Resonance-aware Subtraction in the Dipole Method

- QCD@LHC Conference -

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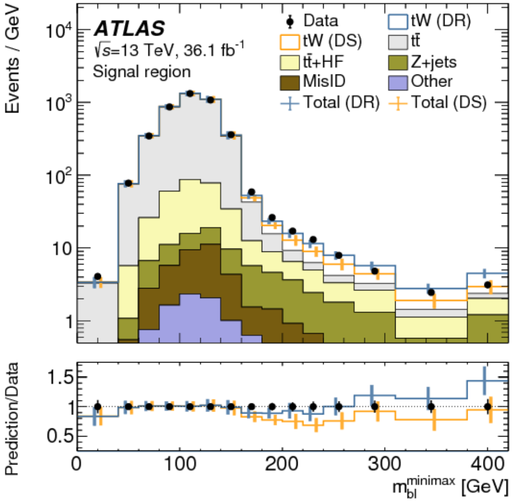
Motivation



ATLAS [2018]

- Background for new physics: $t\bar{t}$ and single top channels
- Arbitrariness at NLO in differentiation between those two (DR vs. DS)
- Preferably $bW^+\bar{b}W^-$ at NLO
- NLO-subtration with resonances . . .

Recap CS-Subtraction

Contributions to NLO Cross Section

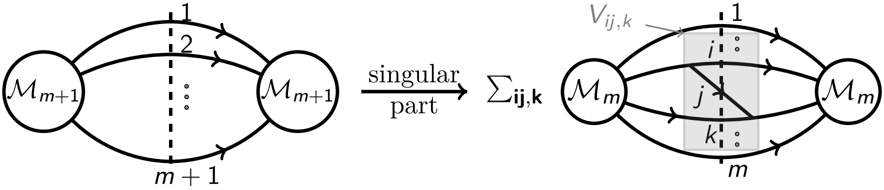
NLO cross section (with no initial state hadrons) for m final state particles

$$\sigma^{\mathrm{NLO}} = \underbrace{\int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{S}} \right)}_{\int_{m+1} \mathrm{d}\sigma^{\mathrm{NLO}}_{m+1}} + \underbrace{\int_{m+1} \mathrm{d}\sigma^{\mathrm{S}} + \int_m \mathrm{d}\sigma^{\mathrm{V}} + \int_m \mathrm{d}\sigma^{\mathrm{LO}}}_{\int_m \mathrm{d}\sigma^{\mathrm{NLO}}_m}$$

- $\mathrm{d}\sigma^{\mathrm{S}} \ldots$ subtraction terms with $\mathrm{d}\sigma^{\mathrm{S}} = \mathrm{d}\sigma^{\mathrm{R}}$ when phase space hits singular region
- $\int_1 \mathrm{d}\sigma^{\mathrm{S}} = \mathrm{d}\sigma^{\mathrm{I}}$ is once and for all integrated in D-dimensions $\Rightarrow$ poles of ϵ^{-1} and ϵ^{-2} cancel with D-dimensional $\mathrm{d}\sigma^{\mathrm{V}}$
- Both $\mathrm{d}\sigma^{\mathrm{NLO}}_{m+1}$ (RS-terms) and $\mathrm{d}\sigma^{\mathrm{NLO}}_m$ (BVI-terms) are separately finite and integrable in 4 dimensions

How to obtain $\mathrm{d}\sigma^{\mathrm{S}}$?

Singularities do not completely factorise.



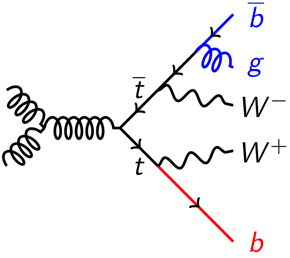
$$\left|\mathcal{M}_{m+1}\right|^2(p_1,\dots,p_{m+1}) \to \sum_{\substack{\text{pairs}\\ i\neq j}} \sum_{\substack{\text{spectators}\\ k\neq i,j}} \mathcal{D}_{ij,k}(p_1,\dots,p_{m+1}) + \text{finite}$$

$\mathcal{D}_{ij,k}$ is an absolute-squared m-parton matrix element
(with insertion operator $V_{ij,k}$).

