Multijet Events at Hadron Colliders

New Physics Signals and QCD Backgrounds

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Overview

- Motivation: Why consider multijet final states?
- The challenge of modelling them
- Combining matrix elements and parton showers
  - A new algorithm[a]
- Validation
  - Drell-Yan production at Tevatron
- Application
  - Color octets at LHC[b]
- Summary and Outlook

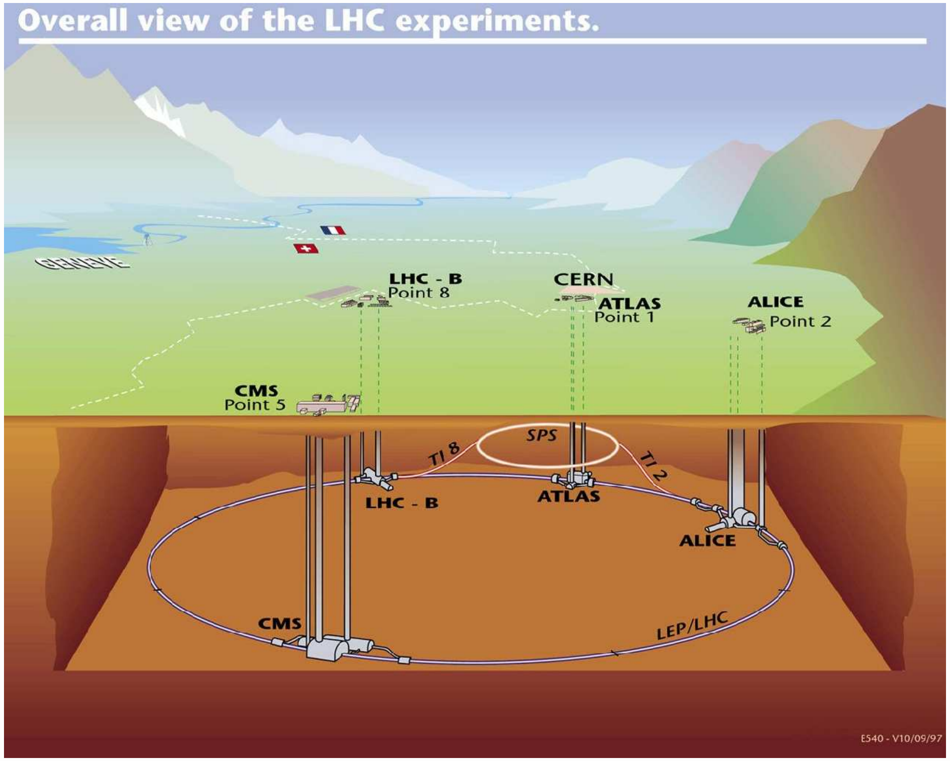
[a] Höche, Krauss, S., Siegert arXiv:0903.1219 [hep-ph]

[b] Kilic, S., Son JHEP04 (2009) 128

Multijet Final States At Hadron Colliders

How is the electroweak symmetry broken?
Hierarchy between $v = 246\ \mathrm{GeV}$ and $M_{\mathrm{Planck}} = 10^{19}\ \mathrm{GeV}$?
Nature of dark matter?

$\rightsquigarrow$ **probe TeV scale physics: Higgs boson(s), SUSY, ED, Compositeness...**

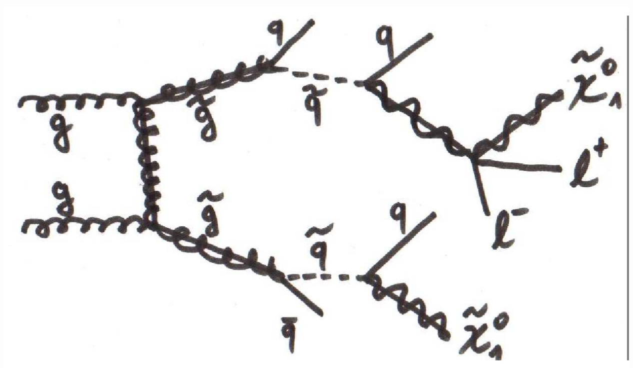


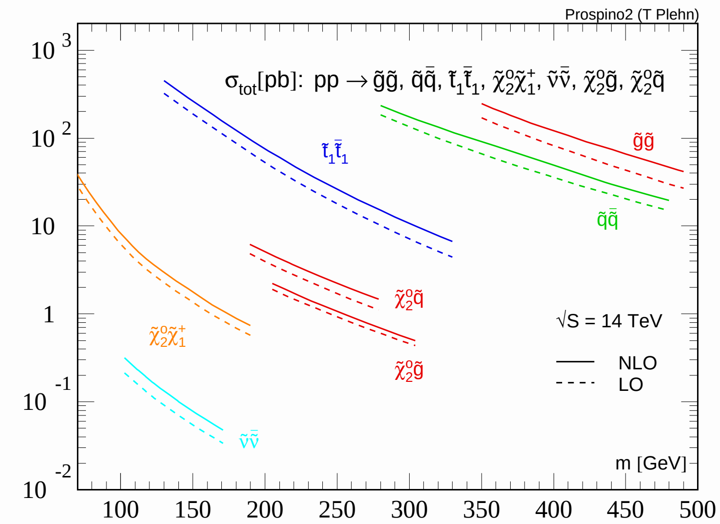
Tevatron $p\bar{p}$ @ $2\ \mathrm{TeV}$

LHC pp @ $10 - 14\ \mathrm{TeV}$

Multijet Final States At Hadron Colliders

example: cascade decays in the MSSM





- large cross sections for $\tilde{g}$, $\tilde{q}$ production
- spectrum/decays depend on SUSY breaking mechanism
- generic signals: #-leptons + #-jets + $\not{E}_T$

  [nature of new physics encoded in energies, flavours, edges] [SUSY vs. ED]
- SM backgrounds: V+jets, VV+jets, $t\bar{t}$+jets, QCD jets

$\leadsto$ **wide range of signatures – challenged by SM backgrounds**

example: new color octets – multijet resonances

- topgluons, axigluons, sgluons, KK-gluons [boosted tops, like-sign tops]
- composites: technihadrons, e.g. $\rho_{\mathrm{T},8}$, $\pi_{\mathrm{T},8}$, gluinonia, ...

