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QED corrections to Higgs boson decay into four leptons at the LHC

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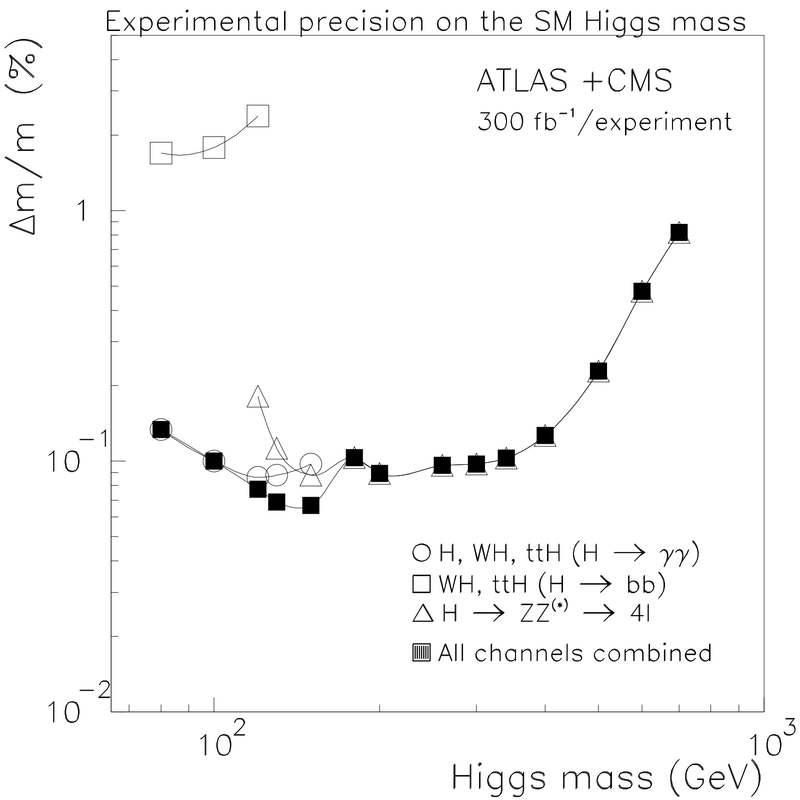
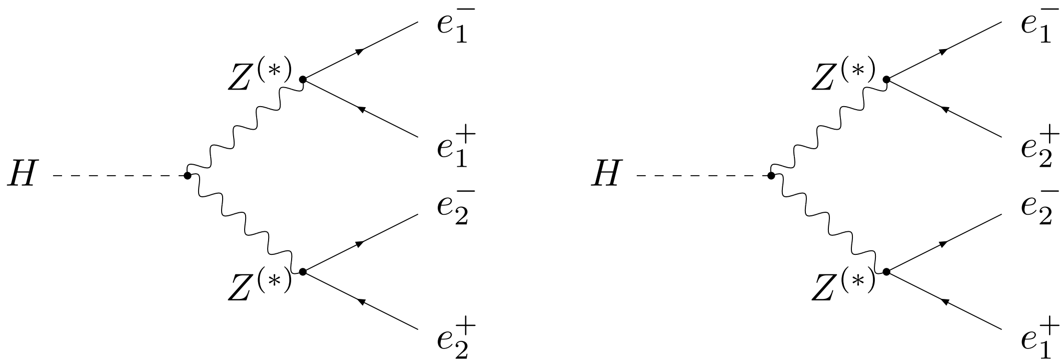
The LHC will allow a precision measurement of the Higgs mass up to few 0.1% (with high luminosity) on a wide range of mass

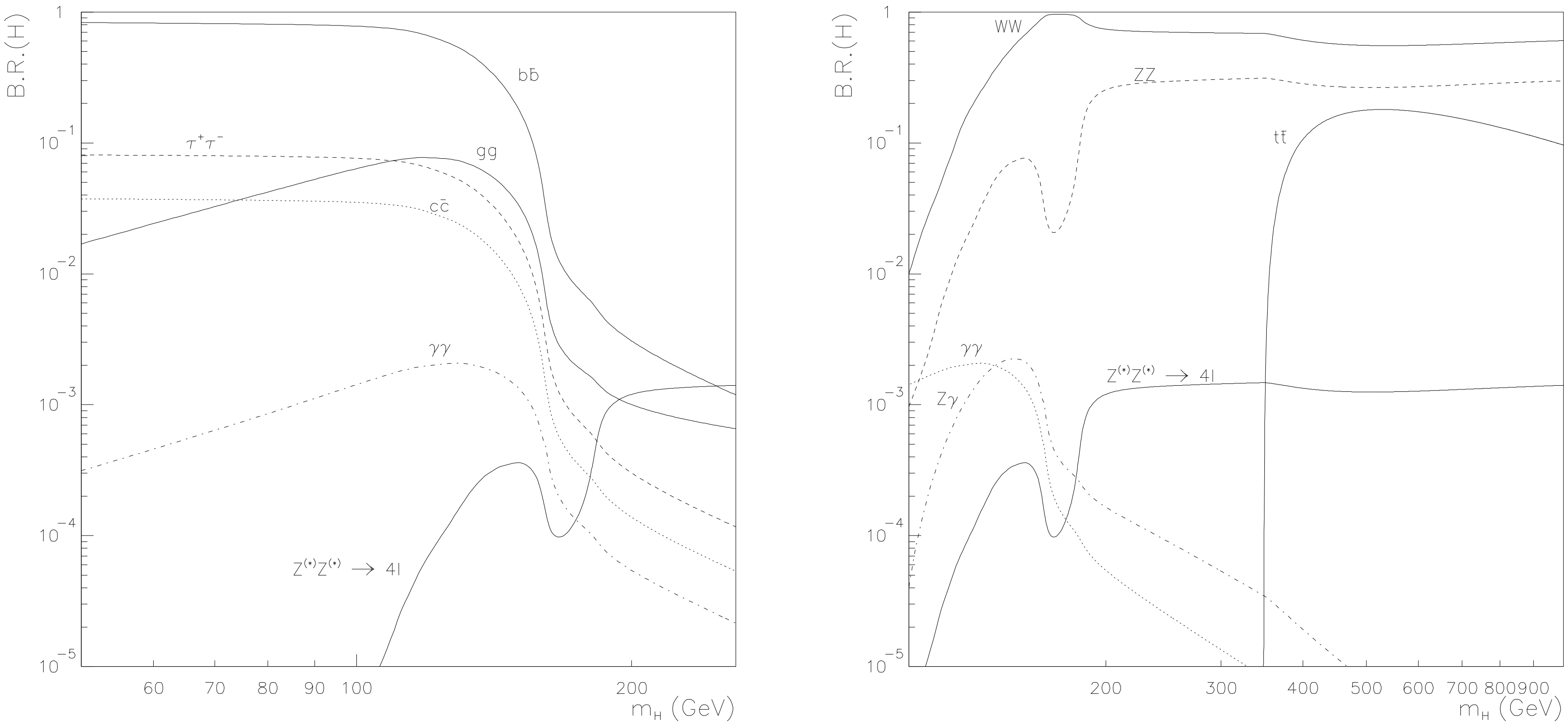
The most sensible channel is $gg \to H \to 4l$



