Luca Barzè

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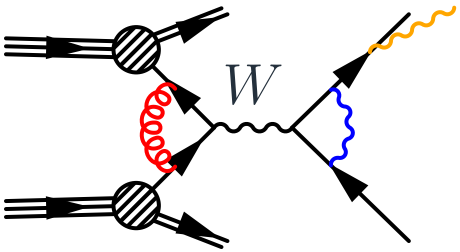
- I'm a third (last) year PhD student in Pavia, member of LHCPhenonet network;
- my research activity is principally related to EW physics at hadron colliders:
  - NLO calculations interfaced to Parton Showers;
  - mixing of EW with QCD NLO;
- in collaboration with M. Chiesa, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini & V. Prosperi.

Ongoing work

- combination of EW & QCD NLO corrections in the `POWHEG-BOX` framework;

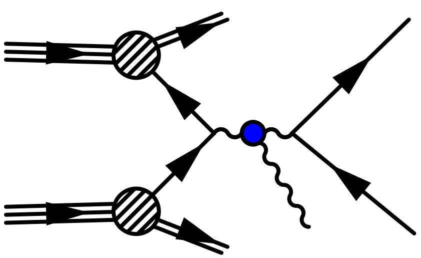


  - ☑ $W^{\pm}$ production
  - ☐ Z^0/γ^* production

    $\Rightarrow$ precision physics (W/Z mass, width)

    $\Rightarrow$ EW Sudakov logs ($\log s/M_V^2$) $\Rightarrow$ background for NP

- $W\gamma$ - useful to probe $W\gamma$ anomalous coupling:



  - ☐ NLO QCD in `POWHEG-BOX`;
  - ☐ NLO EW.

QCD/EW NLO (subtraction procedure)

$$d\sigma_{NLO} = \Bigg\{ B(\Phi_n) + \underbrace{\overbrace{V^b(\Phi_n)}^{-\infty} + \overbrace{\int C(\Phi_n, \Phi_{rad}) d\Phi_{rad}}^{\infty}}_{<\infty} +$$

$$\underbrace{\int \left[\overbrace{R(\Phi_n, \Phi_{rad})}^{\infty} - \overbrace{C(\Phi_n, \Phi_{rad})}^{\infty} \right] d\Phi_{rad}}_{<\infty} \Bigg\} d\Phi_n$$

$$V^b = V^b_{EW} + V^b_{QCD}$$

$$R = R_{EW} + R_{QCD} \quad C = C_{QED} + C_{QCD}$$

C_{QED} calculated (in principle) for every process;
R_{EW} could be calculated with automatic algorithms.

Virtual part (process dependent)

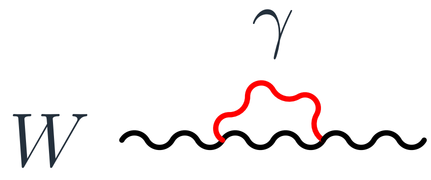
$$V^b = V^b_{QCD} + V^b_{EW}$$

✓ V^b_{QCD} already implemented in `POWHEG-BOX`

- V^b_{EW} calculated and checked from different groups.
  - We chose to use **Dittmaier & Krämer** - 2002
    - finite part of dimensional regularization of IR divergent scalar functions ($m_q^{in} = m_\gamma = 0, m_\ell \neq 0 \Rightarrow$ FSR description)
    - factorizing out $\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\left(\frac{\mu_R^2}{Q^2}\right)^\epsilon$

    $\Rightarrow$ direct extension of subtraction procedure

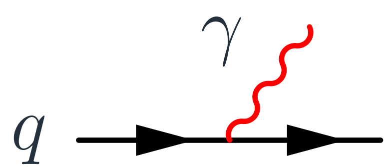
Virtual part - details



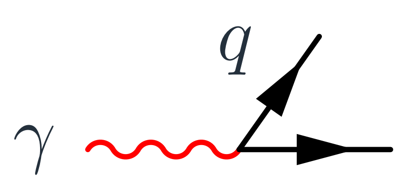
$$\propto \log(\hat{s} - M_W^2) \xrightarrow{\hat{s} \to M_W^2} \infty$$

- Dyson resummation $\Rightarrow M_W^2 \to M_W^2 - i\Gamma_W M_W$
  - substitute M_W only in $\log(\hat{s} - M_W^2)$;
  - complex mass scheme.

