QCD Corrections to $pp \rightarrow e^- \bar{\nu}_e \gamma j$

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in collaboration with Christoph Englert, Francisco Campanario
and Dieter Zeppenfeld

- Progress in VBFNLO
- Motivation for $pp \rightarrow e^- \bar{\nu}_e \gamma j$
- Elements of the calculation, some preliminary results
- Outlook

New version of VBFNLO has been published

[Arnold et al. `08]
[www-itp.physik.uni-karlsruhe.de/~vbfnloweb]

→ Fully flexible Monte-Carlo program for selected Higgs and ELW boson production processes

Ongoing work for next version:

- $ZZ\gamma/WW\gamma$ (Bozzi, Campanario, Zeppenfeld)
- $W\gamma Jet$ (Campanario, Englert, MS, Zeppenfeld)
- $WZ\gamma$ (Bozzi, Campanario, Rauch, Rzehak, Zeppenfeld)
- $Hjjj$ SUSY-QCD corrections in GF (Campanario, Kubocz, Zeppenfeld)

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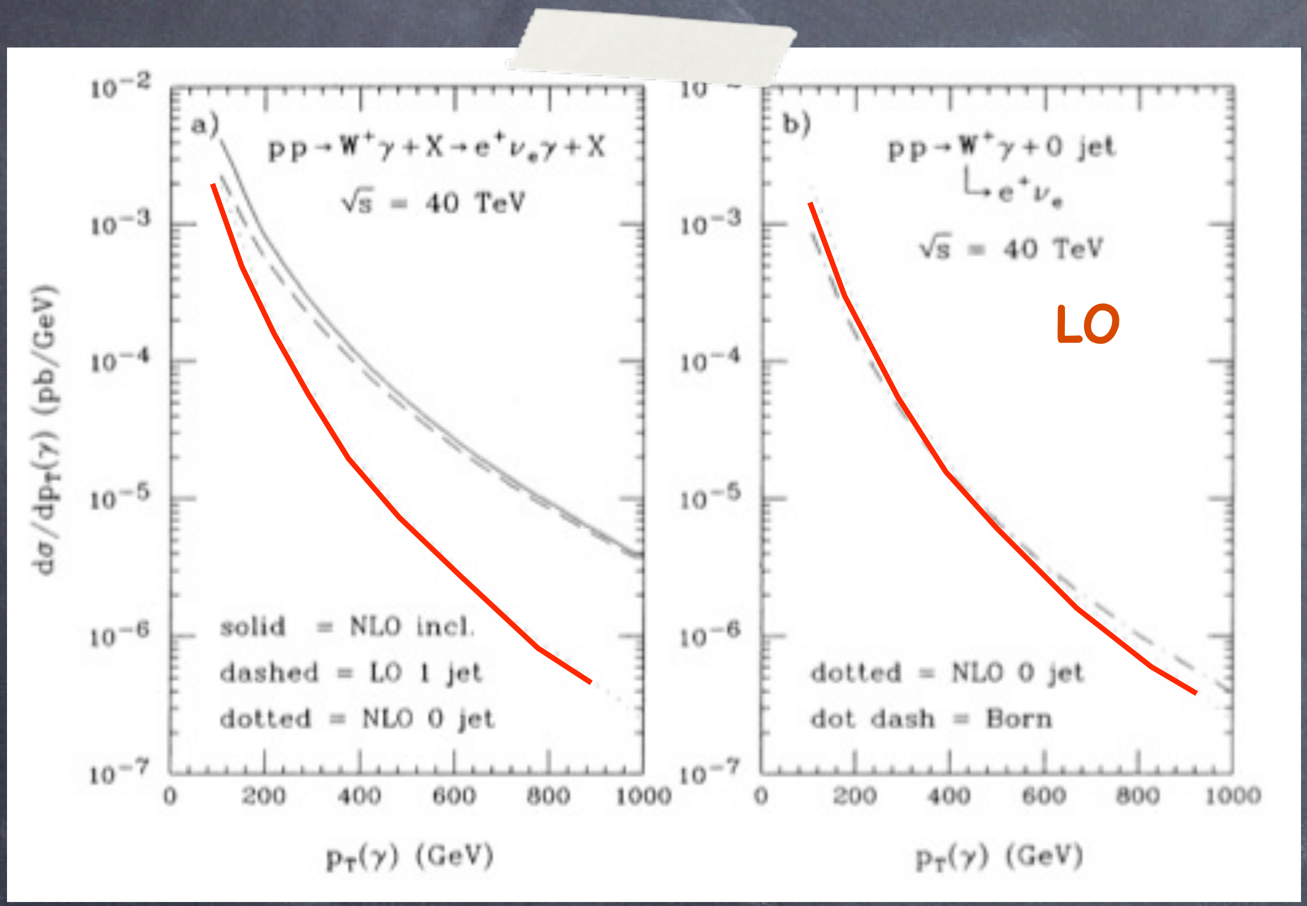

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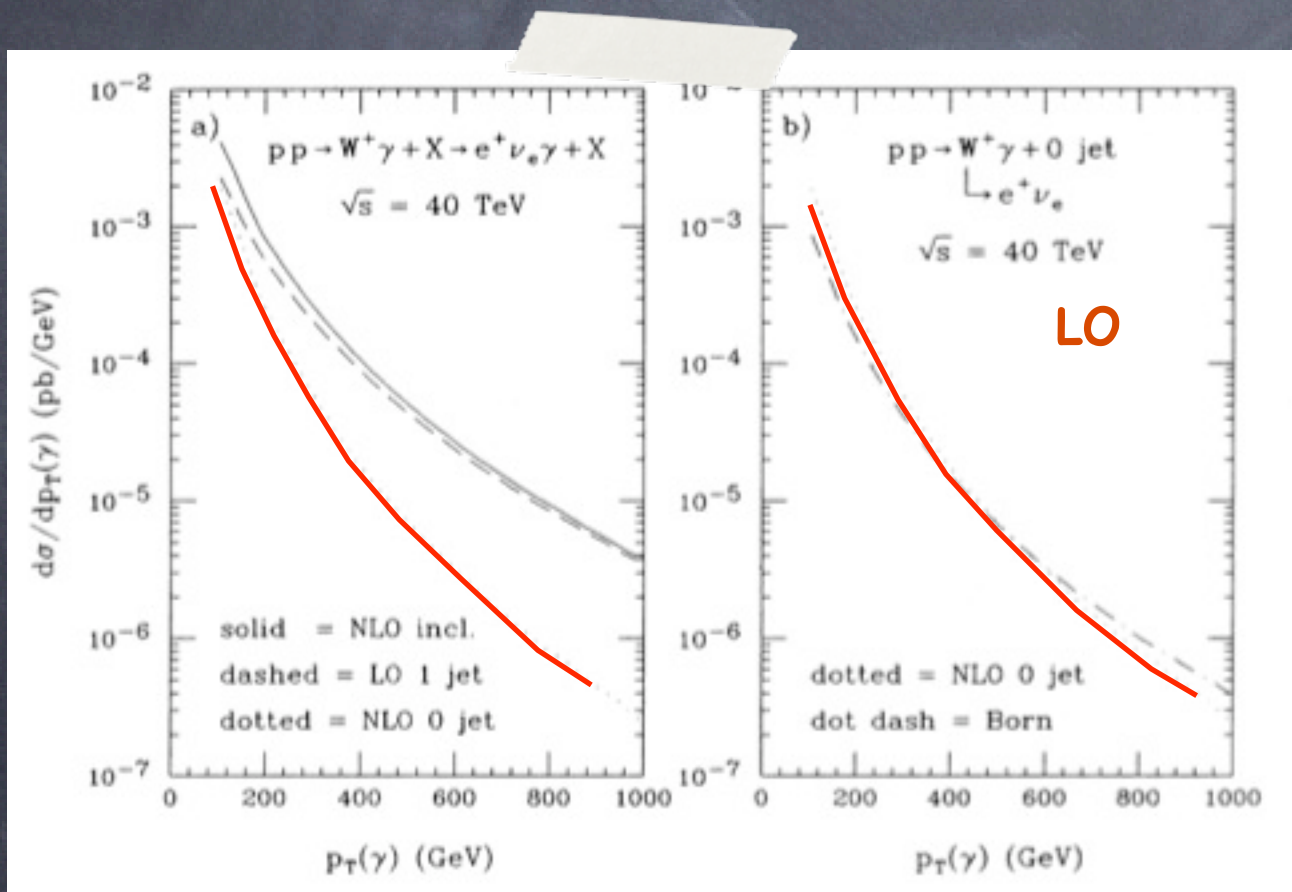

