Differential distributions in WW + 1-jet production at NLO QCD

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Work in collaboration with S.Dittmaier, S. Kallweit

Contents

WW + 1-Jet — Motivation

Why is WW + 1 Jet important ?

- Large fraction of WW with additional jet activity

  → Precise understanding important for tests of the SM at high scale, i.e. electro-weak gauge-boson coupling analysis

- WWj@NLO contributes to WW@NNLO

  Recent progess concerning the 2-loop amplitudes [Czakon 07,08]

- Important background process

  → Higgs search at LHC

WW + 1-Jet — Motivation: Higgs search (LHC)

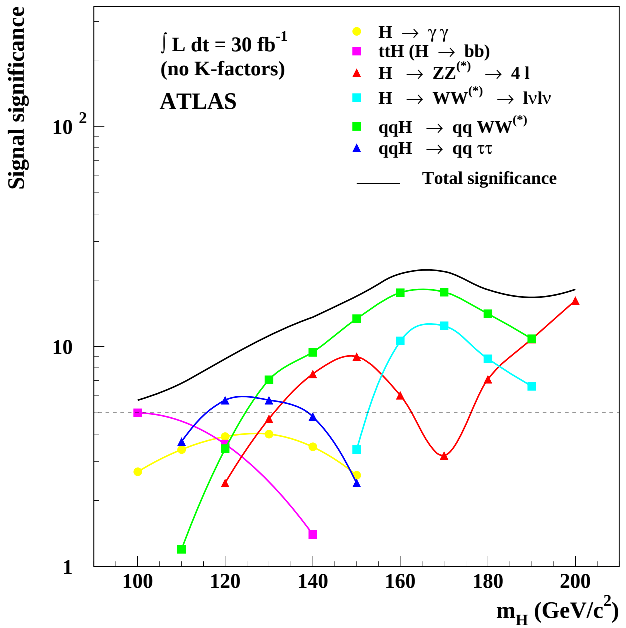
Range 160-170 GeV now excluded by Tevatron, [Moriond 09]

- For 135 GeV < m_h < 185 GeV:

  H → WW is dominant channel

- For 130 GeV < m_h < 190 GeV,

  Vector **B**oson **F**usion (VBF) dominates over gg→H as far as signal significance is concerned



[Atlas ‘03]

WW + 1-Jet — Motivation: Higgs search

NLO corrections for Higgs production via VBF known:

- Total cross section [Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00]
- Differential distributions [Figy, Oleari, Zeppenfeld '03, Berger,Campbell '04]
  → QCD uncertainty ~ 4%

Experimental Signature:

Two forward tagging jets + "Higgs"

Background reactions:

WW + 2 Jets, WW + 1 Jet

NLO corrections unknown

Top of the Les Houches list '07

If only leptonic decay of W´s and only 1 forward Jet is demanded
(→improved signal significance)

[Mellado, Quayle, Wu, '05,'07]

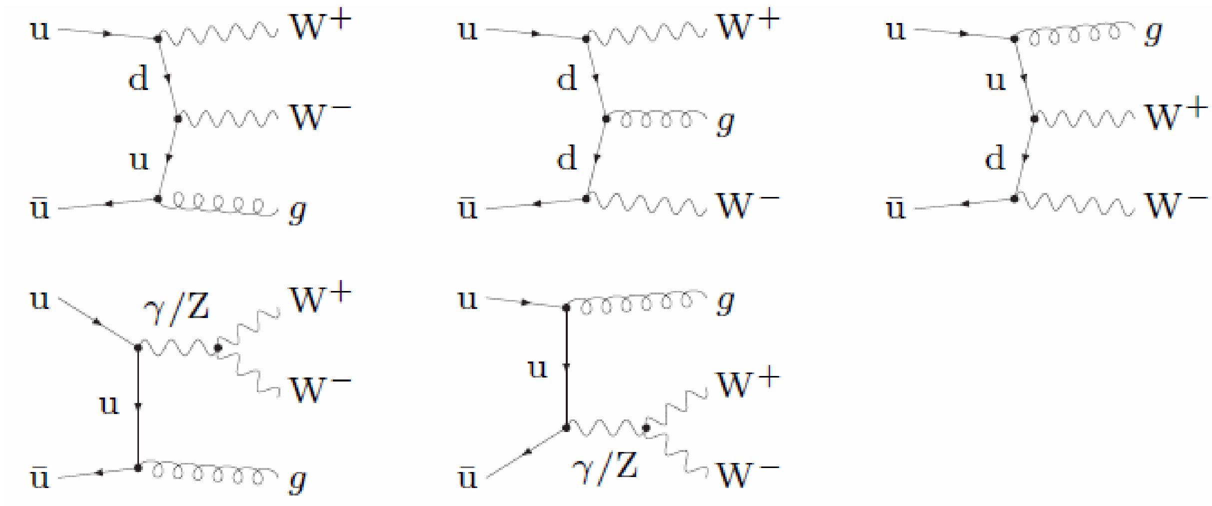
Leading-order results

Basic process: $0 \rightarrow W^{+}W^{-}q\bar{q}g$

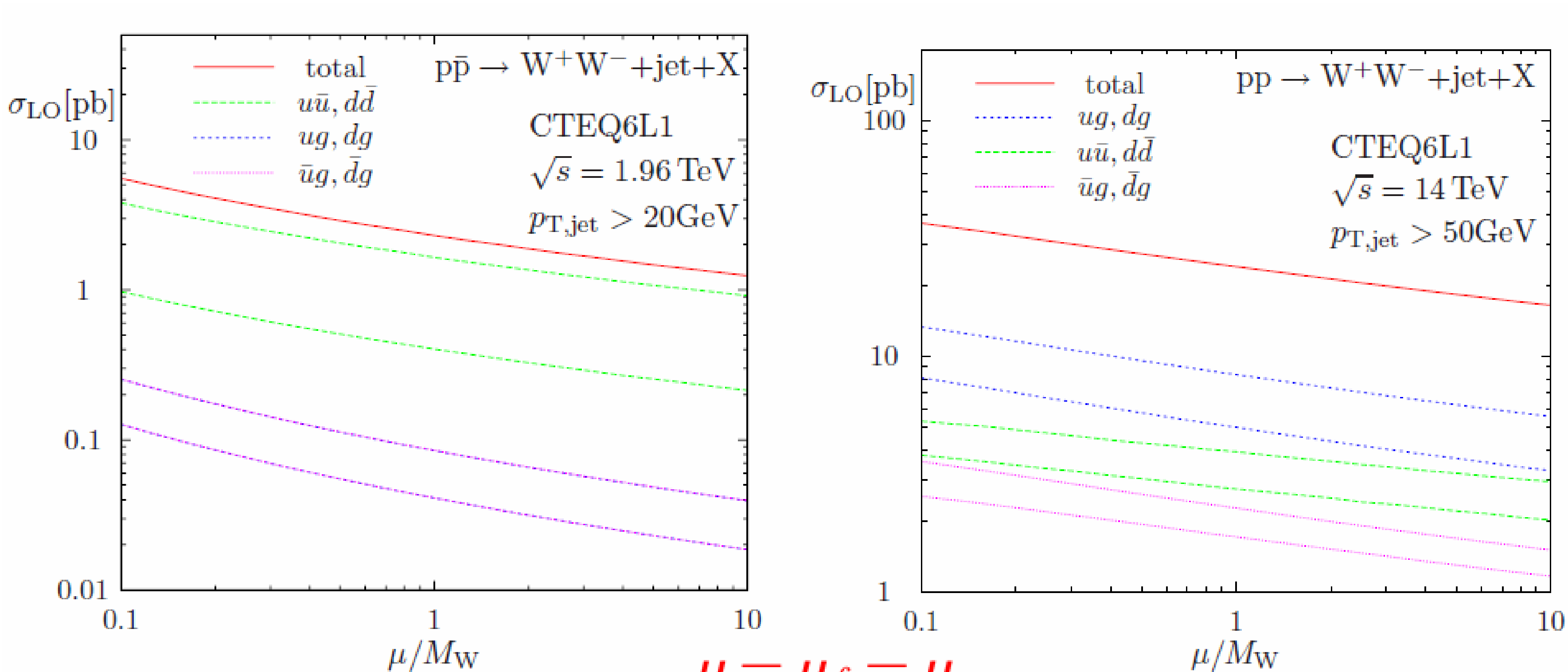
Different quark flavours + crossing

→ 3 x 4 = 12 different partonic channels

Diagrams for uu:



