On the way to future circular colliders

New physics opportunities with top quarks and Higgs bosons

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Outline

Future circular collider studies

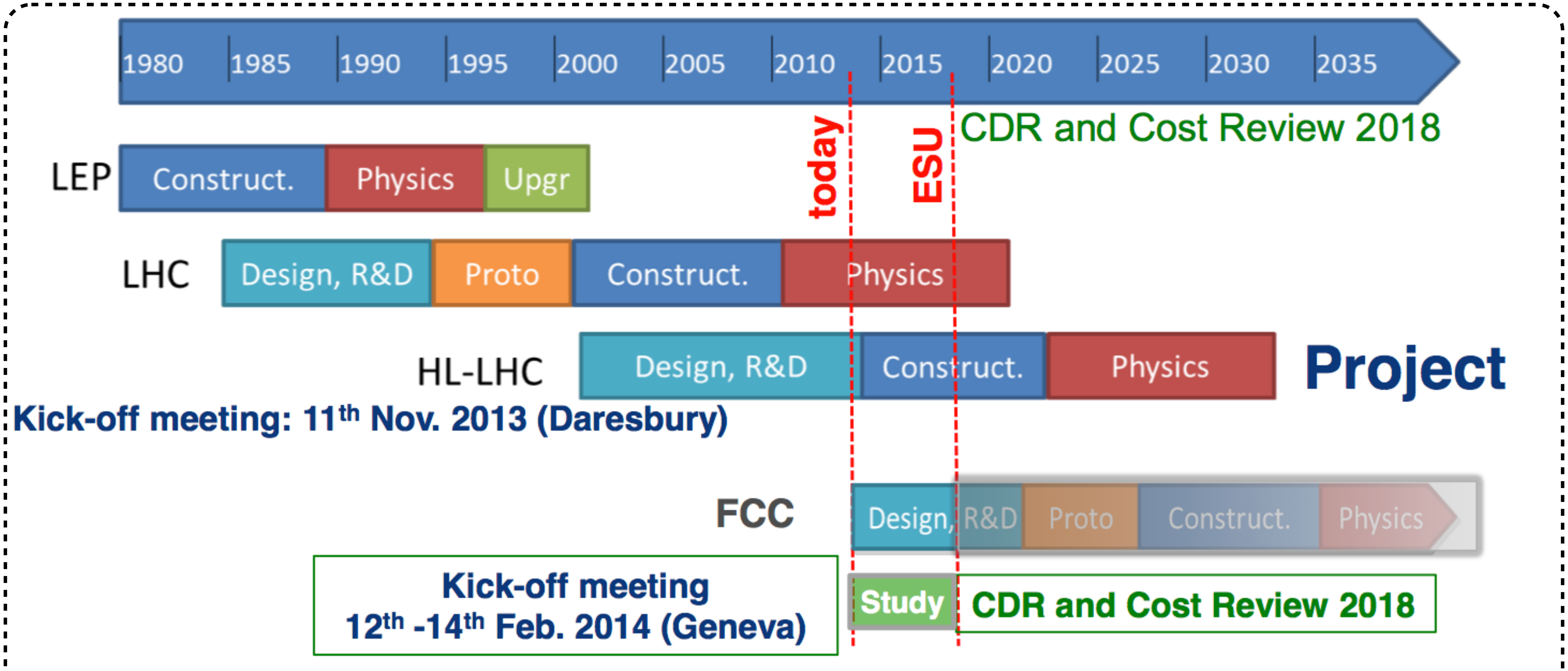
✦ Pushing the energy frontier to higher and higher values

- ✤ High priority within the European Strategy for Particle Physics
  - ★ Top priority is the exploitation of the full potential of the LHC
  - ★ LHC: 3000 fb^{-1} of data by 2035 (HL-LHC project; 3-4 fb^{-1}/day; 300 fb^{-1}/year)
  - ★ CERN should undertake design studies for post-LHC accelerator projects (including high field magnets, high-gradient accelerating structures, *etc.*)
- ✤ Circular high energy colliders are suitable machines (pp, ee, ep, heavy ions, *etc.*)

✦ The LHC will run for about 25 years (2009-2035; 3000 fb^{-1})

- ✤ We have time for physics case studies, R&D, *etc.*
  - ★ The design of the LHC started in 1983
  - ★ More than 25 years were needed
  - ★ Starting now means being ready in 2035/2040
- ✤ We need to be ready with plans according to future LHC results
- ✤ Those plans must be ready by 2018 (update of the European Strategy)

Future circular collider potential timeline

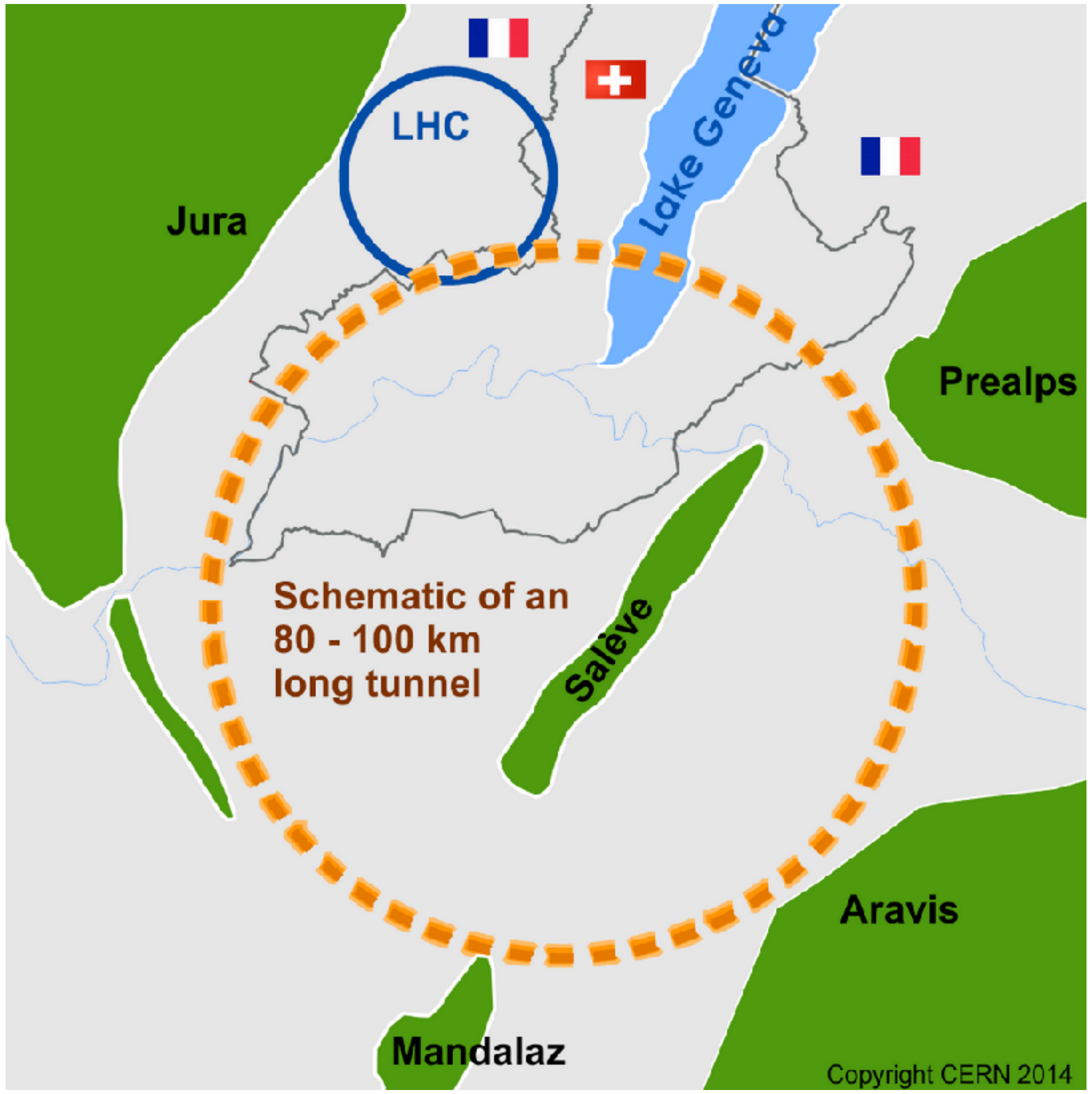


[from M. Benedikt]

Intermediate and long term goals

✦ A future circular collider at CERN

- A new 80/100 km tunnel in the Geneva area
- Long term: a pp machine
  - ★ With 50 TeV beams ($\sqrt{S}$ = 100 TeV)
  - ★ Achievable with 16T/20 T magnets
- Potential intermediate step: an e^+e^- collider
  - ★ Precision measurements
  - ★ Study of Z, W, Higgs and top physics (4 operation points: tera-Z, oku-W, mega-t, mega-H)
  - ★ Possible upgrade at 500 GeV
- Other options:
  - ★ ep collisions
  - ★ Heavy ions
- China has a similar project



Challenges for the proton-proton machine

- ✦ Some of the technical challenges (for the pp machine)
  - ✤ Energy stored in the beams: 20 times more than LHC (8 GJ/beam)
    - ★ Shielding & collimation (*cf.* beam losses)
  - ✤ High synchrotron radiation load on the beam pipe: 25 times more than LHC
    - ★ Absorption, cooling
  - ✤ Feasibilities of magnet technology
    - ★ 20T magnet challenging but not impossible: high-temperature supra-conductors
    - ★ 16T magnet models to be ready by this year
    - ★ Quench protection

Physics motivations (I)

