Top physics at future accelerators

TOP 2015
Ischia, Sept 14-18 2015

Michelangelo L. Mangano
michelangelo.mangano@cern.ch
CERN, PH-TH

Nature of top properties and interactions

Nature of top properties and interactions

- **Basic top properties: m_{top}, V_{tq} (q=d,s,b)**

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
    - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
    - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
    - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
    - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: $X \to t + Y$, as in

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: X→t +Y, as in
    - Z' →tt, stop→tχ^0, gluino→t stop, T→tZ^0, etc

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: X→t +Y, as in
    - Z’ →tt, stop→tχ^0, gluino→t stop, T→tZ^0, etc
  - anomalous production properties:

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: X→t +Y, as in
    - Z' →tt, stop→tχ^0, gluino→t stop, T→tZ^0, etc
  - anomalous production properties:
    - A_C, spin correlations, angular distributions, etc.

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: X→t +Y, as in
    - Z' →tt, stop→tχ^0, gluino→t stop, T→tZ^0, etc
  - anomalous production properties:
    - A_C, spin correlations, angular distributions, etc.
  - non-SM decays:

Nature of top properties and interactions

- ***Basic top properties: m_{top}, V_{tq} (q=d,s,b)***
  - free params of SM. Precision will reflect on relations among other SM observables (e.g. EW precision tests, flavour physics, ...)
- ***Gauge and Yukawa couplings: g_V, g_A, weak- and chromomagnetic moments, y_{top}***
  - fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
- ***Direct BSM probes:***
  - production from BSM objects: X→t +Y, as in
    - Z' →tt, stop→tχ^0, gluino→t stop, T→tZ^0, etc
  - anomalous production properties:
    - A_C, spin correlations, angular distributions, etc.
  - non-SM decays:
    - t→qH, t→qZ, t→qγ, t→q$\ell\ell$', etc

Remarks

Remarks

- Short-distances (and possible BSM) can be probed by
  - high precision (small systematics and high statistics)
  - high Q^2 observables (mass reach)

Remarks

- Short-distances (and possible BSM) can be probed by
  - high precision (small systematics and high statistics)
  - high Q^2 observables (mass reach)
- High-Q^2 can compensate for lesser cleaness (can be used to reduce backgrounds and several systematics)

Remarks

- Short-distances (and possible BSM) can be probed by
  - high precision (small systematics and high statistics)
  - high Q^2 observables (mass reach)
- High-Q^2 can compensate for lesser cleaness (can be used to reduce backgrounds and several systematics)
- High complementarity/synergy between e^+e^- and pp

Remarks

- Short-distances (and possible BSM) can be probed by
  - high precision (small systematics and high statistics)
  - high Q^2 observables (mass reach)
- High-Q^2 can compensate for lesser cleaness (can be used to reduce backgrounds and several systematics)
- High complementarity/synergy between e^+e^- and pp
- It’s important to start now exploring the opportunities and challenges that future facilities offer for top physics (⇒impact on detector design)

Remarks

- Short-distances (and possible BSM) can be probed by
  - high precision (small systematics and high statistics)
  - high Q^2 observables (mass reach)
- High-Q^2 can compensate for lesser cleaness (can be used to reduce backgrounds and several systematics)
- High complementarity/synergy between e^+e^- and pp
- It's important to start now exploring the opportunities and challenges that future facilities offer for top physics (⇒impact on detector design)
- The picture of what can be obtained from e^+e^- collisions is already well established. The pp prospects are emerging only now, the picture is still very much incomplete, and will evolve in view of results from the LHC and flavour physics. I'll give a summary overview of what's been acieved so far. You're all welcome to join the efforts!!

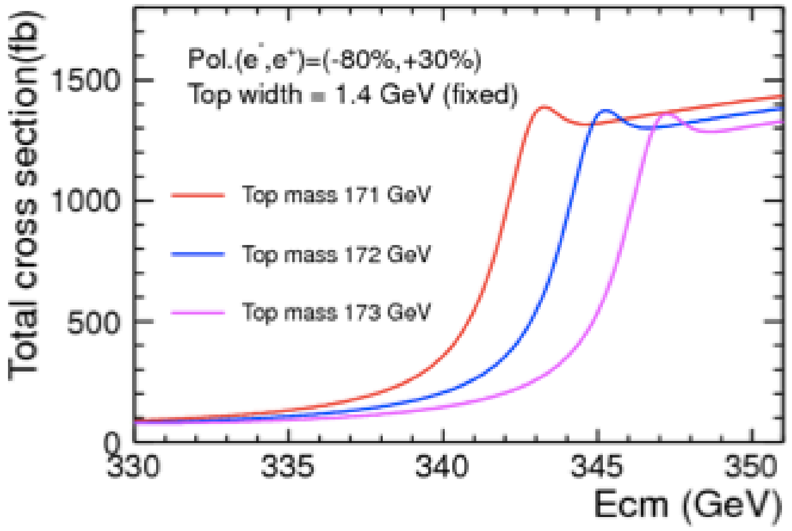
Most recent reference literature

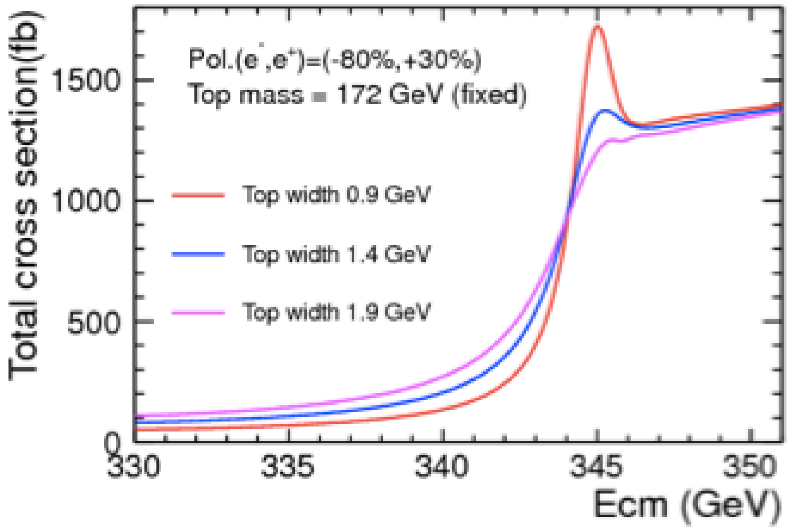
- **Physics at the e^+e^- Linear collider:**
  - G.Moortgat-Pick et al, arXiv:1504.01726
  - K. Fujii, et al., Physics Case for the International Linear Collider- arXiv:1506.05992
- **LC top workshop**:
  - http://ific.uv.es/~toplc15/index.html
- **CLIC Conceptual Design Report**:
  - L. Linssen et al, arXiv:1202.5940
- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - P.Janot, Top-quark electroweak couplings at the FCC-ee, arXiv:1503.01325
- **CEPC/SPPC**: Physics and Detectors pre-CDR:

  http://cepc.ihep.ac.cn/preCDR/volume.html
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: no document as yet (in progress, expected by end of 2015). See Twiki page:

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Top mass from an LC threshold scan





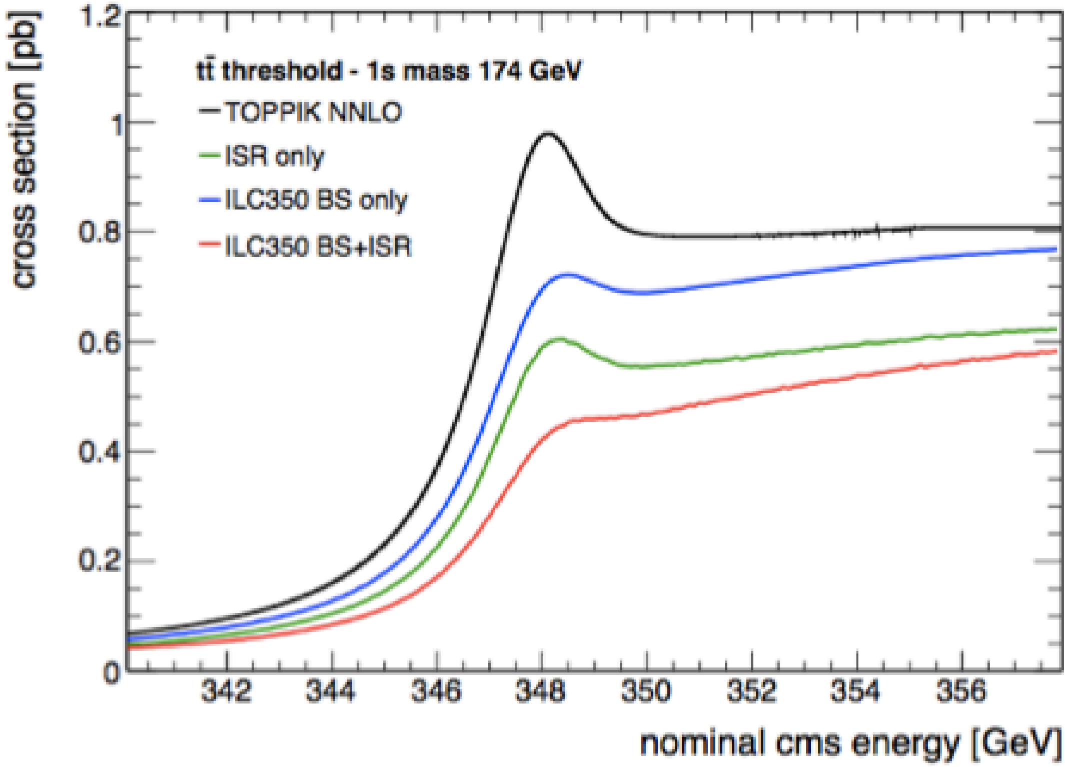
Threshold shape depends strongly on mass, width. Normalization sensitive to strong coupling constant and top Yukawa coupling.

Kuhn, Acta Phys.Polon. B12 (1981) 347

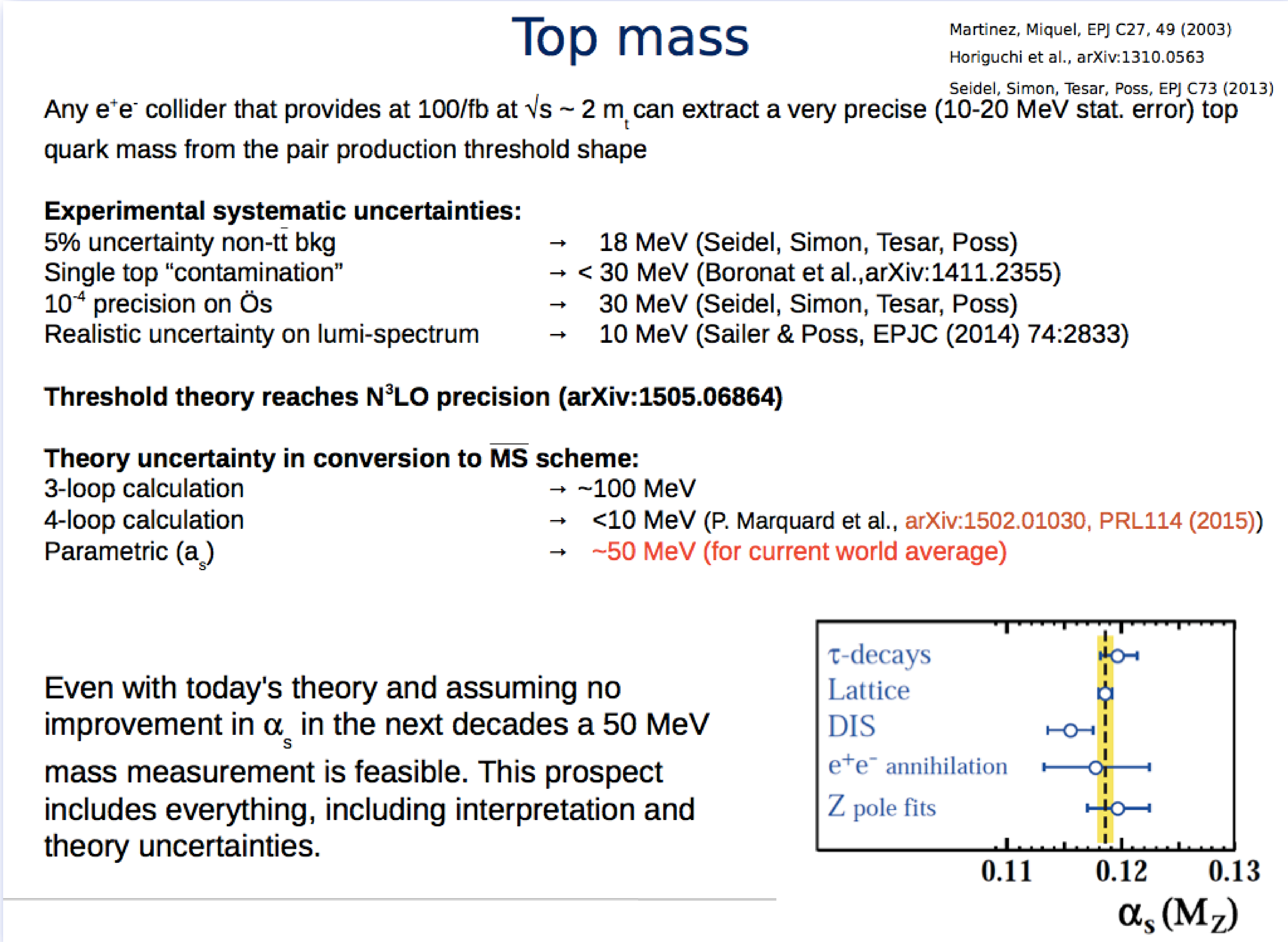
Beam energy spread and ISR smear the shape

