Perspectives for top physics at future circular colliders

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Outline

1. Future Circular Colliders at CERN

2. Top pair and multitop production

3. Rare and single-top processes: flavor changing neutral currents

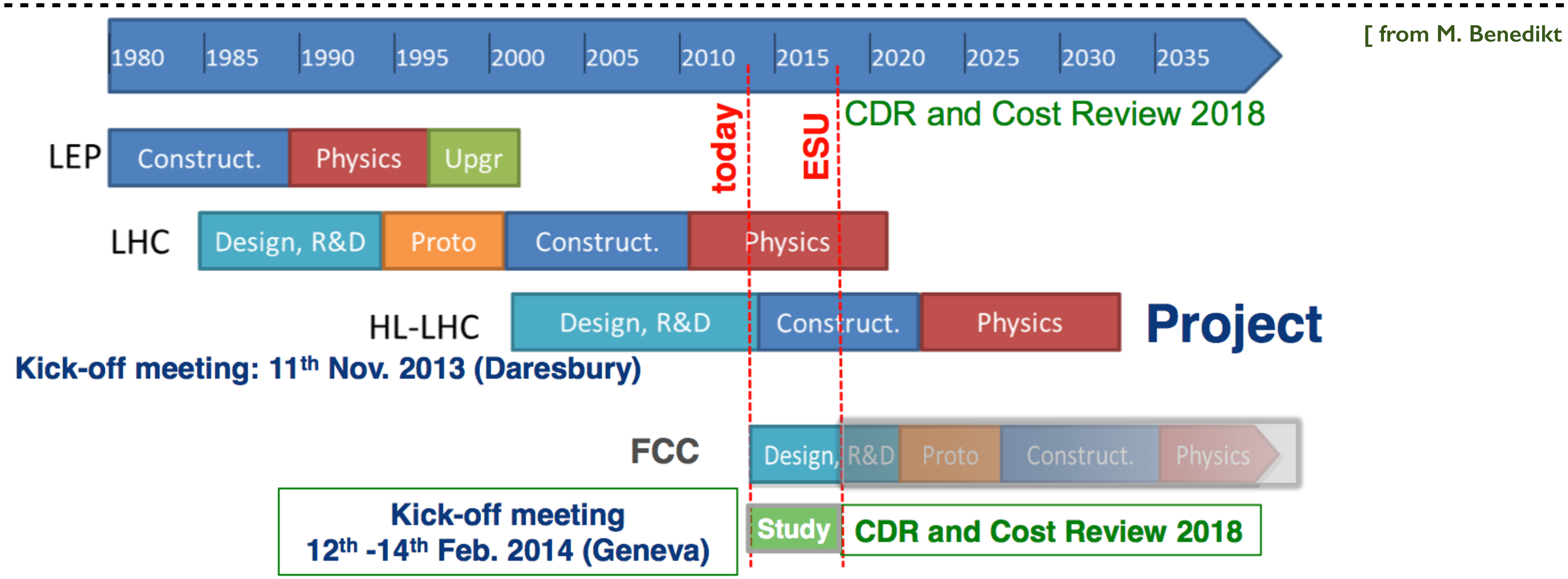
4. Parton densities

5. Conclusions - summary

Future circular collider studies

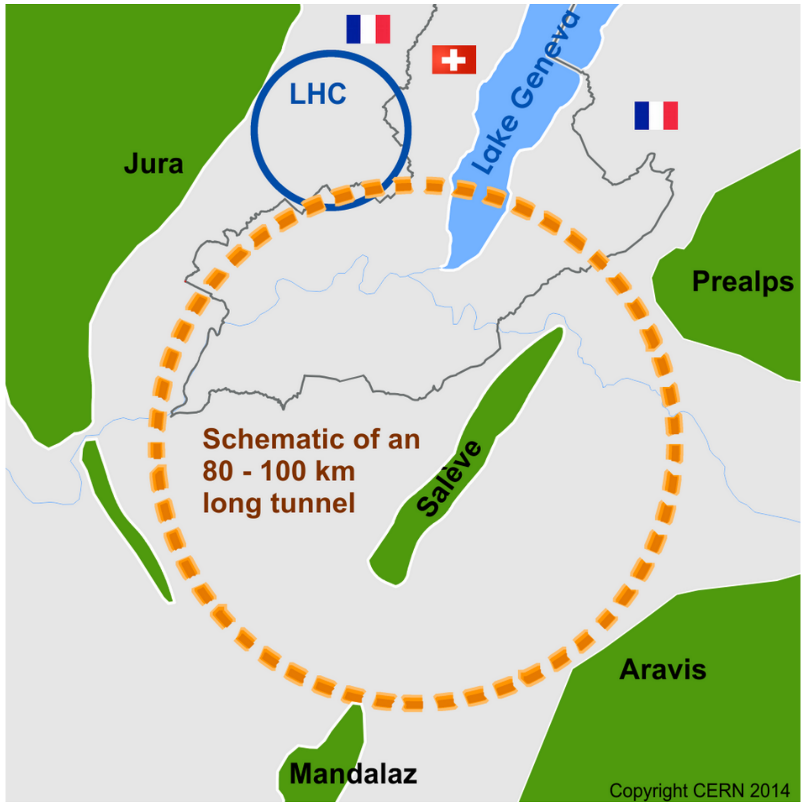
- Pushing the energy frontier to higher and higher values
  - High priority within the European Strategy for Particle Physics
    - ★ Top priority is the exploitation of the full potential of the LHC (including HL-LHC: 3000 fb^{-1})
    - ★ CERN should undertake design studies for post-LHC accelerator projects (including high field magnets, high-gradient accelerating structures, *etc.*)
  - Circular high energy colliders are suitable machines (all options: proton-proton, e^+e^-, $e^\pm$-proton)

- The LHC will run for about 20 years (2009-2035)
  - The LHC design started in 1983 (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 for Particle Physics)



Intermediate and long term goals

- A future circular collider at CERN
  - A new 80/100 km tunnel in the Geneva area
  - Long term: a proton-proton machine
    - ★ With 50 TeV beams ($\sqrt{S}$ = 100 TeV)
    - ★ Achievable with 16T/20 T magnets
  - Potential intermediate step: a lepton collider
    - ★ Precision measurements to get a handle on the new physics scale
    - ★ Study of rare Z, W, Higgs and top decays (four operation points: teraZ, okuW, megatop, megaH)
    - ★ Possible upgrade at 500 GeV
  - A lepton-proton option will also be studied



- Cost review to be performed by 2018

- Some of the technical challenges
  - Energy stored in the beams: 20 times more than LHC (8 GJ/beam)
  - High synchrotron radiation load on the beam pipe: 25 times more than LHC
  - Quench protection of the magnets
  - Feasibilities of 20T magnet technology (challenging but not impossible: high-temperature supra-conductor magnets)
  - Shielding & collimation (*cf.* beam losses)

Physics cases

✦ Two interesting physics cases for a 100 TeV hadron collider

- ✤ New physics is discovered at the LHC ($\sqrt{S}$ = 13-14 TeV) and is heavy (not seen at $\sqrt{S}$ = 8 TeV)
  - ★ Large luminosity and energy required for a detailed study of its properties; complete the spectrum, *etc.*
- ✤ 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 new physics of indications for it are found

- ✤ Higgs-related questions may need higher-energy machines (an ILC might not be enough)
  - ★ Longitudinal vector boson scattering (is the Higgs playing its role?)
  - ★ Multiple-Higgs production
  - ★ Naturalness (top partners?)
- ✤ Baryon and lepton number violation via anomalies (requires at least 30 TeV)
- ✤ Flavor physics
- ✤ Dark matter
- ✤ *etc.*

Top physics at 100 TeV (and high luminosity)

✦ With 100 fb^{-1} of proton-proton collisions at 100 TeV

- Production of 10^{10} top quarks (500 times what we have today)
  - ★ And therefore, 10^{10} W-bosons originating from top decays
- A much larger luminosity is expected
  - ★ Precision measurements
  - ★ Rare processes (e.g, FCNC, CP violation)
  - ★ Portal to new physics

✦ Key issue

- With 100 TeV collisions, most of the produced final-state objects are boosted
- Boosted tops, Higgs and weak bosons as well as jets all look like jets
- Jet substructure identification (energy and angular resolution): benchmark for detector design

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Top-antitop system with a large invariant mass

[Aguilar Saavedra, BF, Mangano]

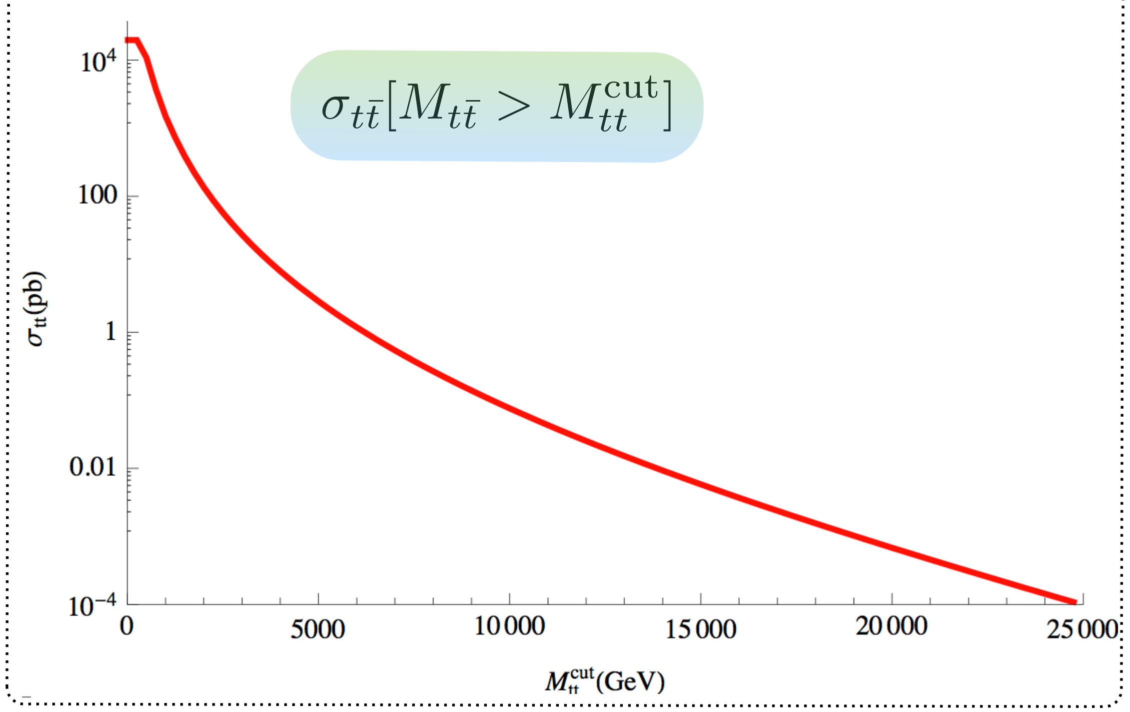
✦ Probing top-antitop production at large invariant mass

