Higgs Chapter of the report on Physics at 100 TeV: the "SM Higgs" section

Editors: M.L. Mangano, G.Zanderighi, H.Gray + several subsection editors and contributors

- Document rates and distributions for a broad range of Higgs production channels, at 100 TeV
  - Show results in terms of acceptances (e.g. w.r.t. p_T, η), to be used as reference for detector design
  - Consider rare production modes like multi-H production and associated production with multiple SM objects (VVH, etc)
- Study both inclusive production, and production in kinematical configurations at large Q^2, up to where rates reach the O(1 event/ab^{-1})
- Discuss reliability of current theoretical modeling (e.g. $m_{top}=\infty$ approximation of ggH channels vs exact results with finite m_{top})
- "Phenomenology":
  - Discuss opportunities for precision measurements in the % range, and provide benchmarks for the performance of FCC-hh detectors
  - Discuss opportunities for measurements of rare decay modes
- Phenomenology studies driven **so far** mostly by considerations of statistics, SM physics bgs, basic detector properties such as p_T, η acceptance, mass resolution, ... Typically at parton level. Main goal is to ***quickly*** identify interesting channels/ observables, where more detailed detector/DELPHES-level studies can be done.

Draft outline (each topic below is a "guaranteed deliverable": some material is already available, and contributors/sub-editors exist for the various topics)

- **ggH**
  - inclusive, p_T spectrum at small p_T and at very large p_T, far off-shell production
  - H+multijets
  - phenomenology (e.g. BR ratios at %-level, width determination from far off-shell production, etc)
- **V+H**
  - inclusive rates, spectra vs p_T and m(VH)
  - phenomenology (e.g. $B(H\to bb)/B(H\to\gamma\gamma)$, reach at very large m(VH), ...)
- **VBF**
  - inclusive production, VBF plus jets
  - jet eta spectra, jet pt spectra at large eta, detector design implications, review issue of what's the best VBF selection criterion: select leading pt jets, or most fwd jets? shower effects and systematics
- **ttH**
  - rates, pt spectra, prospects for determination of SM ttH coupling (from arXiv:1507.08169)
- **HH** (here pheno will go in the Section edited by G.Panico)
  - gg channel: total XS, m(HH) spectra. Study mtop=infty vs mtop=173, at LO and approx-NLO at large mHH
  - VBF channel: total XS, jet spectra (eta_max, pt of most fwd jet, …), rates at large m(HH)
  - other channels (eg ttHH, VHH, …): document rates, discuss why should they be interesting
- **Other rare production modes** (here pheno could go in the Section edited by G.Panico)
  - "multiple heavy objects" (e.g. prod with multiple gauge bosons)
  - production of more than 2 Higgs bosons:
  - rates, and document existing studies of detectability at 100 tev
- **Rare Higgs decays** (1st generation, exclusive decays)

Additional relevant material will appear also in the “SM at 100 TeV” Chapter

- **Inclusive diboson production**
  - VV and V gamma production
  - diboson+jets
  - Anomalous couplings
  - gamma gamma production
    - high mass
    - **m(gamma gamma) ~ mH**, at various pt ranges (inclusive, large pt)
  - EW corrections

- **VBF production of gauge bosons and VB scattering**
  - W/Z production
  - pairs (OS, SS): inclusive production, high mVV production
  - Define VBF cuts, characterize in terms of fwd jet spectra (eta, pt)
    - these may differ for single and double VB production
    - acceptance vs leptonic decay products (etamax, ptmin)
  - EW corrections

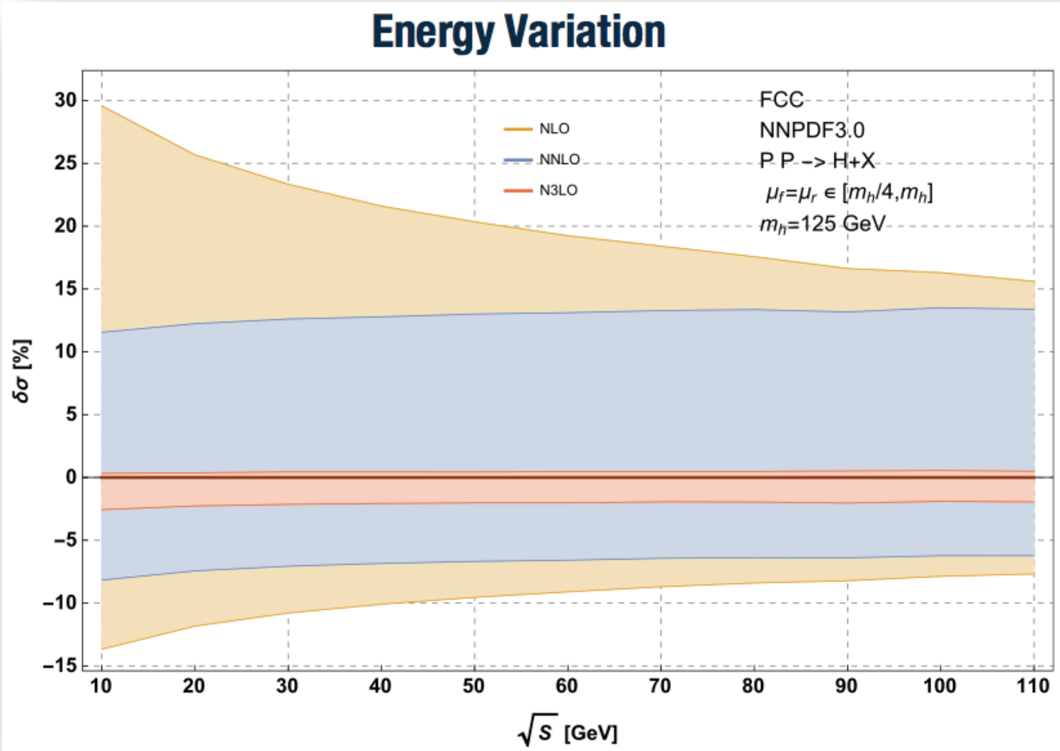
Overview of candidate material

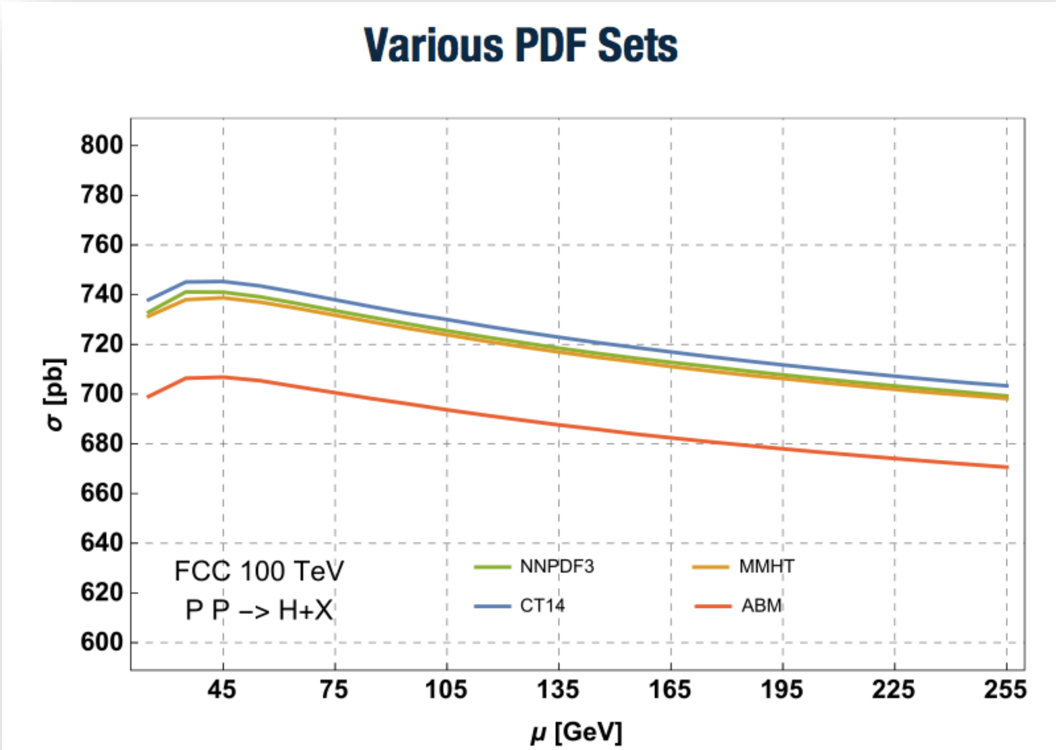
(more is available, this is just a partial sample)

(where indicated, material was shown at the “SM@100 TeV” Workshop, Oct 7-9, more details to be found there: http://indico.cern.ch/event/437912/other-view?view=standard)