CLIC has slightly more pronounced tail in luminosity spectrum

FCC-ee luminosity spectrum is broader, but more symmetric



courtesy Marcel Vos



Top mass

Martinez, Miquel, EPJ C27, 49 (2003)
Horiguchi et al., arXiv:1310.0563
Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Any e^+e^- collider that provides at 100/fb at √s ~ 2 m_t can extract a very precise (10-20 MeV stat. error) top quark mass from the pair production threshold shape

Experimental systematic uncertainties:

5% uncertainty non-$t\bar{t}$ bkg	→ 18 MeV (Seidel, Simon, Tesar, Poss)
Single top "contamination"	→ < 30 MeV (Boronat et al.,arXiv:1411.2355)
10^{-4} precision on Ös	→ 30 MeV (Seidel, Simon, Tesar, Poss)
Realistic uncertainty on lumi-spectrum	→ 10 MeV (Sailer & Poss, EPJC (2014) 74:2833)

Threshold theory reaches N^3LO precision (arXiv:1505.06864)

Theory uncertainty in conversion to $\overline{MS}$ scheme:

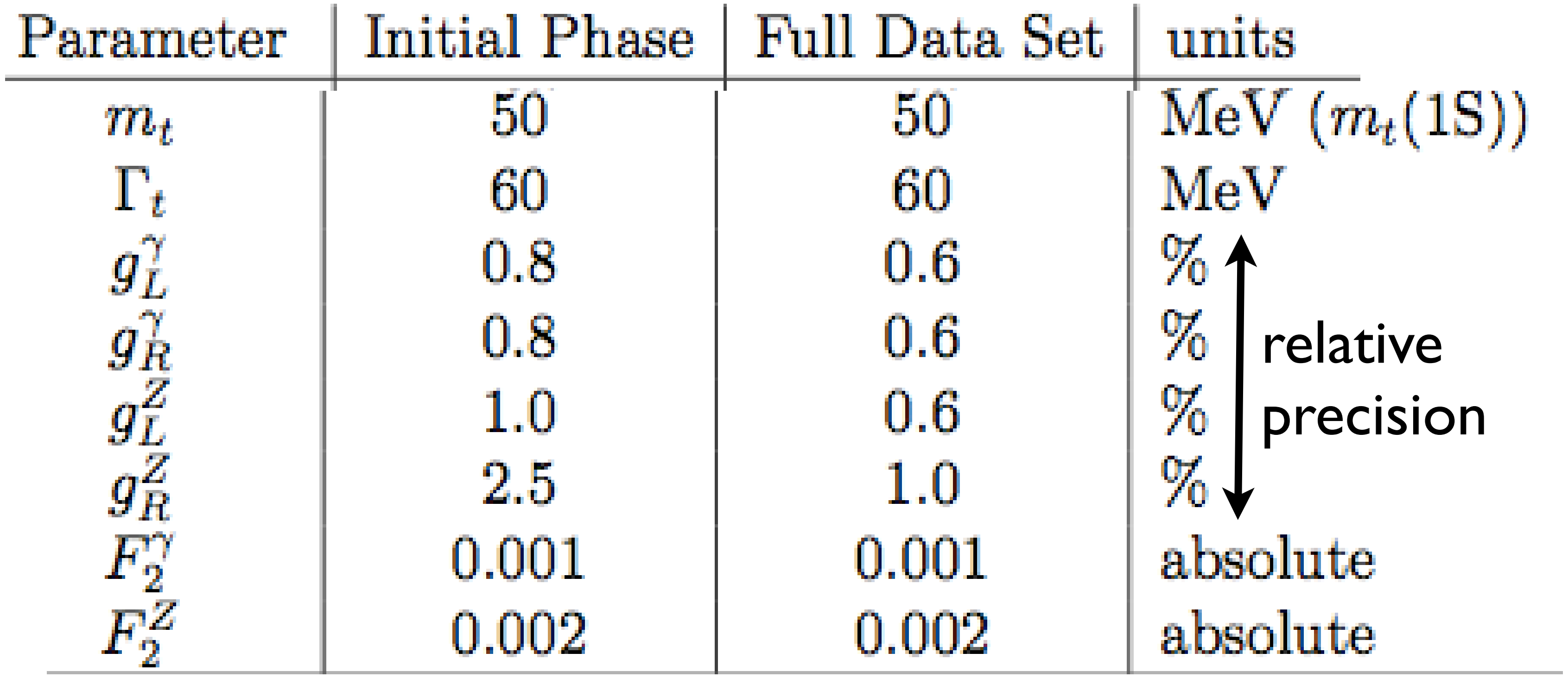
3-loop calculation	→ ~100 MeV
4-loop calculation	→ <10 MeV (P. Marquard et al., arXiv:1502.01030, PRL114 (2015))
Parametric (a_s)	→ ~50 MeV (for current world average)

Even with today's theory and assuming no improvement in α_s in the next decades a 50 MeV mass measurement is feasible. This prospect includes everything, including interpretation and theory uncertainties.

courtesy Marcel Vos

Summary of top properties determinations at ILC/FCC-ee

ILC: arXiv:1506.05992



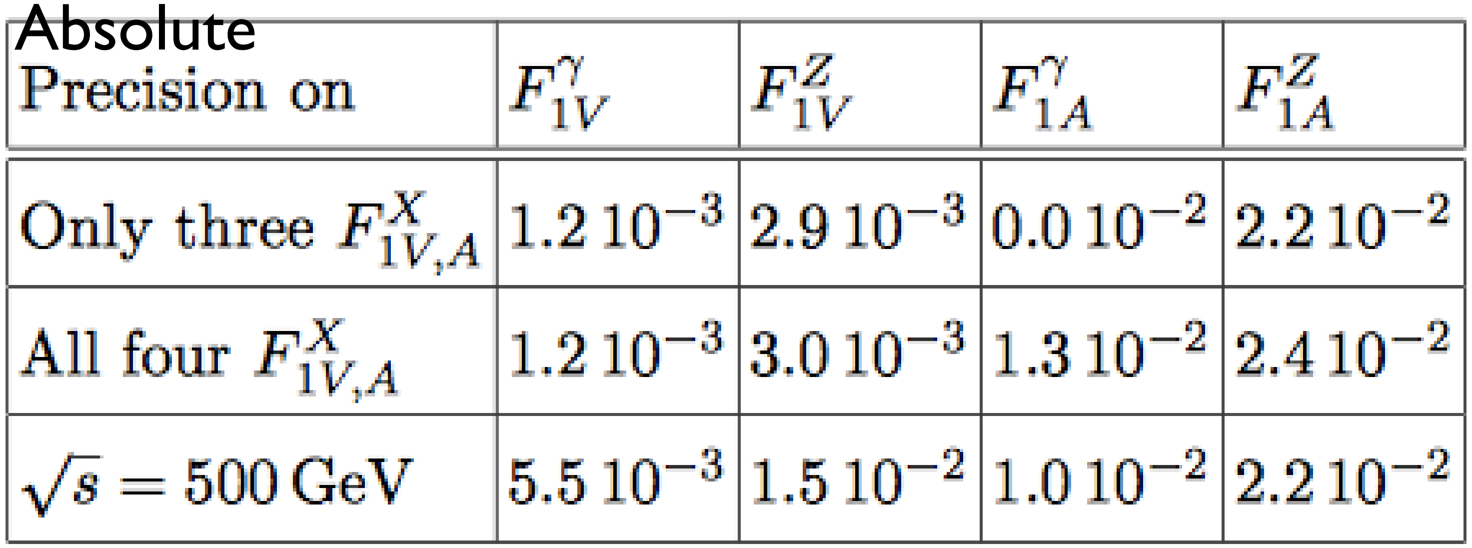
Parameter	Initial Phase	Full Data Set	units
m_t	50	50	MeV ($m_t(1S)$)
Γ_t	60	60	MeV
g_L^γ	0.8	0.6	%
g_R^γ	0.8	0.6	%
g_L^Z	1.0	0.6	%
g_R^Z	2.5	1.0	%
F_2^γ	0.001	0.001	absolute
F_2^Z	0.002	0.002	absolute

relative precision

m_t, Γ_t from runs at threshold
⇒ ultimately dominated by TH

syst, comparable results at FCC-ee

FCC-ee: arXiv:1503.01325 2.4 ab^{-1} at 365 GeV



Absolute Precision on	F_{1V}^γ	F_{1V}^Z	F_{1A}^γ	F_{1A}^Z
Only three $F_{1V,A}^X$	$1.2\,10^{-3}$	$2.9\,10^{-3}$	$0.0\,10^{-2}$	$2.2\,10^{-2}$
All four $F_{1V,A}^X$	$1.2\,10^{-3}$	$3.0\,10^{-3}$	$1.3\,10^{-2}$	$2.4\,10^{-2}$
$\sqrt{s} = 500\,\mathrm{GeV}$	$5.5\,10^{-3}$	$1.5\,10^{-2}$	$1.0\,10^{-2}$	$2.2\,10^{-2}$

Top Yukawa coupling at an e^+e^- linear collider

$\sqrt{S}$	350 GeV	500 GeV	+1000 GeV
L_{nominal}	200 fb^{-1}	+500 fb^{-1}	+2 ab^{-1}
$\delta h_t/h_t$	20%	18%	3.1%
L_{upgrade}	–	+3500 fb^{-1}	+1.5 ab^{-1}
$\delta h_t/h_t$	20%	6.3%	1.9%

ILC: arXiv:1506.05992

Top at 100 TeV

10 ab^{-1} at 100 TeV imply:

$\sigma_{tt} \sim 30$ nb

10^{12} top quarks => 5 10^4 x today

=> 10^{12} W bosons from top decays ⇒ rare W decays

=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

=> 10^{11} $t \to W \to$ taus ⇒ rare decays $\tau \to 3\mu$, $\mu\gamma$, CPV

=> few x10^{11} $t \to W \to$ charm hadrons

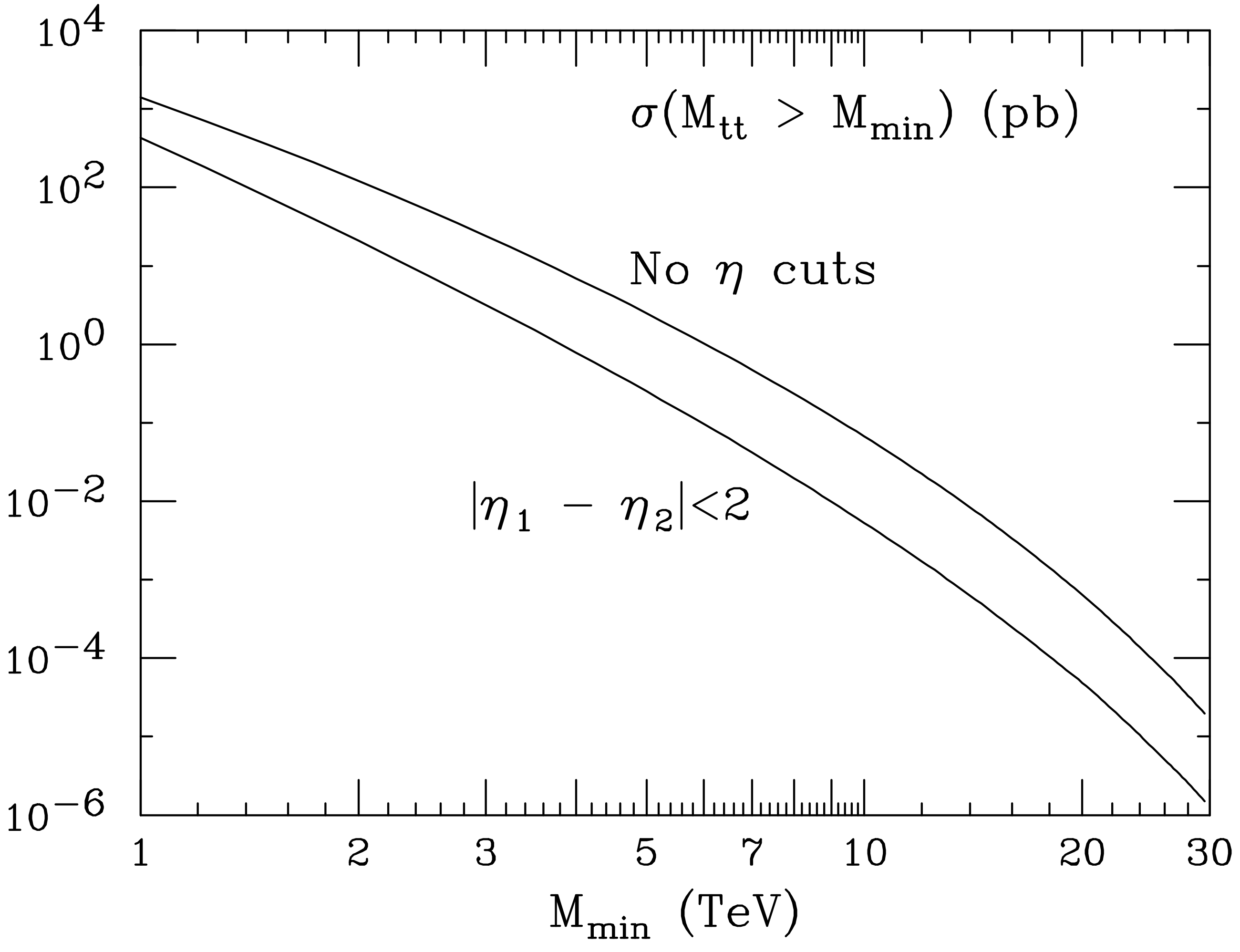
⇒ rare decays $D \to \mu^+\mu^-$, ..., CPV

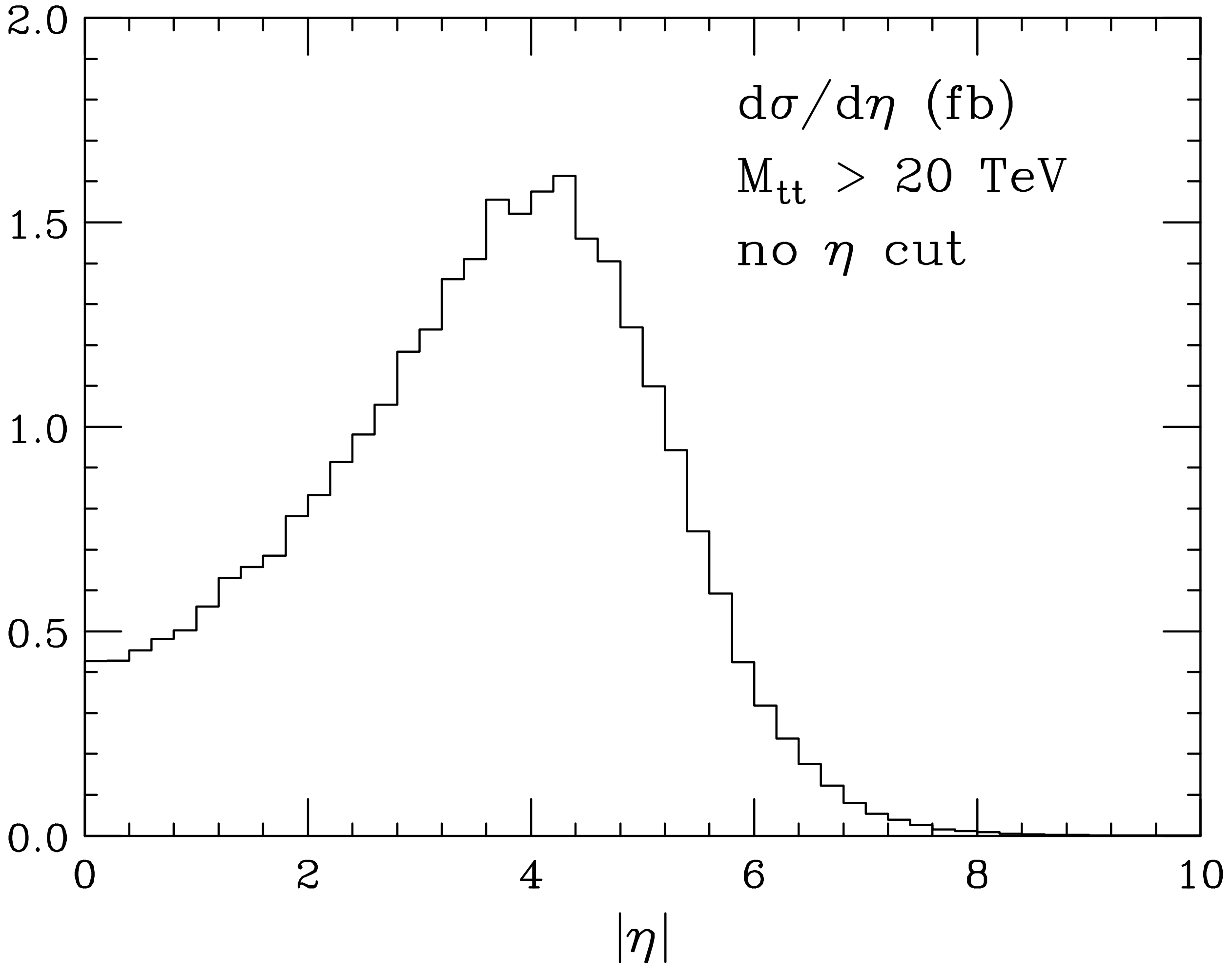
The possibility of detectors dedicated to top physics (more in general, to final states in the 0.1 - 1 TeV region deserves, e.g. for Higgs physics) deserves very serious thinking

