An overview of spin correlations and FCNC at the HL-LHC

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Seattle Snowmass Summer Meeting
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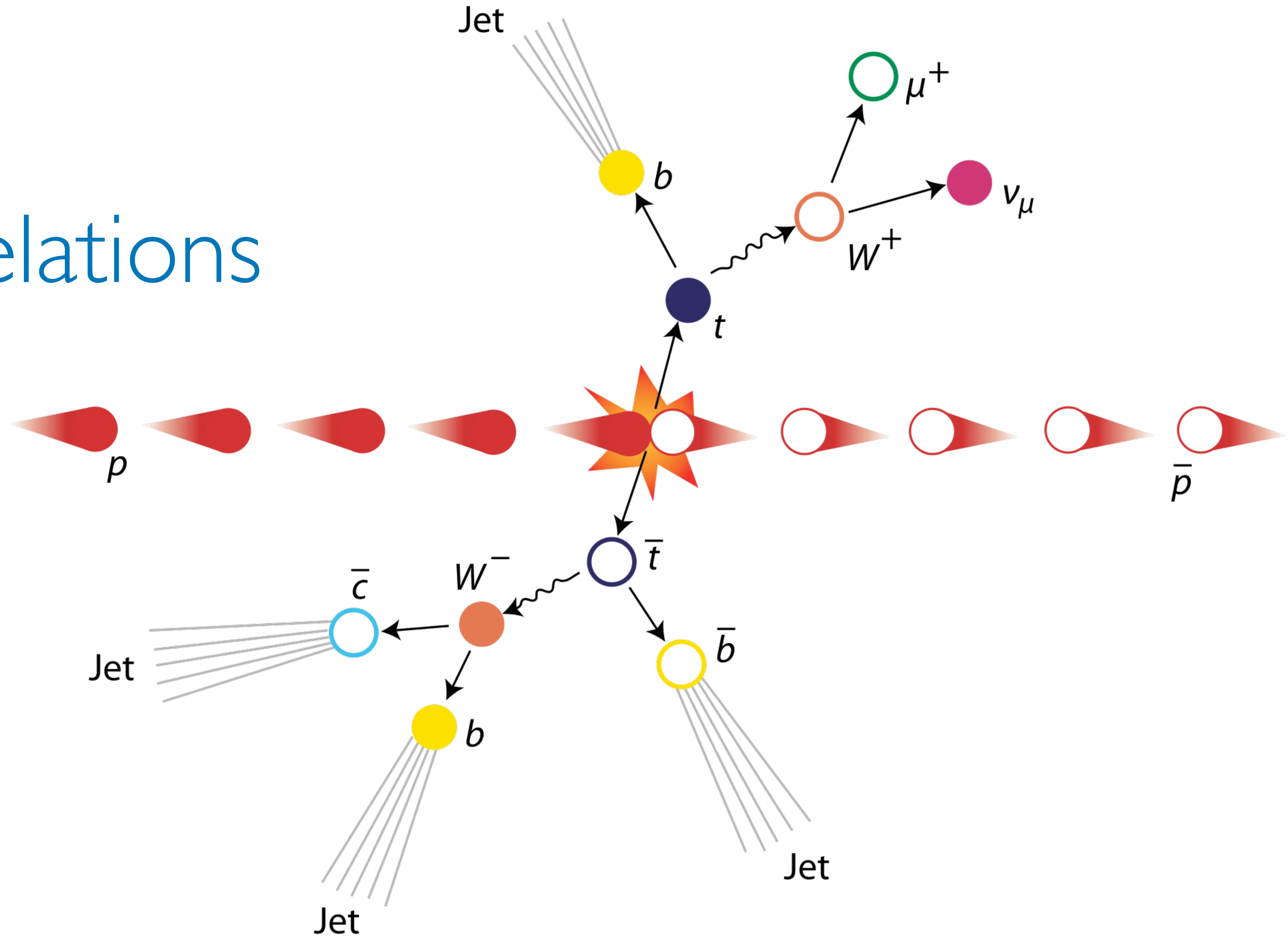
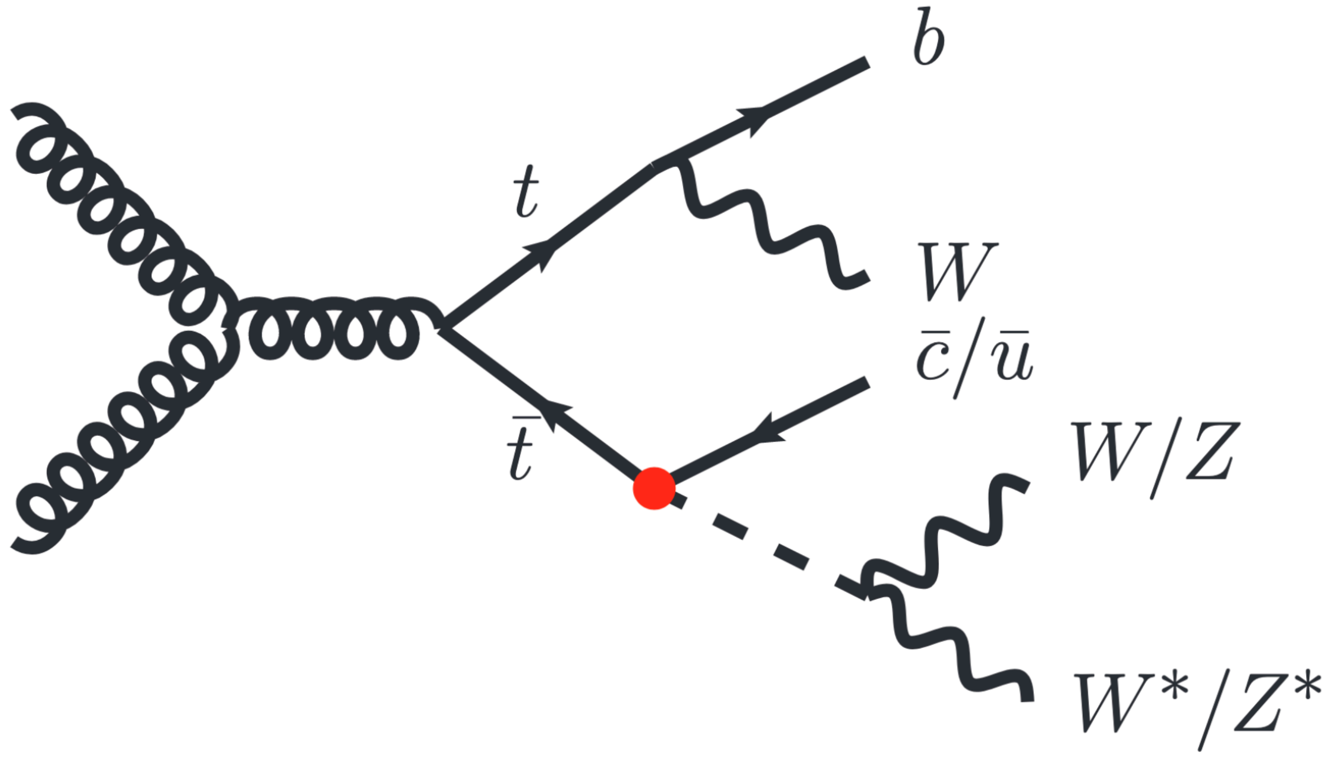
This talk

$t\bar{t}$ spin correlations



FCNC in the top-quark sector

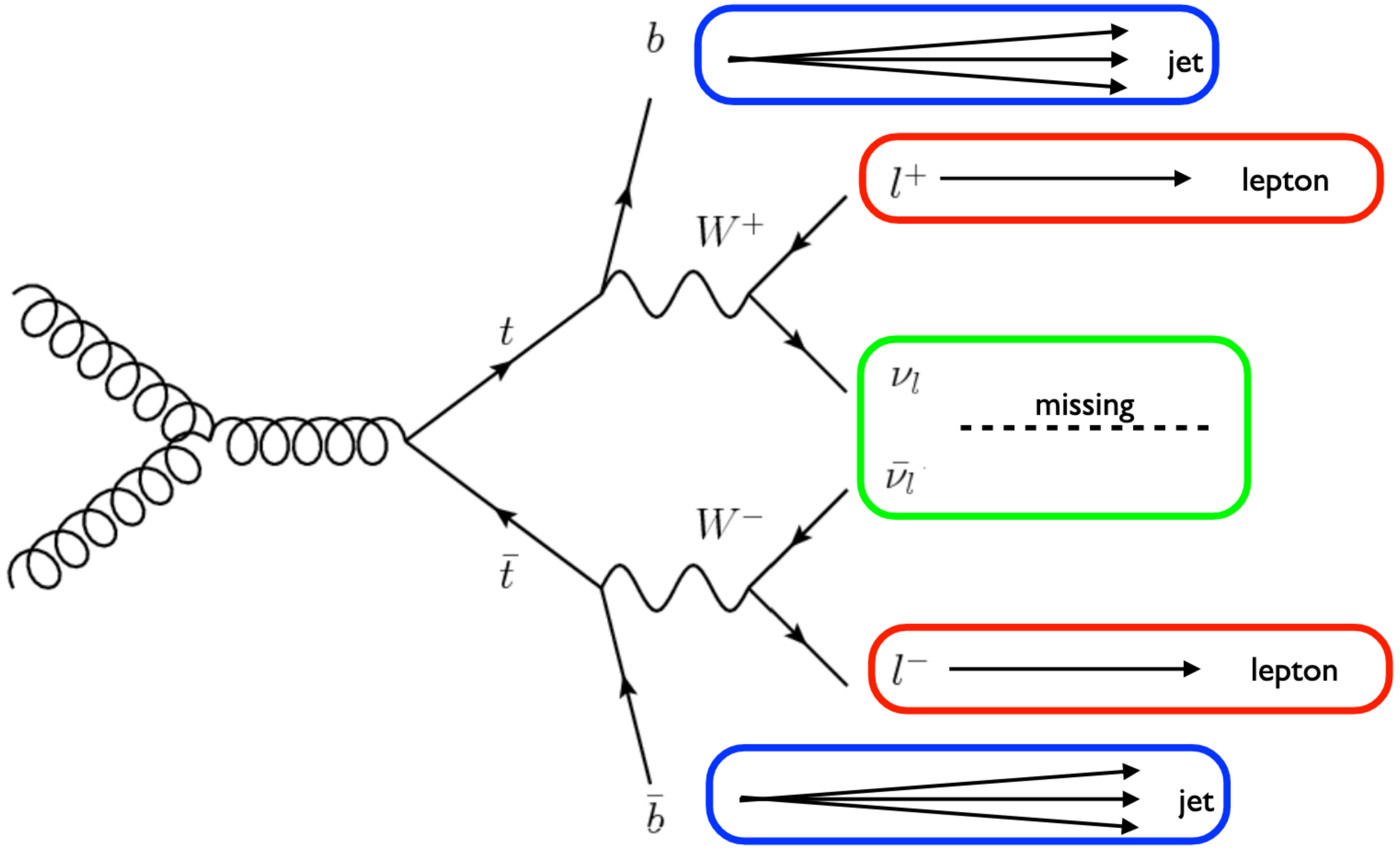


$t\bar{t}$ spin correlations

- The top quark is an ideal candidate for spin measurements !
  - Decays before forming any bound states.
  - Spin information is relayed onto daughter particles.
- In the SM, $t\bar{t}$ production is (approximately) unpolarized.
  - But, the spins are highly correlated.
- Top spin measurements are a great probe to BSM physics
  - Suppression -> s-channel dark matter
  - Enhancement -> new scalars ?

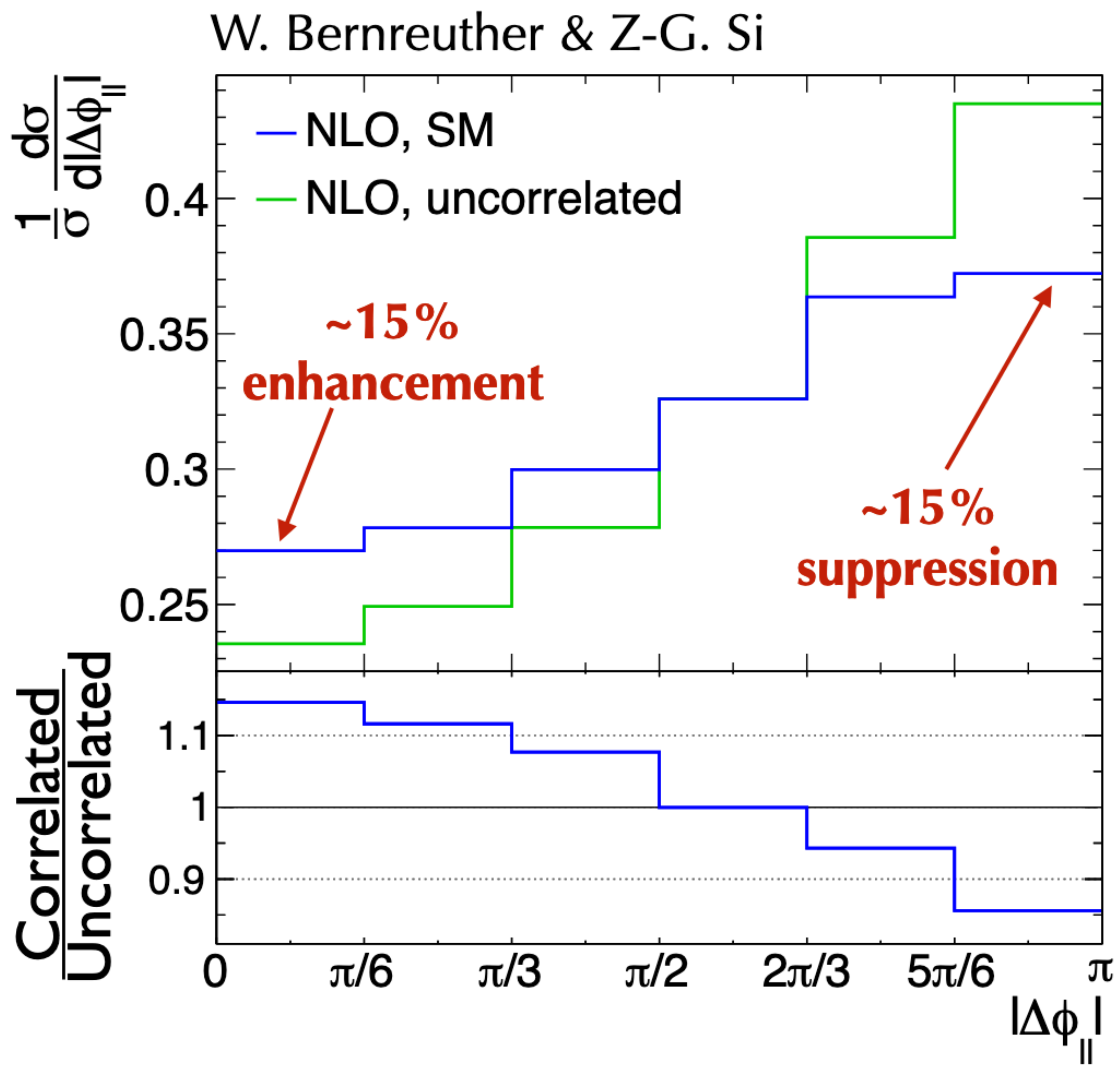
lifetime $<$ QCD timescale $\ll$ spin-flip timescale

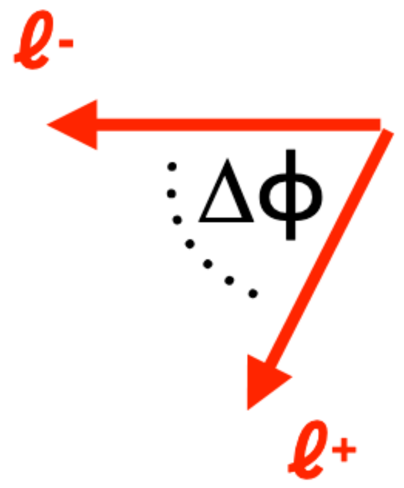
$$10^{-25}\,\mathrm{s} \;<\; 10^{-24}\,\mathrm{s} \;\ll\; 10^{-21}\,\mathrm{s}$$



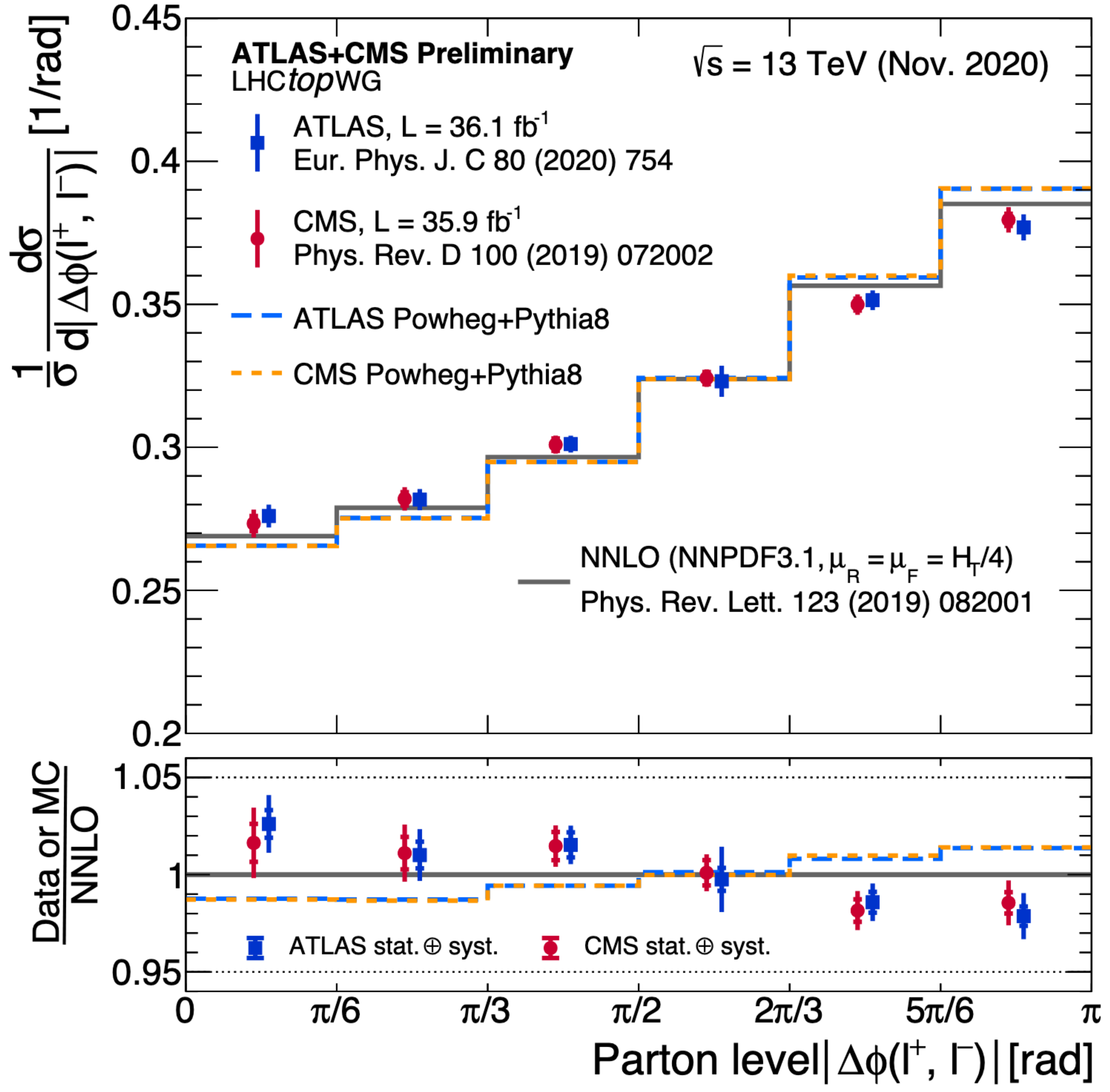
Indirect measurements

- Direct measurement of spin correlations require full reconstruction of the top and anti-top.
- Spin correlations can however be indirectly probed using leptons
  - A charged lepton is a perfect spin analyzer, very well reconstructed at the LHC -> study the dilepton channel.
- For instance the angle between leptons in the transverse plane (lab frame) $\Delta\phi$
  - Most of the shape of the distribution comes from tops kinematics



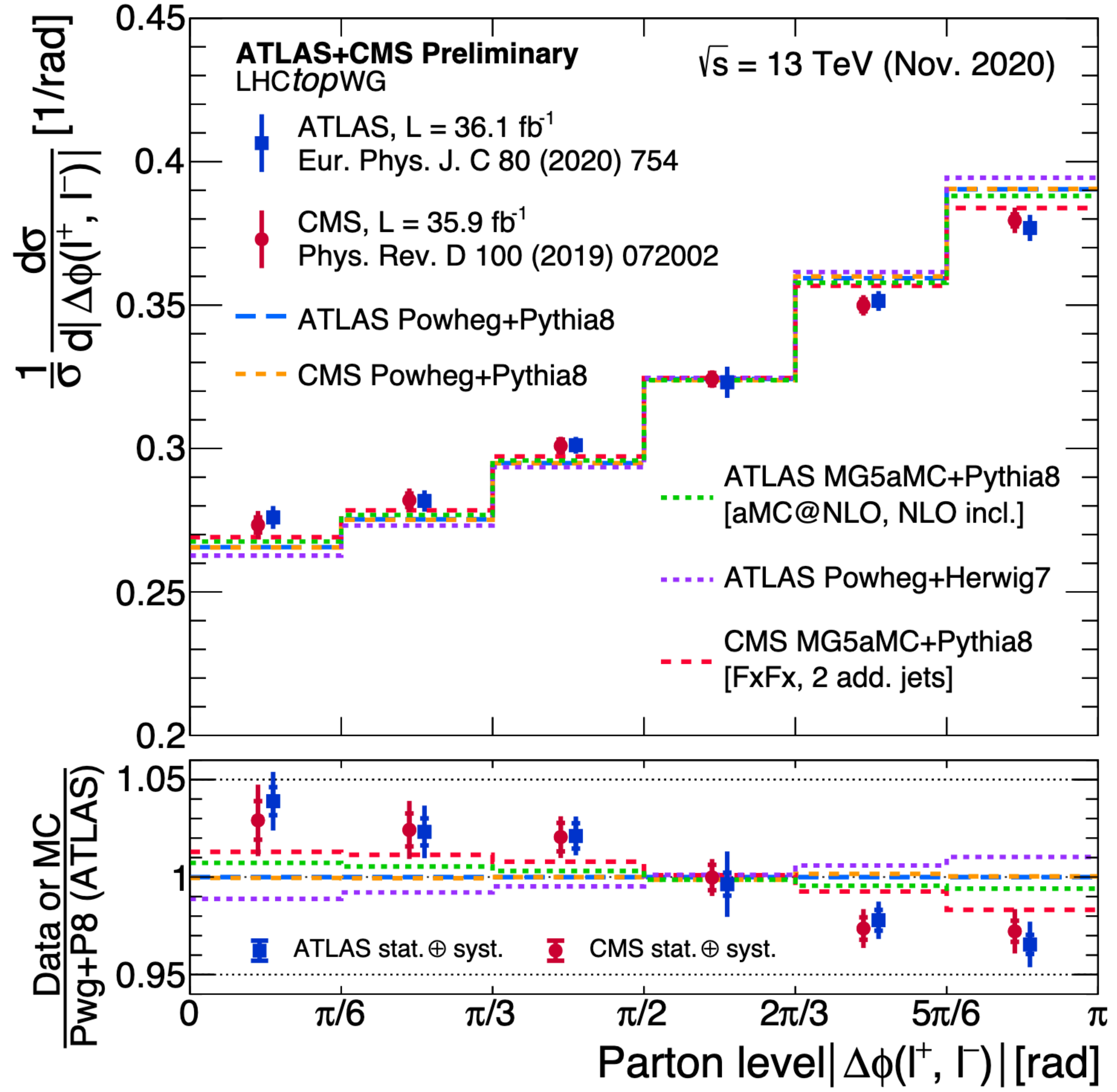


Indirect measurements



Correct $\Delta\phi$ distribution with acceptance and efficiency (unfold).

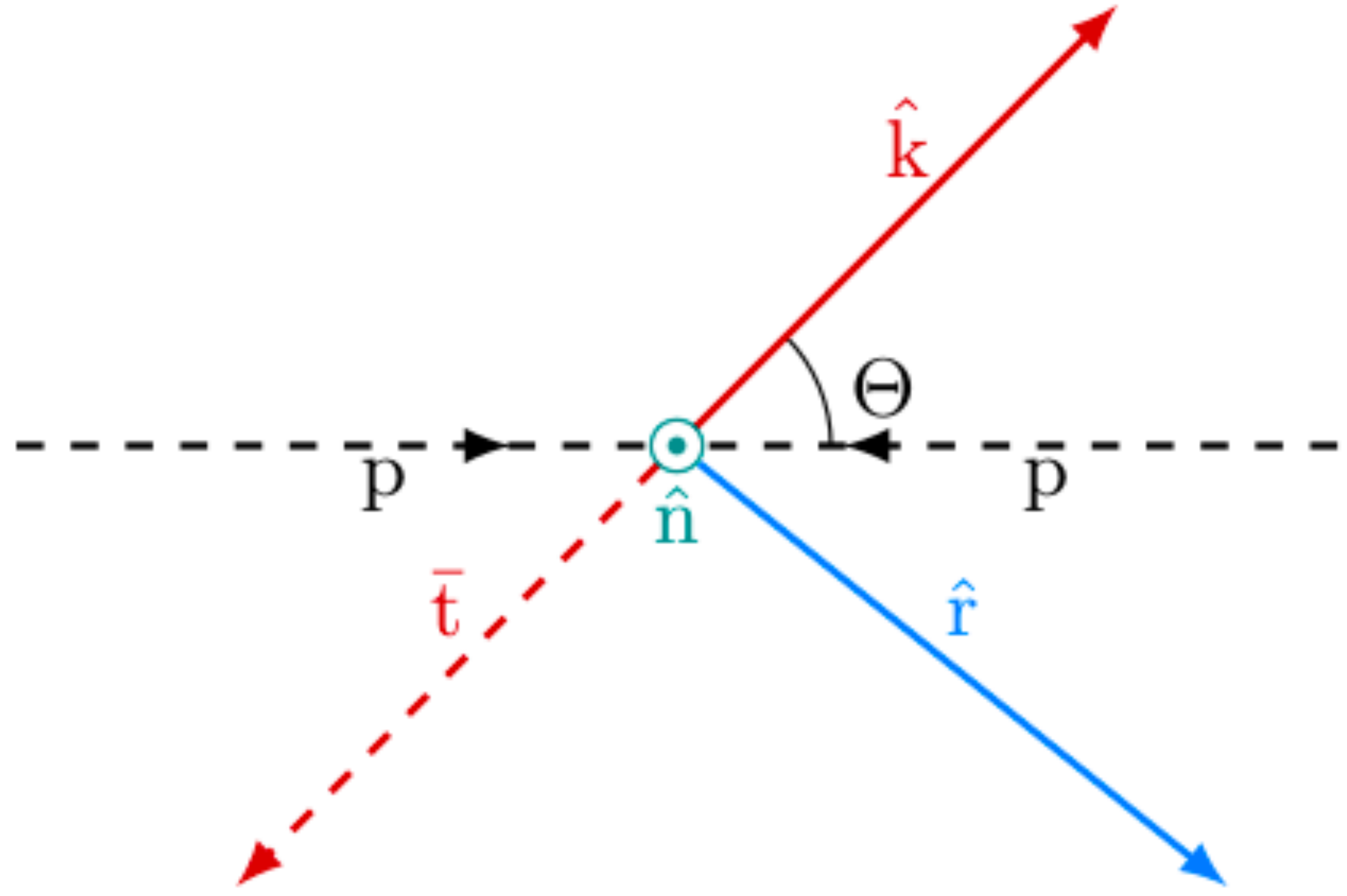
With 2016 datasets, both ATLAS and CMS saw discrepancies between data and NLO MC.