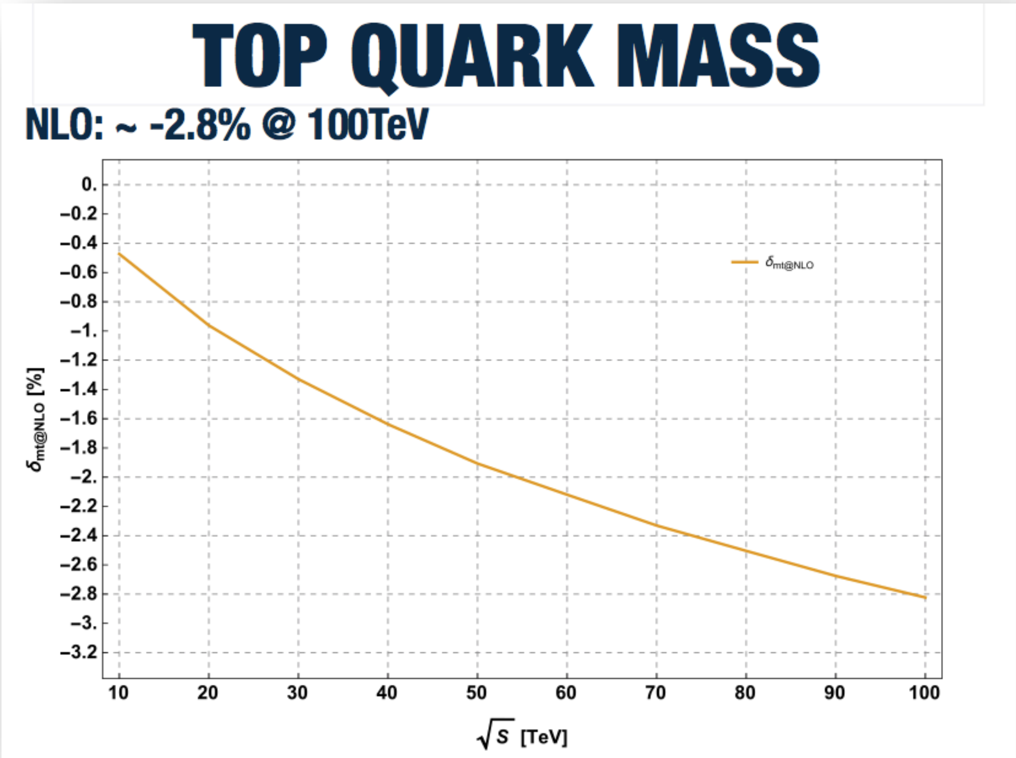
gg→H inclusive

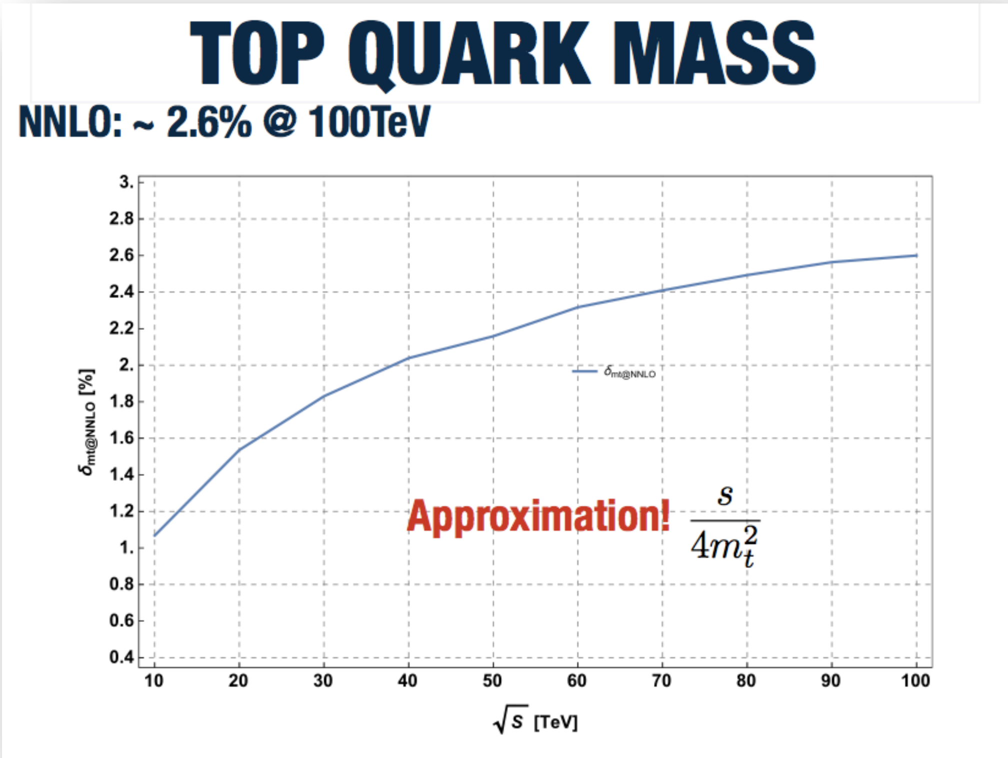
Mistlberger SM@100 TeV





⇒ Scale and PDF systematics stable over range 14 - 100 TeV





⇒ Finite mass effect grow with E, but strong cancellation in NLO+aNNLO persists

gg→H inclusive

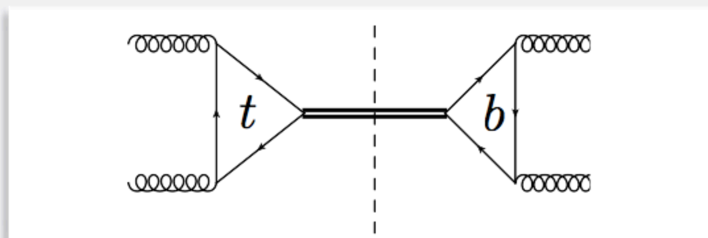
Mistlberger SM@100 TeV

MASS EFFECTS

Bottom/Charm Quarks: Large negative effect at LO

Included up to full NLO: ~-6%

Also benefit from full NNLO!



Uncertainty: ~1.5 %

ELECTRO-WEAK

Energy independent EWK corrections

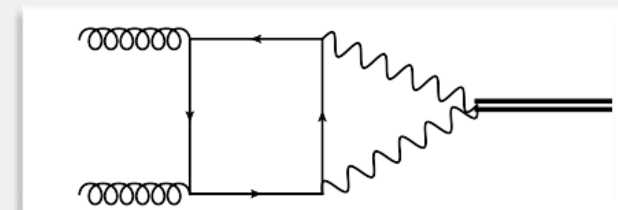
$$\sigma = \sigma_{QCD} \times (1 + \delta_{EWK})$$ + ~5 %

$\mathcal{O}(\alpha\alpha_S)$ Approximation

[Actis,Passarino,Sturm,Uccirati;Degrassi,Maltoni; Anastasiou,Boughezal,Petriello,….]

Residual Error Large!

$<\sim 5\%$



Corrections to H+J (Energy dependent) [Keung,Petriello]

CONCLUSIONS

QCD Effective: N3LO

QCD Full: NLO+

EWK: $\mathcal{O}(\alpha)$ +

We know a lot

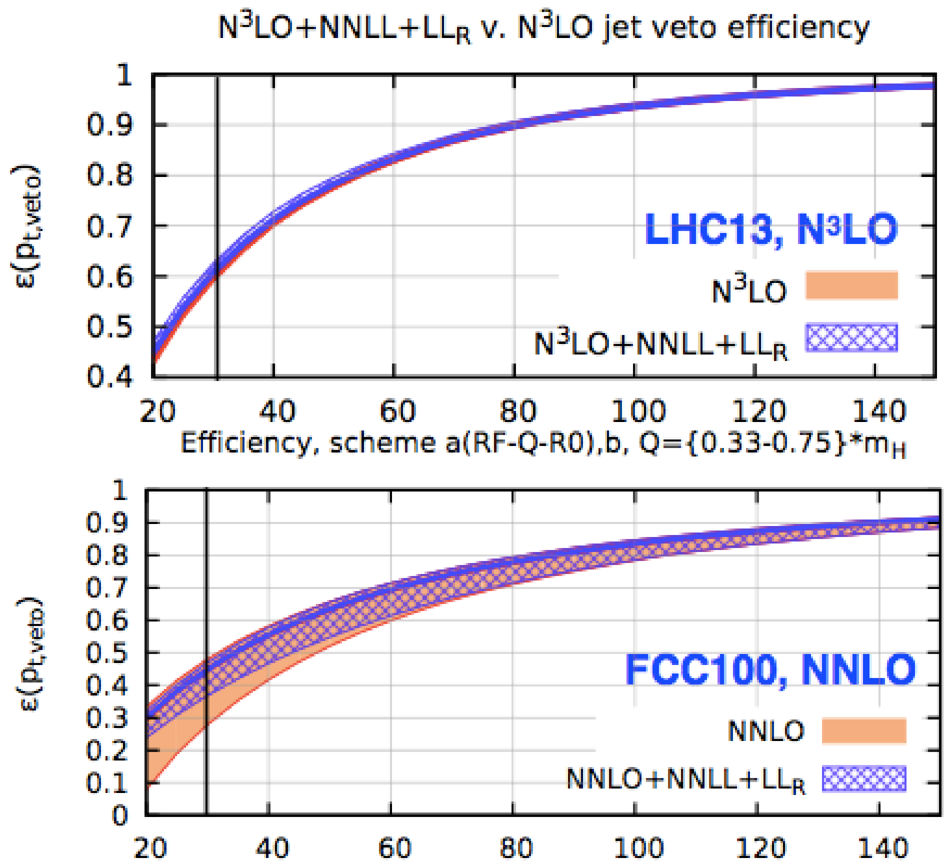
XS increase by ~1600%

$$\sigma_{gg\to H+X} = 792.5pb \pm 2\%\, QCD \pm 3\%\, EWK \pm 2\%\, t \pm 1\%\, b$$

gg→H + jet

Caola SM@100 TeV

Small p_T, jet-veto issues



$$\epsilon(p_{t,\mathrm{veto}}) = \sigma_{0-\mathrm{jet\ exc.}}/\sigma_{\mathrm{tot}}$$

LHC13: ~40% of Higgs events have at least one 30 GeV jet

FCC100: ~55% of Higgs events have at least one 30 GeV jet

→ TH jet-veto systematics will be reduced with higher-order calculations, but mostly with direct measurement (e.g. H→ZZ*)

NB jet-vetoed rates grow less than σ_H^{tot} when 14→100 TeV !!