- ✤ Larger gain with stronger invariant mass cut when comparing 14 TeV to 100 TeV collisions
- ✤ We can access phase space regions not accessible at the LHC

σ_{LO} [pb]	No M_{tt} cut	M_{tt} > 1 TeV	M_{tt} > 2 TeV	M_{tt} > 3TeV	M_{tt} > 5 TeV
LHC-14	560 pb	14.5 pb	0.31 pb	0.017 pb	9.93 10^{-5} pb
FCC-100	19700 pb (x35)	1510 pb (x100)	135.9 pb (x440)	27.2 pb (x1600)	2.86 pb (x30000)

✤ Interesting working points at large invariant-mass

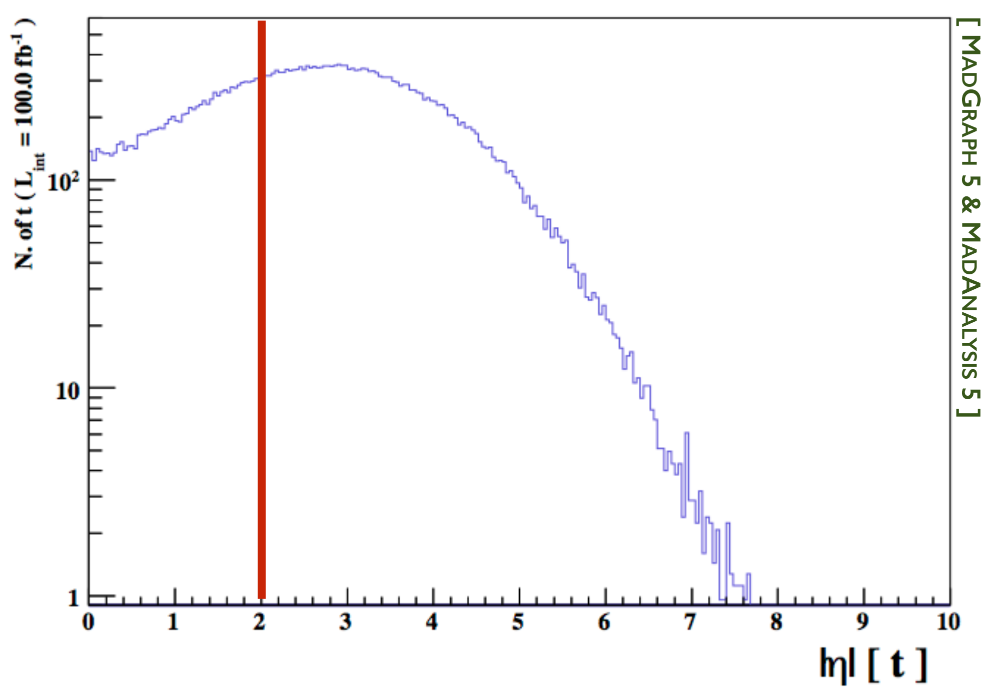
- ★ Large cross sections ➢ not small event numbers
- ★ Possibly smaller background
- ★ New physics effects could appear
- ★ Entering the super-boosted regime

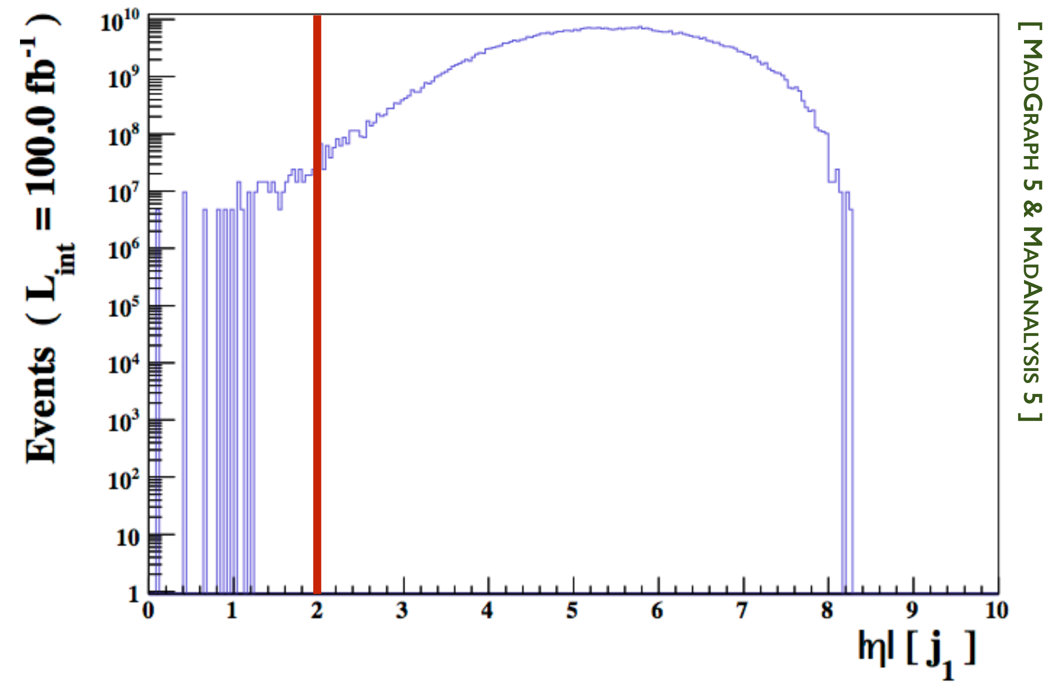


Top pair *versus* dijet production at large invariant mass

[Aguilar Saavedra, BF, Mangano]

✦ Background (dijet) rejection suggests to focus on central jets





✤ Orders of magnitude differences that could be tamed by setting $|\eta| < 2$

✦ Total rates (restrictions of $|\eta| < 2$; semi-muonic top-pair decay)

✤ σ_{LO} (p p → j j) ≈ 235 pb and σ_{LO} (p p → t $\bar{t}$) ≈ 65 fb (for an invariant mass cut of 5 TeV)

✤ Do current boosted top techniques work at 100 TeV?

★ How to observe tops within the huge dijet background?

Try simple ideas

Distinguishing top and light jets: using muons

[Aguilar Saavedra, BF, Mangano]

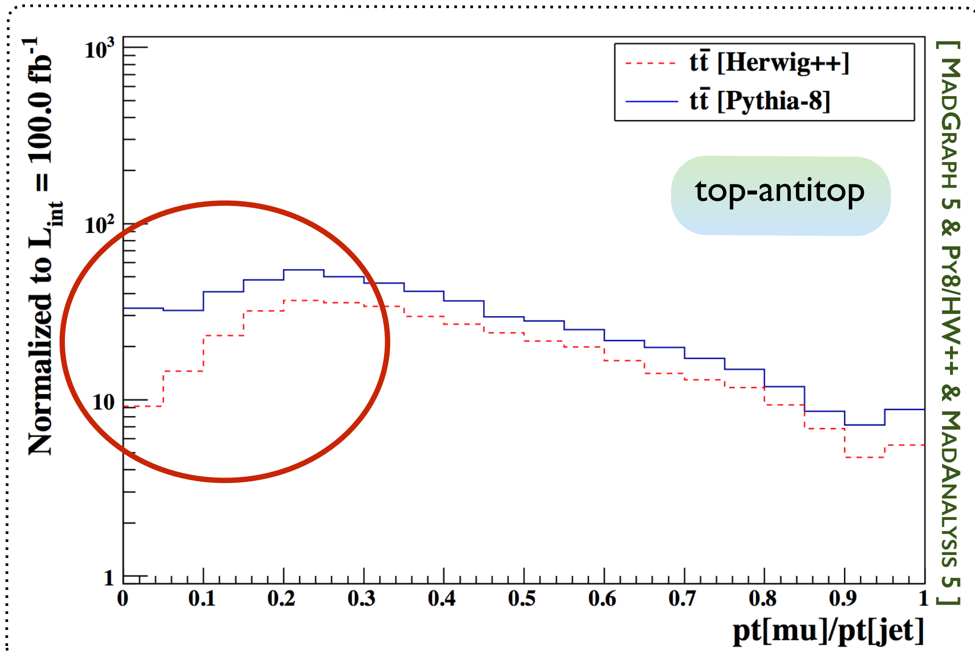
✦ Event selection (differences PYTHIA8 and HERWIG++)