Direct measurements

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

- Dilepton distribution probes top spin in 3-dimensions:
  - Leptons follow parent top spin, average polarization given by $B^i_{1/2}$.
  - Relative lepton directions follow 3x3 spin correlation matrix C.
- Combined, these 15 coefficients completely characterize the spin dependance of $t\bar{t}$ production.



Phys. Rev. D 100, 072002

Direct measurements

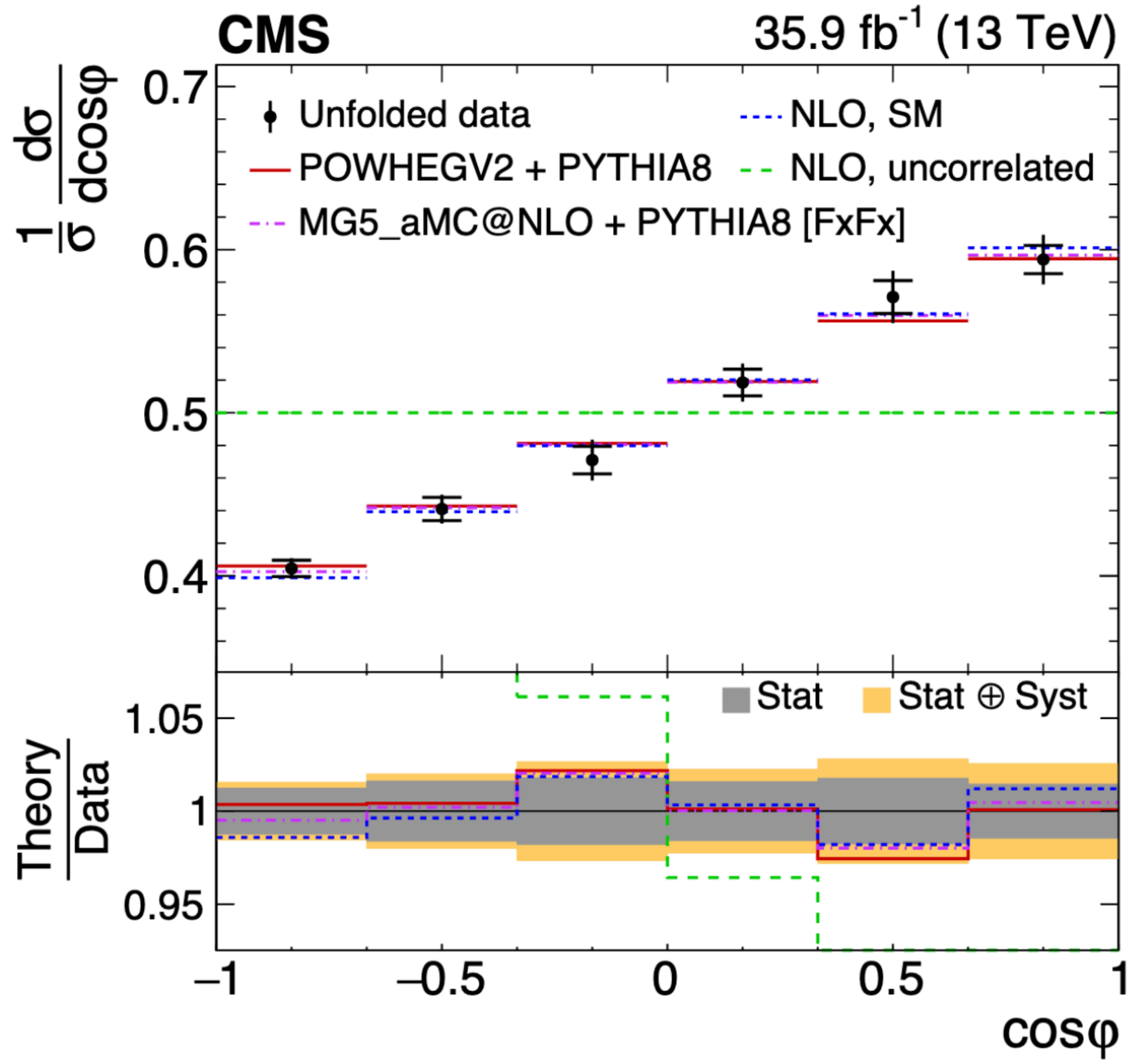
- Opening angle between the leptons $cos\varphi = \hat{\ell}^{+} . \hat{\ell}^{-}$ (in the parent top rest frame) has maximal sensitivity to the degree of alignment of top quark spins.

- By far the single most precise variable from Run2 measurements

  - Uncertainty ~ 5% .

- One can extract the fraction of SM-like spin correlation events (f_{SM}) using such precise variables.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\ \cos\varphi)$$



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Projected values for f_{SM}

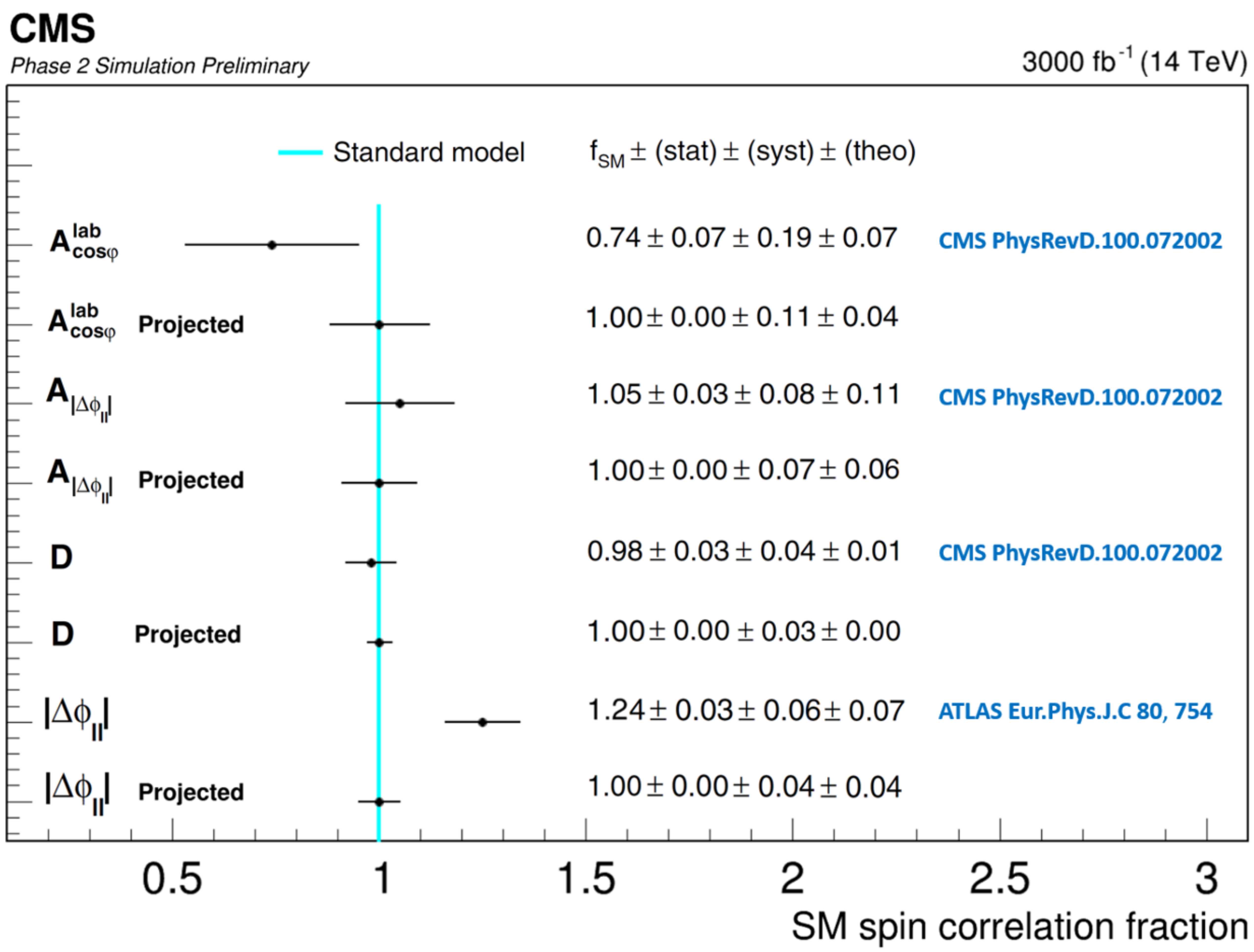
- Extraction of f_{SM} requires a $t\bar{t}$ sample with spin correlations turned off.

- Then for a given observable (say D) :

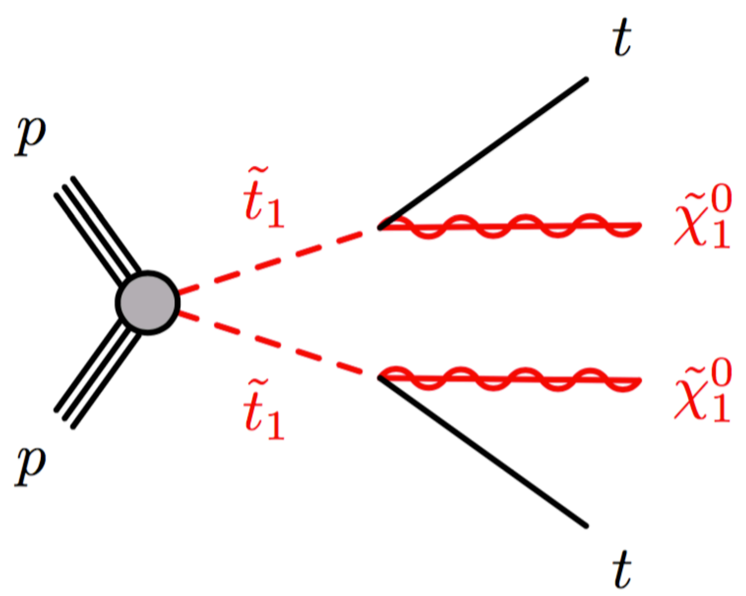
$$f_{SM} = \frac{D_{measured} - D_{theory,uncorrelated}}{D_{theory,correlated} - D_{theory,uncorrelated}}$$

- Jet energy scales and resolution uncertainties dominate.

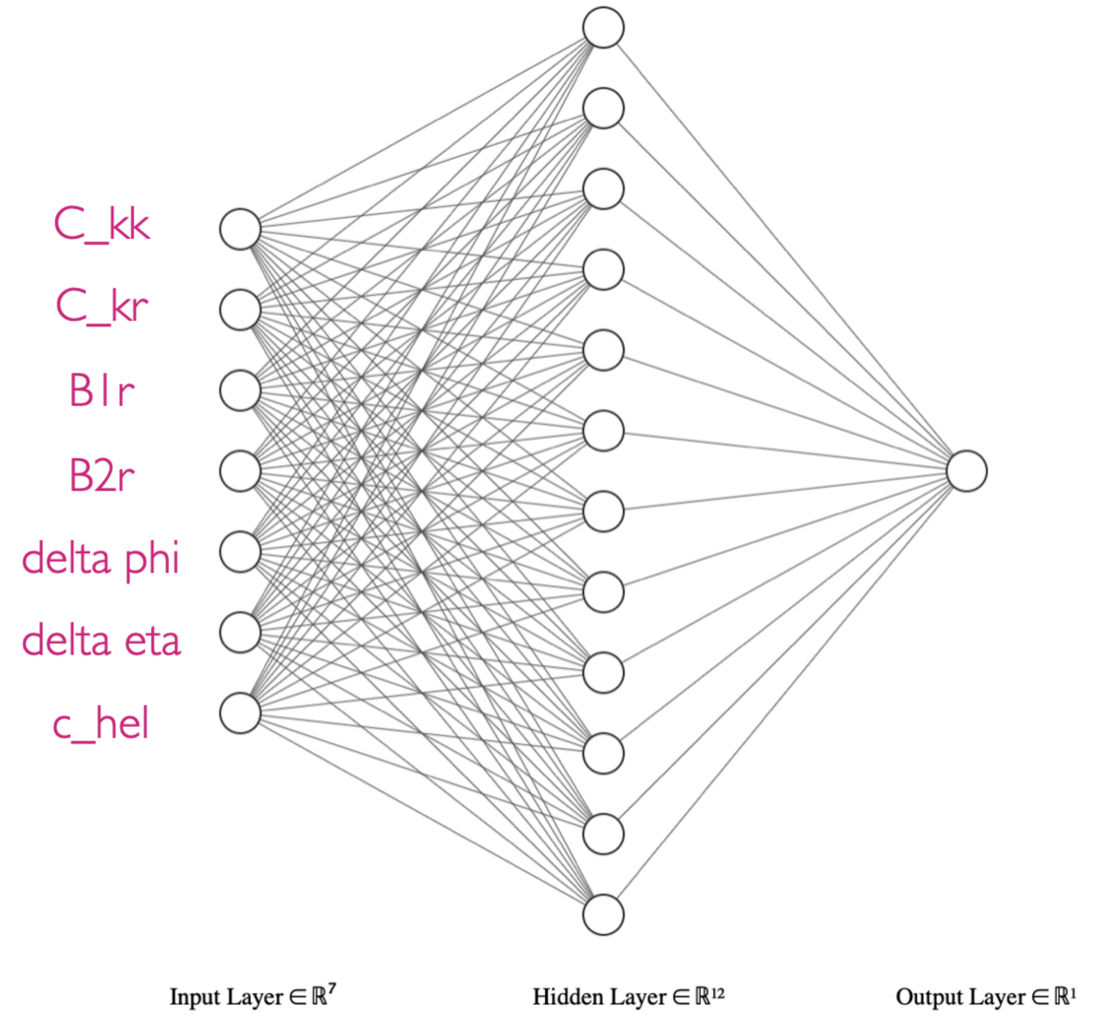
- Ongoing study for spin corr projection at FCC-hh



CMS PAS FTR-18-034



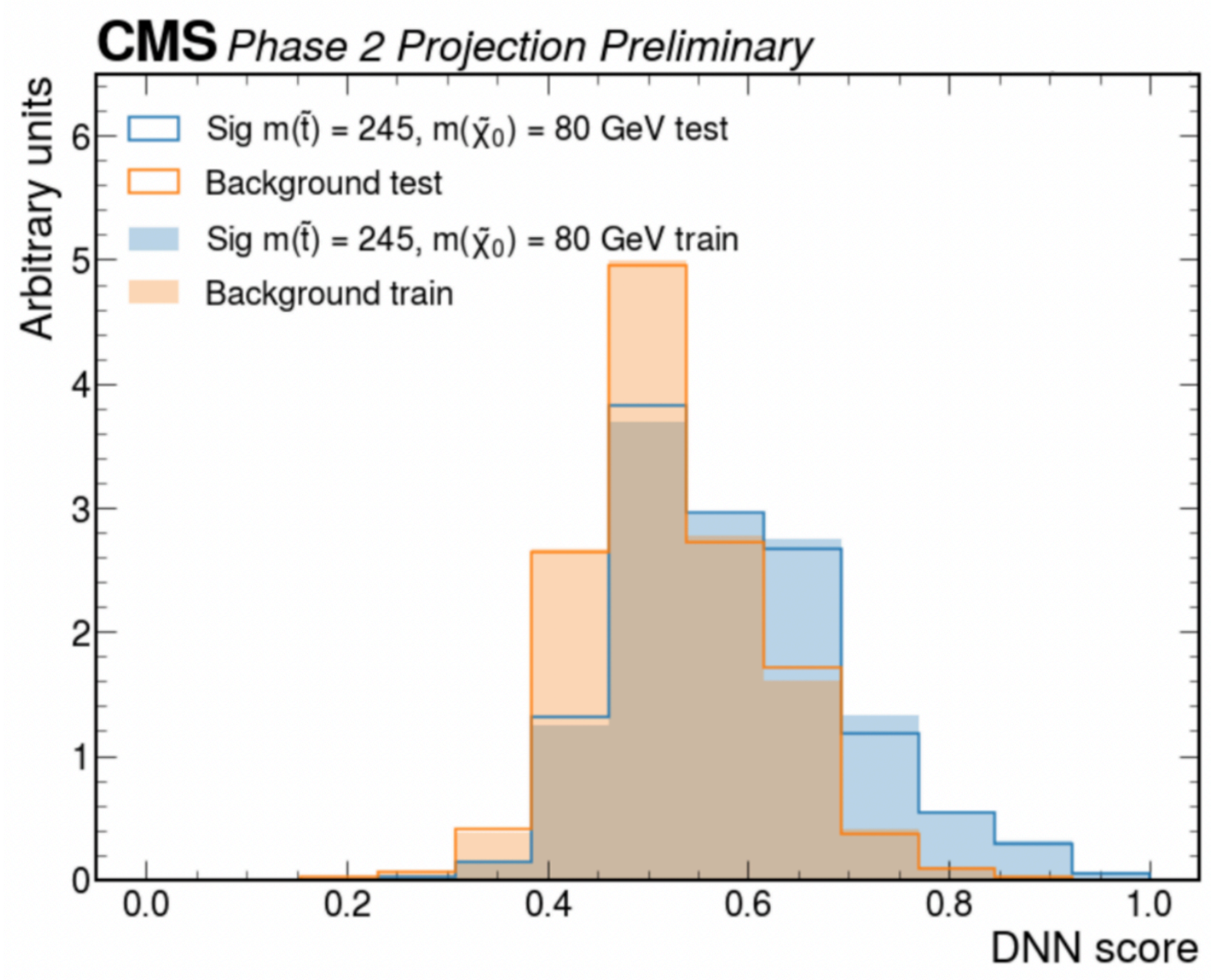
SUSY interpretation

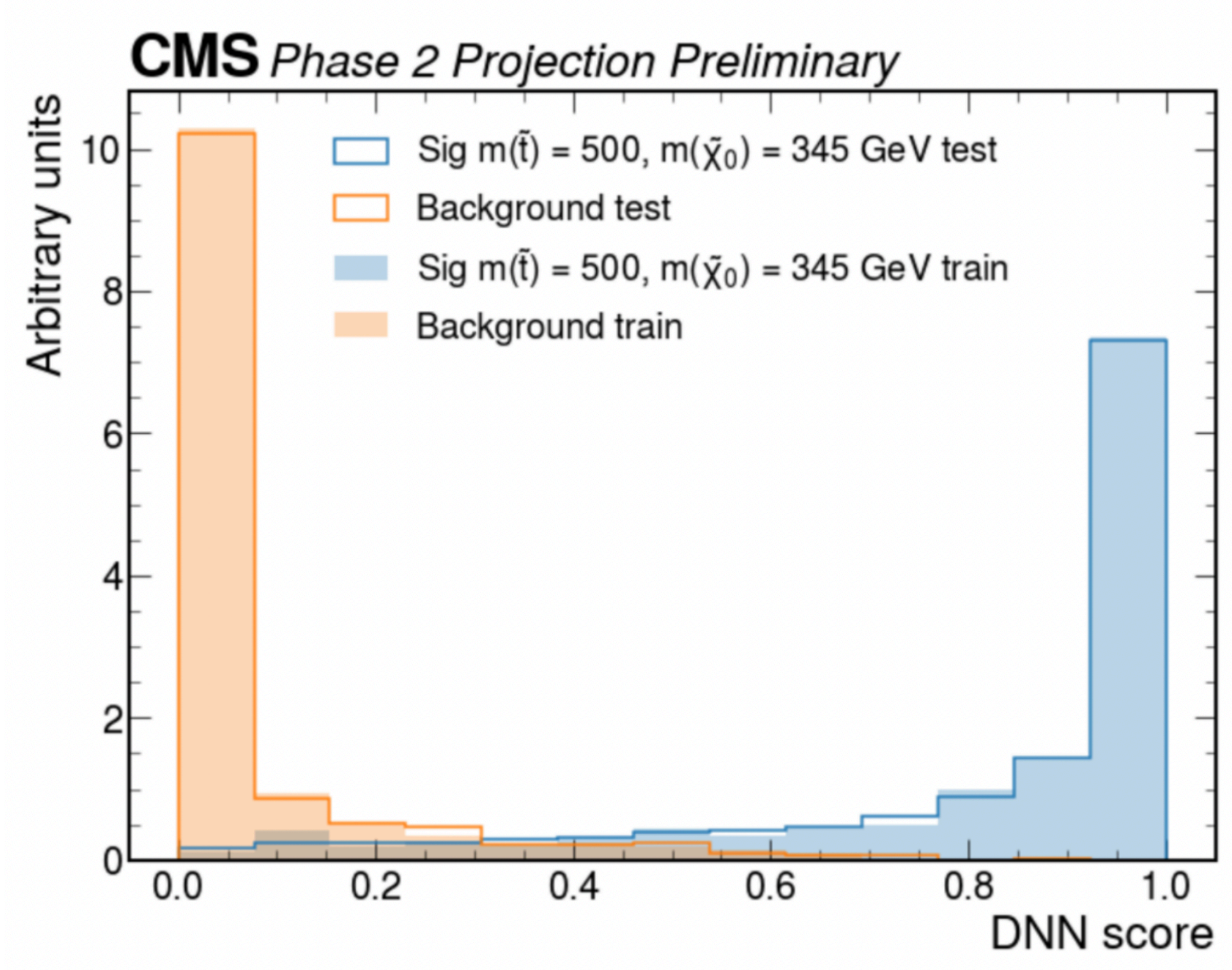


- Spin correlations are sensitive to new physics models that involve a top quark partner.

- For our projection we considered top squark partners in the top corridor upto a mass of 900 GeV.

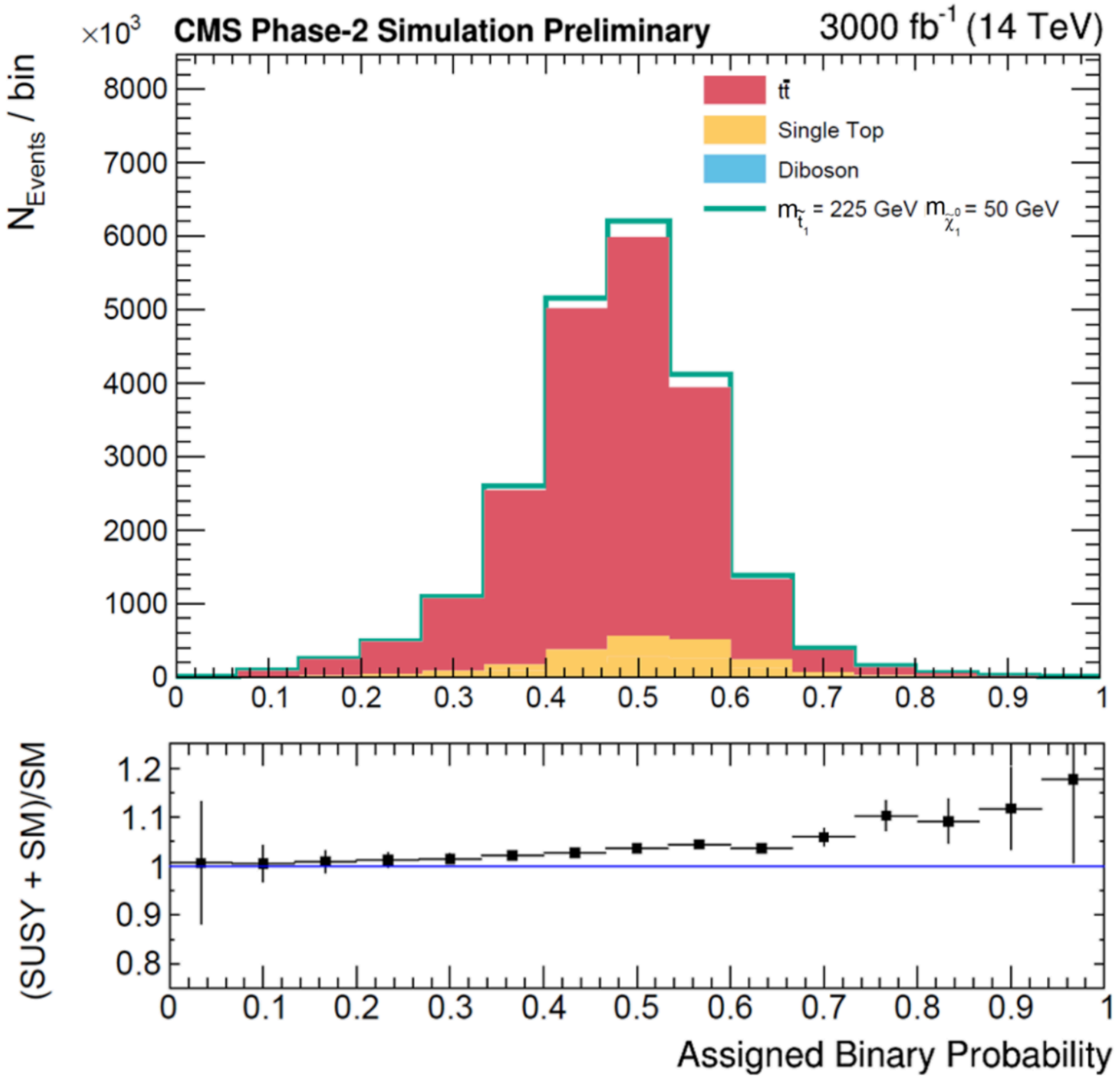
- With 18 spin correlation variables as input, we use a parametric DNN to construct a discriminant sensitive to new physics.





