

Improving SUSY limits through Merging, Resummation and Combination

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Outline

Motivation

Merging of processes with multiple jets

Threshold resummation of soft gluons

Combination of Signal Regions

Results

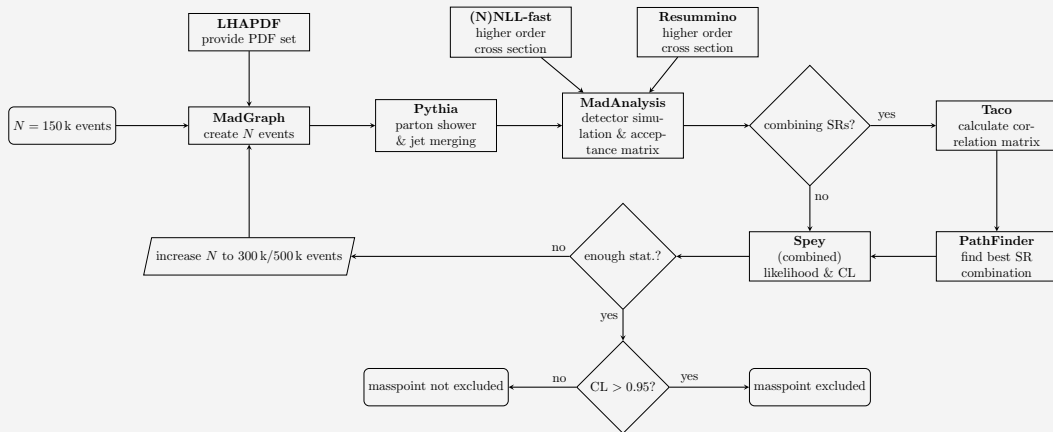
Conclusion

Motivation for Electroweak SUSY processes

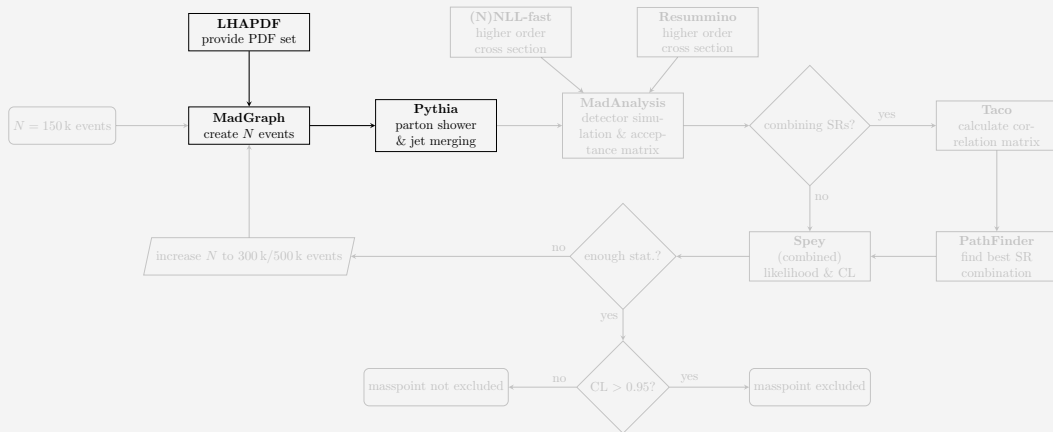
- ▶ In the MSSM R-Parity implies production of SUSY particles in even numbers
- ▶ Expect dominant production of squark pairs and gluino pairs
- ▶ But, production at the LHC might be restricted by heavy masses
 - ▶ Electroweak production of slepton pairs or electroweakino pairs
 - ▶ Semi strong production of electroweakino-squark or electroweakino-gluino
- ▶ Electroweak regime has more interesting parameters to study (masses and couplings)
- ▶ R-Parity prevents LSP from decaying $\implies$ neutralino is a DM candidate
- ▶ New ATLAS paper on pMSSM scan of EW sector this Monday²

²Aad, G. et al. [arXiv: 2402.01392 \[hep-ex\]](https://arxiv.org/abs/2402.01392) (Feb. 2024).

The Toolchain

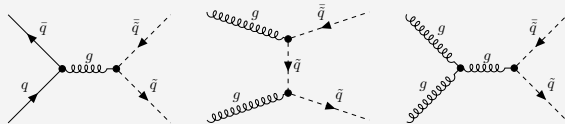


Merging of processes with multiple jets

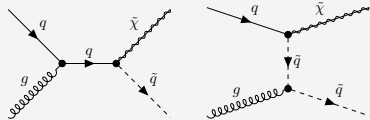


MSSM demonstration processes

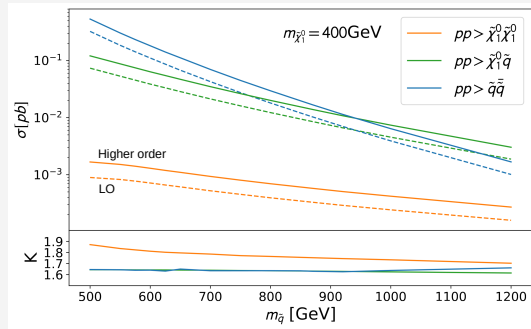
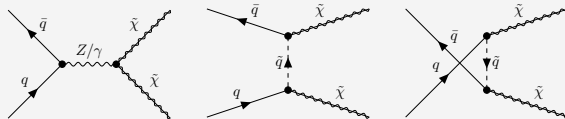
$\tilde{q}\tilde{q}^*$, squark-squark, $\mathcal{O}(\alpha_S^2)$:



$\tilde{q}\tilde{\chi}$, gaugino-squark, $\mathcal{O}(\alpha_S\alpha)$:



$\tilde{\chi}\tilde{\chi}$, gaugino-gaugino, $\mathcal{O}(\alpha^2)$:

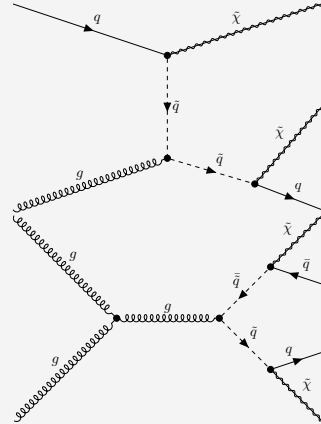


Scenario: LSP Bino

- ▶ diagonal neutralino mixing $\tilde{\chi}_1^0 = \tilde{B}^0$
- ▶ $m_{\tilde{\chi}_1^0} < m_{\tilde{u}_R}$
- ▶ single squark $\tilde{u}_R$, other SUSY particles decoupled

MSSM demonstration processes

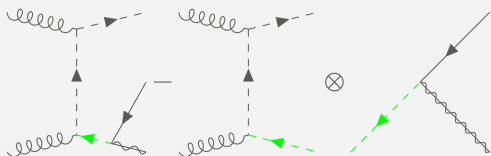
- ▶ Can not generate events at NLO or higher for all processes in reasonable time
- ▶ $\Rightarrow$ Generate events with more jets and merge them ($\sim$ real corrections)
- ▶ $p + p \rightarrow$
 - $\tilde{q} + \bar{\tilde{q}}$
 - $\tilde{q} + \bar{\tilde{q}} + j$
 - $\tilde{q} + \bar{\tilde{q}} + j + j$
 - $\tilde{q} + \tilde{\chi}$
 - $\tilde{q} + \tilde{\chi} + j$
 - $\tilde{q} + \tilde{\chi} + j + j$
 - $\tilde{\chi} + \tilde{\chi}$
 - $\tilde{\chi} + \tilde{\chi} + j$
 - $\tilde{\chi} + \tilde{\chi} + j + j$



Breit-Wigner cut

Careful treatment of overlapping diagrams is necessary to avoid double counting between decays and on-shell resonances

- In NLO computation one would use Diagram Removal or Diagram Subtraction methods



Regularize on-shell divergence:

$$\frac{1}{p_{\text{res}}^2 - m_{\tilde{q}}^2} \rightarrow \frac{1}{p_{\text{res}}^2 - m_{\tilde{q}}^2 \pm im_{\tilde{q}}\Gamma_{\tilde{q}}}$$

$$\frac{1}{(p_{\text{res}}^2 - m_{\tilde{q}}^2)^2} \rightarrow \frac{1}{(p_{\text{res}}^2 - m_{\tilde{q}}^2)^2 + m_{\tilde{q}}^2\Gamma_{\tilde{q}}^2}$$

MadGraph instead:

- simulates the decay and can shift contributions between on-shell to off-shell region
- uses a Breit-Wigner cut of 35% of the particle width Γ to define if particle is to be considered on-shell

Catani-Krauss-Kuhn-Webber & Lönnblad (CKKW-L)³

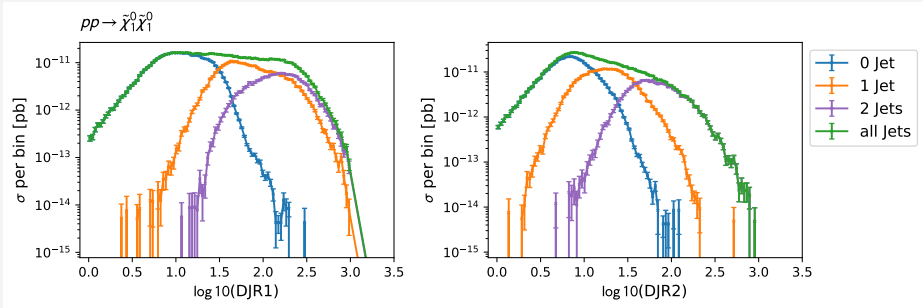
Another type of double counting comes from attaching soft-collinear/parton-shower emissions

- ▶ generate events: merging scale Q_{MS} , fixed coupling α_S , highest jet multiplicity $N = 2$
- ▶ pick multiplicity n (0,1,2 jets) based on integrated jet rates
- ▶ reconstruct parton shower: select one possible path with probability according to splitting functions
→ sequence of intermediate states $(S_2, S_3, \dots, S_n)$ and emission scales $(\rho_2, \rho_3, \dots, \rho_n)$
- ▶ reweight event with $\prod_i \frac{\alpha_s(\rho_i)}{\alpha_s(\mu)}$
- ▶ generate emission at S_i with scale ρ : if $\rho_i > \rho > \rho_{i+1}$ reject event, else continue
- ▶ two cases for last step:
 - ▶ if $n < N$: emission of state S_n accepted if not in ME regime (Q_{MS}) → continue cascade
 - ▶ if $n = N$: emission accepted and start cascade $\Rightarrow$ highest jet multiplicity is inclusive
- ▶ $\Rightarrow$ inclusive final states become exclusive with first N emissions $\mathcal{O}(\alpha_S^N)$ exact

³Catani, S. et al. JHEP **11**, 063. arXiv: [hep-ph/0109231](#) (2001), Lönnblad, L. JHEP **05**, 046. arXiv: [hep-ph/0112284](#) (2002).

