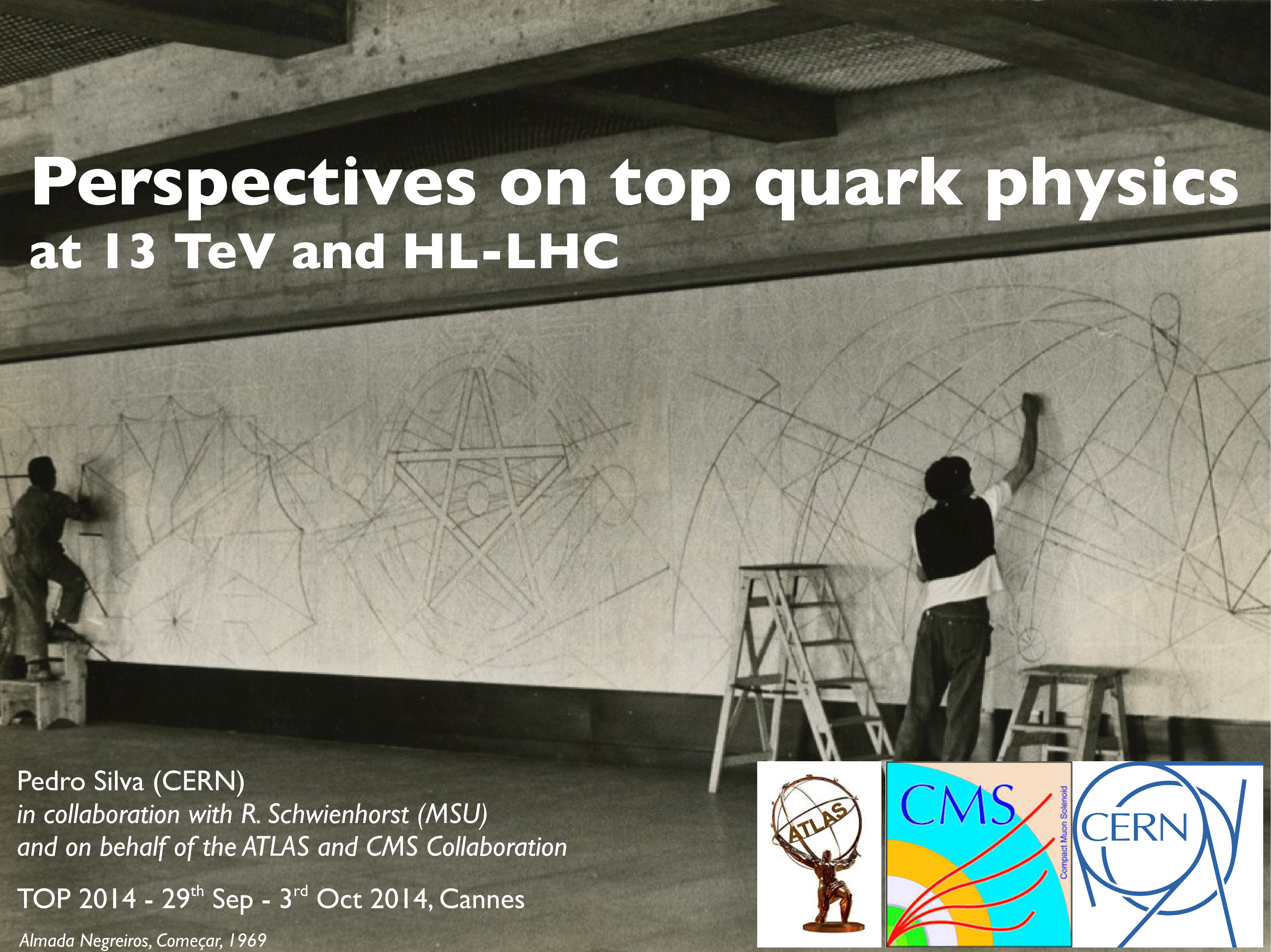
Perspectives on top quark physics
at 13 TeV and HL-LHC

Pedro Silva (CERN)

in collaboration with R. Schwienhorst (MSU)

and on behalf of the ATLAS and CMS Collaboration

TOP 2014 - 29th Sep - 3rd Oct 2014, Cannes

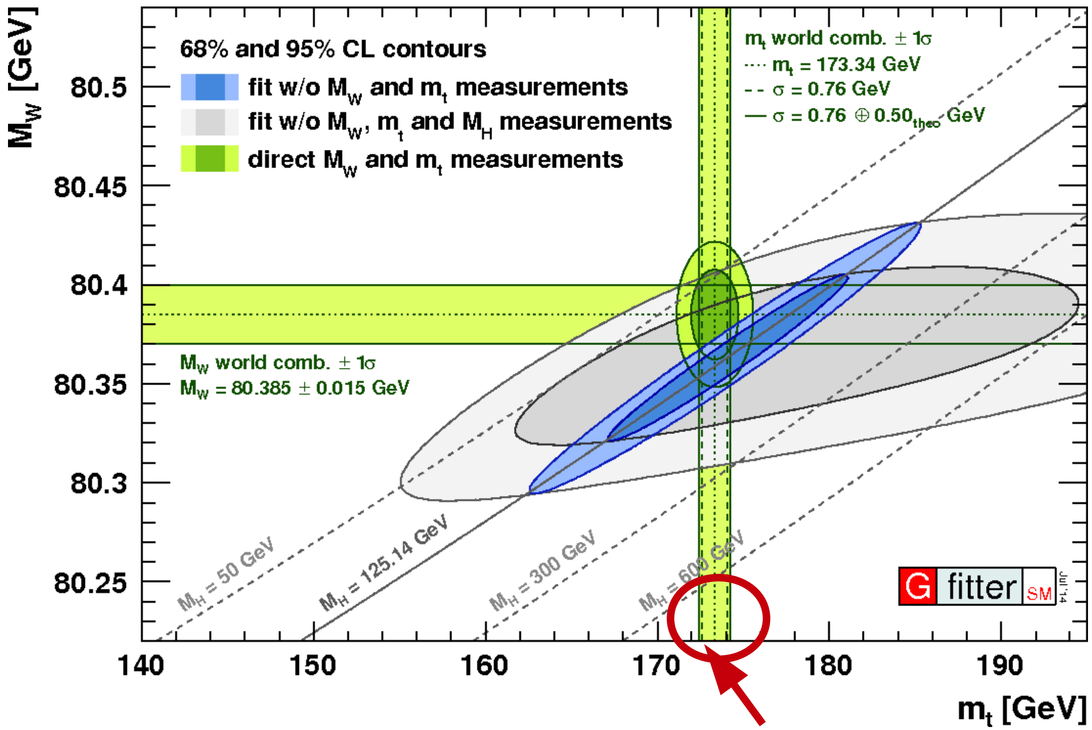


Almada Negreiros, Começar, 1969

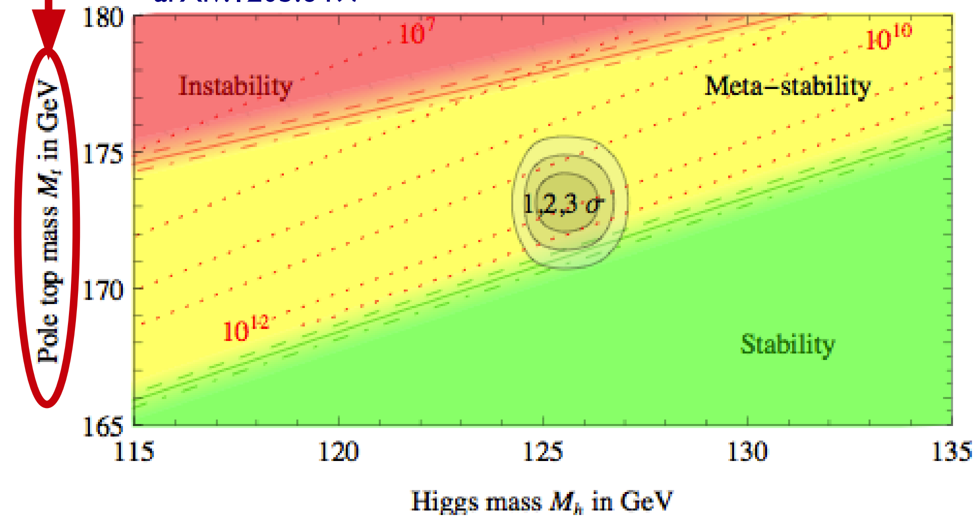
Looking ahead after the Higgs era

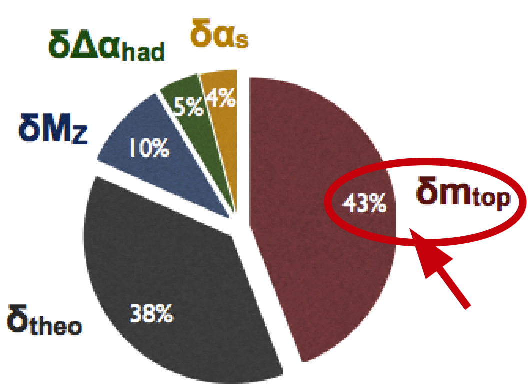
Higgs knows about its "force", but top quarks know about QCD, EWK and Higgs

EPJC72 (2012) 2205



arXiv:1205.6497



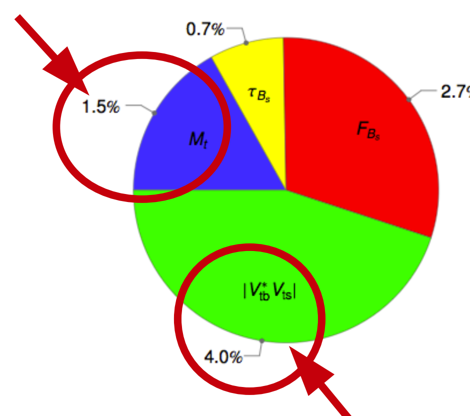


$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

$$= 80.359 \pm 0.011_{tot}$$

PRD69:053006,2004

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.25 \times 10^{-9}\left(\frac{M_t}{173.2\,\mathrm{GeV}}\right)^{3.07}\left(\frac{F_{B_s}}{225\,\mathrm{MeV}}\right)^{2}\left(\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right)\left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^2$$



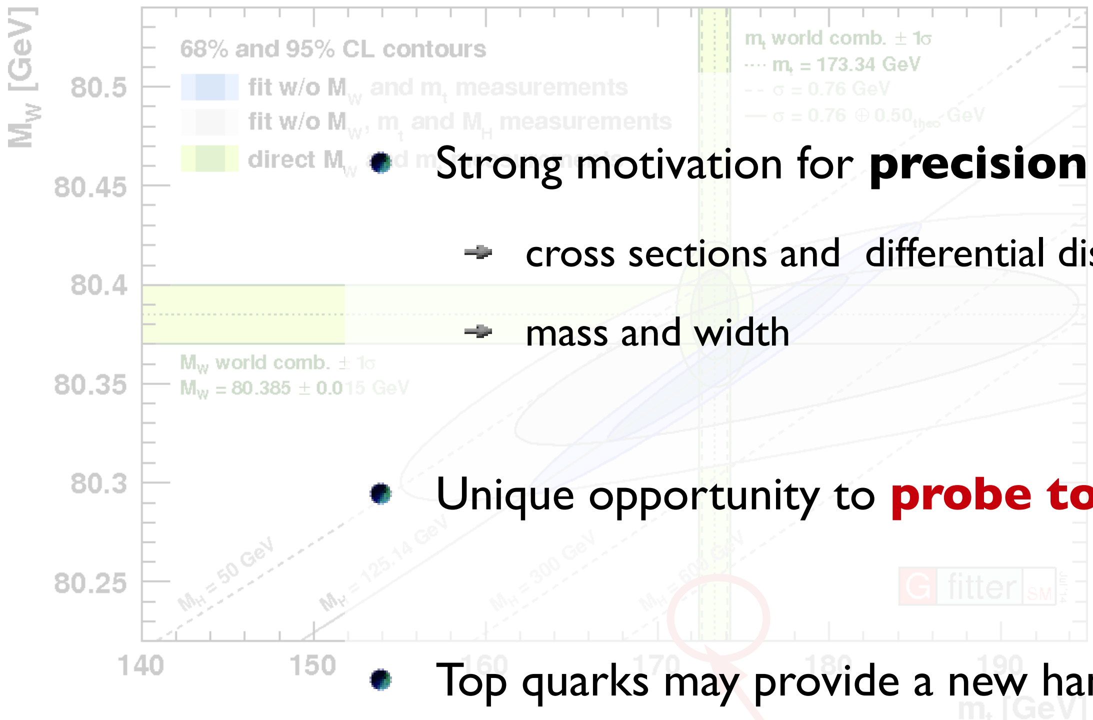
JHEP 1307 (2013) 77

Looking ahead after the Higgs era

Higgs knows about its “force”, but top quarks know about QCD, EWK and Higgs

- Strong motivation for **precision top physics measurements**
  - cross sections and differential distributions
  - mass and width
- Unique opportunity to **probe top – Higgs interactions**
- Top quarks may provide a new handle on **flavour physics**
- Preferential window for **exotic scenarios**

EPJC72 (2012) 2205



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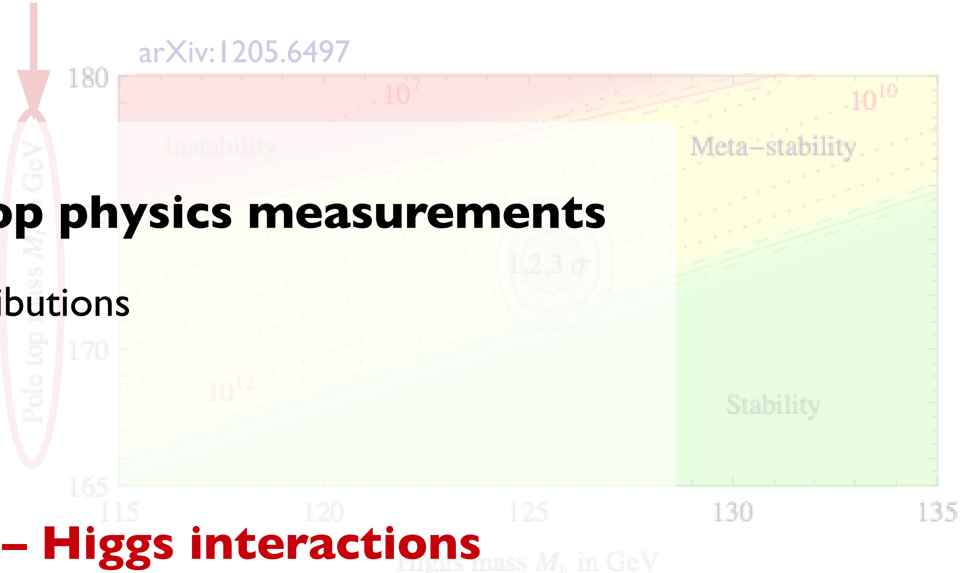

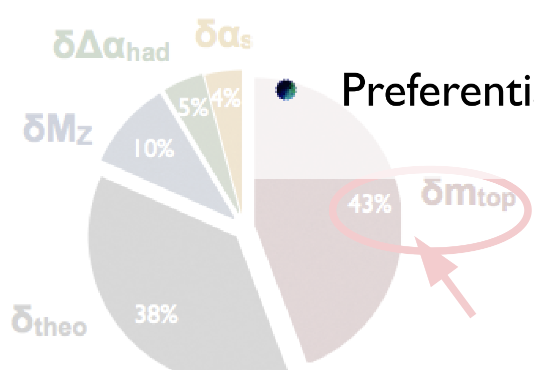

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}} = 80.359 \pm 0.011_{tot}$$

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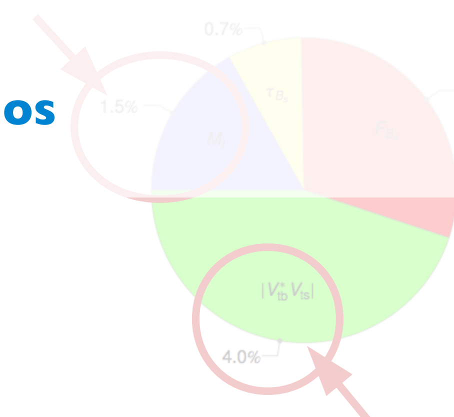

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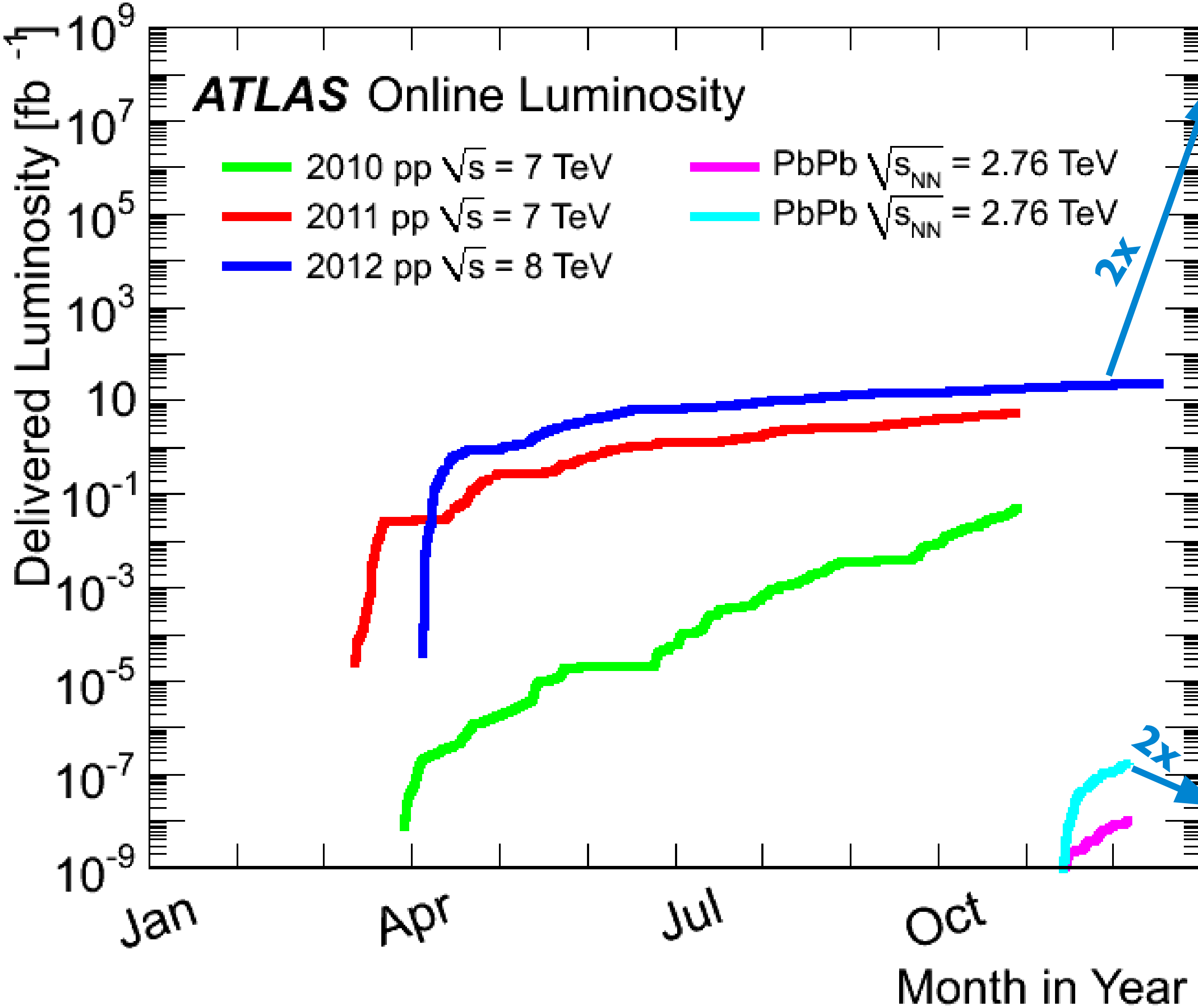
JHEP 1307 (2013) 77