CMS PAS FTR-18-034

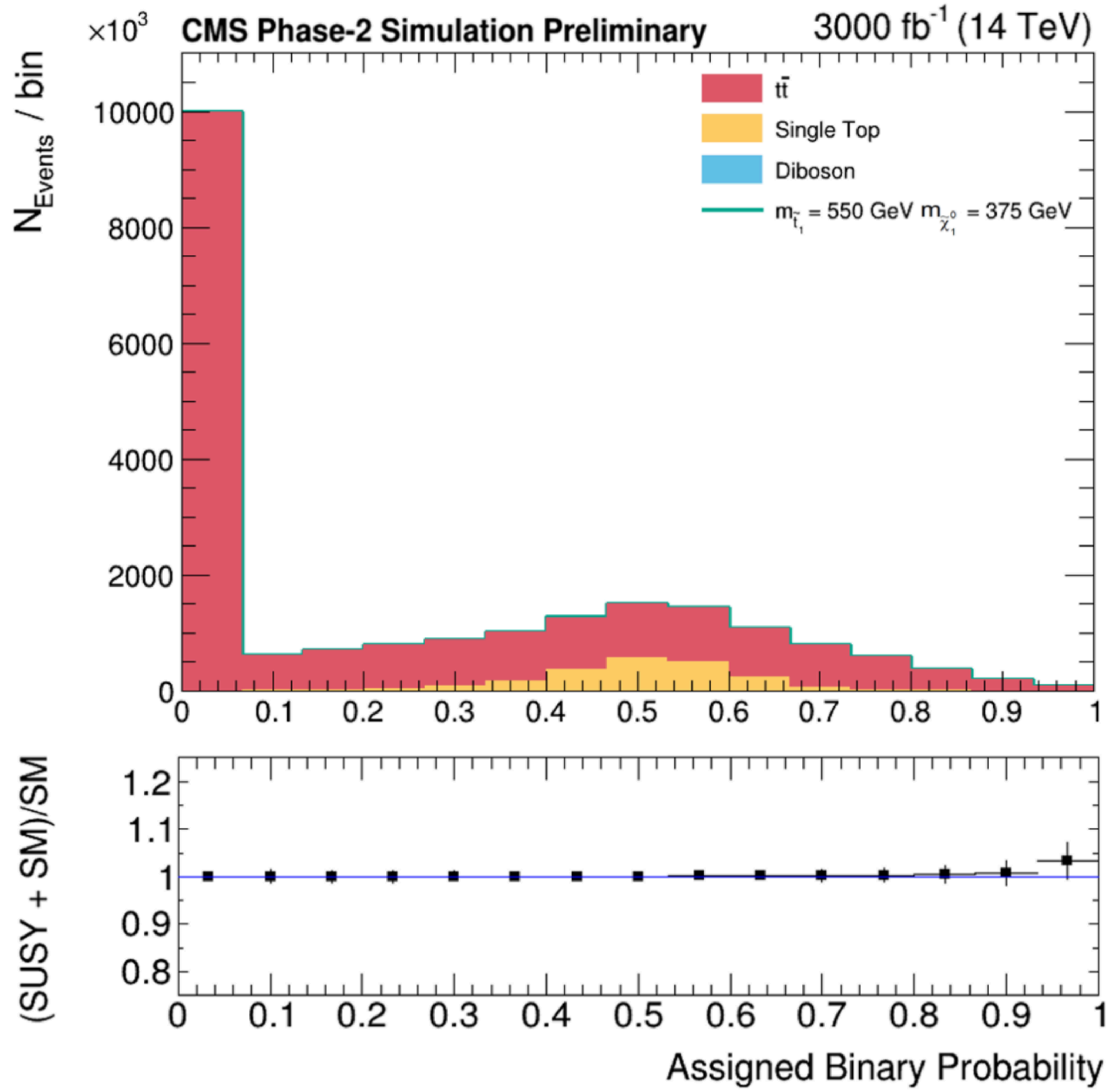
DNN outputs along the top corridor



CMS PAS FTR-18-034

Higher stop masses are easier to separate using a DNN.

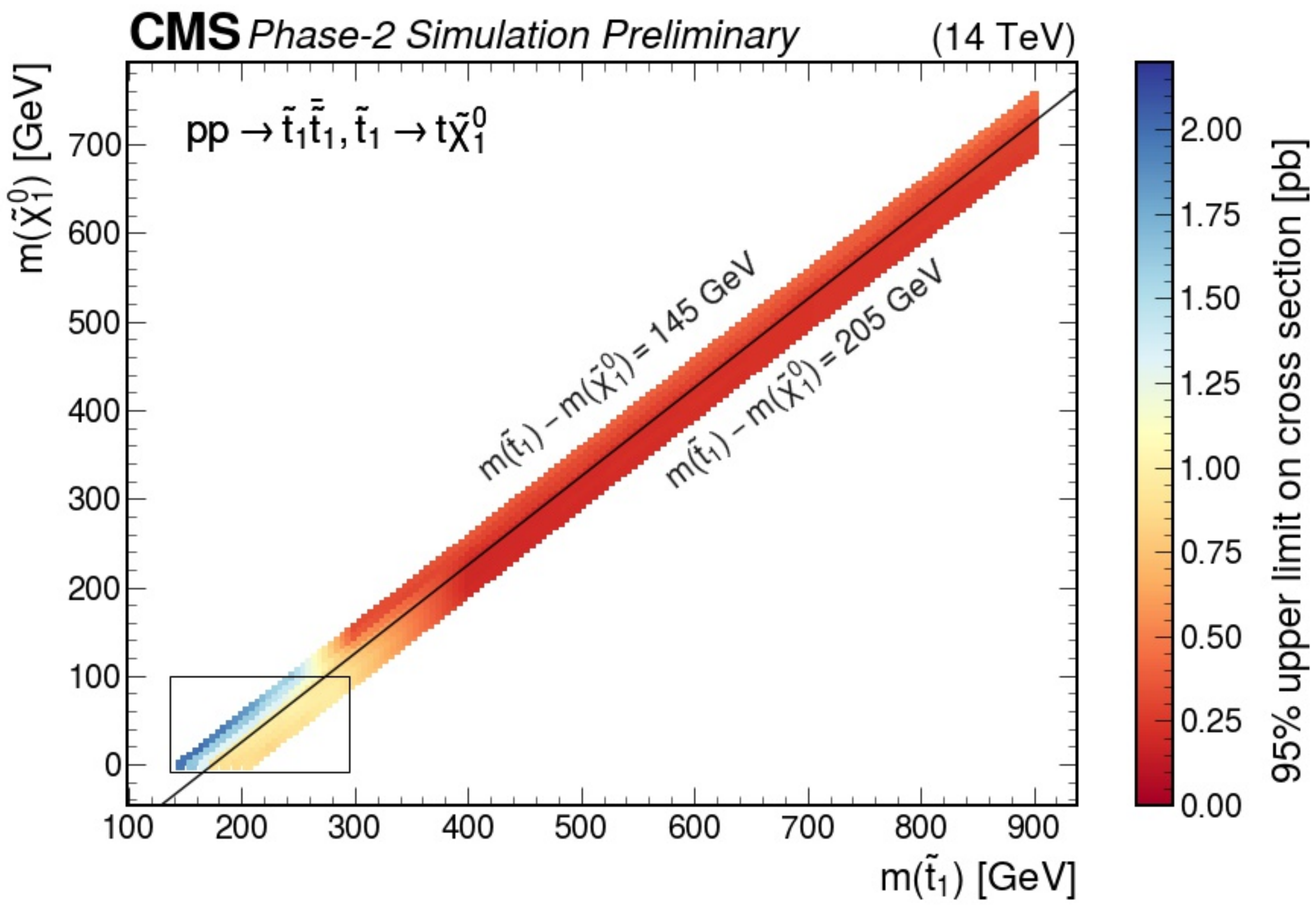
However, the cross-section drops exponentially, and the limits get tight



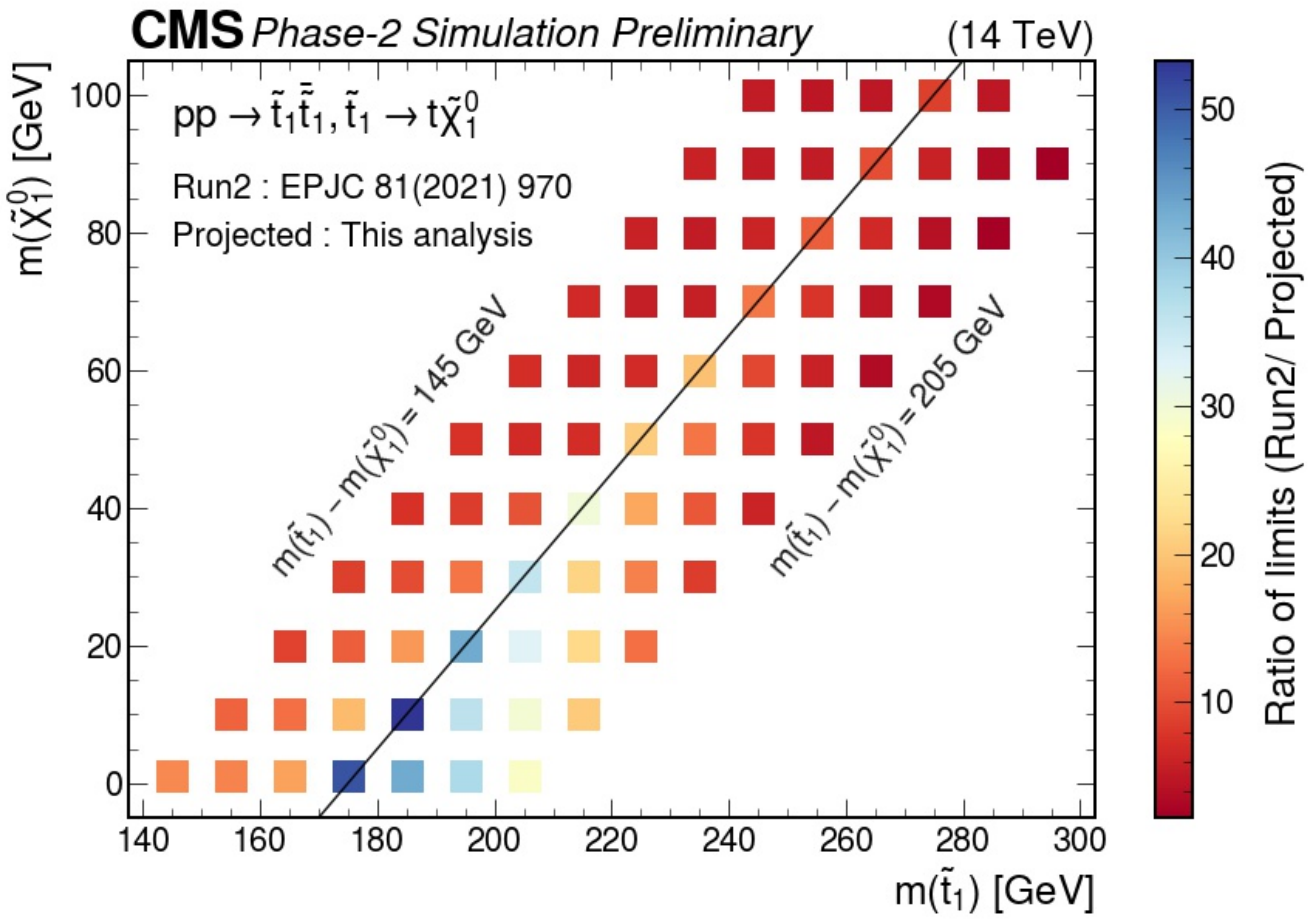
Parametric DNN output at different points along the top corridor

Limits

CMS PAS FTR-18-034



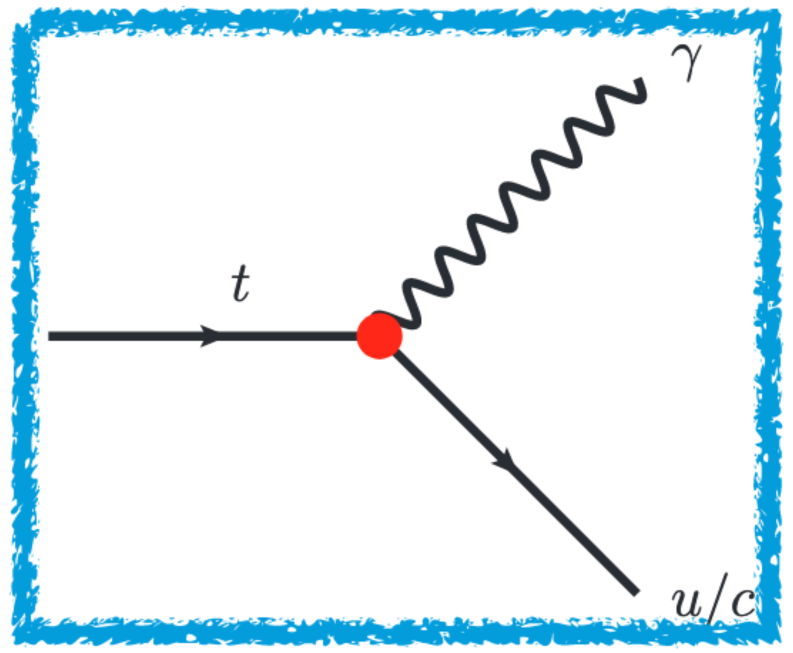
CMS PAS FTR-18-034



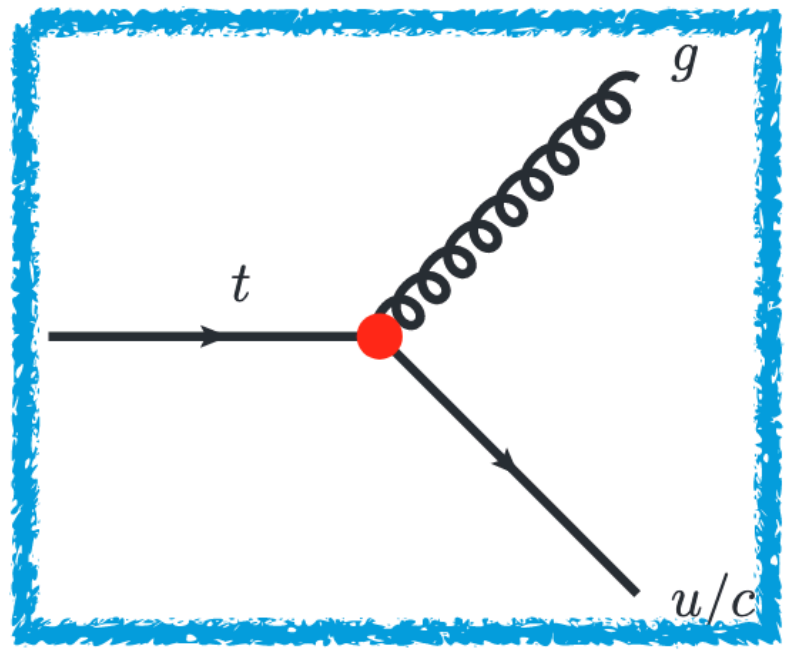
Order of magnitude improvement over existing limits.
Gains by adding spin corr variables.

Flavor Changing Neutral Currents

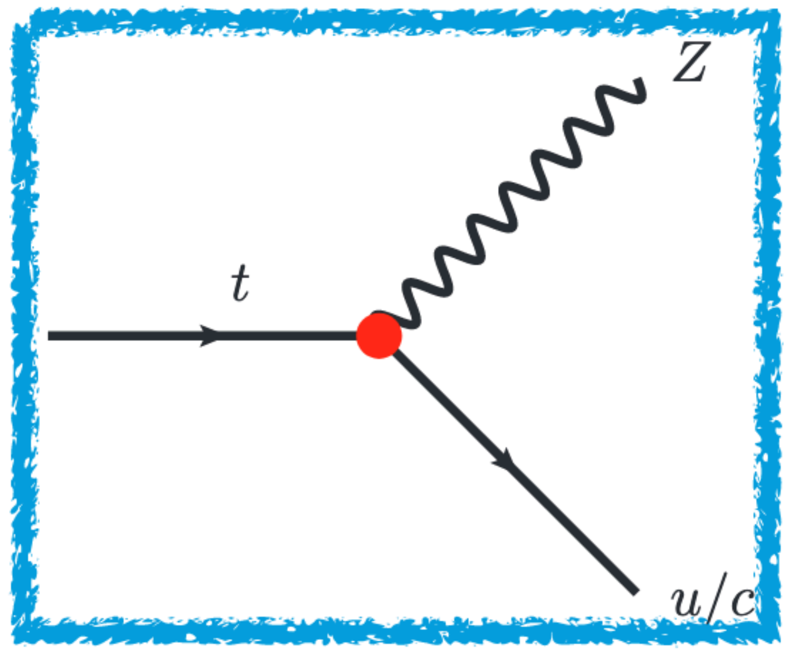
- Flavor changing neutral currents are forbidden at LO in the SM.
- At tree level supressed by :
  - The GIM mechanism and small CKM matrix elements.
- Predicted branching fractions very small $O(10^{-15} \sim 10^{-17})$
  - Significantly enhanced however in BSM extensions | MSSM $O(10^{-7})$ Extra dimensions $O(10^{-5})$



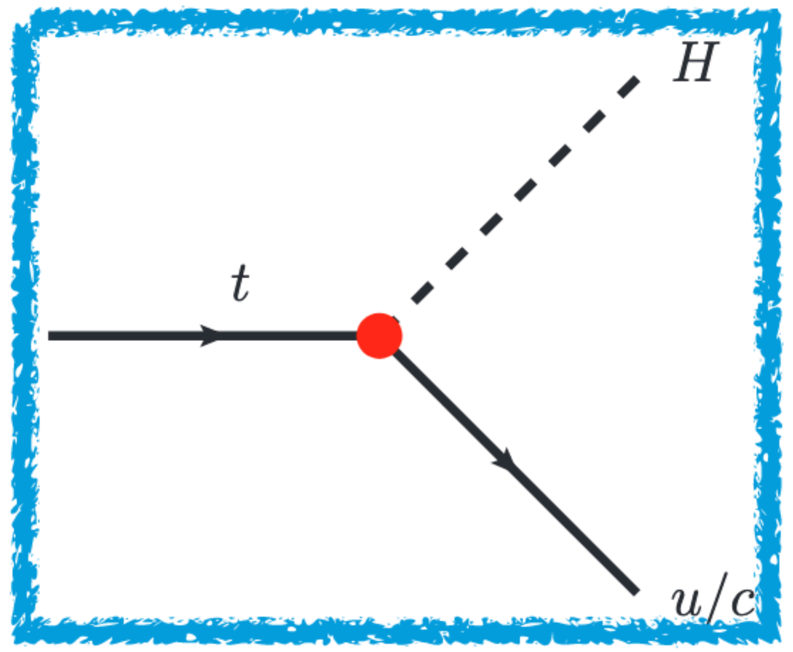
$t \to \gamma q$



$t \to gq$



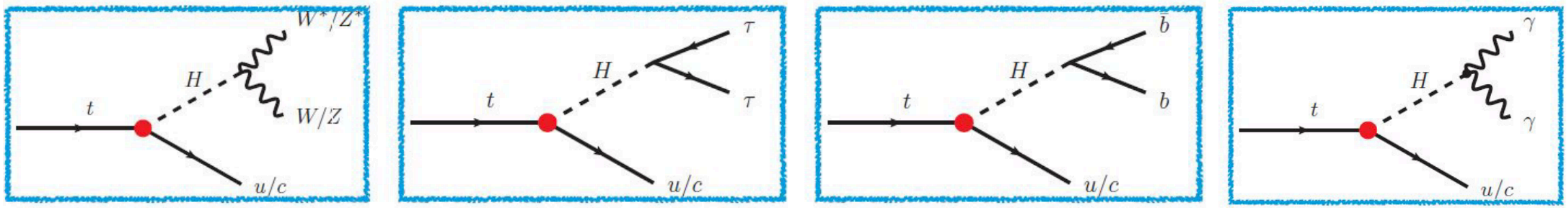
$t \to Zq$



$t \to Hq$

Graphics from https://moriond.in2p3.fr/2019/EW/slides/

Probing the tHq vertex



$H \to WW^*/ZZ^*$ $H \to \tau\tau$ $H \to b\bar{b}$ $H \to \gamma\gamma$

- Many accessible signatures depending upon the Higgs decay channel.
- Dedicated analyses for each channel, final combination by ATLAS.

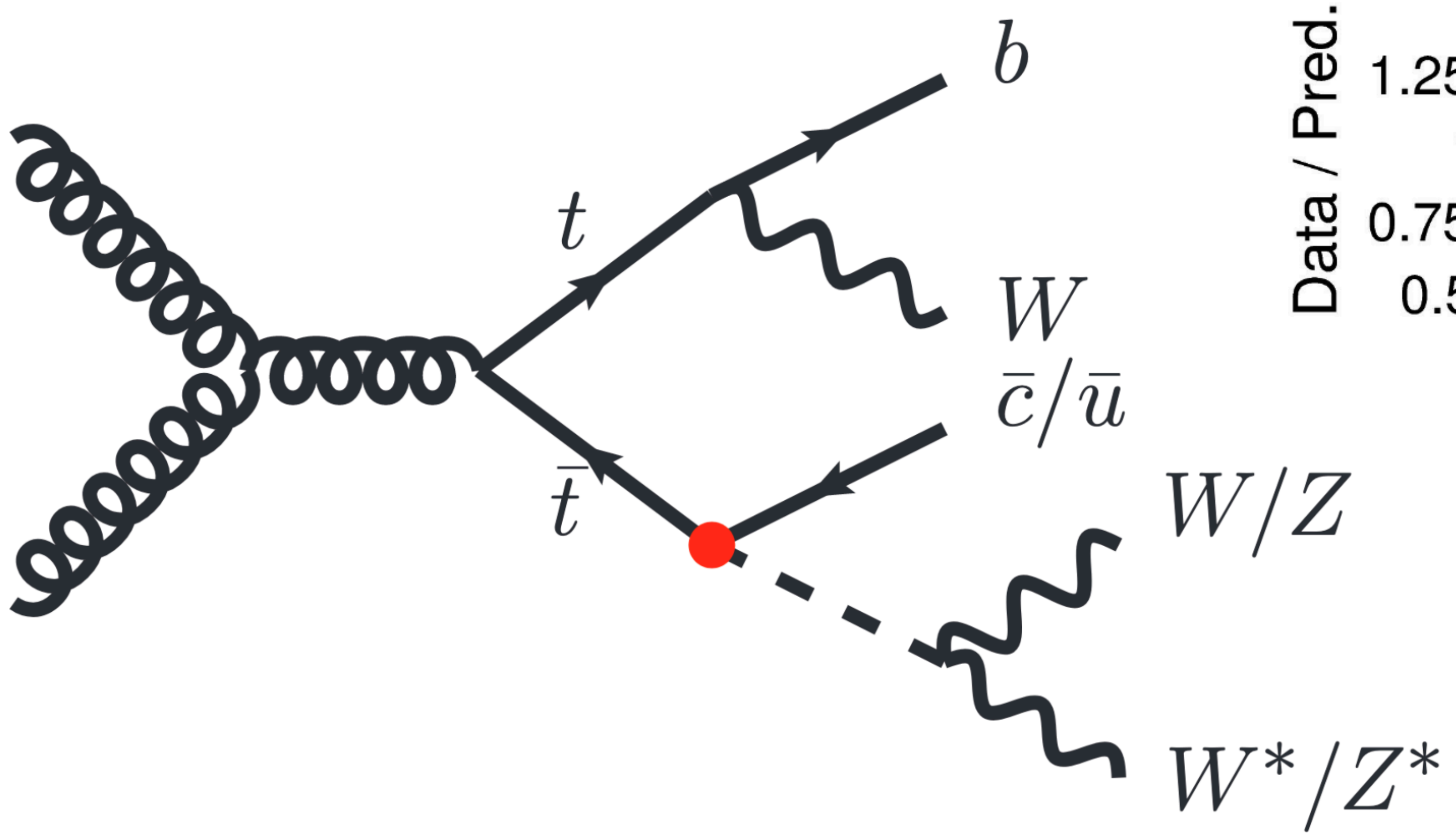
Probing the tHq vertex

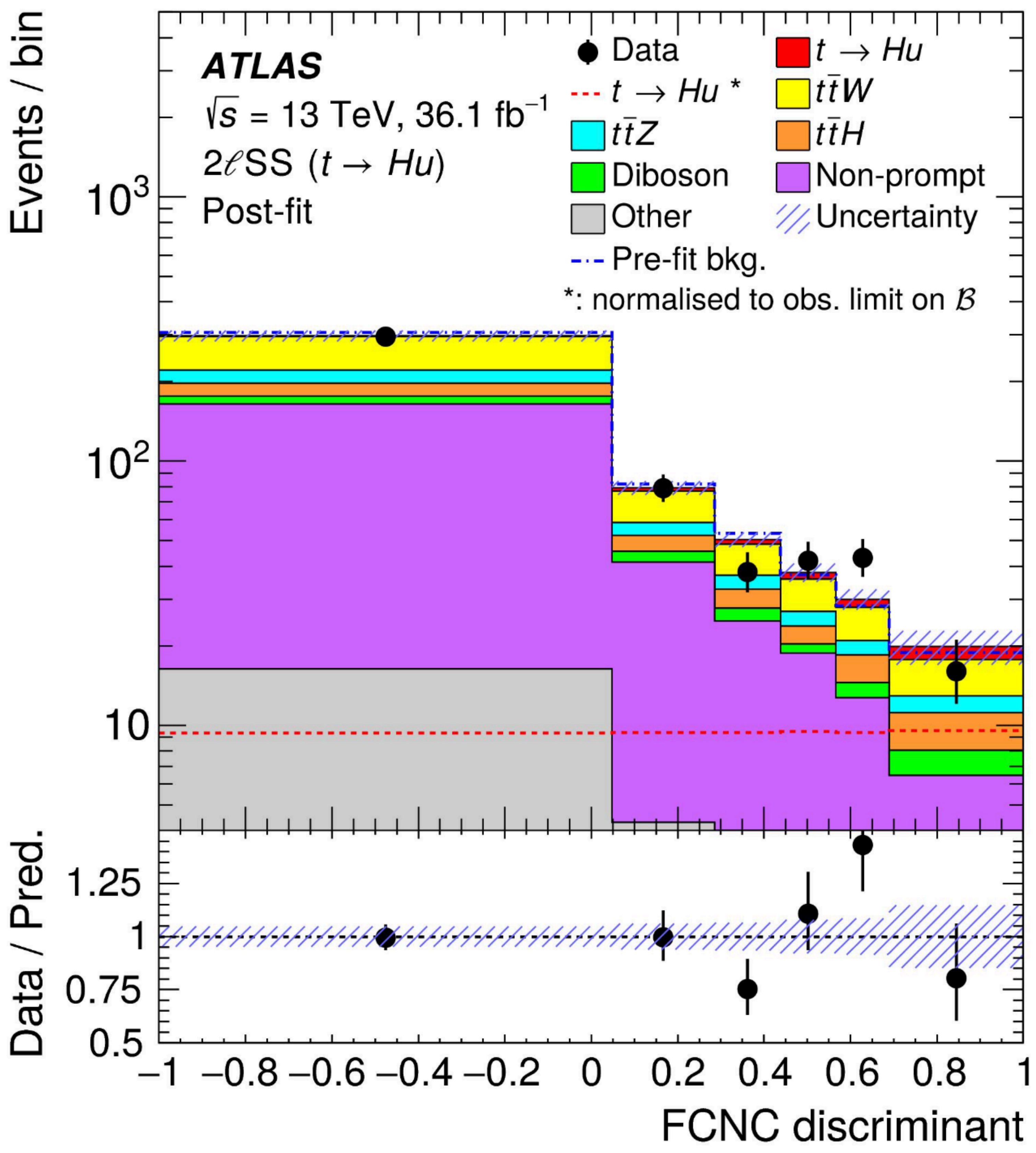
- The Diboson final state provides for a very clean signature :
  - 2 same-sign leptons / 3 leptons
- Main backgrounds are the ttW and non-prompt leptons.
- Dominant systematics : modeling uncertainties, statistics for data-driven estimates

$$t \rightarrow H(WW^*/ZZ^*)q$$

$$\mathscr{B}(t \rightarrow Hu) < 1.9(1.5) \times 10^{-3}$$

$$\mathscr{B}(t \rightarrow Hc) < 1.6(1.5) \times 10^{-3}$$





Phys. Rev. D 98, 032002 (2018)

