# Higgs TH Summary

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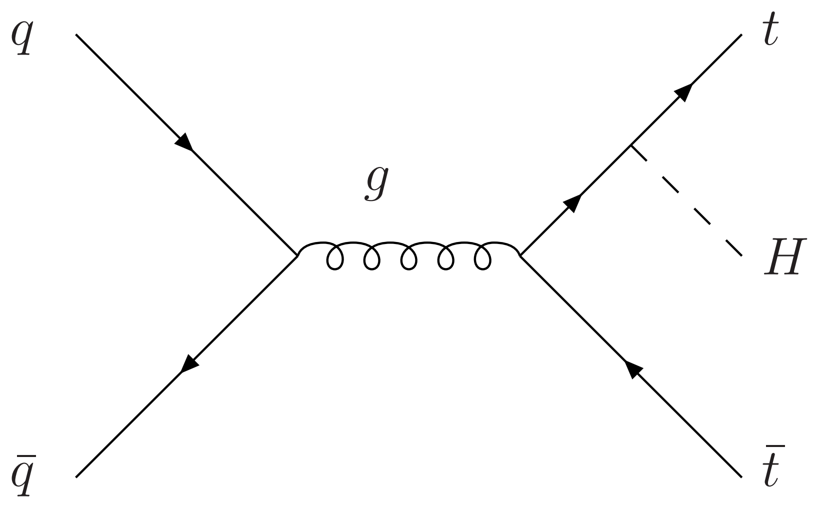
Universidad de Buenos Aires - Argentina

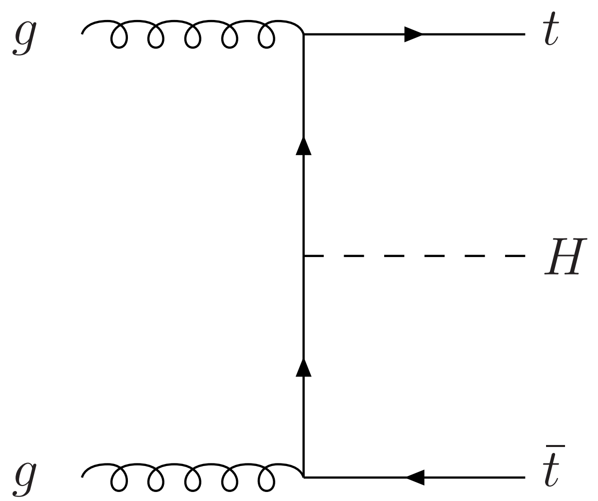
**Les Houches 2013**

HEP
UBA

www.hep.df.uba.ar

# *Heavy Quark Associated production*





$t\bar{t}H$

Yukawa
coupling

Pythia

POWHEG (PowHel collaboration) more accurate
for experimental purposes : NLO + PS

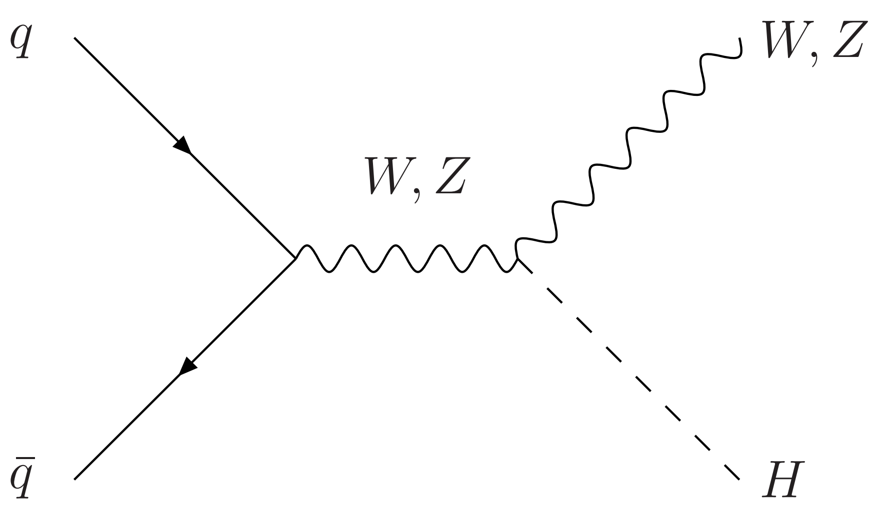
**M.V. Garzelli**

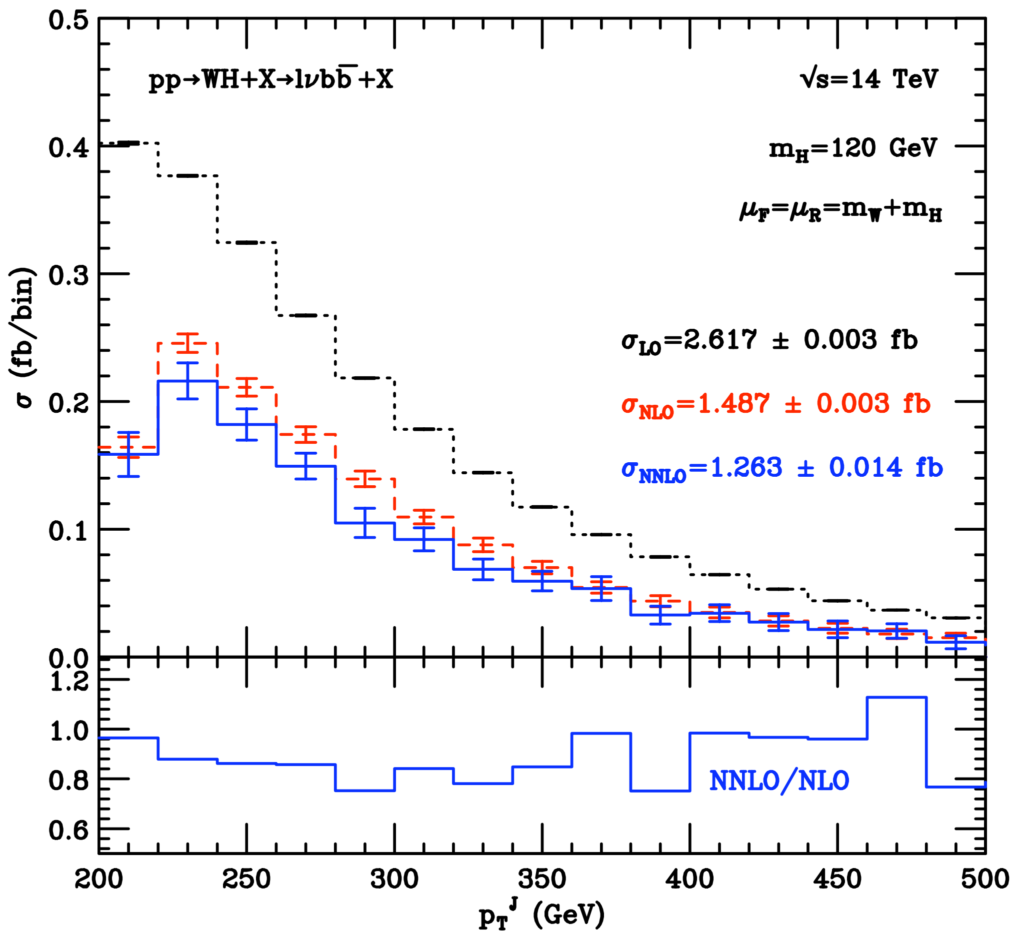
fiducial cross sections,
efficiencies +uncertainties for
this channel

# *Associated VH production*

- DY approach : fully exclusive NNLO calculation

Ferrera, Grazzini, Tramontano (2011)





- Fixed order challenged at LHC (boosted analysis with jet veto)

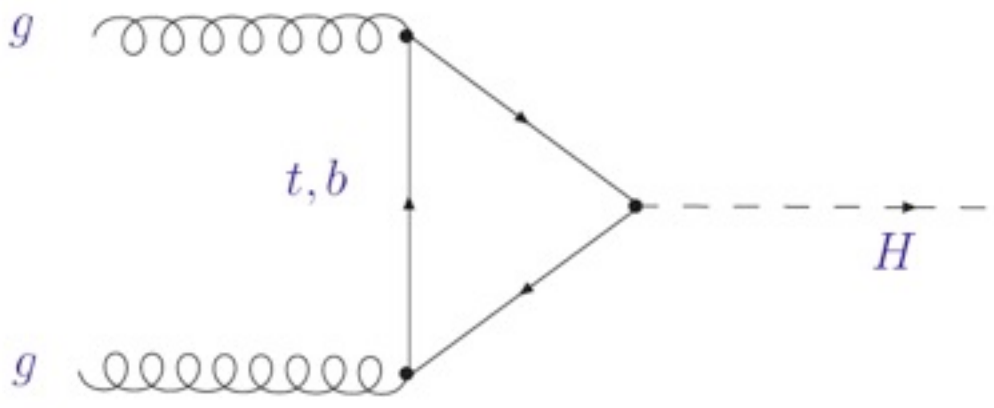
**F.Tackmann - P.F. Monni**

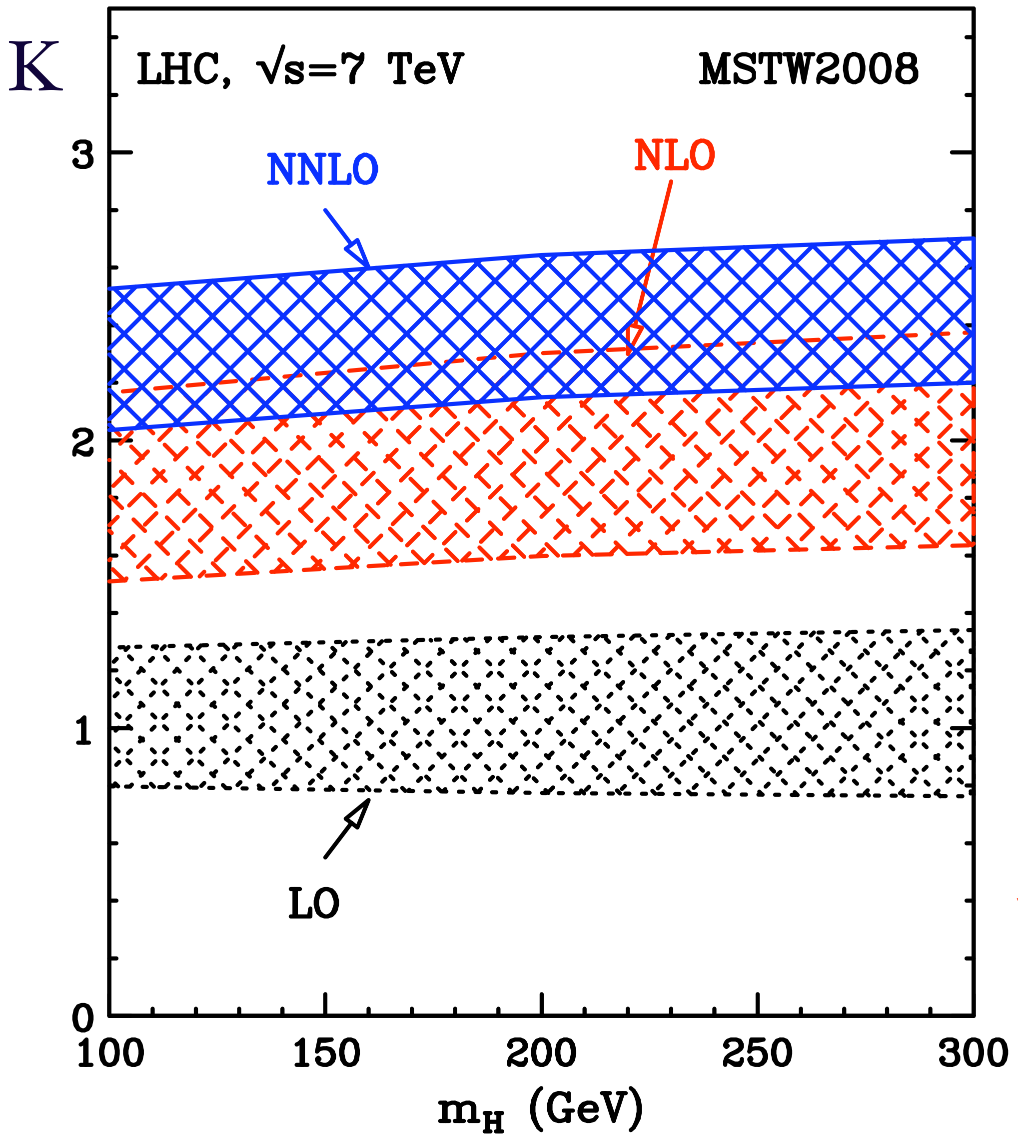
Can be improved using jet-veto resummation (DY)

ZH @ NNLO **M. Grazzini**

new studies on tTH and WH using Z+jets as control sample **N. Orlando**

# *gg fusion*





Large QCD corrections : new attempts to approximate N3LO

combination of small x and threshold

**S. Forte**

combination of threshold + scale dependence

**A. Lazopoulos**

# All N3LO logs of scales can be predicted from NNLO

Renormalization
Factorization
Wilson Coefficient

$$\tilde{\sigma}_{ij}^{(n,m)}(x) = a_{ij}^{(n,m)}\,\delta(1-x) + \sum_k b_{ij}^{(n,m),k}\,\mathcal{D}_k(1-x) + c_{ij}^{(n,m)}(x)$$

@μ=m_h all the logs vanish and the partonic XS

$$\mathcal{D}_k(1-x) = \left[\frac{\log^k(1-x)}{1-x}\right]_+$$

$$f_i \otimes f_j \otimes c_{ij}^{(3,0)}(z) = K\left(f_i \otimes f_j \otimes c_{ij}^{(2,0)}(z)\right) \qquad a_{ij}^{(3,0)} = K\,a_{ij}^{(2,0)}$$

