HADCALC

A Program for the Calculation of Hadronic Cross Sections

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$\Delta x \Delta p_x \geq \hbar$
Theoretical Physics Division

Making Theoretical Predictions

" It's all about Feynman diagrams."

Recipe for calculating a Feynman diagram up to one loop:

- Create the topologies
- Insert all possible fields according to the model
- Apply the Feynman rules

} FEYNARTS [Küblbeck, Eck, Hahn 1991-2004]

- Contract the indices and calculate traces
- Write FORTRAN program

} FORMCALC [Hahn, Perez-Victoria 1996-2004]

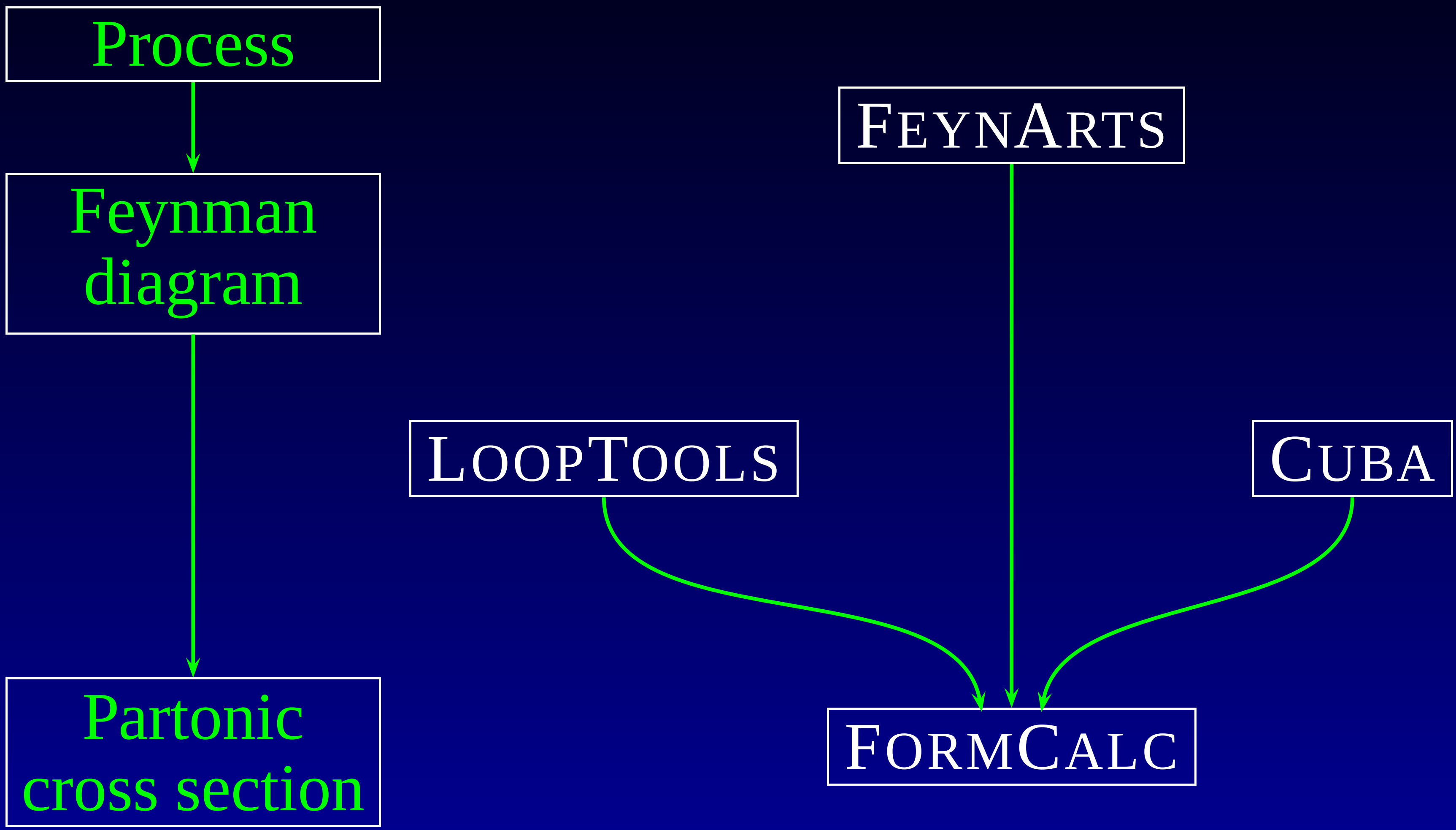
- Implementation of the loop integrals

} LOOPTOOLS [Hahn 1998-2004, FF: van Oldenburgh 1991-2003]

- Numerical phase space integration

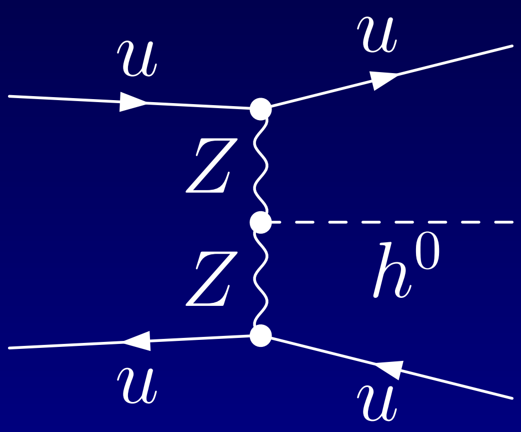
} CUBA [Hahn 2004]

The Programs in Detail



The basic Problem

Feynman rules operate on the quark level and give partonic cross sections



$\longrightarrow \sigma_{\text{partonic}}$

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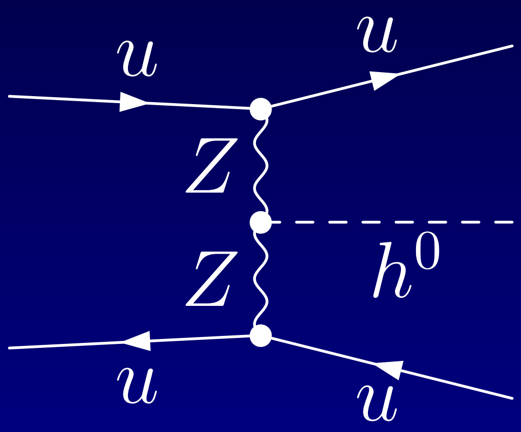
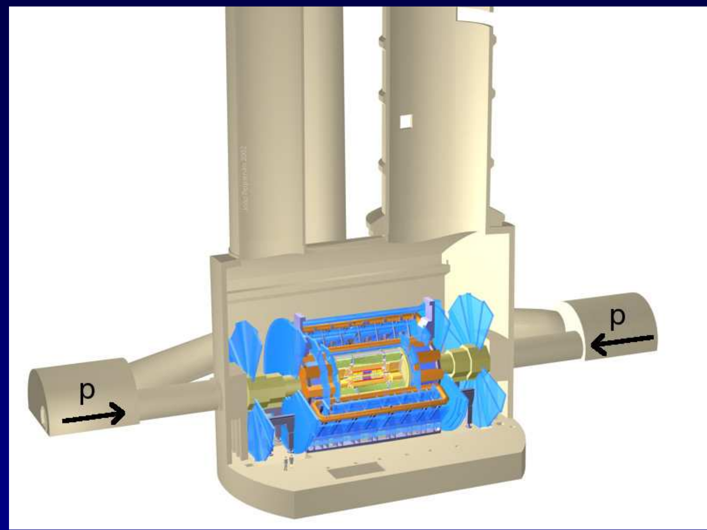


