Title: Soft and Coulomb resummation: squark and gluino production at the LHC

Date: Jul 09, 2013 01:00 PM

URL: http://pirsa.org/13070034

Abstract: We consider the production of strongly interacting, heavy SUSY pairs at the LHC. When the centre of mass energy is close to the production threshold of the pair, the corresponding cross sections receive large higher-loop QCD corrections. These corrections are classified as the so-called soft logarithms and Coulomb singularities and they lead to a break down of the usual perturbation expansion. In this talk I review the origin of these large corrections and explain how they can be resummed by using Effective Field theories. Finally, I will present some resummed results for the pair production cross sections of heavy squarks and gluinos. Based on: arXiv:1202.2260 and 1211.3408.

Soft and Coulomb resummation: squark and gluino production at the LHC

Chris Wever (ITF Utrecht, NCSR Demokritos)

Based on: P. Falgari, C. Schwinn, CW [arXiv: 1202.2260 [hep-ph], 1211.3408 [hep-ph]]

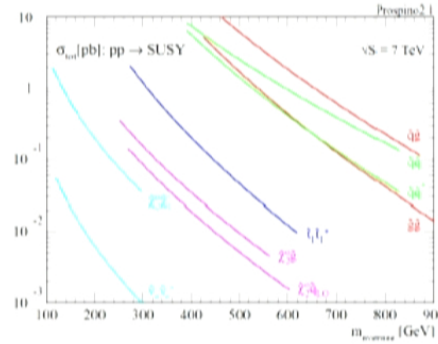
Particle Physics Seminar, Perimeter Institute, 9 July 2013

Outline

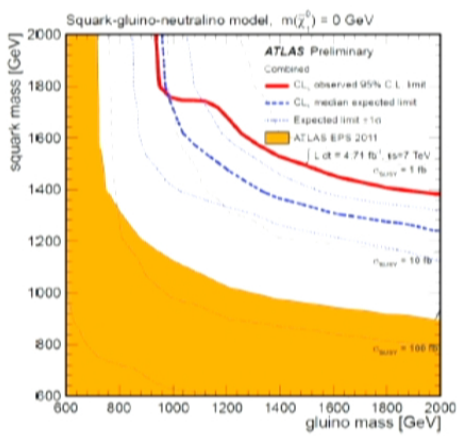
- Squark and gluino pair production
- Threshold corrections
- EFT: factorization & resummation
- Scales and errors
- Results
- Summary and outlook

Motivation

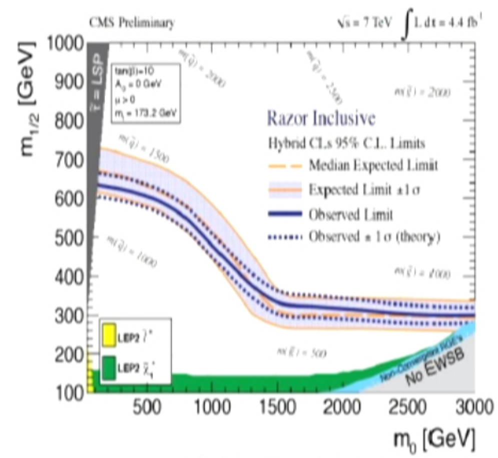
- SUSY searches important at LHC
- In R-parity conserving models (e.g. MSSM) SUSY particles are produced in pairs
- Main production: squark and gluino pairs
- Strongly model dependent: SUSY bounds
- Model independent predictions required



[Plehn, Prospino 2.1]



[ATLAS, 03-2012]



[CMS, 03-2012]

Squark and gluino production

- Hadronic processes: $PP \to \tilde{s}\tilde{s}' X$ $\tilde{s}, \tilde{s}'$ = squarks, gluinos

  Factorize hadronic cs in parton luminosities and partonic cs:

$$\sigma_{PP \to \tilde{s}\tilde{s}' X}(s) = \int_{\tau_0}^{1} d\tau \sum_{p,p'=q,\bar{q},g} L_{pp'}(\tau, \mu_f)\hat{\sigma}_{pp' \to \tilde{s}\tilde{s}' X}(\tau s, \mu_f)$$

- Partonic processes:

$$\begin{aligned} gg,\, q_i\bar{q}_j &\to \tilde{q}\bar{\tilde{q}} \\ q_i q_j &\to \tilde{q}\tilde{q} \qquad \bar{q}_i\bar{q}_j \to \bar{\tilde{q}}\bar{\tilde{q}} \\ g q_i &\to \tilde{g}\tilde{q} \qquad g\bar{q}_i \to \tilde{g}\bar{\tilde{q}} \\ gg,\, q_i\bar{q}_i &\to \tilde{g}\tilde{g} \end{aligned}$$

- Primarily proceed through strong interactions ⟶ focus on QCD interactions

Squark and gluino production

- Hadronic processes: $PP \to \tilde{s}\tilde{s}' X$ $\quad \tilde{s}, \tilde{s}' = \text{squarks, gluinos}$

  Factorize hadronic cs in parton luminosities and partonic cs:

$$\sigma_{PP \to \tilde{s}\tilde{s}' X}(s) = \int_{\tau_0}^{1} d\tau \sum_{p,p'=q,\bar{q},g} L_{pp'}(\tau, \mu_f) \hat{\sigma}_{pp' \to \tilde{s}\tilde{s}' X}(\tau s, \mu_f)$$

- Partonic processes:

$$\begin{aligned} gg,\, q_i\bar{q}_j &\to \tilde{q}\bar{\tilde{q}} \\ q_i q_j &\to \tilde{q}\tilde{q} \qquad \bar{q}_i\bar{q}_j \to \bar{\tilde{q}}\bar{\tilde{q}} \\ g q_i &\to \tilde{g}\tilde{q} \qquad g\bar{q}_i \to \tilde{g}\bar{\tilde{q}} \\ gg,\, q_i\bar{q}_i &\to \tilde{g}\tilde{g} \end{aligned}$$

- Primarily proceed through strong interactions ⟶ focus on QCD interactions

• Analytic LO calculations in 80's [Kane, Leveille '82; Harisson, Smith '83; Dawson, Eichten, Quigg '85]
• Numeric NLO calculations in 90's [Beenakker et al. '95-'97; Prospino 1]
• Prospino 2 [Plehn '04-'12]

- Heavy pairs $s \gtrsim 2M := m_{\tilde{s}} + m_{\tilde{s}'}$ ⟶ close to threshold

Squark and gluino production

- Hadronic processes: $PP \to \tilde{s}\tilde{s}' X$ $\quad \tilde{s}, \tilde{s}' = \text{squarks, gluinos}$

  Factorize hadronic cs in parton luminosities and partonic cs:

$$\sigma_{PP\to\tilde{s}\tilde{s}'X}(s) = \int_{\tau_0}^{1} d\tau \sum_{p,p'=q,\bar{q},g} L_{pp'}(\tau,\mu_f)\hat{\sigma}_{pp'\to\tilde{s}\tilde{s}'X}(\tau s,\mu_f)$$

- Partonic processes:

$$\begin{aligned} gg,\ q_i\bar{q}_j &\to \tilde{q}\bar{\tilde{q}} \\ q_iq_j &\to \tilde{q}\tilde{q} \qquad \bar{q}_i\bar{q}_j \to \bar{\tilde{q}}\bar{\tilde{q}} \\ gq_i &\to \tilde{g}\tilde{q} \qquad g\bar{q}_i \to \tilde{g}\bar{\tilde{q}} \\ gg,\ q_i\bar{q}_i &\to \tilde{g}\tilde{g} \end{aligned}$$

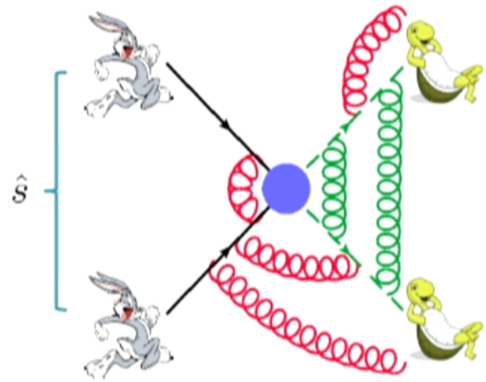
- Primarily proceed through strong interactions $\longrightarrow$ focus on QCD interactions

• Analytic LO calculations in 80's [Kane, Leveille '82; Harisson, Smith '83; Dawson, Eichten, Quigg '85]
• Numeric NLO calculations in 90's [Beenakker et al. '95-'97; Prospino 1]
• Prospino 2 [Plehn '04-'12]

- Heavy pairs $s \gtrsim 2M := m_{\tilde{s}} + m_{\tilde{s}'}$ $\longrightarrow$ close to threshold

Threshold

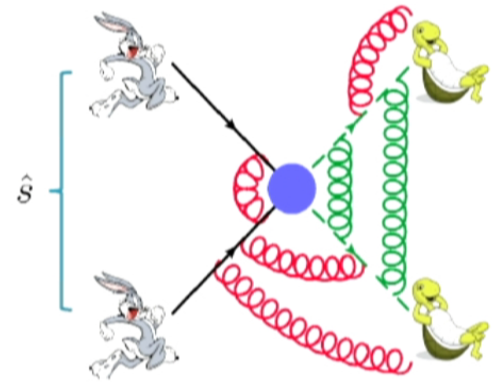
- Partonic processes: $pp' \to \tilde{s}\tilde{s}' X$ $\quad p, p' = \text{partons}$, $\tilde{s}, \tilde{s}' = \text{squarks,gluinos}$
- Threshold region: $\beta := \sqrt{1 - \frac{(2M)^2}{\hat{s}}} \ll 1, \quad M := \frac{m_{\tilde{s}} + m_{\tilde{s}'}}{2}, \quad \hat{s} = \tau s = \text{partonic cm energy}$



- Two types of large corrections near threshold:

Threshold

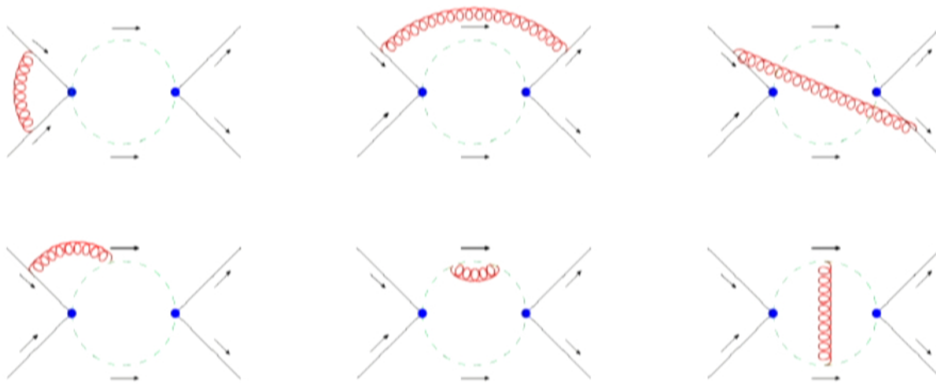
- Partonic processes: $pp' \to \tilde{s}\tilde{s}' X$ $\quad p, p' = \text{partons}$, $\tilde{s}, \tilde{s}' = \text{squarks,gluinos}$
- Threshold region: $\beta := \sqrt{1 - \frac{(2M)^2}{\hat{s}}} \ll 1, \quad M := \frac{m_{\tilde{s}} + m_{\tilde{s}'}}{2}, \quad \hat{s} = \tau s = \text{partonic cm energy}$



- Two types of large corrections near threshold:
- Soft/Sudakov logarithms from soft gluon exchanges: $\alpha_s^k \ln^l \beta$ (soft: $k_0 \sim |k| \sim M\beta^2$)
- Coulomb corrections from potential gluon exchanges: $(\alpha_s/\beta)^n$ (potential: $k_0 \sim M\beta^2, |k| \sim M\beta$)

Threshold: one-loop corrections

- Soft logarithms from soft gluons: $k_0 \sim |k| \sim M\beta^2$



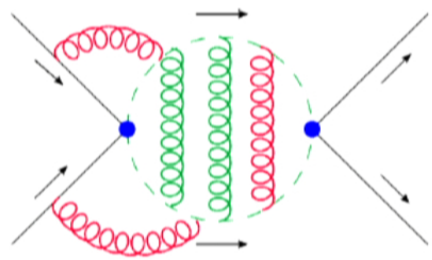
$\sim \alpha_s(\ln^2\beta + \ln\beta + \ldots)$

