Top dipole moments, parton densities and polarized proton collisions at 100 TeV

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With J.A. Aguilar-Saavedra and M.L. Mangano: arXiv:1412.6654 [hep-ph]
With J. Proudom, J. Rojo and I. Schienbein: JHEP 1405 (2014) 045

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Exploring the Physics Frontier with Circular Colliders

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Outline

1. Top dipole moments at past, present and future colliders
   - Definition and conventions
   - Tevatron and LHC constraints
   - Future circular collider sensitivity

2. Motivating polarized proton-proton collisions at 100 TeV
   - New physics and polarized proton collisions
   - Polarized parton densities
   - Polarizing the FCC - physics cases

3. Conclusions

Top dipole moments in a nutshell

✦ Prospects for Run II and future accelerators

- ✤ Great expectation for new physics discovery
- ✤ Could be indirectly found: precision measurements of the Standard Model properties
  - ★ Important role of the top quark (top mass close to the electroweak scale)
  - ★ Intense research program dedicated to the top properties: in particular the dipole moments

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

- ✤ Parameterized by adding to the Standard Model $\mathcal{L}_{\rm tg} = \frac{g_s}{m_t} \bar{t} \sigma^{\mu\nu} (d_V + i d_A \gamma_5) \frac{\lambda_a}{2} t\, G^a_{\mu\nu}$
- ✤ Generated by the dimension-six effective operator $O^{33}_{uG\phi} = (\bar{q}_{L3} \lambda_a \sigma^{\mu\nu} t_R) \tilde{\phi}\, G^a_{\mu\nu}$

✦ 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

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

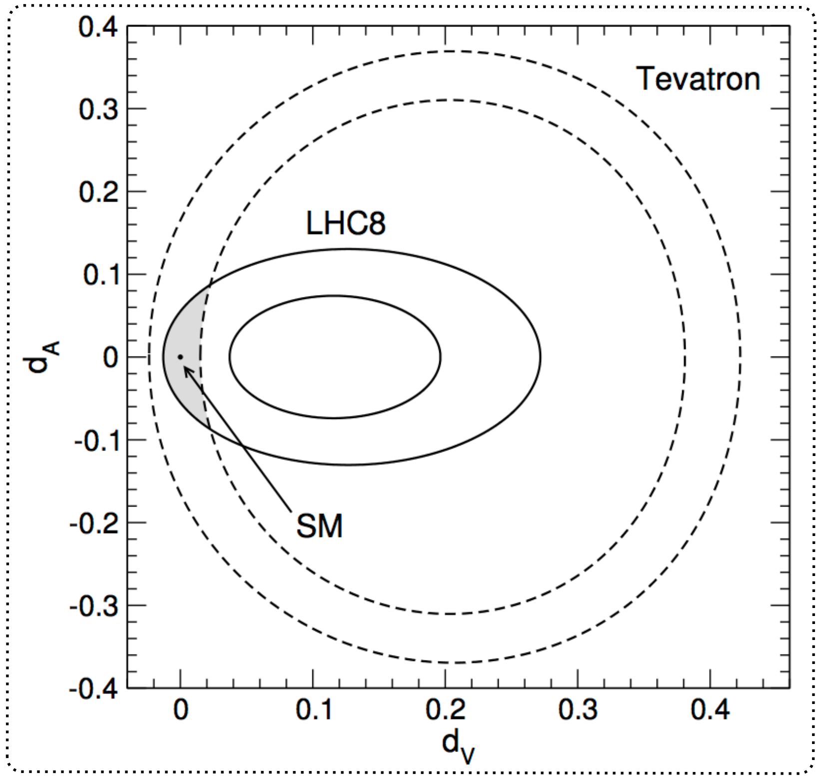
$|\, d_A \,| \leq 1.2\ 10^{-3}$ @ 95% CL
$-3.8\ 10^{-3} \leq d_V \leq 1.2\ 10^{-3}$ @ 95% CL

Top dipole moments at the Tevatron and the LHC

- Top-antitop total production 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
  - Standard Model predictions defined by $(d_V,d_A) = (0,0)$
  - Favored parameter space regions: different shapes
  - Combination more constraining than a single collider

$|d_A| \leq 8.7\ 10^{-2}$

$-1.2\ 10^{-2} \leq d_V \leq 2.3\ 10^{-2}$



Possible improvements at LHC-14

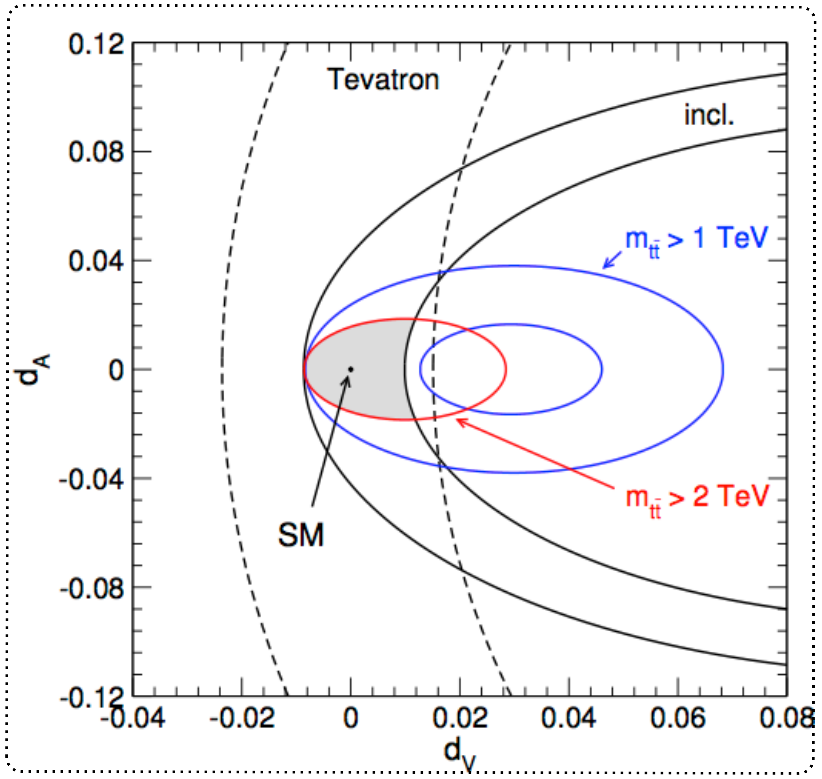
- Important amount of top-antitop pairs to be collected
  - Going beyond the use of total rate measurements
  - Benefitting from differential cross sections
- Three representative cases
  - (1) Total rate
  - (2) Production rate of top-antitop systems with $m_{tt} > 1$ TeV
  - (3) Production rate of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

