Events' structure at 100 TeV: a first look

International Workshop on

Future High Energy Circular Colliders

IHEP, Beijing, Dec 16-17 2013

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- Jet rates:
  - high pt reach
  - low-pt to saturate sigma total
  - structure of MB events ?
- Top quarks:
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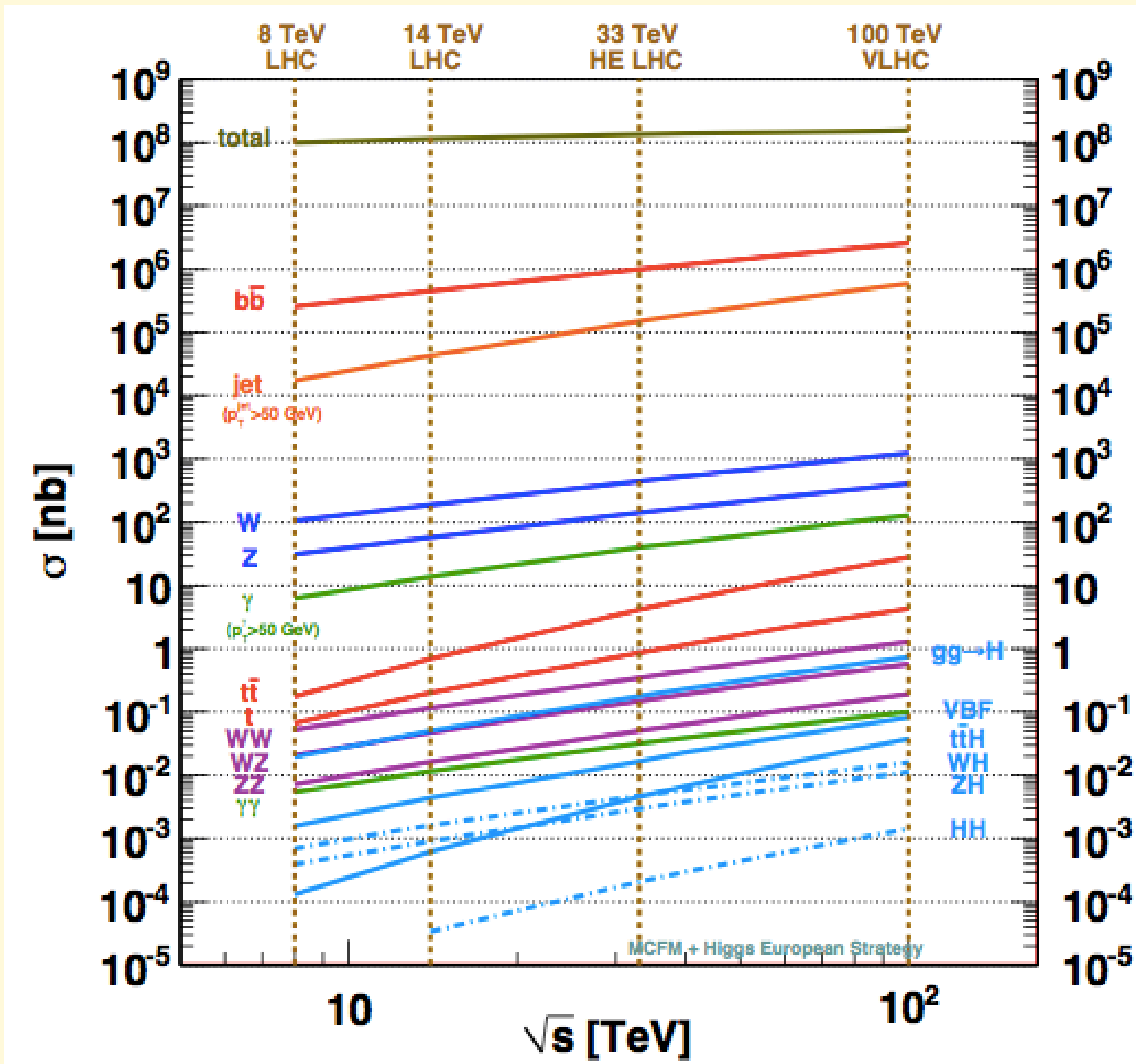
  - top pt and mtt spectra
- W production: lepton distributions, acceptances. W pt spectrum
  - associated production of jets and W's
  - multi-W rates
- WW and HH in VBF: jet spectra, rates vs m(WW), m(HH)
- tt H production, high pt(top)
- Energy vs luminosity

Relevant Snowmass docs

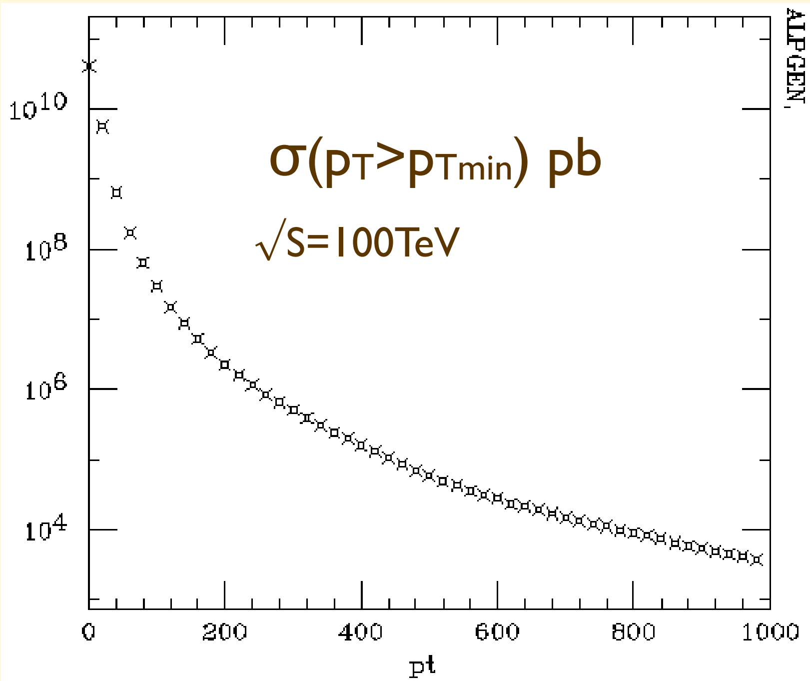
- Methods and Results for Standard Model Event Generation at sqrt{s} = 14 TeV, 33 TeV and 100 TeV Proton Colliders http://arxiv.org/abs/1308.1636v2
- Report of the Snowmass 2013 energy frontier QCD working group, http://arxiv.org/abs/1310.5189v1

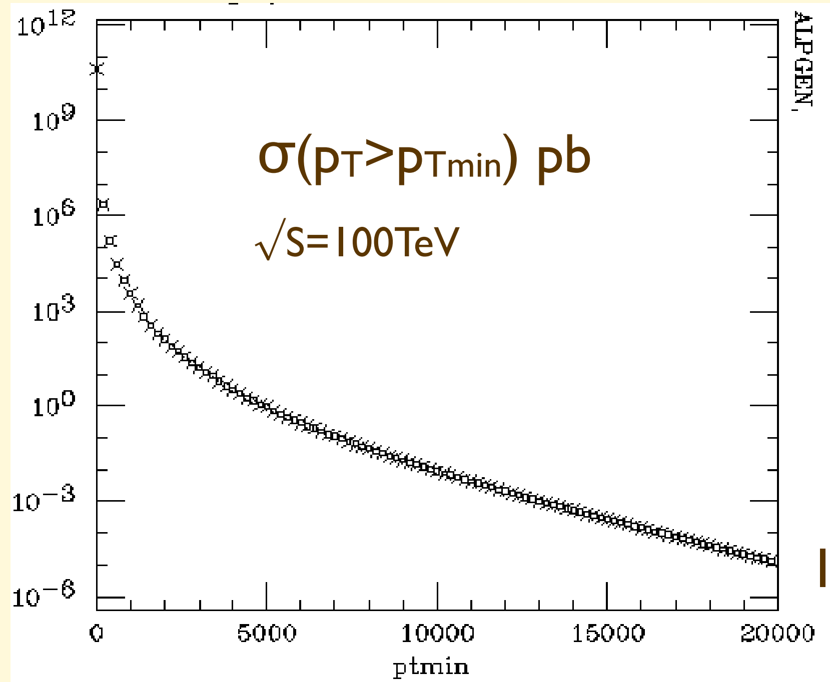


Inclusive jets

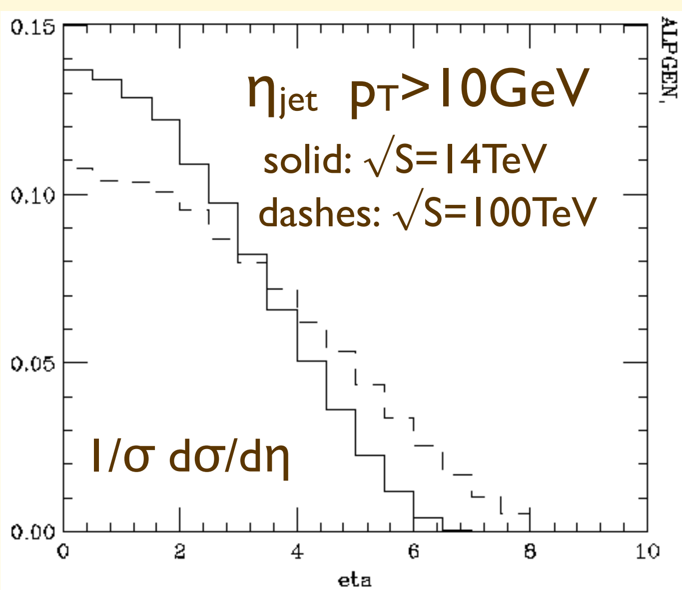
$\sigma(pt > 5\ \text{GeV}) = 240\ \text{mb} \sim 2 \times \sigma_{TOT}(pp)$

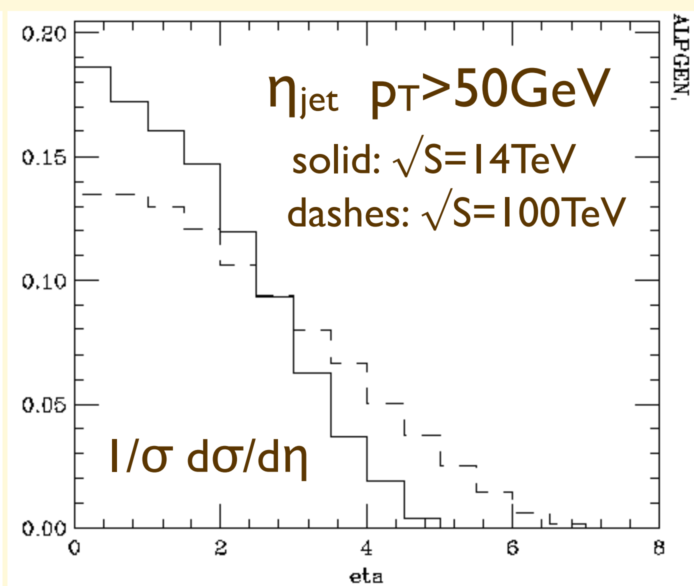
$\sigma(pt > 10\ \text{GeV}) = 40\ \text{mb} \sim 1/3 \times \sigma_{TOT}(pp)$

