Electroweak Physics
From Low To High Energies

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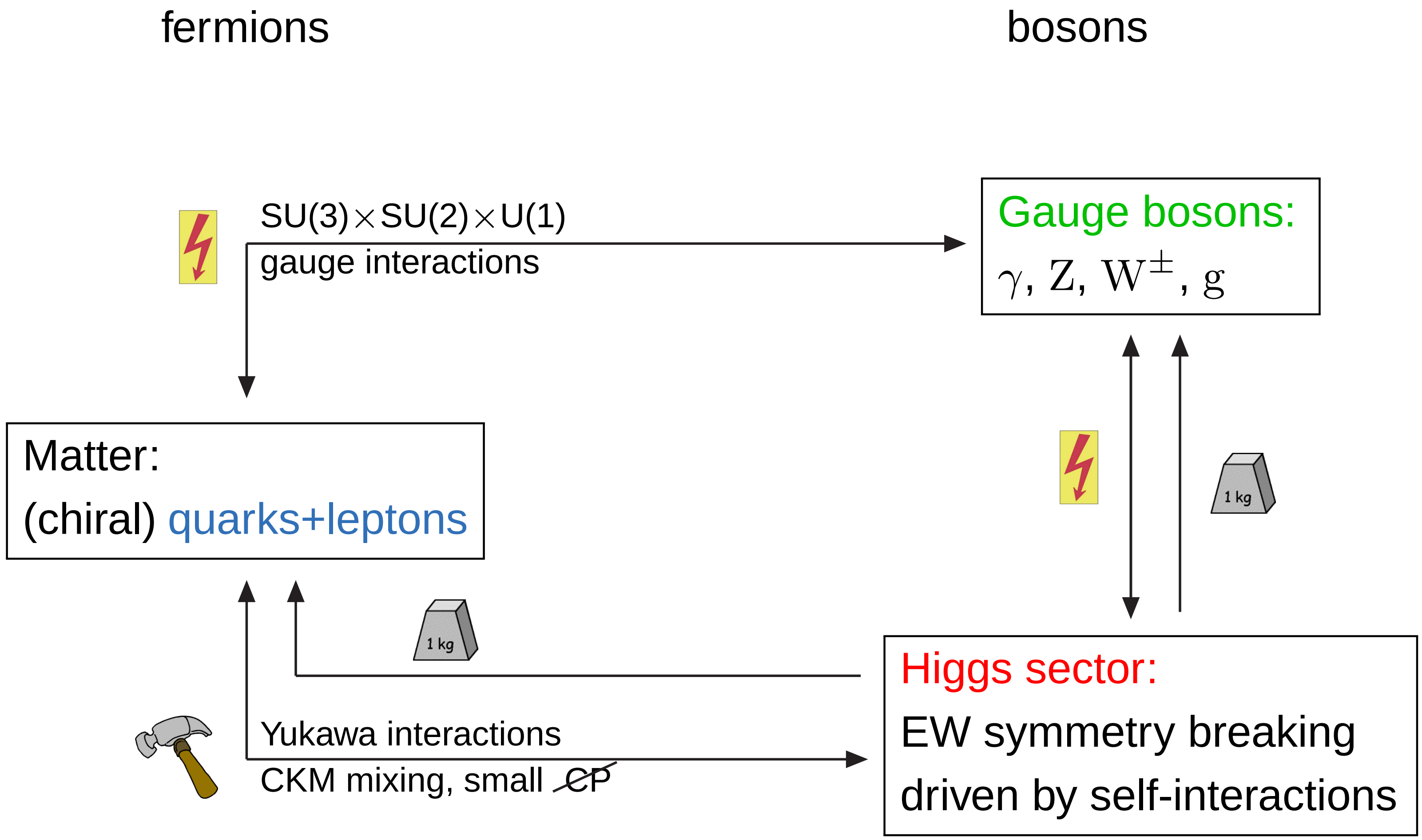
Electroweak Physics ...

The Standard Model and ideas beyond



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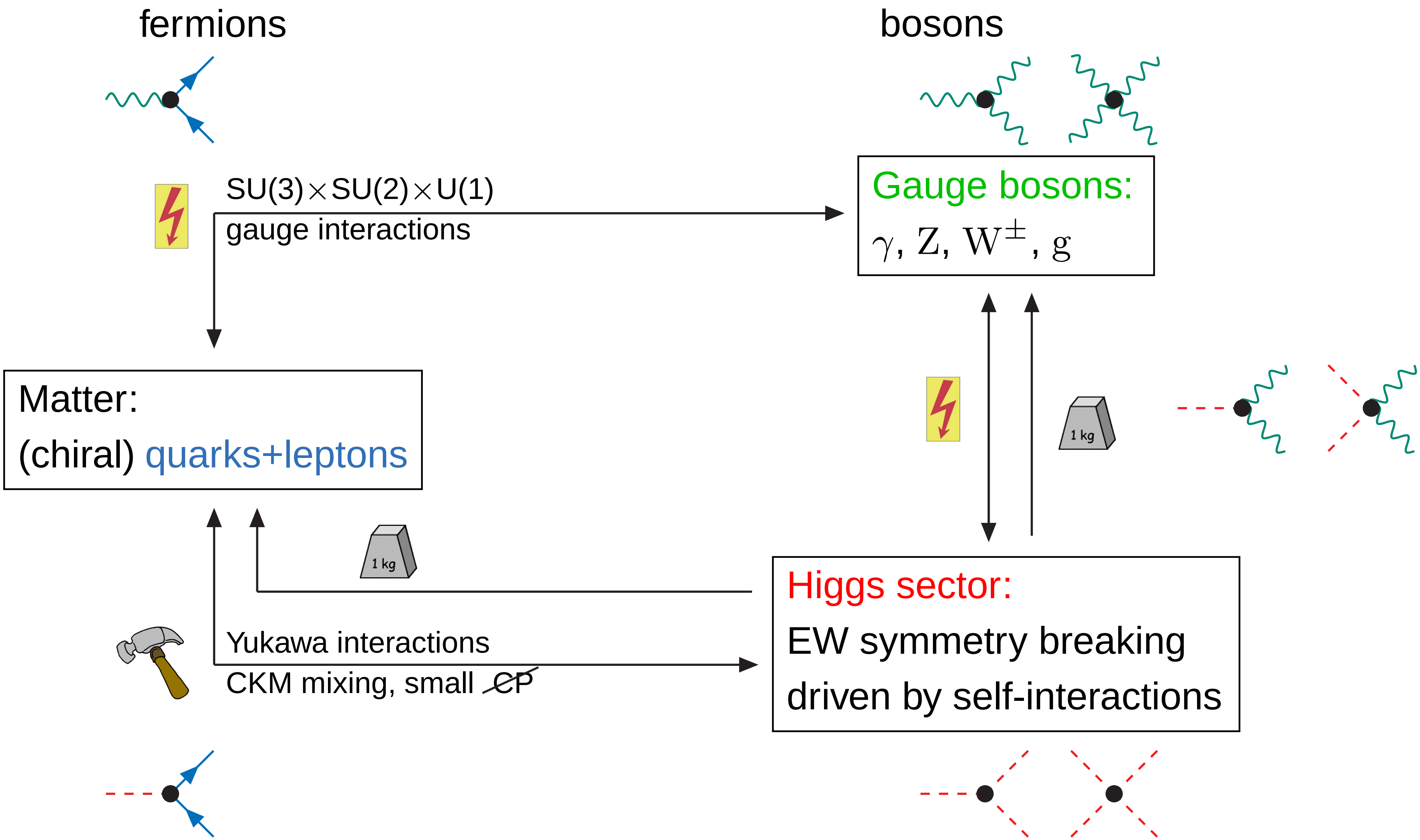

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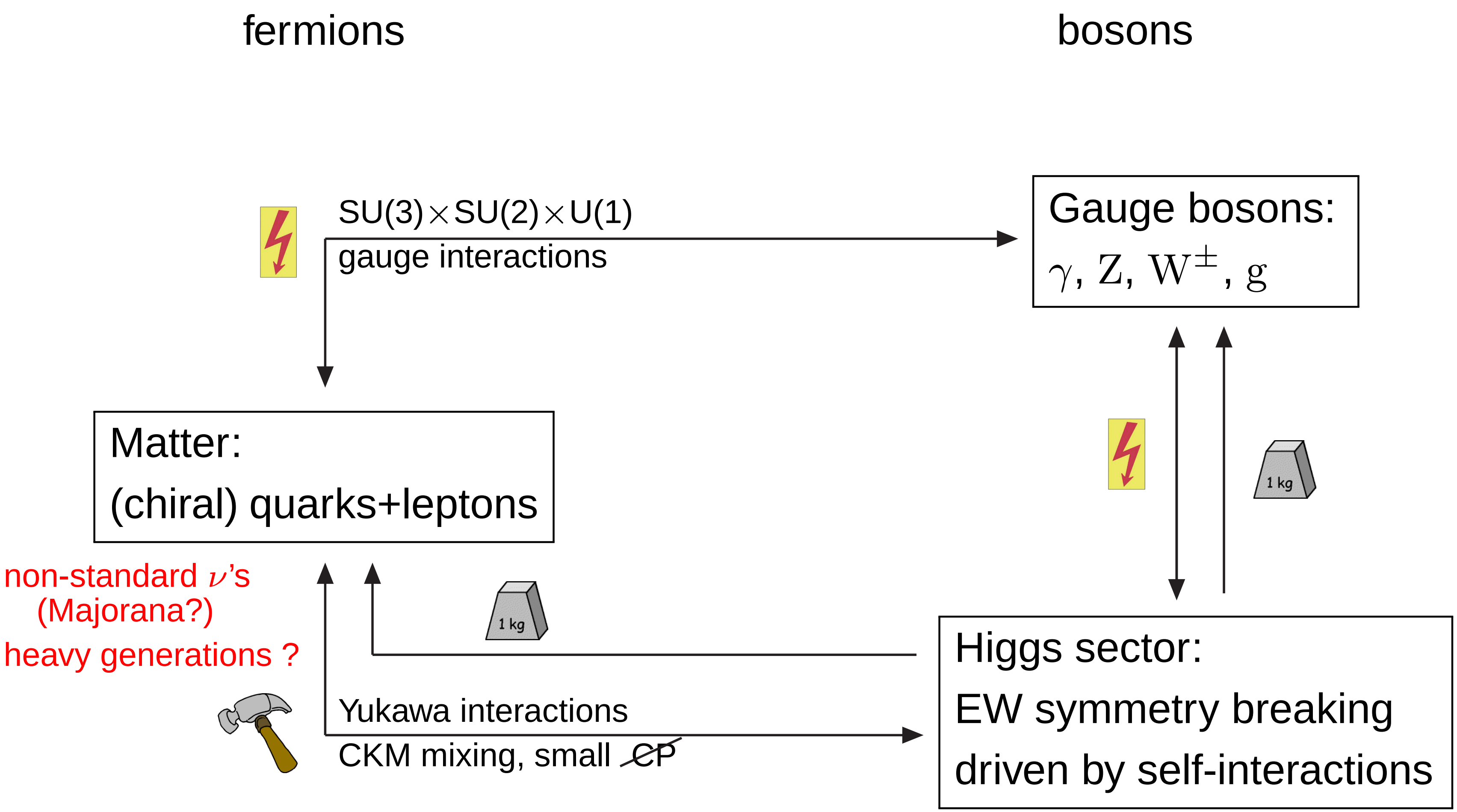

