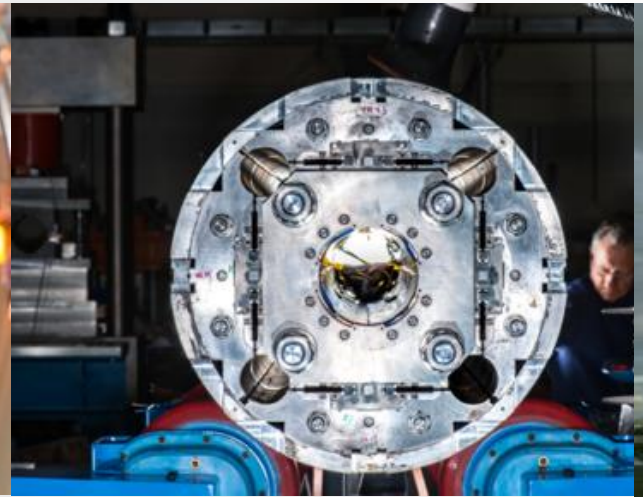
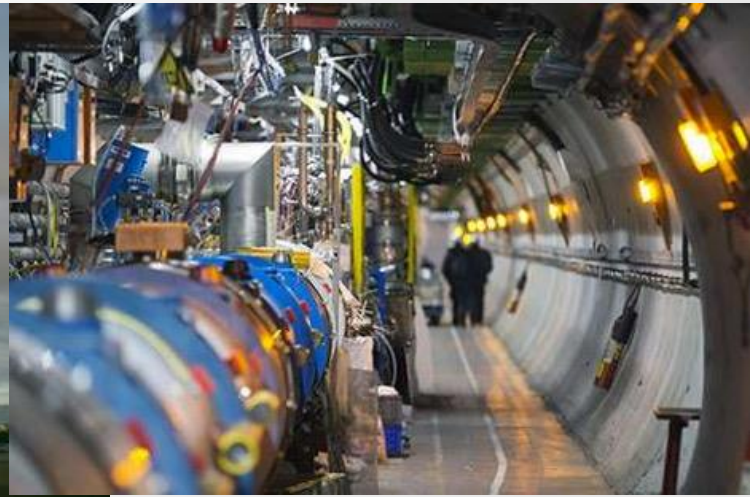
TOP QUARK PHYSICS
HL/HE-LHC PHYSICS WORKSHOP

R. SCHÖFBECK, HEPHY VIENNA



WHAT ARE WE SUPPOSED TO DO?

- Indico is explicit on the objective for today:

Description This is the final event of the Workshop on Physics at HL-LHC, and perspectives for HE-LHC, which started with the kickoff meeting of October 30 2017.

This jamboree will present the findings of the five WGs, documented in the respective Reports. It will be an ideal occasion to celebrate the success of the Workshop, and to reflect on the impressive prospects of the future LHC programme!

Let's follow orders now.

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But why? Partly because WG1 chapter is on arXiv!

And How?
By going through p120-160!

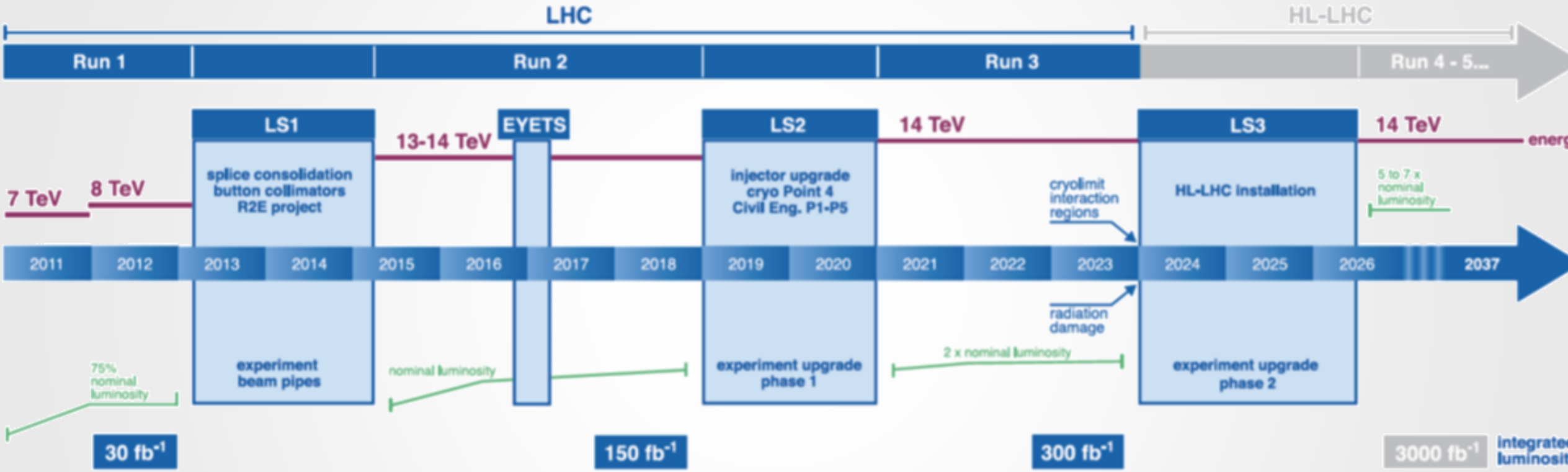
… and the 1377 pages in Vol. 2 on the arXiv yesterday!

1902.04070.pdf 120 / 219

6 Top quark physics

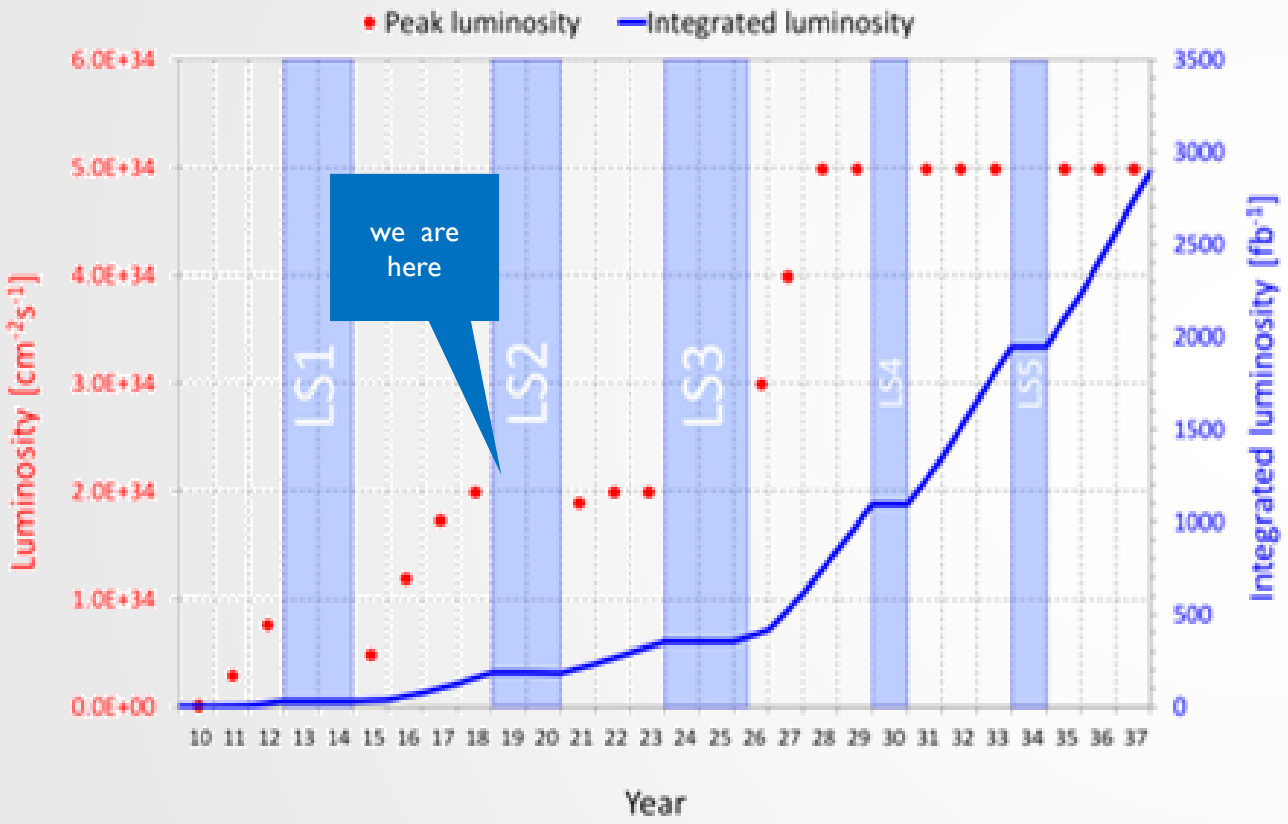
Precision measurements of top quark properties present an important test of the SM. As the heaviest particle in the SM, the top quark plays an important role for the electroweak symmetry breaking and becomes a sensitive probe for physics beyond the SM.

LHC / HL-LHC PLAN



- Scenarios for projections
  - HL-LHC pp running at 14 TeV, 200 PU (5 $10^{34}cm^{-2}s^{-1}$), 3/ab or 4/ab in the 'ultimate' scenario
  - HE-LHC pp running at 27 TeV, 15/ab