Kinematical properties of top production at multi-TeV energies

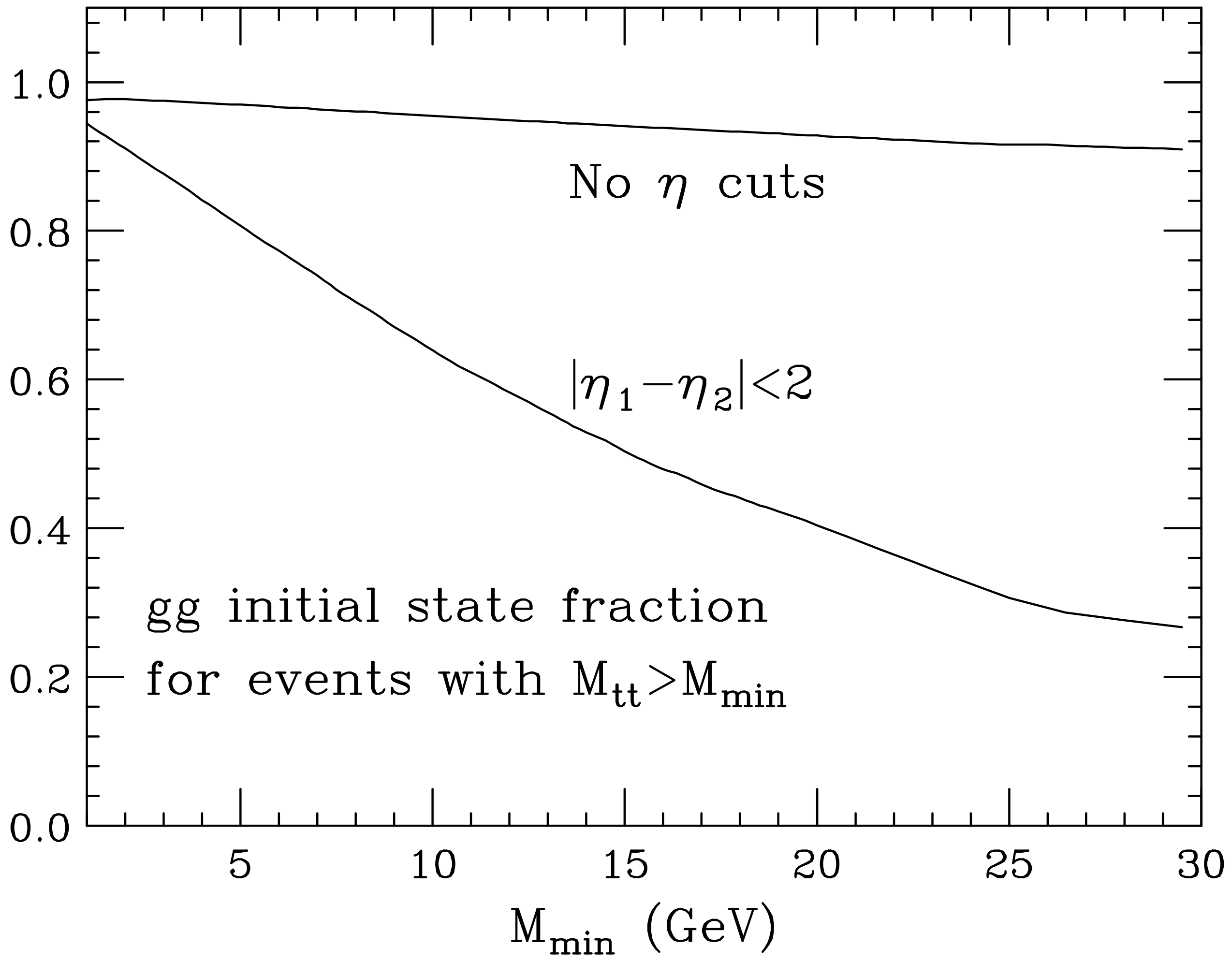
Dominance of small-angle t-channel ⇒

central production ~ 10% of total production

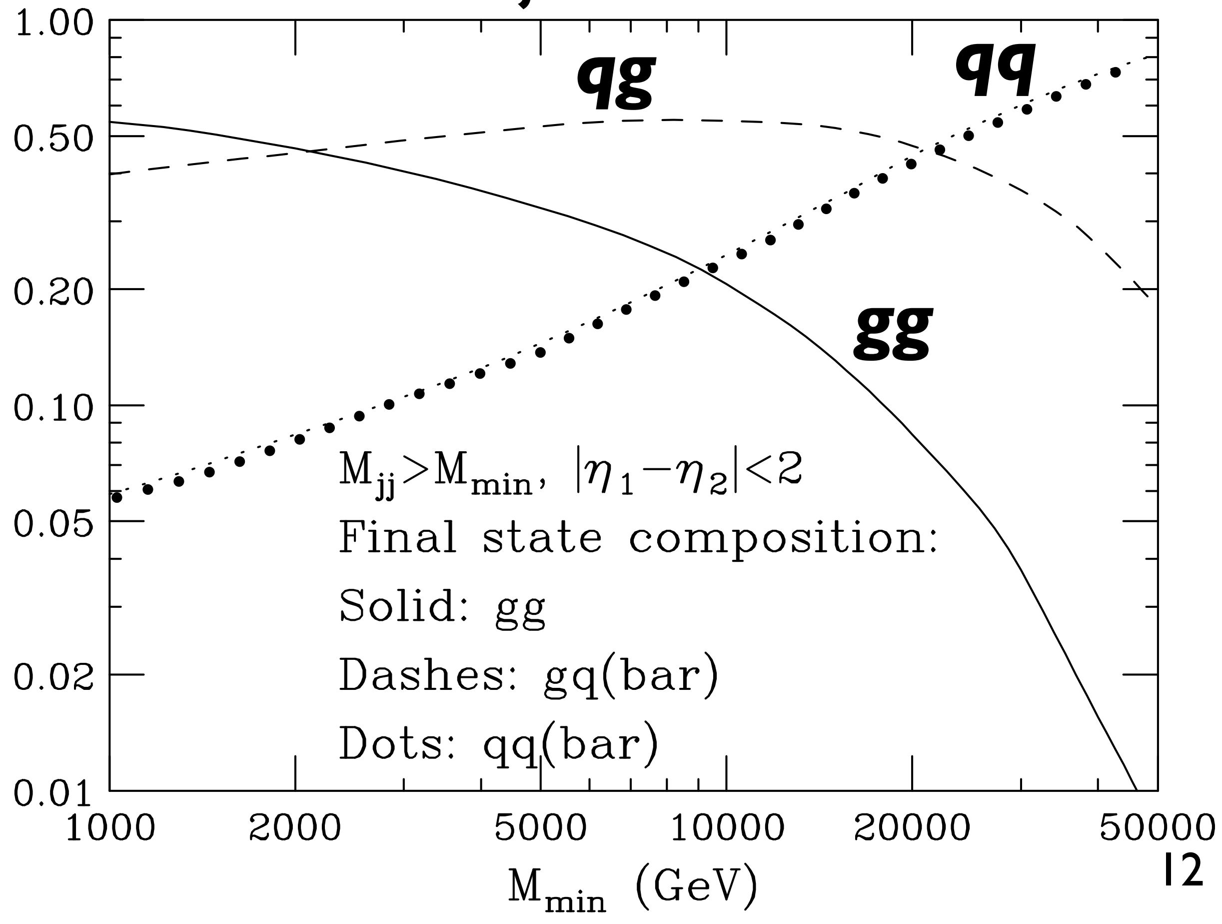




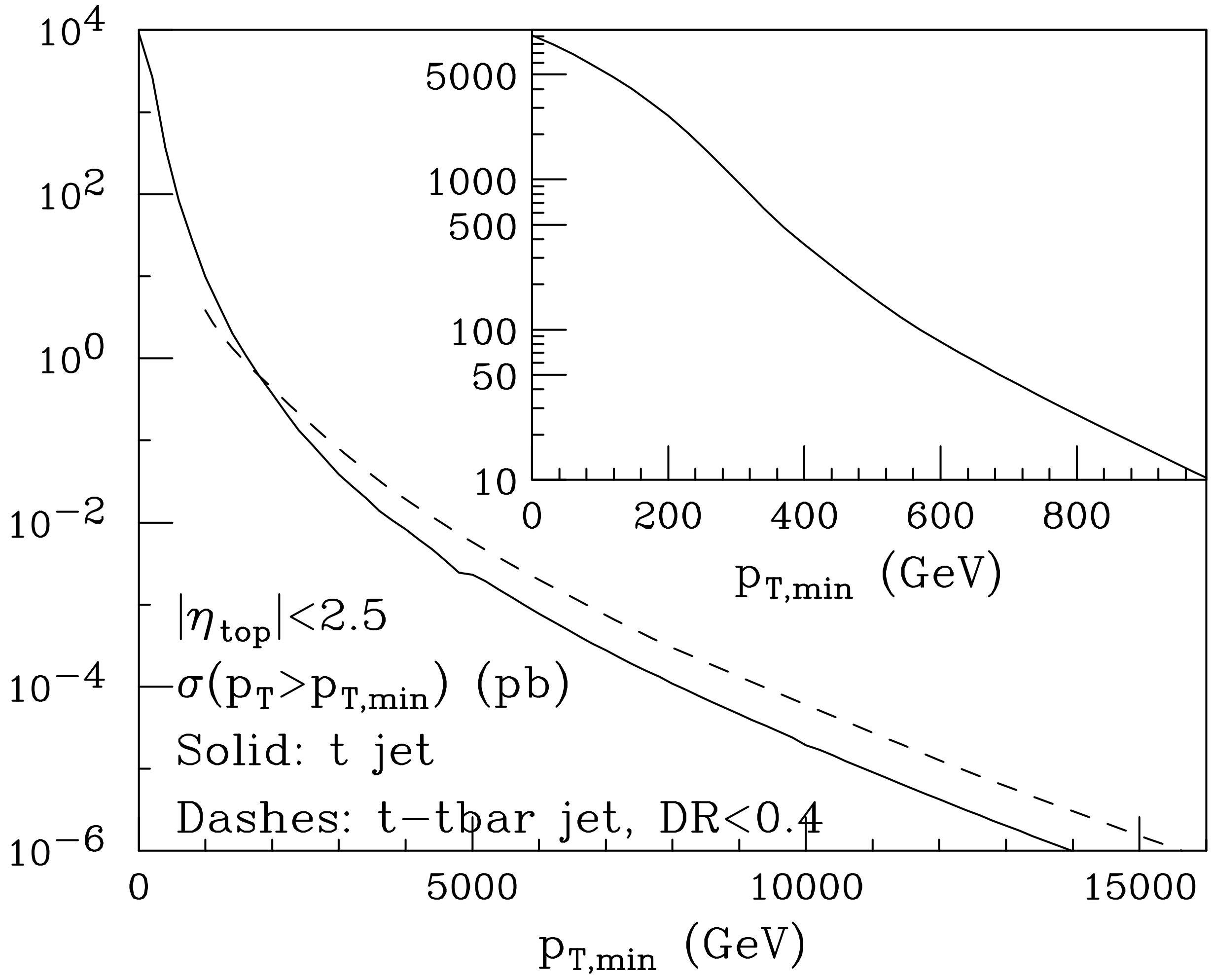
Dominance of gg initial state:
- for all t-tbar masses in inclusive production
- up to M_{tt}~15 TeV for very central production



cfr initial-state composition
in central dijet events:



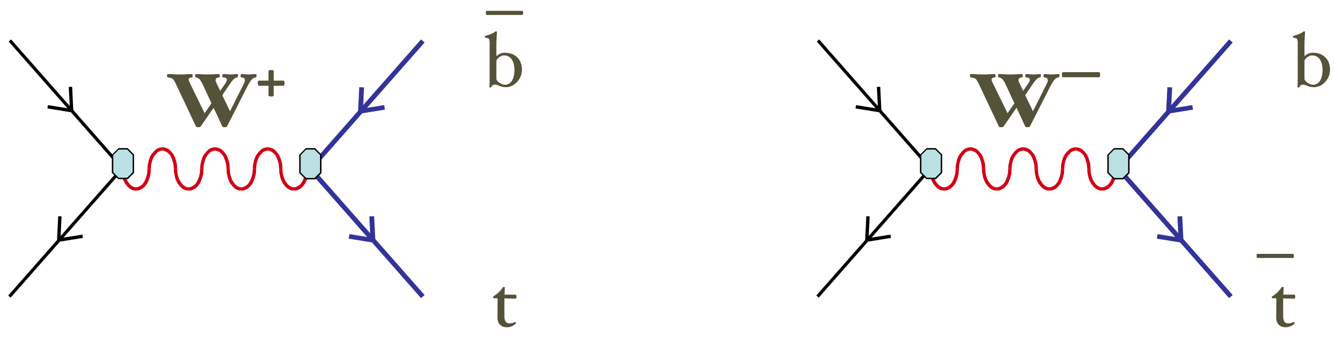
Dominance of g→tt at high p_T

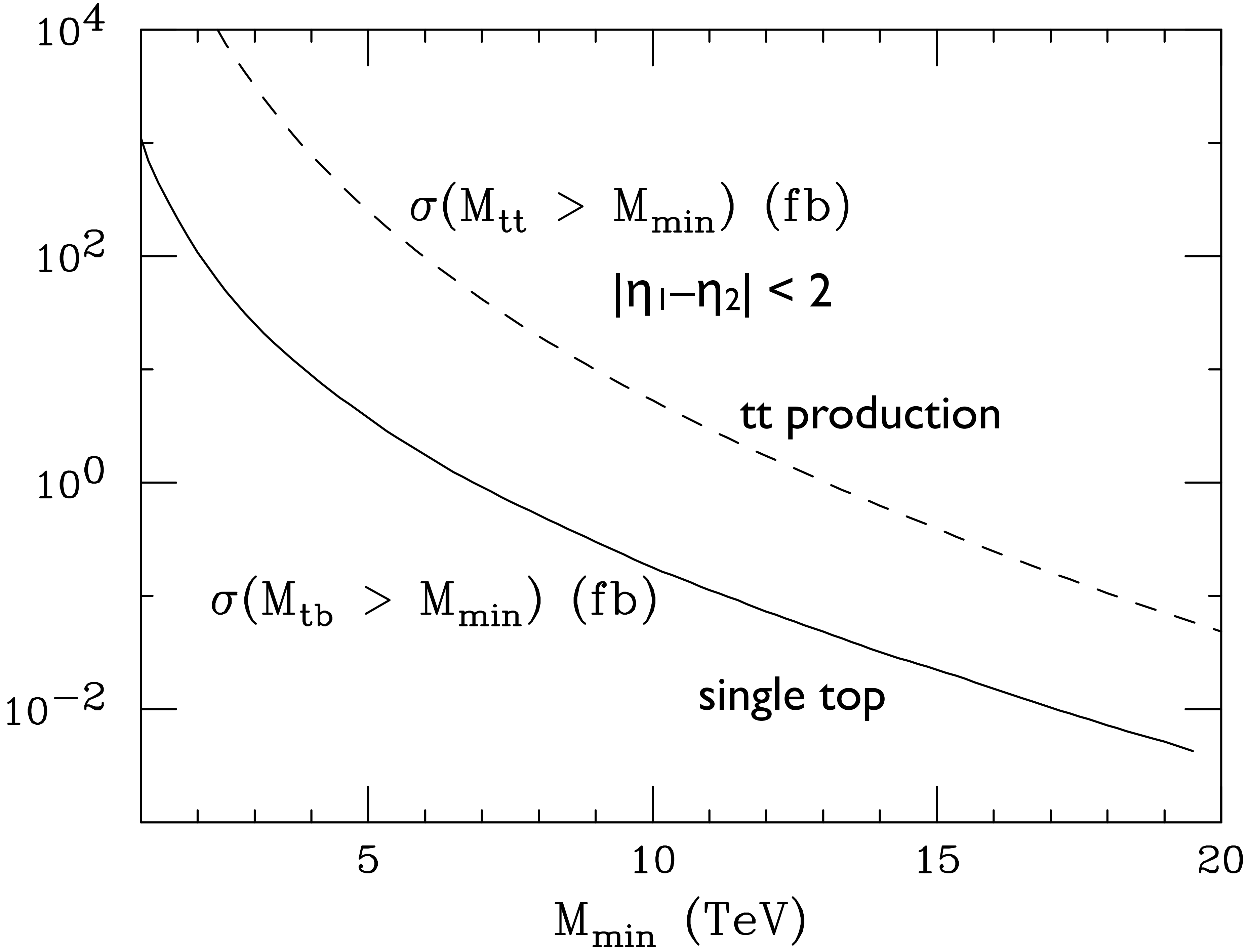


possible impact on top tagging at high pt ?

