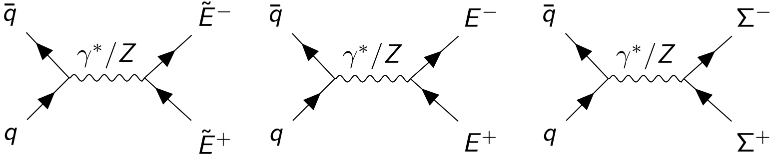
Precision predictions for exotic lepton production
arXiv:2301.03640

Ajjath A. H., Benjamin Fuks, Hua-Sheng Shao & **Yehudi Simon**



LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

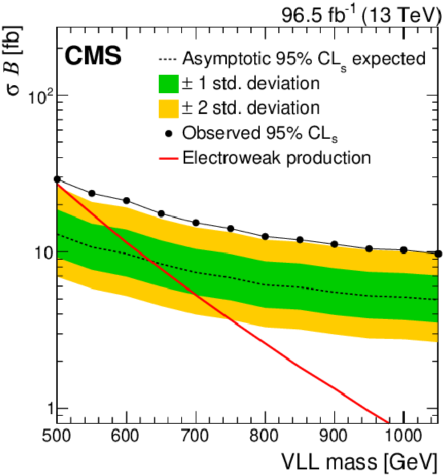
SORBONNE UNIVERSITÉ

Content

Particles and motivation

Motivations

- Precision era of LHC: also theoretical predictions !
- Vector-Like-Leptons: arise in composite or "4321" models (2208.09700)
- Type-III seesaw (1711.02180): generation of ν masses *via* $SU(2)_L$ triplet



Particles and motivation

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- Precision era of LHC: also theoretical predictions !
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Focus on new particles

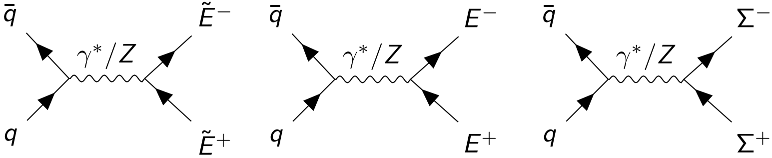
Field	Representation	Name
L^0	$(\mathbf{1},\mathbf{2})_{-1/2}$	VLL0
$\tilde{N}^0$	$(\mathbf{1},\mathbf{1})_0$	VLN0
$\tilde{E}^0$	$(\mathbf{1},\mathbf{1})_{-1}$	VLE0
Σ^k	$(\mathbf{1},\mathbf{3})_0$	Sigw

Accurate, **precise** and kinematically correct predictions $\rightarrow$ higher orders

Our work

Public UFO models in the FeynRules repository

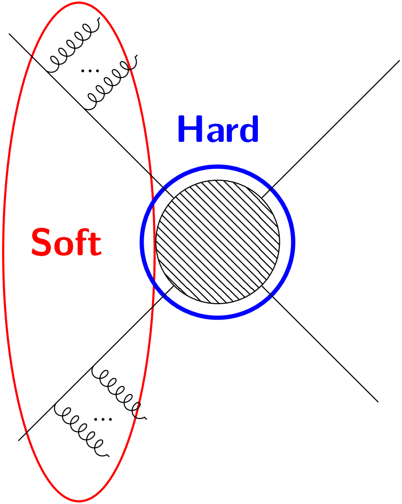
- So far $\mathrm{LO} + \mathrm{PS}$ available $\rightarrow$ with this work: NLO
- MadGraph5_aMC@NLO (and Pythia8) automatically generates NLO $(+\mathrm{PS})$: try yourself !



Increasing theoretical precision: resummation

- Reducing scale dependance when going to higher order
- Going further by **resumming** at $\mathrm{N^k}$ Large Logarithm accuracy

About soft gluon threshold resummation



- Factorization theorem: Soft scale vs. Hard scale
- Large logarithms arising from soft gluon emissions
- Threshold: $z = \frac{M^2}{\hat{s}} \to 1$
- $z \to 1 \leftrightarrow N \to \infty$ in Mellin space, need to resum $\log(1-z)$ or $\log(N)$ terms

Threshold resummation for Drell-Yan like processes

- Only massless initial states quarks emitting gluons
  $\rightarrow$ apply to all similar processes: Drell-Yan like
- Universal *soft part* known up to $\mathrm{N^3LL}$

$$\Delta^{\mathrm{res}}_{q\bar{q}}(N, M^2, \mu_F^2)\Big|_{\mathrm{N^kLL}} = \tilde{g}_{0,q\bar{q}}(M^2, \mu_F^2, \mu_R^2)\Big|_{\mathrm{N^kLO}} \times \exp\left(g_{1,q\bar{q}}(\omega)\ln N + \sum_{j=2}^{k+1} a_s^{j-2}(\mu_R^2) g_{j,q\bar{q}}(\omega)\right)$$

