# Standard Model measurements

(excluding Higgs and heavy flavour physics)

# – updated studies –

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on behalf of the

ATLAS, CMS and LHCb Collaborations

Aix-les-Bains, October 2016

3rd ECFA High Luminosity LHC

Experiments Workshop

# Physics opportunities at the HL-LHC

## Examine Higgs boson and boundaries of the Standard Model

- precise determination of mass, couplings, decay modes
- searches for New Physics and dark matter

## Need to understand SM processes

- production of $\gamma$, $W$, $Z$, or top quarks + jets
- always appear as irreducible or reducible background

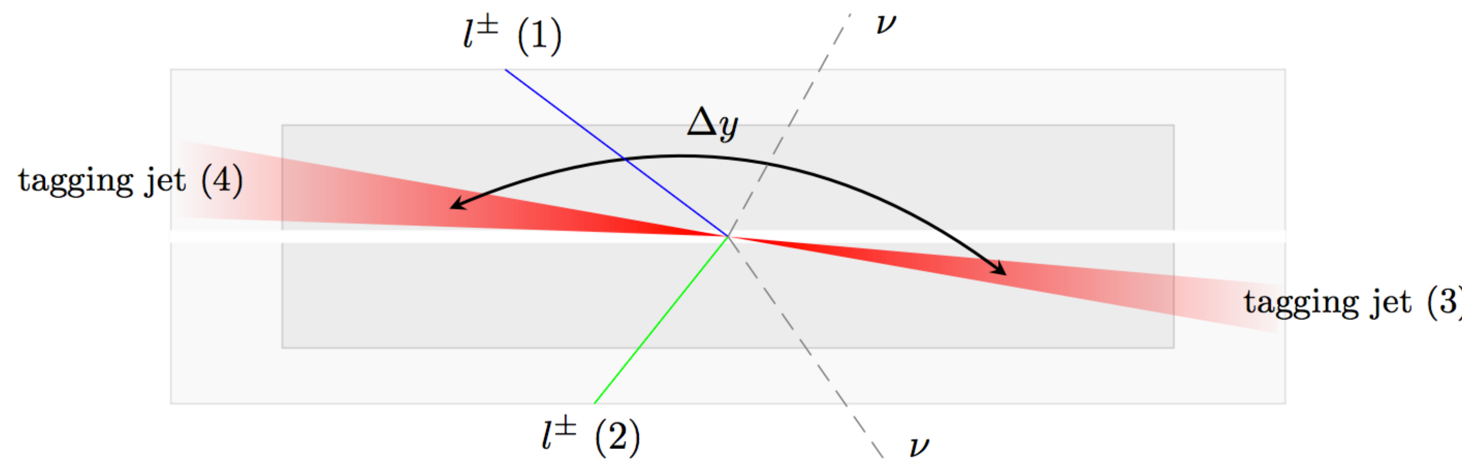
## Have their own intrinsic interest, e.g.

- SM electroweak parameters, $t\bar{t}$ cross section, …
  - need improved theoretical understanding and inclusion in event generators
- improved determination of PDF
- searches for anomalous gauge boson couplings
- tests of the unitarity-cancellation mechanism in the SM
- top-quark mass

# Topics for this presentation

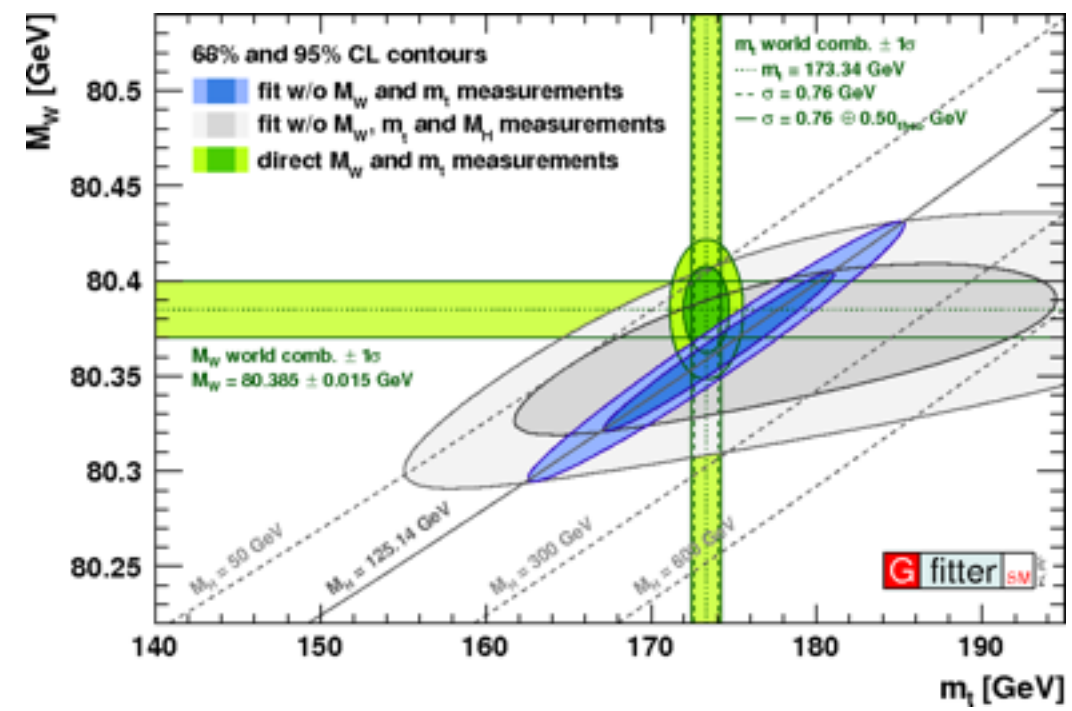
## Standard Model studies

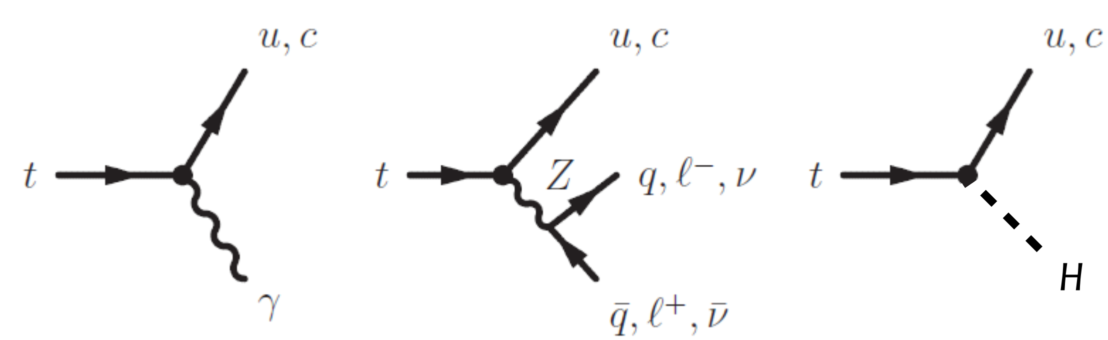
- vector boson scattering
  - $W^{\pm}W^{\pm}$ and $WZ$ scattering
- forward region physics
  - e.g. PDFs, intrinsic charm




## Top quark studies

- mass
  - classic methods
  - with less dependence on jet systematics
  - indirect pole mass determination
- forward region
- flavour changing neutral currents
  - single top quark $qg \rightarrow t\gamma$ production
  - $t \rightarrow Zq \rightarrow \ell\ell q$ decay
  - $t \rightarrow Hq \rightarrow b\bar{b}q$ decay



# VBS – motivation and current results

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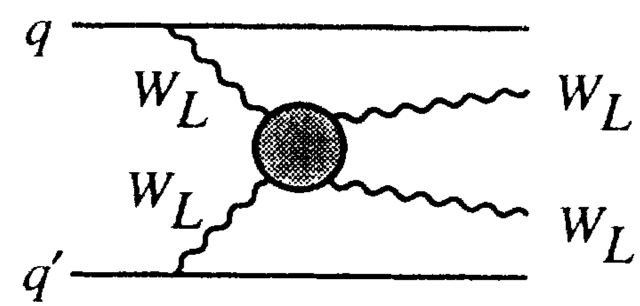
## Electroweak $VV \to VVjj$ scattering

- via TGC, QGC or Higgs boson exchange
- cancellation → sensitive probe of new physics
- distinct signature in detector, good S/B ratio ($VV$ QCD, $t\bar{t}$, $V$+jets, … )




## Run-1

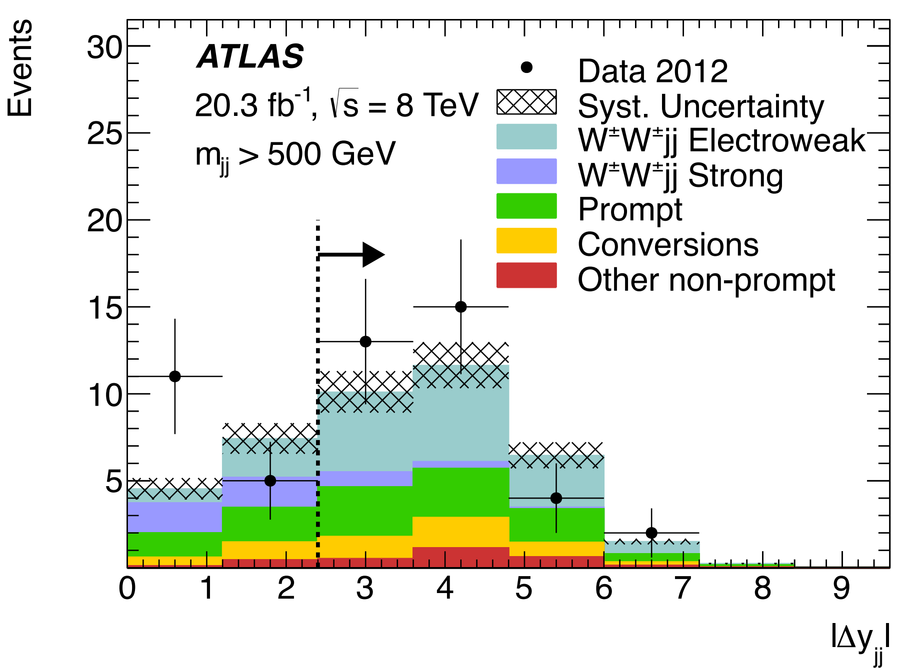
PRL 113 (2014) 141803 PRL 114 (2015) 051801

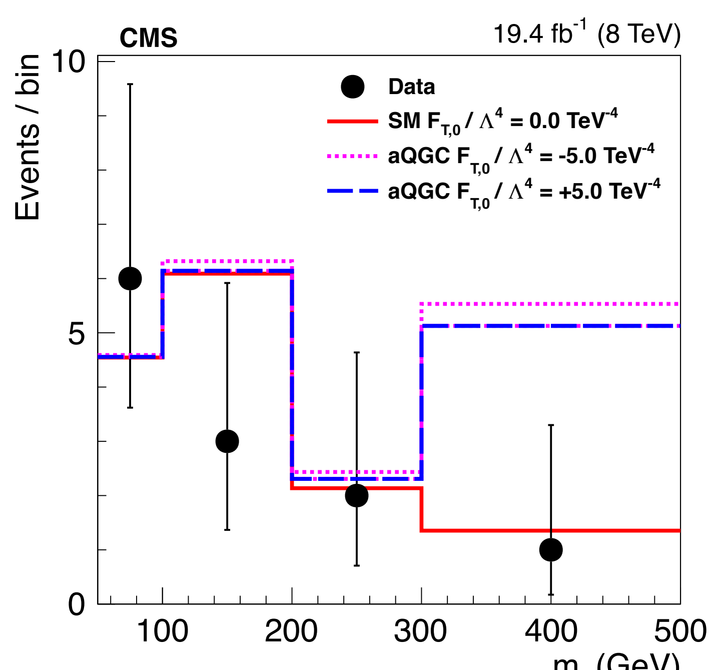
- fiducial $W^{\pm}W^{\pm}jj \to \ell^{\pm}\ell^{\pm}$ + tag jets + $E_T^{miss}$
  - evidence of EWK production at 3.6 σ (1.9 σ), with 2.8 σ (2.9 σ) expected by ATLAS (CMS)
  - fiducial cross-sections with $\Delta\sigma/\sigma$ = 30% (60%)
  - interpret as limit on anomalous QGC (or $H^{\pm\pm}$)

