QCD background for *Higgs* $\to \gamma\gamma$

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Transverse momentum (q_T) distributions in $p\bar{p}^{(-)} \to \gamma\gamma X$

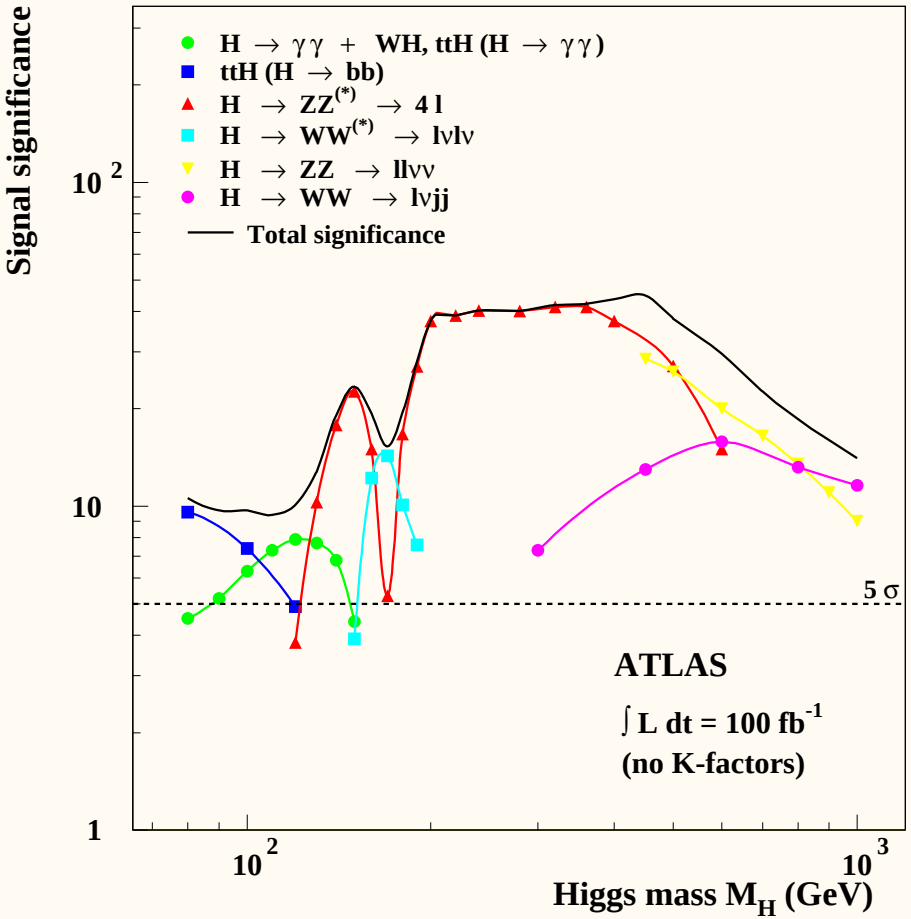
We use q_T resummation to compute fully differential distributions of prompt $\gamma\gamma$ pairs (including q_T dependence) at NNLL accuracy

References

1. *C. Balázs, E. Berger, **P. N.**, C.-P. Yuan, hep-ph/0603037*
2. *C. Balazs, E. Berger, S. Mrenna, C.-P. Yuan, PRD 57, 6934 (1998)*
3. *C. Balazs, **P. N.**, C. Schmidt, C.-P. Yuan, PLB 489, 157 (2000)*
4. ***P. N.**, C. Schmidt, PLB 558, 63 (2003)*

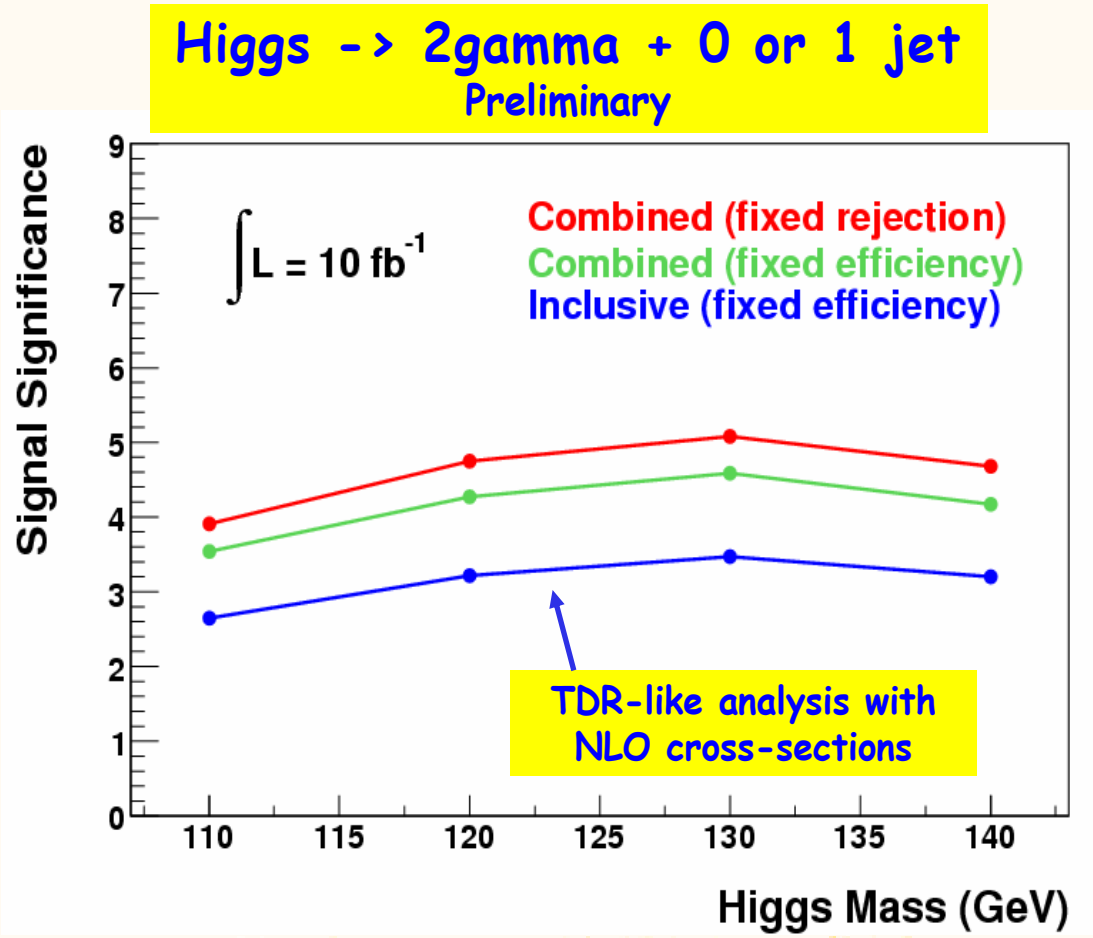
The results are implemented in a MC integrator program ResBos

SM Higgs boson search at the LHC



- $gg \to H \to \gamma\gamma$ (via t-quark loop) is the crucial and challenging search mode for $115 < M_H < 140$ GeV
- QCD background processes for $\gamma\gamma$ production are complicated; must be understood for successful Higgs discovery and measurement of Higgs cross sections
- An interesting QCD process on its own!

