Matching NLO calculations with PS: recent developments in `POWHEG BOX`

Tomáš Ježo
Università di Milano-Bicocca
INFN, Sezione di Milano-Bicocca

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Westfälische
Wilhelms-Universität
Münster

Università degli studi di Milano
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Matching NLO calculations with PS: recent developments in POWHEG BOX

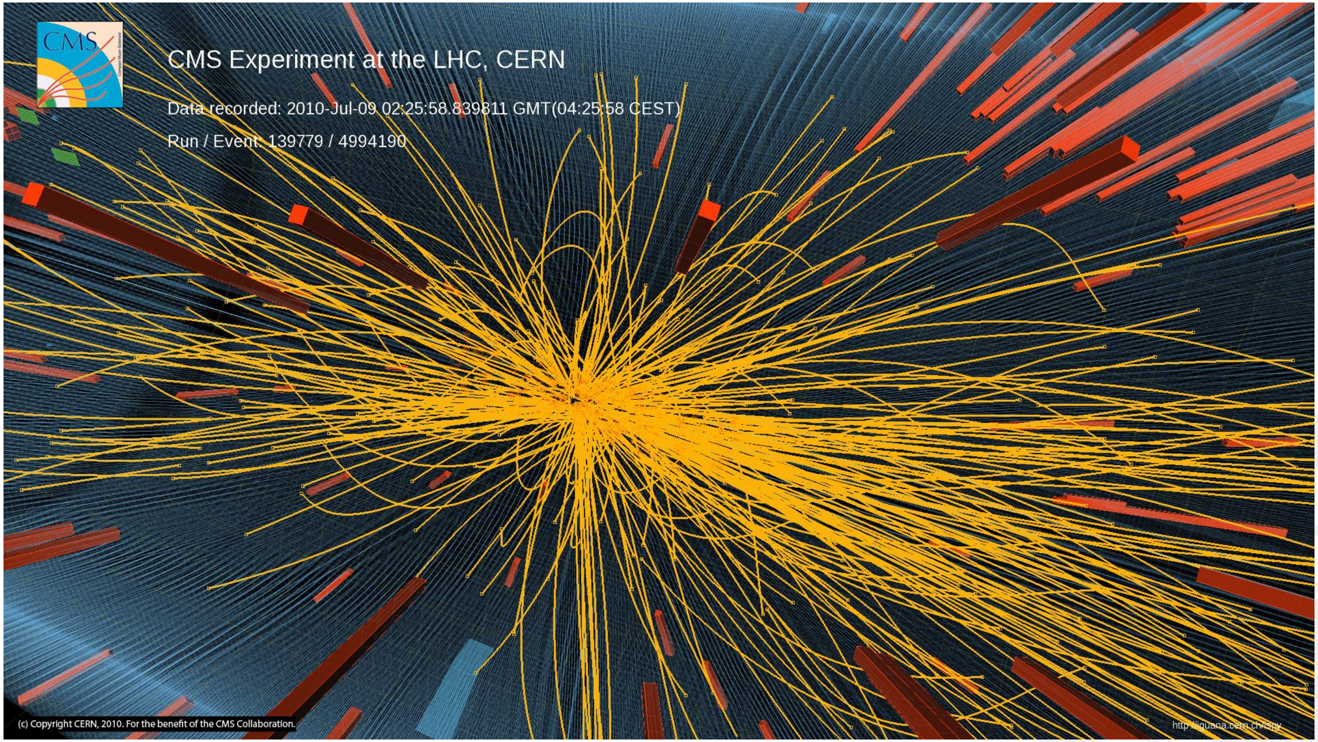
- Matching fixed Next-to-Leading Order (NLO) calculations with Parton Shower (PS): NLO+PS

- Explain all the ingredients of a calculation at NLO+PS accuracy:
  - fixed order (FO): LO, NLO (real/virtual corrections)
  - parton shower (PS)
  - PS applied to NLO: NLO+PS

- Recent developments:
  - core POWHEG BOX: treatment of resonances
  - new processes: top-pair beyond SM, photonproduction

Hadronic collisions

- Typical proton-proton collision



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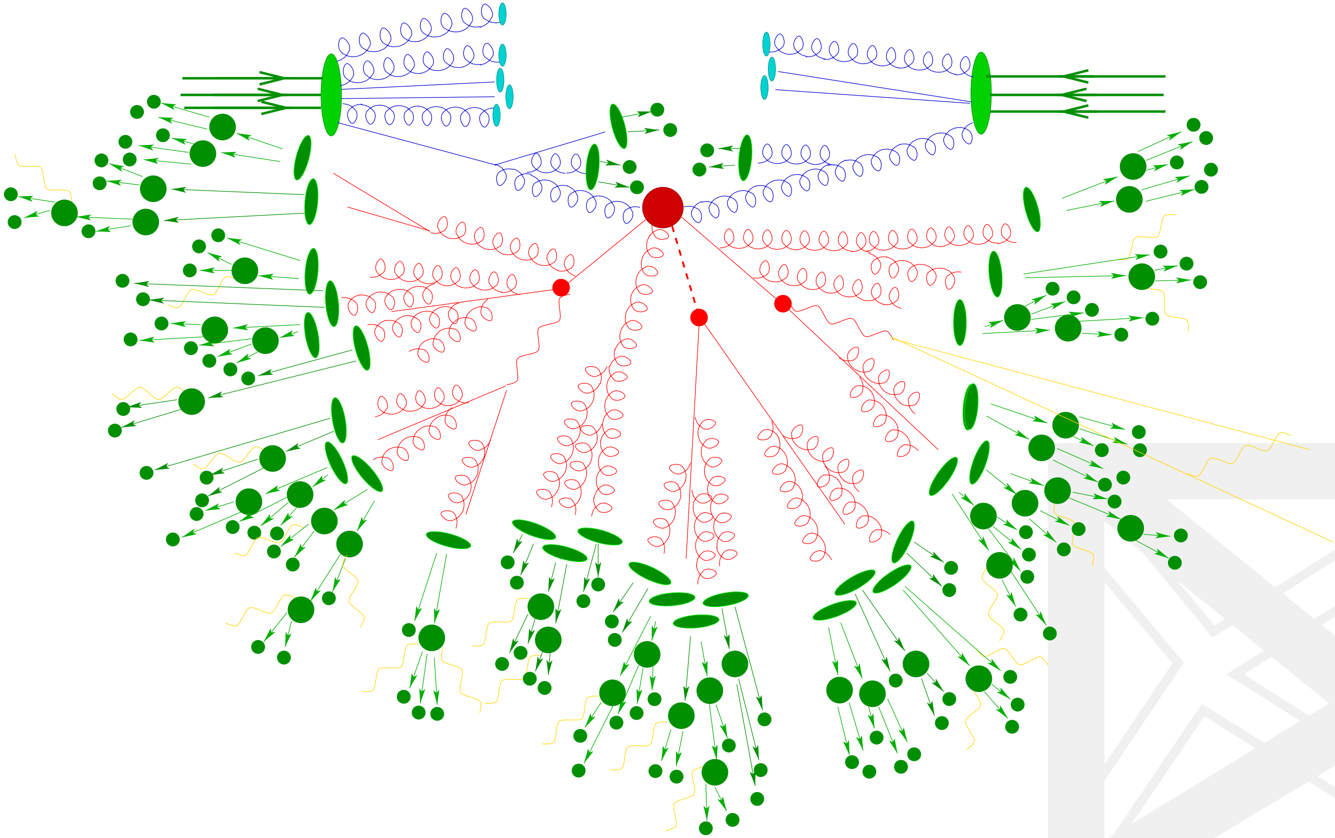

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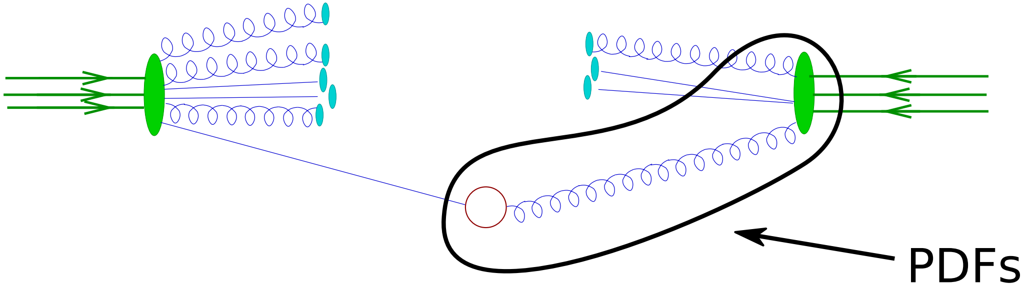

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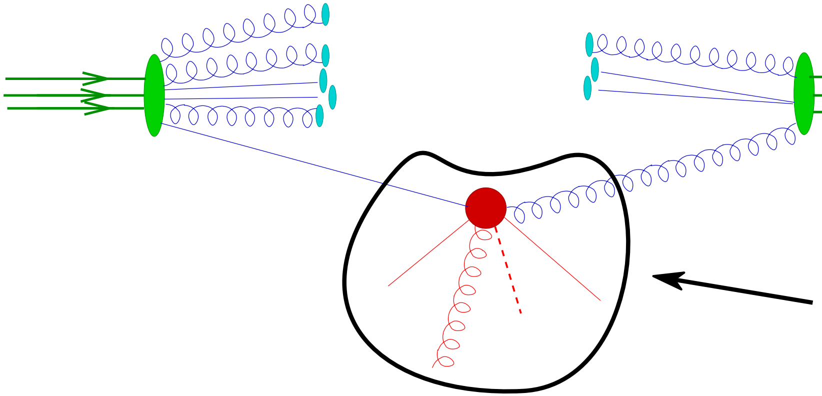