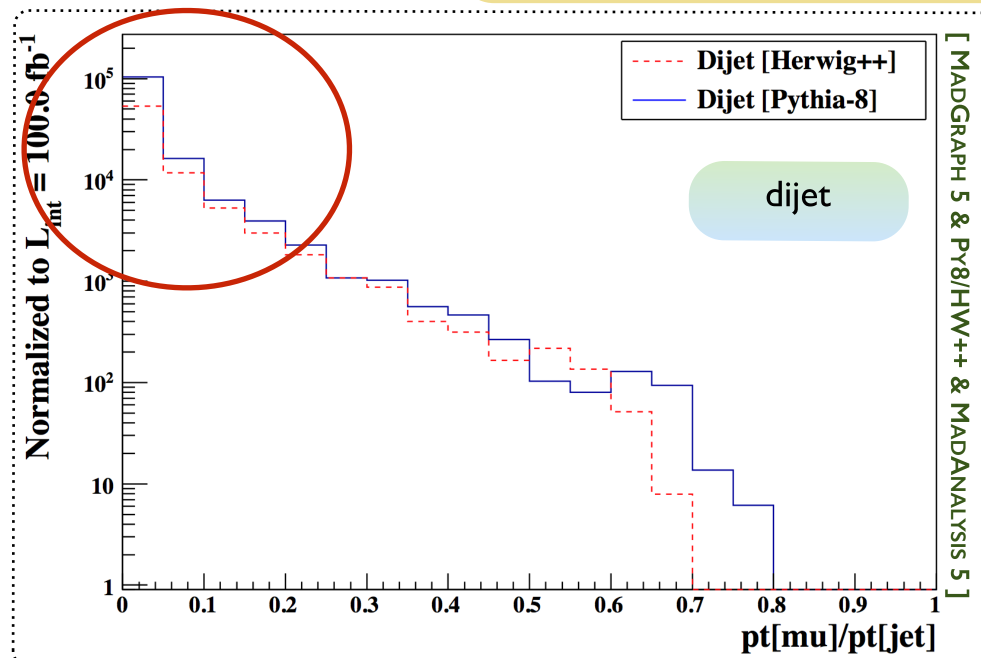
- Jets are reconstructed with a cone of R=0.2 (highly boosted objects are very-well collimated)
- The invariant mass of the system of the two hardest jets is constrained to be above 6 TeV
- The two hardest jets are required to have a p_T larger than 1 TeV and $|\eta| < 2$
- At least one jet with a p_T larger than 1 TeV contains a muon

✦ Signal event kinematics: simple choices are very good

- Hard muon or harder jet requirements are probably not optimal

Implementing a muon selection relatively to the jet p_T





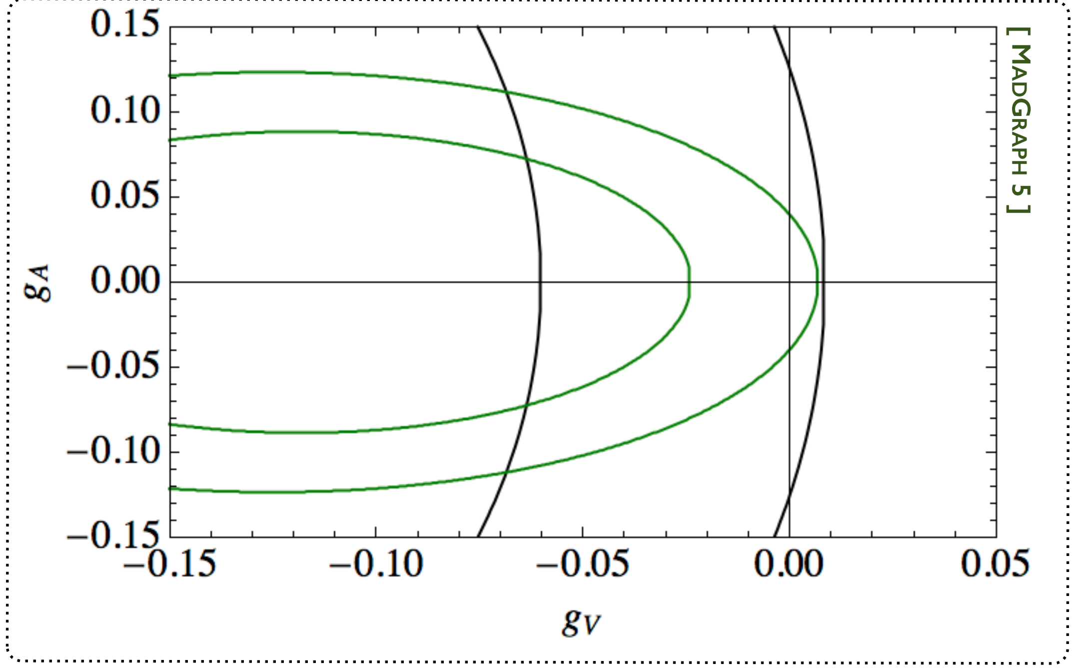
✦ Results

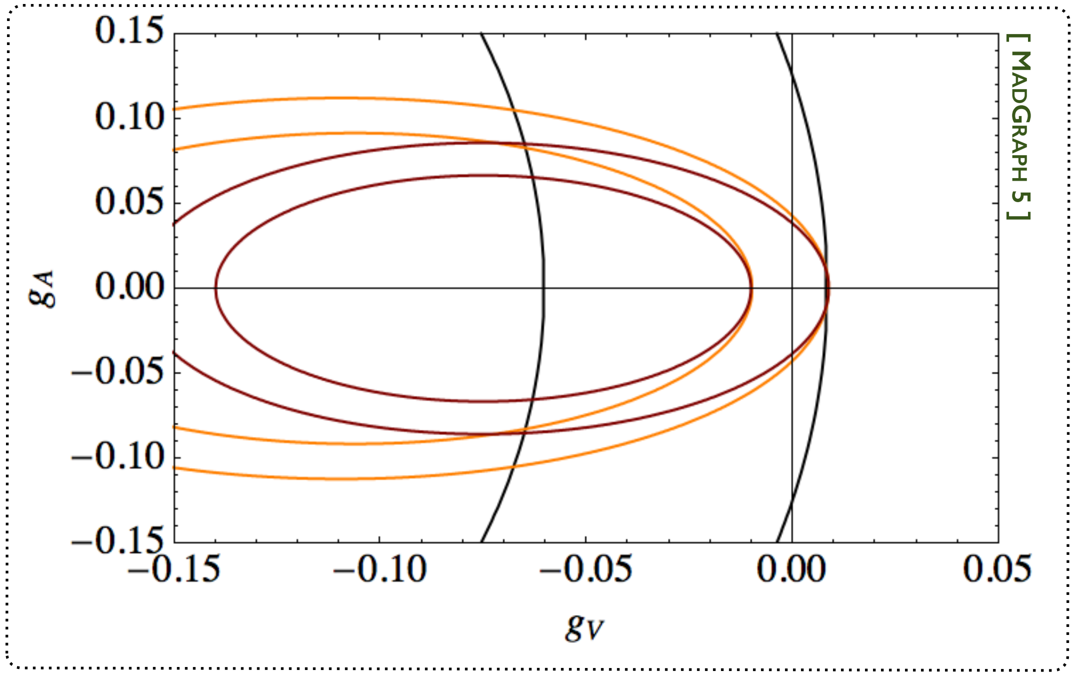
- M_{jj} > 6 TeV: 5σ reachable for 100 fb^{-1} (200-300 signal events)
- M_{jj} > 10 TeV: 5σ reachable for 1 ab^{-1} (100-200 signal events)
- M_{jj} > 15 TeV: 5σ reachable for 10 ab^{-1} (50-200 signal events)

Applications: chromoX moments of the top quark

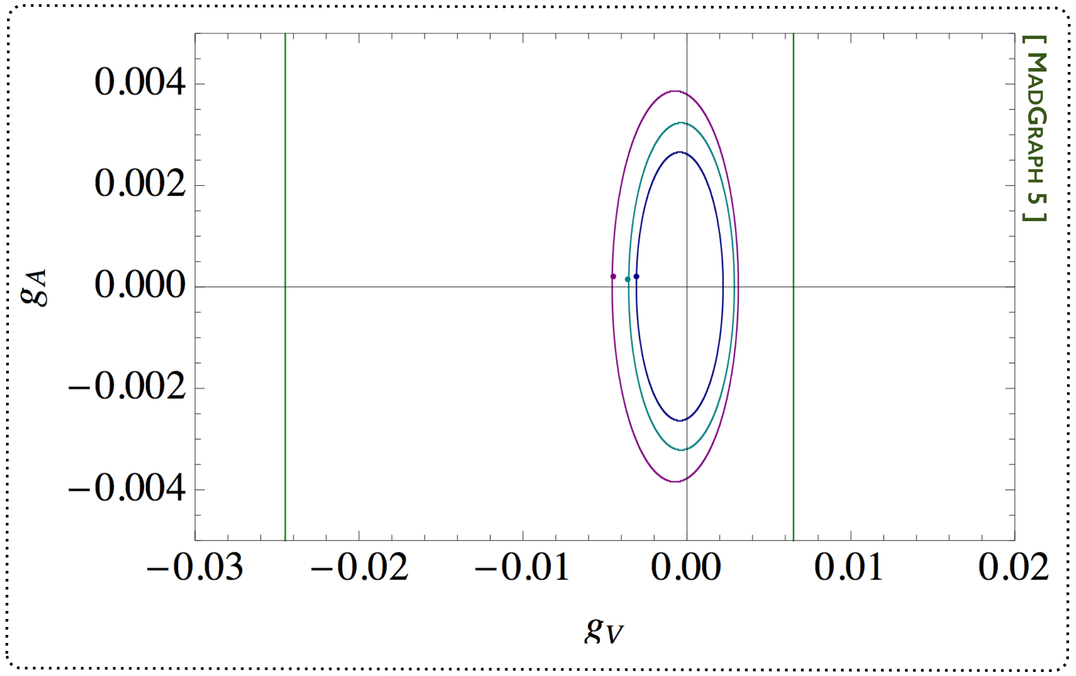
[Aguilar Saavedra, BF, Mangano]

✦ Top chromomagnetic and chromoelectric moments $\mathcal{L} = \frac{ig_s}{m_t} \bar{t} \sigma^{\mu\nu} \left[g_V + i g_A \gamma_5 \right] T_a t G^a_{\mu\nu}$



