Top physics at future hadron colliders

Lepton and Future Colliders 2015
Trento

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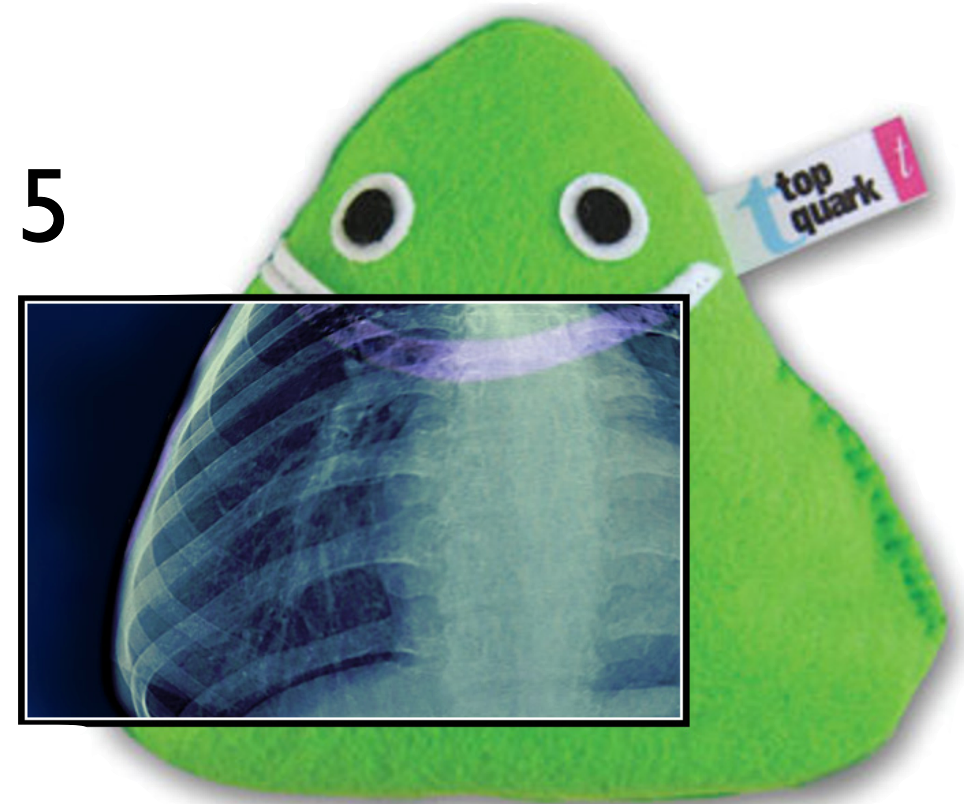
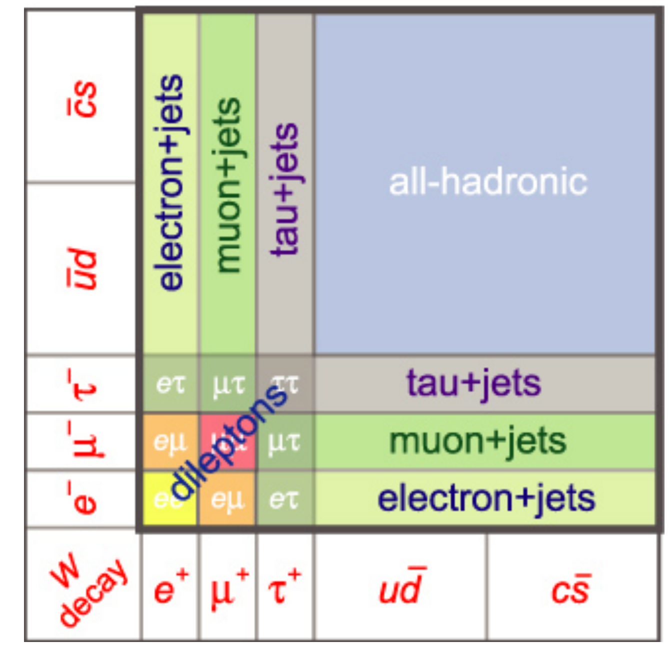
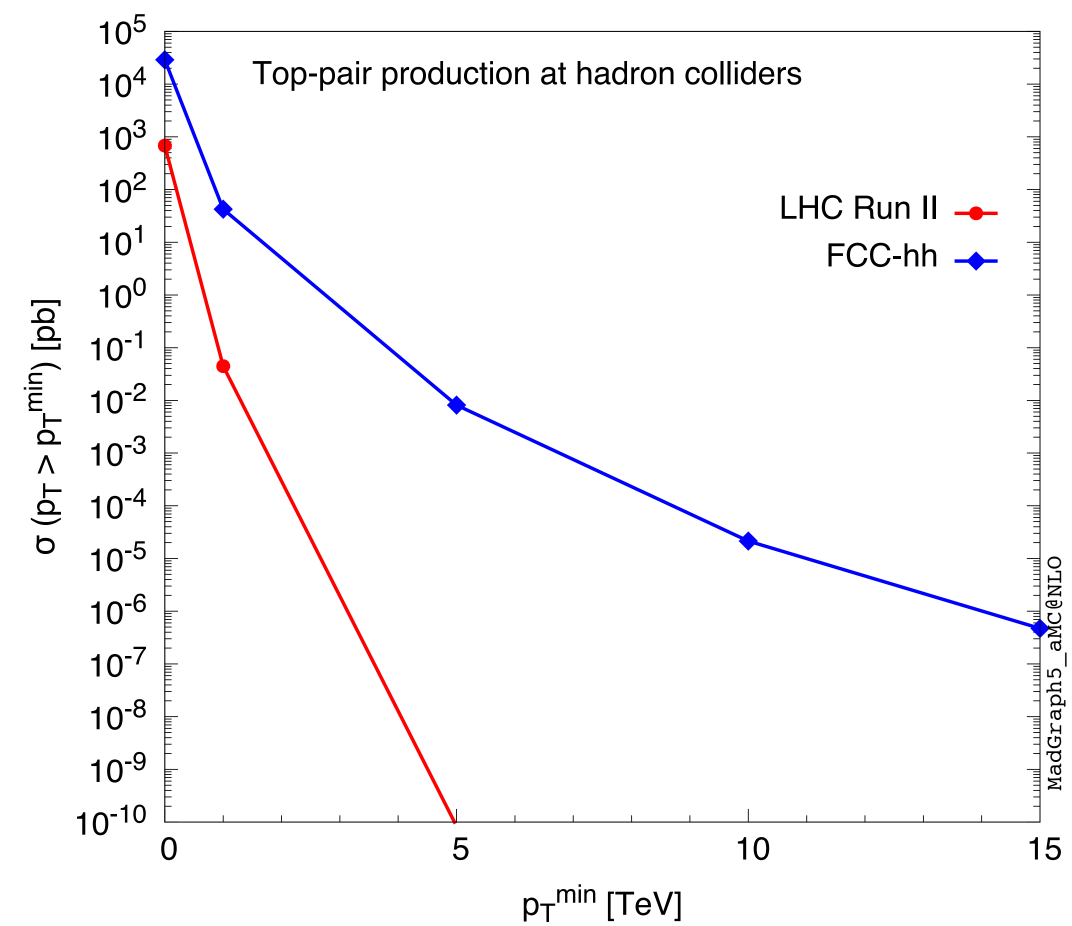


Top & FCC-hh facts

- A huge amount of top-quark pairs will be produced at a 100 TeV hadron collider: σ_{NLO}~30nb (~40x LHC run II)
  - $3 \cdot 10^{10}$ top pair produced with $10ab^{-1}$
  - Many tops will be boosted
- Can we detect all them?
- What can we do with them?
- Is it just $t\bar{t}$?

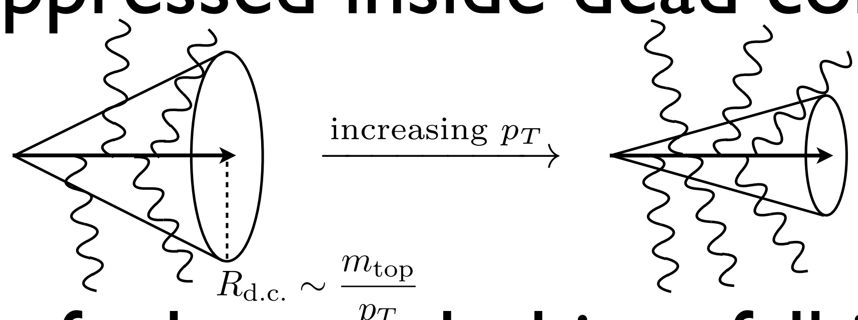




Tagging top quarks at a FCC-hh

Larkoski, Maltoni, Selvaggi, arXiv:1503.03347

- Challenges:
  - Boosted objects radiate a lot, both ISR and FSR (before the decay). Jet-mass measurement affected:
    $m^2 \sim m_t^2 + p_T\, p_T^{ISR} R^2$
    In the very boosted regime (p_T~10TeV), p_T^{ISR} ~ 5 GeV can give large distortions for R~1
    Grooming methods never studied in such an extreme regime
    FSR radiation suppressed inside dead cone: $R_{dc} \sim m_t/p_T$



  - Decay products of a boosted object fall inside a very narrow cone: $R \sim 2m_t/p_T$.
    R~0.05 for p_T=7.5 TeV, comparable with the resolution of ATLAS/CMS E-M calorimeters.

