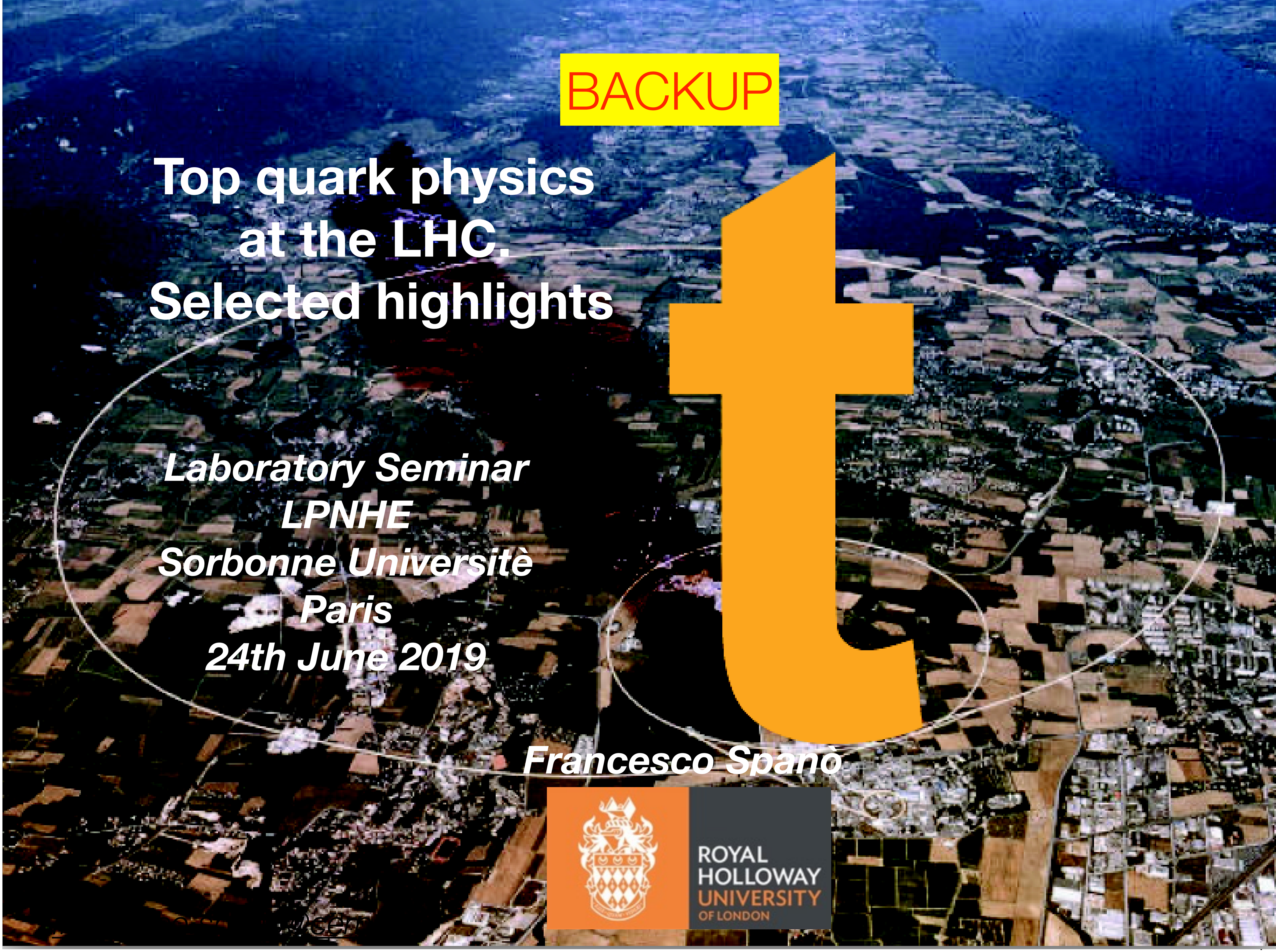


BACKUP

Top quark physics at the LHC. Selected highlights

Laboratory Seminar
LPNHE
Sorbonne Universitè
Paris
24th June 2019

Francesco Spanò

ROYAL HOLLOWAY UNIVERSITY OF LONDON

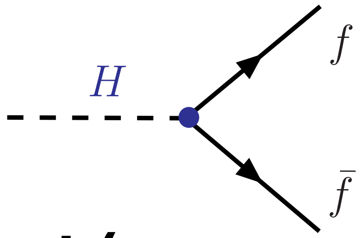
BACK-UP

General top quark features

Why heavy (quarks) at multi-purpose colliders? (I)

“Special” reasons

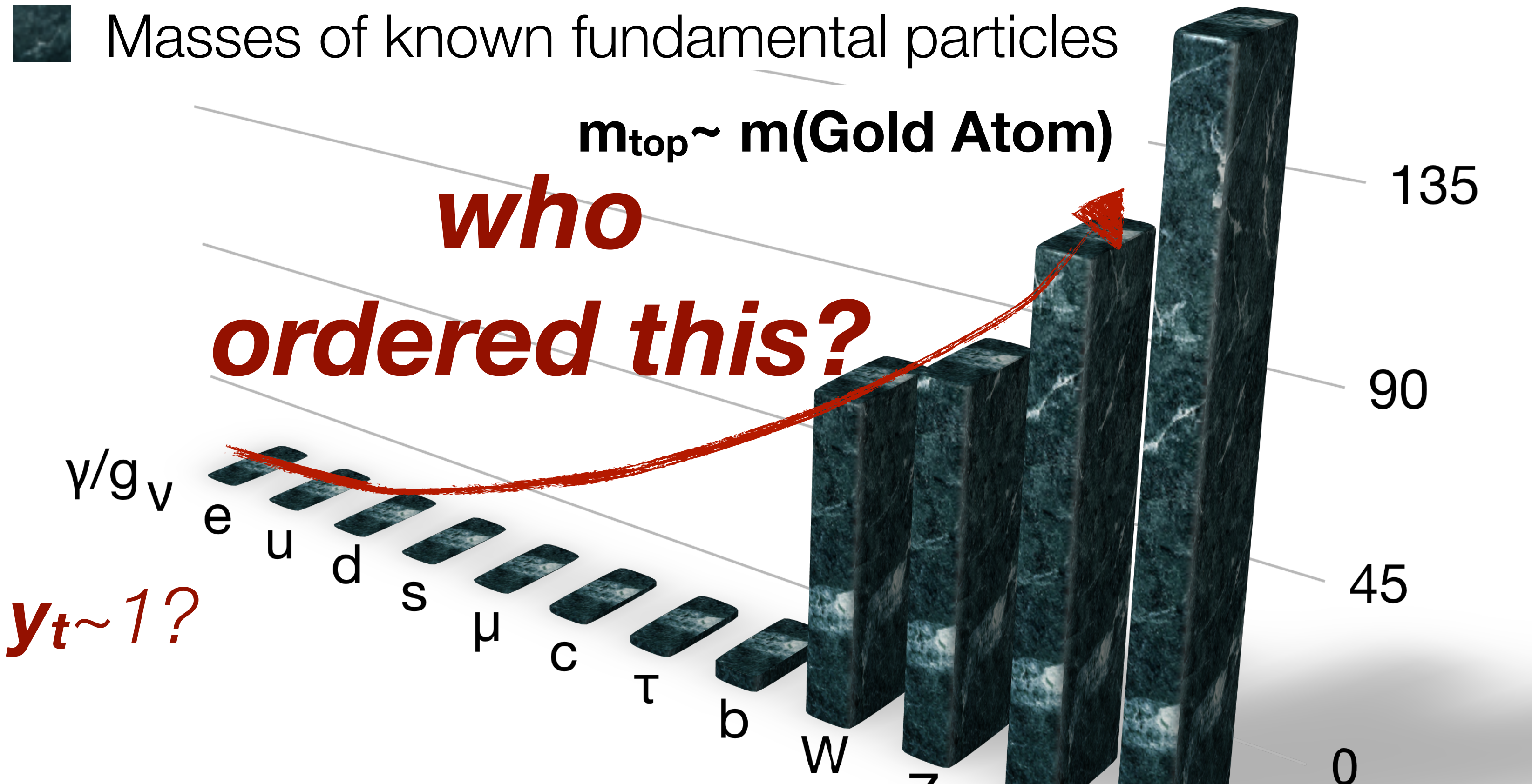
top & b are the most massive known **quarks**



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

y_t ***Hff***

largest (unmeasured) coupling y_t to Higgs boson → ***Is $y_t \sim 1$?***



$m_{top} \sim$ m(Gold Atom)

who ordered this?

New W mass by ATLAS

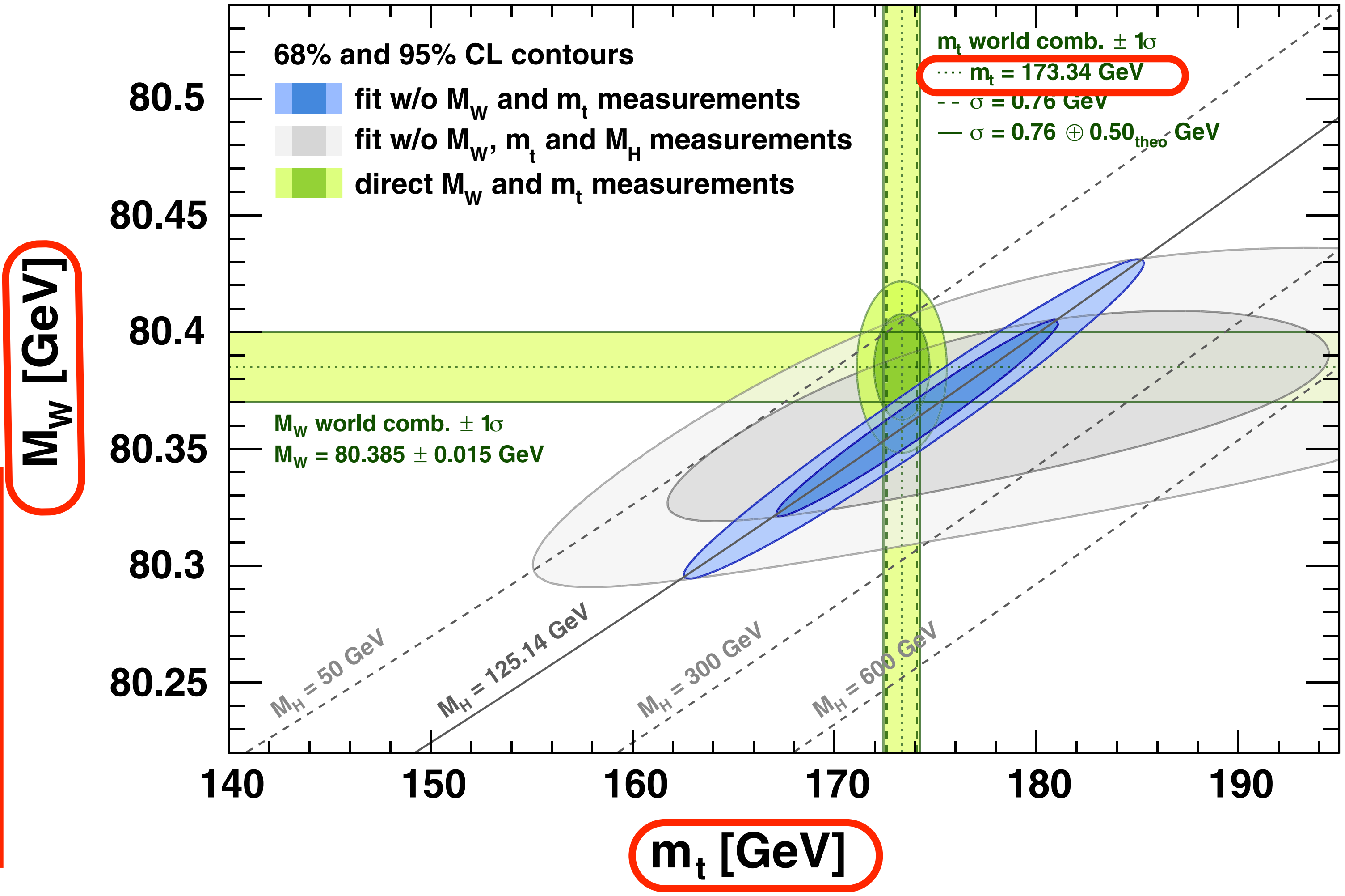
m_W = 80370 ± 7 (stat) ± 11 (exp syst) ± 14 (mod sys) MeV= 80370 ± 19 MeV

7 TeV pp-collision data

Tevatron indirect W mass

m_W = 80351 ± 15 (stat) ± 10 (syst) = 80351 ± 18 MeV

using 1.9 TeV p-antip collision



The GFitter Group, Eur. Phys. J. C 74:3046 (2014)

The reason(s) for mass hierarchy ***is (are) still a mystery***

top quark production

The SM Lagrangian (2019)

reminder(II)

The Standard Model

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+\mathbf{H} \end{pmatrix}$$

$$\boxed{\begin{aligned}\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.\end{aligned}}$$

H=*Higgs particle*

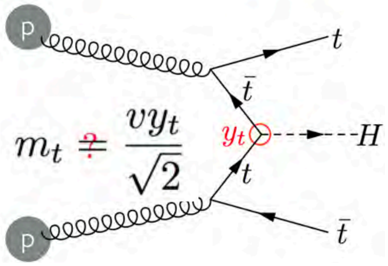
$$L_W \sim g^2 (v+H)^2 W^+_\mu W^{-\mu}$$

$$M_W = \frac{1}{2} g_2 v = \left(\frac{\sqrt{2} g^2}{8 G_\mu}\right)^{1/2}$$

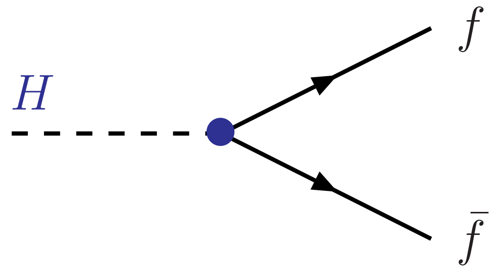
$$v = \frac{1}{(\sqrt{2} G_\mu)^{1/2}} \longrightarrow v \sim 246 \text{ GeV} \longrightarrow$$

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

mass term　　　interaction term



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



$m_{b,obs} \sim 4$ GeV　　$m_t \sim 173$ GeV

top: largest (unmeasured) coupling y_t to Higgs boson

replacing values gives $y_{top} = \sqrt{2}\, m_{top}/v \sim \sqrt{2}\ 173/246 \sim 0.99$

Is y_t~*1? Is it SM Higgs?*

The SM Lagrangian (2019)

reminder(I)

The Standard Model: QF theory invariant under SU(2) x U(1) X SU(3)

$$\boxed{\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.\end{aligned}}$$

observed

Gauge fields are in kinetic terms and co n. derivative D μ

Spontaneous symmetry breaking*: the Lagrangian shows the* ***possibility that at a given energy scale****,* ***the symmetry of the observed physical states is different from the symmetry of the Lagrangian interactions****, by realising one of multiple asymmetric configurations (minimum potential energy state)*

spin-1 W&Z bosons emerge as massive *by coupling to H* ***photon remains massless***

g$_2$ SU(2) gauge coupling

$$L_{W,Z} \sim g_2^2 (v+H)^2 W^+_\mu W^{-\mu} + g_2^2/8\cos\theta_W Z_\mu Z^\mu$$

$$M_W = \frac{1}{2} g_2 v = \left(\frac{\sqrt{2} g^2}{8 G_\mu}\right)^{1/2} \qquad M_Z \cos\theta_W = M_W$$

$$v = \frac{1}{(\sqrt{2} G_\mu)^{1/2}} \longrightarrow v \sim 246 \text{ GeV}$$

spin-0 H=Higgs boson emerges

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

spin1/2 fermions (u,c,d,s,b,..)

- *negative chirality (F$_L$) state* ***couple to W, Z*** *by covariant derivative*
- *obtain mass from* ***assuming gauge invariant coupling*** *terms (Yukawa coupling)* ***to ϕ*** *: $F_L \phi f_R = y\,(v+H)\, f_L f_R$*

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.}$$

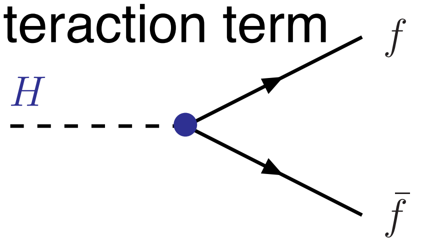
Diagonalise Y and replace ϕ from SSB

$$L_f = m_f f_L \bar{f}_R + y_f H f_L \bar{f}_R/\sqrt{2} + h.c$$

mass term

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

fermion-HIggs interaction term



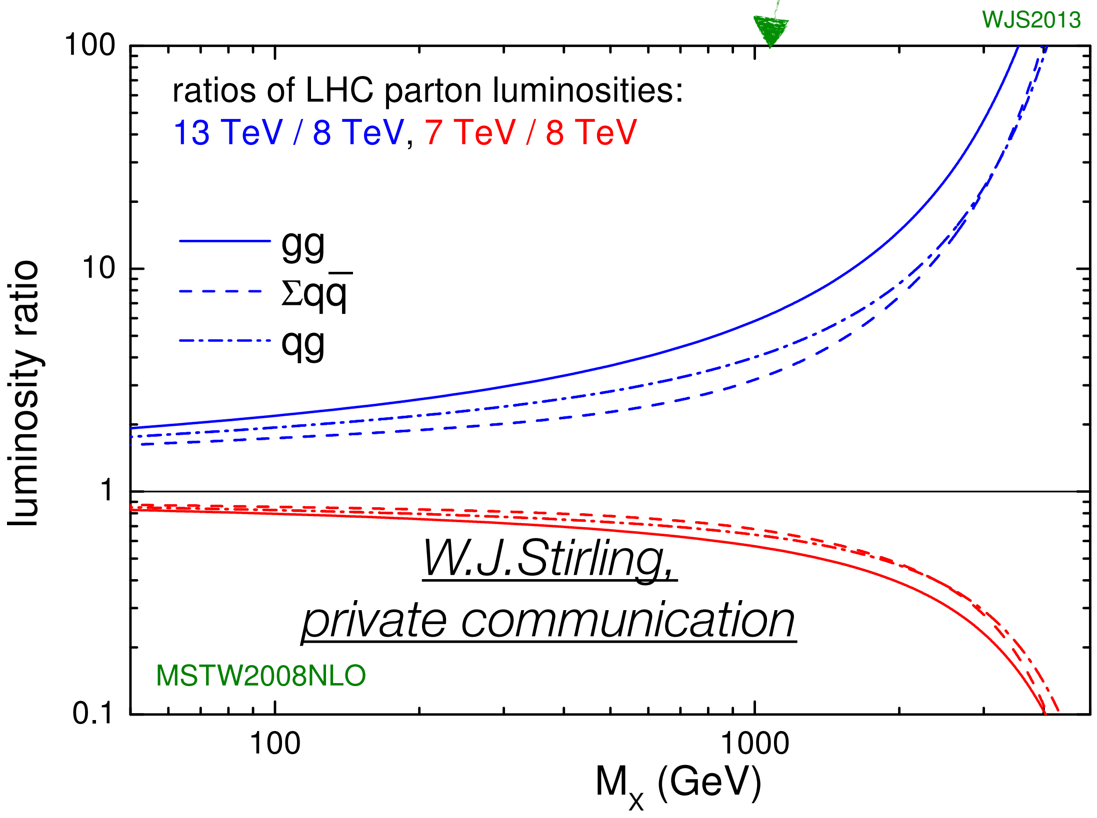
Top production @ LHC: differential growth

(Campbell et al, Rept.Prog.Phys.70:892007)

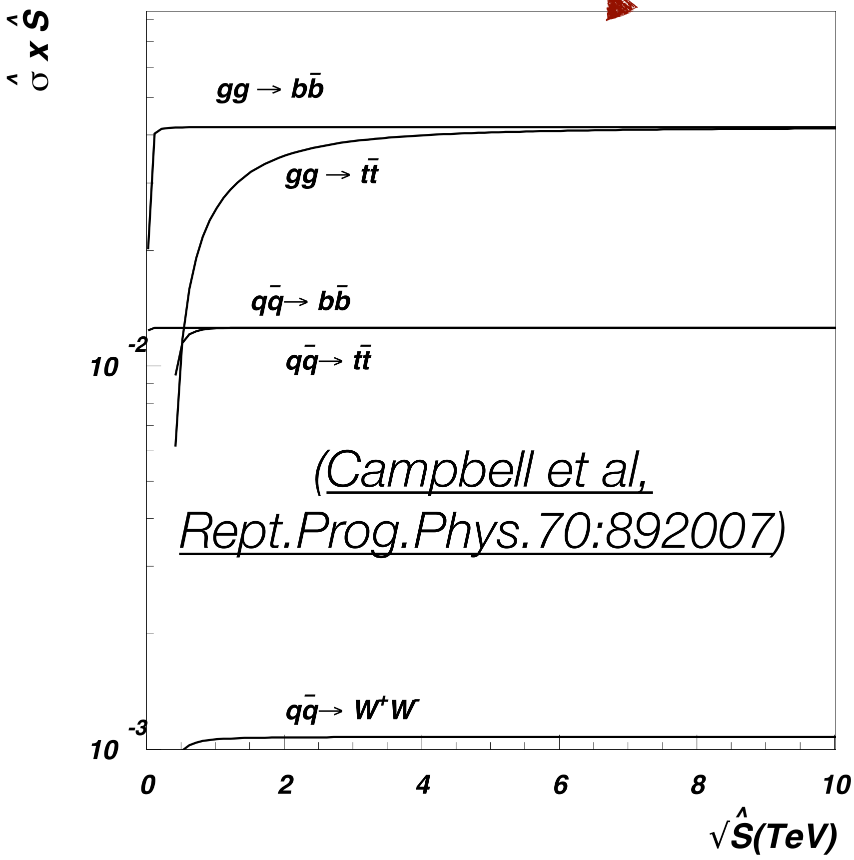
$$\sigma = \sum_{i,j}\int_0^1 dx_1\,dx_2\,f_i(x_1,\mu)\,f_j(x_2,\mu)\,\hat{\sigma}_{ij} = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}\,dy\right)\boxed{\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)}(\hat{s}\,\hat{\sigma}_{ij}) \sim \sum_{i,j}\frac{\Delta\hat{s}}{\hat{s}}\boxed{\left(\frac{dL_{ij}}{d\hat{s}}\right)}(\hat{s}\,\hat{\sigma}_{ij})$$

$$\boxed{\frac{dL_{ij}}{d\hat{s}\,dy}} = \boxed{\frac{1}{s}}\,\frac{1}{1+\delta_{ij}}\boxed{[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)]}$$

- Different **x-range** **and center of mass** dependence incorporated in **parton luminosities**→
  - **gg→X** dominated processes **grow more than qq →X** ones
  - **larger gains at high multi-TeV masses** ~up to O(100)



W.J.Stirling, private communication



(Campbell et al, Rept.Prog.Phys.70:892007)

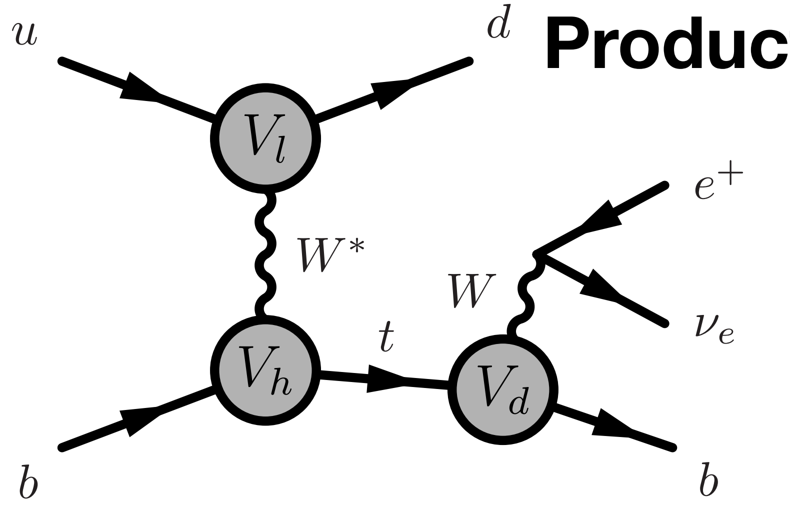
Magano, Rojo, JHEP{1208},2012:10

$R^{th,nnpdf}$ = 14TeV to 8 TeV xsec ratios

Cross Section	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar{t}/Z$	2.12	$\pm$ 1.3	$-0.8 - 0.8$	$-0.4 - 1.1$
$t\bar{t}$	3.90	$\pm$ 1.1	$-0.5 - 0.7$	$-0.4 - 1.1$
$t\bar{t}(M_{tt} \geq 1$ TeV)	8.18	$\pm$ 2.5	$-1.3 - 1.1$	$-1.6 - 2.1$
$t\bar{t}(M_{\rm tt} \geq 2$ TeV)	24.9	$\pm$ 6.3	$-0.0 - 0.3$	$-3.0 - 1.1$

- **Cross sections in "tails" increase more rapidly than** inclusive value

Top quark predictions@ LHC- the NNLO revolution : single top



Production and decay @ NNLO, decay in narrow width approx

@ $\sqrt{s}$ = 8 TeV

Phys. Rev. D 94, 071501 (2016)

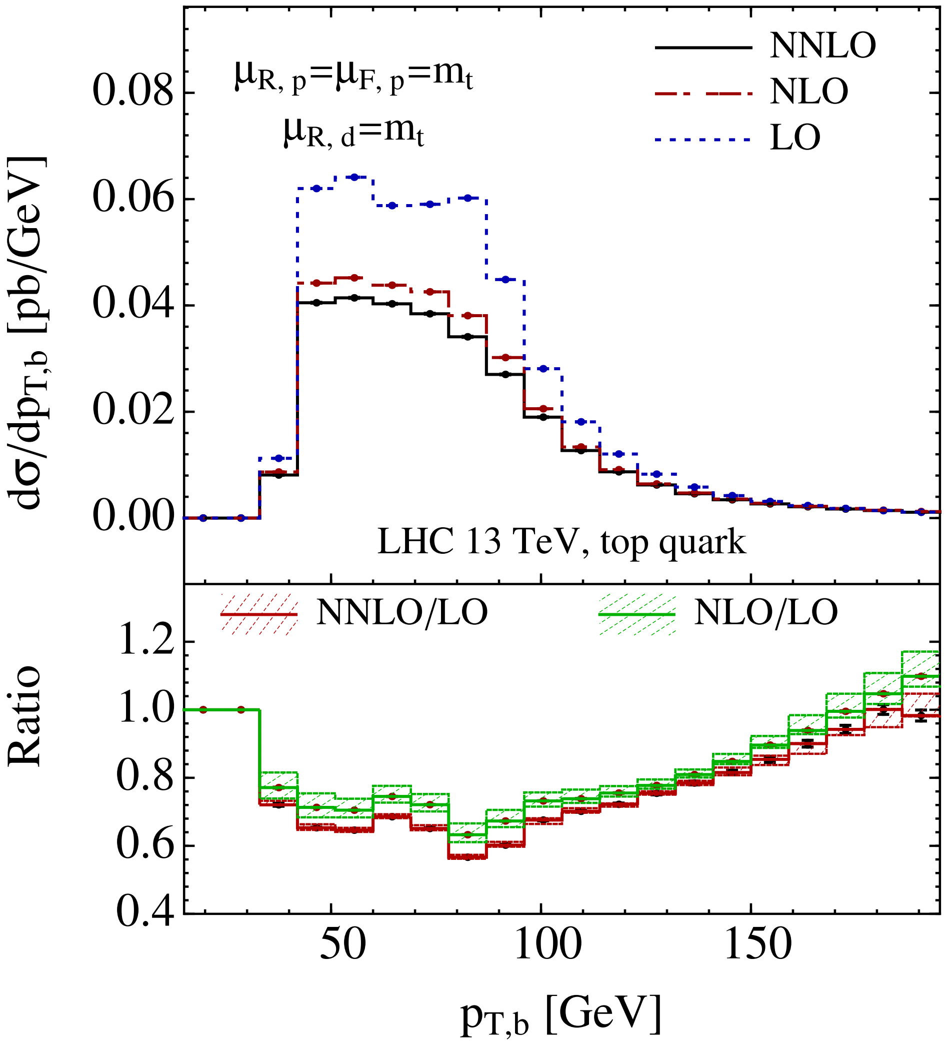
inclusive [pb]	LO	NLO	NNLO
t quark	$143.7^{+8.1\%}_{-10\%}$	$138.0^{+2.9\%}_{-1.7\%}$	$134.3^{+1.0\%}_{-0.5\%}$
$\bar{t}$ quark	$85.8^{+8.3\%}_{-10\%}$	$81.8^{+3.0\%}_{-1.6\%}$	$79.3^{+1.0\%}_{-0.6\%}$

$V_{l,h,q}$ = three corrections to light quark line, heavy quark line and decay including ***corrections from two loop, one loop+1 real emission**, **two real emission***

2jets, 1b-jet antik_T R=0.5
$p_{T,jet}$ >40 GeV, $|\eta_{jet}|$<5 (2.4 for b-jet)
$p_{T,lep}$ > 30 GeV $|\eta_{lep}|$ <2.4

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13
$\bar{t}$ quark	total	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	$1.62^{+1.2\%}_{-0.8\%}$
	corr. in pro.		-0.46	-0.15
	corr. in dec.		-0.21	-0.08

Differential distributions also available @NNLO

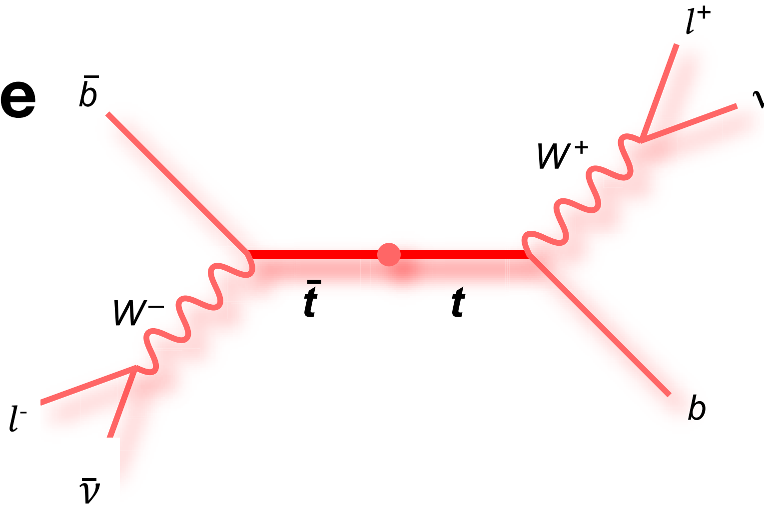


stable values
reduced uncertainties

Standard reasons: Extreme test of SM: $d\sigma_{tt}/dp_T$ “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**
  - **$m(\ell^+\ell^-)$ > 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 with kinematic reco**

90% efficient on tt

choose (ℓ,jet) assignment to tt **with largest # of b-jets** → smear **4-momenta of ℓ and jets** *with expected resolution* → assume **p_T^{miss} = 2 ν** + *impose* ***6 constraints on (2ℓ, jets, 2 ν)*** *: total p_T , m_W x2, m_{top} x2* → *solve for* ***both*** *ν* ***3-mom such that m_{tt} is smallest*** *(resolve ambiguity)* → ***weight for solution =*** *prob M(**ℓ,jet) <180 GeV in top and in anti-top***

↓

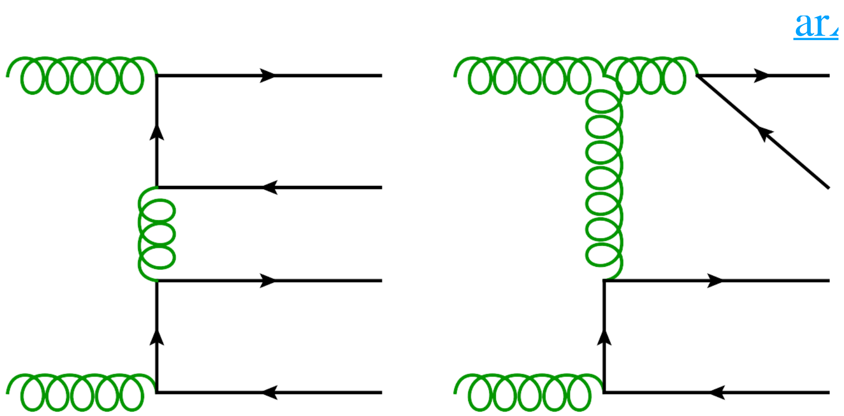
two separate ν 3-momenta for given assignment = weighted average of 100 smeared repetitions

↓

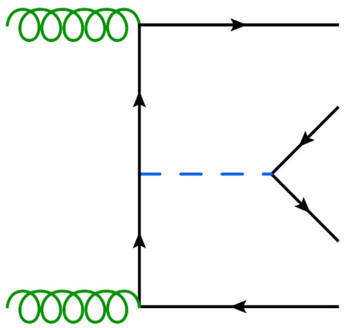
keep (ℓ,jet) assignment with maximum Σ weights

- **Bkg-subtract & Unfold to parton and particle level → $d\sigma_{tt}/dX$** →

Status of Search for observation of 4 top quarks



Leading: O(α_S^4)



Sub-Leading:
O($\alpha_S^2 y_t^4$), O($\alpha_S^2 \alpha^2$)

$\sigma^{NLO}(tttt)$ = 11.97 fb at NLO QCD + NLO QED 13 TeV

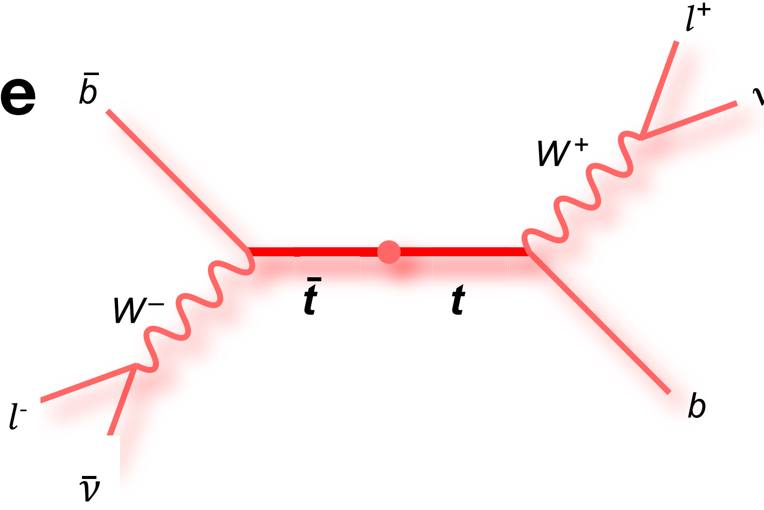
Significance obs. (exp.) [σ]	ATLAS 36 fb^{-1}	CMS 36 fb^{-1}	CMS 139 fb^{-1}
SS/ML	3.0 (0.8) 1	1.6 (1.0) 3	2.6 (2.7) 6
1L/OS	1.0 (0.6) 2	0.0 (0.4) 4	-
Combination	2.8 (1.0) 2	1.4 (1.1) 4	-

(table and diagrams by Nedaa Alexandra Asbah)

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($\ell^+\ell^-$) > 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 with kinematic reco**

90% efficient on tt

choose (ℓ,jet) assignment to tt **with largest # of b-jets**

smear **4-momenta of ℓ and jets** *with expected resolution*

assume **p_T^{miss} = 2 ν** + *impose* ***6 constraints on (2ℓ, jets, 2 ν)*** *: total p_T , m_W x2, m_{top} x2*

solve for ***both ν 3-mom such that m_{tt} is smallest*** *(resolve ambiguity)*

weight for solution = *prob M(**ℓ,jet) <180 GeV in top and in anti-top***

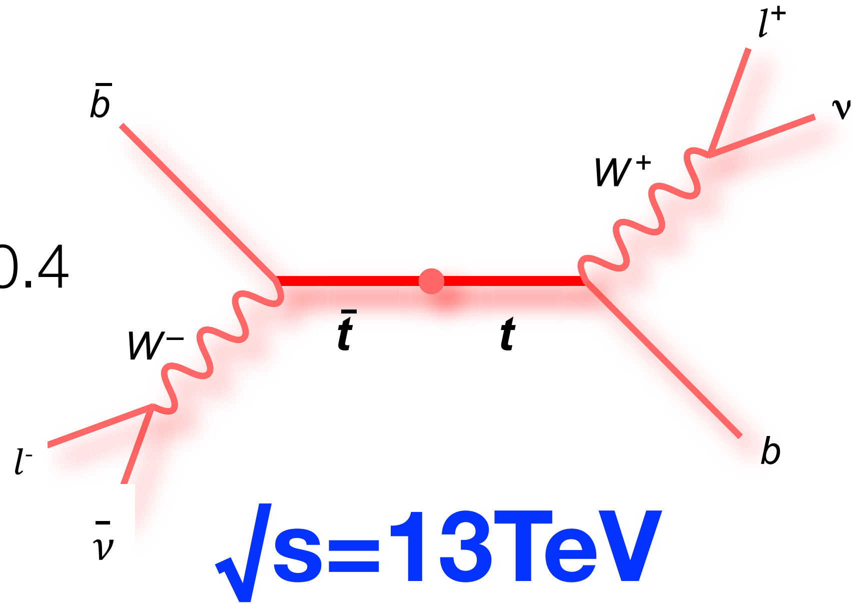
two separate ν 3-momenta for given assignment = weighted average of 100 smeared repetitions

keep (ℓ,jet) assignment with maximum Σ weights

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

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

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



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

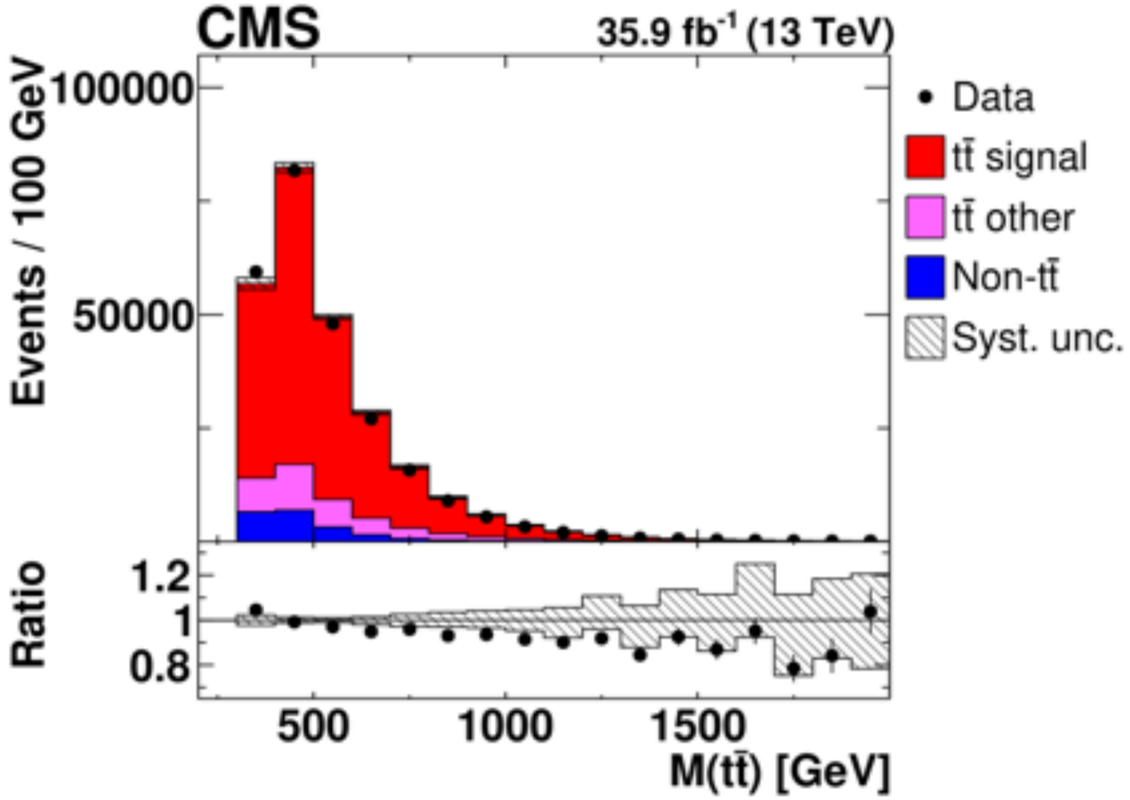
√s=13TeV

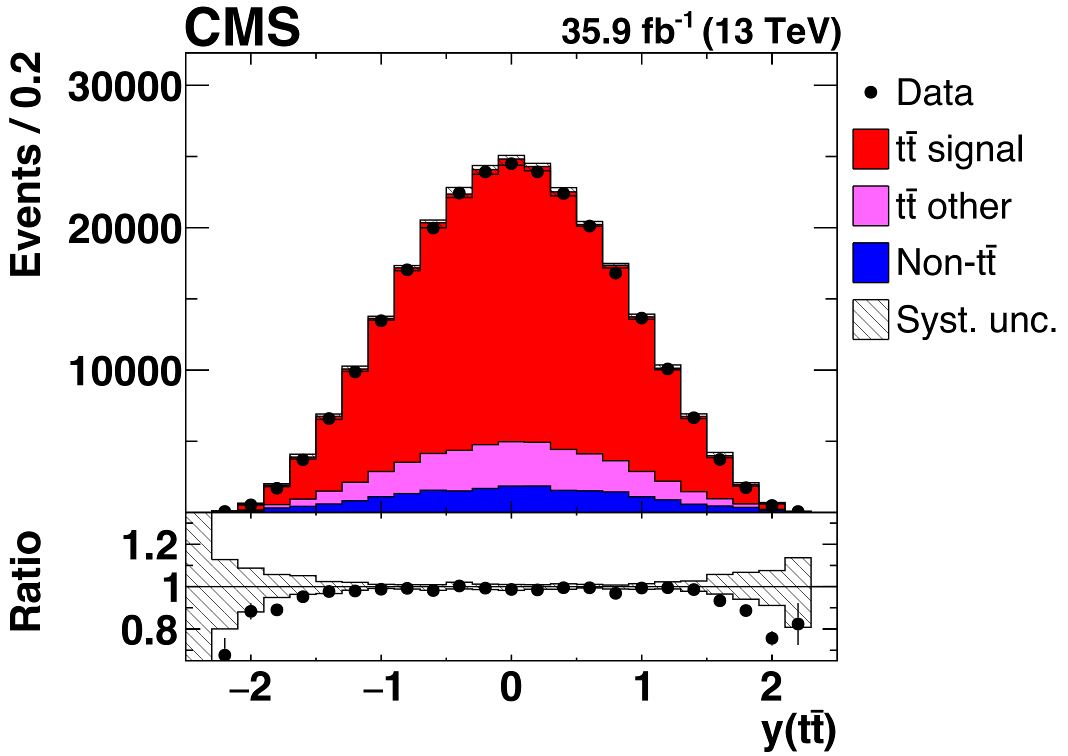
standard for 2d distributions

- 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

- assume $\mathbf{p_T^{miss} = 2\,\nu}$ + p_Z^{miss}=**p(ℓ⁺ℓ),E(ℓ⁺ℓ)** , **m(2 ν)>0, m(WW)≧ 2 M$_W$**
- keep (ℓ,jet) assignment with maximum p_T jets
- $[M_{tt}, y_{tt}, N_{\text{extra jets}}]$ 2 bins (0,1) and 3 bins (0,1,2)



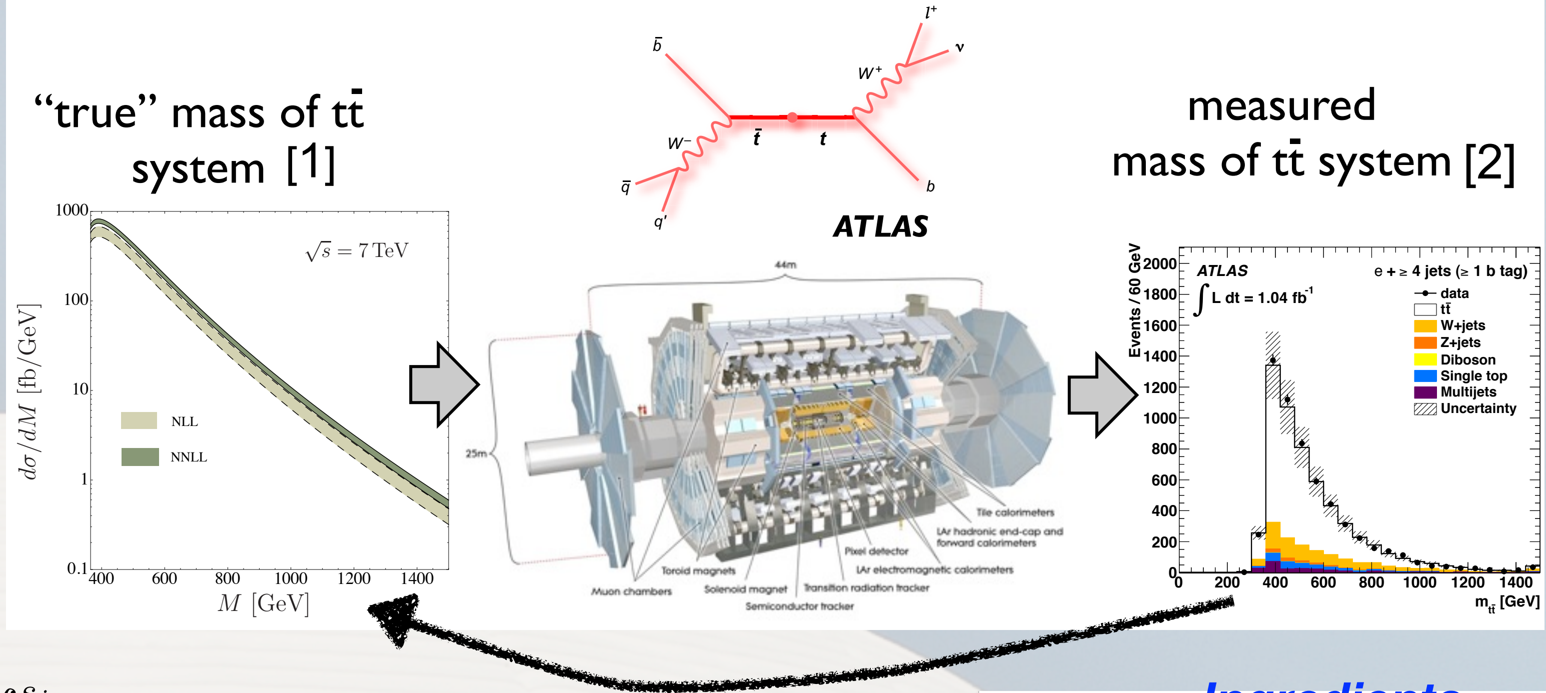


Unfolding Foundations

Unfolding

- Unfolding: **infer an unknown distribution f(y)** for a variable y **from the measured distribution g(s)** by using knowledge and/or assumptions on the probability distribution that links the observation to the “true” value.

$$g(\mathbf{s}) = \int_\Omega K(\mathbf{s},\mathbf{y})f(\mathbf{y})d\mathbf{y} + b(\mathbf{s})$$



FS
EPJ Web of conference vol 55 (2013) 03002

$$\nu_i = \int_{s_{i-1}}^{s_i} g(s)ds$$

$$\mu_j = \int_{y_{j-1}}^{y_j} f(y)dy$$

$$E[n_i] = \nu_i = \sum_{j=1}^{M} R_{i,j}\mu_j + \beta_i$$

$$E[\mathbf{n}] = \boldsymbol{\nu} = R\boldsymbol{\mu} + \boldsymbol{\beta}$$

Ingredients

- response matrix *R: prob true in bin i is reco in bin j*
- number of observed events n
- reconstruction efficiency
- estimate of expected bkg ***β***

the Max LKL solution

$$E[\mathbf{n}] = \boldsymbol{\nu} = R\boldsymbol{\mu} + \boldsymbol{\beta} \quad \Longleftrightarrow \quad \mathcal{L} = \prod_{i=1}^{N} \nu_i^{n_i}\frac{e^{-\nu_i}}{n_i!}$$

$$\partial \log\mathcal{L}(\mu_i)/\partial\mu_i = 0\ \forall\ i$$

Small changes in input (can) **lead to large changes** in the ML estimate.