- Coulomb corrections from potential gluon exchanges: $k_0 \sim M\beta^2, |k| \sim M\beta$

$\sim (\alpha_s/\beta)$

Threshold: higher-loop corrections

- Higher loop amplitudes containing both soft and potential gluon exchanges:



$\longrightarrow \quad \sim \alpha_s^k \ln^l \beta / \beta^m$

- Threshold: $\longrightarrow \quad \beta \ll 1 \quad \longrightarrow \quad (\alpha_s/\beta)^n, \alpha_s^n \ln^m \beta \gg 1$

$\longrightarrow$ usual perturbative series breaks down

- Form only depends on structure of QCD interactions $\longrightarrow$ all SM extensions

Perturbation breakdown

- Threshold: $\longrightarrow$ $\beta \ll 1$ $\longrightarrow$ $(\alpha_s/\beta)^n, \alpha_s^n \ln^m \beta \gg 1$
- Partonic cs enhanced near threshold by soft and Coulomb corrections $\longrightarrow$ need to resum
- Parametrize: $\alpha_s \ll 1$ $\longrightarrow$ $\alpha_s \ln \beta, \left(\frac{\alpha_s}{\beta}\right) \sim 1$

$$\hat{\sigma}_{pp'}(\hat{s}) \sim \hat{\sigma}^{(0)}_{pp'} \sum_{k=0} f_k(\beta)\alpha_s^k \longrightarrow \hat{\sigma}_{pp'}(\hat{s}) \sim \hat{\sigma}^{(0)}_{pp'} \sum_{k,l,m=0} \tilde{f}_{klm}(\beta)\left(\frac{\alpha_s}{\beta}\right)^k \alpha_s^l \ln^m \beta$$

Perturbation breakdown

- Threshold: $\longrightarrow$ $\beta \ll 1$ $\longrightarrow$ $(\alpha_s/\beta)^n, \alpha_s^n \ln^m \beta \gg 1$
- Partonic cs enhanced near threshold by soft and Coulomb corrections $\longrightarrow$ need to resum
- Parametrize: $\alpha_s \ll 1$ $\longrightarrow$ $\alpha_s \ln \beta, \left(\frac{\alpha_s}{\beta}\right) \sim 1$

$$\hat{\sigma}_{pp'}(\hat{s}) \sim \hat{\sigma}^{(0)}_{pp'} \sum_{k=0} f_k(\beta)\alpha_s^k \longrightarrow \hat{\sigma}_{pp'}(\hat{s}) \sim \hat{\sigma}^{(0)}_{pp'} \sum_{k,l,m=0} \tilde{f}_{klm}(\beta)\left(\frac{\alpha_s}{\beta}\right)^k \alpha_s^l \ln^m \beta$$

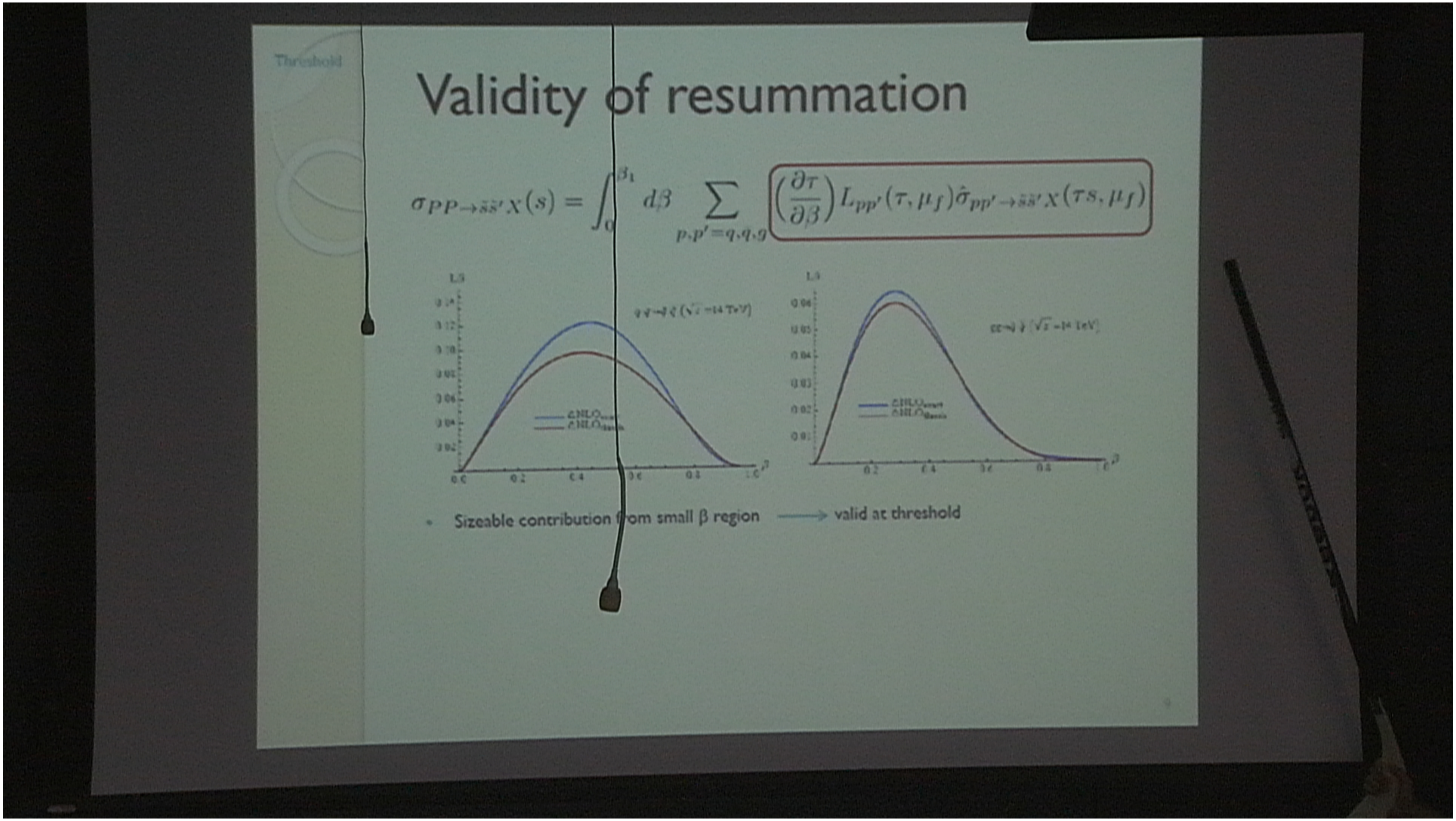
[Beneke, Falgari, Schwinn '10]

- Resummed partonic cs:

$$\hat{\sigma}_{pp'}(\hat{s}) \sim \hat{\sigma}^{(0)}_{pp'} \sum_{k=0} \left(\frac{\alpha_s}{\beta}\right)^k \exp[\underbrace{\ln\beta g_0(\alpha_s \ln\beta)}_{(\mathrm{LL})} + \underbrace{g_1(\alpha_s \ln\beta)}_{(\mathrm{NLL})} + \underbrace{\alpha_s g_2(\alpha_s \ln\beta)}_{(\mathrm{NNLL})} + \ldots]$$
$$\times \{1(\mathrm{LL,NLL}); \alpha_s, \beta(\mathrm{NNLL}); \alpha_s^2, \alpha_s\beta, \beta^2(\mathrm{NNNLL}); \ldots\}$$

- Hadronic cs integrates over region away from threshold

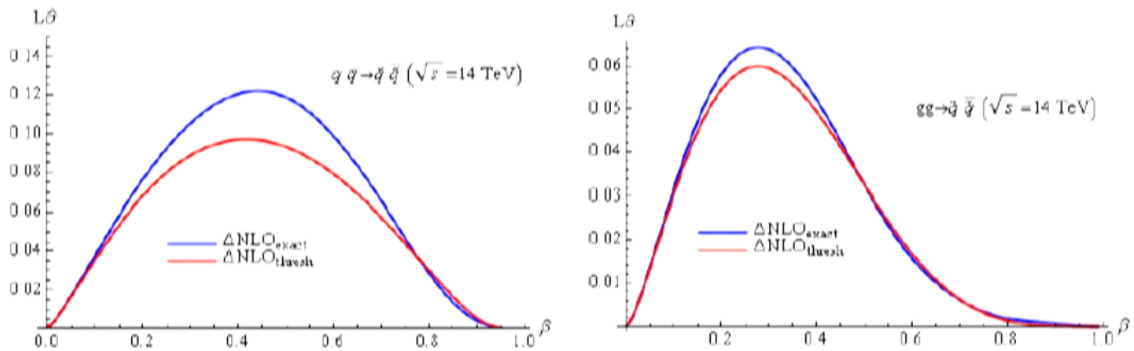
$\longrightarrow$ Is resummation relevant for the hadronic cross section?



Threshold
Validity of resummation
$\sigma_{PP\to\tilde{s}\tilde{s}'X}(s) = \int_0^{\beta_1} d\beta \sum_{p,p'=q,q,g} \left(\frac{\partial\tau}{\partial\beta}\right) L_{pp'}(\tau,\mu_f)\hat{\sigma}_{pp'\to\tilde{s}\tilde{s}'X}(\tau s,\mu_f)$
Sizeable contribution from small β region
valid at threshold

Validity of resummation

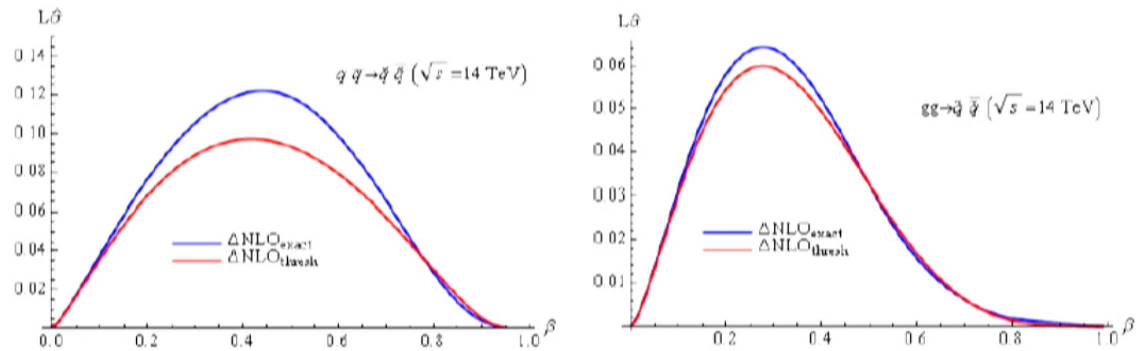
$$\sigma_{PP\to\tilde{s}\tilde{s}'X}(s) = \int_0^{\beta_1} d\beta \sum_{p,p'=q,\bar{q},g} \left(\frac{\partial\tau}{\partial\beta}\right) L_{pp'}(\tau,\mu_f)\hat{\sigma}_{pp'\to\tilde{s}\tilde{s}'X}(\tau s,\mu_f)$$



- Sizeable contribution from small β region ⟶ valid at threshold

Validity of resummation

$$\sigma_{PP\to\tilde{s}\tilde{s}'X}(s) = \int_0^{\beta_1} d\beta \sum_{p,p'=q,\bar{q},g} \left(\frac{\partial\tau}{\partial\beta}\right) L_{pp'}(\tau,\mu_f)\hat{\sigma}_{pp'\to\tilde{s}\tilde{s}'X}(\tau s,\mu_f)$$