For more complicated processes ($WW/ZZ/\ldots$)
complex mass scheme is (almost) the only possible solution.



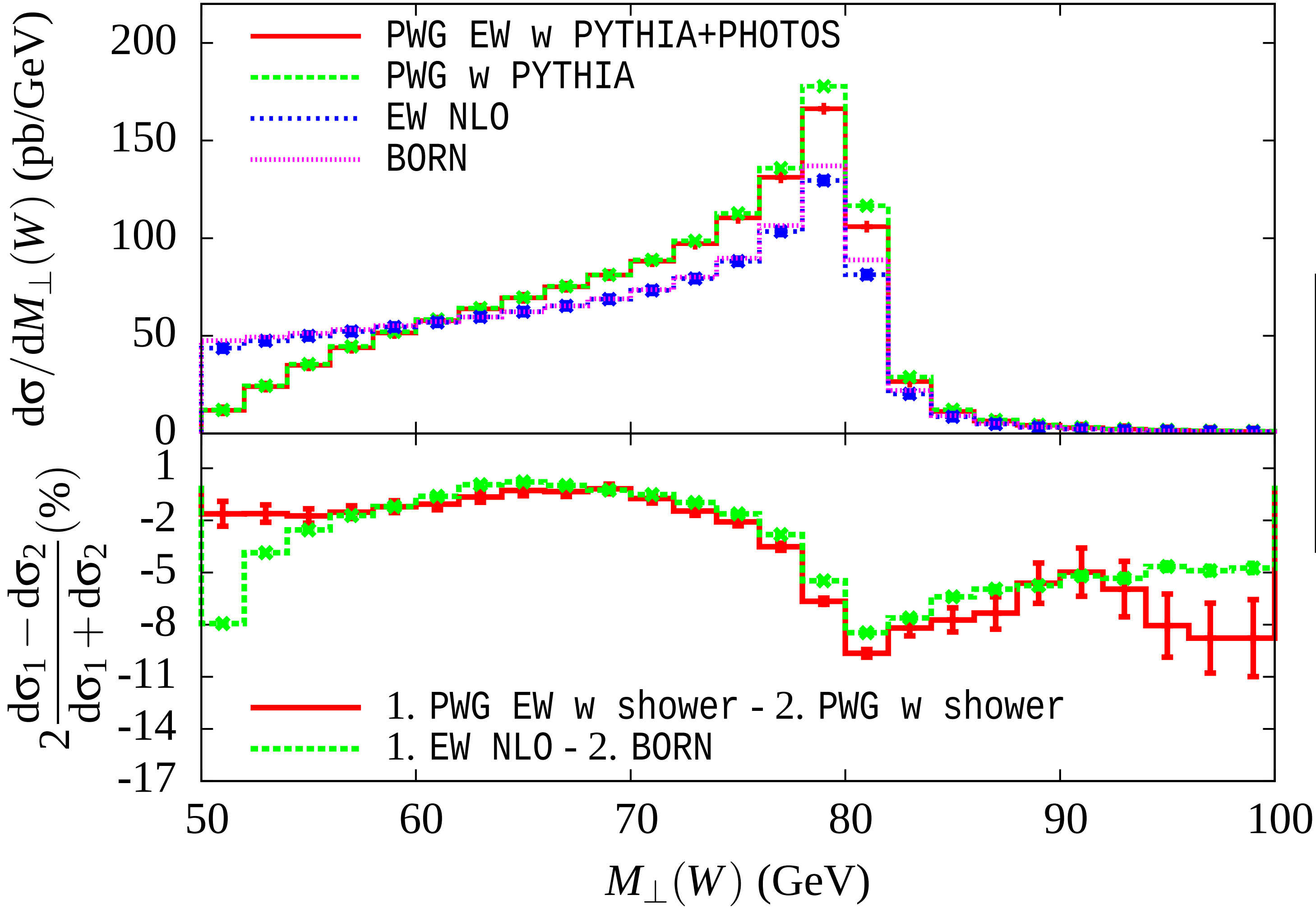
~~(in)~~finite terms



