PRECISION HIGGS PHYSICS AT COLLIDERS

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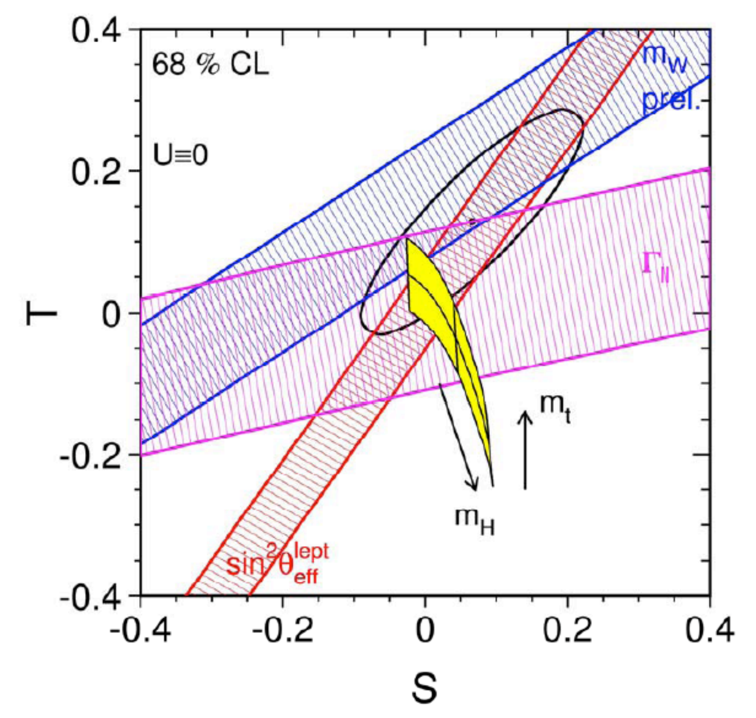
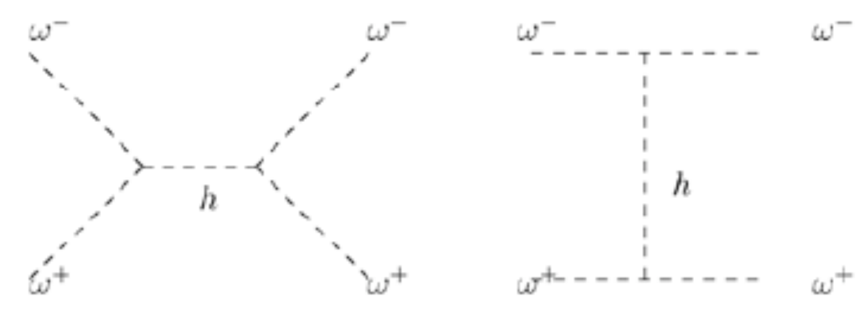
Outline

- Review of experiment, theory for SM Higgs
- The gluon-fusion mechanism: a precision QFT playground
- Electroweak corrections and the Higgs effective theory at 3-loops
  Anastasiou, Boughezal, FP 0811.3458
- Updated numerics, the Tevatron exclusion limit, and fun with PDFs Anastasiou, Boughezal, FP 0811.3458
- Electroweak and quark-mass effects at high Higgs pT
  W.-Y. Keung, FP 0905.2775
- Low-pT resummation using soft-collinear effective theory
  S. Mantry, FP, in progress

Why we expect a TeV scale Higgs

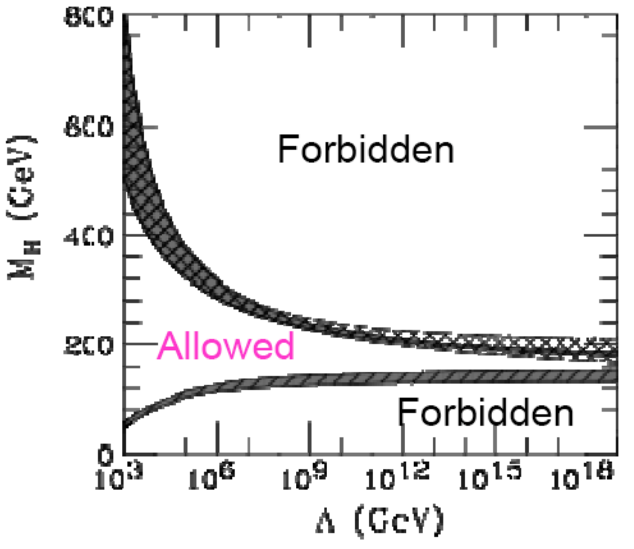
- Last undiscovered particle of the SM
- Many reasons to expect it (or something else) to be observed soon





$$a_0^0 \to -\frac{s}{32\pi v^2}$$

$$\Lambda_{NP} \leq 1.7\,\mathrm{TeV}$$

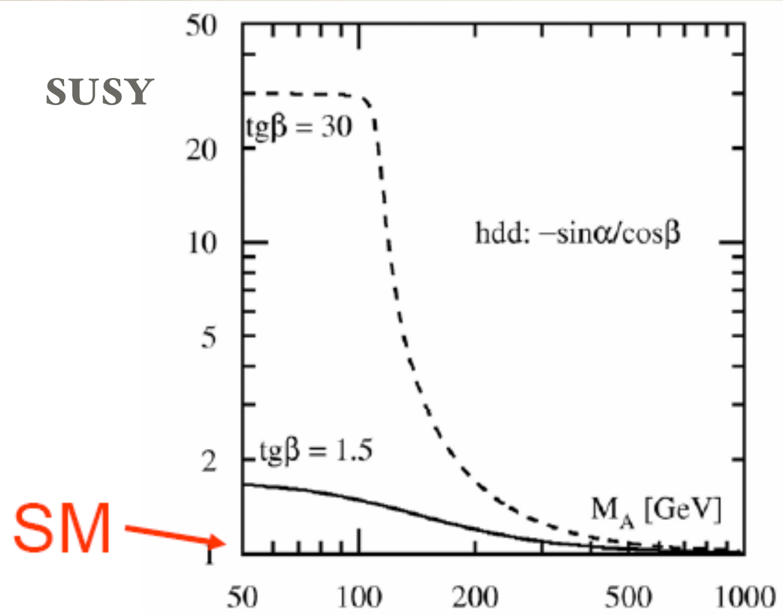


$$M_H^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{Q^2}{v^2}\right)}$$

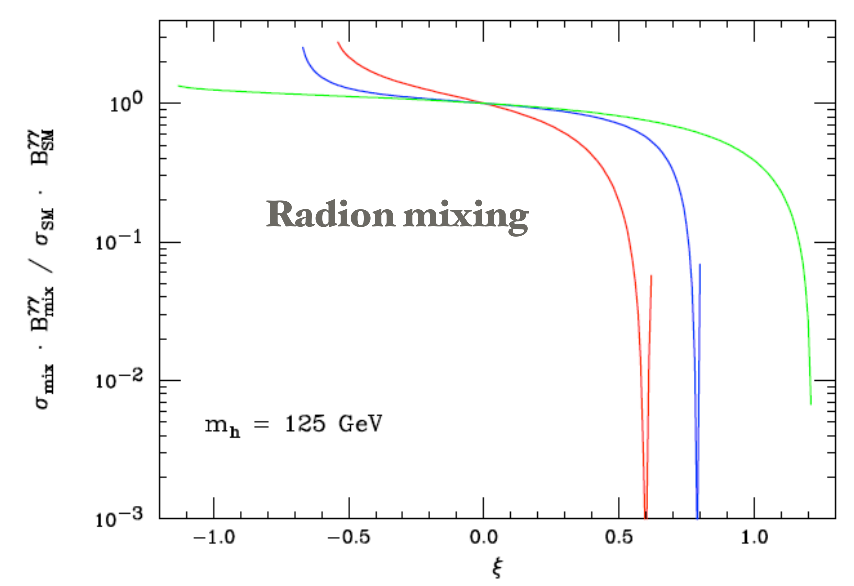
$$M_H^2 > \frac{3v^2}{2\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

Higgs in SM extensions

The uncertainty in EWSB mechanism makes Higgs a portal into new physics at the TEV scale

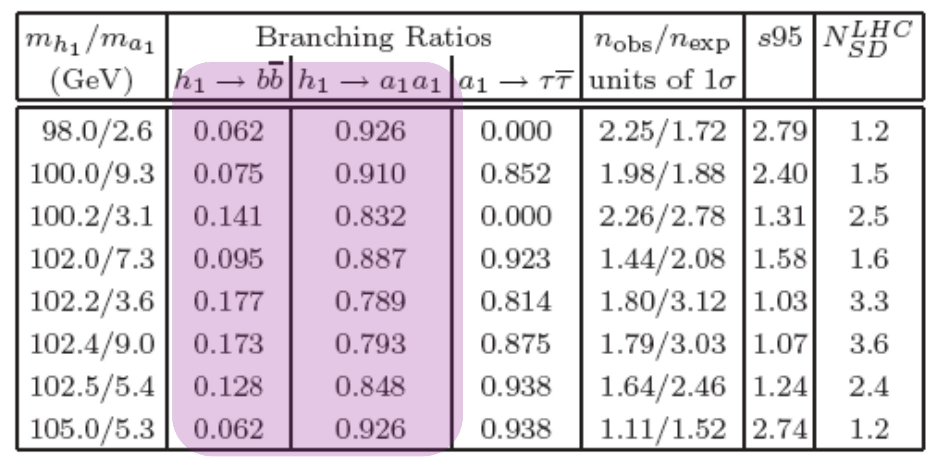


S. Dawson



Hewett, Rizzo hep-ph/0202155

NMSSM



m_{h_1}/m_{a_1}	Branching Ratios			n_{obs}/n_{exp}	$s95$	N_{SD}^{LHC}
(GeV)	$h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau\bar{\tau}$	units of 1σ		
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2

