BLHA: The Binoth Les Houches Accord
Interfacing one-loop programs

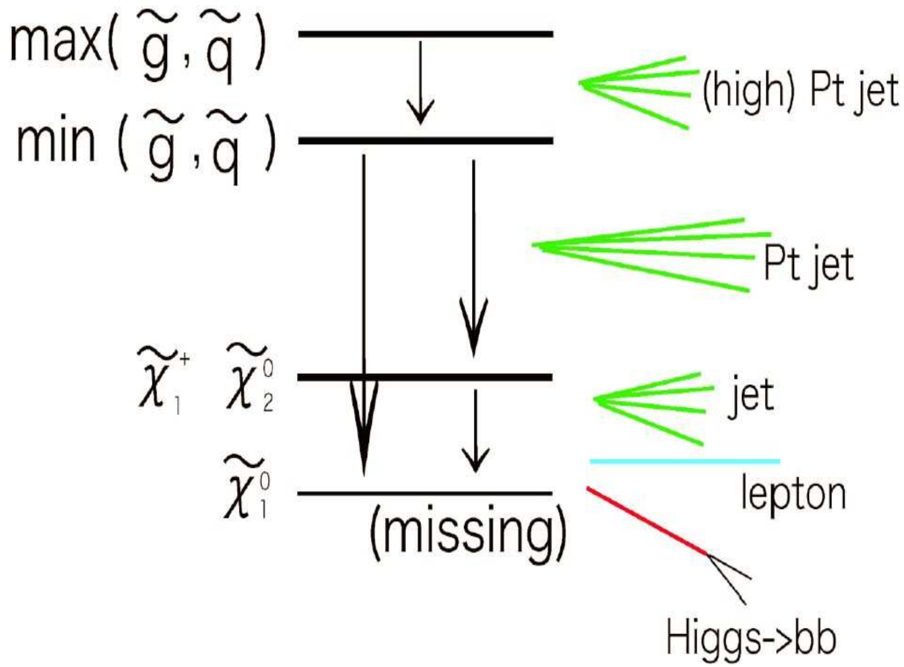
and

Monte Carlo Tools

Fawzi BOUDJEMA LAPTH-Annecy, France

Turn on the machine!

in 1998 we were told to expect an early SUSY discovery



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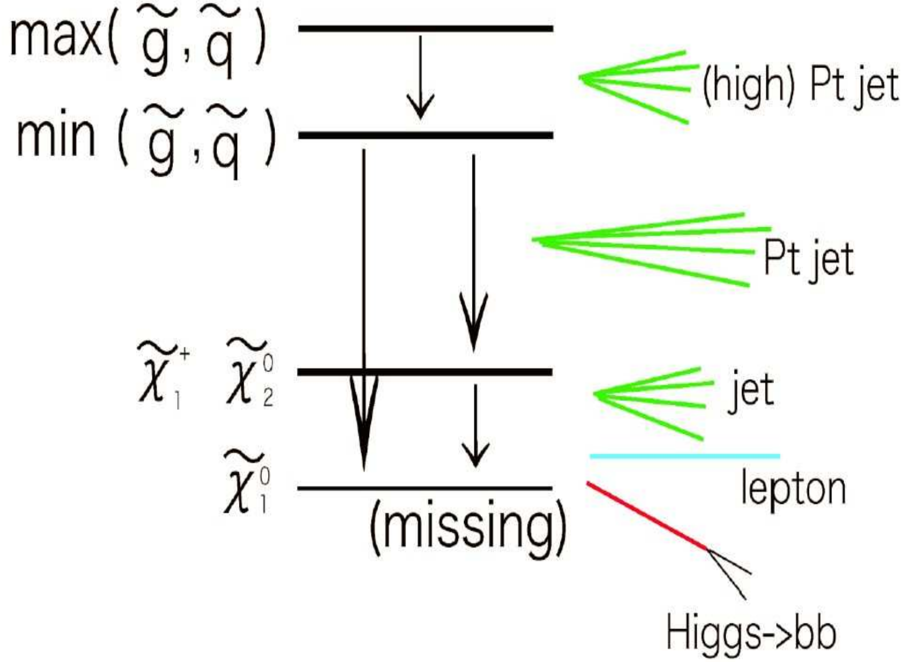
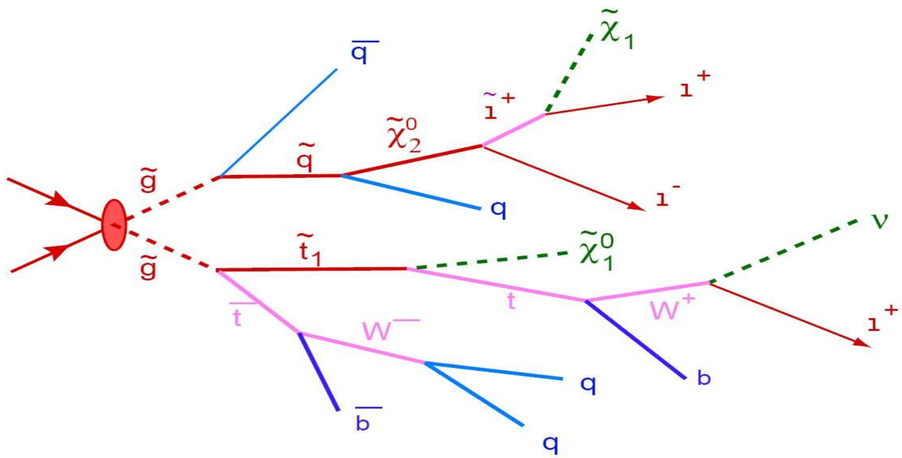
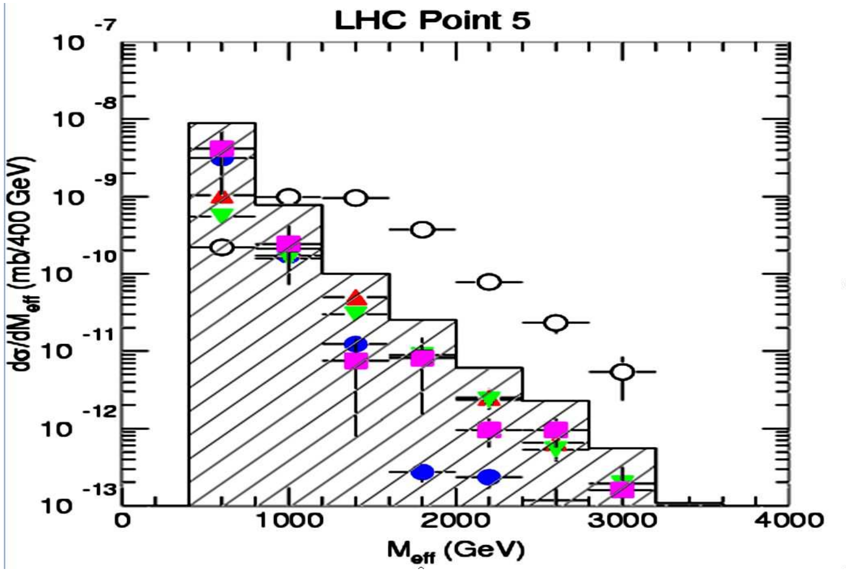


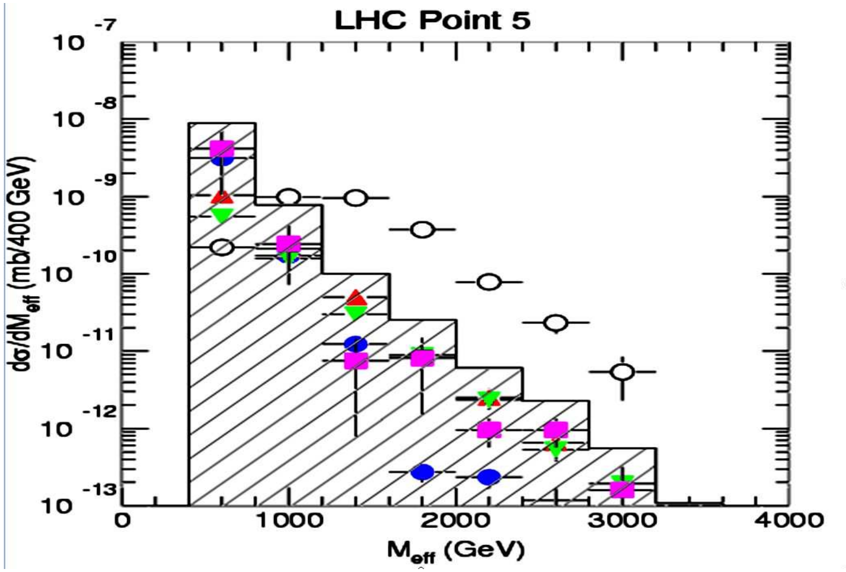


ATLAS TDR (same with CMS)



ATLAS TDR 98

(mSUGRA point, PreWMAP)



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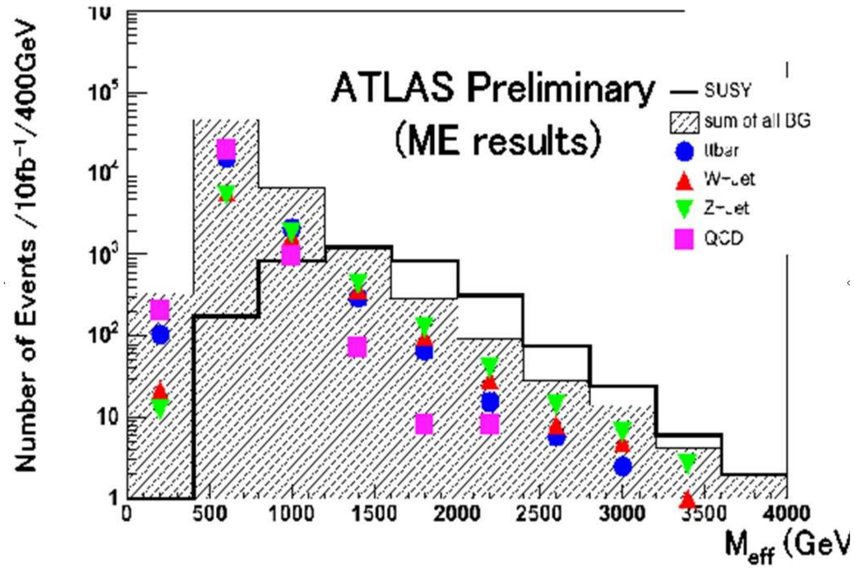

ATLAS 2006

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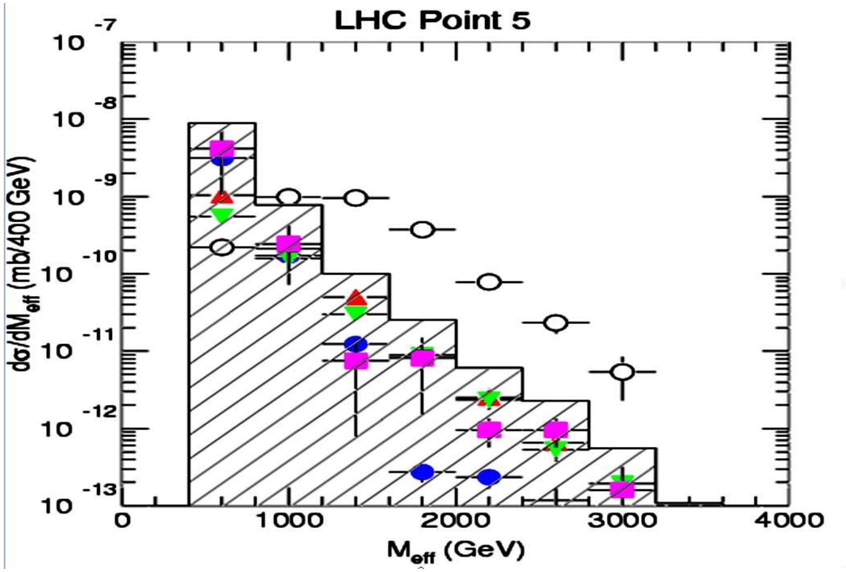

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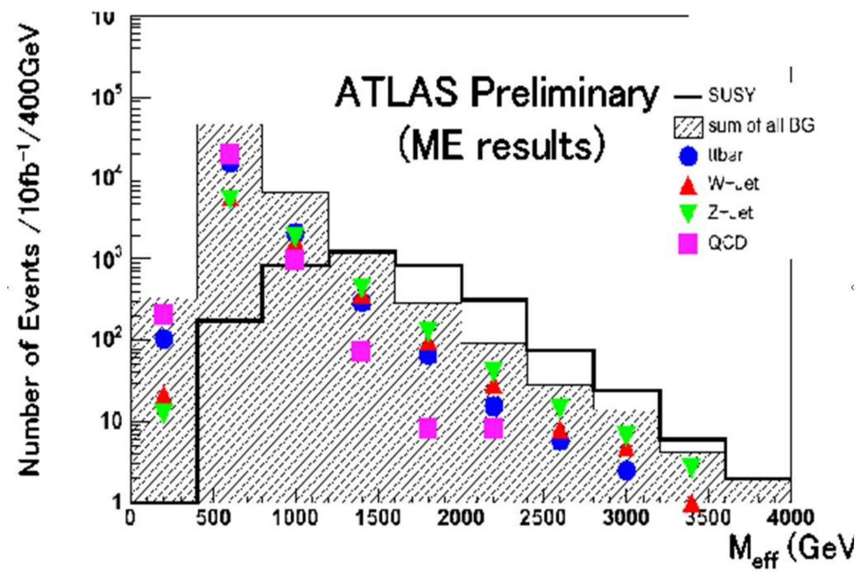
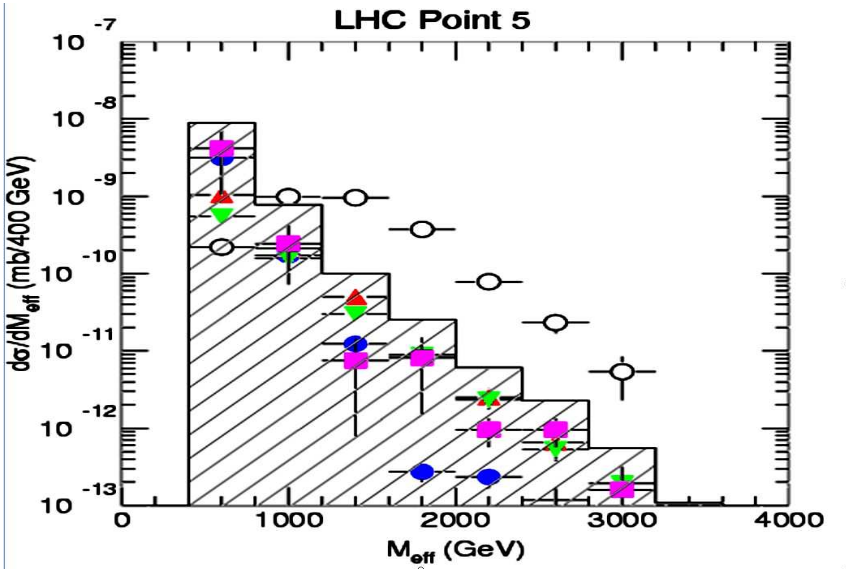


ATLAS 2006

What happened?