After Run I…



≈ 7.4 x 10⁶ top quark pairs
$\sigma(t\bar{t}) \sim 246$ pb PRL 110 (2013) 252004

≈ 2.6 x 10⁶ single top (t-ch)
$\sigma_t(t) \sim 87$ pb arXiv:1205.3453

≈ 1.7 x 10⁵ single top (s-ch)
$\sigma_s(t) \sim 5.6$ pb arXiv:1205.3453

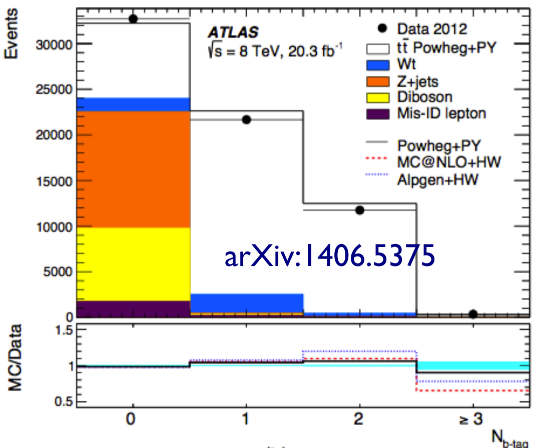
≈ 12 x 10³ tt+W/Z
$\sigma(t\bar{t}+V) \sim 0.403$ pb JHEP07(2014)079

≈ 3.9 x 10³ tt+H
$\sigma(t\bar{t}+H) \sim 0.129$ pb CERN-2013-004

≈ 560 top quark pairs
$\sigma_{PbPb}(t\bar{t}) \sim 3.5\ \mu b$ arXiv:1210.0116

...what did we learn about the top quark?

Cross sections



arXiv:1406.5375

CMS-PAS-TOP-14-016
ATLAS-CONF-2014-054 $\sigma(t\bar{t}) = 241.5 \pm 8.5$ pb 3.5% unc.

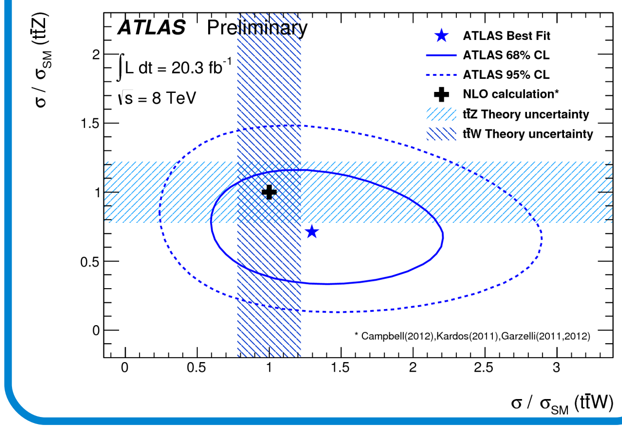
CMS-PAS-TOP-12-002
ATLAS-CONF-2013-098 $\sigma(t-ch) = 85 \pm 12$ pb 14% unc.

CMS-PAS-TOP-14-009
ATLAS-CONF-2014-038 $\sigma(tW) = 25.0 \pm 4.7$ pb 18% unc.

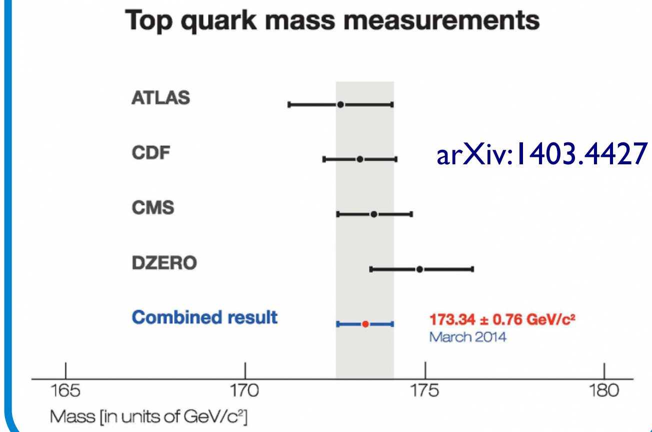
CMS-PAS-TOP-13-009
ATLAS-CONF-2011-118 $\sigma(s-ch) < 11.5$ pb

evidence for associated production with W or Z

arXiv:1406.7830, ATLAS-CONF-2014-038

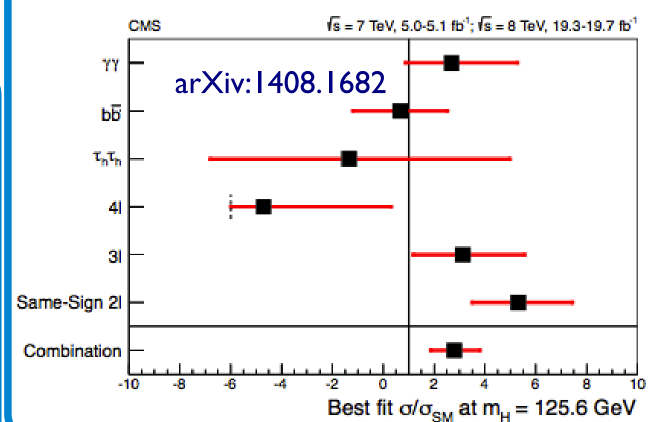


m_{top} : 0.4% unc.



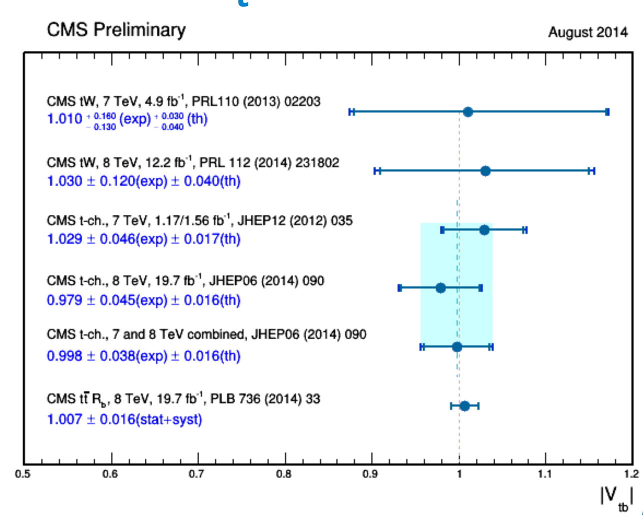
arXiv:1403.4427

approaching ttH vertex

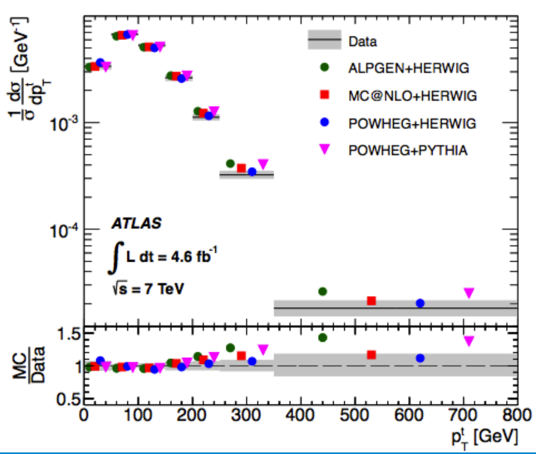


arXiv:1408.1682

$|V_{tb}|$: 1.6% unc.
Γ_t : 9% unc.



testing pQCD predictions



arXiv:1407.0371, EPJ C73 (2013) 2339

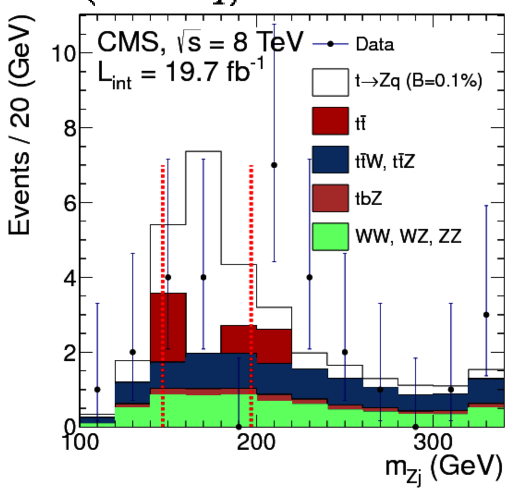
...just some highlights, more in C. Schwanenberger's exp. summary

...what didn't we learn yet about the top quark?

FCNCs ? BNV?

PRL 112 (2014) 171802

$\mathcal{B}(t \to Zq) < 0.05\%$



ATLAS-CONF-2013-063

$\mathcal{B}(t \to ug) < 0.0031\%$

$\mathcal{B}(t \to cg) < 0.016\%$

CMS PAS-HIG-13-034 (JHEP06(2014)008)

$\mathcal{B}(t \to c(q)H) < 0.56\%(0.79\%)$

CMS-PAS-TOP-14-003

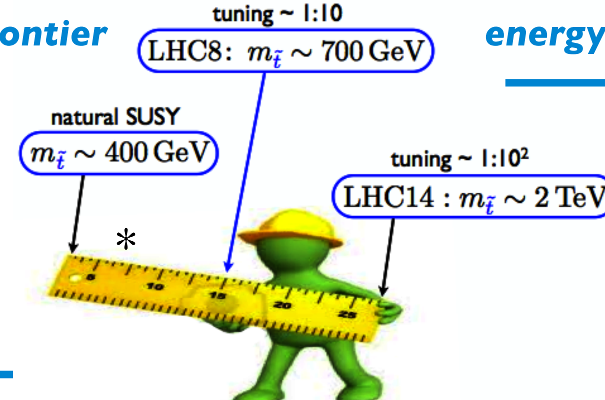
$\mathcal{B}(t \to u\gamma) < 0.0161\%$

$\mathcal{B}(t \to c\gamma) < 0.182\%$

PLB 731 (2014) 173

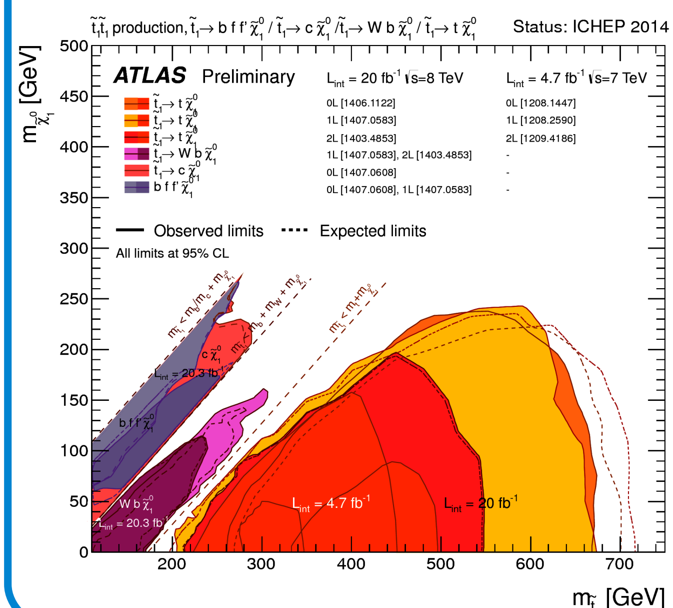
$\mathcal{B}(t \to bue/bc\mu) < 0.15\%$

intensity/precision frontier ← → *energy frontier*



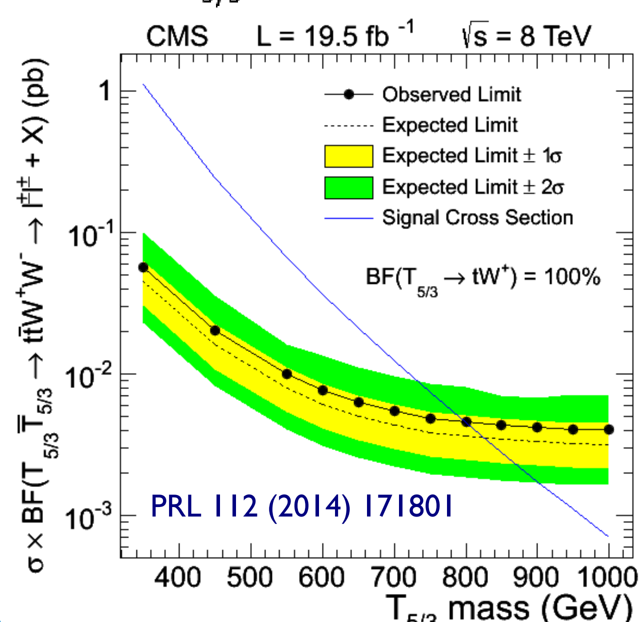
coupling to SUSY partners?

$m_{\tilde{t}} > 700$ GeV $m_{\tilde{g}} > 1.3$ TeV



coupling to vectorial partners?

$m_{T_{5/3}} > 800$ GeV



… again just some highlights, more in C. Schwanenberger's exp. summary

(*) cartoon taken from G. Perez @ TOPLHCWG May 2014

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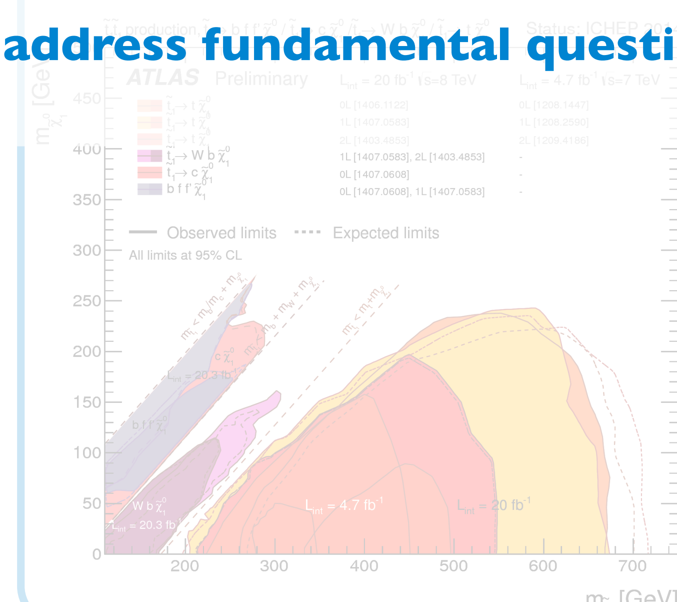
intensity/precision frontier

energy frontier

coupling to SUSY partners?