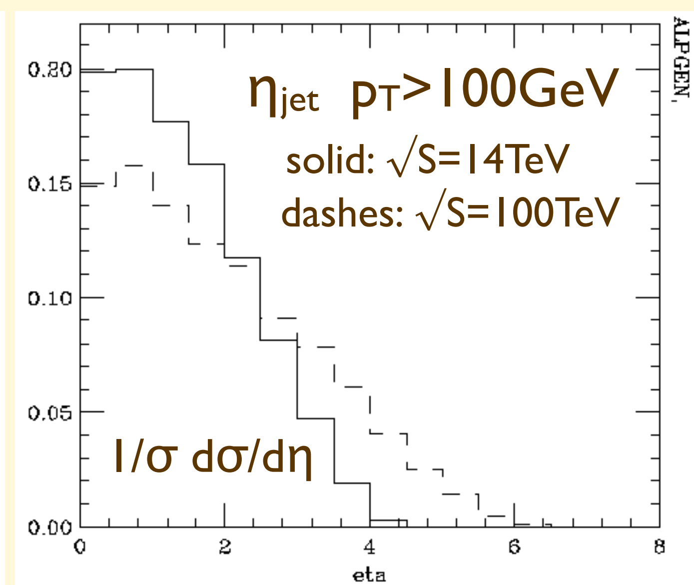




1 event/100fb^{-1}

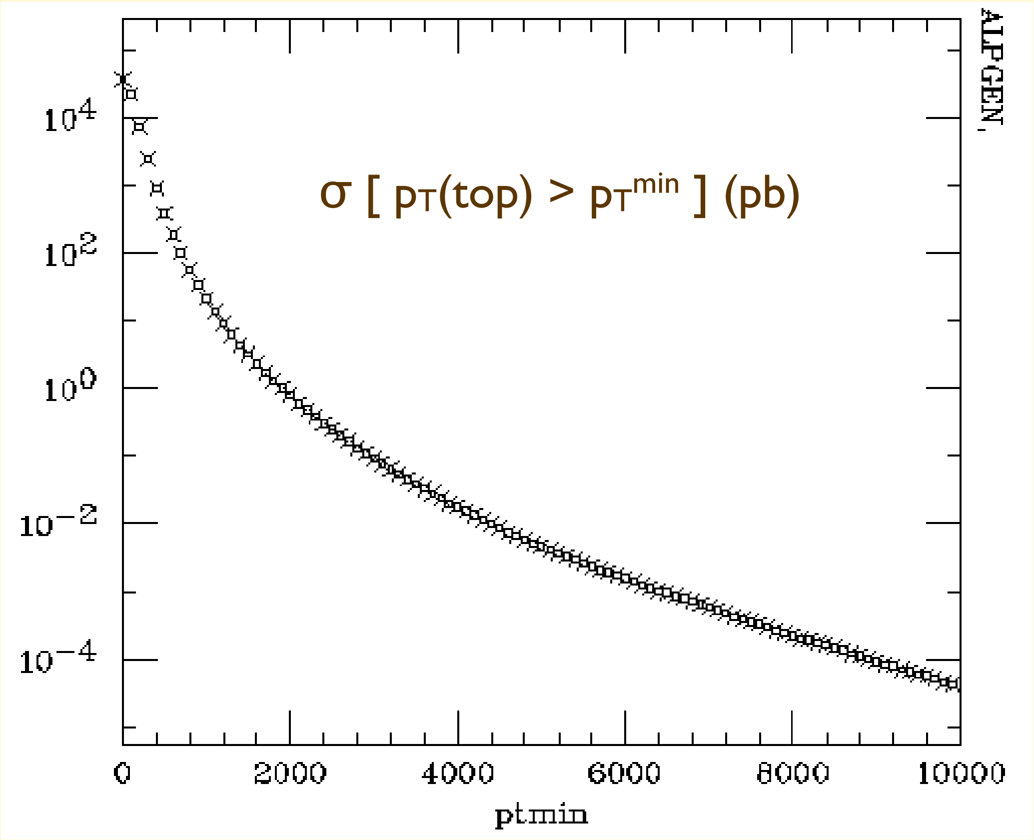


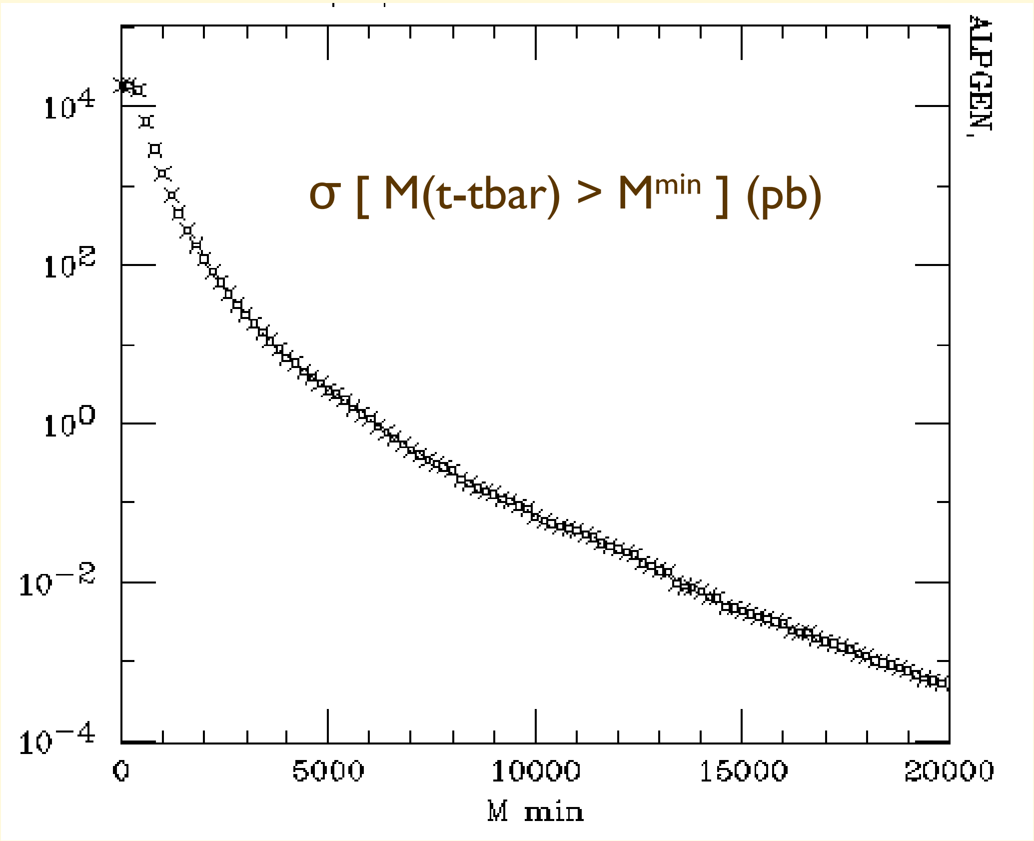




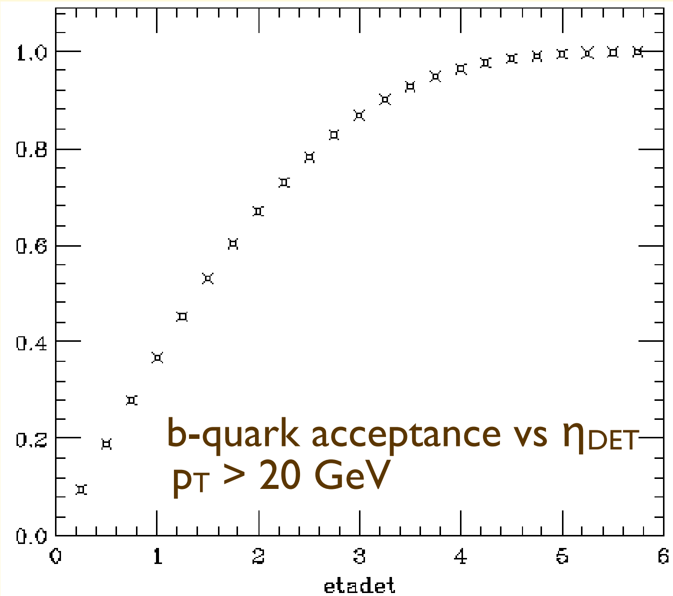
Inclusive t-tbar production: cross sections

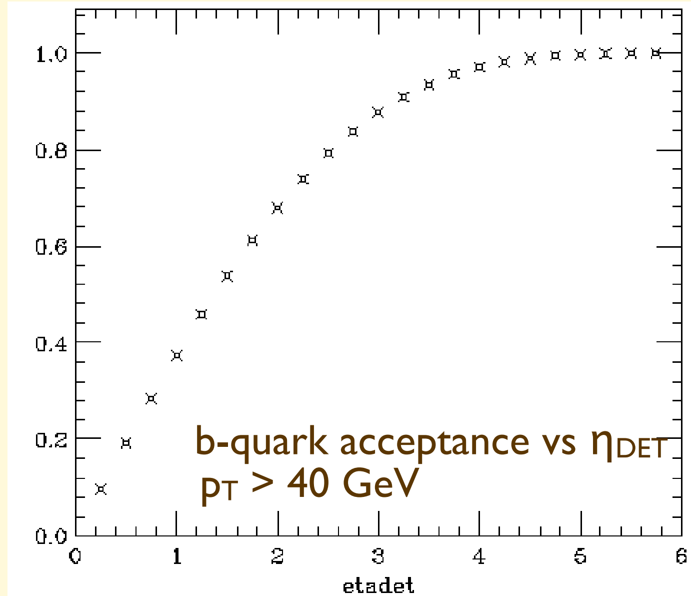
$\sigma \sim 30\text{nb} \Rightarrow 3 \times 10^{10}$ pairs / 1000 fb^{-1}

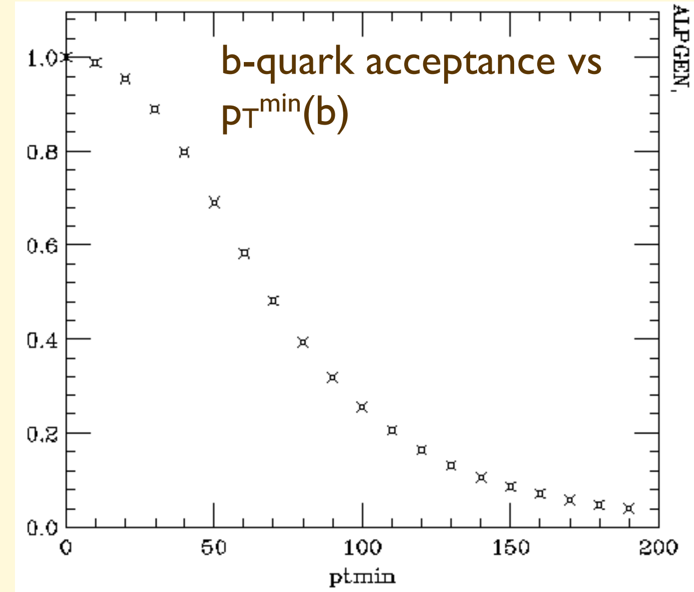


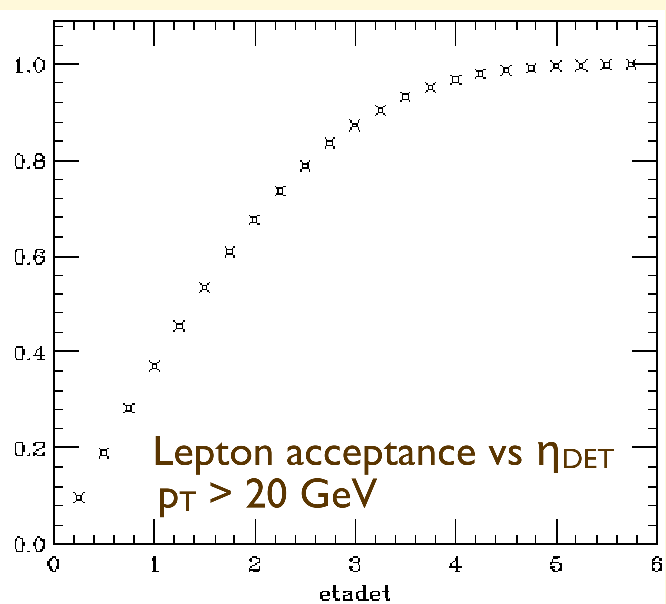


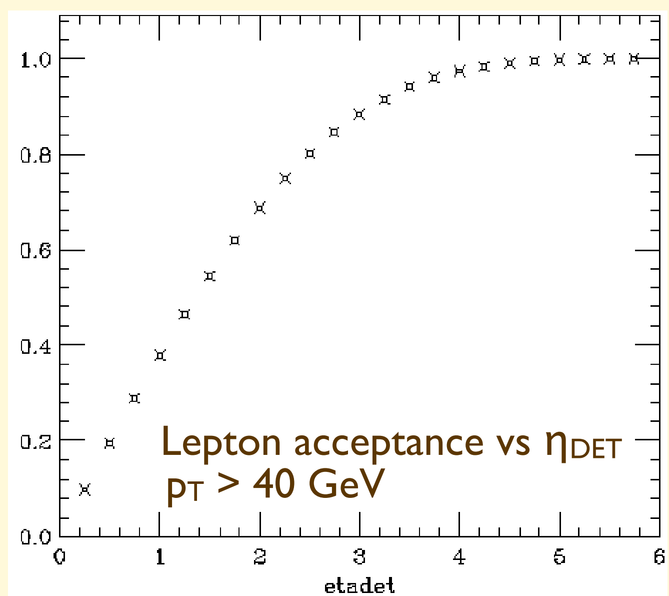
Inclusive t-tbar production: lepton and b-quark acceptances