ATLAS TDR (same with CMS)



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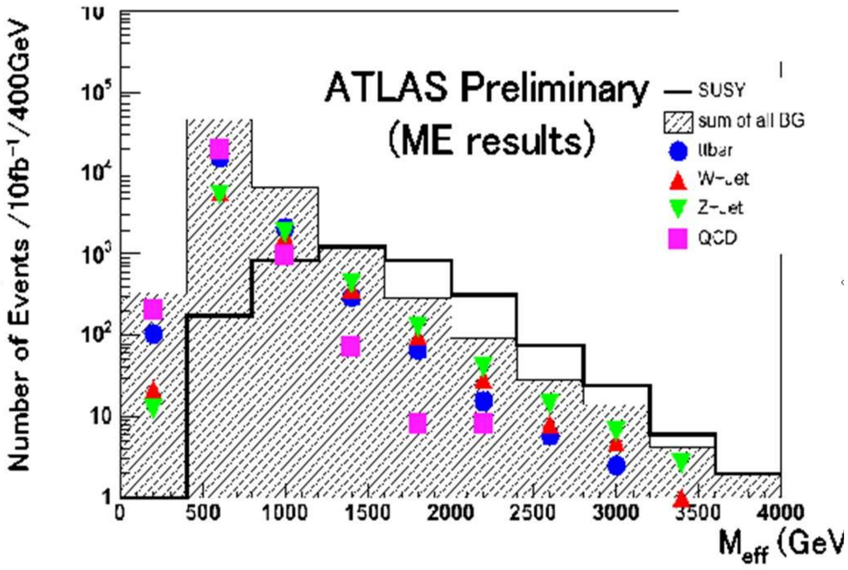
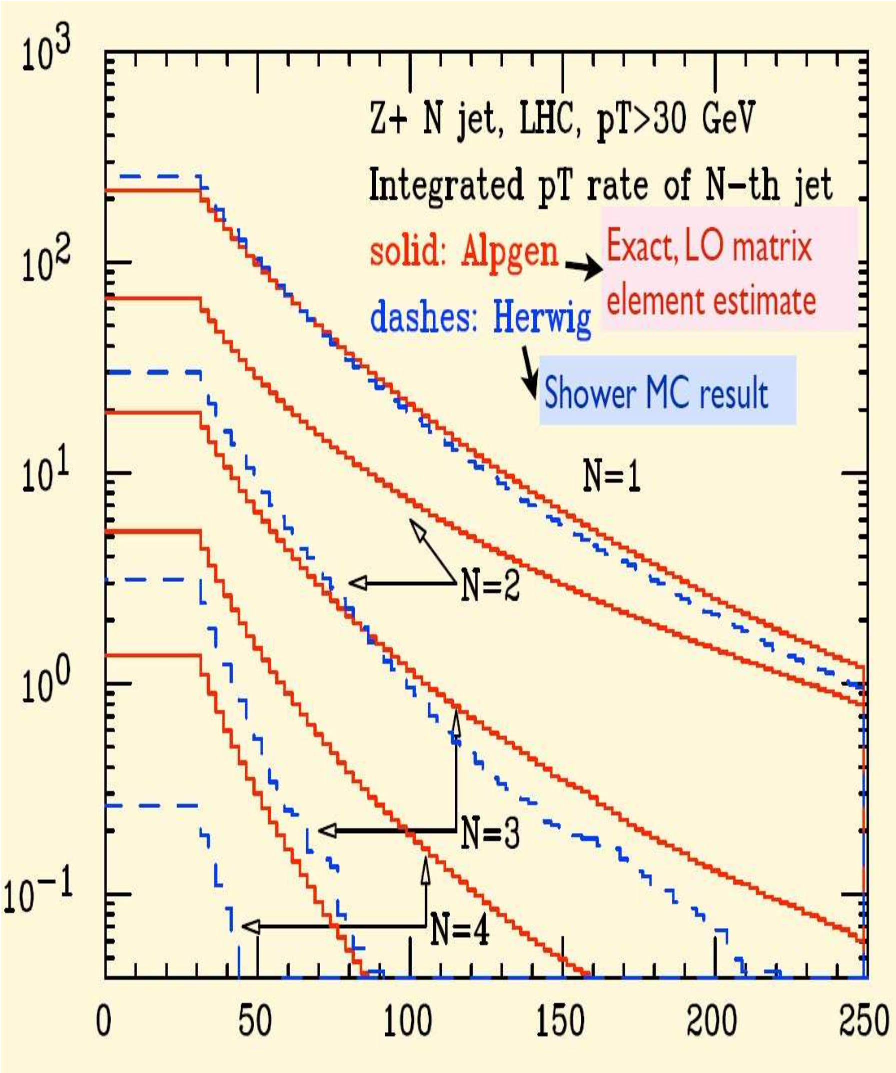


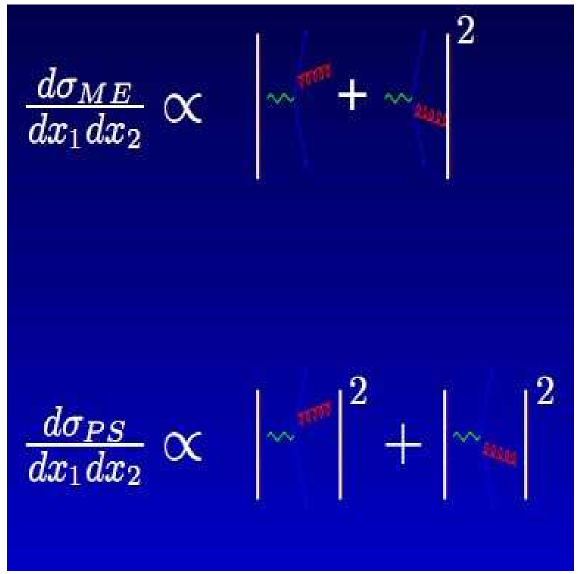
ATLAS 2006

QCD and SM processes can also produce hard jets! and these are/were lacking in PS/MC

ME vs PS: Limitations of PS

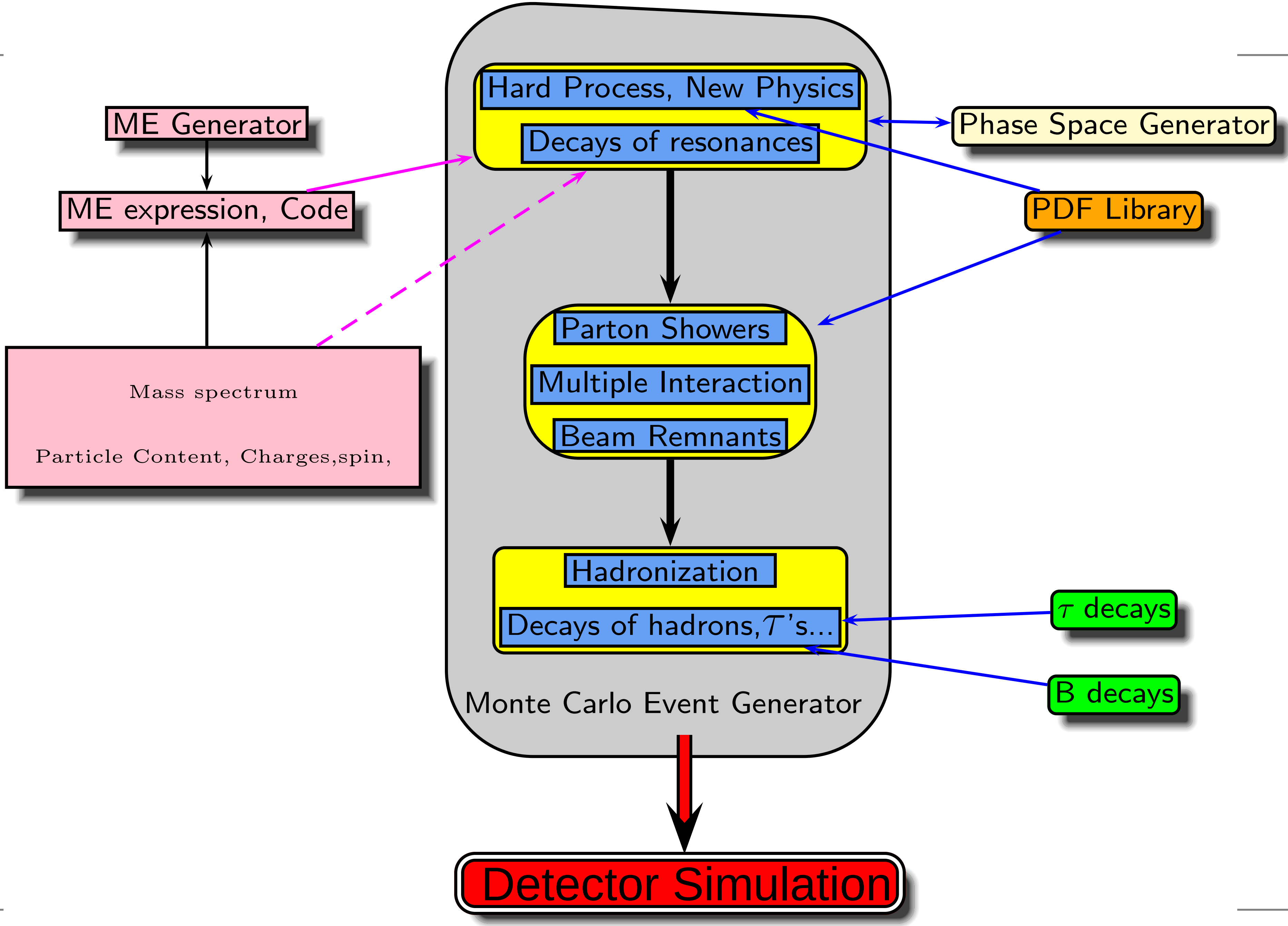


- PS do not describe hard jets
- ME do but in practice can not produce as many jets as PS
- ME evaluates the complete set of all diagrams/configurations: costly
- some real progress has been made in interfacing ME with PS

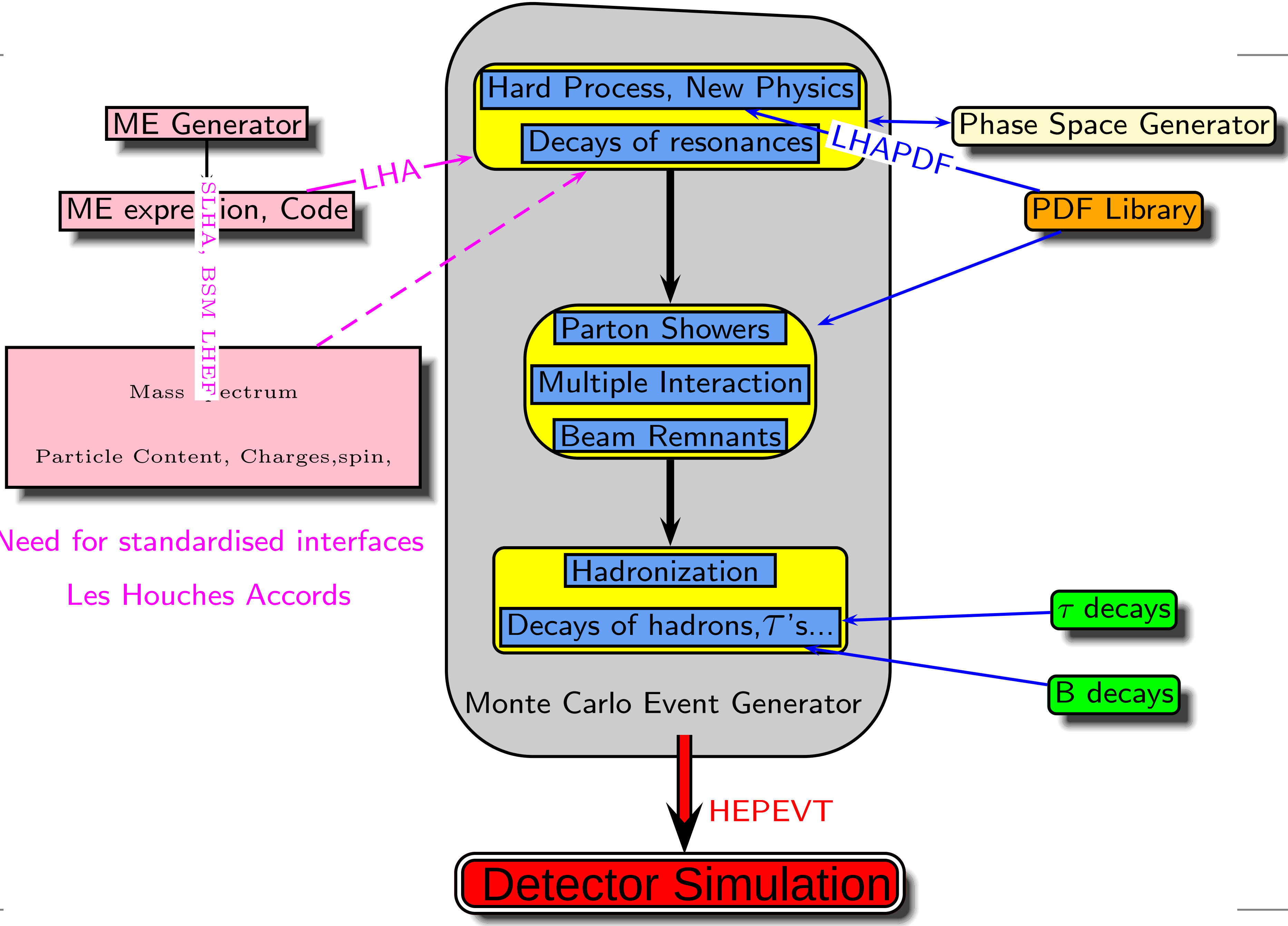


Still, all of this at leading order

Putting all together



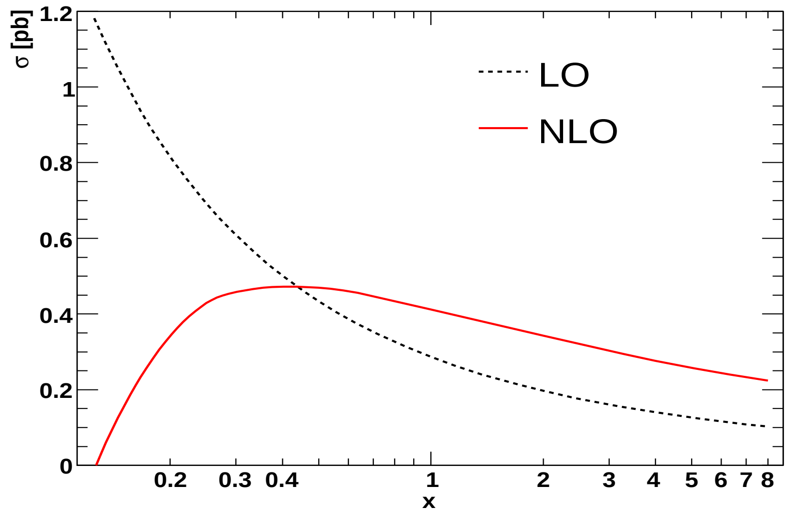
Putting all together, Les Houches Accords



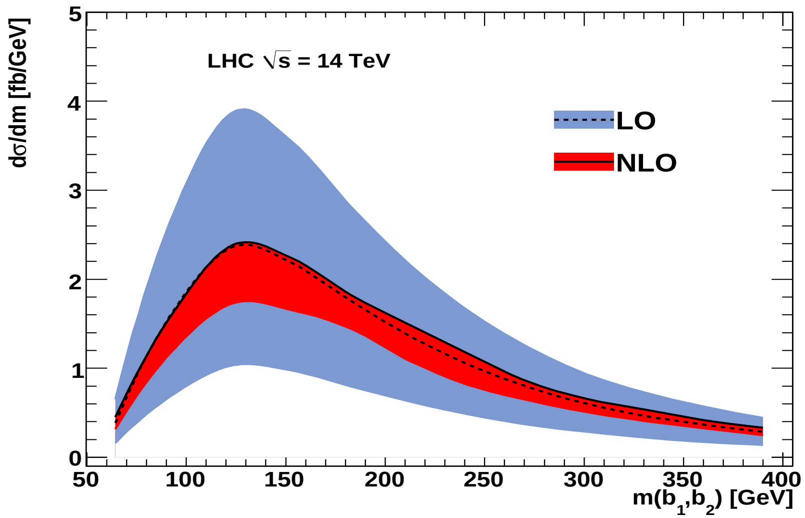
Need for standardised interfaces

Les Houches Accords

Need for NLO: example from Thomas and Annecy friends, $4b$ at NLO



The dependence of the LO and NLO prediction of $pp(q\bar{q}) \to b\bar{b}b\bar{b} + X$ at the LHC ($\sqrt{s} = 14$ TeV) on the renormalisation scale $\mu_R = x\mu_0$ with $\mu_0 = \sqrt{\sum_j p_T^2(b_j)}$. The factorisation scale is fixed to $\mu_F = 100$ GeV.



Invariant mass (m_{bb}) distribution of the two leading b-quarks . The LO/NLO bands are obtained by varying the renormalisation scale μ_R between $\mu_0/4$ and $2\mu_0$ with $\mu_0 = \sqrt{\sum_j p_T^2(b_j)}$. The full (dashed) line shows the NLO (LO) prediction for the value $\mu_R = \mu_0/2$.

- LO predictions only qualitative, due to poor convergence of perturbative expansion $\alpha_s \sim 0.1 \rightarrow$ NLO can be $\mathcal{O}(30-100)\%$
- First prediction of normalization of cross-sections is at NLO less sensitivity to unphysical input scales (renormalization,factorization)
- more physics at NLO
  - parton merging to give structure in jets
  - more species of incoming partons enter at NLO
  - initial state radiation effects
- a prerequisite for more sophisticated calculations which match NLO with parton showers

Usual procedure and normalisation with data.....

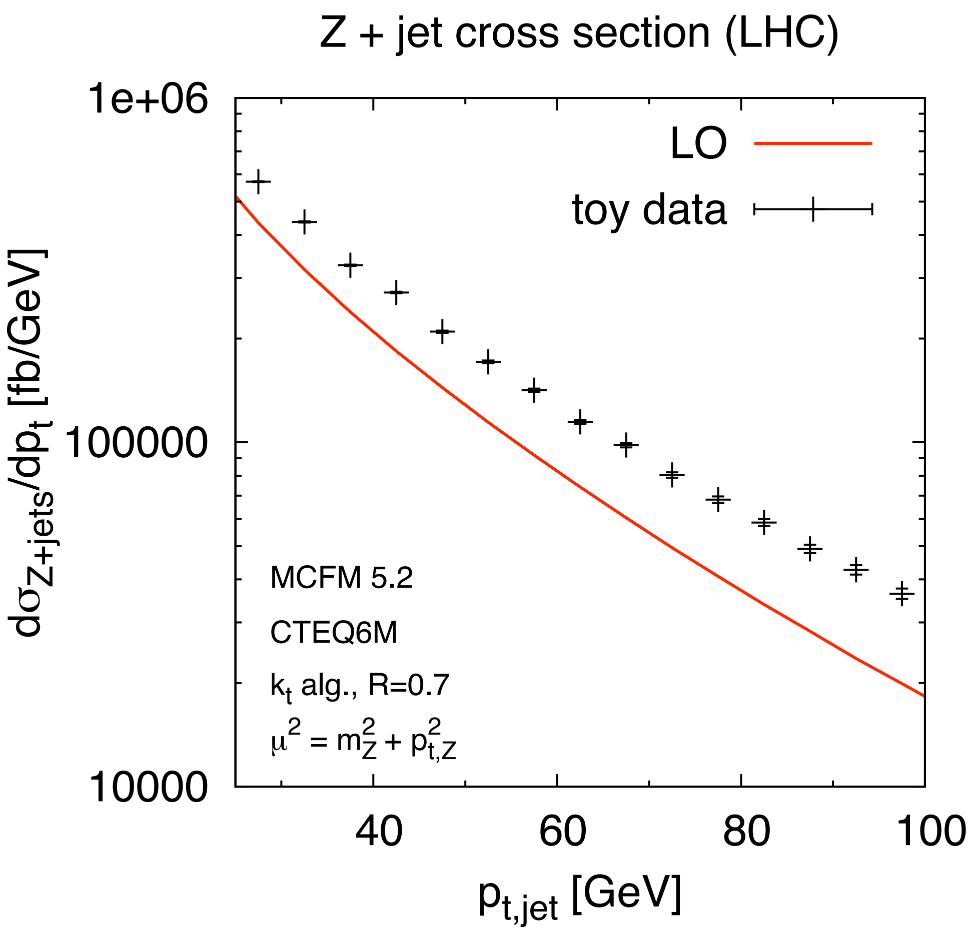
- Stage 1: get control sample in low pt region (little SUSY contamination)
- Stage 2: once LO is validated using data, trust it in signal region

Example for Salam, Zanderighi et al, high Use W+1 jet known at NLO to see how good this works

Is NLO really needed?