Hard interaction

Hadronic collisions

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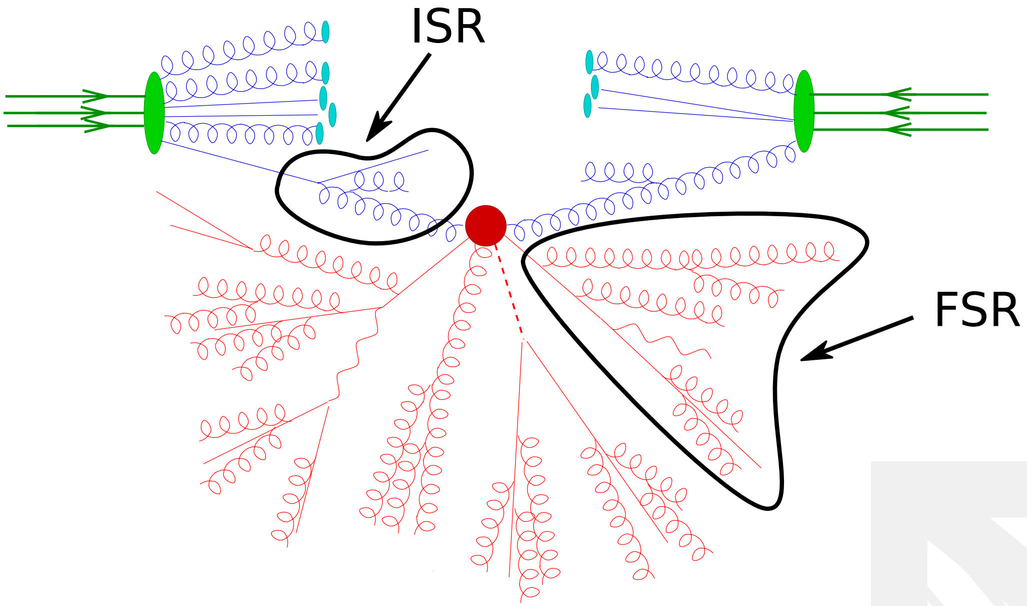

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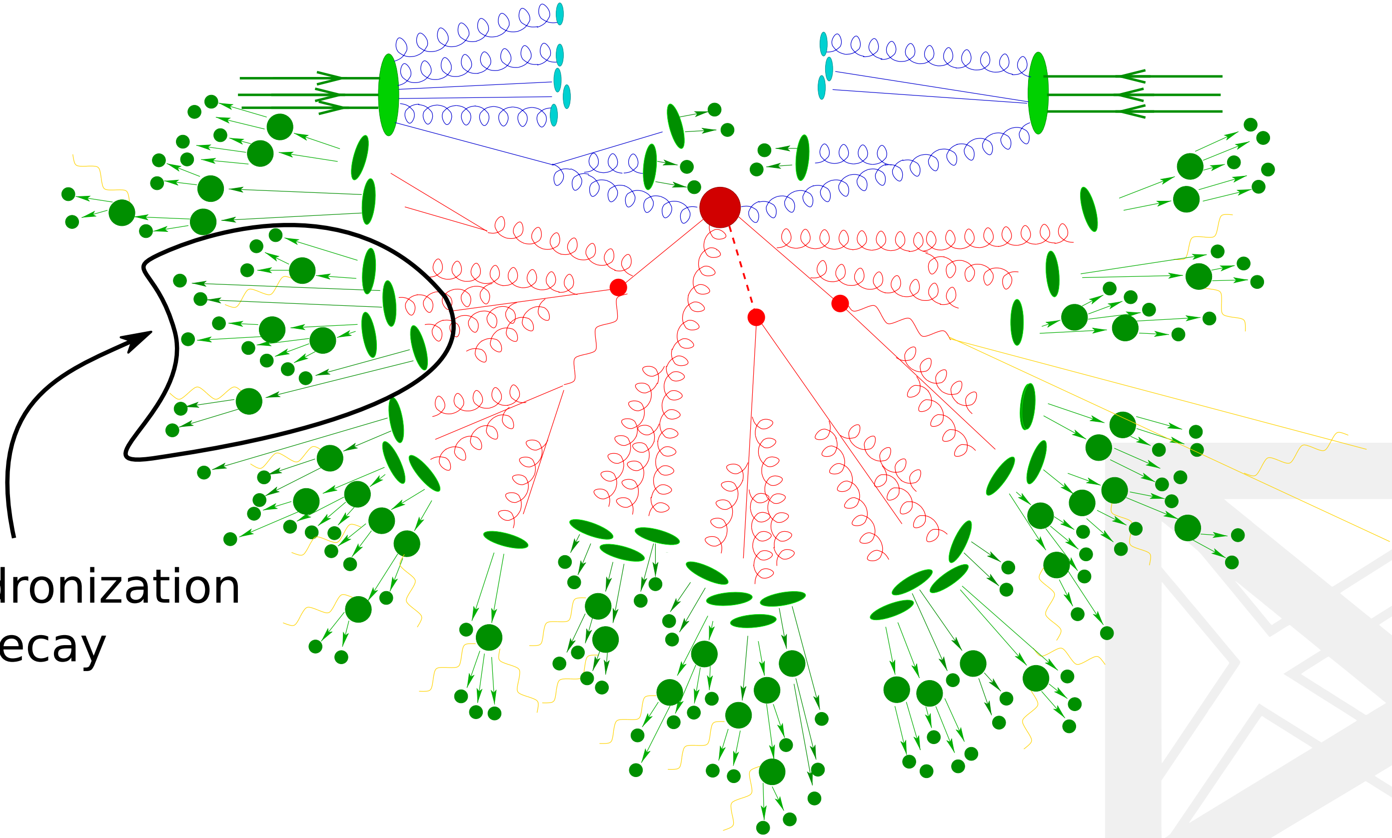
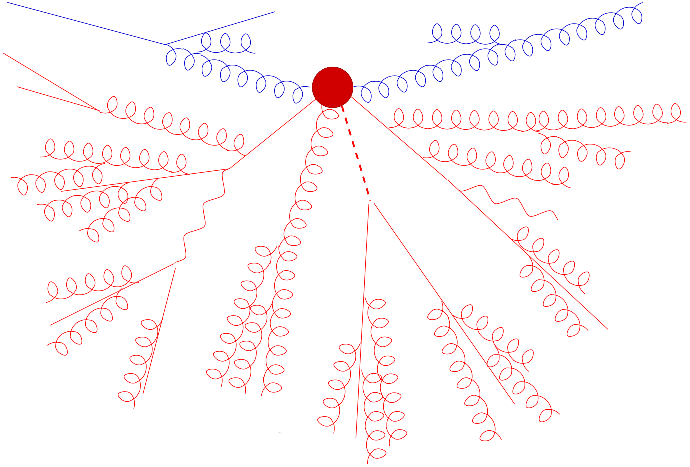


Hadronization
& decay

Hadronic collisions

- Typical proton-proton collision
    - I focus on interplay of FO calculations and PS @ NLO



Hadronic collisions

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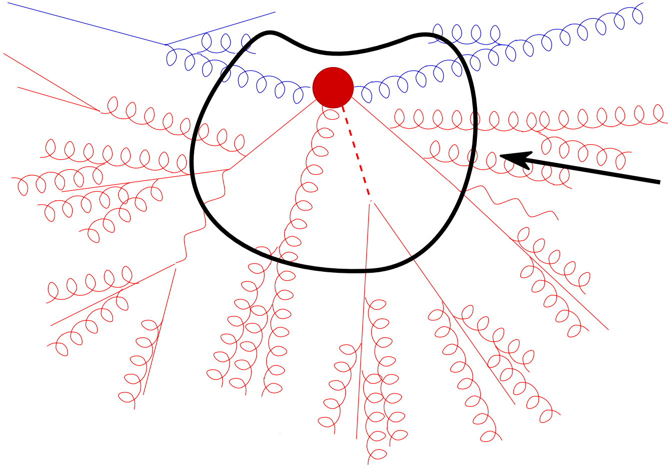

Hard interaction

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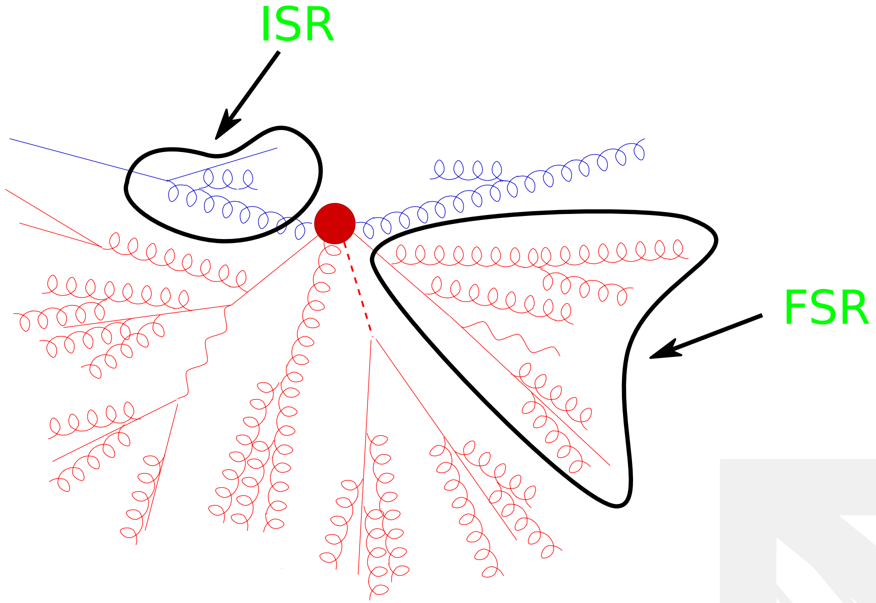
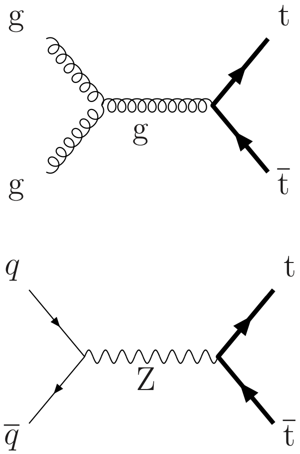