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Collinear W approximation:

$$d\sigma(q_1 g \to W\gamma q_1)$$

$$= d\sigma(q_1 g \to \gamma q_1)\frac{g_W^2}{16\pi^2}\ln^2\frac{p_T^2(\gamma)}{m_W^2}$$

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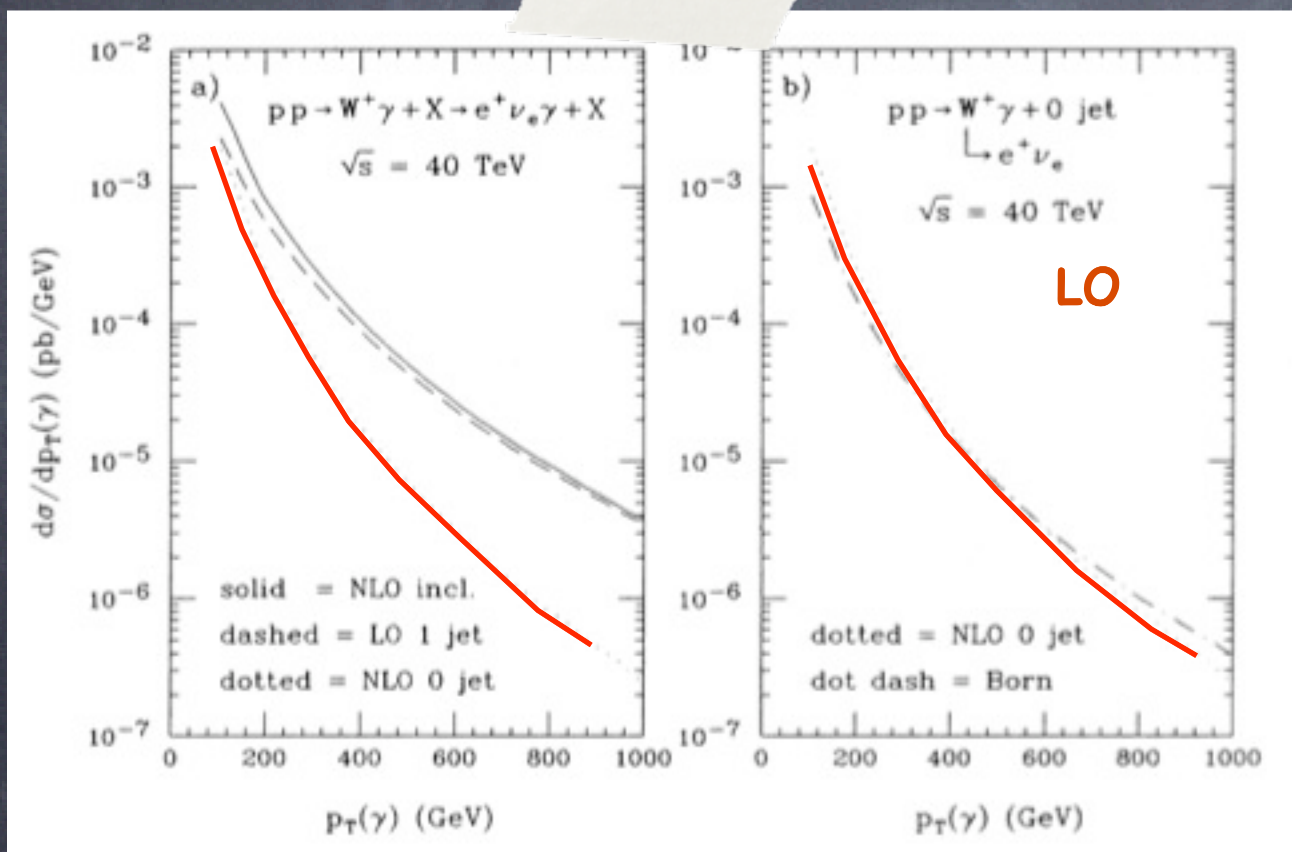

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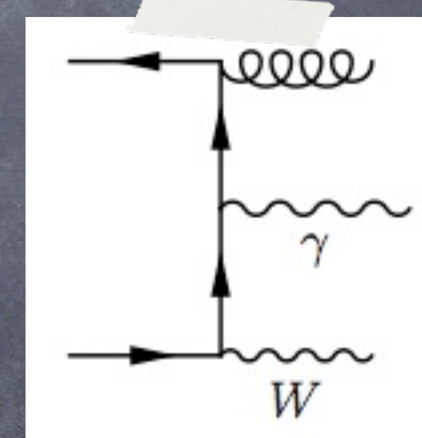

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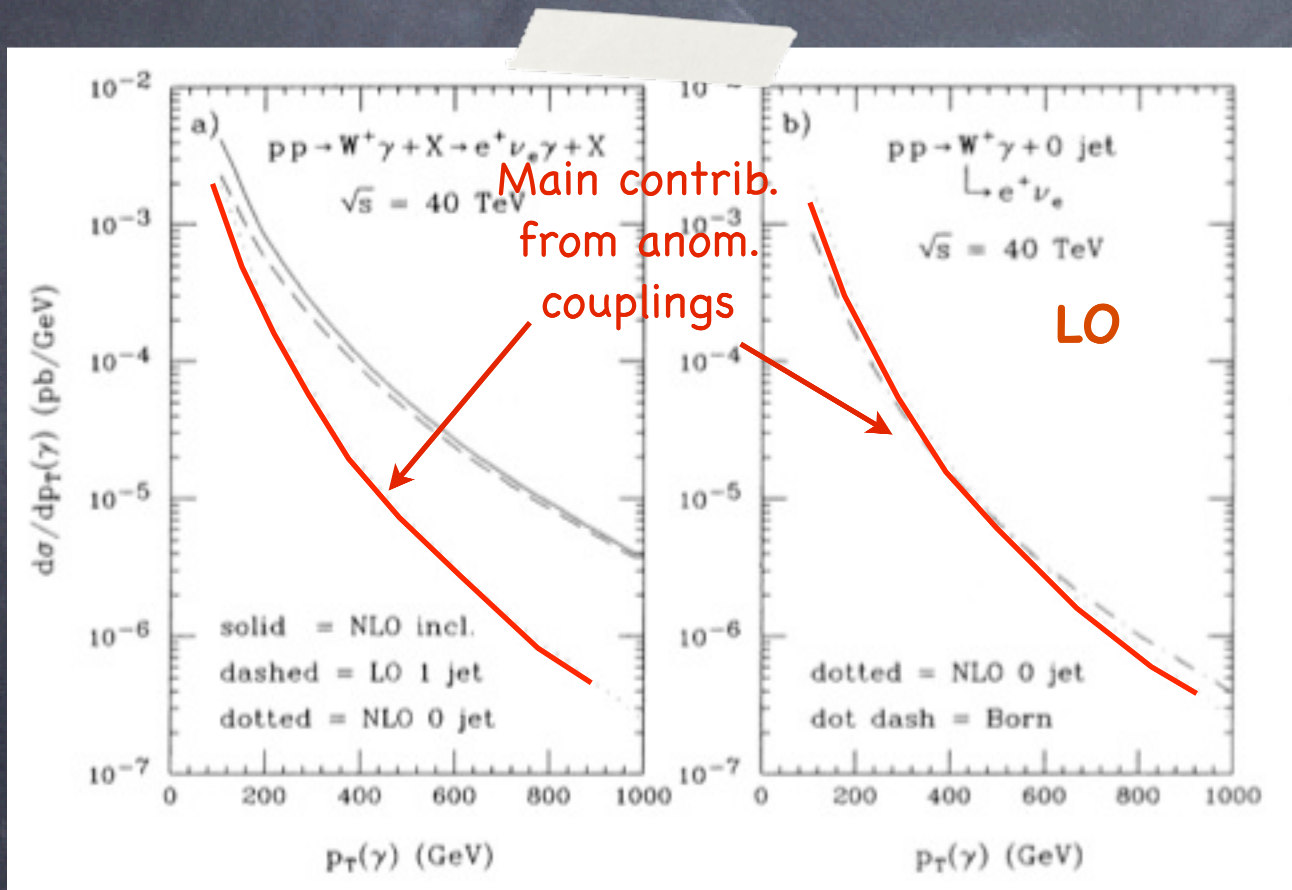

