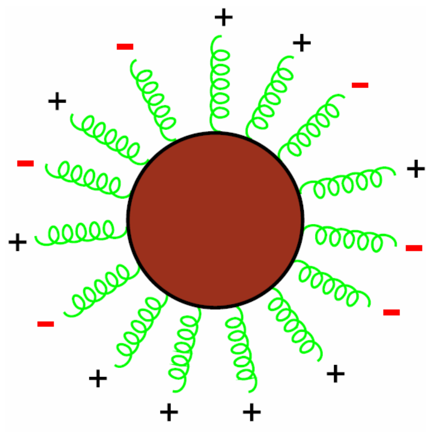
QCD at Colliders

Lecture 4



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Berlin 2 Oct. 2009

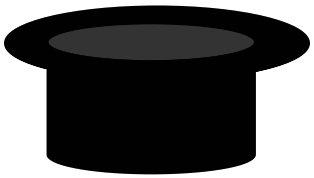
Lecture 4 Outline

- NLO *W* + 3-jet production at hadron colliders
  - Lessons about scales
- QCD corrections and the Higgs [$\rightarrow \gamma\gamma$] at the LHC

W + 3 jets at NLO

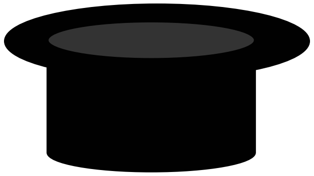
C.F.Berger, Z. Bern, LD, D. Forde, F. Febres Cordero, T. Gleisberg, H. Ita, D. Kosower, D. Maître, 0902.2760, 0907.1984

- Motivated as a background to SUSY searches in the "JETS + MET" channel, when the charged lepton in $W \to l\ \nu_l$ is lost
- Also closely related to Z + 3 jets (in progress), another SUSY background when $Z \to \nu\,\nu$
- Many different kinematic configurations can appear in final state – have to be careful to choose scale μ correctly to avoid pathologies!
- First phenomenologically interesting results from BlackHat [+Sherpa]

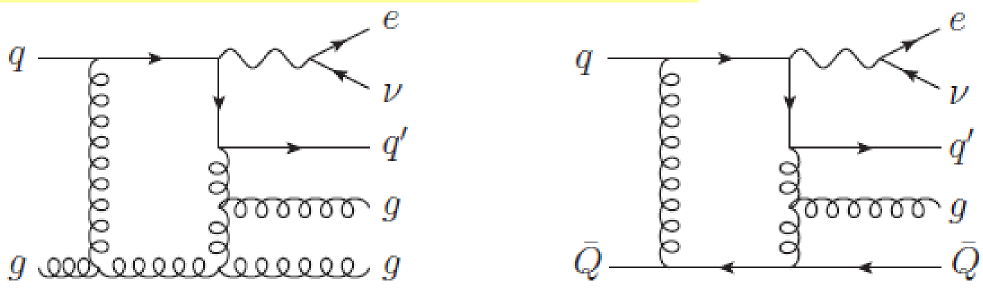


Related work by Ellis, Melnikov, Zanderighi 0901.4101, 0906.1445

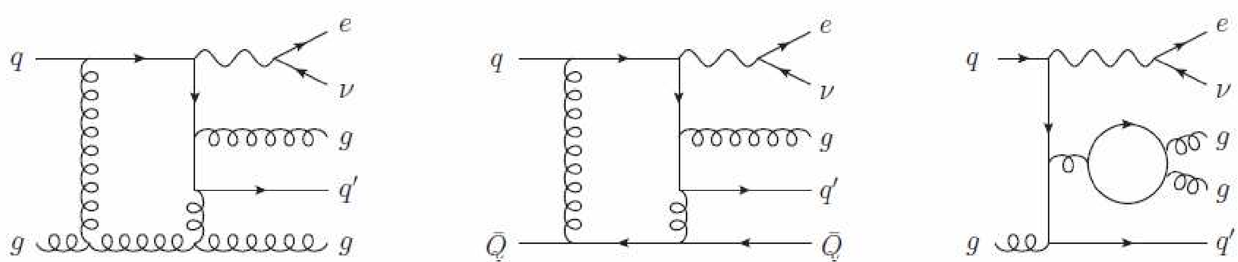
Virtual Corrections



- Divide into leading-color terms, such as:



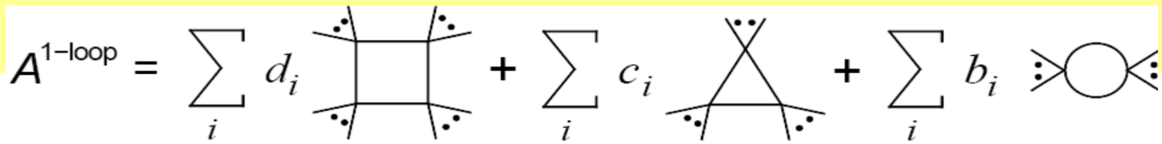
and subleading-color terms, such as:



The latter include many more terms, and are much more time-consuming for computer to evaluate. But they are much smaller (~ 1/30 of total cross section) so evaluate them much less often.

Numerical Stability of Virtual Terms

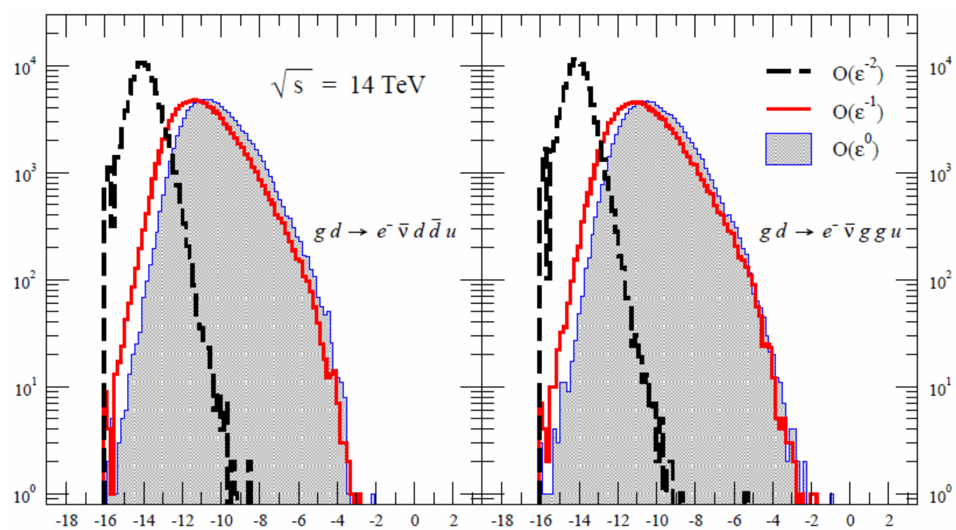
• Nontrivial because there are many kinematic regions where there are large cancellations between terms in this expansion, leading to roundoff error:



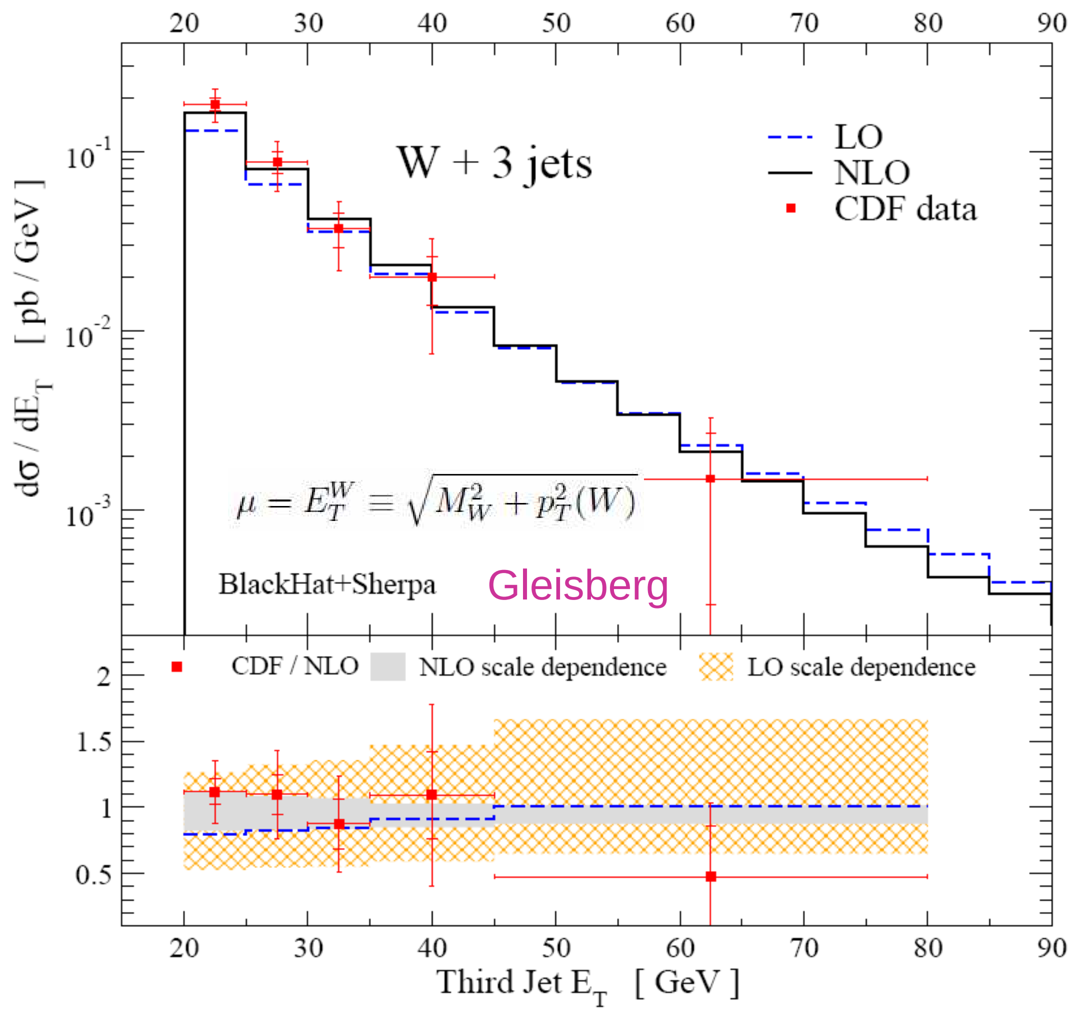
$$+ \ R \ + \mathcal{O}(\epsilon)$$

• BlackHat has a lot of tests for instability; if a piece of $A^{1\text{-loop}}$ is unstable, it recomputes that piece with higher precision (~32 digits).

