QCD for (future) hadron colliders

ICTP Summer School

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Lecture 4

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8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

$E_{1,2}$: different beam energies

X,Y: different hard processes

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \quad \longrightarrow$$

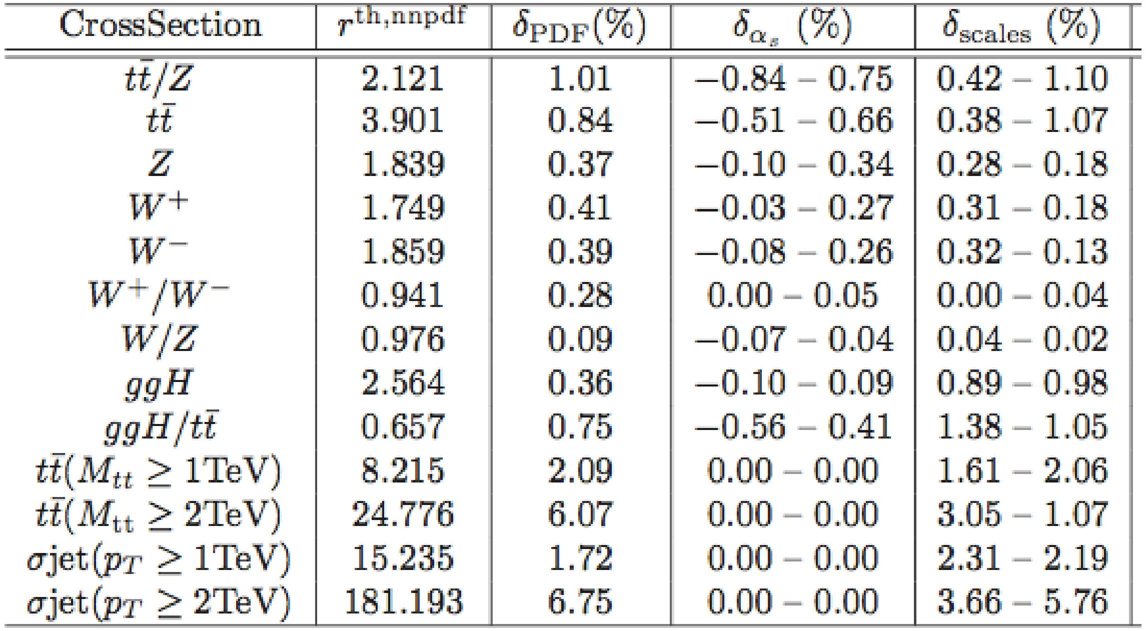
- TH: reduce "scale uncertainties"
- TH: reduce parameters' systematics: PDF, m_{top}, α_S, ... at E_1 and E_2 are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst's from acceptance, efficiency, JES, ...

$$R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)} \quad \longrightarrow$$

- TH: possible further reduction in scale and PDF syst's
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst's (e.g. X,Y=W^+,W^-)

Following results obtained using best available TH predictions: NLO, NNLO, NNLL resummation when available

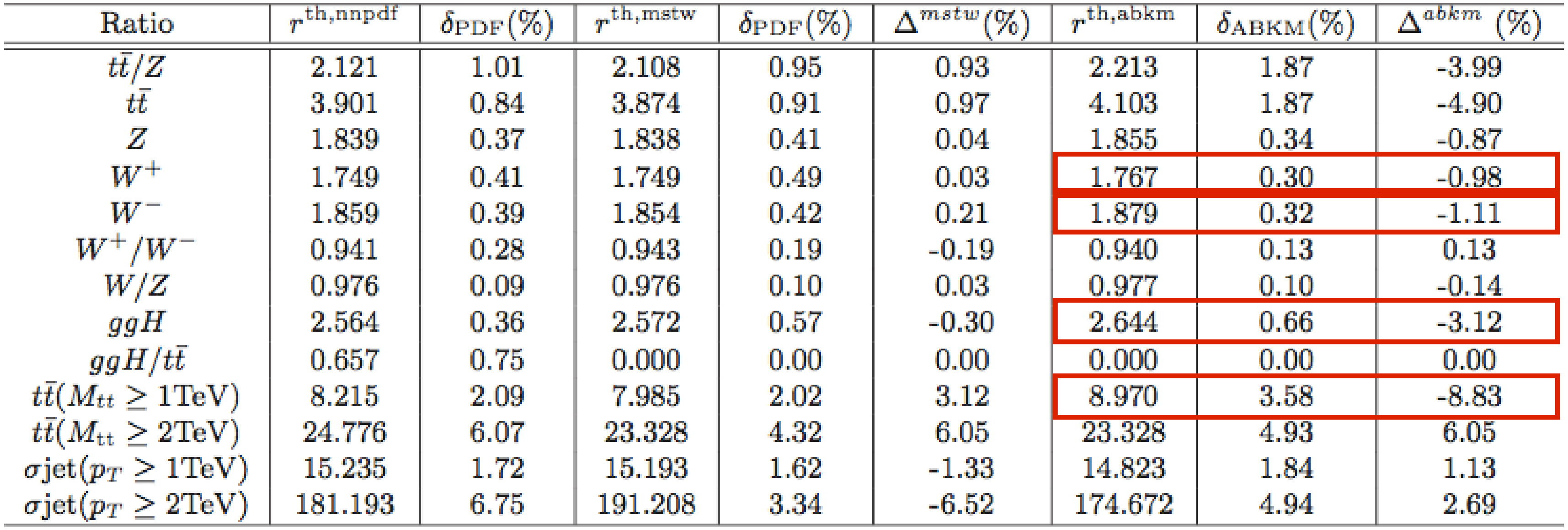
14 TeV / 8 TeV: NNPDF results



CrossSection	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	2.121	1.01	−0.84 – 0.75	0.42 – 1.10
$t\bar{t}$	3.901	0.84	−0.51 – 0.66	0.38 – 1.07
Z	1.839	0.37	−0.10 – 0.34	0.28 – 0.18
W^+	1.749	0.41	−0.03 – 0.27	0.31 – 0.18
W^-	1.859	0.39	−0.08 – 0.26	0.32 – 0.13
W^+/W^-	0.941	0.28	0.00 – 0.05	0.00 – 0.04
W/Z	0.976	0.09	−0.07 – 0.04	0.04 – 0.02
ggH	2.564	0.36	−0.10 – 0.09	0.89 – 0.98
$ggH/t\bar{t}$	0.657	0.75	−0.56 – 0.41	1.38 – 1.05
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	0.00 – 0.00	1.61 – 2.06
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	24.776	6.07	0.00 – 0.00	3.05 – 1.07
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	0.00 – 0.00	2.31 – 2.19
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	0.00 – 0.00	3.66 – 5.76

- $\delta < 10^{-2}$ in $W^{\pm}$ ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta \sim 10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{\mathrm{scale}} < \delta_{\mathrm{PDF}}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM



Ratio	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$r^{\mathrm{th,mstw}}$	$\delta_{\mathrm{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\mathrm{th,abkm}}$	$\delta_{\mathrm{ABKM}}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
W^-	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
W^+/W^-	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
W/Z	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
ggH	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of 3-4σ discrepancies between predictions of different PDF sets, even in the case of W and Z rates

Xsection ratios as probes of BSM contributions

Assume the final state **X** receives both SM and BSM contributions:

$$\sigma^{exp}(pp \to X) = \sigma^{SM}(pp \to X) + \sigma^{BSM}(pp \to X)$$

Define the ratio:

$$R^X_{7/8} = \frac{\sigma^{exp}(pp \to X; 7\ \mathrm{TeV})}{\sigma^{exp}(pp \to X; 8\ \mathrm{TeV})} = \frac{\sigma^{exp}_X(7)}{\sigma^{exp}_X(8)}$$

We easily get:

$$R^X_{7/8} \sim \frac{\sigma^{SM}_X(7)}{\sigma^{SM}_X(8)} \times \left\{ 1 + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)}\ \Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] \right\}$$

where:

$$\Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] = 1 - \frac{\sigma^{BSM}_X(8)/\sigma^{SM}_X(8)}{\sigma^{BSM}_X(7)/\sigma^{SM}_X(7)} \sim 1 - \frac{\mathcal{L}^{BSM}_X(8)/\mathcal{L}^{BSM}_X(7)}{\mathcal{L}^{SM}_X(8)/\mathcal{L}^{SM}_X(7)} = \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

Therefore:

relative BSM
contamination

$$\frac{\delta R^X_{7/8}}{R^X_{7/8}} = \frac{\delta R^{SM}_{7/8}}{R^{SM}_{7/8}} + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)} \times \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

theory systematics in
7→8 TeV extrapolation

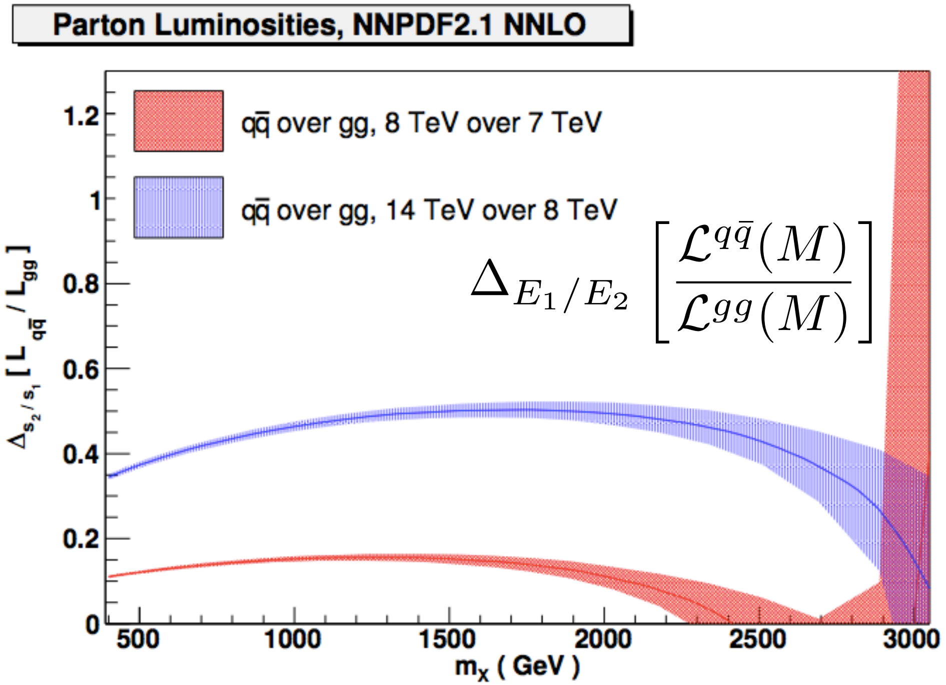
Energy dependence of the
relative BSM contamination

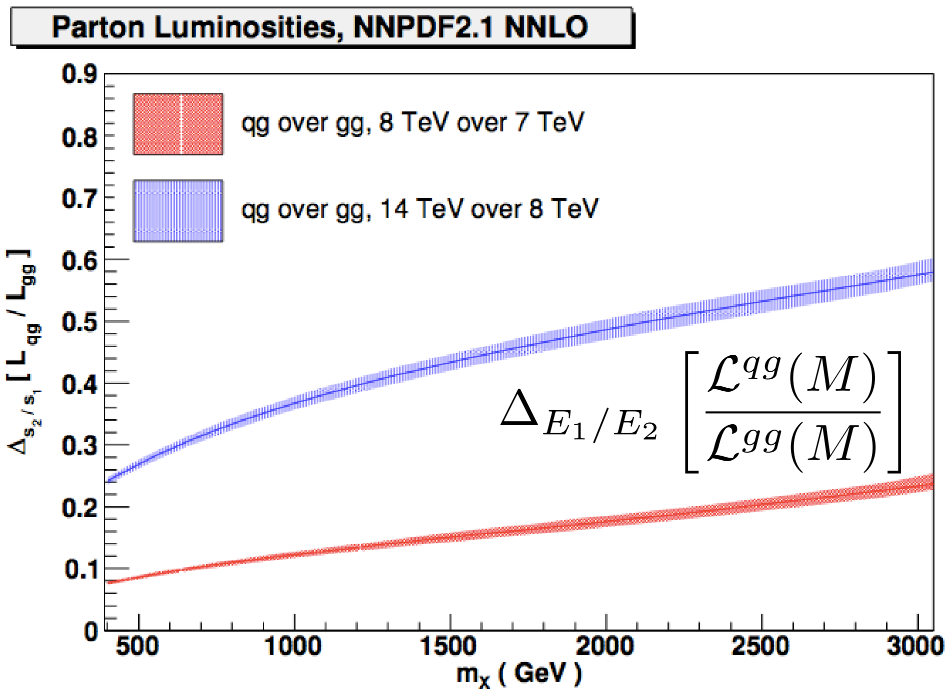
E.g., assuming $\sigma_{SM}(pp\rightarrow X)=\sigma(gg\rightarrow X)$ and $\sigma_{BSM}(pp\rightarrow X)=\sigma(qq\rightarrow X)$ (*)

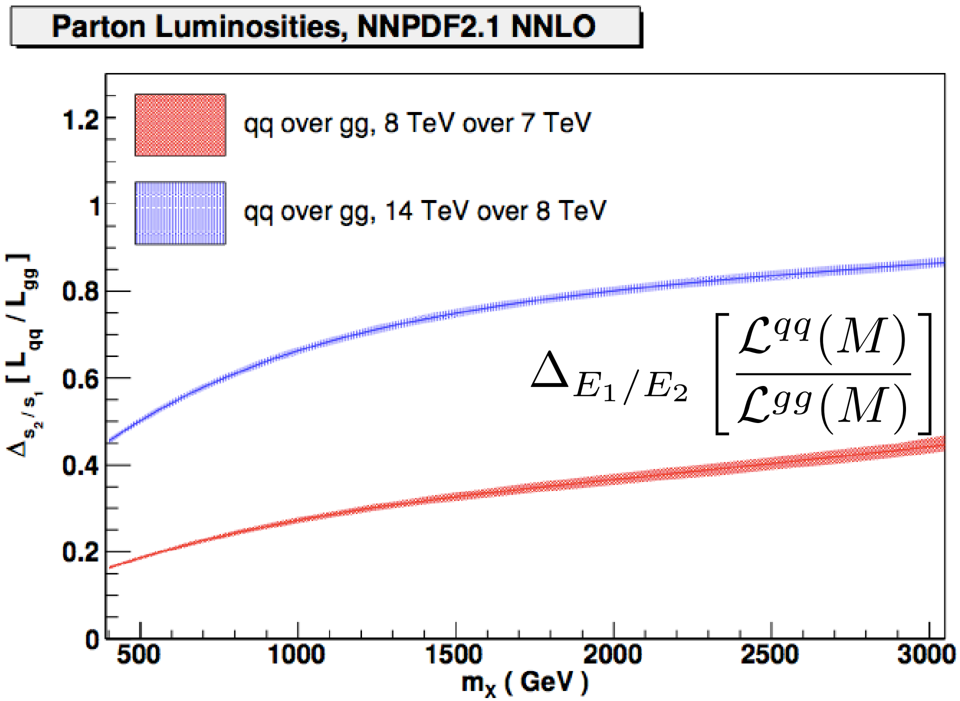
$$\Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right] = \Delta_{7/8}\left[\frac{\mathcal{L}^{q\bar{q}}(M)}{\mathcal{L}^{gg}(M)}\right]$$

(*) e.g. SM: gg→tt and BSM: qqbar→Z'→tt

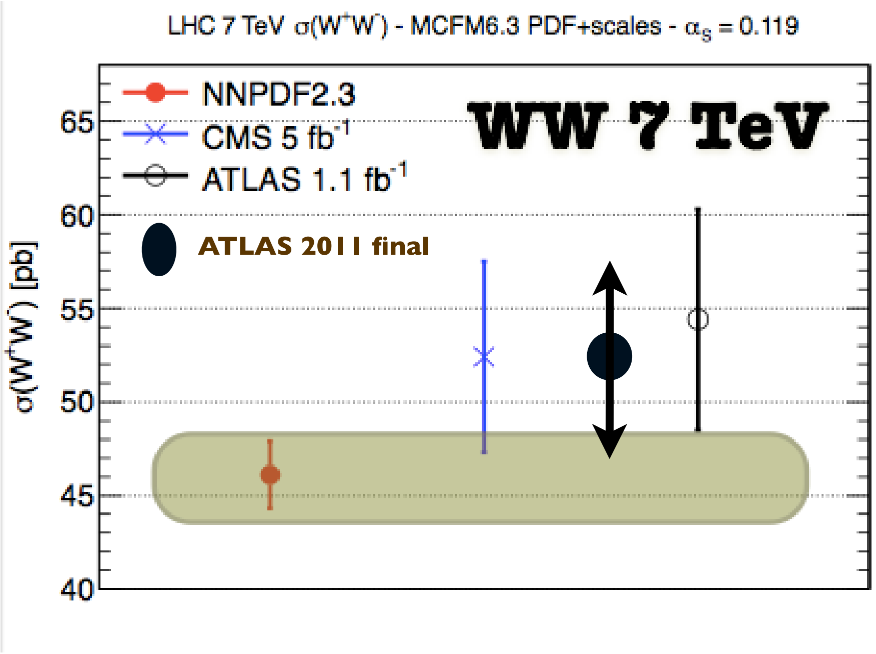
Examples of E-dependence of luminosity ratios

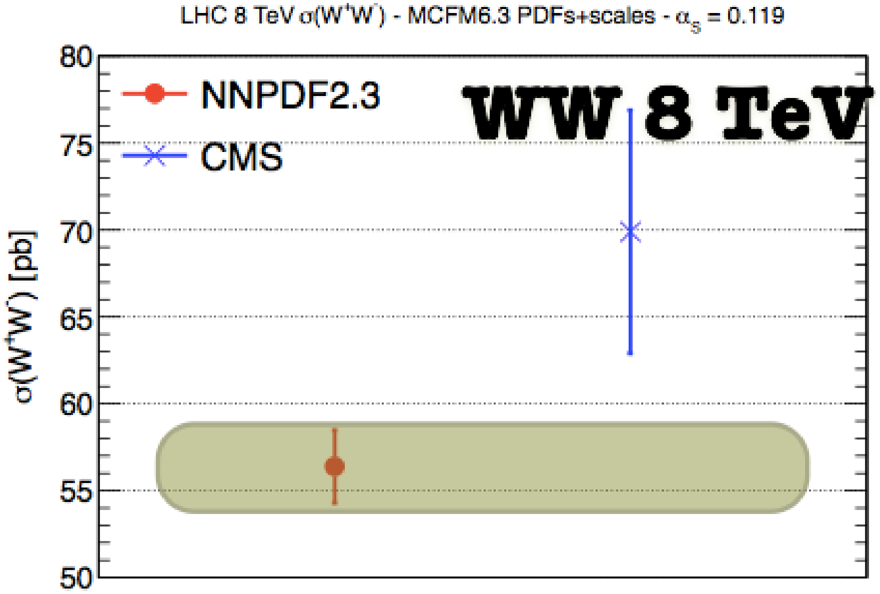


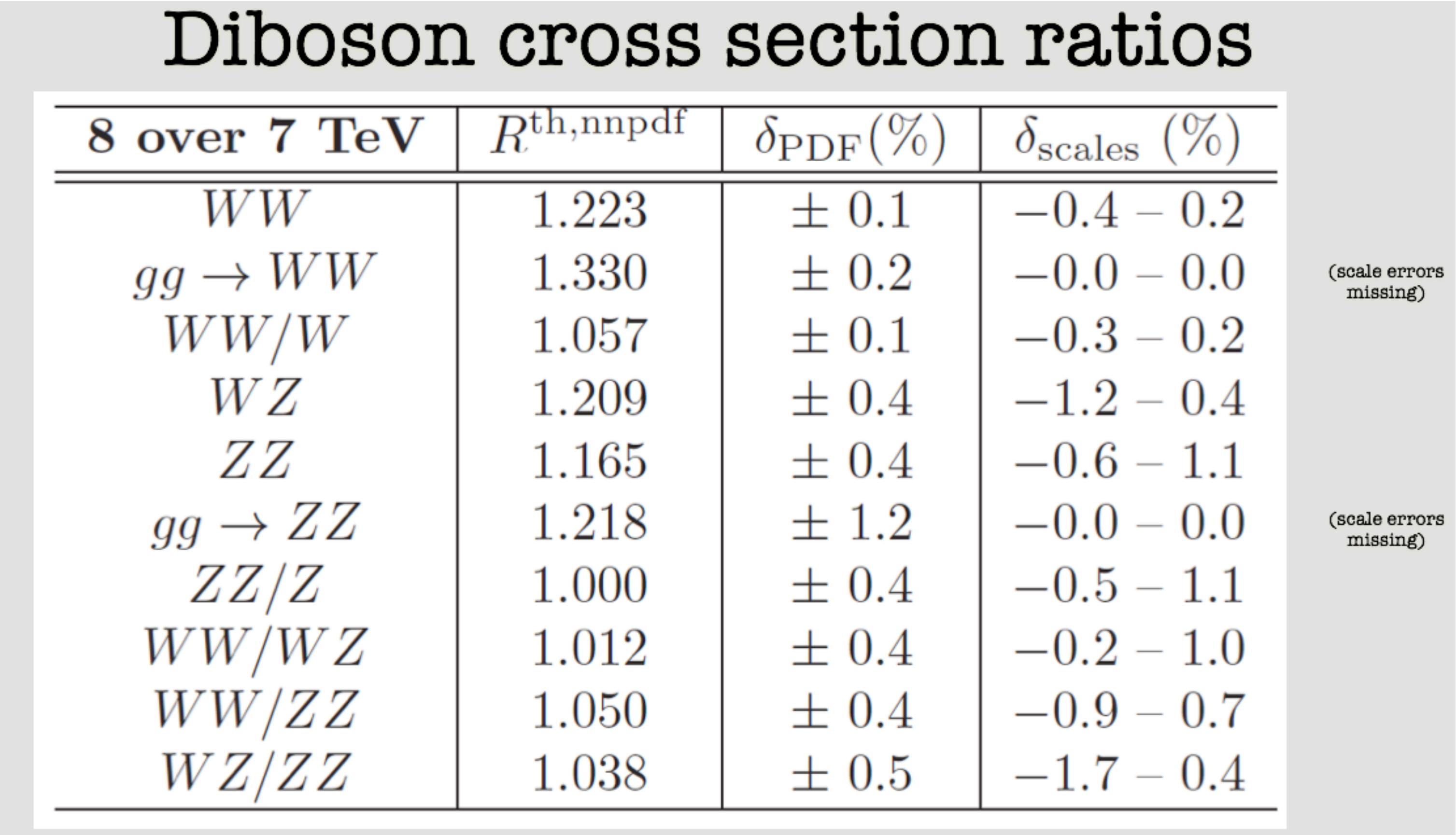




Given the sub-% precision of the SM ratio predictions, there is sensitivity to BSM rate contributions at the level of few% **(to be improved with better PDF constraints, especially for 8/14 ratios)**