If N3LO cross section known at one scale

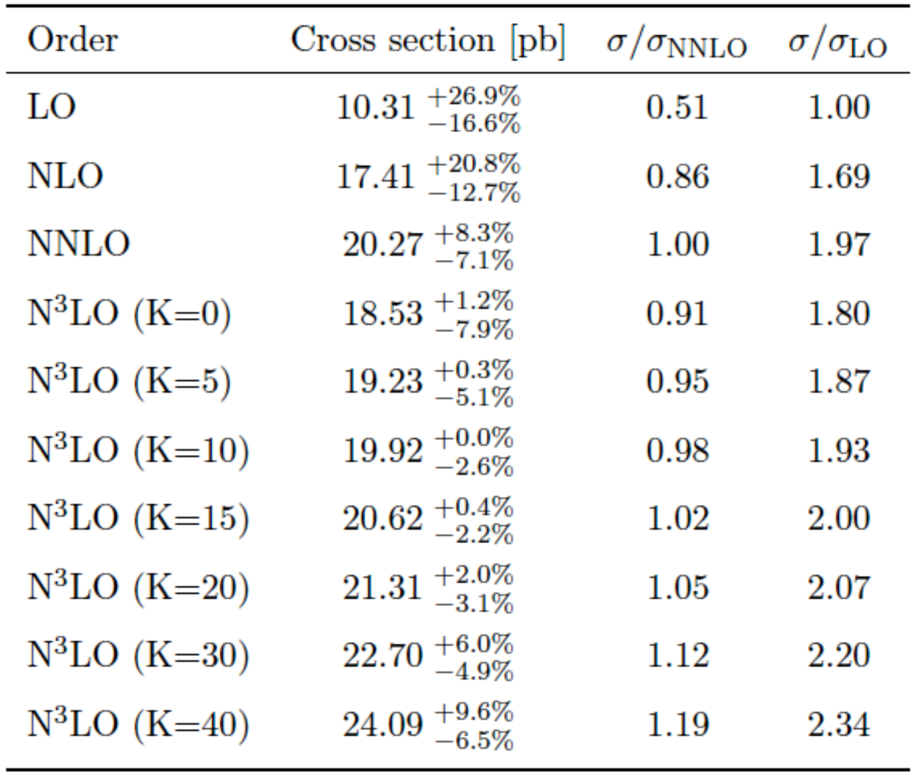
→ Know full scale dependence

new
at LH

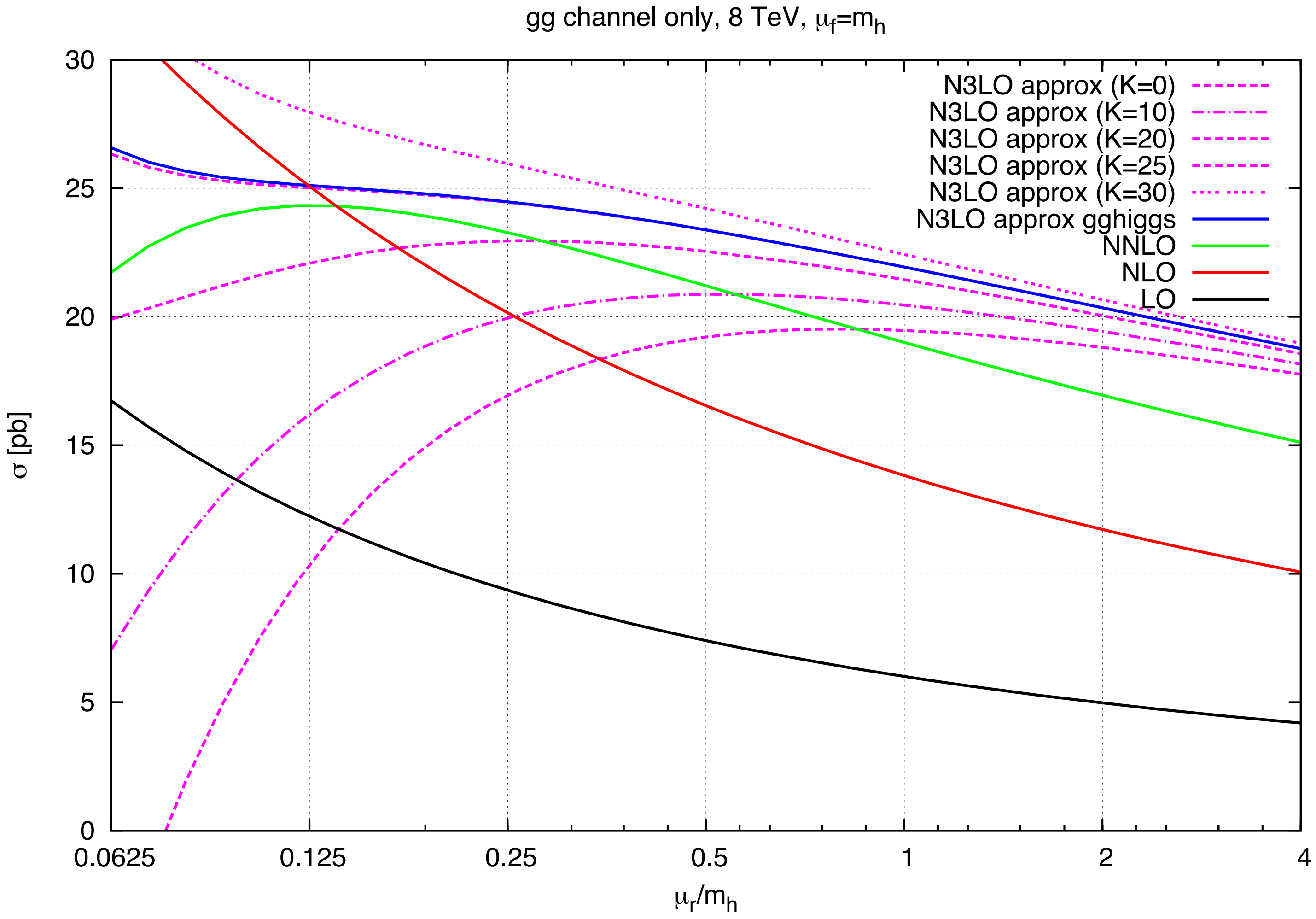
**A. Lazopoulos**

all driven by
renormalization scale

# Scale dependence at N3LO



| Order | Cross section [pb] | $\sigma/\sigma_{\mathrm{NNLO}}$ | $\sigma/\sigma_{\mathrm{LO}}$ |
|---|---|---|---|
| LO | $10.31^{+26.9\%}_{-16.6\%}$ | 0.51 | 1.00 |
| NLO | $17.41^{+20.8\%}_{-12.7\%}$ | 0.86 | 1.69 |
| NNLO | $20.27^{+8.3\%}_{-7.1\%}$ | 1.00 | 1.97 |
| $\mathrm{N^3LO}$ (K=0) | $18.53^{+1.2\%}_{-7.9\%}$ | 0.91 | 1.80 |
| $\mathrm{N^3LO}$ (K=5) | $19.23^{+0.3\%}_{-5.1\%}$ | 0.95 | 1.87 |
| $\mathrm{N^3LO}$ (K=10) | $19.92^{+0.0\%}_{-2.6\%}$ | 0.98 | 1.93 |
| $\mathrm{N^3LO}$ (K=15) | $20.62^{+0.4\%}_{-2.2\%}$ | 1.02 | 2.00 |
| $\mathrm{N^3LO}$ (K=20) | $21.31^{+2.0\%}_{-3.1\%}$ | 1.05 | 2.07 |
| $\mathrm{N^3LO}$ (K=30) | $22.70^{+6.0\%}_{-4.9\%}$ | 1.12 | 2.20 |
| $\mathrm{N^3LO}$ (K=40) | $24.09^{+9.6\%}_{-6.5\%}$ | 1.19 | 2.34 |



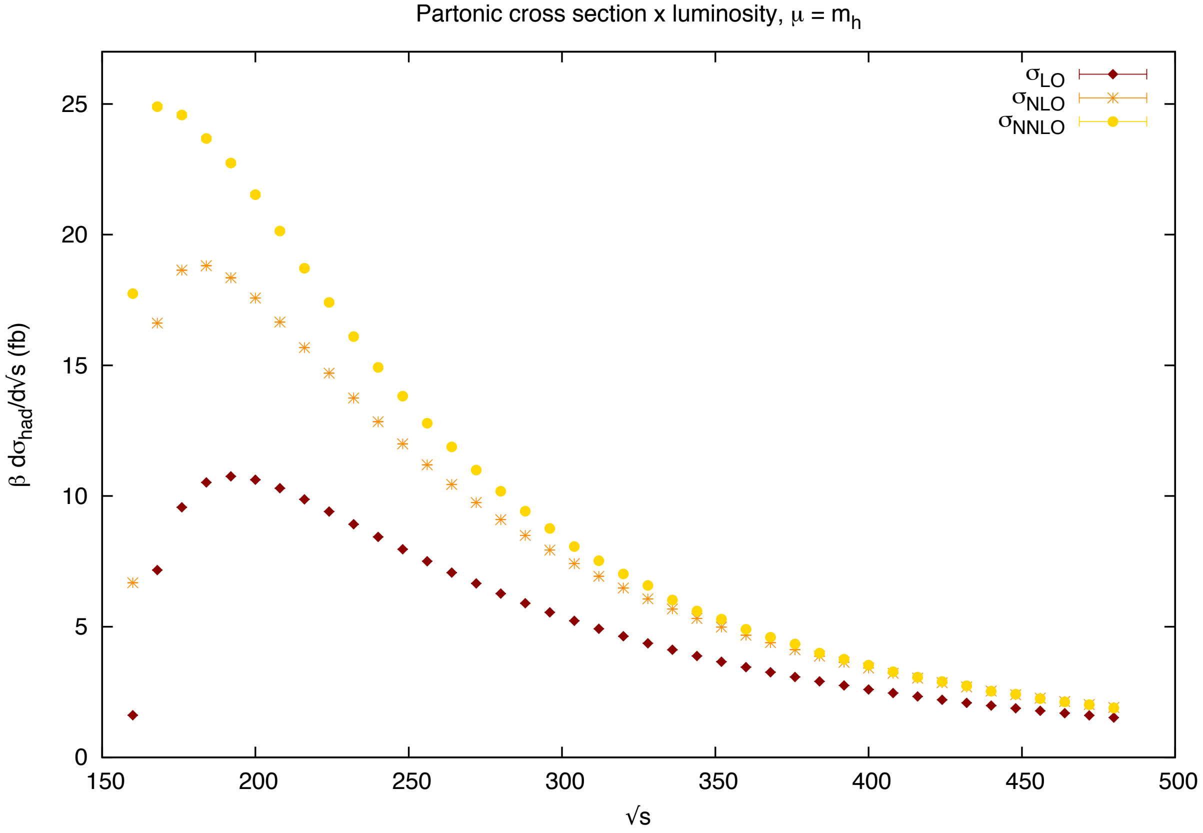
How large are the ‘regular’ pieces of the N3LO XS?
We can estimate the answer, but to know it we need to wait for the complete N3LO computation

**A. Lazopoulos**

Full N3LO within 1-2 years?

# H+jet at NNLO

R.Boughezal, F.Caola, K.Melnikov, F.Petriello, M.Schulze (2013)



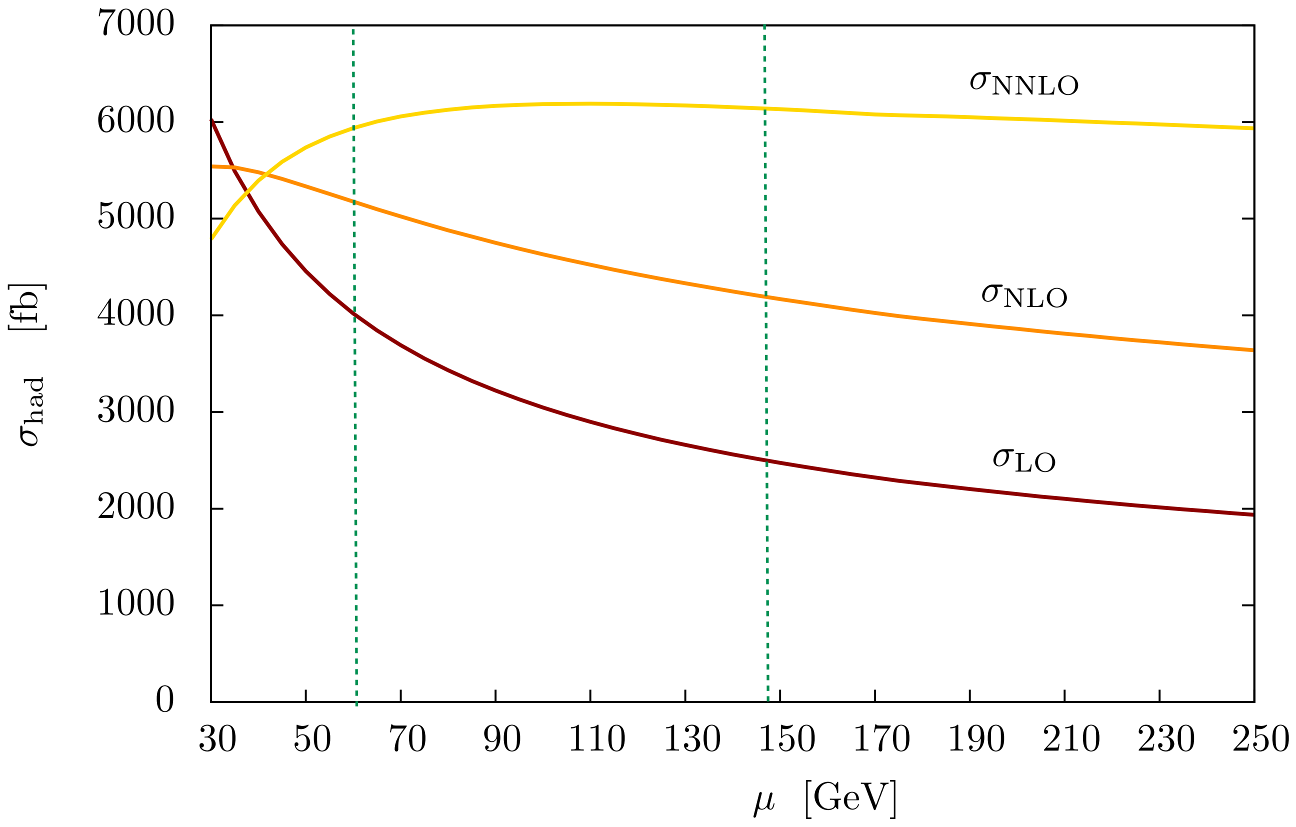
$$p_T^{jet} > 30\text{GeV}$$

$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776}\ \text{fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738}\ \text{fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242}\ \text{fb}.$$