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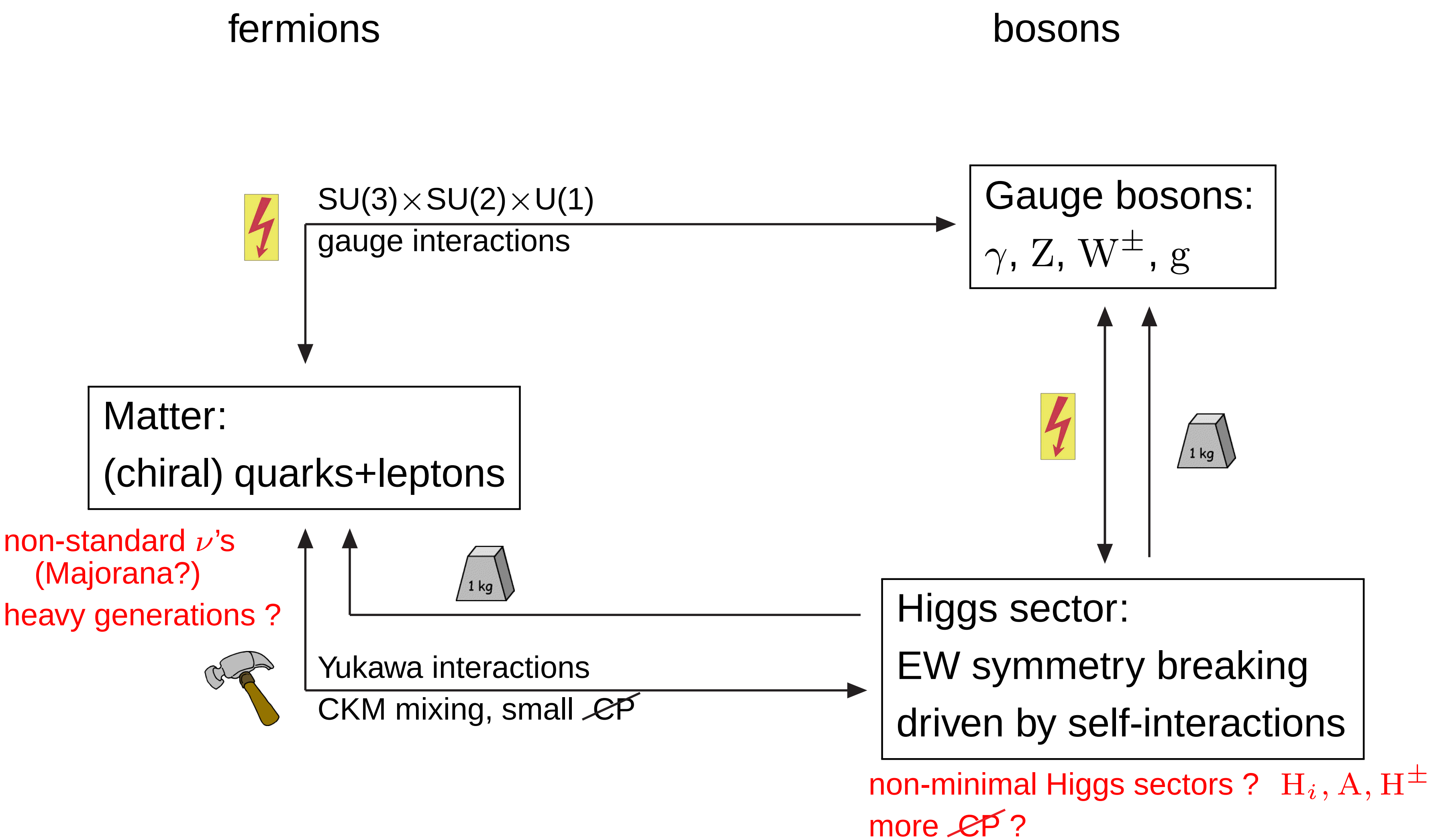

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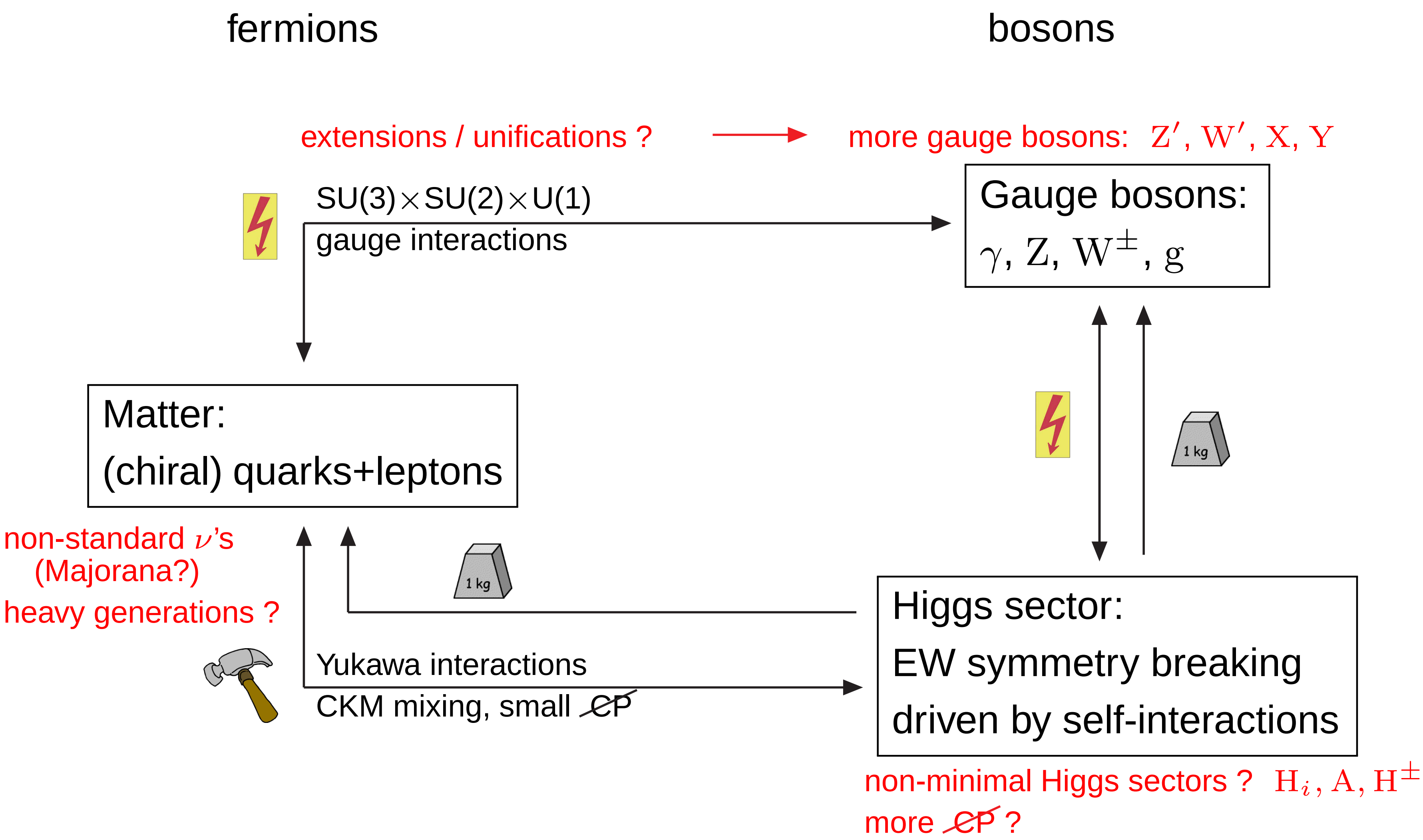

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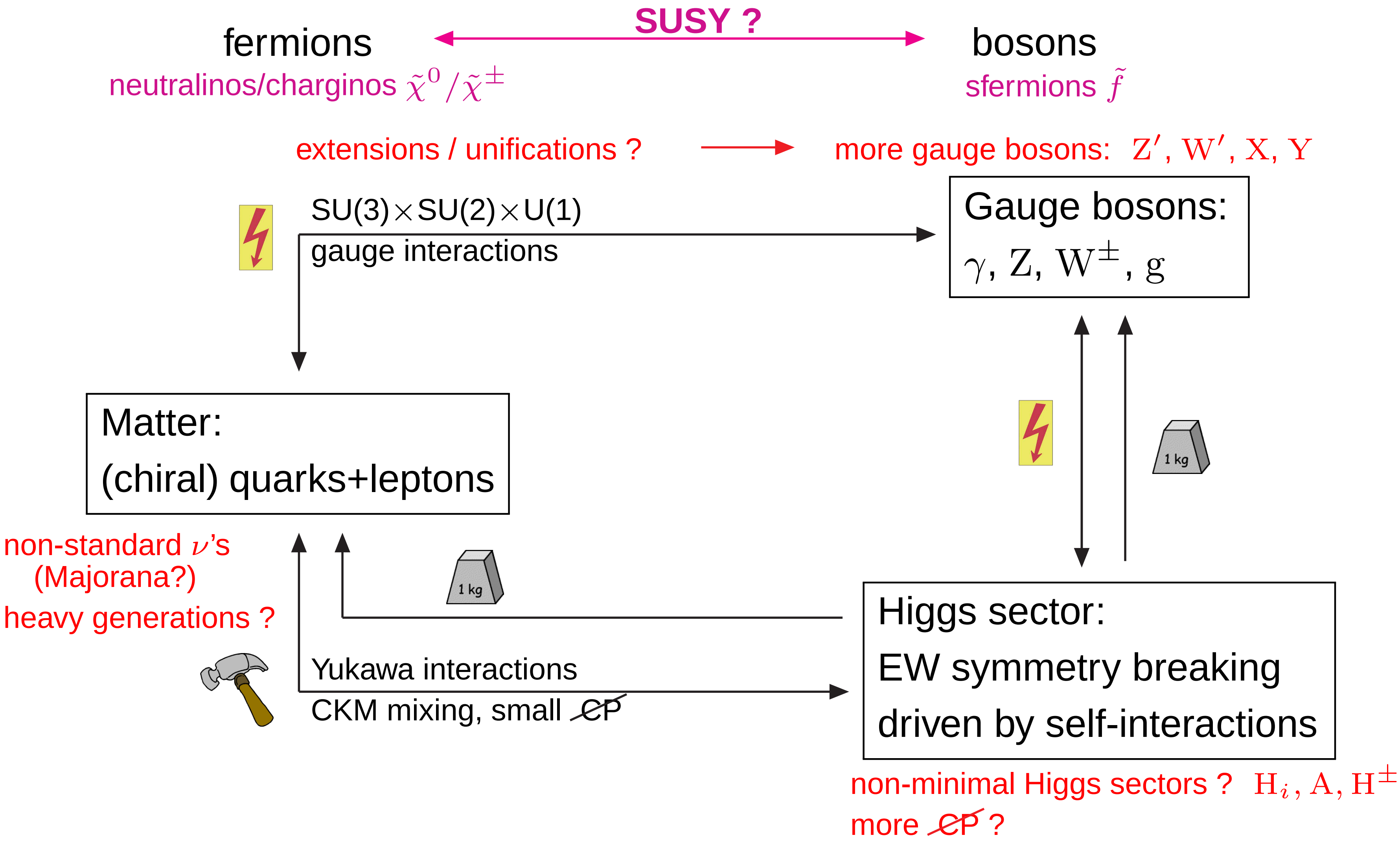


Electroweak Physics ...

The Standard Model and ideas beyond

fermions ⟵ **SUSY ?** ⟶ bosons

neutralinos/charginos $\tilde{\chi}^0/\tilde{\chi}^\pm$ — sfermions $\tilde{f}$

extensions / unifications ? ⟶ more gauge bosons: Z', W', X, Y

SU(3)×SU(2)×U(1) gauge interactions ⟶ **Gauge bosons:** γ, Z, $W^\pm$, g

Matter: (chiral) quarks+leptons

non-standard ν's (Majorana?)

heavy generations ?

Yukawa interactions

CKM mixing, small $\not{CP}$

Higgs sector: EW symmetry breaking driven by self-interactions

non-minimal Higgs sectors ? H_i, A, $H^\pm$

more $\not{CP}$?

+ more exotic ideas (extra dimensions, little Higgs, . . .)

Intention of the talk:

- brief overview over empirical tests of the electroweak theory
- highlight some important examples
- emphasis on Standard Model predictions and the role of precision

Contents

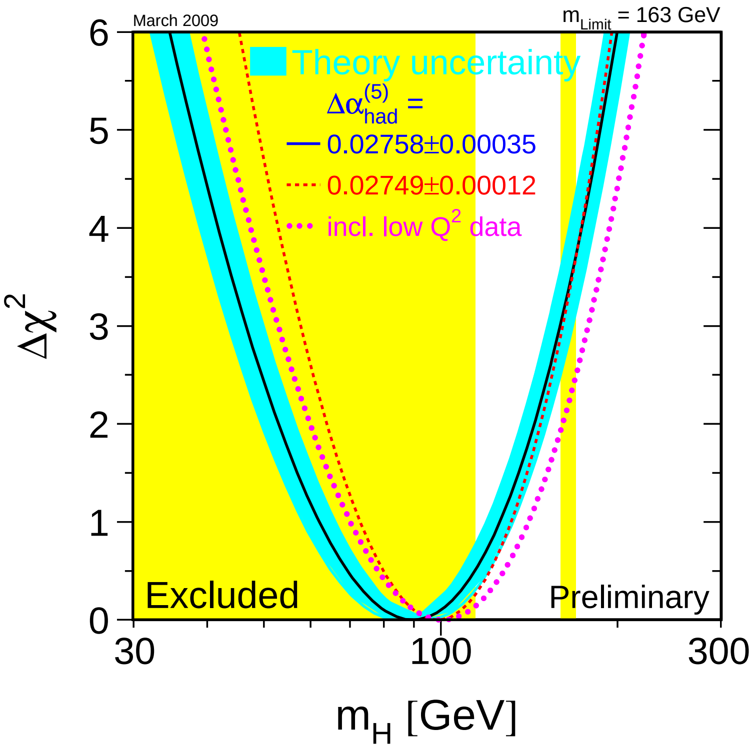
... after the LEP era

Experiments at LEP/SLC/Tevatron

- confirmation of Standard Model as quantum field theory
  (quantum corrections significant)
- top mass m_t indirectly constrained by quantum corrections
  $\leftrightarrow$ in agreement with m_t measurement of Tevatron
- Higgs mass M_H indirectly constrained by quantum corrections
  $\hookrightarrow$ impact on Higgs searches