ATLAS TDR

Exact tree-level matrix element for $H \to e^+e^-\mu^+\mu^-$ and $H \to l^+l^-l^+l^-$ $(l = e, \mu)$





Higgs mass determined with measurement of $M(4l)$

- Aiming at a precision measurement, QED radiative corrections to the decay width can be expected to give a sizeable contribution, if the selection criteria are not inclusive enough
- Being a process mediated by neutral Z bosons, QED corrections can be calculated in a gauge invariant way as a subset of electroweak corrections
- Two complementary approaches used for the calculation of QED corrections:
  1. Leading Logarithmic corrections (taking correctly into account soft and/or collinear singularities) with Parton Shower technique, which allows to evaluate all orders contributions
  2. Exact $\mathcal{O}(\alpha)$ perturbative calculation
- Being strongly dependent on the selection criteria, the impact of QED corrections has to be estimated by means of a realistic simulation
- The evaluation of the QED effects has to be carried out considering also the production process, giving rise to longitudinal boosts (the applied selection criteria of leptons are not boost invariant)
- The effect of Higgs $p_\perp$ (IS QCD corrections) should also be included. Neglected at the moment

The Parton Shower algorithm

e.g. C.M. Carloni Calame et al., Nucl. Phys. **B584** (2000) 459
C.M. Carloni Calame, Phys. Lett. **B520** (2001) 16

- As in QCD, the QED DGLAP equation can be exactly solved by means of the Parton Shower algorithm
  - ⋆ it allows an exclusive photons generation (angular variables can be recovered)
  - ⋆ a full "radiation" event simulation can be done
- in order to study the HO relative effect, the PS can be run
  - ⋆ up to all orders or
  - ⋆ at order α, by a "truncated" algorithm which (consistently) stops at first branching

By comparing full PS to $\mathcal{O}(\alpha)$ PS the effects of HO QED corrections can be estimated

Exact $\mathcal{O}(\alpha)$ QED corrections to the decay $H \to 4l$

One-loop perturbative calculation consists of virtual and real corrections

$$(d\Gamma)_B + (d\Gamma)_V + (d\Gamma)_R$$

- QED one-loop corrections are a gauge invariant subset of the full e.w. corrections
- Infrared divergences $(d\Gamma)_V$ and $(\Gamma)_R$ regularized with a small photon mass λ
- Real corrections split into soft and hard contributions
  1. soft contribution $\lambda \leq E_\gamma \leq k_0$ calculated analytically in the soft approximation
  2. hard matrix elements calculated by means of the `ALPHA` algorithm and `FORM` with $m_\gamma = 0$ and finite fermion masses

F. Caravaglios, M. Moretti, Phys. Lett. **B358** (1995)

J.A.M. Vermaseren, `math-ph/0010025`

- virtual corrections (evaluated with $m_f = 0$ wherever possible) consist of
  1. fermion self-energies
  2. vertex diagrams
  3. pentagon diagrams (4 for $e^+e^-\mu^+\mu^-$, 8 for $l^+l^-l^+l^-$)

- Self-energies and vertex corrections evaluated by means of standard Passarino-Veltman technique. Scalar form factors evaluated numerically with `LoopTools`

T. Hahn, M.Perez-Victoria, CPC 118 (1999)

- Pentagon diagrams reduced (with the help of `FORM`) to combinations of 4-point form factors with the techniques introduced by Denner & Dittmaier

A. Denner and S. Dittmaier, Nucl. Phy. **B658** (2003) 175

in order to avoid numerical instabilities due to Gram determinants

The method has been already successfully used for the calculation of $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to 4$ fermions ($e^+e^- \to \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$, $u\bar{d}\mu^-\bar{\nu}_\mu$, $u\bar{d}s\bar{c}$), where also six point functions are involved.

A. Denner, S. Dittmaier, M. Roth and L.H. Wieders,
Phys. Lett. **B612** (2005) 223, [hep-ph/0502063]; [hep-ph/0505042]

A. Denner, S. Dittmaier, [hep-ph/0509141]

Problems due to the Z^0 instability

The presence of two virtual Z bosons requires the introduction of the width in the propagator in order to avoid the singularities in the phase space

Introducing the width breaks gauge invariance, even if for the case at hand it should not be numerically crucial

On the other hand it is crucial to have a consistent treatment of the widths in both virtual and real corrections, otherwise the IR divergence cancellation would be spoiled

A way out is given by the complex mass scheme introduced in

A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. **B560** (1999) 33

for tree-level calculations

The method has been generalised for one-loop calculations in

A. Denner, S. Dittmaier, M. Roth and L.H. Wieders,
Phys. Lett. **B612** (2005) 223, [hep-ph/0502063]; [hep-ph/0505042]

Fermion self-energies and vertex corrections (neglecting fermion masses whenever possible) factorize over the tree-level amplitude

For $H \to 4l$ the non factorizable corrections are given by five point diagrams, which are IR divergent, cancelled by the interference between real radiation from different external legs

With complex M_Z in the loop integrals, the IR singularity can be factorized over the tree level for the five point diagrams, leading to three point scalar form factors

We can define the $\mathcal{O}(\alpha)$ QED corrected Γ_H as

$$(d\Gamma)_B \times \left(1 + \delta_V^{FACT} + \delta_V^{IR5}\right) \quad + \quad (d\Gamma)_R \quad + \quad \left[(d\Gamma)_V^{NF} - (d\Gamma)_B \times \delta_V^{IR5}\right]$$

A library has been developed for the calculation of 5-point functions, based on `LoopTools` for the evaluation of scalar and tensor form factors ($\Gamma_Z = 0$)