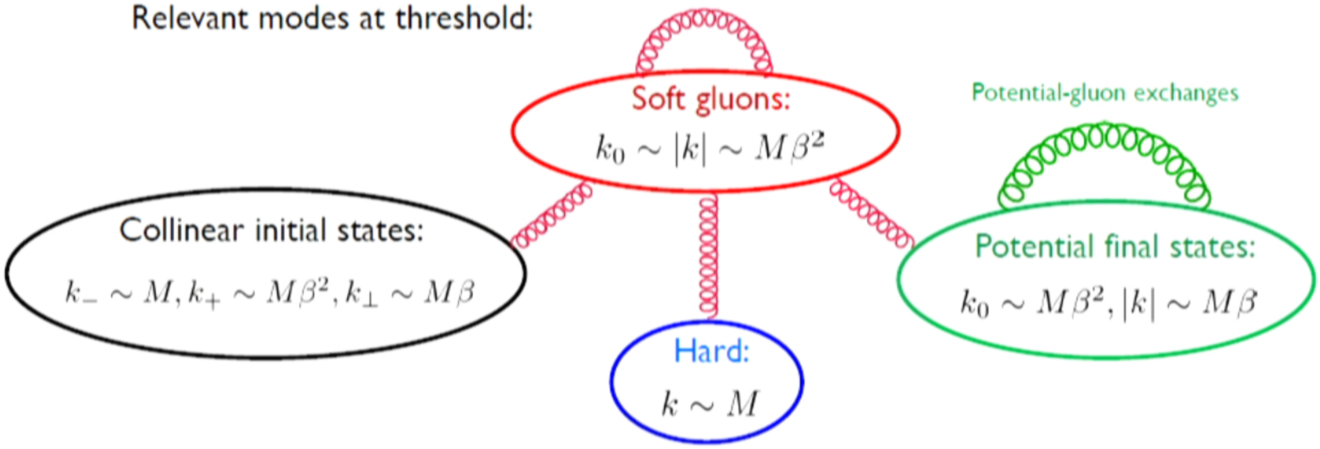
- Sizeable contribution from small β region ⟶ valid at threshold
- Threshold enhanced terms also approximate well away from threshold

• Soft logarithms resummation [Catani et al. '96; Becher, Neubert '06; Kulesza, Motyka '08; Langenfeld, Moch '09; Beenakker et al. '09, '11: NLLFast]
• Coulomb resummation [Fadin, Khoze '87-'89; Fadin, Khoze, Sjostrand '90; Kulesza, Motyka '09]
• Simultaneous soft and Coulomb resummation for squark-antisquark at NLL [Beneke, Falgari, Schwinn '10] and top-quark pairs at NNLL [Beneke et al. '11/12: TOPIXS]

Modes and EFT's

- Hierarchy in scales: $M \gg M\beta \gg M\beta^2$ ⟶ use EFT

  Relevant modes at threshold:



No initial state hard modes!

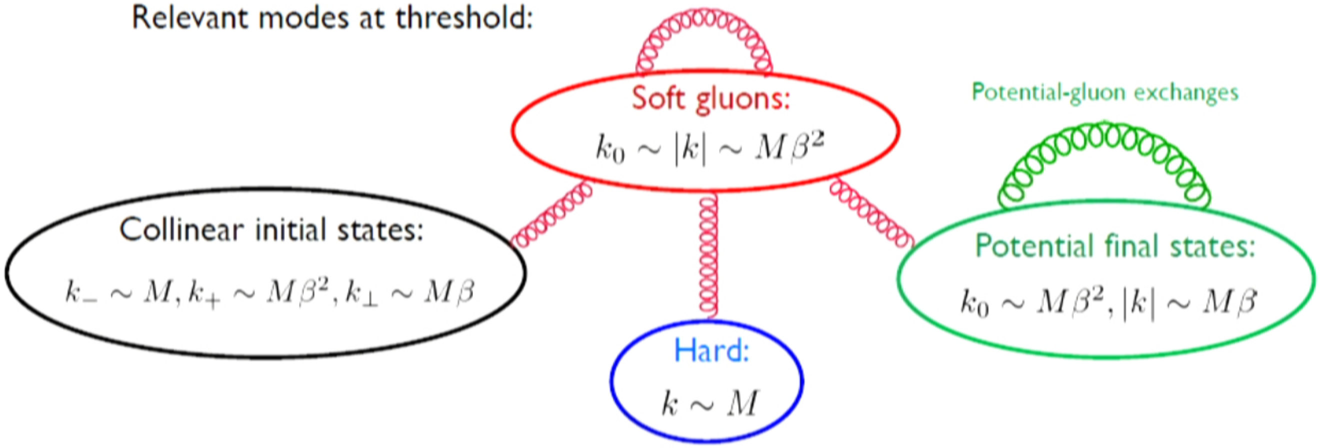
[Caswell, Lepage, Braaten et al. '86-'94; Bauer et al. '00; Beneke et al. '02;...]

- Integrate out hard modes: $M \gg M\beta, M\beta^2$ ⟶ NRQCD, SCET

Modes and EFT's

- Hierarchy in scales: $M \gg M\beta \gg M\beta^2$ ⟶ use EFT

Relevant modes at threshold:



No initial state hard modes!

[Caswell, Lepage, Braaten et al. '86-'94; Bauer et al. '00; Beneke et al. '02;...]

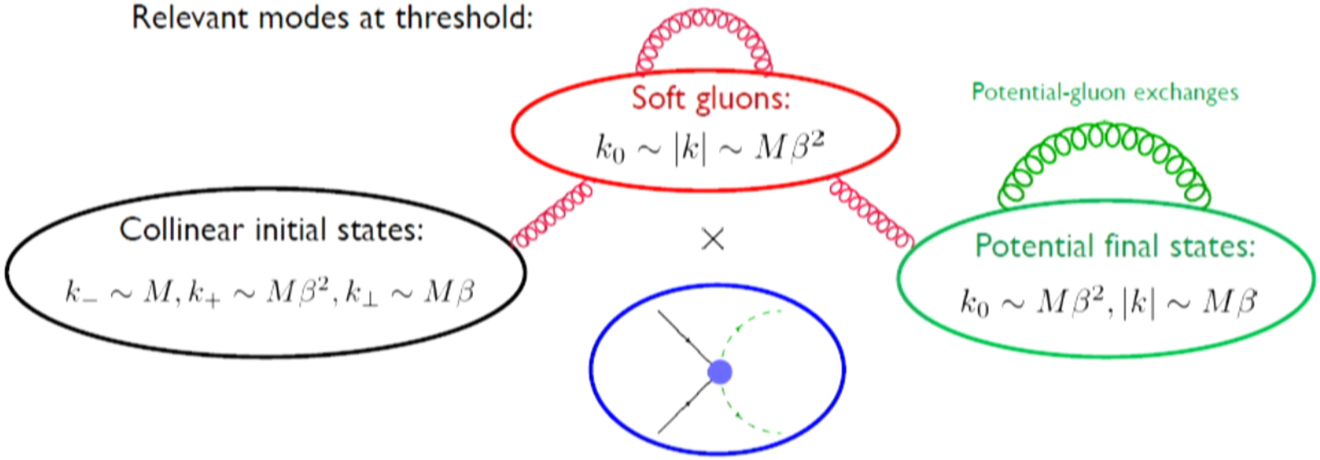
- Integrate out hard modes: $M \gg M\beta, M\beta^2$ ⟶ NRQCD, SCET

EFT

Modes and EFT's

- Hierarchy in scales: $M \gg M\beta \gg M\beta^2$ ⟶ use EFT

Relevant modes at threshold:



Hard matching coefficients

[Caswell, Lepage, Braaten et al. '86-'94; Bauer et al. '00; Beneke et al. '02;...]

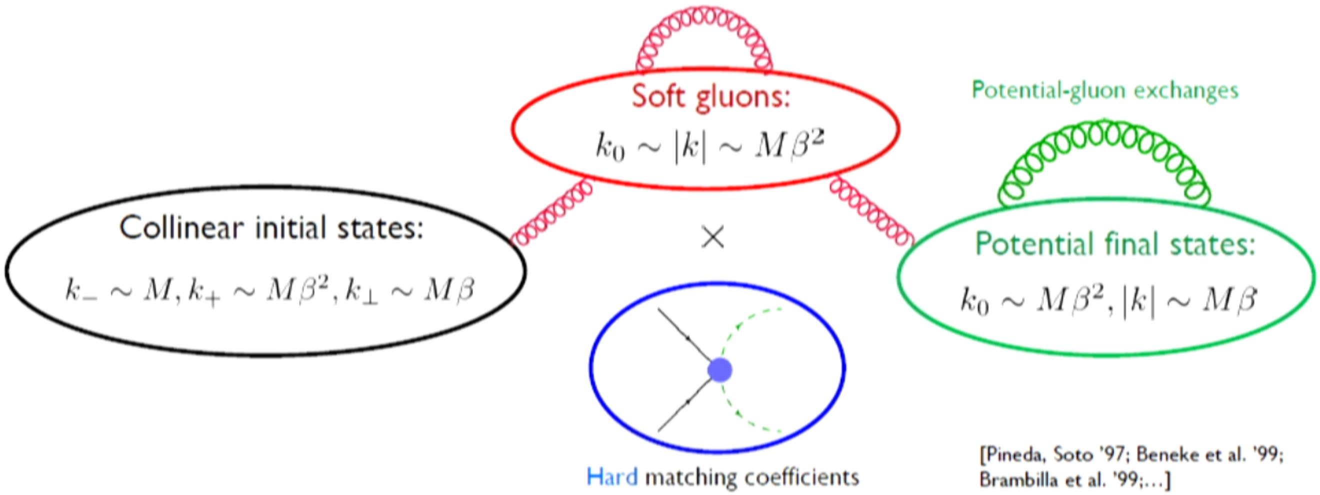
- Integrate out hard modes: $M \gg M\beta, M\beta^2$ ⟶ NRQCD, SCET

$$\mathcal{L}_{SCET} = \bar{\xi}_c \left(in.D_s + i\not{D}_{\perp c} \frac{1}{i\bar{n}D_c} i\not{D}_{\perp c} \right) \frac{\not{\bar{n}}}{2} \xi_c - \frac{1}{2} tr \left(F_c^{\mu\nu} F^c_{\mu\nu} \right) + \mathcal{L}_s + \mathcal{O}(\beta\text{-suppressed})$$

$$\mathcal{L}_{NRQCD} = \psi^\dagger \left(iD^0 + \frac{\vec{D}^2}{2m_{\tilde{s}}} \right) \psi + \psi'^\dagger \left(iD^0 + \frac{\vec{D}^2}{2m_{\tilde{s}'}} \right) \psi' + (\psi, \psi' \to \chi, \chi') + \mathcal{O}(1/m)$$

SCET and (p)NRQCD

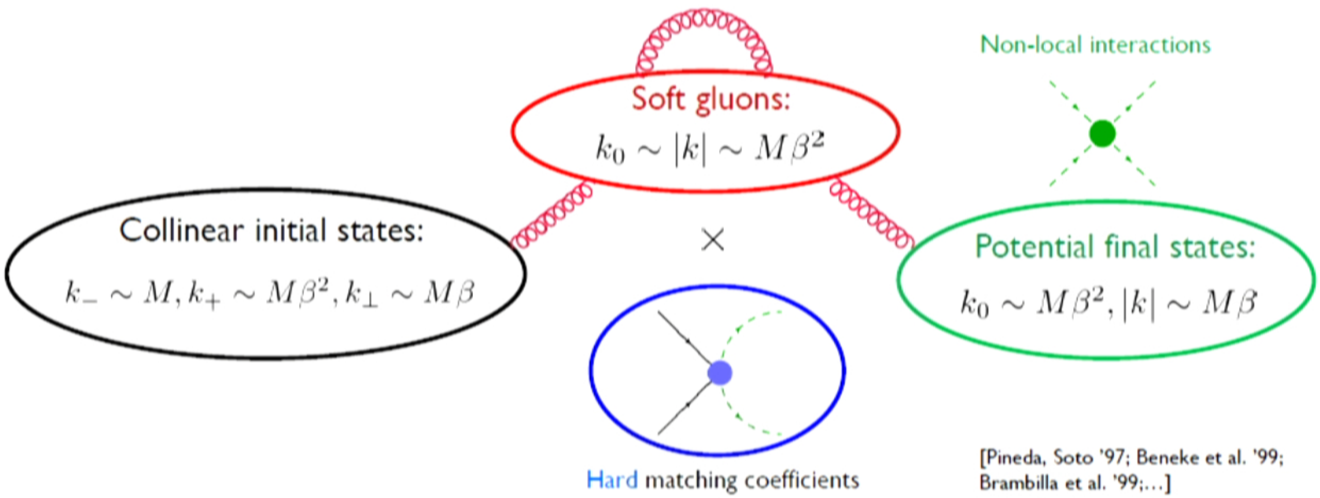
- Use further hierarchy: $M\beta \gg M\beta^2$



- Integrate out potential gluons: $\mathcal{L}_{NRQCD} \longrightarrow \mathcal{L}_{PNRQCD}$

SCET and (p)NRQCD

- Use further hierarchy: $M\beta \gg M\beta^2$



[Pineda, Soto '97; Beneke et al. '99; Brambilla et al. '99;…]