Stage 1:

get control sample (K-factor)



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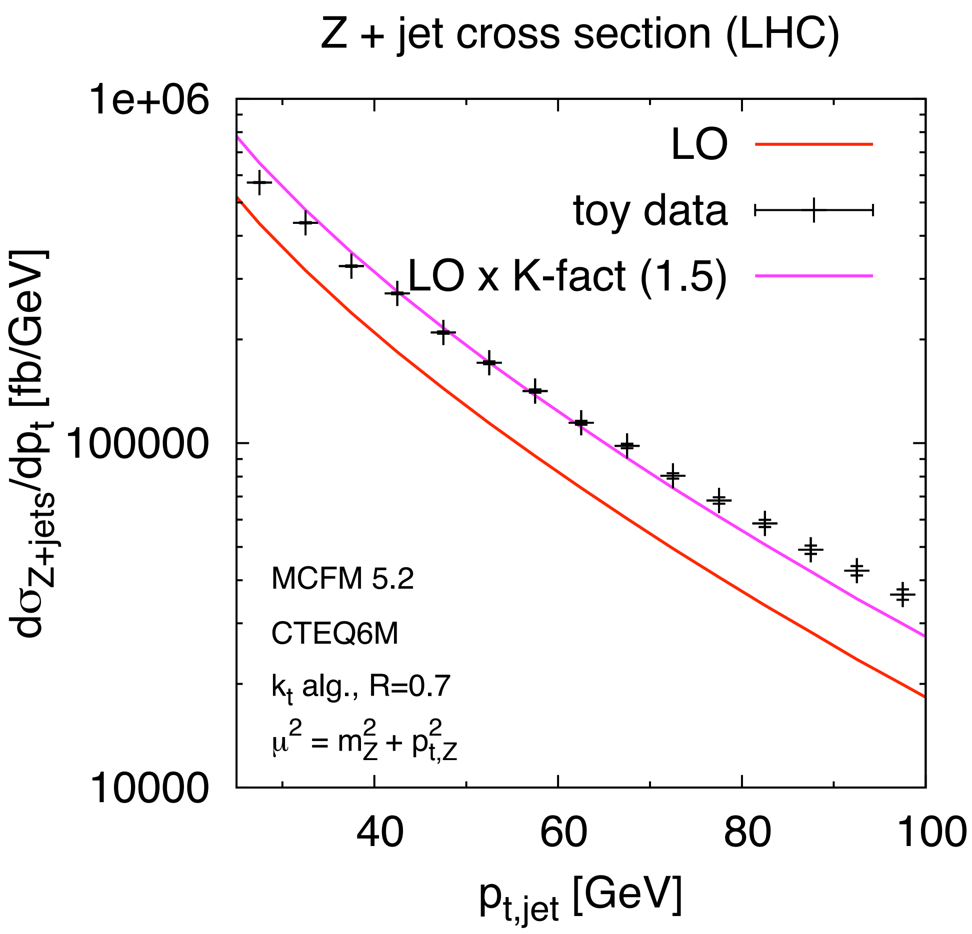

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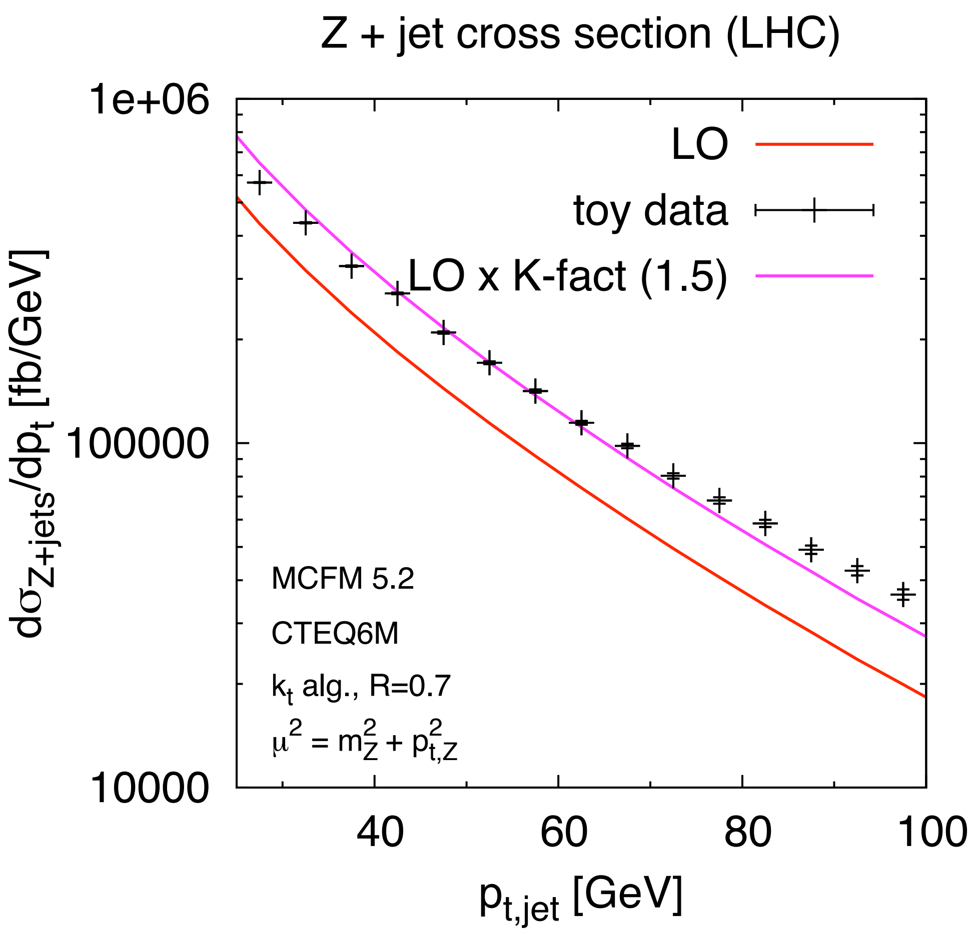
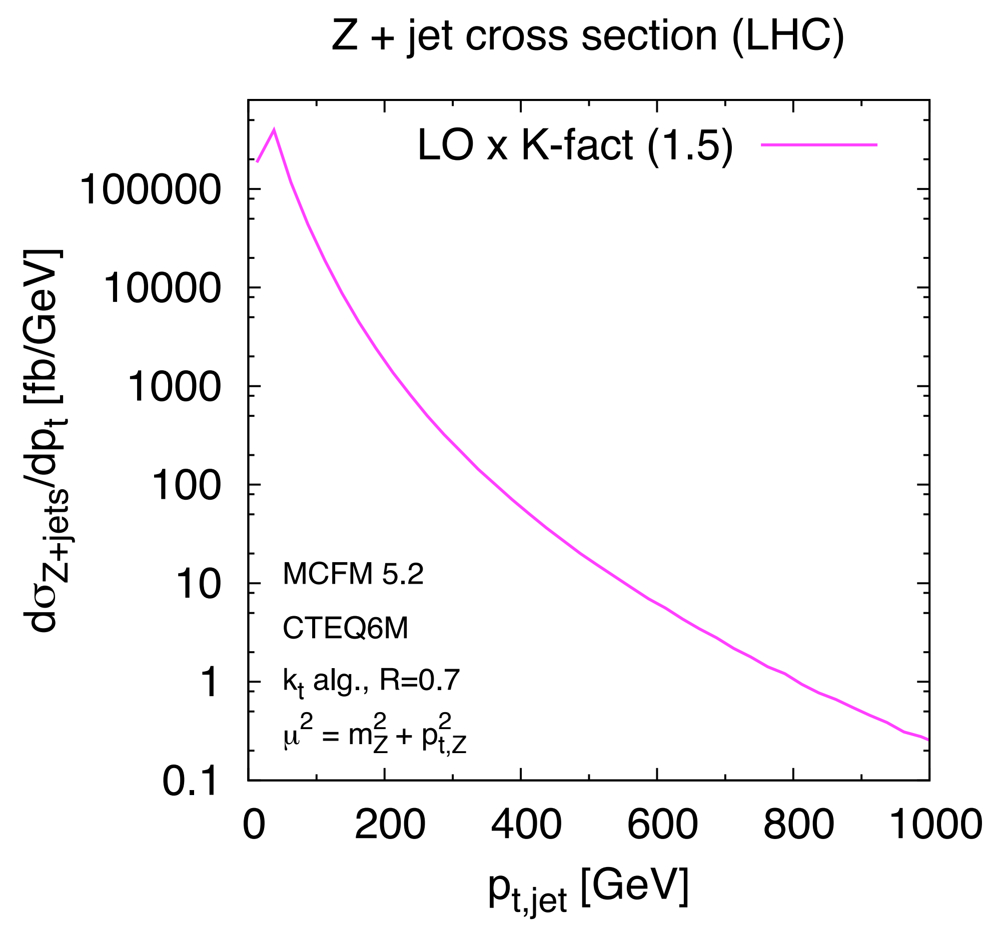


Stage 2:
extrapolate to the signal region



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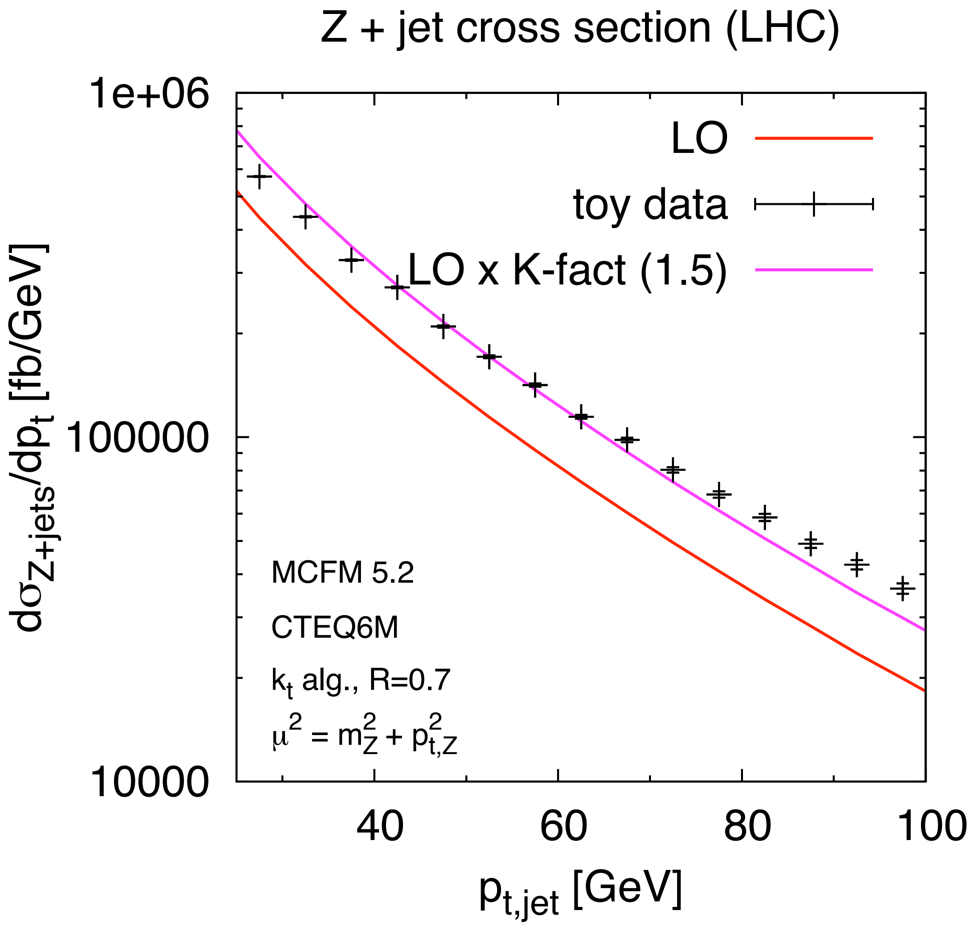

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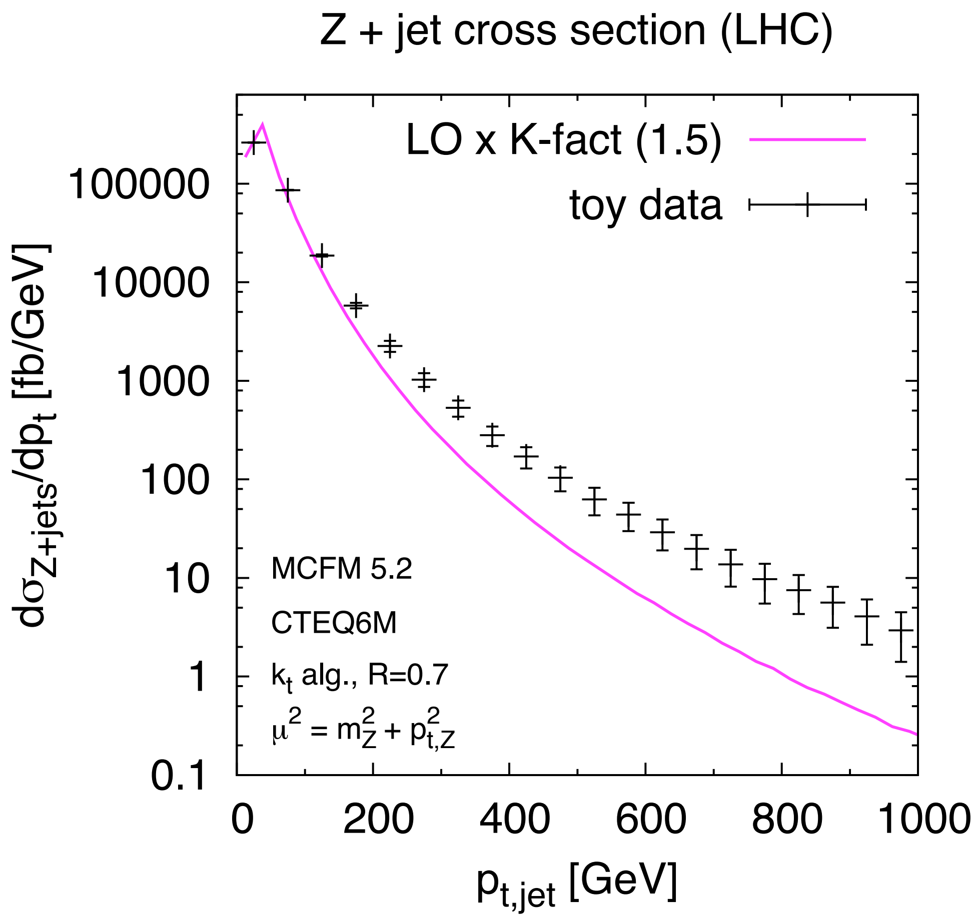

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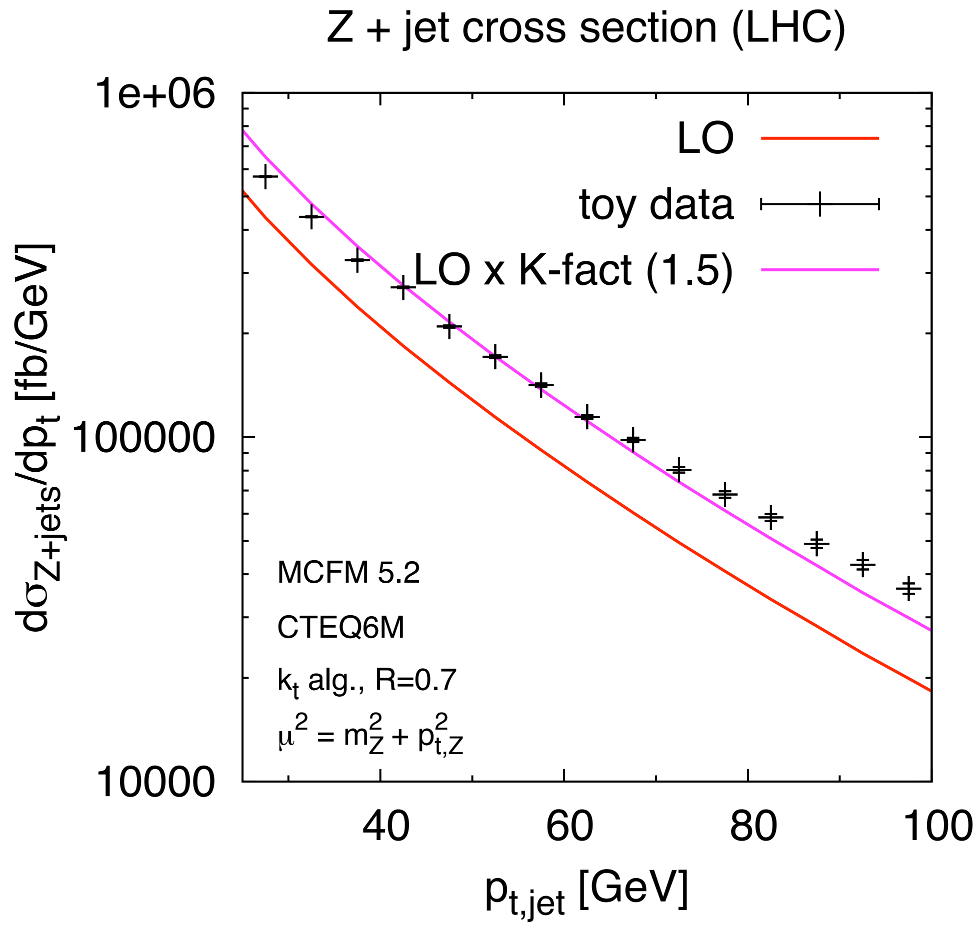