Single top s-channel production

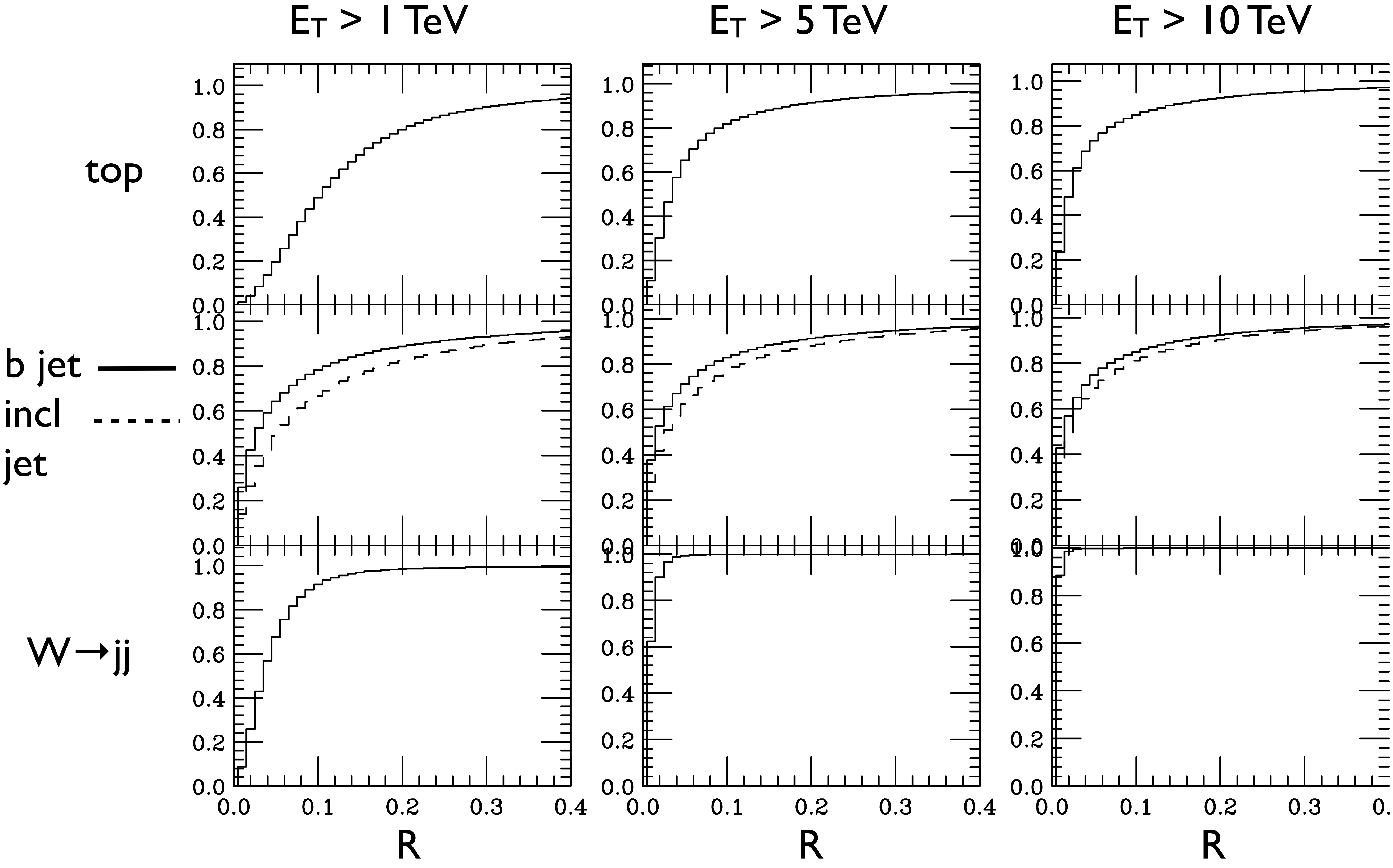
Probe Wtb vertex at multi-TeV Q^2





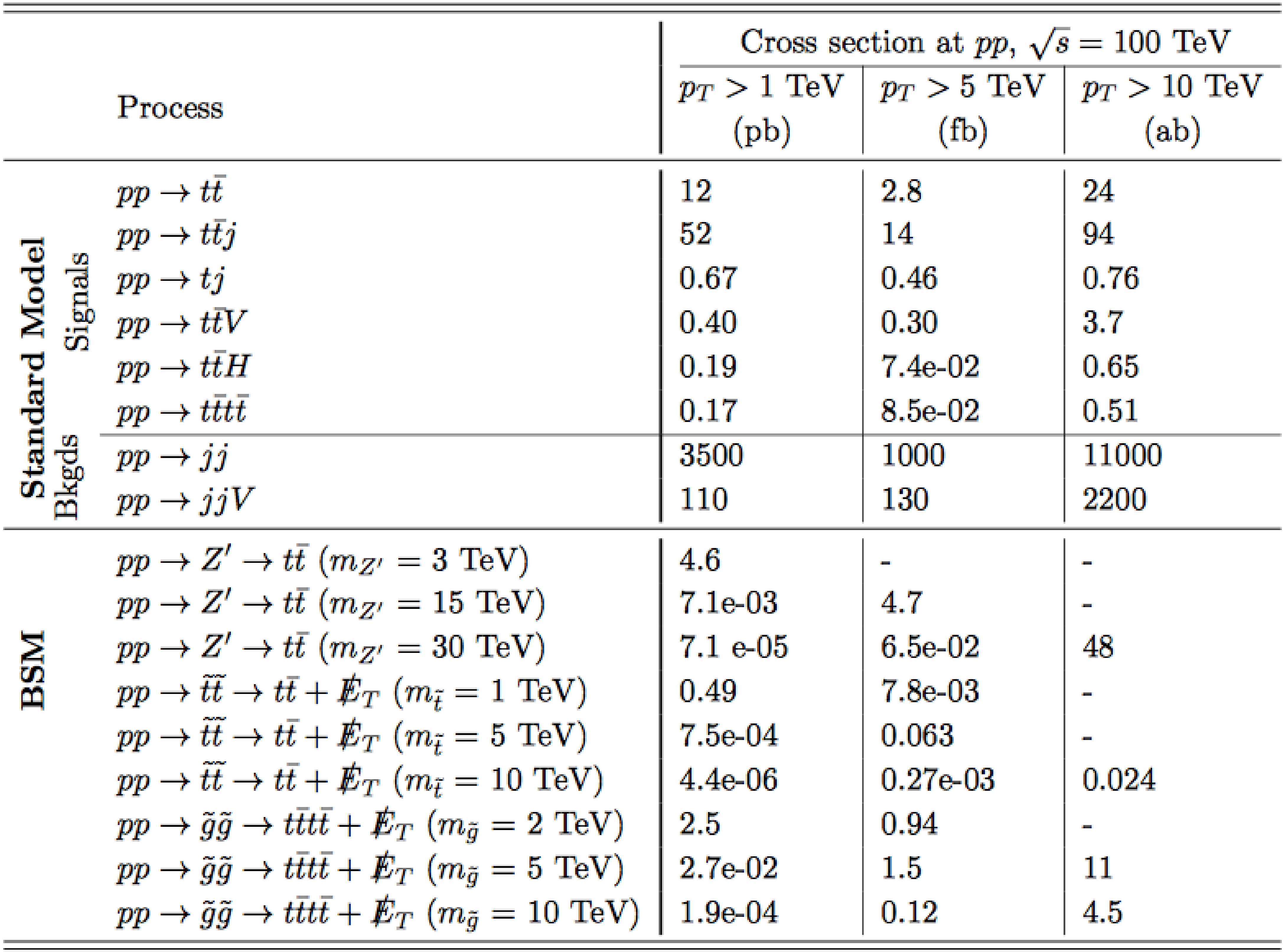
Properties of high-pt top jets.

Example: Energy shape: E(r<R) / E(r<1)



Tracking down hyper-boosted top quarks,

Larkowski et al, arXiv:1503.03347

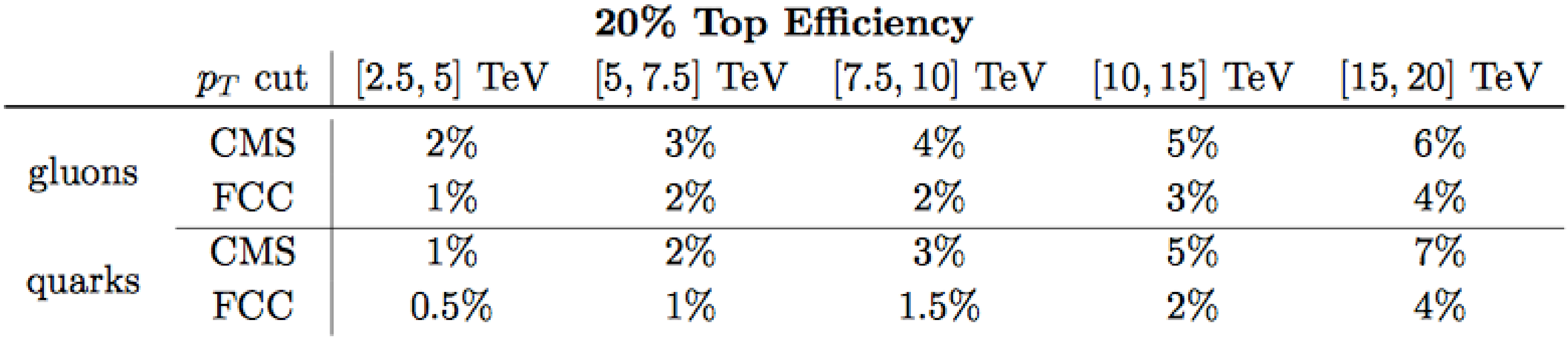


		Process	Cross section at pp, $\sqrt{s} = 100$ TeV		
			$p_T > 1$ TeV (pb)	$p_T > 5$ TeV (fb)	$p_T > 10$ TeV (ab)
Standard Model	Signals	$pp \to t\bar{t}$	12	2.8	24
		$pp \to t\bar{t}j$	52	14	94
		$pp \to tj$	0.67	0.46	0.76
		$pp \to t\bar{t}V$	0.40	0.30	3.7
		$pp \to t\bar{t}H$	0.19	7.4e-02	0.65
		$pp \to t\bar{t}t\bar{t}$	0.17	8.5e-02	0.51
	Bkgds	$pp \to jj$	3500	1000	11000
		$pp \to jjV$	110	130	2200
BSM		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 3$ TeV)	4.6	-	-
		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 15$ TeV)	7.1e-03	4.7	-
		$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 30$ TeV)	7.1 e-05	6.5e-02	48
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 1$ TeV)	0.49	7.8e-03	-
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 5$ TeV)	7.5e-04	0.063	-
		$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 10$ TeV)	4.4e-06	0.27e-03	0.024
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 2$ TeV)	2.5	0.94	-
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 5$ TeV)	2.7e-02	1.5	11
		$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 10$ TeV)	1.9e-04	0.12	4.5

Tracking down hyper-boosted top quarks,

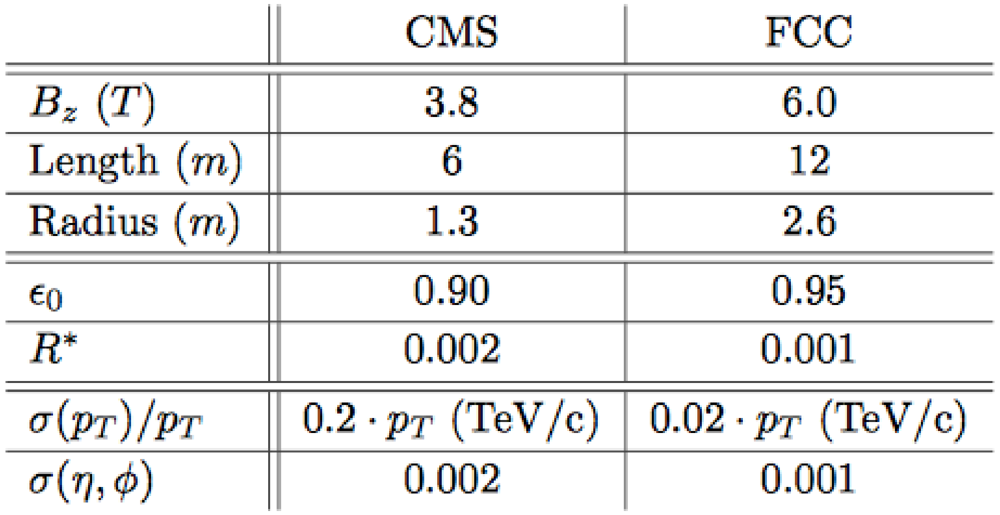
Larkowski et al, arXiv:1503.03347

bg efficiency, per jet



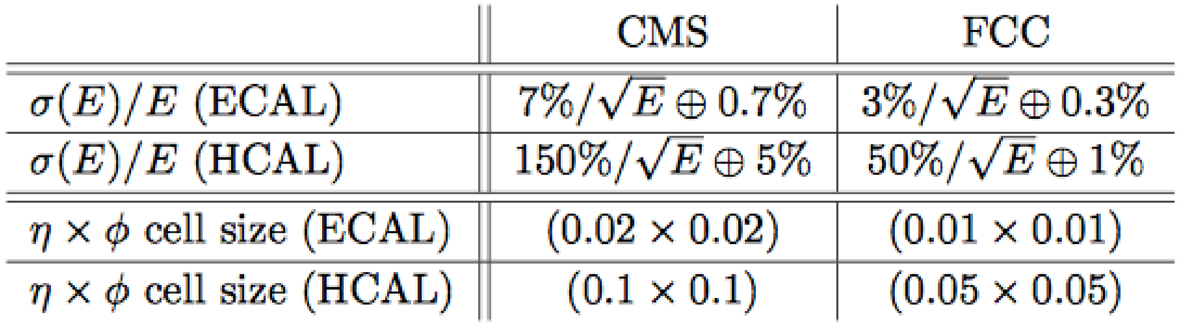
20% Top Efficiency

	p_T cut	[2.5, 5] TeV	[5, 7.5] TeV	[7.5, 10] TeV	[10, 15] TeV	[15, 20] TeV
gluons	CMS	2%	3%	4%	5%	6%
	FCC	1%	2%	2%	3%	4%
quarks	CMS	1%	2%	3%	5%	7%
	FCC	0.5%	1%	1.5%	2%	4%



	CMS	FCC
B_z (T)	3.8	6.0
Length (m)	6	12
Radius (m)	1.3	2.6
ϵ_0	0.90	0.95
R^*	0.002	0.001
$\sigma(p_T)/p_T$	$0.2 \cdot p_T$ (TeV/c)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(\eta, \phi)$	0.002	0.001

Table 2: Tracking-related parameters for the CMS and FCC setup in Delphes.