Differential Jet Rate (DJR)

- ▶ Check if jet merging was successful
- ▶ Show transition between $n - 1$ and n final state hard jets $\rightarrow$ should be smooth and without bumps
- ▶ Cross section of every jet multiplicity state as a function of $\log \sqrt{d_{ij}}$ at this transition
- ▶ d_{ij} is the minimized distance measure between two particles as defined by a jet algorithm, e.g. $d_{ij} = \min(p_{t,i}^2, p_{t,j}^2) \frac{\Delta R_{ij}^2}{R^2}$



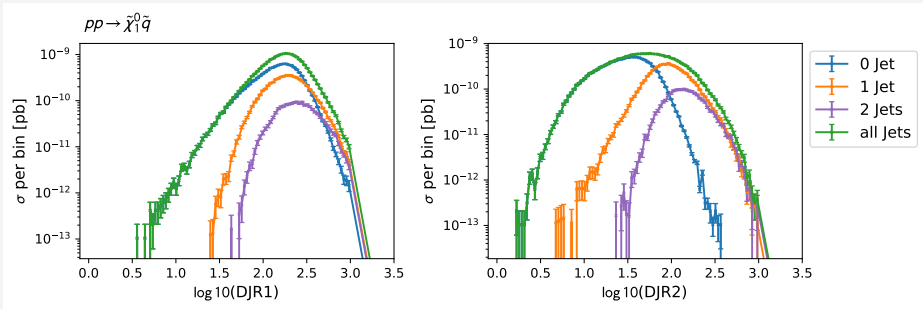
$$m_{\tilde{\chi}_1^0} = 200 \text{ GeV}, m_{\tilde{u}_R} = 600 \text{ GeV}, Q_{MS} = p_T = 50 \text{ GeV}$$

Differential Jet Rate (DJR)

- ▶ use transverse momentum as scale and set merging scale to 1/4 of hard scale

$$Q_{MS} = p_T^j = \begin{cases} \frac{1}{4} m_{\tilde{\chi}_1^0} & \text{for } pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \\ \frac{1}{8} (m_{\tilde{q}} + m_{\tilde{\chi}_1^0}) & \text{for } pp \rightarrow \tilde{\chi}_1^0 \tilde{q} \\ \frac{1}{4} m_{\tilde{q}} & \text{for } pp \rightarrow \tilde{q} \tilde{q} \end{cases} . \quad (1)$$

- ▶ checked DJR for multiple masspoints for all three process



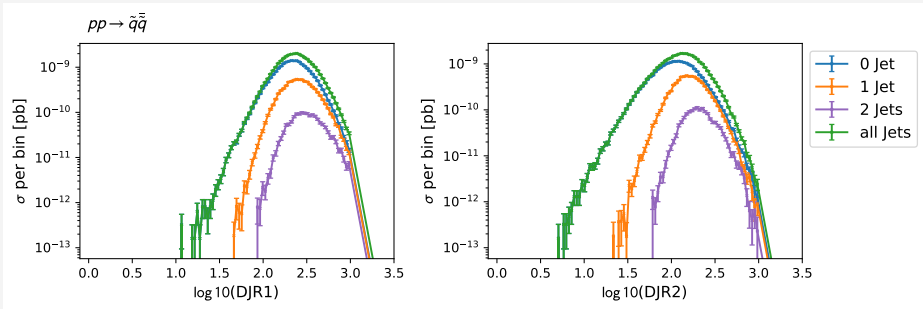
$$m_{\tilde{\chi}_1^0} = 200 \text{ GeV}, m_{\tilde{u}_R} = 600 \text{ GeV}, Q_{MS} = p_T = 100 \text{ GeV}$$

Differential Jet Rate (DJR)

- ▶ use transverse momentum as scale and set merging scale to 1/4 of hard scale

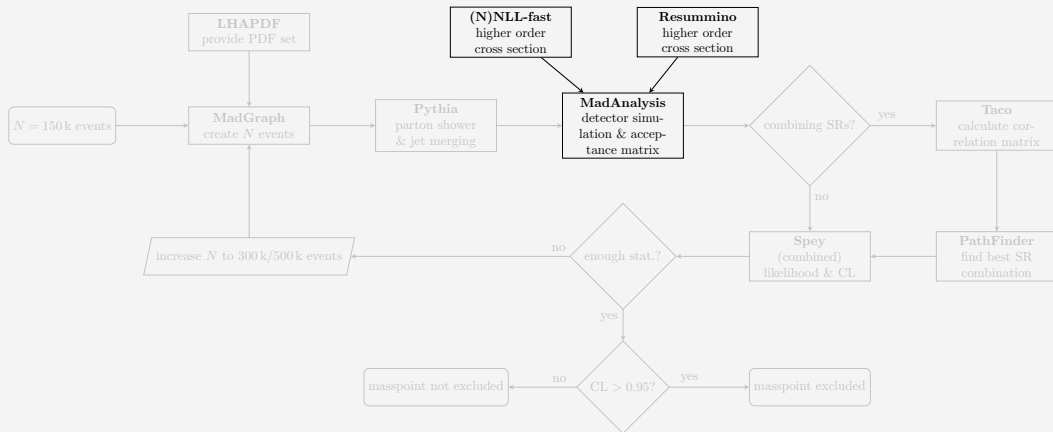
$$Q_{MS} = p_T^j = \begin{cases} \frac{1}{4} m_{\tilde{\chi}_1^0} & \text{for } pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \\ \frac{1}{8} (m_{\tilde{q}} + m_{\tilde{\chi}_1^0}) & \text{for } pp \rightarrow \tilde{\chi}_1^0 \tilde{q} \\ \frac{1}{4} m_{\tilde{q}} & \text{for } pp \rightarrow \tilde{q} \tilde{q} \end{cases} . \quad (1)$$

- ▶ checked DJR for multiple masspoints for all three process



$$m_{\tilde{\chi}_1^0} = 200 \text{ GeV}, m_{\tilde{u}_R} = 600 \text{ GeV}, Q_{MS} = p_T = 150 \text{ GeV}$$

Threshold resummation of soft gluons



Resummation

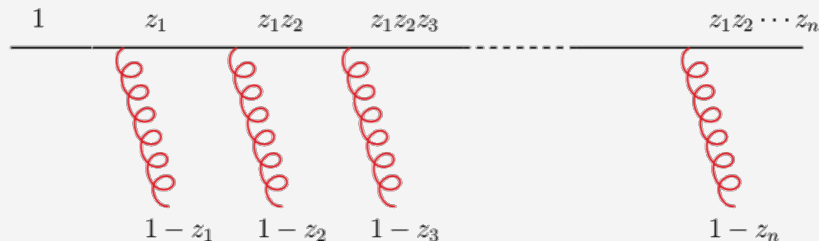
- ▶ Massive particles are mostly produced close to threshold ($M^2/s = z \rightarrow 1$)⁴
- ▶ Perturbative expansion in α_s is spoiled by

Large Sudakov logarithms ($m \leq 2n - 1$)

$$\left(\frac{\alpha_s}{2\pi}\right)^n \frac{\log^m(1-z)}{1-z}$$

$$\left(\frac{\alpha_s}{2\pi}\right)^n \log^m\left(\frac{M^2}{p_T^2}\right)$$

- ▶ Solution: Resummation of all soft emitted gluons



⁴Catani, S. & Trentadue, L. *Nucl. Phys. B* **327**, 323–352 (1989).

Resummation

► Transforming to Mellin space

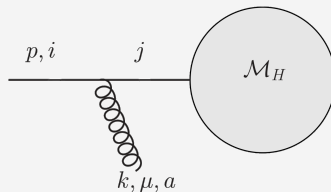
$$F(N) = \int_0^1 dy y^{N-1} F(y) \quad \Rightarrow \quad \left[\frac{\log^m(1-z)}{1-z} \right]_+ \xrightarrow{F} \sim \log^{m+1} N + \dots$$

factorizes the phase space

$$\int dz z^{N-1} d\phi_{2+n}(z) \approx d\phi_2 \times d\phi_n(N)$$

► Dynamical Factorisation is achieved by the eikonal approximation

$$\Gamma_{\text{eik}}^\mu = g_s T^j \frac{\Delta_i v^\mu}{\delta_i v \cdot k + i\epsilon}$$



Resummation

- ▶ From factorization theorem we split hard and long distance behaviour

$$\sigma(M^2, m^2) = \mathcal{H}(M^2/\mu_F^2) \mathcal{S}(m^2/\mu_F^2)$$

- ▶ Require independence on scale μ_F

$$\sigma(M^2, m^2) = \mathcal{H}(1) \mathcal{S}(1) \exp \left[- \int_{m^2}^{M^2} \frac{dk}{k^2} \gamma_s(k^2) \right]$$

- ▶ From applying the RGEs we get⁵:

$$\sigma^{\text{Res.}}(N, M^2, \mu_R^2, \mu_F^2) = \mathcal{H}_{ab}(M^2, \mu_R^2, \mu_F^2) \exp [G_{ab}(N, M^2, \mu_R^2, \mu_F^2)] + \mathcal{O} \left(\frac{1}{N} \right)$$

with

$$G_{ab}(N, M^2, \mu_R^2, \mu_F^2) = \underbrace{LG_{ab}^{(1)}(N)}_{\text{Leading Log } \sim \log^2(N)} + \underbrace{G_{ab \rightarrow ij}^{(2)}(N, M^2, \mu_F^2, \mu_R^2)}_{\text{Next-to-Leading Log } \sim \log(N)} + \dots$$

⁵Kidonakis, N. et al. *Nucl. Phys. B* **525**, 299–332. [arXiv: hep-ph/9801268 \(1998\)](#).

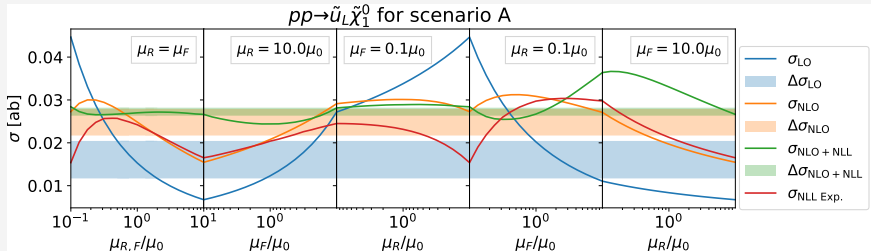
Re-expansion

► To avoid double counting in:

$$\sigma_{ab}^{\text{NLO+NLL}} = \sigma_{ab}^{\text{NLO}} + \underbrace{\sigma_{ab}^{\text{Res.}} - \sigma_{ab}^{\text{Exp.}}}_{\sigma_{ab}^{\text{NLL}}}$$

► Subtract expansion in α_s :

$$\begin{aligned} \sigma_{ab}^{\text{Exp.}} &= \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) \\ &\times \left(\left(A_a^{(1)} + A_b^{(1)} \right) \left(\log \bar{N} + \log \frac{\mu_F^2}{s} \right) - 2D_{ab \rightarrow ij}^{(1)} \right) \log \bar{N} \end{aligned}$$



(Note: panels 2 and 3 are inverted.)