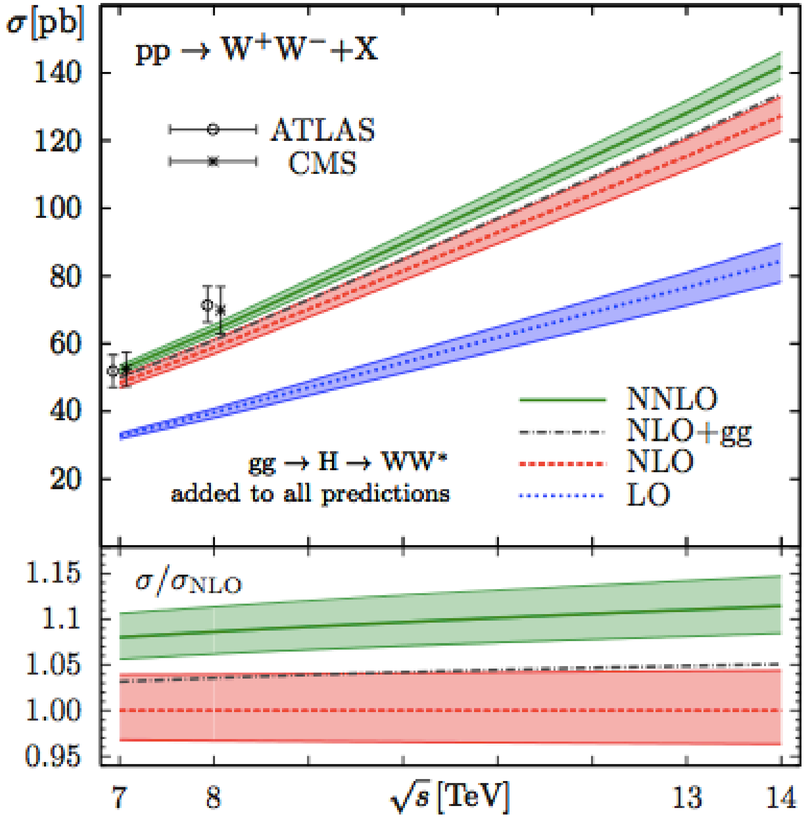


Diboson cross section ratios

8 over 7 TeV	$R^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{scales} (%)	
WW	1.223	± 0.1	−0.4 – 0.2	
$gg \to WW$	1.330	± 0.2	−0.0 – 0.0	(scale errors missing)
WW/W	1.057	± 0.1	−0.3 – 0.2	
WZ	1.209	± 0.4	−1.2 – 0.4	
ZZ	1.165	± 0.4	−0.6 – 1.1	
$gg \to ZZ$	1.218	± 1.2	−0.0 – 0.0	(scale errors missing)
ZZ/Z	1.000	± 0.4	−0.5 – 1.1	
WW/WZ	1.012	± 0.4	−0.2 – 1.0	
WW/ZZ	1.050	± 0.4	−0.9 – 0.7	
WZ/ZZ	1.038	± 0.5	−1.7 – 0.4	

Inclusion of NNLO QCD corrections

Gehrmann, Grazzini, Kallweit, Maierhoefer, von Manteuffel, Pozzorini, Rathlev, Tancredi; 1408.5243



- NNLO corrections range from 9% to 12%
- gg fusion contribution is about 35% of the NNLO correction

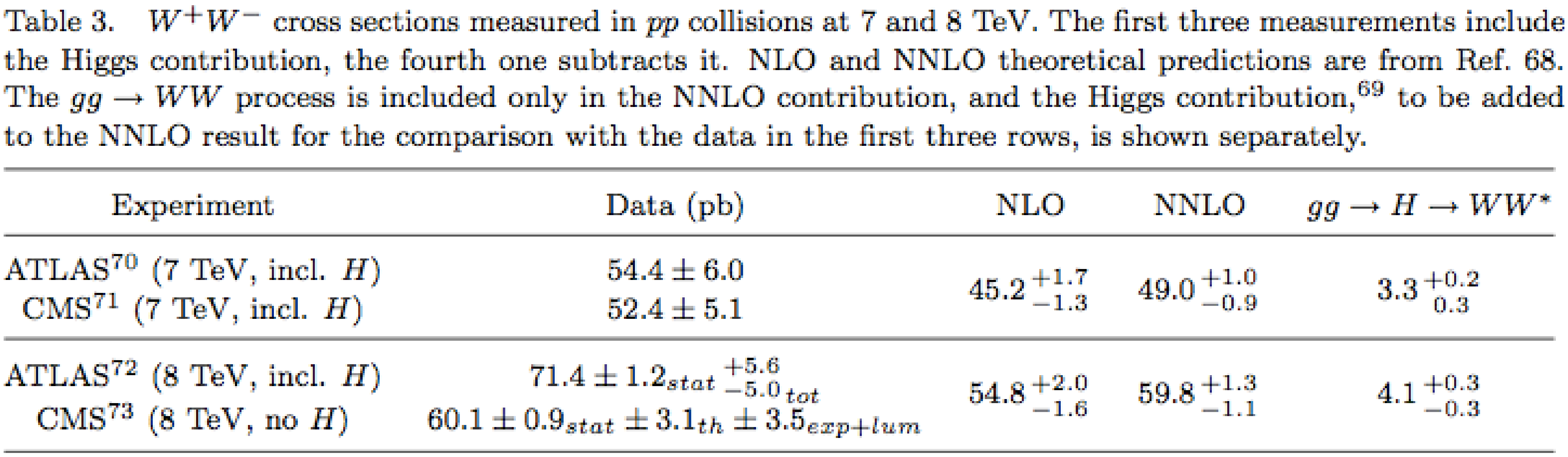
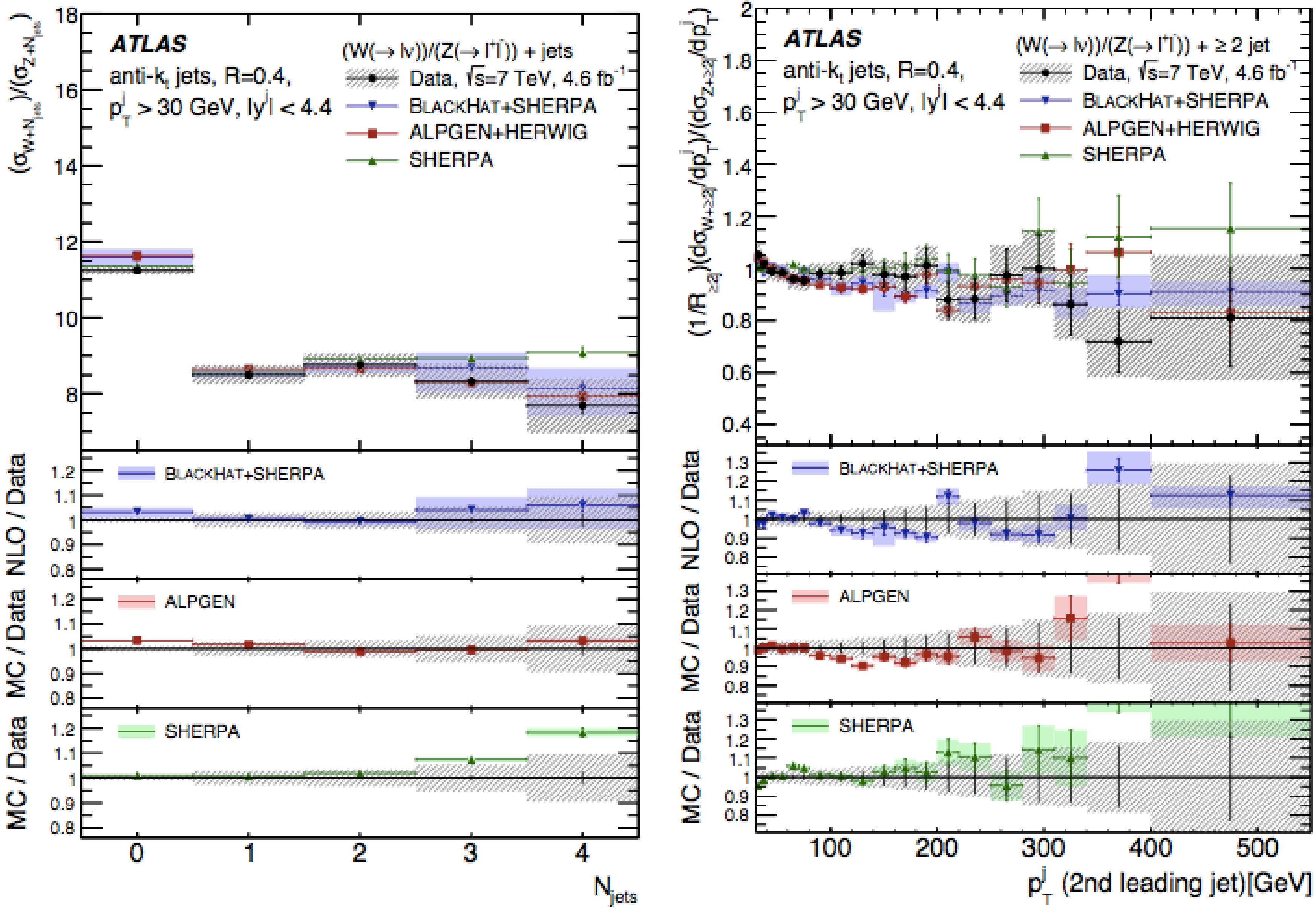


Table 3. W^+W^- cross sections measured in pp collisions at 7 and 8 TeV. The first three measurements include the Higgs contribution, the fourth one subtracts it. NLO and NNLO theoretical predictions are from Ref. 68. The $gg \to WW$ process is included only in the NNLO contribution, and the Higgs contribution,[69] to be added to the NNLO result for the comparison with the data in the first three rows, is shown separately.

Experiment	Data (pb)	NLO	NNLO	$gg \to H \to WW^*$
ATLAS[70] (7 TeV, incl. H)	54.4 ± 6.0	$45.2^{+1.7}_{-1.3}$	$49.0^{+1.0}_{-0.9}$	$3.3^{+0.2}_{0.3}$
CMS[71] (7 TeV, incl. H)	52.4 ± 5.1			
ATLAS[72] (8 TeV, incl. H)	$71.4 \pm 1.2_{stat}\,{}^{+5.6}_{-5.0}{}_{tot}$	$54.8^{+2.0}_{-1.6}$	$59.8^{+1.3}_{-1.1}$	$4.1^{+0.3}_{-0.3}$
CMS[73] (8 TeV, no H)	$60.1 \pm 0.9_{stat} \pm 3.1_{th} \pm 3.5_{exp+lum}$			

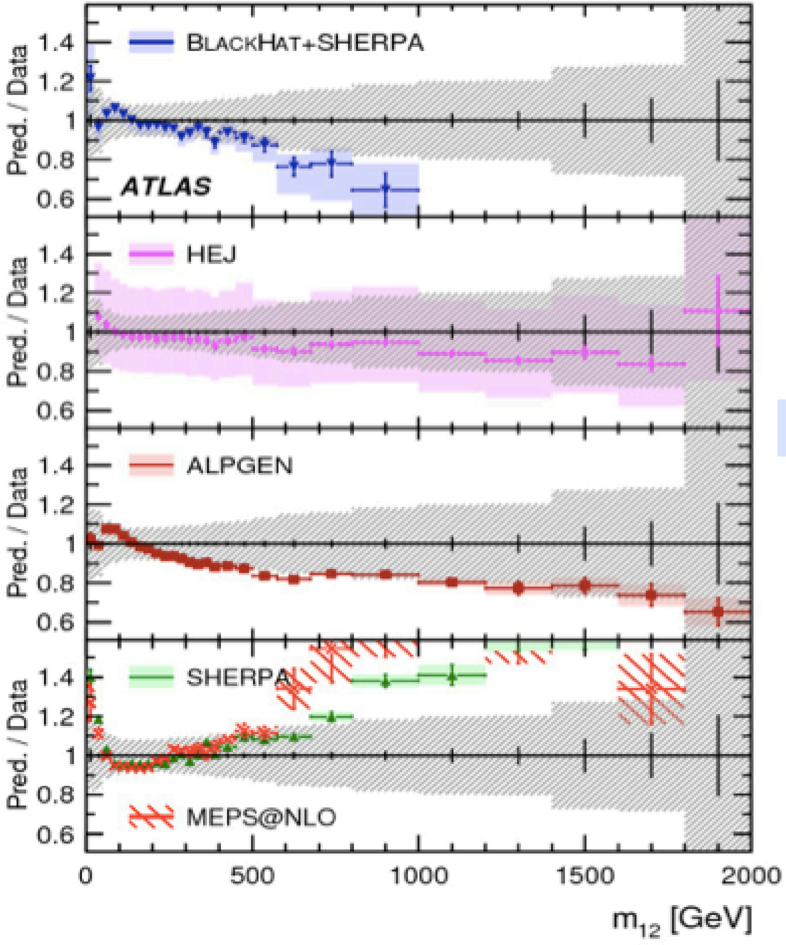
(W+jets)/(Z+jets) ratios

ATLAS, Eur. Phys. J. C (2014) 74:3168

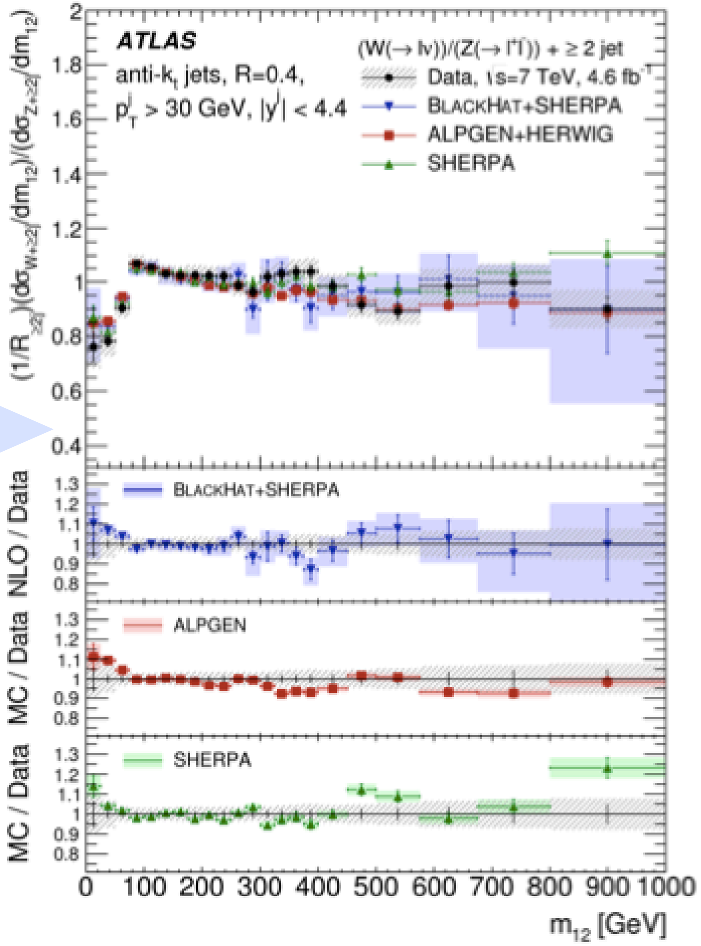


Potential for %-level precision comparisons between TH and data

W+jets



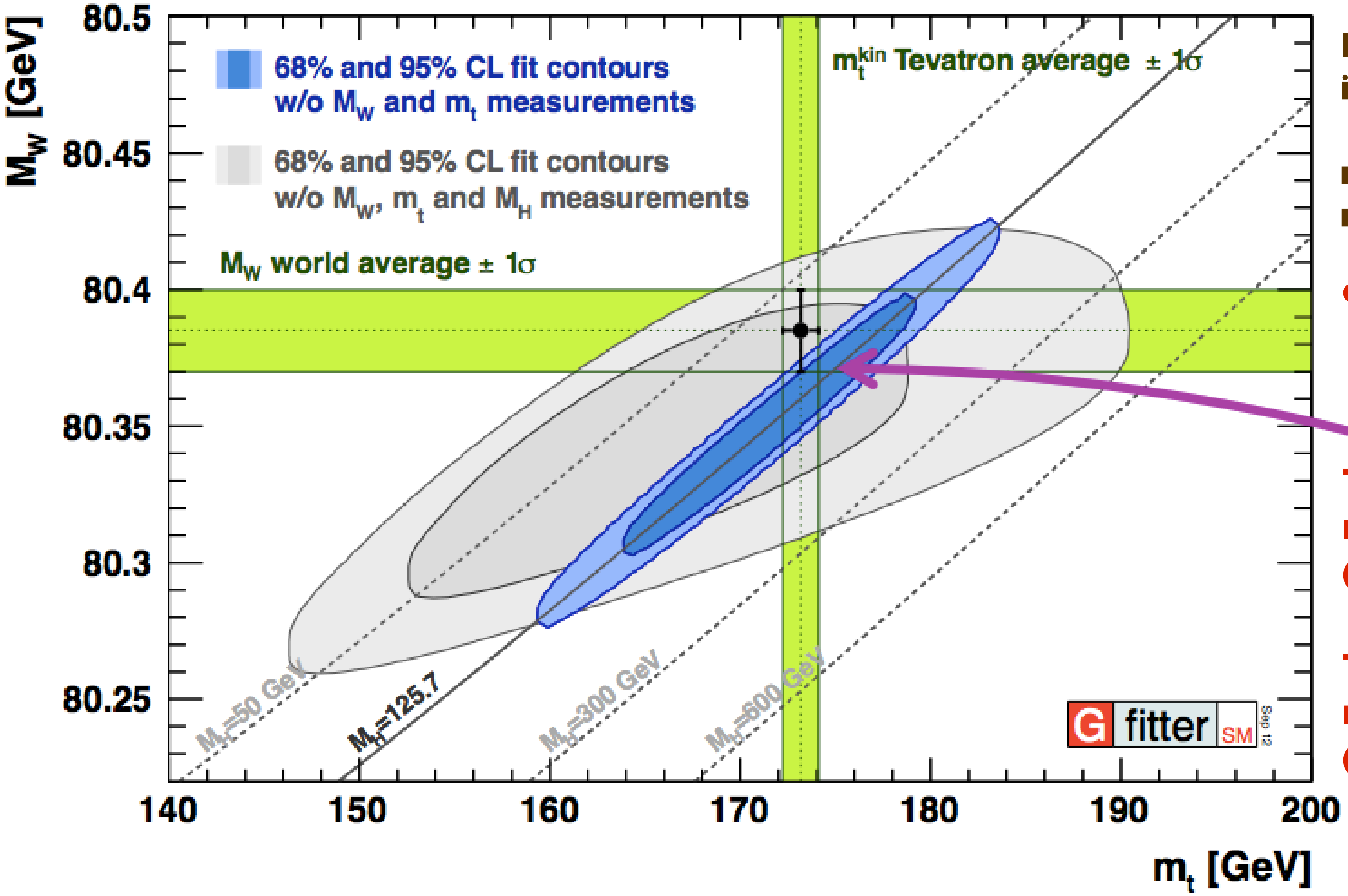
W+jets / Z+jets



Possible mis-modeling of individual processes cancels in the ratios. Ratios are more robust. Ratios can therefore be affected by BSM physics, feeding only the W or the Z channel

Top quark and W mass

Inclusion of m_H in EW fits greatly tightens correlation between m_W and m_{top}
introducing perhaps a slight tension ?



New EW fit results, including m_{Higgs} :

$m_{top} = 175.8^{+2.7}_{-2.4}$ GeV
$m_W = 80359 \pm 11$ MeV

cfr:

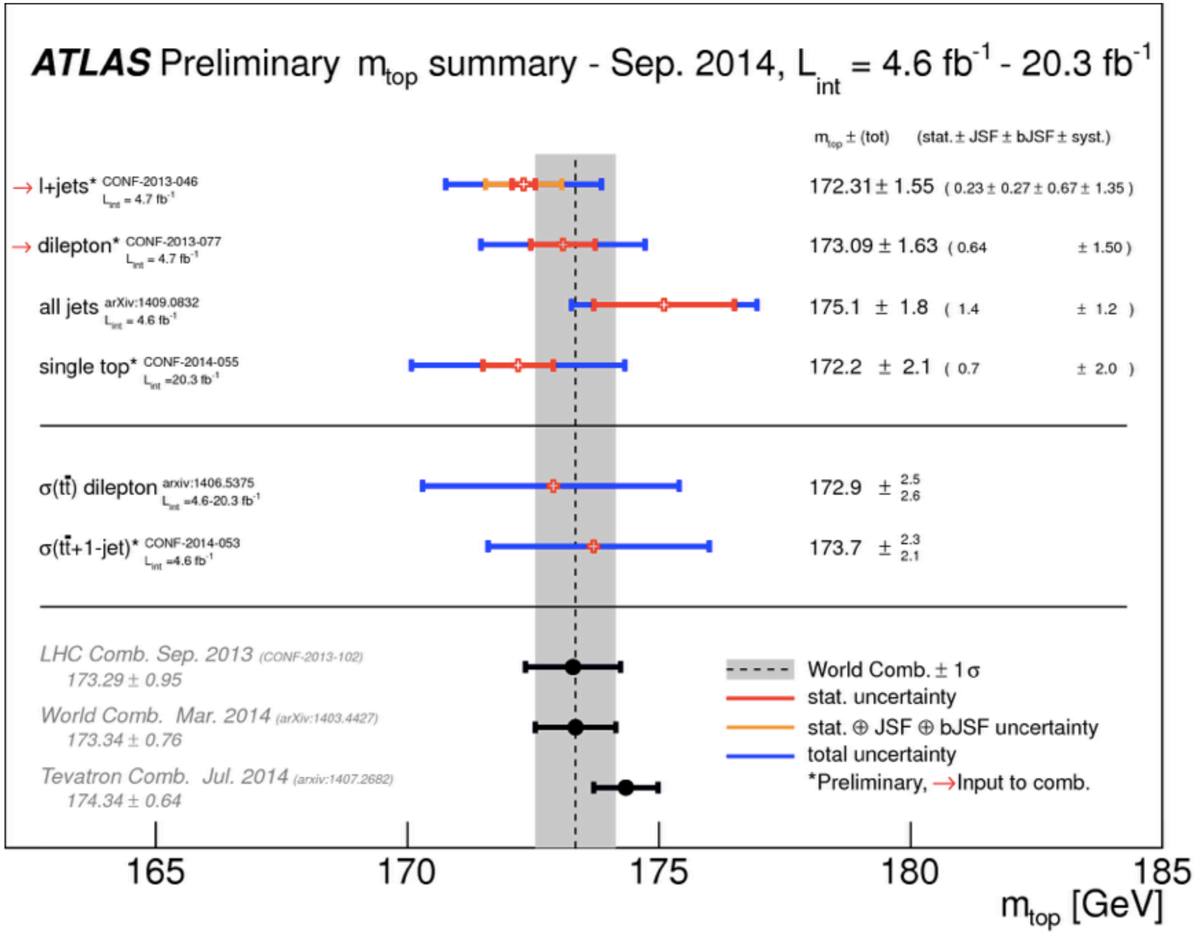
Tevatron+LEP2:
$M_W = 80385 \pm 15$ MeV

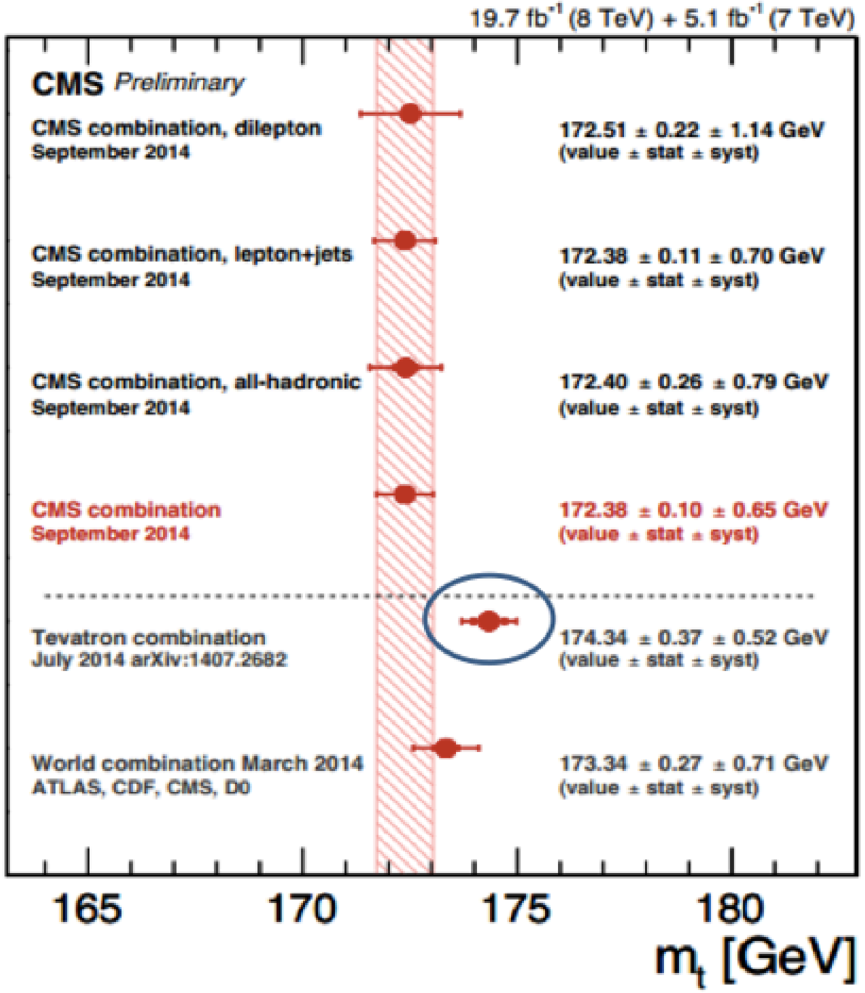
Tevatron+LHC:
$m_t = 173.34 \pm 0.76$ GeV
(Mar 2014)