Fixed order calculations

- Take for example top-pair production SM

Born



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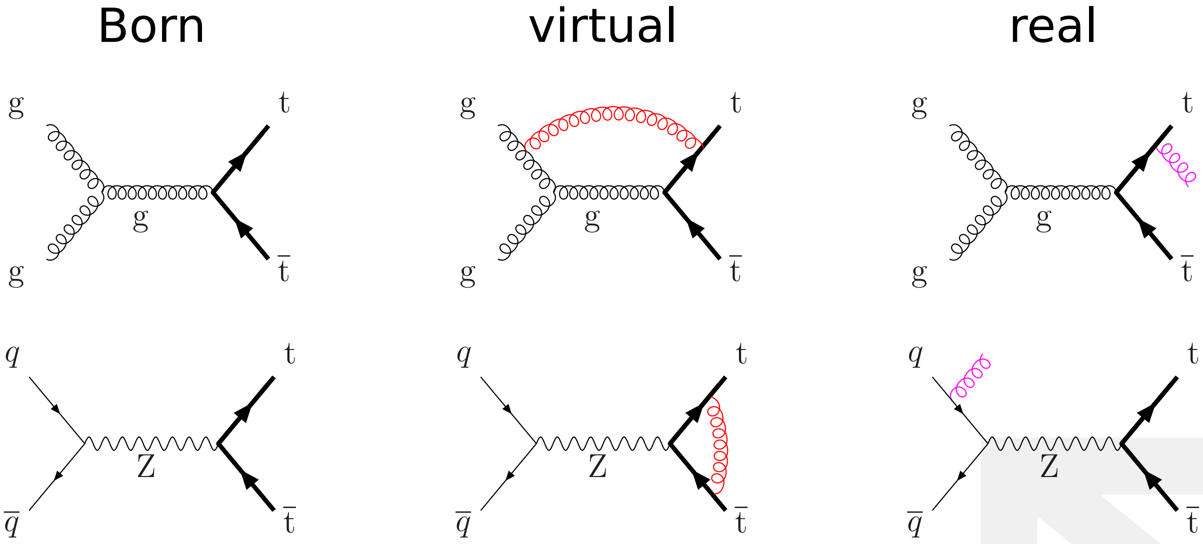

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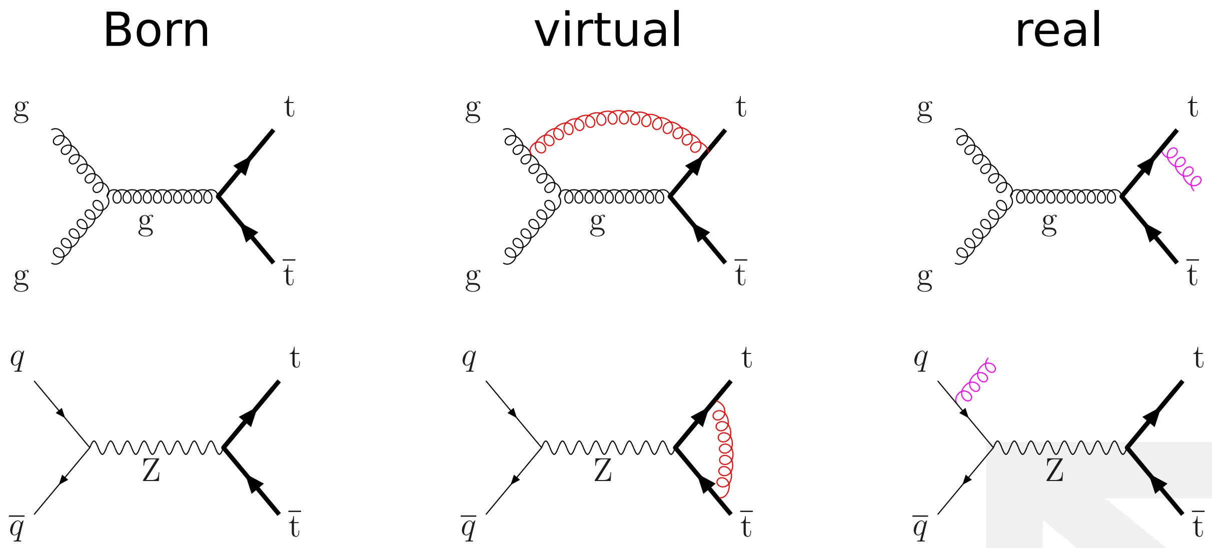

Born virtual real

$$\hat{\sigma}^{\mathrm{NLO}} = \hat{\sigma}(\alpha_S^2) + \hat{\sigma}(\alpha_W^2) + \hat{\sigma}(\alpha_S^3) + \hat{\sigma}(\alpha_S^2\alpha_W) + \hat{\sigma}(\alpha_S\alpha_W^2) + \hat{\sigma}(\alpha_W^3)$$

Fixed order calculations

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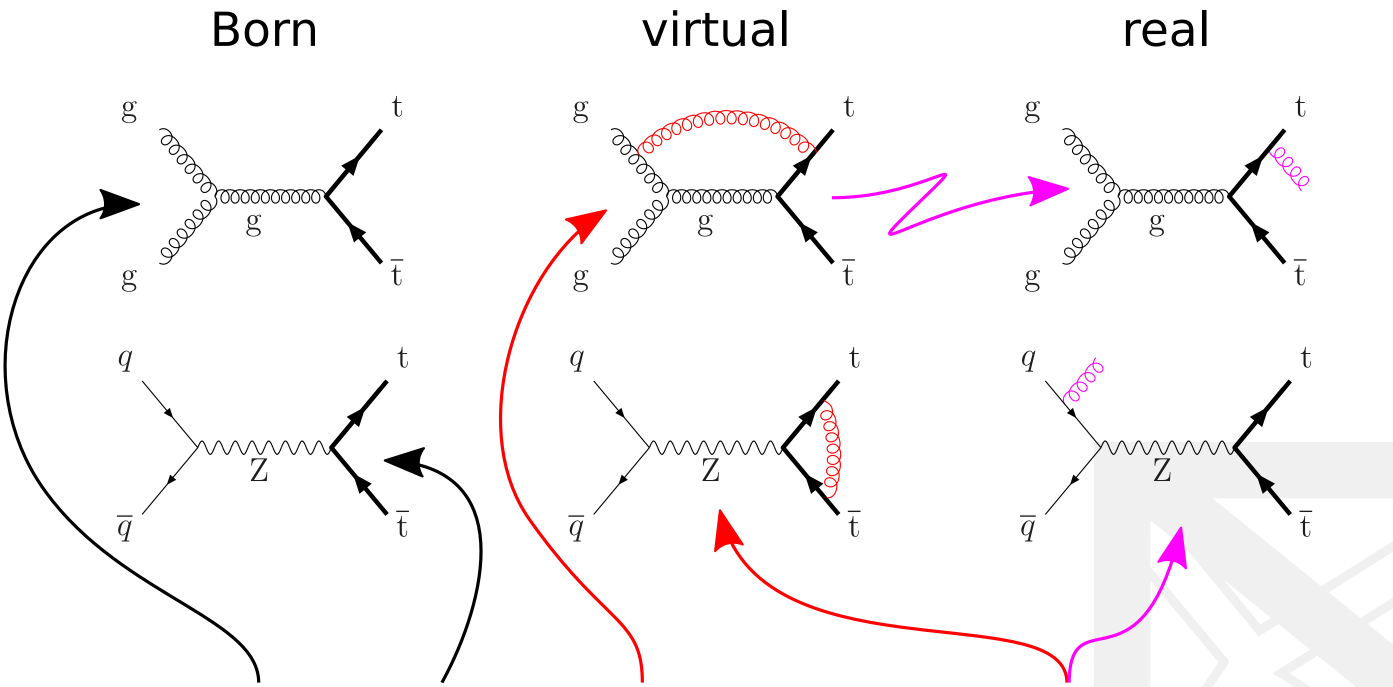

Born

virtual

real

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Fixed order calculations @ NLO

- Total cross section for a $2 \to n$ scattering at NLO

$$\sigma_{\mathrm{NLO}} = \int d\mathbf{\Phi}_n \Big[\mathcal{B}(\mathbf{\Phi}_n) + \mathcal{V}(\mathbf{\Phi}_n)\Big] + \int d\mathbf{\Phi}_{n+1} \mathcal{R}(\mathbf{\Phi}_{n+1})$$

Separately infinite

Fixed order calculations @ NLO

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- UV divergences renormalized away $\mathcal{V} \to \mathcal{V}_{\mathbf{b}}$; IR divergences cancel in the sum of real and virtual contributions