An independent library has also been developed for scalar and higher rank (up to 2) form factors with complex M_Z, based on tensor reduction by Denner & Dittmaier NPB 658. Successfully checked with the previous one at $\Gamma_Z = 0$

Work in progress for an optimized evaluation of scalar form factors with complex masses

An independent approach could be represented by the fudge scheme, where the whole calculation is performed with $\Gamma_Z = 0$ with suitable fudge factors

Event Selection

Photons recombination with an e^+ or e^- if in the electromagnetic calorimeter they fall close within a cone R in the $\Delta\eta$, $\Delta\phi$ plane

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

$$\Delta R = 0.19, \quad \Delta\eta = 0.075, \quad \Delta\phi = 0.175$$

ATLAS TDR

Kinematical cuts

- $|\eta_l| < 2.5$
- at least a pair of leptons with $p_T > 20$ GeV
- $p_T > 7$ GeV for the remaining leptonic pair
- a pair of leptons with

$$m_Z - \Delta m < m_{inv}^{l^+l^-} < m_Z + \Delta m,$$

  Δm, m_H dependent, ~ 10 GeV

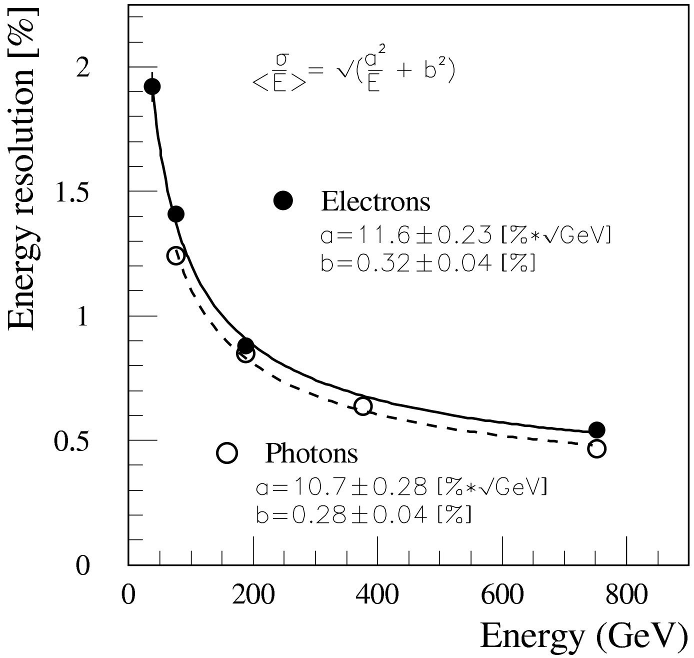
- the other leptonic pair with $m_{inv} > m_0$,
  m_0, m_H dependent, of the order of a few tens of GeV

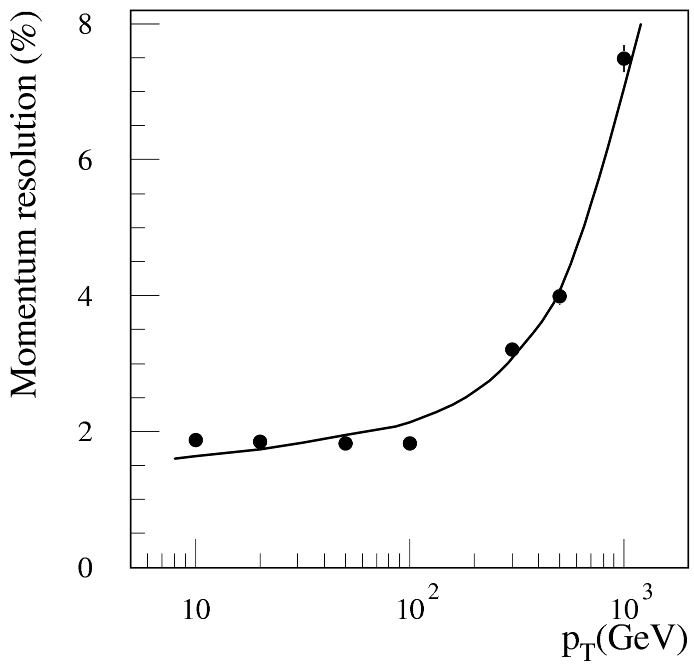
Smearing due to finite resolutions

Electrons and photons energy resolution

$$\eta\text{: } \frac{\sigma}{\langle E\rangle} = \sqrt{\left(\frac{a^2}{E} + b^2\right)}$$

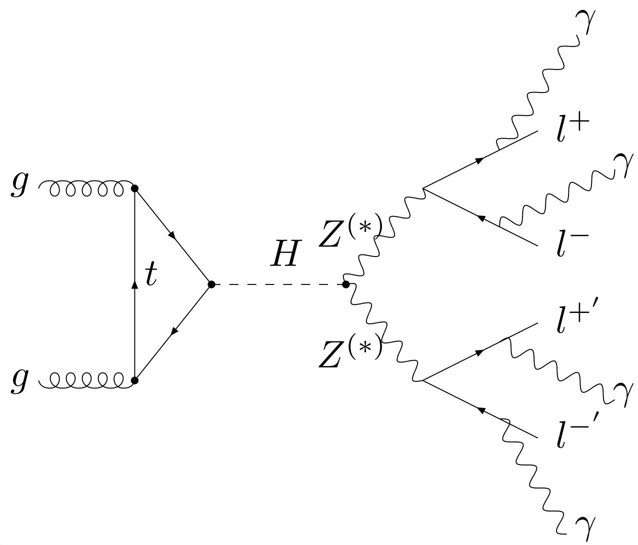
Muons p_T resolution $\sigma(p_T) \approx p_T$





ATLAS TDR

The process $pp \to H \to 4l + (n\gamma)$



$$\sigma(pp \to H \to 4l + (n\gamma)) \;=\; \int \mathrm{d}x_1 \mathrm{d}x_2 f_g(x_1,\mu) f_g(x_2,\mu) \hat{\sigma}_{gg\to H}(q^2)\, \frac{1}{\pi} \frac{\Gamma_{tot} M_H}{(q^2 - M_H^2)^2 + \Gamma_{tot}^2 M_H^2} \mathrm{d}q^2$$

$$\times \int \frac{\mathrm{d}\Gamma(H(q^2) \to 4l + (n\gamma))}{\Gamma_{tot}} \Theta(cuts)$$