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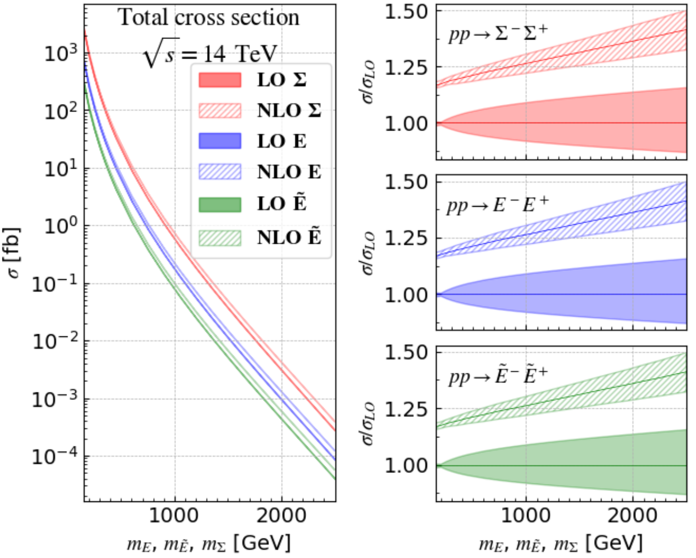
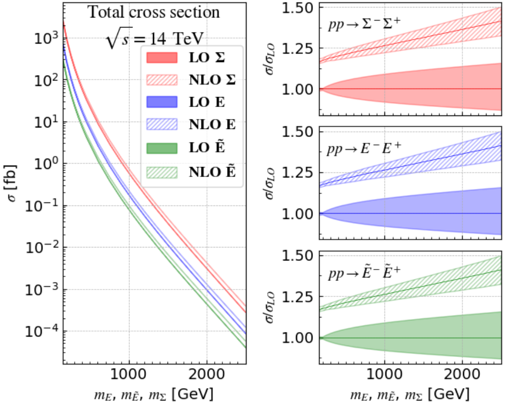


Figure: Total cross sections NLO/LO comparison

NLO impact on total cross sections



Remarkable features

- Important impact of NLO corrections $= O(15 - 50\%)$
- Outside of LO error bars: scale variation not trustworthy for LO
- K factor not constant
- Same behaviour for all processes: Drell-Yan like

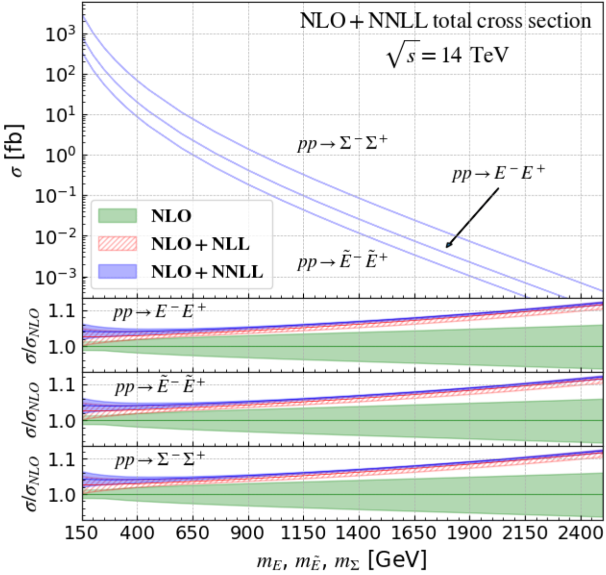
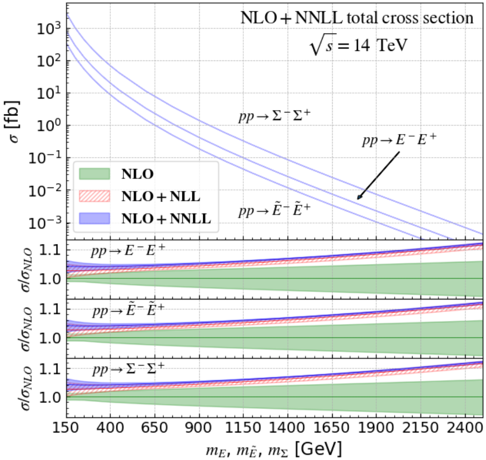


Figure: Scale ucertainties reduction with resummation

Resummation improvement



Remarkable features

- Decrease of scale uncertainties:
  $\mathrm{NLO} = O(5\%)$
  $\mathrm{NLO} + \mathrm{NLL} = O(1\%)$
  $\mathrm{NLO} + \mathrm{NNLL} = O(0.5\%)$
- Significant increase: $\mathrm{NLO} \to \mathrm{NLO} + \mathrm{NNLL} = O(10\%)$
- α_s expansion convergence improved

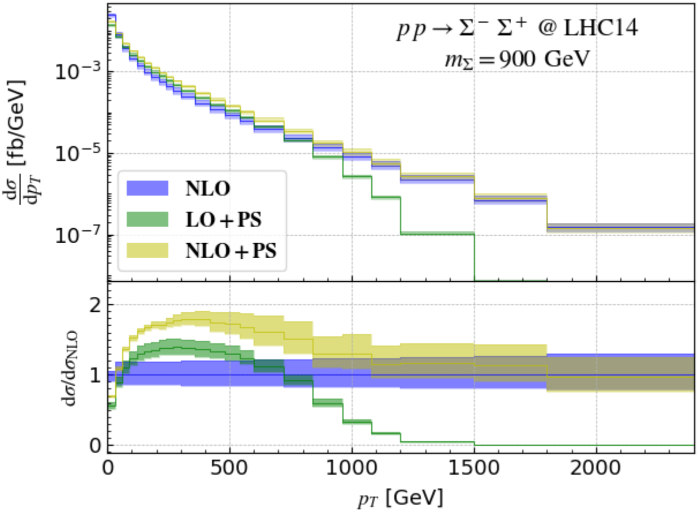
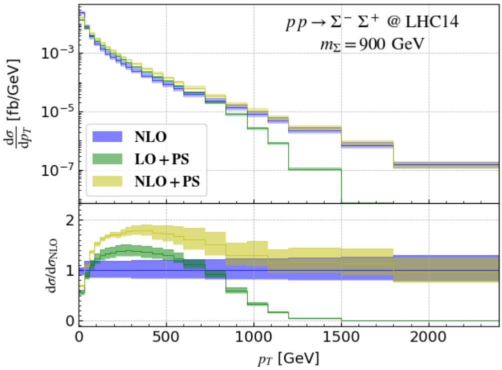