• Resulting distributions of log(relative error) →



W + 3 jets at Tevatron at NLO



same cuts as CDF

$$E_T^{\rm jet} > 20\,{\rm GeV}\,, \qquad |\eta^{\rm jet}| < 2$$

$$E_T^e > 20\,{\rm GeV}\,, \qquad |\eta^e| < 1.1\,,$$

$$\not{E}_T > 30\,{\rm GeV}\,, \qquad M_T^W > 20\,{\rm GeV}$$

$$M_T^W = \sqrt{2E_T^e E_T^\nu(1 - \cos(\Delta\phi_{e\nu}))}$$

Except: we use SISCone; CDF used IR unsafe JETCLU

- Much smaller uncertainties than at LO.
- Agrees well with data; more data coming soon.

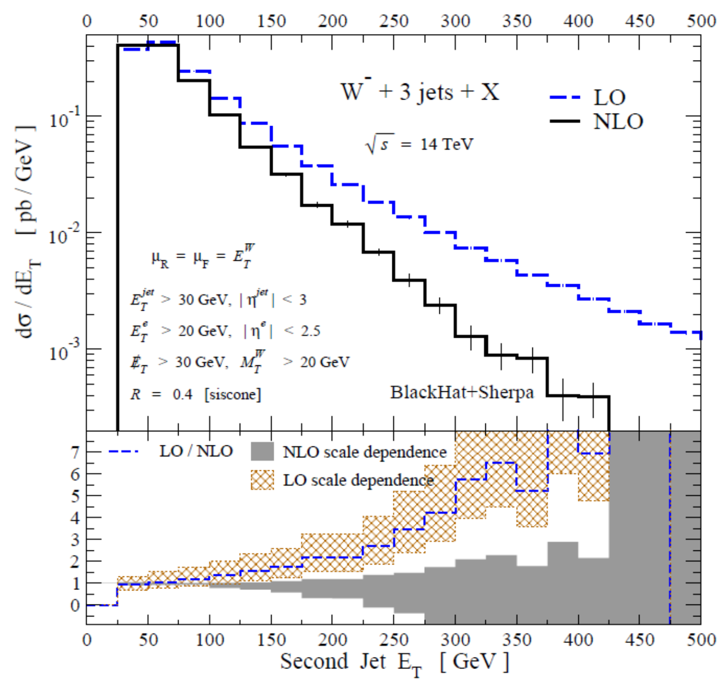
W + 3 jets at LHC at NLO

• LHC has a much greater dynamic range; there will be events with jet E_Ts much larger than M_W. Have to be more careful how we choose the renormalization + factorization scale.

• Indeed, the scale we used at the Tevatron,

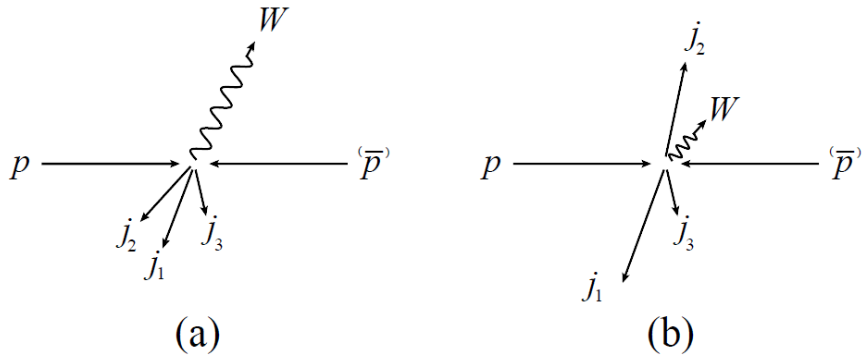
$$\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$$

which was also used in several other LO studies, turns out to be a really bad choice – NLO cross section can even dive negative! →



Better Scale Choice(s)

• What's going on? Consider these 2 configurations:



• If (a) dominates, then $\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$ is OK

• But if (b) dominates, then the scale $E_T{}^W$ is way too low.
• Looking at large E_T for the 2nd jet forces configuration (b).

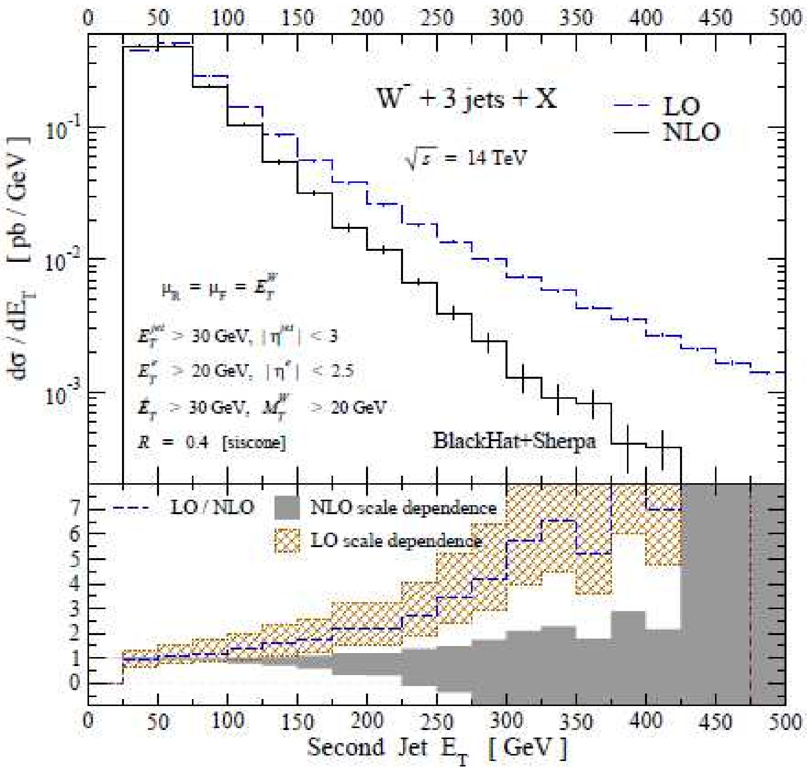
• The total (partonic) transverse energy is a better variable; gets large properly for both (a) and (b)

$$\hat{H}_T = \sum_p E_T^p + E_T^e + E_T^\nu$$

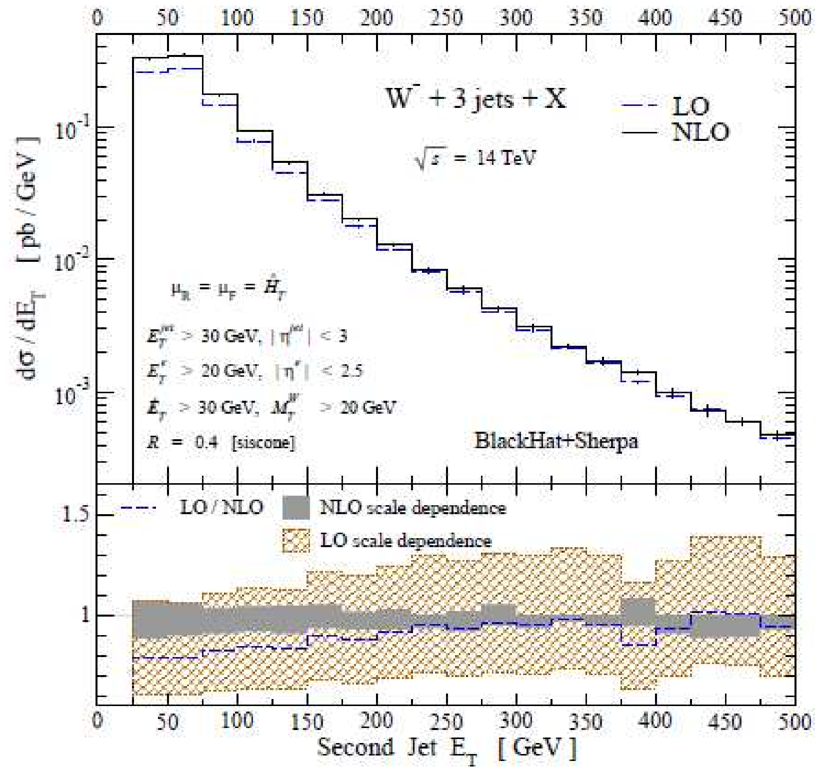
• Another reasonable scale is invariant mass of the n jets