Multijet Final States At Hadron Colliders

example: new color octets – multijet resonances

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Strawman: Scaled-up QCD [Kilic, Okui, Sundrum '08; Kilic, S., Son '08]

- extend SM by set of fermions charged under QCD and HyperColor only

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4} H_{\mu\nu} H^{\mu\nu}$$

$\rightsquigarrow$ hypercolor confining at scale Λ_{HC}

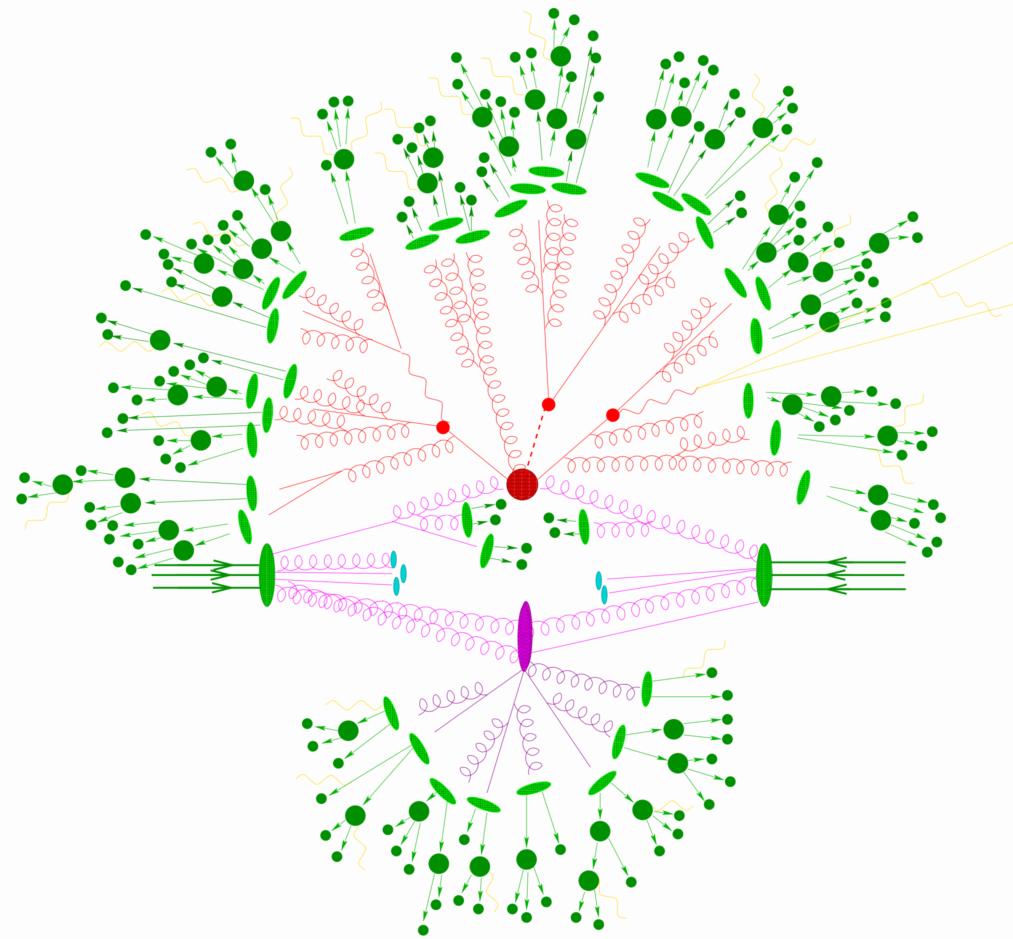
- below Λ_{HC} bound states $\langle\bar{\psi}\psi\rangle$ exist charged under QCD, e.g.
  - $SU(3)_c$ adjoint vector $\tilde{\rho}_\mu$ (coloron)
  - $SU(3)_c$ adjoint scalar $\tilde{\pi}$ (hyperpion)
- quantitative: 3 massless $\psi'\mathrm{s} = (3, \bar{3})$ charged under $SU(3)_c \otimes SU(3)_{HC}$

$\rightsquigarrow$ LHC signatures: $pp \to \tilde{\pi}\tilde{\pi}$ & $pp \to \tilde{\rho}\tilde{\rho}$ with $\tilde{\pi} \to gg$ & $\tilde{\rho} \to \tilde{\pi}\tilde{\pi}$

$\rightsquigarrow$ resonance search in four- & eight-jet final states [details later]

Monte Carlo event generators

- **Hard interaction**
  exact matrix elements $|\mathcal{M}|^2$
- **QCD bremsstrahlung**
  parton showers in the initial and final state
- **Multiple Interactions**
  beyond factorisation: modelling
- **Hadronisation**
  non perturbative QCD: modelling
- **Hadron Decays**
  phase space or effective theories



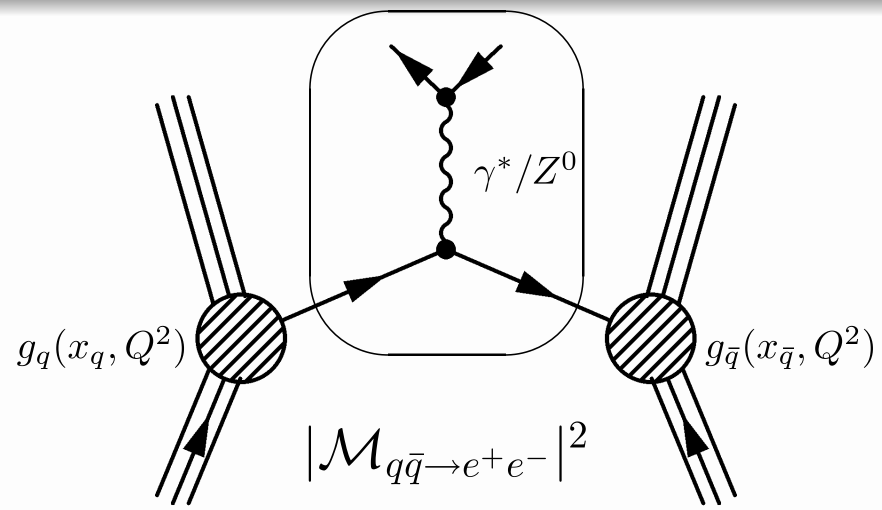
➔ **fully exclusive hadronic final states**

➔ **direct comparison with experimental data**

Herwig, Pythia, Sherpa

[Gleisberg et. al '04, '09]

Matrix Elements: Drell-Yan Production



$$\sigma_{pp\to e^+e^-}(Q^2) = \sum_q \int \mathrm{d}x_q \mathrm{d}x_{\bar{q}}\; g_q(x_q, Q^2) g_{\bar{q}}(x_{\bar{q}}, Q^2)\; \mathrm{d}\hat{\sigma}_{q\bar{q}\to e^+e^-}$$

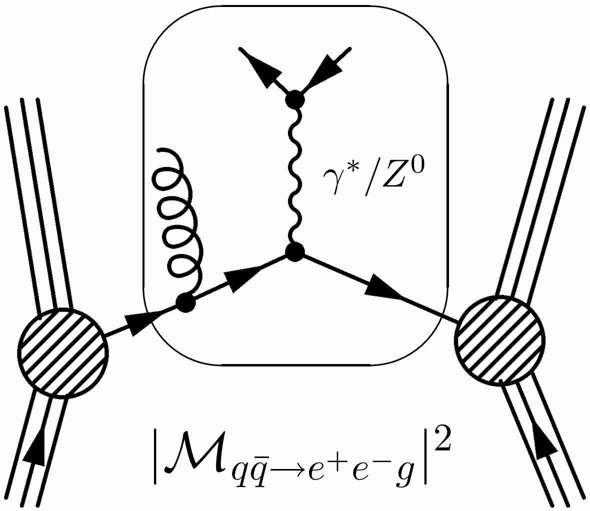
- partonic matrix element [encodes fundamental physics, interferences, off-shell effects]