Figure: Differential cross section w.r.t. p_T for Type-III triplet

Parton shower for p_T distribution



Remarkable features

- LO $\propto \delta(p_T)$ not shown
- LO + PS drops too fast compared to NLO
- NLO + PS distored at low-p_T and captures NLO at high-p_T

Content

In conclusion

- NLO UFO models for VLL and Type-III seesaw
- UFO embed the complete models $\rightarrow$ any NLO computation and tunable models: any ideas or upcoming interesting searches ?
- Higher orders: *accuracy*, **precision** and correct kinematics

NLO + PS now publicly available, ready to use within MadGraph5_aMC@NLO.
Further improved by resummation with NLO + NNLL/NLO K factor when available
Feel free to come back to us if needed.

Thank you for your attention!

Backup

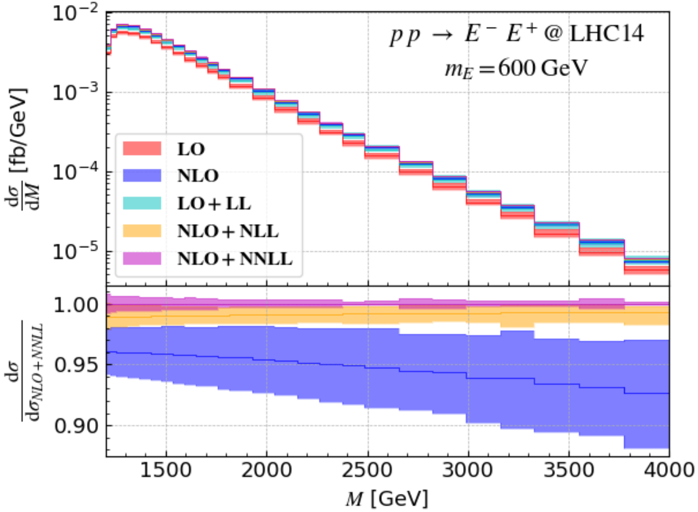
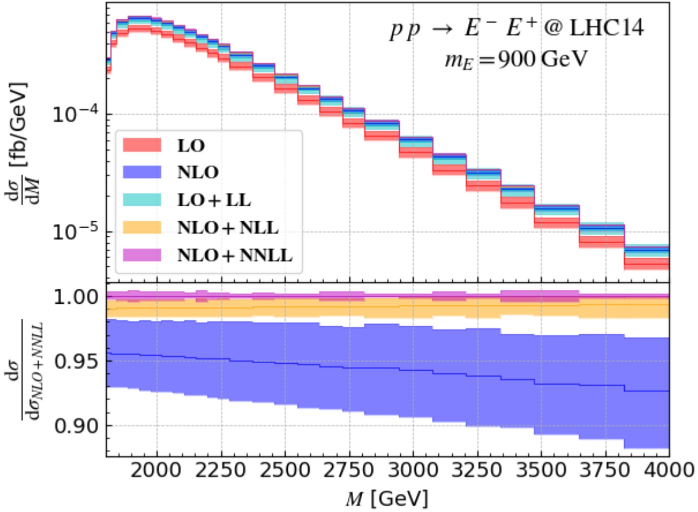


Figure: Differential cross section w.r.t. invariant mass for VLL doublet



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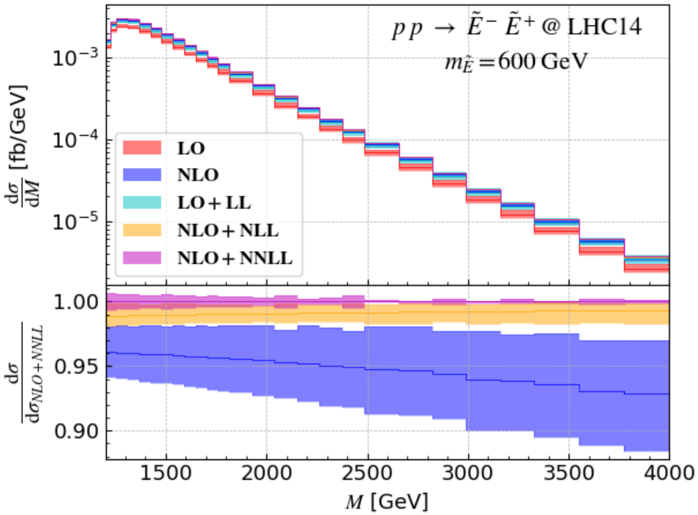