Higgs discovery significance is improved by...



Bruce Mellado, ATLAS Physics Workshop 07/06/05

- ... NLO corrections
- ... use of q_T of $\gamma\gamma$ pair as a discriminating variable
  - Significance increased by $20 - 40\%$
- ... combination of inclusive $H \to \gamma\gamma$ and $H \to \gamma\gamma + 1$ jet analyses
- ... optimization of γ detection and jet rejection

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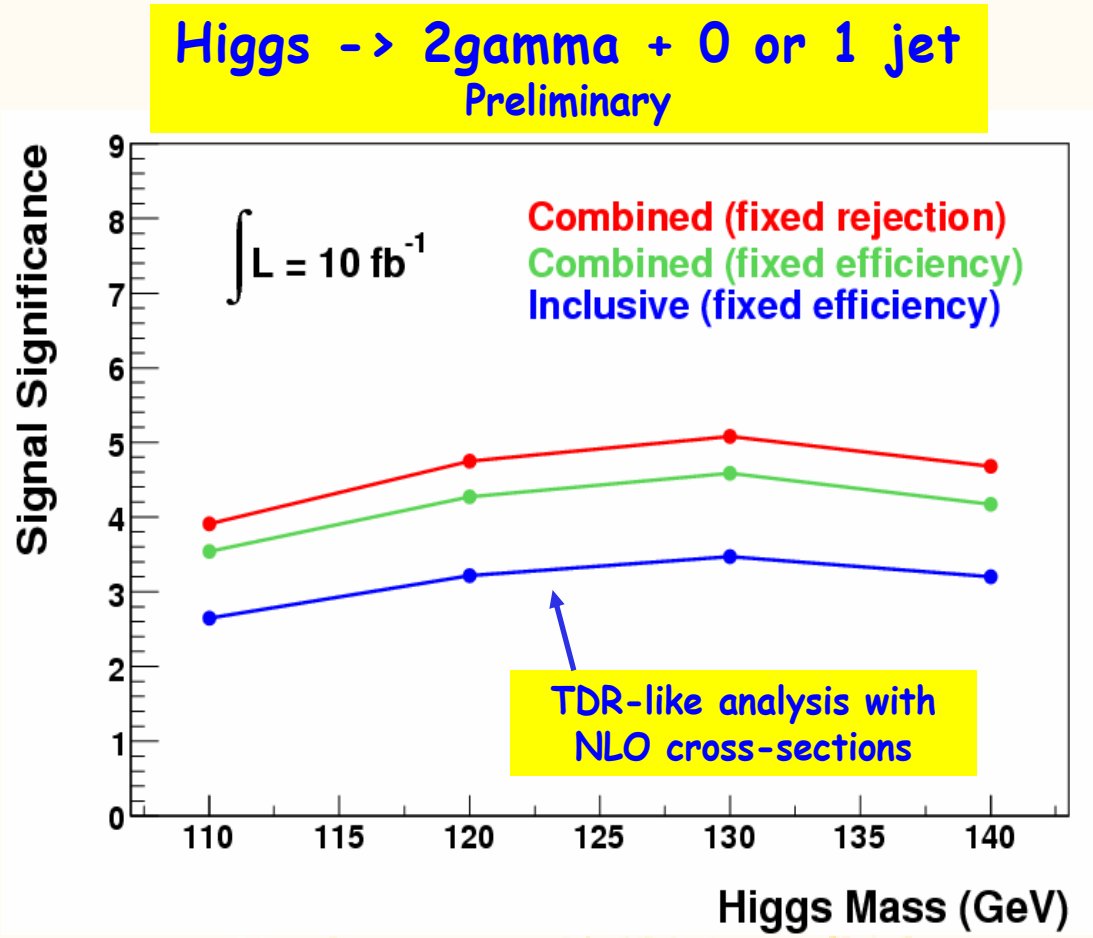

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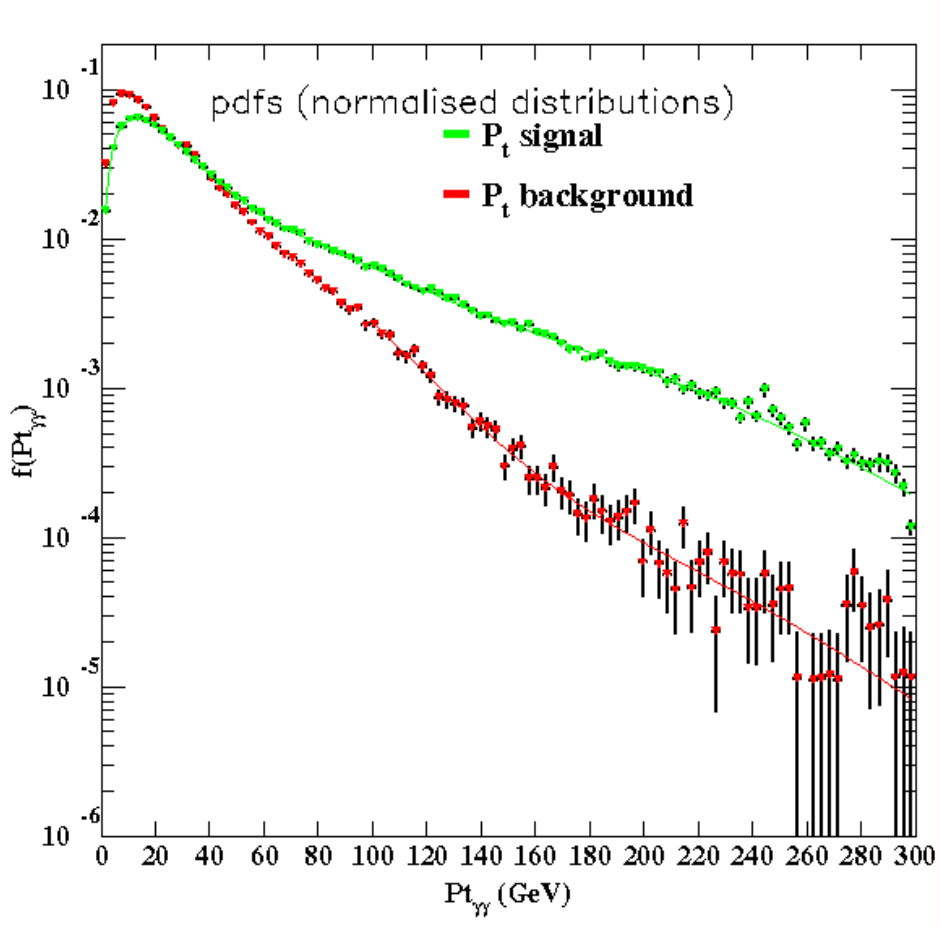
Knowledge of q_T optimizes Higgs boson search