- **Regularize** = Reduce impact of high frequency while keeping info of high significance, stable components → **reduction in variance** w.r.t. ML estimator

Example $d\sigma_{tt}/dp_{T,top(-jet)}$ l+jets @ particle level (PL)- √s =8 TeV

Phys. Rev. D 93, 032009 (2016)

Reco selected out

Pass Reco, Pass PL | **Pass Reco**, Fail PL | Fail Reco Pass PL | Fail Reco, Fail PL

to correct to

similar (simpler) formulas for parton level

$$\frac{d\sigma_{t\bar{t}}}{dp_{\mathrm{T,ptcl}}}(p^i_{\mathrm{T,ptcl}}) = \frac{1}{\Delta p^i_{\mathrm{T,ptcl}}\mathcal{L} f^i_{\mathrm{ptcl!reco}}} \cdot \sum_j M^{-1}_{ij} f^j_{\mathrm{reco!ptcl}} f_{t\bar{t},\ell+\mathrm{jets}}(N^j_{\mathrm{reco}} - N^j_{\mathrm{reco,bgnd}})$$

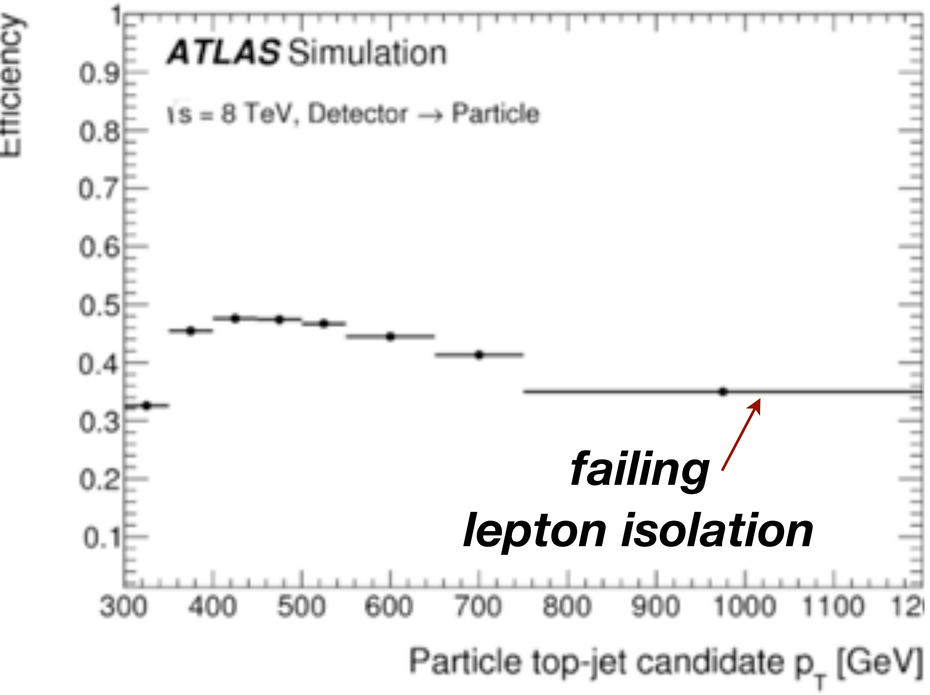
$$\frac{\textit{events that pass particle \& reco}}{\textit{events that pass particle}}$$

restore Fail Reco Pass PL

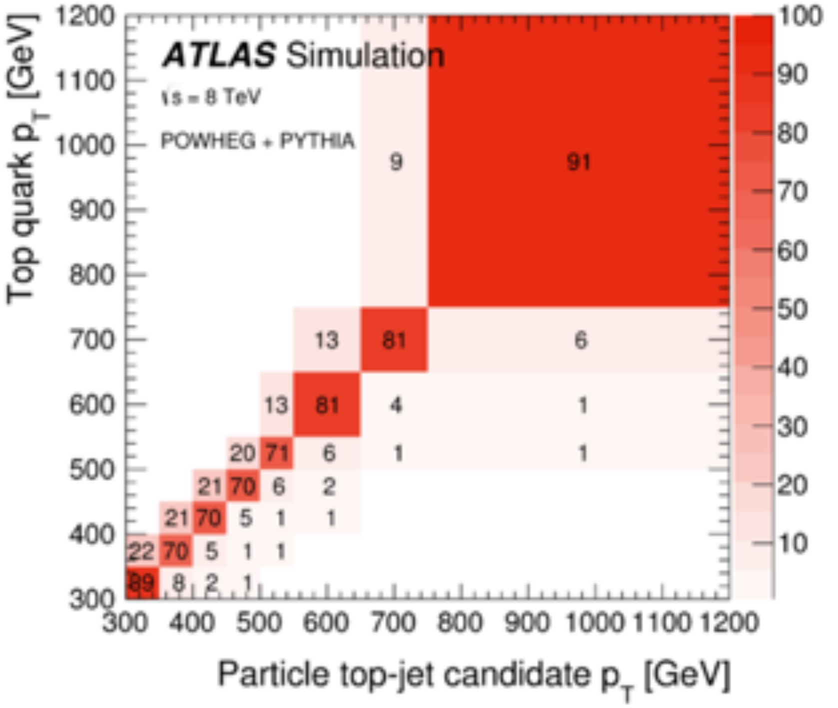
Unfold at level of **Pass Reco**, Pass PL

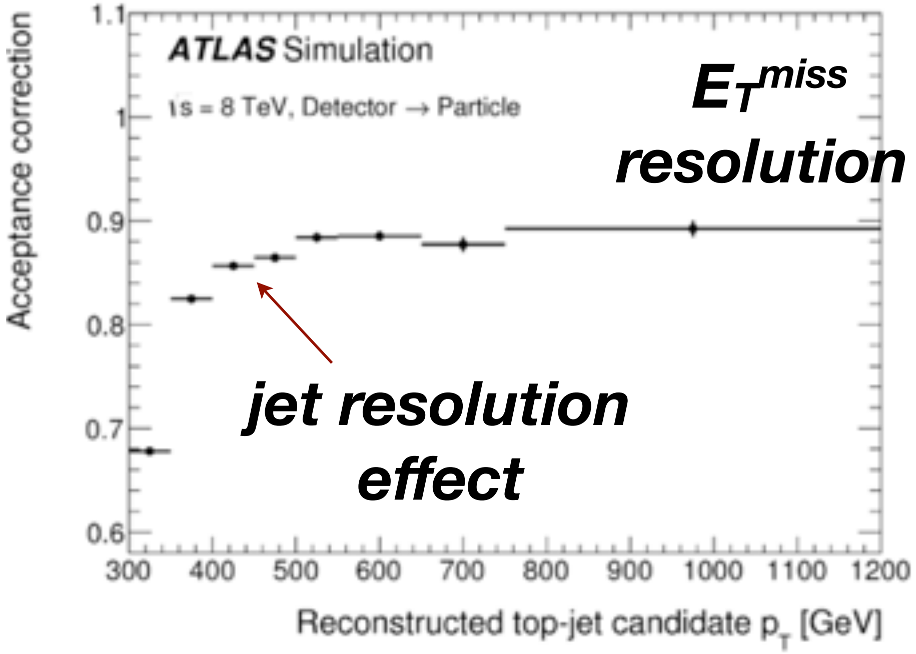
$$\frac{\textit{events that pass reco \& part}}{\textit{events that pass reco}}$$

take **Pass Reco**, Fail PL **away**



failing lepton isolation





E_T^{miss} resolution

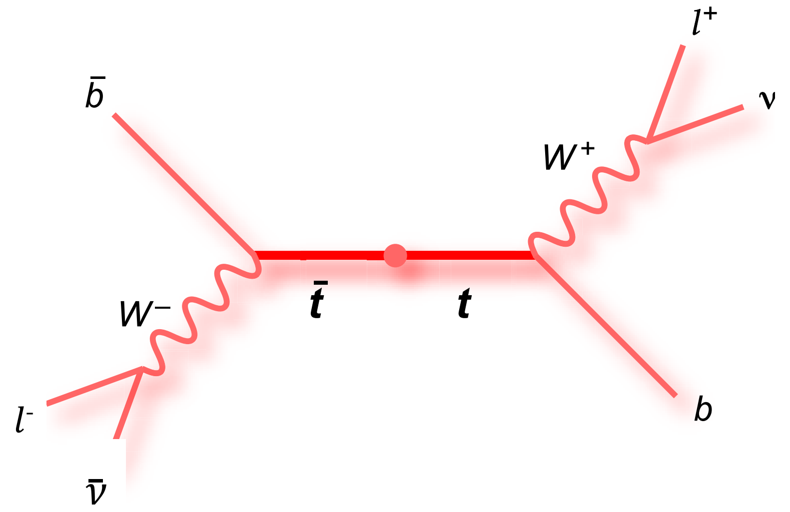
jet resolution effect

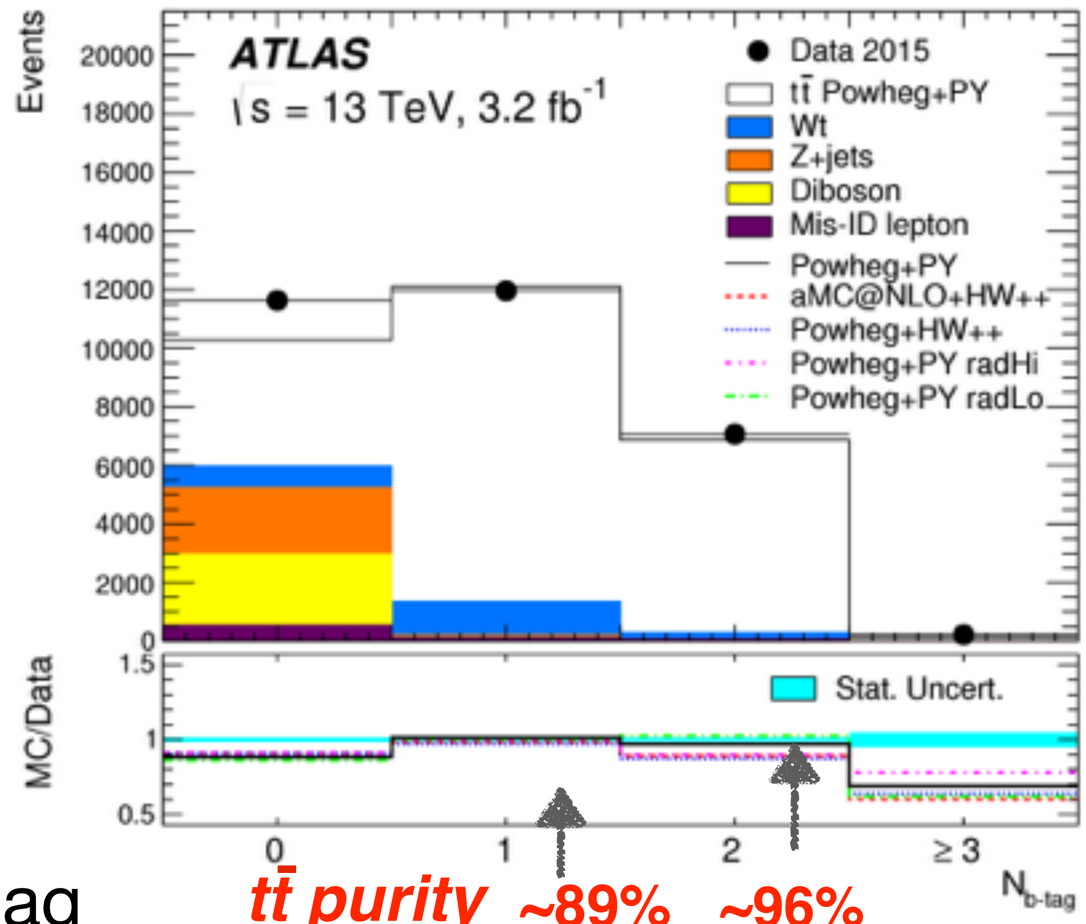
Special reasons: measure σ_{tt} - dilepton @ $\sqrt{s}$ =13 TeV

example from ATLAS

Phys. Lett. B761 (2016) 136

- Select **opposite sign eμ**, *minimal use of jet/ E_T^{miss} info*
- **Bkg: mostly single top** (Wt) data-driven fake leptons Z +jets





$t\bar{t}$ **purity** **~89%** **~96%**

- **Simultaneously fit for σ_{tt} and ε_b, efficiency to select, reconstruct and recognize b-jet in** 1-b-tag and 2-b-tag samples → **minimize jet & b-tag syst**

from simulation

$$N_1 = \mathcal{L}\sigma_{t\bar{t}}\underline{\epsilon_{e\mu}}2\epsilon_b(1 - \underline{C_b}\epsilon_b) + N_1^{bkg}$$
$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\underline{\epsilon_{e\mu}}C_b\epsilon_b^2 + N_2^{bkg}$$

- **Dominated by "External" Systematic effects:** *Luminosity (1.5%), Beam (2.3%) energy*
- tt Modelling uncertainty reduced from parton (~3%) to particle (~2%)

- **Extrapolate to** particle (called fid) & parton level

$$\sigma_{t\bar{t}} = 818 \pm 8\ (\text{stat}) \pm 27\ (\text{syst}) \pm 19\ (\text{lumi}) \pm 12\ (\text{beam})\ \text{pb}$$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~4.4 %

$$\sigma_{t\bar{t}}^{\text{fid}} = 11.32 \pm 0.10\ (\text{stat}) \pm 0.29\ (\text{syst}) \pm 0.26\ (\text{lumi})$$

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ ~3.9

NNLO+NNL prediction : 832 +40-46 pb

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

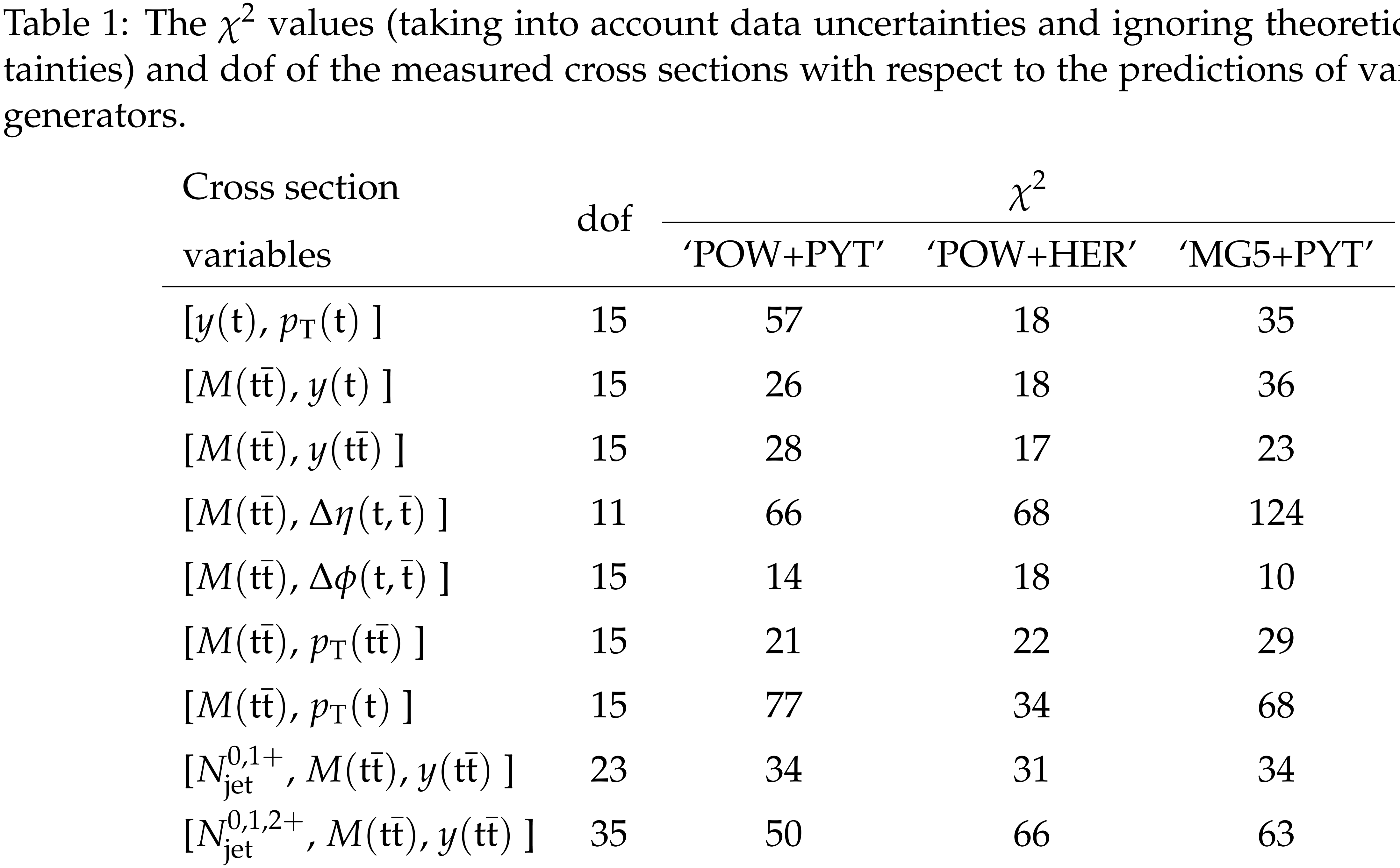


Table 1: The χ^2 values (taking into account data uncertainties and ignoring theoretical uncertainties) and dof of the measured cross sections with respect to the predictions of various MC generators.

Cross section variables	dof	χ^2		
		'POW+PYT'	'POW+HER'	'MG5+PYT'
$[y(\mathrm{t}), p_{\mathrm{T}}(\mathrm{t})]$	15	57	18	35
$[M(\mathrm{t\bar{t}}), y(\mathrm{t})]$	15	26	18	36
$[M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	15	28	17	23
$[M(\mathrm{t\bar{t}}), \Delta\eta(\mathrm{t},\mathrm{\bar{t}})]$	11	66	68	124
$[M(\mathrm{t\bar{t}}), \Delta\phi(\mathrm{t},\mathrm{\bar{t}})]$	15	14	18	10
$[M(\mathrm{t\bar{t}}), p_{\mathrm{T}}(\mathrm{t\bar{t}})]$	15	21	22	29
$[M(\mathrm{t\bar{t}}), p_{\mathrm{T}}(\mathrm{t})]$	15	77	34	68
$[N_{\mathrm{jet}}^{0,1+}, M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	23	34	31	34
$[N_{\mathrm{jet}}^{0,1,2+}, M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	35	50	66	63

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

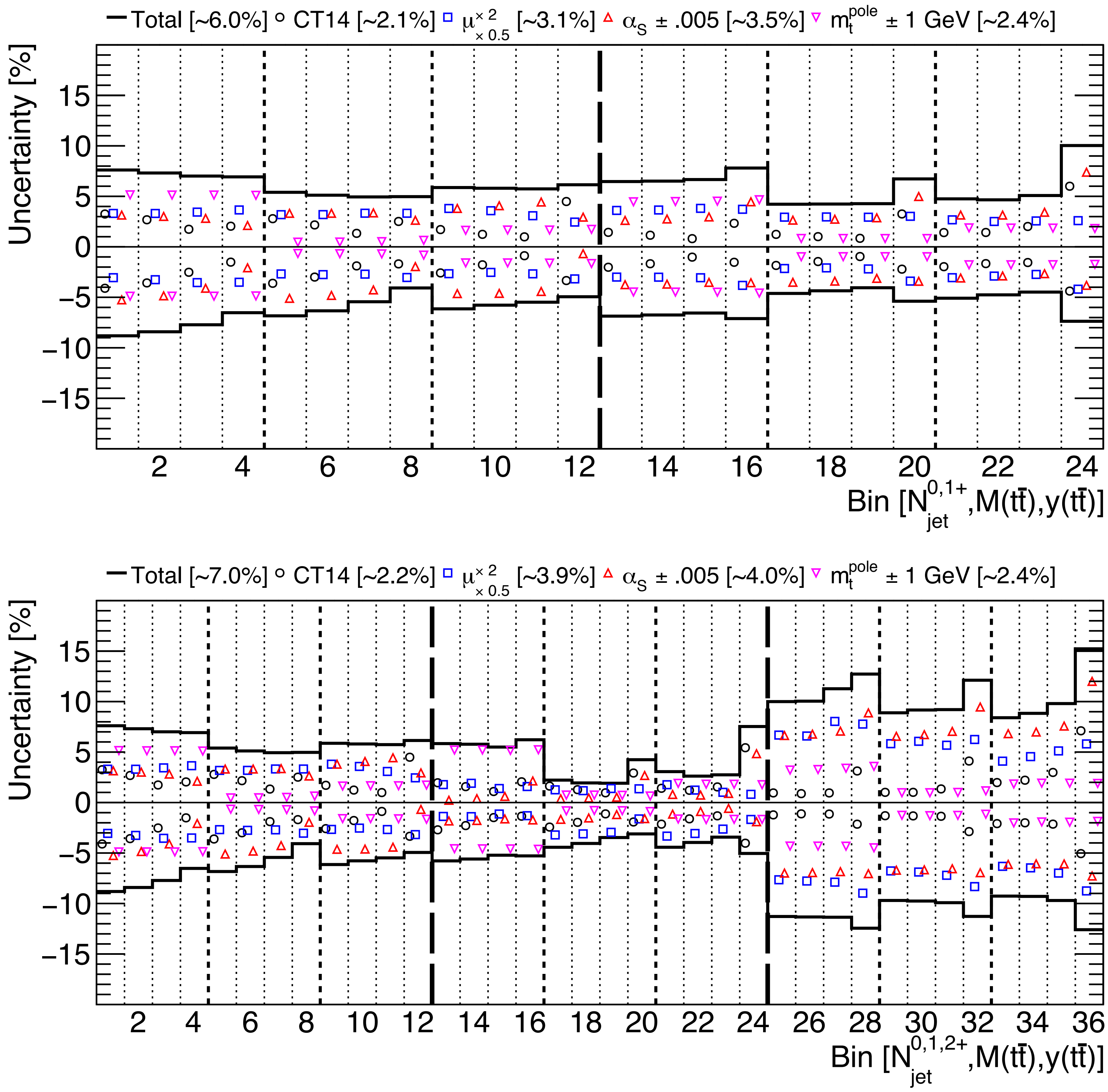
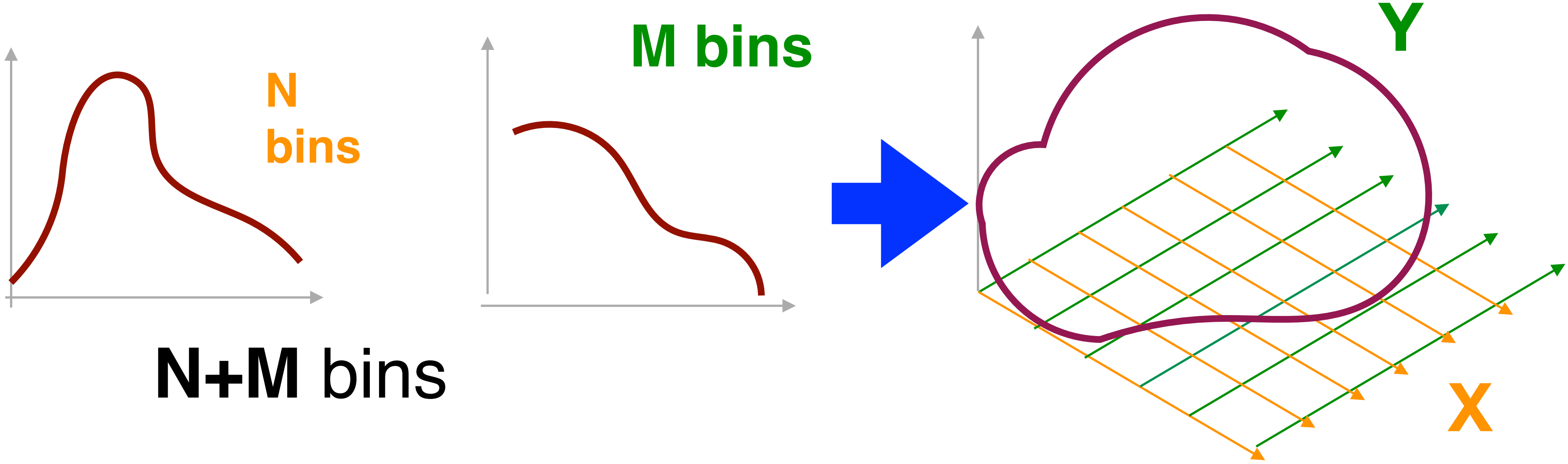


Figure 13: The theoretical uncertainties for [$N_{\mathrm{jet}}^{0,1+}$, $M(\mathrm{t\bar{t}})$, $y(\mathrm{t\bar{t}})$] (upper) and [$N_{\mathrm{jet}}^{0,1,2+}$, $M(\mathrm{t\bar{t}})$, $y(\mathrm{t\bar{t}})$] (lower) cross sections, arising from PDF, $\alpha_S(m_Z)$, and $m_{\mathrm{t}}^{\mathrm{pole}}$ variations, as well as the total theoretical uncertainties, with their bin-averaged values shown in brackets. The bins are the same as in Figs. 10 and 11.

1 Extreme test of SM: Double differential cross section @13 TeV

“Multiply" number of new regions!



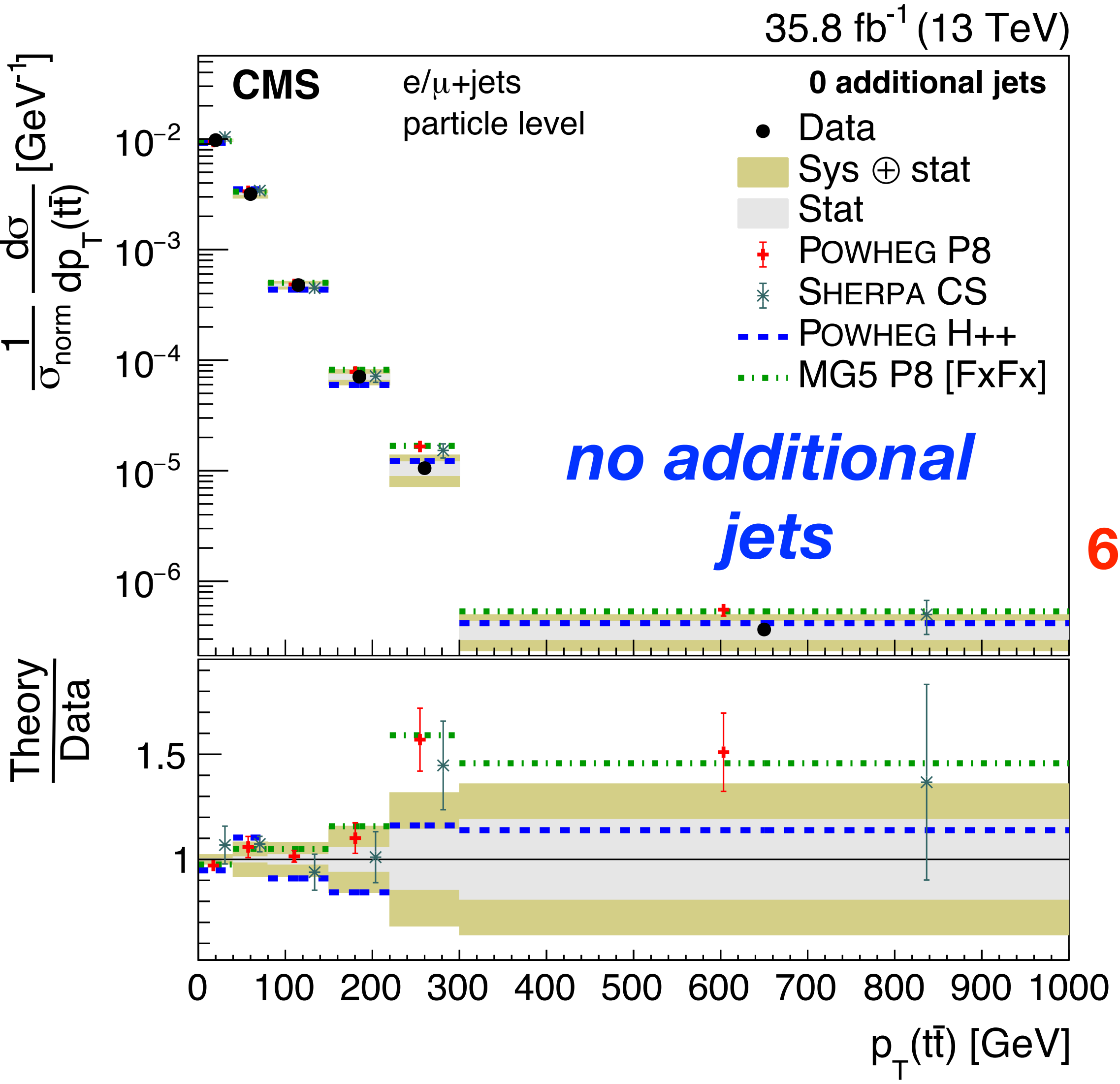
N+M bins

$d^2\sigma_{tt}/dXdY$

NxM bins

- Pros: Add novel information from correlation bins

global inconsistency in $p_{T,tt}$ in bins of N_{jet} @ particle level vs NLO+PS



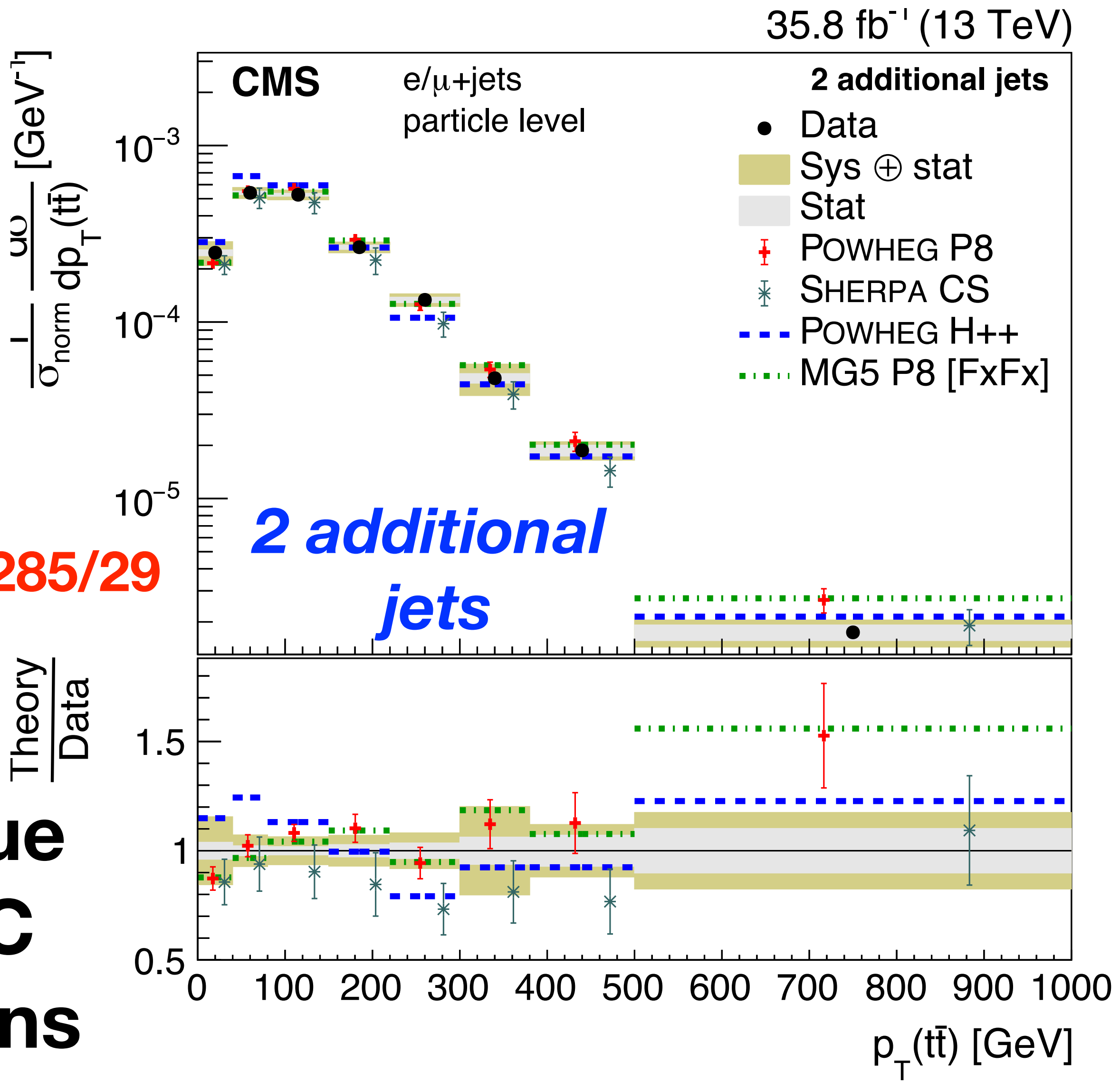
no additional jets

Phys. Rev. D 97, 112003 (2018)

$64/29<\chi^2/DOF<285/29$

$p<0.01$

low p-value for all MC descriptions



2 additional jets

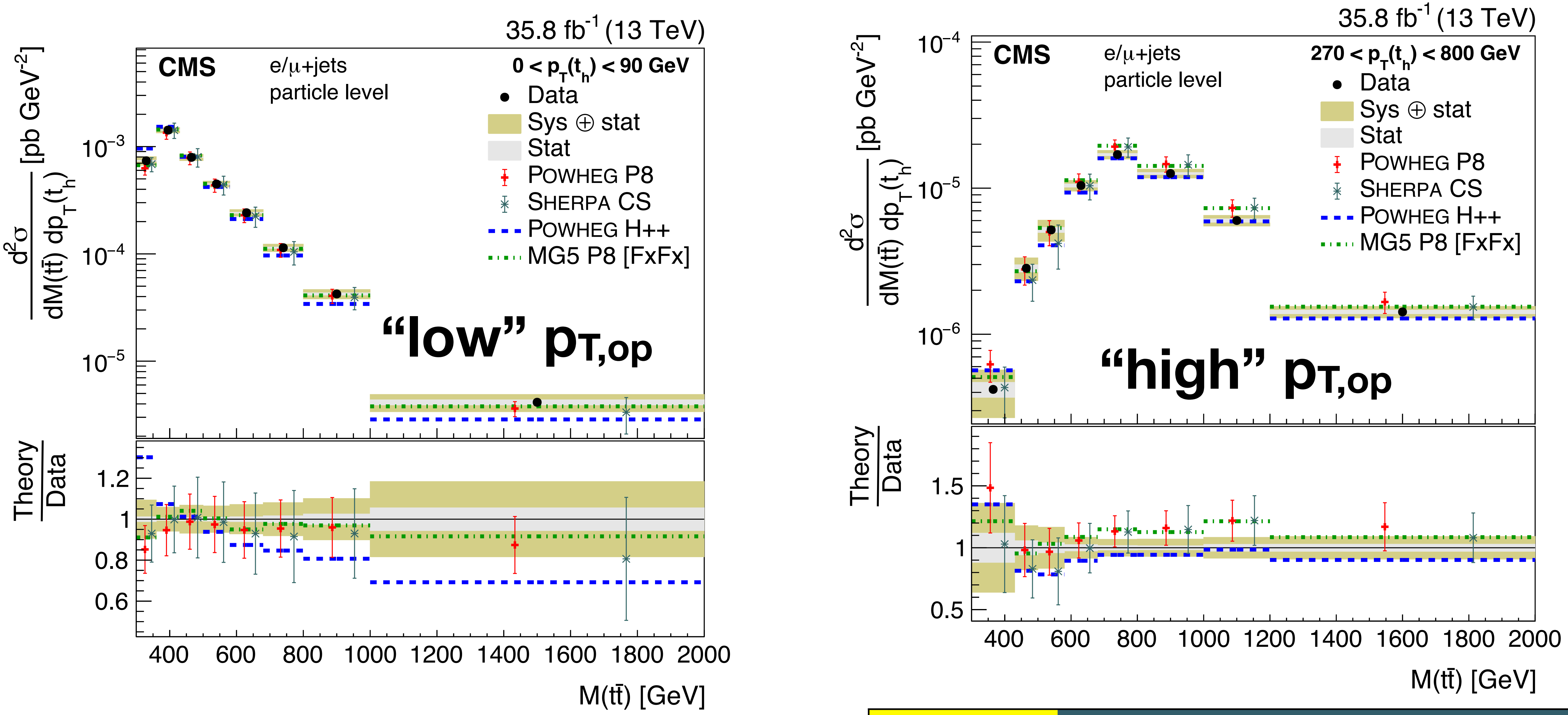
1

Extreme test of SM:Double differential cross section @13 TeV

@ particle level

Phys. Rev. D 97, 112003 (2018)

check m_{tt} consistency as Lorentz boost increases (larger $p_{T,op}$)



"low" $p_{T,op}$

"high" $p_{T,op}$

N_{dof} = 32	no theory unc.		with theory unc.	
NLO+PS	χ^2	p-val	χ^2	p-val
PW+PY8	73.2	<0.01	47.4	0.039
SHERPA	66.5	<0.01	57.2	<0.01
PW+H++	152	<0.01		
MG5+PY	48.9	0.028		

- **"Inconsistency" reduced to "tension" by including theory uncertainties**
- **same @ parton**

2 Measuring SM variables: gluon PDF

@8 TeV

Eur. Phys. J. C 77 (2017) 804

- χ^2 **Fit** *(xFitter)*

NLO predictions *(MCFM +ApplGRID)* **with free gluon PDF parameters**

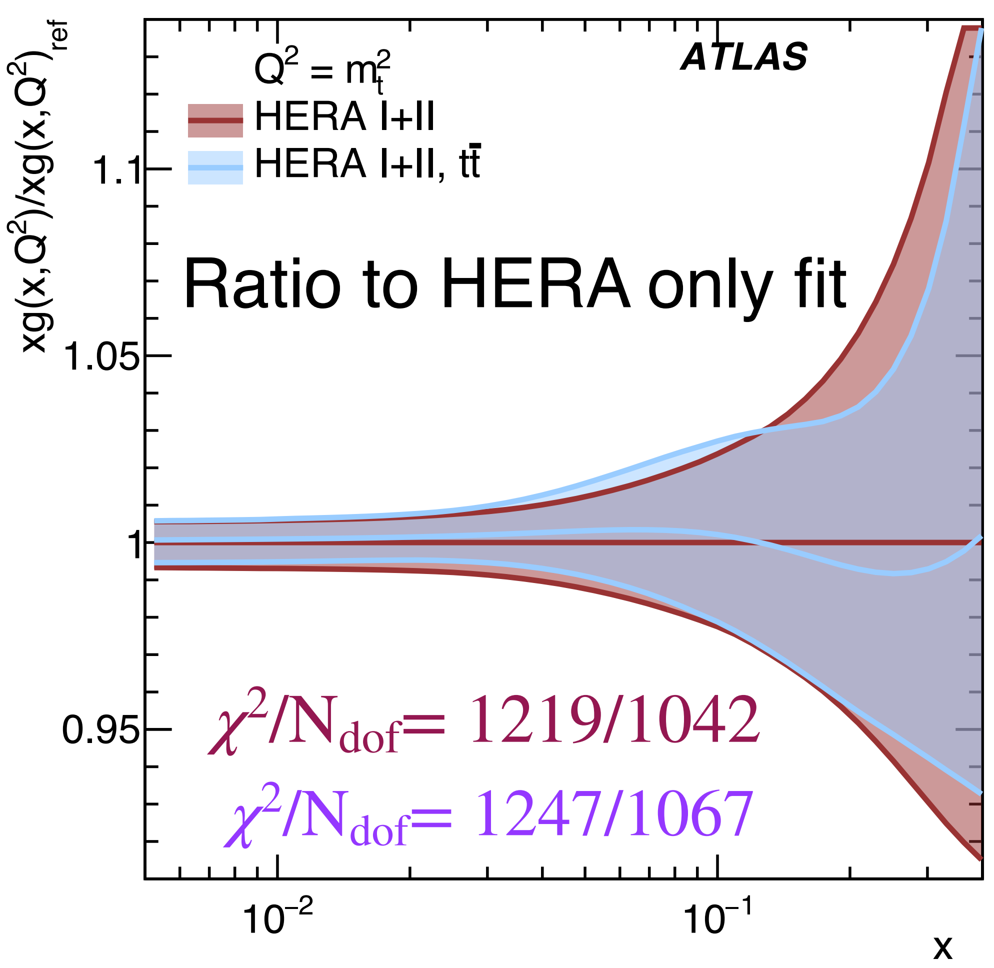
to

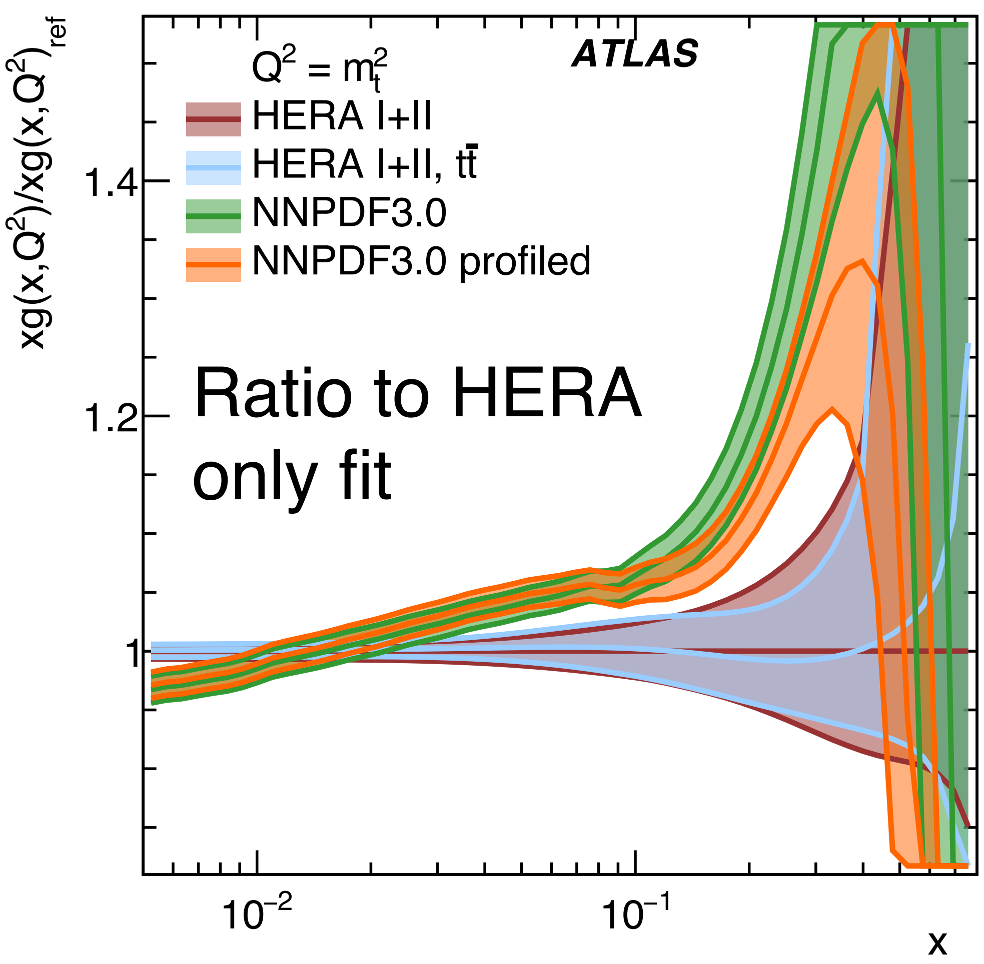
Measurements

- HERA **DIS**
- LHC **measurements in NNPDF /CT14**

with & w/o ATLAS **$1/\sigma_{tt}\ d\sigma_{tt}/dX$** with X= $|\eta^{\ell}|$, $y^{e\mu}$, $E^e + E^{\mu}$

⇒ **extract gluon PDF parameters**



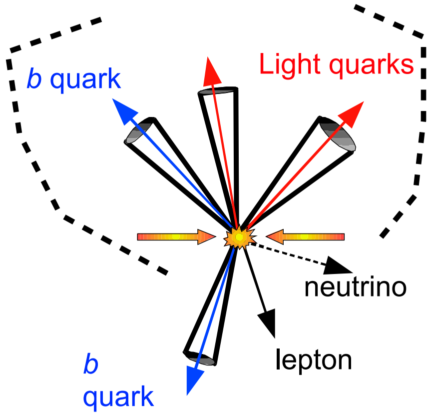


Adding tt info to HERA reduces uncertainty by 10 to 25%

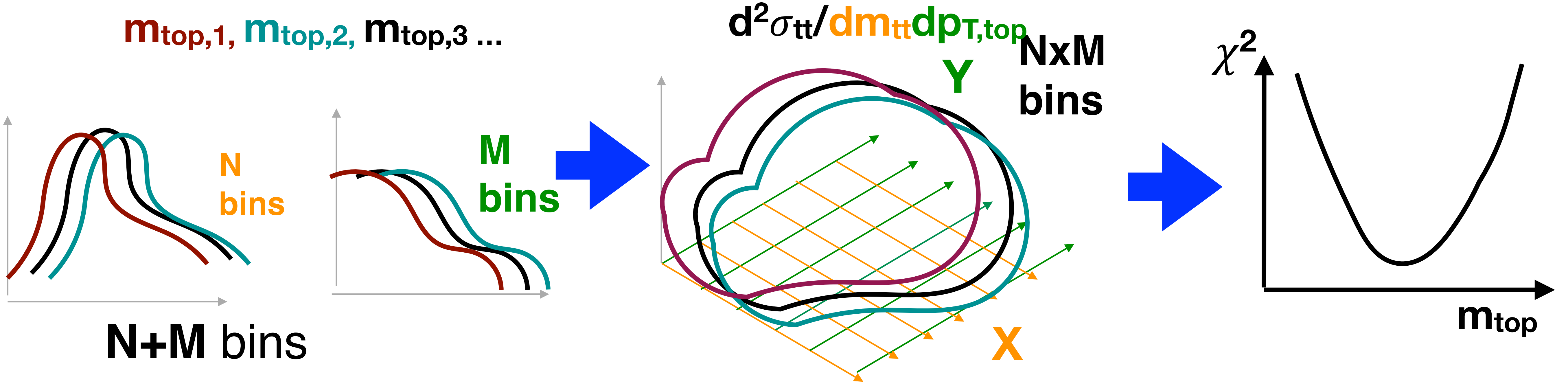
Including tt info in NNPDF/CT14 lowers gluon pdf at high x

Looking at the future: top quark mass from $d\sigma_{tt}/dXdY$

Measure $d\sigma_{tt}/dXdY$ in l+jets



- σ_{tt} **depends on top quark mass** (m_{top}) → **Measure m_{top} using $d\sigma_{tt}/dm_{tt}dp_{T,top}$**



- **Pros:Add novel information from correlation bins +use most precise predictions**
- Cons(?):..requires more events, larger sensitivity to modelling?

- Minimise $\chi^2$of **$d^2\sigma_{tt}/dm_{tt}dp_{T,top}$** vs **NNLO m_{top}-dependent prediction**

Extreme test of SM:double differential cross sections

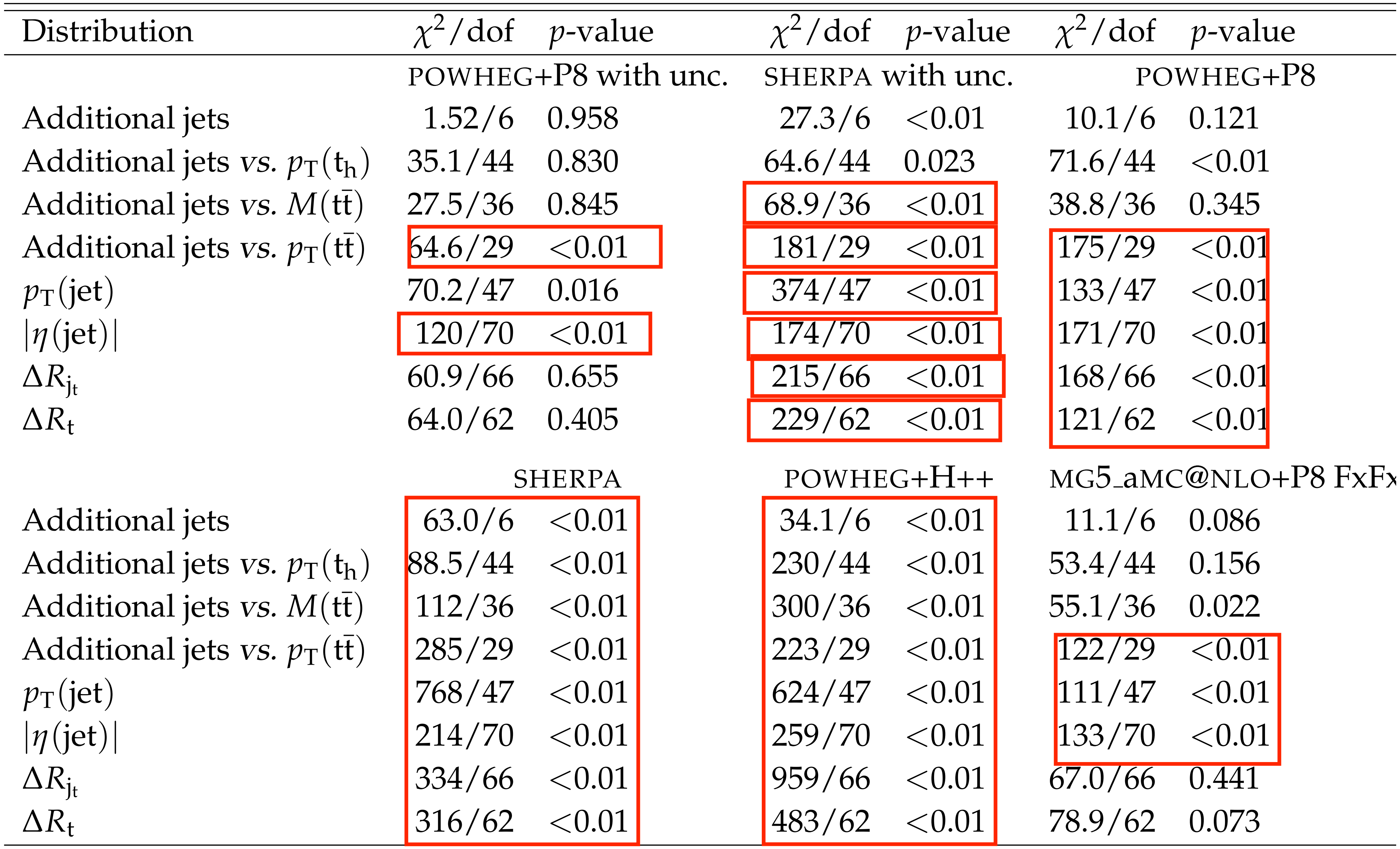
Extreme test of SM: Double differential cross sections

Phys. Rev. D 97, 112003 (2018)

Absolute @ particle level

kine vs jet multiplicities and final state objects

- **FxFx** has up to 2 partons @NLO: it is **more consistent with 2d diffxsec** even without theory uncertainties
- $p_{T,tt}$ is only observable with global inconsistency



Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
Additional jets	1.52/6	0.958	27.3/6	<0.01	10.1/6	0.121
Additional jets *vs.* $p_T(t_h)$	35.1/44	0.830	64.6/44	0.023	71.6/44	<0.01
Additional jets *vs.* $M(t\bar{t})$	27.5/36	0.845	68.9/36	<0.01	38.8/36	0.345
Additional jets *vs.* $p_T(t\bar{t})$	64.6/29	<0.01	181/29	<0.01	175/29	<0.01
$p_T(\text{jet})$	70.2/47	0.016	374/47	<0.01	133/47	<0.01
$\|\eta(\text{jet})\|$	120/70	<0.01	174/70	<0.01	171/70	<0.01
ΔR_{jt}	60.9/66	0.655	215/66	<0.01	168/66	<0.01
ΔR_t	64.0/62	0.405	229/62	<0.01	121/62	<0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
Additional jets	63.0/6	<0.01	34.1/6	<0.01	11.1/6	0.086
Additional jets *vs.* $p_T(t_h)$	88.5/44	<0.01	230/44	<0.01	53.4/44	0.156
Additional jets *vs.* $M(t\bar{t})$	112/36	<0.01	300/36	<0.01	55.1/36	0.022
Additional jets *vs.* $p_T(t\bar{t})$	285/29	<0.01	223/29	<0.01	122/29	<0.01
$p_T(\text{jet})$	768/47	<0.01	624/47	<0.01	111/47	<0.01
$\|\eta(\text{jet})\|$	214/70	<0.01	259/70	<0.01	133/70	<0.01
ΔR_{jt}	334/66	<0.01	959/66	<0.01	67.0/66	0.441
ΔR_t	316/62	<0.01	483/62	<0.01	78.9/62	0.073

theo uncertainties available only for POWHEG+PY & SHERPA

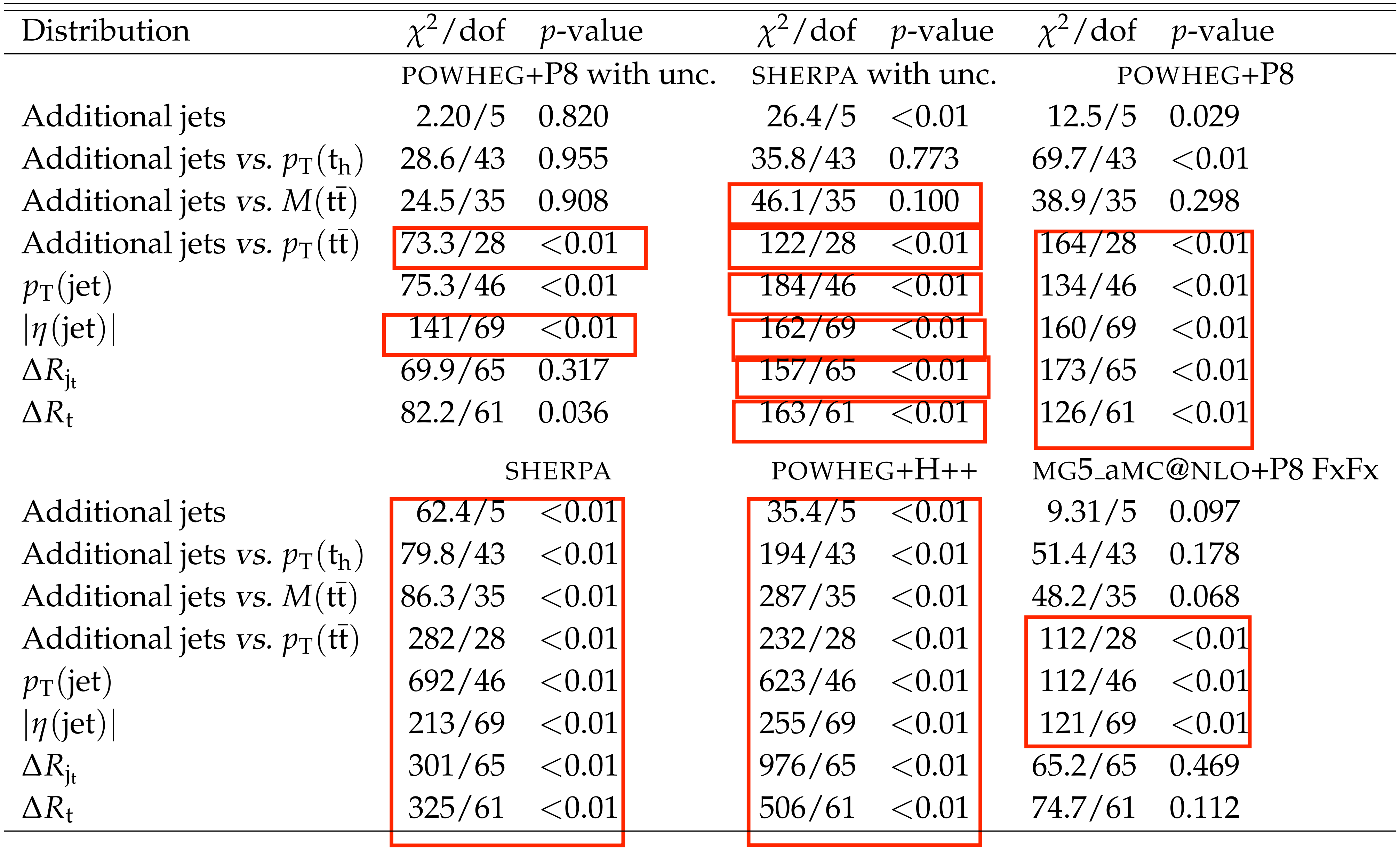
Additional jets = jet multiplicities up to 5 additional jets with p_T> 30 GeV

Extreme test of SM: Double differential cross sections

Phys. Rev. D 97, 112003 (2018)

Normalised @ particle level

kine vs jet multiplicities and final state objects



Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
Additional jets	2.20/5	0.820	26.4/5	<0.01	12.5/5	0.029
Additional jets *vs.* $p_{\mathrm{T}}(\mathrm{t_h})$	28.6/43	0.955	35.8/43	0.773	69.7/43	<0.01
Additional jets *vs.* $M(\mathrm{t\bar{t}})$	24.5/35	0.908	46.1/35	0.100	38.9/35	0.298
Additional jets *vs.* $p_{\mathrm{T}}(\mathrm{t\bar{t}})$	73.3/28	<0.01	122/28	<0.01	164/28	<0.01
$p_{\mathrm{T}}(\mathrm{jet})$	75.3/46	<0.01	184/46	<0.01	134/46	<0.01
$\lvert\eta(\mathrm{jet})\rvert$	141/69	<0.01	162/69	<0.01	160/69	<0.01
ΔR_{jt}	69.9/65	0.317	157/65	<0.01	173/65	<0.01
ΔR_{t}	82.2/61	0.036	163/61	<0.01	126/61	<0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
Additional jets	62.4/5	<0.01	35.4/5	<0.01	9.31/5	0.097
Additional jets *vs.* $p_{\mathrm{T}}(\mathrm{t_h})$	79.8/43	<0.01	194/43	<0.01	51.4/43	0.178
Additional jets *vs.* $M(\mathrm{t\bar{t}})$	86.3/35	<0.01	287/35	<0.01	48.2/35	0.068
Additional jets *vs.* $p_{\mathrm{T}}(\mathrm{t\bar{t}})$	282/28	<0.01	232/28	<0.01	112/28	<0.01
$p_{\mathrm{T}}(\mathrm{jet})$	692/46	<0.01	623/46	<0.01	112/46	<0.01
$\lvert\eta(\mathrm{jet})\rvert$	213/69	<0.01	255/69	<0.01	121/69	<0.01
ΔR_{jt}	301/65	<0.01	976/65	<0.01	65.2/65	0.469
ΔR_{t}	325/61	<0.01	506/61	<0.01	74.7/61	0.112