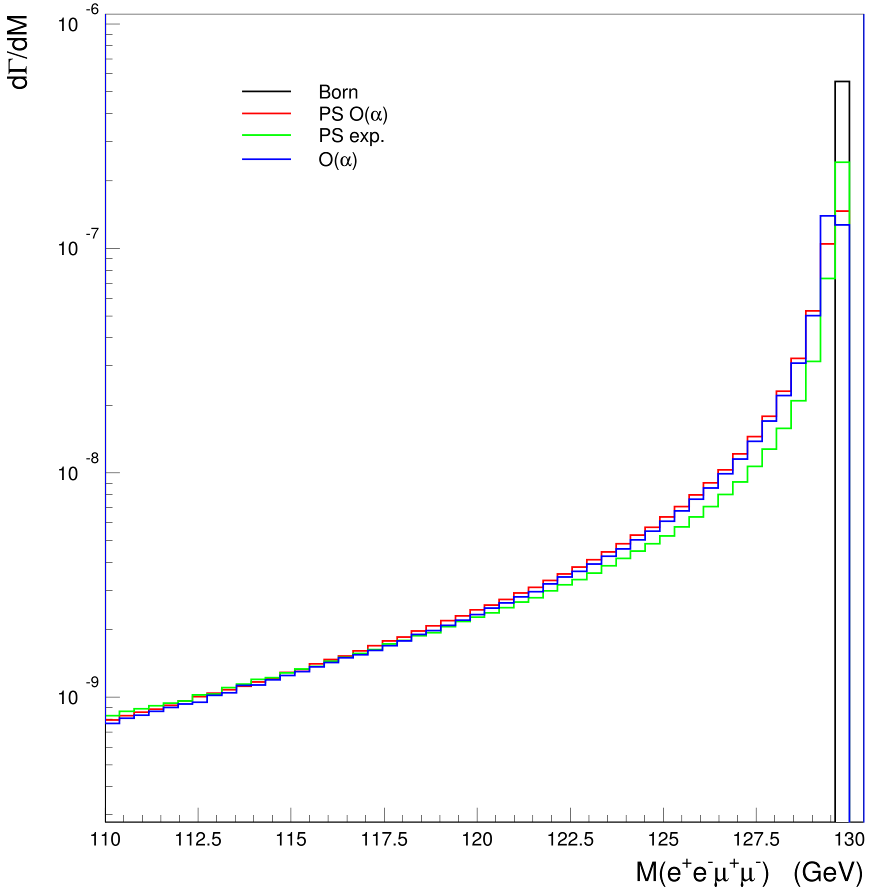
- Production $\longrightarrow$ `ALPGEN`

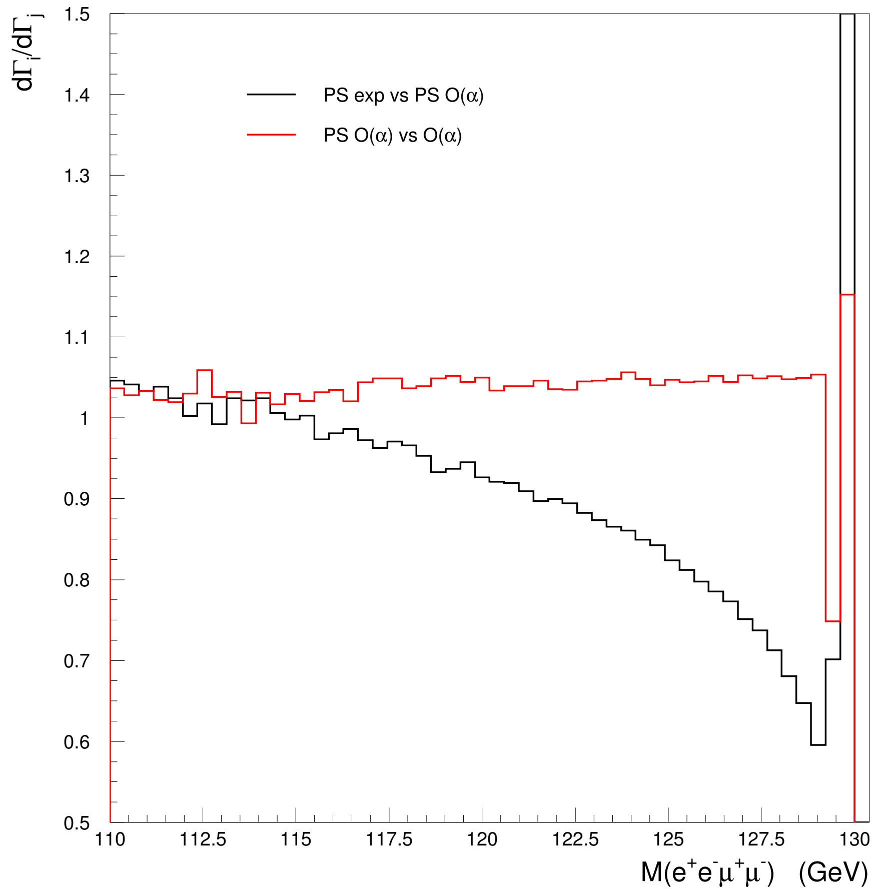
  M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A. D. Polosa, JHEP 0307 (2003) 001