(Abdullin et al., 1998; Balazs, P.N., Schmidt, Yuan; de Florian, Kunszt, 1999; Berger, Qiu, 2003)



M. Escalier, 2005; ResBos (2,3)

- At $q_T \ll Q$,

$$\left(\frac{d\sigma}{dq_T^2}\right)_{q_T^2 \ll Q^2} \approx \sum_{k=0}^{\infty} \alpha_s^k \left[c_k \delta(\vec{q}_T) + q_T^{-2} \cdot \sum_{n=0}^{2k-1} d_{nk} \ln^n(Q^2/q_T^2) \right];$$

the large terms are summed to all orders in α_s by means of Collins-Soper-Sterman (CSS) resummation

- Higgs $\langle q_T \rangle$ is enhanced by a larger soft (Sudakov) factor and gluon PDF shape in $gg \to H$ scattering

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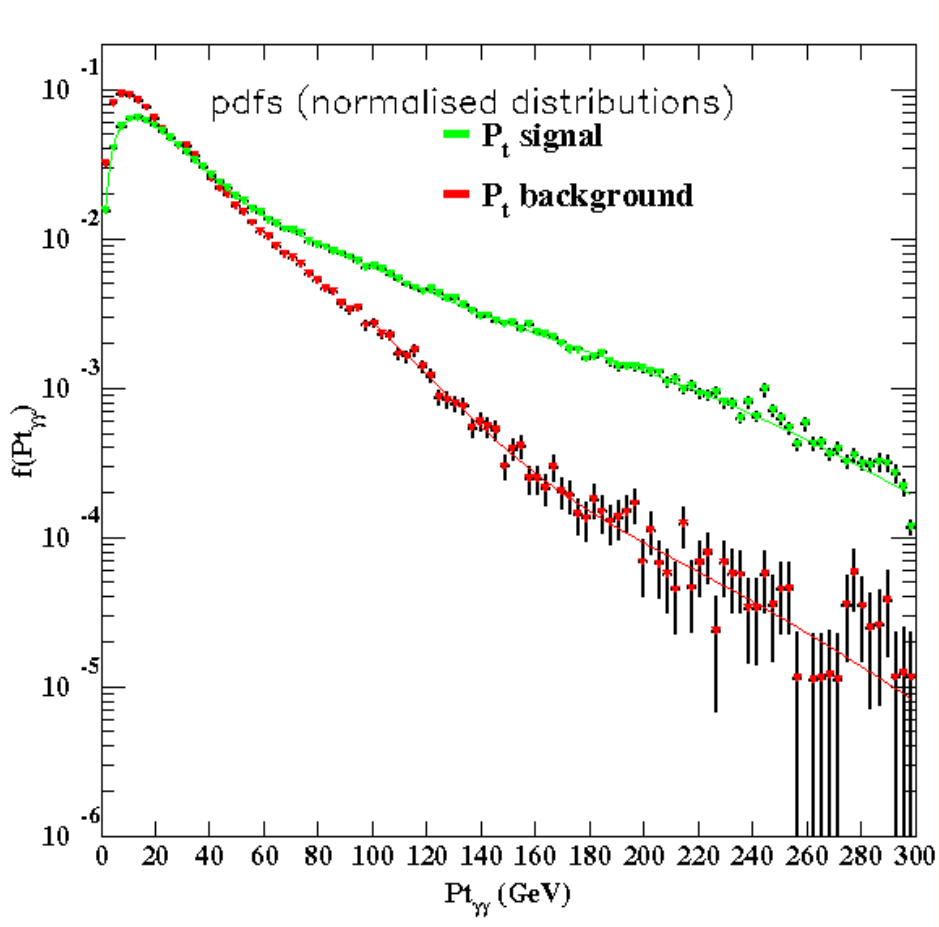


- Higgs signal has a larger $\langle q_T \rangle$ than the background (a prediction of q_T resummation)
- An efficient q_T-dependent likelihood analysis is possible

M. Escalier, 2005; ResBos (2,3)

q_T resummation for $\gamma\gamma$ production

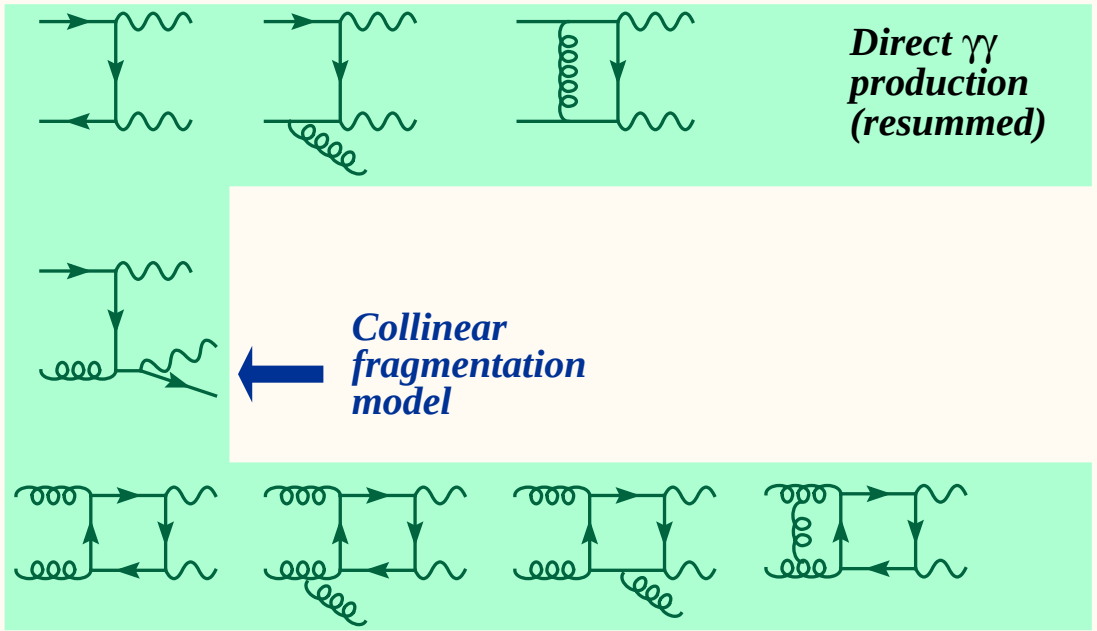
(QCD background)

- new PQCD corrections to production in **direct** $q\bar{q} + qg$ and gg channels
- improved treatment of the **fragmentation** region
- improved model for nonperturbative resummed contributions *(A. Konychev, **P. N.**, PLB 633, 710 (2006))*
  - non-pert. terms constrained by low-Q and Tevatron Z data
- automated matching at the ntuple level; optimized Monte-Carlo integration
  - new ResBos code is easy to use!