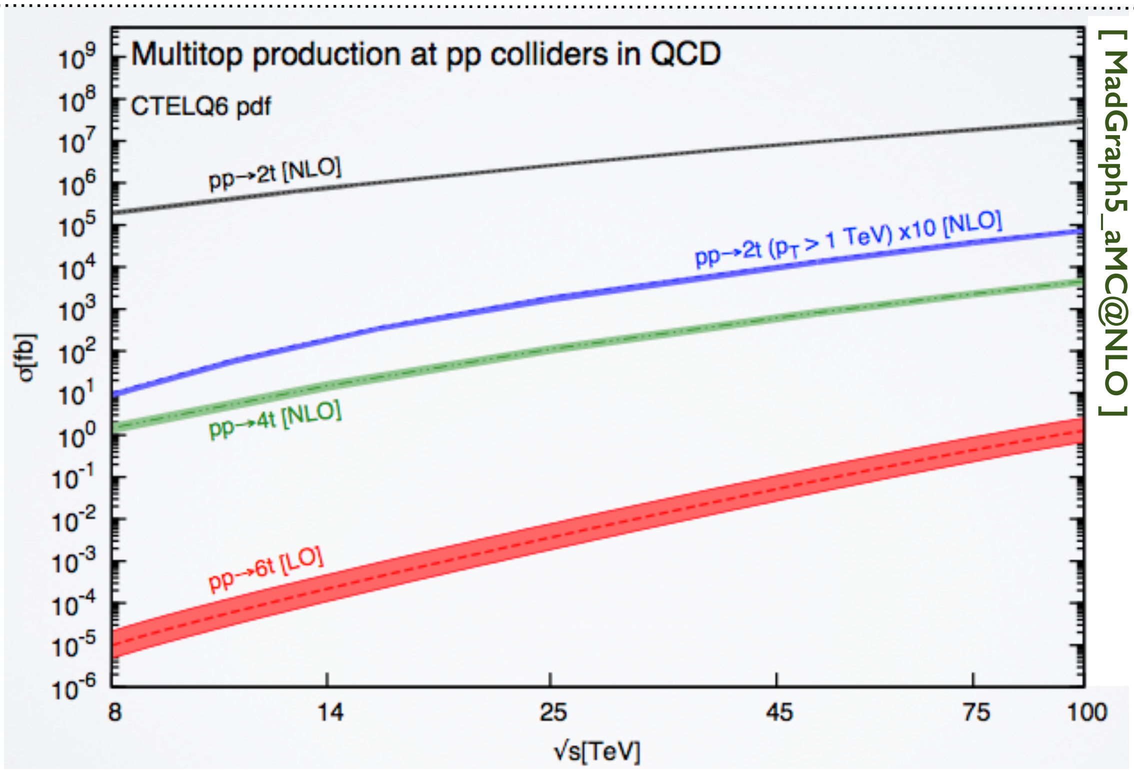


- ✤ Top pair-production total cross sections
  - ➢ constraints on g_A and g_V
- ✤ Existing data: Tevatron; LHC-8
- ✤ Predictions: LHC-14; FCC-100
  - ★ Major improvement not foreseen…
  - ★ LHC: assuming 5% syst. + stat. for 100 fb^{-1}
  - ★ FCC: assuming 5% syst. + stat. for 1 ab^{-1}
- ✤ Using instead highly massive top pairs
  - ★ M_{jj} > 6 TeV or 10 TeV or 15 TeV



Opening the multitop window

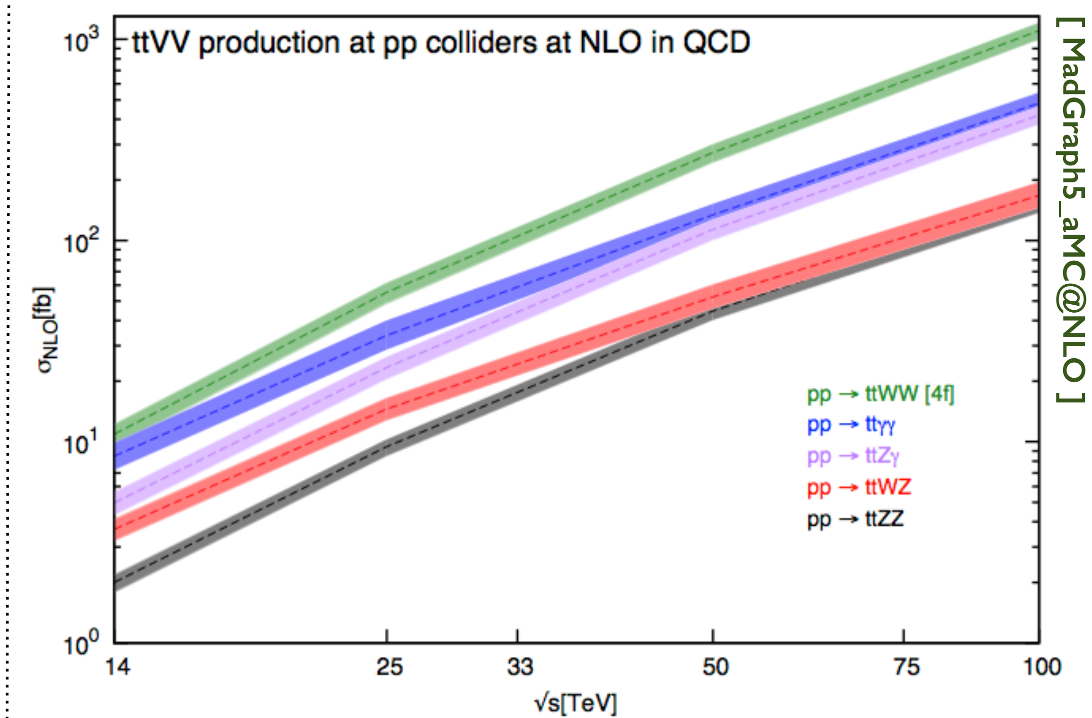
✦ Multitop hadroproduction



- ✤ 100 fb^{-1}: thousands of tttt events (≈5 with 300 fb^{-1} LHC collisions at 14 TeV)
- ✤ Large number of very hard tt pairs

[Deandrea & Deutschmann (JHEP '14)]

✦ Top-antitop production with gauge boson pairs



Process	σ(100 TeV) / σ (14 TeV)
ttWW	≈100
ttγγ	≈60
ttγZ	≈80
ttWZ	≈50
ttZZ	≈70

- ✤ Largest enhancement: ttWW production (≈10000 expected events for 100 fb^{-1})

[Torrielli]

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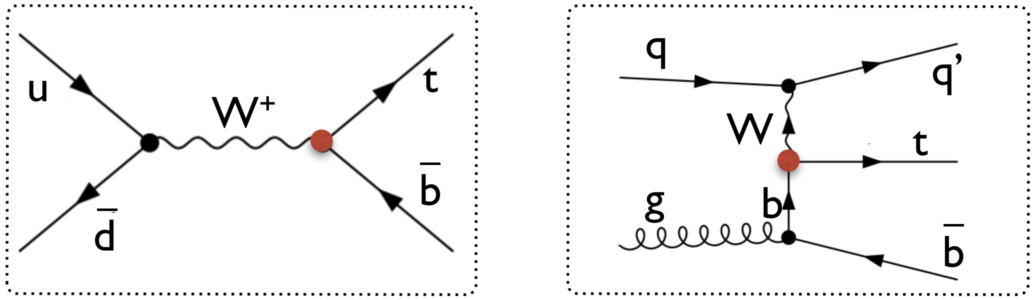
Single top production at 100 TeV

✦ Single top production and W-t-b anomalous couplings

$$\mathcal{L}_{\rm eff} = \frac{g g_R}{2\sqrt{2} m_W} \bar{b}_L \sigma^{\mu\nu} t_R W_{\mu\nu}$$

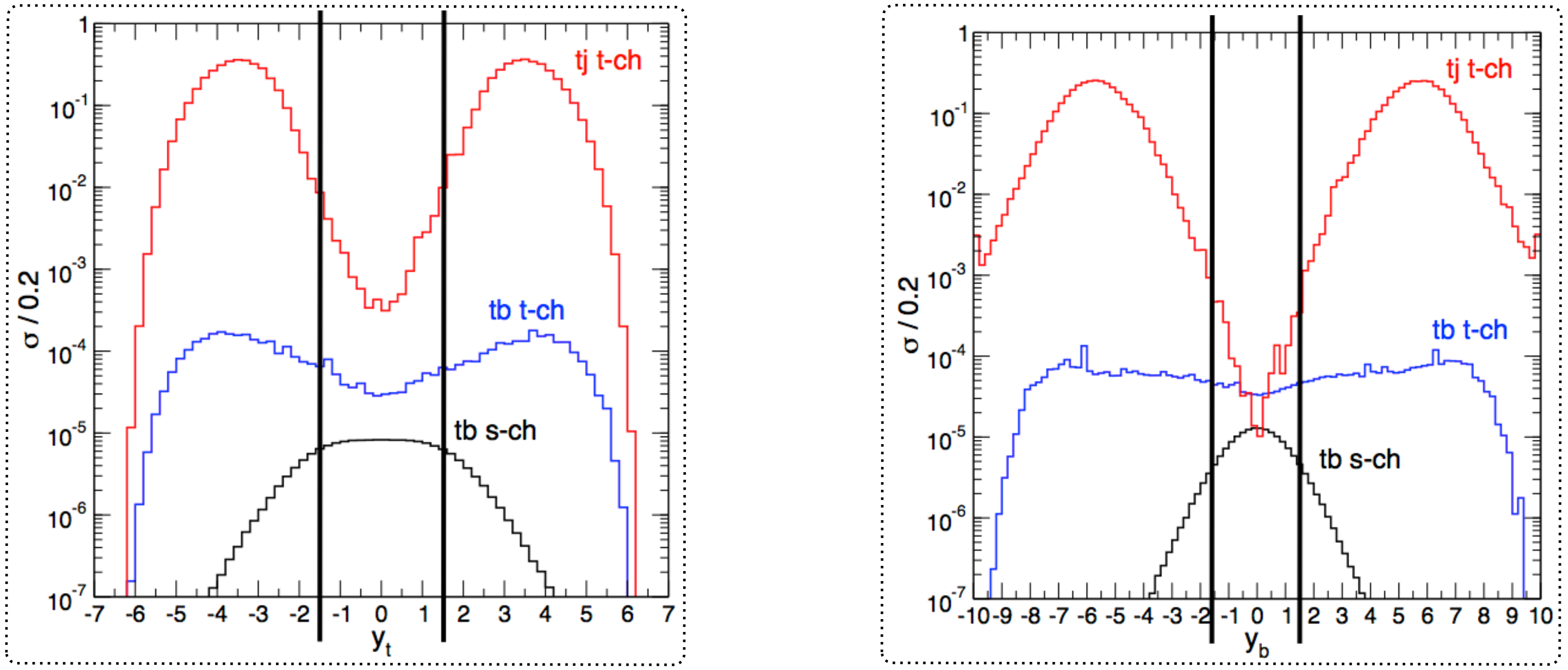
- Production of a top-bottom pair (possibly with extra jets) probe at high momentum transfer
  - ★ New physics effects in W-t-b interactions