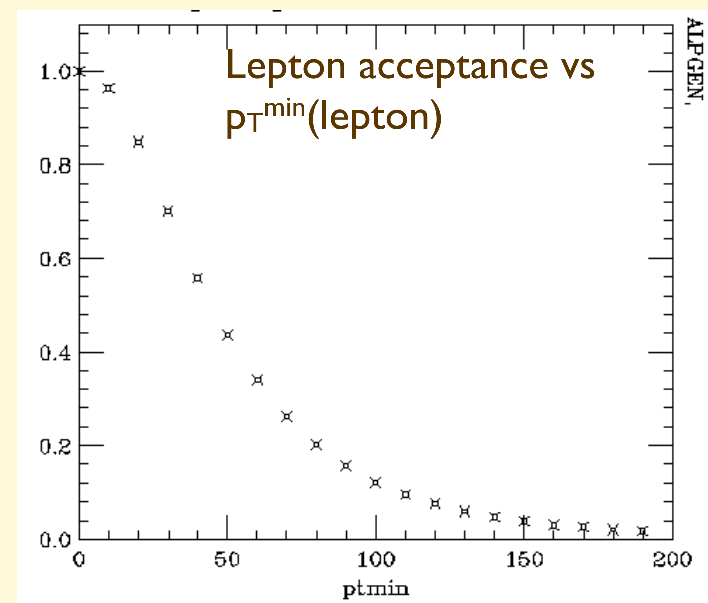






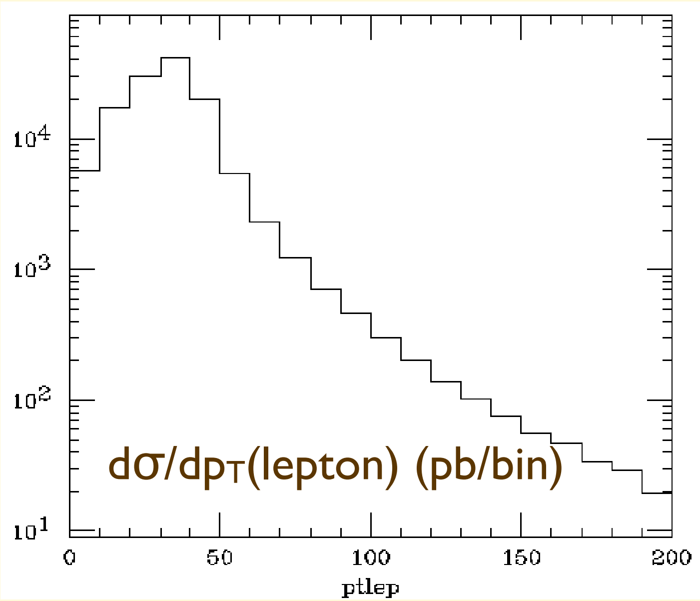


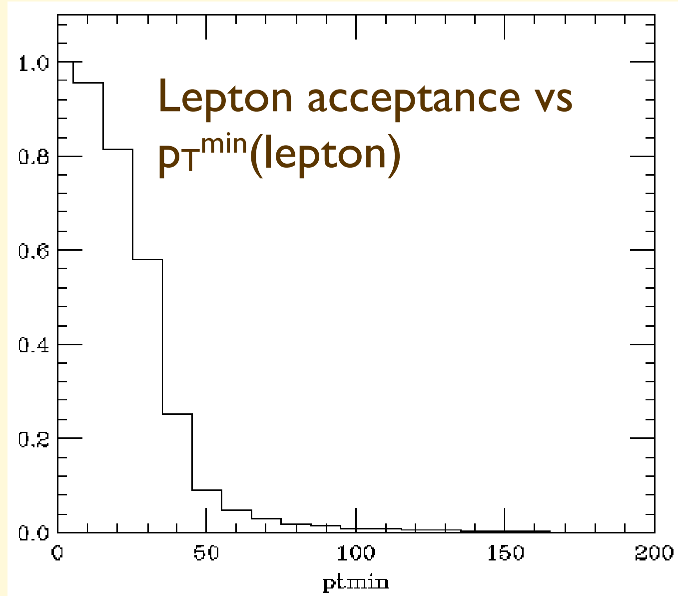


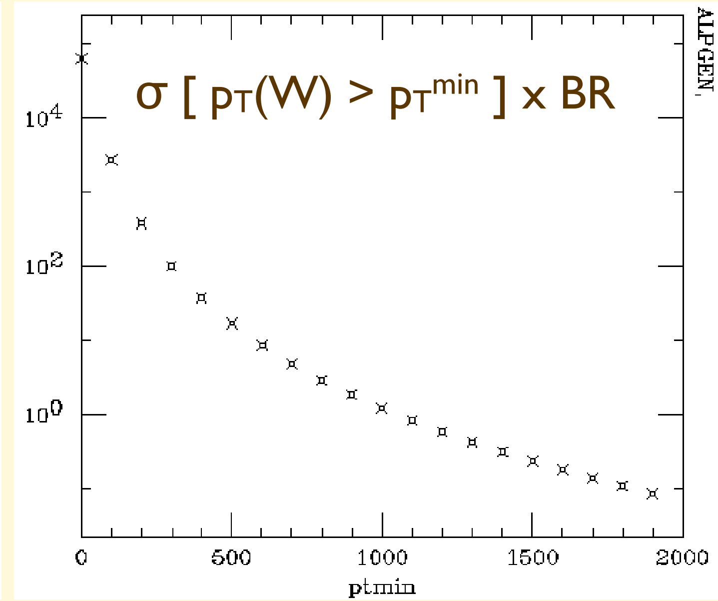


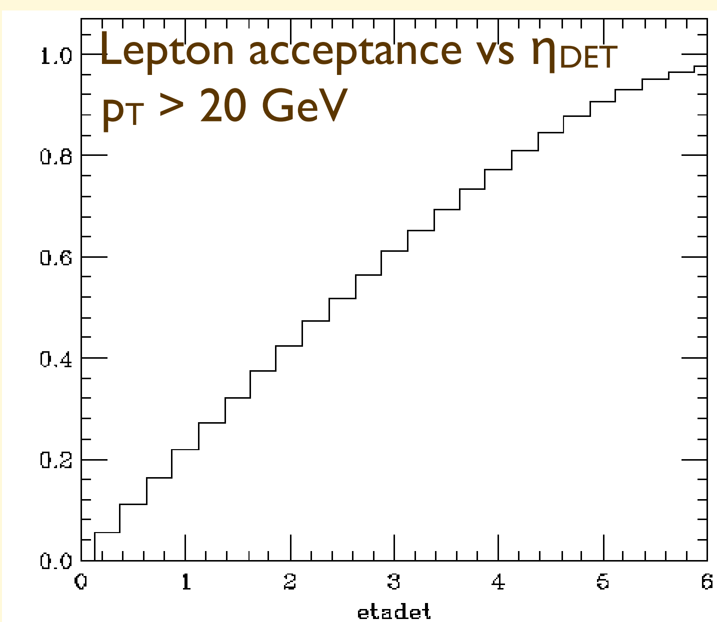
Inclusive W production

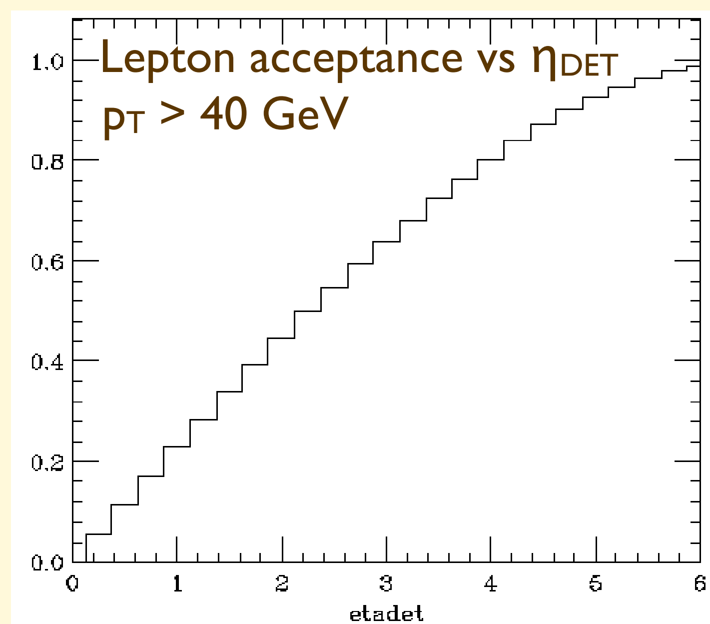
$\sigma \sim 1\,\mu b \sim 10^{-5}\,\sigma_{tot} \Rightarrow 10^{12}\,W\,/\,1000\,fb^{-1}$





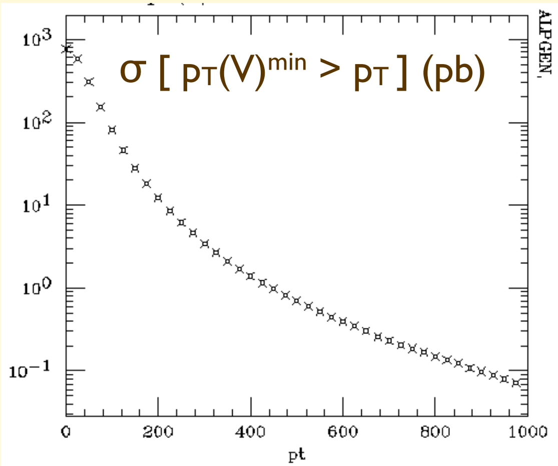


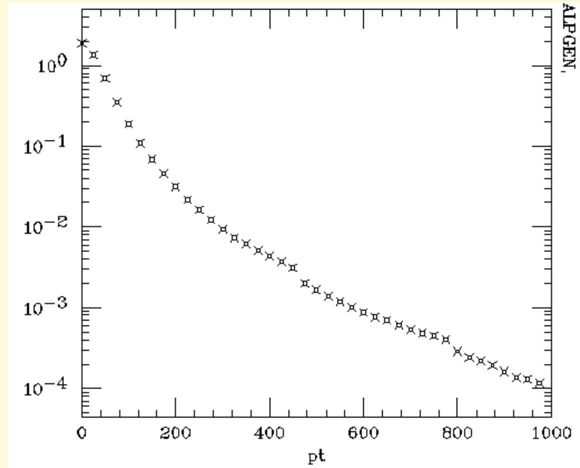


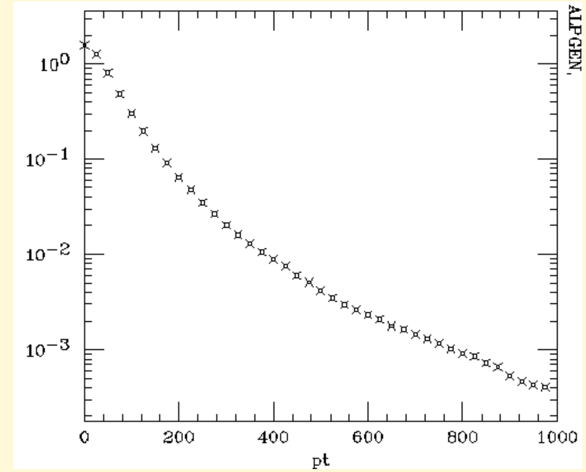


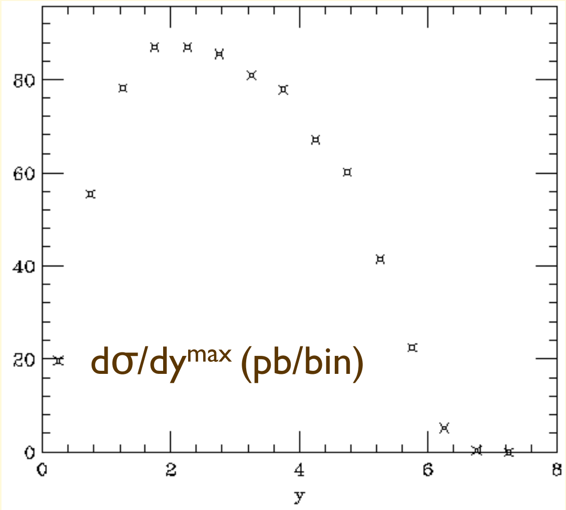
Multi-gauge boson production (LO rates, no BR included)

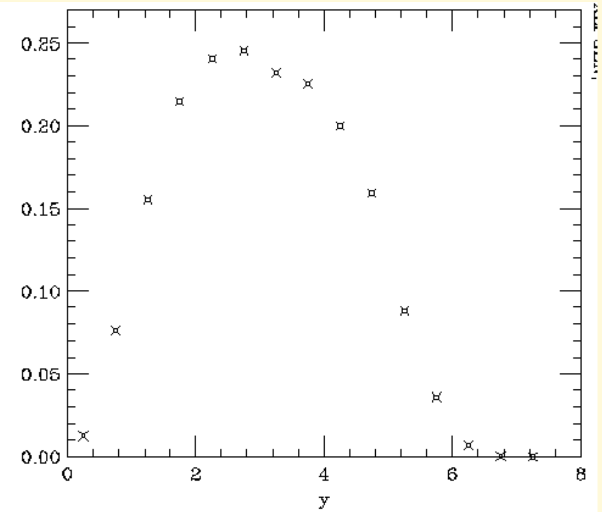
WW σ=770 pb | **WWW σ= 2 pb** | **WWZ σ= 1.6 pb**

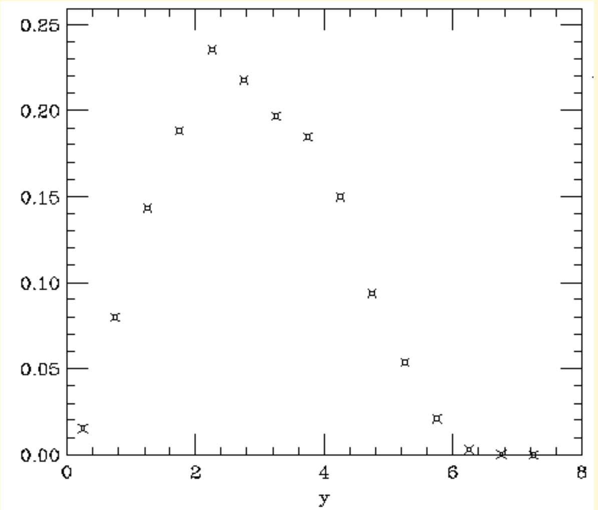






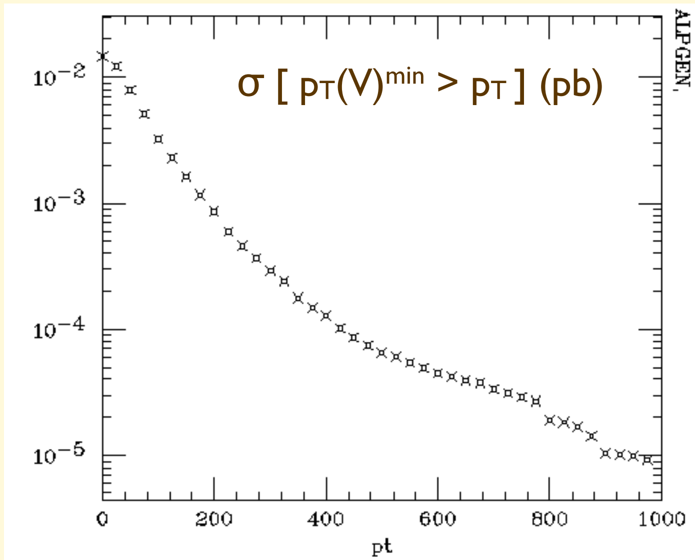


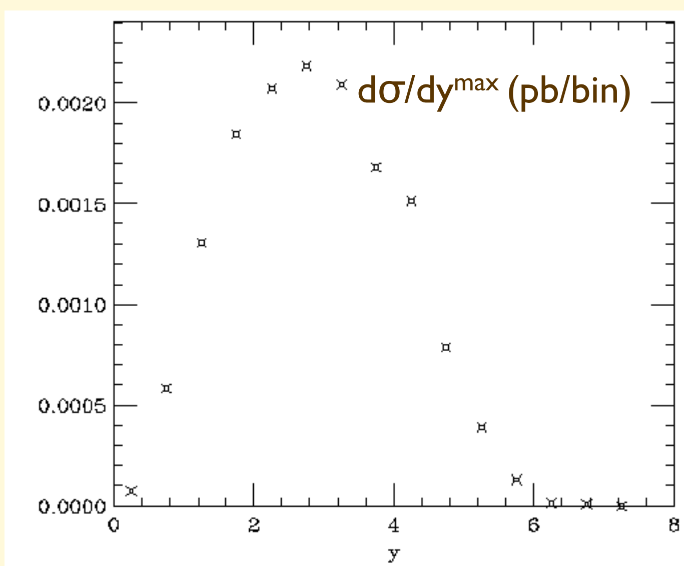




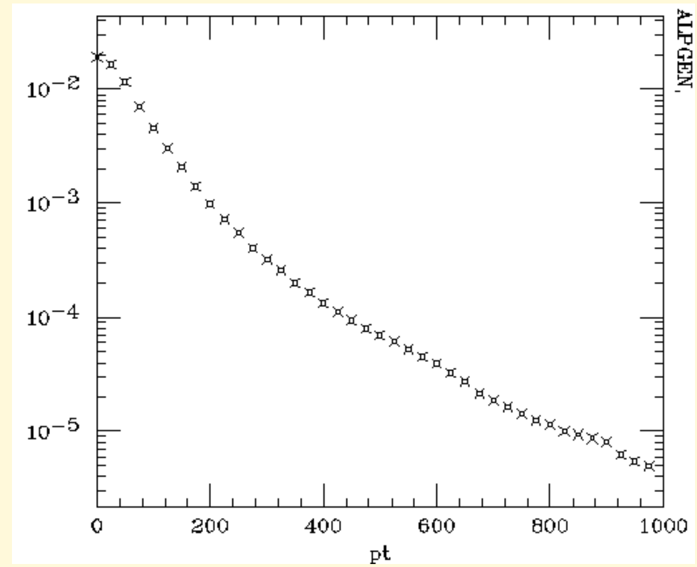
Multi-gauge boson production (no BR included)

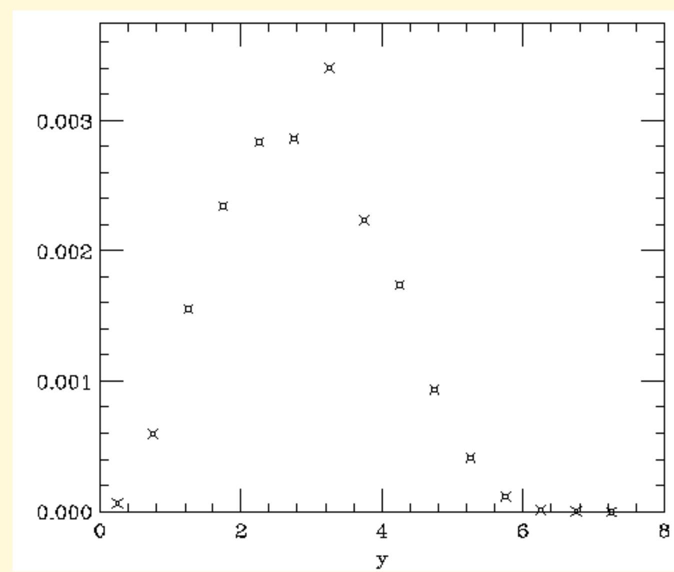
WWWW σ= 15 fb





WWWZ σ= 20 fb



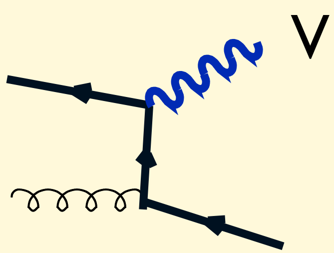


Production of gauge bosons in high-energy final states ($\sqrt{s} \gg M_V$)

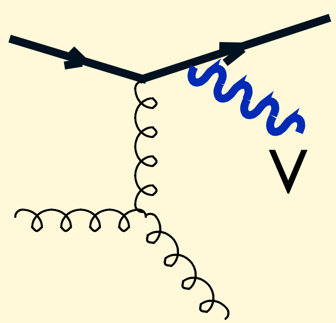
Study observables sensitive to the large-log enhancements, which may require resummation, or anyway suggest the use of a shower-like approach to V emissions:

$E_T^{(\text{leading jet})}$
M_{jj}
H_T
.....