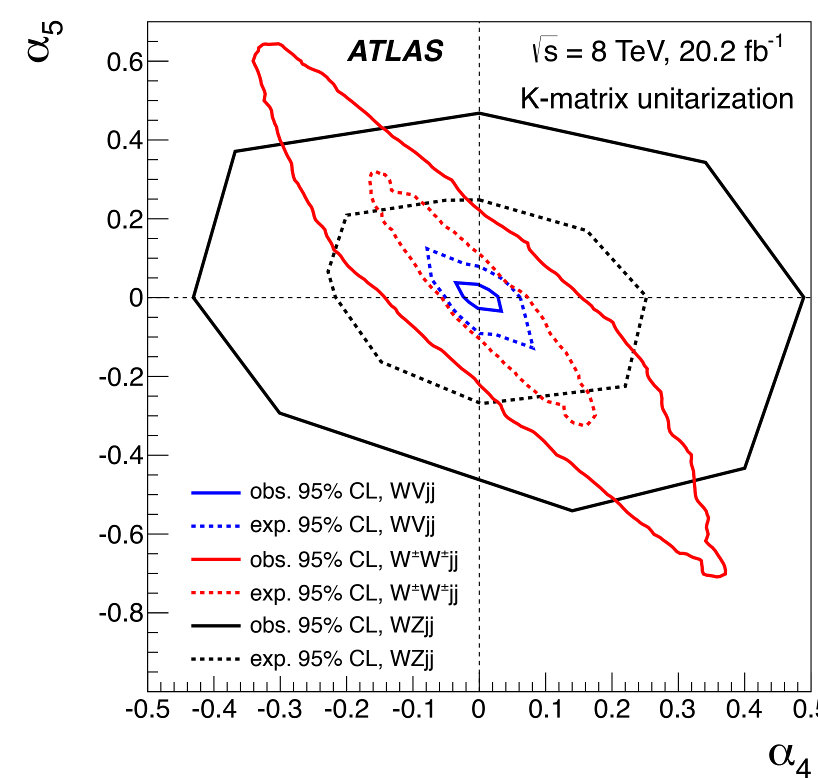
## Latest result

1609.05122 subm. to PRD

- $W^{\pm}Vjj \to \ell^{\pm}$ + had + tag jets + $E_T^{miss}$
  - $V = W, Z$ → decaying hadronically
  - reconstructed as 2 jets or 1 large-$R$ jet
  - interpret as limit on anomalous QGC



# VBS – previous HL-LHC studies

## Before 2015

- exploring all channels $pp \rightarrow W^{\pm}W^{\pm}jj$, $WZjj$, $ZZjj$
- discovery potential for observing longitudinal VBS & aQGC

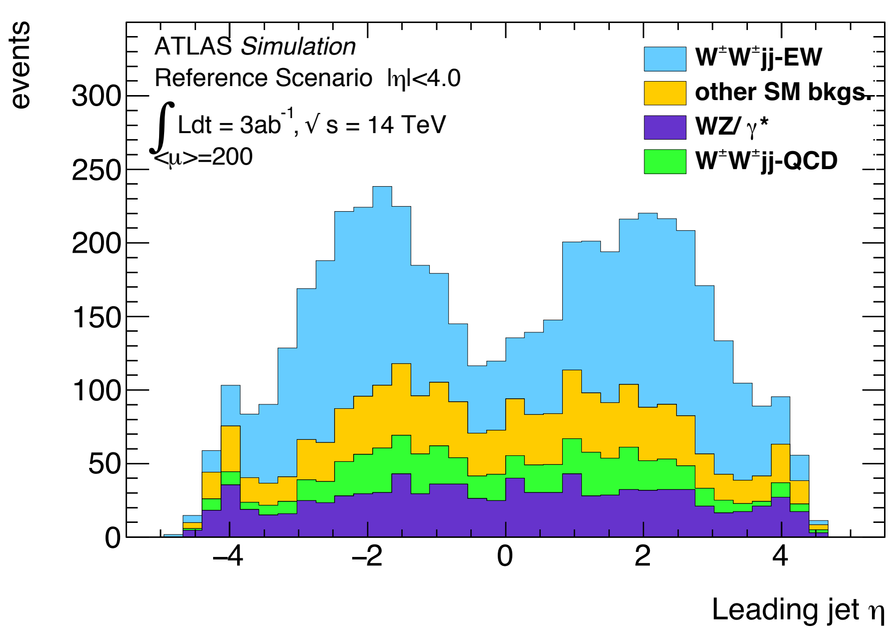
**ATL-PHYS-PUB-2012-001**
**ATL-PHYS-PUB-2012-005**
**ATL-PHYS-PUB-2013-006**
**CMS PAS FTR-13-006**

## Scoping document: $W^{\pm}W^{\pm}jj$

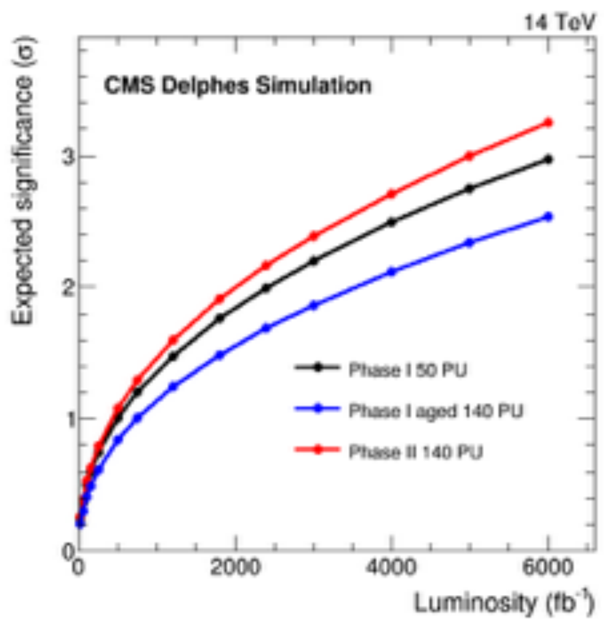
- backgrounds from Run-1 analysis
  - dominant ones scaled to account for all
- main gains from extended tracking
  - greater lepton coverage (reduces $WZ$)
  - greater pile-up jet rejection
- expectations for EKW $W^{\pm}W^{\pm}jj$
  - $Z_{\sigma B}$ significance ~11, $\Delta\sigma/\sigma$ = 5.9%

## Technical Proposal: $W^{\pm}Vjj$

- use global fake rate scale factor
- main gains from
  - better jet-$\ell$ fake rate, larger coverage
  - better pile-up rejection (fwd calorimeter)
- expectations for
  - $W^{\pm}W^{\pm}jj$ with $\Delta\sigma/\sigma$ = 5%, $WZjj$
  - polarisation: $V_L V_L \rightarrow V_L V_L$ at 2.75$\sigma$




**CERN-LHCC-2015-020 (LHCC-G-166)**
**CERN-LHCC-2015-010 (LHCC-P-008)**

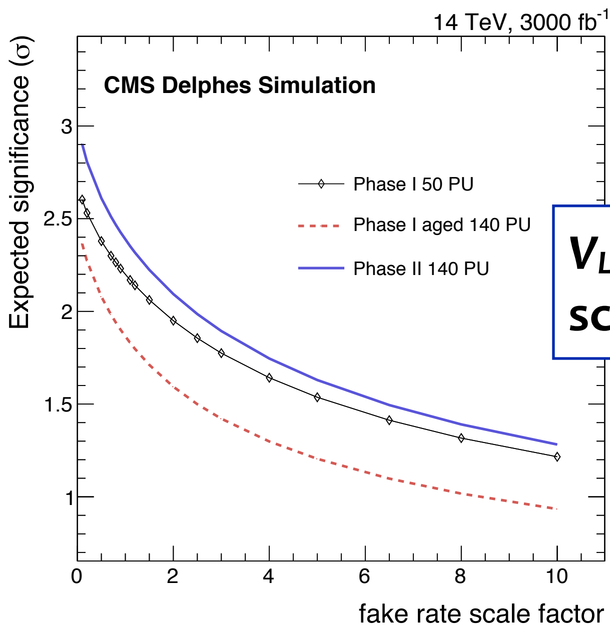


# VBS – new study (CMS)

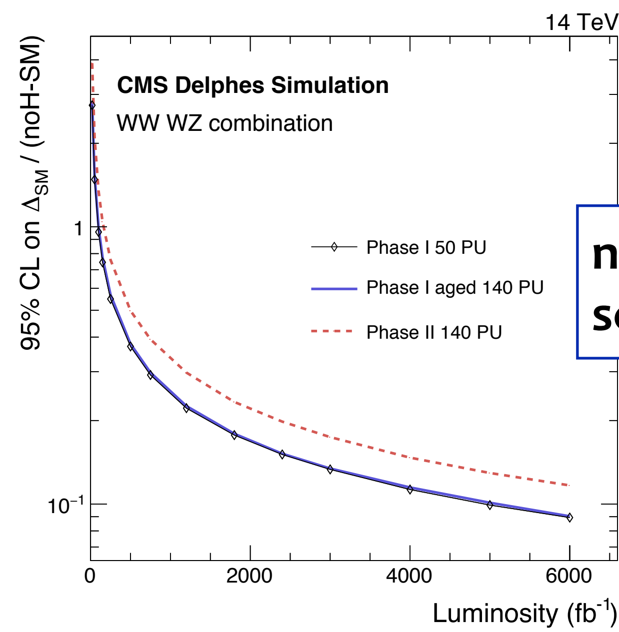
**CMS PAS SMP-14-008**

## Same channels as in Technical Proposal

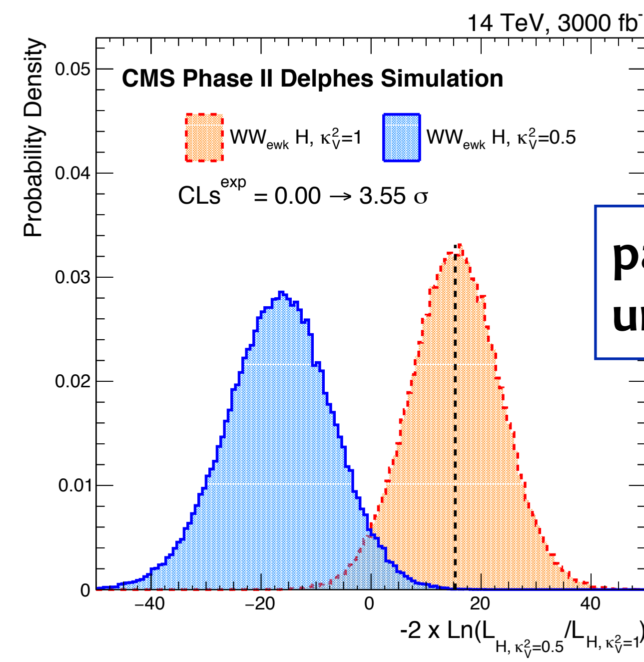
- now including all sources of background, including reducible and fakes
- report results as a function of data/MC fake rate scale factor
- expect $\Delta\sigma/\sigma \leq 10\%$ for *WW* and *WZ* VBS and 2.75 $\sigma$ for $V_L V_L$ scattering




$V_L V_L$ scattering




no Higgs scenario




partial unitarization

## Sensitivity to different BSM scenarios

- generic no-Higgs scenario
- presence of additional dim-8 operators in EFT framework
- partial unitarization