- Integrate out potential gluons: $\mathcal{L}_{NRQCD} \longrightarrow \mathcal{L}_{PNRQCD}$

Collinear-soft: $\mathcal{L}_{SCET} = \bar{\xi}_c\left(in.D_s + i\not{D}_{\perp c}\frac{1}{i\bar{n}D_c}i\not{D}_{\perp c}\right)\frac{\not{\bar{n}}}{2}\xi_c - \frac{1}{2}tr\left(F_c^{\mu\nu}F^c_{\mu\nu}\right) + \mathcal{L}_s + \mathcal{O}(\beta\text{-suppressed})$

Potential-soft:

$$\mathcal{L}_{PNRQCD} = \psi^\dagger\left(iD_s^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}}} + \frac{i\Gamma_{\tilde{s}}}{2}\right)\psi + \psi'^\dagger\left(iD_s^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}'}} + \frac{i\Gamma_{\tilde{s}'}}{2}\right)\psi'$$
$$+ \int d^3\vec{r}\,[\psi^\dagger \mathbf{T}^{(R)a}\psi](\vec{r})\left(\frac{\alpha_s}{r}\right)[\psi'^\dagger \mathbf{T}^{(R')a}\psi'](0) + \mathcal{O}(\beta\text{-suppressed})$$

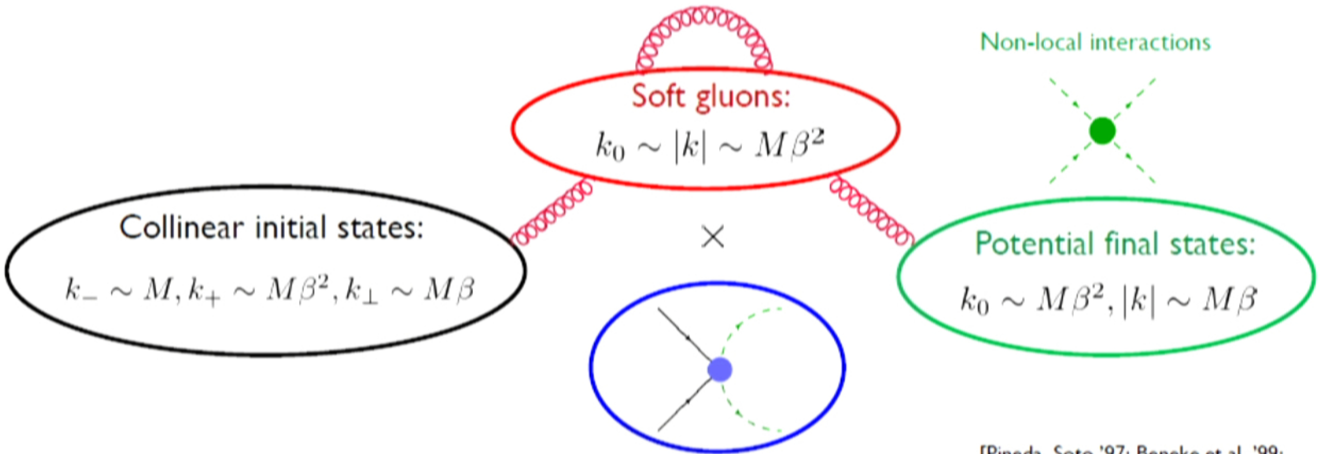
Total: $\mathcal{L}_{EFT} = \mathcal{L}_{SCET} + \mathcal{L}_{PNRQCD}$

11

EFT

SCET and (p)NRQCD

- Use further hierarchy: $M\beta \gg M\beta^2$



[Pineda, Soto '97; Beneke et al. '99; Brambilla et al. '99;...]

- Integrate out potential gluons: $\mathcal{L}_{NRQCD} \longrightarrow \mathcal{L}_{PNRQCD}$

Collinear-soft: $\mathcal{L}_{SCET} = \bar{\xi}_c\left(in.D_s + i\not{D}_{\perp c}\frac{1}{i\bar{n}D_c}i\not{D}_{\perp c}\right)\frac{\not{\bar{n}}}{2}\xi_c - \frac{1}{2}tr\left(F_c^{\mu\nu}F^c_{\mu\nu}\right) + \mathcal{L}_s + \mathcal{O}(\beta\text{-suppressed})$

Potential-soft:
$$\mathcal{L}_{PNRQCD} = \psi^\dagger\left(iD_s^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}}} + \frac{i\Gamma_{\tilde{s}}}{2}\right)\psi + \psi'^\dagger\left(iD_s^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}'}} + \frac{i\Gamma_{\tilde{s}'}}{2}\right)\psi' + \int d^3\vec{r}\,[\psi^\dagger\mathbf{T}^{(R)a}\psi](\vec{r})\left(\frac{\alpha_s}{r}\right)[\psi'^\dagger\mathbf{T}^{(R')a}\psi'](0) + \mathcal{O}(\beta\text{-suppressed})$$

Total: $\mathcal{L}_{EFT} = \mathcal{L}_{SCET} + \mathcal{L}_{PNRQCD}$

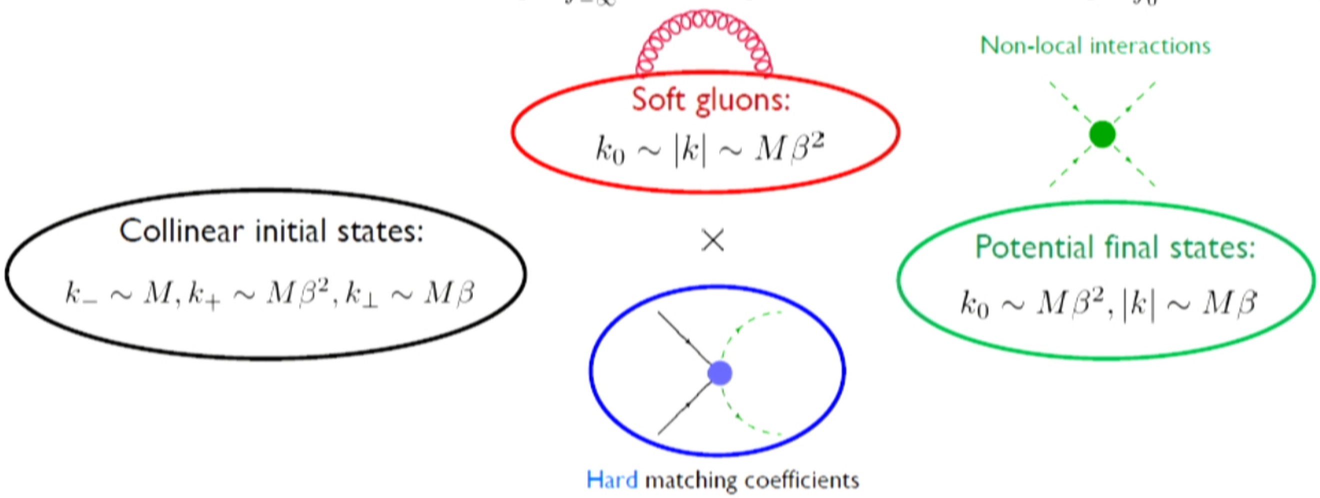
11

Soft-gluon decoupling

[Bauer, Pirjol, Stewart '02; Beneke, Falgari, Schwinn '10]

- Field redefinitions:

$$\xi_c \to S_n^{(3)}\xi_c,\ A_c \to S_n^{(8)} A_c,\ S_n^{(r)} = \mathrm{P}\exp\left[ig_s \int_{-\infty}^{0} n.A_s{}^c T^{(r)c}\right],\ \psi \to S_w^{(R)}\psi,\ S_w^{(R)} = \bar{\mathrm{P}}\exp\left[ig_s \int_{0}^{\infty} w.A_s{}^c T^{(R)c}\right]$$



LO collinear-soft decoupling:

$$\mathcal{L}_{SCET} = \bar{\xi}_c\left(in.\partial + i\not{D}_{\perp c}\frac{1}{i\bar{n}D_c}i\not{D}_{\perp c}\right)\frac{\not{\bar{n}}}{2}\xi_c - \frac{1}{2}tr\left(F_c^{\mu\nu}F_{\mu\nu}^c\right) + \mathcal{L}_s + \mathcal{O}(\beta\text{-suppressed})$$

LO potential-soft decoupling:

$$\mathcal{L}_{PNRQCD} = \psi^\dagger\left(i\partial^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}}} + \frac{i\Gamma_{\tilde{s}}}{2}\right)\psi + \psi'^\dagger\left(i\partial^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}'}} + \frac{i\Gamma_{\tilde{s}'}}{2}\right)\psi'$$
$$+ \int d^3\vec{r}\,[\psi^\dagger \mathbf{T}^{(R)a}\psi](\vec{r})\left(\frac{\alpha_s}{r}\right)[\psi'^\dagger \mathbf{T}^{(R')a}\psi'](0) + \mathcal{O}(\beta\text{-suppressed})$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SCET} + \mathcal{L}_{PNRQCD}$$

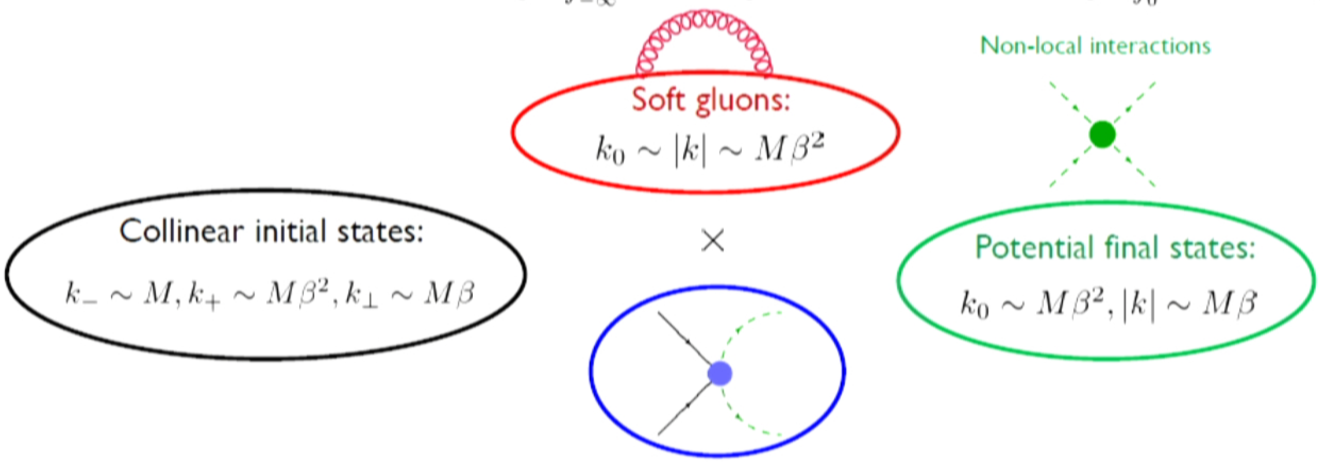
EFT decoupling

Soft-gluon decoupling

[Bauer, Pirjol, Stewart '02; Beneke, Falgari, Schwinn '10]

- Field redefinitions:

$$\xi_c \to S_n^{(3)}\xi_c,\ A_c \to S_n^{(8)} A_c,\ S_n^{(r)} = \mathrm{P}\exp\left[ig_s\int_{-\infty}^{0} n.A_s{}^c T^{(r)c}\right],\ \psi \to S_w^{(R)}\psi,\ S_w^{(R)} = \bar{\mathrm{P}}\exp\left[ig_s\int_{0}^{\infty} w.A_s{}^c T^{(R)c}\right]$$



- Effective lagrangians for NNLL:

LO soft decoupling + no contribution from $\mathcal{O}(\beta\text{-suppr})$ at NNLL:

$$\mathcal{L}_{SCET} = \bar{\xi}_c\left(in.\partial + i\not{D}_{\perp c}\frac{1}{i\bar{n}D_c}i\not{D}_{\perp c}\right)\frac{\not{\bar{n}}}{2}\xi_c - \frac{1}{2}tr\left(F_c^{\mu\nu}F_{\mu\nu}^c\right) - \frac{1}{2}tr\left(F_s^{\mu\nu}F^s{}_{\mu\nu}\right)$$

$$\mathcal{L}_{PNRQCD} = \psi^\dagger\left(i\partial^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}}} + \frac{i\Gamma_{\tilde{s}}}{2}\right)\psi + \psi'^\dagger\left(i\partial^0 + \frac{\vec{\partial}^2}{2m_{\tilde{s}'}} + \frac{i\Gamma_{\tilde{s}'}}{2}\right)\psi' + \int d^3\vec{r}\,[\psi^\dagger\mathbf{T}^{(R)a}\psi](\vec{r})\left(\frac{\alpha_s}{r}\right)[\psi'^\dagger\mathbf{T}^{(R')a}\psi'](0)$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SCET} + \mathcal{L}_{PNRQCD}$$