- Heavy top-antitop systems
  - Enhanced sensitivity to top dipole moments (large momentum transfer favored)
  - More statistically challenged
- Rely on boosted top tagging techniques to reject multijet background
  - Boosted top similar to boosted jet
  - Restriction to the central part of the detector ($|\eta| < 2$)
    - ★ Better detector granularity ➢ better background rejection
  - Choice: CMS WP3 [CMS-PAS-JME-13-007]
    - ★ $\approx$ 12% of tagging efficiency
    - ★ $\approx$ 0.03% of mistagging rate of a QCD jet as a top quark

LHC-14 prospects on top dipole moments

- 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:

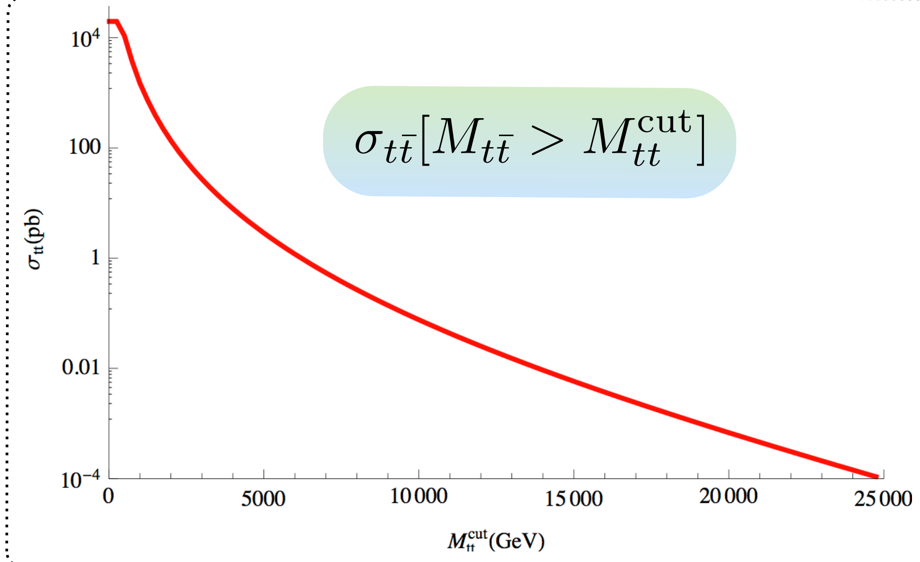
$|d_A| \leq 1.9\ 10^{-2}$
$-8.6\ 10^{-3} \leq d_V \leq 1.2\ 10^{-2}$ ⇔ $\Lambda > 5$ TeV



Observing boosted top-antitop pairs at 100 TeV

✦ Production of a significant number of heavy top-antitop systems (tops are boosted)

- Jet substructure identification tied to detector details
  - ★ Heavily boosted objects are very collimated
  - ★ 5 TeV top: decays products in an R≈0.05 cone
- New techniques will have to be designed
  - ★ Potential improvement of our results
- Safe and robust feature for any detector design
  - ★ Muon properties (different in top and QCD jets)
  - ★ QCD muons: softer (from B- and D-decays)
  - ★ Top muons: harder (prompt decays)



✦ Event selection

- Only jets with p_T > 1 TeV and |η| < 2 are retained, and at least one of them must contain a muon
- The invariant mass of the two hardest jets system m_{tt} is constrained to be above XX TeV

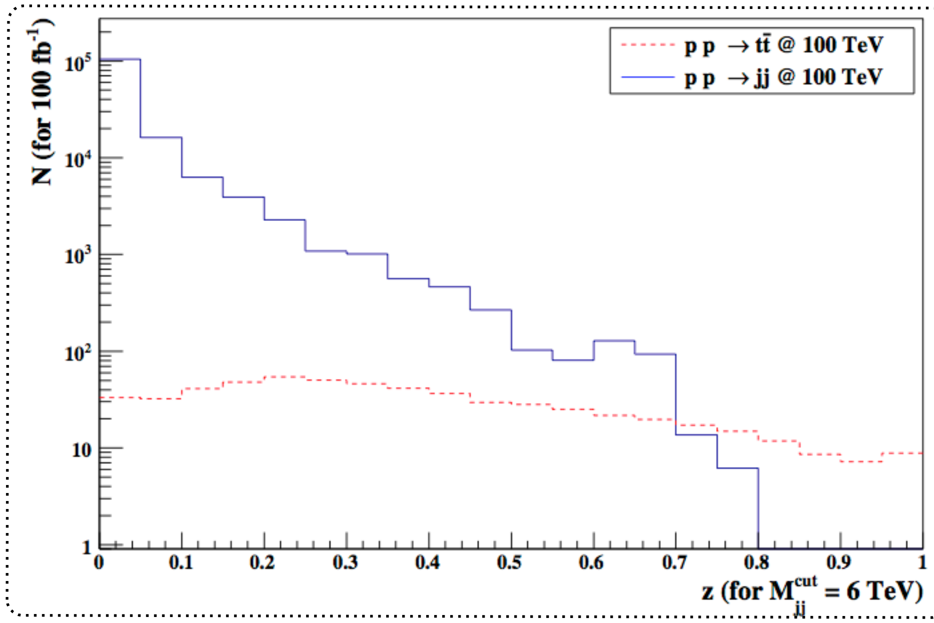
✦ Key observable: the muon p_T relative to the jet p_T