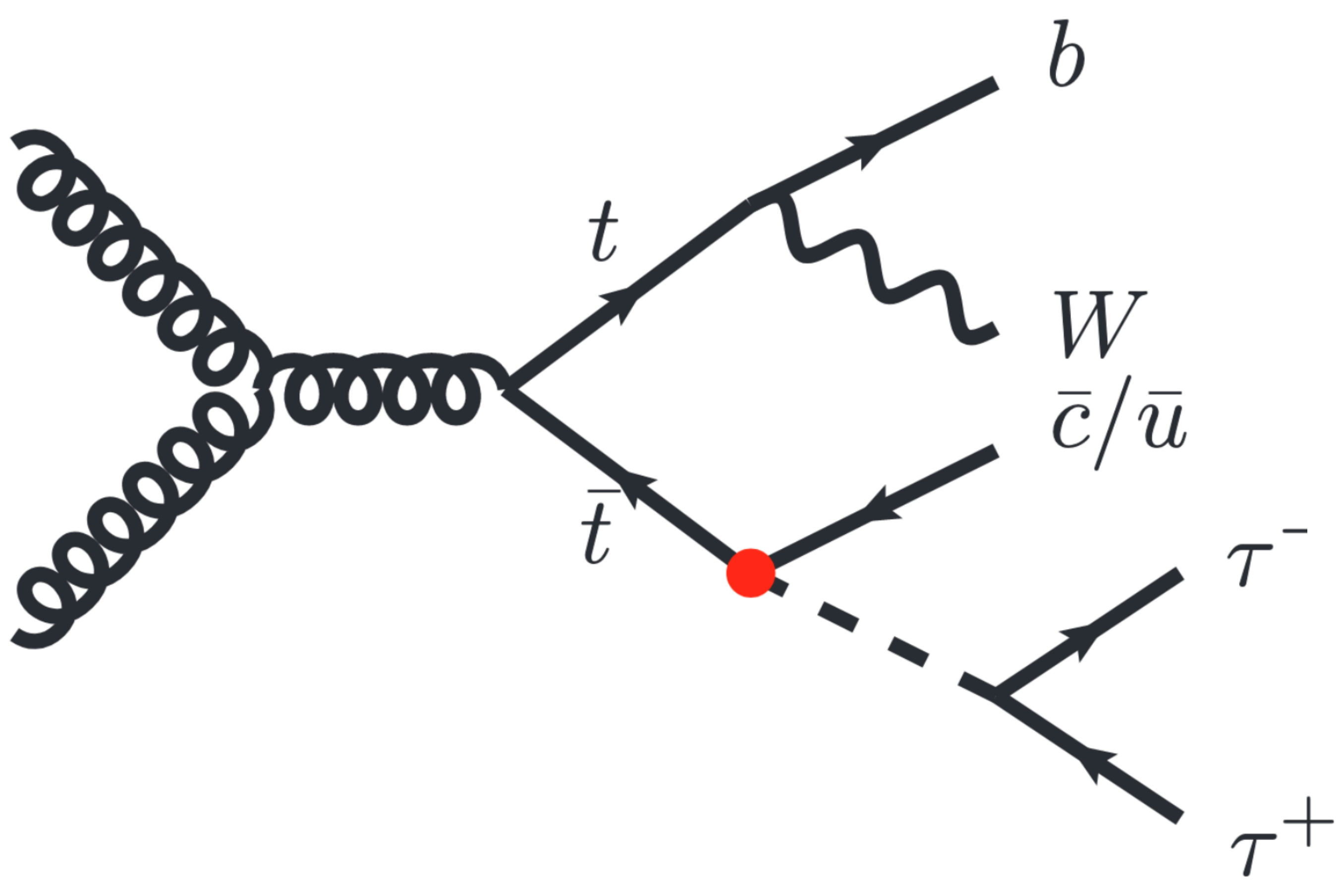
Probing the tHq vertex

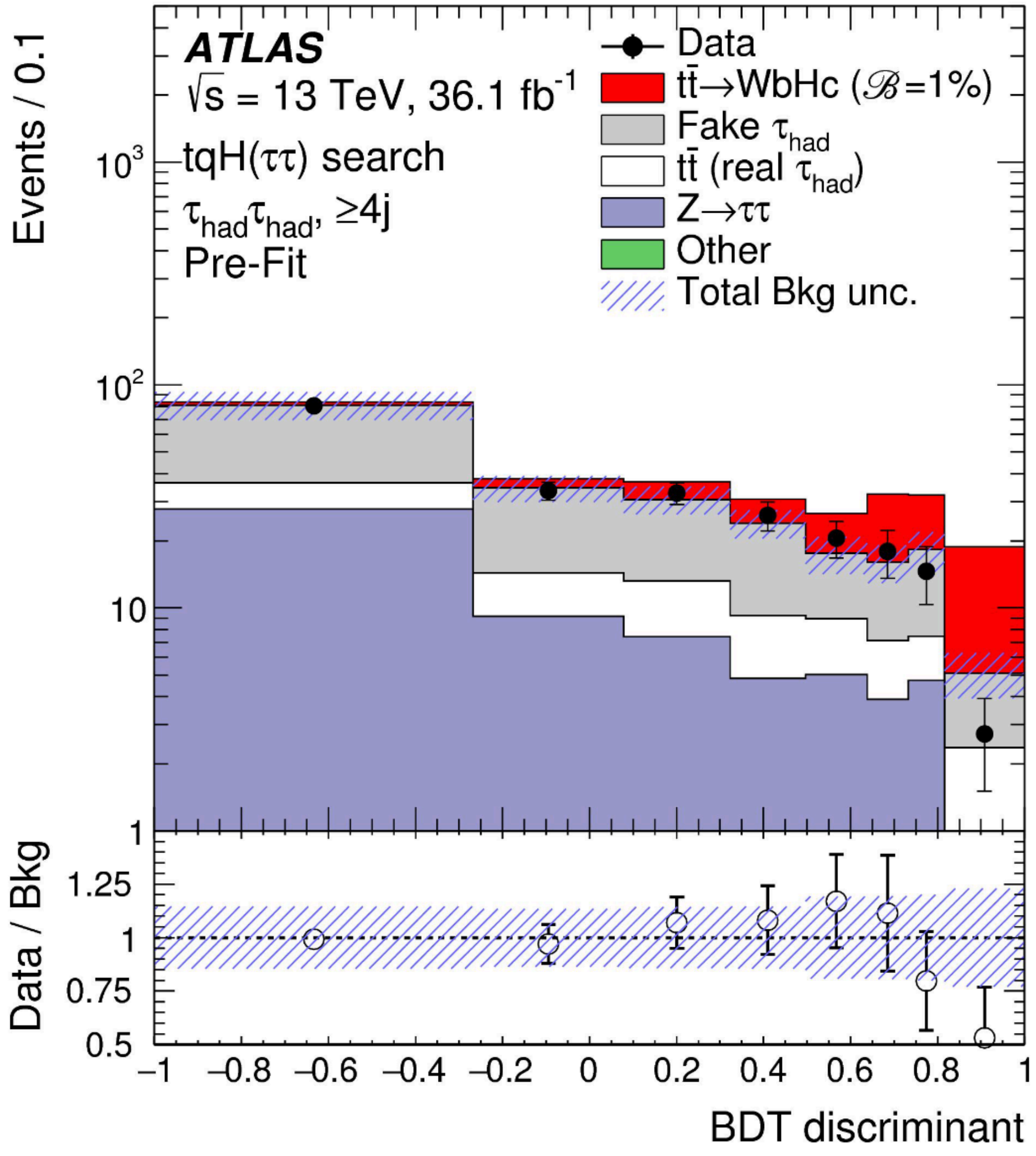
- Select events with :
  - Leptons and/or hadronic taus
- Main backgrounds from fake taus
- Dominant systematics : fake tau modeling uncertainties

$$t \to H(\tau\tau)q$$

$$\mathcal{B}(t \to Hu) < 1.7\ (2.0) \times 10^{-3}$$

$$\mathcal{B}(t \to Hc) < 1.9\ (2.1) \times 10^{-3}$$





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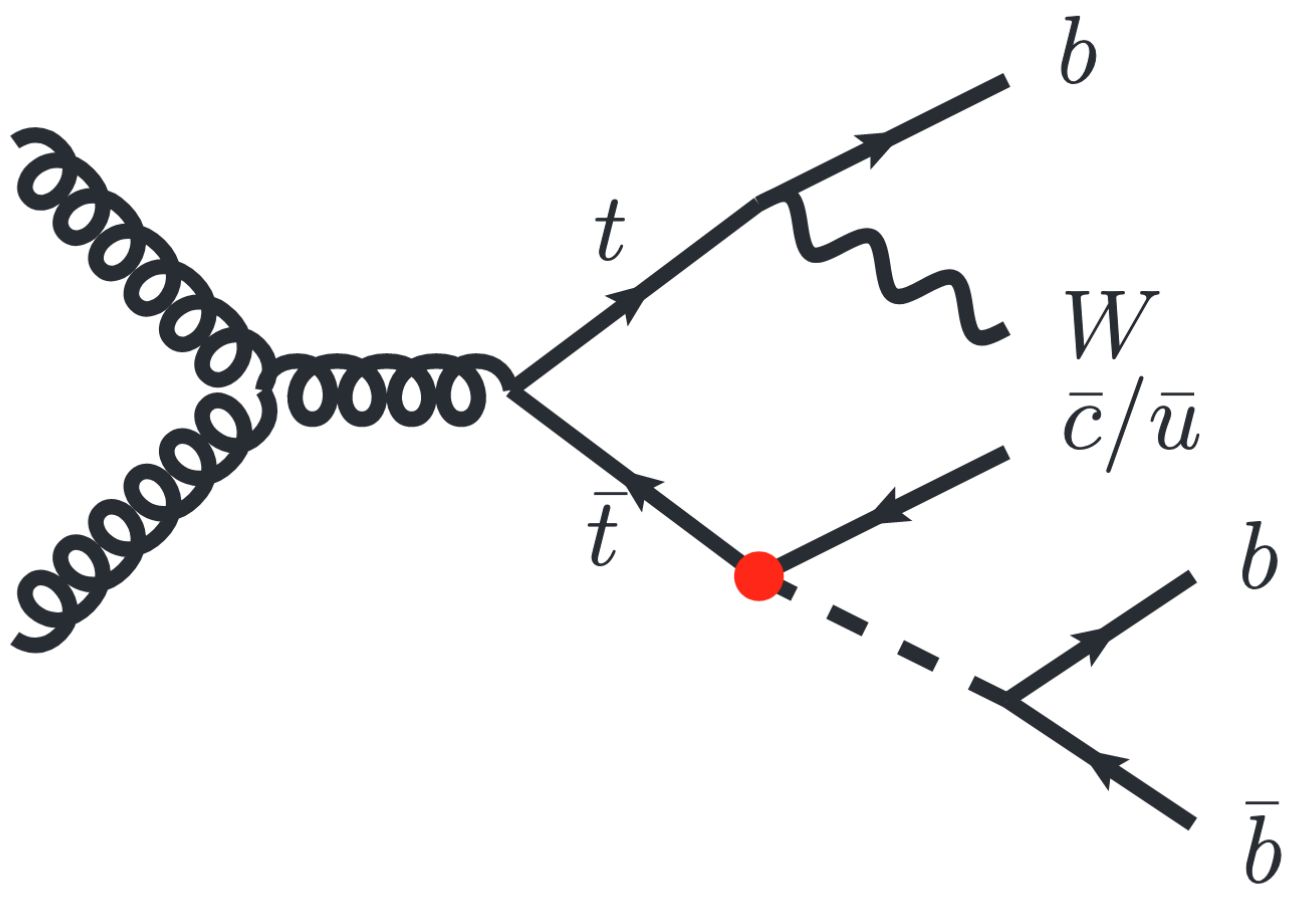
Probing the tHq vertex

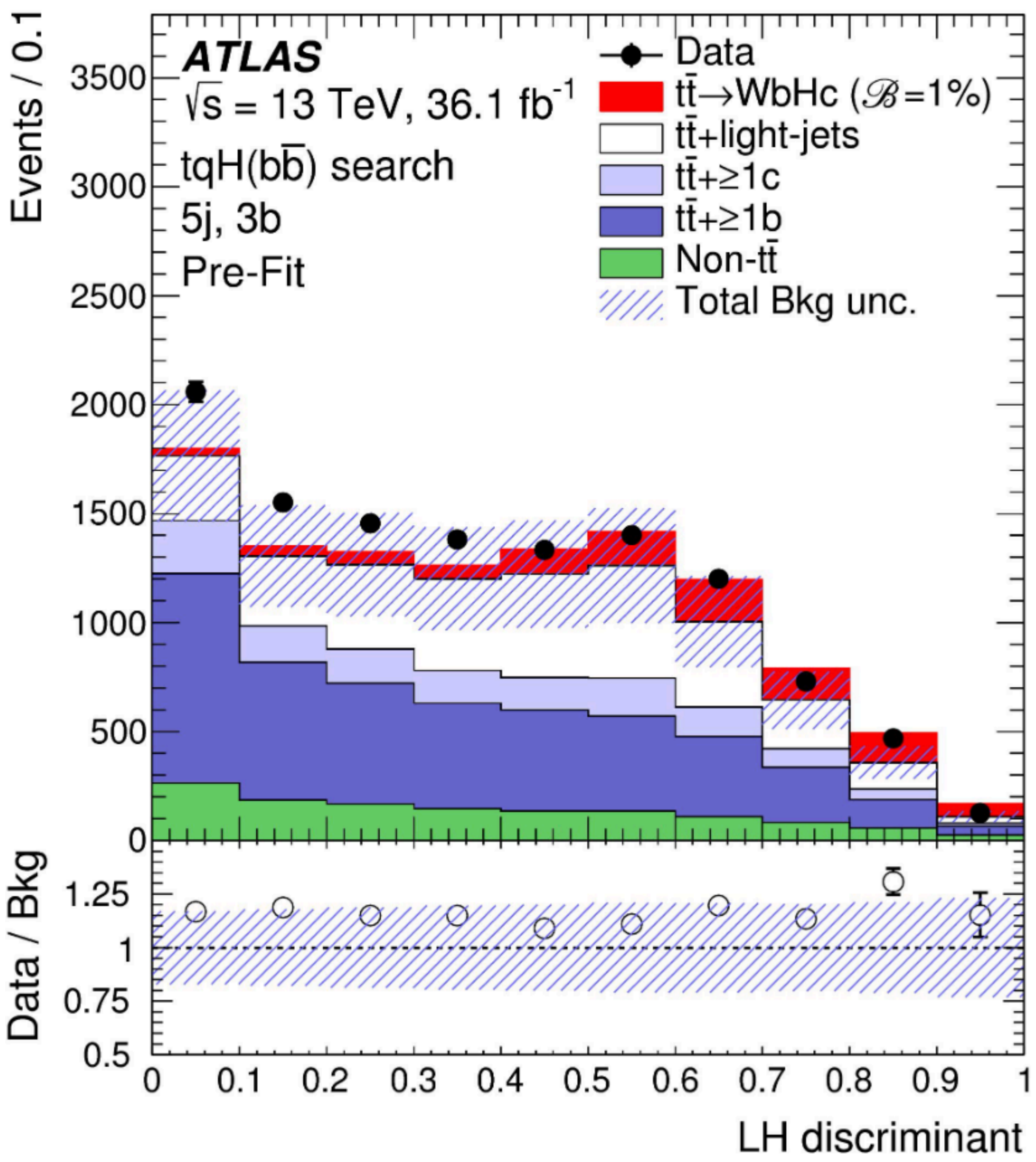
- Final state looks like :
  - 1-lepton and several b-jets
- Main backgrounds from $t\bar{t}$ and heavy flavor jets.
- Dominant systematics : c-jet mistagging

$$t \to H(b\bar{b})q$$

$$\mathcal{B}(t \to Hu) < 5.2\ (4.9) \times 10^{-3}$$

$$\mathcal{B}(t \to Hc) < 4.2\ (4.0) \times 10^{-3}$$





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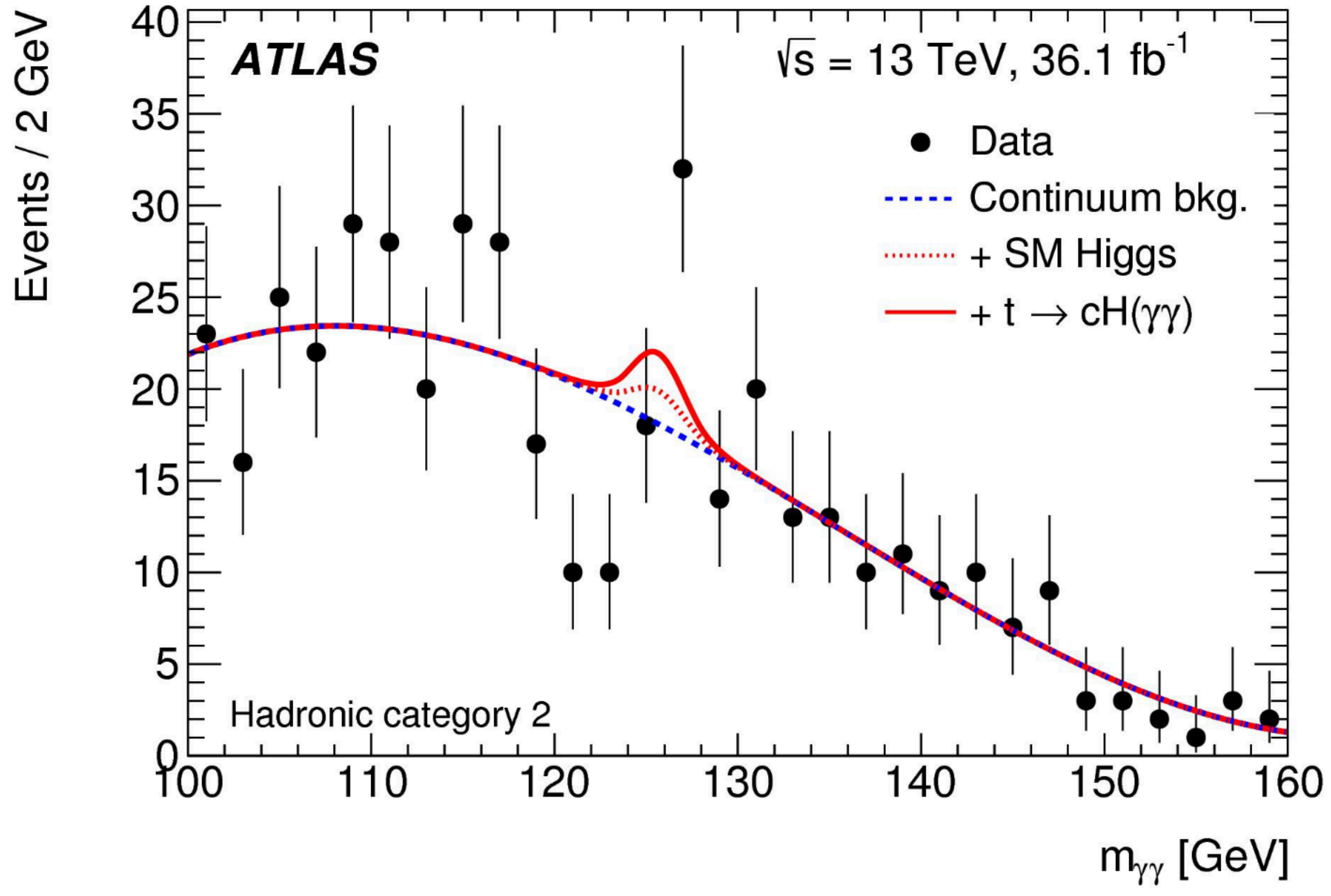
Probing the tHq vertex



$\mathscr{B}(t \to Hu) < 1.2\ (0.83) \times 10^{-3}$

$\mathscr{B}(t \to Hc) < 1.1\ (0.83) \times 10^{-3}$

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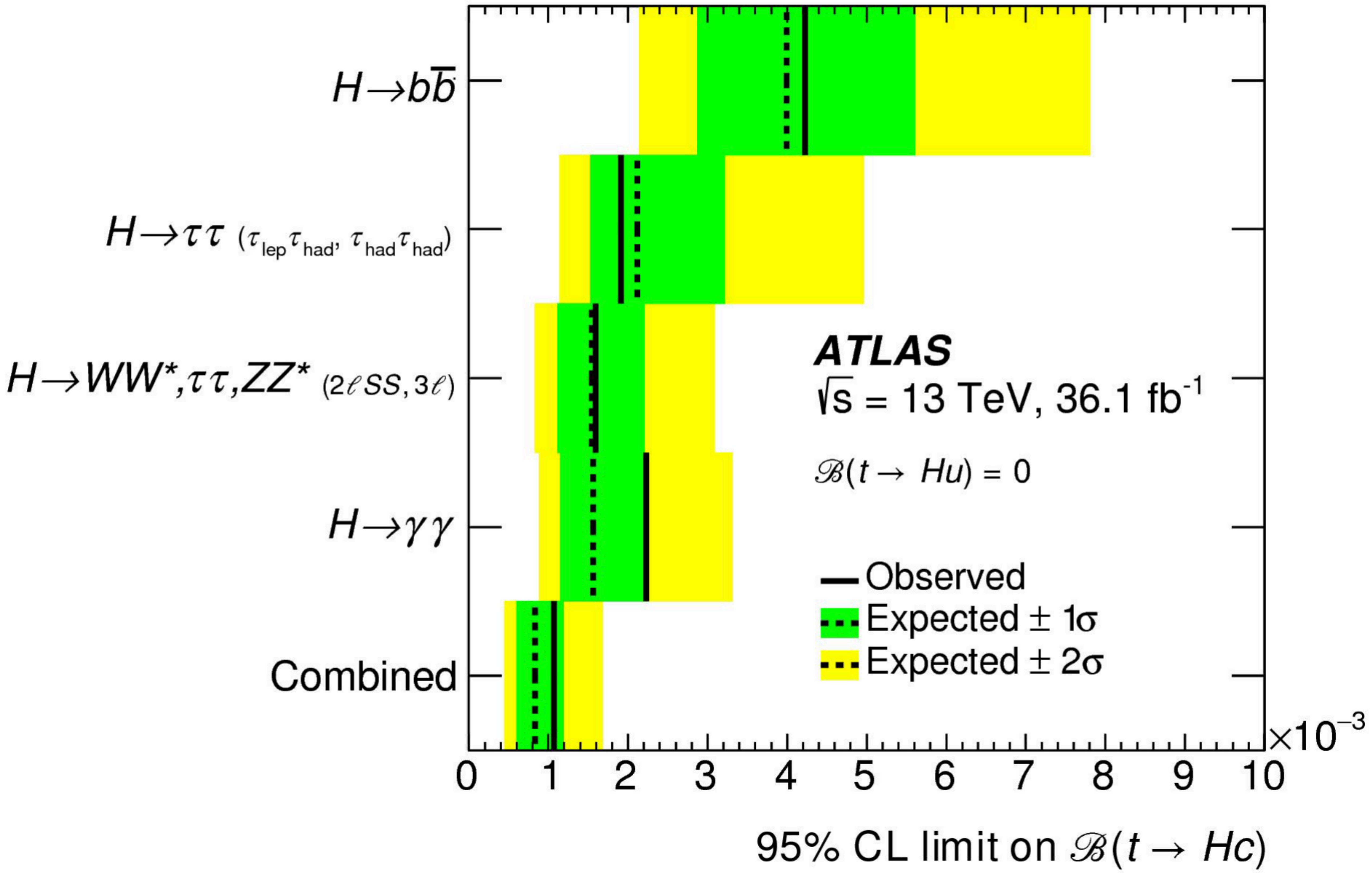
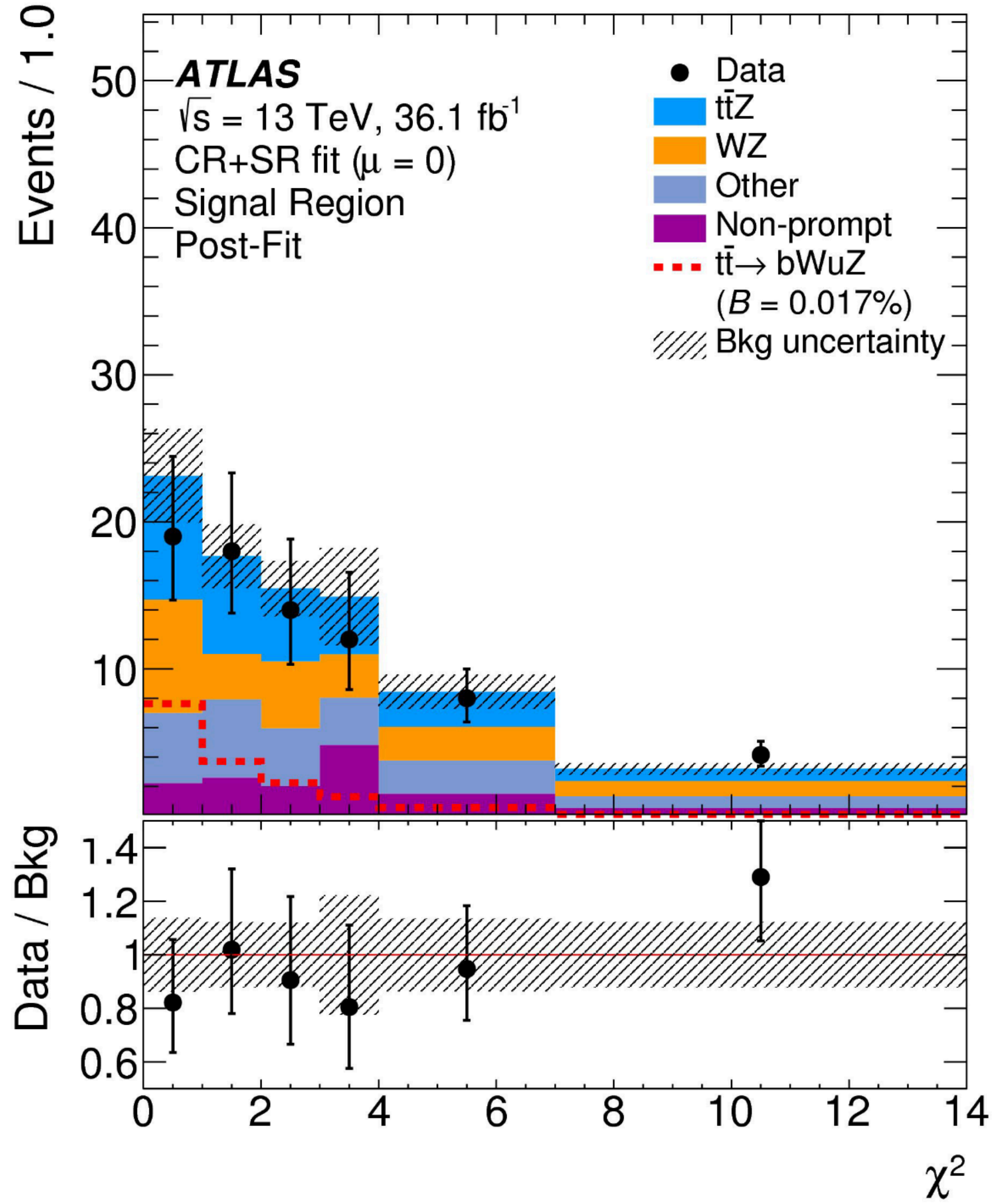