✦ Two interesting physics cases for a 100 TeV hadron collider

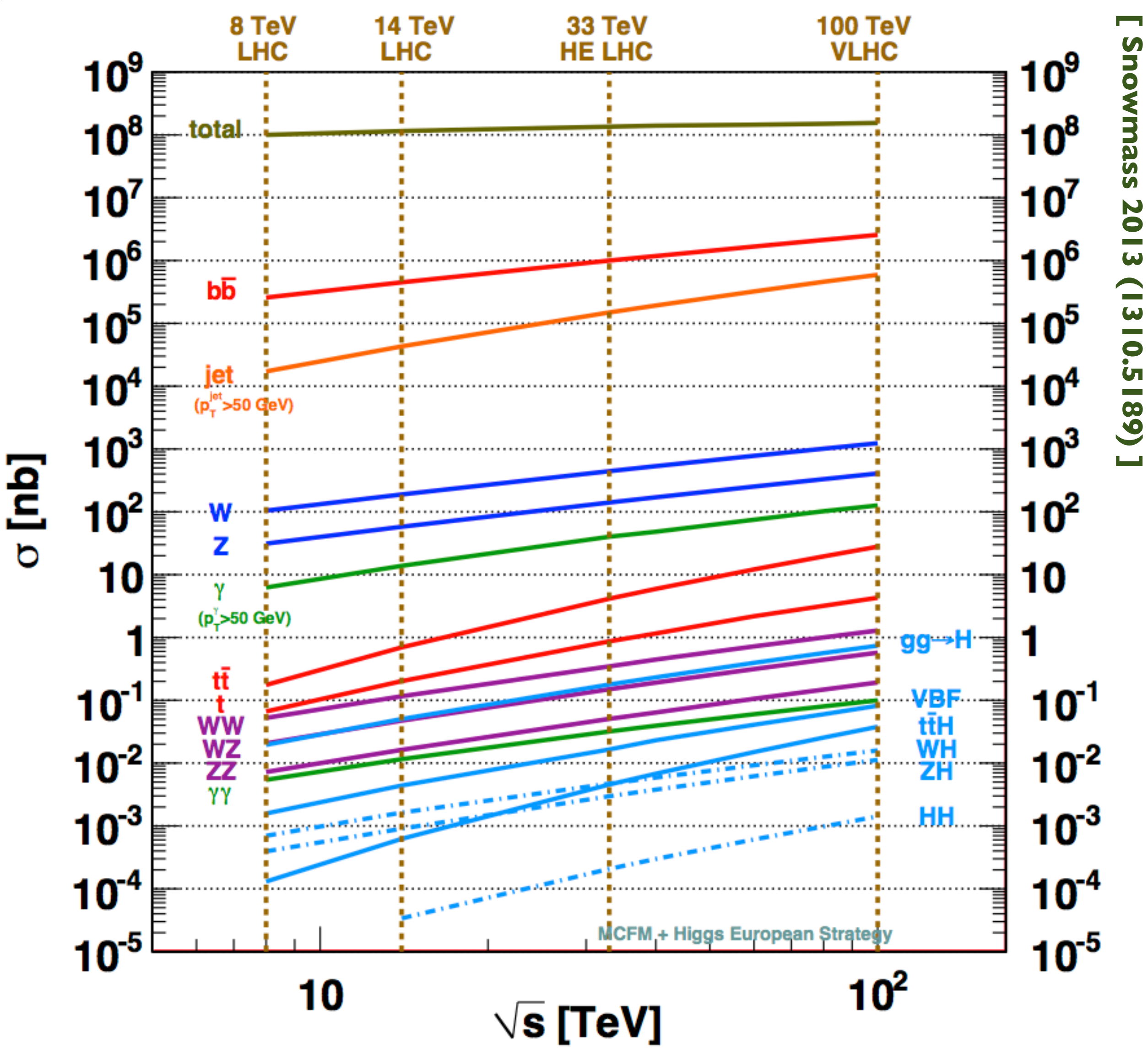
- ✤ New physics is discovered at the LHC and is heavy (not seen at 8 TeV)
  - ★ Large luminosity and energy ⇔ detailed study of its properties
  - ★ Complete the spectrum
- ✤ Indications of a new physics scale of 10-50 TeV are found at the LHC
  - ★ Strong case for a 100 TeV collider (direct probe of the new physics scale)

✦ However, if no hint for new physics is found

- ✤ Higgs-related questions need higher-energy machines
  - ★ Longitudinal vector boson scattering (is the Higgs playing its role?)
  - ★ Multiple-Higgs production (and the Higgs self-couplings)
  - ★ Naturalness (top partners?)
- ✤ Flavor physics
- ✤ Top quark physics
- ✤ Dark matter
- ✤ *etc.*

Physics motivations (2)

✦ Standard Model cross sections



✤ Larger cross sections

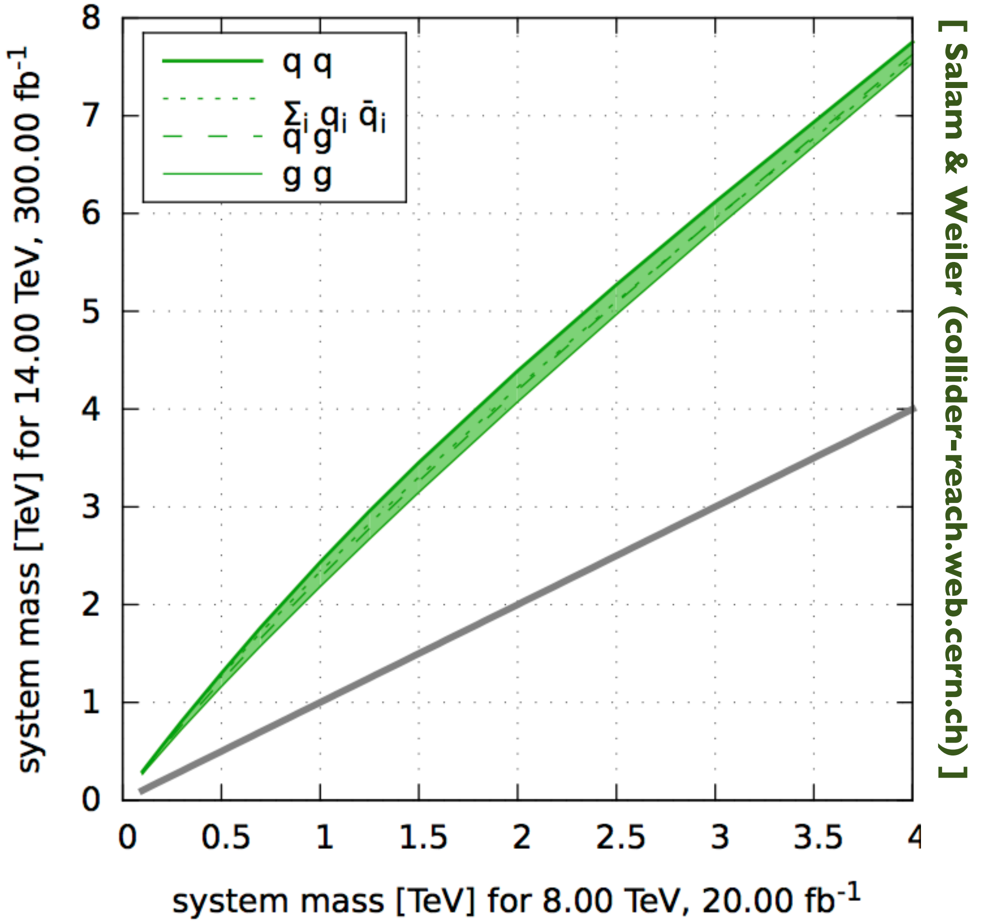
Process	$\sigma_{100\text{ TeV}} / \sigma_{14\text{ TeV}}$
W/Z	≈7
diboson	≈10
top pair	≈30
single top	≈20
Higgs	≈15

✤ Naively: more precision physics

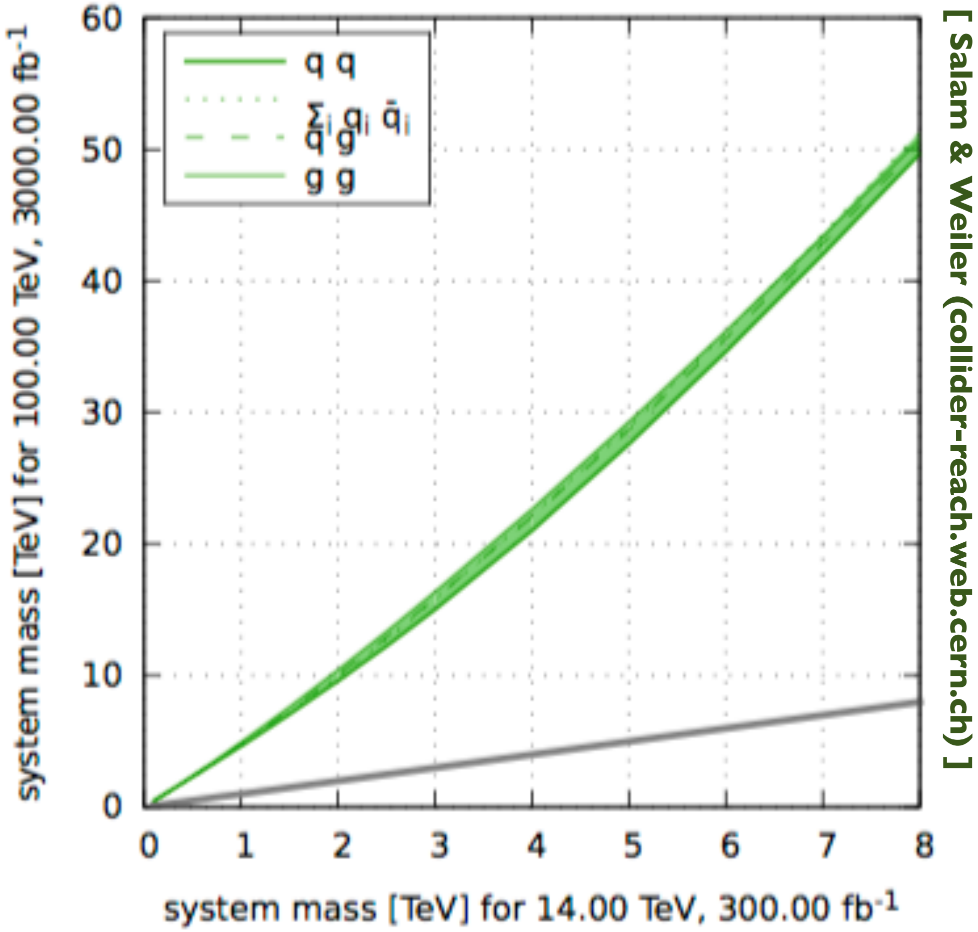
✤ But…
- ★ More jets (harder selections)
- ★ Background rejection?
- ★ Highly boosted objects

Physics motivations (3)

✦ Being energetic: exploration of a new territory (larger invariant mass reach)



LHC-8 [20 fb^{-1}] *vs.* LHC-14 [300 fb^{-1}]
Gain of 1-2



LHC-14 [300 fb^{-1}] *vs.* FCC-100 [3000 fb^{-1}]
Gain of about 5-6

✤ Ingredients: parton luminosities + generic invariant-mass dependence of a cross section

✤ Efficiencies for signal and background scale similarly for both colliders

Physics motivations (4)

✦ New physics effects could also be hidden in the Higgs (self-)couplings

✤ Multiple-Higgs production

$\sqrt{s}$ (TeV)	Cross sections (fb) and theoretical uncertainties (%) $gg \to HH$ NLO	$qq \to qqHH$ NLO	$q\bar{q} \to WHH$ NNLO	$q\bar{q} \to ZHH$ NNLO	$q\bar{q}/gg \to t\bar{t}HH$ LO
14	$33.89^{+37.2\%}_{-29.8\%}$	$2.01^{+7.6\%}_{-5.1\%}$	$0.57^{+3.7\%}_{-3.3\%}$	$0.42^{+7.0\%}_{-5.5\%}$	1.02
100	$1417.83^{+29.7\%}_{-24.7\%}$	$79.55^{+6.2\%}_{-4.1\%}$	$8.00^{+4.2\%}_{-3.7\%}$	$8.27^{+8.4\%}_{-8.0\%}$	77.82

[Snowmass 2013 (1310.8361)]

Difficult or impossible for the LHC

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

Precision measurement of the Higgs quartic coupling (via di-Higgs production)

✦ Rare Higgs production processes

Difficult or impossible for the LHC

✤ Htj production (golden channel for the sign of y_t)

✤ HVV, HVjj production (Higgs-boson couplings to gauge bosons)

✤ Triple Higgs production

Outline

Top dipole moments

New physics (at colliders) and the top quark

✦ New physics at the LHC

- ✤ Great expectation for new physics discovery
- ✤ Could be indirectly found via precision measurements of the Standard Model
  - ★ Important role of the top quark due to its mass close to the electroweak scale
  - ★ Intense research program dedicated to the top properties at the LHC

✦ The top quark at present, past and future colliders

- ✤ Tevatron: $\approx 10^5$ top quarks
- ✤ LHC: $\approx 8\times10^6$ top quarks at 7-8 TeV; $\approx 10^8$ top quarks for 100 fb^{-1} of 14 TeV collisions
- ✤ FCC-hh (30 ab^{-1} of pp collisions at 100 TeV): $\approx 3.10^{12}$ top quarks

Precision era for top physics

Effective field theories

✦ The effective field theory (EFT) approach

- ✤ New phenomena assumed to appear at some large scale Λ
- ✤ No assumption on the form of new physics
  - ★ Addition of higher-dimensional operators