- For a given event: all muons are considered

$$z = \max_{i=1,\dots,n} \frac{p_T(\mu_i)}{p_T(j_i)}$$ (Figure: XX = 6 TeV)

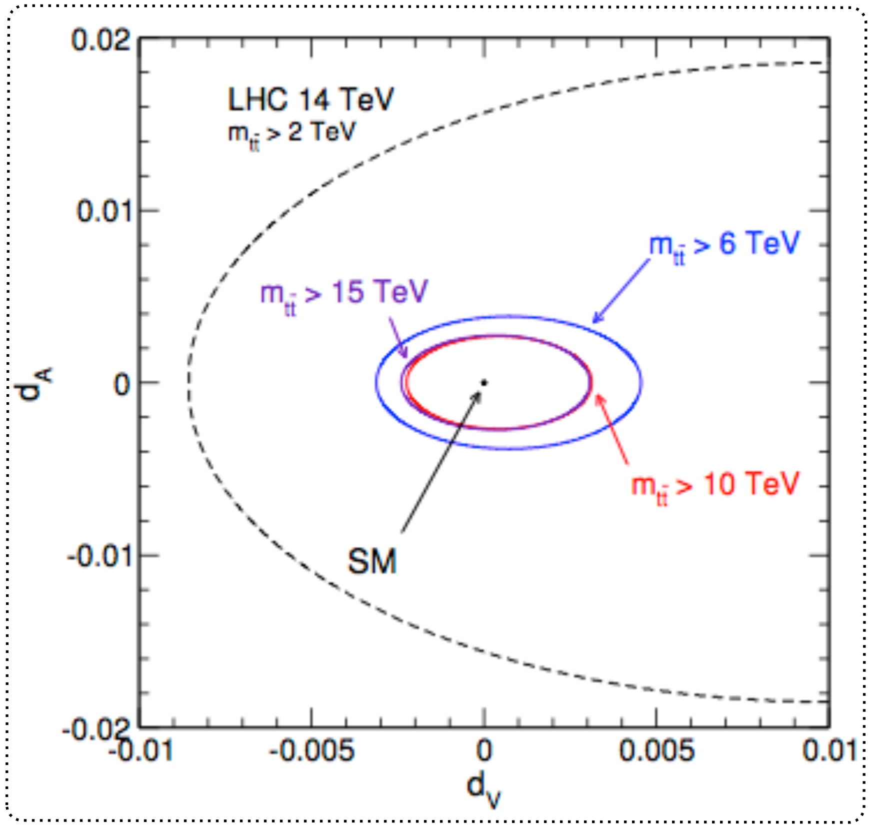
✦ Results for observing heavily boosted $t\bar{t}$ systems

- XX = 6 TeV: z>0.5 ⇔ 5σ reachable for ≈35 fb^{-1}
- XX = 10 TeV: z>0.5 ⇔ 5σ reachable for ≈200 fb^{-1}
- XX = 15 TeV: z>0.4 ⇔ 5σ reachable for ≈2 ab^{-1}



FCC prospects on top dipole moments

- FCC predictions (for 10 ab^{-1})
  - Dashed black: LHC-14 with 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



- Larger center-of-mass energy and luminosity
  - Gain of one order of magnitude (for m_{tt}>10 TeV)

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

- Reminder: current constraints

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Polarized proton-proton collisions at RHIC

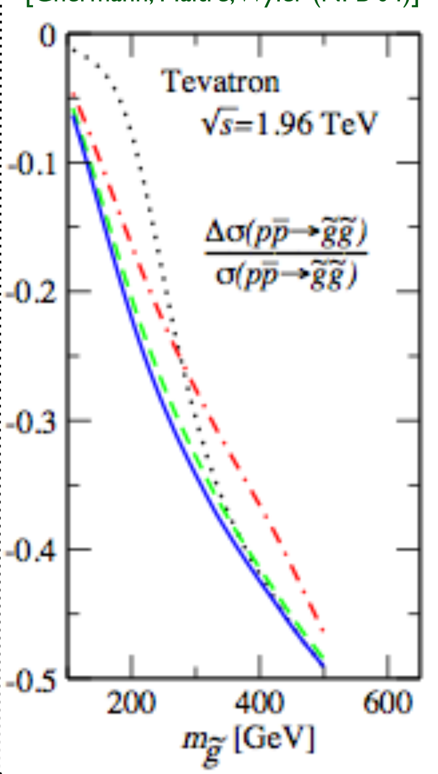
- ✦ The RHIC case (focusing on the proton-proton mode)
  - ✤ A successful machine
    - ★ A center-of-mass energy ranging of 200 GeV and 500 GeV
    - ★ 11 runs (1.3 fb^{-1})
    - ★ Beams polarized at 70%-80%
  - ✤ Spin structure of the proton:
    - ★ Measuring flavor-identified quark and antiquark contributions to the proton spin
    - ★ Probing gluon polarization
  - ✤ No new physics experimental studies - several phenomenological works

- ✦ Phenomenological works → RHIC's capabilities for constraining/discovering new physics
  - ✤ Deviations from QCD in contact interactions [Taxil & Virey (PRD'97)]
    - ★ TeV-scale new physics leads to a different sign in double-spin asymmetries (dijet production)
  - ✤ Leptophobic gauge bosons in dijet production [Taxil, Tugcu & Virey (EPJC'02)]
    - ★ Single spin-asymmetry in $\sqrt{s}$ = 500 GeV collisions
  - ✤ Single spin asymmetries in squark and gluino production [Ghermann, Maître & Wyler (NPB'04)]
    - ★ Extracting the squark and gluino masses
  - ✤ Light sleptons, charginos and neutralinos production [Bozzi, BF & Klasen (PLB'04); Debove, BF & Klasen (PRD'08)]
    - ★ Constrains on the supersymmetry-breaking parameters from single spin-asymmetries

