Maximizing Experimental precision

Olivier Mattelaer
Université Catholique de Louvain
CP3-FNRS

Based on:

- P.Artoisenet, V.Lemaître, F. Maltoni, OM: JHEP 1012:068
- J. Alwall, A. Freytas, OM: PRD83:074010
- P.D. Aquino, P.Artoisenet, F. Maltoni, OM : PRL111,091802
- P.Artoisenet, OM: In preparation

From Theory to Detector

Lagrangian

Detector events

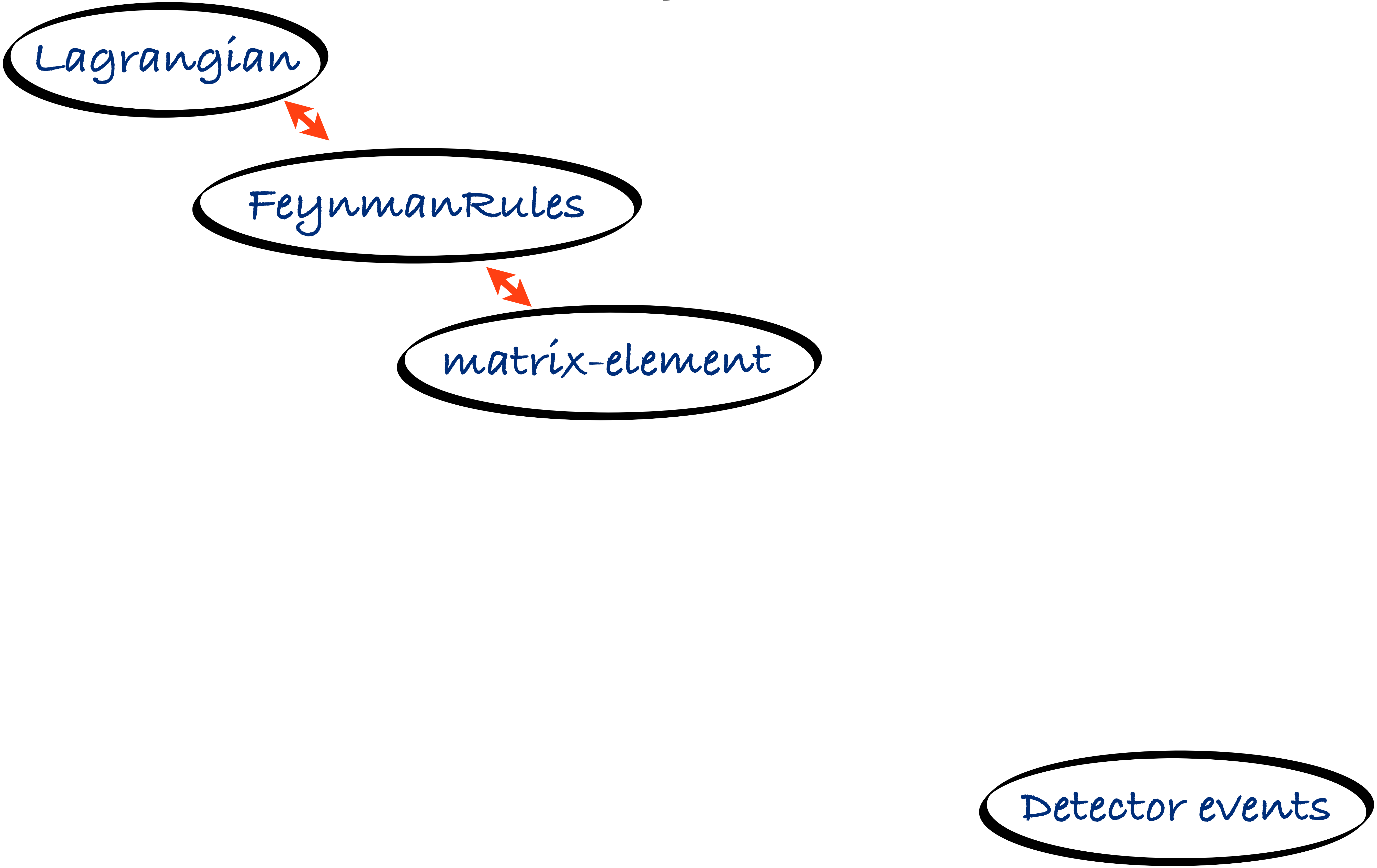
From Theory to Detector

Lagrangian

FeynmanRules

Detector events

From Theory to Detector



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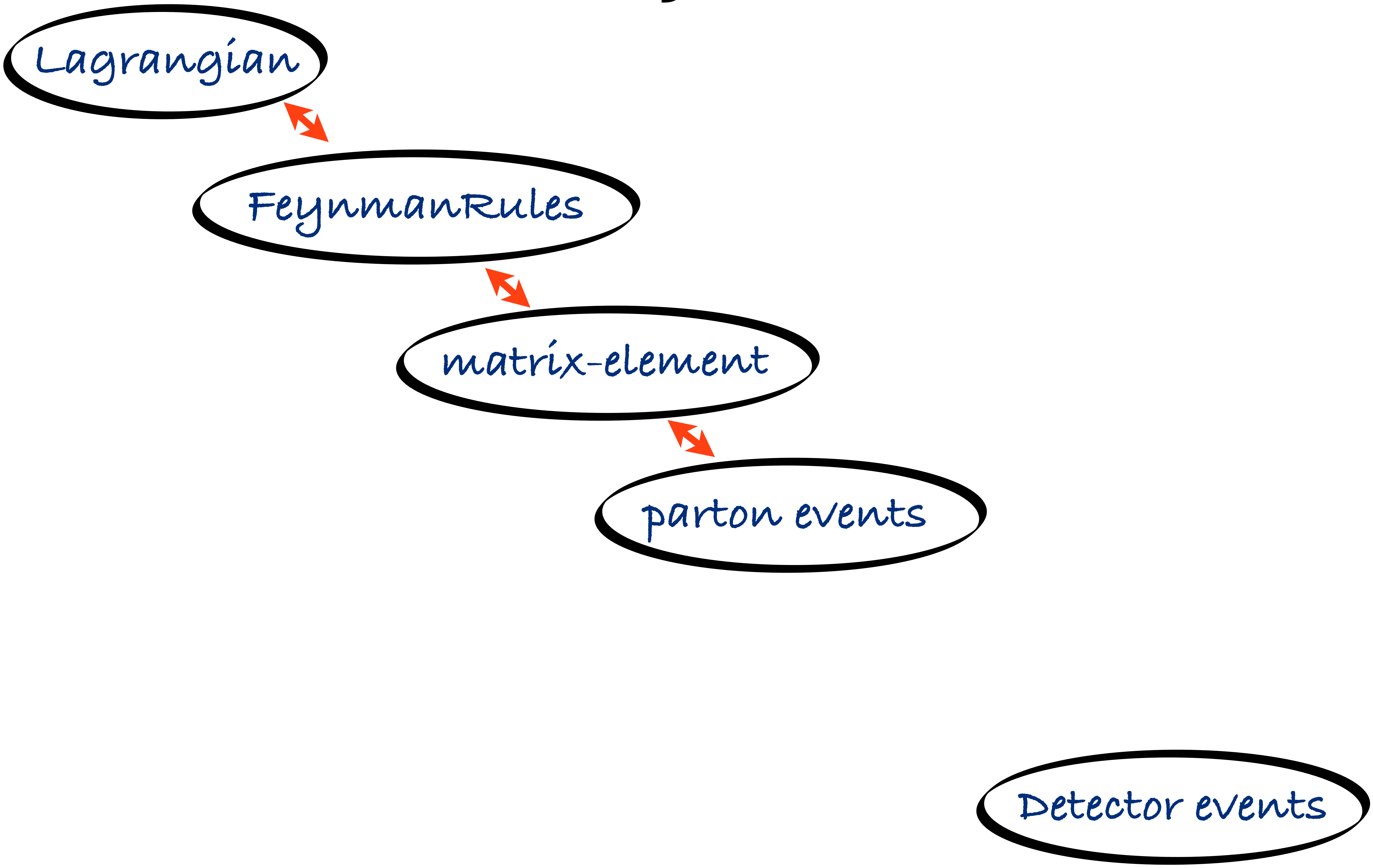

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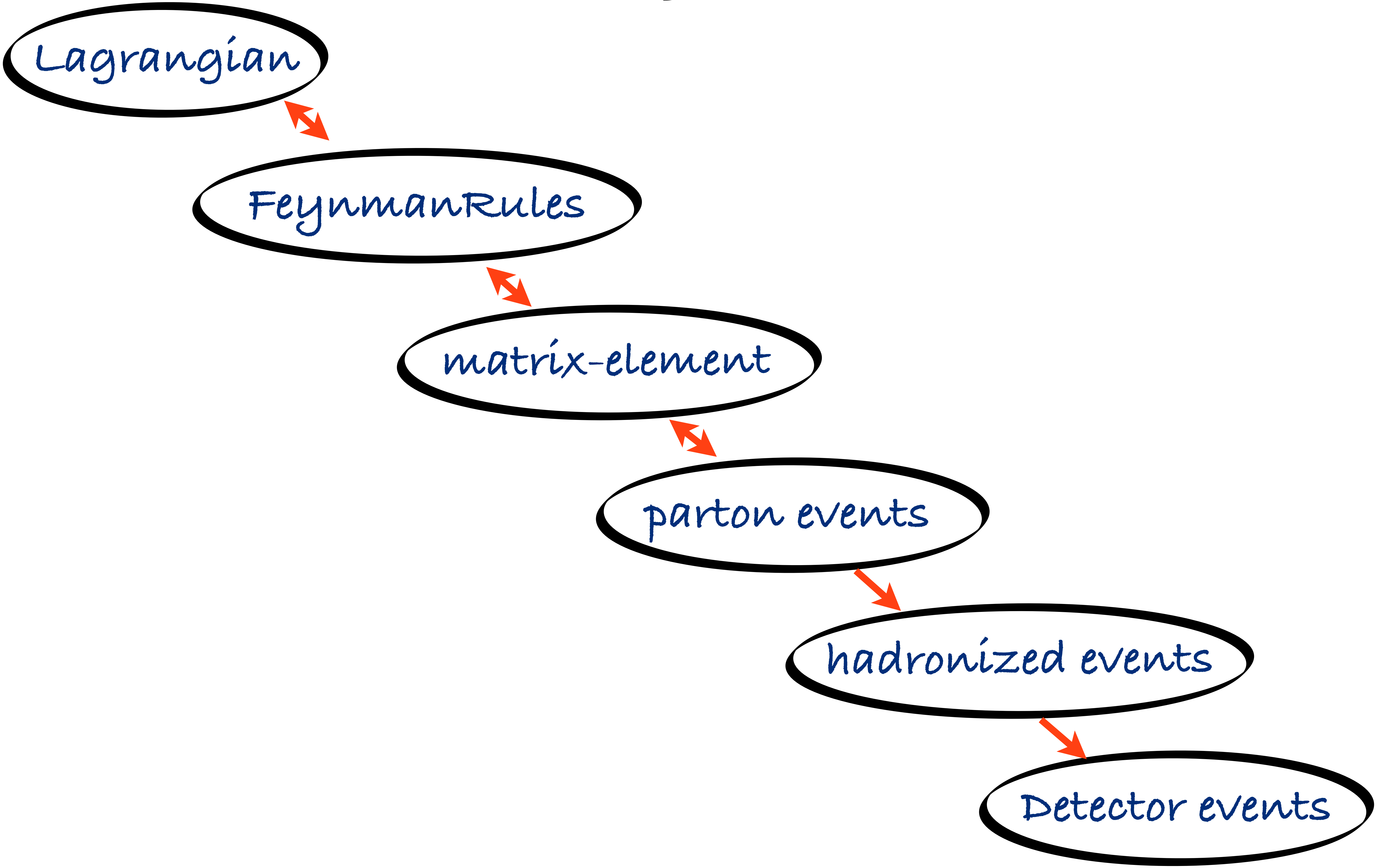

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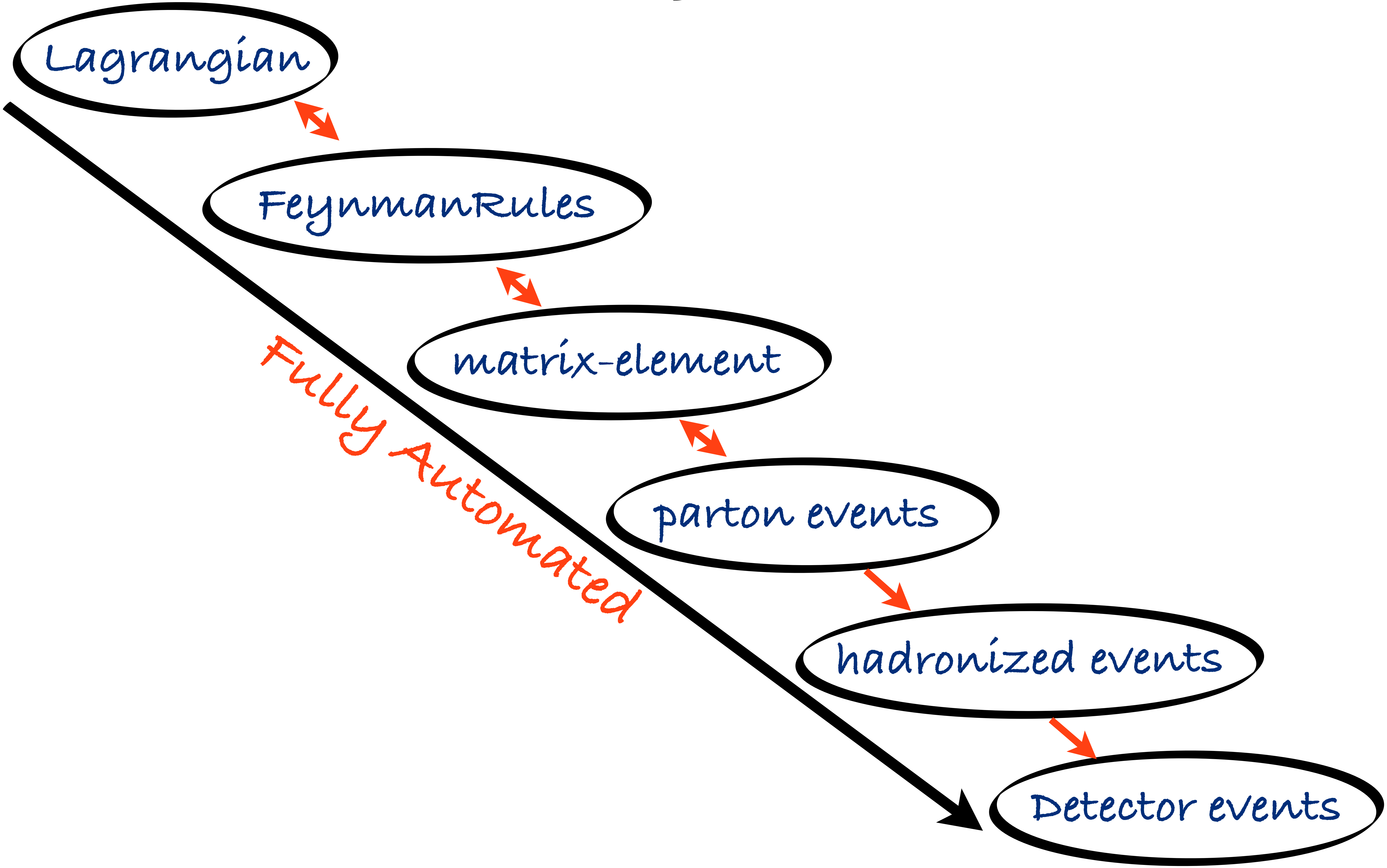