Leading-order results



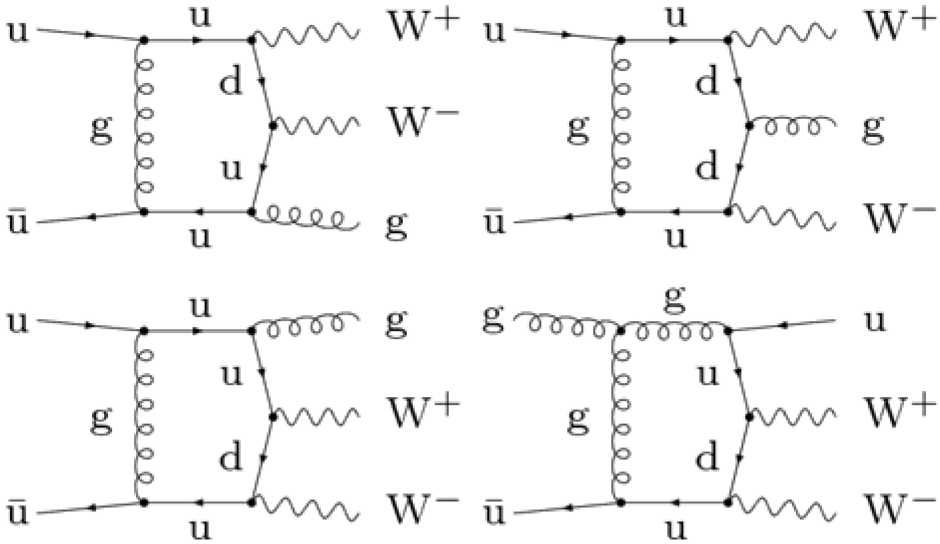
$\mu = \mu_f = \mu_r$

Some features:

- Jet algorithm required to render cross section finite → Ellis-Soper-Algorithm, no recombination at LO
- Dependence on 2x2-"CKM" matrix cancels (unitarity)
- Significance of individual channels due to PDF's
- Residual scale dependance: LHC: 12(30)% for change 2(5)
  Tevatron: 25(75)% for change 2(5)

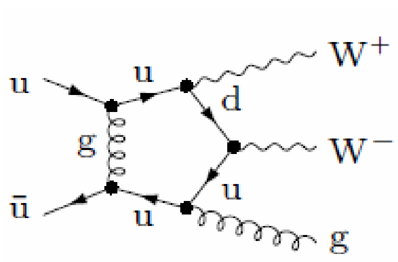
Virtual corrections

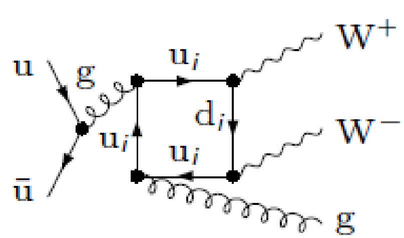
Sample diagrams



Again many different channels!

Further decomposition possible:





“bosonic corrections” “fermionic corrections”

Real corrections

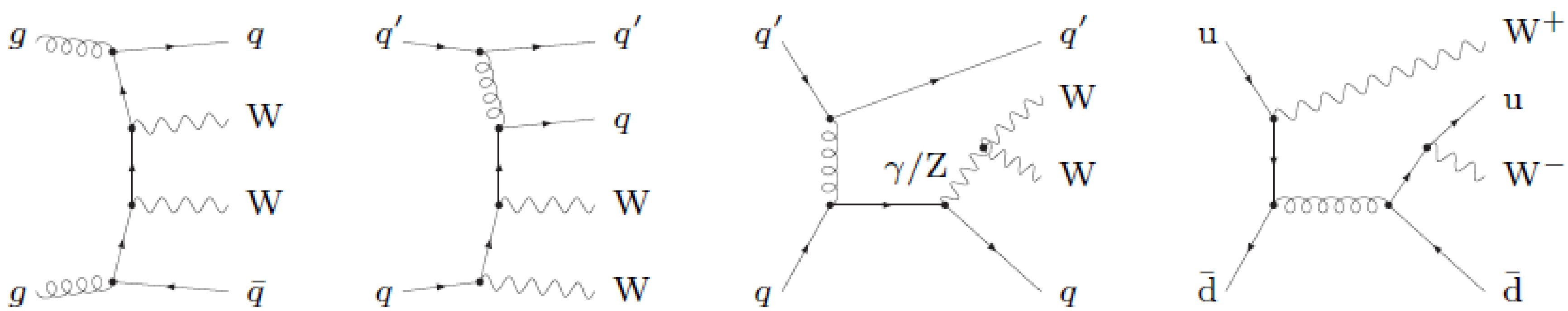
Generic amplitudes: $0 \rightarrow W^+W^-gg, \quad 0 \rightarrow W^+W^-q\bar{q}q'\bar{q}'$

Crossing + non-diagonal 2x2 flavour structure:

Some book keeping required

→ 136 different channels

Sample diagrams:



Two independent computer codes, based on:

- Short analytic expressions, using spinor helicity methods
- Madgraph [Stelzer, Long '94]

Checks of the NLO calculation

- Leading-order amplitudes checked with Madgraph
- Subtractions checked in singular regions
- Structure of UV singularities checked
- Structure of IR singularities checked

Most important:

- Two complete independent programs for all parts of the calculation, in particular:

complete numerics done twice !

Detailed comparison with other groups

Campbell, Ellis, Zanderighi (CEZ), JHEP 0712:056,2007

Binoth, Guillet, Karg, Kauer, Sanguinetti (in progress) (BGKKS)

Stefan Kallweit LL2008

- Integrated LO results checked:

$pp \to W^+W^-$+jet+X	σ_{LO} [fb]
DKU	10371.7(12)
CEZ	10372.26(97)
BGKKS	10371.7(11)

- Results for virtual corrections checked at one phase-space point:

$u\bar{u} \to W^+W^-g \qquad |\mathcal{M}_{LO}|^2/e^4 g_s^2 = 0.9963809154477200 \cdot 10^{-3}$

$$2\mathrm{Re}\{\mathcal{M}_V^* \cdot \mathcal{M}_{LO}\} = e^4 g_s^2 \Gamma(1+\varepsilon)\left(\frac{4\pi\mu^2}{M_W^2}\right)^{\varepsilon}\left(\frac{1}{\varepsilon^2}c_{-2} + \frac{1}{\varepsilon}c_{-1} + c_0\right)$$

All bosonic contributions:

$u\bar{u} \to W^+W^-g$	c_{-2} [GeV^{-2}]	c_{-1}^{bos} [GeV^{-2}]	c_0^{bos} [GeV^{-2}]
DKU	$-1.080699305508758 \cdot 10^{-4}$	$7.842861905263072 \cdot 10^{-4}$	$-3.382910915425372 \cdot 10^{-3}$
CEZ	$-1.080699305505865 \cdot 10^{-4}$	$7.842861905276719 \cdot 10^{-4}$	$-3.382910915464027 \cdot 10^{-3}$
BGKKS	$-1.080699305508814 \cdot 10^{-4}$	$7.842861905263293 \cdot 10^{-4}$	$-3.382910915616242 \cdot 10^{-3}$

Fermionic contributions for 2 light generations in the loop:

$u\bar{u} \to W^+W^-g$	$c_{-1}^{ferm1+2}$ [GeV^{-2}]	$c_0^{ferm1+2}$ [GeV^{-2}]
DKU	$2.542821895320379 \cdot 10^{-5}$	$4.372323372044527 \cdot 10^{-7}$
CEZ	$2.542821895311753 \cdot 10^{-5}$	$4.372790378087550 \cdot 10^{-7}$
BGKKS	$2.542821895314862 \cdot 10^{-5}$	$4.372324288356448 \cdot 10^{-7}$

[Les Houches report 07,08]

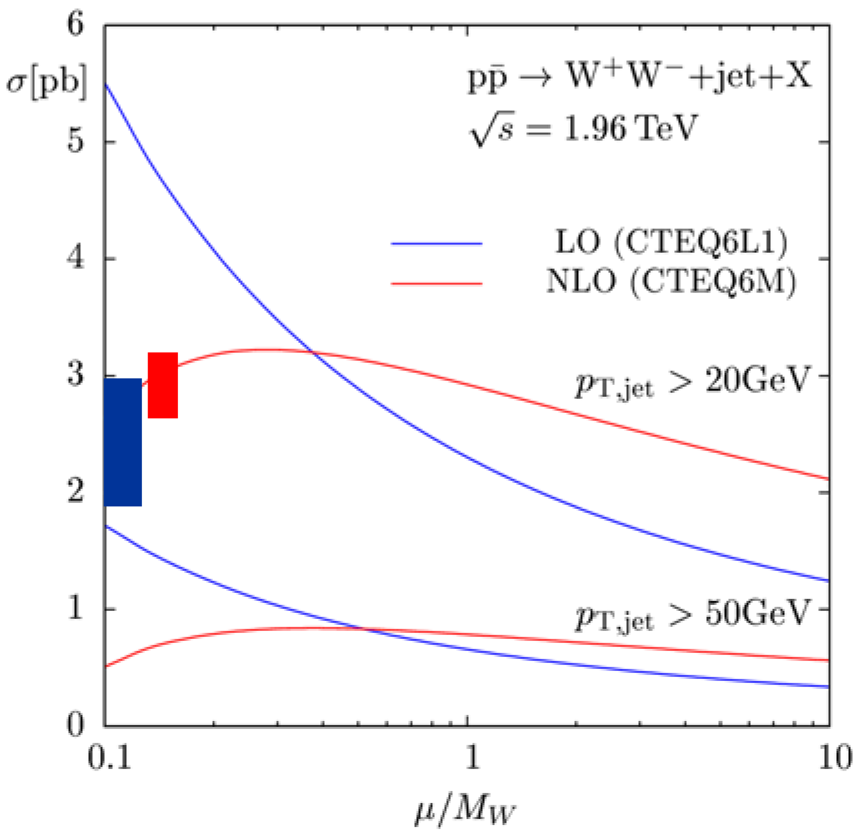
→ Very good agreement !