Tevatron:
$m_t = 174.34 \pm 0.64$ GeV
(Jul 2014)

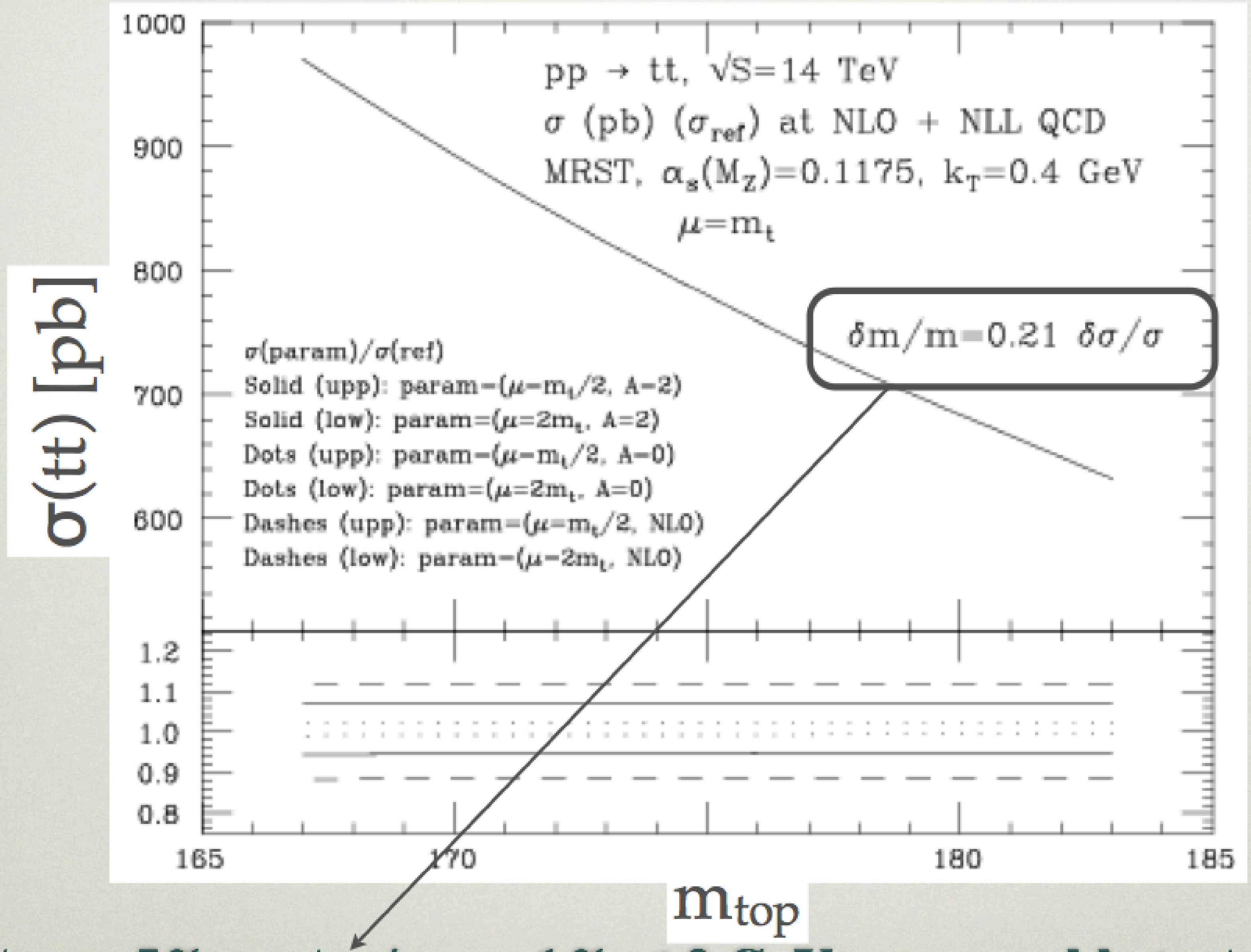
Continued improvement in the direct determination of m_W and m_{top} remains a high priority

Top quark mass





m_{top} from t-tbar cross section at the LHC



$\Delta\sigma/\sigma = \pm 5\%$ ⇔ $\Delta m/m = \pm 1\% \lesssim 2$ GeV, ~~comparable to~~ Δm_{direct}

~ 2 larger than

Top decay

Exercise

t→bW

$\frac{m_t}{16\pi} y_t^2$

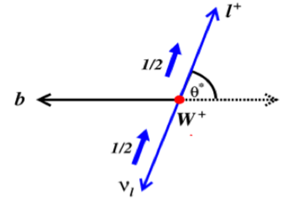
Coupling to longitudinal W, i.e. Goldstone boson

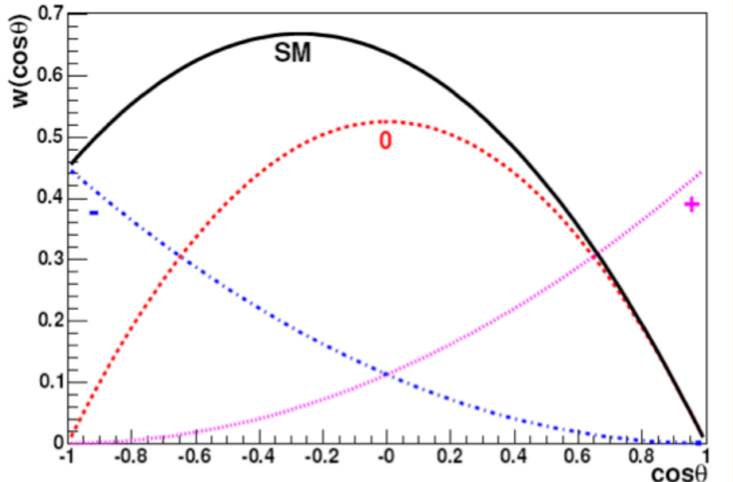
Coupling to transverse W d.o.f.

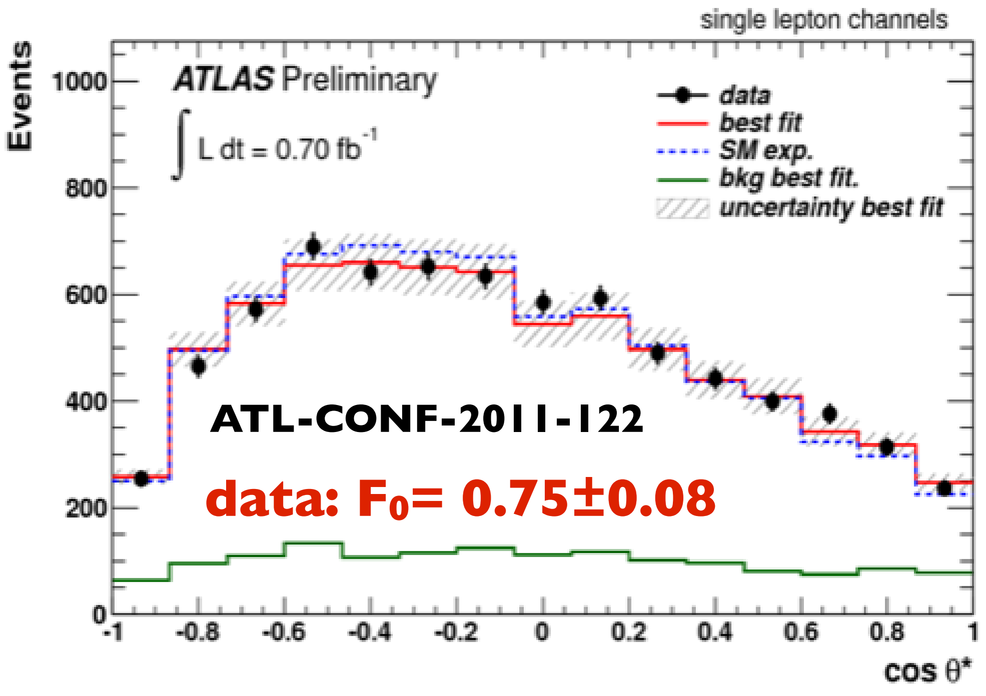
$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

1) #($W_{\text{longitudinal}}$) = $m_t^2/(m_t^2 + 2M_W^2)$ = 0.687±0.005

Cos θ* = angle between charged lepton and top direction in W rest-frame



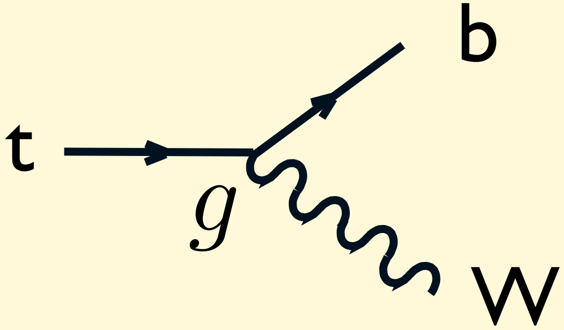




ATL-CONF-2011-122

data: F_0= 0.75±0.08

Exercise



$$\Gamma_t = \frac{g^2 m_t}{64\pi}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(2+\frac{m_t^2}{M_W^2}\right)$$

This expression is ill defined when $M_W = 0$.

Questions:

Can the limit $M_W \to 0$ be defined? Is there a unique way of defining this limit? Which possible scenarios should one consider? What are the implications of $M_W \to 0$?

Top decay

Exercise

t→bW

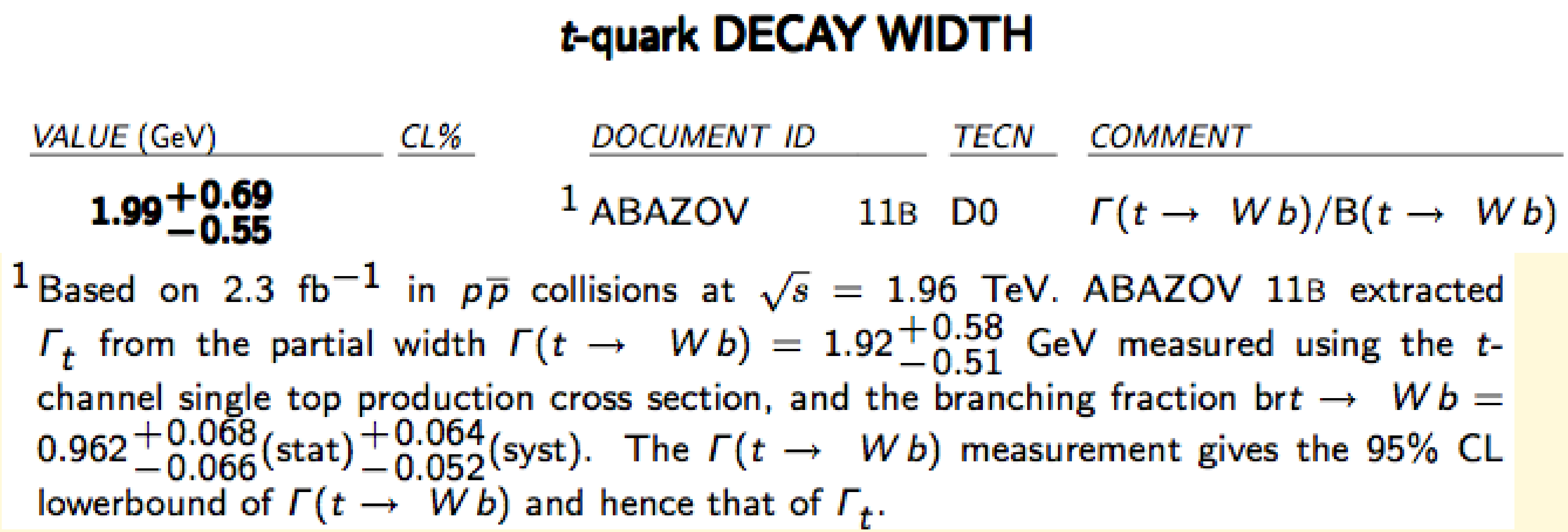
$$\frac{m_t}{16\pi}y_t^2$$

Coupling to longitudinal W, i.e. Goldstone boson

Coupling to transverse W d.o.f.

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

2) Γ_{top} ~ 1.34 GeV > T_{had}^{-1} ~ Λ_{QCD}



t-quark DECAY WIDTH

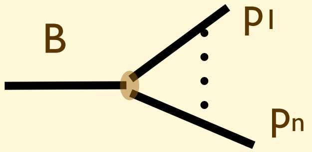
VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$1.99^{+0.69}_{-0.55}$		[1] ABAZOV	11B	D0	$\Gamma(t \to Wb)/B(t \to Wb)$

[1] Based on 2.3 fb^{-1} in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. ABAZOV 11B extracted Γ_t from the partial width $\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51}$ GeV measured using the t-channel single top production cross section, and the branching fraction $\text{br}t \to Wb = 0.962^{+0.068}_{-0.066}(\text{stat})^{+0.064}_{-0.052}(\text{syst})$. The $\Gamma(t \to Wb)$ measurement gives the 95% CL lowerbound of $\Gamma(t \to Wb)$ and hence that of Γ_t.

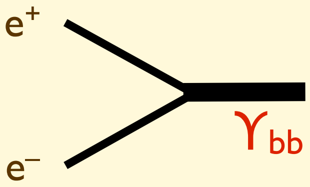
⇒Top quark decays before hadronizing: there are no top-hadrons

Measurement of the b-quark mass:

1. First measure mass of B-hadrons or Υ_{bb}



$$m_B^2 = \left(\sum_{i=1,\dots,n} p_i \right)^2$$



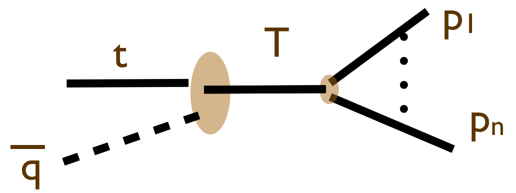
$$m_\Upsilon = \sqrt{S_{e^+e^-}}$$

2. Then extract b-quark mass from b-hadron mass:

$m_b = F_{\text{lattice/potential models}} \, (m_B, m_\Upsilon, \Lambda_{QCD}, \alpha_{QCD})$

Why is it hard to measure/define m_{top} at the LHC ?

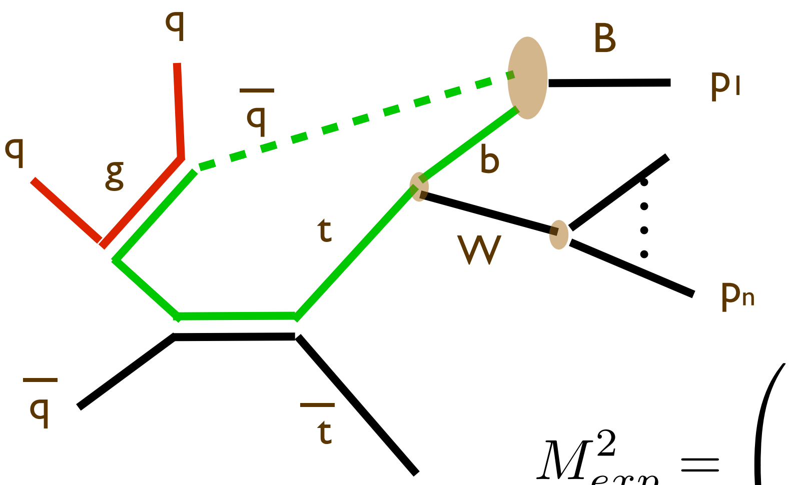
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

$m_t = F_{\text{lattice/potential models}} (m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



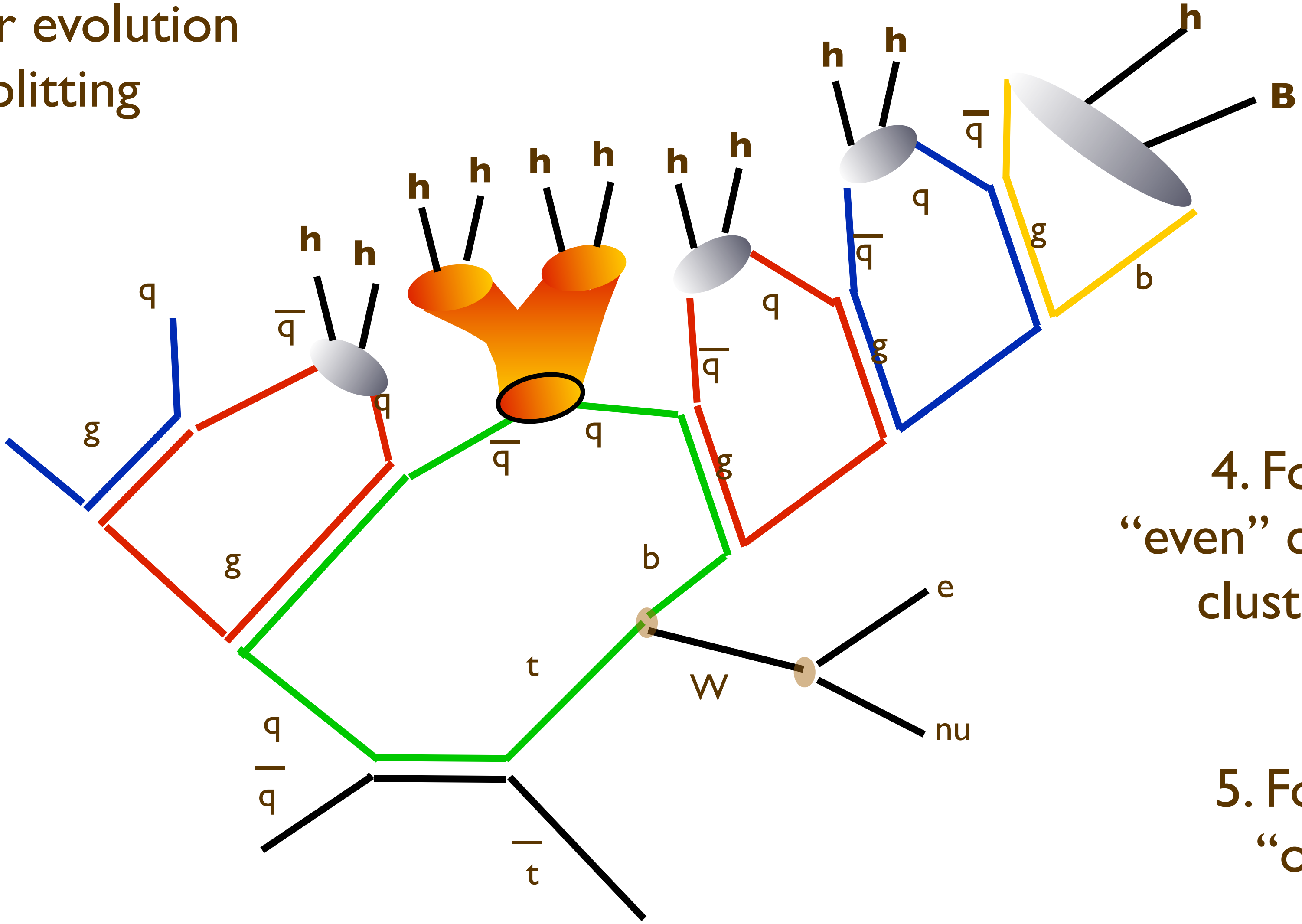
$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top}) \sim 1$ GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

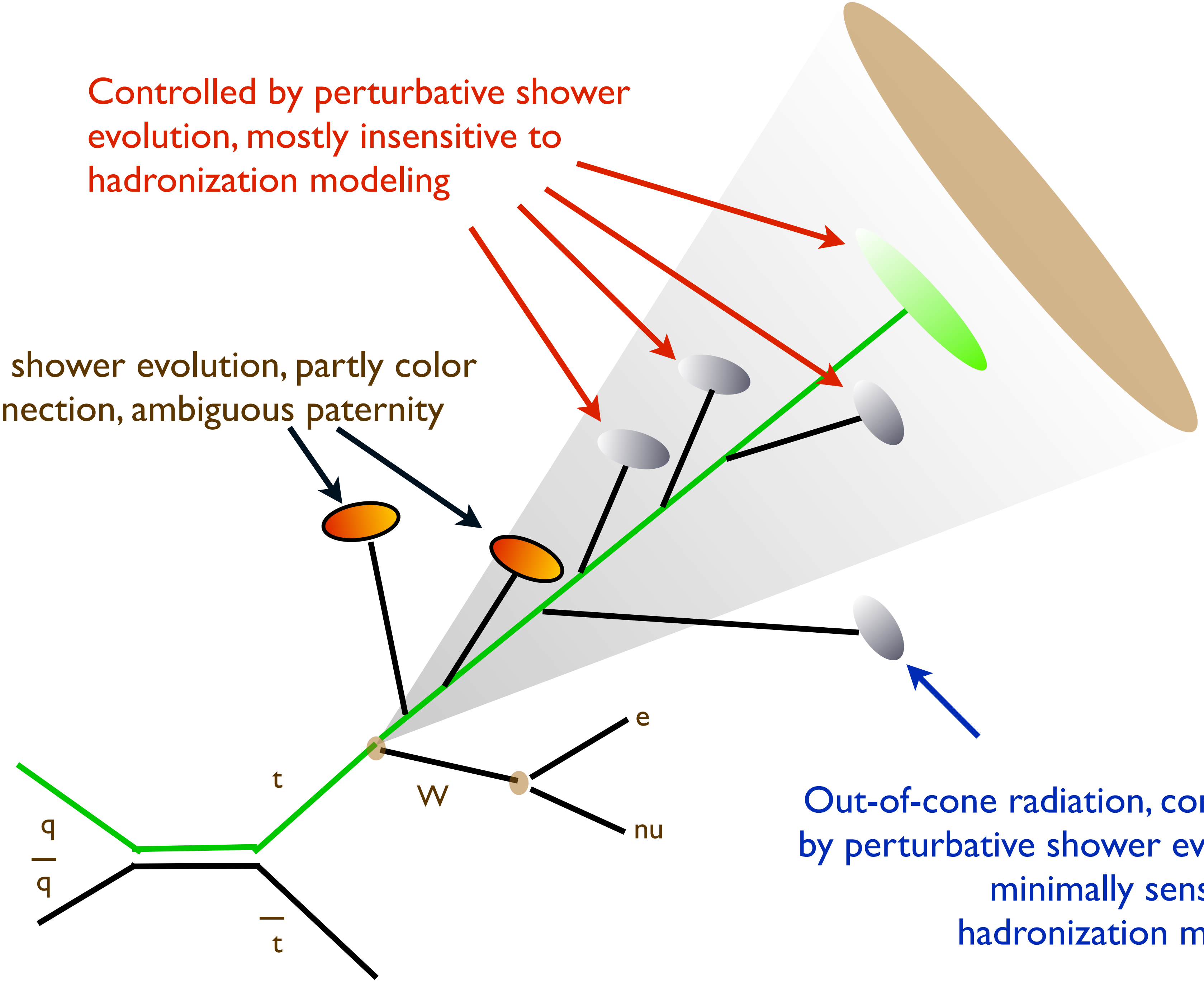
1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of “even” clusters and cluster decay to hadrons

5. Formation of “odd” cluster

6. Decay of “odd” clusters, if large cluster mass, and decays to hadrons



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling

Partly shower evolution, partly color reconnection, ambiguous paternity

Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling

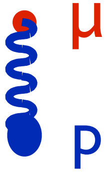
m_{MC} vs m_{pole}

Consider a simplified example

Take $\mu \to e\nu\nu$.

