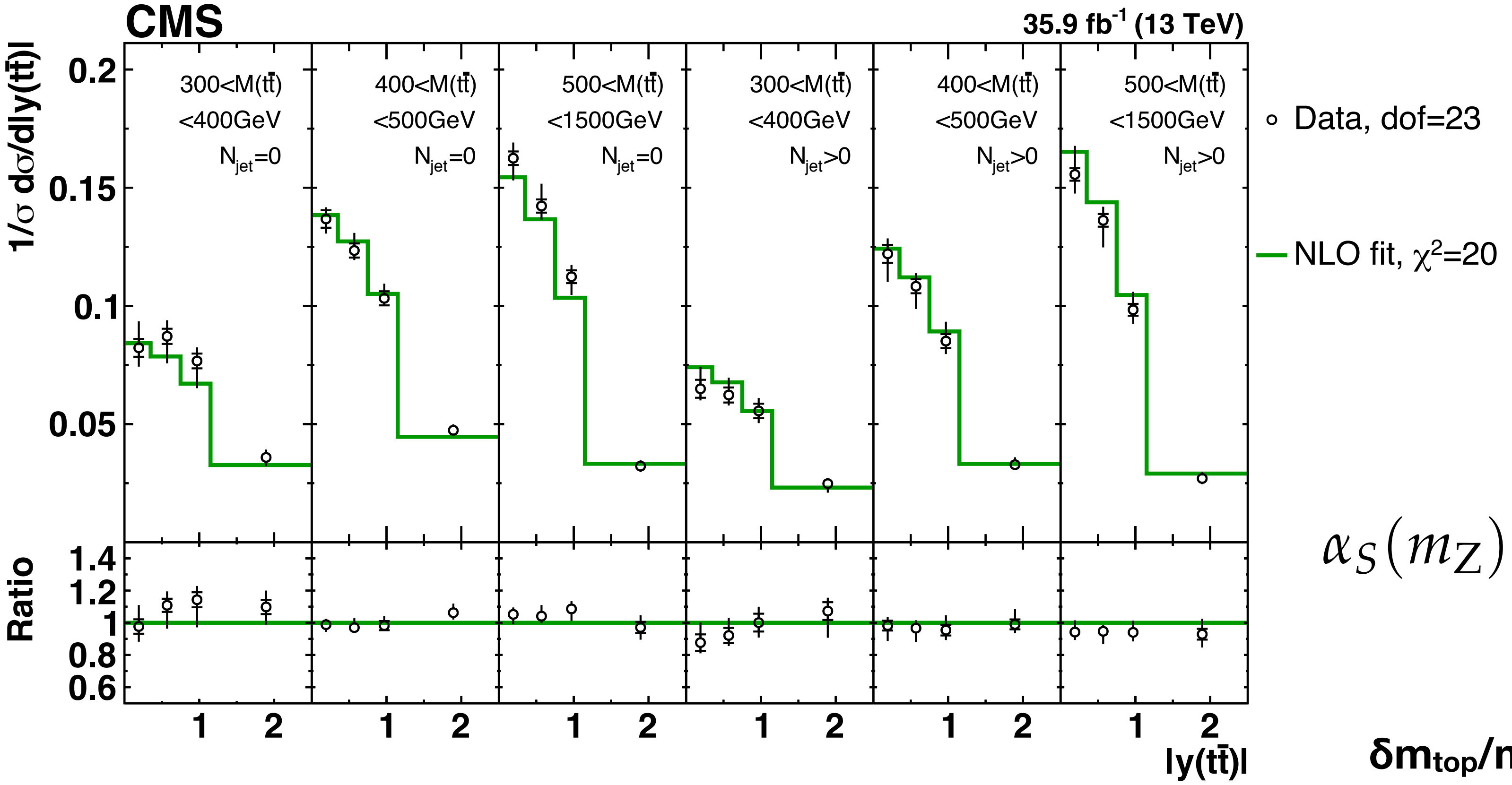


maximal sensitivity



δm$_{top}$/m$_{top}$ ~0.39-0.41%

Simultaneous fit ATLAS+ combined HERA DIS



$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

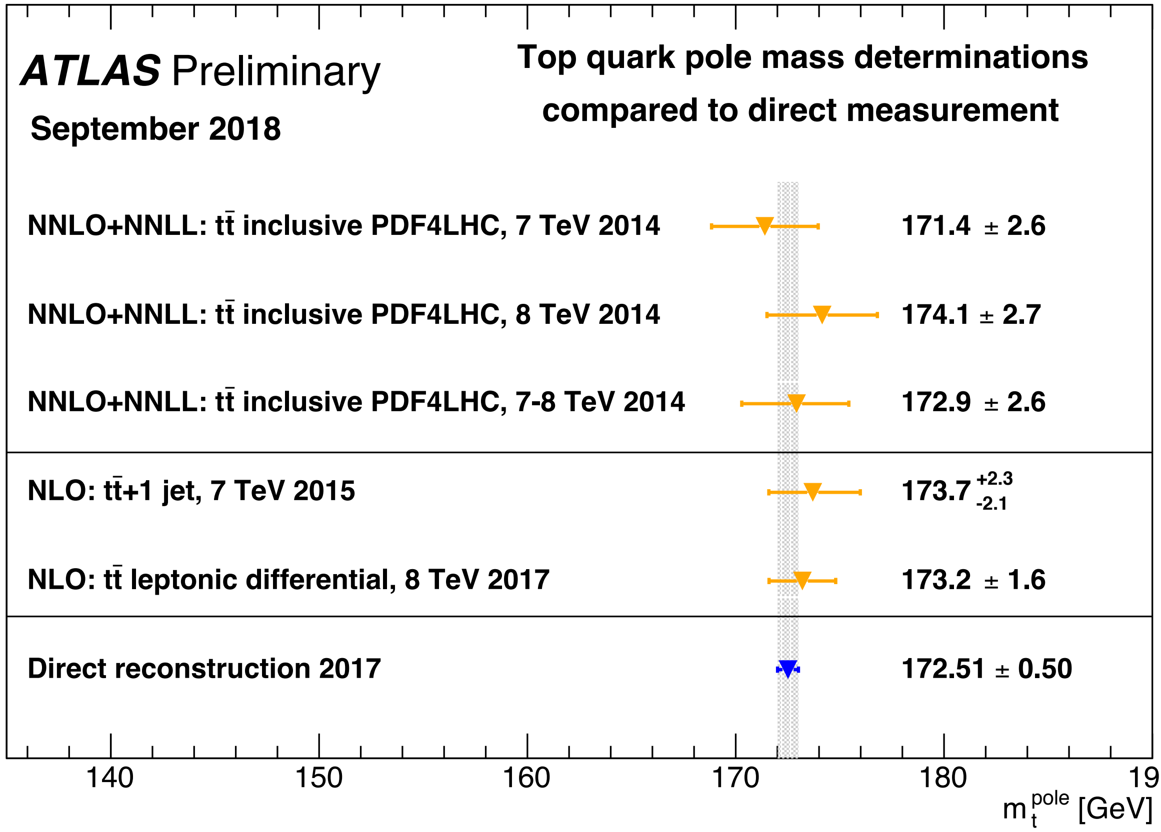
δm$_{top}$/m$_{top}$ ~0.46%

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

Special reasons: summary of indirect measurements of m_{top}

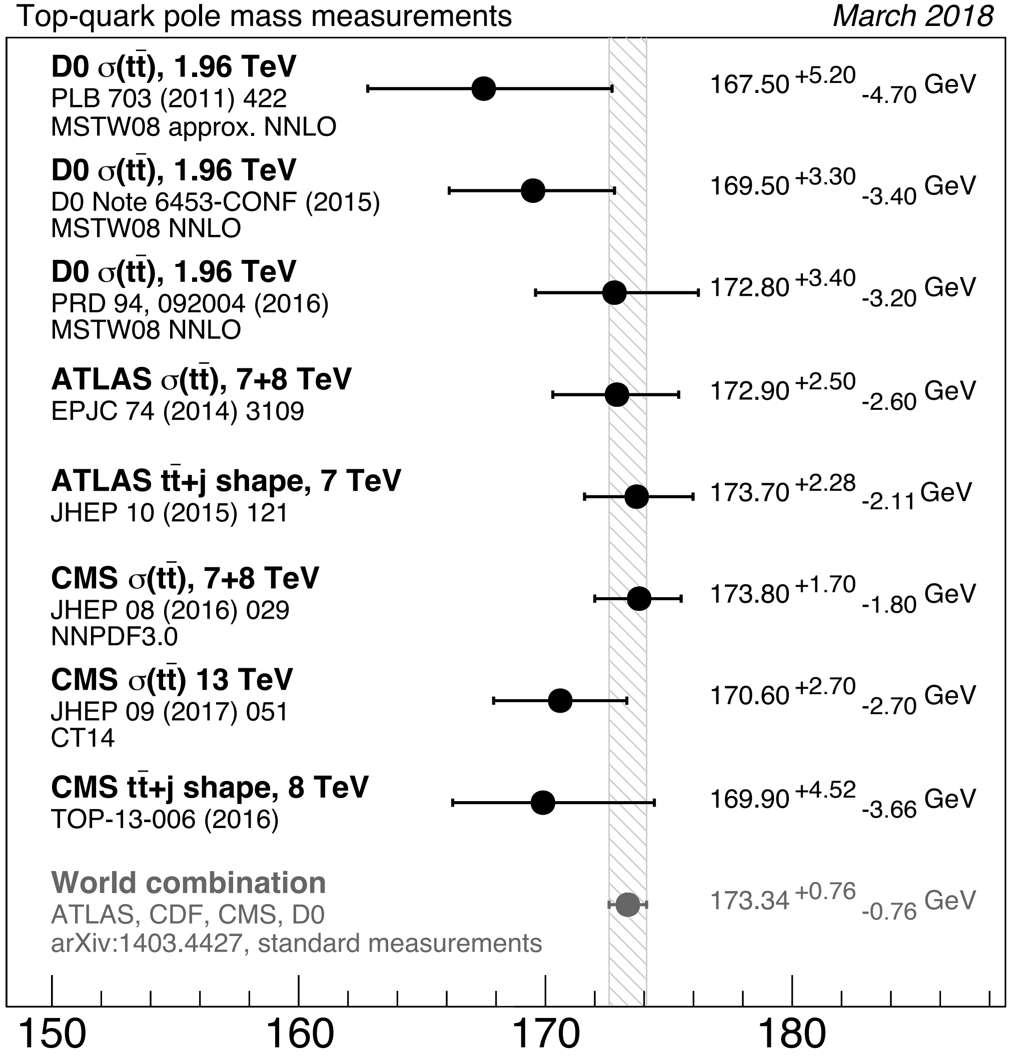
CMS Top Summary Plots

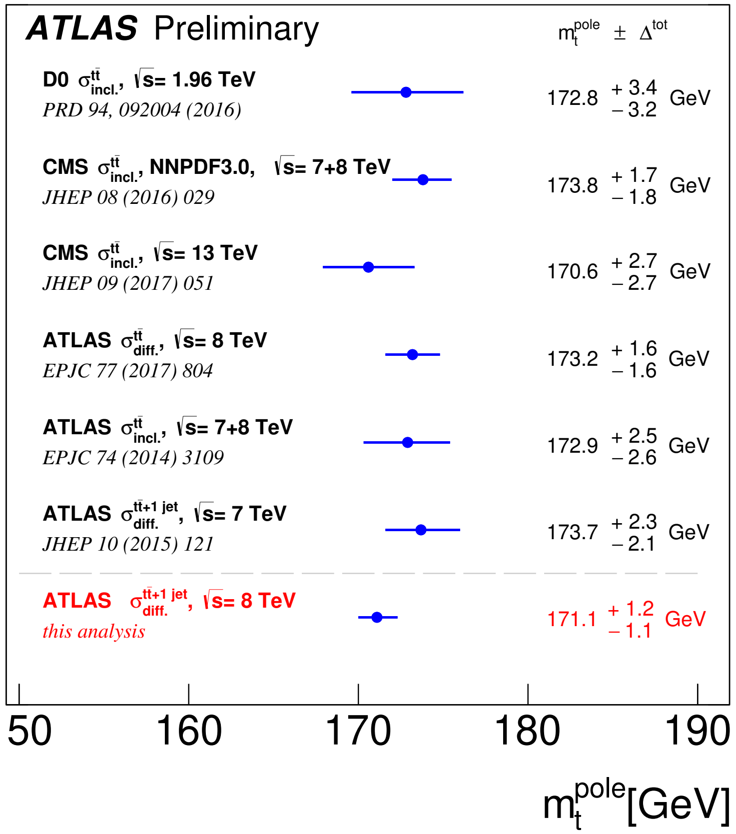
ATLAS Top Summary Plots



$\delta m_{top}/m_{top}$ ~1.03%

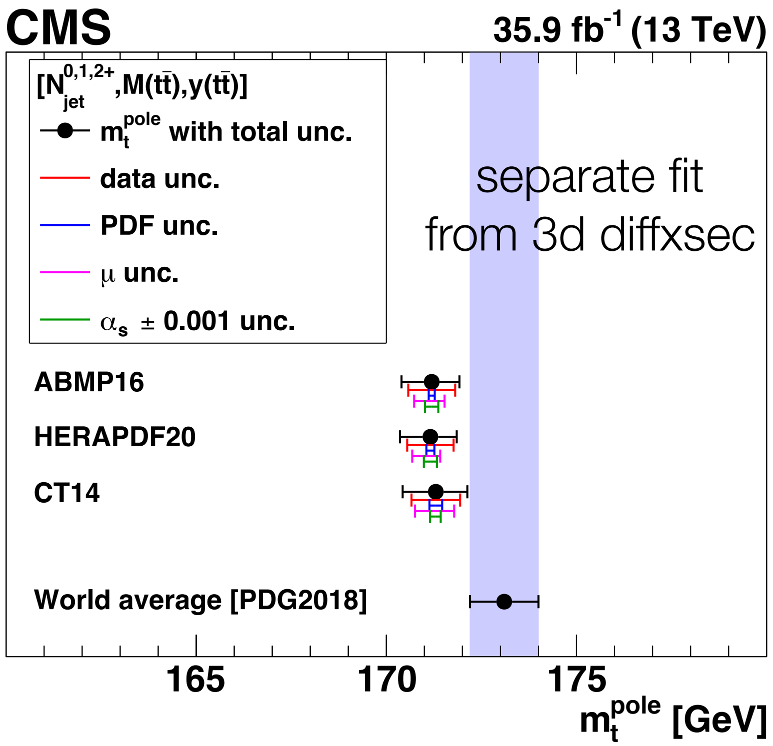
$\delta m_{top}/m_{top}$ ~0.92%





April 2019

$\delta m_{top}/m_{top}$ ~0.70%



separate fit
from 3d diffxsec

simultaneous
fit from 3d diffxsec

$170.5 \pm 0.8(\text{total})$ GeV

$\delta m_{top}/m_{top}$ ~0.46%