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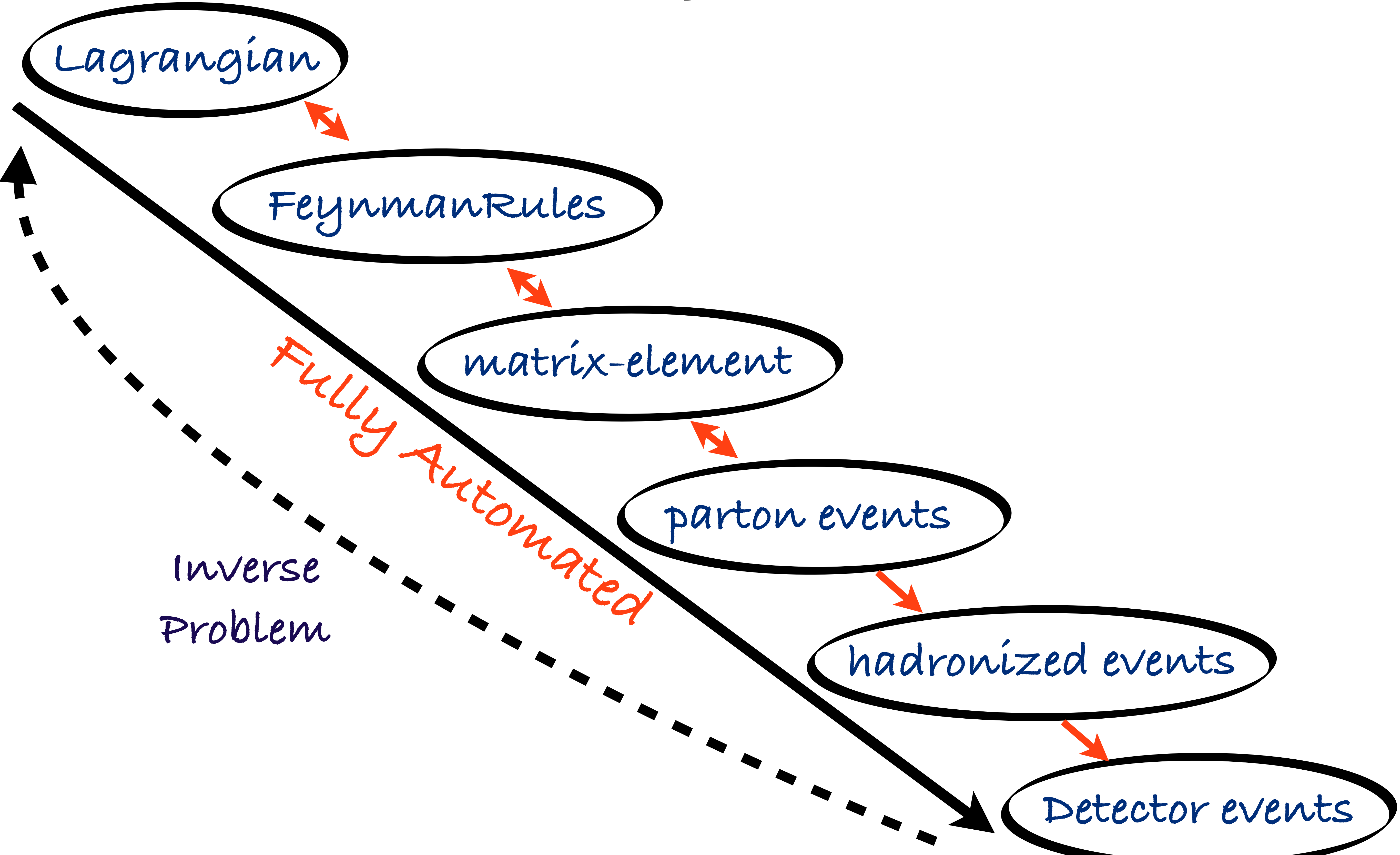
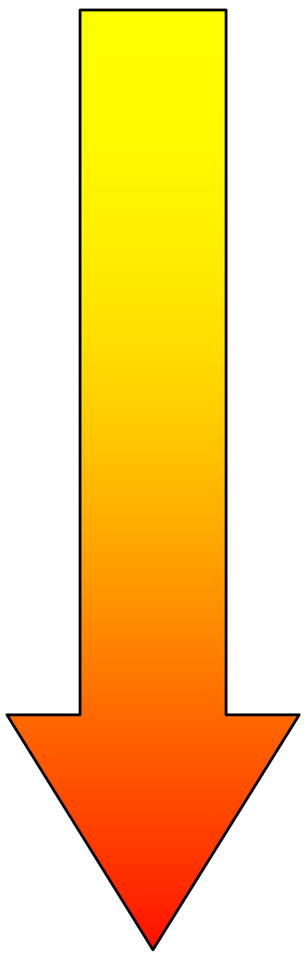


Types of Technique

Few

assumptions



Many

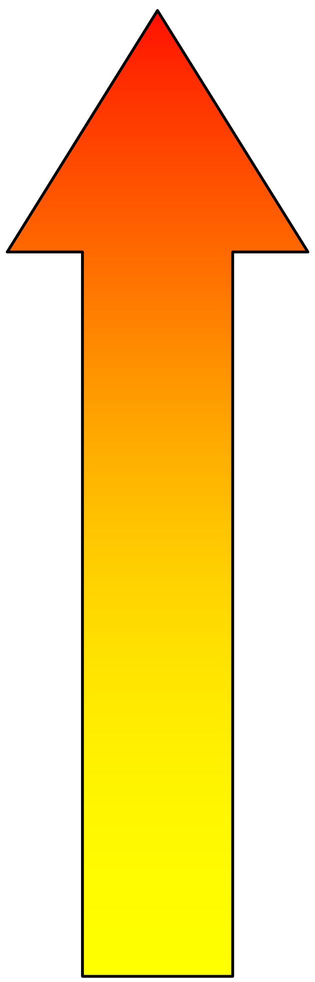
assumptions

- Missing transverse momentum
- M_eff, H_T
- s Hat Min
- M_T
- M_TGEN
- M_T2 / M_CT
- M_T2 (with “kinks”)
- M_T2 / M_CT (parallel / perp)
- M_T2 / M_CT (“sub-system”)
- “Polynomial” constraints
- Multi-event polynomial constraints
- Whole dataset variables
- Cross section
- Max Likelihood / Matrix Element

Slide from Lester: arXiv:1004.2732

Types of Technique

Robust



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Types of Technique

Vague

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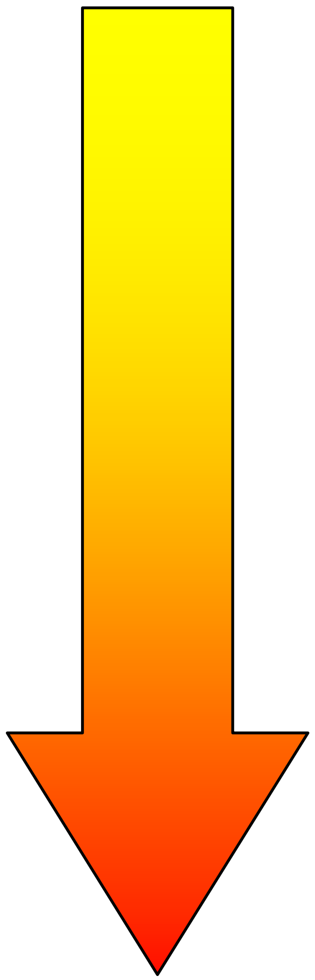

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Outline

- Introduction to Matrix Element re-weighting
- Automation of the method: MadWeight
- Presence of Radiation
- TTH Analysis
- Conclusions

Matrix Element weight

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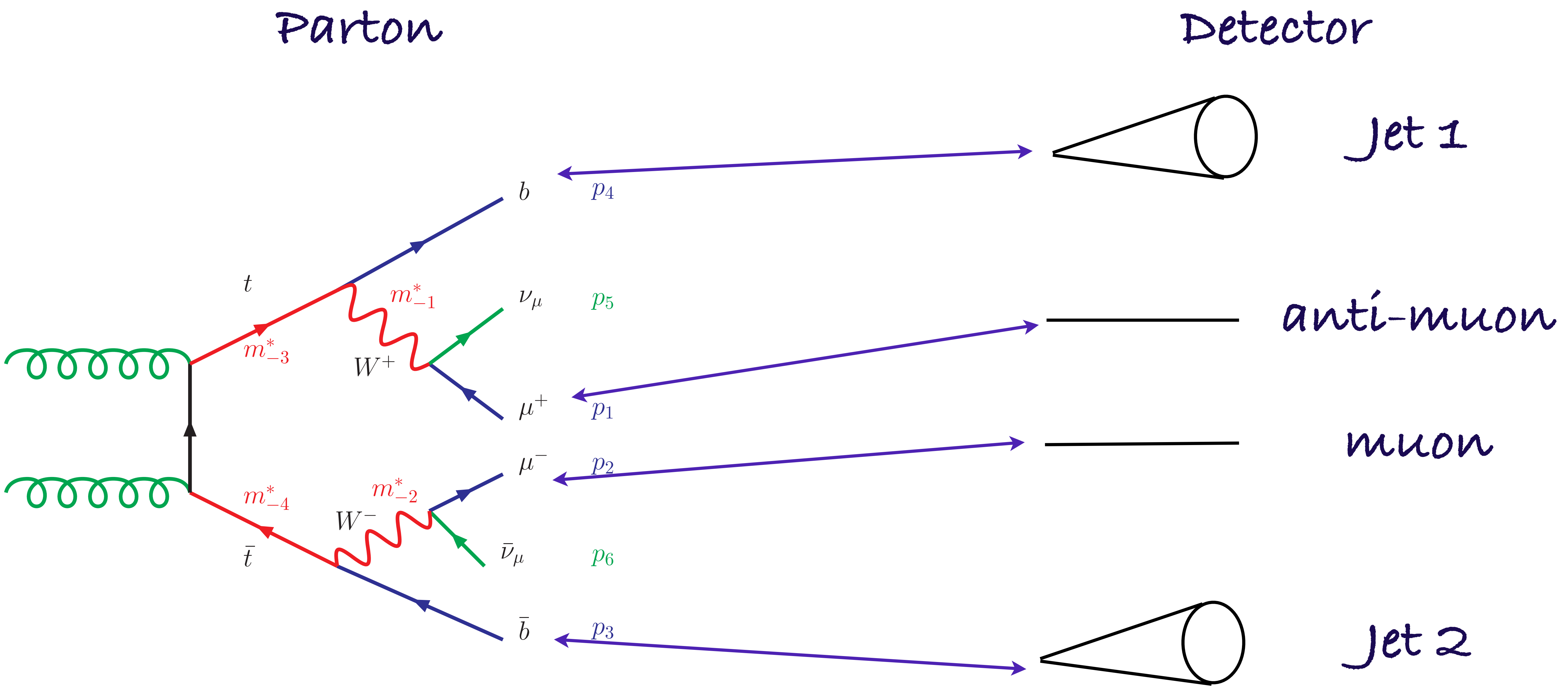
  - σ_α^{vis} is the cross-section (after cuts)



Parton
Detector
Jet 1
anti-muon
muon
Jet 2
b
p_4
t
m^*_{-1}
ν_μ
p_5
m^*_{-3}
W^+
μ^+
p_1
μ^-
p_2
m^*_{-4}
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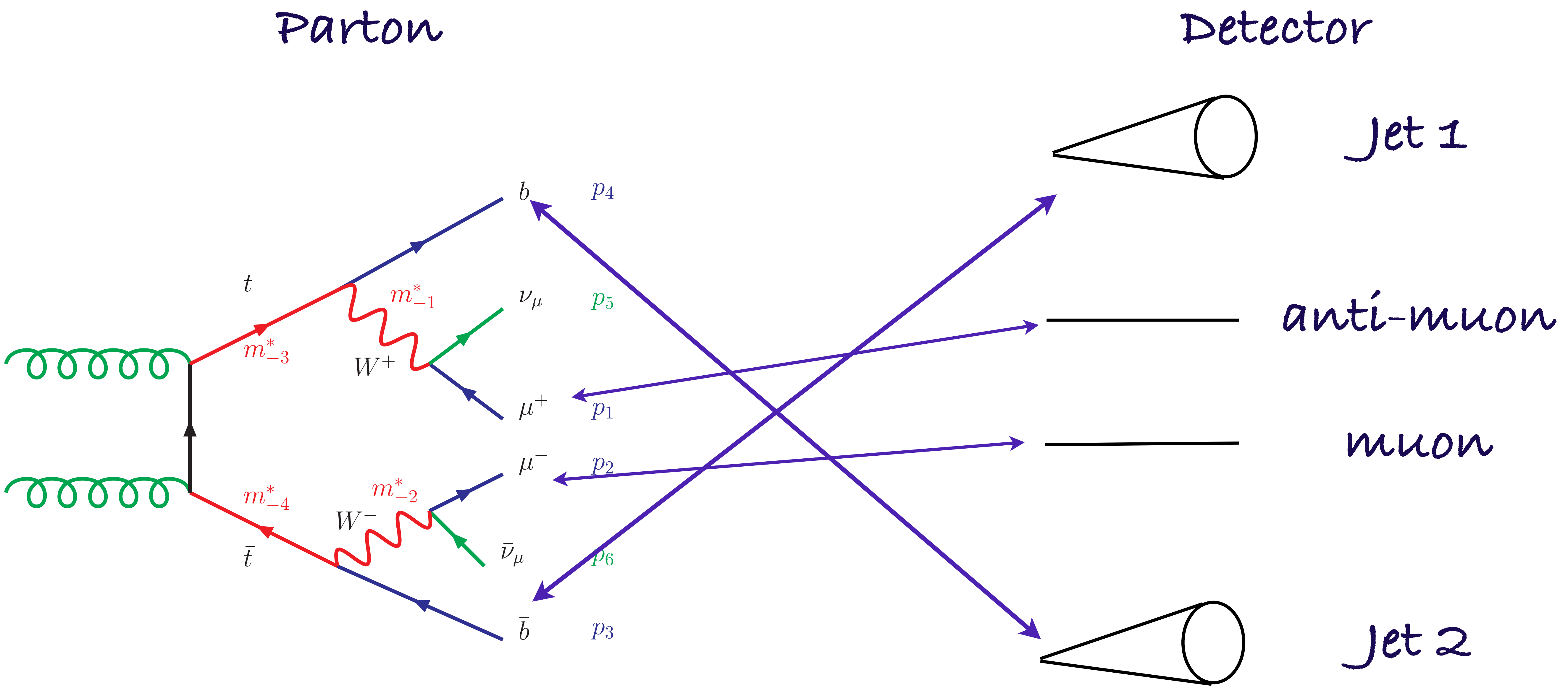
W^-
$\bar{t}$
$\bar{\nu}_\mu$
p_6
$\bar{b}$
p_3