EFT factorization

Factorization: amplitude

[Beneke, Falgari, Schwinn '10]

- Production operator: $\mathcal{O}^i = c^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; c^i = \text{colour tensor}$

↓

- Soft-gluon decoupling transformation: $\mathcal{O}^i = \mathcal{S}^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; \mathcal{S}^i := c^i S_n S_{\bar{n}} S_w^\dagger S_w^\dagger$

$$\mathcal{A}(pp' \to HH'X) = \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'X|\mathcal{O}^i|pp'\rangle$$

$$= \langle 0|\phi_c|p\rangle\langle 0|\phi_{\bar{c}}|p'\rangle \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'|\psi^\dagger \psi'^\dagger|0\rangle\langle X|\mathcal{S}^i|0\rangle$$

13

EFT
factorization

Factorization: amplitude

[Beneke, Falgari, Schwinn '10]

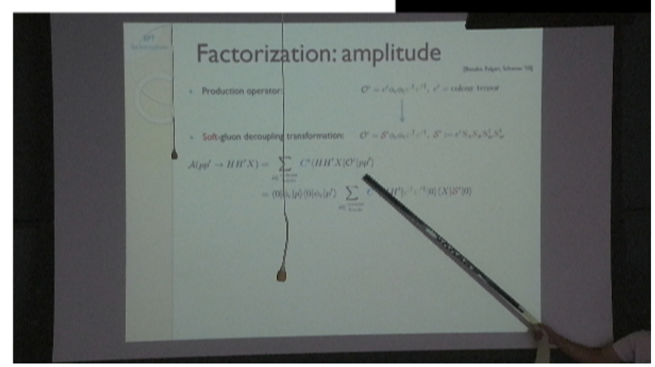
- Production operator: $\mathcal{O}^i = c^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; c^i = \text{colour tensor}$

$$\downarrow$$

- Soft-gluon decoupling transformation: $\mathcal{O}^i = \mathcal{S}^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; \mathcal{S}^i := c^i S_n S_{\bar{n}} S_w^\dagger S_w^\dagger$

$$\mathcal{A}(pp' \to HH'X) = \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'X|\mathcal{O}^i|pp'\rangle$$

$$= \langle 0|\phi_c|p\rangle\langle 0|\phi_{\bar{c}}|p'\rangle \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'|\psi^\dagger \psi'^\dagger|0\rangle\langle X|\mathcal{S}^i|0\rangle$$



Factorization: amplitude

[Beneke, Falgari, Schwinn '10]

- Production operator: $\mathcal{O}^i = c^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; c^i = \text{colour tensor}$

- Soft-gluon decoupling transformation: $\mathcal{O}^i = \mathcal{S}^i \phi_c \phi_{\bar{c}} \psi^\dagger \psi'^\dagger, \; \mathcal{S}^i := c^i S_n S_{\bar{n}} S_w^\dagger S_w^\dagger$

$$\mathcal{A}(pp' \to HH'X) = \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'X|\mathcal{O}^i|pp'\rangle$$

$$= \langle 0|\phi_c|p\rangle\langle 0|\phi_{\bar{c}}|p'\rangle \sum_{i \in \substack{\text{colour} \\ \text{basis}}} C^i \langle HH'|\psi^\dagger \psi'^\dagger|0\rangle\langle X|\mathcal{S}^i|0\rangle$$

Scattering amplitude = Hard matching coefficients × Coulomb contributions (potential gluons exchange) × Soft contributions (soft gluons exchange)

EFT factorization

Factorization: partonic cs

[Beneke, Falgari, Schwinn '10]

$$\longrightarrow \quad \hat{\sigma} \sim \sum_{X,i,i',\ldots} \int dPS_X dPS_{HH'} |\mathcal{A}(pp' \to HH'X)|^2$$

$$\sim \underbrace{\langle p|\phi_c^\dagger \phi_c|p\rangle \langle p'|\phi_{\bar{c}}'^\dagger \phi_{\bar{c}}'|p'\rangle}_{\text{Absorbed in PDF}} \sum_{i,i'} \underbrace{(C_i C_{i'}^*)}_{\text{Hard } H} \int \underbrace{\langle 0|\psi'\psi\psi^\dagger\psi'^\dagger|0\rangle}_{\text{Coulomb } J} \underbrace{\langle 0|\mathcal{S}^{i'*}\mathcal{S}^i|0\rangle}_{\text{Soft } W}$$

- Factorization of partonic cs directly in momentum space (at threshold $E = \sqrt{\hat{s}} - 2M \simeq M\beta^2$):

$$\hat{\sigma}_{pp'}(\hat{s}, \mu_f) = \sum_{R_\alpha} H_{pp'}^{R_\alpha}(m_{\tilde{q}}, m_{\tilde{g}}, \mu_f) \int d\omega \; J_{R_\alpha}(E - \frac{\omega}{2}) \, W^{R_\alpha}(\omega, \mu_f)$$

EFT factorization

Factorization: partonic cs

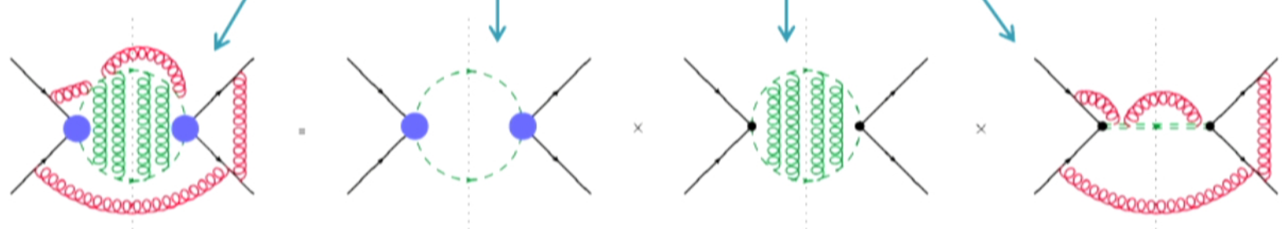
[Beneke, Falgari, Schwinn '10]

$$\longrightarrow \hat\sigma \sim \sum_{X,i,i',\ldots} \int dPS_X\, dPS_{HH'}\, |\mathcal{A}(pp' \to HH'X)|^2$$

$$\sim \underbrace{\langle p|\phi_c^\dagger\phi_c|p\rangle\langle p'|\phi_c'^\dagger\phi_c'|p'\rangle}_{\text{Absorbed in PDF}} \sum_{i,i'} \underbrace{(C_i C_{i'}^*)}_{\text{Hard } H} \int \underbrace{\langle 0|\psi'\psi\psi^\dagger\psi'^\dagger|0\rangle}_{\text{Coulomb } J} \underbrace{\langle 0|\mathcal{S}^{i'*}\mathcal{S}^{i}|0\rangle}_{\text{Soft } W}$$

- Factorization of partonic cs directly in momentum space (at threshold $E = \sqrt{\hat s} - 2M \simeq M\beta^2$):

$$\hat\sigma_{pp'}(\hat s,\mu_f) = \sum_{R_\alpha} H^{R_\alpha}_{pp'}(m_{\tilde q}, m_{\tilde g},\mu_f) \int d\omega\, J_{R_\alpha}(E-\frac{\omega}{2})\, W^{R_\alpha}(\omega,\mu_f)$$



Partonic cross section — Hard contributions — Coulomb contributions (potential gluons exchange) — Soft contributions (soft gluons exchange)

- Coulomb contributions also contain bound-state effects below threshold
- Factorization valid up to NNLL for S-wave processes and for P-wave processes [Falgari et al. '12]
- Strength: only model and process dependence in H and initial-final colour decomposition

Factorization: partonic cs

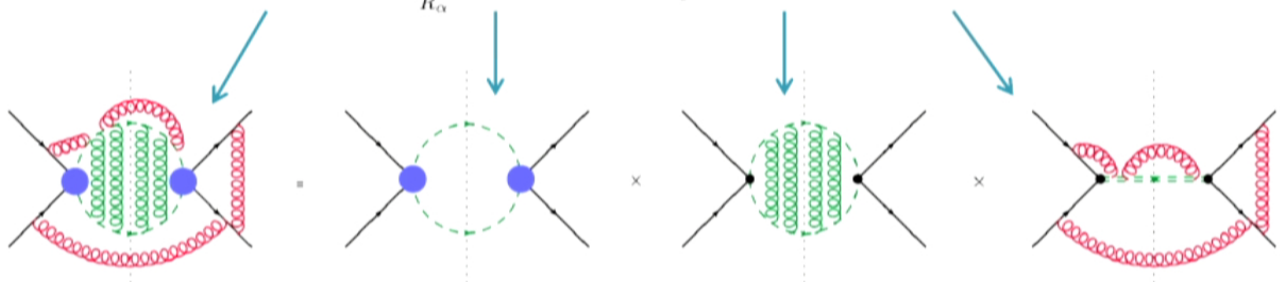
[Beneke, Falgari, Schwinn '10]

$$\hat{\sigma} \sim \sum_{X,i,i',\dots} \int dPS_X \, dPS_{HH'} |\mathcal{A}(pp' \to HH'X)|^2$$

$$\sim \underbrace{\langle p|\phi_c^\dagger \phi_c|p\rangle \langle p'|\phi_{\bar{c}}'^\dagger \phi_{\bar{c}}'|p'\rangle}_{\text{Absorbed in PDF}} \sum_{i,i'} \underbrace{(C_i C_{i'}^*)}_{\text{Hard } H} \int \underbrace{\langle 0|\psi'\psi\psi^\dagger\psi'^\dagger|0\rangle}_{\text{Coulomb } J} \underbrace{\langle 0|\mathcal{S}^{i'*}\mathcal{S}^i|0\rangle}_{\text{Soft } W}$$

- Factorization of partonic cs directly in momentum space (at threshold $E = \sqrt{\hat{s}} - 2M \simeq M\beta^2$):

$$\hat{\sigma}_{pp'}(\hat{s},\mu_f) = \sum_{R_\alpha} H^{R_\alpha}_{pp'}(m_{\tilde{q}}, m_{\tilde{g}}, \mu_f) \int d\omega \, J_{R_\alpha}(E - \frac{\omega}{2}) \, W^{R_\alpha}(\omega, \mu_f)$$



Partonic cross section — Hard contributions — Coulomb contributions (potential gluons exchange) — Soft contributions (soft gluons exchange)

- Coulomb contributions also contain bound-state effects below threshold
- Factorization valid up to NNLL for S-wave processes and for P-wave processes [Falgari et al. '12]
- Strength: only model and process dependence in H and initial-final colour decomposition

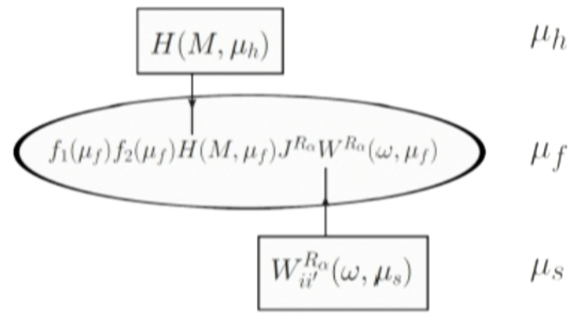
Resummation using RG flow

[Beneke, Falgari, Schwinn '10]

IR QCD amplitude structure ⟶ H evolution equations

Hadronic cs scale independent ⟶ W evolution equations

- RG flow resums logs $\ln(\frac{\mu_f}{\mu_h}), \ln(\frac{\mu_f}{\mu_s})$ $\quad \sigma(s) \sim$