$O(\alpha_S)$



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

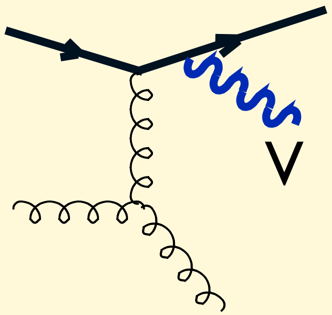


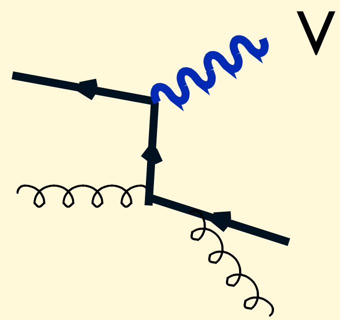
$O(\alpha_S^2)$, but enhanced by t-channel g exchange, and by $\log(p_T^{jet}/M_W)$

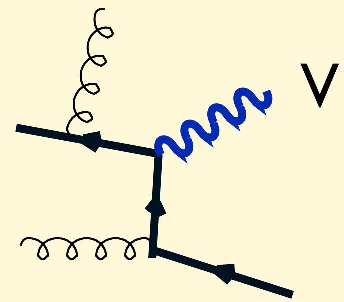
$\Rightarrow$ could be larger than $O(\alpha_S)$
$\Rightarrow$ no strong ordering between p_T^V and M_V

- Need to include $O(\alpha_S^2)$ in order to capture all sources of V production.
- This requires, in principle, the complete $O(\alpha_S^2)$ calculation, inclusive of virtual corrections to $O(\alpha_S)$.

V rate vs $E_T^{(\text{leading jet})}$







➤ divergent for p_T(quark)→0 (leading jet = gluon)
(leading jet = gluon, so this is a higher-order correction to qqbar→gV)

➤ divergent for p_T(gluon)→0
(leading jet = quark, so this is a higher-order correction to qg→qV)

⇒ needs virtual corrections.

However**, can define a final state that is finite at $O(\alpha_s^2)$, dominates the rate over $O(\alpha_s)$, and correctly probes the dynamics of V emission at high energy**

- **$N_{jet}=2$**
- **$p_T^{jet} > p_T^{min}$, with $p_T^{min} \ll \sqrt{s}$**

Must verify though that contributions $O(\text{Log}\ \sqrt{s}/p_T^{min})$ are subdominant

Define

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

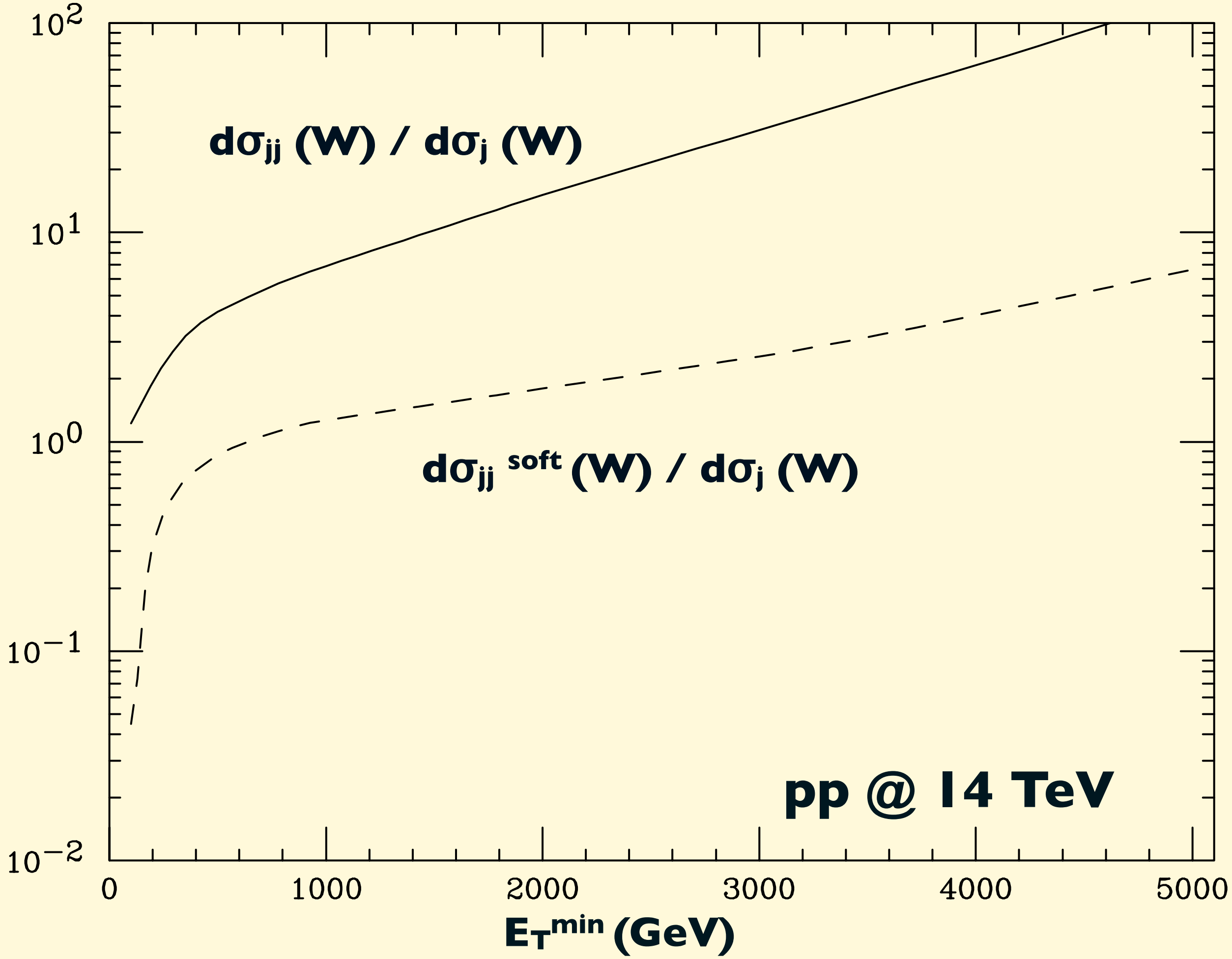
inclusive W production rate, in events with 2 jets of $E_T>30$ GeV, $|\eta|<5$, with $E_T^{(leading\ jet)} > E_T^{min}$

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

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

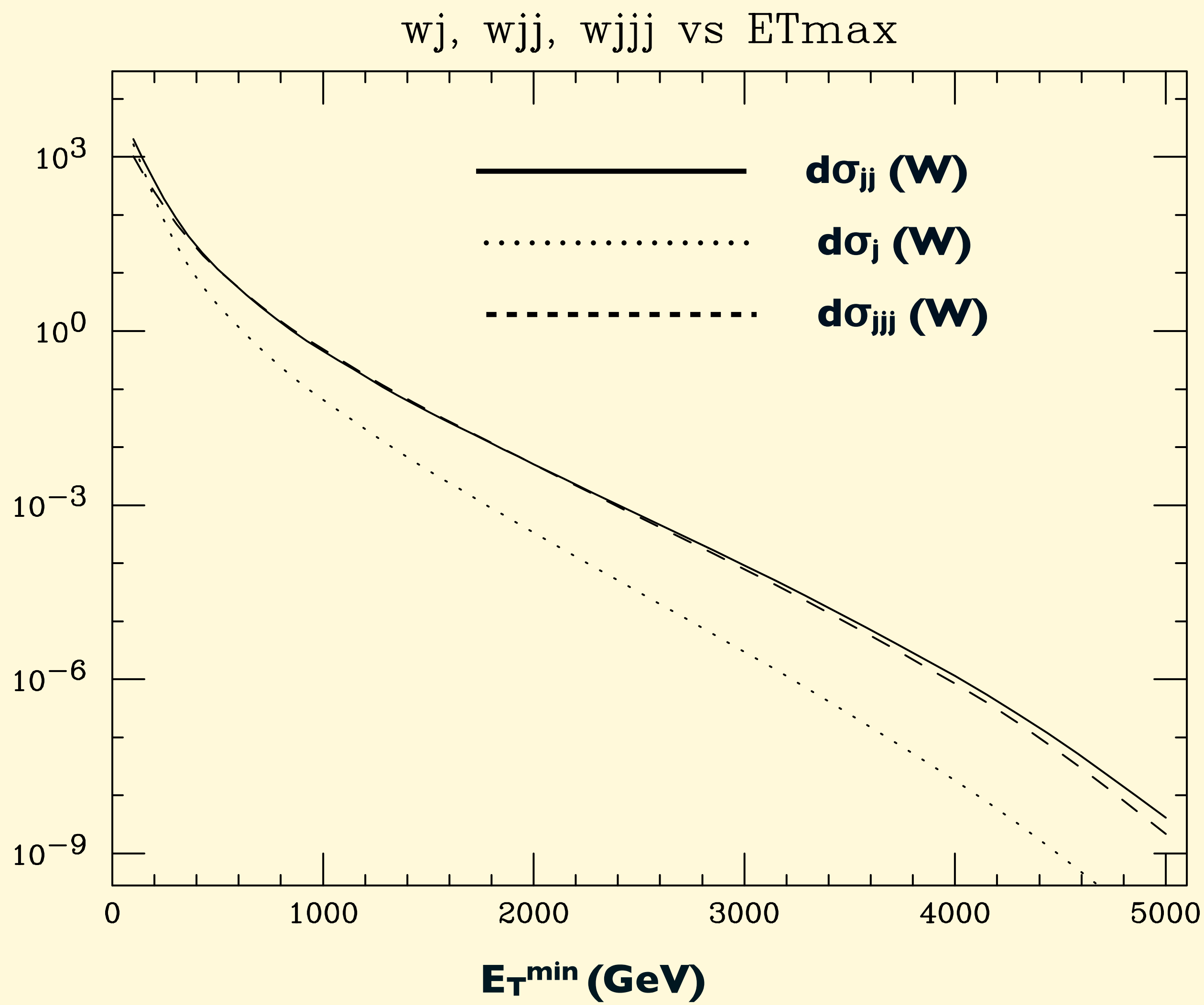
$d\sigma_j(W)$:

same, with just 1 jet



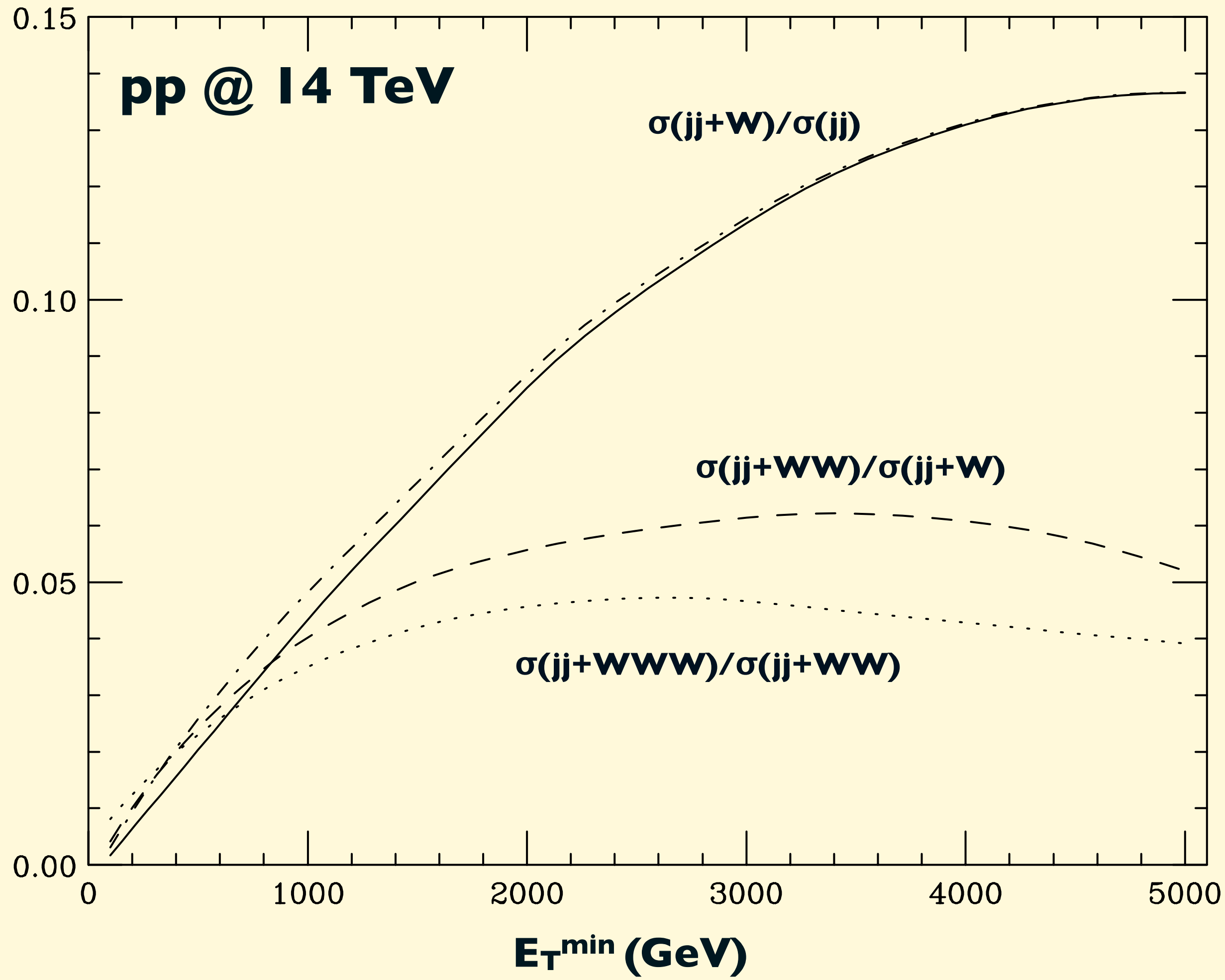
- $\sigma_j \ll \sigma_{jj}$ $\Rightarrow$ the dynamics is dominated by kinematical configurations other than W+jet