For a 30 GeV jet

$$\sigma^{\mathrm{NN}}_{0-j}(100\ \mathrm{TeV}) = 335^{+40}_{-70}\ [\mathrm{pb}]$$

$$\sigma^{\mathrm{N^3LO}}_{0-j,\mathrm{f.o.}}(100\ \mathrm{TeV}) = 330\ [\mathrm{pb}]$$

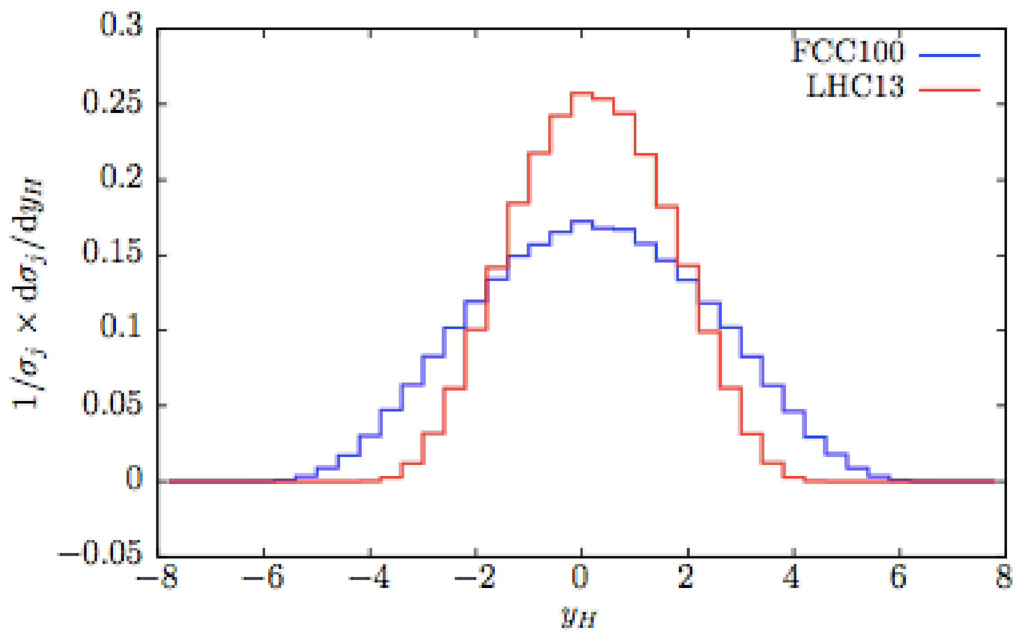
$$\sigma^{\mathrm{N^3}}_{0-j}(13\ \mathrm{TeV}) = 28^{+0.8}_{-1.1}\ [\mathrm{pb}]$$

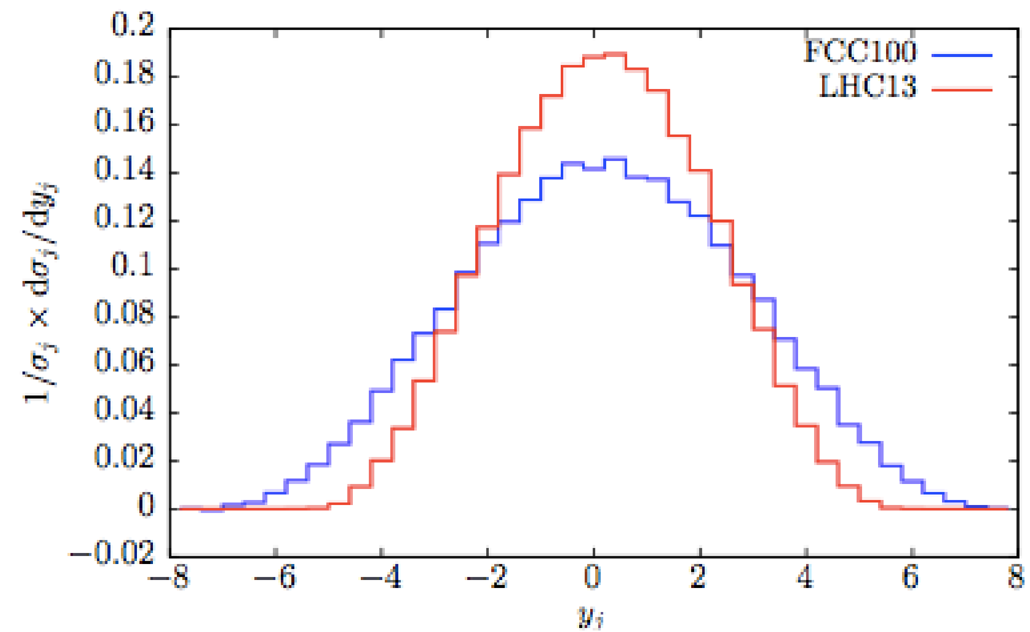
x10 enhancement

gg→H + jet

Caola SM@100 TeV

Inclusive acceptance aspects





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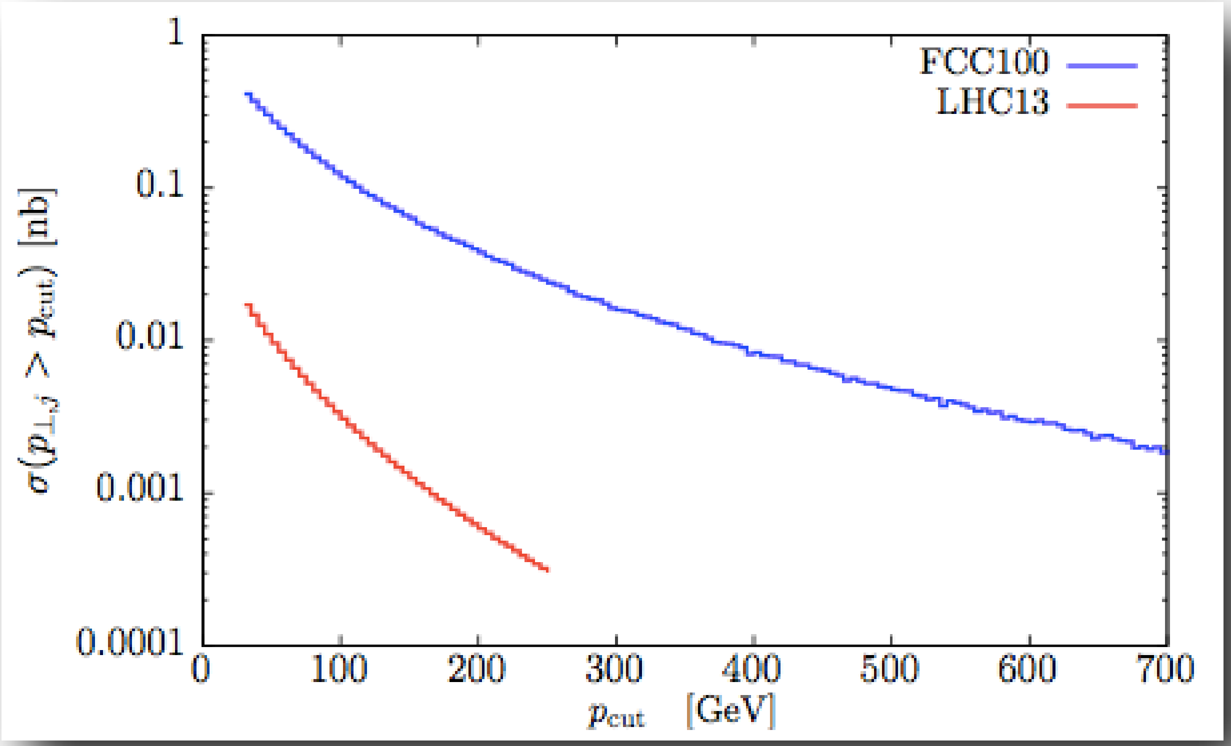
x10 enhancement

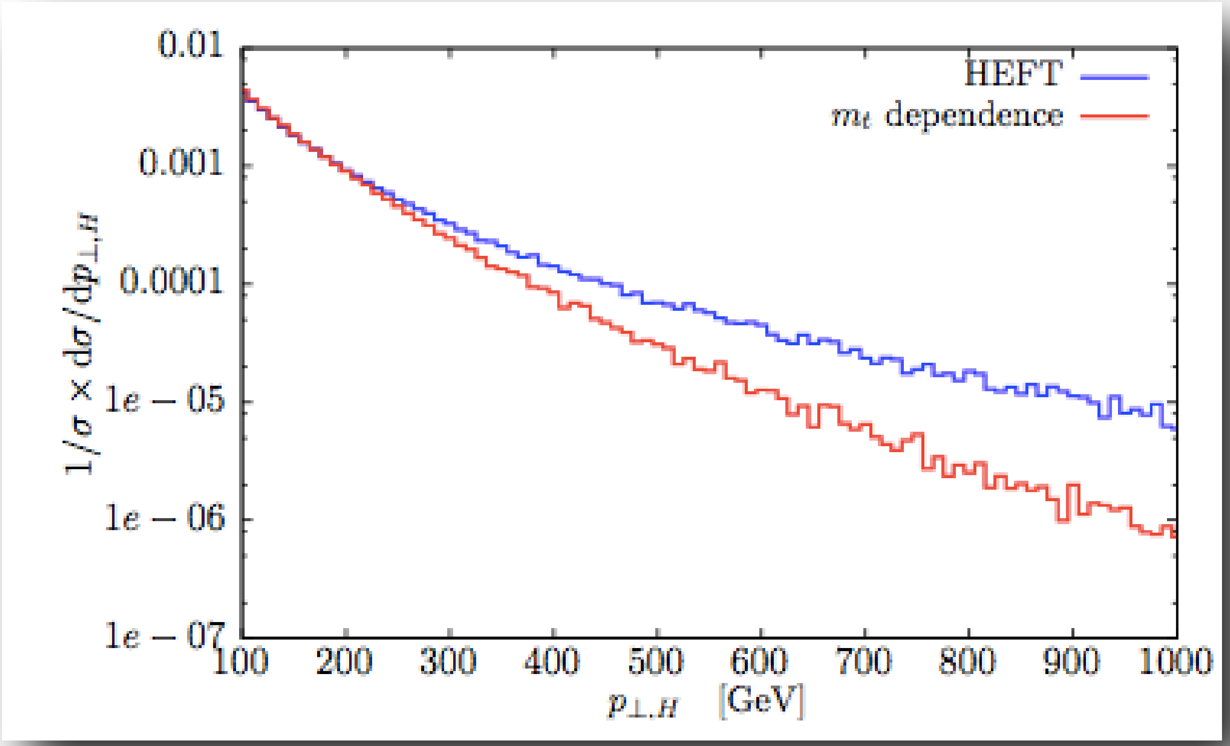
gg→H + jet

Caola SM@100 TeV

Production at high p_T



Relevance of exact m_{top} effects



High-pt H for BR ratios measurements

1 pb rate (i.e. 10^7 events) with $p_T(H) > 1$ TeV

MLM, Goertz

Exploit:
- Improved S/B for many final states at large p_T
- Reduced TH and exp systematics?
- More robust measurement/modeling of BR ratios between different channels, eg:
  + $B(H\to\mu\mu)/B(H\to\gamma\gamma)$, $B(H\to\tau\tau)/B(H\to\gamma\gamma)$, $B(H\to WW)/B(H\to\gamma\gamma)$, $B(H\to Z\gamma)/B(H\to\gamma\gamma)$

Example: $H\to\mu\mu$ statistical precision vs $p_T^{min}(\mu)$ vs $\Delta m_{\mu\mu}$ resolution (Bkg=off-shell DY)