Bauer, Lange 0905.4739

Compare the Two Scale Choice(s)



$\mu = E_T^W$ very poor



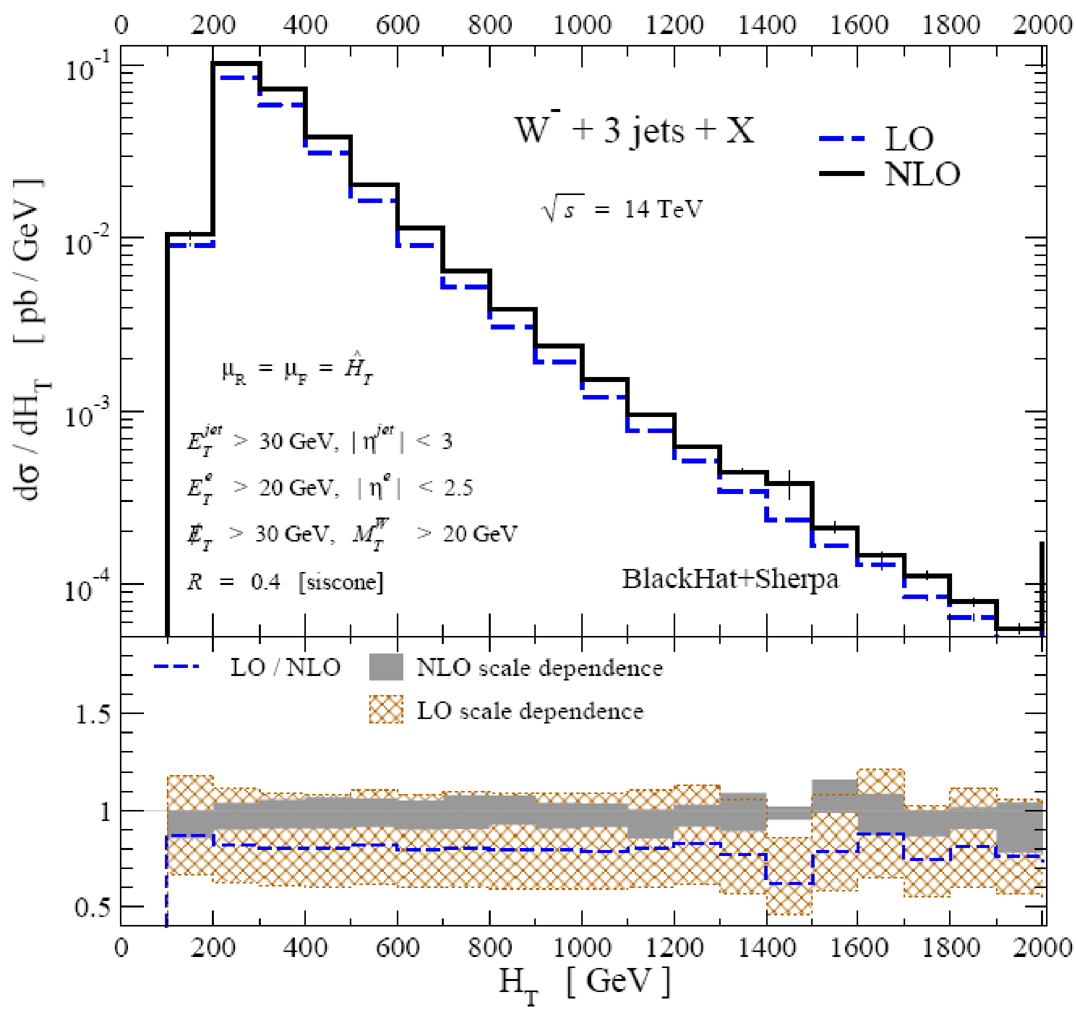
$\mu = \hat{H}_T$ excellent!

– LO/NLO quite flat, and also for many other observables

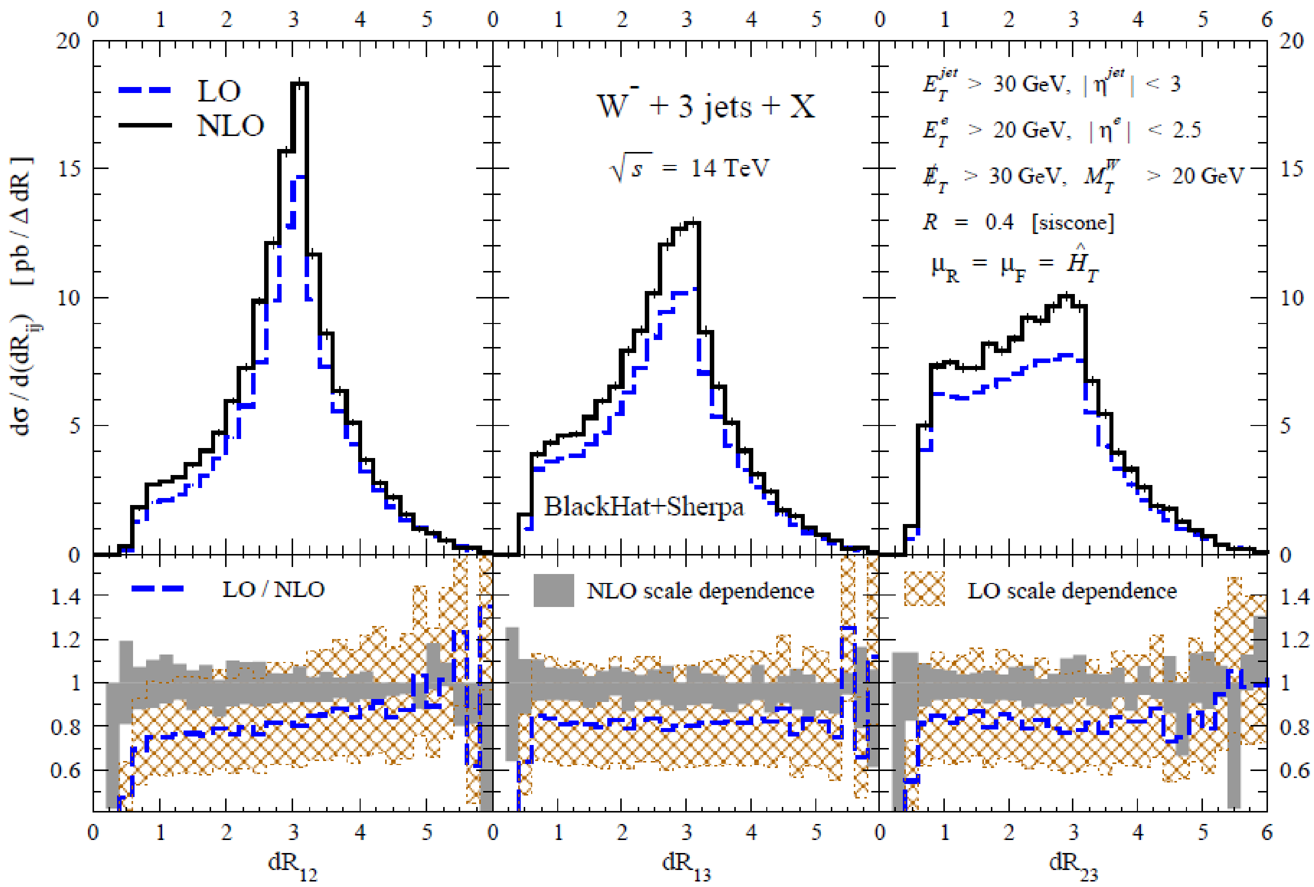
Total Transverse Energy H_T at LHC

$$H_T = \sum_j E_{T,j}^{\text{jet}} + E_T^e + E_T^\nu$$

often used in supersymmetry searches



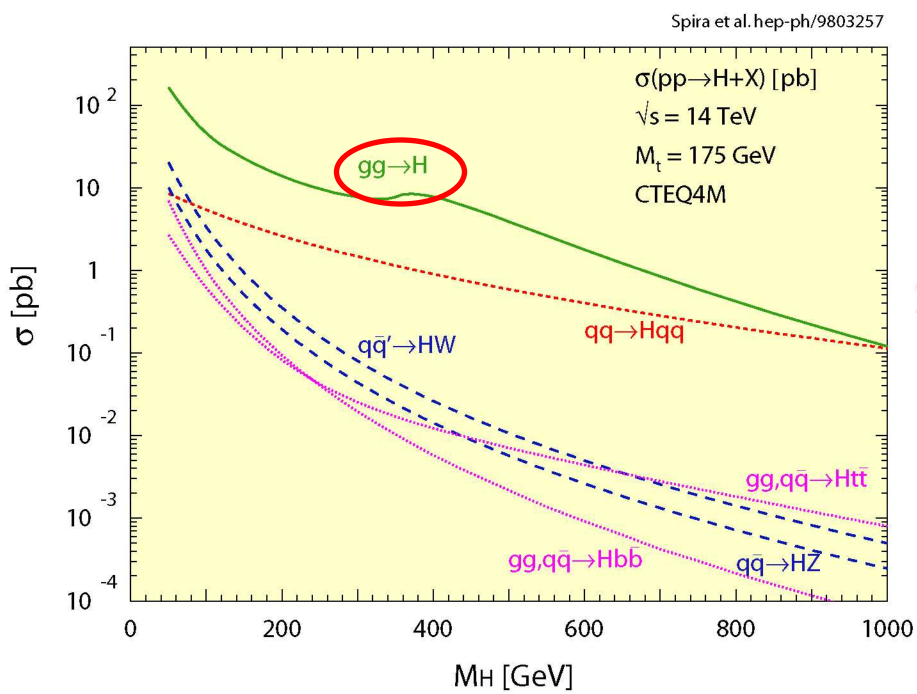
Jet Separations $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$