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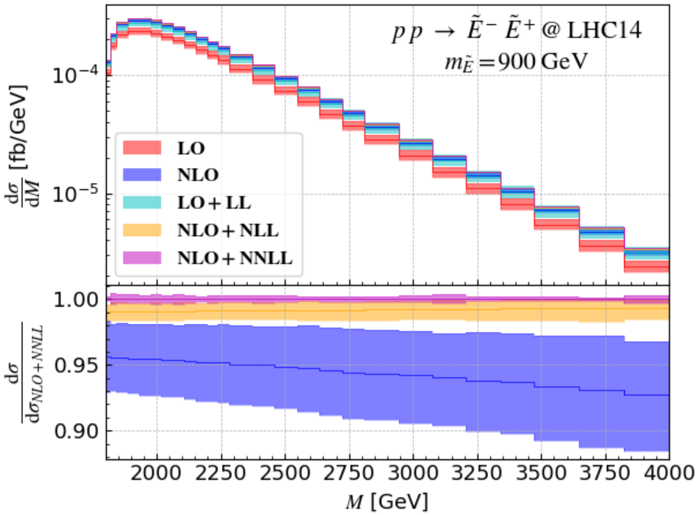

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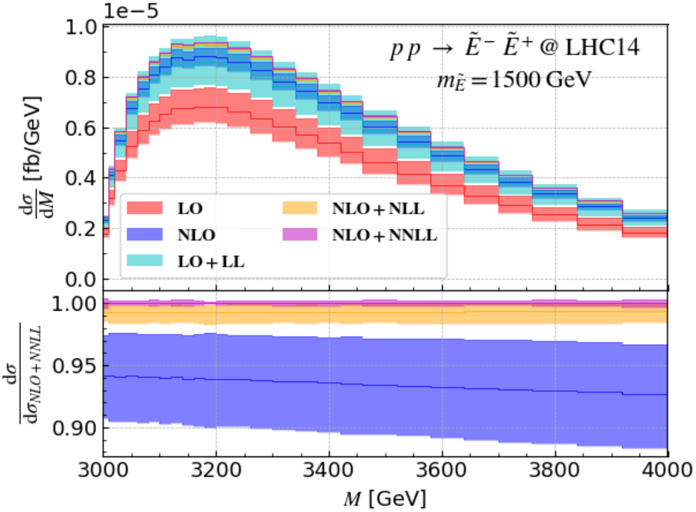

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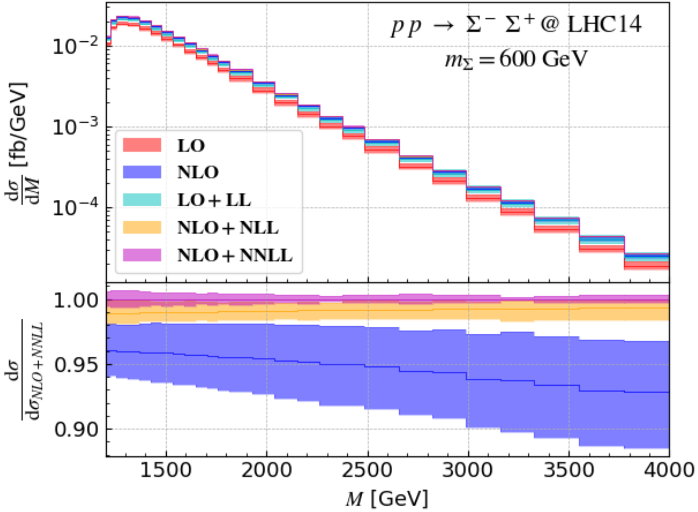

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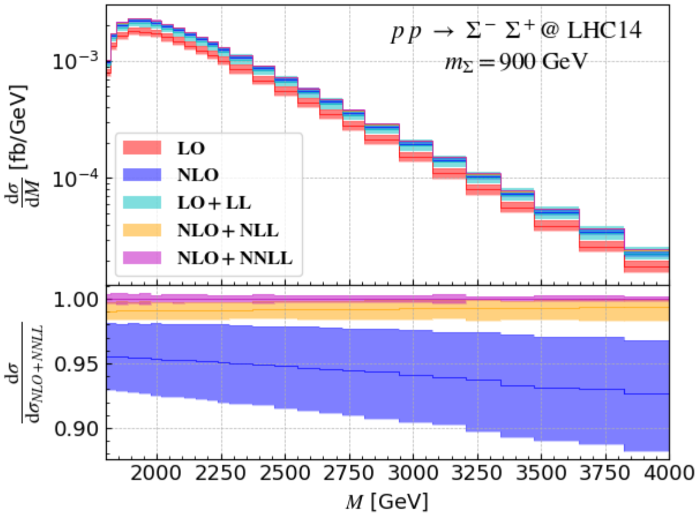