LUMINOSITY AND UNCERTAINTIES



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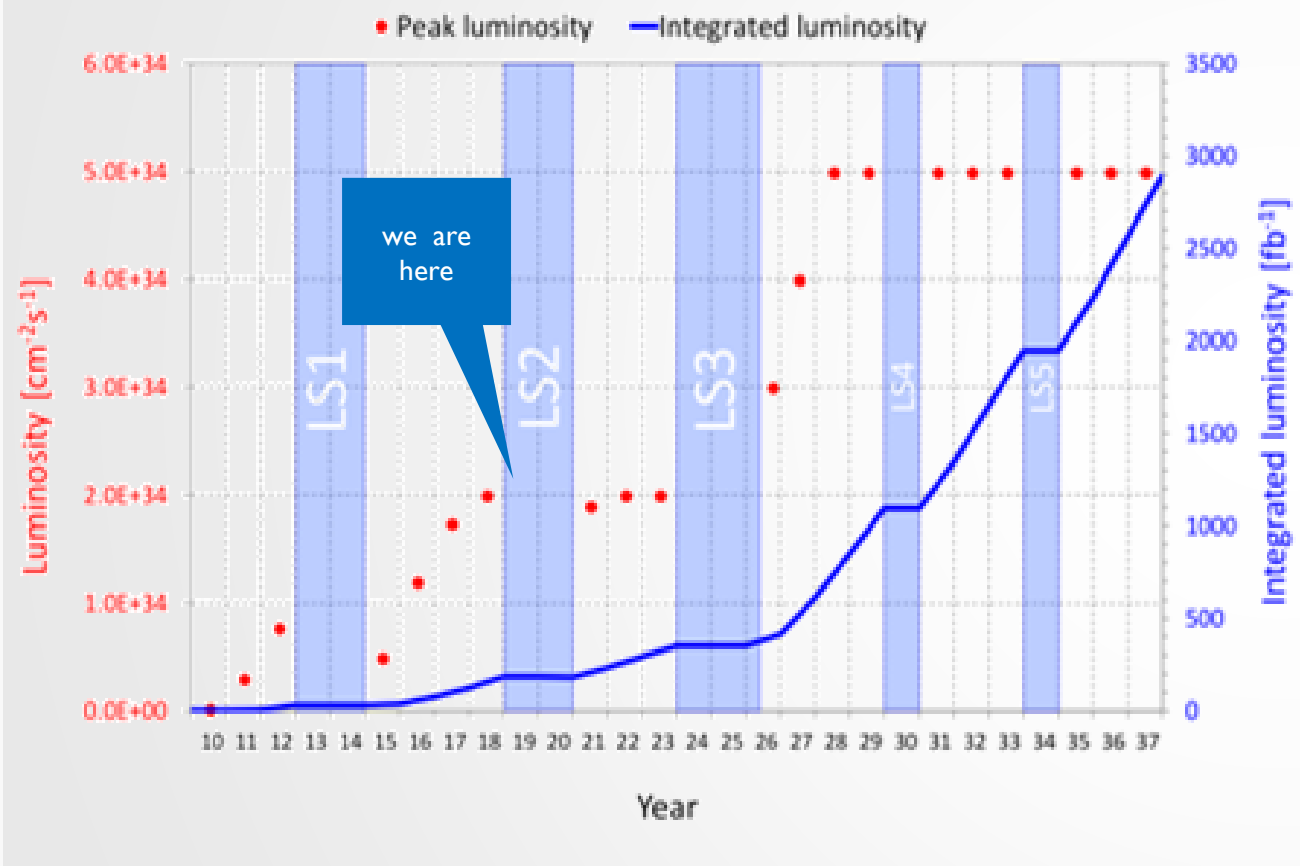


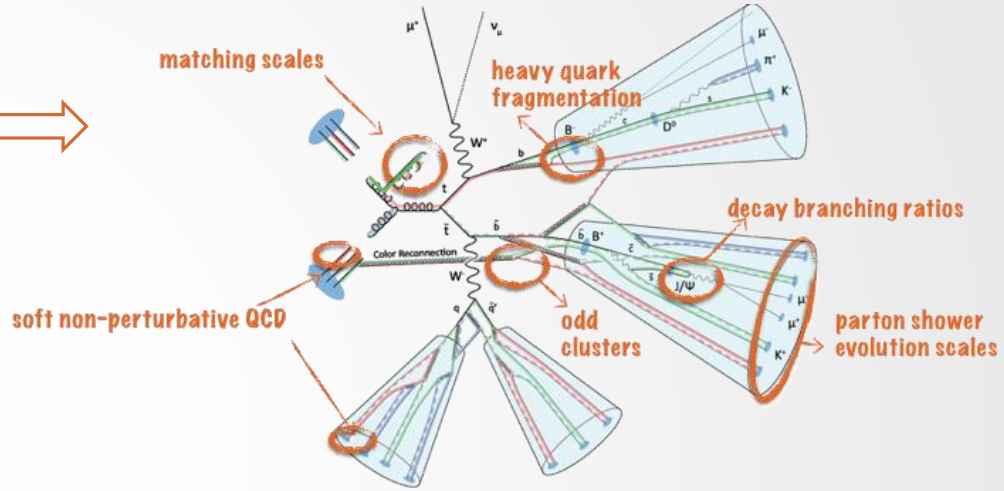
"Frequently made assumptions"

- uncertainties in object performance
  - machine upgrades (PU≈200) and detector approximately compensate
- theoretical uncertainties reduce by factor 2
  - PDF, better PS tunes, ME corrections, etc.
- statistical uncertainty scales with luminosity
- we will be able to afford computing
  - do not consider statistical uncertainty of MC

- more details in the backup

SETTING THE STAGE FOR PHYSICS WITH THE TOP QUARK

- A great many things have to come together
  1. state of the art theoretical tools/calculations
     - estimate of 10+ years of future development
  2. low-level understanding of sub-detector performance
  3. object performance – realistic projections
  4. novel analysis ideas that incorporate 1-3



SETTING THE STAGE FOR PHYSICS WITH THE TOP QUARK

Phys. Rev. Lett. 116 (2016) 8, 082003

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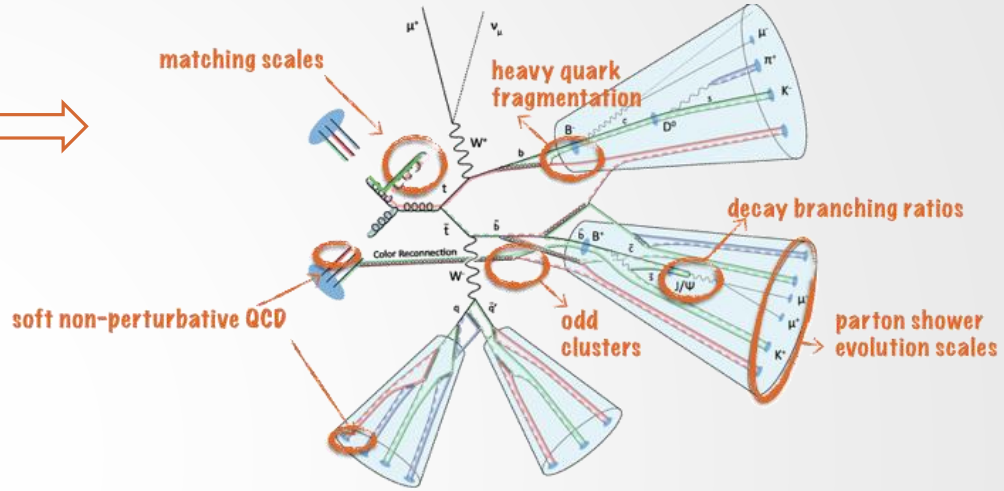
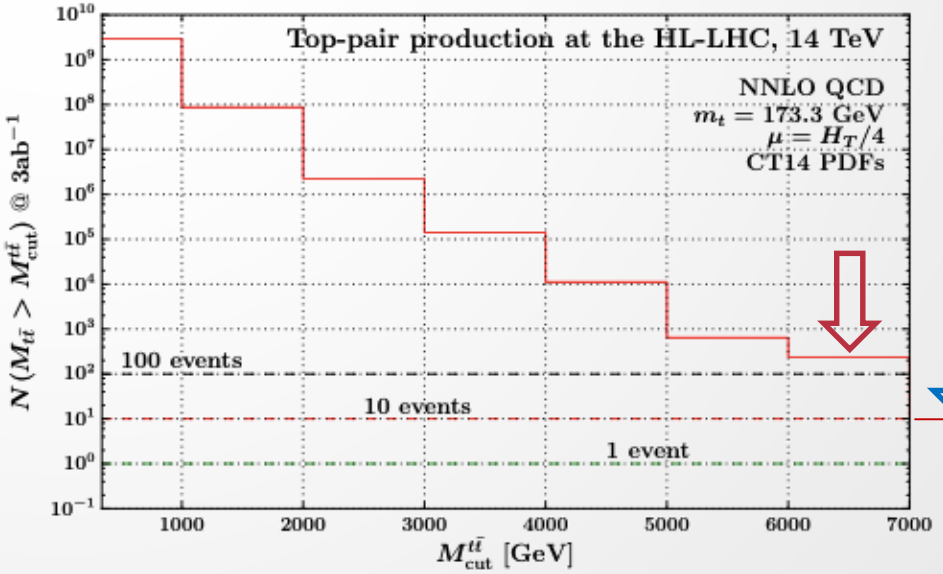


- first question: How far do we reach in top quark pair kinematics?
- Let's set the stage with the differential top cross section theory calculation
  - NNLO QCD for HL-LHC 14 TeV with 3/ab
  - NLO QCD for HE-LHC 27 TeV with 15/ab
  - NB: EWK corrections will be essential

Cumulative M^{tt} distribution for HL-LHC



equivalent count currently (36/fb) at $M^{tt} \gtrsim 2.5$ TeV

≈10 events $M^{tt} > 7$ TeV

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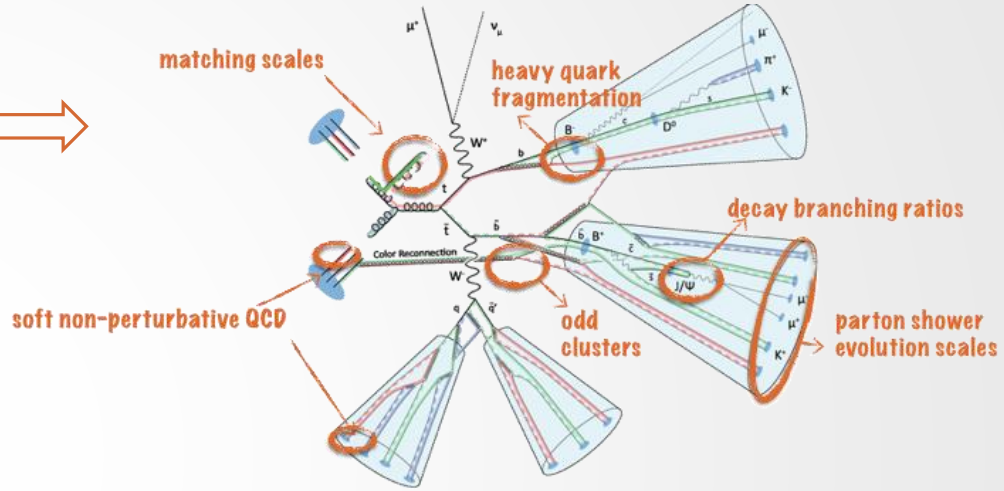

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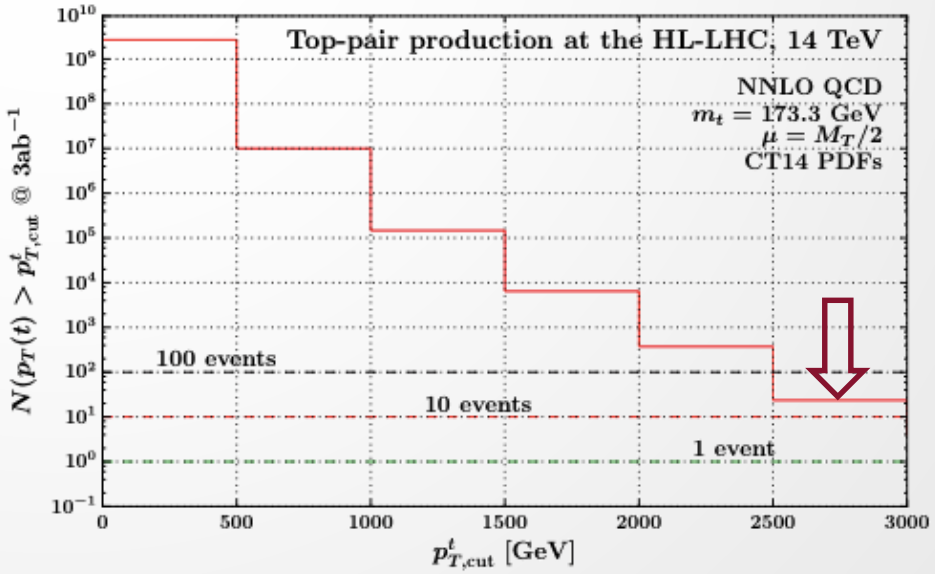
Cumulative $p_T(t)$ distribution for HL-LHC