Results

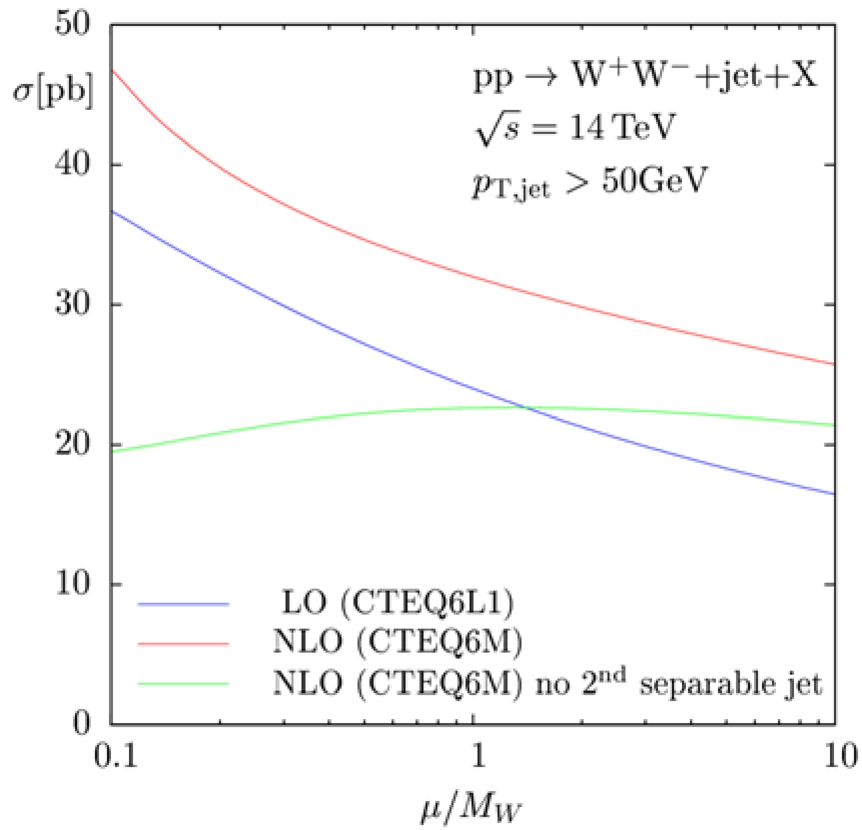
Results WW+1-Jet — Tevatron

[Dittmaier, Kallweit, Uwer
Phys.Rev.Lett.100:062003,2008]

Tevatron



LHC



Scale dependence at LHC only improved after jet-veto !

Steps towards more realistic predictions

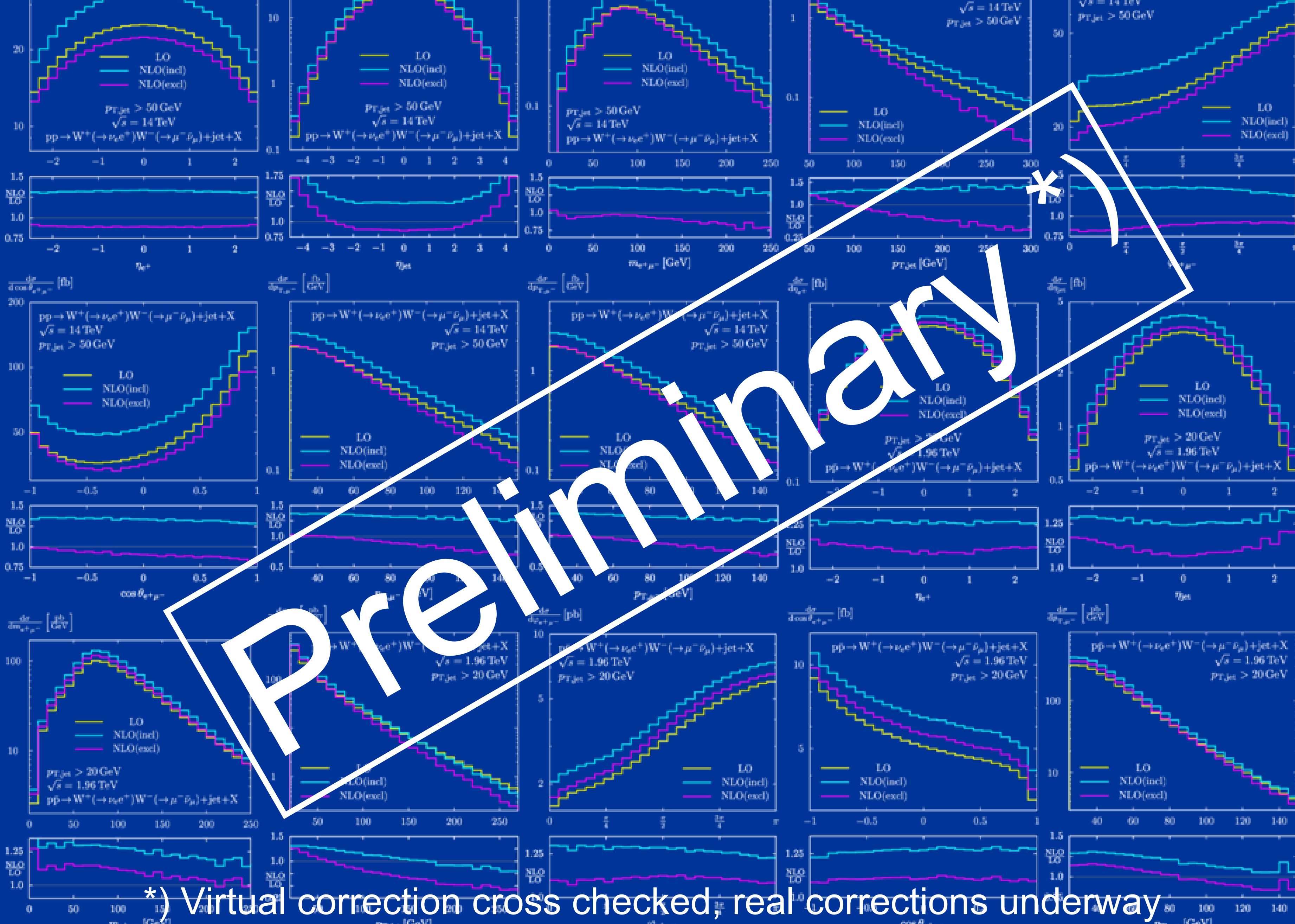
- Consider also differential distributions
  - Catani-Seymour subtraction allows calculation of distributions without modification
  - Only book keeping problem → every dipole is binned separately
- Include decay of the W-bosons
  - On-shell approximation
  - Two different options: spin density approach or replace W-polarisation by decay current