LO only, no K factors

$\sqrt{B}/S$ for $10ab^{-1}$, $\Delta m_{\mu\mu} = \pm$ 2.5 GeV

pt mu min	*pt H min* 30	50	100	150	200
20.00	0.141E-01	0.160E-01	0.185E-01	0.197E-01	0.206E-01
30.00	0.149E-01	0.170E-01	0.193E-01	0.201E-01	0.209E-01
40.00	0.165E-01	0.185E-01	0.201E-01	0.206E-01	0.212E-01
50.00	0.194E-01	0.204E-01	0.209E-01	0.213E-01	0.218E-01
75.00	0.235E-01	0.235E-01	0.234E-01	0.232E-01	0.233E-01
100.00	0.254E-01	0.254E-01	0.254E-01	0.254E-01	0.252E-01

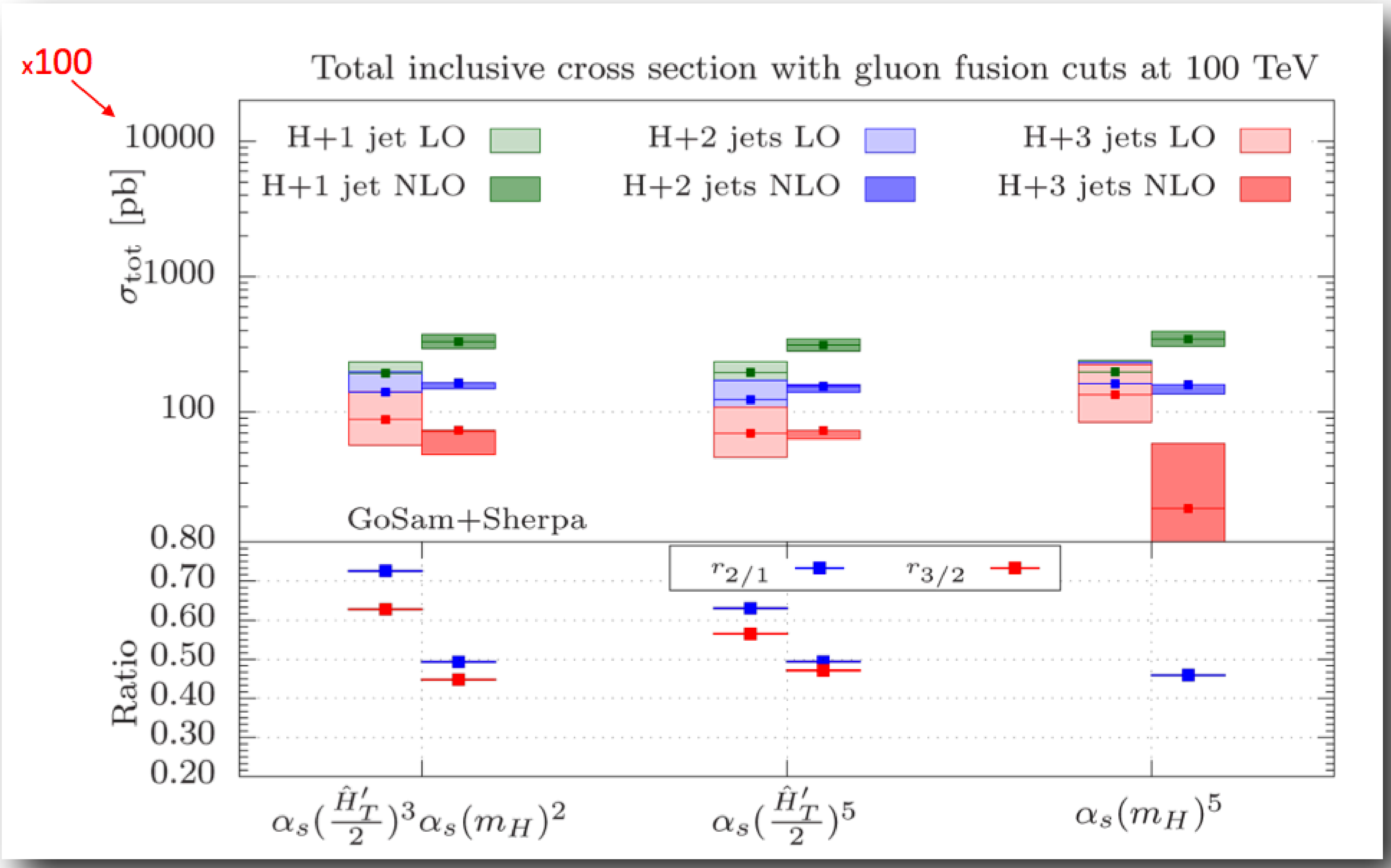
$\sqrt{B}/S$ for $10ab^{-1}$, $\Delta m_{\mu\mu} = \pm$ 1 GeV

pt mu min	*pt H min*				
20.00	0.902E-02	0.102E-01	0.119E-01	0.128E-01	0.135E-01
30.00	0.953E-02	0.109E-01	0.124E-01	0.130E-01	0.137E-01
40.00	0.105E-01	0.119E-01	0.129E-01	0.134E-01	0.139E-01
50.00	0.124E-01	0.131E-01	0.135E-01	0.139E-01	0.143E-01
75.00	0.153E-01	0.153E-01	0.153E-01	0.152E-01	0.153E-01
100.00	0.168E-01	0.168E-01	0.168E-01	0.168E-01	0.167E-01

gg→H + jets

Luisoni SM@100 TeV

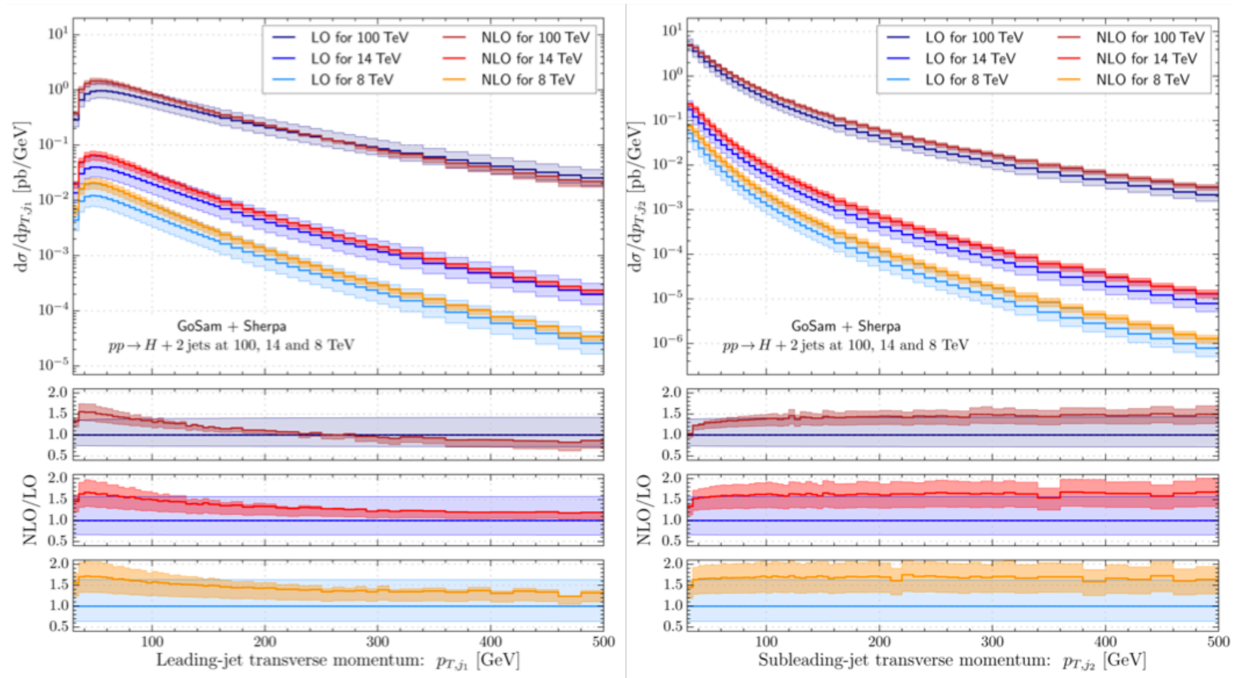
NB: NLO H+2,3 jets with $m_{top}=\infty$