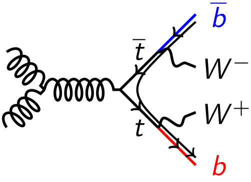
The Problem

The Problem of Resonances

Real Correction



Subtraction Term



Recoil flows through top-quarks.

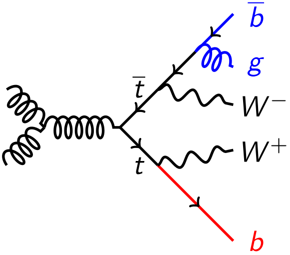
- In real corrections and subtraction terms, top-quarks have different virtuality p_t^2
- Top-quark propagator $\sim \left(p_t^2 - m_t^2 + i m_t \Gamma_t\right)^{-1}$
- $\left(\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{S}}\right)$ has narrow peaks for small Γ_t
  $\Rightarrow$ MC-Integration of RS-terms is unstable
  and distorted distributions in NLO+PS

The Solution: Pseudo-Dipoles

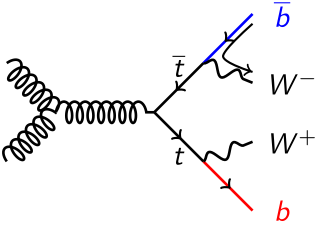
Solution: Alternative Momentum Mapping

... requires change of dipoles: $\mathcal{D}^{\mathrm{CS}}_{ij,k} \to \mathcal{D}^{\mathrm{ID}\ (n)}_{ij,k}$ (pseudo-dipoles) while maintaining their singular limit and integrability.

Real Correction



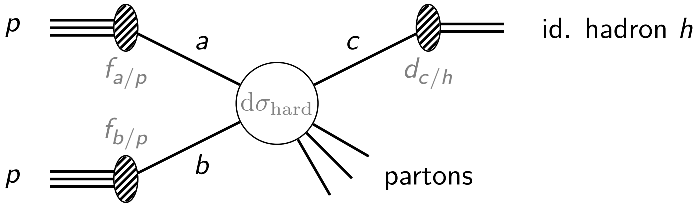
Subtraction Term



Recoil does not flow through top-quarks.

Pseudo-Dipoles . . .

. . . were introduced by Catani, Seymour [1997] to cope with the situation of identified hadrons.

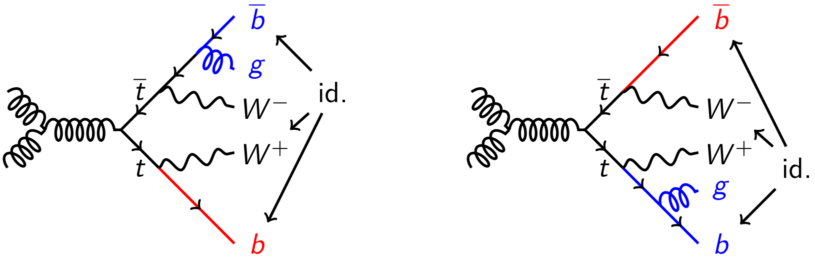


- A parton which fragments in an identified hadron cannot absorb a recoil.
- The recoil is instead transferred to all final state **particles**, which do not fragment into identified hadrons. (colour spec. $\neq$ kin. spec)
- Recoil mapping is a Lorentz transform.