Parton
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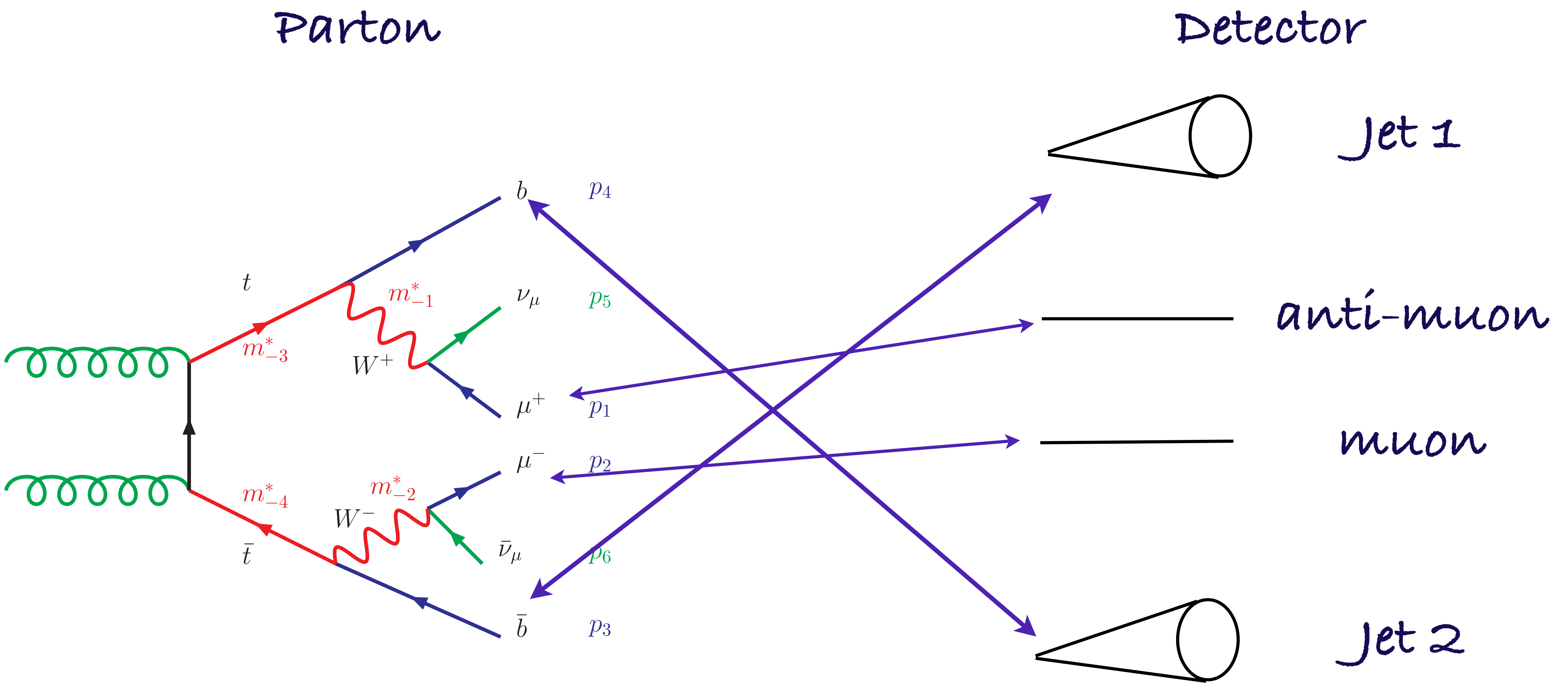

- Need to sum over the jet/parton assignments.

Matrix Element Method

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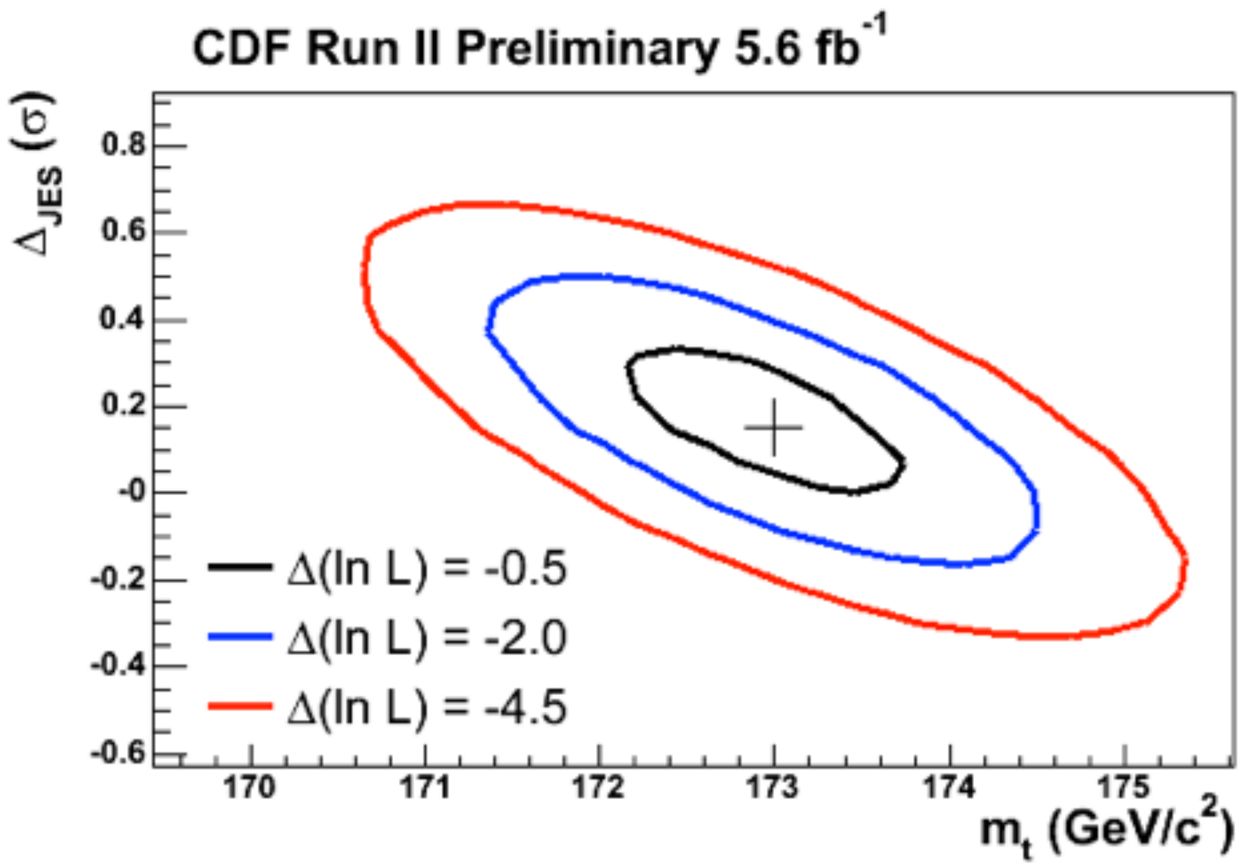

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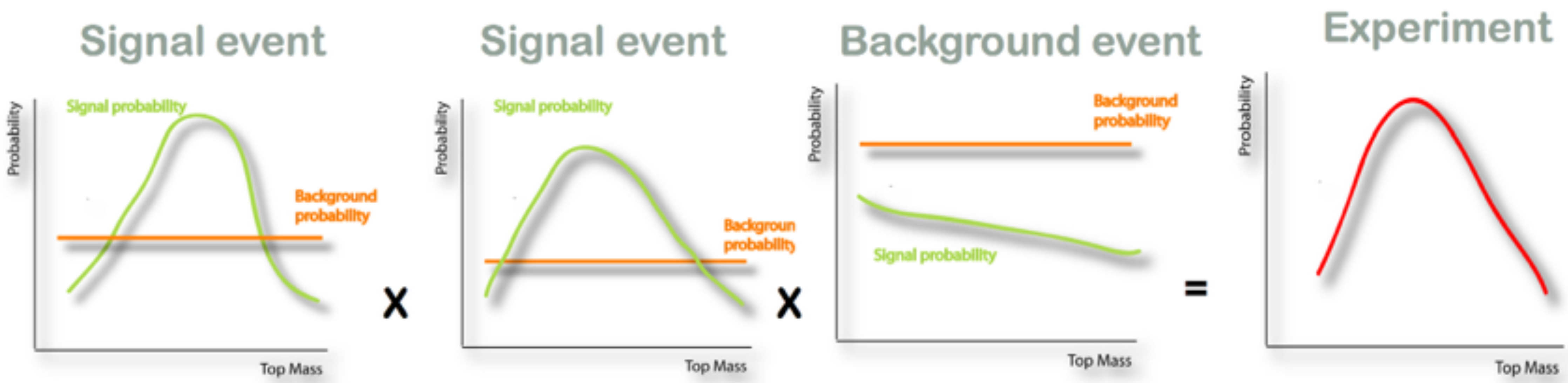
Semi-leptonic decay

$$m_{top} = 173.0 \pm 1.2\text{GeV}$$

Signal/Background

- Fraction of Signal/Event extracted at the same time:

$$P(p^{vis}|\alpha) = c_S P_S(p^{vis}|\alpha) + c_B P_B(p^{vis})$$



- Single Template Analysis:

$$d(p^{vis}) = \frac{P_{Signal}}{(P_{Signal} + P_{Background})}$$

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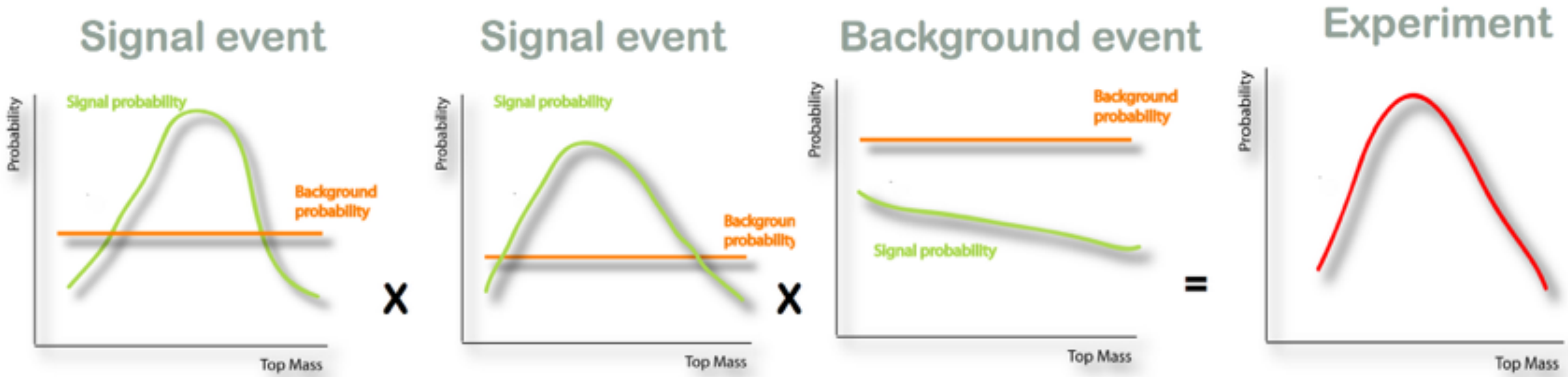

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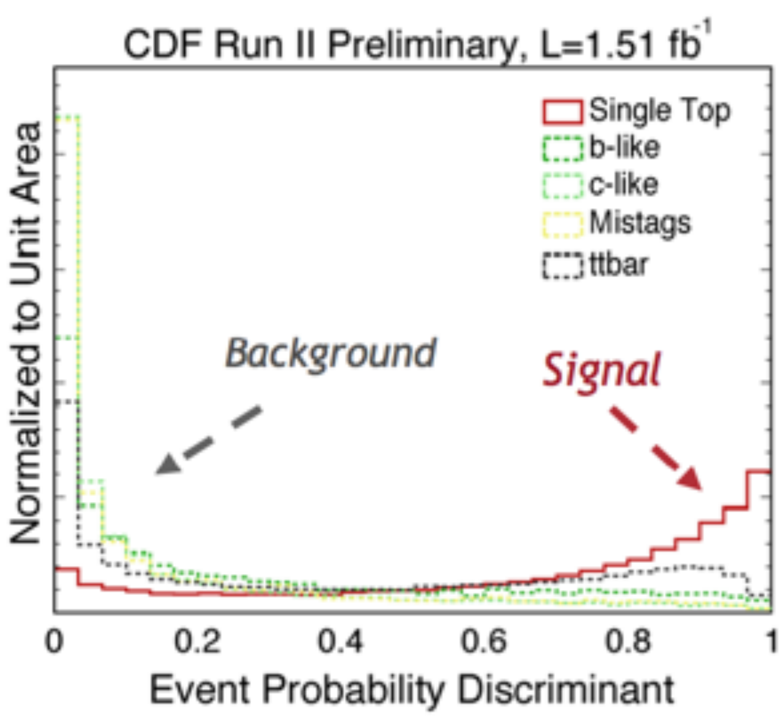

Matrix Element weight

How to evaluate those weights?

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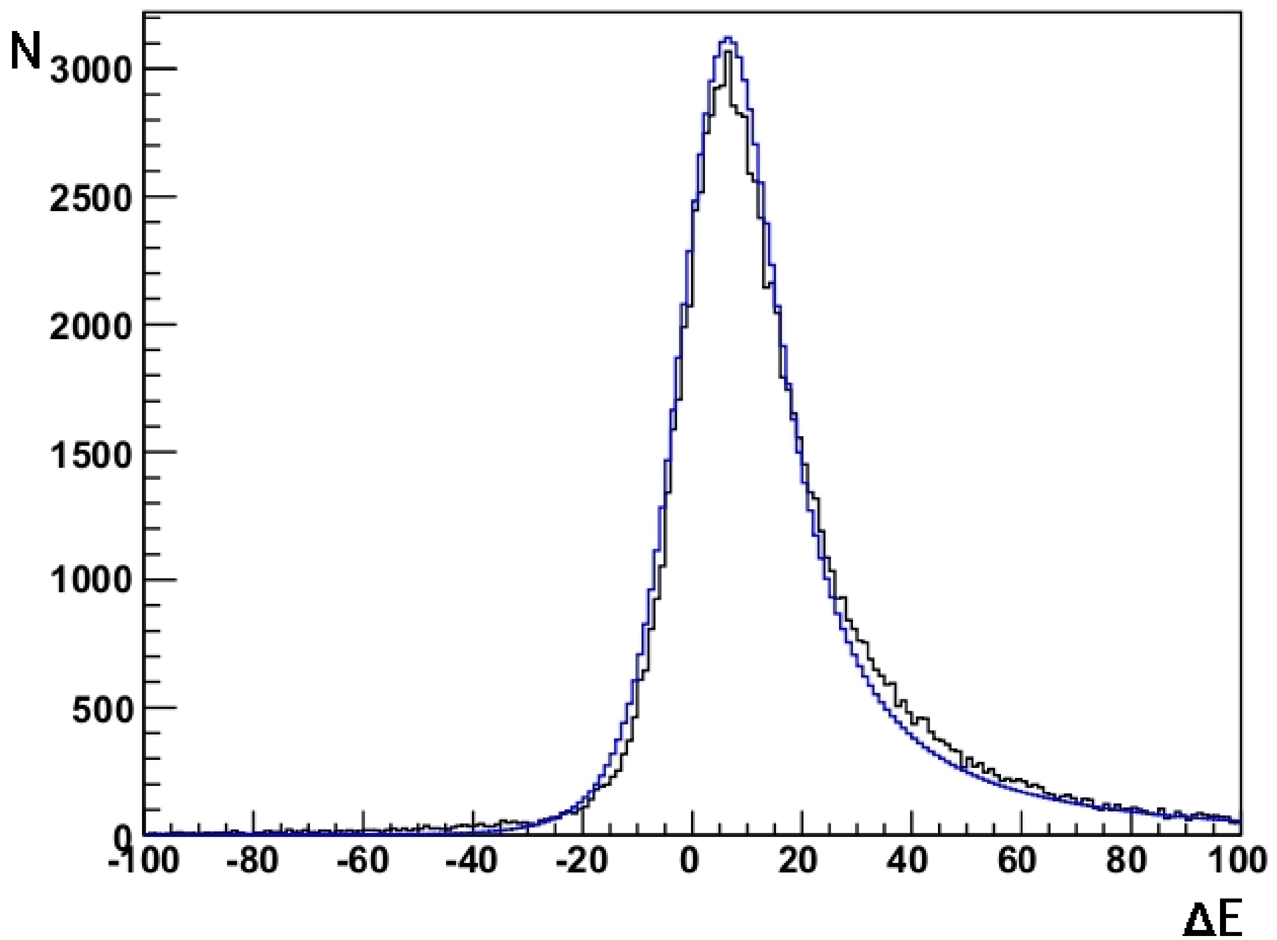

- Each partonic particles has it's own Transfer functions

$$W(\boldsymbol{x},\boldsymbol{y}) \approx \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{(x_i-y_i)^2}{2\sigma_i^2}}$$

- Forbids any additional jets and therefore NLO.