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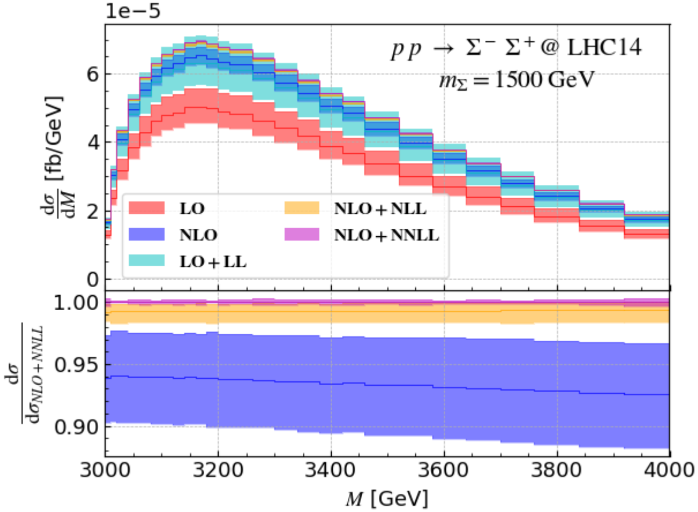

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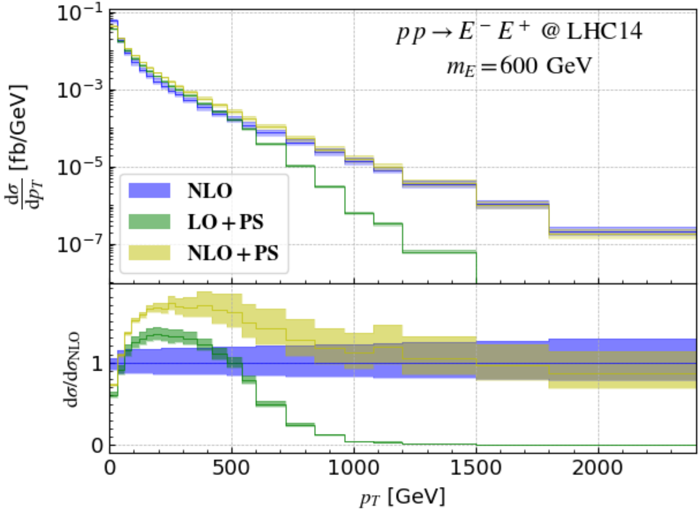

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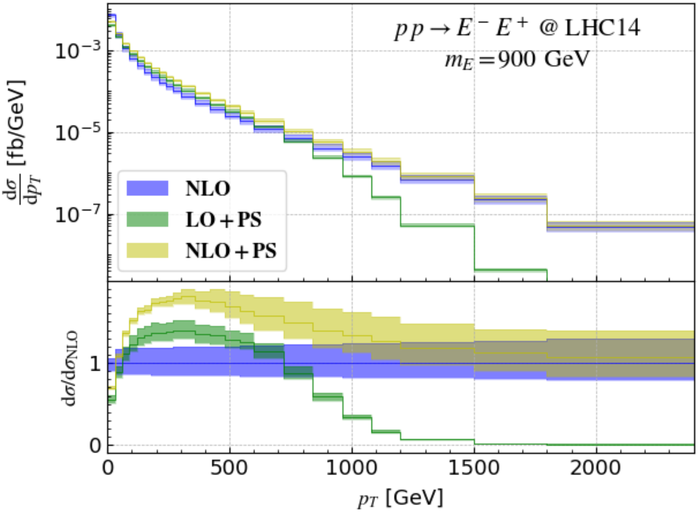

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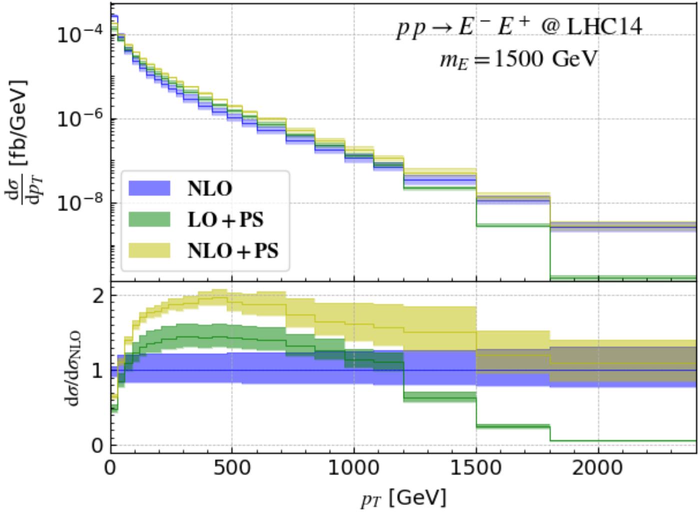

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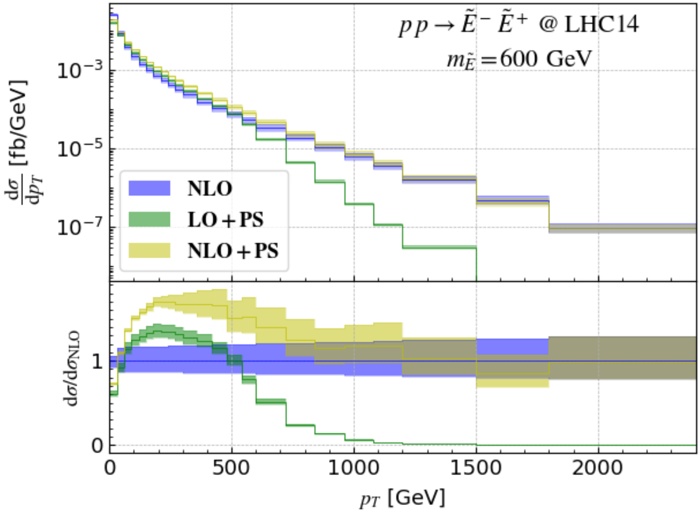