Application to Resonance-aware Subtraction

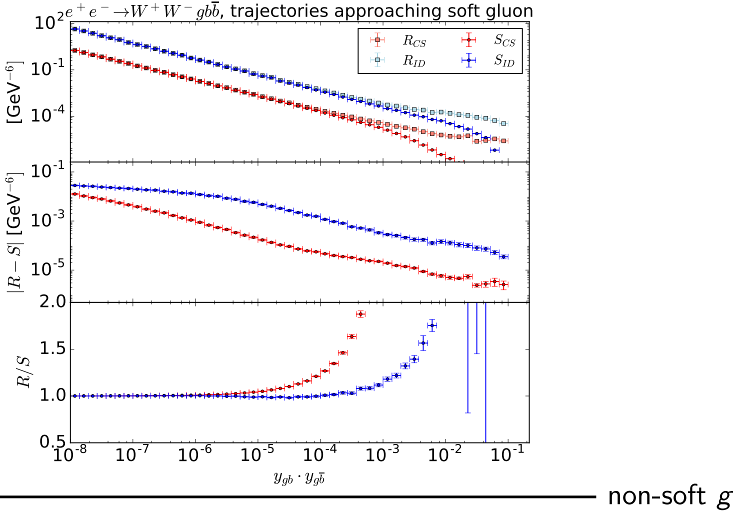
- Do not identify partons throughout the calculation, but identify different particles **depending** on subtraction term.

$\overline{b}$-quark emitter **b-quark emitter**



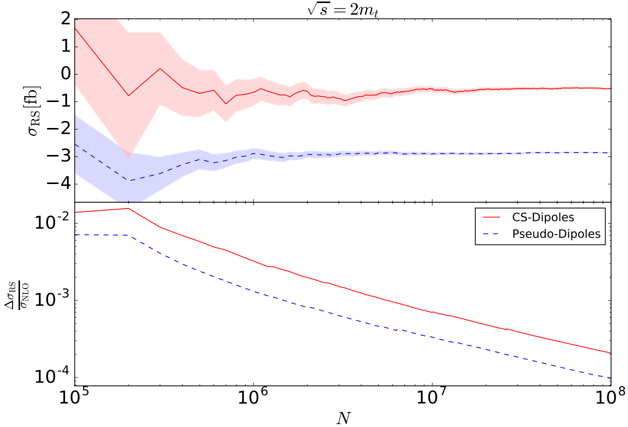
- Do not fix direction of identified particle's momenta, but integrate over them. ⇒ Partonic fragmentation functions drop out.

Singular Limits



Höche, SL, Siegert [2018]

Physical Cross Section for $e^+e^- \to W^+W^-b\bar{b}$



Höche, SL, Siegert [2018]

Physical Cross Section for $e^+e^- \to W^+W^-b\bar{b}$

- between CS- and pseudo-dipoles RS/BVI cross sections are different,
- but their sum is (of course) unchanged

σ[fb]	$\sqrt{s} = 3m_W$		$\sqrt{s} = 2m_t$		$\sqrt{s} = 4m_t$	
	CS	ID	CS	ID	CS	ID
RS	−0.00772(6)	−0.00140(5)	−0.52(3)	−2.85(1)	−9.5(4)	−5.3(1)
BVI	0.16143(13)	0.15506(13)	148.07(9)	150.55(9)	230.0(2)	226.0(2)
$\sum$	0.15371(14)	0.15366(14)	147.55(9)	147.70(9)	220.5(4)	220.7(2)

Summary & Outlook

Summary:

- Dipoles are associated with a momenta mapping $\{p_1, \ldots, p_{m+1}\} \to \{p_1, \ldots, p_m\}$
- In the presence of resonances, recoil alters CS-subtraction terms significantly
  - Causes instabilities in MC-integration
  - Mismatch in parton shower

  $\Rightarrow$ Alter mapping / dipoles to avoid those

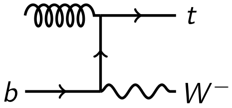
Outlook:

- Extend procedure to hadronic initial states
- Match resonances-aware subtraction to parton shower

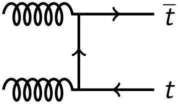
Appendix

Single-top/$t\bar{t}$ Interference

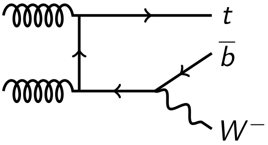
Single-top Production



$t\bar{t}$ Production



QCD-Real Corrections:
E.g. $g + g \to \bar{b} + t + W^-$

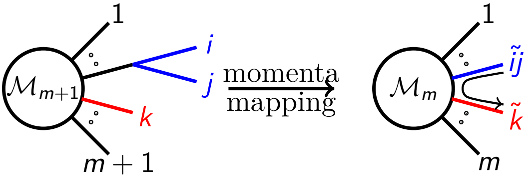


- In on-shell region $(p_W + p_b)^2 \approx m_t^2$, this diagram actually contributes to $t\bar{t}$ production
- Subtract that contribution (diagram removal/subtraction) $\Rightarrow$ theoretical uncertainty