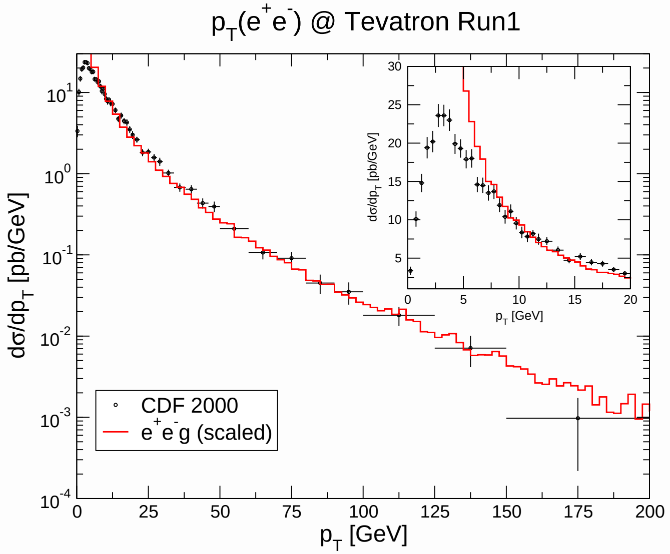
$$\mathrm{d}\hat{\sigma}_{q\bar{q}\to e^+e^-} = |\mathcal{M}_{q\bar{q}\to e^+e^-}|^2\; \mathrm{d}LIPS$$

- universal PDF $g_{q/g}(x, Q^2)$
- resummation of soft/collinear initial-state radiation in PDFs

  $\leadsto$ **factorisation into hard and soft contribution at Q^2**

Matrix Elements: Drell-Yan Production





- cross section enhanced for small gluon p_T [plus soft emissions]

$$|\mathcal{M}_{q\bar{q}\to e^+e^-g}|^2 \sim |\mathcal{M}_{q\bar{q}\to e^+e^-}|^2 \frac{\alpha_S(\mu_R^2)}{p_T^2} \rightsquigarrow \sigma_{pp\to e^+e^-g} \sim \sigma_{pp\to e^+e^-} \alpha_S(\mu_R^2) \log \frac{p_T^{\max}}{p_T^{\min}}$$

$\rightsquigarrow$ $|\mathcal{M}|^2$ factorise in IR limes (universal)

$\rightsquigarrow$ large logs need to be resummed to all orders

$\rightsquigarrow$ parton shower approach

punchline

- proper description of soft/collinear *and* hard emissions
- combine QCD matrix elements of different parton multiplicity with showers

  [CKKW: Catani et. al ’01, MLM: Mangano et. al ’01, CKKW-L: Lönnblad ’01]

Parton Showers

starting point for showers: QCD evolution equation

$$\frac{\partial}{\partial \log(t/\mu^2)} \frac{g_a(z,t)}{\Delta_a(\mu^2,t)} = \frac{1}{\Delta_a(\mu^2,t)} \int_z^{\zeta_{\max}} \frac{d\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t)\, g_b(z/\zeta,t)$$

Sudakov form factor

$$\Delta_a(\mu^2,t) = \exp\left\{ -\int_{\mu^2}^{t} \frac{d\bar{t}}{\bar{t}} \int_{\zeta_{\min}}^{\zeta_{\max}} d\zeta \sum_{b=q,g} \frac{1}{2} \mathcal{K}_{ba}(\zeta,\bar{t}) \right\}$$

$\hookrightarrow$ IR cut-off

$\hookrightarrow$ resolution criterium

- Kernels describe parton splittings:

$$\mathcal{K}_{ba}(z,t) \stackrel{\rm IR}{\rightarrow} \frac{1}{d\hat{\sigma}_a^{(N)}(\Phi_N)} \frac{d\hat{\sigma}_b^{(N+1)}(z,t;\Phi_N)}{d\log(t/\mu^2)\, dz}\Bigg|_{\mathrm{N_c}\to\infty}$$

[IR (shower) factorisation scheme: collinear, dipole or antenna subtraction]

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[IR (shower) factorisation scheme: collinear, dipole or antenna subtraction]

- defines shower no-branch probabilities between two scales

$$\mathcal{P}^{(B)}_{\mathrm{no},\,a}(z,t,t') = \frac{\Delta_a(\mu^2,t')\,g_a(z,t)}{\Delta_a(\mu^2,t)\,g_a(z,t')} = \exp\left\{ -\int_t^{t'} \frac{\mathrm{d}\bar{t}}{\bar{t}} \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,\bar{t}) \frac{g_b(z/\zeta,\bar{t})}{g_a(z,\bar{t})} \right\}$$

Matrix Elements And Parton Showers

construction criteria

- describe hardest emissions through full matrix elements

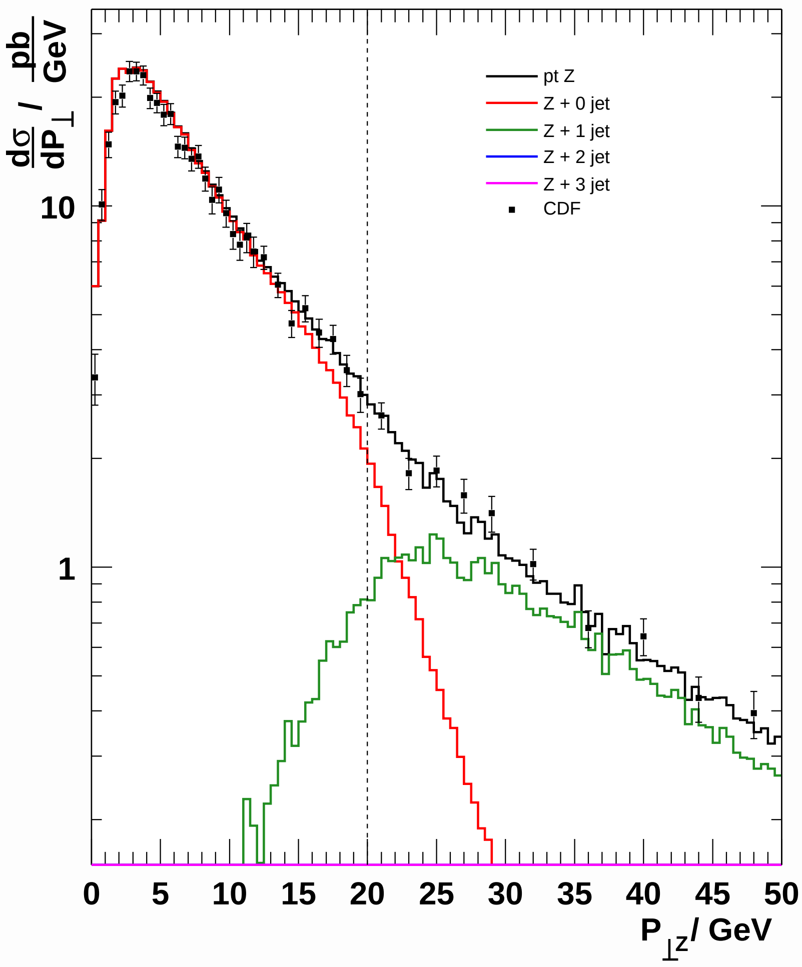
$$\mathcal{K}_{ba}(z,t) \to \frac{1}{\mathrm{d}\hat{\sigma}_a^{(N)}(\Phi_N)} \frac{\mathrm{d}\hat{\sigma}_b^{(N+1)}(z,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}z}$$