Measuring Top quark coupling

special reasons

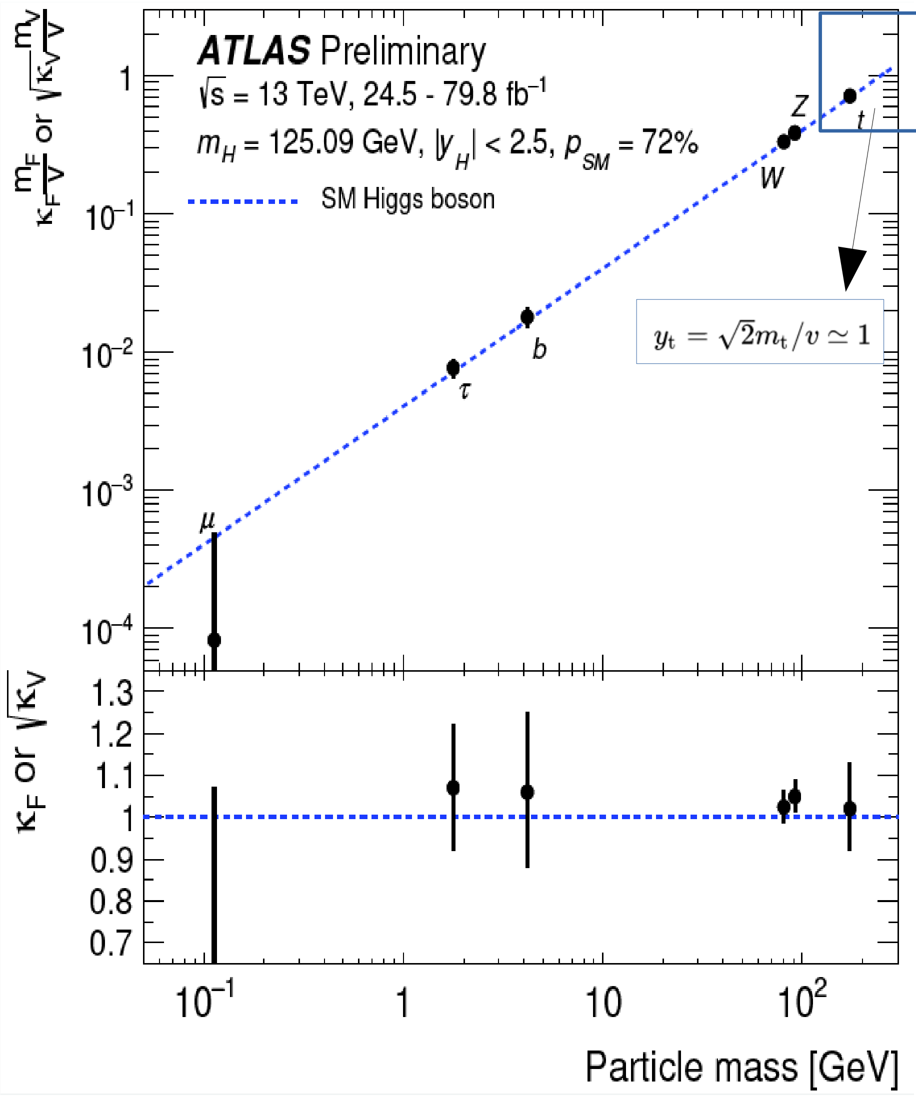
Special reasons: **The top yukawa coupling in a nutshell**

- Higgs coupling to fermions included by “adding” Yukawa terms

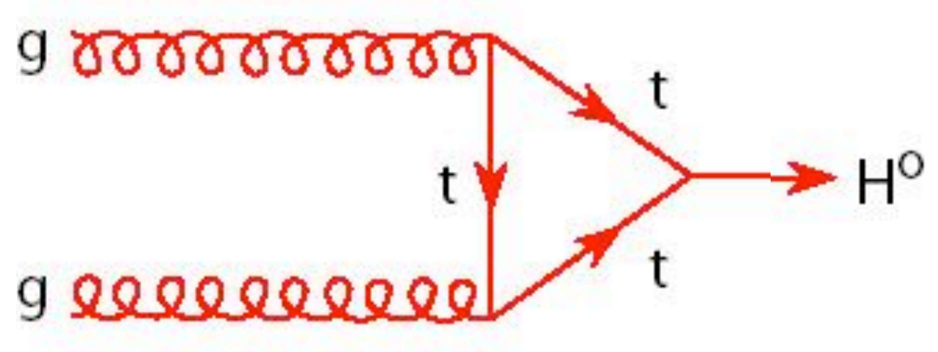
$$\mathcal{L}_f = m_f \bar{f}_L f_R + y_f H \bar{f}_L f_R/\sqrt{2} + h.c.$$

mass term — interaction term

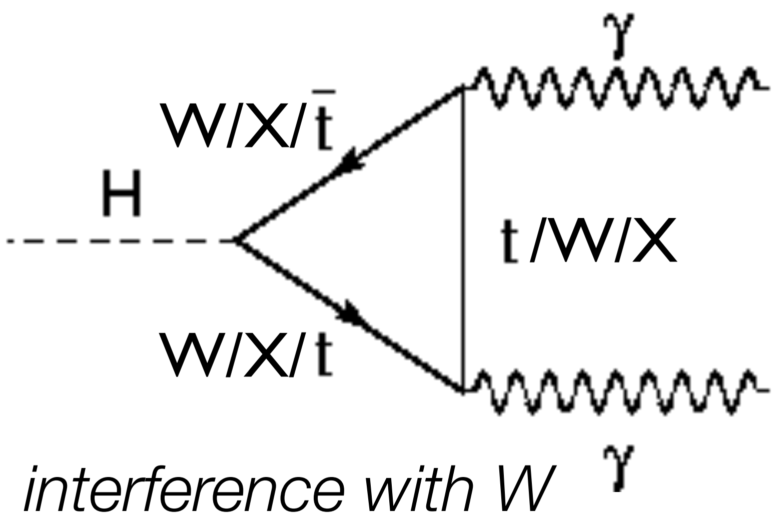
$$m_f = y_f v/\sqrt{2}$$



- **Indirect** : evidence for SM-like Y_t obtained from Higgs production (ggF) and decay ($H \to \gamma\gamma$): loops

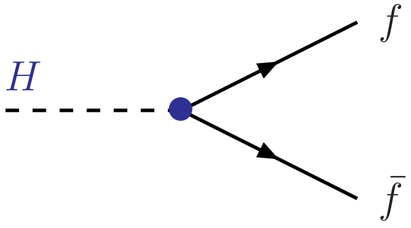


***gg H (F**usion): dominant @LHC*



interference with W boson in ***H***$\to\gamma\gamma$

- **Direct** : **tree level process cross section is proportional to y_t^2, probe up-type quarks**