- **FxFx** has up to 2 partons @NLO: it is **more consistent with 2d diffxsec** even without theory uncertainties
- $p_{T,tt}$ is only observable with global inconsistency

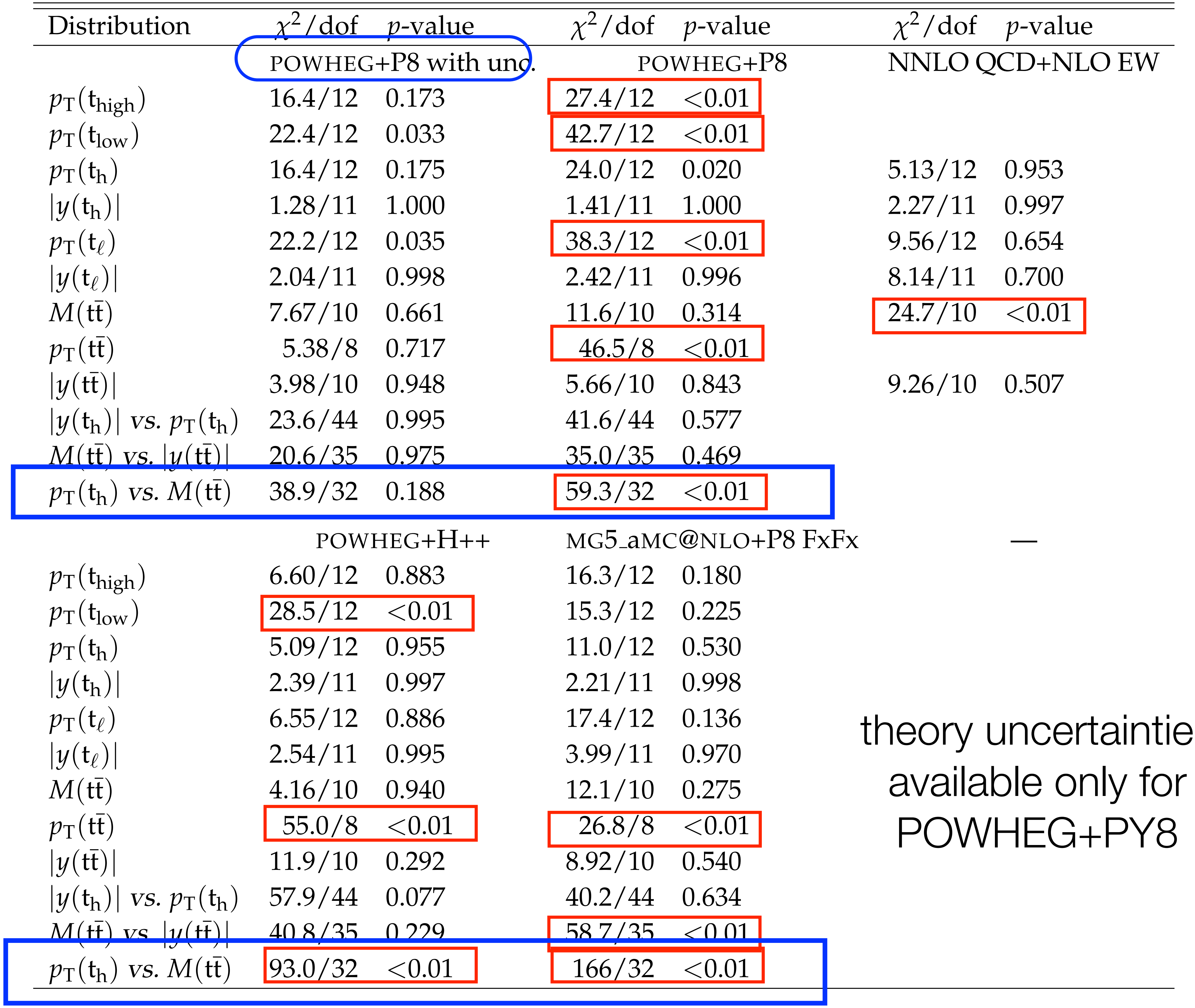
theo uncertainties available only for POWHEG+PY & SHERPA

Additional jets = jet multiplicities up to 5 additional jets with $p_T > 30$ GeV

Extreme test of SM: Double differential cross section @13 TeV

Phys. Rev. D 97, 112003 (2018)

Absolute @ parton level



Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		POWHEG+P8		NNLO QCD+NLO EW	
$p_{\mathrm{T}}(\mathrm{t_{high}})$	16.4/12	0.173	27.4/12	<0.01		
$p_{\mathrm{T}}(\mathrm{t_{low}})$	22.4/12	0.033	42.7/12	<0.01		
$p_{\mathrm{T}}(\mathrm{t_h})$	16.4/12	0.175	24.0/12	0.020	5.13/12	0.953
$\|y(\mathrm{t_h})\|$	1.28/11	1.000	1.41/11	1.000	2.27/11	0.997
$p_{\mathrm{T}}(\mathrm{t_\ell})$	22.2/12	0.035	38.3/12	<0.01	9.56/12	0.654
$\|y(\mathrm{t_\ell})\|$	2.04/11	0.998	2.42/11	0.996	8.14/11	0.700
$M(\mathrm{t\bar{t}})$	7.67/10	0.661	11.6/10	0.314	24.7/10	<0.01
$p_{\mathrm{T}}(\mathrm{t\bar{t}})$	5.38/8	0.717	46.5/8	<0.01		
$\|y(\mathrm{t\bar{t}})\|$	3.98/10	0.948	5.66/10	0.843	9.26/10	0.507
$\|y(\mathrm{t_h})\|$ vs. $p_{\mathrm{T}}(\mathrm{t_h})$	23.6/44	0.995	41.6/44	0.577		
$M(\mathrm{t\bar{t}})$ vs. $\|y(\mathrm{t\bar{t}})\|$	20.6/35	0.975	35.0/35	0.469		
$p_{\mathrm{T}}(\mathrm{t_h})$ vs. $M(\mathrm{t\bar{t}})$	38.9/32	0.188	59.3/32	<0.01		
	POWHEG+H++		MG5_aMC@NLO+P8 FxFx		—	
$p_{\mathrm{T}}(\mathrm{t_{high}})$	6.60/12	0.883	16.3/12	0.180		
$p_{\mathrm{T}}(\mathrm{t_{low}})$	28.5/12	<0.01	15.3/12	0.225		
$p_{\mathrm{T}}(\mathrm{t_h})$	5.09/12	0.955	11.0/12	0.530		
$\|y(\mathrm{t_h})\|$	2.39/11	0.997	2.21/11	0.998		
$p_{\mathrm{T}}(\mathrm{t_\ell})$	6.55/12	0.886	17.4/12	0.136		
$\|y(\mathrm{t_\ell})\|$	2.54/11	0.995	3.99/11	0.970		
$M(\mathrm{t\bar{t}})$	4.16/10	0.940	12.1/10	0.275		
$p_{\mathrm{T}}(\mathrm{t\bar{t}})$	55.0/8	<0.01	26.8/8	<0.01		
$\|y(\mathrm{t\bar{t}})\|$	11.9/10	0.292	8.92/10	0.540		
$\|y(\mathrm{t_h})\|$ vs. $p_{\mathrm{T}}(\mathrm{t_h})$	57.9/44	0.077	40.2/44	0.634		
$M(\mathrm{t\bar{t}})$ vs. $\|y(\mathrm{t\bar{t}})\|$	40.8/35	0.229	58.7/35	<0.01		
$p_{\mathrm{T}}(\mathrm{t_h})$ vs. $M(\mathrm{t\bar{t}})$	93.0/32	<0.01	166/32	<0.01		

- **POWHEG +PY8 inconsistency is reabsorbed if theory uncertainties are included**

theory uncertainties available only for POWHEG+PY8

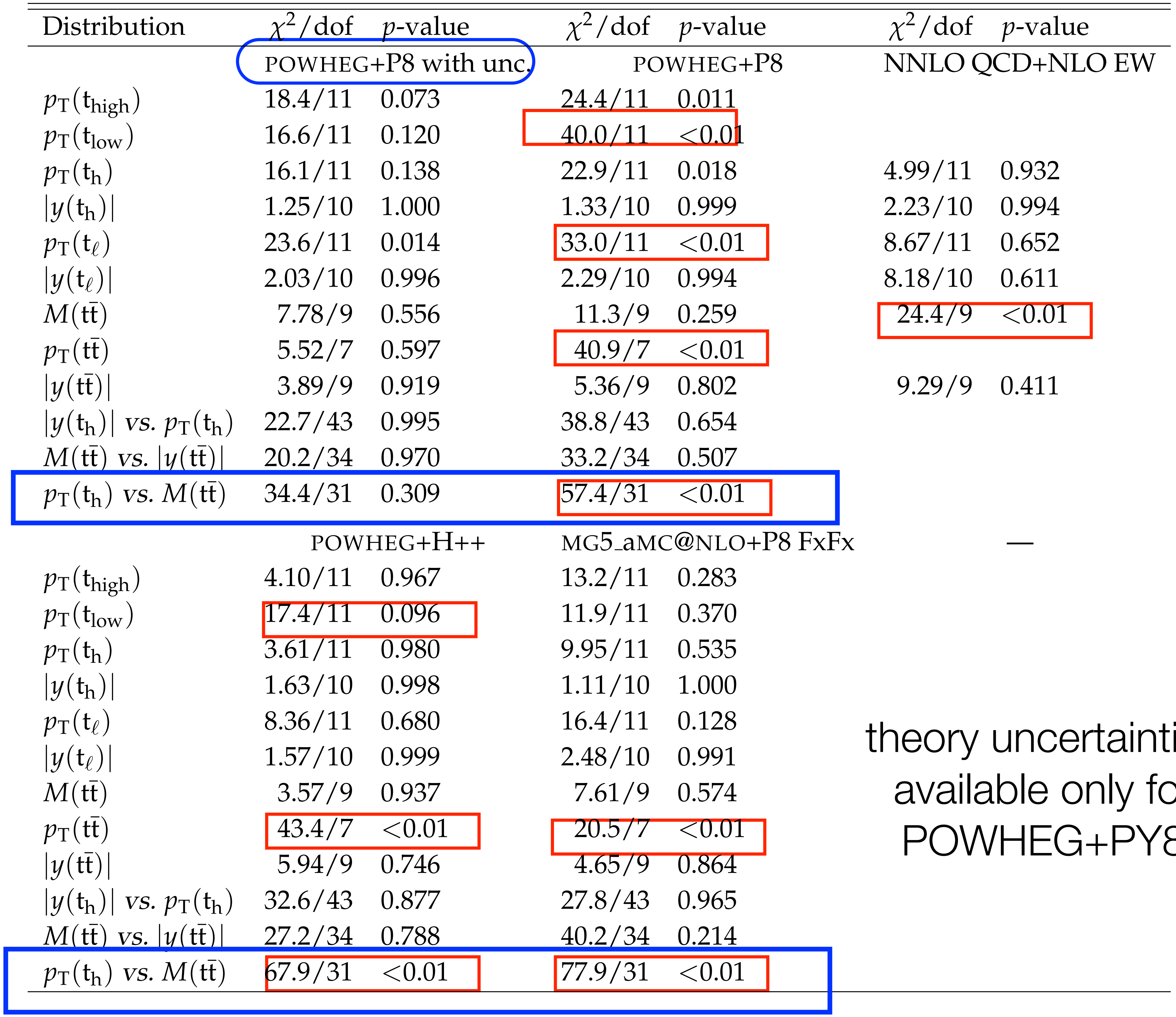
Extreme test of SM: Double differential cross section @13 TeV

Phys. Rev. D 97, 112003 (2018)

Normalised @ parton level

- **POWHEG +PY8 inconsistency is reabsorbed if theory uncertainties are included**

consistent with absolute



Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		POWHEG+P8		NNLO QCD+NLO EW	
$p_\mathrm{T}(\mathrm{t_{high}})$	18.4/11	0.073	24.4/11	0.011		
$p_\mathrm{T}(\mathrm{t_{low}})$	16.6/11	0.120	40.0/11	<0.01		
$p_\mathrm{T}(\mathrm{t_h})$	16.1/11	0.138	22.9/11	0.018	4.99/11	0.932
$\lvert y(\mathrm{t_h})\rvert$	1.25/10	1.000	1.33/10	0.999	2.23/10	0.994
$p_\mathrm{T}(\mathrm{t_\ell})$	23.6/11	0.014	33.0/11	<0.01	8.67/11	0.652
$\lvert y(\mathrm{t_\ell})\rvert$	2.03/10	0.996	2.29/10	0.994	8.18/10	0.611
$M(\mathrm{t\bar{t}})$	7.78/9	0.556	11.3/9	0.259	24.4/9	<0.01
$p_\mathrm{T}(\mathrm{t\bar{t}})$	5.52/7	0.597	40.9/7	<0.01		
$\lvert y(\mathrm{t\bar{t}})\rvert$	3.89/9	0.919	5.36/9	0.802	9.29/9	0.411
$\lvert y(\mathrm{t_h})\rvert$ vs. $p_\mathrm{T}(\mathrm{t_h})$	22.7/43	0.995	38.8/43	0.654		
$M(\mathrm{t\bar{t}})$ vs. $\lvert y(\mathrm{t\bar{t}})\rvert$	20.2/34	0.970	33.2/34	0.507		
$p_\mathrm{T}(\mathrm{t_h})$ vs. $M(\mathrm{t\bar{t}})$	34.4/31	0.309	57.4/31	<0.01		
	POWHEG+H++		MG5_aMC@NLO+P8 FxFx		—	
$p_\mathrm{T}(\mathrm{t_{high}})$	4.10/11	0.967	13.2/11	0.283		
$p_\mathrm{T}(\mathrm{t_{low}})$	17.4/11	0.096	11.9/11	0.370		
$p_\mathrm{T}(\mathrm{t_h})$	3.61/11	0.980	9.95/11	0.535		
$\lvert y(\mathrm{t_h})\rvert$	1.63/10	0.998	1.11/10	1.000		
$p_\mathrm{T}(\mathrm{t_\ell})$	8.36/11	0.680	16.4/11	0.128		
$\lvert y(\mathrm{t_\ell})\rvert$	1.57/10	0.999	2.48/10	0.991		
$M(\mathrm{t\bar{t}})$	3.57/9	0.937	7.61/9	0.574		
$p_\mathrm{T}(\mathrm{t\bar{t}})$	43.4/7	<0.01	20.5/7	<0.01		
$\lvert y(\mathrm{t\bar{t}})\rvert$	5.94/9	0.746	4.65/9	0.864		
$\lvert y(\mathrm{t_h})\rvert$ vs. $p_\mathrm{T}(\mathrm{t_h})$	32.6/43	0.877	27.8/43	0.965		
$M(\mathrm{t\bar{t}})$ vs. $\lvert y(\mathrm{t\bar{t}})\rvert$	27.2/34	0.788	40.2/34	0.214		
$p_\mathrm{T}(\mathrm{t_h})$ vs. $M(\mathrm{t\bar{t}})$	67.9/31	<0.01	77.9/31	<0.01		

theory uncertainties available only for POWHEG+PY8

Extreme test of SM: Double differential cross section **@13 TeV**

Absolute @ particle level

- **POWHEG +PY8 inconsistency is reabsorbed if theory uncertainties are included**
- **FxFx is the most consistent** already **without theory uncertainties**

consistent with absolute

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
$p_T(t_h)$	15.9/12	0.197	7.21/12	0.844	29.5/12	<0.01
$\lvert y(t_h)\rvert$	1.96/11	0.999	1.48/11	1.000	2.23/11	0.997
$p_T(t_\ell)$	27.0/12	<0.01	22.3/12	0.034	80.2/12	<0.01
$\lvert y(t_\ell)\rvert$	4.55/11	0.951	5.07/11	0.928	4.99/11	0.932
$M(t\bar{t})$	5.83/10	0.829	2.40/10	0.992	9.07/10	0.525
$p_T(t\bar{t})$	4.96/8	0.761	28.9/8	<0.01	41.2/8	<0.01
$\lvert y(t\bar{t})\rvert$	5.93/10	0.821	6.63/10	0.760	8.61/10	0.570
$\lvert y(t_h)\rvert$ vs. $p_T(t_h)$	35.7/44	0.810	29.6/44	0.953	64.1/44	0.025
$M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$	25.9/35	0.867	24.2/35	0.914	56.2/35	0.013
$p_T(t_h)$ vs. $M(t\bar{t})$	47.4/32	0.039	57.2/32	<0.01	73.2/32	<0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
$p_T(t_h)$	13.5/12	0.335	32.1/12	<0.01	17.4/12	0.137
$\lvert y(t_h)\rvert$	2.32/11	0.997	4.89/11	0.936	3.16/11	0.988
$p_T(t_\ell)$	39.4/12	<0.01	21.8/12	0.040	47.7/12	<0.01
$\lvert y(t_\ell)\rvert$	5.54/11	0.902	4.04/11	0.969	7.22/11	0.781
$M(t\bar{t})$	2.86/10	0.985	52.8/10	<0.01	5.45/10	0.859
$p_T(t\bar{t})$	68.7/8	<0.01	46.8/8	<0.01	21.3/8	<0.01
$\lvert y(t\bar{t})\rvert$	12.1/10	0.276	18.6/10	0.046	8.13/10	0.616
$\lvert y(t_h)\rvert$ vs. $p_T(t_h)$	48.3/44	0.305	116/44	<0.01	44.9/44	0.434
$M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$	41.5/35	0.208	219/35	<0.01	55.7/35	0.014
$p_T(t_h)$ vs. $M(t\bar{t})$	66.5/32	<0.01	152/32	<0.01	48.9/32	0.028

theory uncertainties available only for POWHEG+PY8 & SHERPA

Extreme test of SM: Double differential cross section @13 TeV

Normalised @ particle level

- **POWHEG +PY8 inconsistency is reabsorbed if theory uncertainties are included**
- **FxFx is the most consistent** already **without theory uncertainties**

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8 with unc.		SHERPA with unc.		POWHEG+P8	
$p_T(t_h)$	14.9/11	0.186	6.99/11	0.800	29.4/11	<0.01
$\lvert y(t_h)\rvert$	1.77/10	0.998	1.25/10	1.000	1.90/10	0.997
$p_T(t_\ell)$	25.3/11	<0.01	28.0/11	<0.01	74.0/11	<0.01
$\lvert y(t_\ell)\rvert$	4.50/10	0.922	4.88/10	0.899	5.00/10	0.891
$M(t\bar{t})$	5.69/9	0.770	2.17/9	0.989	9.33/9	0.407
$p_T(t\bar{t})$	5.36/7	0.616	12.5/7	0.086	34.8/7	<0.01
$\lvert y(t\bar{t})\rvert$	5.79/9	0.761	6.68/9	0.671	8.48/9	0.486
$\lvert y(t_h)\rvert$ vs. $p_T(t_h)$	27.6/43	0.967	32.7/43	0.872	53.8/43	0.126
$M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$	26.5/34	0.817	22.7/34	0.931	54.0/34	0.016
$p_T(t_h)$ vs. $M(t\bar{t})$	42.5/31	0.082	39.2/31	0.149	64.8/31	<0.01
	SHERPA		POWHEG+H++		MG5_aMC@NLO+P8 FxFx	
$p_T(t_h)$	13.9/11	0.238	34.1/11	<0.01	15.2/11	0.173
$\lvert y(t_h)\rvert$	1.60/10	0.999	3.81/10	0.955	2.73/10	0.987
$p_T(t_\ell)$	37.3/11	<0.01	25.0/11	<0.01	40.5/11	<0.01
$\lvert y(t_\ell)\rvert$	5.28/10	0.872	3.92/10	0.951	5.54/10	0.853
$M(t\bar{t})$	2.99/9	0.965	51.7/9	<0.01	4.98/9	0.836
$p_T(t\bar{t})$	59.4/7	<0.01	43.8/7	<0.01	17.9/7	0.013
$\lvert y(t\bar{t})\rvert$	11.3/9	0.253	18.2/9	0.033	8.37/9	0.498
$\lvert y(t_h)\rvert$ vs. $p_T(t_h)$	47.7/43	0.287	108/43	<0.01	40.9/43	0.561
$M(t\bar{t})$ vs. $\lvert y(t\bar{t})\rvert$	37.6/34	0.308	234/34	<0.01	55.5/34	0.011
$p_T(t_h)$ vs. $M(t\bar{t})$	63.2/31	<0.01	126/31	<0.01	43.0/31	0.074

consistent with absolute

theory uncertainties available only for POWHEG+PY8 & SHERPA

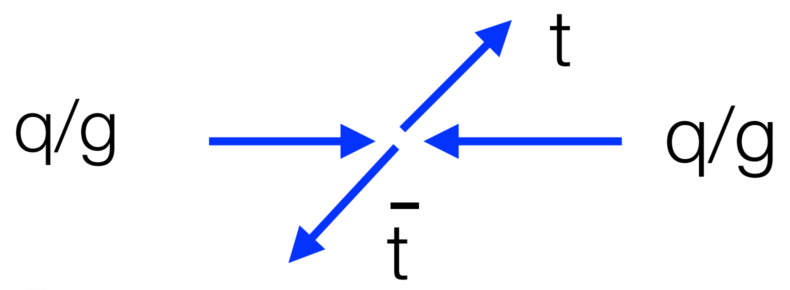
REMINDER

Parton distributions functions and top quark : the connection (II)

In c.m. frame of pp system, the parton momentum components are written

$$p_1^\mu = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1) \quad p_2^\mu = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)\,.$$

(assume massless partons)



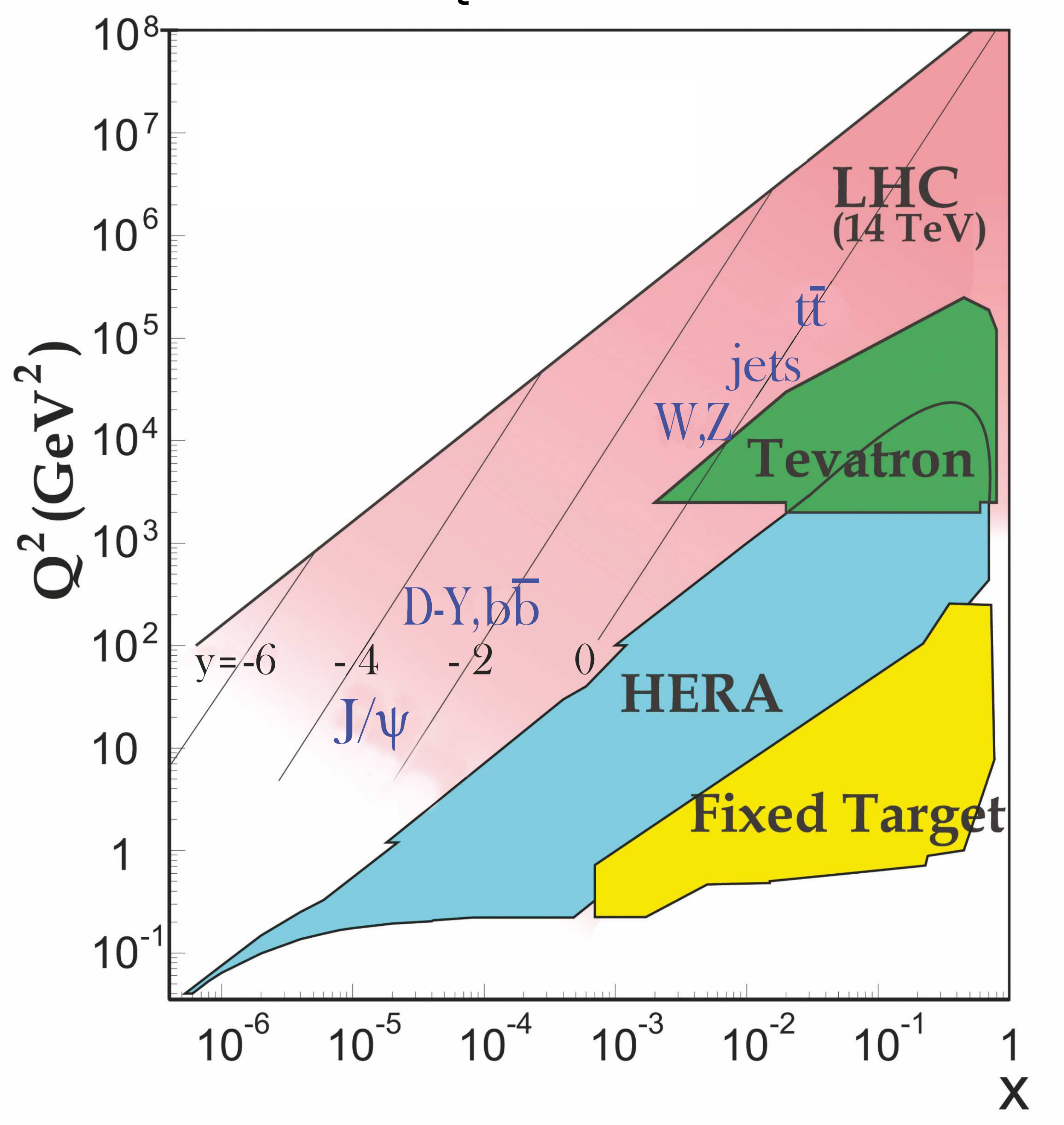
Using conservation of momentum & parsons in the leading order picture for $f\bar{f} \rightarrow t\bar{t}$, the rapidity of the top quark pair is

$$y(t\bar{t}) = \frac{1}{2}\ln\left(\frac{E(t\bar{t}) + p_z(t\bar{t})}{E(t\bar{t}) - p_z(t\bar{t})}\right) = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

$$\hat{s} = x_1 x_2 s = M(t\bar{t})$$

$$x_1 = \frac{M(t\bar{t})}{\sqrt{s}}e^{y} \quad x_2 = \frac{M(t\bar{t})}{\sqrt{s}}e^{-y}$$

- **maximum probed x at 13 TeV is ~0.25** given the bins of the rapidity and tt mass distributions ranges



The Top p_T saga, including the new chapter @13 TeV

What we measured at $\sqrt{s}=7,8$ TeV: X in $d\sigma_{(tt/t)}/dX$

Overview of current results at LHC

- Increasing variety of differential cross section results
  - More measurements in fiducial PS, exploiting particle-level object definition and pseudo-top
  - Pioneering results in boosted regime, first absolute differential cross sections appearing

15-30%
20-40%

$p_{T,top\text{-}jet}$

3-6%
10-20% (single top)

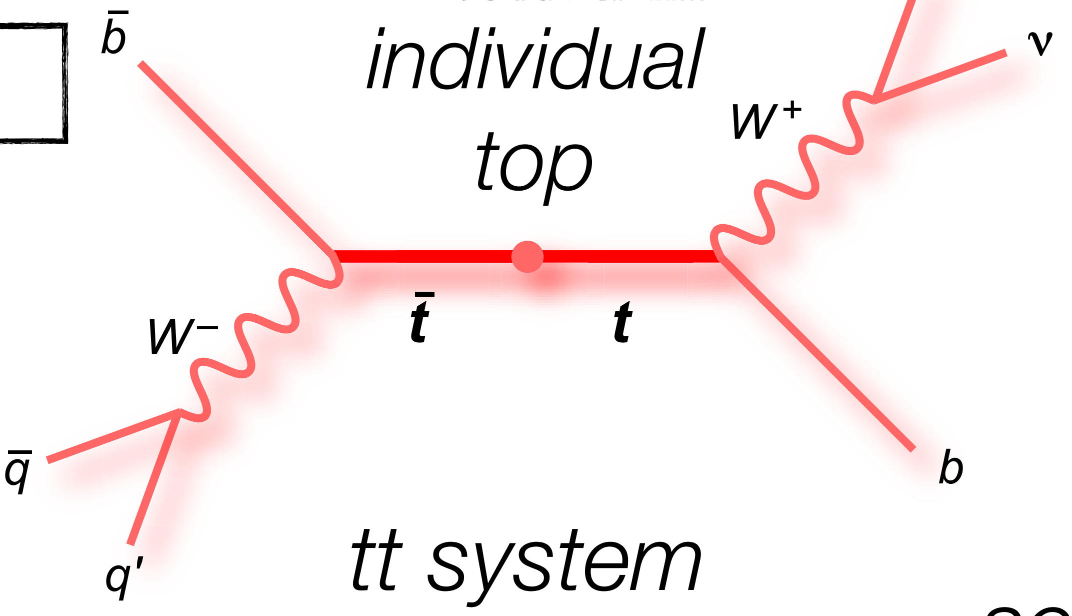
y_{top}
$p_{T,top}$,

individual top

η_{lep} $p_{T,lep}$ 4-6%

4-6% **$\eta_{b\text{-}jet}$ $p_{T,b\text{-}jet}$,**

$p_{T,lep\text{-}lep}$
$m_{lep\text{-}lep}$ 4-6%



15-40% **$p_{T,jet}$,$N_{,jet}$**
$Q_{jet(veto)}$

tt system

sensitive to resonant&
non resonant new phys

higher order
corrections (radiation)

m_{tt}
y_{tt} (rapidity)
$p_{T,tt}$

5-10%
3-6%

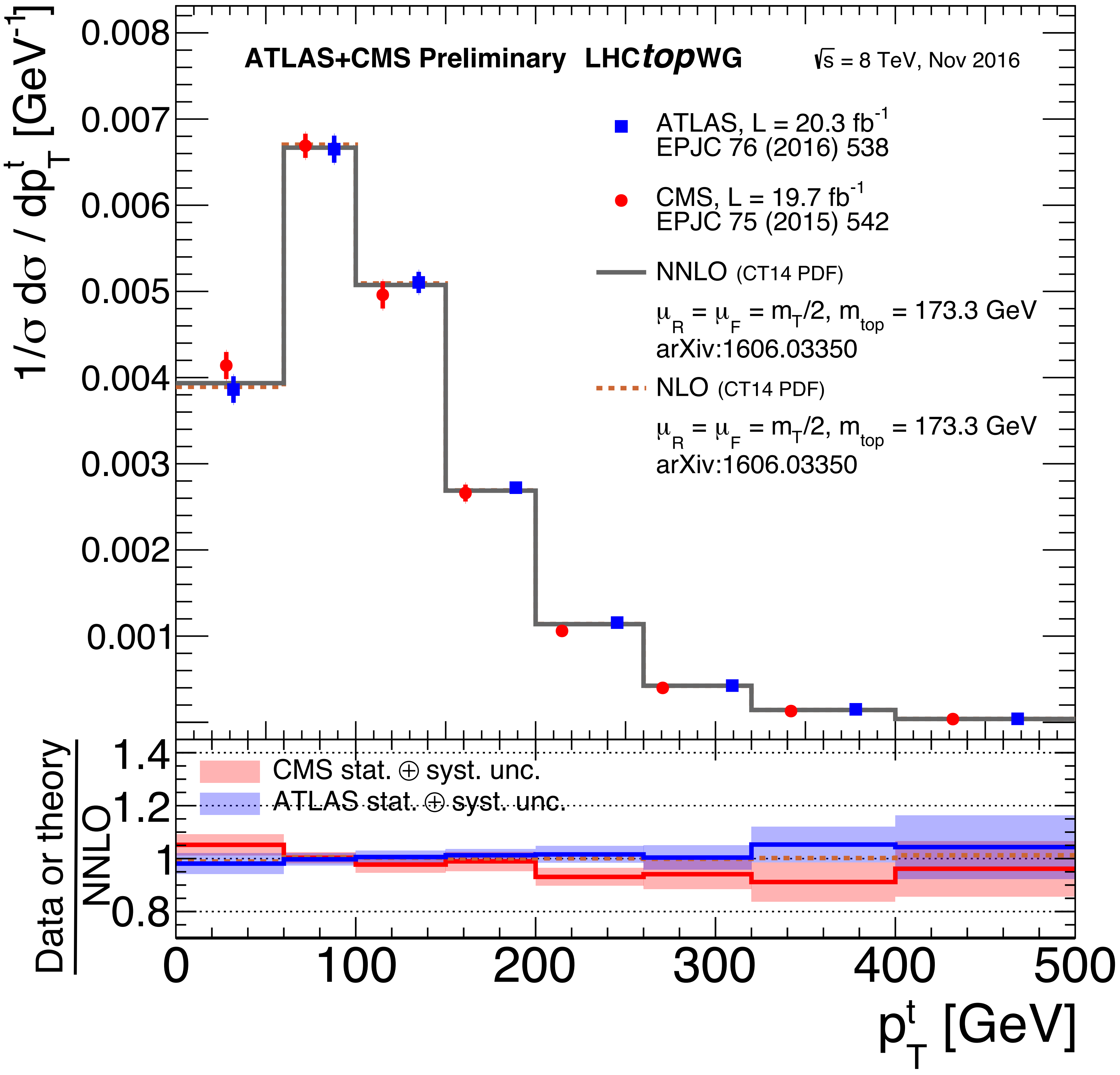
parton level

ATLAS vs CMS *vs NNLO Theory* :$1/\sigma_{tt}\, d\sigma_{tt}/dp_{T,top}$ @ $\sqrt{s}$ = 8 TeV

parton level

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

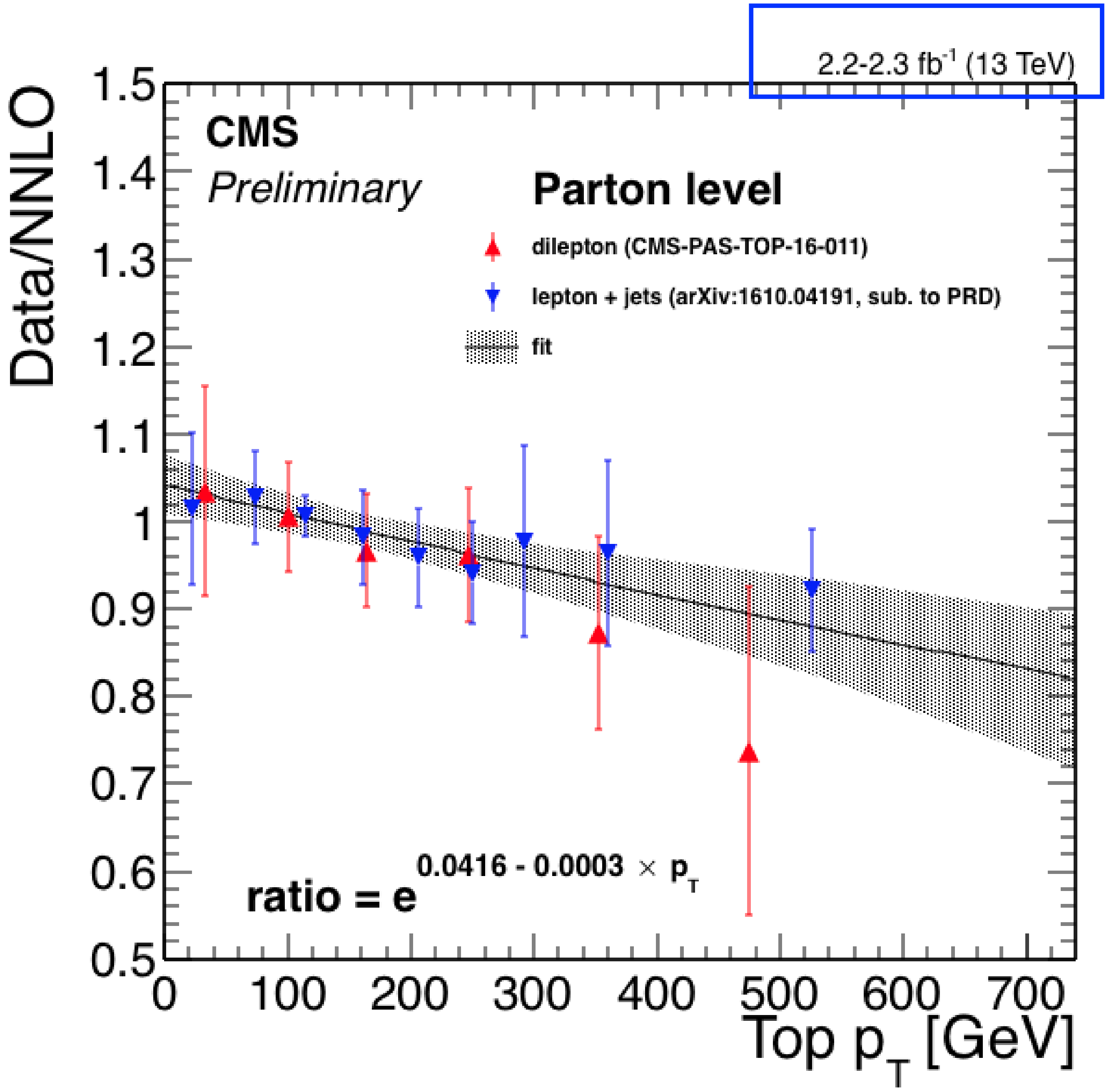
Qualitative statement, no statistical test performed yet

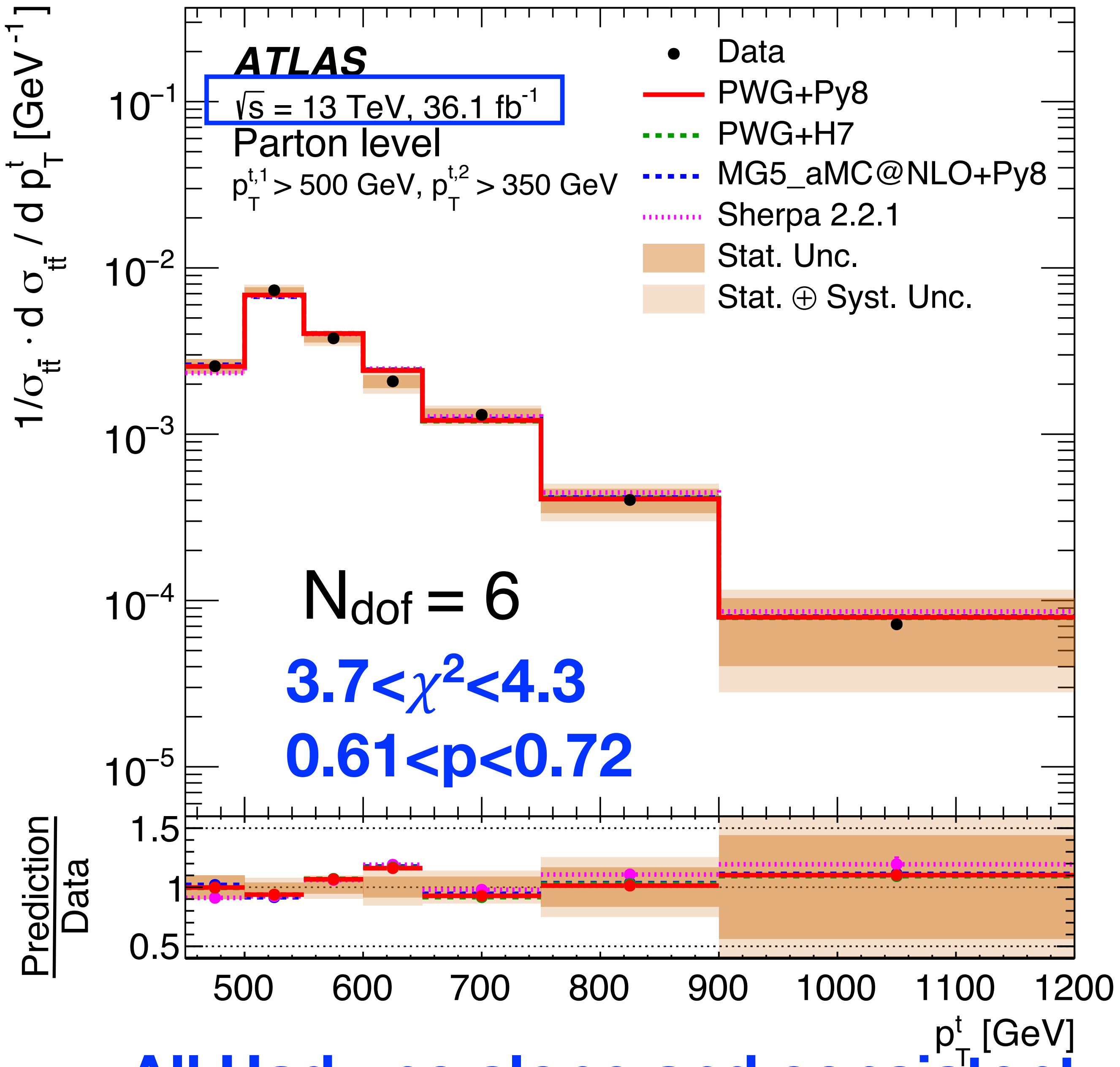


The Top p_T saga: NLO+PS @13 TeV

$p_{T,top}$

Parton level vs NLO+PS





$N_{dof} = 6$

$3.7<\chi^2<4.3$

$0.61<p<0.72$

ℓ+jets and dilepton "resolved"

softer, but compatible with standard model within uncertainties
measurement and theory.

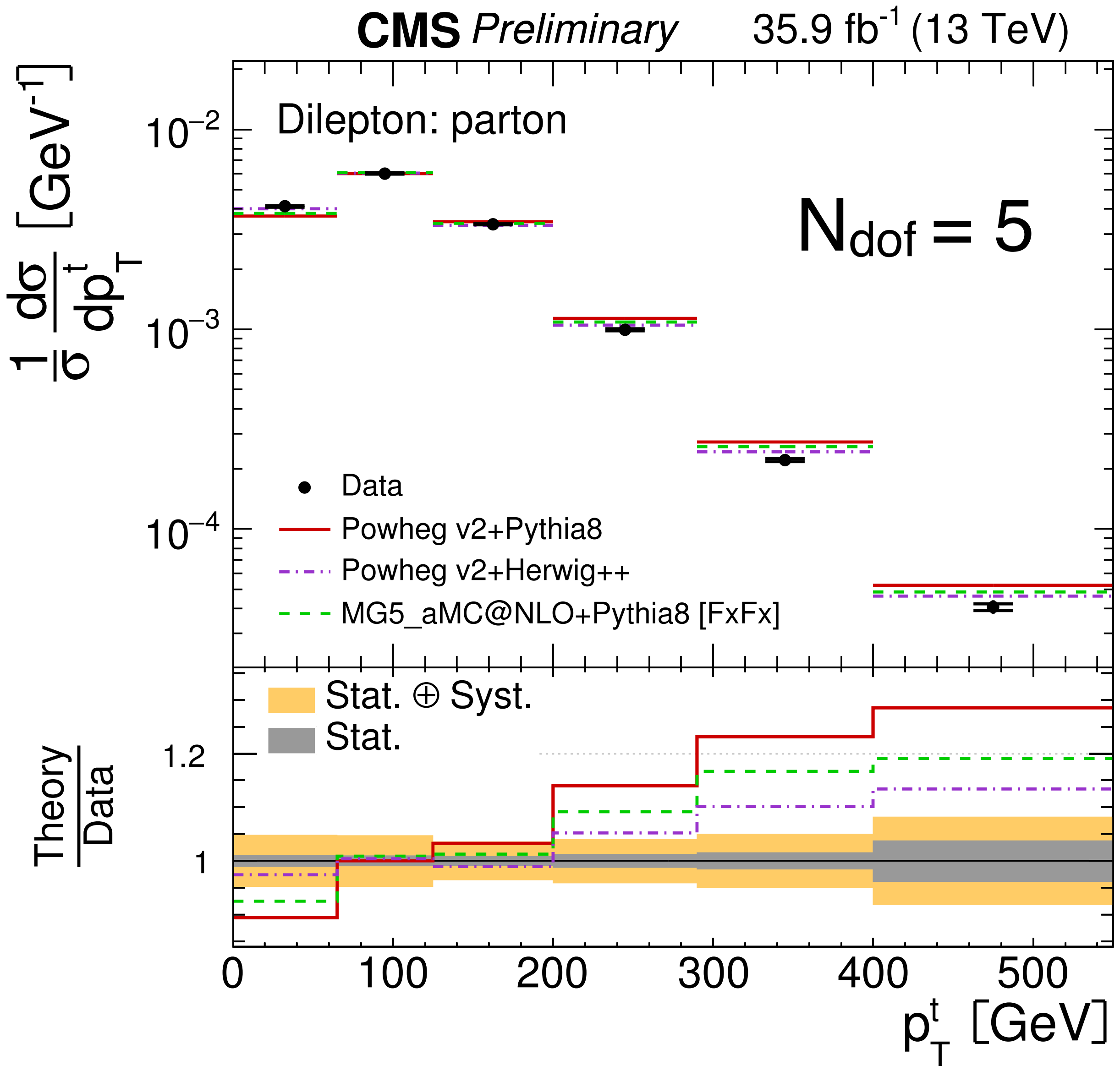
All Had : no slope and consistent

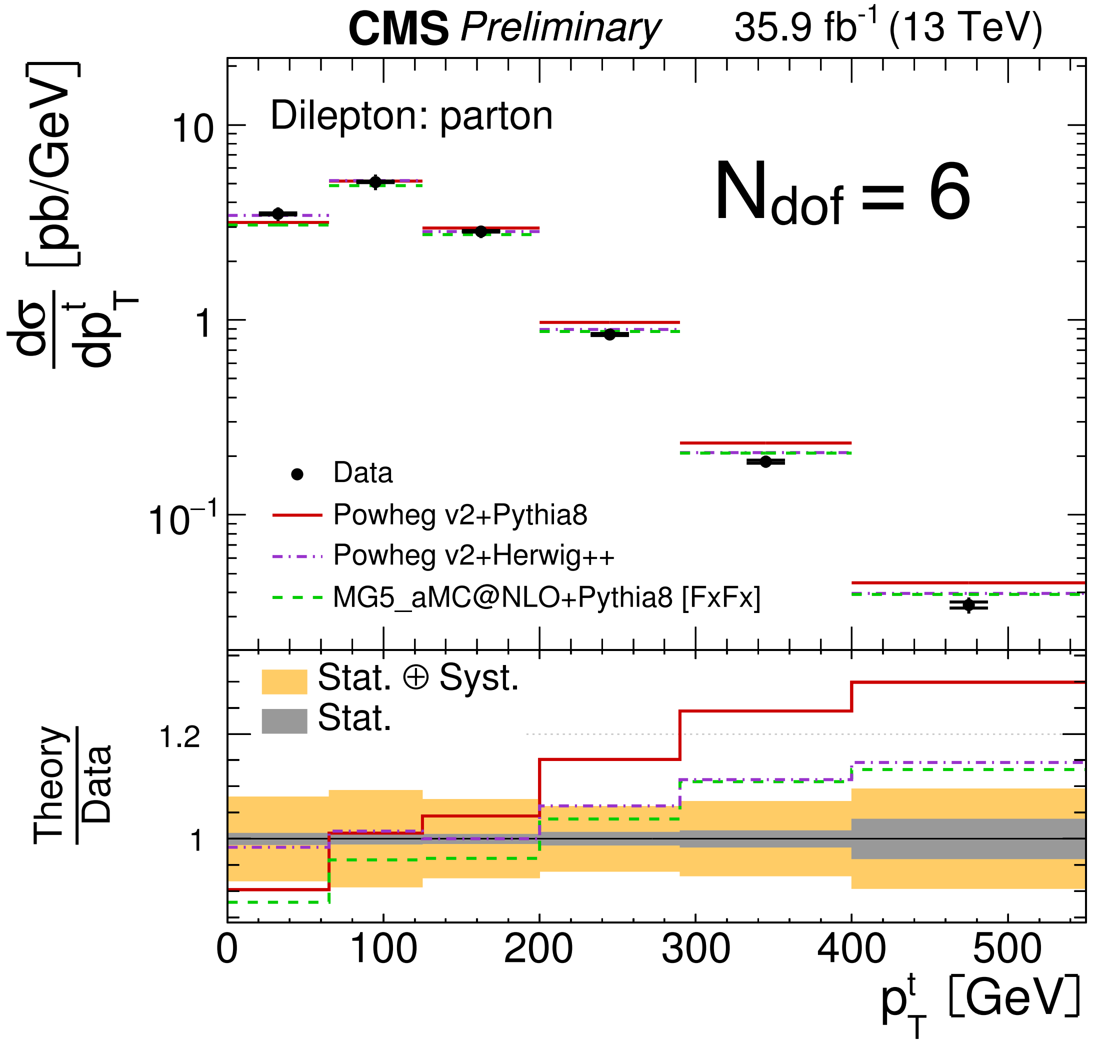
larger stat uncertainties

no theory uncertainty

The Top p_T saga: dilepton NLO+PS @13 TeV

CMS-PAS-TOP-17-014





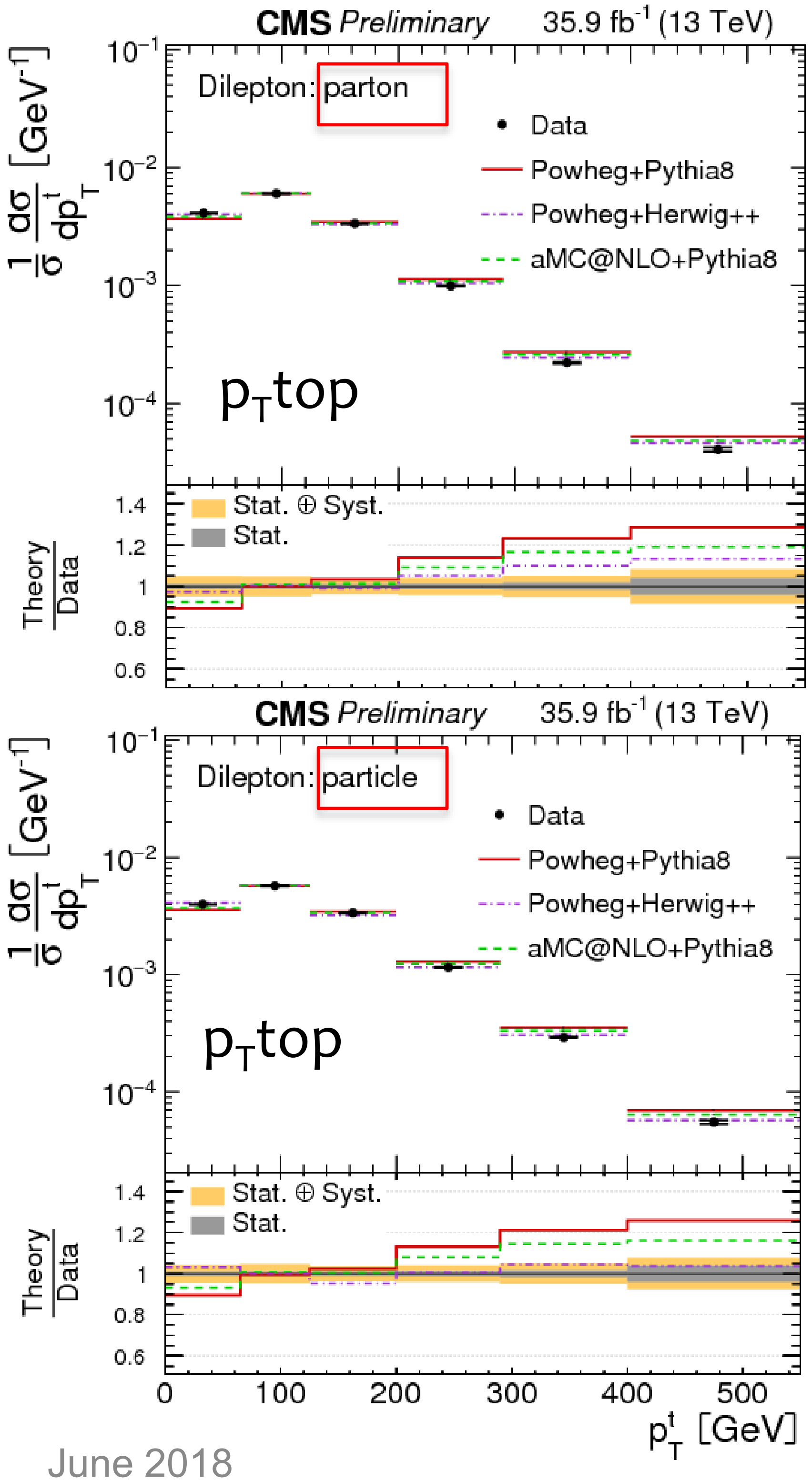
N_{dof} =5 o 6	normalised		absolute	
NLO+PS	χ^2	**p-val**	χ^2	**p-val**
PW+PY8	**63.5**	**<10^{-3}**	**51**	**<10^{-3}**
PW+H++	**10**	**0.087**	**8**	**0.239**
MG5+PY8	**28**	**<10^{-3}**	**18**	**0.007**

no theory uncertainties included

mind p_T range: up to 500 GeV

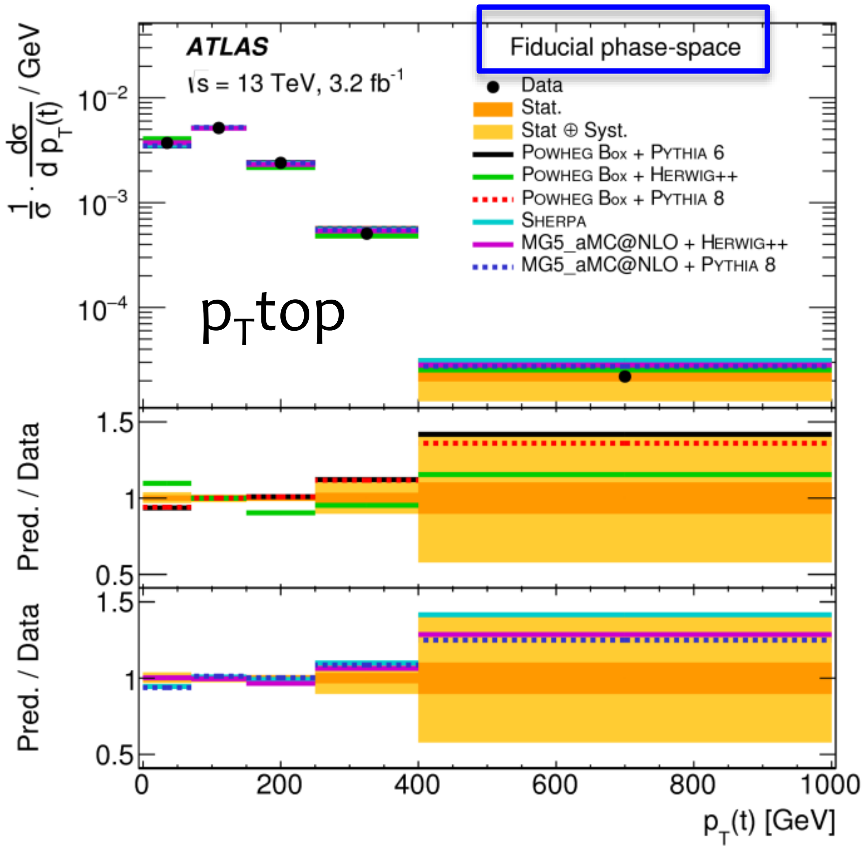
Dilepton differential

CMS-TOP-17-014



- 13TeV eμ 35.9fb^{-1} (2016)
- Parton level in the full phase space
- Particle level, within a phase space close to experimental acceptance (fiducial phase-space)