$m_{\tilde{t}} > 700\ \mathrm{GeV} \quad m_{\tilde{g}} > 1.3\ \mathrm{TeV}$



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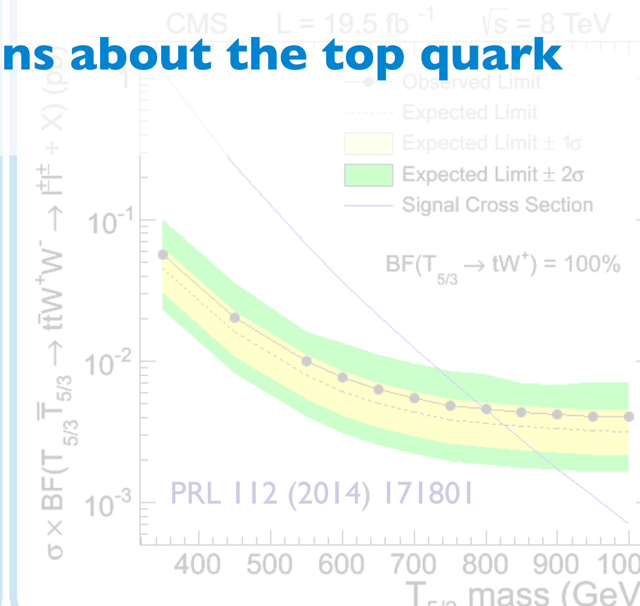


We need more data to address fundamental questions about the top quark

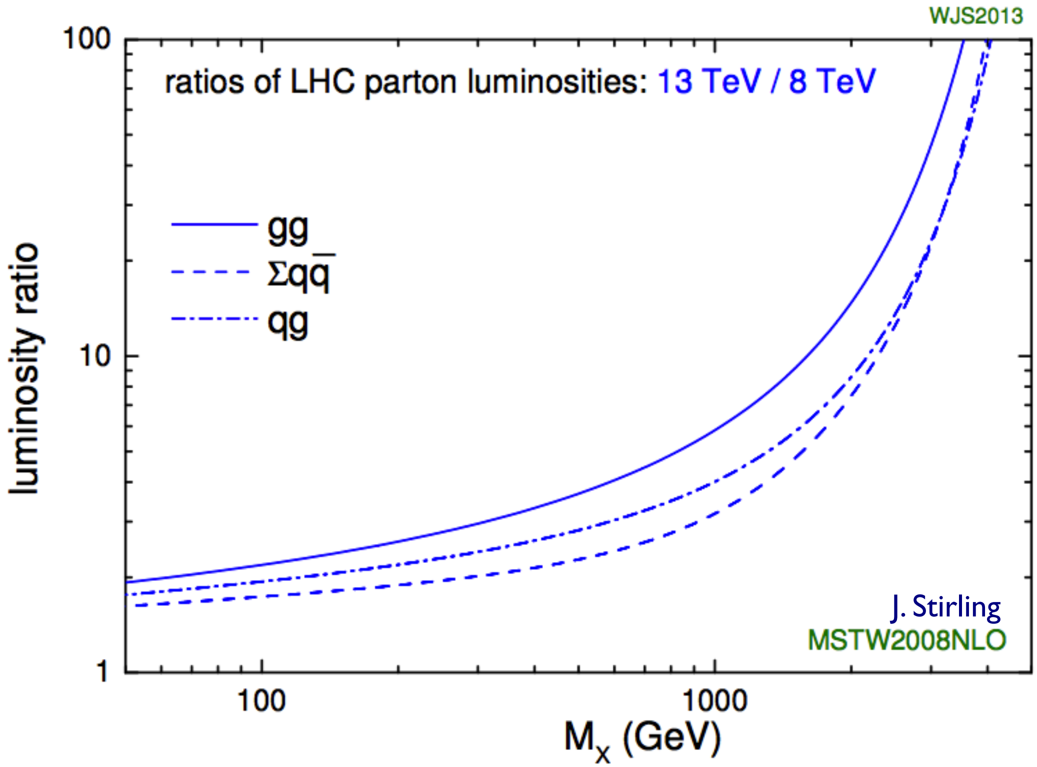
… again just some highlights, more in C. Schwanenberger's exp. summary

(*) cartoon taken from G. Perez @ TOPLHCWG May 2014

Experimental prospects for Run II

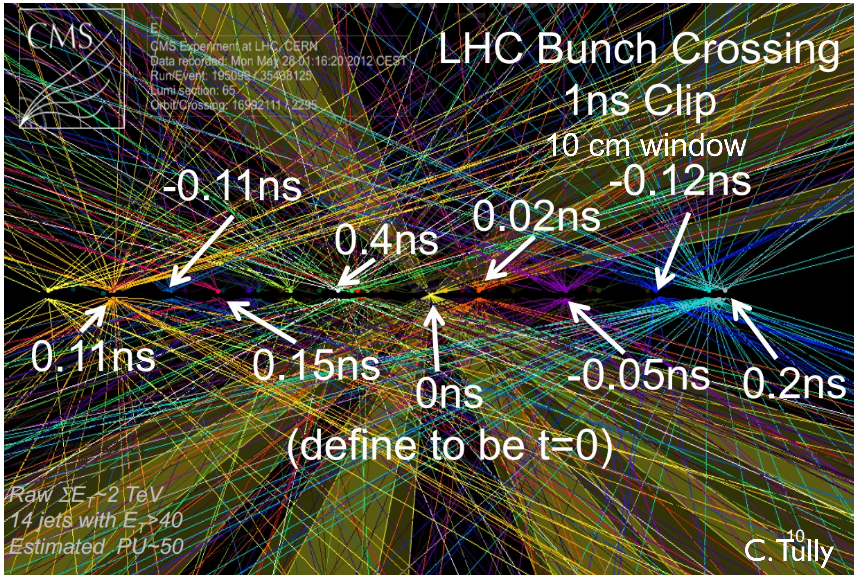
Target energy : 6.5 TeV

- *Physics prospects*:
  - **gg** production **dominates**
  - 8 TeV sensitivity reached with ~ 2 fb^{-1}
  - large benefit for **M_x >1 TeV: O(10) gain**
- *LHC challenges*: quench margins, tolerance to beam loss, intensity set-up beams, hardware pushed closer to maximum



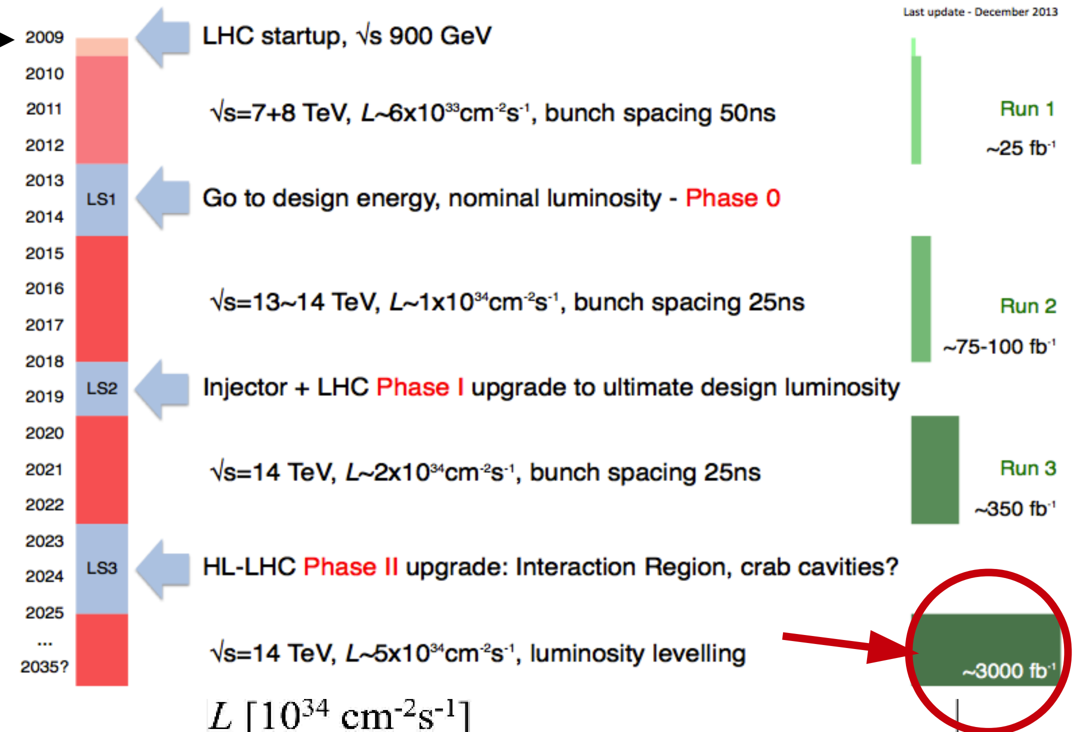
Bunch spacing : 25 ns

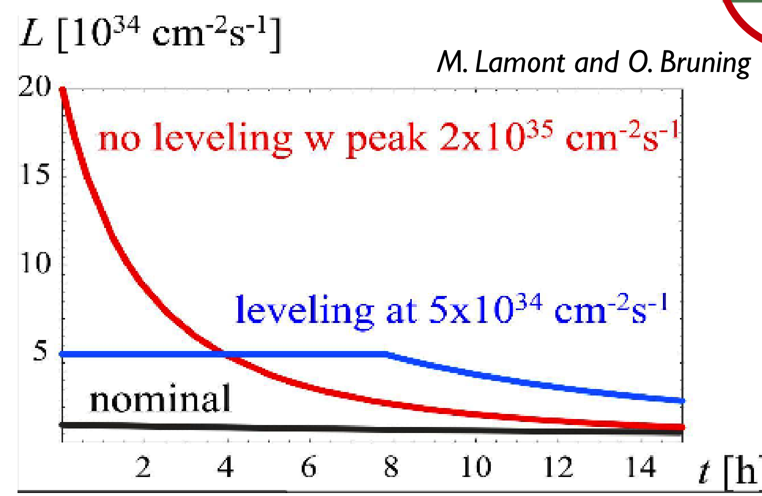
- *LHC challenges*: limit pileup to 50, electron cloud, UFOs, long range collisions, higher β* (80-40 cm), higher beam current and intensity / injection
- *Detector challenges*:
  - keep trigger thresholds as loose as possible
  - calorimeters cope with high occupancy + energy flux
  - maintain high performance until O(300 fb^{-1})



Experimental prospects for the HL-LHC

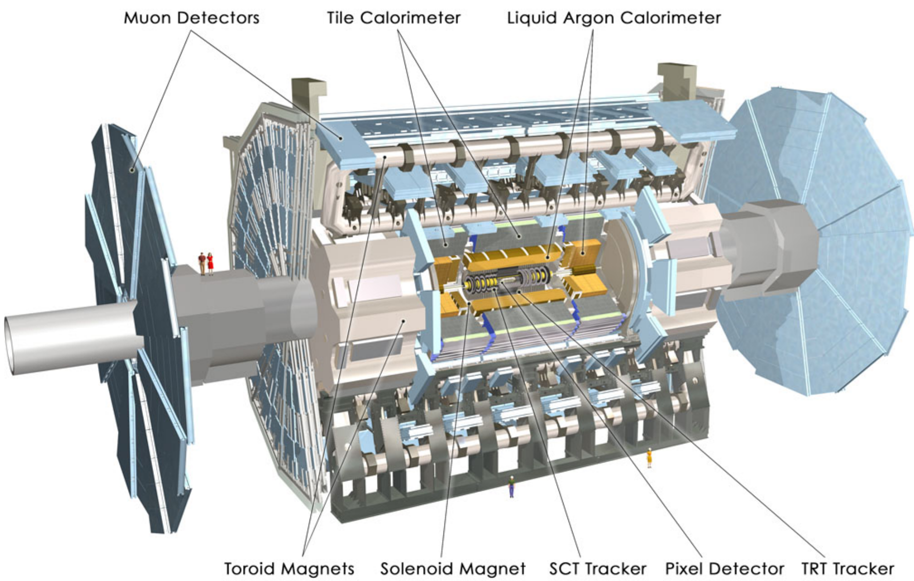
- **Fully exploit LHC potential at 14 TeV ▶**
  - Collect 10x more data than initial design
  - 5 x 10^{34} cm^{-2} s^{-1} leveled luminosity, **<PU>=140**
  - 3 fb^{-1} per day → 3 ab^{-1} after 10 years
- **Higgs factory**
  - couplings 2-10%, self couplings ~30%
  - Test $V_L V_L \to V_L V_L$ unitarity
- **Ultimate precision at the LHC**
  - Top Yukawa 7-10%
  - exceed SM exp. unc. for Z/γ couplings
  - probe FCNCs down to 10^{-2}-10^{-4} %
  - $\delta m_{top} \sim \Lambda_{QCD}$
- **Keep searching for new physics**
  - Characterize Run 2/3 discoveries ?
  - Push the energy frontier ?
  - Uncover deviations from SM or rare processes?

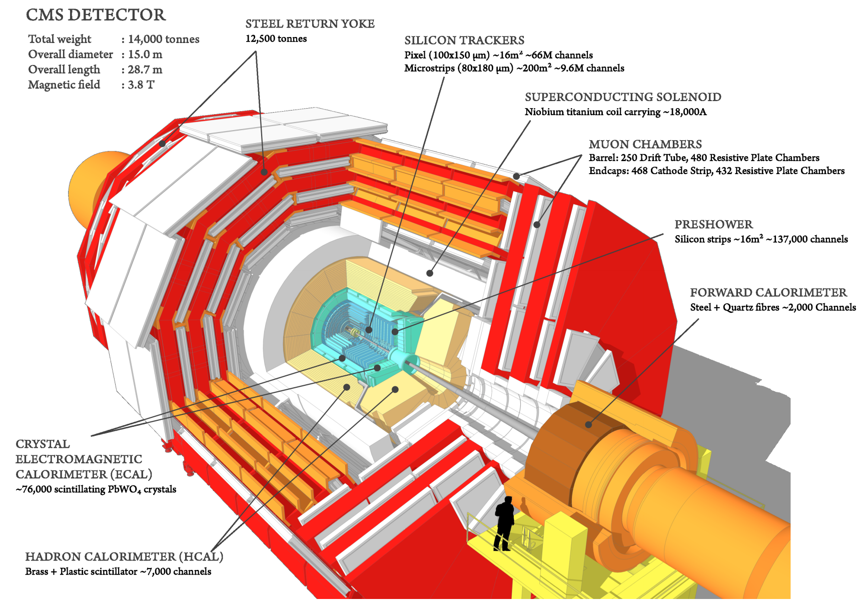




The HL-LHC offers the potential to fully explore discoveries made in Run II

Towards the HL-LHC: detector upgrade strategies





Consolidate detectors, address operational issues, prepare for high pileup

Phase 0

2013-2014

- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- CMS : Replace HCAL forward PMTs and outer HPD → SiPM
- ATLAS : Diamond beam monitor, additional pixel layer

Mantain / improve performance at high pileup

Phase I

2018-2019

- CMS: new pixels, HCAL SiPMs, electronics, and L1-Trigger
- ATLAS: L1 trigger improvement, fast track trigger at L2, new muon small wheels

Mantain / improve performance at extreme pileup : sustain rate + radiation doses

Phase II

2023-2024

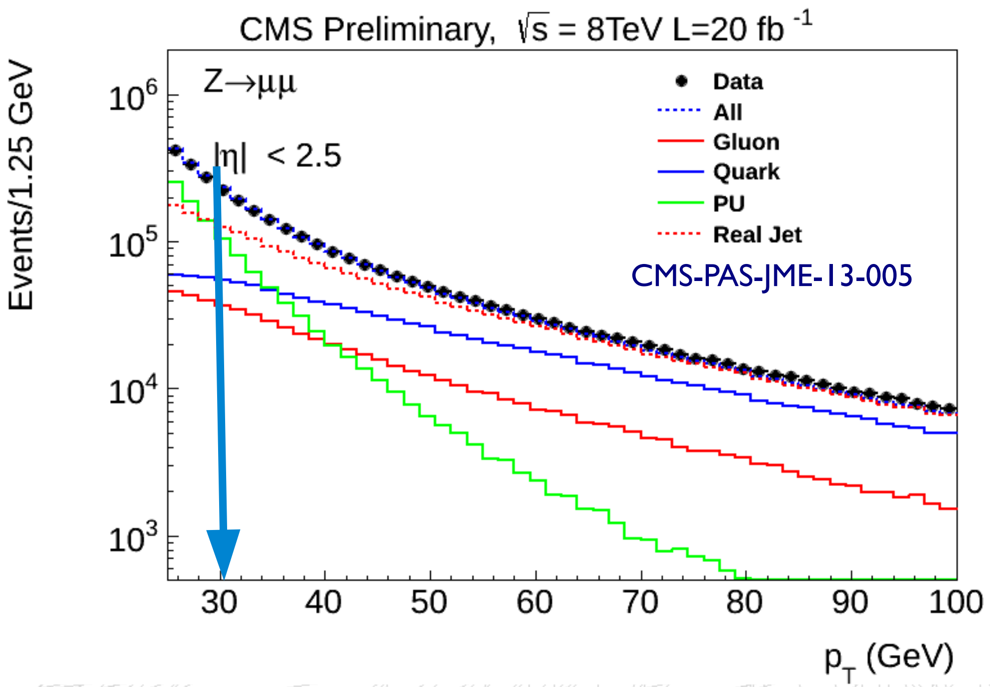
- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- CMS: track trigger, replace endcap calorimeters
- ATLAS: replace inner tracker, new forward calorimeter

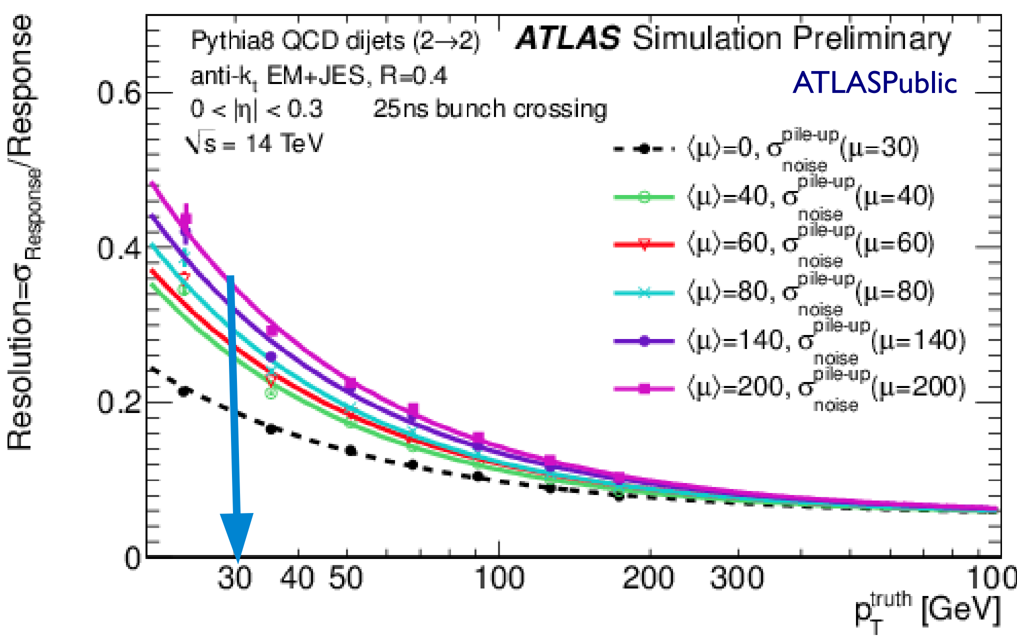
Facing the increase in pileup

- **Main challenge: ability to tame pileup at different levels**
  - tighter trigger requirement for leptons will help sustain approximately the same p_T thresholds
  - need more careful study of the isolation, in particular effect of out-of-time pileup
  - main concern for top physics: jets

Jet rate increases due to diffuse superposition of pileup energy flow

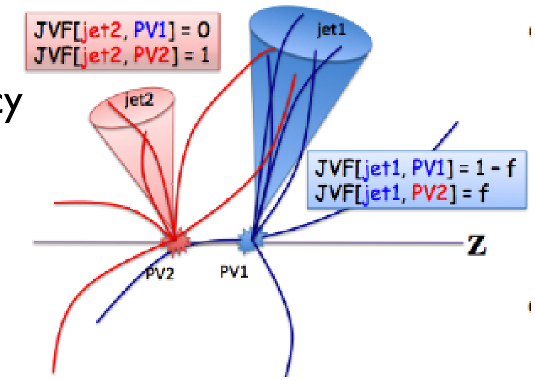
Jet resolution degrades naturally due to local pileup fluctuations