Polarized pp collisions at the LHC and the Tevatron

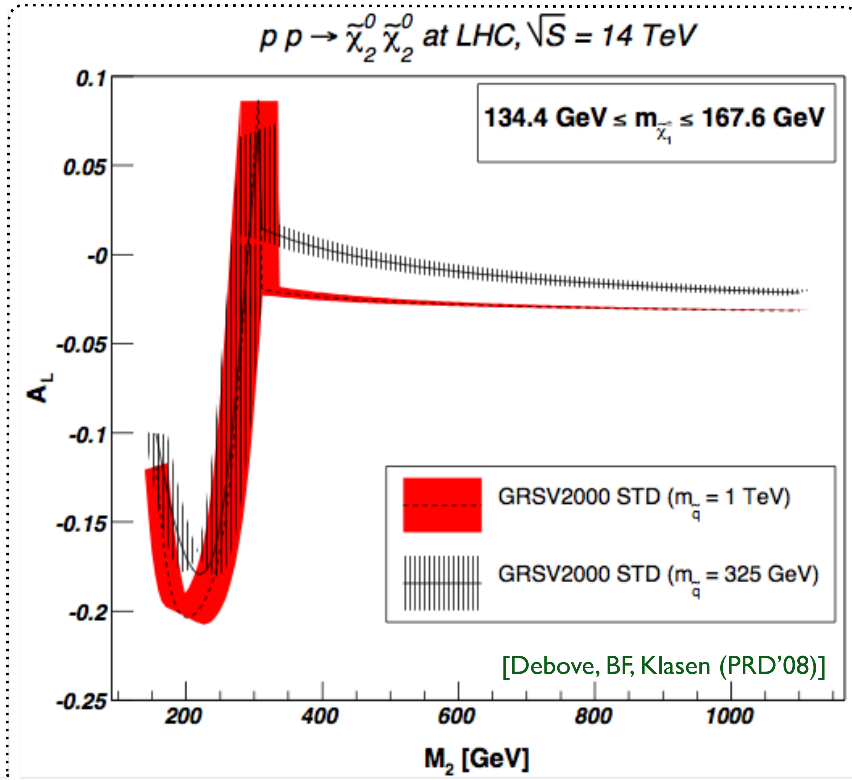
- ✦ Spin asymmetries could have provided useful information in the context of new physics
  - ✤ New physics is likely to be heavy: RHIC luminosity and $\sqrt{s}$ are not large enough

[Ghermann, Maître, Wyler (NPB'04)]



- ✦ Polarization of the Tevatron beams
  - ✤ Proposal to polarize one of the beams [SPIN collaboration (1995)]
  - ✤ Interesting case for new physics: large spin asymmetries ⇒ constraints
- ✦ Polarization of the LHC beams
  - ✤ Proposal to polarize one of the beams [DESY workshop on polarized collisions (1999)]
  - ✤ Spin asymmetries ⇒ constraints on new physics
  - ✤ Parton density uncertainties are large

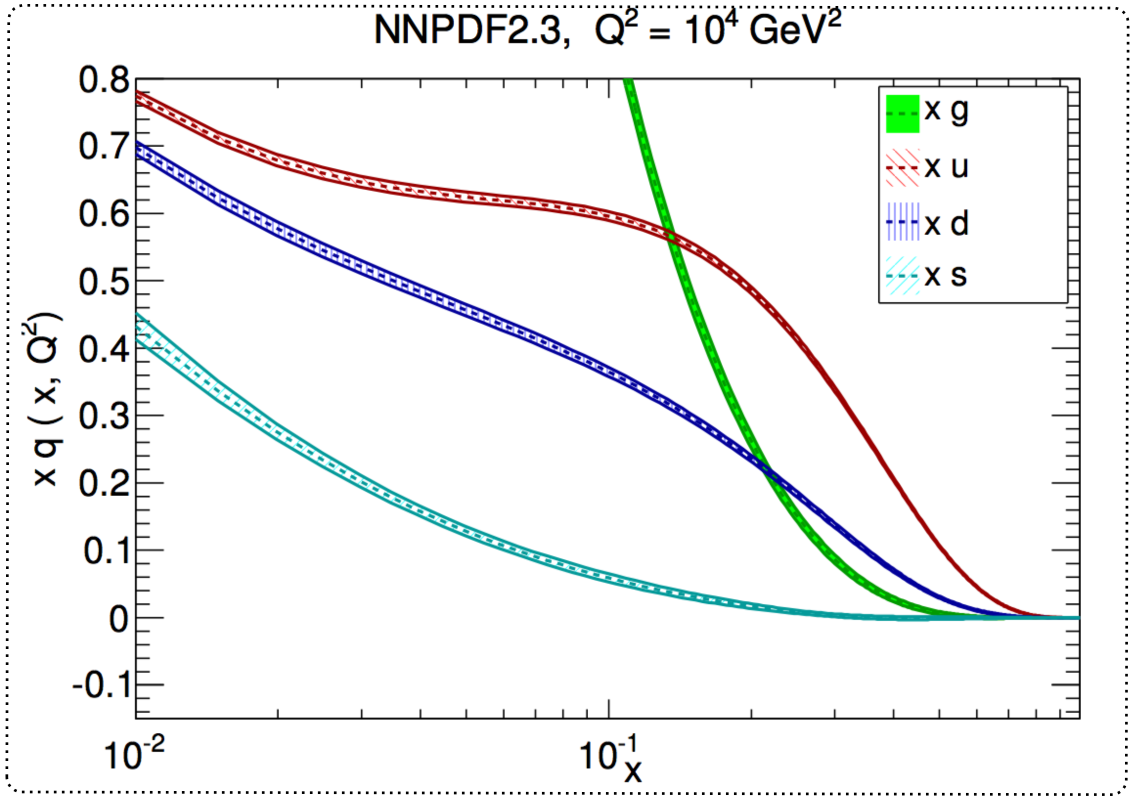
★ The Tevatron is now shut down
★ Polarizing the LHC is likely not to be considered
★ What about a polarized FCC ?