NEW



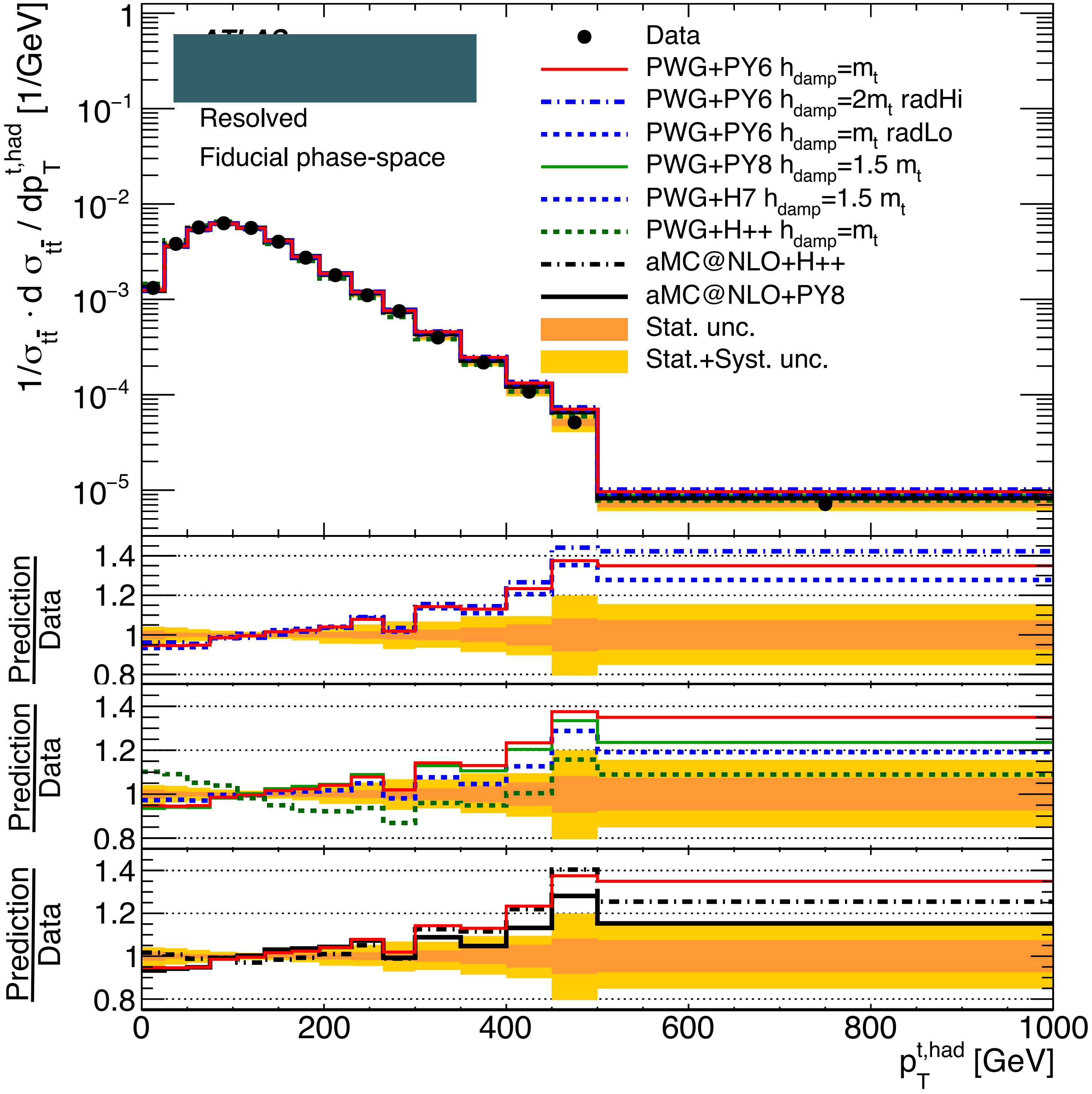
- **PowhegV2+Pythia8** (NLO) chosen as default generator setup in ATLAS and CMS for Run2:
  - ❖ Reasonable agreement except in top quark “direct” observables p_T, p_T^{tt}, m_{tt}
  - ❖ Need for full NNLO MC + PS predictions
- Similar results in eμ ATLAS: Eur. Phys. J. C77 (2017) 299

particle level

Extreme test of SM: the top p_T “saga” **@13TeV**

Particle level vs NLO+PS

$1/\sigma_{tt}\, d\sigma_{tt}/dX$ *JHEP 11 (2017) 191*



ℓ+jets “resolved”

$N_{dof} = 14$

$21.5<\chi^2<24.4$

$0.03<p<0.09$

Different radiation

Different hadronization → *except for POWHEG+HERWIG* **χ^2=15.4 p=0.35 (-)**

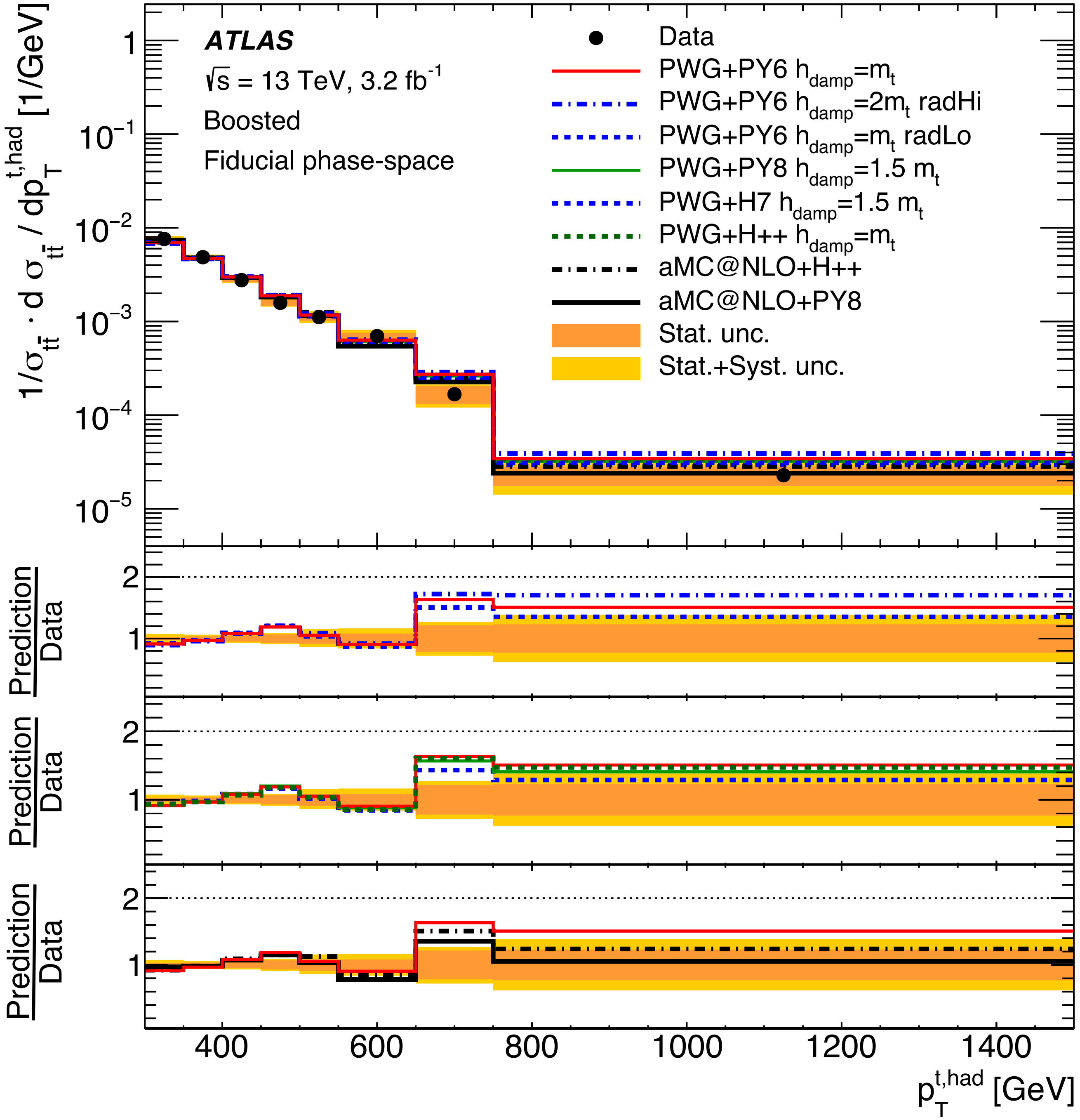
Different generator & hadronization

- **Tension with most NLO+PS predictions: slope w.r.t measurement**

Extreme test of SM: the top p_T "saga" @13TeV

Particle level vs NLO+PS

$1/\sigma_{tt}\, d\sigma_{tt}/dX$ *JHEP 11 (2017) 191*



ℓ+jets "boosted"

Different Radiation

Different Hadronization

Different generator & hadronization

$N_{dof} = 7$

$9.9<\chi^2<11.5$

$0.12<p<0.20$

- **Tension with most NLO+PS predictions: slope w.r.t measurement.**
- **Less tension than in "resolved", larger statistical uncertainties**

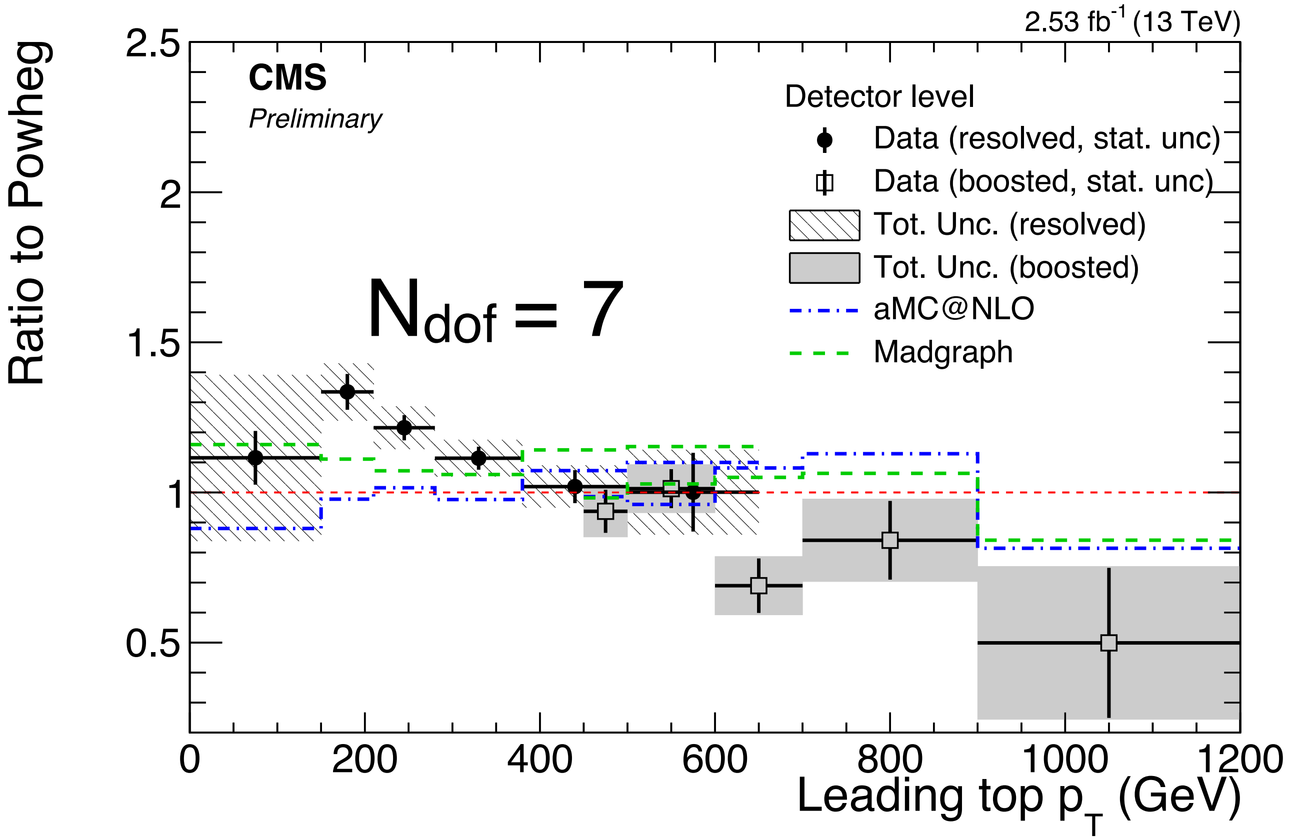
Extreme test of SM: the top p_T “saga” @13TeV

Particle level vs NLO+PS

$p_{T,\mathrm{lead\ top}}$

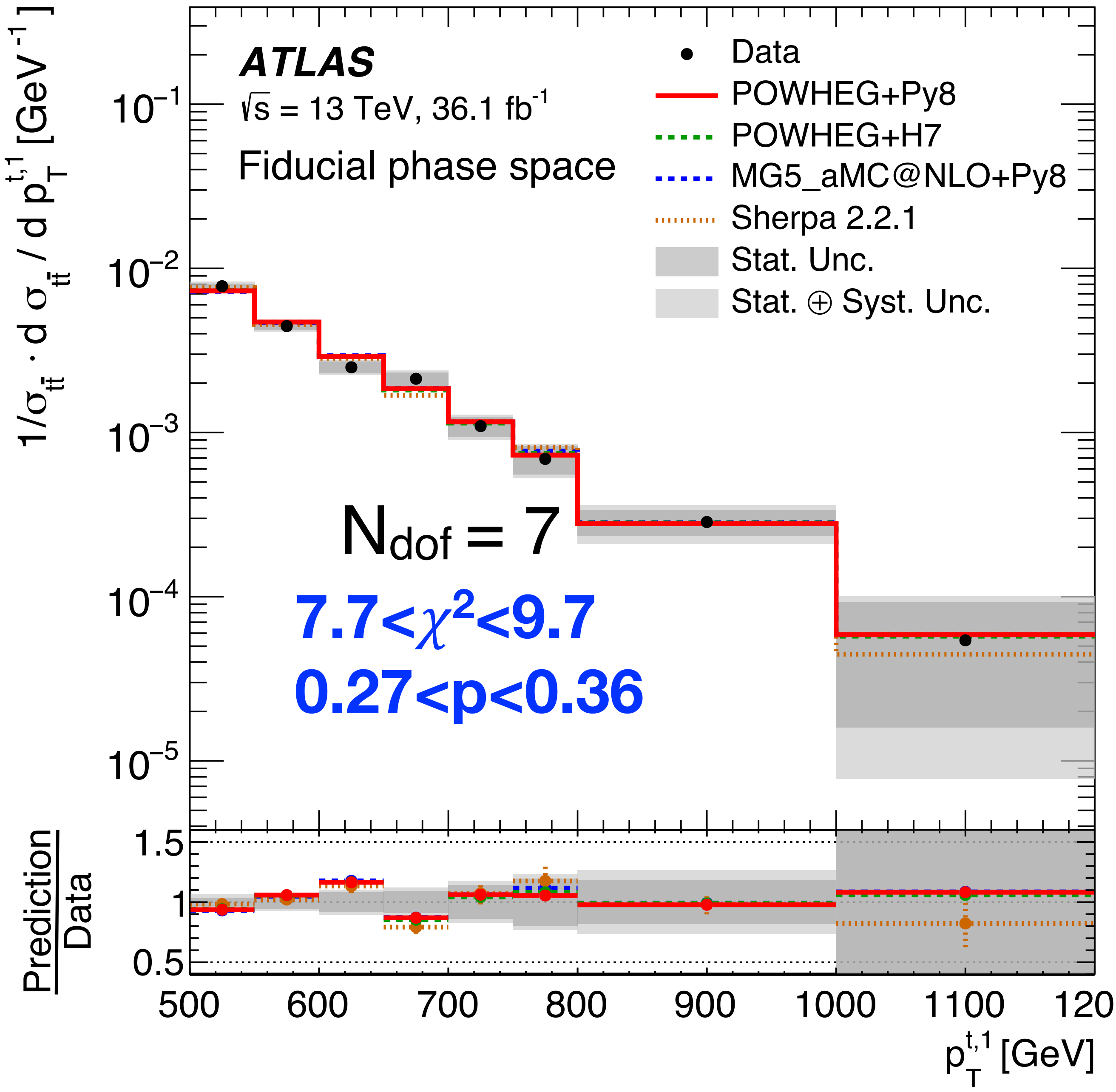
Reco level

CMS-TOP-16-013, 2.5 fb^{-1}, 13 TeV



$N_{\mathrm{dof}} = 7$

Particle level vs NLO+PS



$N_{\mathrm{dof}} = 7$

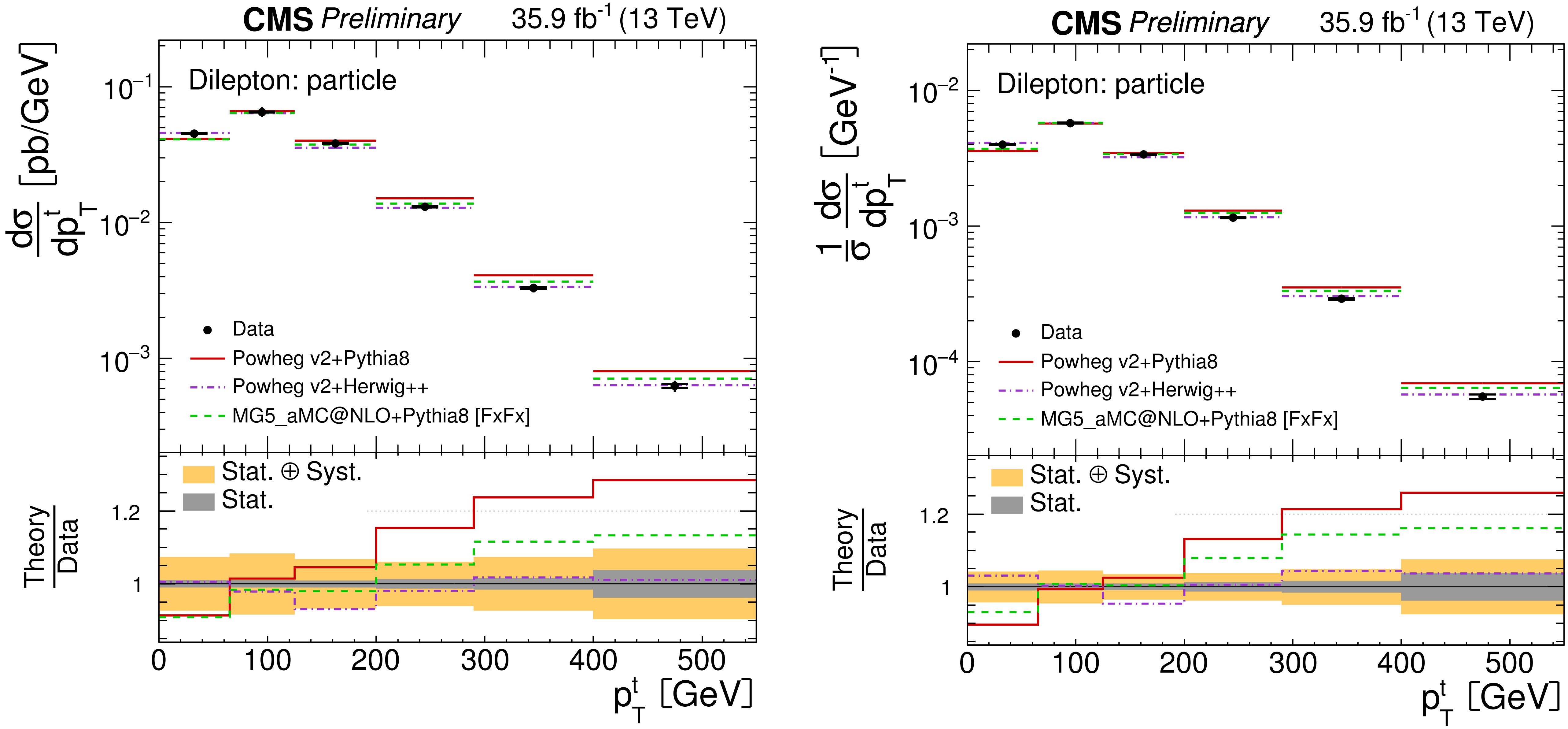
$7.7<\chi^2<9.7$

$0.27<p<0.36$

- **Measurements agree with predictions**

The Top p_T saga: dilepton NLO+PS @13 TeV

CMS-PAS-TOP-17-014



N_{dof} =5 o 6	normalised		absolute	
NLO+PS	χ^2	**p-val**	χ^2	**p-val**
PW+PY8	**128**	**<10^{-3}**	**52**	**<10^{-3}**
PW+H++	**6**	**0.306**	**3**	**0.830**
MG5+PY8	**45**	**<10^{-3}**	**17**	**0.008**

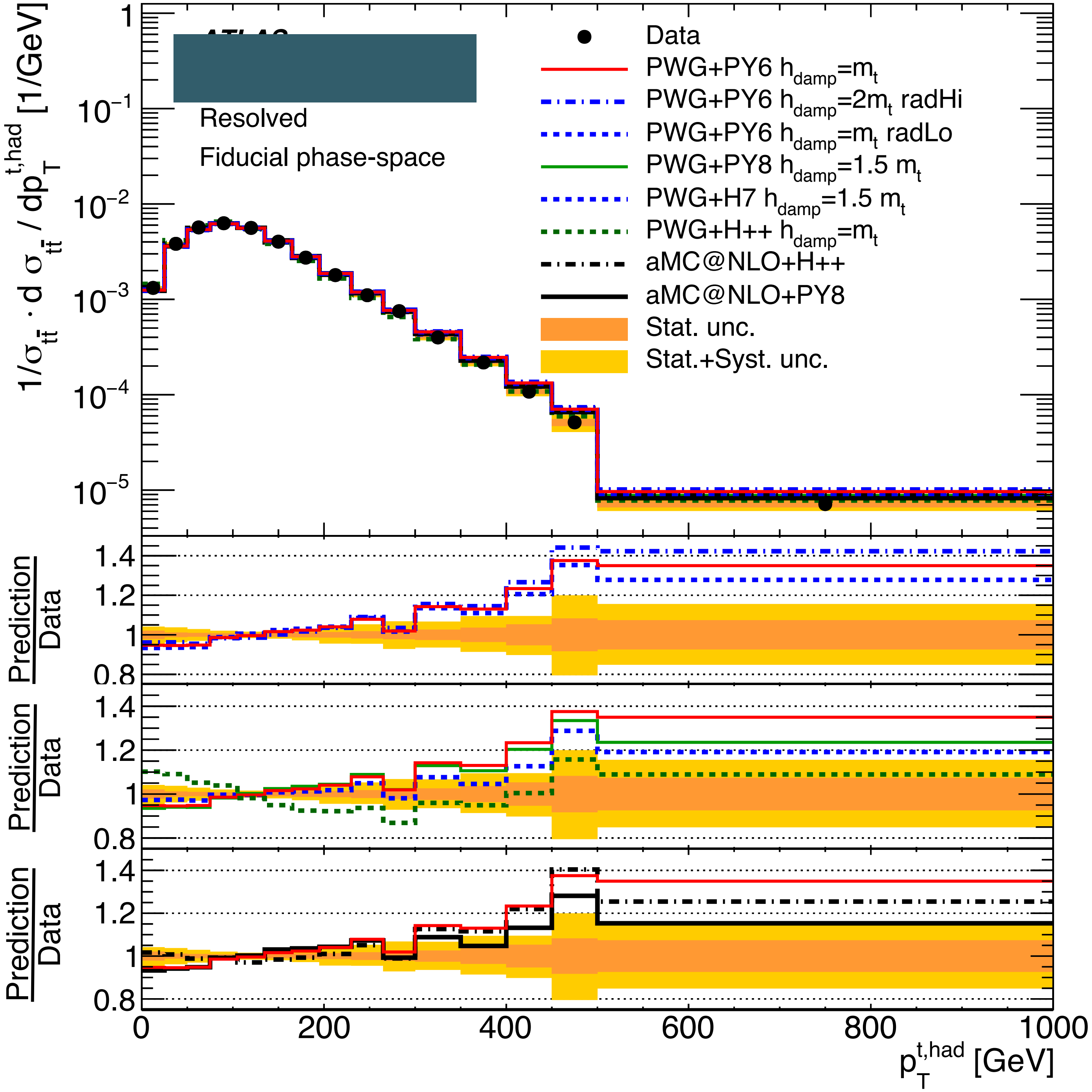
no theory uncertainties included

particle level

Extreme test of SM: the top p_T “saga” @13TeV

Particle level vs NLO+PS

$1/\sigma_{tt}\, d\sigma_{tt}/dX$ *JHEP 11 (2017) 191*



ℓ+jets “resolved”

$N_{dof} = 14$

$21.5<\chi^2<24.4$

$0.03<p<0.09$

Different radiation

Different hadronization →

except for POWHEG+HERWIG

χ^2=15.4 p=0.35 (-)

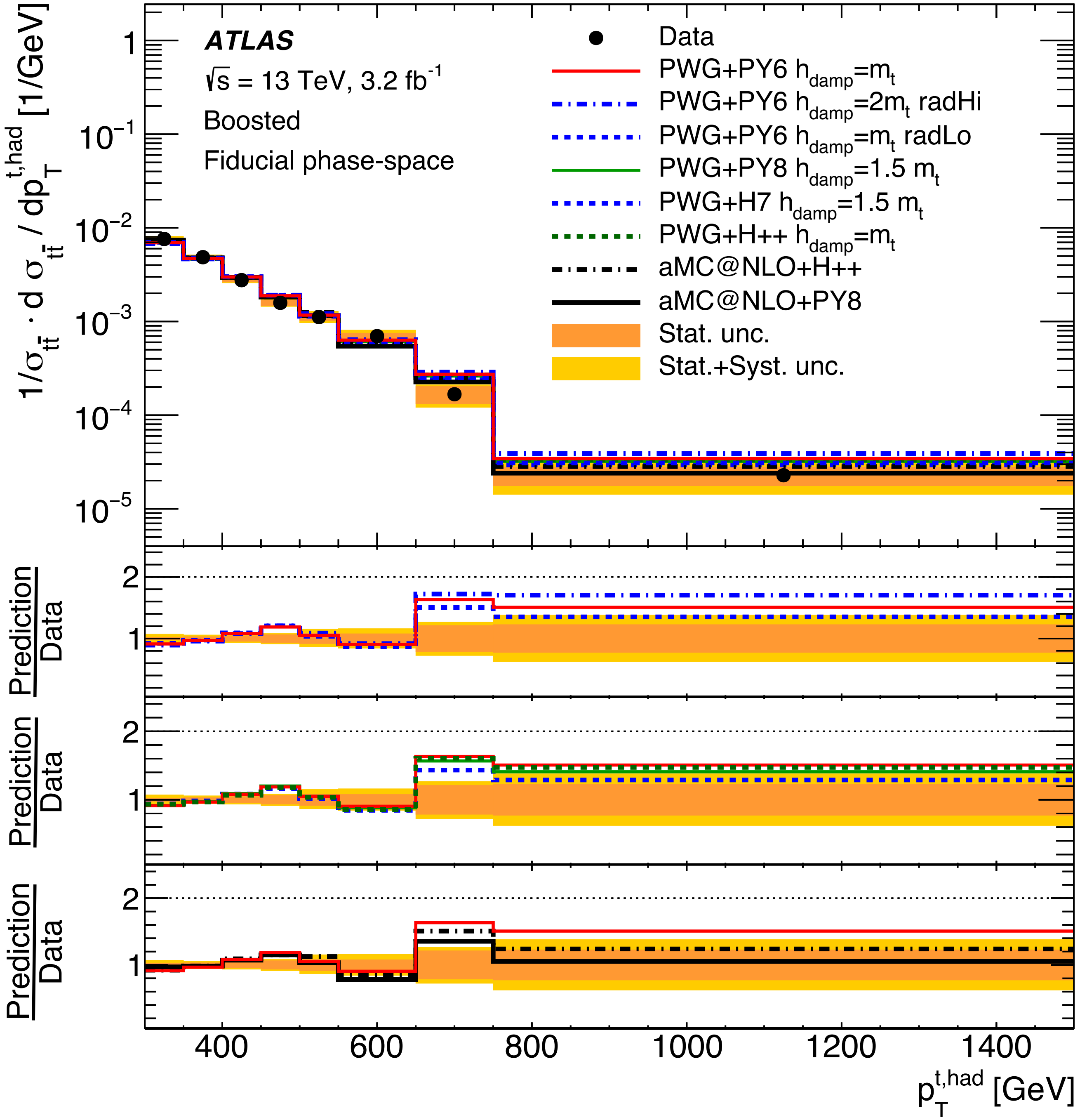
Different generator & hadronization

- **Tension with most NLO+PS predictions: slope w.r.t measurement**

Extreme test of SM: the top p_T “saga” @13TeV

Particle level vs NLO+PS

$1/\sigma_{tt}\, d\sigma_{tt}/dX$ *JHEP 11 (2017) 191*



ℓ+jets “boosted”

Different
Radiation

Different
Hadronization

Different
generator
& hadronization

$N_{dof} = 7$

$9.9<\chi^2<11.5$
$0.12<p<0.20$

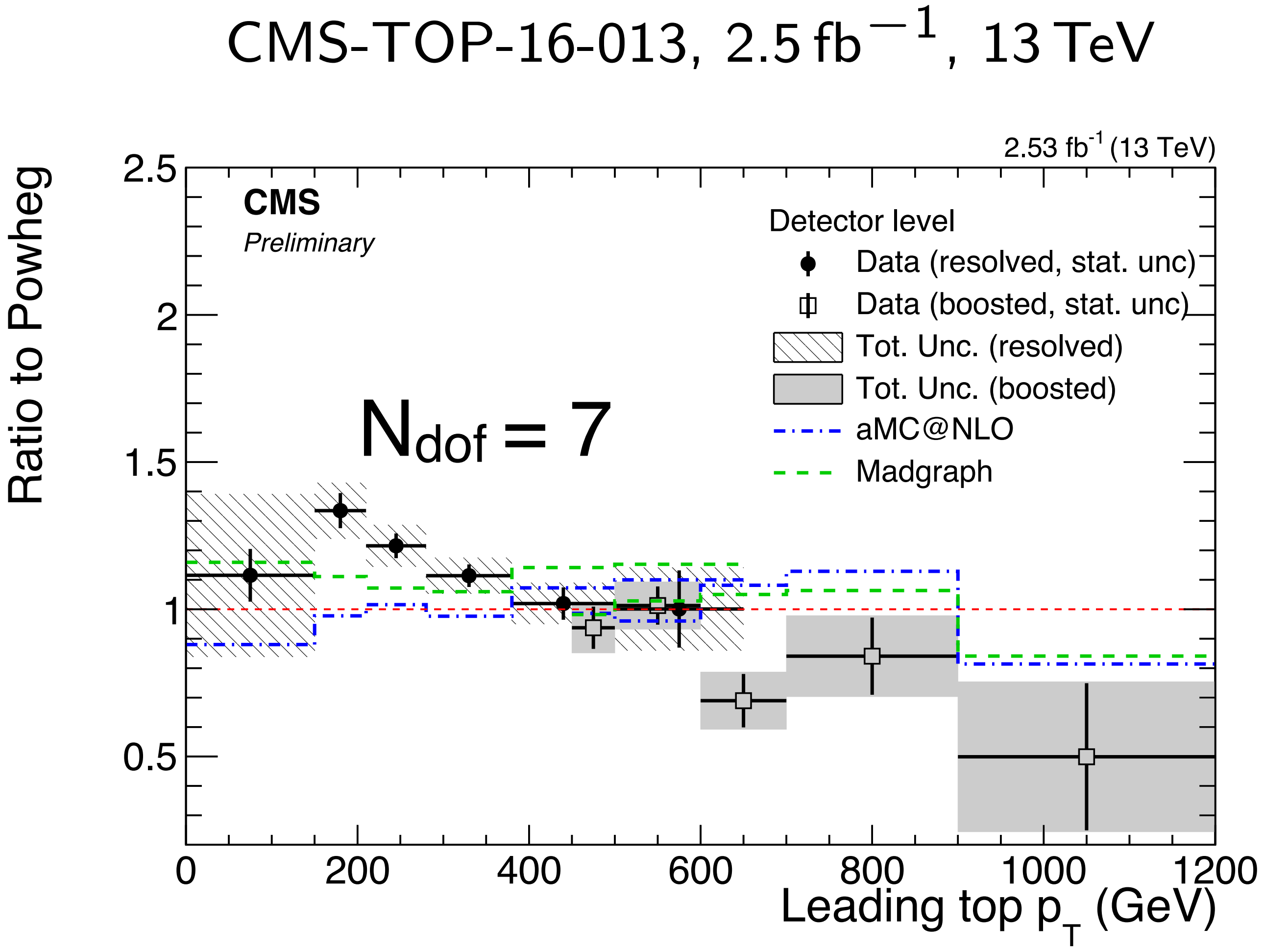
- **Tension with most NLO+PS predictions: slope w.r.t measurement.**
- **Less tension than in “resolved”, larger statistical uncertainties**

Extreme test of SM: the top p_T “saga” *@13TeV*

Particle level vs NLO+PS

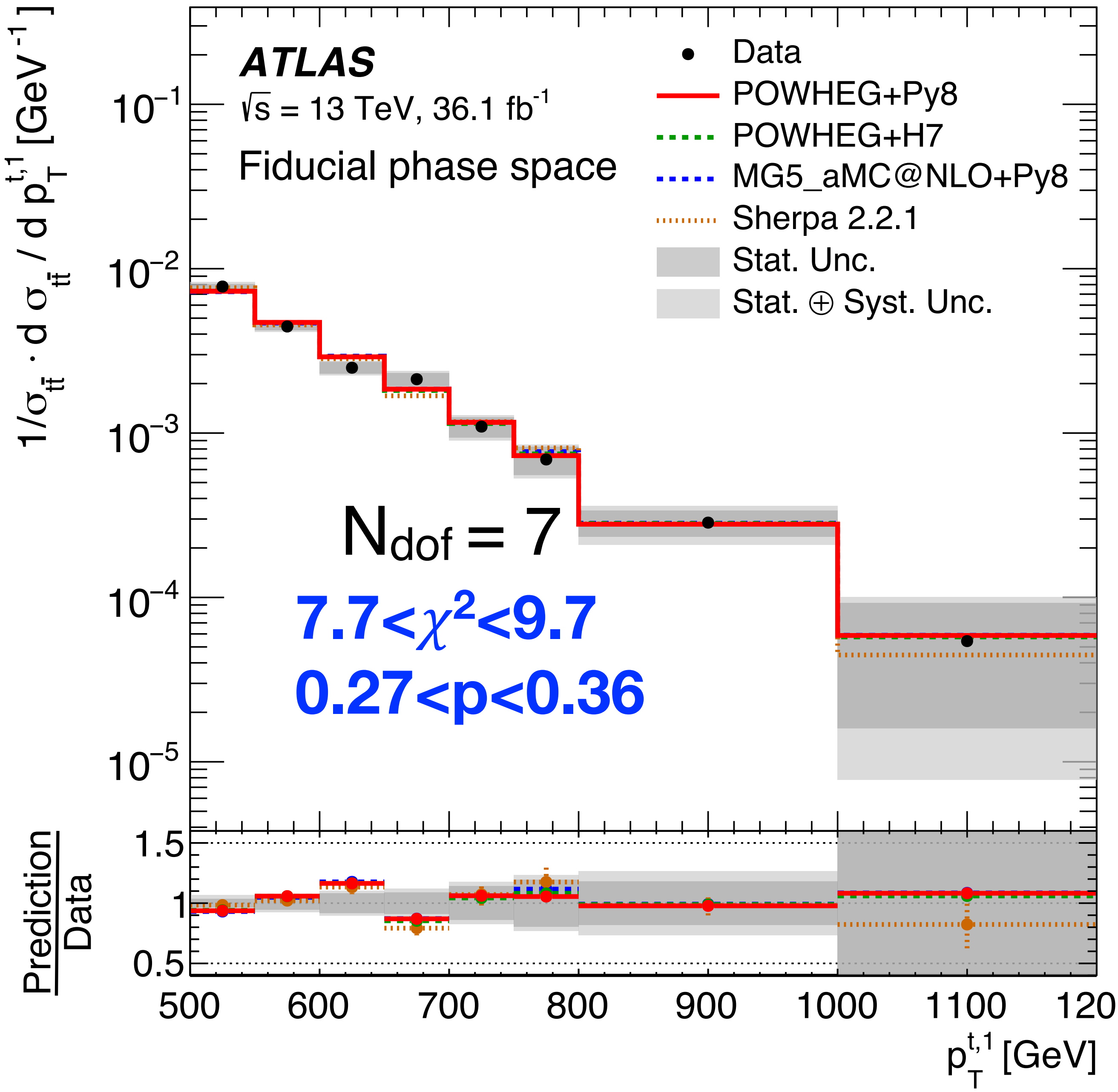
$p_{T,lead\ top}$

Reco level



$N_{dof} = 7$

Particle level vs NLO+PS



$N_{dof} = 7$

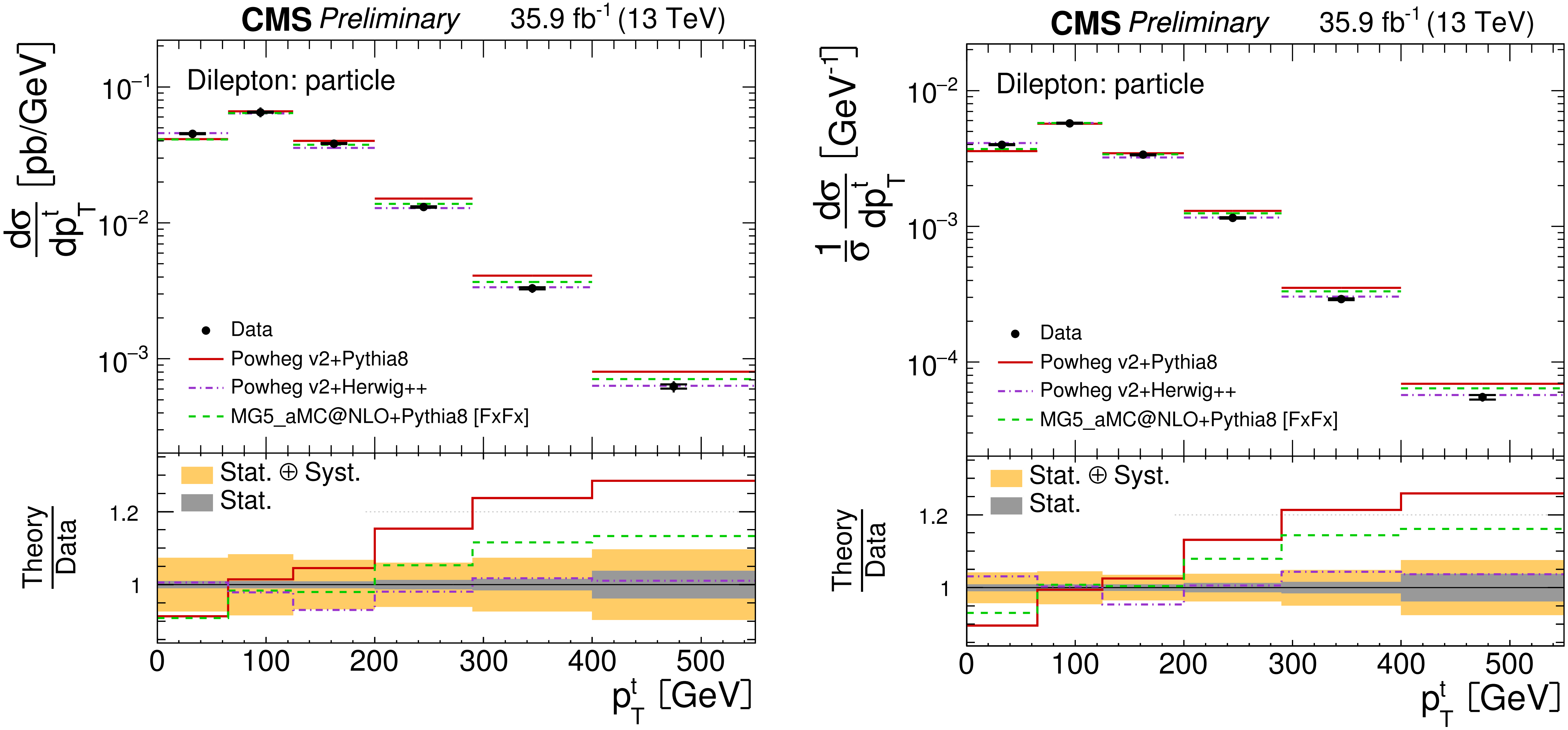
$7.7 < \chi^2 < 9.7$

$0.27 < p < 0.36$

- **Measurements agree with predictions**

The Top p_T saga: dilepton NLO+PS @13 TeV

CMS-PAS-TOP-17-014



N_{dof} =5 o 6	normalised		absolute	
NLO+PS	χ^2	p-val	χ^2	p-val
PW+PY8	**128**	**$<10^{-3}$**	**52**	**$<10^{-3}$**
PW+H++	**6**	**0.306**	**3**	**0.830**
MG5+PY8	**45**	**$<10^{-3}$**	**17**	**0.008**

no theory uncertainties included

O, HIndrichs

CMS-TOP-16-013, 2.5 fb^{-1}, 13 TeV

ALL HADRONIC CMS @ 13 TeV (still preliminary)

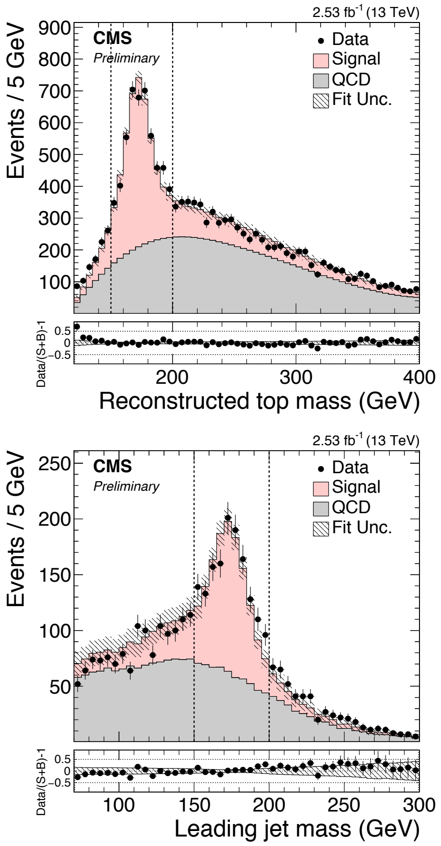
In all-jets final state

Resolved

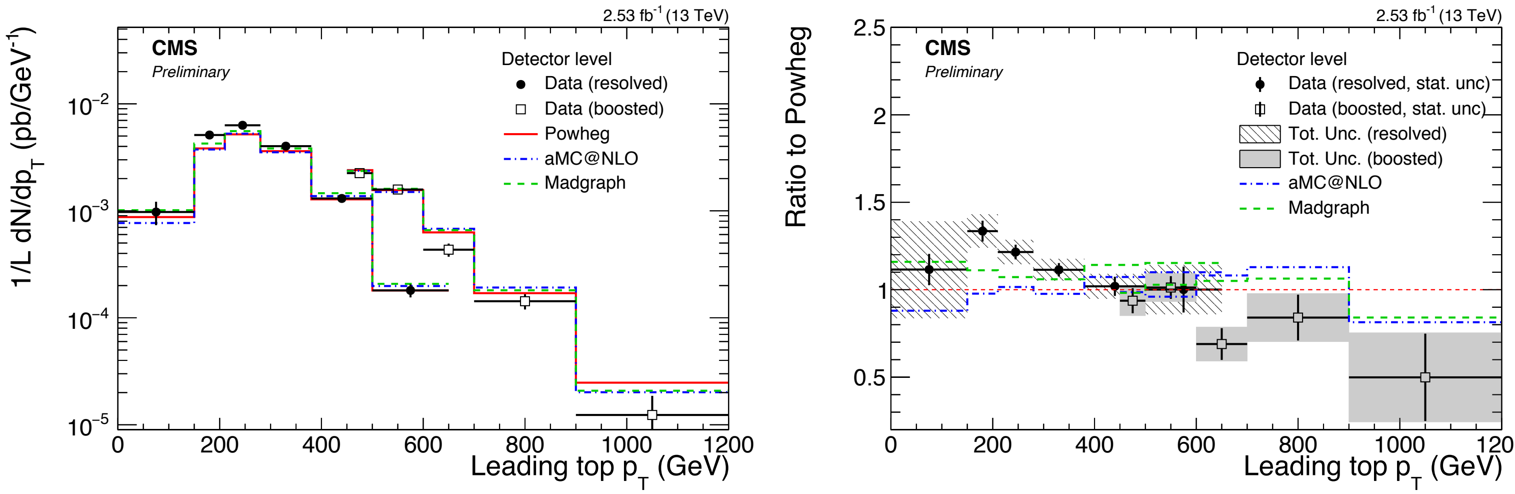
- Selection: at least 6 jets, 2 b tagged.
- Perform kinematic fit for $\mathrm{t\bar{t}}$ reconstruction (based on W and top mass constrains)
- Accept events with $150 < m_{\mathrm{t}}^{\mathrm{fit}} < 200$ GeV, and fit probability greater than 0.02.

Boosted

- 1 jet $p_{\mathrm{T}} > 200$ GeV and 1 jet $p_{\mathrm{T}} > 450$ GeV
- each jet: softdrop mass > 50 GeV, b tagged subjet, n-jettiness requirements.



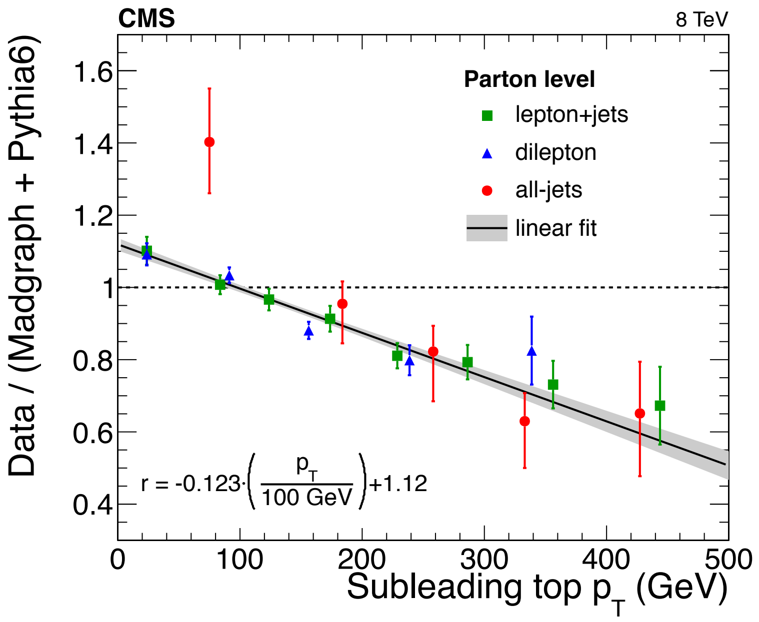
Template Fit: Signal template from MC, background template from data by inverting b tagging.

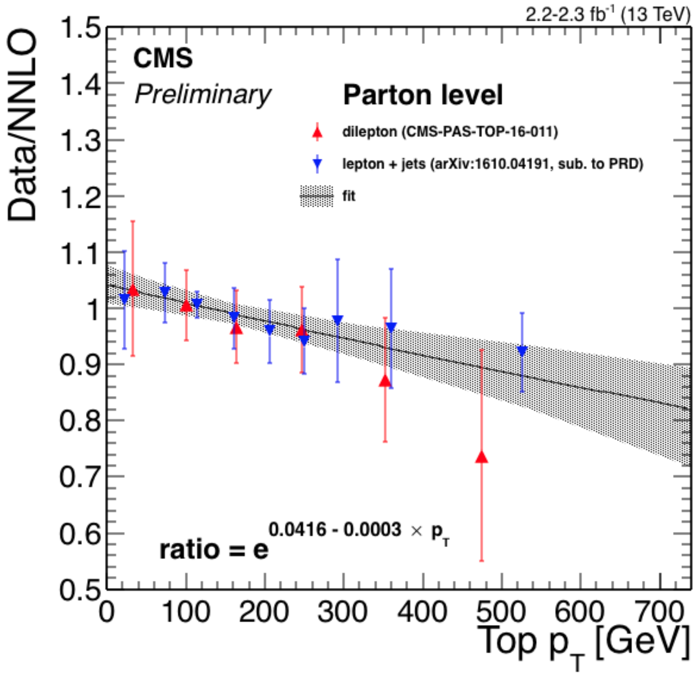


Soft $p_{\mathrm{T}}(\mathrm{t})$ confirmed in all-jets channel and persisting in boosted regime.

Summary differential cross sections

- Measurements at 7, 8, and 13 TeV in various $\mathrm{t\bar{t}}$ decay channels.
- $p_{\mathrm{T}}(\mathrm{t})$ observed softer, but compatible with standard model within uncertainties in measurement and theory.
- Persistent in boosted regime $p_{\mathrm{T}}(\mathrm{t}) > 400\,\mathrm{GeV}$.