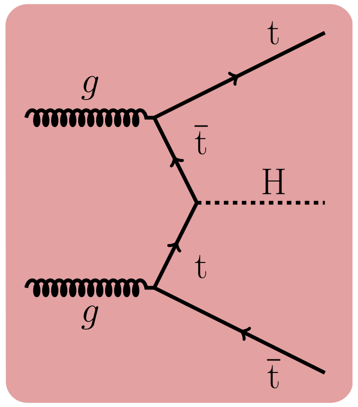


3rd gen

$H \to \tau\tau$

$H \to bb$

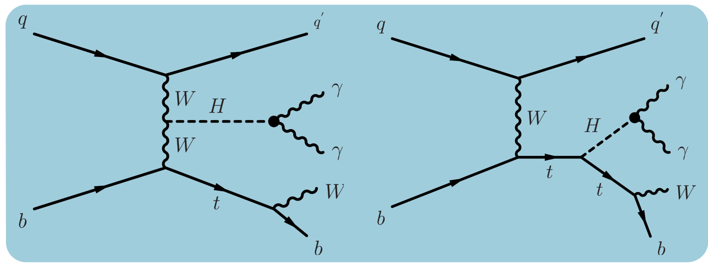
1.ttH



2.tHq: interference with Wt and sign of Y_t

3.4 top quarks production

4.Differential tt production



- **test BSM effects, assumed absent in loops**

Special reasons: **t-coupling to bosons**

JHEP02(2016)113

- **σ(tt+X) ~10^{-3} tt**

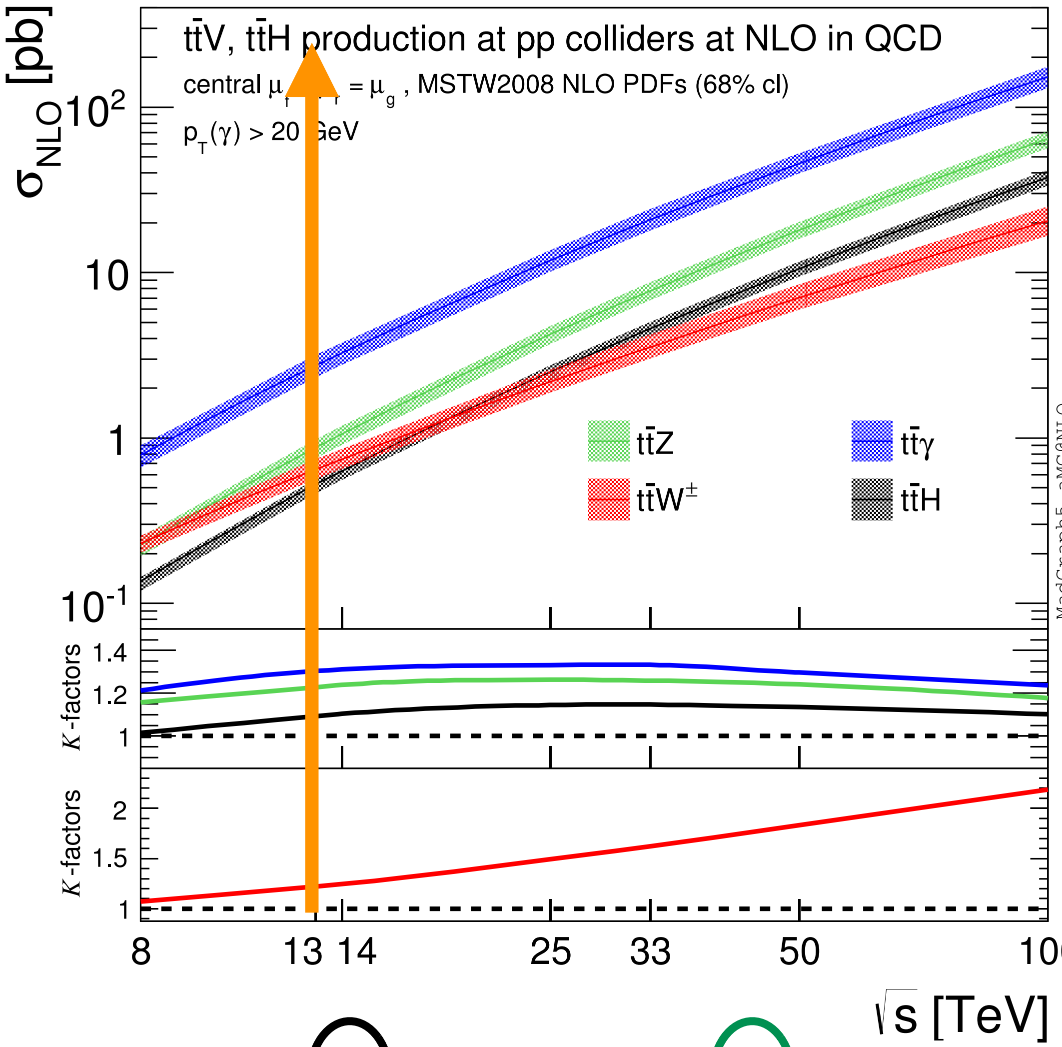
σ [pb]	8 TeV	13 TeV
$t\bar{t}Z$	$0.226^{+9.0\%}_{-11.9\%}{}^{+2.6\%}_{-3.0\%}$	$0.874^{+10.3\%}_{-11.7\%}{}^{+2.0\%}_{-2.5\%}$
$t\bar{t}W^{\pm}$	$0.23^{+9.6\%}_{-10.6\%}{}^{+2.3\%}_{-1.7\%}$	$0.645^{+13.0\%}_{-11.6\%}{}^{+1.7\%}_{-1.3\%}$
$t\bar{t}\gamma$	$0.788^{+12.7\%}_{-13.5\%}{}^{+2.1\%}_{-2.4\%}$	$2.746^{+14.2\%}_{-13.5\%}{}^{+1.6\%}_{-1.9\%}$
$t\bar{t}H$	$0.136^{+3.3\%}_{-9.1\%}{}^{+2.8\%}_{-3.2\%}$	$0.522^{+6.0\%}_{-9.4\%}{}^{+2.1\%}_{-2.6\%}$

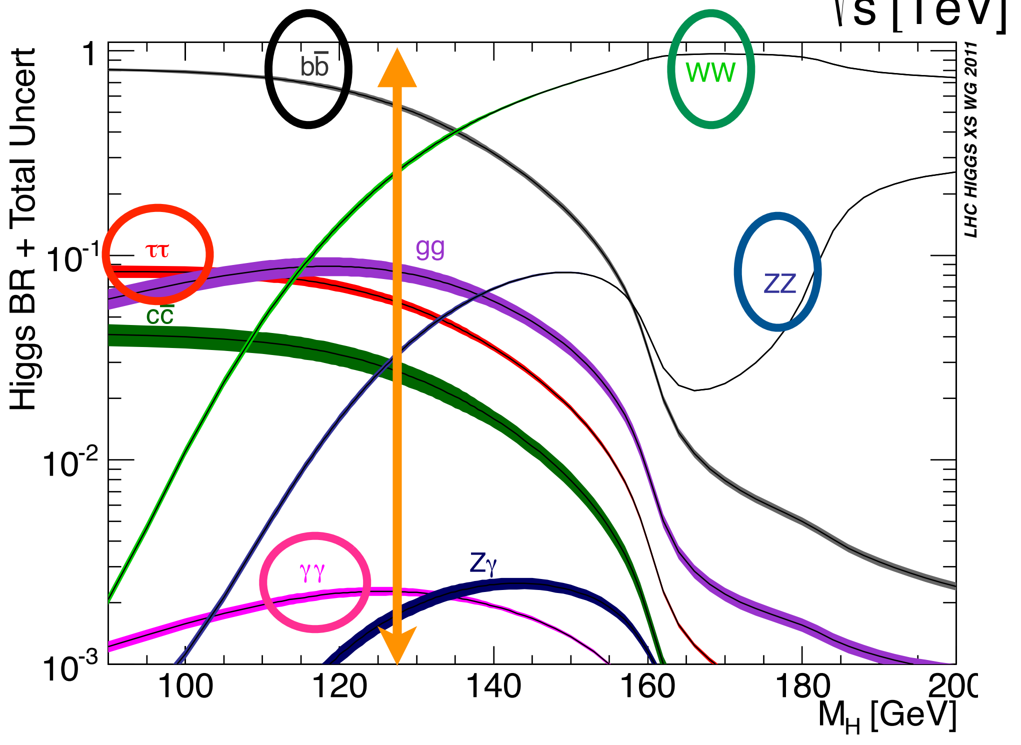
$\sigma_{13\ TeV}$/ σ_{8TeV}
3.9
2.8
3.5
3.8

σ(pb)	**8 TeV**	**13 TeV**
tt	**$245^{+6.2}_{-8.4}{}^{+6.2}_{-6.}$**	**$831^{+19}_{-29}{}^{+35}_{-35}$**

ttH is much rarer than tt !

Direct search for ttH with H→bb,WW/ZZ, ττ, γγ





Special reasons: **Observation of ttH production**

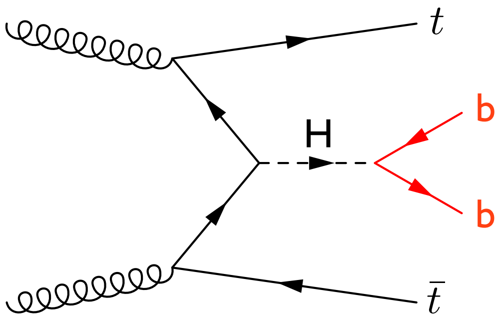
Phys. Lett. B 784 (2018) 173
ATLAS-CONF-2019-004

figures by M. Owen @ TOP2014
and CMS-PAS-HIG-17-004

example from ATLAS

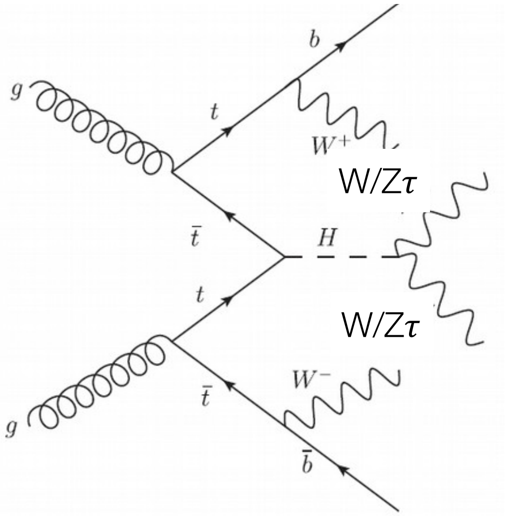
higher yield

H→bb



- Select single and dilepton tt-like decays, main bkg: tt+jets (tt+b)
- **Categorise in N(jet), N(b-jet)**,
- **Build signal/bkg discriminators** (BDT built from matrix element, likelihood, reco BDT) in 9 signal regions + 10 control regions

H →ZZ* →4ℓ (e,μ)

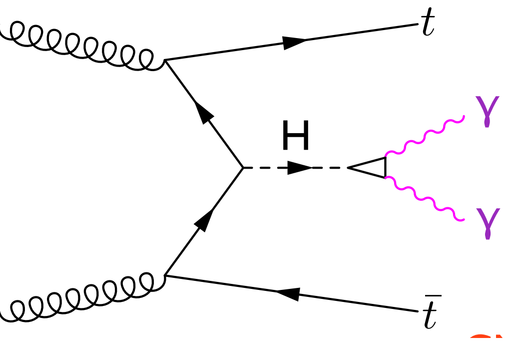


- Select ≥ **4ℓ= 2 opposite sign pairs, m(4ℓ)~ m_H ,≥1b-jet** bkg: simul. tt+W/Z, other ttH
- **Signal tt-HAD:** ≥ 3 jets & no other **ℓ** , **tt-LEP: ≥ 1 other jet, ≥ 1 other ℓ**
- **Build signal/bkg discriminator in tt-HAD:** BDT from $\Delta\eta$,ΔR between jets and lepton system,dijets kine, (b-)jets multiplicity → use 2 bins in HAdBDT+ LEP region