pure gluon only

+60% NLO
+30-40% NNLO

more stable results for
$\mu = M_H/2$



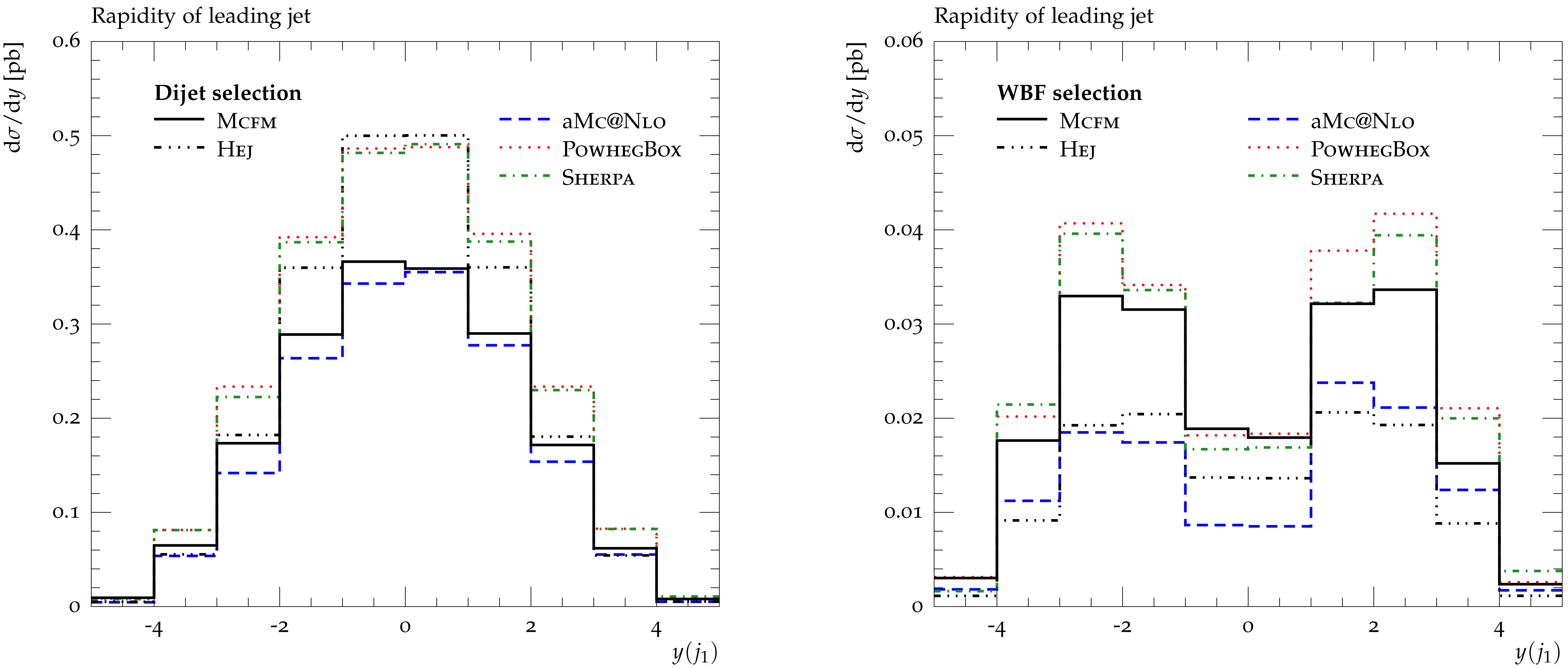
**F. Caola**

LH : full NNLO
(all channels)

Interface with
jet-veto resummation

# $pp \to H + $ 2jets comparative study

Jeppe Andersen, Marek Schönherr



- preliminary results collected for YR3
- large differences for predictions and cut efficiencies between generators
- no uncertainties quantified yet

# pp → H + 2jets comparative study

**Jeppe Andersen, Marek Schönherr**

Purpose of this study:

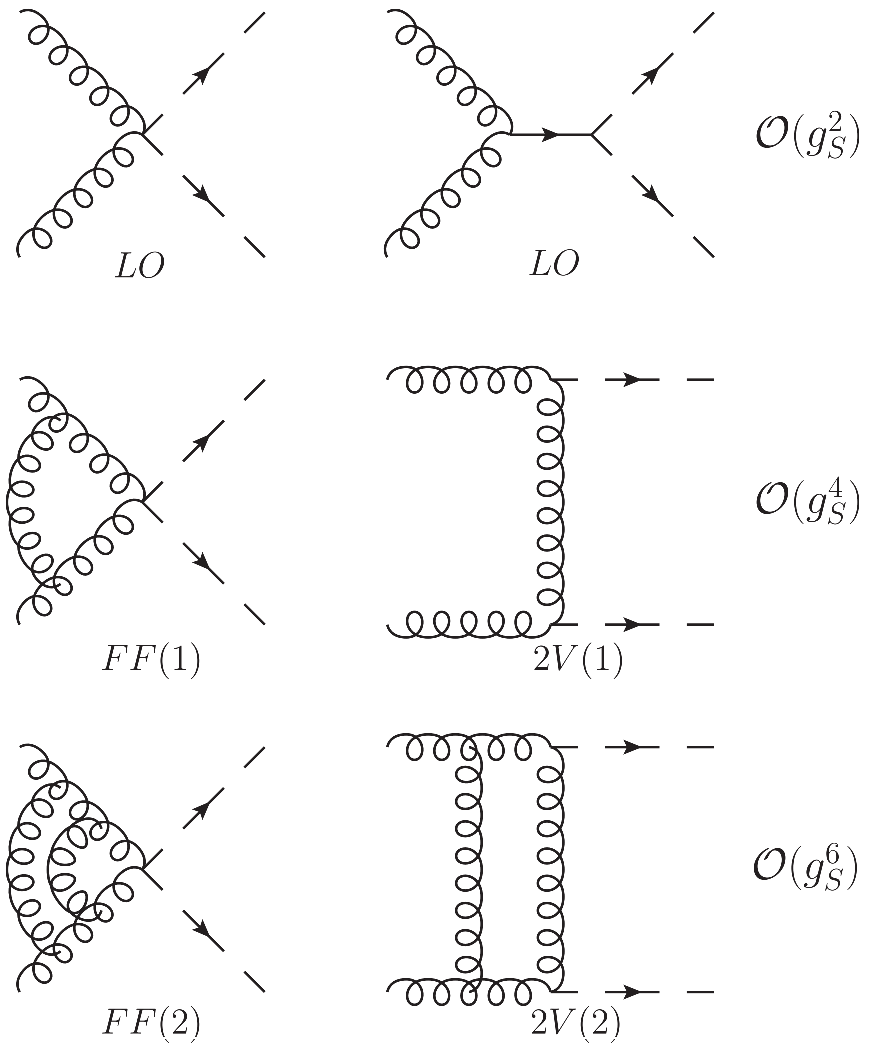
- investigate predictions of modern generators for gluon fusion contribution to Higgs production in VBF topologies
- quantify perturbative uncertainties
- continue effort started for YR3

Event selection and observables:

- Wiki page linked from Higgs working group page:
  `http://phystev.in2p3.fr/wiki/2013:groups:sm:higgs:hdijets`
  ⇒ contains agreed upon event selections and observables
  ⇒ **indicate your planned contribution**
- study the evolution from dijet selection to VBF selection
- study the effects of different dijet definitions (leading jet vs. forward-backward)
- standardised Rivet analysis is provided

| | |
|---|---|
| **M. Schönherr, K. Zapp** | Sherpa MEPS@NLO |
| **J.Andersen, J. Smillie** | HEJ |
| **S.Prestel, L.Lönnblad** | Pythia 8 UNLOPS, HJJ POWHEG |

# Double Higgs production



## Direct access to Higgs self-coupling

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

in SM

$$\lambda = \lambda' = M_H^2/(2v^2)$$

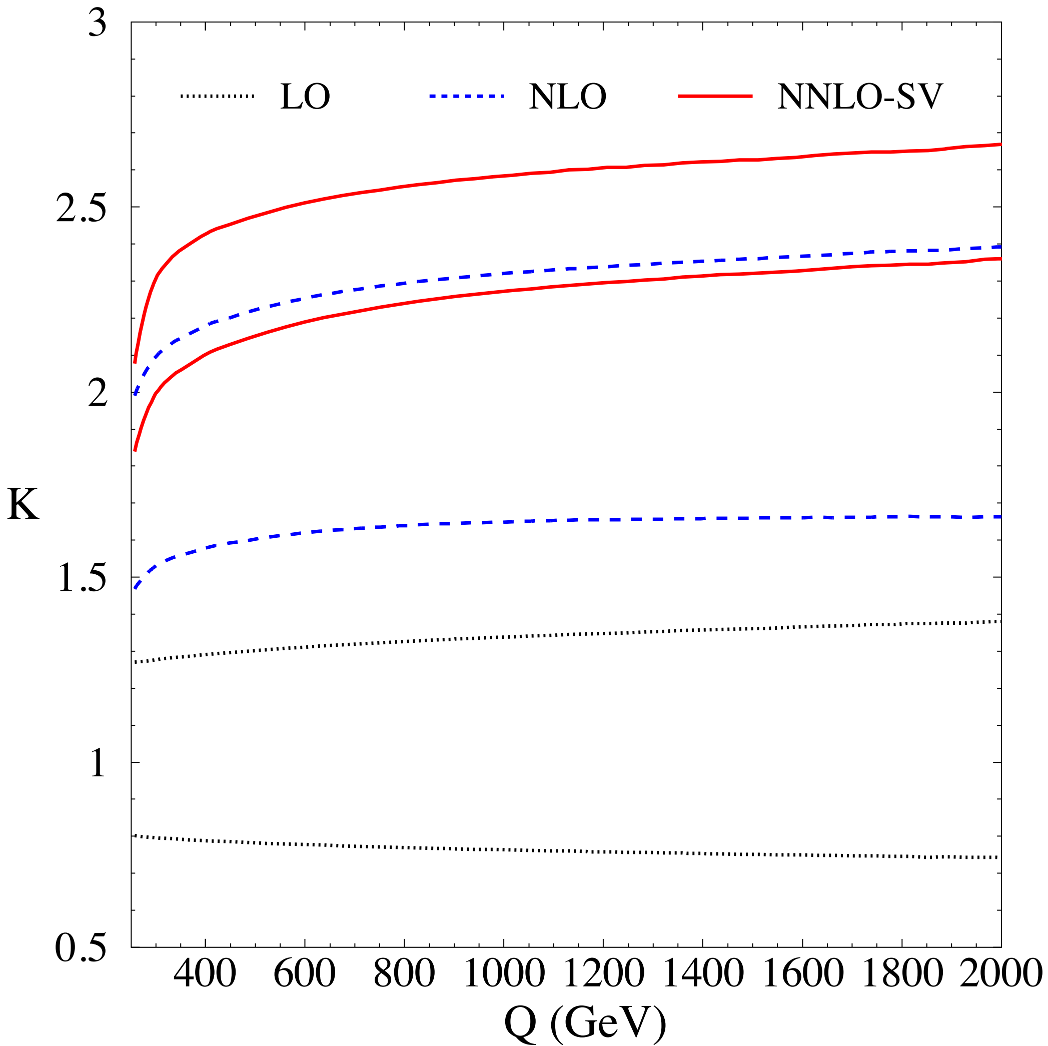
NLO computed within effective Lagrangian (large K)

Dawson, Dittmaier, Spira (1998)

New : two-loop corrections and NNLO-SV approximation deF, Mazzitelli (2013)

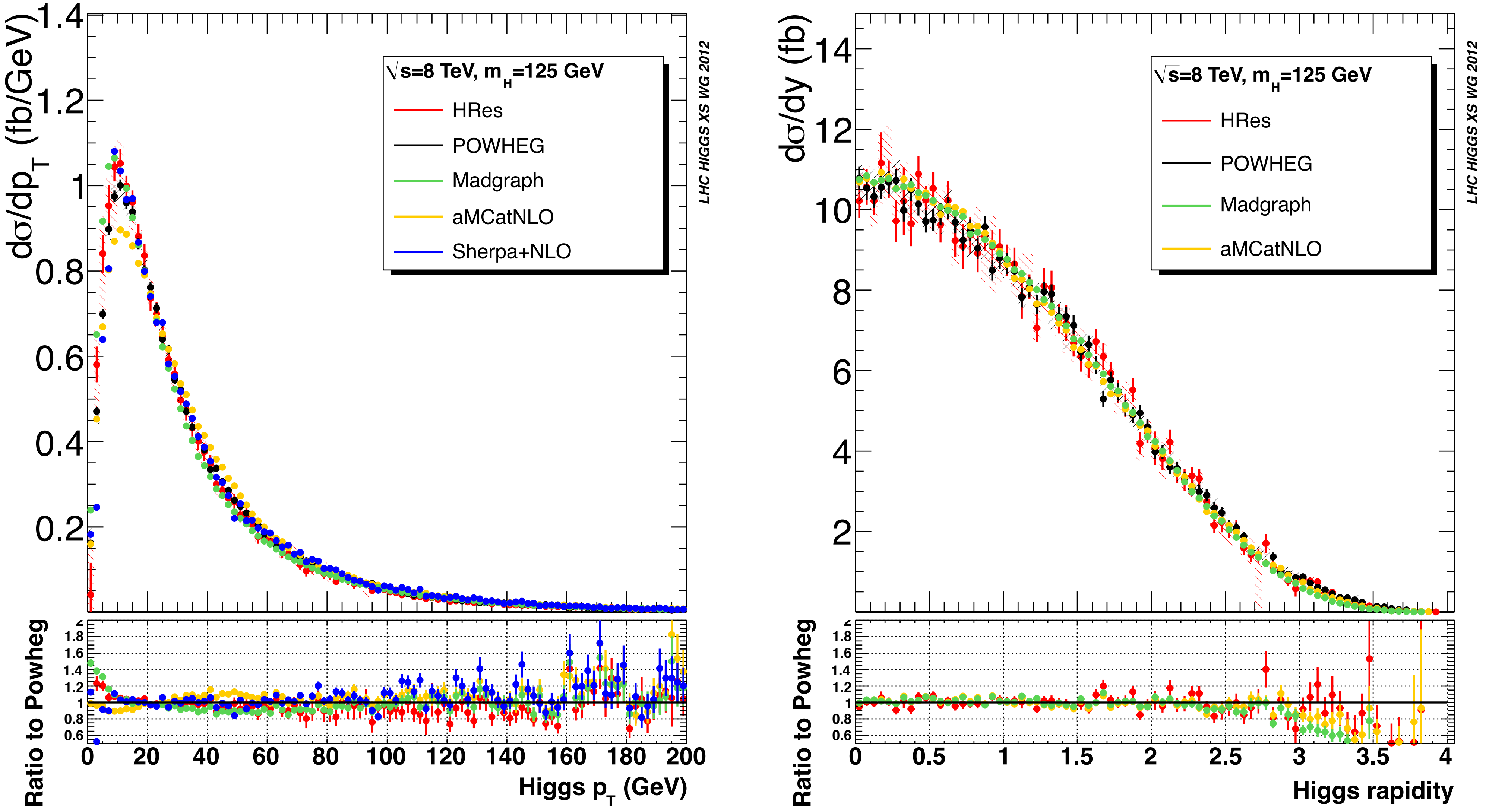
**D.deF.**
**J. Mazzitelli**

LH : full NNLO
(inclusive and exclusive)



# Merging NLO with Parton Showers

- Resummation to NLL accuracy + realistic final states
- Allow to carry NLO precision to all aspects of experimental analysis
- (Formally) Same Logarithmic accuracy but numerical differences