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- In a general subtraction framework

$$\begin{aligned} \sigma_{\mathrm{NLO}} = & \int d\boldsymbol{\Phi}_n \Big\{\mathcal{B}(\boldsymbol{\Phi}_n) + \mathcal{V}_{\mathrm{b}}(\boldsymbol{\Phi}_n) + \sum_{\boldsymbol{\alpha}} \Big[\bar{\mathcal{C}}\,(\boldsymbol{\Phi}_n)\Big]_{\boldsymbol{\alpha}}\Big\} \\ & + \int d\boldsymbol{\Phi}_{n+1} \Big\{\mathcal{R}(\boldsymbol{\Phi}_{n+1}) - \sum_{\boldsymbol{\alpha}} \Big[\mathcal{C}(\boldsymbol{\Phi}_{n+1})\Big]_{\boldsymbol{\alpha}}\Big\} \end{aligned}$$

- $\Big[\mathcal{C}(\boldsymbol{\Phi}_{n+1})\Big]_{\boldsymbol{\alpha}}$: real CTs; $\Big[\bar{\mathcal{C}}\,(\boldsymbol{\Phi}_n)\Big]_{\boldsymbol{\alpha}}$: integrated CTs

- $\boldsymbol{\alpha}$ labels singular regions

Fixed order calculations @ NLO

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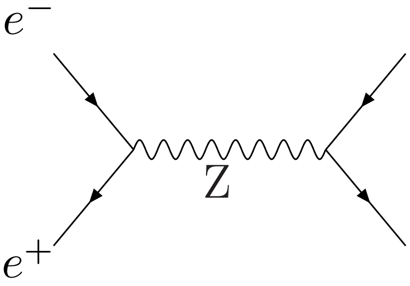
Parton shower

- Parton showers can be automated



$$W = W_B$$

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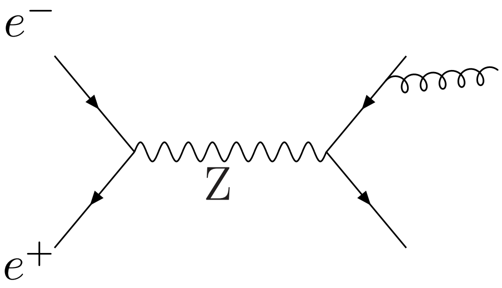
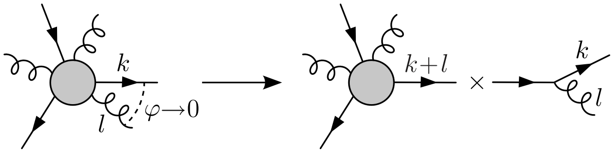


$$W = W_B \times V$$

- Real corrections in collinear approximation:



$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \to |\mathcal{M}_n|^2 d\Phi_n \times \overbrace{\frac{\alpha_S}{2\pi}\frac{dt}{t}P_{q,qg}(z)dz\frac{d\phi}{2\pi}}^{V}$$

Parton shower

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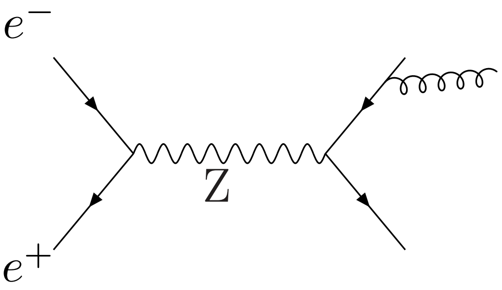

$$W = W_B \times V \times \Delta$$

- Virtual corrections in collinear approximation:

$$\Delta \qquad dP(t, t+dt) = \frac{\alpha_S}{2\pi}\frac{dt}{t}\int\frac{d\phi}{2\pi}\int P_{i,jl}(z)dz$$

  - dP probability of $i \rightarrow jl$ splitting in $[t, t+dt]$
  - $1 - dP$ probability of no radiation equivalent to virtual contribution

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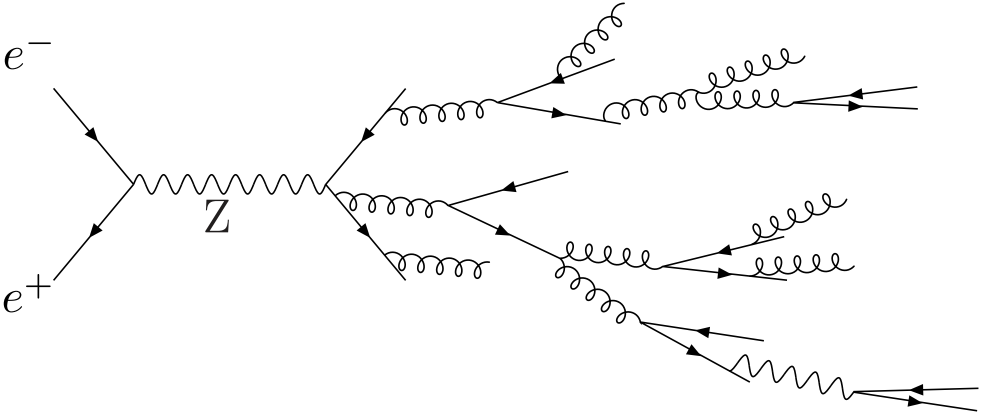

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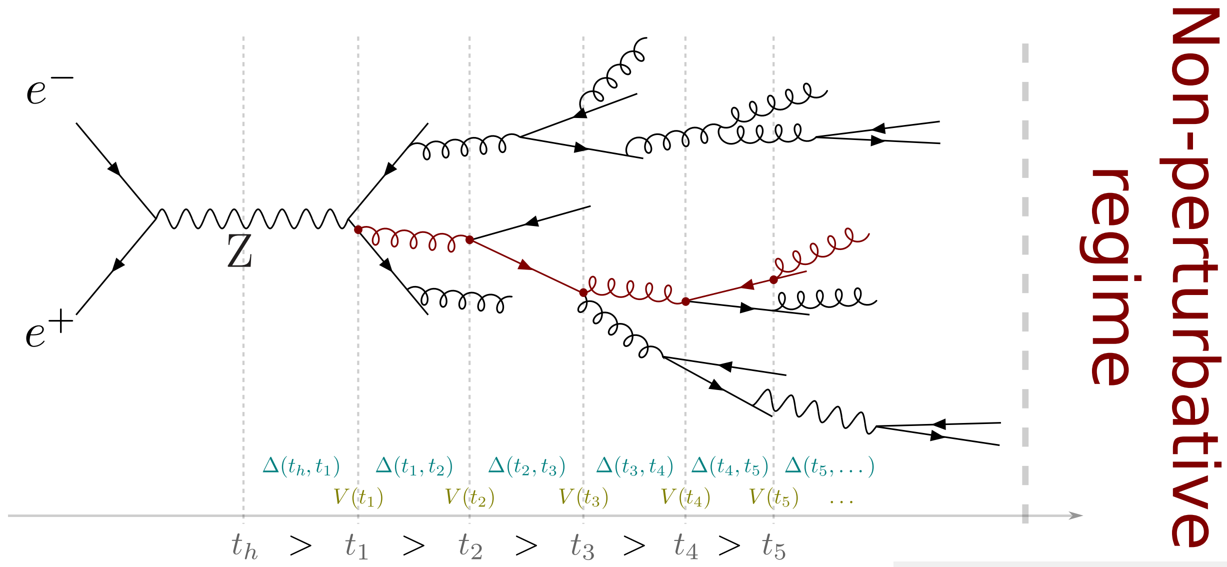


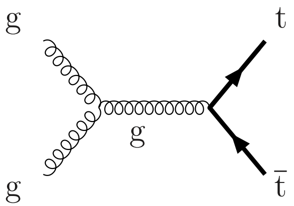
- Variable t measures hardness
    - vanishes in the collinear limit

- Weight of the event is the Born weight times the splitting and Sudakov factors

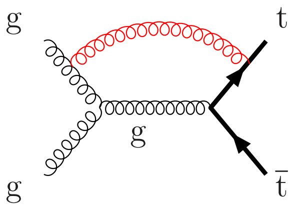
NLO & PS

- Fixed order calculation @ Next-to-Leading Order (NLO)

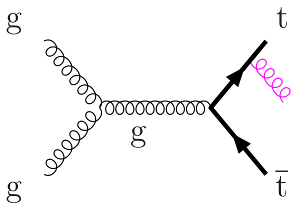
Born



virtual



real



NLO & PS

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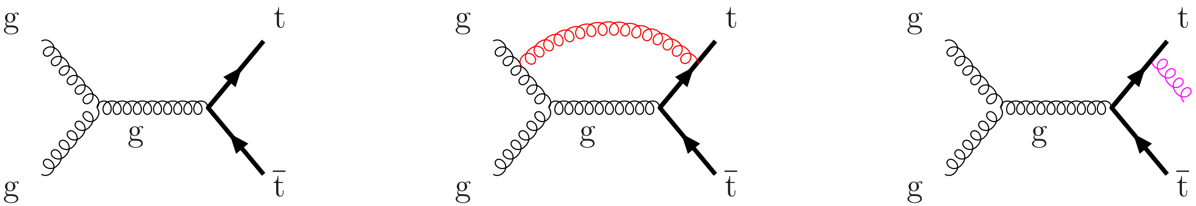
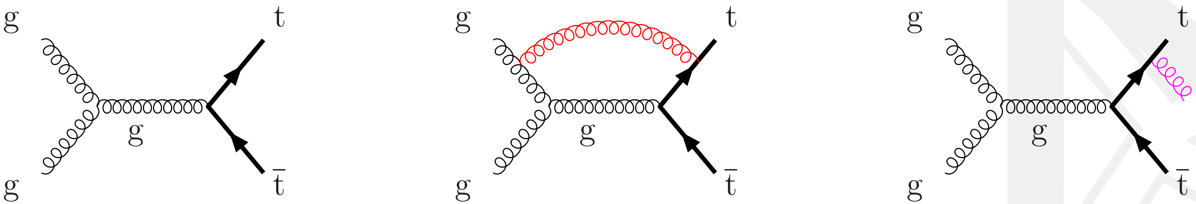
Born virtual real