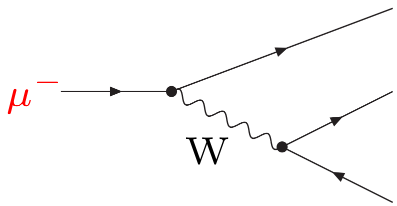
Great success of precision physics

- $M_\mathrm{H} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)
  $\mathrm{e}^+\mathrm{e}^- \not\to \mathrm{ZH}$ at LEP2
- $M_\mathrm{H} < 160\,\mathrm{GeV}$ and $M_\mathrm{H} > 170\,\mathrm{GeV}$
  $\mathrm{p}\bar{\mathrm{p}} \not\to \mathrm{H}\to\mathrm{WW}$ at Tevatron (CDF/D0 '09)
- $M_\mathrm{H} < 163\,\mathrm{GeV}$ (LEPEWWG '09)
  fit to precision data
  i.e. via quantum corrections



Important electroweak experiments

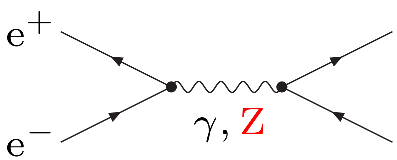
- Muon decay: $\mu^- \to \nu_\mu \mathrm{e}^- \bar{\nu}_\mathrm{e}$



determination of the Fermi constant

$$G_\mu = \frac{\pi \alpha M_\mathrm{Z}^2}{\sqrt{2} M_\mathrm{W}^2 (M_\mathrm{Z}^2 - M_\mathrm{W}^2)} + \ldots$$

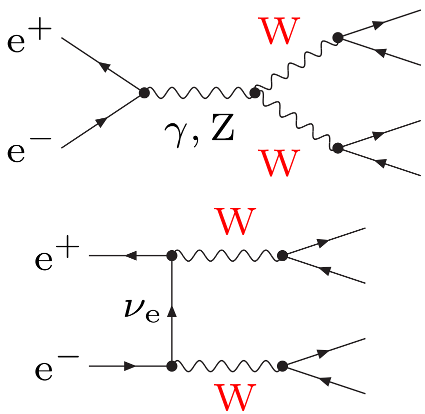
- Z production (LEP1/SLC): $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z} \to f\bar{f}$



various precision measurements at the Z resonance: $M_\mathrm{Z}, \Gamma_\mathrm{Z}, \sigma_\mathrm{had}, A_\mathrm{FB}, A_\mathrm{LR}$, etc.

$\Rightarrow$ good knowledge of the $\mathrm{Z}f\bar{f}$ sector

- W-pair production (LEP2/ILC): $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW} \to 4f(+\gamma)$



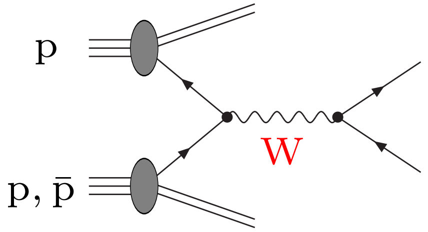
– measurement of M_W

– $\gamma\mathrm{WW}$/ZWW couplings

– quartic couplings: $\gamma\gamma\mathrm{WW}$, $\gamma\mathrm{ZWW}$

Important electroweak experiments (continued)

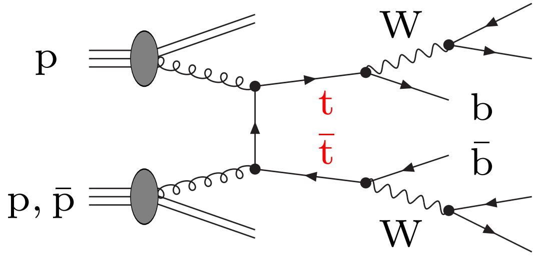
- W production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{W} \to l\nu_l(+\gamma)$



  – measurement of M_{W}

  – $\gamma\mathrm{WW}$ coupling

- top-quark production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{t\bar{t}} \to 6f$



  – measurement of m_{t}

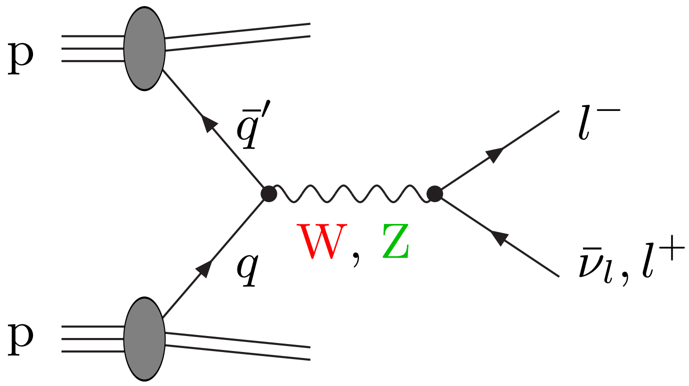
Theoretical predictions

parametrized by $\alpha(M_{\mathrm{Z}})$, M_{W}, M_{Z}, m_{t}, m_f, $\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$ and M_{H}

$\hookrightarrow$ global fit of SM to data yields bounds on M_{H}

Note: fit is particularly sensitive to m_{t}, M_{W}, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

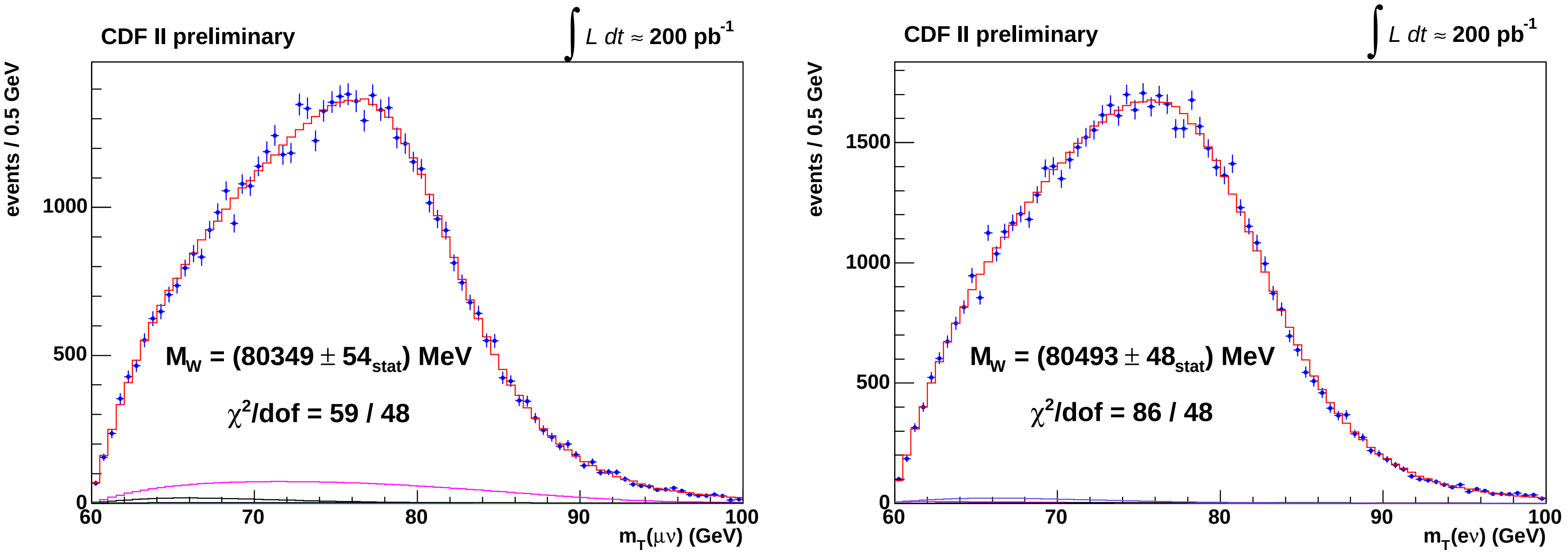
Example: W- and Z-boson production at hadron colliders



Physics goals:

- M_Z $\to$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ $\to$ comparison with results of LEP1 and SLC
- M_W $\to$ improvement to $\Delta M_W \sim 15\,\mathrm{MeV}$, strengthen EW precision tests (W/Z shape comparisons even sensitive to $\Delta M_W \sim 7\,\mathrm{MeV}$ at LHC)
  Besson et al. '08
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{T,l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{T,l\nu_l}$
- information on PDFs

Fits of M_W to W transverse mass at the Tevatron



Theory prediction based on QCD resummations (improved by some EW corrections)

Result from CDF: $M_\mathrm{W} = 80.413 \pm 0.048\,\mathrm{GeV}$ (=most precise single measurement)

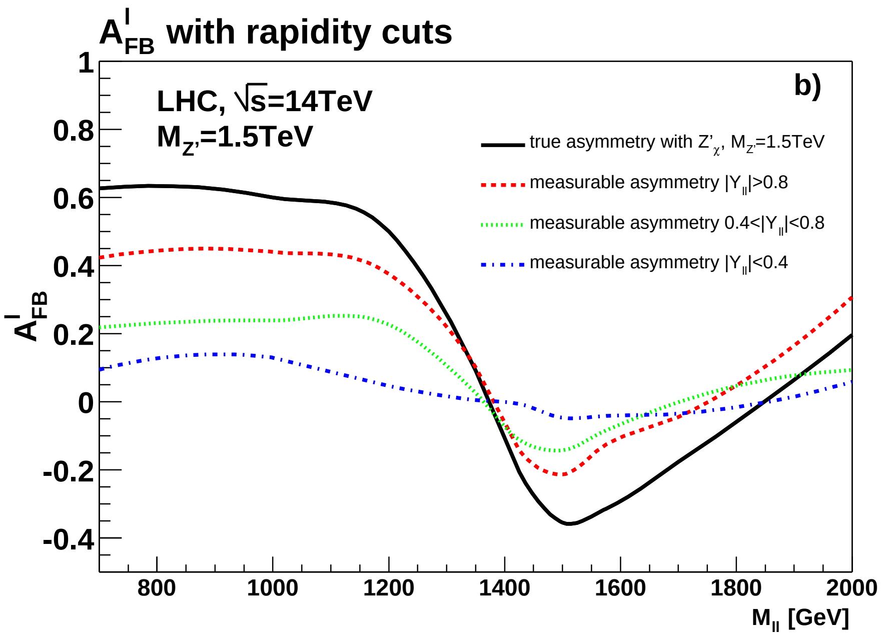
Combined with D0: $M_\mathrm{W} = 80.420 \pm 0.031\,\mathrm{GeV}$ (from Fermilab homepage)

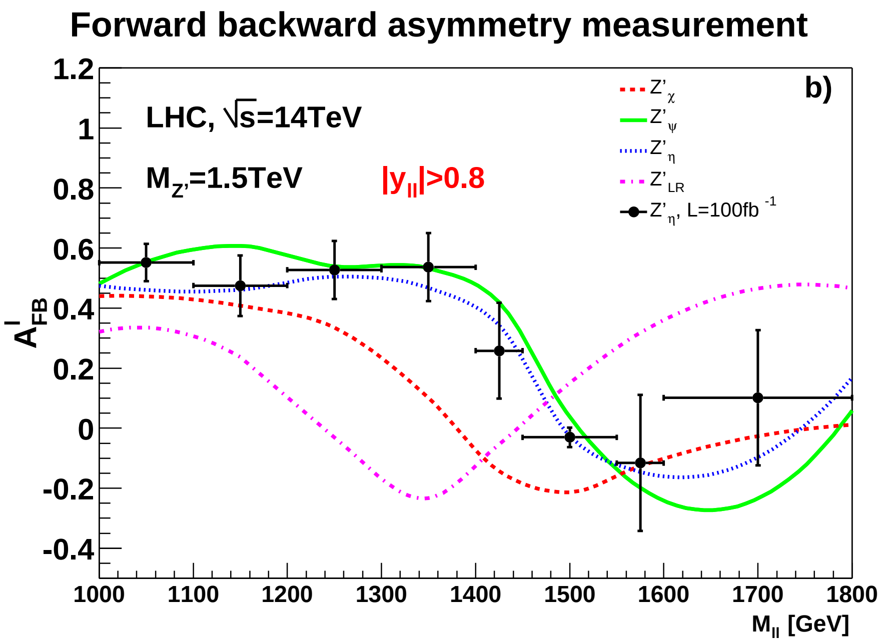
Result from LEP: $M_\mathrm{W} = 80.376 \pm 0.033\,\mathrm{GeV}$

World average 2009: $M_\mathrm{W} = 80.399 \pm 0.023\,\mathrm{GeV}$

Z' studies via FB asymmetry at the LHC

Dittmar, Djouadi, Nicollerat '03





- Naive definition: $A_{\mathrm{FB}} = 0$ in pp collisions (no preferred direction!)