Direct diphotons

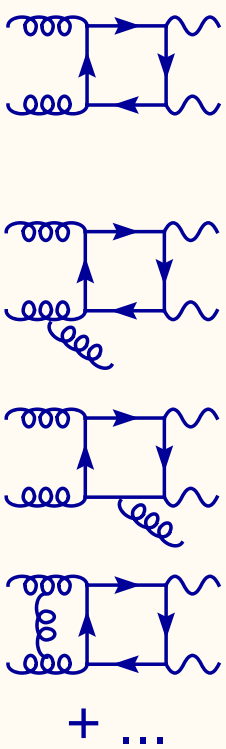
The dominant production mode; evaluated here up to full NLO/NNLL accuracy

Balazs, Berger, Nadolsky, Yuan, 2006



- *qg* and *gg* channels are enhanced at $x \sim Q^2/s \ll 1$ by large gluon PDF
- $q\bar{q}$ and *qg* channels at NLO: *Aurenche et al.; Bailey, Owens, Ohnemus*
- *gg* channel at NLO: *Balazs, PN, Schmidt, Yuan; de Florian, Kunzst; Bern, De Freitas, Dixon; Bern, Dixon, Schmidt*

$gg \to \gamma\gamma X$ in the $q_T \to 0$ limit

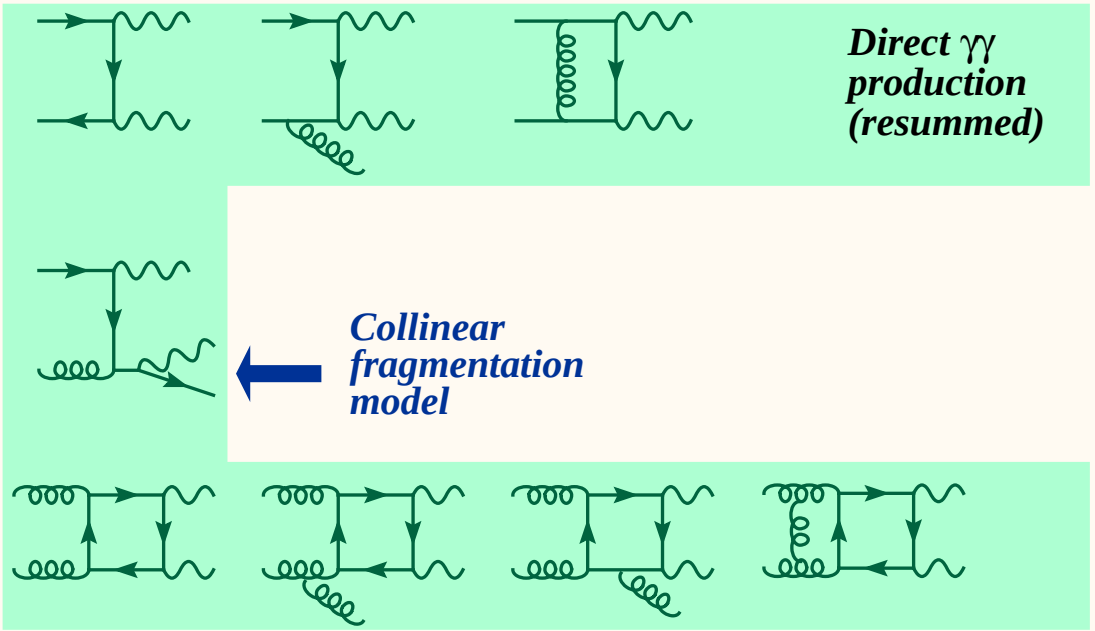


- $\mathcal{O}(\alpha_s^3)$ 1-loop 5-leg (pentagon) diagrams
  - are computed in the helicity amplitude formalism
  - numerically checked against the "sector decomposition" calculation (Binoth, Guillet, Mahmoudi)
  - small-q_T limit is derived at the matrix-element level using the splitting amplitude method
- 2-loop box diagrams are added at $q_T = 0$; the full cross section is resummed in the $q_T \to 0$ limit

Fragmentation model

The *qg* fragmentation collinear singularity is removed by combination of quasi-experimental and smooth-cone isolation

Balazs, Berger, Nadolsky, Yuan, 2006



- sufficient for description of small fragmentation contributions relevant for the Tevatron and LHC
- good agreement with the Tevatron data