A variable-R jet algorithm

- Jet-mass degradation due to ISR can be reduced using a jet radius $R(p_T) = C\, m_t / p_T$
  - First cluster jets using anti-k_T with fixed R
  - Recluster the constituents of each jet with $R(p_T)$
  - Keep the hardest subjet as the top jet
  - Mass jet contamination now reduced to $m^2 = m_t^2\,(1 + C^2\, p_T^{ISR}/p_T)$
  - Dead-cone effect also reduces contamination from FSR

A variable-R jet algorithm: effects on jet-mass distribution

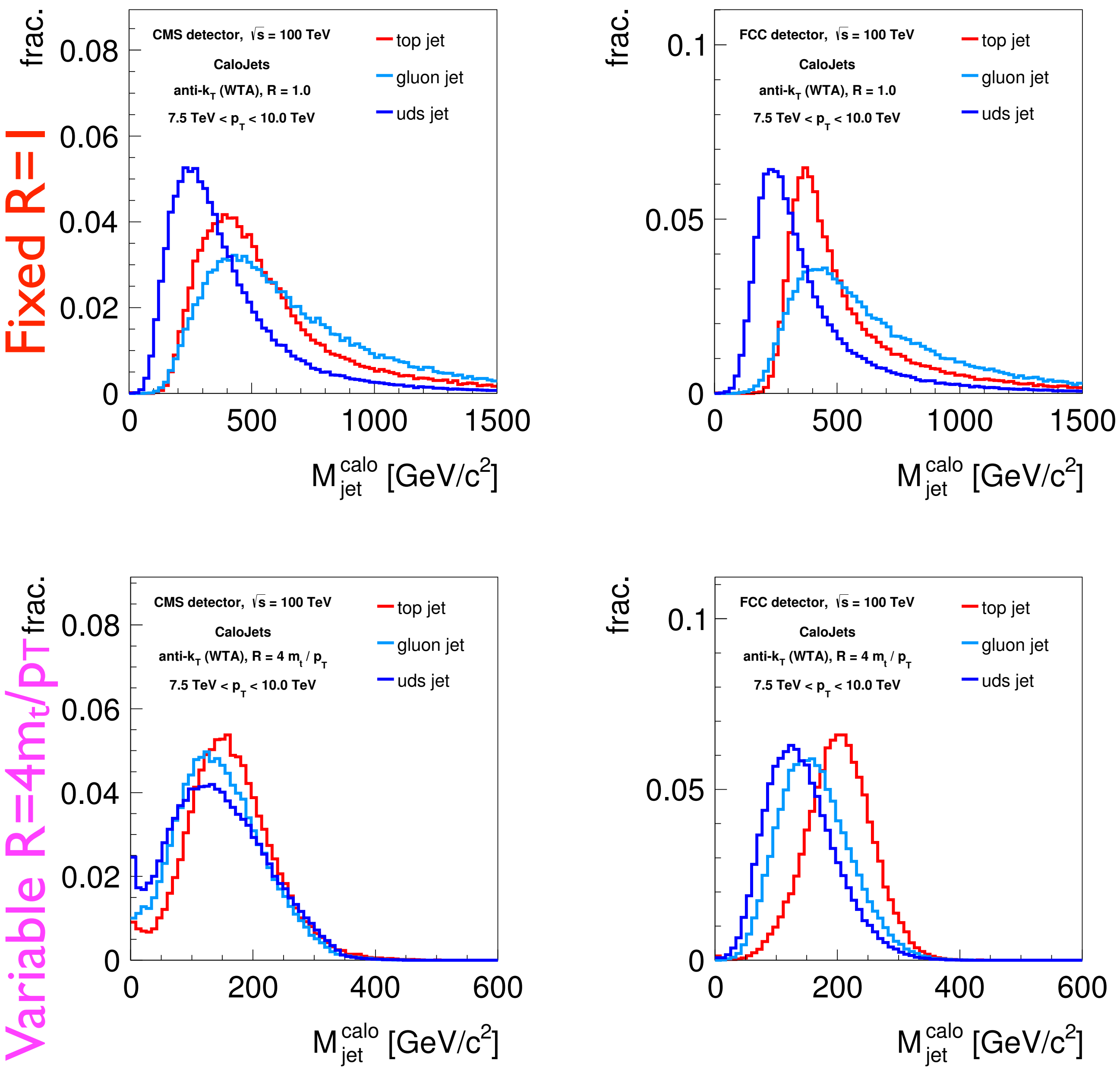
- Fixed-radius jets show poor mass discrimination between signal and background
- Using a p_T-dependent radius improves the picture, but effects due to calorimeter granularity appear
- Calo-only based analysis insufficient Cutting on the mass will degrade tagging efficiency

CMS-like detector

FCC detector

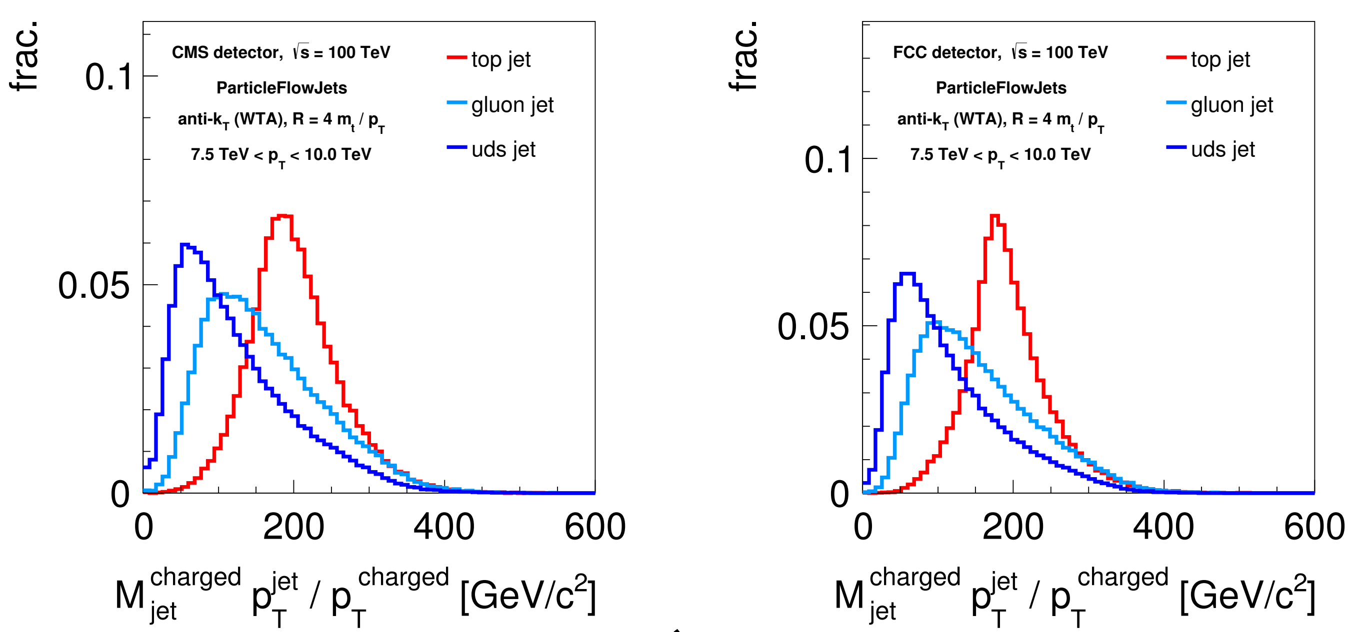
Fixed R=1

Variable R=$4m_t/p_T$



Improving the mass resolution with tracks

- Track-based information can help to achieve a better mass resolution
- Use charged tracks and reconstruct full jet mass as
  $m = m^{ch}\, p_T/p_T^{ch}$
- Mass discrimination much improved, even for detectors with poor calo granularity
- Further improvements based on jet substructure