✦ Enhancements of the top anomalous coupling contributions

[Aguilar Saavedra, Mangano]

- New physics effects are much larger in the s-channel
  - ★ Suppression of the *t*-channel contributions
  - ★ Requirements of large invariant mass (> 10 TeV) and centrality ($|\eta_{t,b}| < 1.5$)

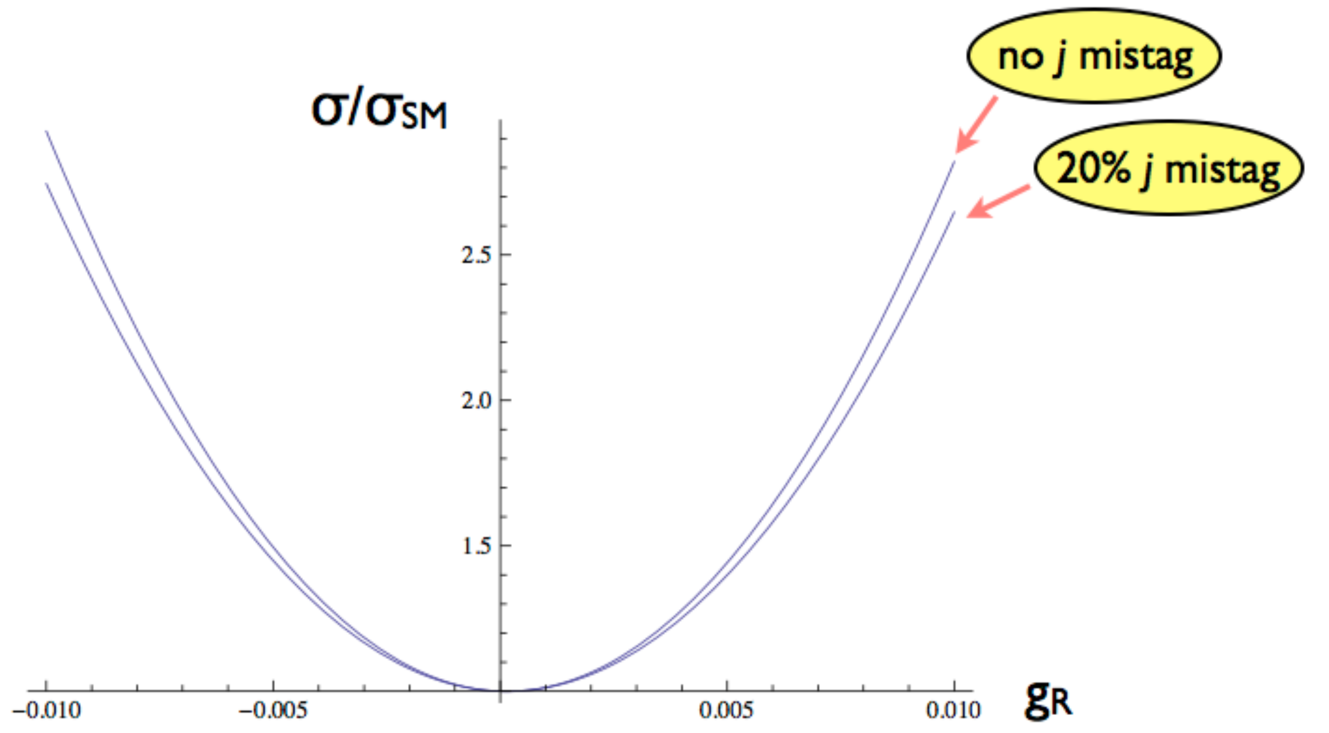


Anomalous W-t-b couplings (2)

$$\mathcal{L}_{\rm eff} = \frac{g g_R}{2\sqrt{2} m_W} \bar{b}_L \sigma^{\mu\nu} t_R W_{\mu\nu}$$

Using top/antitop asymmetries to constrain new physics

- Results for: (number of top) - (number of antitops)
  - Kills the top-antitop contribution (symmetric)



[Aguilar Saavedra, Mangano]

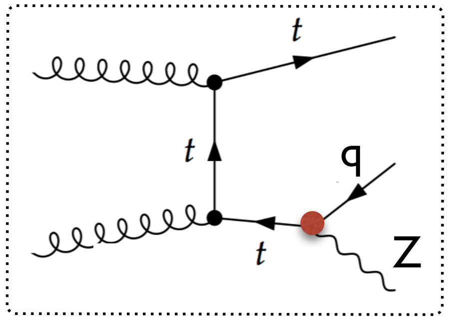
Predictions on the reachable new physics scale

[Aguilar Saavedra, Mangano]

- 10 ab^{-1} of collisions at 100 TeV and statistical uncertainties only: $\frac{\sqrt{2}}{v^2} g_R \in [-0.043, 0.046]\,\mathrm{TeV}^{-2}$
- Projected LHC limit: $[-0.3, 0.3]$ TeV^{-2}
- ILC predictions: $[-0.128, 0.140]$ TeV^{-2} [Aguilar Saavedra, Fiolhais, Onofre (JHEP'12)]
- FCC-ee predictions: $[-0.083, 0.083]$ TeV^{-2}

Rare top decays

- Many decay modes can be probed
  - Decays into a lighter quark (q=u,c) and a boson: t→qZ, t→qh, t→qg, t→qγ, t→q$\not{E}_T$
  - Flavor insensitive (except with charm tagging)
  - GIM suppressed in the Standard Model ➢ observation ≡ new physics
- A rare top decay often implies a rare single top production processes
  - Production allows one to get a handle on the light quark flavour



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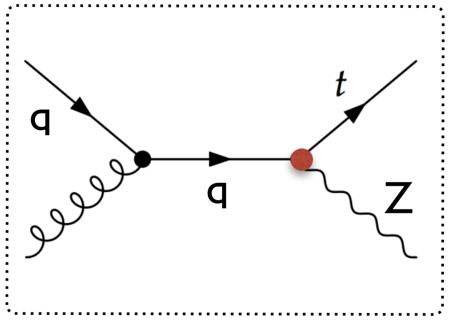
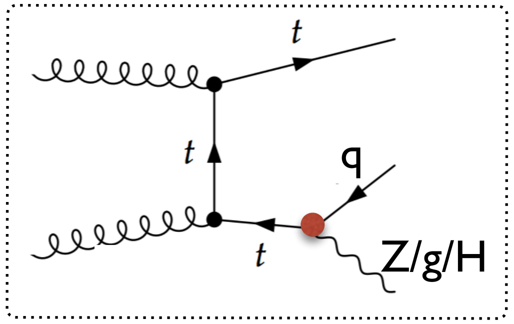


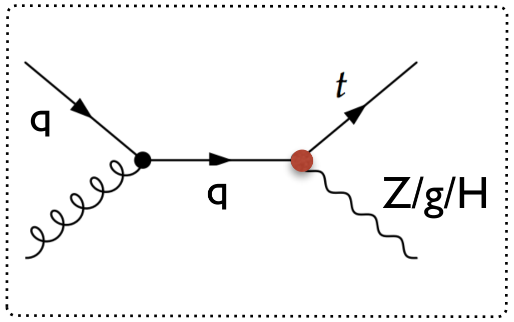
- In general, a rare top decay implies other top decay and production processes
  - *cf.* gauge invariance, in particular within an effective field theory picture
  - Combining different measurements / predictions

How are those new interactions reachable in 100 TeV collisions?

Rate top decays at 8/100 TeV

- New physics can be parameterized via a minimal set of effective operators [Aguilar-Saavedra (NPB '06)]
  - Three examples
    - ★ t-q-Z: $\mathcal{O}^{w}_{LR} = g_2[\bar{Q}_3\sigma^{\mu\nu}\sigma^a\tilde{H}]c_R W^a_{\mu\nu} + \text{h.c.}$
    - ★ t-q-g: $\mathcal{O}^{g}_{RL} = g_s[\bar{Q}_2\sigma^{\mu\nu}\tilde{H}]T^A t_R G^A_{\mu\nu} + \text{h.c.}$
    - ★ t-q-H: $\mathcal{O}^{h^3}_{RL} = [\bar{Q}_2\tilde{H}]t_R(H^\dagger H) + \text{h.c.}$





- ATLAS and CMS bounds (for order one coefficients)

	$t \to c$	$t \to u$
$\mathcal{O}^{w}_{LR}$	$\Lambda > 0.75$ TeV	$\Lambda > 0.75$ TeV
$\mathcal{O}^{g}_{RL}$	$\Lambda > 4.0$ TeV	$\Lambda > 5.8$ TeV
$\mathcal{O}^{h^3}_{RL}$	$\Lambda > 0.73$ TeV	$\Lambda > 0.73$ TeV

- FCC (rough) expectations (statistics rescaling for 10 ab^{-1}) [Zupan *et al.*]