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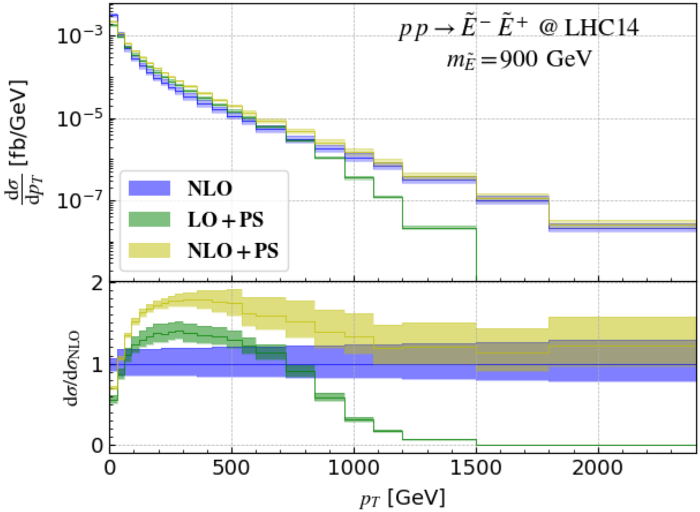

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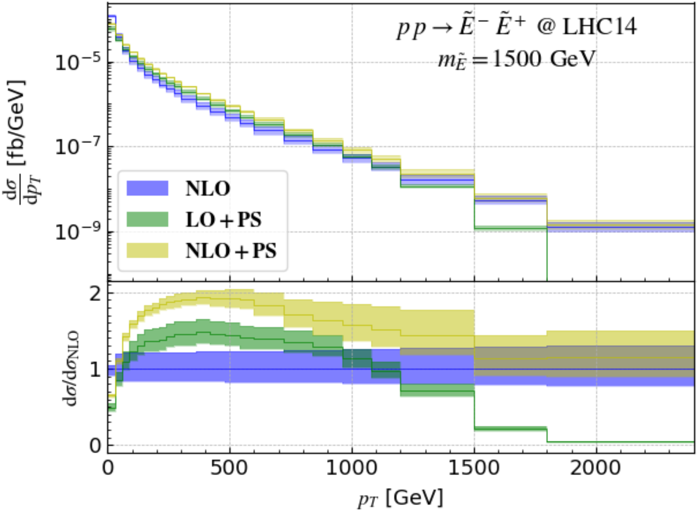

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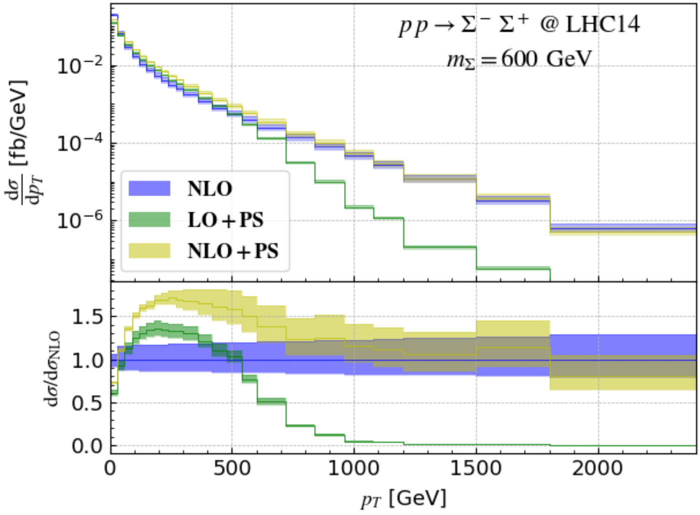

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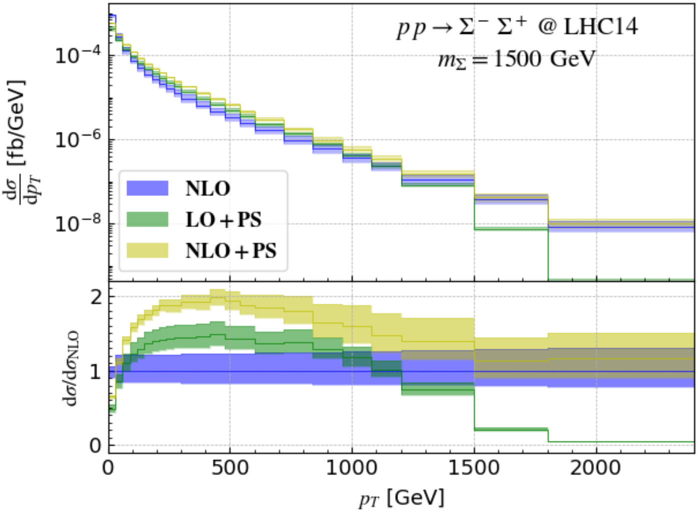

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Large logs

$$d\hat{\sigma}^N_{p_1 p_2 \to \ldots} = \frac{d\Phi_n}{F} \overline{\sum} |\mathscr{M}^N_{p_1 p_2 \to \ldots}|^2$$