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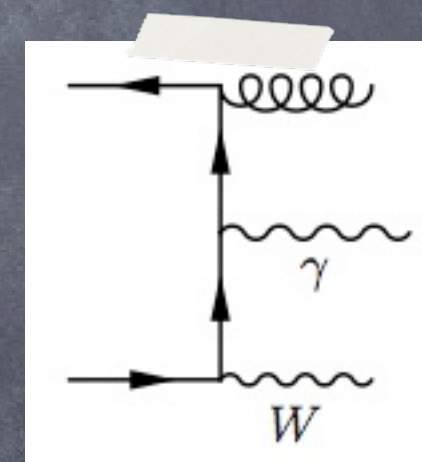

$\Longrightarrow$ jet veto projects on interesting phasespace region

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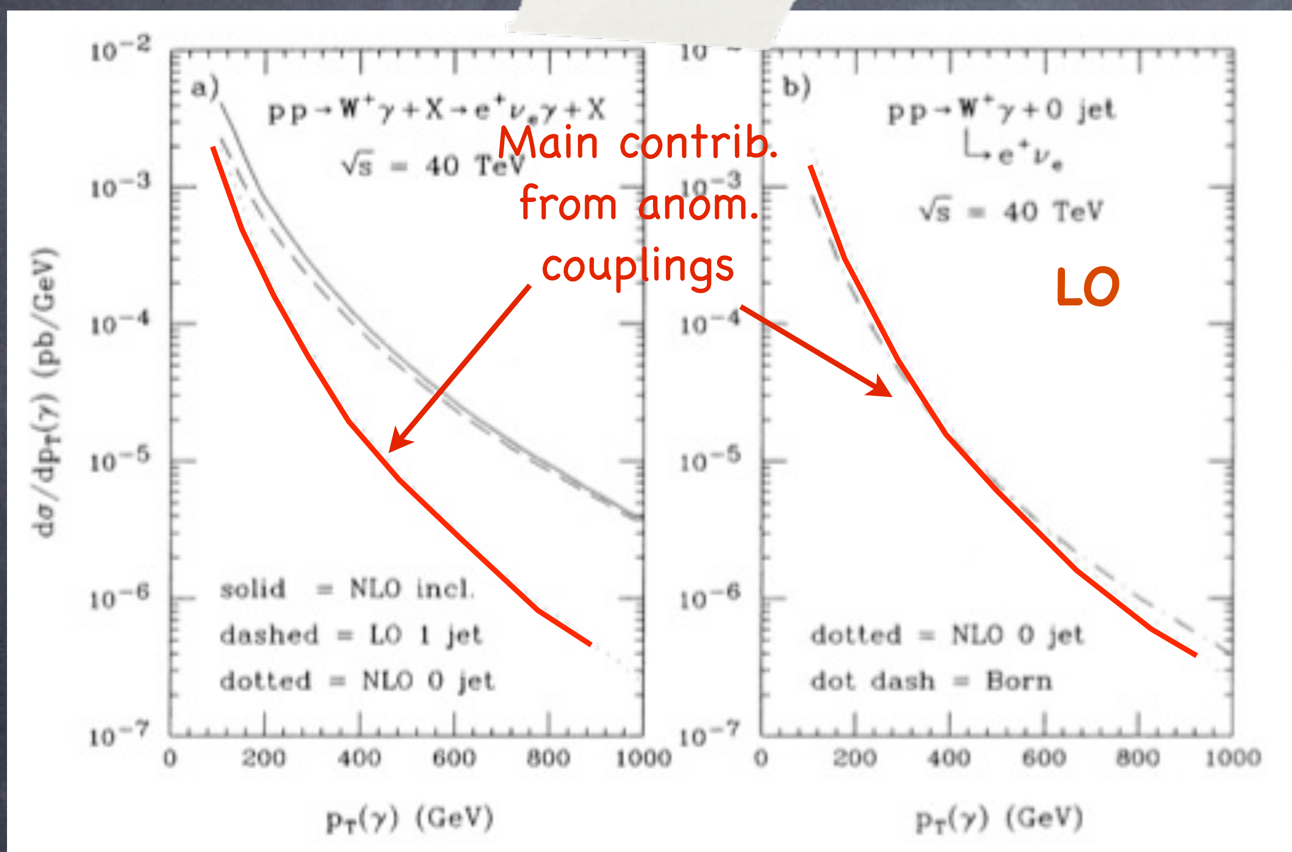

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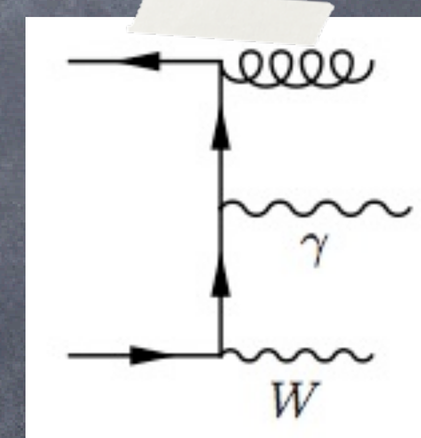

$\Longrightarrow$ jet veto projects on interesting phasespace region

... yet jet veto is a leading order subtraction! Scale dep. $\mathcal{O}(20\%)$

Elements of the Calculation

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- 3 basic subprocesses $\mathcal{O}(\alpha^2\alpha_s)$

$$\bar{u}d \to e^-\bar{\nu}_e\gamma g$$
$$\bar{u}g \to e^-\bar{\nu}_e\gamma\bar{d}$$
$$dg \to e^-\bar{\nu}_e\gamma\bar{u}$$

+ initial state interchanged

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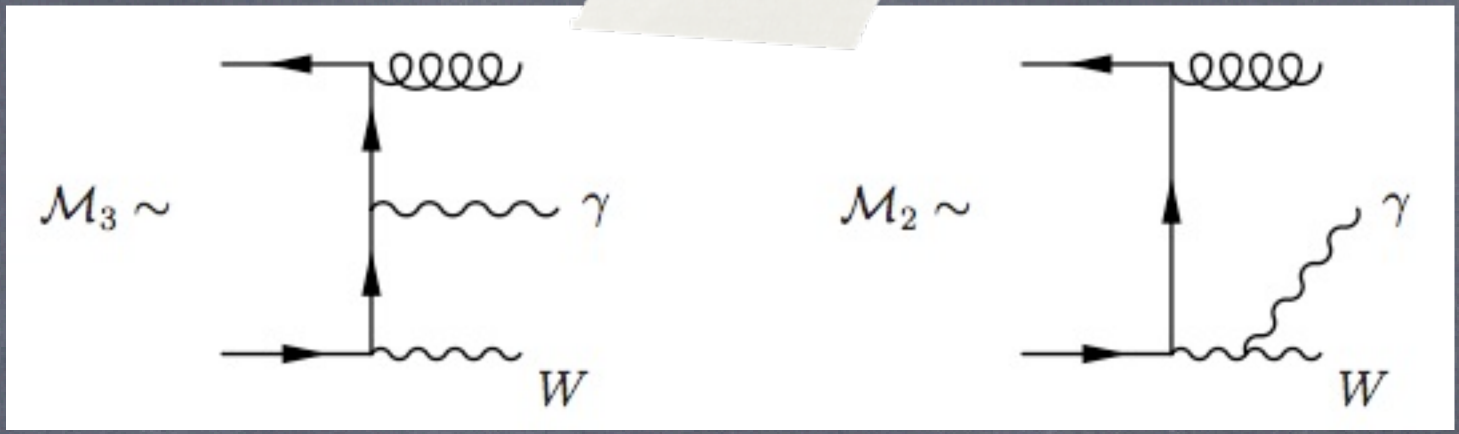