- Decay $\longrightarrow$ `H24F`

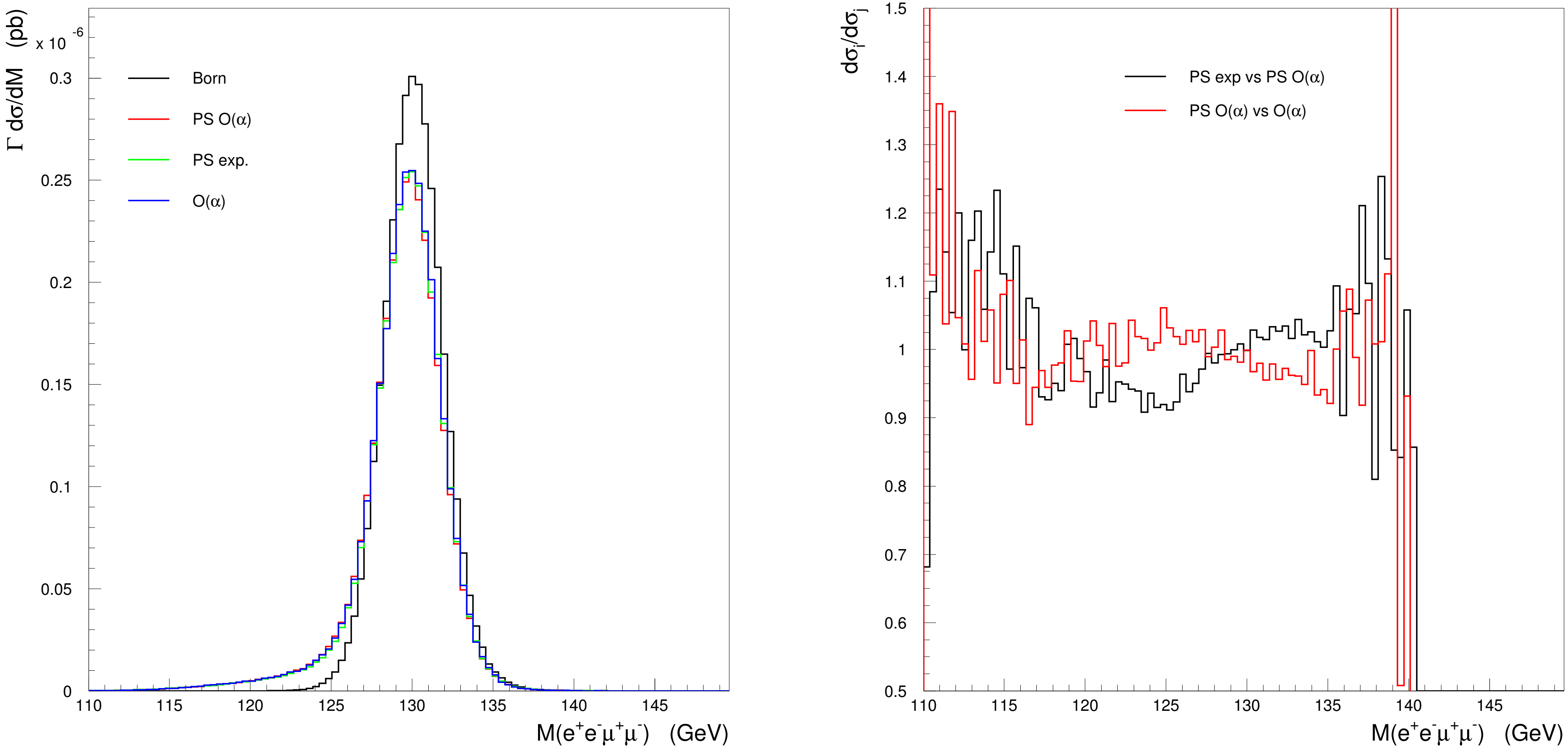
- The code runs in parallel with `MPI` libraries: a bunch of Higgs momenta are generated by `ALPGEN`, decayed by `H24F` in the c.m. system and boosted back to the laboratory frame where cuts are applied