Reweighting of events

- ▶ Number of signals $n_s^{\text{proc}} = \epsilon_{\text{detector}} \mathcal{L} \cdot \sigma^{\text{proc}}$
- ▶ Run 2 Luminosity $\mathcal{L} = 137 \text{ fb}^{-1}$ to 139 fb^{-1}
- ▶ Number of total signals $n_s = \sum_{\text{proc}} n_s^{\text{proc}}$
- ▶ K -factor reweighting to (a)NLO+(N)NLL

$$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 : \quad \sigma = \sigma(\text{LO})_{\text{LO}}^{\text{MG}} \frac{\sigma(\text{aNNLO+NNLL})_{\text{NLO}}^{\text{RS}}}{\sigma(\text{LO})_{\text{LO}}^{\text{RS}}}$$

$$pp \rightarrow \tilde{\chi}_1^0 \tilde{q} : \quad \sigma = \sigma(\text{LO})_{\text{LO}}^{\text{MG}} \frac{\sigma(\text{NLO+NLL})_{\text{NLO}}^{\text{RS}}}{\sigma(\text{LO})_{\text{LO}}^{\text{RS}}}$$

$$pp \rightarrow \tilde{q} \tilde{q} : \quad \sigma = \sigma(\text{LO})_{\text{LO}}^{\text{MG}} \frac{\sigma(\text{NLO})_{\text{LO}}^{\text{nllfast}}}{\sigma(\text{LO})_{\text{LO}}^{\text{nllfast}}} \frac{\sigma(\text{aNNLO+NNLL})_{\text{NNLO}}^{\text{nllfast}}}{\sigma(\text{NLO})_{\text{NLO}}^{\text{nllfast}}}$$

Likelihood description in Spey⁶

MadAnalysis5 run: $(n_s, n_{\text{obs}}, n_b, \Delta n_b)$

$$\begin{aligned}\mathcal{L}(\mu, \theta) &= \text{Poiss}(n_{\text{obs}} | \mu n_s + n_b + \theta \cdot \Delta n_b) \text{Gauss}(n_b + \theta \cdot \Delta n_b | n_b, \Delta n_b) \\ &= \frac{(\mu n_s + n_b + \theta \cdot \Delta n_b)^{n_{\text{obs}}}}{n_{\text{obs}}!} e^{-(\mu n_s + n_b + \theta \cdot \Delta n_b)} \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{(n_b + \theta \cdot \Delta n_b) - n_b}{\Delta n_b} \right)^2}\end{aligned}$$

strength parameter $\mu \in [0, 1]$

null hypothesis $\mu = 0$

alternative hypothesis $\mu = 1$

nuisance parameter θ

observed exclusion limit

$\rightarrow n_{\text{obs}}$ are true number of events

⁶Araz, J. Y. *SciPost Phys.* **16**, 032. arXiv: 2307.06996 [hep-ph] (2024).

Likelihood description in Spey⁶

MadAnalysis5 run: $(n_s, n_{\text{obs}}, n_b, \Delta n_b) \rightarrow (n_s = \sum_p n_s^{(p)}, n_{\text{obs}}, n_b, \Delta n_b)$

$$\mathcal{L}(\mu, \theta) = \text{Poiss}(n_b | \mu n_s + n_b + \theta \cdot \Delta n_b) \text{Gauss}(n_b + \theta \cdot \Delta n_b | n_b, \Delta n_b)$$

$$= \frac{(\mu n_s + n_b + \theta \cdot \Delta n_b)^{n_b}}{n_b!} e^{-(\mu n_s + n_b + \theta \cdot \Delta n_b)} \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{(n_b + \theta \cdot \Delta n_b) - n_b}{\Delta n_b} \right)^2}$$

strength parameter $\mu \in [0, 1]$

null hypothesis $\mu = 0$

alternative hypothesis $\mu = 1$

nuisance parameter θ

observed exclusion limit

$\rightarrow n_{\text{obs}}$ are true number of events

expected exclusion limit

$\rightarrow n_b$ are true number of events

⁶Araz, J. Y. SciPost Phys. **16**, 032. arXiv: 2307.06996 [hep-ph] (2024).

Analyses

cuts	ATLAS-EXOT	ATLAS-CONF	CMS-SUS	CMS-EXO
veto	e, μ, τ, γ	e, μ	e, μ, γ	$e, \mu, \tau, \gamma, b\text{-jet}$
N_j	≥ 1	≥ 2	≥ 2	≥ 1
E_T^{miss}	$> 200 \text{ GeV}$	$> 300 \text{ GeV}$	-	$> 250 \text{ GeV}$
$ \eta $	< 2.4	-	< 2.4	< 2.4
$p_T(j_1)$	$> 150 \text{ GeV}$	$> 200 \text{ GeV}$	-	$> 100 \text{ GeV}$
$p_T(j_2, \dots, j_{N_j})$	$> 30 \text{ GeV}$	$> 50 \text{ GeV}$	-	-
$\Delta\Phi(\text{jet}, \mathbf{p}_T^{\text{miss}})$	> 0.4	> 0.2	> 0.5	> 0.5
m_{eff}	-	$> 800 \text{ GeV}$	-	-
H_T	-	-	$> 300 \text{ GeV}$	-
$ \vec{H}_T^{\text{miss}} $	-	-	$> 300 \text{ GeV}$	-

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{p_T > 50 \text{ GeV}} p_T(j)$$

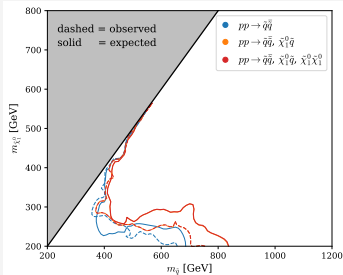
$$H_T = \sum_{|\eta| < 2.4} p_T(j)$$

$$\vec{H}_T^{\text{miss}} = \sum_{|\eta| < 5} \vec{p}_T(j)$$

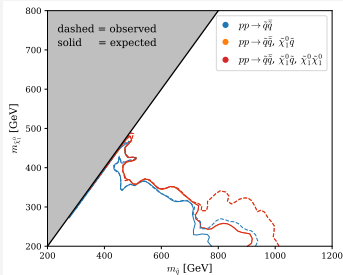
- These preselection cuts are applied always, smaller segments are combined into Signal Regions (SR)

Single analysis exclusion

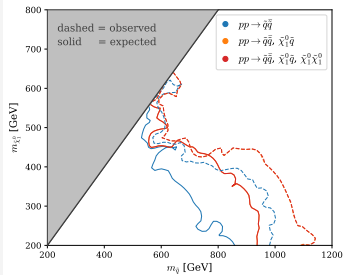
ATLAS-
EXOT



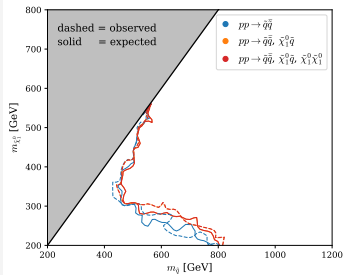
ATLAS-
CONF



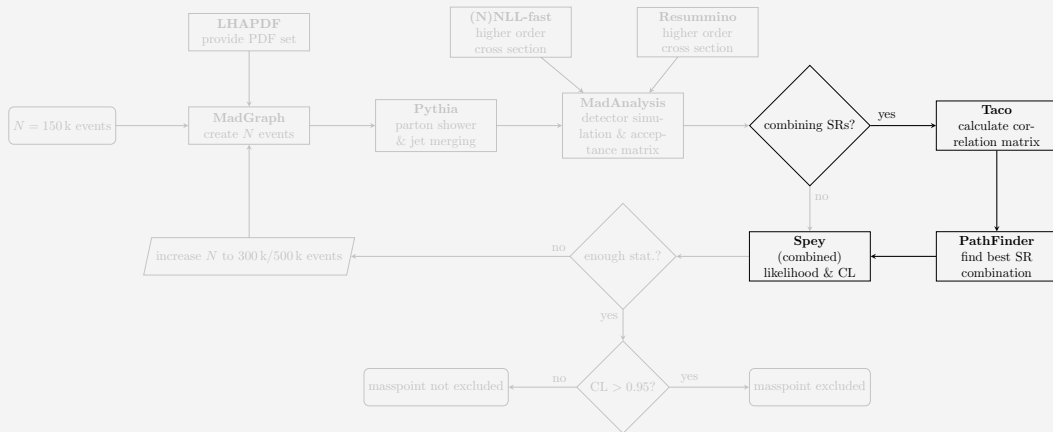
CMS-
SUS



CMS-
EXO



Combination of Signal Regions



Acceptance matrix

► Does an event trigger a signal region?

$$\begin{array}{c} \text{event1}_p \\ \text{event2}_p \\ \vdots \\ \text{event}N_p \end{array} \begin{pmatrix} \text{SR1}_a & \text{SR2}_a & \dots & \text{SR}n_a \\ 1 & 0 & \dots & 1 \\ 0 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{pmatrix}$$

Analysis a with n_a SRs in total

N_p events created for process p

Acceptance matrix

Extension to multiple analyses:

$$\begin{matrix} & S1_1 & S2_1 & \dots & Sn_1 \\ e1_p & \left(\begin{array}{cccc} 1 & 1 & \dots & 1 \end{array} \right) \\ e2_p & \left(\begin{array}{cccc} 1 & 0 & \dots & 1 \end{array} \right) \\ \vdots & \left(\begin{array}{cccc} \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ eN_p & \left(\begin{array}{cccc} 0 & 0 & \dots & 1 \end{array} \right) \end{matrix} \oplus \dots \oplus \begin{matrix} & S1_4 & S2_4 & \dots & Sn_4 \\ e1_p & \left(\begin{array}{cccc} 1 & 0 & \dots & 1 \end{array} \right) \\ e2_p & \left(\begin{array}{cccc} 0 & 1 & \dots & 0 \end{array} \right) \\ \vdots & \left(\begin{array}{cccc} \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ eN_p & \left(\begin{array}{cccc} 1 & 0 & \dots & 0 \end{array} \right) \end{matrix}$$

$$\begin{matrix} & S1_1 & \dots & Sn_1 & S1_2 & \dots & Sn_2 & S1_3 & \dots & Sn_3 & S1_4 & \dots & Sn_4 \\ = & e1_p & \left(\begin{array}{ccccccccc} 1 & \dots & 1 & 0 & \dots & 1 & 0 & \dots & 0 & 1 & \dots & 1 \end{array} \right) \\ \text{horizon.} & e2_p & \left(\begin{array}{ccccccccc} 1 & \dots & 1 & 1 & \dots & 0 & 0 & \dots & 1 & 0 & \dots & 0 \end{array} \right) \\ & \vdots & \left(\begin{array}{ccccccccc} \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ & eN_p & \left(\begin{array}{ccccccccc} 0 & \dots & 1 & 1 & \dots & 1 & 0 & \dots & 0 & 1 & \dots & 0 \end{array} \right) \end{matrix}$$