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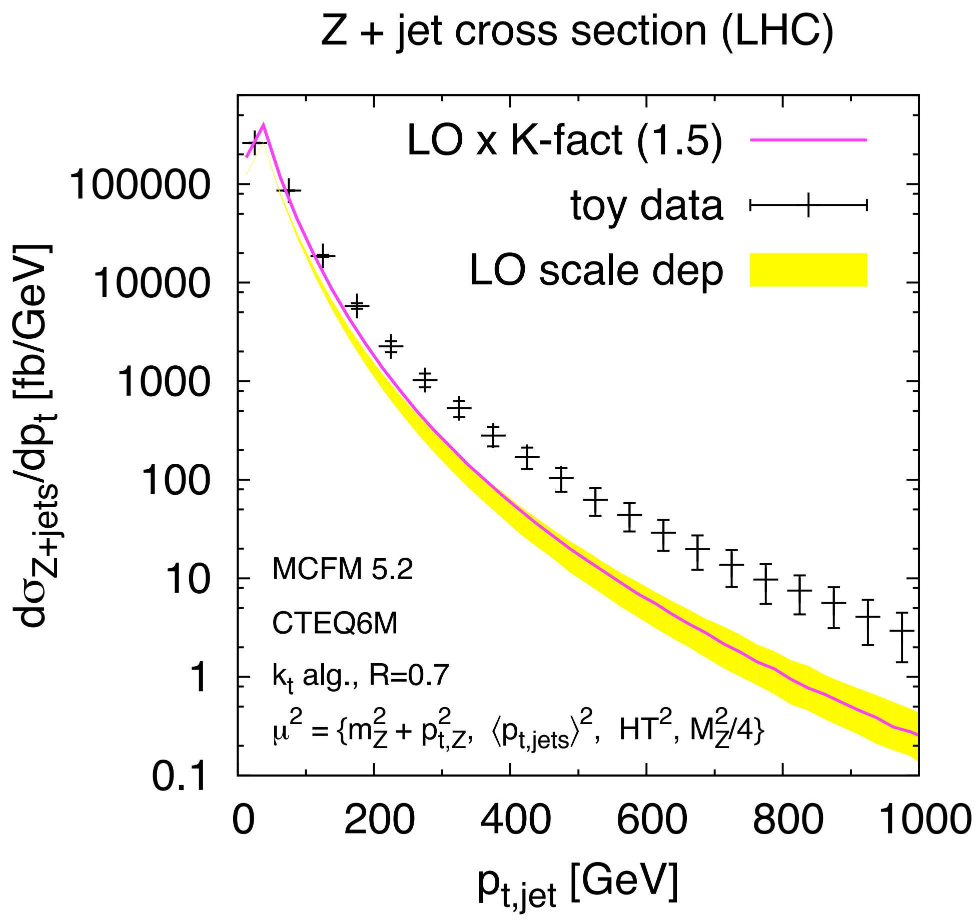

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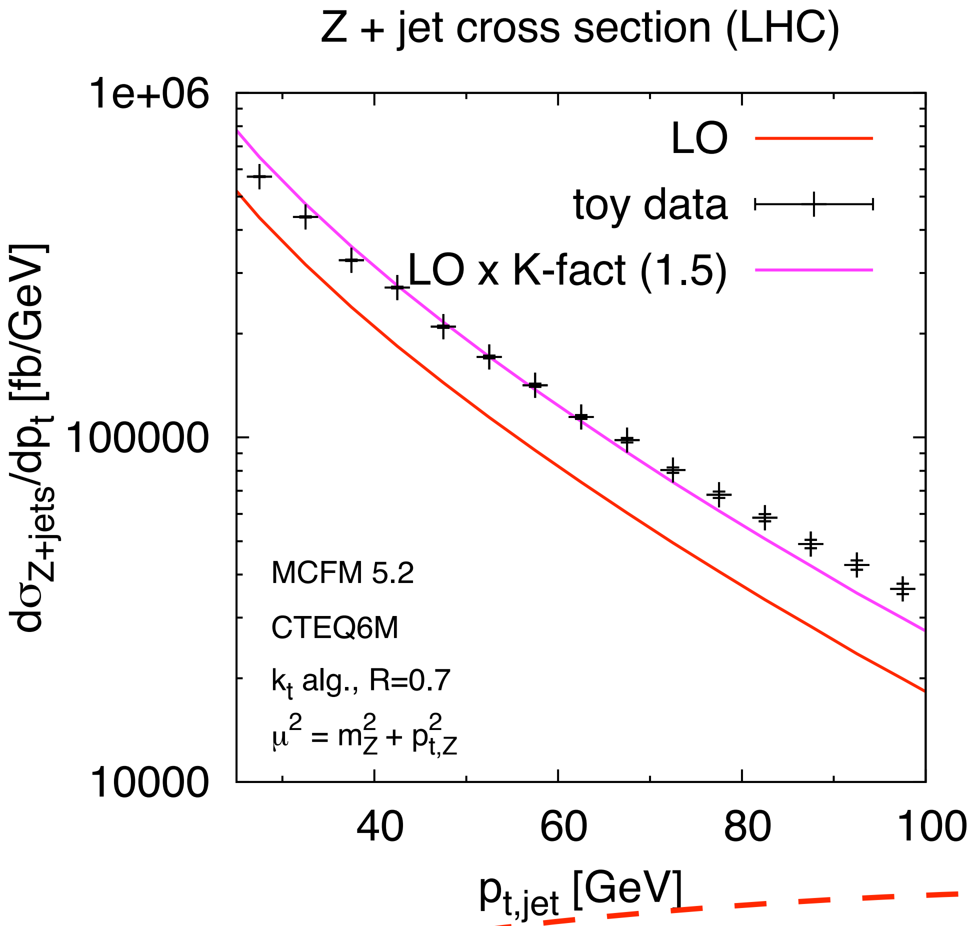

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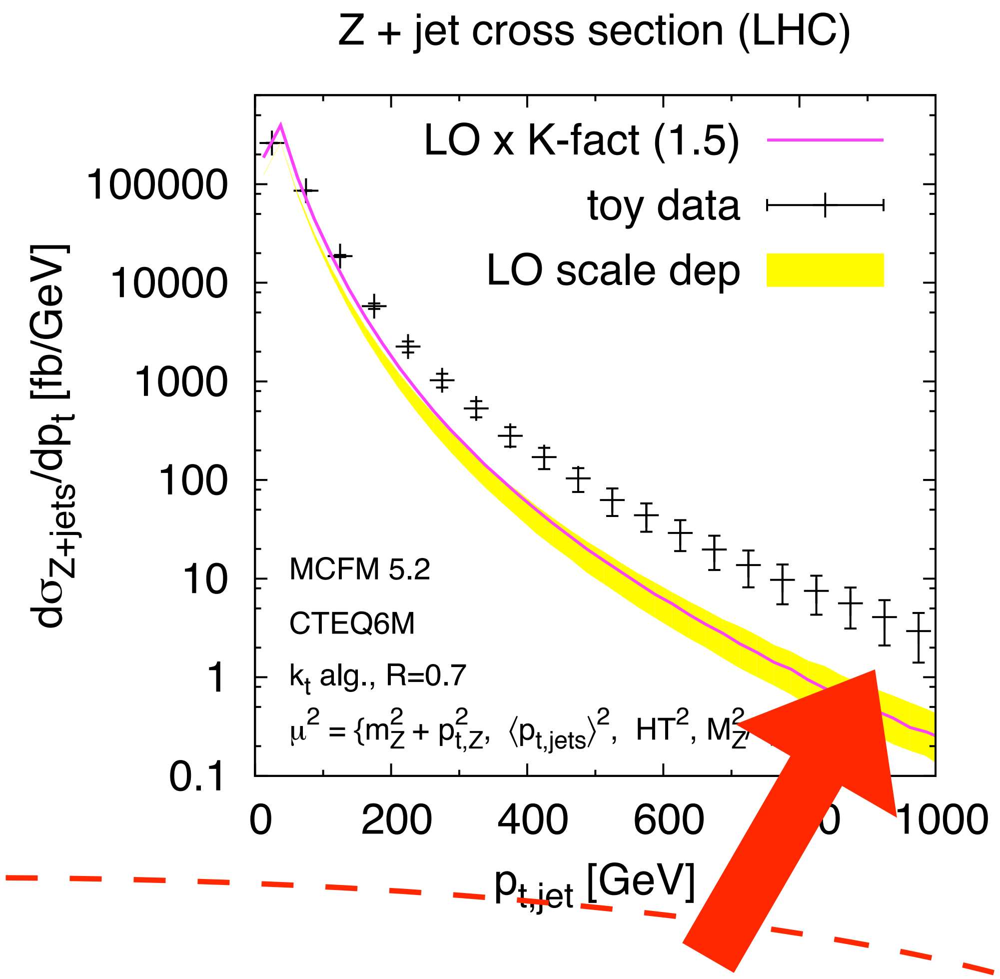
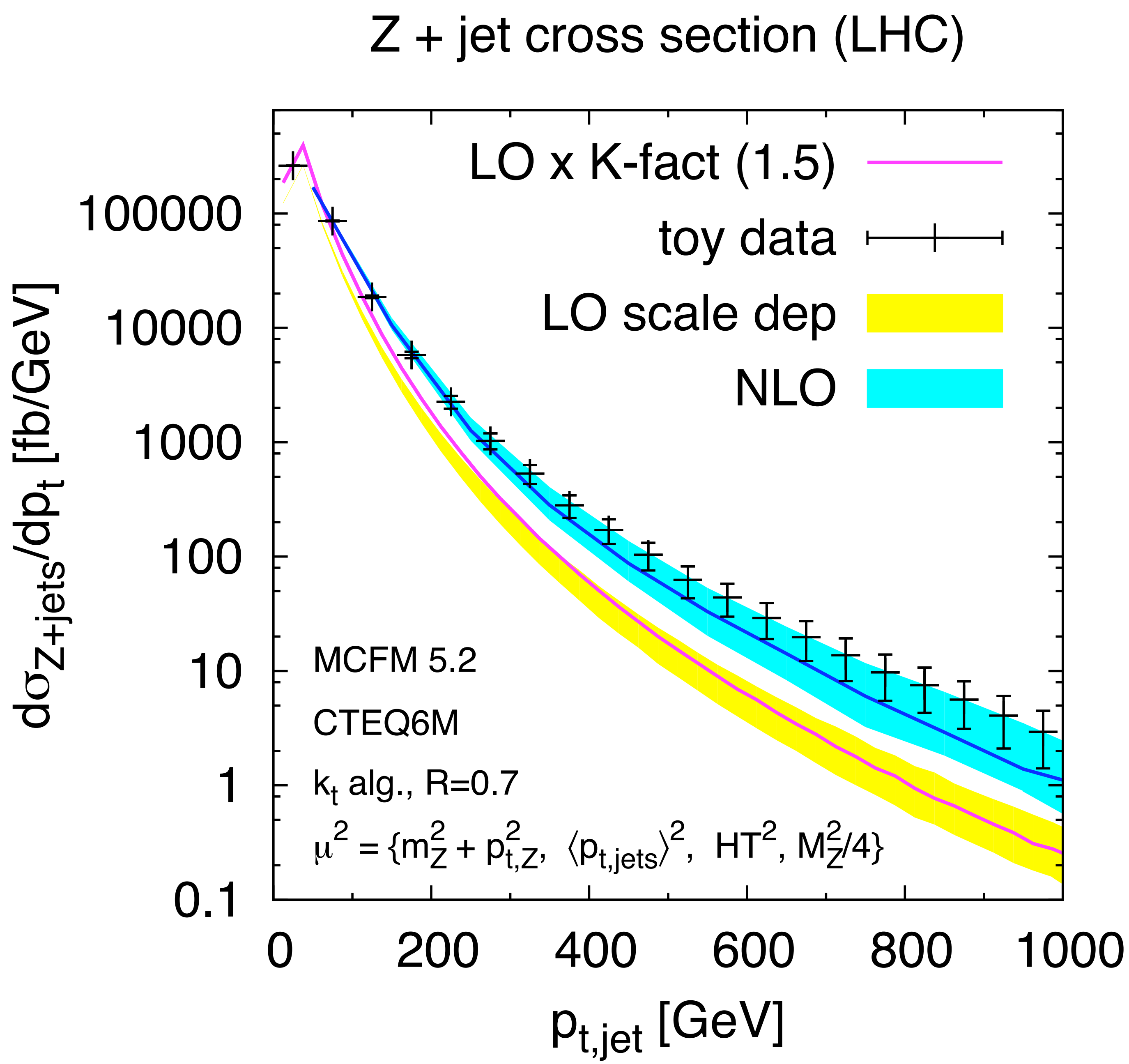


Factor 10 excess. *6σ deviation.*

Discovery ??

No, just plain NLO QCD...



NB: source of large K-factor understood [soft Z radiated from hard jets]

See Butterworth, Davison, Salam, Rubin '08

The dreamer's wishlist for NLO processes

Single boson	Diboson	Triboson	Heavy flavor
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		$b\bar{b}\,t\bar{t}$
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Les Houches 2009 Experimenter's Wishlist

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld (see also Binoth/Ossola/Papadopoulos/Pittau)
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa and Rocket collaborations
Calculations remaining from 2005,	**completed since**
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. **NNLO QCD+NLO EW for W/Z**	precision calculation of a SM benchmark

- End of 80's:

  Applications to LEP 1: 1-loop to $Z \to f\bar{f}$

  Labour of many years and many groups

  Essentially 2-point and 3-point vertex functions (some 4-points, 2-loop for self-energies)

  few ten's of diagrams

- Early 90's:

  Applications to LEP 2.

  3 years to achieve $e^+e^- \to W^+W^-$ (Leiden-Wurzburg)

- Year 95 (LEP2 WG):

  6 months to include the box needed for $b\bar{b}$ production!

- 2001: first full $2 \to 3$ NLO `GRACE-loop`

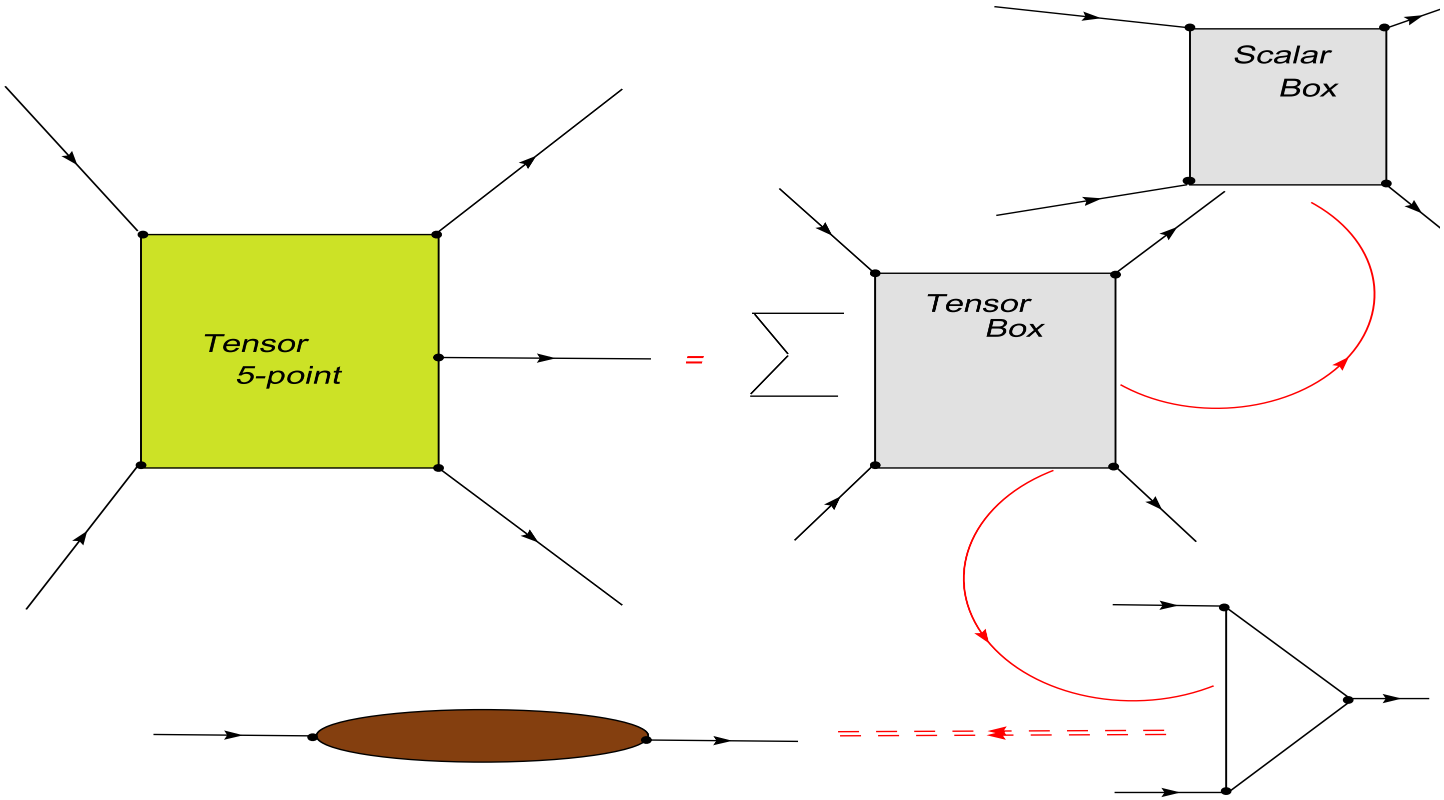
- up to 2009

  $e^+e^- \to \nu\nu HH$ Boudjema et al,.

  $e^+e^- \to 4f$ Denner et al,.