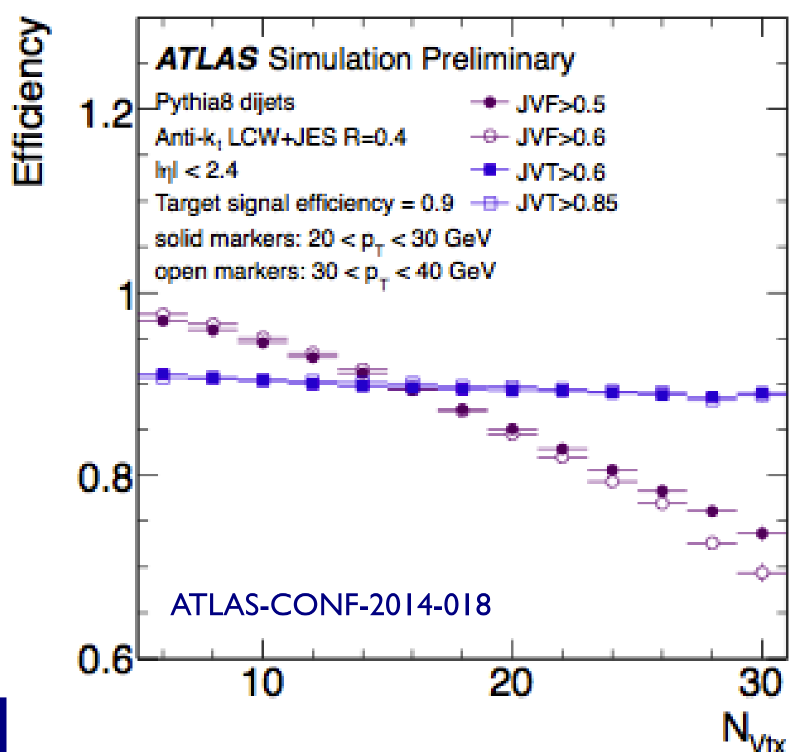


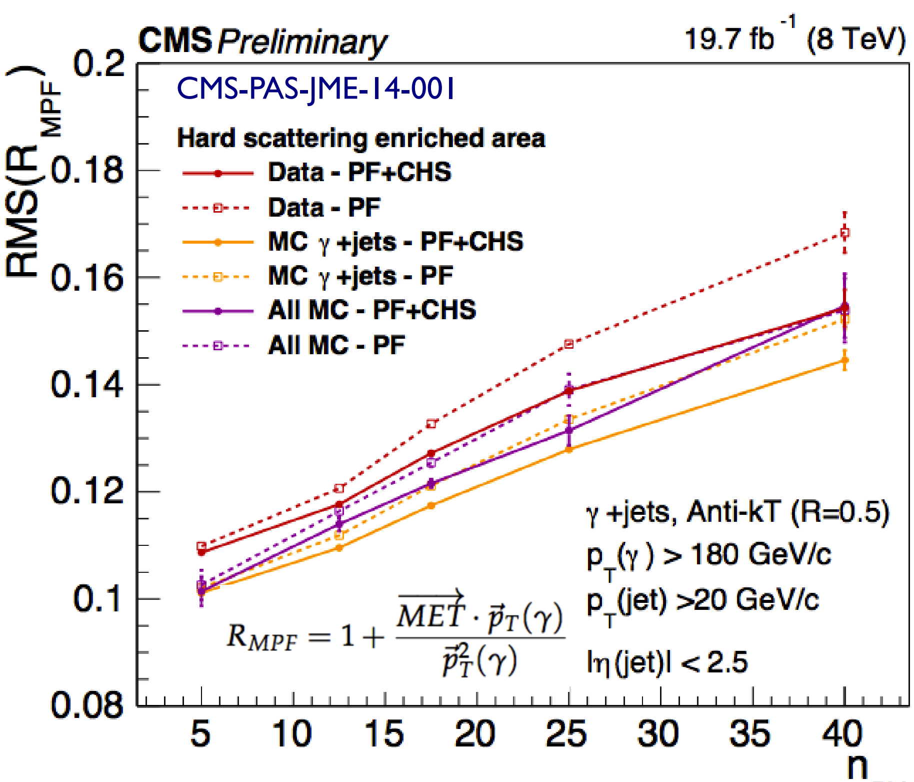
In-time pileup mitigation techniques

- **Jet vertex tagger (JVT)**
  - correct fraction of tracks associated to a jet and other PV for pileup dependency
  - combine in a likelihood with jet p_T fraction carried by tracks from PV



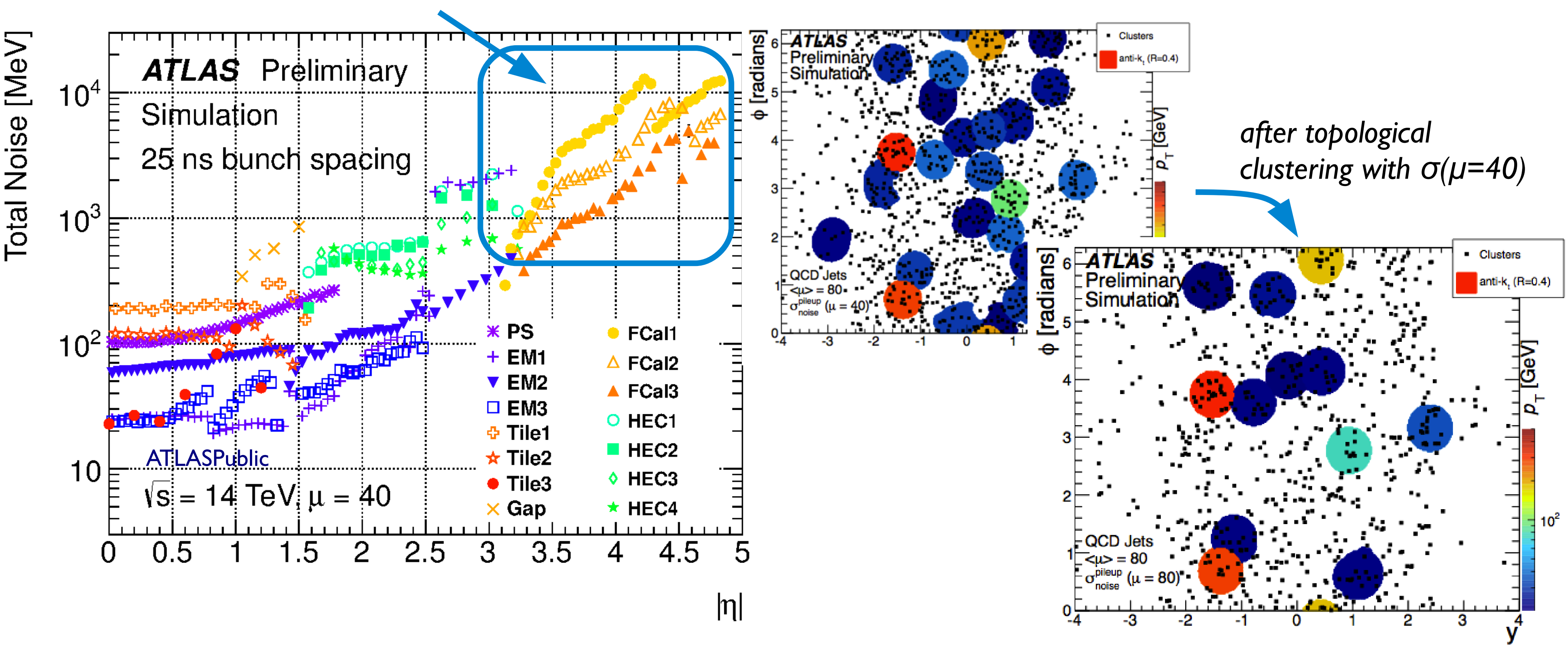
- **Charged hadron subtraction (CHS)**
  - already pioneered at 8 TeV : removes tracks entering the fits of other PVs
  - applying CHS reduces the rate of pileup jets from 20% to 5%
  - improved resolution on top of particle flow, in particular at high pileup





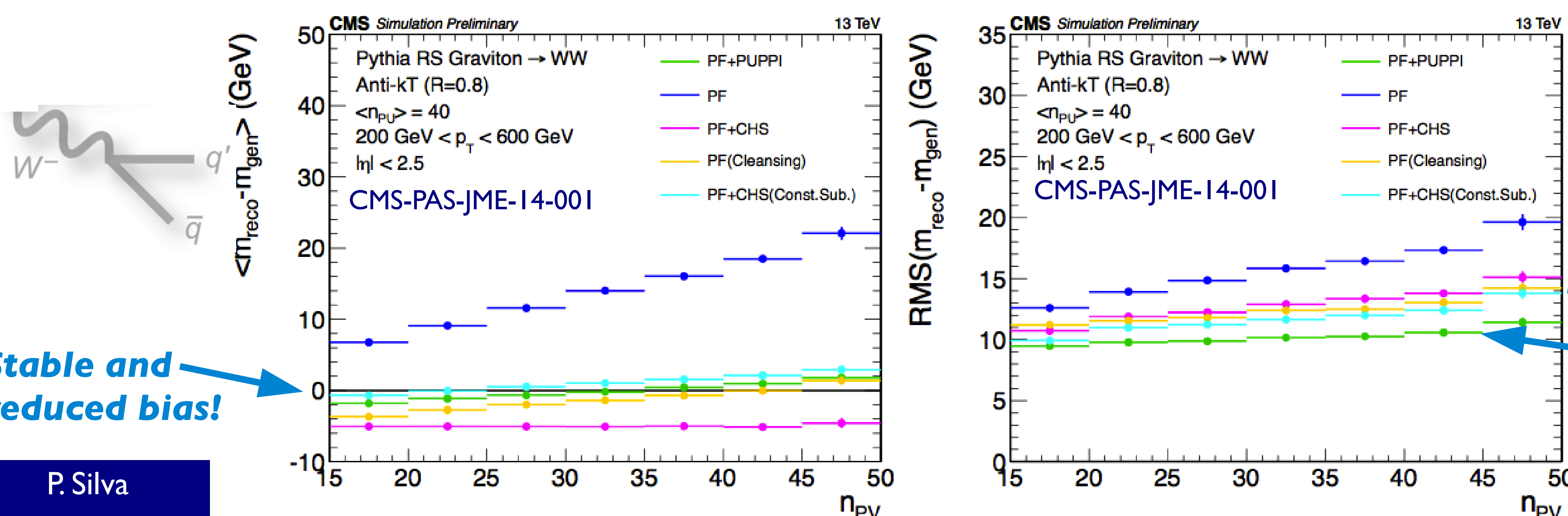
From topological clustering...

- When calorimeter granularity allows can use topological clustering to reduce noise and pileup
  - Iterate clustering starting from seeds well above noise, e.g. ($E_{cell}/\sigma>4$)
  - Cluster with high significance neighbours ($E_{cell}/\sigma>2$) and boundaries ($E_{cell}/\sigma>0$)
  - σ provides particle (cluster) level pileup subtraction → needs to be adjusted to pileup scenario



...to pileup per particle id

- **Constituent subtraction** JHEP 1406 (2014) use ghost particles within the jet area to subtract pileup energy
- **Jet cleansing** arXiv:1309.4777 use shape and tracking to correct at subjet level $p_T^{tot} = \frac{p_T^{C,PU}}{\gamma_0} + \frac{p_T^{C,LV}}{\gamma_1}$
  - *charged from PV and PU*
  - *tunable for optimal performance*
- **Pileup per particle identification** arXiv:1407.6013 contrast collinear QCD structure with pileup
  - discriminating variable $\alpha_i = \log \sum_{j \in Ch,PV} \left(\frac{p_{T,j}}{\Delta R_{ij}}\right)^2 \Theta(R_0 - \Delta R_{ij})$, if only calorimeter use $p_T/\Delta R$ or p_T as metric
  - assign weight per particle based on the cumulative χ^2 distribution

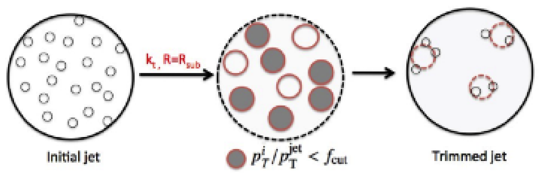


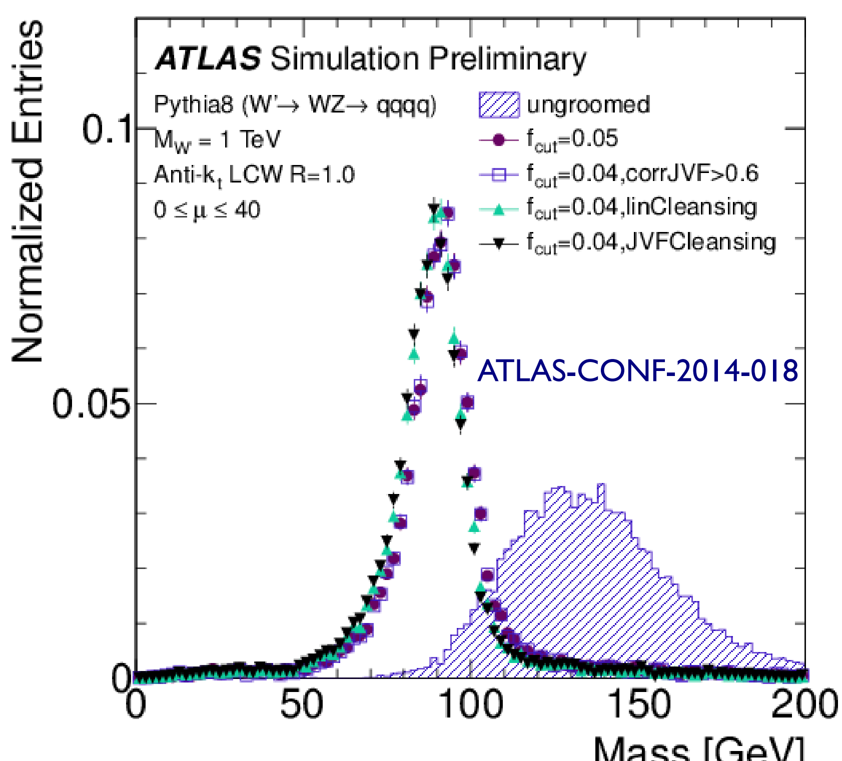
Stable and reduced bias!

PUPPI yields best / most stable resolution

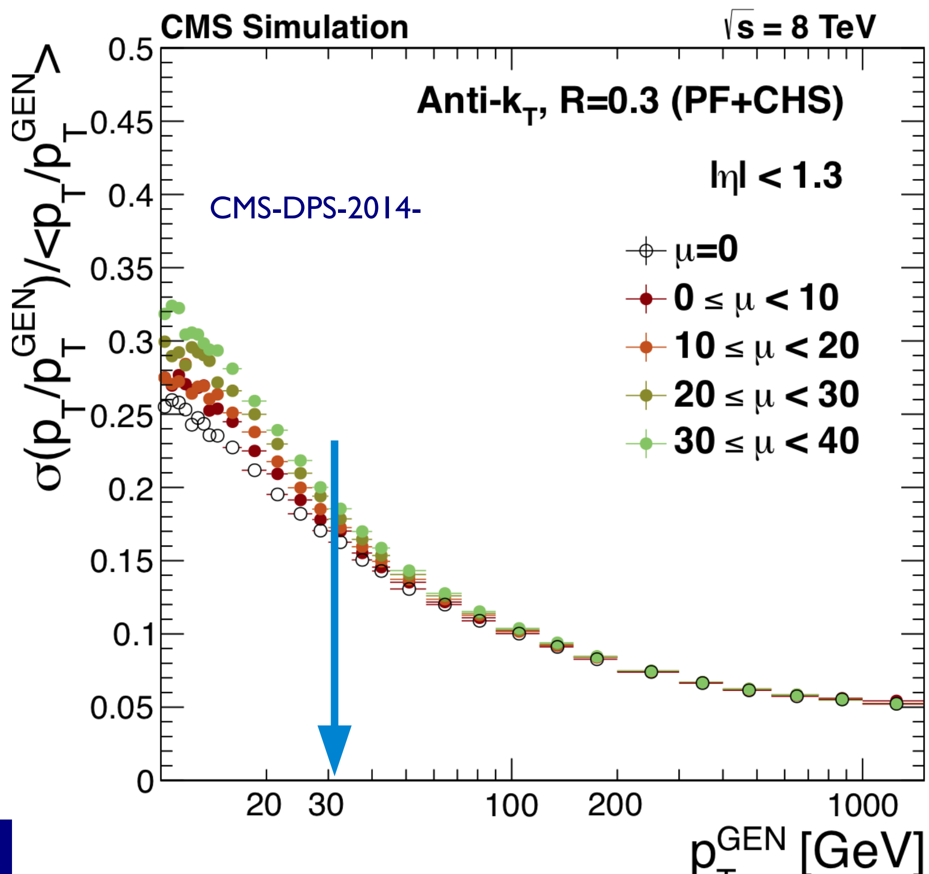
Other techniques to mitigate pileup

- Systematic removal of a subset of jet constituents
  - profit from substructure **grooming algorithms**
  - complement with tracking or PUPPI-weights
  - significant improvement on jet mass, stable against PU



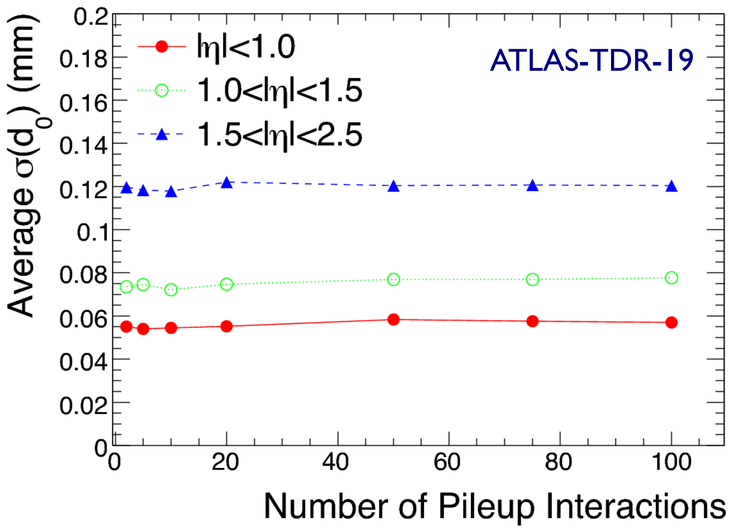


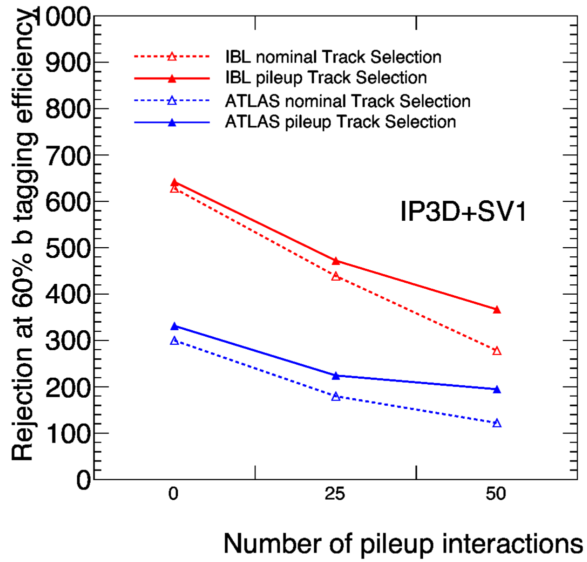
- **Tighten further** the **jet cone**
  - minimize degradation on jet energy resolution
  - decrease corrected response (~2% for R=0.3)
  - tt events have the potential to be used to optimize the jet algorithm using W → qq'