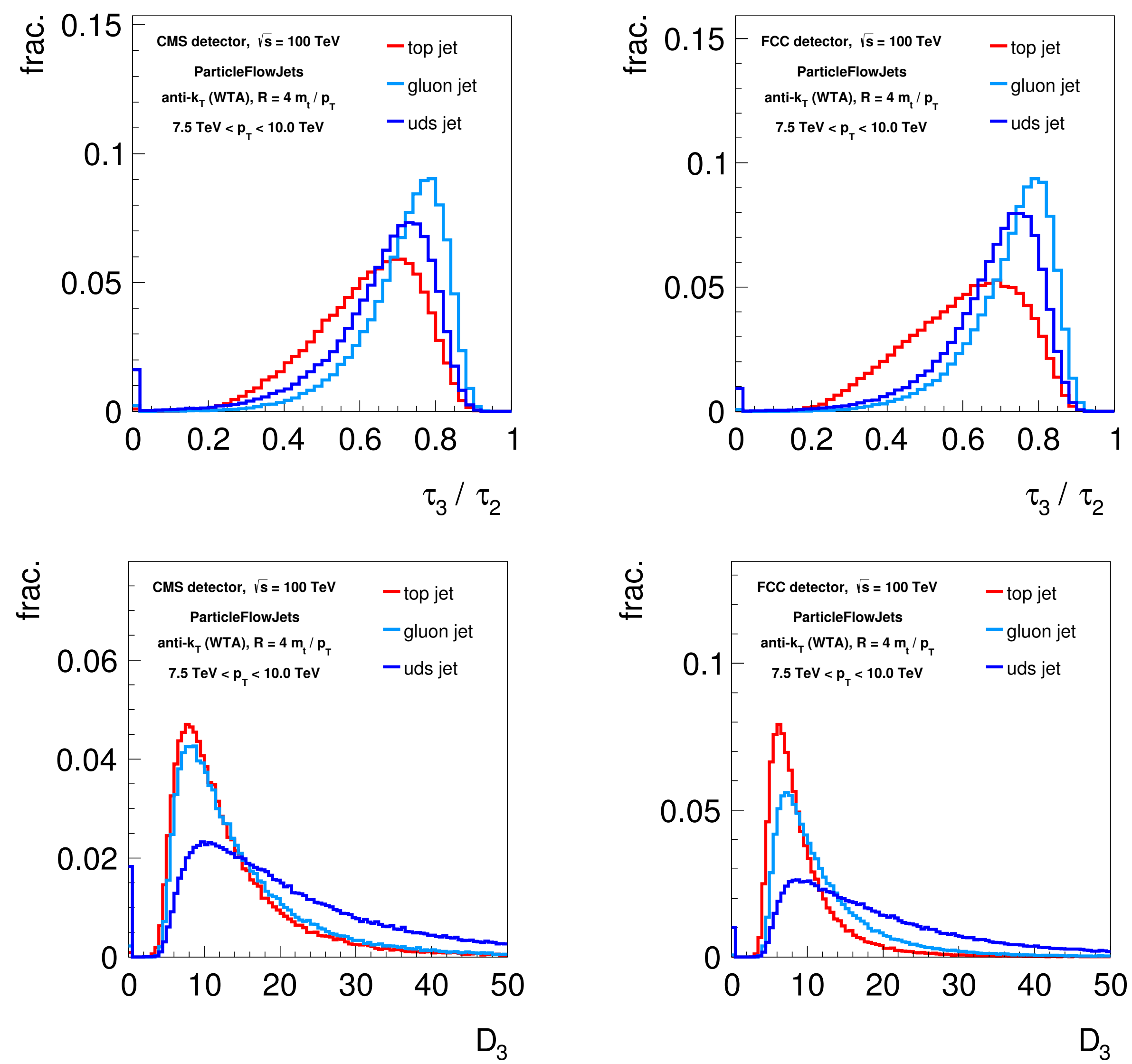
(a) (b)

Exploiting substructure information

- Select 3-prongs-like jets using N-subjettiness ratio $\tau_{3,2}$ and ECF D_3
- N-subjettiness sensitive to top/gluon discrimination, ECF to top/uds
- @50% top efficiency:
  - mass cut + $\tau_{3,2}$ → 83% gluon rejection
  - mass cut + D_3 → 94% uds rejection