$m_\mu = m_{pole}$ and $m_\mu{}^2 = [p(e)+p(\nu)+p(\nu)]^2$

Take μ interacting with an external field, e.g. bound with a proton in an atom:



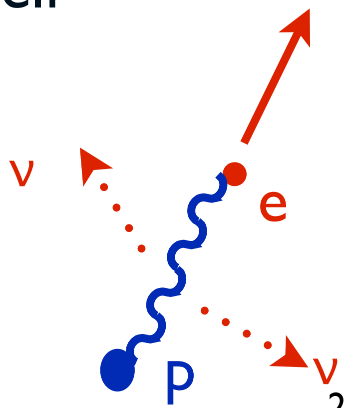
$$E = m_p + m_\mu + (K+V)_\mu = m_p + m_\mu - m_\mu\,\alpha^2/2 = m_p + m_\mu^*$$

$m_\mu^* = m_\mu\,(1-\alpha^2/2)$ absorbs part of the potential energy into itself

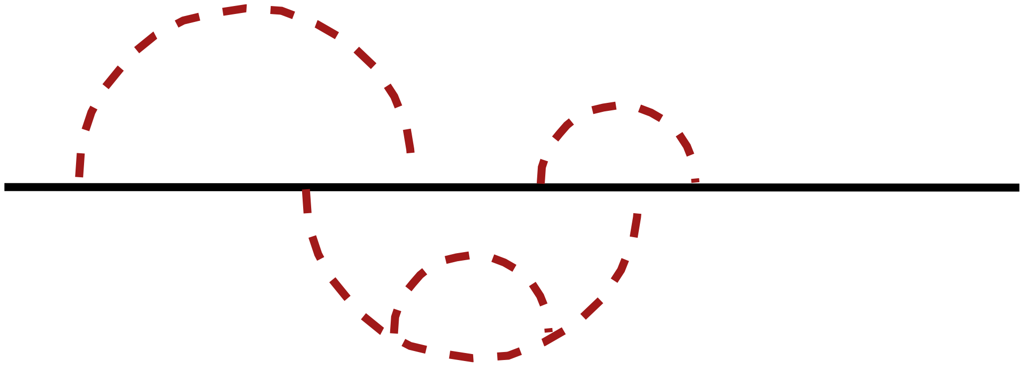
It is a "useful" mass, since, once the muon decays,

$[p(e)+p(\nu)+p(\nu)]^2 = m_\mu^{*\,2}$, which $\neq m_\mu^2$ by $O(\alpha^2)$

The reason is that the electron, to escape, must overcome the Coulomb potential, and its energy will be shifted by $V = -m_\mu\alpha^2$

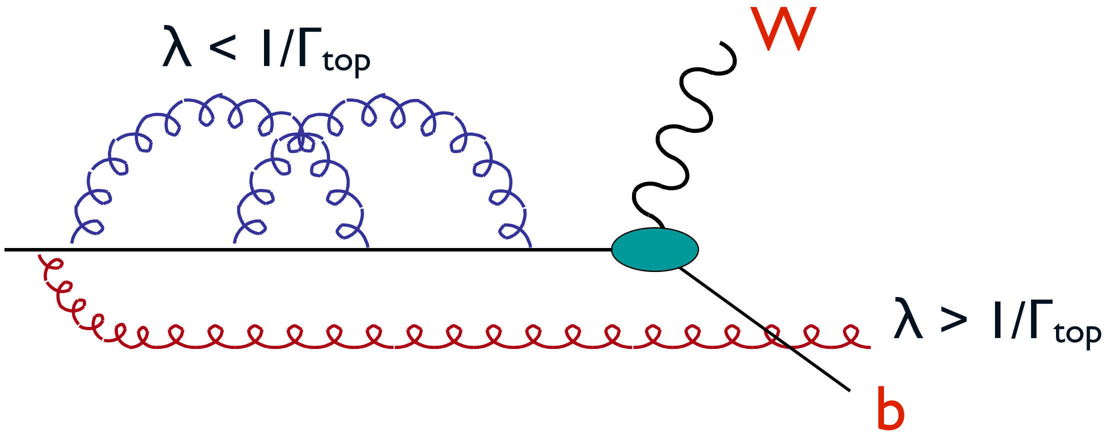


In the case of a quark, the potential is the due to the interaction with its own gluon field (as well as with the others partons in the event)



The pole mass is defined by resumming the effects of all these diagrams, absorbing all divergences. However, we know that we find problems if we integrate the loop momenta below the scale Λ_{QCD}, where perturbation theory breaks down. If we do it, to define m_{pole}, the perturbative series can only be resummed up to a (“renormalon”) ambiguity. If we stop before, at some scale, we dump into a m^* mass the self-energy potential due to modes with wavelength above that scale.

This is further justified for the top, which anyway only lives $1/\Gamma_{top}$, so gluons with wavelength > $1/\Gamma_{top}$ are cutoff:

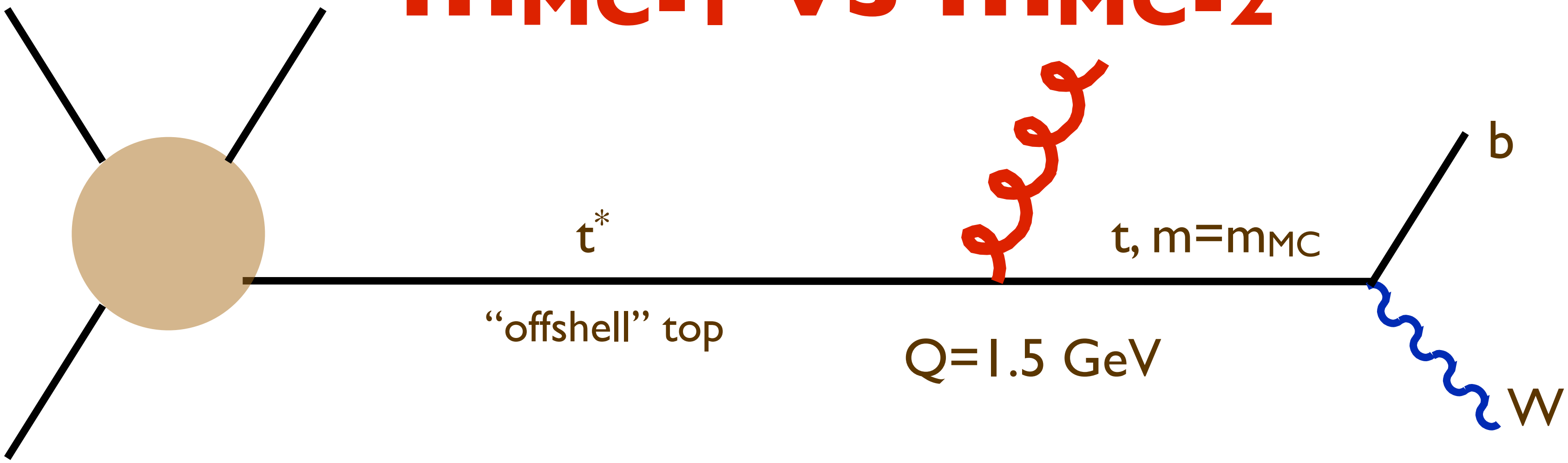


In this case,

$$\delta m \sim \alpha_S \, \Gamma_{top}$$

what is the coefficient ?

$m_{MC\text{-}1}$ vs $m_{MC\text{-}2}$

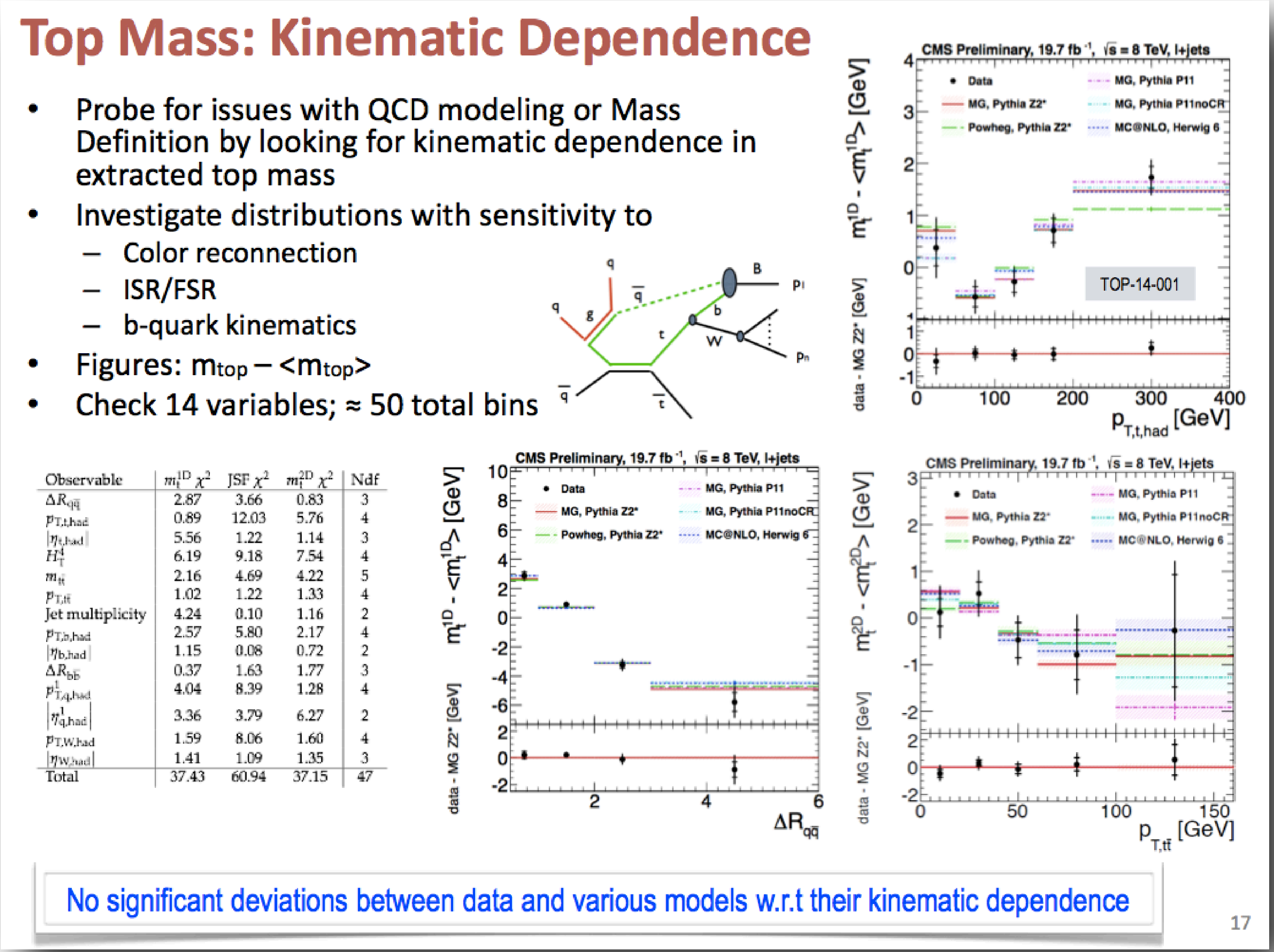


This emission at scale Q=1.5 GeV may or may not be present in the MC, depending on the IR cutoff scale of the shower (e.g. 1 GeV vs 2 GeV). One may consider this is as using m_{MSR} defined at different scales, or as using different top-mass definitions.

The question is whether the emission of the extra gluons in the region ($\text{cutoff}_{MC\text{-}1}$ – $\text{cutoff}_{MC\text{-}2}$) affects the observables used to measure m_{MC} and change the measured value

Typically we consider these possible differences as part of the shower/hadronization systematics. There is no evidence that they exceed the 100 MeV level.

Studies like those shown by CMS (mtop vs different production configurations) are crucial to understand the sensitivity to these effects, the consistency of the modeling in different MC, with data and with themselves



Top Mass: Kinematic Dependence

- Probe for issues with QCD modeling or Mass Definition by looking for kinematic dependence in extracted top mass
- Investigate distributions with sensitivity to
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics
- Figures: $m_{top} - \langle m_{top} \rangle$
- Check 14 variables; ≈ 50 total bins

Observable	$m_t^{1D}\ \chi^2$	JSF χ^2	$m_t^{2D}\ \chi^2$	Ndf
$\Delta R_{q\bar{q}}$	2.87	3.66	0.83	3
$p_{T,t,had}$	0.89	12.03	5.76	4
$\lvert\eta_{t,had}\rvert$	5.56	1.22	1.14	3
H_T^4	6.19	9.18	7.54	4
$m_{t\bar{t}}$	2.16	4.69	4.22	5
$p_{T,t\bar{t}}$	1.02	1.22	1.33	4
Jet multiplicity	4.24	0.10	1.16	2
$p_{T,b,had}$	2.57	5.80	2.17	4
$\lvert\eta_{b,had}\rvert$	1.15	0.08	0.72	2
$\Delta R_{b\bar{b}}$	0.37	1.63	1.77	3
$p_{T,q,had}^1$	4.04	8.39	1.28	4
$\lvert\eta_{q,had}^1\rvert$	3.36	3.79	6.27	2
$p_{T,W,had}$	1.59	8.06	1.60	4
$\lvert\eta_{W,had}\rvert$	1.41	1.09	1.35	3
Total	37.43	60.94	37.15	47

No significant deviations between data and various models w.r.t their kinematic dependence

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CMS-PAS-TOP-12-031

$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat) \pm 122\ (syst.)\ MeV$$

remarks

QCD effects depend on how long the top actually lives. Should one change m_{MC} *as a function of lifetime, event by event ?*

When a top lives longer than $1/\Lambda_{QCD}$ *(prob ~* $\exp(-\Gamma_{top}/\Lambda_{QCD})$*) it likely hadronizes*

Jets at high E_T

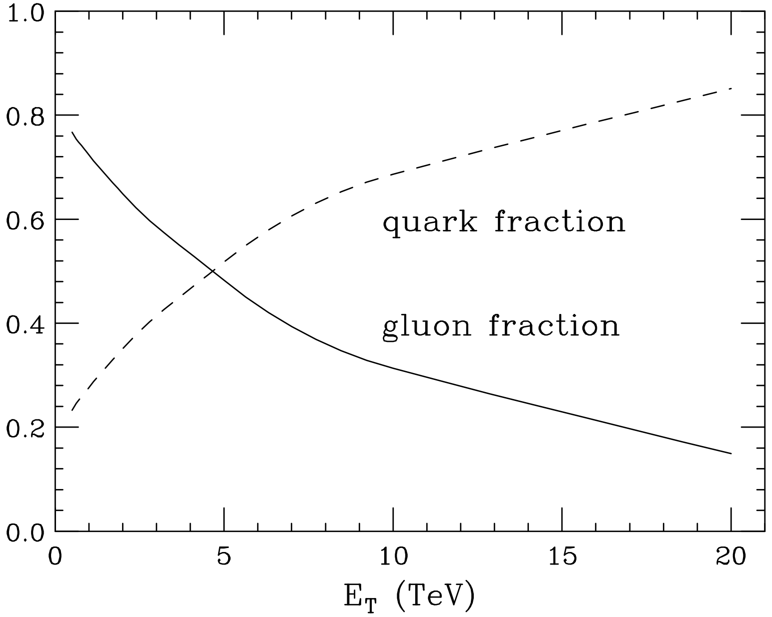
Consider some features of jet structure at high E_T. Compare jets from:

- top quark (hadronic) decay
- bottom quark
- inclusive jets
- W hadronic decay

Jets are defined by anti-k_T . Use R=1 to define jet, then look inside at smaller R.
No soft UE, no pileup.

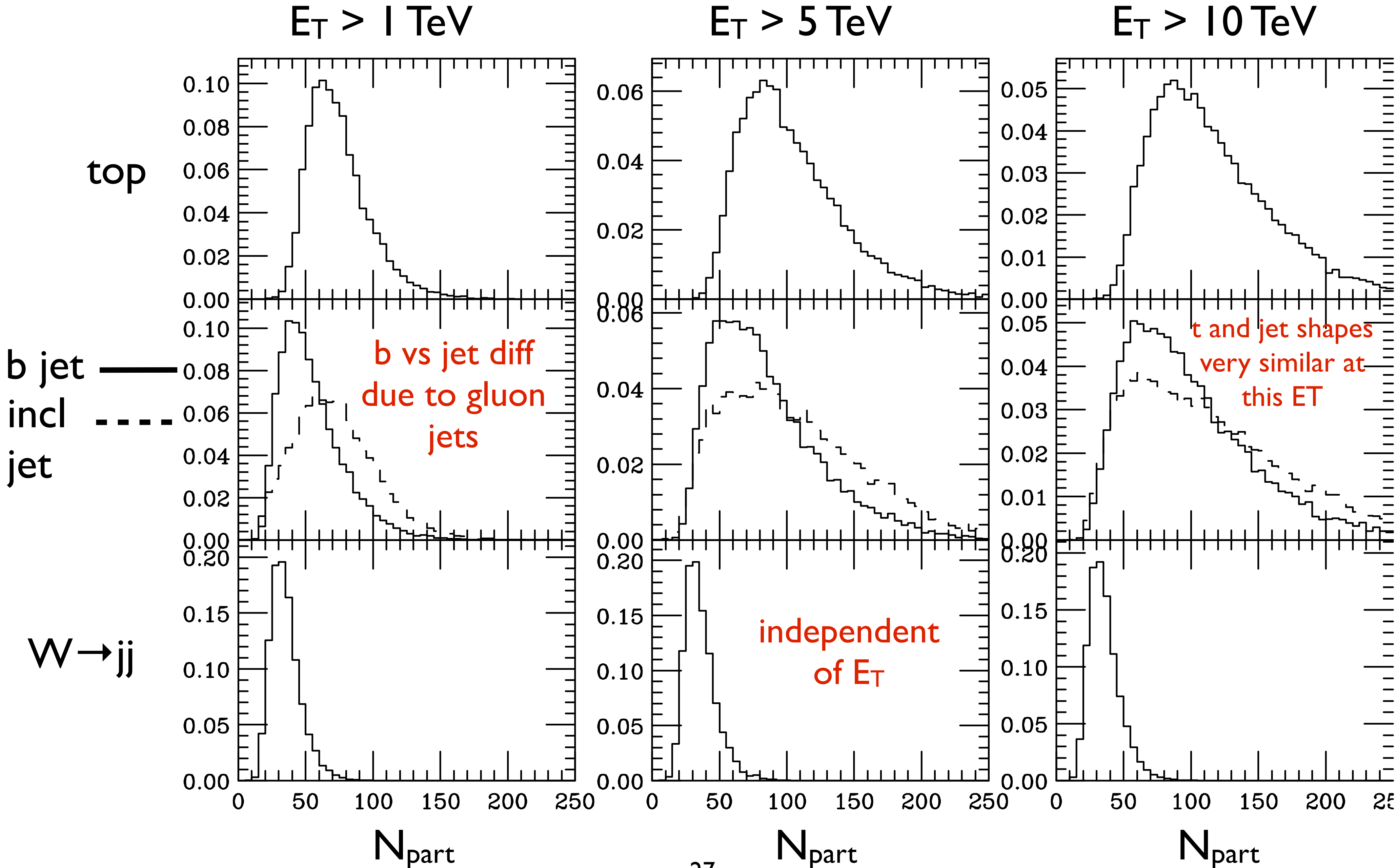
Generation: Alpgen + Herwig

NB: Inclusive jets here means jets from the QCD background. Thus they include a mixture of light quark and gluon jets, which varies vs E_T



Particle multiplicity distribution: $1/\sigma \, d\sigma/dN_{part}$

(particle: everything except neutrinos, neutral and charged, with stable π^0)



$E_T > 1$ TeV

$E_T > 5$ TeV

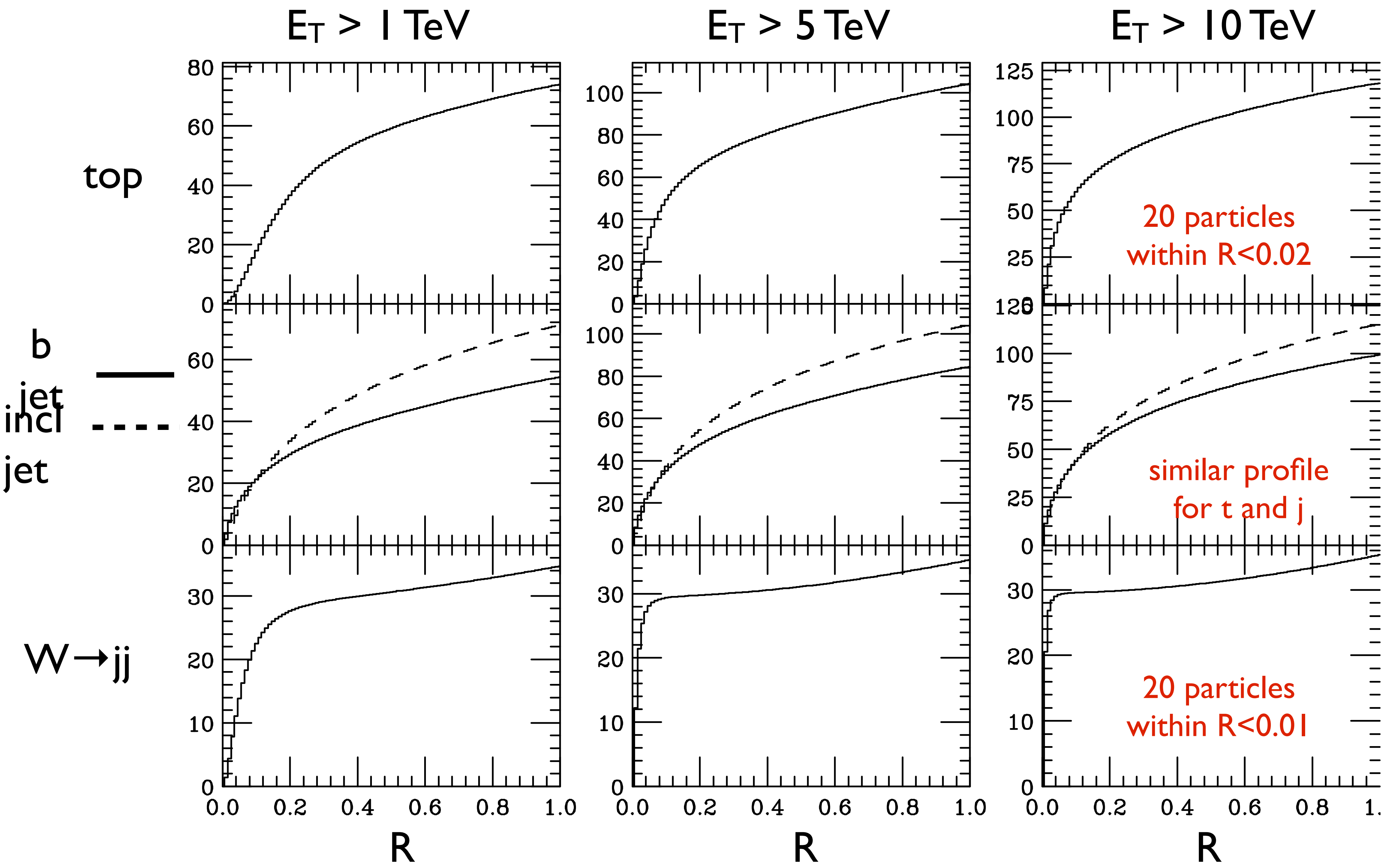
$E_T > 10$ TeV

b vs jet diff due to gluon jets

t and jet shapes very similar at this ET

independent of E_T

Average particle multiplicity shape: N_{part} (r<R)