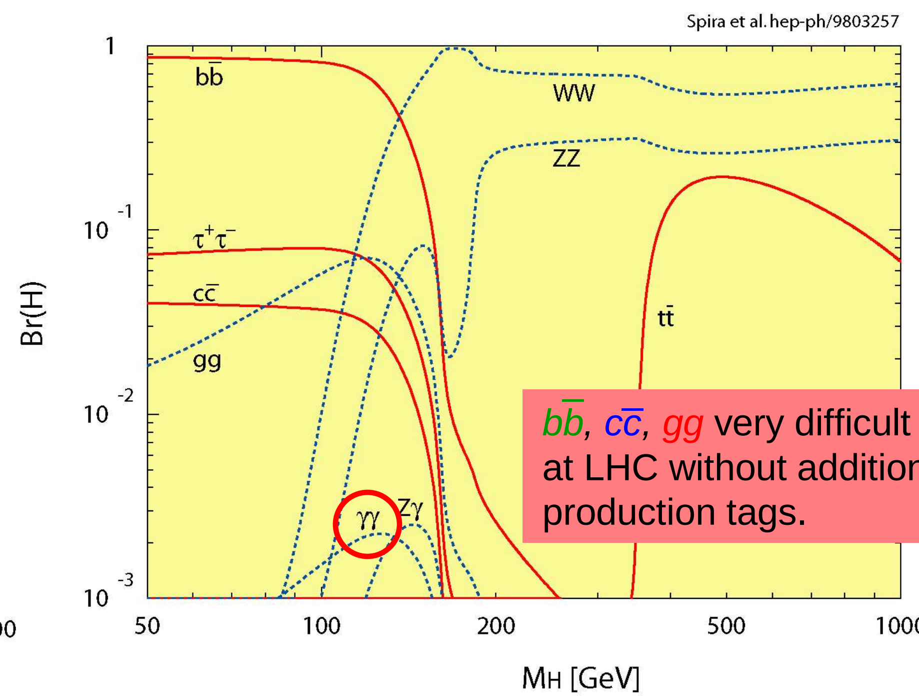


Pretty well modeled by LO, except for first 2 jets

QCD Corrections and the Higgs [→ $\gamma\gamma$] at the LHC

Production & decay mechanisms





bb̄, *cc̄*, *gg* very difficult at LHC without additional production tags.

Here focus on:

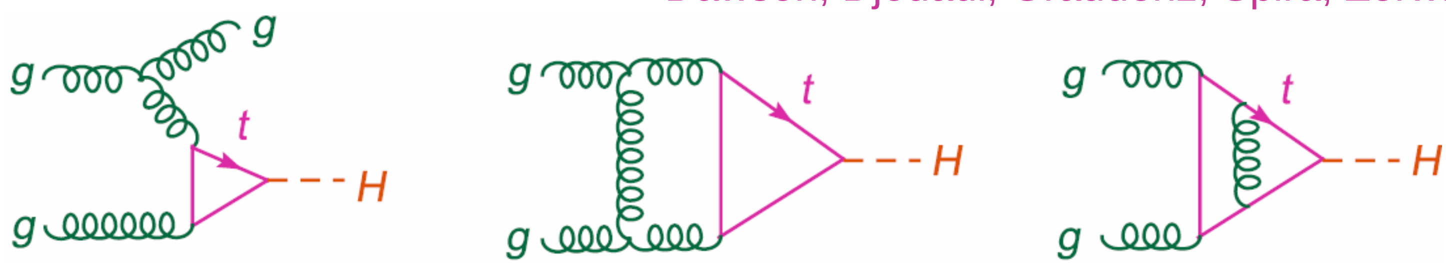
$gg \longrightarrow H$ largest, but largest QCD uncertainties

$H \longrightarrow \gamma\gamma$ very small, but also clean bump

$gg \to H \to \gamma\gamma$ Signal

- Height proportional to $\sigma(pp \to H + X) \times \mathrm{Br}(H \to \gamma\gamma)$
- Compute σ and Br as expansion in α_s
- Series for Br is quite convergent, ~6% uncertainty from m_b in Γ_H
- Series for σ is *poorly* behaved: first correction (NLO) is 80% !

Dawson; Djouadi, Graudenz, Spira, Zerwas (1991)

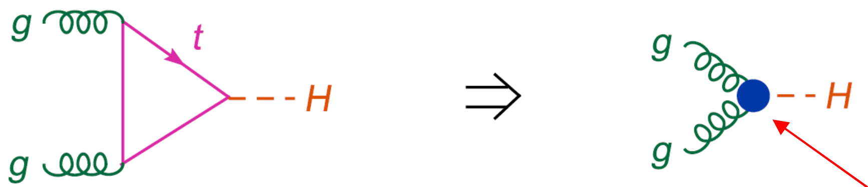


- Drove big theoretical effort to compute NNLO term

Catani, DeFlorian, Grazzini; Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven (2001–03)

$\sigma(pp \to H + X)$ at NNLO

To make tractable, use large m_t approximation:
reduces number of loops by 1

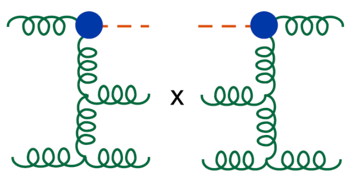


$$C(m_t) H G^a_{\mu\nu} G^{a\,\mu\nu}$$

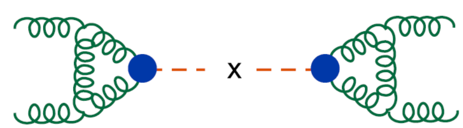
effective vertex

Still many amplitude interferences, with different numbers of final state gluons (or quarks). Each diverges; only sum is finite.

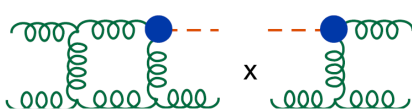
- real x real



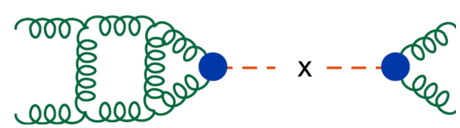
- virtual x virtual



- virtual x real

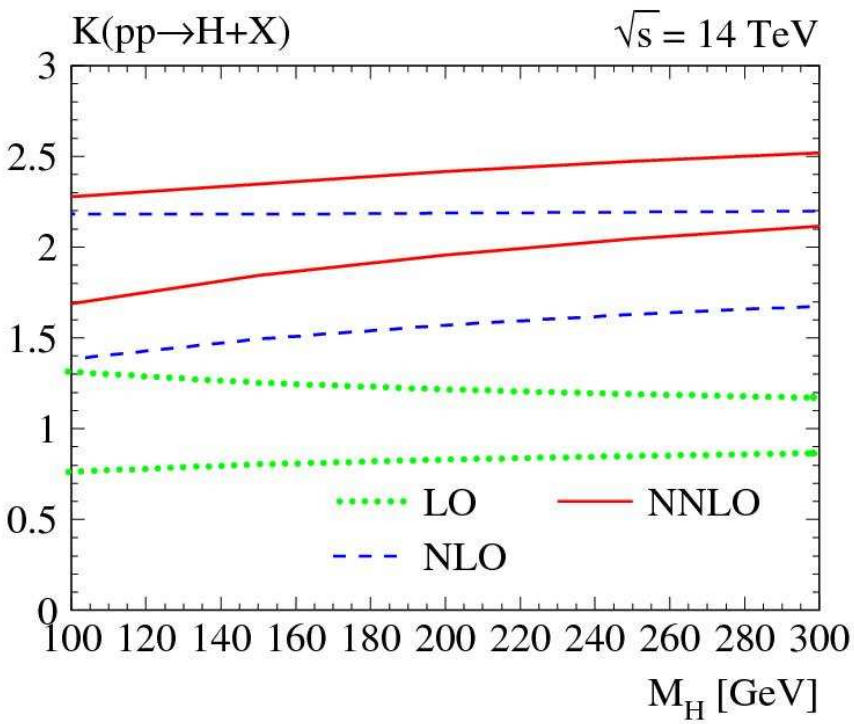


- doubly-virtual x real



$\sigma(pp \to H + X)$ at NNLO

Results expressed as *K* factor:



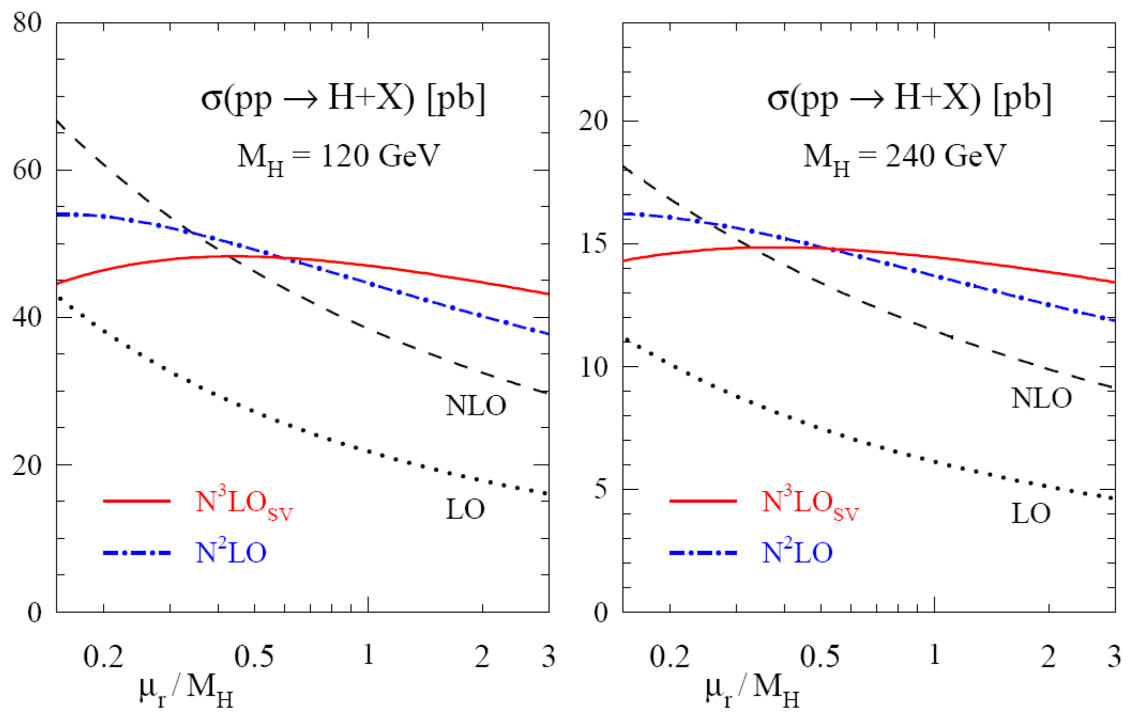
$$K_{\text{NNLO}} = \frac{\sigma_{\text{NNLO}}}{\sigma_{\text{LO}}}$$

$$K_{\text{NLO}} = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$$

Series stabilized;
residual uncertainty
~ 10-20%

$\sigma(pp \rightarrow H + X)$ at N^3LO_{SV}

Using partial (logarithmically enhanced) results at N^3LO, even more stable results are obtained :



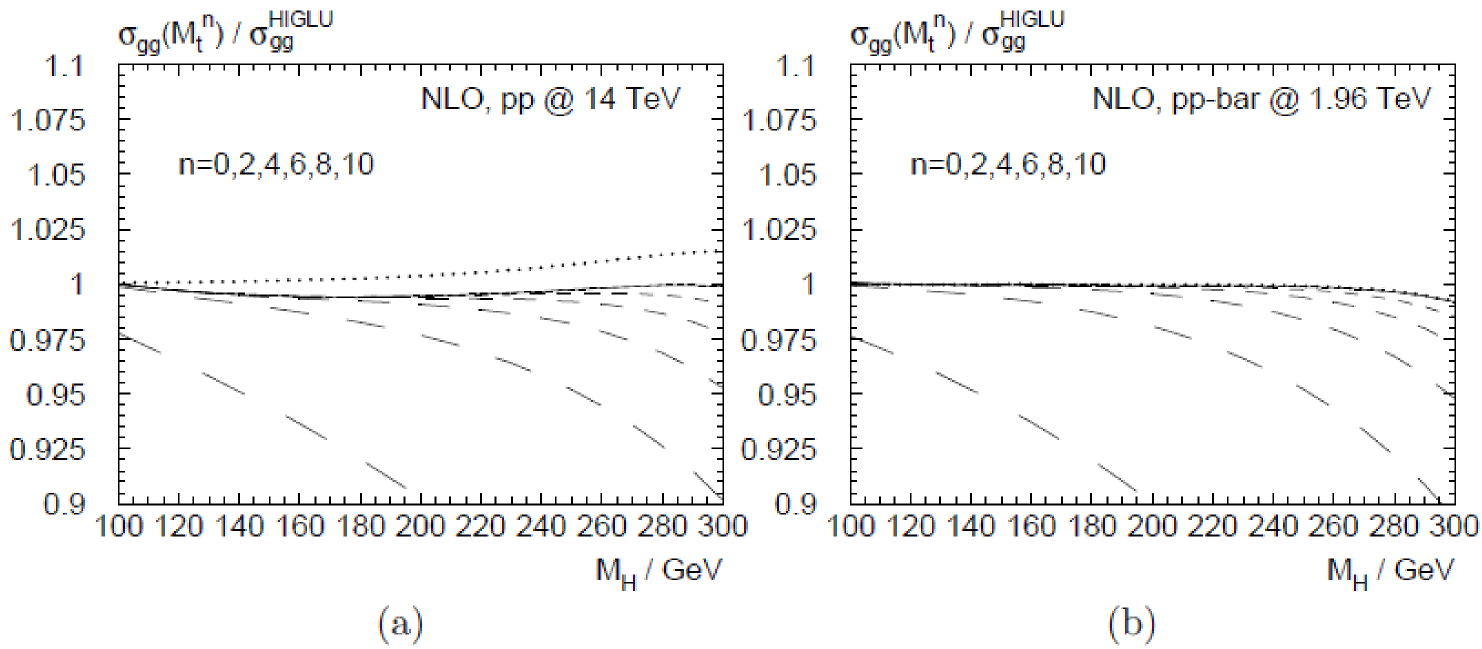
Moch, Vogt, hep-ph/0508265 (also Ravindran, hep-ph/0603041)

- Now residual uncertainty on σ^{tot} ~ ± 5%
- Plus gluon pdf uncertainty (next slide)

Corrections to large m_t approximation

Harlander, Ozeren, 0909.3420

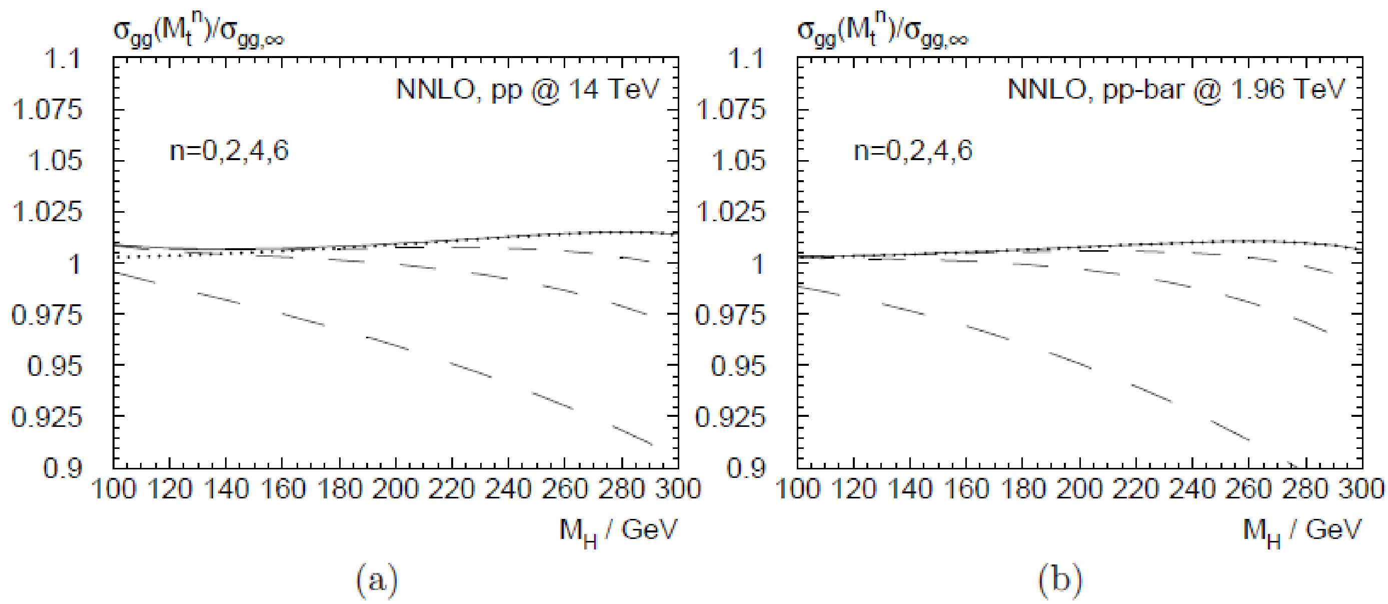
Recent evaluation of these corrections at NLO (to check convergence against the known exact result):



Corrections to large m_t approx. (cont.)