✦ Leading new physics effects: dimension-six operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_x \frac{C_x}{\Lambda^2} O_x$$

- ✤ Effective terms [Burges & Schnitzer (NPB'83); Leung, Love & Rao (Z.Phys.C'86); Buchmuller & Wyler (NPB'86)]
  - ★ Modification of the Standard Model interactions
  - ★ New interactions not present at tree-level (example: fermion dipole moments)

Top dipole moments: conventions

✦ Top dipole moments d_V and d_A [Buchmuller & Wyler (NPB'86); Aguilar-Saavedra (NPB'09)]

- Parameterized by $$\mathcal{L}_{\rm tg} = \frac{g_s}{m_t}\bar t \sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$
- Generated by the dimension-six effective operator $(\bar q_{L3}\lambda_a\sigma^{\mu\nu}t_R)\tilde\phi\, G^a_{\mu\nu}$
  - ★ Chromomagnetic moment $$d_V = \frac{\sqrt{2} v m_t}{g_s\Lambda^2}\,{\rm Re}\, C$$
  - ★ Chromoelectric moment $$d_A = \frac{\sqrt{2} v m_t}{g_s\Lambda^2}\,{\rm Im}\, C$$

✦ In the case of TeV-scale new physics and O(1) Wilson coefficients

- d_V and d_A are of about 0.05
- Largely exceeds the Standard Model predictions
  - ★ $d_V^{(SM)} = -0.007$ [Martinez, Perez & Poveda (EPJC'08)]
  - ★ $d_A^{(SM)} \approx 0$ [Soni & Xu (PRL'92)]

Top dipole moment measurements as probes of new physics

Current constraints on the top dipole moments

✦ Direct searches

- ✤ Effects on the top-antitop production cross total section
  - ★ Investigated at the Tevatron, LHC-7 and LHC-8
    [Haberl, Nachtmann & Wilsh (PRD'96); Hioki & Ohkuma (EPJC'11, PRD'13)]
- ✤ Effects on top-antitop differential distributions
  - ★ Investigated at the Tevatron, LHC-7 and LHC-8
    [Cheung (PRD'96); Hioki & Ohkuma (PRD'11); Kamenik, Papucci & Weiler (PRD'12)]
- ✤ Spin correlations in top-antitop production
  - ★ Computed at the LHC-7 and LHC-8 setups
    [Bernreuther & Si (PLB'13)]

✦ Indirect searches

- ✤ Neutron electric dipole moments [Kamenik, Papucci & Weiler (PRD'12)]
- ✤ Rare B-meson decays [Martinez & Rodriguez (PRD'02)]

$|d_A| \leq 1.2\ 10^{-3}$ @ 95% CL

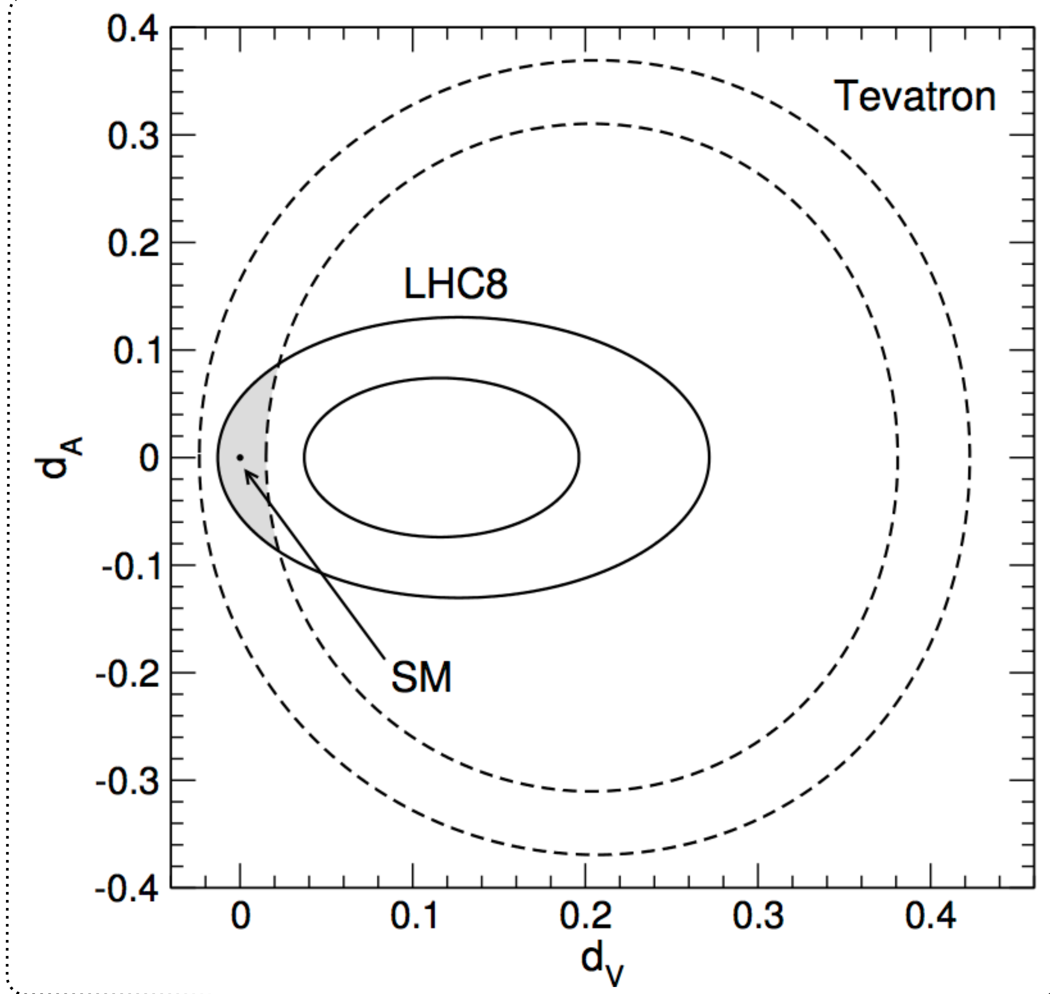
$-3.8\ 10^{-3} \leq d_V \leq 1.2\ 10^{-3}$ @ 95% CL

Collider constraints

Top dipole moments at the Tevatron and the LHC

[Aguilar-Saavedra, BF, Mangano (PRD'15)]

- Top-antitop total rate: complementarity of both colliders
  - Proton-proton *versus* proton-antiproton collisions
  - Different center-of-mass energies (1.96 TeV *versus* 8 TeV)
  - Different functional form of the cross section on the top dipole moments
- Joint use of Tevatron and LHC-8 results
  - Different shapes of the contours
  - Combination yields stronger constraints than a single collider
- LHC-14 predictions
  - Mild improvement expected



Reminder (indirect constrains):

$| d_{A,V} | \lesssim 10^{-3}$

Possible improvements at LHC-14

[Aguilar-Saavedra, BF, Mangano (PRD'15)]

- ✦ Important amount of top-antitop pairs to be collected
  - ✤ Going beyond the use of total rate measurements
  - ✤ Benefitting from differential cross sections
- ✦ Three representative cases
  1. (1) Total rate (as before)
  2. (2) Production rate of top-antitop systems with m_{tt} > 1 TeV
  3. (3) Production rate of top-antitop systems with m_{tt} > 2 TeV

- ✦ Heavier top-antitop systems
  - ✤ Enhanced sensitivity to dipole moments (large momentum transfer)
  - ✤ More statistics is needed
- ✦ Boosted top tagging techniques to reject the multijet background
  - ✤ Boosted top similar to boosted jet (12% efficiency; 0.03% mistag rate) [CMS-PAS-JME-13-007]
  - ✤ Restriction to the central part of the detector ($|\eta| < 2$)
    - ★ Better detector granularity ➢ better background rejection

LHC-14 prospects on top dipole moments

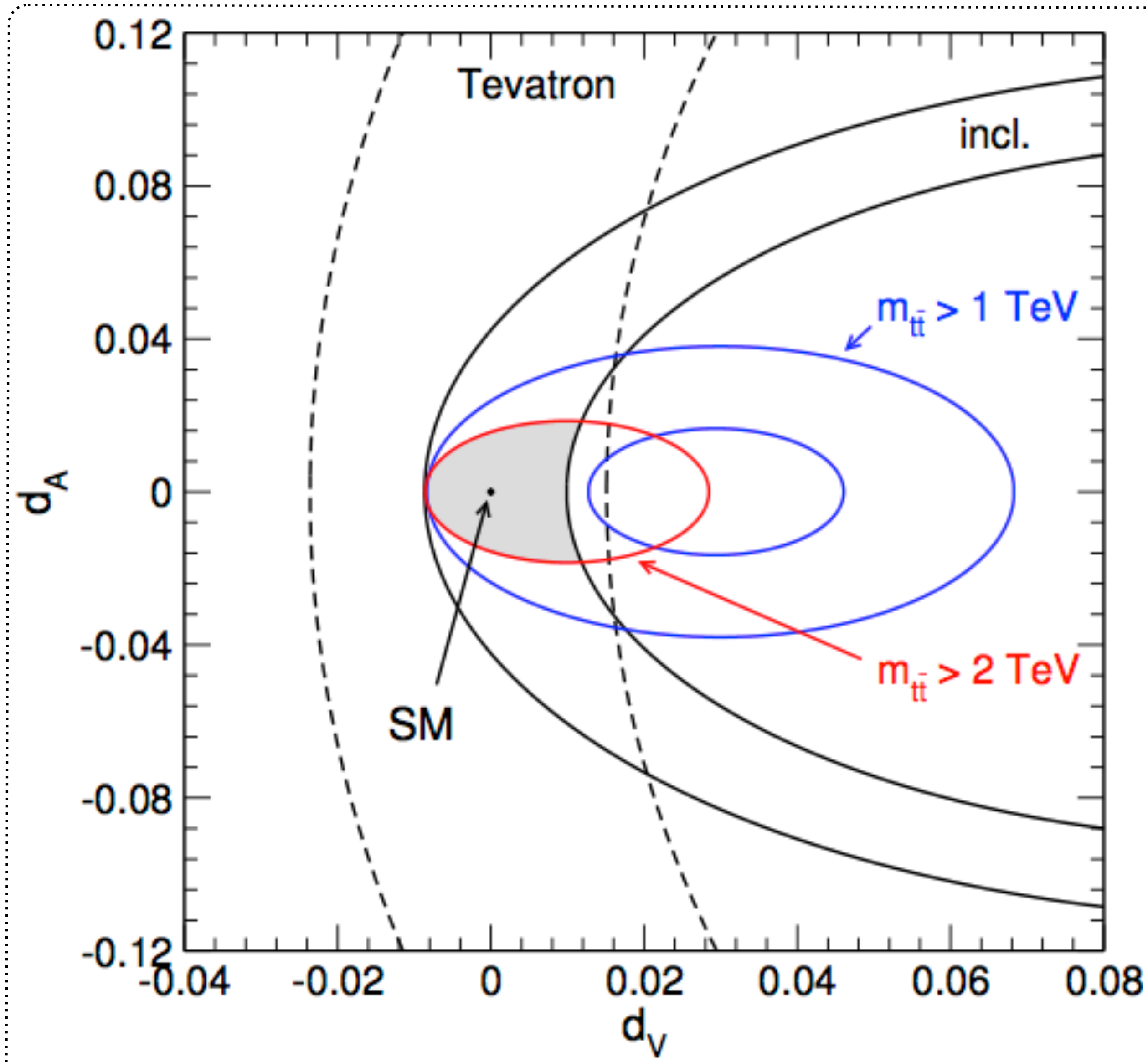
[Aguilar-Saavedra, BF, Mangano (PRD'15)]