Dermisek, Gunion hep-ph/0510322

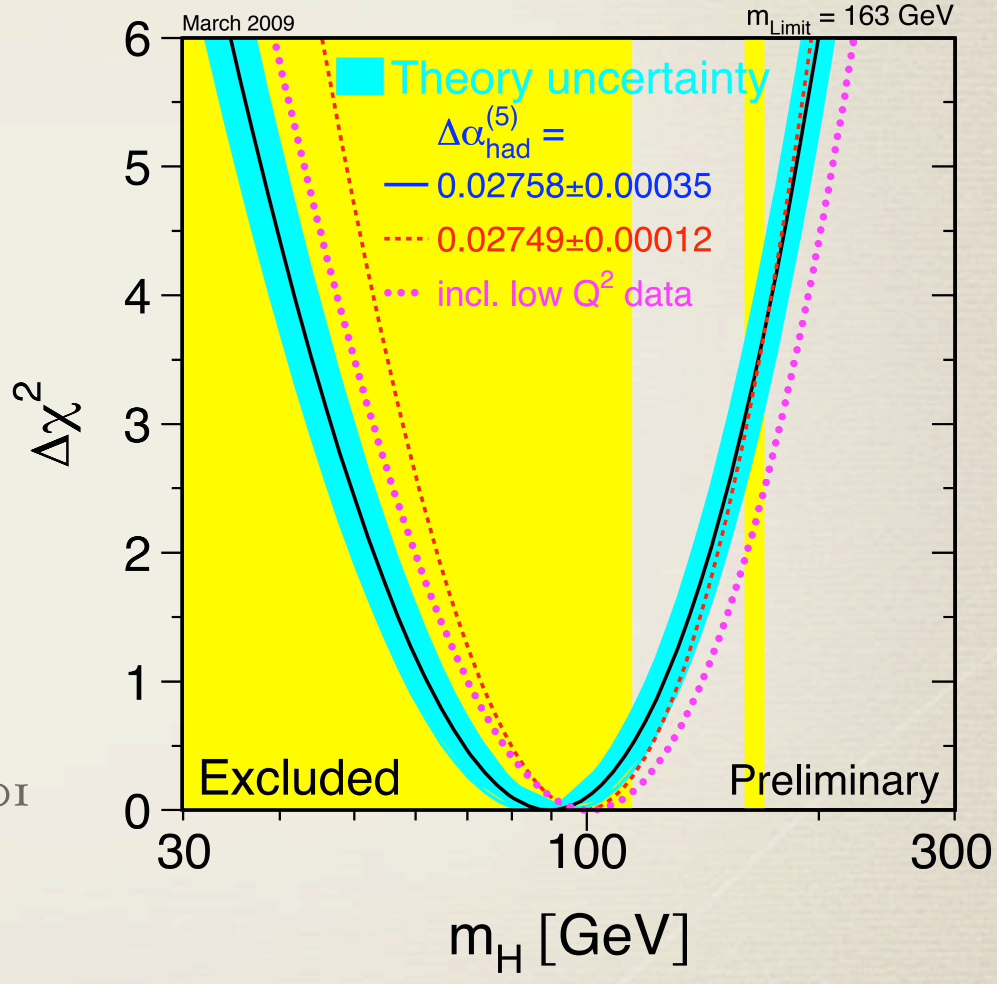
- Loop-induced gluon, photon modes can have O(1) deviations
- Non-standard decays can drastically change collider signals

SM Higgs circa 2009

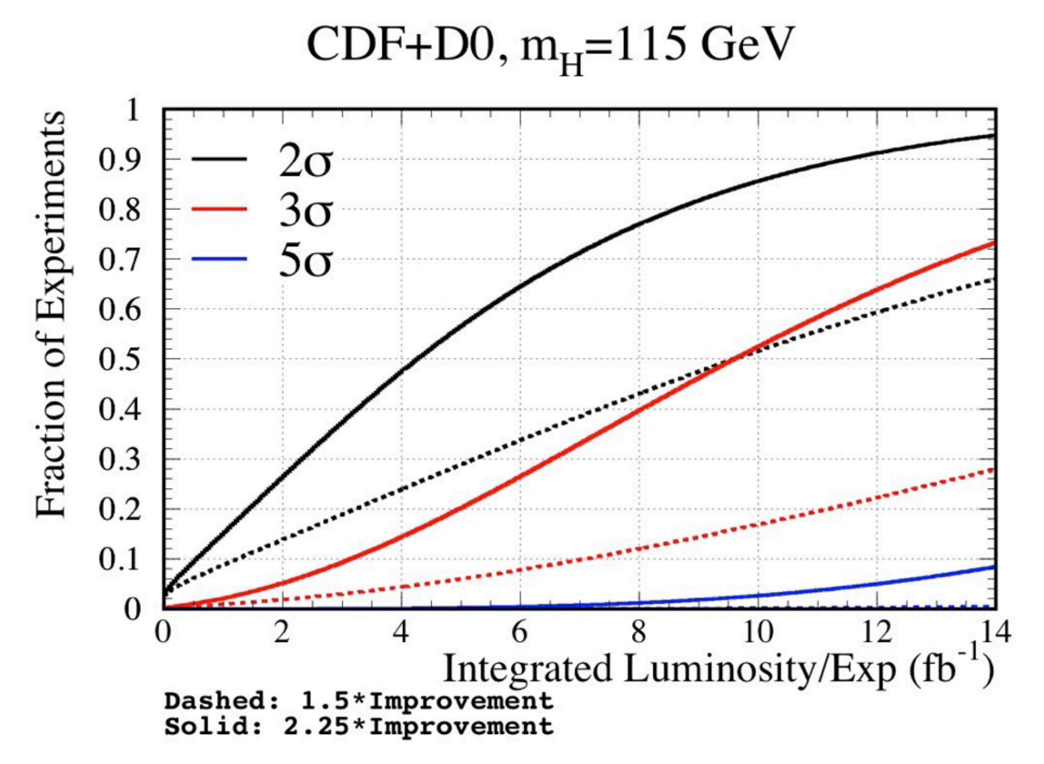
Precision EW upper bound and direct search lower bound at 95% CL:

$$114 < M_H/\mathrm{GeV} < 163$$

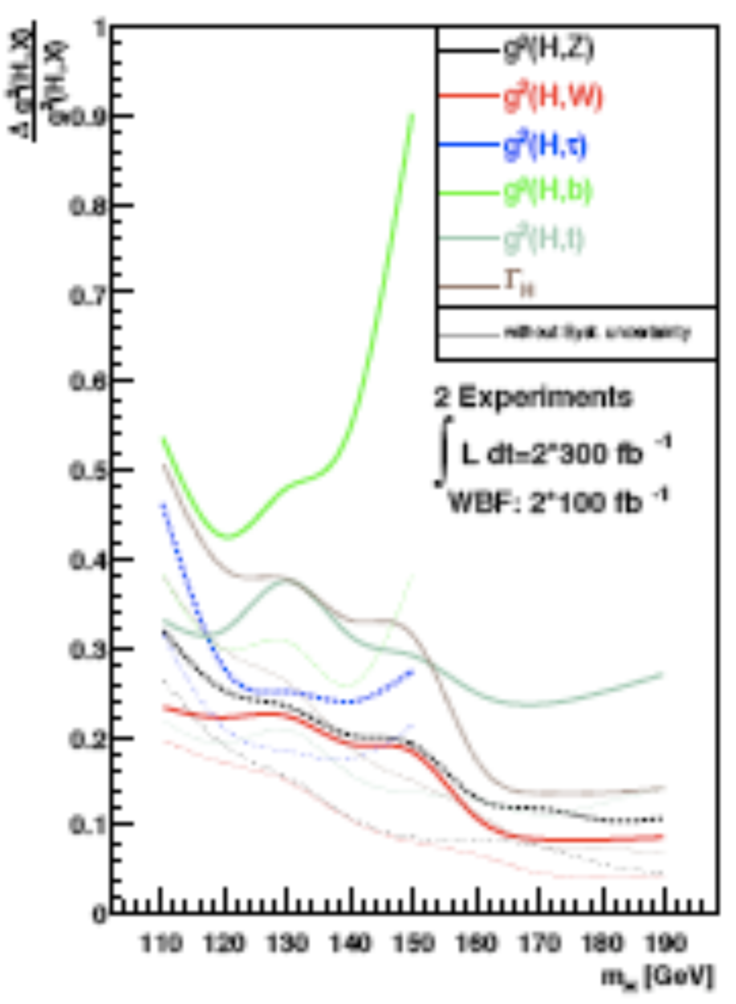
News from the Tevatron: First exclusion in 2008; new combined results exclude 160-170 GeV SM Higgs at 95% CL arXiv:0903.4001



The Higgs in the future

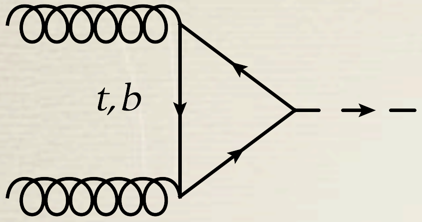


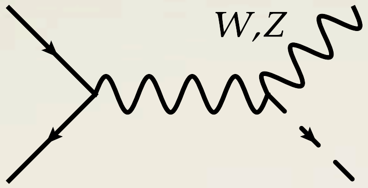
Duhrssen et al., hep-ph/0406323

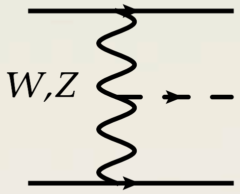


- Discovery program over entire mass range at Tevatron+LHC
- Coupling measurements to 10% possible; spin, CP