  "Good" definition: identify boost direction of l^+l^- pair with quark direction

  (x spectra of q / $\bar{\mathrm{q}}$ on average lead to boost in q direction)

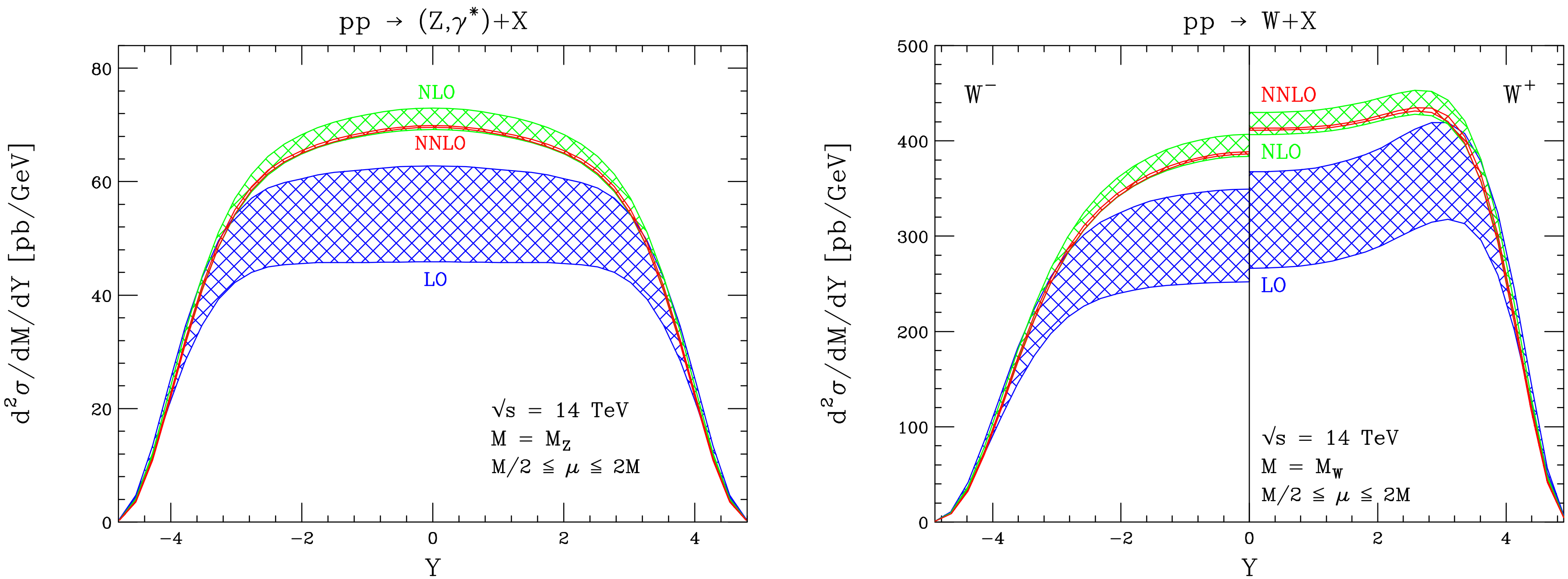
- Measureable A_{FB} can be enhanced upon excluding small Z rapidity Y_{ll}

  $\hookrightarrow$ require e.g. $|Y_{ll}| > 0.8$

- A_{FB} can discriminate between different Z' models at the LHC

NNLO QCD corrections for single W/Z production

- total cross section Hamberg, v.Neerven, Matsuura '91; v.Neerven, Zijlstra '92
  Harlander, Kilgore '02
- $\mathrm{W/Z}$ rapidity distribution Anastasiou et al. '03



- fully differential cross section $\mathrm{pp}(\to \mathrm{W}) \to l\nu_l + X$ Melnikov, Petriello '06; Catani et al. '09

Further improvements:

- Soft-gluon resummation (partially combined with γ emission) Balazs, Yuan '97; Landry et al. '02
  Cao, Yuan '04
- NLO EW corrections

NLO EW corrections to W/Z production:

- NLO EW correction to W production — Baur, Keller, Wackeroth '98; S.D., Krämer '02; Baur, Wackeroth '04; Arbuzov et al. '05; Carloni Calame et al. '06
- NLO EW correction to Z production — Baur, Keller, Sakumoto '97; Baur, Wackeroth '99; Brein, Hollik, Schappacher '99; Arbuzov et al. '06
- multi-photon radiation via leading logs — Baur, Stelzer '99; Carloni Calame et al. '03; Placzek, Jadach '04; Brensing et al. '07
- NLO SUSY corrections in the MSSM — Brensing et al. '07

Comparison of NLO EW corrections to W production:

$\mathrm{pp} \to \nu_l l^+ (+\gamma)$ at $\sqrt{s} = 14\,\mathrm{TeV}$ — Les Houches SMH proceedings '06

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$
σ_0/pb						
DK	$2112.2(1)$	$13.152(2)$	$0.9452(1)$	$0.057730(5)$	$0.0054816(3)$	$0.00026212(1)$
$\delta_{\mu^+\nu_\mu}/\%$						
DK	$-2.75(1)$	$-5.03(2)$	$-7.98(1)$	$-14.43(1)$	$-21.99(1)$	$-32.15(1)$
HORACE	$-2.77(1)$	$-5.08(1)$	$-8.01(1)$	$-14.44(1)$	$-21.99(1)$	$-32.16(1)$
SANC	$-2.76(2)$	$-5.06(2)$	$-7.96(2)$	$-14.41(2)$	$-21.94(2)$	$-32.12(2)$
WGRAD	$-2.69(1)$	$-4.84(1)$	$-7.96(1)$	$-14.48(1)$	$-22.03(1)$	$-32.3(1)$

Large corrections at high transverse W mass $M_{\mathrm{T},\nu_l l}$ (EW Sudakov logs, etc.)

Combination of NLO QCD and EW corrections in progress

Issue unambiguously fixed only by calculating the 2-loop $\mathcal{O}(\alpha\alpha_s)$ corrections, until then rely on approximations and estimate the uncertainties:

- Comparison of two extreme alternatives:

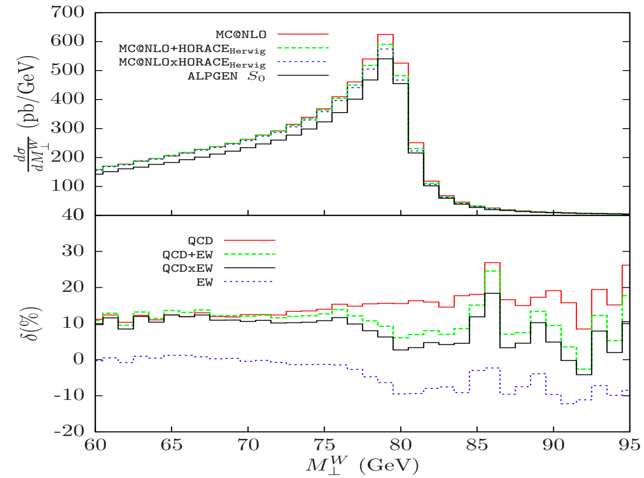
$$(1 + \delta_{\rm QCD}^{\rm NLO} + \delta_{\rm EW}^{\rm NLO})$$

versus

$$(1 + \delta_{\rm QCD}^{\rm NLO}) \times (1 + \delta_{\rm EW}^{\rm NLO})$$

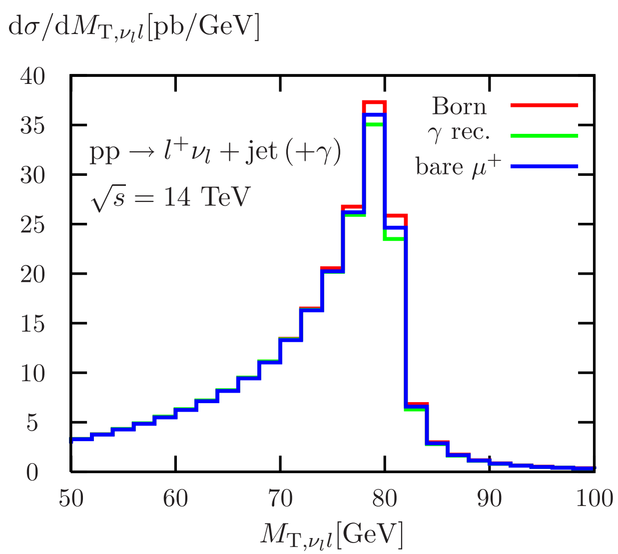
$\hookrightarrow$ underlines significance of $\mathcal{O}(\alpha\alpha_s)$ effects

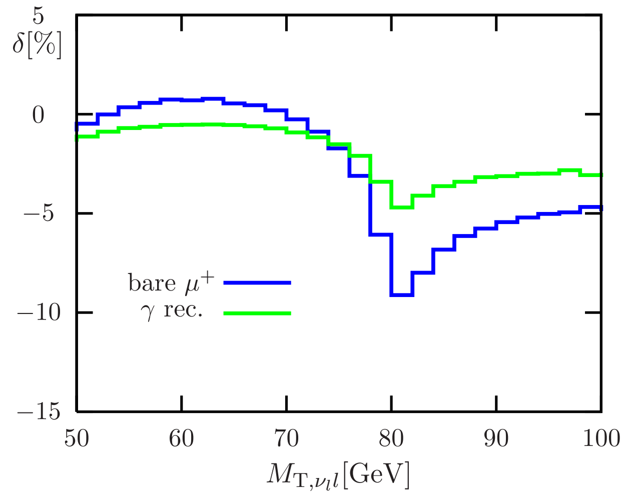
Balossini et al. '09



- Compare EW corrections to $\rm V$ and $\rm V + jet$ production

Denner, S.D., Kasprzik, Mück '09





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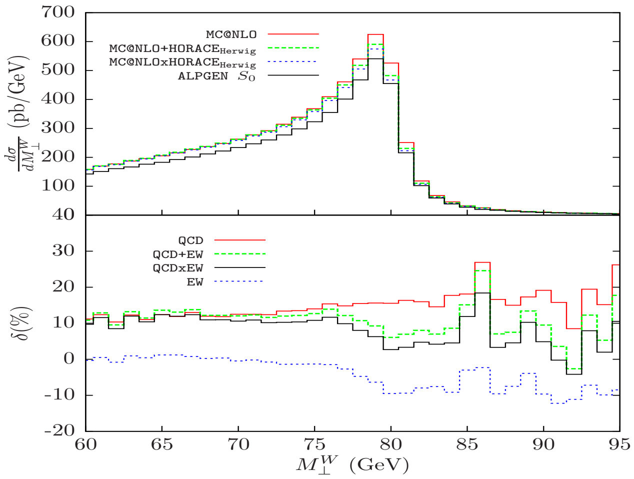

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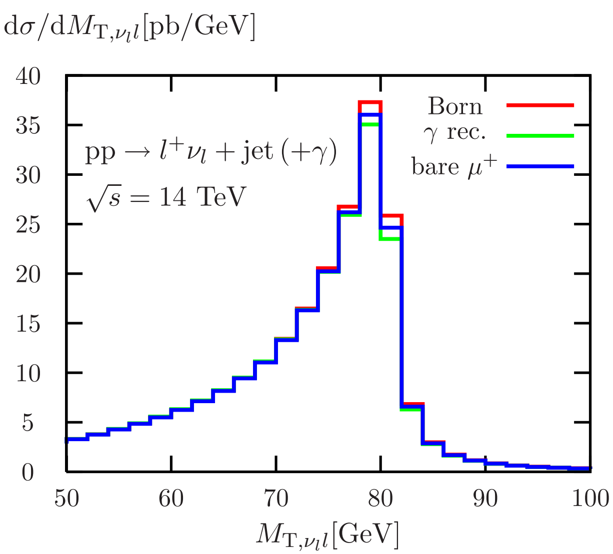
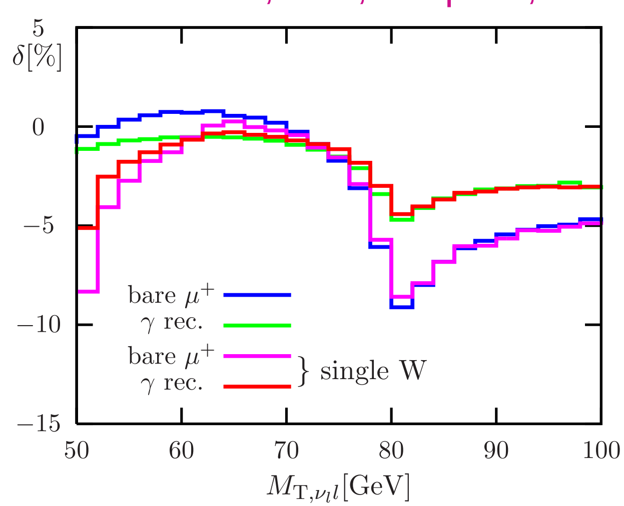




relative EW corrections practically identical near Jacobian peak

$\hookrightarrow$ supports factorization approach

Electroweak physics

... at the advent of the LHC

Electroweak issues for the LHC:

- Continue electroweak precision tests

  $\hookrightarrow$ indirect window to new physics

- Further analyze structure of gauge-boson self-interactions

  $\hookrightarrow$ triple couplings via gauge-boson pair production,
  quartic couplings via triple-gauge-boson production and
  gauge-boson scattering

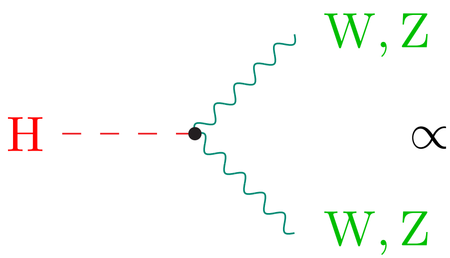
- Search for the Higgs boson(s)

  $\hookrightarrow$ either "Higgs": perform first studies of the Higgs profile

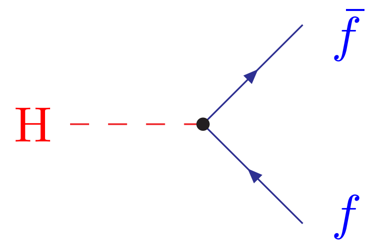
  or "no Higgs": look for alternative mechanisms
  of electroweak symmetry breaking

Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



$\propto M_{\rm W}$

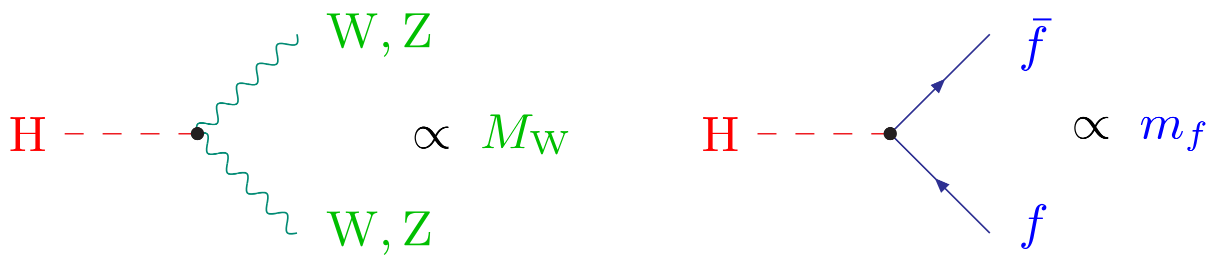


$\propto m_f$

$\Rightarrow$ Higgs production mainly via coupling to W/Z bosons or top quarks

Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



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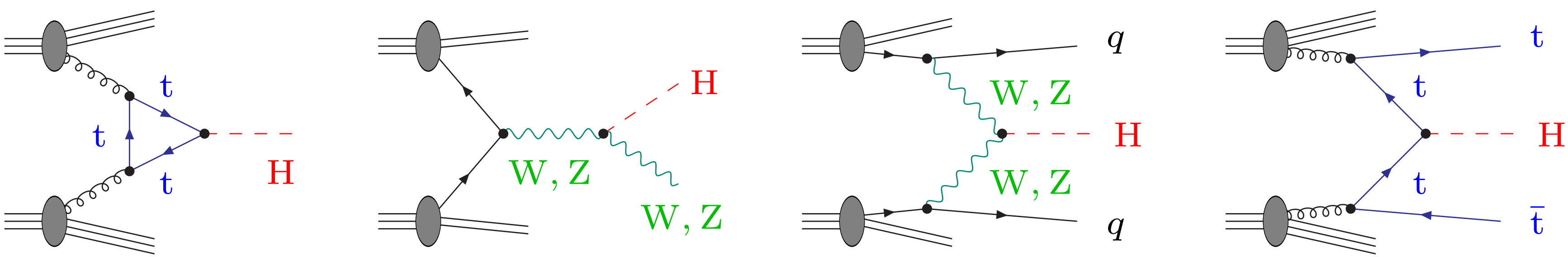
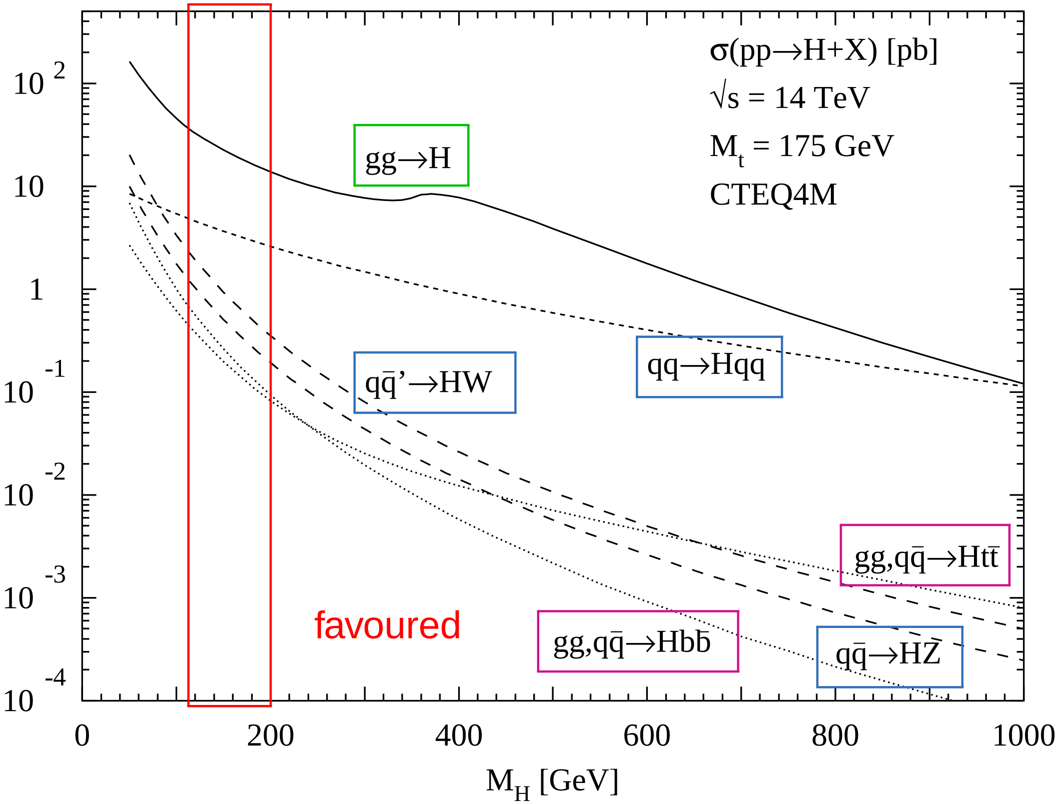
Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):

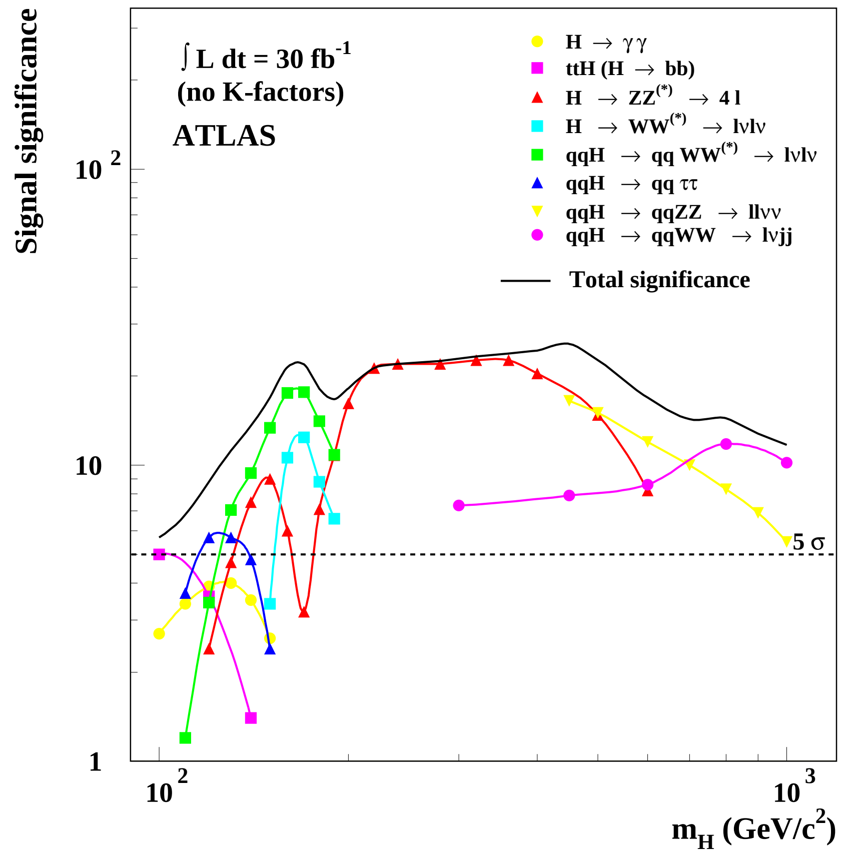


Cross sections and significance of the Higgs signal at the LHC

Spira et al. '98



ATLAS '04



Typical size perturbative corrections at next-to-leading order (NLO):

QCD: $\mathcal{O}(\alpha_s) \sim 10\text{–}100\%$ Electroweak: $\mathcal{O}(\alpha) \sim 10\%$

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($q\bar{q} \sim 5\%$, $gg \sim 10\%$) and experimental uncertainties

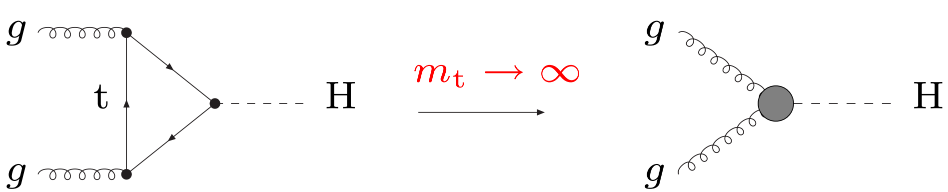
Complication: task requires "multi-loop" or "multi-leg" computations

A multi-loop example: Higgs production via gluon fusion at the LHC

- QCD corrections:
  - complete NLO correction known — Graudenz, Spira, Zerwas ’93; Djouadi, Graudenz, Spira, Zerwas ’95
  - NNLO correction known in limit $m_t \to \infty$ — Harlander, Kilgore ’01,’02; Catani, de Florian, Grazzini ’01; Anastasiou, Melnikov ’02; Ravindran, Smith, v.Neerven ’03,’04; Anastasiou, Melnikov, Petriello ’04

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

  - resummations / virtual / soft terms to NNNLO in limit $m_t \to \infty$ — Catani et al. ’03; Moch, Vogt ’05; Laenen, Magnea ’05; Idilbi, Ji, Ma, Yuan ’05; Ravindran ’05,’06; Ravindran, Smith, v.Neerven ’06; Ahrens, Becher, Neubert, Yang ’08; Pak, Rogal, Steinhauser ’09