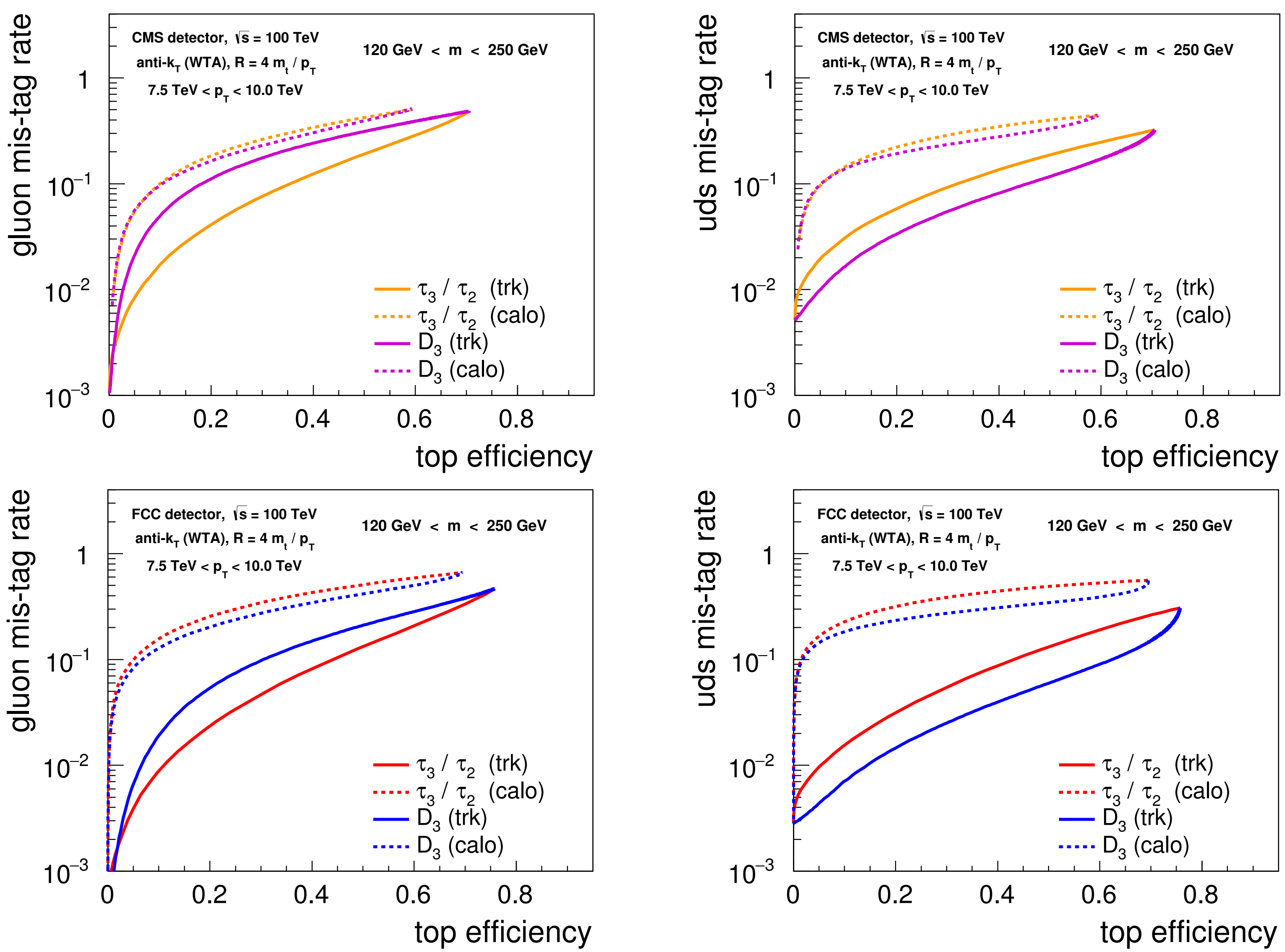
CMS-like detector

FCC detector



120<m<250

Performance: top efficiency vs mistag rate



Exploring top properties #1: The chromo-electric/magnetic moment

Aguilar-Saavedra, Fuks, Mangano, arXiv:1412.6654

- Top dipole moments are generated via loops in the SM, and are very small

chromo-magnetic

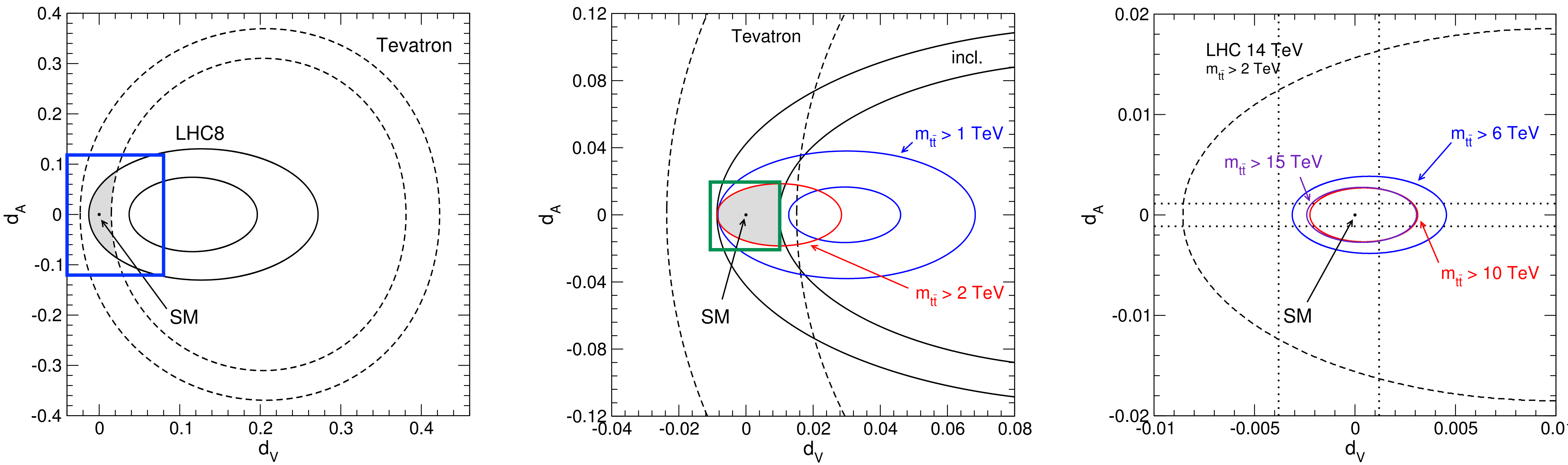
$$\mathcal{L}_{\rm tg} = -g_s \bar{t} \gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t} \bar{t} \sigma^{\mu\nu} (d_V + i d_A \gamma_5) \frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

chromo-electric

- Most stringent bounds from low-Q^2 ($|d_{V,A}| \lesssim 10^{-3}$)
- In the SM $d_V^{1loop}=0.007$, d_A negligible
- Weakly interacting NP at the TeV scale → $d_{V,A} \sim 0.05$
- The cross-section depends on $d_{V,A}$ as a polynomial → cross-section measurements can be used to constrain the moments

$$\begin{aligned}\sigma^{(8)}_{t\bar{t}}(\text{nb}) &= \sigma^{(8)}_{\rm SM}(\text{nb}) - 1.53\, d_V + 10.1\, d_V^2 - 23.0\, d_V^3 \\ &\quad + 28.6\, d_V^4 + 7.0\, d_A^2 + 28.6\, d_A^4 - 23.1\, d_V d_A^2 + 57.3\, d_V^2 d_A^2\end{aligned}$$

Present and future constraints on dipole moments



Tevatron and LHC Run I

- Use most recent experimental measurements + σ_{SM} @NNLO
- Stronger bounds than those from spin-correlations

Bernreuther, Si, arXiv:1305.2066
CMS-PAS-TOP-14-005

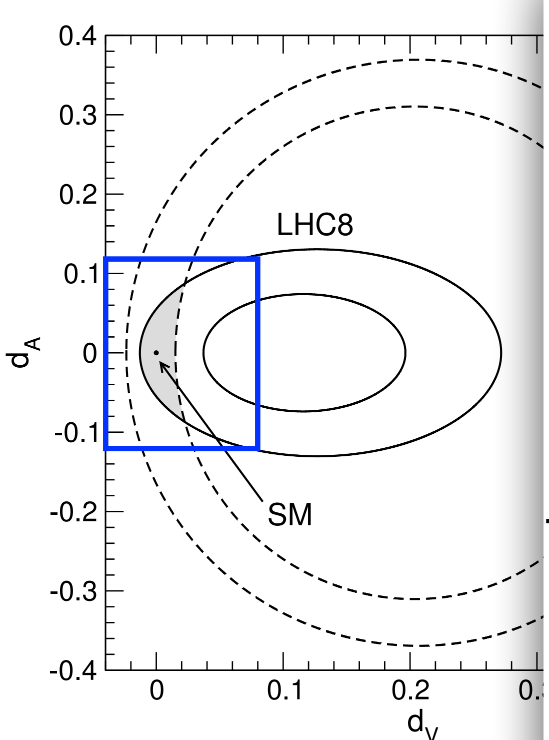
LHC Run II (100fb^{-1})

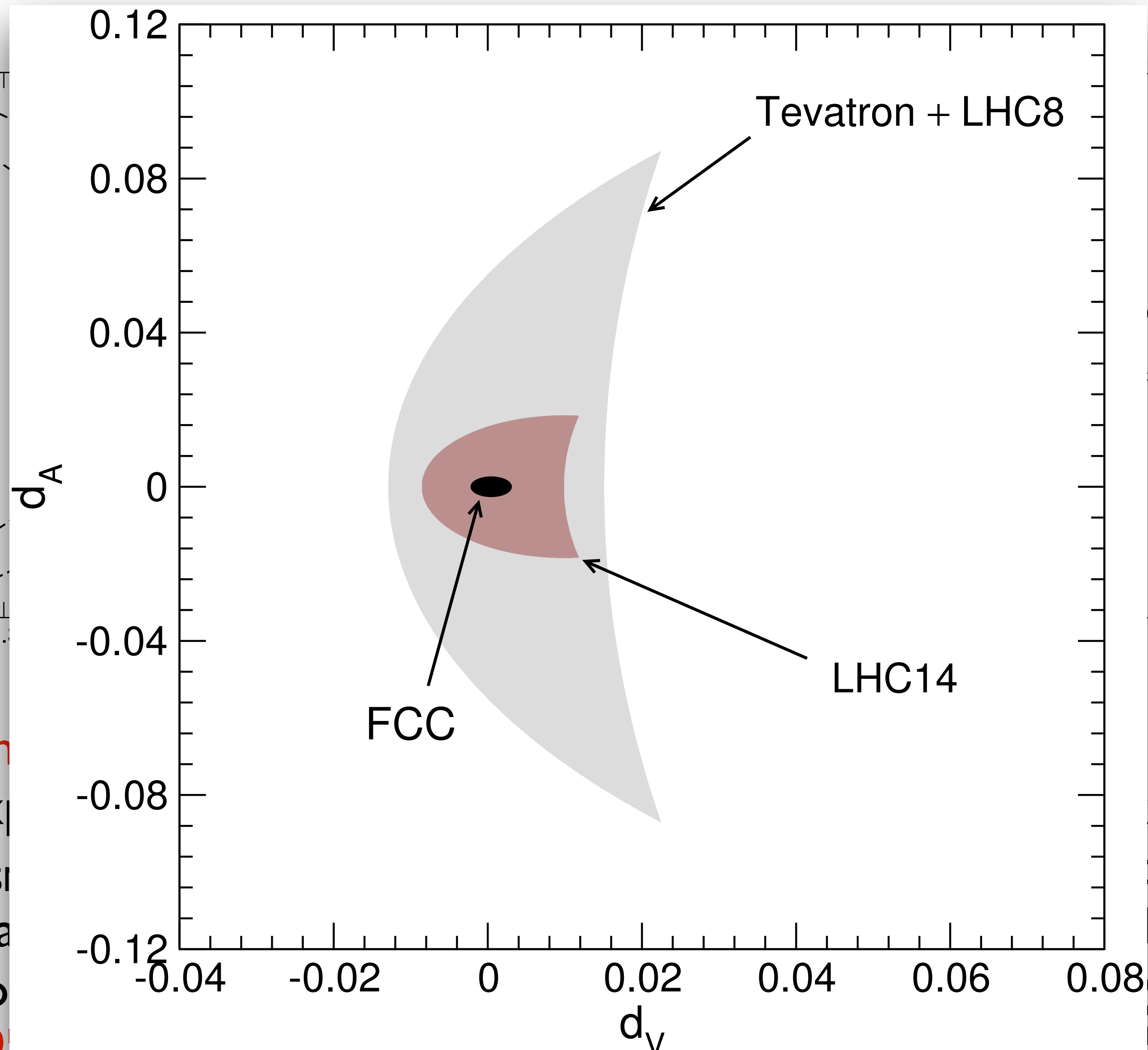
- Use information both on total xsect and on xsect at large invariant mass
- Use CMSTopTagger (WP3) for boosted tops