SM Higgs production

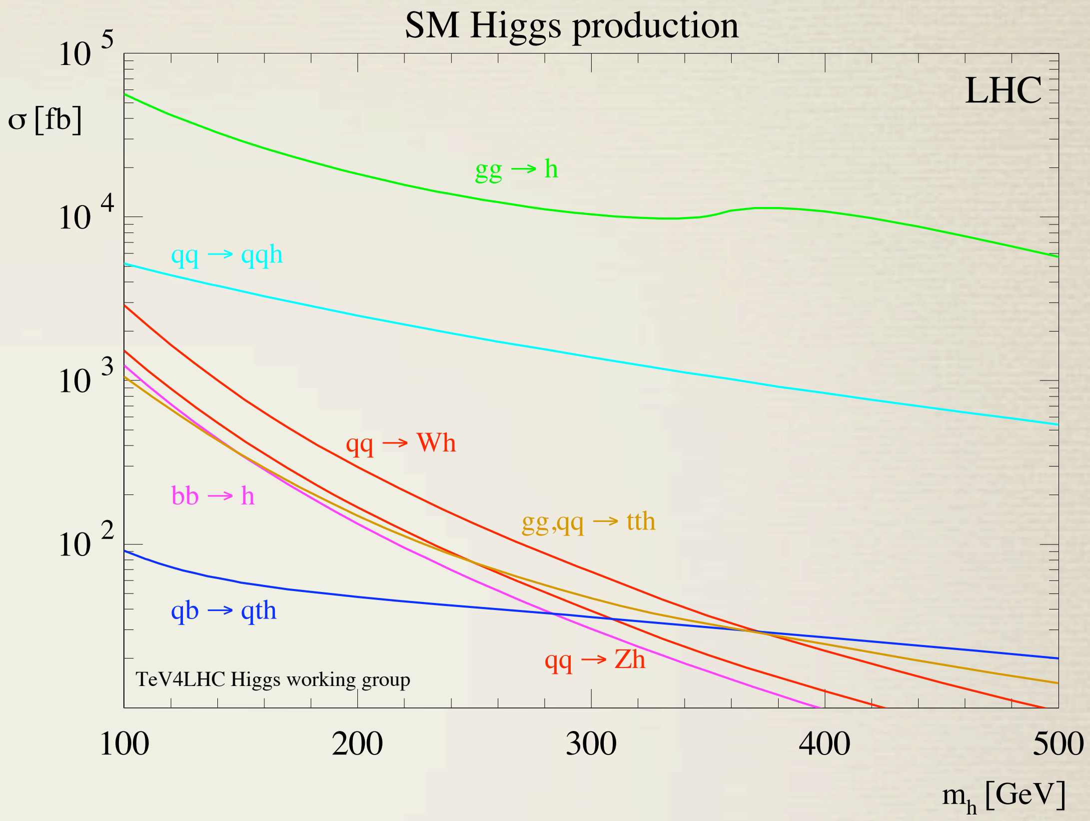


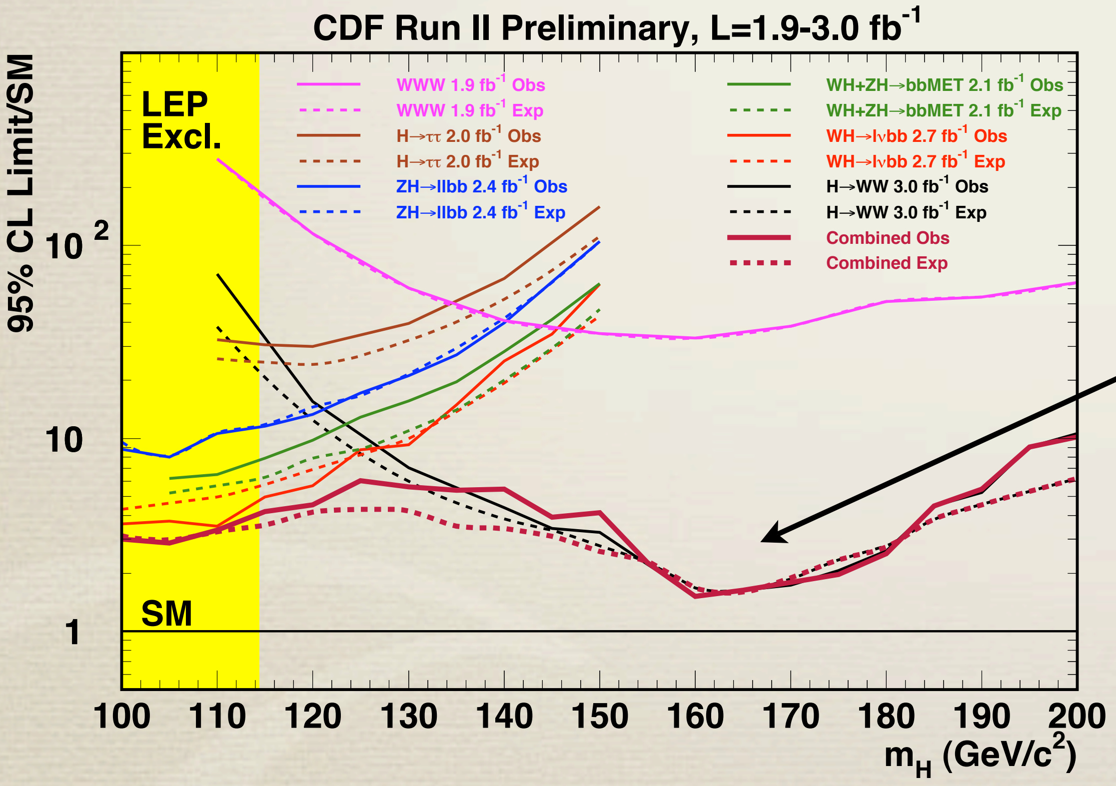




gg fusion dominant by factor of 10

Associated production, WBF essential for light Higgs

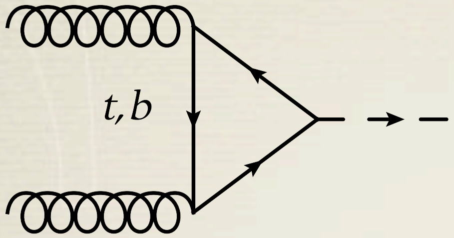




Tevatron exclusion limit entirely from gg→H→WW above 130 GeV

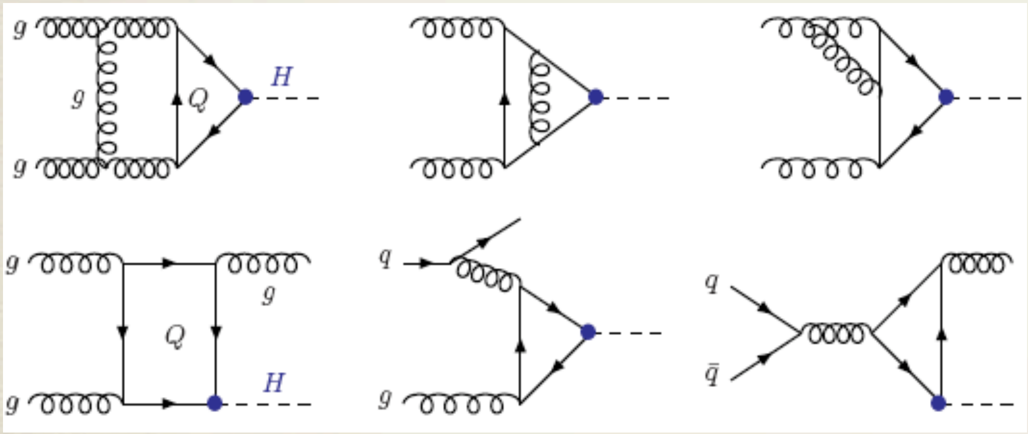
BR(H→WW) > 90% for 160-170 GeV Higgs

Gluon-fusion at NLO



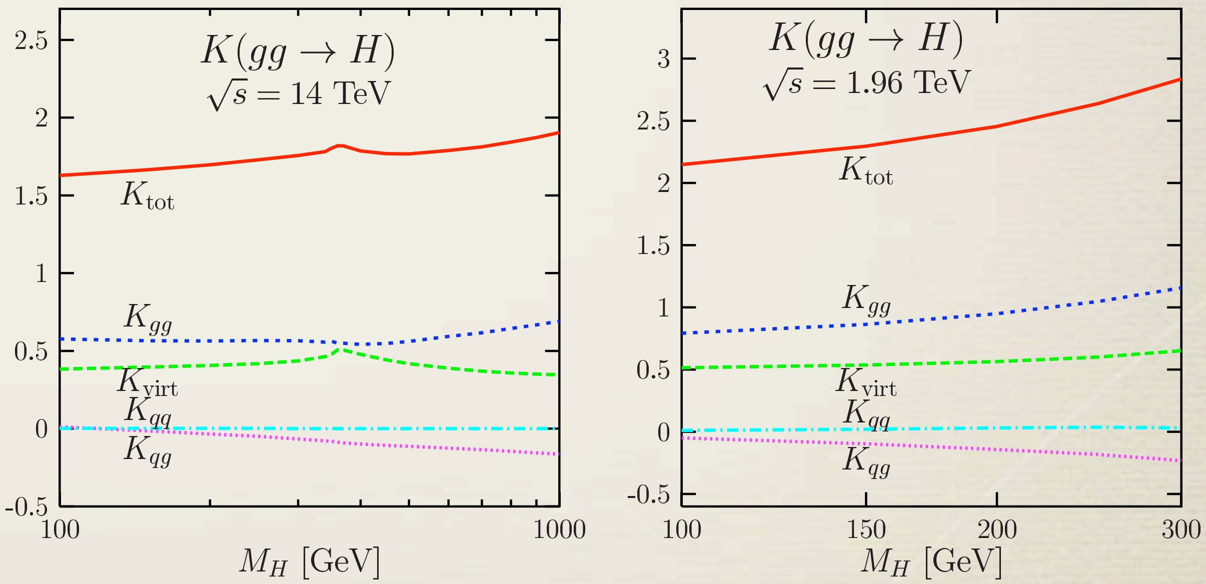
Top-loop dominant; bottom loop gives -5% correction from interference

What makes is sensitive to new physics (begins at 1-loop) also makes it tough to calculate...



Djouadi, Graudenz, Spira, Zerwas PLB 264 (1991), hep-ph/9504378

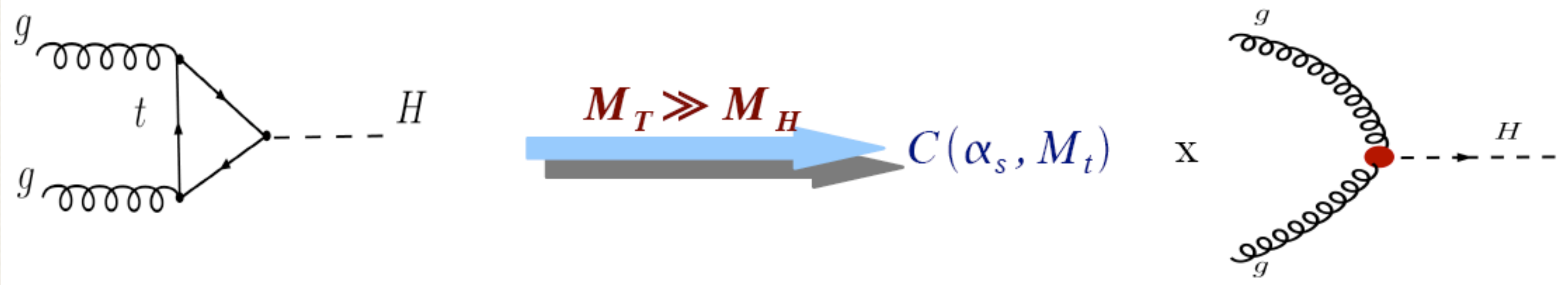
$K=\sigma_{NLO}/\sigma_{LO}$



Can reach $K_{NLO}=\sigma_{NLO}/\sigma_{LO}\approx 2$ at LHC, 3 at Tevatron; why so large?

Effective theory for Higgs

- Difficult to go to NNLO and check convergence of expansion
- NLO analytic expressions unwieldy to study, develop intuition about
- Use EFT instead for top (Shifman et al. 1979; Ellis et al. 1988; S. Dawson; Djouadi, Spira, Zerwas 1991)

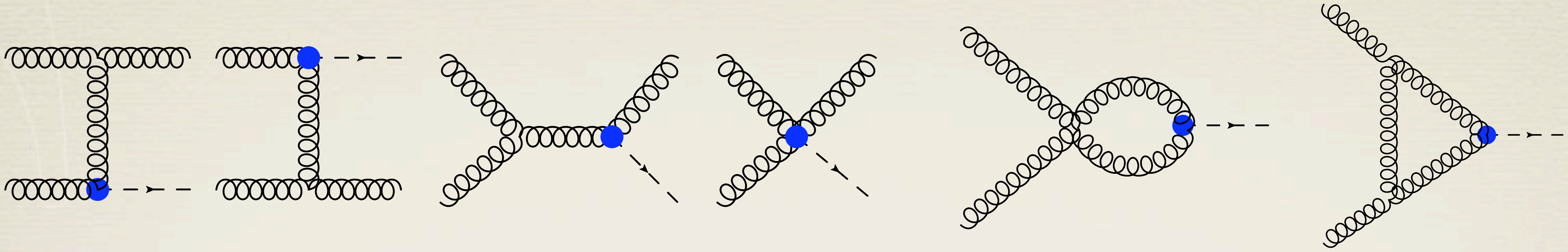


$$L_{ggh} = \frac{-H}{4v} C(\alpha_s) G^a_{\mu\nu} G^{\mu\nu}_a$$

Region of validity: $M_H < 2m_t$

known through $O(\alpha_s^5)$:
Schroder, Steinhauser; Chetyrkin, Kuhn, Sturm hep-ph/0512058, 0512060