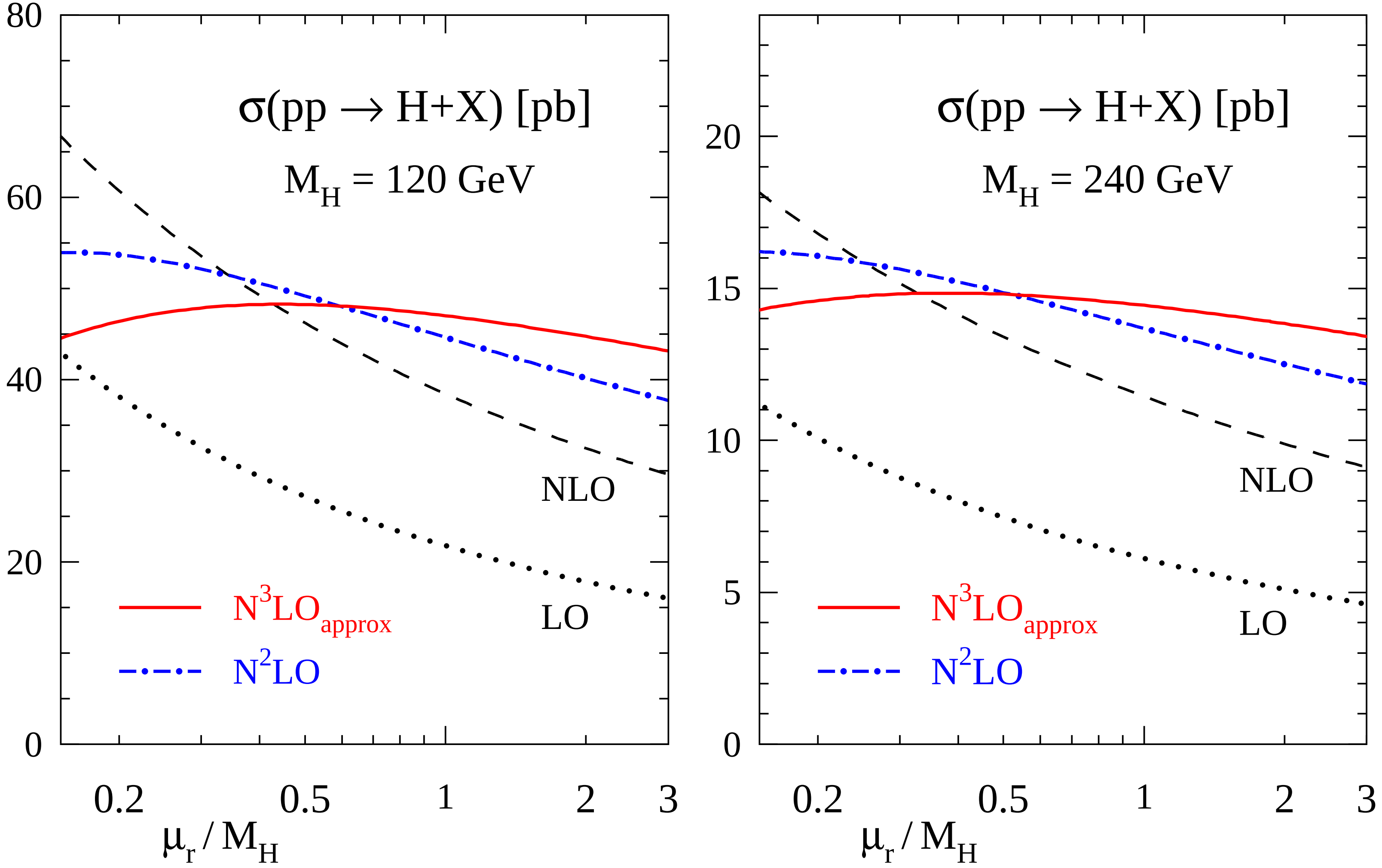


- EW corrections
  - complete NLO correction known $\sim \mathcal{O}(5\%)$ — Aglietti, Bonciani, Degrassi, Vicini ’04,’06; Degrassi, Maltoni ’04; Actis, Passarino, Sturm, Uccirati ’08
  - mixed $\mathcal{O}(\alpha\alpha_s)$ corrections for small M_H — Anastasiou, Boughezal, Petriello ’08

- Combination of production in NNLO QCD with Higgs decays
  - $H \to \gamma\gamma$ — Anastasiou, Melnikov, Petriello ’05; Catani, Grazzini ’07
  - $H \to WW \to l\nu l\nu$ — Anastasiou, Dissertori, Stöckli ’07; Grazzini ’08; Anastasiou, Dissertori, Stöckli, Webber ’08
  - $H \to ZZ \to 4l$ — Grazzini ’08

QCD scale dependence of predictions for inclusive $gg \to \mathrm{H}$

Moch, Vogt '05



Reduction of renormalization-scale dependence with increasing orders !

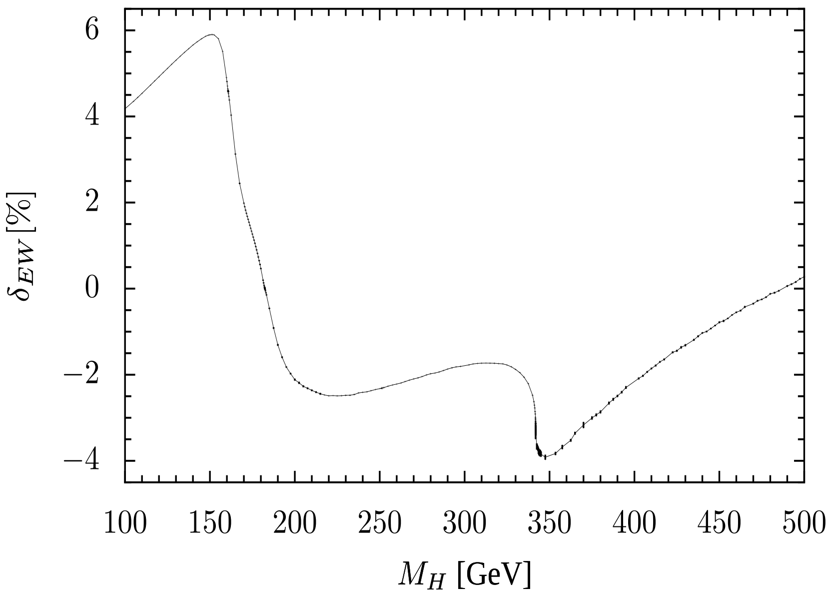
$\hookrightarrow$ residual scale uncertainty $\lesssim 5{-}10\%$

Recent error estimate with MSTW2008 NNLO: $\delta_{\mathrm{PDF}} \lesssim 3\%$ de Florian, Grazzini '09

NLO EW corrections

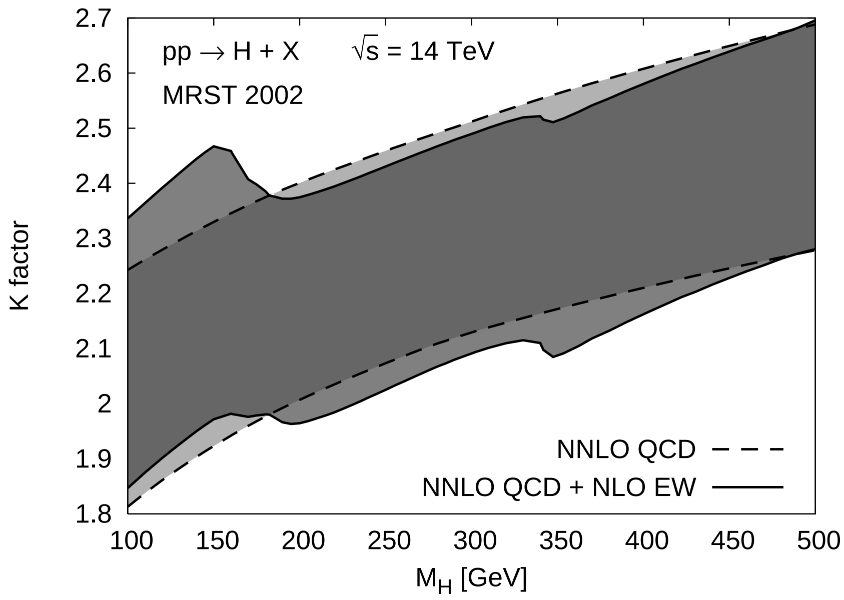
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:



K factors for pp cross section:

(band width: $M_{\mathrm{H}}/2 < \mu_{\mathrm{R/F}} < 2M_{\mathrm{H}}$, $\mu_{\mathrm{R}}/2 < \mu_{\mathrm{F}} < 2\mu_{\mathrm{R}}$)

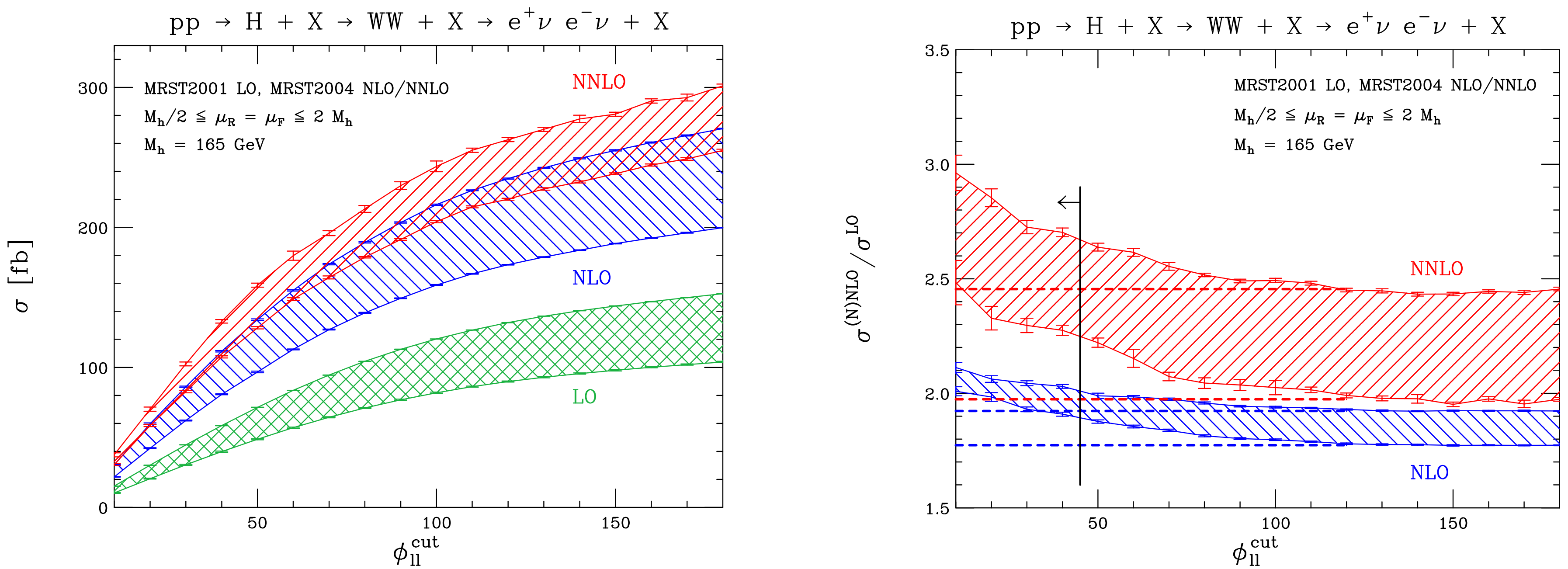


EW corrections ...

- matter at the 5% accuracy level
- show non-trivial structures near WW, ZZ, $\mathrm{t\bar{t}}$ thresholds
  $\hookrightarrow$ finite widths of particles in loops required (otherwise unphysical peaks)
- mixed $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for small M_{H} Anastasiou, Boughezal, Petriello '08
  suggest factorization of QCD and EW corrections within good accuracy

Combination of Higgs production and decay $\mathrm{H} \to \mathrm{WW} \to ll\nu\nu$

Anastasiou, Dissertori, Stöckli '07



ϕ_{ll} = angle between charged decay leptons in the transverse plane

K factors in general depend on decay phase space.

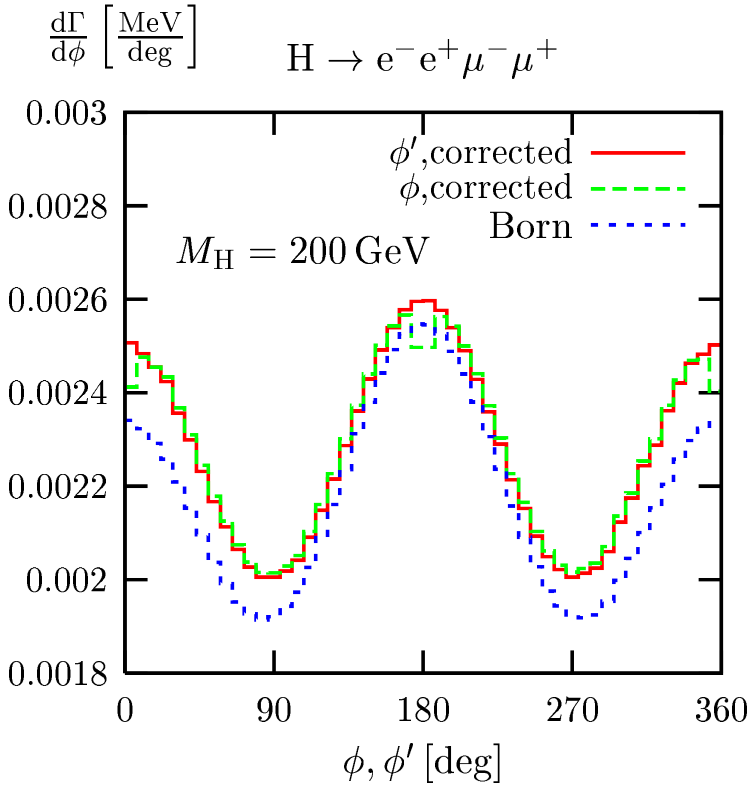
Comment on EW corrections to $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ decays