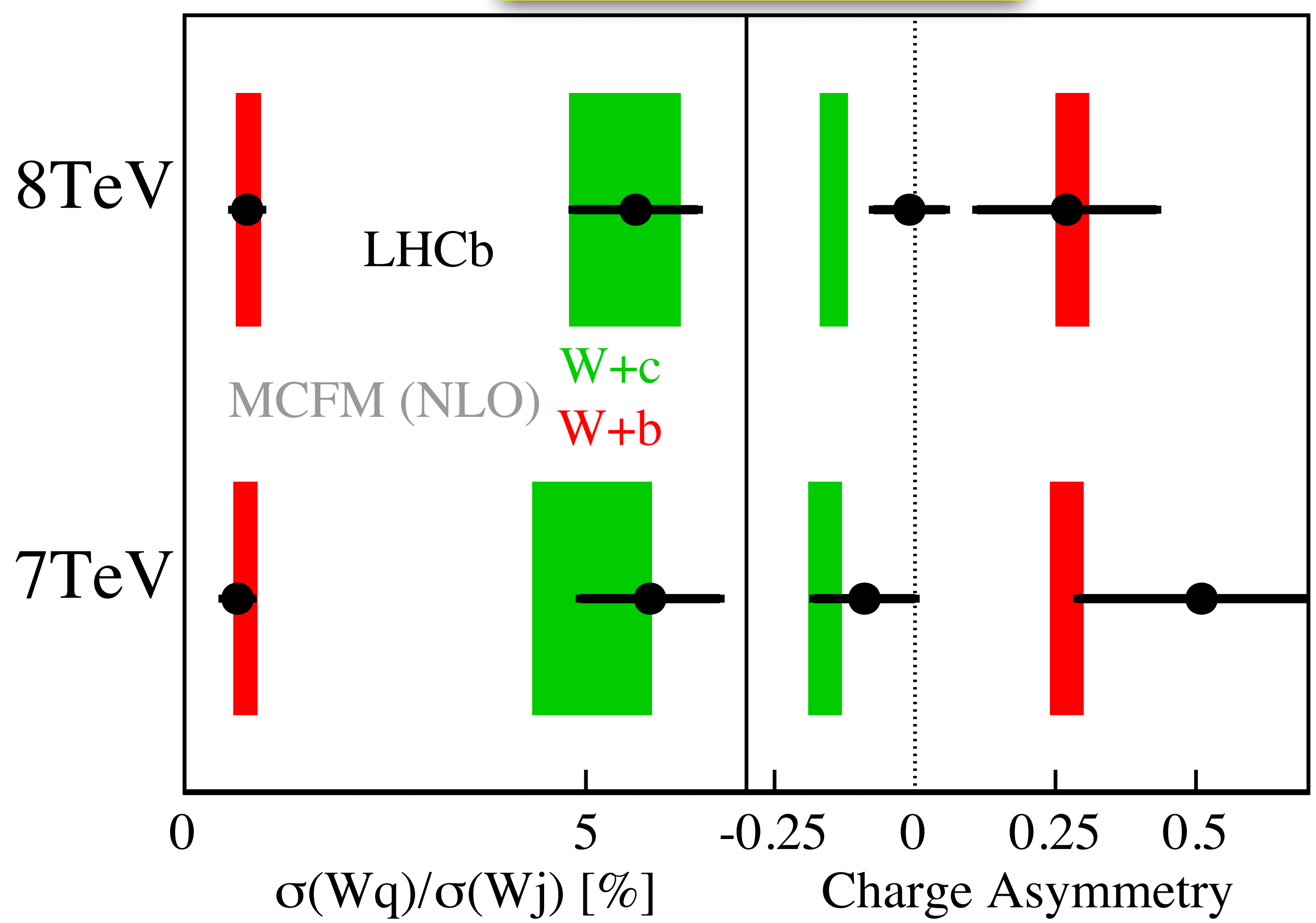
## Comparing scenarios (current, aged, upgraded)

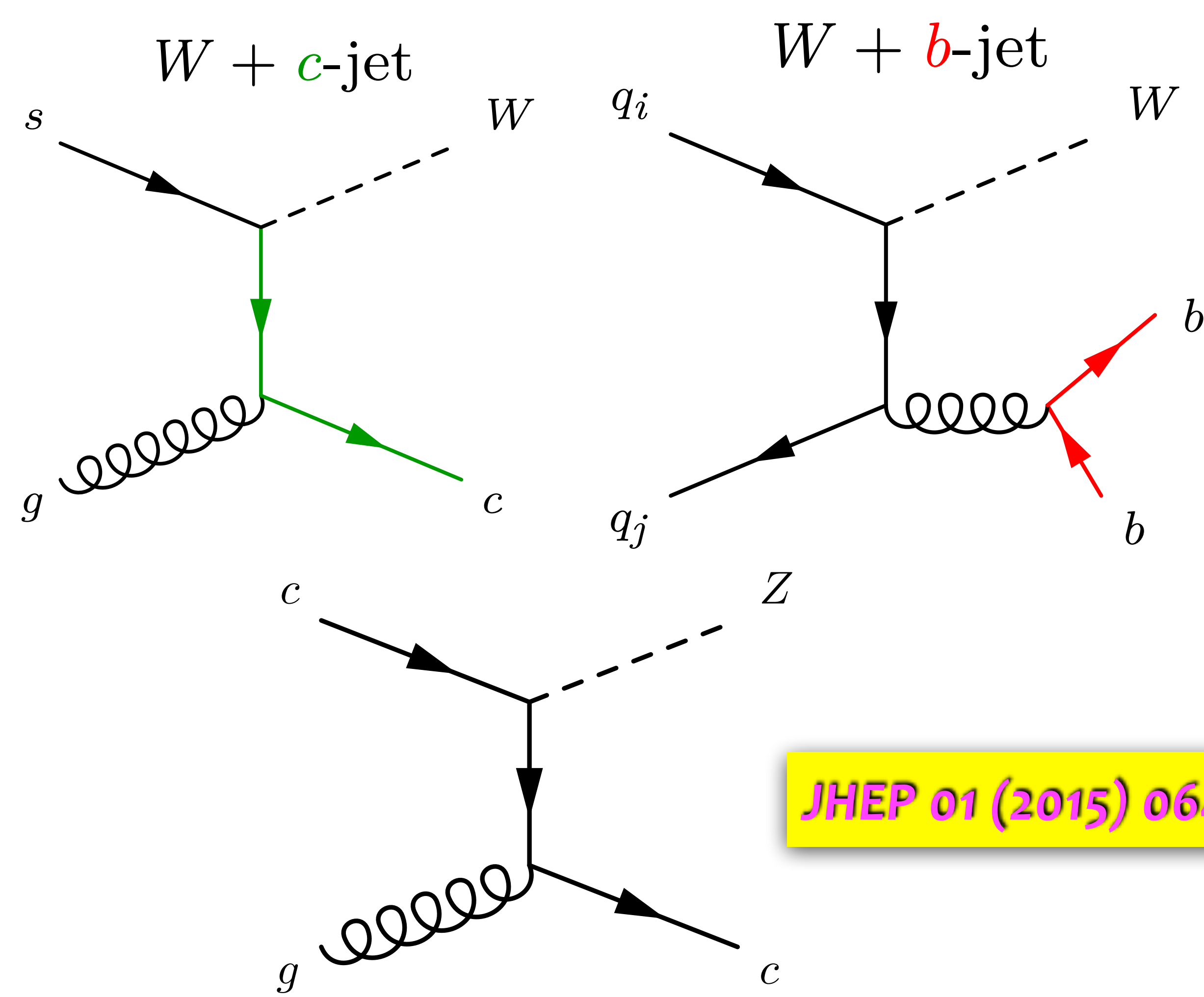
- detector upgrade recovering performance lost from ageing of CMS detector

## Run 1 results agree with SM predictions

- expect factors of 10 (Run-2) to 600 (HL-LHC) more *W*+HF events
- allows for double-differential measurements

*PRD 92 (2015) 052001*




*JHEP 01 (2015) 064*

## Proton charm content

- highly sensitive to a possible "intrinsic" (non-perturbative) charm at HL-LHC

*Boettcher, Ilten and Williams, PRD 93 (2016) 074008*

# $m_{top}$ – motivation and current results

## Fundamental parameter of theory

- related to other EWK parameters - stringent tests of SM
- important for $m_W$ or BF($B_s \to \mu\mu$) predictions
- vacuum stability depends on exact value of $m_{top}$

## Most precise measurements, with $\Delta m_{top}/m_{top}$ < 1 GeV

- 172.35 ± 0.51 GeV (CMS $\ell$+jets)
- 172.32 ± 0.64 GeV (CMS all had.)
- 174.98 ± 0.75 GeV (DØ $\ell$+jets)
- 172.99 ± 0.81 GeV (ATLAS dilepton)

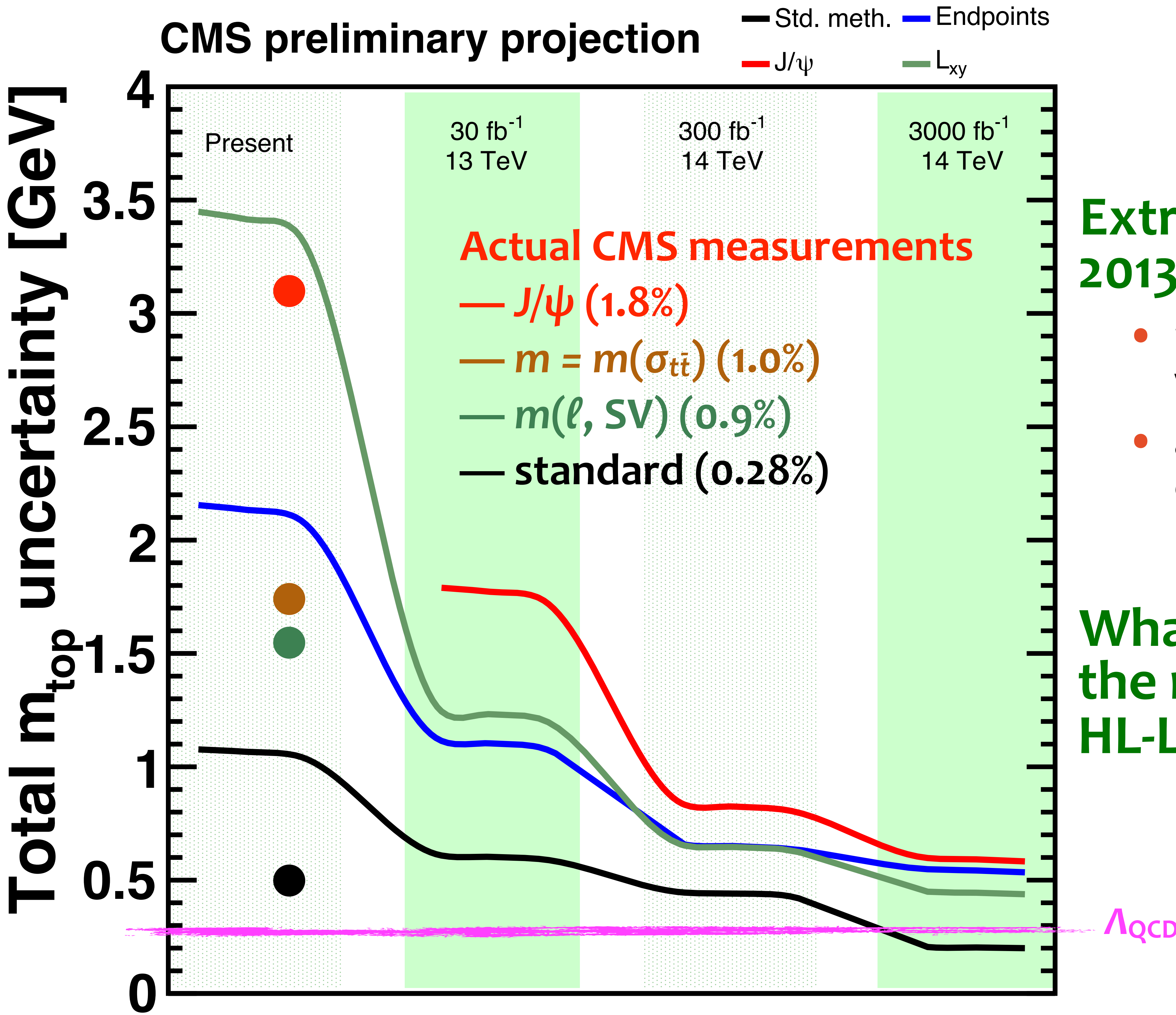
  → extracting the *Monte-Carlo mass*

## Alternative approaches

- indirect extraction of pole mass, e.g. $\sigma_{t\bar{t}}$
- less dependence on JES: using $m(J/\psi, \ell)$, $m(SV, \ell)$, $p_T(\ell\ell)$, $m_{T2}$
- different environment: single top

# $m_{top}$ – previous studies

CMS-PAS-FTR-13-016




## Extrapolation from 2013

- relative uncertainties were right
- all analyses may enter scales of $\Lambda_{QCD}$