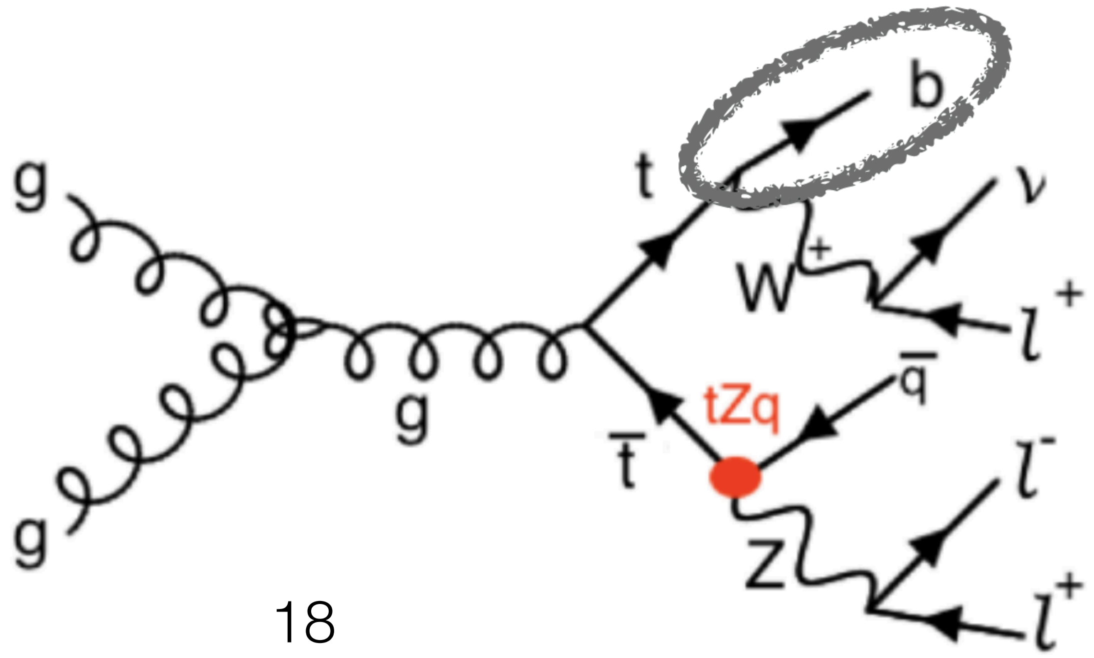
Probing the tZq vertex

$\mathcal{B}(t \to Zu) < 1.7\ (2.4) \times 10^{-4}$

$\mathcal{B}(t \to Zc) < 2.4\ (3.2) \times 10^{-4}$

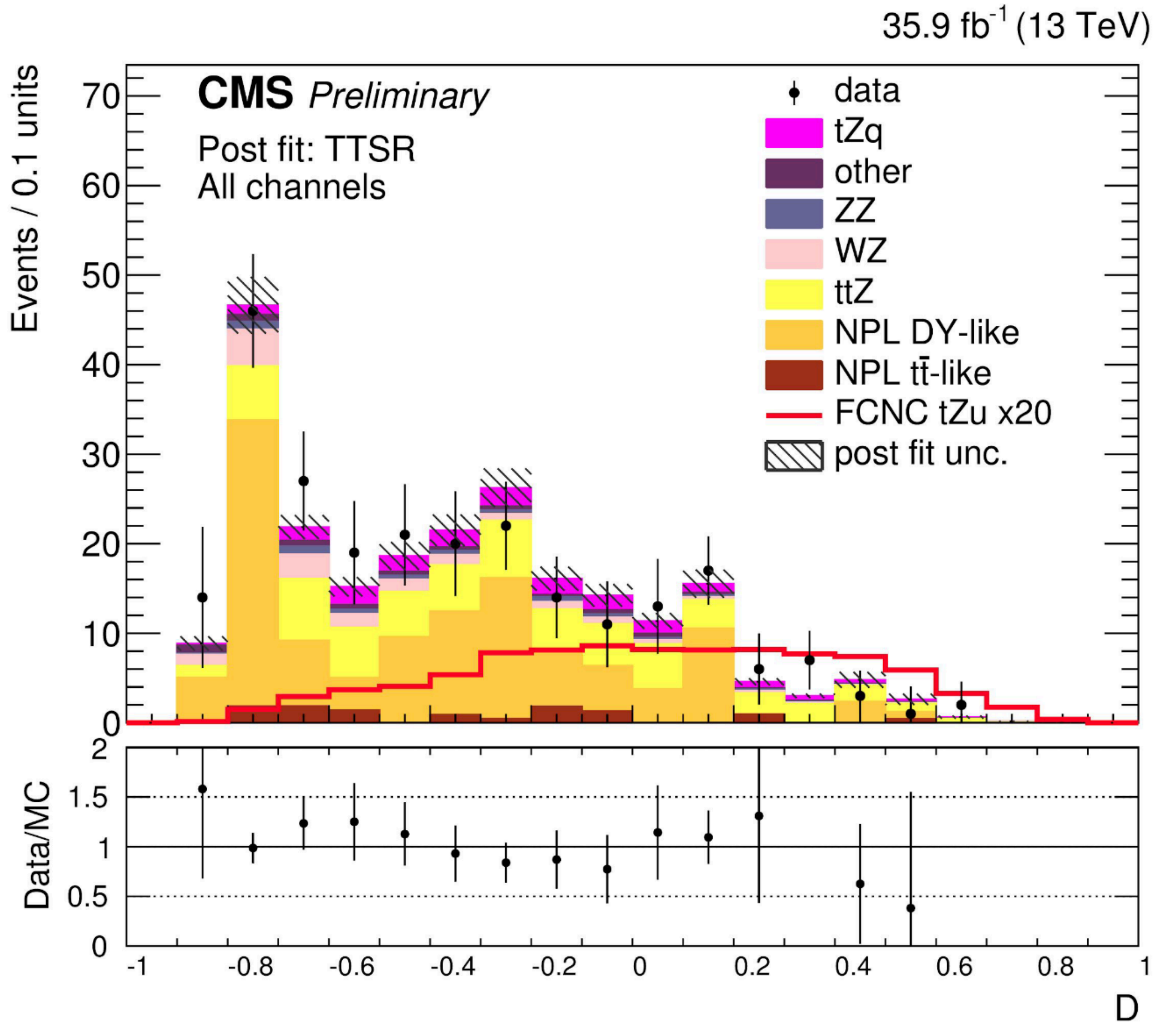


- The tZq vertex also has a clear experiment signature :
    - 3 leptons (2 with m_{ll} close to Z peak)
- Dominant backgrounds : ttZ
- Dominant systematics : background modeling



$\mathcal{B}(t \to Zu) < 2.4\ (1.5) \times 10^{-4}$

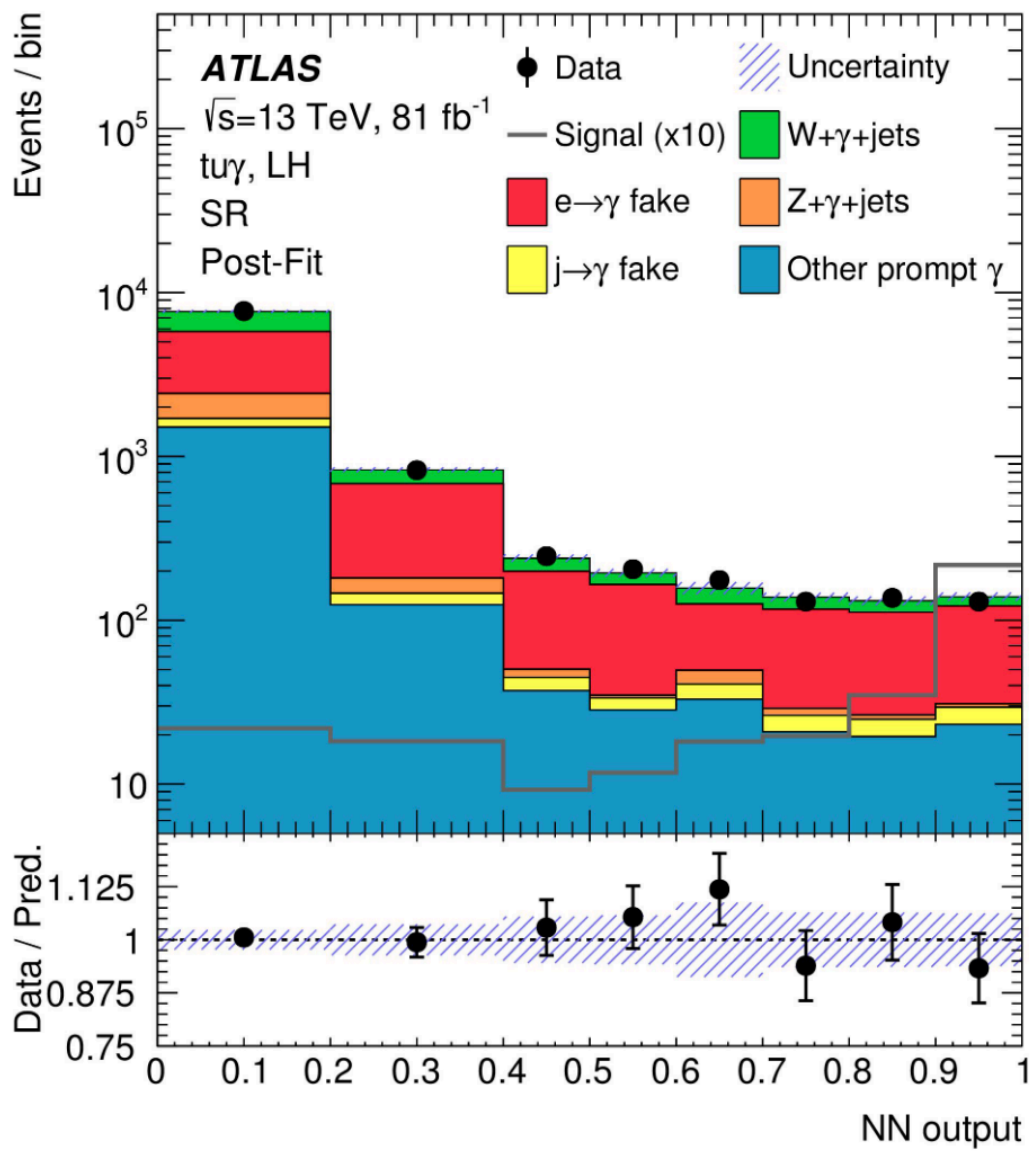
$\mathcal{B}(t \to Zc) < 4.5\ (3.7) \times 10^{-4}$



CMS-PAS-TOP-17-017

Probing the tγq and tgq vertices

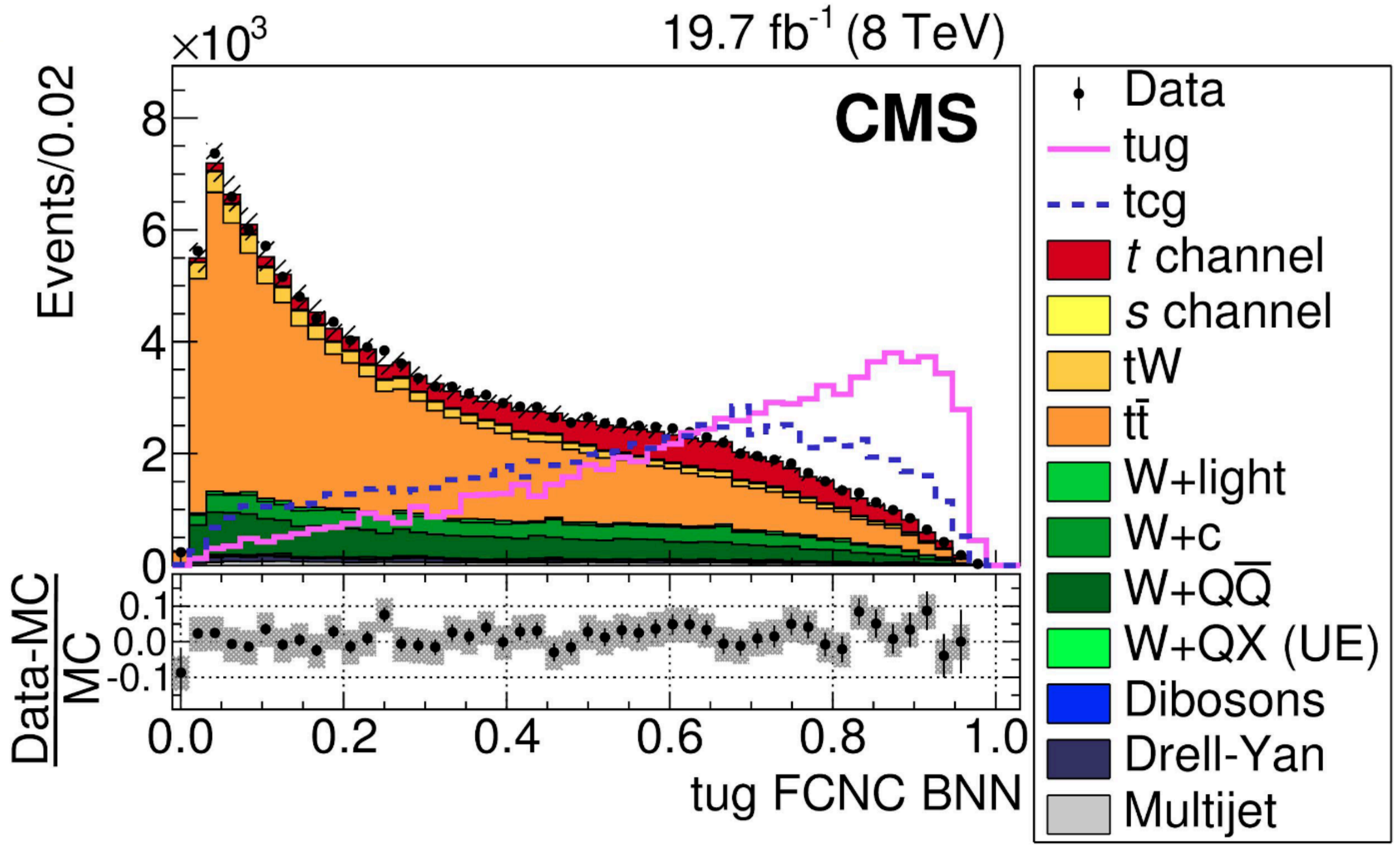
Phys. Lett. B 800 (2019) 135082



$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

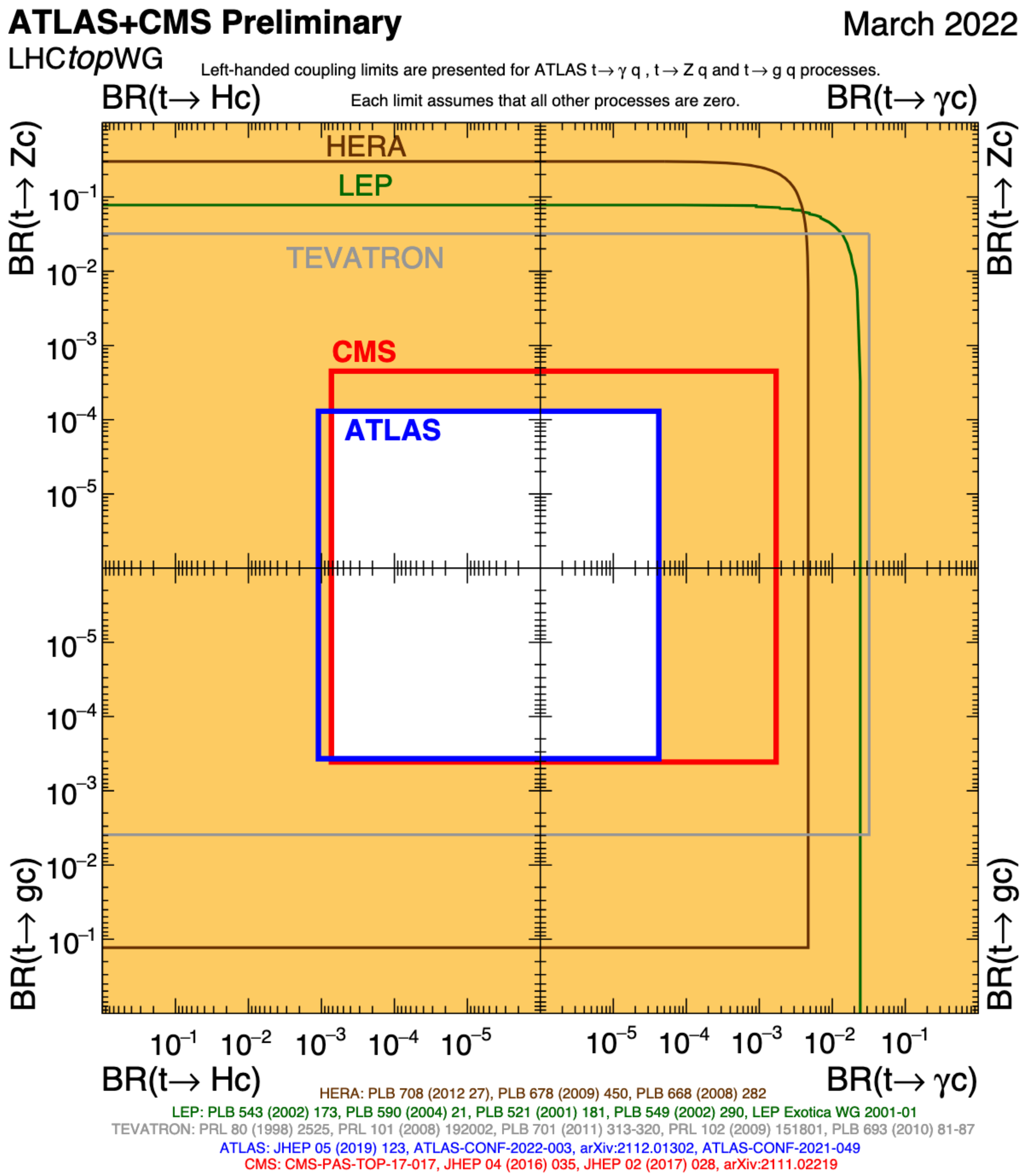
$$\mathcal{B}(t \to gu) < 2.0\,(2.8) \times 10^{-5}$$

$$\mathcal{B}(t \to gc) < 4.1\,(2.8) \times 10^{-4}$$

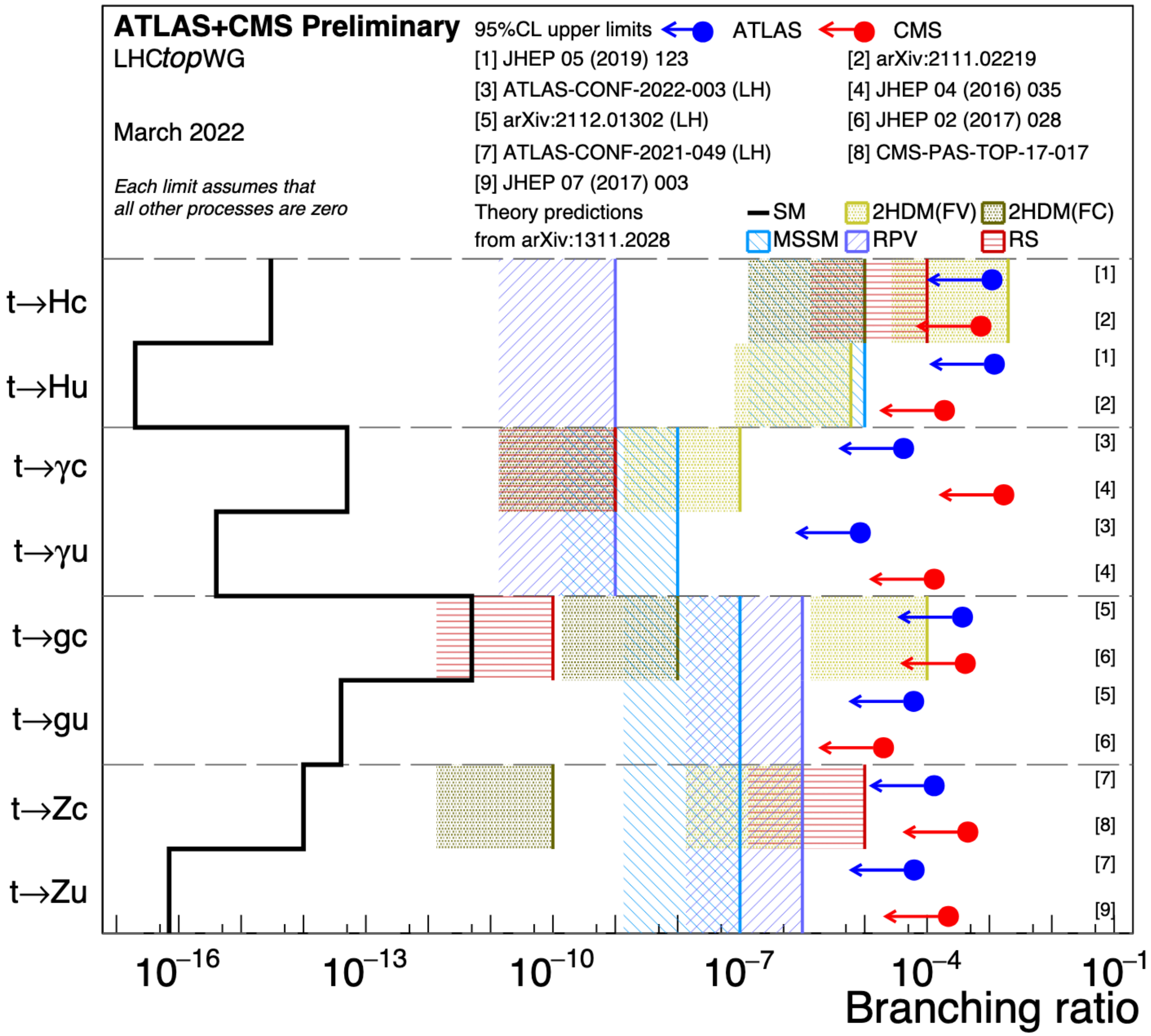


JHEP 02 (2017) 028

Status of Run2 measurements



Snowmass
TOPHF Report

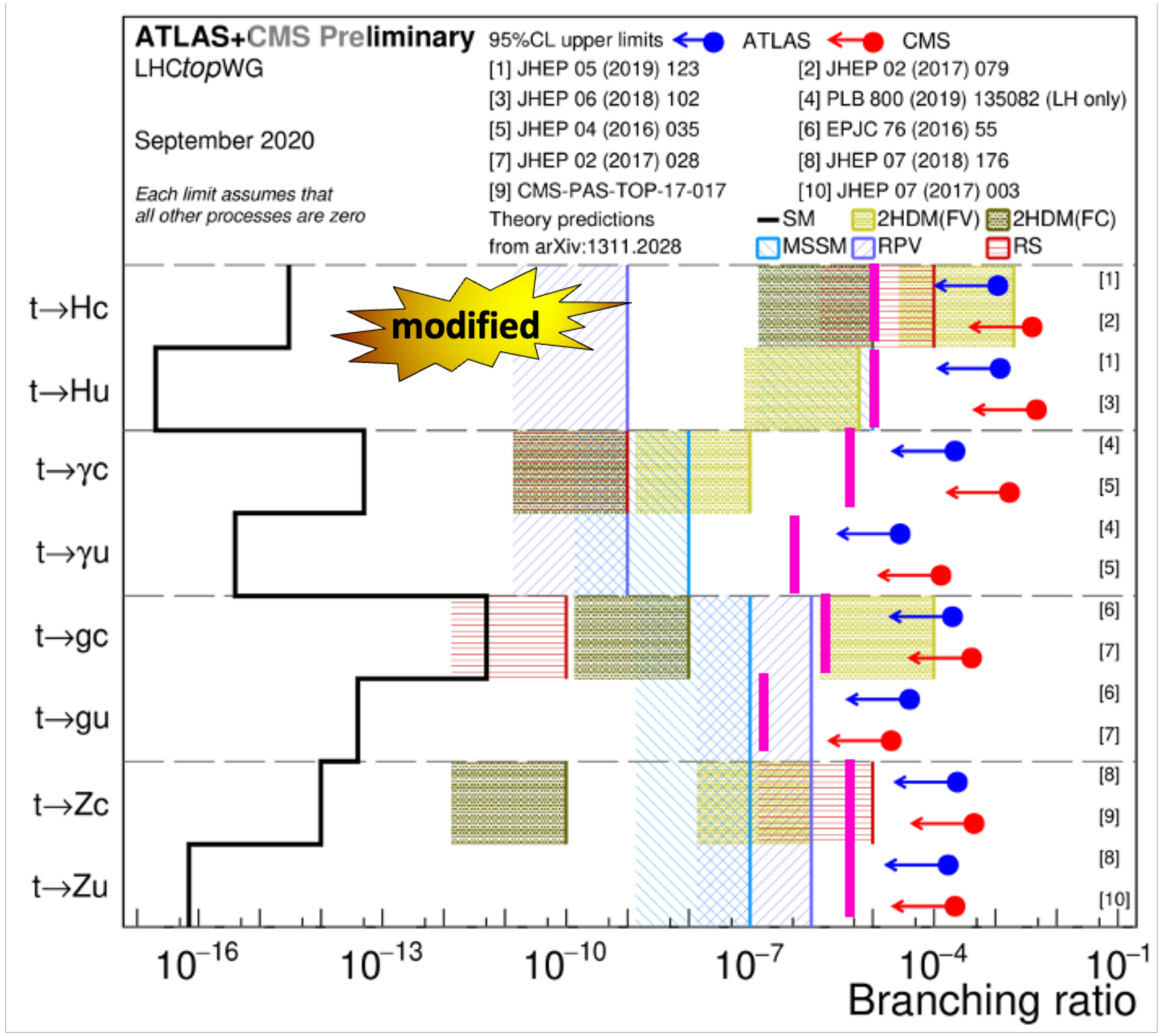


HL-LHC projections

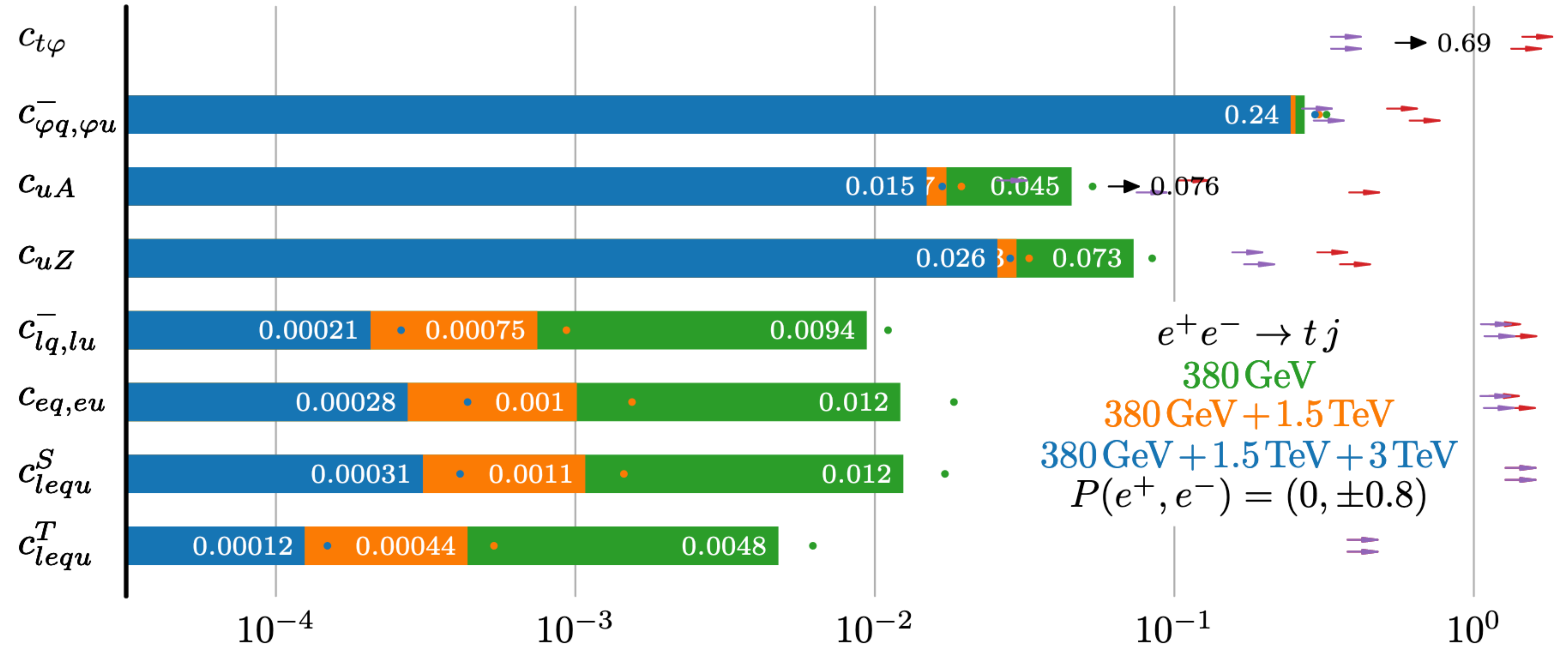
$t \to gu$	$t \to gc$	$t \to qZ$	$t \to \gamma u$	$t \to \gamma c$	$t \to Hq$
3.8×10^{-6}	3.2×10^{-5}	$2.4 - 5.8 \times 10^{-5}$	8.6×10^{-6}	7.4×10^{-5}	10^{-4}