finite contribution

} γ in PDF

W^+ transverse mass



$pp \to W^+ \to \mu^+ \nu_\mu$

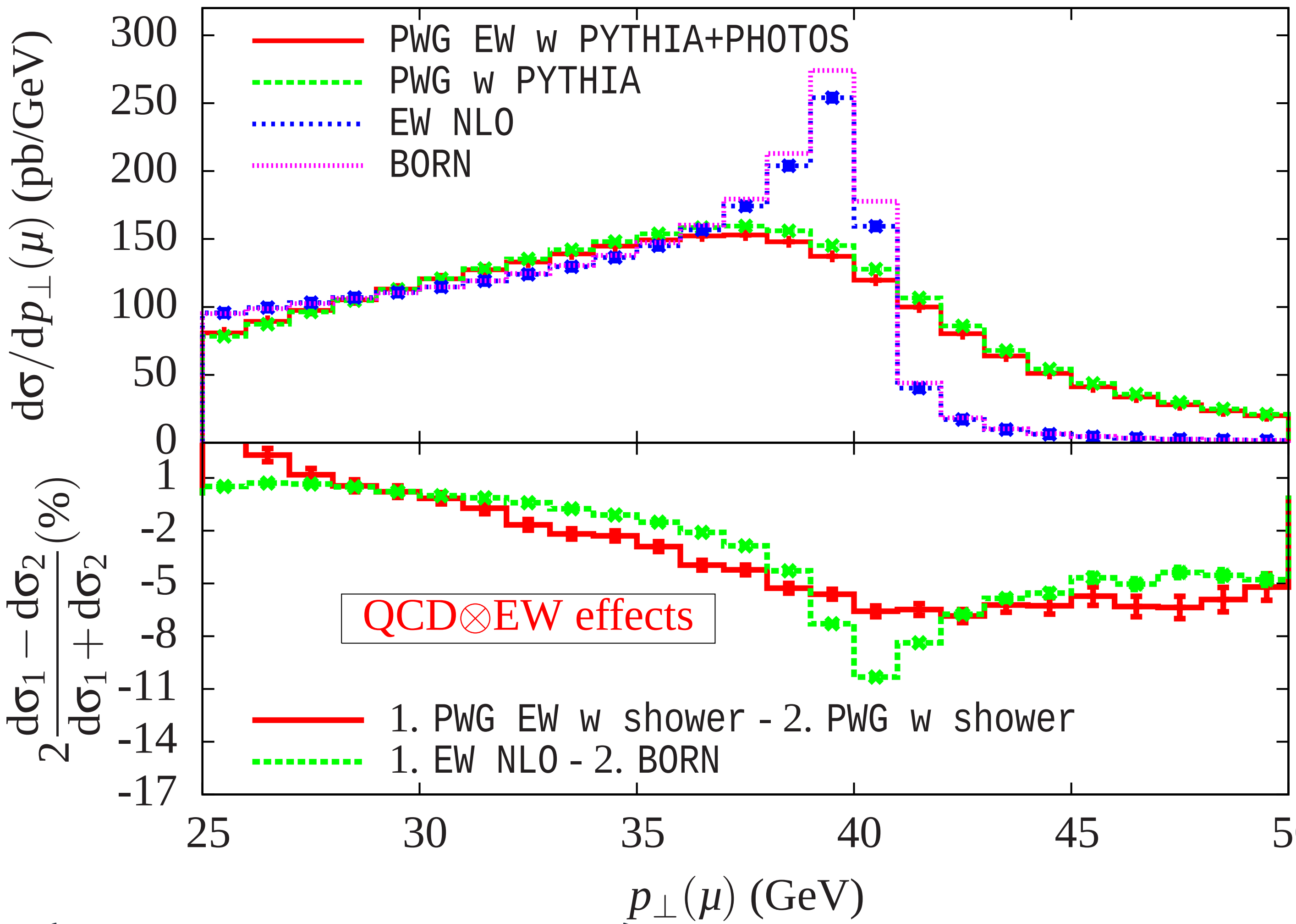
$p_\perp^\mu, \not{E}_\perp \geq 25$ GeV, $|\eta_\mu| \leq 2.5$