Extension to multiple processes:

$$\begin{matrix} & S1_1 & \dots & Sn_4 \\ e1_1 & \left(\begin{array}{ccc} 1 & \dots & 1 \end{array} \right) \\ e2_1 & \left(\begin{array}{ccc} 0 & \dots & 1 \end{array} \right) \\ \vdots & \left(\begin{array}{ccc} \vdots & \ddots & \vdots \end{array} \right) \\ eN_1 & \left(\begin{array}{ccc} 0 & \dots & 1 \end{array} \right) \end{matrix} \oplus \dots \oplus \begin{matrix} & S1_1 & \dots & Sn_4 \\ e1_3 & \left(\begin{array}{ccc} 0 & \dots & 1 \end{array} \right) \\ e2_3 & \left(\begin{array}{ccc} 1 & \dots & 0 \end{array} \right) \\ \vdots & \left(\begin{array}{ccc} \vdots & \ddots & \vdots \end{array} \right) \\ eN_3 & \left(\begin{array}{ccc} 0 & \dots & 0 \end{array} \right) \end{matrix} \overset{=}{\text{vert.}} \begin{matrix} & S1_1 & S2_2 & \dots & Sn_4 \\ e1_1 & \left(\begin{array}{cccc} 1 & 0 & \dots & 1 \end{array} \right) \\ \vdots & \left(\begin{array}{cccc} \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ eN_1 & \left(\begin{array}{cccc} 0 & 1 & \dots & 1 \end{array} \right) \\ e1_2 & \left(\begin{array}{cccc} 0 & 0 & \dots & 1 \end{array} \right) \\ \vdots & \left(\begin{array}{cccc} \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ eN_2 & \left(\begin{array}{cccc} 1 & 1 & \dots & 1 \end{array} \right) \\ e1_3 & \left(\begin{array}{cccc} 0 & 1 & \dots & 1 \end{array} \right) \\ \vdots & \left(\begin{array}{cccc} \vdots & \vdots & \ddots & \vdots \end{array} \right) \\ eN_3 & \left(\begin{array}{cccc} 0 & 0 & \dots & 0 \end{array} \right) \end{matrix}$$

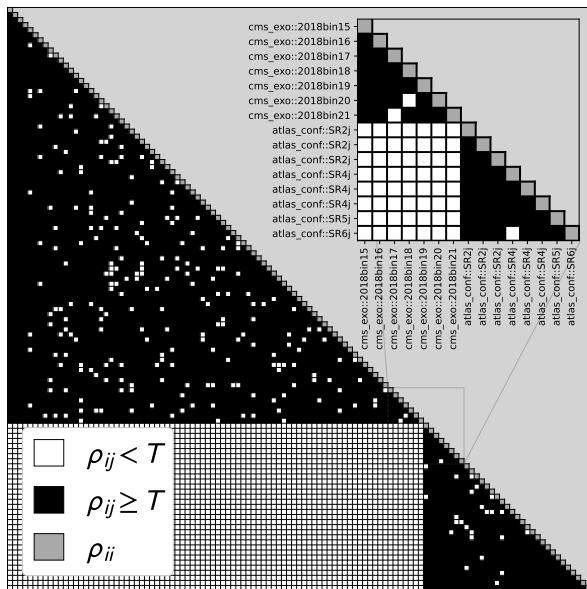
Correlation matrix in TACO⁷

- ▶ Symmetric $\text{SR} \times \text{SR}$ matrix
- ▶ Incorporates all SRs
- ▶ Pearson correlation coefficient

$$\begin{array}{c} \text{SR}1_1 \\ \text{SR}2_1 \\ \vdots \\ \text{SR}(n_4 - 1) \\ \text{SR}n_4 \end{array} \begin{pmatrix} \text{SR}1_1 & \text{SR}2_1 & \cdots & \text{SR}(n_4 - 1) & \text{SR}n_4 \\ 1 & 0.73 & \cdots & 0.002 & 0.43 \\ 0.73 & 1 & \cdots & 0.6 & 0.005 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0.002 & 0.6 & \cdots & 1 & 0.82 \\ 0.43 & 0.005 & \cdots & 0.82 & 1 \end{pmatrix}$$

⁷Araz, J. Y. et al. *SciPost Phys.* **14**, 077. [arXiv: 2209.00025 \[hep-ph\]](#) (2023).

Correlation matrix



► Scenario:

$$pp \rightarrow \tilde{q}\tilde{q}$$

$$m_{\tilde{q}} = 850 \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} = 350 \text{ GeV}$$

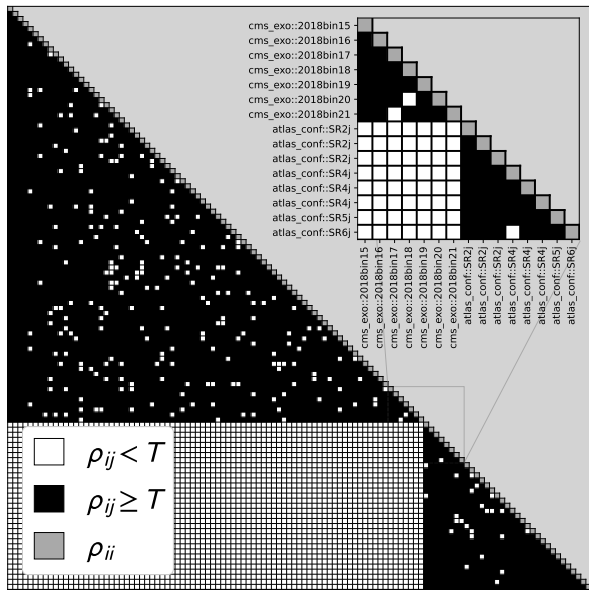
► Threshold $T = 0.01$

► Correlation ρ_{ij}

► White := uncorrelated

► Black := correlated

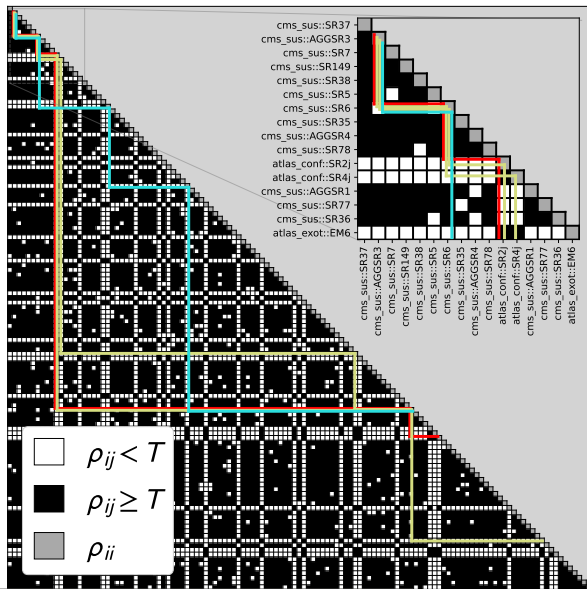
► ATLAS and CMS SRs uncorrelated



$$\mathcal{L}_{\text{combined}}(\mu, \theta) = \prod_{i \in \text{SRs}} \mathcal{L}_i(\mu, \theta_i)$$

$$\mathcal{W} = -\log \left(\frac{\mathcal{L}(1, \hat{\hat{\theta}}(1))}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right)$$

- ▶ Sort signal regions by weight $\mathcal{W}$
- ▶ Combine uncorrelated “path” of signal regions



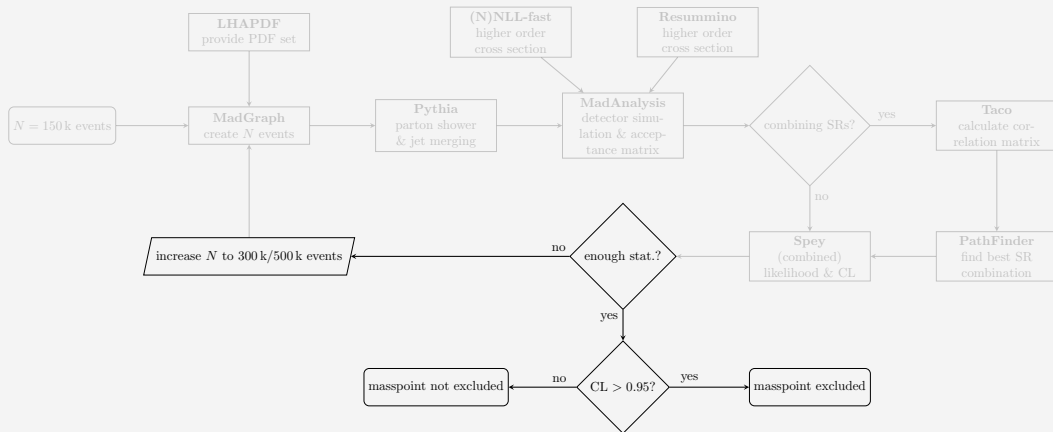
$$\mathcal{L}_{\text{combined}}(\mu, \theta) = \prod_{i \in \text{SRs}} \mathcal{L}_i(\mu, \theta_i)$$

$$\mathcal{W} = -\log \left(\frac{\mathcal{L}(1, \hat{\hat{\theta}}(1))}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right)$$

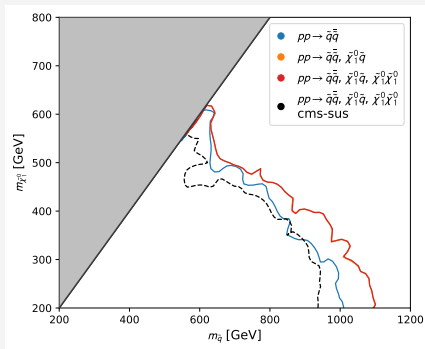
- ▶ Sort signal regions by weight $\mathcal{W}$
- ▶ Combine uncorrelated “path” of signal regions

⁸<https://github.com/J-Yellen/PathFinder>. [Accessed 08-02-2024].