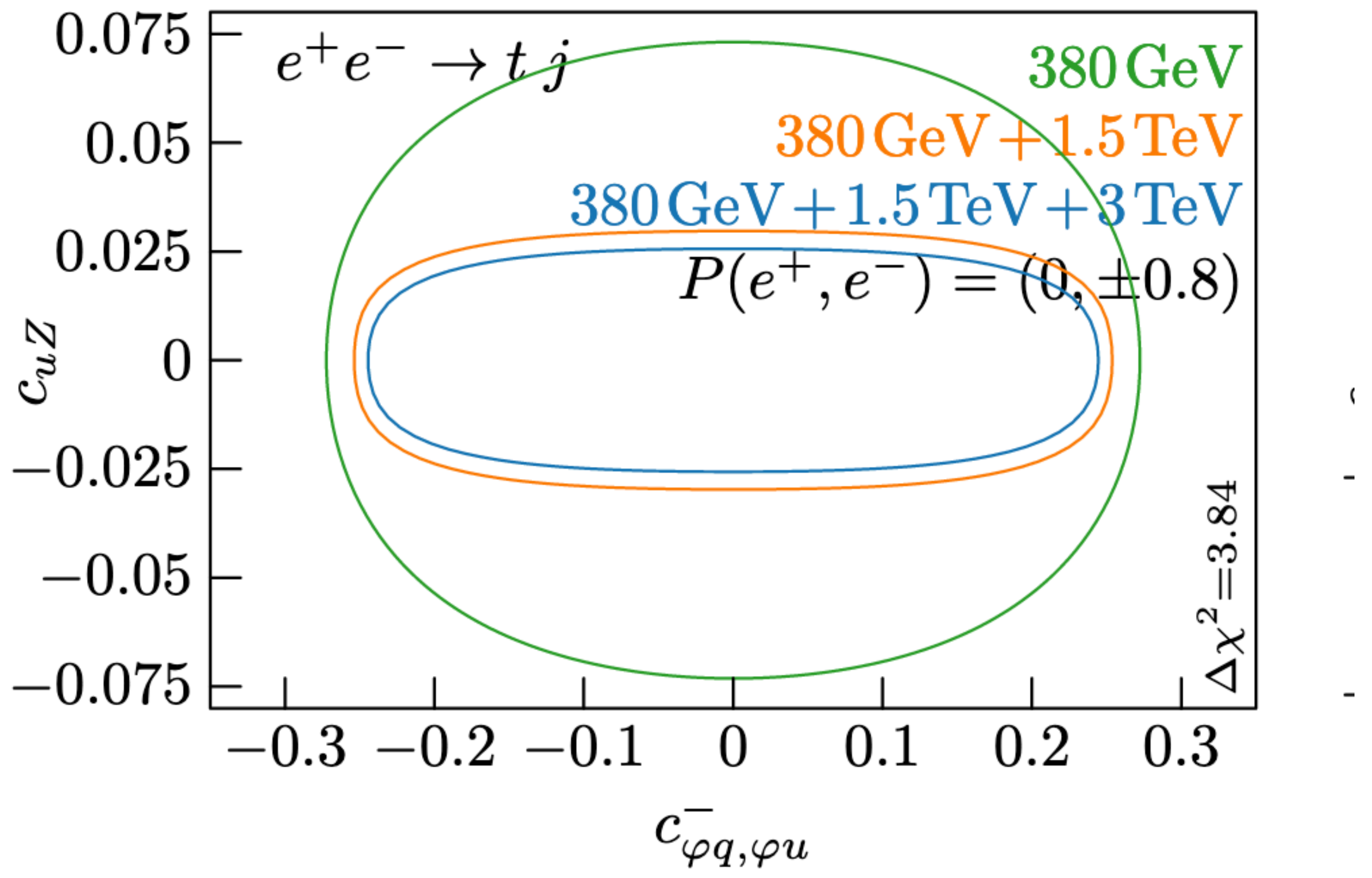
CERN-LPCC-2018-03

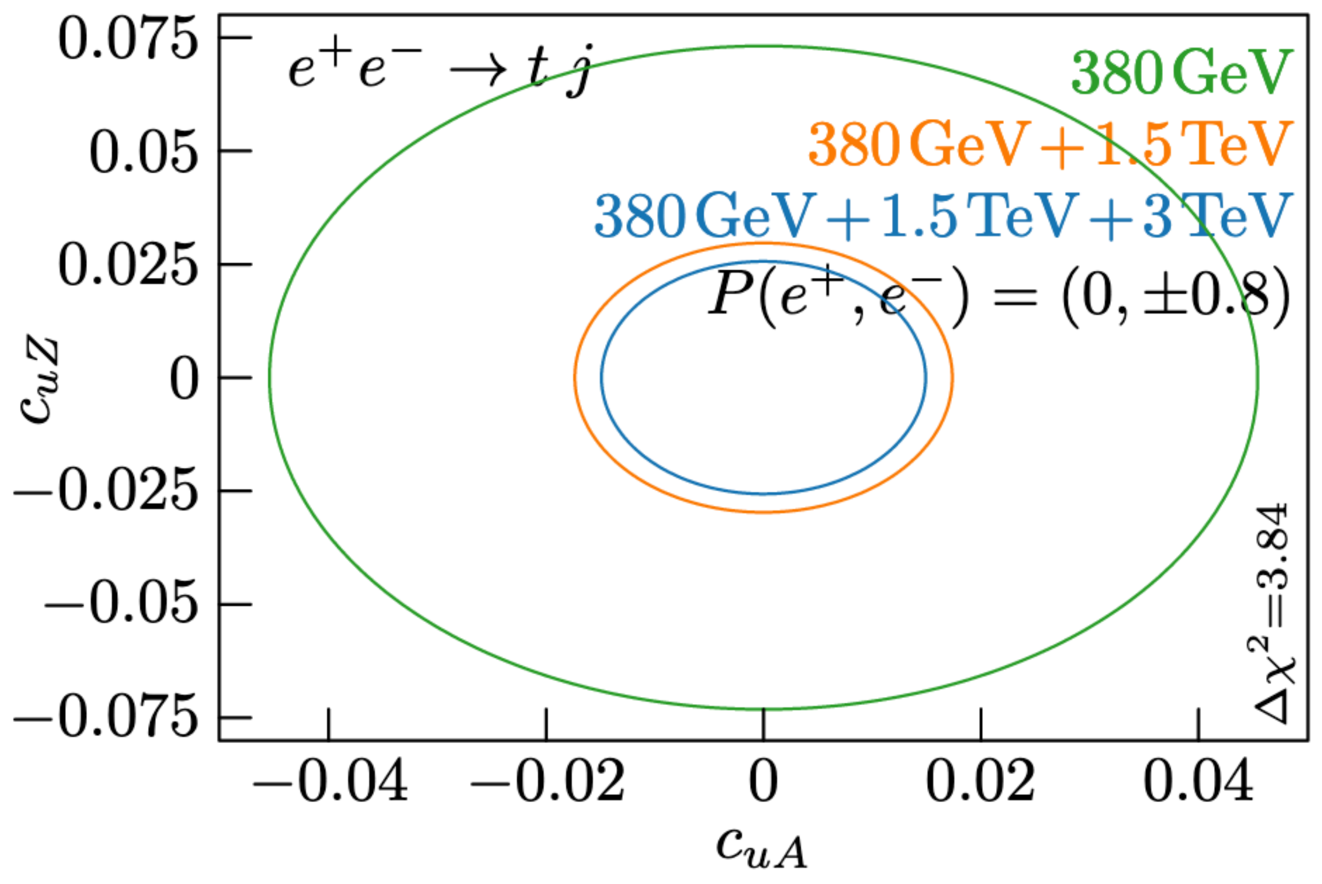
- The magenta line shows the projected bounds on FCNC branching ratios at the HL-LHC.
- Caveat :
  - "We typically tend to do better than projections, and so we could hope to challenge more of the potential SM extensions" : Jung @TOP2019.



FCNC at alternative detectors







ILC report to Snowmass

Summary

- Bright prospects for top quark physics at the HL-LHC and beyond.
  - Ongoing study for spin correlation projection at FCC-hh.
- Projections of stop quark cross-sections and FCNC branching ratios show an order of magnitude reduction in the limits.
- Abundance of statistics and reduction in systematics open the door to study many BSM scenarios, plenty of room for discovery/ exclusions.
- Thank you !

BACKUP

Outline of the talk

- $t\bar{t}$ spin correlations
  - Indirect and direct measurement of spin correlations
  - Projections of f_{SM} at $\sqrt{s} = 14$ TeV and $3ab^{-1}$
  - SUSY interpretation
- FCNC in the top-quark sector
  - Probing different vertices
  - FCNC projections for the HL-LHC, alternative detectors

BSM physics with tops

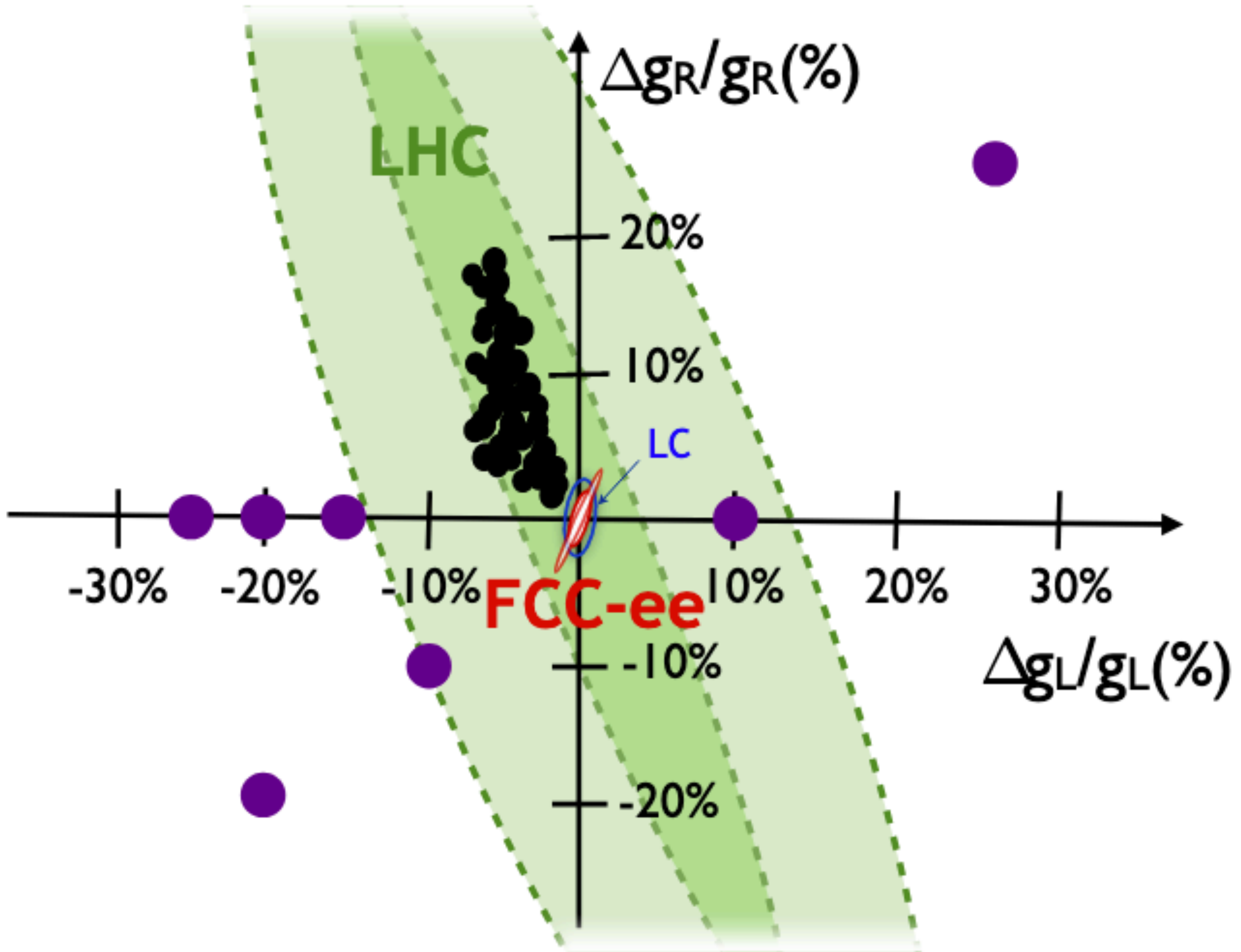


Figure 1-22. *Expected relative precision on the Zt_Lt_L and Zt_Rt_R couplings at the LHC (lighter green), the HL-LHC (darker green), the ILC (blue) and the FCC-ee (orange, red). The black dots indicate the deviations expected for different parameter choices of 4D composite Higgs models, with $f < 2$ TeV (purple dots: examples for typical deviations in various BSM models). From [478].*

BSM physics with tops

1.6.2 Azimuthal angular correlation as a new boosted top jet substructure

Summary of white paper contribution [480]

When a top quark is highly boosted, the W boson from its decay has a substantial linear polarization that results in a $\cos 2\phi$ azimuthal angular correlation among the top decay products [480]. The angle ϕ is shown in the sketch in Figure 1-24. This correlation can be measured for hadronically decayed boosted top quarks, and its magnitude provides a way to measure the longitudinal polarization of a boosted top quark, which is an important probe of new physics that couples to the top-quark sector.

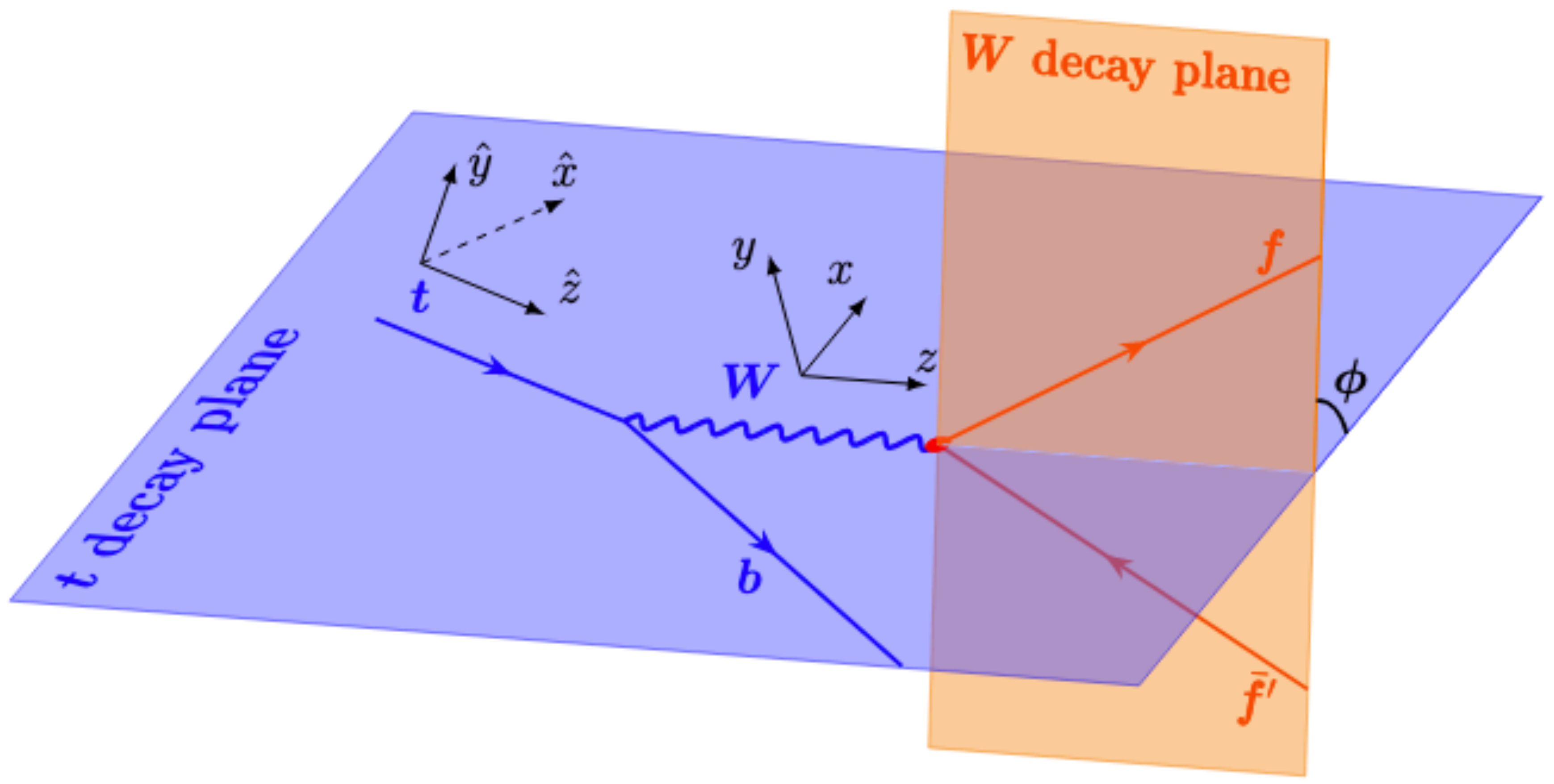
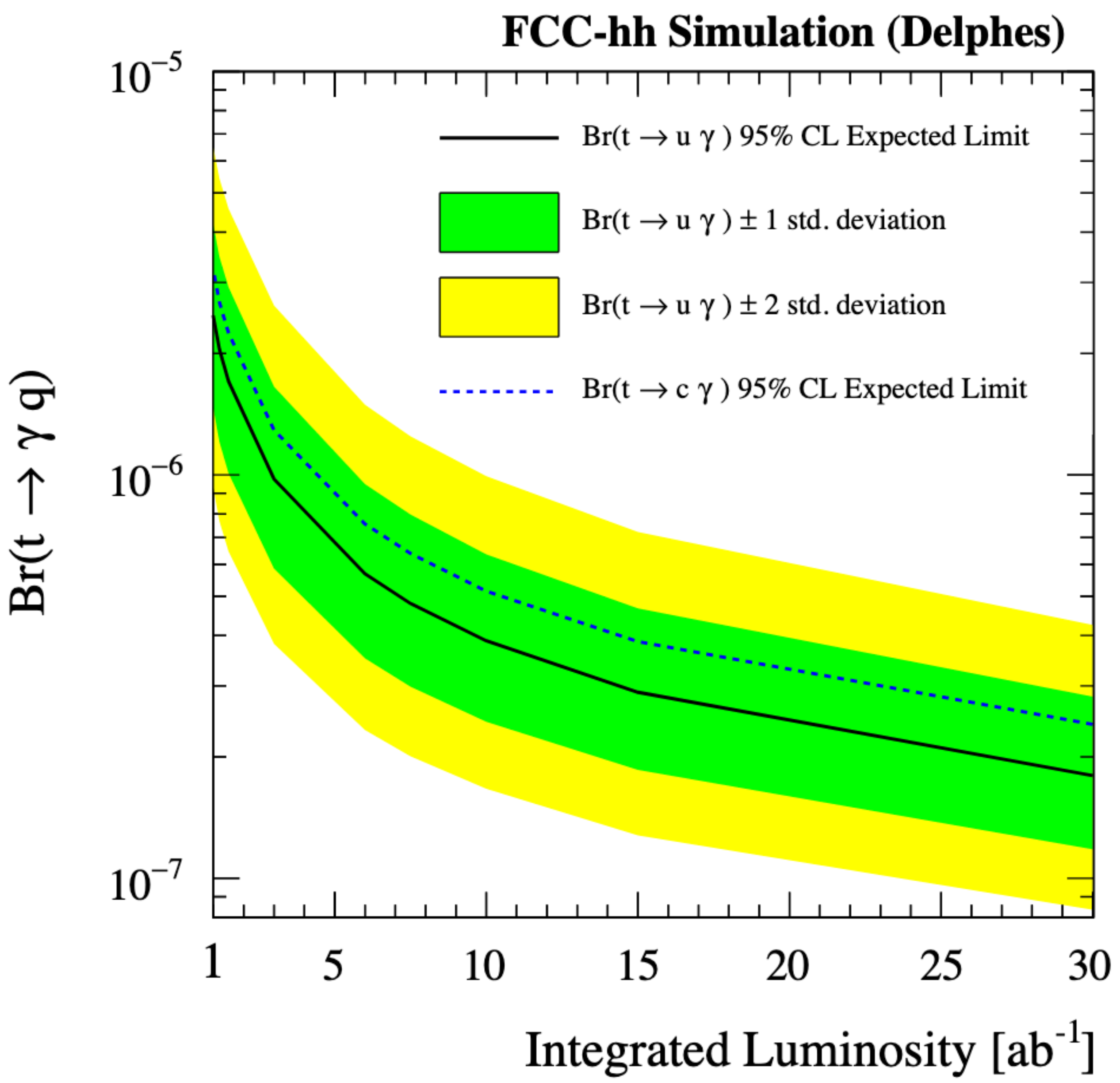
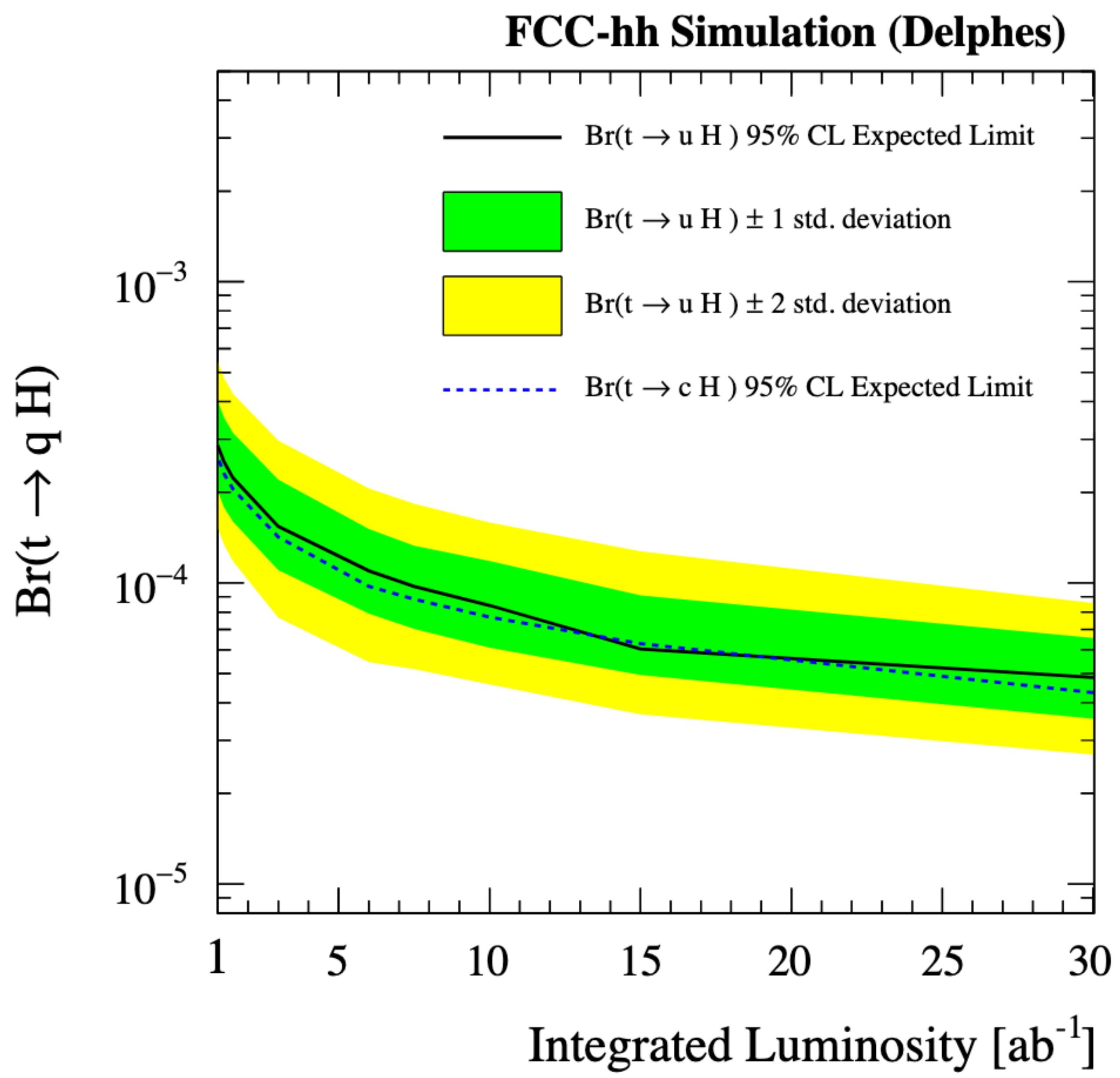