≈20 events
p_T > 2.5 TeV
TeV scale jets/leptons collimated to slim jets: $\Delta R \approx 0.13$ (16cm @ CMS ECAL)

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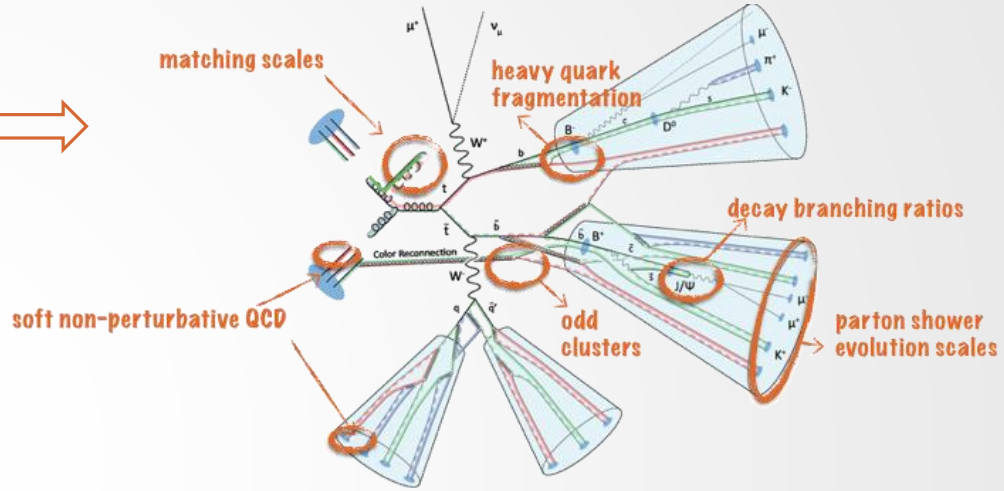

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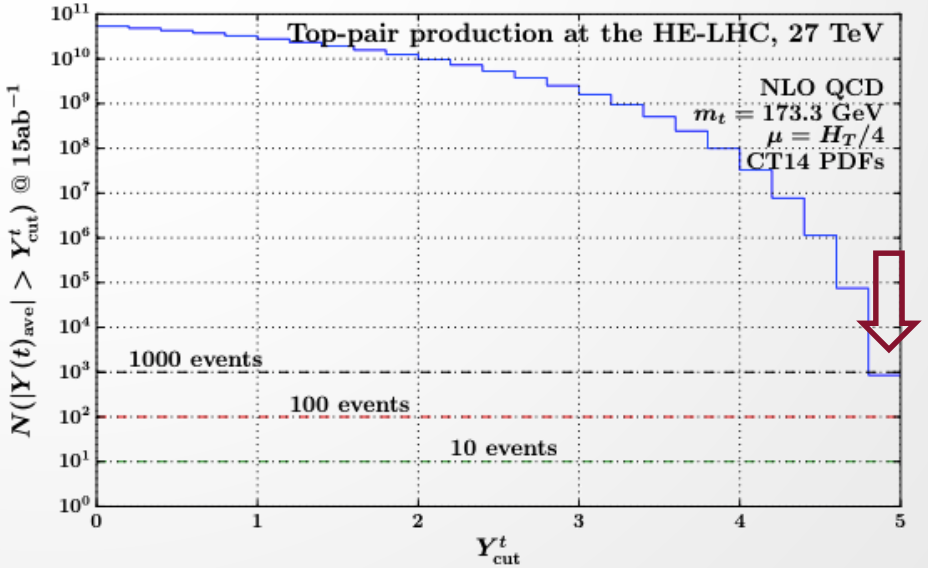
HE-LHC η(t) distribution for HE-LHC



≈1000 events with η(t)>4.8

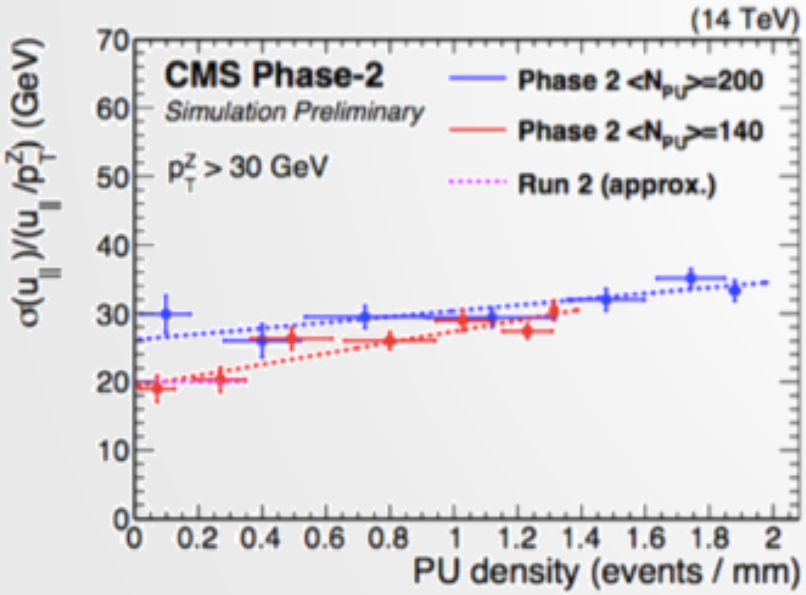
large overlap in phase space with LHCb

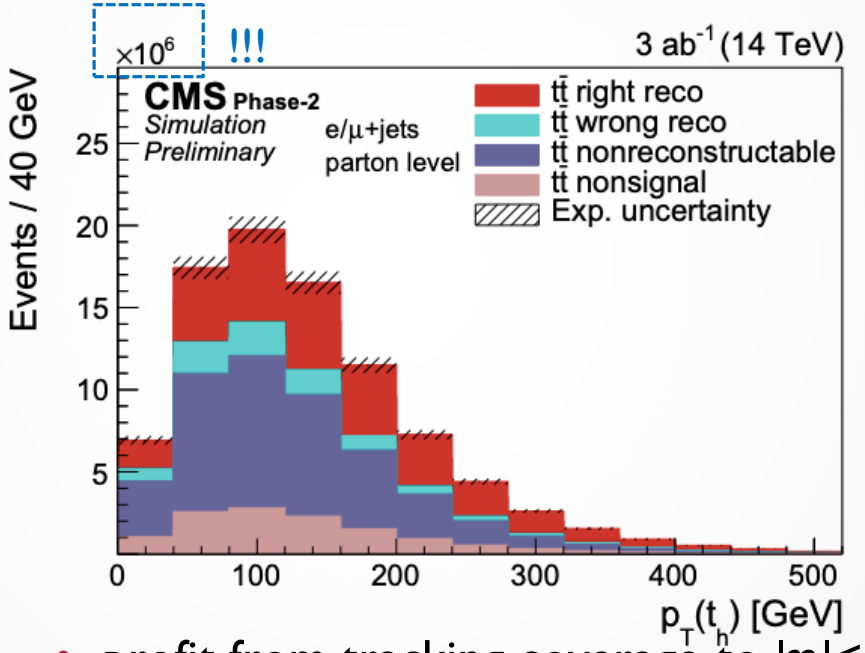
PRECISION FROM THE BULK

CMS-FTR-18-015, CMS-NOTE-2018-006

- differential top cross section measurement (HL-LHC 3/ab, 14 TeV)
- extrapolation based on Delphes, single lepton channel
- PU mitigation for E_T^{miss} required

Puppi E_T^{miss} resolution for $p_T(Z)>30$





- profit from tracking coverage to $|\eta|<4$
- unfolding purity and stability similar to Run-II, despite the higher PU

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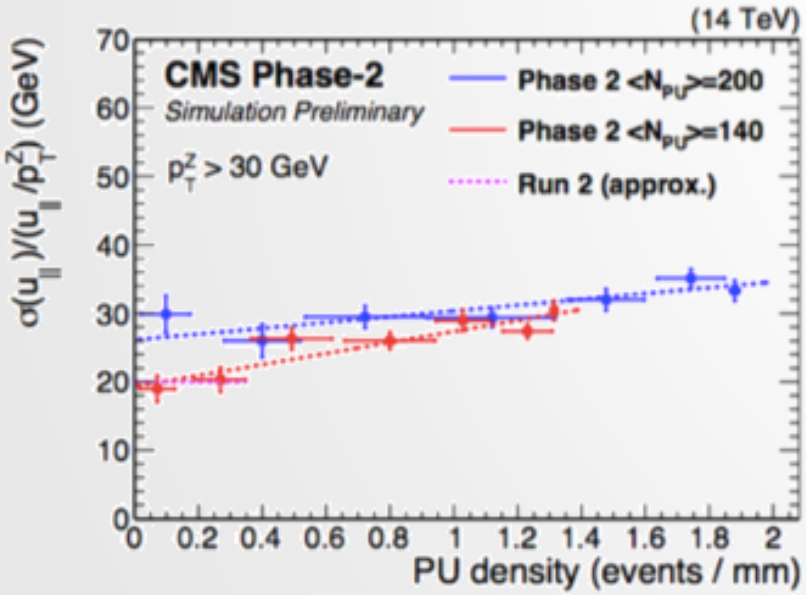