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



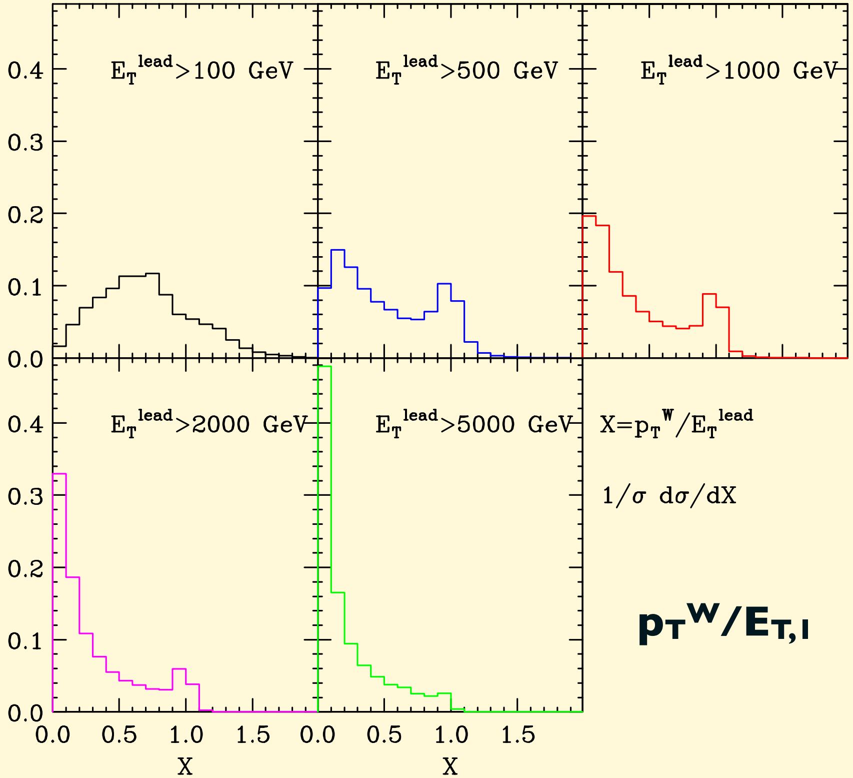
While $d\sigma_{jj} \gg d\sigma_j$, we find $d\sigma_{jjj} \lesssim d\sigma_{jj}$,
showing that no new dynamics appears when going to 3 jets.
Wjjj can be seen as a HO correction to Wjj.

Multiple W production

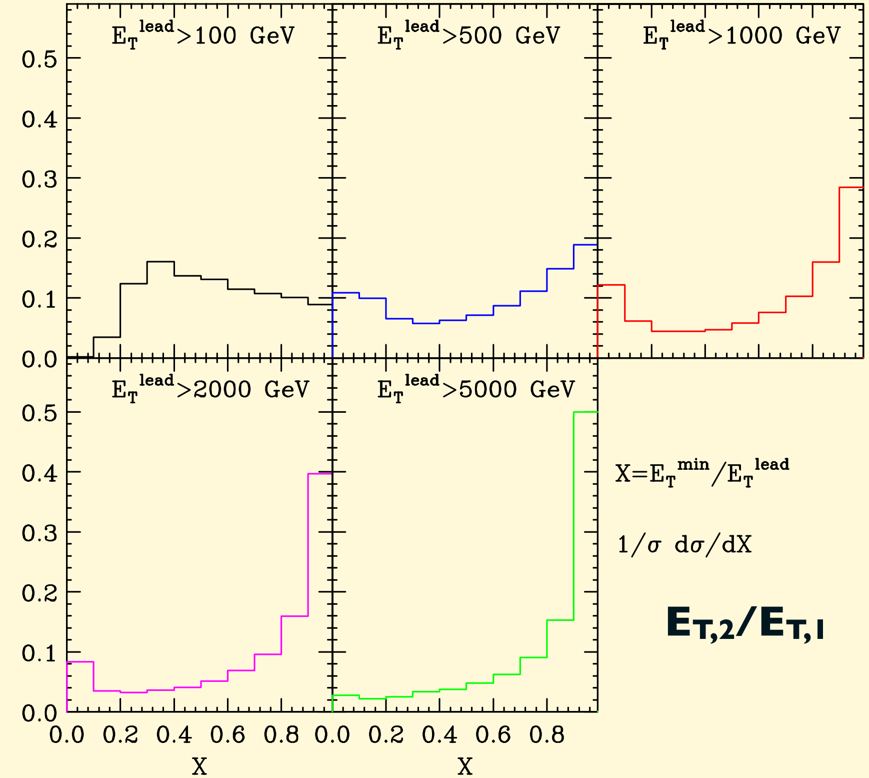


Dotdashes: σ(jj) in the denominator replaced by σ(jj, no gg→gg)

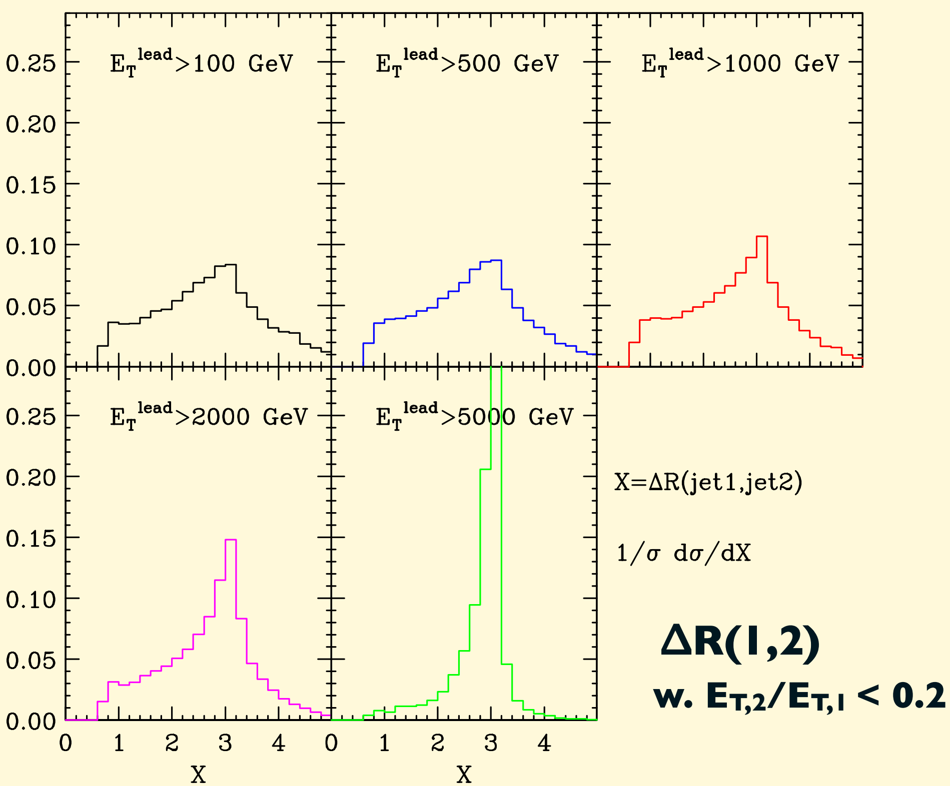
- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **Emission probabilities are however still small enough that fixed-order PT is likely the most reliable way to model rates and kinematics**
- **It would be interesting to go after these W and Zs, and verify their emission properties**



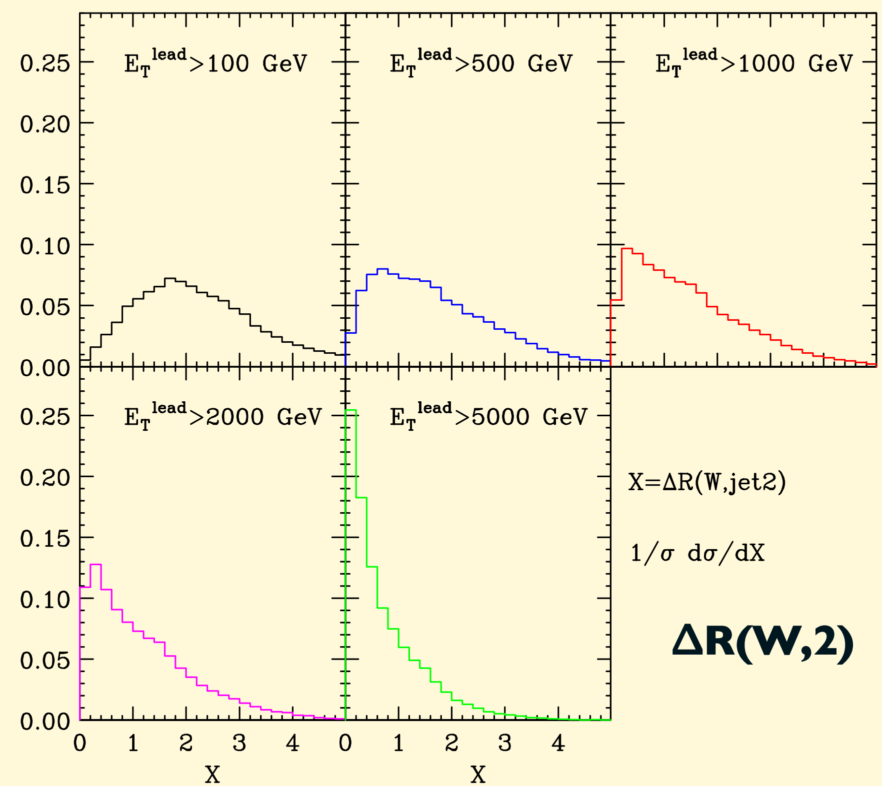
E_T^{lead}>100 GeV
E_T^{lead}>500 GeV
E_T^{lead}>1000 GeV
E_T^{lead}>2000 GeV
E_T^{lead}>5000 GeV
$X=p_T^W/E_T^{lead}$
$1/\sigma\ d\sigma/dX$
$p_T^W/E_{T,1}$
X



E_T^{lead}>100 GeV
E_T^{lead}>500 GeV
E_T^{lead}>1000 GeV
E_T^{lead}>2000 GeV
E_T^{lead}>5000 GeV
$X=E_T^{min}/E_T^{lead}$
$1/\sigma\ d\sigma/dX$
$E_{T,2}/E_{T,1}$
X

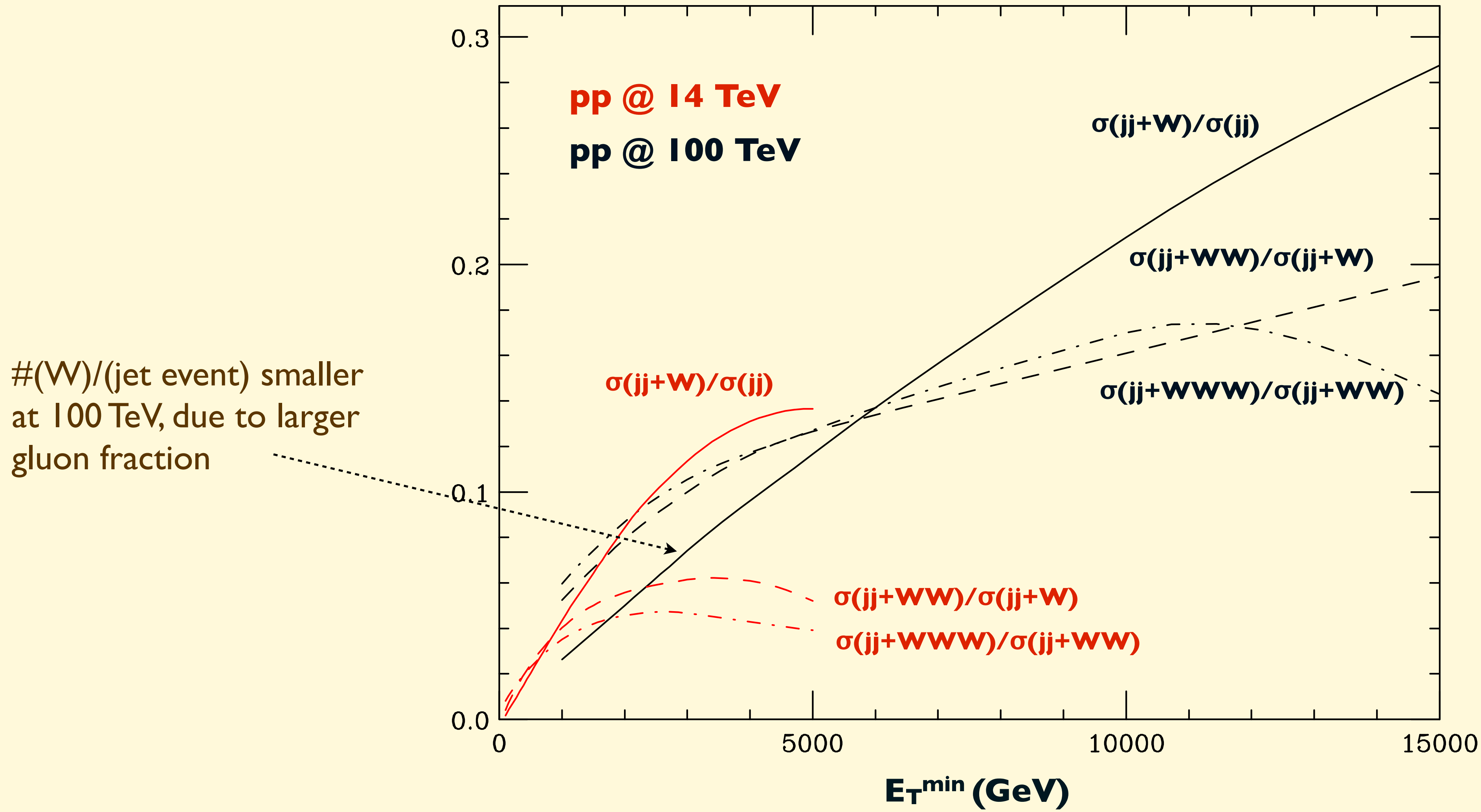


E_T^{lead}>100 GeV
E_T^{lead}>500 GeV
E_T^{lead}>1000 GeV
E_T^{lead}>2000 GeV
E_T^{lead}>5000 GeV
$X=\Delta R$(jet1,jet2)
$1/\sigma\ d\sigma/dX$
$\Delta R(1,2)$
w. $E_{T,2}/E_{T,1} < 0.2$
X