- pNRQCD function J resums Coulomb singularities, contains bound-states (Quarkonia physics):

$$J_{R_\alpha}(E) = \frac{(2m_r)^2 \pi D_{R_\alpha} \alpha_s}{2\pi} \left(e^{\pi D_{R_\alpha} \alpha_s \sqrt{\frac{2m_r}{E}}} - 1 \right)^{-1} \qquad E > 0$$

$$J_{R_\alpha}^{\text{bound}}(E) = 2 \sum_{n=1}^{\infty} \delta(E - \left(- \frac{2m_r \alpha_s^2 D_{R_\alpha}^2}{4n^2} \right)) \left(\frac{2m_r(-D_{R_\alpha})\alpha_s}{2n} \right)^3 \qquad E < 0$$

- One-loop SUSY hard matching coefficients: squark-antisquark [Beenakker et al. '11], gluino-gluino production [Kauth et al. '11, Langenfeld '12] and rest [Beenakker et al. '13]

EFT resummation

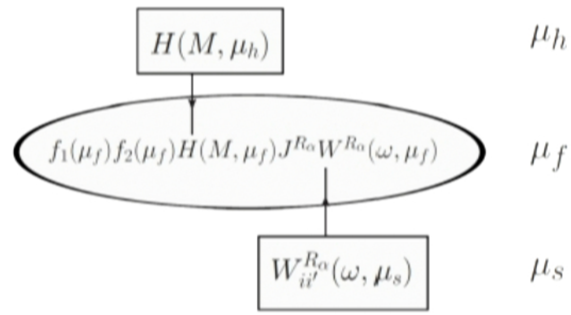
Resummation using RG flow

[Beneke, Falgari, Schwinn '10]

IR QCD amplitude structure ⟶ H evolution equations

Hadronic cs scale independent ⟶ W evolution equations

- RG flow resums logs $\ln(\frac{\mu_f}{\mu_h}), \ln(\frac{\mu_f}{\mu_s})$ $\quad \sigma(s) \sim$



- pNRQCD function J resums Coulomb singularities, contains bound-states (Quarkonia physics):

$$J_{R_\alpha}(E) = \frac{(2m_r)^2\pi D_{R_\alpha}\alpha_s}{2\pi}\left(e^{\pi D_{R_\alpha}\alpha_s\sqrt{\frac{2m_r}{E}}}-1\right)^{-1} \qquad E>0$$

$$J^{\text{bound}}_{R_\alpha}(E) = 2\sum_{n=1}^{\infty}\delta(E-\left(-\frac{2m_r\alpha_s^2 D_{R_\alpha}^2}{4n^2}\right))\left(\frac{2m_r(-D_{R_\alpha})\alpha_s}{2n}\right)^3 \qquad E<0$$

- One-loop SUSY hard matching coefficients: squark-antisquark [Beenakker et al. '11], gluino-gluino production [Kauth et al. '11, Langenfeld '12] and rest [Beenakker et al. '13]

Scales and errors

[Beneke, Falgari, Schwinn;...]

- Scales taken such as to minimize higher order corrections:

$$\mu_R = \mu_f = k_f M, \qquad \mu_h = 2k_h M, \qquad \mu_s = k_s \text{Max}\{M\beta^2, M\beta^2_{cut}\}$$

$$\mu_C = k_C \text{Max}\{2\alpha_s(\mu_C) m_r |D_{R_\alpha}|, 2\sqrt{2m_r M}\beta\} \qquad k_f, k_h, k_C, k_s \sim 1$$

- Theoretical errors:

1) Scale variations: $\frac{1}{2} \leq k_f, k_h, k_C, k_s \leq 2$; $0.8\beta^{(0)}_{cut} \leq \beta_{cut} \leq 1.2\beta^{(0)}_{cut}$

2) Parameterization errors: $E = \sqrt{\hat{s}} - 2M, \quad \beta$

3) PDF and α_s errors

Scales and errors

[Beneke, Falgari, Schwinn;...]

- Scales taken such as to minimize higher order corrections:

$$\mu_R = \mu_f = k_f M, \qquad \mu_h = 2k_h M, \qquad \mu_s = k_s \text{Max}\{M\beta^2, M\beta^2_{cut}\}$$
$$\mu_C = k_C \text{Max}\{2\alpha_s(\mu_C) m_r |D_{R_\alpha}|, 2\sqrt{2m_r M}\beta\} \qquad k_f, k_h, k_C, k_s \sim 1$$

- Theoretical errors:

1) Scale variations:
$$\begin{cases} \frac{1}{2} \leq k_f, k_h, k_C, k_s \leq 2 \\ 0.8\beta^{(0)}_{cut} \leq \beta_{cut} \leq 1.2\beta^{(0)}_{cut} \end{cases}$$

2) Parameterization errors: $E = \sqrt{\hat{s}} - 2M, \quad \beta$

3) PDF and α_s errors

- We use the MSTW2008NLO PDF's and match the cross section to the full NLO result from Prospino 2.1 [Plehn]:

$$\hat{\sigma}^{\text{matched}}_{pp'}(\hat{s}) = [\hat{\sigma}^{\text{NLL}}_{pp'}(\hat{s}) - \hat{\sigma}^{\text{NLL}(1)}_{pp'}(\hat{s})] + \hat{\sigma}^{\text{NLO}}_{pp'}(\hat{s})$$

Next: results for MSSM resumming both soft and Coulomb terms at NLL

Scales and errors

[Beneke, Falgari, Schwinn;...]

- Scales taken such as to minimize higher order corrections:

$$\mu_R = \mu_f = k_f M, \qquad \mu_h = 2k_h M, \qquad \mu_s = k_s \mathrm{Max}\{M\beta^2, M\beta_{cut}^2\}$$
$$\mu_C = k_C \mathrm{Max}\{2\alpha_s(\mu_C) m_r |D_{R_\alpha}|, 2\sqrt{2m_r M}\beta\} \qquad k_f, k_h, k_C, k_s \sim 1$$

- Theoretical errors:

1) Scale variations: $\begin{cases} \frac{1}{2} \leq k_f, k_h, k_C, k_s \leq 2 \\ 0.8\beta_{cut}^{(0)} \leq \beta_{cut} \leq 1.2\beta_{cut}^{(0)} \end{cases}$

2) Parameterization errors: $E = \sqrt{\hat{s}} - 2M, \quad \beta$

3) PDF and α_s errors

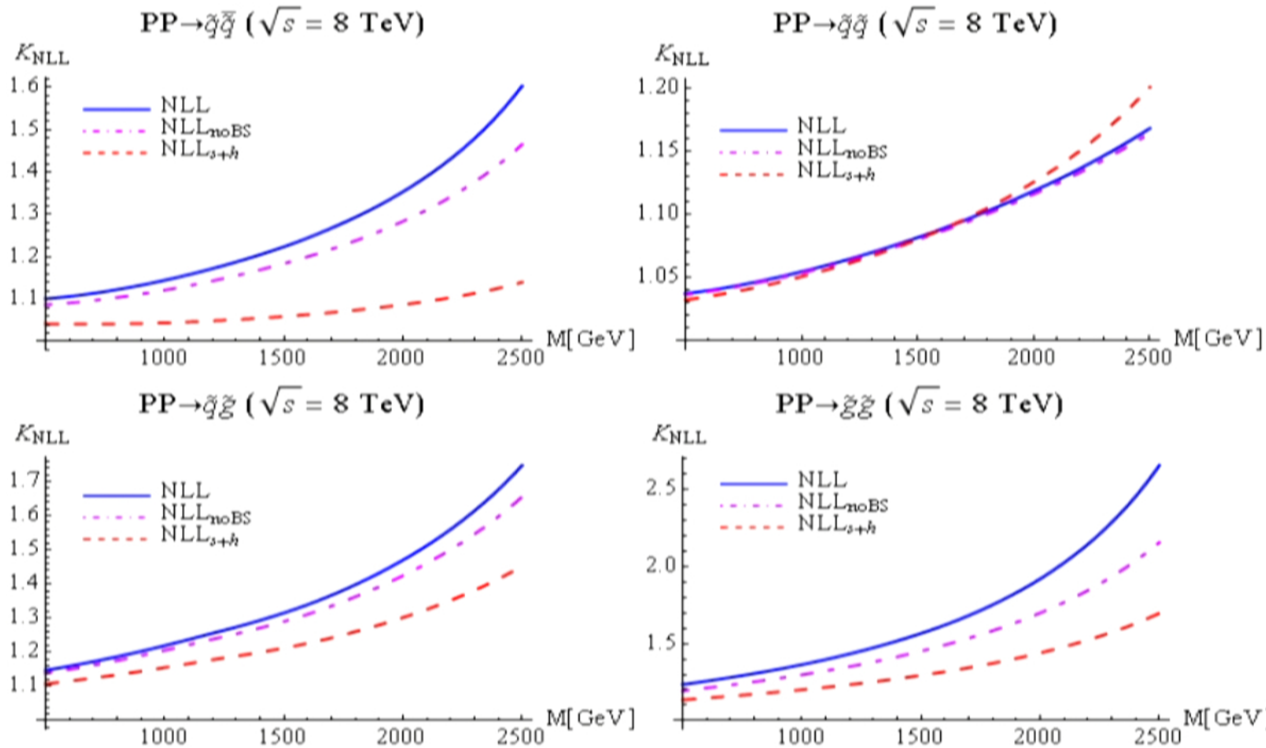
- We use the MSTW2008NLO PDF's and match the cross section to the full NLO result from Prospino 2.1 [Plehn]:

$$\hat{\sigma}_{pp'}^{\mathrm{matched}}(\hat{s}) = [\hat{\sigma}_{pp'}^{\mathrm{NLL}}(\hat{s}) - \hat{\sigma}_{pp'}^{\mathrm{NLL(1)}}(\hat{s})] + \hat{\sigma}_{pp'}^{\mathrm{NLO}}(\hat{s})$$

Next: results for MSSM resumming both soft and Coulomb terms at NLL

$$K_{\mathrm{NLL}} = \frac{\sigma^{\mathrm{matched}}}{\sigma^{\mathrm{NLO}}}$$

[Falgari, Schwinn, W '12]



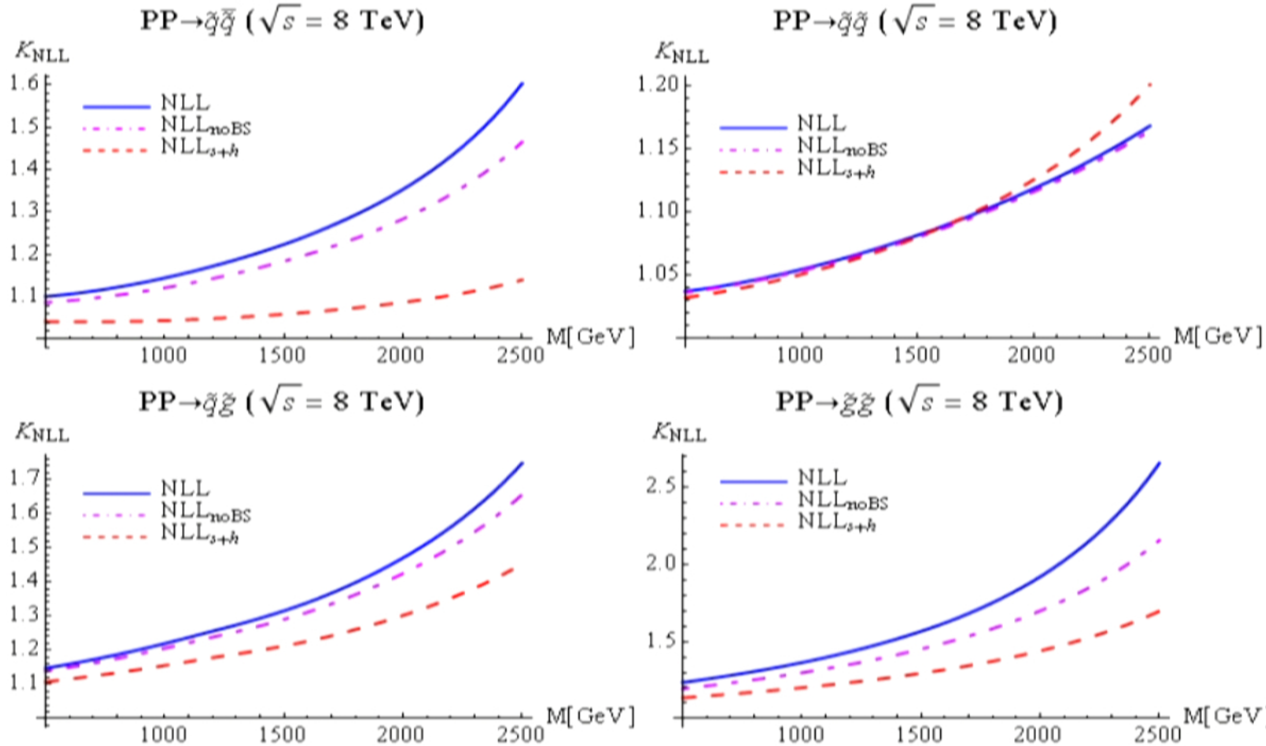
Equal squark and gluino masses:

- NLL: combined soft and Coulomb resummation
- $\mathrm{NLL}_{\mathrm{noBS}}$: no bound-state effects
- $\mathrm{NLL}_{\mathrm{s+h}}$: no Coulomb resummation

- Large corrections: 5-160% of NLO
- Coulomb corrections: 0-90%
- Bound state corrections: 0-40%

$$K_{\mathrm{NLL}} = \frac{\sigma^{\mathrm{matched}}}{\sigma^{\mathrm{NLO}}}$$

[Falgari, Schwinn, W '12]



Equal squark and gluino masses:

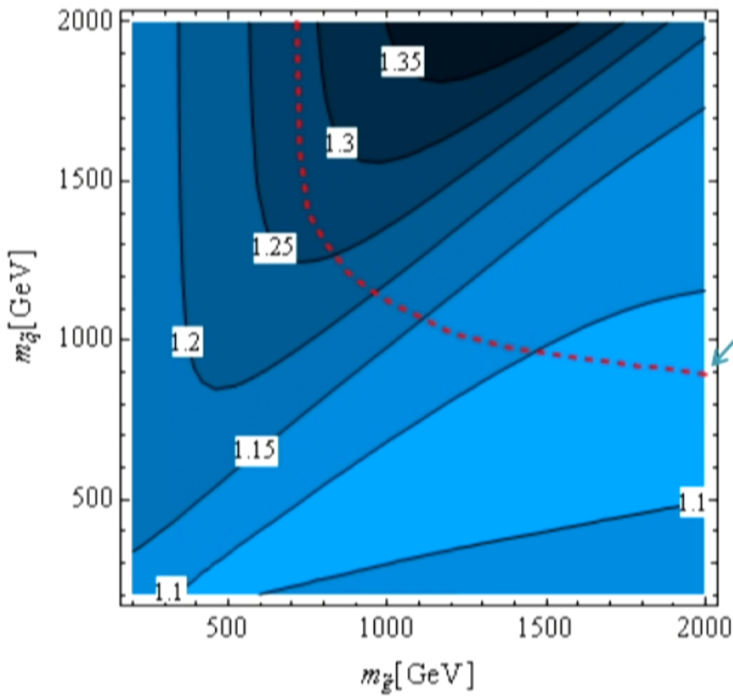
- NLL: combined soft and Coulomb resummation
- $\mathrm{NLL}_{\mathrm{noBS}}$: no bound-state effects
- NLL_{s+h}: no Coulomb resummation

- Large corrections: 5-160% of NLO
- Coulomb corrections: 0-90%
- Bound state corrections: 0-40%

Contour plot K_{NLL}

[Falgari, Schwinn, W '12]

$$PP \to \tilde{q}\bar{\tilde{q}} + \tilde{q}\tilde{q} + \tilde{q}\tilde{g} + \tilde{g}\tilde{g} \ (\sqrt{s} = 8 \text{ TeV})$$



- Public NLL grids:

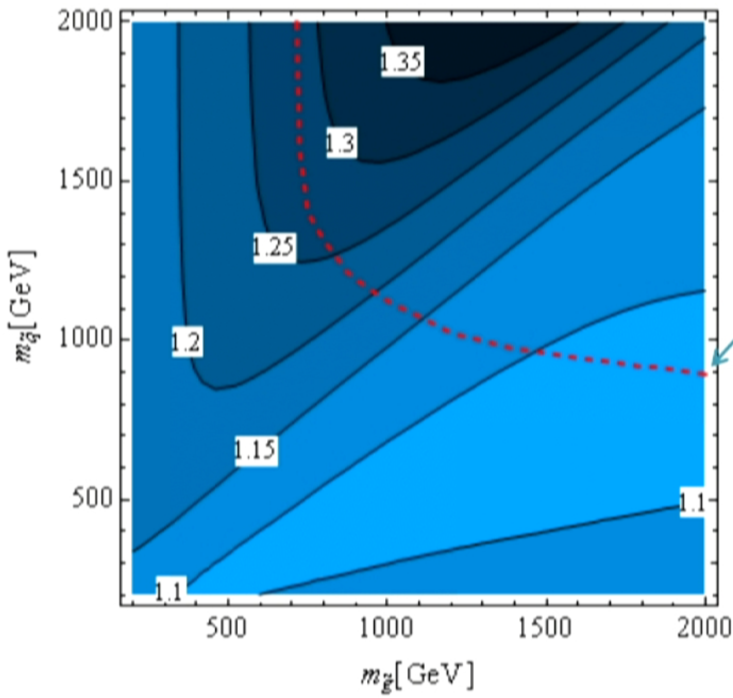
[http://omnibus.uni-freiburg.de/~cs1010/susy.html]

- Corrections can become as large as 40%, if squark mass is larger than gluino mass
- Exclusion bound goes through large K_{NLL} regions

Contour plot K_{NLL}

[Falgari, Schwinn, W '12]

$$PP \to \tilde{q}\bar{\tilde{q}} + \tilde{q}\tilde{q} + \tilde{q}\tilde{g} + \tilde{g}\tilde{g} \ (\sqrt{s} = 8 \text{ TeV})$$



An (old) ATLAS 7 TeV exclusion bound

- Public NLL grids:

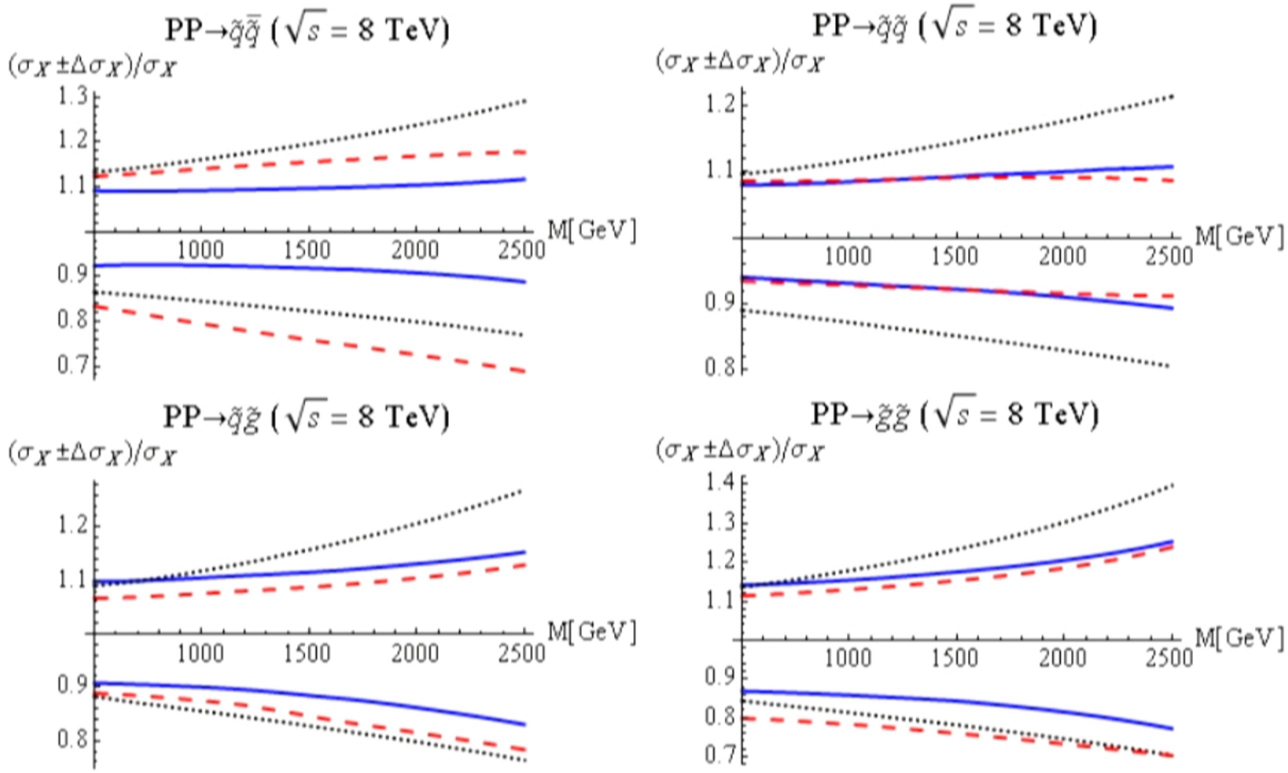
[http://omnibus.uni-freiburg.de/~cs1010/susy.html]

- Corrections can become as large as 40%, if squark mass is larger than gluino mass
- Exclusion bound goes through large K_{NLL} regions

Results

Uncertainties

[Falgari, Schwinn, W '12]



Scale and parameterization errors of:

- NLL: combined soft and Coulomb resummation
- NLL_{s+h}: no Coulomb resummation
- NLO: fixed order calculation to α_s^3

- Equal squark and gluino masses
- Corrections reduce NLO errors to $\pm 10\%$
- Soft-Coulomb interference reduces errors

19

Finite width

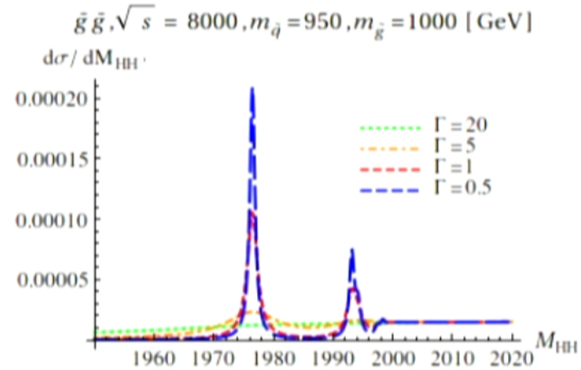
[Falgari, Schwinn, W '12]

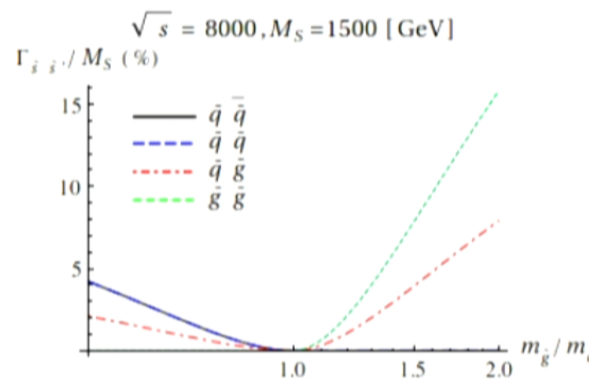
- Squarks and gluinos decay
- Finite width taken into account by:

$$E \rightarrow E + i\Gamma$$

Bound state peaks smeared out
Soft logs: $\alpha_s^n \ln^m \beta \rightarrow \alpha_s^n \ln^m (\beta^4 + (\Gamma/M)^2)^{1/4}$
Coulomb: $(\alpha_s/\beta)^n \rightarrow (\alpha_s/(\beta^4 + (\Gamma/M)^2)^{1/4})^n$

- Only resonant diagrams and LO widths





- Q: How much does the width effect our previous results?