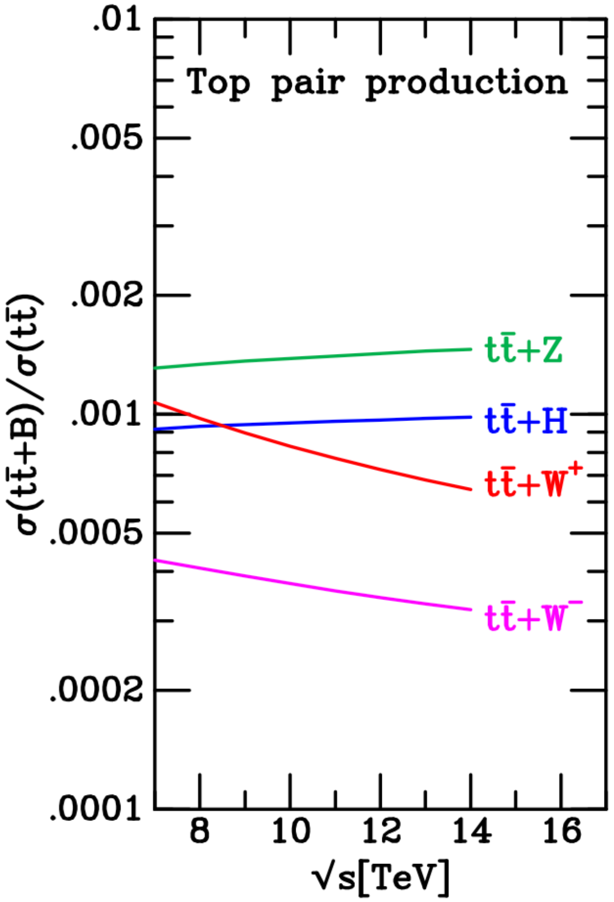


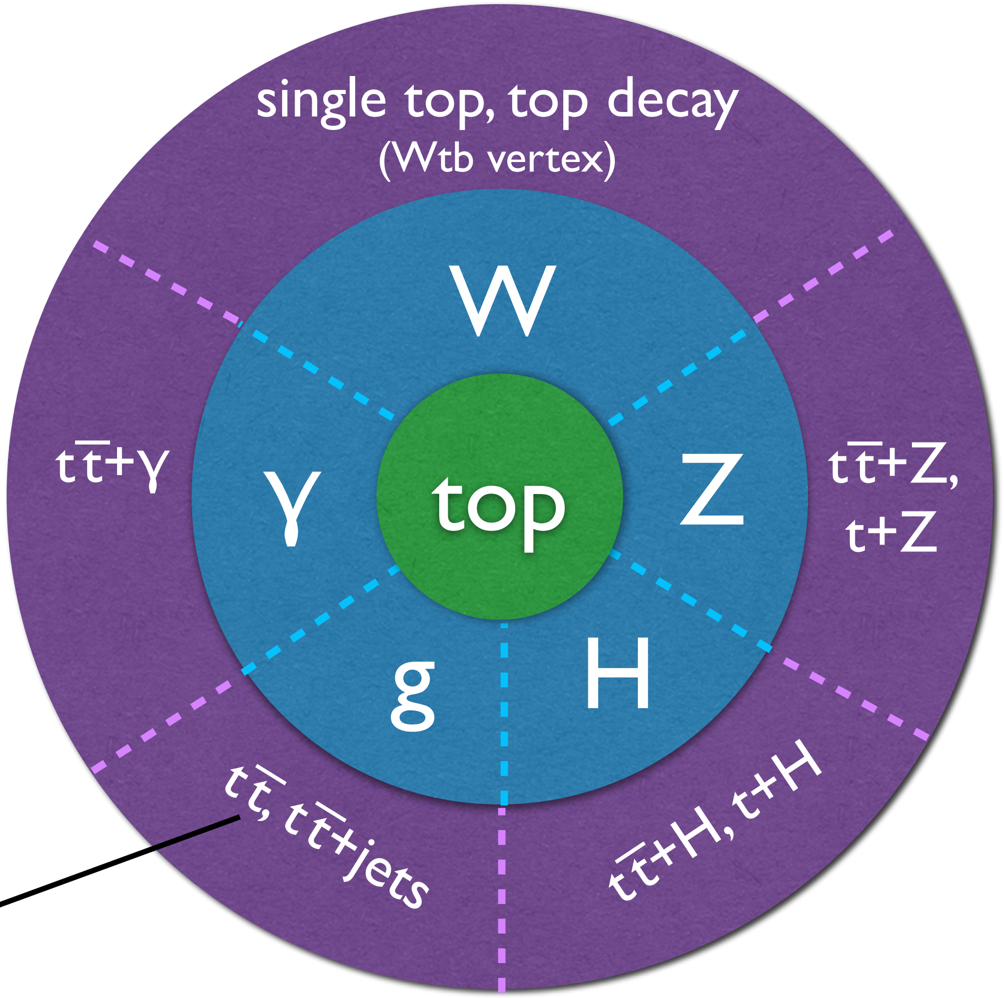
top pair associated production

Motivation

- The top quark couples to other SM fields through its **gauge** and **Yukawa interactions**
- t→Wb coupling measured already at the Tevatron

High statistics top physics at the LHC: $t\bar{t}$ + bosons (γ, Z and H) becomes accessible!
First evidence on the coupling of the top quark to these particles from **production rate**
Important Standard Model test: **new physics** modifies the structure of the EW couplings



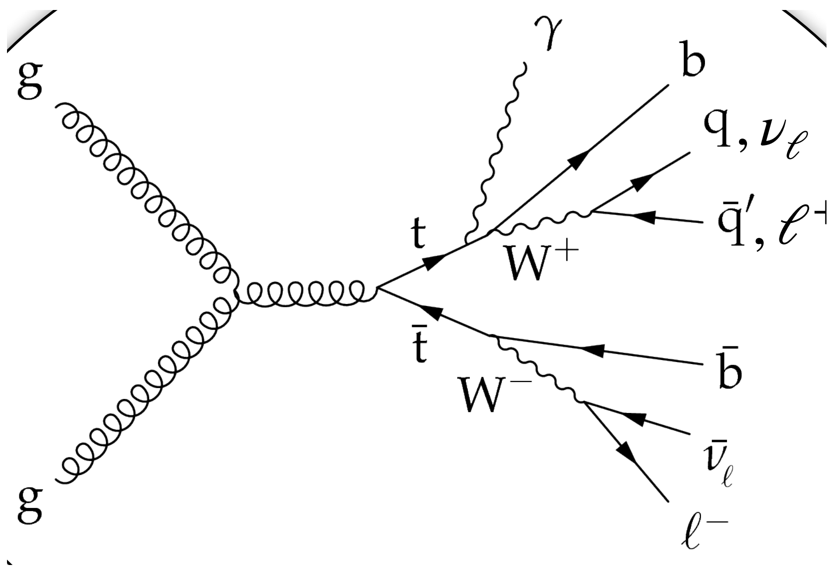


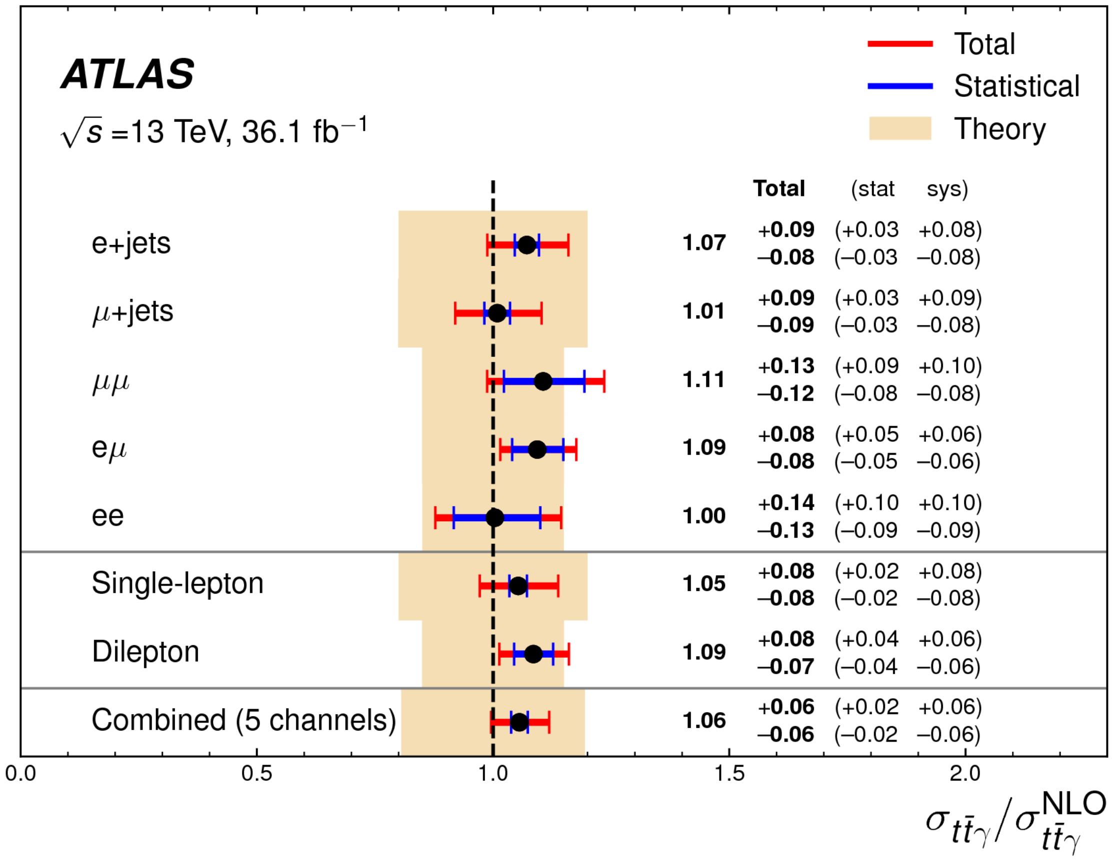
[T. Vazquez Schroder @ Top2014](#)

see inclusive top cross section
& dσ/dX with jets
(Lecture 5)

Top + X coupling, how to measure it?

tt+photon: latest ATLAS





		Total	(stat	sys)
e+jets	1.07	+0.09 −0.08	(+0.03 (−0.03	+0.08) −0.08)
μ+jets	1.01	+0.09 −0.09	(+0.03 (−0.03	+0.09) −0.08)
$\mu\mu$	1.11	+0.13 −0.12	(+0.09 (−0.08	+0.10) −0.08)
eμ	1.09	+0.08 −0.08	(+0.05 (−0.05	+0.06) −0.06)
ee	1.00	+0.14 −0.13	(+0.10 (−0.09	+0.10) −0.09)
Single-lepton	1.05	+0.08 −0.08	(+0.02 (−0.02	+0.08) −0.08)
Dilepton	1.09	+0.08 −0.07	(+0.04 (−0.04	+0.06) −0.06)
Combined (5 channels)	1.06	+0.06 −0.06	(+0.02 (−0.02	+0.06) −0.06)

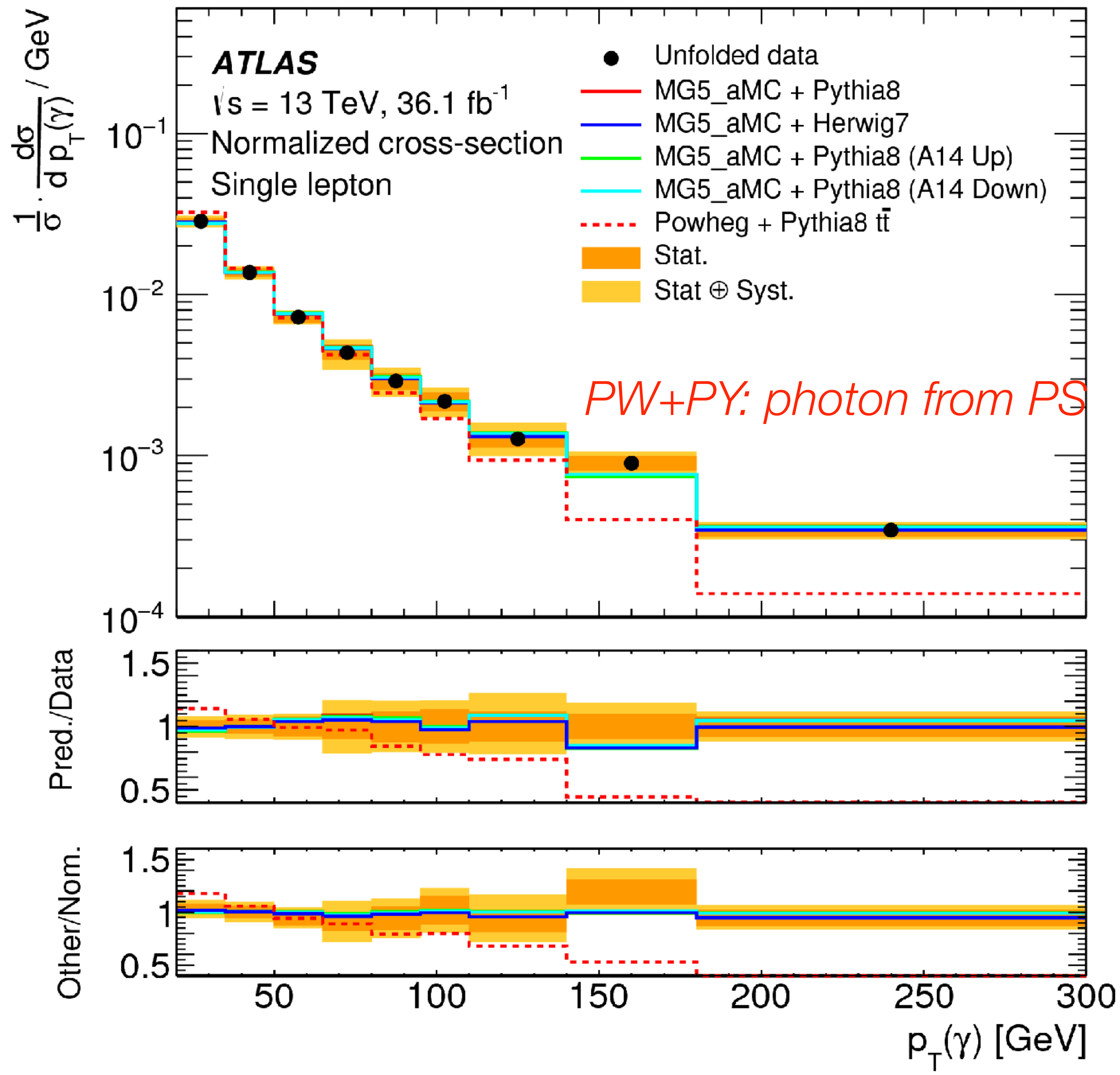
Eur. Phys. J. C 79 (2019) 382

$$\sigma^{SL}_{fid.} = 521 \ \pm \ 9 \text{ (stat.)} \ \pm \ 41 \text{ (syst.) fb}$$

in agreement with NLO prediction: $\sigma^{pred}_{fid.} = 495 \ \pm \ 99$ fb

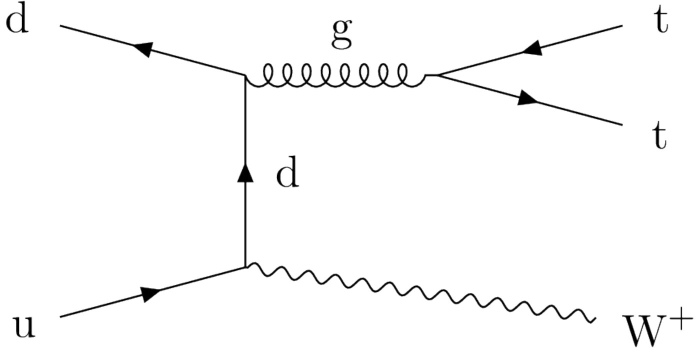
$$\sigma^{DL}_{fid.} = 69 \ \pm \ 3 \text{ (stat.)} \ \pm \ 4 \text{ (syst.) fb}$$

in agreement with NLO prediction: $\sigma^{pred}_{fid.} = 63 \ \pm \ 9$ fb

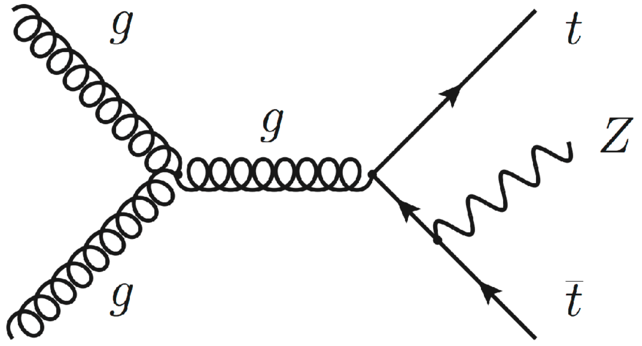


PW+PY: photon from PS

tt+W/Z



multi-lepton (2ℓ,3ℓ,4ℓ)



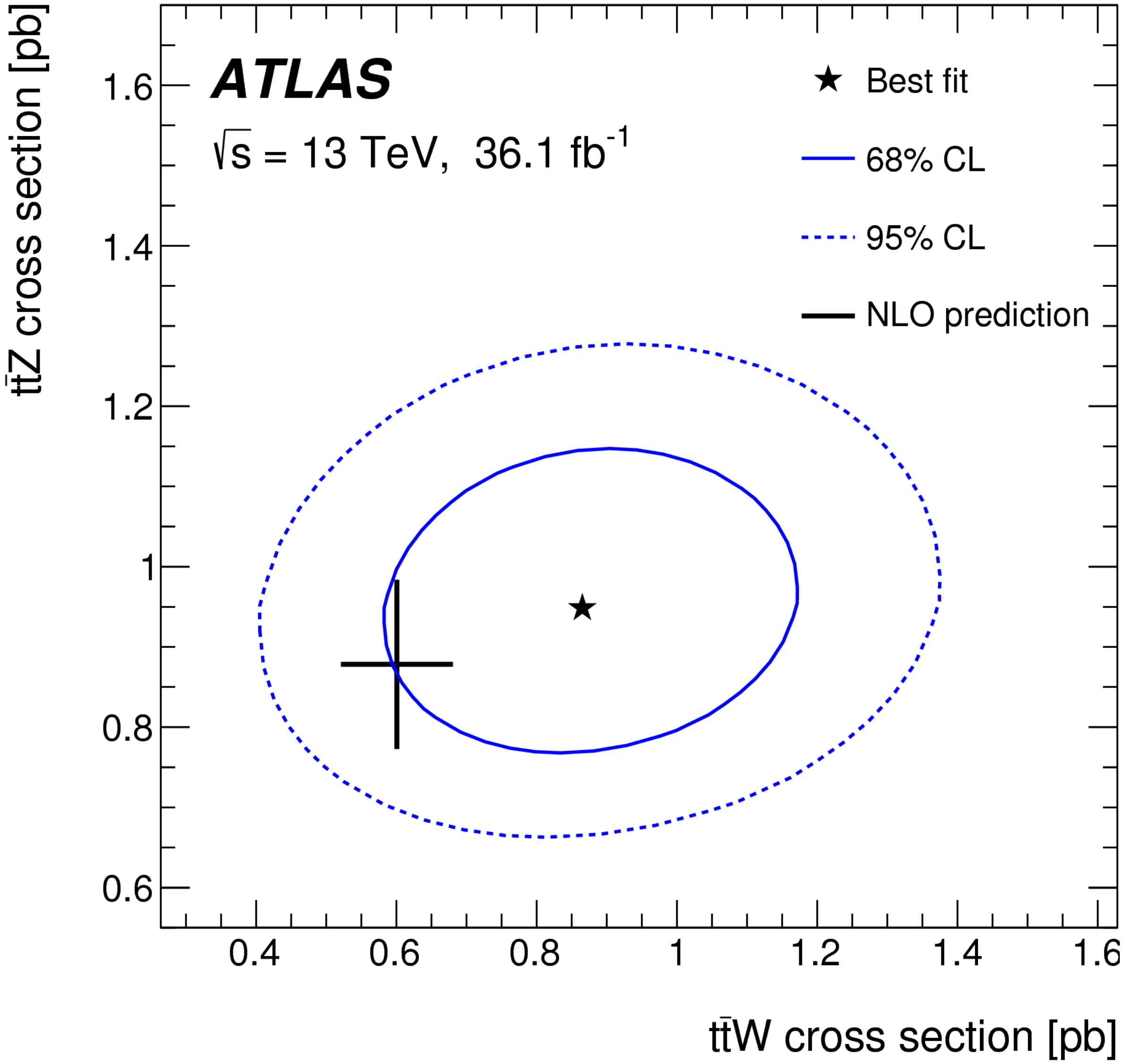
ATLAS (36/fb)

$$\sigma_{t\bar{t}Z} = 0.95 \ \pm 0.08 \text{ (stat.)} \ \pm 0.10 \text{ (syst.) pb}$$
$$\sigma_{t\bar{t}W} = 0.87 \ \pm 0.13 \text{ (stat.)} \ \pm 0.14 \text{ (syst.) pb}$$

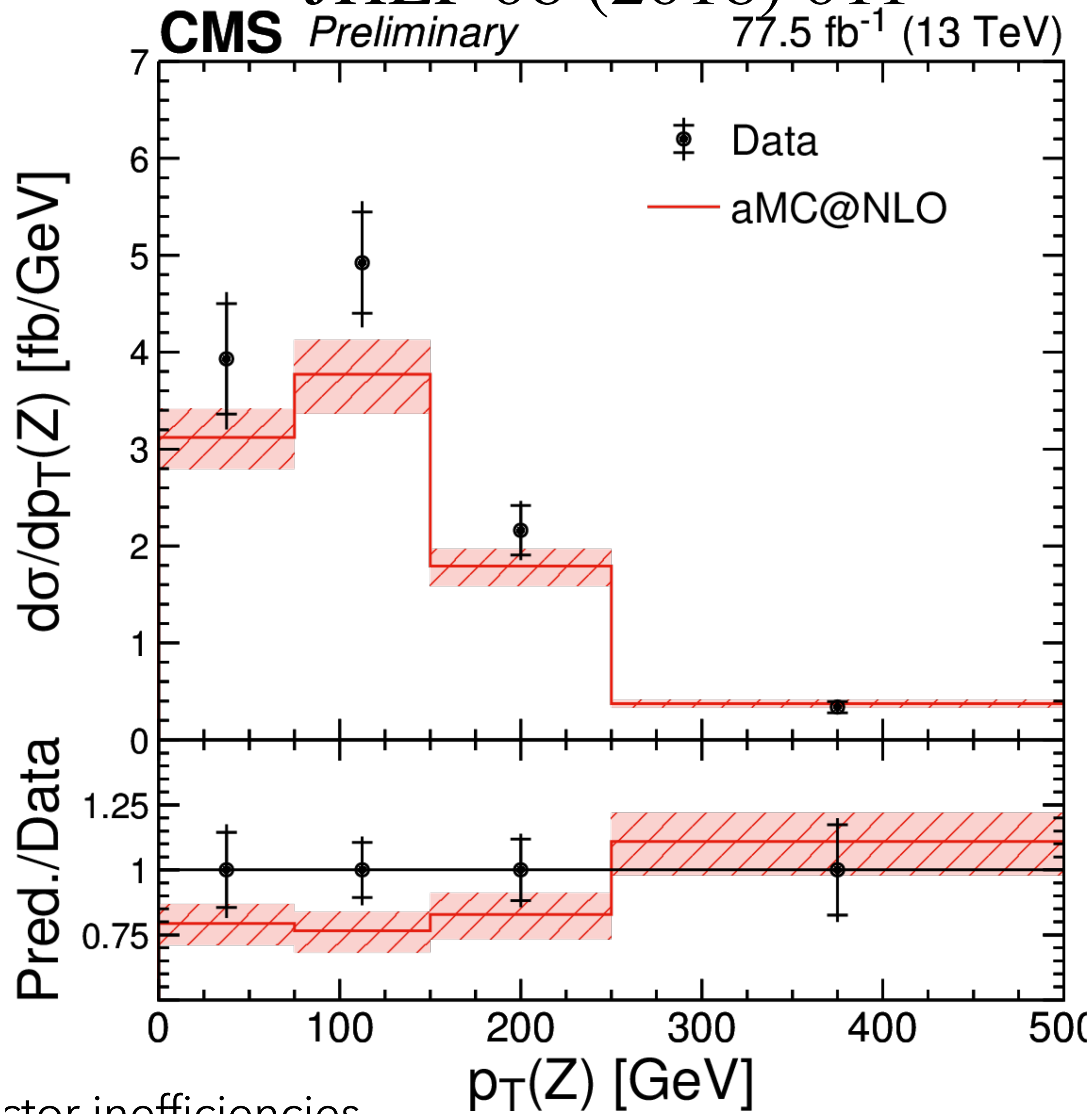
CMS (75/fb)

$$\sigma_{t\bar{t}W} = 0.77 \ ^{+0.12}_{-0.11} \text{ (stat.)} \ ^{+0.13}_{-0.12} \text{ (syst.) pb}$$
$$\sigma_{t\bar{t}Z} = 0.99 \ ^{+0.09}_{-0.08} \text{ (stat.)} \ ^{+0.12}_{-0.10} \text{ (syst.) pb}$$

Phys. Rev. D 99 (2019) 072009



JHEP 08 (2018) 011



ctor inefficiencies

tt+W

ATLAS (36/fb)

Phys. Rev. D 99 (2019) 072009

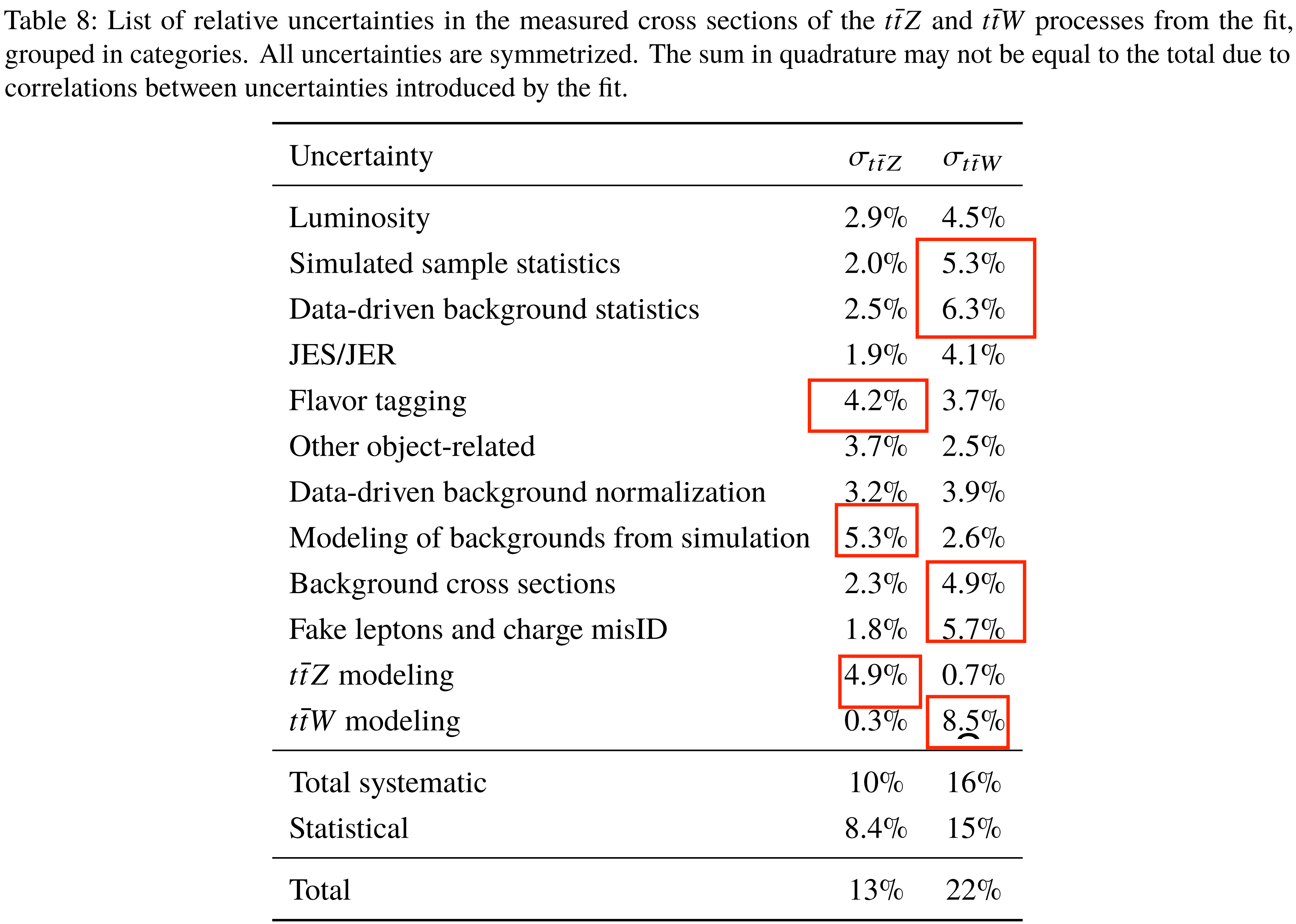


Table 8: List of relative uncertainties in the measured cross sections of the $t\bar{t}Z$ and $t\bar{t}W$ processes from the fit, grouped in categories. All uncertainties are symmetrized. The sum in quadrature may not be equal to the total due to correlations between uncertainties introduced by the fit.

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

Top Properties : Spin correlations

Standard reasons:Top quark (*t*) properties

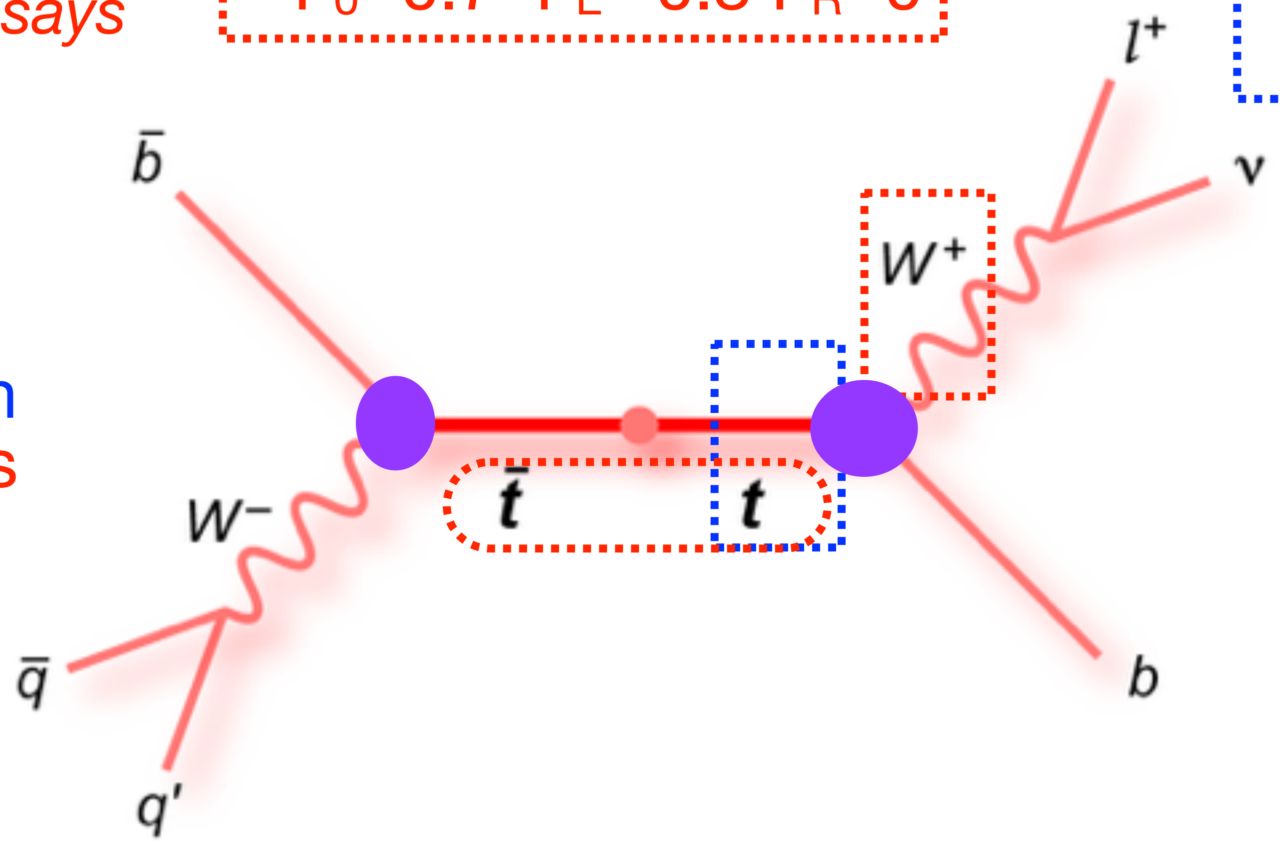
top quark decays before its spin flips → Spin information is passed to decay products

undiluted by hadronization→angles of $t\bar{t}$ decay products are correlated

- W helicity in Wtb vertex? SM says $F_0\sim0.7$ $F_L\sim0.3$ $F_R\sim0$

- *is top polarised in single top production? SM says YES*

- is top quark unpolarised in pp→ $t\bar{t}$ production? SM says yes



- are t and anti-t angular distribution different ? SM says yes @NLO

- Are $t\bar{t}$ spins correlated in pp → $t\bar{t}$ production? SM says YES

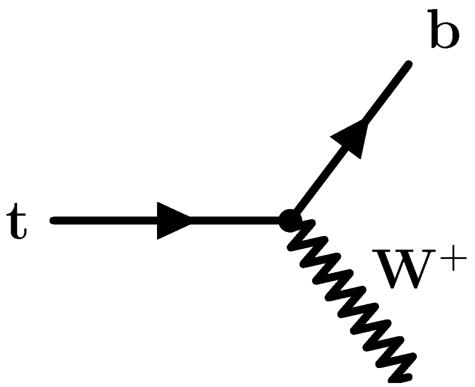
- is CP violation visible in b-decay from $t\bar{t}$? SM says yes at $<10^{-2}$

- Wtb vertex ? SM says V-A: i.e. **spin density matrix** as foreseen in combination of $t\bar{t}$ production and decay?

All angular properties are found to be consistent with SM

The spin of the top quark

see Liss,Maltoni,Quadt,
PDG Review, 2016



$1/m_t$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2

Production time < Lifetime < Hadronization time < Spin decorrelation time

Spin for

individual top quark

- chiral coupling in SM Wtb vertex enhances specifically polarized W-boson and b-quark

top quark pairs

- in qq/gg tt interaction at pp collider
  - top and anti-top quarks are ~unpolarised (as the initial g and q)
  - the spins of t and t are correlated

single top

- **Angular distribution of top quark decay products** follows the predictions of the top quark spin *(differently from b quark in which B meson decays isotropically)*
- Top quark polarization and (and consequently its spin) is directly observable by such angular distributions

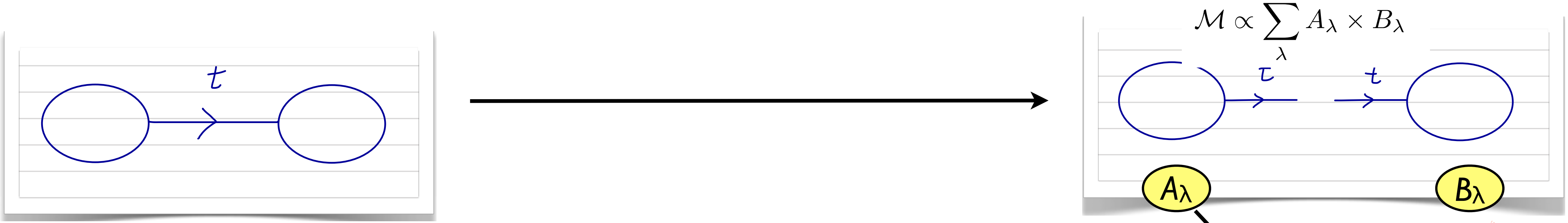
- **Observation of the top quark spin is strongly linked to its production and decay process**

The spin of the top quark in pp → tt

B Lemmer, arXiv 1410.1791 J A Saavedra @ Top2014

- Top is narrow resonance: $\Gamma_t/m_t \ll 1$ → the $q\bar q$/gg $t\bar t$ production amplitude is factorizable in decay and production in the leading pole approx

$$\mathcal{M} \propto \sum_\lambda A_\lambda \times B_\lambda$$



$$\left(\frac{1}{3^2 \text{ or } 8^2}\sum_{\text{colours}}\right)\left(\frac{1}{2^2}\sum_{\text{spins}}\right)\left|\mathcal{M}(\,q\bar q/gg \to t\bar t \to (f_1\bar f_1' b)\,(\bar f_2 f_2'\bar b)\,)\right|^2 = \lambda_{ab}\,\rho_{ab,\bar a\bar b}\,\bar\lambda_{\bar a\bar b}$$

a,b: top /anti-top quark spins, f : decay products ⟨O⟩ = tr[ρO]

$\rho_{ab,\bar a\bar b}$ Hermitian **production spin density matrix** → **if spin$_{top}$ =1/2 ,Pauli matrices are a basis**

$$\rho_{ab,\bar a\bar b} \equiv \frac{1}{4}M^{00}\left(\delta_{ab}\,\delta_{\bar a\bar b} + P^i\,\sigma^i_{ab}\,\delta_{\bar a\bar b} + \bar P^{\bar i}\,\delta_{ab}\,\sigma^{\bar i}_{\bar a\bar b} + \widehat{C}^{i\bar i}\,\sigma^i_{ab}\,\sigma^{\bar i}_{\bar a\bar b}\right)$$

$P_i = \langle 2S_i\rangle$ *top quark polarization* *S, top quark spin*

$\widehat{C}_{i\bar i} = \langle 4S_i\bar S_{\bar i}\rangle$ *top-anti-top spin correlation*

λ_{ab} is the decay spin density matrix; if integrated over all decay product phase space, but one

$$\tilde\lambda\,(\vec e)_{ab} \sim \delta_{ab} + \alpha_i\vec e_i\cdot\vec\sigma_{ab}$$

Including production and integrated decay density matrix in $|ME|^2$ gives

$$\frac{d\sigma}{d^2\vec e_i d\vec e_j} \sim 1 + \alpha_i\vec P\vec e_i + \alpha_j\vec{\bar P}\vec e_j + \alpha_i\alpha_j\vec e_i\widehat{C}\vec e_j$$

The spin of the top quark in pp collisions

B Lemmer, arXiv 1410.1791 *J A Saavedra @ Top2014*

- Going from generalized quantities to observable quantities requires the **choice of the spin quantization axis :** define spin axis as z direction an use associated polar coordinates

in tt production

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_i d\cos\theta_j} = \frac{1}{4}\left(1 + \underset{\text{top quark polarisation}}{\alpha_i B_1 \cos\theta_i} + \underset{\text{anti-top quark polarisation}}{\alpha_j B_2 \cos\theta_j} + \underset{\text{top-anti-top spin correlation}}{\alpha_i \alpha_j C \cos\theta_i \cos\theta_j}\right)$$

- **Degree of top quark polarization**
  - single top : strong polarization
  - $t\bar{t}$ production: B coefficents vanish at LO (pair invariance) : tt almost unpolarized

- **Degree of top quark pair spin correlations**: depends on choice of spin quantization axis

The ***Wtb*** vertex in ***tt̄*** prod & decay: full **spin density matrix**

JHEP12(2015)026

t & anti-t polarisation *tt̄ spin corr*

<|MatrixEl(tt)|²> ➡ $$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^a_+\,\mathrm{d}\cos\theta^b_-} = \frac{1}{4}(1 + B^a_+\cos\theta^a_+ + B^b_-\cos\theta^b_- - C(a,b)\cos\theta^a_+\cos\theta^b_-)$$

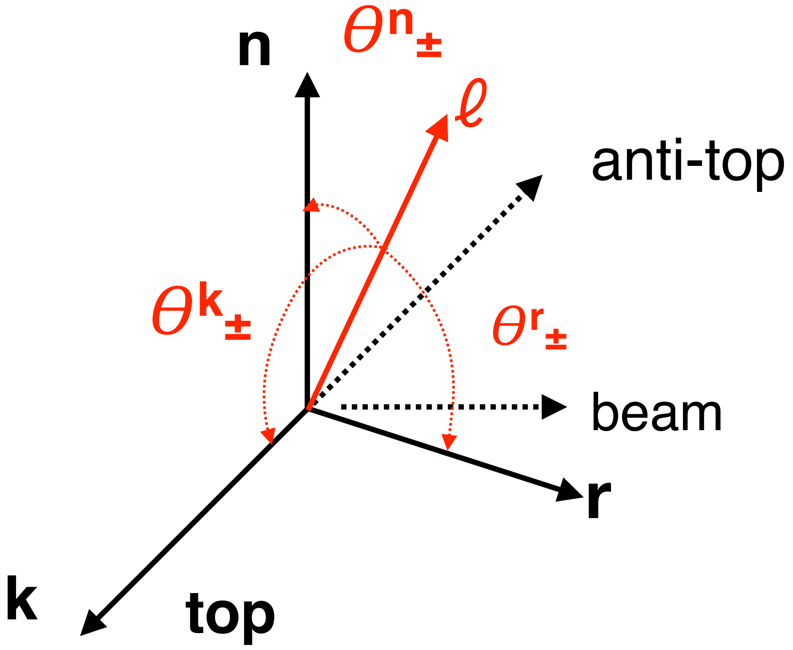
a,b={k,n,r} +=top decay -=anti-top decay

cos$\theta^{a,b}_{\pm}$: **6 angles:** **2 lepton directions** in top/anti-top parent rest frame w.r.t **3 spin quantization axes** (a or b) ➡

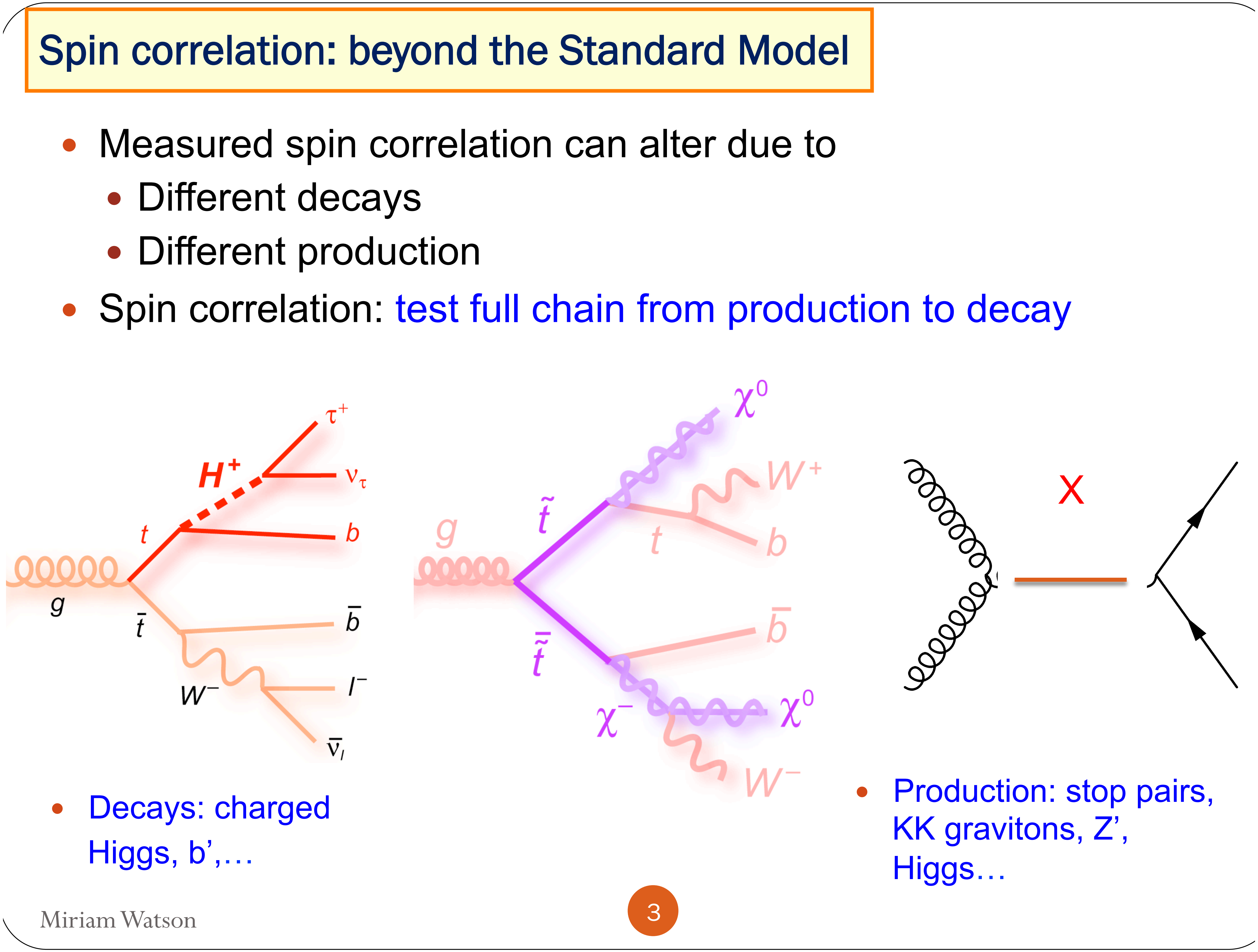
- **k**: top quark direction **in tt̄ rest frame**
- **n**: ⊥ to **k** & **laboratory beam direction**
- **r** : ⊥ to **k** and **n**

➡ 15 spin density matrix elements

dilepton events



- approximate CP symmetry of SM →
  - C (i,j) is symmetric
  - top and anti top quarks have same polarisation coefficients
- QCD invariant under P→ only P even and CP even coefficients are allowed



Spin correlation: beyond the Standard Model

- Measured spin correlation can alter due to
  - Different decays
  - Different production
- Spin correlation: test full chain from production to decay

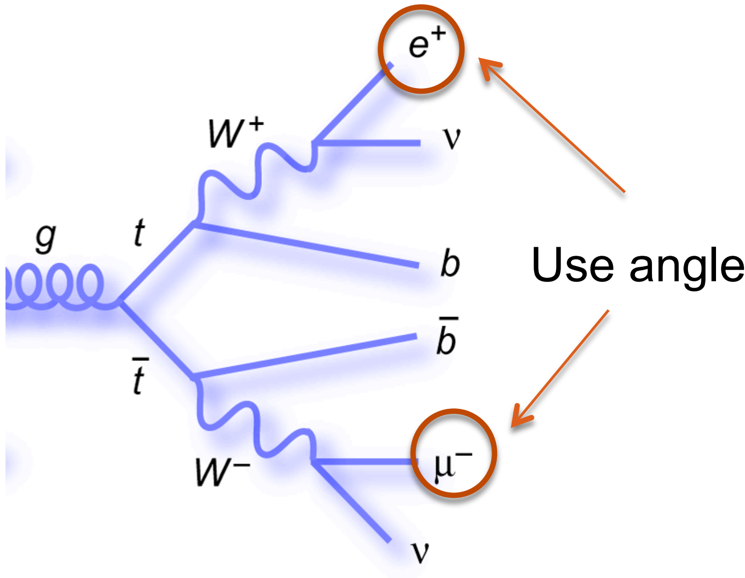
- Decays: charged Higgs, b',…

- Production: stop pairs, KK gravitons, Z', Higgs…

Miriam Watson

Spin density matrix elements are consistent with SM predictions

Spin correlation with Δφ $\sqrt{s}$=13TeV



Use angle

- Dilepton selection: ATLAS: **2 OS ℓ (eμ only), ≥ 1 b-jet,**
  - lepton has highest spin analysing power

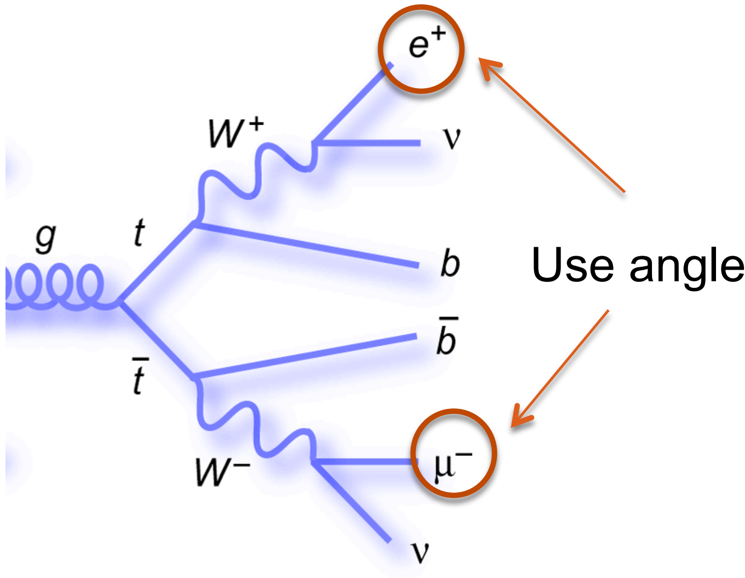
- Derive Δφ difference in azimuthal angle between leptons in lab frame
  - no event reco, use lepton reco and resol

- Reconstruct tt final state :
  - constrains by m_W and m_{top} ,
  - test different η assumptions for 2ν: select assumption highest weight based on E_T^{miss} expected resolution

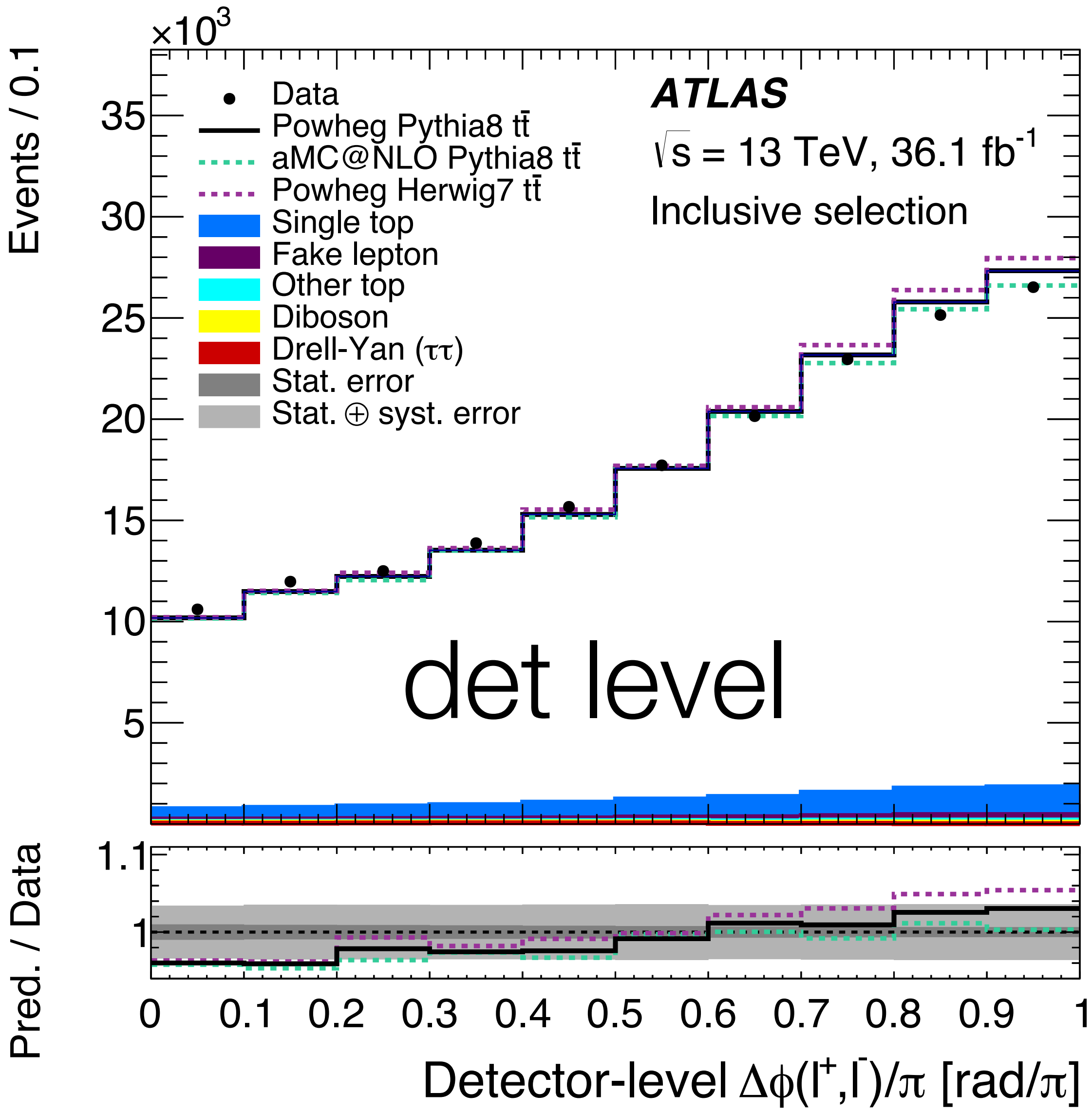
- Subtract bkg and unfold

Spin correlation with $\Delta\varphi$ $\sqrt{s}$=13TeV

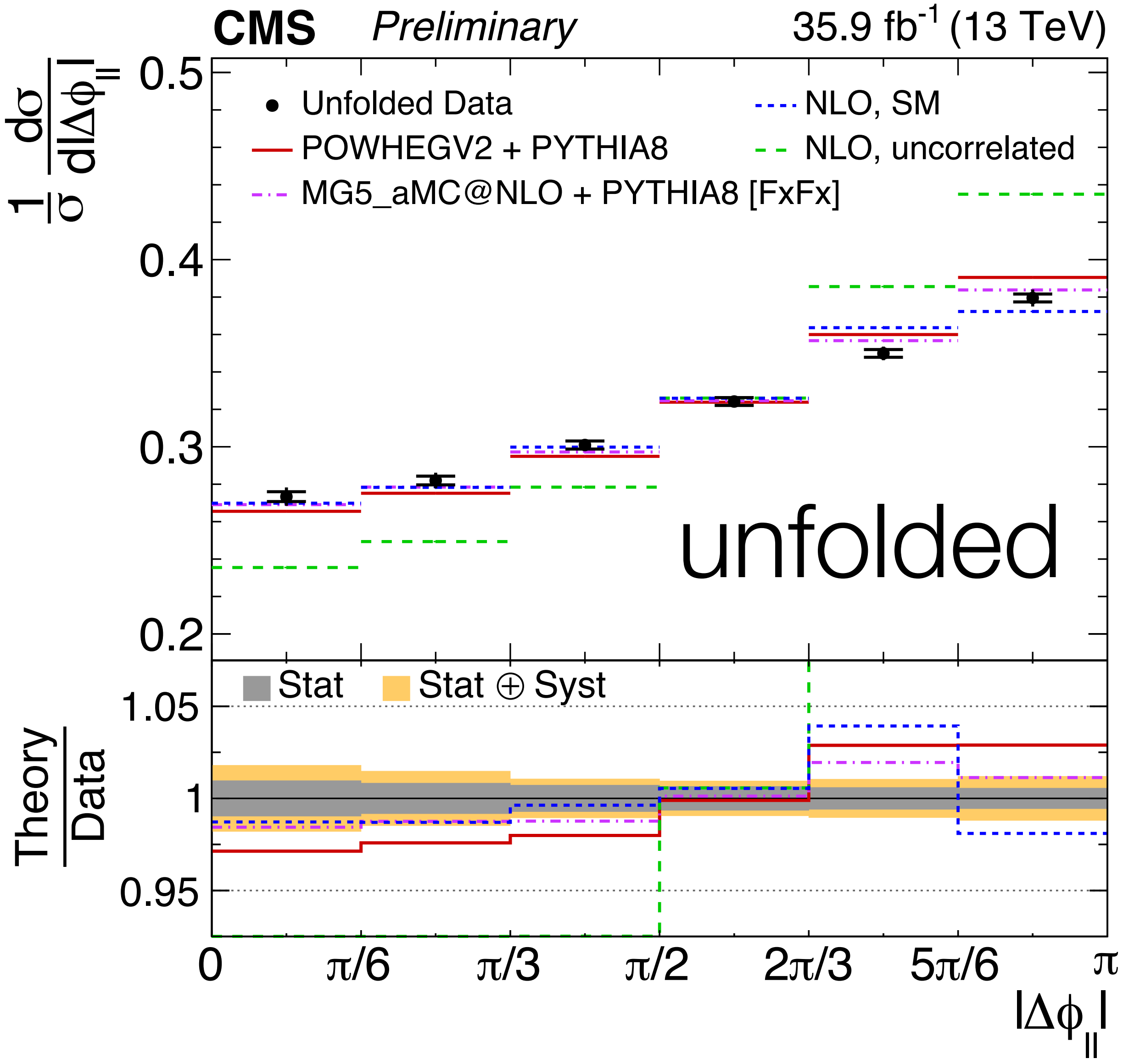
- Dilepton selection: ATLAS: **2 OS ℓ (eμ only), ≥ 1 b-jet,**
  - lepton has highest spin analysing power
- Derive $\Delta\varphi$ difference in azimuthal angle between leptons in lab frame
  - no event reco, use lepton reek and resol