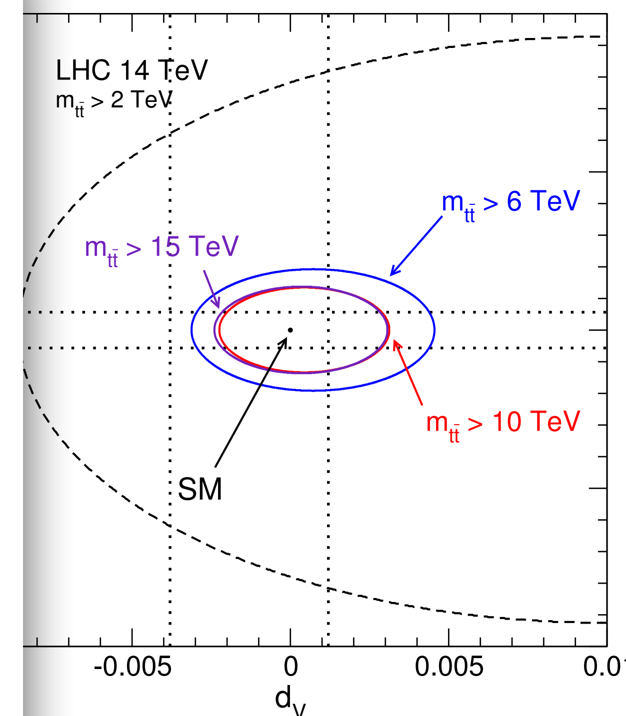
FCC (10ab^{-1})

- Ask one muonic top + cut on muon energy to reject QCD background
- Very high invariant mass region (>15TeV) limited by statistics
- Compatible with current indirect limits

Present and future constraints on dipole moments







Tevatron and LHC Run

- Use most recent ex... measurements + σ_{S}...
- Stronger bounds tha... from spin-correlatio...

Bernreuther, Si, arXiv:130...
CMS-PAS-TOP-14-005

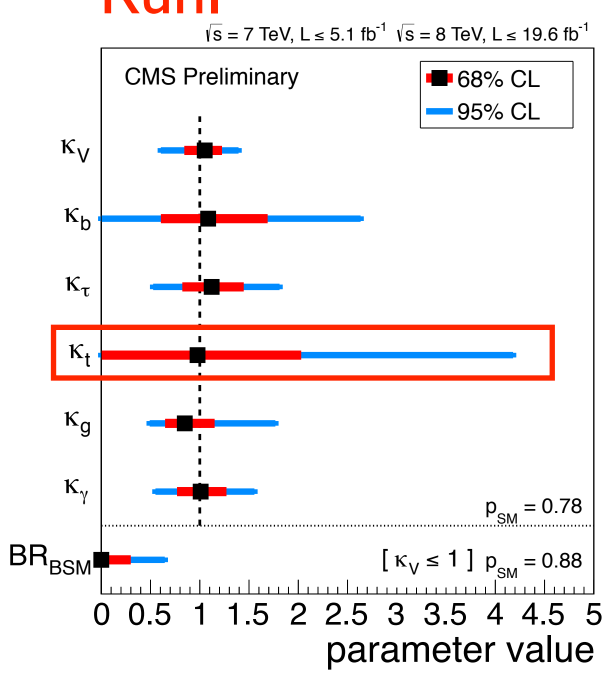
...10ab^{-1})

- ... one muonic top + cut on ...on energy to reject QCD ...kground
- ...y high invariant mass region (...5TeV) limited by statistics
- Compatible with current indirect limits

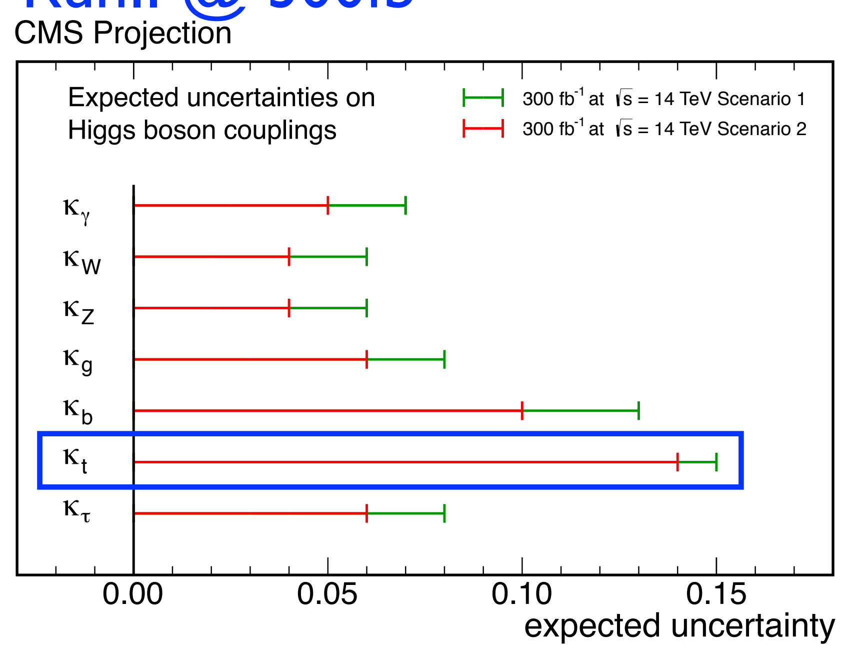
Exploring top properties #2: The top Yukawa coupling

- The determination of the top Yukawa is of utmost importance for present and future colliders
- $t\bar{t}H$ is the only channel where y_t can be **directly** measured
  - Not discovered at the RunI, looking forward for RunII
- Prospects from RunII: y_t known at 7-10% level, with $3ab^{-1}$
- Can we go down to 1% with the FCC?

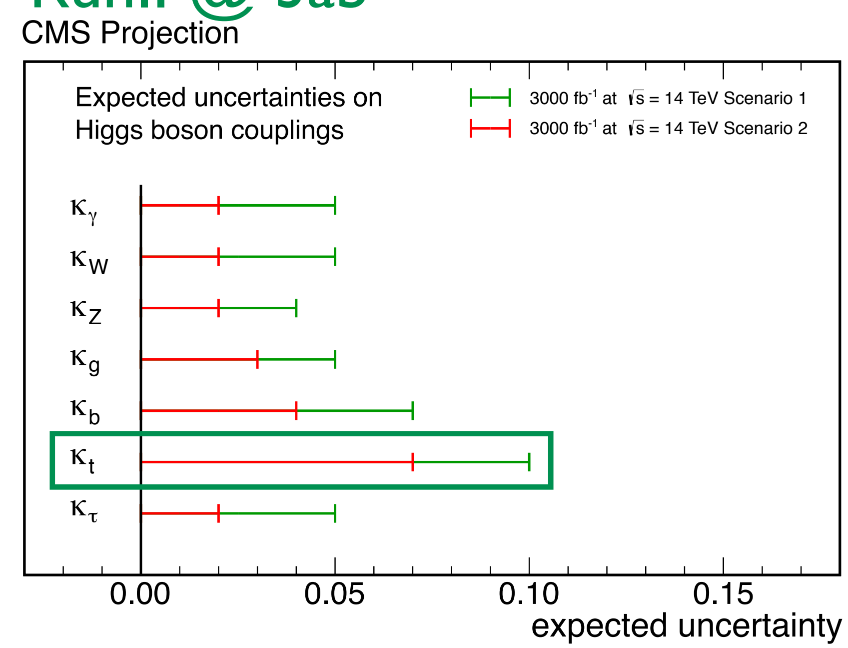
RunI



RunII @ $300fb^{-1}$



RunII @ $3ab^{-1}$



Ratios can help…

Mangano, Plehn, Reimitz, Schell, Shao, arXiv:1507.08169

- $t\bar{t}H$ and $t\bar{t}Z$ are quite similar processes, with rather large theoretical uncertainties (~10%).
  - Dominant production mode (gg) has identical diagrams
    Correlated QCD corrections, scale and α_S systematics

NLO QCD	$\sigma(t\bar{t}H)$ [pb]	$\sigma(t\bar{t}Z)$ [pb]	$\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

  - Almost identical kinematics boundaries (m_Z~m_H)
    Correlated PDF and m_t systematics

100TeV	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
MSTW2008	$0.585^{+1.29\%+0.0526\%}_{-2.02\%-0.0758\%}$
CT10	$0.584^{+1.27\%+0.189\%}_{-1.99\%-0.260\%}$
NNPDF2.3	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