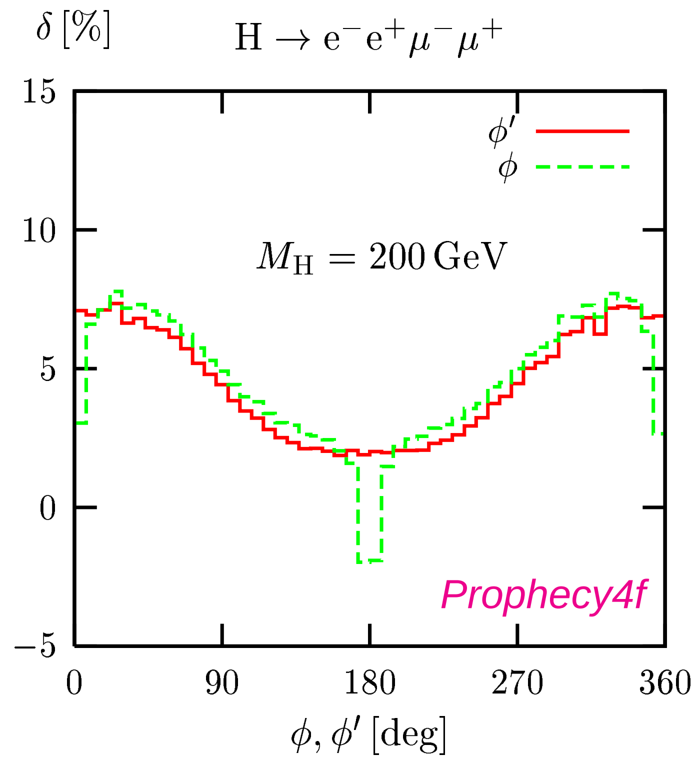
Bredenstein, Denner, S.D., Weber '06

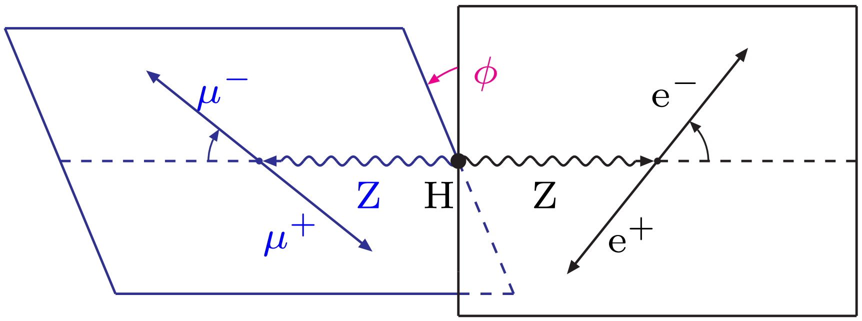
- generic size $\sim$ 5–10%
- in general distortion of distributions

An example: NLO EW corrections to $\mathrm{H} \to \mathrm{ZZ} \to 4l$

Bredenstein, Denner, S.D., Weber '06



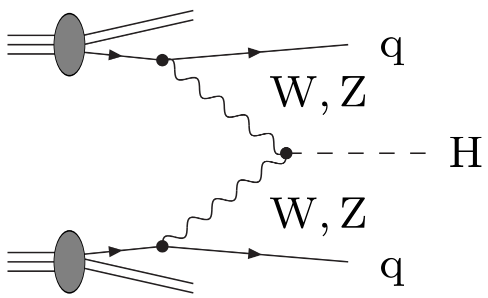




$$\cos\phi = \frac{(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-})(-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-})}{|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}||-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}|}$$

$$\cos\phi' = \frac{(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-})(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mu^-})}{|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}||\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mu^-}|}$$

A multi-leg example: Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

$\Rightarrow$ small QCD corrections

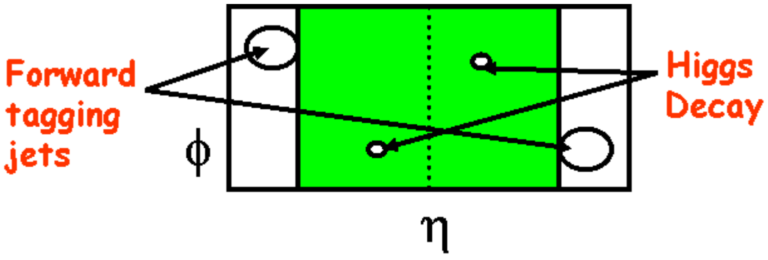
Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ t-channel approximation (vertex corrections)

VBF cuts and background suppression:

- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

signature $=$ Higgs + 2jets



$\hookrightarrow$ Suppression of background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94-'99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in “t-channel approximation” (vertex corrections)
  - ◇ total cross section — Han, Valencia, Willenbrock ’92; Spira ’98; Djouadi, Spira ’00
  - ◇ distributions — Figy, Oleari, Zeppenfeld ’03; Berger, Campbell ’04

  $\hookrightarrow$ impact $\sim 5\text{–}10\%$

- NLO QCD corrections to gluon-initiated channels (effective $\mathrm{H}gg$ coupling) — Campbell, R.K.Ellis, Zanderighi ’06

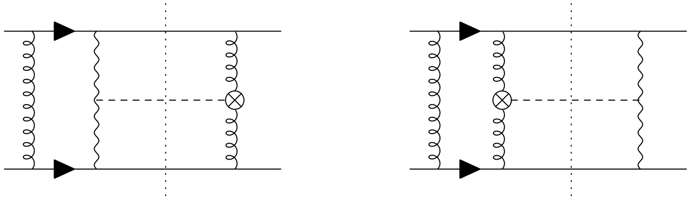
  $\hookrightarrow$ contribution to VBF $\sim 5\%$ — Nikitenko, Vazquez ’07 (NLO scale uncertainty $\sim 35\%$)

- (full) NLO QCD+EW corrections to VBF — Ciccolini, Denner, S.D. ’07

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim 5\text{–}10\%$

- QCD loop-induced interferences between VBF and gluon-initiated channels

  Andersen, Binoth, Heinrich, Smillie ’07
  Bredenstein, Hagiwara, Jäger ’08



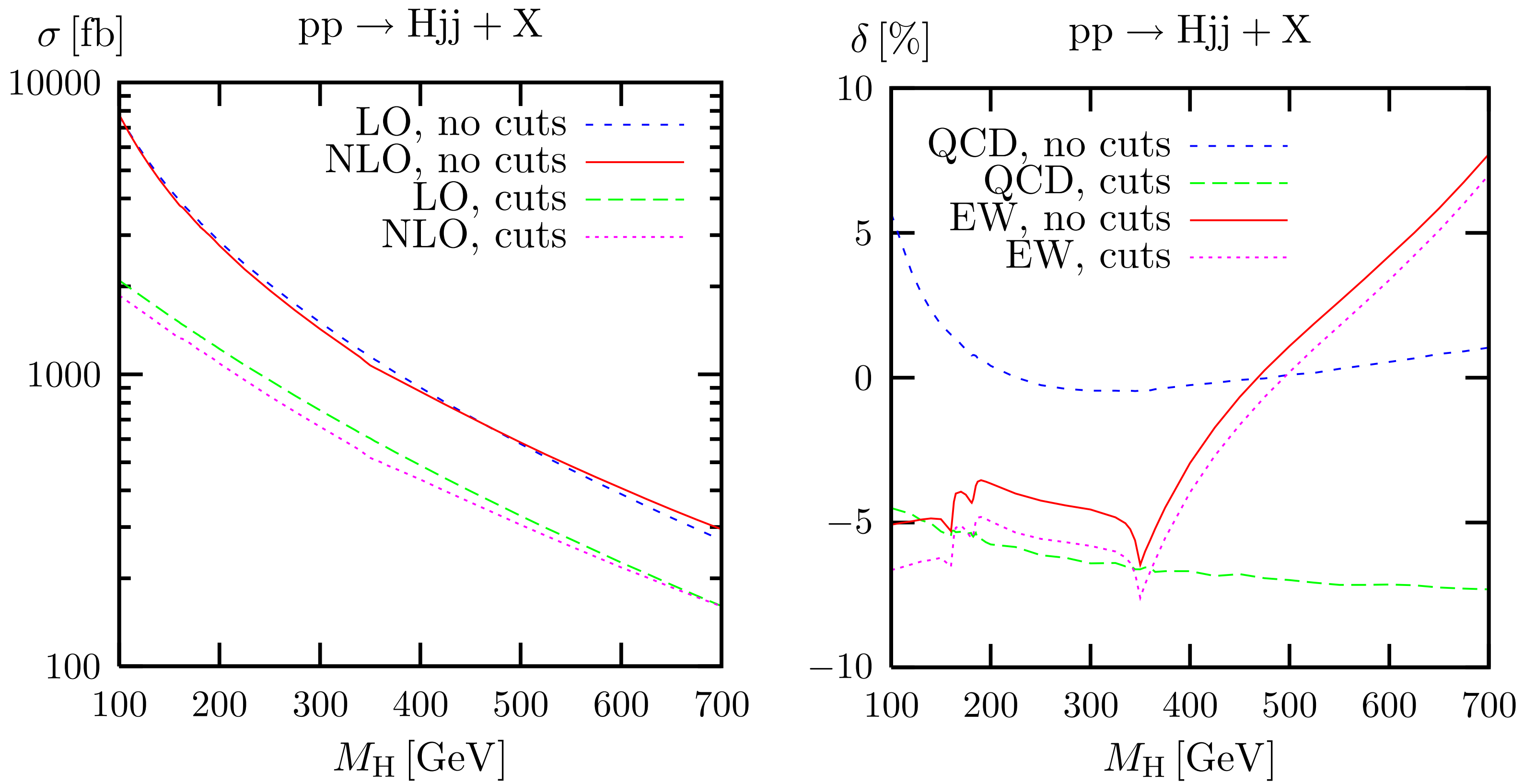
  $\rightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!)

- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak ’08

  $\hookrightarrow$ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points ($2\text{–}4\%$ for low SUSY scales)

Integrated VBF cross section at NLO QCD $\oplus$ EW

Ciccolini, Denner, S.D. '07



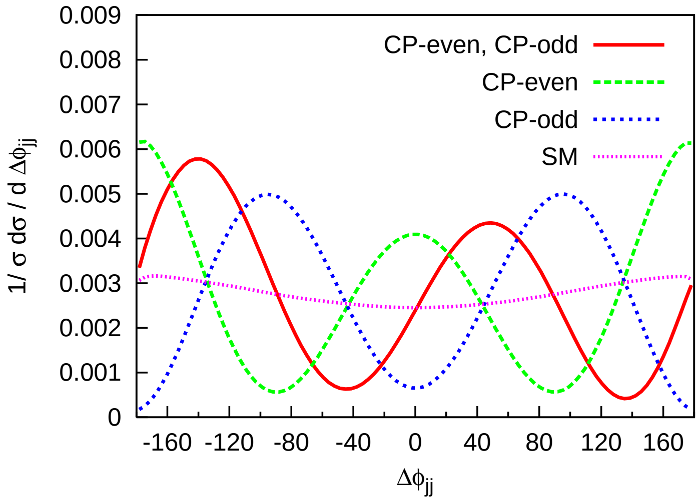
- QCD and EW corrections are of same generic size
- scale uncertainty $\sim 3\%$ within $M_\mathrm{W}/2 < \mu_\mathrm{ren/fact} < 2M_\mathrm{W}$ in NLO ($\sim 10\%$ in LO)
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_\mathrm{H} \sim 700\,\mathrm{GeV}$: $\underbrace{G_\mu M_\mathrm{H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_\mathrm{H}^2)^2}_{\text{2-loop}} \sim 4\%$

  $\hookrightarrow$ breakdown of perturbation theory

Distribution in the azimuthal angle difference $\Delta\phi_{\rm jj}$ of the tagging jets

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy ’06



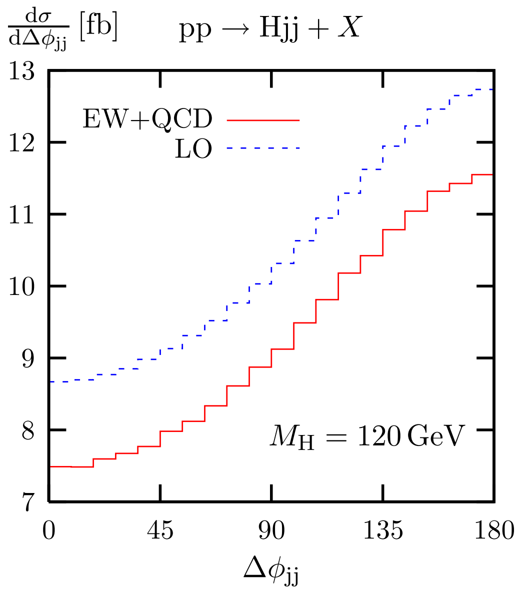
(Individual contributions
without SM)

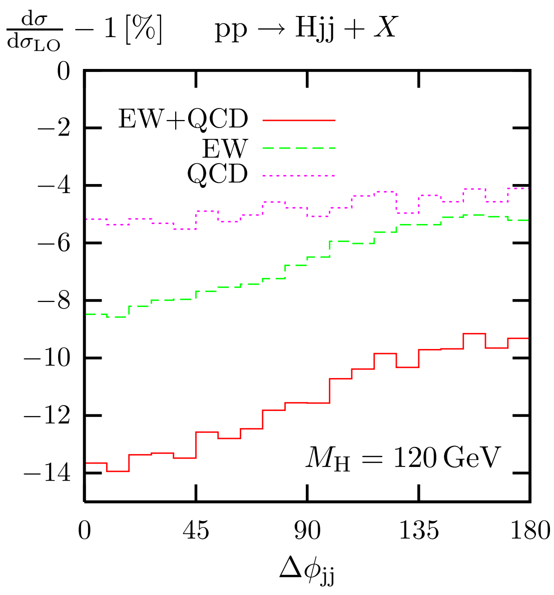
CP-even: $\mathcal{L} \propto HW^{+}_{\mu\nu}W^{-,\mu\nu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^{+}_{\mu\nu}W^{-,\mu\nu}$

Corrections to the $\Delta\phi_{\rm jj}$ distribution:

Ciccolini, Denner, S.D. ’07





Neglected corrections
could be misinterpreted
as non-standard couplings

Electroweak physics

... in the (far) future

Electroweak physics later at the LHC and at future e^+e^- colliders:

- Electroweak gauge bosons

  $\hookrightarrow$ dynamics / interactions at high energies

  (weakly vs. strongly interacting, soft/collinear weak-boson exchange/emission, etc.)