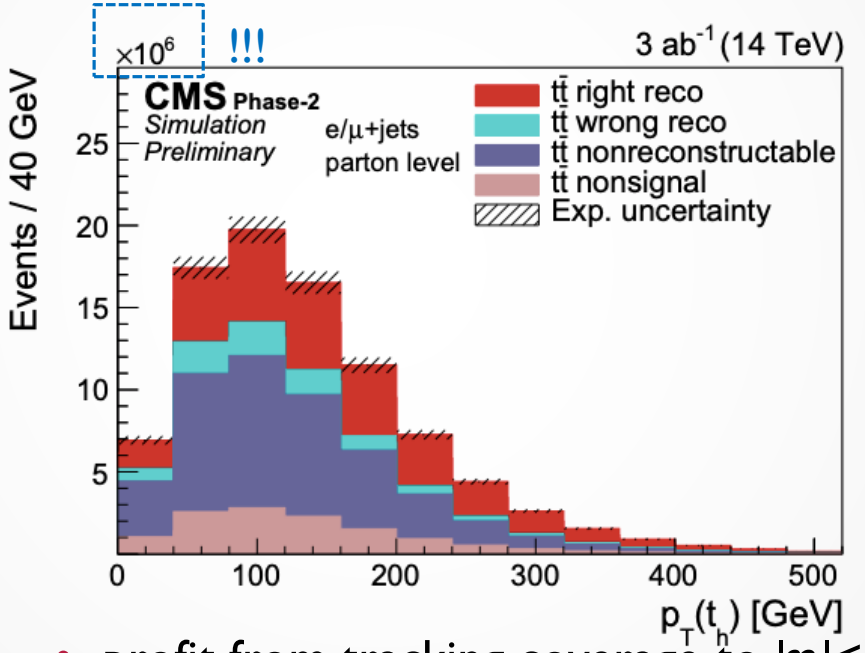

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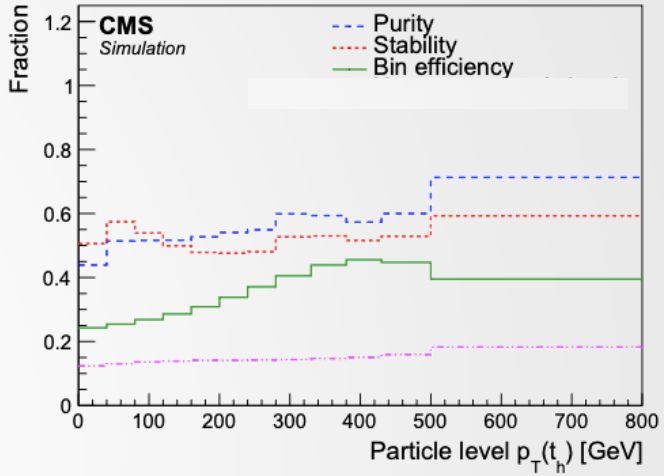
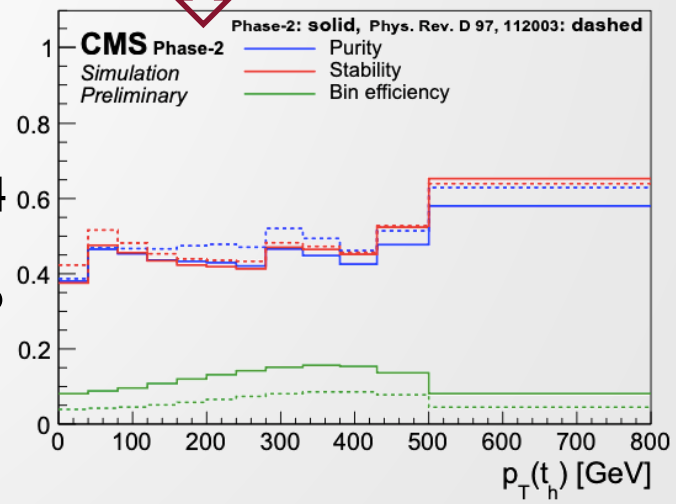


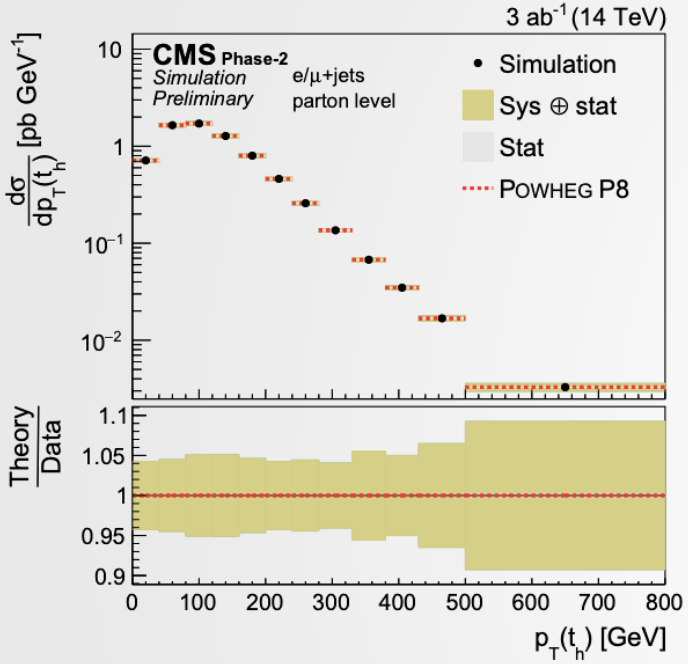
Phase-II

Run-II

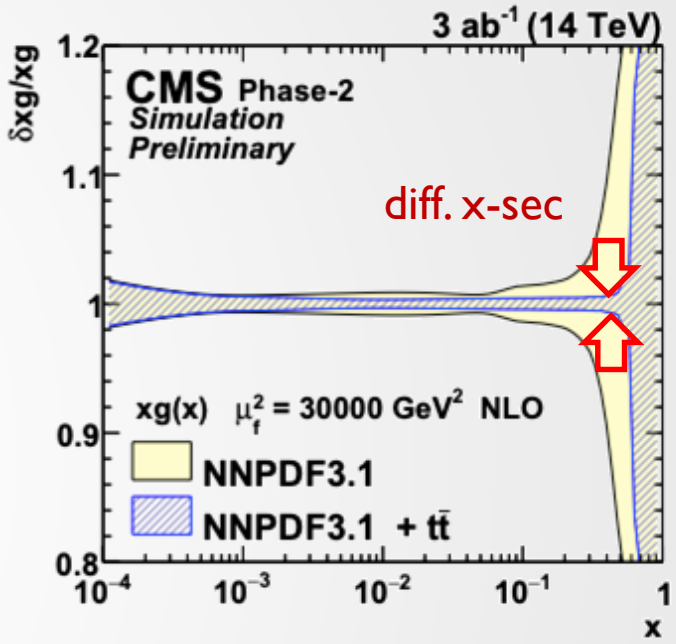


PRECISION FROM THE BULK AND FROM HIGH ETA

CMS-PAS-FTR-18-015, arXiv:1311.1810, arXiv:1808.08865



- uncertainty on differential top x-sec O(5%)
- significant impact on high x gluon PDF
- complemented with forward tops:



background level

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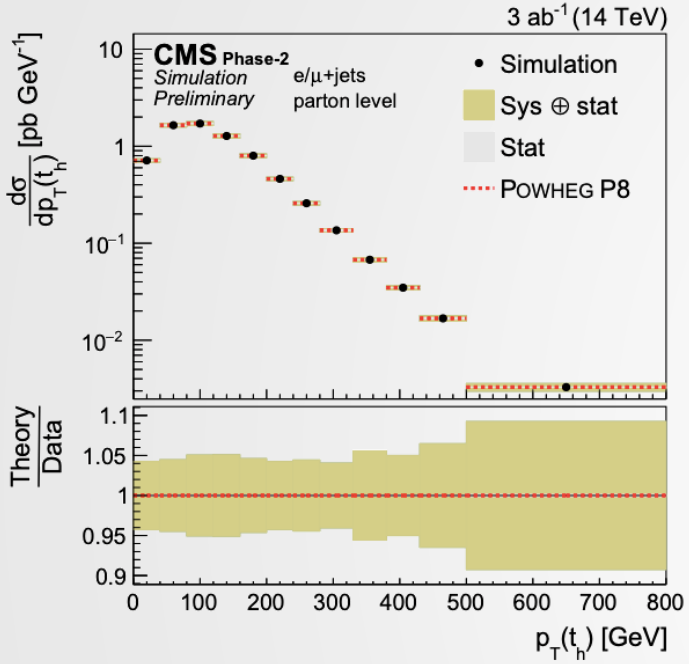
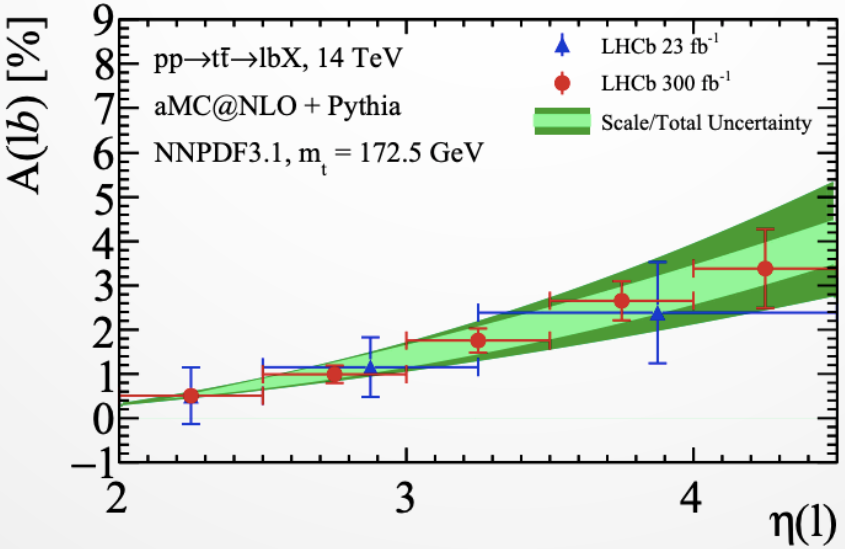
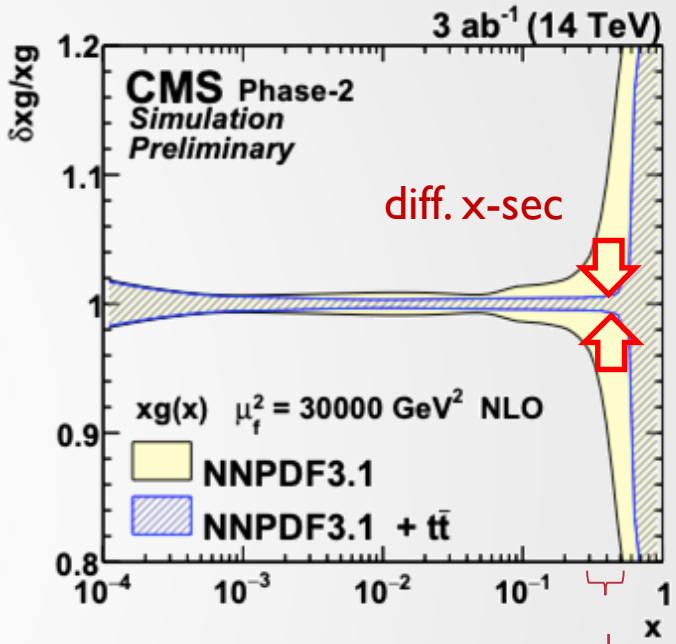


differential $l^{\pm}b$ charge asymmetry prospects from LHCb (300/fb for HL/LHC) sensitivity to quark PDFs