Expected b-tagging performance

- Pixels upgrade is mandatory to maintain performance at high pileup
  - Expected performances in tt events from full simulation including 13 TeV-like pileup scenario





◀ **ATLAS**

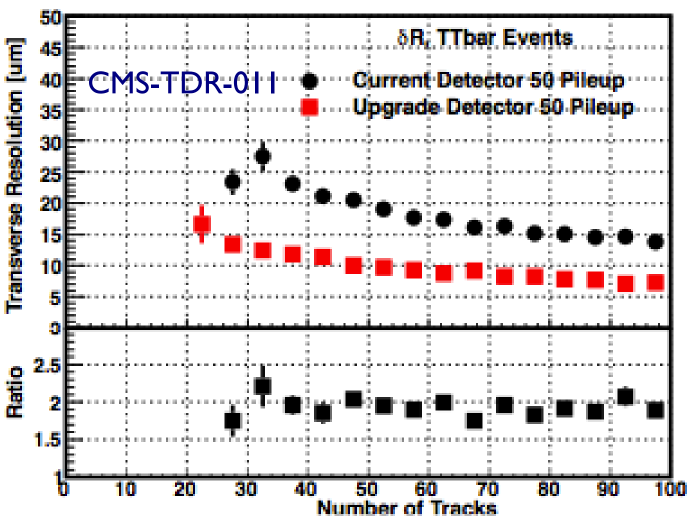
IBL installed May 9th

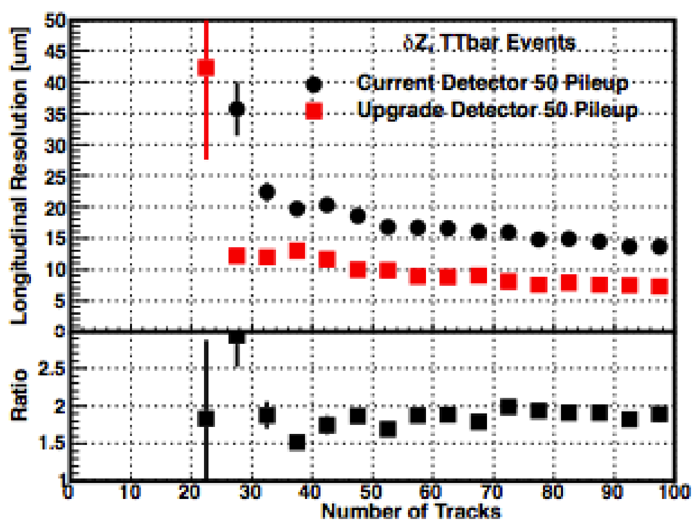
Only 0.1% of channels inactive!

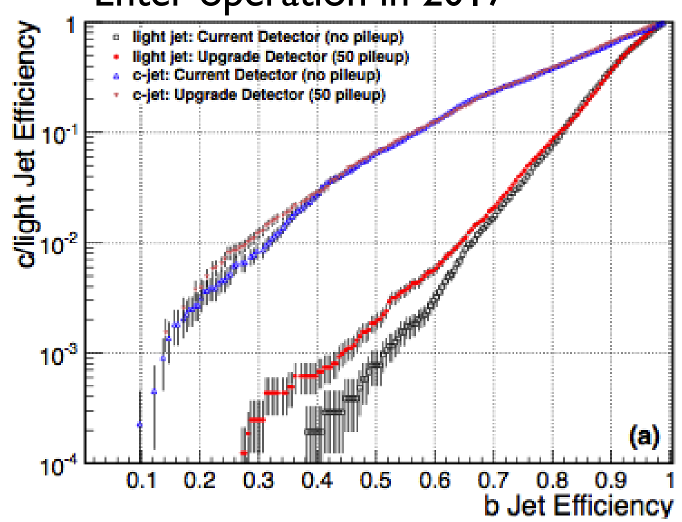
Currently being commissioned.

▼ **CMS**

Enter operation in 2017

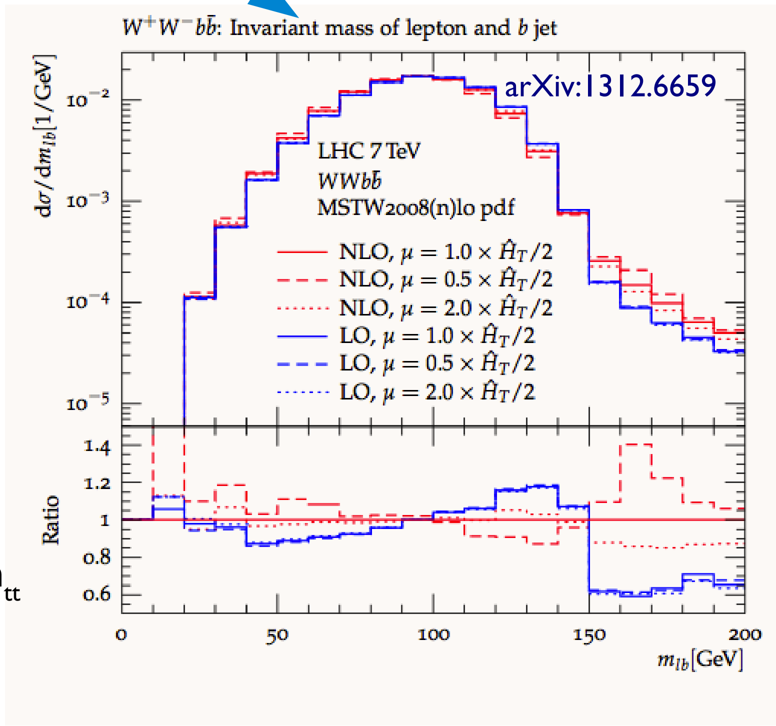






Improvements in signal modelling

- **NLO+PS** is expected to improve our understanding of signal (and backgrounds taken from MC)
  - use techniques from CKKW/MLM and multi-scale improved fixed order NLO or "MINLO"
  - reduced dependency on choices of matrix-element to parton-shower matching and QCD scales
  - automatized prescription for re-weighting for PDFs and scale choice using the same LHE events
  - include non-resonant and resonant diagrams for production of top quarks



- Switching to **Pythia 8 and Herwig++ as hadronizers**
  - better-defined interface to NLO+PS matrix element generators
  - more accurate decay tables and more up to date UE tunes
  - more colour-reconnection models available to test

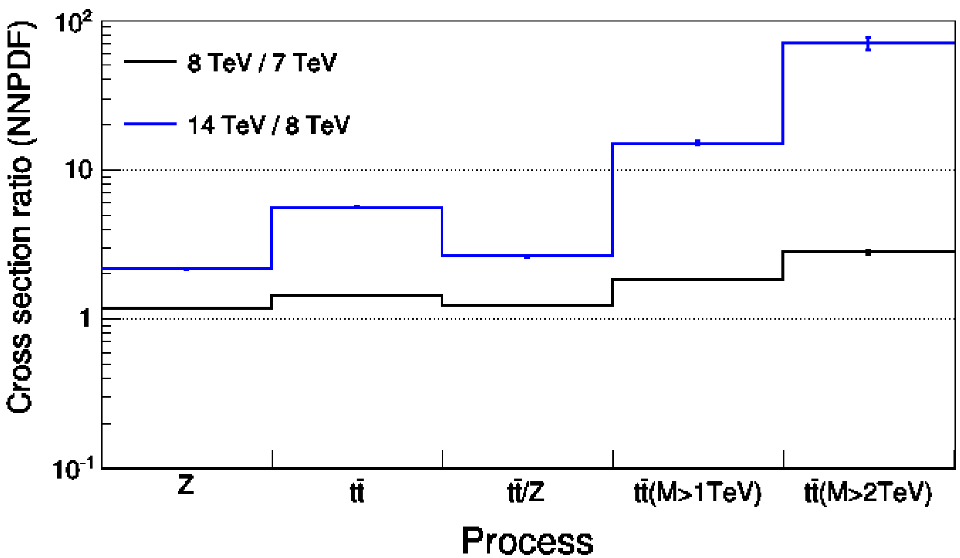
- **NNLO** predictions are also available
  - waiting for differential distributions: charge asymmetry, top p_T, m_{tt}
  - top pairs and single top
  - large impact expected on many searches and precision measurements

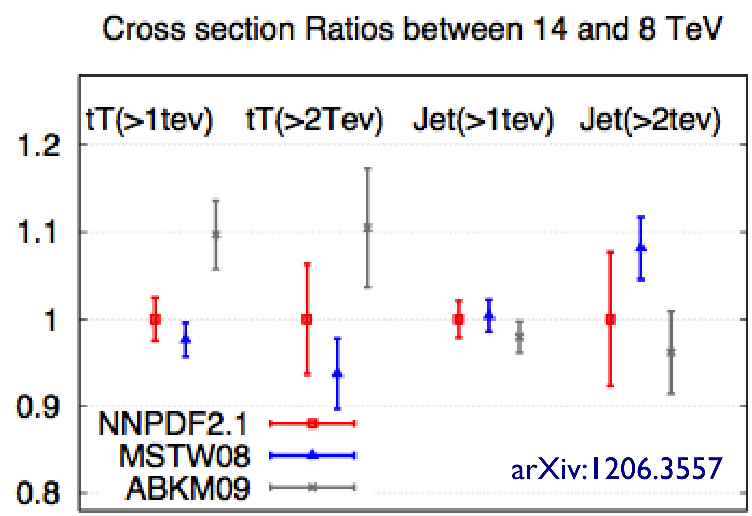
A new start

- **ATLAS** and **CMS are preparing intensively for Run 2 and the HL-LHC**
  - upgraded detectors with enlarged capabilities to face the increase in pileup
  - new techniques for jet reconstruction and pileup subtraction and identification, flavour tagging
  - testing new tools for signal modeling

Re-visiting top quark pair production

- "First day" measurement: **top quark pair production** at a new center-of-mass energy
  - measurements can be furthermore optimized to measure the ratio between different pp energies
  - extending procedure to differential measurements (e.g. M_{tt}) will be a powerful tool
  - strong constraints on NNLO PDFs, in particular large x gluons → crucial for searches
  - with more data: explore gg/qq production, use associated W production as tag for qq production



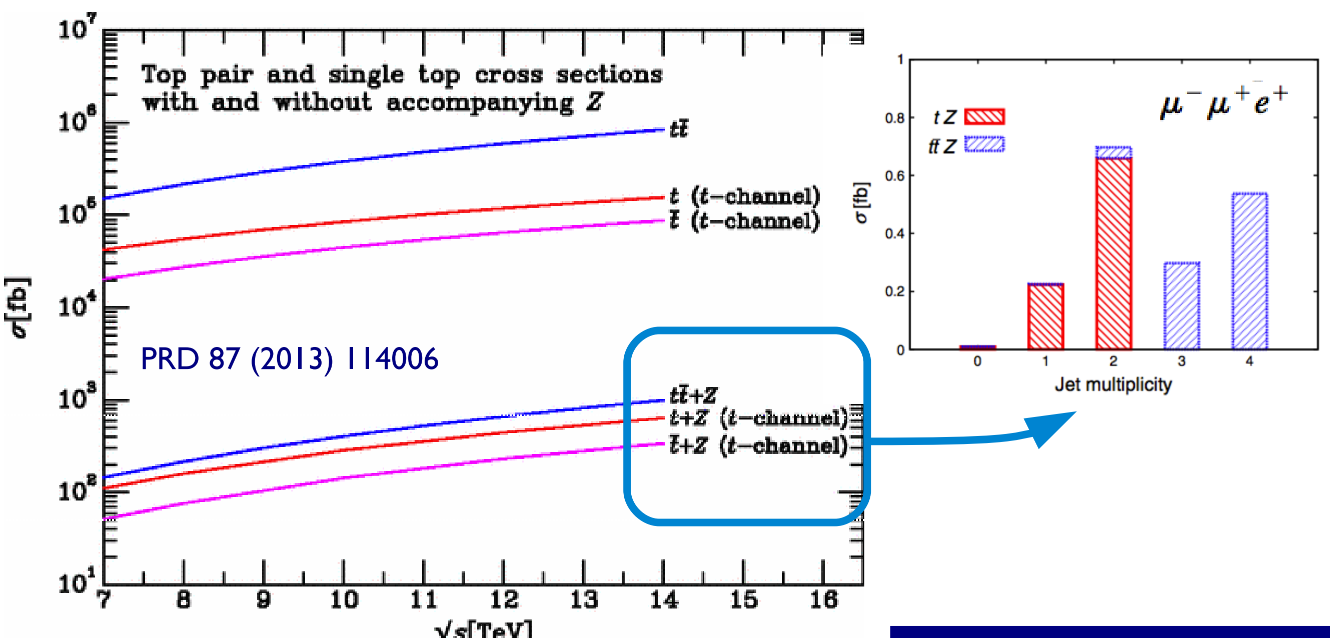


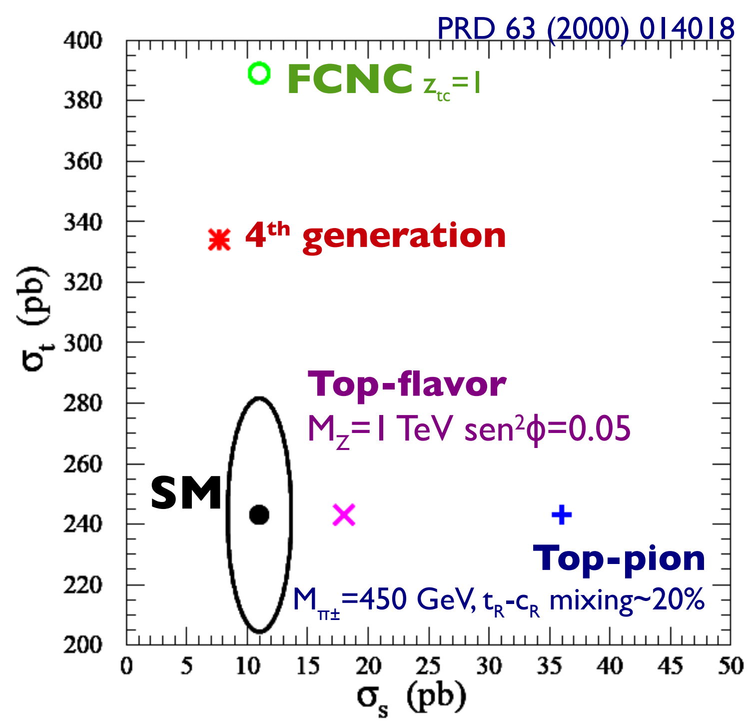
- **σ(tt) can constrain new physics e.g. light stops if we improve on:**
  - theory: signal and single top modeling + PDF ~3.8% unc.
  - experiment: luminosity ~1.9% unc. beam energy ~1.8% unc.
    lepton isolation + JES/JER + b-tagging ~0.9% unc.

using uncertainties from ATLAS σ(tt) in the eμ channel arXiv:1406.5375

Re-visiting single top quark production

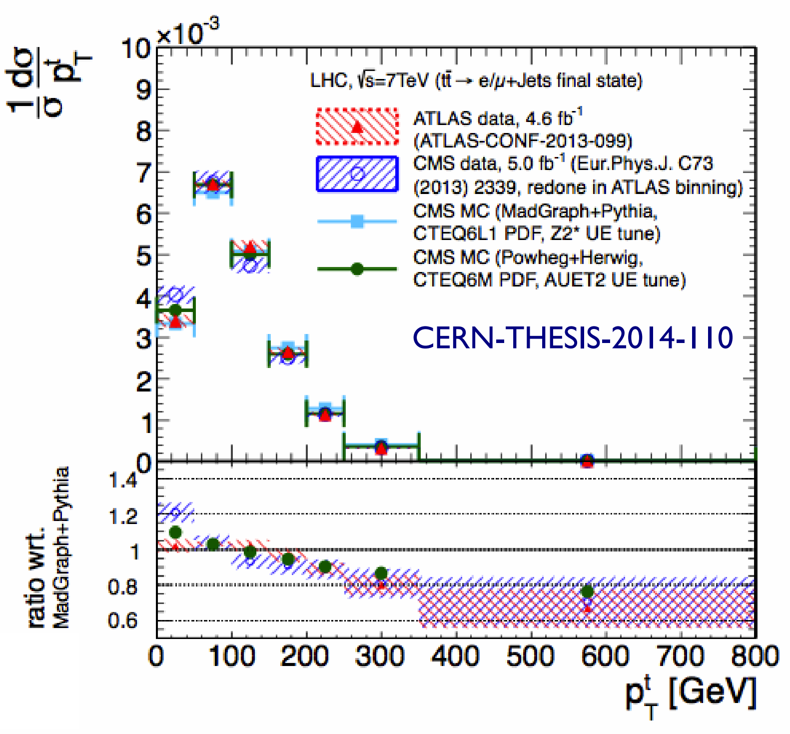
- **Crucial to pursue t-, s-, tW-channels**
  - Need further understanding of top production as whole: resonant and non-resonant production
  - window for FCNC, Higgs and dark matter
- Single top cross sections **do not rise as fast as top pairs due to PDFs**
  - breaking the ~4% unc. barrier on $|V_{tb}|$ → improve on ~9% exp. σ(t) unc. as $$\frac{\Delta V_{tb}}{V_{tb}} = \frac{1}{2}\left(\frac{\Delta\sigma^{meas}}{\sigma^{meas}} \oplus \frac{\Delta\sigma^{th}}{\sigma^{th}}\right)$$
  - expand on differential measurements → constrain more effectively PDFs from charge asymmetry
  - measure associated production e.g. t+Z (irreducible rare background for many searches)
  - m_t and polarization measurements in EWK-production-dominated (high-purity) region