E_T^{lead}>100 GeV
E_T^{lead}>500 GeV
E_T^{lead}>1000 GeV
E_T^{lead}>2000 GeV
E_T^{lead}>5000 GeV
$X=\Delta R$(W,jet2)
$1/\sigma\ d\sigma/dX$
$\Delta R(W,2)$
X

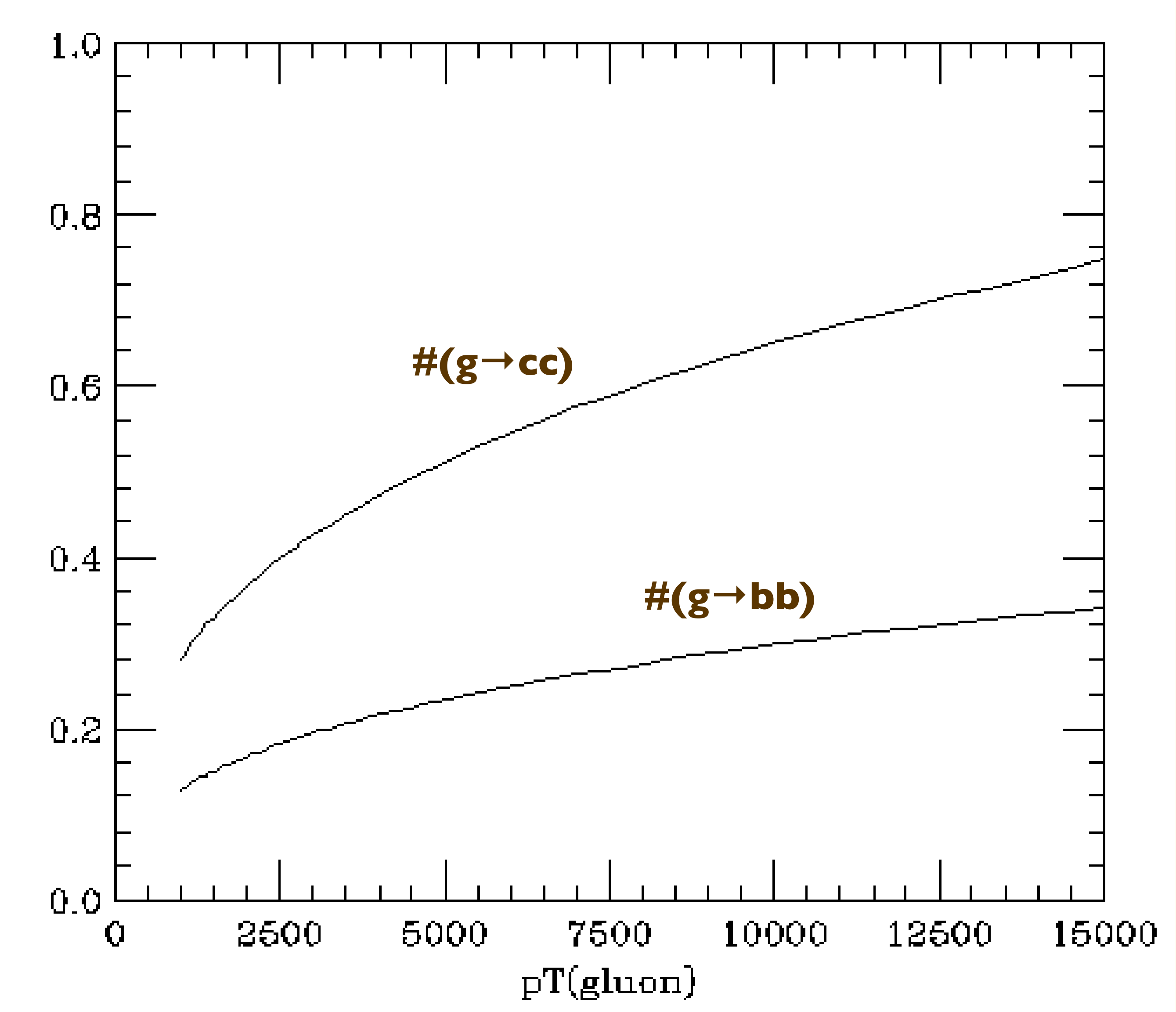
14 TeV vs 100 TeV



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 !!

High-energy WW->WW,HH scattering

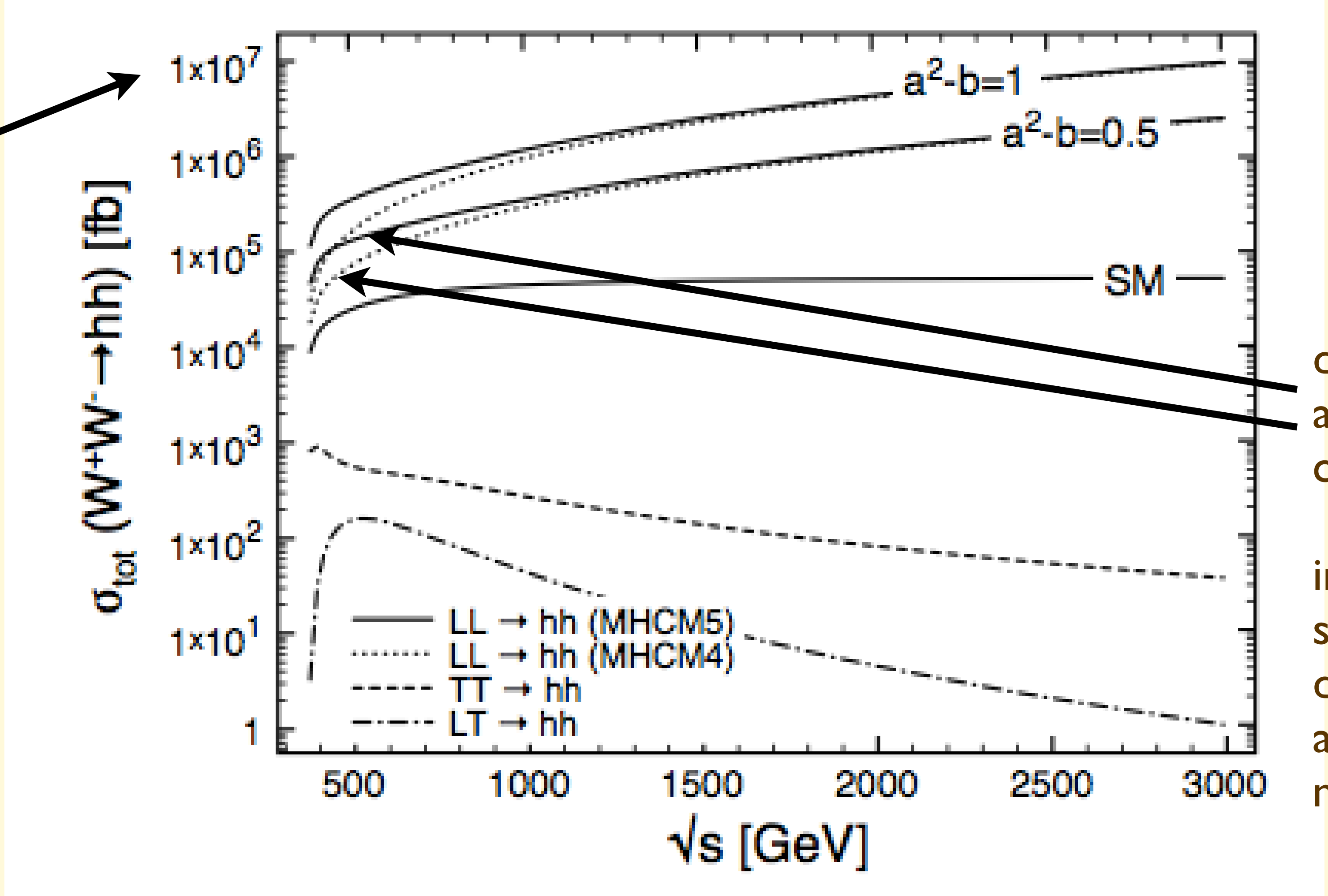
In more detail:

$$\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\Big|_{90^o} = \frac{(1-a^2)^2}{2304}\,\frac{s^2}{M_W^4} \qquad \frac{d\sigma_{LL\to hh}/dt}{d\sigma_{TT\to hh}/dt} = \frac{2s^2}{g^4v^4}\,\frac{(b-a^2)^2}{(a^4+(b-a^2)^2)}$$

Example: WW→HH

R.Contino et al, arXiv:1002.1011v2

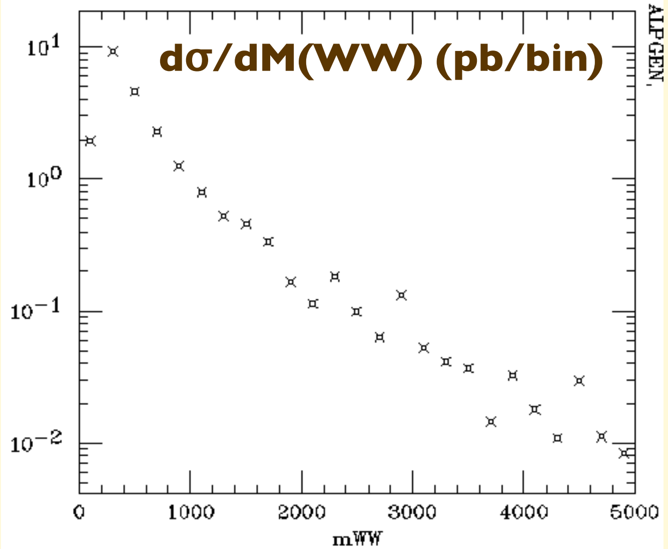
partonic cross sections

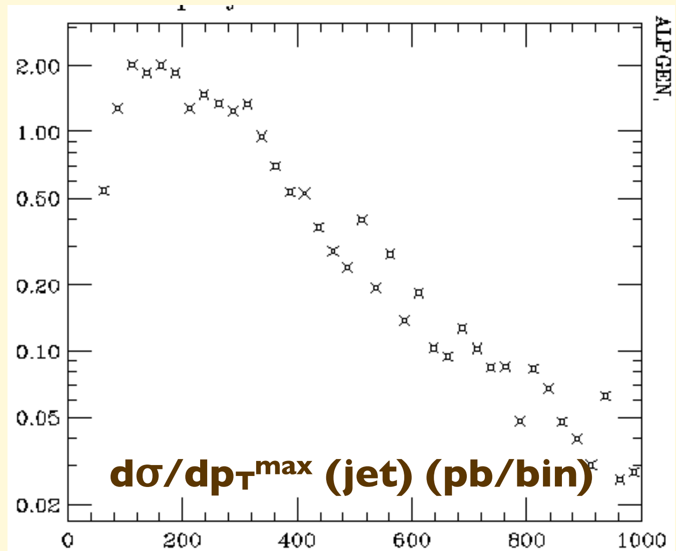


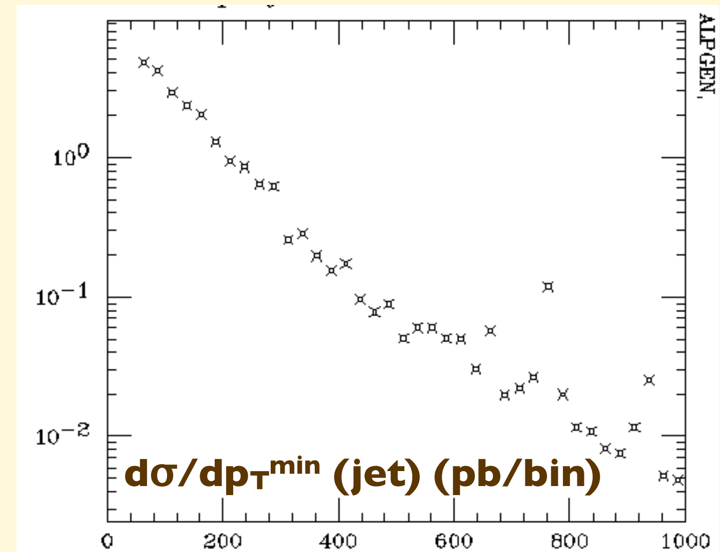
different anomalous HHH couplings:

invariant mass spectrum of HH discriminates among BSM models

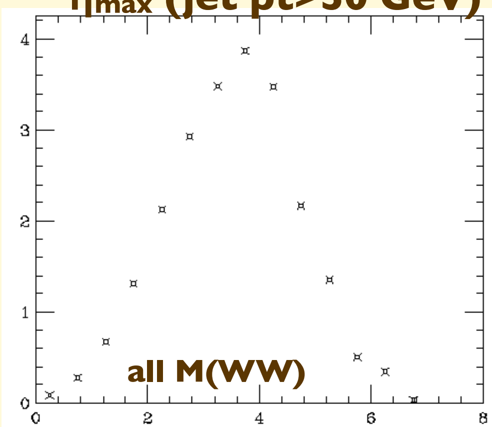
High-mass WW VBF production. p_T^{jet}> 50 GeV