NLO in the EFT

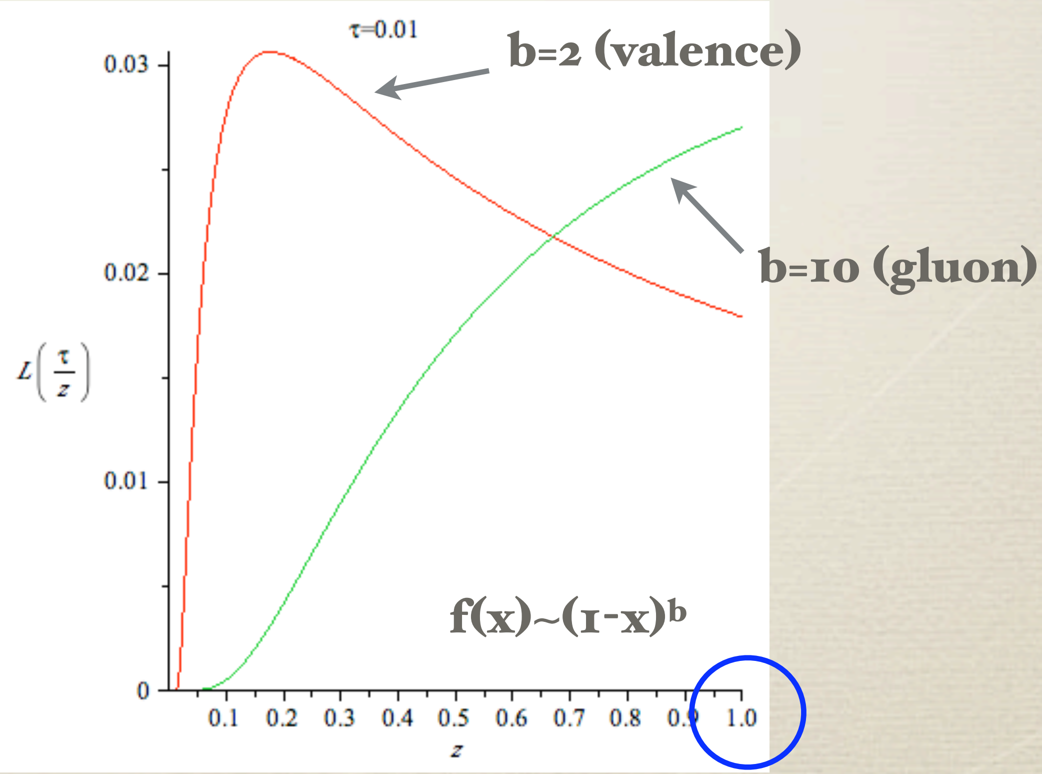


$$\Delta\sigma = \sigma_0\frac{\alpha_s}{\pi}\left\{\left(\frac{11}{2}+\pi^2\right)\delta(1-z)+12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) -6\frac{(z^2+1-z)^2}{1-z}\ln(z)-\frac{11}{2}(1-z)^3\right\}$$

($M^2/s \leq z \leq 1$)

(integration over PDFs⇒integration over z)

- First source of large correction: $11/2+\pi^2 \Rightarrow 50\%$ increase (can even resum these corrections Magnea, Sterman 1990; Ahrens, Becher, Neubert, Yang 0808.3008)
- Second source: shape of PDFs enhances *threshold* logarithm



Unreasonably effective EFT

- In the full theory with top quarks, study eikonal approximation for real emission, Sudakov form factor for virtual

$$\begin{aligned}\Delta\sigma_{top}^{soft} &= \sigma_{top}^{(0)}\, C_A \frac{\alpha_s}{\pi}(1-z)^{-1-2\epsilon}\lambda^{-1-\epsilon}(1-\lambda)^{-1-\epsilon} \\ &\Rightarrow \sigma_{top}^{(0)} \frac{\alpha_s}{\pi} 12 \left[\frac{\ln(1-z)}{1-z}\right]_+\end{aligned}$$

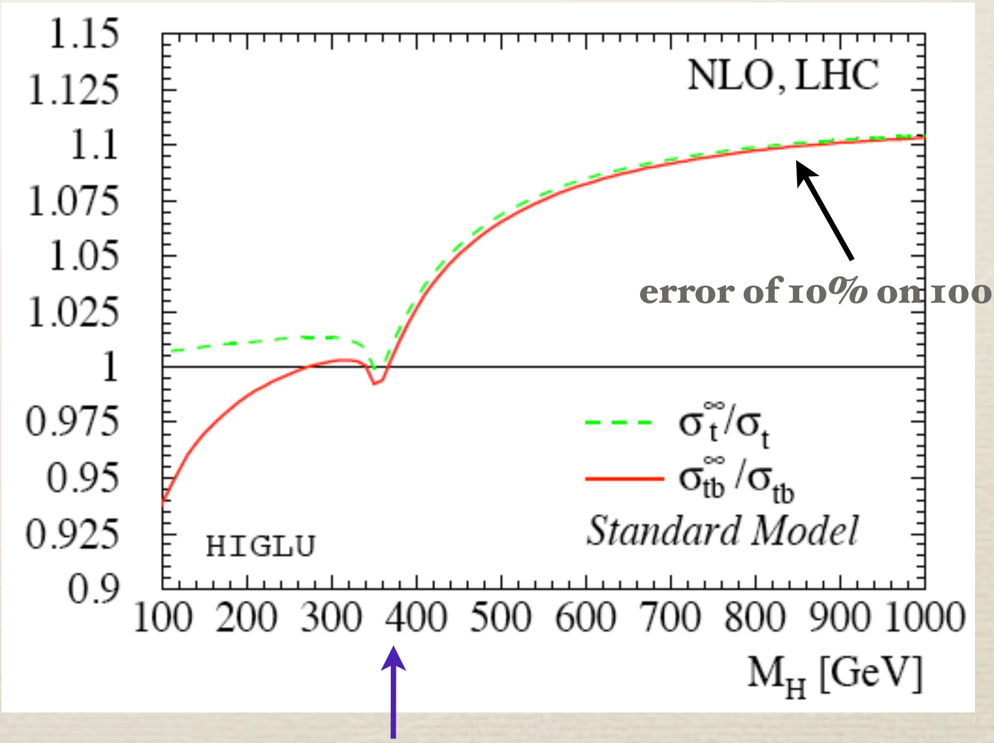
$$\begin{aligned}\Delta\sigma_{top}^{Sud} &= \sigma_{top}^{(0)}\, 2C_A \frac{\alpha_s}{\pi}\frac{1}{\epsilon^2}\left(\frac{-\mu^2}{\hat{s}}\right)^{\epsilon}\delta(1-z) \\ &\Rightarrow \sigma_{top}^{(0)} \frac{\alpha_s}{\pi}\pi^2\delta(1-z)\end{aligned}$$

- Dominant corrections in full and EFT differ only by tree-level cross section ⇒ caused by shape of gluon PDF

$$\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}}\right)\sigma_{LO}^{QCD}$$

%-level or better for $M_H<2m_t$, even
gets >90% of correction above
Threshold structure preserved

Initial NNLO study of $1/m_t$ suppressed operators indicates this persists Harlander, Ozeren 0909.3420

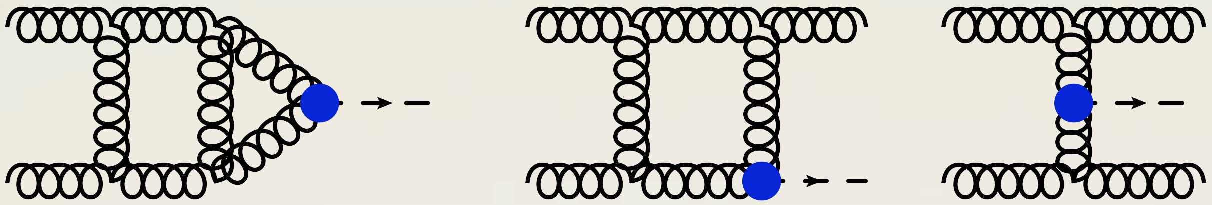


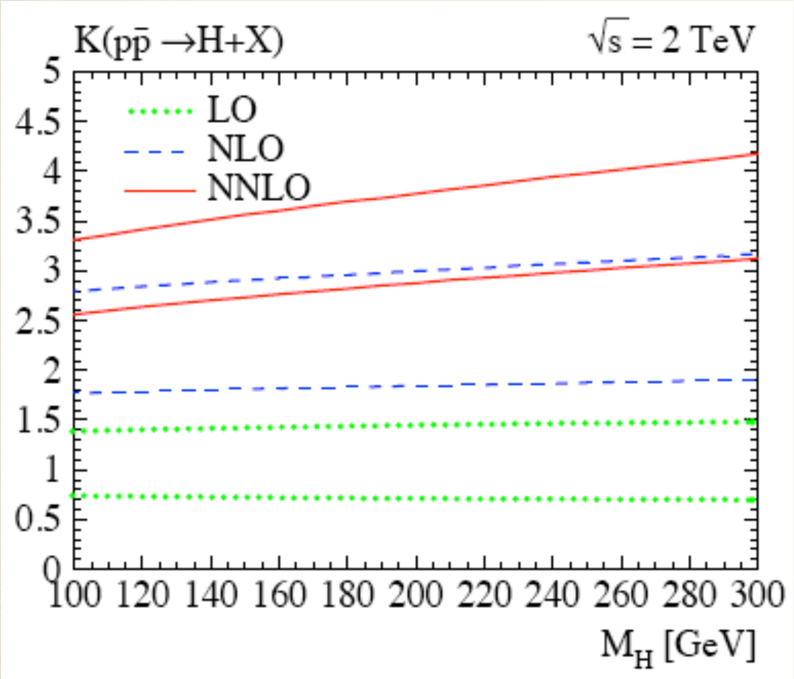
error of 10% on 100% correction

$M_H=2m_t$

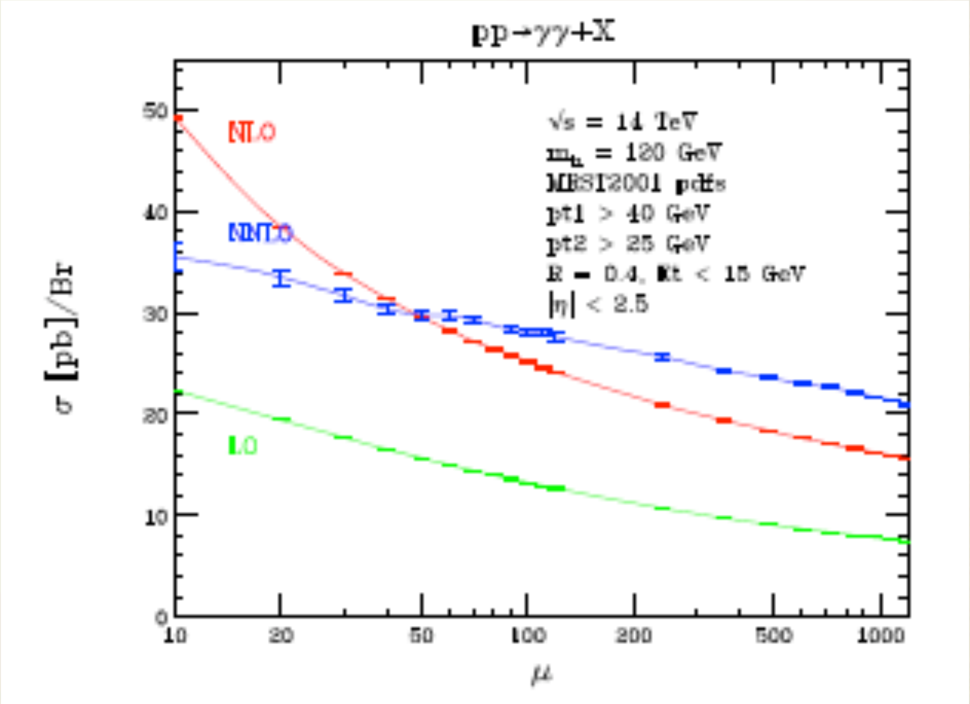
NNLO in the EFT

- Motivates calculation to NNLO in the EFT





Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven 2002-2003

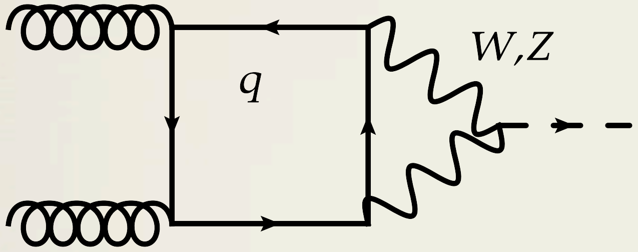


Anastasiou, Melnikov, FP 2005

K-factor: 2 at LHC, 3.5 at Tevatron

Electroweak corrections

- Residual QCD uncertainty ~10% ⇨ EW corrections potentially important to match QCD and experimental precision
- N_F-enhanced sourced of 2-loop light-quark corrections