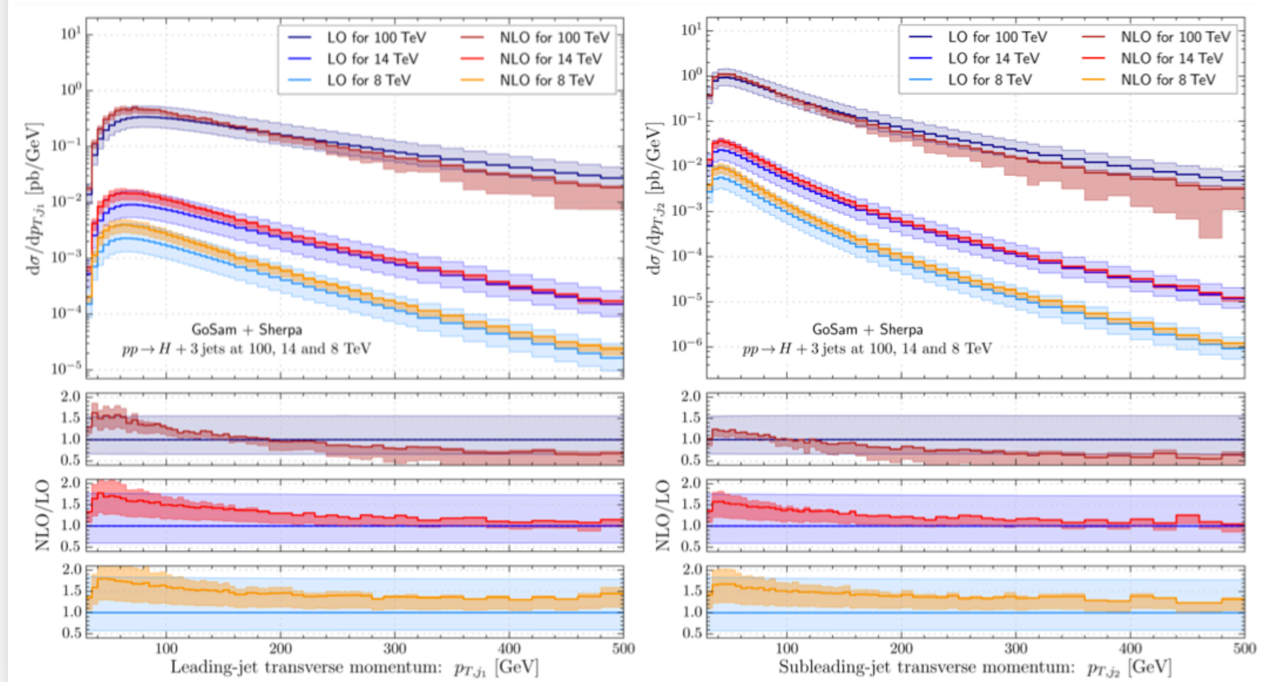
gg→H + jets

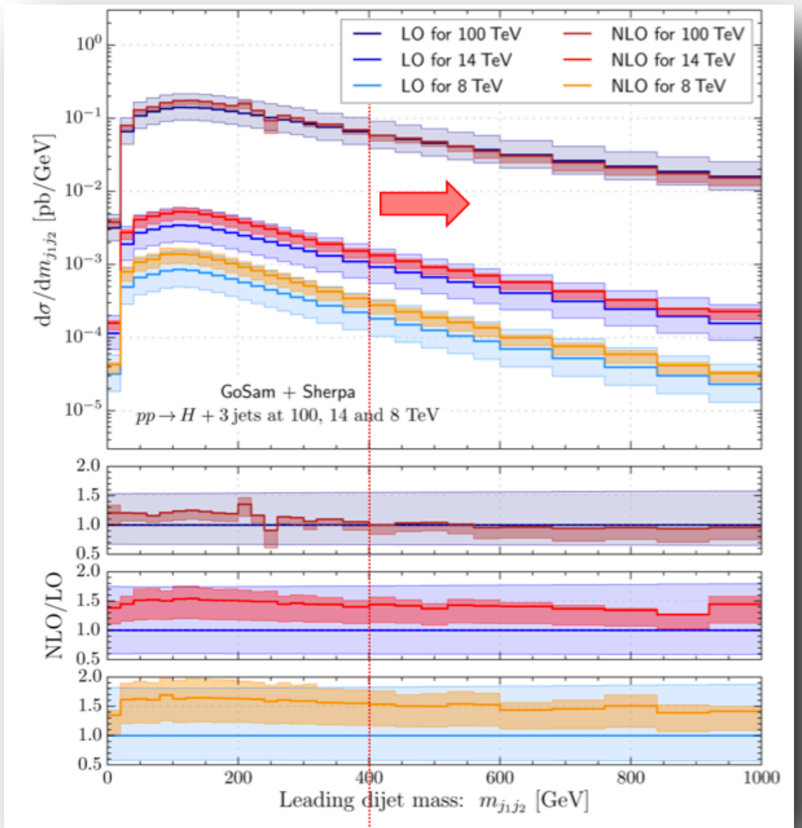
Luisoni SM@100 TeV

H+2 jets at 8, 14 and 100 TeV: jets p_T



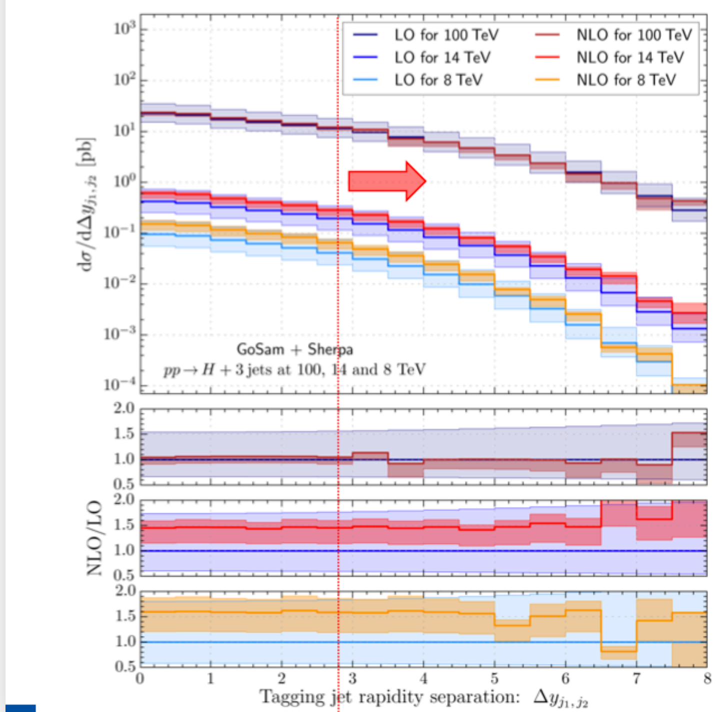
H+3 jets at 8, 14 and 100 TeV: jets p_T





m(jj)

H+3 jets at 8, 14 and 100 TeV: $\Delta y_{j1,j2}$



- Experimental VBF selection cuts based on multivariate analysis
- Typical discriminating variables are
  - $m_{j1,j2}$
  - $\Delta y_{j1,j2}$
  - ..
- Results with VBF-type cuts still running..

studies dedicated to VBF-like topologies are ongoing

100 TeV cross sections

	$\sigma^{(incl)}$ [pb]	$\delta\%$	$\sigma^{(VBF)}$ [pb]	$\delta\%$
LO	79.86	-	7.03	-
NLO	75.58	-5.4	6.30	-10
NNLO	72.81	-3.7	5.98	-5.1
NLO+PS	75.58	-	5.88	-6.7

VBF cuts ($p_{t,j} > 30$ GeV)

$$|\Delta y_{jj}| > 6.5, \qquad y_{j_1} \cdot y_{j_2} < 0$$

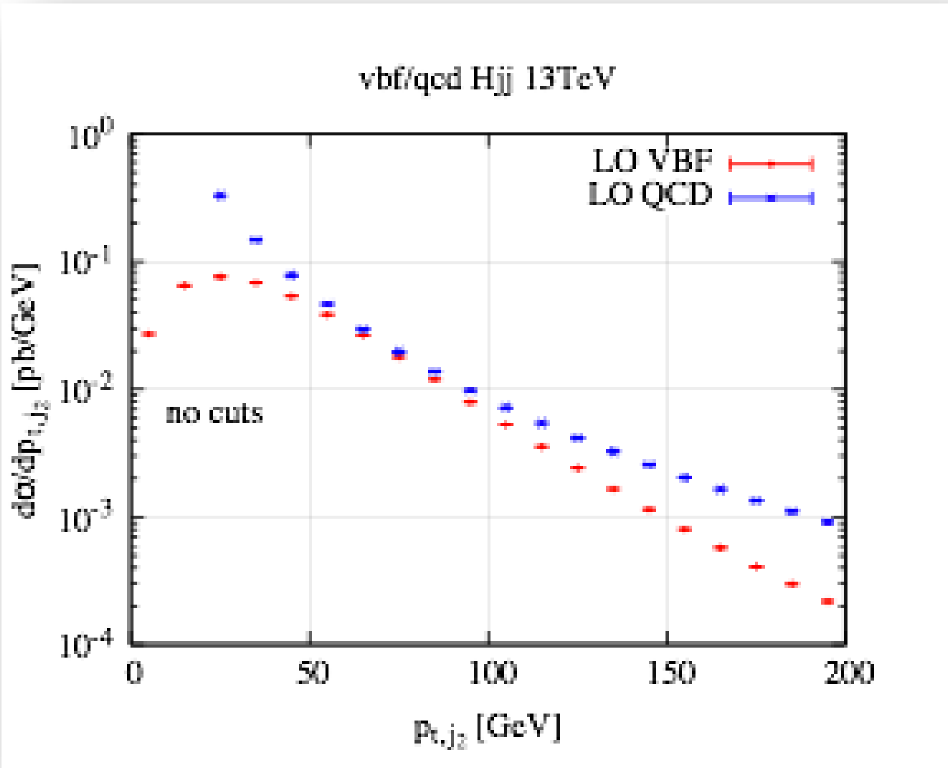
$$M_{jj} > 1600\ \text{GeV}, \qquad \frac{\pi}{4} < \phi_{jj} < \frac{3\pi}{4}$$

$$\sigma^{(incl)}_{100\ \text{TeV}} / \sigma^{(incl)}_{13\ \text{TeV}} \sim 17 \qquad \sigma^{(VBF)}_{100\ \text{TeV}} / \sigma^{(VBF)}_{13\ \text{TeV}} \sim 7$$