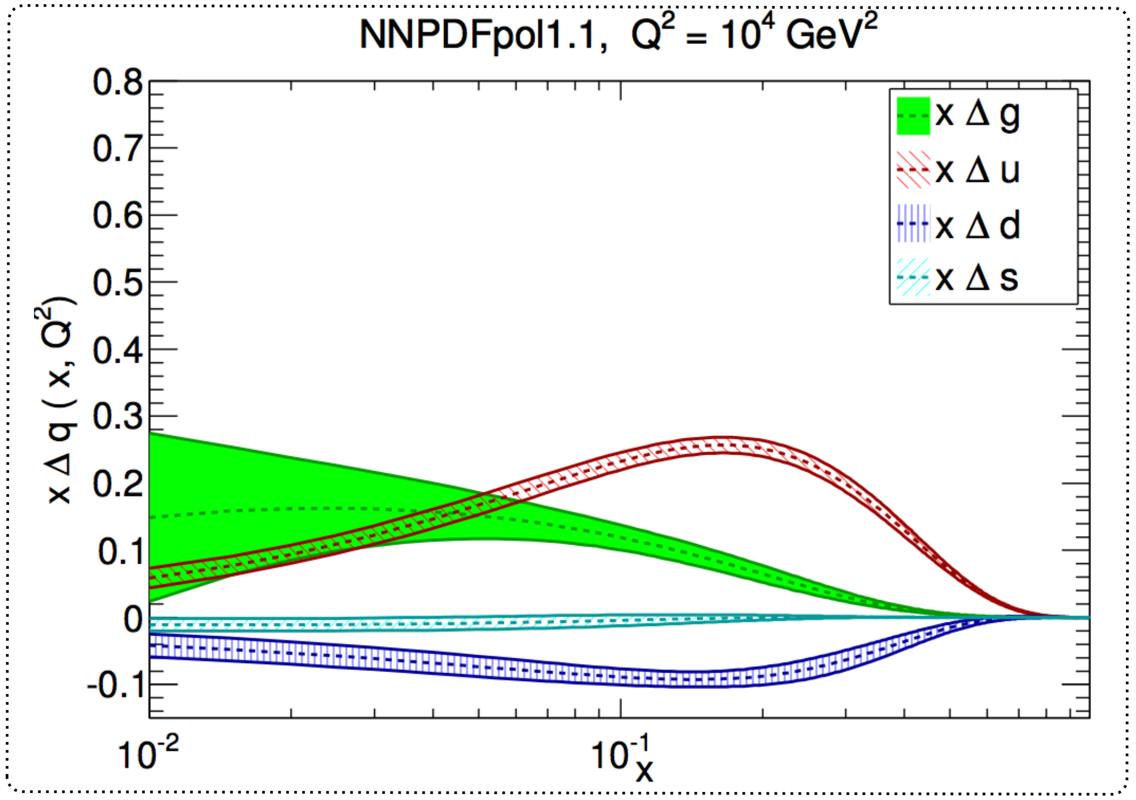


[Debove, BF, Klasen (PRD'08)]

Polarized & unpolarized parton densities

✦ Very different behavior of polarized and unpolarized parton densities





✦ Key properties of polarized parton densities

✤ Smaller than in the unpolarized case for any value of x (positivity condition) [Altarelli, Forte, Ridolfi (NPB'98)]

★ Single-spin asymmetries may be easier

✤ Polarized splitting kernels largely suppressed at small x [Ball, Forte, Ridolfi (NPB'95)]

★ Asymmetries are sizeable for (highly) massive systems ⇒ need of medium and large x values

✤ Initial states of different nature can imply large differences in spin asymmetries (signs of the PDFs)

★ New physics discriminator

Spin asymmetries at the FCC

✦ New physics discriminating power of the spin asymmetries

✤ Naive estimate: parton-level matrix elements approximately cancel in the asymmetries

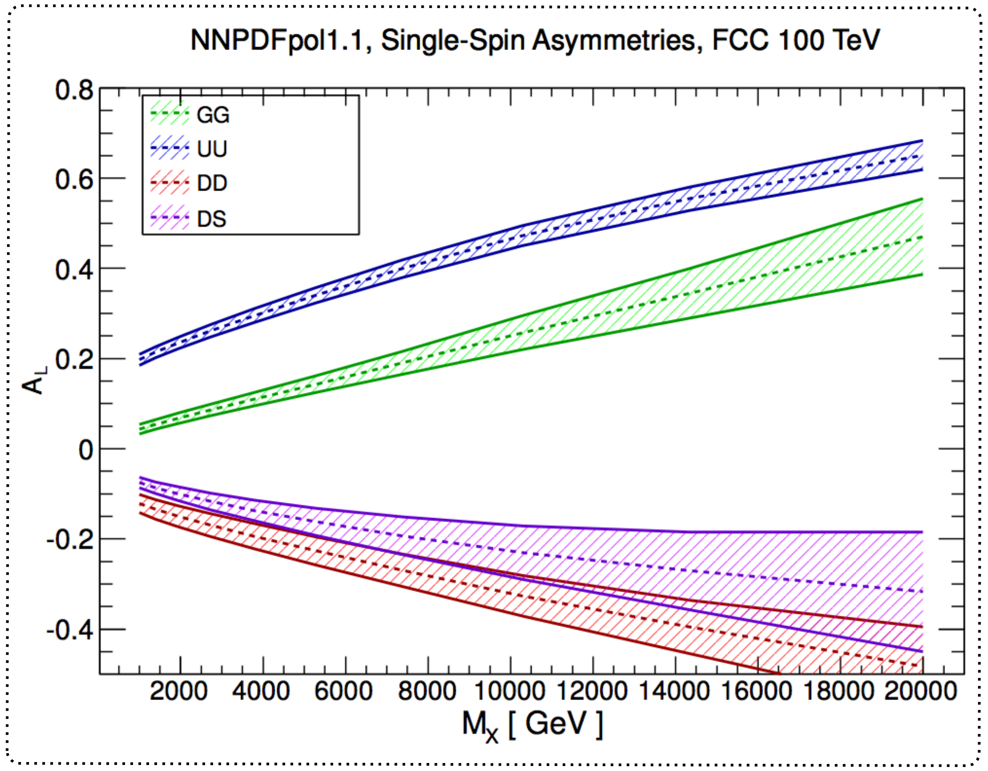
$$\mathcal{L}_{ij} = \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[q_i(x,m_X)\,q_j\left(\frac{\tau}{x},m_X\right) + q_i\left(\frac{\tau}{x},m_X\right)q_j(x,m_X)\right]$$