CTEQ6L(M) / LHC @ 7 TeV

$\mu_R = \mu_F = M_W$

- $M_\perp$ is invariant under a longitudinal boost
  $\Rightarrow$ QCD doesn't modify shape in first approximation

μ^+ transverse momentum



$$\sigma \propto \exp\left\{-\int (R_{EW} + R_{QCD})/B\right\}$$
$$\propto \left(1 + \sum_n \mathcal{O}^n(\alpha_{EW}) + \sum_n \mathcal{O}^n(\alpha_{QCD}) + \sum_n \mathcal{O}^n(\alpha_{QCD}\alpha_{EW}) + \ldots\right)$$

Conclusions / Future developments

- EW NLO and its interplay with QCD will play a role in LHC precision physics program;
- Drell-Yan CC $\rightarrow$ OK $\rightarrow$ general procedure;
- NC is in progress;
- automatize EW NLO ?
  - $W^{\pm}/(Z^{0})$ production is a valid benchmark;
  - $W\gamma$ EW NLO could be the first process.

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THANK YOU!!

BACKUP SLIDES

POsitive Weight Hardest Event Generator

Method to interface NLO with PS (**Nason** - 2004):

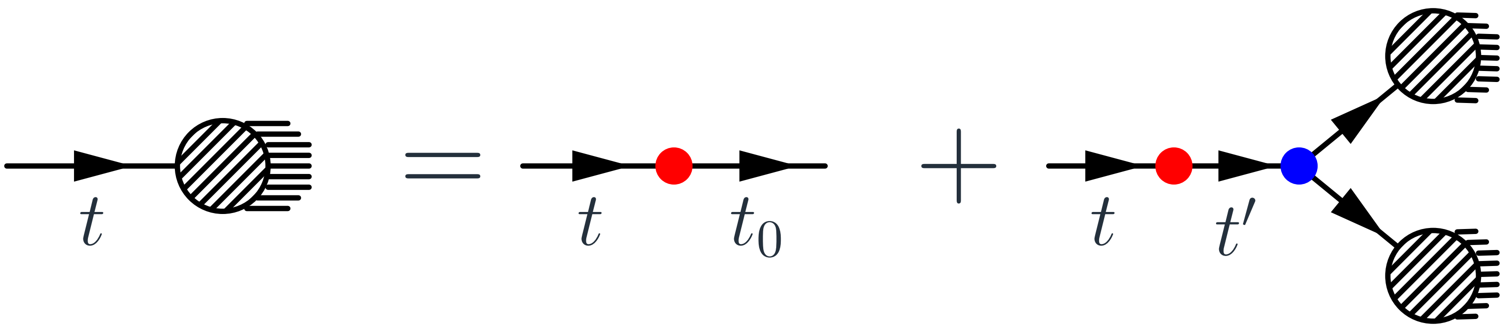
- generate with NLO accuracy the hardest emission;
- events have positive weights;
- shower Monte Carlo interfaced (PYTHIA, HERWIG, ...).

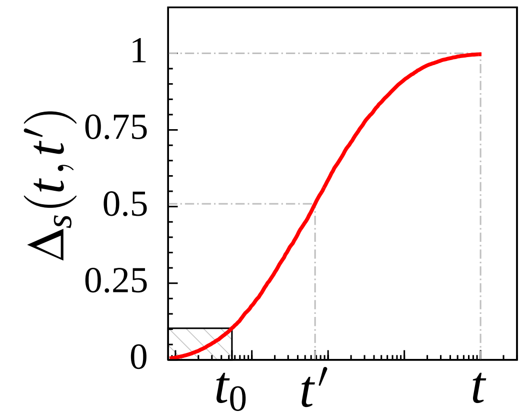
POWHEG-BOX (**Alioli, Nason, Oleari, Re** - 2009) program:

- identifies all the singular regions;
- projects real contributions over the singular regions;
- general FKS subtraction;
- ISR and FSR phase space;
- calculates upper bounds for the generation of radiation;
- generates radiation.