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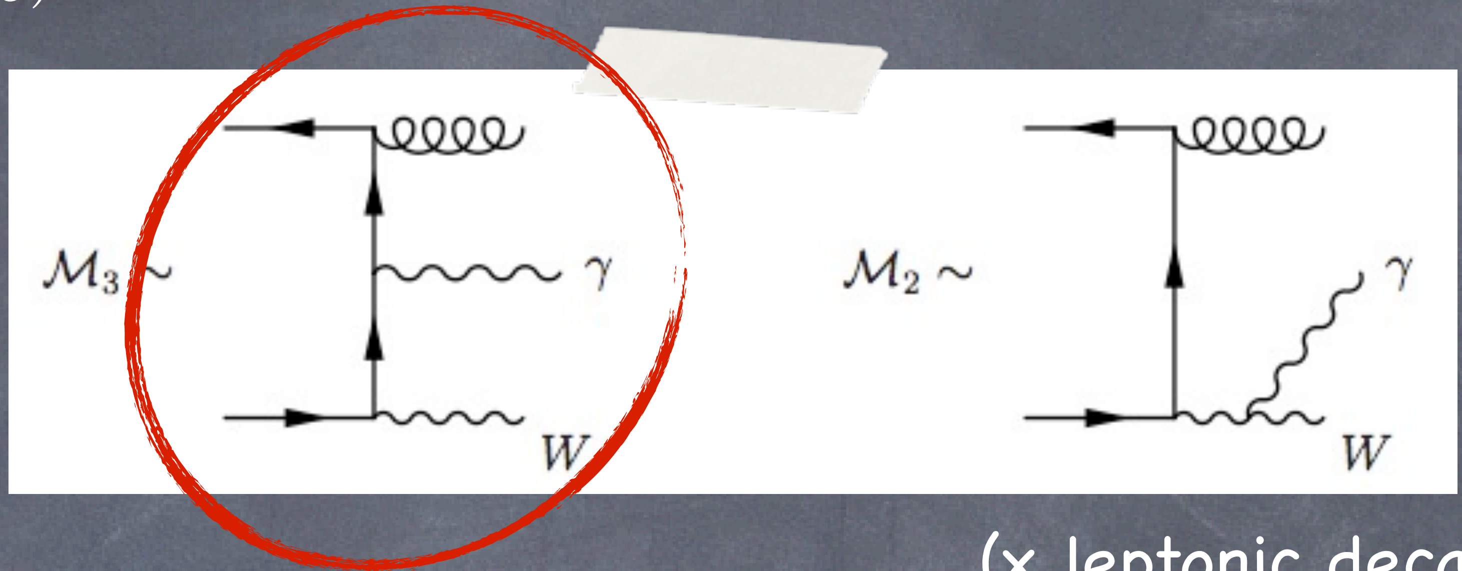

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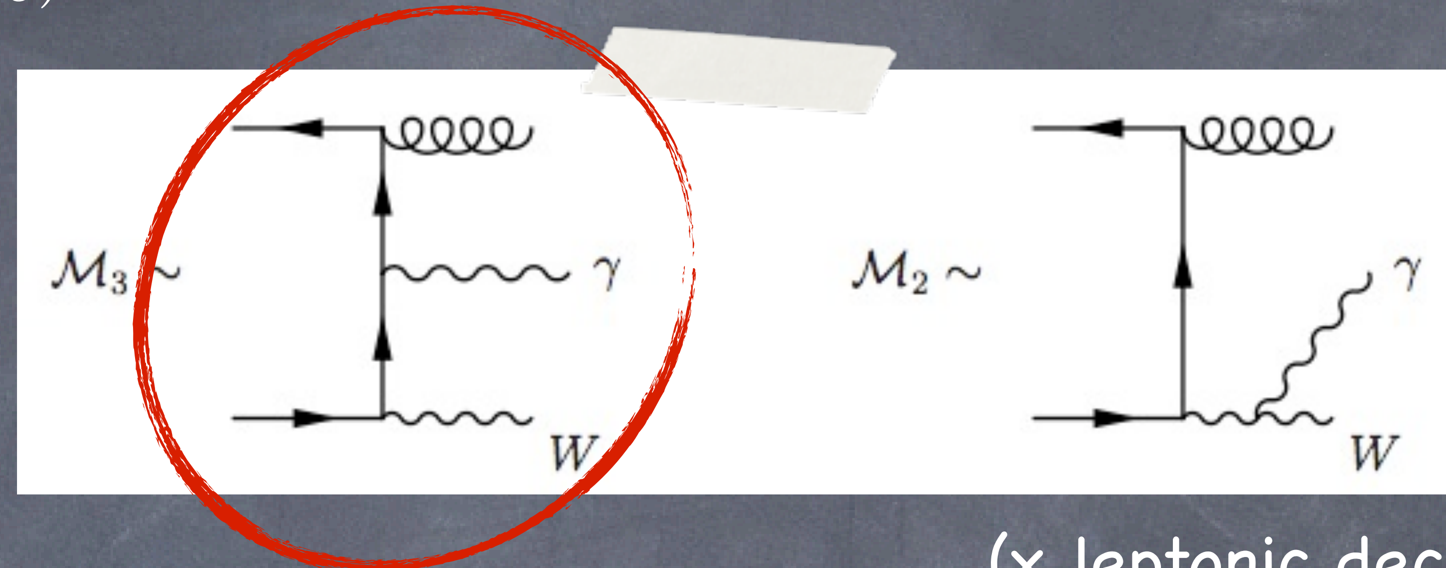

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- MS-bar renormalized virtual contribution in DREG:

$$\begin{aligned}\mathcal{M}_V \quad = \quad & \mathcal{M}_B \frac{\alpha_s(\mu_R^2)}{4\pi}\Gamma(1+\epsilon)\left\{\frac{1}{2}\left(\left(\frac{4\pi\mu_R^2}{-u}\right)^\epsilon + \left(\frac{4\pi\mu_R^2}{-t}\right)^\epsilon\right)\left(-\frac{C_A}{\epsilon^2} - \frac{\gamma_g}{\epsilon}\right)\right. \\ + \quad & \frac{1}{2}\frac{C_A}{C_F}\left(\left(\frac{4\pi\mu_R^2}{-u}\right)^\epsilon + \left(\frac{4\pi\mu_R^2}{-t}\right)^\epsilon - 2\left(\frac{4\pi\mu_R^2}{s}\right)^\epsilon\right)\left(-\frac{C_F}{\epsilon^2} - \frac{\gamma_q}{\epsilon}\right) \\ + \quad & \left. 2\left(\frac{4\pi\mu_R^2}{s}\right)^\epsilon\left(-\frac{C_F}{\epsilon^2} - \frac{\gamma_q}{\epsilon}\right) + F(s,-t,-u)\right\} \\ + \quad & \widetilde{\mathcal{M}}_V\end{aligned}$$

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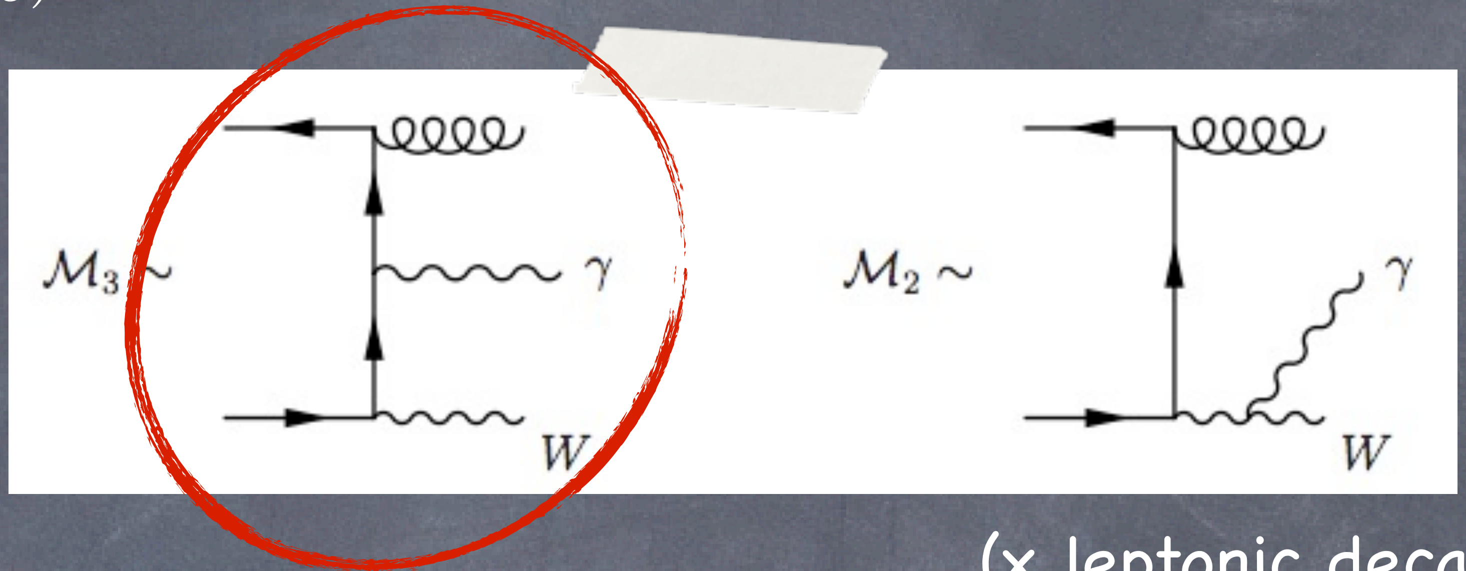