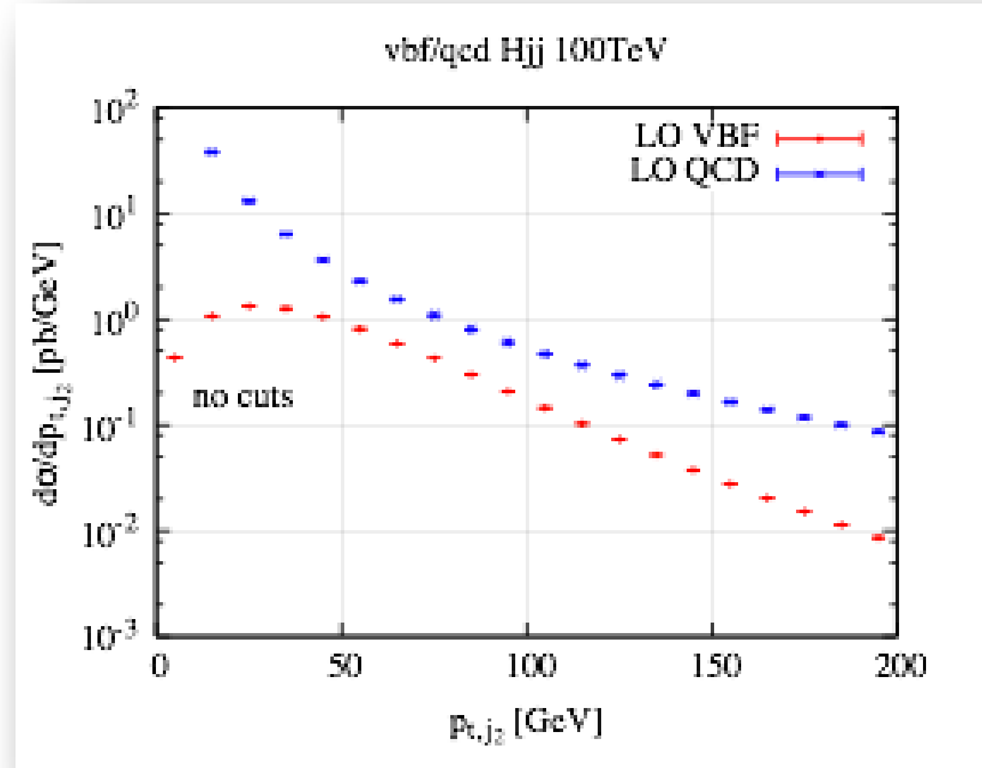
VBF

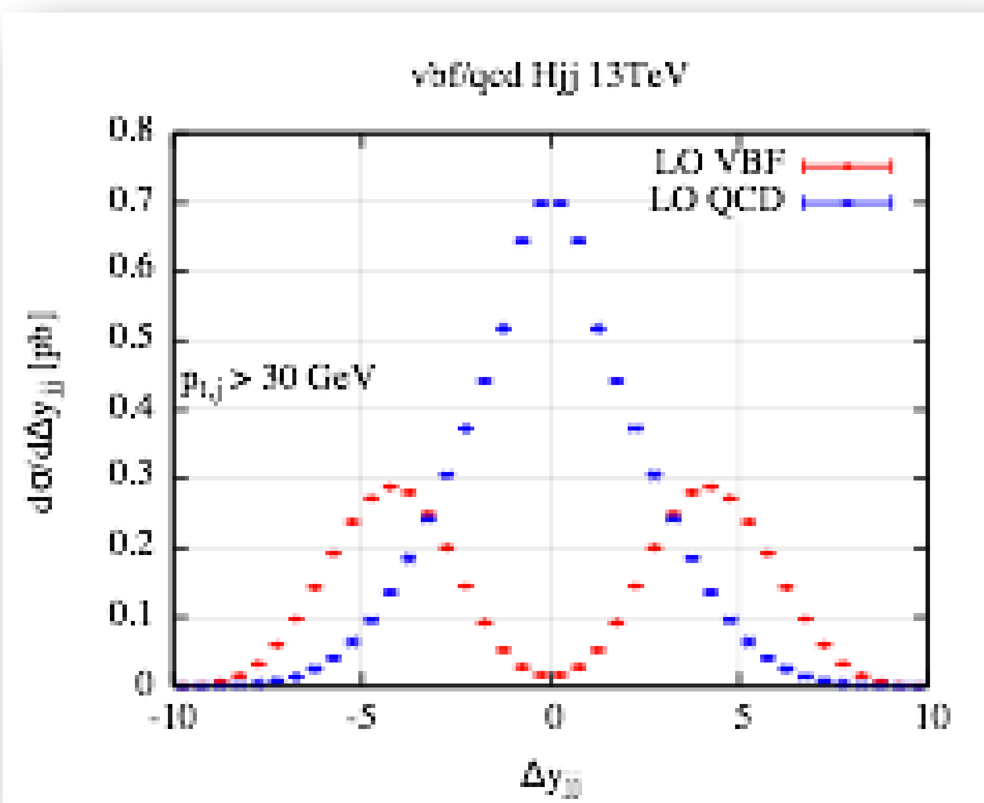
Karlberg SM@100 TeV

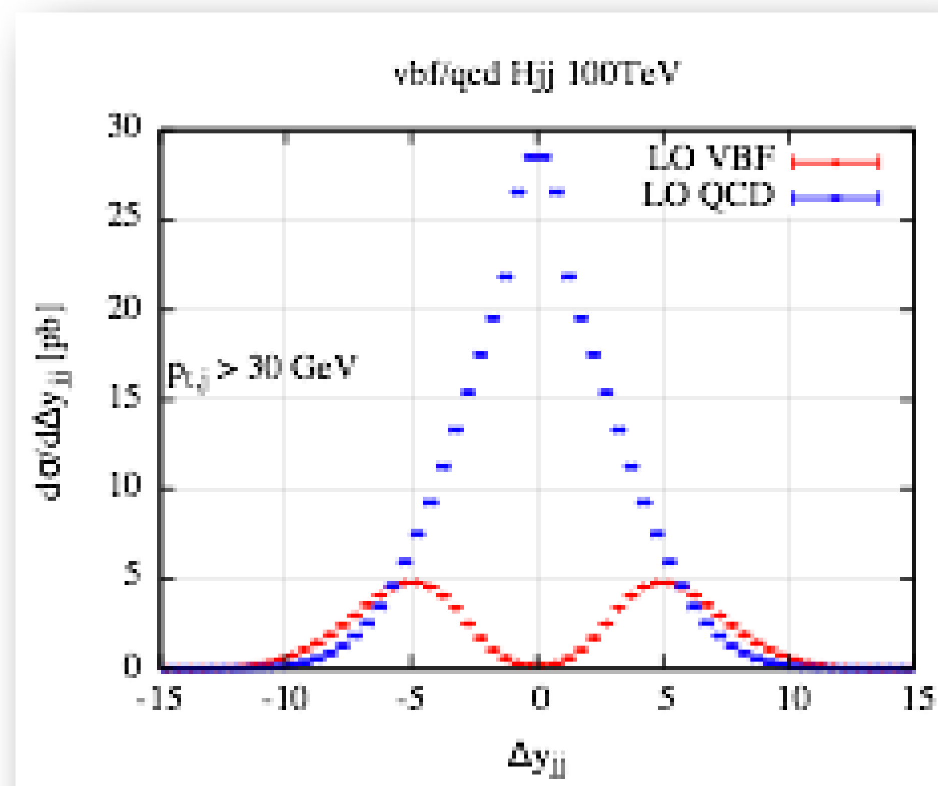
13 TeV



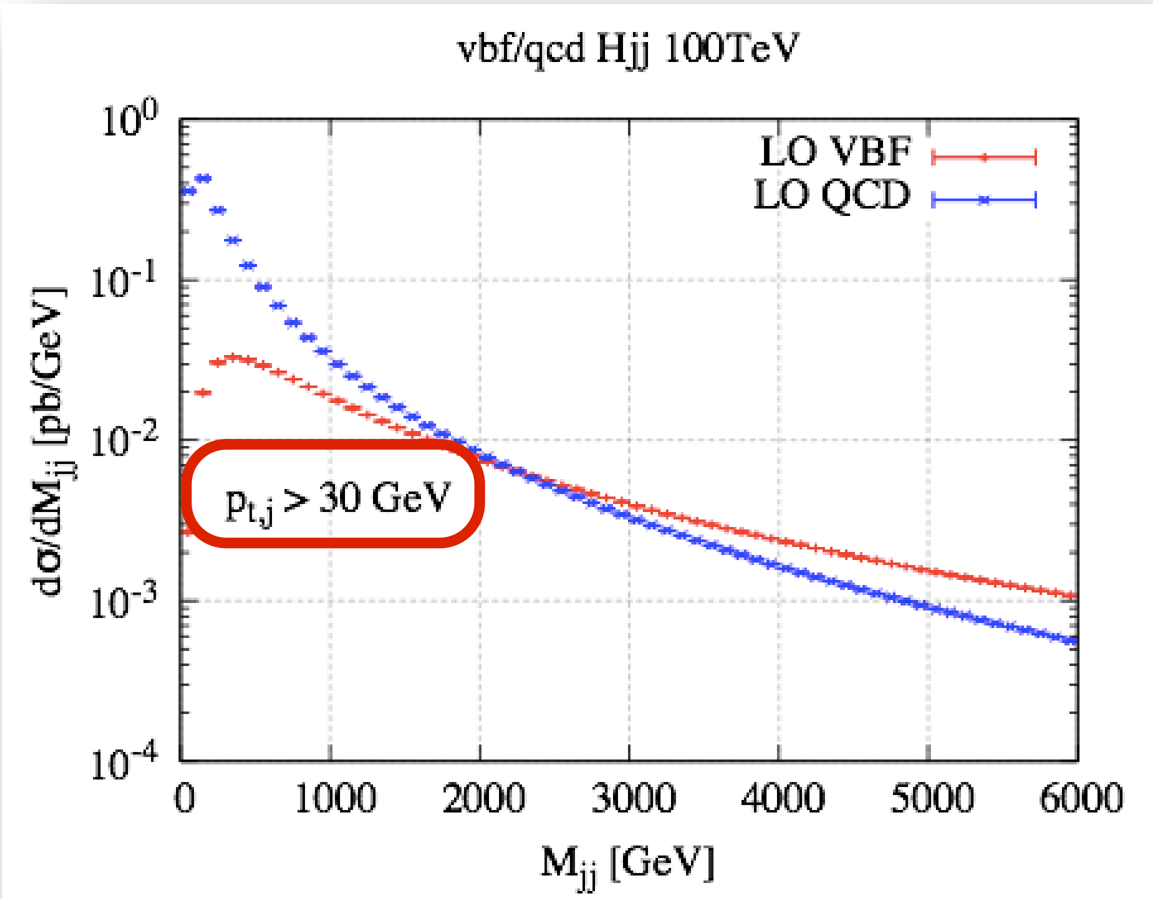
100 TeV

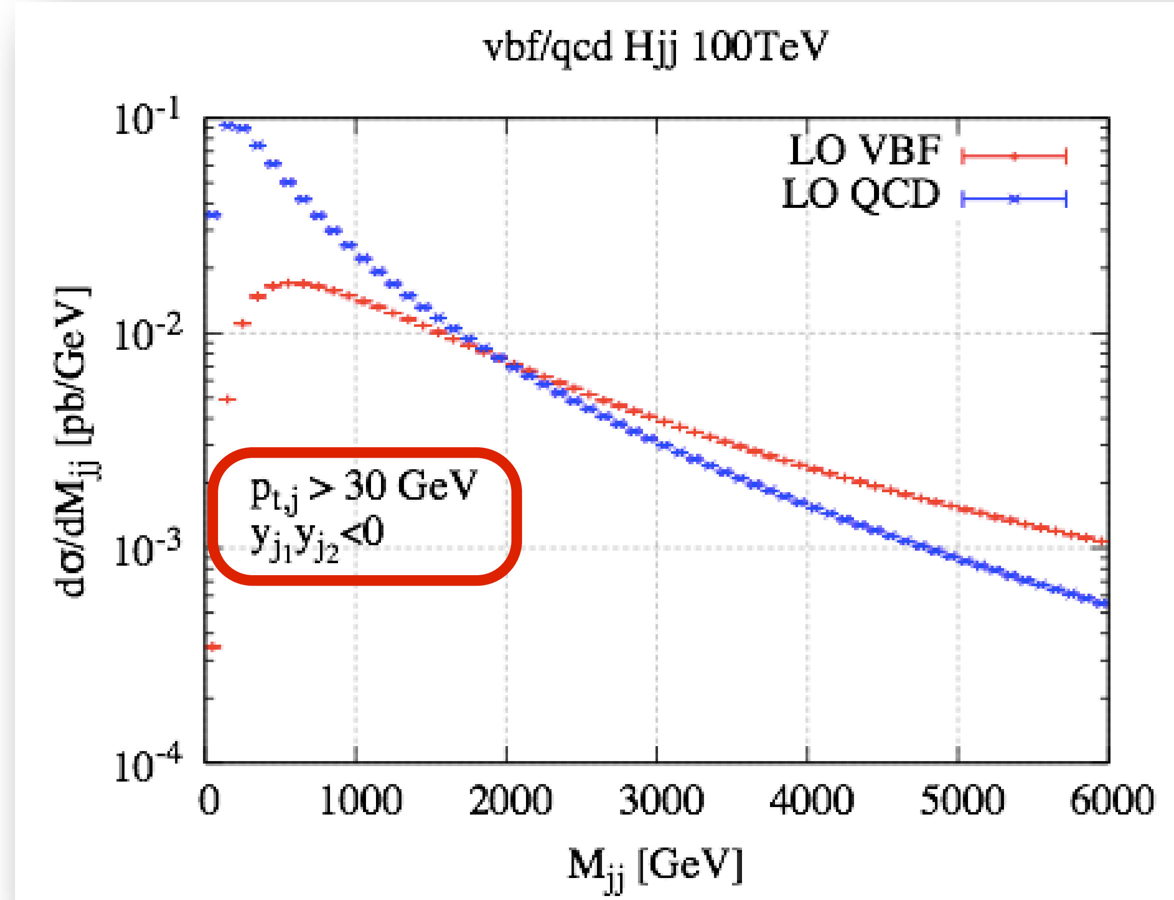


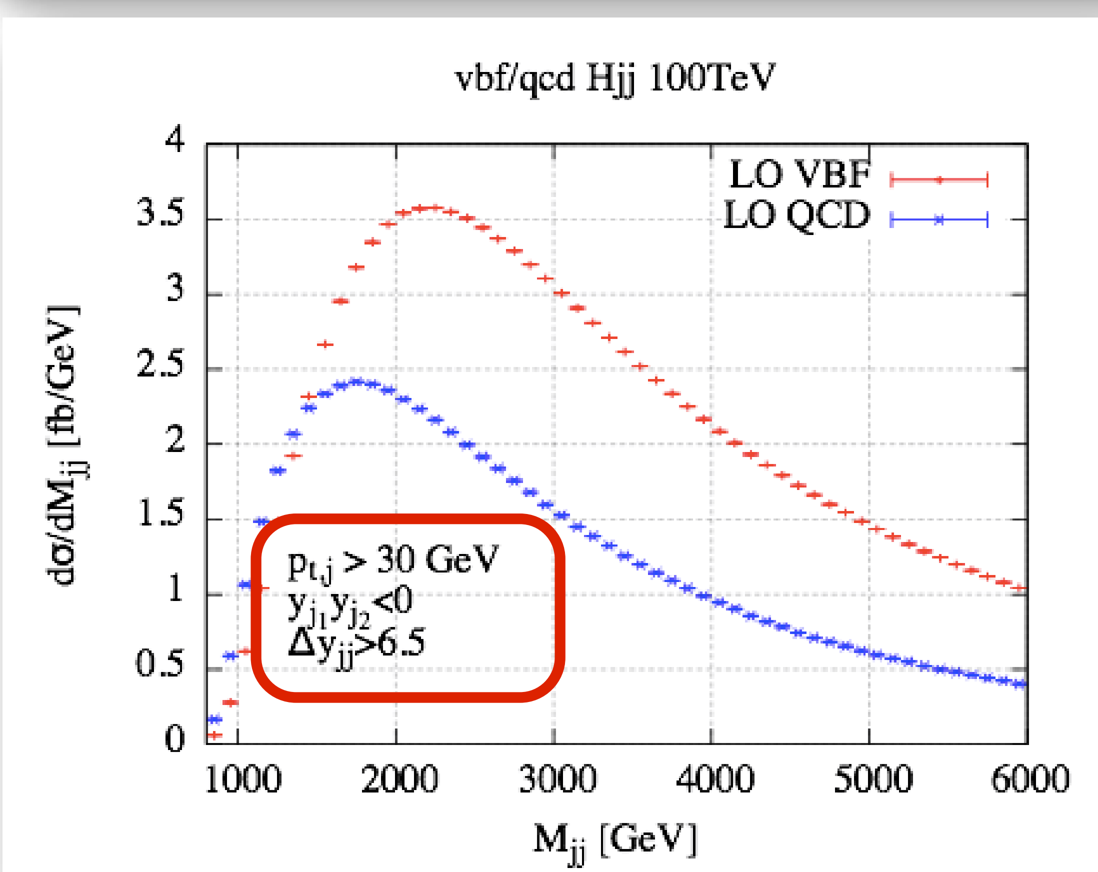


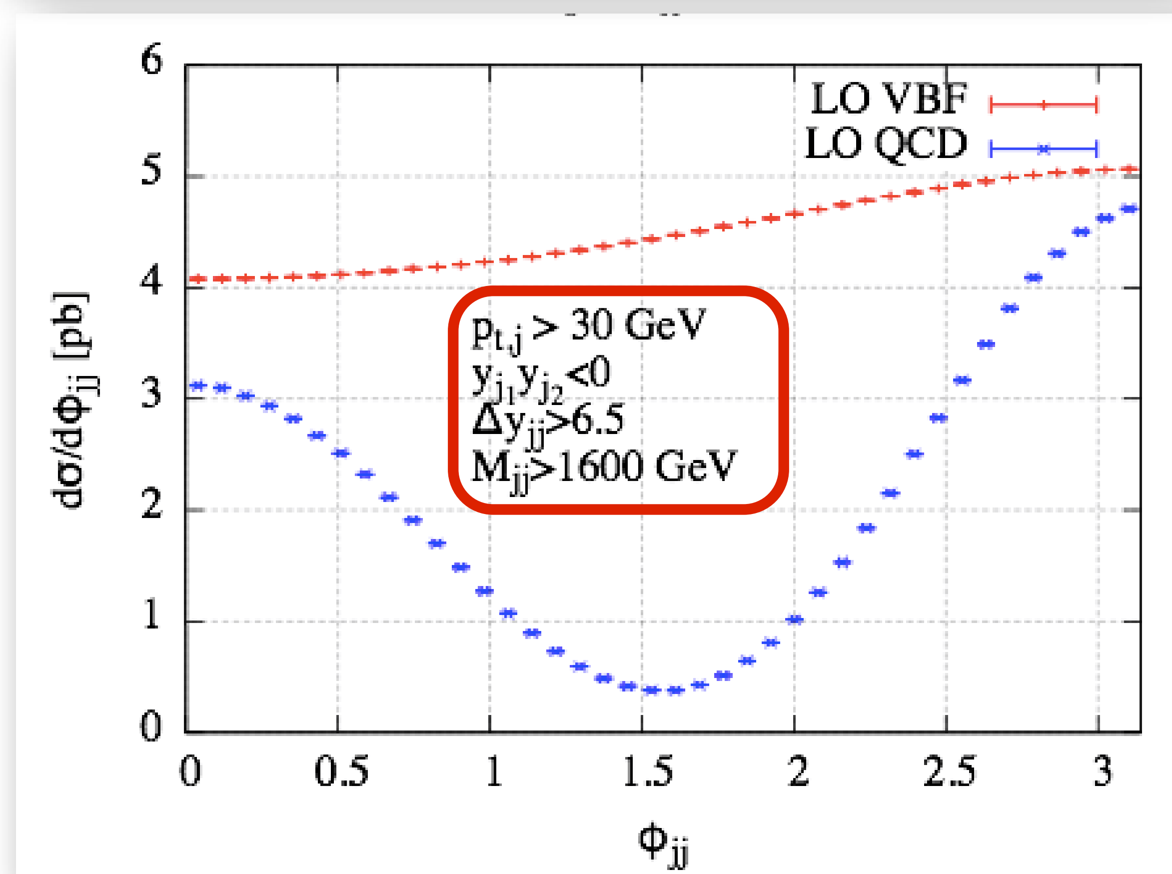


VBF Karlberg SM@100 TeV









VB scattering

Salfelder SM@100 TeV

VBS - current Status

- NLO QCD Corrections to EW_VVjj
  $\rightarrow$ VBFNLO [Bozzi, Jäger, Oleari, Zeppenfeld '06 - '09]
- NLO QCD Corrections to EW_$W^{\pm}W^{\pm}jj$ [Denner, Hošeková, Kallweit '12]
- NLO QCD Corrections to QCD_$W^{+}W^{\pm}jj$ (on-shell W's) [Melia, Melnikov, Rontsch, Zanderighi '10, '11]
- NLO QCD Corrections to QCD_$W^{+}W^{\pm}jj$ (DR contrib.) [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
- NLO QCD Corrections to QCD_VVjj (not $W^{+}W^{-}jj$)
  $\rightarrow$ VBFNLO [Campanario, Kerner, Ninh, Zeppenfeld '13, '14]
- Implementations into the POWHEG-Box (NLO QCD+PS-Effects)
  - QCD_$W^{+}W^{+}jj$ [Melia, Nason, Rontsch, Zanderighi '11]
  - EW_$W^{+}W^{\pm}jj$ and EW_ZZjj [Jäger, Karlberg, Zanderighi '11, '13]
- Evidence for EW_$W^{\pm}W^{\pm}jj$ at 8 TeV [ATLAS & CMS collaborations '14]