$\longrightarrow \sigma_{\text{partonic}}$

$\longleftrightarrow$

Experiments with hadrons yield hadronic cross sections



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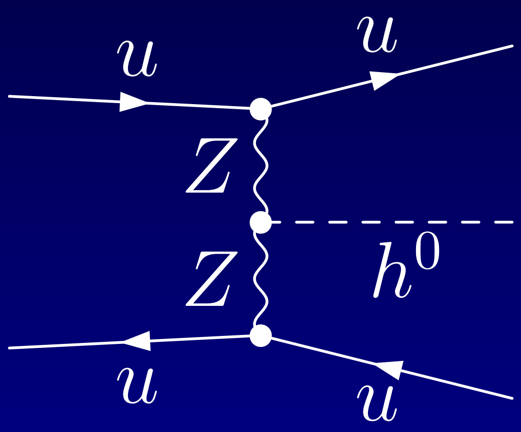

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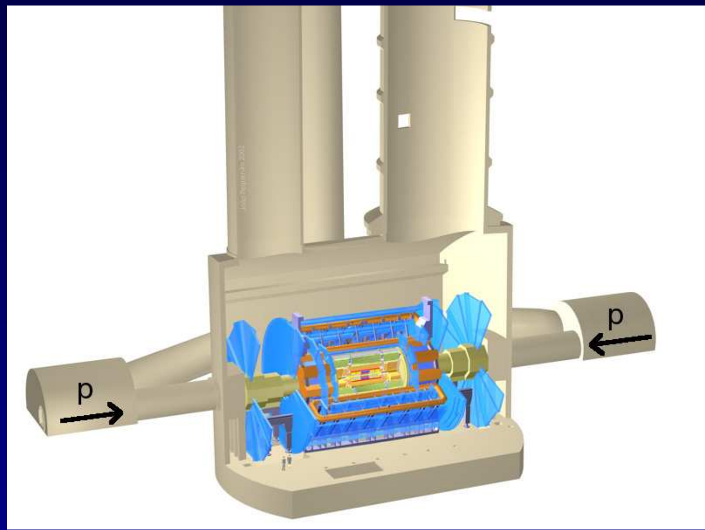


$\longrightarrow \sigma_{\text{partonic}}$

$\longrightarrow \sigma_{\text{hadronic}}$

$\Rightarrow$ Need a procedure to transform the partonic cross sections into hadronic ones.

Transforming Cross Sections

Use the parton model to relate partonic cross sections to hadronic ones:

- Assume that every physically observed hadron consists of partons (quarks and gluons)
- $f_{i/h}$ is the propability of finding parton i with momentum xp ($x \in (0;1)$) in hadron h with momentum p. f is called parton distribution function (PDF)
- Convolute the PDFs with the partonic cross section.

Hadronic Cross Sections

So we arrive at the following expression for an inclusive hadronic cross section at a center of mass energy of protons of $\sqrt{S}$

$$\sigma_{pp\to abc+X} = \sum_{\{m,n\}} \int_{\tau_0}^{1} \mathrm{d}\tau \frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau} \sigma_{mn\to abc}\left(\tau S, \alpha_s(\mu_R)\right)$$