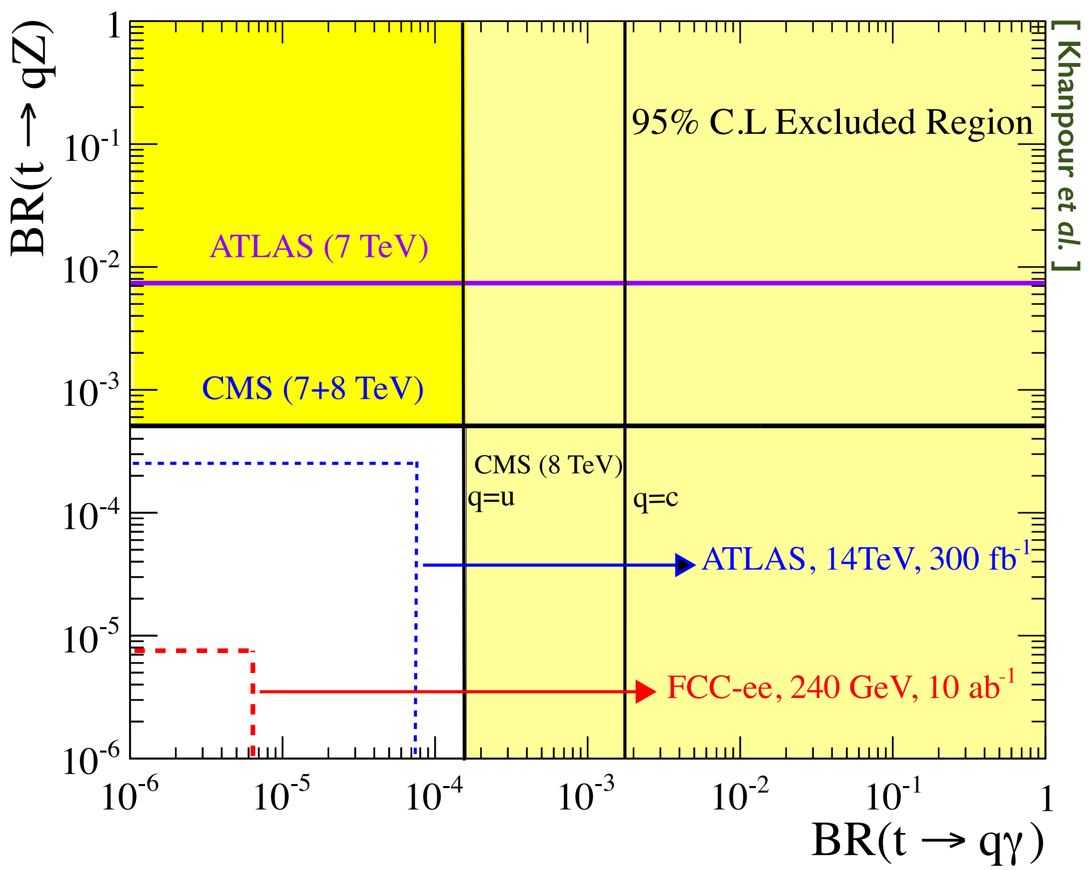
	$t \to c$	$t \to u$
$\mathcal{O}^{w}_{LR}$	$\Lambda \gtrsim 13$ TeV	$\Lambda \gtrsim 13$ TeV
$\mathcal{O}^{g}_{RL}$	$\Lambda \gtrsim 70$ TeV	$\Lambda \gtrsim 80$ TeV
$\mathcal{O}^{h^3}_{RL}$	$\Lambda \gtrsim 13$ TeV	$\Lambda \gtrsim 13$ TeV

- Assumes same FCC and LHC efficiencies: very large new physics reach
- Ignores background scaling from 8 TeV to 100 TeV
- Maybe too naive…

Rate top decays: also an FCC-ee physics case

✦ FCNC production of a top and a light quark

✤ At a center-of-mass energy of 240 GeV

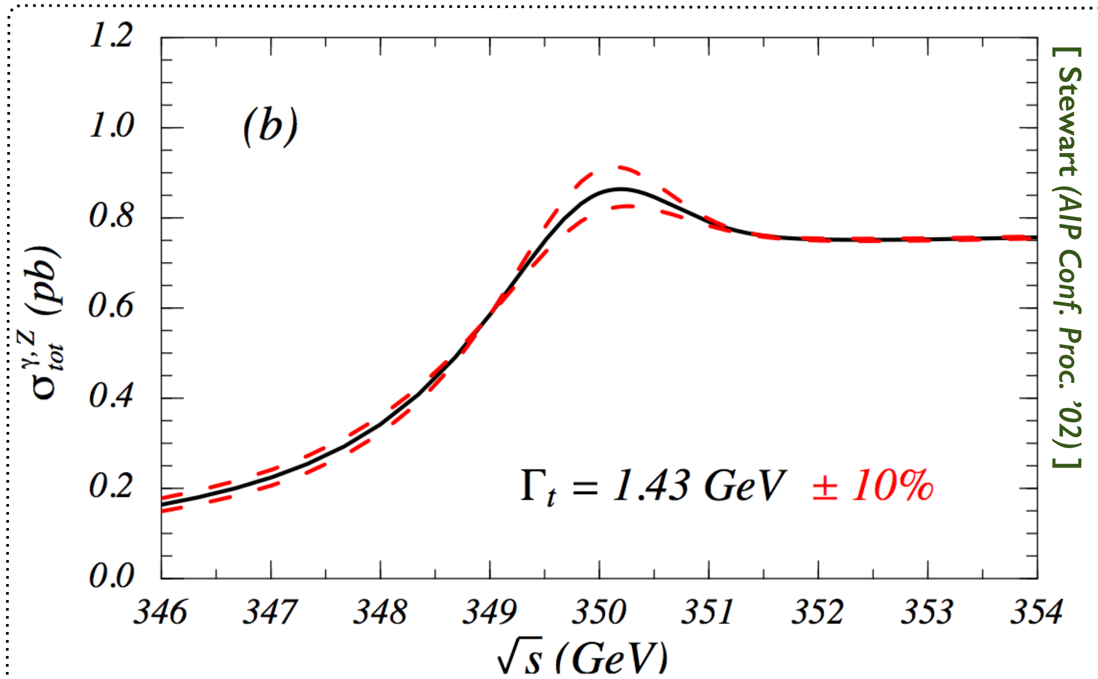


✤ Gain of 1.5 order of magnitude w.r.t. LHC

✦ Inclusive approach via $t\bar{t}$ production cross section

✤ At a center-of-mass energy of 350 GeV

✤ Five-year scan of the top-antitop threshold



[TLEP Design Working Group (JHEP'14)]

	$m_{\rm top}$	$\Gamma_{\rm top}$	$\lambda_{\rm top}$
TLEP	**10 MeV**	**11 MeV**	**13%**
ILC	31 MeV	34 MeV	40%

✤ Indirect constraints from the top width

★ Constraining the magnitude of the rare decay modes

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Constraints on parton densities at 100 TeV

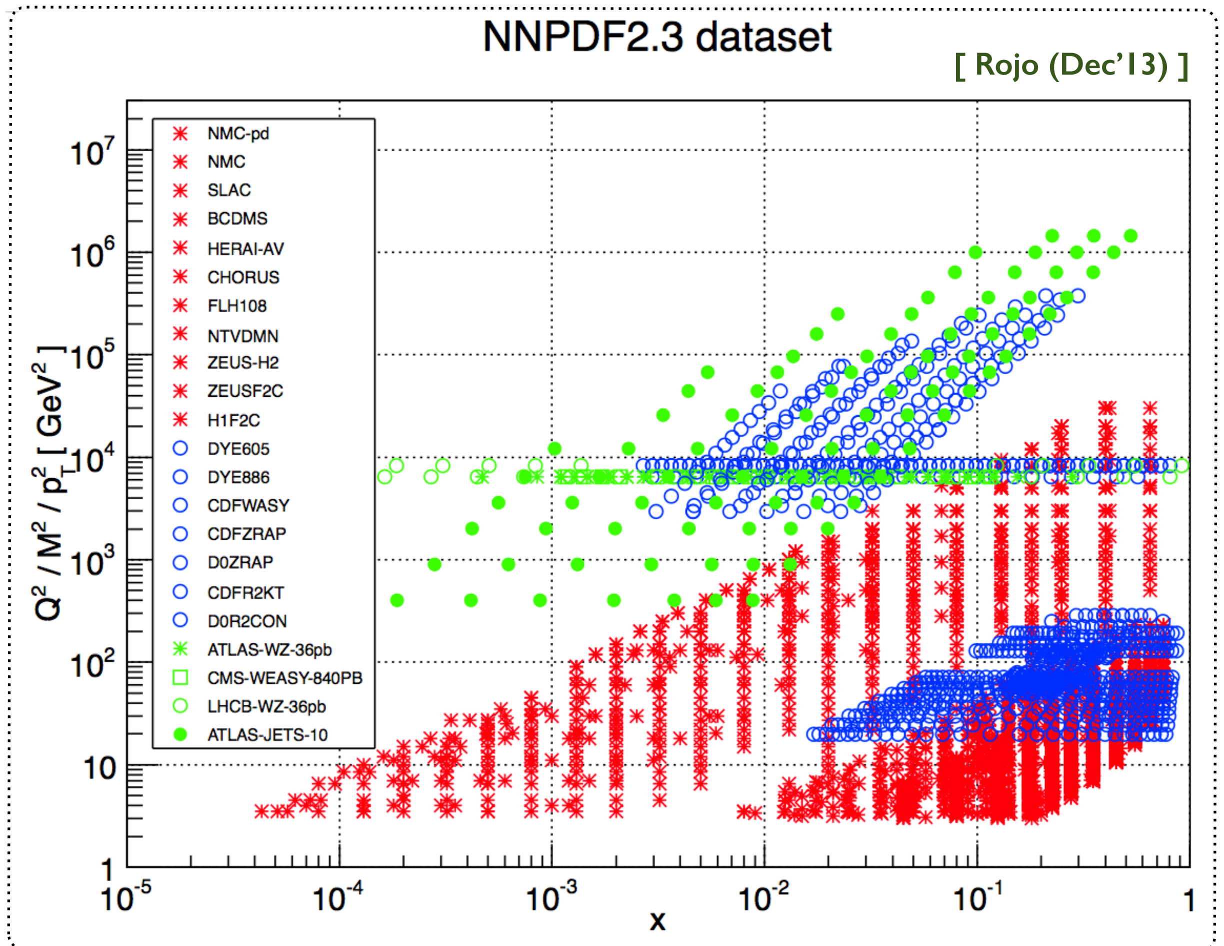
[NNPDF (NPB '13)]

✦ Major changes from a center-of-mass energy of 14 TeV to 100 TeV

- ✤ Probes PDFs at lower momentum fractions x when producing a system of invariant mass M
  - ★ Heavy particles requiring large-x PDFs at the LHC can now be produced with medium-x PDFs
    - ➢ Smaller uncertainties
- ✤ Higher masses can be probed for a given momentum fraction x
- ✤ A new kinematical regime opens for lighter systems production

✦ Drawbacks

- ✤ No constraints for $x < 10^{-4}$
  - ➢ Region never probed; relies on extrapolations
  - ➢ BFKL effects must be accounted for
- ✤ Few constraints on higher x-values
  - ➢ Small coverage of the high-scale region
  - ➢ No constraints for $M > 1$ TeV
  - ➢ Region never probed; relies on DGLAP evolution
- ✤ The top quark density is now relevant
  - ➢ Must be included in the evolution equations
- ✤ Electroweak effects required for larger scales
  - ➢ Evolution including QED and weak corrections
  - ➢ Electroweak boson PDFs