**N.Chanon**

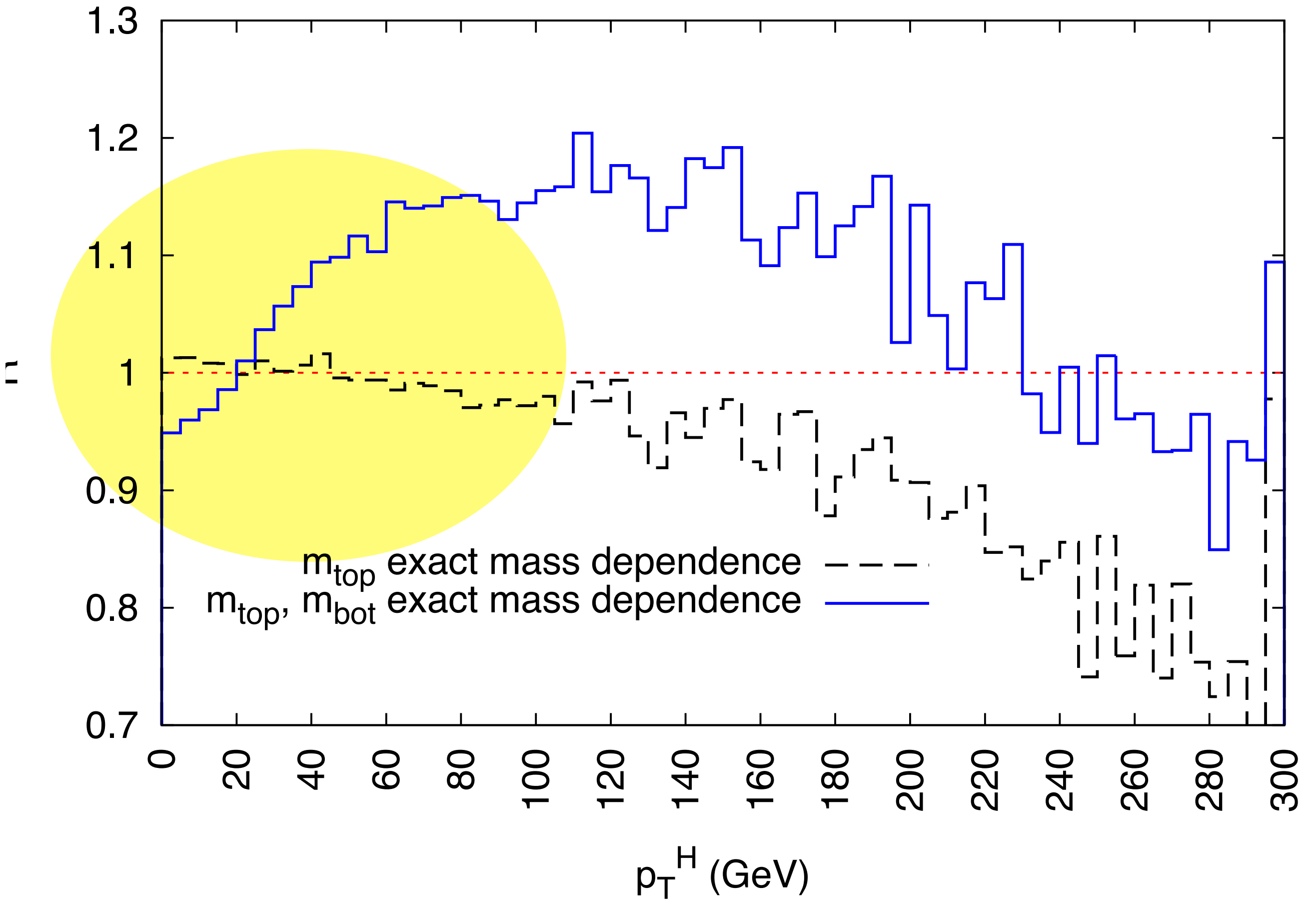
detailed comparison with common setup + uncertainties

Reasonable agreement, but non-negligible differences in the spectrum

# How to include HQ mass effect?

## POWHEG with HQ (t,b,c) masses

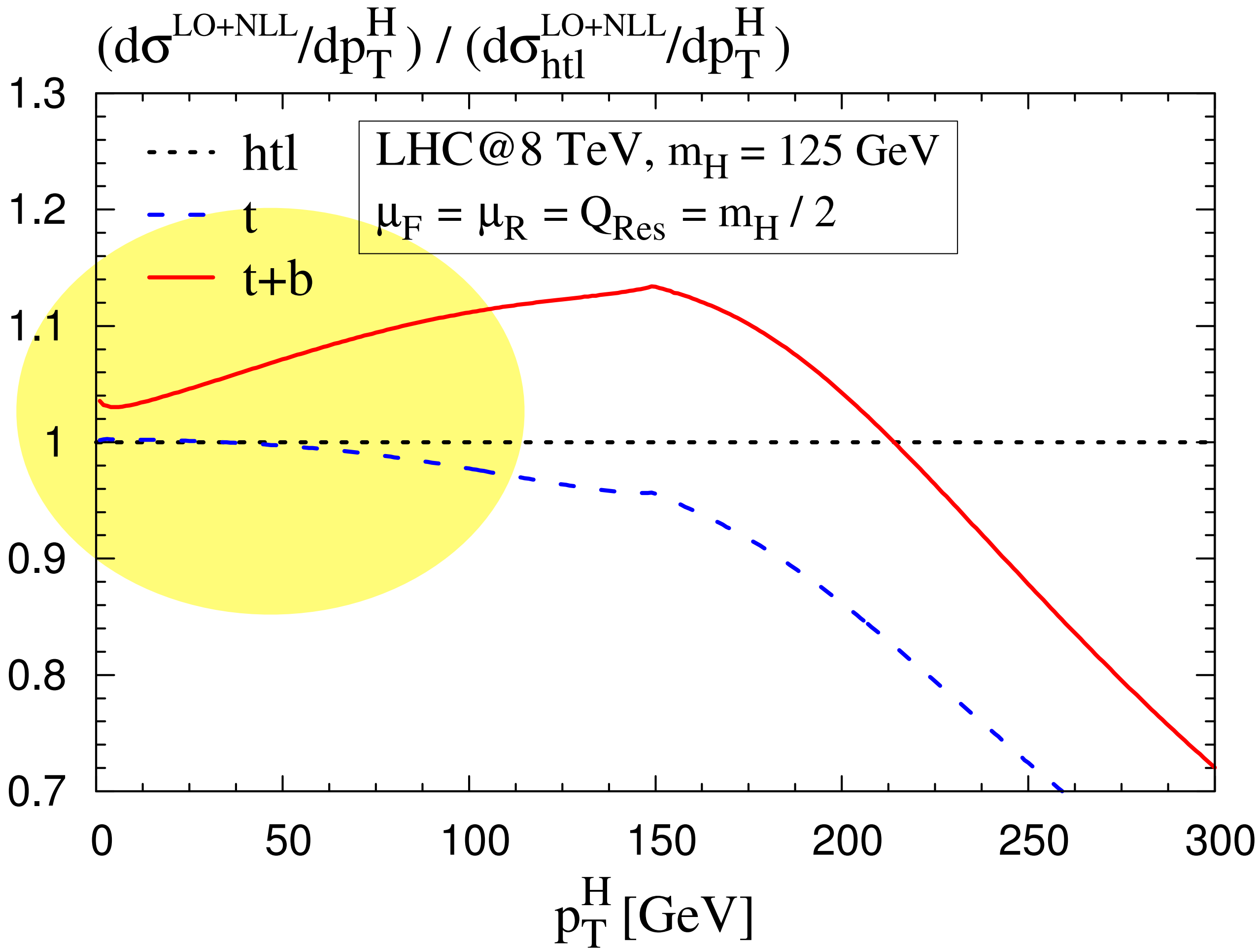
Bagnaschi, Degrassi, Slavich, Vicini



## NLL with HQ (t,b,c) masses

Mantler, Wiesemann

similar MC@NLO



visible effects (depend on implementation)~ TH uncertainty

Several scales in the process $m_t,\ m_b,\ m_H,\ p_T$

**M.Grazzini**

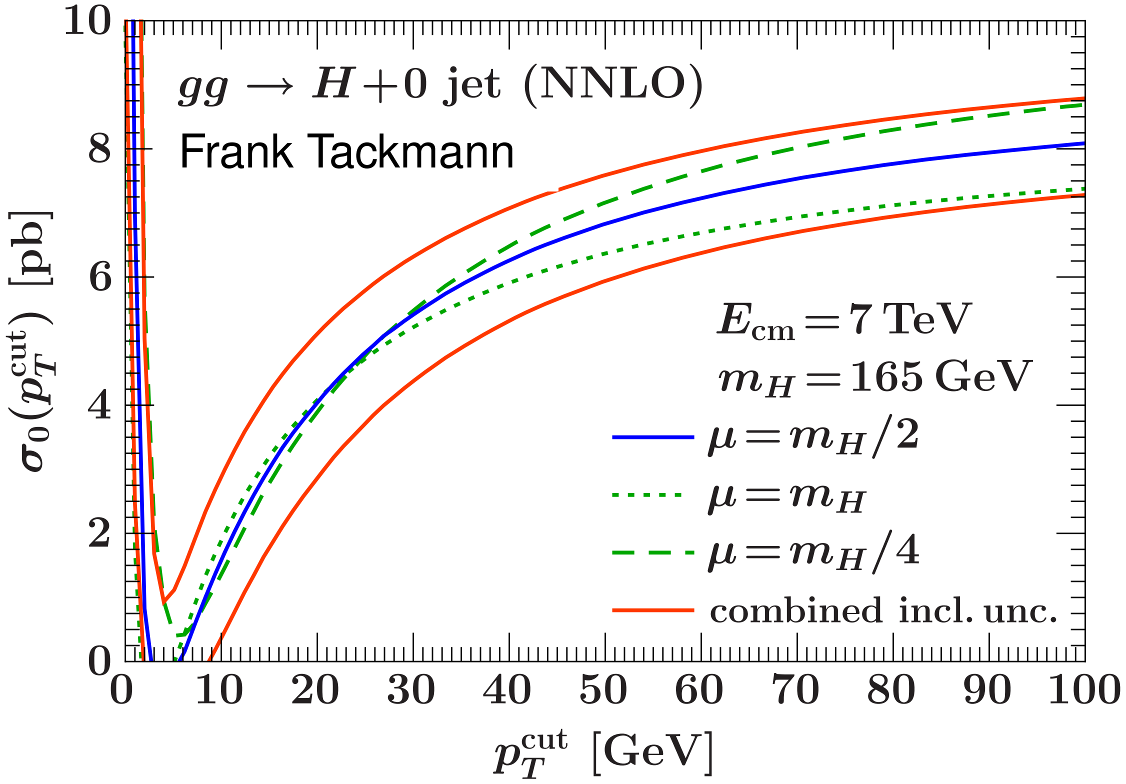
Use different (resummation) scales for b and t

LH : NNLL with b

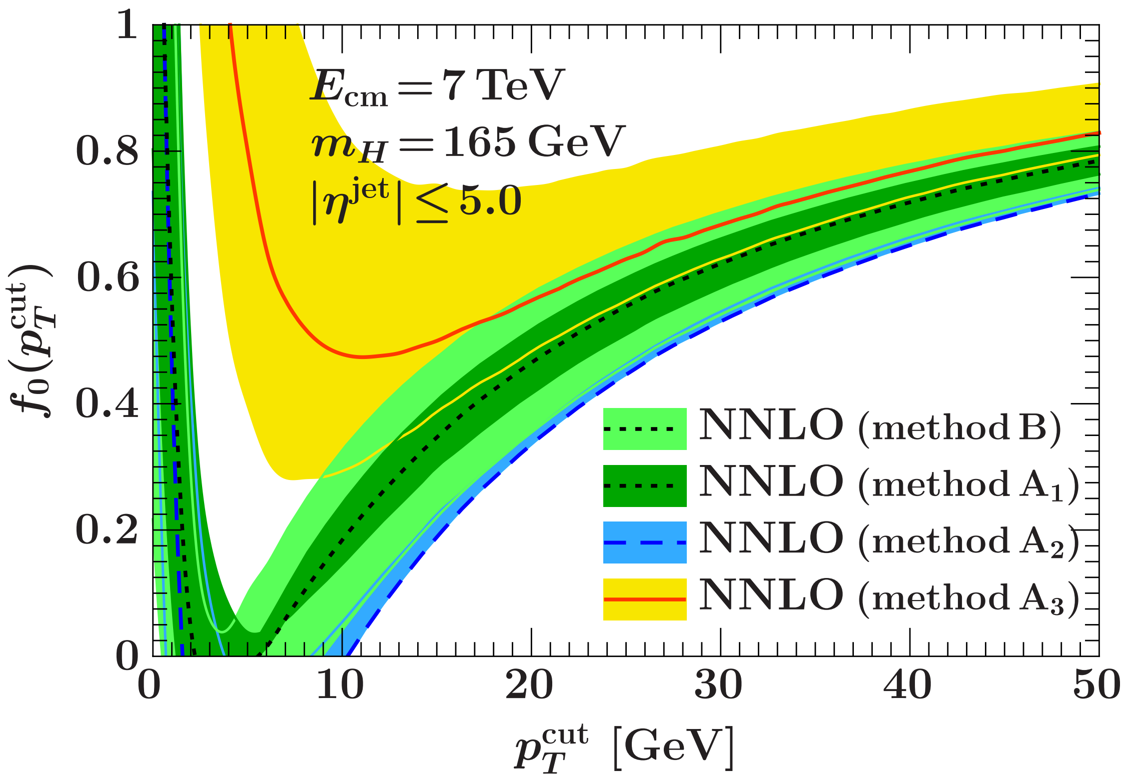
# Jet Veto

Fixed order calculations underestimate uncertainties for jet-veto cross section

ST



efficiencies



Consider *inclusive* jet cross section uncertainties

Transform to *exclusive* jet cross sections

$$\sigma_{\rm total} = \sigma_0(p^{\rm cut}) + \sigma_{\ge 1}(p^{\rm cut})$$

Complete description requires full theory covariance matrix for $\{\sigma_0, \sigma_{\ge 1}\}$

$$C = \begin{pmatrix} (\Delta_0^{\rm y})^2 & \Delta_0^{\rm y}\,\Delta_{\ge 1}^{\rm y} \\ \Delta_0^{\rm y}\,\Delta_{\ge 1}^{\rm y} & (\Delta_{\ge 1}^{\rm y})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm cut}^2 & -\Delta_{\rm cut}^2 \\ -\Delta_{\rm cut}^2 & \Delta_{\rm cut}^2 \end{pmatrix}$$