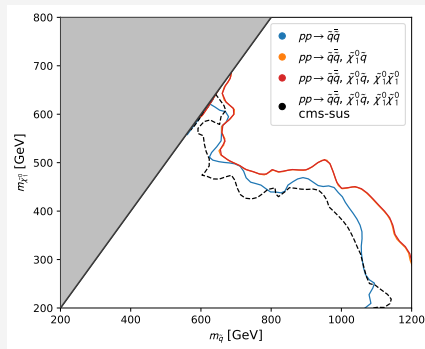
Results



Combined analyses



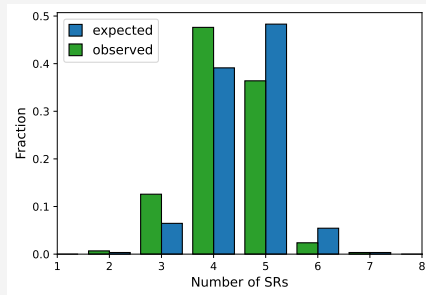
(a) expected



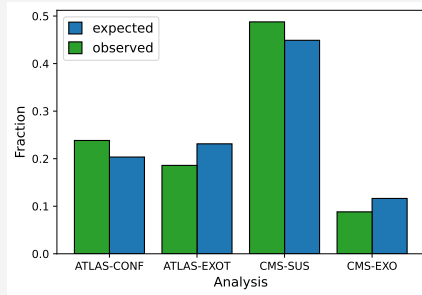
(b) observed

► More gain from combining analyses than from merging events (of different order)

Combined analyses



(a) Number of combined SRs



(b) Share of the different analyses

Conclusion

- ▶ Studied a simplified Bino scenario in the MSSM
- ▶ Higher order events approximated through CKKW-L Merging
- ▶ $\tilde{q}\tilde{\chi}$ process exceeds $\tilde{q}\tilde{q}$ process at $m_{\tilde{q}} \sim 1$ TeV, but $\tilde{\chi}\tilde{\chi}$ is not significant
- ▶ Best analysis for our scenario CMS-SUS, since it's not depending on a hard jets
- ▶ Confidence levels and thereby exclusion limits can be improved by:
 1. Reweighting to higher order resummed cross sections
 2. combining uncorrelated signal regions from different experiments
 3. merging processes samples of similar signature

Thank you!

Matching

- Fixed order calculation with CS-dipole subtraction⁹:

$$\sigma^{\text{NLO}} = \int_3 \left[d\sigma^{\text{R}} - d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_2 \left[d\sigma^{\text{V}} + \int_1 d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_0^1 dx \int_2 \left[d\sigma^{\text{B}}(xp) \otimes (\mathbf{P} + \mathbf{K})(x) \right]_{\epsilon=0}$$

- Hard matching coefficients $C_{ab \rightarrow ij}^{(i)}(M^2, \mu_F^2, \mu_R^2)$

- LO: $C^{(0)} = 1$

$$\mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2)$$

- NLO: compute $C^{(1)} = \sigma_{ab \rightarrow ij}^{(1)}(M^2) / \sigma_{ab \rightarrow ij}^{(0)}(M^2)$ with suppressed 3 particle phase space contributions

$$\mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2) C_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2)$$

⁹Catani, S. et al. *Nucl. Phys. B* **627**, 189–265. arXiv: [hep-ph/0201036](https://arxiv.org/abs/hep-ph/0201036) (2002).

Squark-electroweakino production [2202.13416]

- ▶ Resummed approximate Next-to-Next-to-Leading Order (aNNLO+NNLL) in Resummino for Drell-Yan like process, i.e. slepton-pair or electroweakino-pair
- ▶ SUSY-QCD corrections are only known and matched at NLO (i.e. squark-gluino loop)
- ▶ Valid approximation since they are subdominant due to the large squark and gluino masses
- ▶ Purely electroweak production cross sections for simplified models

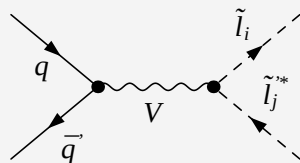


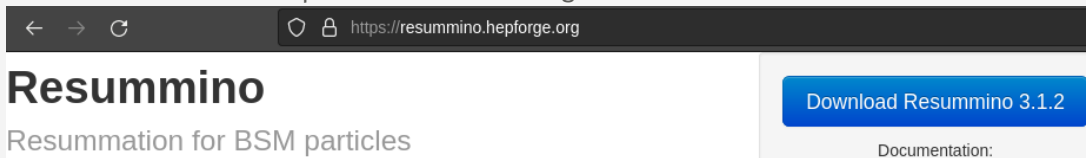
Figure: LO slepton-pair production

final state particle mass	1 TeV	1.5 TeV	2 TeV
$\sigma(13.6 \text{ TeV})/\sigma(13.0 \text{ TeV})$	~ 1.2	~ 1.3	~ 1.6
PDF4LHC21 uncertainty	13-20%	35-60%	>100 %
scale uncertainty	<0.3%	<0.2%	<0.1%

- ▶ Resummation typically reduces the scale dependence from 20% (LO) to 10% (NLO) to <5% (NLO+NLL) to <1% (aNNLO+NNLL)

Resummino

- ▶ Resummino 3.1.2 code published on HEPForge:



- ▶ Approximate NNLO+NNLL for slepton-pair¹⁰, electroweakino-pair¹¹, Z' and W' ¹² production
- ▶ NLO+NLL for electroweakino-gluino¹³ and electroweakino-squark¹⁴ production
- ▶ New in 3.1.2: Apptainer and Docker images¹⁵

¹⁰Fiaschi, J. et al. *JHEP* **04**, 049. arXiv: 1911.02419 [hep-ph] (2020).

¹¹Fiaschi, J. & Klasen, M. *Phys. Rev. D* **102**, 095021. arXiv: 2006.02294 [hep-ph] (2020).

¹²Jezo, T. et al. *JHEP* **12**, 092. arXiv: 1410.4692 [hep-ph] (2014).

¹³Fuks, B. et al. *JHEP* **07**, 053. arXiv: 1604.01023 [hep-ph] (2016).

¹⁴Fiaschi, J. et al. *JHEP* **06**, 130. arXiv: 2202.13416 [hep-ph] (2022).

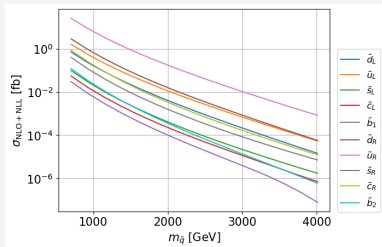
¹⁵Fiaschi, J. et al. *Eur. Phys. J. C* **83**, 707. arXiv: 2304.11915 [hep-ph] (2023).

Python interface to Resummino and others ((N)NLL-fast, SPheno, SoftSusy, Prospino2, FeynHiggs, MadGraph)

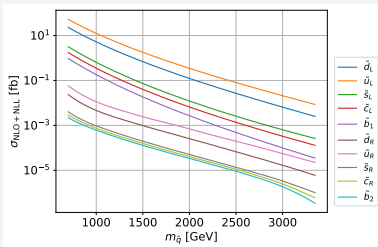
- ▶ Scan masses
- ▶ Scan PDFs and scales and combine them to uncertainty bands
- ▶ Generate Resummino run files for distribution across clusters
- ▶ Collect results into a single json file¹⁶ and plot them
- ▶ Interpolate 1D and 2D json scans (hepi-fast)
- ▶ Install with “pip install hepi”
- ▶ <https://github.com/APN-Pucky/HEPi>
- ▶ <https://hepi.readthedocs.io/en/latest/>

¹⁶Following: <https://github.com/fuenfundachtzig/xsec>

Bino vs Wino



(a) Bino: $pp \rightarrow \tilde{\chi}_1^0$



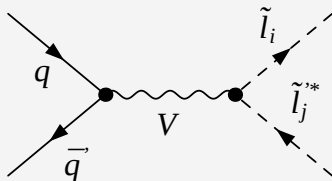
(b) Wino: $pp \rightarrow \tilde{\chi}_2^0$

► Bino is suppressed by one order of magnitude compared to Wino

Resummed approximate Next-to-Next-to-Leading Order

- ▶ NNLO+NNLL resummation for Drell-Yan process requires:

- ▶ Extra NNLL terms¹⁷ to universal expansion of the Sudakov exponential G
- ▶ Hard matching coefficients¹⁸ C to NNLO



- ▶ Supported in Resummino for Drell-Yan like process, i.e. slepton-pair or electroweakino-pair

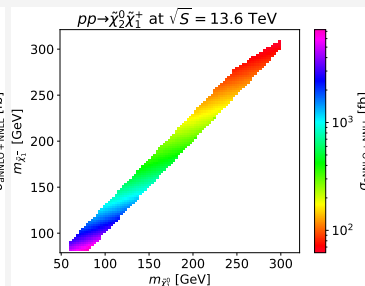
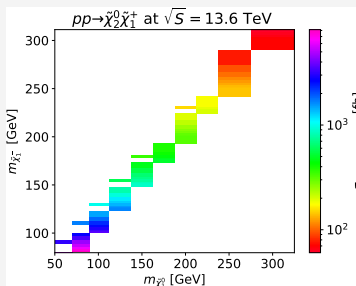
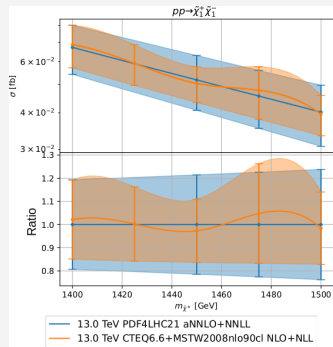
- ▶ But no fixed-order NNLO calculation is available to match against
- ▶ $\implies$ SUSY-QCD (squark-gluino loop) corrections are only matched at NLO
- ▶ Valid approximation since SUSY-QCD corrections are subdominant due to the large squark and gluino masses

¹⁷Vogt, A. *Phys. Lett. B* **497**, 228–234. arXiv: [hep-ph/0010146](#) (2001), Moch, S. et al. *Nucl. Phys. B* **726**, 317–335. arXiv: [hep-ph/0506288](#) (2005).

¹⁸Kidonakis, N. *Int. J. Mod. Phys. A* **19**, 1793–1821. arXiv: [hep-ph/0303186](#) (2004), Kidonakis, N. *Phys. Rev. D* **77**, 053008. arXiv: [0711.0142 \[hep-ph\]](#) (2008).

Interpolation

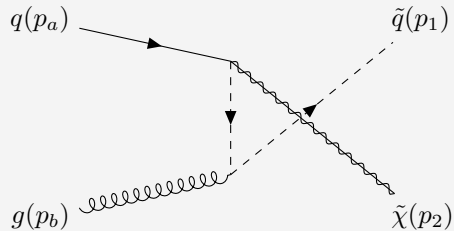
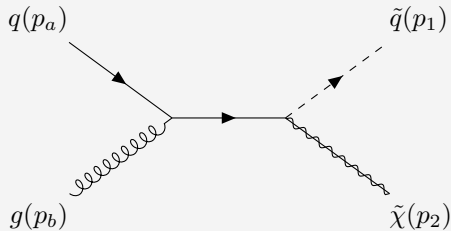
- ▶ Interpolate in Log-space since mass dependence often results in a power law
- ▶ Spline in 1D and LinearND¹⁹ in 2D yield reliable results
- ▶ PDF4LHC21 is better interpolated, but has larger uncertainties in the high mass regime



¹⁹Virtanen, P. et al. *Nature Methods* **17**, 261–272 (2020), Barber, C. B. et al. *ACM Trans. Math. Softw.* **22**, 469–483. ISSN: 0098-3500. <https://doi.org/10.1145/235815.235821> (Dec. 1996).