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[J.Alwall,M. Herquet,F.Maltoni,OM,T. Stelzer 1106.0522]

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- Fit from MC tuned to the detector resolution
- Use of matrix-element generator: MadGraph5
- Need a specific integrator: MadWeight

[P.Artoisenet, V. Lemaitre, F.Maltoni, OM: 1007.3300]

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Difficult point: Numerical Integration

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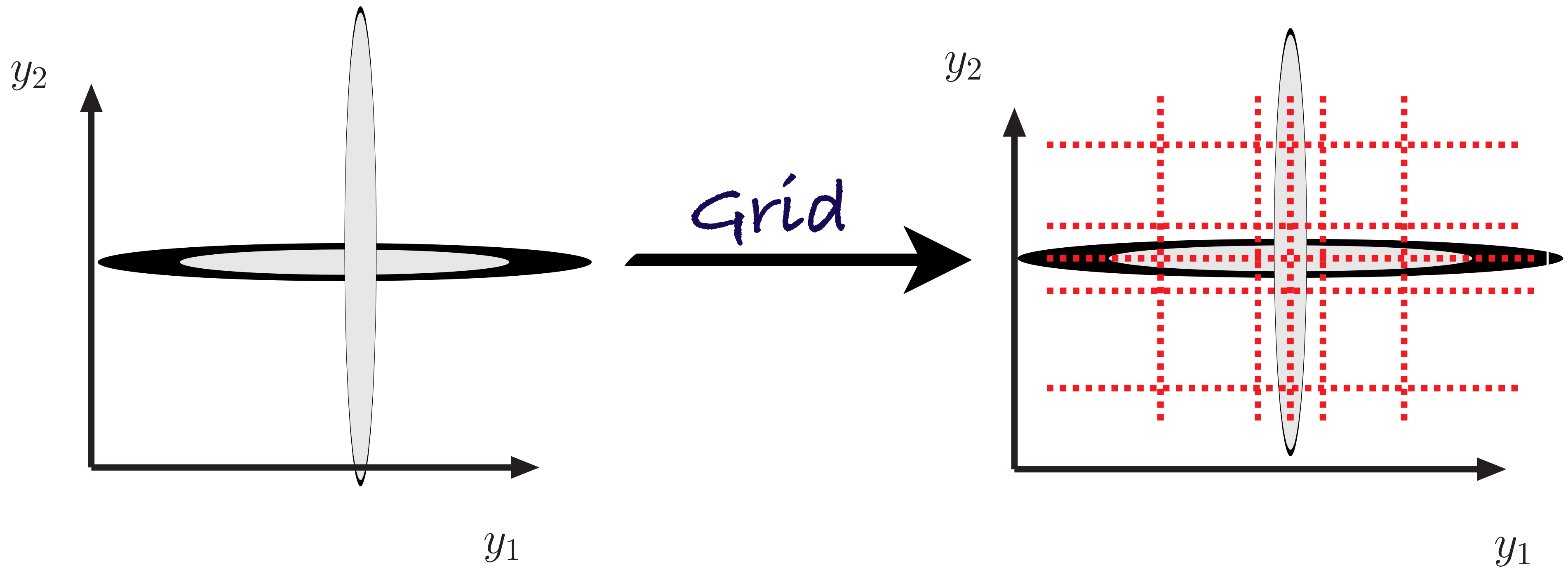
Monte-Carlo Integration

- The choice of the parameterisation has a strong impact on the efficiency



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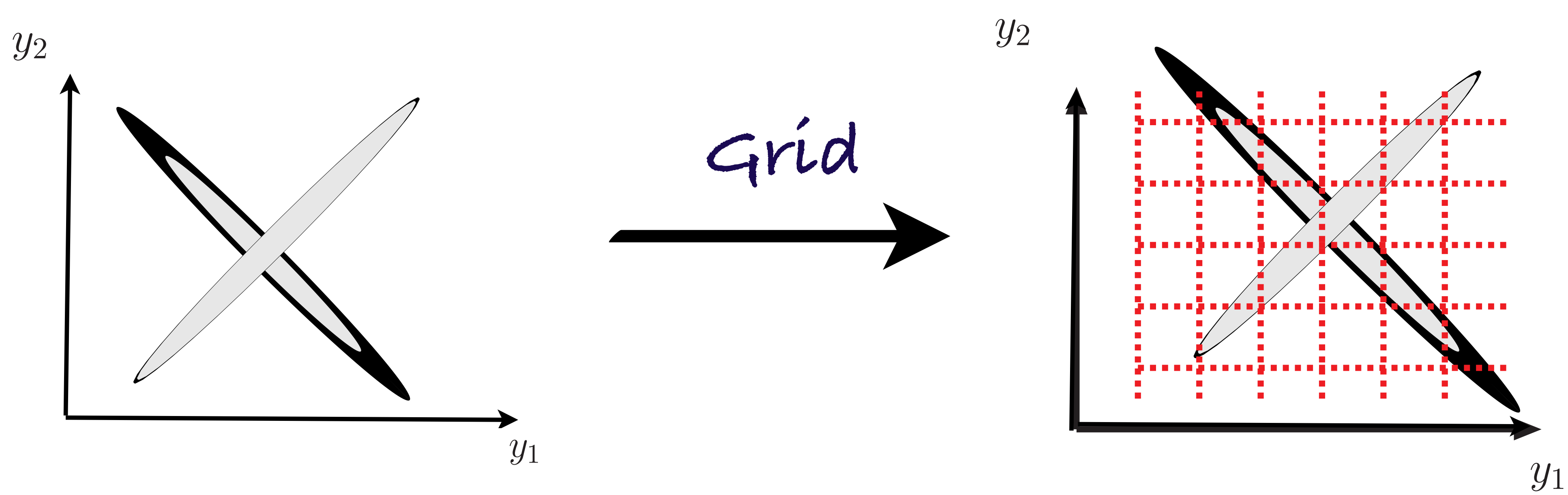

- The adaptive Monte-Carlo Techniques picks points everywhere
  → The integral converges slowly

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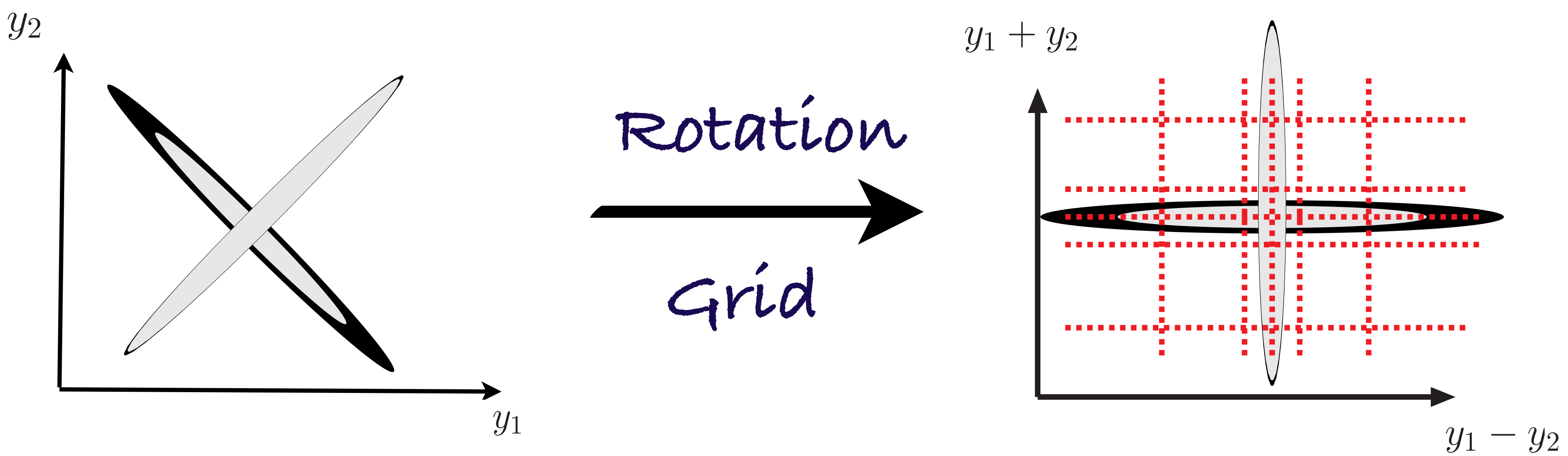

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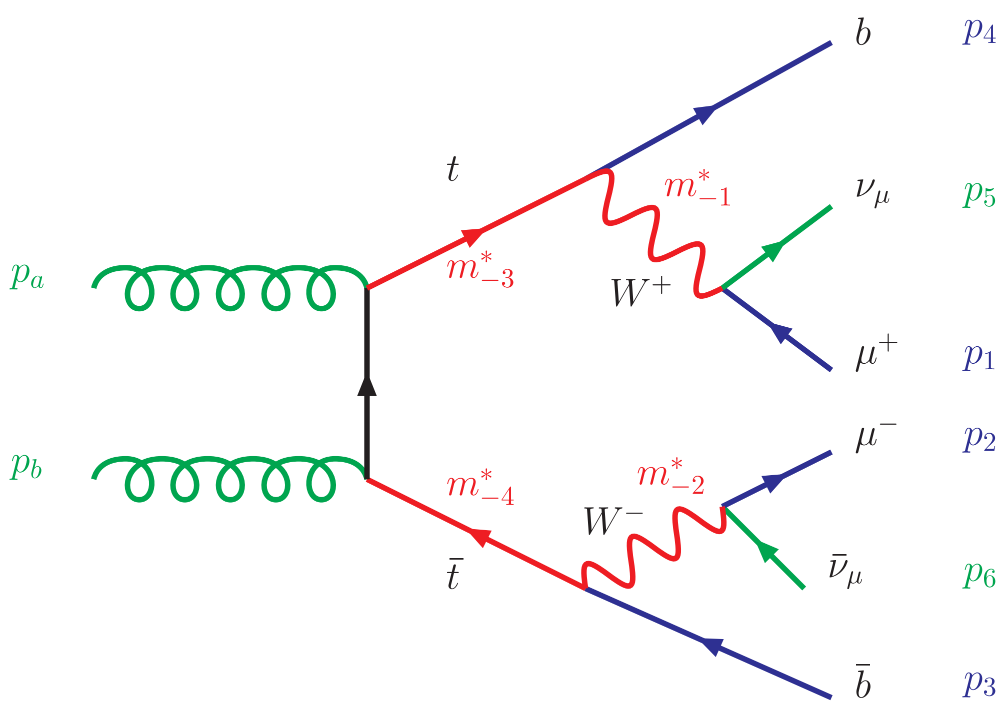
- First Example: di-leptonic top quark pair



- degrees of freedom 16
  - 2: pdf
  - 3 x 6: final states
  - -4: energy-momentum conservation
- peaks 16
  - 4: Breit-Wigner
  - 3 x 4: visible particles

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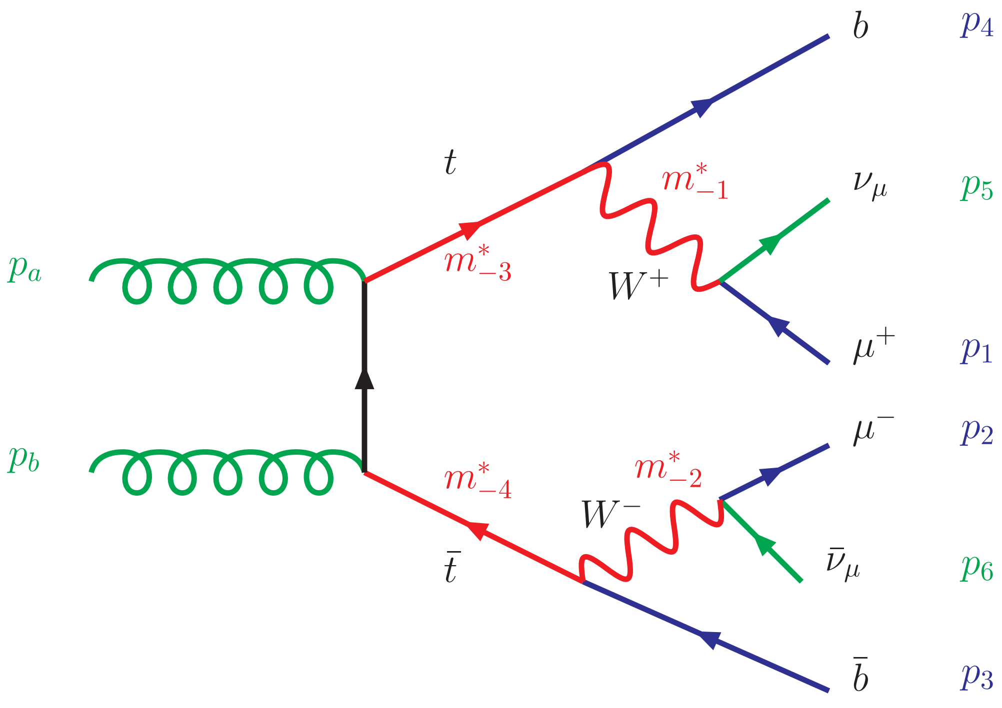

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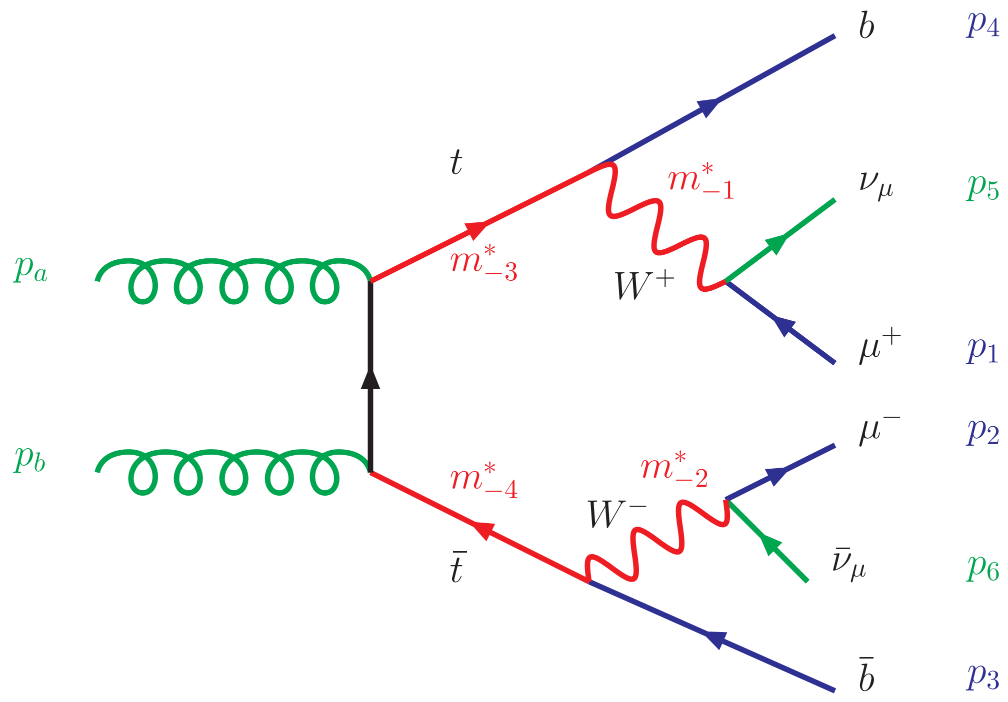