sum over partons

renormalization scale

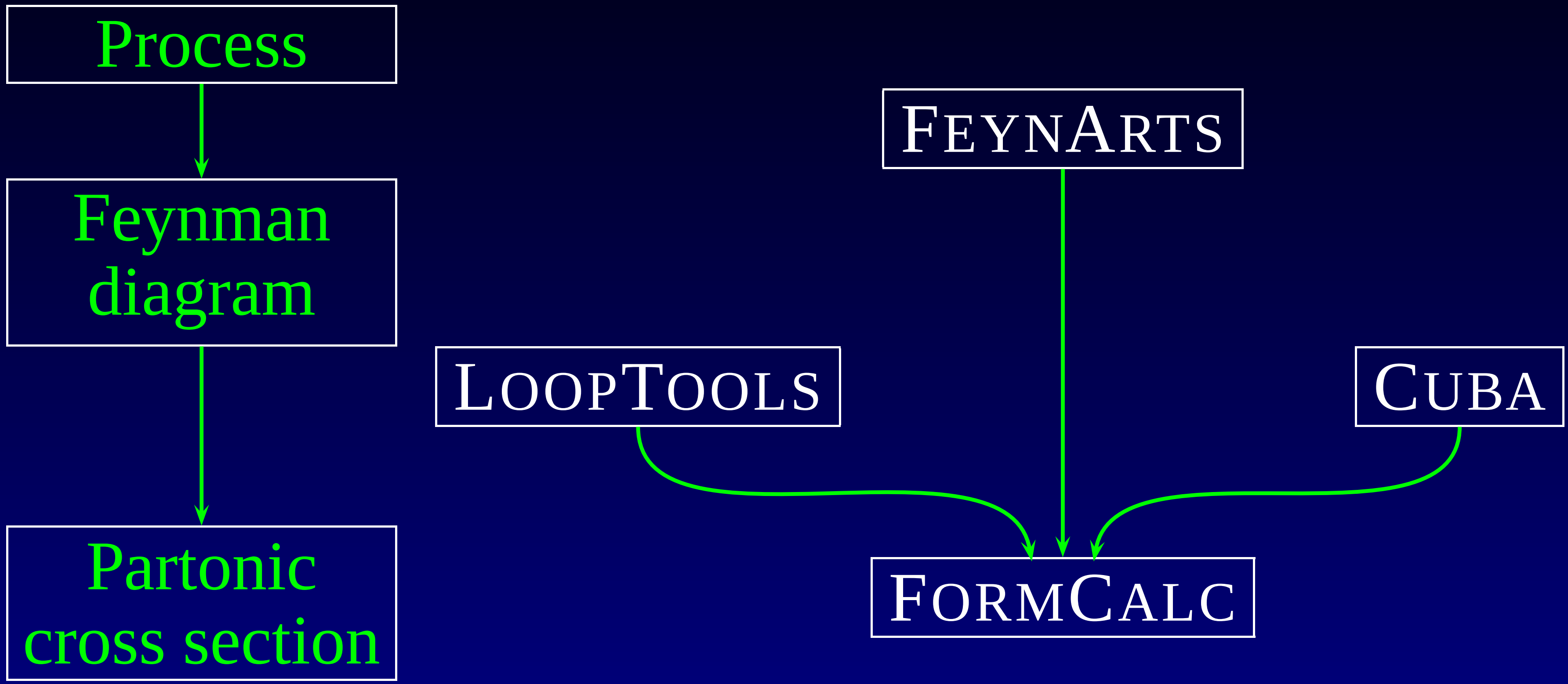
with the parton luminosity

parton density

factorization scale

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau} = \int_{\tau}^{1} \frac{\mathrm{d}x}{x} \frac{1}{1+\delta_{mn}} \Big[f_{m/p}(x,\mu_F) f_{n/p}(\frac{\tau}{x},\mu_F) + f_{n/p}(x,\mu_F) f_{m/p}(\frac{\tau}{x},\mu_F) \Big]$$