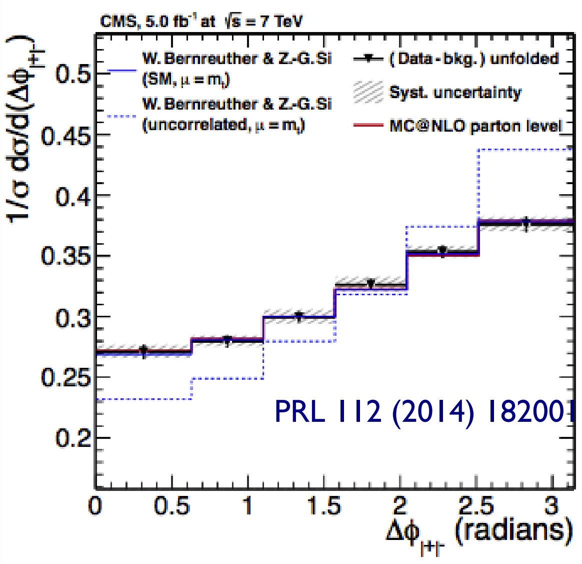


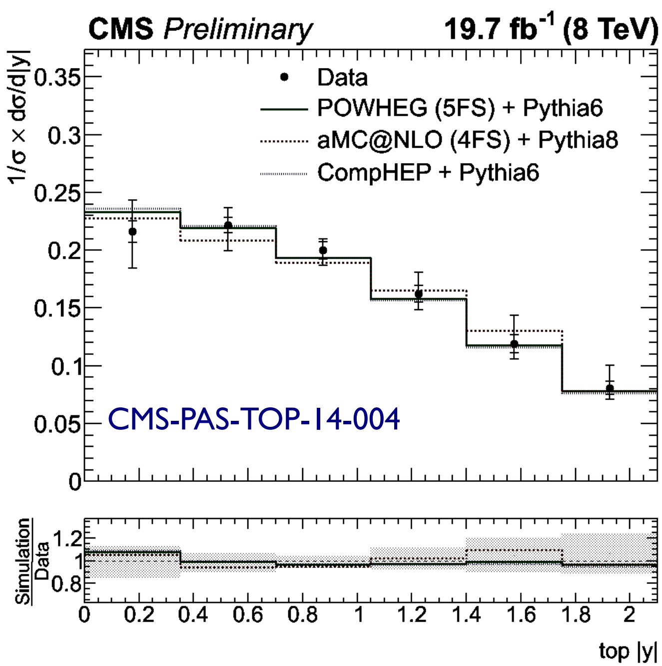


Expanding differential distributions

- **Measure differential the production of top quarks**
  - pair and singly-produced
  - crucial test of alternative signal models → potential to reduce theory systematics, exp. biases
  - a better understanding of the top p_T in Run II will impact many precision measurements and searches
  - improved precision has the potential to constrain further BSM contributions to top production



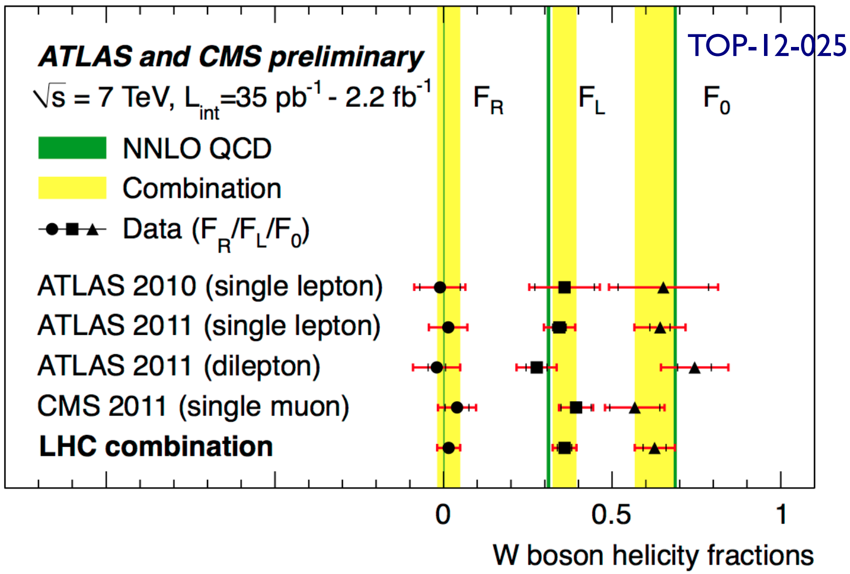




Couplings : spin 1 bosons

tWb vertex

- Fully fixed in the SM, good description of data



- BSM extensions include right-handed + dipole terms

$$\Gamma_\mu^{tWb} = -\frac{g}{\sqrt{2}}\left\{\gamma_\mu\left(V_L P_L + V_R P_R\right) + \frac{i\sigma_{\mu\nu}q^\nu}{\sqrt{2}m_W}\left(g_L P_L + g_R P_R\right)\right\}$$

  - measuring all, including phases, in reach of RunII

- Improving current limits will depend on our understanding of **signal modelling**, **m_{top}**, JES/R and MET in both tt and single top events

Neutral bosons (Z,γ)

- Evidence for associated production in Run I
- Next : measure couplings
  - 10% uncertainty effectively probes BSM models
  - $\delta g_{t\bar{t}Z} \approx 10\% \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$

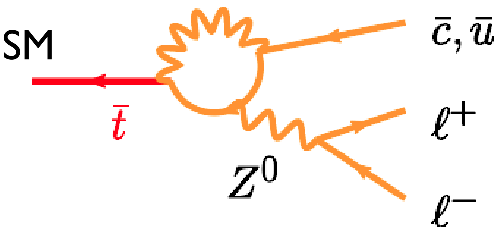
arXiv:1311.2028

Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^γ (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^Z (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^Z (0.6)	0.058	–	0.005
Non-SM couplings			
photon, F_{1A}^γ	0.05	–	–
photon, F_{2V}^γ	0.037	0.025	0.003
photon, F_{2A}^γ	0.017	0.011	0.007
Z boson, F_{2V}^Z	0.25	0.17	0.006
Z boson, ReF_{2A}^Z	0.35	0.25	0.008
Z boson, ImF_{2A}^Z	0.035	0.025	0.015

$$\Gamma_\mu^{ttX} = ie\left\{-\gamma_\mu\left(\left(F_{1V}^X + F_{2V}^X\right) + \gamma_5 F_{1A}^X\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(F_{2V}^X - i\gamma_5 F_{2A}^X\right)\right\}$$

Couplings : FCNCs

- **BSM** models **may give** rise to **FCNC at the level of BR<10^{-4}**
  - via neutral bosons: Z, γ, gluons and Higgs : at the level of 10^{-17}-10^{-12} in the SM
  - higher luminosity will definitely help to reach nearer BSM scenarios



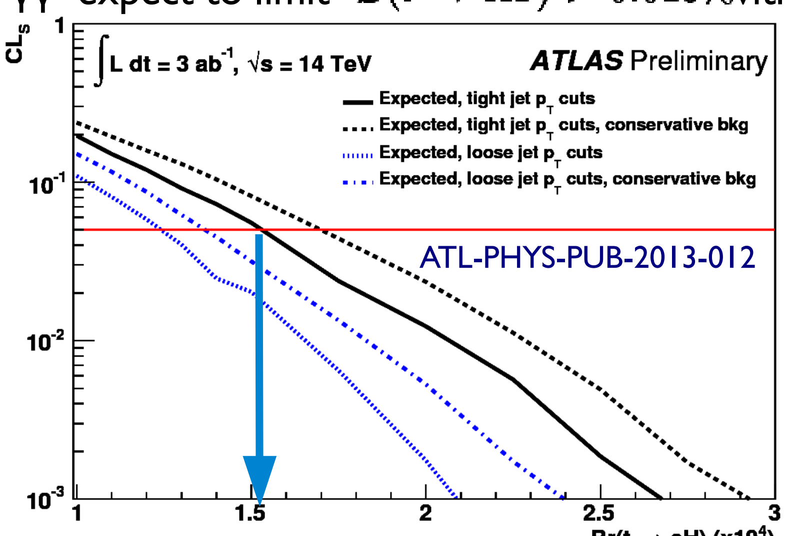
arXiv:1311.2028

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

t → Z/h + c strongest potential for discovery stories at the LHC of flavour-violating or composite-Higgs models

Extrapolating JHEP 06 (2014) 008

- H → γγ expect to limit $\mathcal{B}(t \to cH) > 0.015\%$ with 3 ab^{-1}



Extrapolating PRL 112 (2014) 171802

- Limit $\mathcal{B}(t \to qZ) < 0.027\ (0.01)\%$ with 300 fb^{-1} (3ab^{-1})
- **If $\mathcal{B}(t \to qZ) > 0.02\%$ → 5σ discovery with 3ab^{-1}**

CMS-PAS-FTR-13-016

Uncertainty (%)	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Jet energy scale	13.5	3.5	3.4
$\not{E}_T$ resolution	3.2	3.2	3.2
MC Statistics	5.3	1.4	1.3
σ(tqZ)/ σ(V$t\bar{t}$)	3.1	1.0	0.8
b-tagging	17.7	4.5	4.2
Total	23	7	7

Couplings : FCNCs

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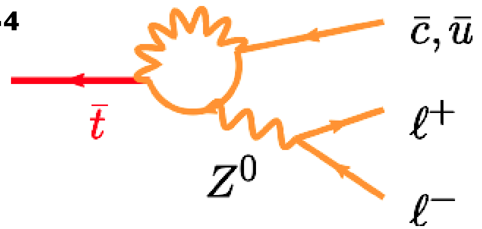
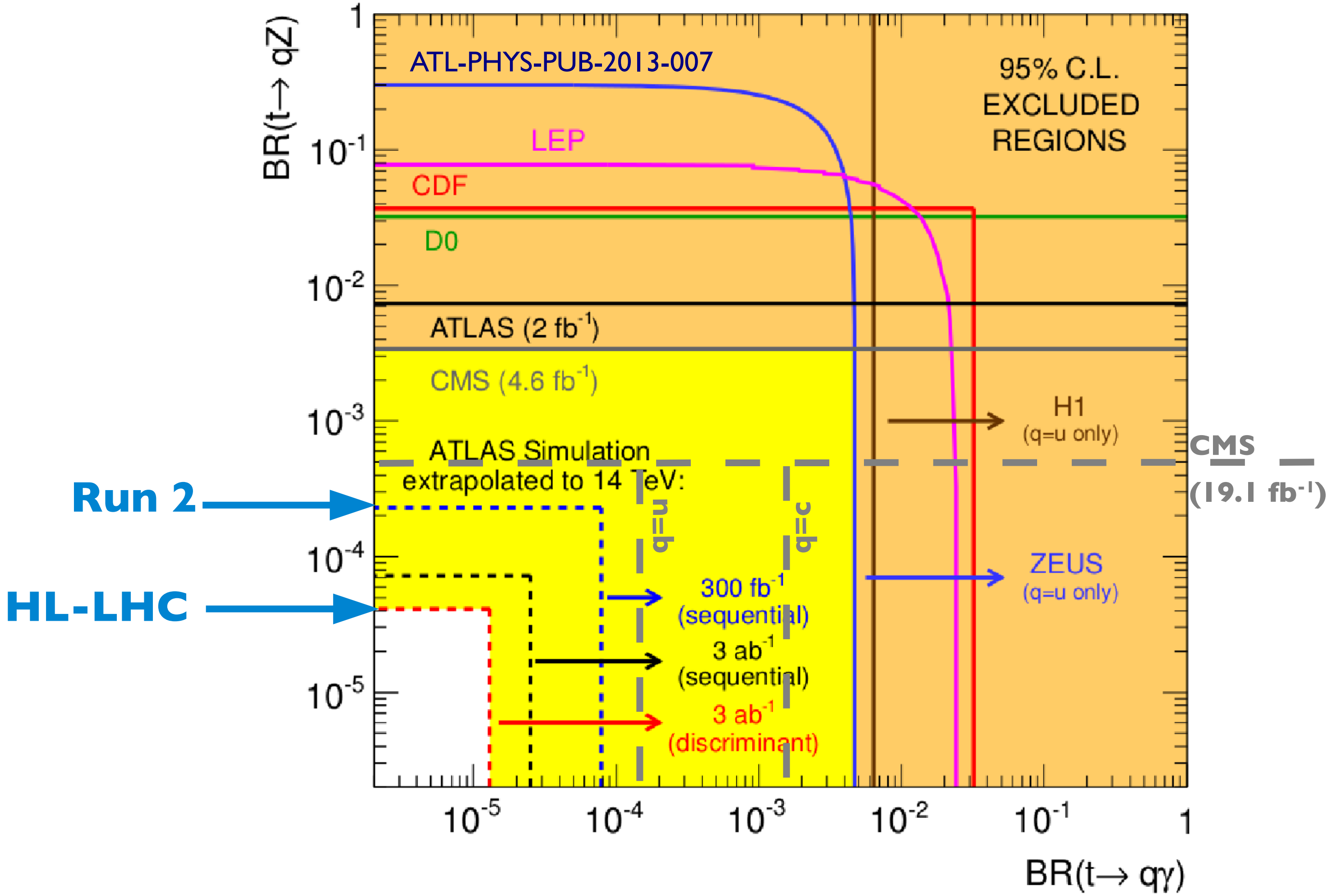
  - would be at the level of 10^{-17}-10^{-12} in the SM
  - higher luminosity will definitely help to reach nearer BSM scenarios

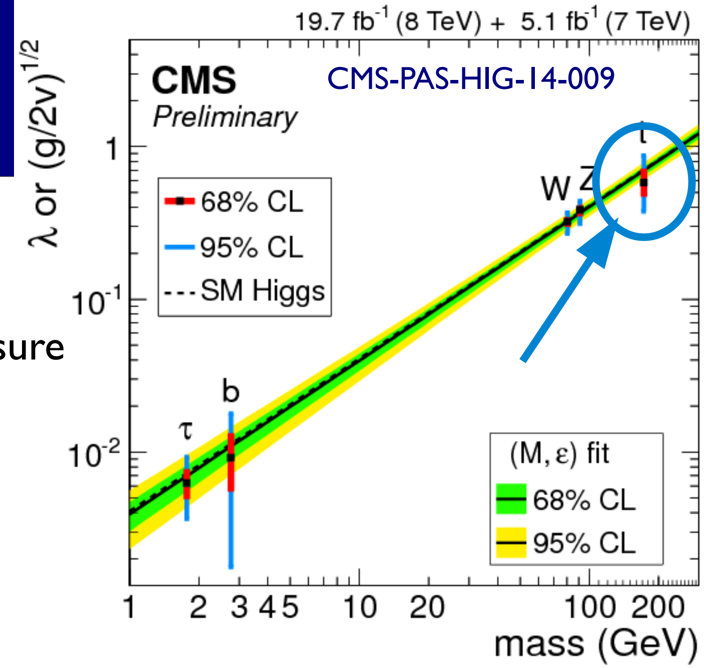




Higher reach in mass than the LHC will ever produce directly

Top quark physics

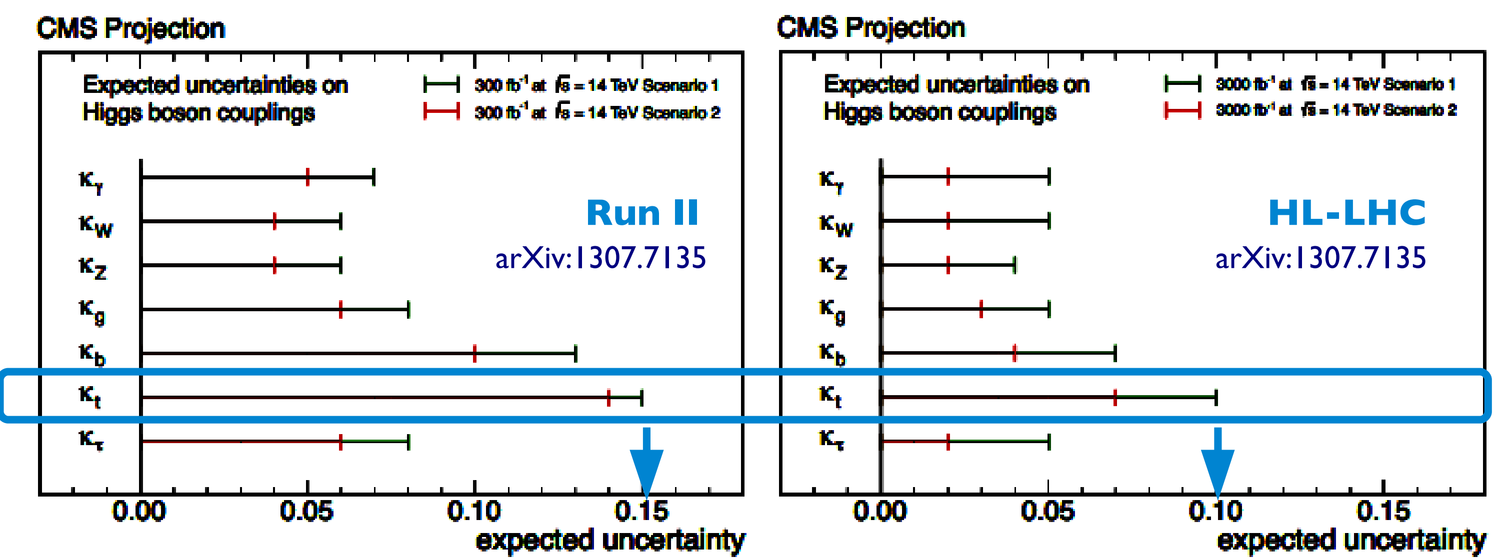
Couplings: Yukawa

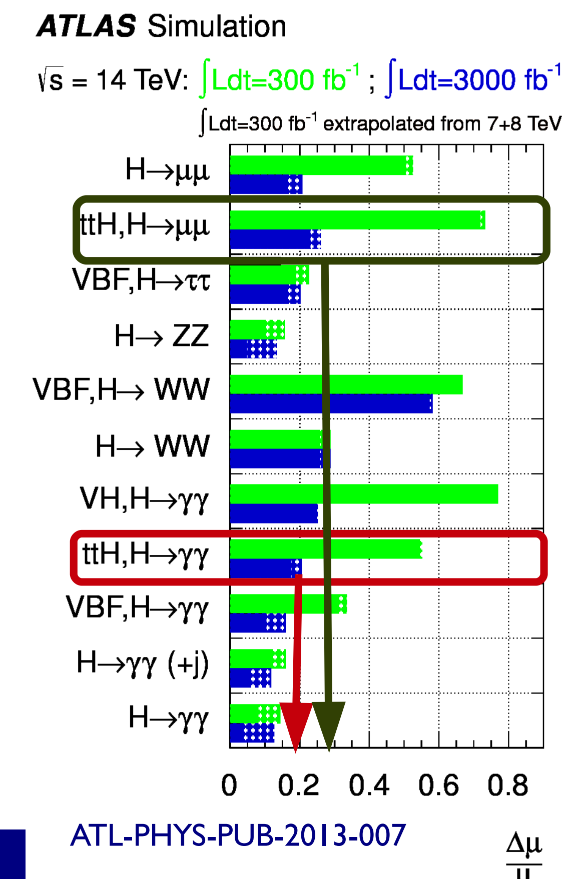


- By far **the "strongest" of the Higgs couplings**
  - **σ(ttH)** = 623 fb at 14 TeV (ratio to 8 TeV : 4.8) → challenging to measure
  - complement golden bb final state with multileptons and γγ
  - NB: moderate excess observed in 8 TeV multilepton search: crucial to follow up with Run II data
- **Projections** for y_t evolution **based on two scenarios**