Use angle



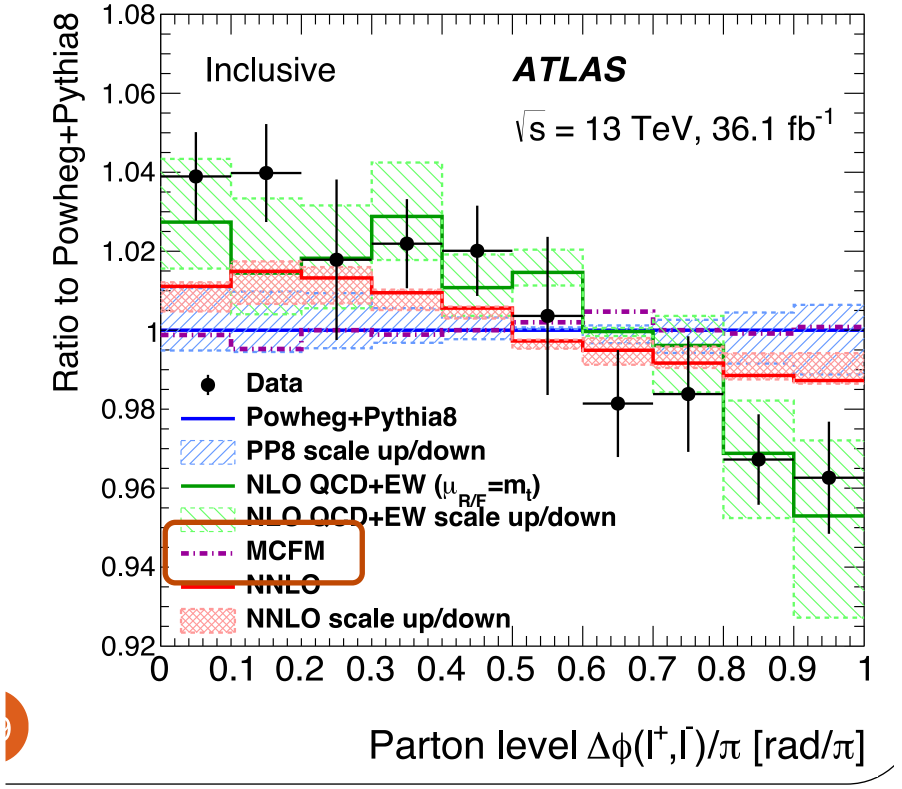
det level



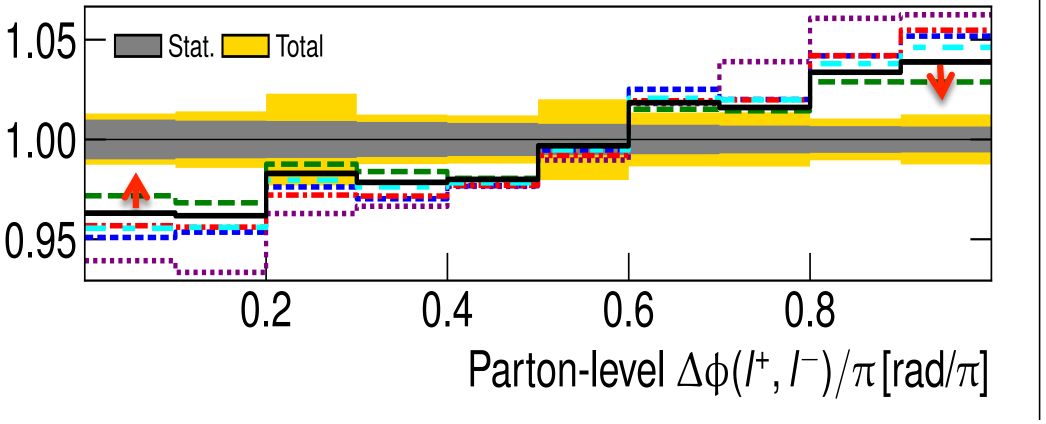
unfolded

ATLAS comparisons (I)

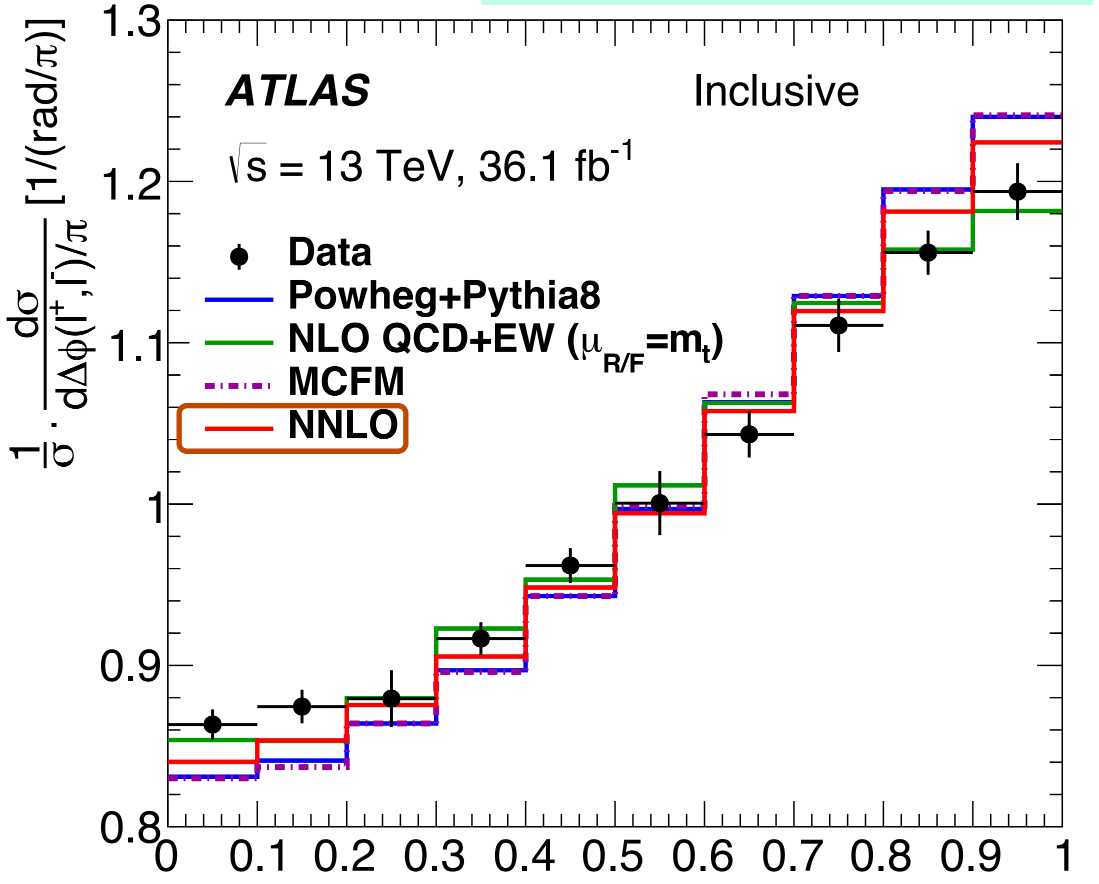
MCFM with NLO in decay



reweight top p_T to match NNLO

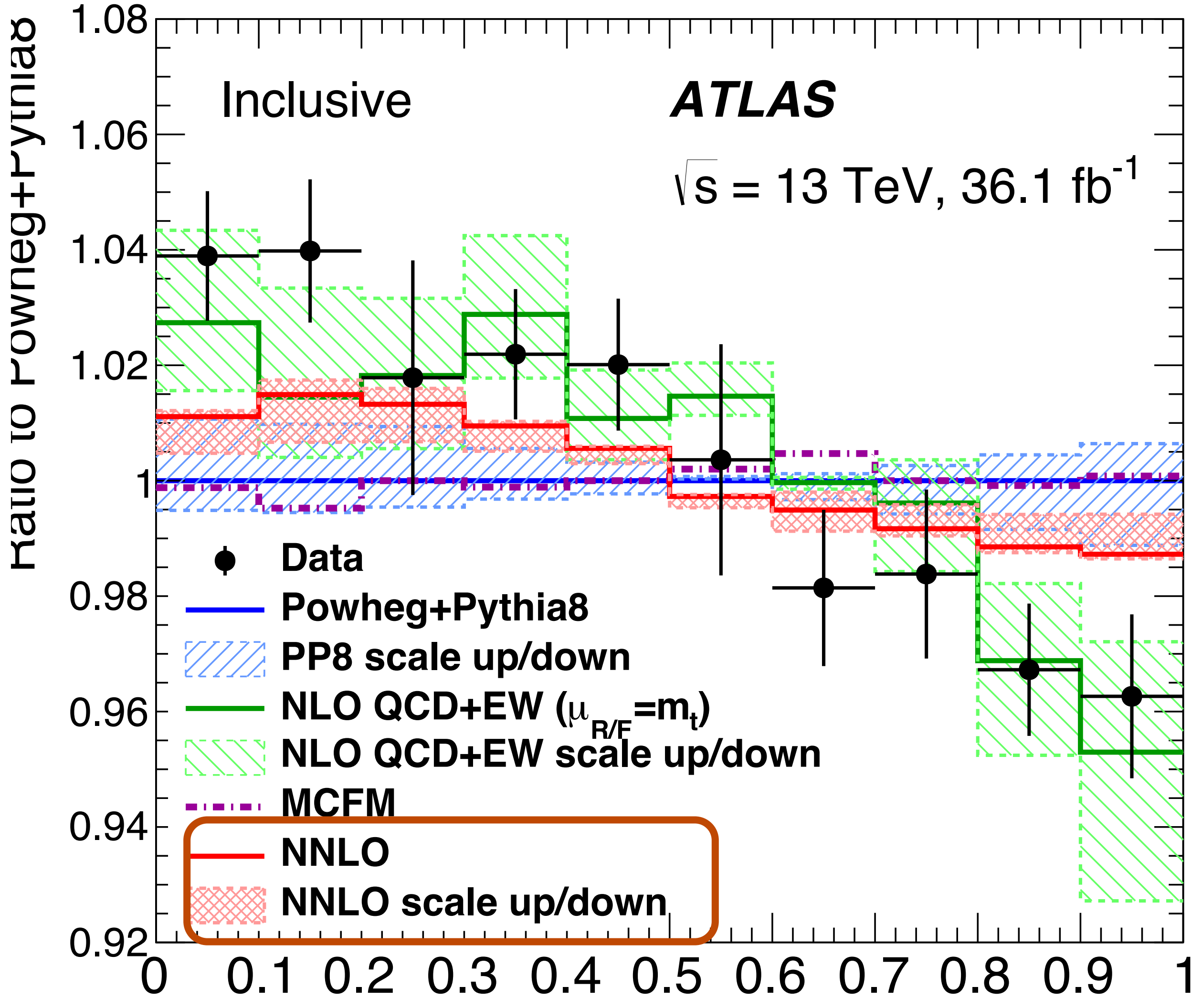


Add NNLO prediction

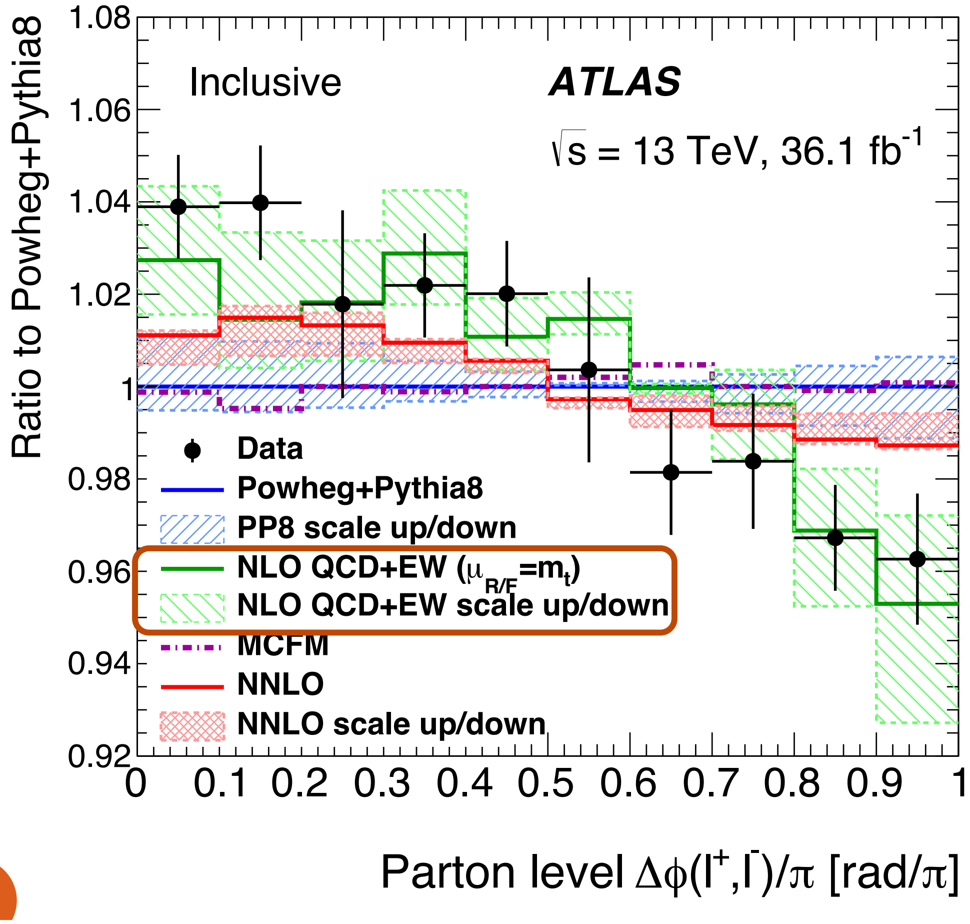


ATLAS comparisons (II)

NNLO inclusive



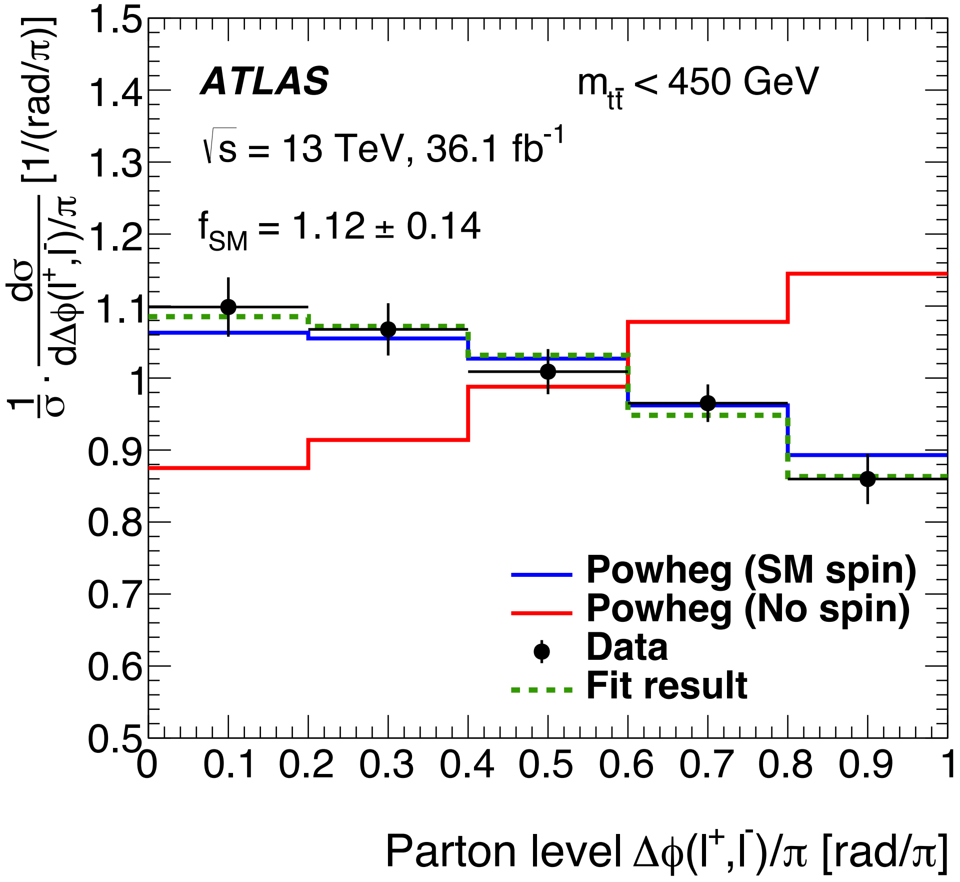
NLO+EWK corr

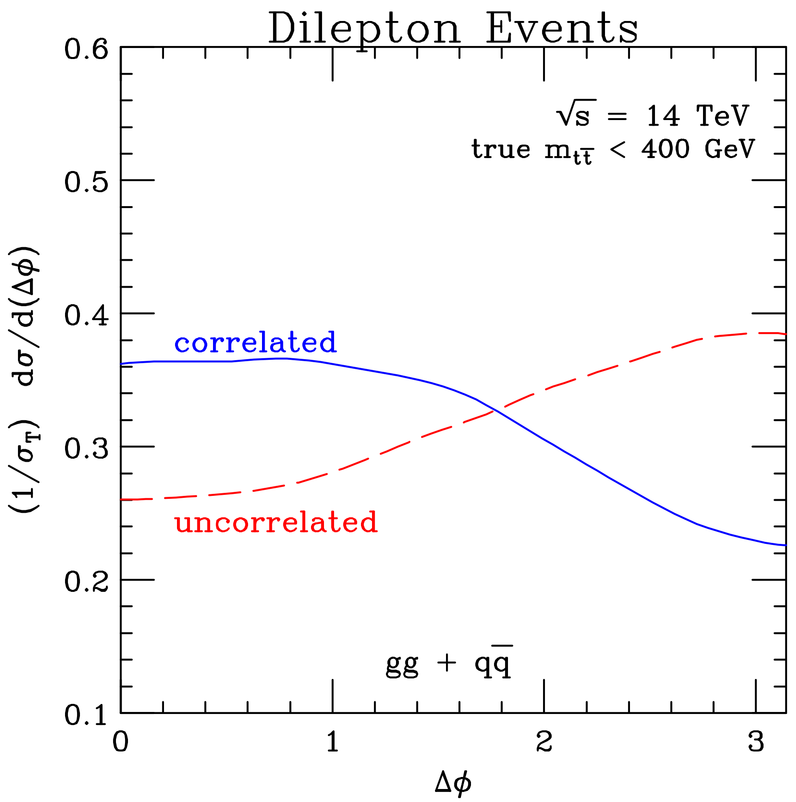


26

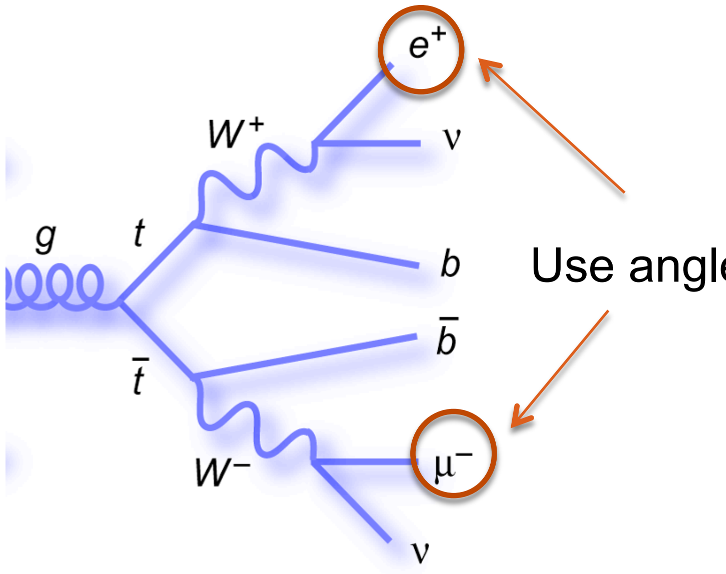
Spin correlation with $\Delta\varphi$

- spin correlation sensitivity to $\Delta\varphi$ is enhanced at low m_{tt}





Mahlon and Parke
Phys. Rev. D 81, 074024



Use angl

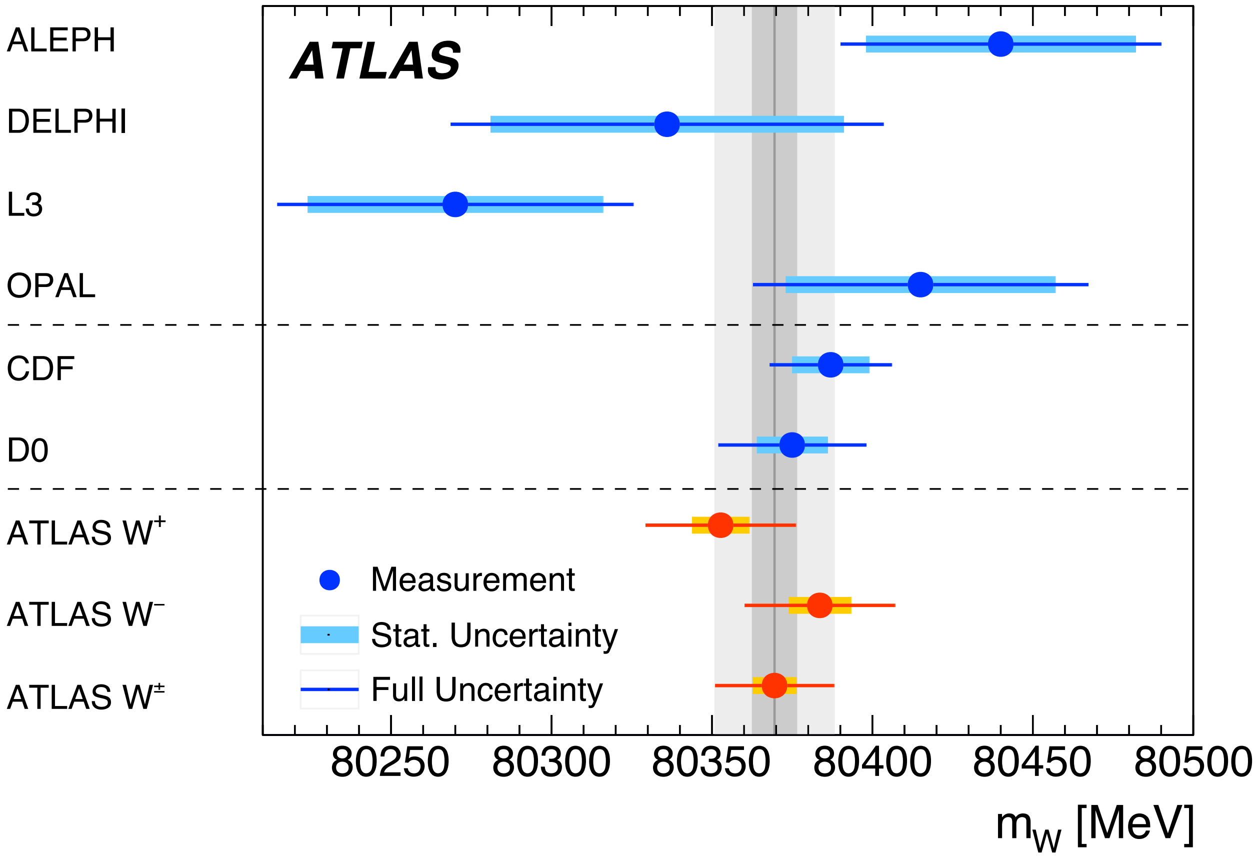
- Reconstruct tt final state : with constrains by mw and motion , test different eta assumptions for nus,select highest weight based on ETmiss expected resolution

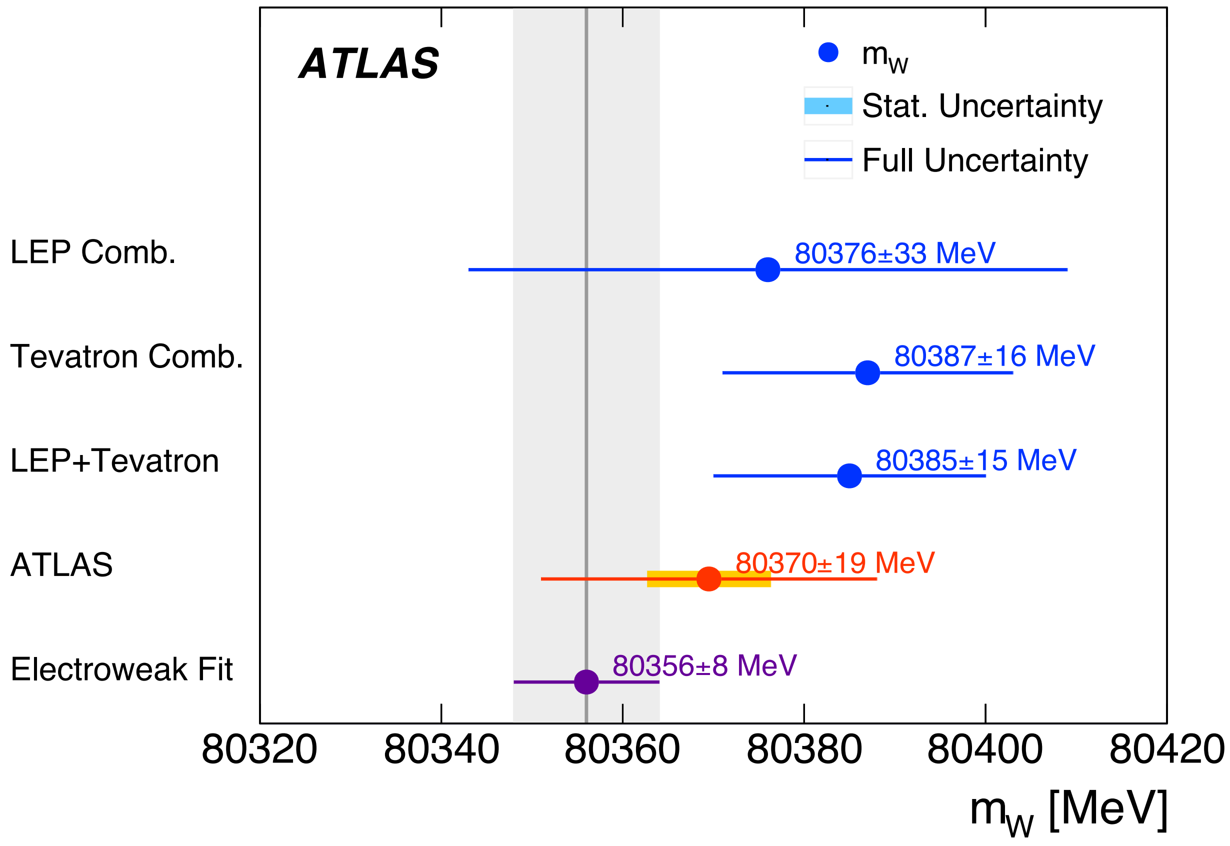
  - Subtract bkg and unfold

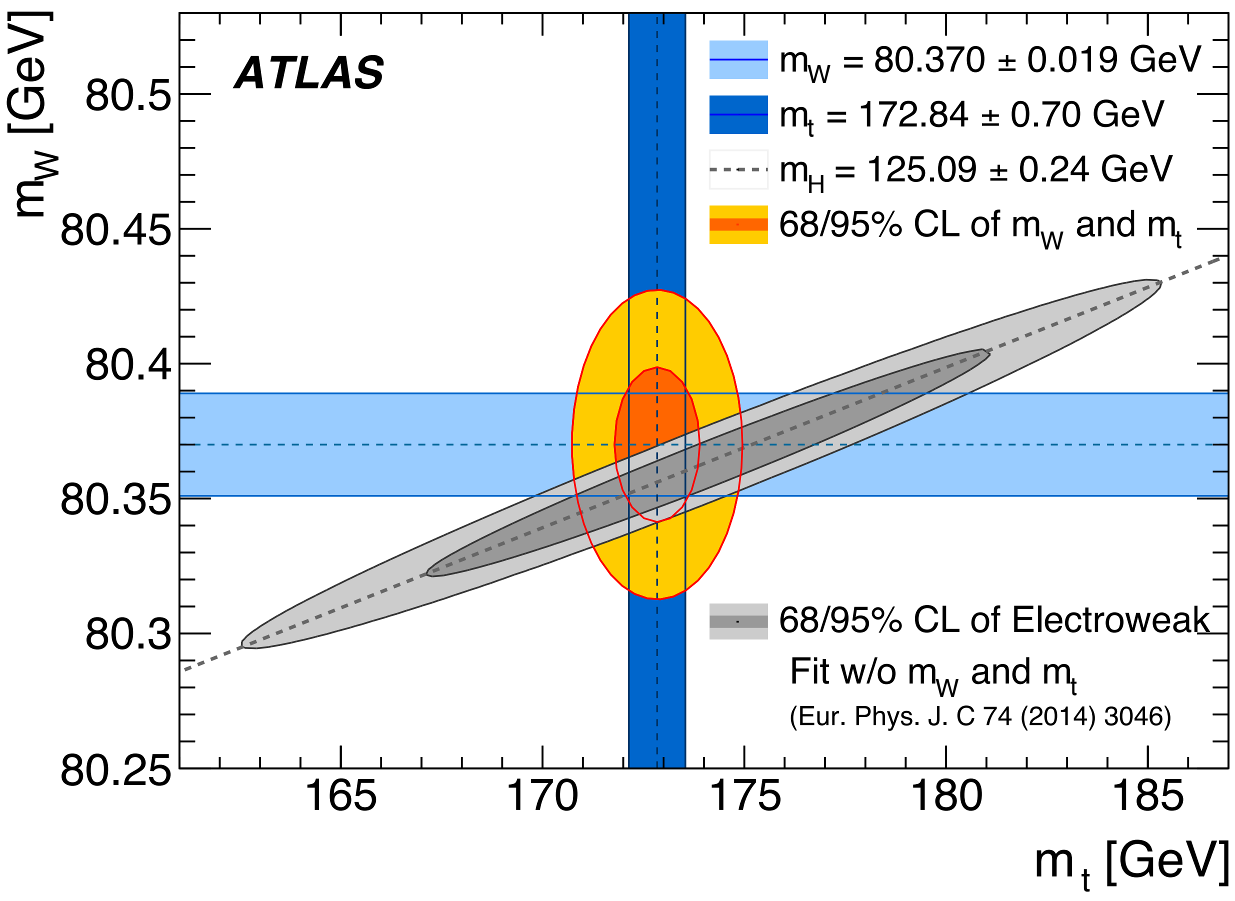
Top quark mass

W mass from ATLAS

arXiv:1701.07240







m_W and m_{top} are from ATLAS measurements

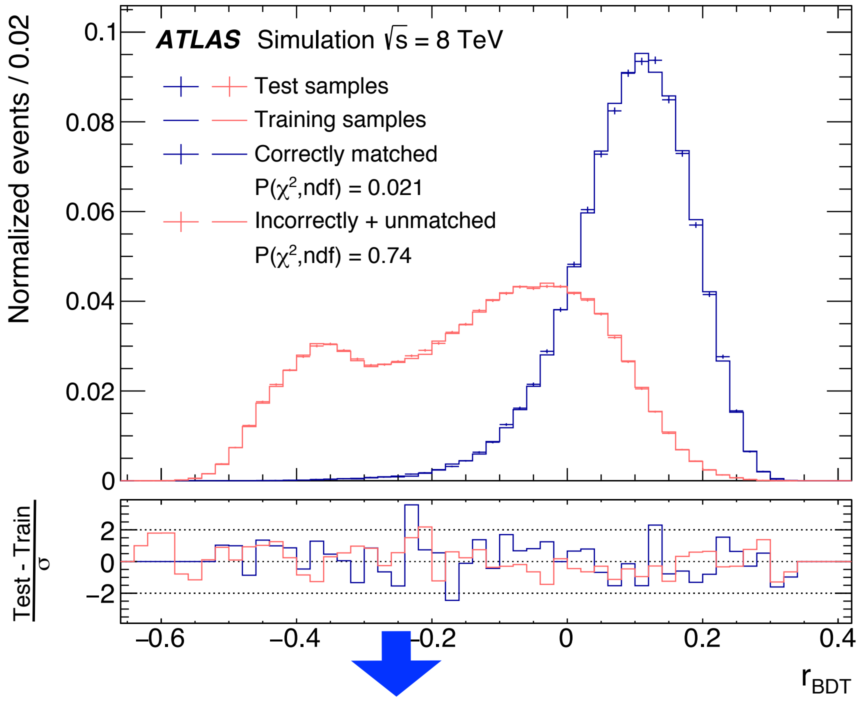
Special reasons:**Measure the top quark mass**

most recent ATLAS from all data @ √s=8 TeV

Eur. Phys. J. C79 (2019) 290

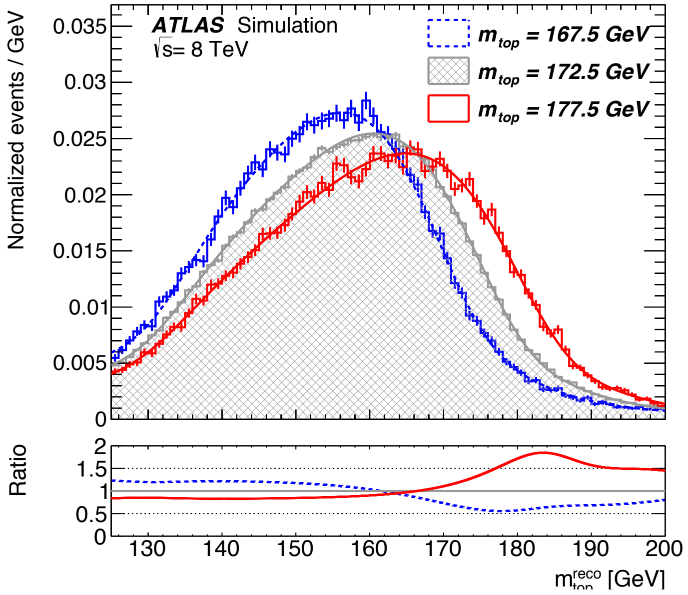
- **Select ℓ+>=4jets events** *(subtract W+jets, fakes, dibosons &sigle top top)*, ***require 2 b-jets***
- Likelihood-based **kinematic fit** (m_W & m_{top} constr)
- Kine variables→ **Boosted Decision Tree→discriminant** to select correct jet/lepton assignment.

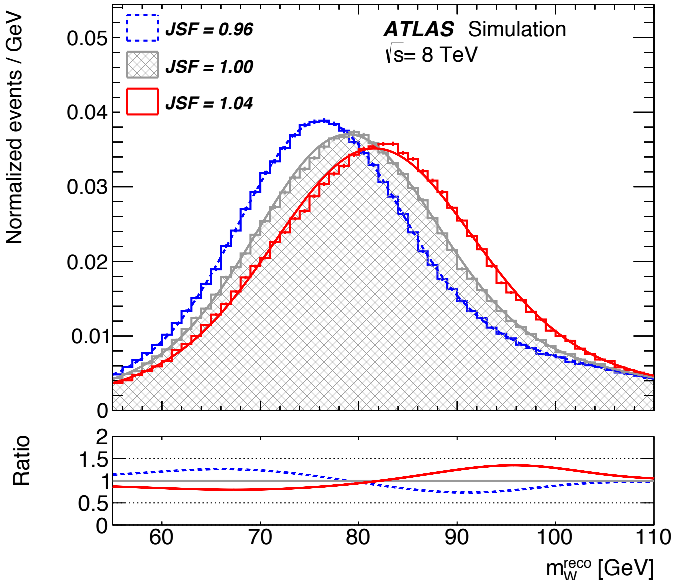
assign jets/ leptons to tt decay products

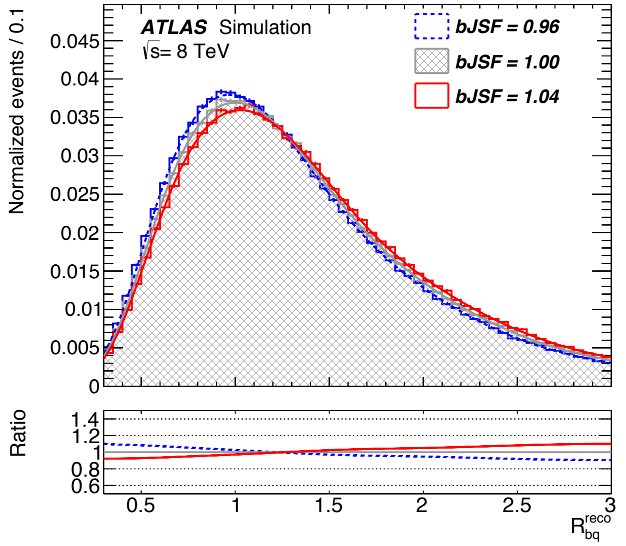


- **likelihood-fit 3 m_{top} sensitive variables to data**
- **m_{top} + 2 scale factors: jet and b-jet-to-light-jet energy** → *reduce dominant jet & b-jet uncertainties*

- **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**





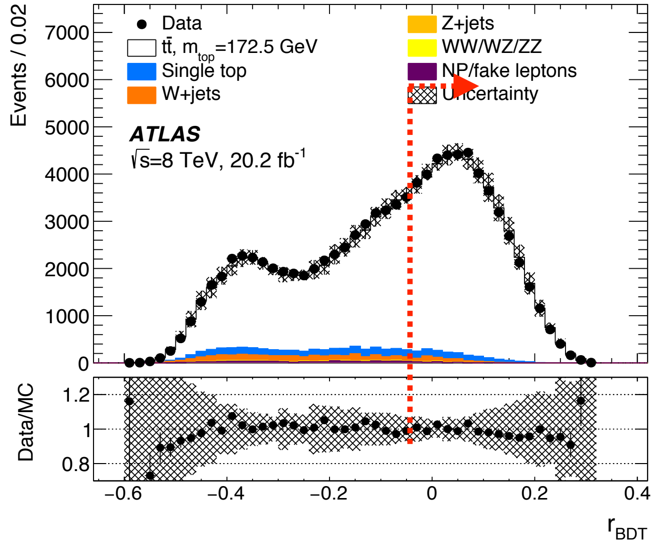


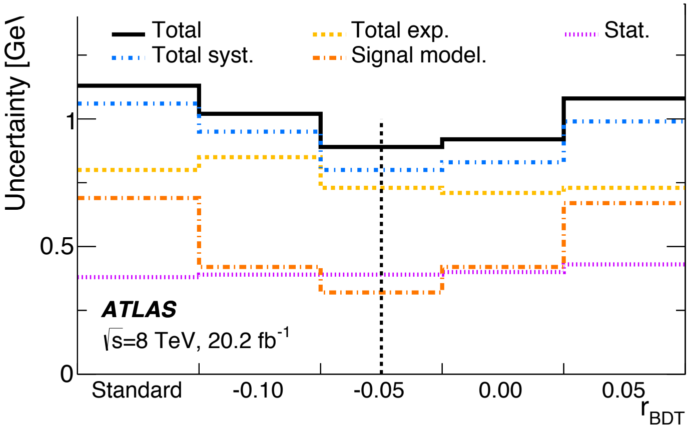
francesco.spano@cern.ch

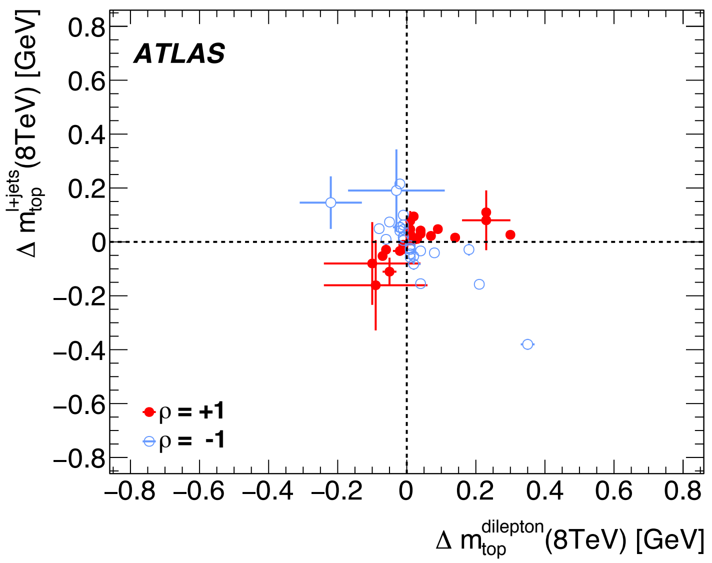
Special reasons:**Measure the top quark mass**

- ***Optimize fit w.rt. BDT: 19% improvement***

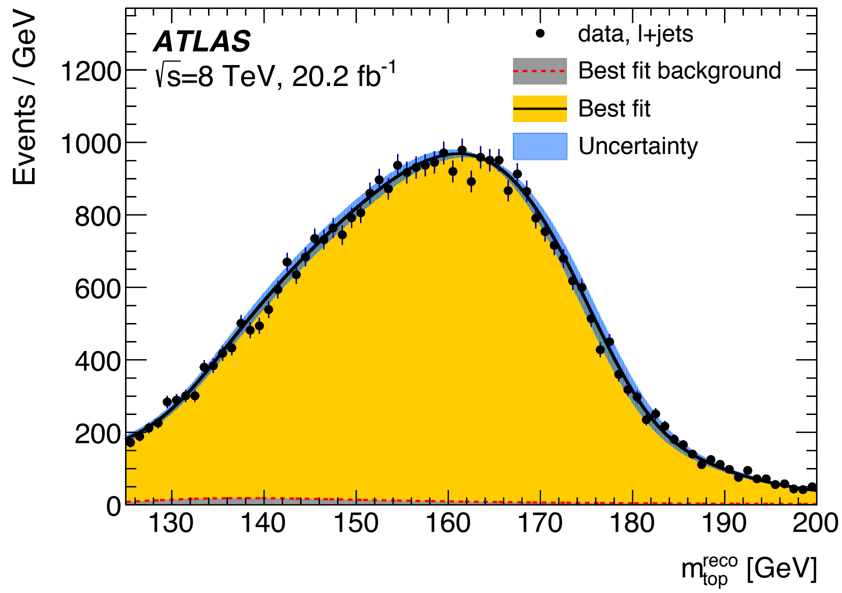
Eur. Phys. J. C79 (2019) 290



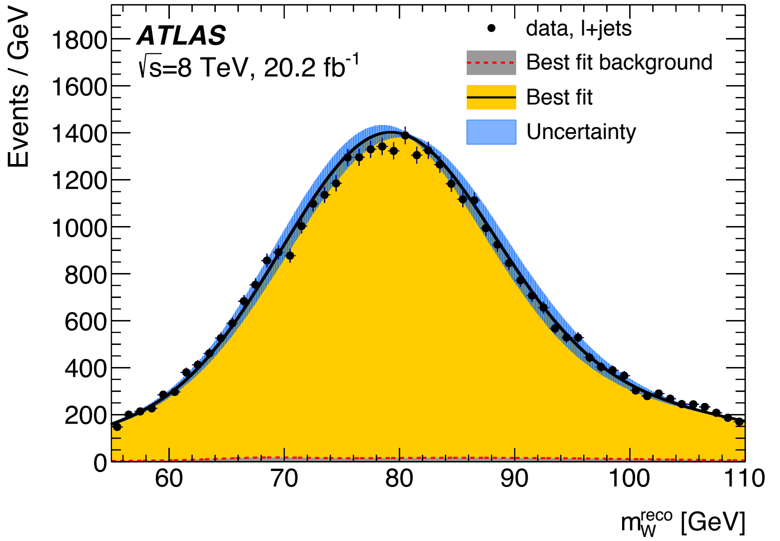




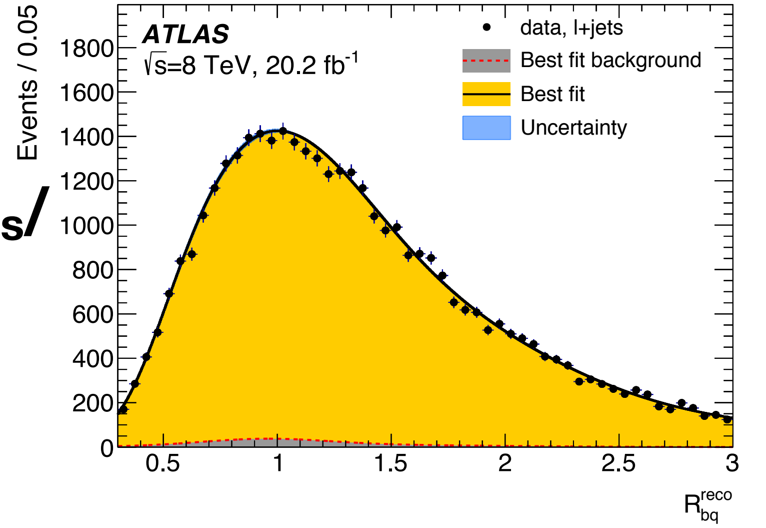
- m_{top}^{reco} sensitive to **m_{top}, JSF, bJSF**



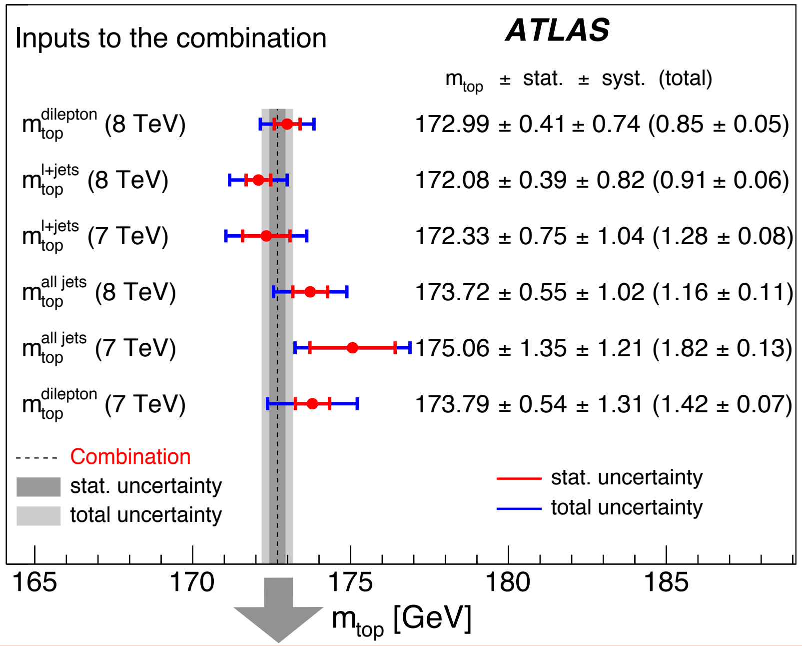
- m_W^{reco} sensitive to **JSF**



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



- ***Combine with dilepton and all jets result***



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

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

Eur. Phys. J. C79 (2019) 290

Measuring SM variables: top mass

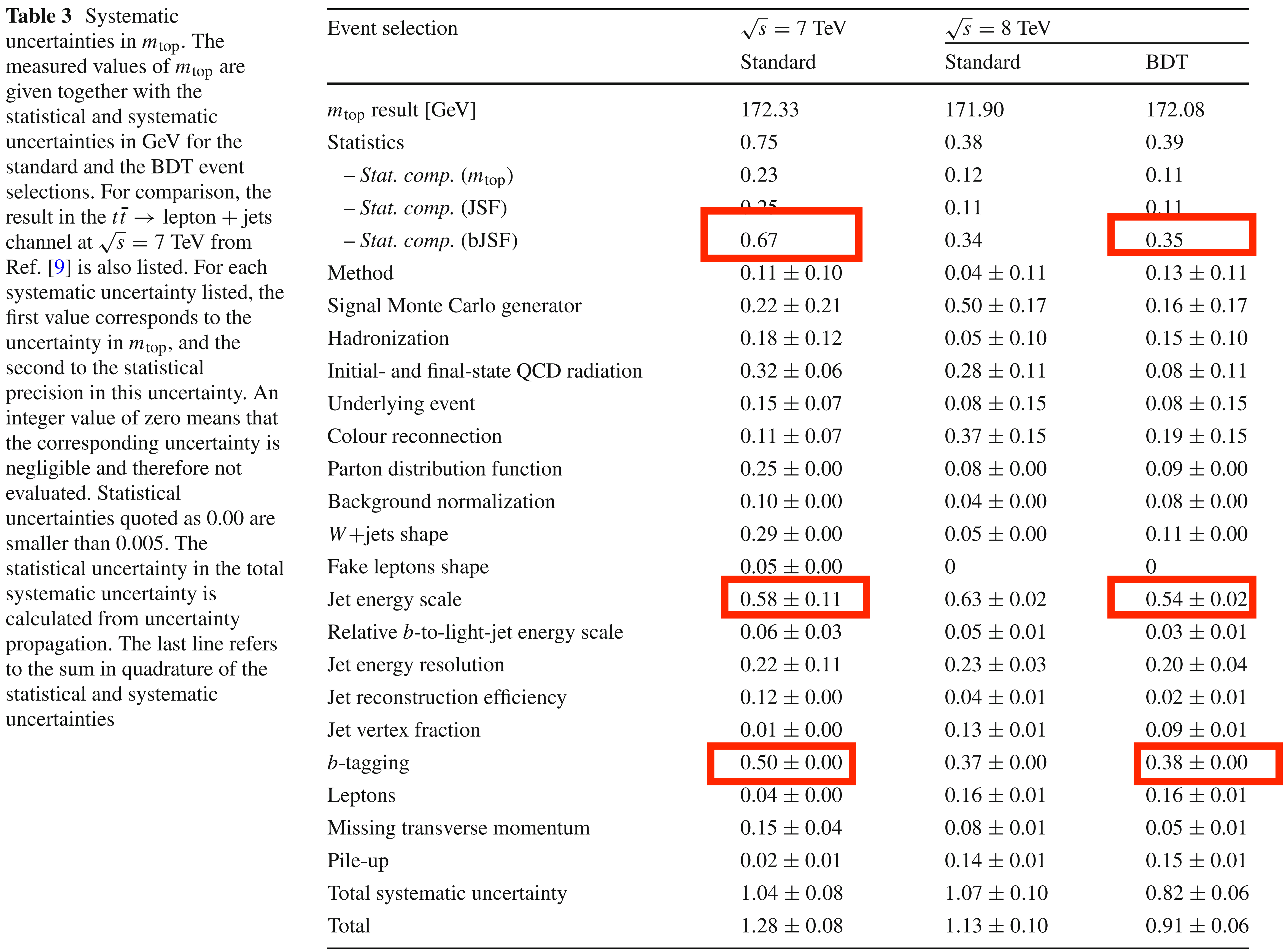


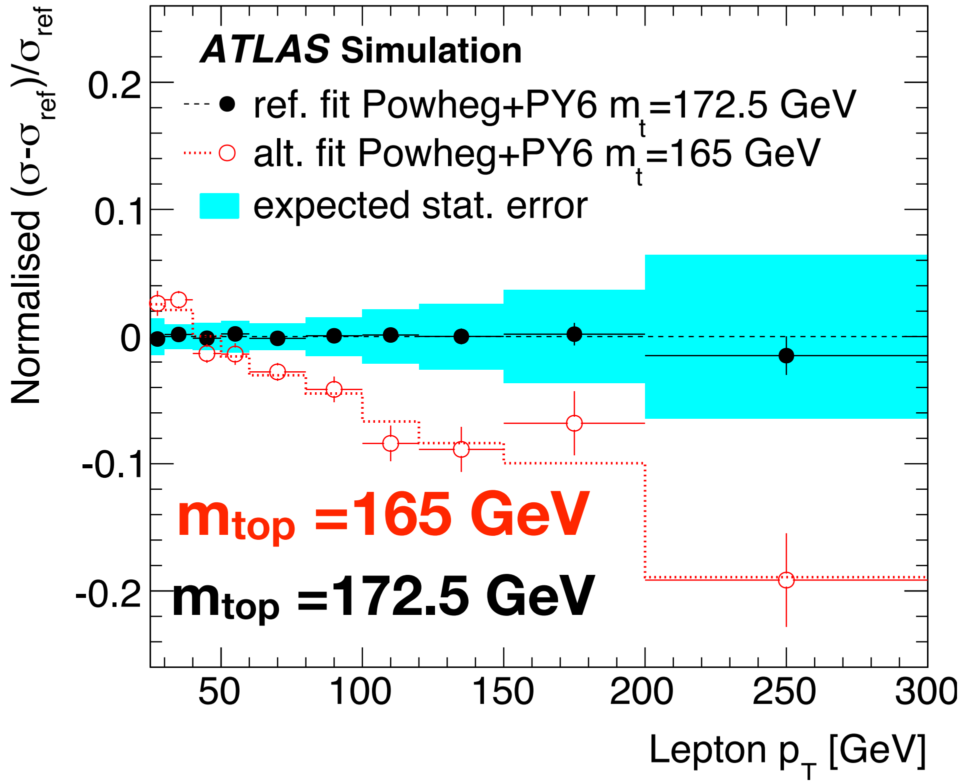
Table 3 Systematic uncertainties in m_{top}. The measured values of m_{top} are given together with the statistical and systematic uncertainties in GeV for the standard and the BDT event selections. For comparison, the result in the $t\bar{t} \to$ lepton + jets channel at $\sqrt{s} = 7$ TeV from Ref. [9] is also listed. For each systematic uncertainty listed, the first value corresponds to the uncertainty in m_{top}, and the second to the statistical precision in this uncertainty. An integer value of zero means that the corresponding uncertainty is negligible and therefore not evaluated. Statistical uncertainties quoted as 0.00 are smaller than 0.005. The statistical uncertainty in the total systematic uncertainty is calculated from uncertainty propagation. The last line refers to the sum in quadrature of the statistical and systematic uncertainties