Squark and Electroweakino Production

- ▶ In the MSSM R-Parity implies production of SUSY particles in even numbers
- ▶ Expect dominant production of squark pairs and gluino pairs
- ▶ Production at the LHC might be restricted by heavy masses



- ▶ Squark and (lighter) electroweakino better LHC production candidate
- ▶ LO²⁰ and NLO²¹ corrections are known

²⁰Dawson, S. et al. *Phys. Rev. D* **31**, 1581 (1985).

²¹Binoth, T. et al. *Phys. Rev. D* **84**, 075005. [arXiv: 1108.1250 \[hep-ph\] \(2011\)](#), Frixione, S. et al. *JHEP* **12**, 008. [arXiv: 1907.04898 \[hep-ph\] \(2019\)](#), Baglio, J. et al. *JHEP* **12**, 020. [arXiv: 2110.04211 \[hep-ph\] \(2021\)](#).

Resummation

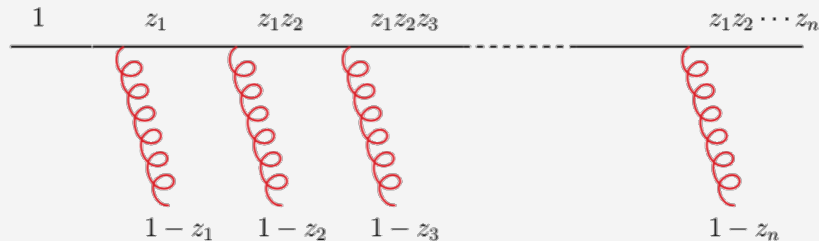
- ▶ Massive particles are mostly produced close to threshold ($M^2/s = z \rightarrow 1$)²²
- ▶ Perturbative expansion in α_s is spoiled by

Large Sudakov logarithms ($m \leq 2n - 1$)

$$\left(\frac{\alpha_s}{2\pi}\right)^n \frac{\log^m(1-z)}{1-z}$$

$$\left(\frac{\alpha_s}{2\pi}\right)^n \log^m \left(\frac{M^2}{p_T^2}\right)$$

- ▶ Solution: Resummation of all soft emitted gluons



²²Catani, S. & Trentadue, L. *Nucl. Phys. B* **327**, 323–352 (1989).

Resummation

► Transforming to Mellin space

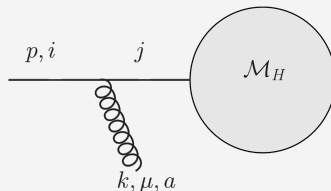
$$F(N) = \int_0^1 dy y^{N-1} F(y) \quad \Rightarrow \quad \left[\frac{\log^m(1-z)}{1-z} \right]_+ \xrightarrow{F} \sim \log^{m+1} N + \dots$$

factorizes the phase space

$$\int dz z^{N-1} d\phi_{2+n}(z) \approx d\phi_2 \times d\phi_n(N)$$

► Dynamical Factorisation is achieved by the eikonal approximation

$$\Gamma_{\text{eik}}^\mu = g_s T^j \frac{\Delta_i v^\mu}{\delta_i v \cdot k + i\epsilon}$$



Resummation

- ▶ From factorization theorem we split hard and long distance behaviour

$$\sigma(M^2, m^2) = \mathcal{H}(M^2/\mu_F^2) \mathcal{S}(m^2/\mu_F^2)$$

- ▶ Require independence on scale μ_F

$$\sigma(M^2, m^2) = \mathcal{H}(1) \mathcal{S}(1) \exp \left[- \int_{m^2}^{M^2} \frac{dk}{k^2} \gamma_s(k^2) \right]$$

- ▶ From applying the RGEs we get²³:

$$\sigma^{\text{Res.}}(N, M^2, \mu_R^2, \mu_F^2) = \mathcal{H}_{ab}(M^2, \mu_R^2, \mu_F^2) \exp [G_{ab}(N, M^2, \mu_R^2, \mu_F^2)] + \mathcal{O} \left(\frac{1}{N} \right)$$

with

$$G_{ab}(N, M^2, \mu_R^2, \mu_F^2) = \underbrace{LG_{ab}^{(1)}(N)}_{\text{Leading Log } \sim \log^2(N)} + \underbrace{G_{ab \rightarrow ij}^{(2)}(N, M^2, \mu_F^2, \mu_R^2)}_{\text{Next-to-Leading Log } \sim \log(N)} + \dots$$

²³Kidonakis, N. et al. [Nucl. Phys. B 525, 299–332. arXiv: hep-ph/9801268 \(1998\).](#)

Matching

- Fixed order calculation with CS-dipole subtraction²⁴:

$$\sigma^{\text{NLO}} = \int_3 \left[d\sigma^{\text{R}} - d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_2 \left[d\sigma^{\text{V}} + \int_1 d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_0^1 dx \int_2 \left[d\sigma^{\text{B}}(xp) \otimes (\mathbf{P} + \mathbf{K})(x) \right]_{\epsilon=0}$$

- Hard matching coefficients $C_{ab \rightarrow ij}^{(i)}(M^2, \mu_F^2, \mu_R^2)$

- LO: $C^{(0)} = 1$

$$\mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2)$$

- NLO: compute $C^{(1)} = \sigma_{ab \rightarrow ij}^{(1)}(M^2) / \sigma_{ab \rightarrow ij}^{(0)}(M^2)$ with suppressed 3 particle phase space contributions

$$\mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2) C_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2)$$

²⁴Catani, S. et al. *Nucl. Phys. B* **627**, 189–265. arXiv: [hep-ph/0201036](https://arxiv.org/abs/hep-ph/0201036) (2002).

Re-expansion

- To avoid double counting in:

$$\sigma_{ab} = \sigma_{ab}^{\text{NLO}} + \underbrace{\sigma_{ab}^{\text{Res.}} - \sigma_{ab}^{\text{Exp.}}}_{\sigma_{ab}^{\text{NLL}}}$$

- Subtract expansion in α_s :

$$\begin{aligned} \sigma_{ab}^{\text{Exp.}} &= \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) \\ &\times \left(\left(A_a^{(1)} + A_b^{(1)} \right) \left(\log \bar{N} + \log \frac{\mu_F^2}{s} \right) - 2D_{ab \rightarrow ij}^{(1)} \right) \log \bar{N} \end{aligned}$$

- PDFs fitted in Mellin space

- Inverse Mellin transformation with the integration contour following the principal value procedure and minimal prescription:

$$M^2 \frac{d\sigma_{AB}}{dM^2}(\tau) = \frac{1}{2\pi i} \int dN \tau^{-N} M^2 \frac{d\sigma_{AB}}{dM^2}(N).$$

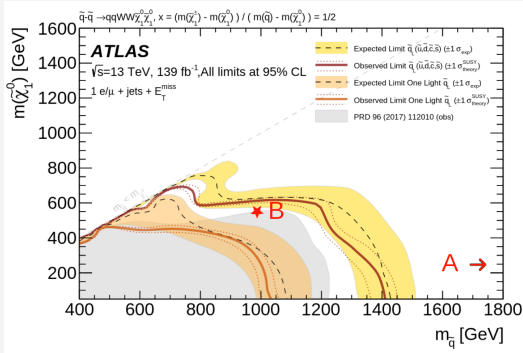
Scenarios

pMSSM-11 scenario A [TeV]		
M_1 0.25	M_2 0.25	M_3 −3.86
$M_{(U,D,Q)_{1,2}}$ 4.0	$M_{(U,D,Q)_3}$ 1.7	μ 1.33
$M_{(L,E)_{1,2}}$ 0.35	$M_{(L,E)_3}$ 0.47	$\tan \beta$ 36
M_A 4.0	A_0 2.8	
$m_{\tilde{\chi}_1^0}$ 0.249	$m_{\tilde{u}}$ 4.07	$m_{\tilde{g}}$ 3.90

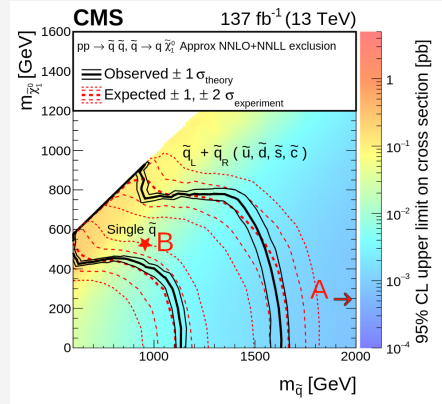
pMSSM-11 scenario B [TeV]		
M_1 0.51	M_2 0.48	M_3 3.00
$M_{(U,D,Q)_{1,2}}$ 0.9	$M_{(U,D,Q)_3}$ 2.0	μ −9.4
$M_{(L,E)_{1,2}}$ 1.85	$M_{(L,E)_3}$ 1.33	$\tan \beta$ 33
M_A 3.0	A_0 −3.4	
$m_{\tilde{\chi}_1^0}$ 0.505	$m_{\tilde{u}}$ 0.96	$m_{\tilde{g}}$ 2.94

Current Limits

ATLAS²⁵



CMS²⁶

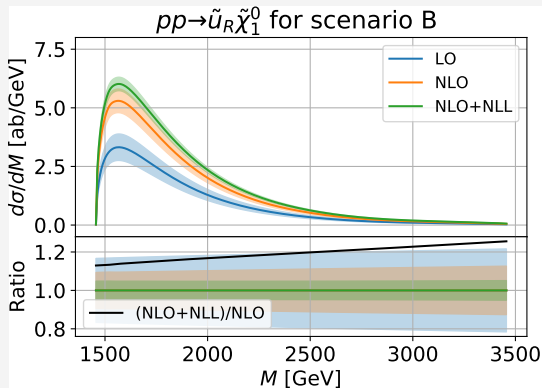
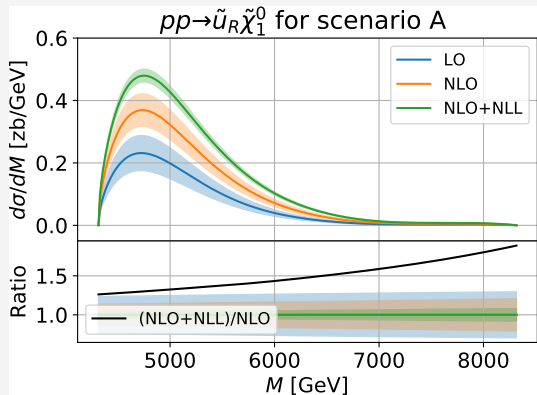


²⁵Aad, G. et al. *Eur. Phys. J. C* **81**. [Erratum: *Eur.Phys.J.C* 81, 956 (2021)], 600. arXiv: 2101.01629 [hep-ex] (2021).