$$\Delta_0^2 = \Delta_{\rm total}^2 + \Delta_{\ge 1}^2$$

assumed uncorrelated

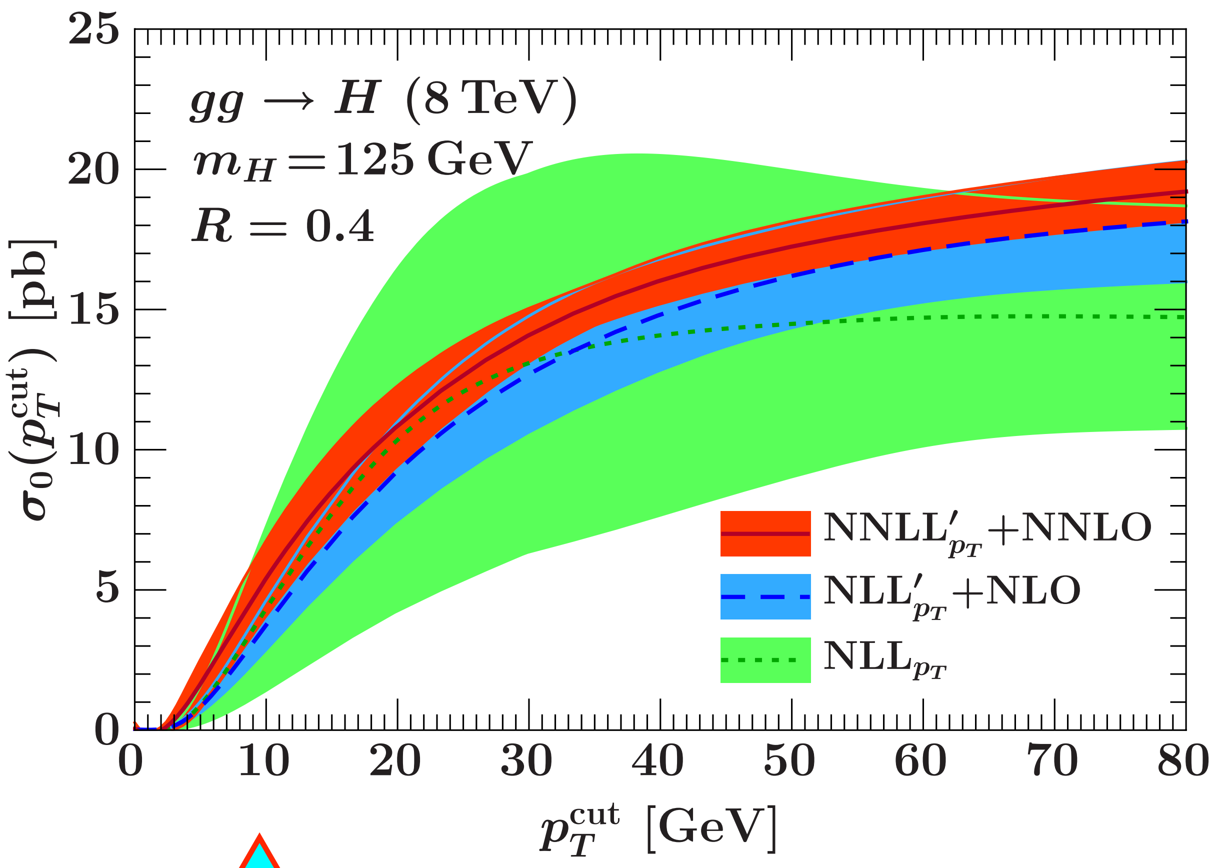
$$\sigma_{0-\rm jet} = \sigma_{\rm tot} \times \epsilon(p_{t,\rm veto})$$

$$\epsilon^{(a)}(p_{\rm t,veto}) = \frac{\sigma_{0-\rm jet}^{\rm NNLO}}{\sigma_{\rm tot}^{\rm NNLO}}$$

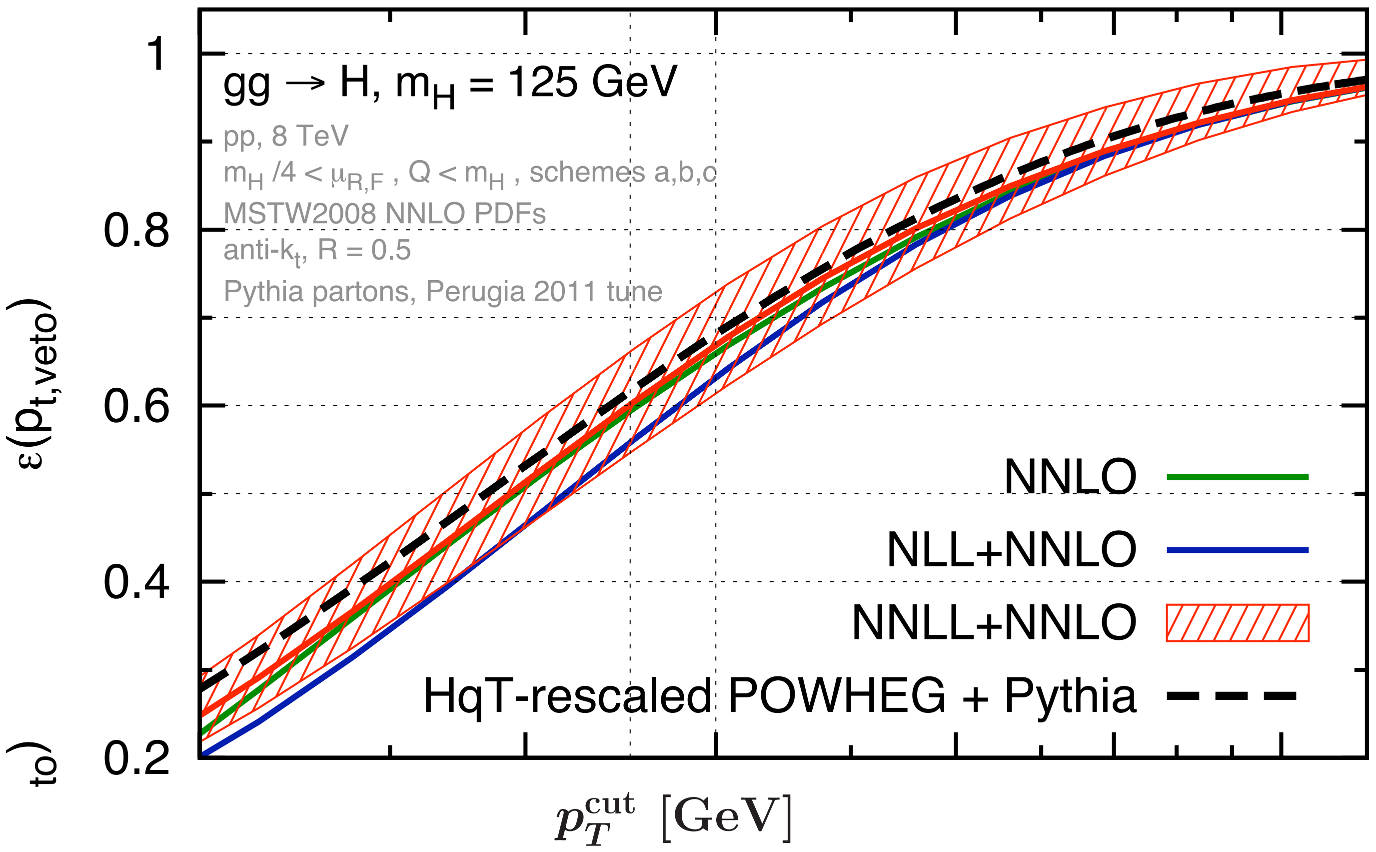
$$\epsilon^{(b)}(p_{\rm t,veto}) = 1 - \frac{\sigma_{\ge 1-\rm jet}^{\rm NLO}}{\sigma_{\rm tot}^{\rm NLO}}$$

$\epsilon^{(c)}(p_{t,\rm veto})$ = strict fixed order expansion

## SCET resummation (F. Tackmann)



## "QCD" resummation (P.F. Monni)



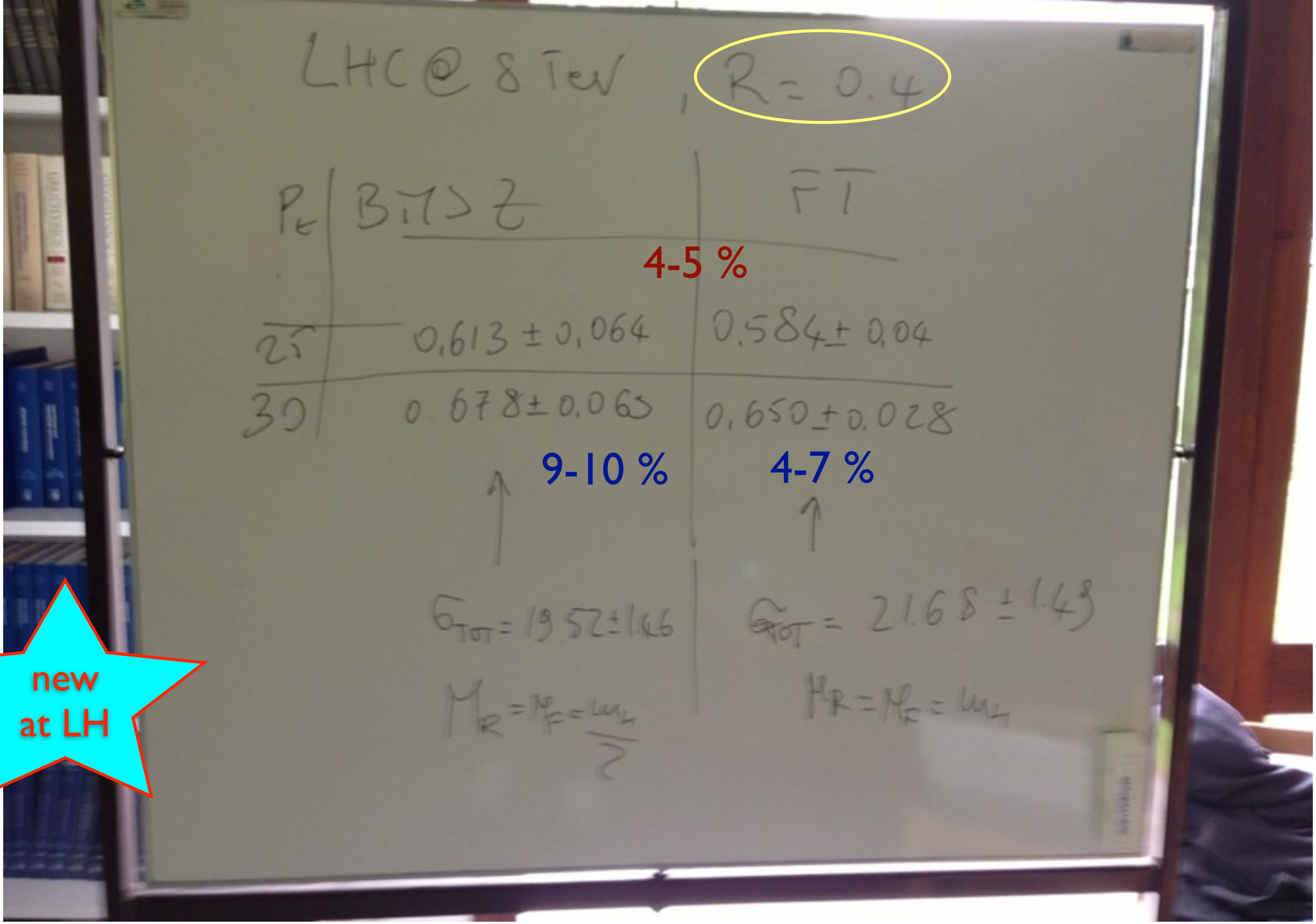
new
at LH

FT

| Preliminary | $\sigma_0(p_T^{\rm cut})$ [pb] | $\sigma_{\geq 1}(p_T^{\rm cut})$ [pb] | $\epsilon_0(p_T^{\rm cut})$ |
|---|---|---|---|
| | NLL$'_{p_T}$+NLO, $\sigma_{\geq 0} = 20.46 \pm 3.37$ (16.5%) | | |
| $R = 0.5$ | | | |
| $p_T^{\rm cut} = 25$ GeV | $12.40 \pm 1.12$ (9.0%) | $9.28 \pm 1.03$ (11.1%) | $0.572 \pm 0.036$ (6.2%) |
| $p_T^{\rm cut} = 30$ GeV | $13.85 \pm 0.87$ (6.3%) | $7.83 \pm 0.94$ (12.0%) | $0.639 \pm 0.026$ (4.1%) |

PFM

| $p_{t,\rm veto}$ | $\epsilon(p_{t,\rm veto})$ | $\sigma_{0-\rm jet}$[pb] | $\sigma_{\geq 1-\rm jet}$[pb] |
|---|---|---|---|
| 25 GeV | $0.601 \pm 0.057$ ($\pm 9\%$) | $11.73 \pm 1.43$ ($\pm 12\%$) | $7.79 \pm 1.26$ ($\pm 16\%$) |
| 30 GeV | $0.667 \pm 0.058$ ($\pm 9\%$) | $13.03 \pm 1.49$ ($\pm 11\%$) | $6.49 \pm 1.22$ ($\pm 19\%$) |



LHC @ 8 TeV, R = 0.4

| $p_t$ | BMSZ | FT |
|---|---|---|
| 25 | 0.613 ± 0.064 | 0.584 ± 0.04 |
| 30 | 0.678 ± 0.065 | 0.650 ± 0.028 |

4-5 %

9-10 %

4-7 %

$\sigma_{TOT} = 19.52 \pm 1.66$

$\mu_R = \mu_F = \frac{m_H}{2}$

$\sigma_{TOT} = 21.68 \pm 1.43$

$\mu_R = \mu_F = m_H$

new at LH

Beware, no bottom mass effects yet (on the way)

**F.Tackmann - P.F. Monni**

LH : more detailed comparison between resummation and uncertainties for jet veto

# Interferences

new
at LH

Heavy Higgs analysis

## $gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$: $H \to WW$ search cuts

| | $gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | cont | $\lvert H_{\text{ofs}}\text{+cont}\rvert^2$ | $R_1$ | $R_2$ |
| $gg\ (\to H) \to WW$ | 0.3124(3) | 0.07607(7) | 0.3988(4) | 1.027(2) | 1.033(2) |
| $gg\ (\to H) \to WW/ZZ$ | 0.4460(5) | 0.09851(8) | 0.5715(6) | 1.050(2) | 1.060(2) |

| | $gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | cont | $\lvert H_{\text{ofs}}\text{+cont}\rvert^2$ | $R_1$ | $R_2$ |
| $gg\ (\to H) \to WW$ | 0.01287(2) | 0.008383(8) | 0.02369(2) | 1.115(2) | 1.189(2) |
| $gg\ (\to H) \to WW/ZZ$ | 0.01949(2) | 0.01265(2) | 0.03824(4) | 1.190(2) | 1.313(3) |