H →WW*/$\tau\tau$ /ZZ`*→multi-ℓ

- **Select 7 classes** by N$_\ell$ and **ℓ**-type using kine requirements and BDTs , bkg: simul. tt+W/Z, data-driven fake **ℓ**/τ
- **Build** BDT discriminator for 5 signal regions, single bin yield in 4 control regions+ 3 signal regions (low population)

H→$\gamma\gamma$



- Select **2γ, 105 GeV<m($\gamma\gamma$)<160 GeV, p_T lead (sublead)γ/m($\gamma\gamma$) ≥ 0.35 (0.25), ≥1b-jet** main bkg: non-resonant di-photon (incuding tH,tt+$\gamma\gamma$,VH)
- **Signal tt-HAD:** ≥ 2 jets & no **ℓ** , **tt-LEP: ≥ 1 ℓ**
- **Build signal/bkg discriminators** (BDT built from jets & photon kine) **in 7 signal regions** (4 in HAD + 3 in LEP)
  - ttH signal yield in BDT bins: from fit to m($\gamma\gamma$)

higher purity

Special reasons: **Observation of ttH production**

Phys. Lett. B 784 (2018) 173
ATLAS-CONF-2019-004

- Derive likelihood L= Π **likelihoods** for distributions of all discriminating variables in all signal + control regions in signal (ttH)+bkg hypothesis

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot \underline{p(\tilde{\theta}|\theta)}$$

Gaussian or log-normal for nuisance par → syst uncertainties

- Maximise L **versus $\mu=\sigma_{obs}/\sigma_{SM}$, θ →extract signal strength μ_{fit}, θ_{fit}** i.e. constrain syst uncertainties, bkg ($b(\theta)$) normalization, background hypothesis

ATLAS

CMS

- **Measurements are consistent with SM predictions**
  - Combination assumes SM branching ratios

Significance

Run I+RunII:**6.3 s.d.** (5.1 s.d. exp)

Run II : **5.8 s.d.** (4.9 s.d. exp)

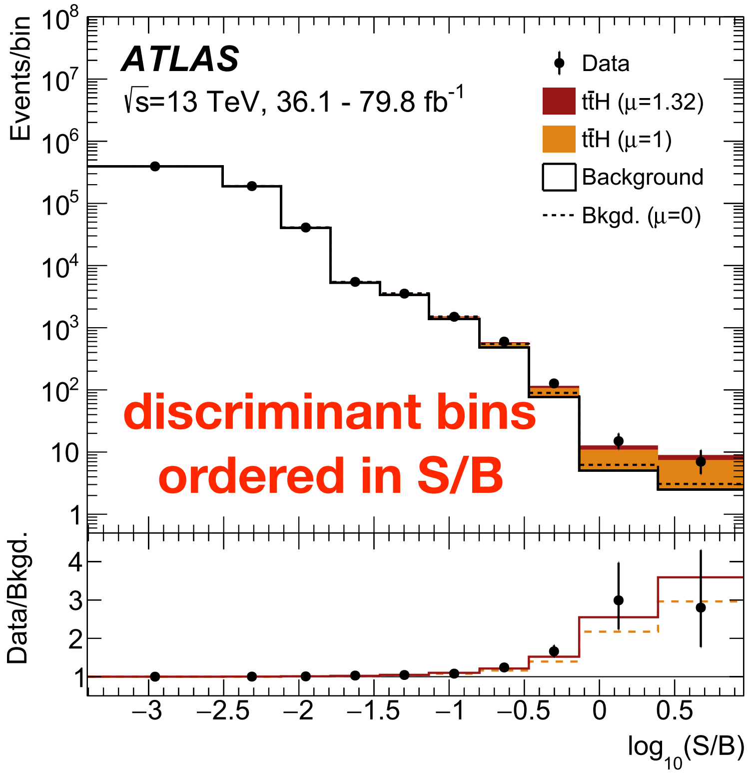
$$\sigma_{\text{ttH}} = 670 \pm 90\ (\text{stat.})\ {}^{+110}_{-100}\ (\text{syst.})\ \text{fb}$$

$$\sigma_{\text{ttH}}^{\text{SM}} = 507^{+35}_{-50}\ \text{fb}$$

Significance

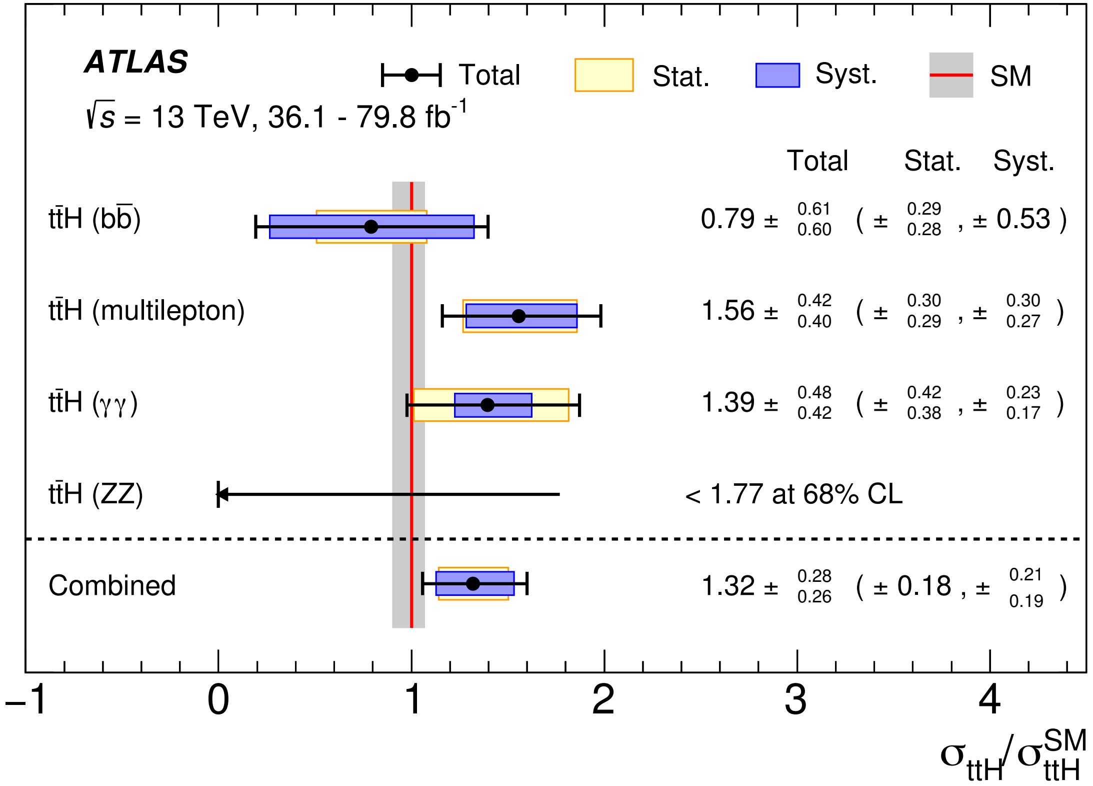
Run I+Run II: **5.2 s.d.**

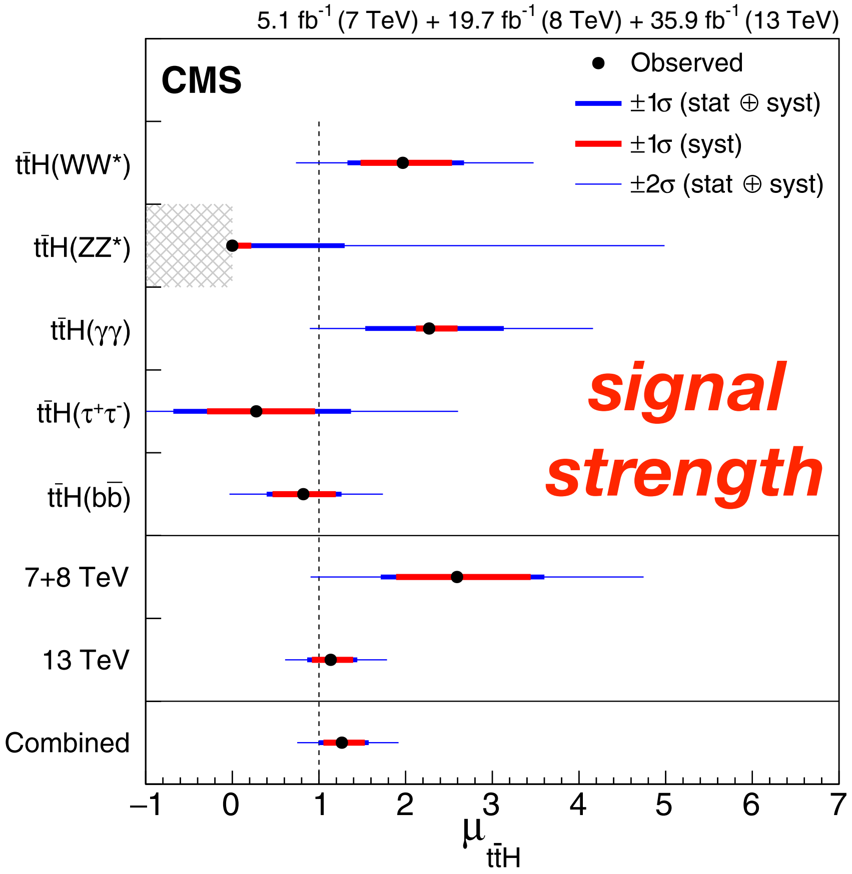
(4.2 s.d. exp)



discriminant bins ordered in S/B

signal strength





signal strength

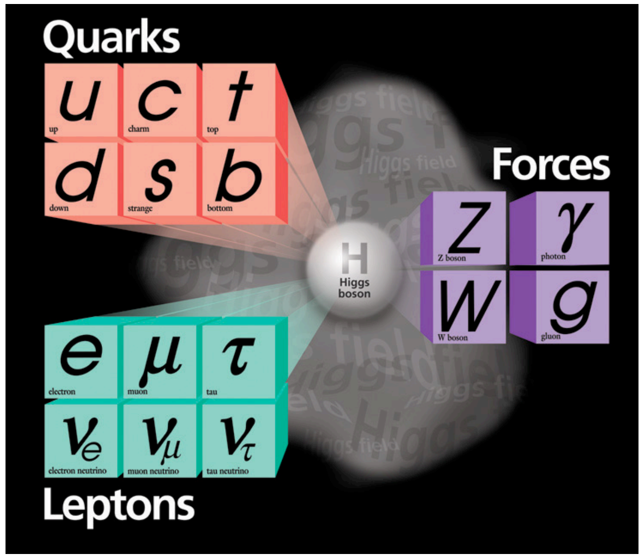
Search for new physics with Top quark

beyond reasons

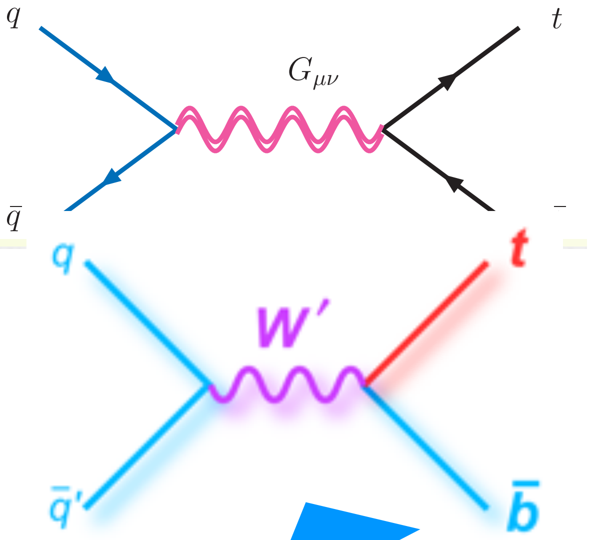
"Beyond" reasons: **top quark as window on new physics**