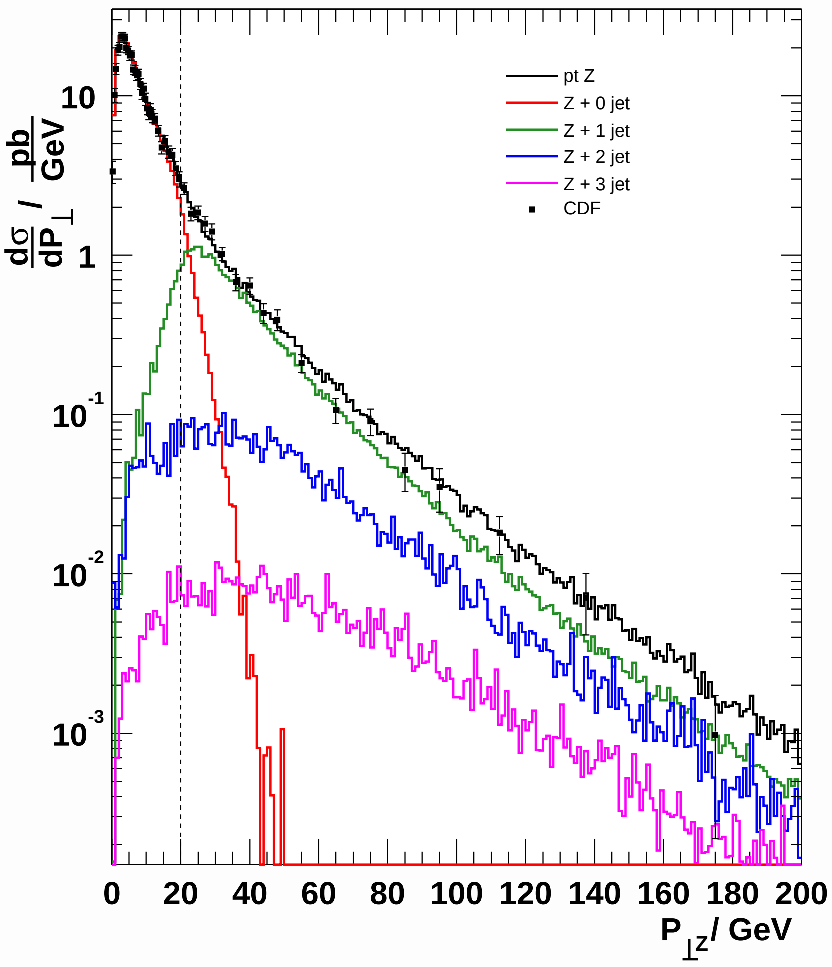
- preserve shower-evolution equation [logarithmic accuracy]
- avoid double counting or empty phase-space regions

$\rightsquigarrow$ **slice emission phase space by parton-separation criterion $Q_{ba}(z,t)$**

sneak preview: Drell-Yan p_T distribution

[Krauss,Schälicke, S., Soff '04]





Matrix Elements And Parton Showers

Phase-space separation

[Höche, Krauss, S., Siegert '09]

$$\mathcal{K}_{ba}^{\rm PS}(z,t) = \mathcal{K}_{ba}(z,t)\,\Theta\left[Q_{\rm cut} - Q_{ba}(z,t)\right] \quad \leftarrow \text{shower regime}$$

$$\mathcal{K}_{ba}^{\rm ME}(z,t) = \mathcal{K}_{ba}(z,t)\,\Theta\left[Q_{ba}(z,t) - Q_{\rm cut}\right] \quad \leftarrow \text{matrix-element regime}$$

$\Rightarrow Q_{ba}(z,t)$ has to identify logarithmically enhanced phase-space regions

Sudakov form factor and no-branch probabilities factorise

$$\Delta_a(\mu^2,t) = \Delta_a^{\rm PS}(\mu^2,t)\,\Delta_a^{\rm ME}(\mu^2,t)$$

$$\rightsquigarrow \mathcal{P}^{(B)}_{{\rm no},\,a}(z,t,t') = \mathcal{P}^{(B)\,{\rm PS}}_{{\rm no},\,a}(z,t,t')\,\mathcal{P}^{(B)\,{\rm ME}}_{{\rm no},\,a}(t,t') = \frac{\Delta_a^{\rm PS}(\mu^2,t')\,g_a(z,t)}{\Delta_a^{\rm PS}(\mu^2,t)\,g_a(z,t')}\,\frac{\Delta_a^{\rm ME}(\mu^2,t')}{\Delta_a^{\rm ME}(\mu^2,t)}$$

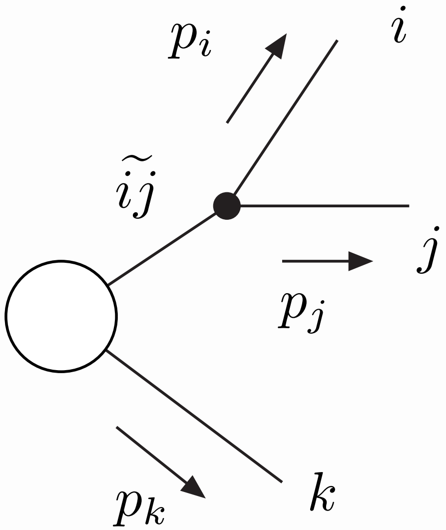
- need to veto shower emissions with $Q > Q_{\rm cut}$
- matrix elements need to be reweighted [made exclusive quantities]

$\hookrightarrow$ think of ME's as predetermined shower emissions, truncated shower

The Phase-Space Separation Criterion (I)

new proposal for phase-space separation [Catani–Seymour inspired]

consider final-state splitting $(\widetilde{ij}) \to i,\, j$



$$Q^2_{ij} \;=\; 2\,p_ip_j\;\min_{k\neq i,j}\;\frac{2}{C^k_{i,j}+C^k_{j,i}}$$

$\hookrightarrow$ minimize over color partners k

$$C^k_{i,j} \;=\; \begin{cases} \dfrac{p_ip_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_ip_j} & \text{if } j=g \\[2ex] 1 & \text{else} \end{cases}$$

- flavor and color dependend measure
- distincts final & initial-state splittings [$a \to (\widetilde{aj})\,j$]

The Phase-Space Separation Criterion (II)

soft limit: $p_j = \lambda q$, $\lambda \to 0$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{2\,p_i\,q}\,\max_{k\neq i,j}\left[\frac{p_i p_k}{(p_i+p_k)\,q} - \frac{m_i^2}{2\,p_i q}\right]$$