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$$d\phi = \prod_{i=1}^{4} \frac{d^3 p_i}{(2\pi)^3 2E_i} \prod_{i=5}^{6} \frac{d^3 p_i}{(2\pi)^3 2E_i} dx_1 dx_2 \delta^4 \left(p_a + p_b - \sum_j p_j \right)$$

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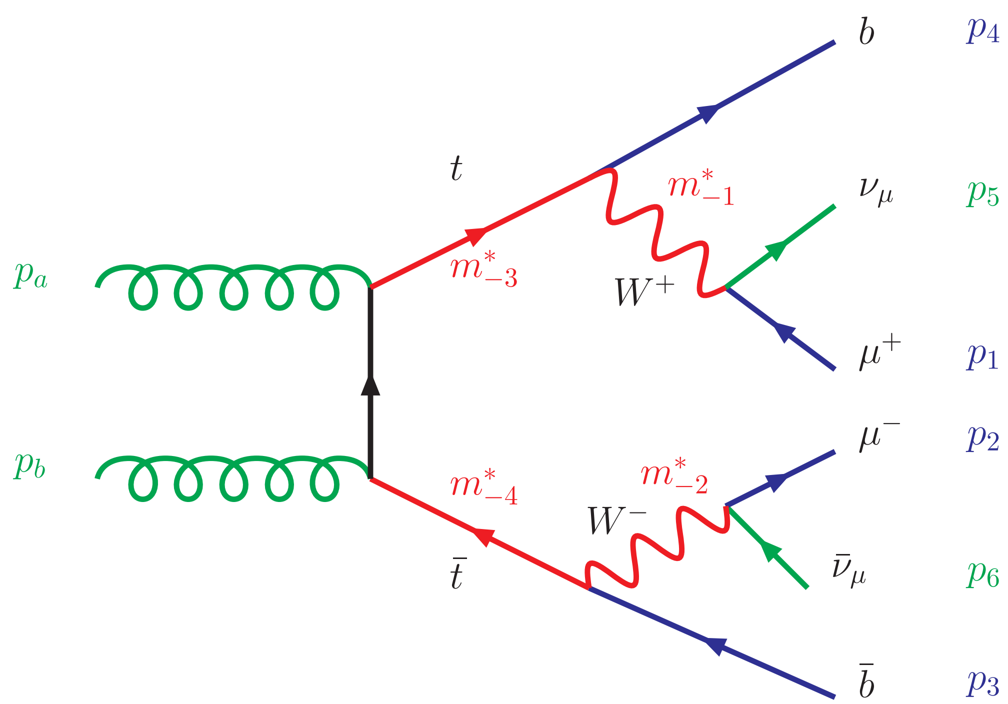

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Pass to →

$$d\phi = \prod_{i=1}^{4} d\theta_i d\phi_i d|\boldsymbol{p}_i| \prod_{j=1}^{4} dm^{*2}_{-j} \times J$$

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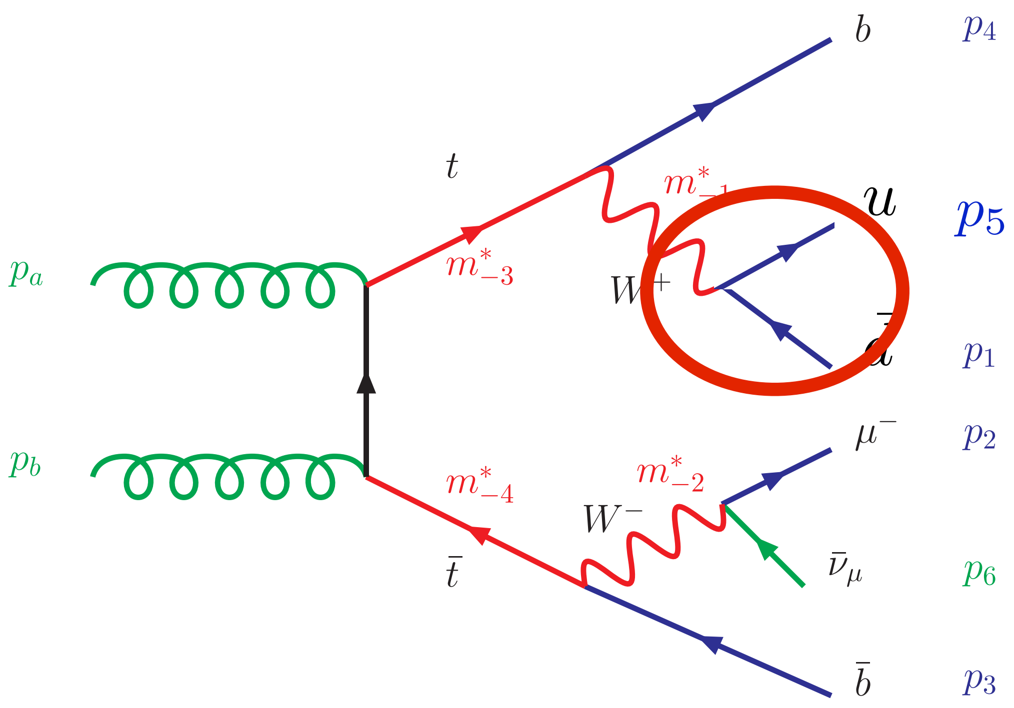

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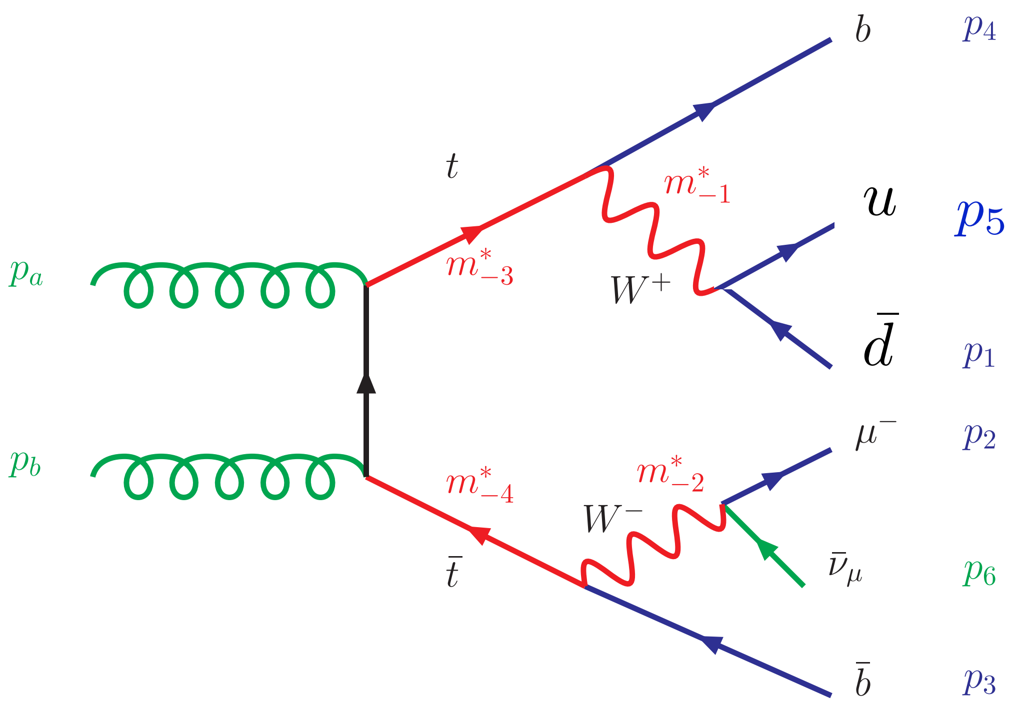

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MADWEIGHT

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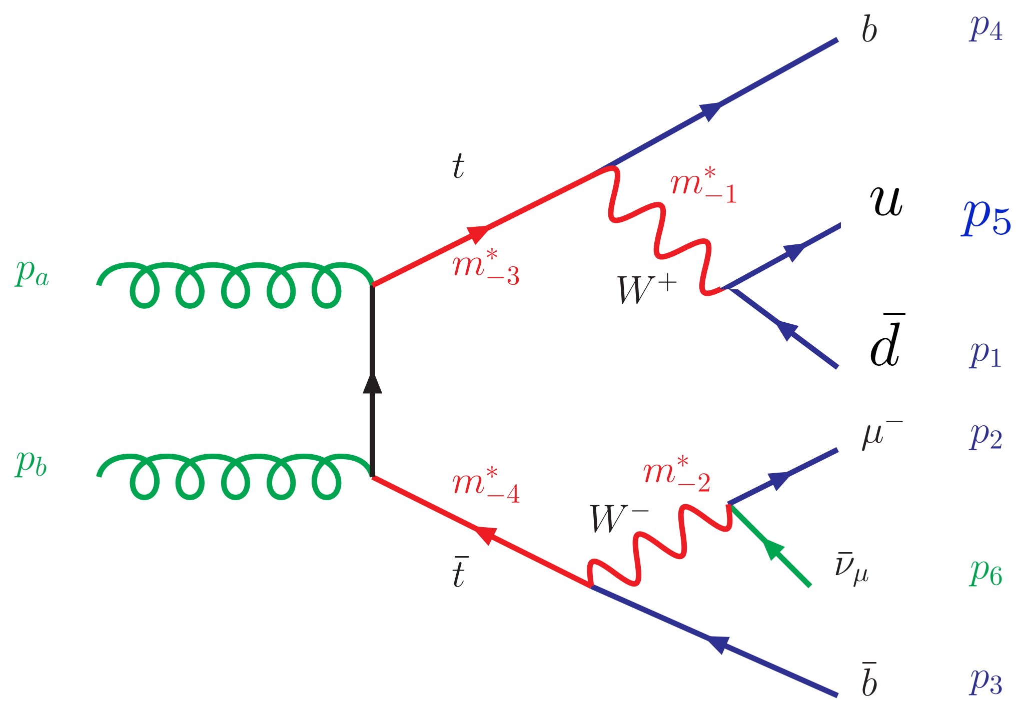

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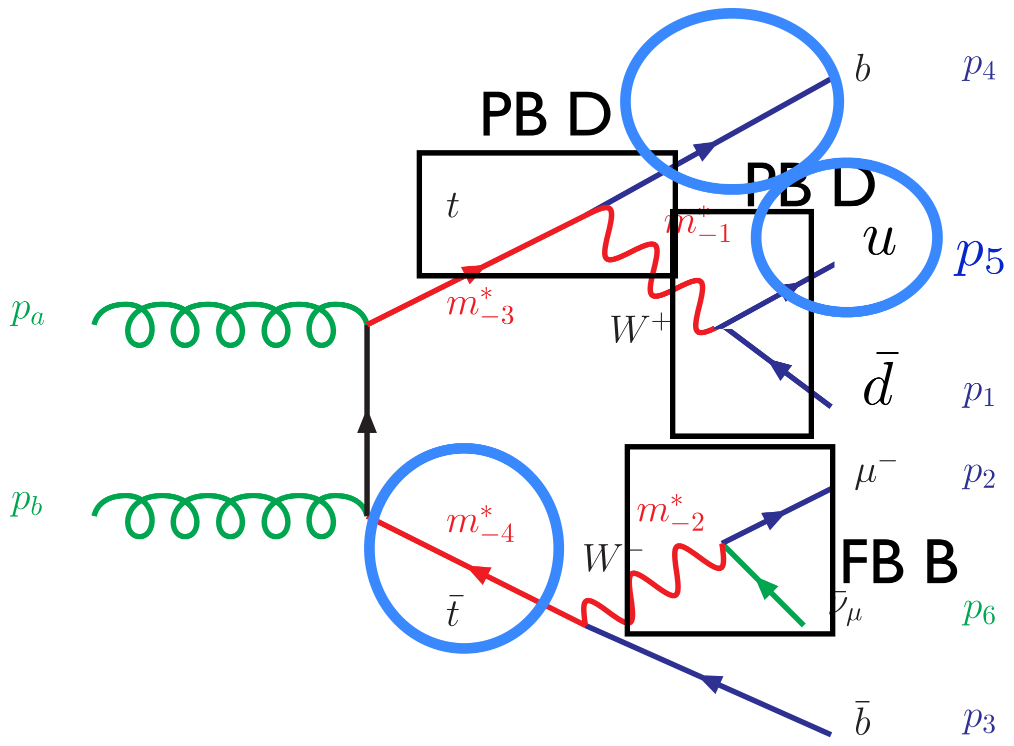

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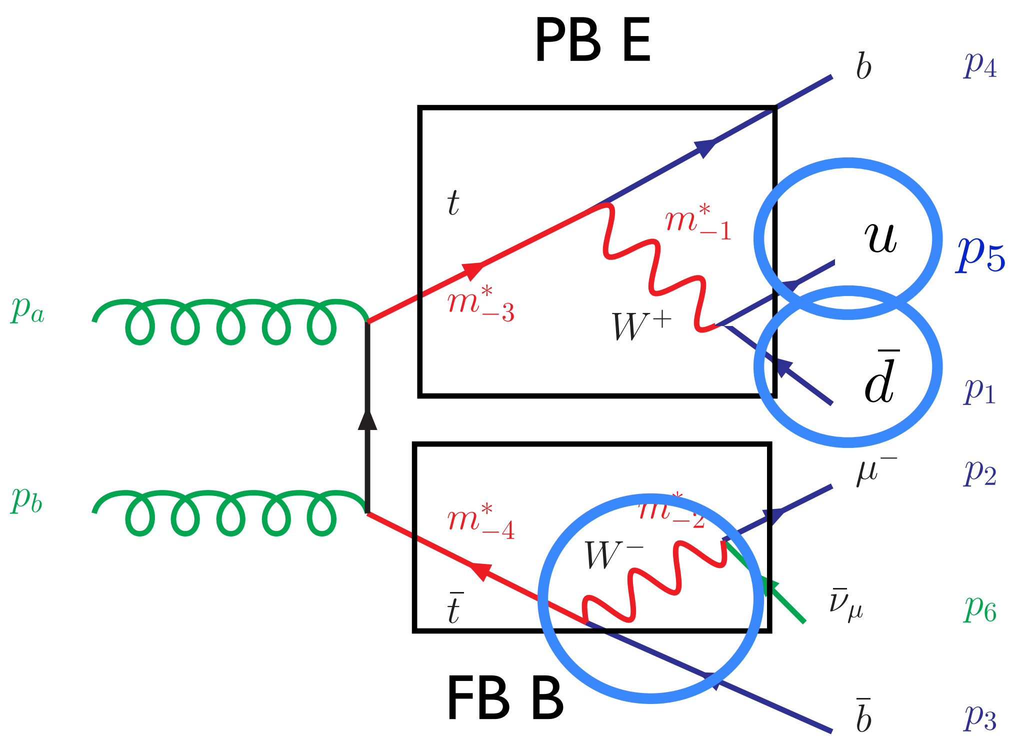