Helicity amplitudes $\mathrm{Tr}[\rho\rho_1\rho_2]$

Madgraph $\varepsilon_\mu \longrightarrow J_\mu = \bar{u}\gamma_\mu v$

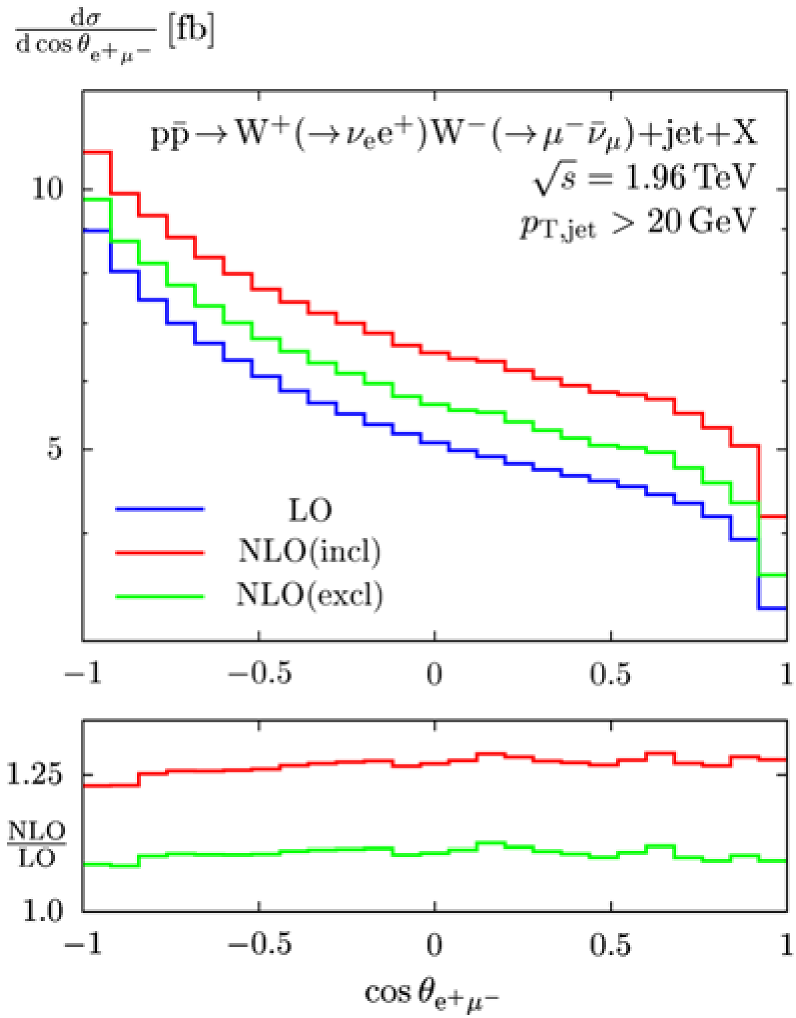
+ minor modifications in the subtraction terms