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  - non-pert. terms constrained by low-Q and Tevatron Z data
- automated matching at the ntuple level; optimized Monte-Carlo integration
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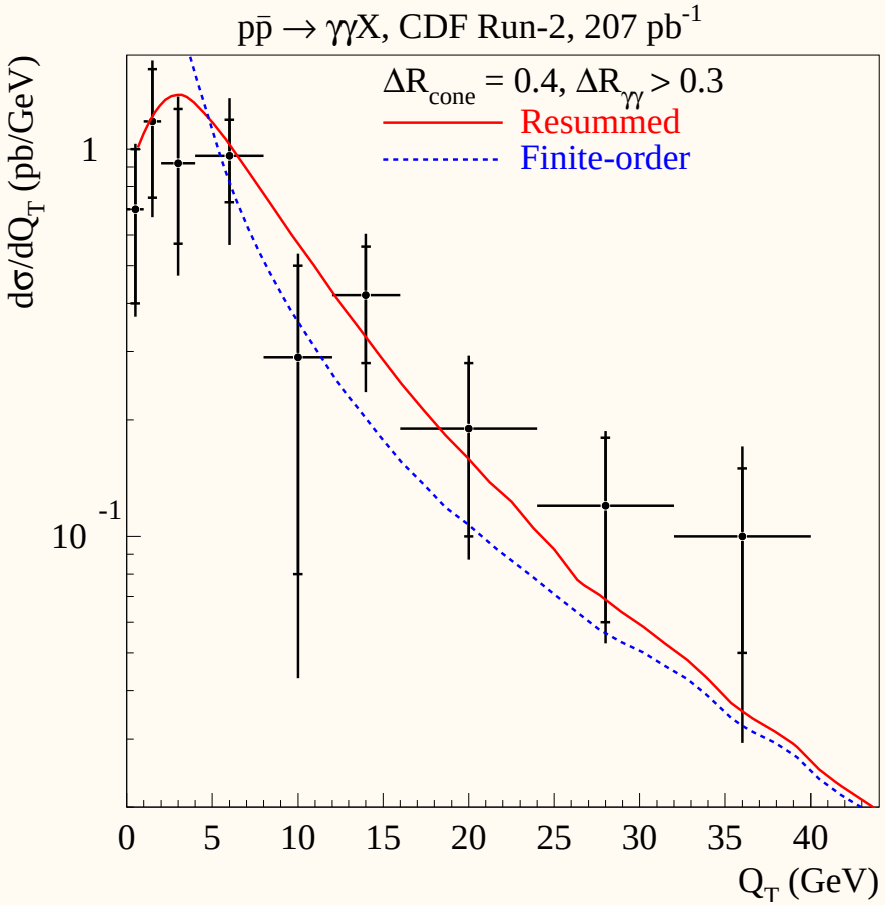
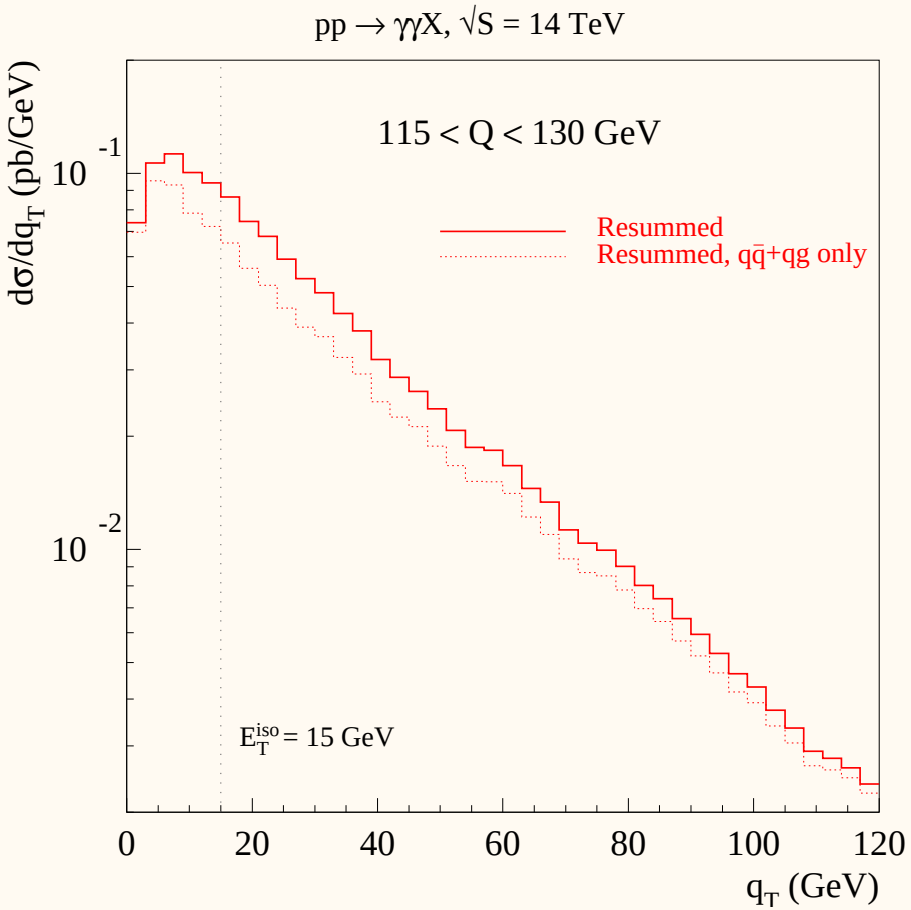
Comparison with the CDF Run-2 data



- The NLO prediction (blue) diverges at low q_T
- The resummed prediction (red) agrees with the data at all q_T; matches the NLO prediction at large q_T

$\gamma\gamma$ production at the LHC

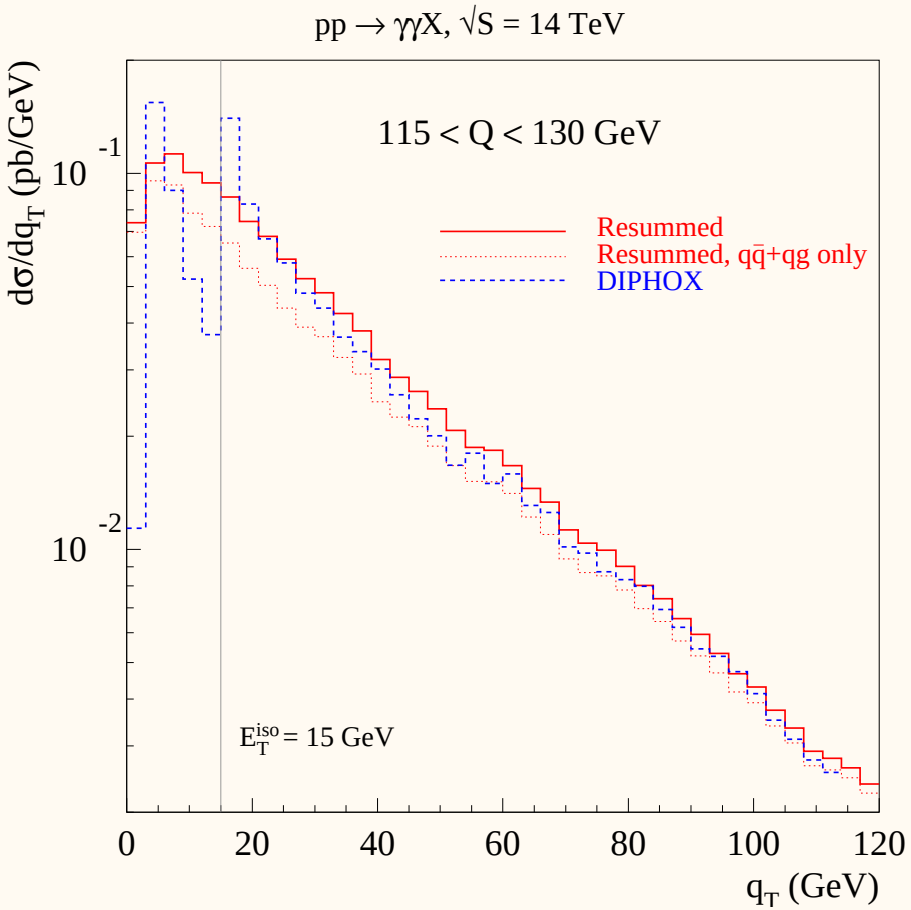


$q\bar{q} : qg : gg$ = 30:50:20

(compare with
$q\bar{q} : qg : gg$ =70:20:10
at the Tevatron)