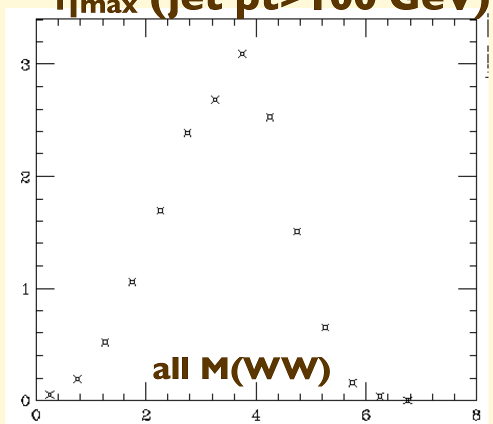




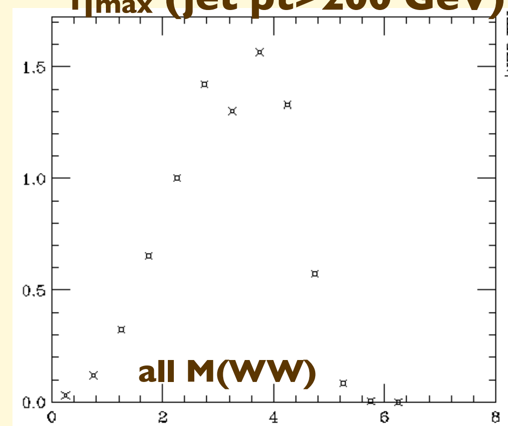
η_{max} (jet pt>50 GeV)



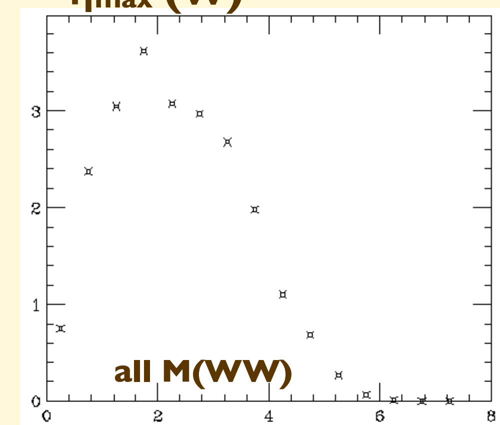
η_{max} (jet pt>100 GeV)

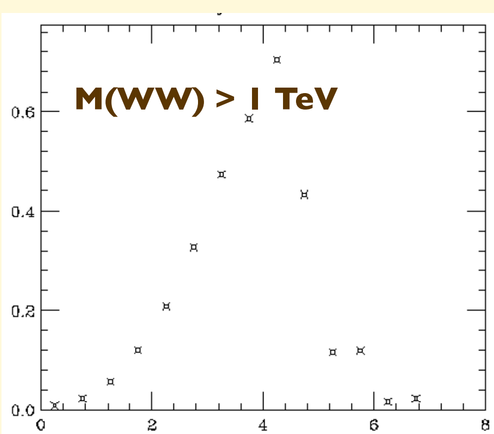


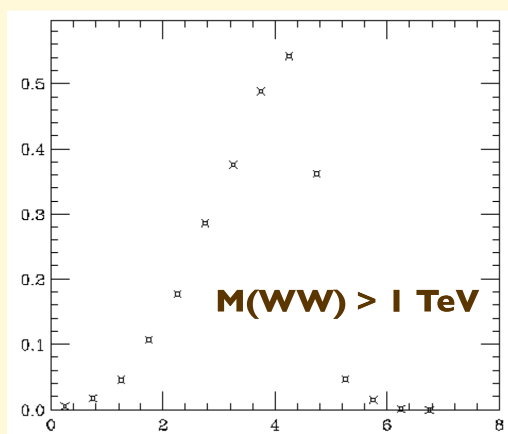
η_{max} (jet pt>200 GeV)

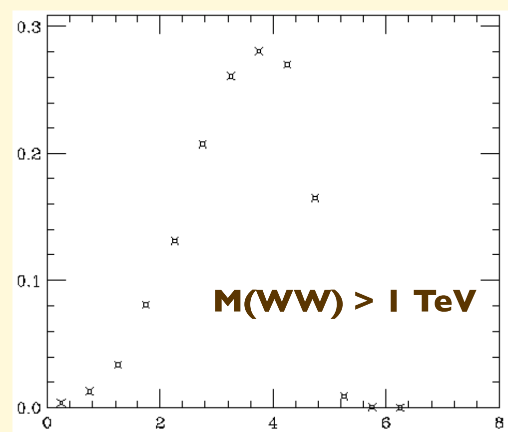


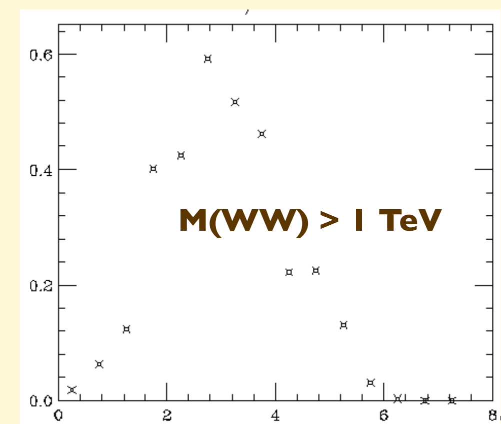
η_{max} (W)



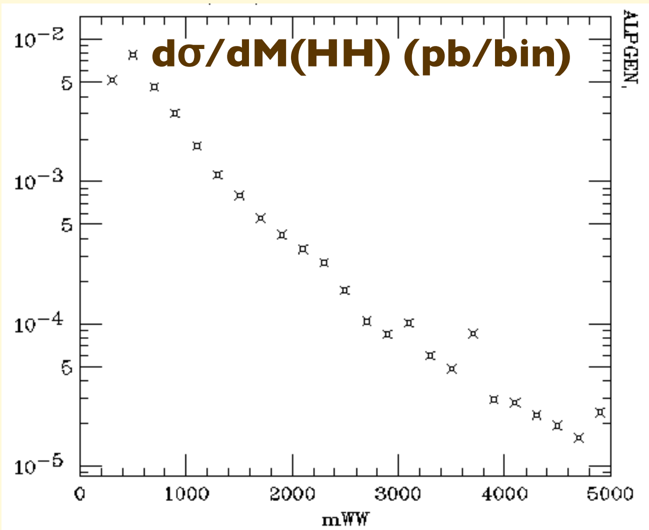


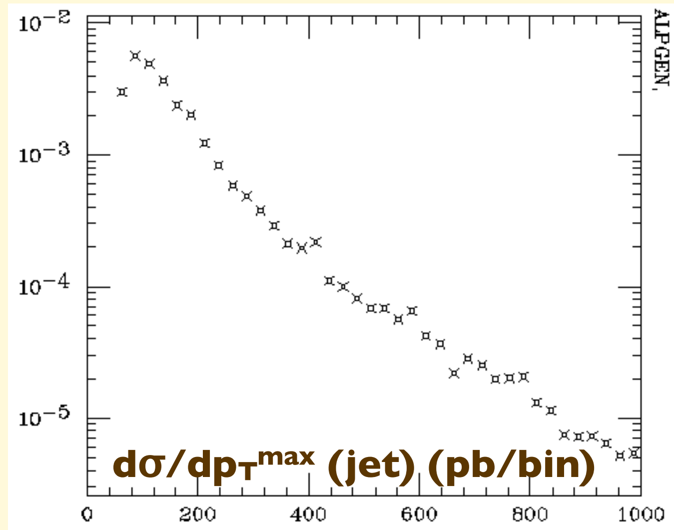


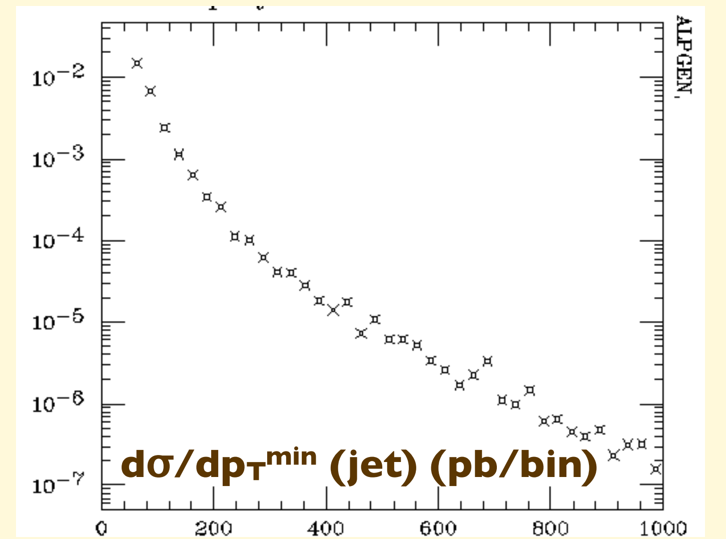




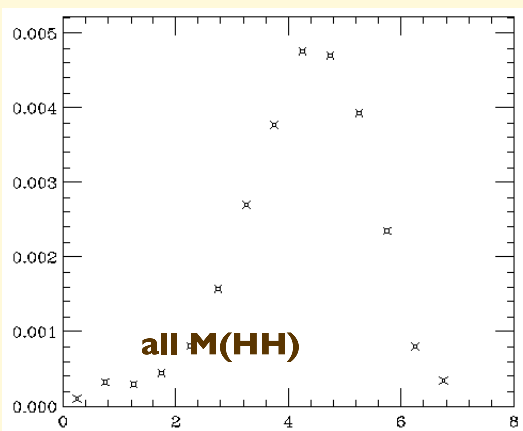
High-mass HH VBF production. p_T^{jet}> 50 GeV

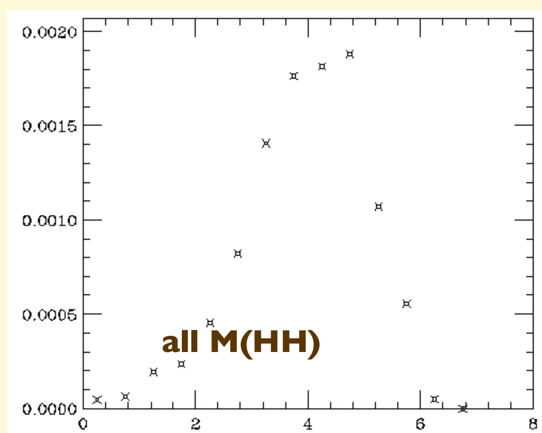


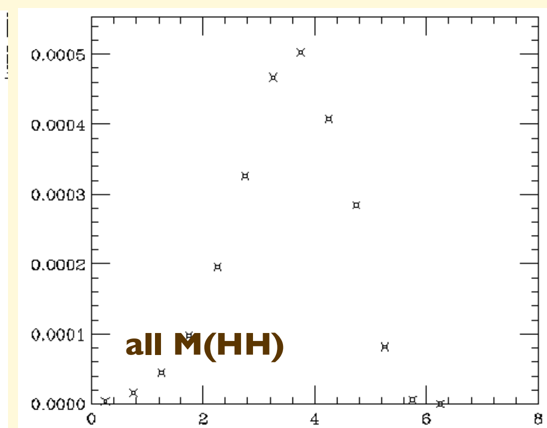


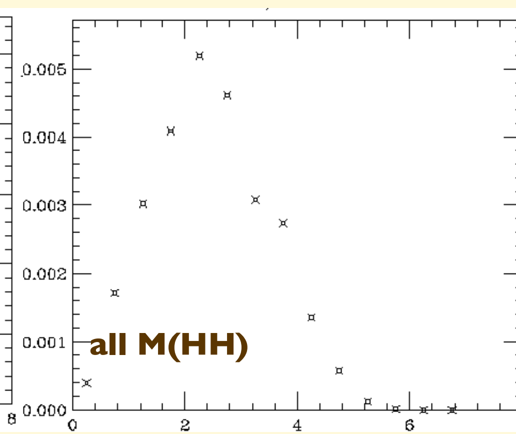


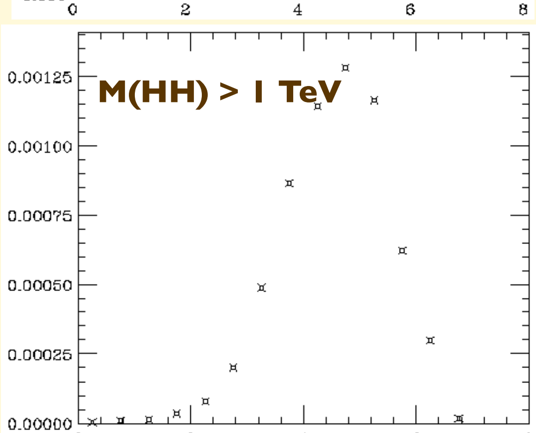
η_{max} (jet pt>50 GeV) η_{max} (jet pt>100 GeV) η_{max} (jet pt>200 GeV) η_{max} (H)