⇨ Up to ~8-9% at threshold relative to LO QCD

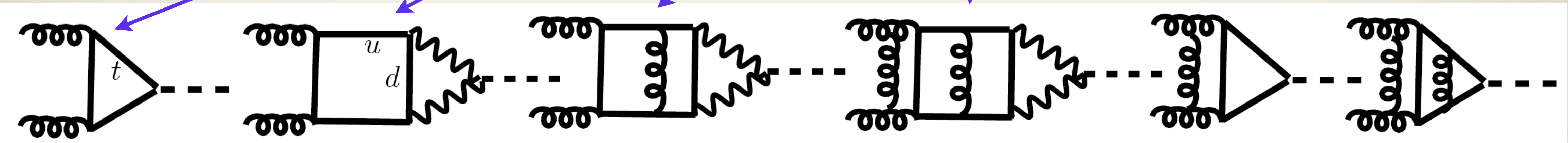
Aglietti, Bonciani, Degrassi, Vicini hep-ph/0404071;
Actis, Passarino, Sturm, Uccirati 0809.1301

- K-factor? Values between 1-4 assumed in literature; do these get same K-factor of top-quark piece?
- First goal: check with 3-loop calculation in EFT

EFT formulation

$$\mathcal{L} = -\alpha_s \frac{C_1}{4v} H G^a_{\mu\nu} G^{a\mu\nu}$$

$$C_1 = -\frac{1}{3\pi}\left\{1 + \lambda_{EW}\left[1 + a_s C_{1w} + a_s^2 C_{2w}\right] + a_s C_{1q} + a_s^2 C_{2q}\right\}$$



- Radius of convergence: $M_H \leq M_W$...
- *However,* dominant corrections from threshold logs and analytic continuation of Sudakov form factor identical in full and EFT
- Calculate K-factor in EFT, normalize to exact 2-loop EW result

Factorization in the EFT

- If the K-factor for light-quark pieces is the same as the top quark, then the Wilson coefficient in the EFT “factorizes”

$$C_1 = -\frac{1}{3\pi}\left\{1 + \lambda_{EW}\left[1 + a_s C_{1w} + a_s^2 C_{2w}\right] + a_s C_{1q} + a_s^2 C_{2q}\right\}$$

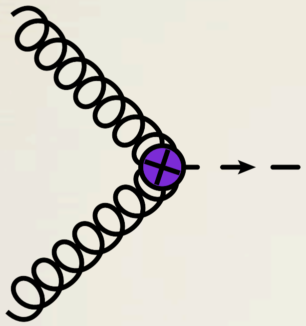
⬇

$$C_1^{fac} = -\frac{1}{3\pi}\left(1 + \lambda_{EW}\right)\left\{1 + a_s C_{1q} + a_s^2 C_{2q}\right\}$$

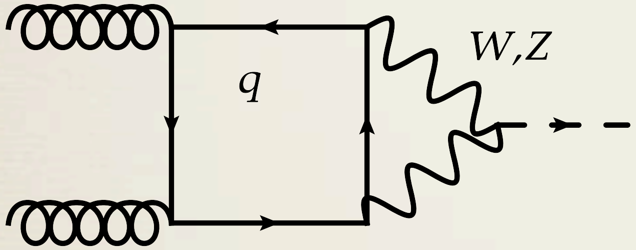
- Factorization holds if $C_{1w} = C_{1q}$; $C_{1q} = 11/4$
- Calculate C_{1w} from 3-loop diagrams, check deviation from C_{1q}, study numerical effect

Matching to the EFT I

- Matching at O($\alpha\alpha_s$):



$$= -\frac{1}{3\pi}\frac{\alpha_s}{v}\lambda_{EW}\mathcal{M}_0$$

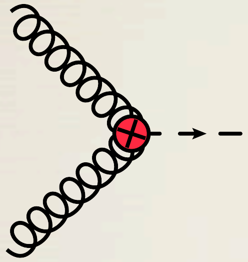


$$= \mathcal{A}^{(2)}(M_H^2 = 0)\mathcal{M}_0 + \mathcal{O}\left(\frac{M_H^2}{M_{W,Z}^2}\right)$$

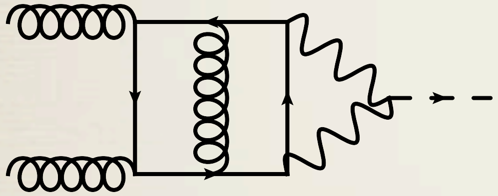
☑ Equate to get λ_{EW}

Matching to the EFT II

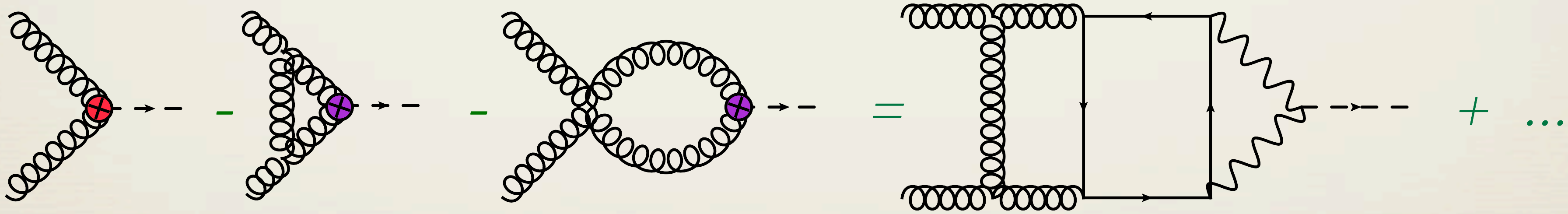
- Matching at O($\alpha\alpha_s^2$):



$$= -\frac{1}{3\pi}\frac{\alpha_s}{v}\lambda_{EW}\left(\alpha_s C_{1w}\right)\mathcal{M}_0$$



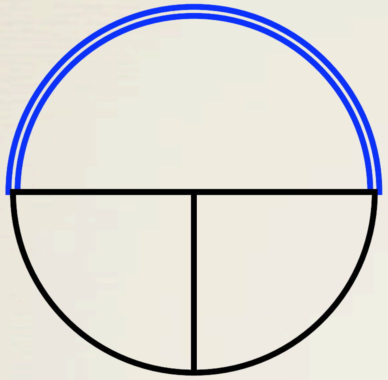
$$= \mathcal{A}^{(3)}(M_H^2 = 0)\mathcal{M}_0 + \mathcal{O}\left(M_H^2/M_{W,Z}^2\right)$$



☑ Equate to get C_{1w}

Calculational strategy

- Expansion in M_H/M_W reduces diagrams to 3-loop vacuum bubbles



$$\begin{aligned}\mathcal{I}(\vec{\nu}_i) &= \int \prod_{j=1}^{3} d^d k_j \frac{1}{k_1^{2\nu_1} k_2^{2\nu_2} (k_3^2 - M_{W,Z}^2)^{\nu_3} (k_1 - k_2)^{2\nu_4} (k_2 - k_3)^{2\nu_5} (k_3 - k_1)^{2\nu_6}} \\ &= \int \prod_{j=1}^{3} d^d k_j \mathcal{D}\end{aligned}$$

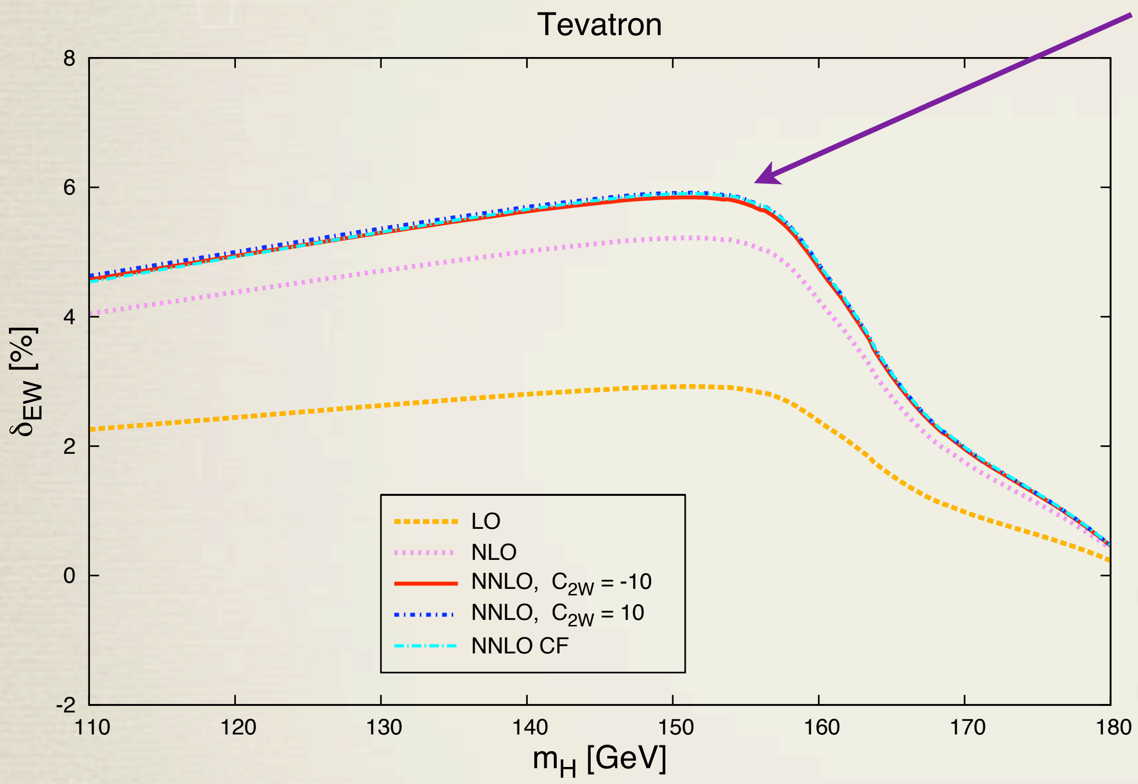
- Use Poincare invariance of loop integrals to facilitate calculation

K. Chetyrkin, F. Tkachov 1981 ⇒ left with two such integrals to evaluate

$$\int \prod_{j=1}^{3} d^d k_j \partial_i \left[k_k \mathcal{D}\right] = 0$$

Factorization violation

- Analytical result: $C_{1w} = 7/6$, compared to $C_{1q} = 11/4$



Difference between factorization hypothesis and actual result irrelevantly small (weak violation)