✦ LHC-14 predictions

- ✤ Dashed black: Tevatron
- ✤ Solid black: LHC inclusive
  - ★ 5% overal uncertainties
- ✤ Solid blue: LHC with m_{tt} > 1 TeV
  - ★ 5% systematics
  - ★ Computed statistics
- ✤ Solid red: LHC with m_{tt} > 2 TeV
  - ★ 5% systematics
  - ★ Computed statistics

✦ Huge gain in being differential

- ✤ Indirect limits still 10x stronger



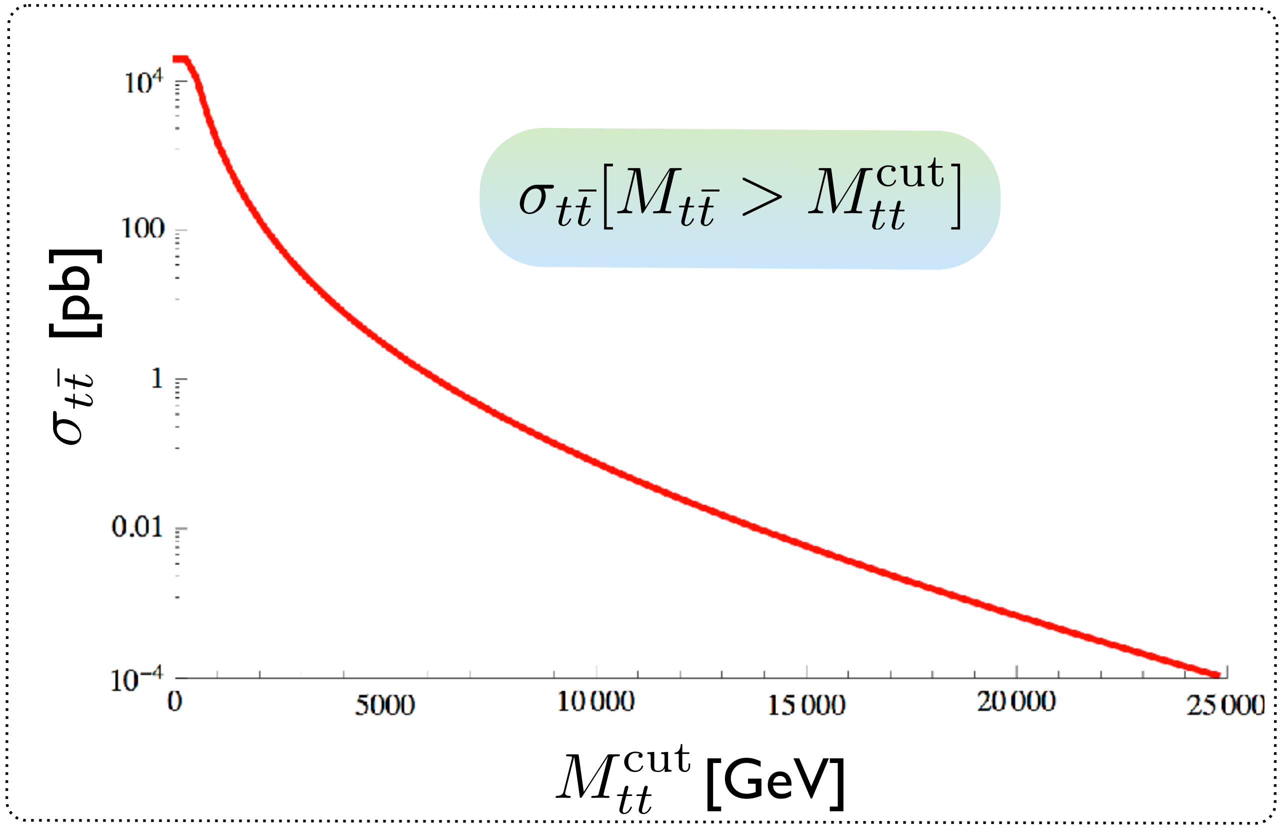
$|d_A| \leq 1.9\ 10^{-2}$
$-8.6\ 10^{-3} \leq d_V \leq 1.2\ 10^{-2}$
⇔ $\Lambda > 5$ TeV

FCC prospects

Top-antitop production at 100 TeV

[Aguilar-Saavedra, BF, Mangano (PRD'15)]

- With 10 ab^{-1} of proton-proton collisions at 100 TeV
  - Production of 10^{12} top quarks
  - A significant number of boosted top-antitop pairs



- Boosted object reconstruction
  - Substructure tied to detector details
    - ★ Heavy boost ⇔ important collimation
    - ★ 5 TeV tops: an R≲0.05 cone
  - Detector independence: muons
    - ★ QCD muons: softer (from B- and D-decays)
    - ★ Top muons: harder (prompt decays)

Distinguishing top and light jets: using muons

[Aguilar-Saavedra, BF, Mangano (PRD'15)]

✦ Event selection

- ✤ Jets are reconstructed with an anti-k_T algorithm with R=0.2 [Cacciari, Salam & Soyez (JHEP'08)]
- ✤ Only jets with p_T > 1 TeV and $|\eta|$ < 2 are retained
- ✤ We retrict the invariant mass of the two-hardest-jet system: m_{tt} > XX TeV
- ✤ At least one jet with a p_T larger than 1 TeV must contain a muon

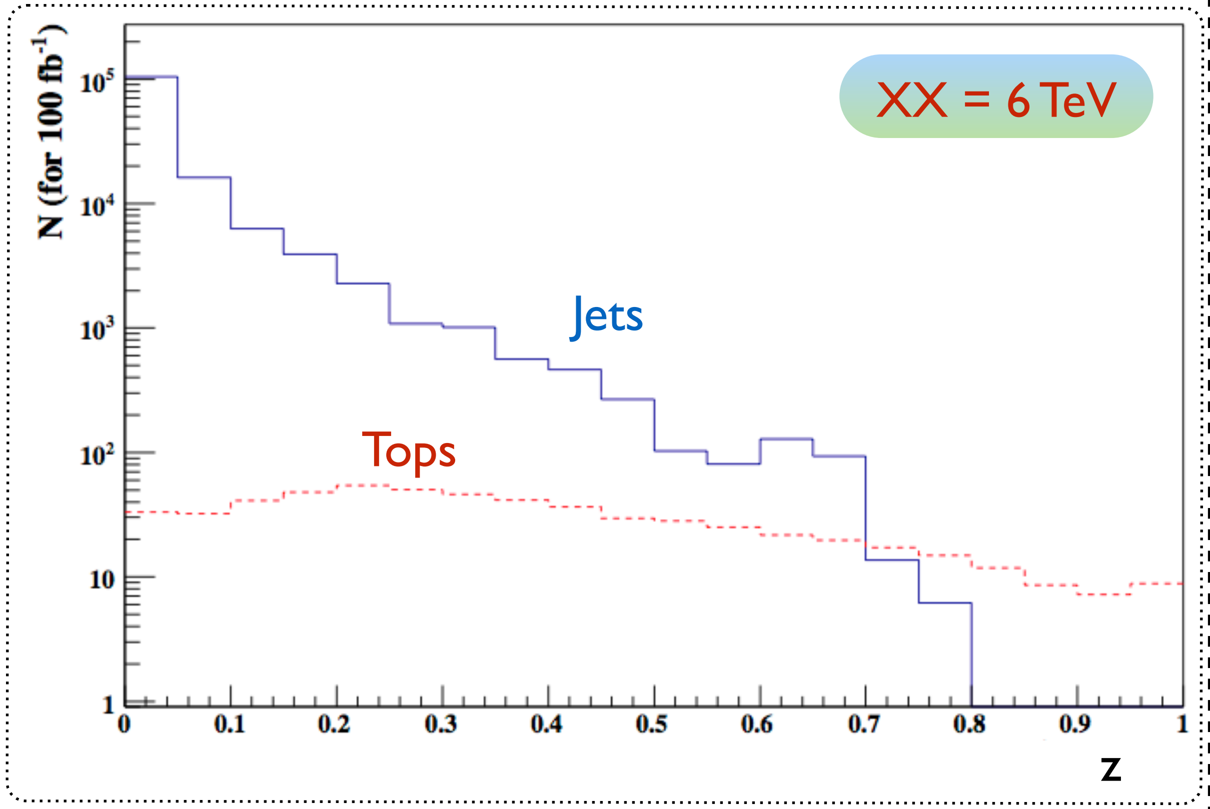
✦ Key observable: the muon p_T relative to the jet p_T

- ✤ For a given event: all muons are considered

$$z = \max_{i=1,\ldots,n} \frac{p_T(\mu_i)}{p_T(j_i)}$$

✦ Observing heavily boosted $t\bar{t}$ pairs

- ✤ XX = 6 TeV, z>0.5 ⇔ 5σ @ 35 fb^{-1}
- ✤ XX = 10 TeV, z>0.5 ⇔ 5σ @ 200 fb^{-1}
- ✤ XX = 15 TeV, z>0.4 ⇔ 5σ @ 2 ab^{-1}



FCC prospects on top dipole moments

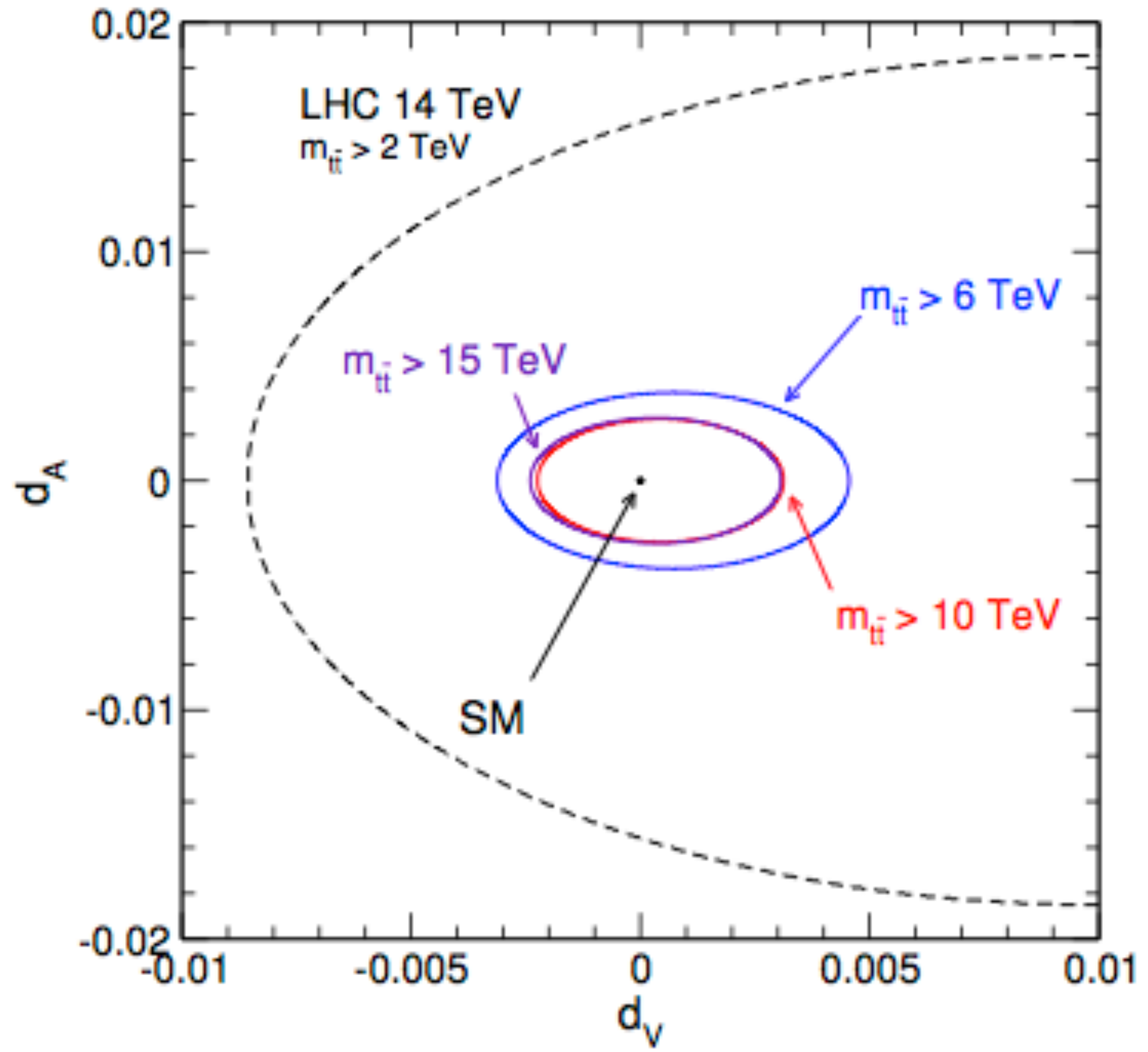
[Aguilar-Saavedra, BF, Mangano (PRD'15)]