- Electroweak symmetry breaking

  ◇ "Higgs" – weakly interacting gauge bosons

  $\hookrightarrow$ detailed analysis of the Higgs profile,
  study of Yukawa couplings (input for flavour models),
  reconstruction of the Higgs potential,
  confirmation of weak interaction of longitudinal gauge bosons

  ◇ "No Higgs" – strongly interacting gauge bosons ?

  $\hookrightarrow$ search for heavy (scalar and/or vector) resonances

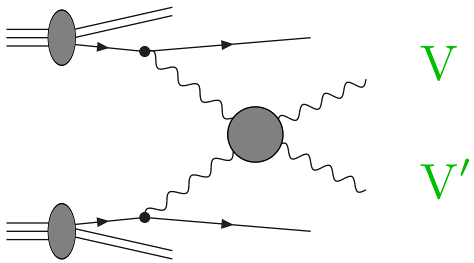
  Alternatively: check whether Higgs is missed for other reasons
  (invisible decays, spread-out Higgs, etc.) see, e.g., van der Bij, arXiv:0804.3534

- New physics – if found

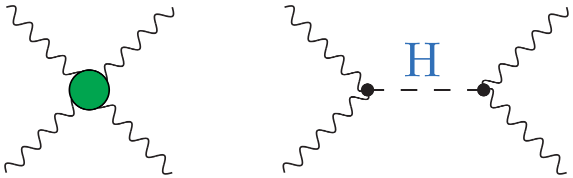
  $\hookrightarrow$ analyse nature of new states ...

  (quantum numbers, couplings, symmetries, SUSY, etc.)

Example: gauge-boson scattering



e.g.



Physics issues:

- link to Higgs production:
  vector-boson fusion with subsequent decay $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$
- triple and quartic gauge-boson self-interaction
  $\hookrightarrow$ high sensitivity, but ambiguities from formfactors
- $\mathrm{V_L V_L} \to \mathrm{V_L V_L}$: strong sensitivity to details of electroweak symmetry breaking
  if no Higgs exists $\quad \to \quad$ unitarity requires scalar and vector resonances

  However:

  ◇ description of resonances is “ad hoc” (different “unitarization models”)
  $\hookrightarrow$ large ambiguities

  ◇ many (more qualitative) studies show that LHC could see the resonances

Comments and questions from a theorist

- Approximations made in many older predictions

  1. "effective vector-boson approximation" (EVA) (∼ Weizsäcker–Williams)
     equivalence theorem (ET) (i.e. $\mathrm{V_L} \sim$ Goldstone boson)
  2. no QCD corrections
  3. no EW corrections (some partial results on $\mathrm{VV} \to \mathrm{VV}$ known)

  Each of these approximations induces uncertainties of several 10% !

- Situation in SM-like scenario: (i.e. no resonances apart from Higgs)
  cross sections small; large background from $q\bar{q}$ annihilation
  $\hookrightarrow$ Can weak-coupling sector for $\mathrm{V_L}$ be experimentally verified ?

- Case with low background: like-sign W-pair production ($\to \mu^+\mu^+ +$ missing p_T)
  $\hookrightarrow$ How promising is this channel ?

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  1. "effective vector-boson approximation" (EVA) (∼ Weizsäcker–Williams)
     equivalence theorem (ET) (i.e. $V_L \sim$ Goldstone boson)
     ↪ results from full $2 \to 6$ matrix elements by Accomando et al.'05,'06
  2. no QCD corrections
     ↪ first NLO QCD results by (Bozzi,) Jäger, Oleari, Zeppenfeld '06–'09
  3. no EW corrections (some partial results on $VV \to VV$ known)

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  ↪ Can weak-coupling sector for V_L be experimentally verified ?

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  ↪ How promising is this channel ?

Results with full $2\to6$ amplitudes (no EVA, no ET)

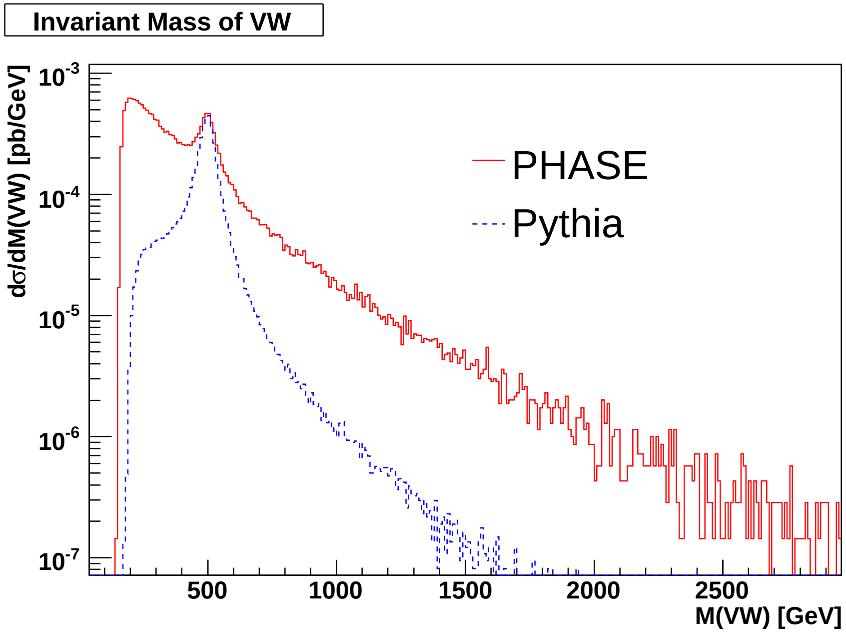
PHASE / PHANTOM = Monte Carlo generators employing full $2\to6$ matrix elements

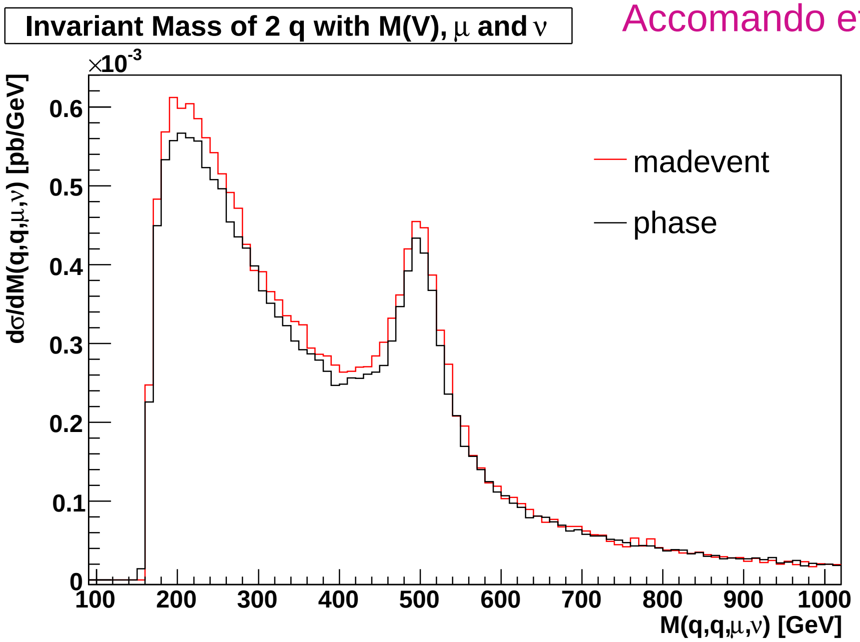
Accomando et al.'05 / Accomando et al.'06

But: no QCD and EW corrections

Comparison of different approaches:

example: processes containing $\mathrm{VW}\to\mathrm{VW}$ with $M_\mathrm{H}=500\,\mathrm{GeV}$





Accomando et al. '05

Phase: all EW $2\to6$ diagrams, no EVA, no ET, but no QCD diagrams

Pythia: only EVA with longitudinal vector bosons

Madevent: no EVA, but on-shell approximation for produced VW pair

Results for $\mathrm{VV} \to \mathrm{VV}$ with NLO QCD corrections

(Bozzi,) Jäger, Oleari, Zeppenfeld '06–'09

Specific processes: $\mathrm{pp} \to \mathrm{W}^{\pm}\mathrm{W}^{\mp}/\mathrm{W}^{\pm}\mathrm{W}^{\pm}/\mathrm{WZ}/\mathrm{ZZ} \to 4l$ in $\mathcal{O}(\alpha^6\alpha_\mathrm{s})$

Approximations: (inspired by "vector-boson fusion cuts")

gauge-invariant subset of t-channel diagrams,

i.e. no s-channel diagrams and neglect of some interferences

$\hookrightarrow$ no colour exchange between incoming partons

Scale dependence of the integrated cross section: $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu + 2q + X$

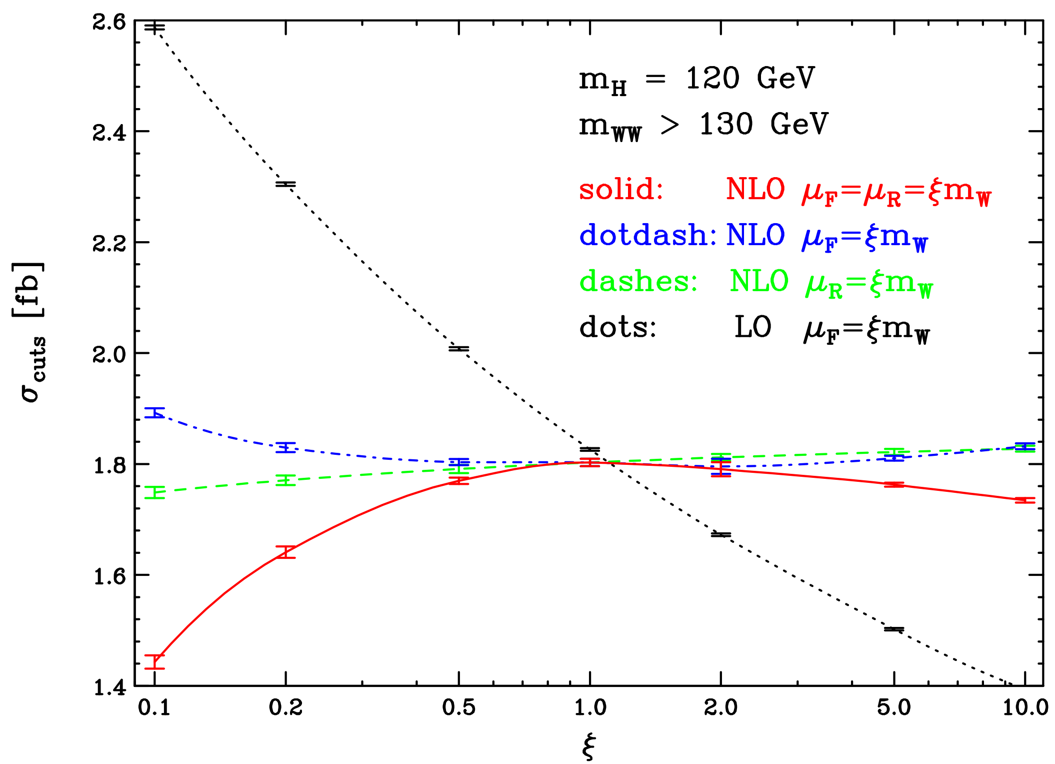
$K \approx 0.98$ at $\mu_\mathrm{fact} = \mu_\mathrm{ren} = M_\mathrm{W}$

scale dependence $\lesssim 10\%$ in NLO

Note:

larger corrections to distributions,

distortion of jet shapes



Concluding remarks

Electroweak physics ...

- experienced exciting previous decades
  (Z @ LEP1/SLC, WW @ LEP2, W @ Tevatron)
  $\hookrightarrow$ electroweak theory established and tested as quantum field theory
- reaches a bifurcation in coming years
  $\hookrightarrow$ "Higgs" or "no Higgs"
- will certainly stay exciting in the future
  "Higgs": precision Higgs physics, extended models, etc.
  "no Higgs": terra incognita, more model building / basic field theory

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—BUT—

- will also keep theorists busy:
  - ◇ high-precision calculations for Drell–Yan processes
  - ◇ more and more realistic predictions for various signals (Higgs, SUSY, etc.)
    $\hookrightarrow$ inclusion of decays, Monte Carlo generators, etc.
  - ◇ construction / evaluation of extended models
  - ◇ solid predictions for background processes at the LHC