Finite width

[Falgari, Schwinn, W '12]

- Squarks and gluinos decay

- Finite width taken into account by:

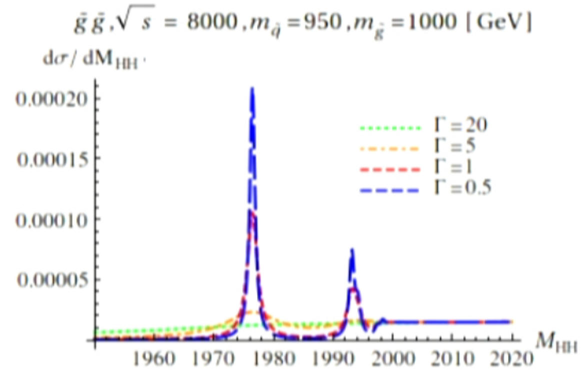
$$E \to E + i\Gamma$$

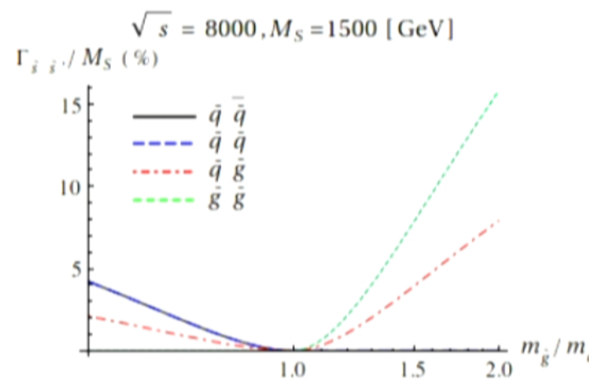
Bound state peaks smeared out

Soft logs: $\alpha_s^n \ln^m \beta \to \alpha_s^n \ln^m (\beta^4 + (\Gamma/M)^2)^{1/4}$

Coulomb: $(\alpha_s/\beta)^n \to (\alpha_s/(\beta^4 + (\Gamma/M)^2)^{1/4})^n$

- Only resonant diagrams and LO widths





- Q: How much does the width effect our previous results?

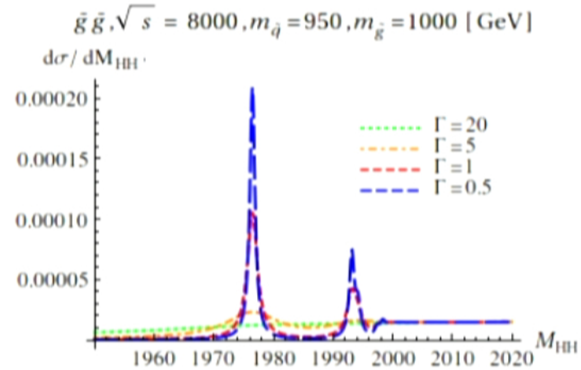
Finite width

[Falgari, Schwinn, W '12]

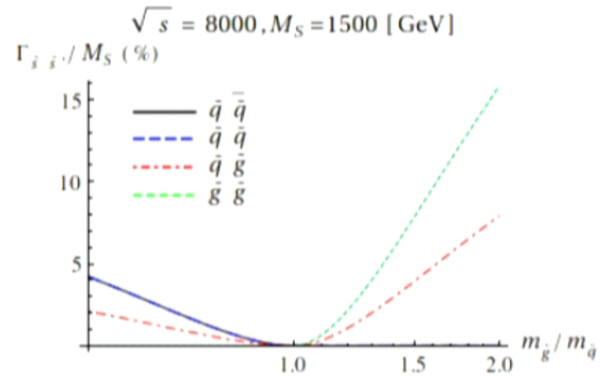
- Squarks and gluinos decay

- Finite width taken into account by:

$$E \to E + i\Gamma$$



Bound state peaks smeared out
Soft logs: $\alpha_s^n \ln^m \beta \to \alpha_s^n \ln^m(\beta^4 + (\Gamma/M)^2)^{1/4}$
Coulomb: $(\alpha_s/\beta)^n \to (\alpha_s/(\beta^4 + (\Gamma/M)^2)^{1/4})^n$



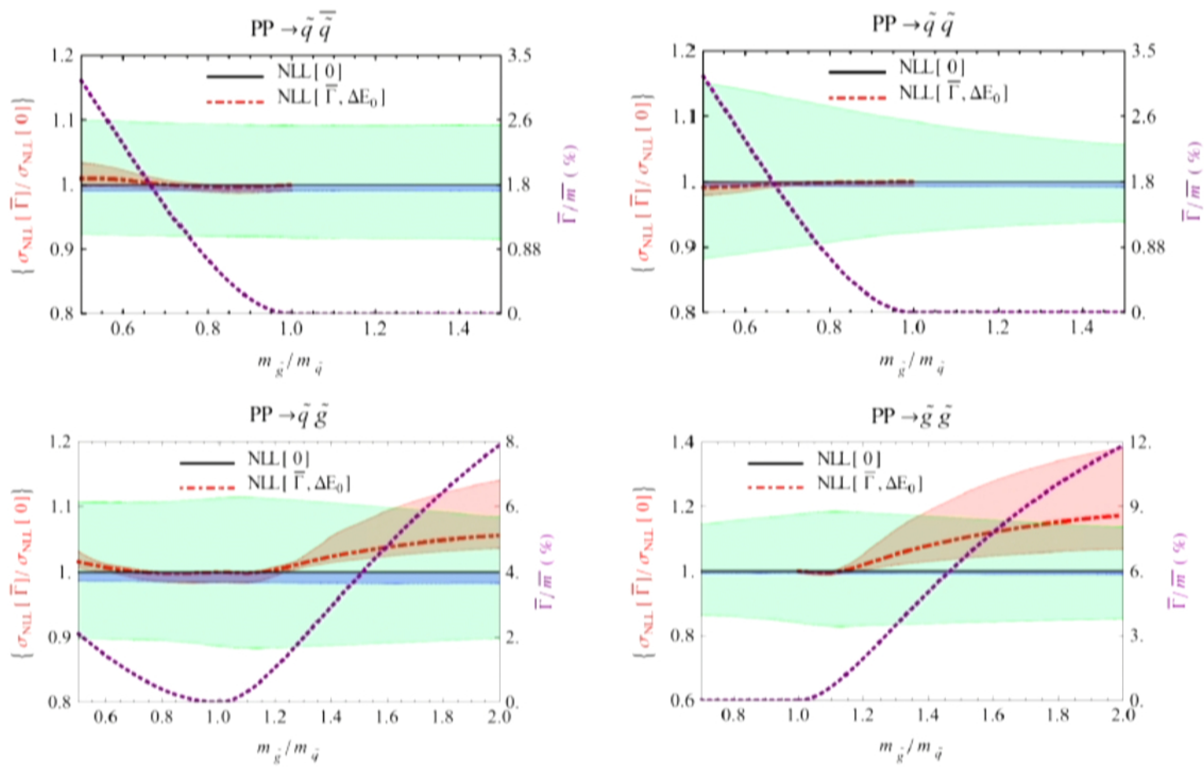
- Only resonant diagrams and LO widths

- Q: How much does the width effect our previous results?

Width

$$\frac{\sigma_{\rm NLL}[\Gamma]}{\sigma_{\rm NLL}[\Gamma=0]}$$

[Falgari, Schwinn, W '12]

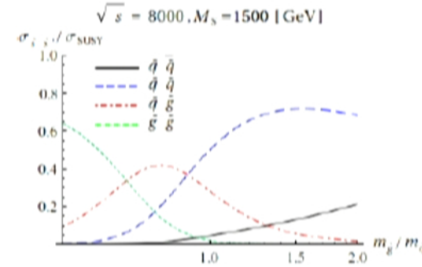


- Green band: total error for zero width
- Red band: finite-width induced errors
- Blue band: E vs β variation

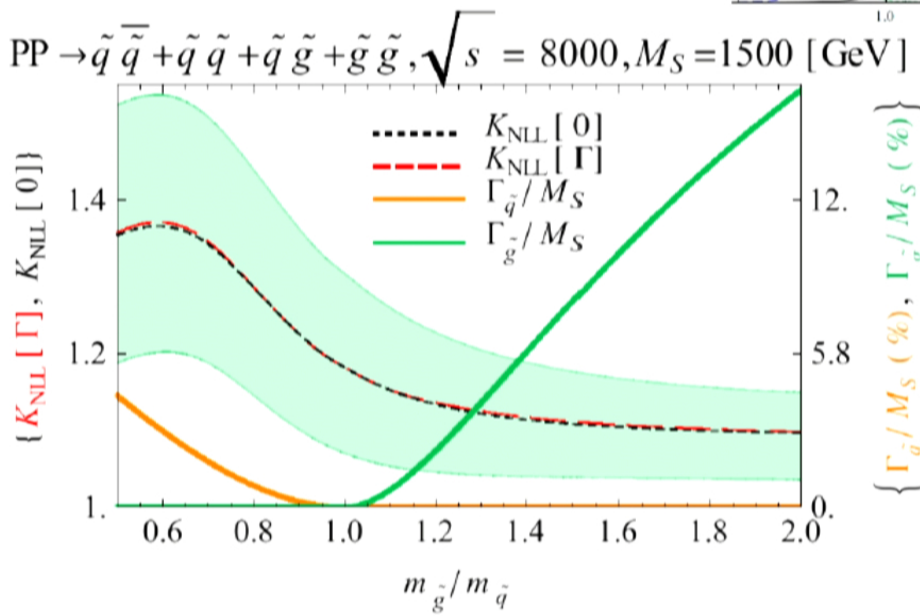
- Finite-width results within total error for $\Gamma/M \lesssim 5\%$
- Finite-width errors become large for $\Gamma/M > 5\%$

→ need to match at exact NLO

$$K_{\mathrm{NLL}}[\Gamma] = \frac{\sigma^{\mathrm{matched}}[\Gamma]}{\sigma^{\mathrm{NLO}}[\Gamma]}$$



- Experimentally relevant total SUSY production:



- Green band: total error for zero width
- Negligible difference ⟶ BS contributions correctly included by delta peaks
- Width can be neglected for the total SUSY process

Summary and Outlook

Outlook

- Extend results to non-degenerate squark masses
- **NNLL resummation** ⟶ compare with Mellin results [Beenakker et al. '11;...]

- NNLL ingredients:

✓ Two-loop (three-loop cusp-)anomalous dimensions [Moch, Vermaseren, Vogt '04/'05; Beneke, Falgari, Schwinn '09]

✓ One-loop soft function and NLO Green's function [Fadin, Khoze '87; Beneke, Signer, Smirnov '99]

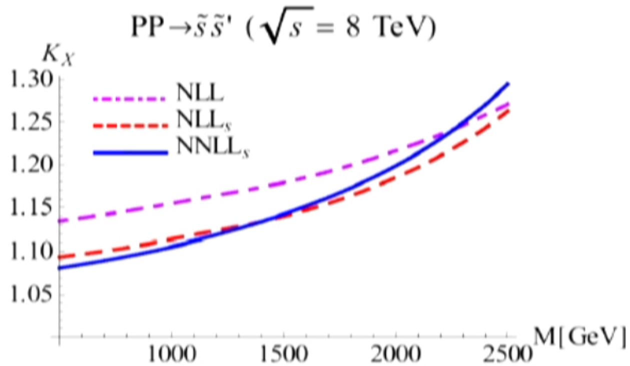
✓ One-loop matching coefficients – very recently [Beenakker et al. '11,'13]

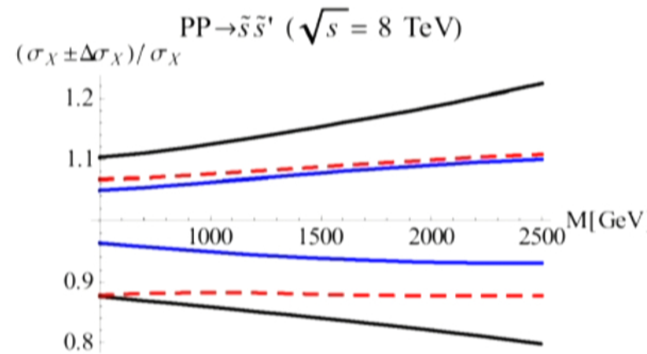
✣ Non-Coulomb Green's function – under way

Summary and Outlook

Partial NNLL soft

Tree level hard matching coefficients:





Scale and parameterization errors of:

- NLL: combined soft and Coulomb resummation
- NLL_s: only soft resummation at NLL
- $NNLL_s$: only soft resummation at NNLL (partial)

- Equal squark and gluino masses
- Soft corrections increased by ~ 8%
- Corrections reduce NLO errors to ± 8%

Summary

- The corrections on total SUSY process can be as large as 15-40%
- Errors reduced to ±10%
- Coulomb corrections can be as large as soft corrections $\longrightarrow$ need to resum them
- Finite width effects on Coulomb and soft corrections of total SUSY process are negligible
- Corrections need to be taken into account for setting more accurate squark-gluino mass (bounds)
- Public squark and gluino NLL grids: http://omnibus.uni-freiburg.de/~cs1010/susy.html
- We anticipate significant error reduction at complete NNLL order