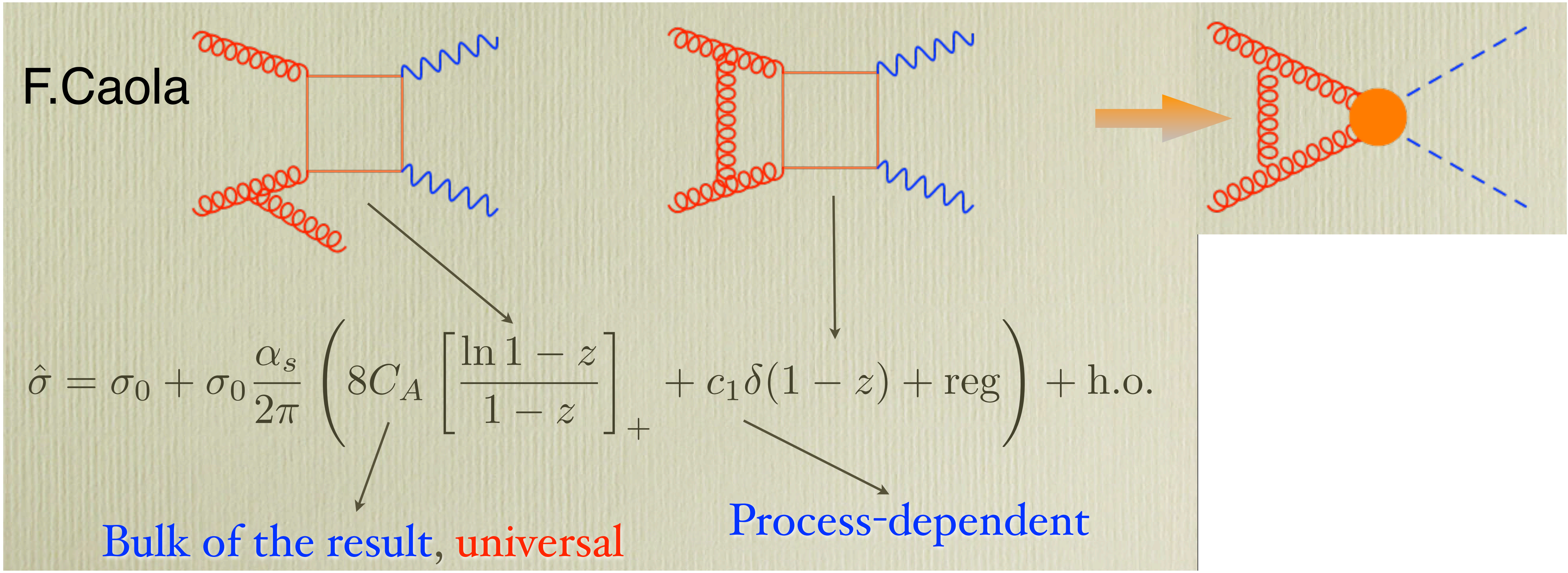
$H \to WW$ search cuts: $p_{T\ell} > 40$ GeV, $|\eta_\ell| < 2.5$, $\not{E}_T > 25$ GeV,
$M_{\ell\bar{\ell}} > 50$ GeV, $\Delta\eta_{\ell\bar{\ell}} < 1$, $p_T(\ell\bar{\ell}) > 30$ GeV, $0.6M_H < M_T < M_H$

$$M_T = \sqrt{(M_{T,\ell\ell} + \not{p}_T)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2} \text{ with } M_{T,\ell\ell} = \sqrt{p_{T,\ell\ell}^2 + M_{\ell\ell}^2}$$

**N. Kauer**

Light and Heavy Higgs
signal-background interferences

# Interferences in WW at NNLO SV approx



F.Caola

$$\hat{\sigma} = \sigma_0 + \sigma_0 \frac{\alpha_s}{2\pi} \left( 8C_A \left[ \frac{\ln 1-z}{1-z} \right]_+ + c_1 \delta(1-z) + \text{reg} \right) + \text{h.o.}$$

Bulk of the result, universal

Process-dependent

A rough estimate: $m_W^2 \ll Q^2 \ll m_t^2 \sim m_b^2$

$-5\ \bar{c}_{1,2} < c_{1,2} < 5\ \bar{c}_{1,2}$

The interference K-factor is very similar to the (gg) Higgs K-factor

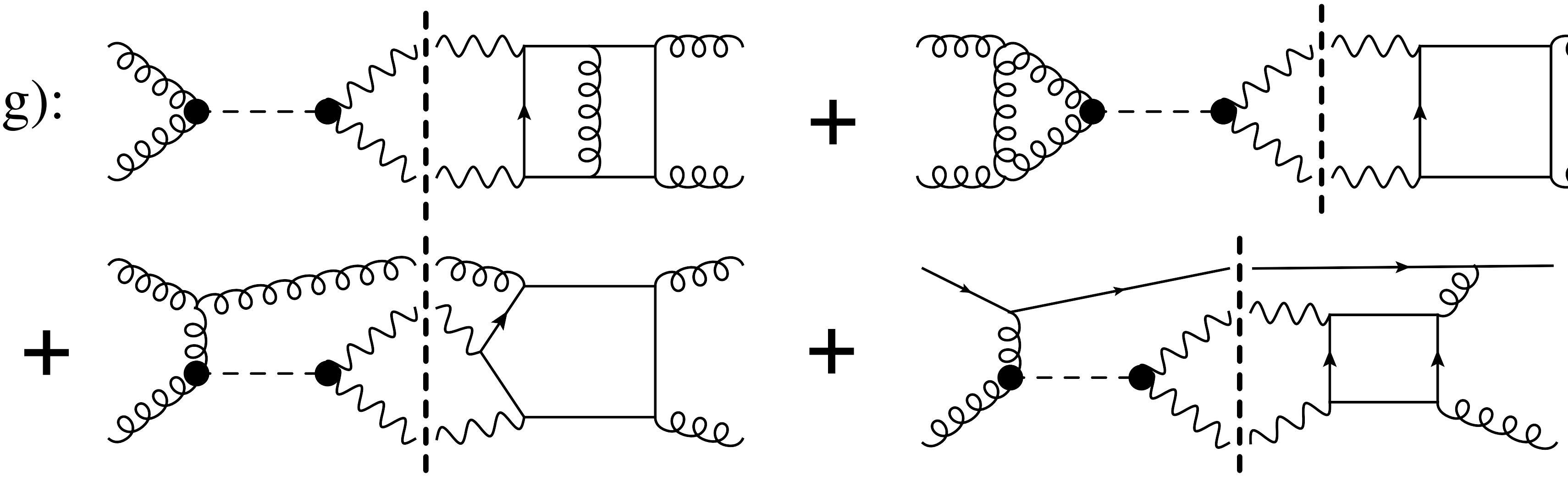
**F. Caola, S. Forte**

include line-shape effects to produce final numbers for heavy Higgs interferenc

Fawzi : what is a Heavy Higgs boson now?

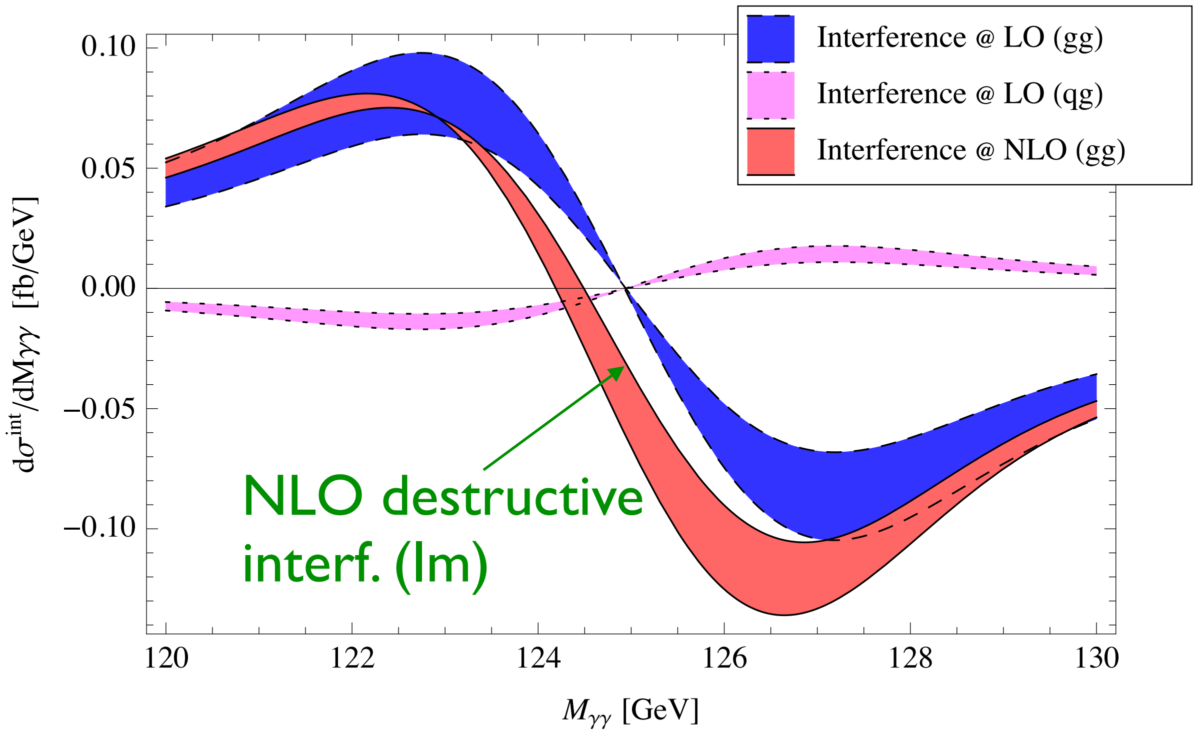
# Diphoton Interference

NLO (gg):



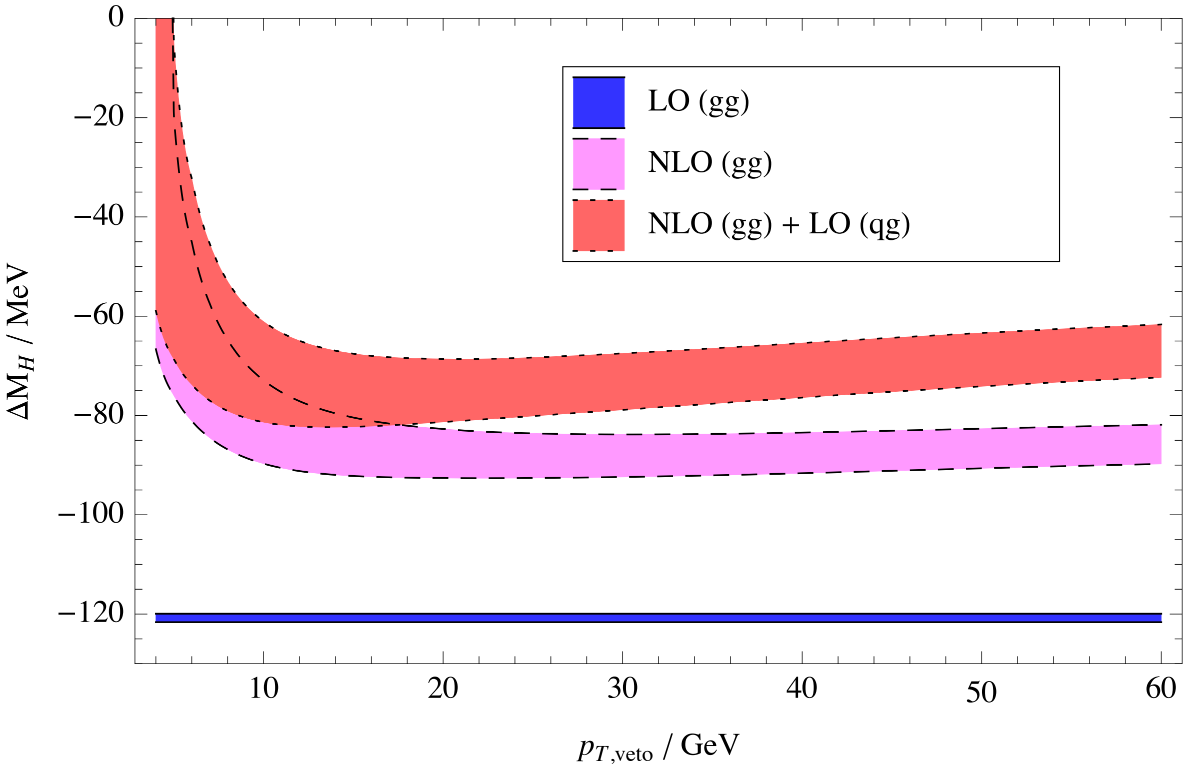
L.Dixon,Y.Li (2013)

## Interferences



NLO destructive interf. (Im)

## Mass shift



Needs realistic experimental analysis of detector effects (shift)

P. Gras

# LH : Accords, Wish-list, Tools, ~~Fondue~~, Joey Huston, Photons !

Reblochonnade

Wiki page linked from Higgs group http://phystev.in2p3.fr/wiki/2013:groups:sm:higgs:photons