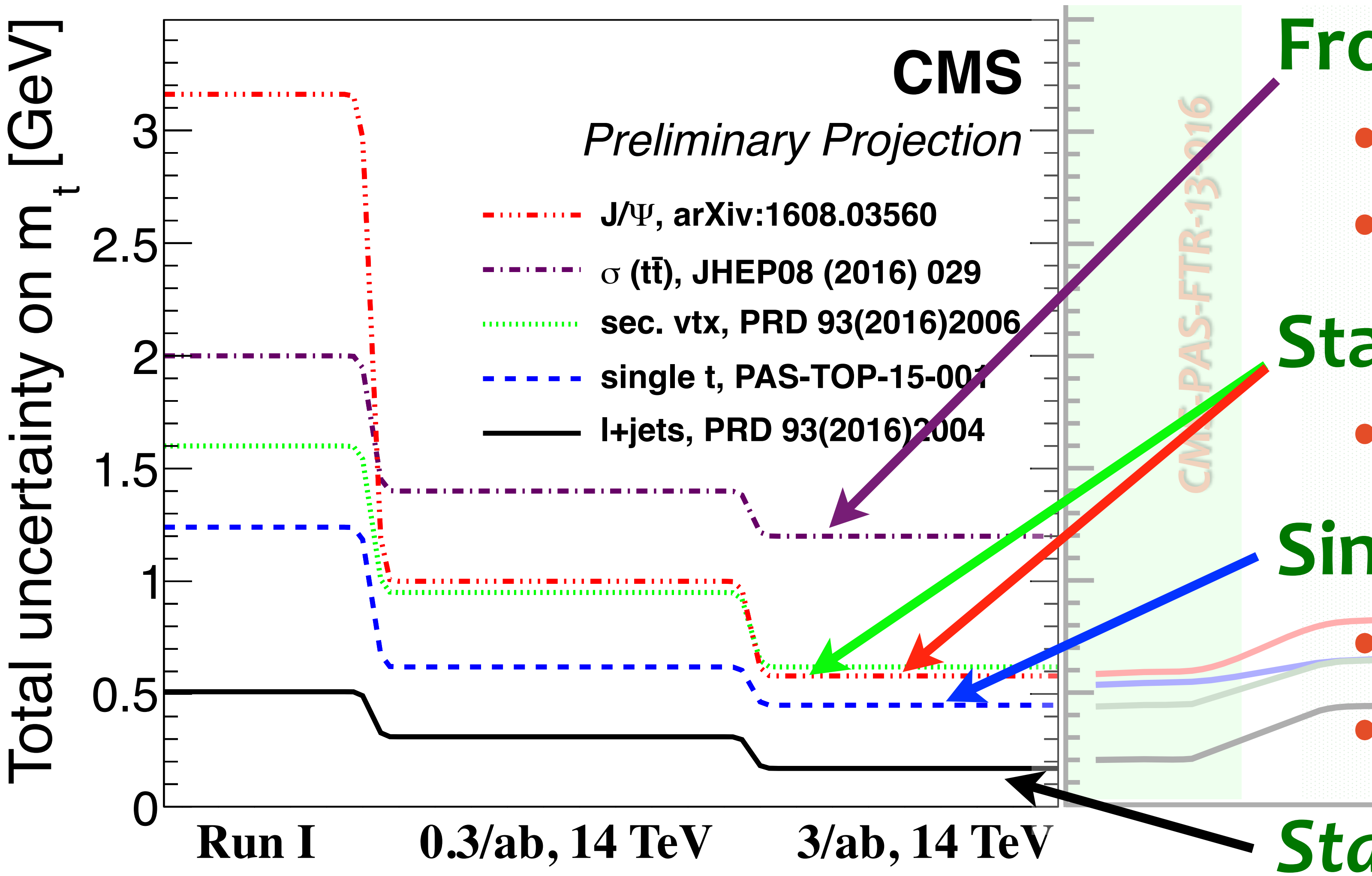
## What did we learn in the mean time for HL-LHC?

# $m_{top}$ – new extrapolation (CMS)

soon to become public
DP–2016/064

## Updated projections with 8 TeV analysis experience

- additional channels: single top, $\sigma_{t\bar{t}}$, sec. vtx
- pile-up expected to be kept under control




## From $t\bar{t}$ cross-section

- limited by theory uncertainty
- and lumi measurement

## Stats. dominated channels

- $J/\psi$ and sec. vtx

## Single top

- presence of forward jet
- EWK process, different CR, PDF

## *Standard ℓ+jets*

- benefit from modeling studies, expect $\Delta m_{top}/m_{top} \sim 0.17$ GeV

## $m_{top}$ measurements will be an important element of HL-LHC

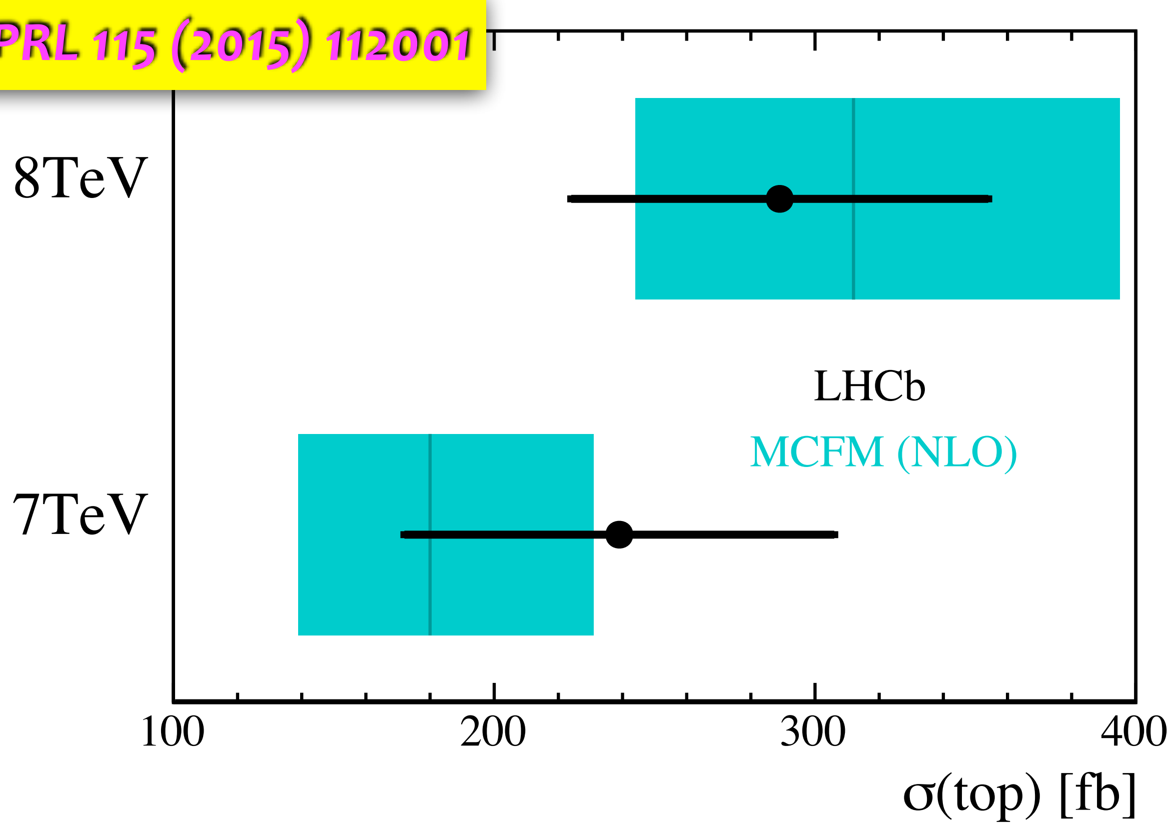
# Top quarks at LHCb

## Top production in the forward region

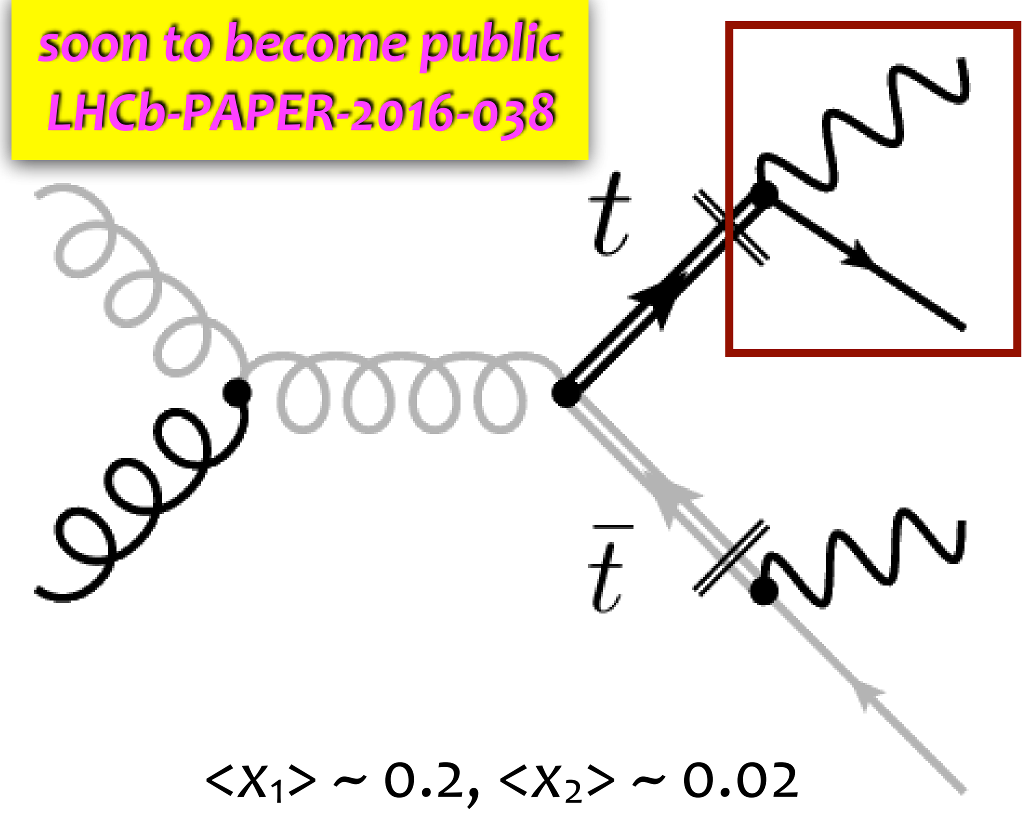
*Kagan, Kamenik, Perez, Stone, PRL 107 (2011) 082003*
*Gauld, JHEP02(2014)126*

- probes the large-x gluon PDF and may be more sensitive to BSM
- LHCb observed top using a reduced fiducial region of the W+b analysis
  - $50 < p_T(\text{jet}) < 100$ GeV; enriches sample in top

PRL 115 (2015) 112001




soon to become public
LHCb-PAPER-2016-038



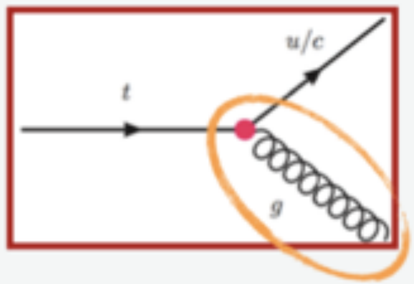

$\langle x_1 \rangle \sim 0.2$, $\langle x_2 \rangle \sim 0.02$

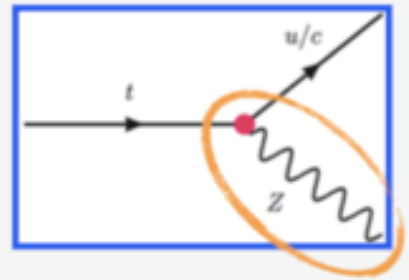
## Top sample

- expect factors of 20 (Run 2) to 1200 (HL-LHC) more top-quark events
- will enable separating $t\bar{t}$ and single-top and (double) differential measurements