E_T > 1 TeV

E_T > 5 TeV

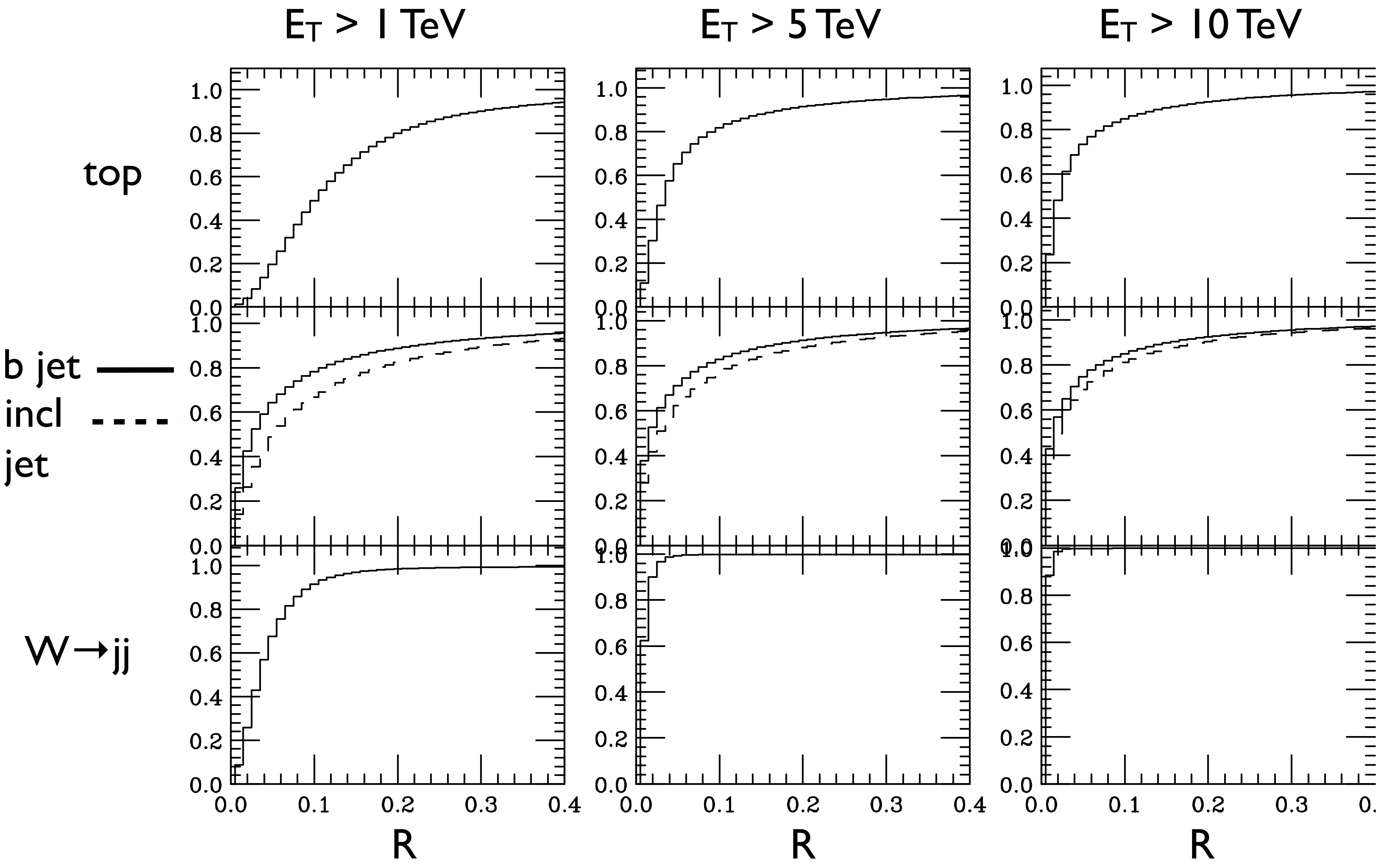
E_T > 10 TeV

20 particles within R<0.02

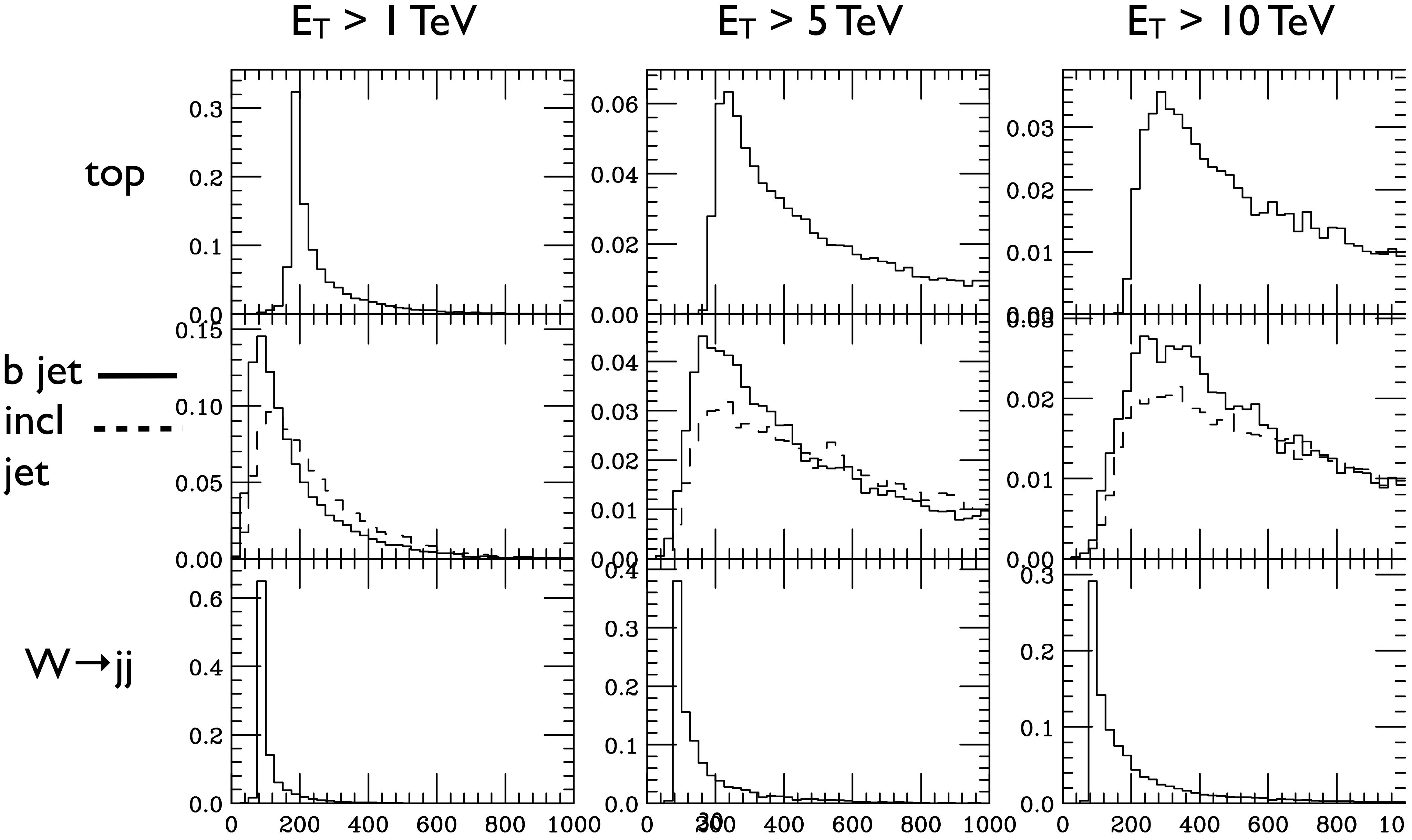
similar profile for t and j

20 particles within R<0.01

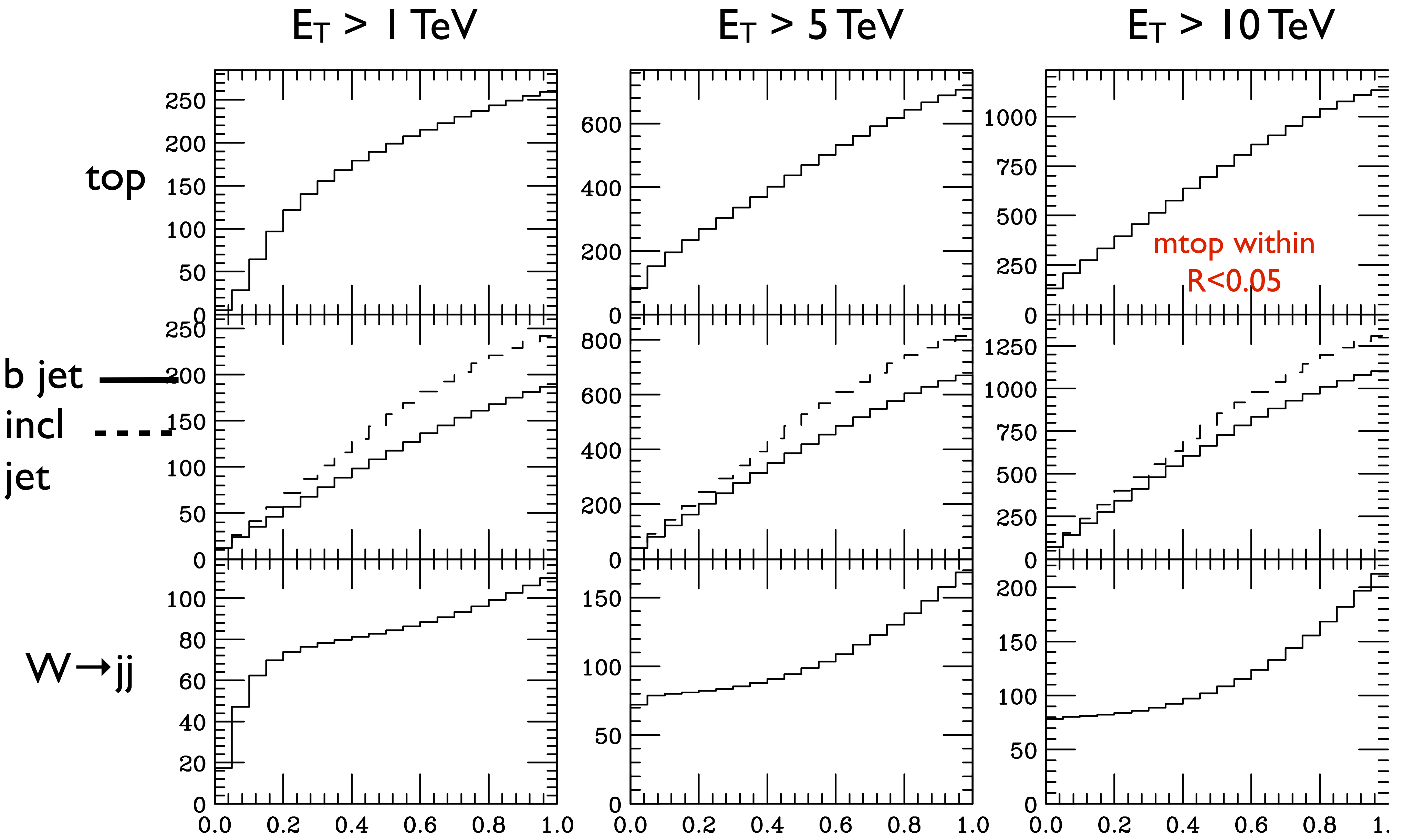
Energy shape: E(r<R) / E(r<1)



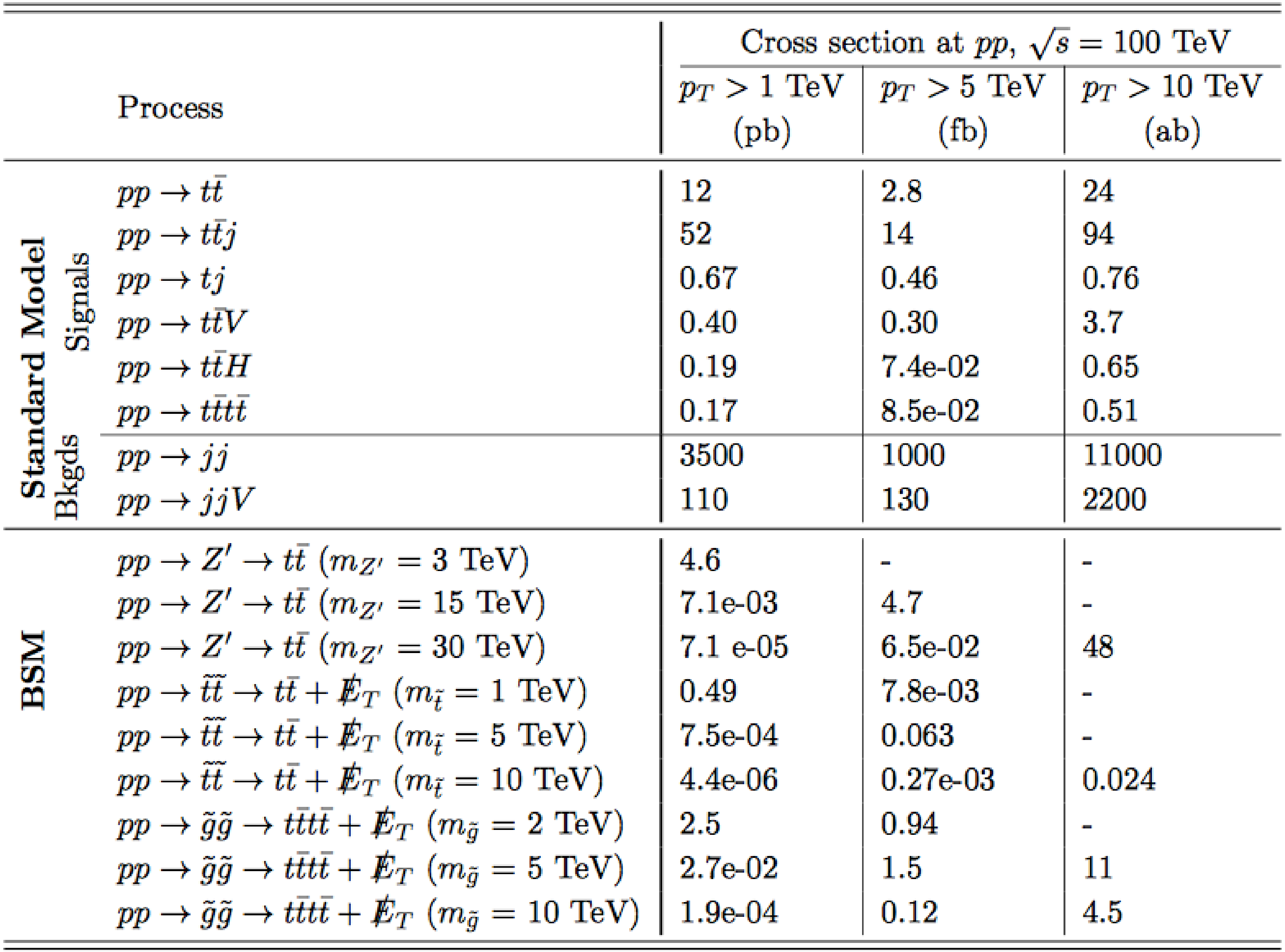
Jet mass distribution: $1/\sigma\, d\sigma/dM_{jet}$



Average jet mass: M(particles with r<R)



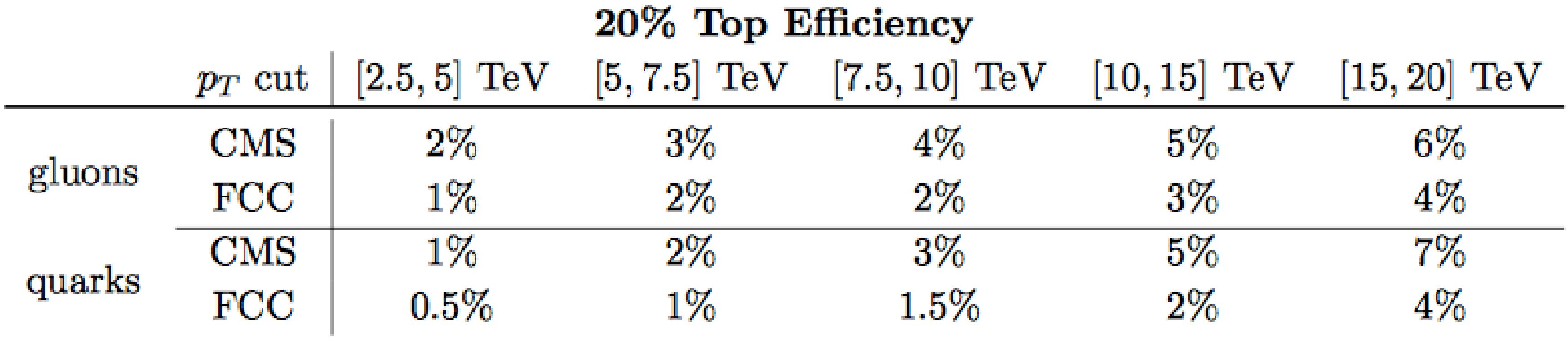
Tracking down hyper-boosted top quarks, Larkowski et al, arXiv:1503.03347



		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

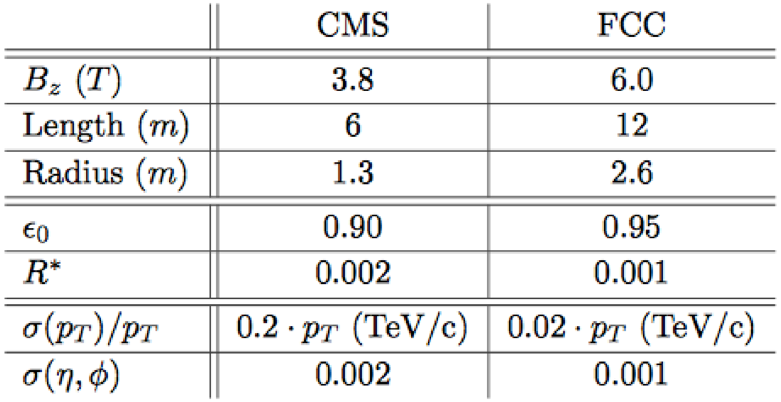
Tracking down hyper-boosted top quarks, Larkowski et al, arXiv:1503.03347

bg efficiency, per jet



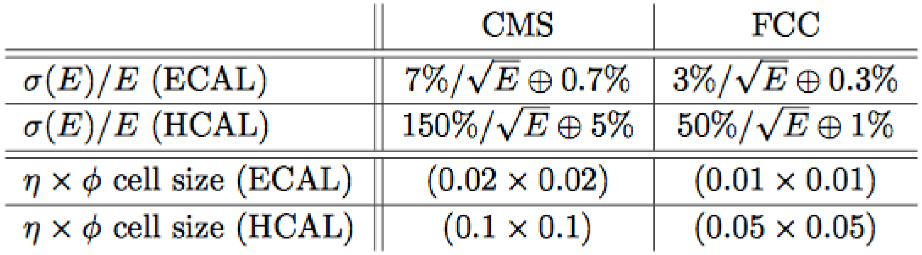
20% Top Efficiency

	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

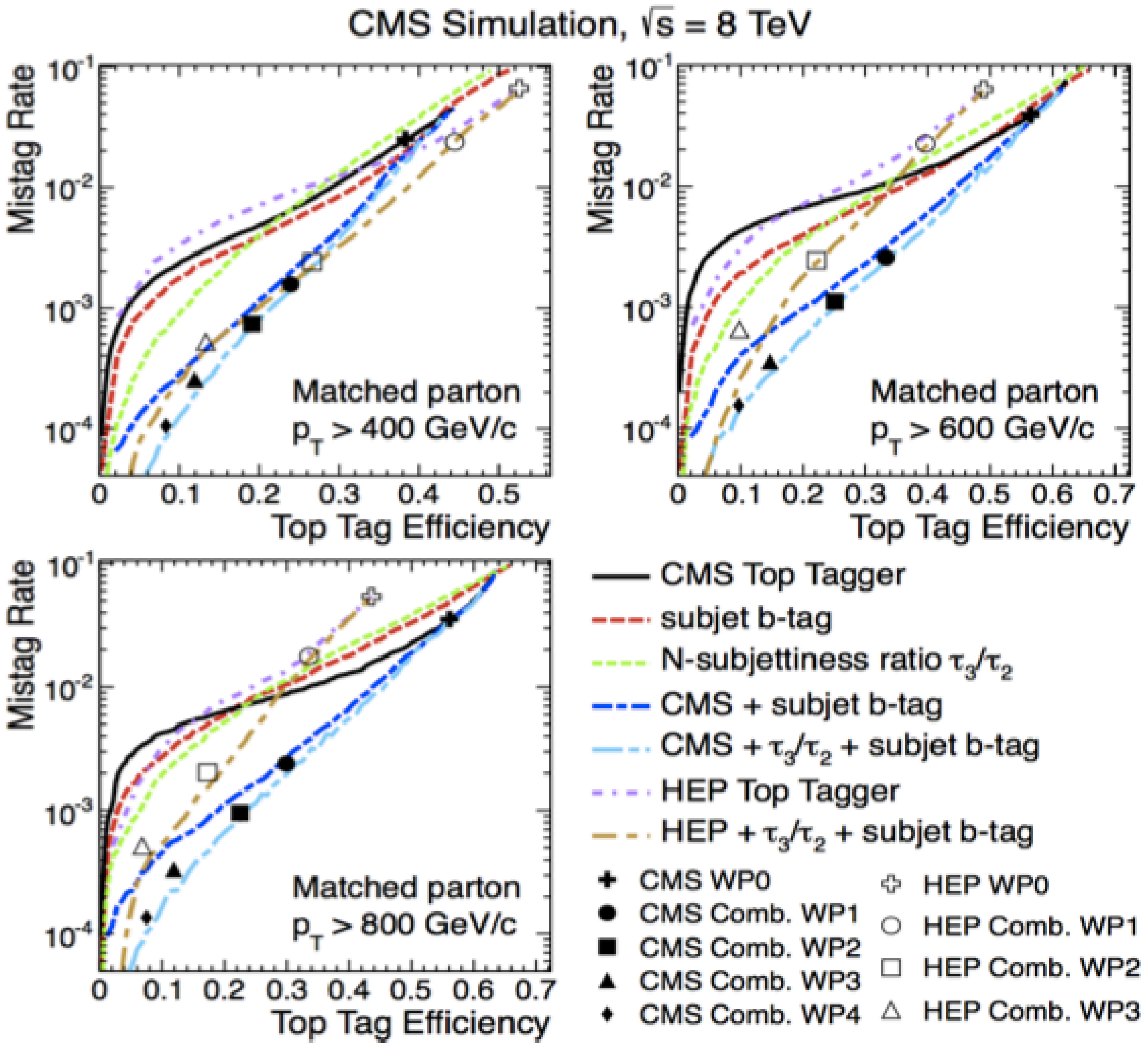
Table 2: Tracking-related parameters for the CMS and FCC setup in Delphes.



	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.