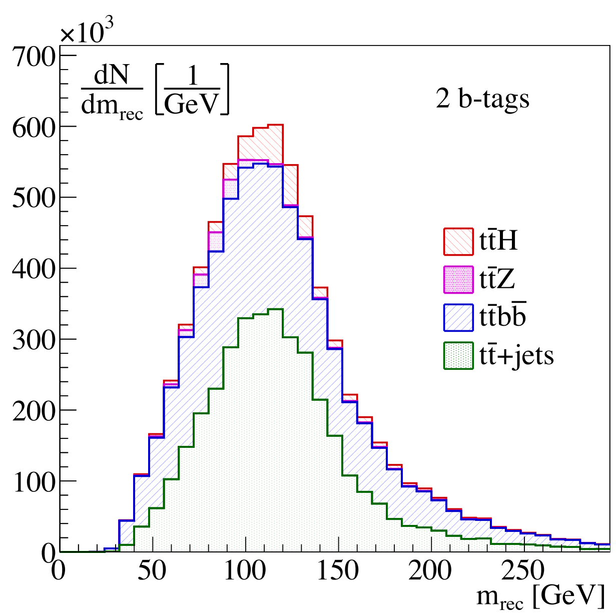
	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
default	$0.585^{+1.29\%}_{-2.02\%}$
$\mu_0 = m_t + m_{H,Z}/2$	$0.580^{+1.16\%}_{-1.80\%}$
$m_t = y_t v = 174.1$ GeV	$0.592^{+1.27\%}_{-2.00\%}$
$m_t = y_t v = 172.5$ GeV	$0.576^{+1.27\%}_{-1.99\%}$
$m_H = 126.0$ GeV	$0.575^{+1.25\%}_{-1.95\%}$

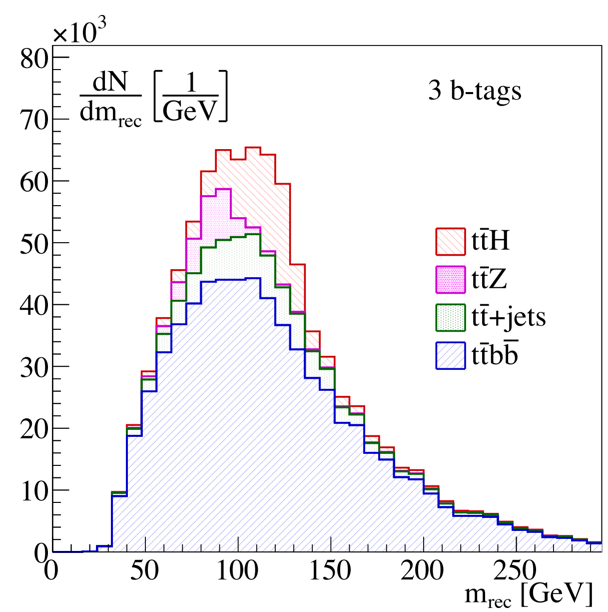
Is a 1% measurement of y_t possible at the FCC?

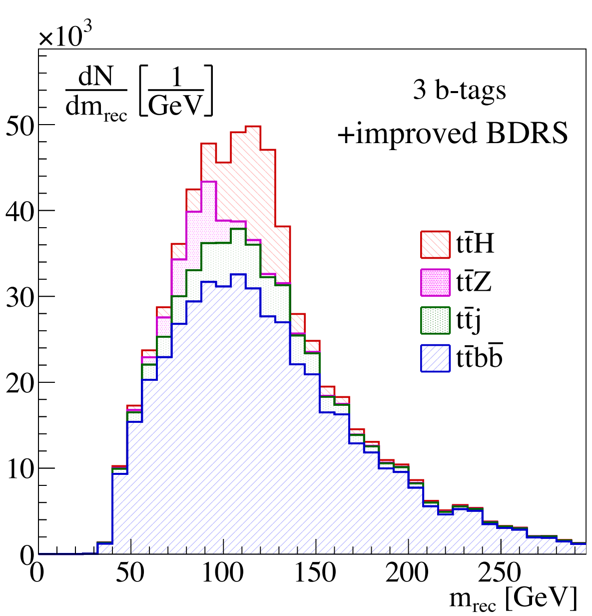
- Exploit $t\bar{t}Z$ measurements and uncertainties correlation in the ratio $t\bar{t}H/t\bar{t}Z$
- Exploit harder spectra at 100TeV than at 13TeV (boosted regime) to enhance S/B
- Use improved HepTopTagger2/BDRS Higgs tagger
  - Add information from N-subjettiness
  - Use OptimalR mode, to reduce the jet size until some decay subjets are dropped

Signal and background processes and selection

- Leading backgrounds to be simulated are $t\bar{t}b\bar{b}$, $t\bar{t}Z$, $t\bar{t}$+jets
- Simulated semileptonic top decay, Higgs and Z decay to bb
- Require:
  - One isolated lepton, $|y_l|<2.5$, $p_T(l)>15$GeV
  - Two fat jets (C/A, R=1.8, $p_T>200$GeV)
    - One HepTopTagged jet
    - One BDRS Higgs Tagged jet, with 2 b-tags inside
    - An extra b-tag in the “rest” of the event (to suppress tt+jets)

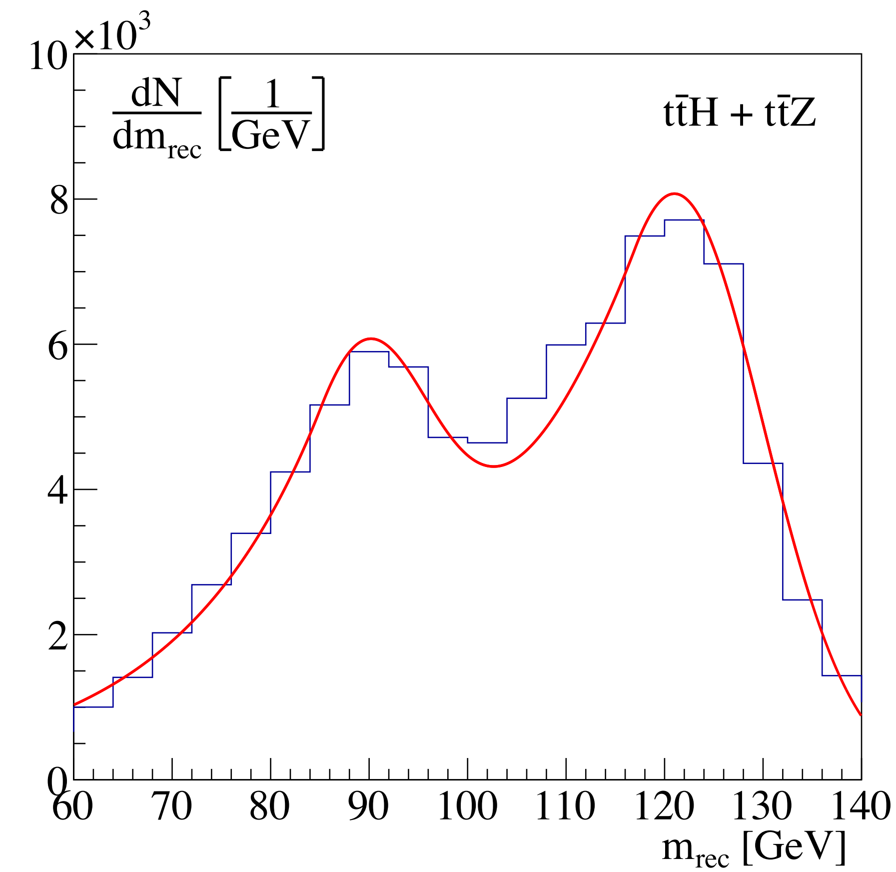






Signal extraction

- Subtract the background by interpolating the two sidebands regions $m_{bb} \in [0,60]$ GeV U [160, 300] GeV
- In the signal region ($m_{bb} \in [104,136]$ GeV one expects 44700 signal events, with S/B ~0.33 (at $20ab^{-1}$)
- Assuming perfect background subtraction the stat. error on signal is N_S=0.013N_S
- N_H/N_Z=2.80±0.03, with systematic and theoretical uncertainties cancelling in the ratio