Standard Open **questions**

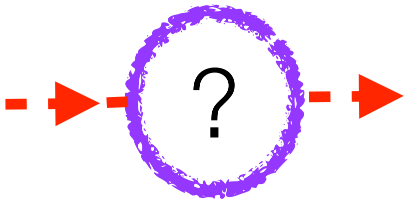
- *What is the **origin of mass**? Why are symmetries of **forces** different from those of **particles**?*



SymmetryMagazineSMHiggs2012

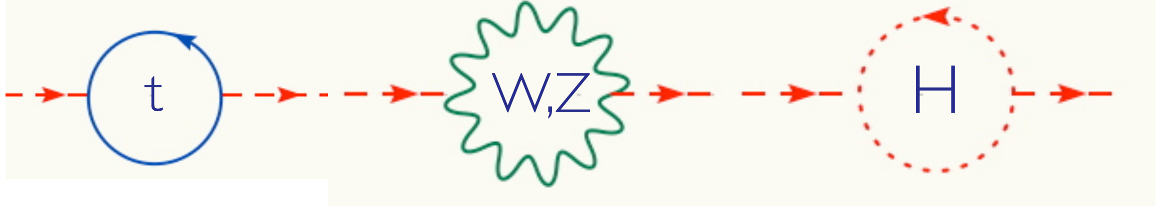


- **If SM is an effective theory valid up to new physics scale Λ**



m

m_{Higgs} has ***m_{top}-dominated virtual corrections***



$$m_H^2 = m_{H0}^2 + \underbrace{\left[-(2\ \mathrm{TeV})^2 + (0.7\ \mathrm{TeV})^2 + (0.5\ \mathrm{TeV})^2 \right] (\Lambda/10\ \mathrm{TeV})^2}_{\delta m_H^2} + ?$$

Λ is unknown. *If Λ >> TeV, $\delta m_H >> m_H$. What balances δm_H is still a mystery.*

Suggestive: ∃ **new particles** with **opposite corrections** to **those from top quark**:

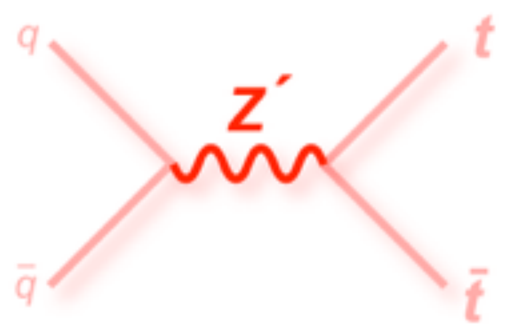
(C.Delaunay @ TOP2014)

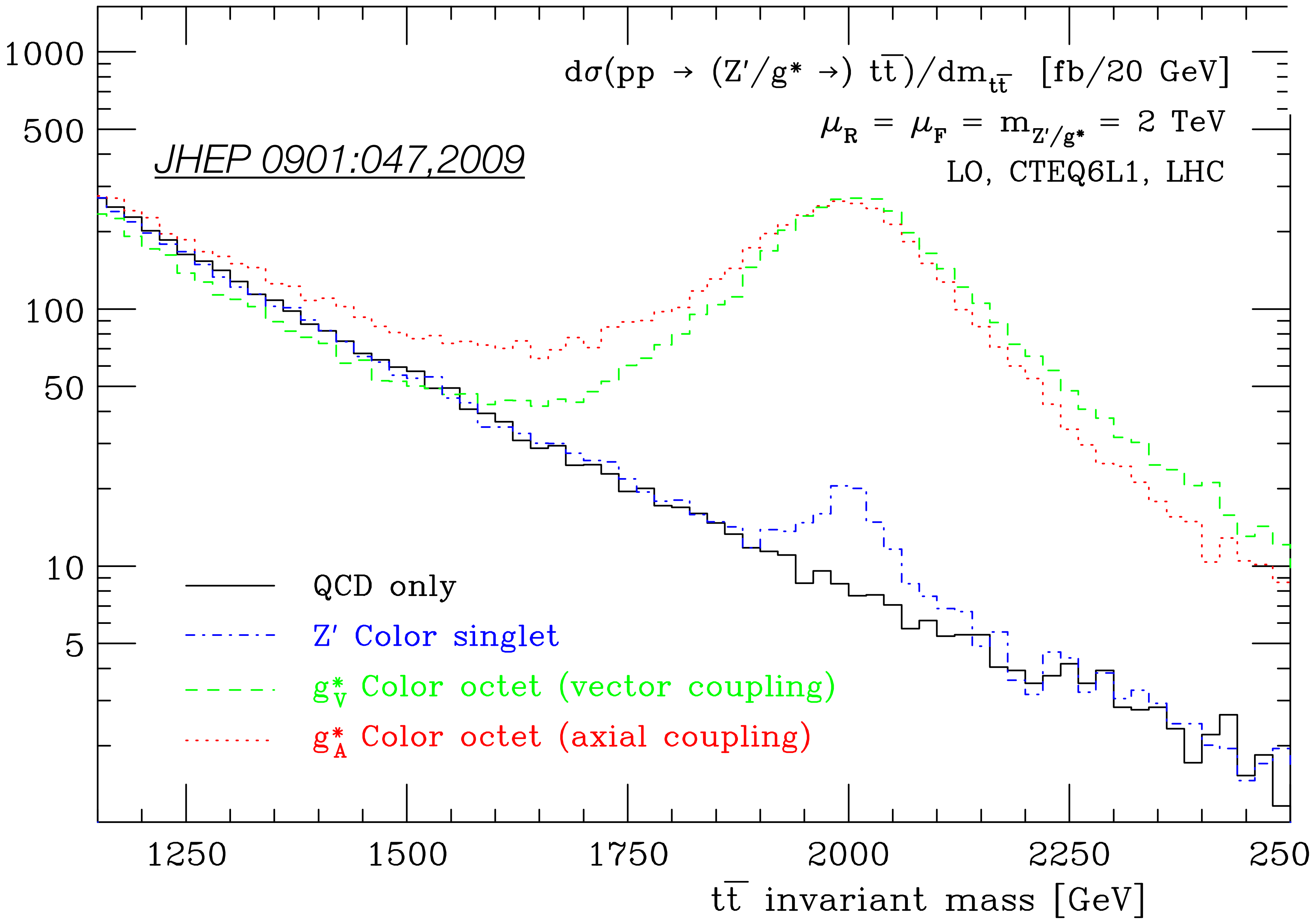
Since [SUSY/global sym, QCD]=0,
top partners are colored*
→ *large production cross-sections at hadron colliders*

strongly coupled to top quark ⇒decay like top quark or to top quarks

search by measuring top quarks

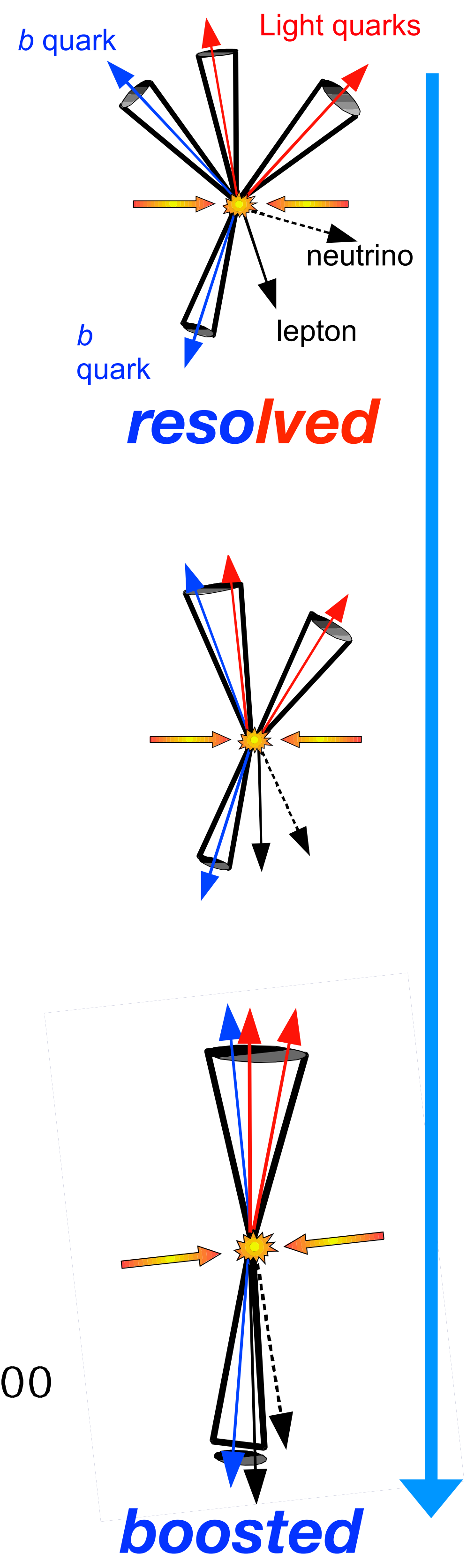
“*Beyond*” *reasons*: **top quark as window on new physics**