VB scattering

Salfelder SM@100 TeV

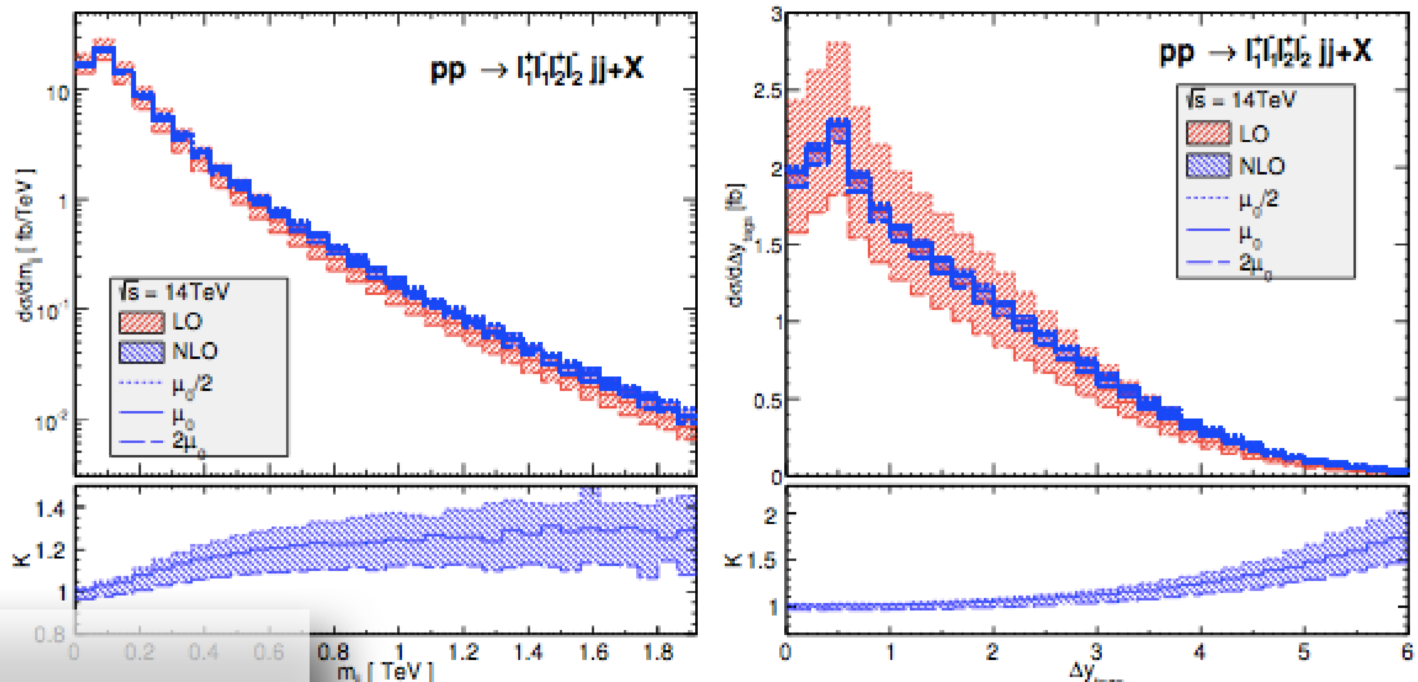
VBS at next-to-leading order

NLO QCD:

- only consider leptonic decays of vector bosons
- available for EW- & QCD-induced channels
- corrections $\lesssim 5 - 10\% \rightarrow$ small! (both process classes)
- small scale dependence, especially with dynamical scale choice($\mu_0 = Q$)

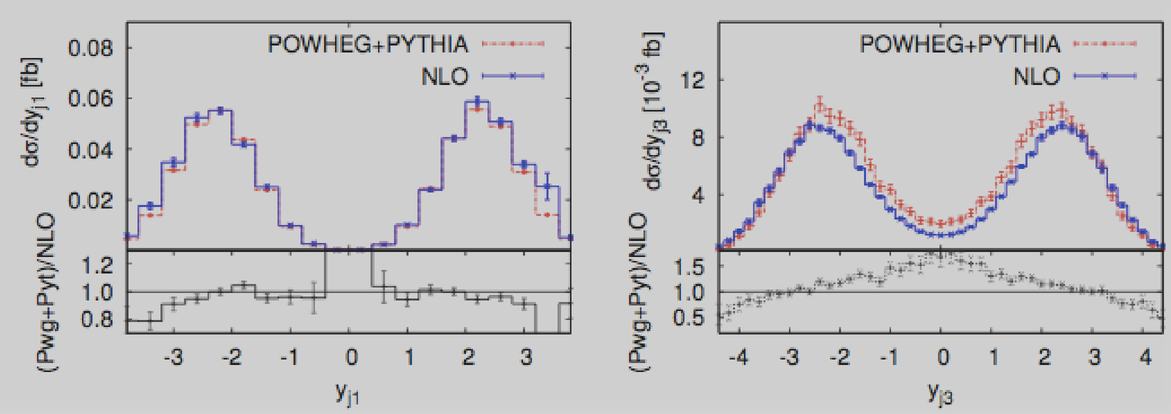
  $\Rightarrow$ EW-ind.: almost constant dynamical K-factors

  $\Rightarrow$ QCD-ind.: shapes get distorted



Parton-shower matching:

- influence on tagging jets small
- third jet shows more sensitivity on the parton shower



VB scattering

Salfelder SM@100 TeV

minimal cuts

- kT-algorithm (D=0.8)
  $p_{T,jet} > 20$ GeV
- $p_{T,l} > 20$ GeV
  $|y_l| < 2.5$
- $\Delta R_{lj} > 0.4$
- for processes with Z's:
  $\Delta R_{ll} > 0.2$
  $M_{ll} > 15$ GeV

VBS-cuts

14 TeV

$M_{j1j2} > 600$ GeV
$\Delta y_{j1j2} > 4$
$y_{j_1} \times y_{j_2} < 0$

100 TeV

$M_{j1j2} > 800$ GeV
$\Delta y_{j1j2} > 5$
$y_{j_1} \times y_{j_2} < 0$

Results for VBS at 100 TeV

LO-XS		no VBS-cuts EW	no VBS-cuts QCD	no VBS-cuts S/B	with VBS-cuts EW	with VBS-cuts QCD	with VBS-cuts S/B
14 TeV	W^+W^-jj [fb]	7.272(4)	-	-	3.109(2)	-	-
	W^+W^+jj [fb]	2.6577(3)	2.0969(4)	5/4	1.2851(4)	0.06088(6)	21/1
	W^+Zjj [fb]	0.47311(6)	14.942(2)	1/31	0.1970(4)	0.5892(4)	1/3
	$ZZjj$ [fb]	0.12513(3)	2.4666(3)	1/20	0.0523(3)	0.0453(3)5	7/6
100 TeV	W^+W^-jj [fb]	142.40(9)	-	-	71.34(5)	-	-
	W^+W^+jj [fb]	52.589(8)	17.225(6)	3/1	28.63(1)	0.221(5)	130/1
	W^+Zjj [fb]	9.650(1)	273.06(5)	1/28	4.7812(2)	10.961(6)	4/9
	$ZZjj$ [fb]	2.9198(8)	50.95(1)	3/50	1.454(1)	1.185(1)	5/4

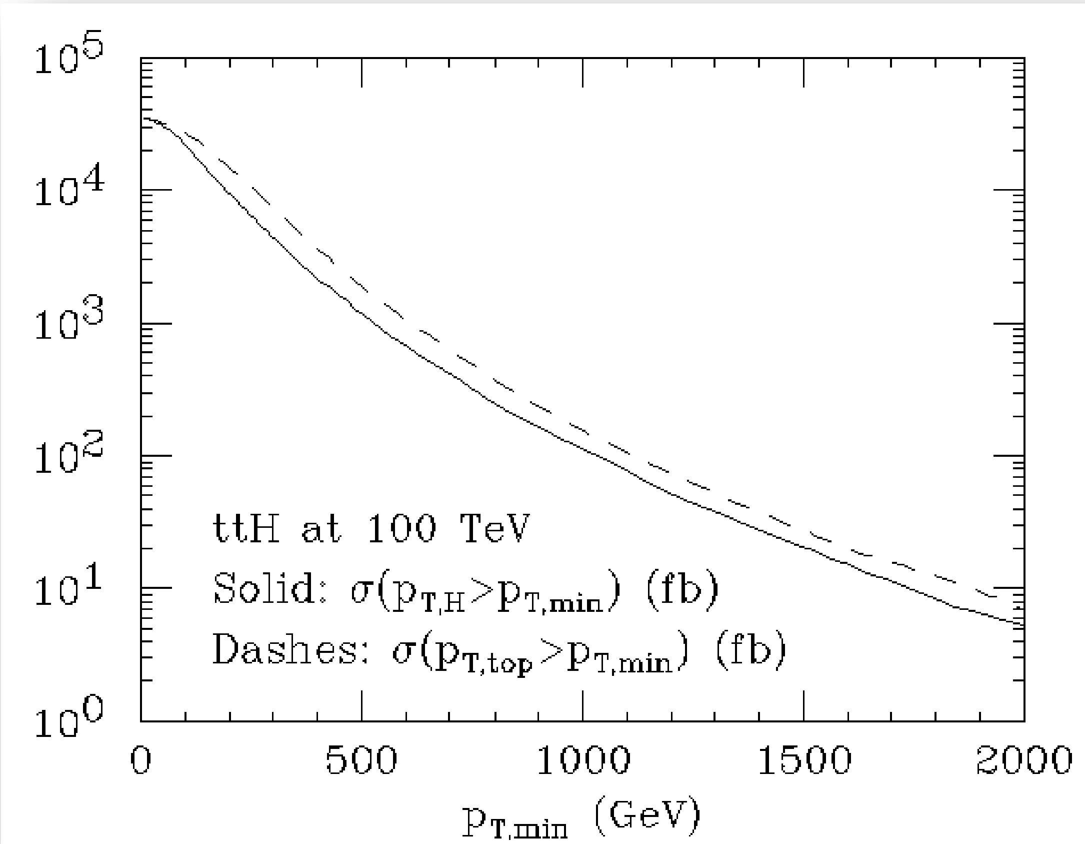
- VBS-cuts reduce XS of EW-ind. to ≈ 50%
- much stronger reduction of QCD-ind. XS
- slight improvement wrt. VBS-cuts at 14 TeV
- even more stingent cuts possible due to high XS
- W^+W^+jj-measurement at 8 TeV:
  EW-XS= 0.88fb (all channels), $S/B \approx 9/1$, 14 EW-events (34 total)

Work ongoing on VBS cuts optimization
(e.g. optimize S/sqrt(B) @ 10ab^{-1} rather than S/B)

ttH

- Rates for tt→lν+jets, 20 ab^{-1}

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



H→bb channel studied in
MLM, Plehn, Reimitz, Schell, Shao arXiv:1507.08169

Bottom line:

- Large rates
- Small TH systematics for ttH/ttZ
- Can exploit boosted topologies for H→bb
- 1% precision on y_{top} reasonable goal