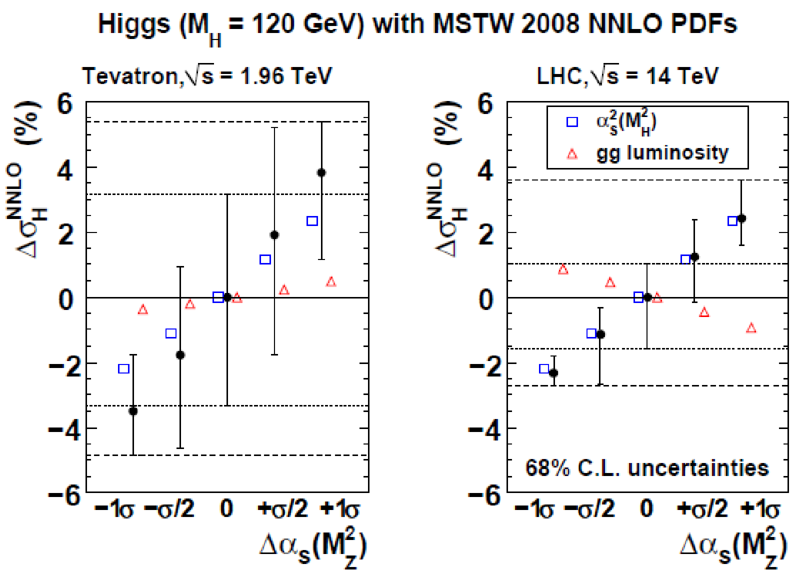
Harlander, Ozeren, 0909.3420

And then at NNLO:

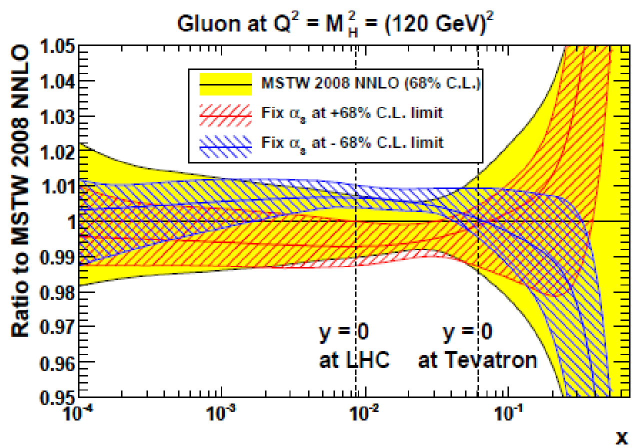


Showing that these corrections are quite small, ~ 1-2%.

$\sigma(pp \to H + X)$ pdf uncertainty



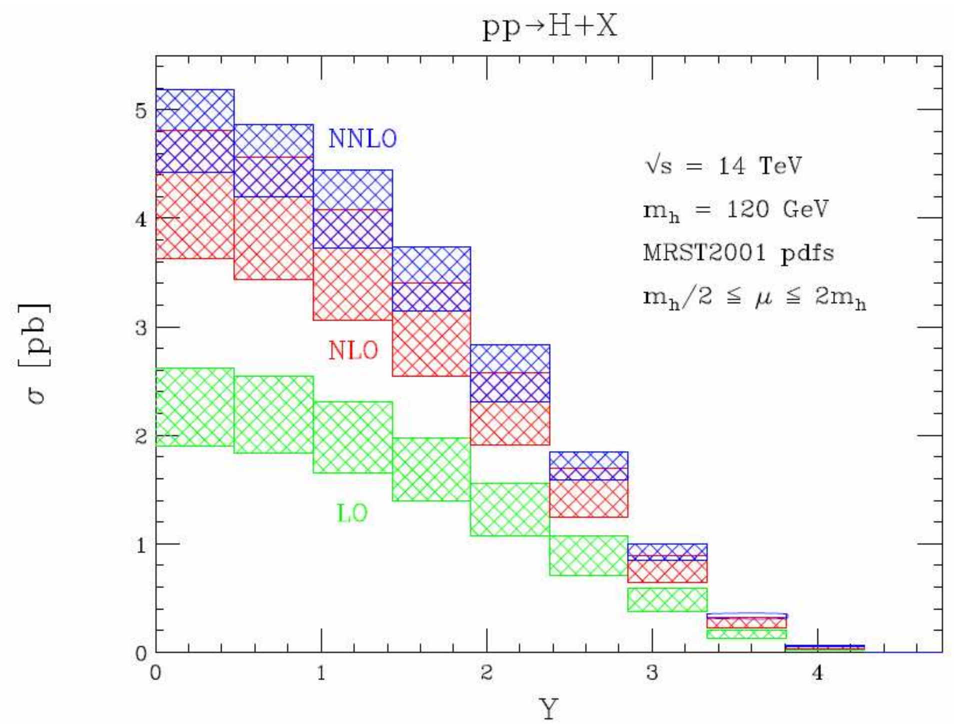
Martin, Stirling, Thorne, Watt, 0905.3531



Uncertainty < 4% at LHC
Highly correlated with value of α_S

$\frac{d\sigma}{dY}(pp \rightarrow H + X)$ at NNLO

Anastasiou, Melnikov, Petriello, hep-ph/0501130



Y = rapidity of Higgs boson

- Can include parton-level event cuts (photon kinematics, isolation, jet or jet veto, …)
- Can use NNLO information to reweight event generators (PYTHIA, MC@NLO) in bins of p_T, Y

Davatz, et al., hep-ph/0604077

$gg \to H \to \gamma\gamma$ interference?

LD, M.S. Siu, hep-ph/0302233

- In principle as important as signal, since it contaminates peak

$$\text{Is} \qquad \text{Signal} = \sigma_{ii\to H} \times \text{Br}(H \to ff) = \frac{\Gamma_i \Gamma_f}{\Gamma} \qquad ?$$

- Resonance-continuum interference would negate this:

$$\mathcal{A}(gg \to \gamma\gamma) = \frac{-\mathcal{A}(gg\to H)\,\mathcal{A}(H\to\gamma\gamma)}{\hat{s} - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\text{cont}}(gg \to \gamma\gamma)$$

- Normally interference effects are small for a narrow resonance, and Γ_H ~ few MeV for Higgs.
- However, this resonance is pretty wimpy, ~ (one-loop)^2

$gg \rightarrow H \rightarrow \gamma\gamma$ interference

- Total $gg \rightarrow \gamma\gamma$ amplitude

$$\mathcal{A}_{gg\rightarrow\gamma\gamma} = \frac{-\mathcal{A}_{gg\rightarrow H}\mathcal{A}_{H\rightarrow\gamma\gamma}}{\hat{s} - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\rm cont}$$

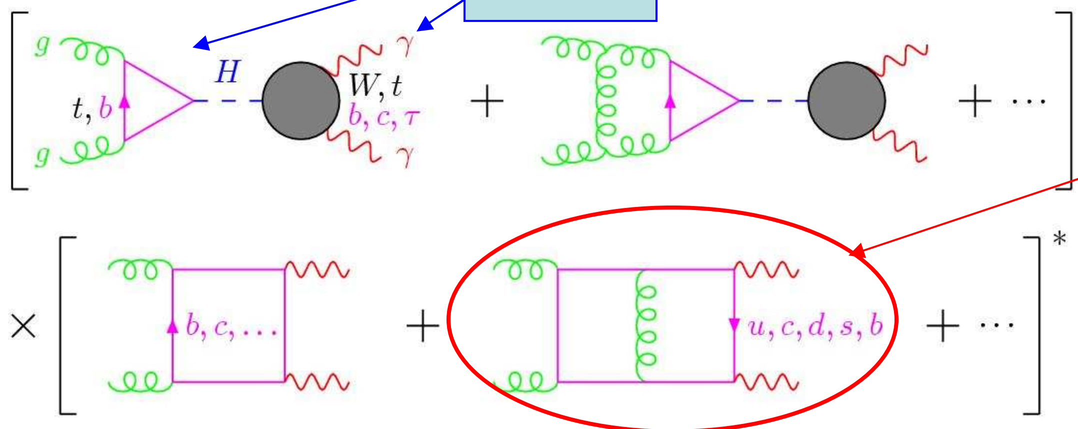
- Interference term has 2 pieces

$$\begin{aligned} \delta\hat{\sigma}_{gg\rightarrow H\rightarrow\gamma\gamma} &= -2(\hat{s} - m_H^2)\frac{\mathrm{Re}\,(\mathcal{A}_{gg\rightarrow H}\mathcal{A}_{H\rightarrow\gamma\gamma}\mathcal{A}^*_{\rm cont})}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \\ &\quad - 2 m_H \Gamma_H \frac{\mathrm{Im}\,(\mathcal{A}_{gg\rightarrow H}\mathcal{A}_{H\rightarrow\gamma\gamma}\mathcal{A}^*_{\rm cont})}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \end{aligned}$$

- "Re" term vanishes upon integration over $\hat{s}$, provided that $\mathcal{A}_{gg\rightarrow H}$, $\mathcal{A}_{H\rightarrow\gamma\gamma}$, $\mathcal{A}_{\rm cont}$ do not vary too quickly. Dicus, Willenbrock
- "Im" term needs relative phase, resonance *vs.* continuum.