CMS Top Tagger

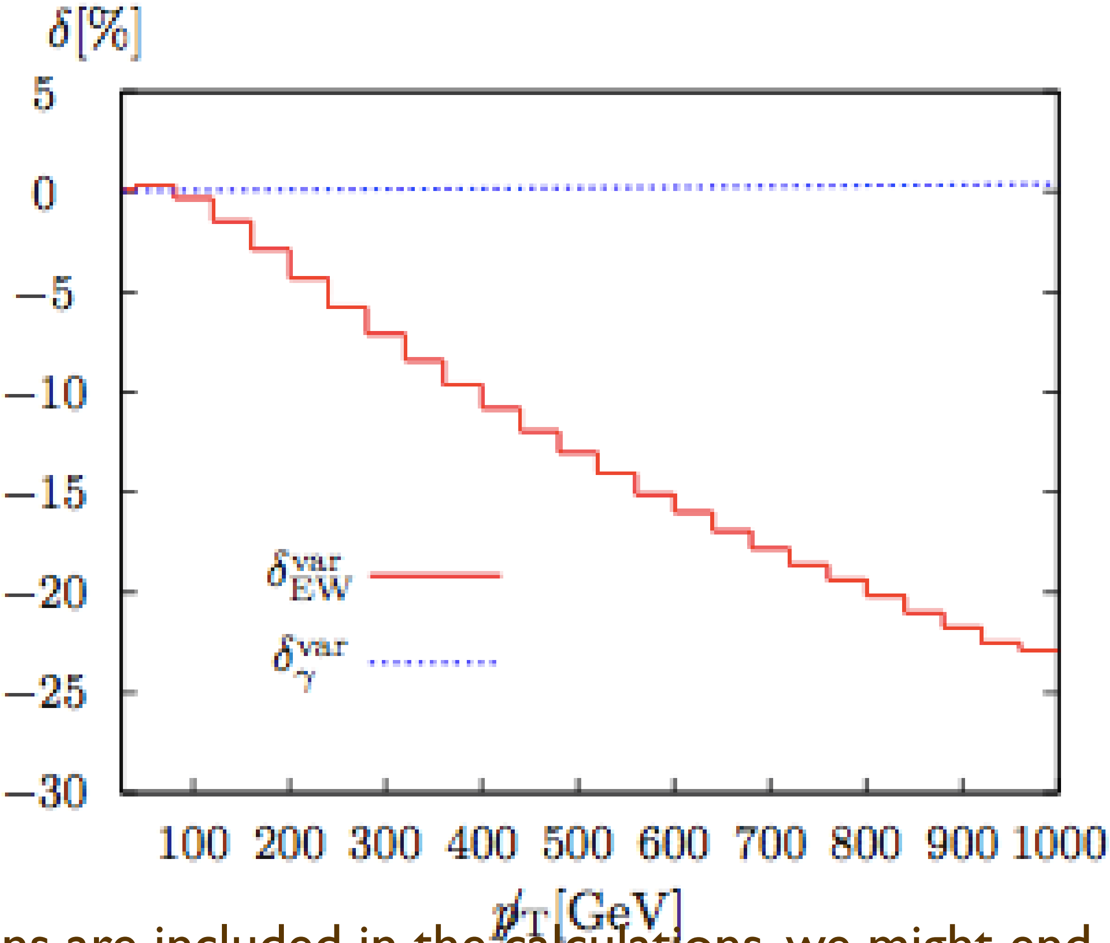


CMS-JME-13-007

EW effects at very high energy. Example:

Jet+MET spectrum from (Z→νν)+jet: corrections due to pure EW and pure EM corrections

Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2

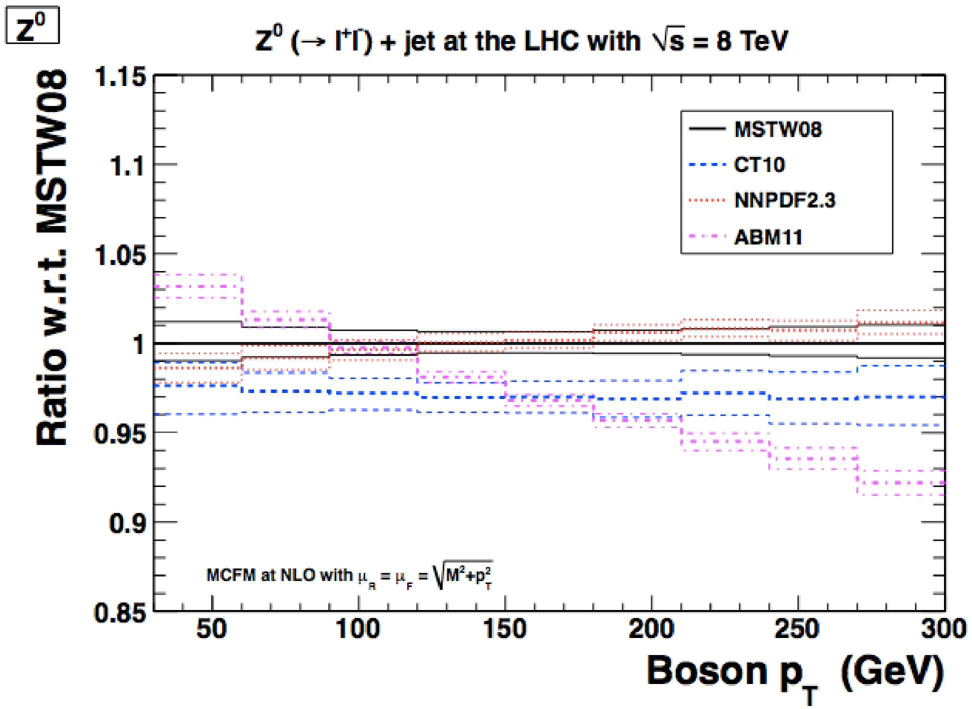


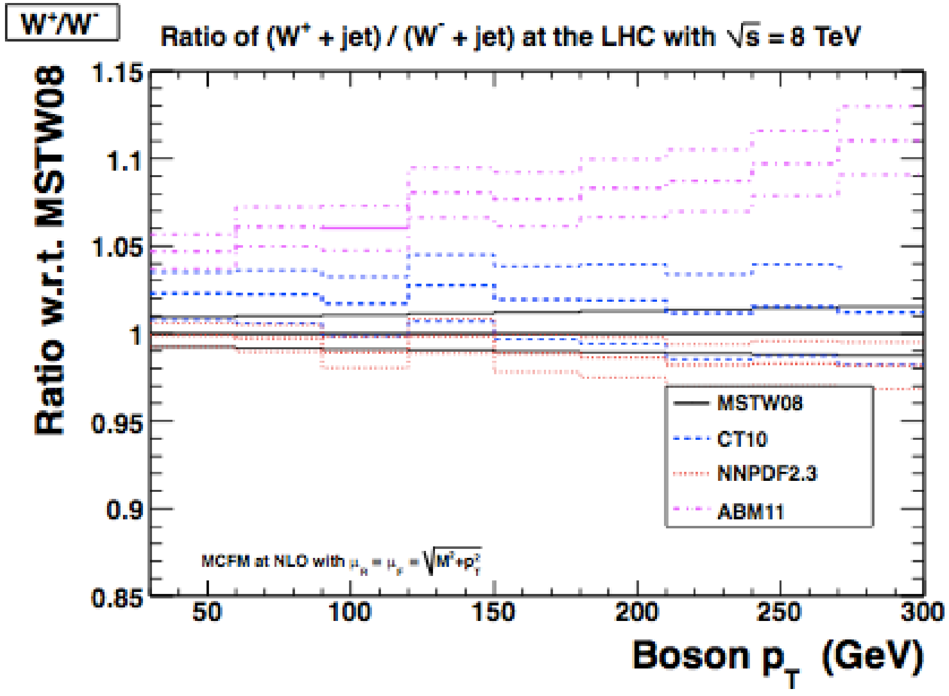
Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the Z pt spectrum by retuning the QCD MCs!

Very-high pt data on the Z pt spectrum are crucial to assess that the effect is indeed so large!

Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to gg→H production

S.Malik and G.Watt, arXiv:1304.2424



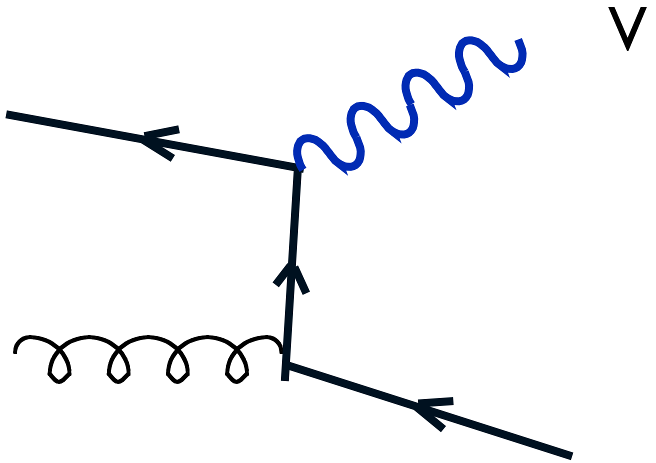


NB Already at 300 GeV the EW effects are as large as the PDF uncertainties we'd like to eliminate ....

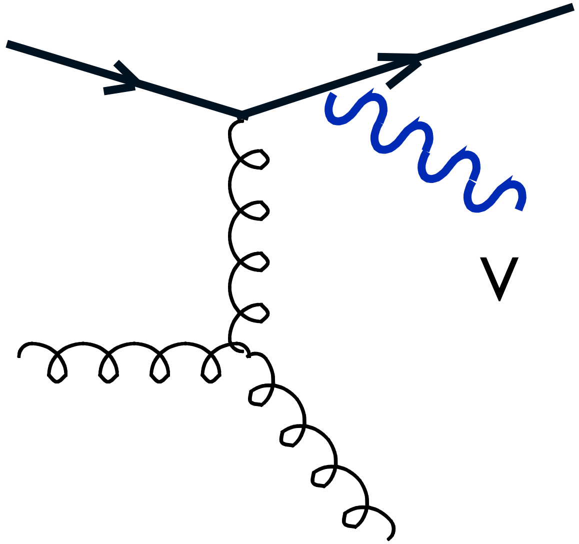
⇒ great potential for becoming a crucial element in the PDF measurement programme, will need the calculation of dσ/dp_T(Z) at NNLO -- in progress..,

Production of gauge bosons in high-energy final states ($\sqrt{s} \gg M_V$)

$O(\alpha_s)$



$\Rightarrow \sqrt{s} \approx p_T^V \gg M_V$



$O(\alpha_s^2)$, but enhanced by t-channel g exchange, and by $\log(p_T^{jet}/M_W)$

$\Rightarrow$ could be larger than $O(\alpha_s)$

$\Rightarrow$ no strong ordering between p_T^V and M_V

Define

$d\sigma_{jj}(W)$:

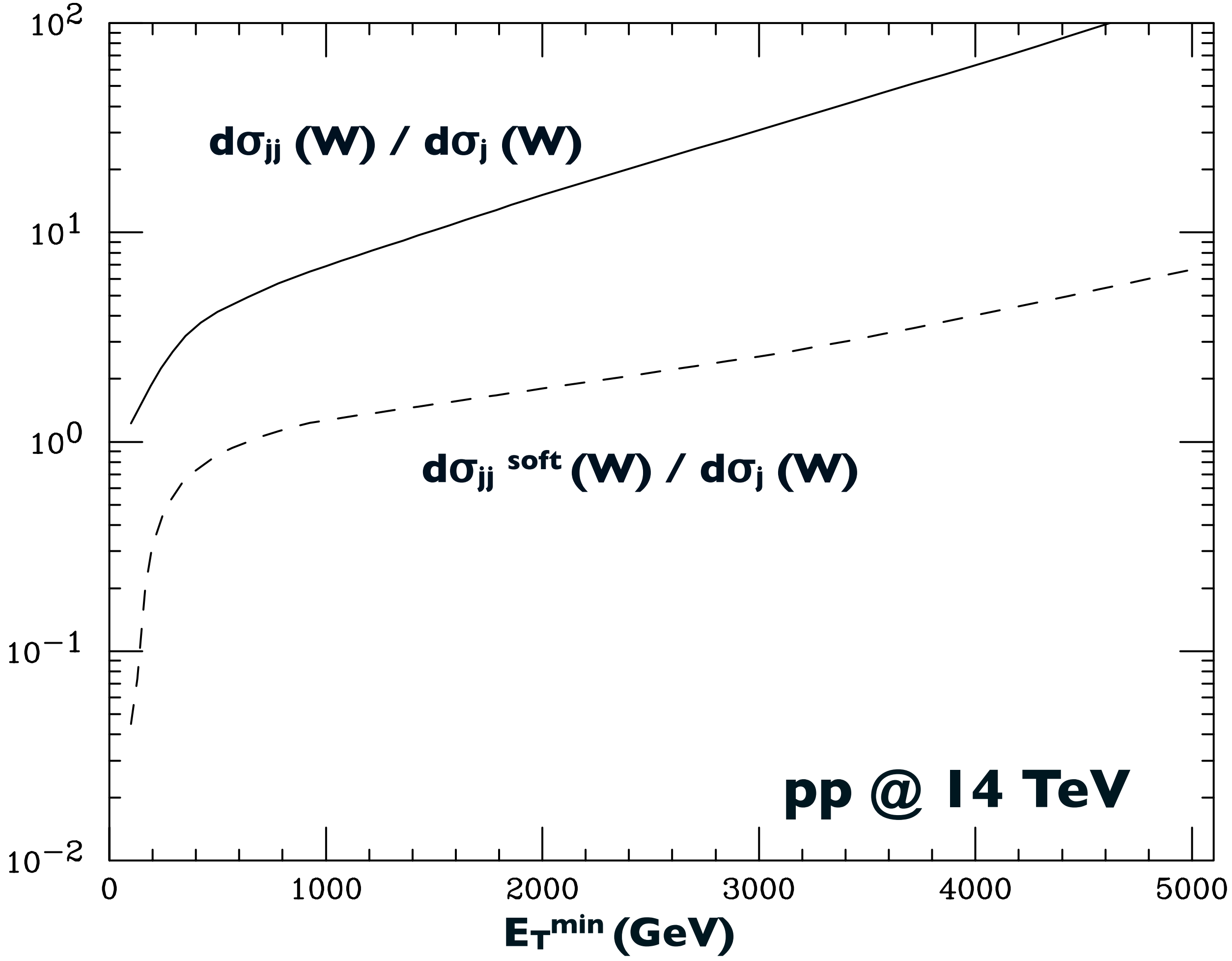
inclusive W production rate, in events with 2 jets of $E_T>30$ GeV, $|\eta|<5$, with $E_T^{(\text{leading jet})} > E_T^{\min}$

$d\sigma_{jj}^{\text{soft}}(W)$:

same, with $E_T^{\text{jet 1}} < 0.2 \times E_T^{\text{jet 2}}$

$d\sigma_j(W)$:

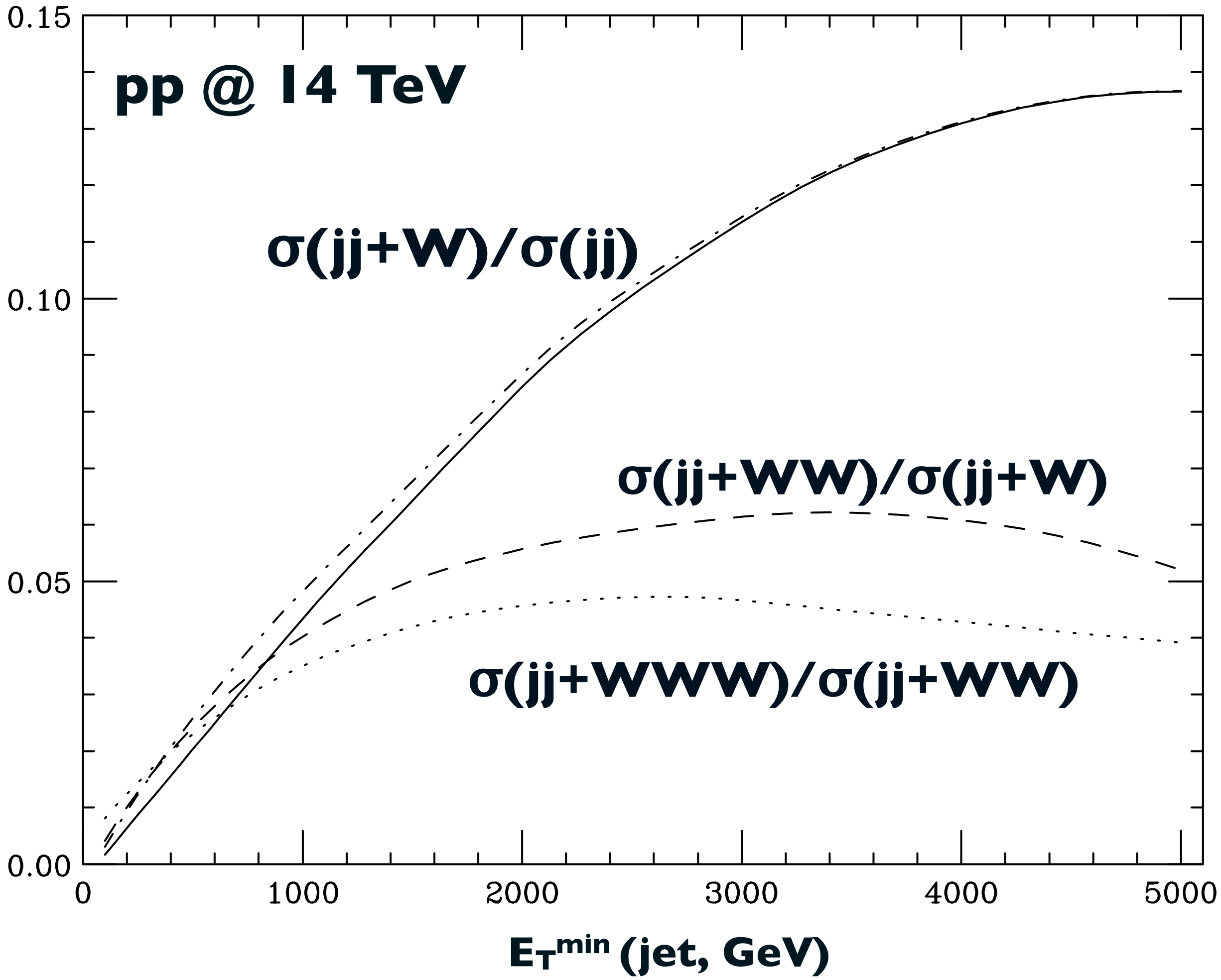
same, with just 1 jet



- $\sigma_j \ll \sigma_{jj}$ ⇒ the dynamics is dominated by kinematical configurations other than W+jet

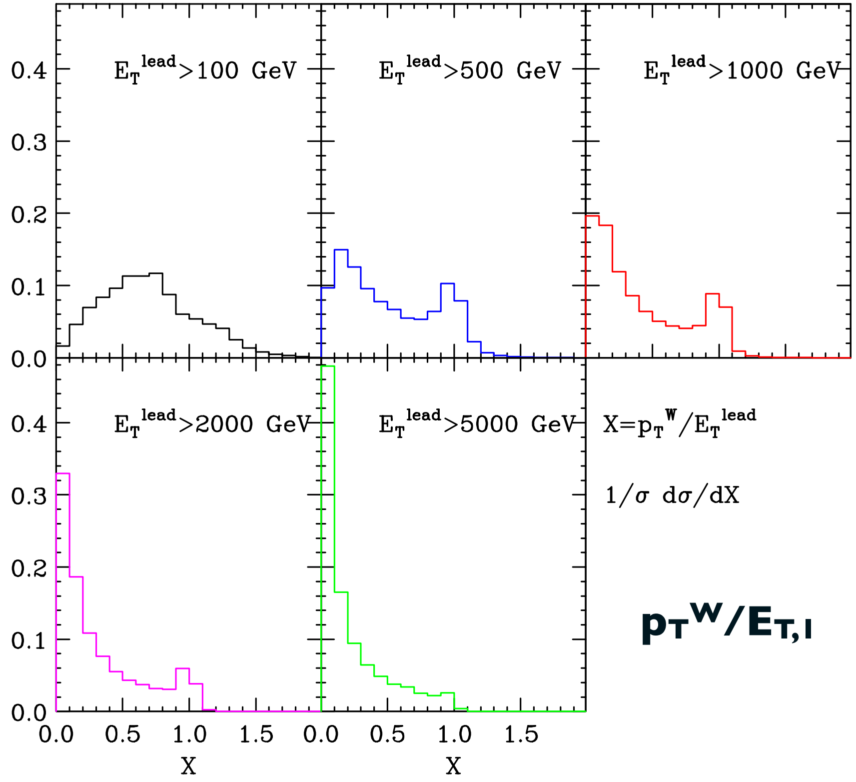
- $\sigma_{jj}^{\text{soft}} \ll \sigma_{jj}$ ⇒ the rate is dominated by final states with a second hard jet, so $E_T^{\min} > 30$ GeV protects against large logs

W production, in events with high-E_T jets

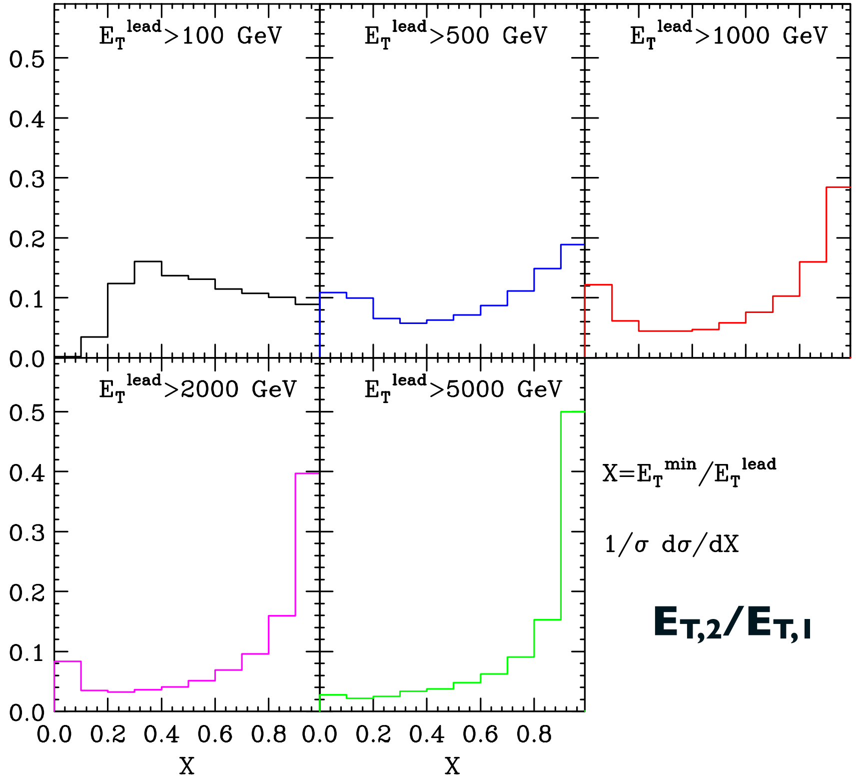


Dotdashes: σ(jj) in the denominator replaced by σ(jj, no gg→gg)