(quasi-)collinear limit: $k_\perp \to \lambda k_\perp$, $m \to \lambda m$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{p_{ij}^2 - m_i^2 - m_j^2}\left(\tilde{C}_{i,j} + \tilde{C}_{j,i}\right)$$

where

$$\tilde{C}_{i,j} = \begin{cases} \dfrac{z}{1-z} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

➔ measure correctly identifies enhanced phase-space regions

A Monte Carlo Algorithm

sadly we can't directly generate MEs in shower scheme, instead:

1. evaluate n-jet MEs, regularised by $Q_{\rm cut}$, at μ_F^2 & μ_R^2

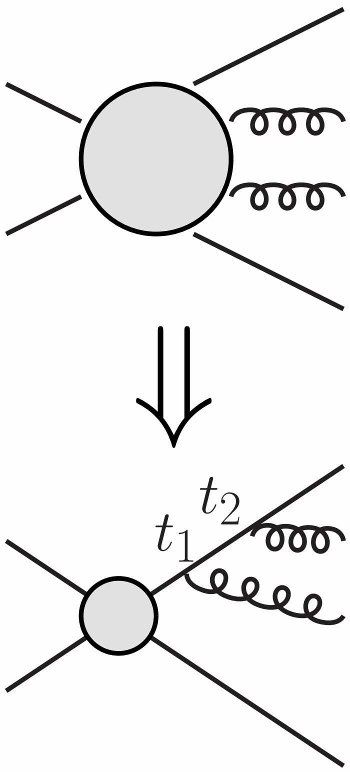
   $[n = 0, 1, .., N_{\rm max}]$

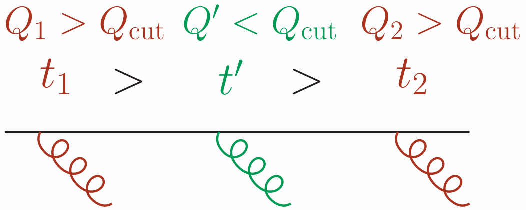
2. generate ME configuration according to σ_n and $d\sigma_n$
3. for given ME configuration reconstruct most probable shower branching history
   - cluster backwards using shower kernels & inverted kinematics
   - chain of ME 'emissions' in terms of shower variables (t_i, z_i, ϕ_i)
4. reweight event with factors $\alpha_S(\mu_i^2)/\alpha_S(\mu_R^2)$, $\mu_i^2 = \mu^2(t_i, z_i)$
5. start shower for core process at $t_{\rm max}$, i.e. μ_F^2
6. *veto the event* if shower generates emission above $Q_{\rm cut}$

   [accounts for $\mathcal{P}_{\rm no}^{(B)\,\rm ME}$, equivalent to analytic Sudakov reweighting]

7. insert ME branchings when crossing corresponding t_i

   $\leadsto$ intermediate lines radiate: truncated shower





Implementation

algorithm implemented in the Sherpa generator

- use new matrix-element generator Comix [Gleisberg, Höche '08]
  - Berends-Giele recursion
  - color-ordered amplitudes [straightforward large-N_c assignment]
- Catani–Seymour subtraction based shower [Krauss, S. '07]
  - emitter–spectator notion
  - invariant splitting variables
  - local momentum recoil
  - soft-color coherence inherent [dipole factorisation]

$\rightsquigarrow$ combination provides optimal analytic control

Validation: Drell-Yan Production At Tevatron

- Stability of cross sections & observables under $Q_{\rm cut}$ and $N_{\rm max}$ variations?
- Comparison to data!

calculational setup

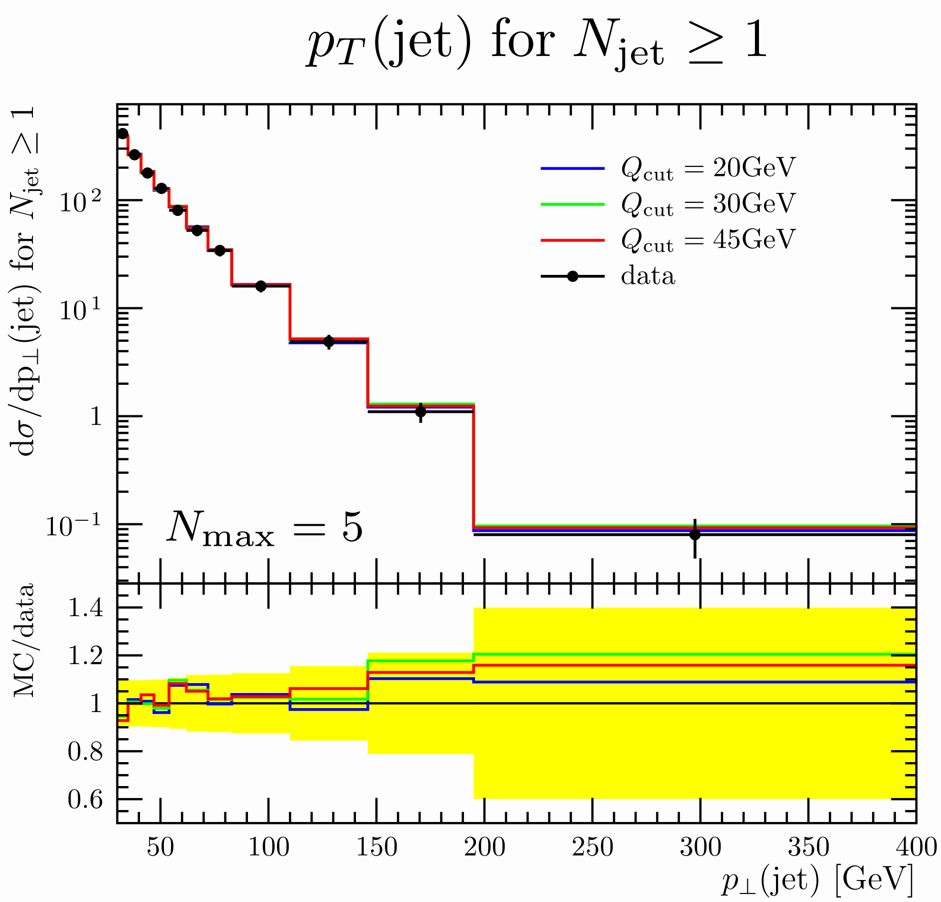
- $p\bar{p} \longrightarrow e^+e^- + X$ with $66\ \mathrm{GeV} \leq M_{e^+e^-} \leq 116\ \mathrm{GeV}$
- $\mu_F^2 = M_{e^+e^-}^2$
- $N_{\rm max} = 0 \ldots 6$ & $Q_{\rm cut} = 20/30/45\ \mathrm{GeV}$