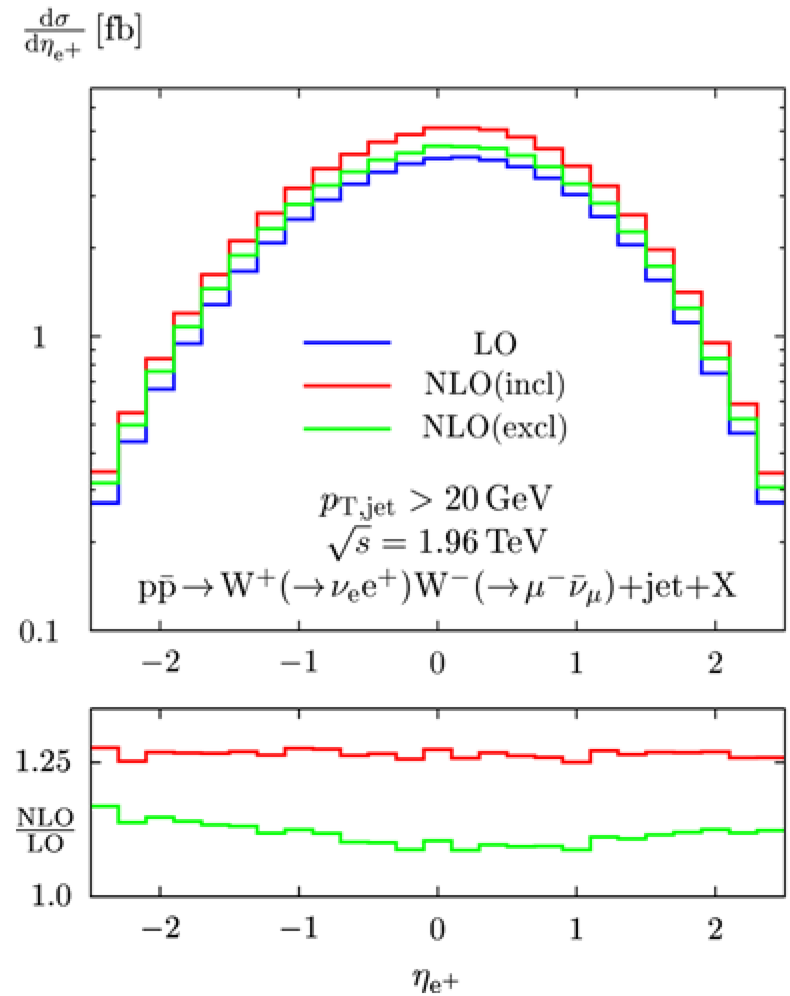
Differential distributions



*) Virtual correction cross checked; real corrections underway

Differential Distributions: Tevatron

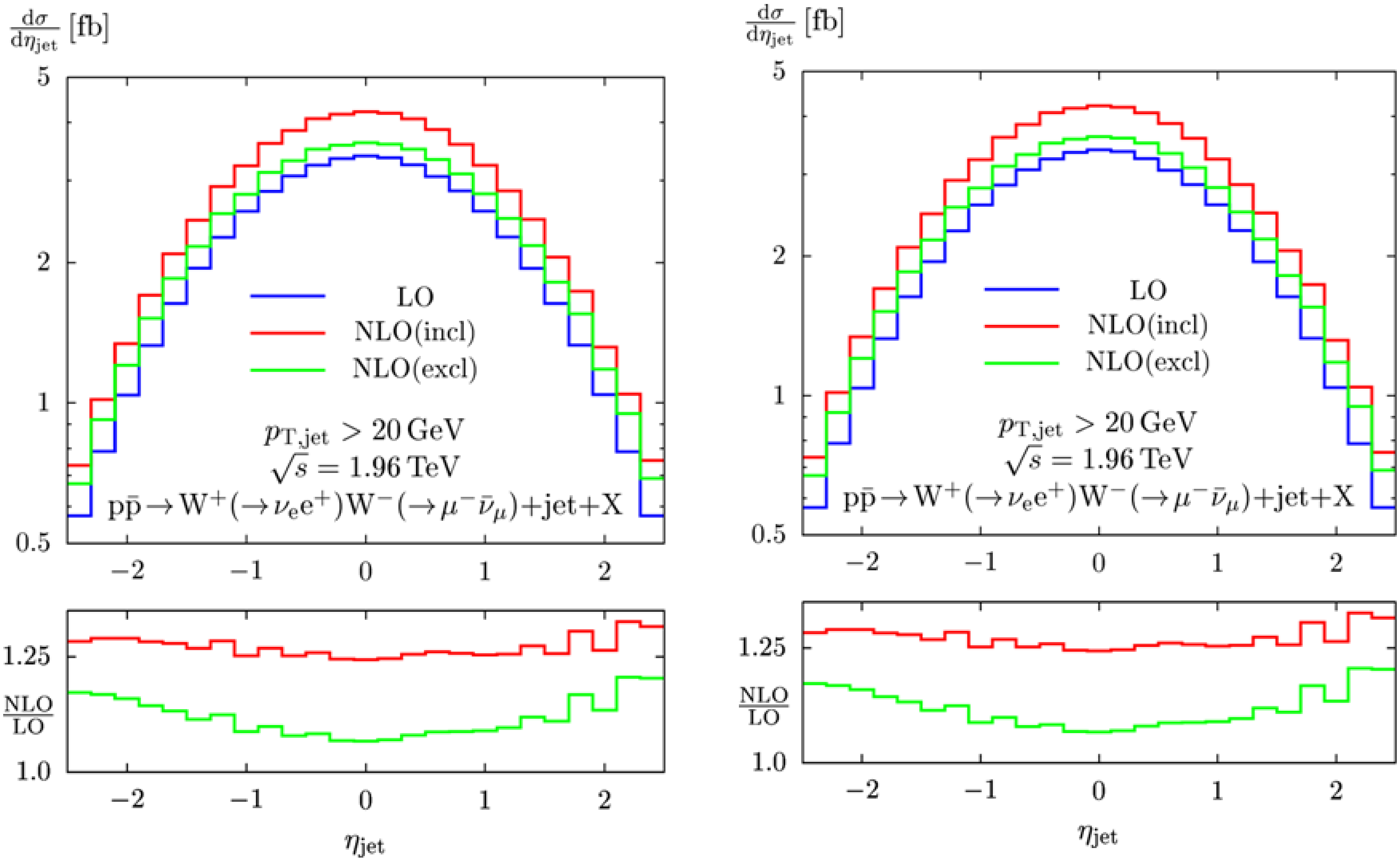




→ Corrections ~25%, smaller for exclusive sample

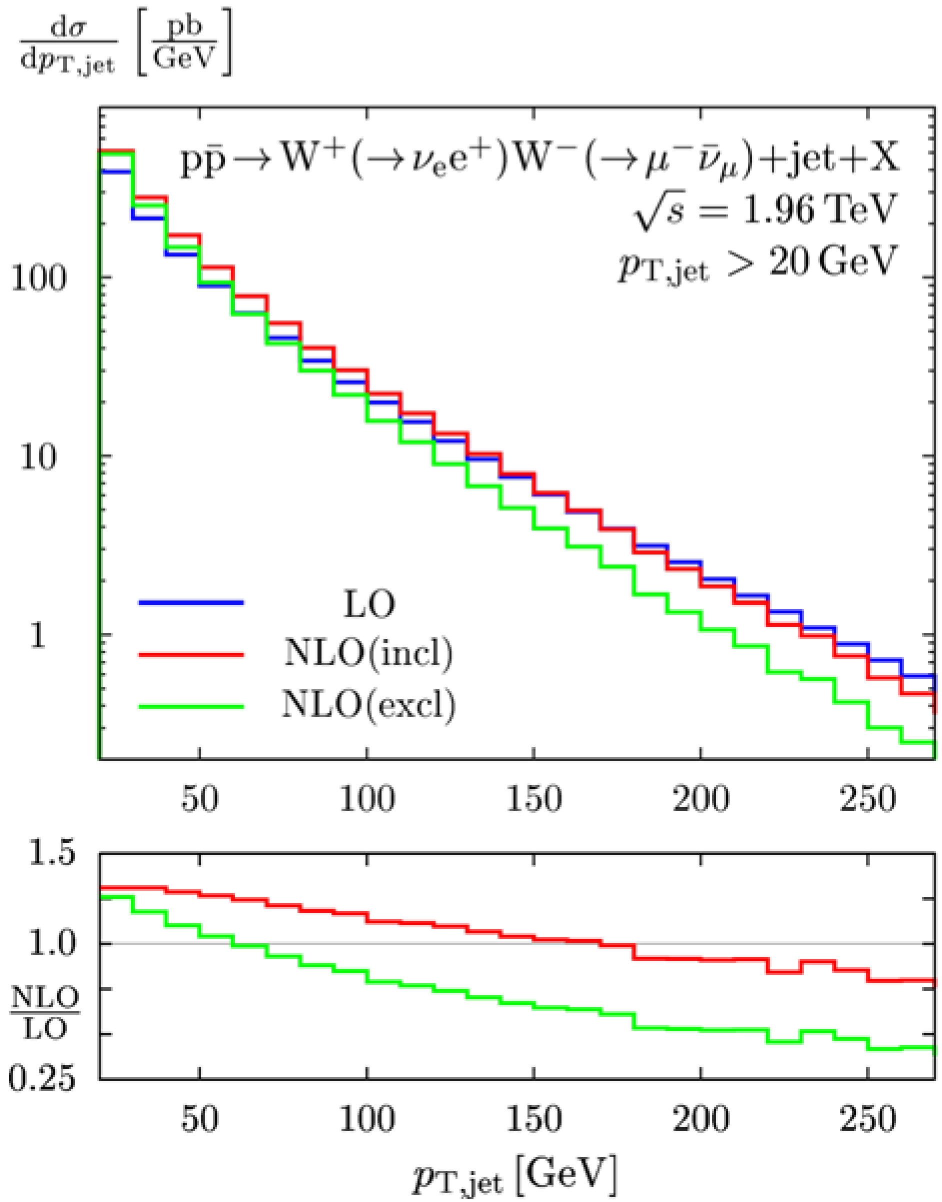
→ Shape almost not affected by corrections, “K-factor” works

Differential Distributions: Tevatron



Similar conclusion as before

Differential distributions: Tevatron

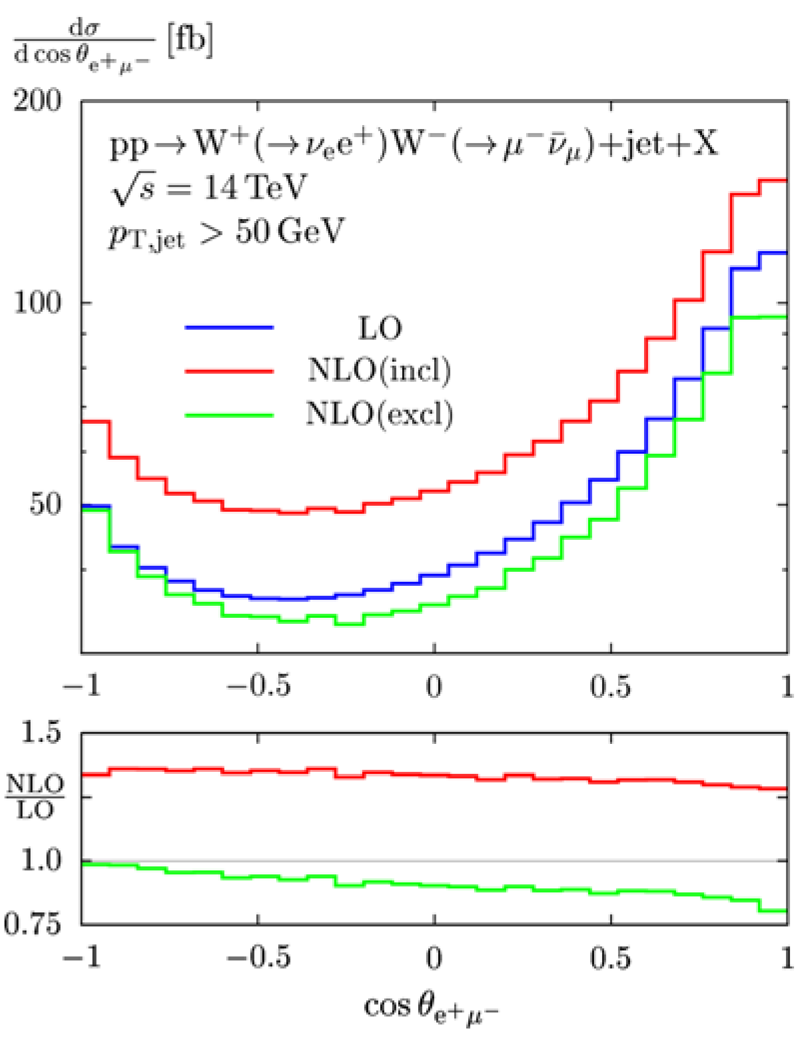


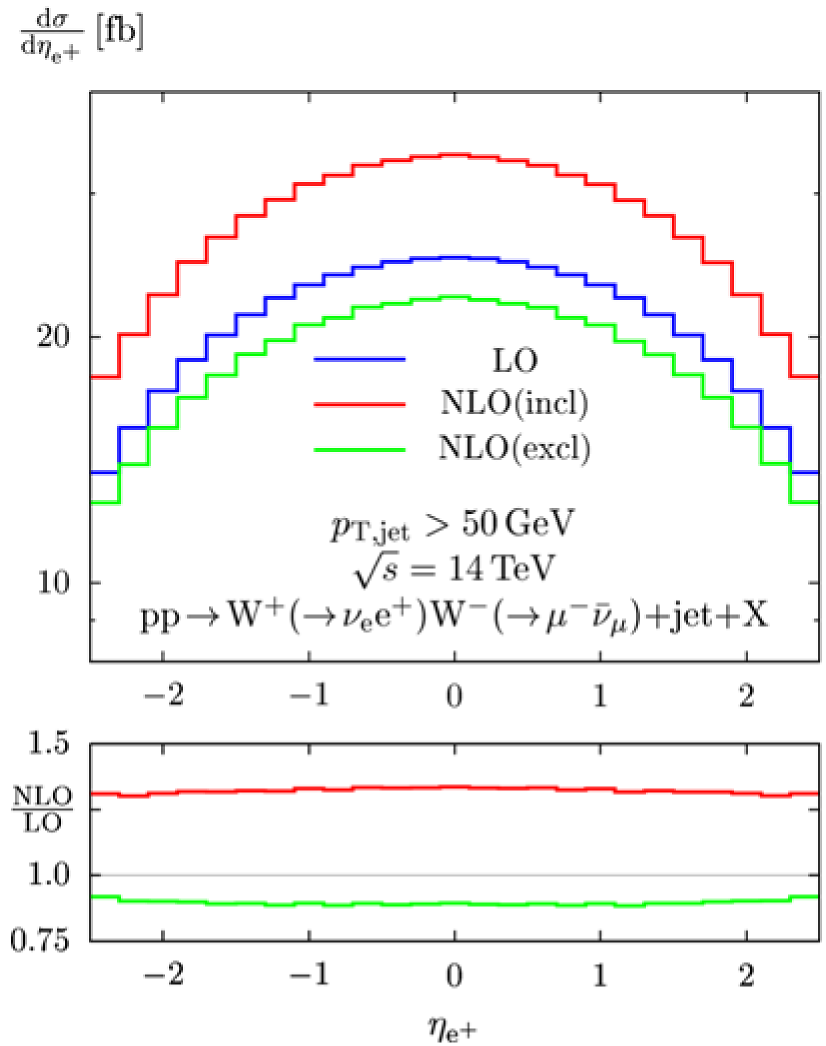
Significant distortion, Phase space dependent K-factor