Loop Integrals and Reduction

$$T^{(N)}_{\underbrace{\mu\nu\cdots\rho}_{M}} = \int \frac{d^n l}{(2\pi)^n} \frac{l_\mu l_\nu \cdots l_\rho}{D_0 D_1 \cdots D_{N-1}}, \quad M \leq N$$



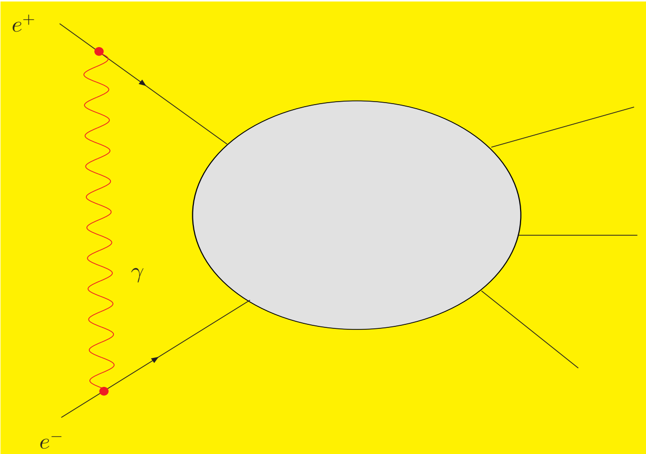
- Tensor integrals and scalar integrals with $N > 4$ reduced to scalars $N = 2, 3, 4$
- ex. rank 4 box need to solve a system of 15×15 equations. System involves, Gram determinants that may lead to severe instabilities

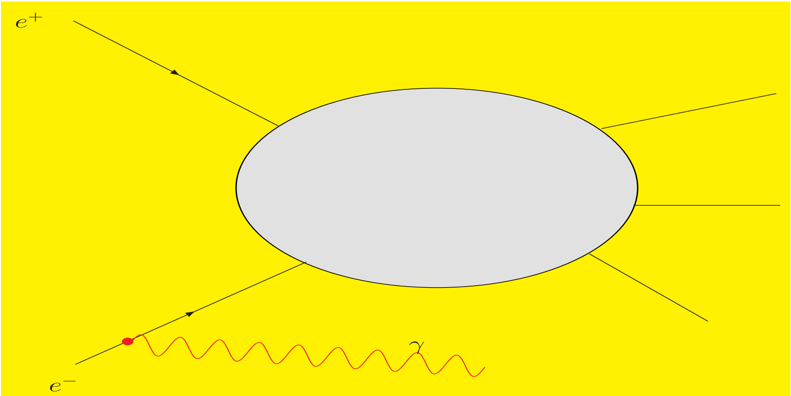
CPU of the various N-point

Process	6-point	5-point	4-point	3-point	Others
$e^+e^- \to e^+e^- H$	-	33%	11%	47%	9%
		20	44	348	98
$e^+e^- \to \nu\bar{\nu}HH$	**67%**	13%	10%	8%	2%
	74	218	734	1804	586

Perhaps that Passarino Veltman no longer adequate for present day purposes. Many developments recently,...

INFRARED/COLLINEAR DIVERGENCES





infrared divergent needs photon mass λ

$d\sigma_V(\lambda)$

collinear sing. need $m_f = m_e, \ldots$.

must include bremsstrahlung

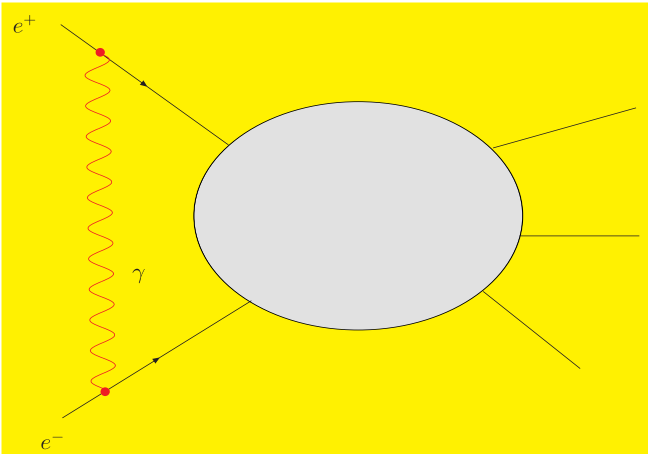
$d\sigma_s(\lambda, E_\gamma < k_c) + d\sigma_H(\lambda, E_\gamma > k_c)$

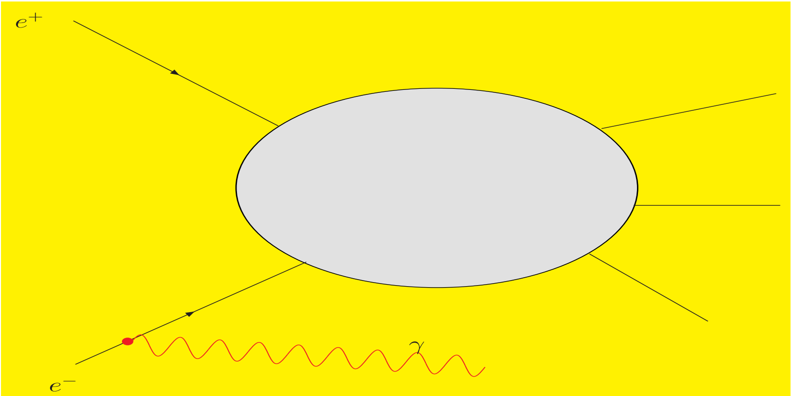
$d\sigma_s \rightarrow$ analytical: factorisation (automatised) ;

$d\sigma_H \rightarrow$ adaptive MC

$$\sigma_{\mathcal{O}(\alpha)} = \underbrace{\int d\sigma_0 \left(1 + \delta_V^{EW}\right)}_{\sigma_0(1+\delta_W)} + \underbrace{\int d\sigma_0 \left(\delta_V^{QED}(\lambda) + \delta_S(\lambda, k_c)\right)}_{\sigma_{V+S}^{QED}(k_c)} + \underbrace{\int d\sigma_H(k_c)}_{\sigma_H(k_c)} .$$

strong cancellation, CPU time consuming for collinear parts in $\sigma_H(k_c)$ and $\sigma_{V+S}^{QED}(k_c)$





infrared divergent needs photon mass λ

$d\sigma_V(\lambda)$

collinear sing. need $m_f = m_e, \ldots$.

Dim Reg: $\lambda, m_e \to 1/\epsilon^2, 1/\epsilon$.

must include bremsstrahlung

$d\sigma_s(\lambda, E_\gamma < k_c) + d\sigma_H(\lambda, E_\gamma > k_c)$

$d\sigma_s \to$ analytical: factorisation (automatised) ;

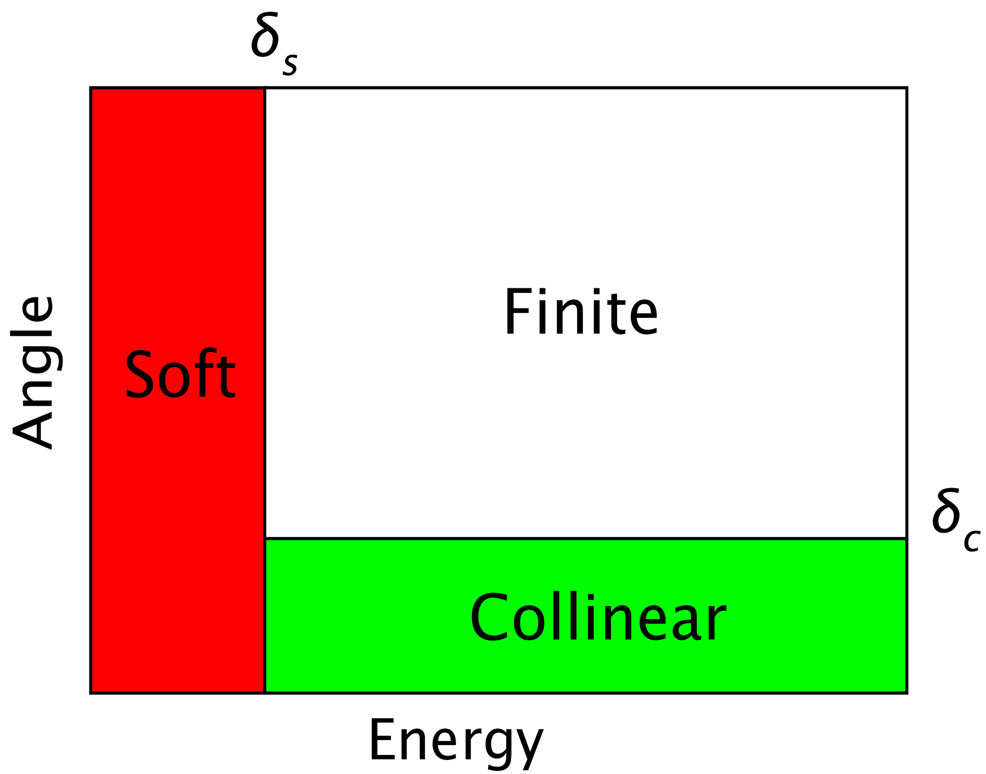
$d\sigma_H \to$ adaptive MC

Dim Reg: $d\sigma_s$ part of $d\sigma_H \to$ Integrate in d-dim.

$$\sigma_{\mathcal{O}(\alpha)} = \underbrace{\int d\sigma_0 \left(1 + \delta_V^{EW}\right)}_{\sigma_0(1+\delta_W)} + \underbrace{\int d\sigma_0 \left(\delta_V^{QED}(\lambda) + \delta_S(\lambda, k_c)\right)}_{\sigma_{V+S}^{QED}(k_c)} + \underbrace{\int d\sigma_H(k_c)}_{\sigma_H(k_c)} .$$

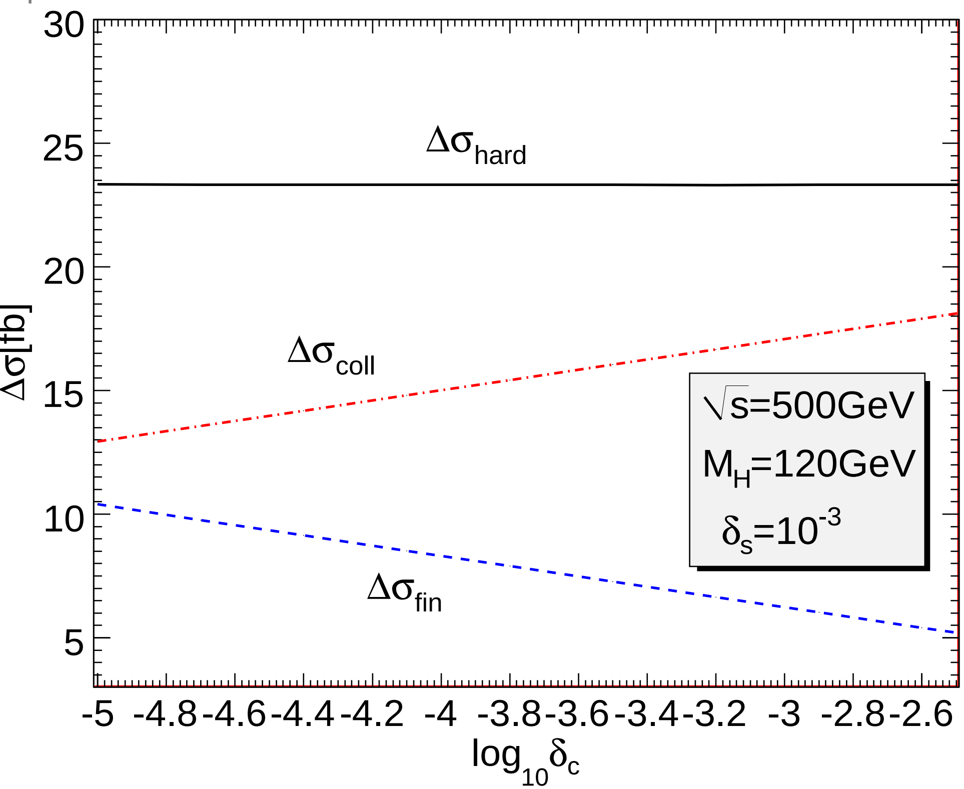
Subtraction based on factorisation of collinear sing., more involved: dipoles, antennas,..but much more efficient (QCD)

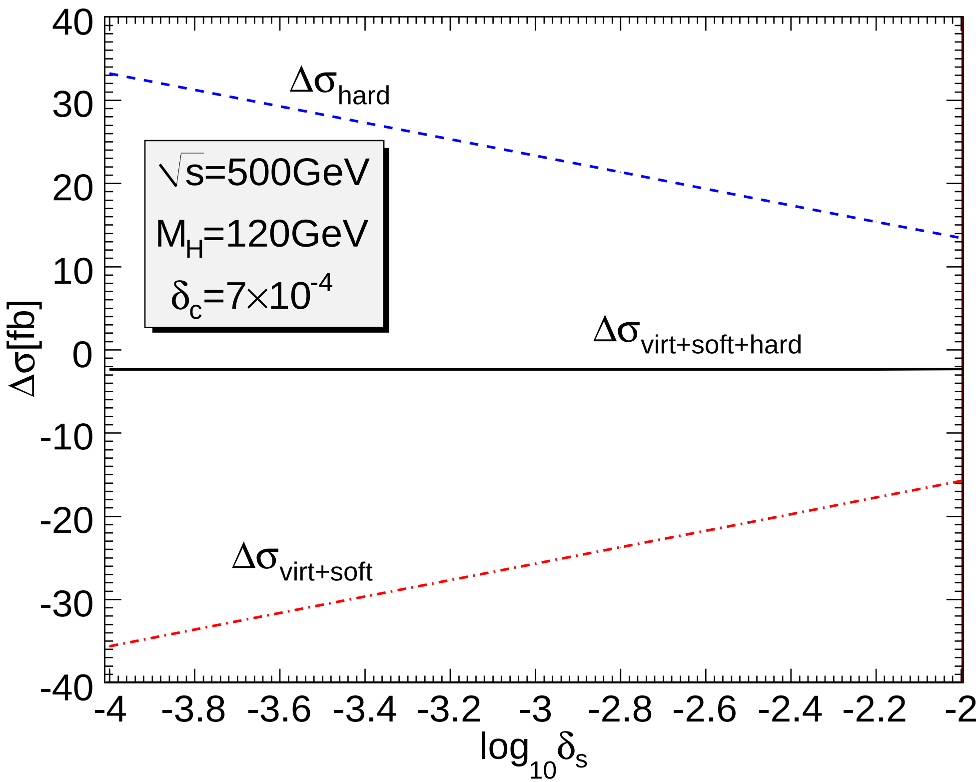
recent example: NLO to $e^+e^- \rightarrow W^+W^-Z$ (Boudjema, Ninh Le Duc, Sun Hao, M. Weber, 2009)



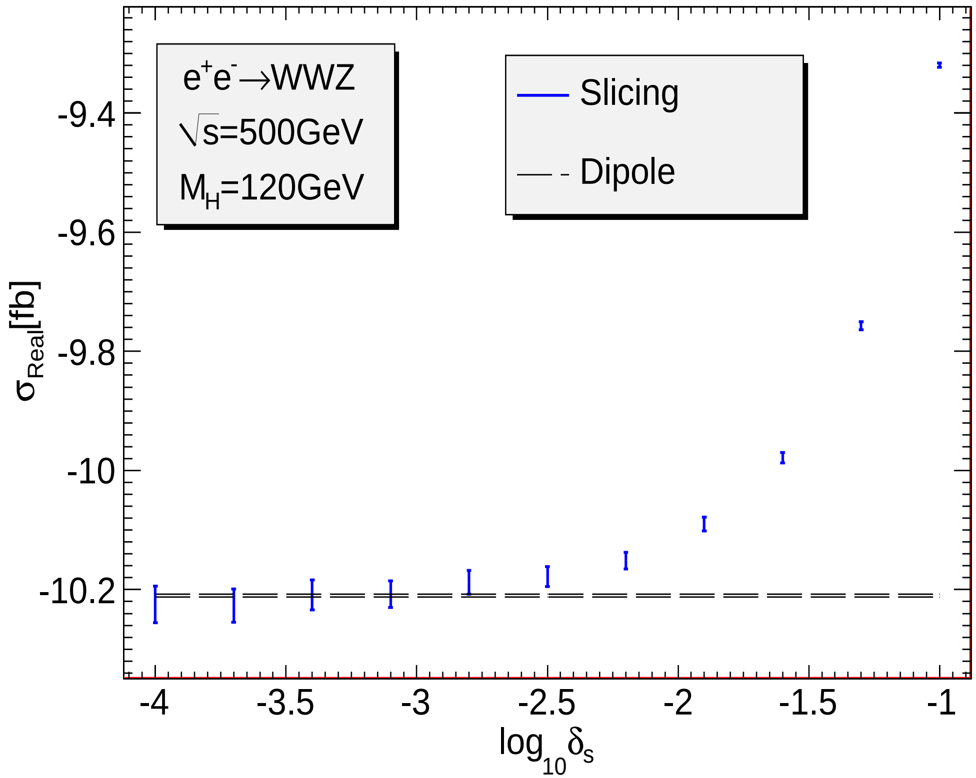
$$
\begin{aligned}
d\sigma^{e^+e^-\rightarrow W^+W^-Z} &= d\sigma_{virt}^{e^+e^-\rightarrow W^+W^-Z} + d\sigma_{real}^{e^+e^-\rightarrow W^+W^-Z\gamma}, \\
d\sigma_{real}^{e^+e^-\rightarrow W^+W^-Z\gamma} &= d\sigma_{soft}^{e^+e^-\rightarrow W^+W^-Z\gamma}(\delta_s) + d\sigma_{hard}^{e^+e^-\rightarrow W^+W^-Z\gamma}(\delta_s), \\
d\sigma_{hard}^{e^+e^-\rightarrow W^+W^-Z\gamma}(\delta_s) &= d\sigma_{coll}^{e^+e^-\rightarrow W^+W^-Z\gamma}(\delta_s,\delta_c) + d\sigma_{fin}^{e^+e^-\rightarrow W^+W^-Z\gamma}(\delta_s,\delta_c),
\end{aligned}
$$

The Old not so good slicing method: careful choice of matching/cuts





Slicing vs Dipole in $e^+e^- \rightarrow W^+W^-Z$

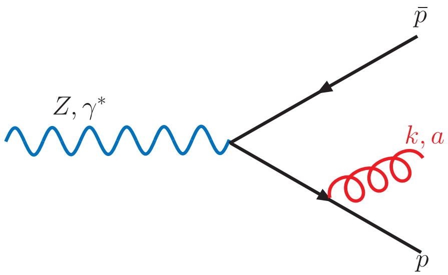


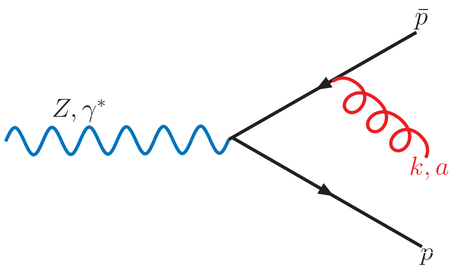
error in the dipole, thickness of line

slicing 10-30 times slower for the same precision.

but even dipole takes longer than (optimised) virtual corrections (factor 2-3).