✦ FCC predictions (for 10 ab^{-1})

- ✤ Dashed black: LHC-14 [m_{tt} > 2 TeV]
  - ★ 5% systematics + computed statistics
- ✤ Solid blue: FCC with m_{tt} > 6 TeV
  - ★ 5% systematics + computed statistics
- ✤ Solid red: FCC with m_{tt} > 10 TeV
  - ★ 5% systematics + computed statistics
- ✤ Solid purple: FCC with m_{tt} > 15 TeV
  - ★ 5% systematics + computed statistics

✦ Comparison with the LHC

- ✤ Gain of one order of magnitude
- ✤ Similar to the indirect limits



$|d_A| \leq 2.6\ 10^{-3}$
$-2.2\ 10^{-3} \leq d_V \leq 3.1\ 10^{-3}$ ⇔ Λ > 17 TeV

Outline

Generalities

New physics contributions to the Higgs potential

✦ New physics effects in the Higgs potential can be modeled generically as

$$V_{\rm h} = \frac{m_h^2}{2} h^2 + (1+\kappa_3)\frac{m_h^2}{2v} h^3 + \frac{1}{4}(1+\kappa_4)\frac{m_h^2}{2v^2} h^4$$

New physics parameters (are they vanishing?)

- Measurements of the κ parameters yield the exact form of the Higgs potential
  - ★ Knowledge of the electroweak symmetry breaking dynamics
- κ_3: may be (modestly) constrained by diHiggs searches at the LHC
  - ★ 2σ deviations from the Standard Model could maybe be observed with 3 ab^{-1} [Baglio et *al.* (JHEP'13)]
- κ_4: impossible to probe at the LHC (too low tri-Higgs cross section)

✦ What about the FCC (pp collisions at 100 TeV)?

- Triple Higgs probes are sensitive to both κ parameters
- Double Higgs can help to constrain κ_3 to the 3-4% level [Azatov, Contino, Panico & Son (PRD'15)]

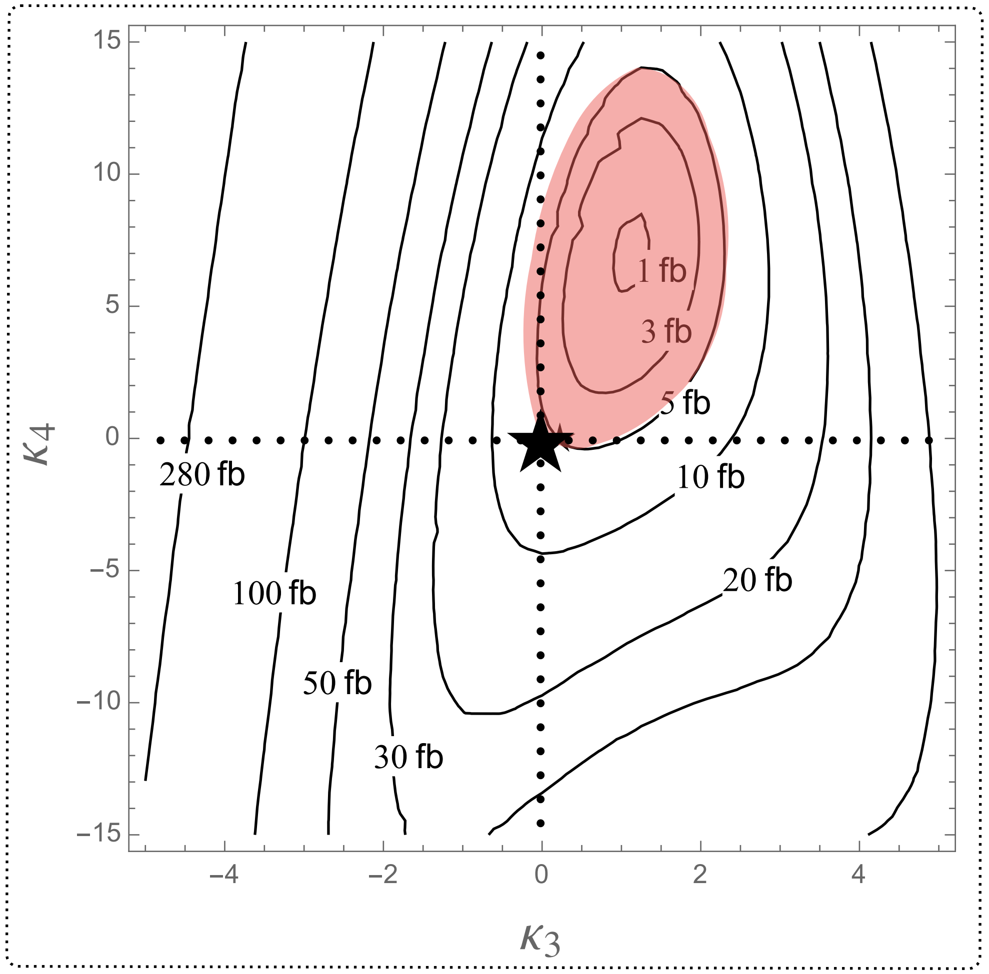
What about κ_4?

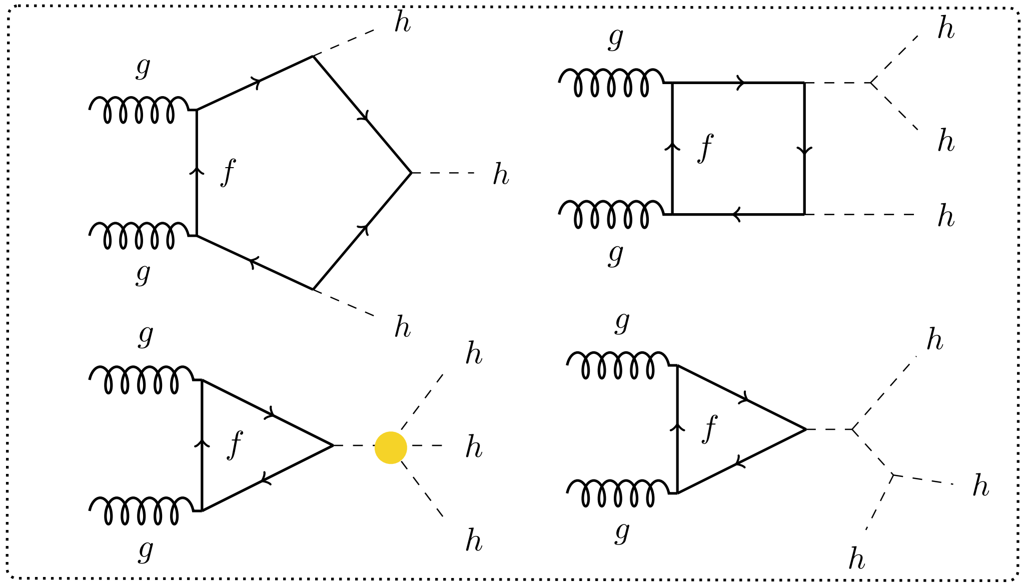
Triple Higgs production at the FCC

[BF, Kim, Lee (PRD'16 & PLB'17)]

✦ HHH production strongly depends on y_t and κ_3; milder dependence on κ_4

- ✤ y_t and κ_3: to be constrained by other means (tth, diHiggs)
- ✤ The milder κ_4 dependence will be left
  - ★ Indirect probes: via loops
  - ★ Direct probes: triple Higgs production





✦ Triple Higgs production at 100 TeV

- ✤ The total rate depends a lot on BSM effects
  - ★ Orders of magnitude are spanned
- ✤ Both κ positive and large: harder to probe
  - ★ Huge destructive interferences
- ✤ Can we get to the SM point?

Triple Higgs signatures

✦ Reminder: the triple (SM) Higgs decay table

✤ Restriction to channels yielding more than 100 events with 30 ab^{-1} in the SM

✦ Most (naively) promising channels

- ✤ 6 b-jets (~20%)
  - ★ Huge expected multijet background
  - ★ Largest signal rate
- ✤ 4 b-jets and 2 W-bosons
  - ★ Backgrounds very large again
  - ★ Already smaller signal rates

The 2l2b4j signature could be used with advanced analysis techniques
[Kilian, Sun, Yan, Zhao & Zhao (JHEP'17)]

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125
$(b\bar{b})(\gamma\gamma)(WW_{1\ell})$	0.057	3.291	98

[From Papaefstathiou & Sakurai (JHEP'16)]

✦ Taus, photons and b-jets

- ✤ 4 bjets and 2 taus (~6.5%): large rate but taus are complicated objects [BF, Kim, Lee (PLB'17)]
- ✤ 4 bjets and 2 photons (~0.25%): small rate but clean

[Papaefstathiou & Sakurai (JHEP'16); Chen, Yan, Zhao, Zhong & Zhao (PRD`16); BF, Kim & Lee (PRD'16)]

The 4b + 2γ channel

The 4b + 2γ channel: generalities

[BF, Kim, Lee (PRD'16)]

✦ Simulation details

- ✤ Parton-level study + smearing of the four-momenta (*à la* ATLAS)
- ✤ b-tagging performance: LHC-inspired working points

How good should the b-tagging be to observe a triple-Higgs signal?

✦ Selection strategy for 20 ab^{-1}

- ✤ Four jets (with an invariant mass smaller than 600 GeV), 2 photons
- ✤ Two dijet systems compatible with a Higgs ($m_{jj} \in [105, 140]$ GeV)
- ✤ The diphoton system compatible with a Higgs ($m_{\gamma\gamma} \in [125\text{-}M, 125\text{+}M]$ GeV)

What is the best M-value?