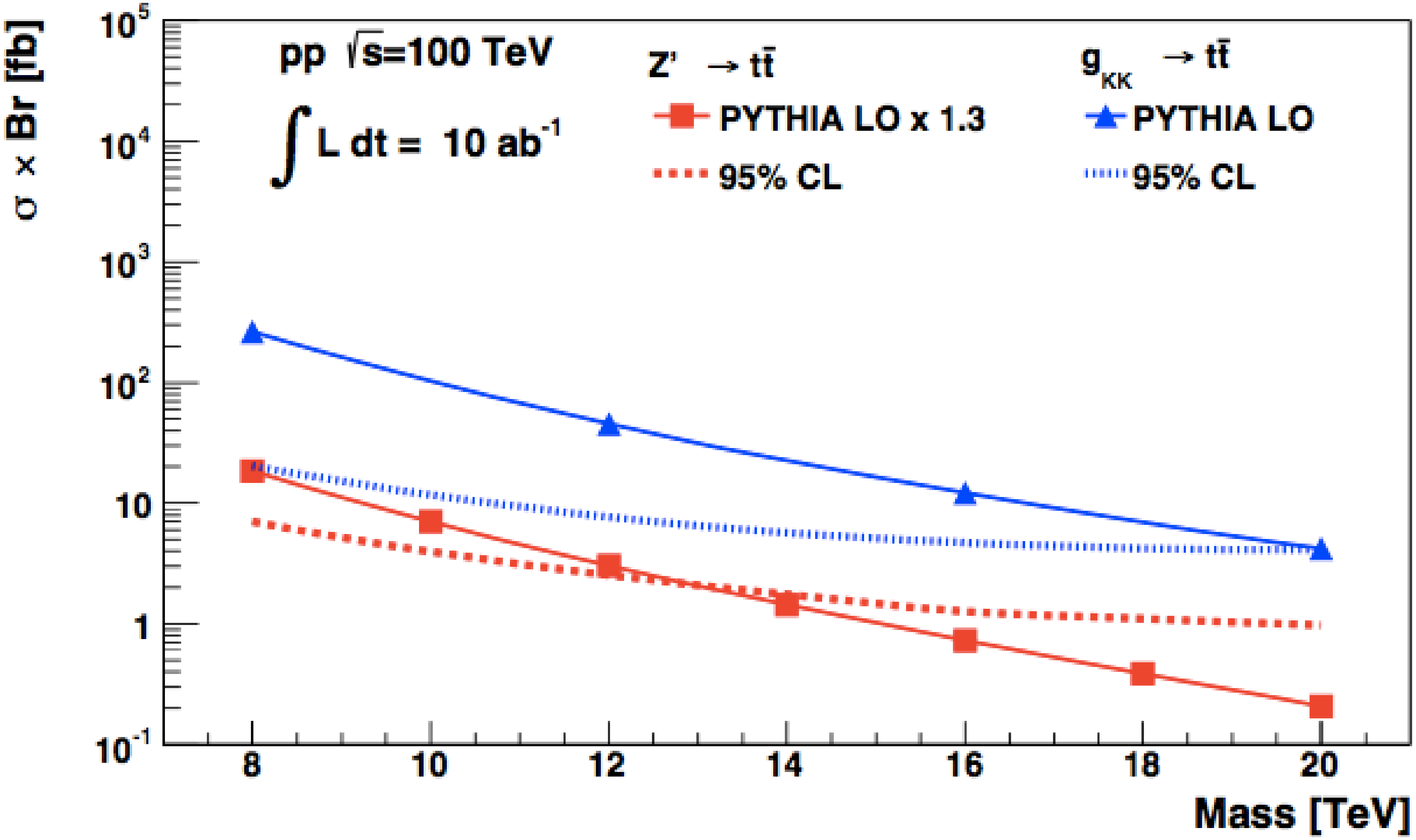


	CMS	FCC
$\sigma(E)/E$ (ECAL)	$7\%/\sqrt{E} \oplus 0.7\%$	$3\%/\sqrt{E} \oplus 0.3\%$
$\sigma(E)/E$ (HCAL)	$150\%/\sqrt{E} \oplus 5\%$	$50\%/\sqrt{E} \oplus 1\%$
$\eta \times \phi$ cell size (ECAL)	(0.02×0.02)	(0.01×0.01)
$\eta \times \phi$ cell size (HCAL)	(0.1×0.1)	(0.05×0.05)

Table 3: Calorimeter parameters for the CMS and FCC setup in Delphes.

Sensitivity to ttbar resonances

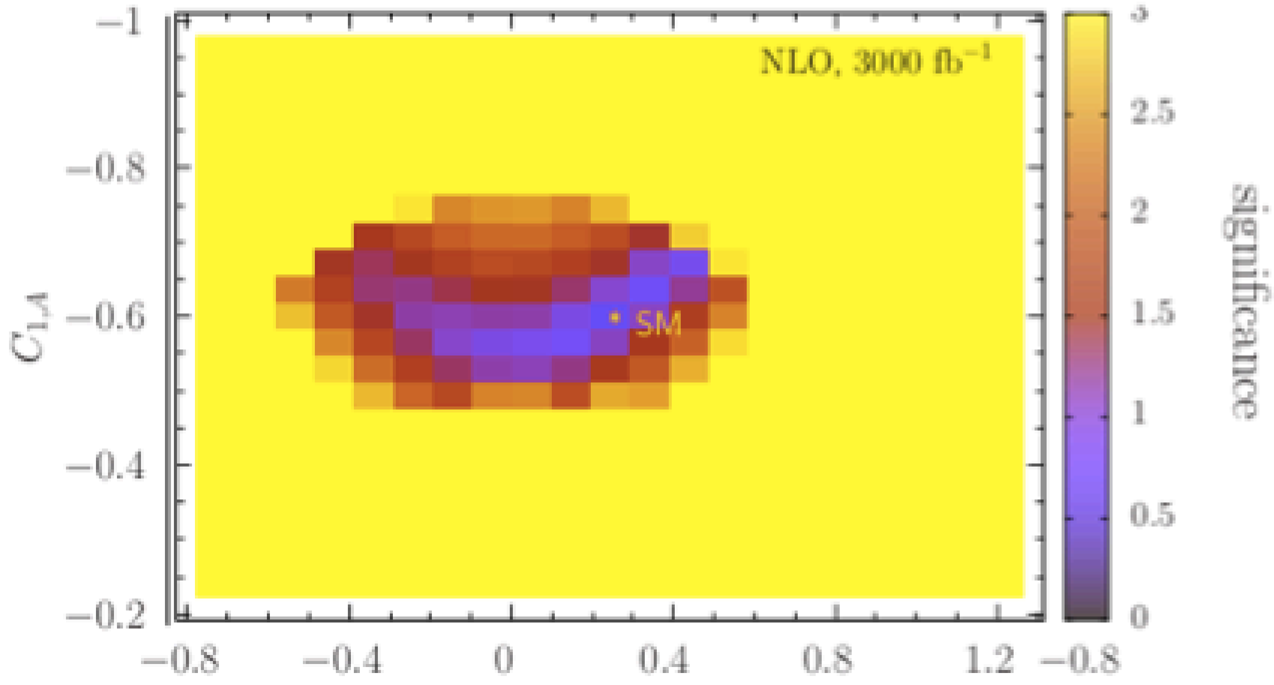
Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



Constraints on *top-Z* vector and axial couplings

[Röntsch,Schulze]

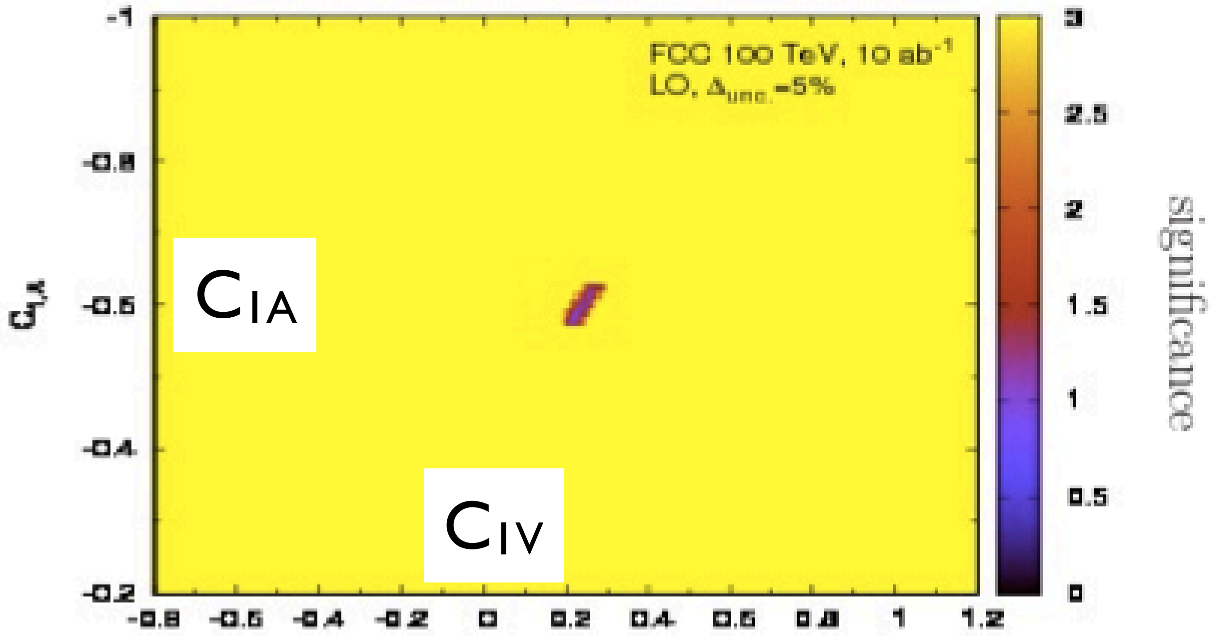
arXiv:1501.05939
arXiv:1404.1005



ttbar + *Z*

LHC 13 TeV, 3000 fb^{-1}

scale+pdfs: ± 15 %



ttbar + *Z*

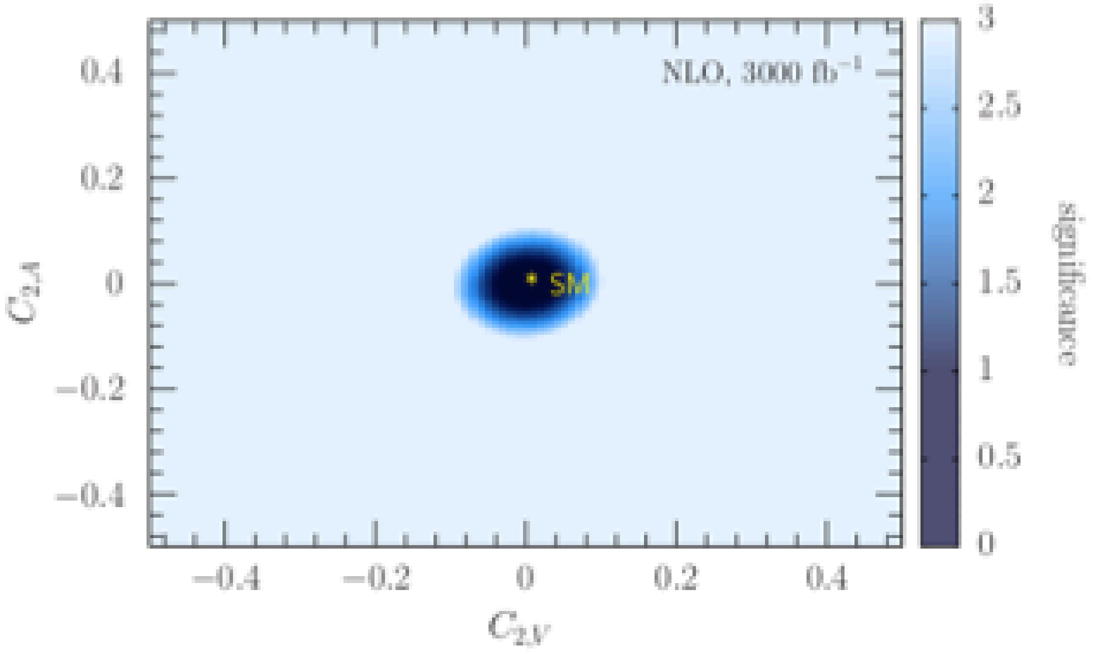
FCC 100 TeV, 10 ab^{-1}

scale+pdfs: ± 5 %

Constraints on *top-Z* weak dipole moments

[Röntsch,Schulze]