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Pass to →

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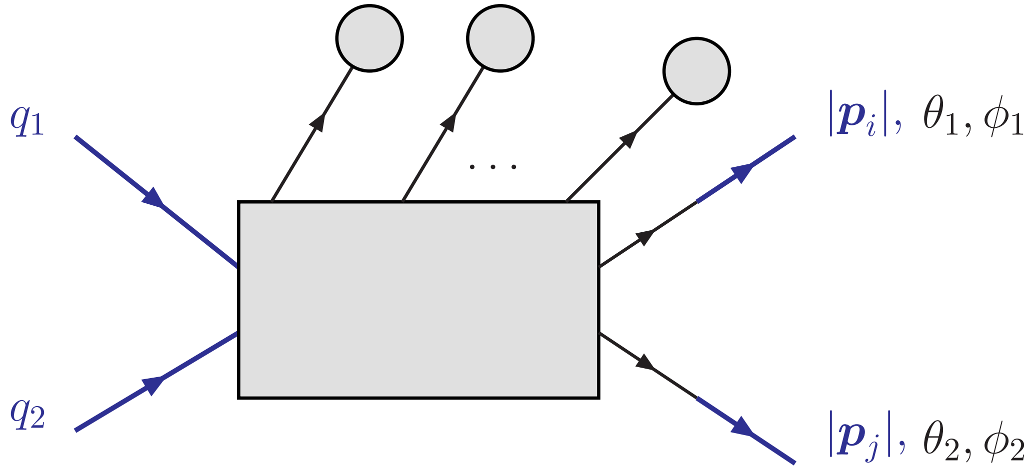
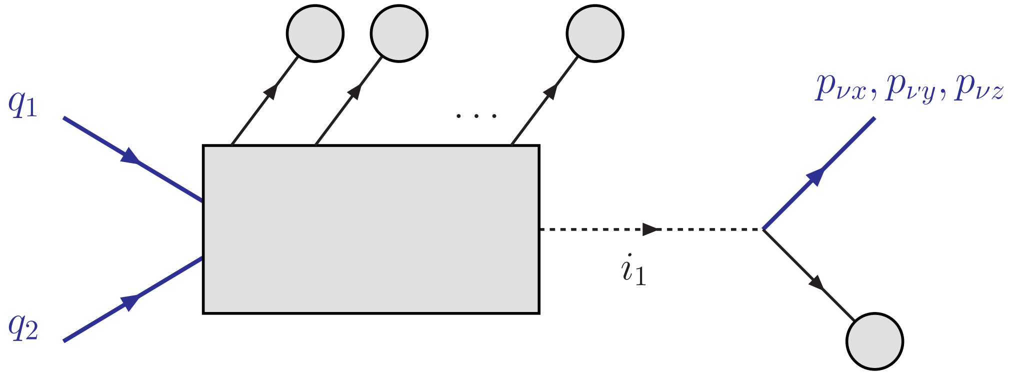
MADWEIGHT

P. Artoisenet, V. Lemaître, F. Maltoni, OM: JHEP 1012:068

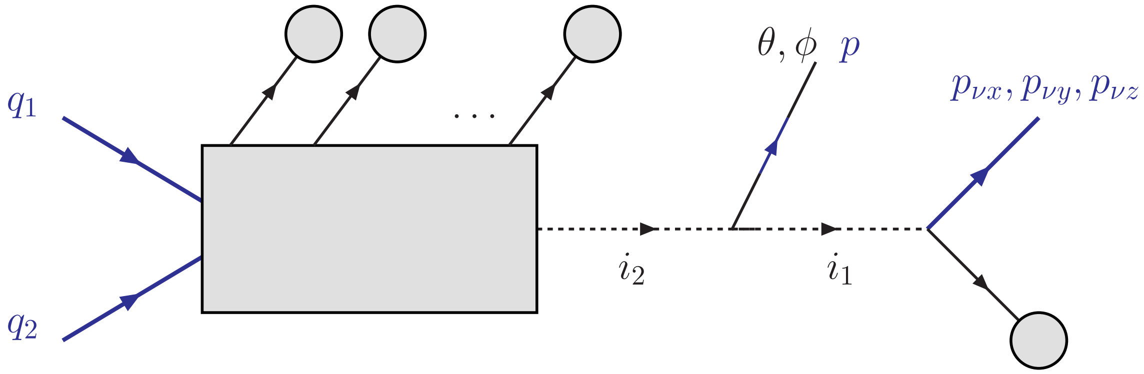
MadWeight



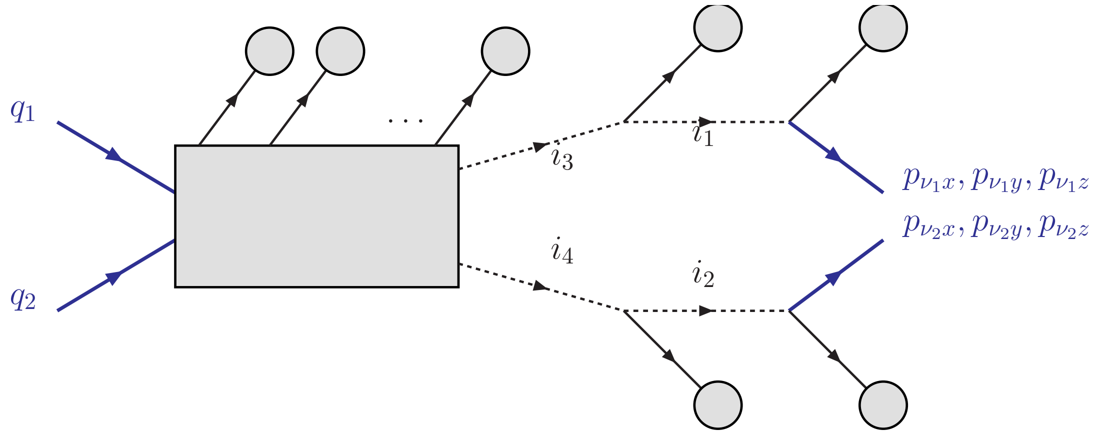
fully hadronic / leptonic process



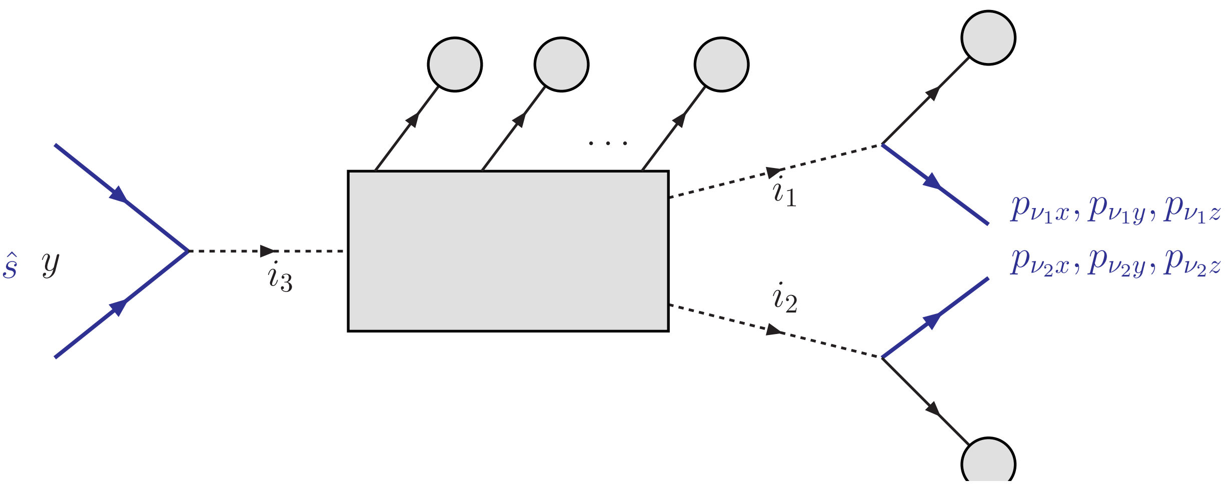
W production



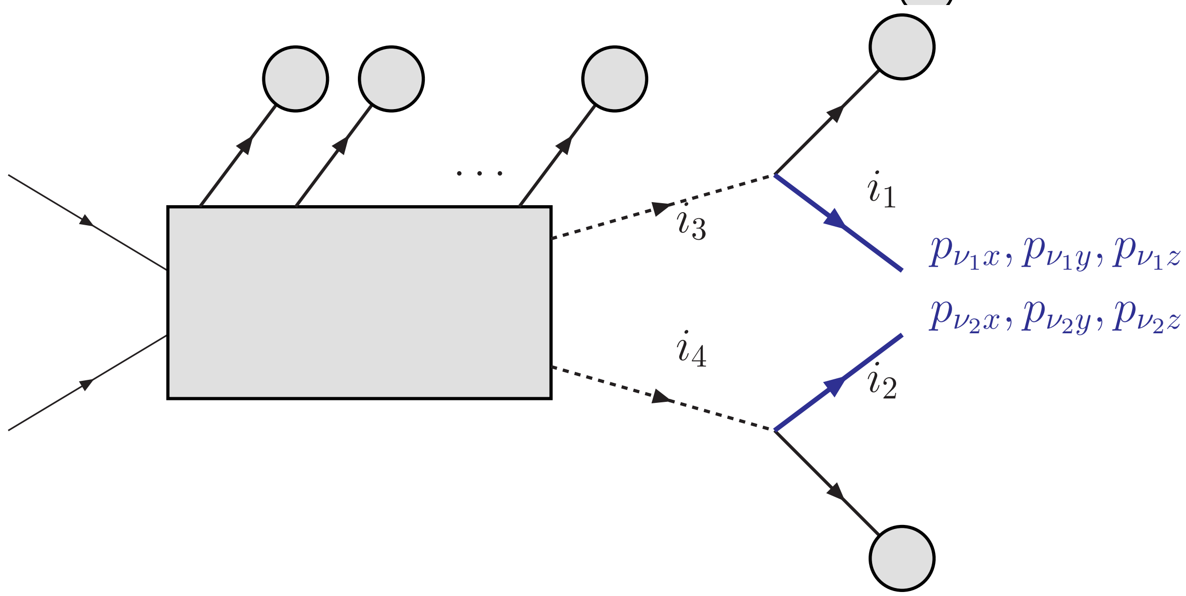
semi-leptonic top quark pair



Fully leptonic top quark pair



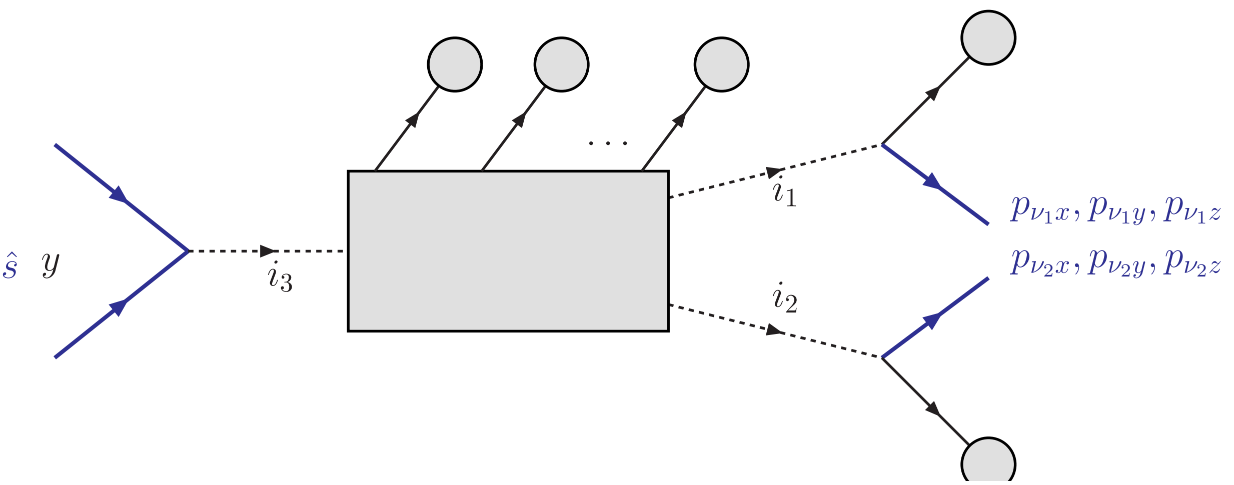
Higss production decaying in W



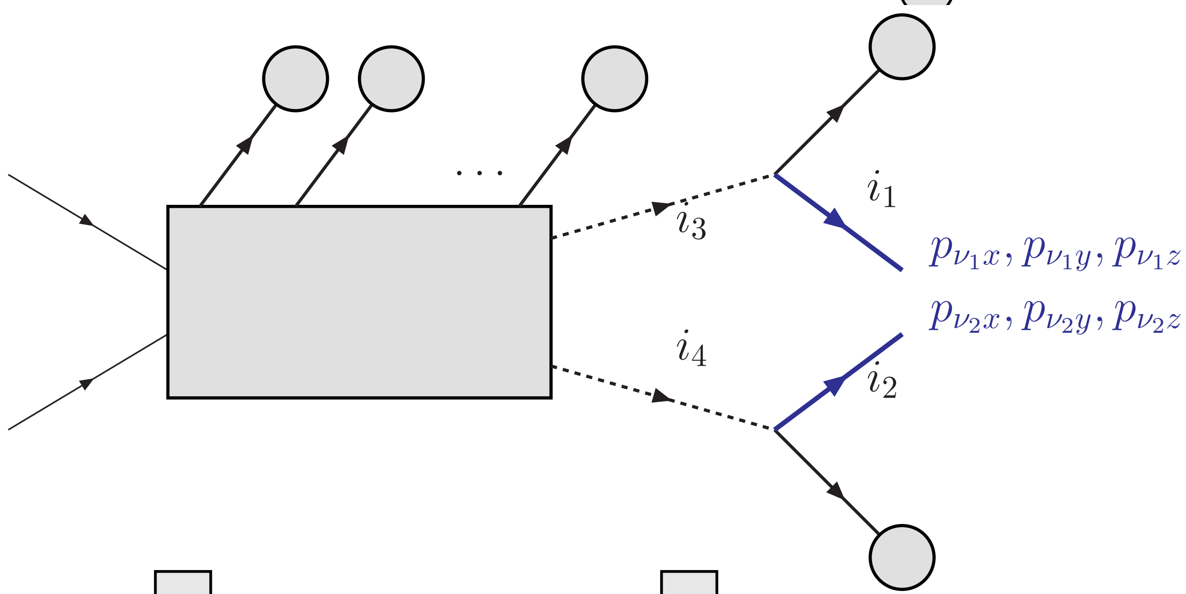
Class F

W+ W- production

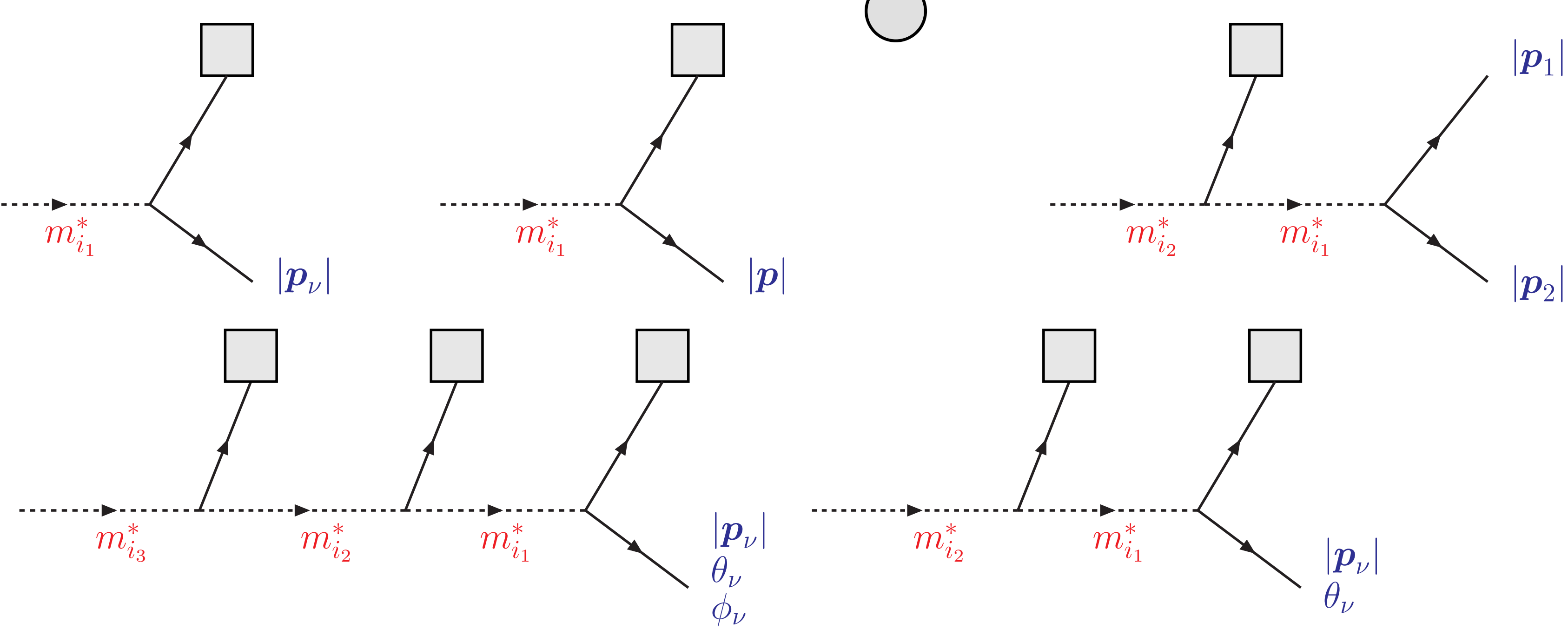
MadWeight



Higss production decaying in W



W+ W- production



Lot of possibility to have more complex process

+1 W

+1 Z

+ ...