Distributions for $e^+e^-\mu^+\mu^-$ final state $(M_H = 130\ \text{GeV})$

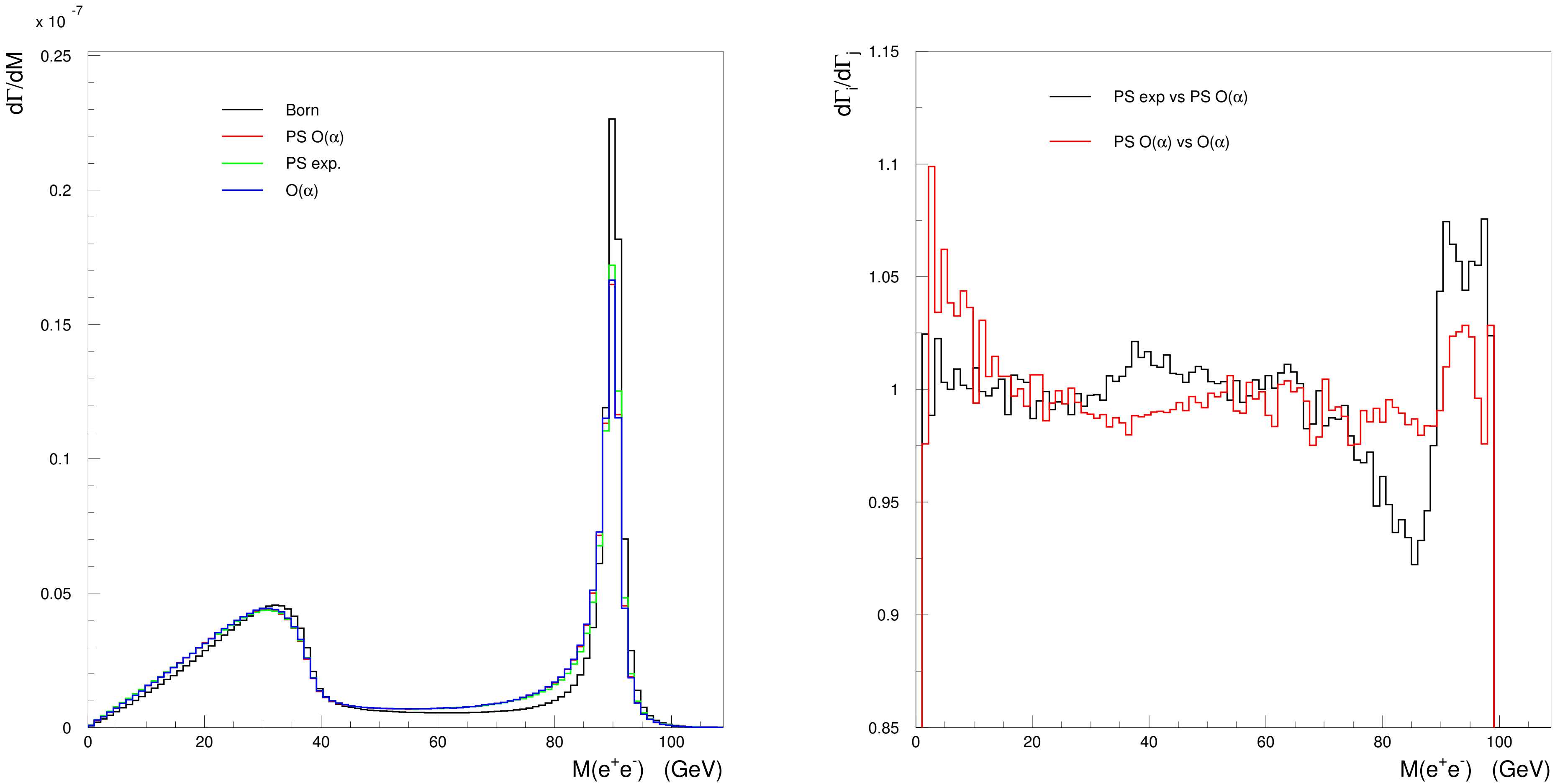




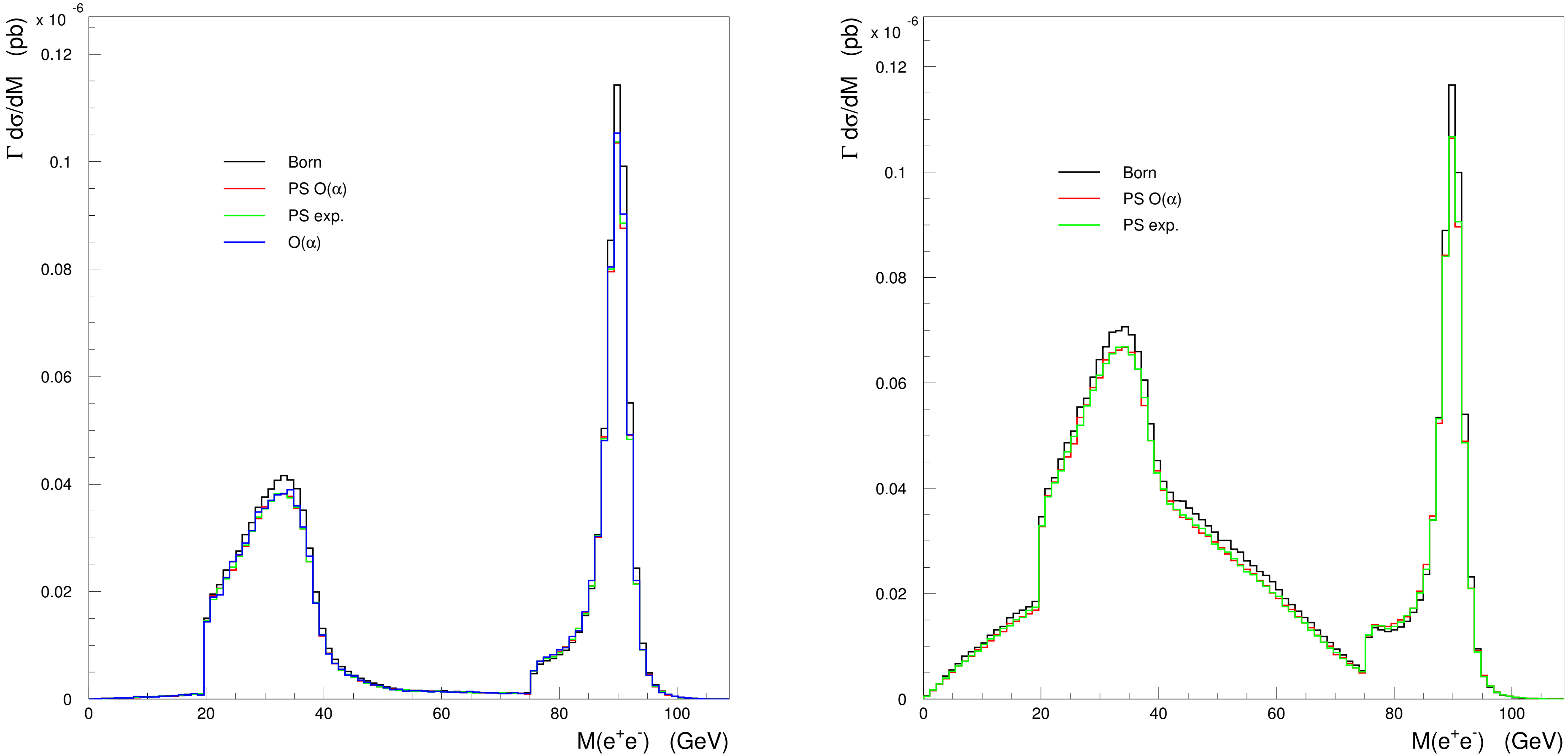
4 lepton invariant mass from Higgs decay (without production), no momentum smearing, cuts on leptons and photon recombination



4 lepton invariant mass from Higgs decay (with production), with momentum smearing, cuts on leptons and photon recombination