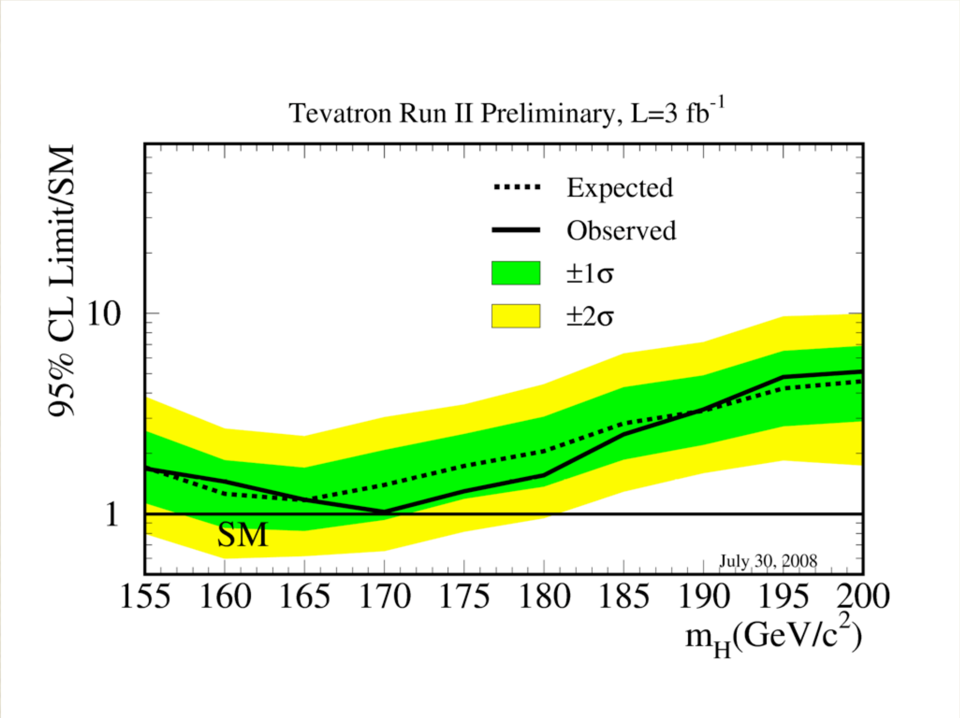
$$\sigma_{3-loop} = \sigma_{2-loop}\left\{\frac{\alpha_s}{\pi}C_{1w} + G^{(1)}_{EFT}\right\}$$

- $\alpha_s(C_{1w}-C_{1q})/\pi \approx 5\%$
- $G^{(1)}_{EFT} \approx 100\%$; contains π^2, $\ln(1-z)$, the large corrections to HGG operator

- K-factor of 3.5 at Tevatron appropriate

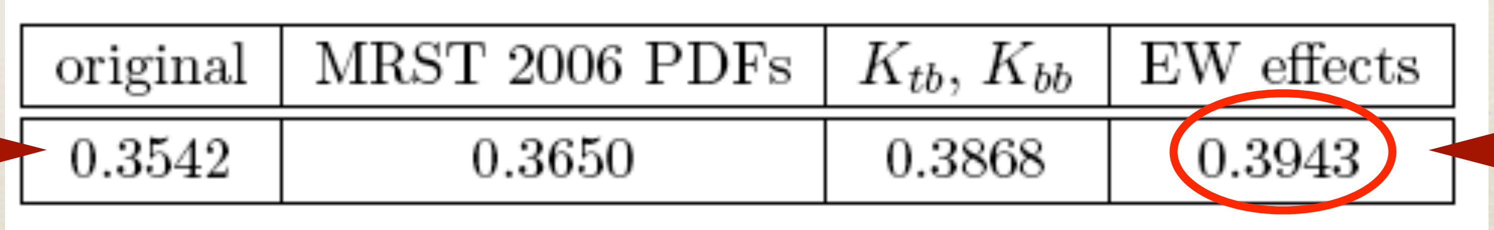
Circa December 2008

- Combine QCD, EW corrections to derive current best prediction, check what is in Tevatron analysis
- First limit: M_H=170 GeV excluded 0808.0534



- Same K-factors assumed for top, EW contributions ✓
- Same K-factor assumed for top, bottom quarks
  K_{tb}~1.5, K_{tt}~3.5 ⇒ needed updating
- MRST 2002 PDFs used
  significant changes in heavy-quark threshold treatment

What they used



original	MRST 2006 PDFs	K_{tb}, K_{bb}	EW effects
0.3542	0.3650	0.3868	0.3943

Update #1

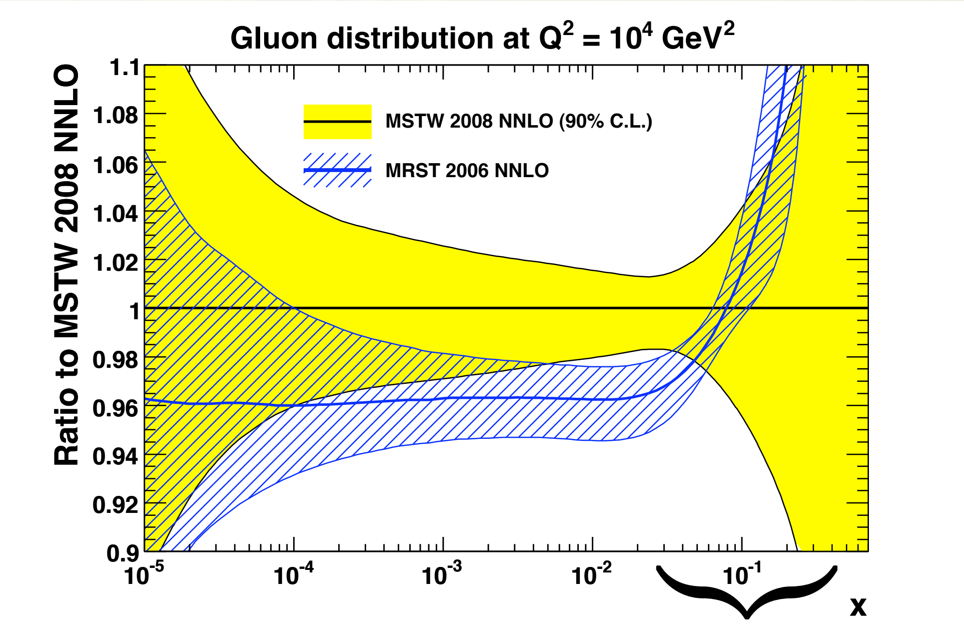
M_H=170 GeV

10% increase

Circa January 2009

MSTW 2008 PDF release arXiv:0901.0002

- Run II inclusive jet data
- Decrease of $\alpha_s(M_Z)$ from 0.119→0.117
- Gluon density decreased at x~0.1
- gg luminosity error increased from 5% ⇒ 10%



Changes in relevant region for Tevatron analyses

Keep in mind for LHC analyses...

M_H=170 GeV:

MRST 2001	MRST 2004	MRST 2006	MSTW 2008
0.3833	0.3988	0.3943	0.3444

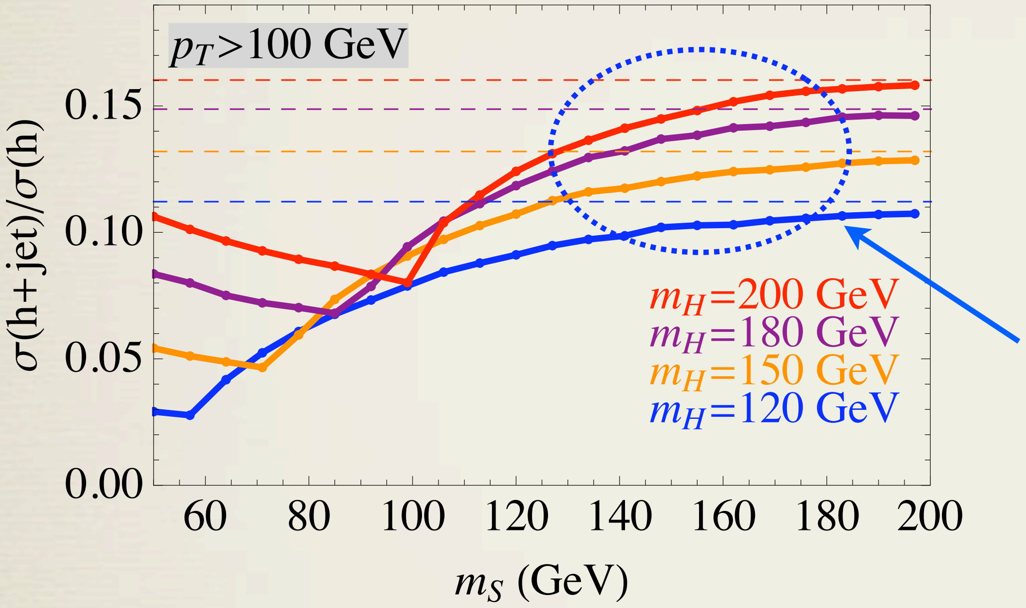
~**15% decrease** in predicted cross section !

$\sigma \sim \alpha_s^3 \times f_g^2$ ⇒ very sensitive to these changes!

- Central value, but not increased error, accounted for in 2009 analysis
- LHC: 25% increase in cross sections at M_H=120 GeV, 10% at 200 GeV after changing PDFs, bottom-quark description, EW effects

The Higgs p_T spectrum

- Other surprises, perhaps in differential distributions?
- Many studies of p_T spectrum as probe of new physics



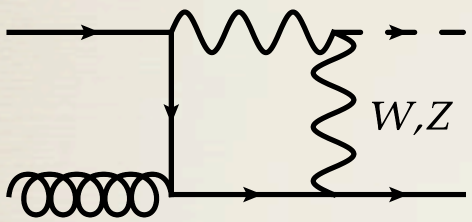
Color-octet scalar induced deviation in integrated ratio Arnesen, Rothstein, Zupan 0809.1429

Motivational region for precision study; new physics or QCD?