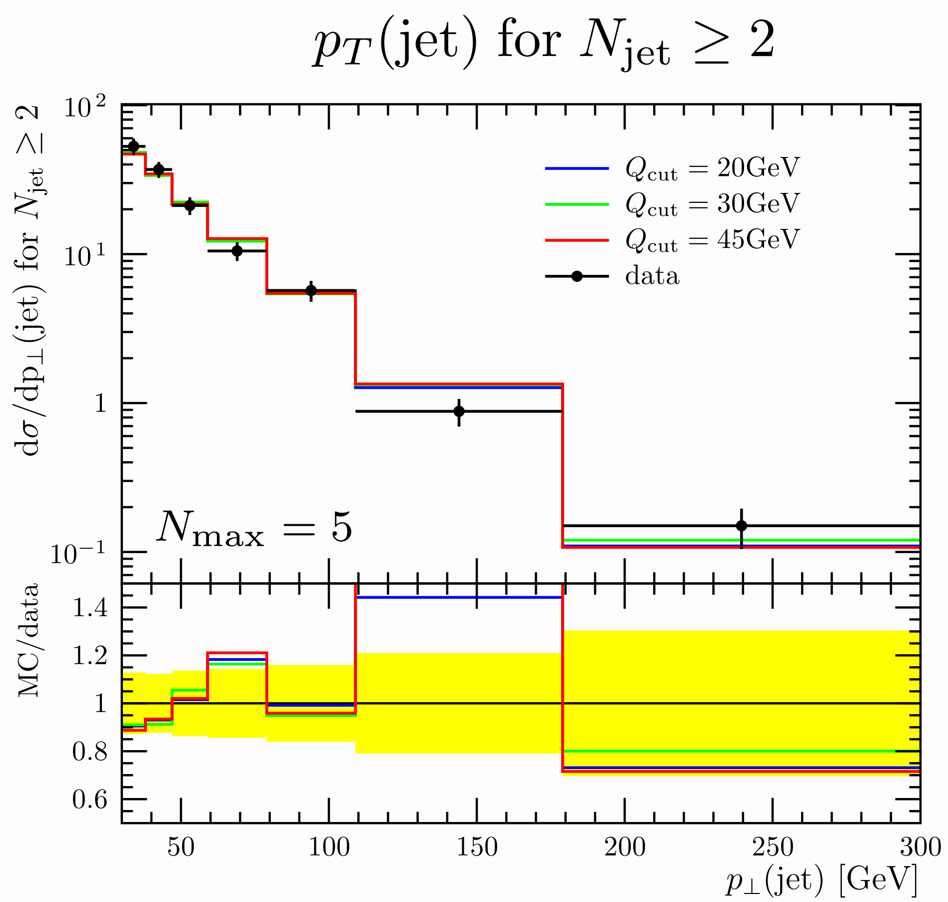
		$N_{\rm max}$						
		0	1	2	3	4	5	6
$Q_{\rm cut}$	20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
	30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
	45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)