For the $q\bar{q} \to Z$ process at NLO:

$$\boxed{d\hat{\sigma}^N_{q\bar{q}\to Z} = d\sigma_0 \left(1 + \frac{\alpha_s}{2\pi}\left[4C_F \ln^2(\overline{N}) - 4C_F \ln(\overline{N}) \ln(m_Z^2/\mu_F^2) + \tilde{C}^{(1)}_{q\bar{q}\to Z}\right]\right)} \tag{1}$$

N Mellin conjugate to $z = \frac{Q^2}{\hat{s}}$, $|N| \to +\infty \longleftrightarrow z \to 1$

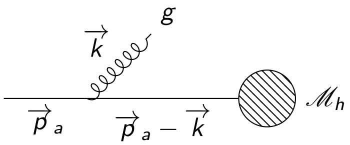
Generic logarithms coming from real emissions of *(collinear-)soft* gluons appear to all orders: can be *resummed*.

Expansion of logarithms

Resumming and exponentiation of logarithms produces a new power series in $\alpha_s L$ at large $L = \ln(N)$: Leading-Logarithms (LL), NLL, N^kLL

$\alpha_s^m L^k$	LO	NLO	...	N^mLO
LL	$m = k = 0$	$k = 2$	...	$m + 1 \leq k \leq 2m$
NLL	$\emptyset$	$m = k = 1$	...	$m \leq k \leq 2m - 1$
...	...	...	...	...
N^pLL	$\emptyset$	$\emptyset$	...	$m + 1 - p \leq k \leq 2m - p$

Eikonal approximation

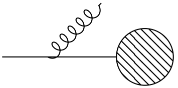


$$\mathscr{M}_e = \mathscr{M}_h \frac{i(\not{p}_a - \not{k} + m)}{(p_a - k)^2 - m^2 + i\epsilon}(-ig_s \mathbf{T}^a \gamma^\mu) u(p_a) \epsilon^*_\mu(k)$$

$$\mathscr{M}_e \underset{k \ll p}{\rightarrow} \mathscr{M}_h u(p_a) g_s \mathbf{T}^a \frac{-p_a^\mu}{p_a.k + i\epsilon} \epsilon^*_\mu(k)$$

Effective Feynman rules for soft ($k \ll p$) gluon radiation and generators depending of particle nature and if it's incomming/outgoing.

Δ building



$$\mathcal{M}_e \underset{Eikonal}{=} \mathcal{M}_{Born} u(p_a) g_s \mathbf{T}^a \frac{-p_a^\mu}{p_a.k + i\epsilon} \epsilon_\mu^*(k)$$

$$d\sigma_e \propto \frac{2p_a.p_b}{E_a E_b k_0^2(1-\cos^2(\theta))} d\sigma_{Born}$$

Phase space factorization:

$$d\Phi_2 = \frac{d^{d-1}k}{(2\pi)^{d-1}2k_0} \frac{2\pi}{\hat{s}} \delta(\frac{2k}{\sqrt{\hat{s}}} - 1 + z)$$

Regularization and resummation

When we add the virtual contribution in the same eikonal approximation to regulate $z \to 1$ divergences and integrate over phase space we get for each massless leg:

$$I = 2C_i \int_0^1 dz \frac{z^{N-1} - 1}{1-z} \int_{-1}^1 \frac{d\cos(\theta)}{1-\cos^2(\theta)} \frac{\alpha_s}{\pi}$$

In the collinear limit $\cos(\theta) \approx 1 - \dfrac{\theta^2}{2}$ and we can approximate $\dfrac{d\theta^2}{\theta^2} \approx \dfrac{dk^2}{k^2}$ where k represents the momentum taken away by the gluon.

$$I = C_i \int_0^1 dz \frac{z^{N-1} - 1}{1-z} \int_{\mu_F^2}^{(1-z)^2 Q^2} \frac{dk^2}{k^2} \frac{\alpha_s(k^2)}{\pi}$$

We can extrapolate this for multiple emissions, decoupled for this LL integral:

$$\Delta_i^{LL} = \sum_{n=0}^{+\infty} \frac{I^n}{n!} = e^I$$

General formalism

In a general way, we can write the factorized formula:

$$d\hat{\sigma}^{N,\, res.}_{ij\to\dots} \propto \mathrm{Tr}\left(\mathbf{H} e^{\int \Gamma^\dagger} \mathbf{S} e^{\int \Gamma}\right) \Delta_i \Delta_j \tag{2}$$

- **H**: "hard" matrix, high energy process part
- **S**: "soft" matrix, low energy emissions and color structure
- Γ: soft anomalous dimension color matrix controlling the evolution over RG of **S**
- Δ_i: (colinear-)soft radiations from initial state massless partons

$$\Delta_i = e^{g_1(\alpha_s \ln(\bar{N}))\ln(\bar{N}) + g_2(\alpha_s \ln(\bar{N})) + \dots}$$

Matching

We can also expand $d\hat{\sigma}^{N,\,res.}$ to NLO in α_s and compare it to the usual NLO cross section (obtained with MadGraph5_aMC@NLO).

Fixed order

$d\sigma_{|_{NLO}}$

Valid away from threshold

Resummed

$d\sigma^{res.}$

Valid near threshold

Resummed @ f. o.