- Parton shower (PS)

Born Δ V



NLO & PS

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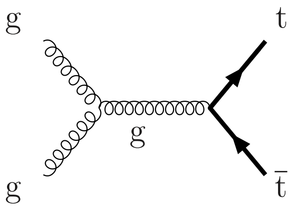
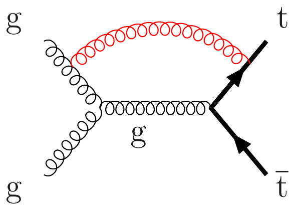
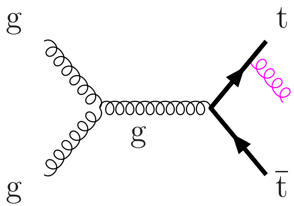
Born



virtual



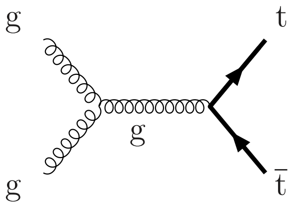
real



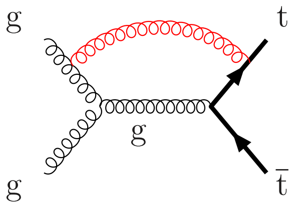
- Parton shower (PS)

aproximation

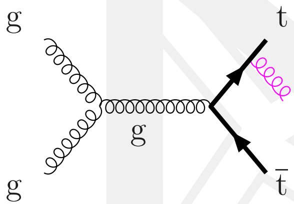
Born



Δ



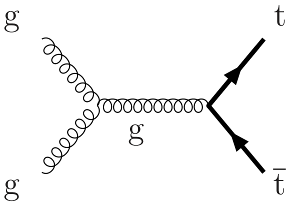
V



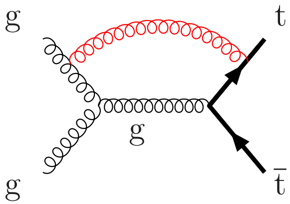
NLO+PS

- NLO merged with PS

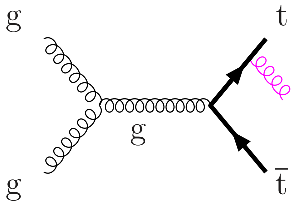
Born



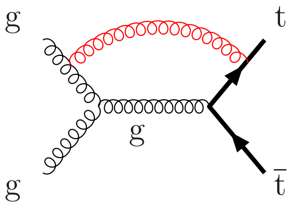
virtual



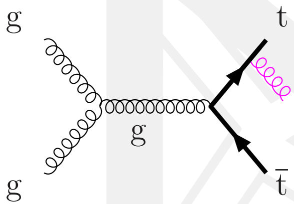
real



Δ



V



NLO+PS

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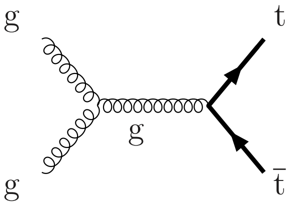
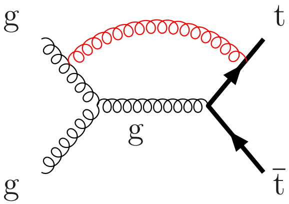
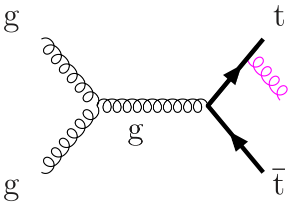
Born



virtual

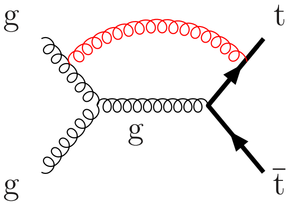


real

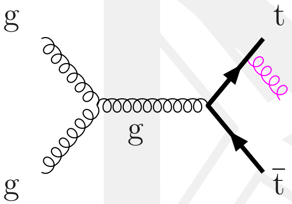


overcounted

Δ



V



NLO+PS

- Naive matching of NLO and PS doesn't work: overcounting
  - Both PS and NLO contain the real and virtual contributions in the collinear limit
- Overcounting can be solved for example by modifying the Sudakov form factor for the first radiation
- Multiple solutions exist
  - Matrix Element (ME) corrections, `Pythia`
    - available only for a few processes
  - MC@NLO: `mg5_aMC`, ...
    - procedure depends on the implementation of the PS algorithm, can lead to events with negative weights
  - POWHEG: `POWHEG BOX`, ...
    - independent of the PS algorithm, positive weighted events
- However some problems remain, both conceptual and technical

NLO+PS in `POWHEG BOX`

- `POWHEG BOX` automatically calculates everything down to the generation of the hardest emission provided the user specifies
  - Born matrix elements $\mathcal{B}(\mathbf{\Phi}_n)$
  - Renormalized virtual matrix elements $\mathcal{V}_{\mathrm{b}}(\mathbf{\Phi}_n)$
  - Real matrix elements $\mathcal{R}(\mathbf{\Phi}_{n+1})$
- Consecutive emissions can be generated by usual tools implementing PS (`Pythia`, `Herwig`, ...)

- It uses the FKS subtraction method

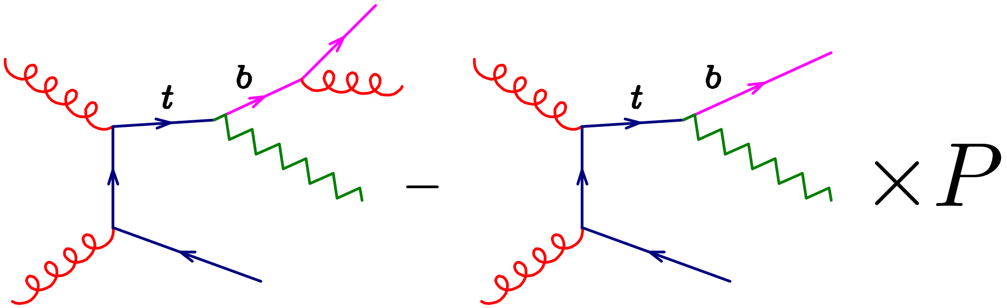
$$\sigma_{\mathrm{NLO}} = \int d\mathbf{\Phi}_n \Big\{ \mathcal{B}(\mathbf{\Phi}_n) + \hat{\mathcal{V}}(\mathbf{\Phi}_n) \Big\} + \int d\mathbf{\Phi}_{n+1} \hat{\mathcal{R}}(\mathbf{\Phi}_{n+1})$$

$$\hat{\mathcal{R}} \equiv \frac{1}{\xi}\left\{ \left(\frac{1}{\xi}\right)_+ \left(\frac{1}{1-y}\right)_+ \left[\xi^2(1-y)\,\mathcal{R}\right] \right\} \qquad \hat{\mathcal{V}} = \frac{\alpha_{\mathrm{S}}}{2\pi}\left(\mathcal{Q}\,\mathcal{B} + \sum_{\substack{i,j\in\mathcal{I} \\ i\neq j}} \mathcal{I}_{ij}\,\mathcal{B}_{ij} + \mathcal{V}_{\mathrm{fin}} \right)$$

Treatment of resonances

in collaboration with P. Nason; arXiv:1509.09071

- Counterterm kinematics does not preserve the mass of the resonance - spoiling IR cancelation



- Mapping from real kinematics into underlying born kinematics does not preserve the mass of the resonance - leading to distortion of radiation observables

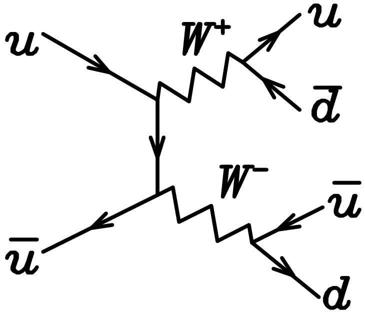
$$\Delta(p_T^2) = \exp\left[-\int \frac{R(\Phi_B, \Phi_{\text{rad}})}{B(\Phi_B)}\theta(k_T(\Phi_{\text{rad}}) - p_T)\mathrm{d}\Phi_{\text{rad}}\right]$$

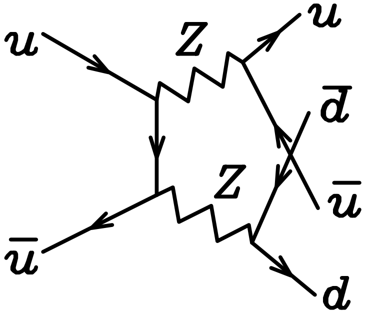
  - R/B large violating the collinear approximanion in region $m^2 \ll \Gamma E$

Treatment of resonances

in collaboration with P. Nason; arXiv:1509.09071

- Mapping from the real to born kinematics has to preserve the masses of the resonances