Origin and justification of PS: soft and collinear divergencies





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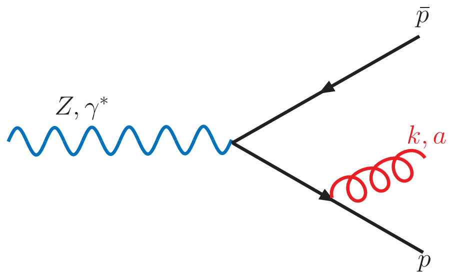
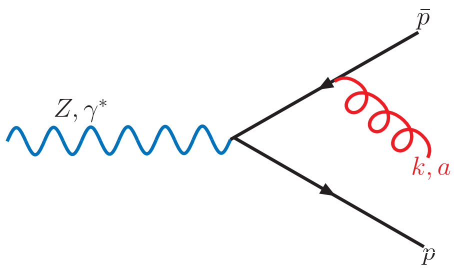


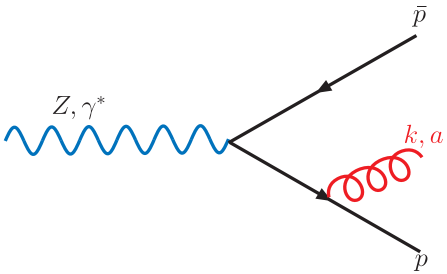


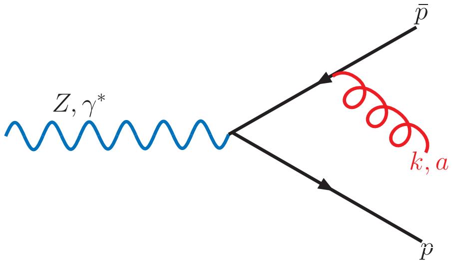
$$\mathcal{A}_\mu = \bar{u}(p)\not{\epsilon}(-ig_s t_a)\frac{-i}{\not{p}+\not{k}}\Gamma_\mu v(\bar{p}) \qquad m_q = 0$$

$$+ \ \bar{u}(p)\Gamma_\mu \frac{i}{\not{\bar{p}}+\not{k}}(-ig_s t_a)\not{\epsilon}v(\bar{p})$$

$$= -g_s\left(\frac{\bar{u}(p)\not{\epsilon}(\not{p}+\not{k})\Gamma_\mu v(\bar{p})}{2p.k} - \frac{\bar{u}(p)\Gamma_\mu(\not{p}+\not{k})\not{\epsilon}v(\bar{p})}{2\bar{p}.k}\right)t_a$$

$$2p.k = 4E_g E_p \sin^2\left(\frac{\theta_{pk}}{2}\right) \rightarrow 0 \text{ for } E_g \rightarrow 0, \quad \theta_{pk} \rightarrow 0$$





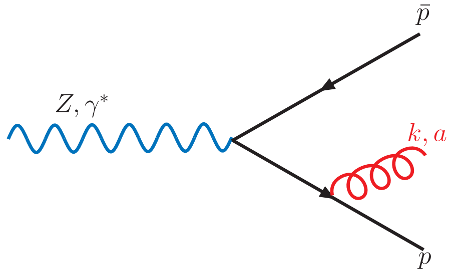
$$\mathcal{A}_\mu = \bar{u}(p)\not{\epsilon}(-ig_s t_a)\frac{-i}{\not{p}+\not{k}}\Gamma_\mu v(\bar{p}) \quad m_q = 0$$

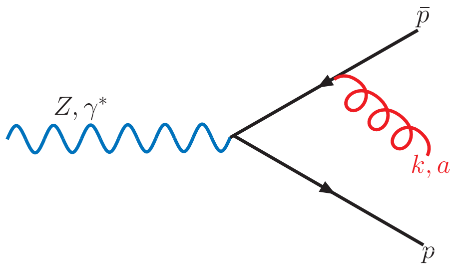
$$+ \bar{u}(p)\Gamma_\mu \frac{i}{\not{\bar{p}}+\not{k}}(-ig_s t_a)\not{\epsilon} v(\bar{p})$$

$$= -g_s\left(\frac{\bar{u}(p)\not{\epsilon}(\not{p}+\not{k})\Gamma_\mu v(\bar{p})}{2p.k} - \frac{\bar{u}(p)\Gamma_\mu(\not{p}+\not{k})\not{\epsilon}v(\bar{p})}{2\bar{p}.k}\right)t_a$$

$$2p.k = 4E_g E_p \sin^2\left(\frac{\theta_{pk}}{2}\right) \rightarrow 0 \text{ for } E_g \rightarrow 0, \quad \theta_{pk} \rightarrow 0$$

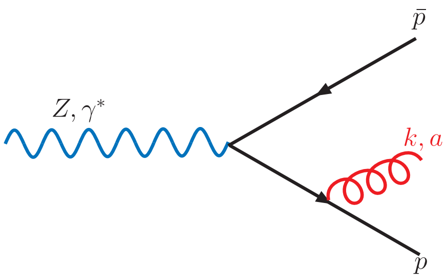
$$\mathcal{A}_{\rm soft}(k \rightarrow 0) = -g_s t_a\left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k}\right)\mathcal{A}_0 \quad \text{diverges } k \rightarrow 0$$

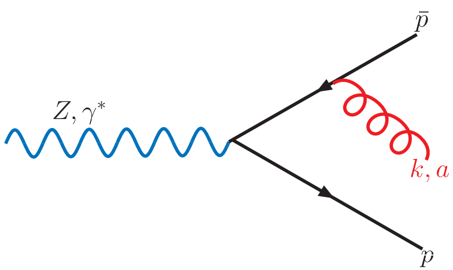




$$\begin{aligned}
\mathcal{A}_\mu &= \bar{u}(p)\not{\epsilon}(-ig_s t_a)\frac{-i}{\not{p}+\not{k}}\Gamma_\mu v(\bar{p}) \quad m_q = 0 \\
&+ \bar{u}(p)\Gamma_\mu \frac{i}{\not{\bar{p}}+\not{k}}(-ig_s t_a)\not{\epsilon} v(\bar{p}) \\
&= -g_s\left(\frac{\bar{u}(p)\not{\epsilon}(\not{p}+\not{k})\Gamma_\mu v(\bar{p})}{2p.k} - \frac{\bar{u}(p)\Gamma_\mu(\not{p}+\not{k})\not{\epsilon} v(\bar{p})}{2\bar{p}.k}\right)t_a \\
2p.k &= 4E_g E_p \sin^2\left(\frac{\theta_{pk}}{2}\right) \;\rightarrow\; 0 \text{ for } E_g \rightarrow 0, \quad \theta_{pk} \rightarrow 0
\end{aligned}$$

$$\mathcal{A}_{1g}(k \rightarrow 0) = -g_s t_a\left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k}\right)\mathcal{A}_{0g}$$





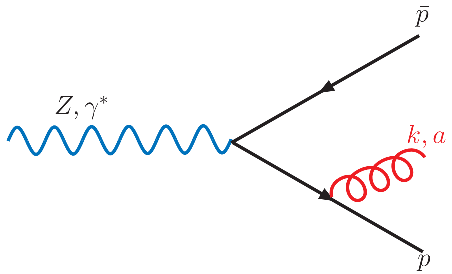
$$\begin{aligned}
\mathcal{A}_\mu &= \bar{u}(p)\not\epsilon(-ig_s t_a)\frac{-i}{\not p + \not k}\Gamma_\mu v(\bar{p}) \quad m_q = 0 \\
&+ \bar{u}(p)\Gamma_\mu \frac{i}{\not{\bar{p}} + \not k}(-ig_s t_a)\not\epsilon v(\bar{p}) \\
&= -g_s\left(\frac{\bar{u}(p)\not\epsilon(\not p + \not k)\Gamma_\mu v(\bar{p})}{2p.k} - \frac{\bar{u}(p)\Gamma_\mu(\not p + \not k)\not\epsilon v(\bar{p})}{2\bar{p}.k}\right)t_a \\
2p.k &= 4E_g E_p \sin^2\left(\frac{\theta_{pk}}{2}\right) \;\rightarrow\; 0 \text{ for } E_g \rightarrow 0, \;\; \theta_{pk} \rightarrow 0
\end{aligned}$$

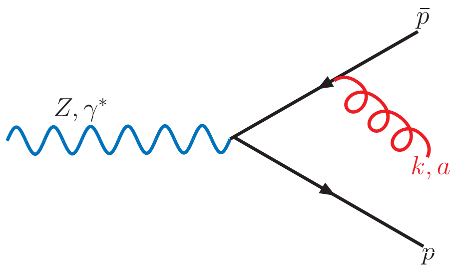
$$\mathcal{A}_{1g}(k \rightarrow 0) = -g_s t_a\left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k}\right)\mathcal{A}_{0g}$$

Universal Radiator Factor

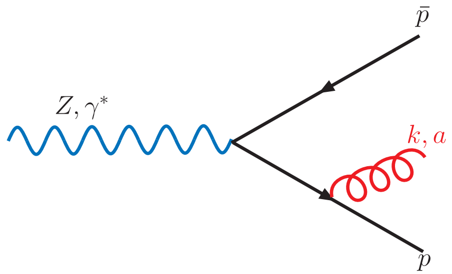
We have **factorisation** of the soft emission (long distance) from the short distance *i.e.* the hard process

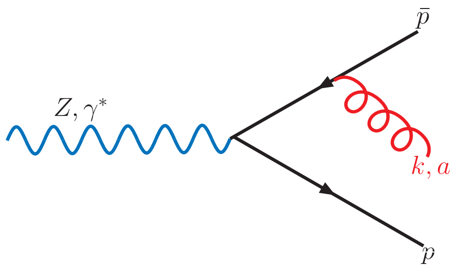
Squaring soft/collinear





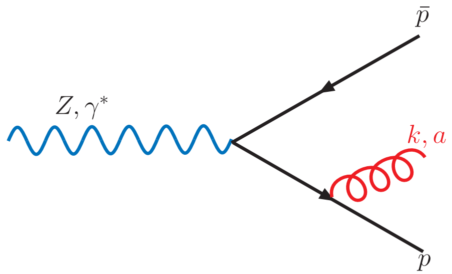
Squaring soft/collinear

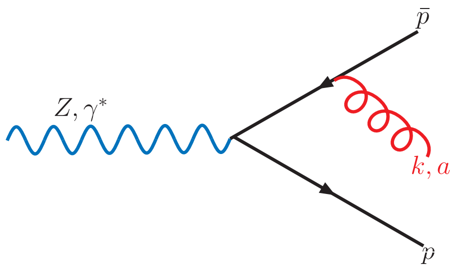




$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$

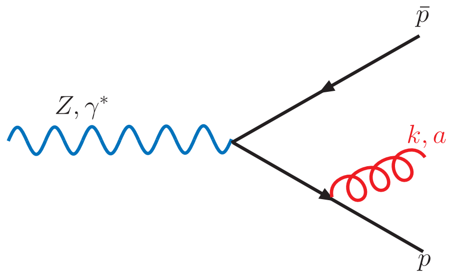
Squaring soft/collinear



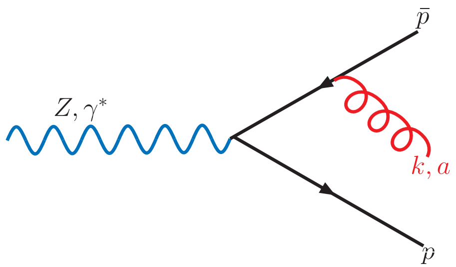


$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$

$$|\mathcal{M}_{1g}|^2 = \sum_{a,pol.(\epsilon)} |\mathcal{A}_{1g}(k \to 0)|^2 = C_F g_s^2 \frac{2p.\bar{p}}{p.k \; \bar{p}.k} |\mathcal{M}_{0g}|^2$$



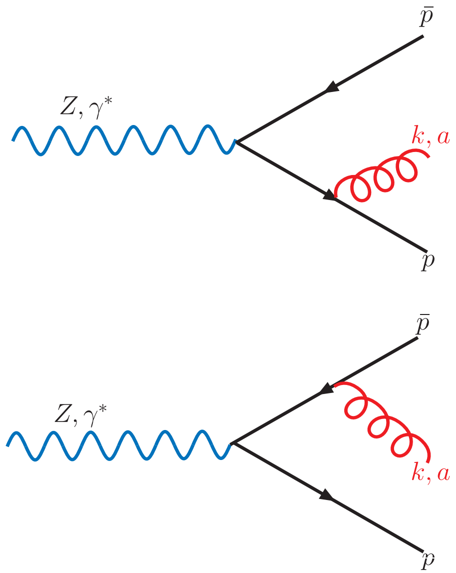
$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$



Phase Space

$$|\mathcal{M}_{1g}|^2 \mathrm{d}\Phi_{q\bar{q}g} = \left(|\mathcal{M}_{0g}|^2 \mathrm{d}\Phi_{q\bar{q}} \right) \mathrm{d}\mathcal{S}; \quad \mathrm{d}\mathcal{S} \simeq \frac{\mathrm{d}^3 \vec{k}}{2\omega_k (2\pi)^3} C_F g_s^2 \frac{2p.\bar{p}}{p.k \; \bar{p}.k}$$

Squaring soft/collinear



$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$

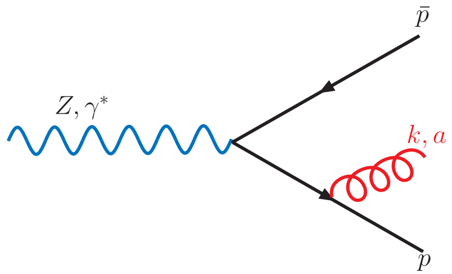
Phase Space

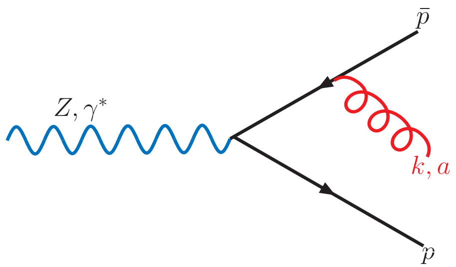
$$|\mathcal{M}_{1g}|^2 \mathrm{d}\Phi_{q\bar{q}g} = \left(|\mathcal{M}_{0g}|^2 \mathrm{d}\Phi_{q\bar{q}} \right) \mathrm{d}\mathcal{S}; \quad \mathrm{d}\mathcal{S} \simeq \frac{\mathrm{d}^3\vec{k}}{2\omega_k (2\pi)^3} C_F g_s^2 \frac{2p.\bar{p}}{p.k\ \bar{p}.k}$$

$$\theta = \theta_{\angle pk} \ , \ \phi = \text{azimuth}$$

$$\mathrm{d}\mathcal{S} \quad \simeq \quad \frac{2\alpha_s C_F}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta}{\sin\theta} \frac{\mathrm{d}\phi}{2\pi}$$

Squaring soft/collinear





$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$

Phase Space

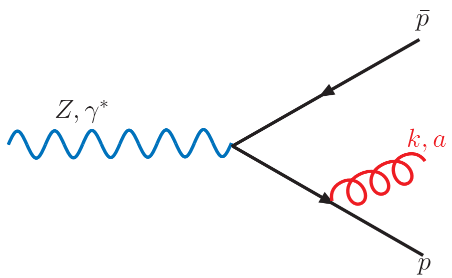
$$|\mathcal{M}_{1g}|^2 \mathrm{d}\Phi_{q\bar{q}g} = \left(|\mathcal{M}_{0g}|^2 \mathrm{d}\Phi_{q\bar{q}} \right) \mathrm{d}\mathcal{S}; \quad \mathrm{d}\mathcal{S} \simeq \frac{\mathrm{d}^3\vec{k}}{2\omega_k (2\pi)^3} C_F g_s^2 \frac{2p.\bar{p}}{p.k\ \bar{p}.k}$$

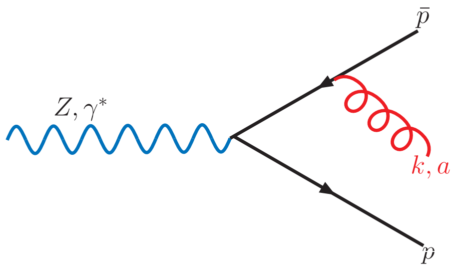
$$\theta = \theta_{\angle pk}\ , \ \phi = \text{azimuth}$$

$$\mathrm{d}\mathcal{S} \quad \simeq \quad \frac{2\alpha_s C_F}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta}{\sin\theta} \frac{\mathrm{d}\phi}{2\pi}$$