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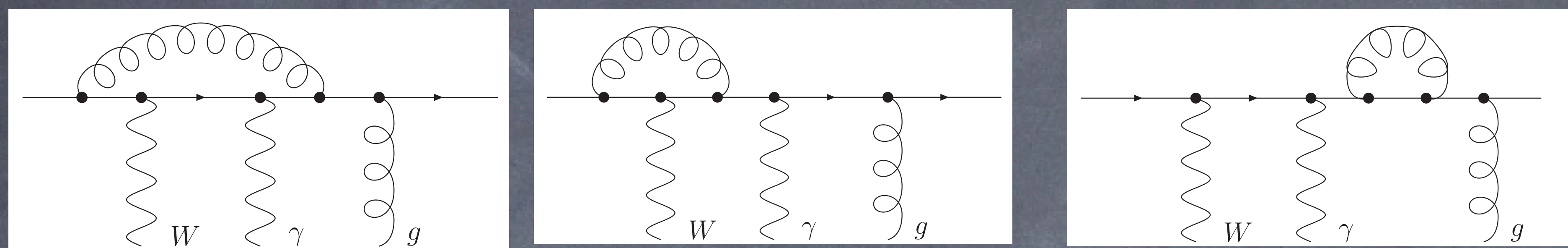
in terms of tensor coefficients à la Denner, Dittmaier

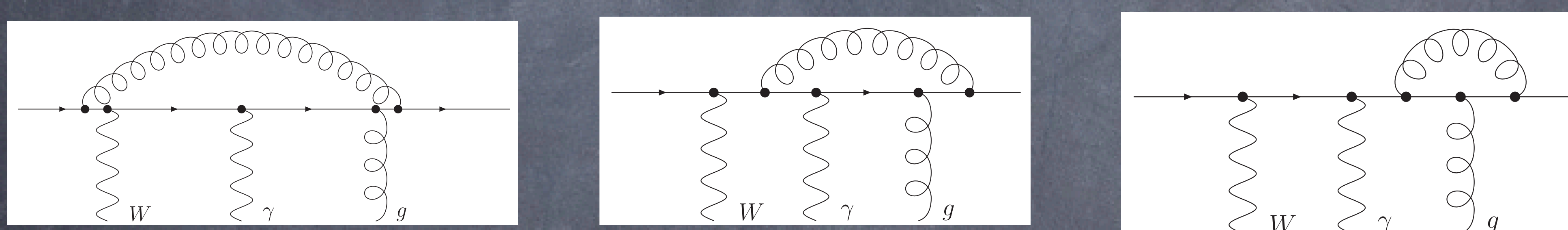
[Denner, Dittmaier `02, `05]

Calculation of $\mathcal{M}_V$

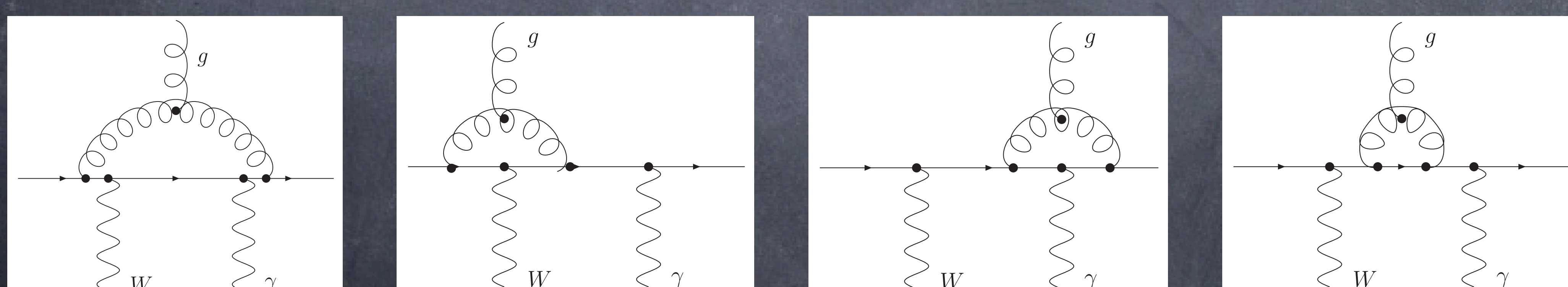
→ Non-abelian pentagons now included in "Pentline routine" of VBFNLO



$\sim C_F$



$\sim \left(C_F - \frac{1}{2} C_A \right)$



$\sim C_A$

Elements of the Calculation

- First way to calculate the virtual contributions:
  - Generate Feynman diagrams with FeynArts
  - Regularization in D-dimensions
  - Dig out soft & collinear parts of the loop integrals
  - Match to the Born (Catani-Seymour)
  - Numerical evaluation of tensor integrals using pent- and boxline routines (abelian and non-abelian)
    - Divergencies factorize to the Born
    - Gauge checks

Both methods are in good agreement!

Elements of the Calculation

- Second way to calculate the virtual contributions:

  - FeynArts for Feynman diagrams
  - UV and IR divergencies are treated separately [Bredenstein, Denner, Dittmaier, Pozzorini 2008]

$$\longrightarrow \quad B(0,0,0) \sim \left(\frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}}\right) \neq 0$$

  - We use D-dimensional identities until UV divergences cancel against counterterms
  - For each diagram we single out the IR-divergencies in terms of three-point functions

$$T^{(N)}_{\mu_1 \ldots \mu_p}(p_0, ..., p_{N-1}, m_0, ..., m_{N-1})|_{sing} = \sum_{n=0}^{N-1} \sum_{k=0}^{N-1} A_{nk} C_{\mu_1, \ldots, \mu_p}(p_n, p_{n+1}, p_k, m_n, m_{n+1}, m_k)$$

[Dittmaier; hep-ph/0308246]

  - No D-dependent pre-factors appear in front of IR-singular integrals - checked
  - Use modified verstion of FormCalc/LoopTools for numerical evaluation [Hahn et al. \`99]

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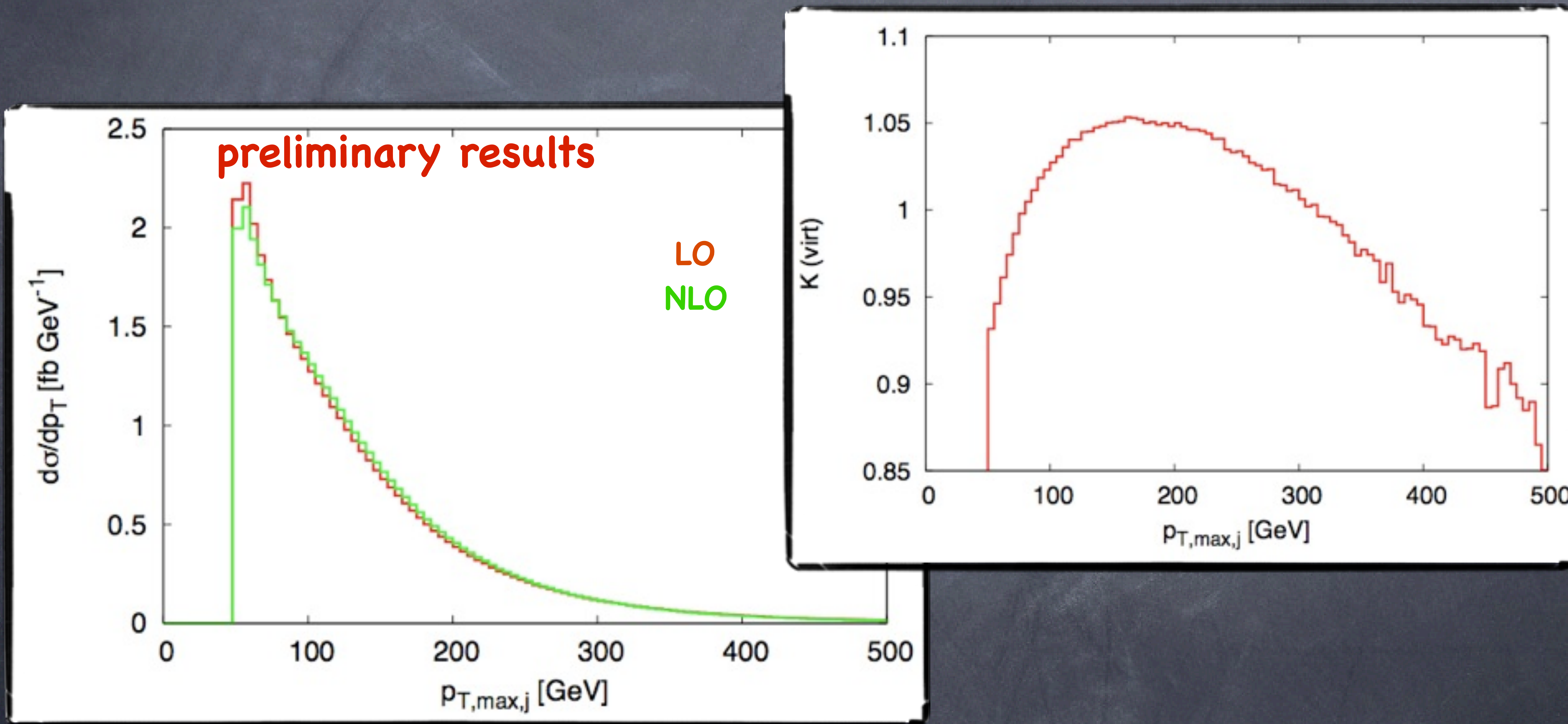
- Numerical agreement for random phasespace points, e.g. abelian pentagons:

	in-house routines		RATIO wrt to modified FormCalc/LoopTools	
Pentagon 1	- 0.003965205272080	-0.001143241748151	1.	0.
Pentagon 2	-0.004800102061452	0.030044547945124	1.	0.
Pentagon 3	0.028546967847664	0.014355918923774	1.	0.
Pentagon 4	0.024991941980560	0.013017938482178	1.	0.
Pentagon 5	-0.006454811173015	0.017158981521681	1.	0.
Pentagon 6	0.001749930491363	0.005421470600930	1.	0.

Virtual contributions: MC results

- Implemented into a fully flexible MC (including finite terms from Dipoles and finite collinear contributions)



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- Real emission matrix element coded in spinor helicity formalism. Optimized, checked @ AMP-Level against MadGraph for different PSPs

(1)	$\bar{u}u \to e^-\bar{\nu}_e\gamma\bar{d}u$	28 Graphs
(2)	$\bar{u}u \to e^-\bar{\nu}_e\gamma\bar{s}c$	14 Graphs $\subset$ (1)
(3)	$gg \to e^-\bar{\nu}_e\gamma\bar{d}u$	46 Graphs

$\otimes$ crossing and flavor summation

approx. 1500 Graphs

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- IR divergencies treated according to CS Dipole formalism [Catani, Seymour `96]

$$\sigma_{\mathrm{NLO}} = \int_m (\mathrm{d}\sigma_v + \mathrm{d}\widetilde{\sigma_{sub}}) + \int_{m+1} (\mathrm{d}\sigma_r - \mathrm{d}\sigma_{sub}) + \int_m \mathrm{d}\sigma_c$$

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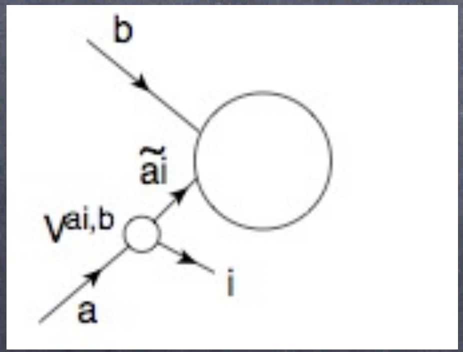

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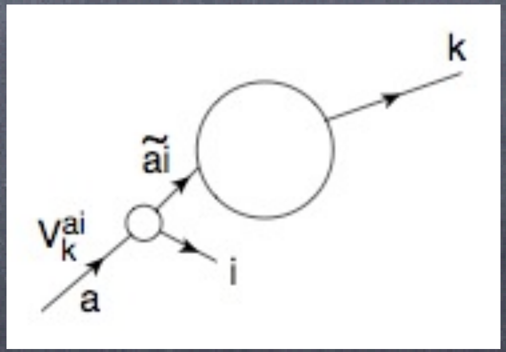

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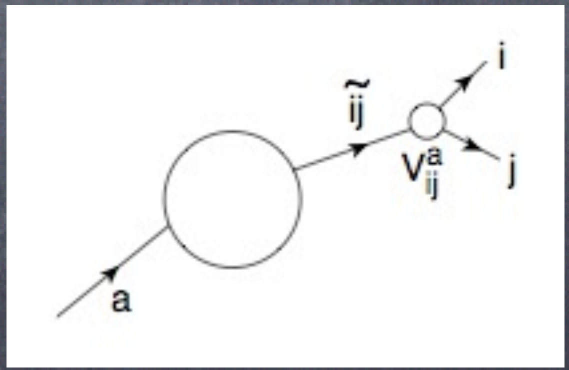

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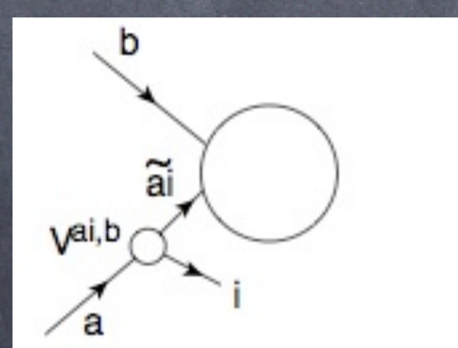

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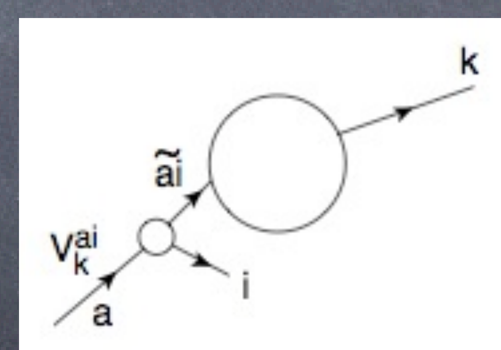

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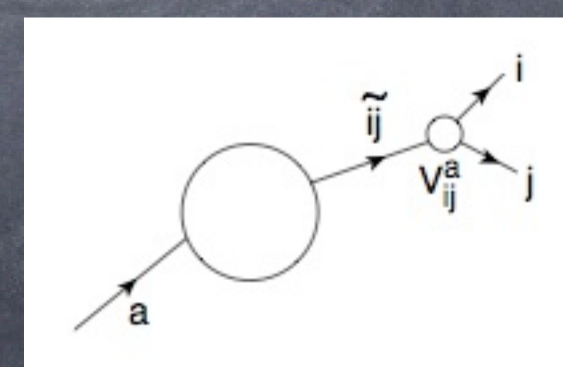

$\Big\}$

- Numerically checked against MadDipole [Gehrmann, Greiner, Frederix `08]

Infrared safety

- Analytical check & finite Terms prop. to Born, e.g.