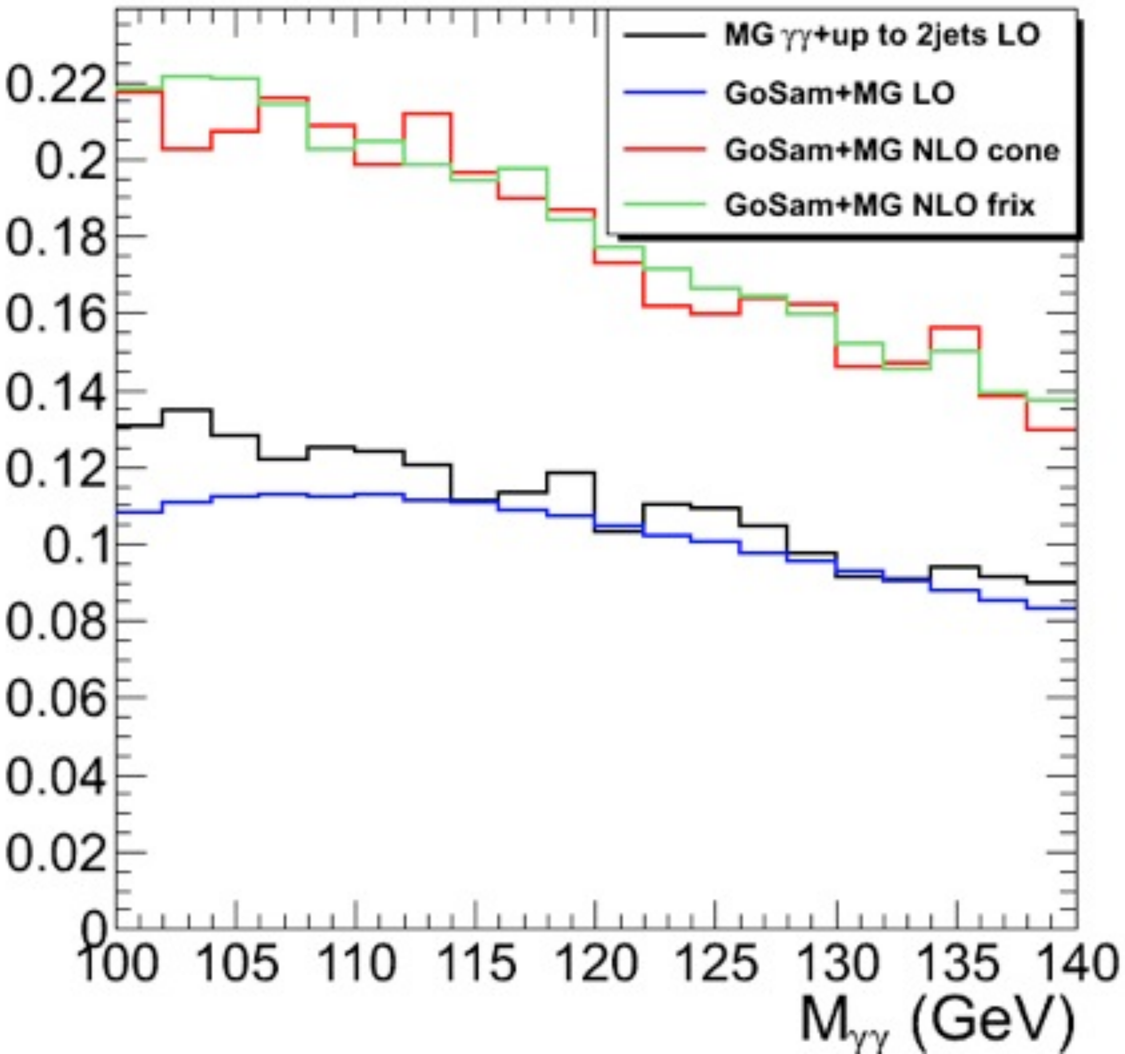
>20 people on mailing list, contact Suzanne if you want to participate!

## Comparison: GOSAM vs Sherpa/MG/Pythia

$$\gamma\gamma + n\,\mathrm{jet}$$

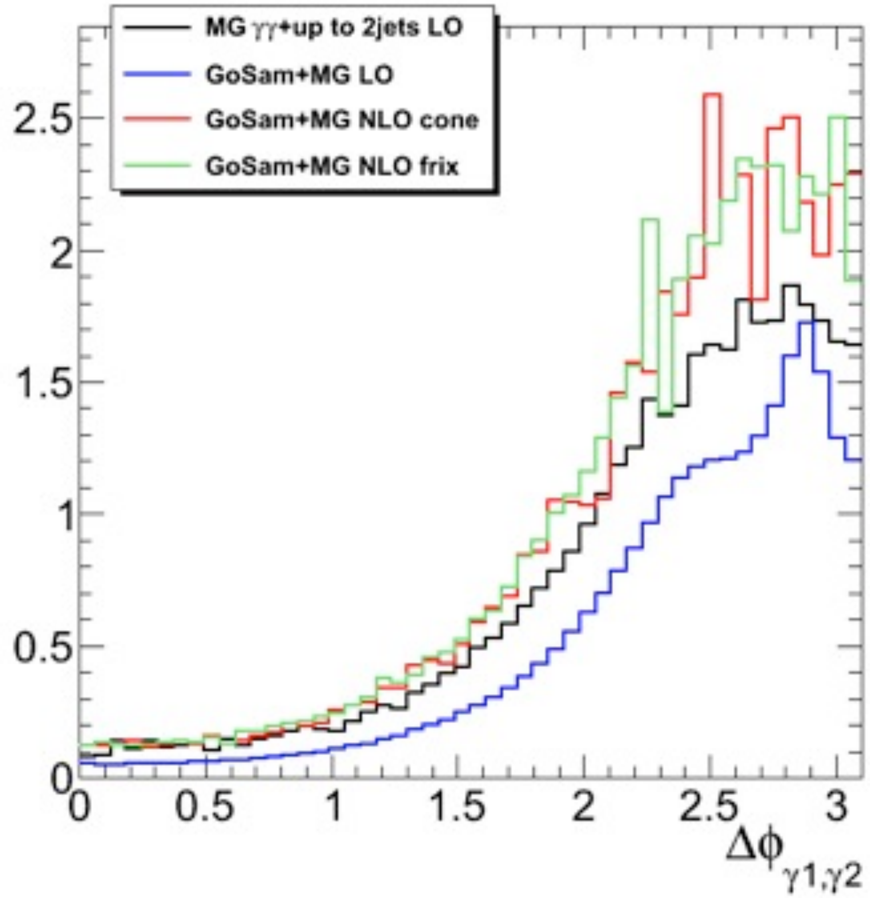
G.Heinrich, N.Chanon,
N.Greiner

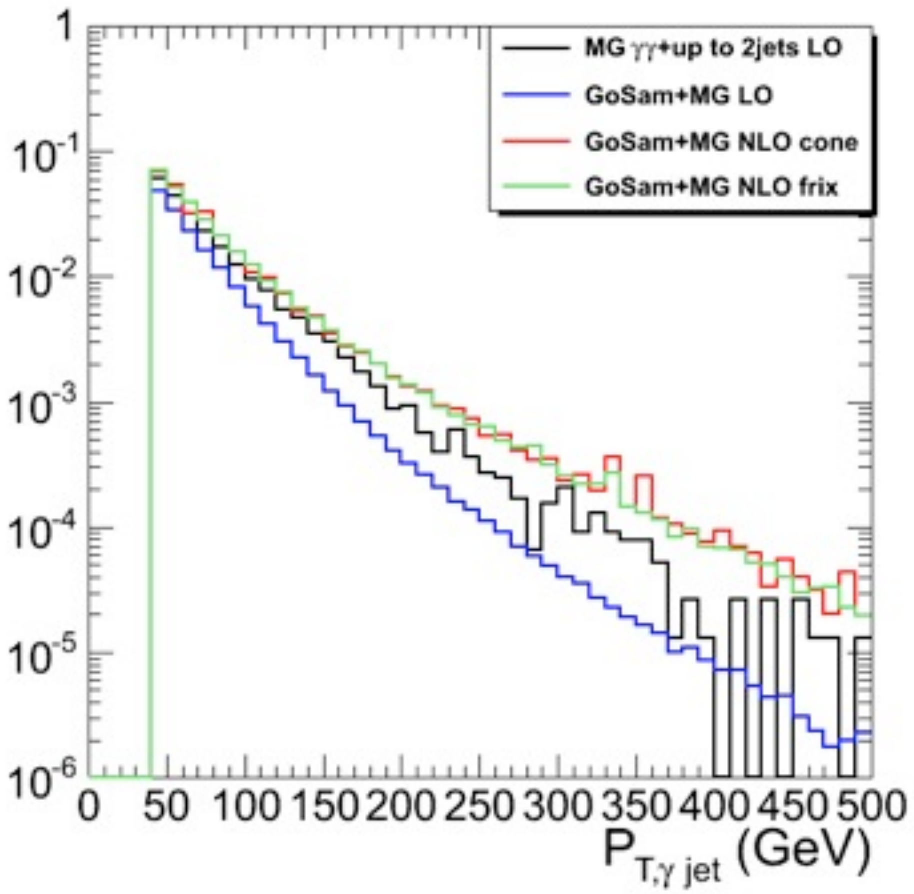
MG diphoton +up to 2 jets (1 jet bin)

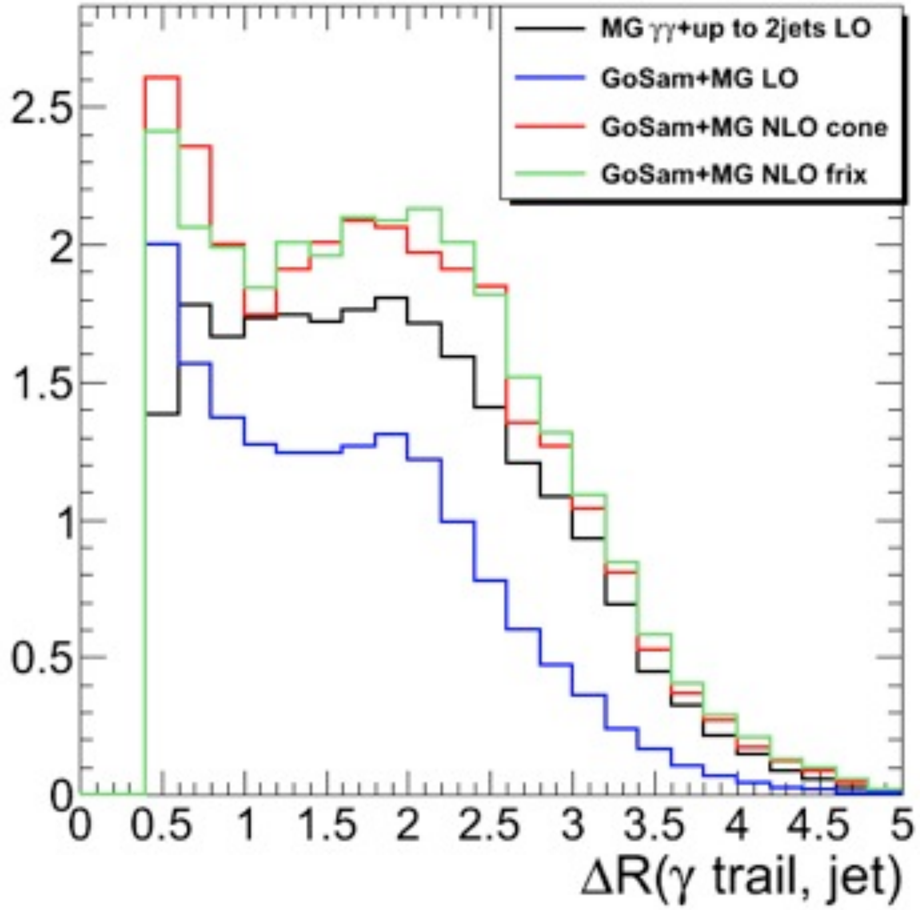


Preliminary

new
at LH





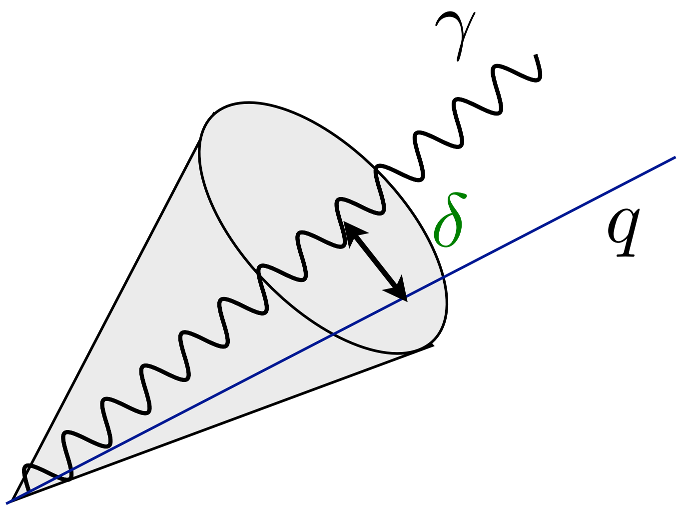


|eta_gamma|< 2.5
PT_hard > 40 GeV
PT_soft > 30 GeV
100 < Mgg< 160 (diphoton invariant mass)
R_gg > 0.5 (photon separation)
Ptjet>40 GeV (anti-Kt with R=0.4)
R_gammajet>0.4
|eta_jet|<2.5
Isolation in dR<0.4: ETiso<0.1*PhotonPt

# GOSAM + PS ? $\gamma\gamma + n\,\mathrm{jet}$

**G.Heinrich**

# PHOTON ISOLATION



Standard Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}$

Smooth Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$

S.Frixione

$$\chi(\delta) = \left( \frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n$$

$\leq 1$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined
- Allows to reach NNLO !!!!

More restrictive than usual cone : lower limit on cross section

Use it as a TH tool, not Experimental!

In real (TH)life... how much different? NLO comparison

# Check less inclusive observables: any significant difference?

**L.Cieri, DdeF**

Diphoton production $\sqrt{s} = 8\,\mathrm{TeV}$ CTEQ6M $\mu_F = \mu_R = M_{\gamma\gamma}$

$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\,soft} \geq 30\,\mathrm{GeV}$