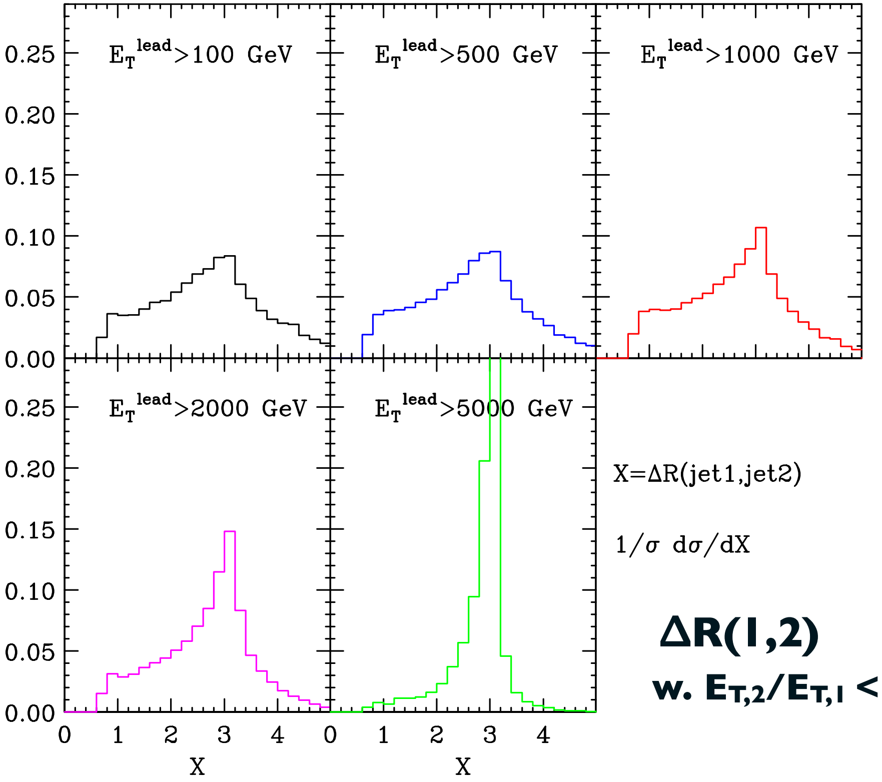
- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **It would be interesting to go after these W and Zs, and verify their production properties**



$p_T^W/E_{T,1}$

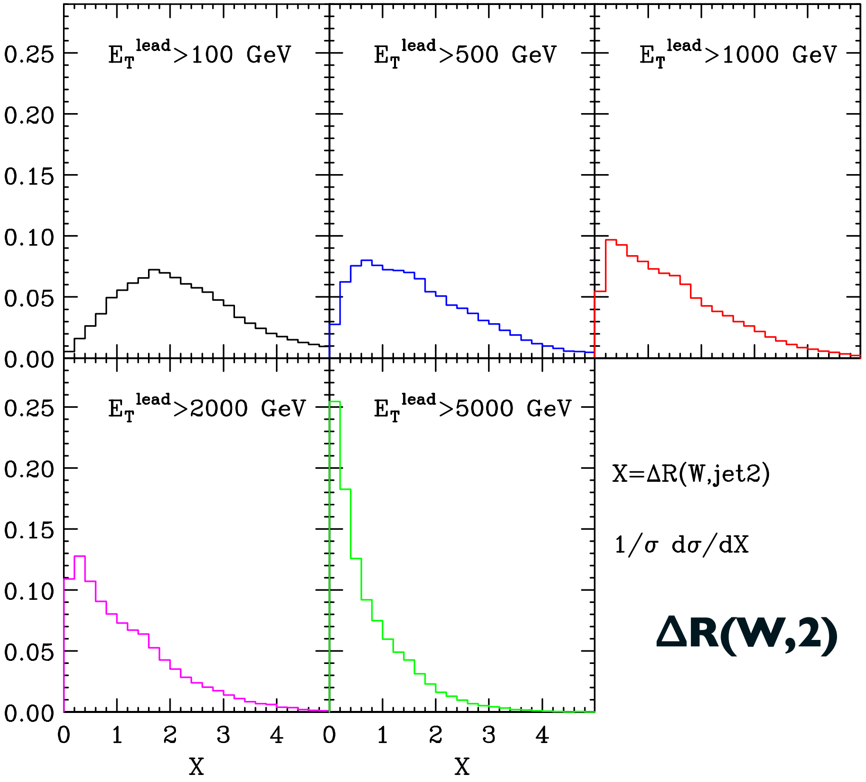


$E_{T,2}/E_{T,1}$



ΔR(1,2)

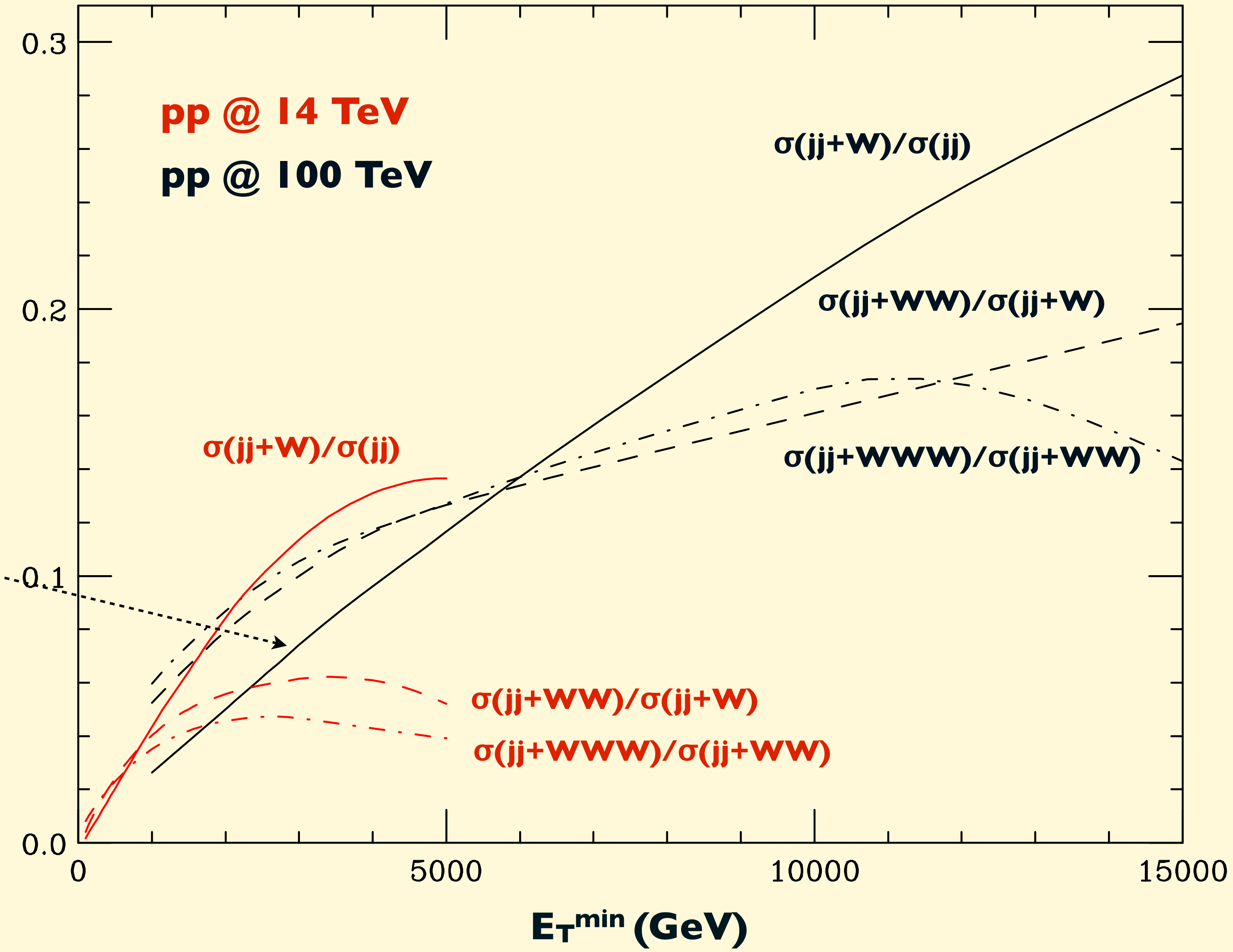
w. $E_{T,2}/E_{T,1} < 0.2$



ΔR(W,2)

14 TeV vs 100 TeV

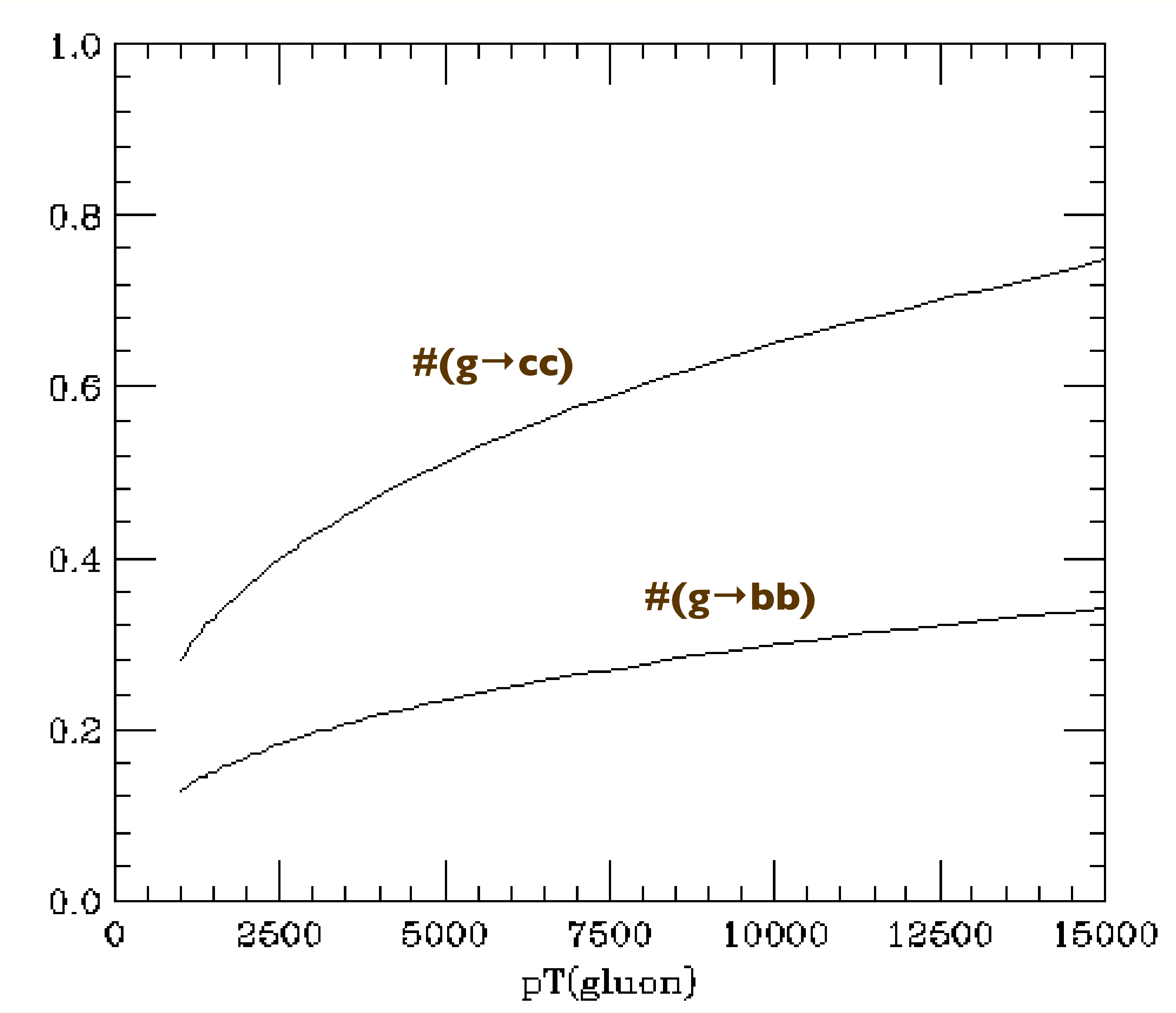
#(W)/(jet event) smaller at 100 TeV, due to larger gluon fraction



Points for possible studies:

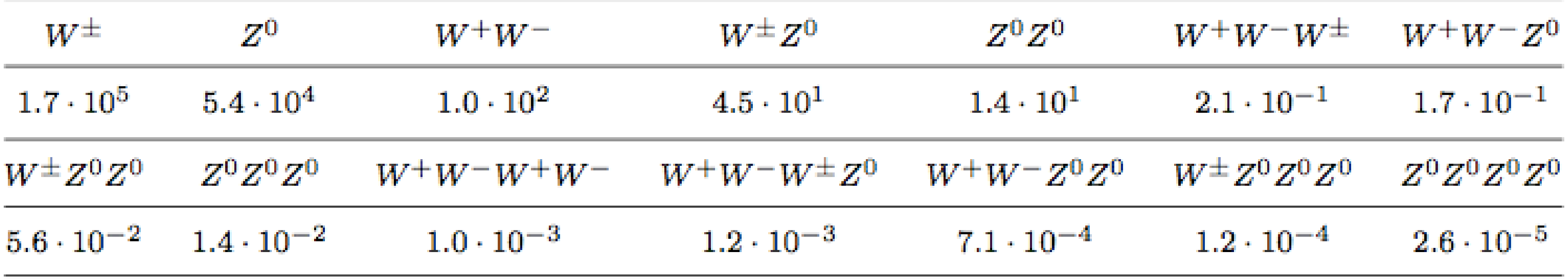
- Impact on bgs to BSM searches (consider both W→hadrons and W→leptons) ?
- Use of W/Z to tag jet flavour ? E.g.
    - o #(W): q vs g discriminator
    - o #(W) vs #(Z): up- vs down-type quark discriminator
    - o b→Wt vs d→uW inside jets

NB: large hvq production (and thus semileptonic decays) **in gluon jets at large pT**



Above 10 TeV, each gluon jet contains one pair of charm or bottom quarks !!

Multi-boson cross sections (pb) at 13 TeV



$W^\pm$	Z^0	W^+W^-	$W^\pm Z^0$	Z^0Z^0	$W^+W^-W^\pm$	$W^+W^-Z^0$
$1.7\cdot10^5$	$5.4\cdot10^4$	$1.0\cdot10^2$	$4.5\cdot10^1$	$1.4\cdot10^1$	$2.1\cdot10^{-1}$	$1.7\cdot10^{-1}$
$W^\pm Z^0Z^0$	$Z^0Z^0Z^0$	$W^+W^-W^+W^-$	$W^+W^-W^\pm Z^0$	$W^+W^-Z^0Z^0$	$W^\pm Z^0Z^0Z^0$	$Z^0Z^0Z^0Z^0$
$5.6\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.0\cdot10^{-3}$	$1.2\cdot10^{-3}$	$7.1\cdot10^{-4}$	$1.2\cdot10^{-4}$	$2.6\cdot10^{-5}$

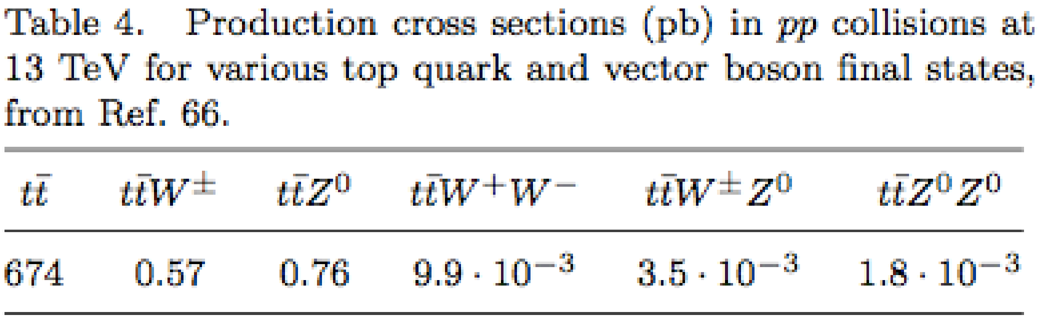


Table 4. Production cross sections (pb) in pp collisions at 13 TeV for various top quark and vector boson final states, from Ref. 66.

$t\bar{t}$	$t\bar{t}W^\pm$	$t\bar{t}Z^0$	$t\bar{t}W^+W^-$	$t\bar{t}W^\pm Z^0$	$t\bar{t}Z^0Z^0$
674	0.57	0.76	$9.9\cdot10^{-3}$	$3.5\cdot10^{-3}$	$1.8\cdot10^{-3}$

Multiple W bosons are more likely produced by top quarks than through direct production!

Ratio determined by couplings among W/Z, SU(2) invariance

Ratio determined by couplings to quarks, u/d PDF

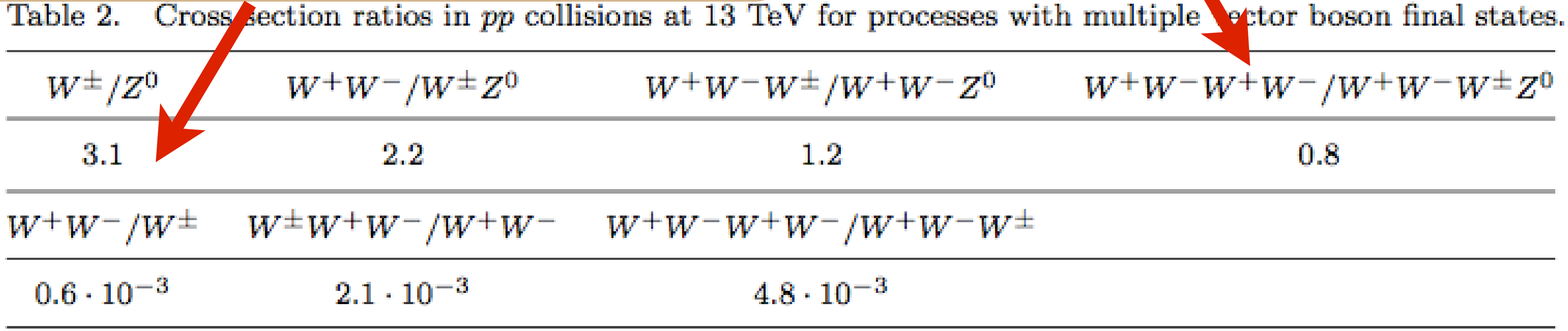
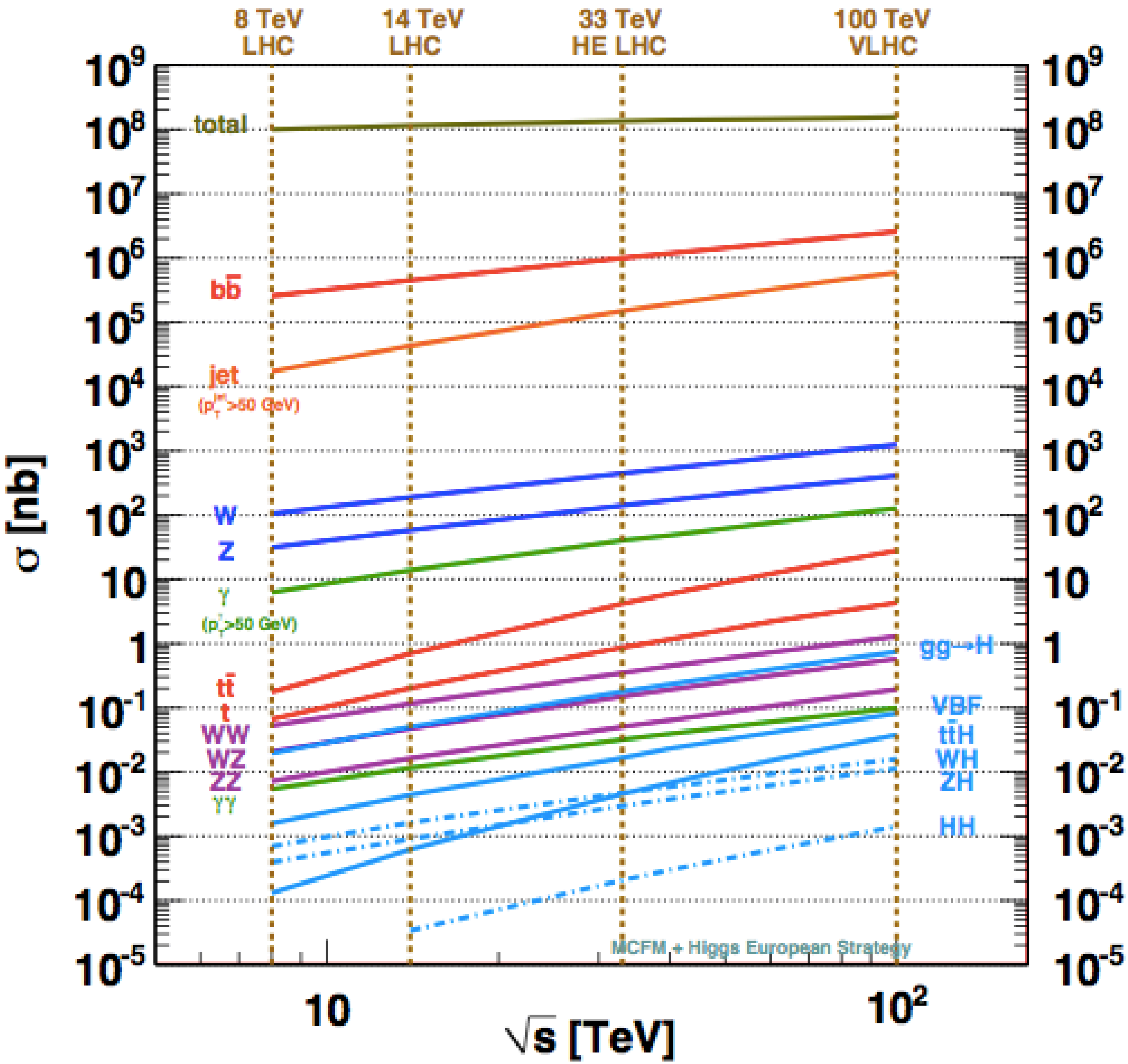


Table 2. Cross section ratios in pp collisions at 13 TeV for processes with multiple vector boson final states.