Fitting HADCALC into the Picture



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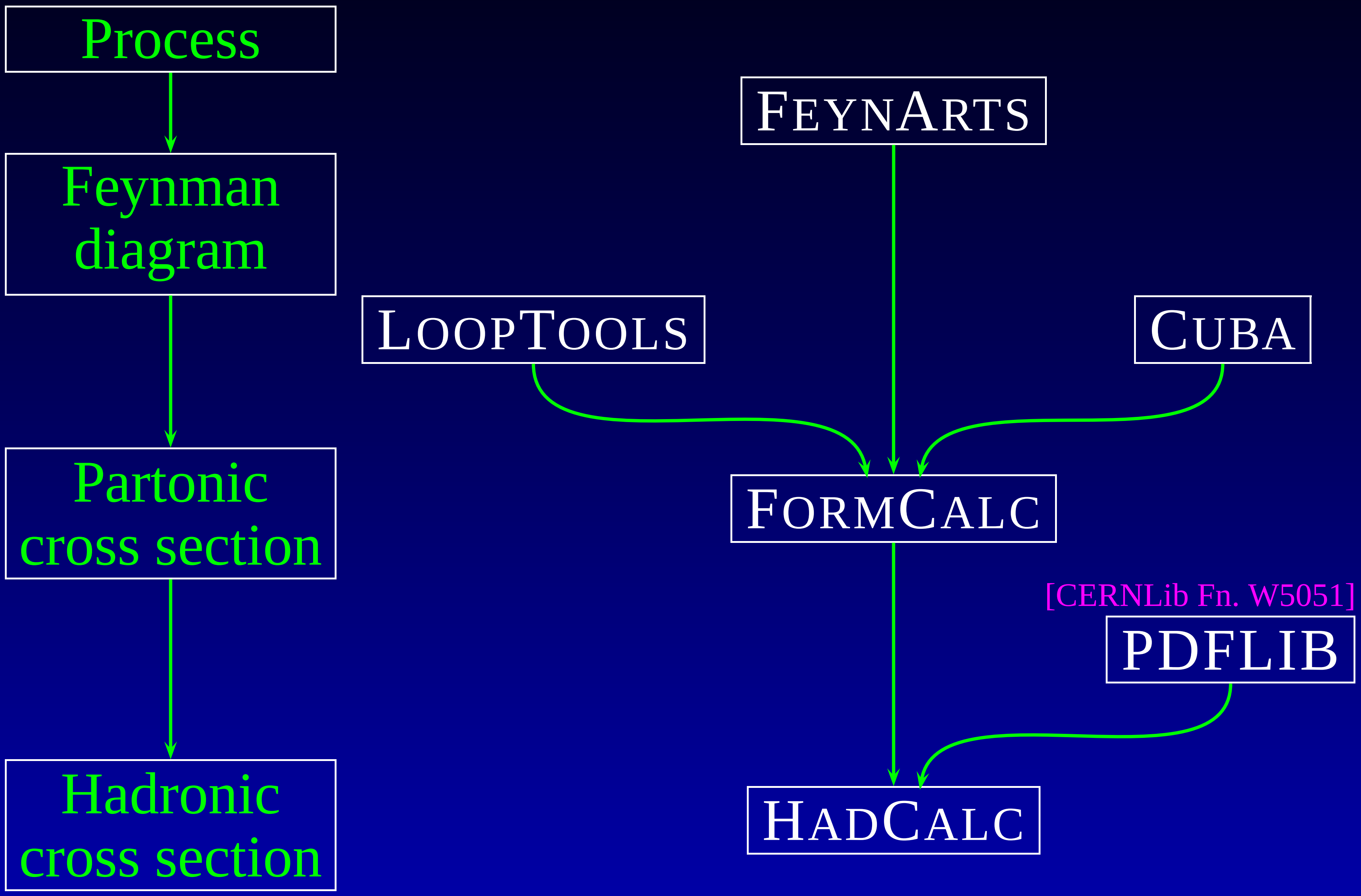

Features of HadCalc

- All possibilities of FormCalc retained:
  - Calculation of differential and integrated partonic $2 \to 2$ and $2 \to 3$ processes
  - SM and MSSM parameters adjustable

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- Two modes:
  - Interactive mode: all parameters adjustable from the console
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- Two modes:
  - Interactive mode: all parameters adjustable from the console
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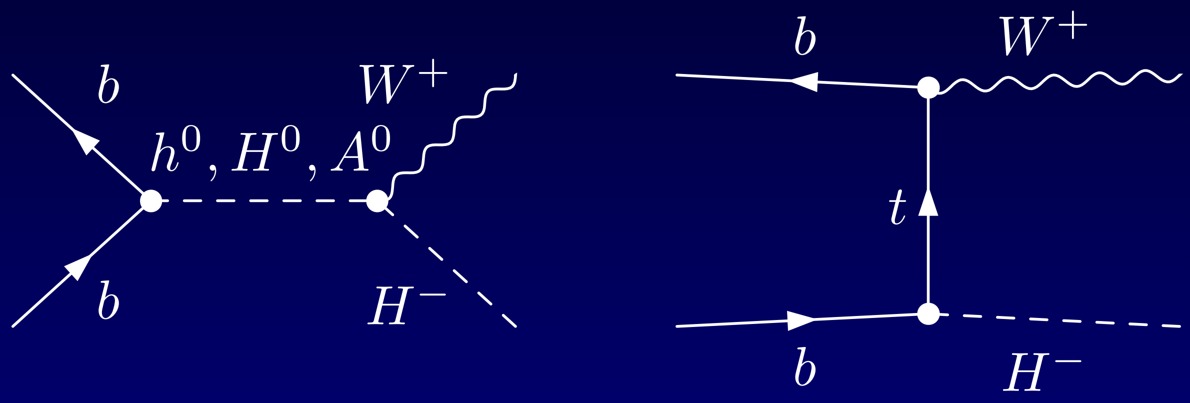
- Diagnostic messages written on screen
- Output written on screen or to file