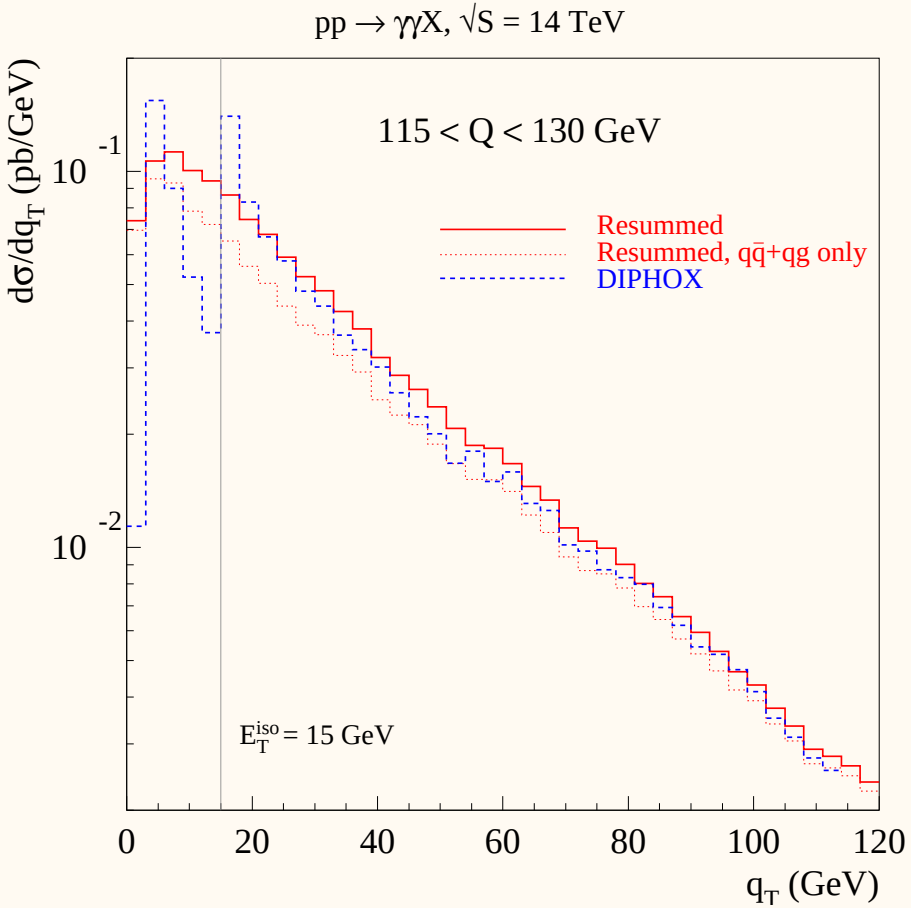
$\mathcal{O}(\alpha_s^2)$ corrections to qg are likely important
($\sigma_{NNLO}/\sigma_{NLO} \sim 20\%$?)

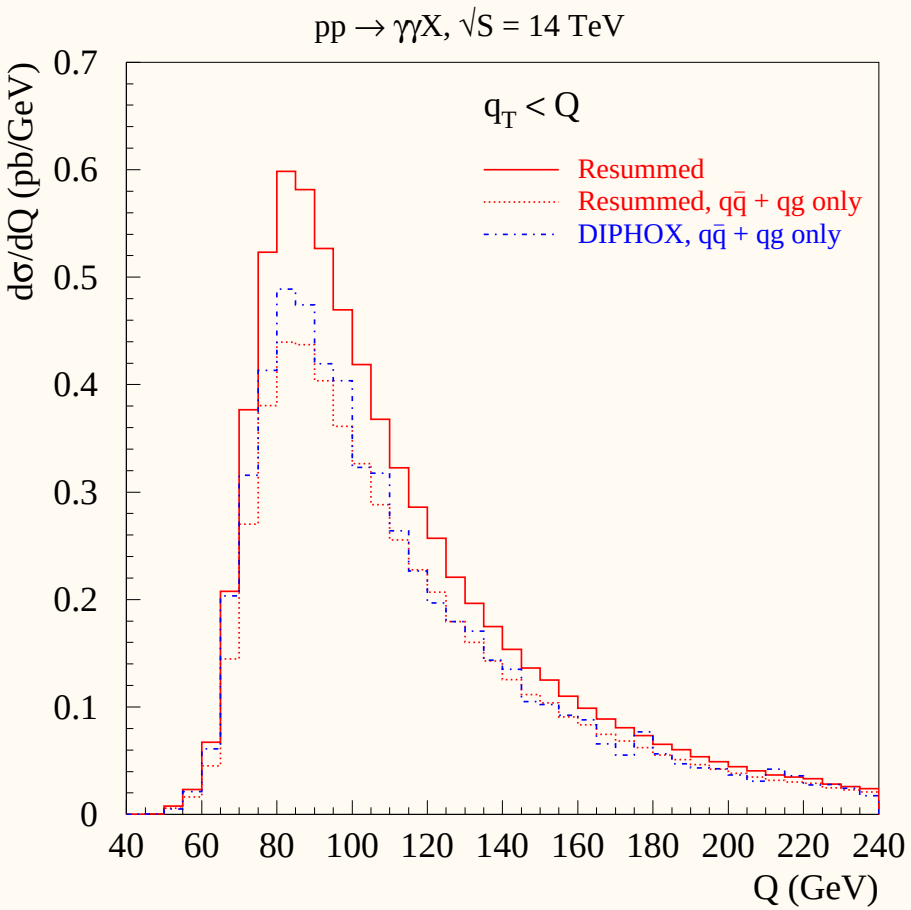
$\gamma\gamma$ production at the LHC



- DIPHOX agrees with the resummation at large q_T; exhibits integrable logarithmic singularities at $q_T < E_T^{iso}$ (E_T^{iso} is the isolation energy)
- RESBOS shows a mild discontinuity at $q_T = E_T^{iso}$

$\gamma\gamma$ production at the LHC





Conclusions

- Knowledge of q_T distributions is important for Higgs boson searches
  - Significance of $H \to \gamma\gamma$ discovery is improved by including information about q_T distributions *(ongoing ATLAS studies)*
  - The shape of $d\sigma/dq_T$ affects $d\sigma/dQ$ and other observables
  - Theory predictions for QCD $\gamma\gamma$ production are most reliable at $E_T^{iso} < q_T < Q$

Conclusions II

- Resummation predicts normalization and shape of $d\sigma/d^3p_{\gamma_1}d^3p_{\gamma_2}$ for direct $\gamma\gamma$ production at NNLL/NLO.
- Large logs are resummed at $q_T \ll Q$
- At $q_T \gtrsim Q$, our results agree with NLO, as well as with DIPHOX calculation within the fragmentation model uncertainty of DIPHOX
- At $q_T < E_T^{iso}$, fragmentation contributions are removed by smooth-cone isolation
  - no logarithmic singularities at $q_T \neq 0$!
- Streamlined matching of resummed and NLO cross sections; optimized phase space integration

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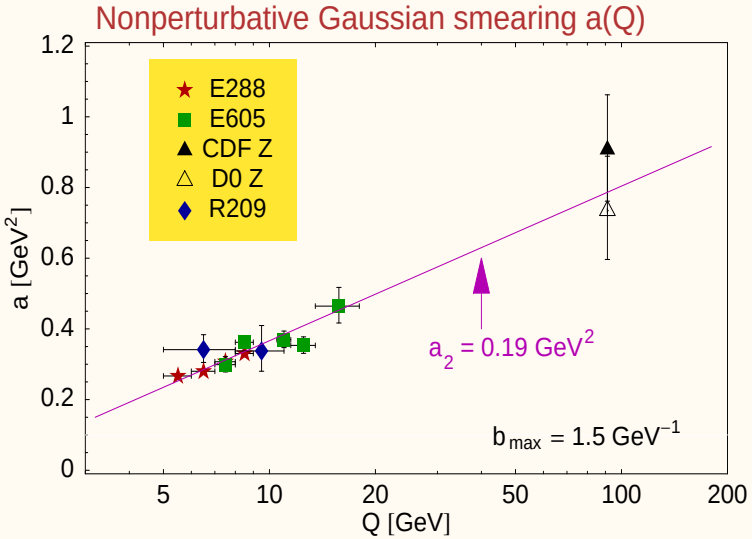
Accurate predictions for future measurements at the Tevatron and LHC!