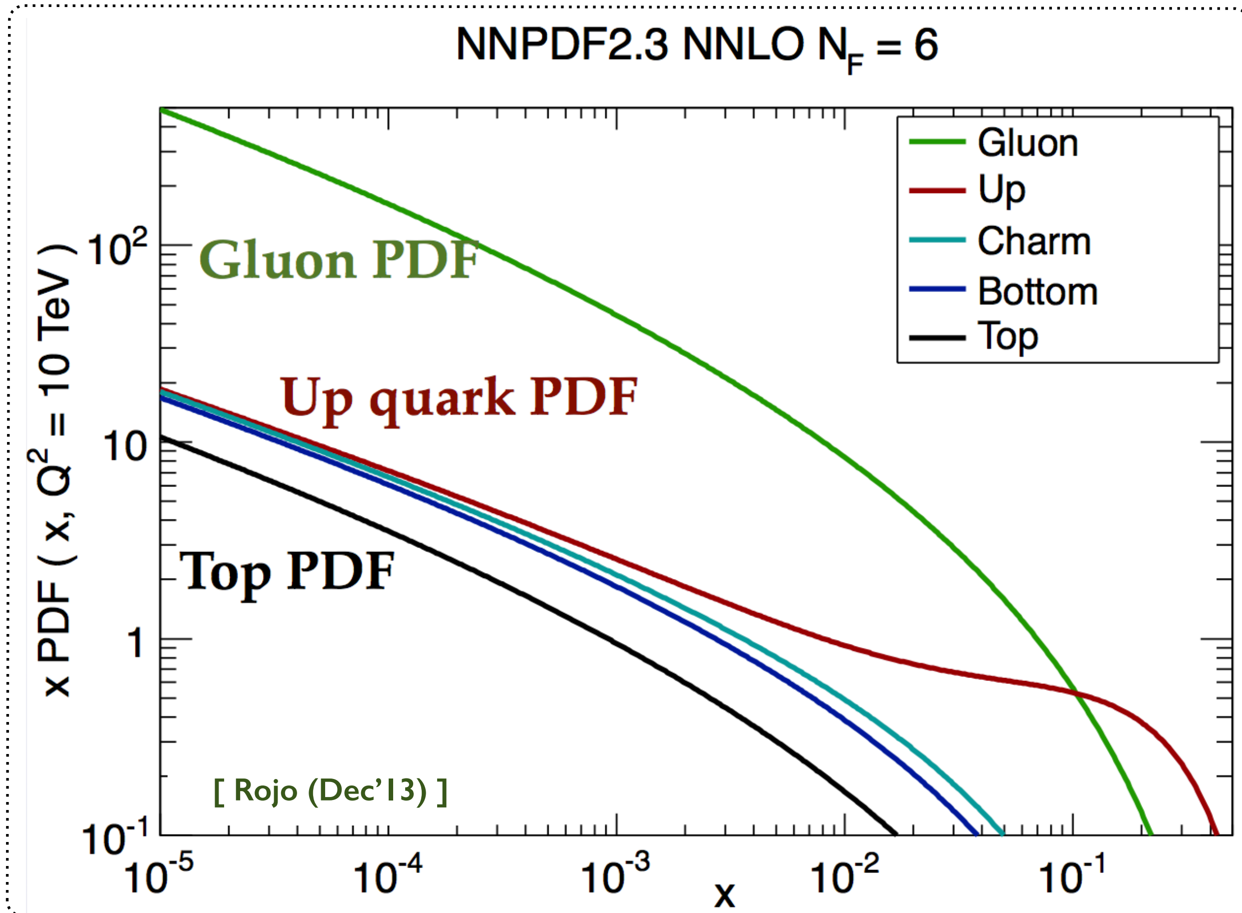
[Rojo (Dec'13)]

The top density at 100 TeV

[NNPDF (NPB '13)]

✦ Top quark parton densities

- ✤ At higher scales, the top can be seen as massless
- ✤ Top PDFs can be generated from gluon spitting
  - ➣ Like for charm and bottom
  - ➣ Resummation of the corresponding collinear logs
- ✤ Effects on other densities
  - ➣ Coupled DGLAP equations
  - ➣ Example: 4% effect on the gluon density
- ✤ The top density is not small
  - ➣ Factor of two smaller than the charm
- ✤ Vanish for scales below the top mass



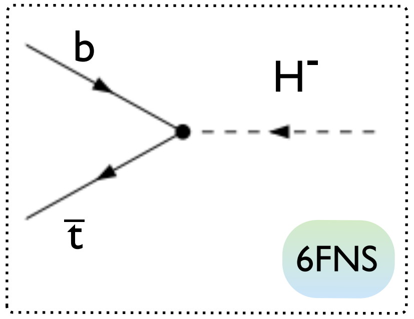
Five-flavor-number (5FNS) and six-flavor-number (6FNS) schemes

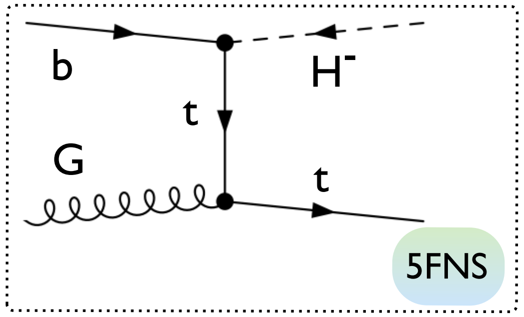
✦ Differences between the two schemes

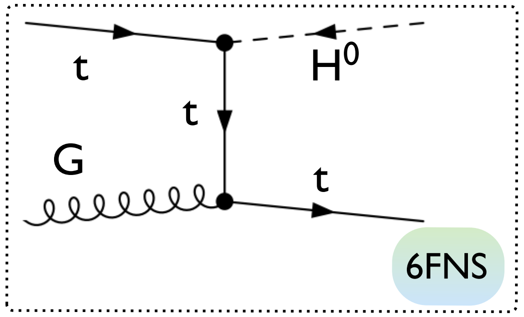
- The differences are related to logarithms of the form $\log(Q^2/m_t^2)$
  - ★ 6FNS: resummation of the logarithms, that are assumed large, into a top density
  - ★ 5FNS: no specific treatment of the logarithms (possible spoiling of the perturbative series)
  - ★ Computations in the 6FNS are simpler (fewer external legs and massless top quarks)
- 5FNS and 6FNS are two alternative organizations of the perturbative series in appropriate regimes
  - ★ Results identical at all orders
- Interpolation possible
  - ★ Is the 6FNS necessary?
  - ★ Do we have to resum logarithms of the top mass?
- Similar issue at the LHC: 4FNS *versus* 5FNS [Maltoni, Ridolfi, Ubiali (JHEP '12)]
  - ★ The logarithms are mild for large classes of processes
  - ★ Predictions in the two schemes usually agree within uncertainties (with appropriate scale choices)
  - ★ 5FNS better for total rates, 4FNS for differential distributions

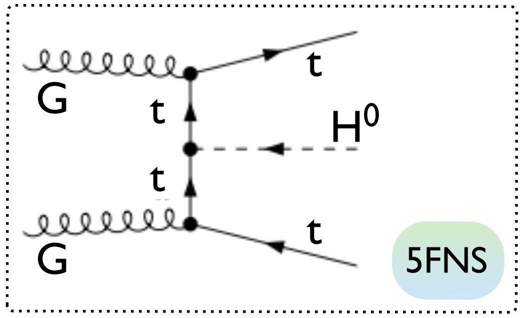
✦ Example for 100 TeV collisions: charged and neutral heavy Higgs production

- $2\to1$ ($2\to2$) leading order process in the 6FNS, $2\to2$ ($2\to3$) in the 5FNS