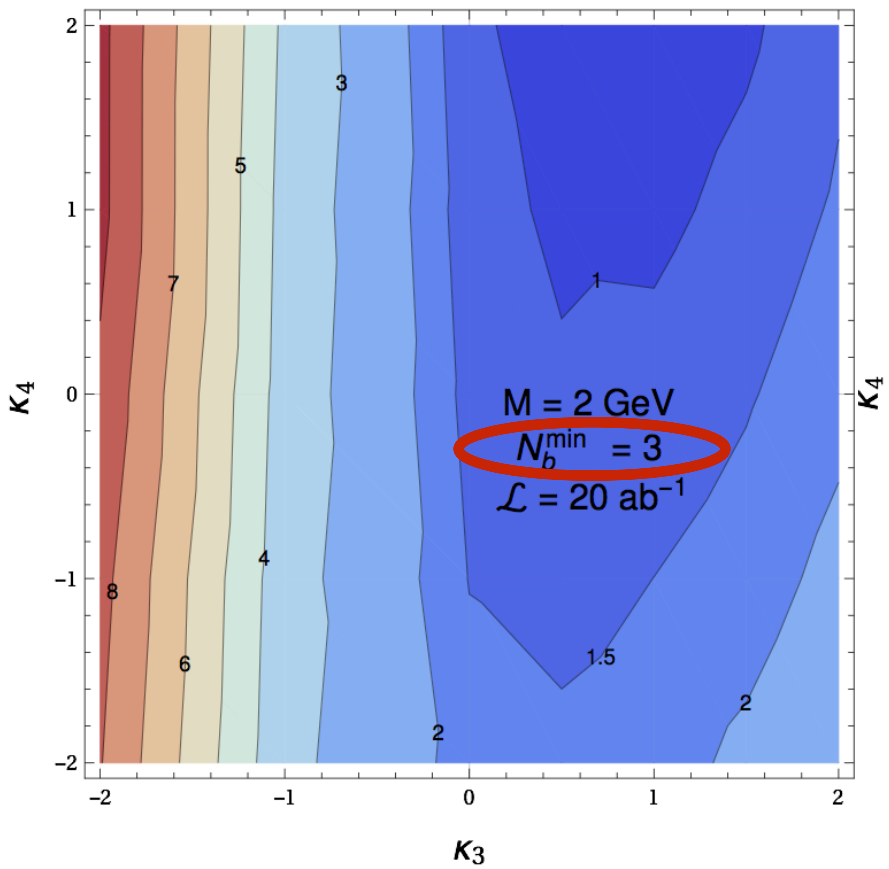
- ✤ At least $N_b^{\rm min}$ b-tagged jets

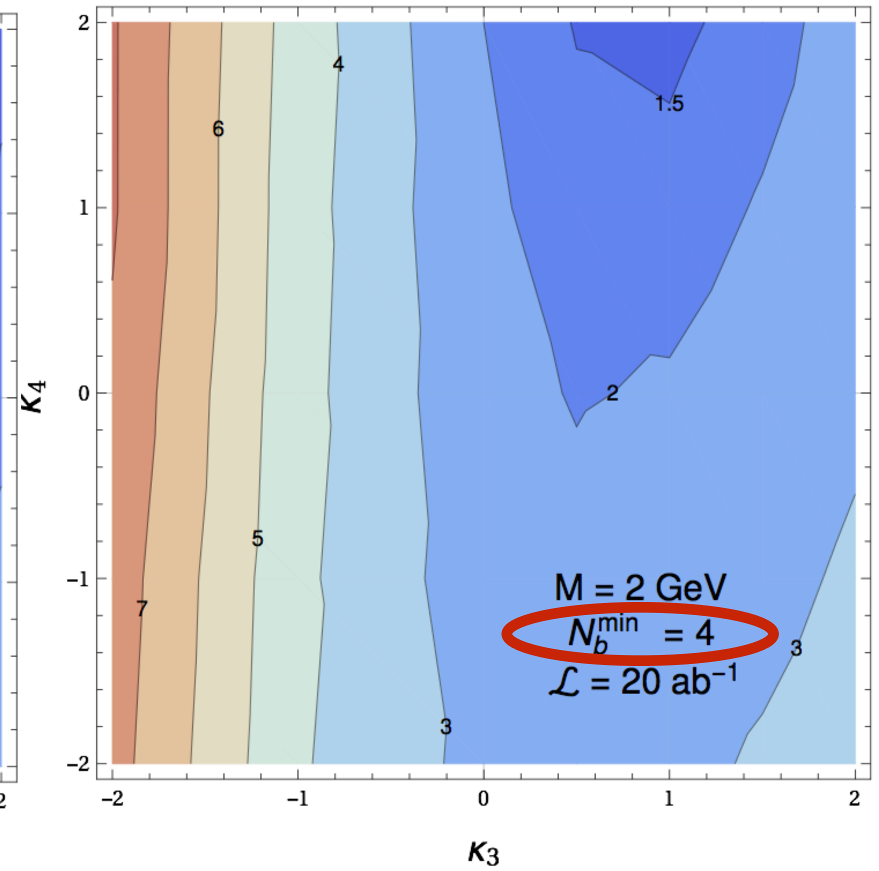
What is the best choice?

The 4b + 2γ channel: b-tagging

[BF, Kim, Lee (PRD'16)]

✦ Sensitivity (in σ)





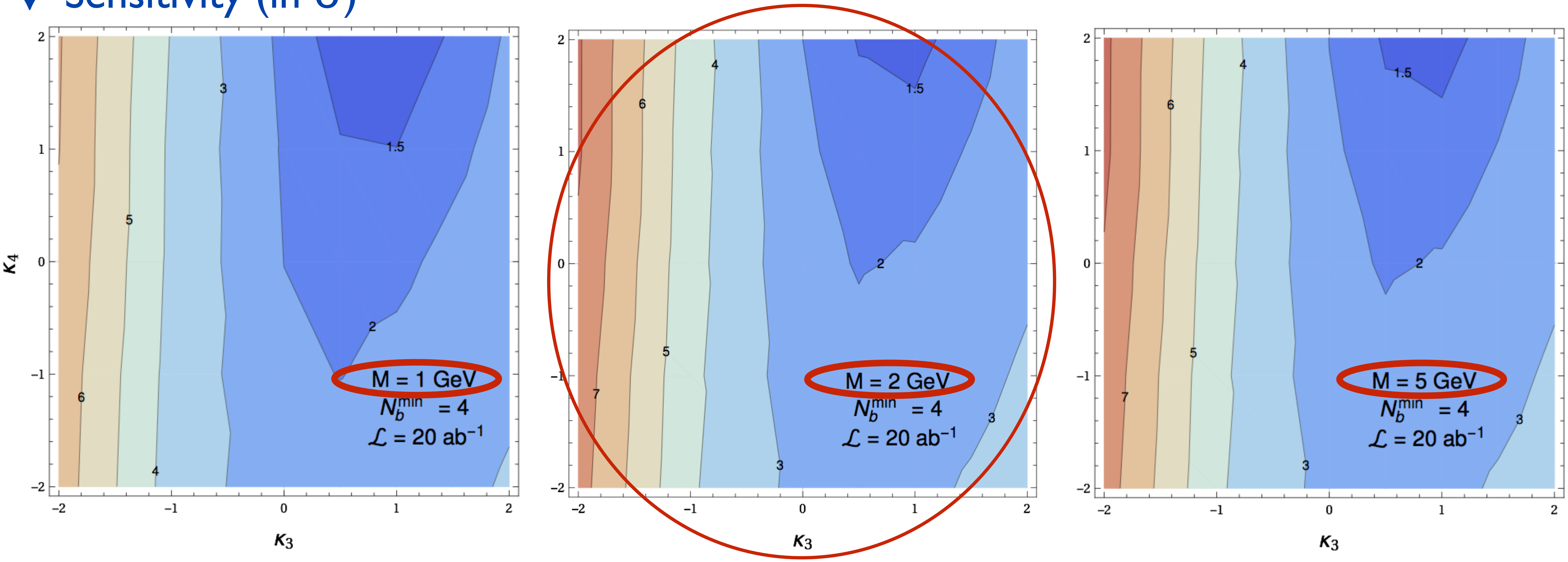
$$\sigma \equiv \sqrt{-2\ \ln \frac{L(S+B|B)}{L(B|B)}}$$

- ✦ A low fake rate (1.8%/0.1%) for a 60% efficiency is primordial for the sensitivity
  - ✤ Poorer results for a fake rate of 18%/1% and a 70% efficiency
    - ★ Better signal acceptance
    - ★ Much worse background contamination due to the fakes
- ✦ Requiring at least 4 b-jets gives slightly better results (the background efficiency drops faster than the signal one)

The 4b + 2γ channel: diphoton mass

[BF, Kim, Lee (PRD'16)]

✦ Sensitivity (in σ)



✦ Photons with a p_T greater than 20 GeV are very well reconstructed ($\sigma/E \sim 0.1/\sqrt{E}$)

- ✤ A loss of signal efficiency implies to maintain M not too small
- ✤ A too large M implies a more important background contamination
  - ★ However, mild effects on the sensitivity

M = 2 GeV gives the best results: between 2σ and 3σ for the SM

The 4b + 2τ channel

The 4b + 2τ channel: handling the taus

[BF, Kim, Lee (PLB'17)]

✦ Simulation details: hadron-level study and object reconstruction

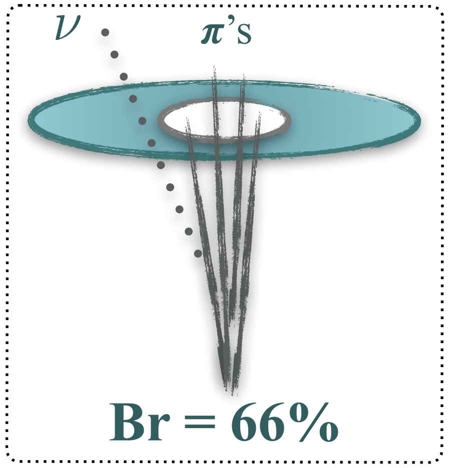
✦ Tau-tagging

✤ Tau-tagging performance: LHC-inspired (50% / 5%)

★ Narrow jet with no activity around it (for R ϵ [0.2, 0.4])

★ The fake rate could in principle be smaller [CMS-PAS-FTR-15-002]

✤ Double hadronic tau tag required

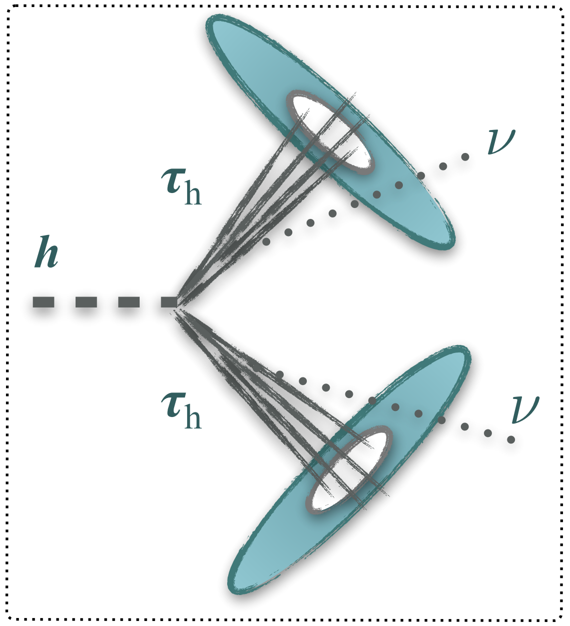


The 4b + 2τ channel: the ditau system

[BF, Kim, Lee (PLB'17)]

✦ Reconstruction of the ditau system

[Barr, Gripaios & Lester (JHEP`09)]
[Barr, French, Frost & Lester (JHEP`11)]