# FCNC – motivation

top quark + gluon

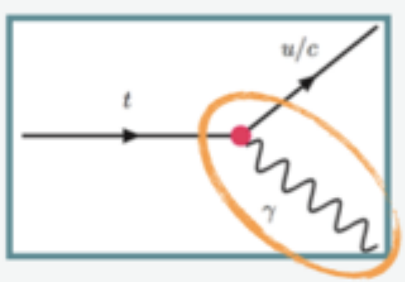


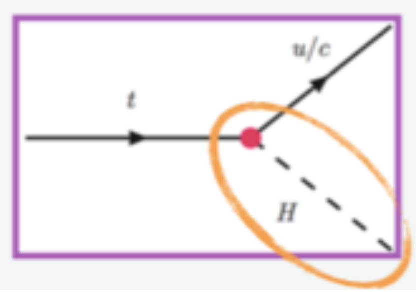




top quark + Z boson

$$\begin{aligned}\mathcal{L} = & \sum_{q=u,c} \Big[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu} \\ & + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\, Z_{\mu\nu} \\ & - e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R)\, q\, A_{\mu\nu} \\ & + \frac{g}{\sqrt{2}} \bar{t}\, \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R)\, q\, H \Big] + \text{h.c.}\end{aligned}$$

top quark + photon




top quark + Higgs

| | SM | 2HDM | MSSM |
|---|---|---|---|
| BF(t→ cg) | $5 \cdot 10^{-12}$ | $10^{-8} - 10^{-4}$ | $10^{-7} - 10^{-6}$ |
| BF(t→ cZ) | $1 \cdot 10^{-14}$ | $10^{-10} - 10^{-6}$ | $10^{-7} - 10^{-6}$ |
| BF(t→ cγ) | $5 \cdot 10^{-14}$ | $10^{-9} - 10^{-7}$ | $10^{-9} - 10^{-8}$ |
| BF(t→ cH) | $3 \cdot 10^{-15}$ | $10^{-5} - 10^{-3}$ | $10^{-9} - 10^{-5}$ |

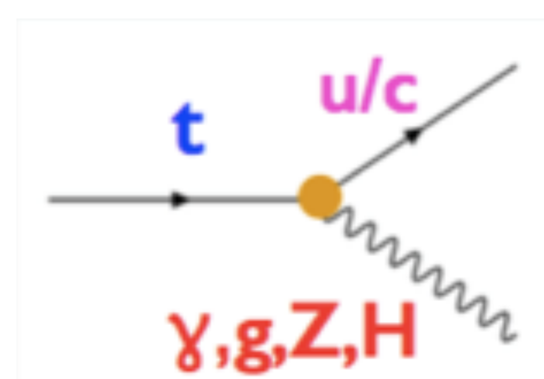
## In Standard Model

- forbidden at tree level
- only via loops, but highly suppressed

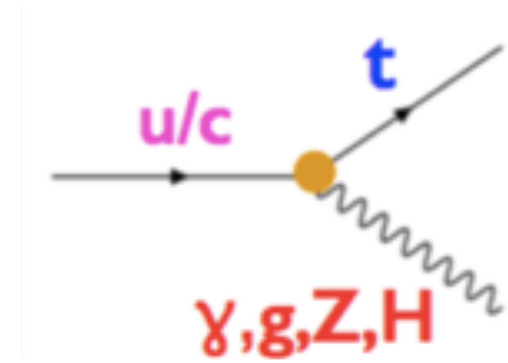
## Search

- single top (production)
- top-quark pair (decay)

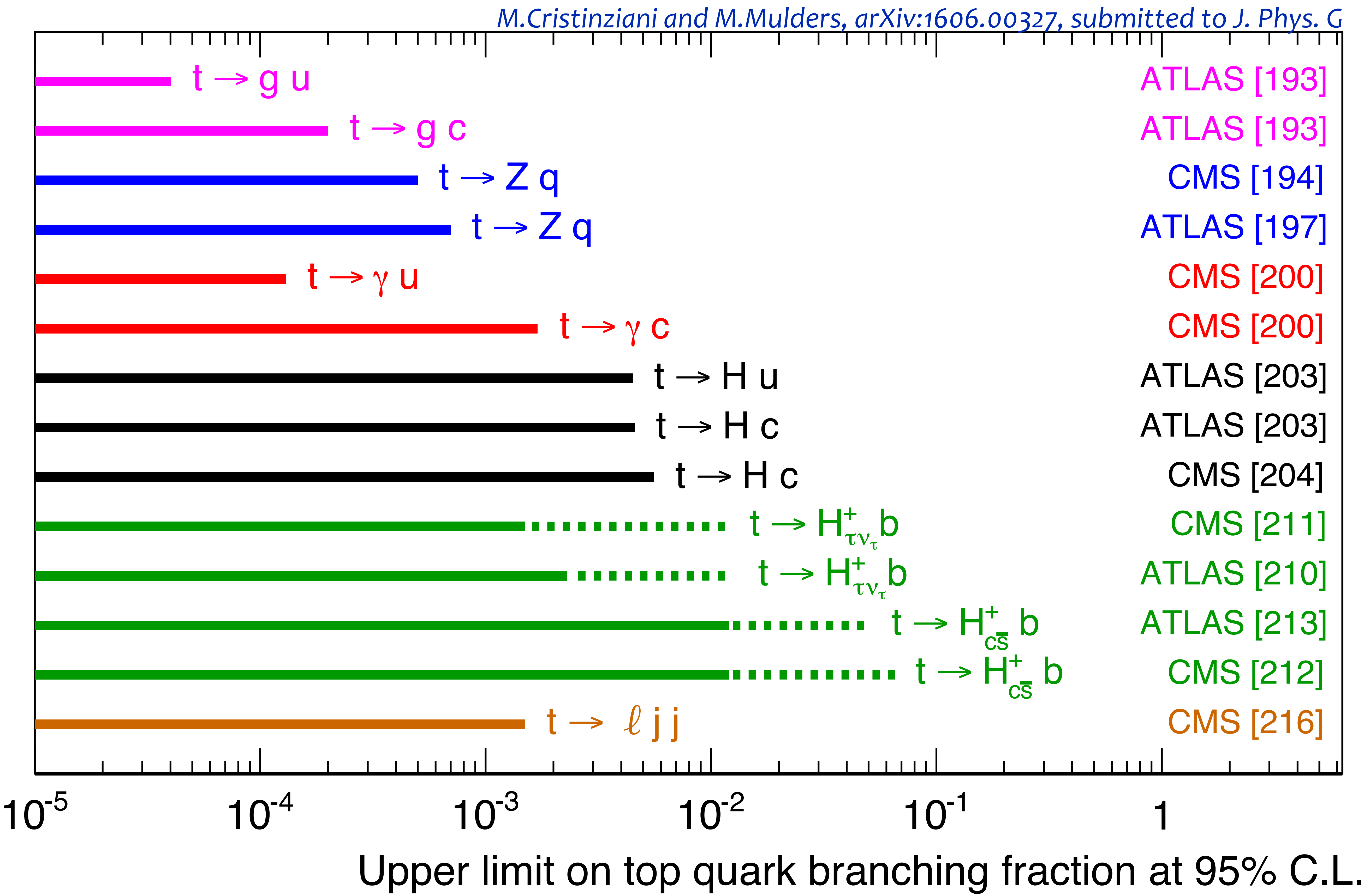
$t\bar{t}$




single top



# FCNC – current status



# FCNC – new $tq\gamma$ study

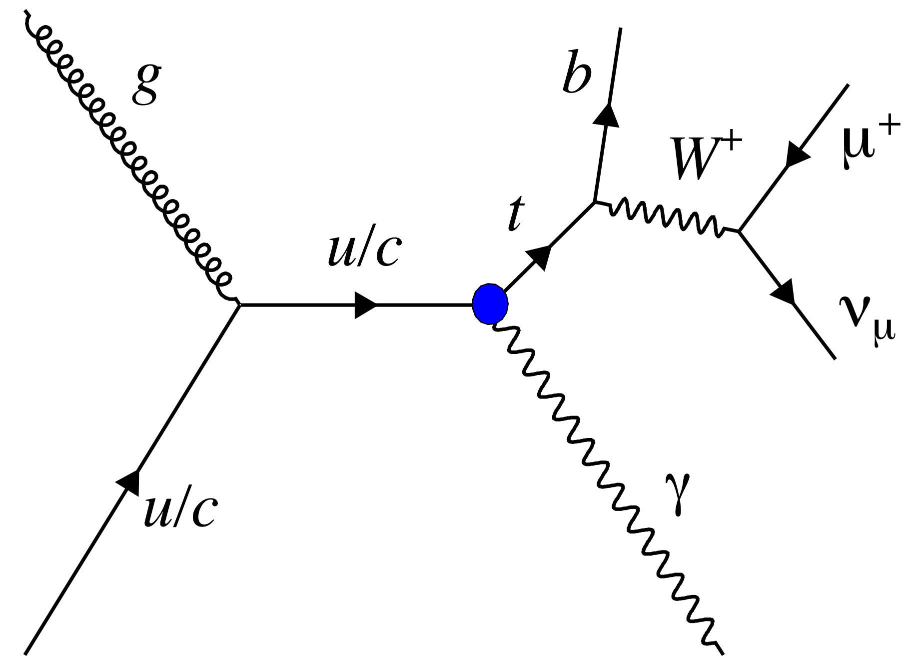
**soon to become public DP–2016/064**

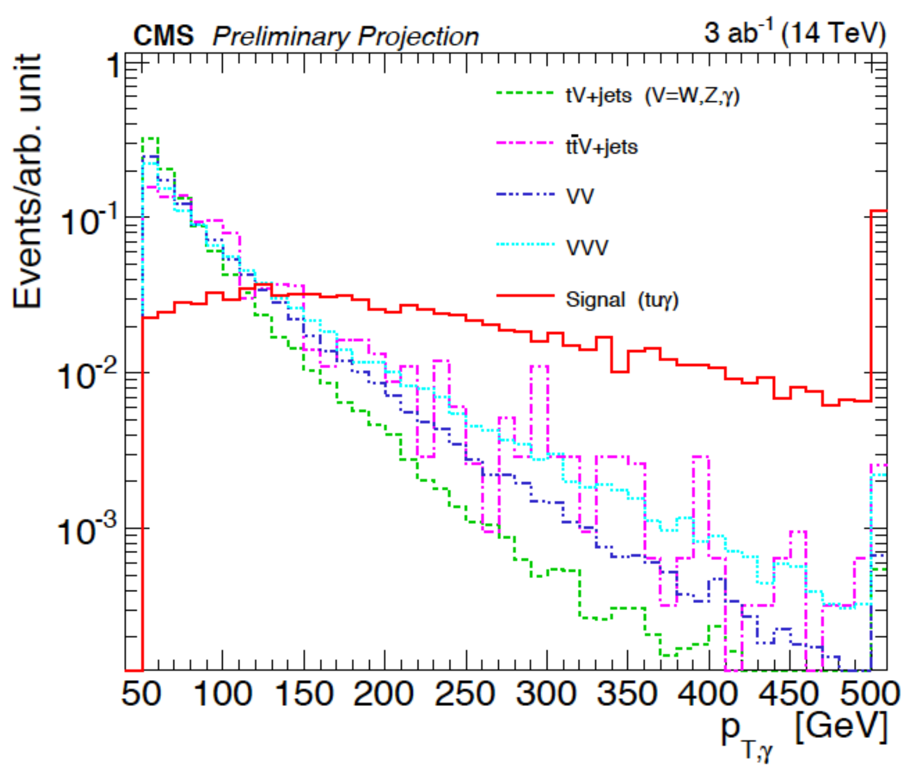
## Following 8 TeV analysis

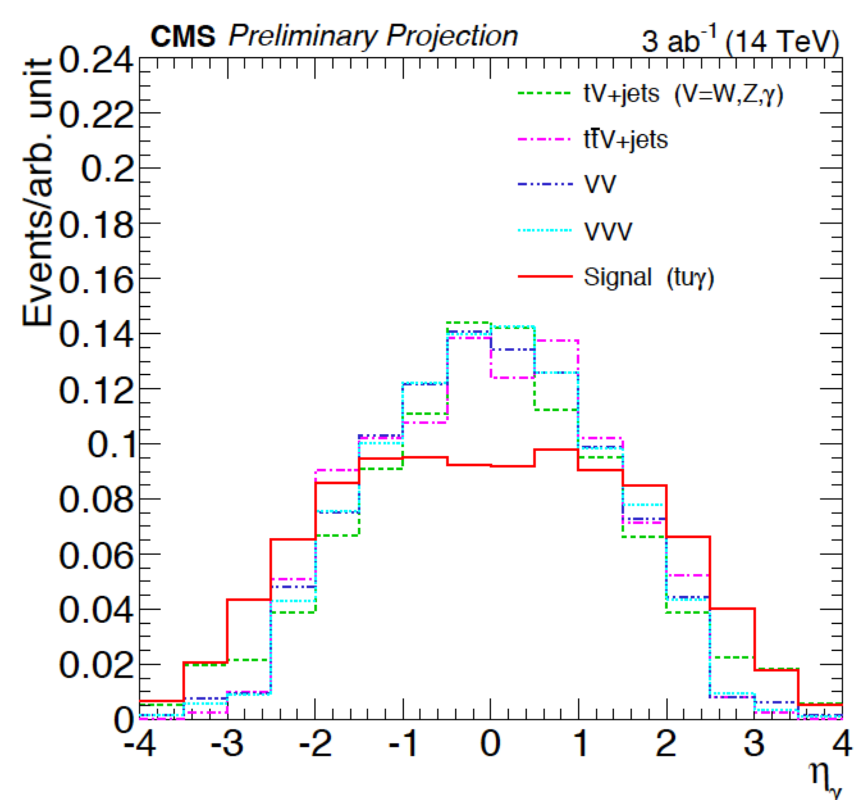
- JHEP 04 (2016) 035 → but cut & count

## Selection (not reoptimised for 14TeV)

- exactly 1 tight, isolated $\mu$
  - veto loose $\mu/e$
- exactly 1 $b$-tagged jet
- exactly 1 isolated high $E_T$ photon
  - well separated from jet and $\mu$, $\Delta R = 0.7$
- reconstructed $130 < m_{top} < 220$ GeV