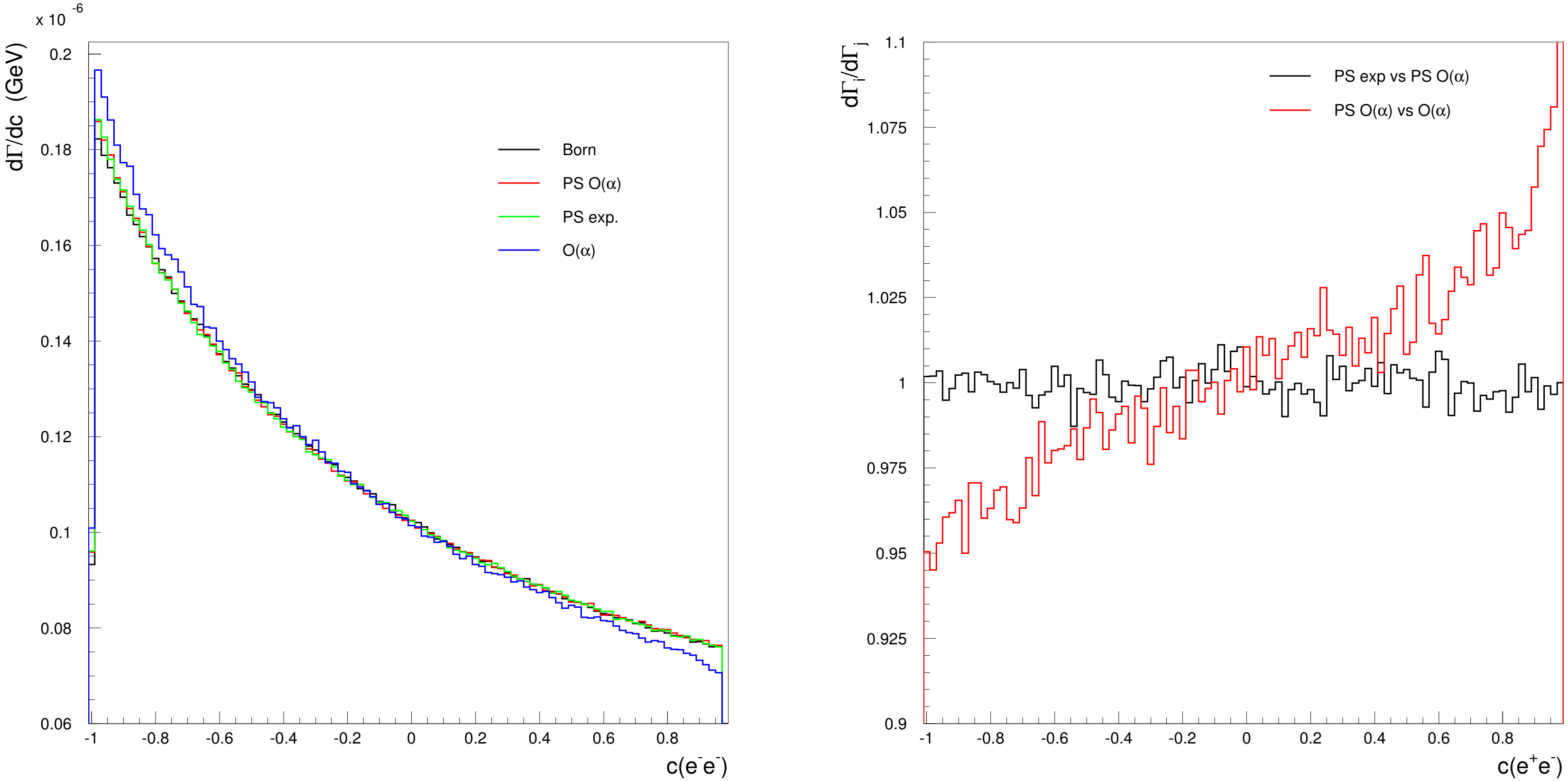
e^+e^- invariant mass from Higgs decay (without production), no momentum smearing, cuts on leptons and photon recombination



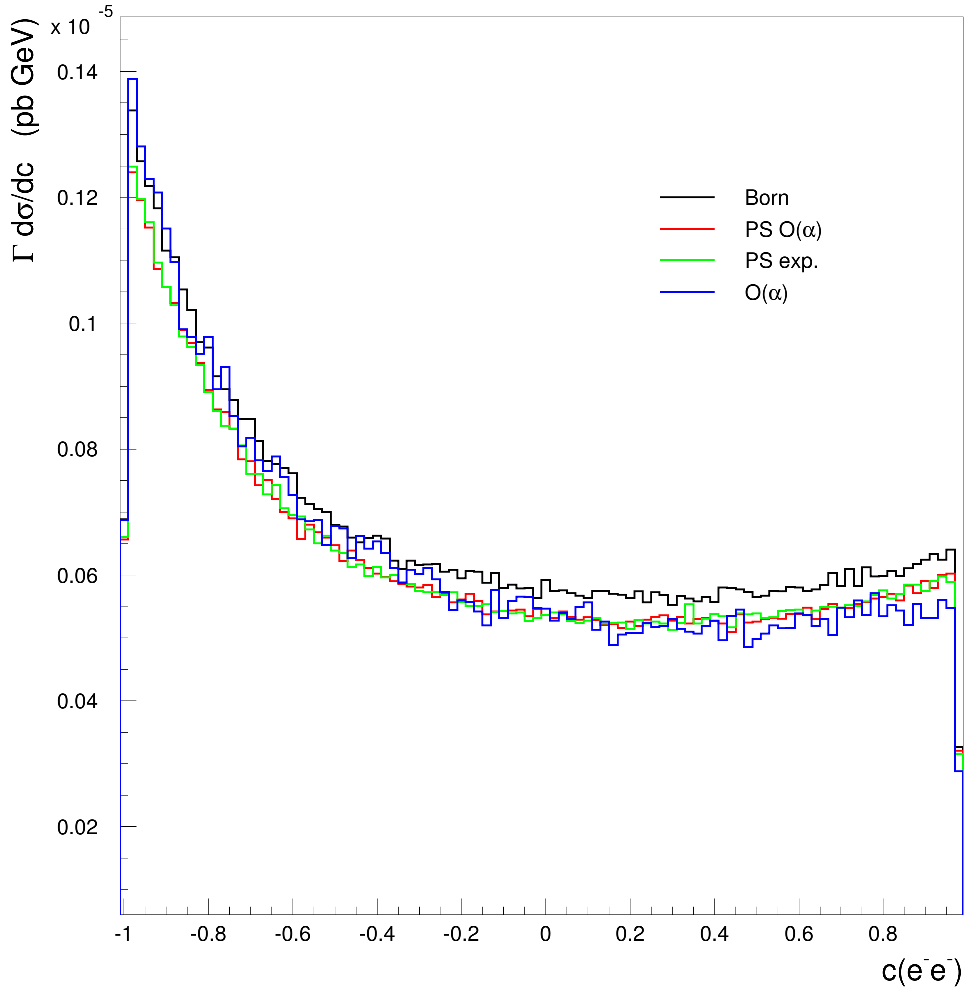
[Left]: e^+e^- invariant mass from Higgs decay in $e^+e^-\mu^+\mu^-$ (with production), with momentum smearing, cuts on leptons and photon recombination

[Right]: the same for the decay in $e^+e^-e^+e^-$ (only PS)