Backup slides

Universality of nonperturbative contributions

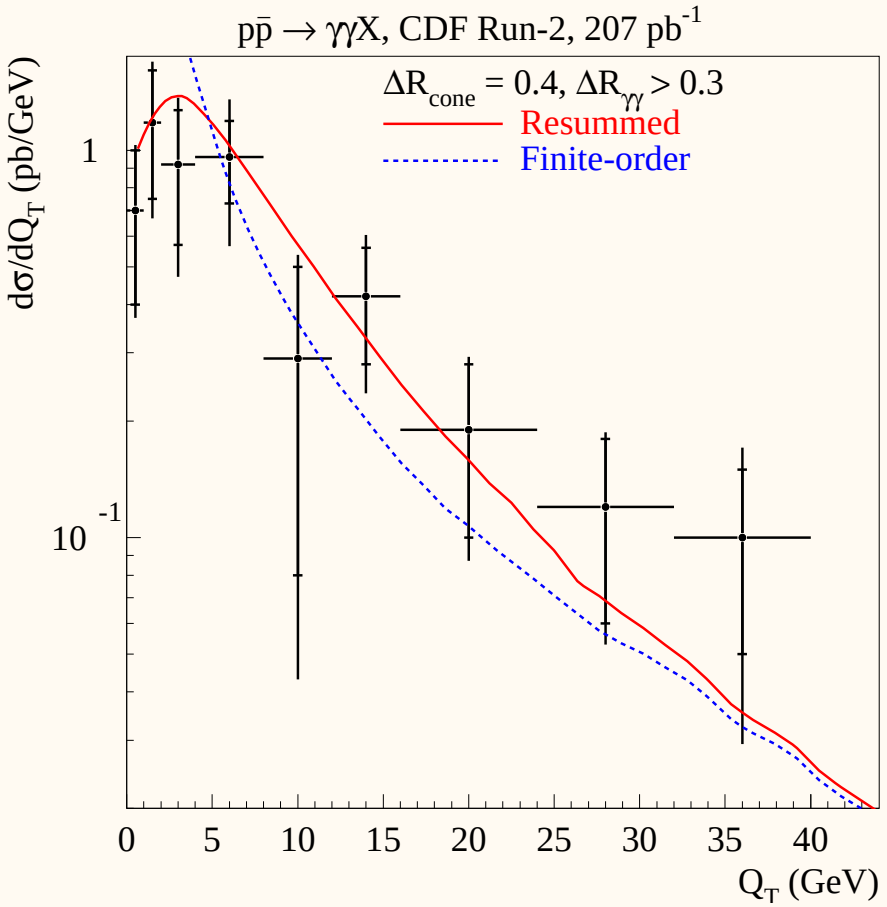
*A. Konychev, **P. N.**, PLB 633, 710 (2006)*



- q_T factorization: initial-state nonperturbative contributions ($\sim$"intrinsic" $\langle k_T^2 \rangle \equiv a$) follow universal quasi-linear dependence on ln Q; this expectation is confirmed by the global analysis of Drell-Yan and Z boson data

- the observed ln Q dependence agrees with the renormalon/lattice estimate
- at $Q \sim M_Z$, soft NP corrections dominate over collinear NP corrections
- the model is employed to predict $\gamma\gamma$ cross sections

Resummation vs. CDF Run-2 data *(PRL 95, 022003 (2005))*



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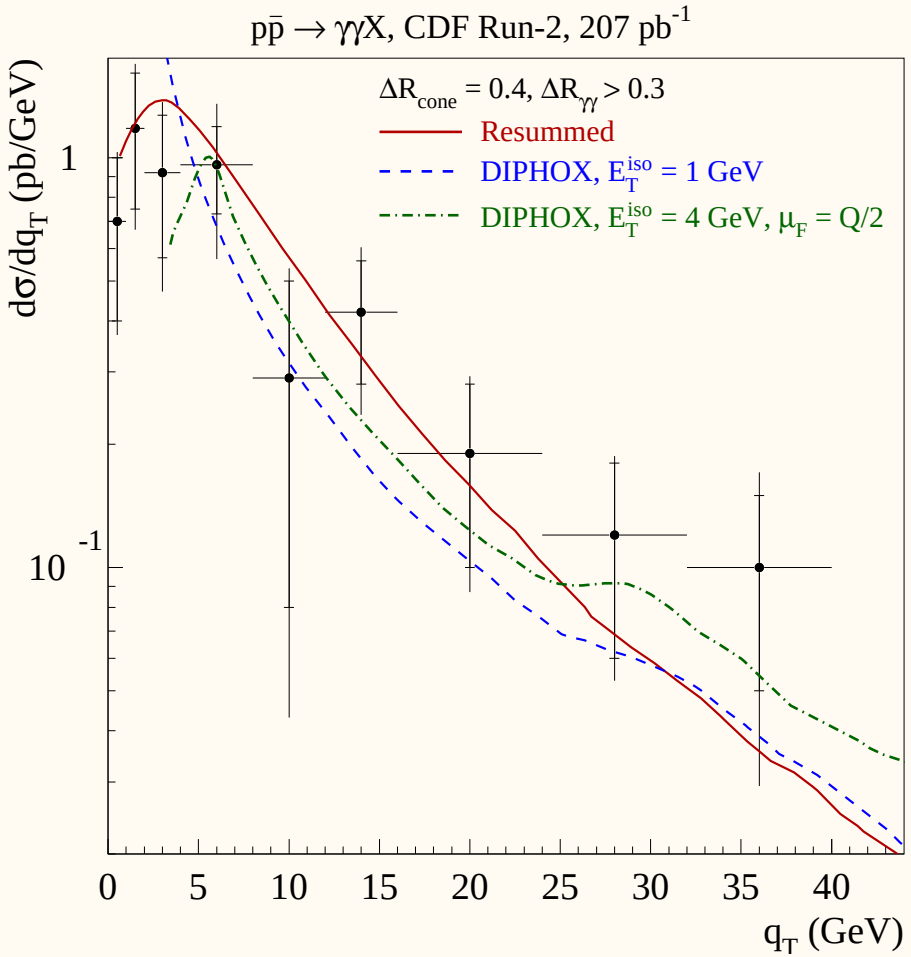