Pt introduces additional scale

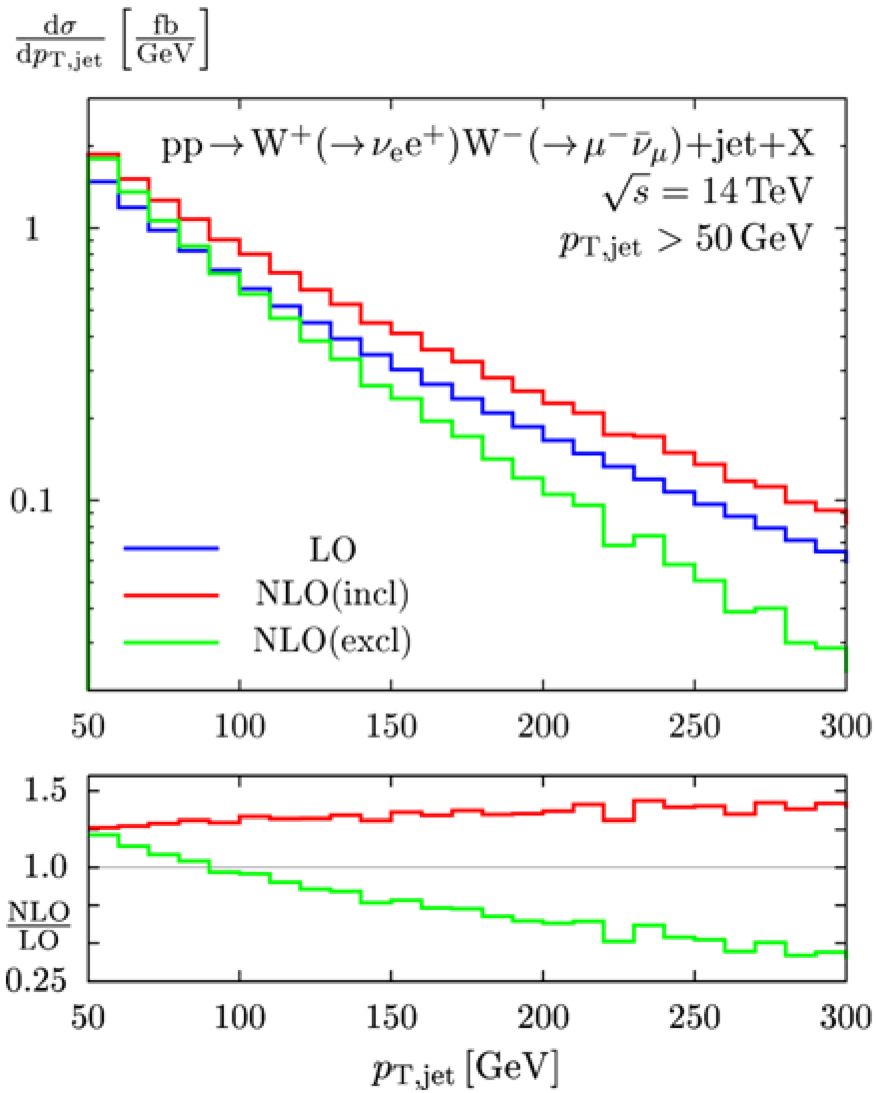
Pt-dependent Renormalization scale?

Differential distributions: LHC





Differential distributions: LHC



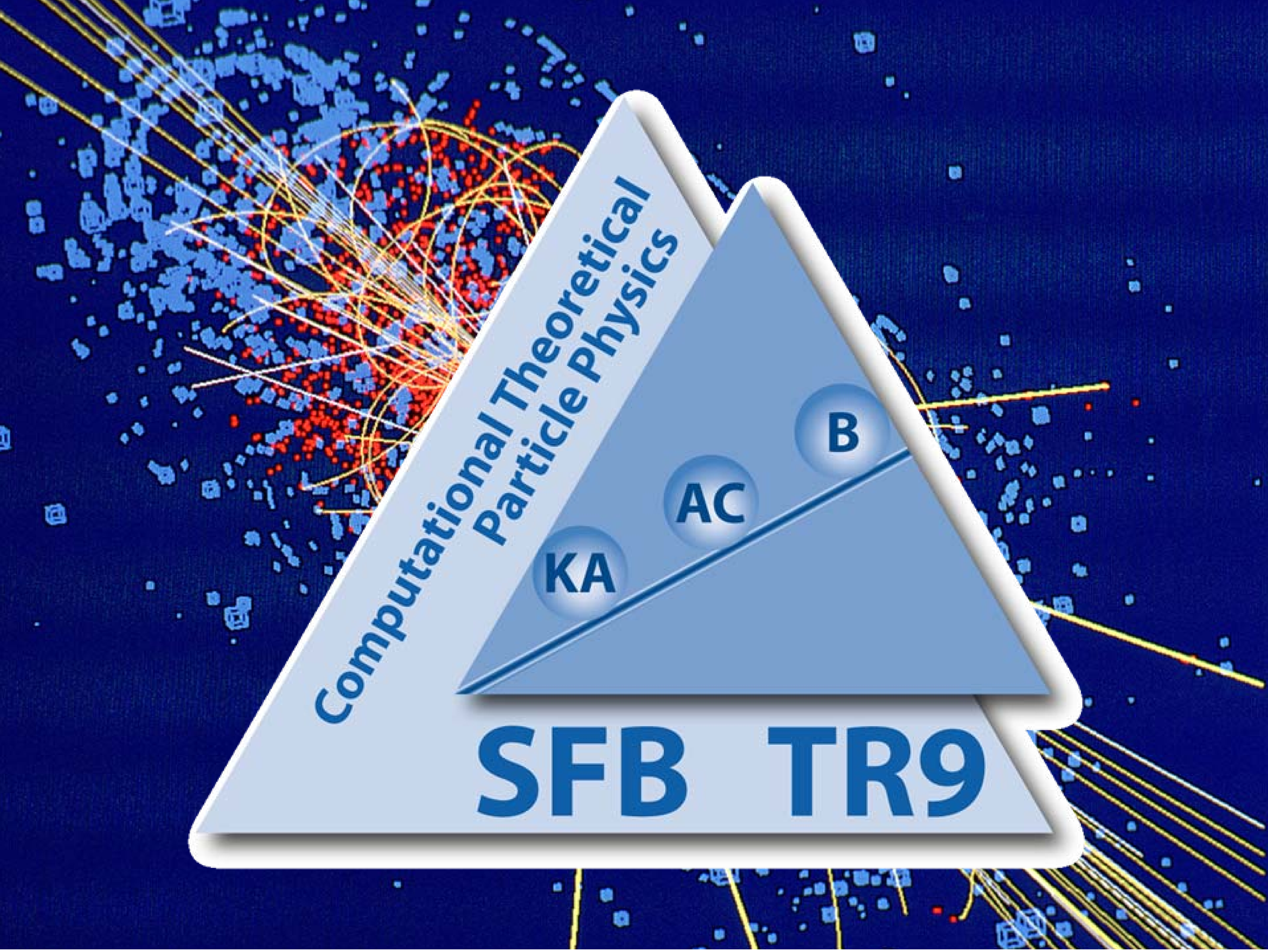
→ Same conclusion as before

Conclusions

- Our group: Two complete independent calculations
- In addition: perfect agreement with two other groups for individual phase space points
- Scale dependence is improved (→LHC jet-veto)
- Corrections are important, 10-30%
- NLO has only mild effect on the shape of most distributions

Outlook

- Apply VBF Higgs boson search cuts
- “Phase space” dependent scale setting ?


Computational Theoretical
Particle Physics
KA
AC
B
SFB TR9

Virtual corrections

Scalar integrals

$$\mathcal{A}_{1-\text{loop}} = \sum_i a_i A_i + \sum_i b_i B_i + \sum_i c_i C_i + \sum_i d_i D_i + R$$

Issues:

- Scalar integrals ✓
- How to derive the decomposition ?