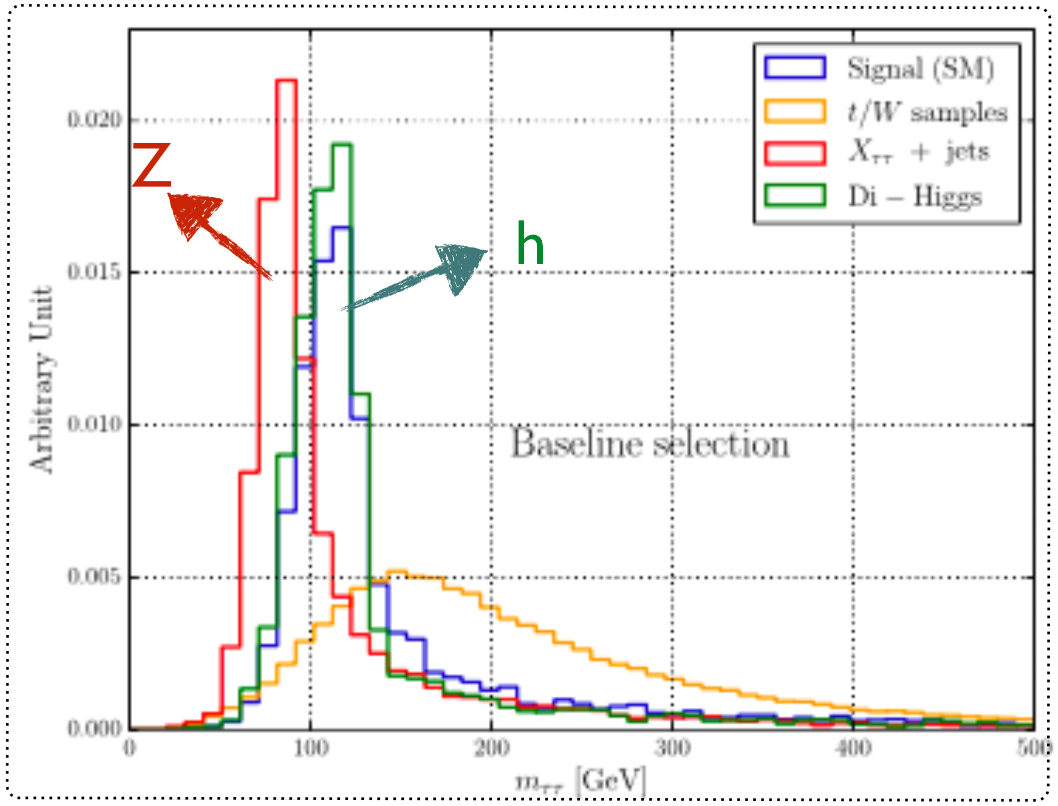


✤ Based on di-Higgs search techniques

- ★ One neutrino is associated with each hadronic tau
- ★ Minimization of the ditau invariant mass over all possible assignments for the missing energy
- ★ Higgs/tau kinematic constraints

✤ The Z → $\tau_h \tau_h$ background can be killed

- ★ Cut on the $m_{\tau\tau}$ variable (Higgs window)

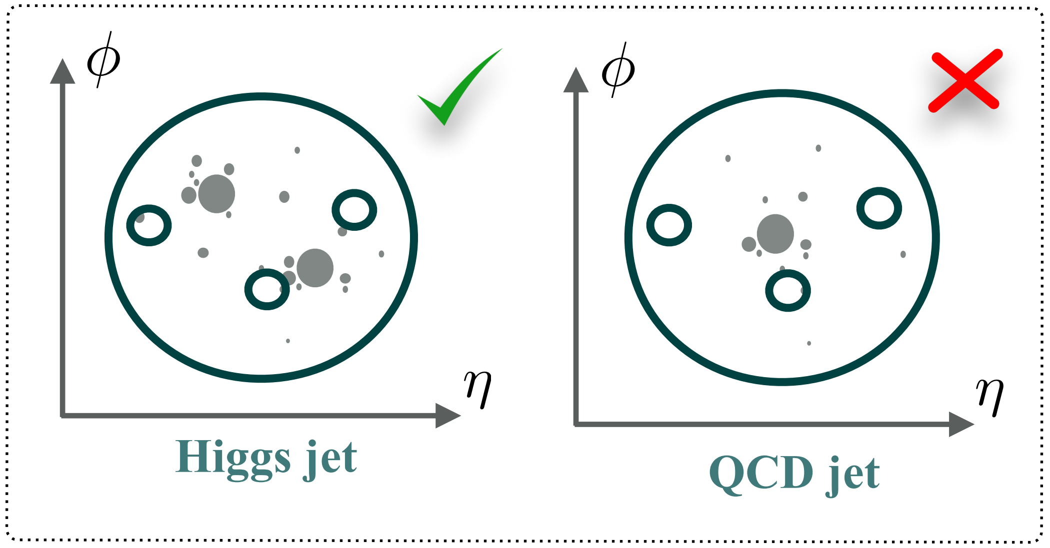


The 4b + 2τ channel: The 'b-Higgses'

[BF, Kim, Lee (PLB'17)]

✦ Boosted Higgs identification based on the Template Overlap Method

- ✤ Using NLO information in the templates (2-body and 3-body templates)

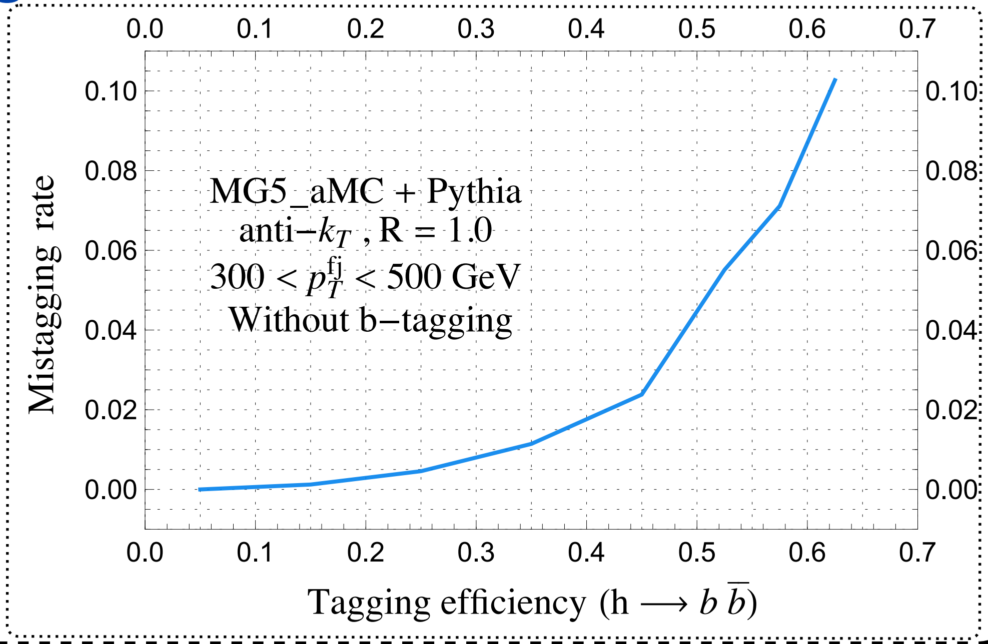


- ✤ Scan over all templates
- ✤ Likelihood of a jet being a Higgs jet
- ✤ Selection on the likelihood (both for 2 and 3 body templates)

[Almeida *et al.* (PRD`10, PRD`12); Kim, Kong, Lee & Mohlabeng (PRD`16)]

✦ Performance: 40% efficiency; 2% mistagging

- ✤ The small fake rate is again critical
- ✤ Cost in signal important
- ✤ We require the last Higgs to be resolved
- ✤ b-tagging: LHC-inspired (70% / 1%)

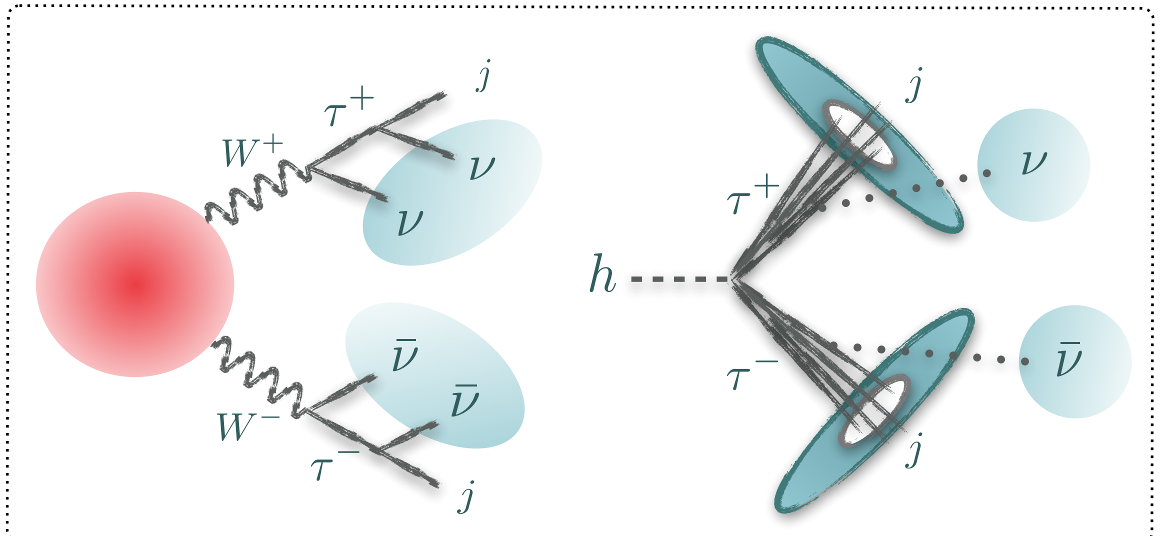


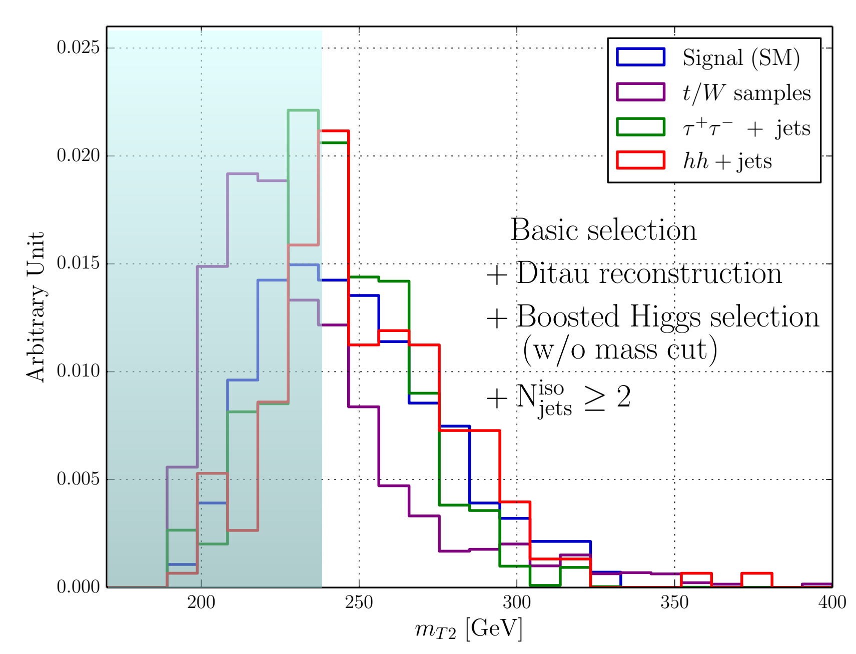
The 4b + 2τ channel: selection

[BF, Kim, Lee (PLB'17)]

✦ Selection strategy for 30 ab^{-1}

- Two hard central taus (p_T > 25 GeV; $|\eta|$ < 2.5) and missing energy (> 25 GeV)
- Minimization of the ditau invariant mass over all possible MET assignments
- One boosted and one resolved Higgs boson
  - ★ One central fat jet (p_T > 300 GeV; $|\eta|$ < 2.5) compatible with a Higgs
  - ★ Two central slim jets compatible with a Higgs
  - ★ One resolved b-tag and one doubly-sub-b-tag
- Using the properties of the M_{T2} variable for a final selection
  - ★ Its upper bound sharply rises for increasing test masses above the true invisible mass
  - ★ Different parent masses: ν arising from τ for the signal, and t/W for the background
  - ★ Different number of neutrinos
  - ★ The rise is 'delayed' for the background