²⁶Sirunyan, A. M. et al. *JHEP* **10**, 244. arXiv: 1908.04722 [hep-ex] (2019).

Invariant Mass

► $\sqrt{S} = 13$ TeV and MSHT20 PDF

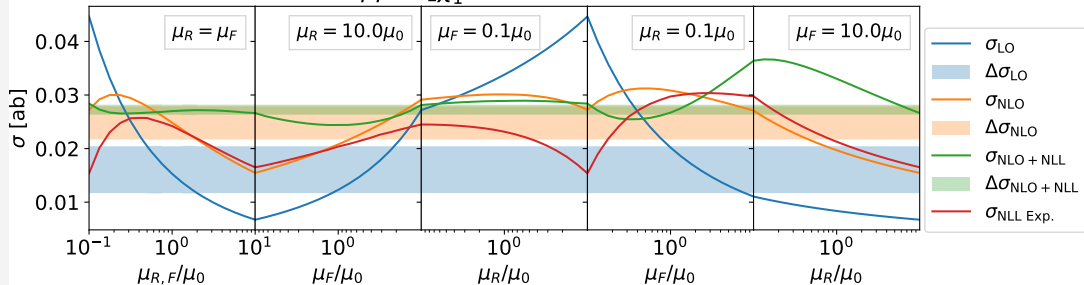


► Large resummation contributions very close to threshold

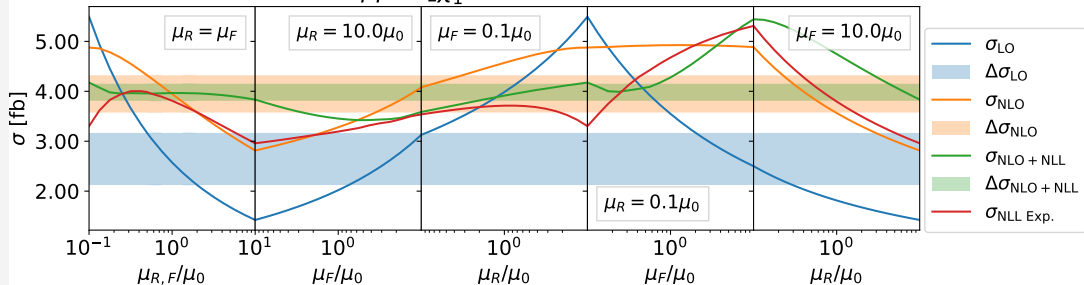
► Seven-point method around scale $\mu = M$ to estimate scale uncertainties

Scale Variation

$pp \rightarrow \tilde{u}_L \tilde{\chi}_1^0$ for scenario A

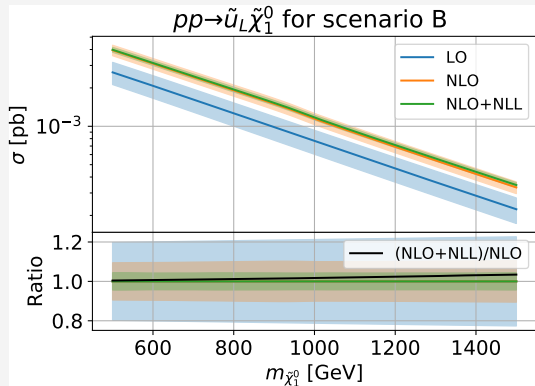
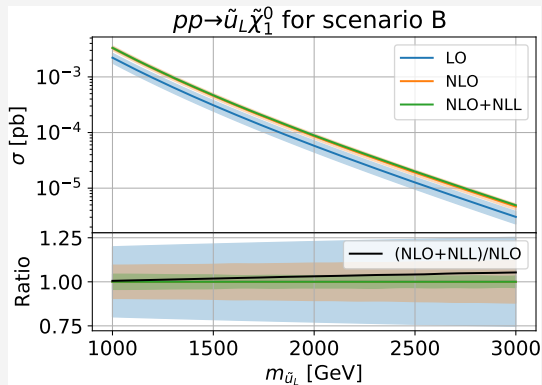


$pp \rightarrow \tilde{u}_L \tilde{\chi}_1^0$ for scenario B



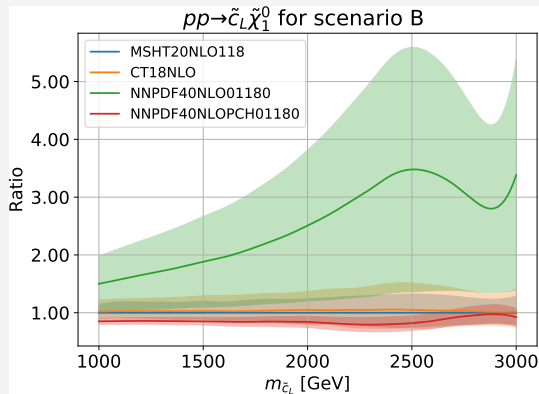
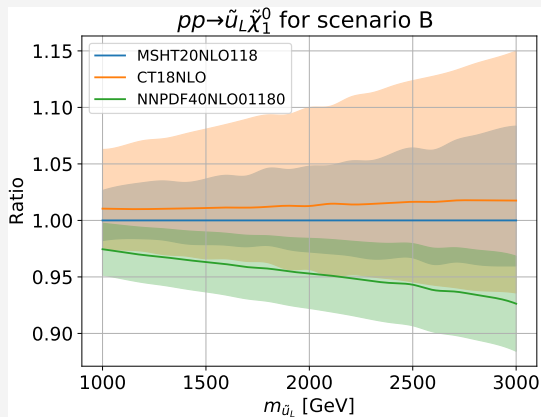
Note: panels 2 and 3 are inverted.

Total Cross sections



- ▶ NLL contributions of up to 6%
- ▶ Scale uncertainty reduced to $< 5\%$

Parton density uncertainties

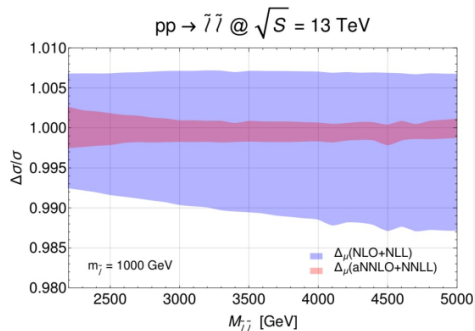
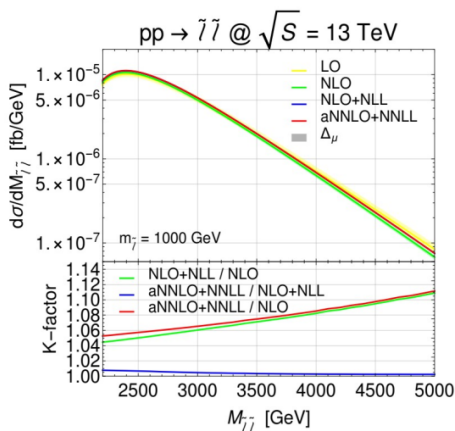


- ▶ Up-PDF uncertainties at 90% CL are consistent
- ▶ For 2 TeV up-squarks they range from $\pm 4\%$ to $\pm 7\%$
- ▶ Difference in NNPDF40's fitted charm and perturbative charm treatment.

Conclusion

- ▶ Production of squark/gluino with gaugino relevant if squark and gluino pair production are too heavy for the LHC
- ▶ We computed QCD-NLO corrections with CS-dipoles and OS-subtraction for the NLL matching of soft gluon emissions
- ▶ Resummation increases the σ_{tot} by 2% to 6% for squark masses ranging from 1 TeV to 3 TeV
- ▶ Renormalisation and Factorisation scale dependence is reduced from 20% (LO) to 10% (NLO) to <5% (NLO+NLL)
- ▶ Current PDF uncertainties are of the same order as scale uncertainties after Resummation

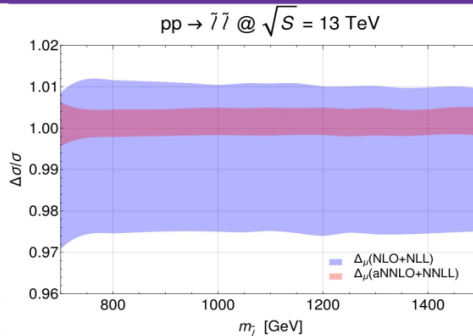
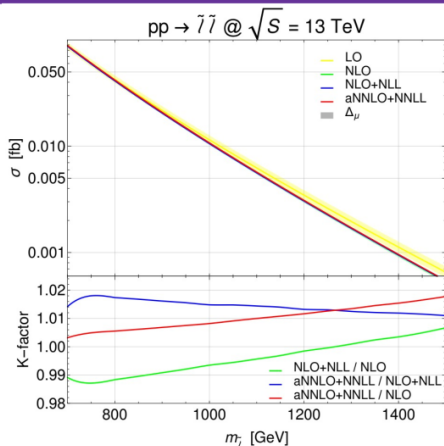
Slepton pair production



➤ Visible reduction of scale uncertainty
from about 1% to about 0.1%.

- Resummation effects at NLL are more important at production threshold.
- K-factor increases from 4.5% to 11%
- The increase from NLO+NLL to aNNLO+NNLL is about 1%

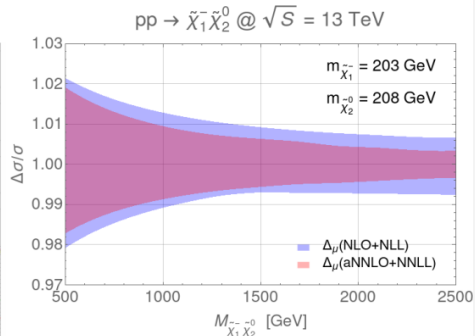
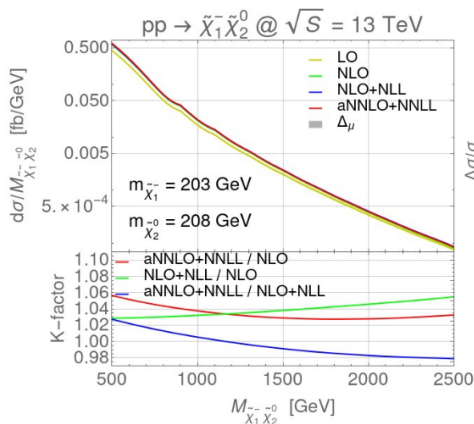
Slepton pair production



➤ Visible reduction of scale uncertainty from few % to few 0.1%.