1 parton PS-integrated Dipoles

$$\left[\mathcal{M}_{\mathrm{B}}^{\bar{q}Q\to g}\otimes\mathbf{I}\right] = -\frac{\alpha_s(\mu_R^2)}{2\pi}\frac{|\mathcal{M}_{Born}^{\bar{q},Q\to g}|^2}{\Gamma(1-\epsilon)}\left[\left(\frac{C_F}{\epsilon^2}+\frac{\gamma_q}{\epsilon}+K_q+\gamma_q-\frac{\pi^2}{3}C_F\right)\right.$$
$$\times\left(\frac{C_A-2C_F}{C_F}\left(\frac{4\pi\mu_R^2}{s}\right)^{\epsilon}-C_A\left(\left(\frac{4\pi\mu_R^2}{-t}\right)^{\epsilon}+\left(\frac{4\pi\mu_R^2}{-u}\right)^{\epsilon}\right)\right)$$
$$\left.-\left(\frac{C_A}{\epsilon^2}+\frac{\gamma_g}{\epsilon}+K_g+\gamma_g-\frac{\pi^2}{3}C_A\right)\left(\left(\frac{4\pi\mu_R^2}{-t}\right)^{\epsilon}+\left(\frac{4\pi\mu_R^2}{-u}\right)^{\epsilon}\right)\right]$$

- Integrated Dipoles cancel divergencies of virtual contributions for IR-safe observables (k_T jets, ...) [Kinoshita `62; Lee, Nauenberg `64]

$$(2\Re\{\mathcal{M}_V\mathcal{M}_B^\star\}-[\mathcal{M}_B\otimes\mathbf{I}])=0+\mathcal{O}(\epsilon^0)\quad\checkmark$$

Infrared safety & isolated photons

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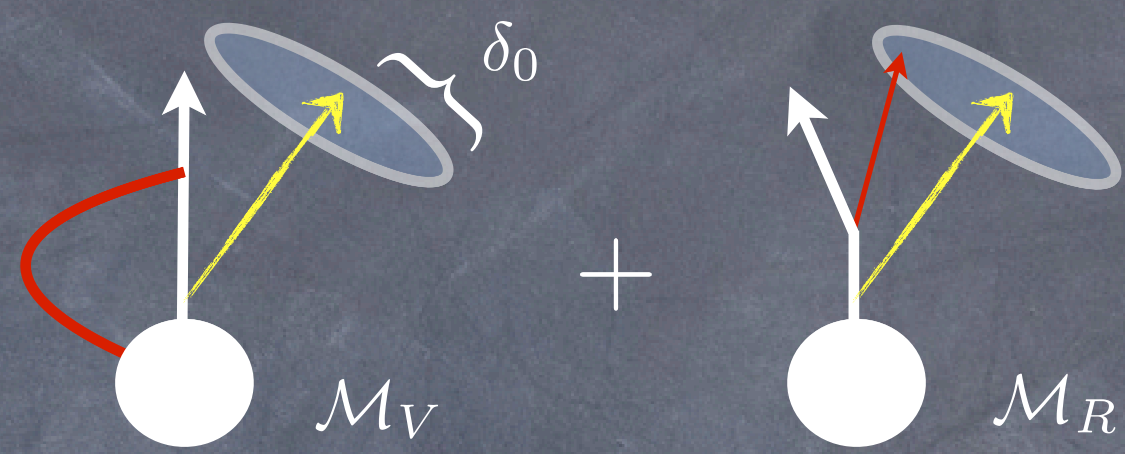
- Avoiding parton fragmentation contributions (q, g, γ collinear) while retaining IR cancellations seemingly contrasts....



vetoing all partons inside the cone spoils IR safety !

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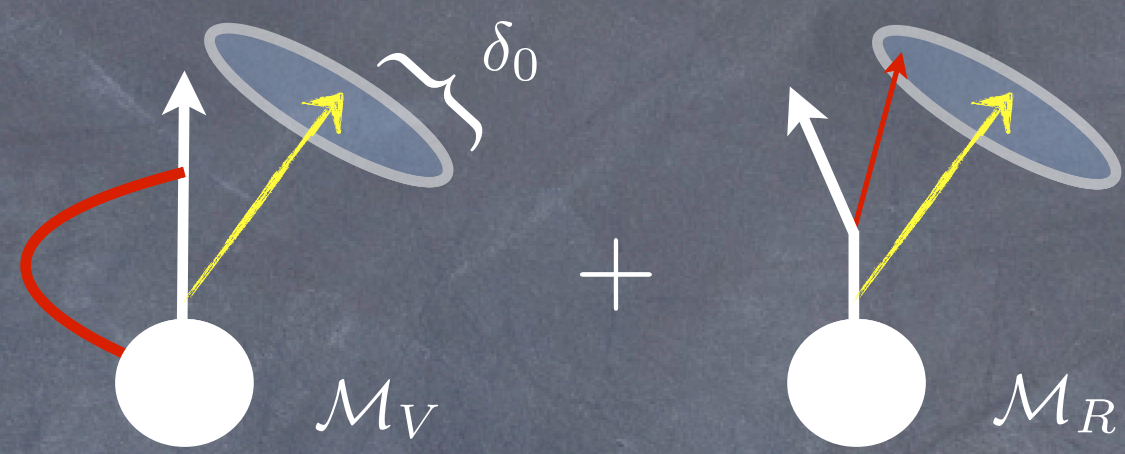

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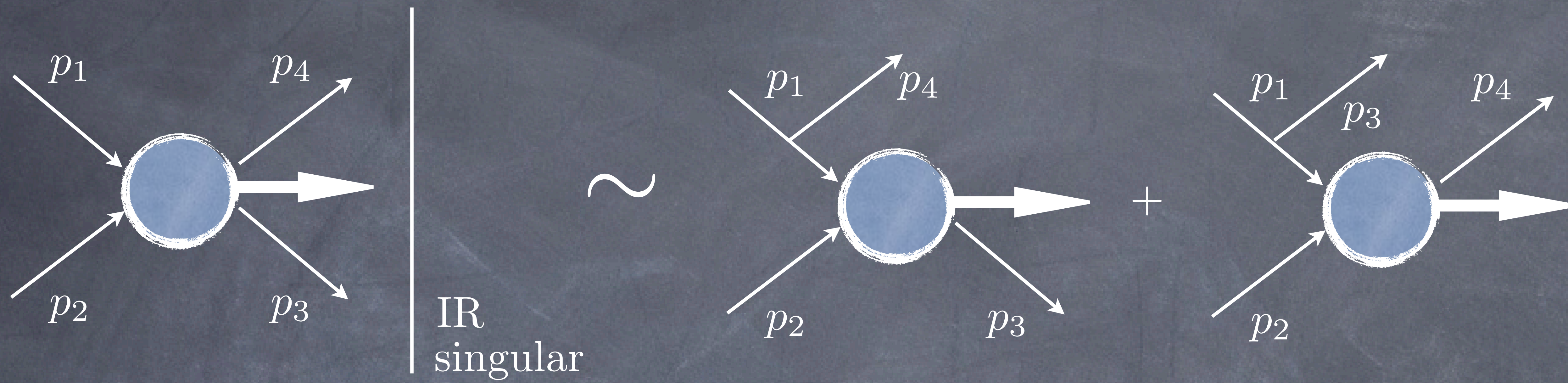
allow soft gluon radiation inside the photon cone to minimize fragmentation contribution: [Frixione `98]

$$\sum_i E_i \theta(\delta - R_{i\gamma}) \leq \kappa(\delta), \ \forall \delta \leq \delta_0 \quad , \quad \lim_{\delta \to 0} \mathcal{K}(\delta) = 0$$

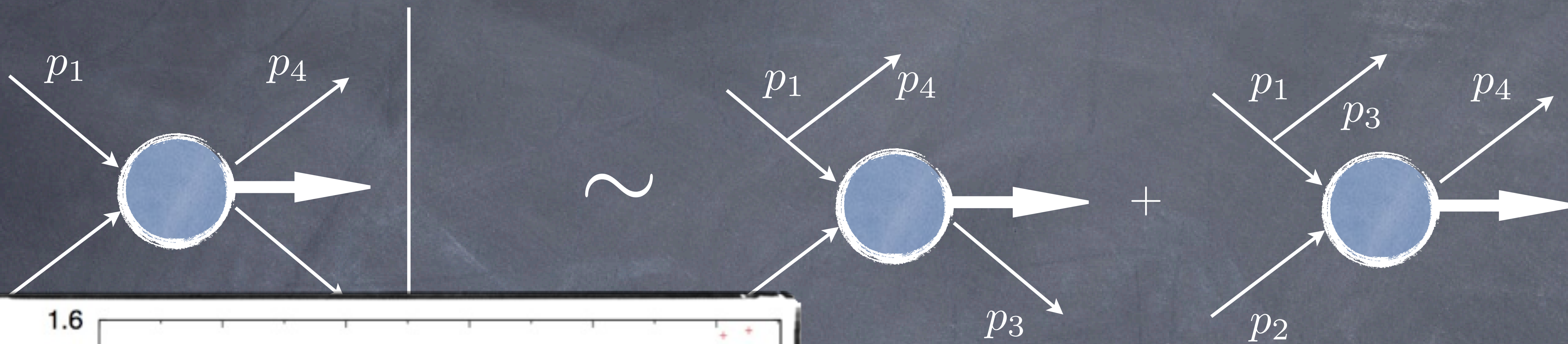
$$R_{i\gamma} = \sqrt{(\eta_i - \eta_\gamma)^2 + (\phi_i - \phi_\gamma)^2}$$