JHEP 0901:047,2009

increasing $p_{T,top}$,m_{tt}



"Beyond" reasons: **Direct search for tt resonances**

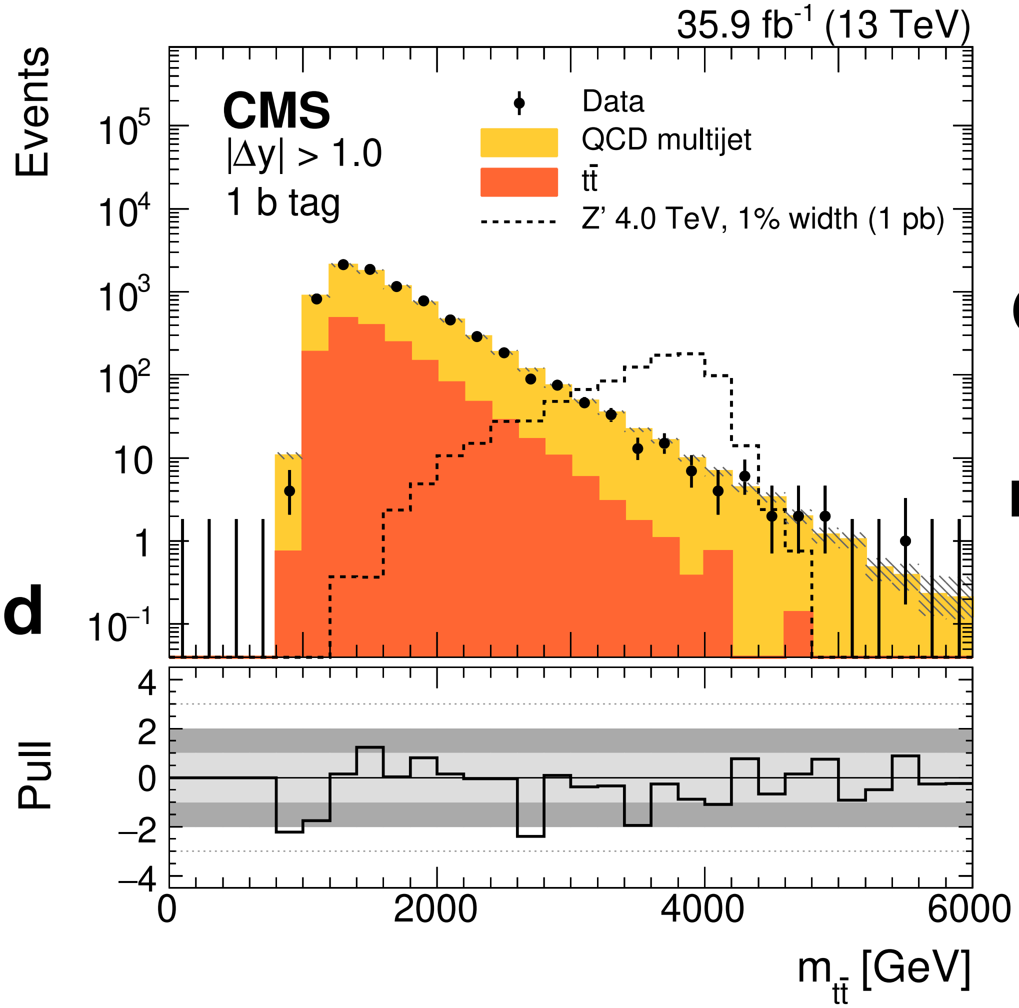
Use shape of specific model

Recognise boosted (& resolved) **top quark decays using**

	CMS	*ATLAS*
	Remove small-p_T, wide angle radiation from jet	
large t-jets	**jet mass**, 3-prong/2-prong	jet **mass**, 3-prong/2-prong away from **ℓ** & **lep-jet**
leptonic top	ΔR(lep,jet), p_T(lep relative to jet)	p_T-dependent isolated **ℓ** 1 "close" small-R jet=**lep-jet**

Combine dilepton **&** l+jets resolved & **boosted** **&** **all had boosted**

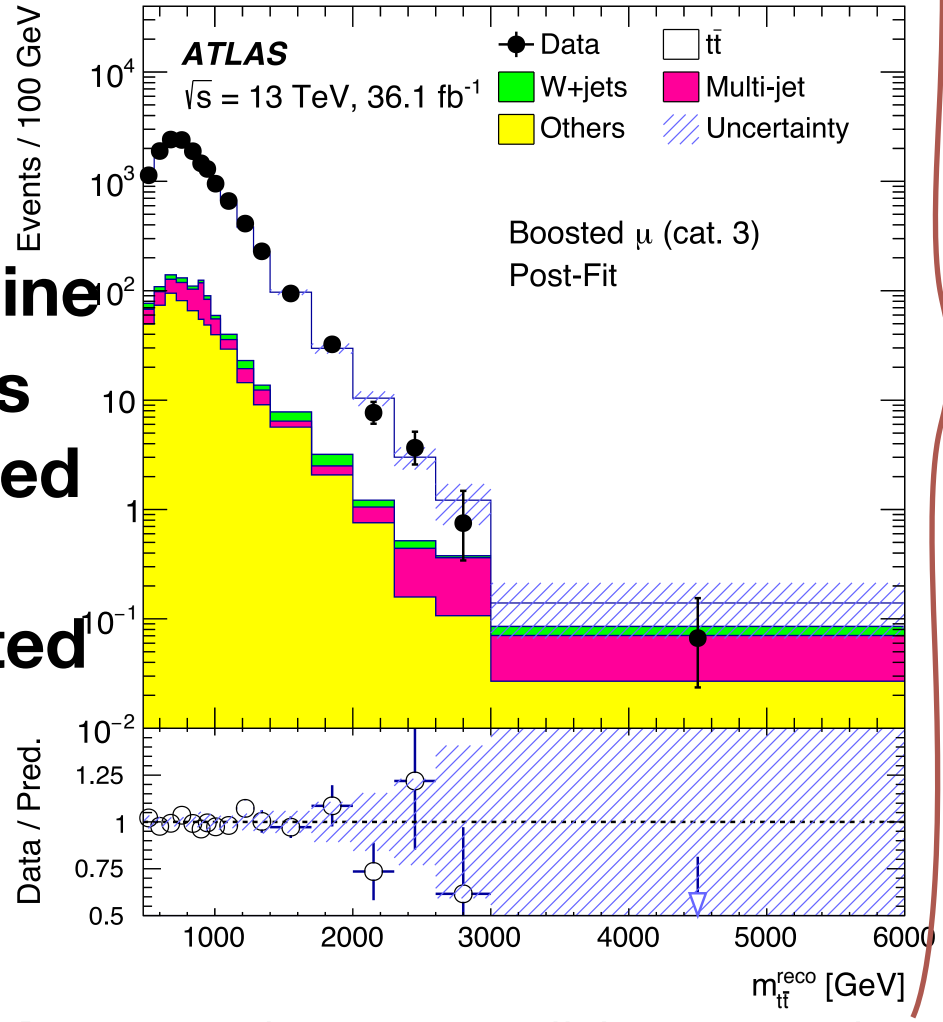
JHEP 04 (2019)031



all had: *2 top-jets, ≥1 subjet matched to b-jet*

Combine l+jets resolved & boosted

Eur. Phys. J. C 78 (2018) 565



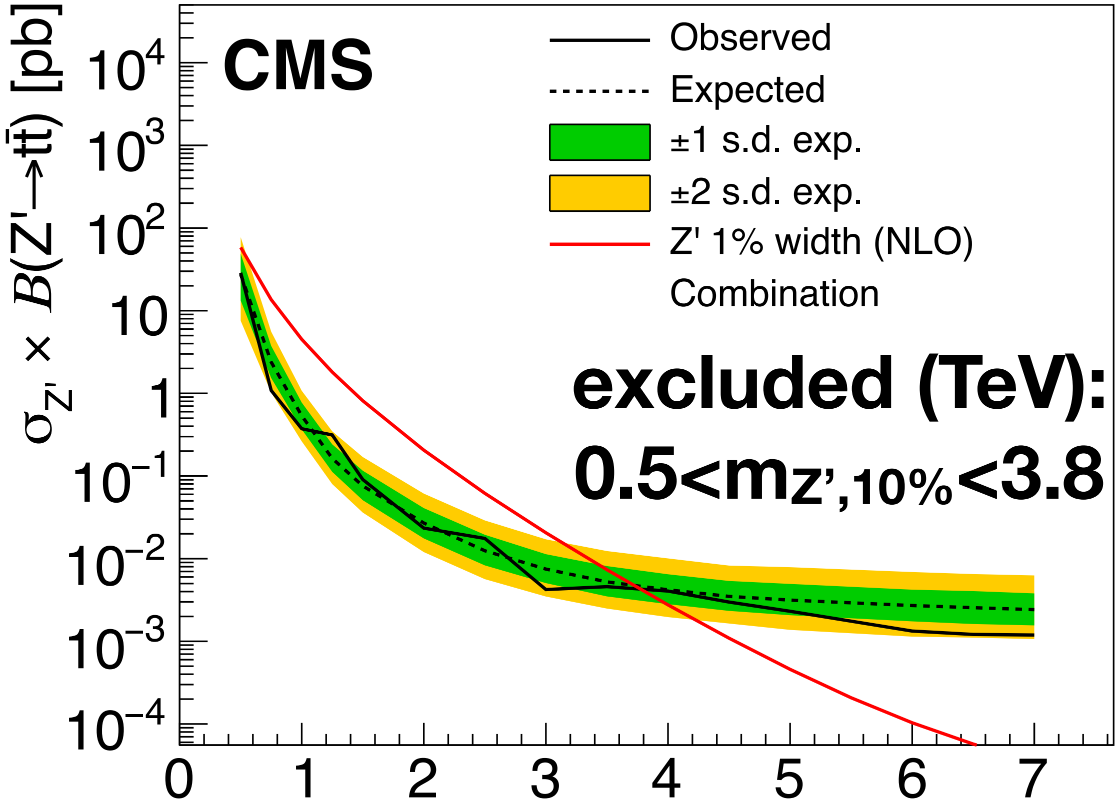
***μ+jets**, each top candidate matches b-jet*

No excess seen. Set limits with frequentist scheme (CLs) →

“Beyond” reasons:**Direct search for tt resonances**

Exclusion regions up to $m_{resonance}$ ~4-5 TeV !