- These cross sections correspond to:
 - more than 10 events at 700 GeV at current integrated luminosity of 139 fb^{-1} ;
 - 3 events at 1 TeV for LHC Run 3 goal of 300 fb^{-1} ;
 - Few events at 1.5 TeV for HL-LHC goal of 3 ab^{-1}
- aNNLO(+NNLL) corrections increase the NLO(+NNLL) prediction by 1% - 2%.

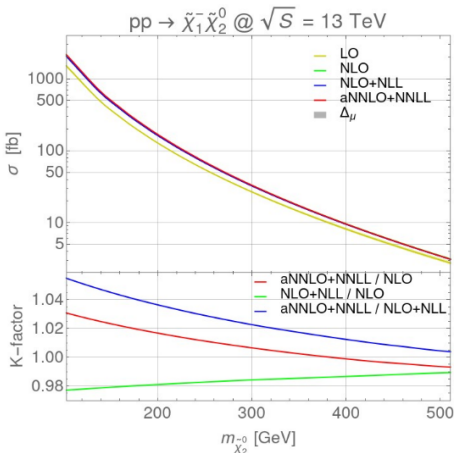
Mostly Higgsino Electroweakinos



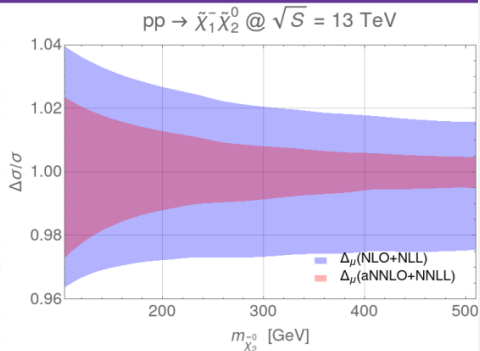
- Visible reduction of scale uncertainty from about from $\pm 2.1\%$ to $\pm 1.8\%$ ($\pm 0.6\%$ to $\pm 0.4\%$) at low (large) invariant masses.

- NLO corrections enhance the LO cross section by about 30%.
- NLL corrections enhance the NLO cross section by another 3-5%.
- aNNLO+NNLL give another $\pm 2\%$ correction to the NLO+NLL cross section.

Mostly Higgsino Electroweakinos



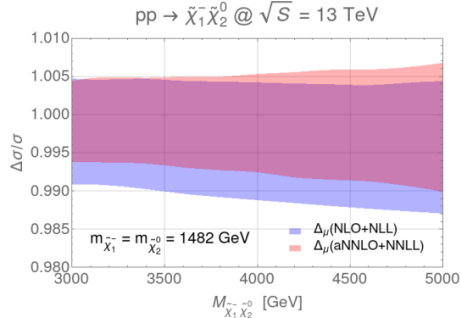
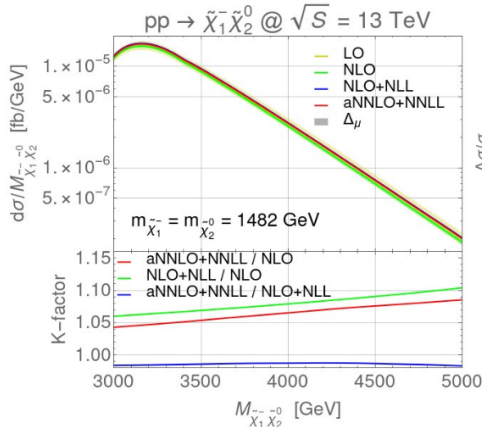
- NLL corrections reduce the NLO cross section by 1% to 2%.
- aNNLO+NNLL corrections increase the NLO+NLL cross section by up to 5% for low higgsino masses.



- Visible reduction of scale uncertainty from about from $\pm 4\%$ to $\pm 2.5\%$ (+1.5% and -2.5% to $\pm 0.5\%$) for light (heavy) Higgsinos

(Scale uncertainties are not so small, because of the relatively light Higgsino masses)

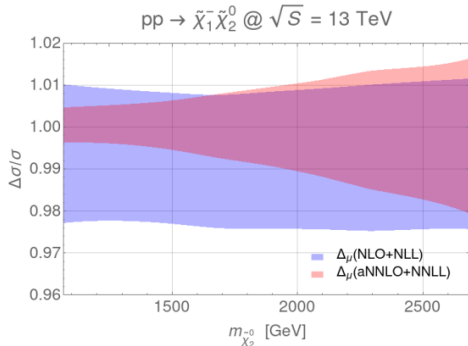
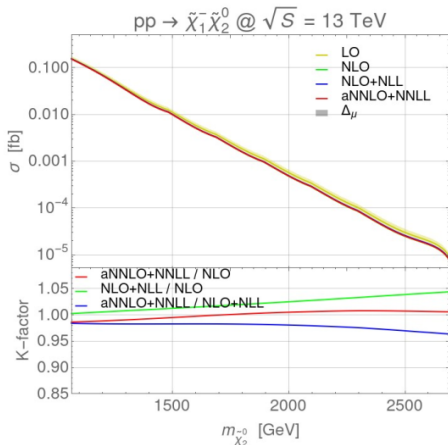
Mostly gauginos Electroweakinos



- Reduction of scale uncertainty on the lower bound from -0.9% to -0.6% at low invariant masses.

- NLL corrections increase the cross section between 5% to 10%.
- A decrease for all invariant masses is observed from NLO+NLL to aNNLO+NNLL.
- This behavior is correlated with large t - and u -channel contributions and large cancellations of the squared s -channel contribution with its interference terms.

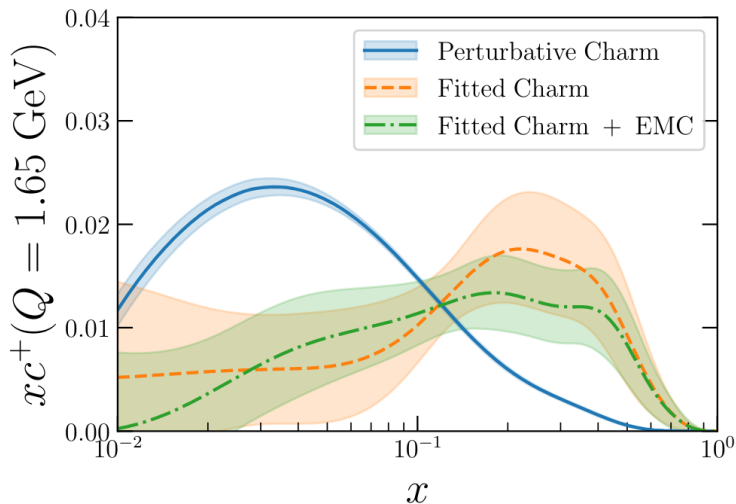
Mostly gauginos Electroweakinos



- Scale uncertainty gets reduced from 3% to about 1% for light gauginos, while it is stable at around 3% for heavy gauginos

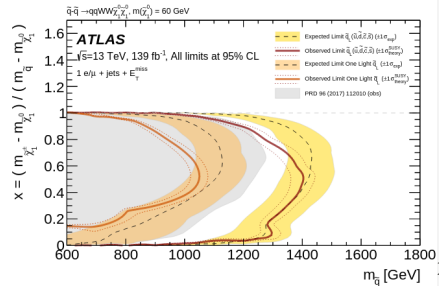
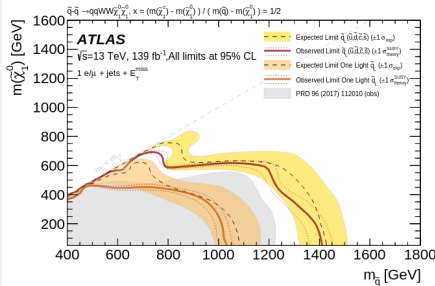
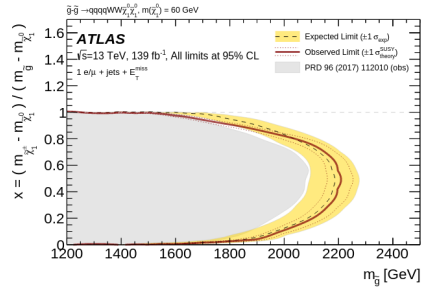
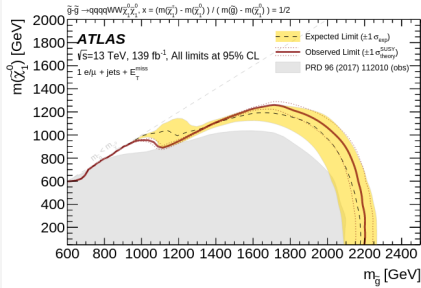
- NLL corrections increase the NLO cross section by up to 5%.
- aNNLO+NNLL corrections reduce the NLO+NLL cross section by up to 4% for high gaugino masses.

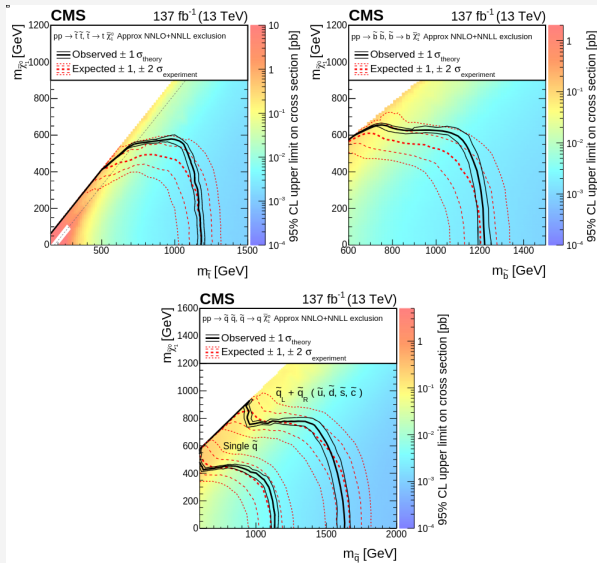
NNPDF40 charm



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²⁷Rojo, J. in 55th Rencontres de Moriond on QCD and High Energy Interactions (Apr. 2021). arXiv: 2104.09174 [hep-ph].





PDF fitting

To perform our computation in Mellin space we still need to transform the PDFs. This is achieved by fitting them in x-space to the function used by the MSTW collaboration

$$f(x) = A_0 x^{A_1} (1-x)^{A_2} (1 + A_3 \sqrt{x} + A_4 x + A_5 x^{\frac{3}{2}}) + A_6 x^2 + A_7 x^{\frac{5}{2}},$$

with the analytical result in Mellin space

$$F(x) = A_0 \Gamma(y) B'(A_1 + N, y) + A_3 B'(A_1 + N + \frac{1}{2}, y) + A_4 B'(A_1 + N + 1, y) \\ + A_5 B'(A_1 + N + \frac{3}{2}, y) + A_6 B'(A_1 + N + 2, y) + A_7 B'(A_1 + N + \frac{5}{2}, y)$$

and

$$B'(x, y) = B'(x, A_2 + 1) = B(x, y) / \Gamma(y) = B(x, y) / \Gamma(y).$$