- $\mathrm{d}\mathcal{S}$ diverges for $\omega \longrightarrow 0$, Infrared divergence (needs virtual loop corrections, we'll say more if time permits)
- $\mathrm{d}\mathcal{S}$ diverges for $\theta \longrightarrow 0$ and $\theta \longrightarrow \pi$, collinear divergence

$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$





Phase Space

$$|\mathcal{M}_{1g}|^2 d\Phi_{q\bar{q}g} = \left(|\mathcal{M}_{0g}|^2 d\Phi_{q\bar{q}} \right) d\mathcal{S}; \quad d\mathcal{S} \simeq \frac{d^3\vec{k}}{2\omega_k (2\pi)^3} C_F g_s^2 \frac{2p.\bar{p}}{p.k \ \bar{p}.k}$$

$$\theta = \theta_{\angle pk} \ , \ \phi = \text{azimuth}$$

$$d\mathcal{S} \simeq \frac{2\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\sin\theta} \frac{d\phi}{2\pi}$$

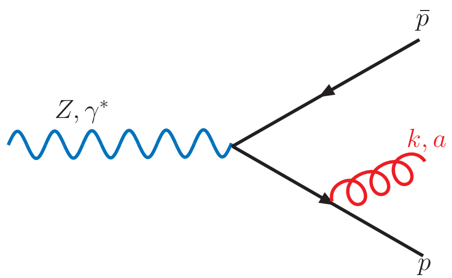
$$x_i = 2E_i/E_{\text{tot}} \quad p \to 1, \quad k \to 3$$

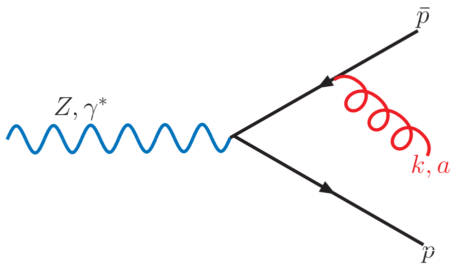
$$d\mathcal{S}_\phi = \frac{\alpha_s C_F}{2\pi} dx_1 dx_2 \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

$$= \frac{\alpha_s C_F}{2\pi} \left(\frac{2}{\sin^2\theta} \frac{1 + (1-x_3)^2}{x_3} - x_3 \right) d\cos\theta \, dx_3$$

- $d\mathcal{S}$ diverges for $\omega \to 0$, Infrared divergence (needs virtual loop corrections, we'll say more if time permits)
- $d\mathcal{S}$ diverges for $\theta \to 0$ and $\theta \to \pi$, collinear divergence

$$\mathcal{A}_{1g}(k \to 0) = -g_s t_a \left(\frac{p.\epsilon}{p.k} - \frac{\bar{p}.\epsilon}{\bar{p}.k} \right) \mathcal{A}_{0g}$$





Phase Space

$$|\mathcal{M}_{1g}|^2 \mathrm{d}\Phi_{q\bar{q}g} = \left(|\mathcal{M}_{0g}|^2 \mathrm{d}\Phi_{q\bar{q}} \right) \mathrm{d}\mathcal{S}; \quad \mathrm{d}\mathcal{S} \simeq \frac{\mathrm{d}^3\vec{k}}{2\omega_k (2\pi)^3} C_F g_s^2 \frac{2p.\bar{p}}{p.k \; \bar{p}.k}$$

$$\theta = \theta_{\angle pk} \; , \; \phi = \mathrm{azimuth}$$

$$\mathrm{d}\mathcal{S} \simeq \frac{2\alpha_s C_F}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta}{\sin\theta} \frac{\mathrm{d}\phi}{2\pi}$$

$$x_i = 2E_i/E_{\mathrm{tot}} \quad p \to 1, \quad k \to 3$$

$$\mathrm{d}\mathcal{S}_\phi = \frac{\alpha_s C_F}{2\pi} \mathrm{d}x_1 \mathrm{d}x_2 \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

$$= \frac{\alpha_s C_F}{2\pi} \left(\frac{2}{\sin^2\theta} \frac{1+(1-x_3)^2}{x_3} - x_3 \right) \mathrm{d}\cos\theta \mathrm{d}x_3$$

- $\mathrm{d}\mathcal{S}$ diverges for $\omega \to 0$, Infrared divergence (needs virtual loop corrections, we'll say more if time permits)
- $\mathrm{d}\mathcal{S}$ diverges for $\theta \to 0$ and $\theta \to \pi$, collinear divergence
- collinear divergence for $x_1 \to 1$ or $x_2 \to 1$ and Infrared divergence for $x_3 \to 0$

Splitting

$$\mathrm{d}\mathcal{S}_\phi \simeq \frac{\alpha_s C_F}{2\pi}\left(\frac{2}{\sin^2\theta}\frac{1+(1-x_3)^2}{x_3}\right)\mathrm{d}\cos\theta\,\mathrm{d}x_3$$

$$\frac{2\mathrm{d}\cos\theta}{\sin^2\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\theta}{1+\cos\theta}=\frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\bar{\theta}}{1-\cos\bar{\theta}}\sim\frac{\mathrm{d}\theta^2}{\theta^2}+\frac{\mathrm{d}\bar{\theta}^2}{\bar{\theta}^2}\quad \text{for}\ \ \theta,\bar{\theta}\sim 0 \ll 1$$

Splitting

$$\mathrm{d}\mathcal{S}_\phi \simeq \frac{\alpha_s C_F}{2\pi}\left(\frac{2}{\sin^2\theta}\frac{1+(1-x_3)^2}{x_3}\right)\mathrm{d}\cos\theta\,\mathrm{d}x_3$$

$$\frac{2\mathrm{d}\cos\theta}{\sin^2\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\theta}{1+\cos\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\bar\theta}{1-\cos\bar\theta} \sim \frac{\mathrm{d}\theta^2}{\theta^2}+\frac{\mathrm{d}\bar\theta^2}{\bar\theta^2} \quad \text{for } \theta,\bar\theta\sim 0 \ll 1$$

q and $\bar q$ as independent emitters, notion of splitting as a probability

$$\mathrm{d}\sigma_{1g} \sim \mathrm{d}\sigma_{0g}\sum_{q\to qg}^{\bar q\to\bar q g} C_F\frac{\alpha_s}{2\pi}\frac{\mathrm{d}\theta^2}{\theta^2}\frac{1+(1-z)^2}{z}\mathrm{d}z \qquad (z\equiv x_3)$$

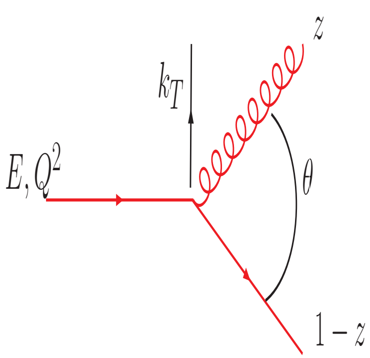
Splitting

$$\mathrm{d}\mathcal{S}_\phi \simeq \frac{\alpha_s C_F}{2\pi}\left(\frac{2}{\sin^2\theta}\frac{1+(1-x_3)^2}{x_3}\right)\mathrm{d}\cos\theta\,\mathrm{d}x_3$$

$$\frac{2\mathrm{d}\cos\theta}{\sin^2\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\theta}{1+\cos\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\bar\theta}{1-\cos\bar\theta} \sim \frac{\mathrm{d}\theta^2}{\theta^2}+\frac{\mathrm{d}\bar\theta^2}{\bar\theta^2} \quad \text{for } \theta,\bar\theta \sim 0 \ll 1$$

q and $\bar q$ as independent emitters, notion of splitting as a probability

$$\mathrm{d}\sigma_{1g} \sim \mathrm{d}\sigma_{0g}\sum_{q\to qg}^{\bar q\to\bar q g} C_F\frac{\alpha_s}{2\pi}\frac{\mathrm{d}\theta^2}{\theta^2}\frac{1+(1-z)^2}{z}\mathrm{d}z \qquad (z\equiv x_3)$$

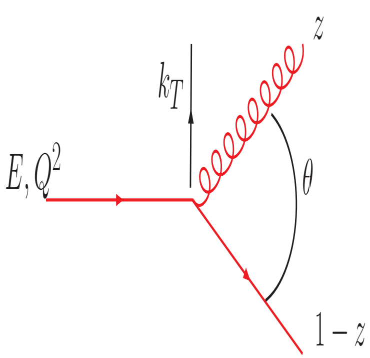


$$\mathrm{d}\mathcal{S}_\phi \simeq \frac{\alpha_s C_F}{2\pi}\left(\frac{2}{\sin^2\theta}\frac{1+(1-x_3)^2}{x_3}\right)\mathrm{d}\cos\theta\,\mathrm{d}x_3$$

$$\frac{2\mathrm{d}\cos\theta}{\sin^2\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\theta}{1+\cos\theta} = \frac{\mathrm{d}\cos\theta}{1-\cos\theta}+\frac{\mathrm{d}\cos\bar\theta}{1-\cos\bar\theta} \sim \frac{\mathrm{d}\theta^2}{\theta^2}+\frac{\mathrm{d}\bar\theta^2}{\bar\theta^2} \quad \text{for} \quad \theta,\bar\theta \sim 0 \ll 1$$

q and $\bar q$ as independent emitters, notion of splitting as a probability

$$\mathrm{d}\sigma_{1g} \sim \mathrm{d}\sigma_{0g} \sum_{q\to qg}^{\bar q\to\bar q g} C_F \frac{\alpha_s}{2\pi}\frac{\mathrm{d}\theta^2}{\theta^2}\frac{1+(1-z)^2}{z}\mathrm{d}z \qquad (z\equiv x_3)$$



different choices of the evolution variables, equivalent in the collinear limit (diff. in practice/different codes)

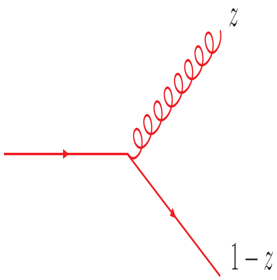
$$Q^2 = E^2 z(1-z)\theta^2 \qquad k_T^2 = E^2 z^2 (1-z)^2\theta^2$$

$$\frac{\mathrm{d}\theta^2}{\theta^2} = \frac{\mathrm{d}Q^2}{Q^2} = \frac{\mathrm{d}k_T^2}{k_T^2}$$

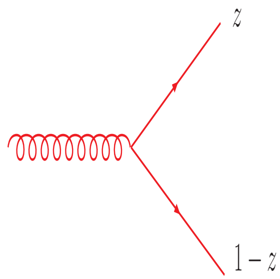
DGLAP

This generalises to different parton branching (gluon, quarks)

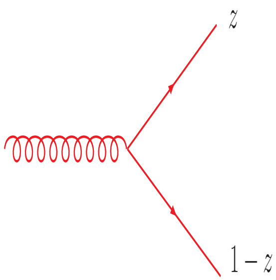
$$\mathrm{d}\sigma_{bc} \sim \mathrm{d}\sigma_a \frac{\alpha_s}{2\pi} \frac{\mathrm{d}\theta^2}{\theta^2} P_{a\to bc}(z)\mathrm{d}z$$



$$P_{gq}(z) = C_F\left(\frac{1+z^2}{1-z}\right)$$

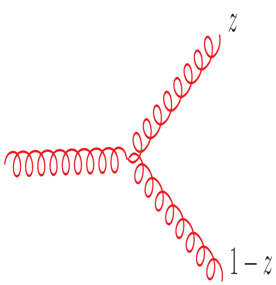


$$P_{qg}(z) = C_F\left(\frac{1+(1-z)^2}{z}\right)$$



$$P_{qg}(z) = T_R\left(z^2 + (1-z)^2\right) \qquad T_R = \frac{n_f}{2}$$

(divergences at $z = 0, 1$ dealt with soft/virtual corr.)

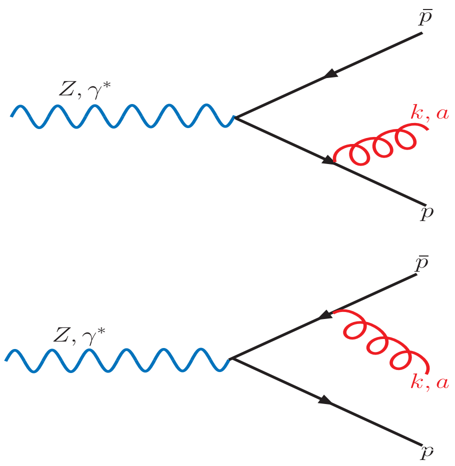


$$P_{gg}(z) = C_A\left(\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\right) \qquad C_A = 3 \qquad (C_F = 4/3)$$

Gluons radiate the most

$P(z,\phi)$ can be defined for polarisation effects

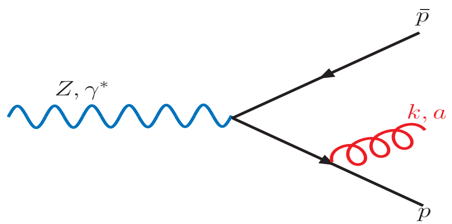
Compensation

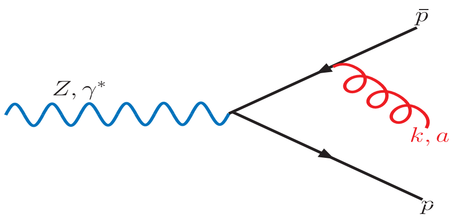


$$\sigma_{\rm real} \sim \frac{C_F \alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon) \right) \sigma_{\rm LO}$$

For $1^\star \to 2$, analytical result, int. easy.

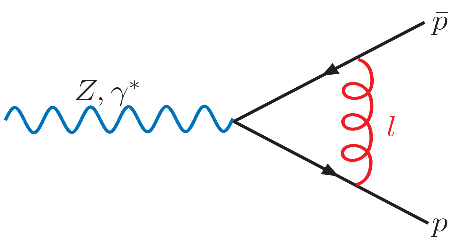
Compensation





$$\sigma_{\rm real} \sim \frac{C_F \alpha_s}{2\pi}\left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon)\right)\sigma_{\rm LO}$$

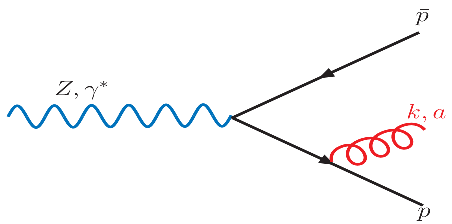
For $1^\star \rightarrow 2$, analytical result, int. easy.



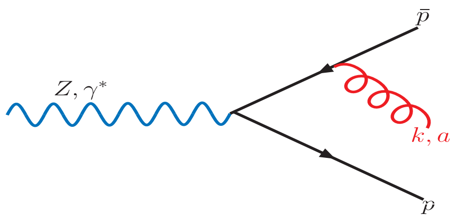
$$\int \frac{d^d l}{(2\pi)^d} \frac{N}{l^2 (l-p)^2 (l+\bar{p})^2}$$

$l \rightarrow 0$ IR div, $l \rightarrow \infty$ UV
$l = xp, y\bar{p}$ Coll Div for any $x, y \rightarrow 0$ For $1^\star \rightarrow 2$, analytical result, int. easy.

$$\sigma_{\rm virt} \sim \frac{C_F \alpha_s}{2\pi}\left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \mathcal{O}(\epsilon)\right)\sigma_{\rm LO}$$

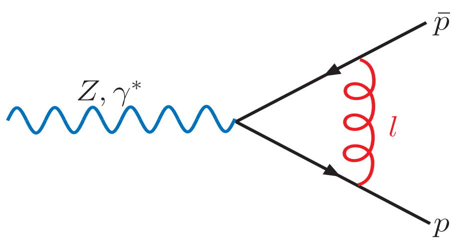


$$\sigma_{\text{real}} \sim \frac{C_F \alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon) \right) \sigma_{\text{LO}}$$



For $1^\star \to 2$, analytical result, int. easy.

$$\int \frac{d^d l}{(2\pi)^d} \frac{N}{l^2 (l-p)^2 (l+\bar{p})^2}$$



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$$\sigma_{NLO} = \left(1 + \frac{\alpha_s}{\pi} \sigma_{LO} \right)$$

- The singularities in the real emission, either soft or collinear factorise and are universal
- *i.e* **Process Independent**
- these universal terms are known, if we subtract their contribution from the full real emission terms, the obtained contribution has no singularity and could therefore be integrated numerically over all of phase space
- the singularities in the real emission compensate those in the virtual emission, this assumes we are using the same regularisation scheme

When dealing with multiparticle final states,

integration over phase space can only be performed numerically

these observation are very important

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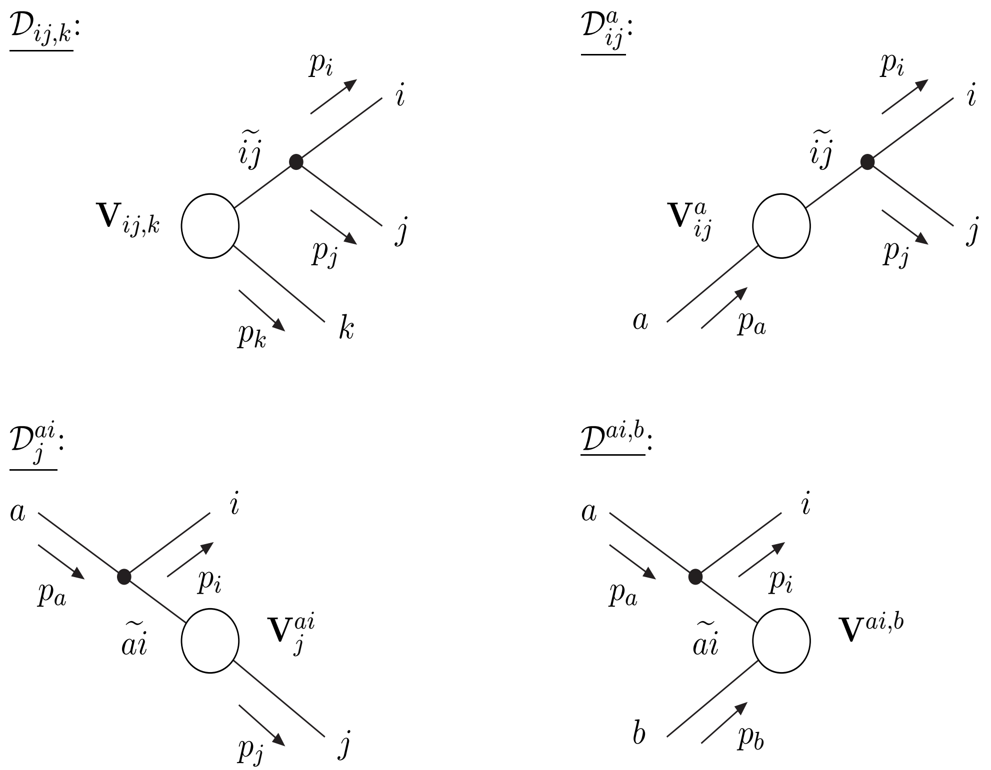
integration over phase space can only be performed numerically

these observation are very important

- Calculate the real terms and subtract the soft/collinear counterterms
- One can then integrate in 4-dimension numerically
- add these counterterms *analytically* to the virtual contribution (properly UV renormalised) to obtain a diff cross section that is soft/coll finite and that can be integrated numerically
- some massaging to do, can be automated: $dPS_{LO+1} \to dPS_{LO} \times dPS_{\text{gluon}}$ (boosts,...)
- there can be a lot of emitters/dipoles!