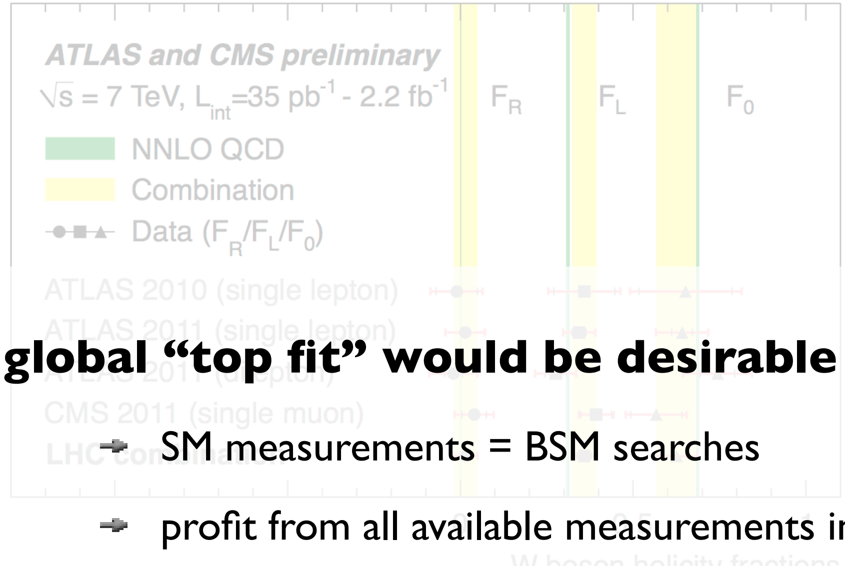
  1. saturated systematics

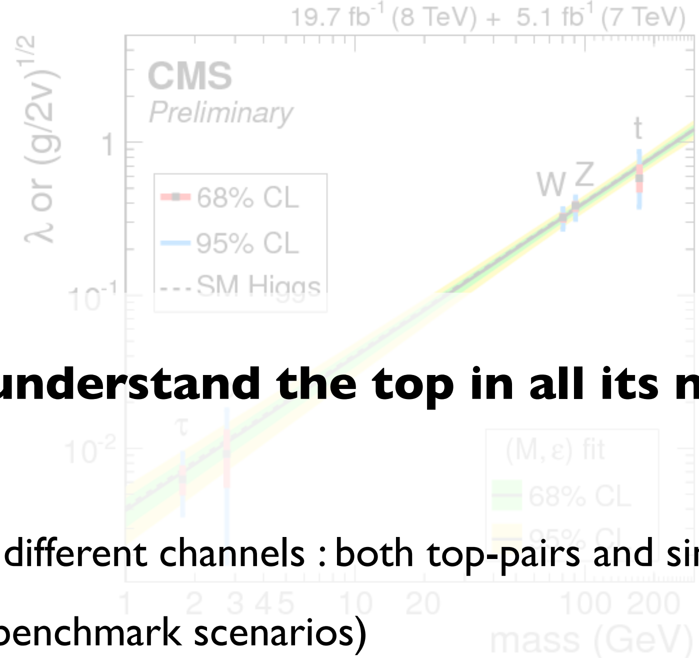
  2. theory reduced by ½, exp. scaling with integrated luminosity



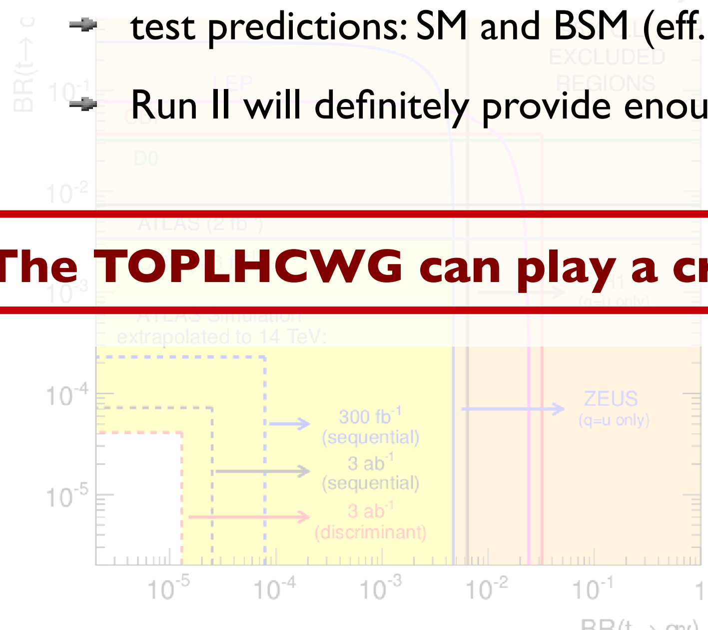


Couplings: interim summary





- **A global "top fit" would be desirable to understand the top in all its magnitude:**
  - SM measurements = BSM searches
  - profit from all available measurements in the different channels : both top-pairs and single top
  - test predictions: SM and BSM (eff. theory or benchmark scenarios)
  - Run II will definitely provide enough data to accomplish this task



Coupling	LHC		ILC/CLIC
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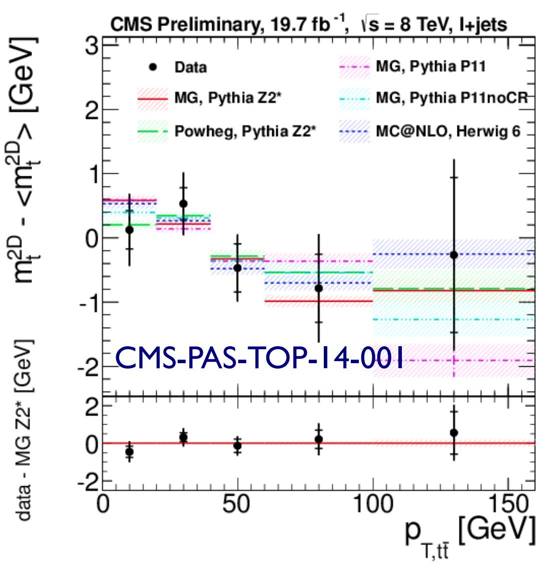
The TOPLHCWG can play a crucial role in bringing exp. and th. together

Mass : quo vadis? I

- The most ~~fundamental~~ ~~crucial~~ ~~interesting~~ ambiguous parameter of the standard model
- Most **measurements rely on** an intrinsic **calibration to** a LO/NLO **MC** definition
  - may assume that ambiguity can in principle be resolved up to $O(\Lambda_{QCD})$ – *see A. Hoang's talk*
  - e.g. measure mass in MC, use observables calculated in well defined schemes, use short-range definition
  - from the experimental point of view **Run 2 and HL-LHC have potential for more precise m_t**

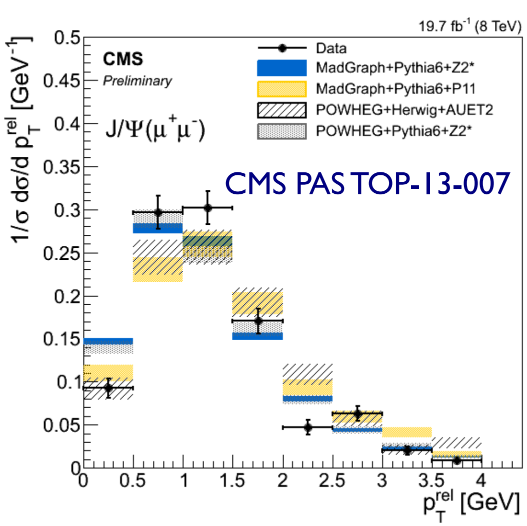
Diff. m_t measurements

constrain in-situ main uncertainties



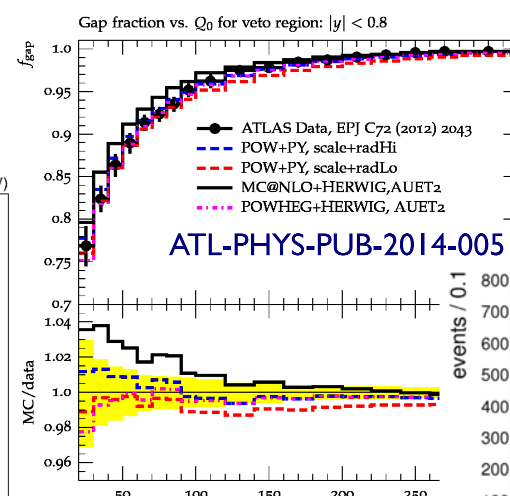
Measurements of the UE and fragmentation in tt:

tune signal model with data



Measurements of radiation in tt

constrain pQCD signal model uncertainties

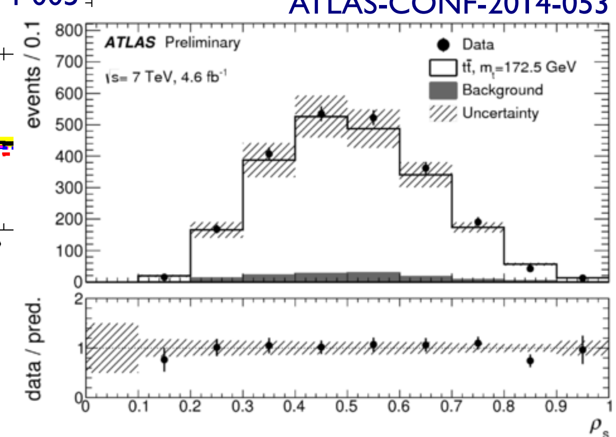


$$f(Q_0) = \frac{n(Q_0)}{N}$$

Alternative methods

Improve precision on "theory safe" observables, profit from high stats and also NNLO signal modelling

ATLAS-CONF-2014-053



Mass : quo vadis? II

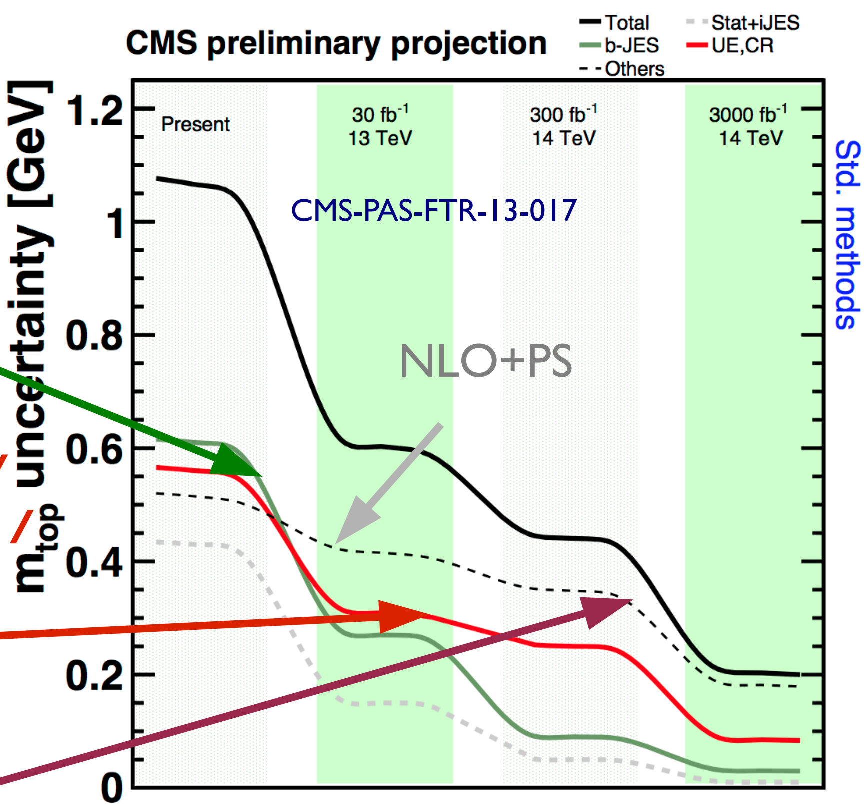
- Use flagship measurements @ the LHC to project roadmap towards HL-LHC
  - improved fitting techniques. dedicated signal modeling studies
  - standard methods expected to lead m_{top} measurements
  - to be accompanied with improvements from theory

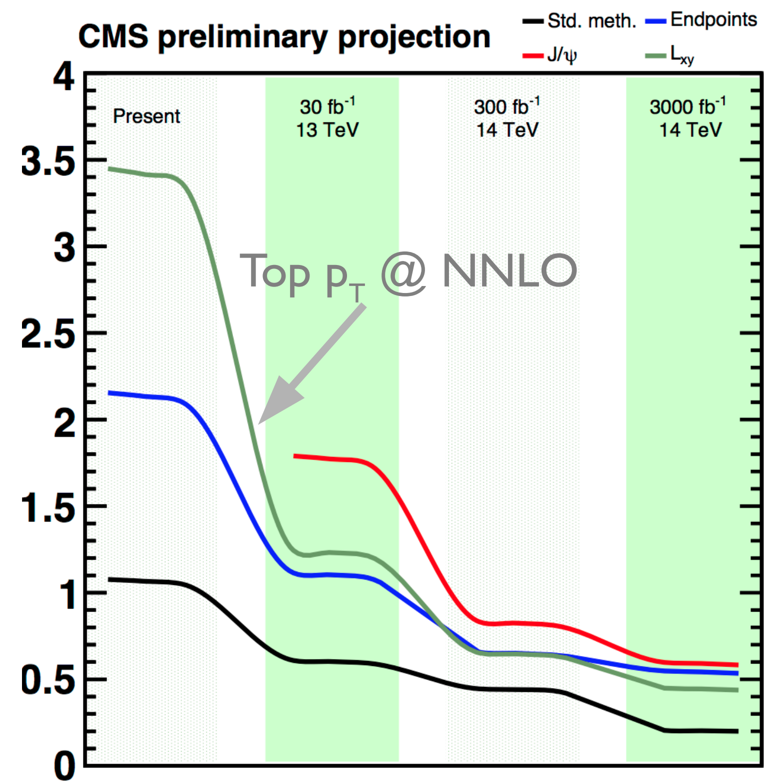
expect $\sigma(m_t) \sim \Lambda_{QCD}$ at the end of HL-LHC!

move to 3D fit (light JES+b JES)

dedicated UE / fragmentation / hadronization studies

fully differential measurement





From the mass to the width

- The width is **accurately predicted at NLO**

  $\Gamma_t = 1.33 \pm 0.01$ GeV

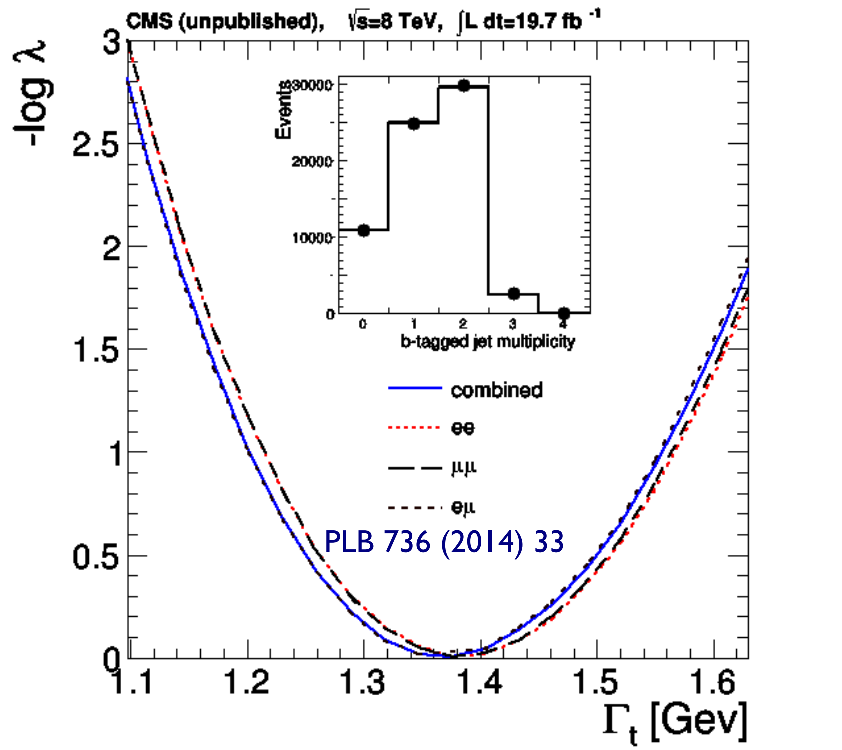
  - Deviation signals NP coupling with the top quark

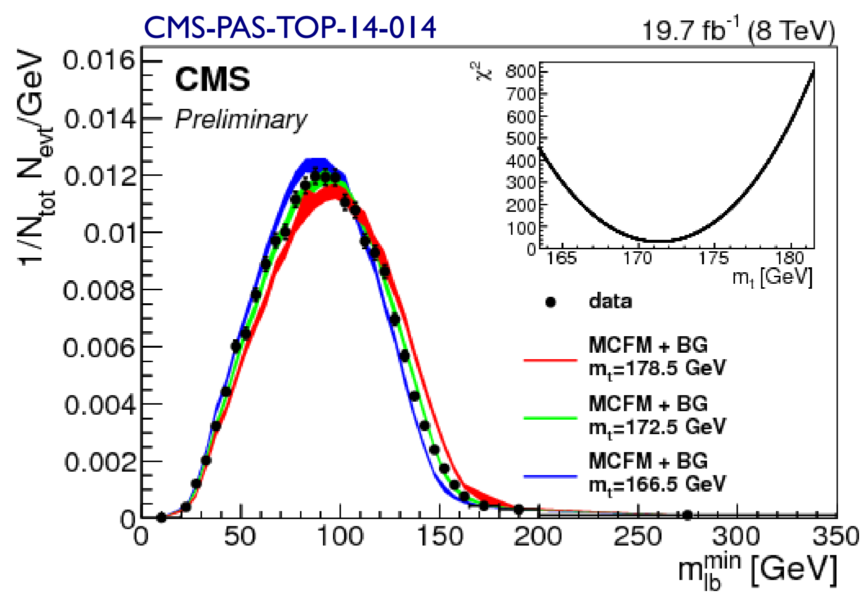
- **Measured indirectly in Run I ▶**
  - through a combination of R_b and σ(t-ch) arXiv:1009.5686
  - 11% uncertainty is dominated by $\Delta\sigma$(t-ch)

    profit from more recent NNLO QCD calculations arXiv:1404.7116

- Direct **measurement from mass shape**
  - pioneered by CDF PRL 111 (2013)
  - expect competitive results based on latest mass determinations at the LHC with $\sigma(m_t)$<1 GeV