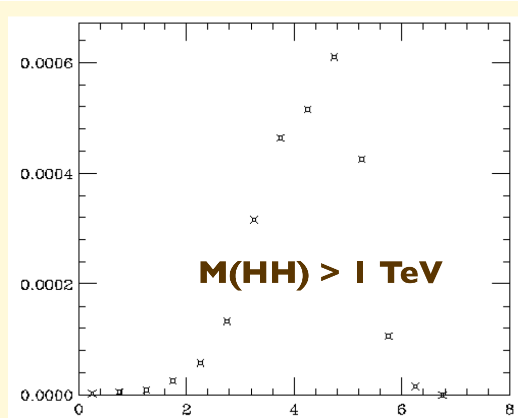


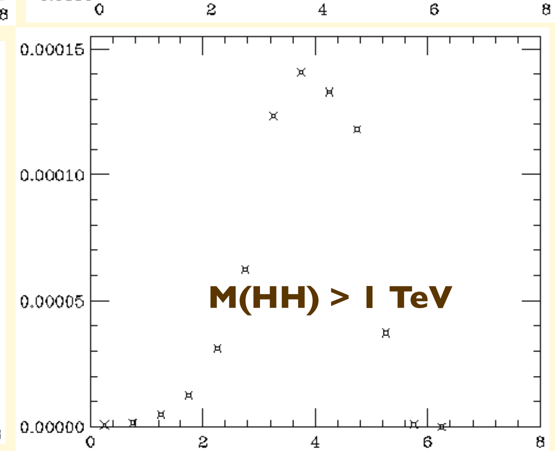


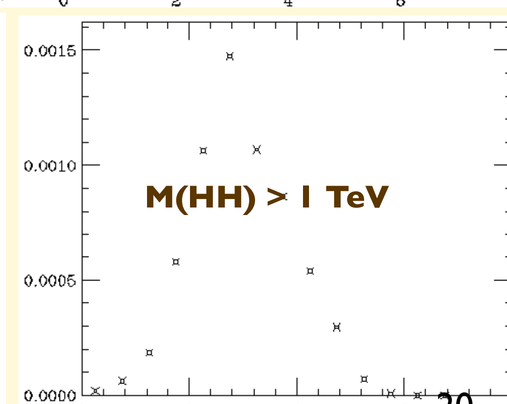












Higgs rates at high energy

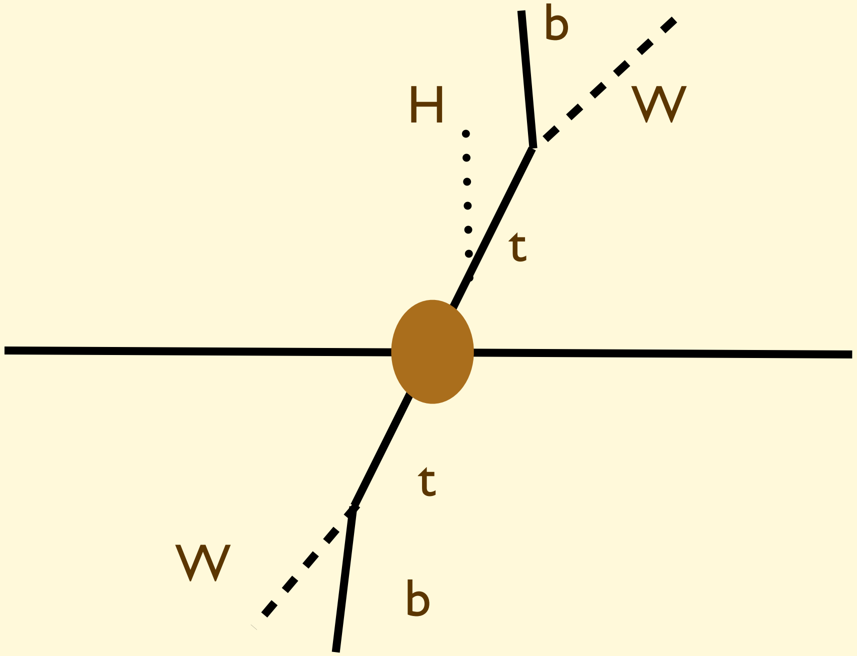
NLO rates **R(E)** = σ(E TeV)/σ(14 TeV)

	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: ttH at large pt(top)



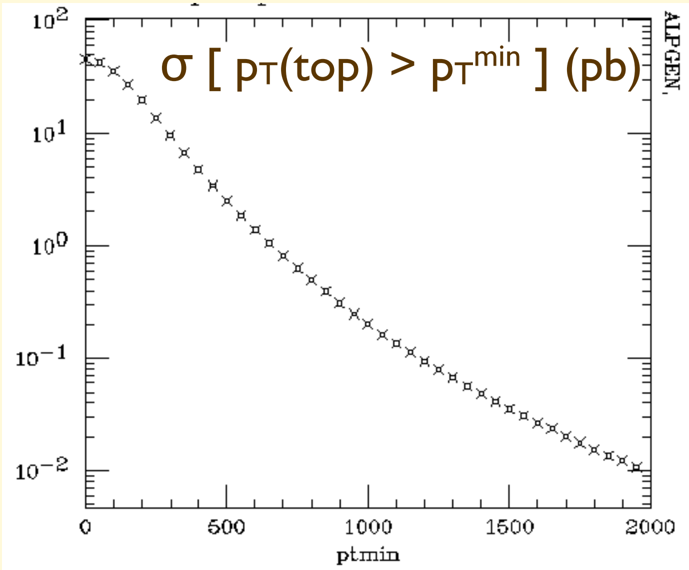
- Reduced backgrounds
- Reduced combinatorics

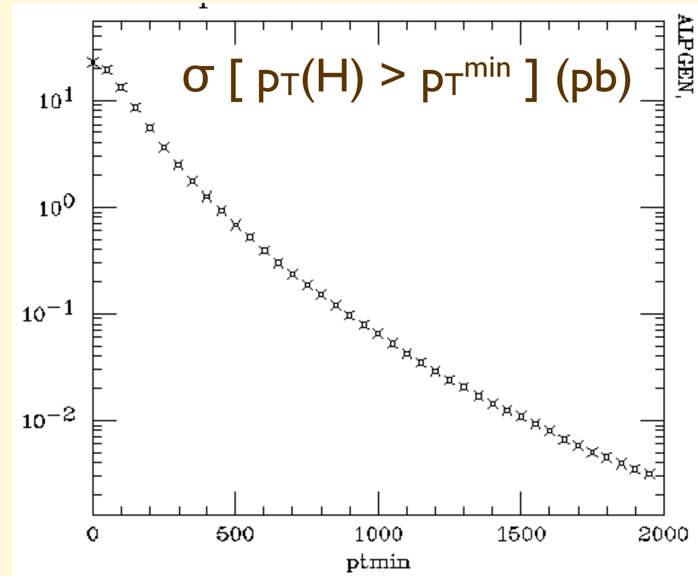
⇒ more reliable measurement of y_{top}

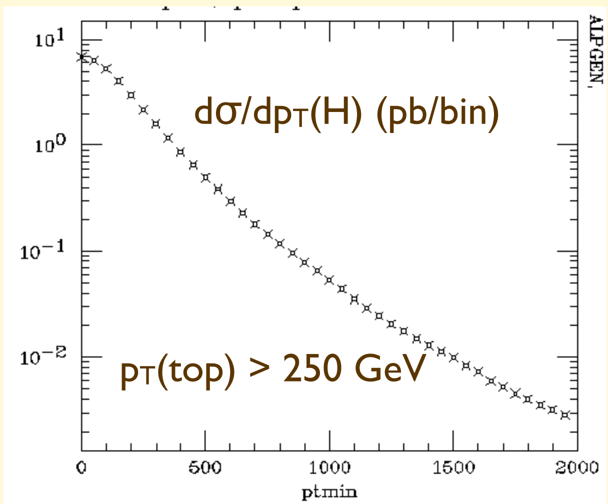
pp→ttH	**14 TeV**	**33 TeV** (33/14)	**60 TeV** (60/14)	**100 TeV** (100/14)
σ_{TOT}	0.4 pb	2.8 pb (x 7)	9.7 pb (x 24)	25 pb (x 60)
$\sigma(p_T^{top} > 0.5$ TeV$)$	1.6 fb	26 fb (x 16)	120 fb (x 75)	400 fb (x 250)

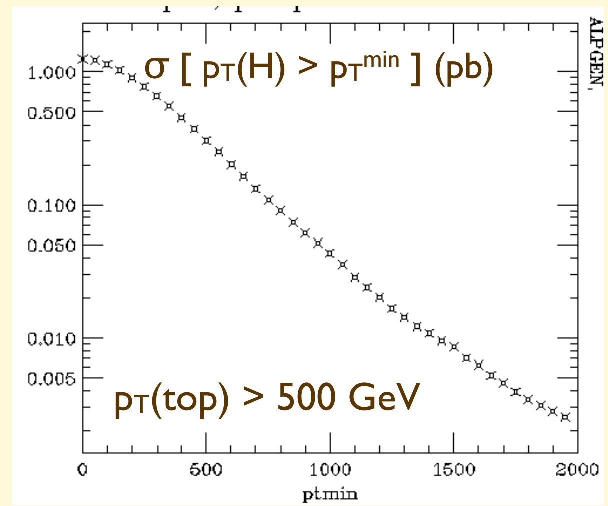
(LO rates)

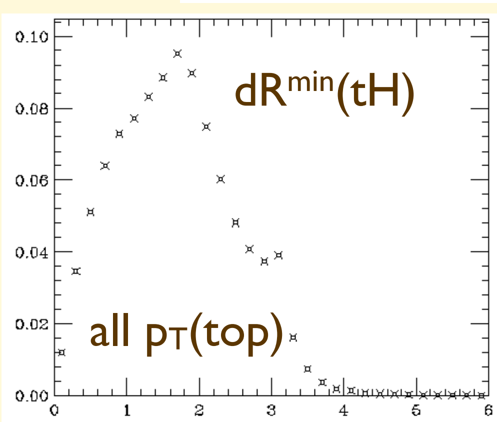
ttH production

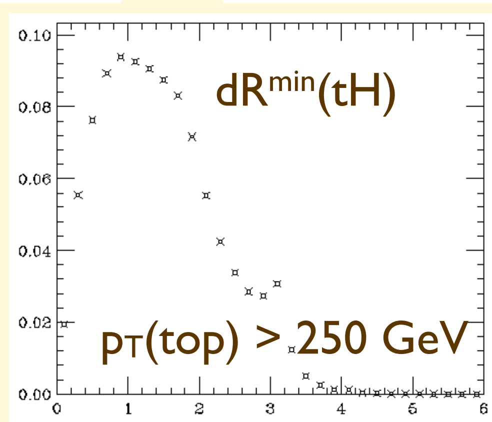


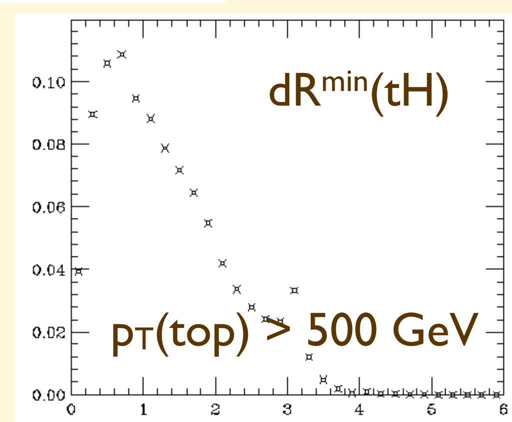




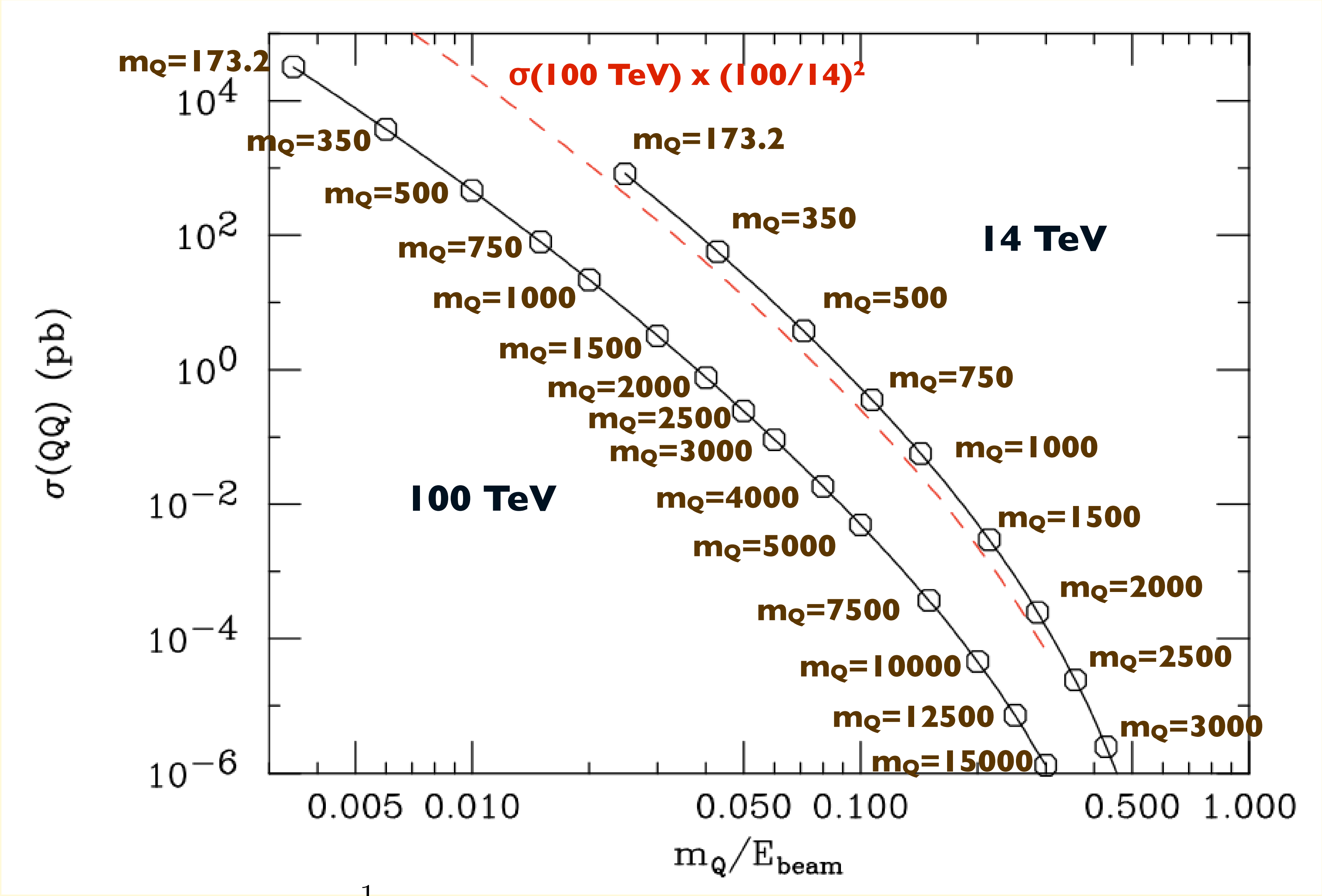








Energy vs luminosity. Ex: production of new heavy quark pairs



$$\sigma(m_Q) \sim \hat{\sigma}(m_Q) \otimes L(m_Q/E_{beam}) \sim \frac{1}{S}\,\hat{\sigma}(m_Q/E_{beam}) \otimes L(m_Q/E_{beam})$$

1 event/ab^{-1} ⇒ m_Q = 3.2 TeV → 15 TeV for E_{beam} = 7 TeV → 50 TeV

⇒ at fixed integrated luminosity the discovery reach $\mathbf{m_Q \propto 2/3\ E_{beam}}$

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  - role of dedicated, "low-pt" detectors, with high efficiency for W/Z, top and H physics (equivalent of LHCb for the LHC ....) ?
- What is the potential to push precision measurements (m_W, m_{top}, top and Higgs properties, rare decays, etc), possibly in dedicated detectors ?