# FCNC – new $tq\gamma$ study

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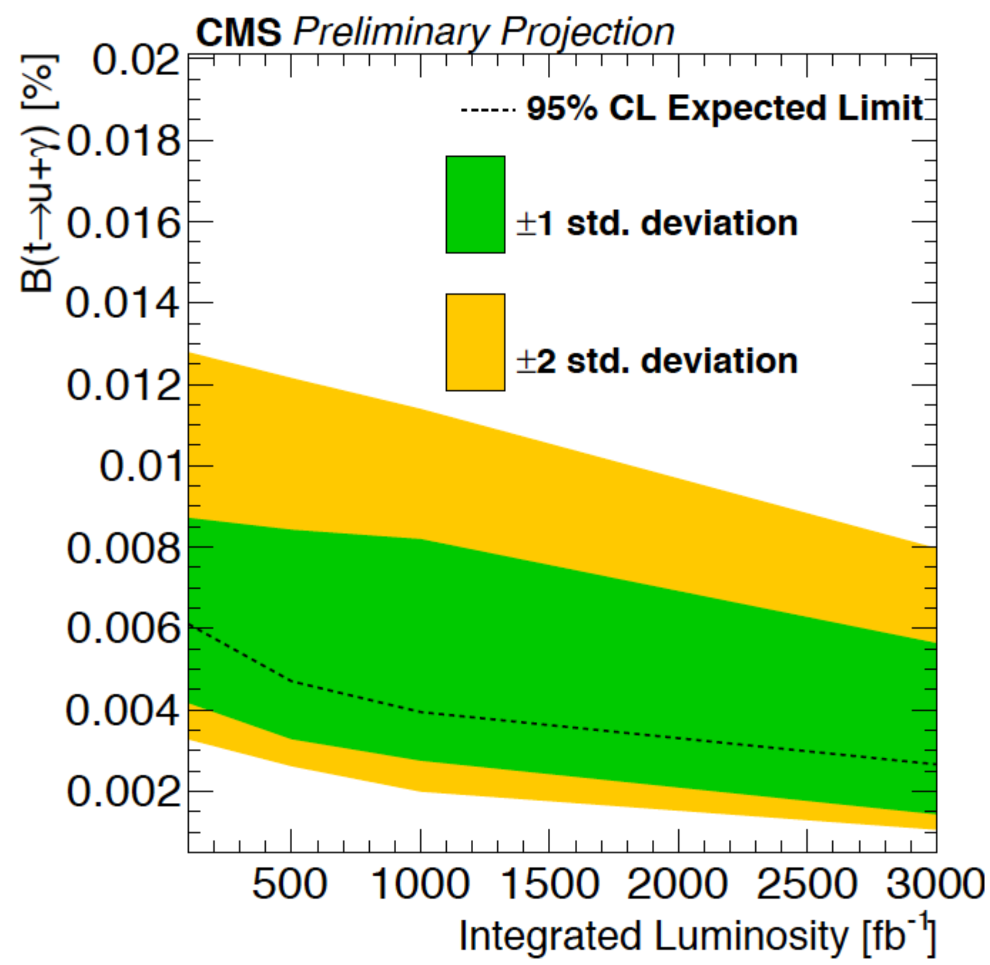
CMS DP–2016/06x

## Dominant contributions from backgrounds

- assumed to be controllable with large statistics from 3 $ab^{-1}$

## Consider two scenarios for systematics

- scenario 1 : no change w.r.t. 8 TeV result
- scenario 2
  - theory uncertainties scaled by 0.5
  - experimental uncertainties based on studies with Phase II detector and luminosity




| | 19.7 $fb^{-1}$ at 8 TeV | 3 $ab^{-1}$ at 14 TeV (Scenario 1) | 3 $ab^{-1}$ at 14 TeV (Scenario 2) |
|---|---|---|---|
| $B(t \to u + \gamma)$ | $1.3 \times 10^{-4}$ | $4.6 \times 10^{-5}$ | $2.7 \times 10^{-5}$ |
| $B(t \to c + \gamma)$ | $1.7 \times 10^{-3}$ | $3.4 \times 10^{-4}$ | $2.0 \times 10^{-4}$ |

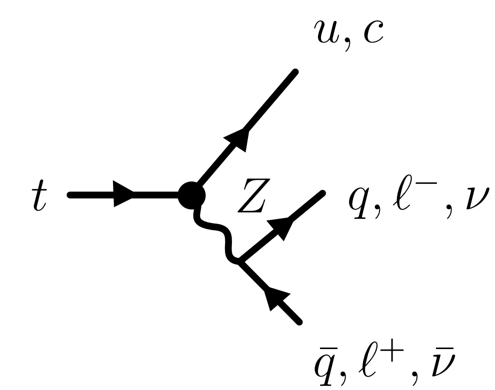
→ Sensitivity increase by factor 3 to 10 (depending on channel and scenario)

# FCNC – new *tZq* study

ATLAS-PUB-2016-019

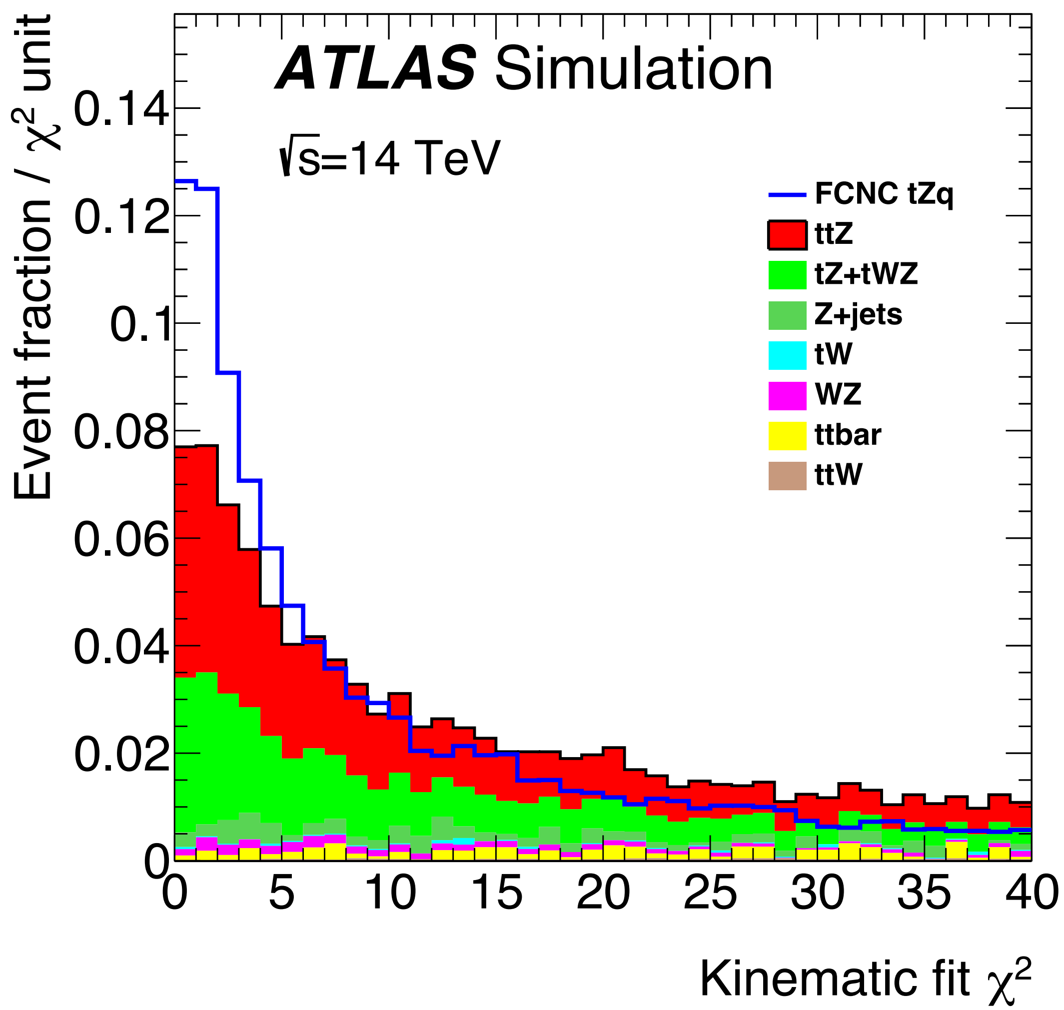
## Selection

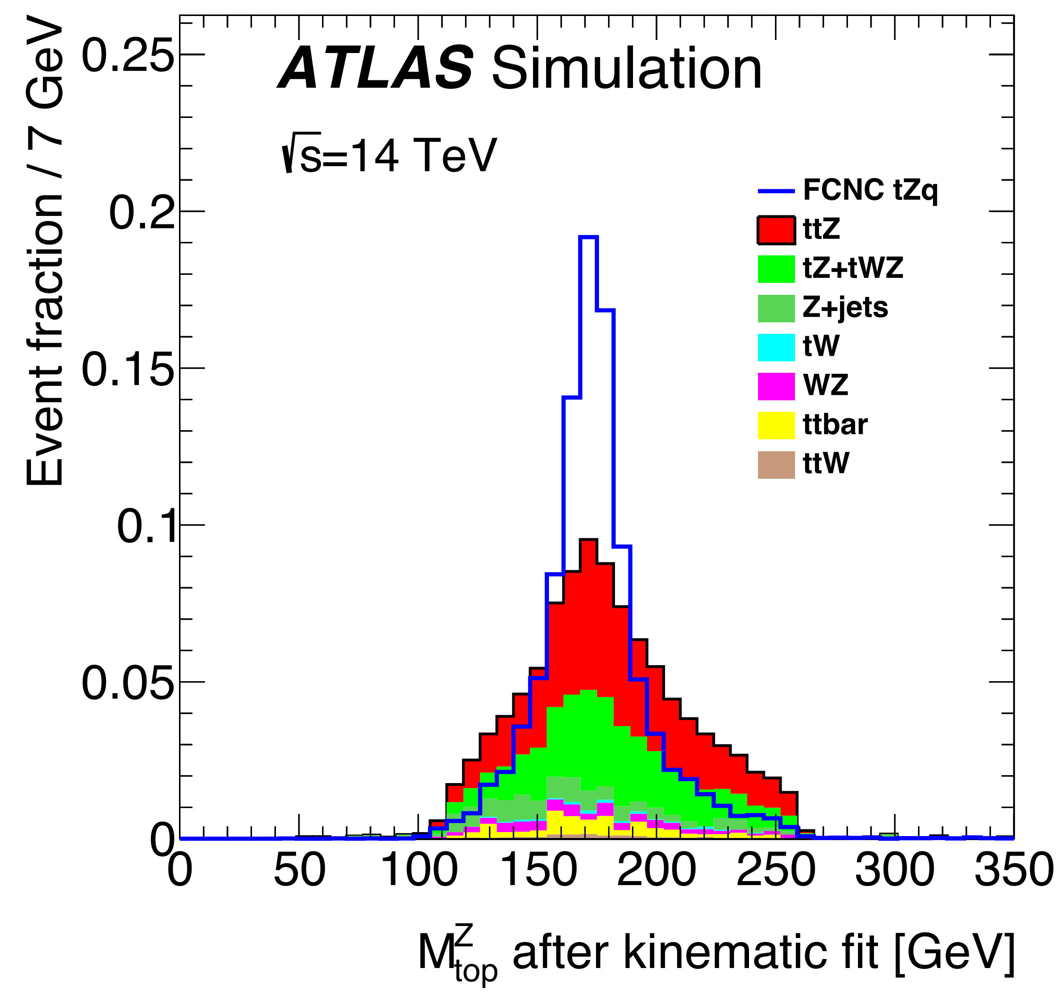
- three leptons, one OSSF in *Z*-mass window
- ≥1 *b*-jet, ≥ 1 non-*b*-jet