$\sim$ process independent $\longrightarrow$ Needs only $B_{(jk)}$, R, $\mathrm{d}\Phi_n$ and V^b

Parton Shower





First emission:

$$\Delta_t^{SMC} = \exp\left\{ - \int \frac{\alpha_s(t')}{2\pi} \frac{1}{t'} \mathcal{P}(z') \, \vartheta(t' - t) \, \mathrm{d}\Phi'_{rad} \right\}$$

$$\mathrm{d}\sigma_{SMC} = \overbrace{B \, \mathrm{d}\Phi_n}^{\mathrm{d}\sigma_{LO}} \left[\Delta_{t_0}^{SMC} + \Delta_t^{SMC} \frac{\alpha_s(t)}{2\pi} \frac{1}{t} \mathcal{P}(z) \mathrm{d}\Phi_{rad} \right]$$

Subsequent emissions $t \geq t'' \geq t''' \ldots$

NLO + PS with POWHEG

In POWHEG $p_\perp$ of hardest radiation generated according to:

$$\Delta_{p_\perp} = \exp\left\{-\int \frac{R}{B}\,\vartheta(p'_\perp - p_\perp)\,\mathrm{d}\Phi'_{rad}\right\}$$

$p_\perp$ veto of subsequent emissions $\Rightarrow$ **no double-counting**

$$\mathrm{d}\sigma = \overbrace{\tilde{B}\,\mathrm{d}\Phi_n}^{\mathrm{d}\sigma_{NLO}}\left[\Delta_{p_\perp^-} + \Delta_{p_\perp}\frac{R}{B}\mathrm{d}\Phi_{rad}\right]$$

Small $p_\perp$ $\rightarrow$ $\tilde{B} \simeq B(1 + \mathcal{O}(\alpha))$, $\frac{R}{B} \rightarrow \frac{\alpha}{2\pi}\frac{1}{t}\mathcal{P}$

Large $p_\perp$ $\rightarrow$ $\mathrm{d}\sigma \simeq \tilde{B}\frac{R}{B} \simeq R(1 + \mathcal{O}(\alpha))$

NLO accuracy

QCD/EW NLO + PS

$$\Delta^{\mathtt{POWHEG}}_{\max(k_\perp, p_\perp)} \equiv \Delta^{QCD}_{p_\perp} \Delta^{EW}_{k_\perp}$$

2 different $p_\perp$ scales: $\begin{cases} m_\ell & \text{for leptons} \\ \Lambda_{QCD} & \text{for quarks} \end{cases}$