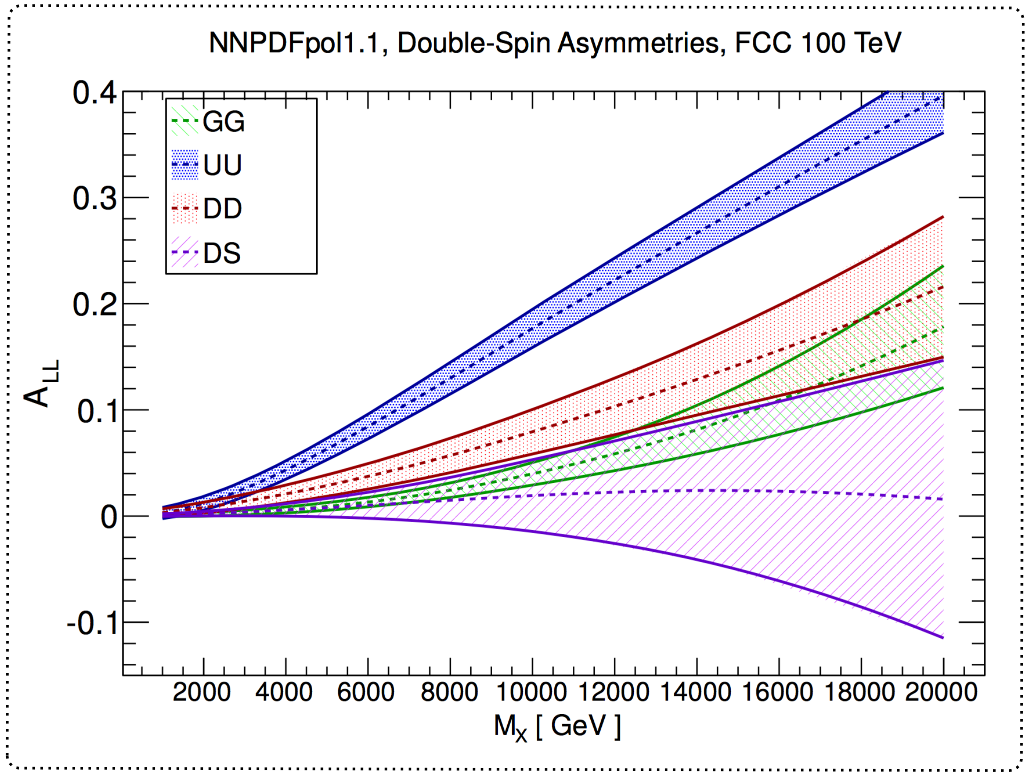
$$\mathcal{L}^L_{ij} = \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[q_i(x,m_X)\,\Delta q_j\left(\frac{\tau}{x},m_X\right) + q_i\left(\frac{\tau}{x},m_X\right)\Delta q_j(x,m_X)\right]$$

$$\mathcal{L}^{LL}_{ij} = \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[\Delta q_i(x,m_X)\,\Delta q_j\left(\frac{\tau}{x},m_X\right) + \Delta q_i\left(\frac{\tau}{x},m_X\right)\Delta q_j(x,m_X)\right]$$

$$A_L = \frac{(\Downarrow + \Uparrow)\Uparrow - (\Downarrow + \Uparrow)\Downarrow}{(\Downarrow + \Uparrow)\Uparrow + (\Downarrow + \Uparrow)\Downarrow} = \frac{\mathcal{L}^L_{ij}}{\mathcal{L}_{ij}}$$

$$A_{LL} = \frac{(\Downarrow\Downarrow + \Uparrow\Uparrow) - (\Uparrow\Downarrow + \Downarrow\Uparrow)}{(\Downarrow\Downarrow + \Uparrow\Uparrow) + (\Uparrow\Downarrow + \Downarrow\Uparrow)} = \frac{\mathcal{L}^{LL}_{ij}}{\mathcal{L}_{ij}}$$





★ The sign of the asymmetry is driven by the nature of the initial state

★ Uncertainties are large

★ Need for a PDF program in polarized collisions at high energies

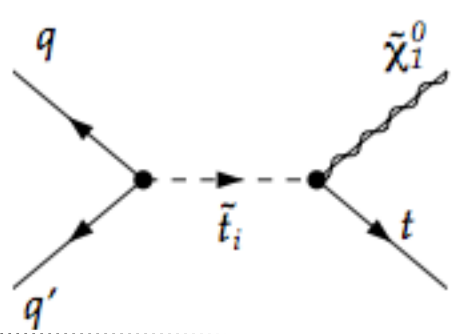
A physics case: monotops at hadron colliders

[Andrea, BF, Maltoni (PRD '11)]

✦ Production of a top quark in association with missing energy: predicted by many models

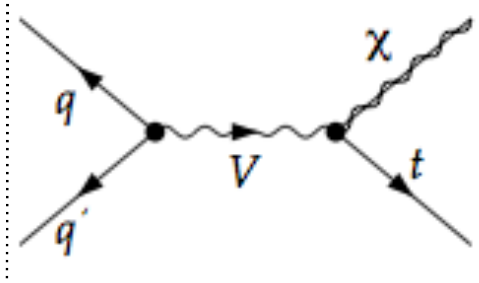
✤ R-parity violating supersymmetry

[Barbier *et al.* (PR'05)]