Example Session

Process: $\bar{b}b \to W^+H^-$ in the framework of the MSSM (Minimal Supersymmetric Standard Model)



Start

But that's not all . . .

- Calculation of integrated hadronic cross sections for $2 \to 1$ processes

  (e.g. Higgs production via gluon fusion)

- Calculation of differential hadronic cross sections

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  - Invariant Mass

$$M_{inv} \equiv \sqrt{\hat{s}} = \sqrt{\tau S} = \sum p_{\text{final state}}$$

(partonic center of mass energy)

But that's not all . . .

- Calculation of integrated hadronic cross sections for $2 \longrightarrow 1$ processes

  (e.g. Higgs production via gluon fusion)

- Calculation of differential hadronic cross sections
  - Invariant Mass
  - Rapidity

$$M_{inv} \equiv \sqrt{\hat{s}} = \sqrt{\tau S} = \sum p_{\text{final state}}$$

$$\eta = \text{artanh}\,\frac{p_z}{E}$$

$$\eta(p_1\vec{e}) + \eta(p_2\vec{e}) = \eta\left(\frac{p_1+p_2}{1+p_1p_2}\right)$$

$$\eta_p = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = \eta(m \longrightarrow 0) \text{ (Pseudo Rapidity)}$$

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- Calculation of integrated hadronic cross sections for $2 \longrightarrow 1$ processes

  (e.g. Higgs production via gluon fusion)

- Calculation of differential hadronic cross sections
  - Invariant Mass
  - Rapidity
  - Transverse Momentum

$$M_{inv} \equiv \sqrt{\hat{s}} = \sqrt{\tau S} = \sum p_{\text{final state}}$$

$$\eta = \text{artanh}\, \frac{p_z}{E}$$

$$p_T = \left|\vec{p} \times \vec{e}_{\text{beam axis}}\right|$$

(momentum perpendicular to the beam axis)

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  - Invariant Mass $M_{inv} \equiv \sqrt{\hat{s}} = \sqrt{\tau S} = \sum p_{\text{final state}}$
  - Rapidity $\eta = \text{artanh}\, \frac{p_z}{E}$
  - Transverse Momentum $p_T = |\vec{p} \times \vec{e}_{\text{beam axis}}|$

(Vector Boson production associated with a jet at the LHC (M. Fürst))