$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$

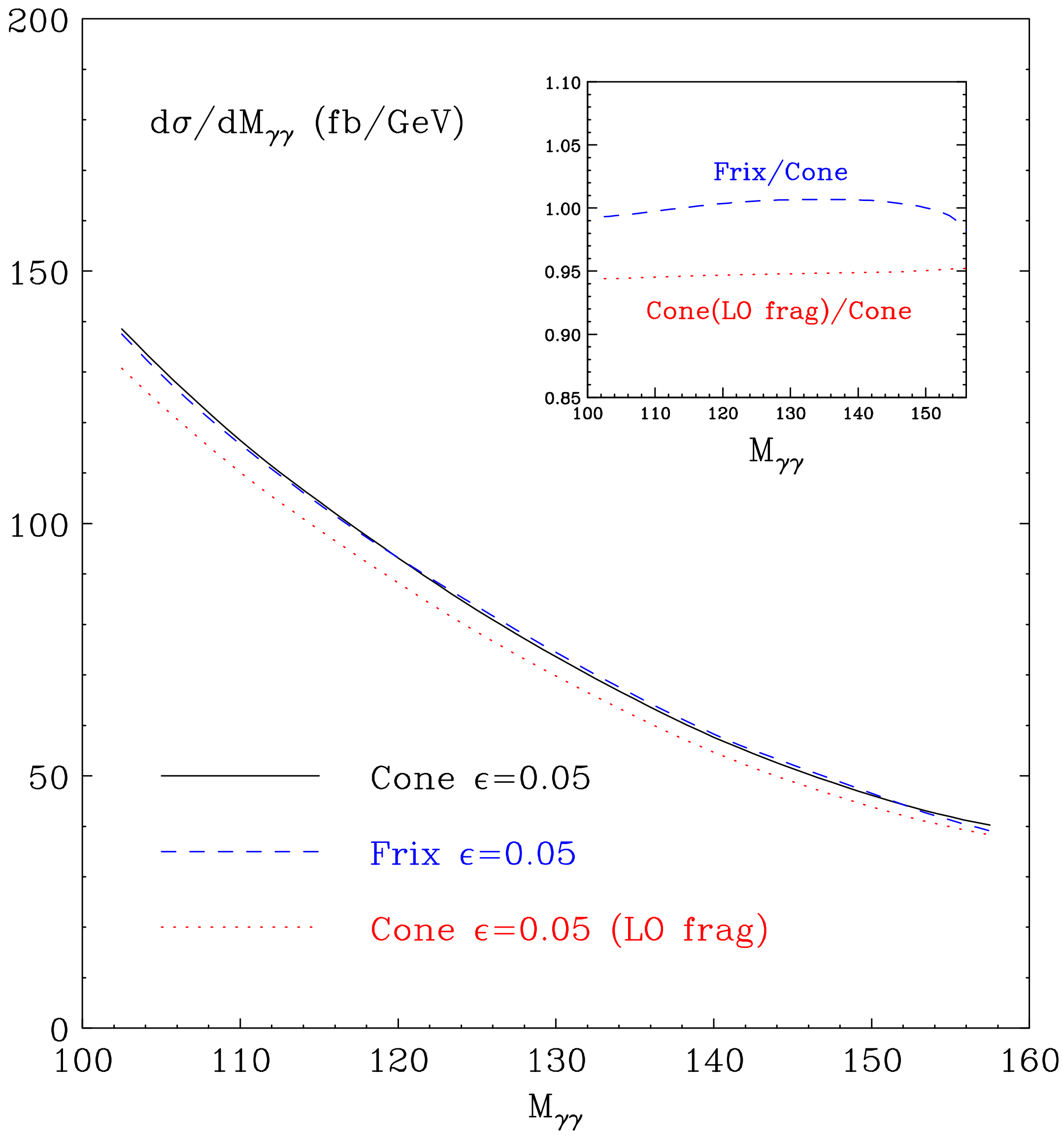
$|\eta^\gamma| \leq 2.5$

$R_{\gamma\gamma} \geq 0.45$

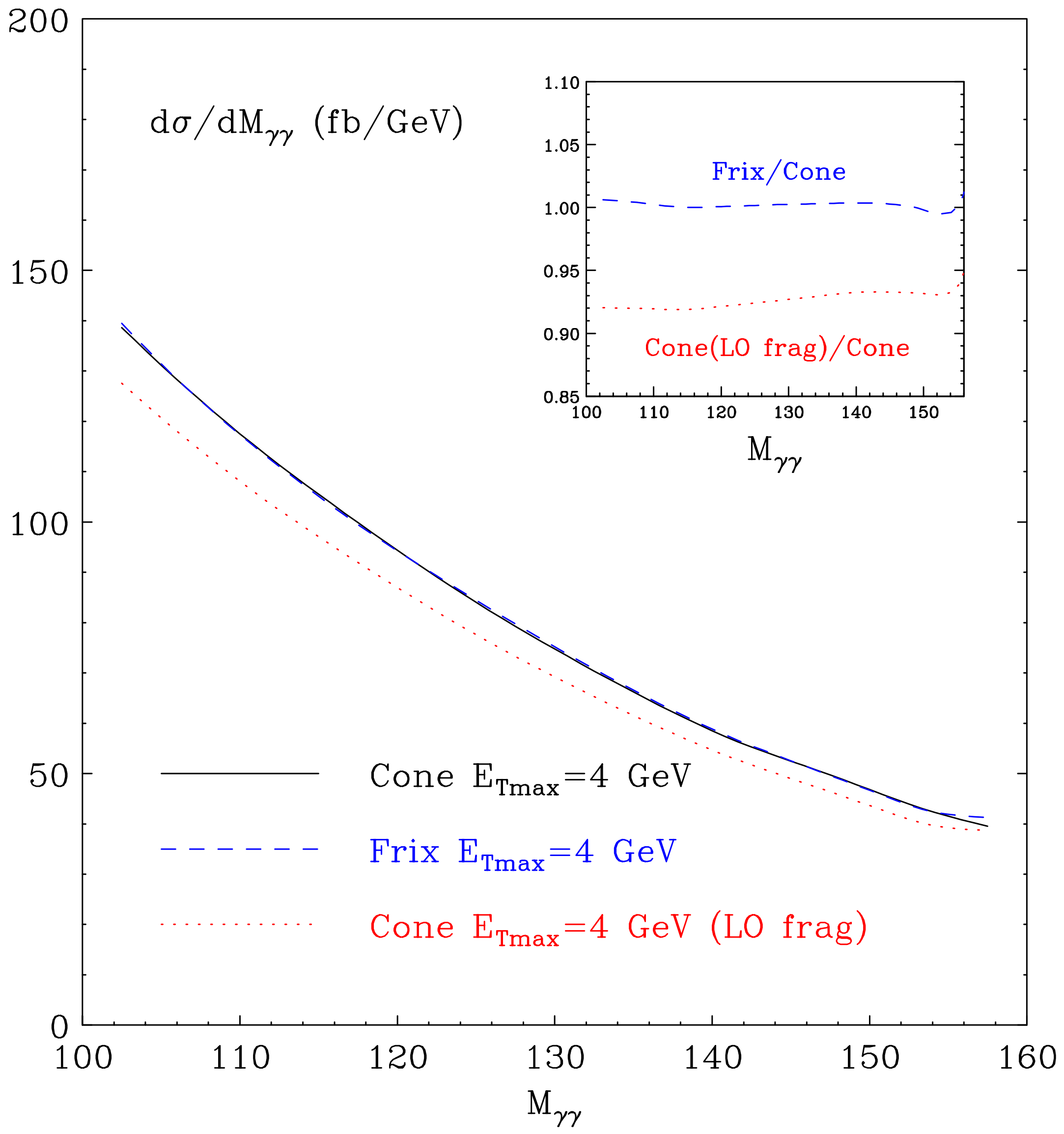
new
at LH

full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

$E_{T\,max}^{had} = \epsilon\, p_T^\gamma \quad \epsilon = 0.05$



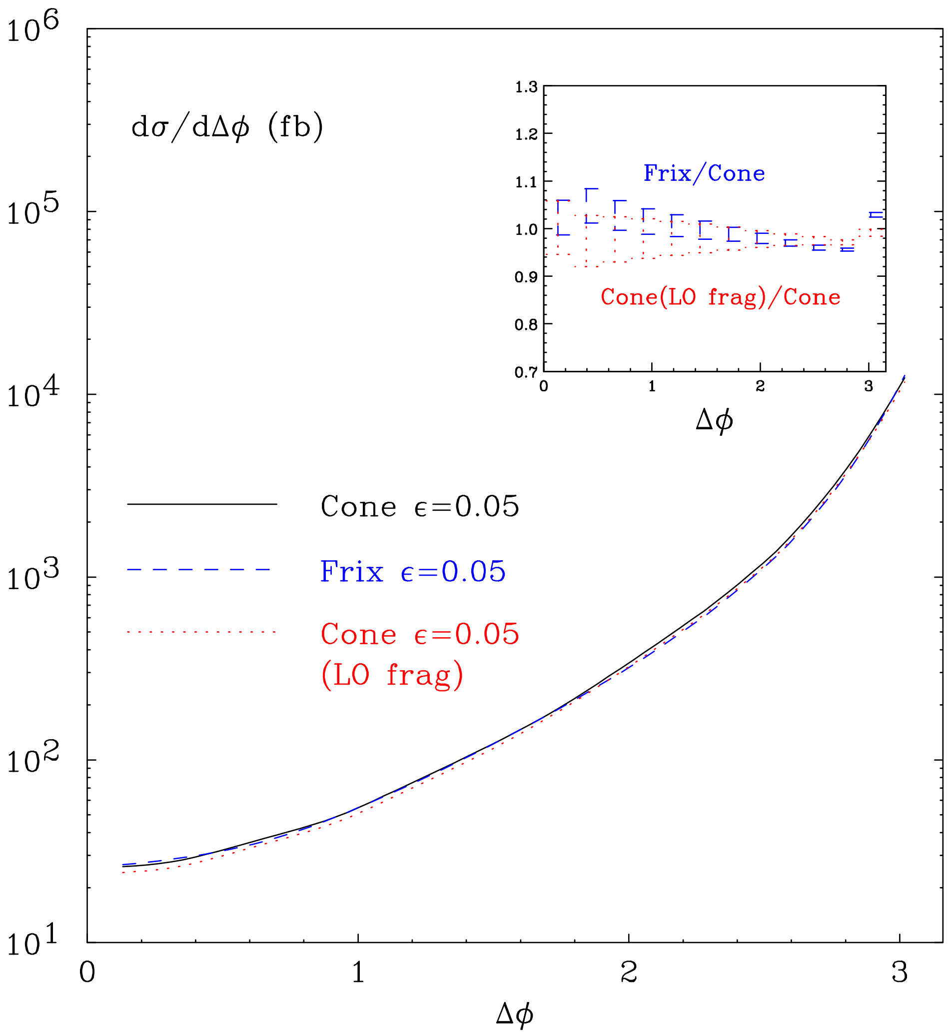
$E_{T\,max}^{had} = 4\,\mathrm{GeV}$

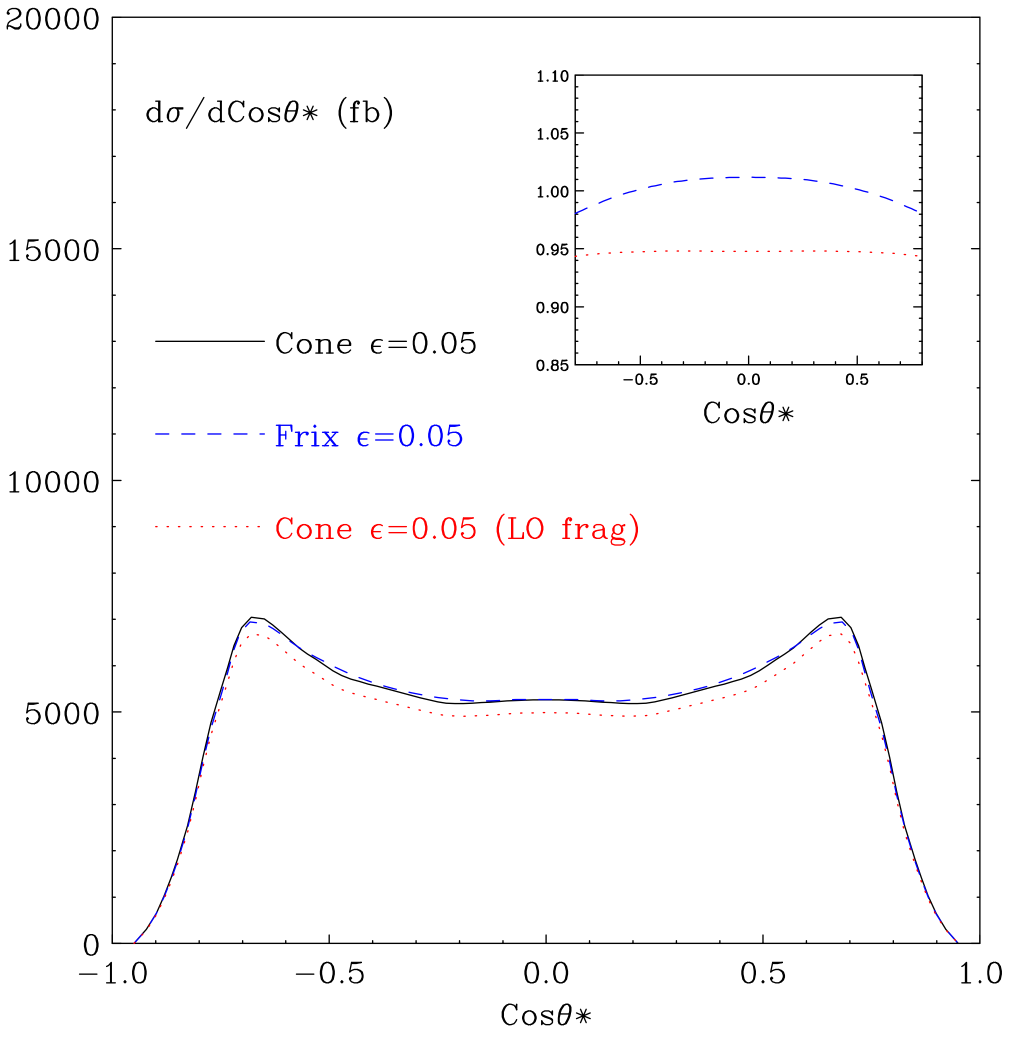


# Azimuthal and CosTheta* Distribution

new
at LH

## Usually claimed that “fragmentation effects” large at small azimuth





PRELIMINARY!
Still some statistical fluctuations (short run..)

Same feature for all distributions

Smooth cone @NLO ~ Cone @ NLO 1-2% level

Cone + LO fragmentation component worse than 5%

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n$$

Eric: that was proposed because it matches e+e- dynamics

In hadronic collisions better use $2\left(\cosh(\Delta y) - \cos(\Delta\phi)\right) \sim [(\Delta y)^2 + (\Delta\phi)^2] = r^2$

$$E_T^{had} \leq E_{T\,max}^{had} \left(\frac{r}{R}\right)^{2n}$$

new
at LH

|  | Isolation | $\sum E_T^{had} \leq$ | $\chi(r)$ | $\sigma_{total}^{NLO}$(fb) |
|---|---|---|---|---|
| i | Frixione | 2GeV | $\left(\frac{1}{2} - \frac{1}{2}\cos(\frac{\pi r}{R})\right)$ | 3760 |
| ii | Frixione | 2GeV | $\left(\frac{1}{2} - \frac{1}{2}\cos(\frac{\pi r}{R})\right)^{0.5}$ | 3921 |
| iii | Frixione | 2GeV | $r/R$ | 3769 |
| iv | Frixione | 2GeV | $(r/R)^2$ | 3731 |
| v | Frixione | 2GeV | $\left(\frac{1-\cos(r)}{1-\cos(R)}\right)$ | 3724 |
| v | Standard | 2GeV | 1 | 3731 |

⟵ Eric

⟵ Cone

“LH tight photon isolation accord”

- EXP: use (tight) Cone isolation        solid and well understood

- TH: use smooth cone with same R and $E_{Tmax}$

accurate, better than using
cone with LO fragmentation

Estimate TH isolation uncertainties
using different profiles in smooth cone

**L.Cieri + ALL**

Define “tight isolation” + conventional parameters

# $H \rightarrow \gamma\gamma$

NNLO for signal and background + NLO interference

Use these tools for better understanding of background:
training and test of MVA at particle level

How to?

2D reweighting of LO/LO+ codes for 2gamma using 2gammaNNLO

L.Cieri, N.Chanon,

2D reweighting of LO/LO+ codes for gamma+h using DIPHOX NLO

S. Gascon-Shotkin

First check reweighting makes sense!

Thanks to the organizers and participants!

Feliz cumpleaños Aylen