Angular correlation between equal-sign leptons → spin zero of the Higgs

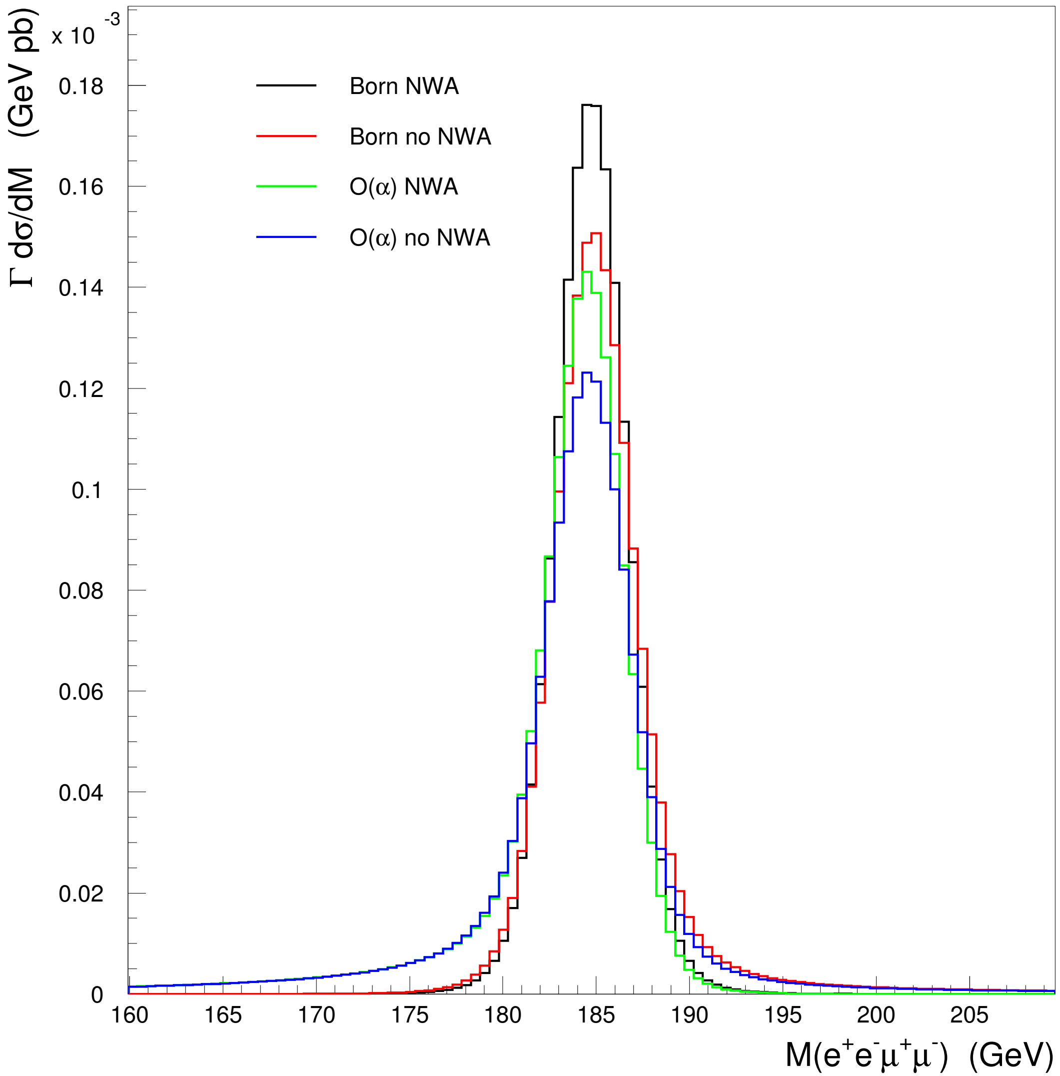


$\cos(e^-\mu^-)$ from Higgs decay (without production), no momentum smearing, cuts on leptons and photon recombination



$\cos(e^-\mu^-)$ from Higgs decay (with production), with momentum smearing, cuts on leptons and photon recombination in the $4l$ rest-frame

Narrow width approx. vs exact (M_H = 185 GeV)



e.g., NWA seems too crude at M_H = 185 GeV, where $\Gamma_{tot} \simeq 0.83$ GeV (HDECAY)

Djouadi, Kalinowski, Spira, CPC 108 (1998), hep-ph/9704448

Estimating QED effect on the fitted m_H

1. generate a sample of pseudo-data at Born level (i.e., without QED corrections) for a reference m_H mass, $m_H^{ref} = 130$ GeV
2. consider the $M(4l)$ spectrum and bin it into 100 bins within the fit region 110 - 150 GeV
3. consider N different Higgs mass values around m_H^{ref} with 20 MeV granularity and generate N $LL\mathcal{O}(\alpha)$, exact $\mathcal{O}(\alpha)$, all orders-corrected $M(4l)$ spectra
4. for each mass, calculate the χ^2 between each kind of QED correction and Born spectra

$$\chi^2(m_H) = \sum_{i=bins} \left(\frac{d\sigma_{i,QED}}{\sigma_{QED}} - \frac{d\sigma_{i,Born}}{\sigma_{Born}} \right)^2 / \left[\left(\Delta \frac{d\sigma_{i,QED}}{\sigma_{QED}} \right)^2 + \left(\Delta \frac{d\sigma_{i,Born}}{\sigma_{Born}}^2 \right) \right]$$

5. at the minimum of the χ^2 distribution, read the m_H shift

For HO corrections, the procedure is the same, but

Born $\Rightarrow \mathcal{O}(\alpha)$
$\mathcal{O}(\alpha) \Rightarrow$ all orders

QED effects on m_H determination (PRELIMINARY)

χ^2 minimum obtained with a mass scan with 20 MeV spacing

Process	$\|\Delta(QED)^{(\alpha)}\|$	$\|\Delta(QED)^{(\exp)} - \Delta(QED)^{(\alpha)}\|$
$e^+e^-e^+e^-$	160 MeV	$\leq$ 20 MeV
$e^+e^-\mu^+\mu^-$	340 MeV	$\leq$ 50 MeV
$\mu^+\mu^-\mu^+\mu^-$	600 MeV	$\sim$ 100 MeV

Within the resolution of 20 MeV

exact $\mathcal{O}(\alpha)$ and PS $\mathcal{O}(\alpha)$ give the same mass shift

Summary and outlook

- $H \to 4$ lepton channel is important for a precise Higgs boson mass determination at LHC with high luminosity
- We computed QED radiative corrections in different approximations:
  1. exact $\mathcal{O}(\alpha)$ in factorizable approximation
  2. Non-factorizable corrections calculated (need to be optimized)
  3. LL $\mathcal{O}(\alpha)$ with PS algorithm
  4. Higher order corrections within PS algorithm
- Mass shift due to QED corrections estimated with a realistic simulation
- They result to be relevant when aiming at a $\mathcal{O}(100)$ MeV accuracy
- comparison between complex mass and fudge schemes for the non-factorizable virtual corrections
- extension of the virtual calculation to the $l^+l^-l^+l^-$ (identical) channel
- inclusion of Higgs $p_\perp$ in the simulation