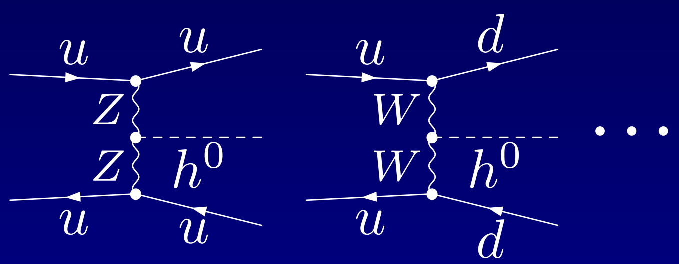
A Second Example

Higgs production via Vector Boson Fusion in the Standard Model

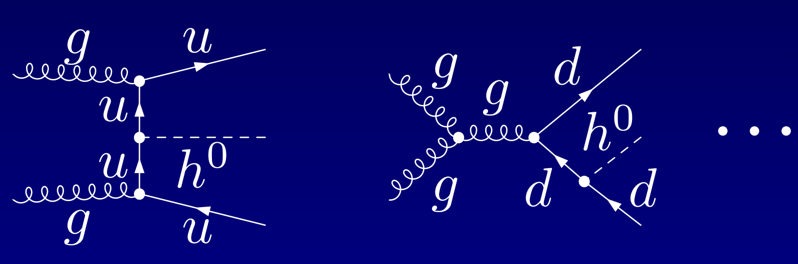
[Berger, Campbell 2004 et al.]

Physical Motivation:
extract $V - V - H$ coupling with $V \in \{W, Z\}$

Signal process:



Background process:



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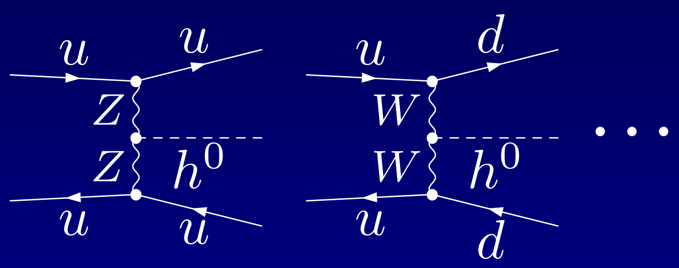

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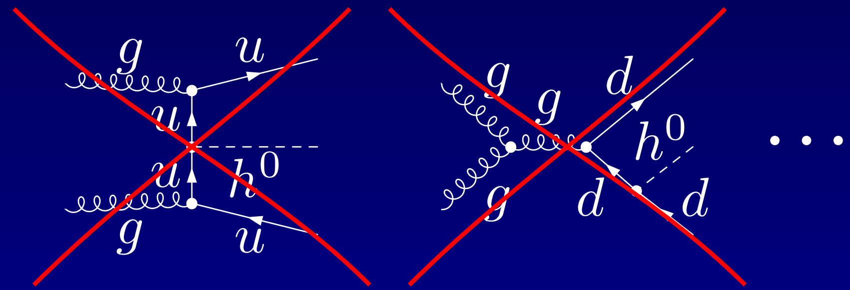

Theory: Select only appropriate diagrams
Experiment: ???

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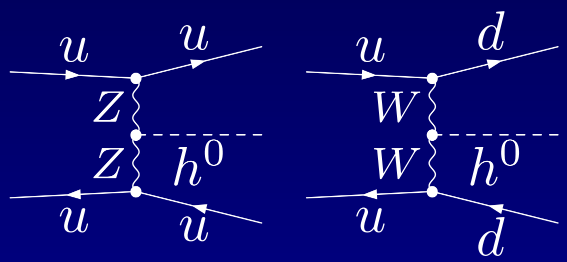

$\ldots$

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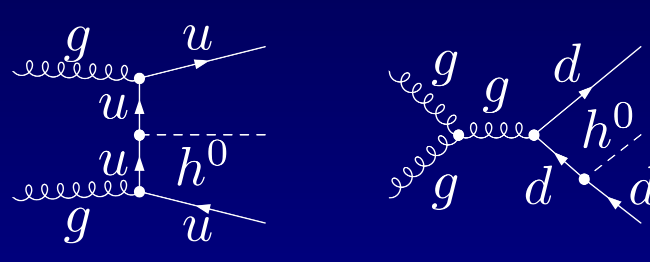