MadWeight History

- 2009: MadGraph4 Implementation
- 2011: Private Implementation in MadGraph5
  - Initial State Radiation Support
  - SubProcess grouping (speed)
  - NWA (speed)
- 2013: MadWeight5 beta
  - Improve cluster support (speed)
  - MC over jet/parton assignment (speed)
  - pre-training (speed)
  - better multi-channel (speed)
- 2014: MadWeight5 in MG5_aMC
  - Support for multi-transfert function estimated on the same phase-space point (speed)
  - Module of preselection of the jet/parton assignment (speed)

cpu-time

- Number of integration to evaluate:
  - Number of events: ~1000
  - Number of theoretical hypothesis: ~10
  - Systematics (JES): ~5
  - Jet-Parton assignment: ~12

  - Total: ~600k

Each of them needs to be Fast

Speed Benchmark

process	perm	MW4	MW5
tt semi lept	24	1h16	41s
tt fully lept	2	46s	10s
tth semi lept	720	> 2 days	10min
tth semi lept	48	> 3h	6min
tth fully lept	24	>1h	1min
h> w+ w- > 1lept	2	59s	<5s
h> w+ w- > 2lept	1	8s	<5s
z b b	24	39m	18s
zh	24	43m	<5s

running on 1core of a Intel core i7 2.3Ghz

cpu-time

- Number of integration to evaluate:
  - Number of events: ~1000
  - Number of theoretical hypothesis: ~10
  - Systematics (JES): ~~~5~~ 1
  - Jet-Parton assignment: ~~~12~~ 1

  - Total: ~10k

Each of them needs to be Fast

CRITICS OF THE METHOD

- The Likelihood methods builds the BEST discriminating variable
- Fully Model dependent
- Transfer Function approximation
  - Factorize for each parton
  - Not valid for hard radiation
- Pure LO approximation
- Strong sensitivity in analysis cut
- Computing time ($N_{event} * N_{th}$ integrals)

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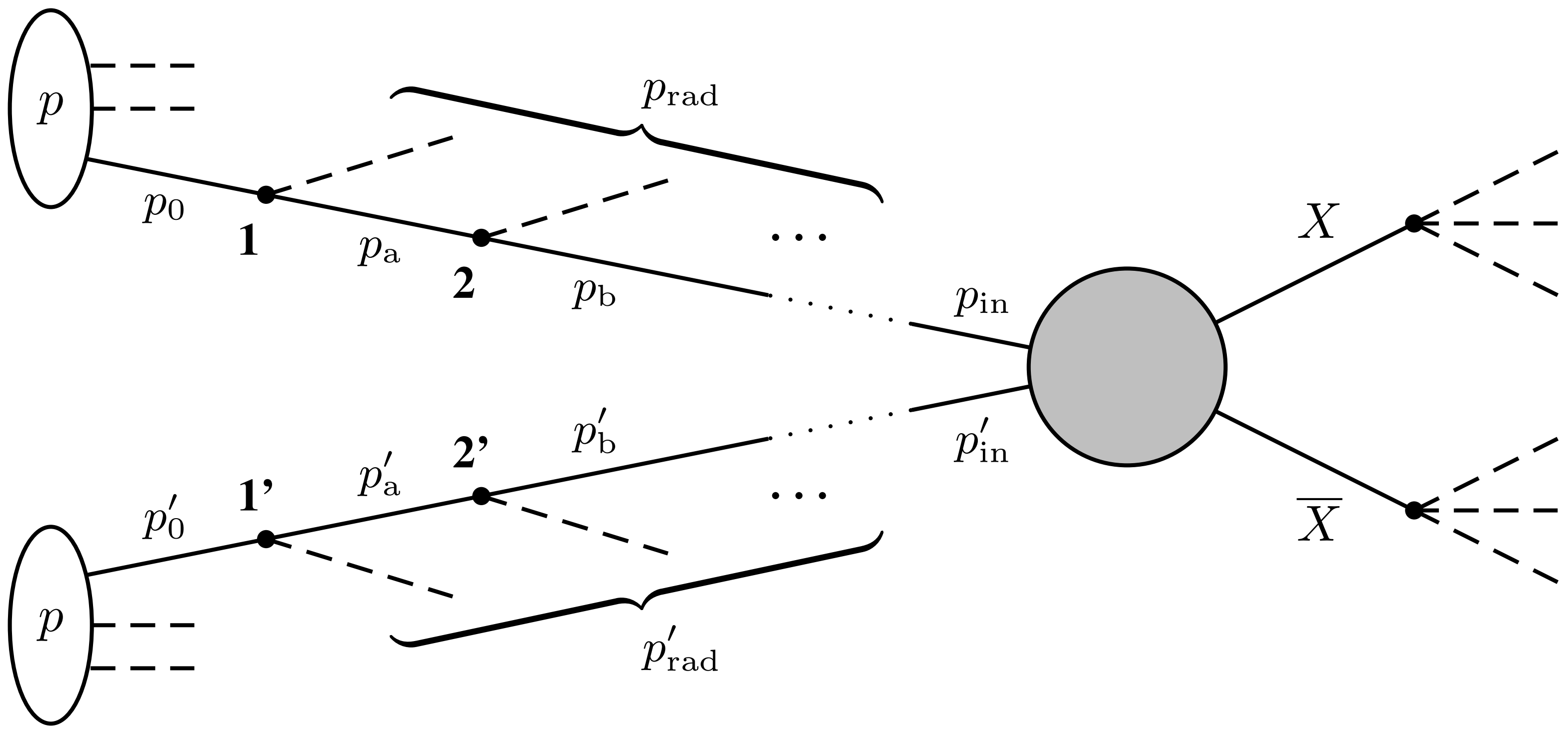
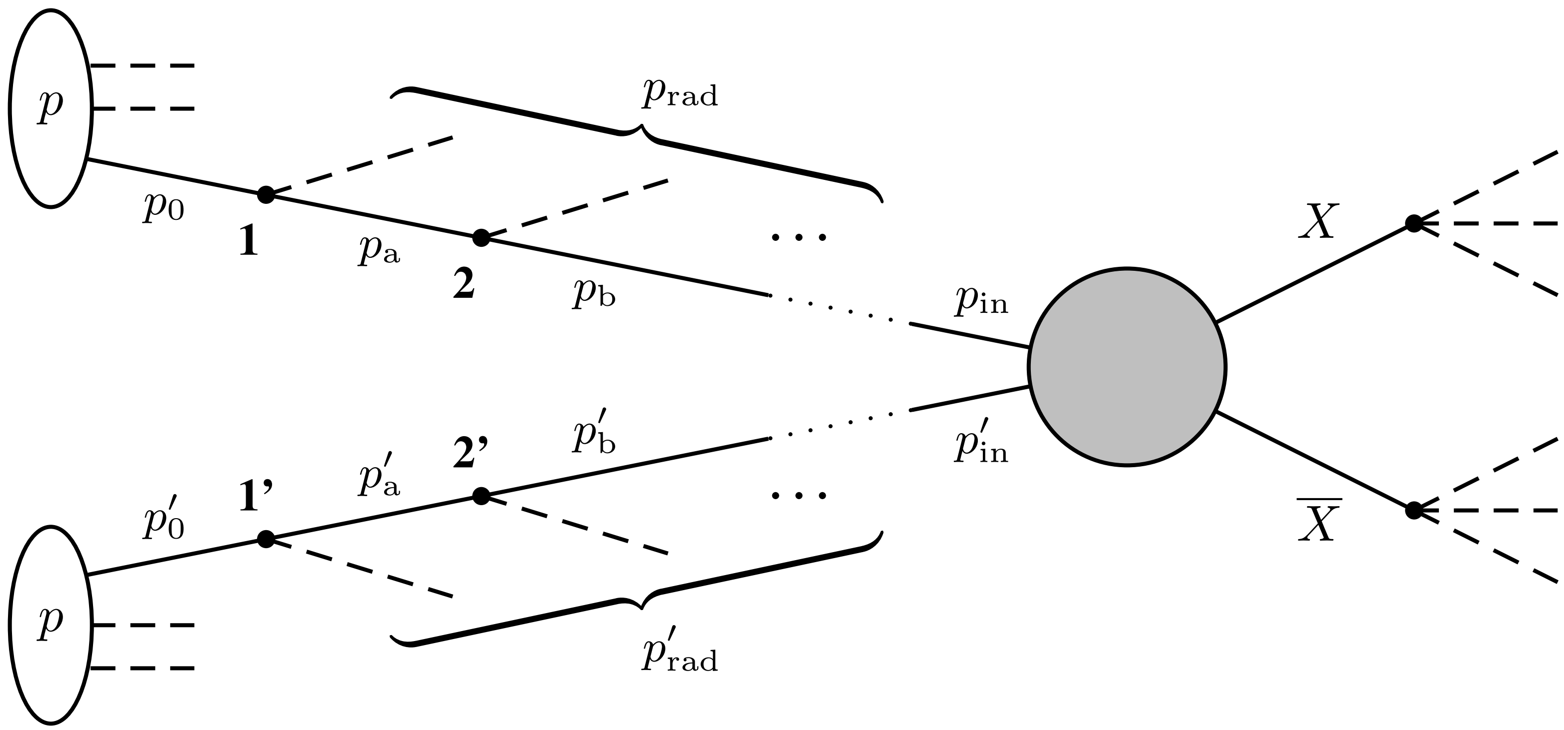
MEM with radiation / NLO

Radiations



- ISR
  - Main Effect is to induce a transverse boost.
  - Different PDF
- FSR
  - ➡ Need to be parameterize in the TF
  - ➡ Having a one parton evolving in two jets TF

Radiations



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Here I will focus on ISR

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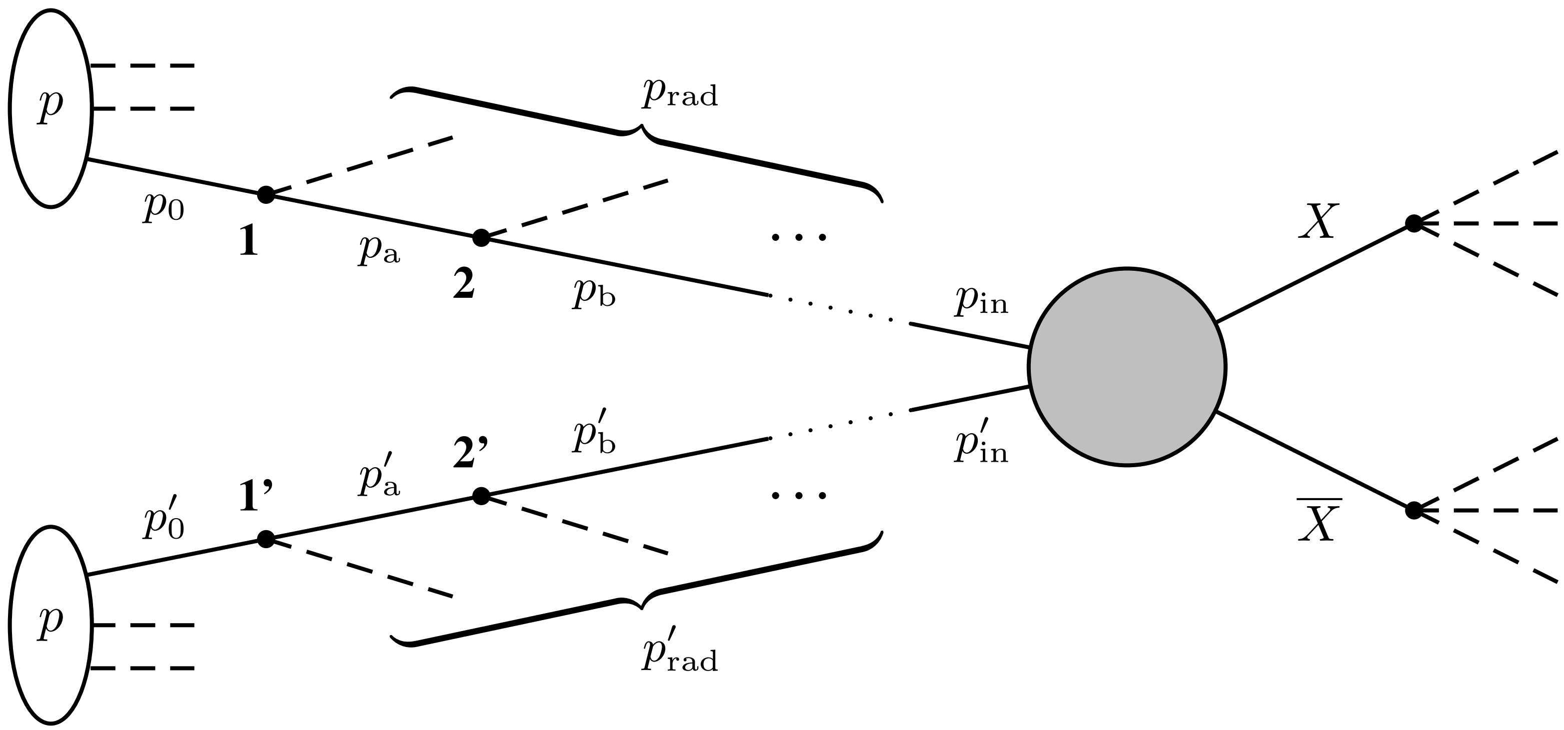
Radiations