Traditional approach: Passarino-Veltman reduction

Large expressions → numerical implementation

Numerical stability and speed are important

Reduction of tensor integrals — what we did…

Four and lower-point tensor integrals:

Reduction à la Passarino-Veltman,
with special reduction formulae in singular regions,

Five-point tensor integrals:

- Apply 4-dimensional reduction scheme, 5-point tensor integrals are reduced to 4-point tensor integrals

→ No dangerous Gram determinants! [Denner, Dittmaier ‘02]

Based on the fact that in 4 dimension 5-point integrals can be reduced to 4 point integrals
[Melrose ´65, v. Neerven, Vermaseren ‘84]

Two independent computer codes based on:

- Feynarts 1.0 + Mathematica library + Fortran library
- Feynarts 3.2 [Hahn ‘00] + FormCalc/LoopTools [Hahn, Perez-Victoria ’98]

Next-to leading order corrections

$$\sigma_{\text{NLO}} = \underbrace{\int_{m+1} \sigma_{\text{real}} + \int_m \sigma_{\text{virt.}} + \int dx \int_m \sigma_{\text{fact.}}(x)}$$

Every piece is individually divergent,
only in the combination a finite result is obtained

Standard procedure: [Frixione,Kunszt,Signer ´95, Catani,Seymour ´96, Nason,Oleari 98, Phaf, Weinzierl, Catani,Dittmaier,Seymour, Trocsanyi ´02]

Dipole subtraction method

$$\sigma_{\text{NLO}} = \underbrace{\int_{m+1} [\sigma_{\text{real}} - \sigma_{\text{sub}}]}_{\text{finite}} + \underbrace{\int_m [\sigma_{\text{virt.}} + \bar{\sigma}^1_{\text{sub}}]}_{\text{finite}} + \underbrace{\int dx \int_m [\sigma_{\text{fact.}}(x) + \bar{\sigma}_{\text{sub}}(x)]}_{\text{finite}}$$

With:

$$0 = -\int_{m+1} \sigma_{\text{sub}} + \int_m \bar{\sigma}^1_{\text{sub}} + \int dx \int_m \bar{\sigma}_{\text{sub}}(x)$$

$\sigma_{\text{sub}} \longrightarrow \sigma_{\text{real}}$ in all single-unresolved regions

Dipole subtraction method

$$\sigma_{\rm NLO} = \underbrace{\int_{m+1} [\sigma_{\rm real} - \sigma_{\rm sub}]}_{\text{finite}} + \underbrace{\int_m [\sigma_{\rm virt.} + \bar{\sigma}^1_{\rm sub}]}_{\text{finite}} + \underbrace{\int dx \int_m [\sigma_{\rm fact.}(x) + \bar{\sigma}_{\rm sub}(x)]}_{\text{finite}}$$

Universal structure:

$$\sigma_{\rm sub} = \sum_{\rm dipoles} D_{ij,k}(p_i, p_j, p_k)$$

Generic form:

$$D_{ij;k} = -\frac{1}{(p_i + p_j) - m_{ij}^2} \langle \ldots, \widetilde{ij}, \ldots, \tilde{k}, \ldots \Big| \underbrace{\frac{\mathbf{T}_a \cdot \mathbf{T}_{ij}}{\mathbf{T}_{ij}} V_{ij,k}}_{\text{universal}} \Big| \ldots, \widetilde{ij}, \ldots, \tilde{k}, \ldots \rangle$$

Leading-order amplitudes
Vector in color space

Color charge operators, induce color correlation !

Spin dependent part, induces spin correlation !

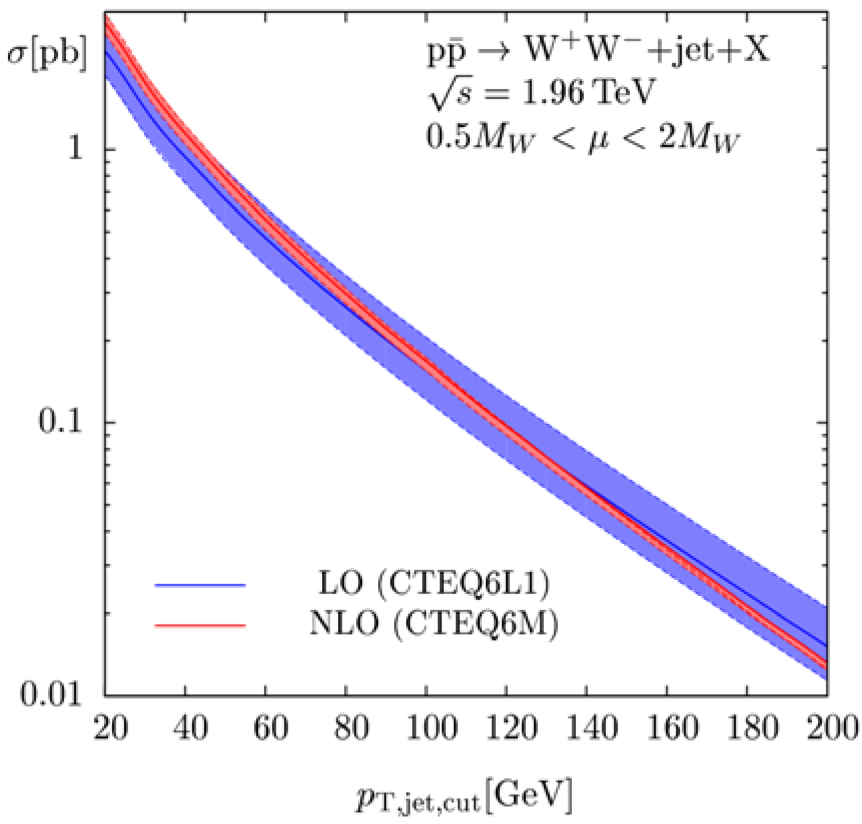
Example: $u\bar{u} \to W^+W^-gg$

→ 10 dipoles required

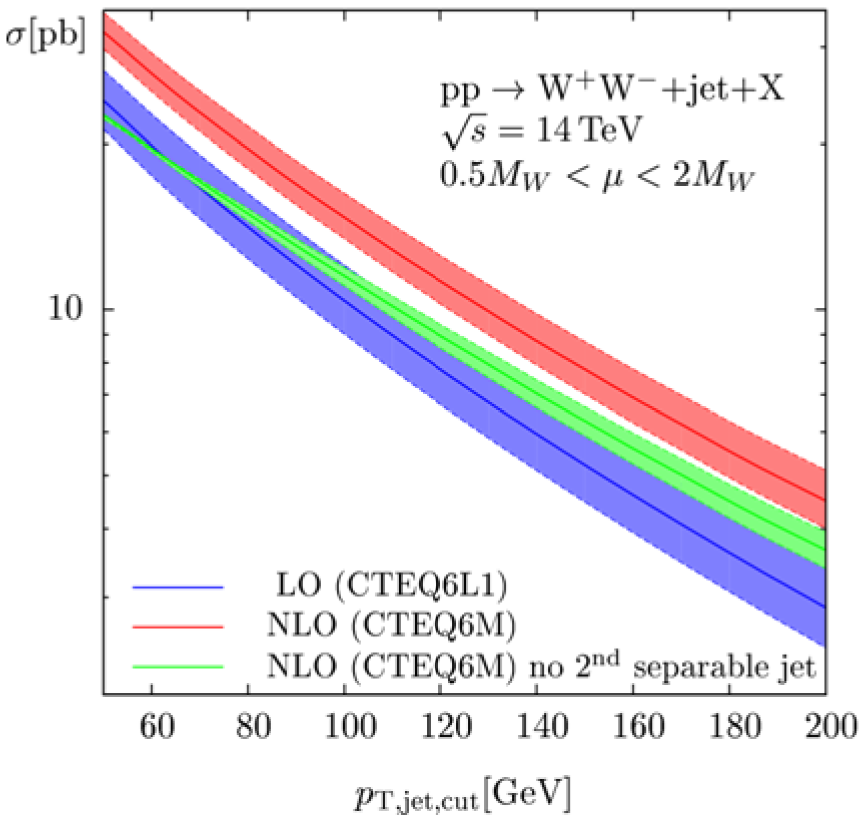
Results WW + 1-Jet — LHC: cut dependence