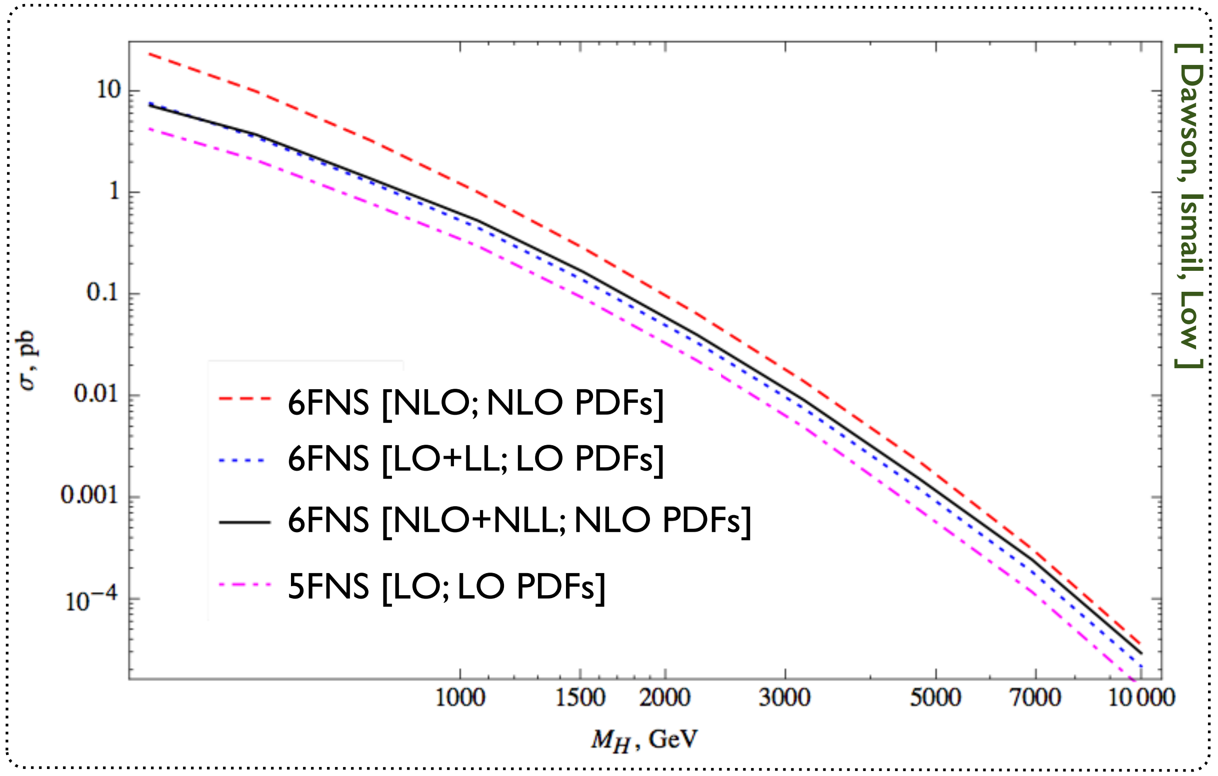




Charged Higgs production (at 100 TeV) in the 5FNS and 6FNS

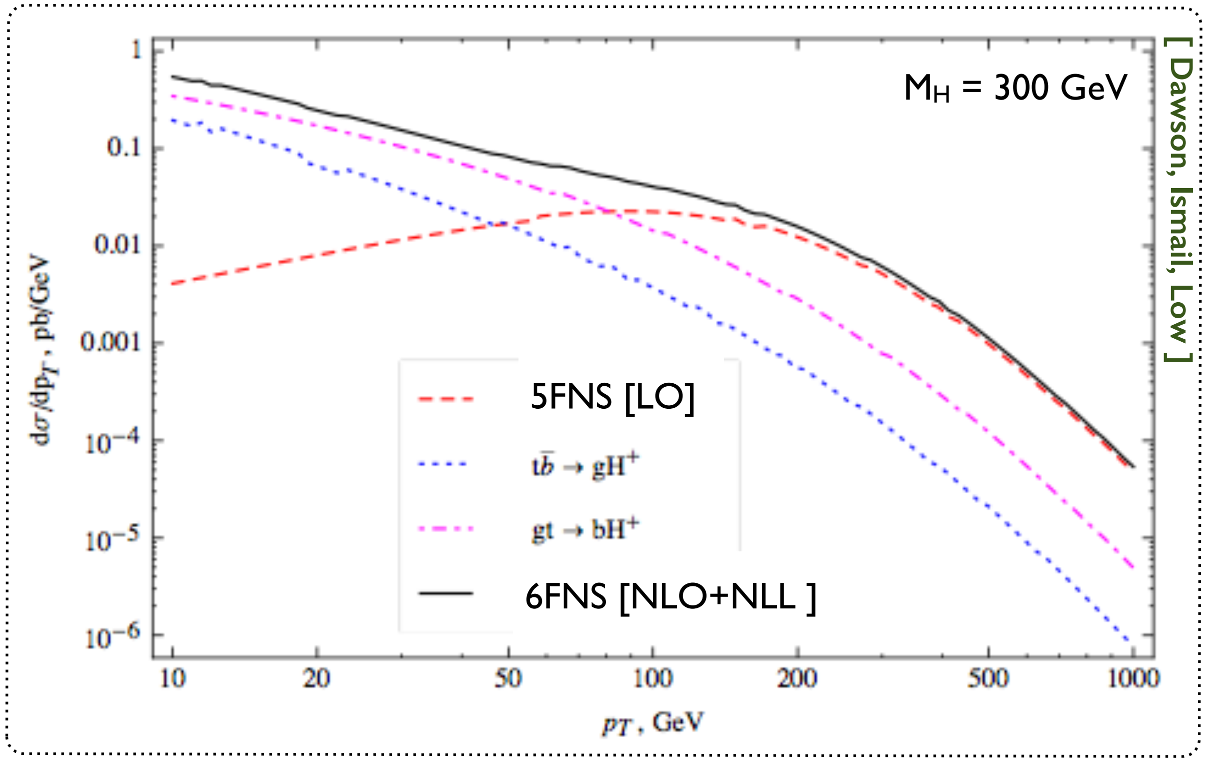
[Dawson, Ismail, Low (PRD '14)]

✦ Total cross section and transverse momentum distribution for charged Higgs production



✤ 5FNS and 6FNS-NLL predictions differ by 2-3
- ★ 6FNS-unmatched overestimates the rate
- ★ Use of 6FNS alone is not justified
- ★ 6FNS-(N)LL includes matching with 5FNS results
- ★ Fair agreement when adding scale uncertainties

✤ Reduced effects of the logarithms
- ★ From 6FNS results @LO+LL and @NLO+NLL
- ★ Much smaller than for the bottom or charm cases



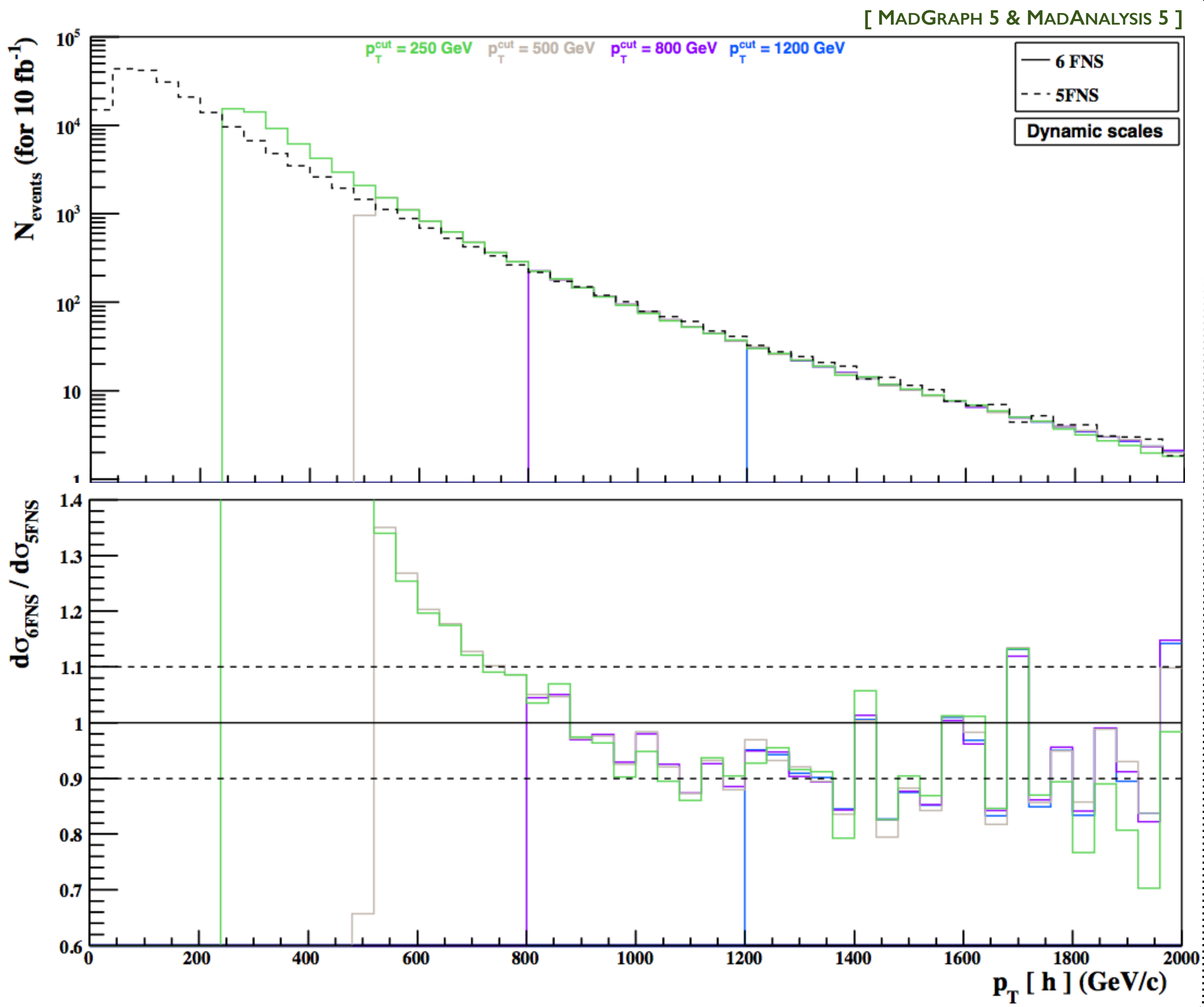
✤ Reliability of the 5FNS results
- ★ Reliable in the large p_T region (top mass effects)
- ★ Not sufficient in the low p_T region
- ★ The turnover is dictated by the top mass value
- ★ 5FNS-NLO more difficult than a 6FNS-NLL calculation

✤ Main differences with the bottom case (4FNS)
- ★ Small m_b: reliable 4FNS results over a large p_T-range

Neutral Higgs production (at 100 TeV) in the 5FNS and 6FNS

[BF, Mangano, Melia, Rojo]

✦ Total cross section for neutral Higgs production (enforcing a hard final state top)



✤ Higgs transverse-momentum spectrum

★ Dynamic scales: average final state particle transverse mass

★ No top PDFs for scales lower than m_t

★ 10% agreement for sufficiently high p_T cuts

Both schemes agree for p_T cuts larger than 500 GeV

✤ 6FNS *versus* 5FNS

★ Calculations easier in the 6FNS

★ Exclusive observables: the 6FNS may fail

★ 5FNS/6FNS choice driven by the relevant phase-space regions

★ 6FNS-unmatched gives incorrect rates for total cross sections

Outline

1. Future Circular Colliders at CERN
2. Top pair and multitop production
3. Rare and single-top processes: flavor changing neutral currents
4. Parton densities
5. Conclusions - summary

Opportunities for top physics at Future Circular Colliders

✦ Pushing the energy frontier to higher and higher values

- ✤ High priority within the European Strategy for particle physics
- ✤ Circular high energy colliders are suitable machines

✦ New window for top-pair production studies

- ✤ Billions of top-antitop pairs will be produced
- ✤ Top-antitop systems with a very large invariant mass will be probed
- ✤ Have to deal with a super-boosted regime (new techniques to be developed)
- ✤ New handles on new physics

✦ Single top and top FCNC

- ✤ Top FCNC are possible sources for new physics
- ✤ Stronger constraints on any associated new physics effective operator
- ✤ Opens the door of a new kinematic regime

✦ Parton densities

- ✤ The top content of the proton will be probed
- ✤ 6FNS *versus* 5FNS problematics