## Kinematic reconstruction

$$\chi^2 = \frac{\left(m_Z - m^{\text{reco}}_{\ell_1\ell_2}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m^{\text{reco}}_{\ell_3\nu}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_3\nu j_b}\right)^2}{\sigma_{t\to Wb}^2} + \frac{\left(m_t - m^{\text{reco}}_{\ell_1\ell_2 j_u}\right)^2}{\sigma_{t\to Zq}^2}$$



# FCNC – new *tZq* study

## Systematic uncertainties: two scenarios considered

ATLAS-PUB-2016-019

### Set A

- 2% lumi
- 6% *WZ* and signal
- 62% *Z*+jets, $t\bar{t}$
- 50% *tZ*, *tWZ*
- 30% $t\bar{t}V$

### Set B

- 2% lumi
- 6% *WZ* and signal
- 30% *Z*+jets, $t\bar{t}$
- 10% *tZ*, *tWZ*
- 6% $t\bar{t}V$

| Layout | Set | "$\gamma$" $t\to Zu$ | "$\sigma$" $t\to Zu$ | "$\gamma$" $t\to Zc$ | "$\sigma$" $t\to Zc$ | "$\gamma$" $t\to Zu+Zc$ | "$\sigma$" $t\to Zu+Zc$ |
|---|---|---|---|---|---|---|---|
| Reference | A | $18\cdot10^{-5}$ | $16\cdot10^{-5}$ | $41\cdot10^{-5}$ | $36\cdot10^{-5}$ | $13\cdot10^{-5}$ | $12\cdot10^{-5}$ |
| | B | $13\cdot10^{-5}$ | $13\cdot10^{-5}$ | $24\cdot10^{-5}$ | $23\cdot10^{-5}$ | $8.9\cdot10^{-5}$ | $8.3\cdot10^{-5}$ |
| Middle | A | $18\cdot10^{-5}$ | $18\cdot10^{-5}$ | $44\cdot10^{-5}$ | $40\cdot10^{-5}$ | $13\cdot10^{-5}$ | $13\cdot10^{-5}$ |
| | B | $13\cdot10^{-5}$ | $13\cdot10^{-5}$ | $26\cdot10^{-5}$ | $25\cdot10^{-5}$ | $9.0\cdot10^{-5}$ | $8.9\cdot10^{-5}$ |
| Low | A | $18\cdot10^{-5}$ | $17\cdot10^{-5}$ | $48\cdot10^{-5}$ | $43\cdot10^{-5}$ | $14\cdot10^{-5}$ | $13\cdot10^{-5}$ |
| | B | $14\cdot10^{-5}$ | $13\cdot10^{-5}$ | $29\cdot10^{-5}$ | $28\cdot10^{-5}$ | $9.8\cdot10^{-5}$ | $9.3\cdot10^{-5}$ |

$$\mathcal{L}_{tZu} = -\frac{g}{2c_W}\bar{u}\gamma^{\mu}\left(X^L P_L + X^R P_R\right) tZ_{\mu} - \frac{g}{2c_W}\bar{u}\frac{i\sigma^{\mu\nu}(p_t^{\nu} - p_u^{\nu})}{M_Z}\left(\kappa^L P_L + \kappa^R P_R\right) tZ_{\mu} + h.c.$$

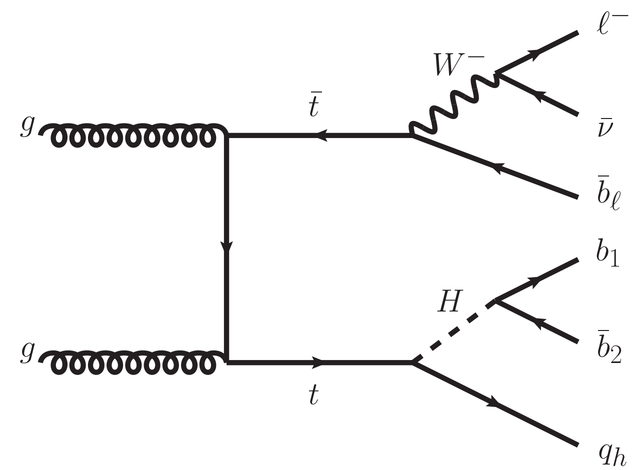
→ Sensitivity increase by factor 2 to 6 (depending on channel and scenario)

# FCNC – new *tHq* study

ATLAS-PUB-2016-019

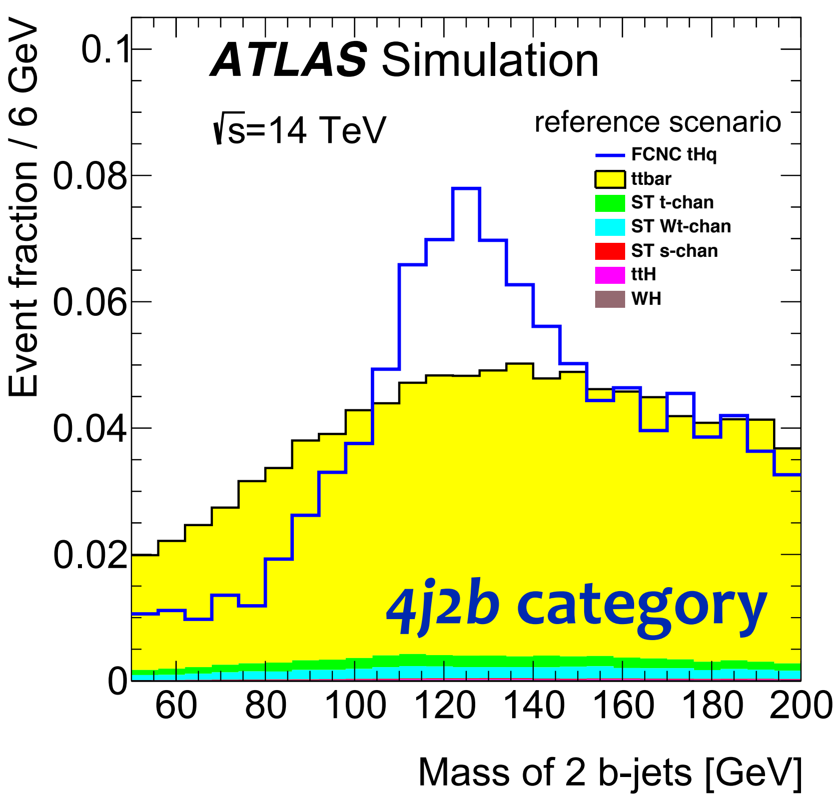
## Consider several final states to cope with acceptance/inefficiency

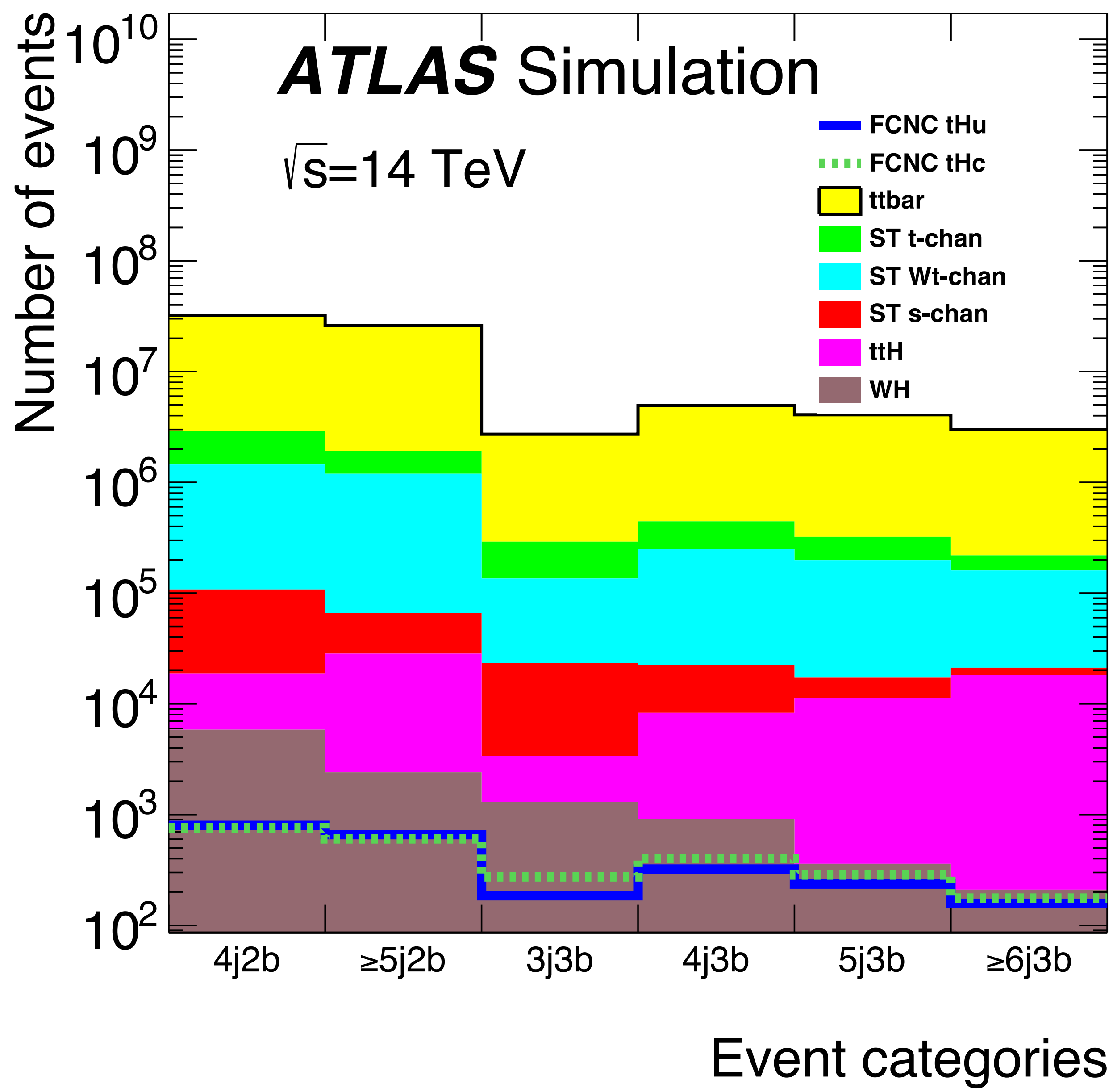
- 2 *b*-jets with 4 or ≥5 jets
- 3 *b*-jets with 3, 4, 5, or ≥6 jets




## Discriminant variable

- constructed in each region
- try to identify Higgs, *W*, top peaks
- using every possible permutation