- Roughly 45% of Tevatron exclusion from 1,2 jet bins M. Herndon
- Some LHC analyses in ττ, γγ select high p_T to remove background; p_T>100 GeV typical Abdullin et al. hep-ph/9805341; Mellado, Quayle, Wu hep-ph/0406095

EW, quark-mass effects

- One possible problem: p_T^2/m_t^2 effects from other EFT operators
- Effects missed previously that contribute to qg, qq channels



  - Same loop-order as previously included effects

- Not useful to compute, but think in terms of operators

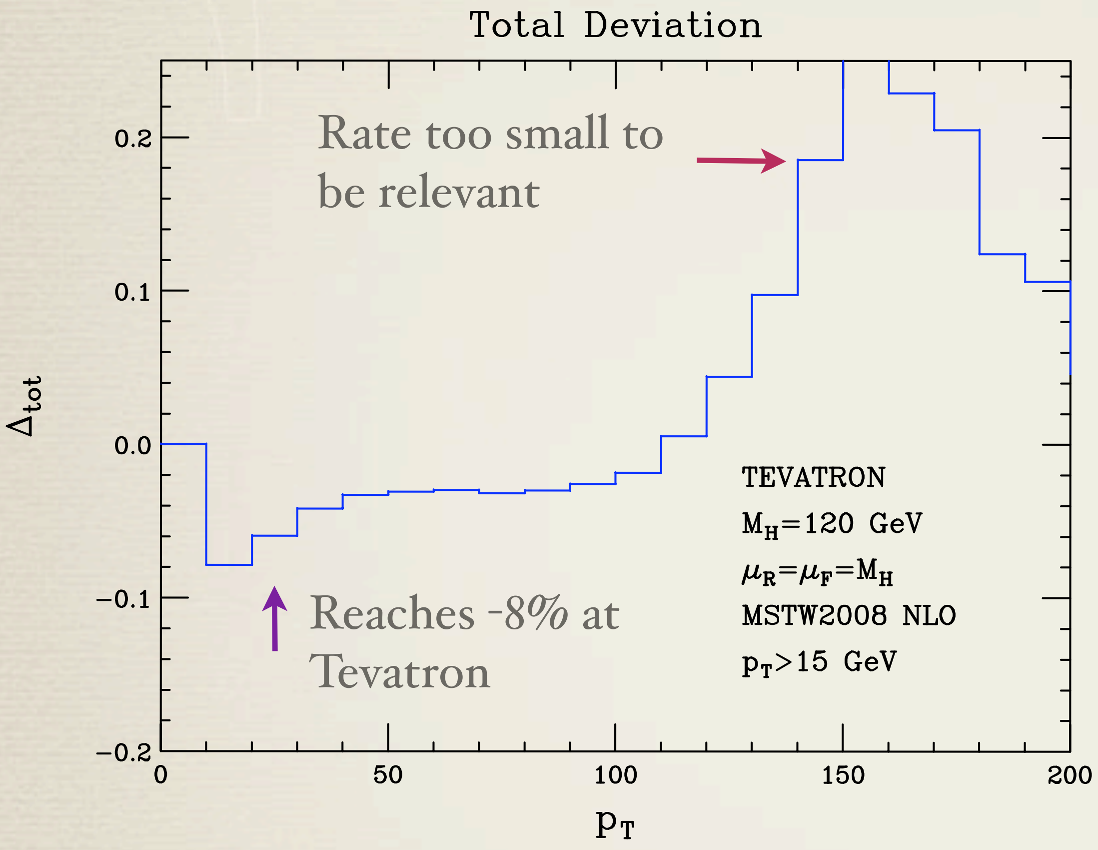
$$\mathcal{O}_{EW} = \frac{H^\dagger D_\mu H}{v^2}\,\frac{\bar{q}G^{\mu\nu}\gamma_\nu q}{M^2_{W,Z}}$$

$$\Rightarrow \frac{p_H \cdot p_g \bar{u}\ \not\epsilon_g u - p_H \cdot \epsilon_g \bar{u}\ \not p_g u}{v\, M^2_{W,Z}}$$

  - Vanishes for p_g-p_1,p_2 ⇒ hard p_T spectrum
  - Interferes, destructively, with EFT contributions

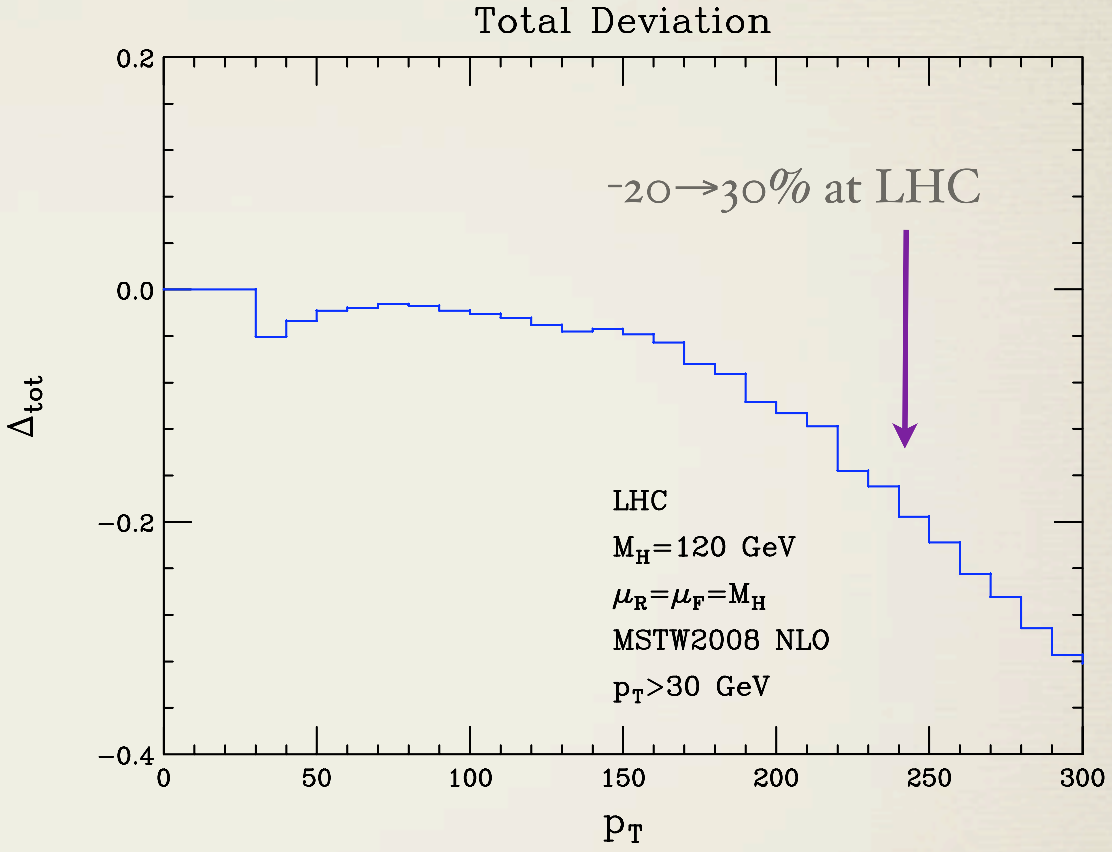
Numerical results

- Both W/Z and p_T^2/m_t^2 act destructively to reduce EFT prediction



Rate too small to be relevant

Reaches -8% at Tevatron



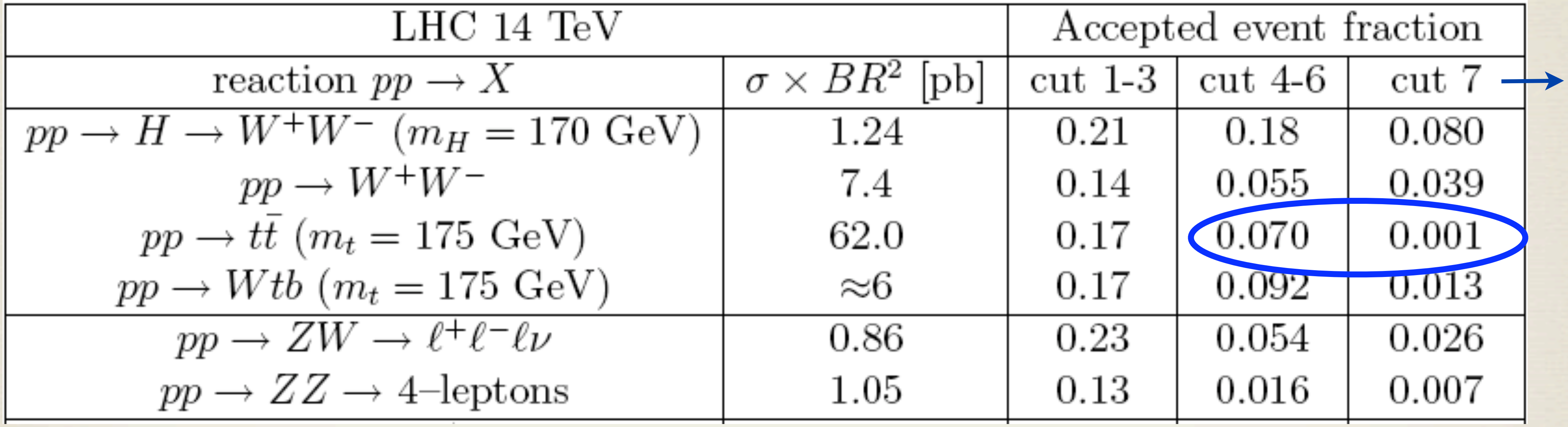
-20→30% at LHC

☑ All effects being included in updated analysis code FEHiP

Anastasiou, Boughezal, Bucherer, FP, Stoeckli, in progress

Low p_T Higgs production

- Other searches restrict the p_T to low values
  - LHC H→WW jet veto: $p_{TJ}<20$ GeV Dittmar, Dreiner hep-ph/9608317



LHC 14 TeV		Accepted event fraction		
reaction $pp \to X$	$\sigma \times BR^2$ [pb]	cut 1-3	cut 4-6	cut 7
$pp \to H \to W^+W^-$ ($m_H = 170$ GeV)	1.24	0.21	0.18	0.080
$pp \to W^+W^-$	7.4	0.14	0.055	0.039
$pp \to t\bar{t}$ ($m_t = 175$ GeV)	62.0	0.17	0.070	0.001
$pp \to Wtb$ ($m_t = 175$ GeV)	≈6	0.17	0.092	0.013
$pp \to ZW \to \ell^+\ell^-\ell\nu$	0.86	0.23	0.054	0.026
$pp \to ZZ \to$ 4–leptons	1.05	0.13	0.016	0.007

→ **jet veto**

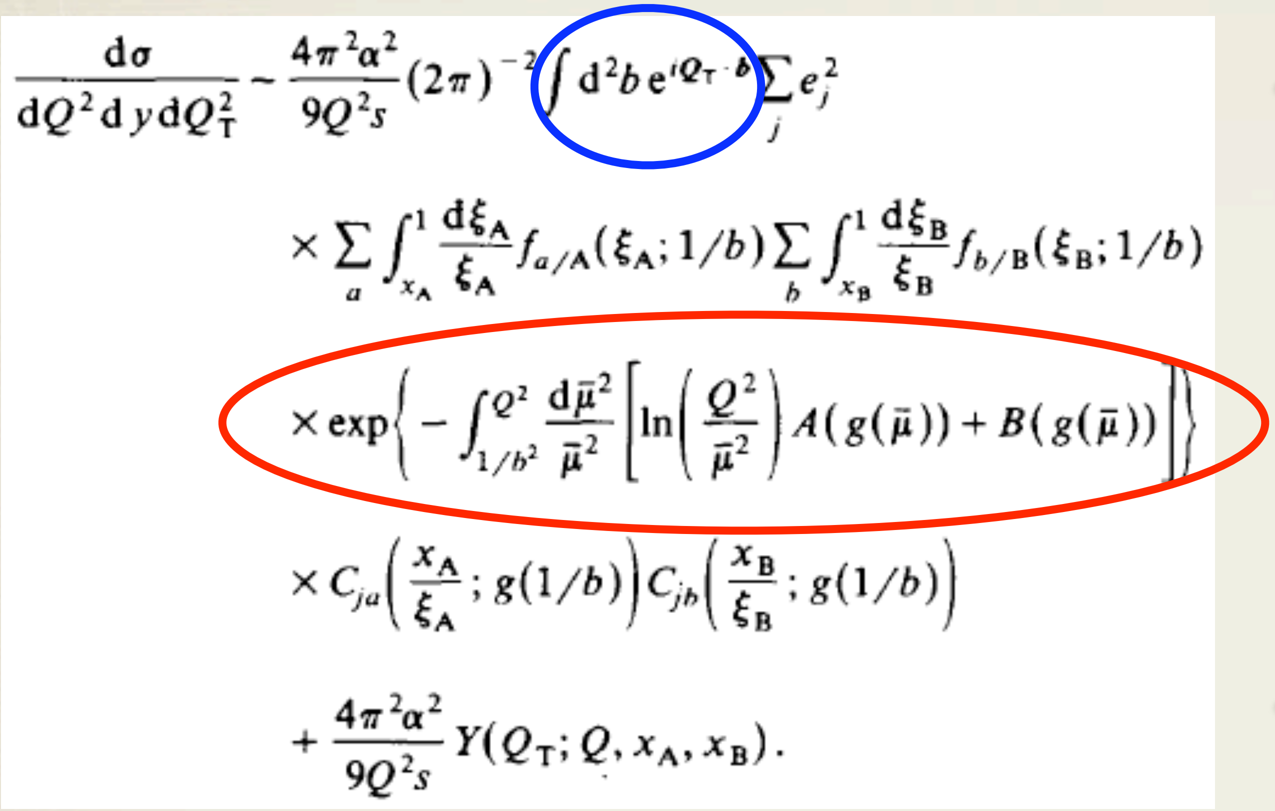
- Leading order prediction for p_T spectrum:

$$\frac{d\sigma}{dp_T^2} \sim \sigma_0 \frac{C_A \alpha_s}{\pi} \frac{1}{p_T^2} \ln \frac{s}{p_T^2}$$