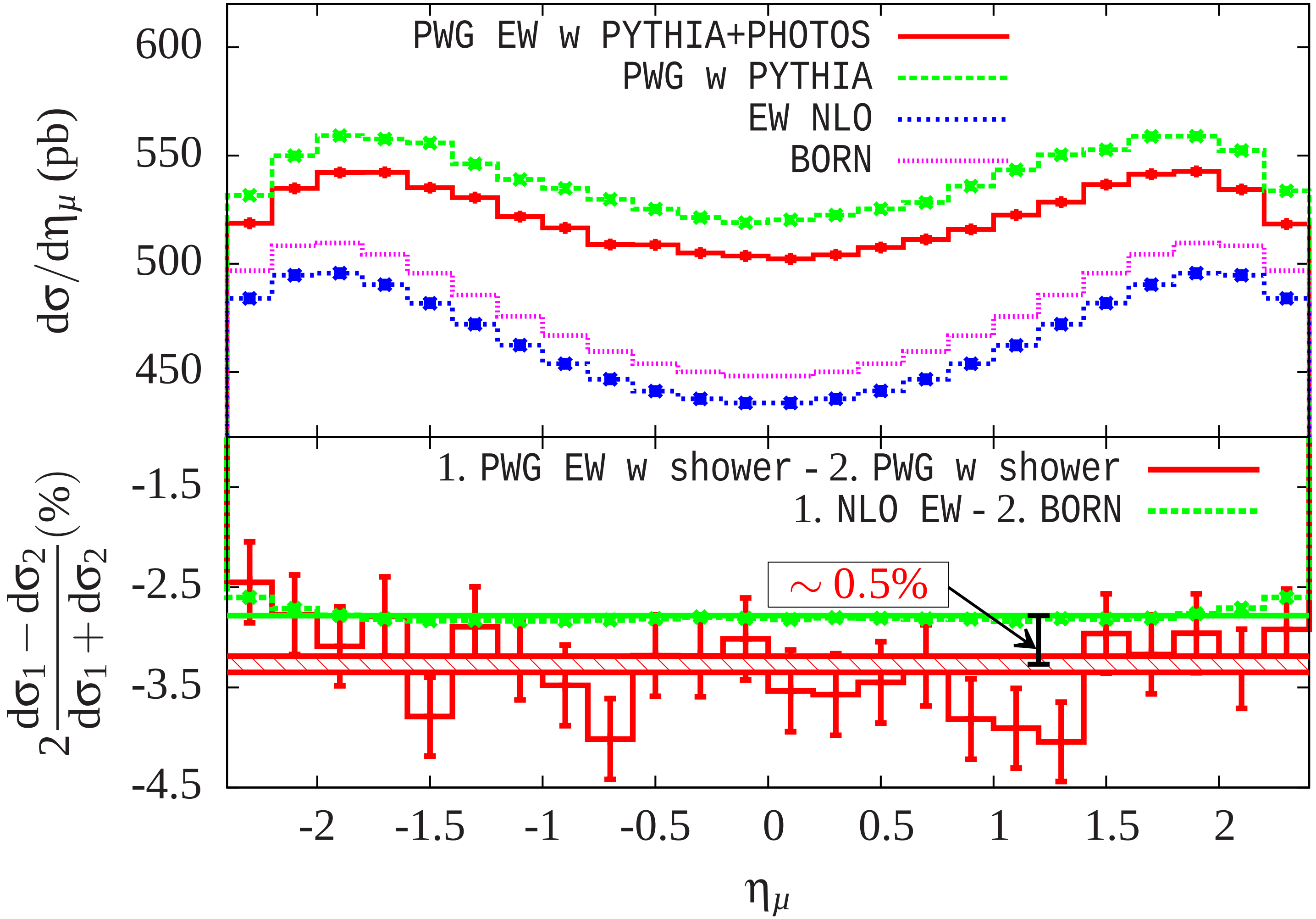
$$\Delta^{QCD}_{p_\perp} = \exp\left\{ - \int \frac{R_{QCD}}{B} \vartheta(p'_\perp - p_\perp)\, \mathrm{d}\Phi'_{rad} \right\}$$

$$\Delta^{EW}_{k_\perp} = \exp\left\{ - \int \frac{R_{EW}}{B} \vartheta(k'_\perp - k_\perp)\, \mathrm{d}\Phi''_{rad} \right\}$$

if $\begin{cases} \text{emitted } \gamma/g/q \; (p_\perp \gtrsim \Lambda_{QCD}) \Rightarrow \text{veto } \gamma/g/q \text{ with } p'_\perp > p_\perp \\ \text{emitted } \gamma \quad (p_\perp \lesssim \Lambda_{QCD}) \Rightarrow \text{veto } \begin{cases} g/q \\ \gamma \text{ with } p'_\perp > p_\perp \end{cases} \end{cases}$

Interfaced to PYTHIA / (HERWIG) $\oplus$ PHOTOS

μ^+ pseudorapidity



$\mathcal{O}(\alpha_{EW}\alpha_{QCD}) \sim$ 0.5 %

Balossini & al. - JHEP 1001 (2010) 013