- uncertainty on differential top x-sec O(5%)
- significant impact on high x gluon PDF
- complemented with forward tops:
  1. 300/fb LHCb data probe high-x PDFs with partially reconstructed top quarks
  2. quark PDFs: use differential charge asymmetry vs. lepton **η**





sensitivity from 300/fb of LHCb data in (partial) t and tt final states

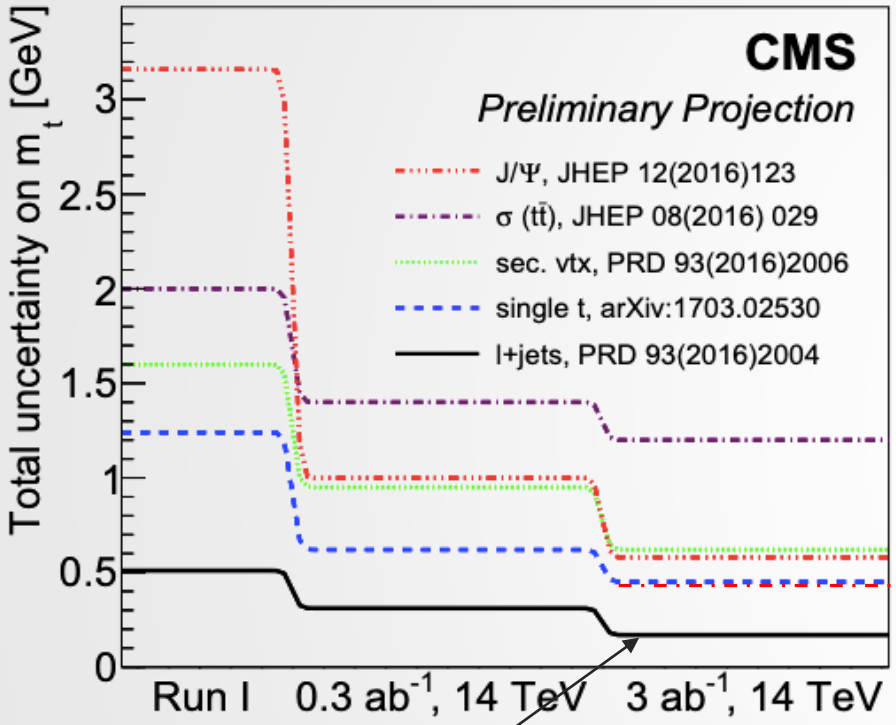
Final state	300 fb^{-1}	$< x >$
ℓb	830k	0.295
$\ell b\bar{b}$	130k	0.368
$\mu e b$	12k	0.348
$\mu e b\bar{b}$	1.5k	0.415

stat precision

background level

TOP MASS

CMS-PAS-FTR-16-006, ATL-PHYS-PUB-2018-042



0.17 GeV ⟶ 0.1 %
dominated by JES

- top mass measurement requires precision on all fronts!

- simple concept:
  1. pick out jets from top
  2. pair up the right jets to each top
  3. calculate mass
- challenges (a selection)
  - efficient b tagging (combinatorics)
  - moderate p_T triggers
  - systematic relating the 'MC mass' to a well defined parameter in a ren. scheme to 100 MeV
  - precision JES & E_T^{miss}, lepton E scale

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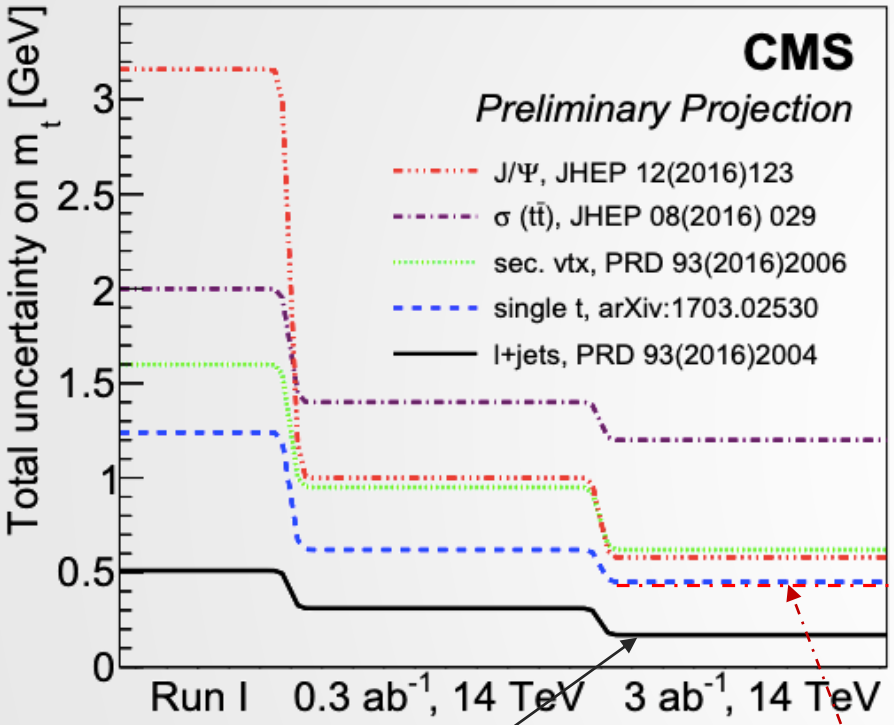

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ATLAS J/Ψ projection
± 0.14 (stat) ± 0.48 sys

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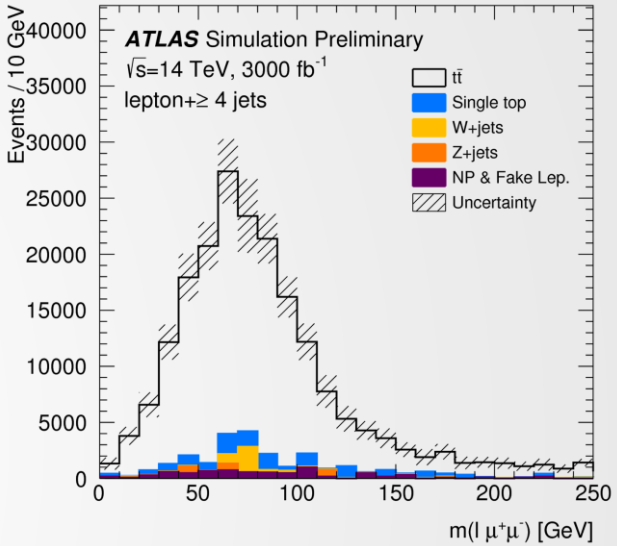
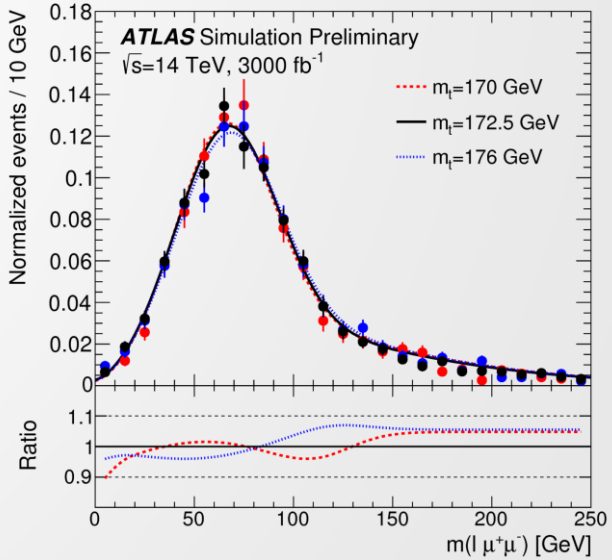
- Mitigate JES by considering 0.04% BR with a J/Psi: $t\bar{t} \rightarrow (W^+b)(W^-b)$ $\rightarrow (\ell\nu_\ell J/\psi(\rightarrow \mu^+\mu^-)X)(qq'b))$

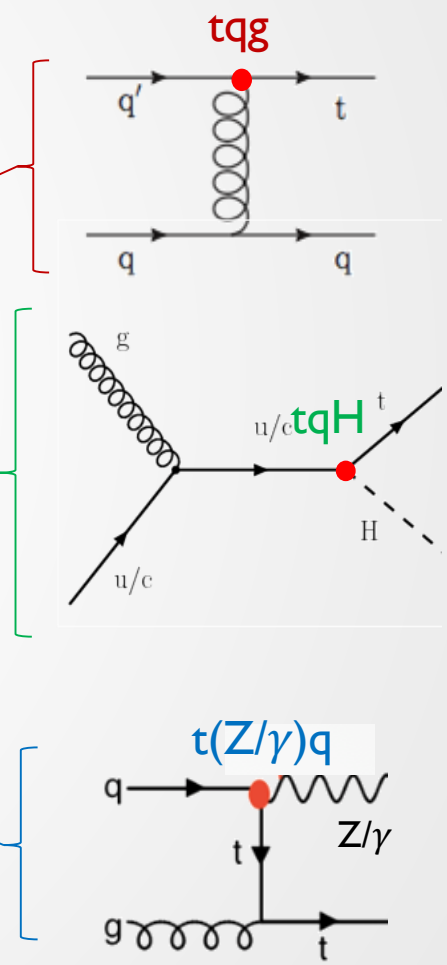




FLAVOR CHANGING NEUTRAL CURRENTS

- FCNC BR suppressed to 10^{-12} – 10^{-15} in SM by GIM mechanism
- sensitive probe BSM models (2HDM, SUSY, RPV, …)
- traditionally use anomalous coupling Lagrangian:

$$\mathcal{L}_{FCNC} = \sum_{q=u,c} \Bigg[\sqrt{2} g_s \frac{\kappa_{tgq}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu} T^a (f^L_{gq} P_L + f^R_{gq} P_R) t\right) G^a_{\mu\nu}$$
$$+ \frac{g}{\sqrt{2}} \kappa_{tqH} \left(\bar{q}(f^L_{Hq} P_L + f^R_{Hq} P_R) t\right) H$$
$$+ e \frac{\kappa_{tq\gamma}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu}(f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) t\right) F_{\mu\nu}$$
$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{tqZ}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu}(\hat{f}^L_{Zq} P_L + \hat{f}^R_{Zq} P_R) t\right) Z_{\mu\nu}$$
$$+ \frac{g}{4 c_W} \zeta_{tqZ} \left(\bar{q}\gamma^\mu(\bar{f}^L_{Zq} P_L + \bar{f}^R_{Zq} P_R) t\right) Z_\mu \Bigg] + \text{h.c.}$$