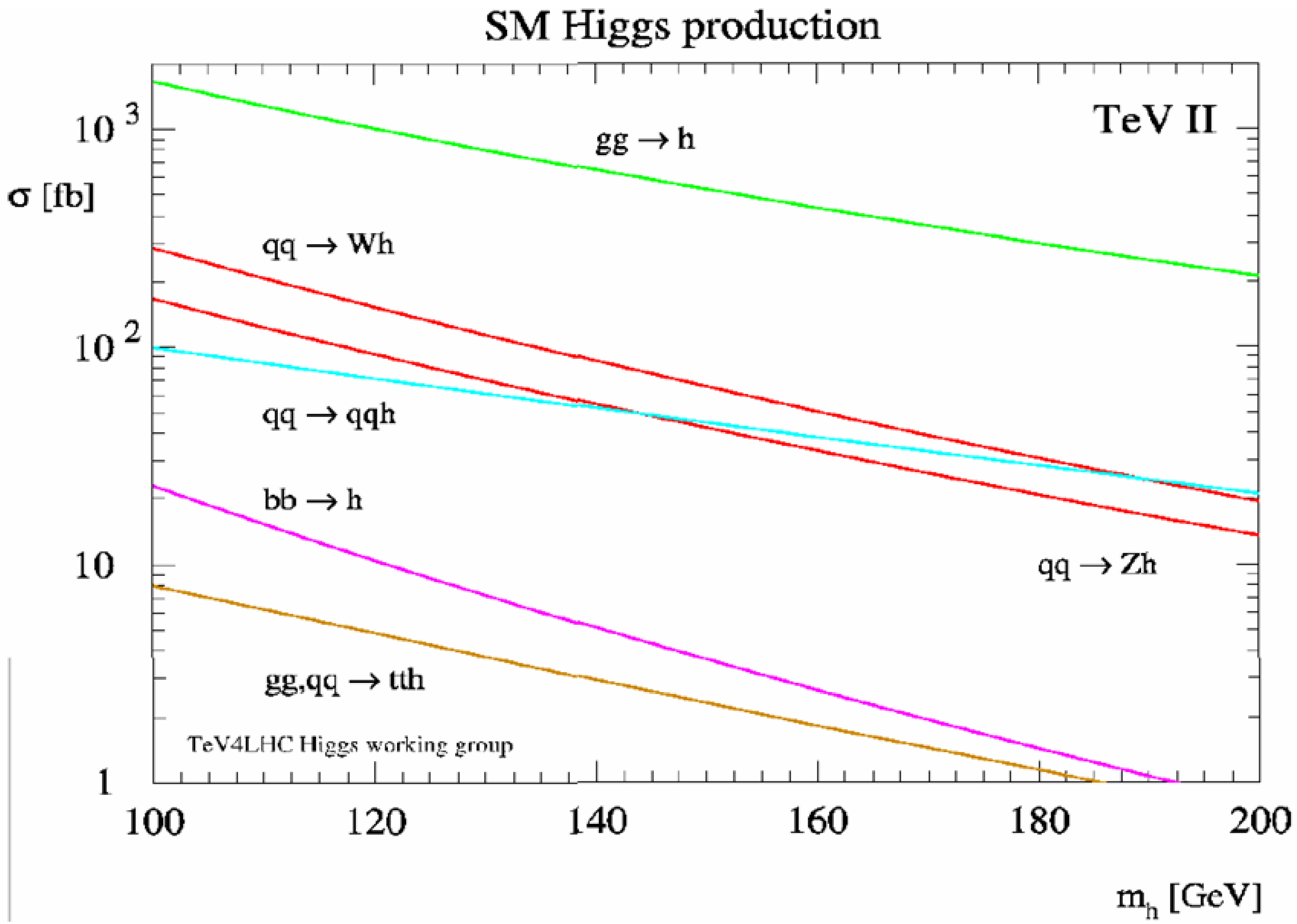
[Dittmaier, Kallweit, Uwer
Phys.Rev.Lett.100:062003,2008]

Tevatron



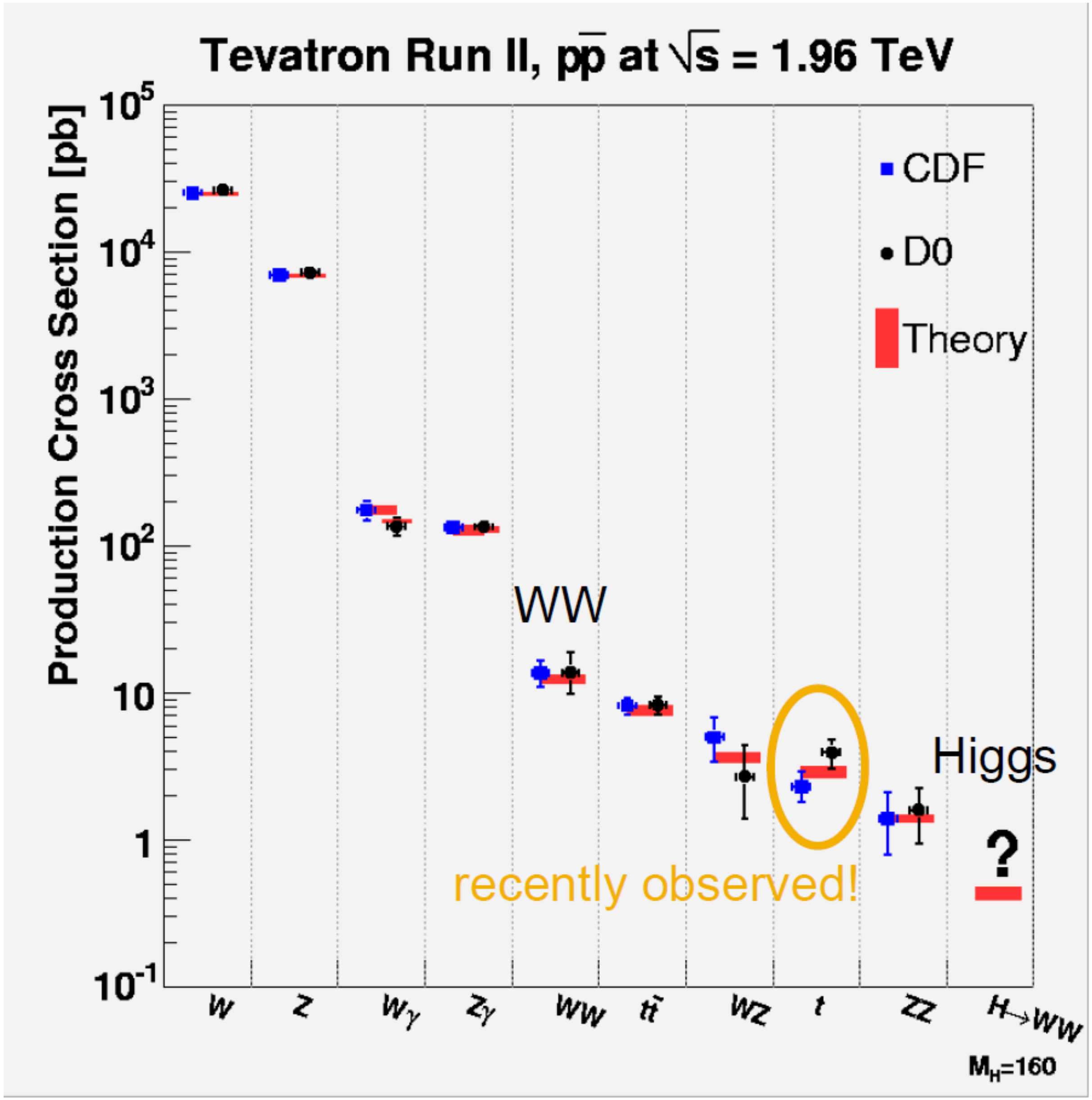
LHC




SM Higgs production
TeV II
σ [fb]
$gg \to h$
$qq \to Wh$
$qq \to qqh$
$bb \to h$
$qq \to Zh$
$gg,qq \to tth$
TeV4LHC Higgs working group
10^3
10^2
10
1
100
120
140
160
180
200
m_h [GeV]

- **New ggH signal x-sections by Florian at Grazzini (arXiv:0901.2427)**
  - included NNLL σ(gg→H), latest MSTW2008 pdf, 2-loop ewk corrections, exact b-quark treatment @ NLO

M_H (GeV/c^2)	$\sigma_{gg\to H}$ (pb)	σ_{WH} (pb)	σ_{ZH} (pb)	σ_{VBF} (pb)	$\mathrm{Br}_{\mathrm{H\to WW}}$
110	1.413	0.208	0.124	0.084	0.044
120	1.093	0.153	0.093	0.072	0.132
130	0.858	0.114	0.071	0.061	0.287
140	0.682	0.086	0.054	0.052	0.483
145	0.611	0.075	0.048	0.048	0.573
150	0.548	0.065	0.042	0.045	0.682
155	0.492	0.057	0.037	0.041	0.801
160	0.439	0.051	0.033	0.038	0.901
165	0.389	0.044	0.029	0.035	0.957
170	0.349	0.039	0.026	0.033	0.965
175	0.314	0.034	0.023	0.031	0.951
180	0.283	0.031	0.021	0.028	0.935
190	0.231	0.024	0.017	0.024	0.776
200	0.192	0.019	0.014	0.021	0.735


Tevatron Run II, $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
Production Cross Section [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
CDF
D0
Theory
WW
Higgs
?
recently observed!
W
Z
Wγ
Zγ
WW
$t\bar{t}$
WZ
t
ZZ
H→WW
M_H=160