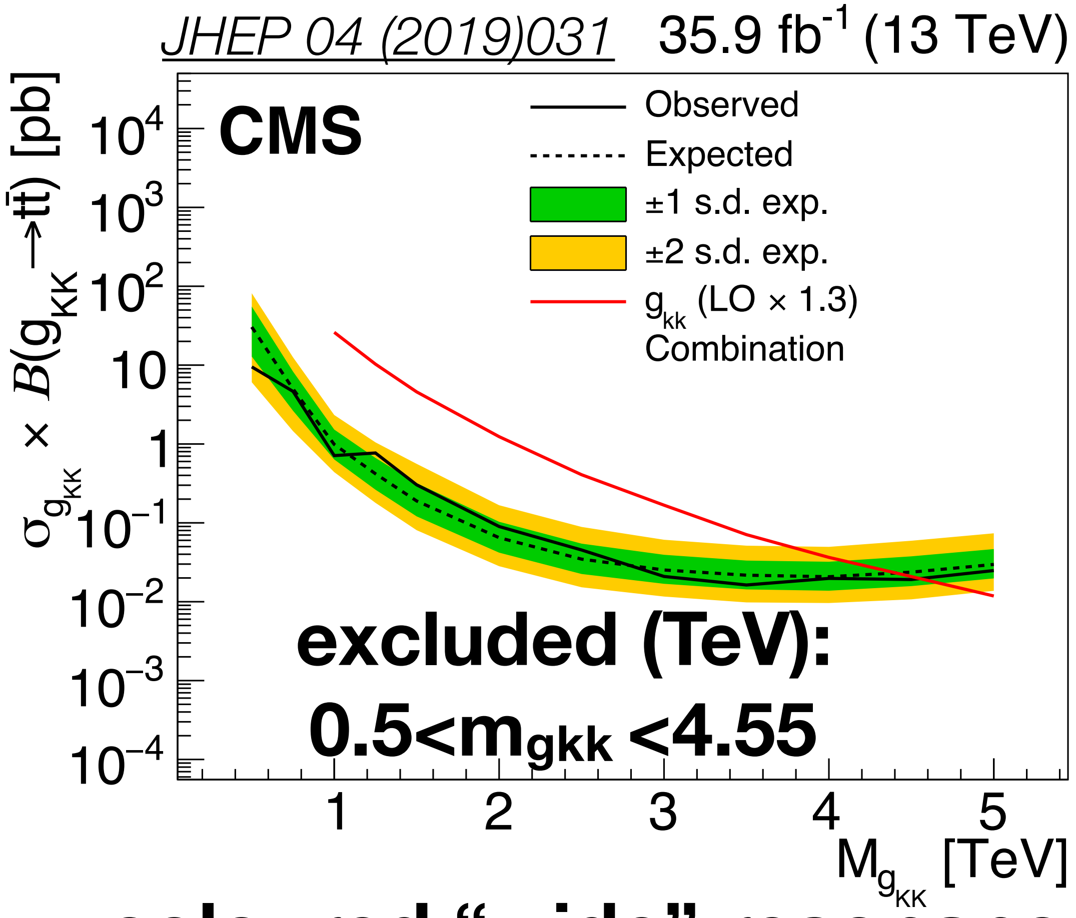
JHEP 04 (2019)031



excluded (TeV):
$0.5<m_{Z',10\%}<3.8$

“narrow” resonance

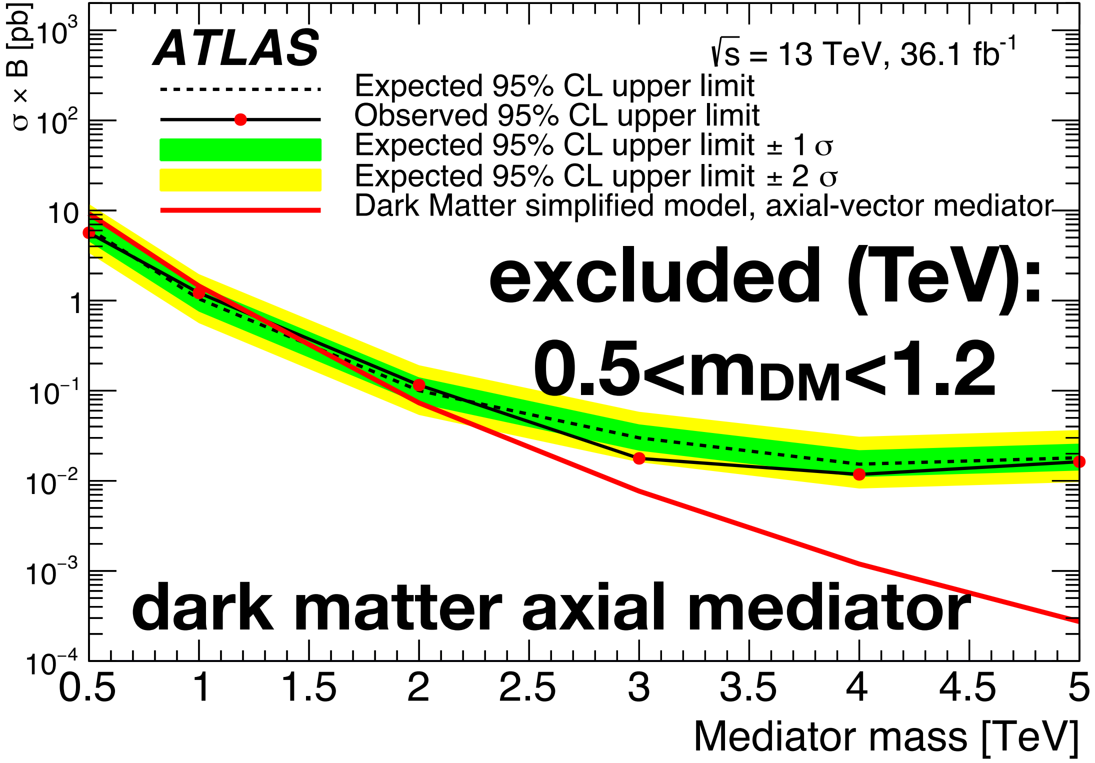
JHEP 04 (2019)031



excluded (TeV):
$0.5<m_{gkk}<4.55$

coloured “wide” resonance

Eur. Phys. J. C 78 (2018) 565



excluded (TeV):
$0.5<m_{DM}<1.2$

dark matter axial mediator

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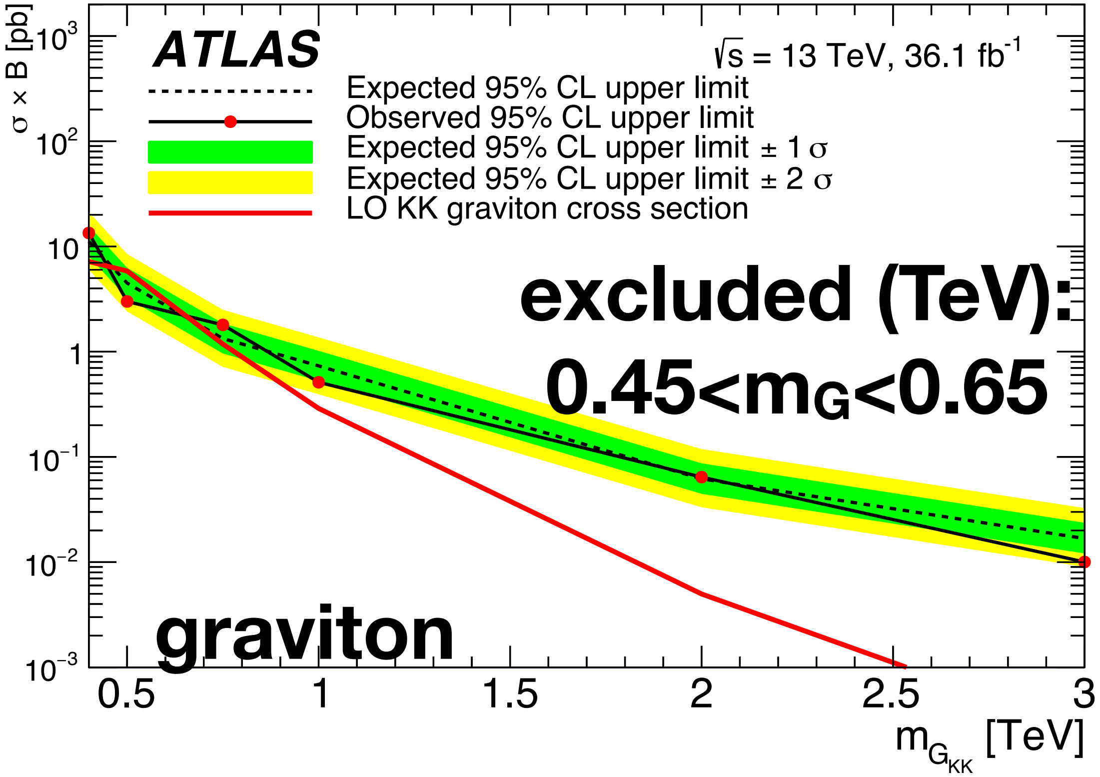


excluded (TeV):
$0.45<m_G<0.65$

graviton

“Beyond” reasons:**Looking at the future: Effective Field Theory fits**

No new light states → **Parametrize** renormalisation effects (momentum divergences) between observed SM scale and **new physics scale** (BSM) **as a function of SM fields**

DETERMINATION OF THE COUPLINGS OF THE SM $\mathcal{L}$ UP TO DIM=6

TopFitter Coll, JHEP04(2016)015

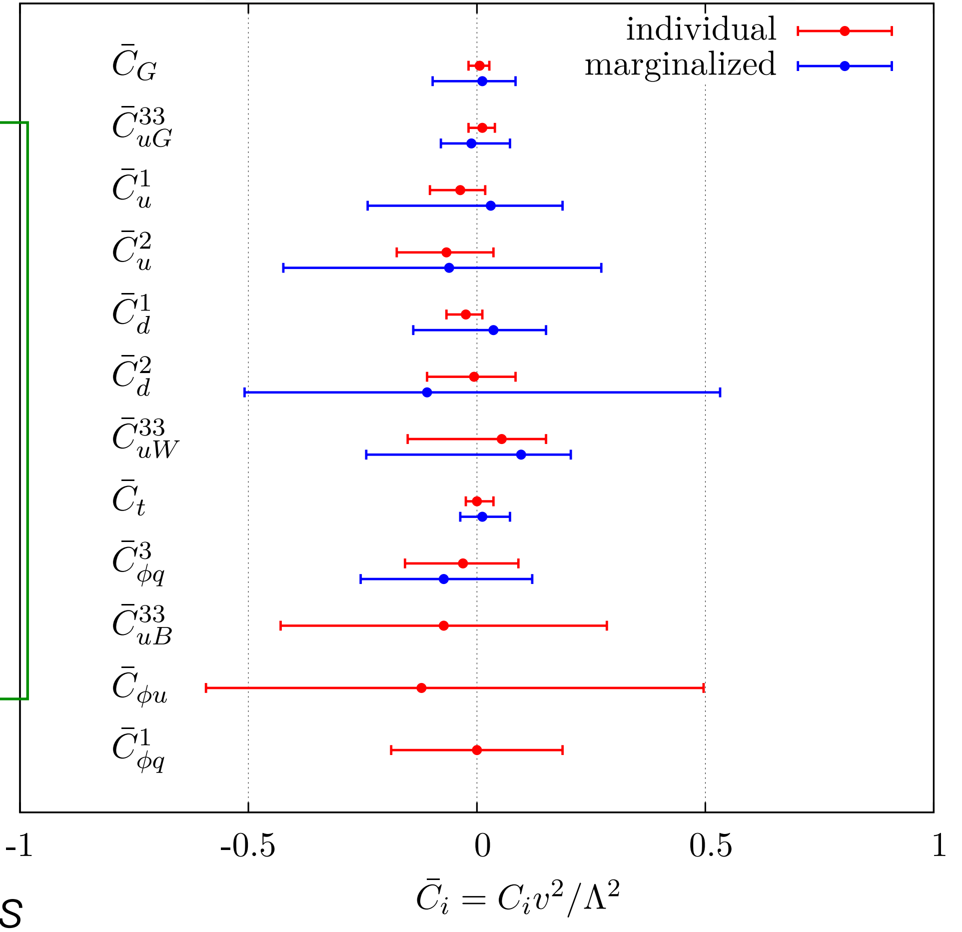
& Phys.Lett.B 763 (2016) 9

initial χ^2 Fit to SM@NLO/NNLO+**EFT@LO**

Measurements include $\sigma_{tt,t}$ & $d\sigma_{tt,t}/dX$

Predictions: polynomials $f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \le j} \gamma_{i,j}^b C_i C_j + \ldots .$

EFT coefficients are consistent with zero



Where to go?

arxiv:1802.07237 & LHCTopWG discussions

- Use **EFT** operators producing top quarks: extend **to NLO** (new operators)

- **Measure $d\sigma_{tt,t}/d\{X\}$**: separate optimisation, provide extended covariances
- Combined **fits** to predictions

EFT couplings

- Common likelihood fit of **$dN_{tt,t}$**/d{X} to predictions with uncertainties constraint