$gg \to H \to \gamma\gamma$ interference

~ real

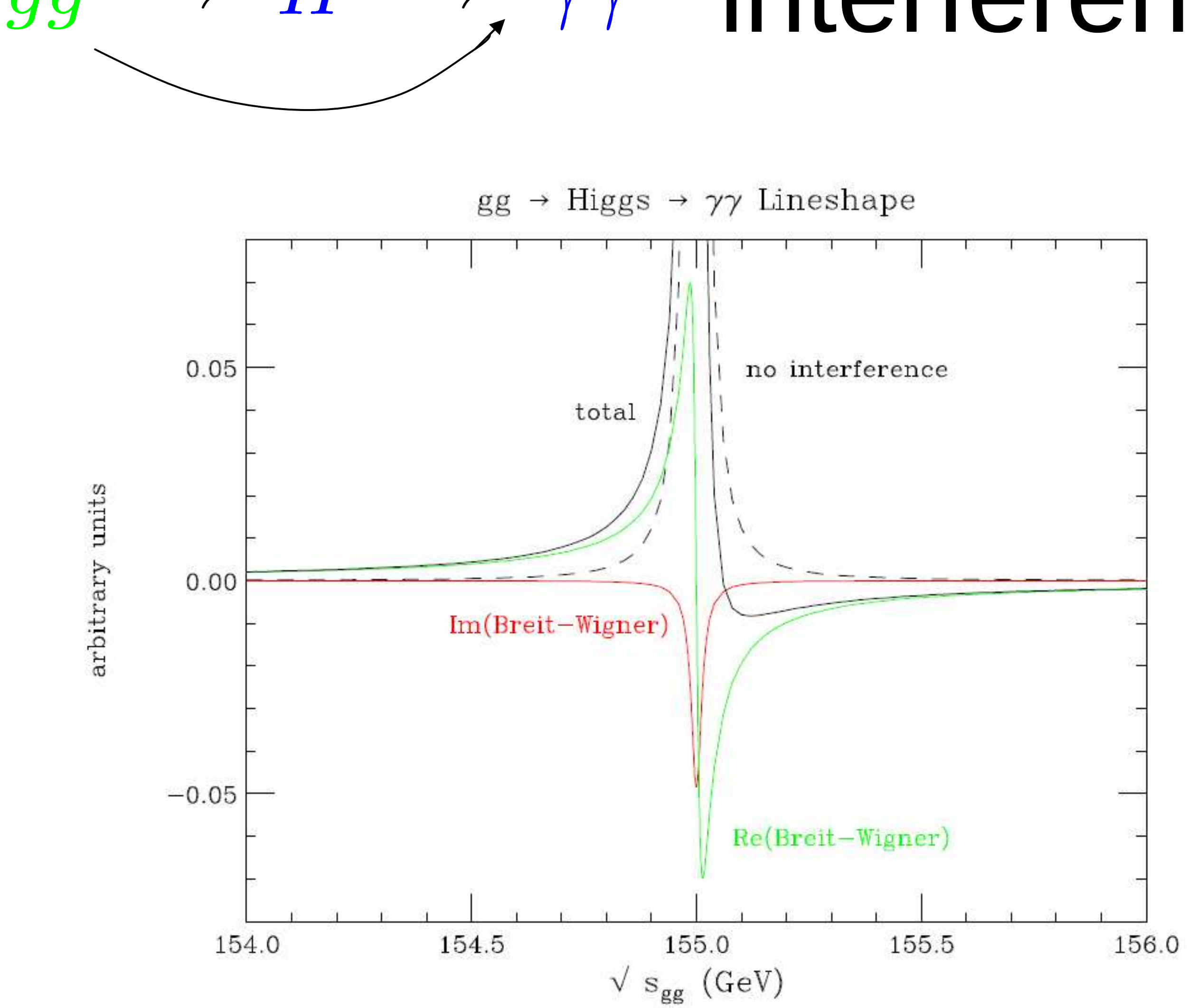


main source of a required phase

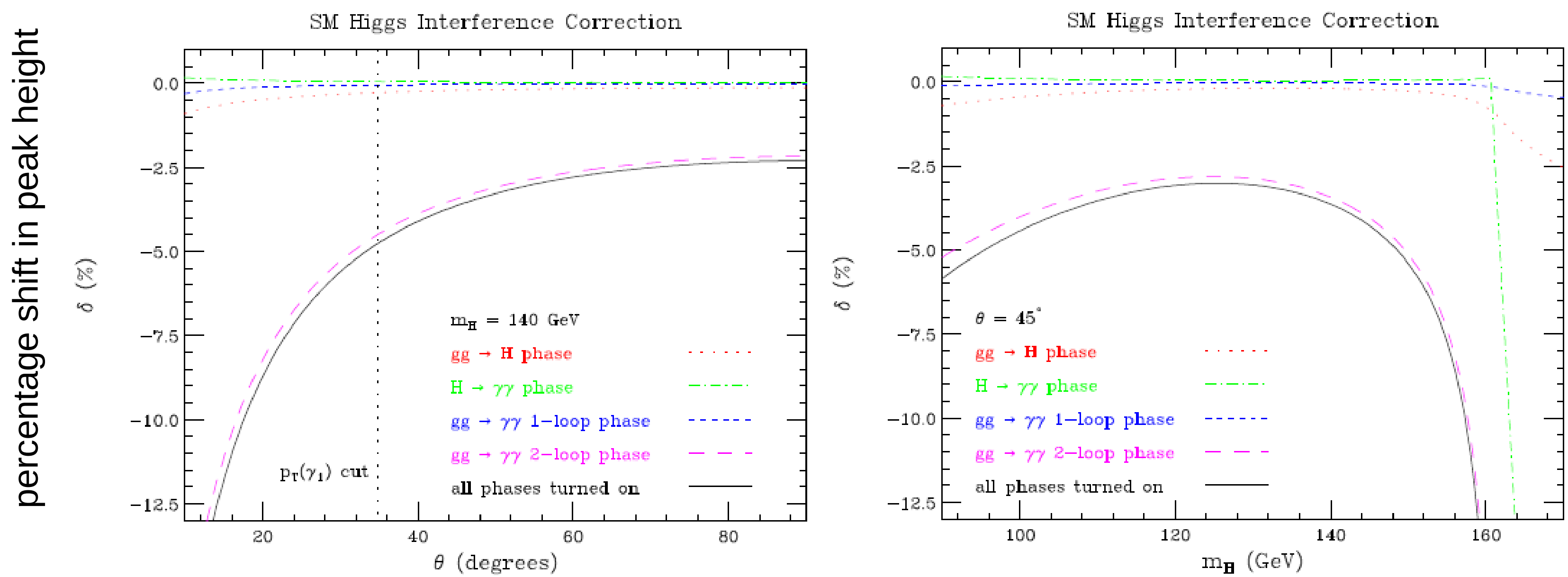
almost real, for $m_q^2 \ll \hat{s}$,
due to "accidental" zero:

$$\mathcal{A}^{\rm tree}(g^\pm g^\pm \to q\bar{q}) = \mathcal{A}^{\rm tree}(q\bar{q} \to \gamma^\pm\gamma^\pm) = 0 \text{ for } m_q = 0$$

$gg \to H \to \gamma\gamma$ interference



$gg \to H \to \gamma\gamma$ interference

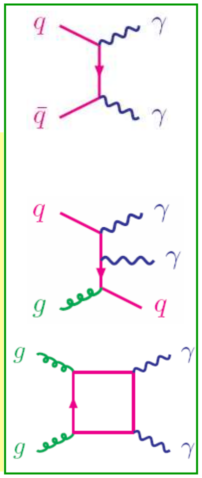


- Effect is $-(2-6)\%$ over region where $\gamma\gamma$ is visible.
- Gets very large near WW threshold.

  But visibility of $\gamma\gamma$ is very poor there

$\gamma\gamma$ backgrounds

- Multiple components, working from the "outside" in:
- Non-photons faking photons: $e^{\pm}$, hadrons
- Real photons from hadronic decay, principally $\pi^0 \rightarrow \gamma\gamma$
- Photons from QED bremsstrahlung from $e^{\pm}$
- Photons from fragmentation – "long" distance radiation from within a hadronic jet, $p_T^{\gamma,\,\mathrm{jet}} < 1$ GeV
- Photons from QCD hard process – "short" distance radiation off quark lines, $p_T^{\gamma,\,q} > 1$ GeV. Hard processes include:
  - $q\bar{q} \rightarrow \gamma\gamma$ LO
  - $qg \rightarrow \gamma\gamma q$ NLO, enhanced by $g(x)$, FS singularity
  - $gg \rightarrow \gamma\gamma$ NNLO, enhanced by $g(x)$

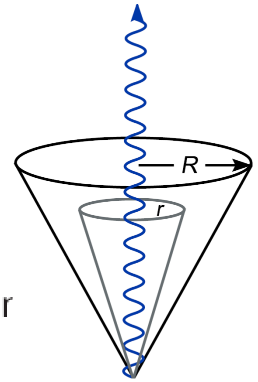


Photon isolation a key tool for suppressing many of the components

Photon isolation criteria

Cut on nearby transverse hadronic energy

- Required to reject jets or π^0s faking γs, reduce fragmentation terms



- Either
  - **standard cone**: Circle, radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ in (η, ϕ) plar
    Require $E_{\rm T} < E_{\rm T\,max}$ inside circle.
  - **smooth (Frixione) cone**: Require $E_{\rm T}(r)$ less than

$$E_{\rm T\,max}(r) \equiv p_{\rm T}(\gamma)\,\epsilon\,\frac{1-\cos r}{1-\cos R}$$

for all circles with $r < R$.