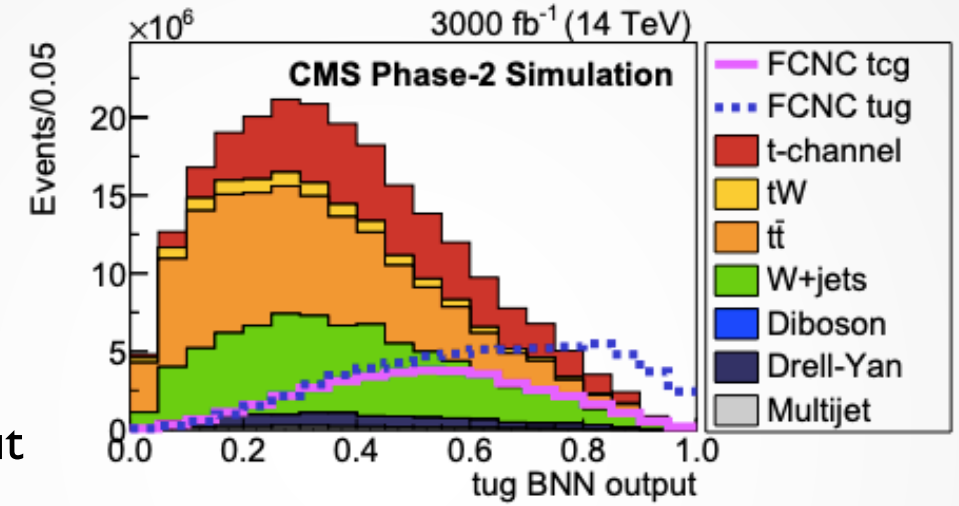


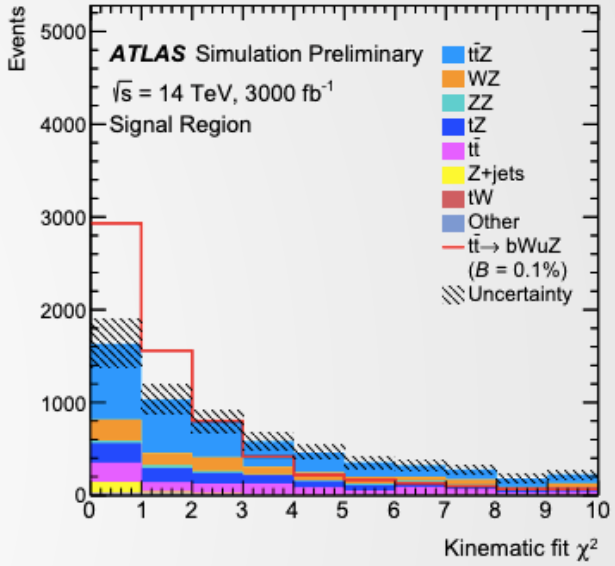
- In practice, often simplify chiral structure, e.g. $f^R = 1$
- q = u,c with more sensitivity to u (higher x-sec)

ATLAS AND CMS ON FCNC

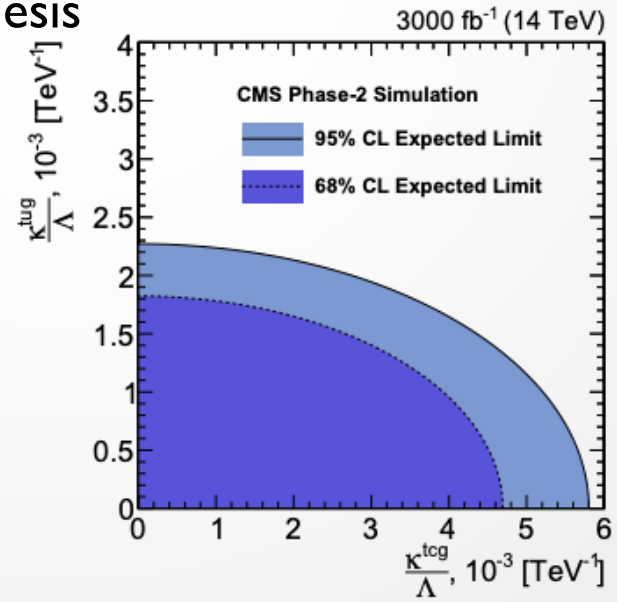
ATL-PHYS-PUB-2019-001, CMS-PAS-FTR-18-004

- Comprehensive studies by ATLAS (tZq) and CMS (tqg)
- Both simulate dedicated signal and background samples and follow the Run-II startegies
- CMS uses BNN on kinematic input
- ATLAS uses χ^2 constructed under FCNC hypothesis
- Improvement typically one order of magnitude





$\mathcal{B}$ limit at 95%C.L.	HL-LHC 3 ab^{-1}, 14 TeV	HE-LHC 15ab^{-1}, 27 TeV	Run-II (36/fb)
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	2×10^{-5}
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	4×10^{-4}
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		$1.7\text{-}2.4 \times 10^{-4}$
$t \to \gamma u$	8.6×10^{-6}		$1.3\ 10^{-4}$
$t \to \gamma c$	7.4×10^{-5}		$2.0\ 10^{-3}$
$t \to Hq$	10^{-4}		$1.1\ 10^{-3}$



- SM-EFT limits:

Operator	Expected limit
$\lvert C_{uB}^{(31)} \rvert$	0.13
$\lvert C_{uW}^{(31)} \rvert$	0.13
$\lvert C_{uB}^{(32)} \rvert$	0.14
$\lvert C_{uW}^{(32)} \rvert$	0.14

THE NEED FOR A COMMON LANGUAGE

- top quark: SM probe in wildly different settings
  - systematically limited high precision differential x-sec meas.
  - rare-event type searches (4t, …)
  - everything in between (T/TT+Z/W/H/γ, FCNC, …)

→ uncertainties evolve differently with time

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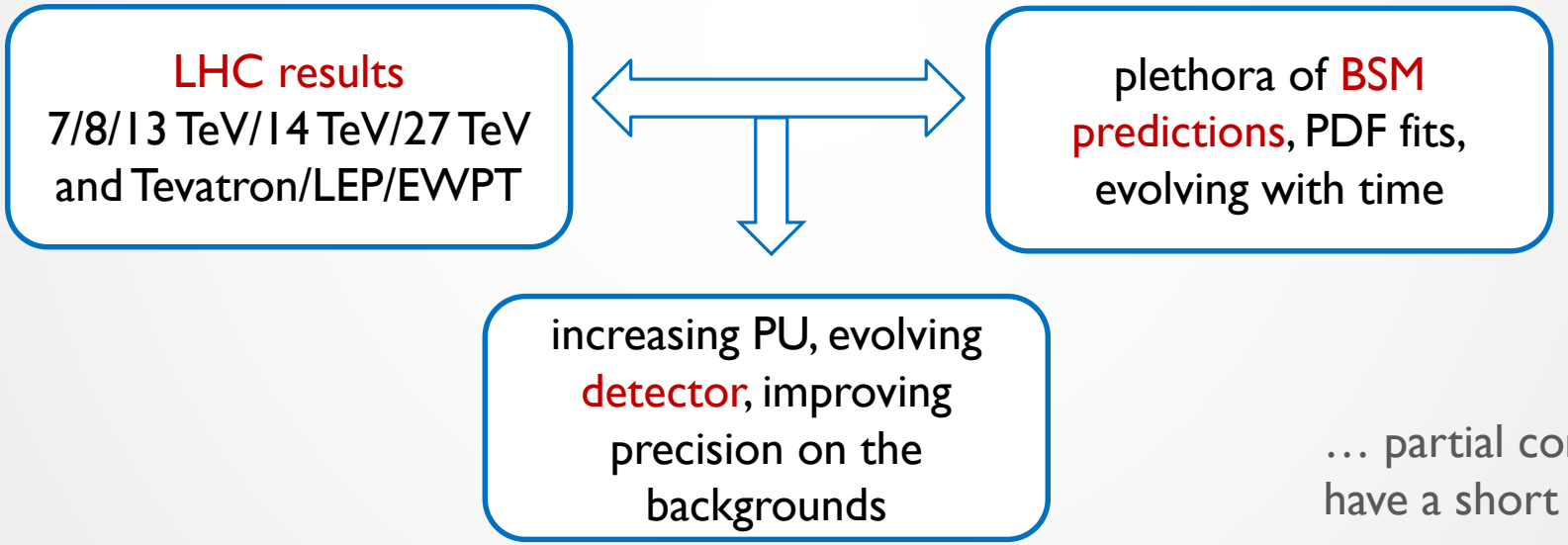
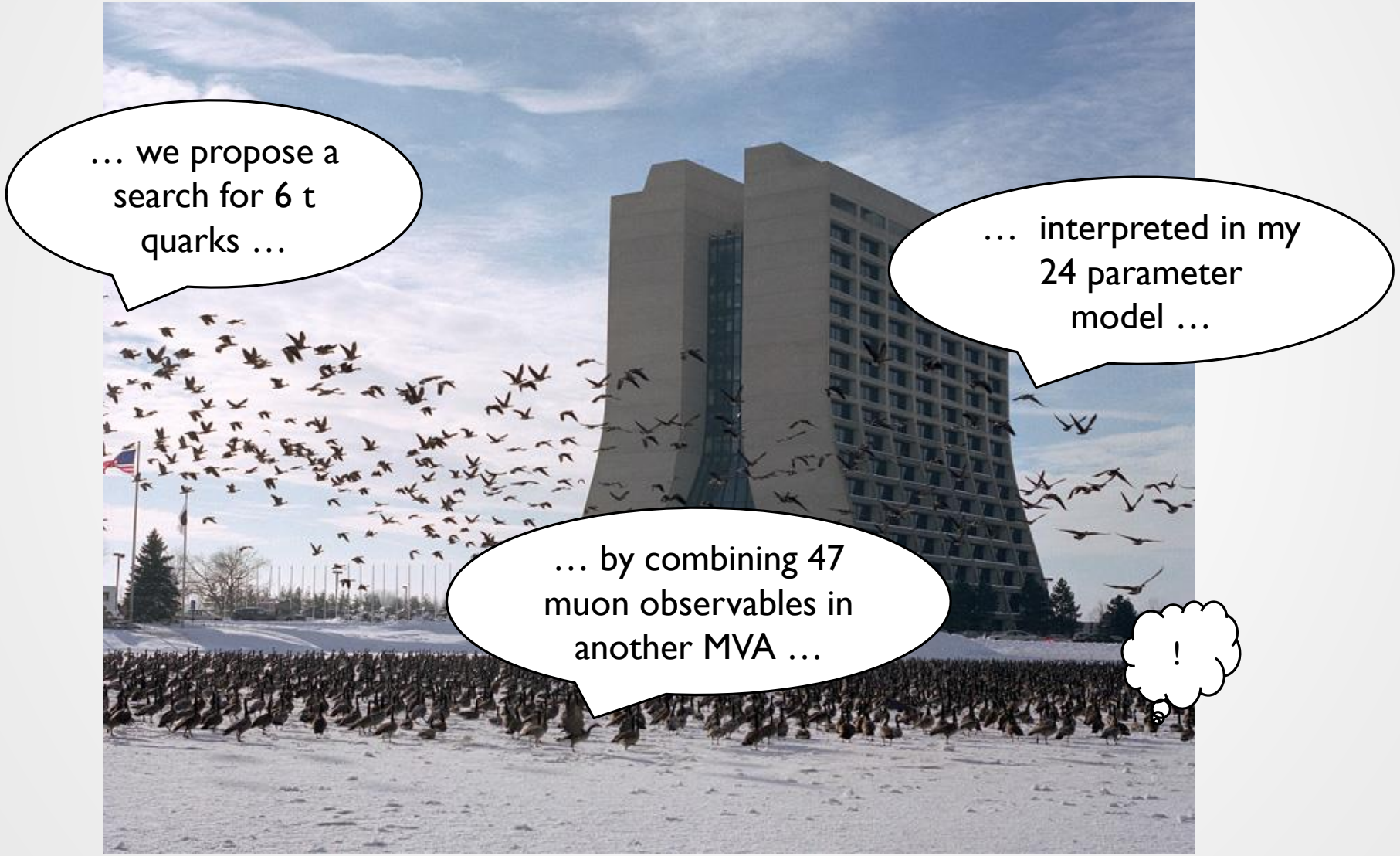


… partial comparisons have a short life.