$d\sigma^{res.}_{|_{NLO}}$

Double counting

Matching: $d\sigma_{|_{NLO}} + d\sigma^{res.} - d\sigma^{res.}_{|_{NLO}}$ valid everywhere

Expected behaviours

- We expect the ratio $\frac{1}{d\sigma^0/dM^2}\left(\frac{d\sigma^{res.}}{dM^2} - \frac{d\sigma^{res.}}{dM^2}\Big|_{NLO}\right) \underset{M^2 \ll S_h}{\longrightarrow} 0$

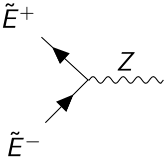
  Away from threshold the logarithmic terms are not important and the behaviour is captured by the first orders of the expansion.

- We expect also $\frac{1}{d\sigma^0/dM^2}\left(\frac{d\sigma^{NLO}}{dM^2} - \frac{d\sigma^{res.}}{dM^2}\Big|_{NLO}\right) \underset{M^2 \to S_h}{\longrightarrow} 0$

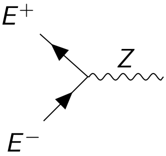
  In the threshold regime, the resummed expanded reproduces the behaviour of original cross section.

To obtain a sensible cross section in all ranges we may consider the combination: $\sigma_{|_{NLO}} + \sigma^{res.} - \sigma^{res.}_{|_{NLO}}$

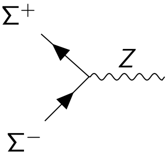
Some Feynman rules



$$ie\gamma^\mu \tan(\theta_w)$$



$$\frac{-ie\gamma^\mu}{\tan(2\theta_w)}$$



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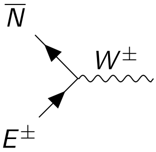
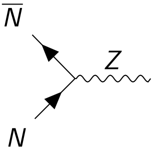


$$\frac{-ie\gamma^\mu}{\sqrt{2}\sin(\theta_w)}$$



$$\frac{ie\gamma^\mu}{\sin(2\theta_w)}$$

g functions

$$
\begin{aligned}
\tilde{g}^{(1)}_{0,q\bar{q}} &= \frac{-64}{3} + \frac{64}{3}\zeta_2 - 8L_{fr} + 8L_{qr}\,, \\
\tilde{g}^{(2)}_{0,q\bar{q}} &= \frac{-1291}{9} + \frac{64\zeta_2}{9} + \frac{368\zeta_2^2}{3} + \frac{4528\zeta_3}{27} \\
&\quad + \frac{188L_{fr}^2}{3} + \frac{4L_{qr}^2}{3} \\
&\quad + L_{fr}\left(\frac{1324}{9} - \frac{1888\zeta_2}{9} + \frac{32\zeta_3}{3}\right) \\
&\quad + L_{qr}\left(\frac{148}{9} - 64L_{fr} + \frac{416\zeta_2}{9} - \frac{32\zeta_3}{3}\right),
\end{aligned} \tag{3}
$$

with $L_{qr} = \ln\frac{M^2}{\mu_R^2}$, $L_{fr} = \ln\frac{\mu_F^2}{\mu_R^2}$ and ζ_n being the Riemann zeta function.

Lagrangians

$$\mathscr{L}_{\rm VLL} = \mathscr{L}_{\rm SM} + i\bar{L}\not{D}L - m_N\bar{N}N - m_E\bar{E}E + i\bar{\tilde{N}}\not{\partial}\tilde{N} - m_{\tilde{N}}\bar{\tilde{N}}\tilde{N} + i\bar{\tilde{E}}\not{D}\tilde{E} - m_{\tilde{E}}\bar{\tilde{E}}\tilde{E}$$
$$+ \sum_{\Psi=E,\tilde{E}}\Big[h\bar{\Psi}\Big(\hat{\kappa}_L^\Psi P_L + \hat{\kappa}_R^\Psi P_R\Big)\ell + \frac{g}{\sqrt{2}}\bar{\Psi}\not{W}^-\kappa_L^\Psi P_L\nu_\ell$$
$$+ \frac{g}{2c_W}\bar{\Psi}\not{Z}\Big(\tilde{\kappa}_L^\Psi P_L + \tilde{\kappa}_R^\Psi P_R\Big)\ell + \text{H.c.}\Big]$$
$$+ \sum_{\Psi=N,\tilde{N}}\Big[h\bar{\Psi}\hat{\kappa}_L^\Psi P_L\nu_\ell + \frac{g}{2c_W}\bar{\Psi}\not{Z}\tilde{\kappa}_L^\Psi P_L\nu_\ell + \frac{g}{\sqrt{2}}\bar{\Psi}\not{W}^+\Big(\kappa_L^\Psi P_L + \kappa_R^\Psi P_R\Big)\ell + \text{H.c.}\Big], \quad (4)$$

$$\mathscr{L}_{\rm TypeIII} = \overline{\mathscr{L}}_{\rm SM} + \mathscr{L}_{\rm kin} + \Big(y_\ell\ \Phi^\dagger L_L.E_R + 2y_\Sigma\ \Phi\cdot\Big[\Sigma^k T^k L_L\Big] + \text{H.c.}\Big). \quad (5)$$