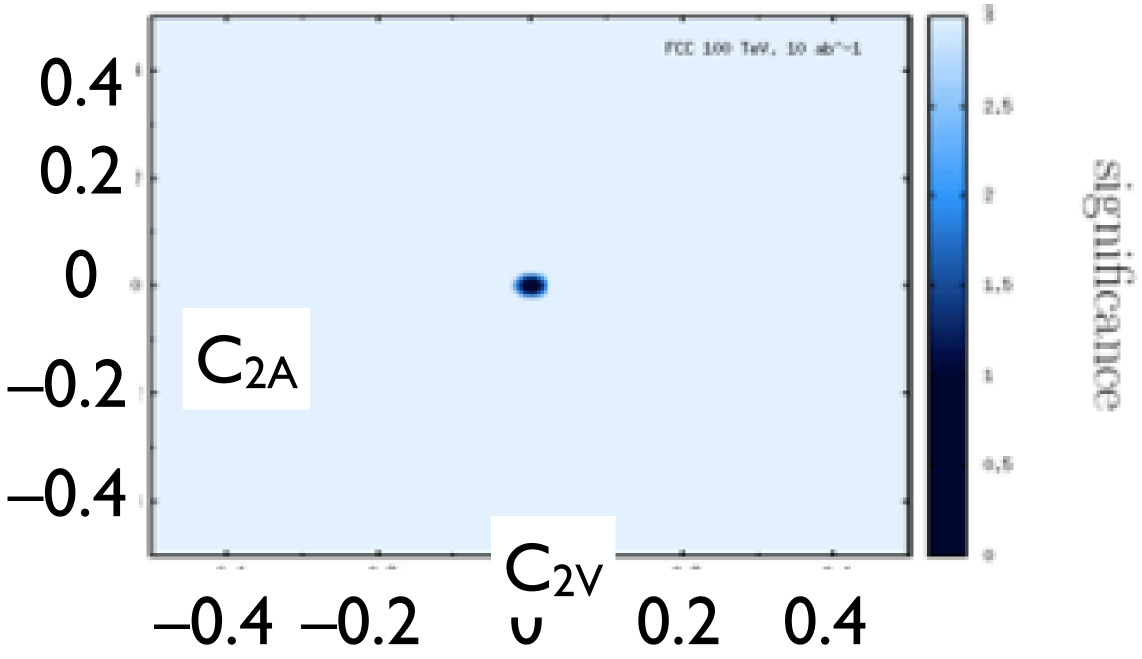
arXiv:1501.05939
arXiv:1404.1005



ttbar + *Z*

LHC 13 TeV, 3000 fb^{-1}

scale+pdfs: ± 15 %



ttbar + *Z*

FCC 100 TeV, 10 ab^{-1}

scale+pdfs: ± 5 %

Top anomalous chromomagnetic moments

J-A Aguilar-Saavedra, Fuks, etal, arXiv:1412.6654

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

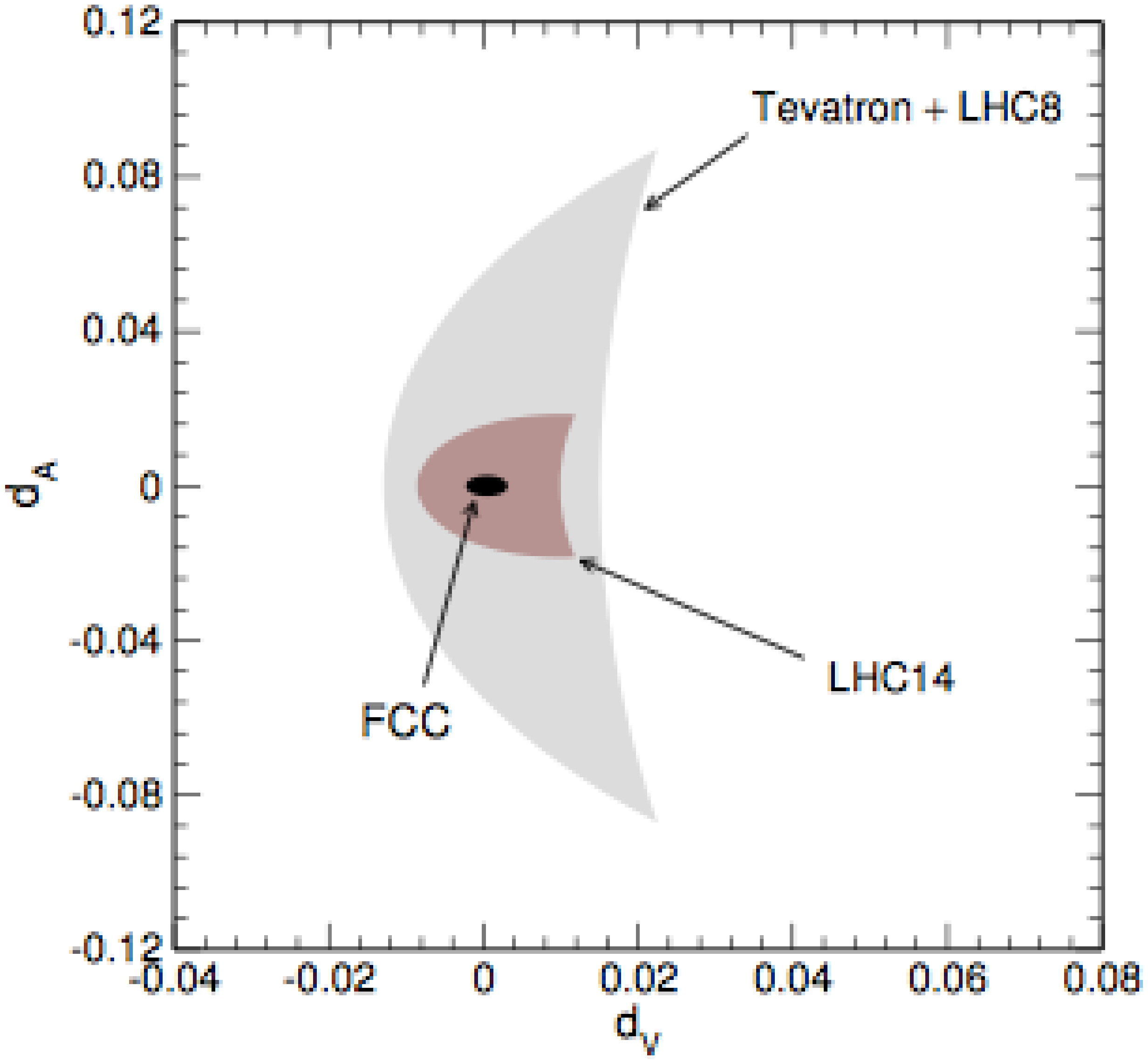
$$O^{33}_{uG\phi} = (\bar{q}_{L3}\lambda_a \sigma^{\mu\nu} t_R)\tilde{\phi}\, G^a_{\mu\nu} \quad \Rightarrow \quad d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Re}\, C^{33}_{uG\phi}\,, \quad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Im}\, C^{33}_{uG\phi}$$

At 100 TeV, constraints from event rate at $M_{tt} > 10$ TeV:

$$-0.0022 \le d_V \le 0.0031$$

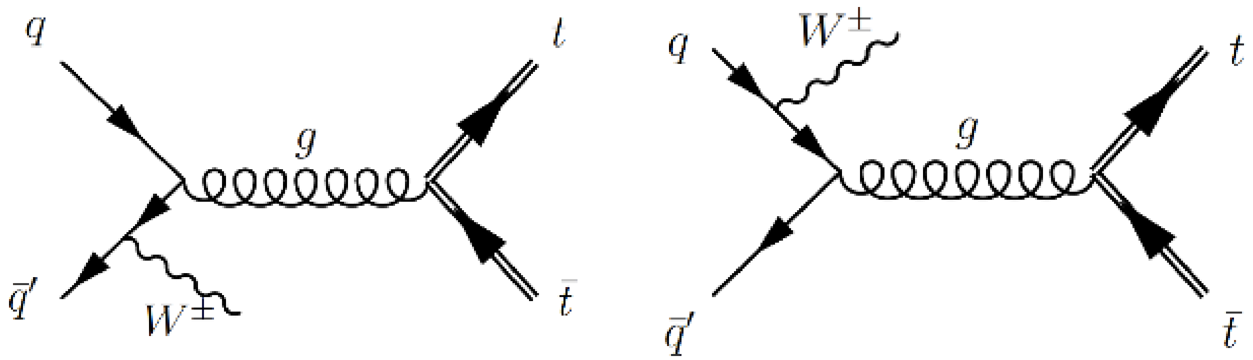
$$|d_A| \le 0.0026$$

$$\Rightarrow \Lambda \gtrsim 17 \text{ TeV}$$



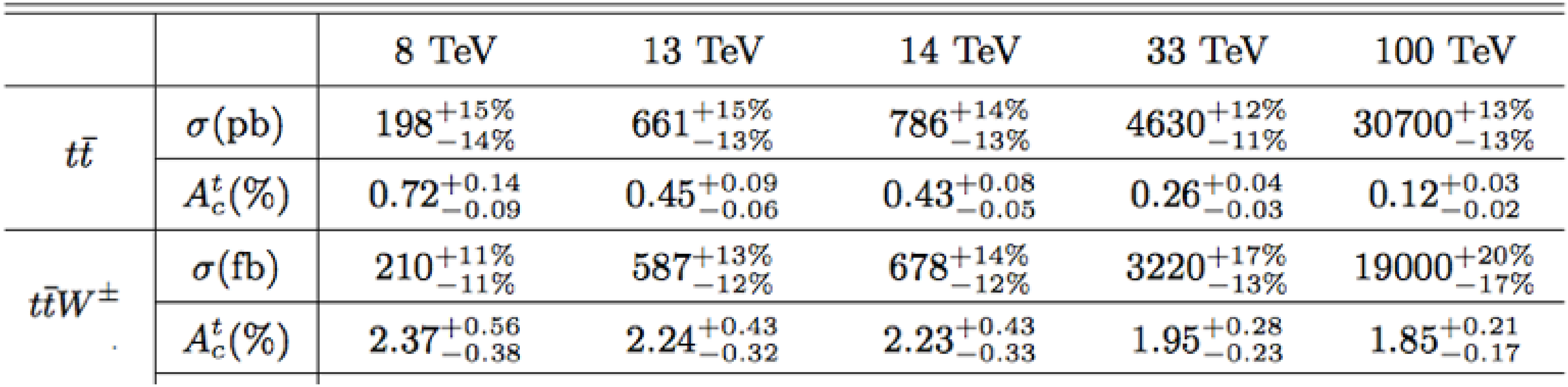
ttW as a probe of A_C

Maltoni, Tsinikos, Zaro, etal, arXiv:1406.3262



At LO only sensitive to q-qbar initial state
⇒ maximizes charge asymmetry

A_C and its scale systematics (NLO, include qg initial state contamination):



		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(%)	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$	$1.95^{+0.28}_{-0.23}$	$1.85^{+0.21}_{-0.17}$

Statistics for ttW channel:

14 TeV, 3000 fb^{-1} ⇒ $\Delta A^t_C / A^t_C = 14\%$

100 TeV, 3000 fb^{-1} ⇒ $\Delta A^t_C / A^t_C = 3\%$

ttH/ttZ at 100 TeV as a probe of y_{top}

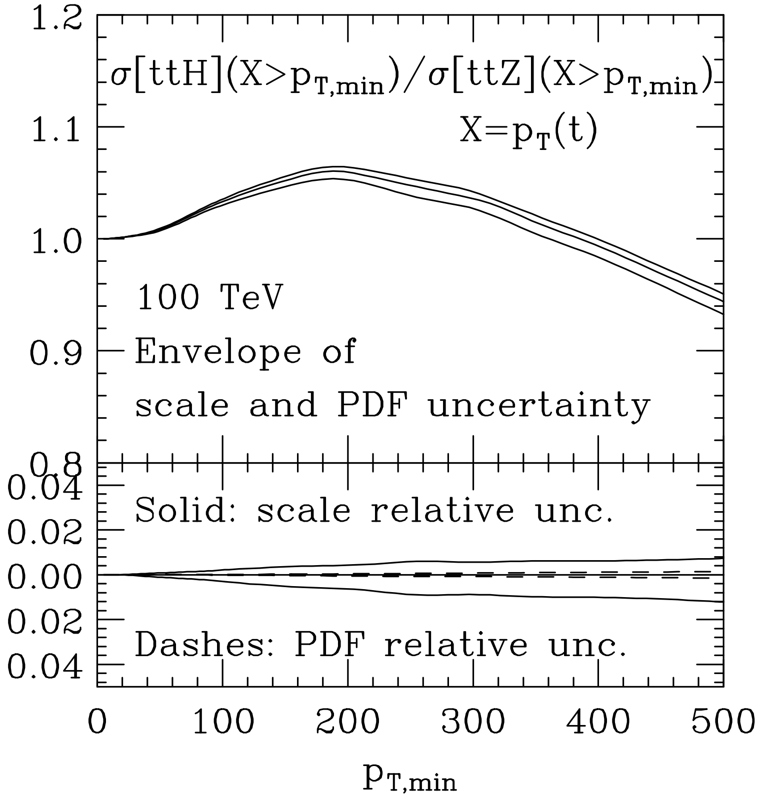
etal, Plehn, Reimitz, Shell, Shao, arXiv:1507.08169

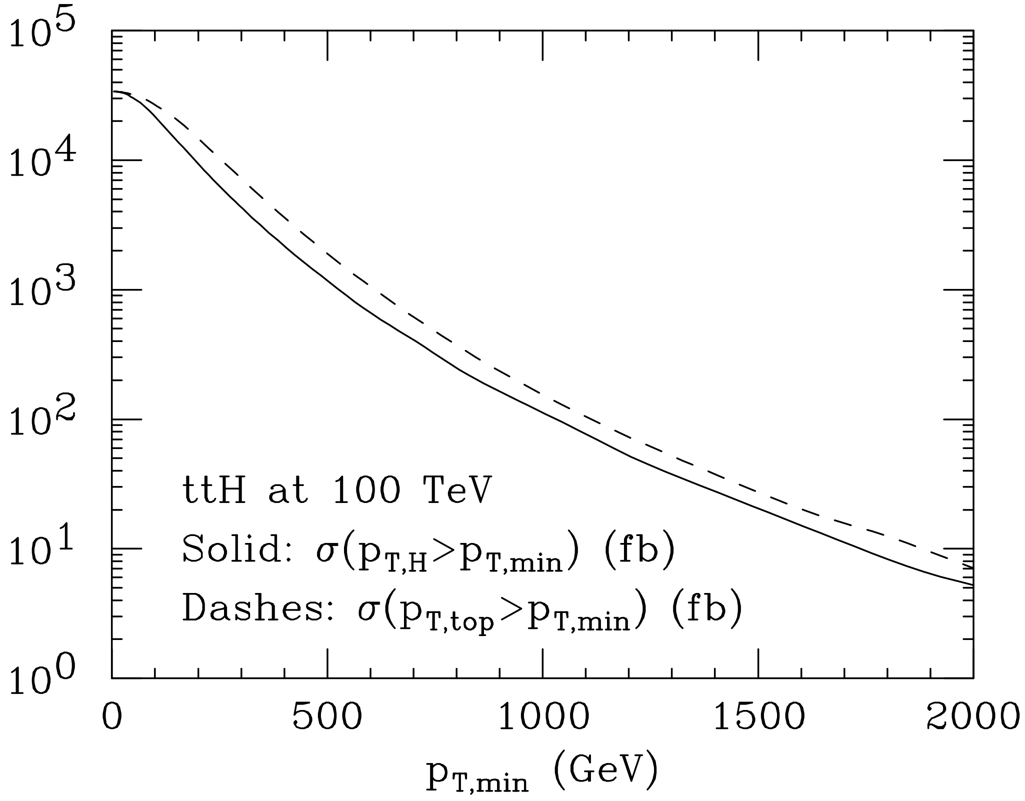
Strong correlations between the two processes in terms of:

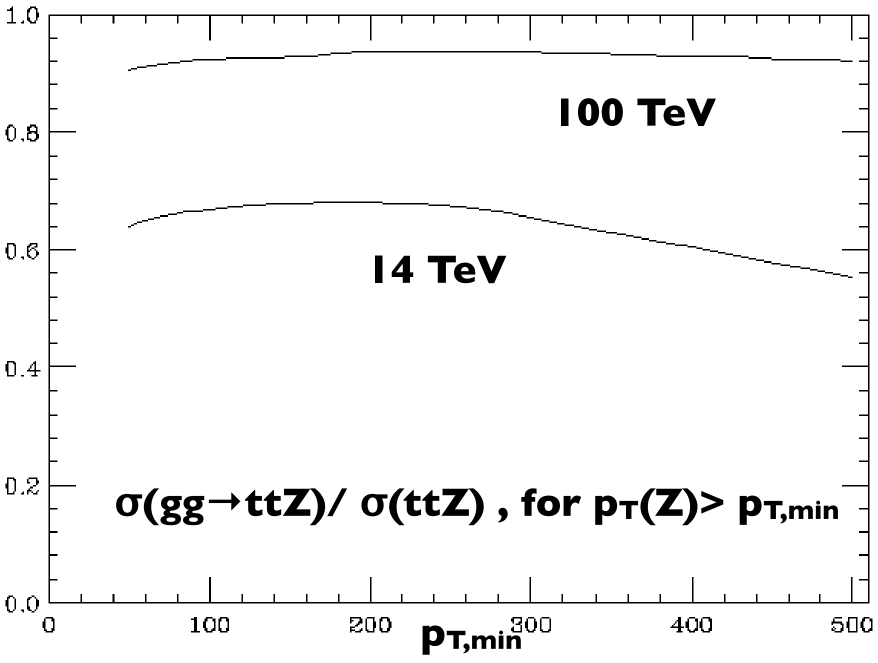
- production dynamics, radiative corrections (⇒reduced scale dependence, MC modeling)
- kinematics ($m_H \sim m_Z$) (⇒reduced PDF systematics, reduced m_{top} systematics, modeling, ...)

At 100 TeV:

- greater dominance of gg initial state w.r.t. 14 TeV ⇒ ttH closer to ttZ
- huge production rates (ttH rate@100 TeV ~ 60 x ttH rate@14 TeV)
- large rate at very high $p_T(H)$ and $p_T(top)$ ⇒ effective use of boosted techniques, reduced combinatorial bg, systematics)
- access to "clean" final states ($H \to \gamma\gamma$, $H \to WW^*$)





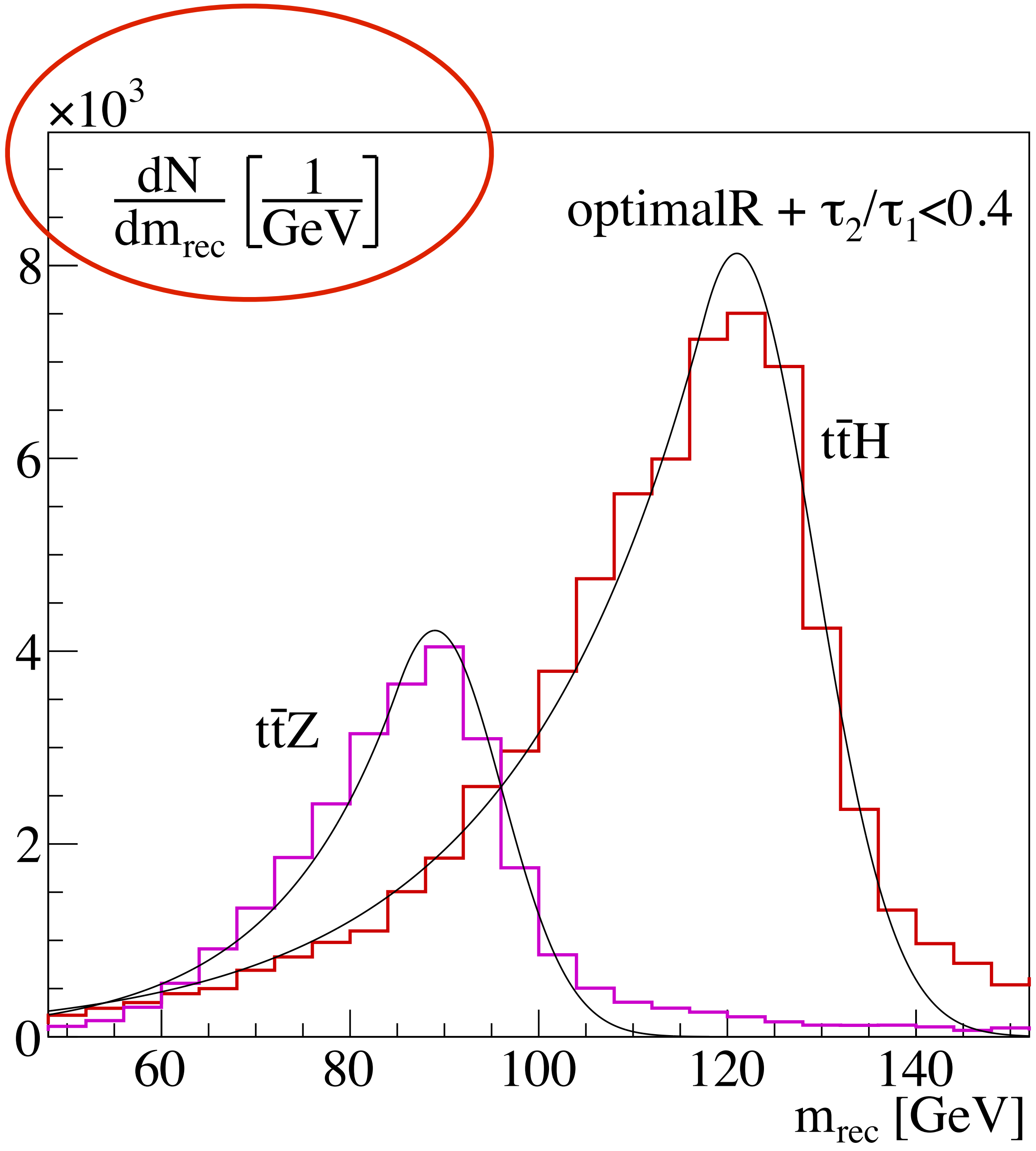


	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$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

Scale + PDF uncert.

N(events) w. 20 ab^{-1}, tt→e/μ + jets

$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$



Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

1% precision on y_{top} within reach

(assuming B(H→bb) known)

arXiv:1507.08169

Conclusions

Conclusions

- LHC findings may give different weight to the possible exptl approaches and facilities

Conclusions

- LHC findings may give different weight to the possible exptl approaches and facilities
- But no matter what LHC finds, the top will remain a key probe of new phenomena (*see Peskin's keynote address*)

Conclusions

- LHC findings may give different weight to the possible exptl approaches and facilities
- But no matter what LHC finds, the top will remain a key probe of new phenomena (*see Peskin's keynote address*)
- Precision will anyway be crucial under all scenarios
  - push further the search for new physics if none is found
  - determine the nature of new physics, if it's found

Conclusions

- LHC findings may give different weight to the possible exptl approaches and facilities
- But no matter what LHC finds, the top will remain a key probe of new phenomena (*see Peskin's keynote address*)
- Precision will anyway be crucial under all scenarios
  - push further the search for new physics if none is found
  - determine the nature of new physics, if it's found
- 100 TeV open new perspectives and opportunities on many fronts of top physics. Some of the emerging new ideas may even bear fruit at the HL-LHC. We must cultivate a culture of high-precision measurements of top properties and interactions