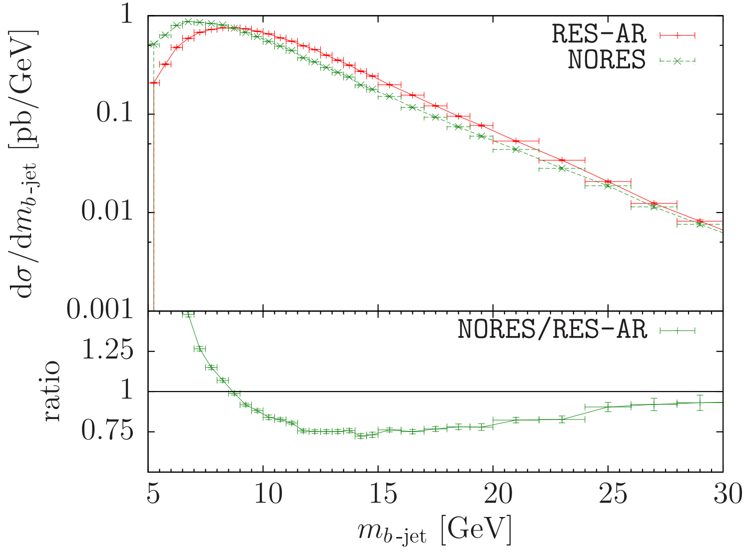
- All contributions needs to be split up into regions with only one dominant resonance structure

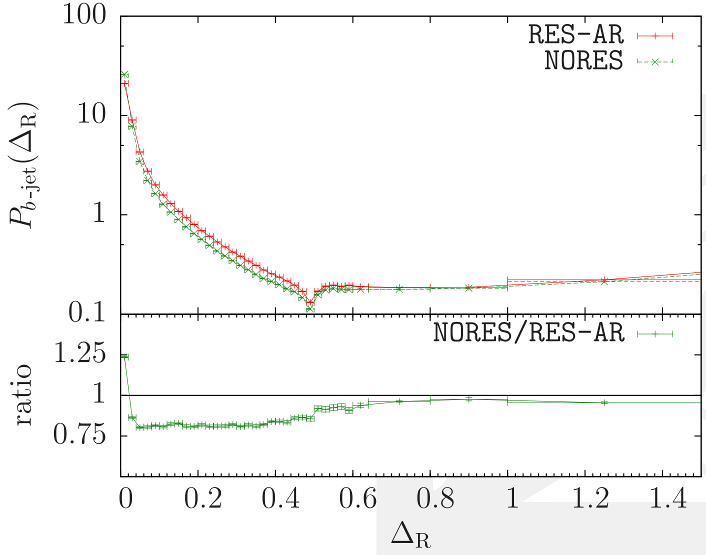
$$\mathcal{B}_1 = \frac{P^1 \mathcal{B}}{P^1 + P^2} \qquad \begin{aligned} P^1 &= \frac{M_W^4}{(s_{34} - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \frac{M_W^4}{(s_{56} - M_W^2)^2 + \Gamma_W^2 M_W^2} \\ P^2 &= \frac{M_Z^4}{(s_{35} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \times \frac{M_Z^4}{(s_{46} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \end{aligned}$$

Treatment of resonances

in collaboration with P. Nason; arXiv:1509.09071

- Implement:
  - ▹ $pp \to \mu^+ \nu_\mu j_b j$ dominated by t-channel single top production at NLO QCD
  - ▹ born and real: `MadGraph4`, virtual: `MG5_aMC@NLO`
- Study impact of proper resonance treatment:
  - ▹ NORES: resonant treatment off
  - ▹ RES-AR: resonant treatment on, 1 hardest emission from resonance + 1 hardest emission from the production

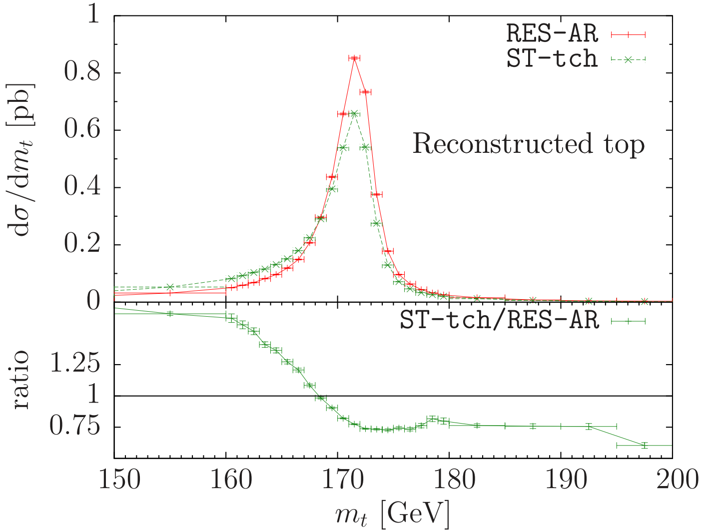




Treatment of resonances

in collaboration with P. Nason; arXiv:1509.09071

- Implement:
  - ▹ $pp \to \mu^+ \nu_\mu j_b j$ dominated by t-channel single top production at NLO QCD
  - ▹ born and real: `MadGraph4`, virtual: `MG5_aMC@NLO`
- Study impact of proper resonance treatment:
  - ▹ ST-tch: top-pair@NLO, top decay@LO
  - ▹ RES-AR: resonant treatment on, 1 hardest emission from resonance + 1 hardest emission from the production



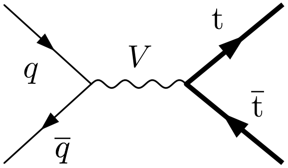
- ▹ average top mass in

$$m_t = 172.5 \pm 15 \text{ GeV}$$

- ▹ ST-tch: $M_{\text{trec}} = 169.59(1) \text{ GeV}$
- ▹ RES-AR: $M_{\text{trec}} = 170.55(2) \text{ GeV}$

Electroweak top-pair @ NLO BSM

in collaboration with R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein; arXiv:1511.xxxxx

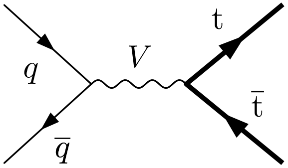


$$V \in \{\gamma, Z, Z'\}$$

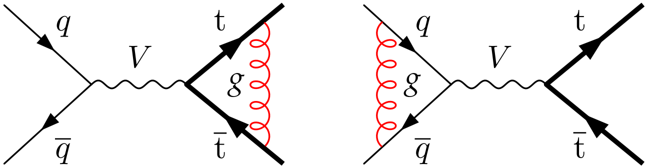
- Z' couplings family diagonal but generic otherwise
  - suitable in particular for simulating models with extended gauge group, for example G(221) models
- amplitudes calculated analyticaly:
  - `QGRAPH/DIANA` + `FORM` tool chain

Electroweak top-pair @ NLO BSM

in collaboration with R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein; arXiv:1511.xxxxx



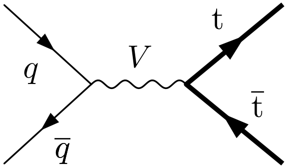
$$V \in \{\gamma, Z, Z'\}$$



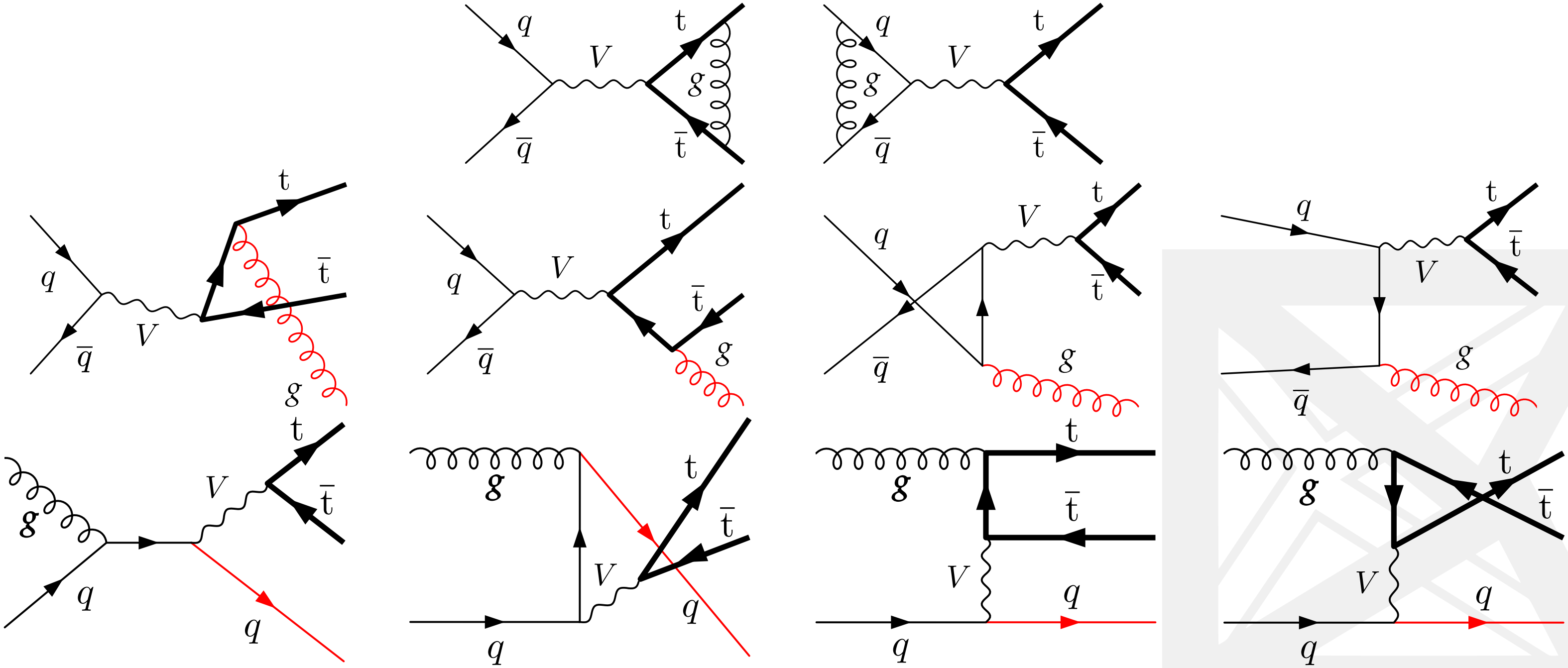
- virtual corrections:
  - loop integrals: IPBs (REDUZE)
  - master integrals: differential equation method (by hand)