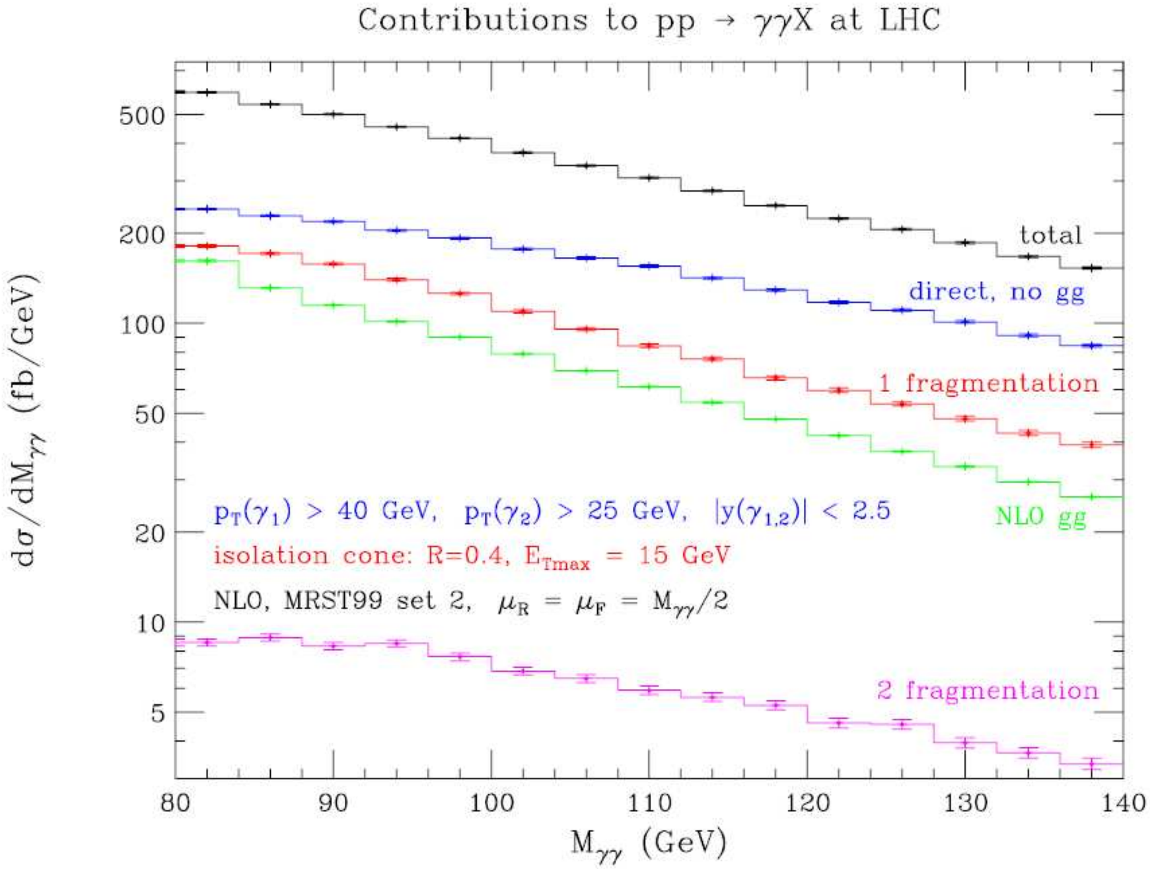
Frixione, hep-ph/9801442

Smooth cone has no fragmentation contribution, but may be difficult to exploit experimentally (transverse shower extent, finite detector granularity).

- Too strict isolation: a) is not infrared safe, and b) lowers efficiency at high *L*

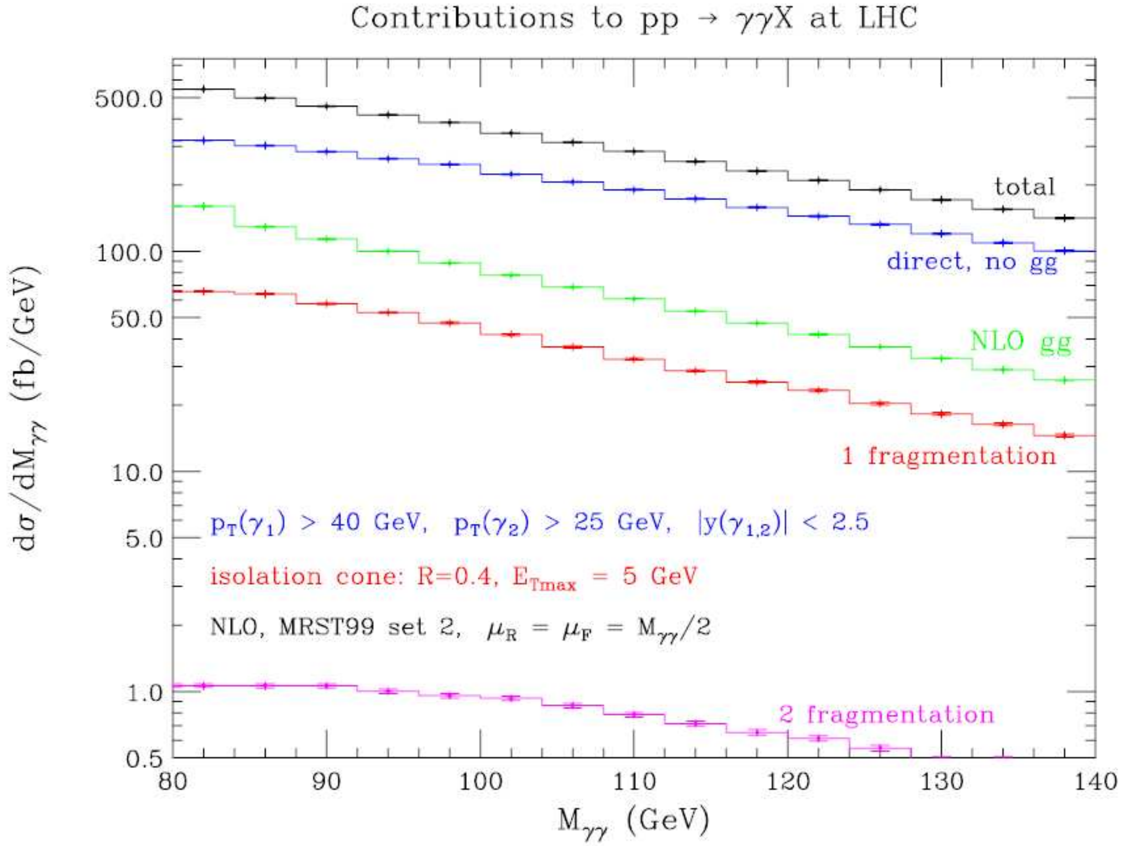
Irreducible $\gamma\gamma$ background

Bern, LD, Schmidt, hep-ph/0206194;
DIPHOX: Binoth, Guillet, Pilon, Werlen, hep-ph/9911340



Irreducible $\gamma\gamma$ background

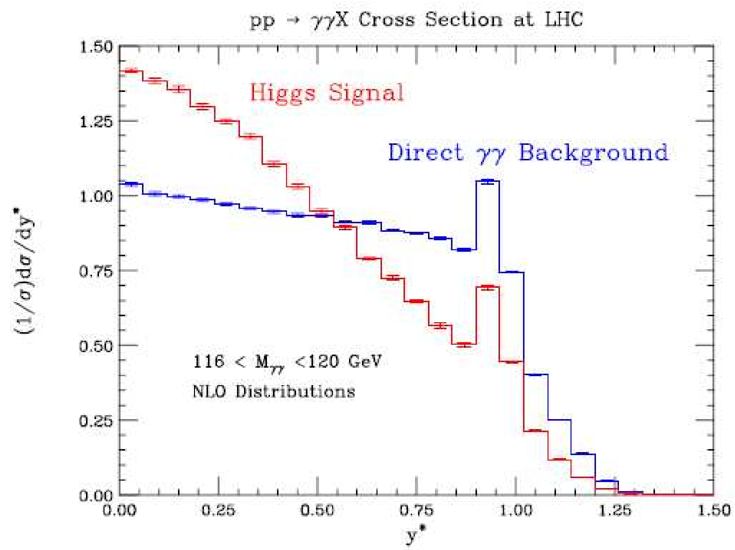
With a tighter E_T cut:



Angular distribution of γ's

- Scalar Higgs decay is flat in $\cos\theta^*$.
  At LO, $\cos\theta^* = \tanh y^*$, where $y^* \equiv \frac{1}{2}(y(\gamma_1) - y(\gamma_2))$.

- QCD background from $q\bar{q}$, qg, and gg enhanced at small θ^*, large y^*, due to t-channel fermion exchange.
  Information can be used to improve $S/\sqrt{B}$, but only marginally.
  better to use in likelihood function than as hard cut



Require additional jet activity?

Abdullin et al., hep-ph/9805341

Motivation:

- Signal dominantly *gg* → *H*, really likes to radiate (8 + 8 → 1).
- Background has $q\bar{q}$ → $\gamma\gamma$, smaller color charge, less radiation

$M_H = 120$ GeV	no $\sqrt{\hat{s}}$ cut	$\sqrt{\hat{s}} > 210$ GeV	$\sqrt{\hat{s}} > 300$ GeV
σ_S^{QCD} fb	10.6	7.0	4.0
σ_S^{EW} fb	1.1	0.81	0.58
σ_B fb/GeV	25.3	9.1	2.9

de Florian, Kunszt, hep-ph/9905283;
de Florian, Kulesza Vogelsang, hep-ph/0511205

- Can play a similar game using transverse momentum of photon pair, $q_T(\gamma\gamma)$.
- Maybe best done via likelihoods as well?

Conclusions

- Higher order QCD for the LHC is an extremely rich field – we only scratched the surface of it here
- At hadron colliders, the physics **is** QCD – up to small, electroweak corrections!
- To uncover new physics of electroweak strength, we will need to understand QCD at colliders quite well
- Fortunately, there are lots of energetic young researchers
- But still, lots of work to be done, even as the data begin to roll in from the energy frontier!