WHEN WE ALL GATHER…



EFFECTIVE FIELD THEORY

- generic extension of the Standard Model

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

$O_{6,x}$ 59 dim-6 gauge-invariant ops.
C_x Wilson coefficients (complex)
Λ scale of dim-6 interactions

- defined in unbroken phase of SM → complex pattern after EWSB
- limited & well defined approximations
  - global way to look for NP in SM measurements
  - parameterizes deviations from higher-order SM predictions

- EFT provides guidance to exp. searches

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

  - e.g. on combination strategy in TT+X (respects gauge symmetries)
  - e.g. on where to include include 4-f ops (global hierarchy)
  - can derive $\boldsymbol{\sigma}$(C) on event level analytically ⟶ curse of dimensionality is lifted.

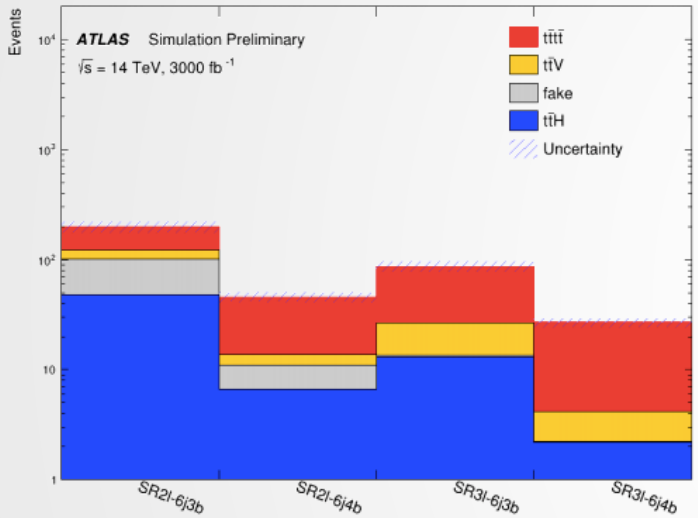
Compare with anomalous coupling approach:
- often break gauge symmetries
- no global hierarchy of effects
- less well defined assumptions
- pro: simpler interpretation

FOUR TOP PRODUCTION

ATL-PHYS-PUB-2018-047

Chin. Phys. C42 (2018) 2, 023104, Phys. Rev. D 95, 053004 (2017)

- 4 tops: complete NLO cross section known and EWK contributions not small (10%)



σ[fb]	LO + NLO	$\frac{\text{LO}(+\text{NLO})}{\text{LO}_{\text{QCD}}(+\text{NLO}_{\text{QCD}})}$
14 TeV	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)
27 TeV	$143.93^{+17\%}_{-20\%}$	1.11 (1.06)

- ATLAS and CMS studies in 2 same charge leptons or 3 lepton channel, ≥ 6 jet, ≥ 3 b-tagged jets
- Uncertainty in fake/nonPrompt is leading systematic, total uncertainty in meas. x-sec is 11% (ATLAS)
- Expect evidence for tttt with 300/fb at 14 TeV

FOUR TOP PRODUCTION

ATL-PHYS-PUB-2018-047

Chin. Phys. C42 (2018) 2, 023104, Phys. Rev. D 95, 053004 (2017)

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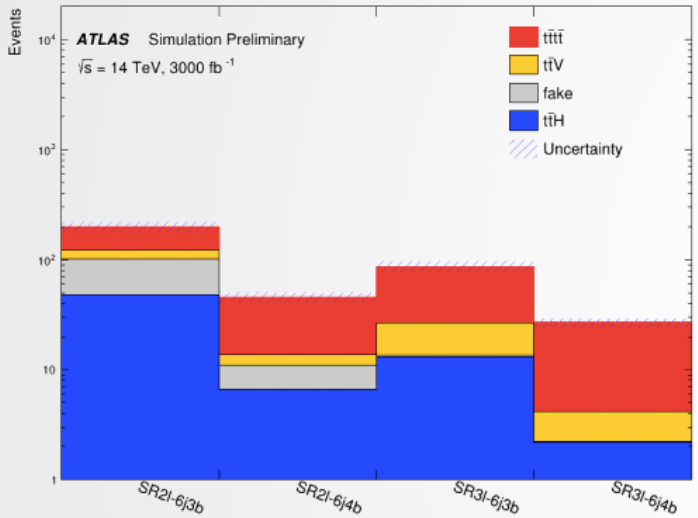

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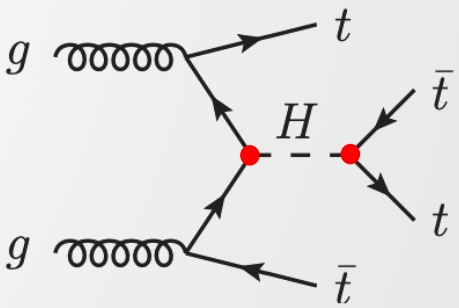
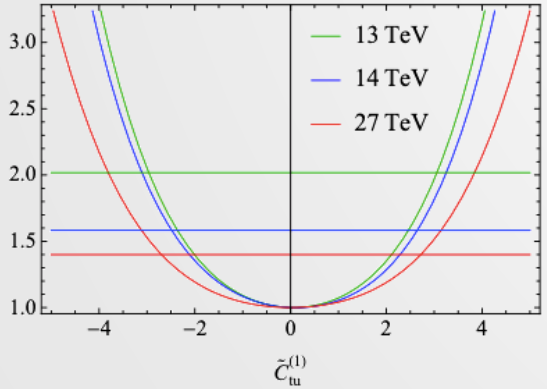
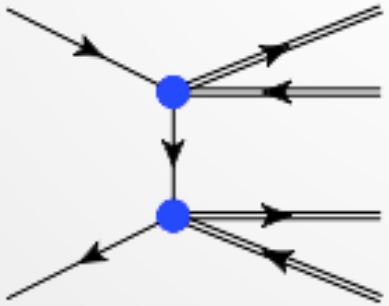


- Sensitivity to top Yukawa coupling modification is high
  - 14 TeV 3/ab $\sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4$ [fb]
  - 27 TeV 15/ab $\sigma(t\bar{t}t\bar{t}) = 115.10 - 15.57\kappa_t^2 + 11.73\kappa_t^4$ [fb]

- EFT limit on qqtt operator reflects 4th power





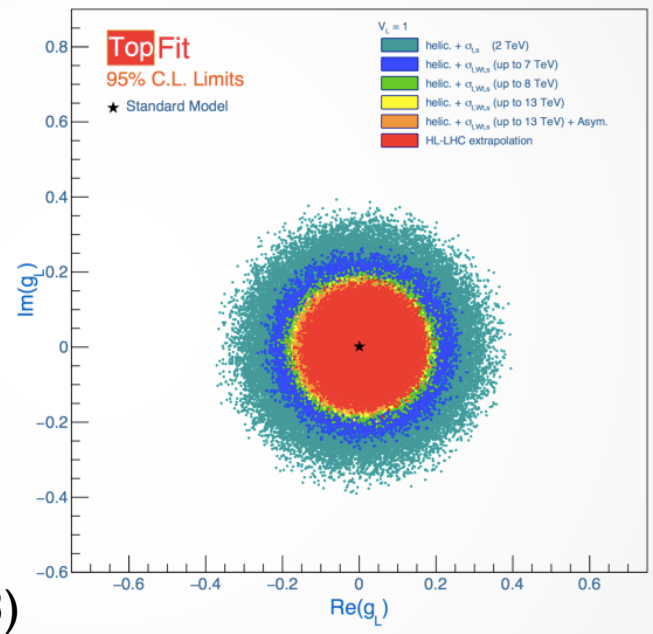
TOP-W COUPLING

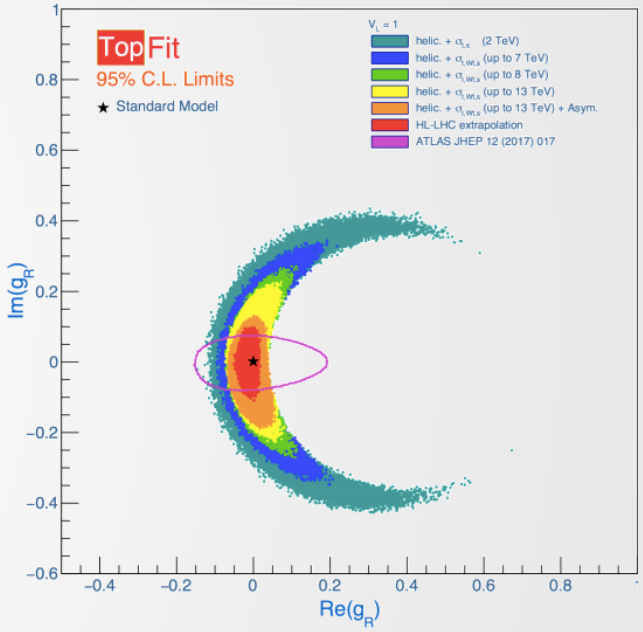
arXiv:1811.02492

- W boson helicity measurements, asymmetries and single top production are able to constrain potential anomalous Wtb couplings:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W^-_{\mu} + \text{h.c.}$$

- comprehensive list of measurements
  - W boson helicity from Tevatron & LHC (8 TeV)
  - A_{FB} from LHC (8 TeV)
  - single top x-sec from Tevatron and LHC (7/8/13)