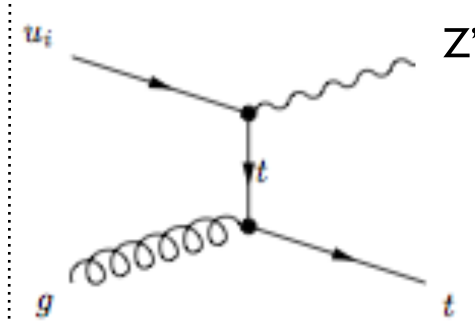
Hylogenesis models

[Davoudiasl *et al.* (IJMPA'12)]



Z' models for dark matter

[Kamenik *et al.* (PRD'11)]



✤ Distinguishing models at the LHC is non trivial [Agram, Andrea, Buttignol, Conte, BF (PRD'14)]

★ Detector effects

★ Rare events

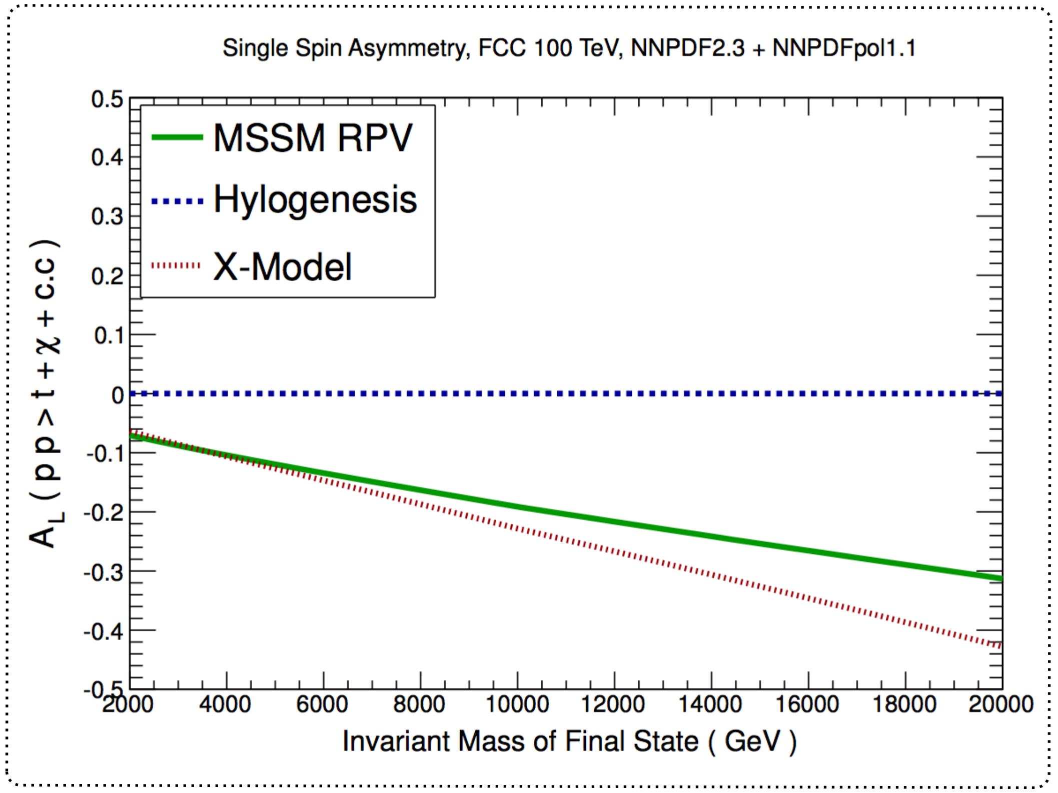
★ Even distinguishing a resonant *vs.* a non-resonant behavior might be difficult

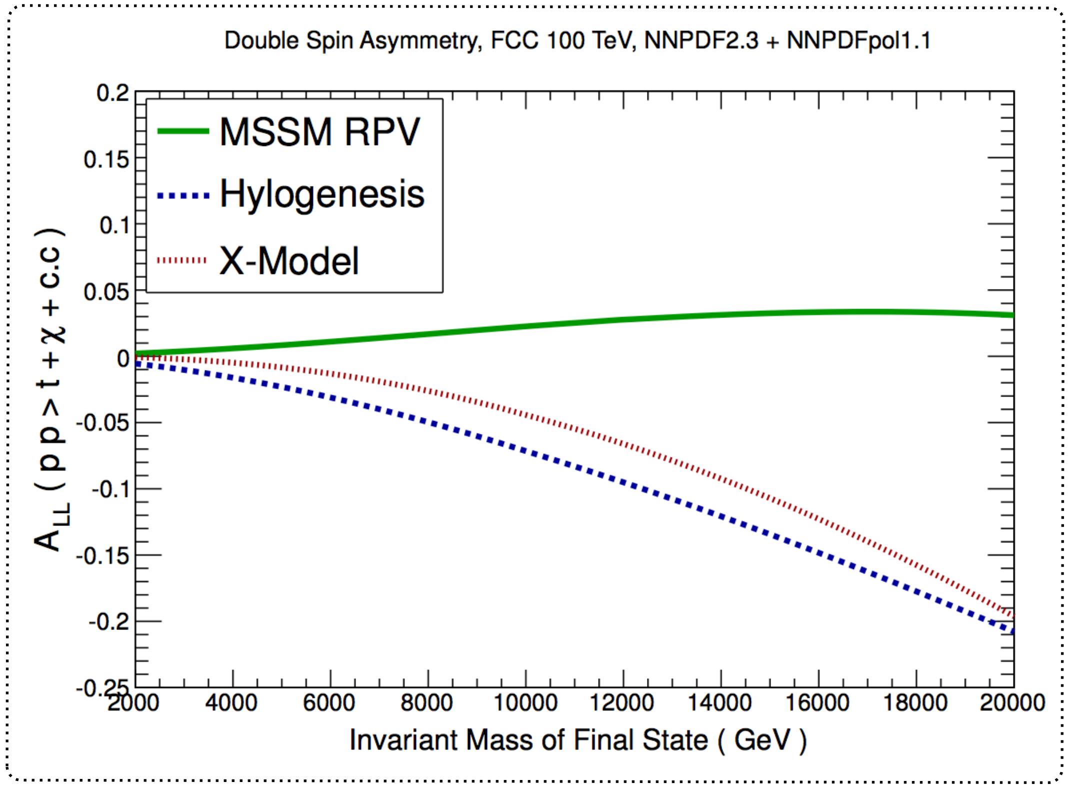
Let's assume a monotop discovery at the LHC.
How could a polarized FCC-hh help to characterize the underlying physics?