$\rightsquigarrow$ **"merging systematics" of $\sigma_{\rm tot} < \pm 3\%$**

Validation: Drell-Yan Production At Tevatron

- Q_{cut} **variation: all-jet p_T spectra (data CDF '08)**

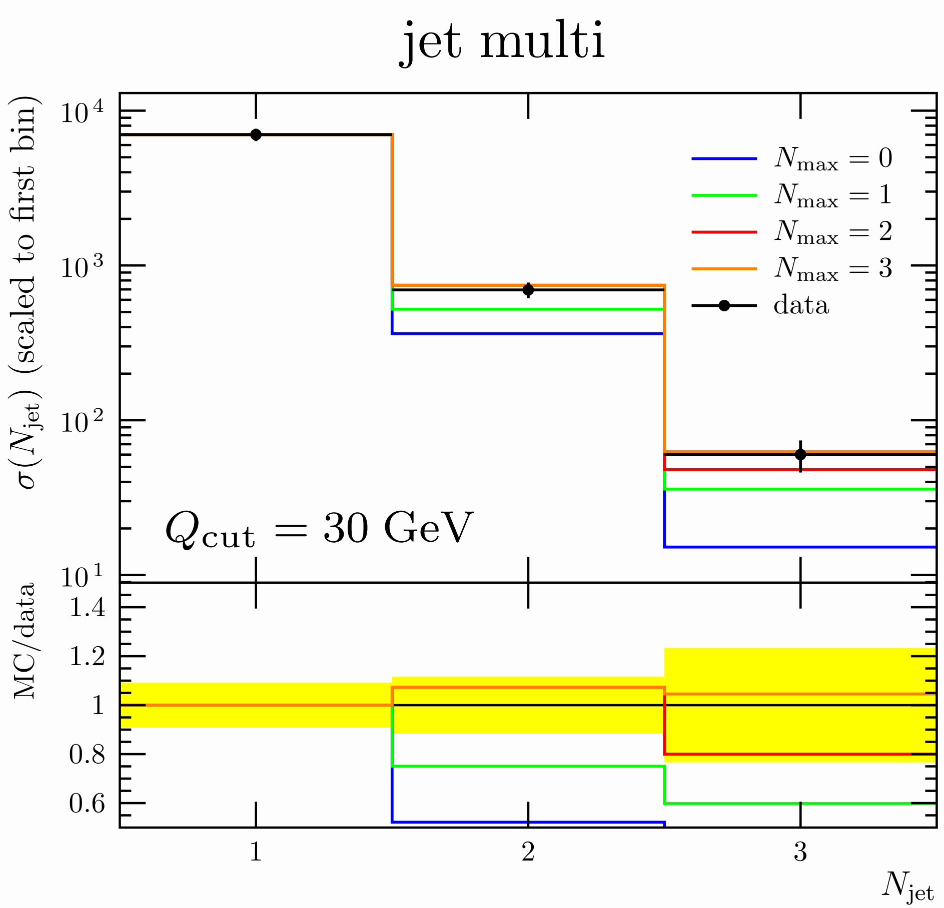


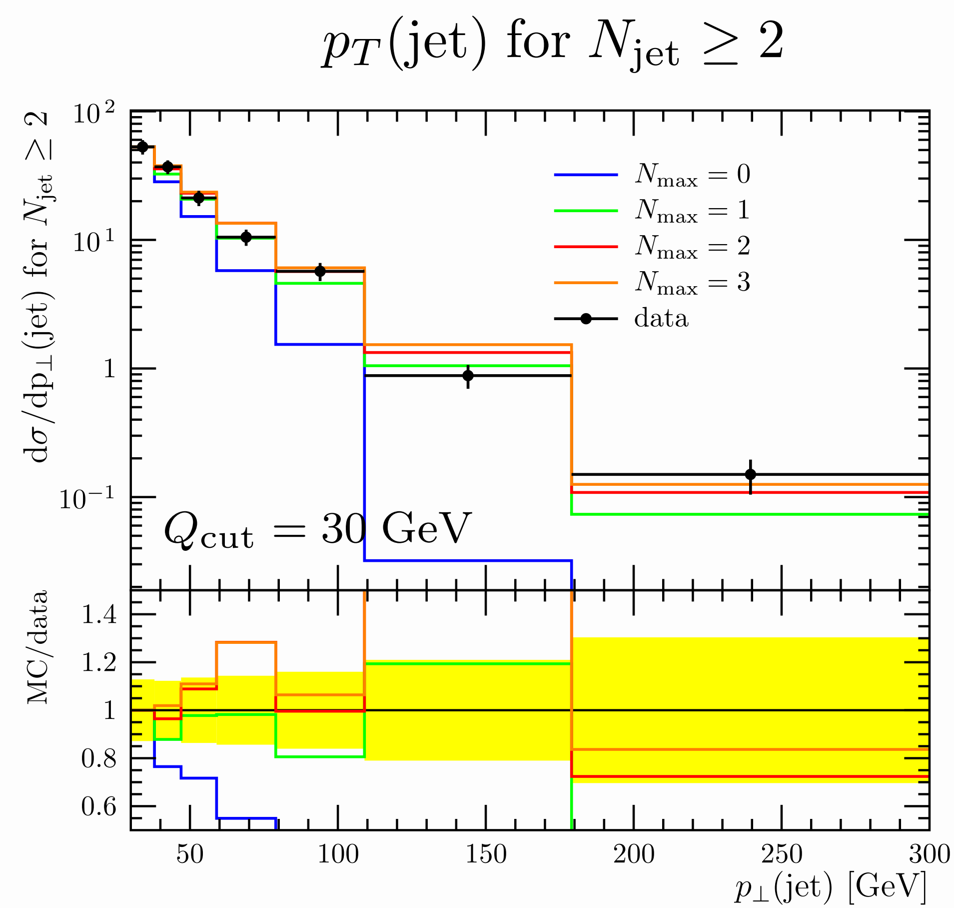


$\rightsquigarrow$ Q_{cut} **variations within $\pm 10\%$**

Validation: Drell-Yan Production At Tevatron

- N_{max} **variation: jet-multi & all-jet p_T (data CDF '08)**





$\rightsquigarrow$ N_{max} **variation observable dependent**

Application: Color octets at the LHC

Strawman model: scaled-up QCD [Kilic, Okui, Sundrum ’08; Kilic, S., Son ’08]

- pheno. Lagrangian for interactions and SM couplings of $\tilde{\rho}_\mu$ and $\tilde{\pi}$

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\text{HC}} = & -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \overline{q} i \gamma^\mu \left(\partial_\mu + i g_3 \left(G_\mu + \varepsilon \tilde{\rho}_\mu\right)\right) q \\
& -\frac{1}{4} \left(D_\mu \tilde{\rho}_\nu - D_\nu \tilde{\rho}_\mu\right)^a \left(D^\mu \tilde{\rho}^\nu - D^\nu \tilde{\rho}^\mu\right)^a + \frac{m^2_{\tilde{\rho}}}{2} \tilde{\rho}^a_\mu \tilde{\rho}^{a\mu} \\
& + \frac{1}{2} (D_\mu \tilde{\pi})^a (D^\mu \tilde{\pi})^a - \frac{m^2_{\tilde{\pi}}}{2} \tilde{\pi}^a \tilde{\pi}^a - g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} f^{abc} \tilde{\rho}^a_\mu \tilde{\pi}^b \partial^\mu \tilde{\pi}^c - \frac{3 g_3^2}{16 \pi^2 f_{\tilde{\pi}}} \text{Tr}\left[\tilde{\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}\right] \\
& + i \chi g_3 \text{Tr}\left(G_{\mu\nu} \left[\tilde{\rho}^\mu, \tilde{\rho}^\nu\right]\right) + \xi \frac{2 i \alpha_s \sqrt{N_{HC}}}{m^2_{\tilde{\rho}}} \text{Tr}\left(\tilde{\rho}_\nu^{\ \mu} \left[G_\sigma^{\ \nu}, G_\mu^{\ \sigma}\right]\right)
\end{aligned}
$$

➔ extract model parameters from hadronic data, i.e. $\Gamma_{\rho \to e^+ e^-}$, $\Gamma_{\rho \to \pi\pi}$, f_π

$$\rightsquigarrow \varepsilon \simeq 0.2\,, \quad g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} \simeq 6\,, \quad \frac{m_{\tilde{\pi}}}{m_{\tilde{\rho}}} \simeq 0.3\,, \quad \frac{f_{\tilde{\pi}}}{\Lambda_{HC}} \simeq \frac{f_\pi}{\Lambda_{QCD}} \quad + \quad \chi = 1, \quad \xi = 0$$

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& + \frac{1}{2} (D_\mu \tilde{\pi})^a (D^\mu \tilde{\pi})^a - \frac{m^2_{\tilde{\pi}}}{2} \tilde{\pi}^a \tilde{\pi}^a - g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} f^{abc} \tilde{\rho}^a_\mu \tilde{\pi}^b \partial^\mu \tilde{\pi}^c - \frac{3 g_3^2}{16\pi^2 f_{\tilde{\pi}}} {\rm Tr}\left[\tilde{\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}\right] \\
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\end{aligned}$$

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➔ Tevatron dijet bounds for resonant $\tilde{\rho}$ & $\tilde{\pi}$ production well met

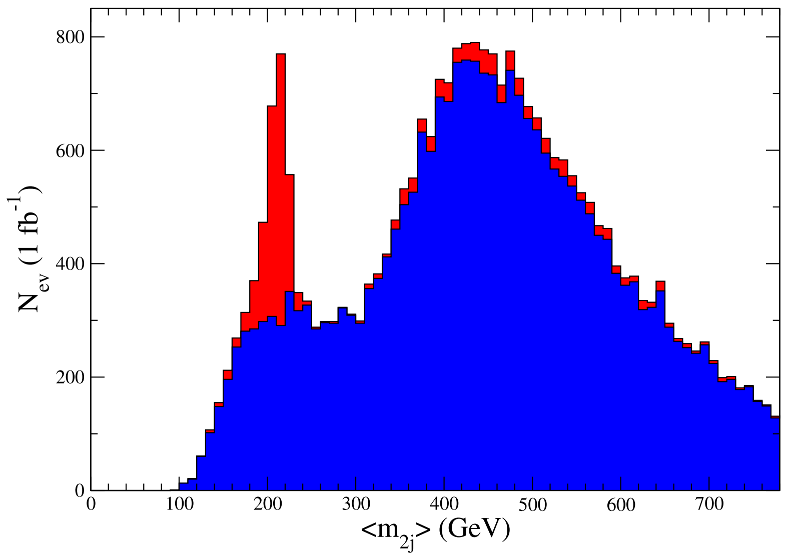
➔ QCD production cross section for $\tilde{\pi}$ & $\tilde{\rho}$ pairs

➔ LHC signatures $pp \to \tilde{\pi}\tilde{\pi} \to 4$ jets & $pp \to \tilde{\rho}\tilde{\rho} \to 4\tilde{\pi} \to 8$ jets

Four-jet Analysis: $pp \longrightarrow \tilde{\pi}\tilde{\pi} \longrightarrow 4$ jets

- consider hyperpion pair production for $m_{\tilde{\pi}} = 225$ GeV
- $\Delta R_{jj} > 0.5, \quad |\eta_j| < 2.0, \quad p_{T,j} > 150$ GeV
- require two jet-pairs with $\Delta m_{2j} < 50$ GeV