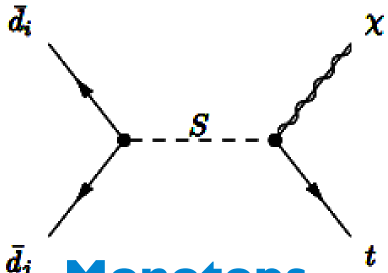
- But also: how important are **off-shell effects?**
  - measure inclusive $WWb\bar{b}$ production (e.g. JHEP06(2014)158)
  - differential distributions may shed light on the width ▶



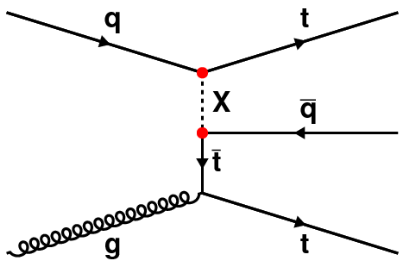


Window of opportunity for new physics

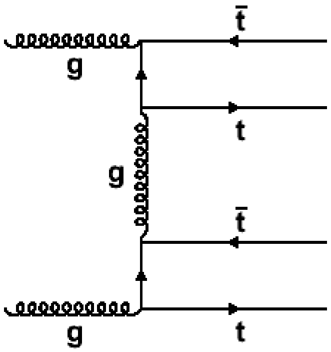
- Many exotic signatures will be worth exploring further at higher energy and int. luminosity



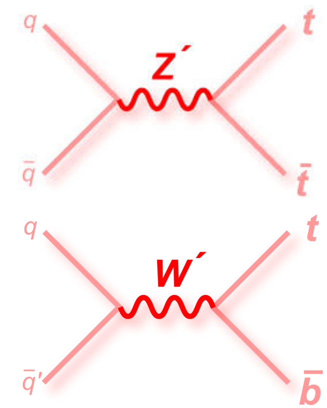
Monotops



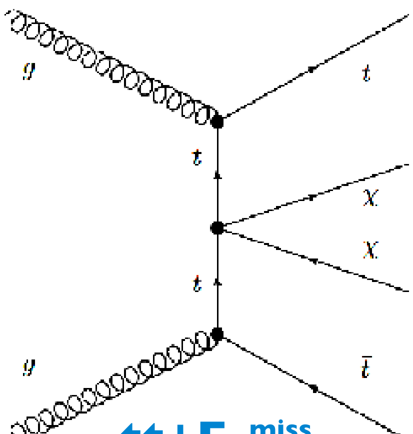
Like-sign tops



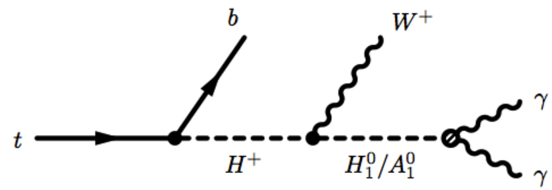
Four tops,
but also ttbb, ttcc



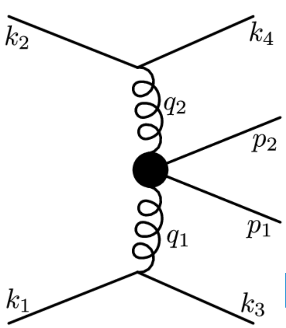
Resonant productions



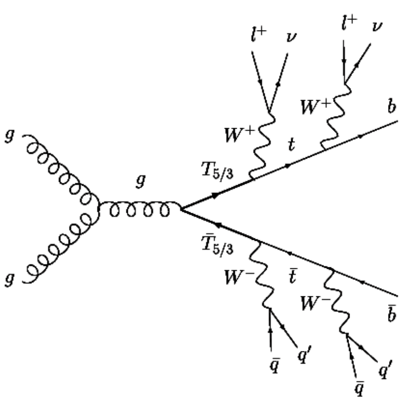
tt+E_T^{miss}
(including H_{inv})



H$^+$ decay cascade after a top decay



tt through vector boson fusion production



Top partners

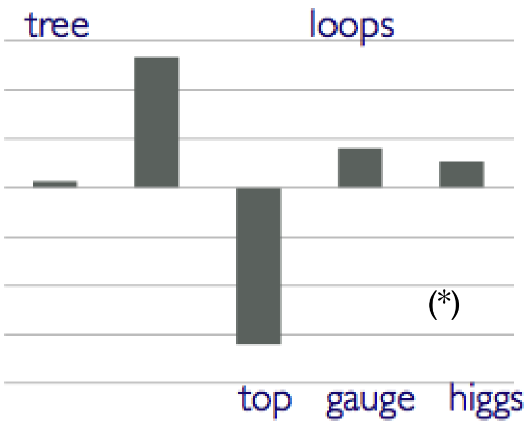
We have looked for most of them in Run I and will keep looking in Run II and HL-LHC.

Specific algorithms needed for specific topologies (e.g. c-tag, jet subtructure, etc.) are in constant evolution.

Probing EWSB naturalness I

- **Top dominates** the **loop contributions to the Higgs mass**
  - cancellations are a bit "un-natural" way in the SM
  - "naturalness" would require relatively light stop/sbottoms ~ TeV
  - would preferentially couple to top quarks

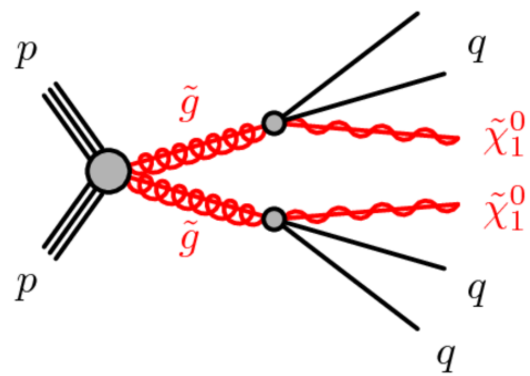
$m_h^2 \sim (125\ \text{GeV})^2$



- **Gluino-induced** or **direct stop production** in "natural" scenarios is within the LHC reach

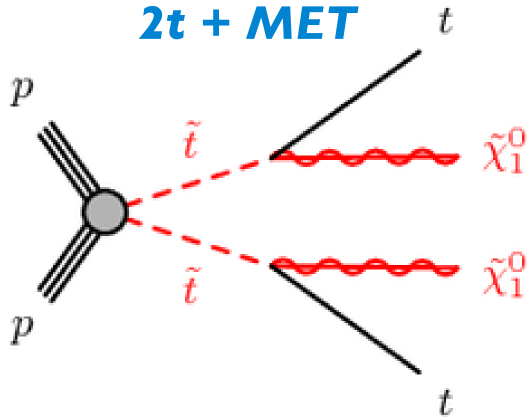
if gluinos are within the LHC reach:

4t / 2t2b + MET



direct production:

2t + MET



$$\frac{\sigma(pp \to \tilde{g}\tilde{g})}{\sigma(pp \to \tilde{t}\bar{\tilde{t}})} \sim 50$$

arXiv:1206.2892

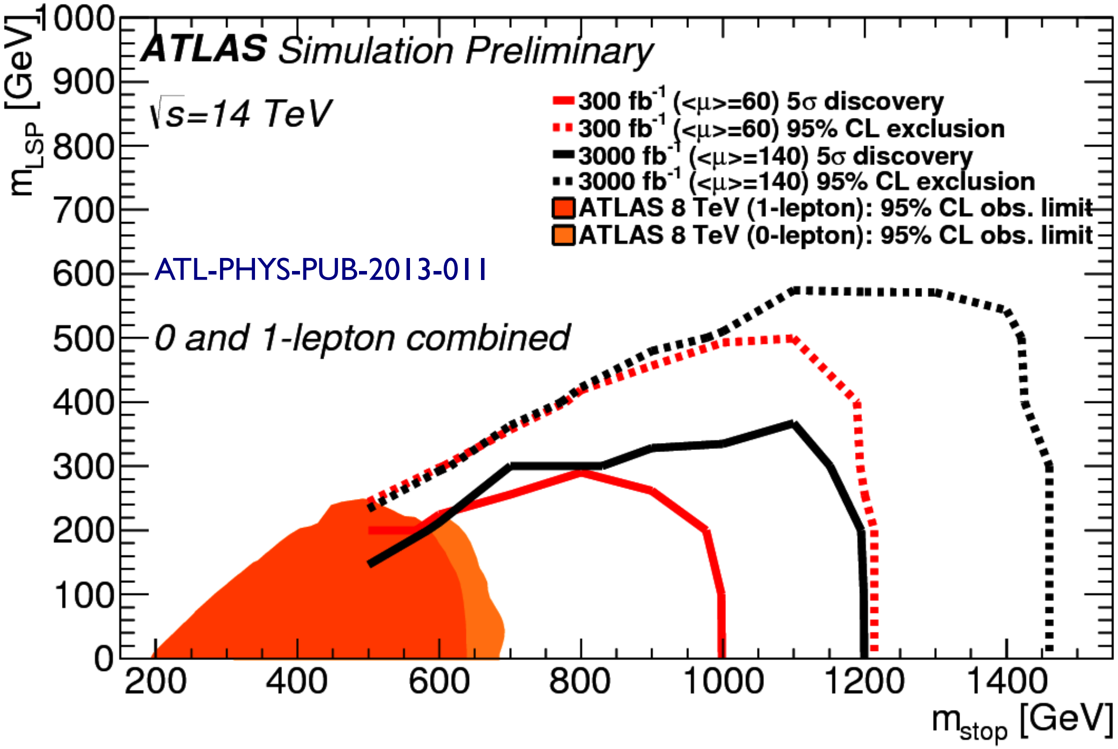
- in both cases strong production benefits from the increase in $s^{1/2}$
- increased integrated luminosity will allow to scan to higher mass scales
- but also to perform dedicated searches for the cases of compressed spectra

sensitivity driven by BR
=0 and =1 lepton channels

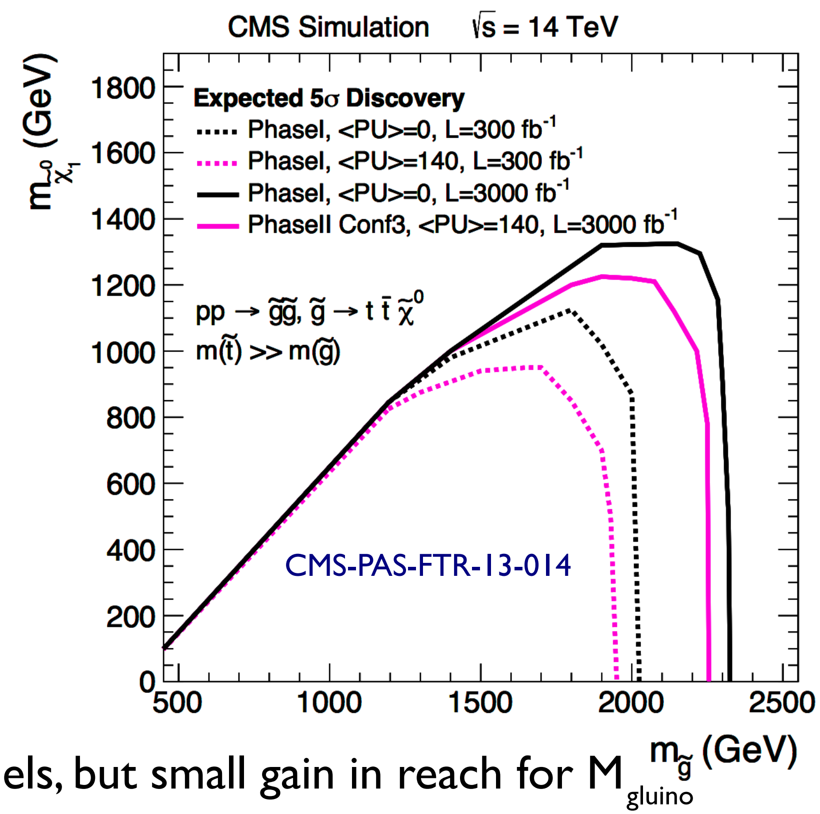
(*) graph from F. Maltoni @ LHCP2013

Probing EWSB naturalness II

- **Search for direct stop production**
- Explore tt + extra E_T^{miss} signature
  - *0 leptons:* $M_T(b, E_T^{miss})$, $N_{jets} \geq 6$, $N_{b\text{-}tags} \geq 2$
  - *1 lepton:* $M_T(l, E_T^{miss})$, $N_{jets} \geq 3$, $N_{b\text{-}tags} \geq 1$



- **Searching for gluino-induced**
- One lepton + ≥6 jets final states
  - Leptonic flux: $S_T^{lep} = p_T^{lep} + E_T^{miss}$
  - Polarization: $\Delta\varphi(l,W)$
  - Categorize in b-tag multiplicity and S_T^{lep}



Expect HL-LHC powerful for challenging models, but small gain in reach for M_{gluino}

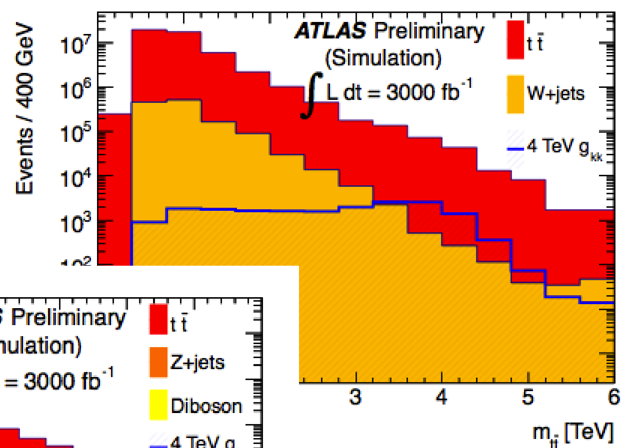
Discovery possible for $M_{\tilde{t}}$~1.2 TeV → test EWKSB tuning to ~1:10²

Probing EWSB naturalness III

X → tt : benchmark for cascade decays

- explore boosted reconstruction techniques
- use m_{tt} in single-leptons or (H_T in di-leptons)

model	$300\,fb^{-1}$	$1000\,fb^{-1}$	$3000\,fb^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{topcolor}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)



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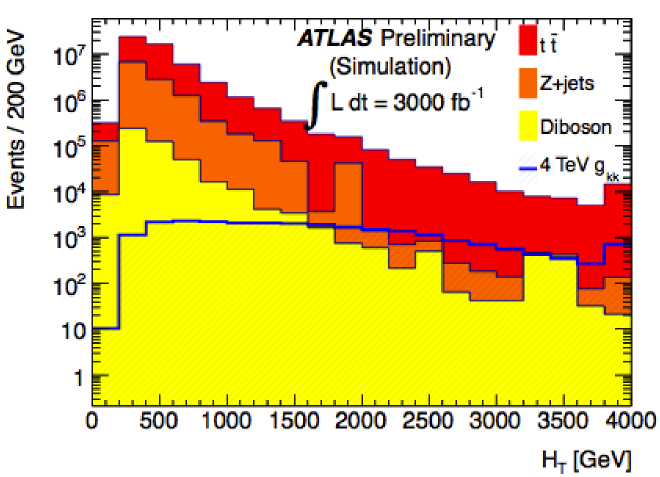

Exotic top partners

- Vector quarks may generate t → t + W/Z/h
- cover all possible final states also boosted topol.
- will benefit from higher integrated luminosity

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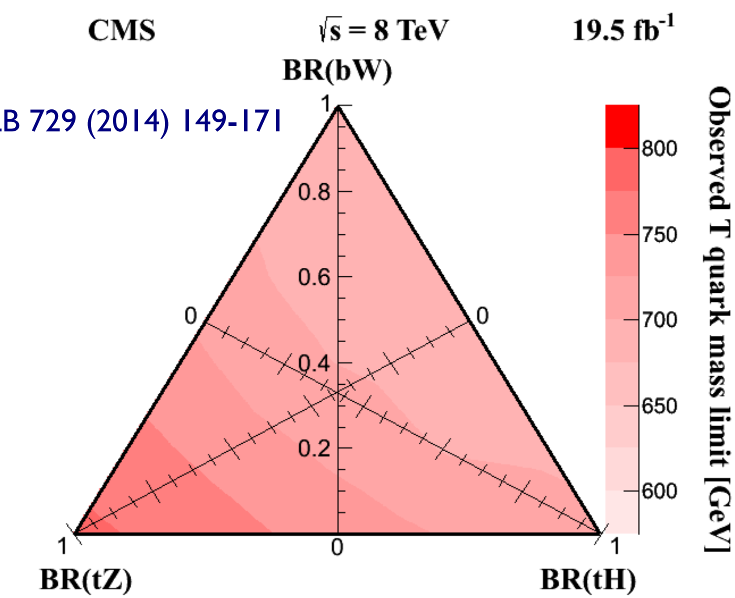

NB: new physics may be elusive

e.g. wide KKG, intermediate T → t+W/Z/h, non-trivial flavour mix,...

control accurately $d\sigma/dm_{tt}$, cover all final states, charm tagging, ...

Conclusions

- **While still learning many things on the top quark from the first LHC run**
  - it's clear **we need more data to be able to take the next step**

- **ATLAS** and **CMS are preparing intensively for Run 2 and the HL-LHC**
  - upgraded detectors with enlarged capabilities to face the increase in pileup
  - new techniques for jet reconstruction and pileup subtraction and identification, flavour tagging

- **Eagerly looking for:**
  - more **precise cross section measurements** including ratios, differential
  - **global view of the couplings** of the top quark
  - the **ultimate top mass** measurement from hadron colliders
  - the **exploration of the naturalness concept**, after the discovery of the Higgs: the relevant parameter range for naturalness will be covered by the end of the HL-LHC era

The exploration of the new data is a new start for top physics:

will the top quark finally reveal its key for the world beyond the terascale?

Backup

Search for FCNCs in single-top topologies