➠ must resum to all orders

Impact-parameter formalism

- Classic analysis of Collins, Soper, Sterman NPB250 199 (1985)



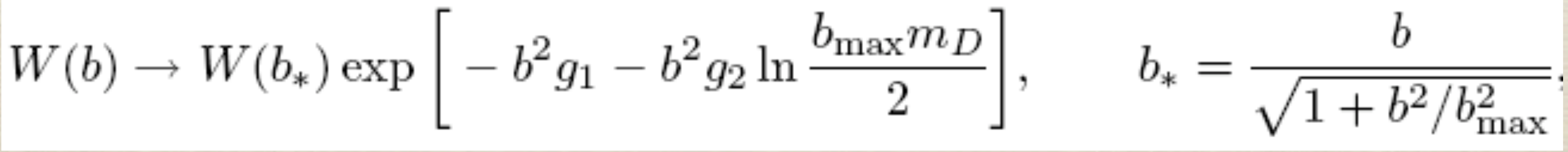
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}Q_\mathrm{T}^2} \sim \frac{4\pi^2\alpha^2}{9Q^2 s}(2\pi)^{-2}\int \mathrm{d}^2b\, \mathrm{e}^{iQ_\mathrm{T}\cdot b}\sum_j e_j^2$$
$$\times \sum_a \int_{x_\mathrm{A}}^1 \frac{\mathrm{d}\xi_\mathrm{A}}{\xi_\mathrm{A}} f_{a/\mathrm{A}}(\xi_\mathrm{A};1/b)\sum_b \int_{x_\mathrm{B}}^1 \frac{\mathrm{d}\xi_\mathrm{B}}{\xi_\mathrm{B}} f_{b/\mathrm{B}}(\xi_\mathrm{B};1/b)$$
$$\times \exp\left\{-\int_{1/b^2}^{Q^2}\frac{\mathrm{d}\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{Q^2}{\bar{\mu}^2}\right)A(g(\bar{\mu}))+B(g(\bar{\mu}))\right]\right\}$$
$$\times C_{ja}\left(\frac{x_\mathrm{A}}{\xi_\mathrm{A}};g(1/b)\right)C_{jb}\left(\frac{x_\mathrm{B}}{\xi_\mathrm{B}};g(1/b)\right)$$
$$+\frac{4\pi^2\alpha^2}{9Q^2 s}Y(Q_\mathrm{T};Q,x_\mathrm{A},x_\mathrm{B}).$$

  - b-space arises from treatment of momentum conservation

$$\delta^{(2)}\left(\vec{p}_T - \sum_i \vec{k}_{Ti}\right) = \int \frac{d^2b}{(2\pi)^2}\, e^{ib\cdot\vec{p}_T}\prod_j e^{-i\vec{b}\cdot\vec{k}_{Tj}}$$

  - Sudakov form factor: A, B contain $\alpha_s(\bar{\mu}^2)$

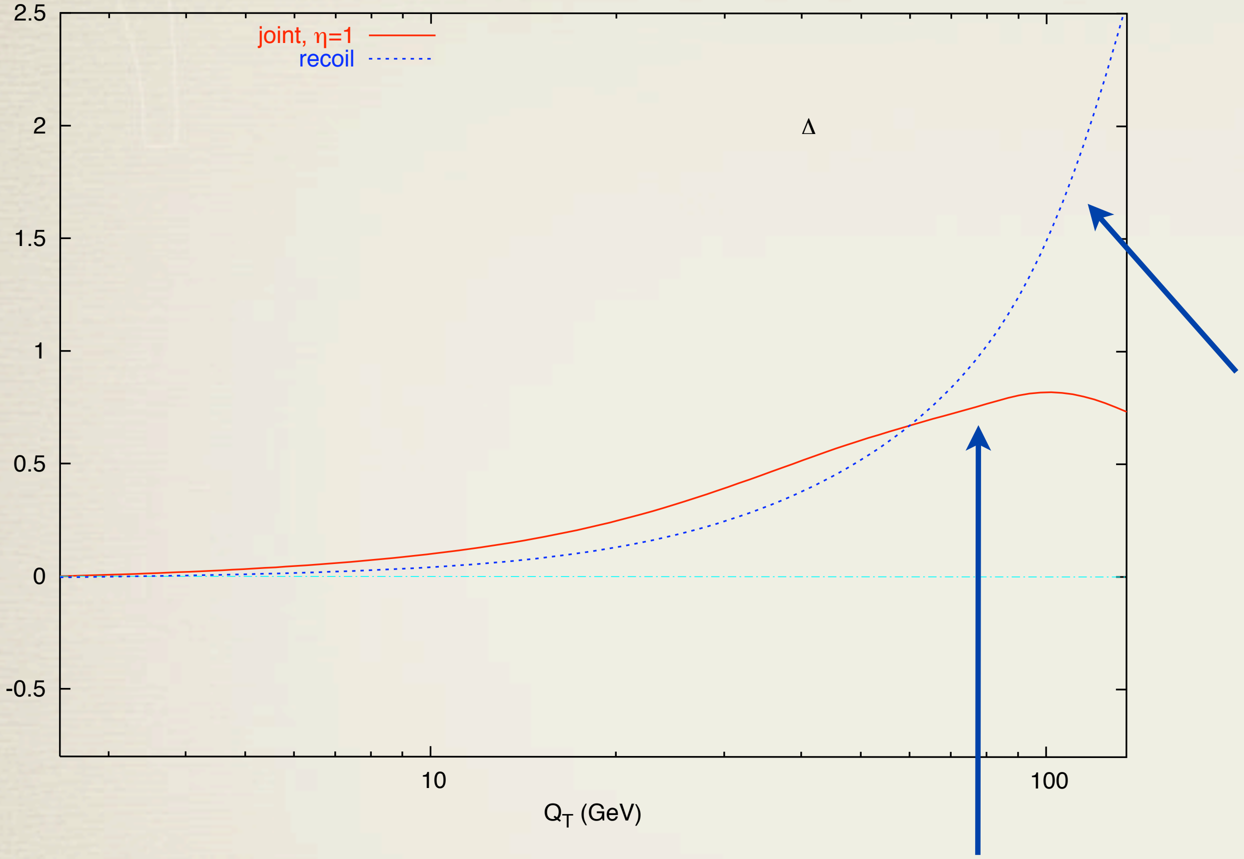
- As b→∞, hit Landau pole of QCD coupling; non-pertubative physics enters (why for $p_T > \Lambda_{QCD}$?)
- A typical approach; others exist (W is the integrand):



$$W(b) \to W(b_*)\exp\left[-b^2 g_1 - b^2 g_2 \ln\frac{b_{\max} m_D}{2}\right], \qquad b_* = \frac{b}{\sqrt{1+b^2/b_{\max}^2}}.$$

More on b-space resummation

- Other issues occur, in the combination with fixed order



$$\Delta \equiv \left[\frac{d\sigma^{\mathrm{fixed}(1)}}{dQ_T} - \frac{d\sigma^{\mathrm{exp}(1)}}{dQ_T}\right] \Big/ \frac{d\sigma^{\mathrm{fixed}(1)}}{dQ_T}$$

Large deviation of expanded b-space result from fixed-order complicates combining phase-space regions

“Joint resummation” Kulesza, Sterman, Vogelsang hep-ph/0309264

- Claim: more convenient framework to formulate low-p_T resummation is soft-collinear effective theory

Overview of SCET

- Lightning overview of SCET: split QCD gluon field into several fields with definite momentum scalings ($\eta \sim p_T/M_H$) and their own gauge transformations
  - $A = A_H + A_{c1} + A_{c2} + A_{us}$
  - $A_H \sim (p^-, p^+, p_T) \sim M_H(1,1,1)$ “hard”
  - $A_{c1} \sim M_H(\eta^2, 1, \eta)$ “collinear”
  - $A_{c1} \sim M_H(1, \eta^2, \eta)$ “collinear”
  - $A_{us} \sim M_H(\eta^2, \eta^2, \eta^2)$ “ultrasoft”

☑ Integrate out hard modes, match to collinear-invariant operators
☑ At leading-power, can decouple u-soft and collinear gluons

$$\begin{aligned} A_c &= Y A_c^{(0)} Y^\dagger \\ Y_c &= P\exp\left\{ ig \int_{-\infty}^{x} ds\, n \cdot A_{us}(sn) \right\} \end{aligned}$$

$A^{(0)}$ has no u-soft couplings; factorize matrix element into u-soft and collinear components

Low p_T in SCET

- Sequence of effective field theories: QCD→SCET$_{p_T}$→SCET$_{\Lambda_{QCD}}$
- Structure after matching to SCET$_{p_T}$:

$$
\begin{aligned}
\frac{d^2\sigma}{dp_T\,dY} &\sim \int dx_1 dx_2\,|C(x_1,x_2;\mu_Q,\mu_T)|^2 \int dk_n^+ dk_{\bar{n}}^- d^2k_n^\perp d^2k_{\bar{n}}^\perp \\
&\times\; J_n^{\alpha\beta}(x_1,k_n^+,k_n^\perp,\mu_T)\,J_{\bar{n}\alpha\beta}(x_2,k_{\bar{n}}^-,k_{\bar{n}}^\perp,\mu_T)S(x_1,x_2,k_{n\bar{n}},\mu_T) \\
|C|^2 &\sim \exp\left\{-\int_{\mu_T^2}^{\mu_Q^2}\frac{d\bar{\mu}^2}{\bar{\mu}^2}\gamma_{\mathcal{O}}(\bar{\mu}^2)\right\}
\end{aligned}
$$

☑ Lower limit of evolution set by matching scale $\mu_T \sim p_T$
☑ Exact momentum conservation still implemented
☑ Non-perturbative effects in power-suppressed operators
☑ Collinear gluon-jet functions valid for other LHC processes; some interesting differences from previous SCET studies...

(Sonny Mantry, FP: soon...)

Conclusions

- Intricate and large quantum effects on Higgs production
- Effective theory for gluon-fusion valid over a larger range than naively expected, excellent framework for pheno studies
- Combination of 3-loop light-quark terms, PDFs have significant effect on Tevatron exclusion limits
- Previously neglected high-p_T effects calculated
- All result being implemented in up-to-date analysis code FEHiP
- Framework for low-p_T resummation in SCET that should make fixed-order matching more convenient