$\sigma_S = 2.2$ pb, $\sigma_{\mathrm{BG}} = 24$ pb



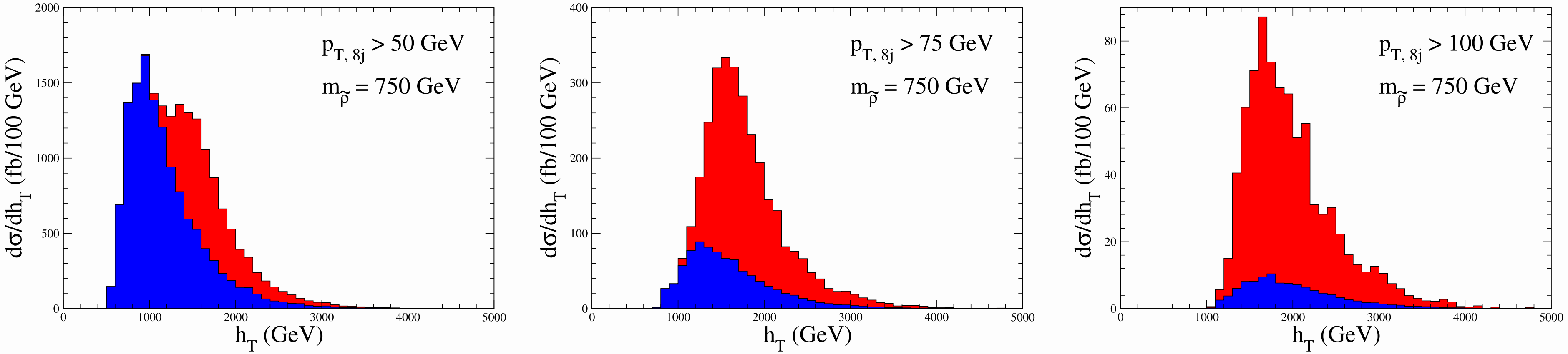
- ➔ clear excess in $\langle m_{2j} \rangle$ distribution $\chi^2_{sig} = \sum_{\mathrm{bins}} \left(\frac{N_{S,\mathrm{bin}}}{\sqrt{N_{B,\mathrm{bin}}}} \right)^2 = 38^2$
- ➔ no significance for resonant coloron production in m_{4j}

Eight-jet Analysis: $pp \longrightarrow \tilde{\rho}\tilde{\rho} \longrightarrow 4\tilde{\pi} \longrightarrow 8$ jets (I)

- consider coloron pair production for $m_{\tilde{\rho}} = 750$ GeV
- $\Delta R_{jj} > 0.5, \quad |\eta_j| < 2.0$
- sliding $p_{T,j}$ cut

$$h_T = \sum_{i=1}^{8} p_{T,j_i}$$

parton level



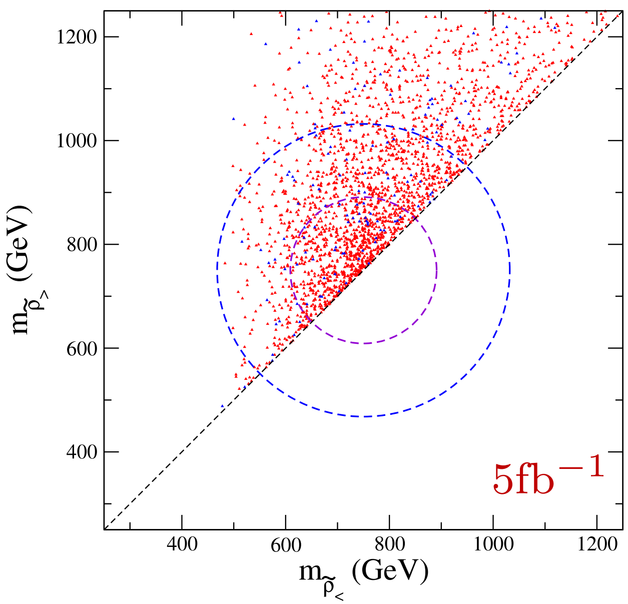
- ➔ signal can overcome QCD 8-jet background
- ➔ background rate uncertainty significant [tree-level estimate $\mathcal{O}(2-5)$]
- ➔ exploit signal's kinematic features

Eight-jet Analysis: $pp \longrightarrow \tilde{\rho}\tilde{\rho} \longrightarrow 4\tilde{\pi} \longrightarrow 8$ jets (II)

- consider coloron pair production for $m_{\tilde{\rho}} = 750$ GeV
- $\Delta R_{jj} > 0.5, \quad |\eta_j| < 2.0$
- $m_{\tilde{\rho}} = 750\ \mathrm{GeV} : p_{T,j_i} > \{320, 250, 200, 160, 125, 90, 60, 40\}\ \mathrm{GeV}$

  $\leadsto$ signal efficiency $\sim 13\%$, $\sigma_S = 3.4\ \mathrm{pb}$ vs. $\sigma_{BG} = 1.2\ \mathrm{pb}$
- four jet-pairs compatible with $\tilde{\pi}$, find $\tilde{\rho}$ candidates, weight all hypotheses

$\sigma_S = 420\ \mathrm{fb}$



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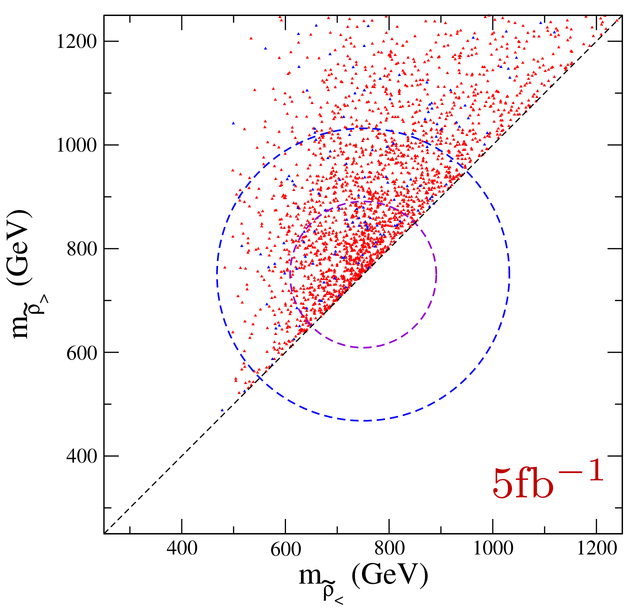

- all-jet channel searches seem feasible

  $\rightsquigarrow$ signals with QCD cross section

  $\rightsquigarrow$ dominant decay to jets
- broad mass range discoverable
- QCD tools ready!

Conclusions/Outlook

multijet final states at hadron colliders

- new physics signatures
- proper modelling of SM (and BSM) backgrounds needed

improved formalism for combining QCD matrix elements and showers

- first proof of correctness in initial-state evolution
- better phase-space separation
- largely reduced merging systematics

$\rightsquigarrow$ calculational framework for multijet studies

ongoing/future directions

- mini-jet veto in WBF Higgs production
- jet radiation in BSM production processes
- extend formalism to include one-loop amplitudes