EFT couplings

measurements are by-product

“Beyond” reasons:**EFT: Constraints on top chromomagnetic moment**

- Top colour charge & spin→ **chromomagnetic moment** (CMDM)
- In EFT, new phys → **dim 6 operator causing anomalous CMDM → alter rates, spin correlation** → change $\Delta\varphi(\ell^+\ell^-)$: azimuthal angle in dilepton tt: prediction available @NLO as a function of C_{tG}/Λ^2 (coupling strength/EFT scale)

- CMS **Dilepton selection & bkg estimate**
- Bkg-subtract and unfold $dN/d\Delta\varphi(\ell^+\ell^-)$→ $d\sigma_{tt}/d\Delta\varphi(\ell^+\ell^-)$
- Minimise

D=data, P=prediction

$$\chi^2(C_{tG}/\Lambda^2) = [\vec{D} - \vec{P}(C_{tG}/\Lambda^2)]^T Cov^{-1}[\vec{D} - \vec{P}(C_{tG}/\Lambda^2)]$$

- Assume Gaussian errors → Derive 95% CL confidence interval by $\Delta\chi^2$
- Theory uncertainties (normal., scales, PDF, m_{top}) **repeat fit, show maximal changes due to theory variations**
- More stringent constraint than previous measurements

Tevatron data	$-0.32 < C_{tG}/\Lambda^2 < 0.73\,\mathrm{TeV}^{-2}$
CMS, √s=8 TeV	$-0.42 < C_{tG}/\Lambda^2 < 0.30\,\mathrm{TeV}^{-2}$
CMS, √s=13 TeV	$\boxed{-0.06 < C_{tG}/\Lambda^2 < 0.41\,\mathrm{TeV}^{-2}}$

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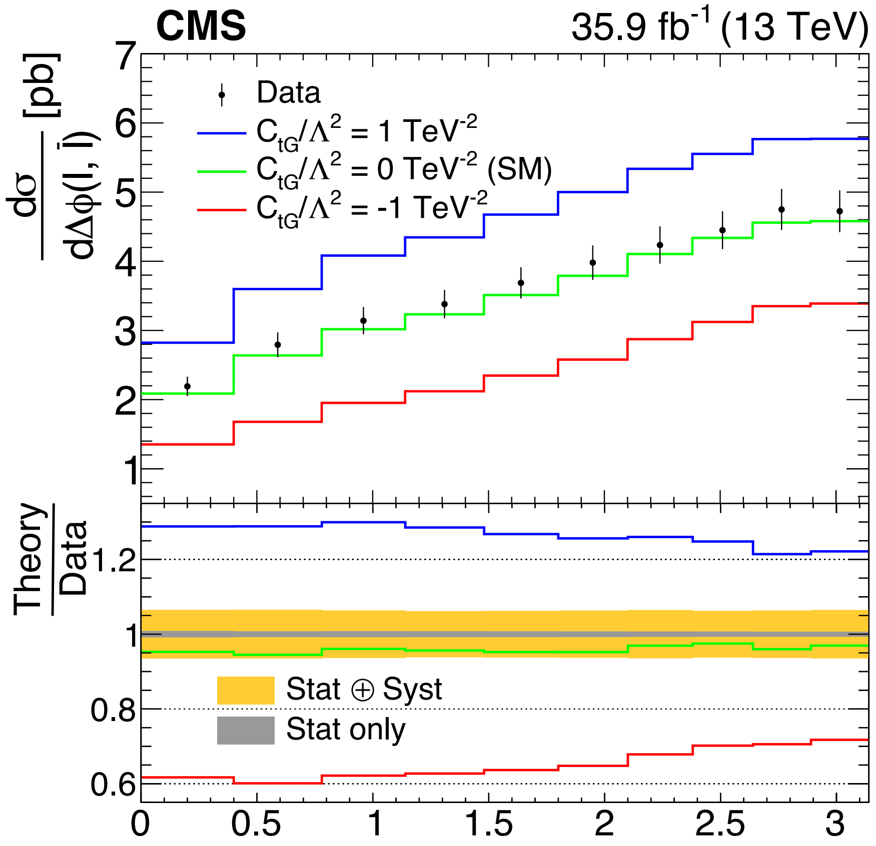
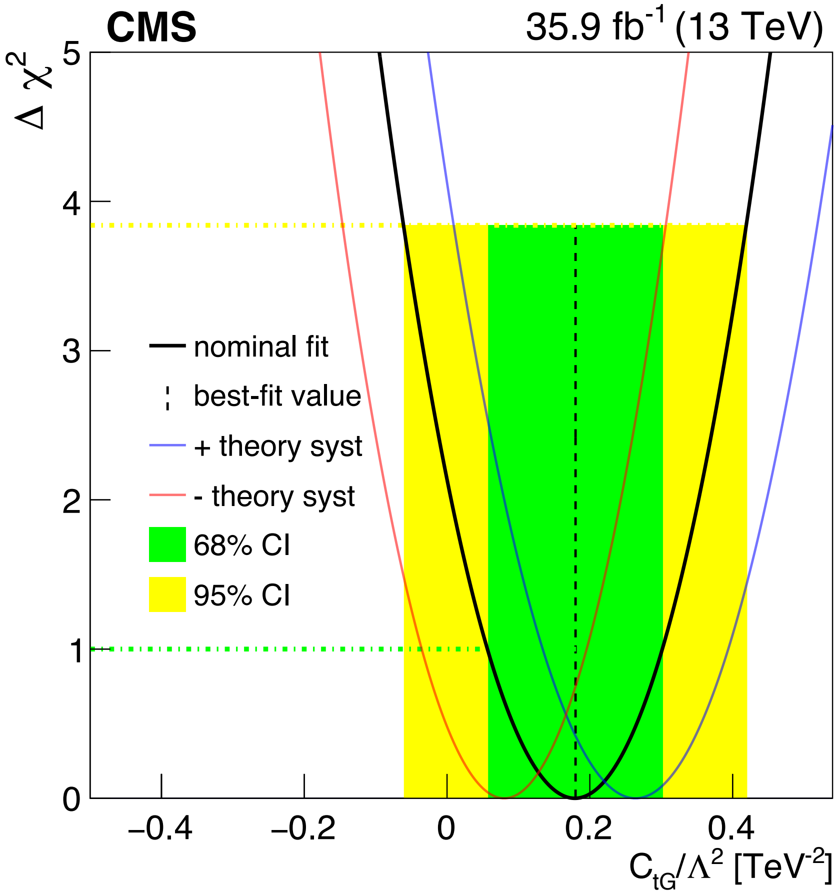




Conclusions, Thoughts, Outlook

- Measurement of top quark production is entering the **precision** (*less than 10% in many cases*), **multi-dimensional differential era**

- Measurements of **top quark mass achieve at the 0.3% (0.5%) level in direct (indirect) measurements** : challenging the understanding of the mass definition

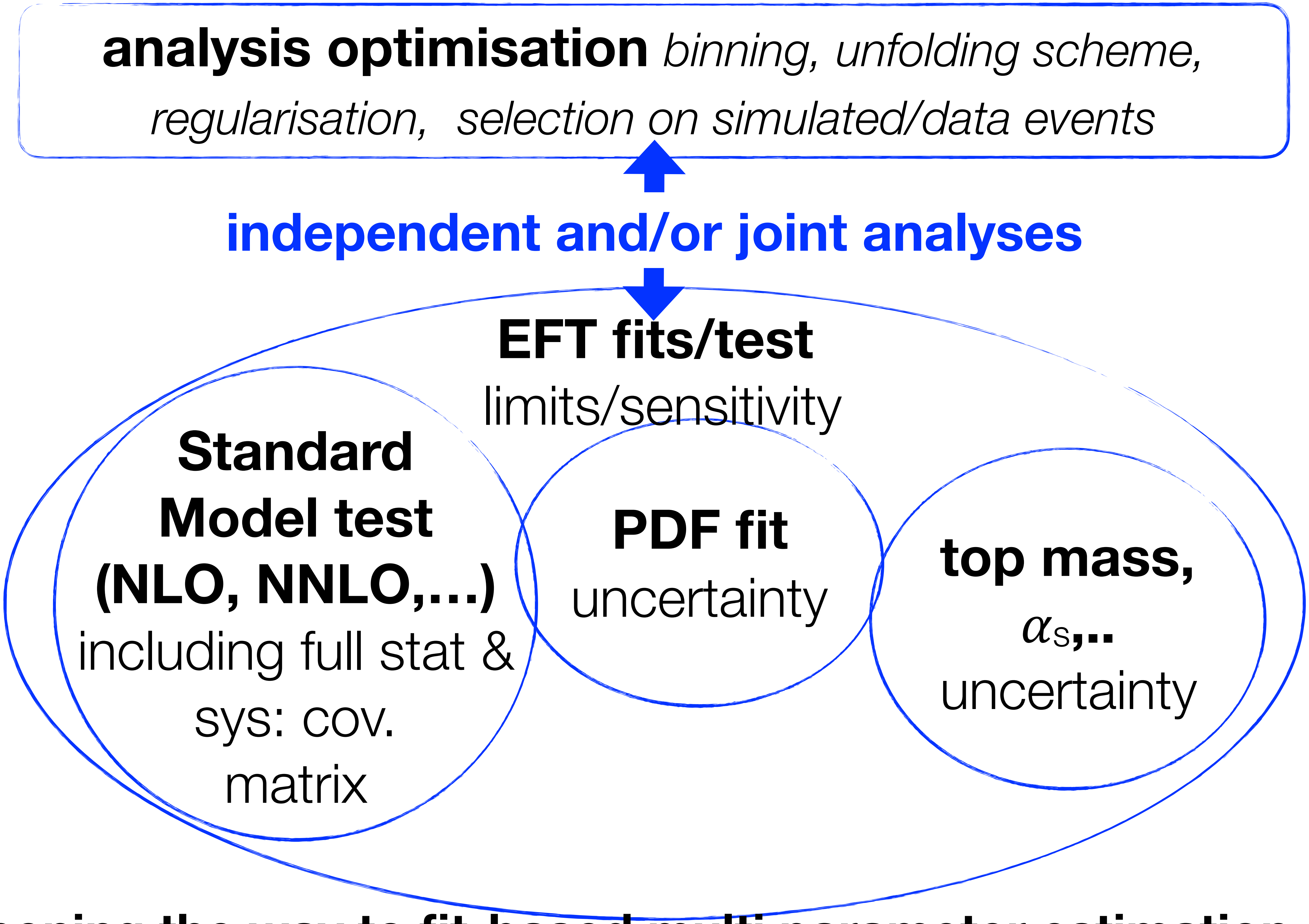
- **Coupling of Higgs and top quark** is directly observed: it is **presently SM-like**

- BSM searches show that **SM is valid at the O(1 TeV) region**

- **EFT** asserts itself as the **complementary new frontier** to direct new physics searches

Conclusion, Thoughts Outlook

d$\sigma_{tt,t}$/d{X} is emerging as multi-analysis laboratory for SM/BSM



analysis optimisation *binning, unfolding scheme, regularisation, selection on simulated/data events*

independent and/or joint analyses

EFT fits/test
limits/sensitivity

Standard Model test (NLO, NNLO,…)
including full stat & sys: cov. matrix

PDF fit
uncertainty

top mass, α_S,..
uncertainty

- **Opening the way to fit-based multi parameter estimation**