Event selection	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
	Standard	Standard	BDT
m_{top} result [GeV]	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronization	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.00
Background normalization	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
Missing transverse momentum	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.04 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.28 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

Measuring SM variables: top mass

Eur. Phys. J. C 77 (2017) 804

$d\sigma_{tt}/dX$ are sensitive to m_{top}



m_{top} =165 GeV

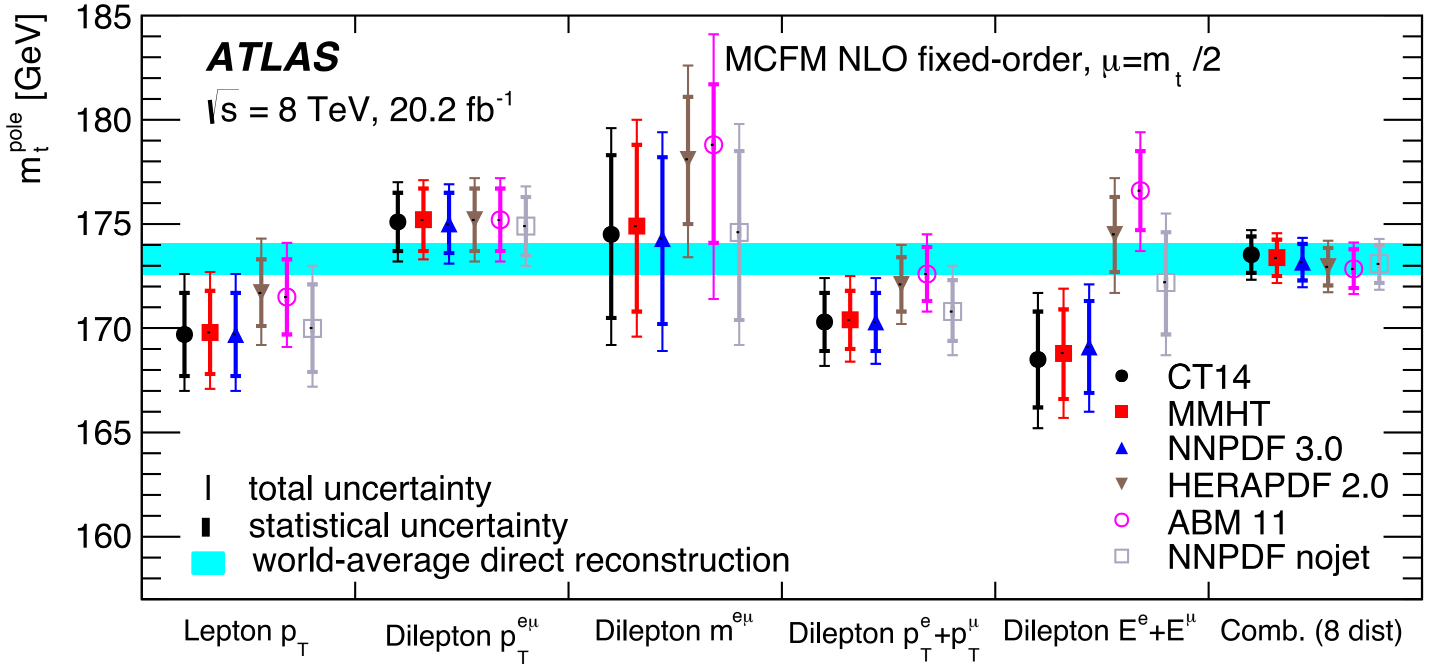
m_{top} =172.5 GeV

@ particle level

Extract m_{top} by minimising

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

- **X=measured** $d\sigma_{tt}/dX$, **P= predictions:** NLO +PS or fixed order NLO (pole scheme)
- **C= covariance matrix**



- **Final m_t^{pole}: combined** (8 dist.) NNPDF **fit**
- Add δm_t^{pole} : PDF (0.3 GeV), dynamic vs static scale (1.1 GeV), $\delta\alpha_s$ ~negligible

$$m_t^{pole} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\,\text{GeV}$$

stat exp theo

$\delta m_t/m_t$ ~0.5%

Comparable to $\delta m_t/m_t$ ~ 0.28% from standard method *(NLO+PS template@reco level)*

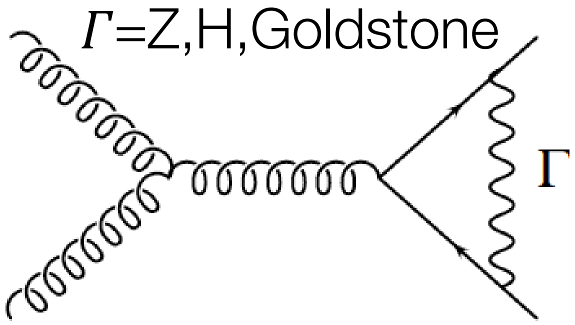
Top Yukawa coupling

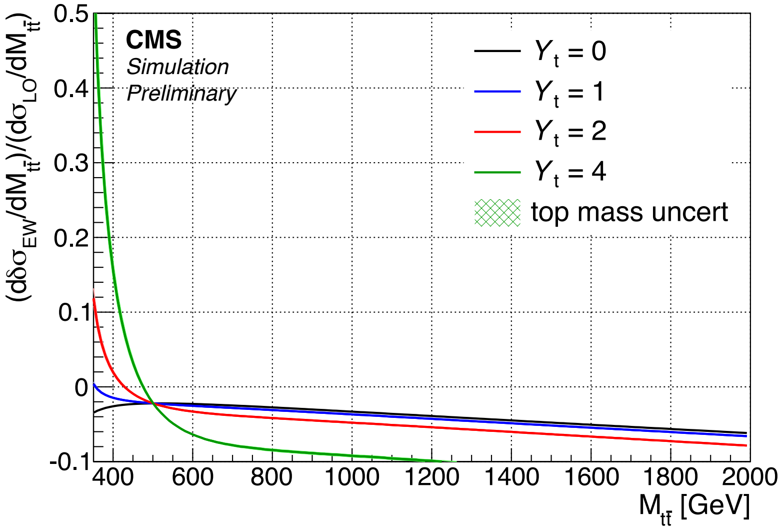
francesco.spano@cern.ch *Top Physics @ LHC: selected highlights* LPNHE Seminar, Sorbonne Université, 24th June 2019

Top Yukawa from $dN/dM_{tt}\,d(y_t - y_{\text{anti-t}})$

CMS -PAS-TOP-17-004

- @ threshold tt-production, Higgs boson mediator in Htt loop at $\alpha_s^2\alpha$ → $d\sigma_{tt}/dX$ depends on Y_t^2





- Require 1 **ℓ (e,mu), ≧3 jets, ≧2 b-tag(s),** $m_T^W < 140$ GeV, if $N_{jets} = 3$ $p_{T,\text{lead b-jet}} > 50$ GeV
- Bkg: data driven multi jets *(from control region)* , simulated single top , W/Z+jets,
- **Reconstruct tt system by likelihood discriminant: extend to 3-jets!**
  - b-jets with largest b-tag weight → b-quarks (2 possibilities)

≧4 jets

- Derive ν momentum: point on ellipse in 3-mom ν space from (m_W,m_{top}) intersection with minimum $\mathbf{D_{\nu,min}}$,distance of (x,y) projection from p_T^{miss}
- $m(b,\ell) > m_{top}$ → discard assignment
- Define discriminant

$$-\ln(\lambda_4) = -\ln(P_m(m_2, m_3)) - \ln(P_\nu(D_{\nu,\min}))$$

prob to reconstruct m_W and m_{top} correct $\mathbf{D_{\nu,min}}$

84% (69%)correct in 4-(5-)jets

=3 jets,

Prob(missing jet is from W) :93%

- find $\mathbf{D_{\nu,min}}$ **for b-jet assignment**
- Discard assignment with no $D_{\nu,\min}$
- Define discriminant

$$-\ln(\lambda_3) = -\ln(P_{m_{t_h}}) - \ln(P_\nu(D_{\nu,\min})$$

prob to reconstruct $m(b_h$+W-jet) correct $\mathbf{D_{\nu,min}}$

80% correct in 3-jets

choose jet assignment with maximum discriminant

Top Yukawa from $dN/dM_{tt}\,d(y_t - y_{anti\text{-}t})$

CMS -PAS-TOP-17-004

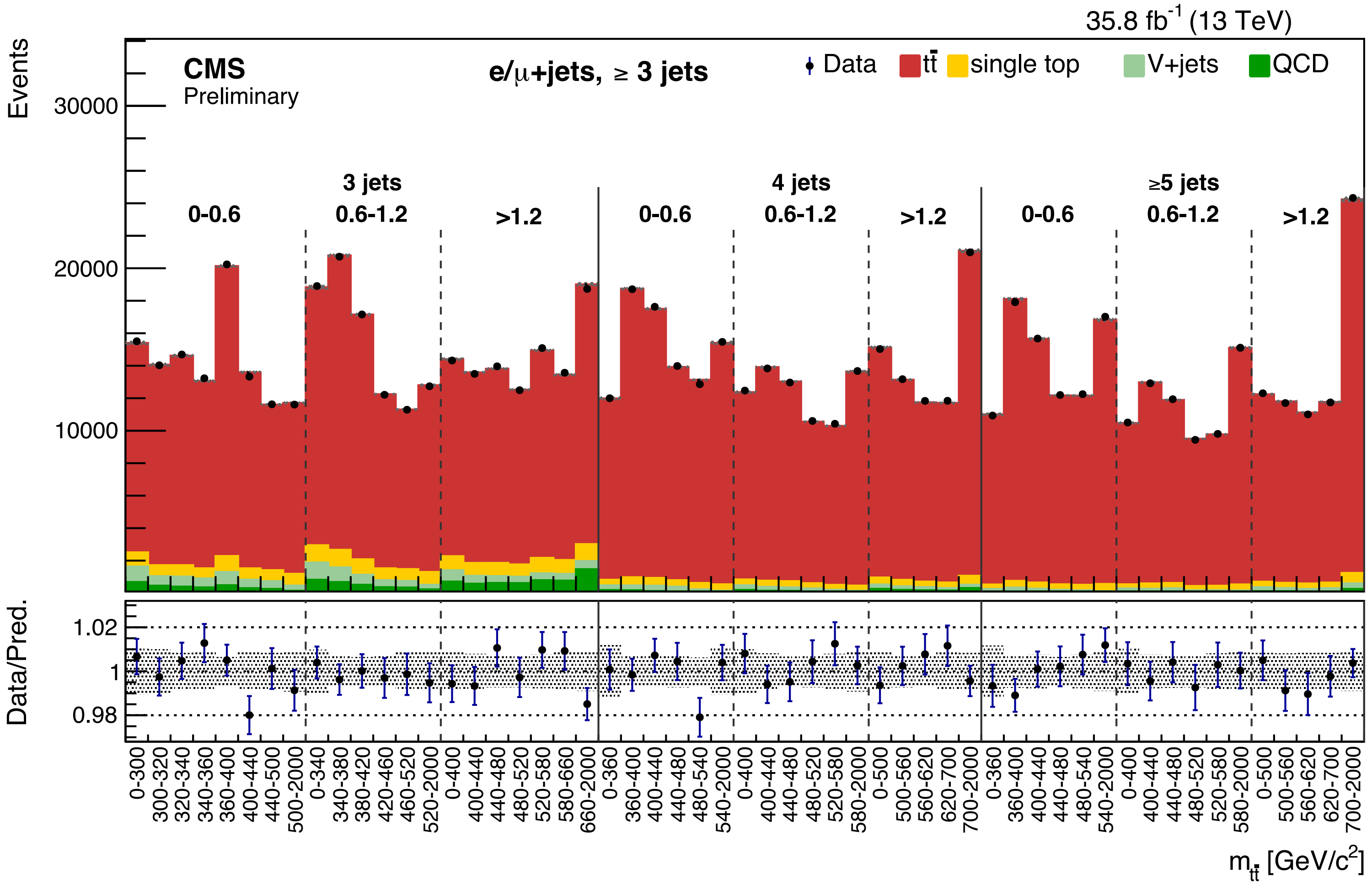
Inclusion of 3-jets events: higher yield at sensitive low M_{tt}, reduce migration in N_{jet} → smaller JES/Had uncertainties

- Build **binned likelihood for $dN/dM_{tt}d(y_t - y_{anti\text{-}t})$** as function of EW correction strength, $R=N_{tt}(Y_t)/N_{tt}(\text{POWHEG})$, a bin-dependent quadratic function of Y_t for 3,4,5 jets and all events

$$\mathcal{L} = \prod_{\text{bin} \in (M_{t\bar{t}}, |\Delta y_{t\bar{t}}|)} \mathcal{L}_{\text{bin}} = \prod_{\text{bin}} \text{Pois}(n^{\text{bin}}_{\text{obs}} | s^{\text{bin}}(\theta) \times R^{\text{bin}}(Y_t) + b^{\text{bin}}(\theta)) \times \rho(\theta|\tilde{\theta})$$

Gaussian for nuisance par → syst uncertainties

- **Scan likelihood to find minimum and upper limit: $Y_t < 1.67$ @ 95% CL**



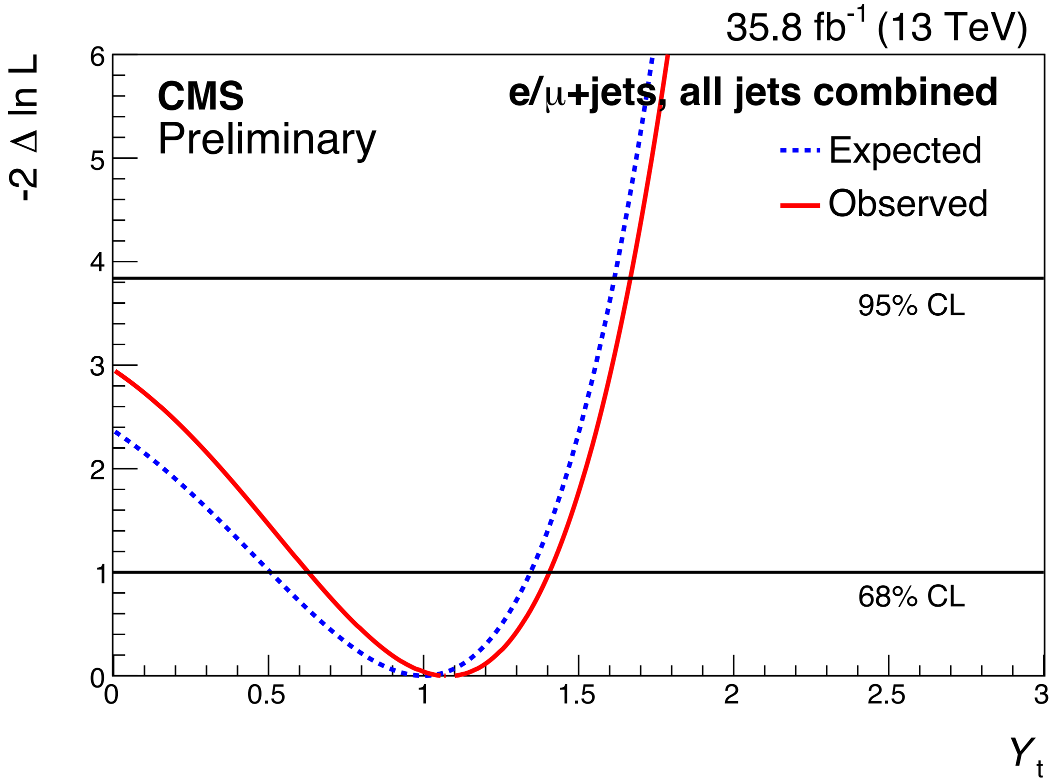


Table 3: The expected and observed 95% CL limits on Y_t

Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_t < 2.17$	$Y_t < 2.59$
4 jets	$Y_t < 1.88$	$Y_t < 1.77$
5 jets	$Y_t < 2.03$	$Y_t < 2.23$
Combined	$Y_t < 1.62$	$Y_t < 1.67$

francesco.spano@cern.ch

Searches for BSM with top

Example: Search for **ttH, H→bb @ $\sqrt{s}$ = 13TeV**

Given model for probability distributions for signal, bkg, systematic uncertainties (det⊗theory) build **likelihood-based variable f(μ) to**

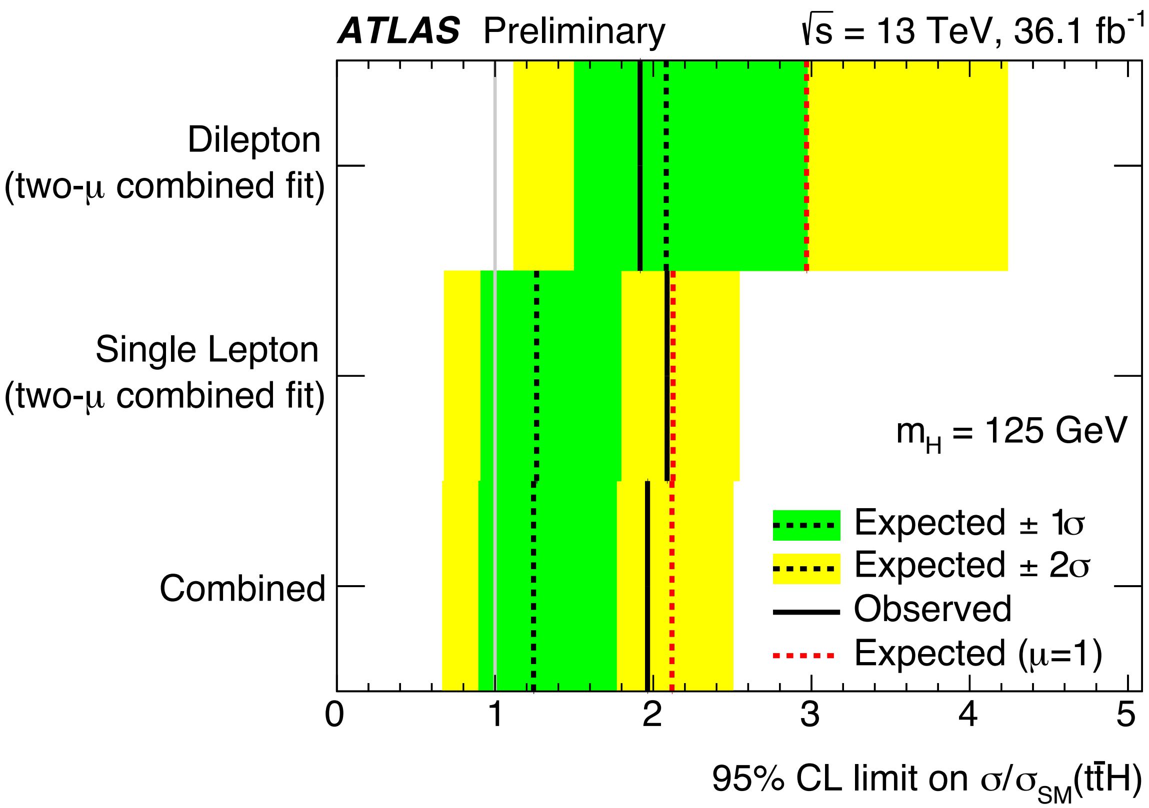
- in the bkg only hypothesis (μ=0), **derive** the probability to observe a more discrepant f-value than the observed one → **test bkg hypothesis**
- in the sig+bkg hypothesis, **derive [0,upper limit] interval** that covers the “true” **μ** value 95% of the times→ **test signal hypothesis**

- Estimate **signal strength** from maximum likelihood fit

upper limit

sig+bkg assumption

bkg only assumption

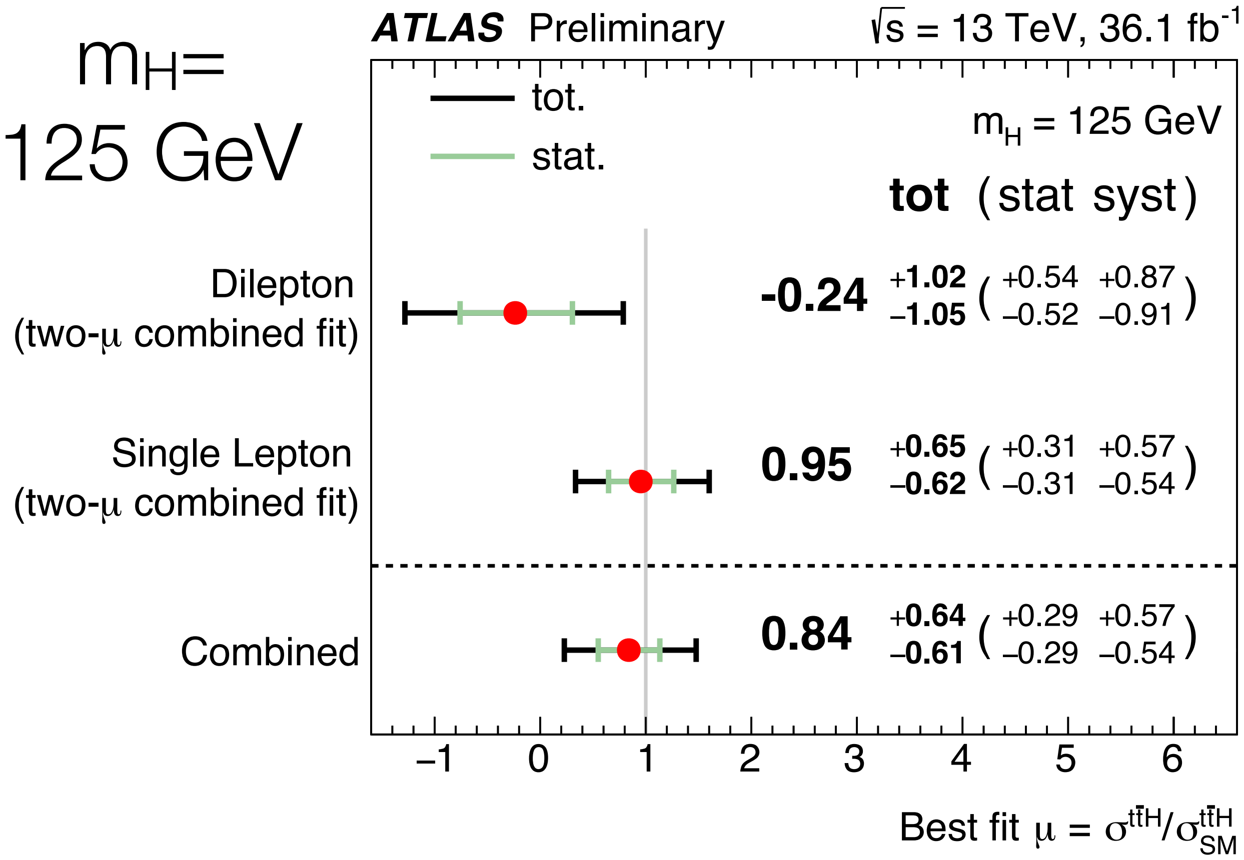


assume

m_H=

125 GeV

signal strength



1.4 sigma significance w.r.t bkg only, excludes μ_{ttH} > 2 at 95%CL

Confidence Interval

What is a "Confidence Interval?

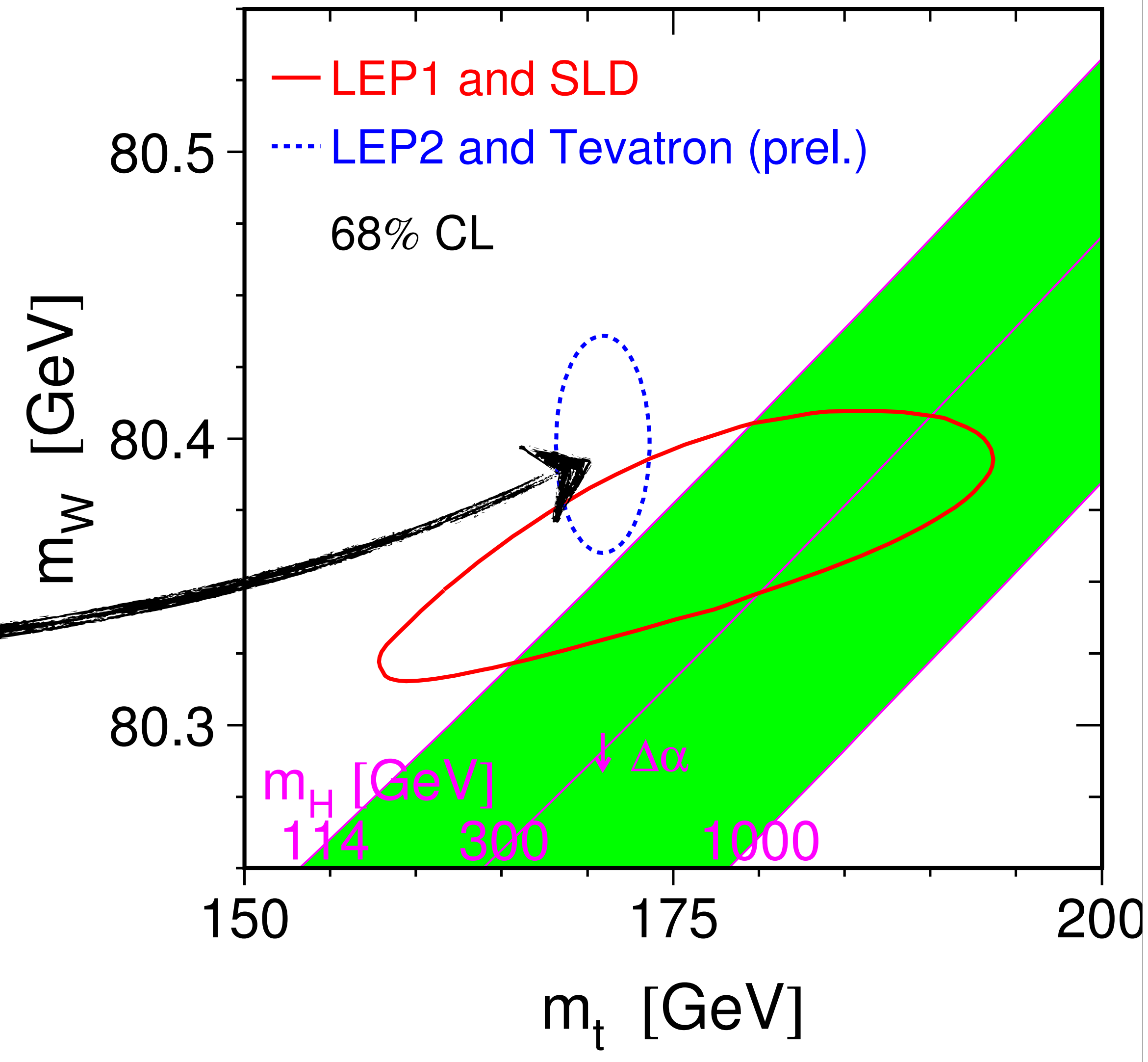
- you see them all the time:

Want to say there is a 68% chance that the true value of (m_W, m_t) is in this interval

- but that's P(theory|data)!

Correct frequentist statement is that the interval **covers** the true value 68% of the time

- remember, the contour is a function of the data, which is random. So it moves around from experiment to experiment



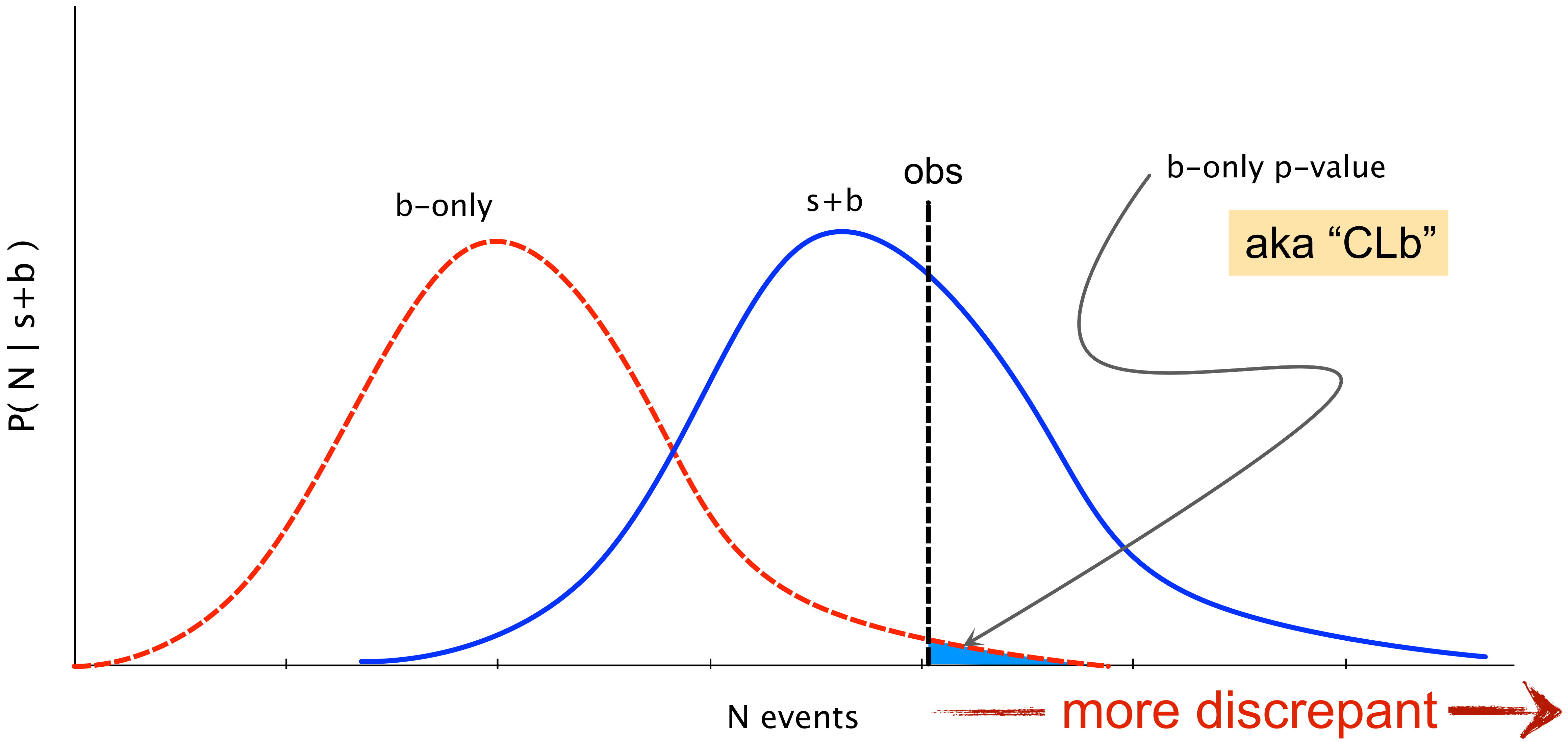
- Bayesian "credible interval" does mean probability parameter is in interval. The procedure is very intuitive:

$$P(\theta \in V) = \int_V \pi(\theta|x) = \int_V d\theta \frac{f(x|\theta)\pi(\theta)}{\int d\theta f(x|\theta)\pi(\theta)}$$

Discovery in pictures

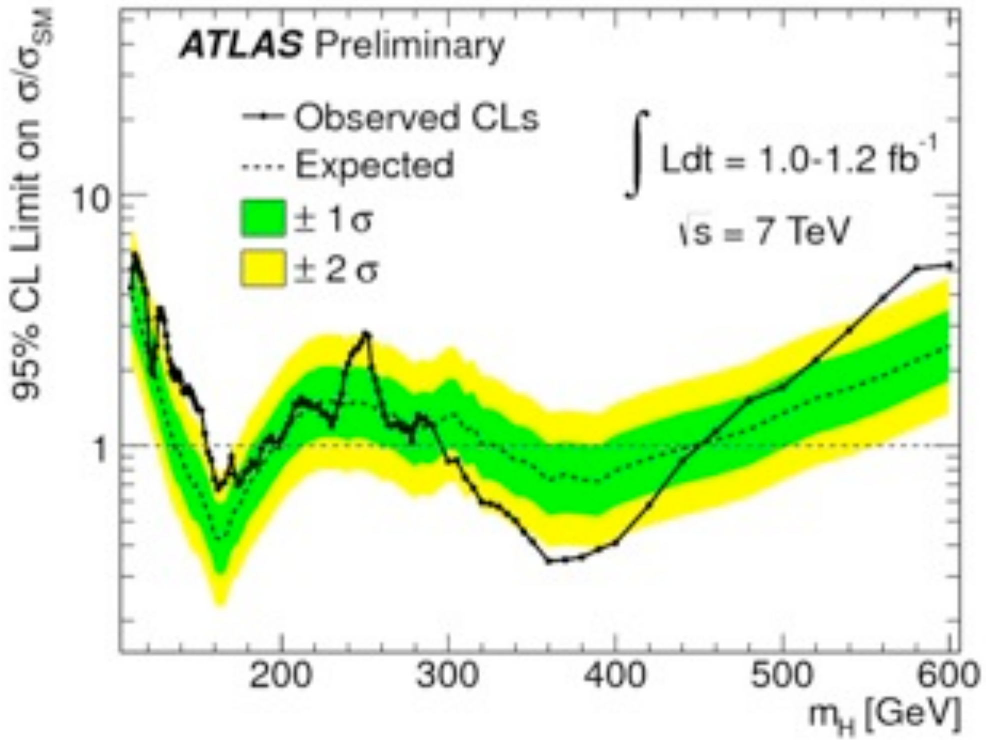
Discovery: test b-only (null: s=0 vs. alt: s>0)

- note, **one-sided** alternative. larger N is “more discrepant”



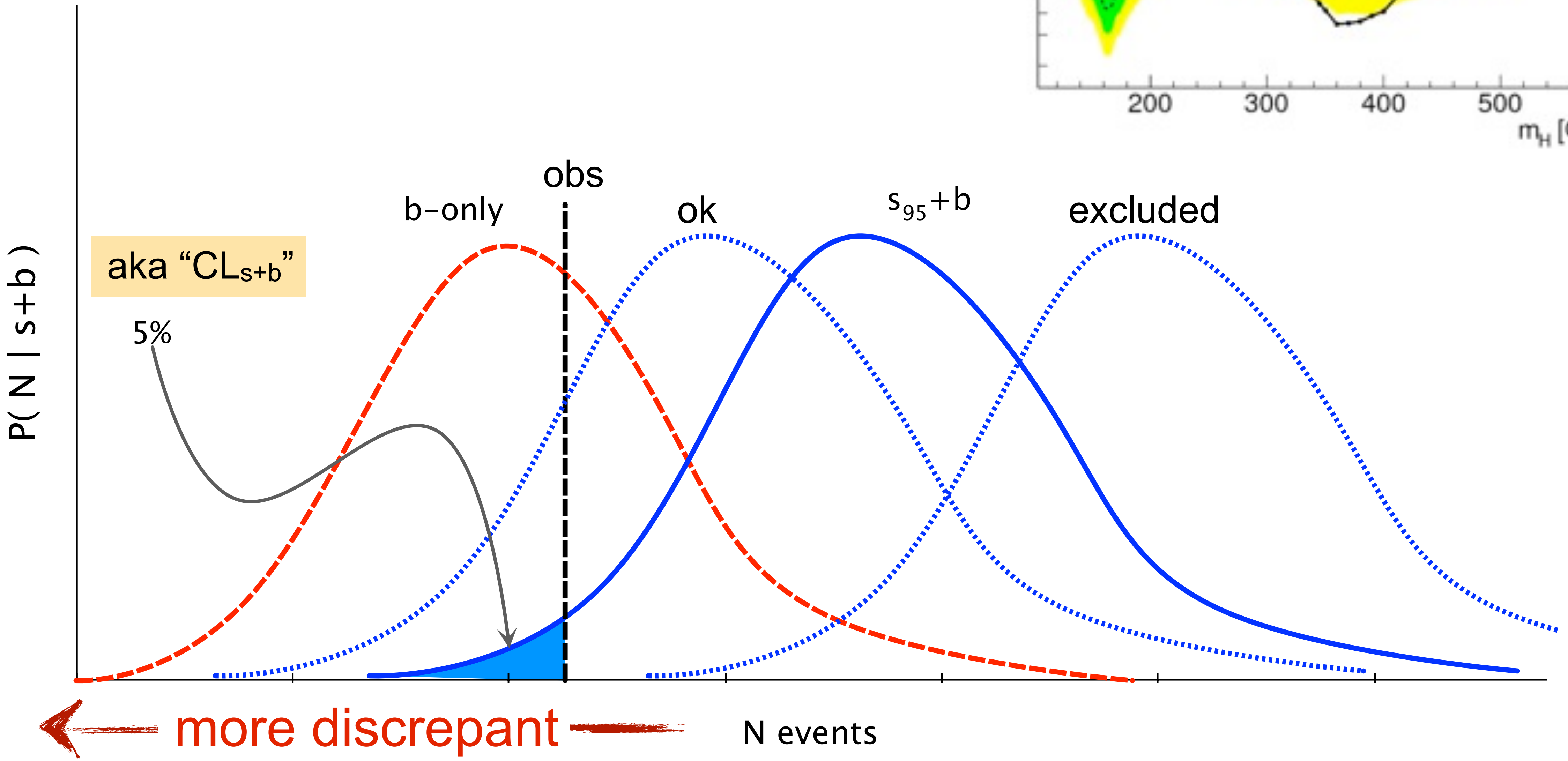
Upper limits in pictures

What is meant by "95% upper limit" ?



See the picture below?

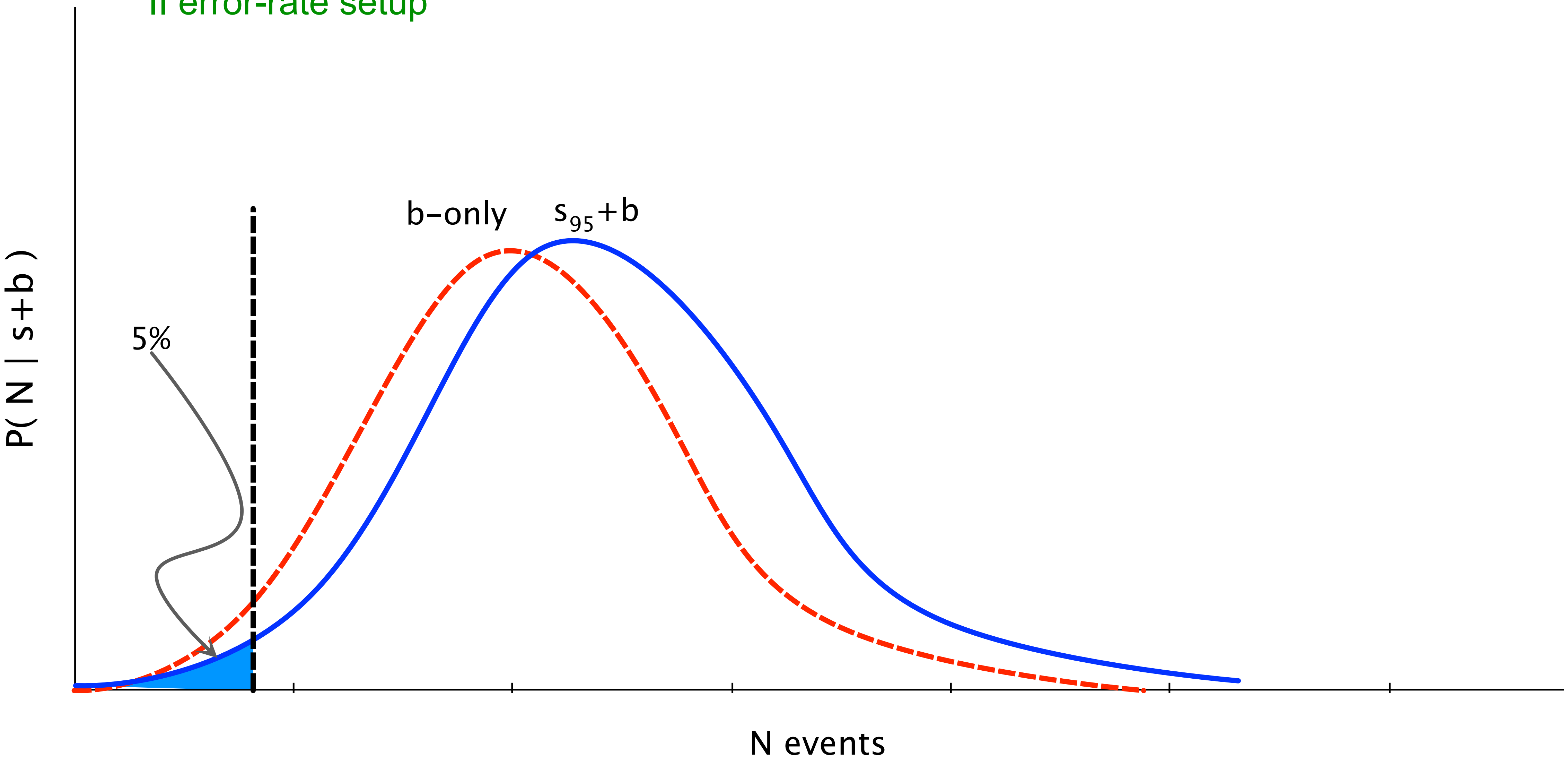
- ie. increase s, until the probability to have data "more discrepant" is < 5%



The sensitivity problem

The physicist's worry about limits in general is that if there is a strong downward fluctuation, one might exclude arbitrarily small values of *s*

- with a procedure that produces proper frequentist 95% confidence intervals, one should expect to exclude the true value of *s* 5% of the time, no matter how small *s* is!
  - This is not a problem with the procedure, but an undesirable consequence of the Type I / Type II error-rate setup



CL_s

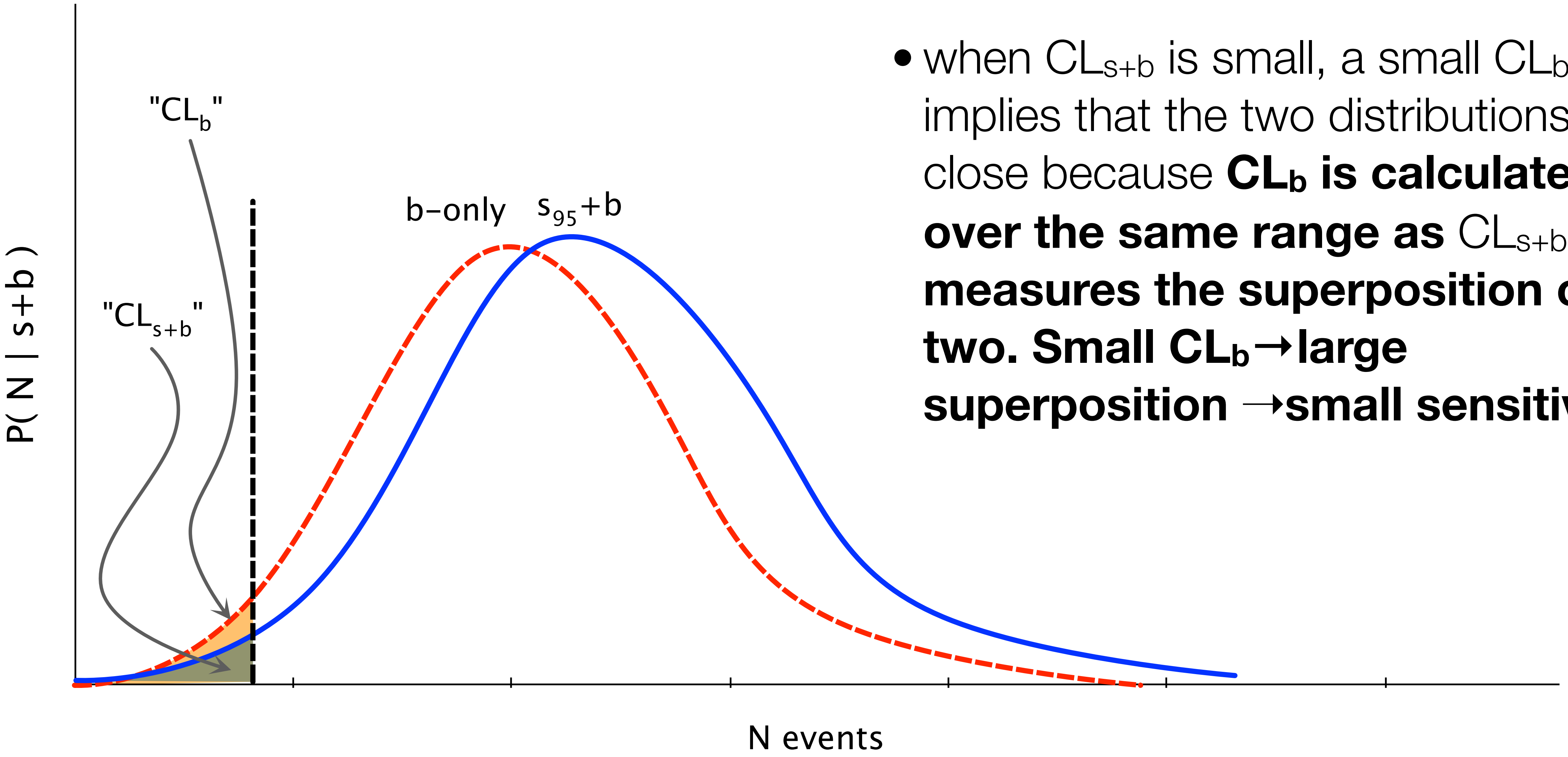
To address the sensitivity problem, CLs was introduced

http://inspirehep.net/record/599622

- common (misused) nomenclature: $CL_s = CL_{s+b}/CL_b$
- idea: only exclude if CL_s<5% (if CL_b is small, CL_s gets bigger)

CL_s is known to be “conservative” (over-cover): expected limit covers with 97.5%

- Note: CL_s is NOT a probability



- when CL_{s+b} is small, a small CL_b implies that the two distributions are close because **CL_b is calculated over the same range as** CL_{s+b} **: it measures the superposition of the two. Small CL_b→large superposition →small sensitivity**

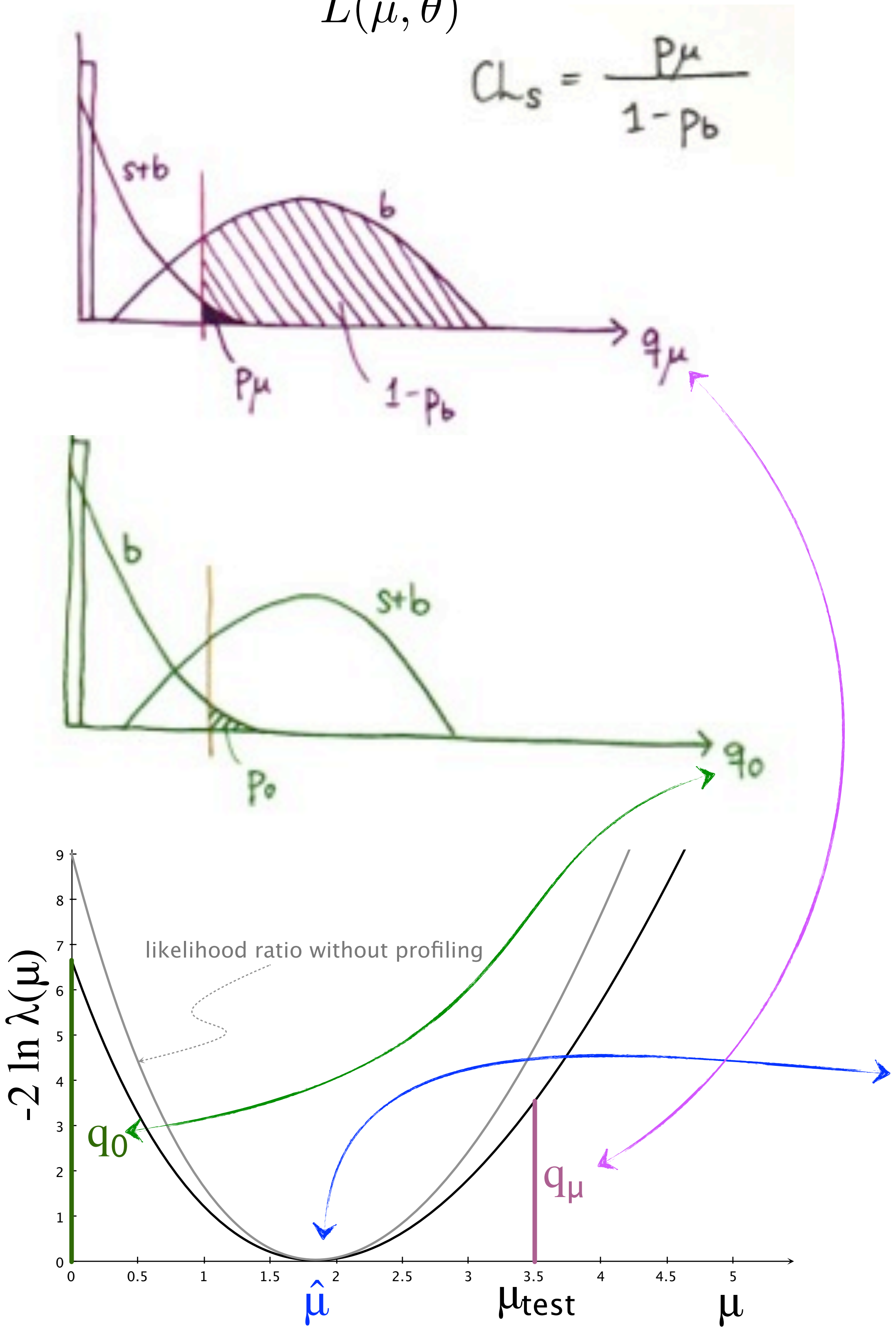
$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$

the 95% CL for mu is determined when prob to have higher vaule of test stat for the sign+bkg hypo is 5% of the prob to have higher test stat for the bkg option: so it means that the bkg only hypothesis can be rare i.e. its tail is small, but the sig+bkg is much rarer as its tail is only 5% of the bkg only tail.