Monotop production in 100 TeV polarized pp collisions

- Single-spin and double-spin asymmetries in all three models
  - Could possibly help to disentangle models leading to the same signature
  - Improvements on the (polarized) parton densities necessary

Assuming infinite improvement on the PDFs





Disentangling the underlying physics becomes possible by measurements at the 5% level (up to uncertainties)

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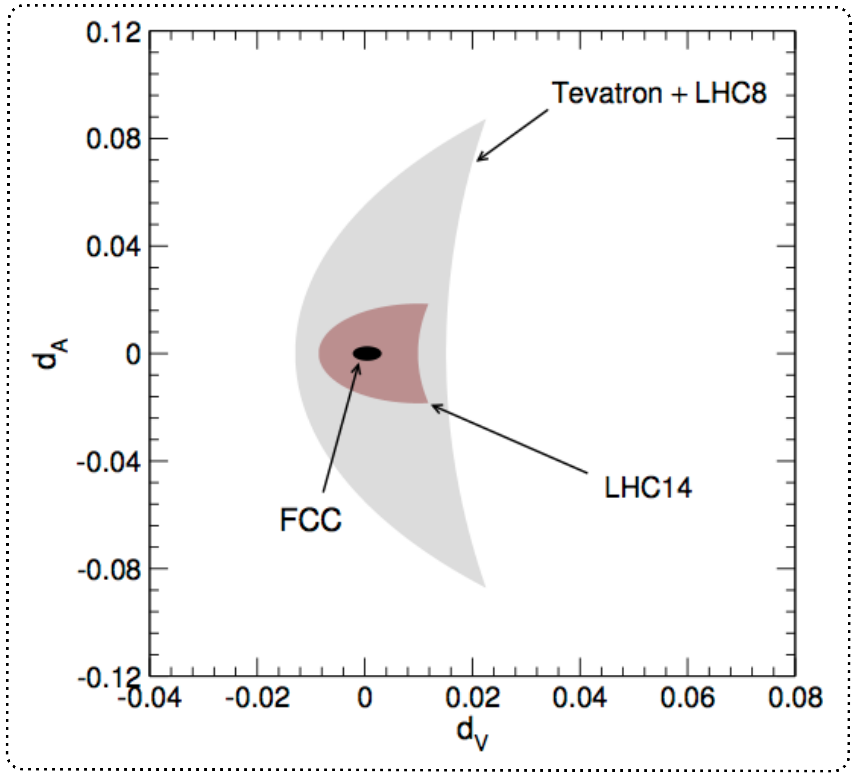
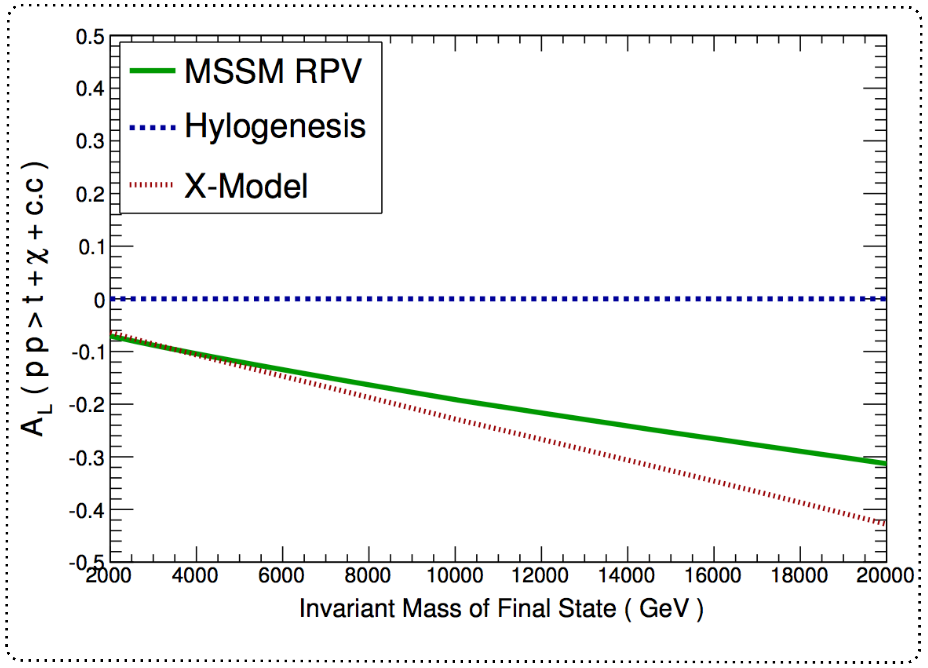
Summary

✦ Top dipole moments at future colliders

- Tevatron, LHC8: bounds derived from total rates
- Differential distributions: using heavily boosted tops
  - ★ Higher-momentum transfers are probed
  - ★ Highly sensitive to top dipole moments
- Improvement of the bounds at LHC14 and FCC
  - ★ FCC (m_{tt} > 10 TeV): $|d_A| \leq 2.6\ 10^{-3}$, $-2.2\ 10^{-3} \leq d_V \leq 3.1\ 10^{-3}$
- Competitive with indirect bounds
- Detailed top-tagging studies at the FCC are in order
  - ★ *cf.* envisaged detector technologies
  - ★ Potential improvement of our results





✦ Polarized collisions can be useful for new physics

- Characterizing a model
- Disentangling various models

✦ Spin asymmetries are the key observables

- Large uncertainties (*cf.* parton densities)
- Need for a polarized parton density program

✦ Polarizing proton beams

- Already thought in the past (in principle feasible)
- @FCC-hh: why could not it be envisaged?
- Useful both for new physics and QCD