Infrared safety: MC implementation

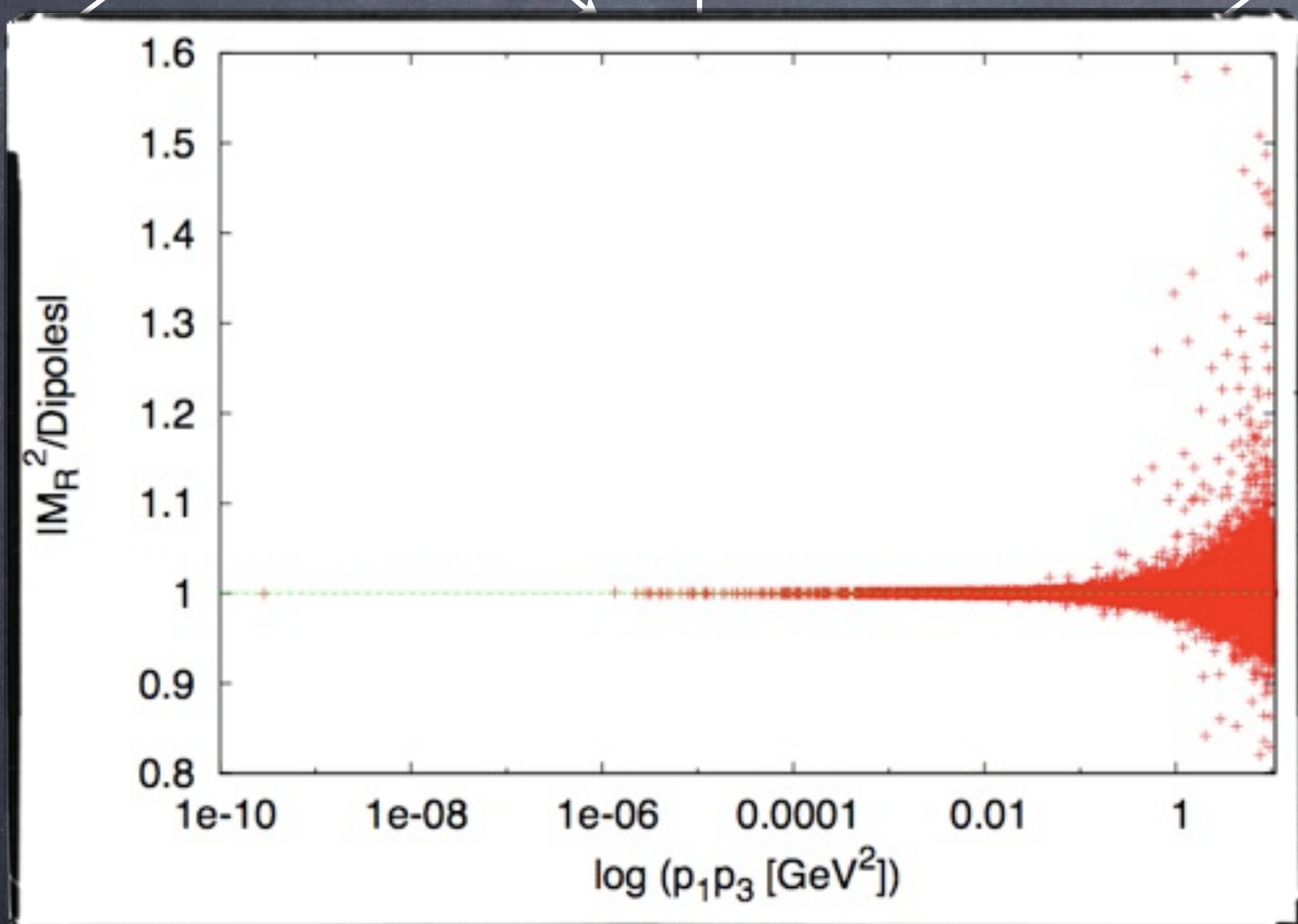


$$+ \quad (p_1 \leftrightarrow p_2) \quad + \quad [p_3, p_4]$$

Infrared safety: MC implementation



$(p_1 \leftrightarrow p_2) \quad + \quad [p_3, p_4]$



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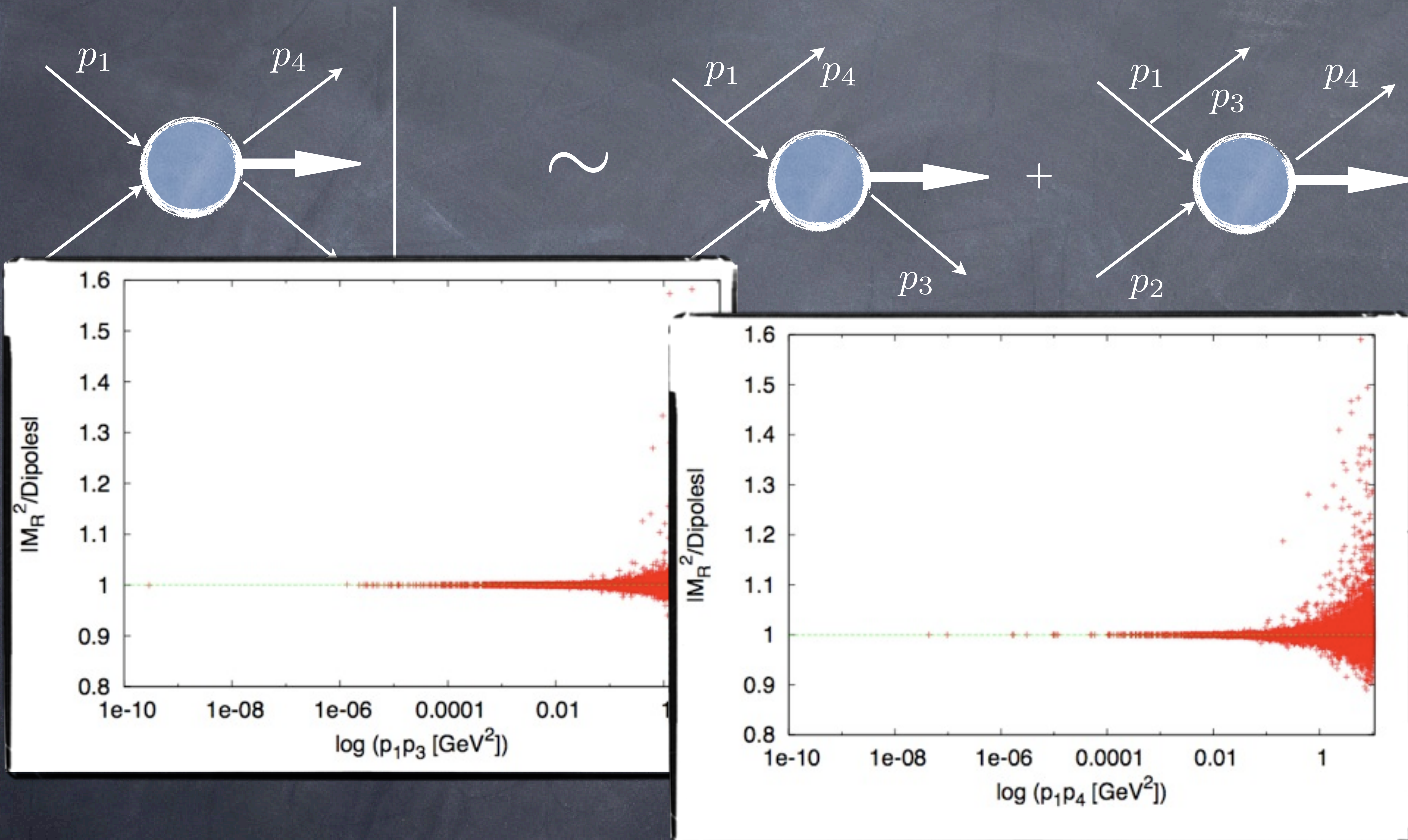

Summary & Outlook

- We have calculated and implemented the NLO-QCD corrections to $pp \to e^- \bar{\nu}_e \gamma j$ into a fully flexible MC program using the vbfnlo framework
- Analytical & numerical checks have been performed along the way (cancellation of IR poles, gauge checks, independent codes using independent approaches, ...)
- The MC is currently running to produce the first full results, more testing mandatory
- Finally start doing physics (NLO veto efficiencies, anomalous couplings....)