Mapping Momenta for FF CS-Dipoles

As the dipoles are (absolute-squared) ***m*-parton** matrix-elements, a mapping from $\{p_1, \ldots, p_{m+1}\}$ to $\{p_1, \ldots, p_m\}$ is required:

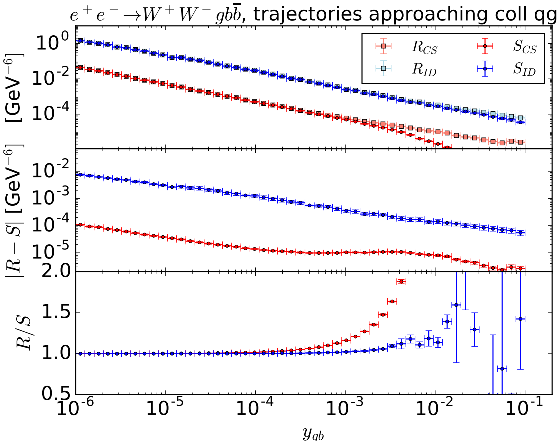
$$\tilde{p}_{ij}^{\mu} = p_i^{\mu} + p_j^{\mu} - \frac{y}{1-y} p_k^{\mu}, \qquad \tilde{p}_k^{\mu} = \frac{1}{1-y} p_k^{\mu}, \qquad \text{with } y = y(p_i, p_j, p_k)$$



which

- renders all momenta **on-shell**, i.e. $p_i^2 = p_j^2 = \tilde{p}_{ij}^2 = 0$ and $p_k^2 = \tilde{p}_k^2 = 0$ and
- ensures **momentum conservation**: $p_i^{\mu} + p_j^{\mu} + p_k^{\mu} = \tilde{p}_{ij}^{\mu} + \tilde{p}_k^{\mu}$.

Singular Limits



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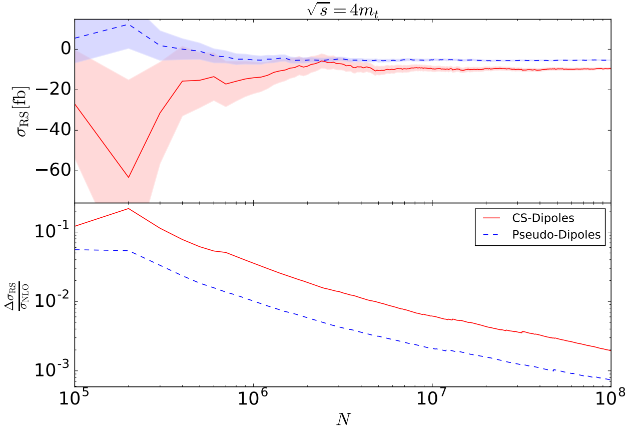

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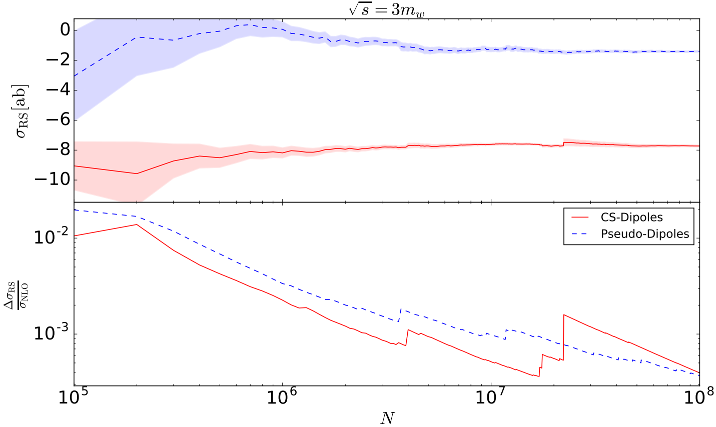

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