Thumbnail of the statistical procedure

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

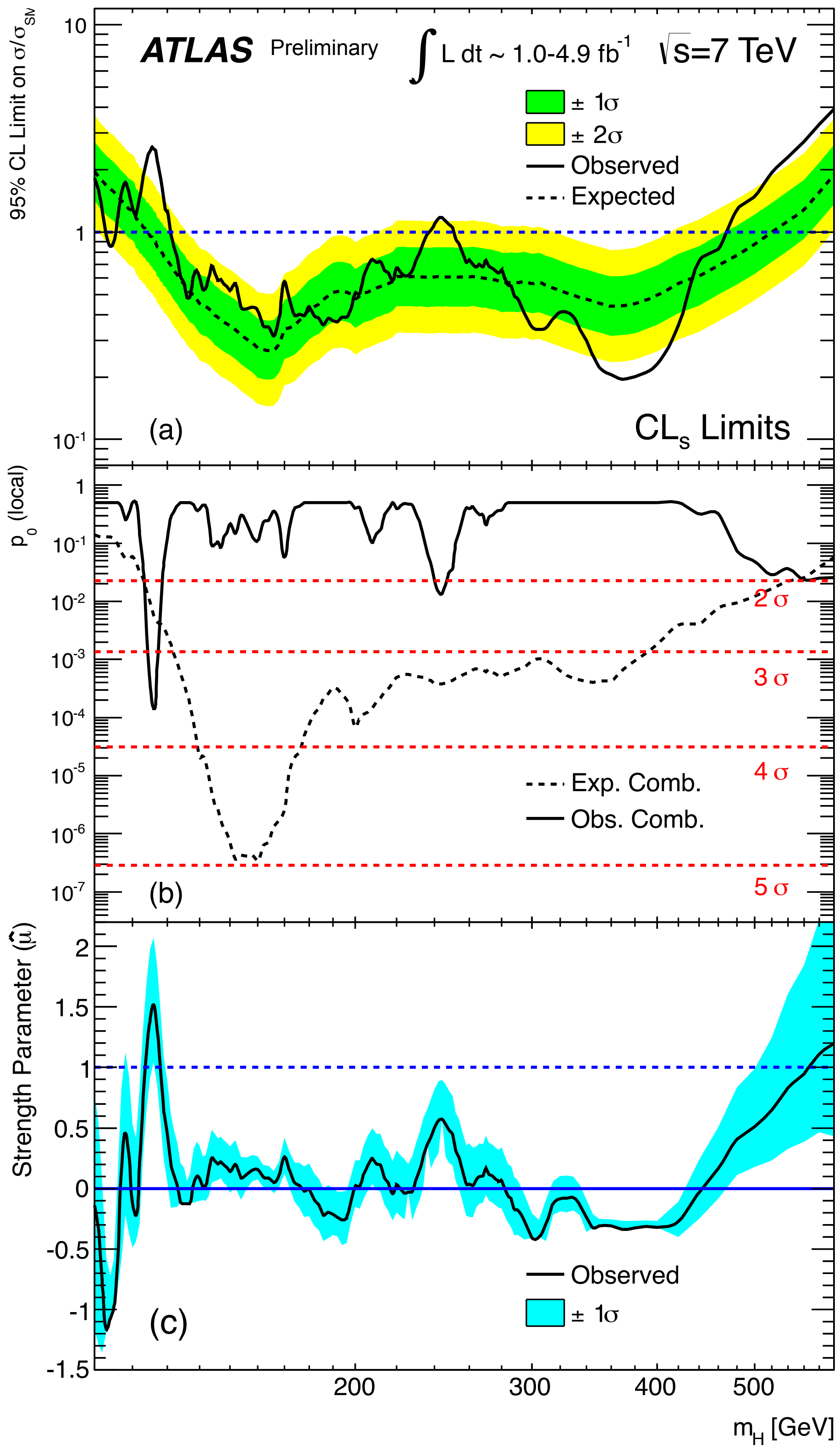
Follow LHC-HCG Combination Procedures



CL_s to test signal hypothesis

p_0 to test background hypothesis

$\hat{\mu}$ to estimate signal strength



CMS top tagging

- **top tagged jet:** anti-k_T (R=0.8) jet with
  - **τ_{32} < 0.65**
  - **105<$m_{jet,SoftDrop}$<210 GeV**
    - ❖soft drop with β=0 , z_{cut} =0.1
    - ❖R0=0.8

Recognising “highly boosted “ top quarks

Math Appendix : Mass, P_T and DR

As we know that for any 4-momentum

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y$$

where

$$m_T^2 = m^2 + p_x^2 + p_y^2 \ .$$

and

The invariant mass M of the two-particle system

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \ln \left(\frac{E + p_z}{m_T} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right) \ .$$

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1) E_T(2) \cosh \Delta y - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \ ,$$

where

$$E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2} \ ,$$

This can be re-written as

$M^2 = m_1^2 + m_1^2 +2[E_T(1) E_T(2)$ cosh(Dy) - $p_T(1) p_T(2)$ cos(DPhi)

where
DPhi =Phi(2)-Phi(1)is the angle between the two momenta in the transverse plane

Now if 1) the masses of the particles are small w.r.t. their momenta and 2) the splitting is quasi collinear i.e. cosDPhi ~1 - $(\mathrm{DPhi})^2/2$ and cosh(Dy)~$1+\mathrm{Dy}^2/2$, so $E_T(I) \sim p_T(i)$

http://en.wikipedia.org/wiki/Hyperbolic_function

$M^2 \sim 2[p_T(1) p_T(2) (1+\mathrm{Dy}^2/2 - 1+ (\mathrm{DPhi})^2/2)]= p_T(1) p_T(2) (\mathrm{Dy}^2/2 + (\mathrm{DPhi})^2)= p_T(1) p_T(2)(\mathrm{DR}(1,2))^2$

So

Labelling i and j such that $p_{tj} < p_{ti}$ and defining $z = p_{tj}/p_t$

$$(p_t = p_{ti} + p_{tj}),$$

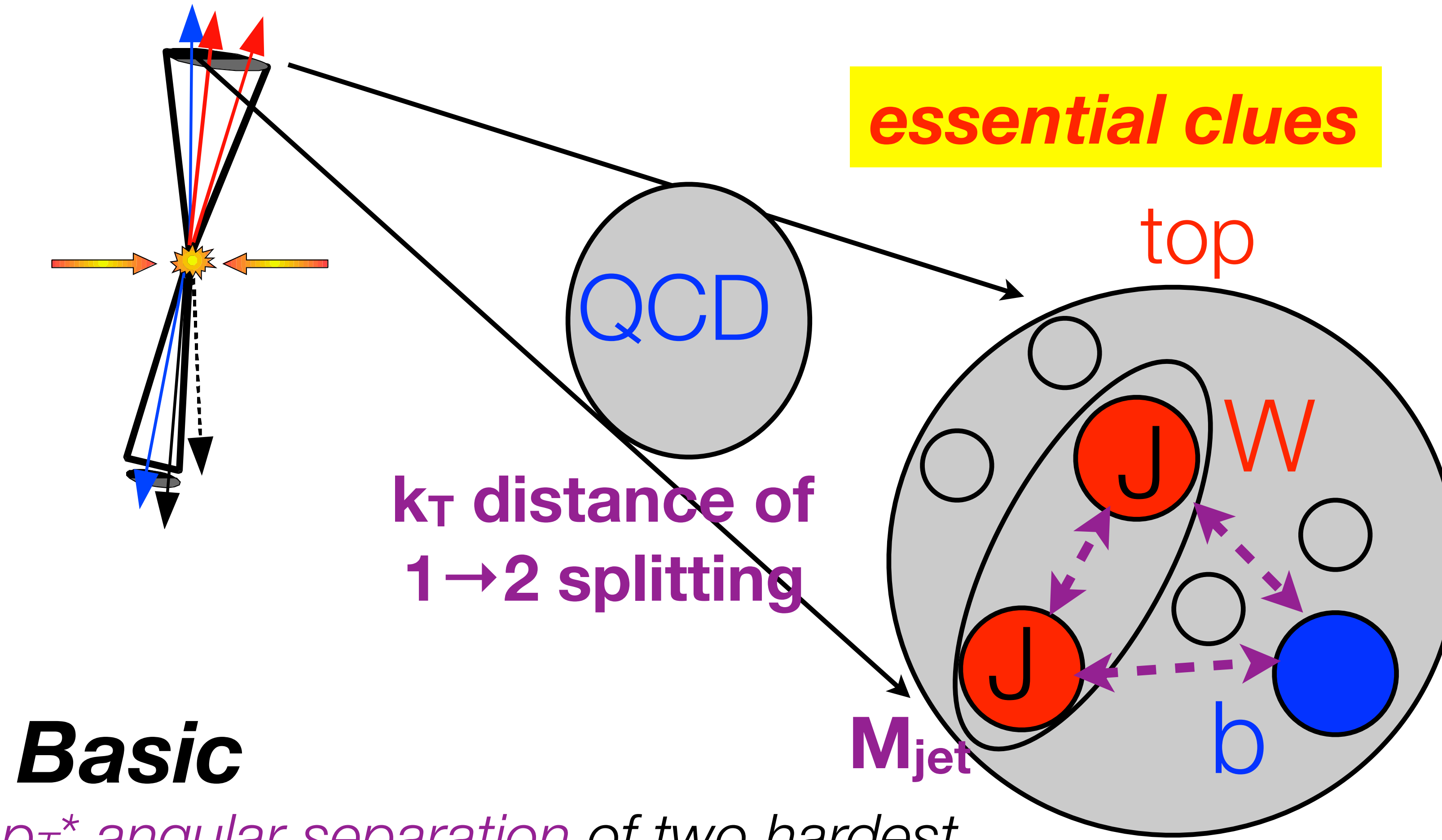
$$m^2 \simeq z(1-z) p_t^2 \Delta R_{ij}^2 \ ,$$

$$d_{ij} = z^2 p_t^2 \Delta R_{ij}^2 \simeq \frac{z}{(1-z)} m^2 \ .$$

How **to tag** a boosted hadronic top quark?

Look into the jet substructure

(see Jose Juknevich, TOP2013)



Basic

Use ***jet mass*** *and product of p_T* angular separation of two hardest jet constituents from jet algorithm*

Declustering

Discard soft coherent radiation (“grooming”) to reveal boosted objects:redefine jets

Soft-Drop mass, YSpliiter, ATLAS TopTagger, Mass-Drop, CMS Top Tagger, HEPTopTagger, Trimming, Pruning…

Pattern/Matrix El./Jet shapes

Recognize energy pattern in unchanged jet

TopTemplate Tagger, Shower deconstruction, N_subjettiness ratio…

How **to tag** a boosted hadronic top quark? (II): Examples

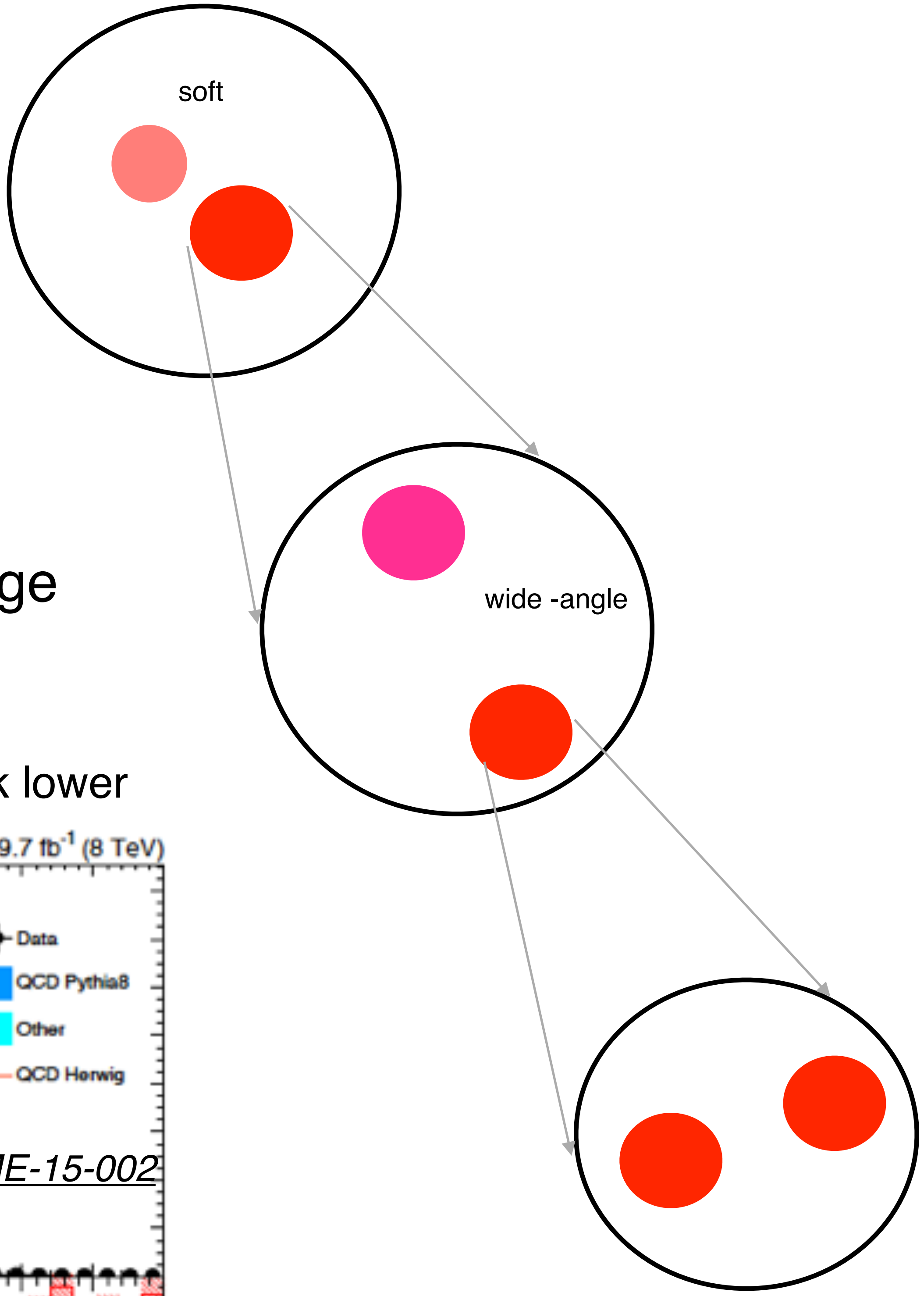
Declustering: redefine jet

Soft-drop Mass *JHEP05(2014)146*

- Revert jet making steps → at each iter. break jet J in 2 subjets j_1 and j_2
- if $$\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

tune β z_{cut}

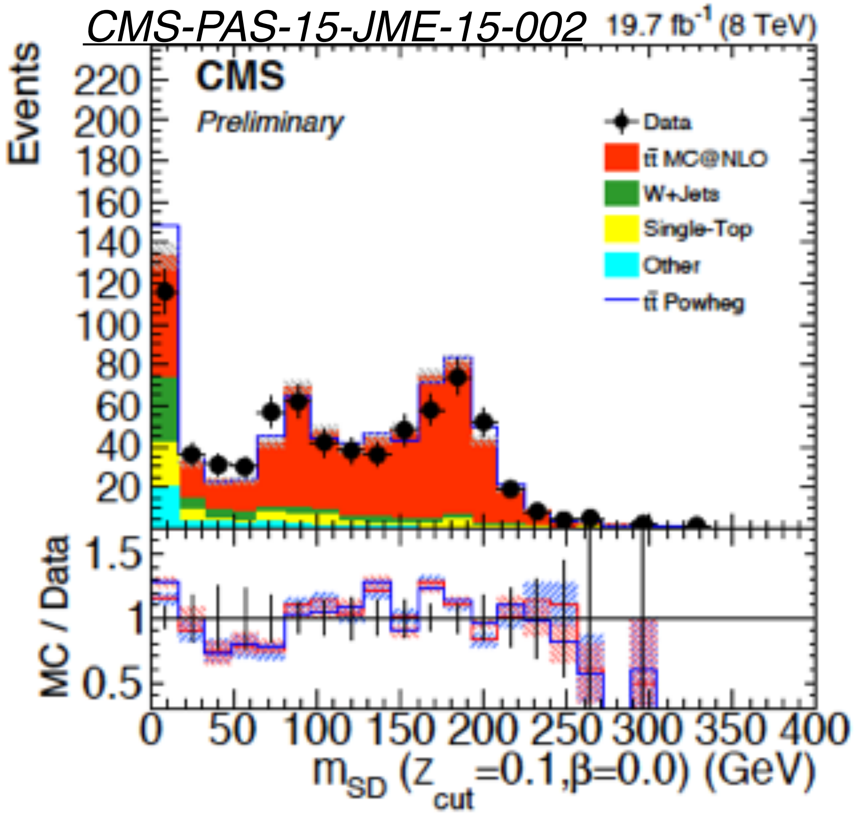
stop: J is the final jet.
Otherwise keep & decluster higher p_T subjet

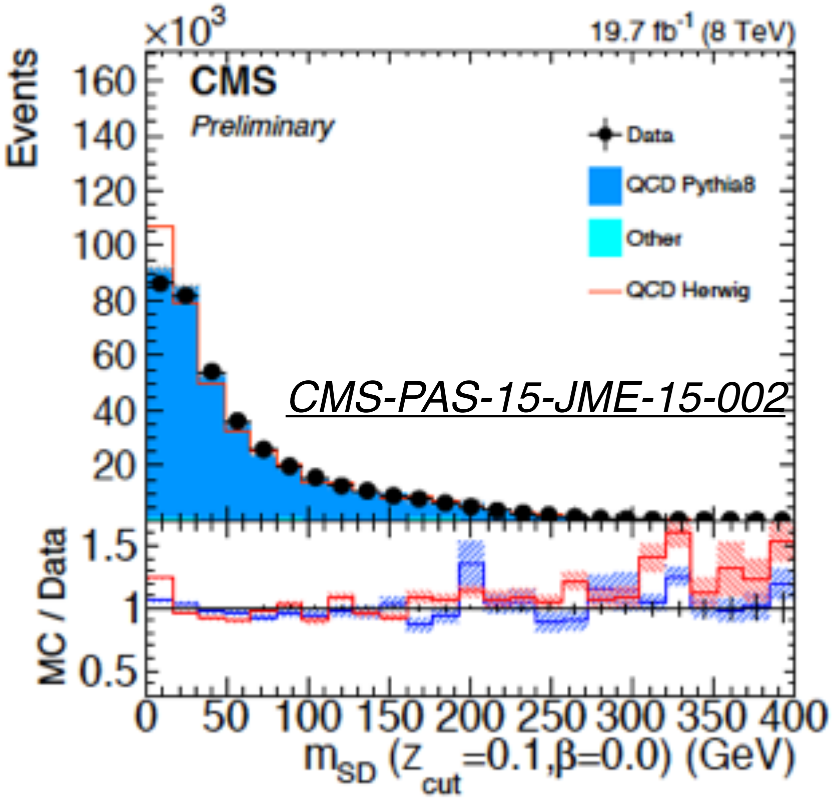


Recursively removes soft (small-p_T), wide angle (large ΔR) radiation from initial state, pile up, rest of event

Mass of final jet closer to top mass, light quark/gluon jet peak lower

CMS-PAS-15-JME-15-002



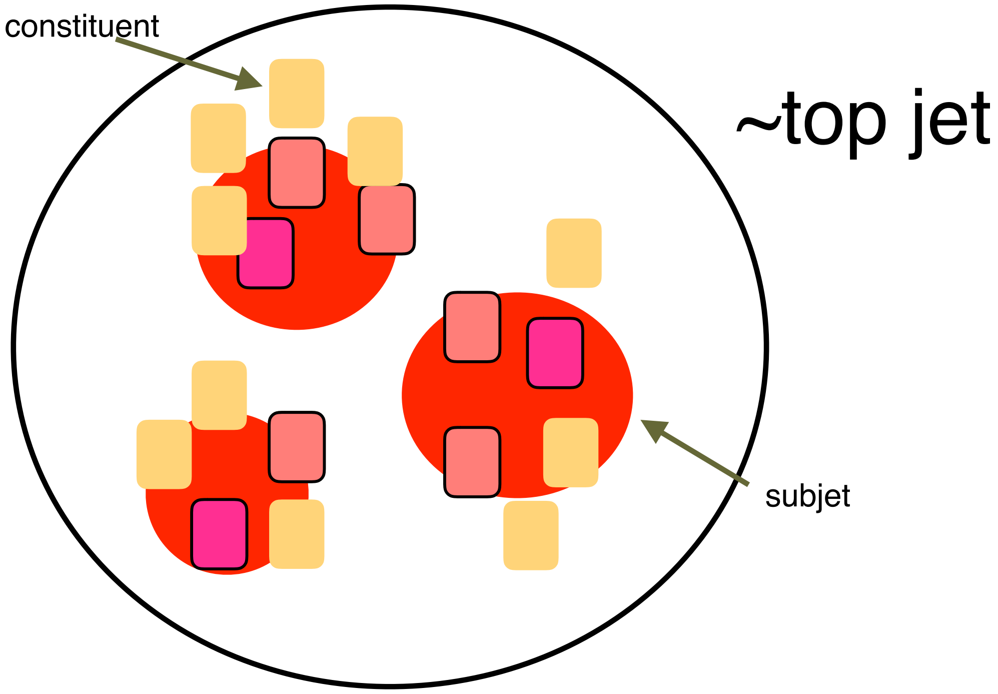


CMS-PAS-15-JME-15-002

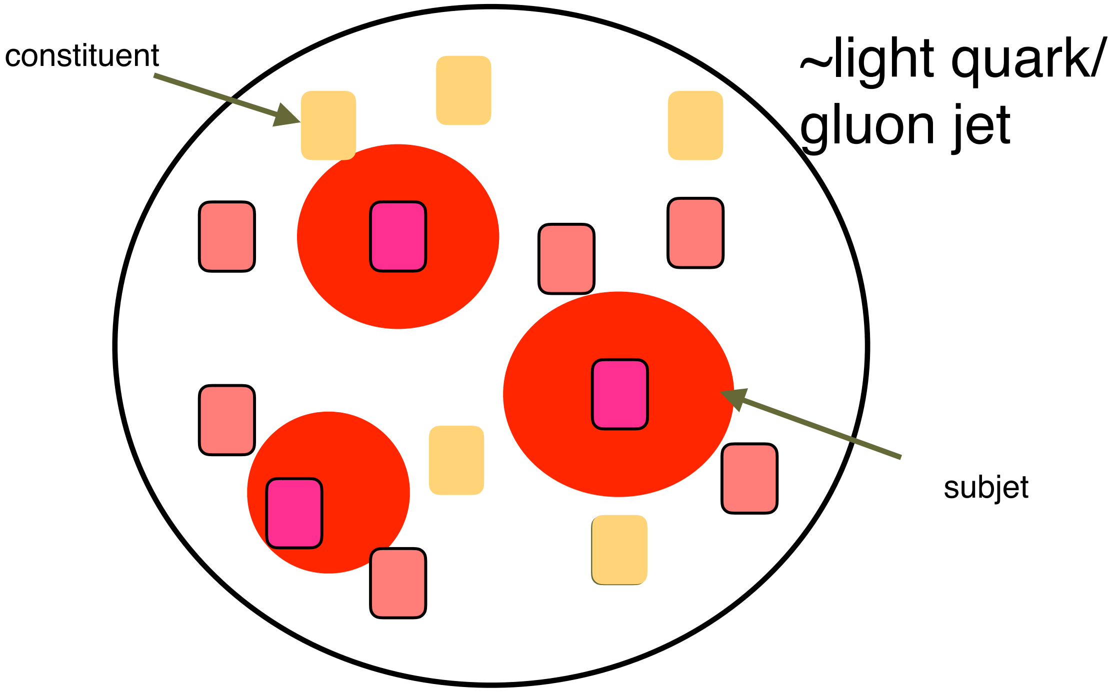
How **to tag** a boosted hadronic top quark? (II): Examples

→ increasing p_T→

Example for N= 3 🟨 🟧 🟪 🟥



small sum of p_T ΔR



large sum of p_T ΔR

Radiation:

N-Subjettiness ratio JHEP03 (2011) 015

- Make jet with N subjets (k_T algo)
- ΔR(const,subjet)-weighted sum of constituents p_T→ alignment of constituents to subjets hypo

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\{\Delta R_{1,k},\Delta R_{2,k},\cdots,\Delta R_{N,k}\}\,. \quad d_0 = \sum_k p_{T,k}R_0$$

jet radius

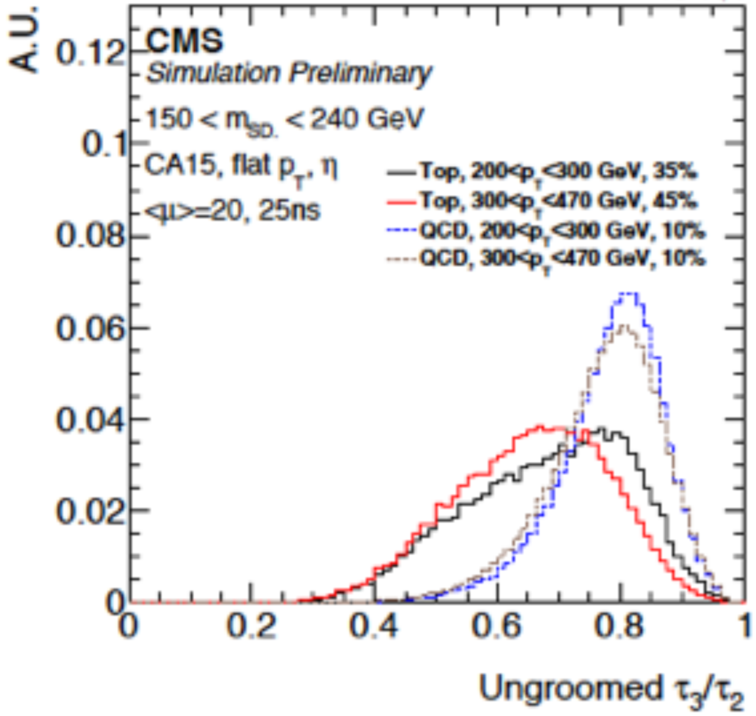
describes how well the jet contains N (τ_N→0) or fewer (τ_N→1) subjets

- Top-jet : 3 subjets ;
- light quark/gluon- jet < 3

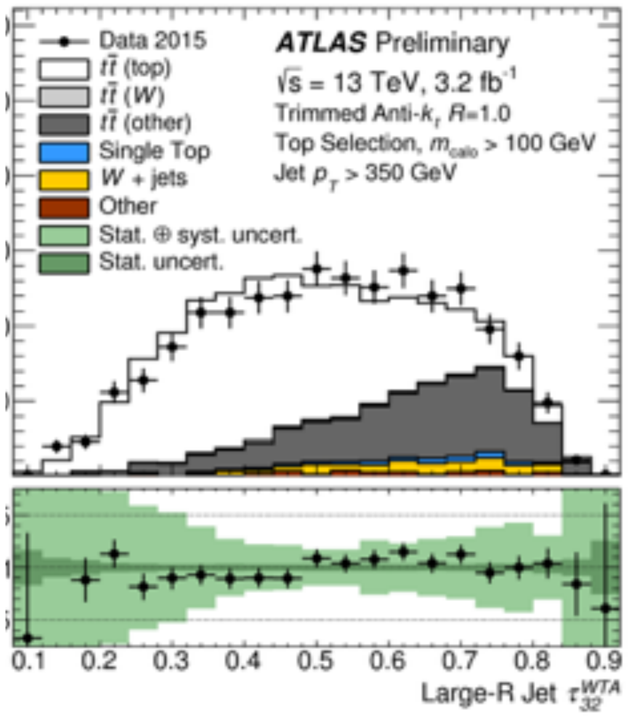
Use $\tau_{32} = \tau_3/\tau_2$

The lower, the more top-like (3-prong)

CMS-PAS-15-JME-15-002



ATLAS JETM-2016-005



How **to tag** a boosted hadronic top quark? (II): Performance

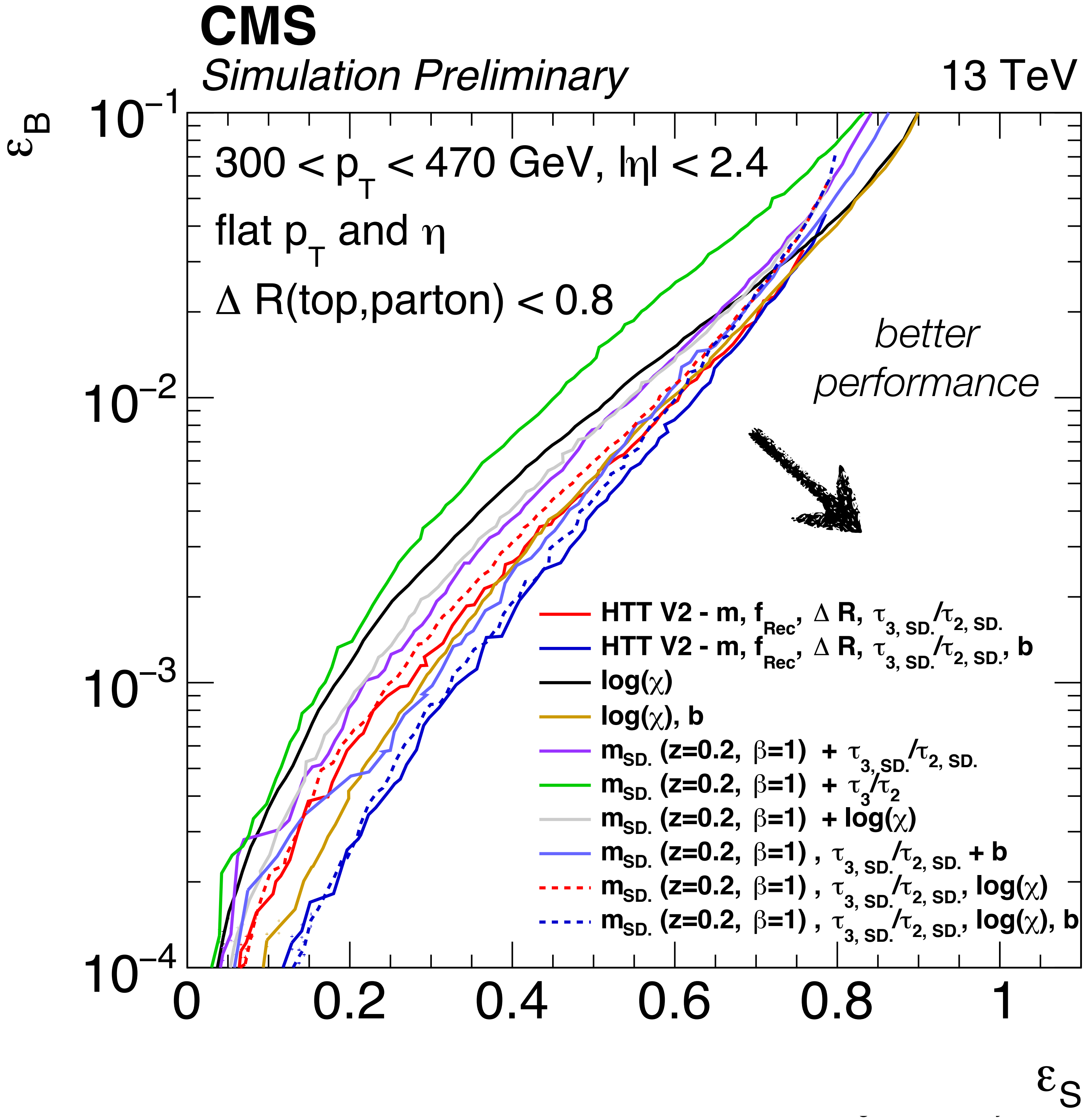
efficiency to tag top jet εs vs **efficiency to mistake a light quark/gluon jet εB**
(or rejection against light-gluon jet)

*(**R**eceiver **O**perating **C**haracteristic **curve**)*

sensitivity to energy from superposed collisions (pile-up)

efficiency to **select the top final state** vs bkg

CMS-PAS-15-JME-15-002



better performance

Combination of different tagging schemes improves performance

Search for excess in “boosted” $t\bar{t}$ production vs $M_{t\bar{t}}$

- *single lepton trigger*

JHEP 07 (2017) 001

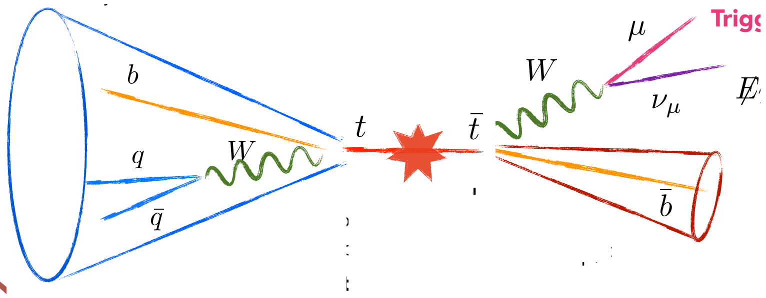
- **exactly 1 high p_T** (>50 GeV) **central lepton** (e,μ) **with 2d isolation** vs fake leptons: ΔR(lep, j)>0.4 or $p_{T,rel}$(lep,j)> 20 GeV
  - ***~90% to 94% efficient***

j = ΔR-closest-to-lep anti-k_T (R=0.4) jet

- **very high E_T^{miss}** (p_T^{lep} + **E_T^{miss}**) >120 (150) GeV in e(**μ**) channel

l+jets $qq\ell\nu bb$

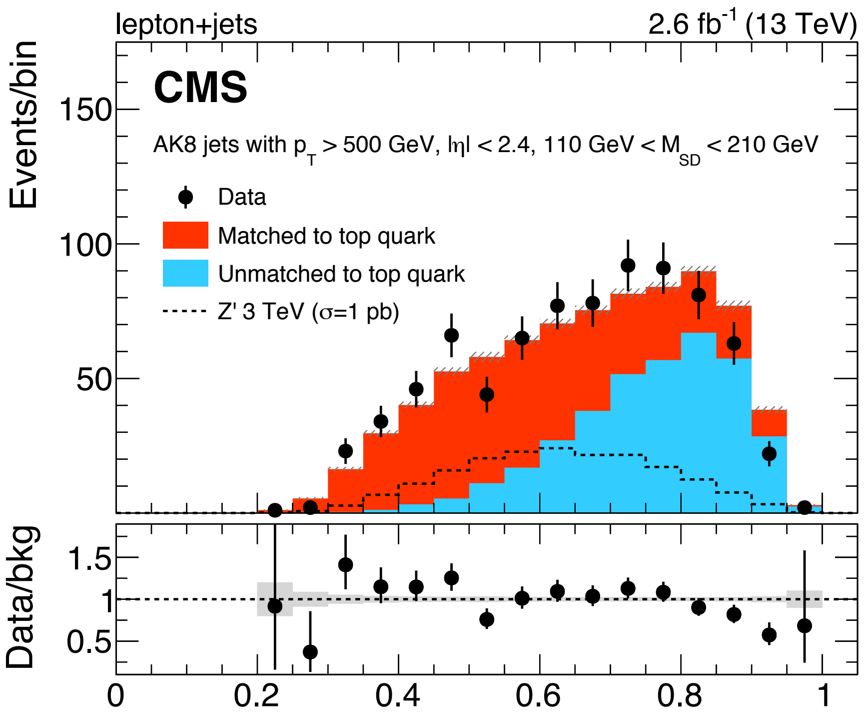
ingredients for leptonic W



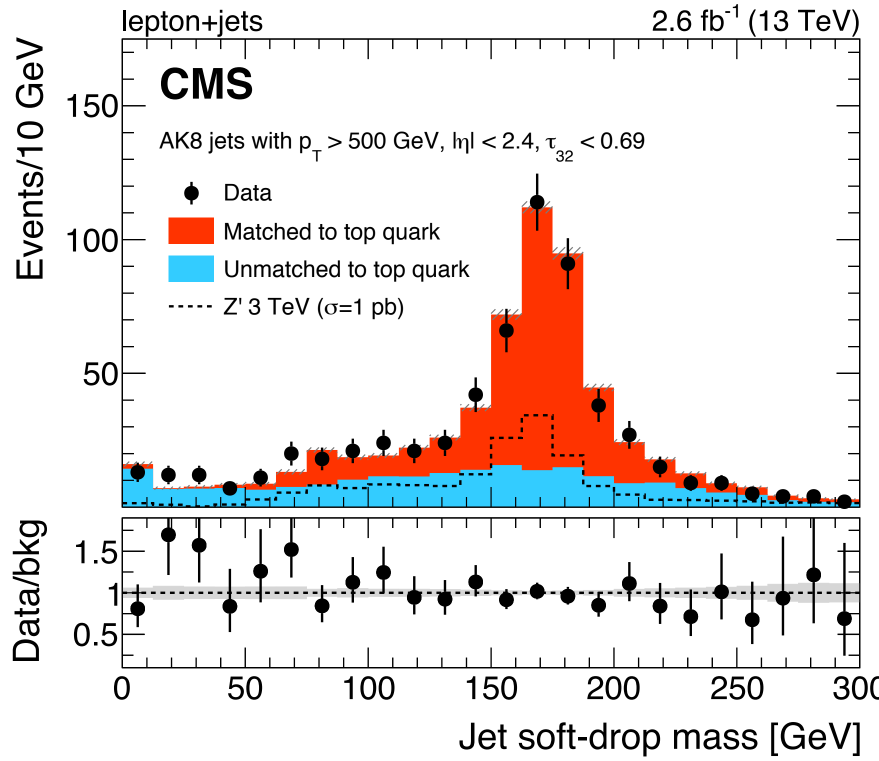
(figure by A Ovcharova (UCSB))

- **≥ 2 small-R** anti-k_T (R=0.4) **jet** with leading p_T > 250 (150 GeV) in e(μ) chan, p_T > 30GeV for all jets
- **only zero or 1 large-R top tagged jet:** anti-k_T (R=0.8) with **τ_{32} < 0.69** and **110<$m_{jet,SoftDrop}$<210 GeV** (50% ε_S, 3% ε_B) (orth. to fully had)
- b-tag on anti-k_T (R=0.4) (65% eff)

ingredients for hadronic & leptonic top



gen level matching



6 selection regions

2 flavours x

	1 top tag	**0 t-tag &1 b-tag**	0 t-tag &0 b-tag
events	394	10447	8971
tt purity(%)	85	82	24

EFT

Effective field theory in a nutshell

We are all Wilsonians now ! (JPreskill, Caltech)

- Current **absence of “light “ new states** in SM → possible **new physics at higher scales/masses** than observed
- Effective Field Theory: ultraviolet divergences = manifestation of new phys. Renormalisation= Lagrangian is “new phys scale”-dependent ←absorb effects of fluctuations/momenta between observed and high new phys. scale in few parameters

(F Maltoni, LHCTopWG open meeting Nov 2016)

- SM measurements “searches for deviations predictions of SM in dim=4 .

dimensionless Wilson coefficients

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

- *Parametric new degrees of freedom in terms of old*

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in a simple and powerful way in terms of one statement:

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

Initial attempt:Top Fitter

TopFitter Coll, JHEP04(2016)015

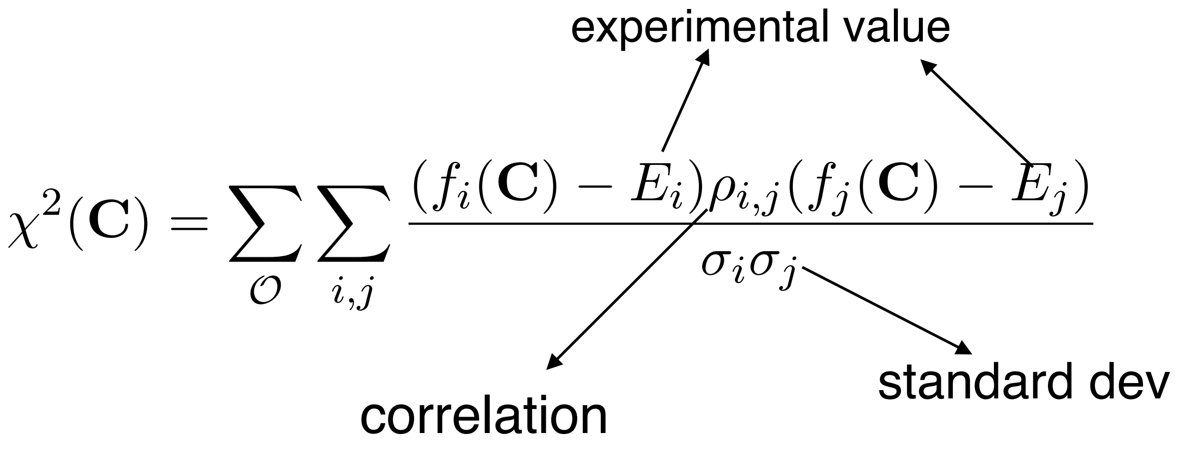
Fit ~40 **measurements** from LHC & Tevatron (five 1-dim differential xsec for tt and single top too) to **predictions** to derive 12 couplings

Buckley et al, TopFitterColl, arxiv:1612.02294

Phys.Lett.B 763 (2016) 9

Predictions as polynomials

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



experimental value

$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

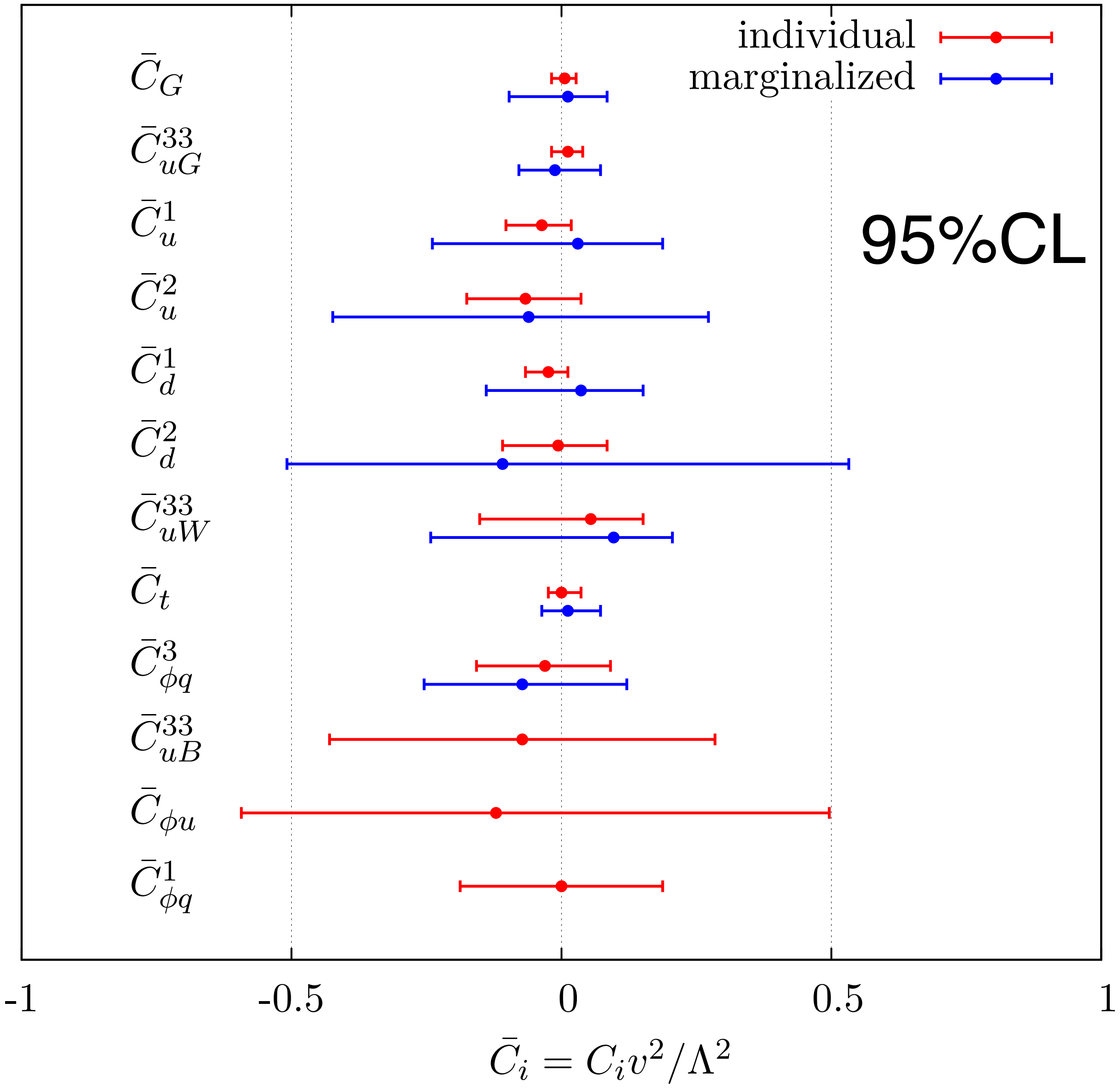
correlation

standard dev

Including covariances where provided by experiments otherwise $\rho_{i,j}$ =$\delta_{i,j}$

fit each operator one at the time

fit globally and marginalise over all other parameters

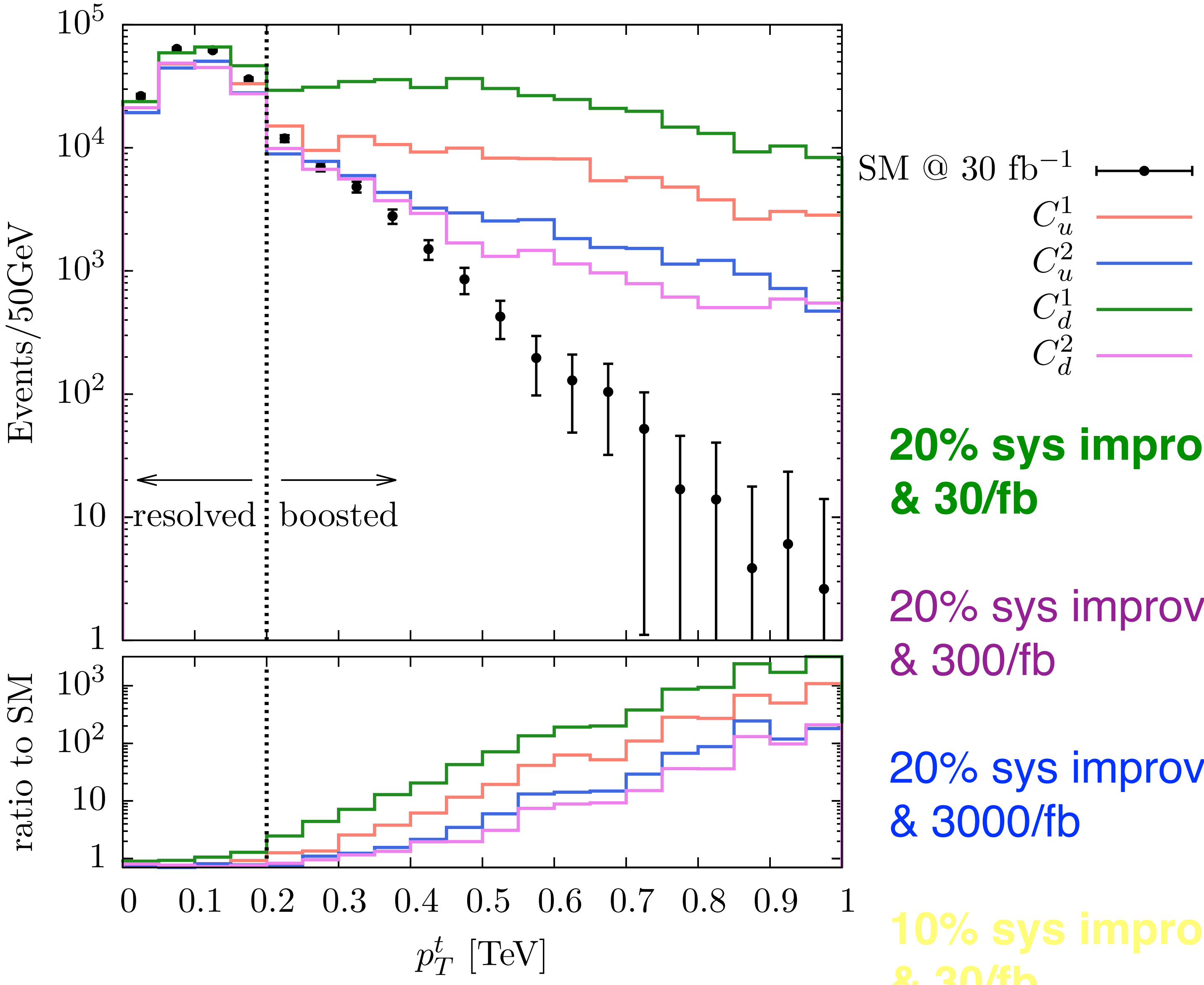


All operators are consistent with zero at 95% CL

Initial attempt:Top Fitter

Buckley et al, TopFitterColl, arxiv:1612.02294

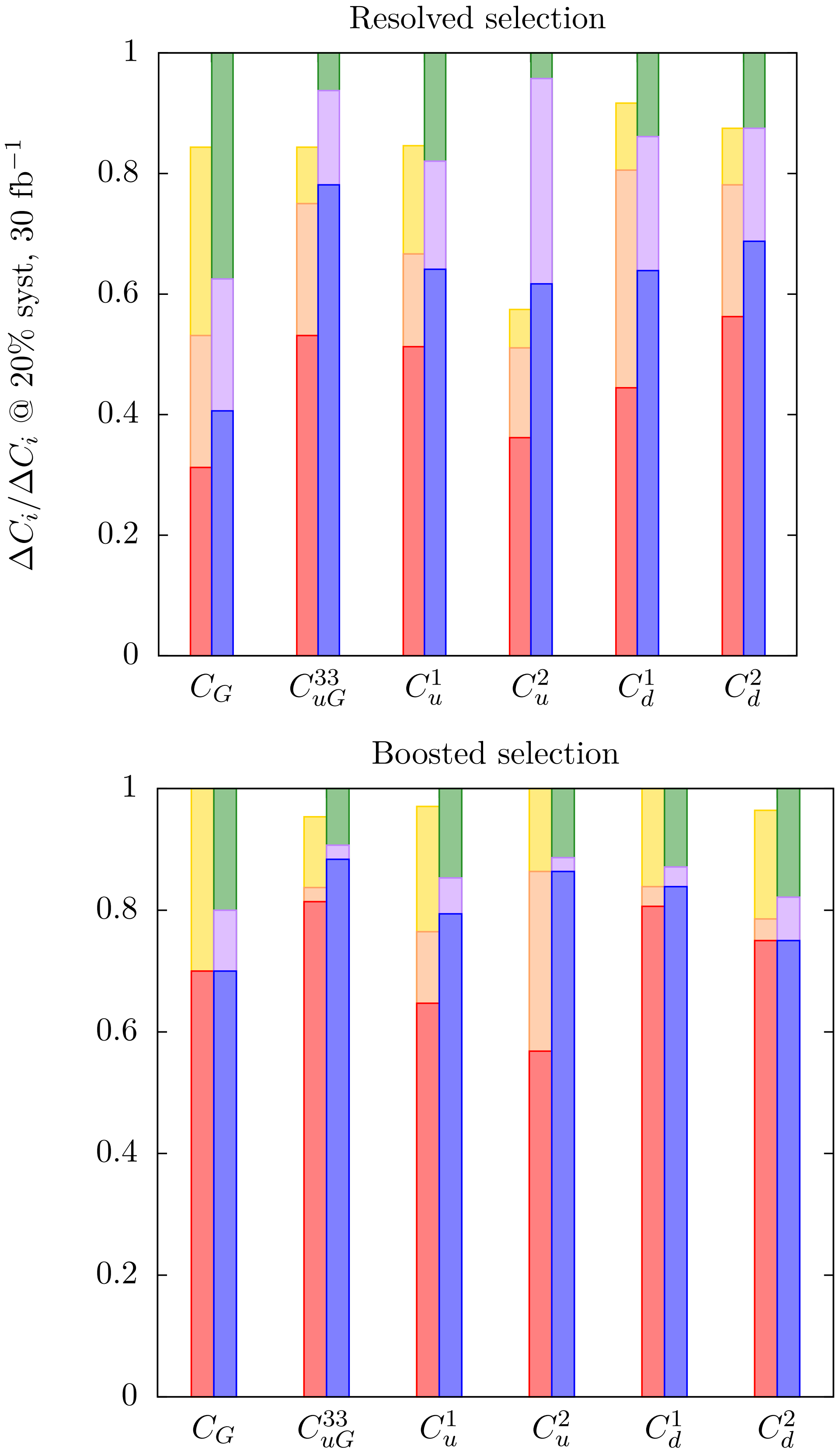
Present bound on coefficients are weak : resulting Scale close to high energy range of $d\sigma_{tt}/dX$ where EFT breaks down



Isolate region that are most sensitive to tails : fit resolved and boosted

More data give modest gain in boosted.

Fractional improvement on 95% CL confidence interval



20% sys improvement & 30/fb

20% sys improvement & 300/fb

20% sys improvement & 3000/fb

10% sys improvement & 30/fb

10% sys improvement & 300/fb

10% sys improvement & 3000/fb