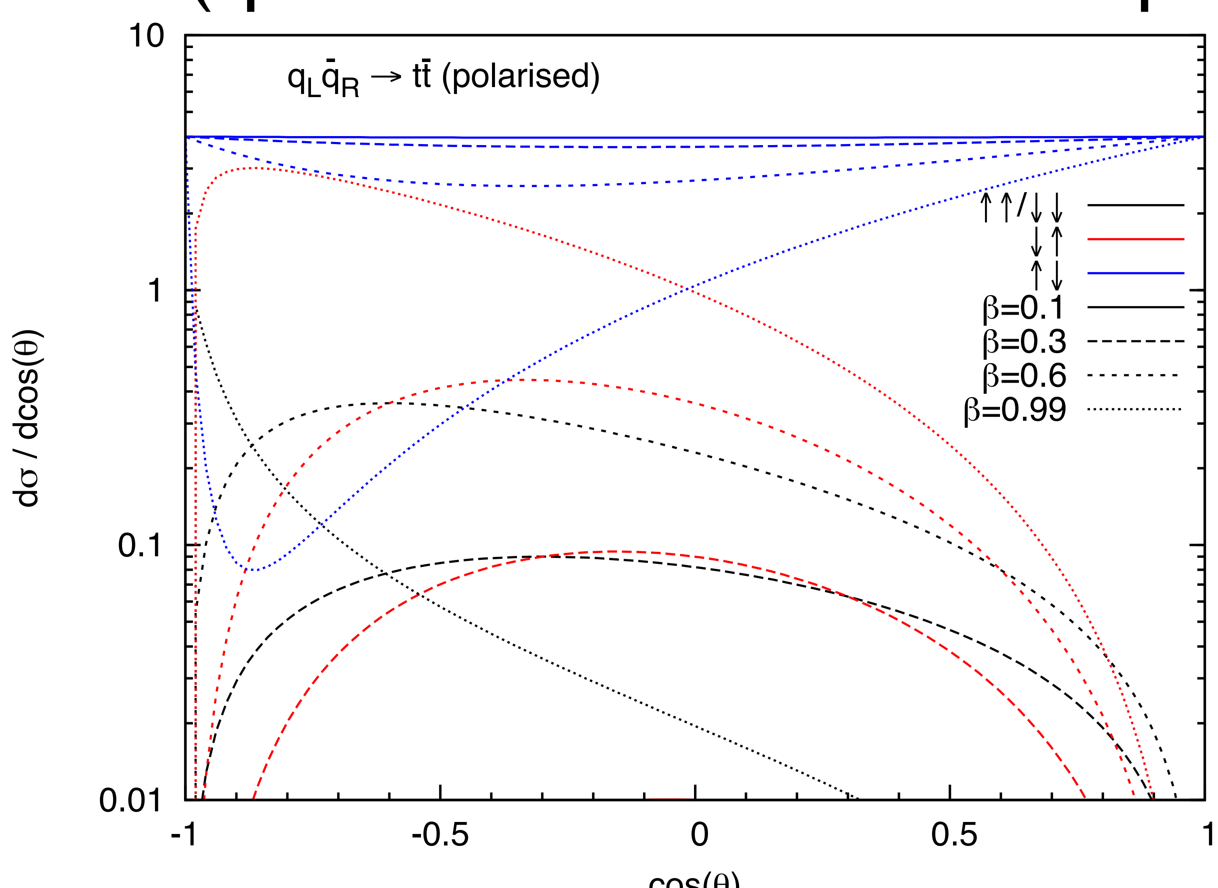
Exploring top properties #3:
Top asymmetry and polarisation in $t\bar{t}W$

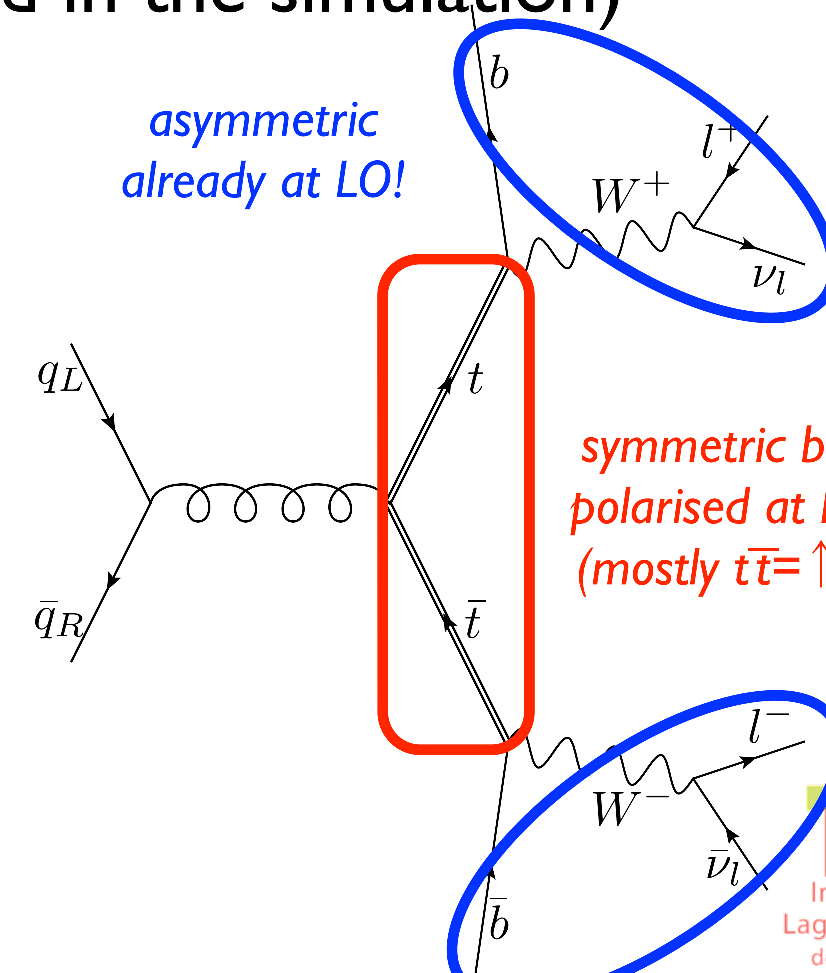
Maltoni, Mangano, Tsinikos, MZ, arXiv:1406.3262

- Top asymmetry and polarisation can provide useful (indirect) informations on the nature of new physics
- A measurement of the top asymmetry does not seem feasible at the FCC, because $t\bar{t}$ is essentially produced via gg only
- $t\bar{t}W$ production can be an alternative
  - $q\bar{q}$ induced at LO, has a rather large asymmetry at NLO
    - A_t^{tt}=0.45, A_t^{ttW}=2.24 @LHC RunII
    - A_t^{tt}=0.12, A_t^{ttW}=1.85 @FCC
  - Top quarks are highly polarised

Polarised top production

- The radiation of a W boson from the initial line has the effect of polarising the light quarks for details see Parke, Shadmi, hep-ph:9606419
  - $t\bar{t}W$ is totally analogous to polarised $q\bar{q}\rightarrow t\bar{t}$ scattering
  - $t\bar{t}$ pair is highly polarised (↑↓ dominates at threshold)
  - The top decay products are asymmetric already at LO (spin-correlations have to be preserved in the simulation)