$W^\pm/Z^0$	$W^+W^-/W^\pm Z^0$	$W^+W^-W^\pm/W^+W^-Z^0$	$W^+W^-W^+W^-/W^+W^-W^\pm Z^0$
3.1	2.2	1.2	0.8
$W^+W^-/W^\pm$	$W^\pm W^+W^-/W^+W^-$	$W^+W^-W^+W^-/W^+W^-W^\pm$	
$0.6\cdot10^{-3}$	$2.1\cdot10^{-3}$	$4.8\cdot10^{-3}$	

Great potential to further exploration of SM particles at 100 TeV

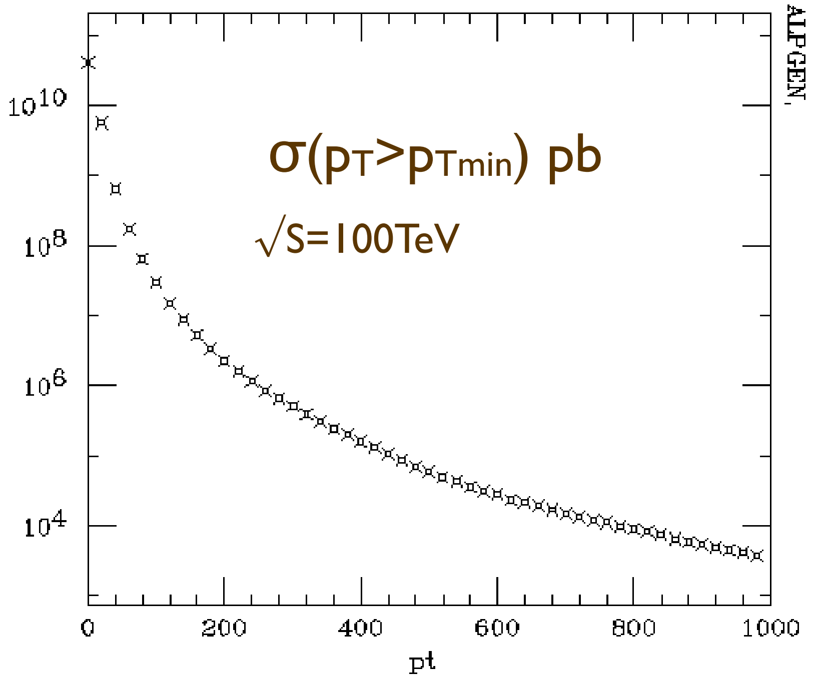


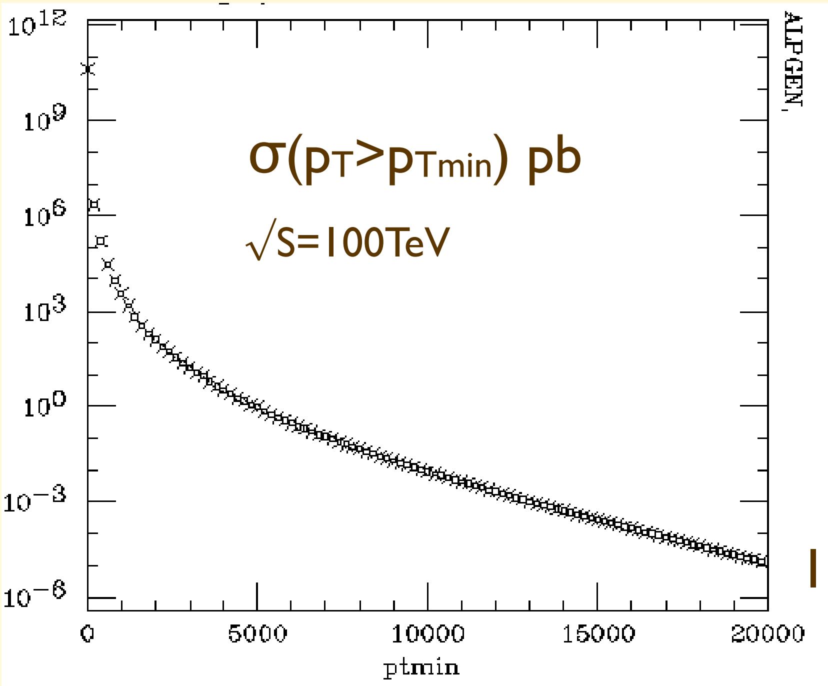
final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets $(p_T>5$ TeV$)$	10^{6}
jets $(p_T>10$ TeV$)$	10^{4}

Inclusive jets

$\sigma(pt > 5\ \text{GeV}) = 240\ \text{mb} \sim 2 \times \sigma_{TOT}(pp)$

$\sigma(pt > 10\ \text{GeV}) = 40\ \text{mb} \sim 1/3 \times \sigma_{TOT}(pp)$

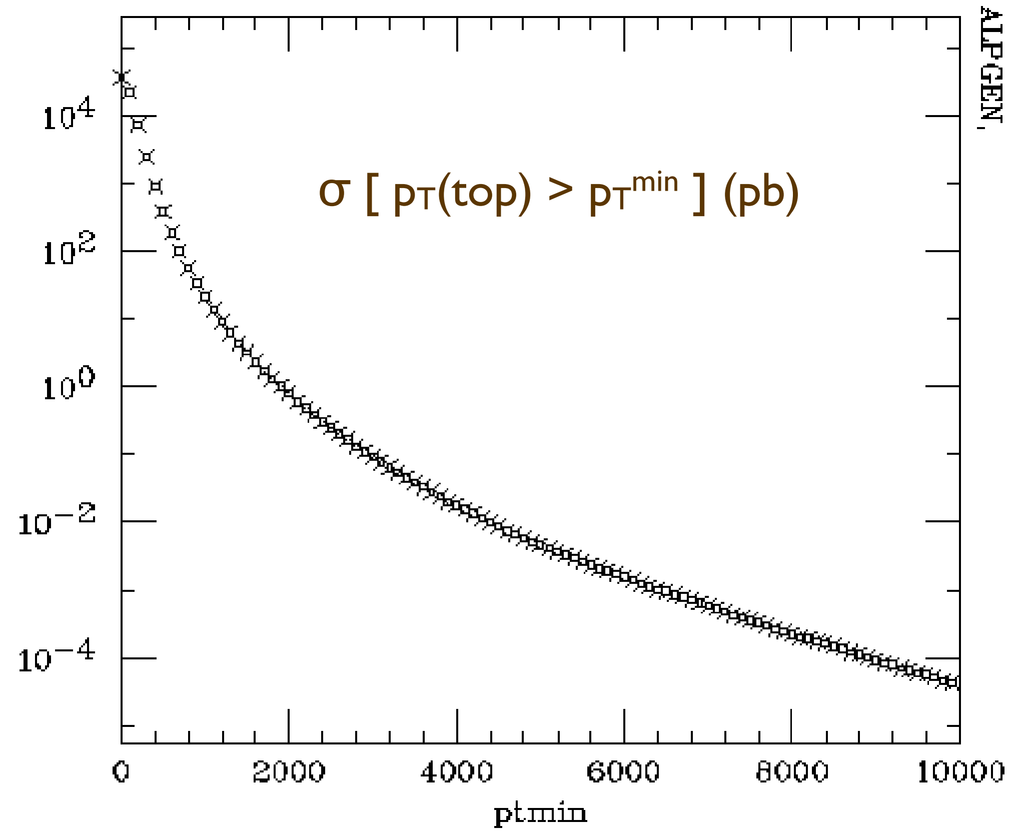




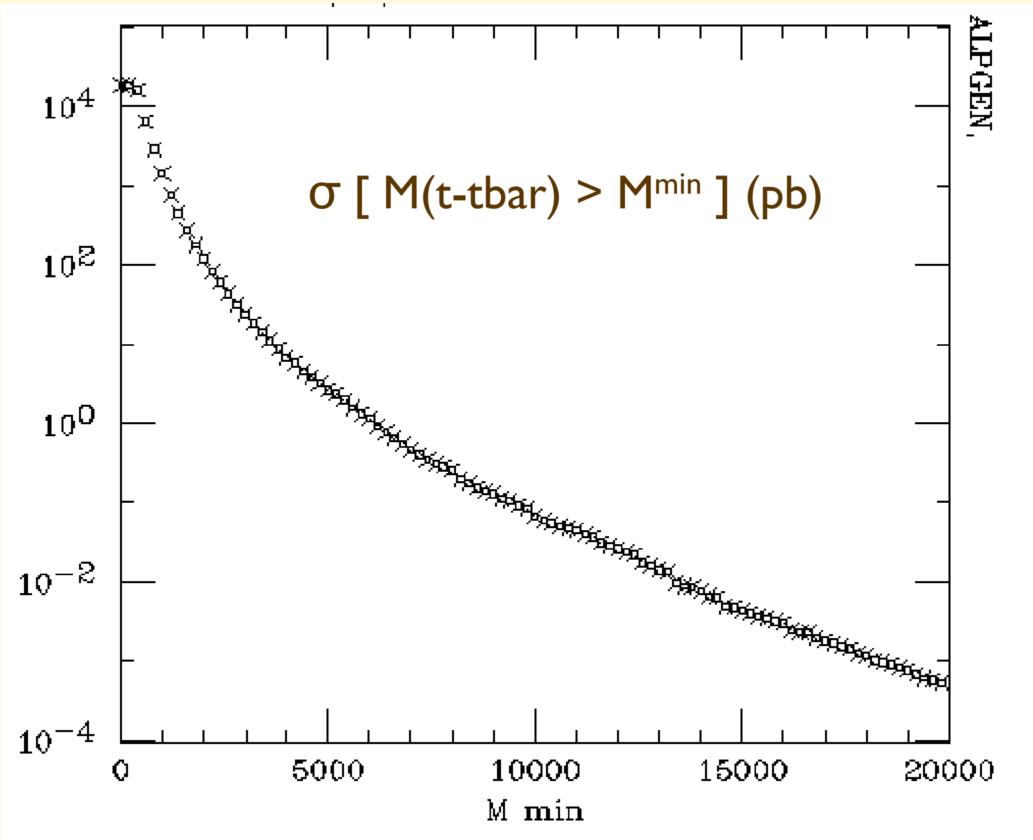
1 event/100fb^{-1}

Inclusive t-tbar production: cross sections

$\sigma \sim 30\text{nb} \Rightarrow 3 \times 10^{10}$ pairs / 1000 fb^{-1}



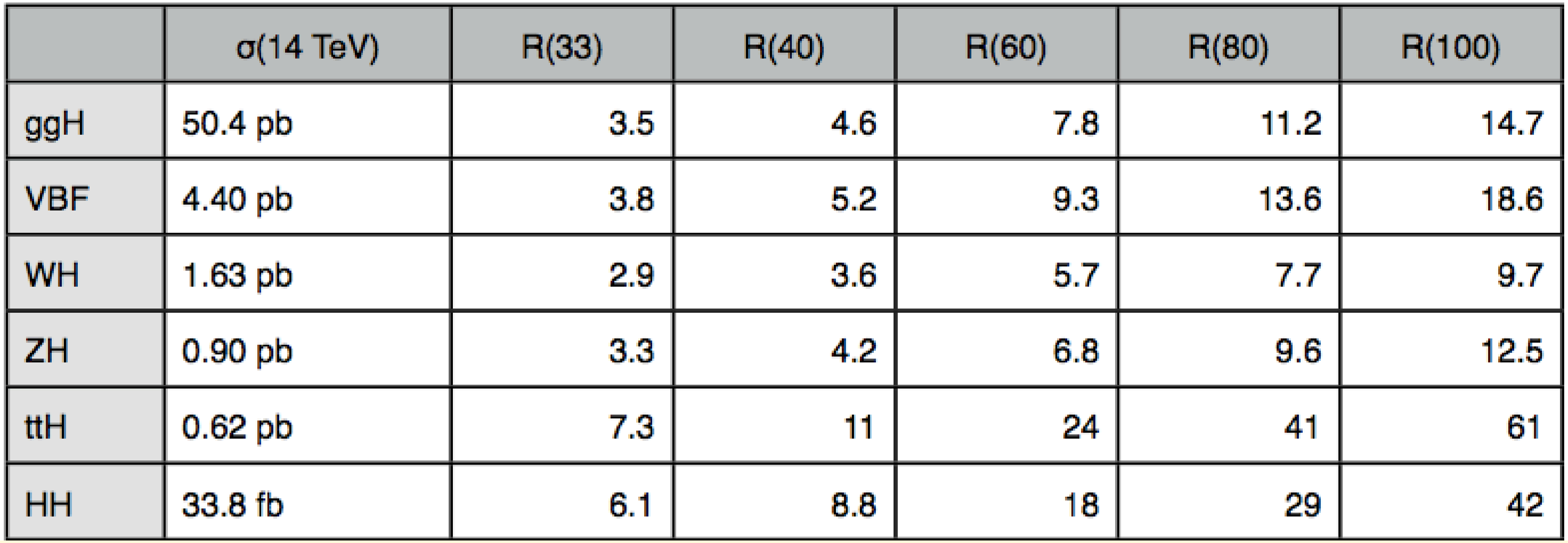
σ [p_T(top) > p_T^{min}] (pb)



σ [M(t-tbar) > M^{min}] (pb)

Higgs rates at high energy

NLO rates **R(E)** = σ(E TeV)/σ(14 TeV)

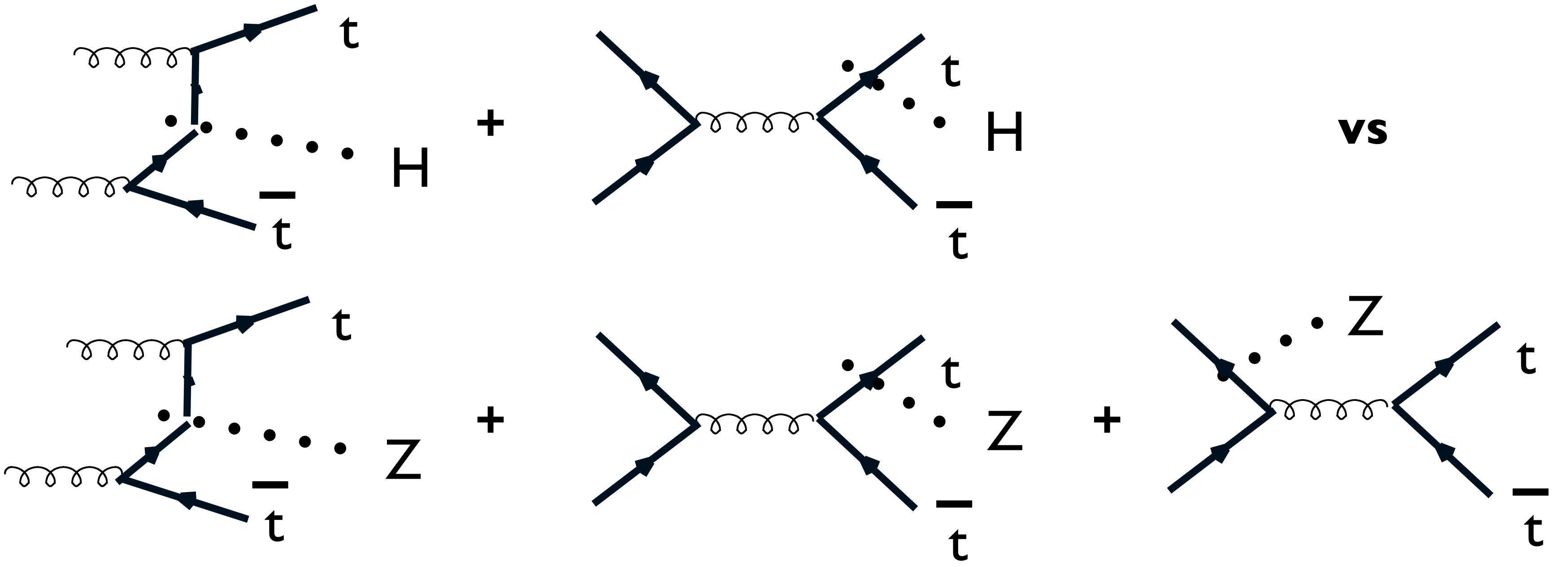


	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

In several cases, the gains in terms of "useful" rate are much bigger.

E.g. when we are interested in the large-invariant mass behaviour of the final states.

Example, y_{top} from pp→tt H/pp→tt Z



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  - **o correlated QCD corrections, correlated scale dependence**
  - **o correlated α_S systematics**

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  - **o correlated PDF systematics**
  - **o correlated m_{top} systematics**

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

NLO scale dependence:

Scan μ_R and μ_F independently, at $\mu_{R,F} = [0.5, 1, 2]\ \mu_0$, with $\mu_0 = m_H+2m_t$

	δσ(ttH)	δσ(ttZ)	**σ(ttH)/σ(ttZ)**	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 9.8%	± 12.3%	**0.608**	**±2.6%**
100 TeV	± 9.6%	± 10.8%	**0.589**	**±1.2%**

PDF dependence (CTEQ6.6 -- similar for others)

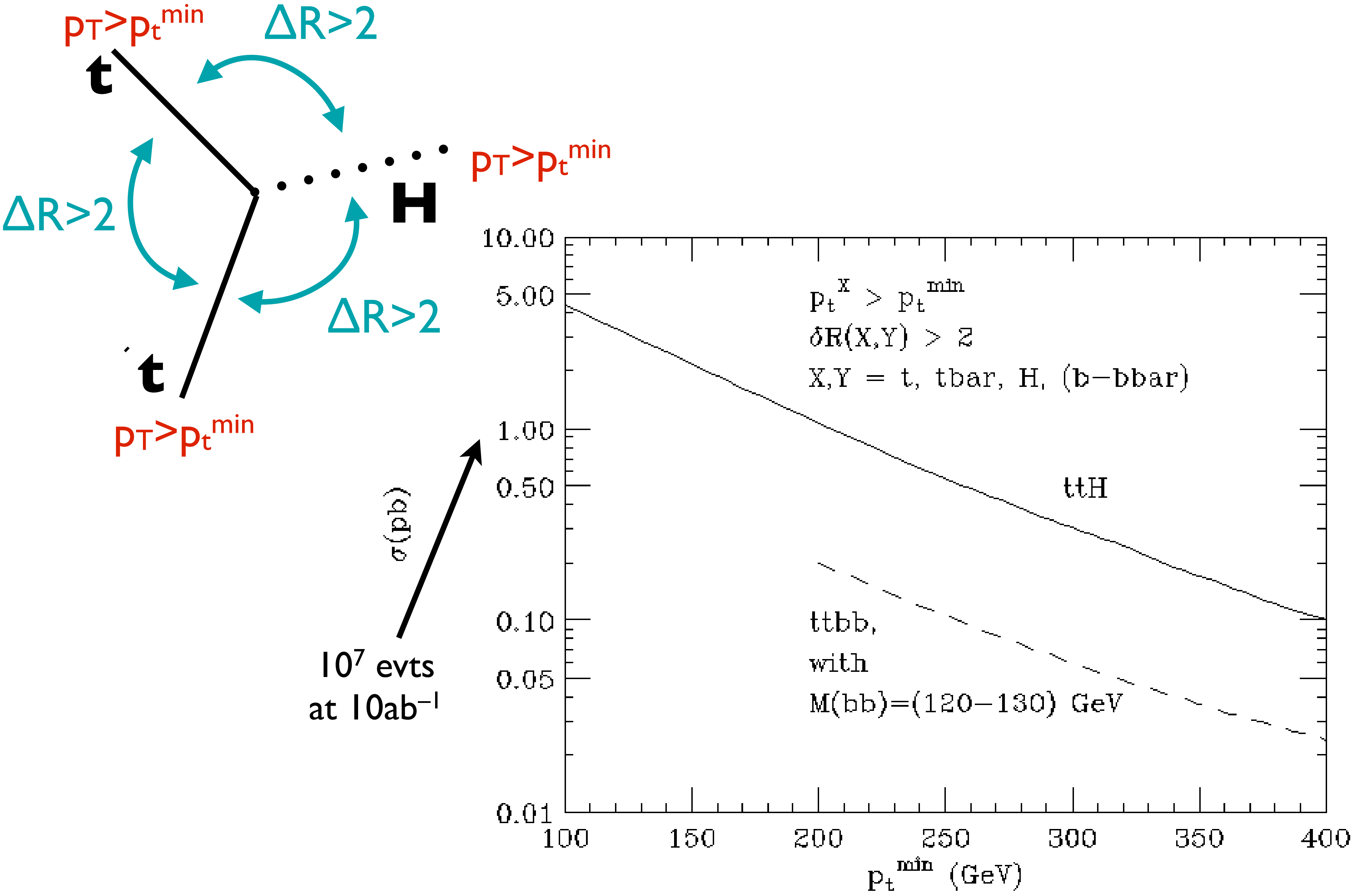
	δσ(ttH)	δσ(ttZ)	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

** The uncertainty reduction survives after applying kinematical cuts to the final states*

** Both scale and PDF uncertainties will be reduced further, well before FCC!*

Example, ttH at large pt

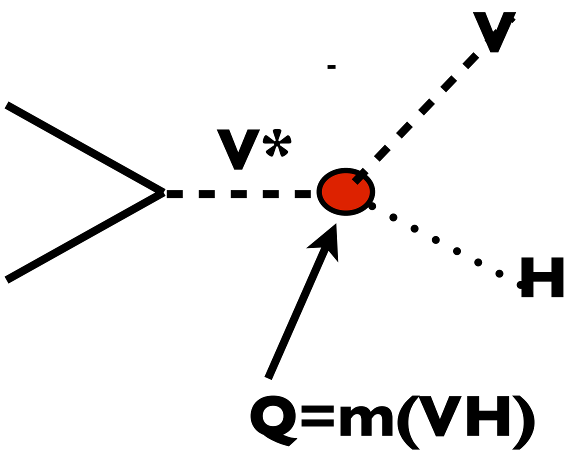
- S/B > 1
- 10 M evts at 10ab^{-1} w. ptmin=200 GeV, before further cuts

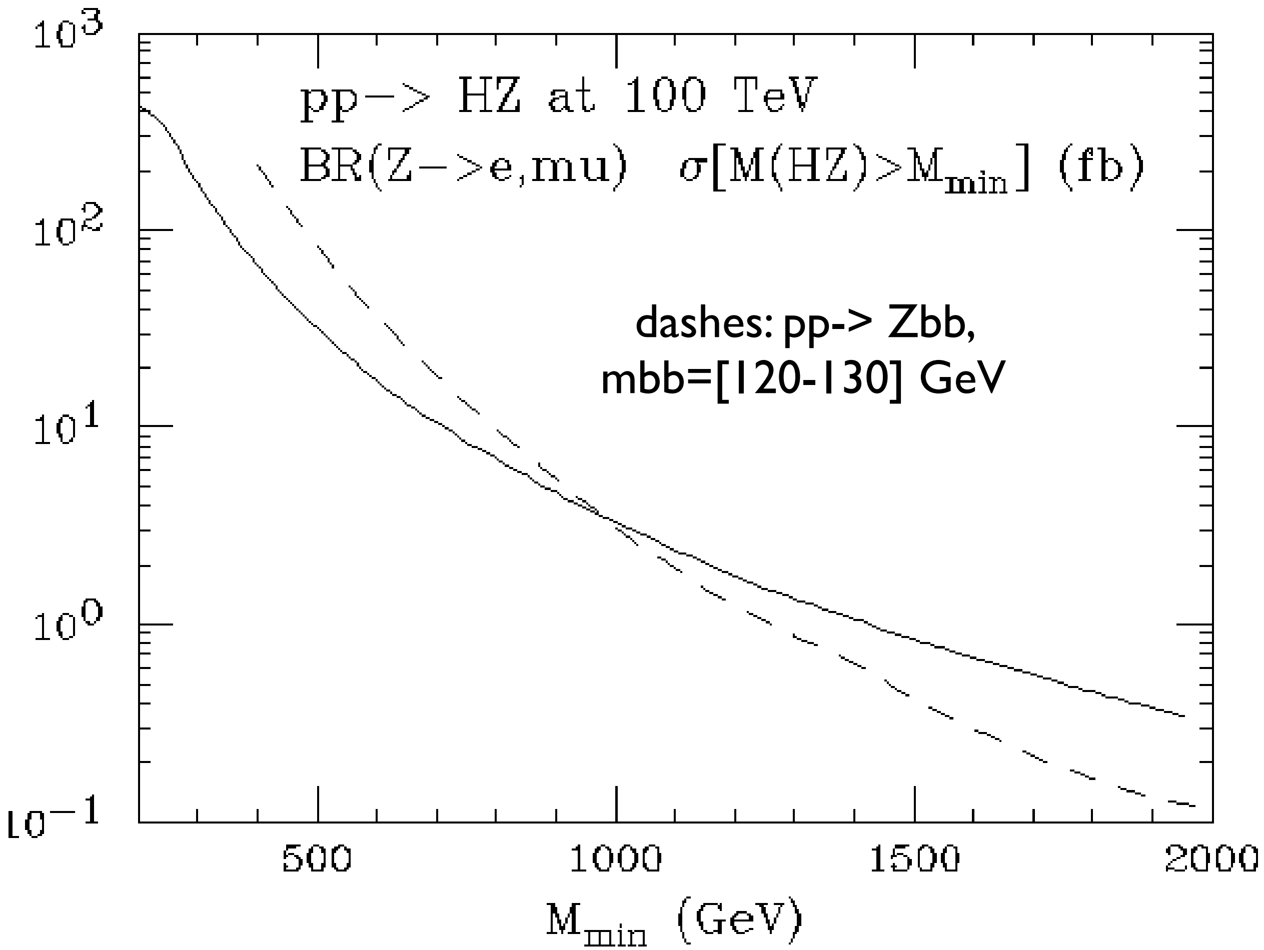


10^{7} evts
at 10ab^{-1}

Example, ZH at large mass

- Sensitivity to anomalous VVH couplings complementary to what given by high-precision B(H→VV) measurements
- Optimal use of boosted object tagging, to access both hadronic and leptonic W/Z decays, H→bb, etc,





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

10^{10} Higgs bosons => 10^4 x today

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

=>10^{12} W bosons from top decays => *probe rare W decays ?*

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

=>10^{11} $t \to W \to$ taus => *can solve the B($W \to \tau\nu$) puzzle ?*

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

=> plenty of new studies and opportunities for measurements become available