The large-q_T "shoulder" in the data occurs at $Q \lesssim 25$ GeV, $Q \lesssim q_T$, $\Delta\varphi < \pi/2$

The DIPHOX cross section

- agrees with NLO RESBOS for the nominal $E_T^{iso} = 1$ GeV, same μ_F
- reproduces the "shoulder" for $E_T^{iso} = 4$ GeV, smaller μ_F

▲ for $E_T^{iso} = 4$ GeV, the 1-fragmentation cross section increases by 400%

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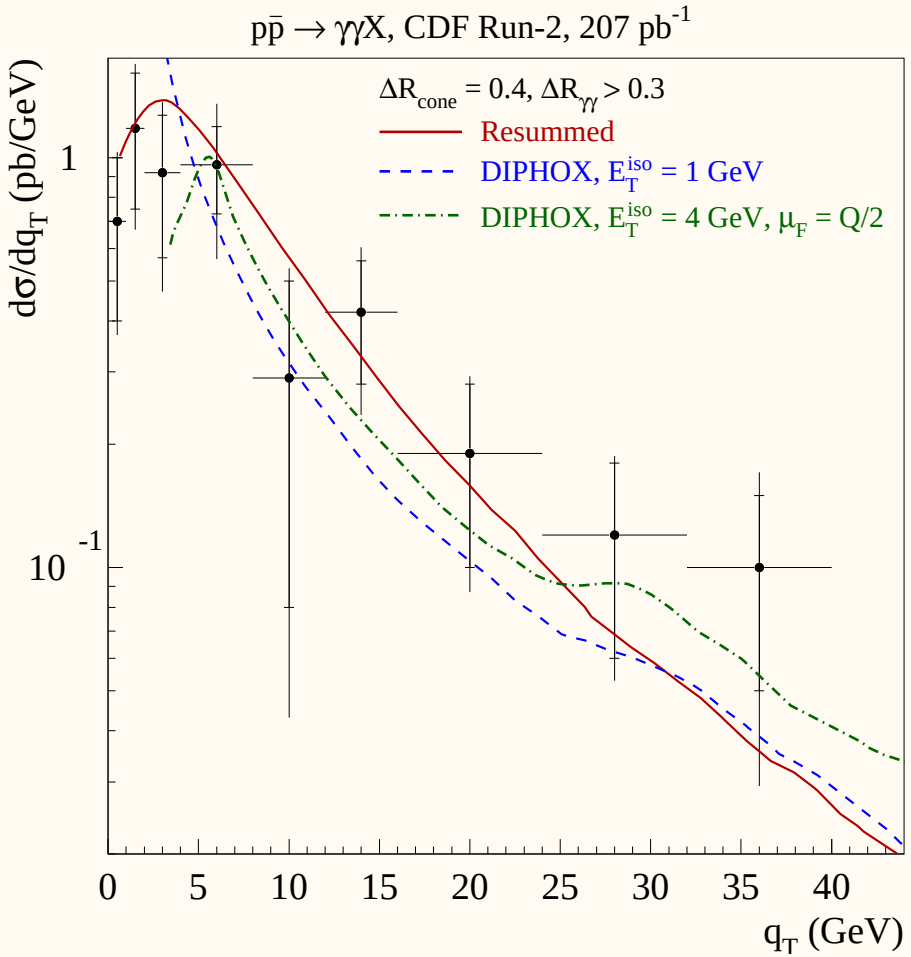

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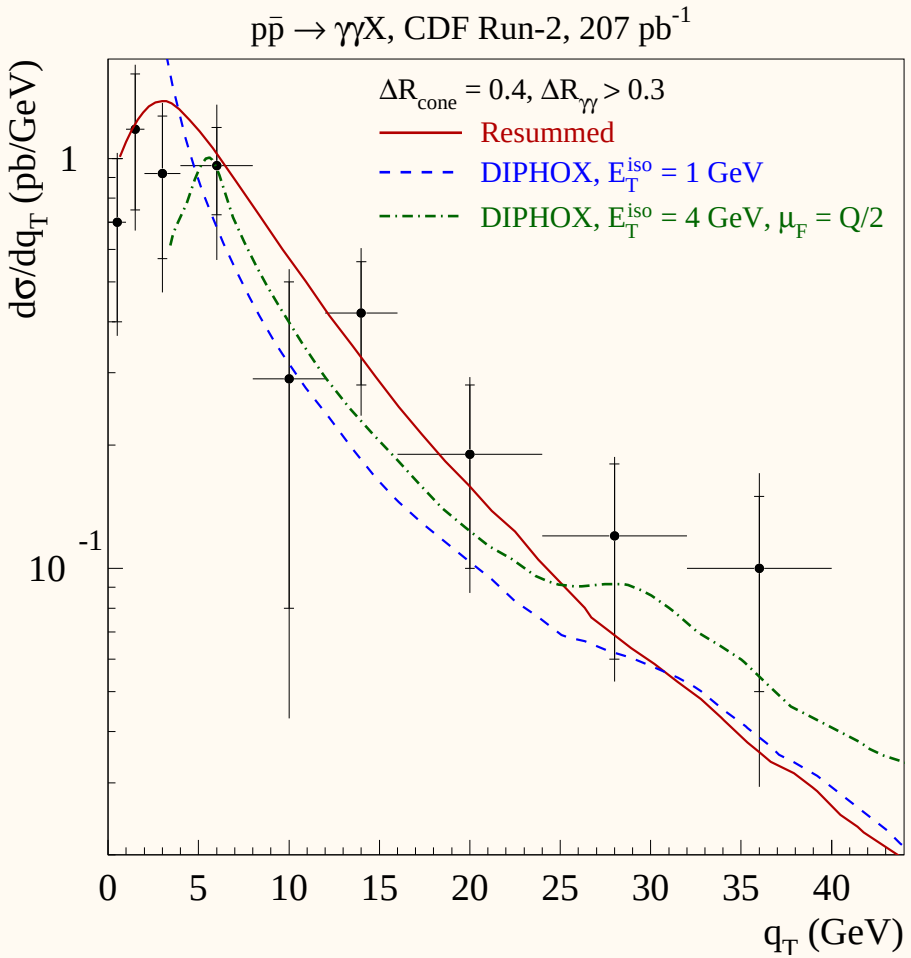

- Other large corrections are known to contribute at $Q \lesssim q_T$ (not in the existing theory calculations)
- The CDF "shoulder" is a low-Q effect, not relevant for the LHC Higgs searches
  - can be removed by a $q_T \leq Q$ cut

Azimuthal angle separation $\Delta\varphi$