Figure 1-24. *Sketch of the top quark decay products defining the azimuthal angle ϕ. Taken from Ref [480].*

FCNC at alternative detectors

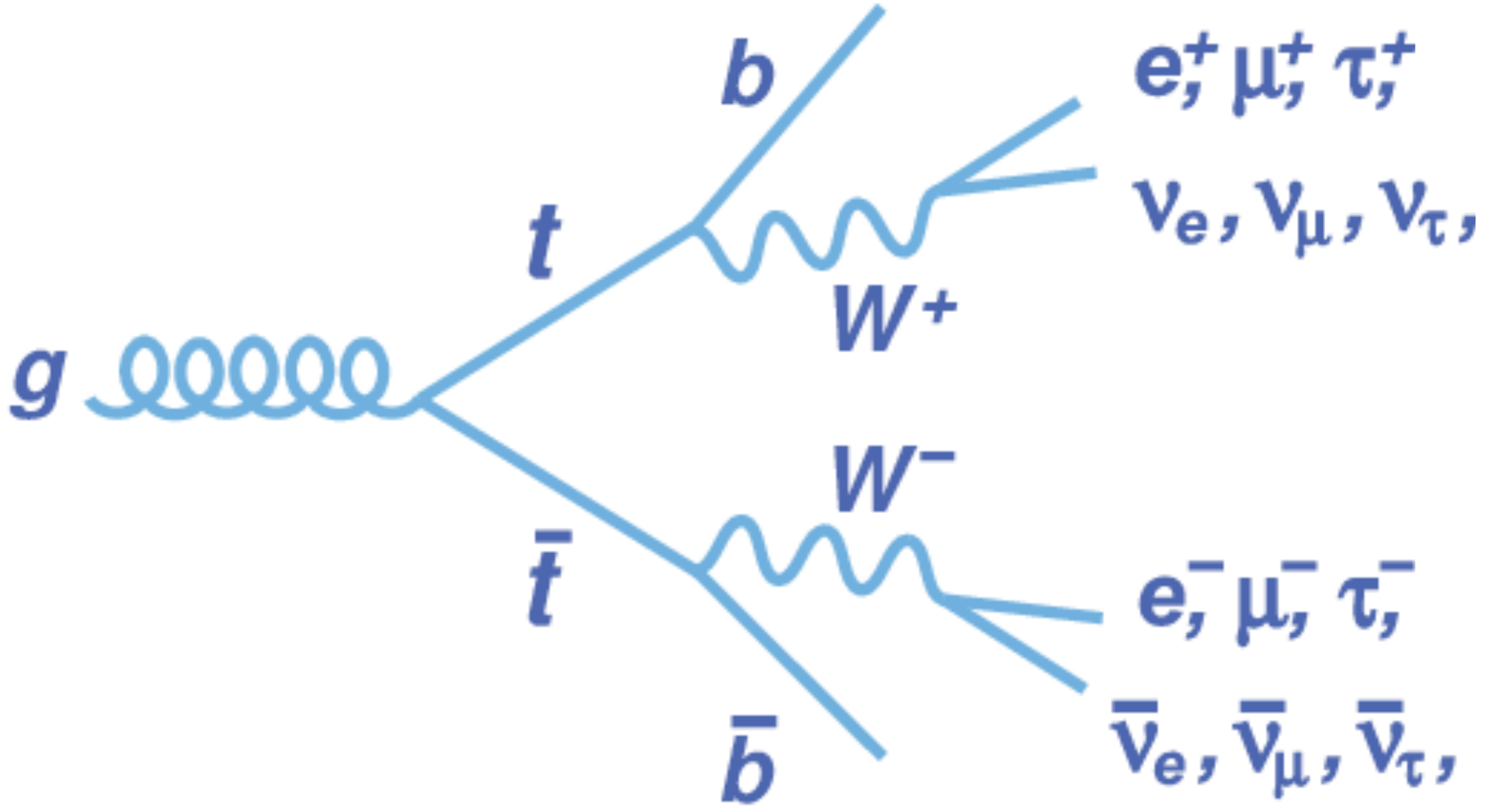




Detector	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$
CMS (19.8 fb^{-1}, 8 TeV)	13×10^{-5}	170×10^{-5}
CMS Phase-2 (300 fb^{-1}, 14 TeV)	2.1×10^{-5}	15×10^{-5}
CMS Phase-2 (3 ab^{-1}, 14 TeV)	0.9×10^{-5}	7.4×10^{-5}
FCC-hh (3 ab^{-1}, 100 TeV)	9.8×10^{-7}	12.9×10^{-7}
FCC-hh (30 ab^{-1}, 100 TeV)	1.8×10^{-7}	2.4×10^{-7}
Detector	$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$
CMS (36.1 fb^{-1}, 13 TeV)	4.7×10^{-3}	4.7×10^{-3}
ATLAS (36.1 fb^{-1}, 13 TeV)	1.9×10^{-3}	1.6×10^{-3}
FCC-hh (3 ab^{-1}, 100 TeV)	8.4×10^{-5}	7.7×10^{-5}
FCC-hh (30 ab^{-1}, 100 TeV)	4.8×10^{-5}	4.3×10^{-5}

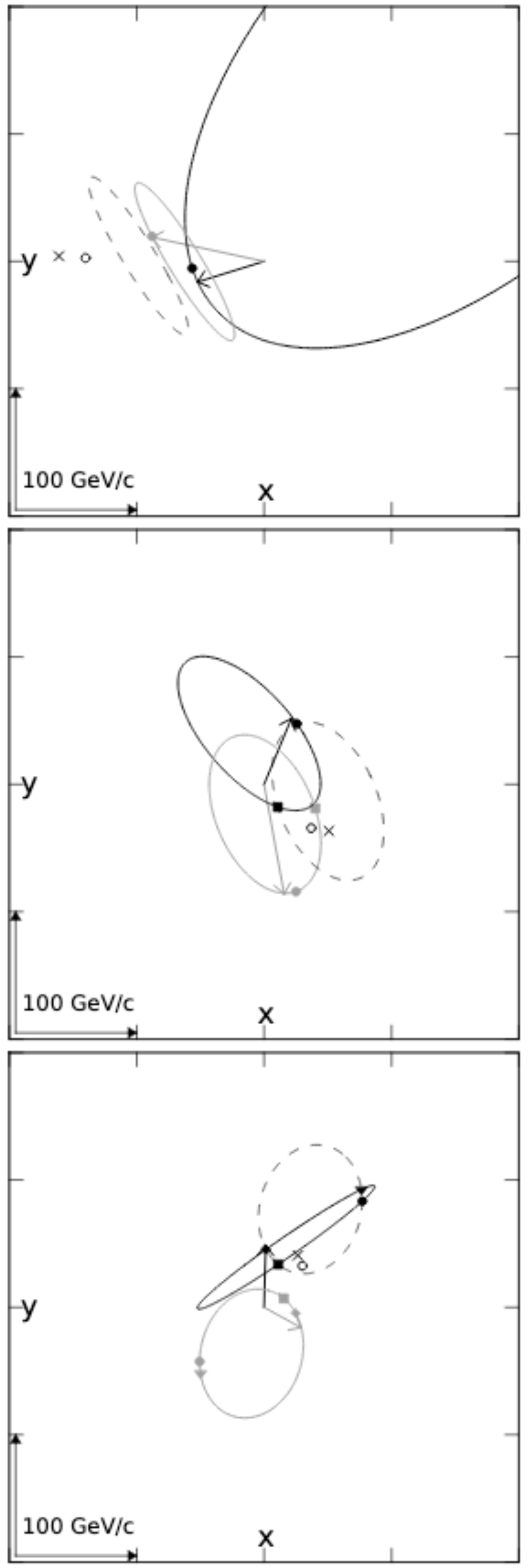
Event selection

- 2 oppositely charged isolated leptons ($e\mu$) [Semi leptonic tau decays also included] :
  - $p_T > 25(20)$ GeV , for leading (trailing) lepton and $|\eta| < 2.4$
  - Charge Hadron Subtracted electron and muon objects
- >= 2 anti-kT jets (R = 0.4) such that :
  - $p_T > 30$ GeV and $|\eta| < 2.4$
  - Jet cleaning : $\Delta R(lepton, jet) > 0.4$
  - >= 1 b-tag
  - PUPPI for Pileup mitigation
- $E_T^{miss} > 40$ GeV



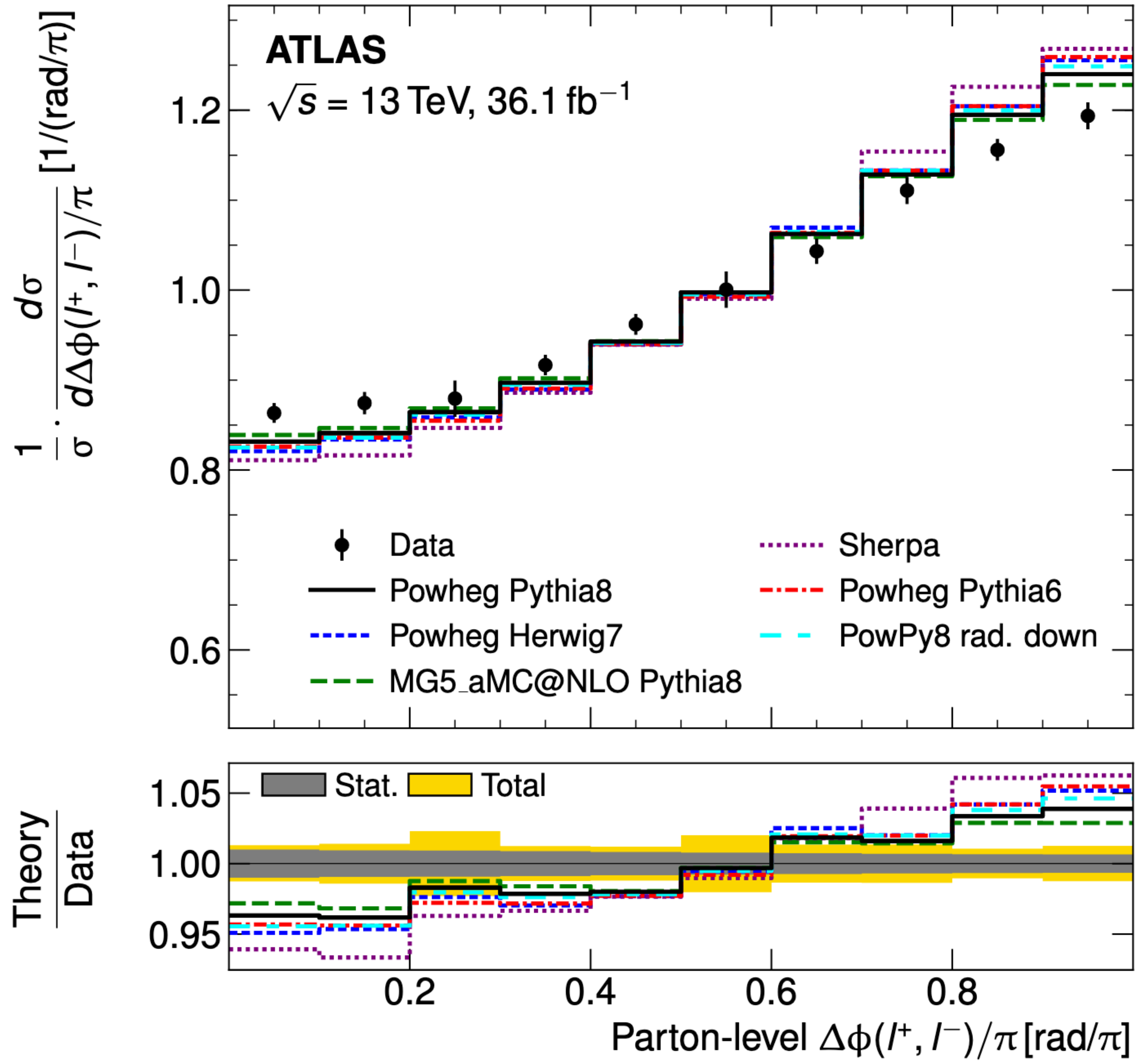
Top quark reconstruction

- In order to add the spin correlation variables the top quark needs to be reconstructed.
- Decays in the dilepton channel are reconstructed using on shell tops and Ws, which gives a set of quadratic equations.
- We use the geometric solver as described in Betchart et al. : arXiv:1305.1878.
- Also used in TOP-19-008.



arXiv:1305.1878

Indirect measurements



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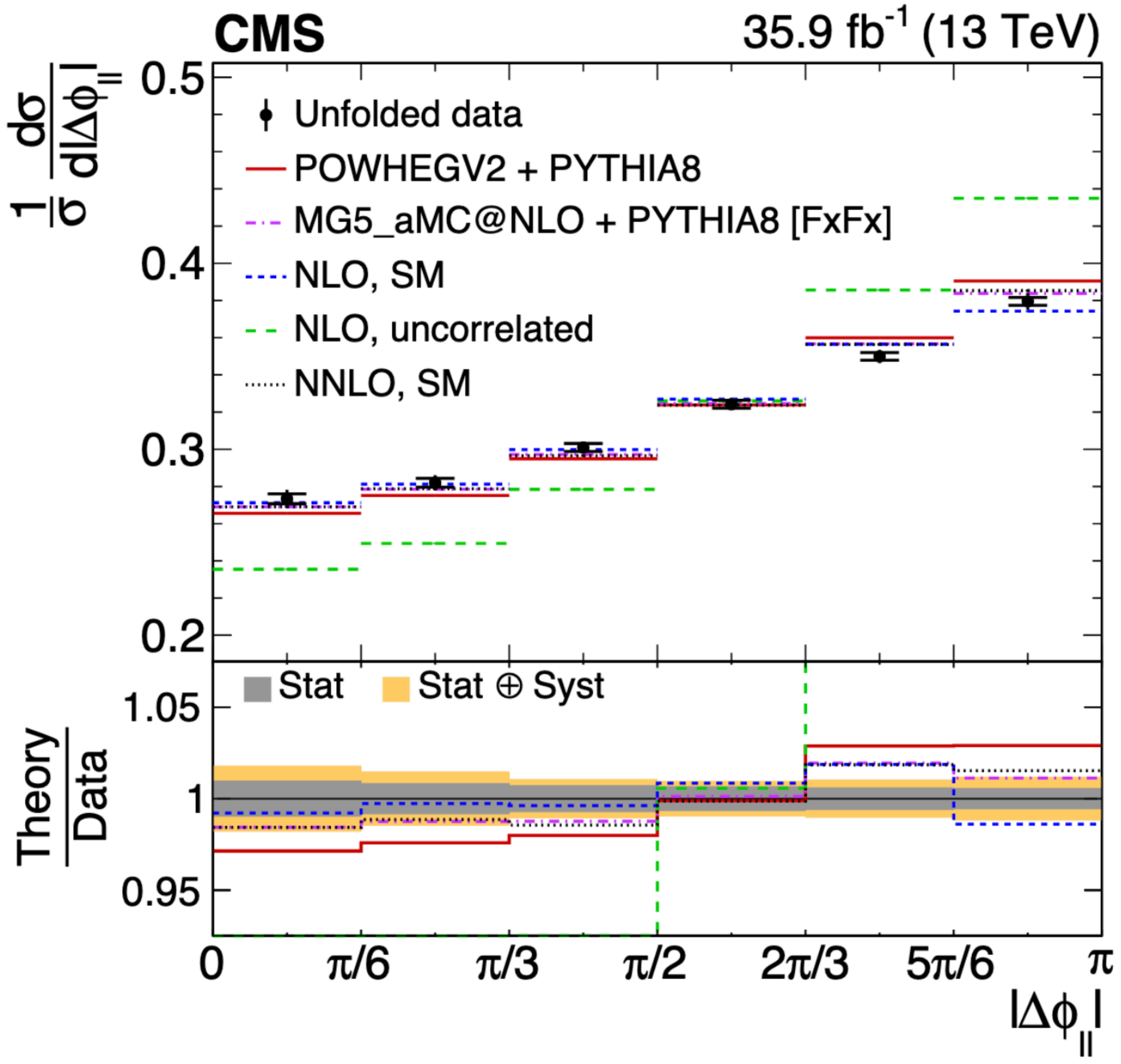
Correct $\Delta\phi$ distribution with acceptance and efficiency (unfold).

With 2016 datasets, both ATLAS and CMS saw discrepancies between data and NLO MC.



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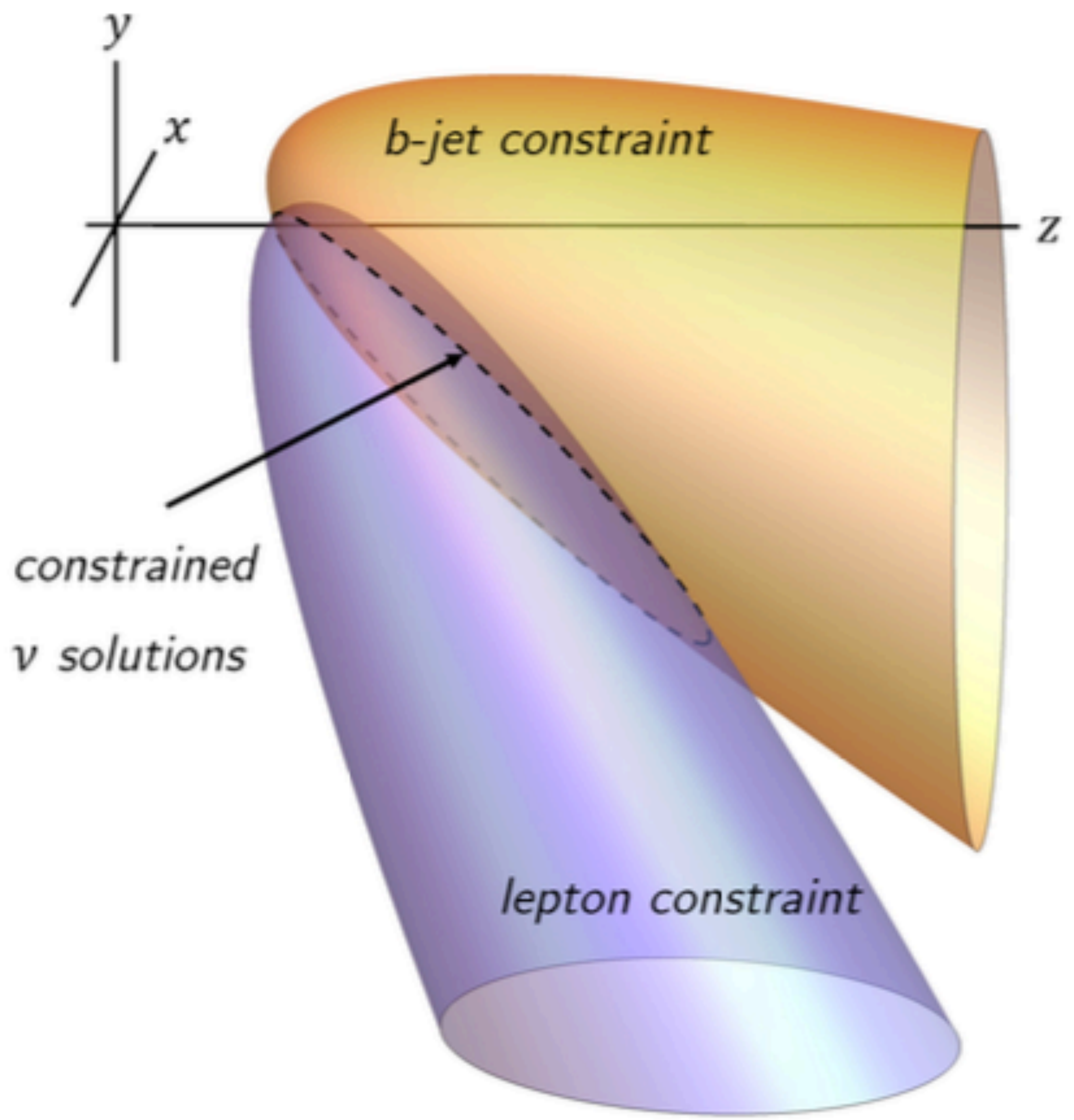
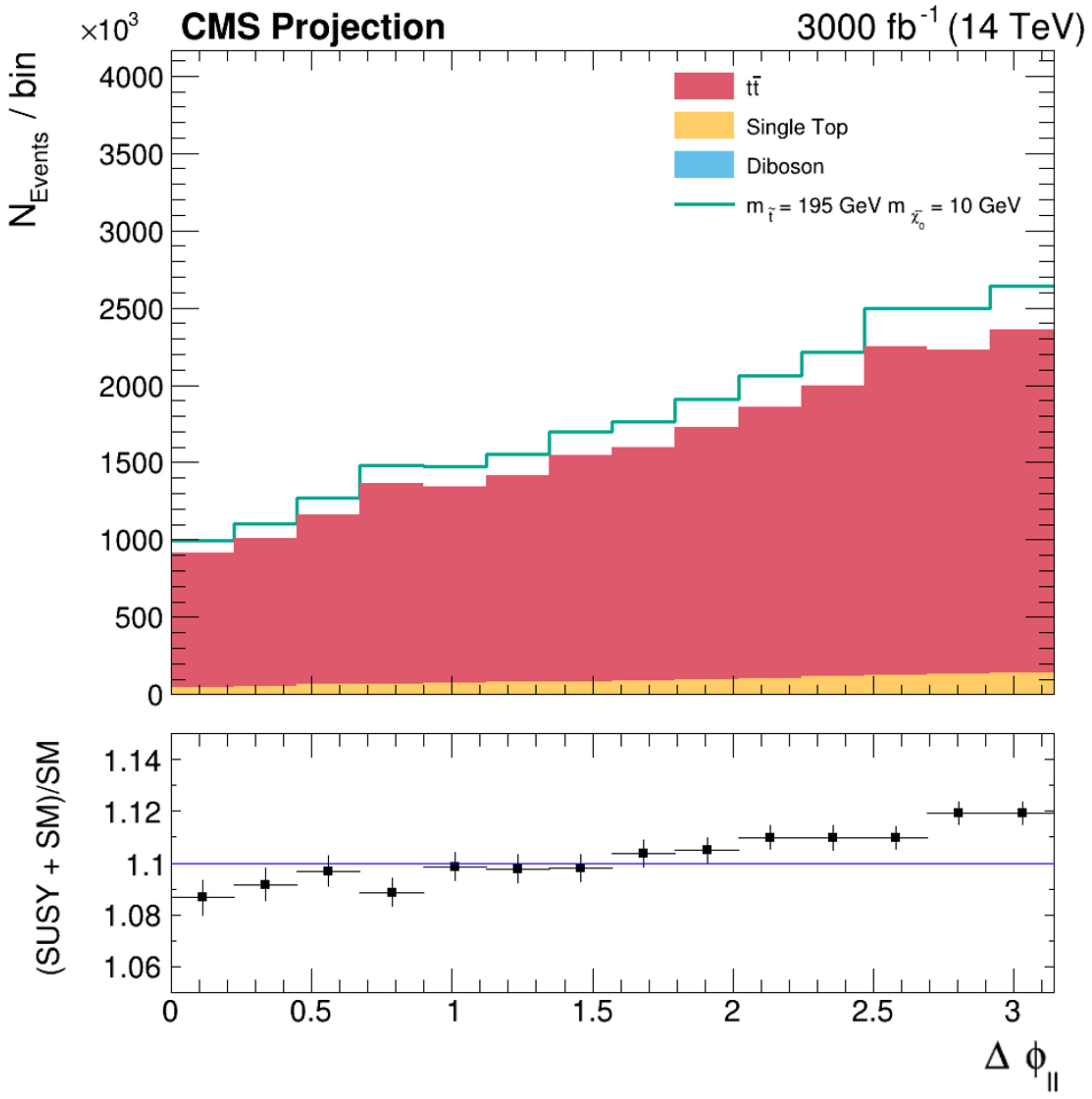
Top quark reconstruction

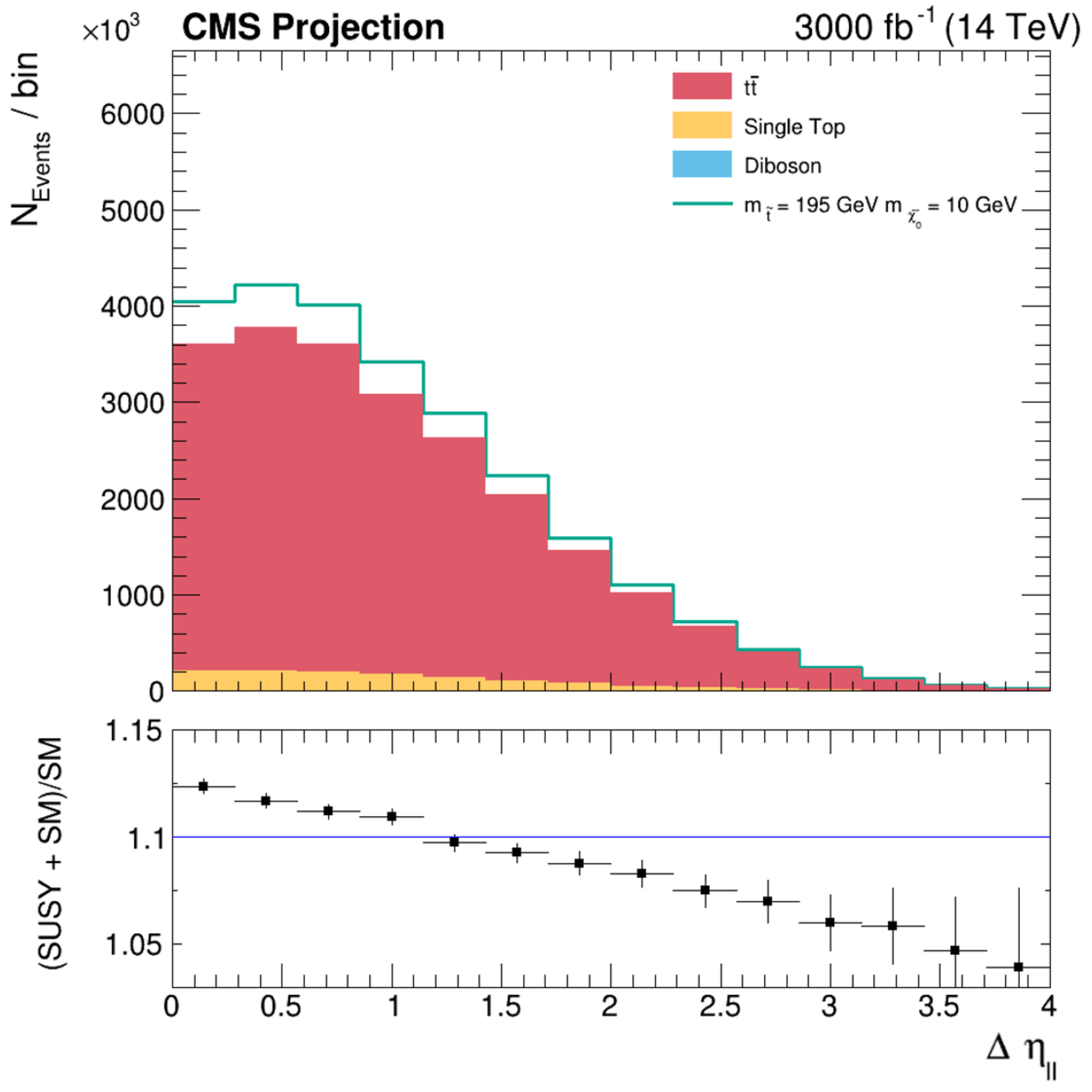
- Using conservation of 4-momentum (with the mass of the top and W boson assumed)
- The measured b and l momenta together help constrain the neutrino momentum to an ellipse.
- For the double neutrino case, an additional MET constraint is imposed.