Electroweak top-pair @ NLO BSM

in collaboration with R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein; arXiv:1511.xxxxx



$$V \in \{\gamma, Z, Z'\}$$



Electroweak top-pair @ NLO BSM

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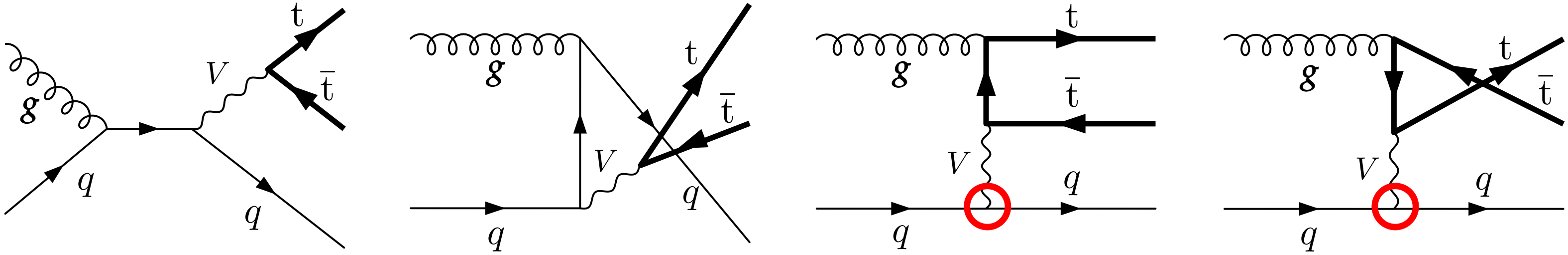
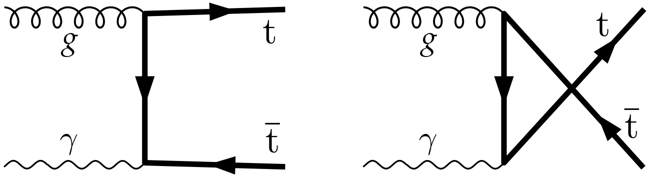


- QED singularity:
  - `POWHEG BOX V2` should be ready to deal with
  - we had to modify the routine searching for singular regions



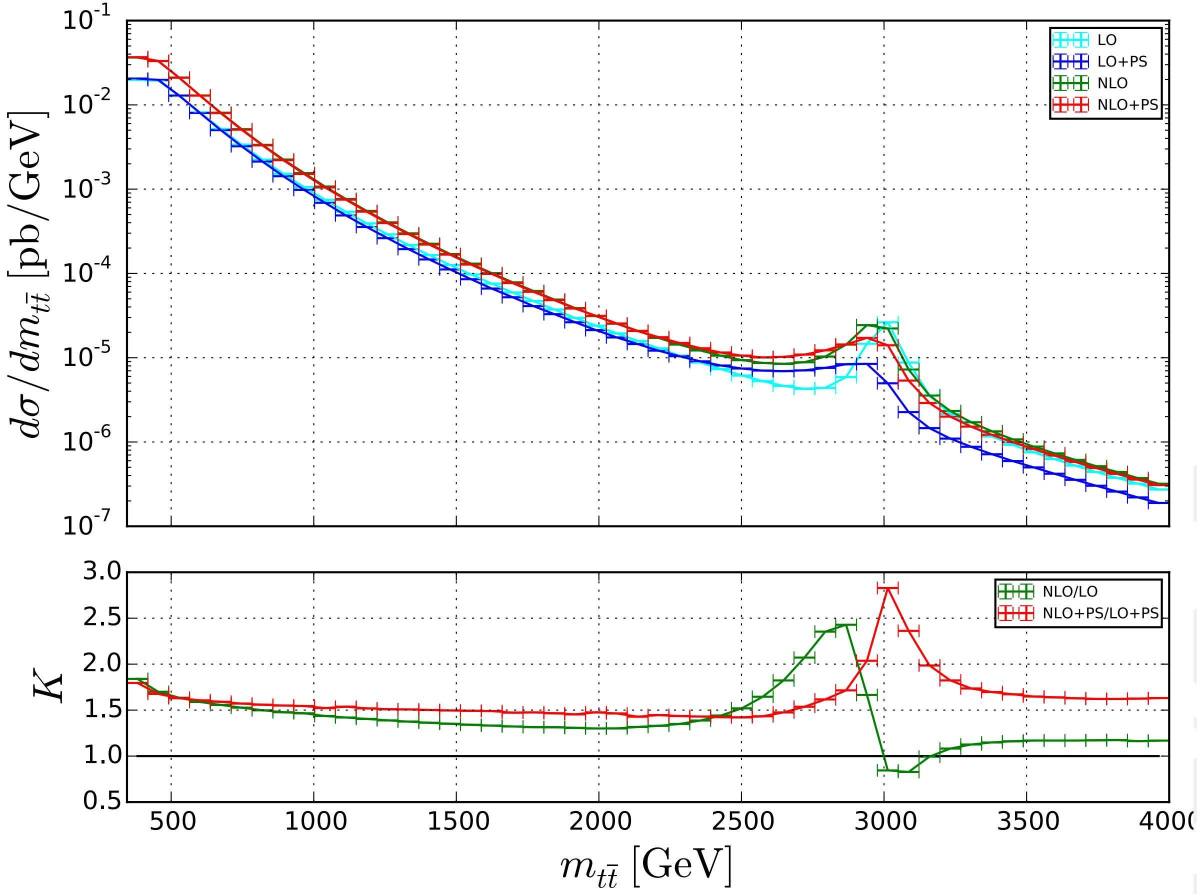
Electroweak top-pair @ NLO BSM

in collaboration with R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein; arXiv:1511.xxxxx

Order	Processes	Model	σ [pb]	σ [pb] ($m_{t\bar{t}} > \frac{3}{4} m_{Z'}$)
LO	$q\bar{q}/gg \to t\bar{t}$		473.93(7)	0.15202(2)
NLO	$q\bar{q}/gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
NLO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
NLO	$q\bar{q}/qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
LO	$q\bar{q} \to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
NLO	$q\bar{q}/qg \to \gamma/Z + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)

Electroweak top-pair @ NLO BSM

in collaboration with R. Bonciani, M. Klasen,
F. Lyonnet, I. Schienbein; arXiv:1511.xxxxx

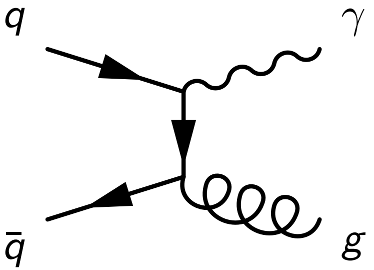


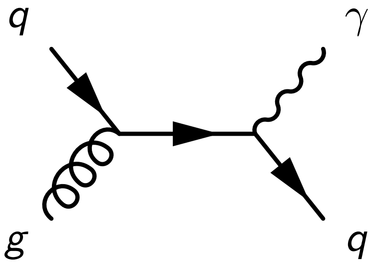
Photonproduction in `POWHEG BOX`

in collaboration with M. Klasen, K. Kovarik, F. König

- direct contribution

LO
$\mathcal{O}(\alpha\alpha_s)$



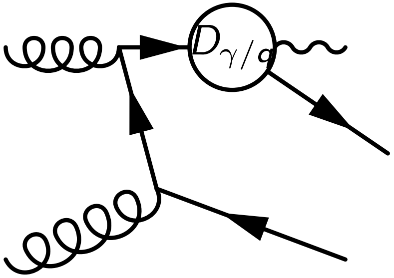


NLO
$\mathcal{O}(\alpha\alpha_s^2)$

+ extra g or $q\bar{q}$ splitting

+ virtual corrections

- fragmentation contribution



Photonproduction in POWHEG BOX

in collaboration with M. Klasen, K. Kovarik, F. König

- At NLO γ radiation off of massless quarks

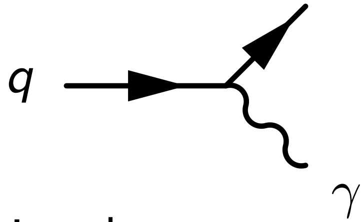
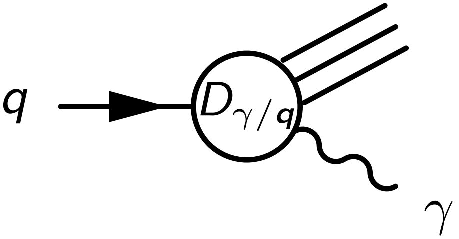
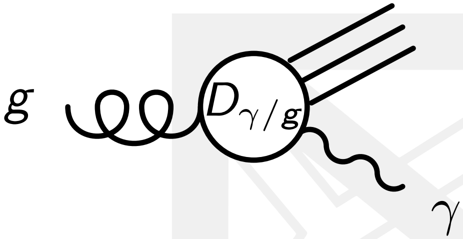