# FCNC – new *tHq* study

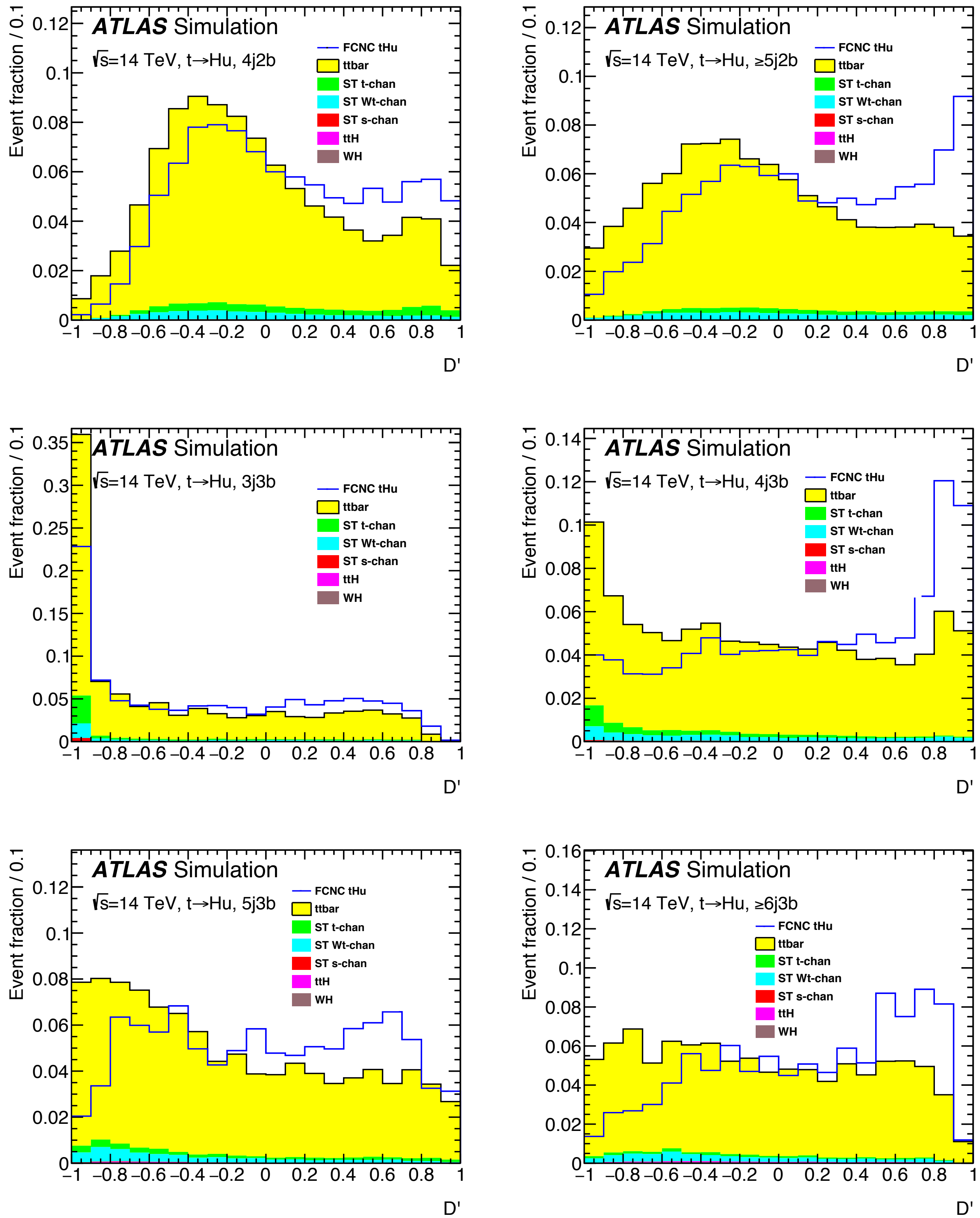


## Discriminant variable

- here shown for the $t \to Hu$ case

## Systematic uncertainties

- Set A and Set B
- more or less conservative



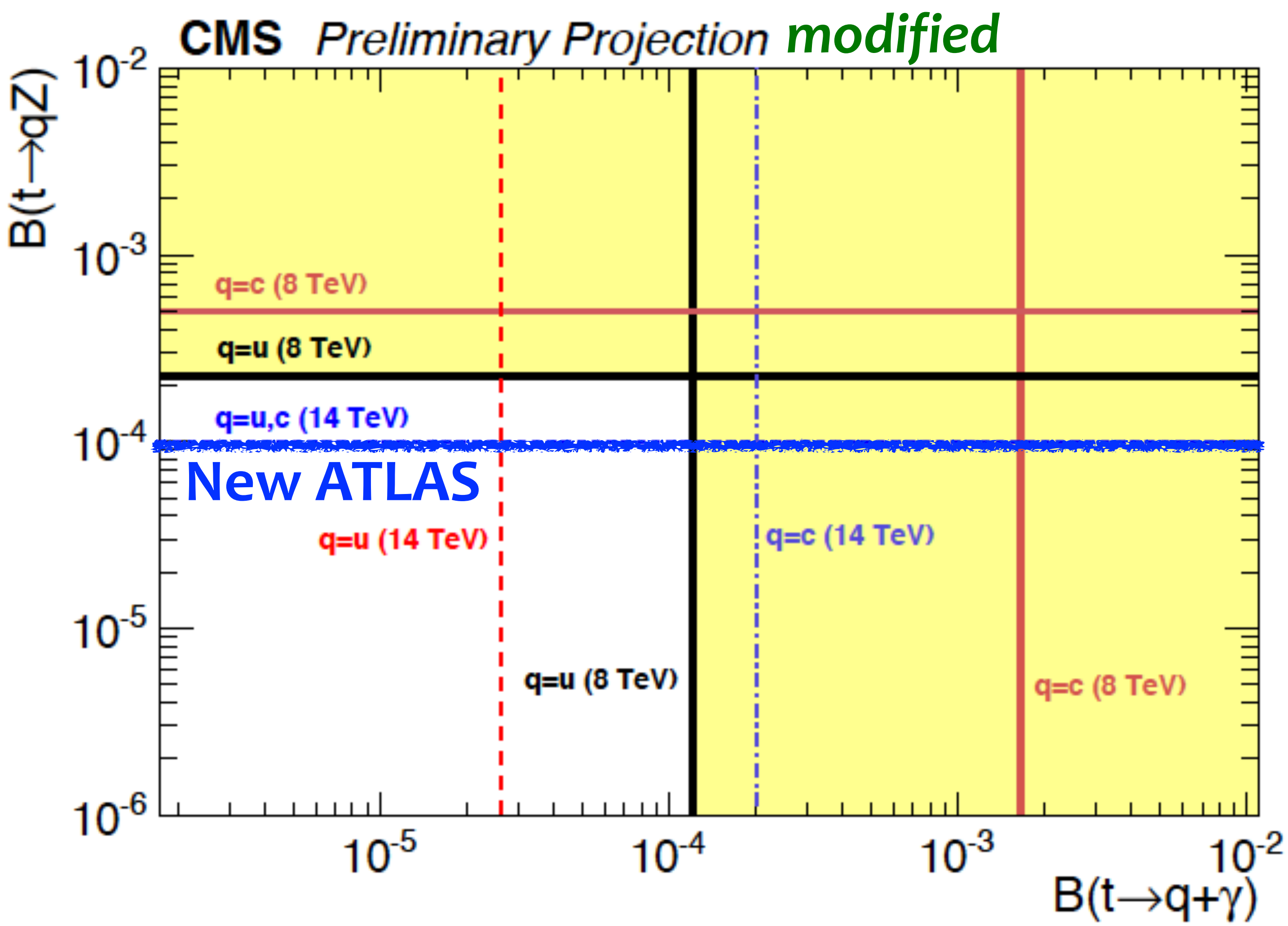

| Layout | Set | $t \to Hu$ | $t \to Hc$ | $t \to Hu+Hc$ |
|---|---|---|---|---|
| Reference | A | $2.4 \cdot 10^{-4}$ | $2.0 \cdot 10^{-4}$ | $1.1 \cdot 10^{-4}$ |
| | B | $2.4 \cdot 10^{-4}$ | $2.0 \cdot 10^{-4}$ | $1.1 \cdot 10^{-4}$ |
| Middle | A | $2.9 \cdot 10^{-4}$ | $2.4 \cdot 10^{-4}$ | $1.3 \cdot 10^{-4}$ |
| | B | $2.9 \cdot 10^{-4}$ | $2.4 \cdot 10^{-4}$ | $1.3 \cdot 10^{-4}$ |
| Low | A | $3.5 \cdot 10^{-4}$ | $3.0 \cdot 10^{-4}$ | $1.7 \cdot 10^{-4}$ |
| | B | $3.5 \cdot 10^{-4}$ | $3.0 \cdot 10^{-4}$ | $1.7 \cdot 10^{-4}$ |

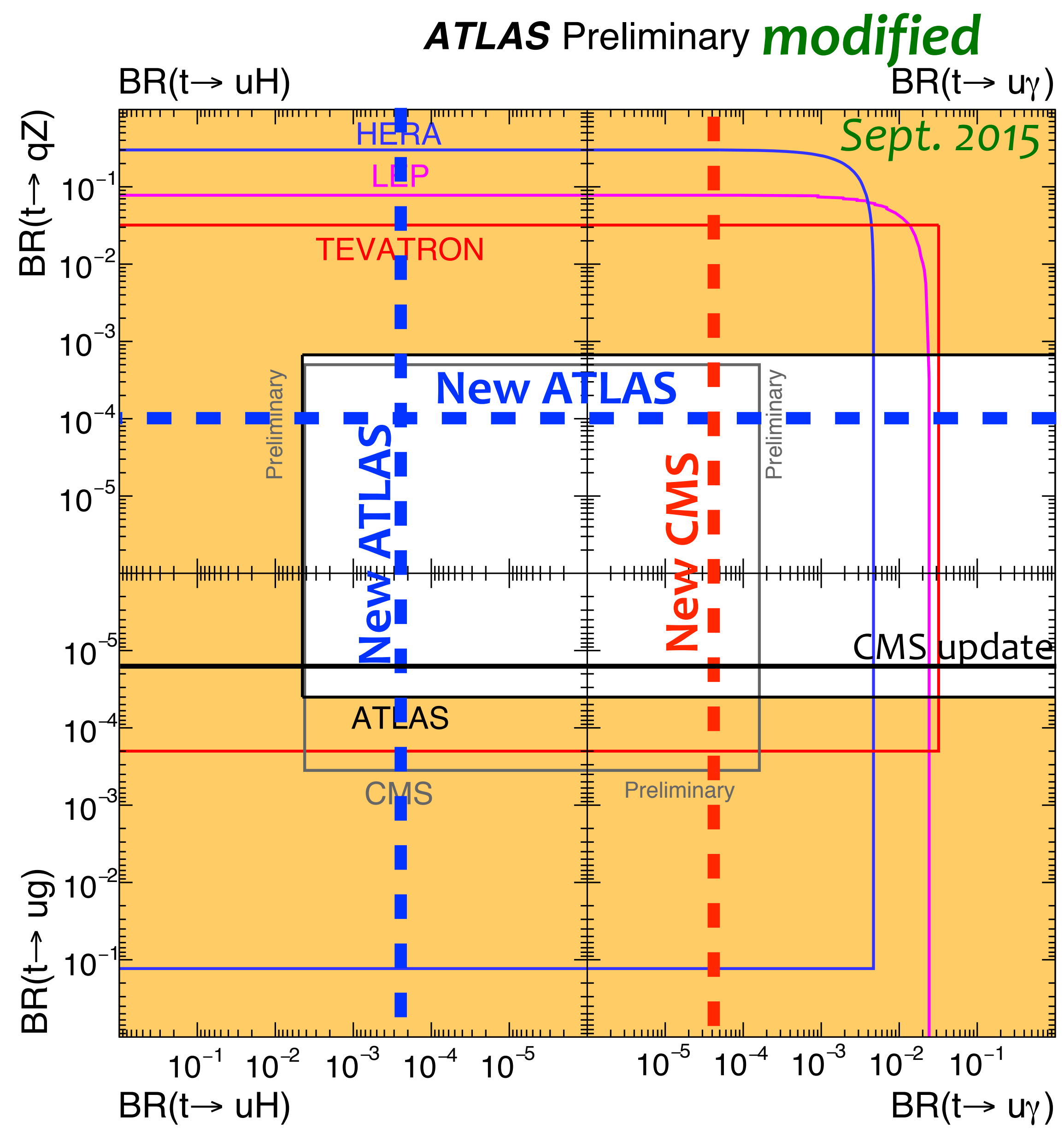
→ Sensitivity increase by factor 20

# Summary of FCNC extrapolations

## FCNC are a gold mine: need to dig deeper

- possibly these are analyses that do need the full simulation and detector performance to express their full potential



# Conclusion

## Opportunities for SM and top physics offered by the HL-LHC

- re-explored in light of Run-1 analyses and first 13 TeV data
- extrapolation not trivial → first results presented
- actual measurements often beat even optimistic prediction (→ top mass)

## For SM physics the large datasets will allow to

- explore extreme regions, very boosted events, high $m_{\ell\ell}$, very high $p_T$ jets
- increase number of dimensions in differential measurements
- study VBS and rare triboson processes

## Top physics continues to be an important physics case

- advancing the precision SM measurement
- finding deviation due to new physics in precision measurements
- rare final states, extreme kinematic phase space
- altogether looking for new particles decaying to top quarks