Decay product asymmetries and prospects for LHC and FCC measurements

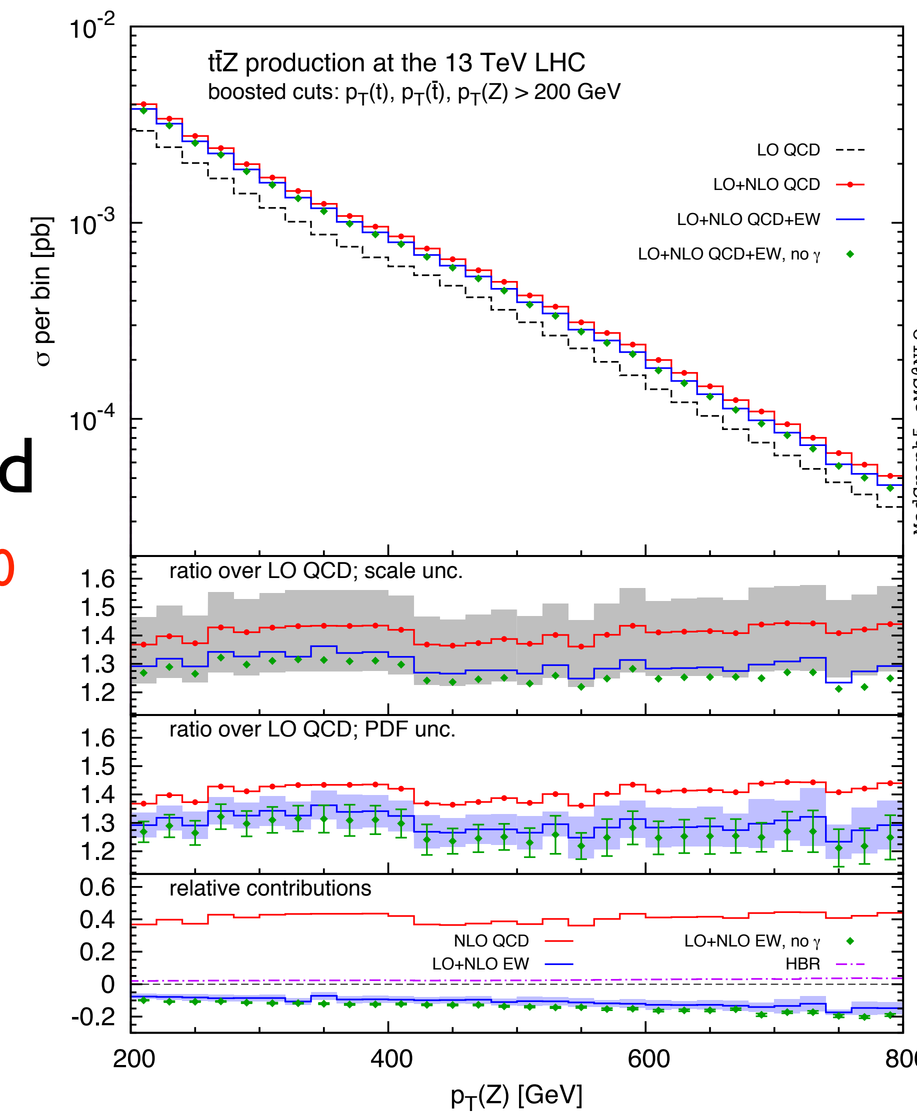
		8 TeV	13 TeV	14 TeV	33 TeV	100 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$	$4630^{+12\%}_{-11\%}$	$30700^{+13\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$	$0.26^{+0.04}_{-0.03}$	$0.12^{+0.03}_{-0.02}$
$t\bar{t}W^\pm$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$	$3220^{+17\%}_{-13\%}$	$19000^{+20\%}_{-17\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$	$1.95^{+0.28}_{-0.23}$	$1.85^{+0.21}_{-0.17}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$	$5.37^{+0.22}_{-0.30}$	$3.36^{+0.15}_{-0.19}$
	$A_c^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$	$-9.21^{-0.87}_{+1.05}$	$-4.94^{-0.63}_{+0.72}$

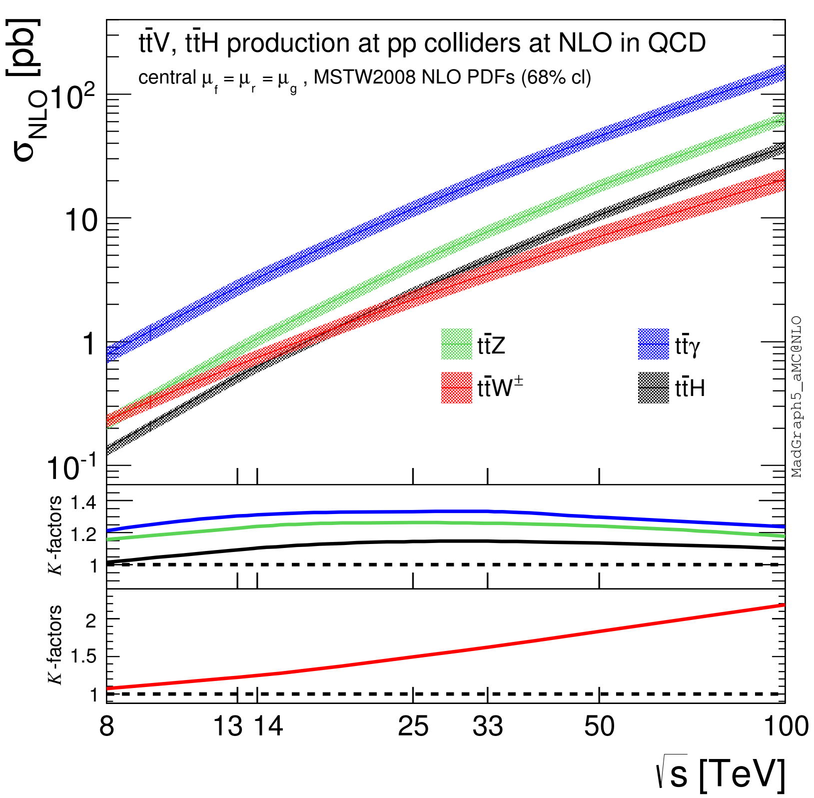
- Expected sensitivity on asymmetries (optimistic estimate)

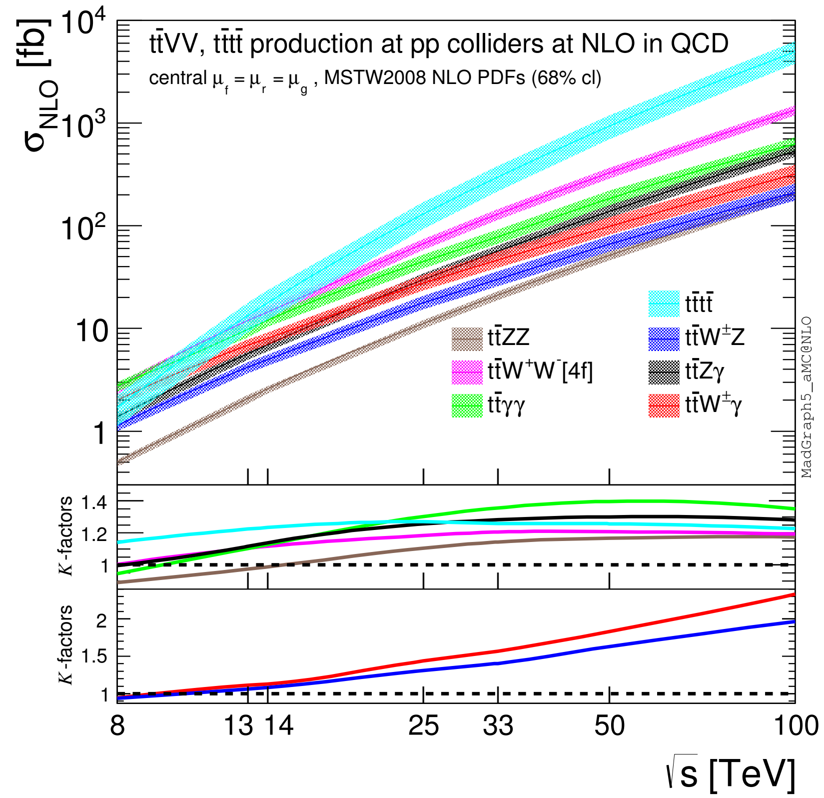
$t\bar{t}W$: δA/A	t	b	e/μ
8TeV 40fb	209%	58%	33%
14TeV 300fb	45%	13%	8%
14TeV 3ab	14%	4%	2%
100TeV 3ab	3%	2%	1%

$t\bar{t}$ + vector bosons: A quick update

- NLO Electroweak corrections to $t\bar{t}$H/Z/W recently computed in
  Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1504.03446
- Rather small at 100 TeV
  - 2% $t\bar{t}$H, 5% $t\bar{t}$Z, 10% $t\bar{t}$W
- Can be important in boosted or very boosted scenarios, and in tails of distributions
- All $t\bar{t}$+V, $t\bar{t}$+VV, $t\bar{t}t\bar{t}$ processes studied and simulated at NLO+PS accuracy in Maltoni, Tsinikos, Pagani, arXiv:1507.05640







Conclusions

- Top quark physics will be one of the key topics at the FCC
- New techniques are being developed to improve tagging capability at large p_T
- The huge amount of top quarks will allow us to measure top properties with incredible precision
- Much more to come!

Backup: substructure observables

- N-subjettines: $\tau_N^{(\beta)} = \sum_{i \in J} p_{Ti} \min\left\{R_{i1}^{\beta}, \ldots, R_{iN}^{\beta}\right\}$

  Thaler, Van Tilburg, arXiv:1011.2268 & 1108.2701
  - 1, N are the candidate subjets
  - It is ~0 if there are N jets or less
  - It is >> 0 if there are at least N+1 subjets
  - Ratio of τ_{N+1}/τ_N ~ 0 when there are N+1 subjets
- Energy correlation functions (ECFs):

  Larkoski, Salam, Thaler, arXiv:1305.0007

$$\mathrm{ECF}(N, \beta) = \sum_{i_1 < i_2 < \ldots < i_N \in J} \left(\prod_{a=1}^{N} p_{T i_a} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b i_c} \right)^{\beta}$$

  - N+1 ECF goes to 0 if there are only N subjets
  - The dimensionless ratio
    ECF(N+1)ECF(N-1) / ECF(N)^2
    goes to 0 if there are N subjets