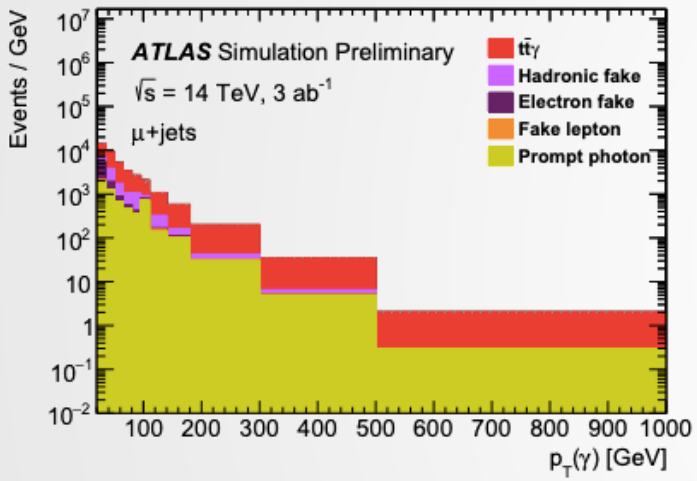


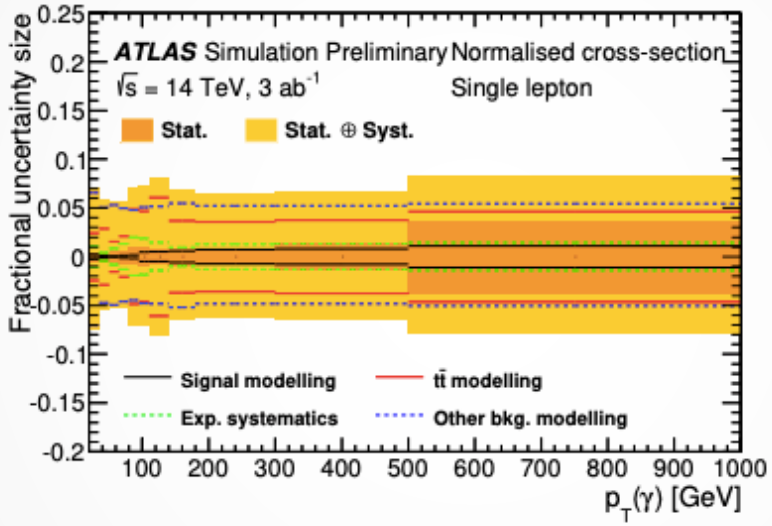
- Extrapolate to 3/ab & include scaled results
  - Reconstruction level uncertainties were kept (b-tagging was divided by two)

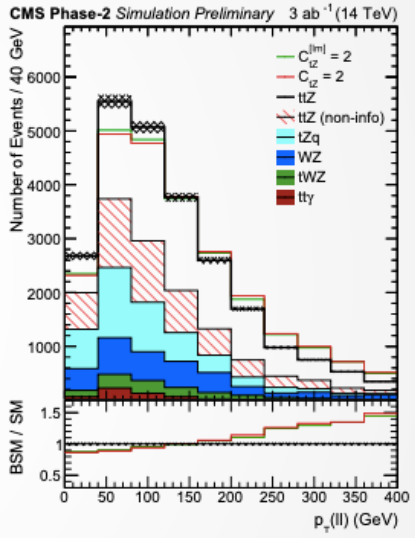
HL-LHC	g_R	g_L	V_R
Allowed Region (Re)	[-0.05 , 0.02]	[-0.17 , 0.19]	[-0.28 , 0.32]
Allowed Region (Im)	[-0.11 , 0.10]	[-0.19 , 0.18]	[-0.30 , 0.30]

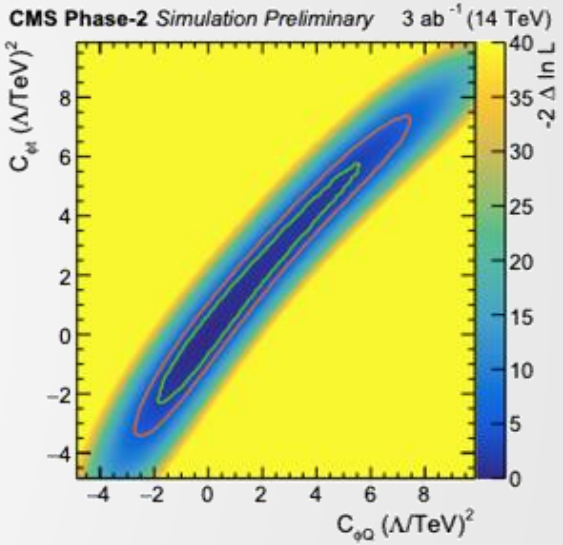
TOP-Z/γ COUPLING MEASUREMENT

- ATLAS/CMSL Delphes based study using $p_T(Z)$ and $p_T(\gamma)$. Constraint operators modifying t-Z/γ coupling
- ATLAS constraints ttγ (1l/2l) and CMS constraints ttZ (3l)









- theoretical uncertainties scaled to 50%
- expect an improvement in sensitivity by factor 4-6

ATLAS projection ⟵linear relations⟶ CMS Delphes based result

Operator	$\mathcal{O}_{tB}$	$\mathcal{O}_{tG}$	$\mathcal{O}_{tW}$
Single lepton	[-0.5,0.3]	[-0.1,0.1]	[-0.3,0.5]
Dilepton	[-0.6,0.4]	[-0.1,0.1]	[-0.4,0.3]

Wilson coefficient	68 % CL $(\Lambda/\text{TeV})^2$	95 % CL $(\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-1.65, 3.37]	[-2.89, 6.76]
$C_{\phi Q}$	[-1.35, 2.92]	[-2.33, 6.69]
C_{tZ}	[-0.37, 0.36]	[-0.52, 0.51]
⟶ $C_{tZ}^{[\mathrm{Im}]}$	[-0.38, 0.36]	[-0.54, 0.51]

≈ factor 4 better than 77/fb at 13 TeV

SUMMARY

- A lot of work has been done!
  - It's really time to celebrate.
  - I apologize for any perceived imbalance in the results presented
- HL/HE LHC significantly extend the kinematic reach for top quarks
- Push deeper into the precision frontier with top quark pairs (PDF) and the top mass
- More and more precise results on top BSM require a common language
- In top quark physics, experimental precision meets theoretical accuracy
  - Effective field theory is a way forward that can efficiently handle both
- Work remains to be done: More 'novel ideas' need to be conceived.
  - Can't happen in a vacuum. The ground work is here now.

UNCERTAINTY DETAILS (TOP MASS)

Source	Value (GeV) 8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	Comment
Method calibration	± 0.04	± 0.02	± 0.02	MC stat. $\times 4$
Lepton energy scale	$+0.01$	± 0.01	± 0.01	unchanged
Global JES	± 0.13	± 0.12	± 0.04	3D fit, differential
★ Flavor-dependent JES	± 0.19	± 0.17	± 0.06	3D fit, differential
Jet energy resolution	-0.03	± 0.02	< 0.01	differential
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	$+0.04$	± 0.04	± 0.04	unchanged
b tagging efficiency	$+0.06$	± 0.03	± 0.03	improved with data
Pileup	-0.04	± 0.04	± 0.04	unchanged
Backgrounds	$+0.03$	± 0.01	± 0.01	cross sections
ME generator	-0.12 ± 0.08	–	–	NLO ME generator
Ren. and fact. scales	-0.09 ± 0.07	± 0.06	± 0.06	NLO ME generator, MC stat.
ME-PS matching	$+0.03 \pm 0.07$	± 0.06	± 0.06	MC stat.
Top quark p_{T}	$+0.02$	< 0.01	< 0.01	improved with data
b fragmentation	< 0.01	< 0.01	< 0.01	unchanged
Semileptonic b hadron decays	-0.16	± 0.11	± 0.06	improved with data
Underlying event	$+0.08 \pm 0.11$	± 0.14	± 0.09	improved with data, MC stat.
Color reconnection	$+0.01 \pm 0.09$	± 0.05	< 0.01	improved with data
PDF	± 0.04	± 0.03	± 0.02	improved with data
Systematic uncertainty	± 0.48	± 0.30	± 0.17	
Statistical uncertainty	± 0.16	± 0.04	± 0.02	
Total	± 0.51	± 0.31	± 0.17	

COMMON SYSTEMATICS

- Renormalization and factorization scales (includes ME and PS): factor 1/2 (improve with more data and more studies)
- Top pt: factor 1/3 or even less (more differential cross sections, NLO generators, 2D-differential NNLO predictions used for differential k-factors.)
- MC statistics: no uncertainty
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics

Object Efficiency	uncertainty	Recommendation
Muons	muon reco+ID (all WP)	0.1%
	muon reco+ID+isolation (all WP)	0.5%
Electrons/photons	electron reco=ID (incl. isolation), all WP (pt > 20 GeV)	0.5%
	photon reco+ID+incl. isolation)	~2% (?)
tau	tau reco+ID+isolation (all WP)	5% as in Run2
		recommend 2.5% for analyses where tau efficiency is one of the diominant uncertainties
flavor tagging	b-jets (all working points)	~ 1% for 30<pt<300 GeV, 2--6% for pt>300 GeV
	c-jets (all working points)	~2%
	light jets (loose WP)	5%
	light jets (medium WP)	10%
	light jets (tight WP)	15%
	subjet b-tagging	
	double-b tag	
Jets	JES	
	abs. scale	0.1-0.2%
	rel. scale	0.1-0.5%
	Pile up	0-2%
	Jet Flavour	0.75%
	JER	
Jet substructure	Jet mass scale uncertainty	1%
	Jet mass resolution	10%
	W tagging efficiency	10% (governed by Herwig vs Pythia)
Integrated luminosity		1%

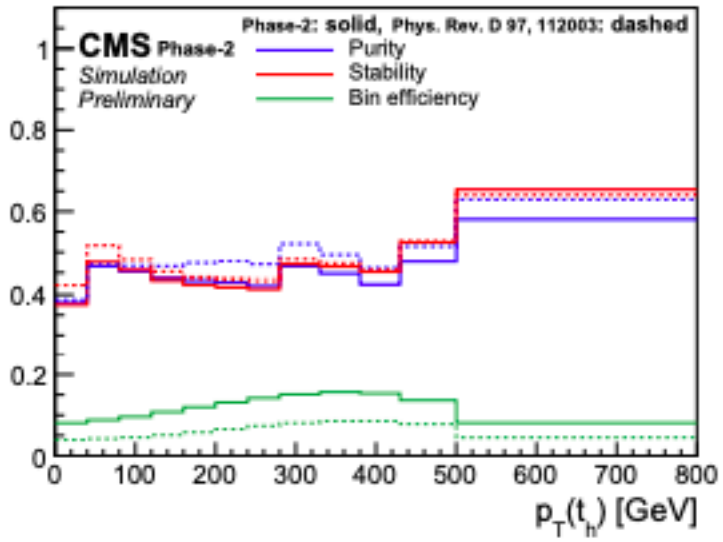


Fig. 70: Expected signal yields (top-left), migration matrices (top-right), and its properties (bottom) for measurements of $p_T(t_h)$ for the HL-LHC (Phase-2) simulation. The purity is defined as the fraction of parton-level top quarks in the same bin at the detector level, the stability as the fraction of detector-level top quarks in the same bin at the parton level, and the bin efficiency as the ratio of the number of events found in a certain bin at detector level and the number of events found at parton-level in the same bin.