Dipoles la Catani-Seymour



Dipoles: final-state emitter with final-state spectator ($\mathcal{D}_{ij,k}$), final-state emitter with initial-state spectator ($\mathcal{D}_{ij}^{a}$), initial-state emitter with final-state spectator ($\mathcal{D}_{j}^{ai}$) and initial-state emitter with initial-state spectator ($\mathcal{D}^{ai,b}$).

Physics!!!

(Gleisberg, Hoeche, Krauss, Schoenher
Schumann, Siegert, Winter)

NLO with **BlackHat+Sherpa**

$$\sigma^{\mathrm{NLO}} = \int_{m+1}\left[\mathrm{d}^{(4)}\sigma^{\mathrm{R}} - \mathrm{d}^{(4)}\sigma^{\mathrm{A}}\right] + \int_{m}\left[\int_{\mathrm{loop}}\mathrm{d}^{(d)}\sigma^{\mathrm{V}} + \int_{1}\mathrm{d}^{(d)}\sigma^{\mathrm{A}}\right]_{\epsilon=0}$$

(S. Catani, M.H. Seymour,1997)

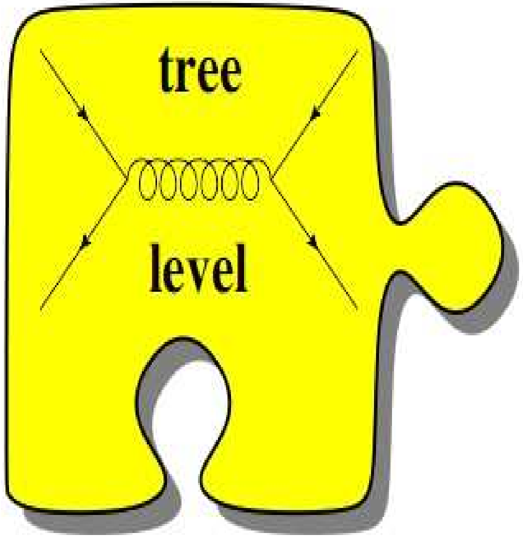
(T. Gleisberg, F. Krauss, 2007)

+

(a glance to NLO automation!)

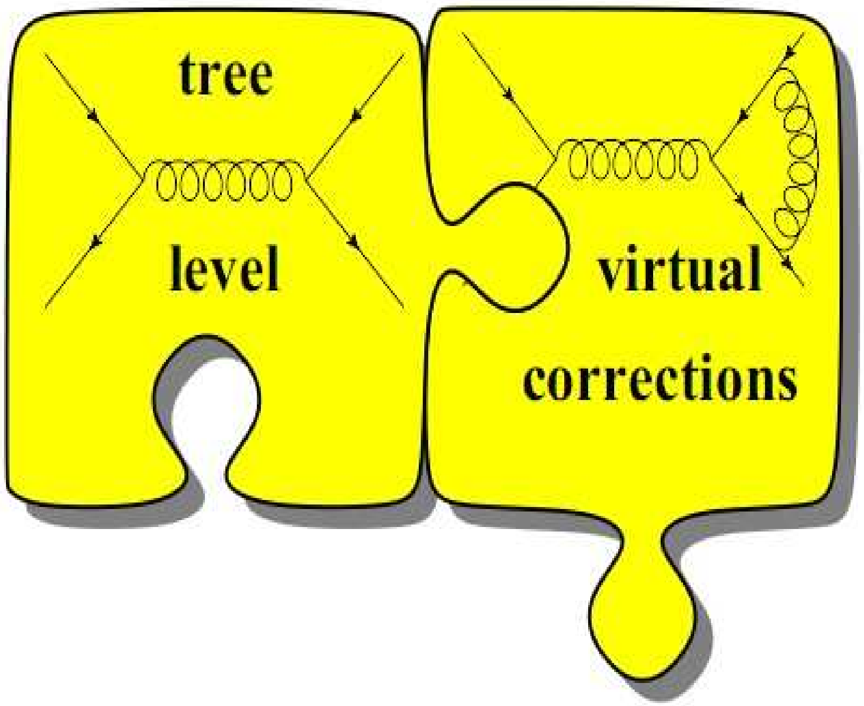
High level of automatisation, public

- `ALPGEN` (Mangano et al.)
- `CalcHEP` (Pukhov,Belyaev,Christensen)
- `CompHEP` (Boos et al.)
- `Grace` (Yuasa et al.)
- `HELAS/PHEGAS` (Papadopoulos et al.)
- `MADGRAPH/MADEVENT` (Maltoni,Stelzer)
- `O'Mega/WHIZARD` (Kilian,Moretti,Ohl,Reuter)
- `SHERPA/Amegic` (Krauss,Kuhn)

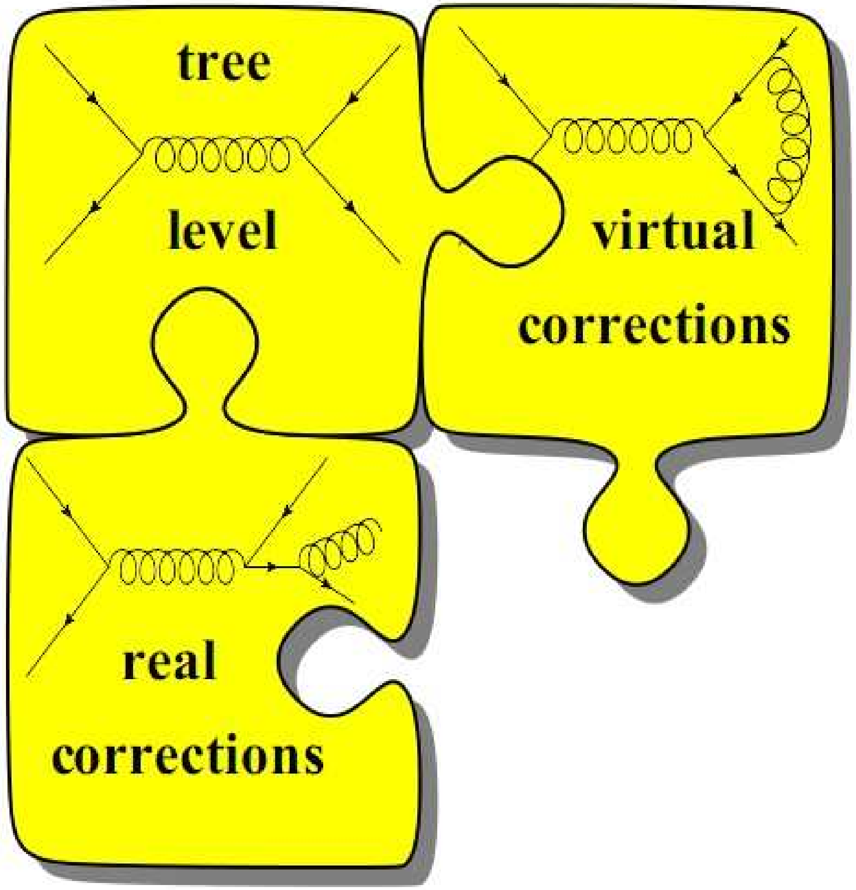


virtual Corrections:

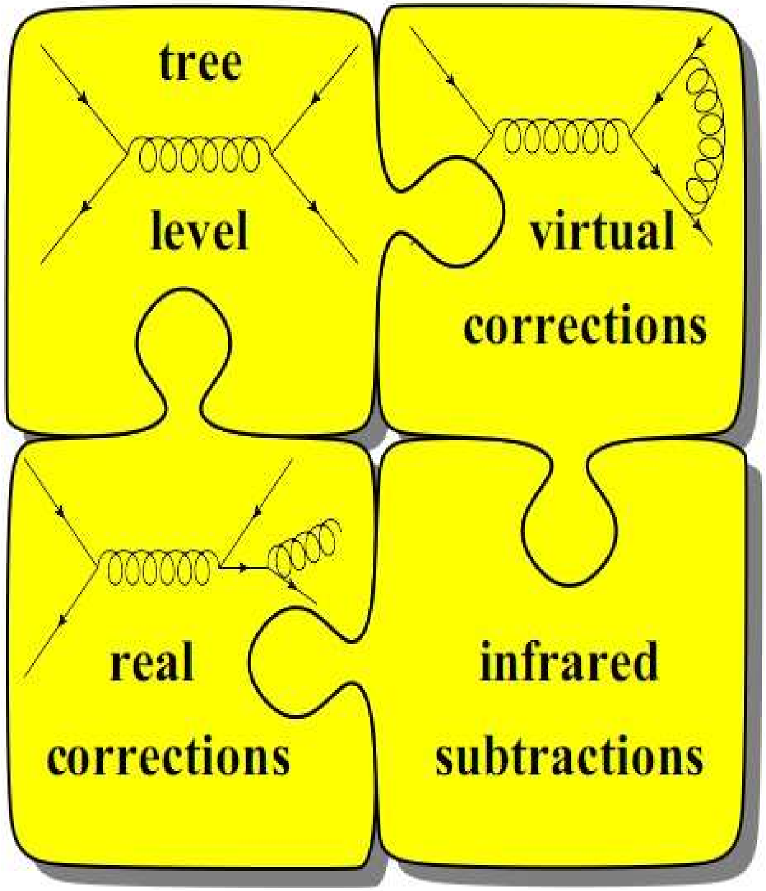
- Feynmanians
  FeynArts/FormCalc (Hahn,Perez-Victoria,v.Oldenborgh
  Grace-loop (Shimzu et al.
  Golem (Binoth et al,)
  SloopS (Boudjema et al.)
  Many Process Specific few)
- Unitaritarians/cuts (at amplitude leve so)
  HELAC-1LOOP+CutTools (v.Hameren,Ossola,Papadopoulos
  BlackHat (Berger et al.)
  Rocket (Ellis, Melnikov, Zanderighi)
  Generalized Color-Dres Unitarity (Giele,Kunszt,Winter



Radiation, in principle same as tree-level



- Catani-Seymour dipoles
  - AutoDipole (Hasegawa, Moch, Uwer)
  - HELAC-DPOLE (Czakon, Papadopoulos, Worek)
  - MadDipole (Frederix, Gehrmann, Greiner)
  - Sherpa (Gleisberg, Krauss)
  - TevJet (Seymour, Tevlin)
- MadFKS (Frederix, Frixione, Maltoni, Stelzer)




2 Higgs phenomenology
3. New NLO calculations/ wishlist
4. NLO techniques Standardization/automation
5. NLO + parton shower
09.06.2009

- hadronic cross section and partonic subprocesses

$$\sigma_{had}(p_1,p_2) = \sum_{a,b} \int dx_1\, f_{a/H_1}(x_1,\mu_{\rm F}^2) \int dx_2\, f_{b/H_2}(x_2,\mu_{\rm F}^2) \times \Big[d\sigma_{ab}^{\rm LO}(x_1p_1,x_2p_2;\mu_{\rm R}^2) + d\sigma_{ab}^{\rm NLO}(x_1p_1,x_2p_2;\mu_{\rm R}^2,\mu_{\rm F}^2) \Big],$$

-

$$\sigma_{ab}^{\rm LO} = \int_m d\sigma_{ab}^{B},$$

$$\sigma_{ab}^{\rm NLO} = \int_{m+1} d\sigma_{ab}^{R} + \int_m d\sigma_{ab}^{V} + \int_m d\sigma_{ab}^{C}(\mu_{\rm F}^2, {\rm F.S.}) .$$

- for $2 \rightarrow m$ (Born, V) and $2 \rightarrow m+1$ (real)

$$d\sigma_{ab}^{V} = d\,\text{LIPS}(\{k_j\})\, \mathcal{I}(\{k_j\}) .$$

- Take DR after renormalisation

$$\mathcal{I}(\{k_j\}, {\rm R.S.}, \mu_{\rm R}^2, \alpha_{\rm S}(\mu_{\rm R}^2), \alpha, \ldots) = C(\epsilon)\left(\frac{A_2}{\epsilon^2} + \frac{A_1}{\epsilon} + A_0\right) .$$

The goal of the interface is to facilitate the transfer of information between

one-loop programs, OLP

and programs which provide

tree amplitude information and incorporate methods to

perform the integration over the phase space:

Monte Carlo tool (MC).

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Interaction works in 2 phases

- `initialisation` exchange of basic information: availability of sub-processes, input parameters, schemes,..
- `Run-time` MC asks OLP for one-loop contributions at points in PS. Finite part may be split (more efficient integration, sampling)

OLP	Input	Output
Initialisation	Model parameters: $\alpha(0)$, $\alpha_{\rm S}(M_Z), \ldots, m_t, m_b, \ldots$, CKM values	confirm values
	Schemes: UV-renormalisation / IR-factorisation	confirm schemes
	Operational information: colour/helicity treatment, approximations, etc.	confirm options

contracts

OLP	Input	Output
Initialisation	Model parameters: $\alpha(0),\ \alpha_{\rm S}(M_Z), \ldots,\ m_t,\ m_b, \ldots,$ CKM values	`confirm values`
	Schemes: UV-renormalisation / IR-factorisation	`confirm schemes`
	Operational information: colour/helicity treatment, approximations, etc.	`confirm options`
Run-time	Events: $(E, p_x, p_y, p_z, M)_{j=1,\ldots,m+2},\ \mu,\ \alpha_{\rm S}(\mu_{\rm R})$	$\left(A_2, A_1, A_0, \lvert\text{Born}\rvert^2\right)$ `optional information`


INITIALIZATION
PHASE
LOOP
ME
FILE
UN PHASE
DECAY?
COMPLEX-MASS
12.06.2009

Example: Here is an example of an order file for the partonic $2 \to 3$ processes, $gg \to t\bar{t}g$, $q\bar{q} \to t\bar{t}g$ and $qg \to t\bar{t}q$, needed for the evaluation of $pp \to t\bar{t}$ + jet

```
# example order file

MatrixElementSquareType   CHsummed
IRregularisation          CDR
OperationMode             LeadingColour
ModelFile                 ModelInLHFormat.slh
SubdivideSubprocess       yes
AlphasPower               3
CorrectionType            QCD

# g g   -> t tbar g
 21 21 -> 6 -6 21
# u ubar -> t tbar g
  2 -2 -> 6 -6 21
# u g   -> t tbar u
  2 21 -> 6 -6  2
```

Example:

```
# example contract file
# contract produced by OLP, OLP authors, citation policy

MatrixElementSquareType CHsummed                | OK
IRregularisation        CDR                     | OK
OperationMode           LeadingColour           | OK
ModelFile               ModelFileInLHFormat.slh | OK
SubdivideSubprocess     yes                     | OK
CorrectionType          QCD                     | OK

# g g -> t tbar g
21 21 -> 6 -6 21       | 2 13 35 # 2 channels: cut-constructable,&
                                      & rational part
# u ubar -> t tbar g
 2 -2 -> 6 -6 21       | 1 29
# u g -> t tbar u
 2 21 -> 6 -6  2       | 3 8 23 57 # 3 channels: leading,&
                         & subleading, subsubleading colour
```

The contract file

Example:

```
# example contract file
# contract produced by OLP, OLP authors, citation policy

MatrixElementSquareType CHsummed | Error: unsupported flag
# CHaveraged is supported
IRregularisation        DRED     | Error: unsupported flag
# CDR, tHV are supported
OperationMode     LeadingColour | Error: unsupported flag
# see OLP Documentation
ModelFile     FavouriteModel.slh | Error: file not found
# Modelfile is called: SM.slh
SubdivideSubprocess yes          | Error: unsupported flag
# no is supported
CorrectionType           EW      | Error: unsupported flag
# QCD is supported
MyWayOfDoingThings true          | Error: unknown option

# g g -> t tbar g
21 21 -> 6 -6 21     |   Error: massive quarks not supported
# u ubar -> t tbar g
 2 -2 -> 6 -6 21     |   Error: process not available
# u g -> t tbar u
 2 21 ->> 6 -6  2    |   Error: check syntax
```

Warning ! Used by Thomas often at LH09

" ....NLO tools are not DAUs..." (Stefan Dittmaier)

DAU= dmmst anzumehmender user = most imaginable ignorant user

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A Dahu, quoi..! as I told him for a multi-leg alpine (?) animal...

Chuss Thomas!