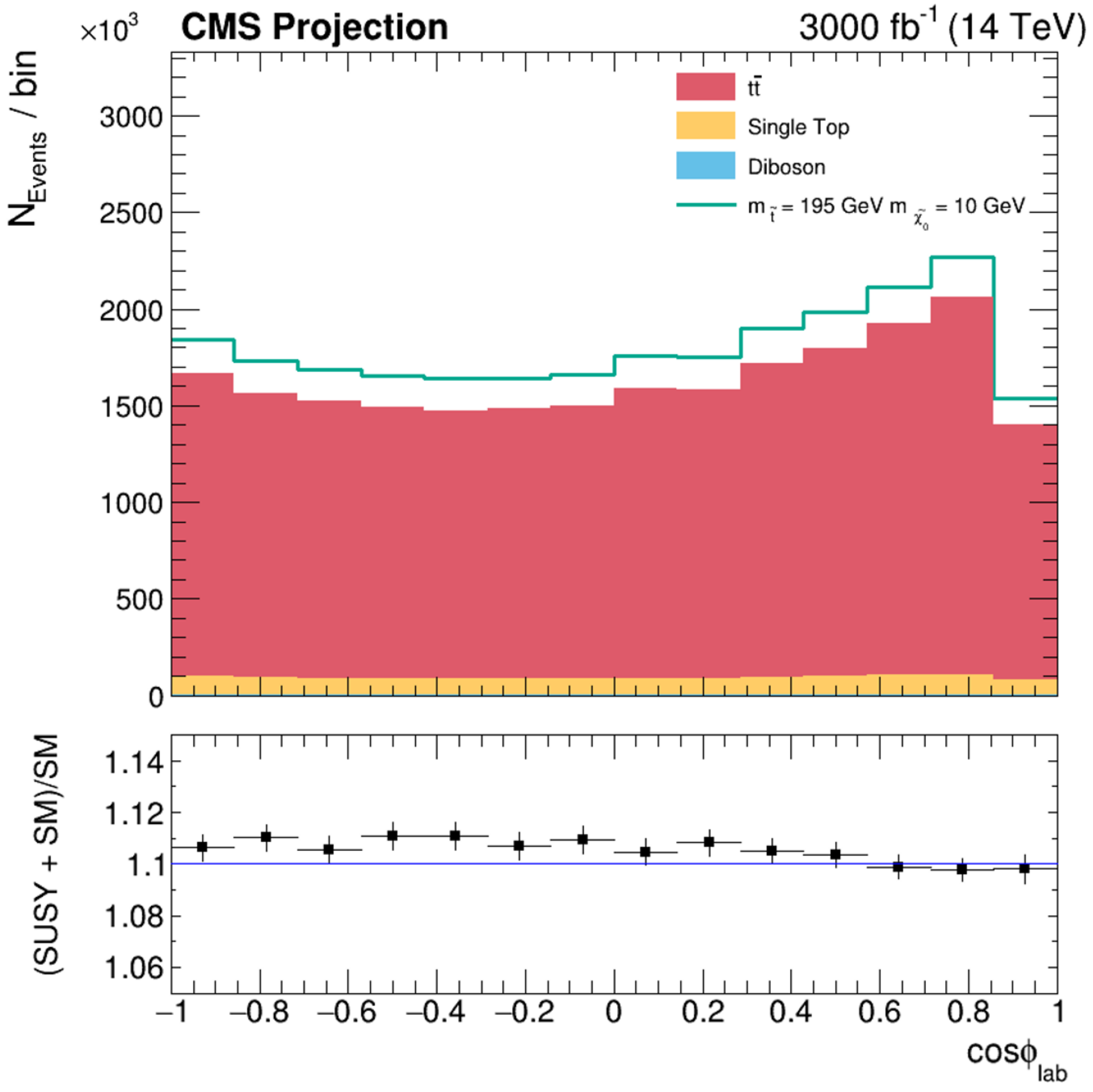


TOP PAG 07/22/20 Evan Ranken

Other spin correlation observables







From PAS

Control plots for other observables used in this analysis

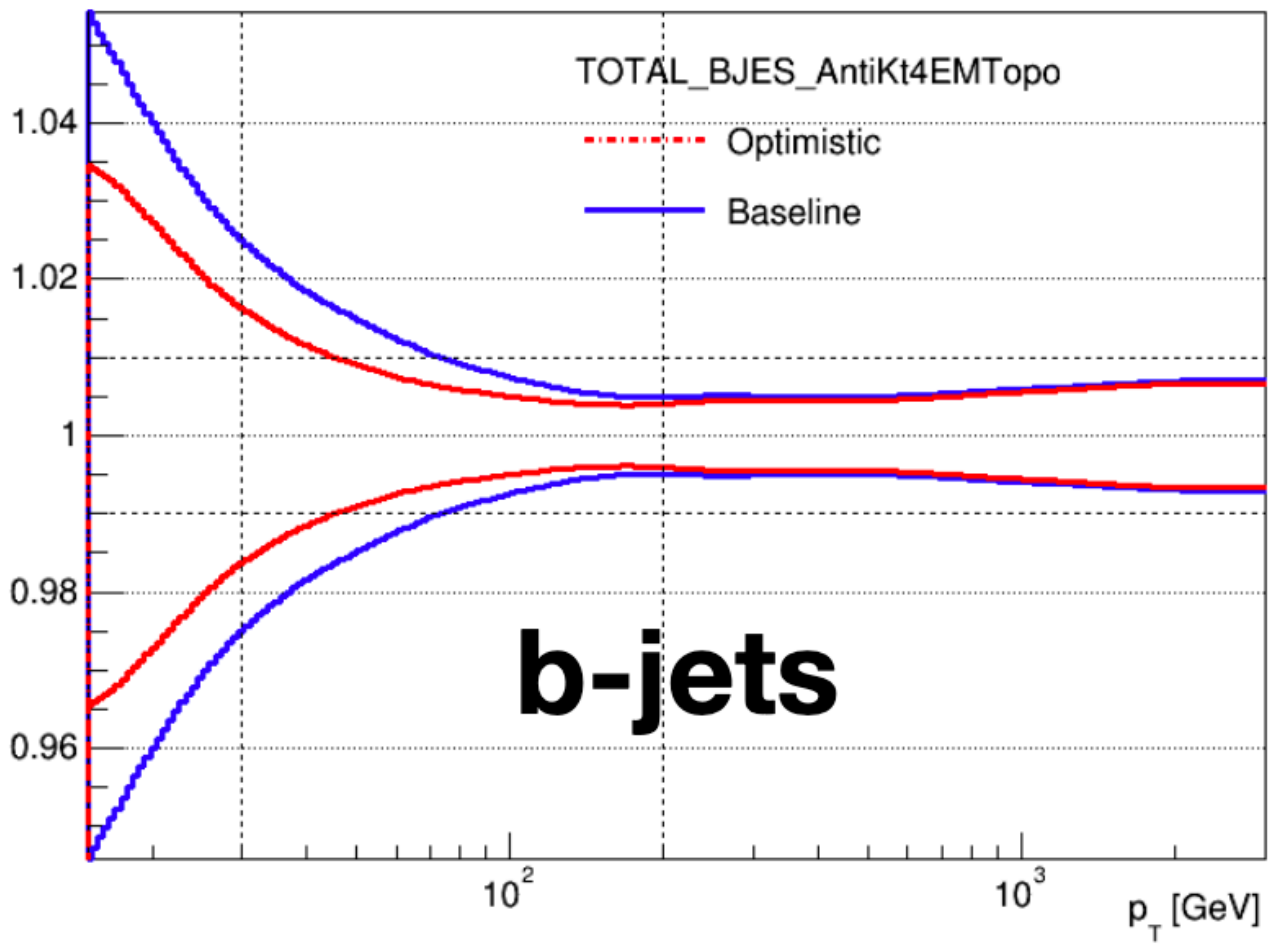
Uncertainties

Uncertainty	Type	Recommendation
Jet Energy Scale	Shape based	HL_YR_JEC.root
Jet Energy Regression	Shape based	3-5 % as a function of eta
PDF	Shape based	Ultimate PDF
Renormalization	Shape based	1/2 of Run 2
Pile Up	Flat	2%
B-Tagging	Flat	1%
Lumi	Flat	1%
Lepton ID	Flat	1% per electron or 0.5% per muon
Xsection	Flat	https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

https://twiki.cern.ch/twiki/bin/viewauth/CMS/YR2018Systematics

Implementing JES and JER

- For JES we use the HL_YR_JEC.root file to look up the percentage errors by pt.
- Different recommendations for b-jets and light-jets.
- JER is modeled as function of η, we see an increase in cumulative uncertainties at $\eta \leq 1$.
- We assume a 3% uncertainty till $\eta \leq 1$, and 5 % for $\eta > 1$ as suggested in the YR systematics document.



https://twiki.cern.ch/twiki/bin/viewauth/CMS/YR2018Systematics

Implementing PDF, scale

- Uncertainties arising due to PDF are assessed by reweighing the samples according to the 100 replicas in the NNPDF3.0 PDF sets.

- Uncertainties arising to renormalization (μ_R) and factorization (μ_F) scales are computed by varying μ_R and μ_F between 0.5 and 2 for a total of 10 variations.

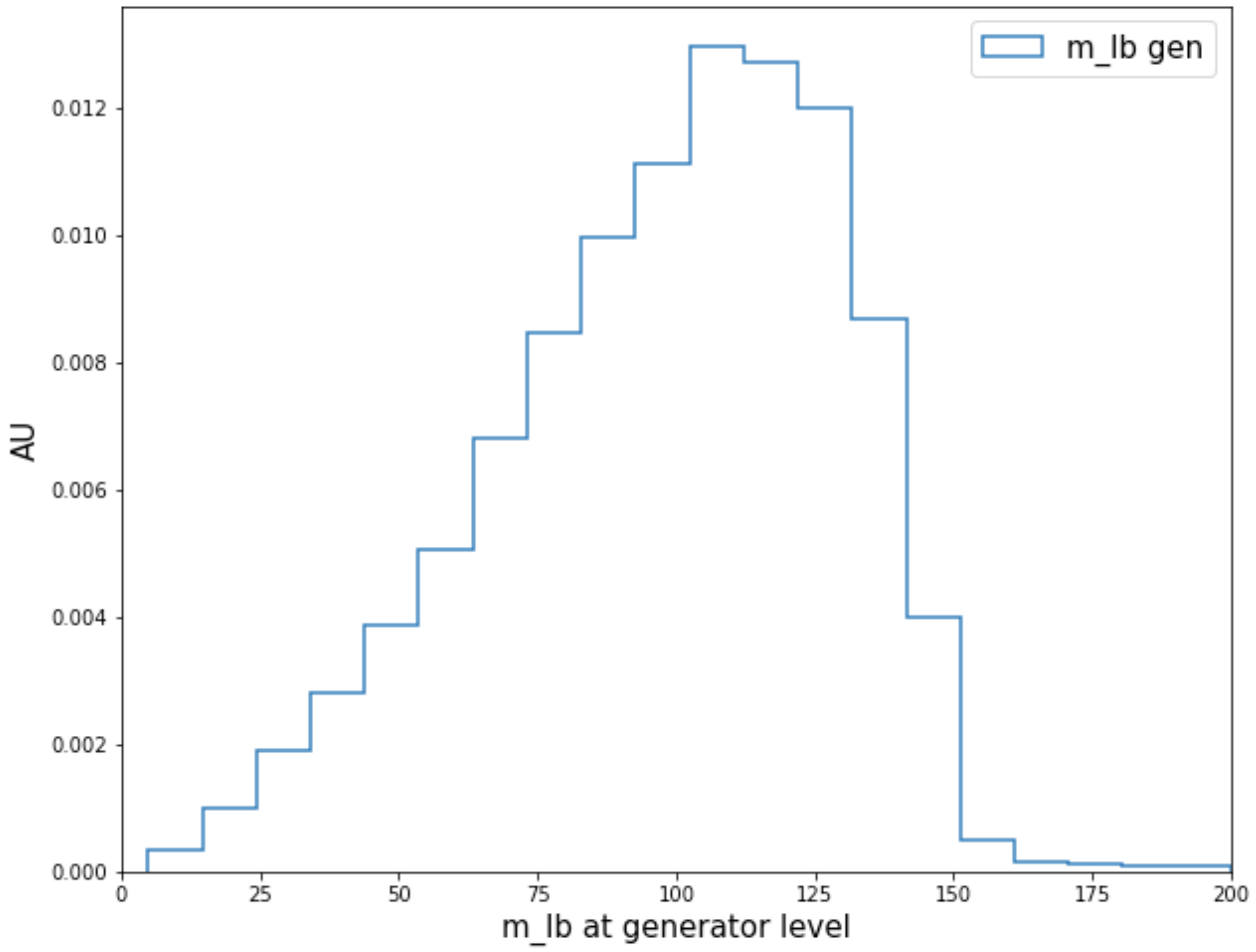
- Final scale uncertainty is reduced by a factor 1/2 as suggested in the YR systematics.

PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)
up-strange luminosity	0.73 (0.67)	0.38 (0.27)	0.42 (0.38)

Table of reduction factors
https://twiki.cern.ch/twiki/bin/viewauth/CMS/YR2018Systematics

Top quark reconstruction : Smearing

- The output of the ellipse solver serves as a good starting point for solution smearing.
- Each solution is smeared 100 times using the jet and lepton energy resolutions.
- The generator level m_lb distribution is then used to assign weights to determine the quality of the solutions.



m_lb distribution for correctly paired lepton and b-quark at generator level

Top quark reconstruction : Smearing

- For each event there are : 100 × N_jets × 2/4 solutions

Choose neutrinos that yield the lowest mttbar

To decide the 2 b-jet candidates we use the number of b-tags and average sum of m_lb weights

From the smearing,
To resolve this, we do a weighted average over solutions

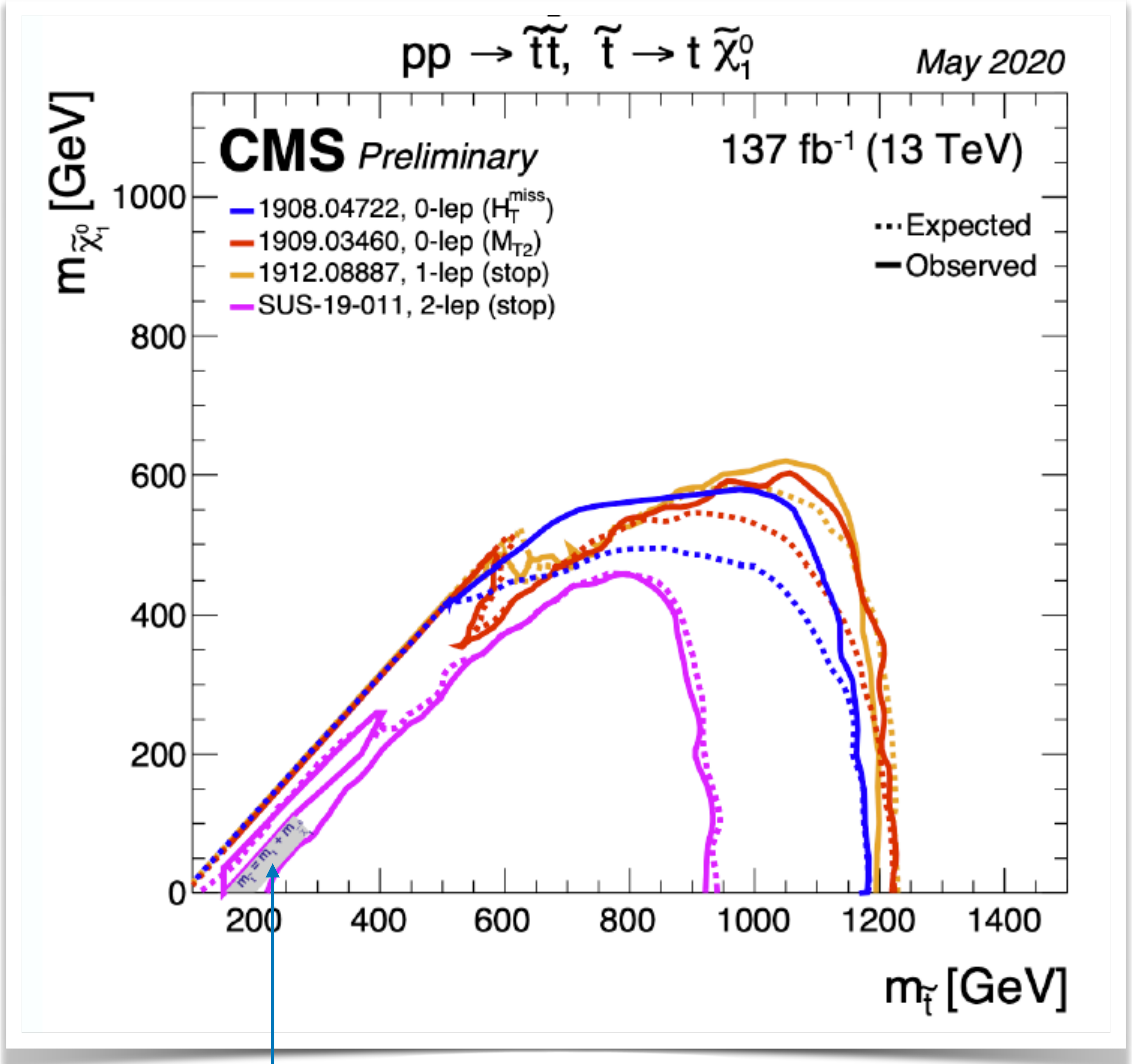
$$< \vec{p}_t >= \frac{\Sigma_{i=1}^{100} w_i \vec{p}_{t,i}}{\Sigma_{i=1}^{100} w_i}.$$

SUSY top quark partners

- For the purposes of our dataset the stealth phase space includes 30 mass points such that :

- $M_{stop} \leq 242.5$ GeV, and
  $M_{stop} - M_{\chi_1^0} = M_{top}$
  (here M_{top} can be 167.5, 175 or 182.5 GeV)

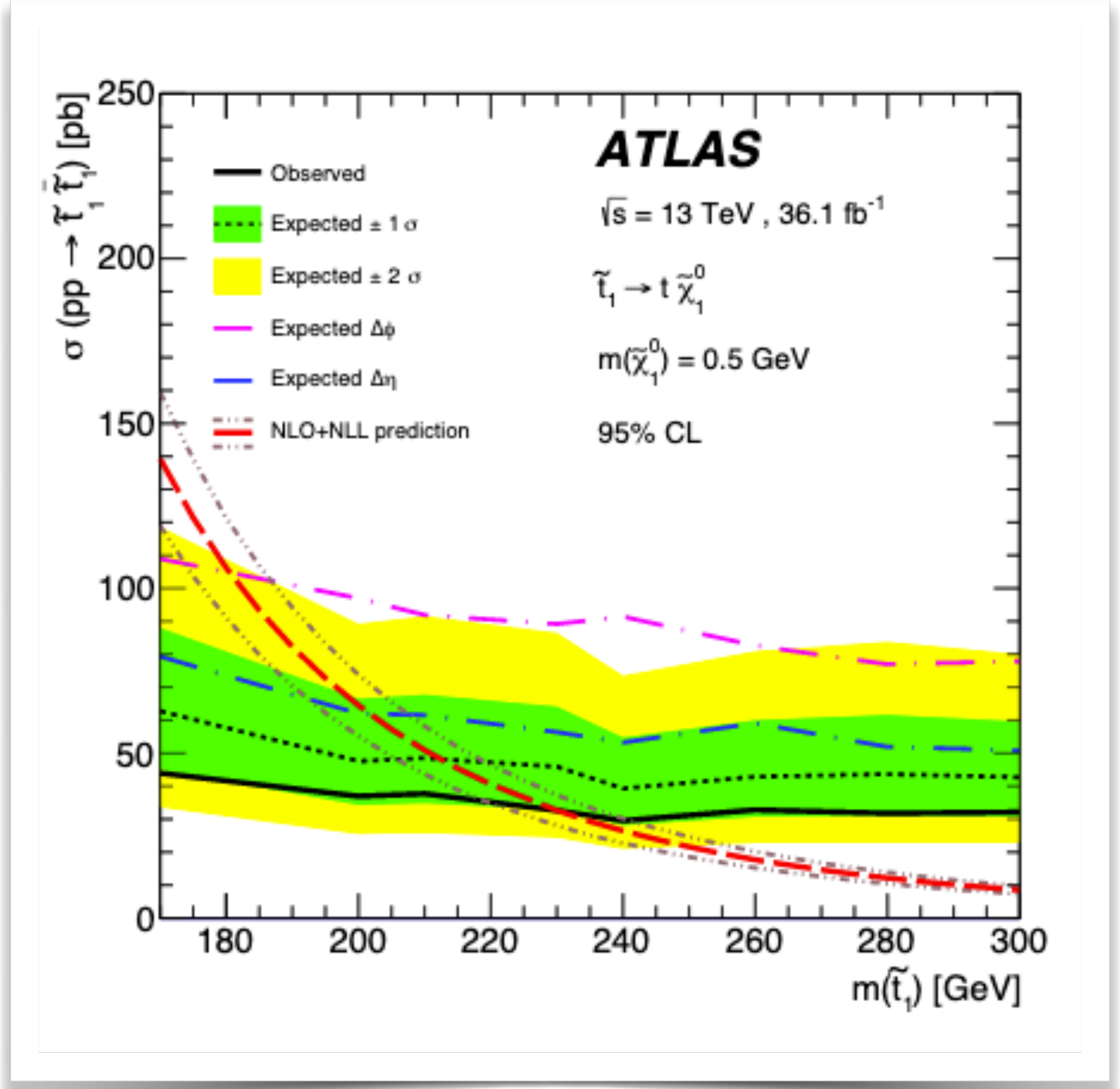
- The acceptance and efficiency change significantly in this region, making exclusion by direct searches harder in this region.



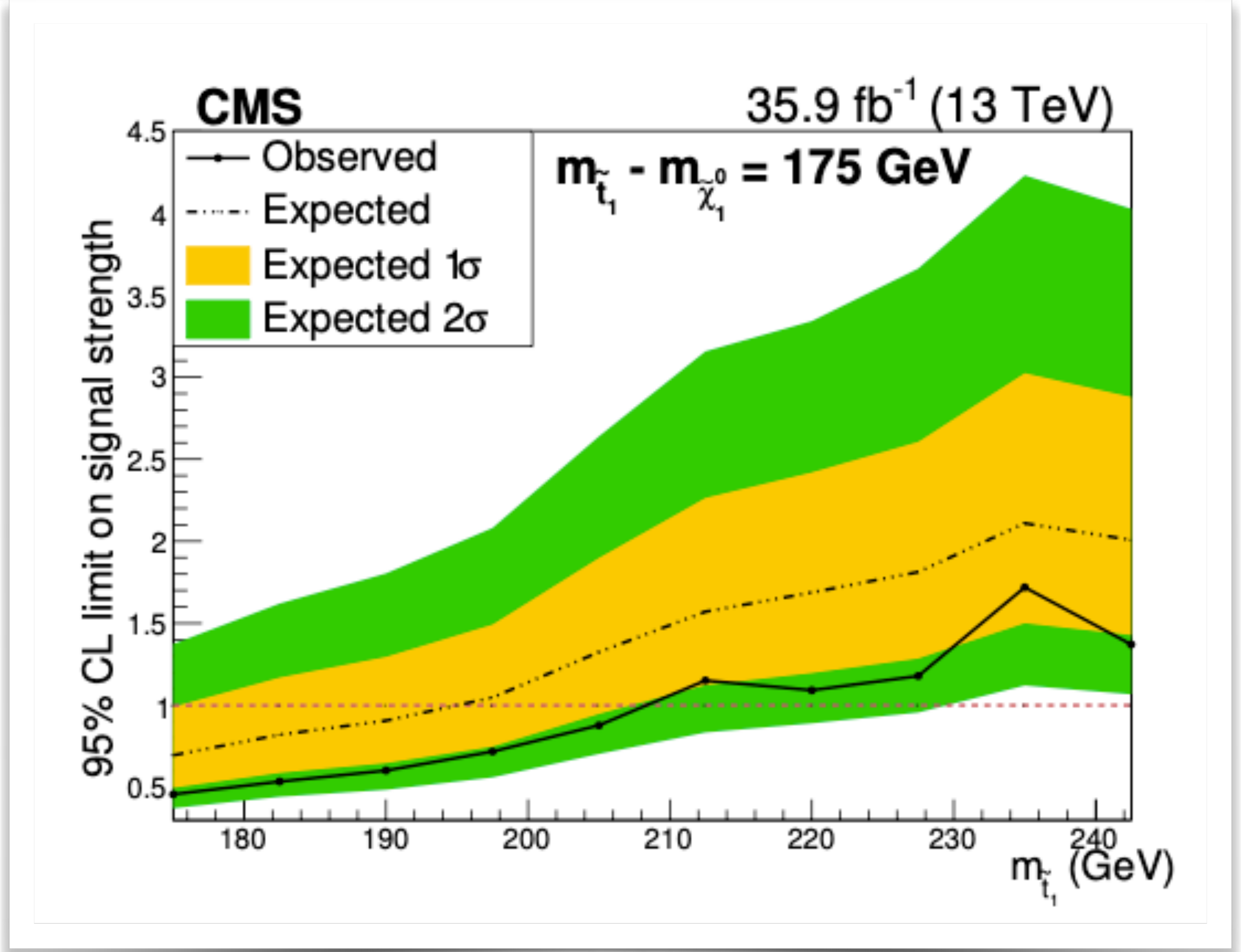
Top Corridor

SUSY top quark partners

- Hence the need for indirect searches.
- Exclusions can be accomplished via precision measurements of top quark properties, spin correlations in this case.
- Currently results in this region using spin correlations are from ATLAS.
- CMS also has results in the dileptonic channel, but using a direct search.



CERN-EP-2019-034. ATLAS



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SUSY top quark partners