exhibit collinear singularities that cannot be cancelled by loops

- these have to be absorbed into γ fragmentation functions $D_{\gamma/k}(z, \mu_D)$





due to γ coupling to QCD bound states

Photonproduction in `POWHEG BOX`

in collaboration with M. Klasen, K. Kovarik, F. König

- At NLO γ radiation off of massless quarks

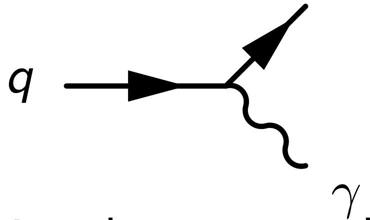
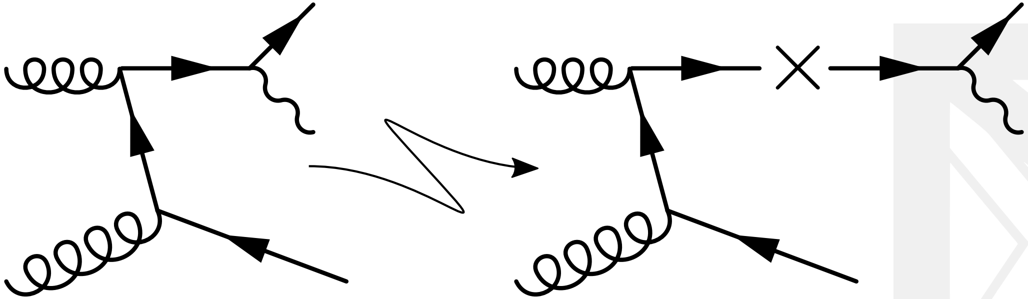


exhibit collinear singularities that cannot be cancelled by loops

- collinear singularity can also be treated by real counterterms generated by FKS



- perhaps rest of the fragmentation contribution can be recovered by parton shower

Photonproduction in POWHEG BOX

in collaboration with M. Klasen, K. Kovarik, F. König

- Calculated:
  - Born, colour and spin-correlated Born $\mathcal{O}(\alpha_{em}\alpha_s)$
  - virtual and real $\mathcal{O}(\alpha_{em}\alpha_s^2)$
  - Born $\mathcal{O}(\alpha_s^2)$

- Extended POWHEG BOX
  - photon radiation off massless particless
  - reweighting with modified R/B ratio

    low efficiency in generation of events with photons: 2%
    with $\alpha_{em} \to 40\alpha_{em}$ the efficiency is: 50%

- To do:
  - consistent generation of consequitive emissions (PS)

Photonproduction in `POWHEG BOX`

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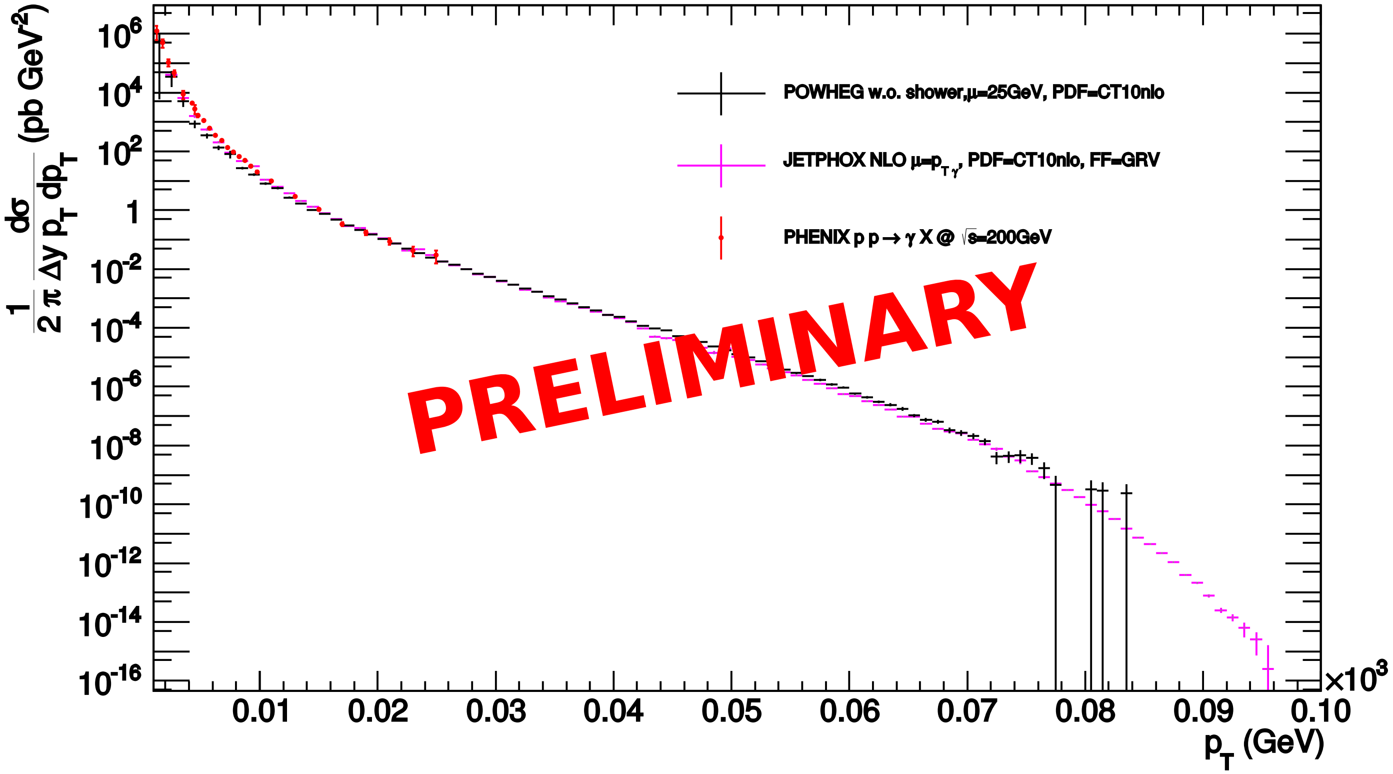
p_T distribution of hardest photon



Photonproduction in `POWHEG BOX`

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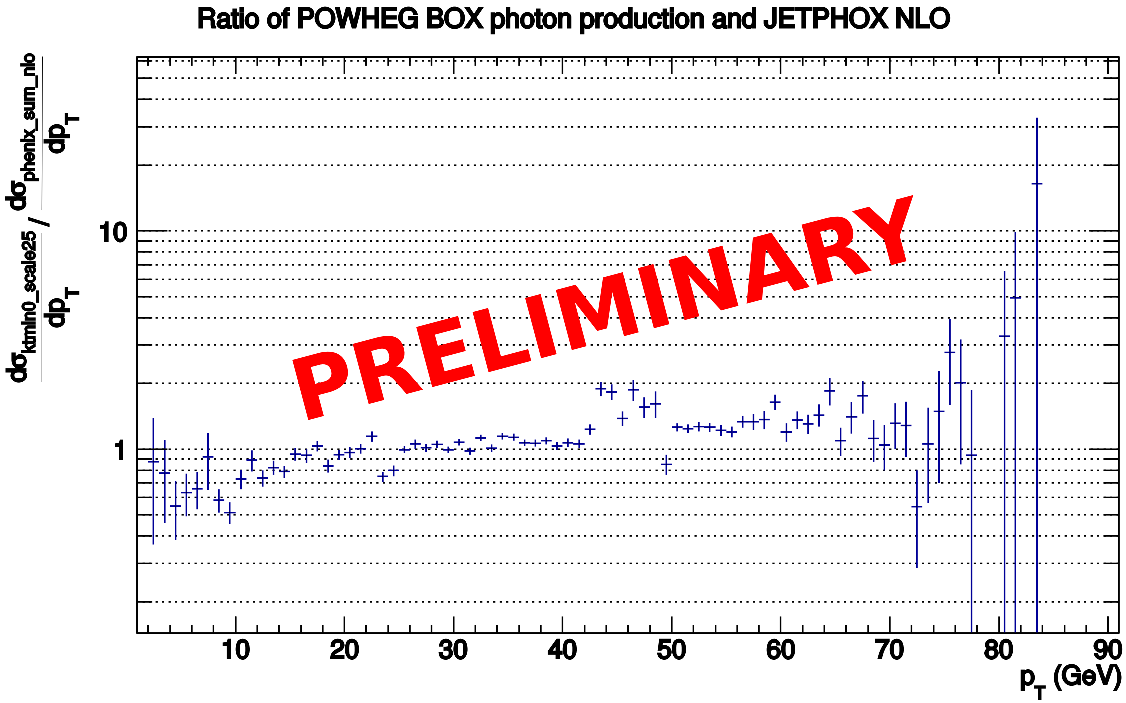

Note that for JETPHOX $\mu = \mu_R = \mu_F = p_{T\gamma}$ and POWHEG $\mu = 25$ GeV (no low-p_T-cut)

Summary and Outlook

- I have reviewed NLO+PS matching
- NLO+PS is a very important and exciting research topic
- POWHEG BOX is leading tool for NLO+PS matching, developped on many fronts
- Research group of M. Klasen actively participates in this effort

- Treatment of resonances:
  - important for the shape of radiation or derived observables, most notably may affect the measurement of top mass
  - top-pair production, HV production still to come in 2015

- New processes:
  - EW top-pair production, single top production beyond SM
  - photonproduction