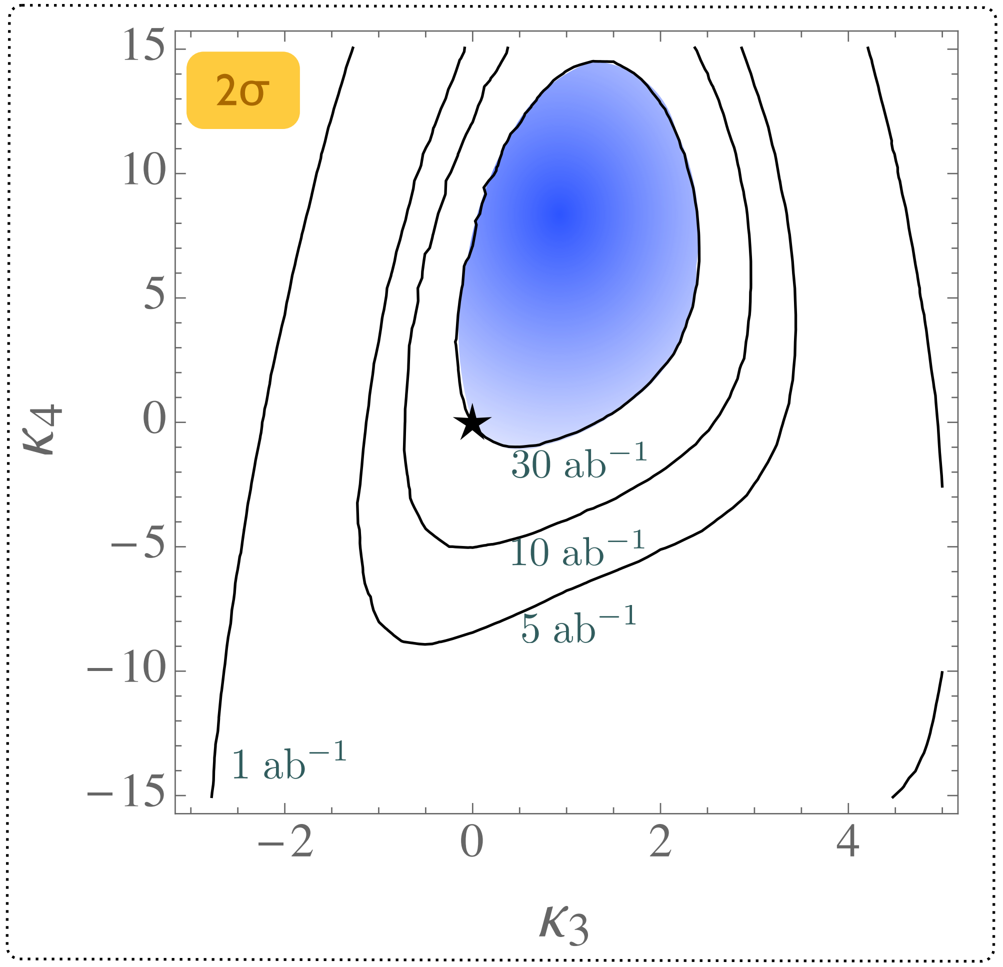




The 4b + 2τ channel: sensitivity

[BF, Kim, Lee (PLB'17)]

✦ The SM point can be in principle accessed at the 2σ level



- Strong constraints for negative κ
  - ★ κ_3 in particular
- Improvements
  - ★ Combination with the diphoton channel?
  - ★ Including leptonic taus?
- An important fraction of the parameter space still unprobed
  - ★ Due to destructive interferences
- Investigating alternative channels?

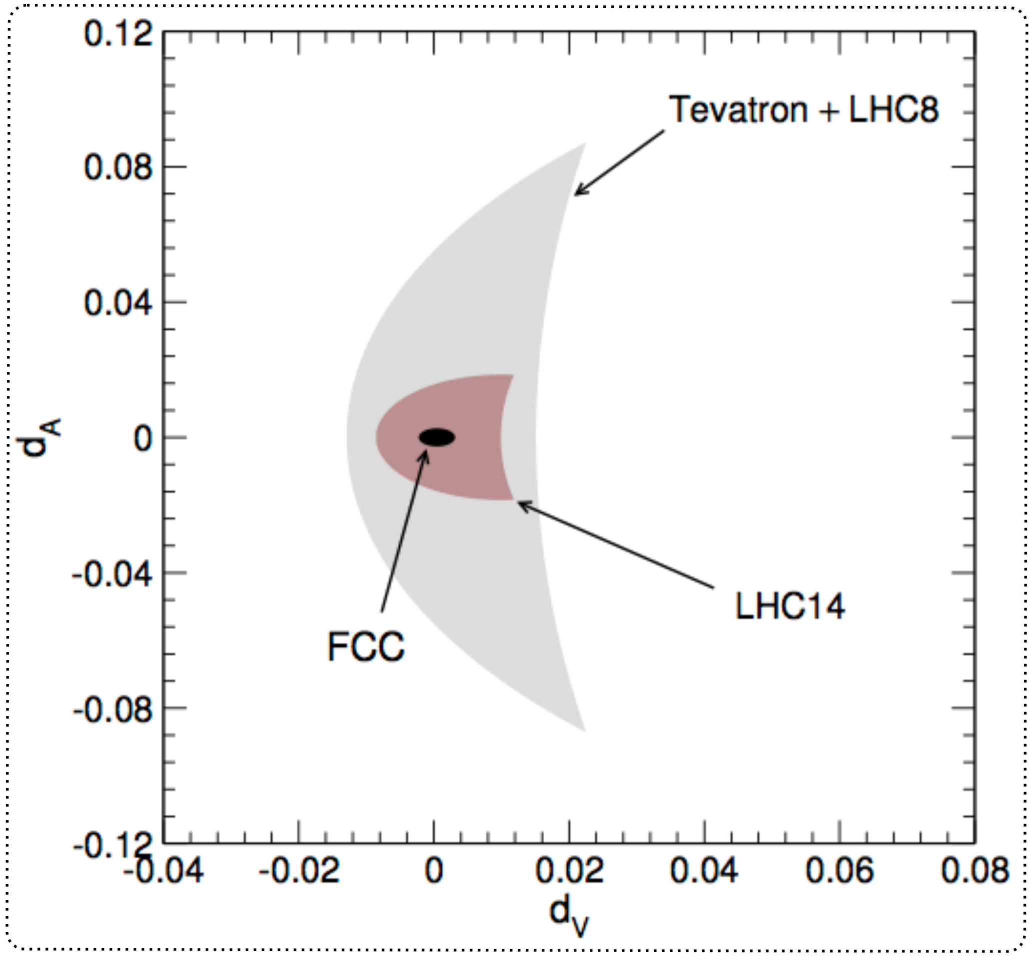
Outline

Top dipole moments at the FCC-hh

[Aguilar-Saavedra, BF, Mangano (PRD'15)]

✦ Future colliders: larger luminosities and center-of-mass energies

- Differential distributions: using heavily boosted tops
  - ★ Higher-momentum transfers are probed
  - ★ Highly sensitive to top dipole moments



- Improvement of the bounds
  - ★ LHC-14 (m_{tt} > 2 TeV):

    $|d_A| \leq 1.9\ 10^{-2}$
    $-8.6\ 10^{-3} \leq d_V \leq 1.2\ 10^{-2}$

  - ★ FCC (m_{tt} > 10 TeV):

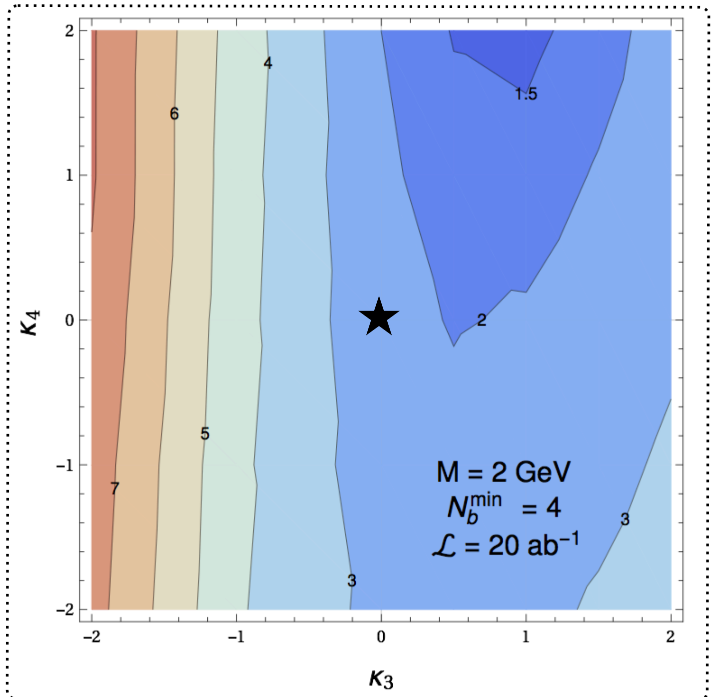
    $|d_A| \leq 2.6\ 10^{-3}$
    $-2.2\ 10^{-3} \leq d_V \leq 3.1\ 10^{-3}$

- Detailed top-tagging studies at the FCC are in order
  - ★ *cf.* envisaged detector technologies
  - ★ Potential improvement of our results

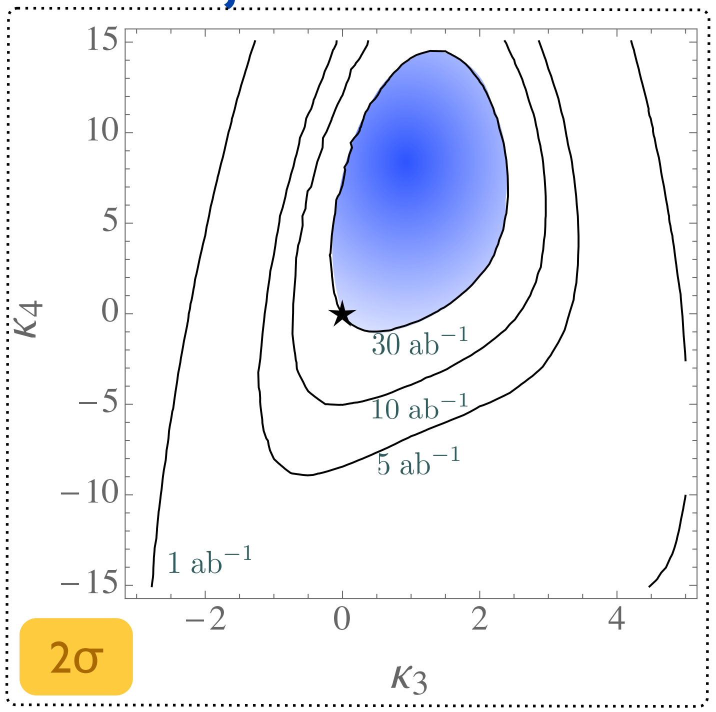
Triple Higgs prospects at the FCC

[BF, Kim, Lee (PRD'16 & PLB'17)]

✦ hhh in 4 b-jets and 2 photons



✦ hhh in 4 b-jets and 2 hadronic taus



✤ Strong constraints for negative κ (κ_3 in particular)

✤ The SM point is reachable at the 2σ level for both channels

✤ An important fraction of the parameter space still unprobed

★ Due to destructive interferences when both κ are positive