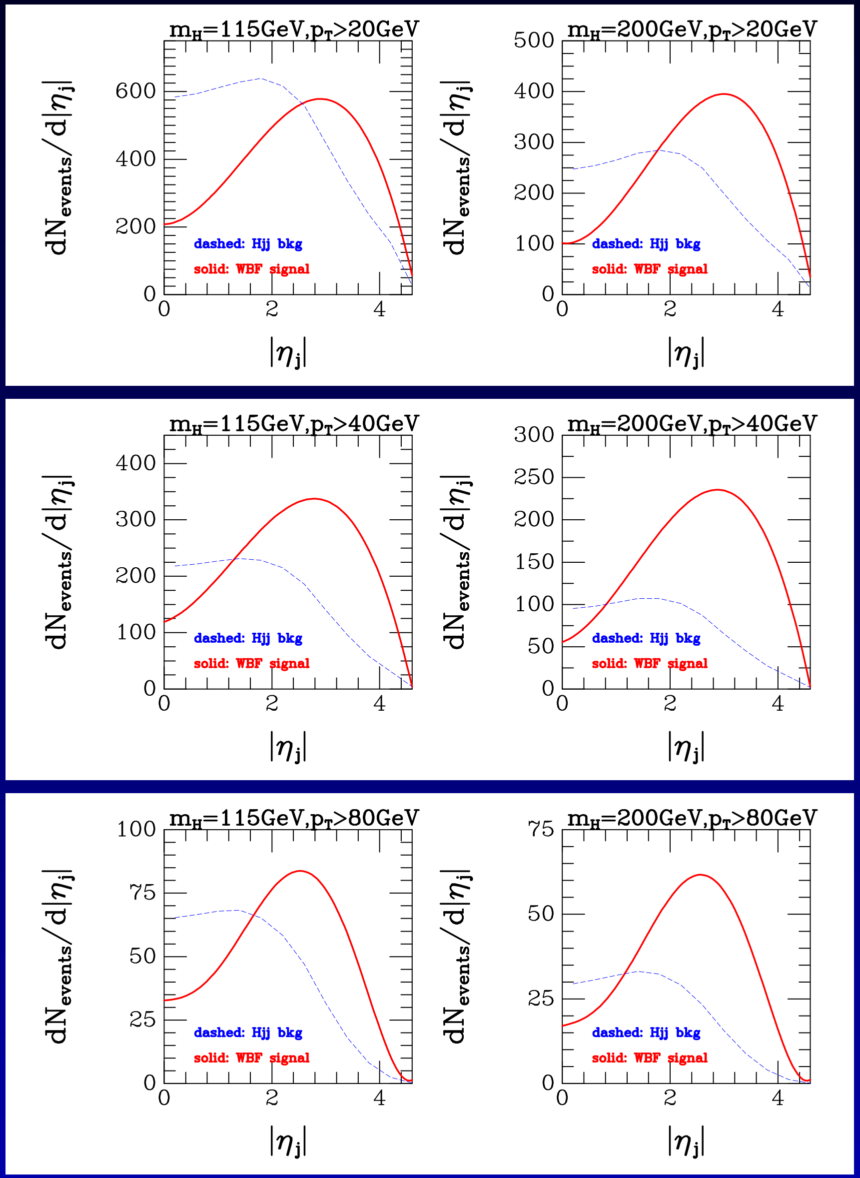
$\ldots$

Experiment: Apply cuts

Improve Purity $\left(\equiv \frac{\text{Signal}}{\text{Signal}+\text{Background}}\right)$

Improved Purity by Cuts

[Berger, Campbell 2004]



$p_T = 20$ GeV

$p_T = 40$ GeV

$p_T = 80$ GeV

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- Transverse Momentum $p_{T\,i}$

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- Jet separation ΔR_{ij}

$$\Delta R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}$$

$\Delta\phi_{ij}$: difference in the azimuthal angles of the two jets in the transverse plane

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Switch whether cut is fulfilled or violated separately adjustable for each cut

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Cut on one particle is translated into shift on integration bounds
$\Rightarrow$ Efficient numerical integration

Conclusions & Outlook

- For calculation of partonic cross section excellent tools available
- Missing part for hadronic cross sections implemented in HadCalc
- For calculation of
  - differential and integrated
  - partonic and hadronic

  cross sections of FormCalc-generated processes
  - with the possibility of applying cuts
- Still work in progress (but physics part complete)
- If interested in beta version, contact me:
  Room 337, `mrauch@mppmu.mpg.de`