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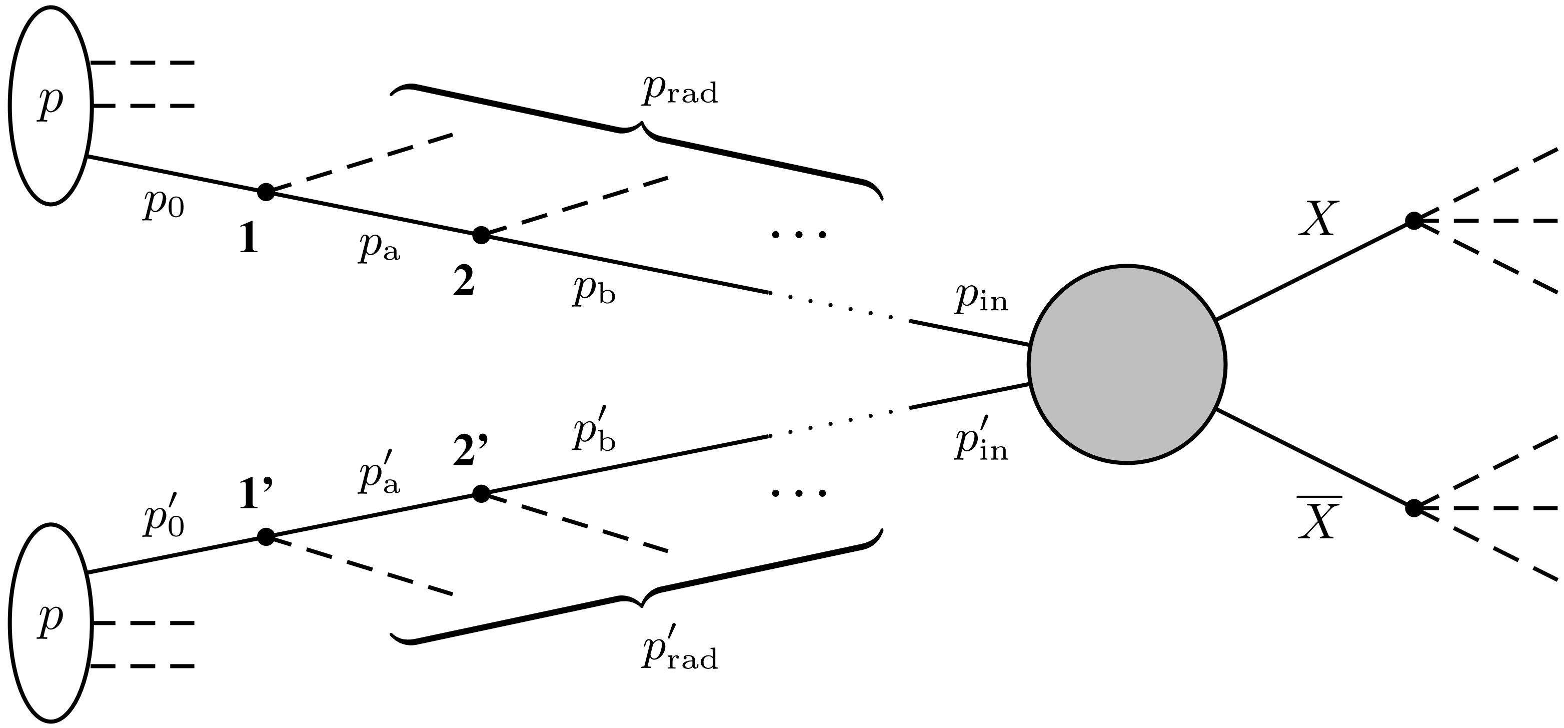
Work in progress

MEM with radiation



- Those radiations are important
  - ttj is 50% at LHC
- 3 Main idea
  - Transfer boost
  - Use ME + N jets
  - NLO

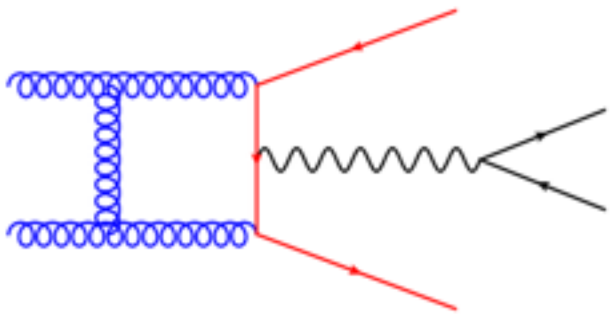
My point of view

- Use ME + N jets
  - Having one more jets at the matrix element level is roughly 10 times slower.
    - number of permutations (assignment jet-parton)
    - complexity of the integrand
    - dimension of the phase-space
  - The radiation problem still occurs (at least for the inclusive sample)
- NLO
  - Basically equivalent to ME + N jets

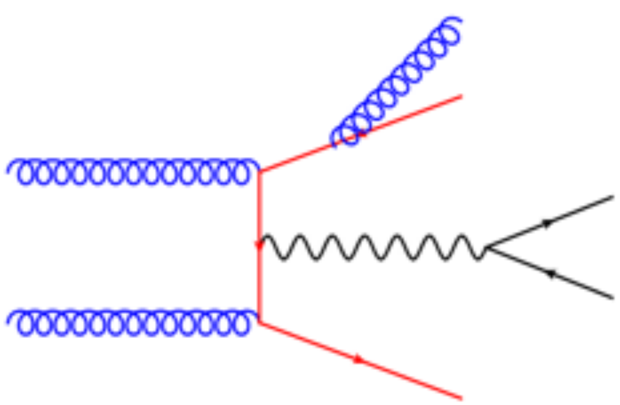
NLO

[J. Campbel, W. Giele, C. Williams,1204.4424]

- Splitting higher order in two pieces depending if you resolve the jet or not
  - If you resolve the jet: use LO ME + 1 jet
  - If you don't:



$$\tilde{\mathcal{P}}_V(\Phi_B) = \frac{f(x_1)f(x_2)}{2x_1x_2s}\left(|\mathcal{M}^{(0)}(\Phi_B)|^2 + 2\mathrm{Re}\left\{\mathcal{M}^{(0)}\mathcal{M}^{(1)^\dagger}(\Phi_B)\right\}\right)$$

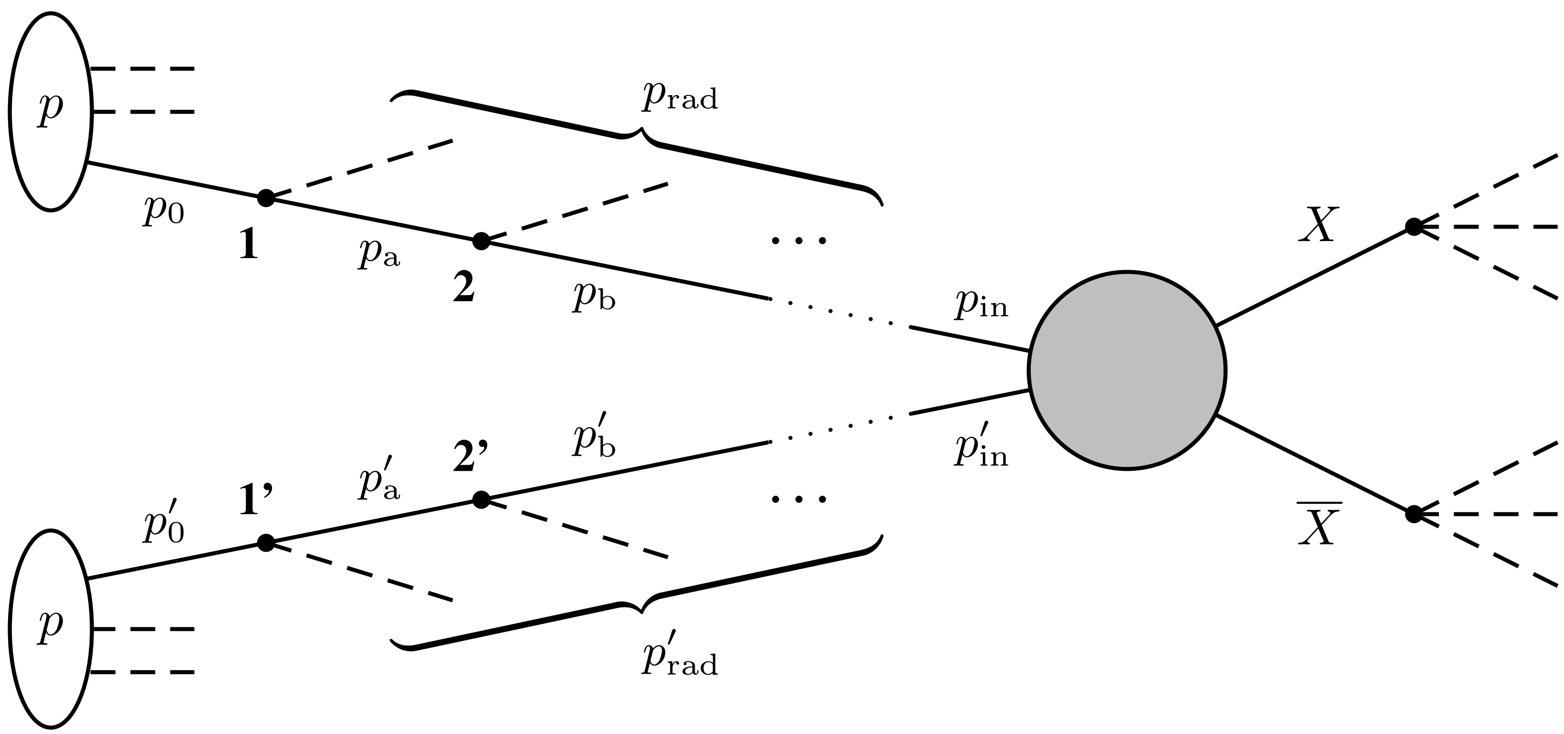


$$\tilde{\mathcal{P}}_R(\Phi_B) = \int d\,\Phi^{IS}_{\mathrm{FBPS}}(\Phi_B) J_x \frac{f(x_a)f(x_b)}{2x_a x_b s}|M_R^{(0)}(\Phi_R(\Phi_B))|^2$$

$$d\Phi(p_a + p_b \to Q + p_r) = d\,\Phi(\widehat{p}_a + \widehat{p}_b \to Q) \times d\,\Phi_{\mathrm{FBPS}}(p_a, p_b, p_r) \times \theta_{\mathrm{veto}}$$

Only improve the no-jet bin!

MEM with radiation



- Those radiations are important
  - ttj is 50% at LHC
- 3 Main idea
  - Transfer boost
  - Use ME + N jets
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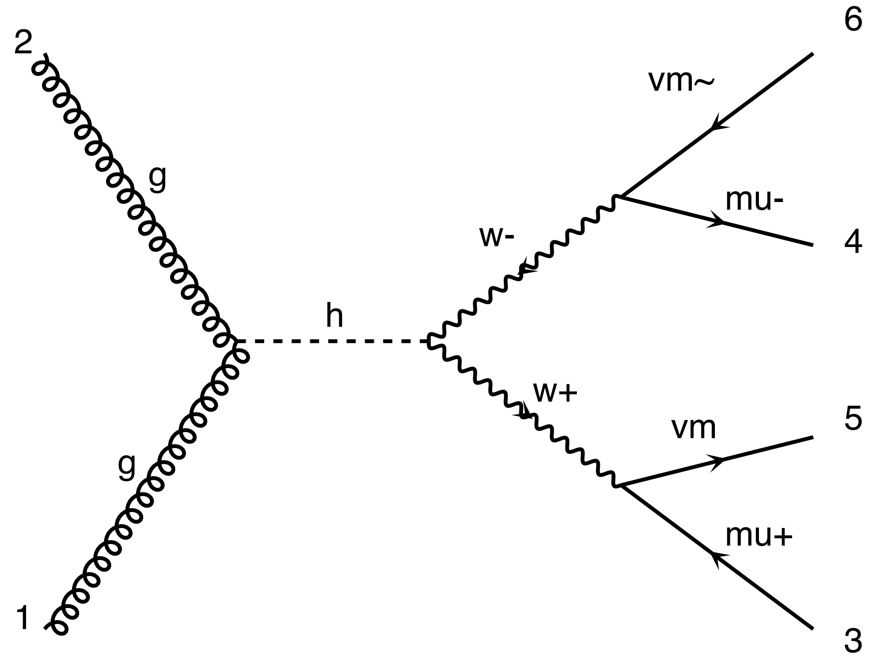
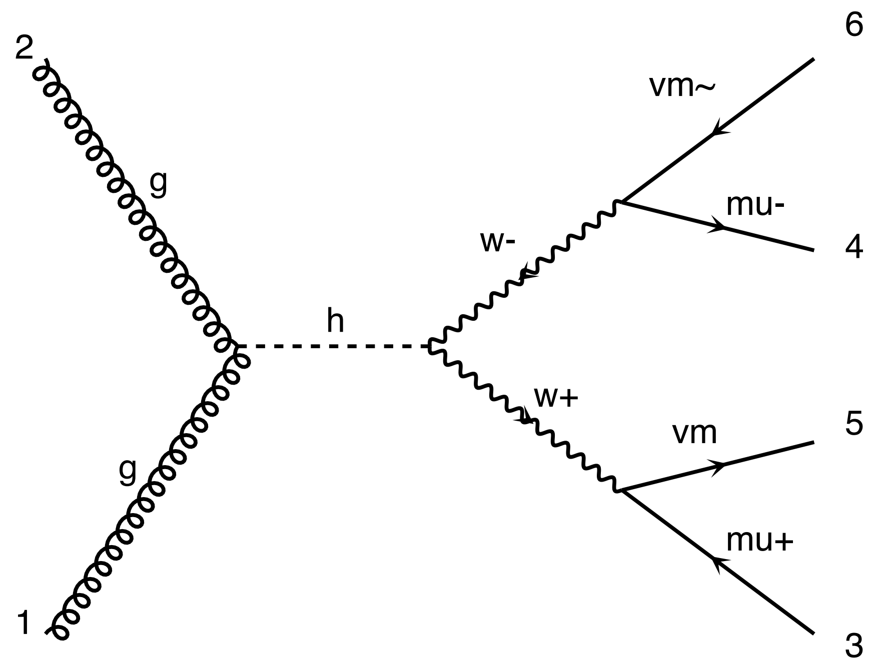
Choices of variables

Higgs production



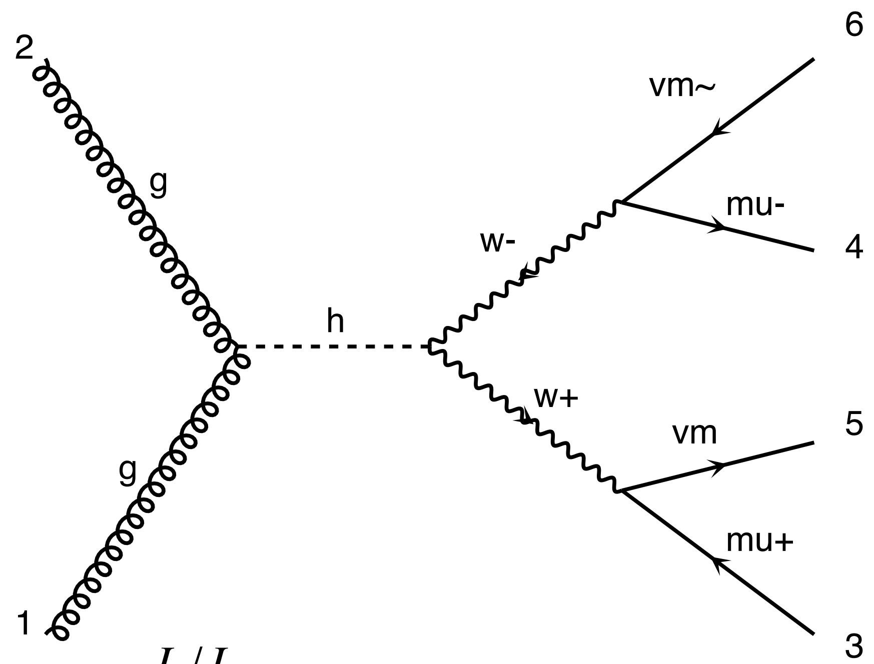
- Higgs Mass
  - s-channel
- No FSR

Initial State Radiation

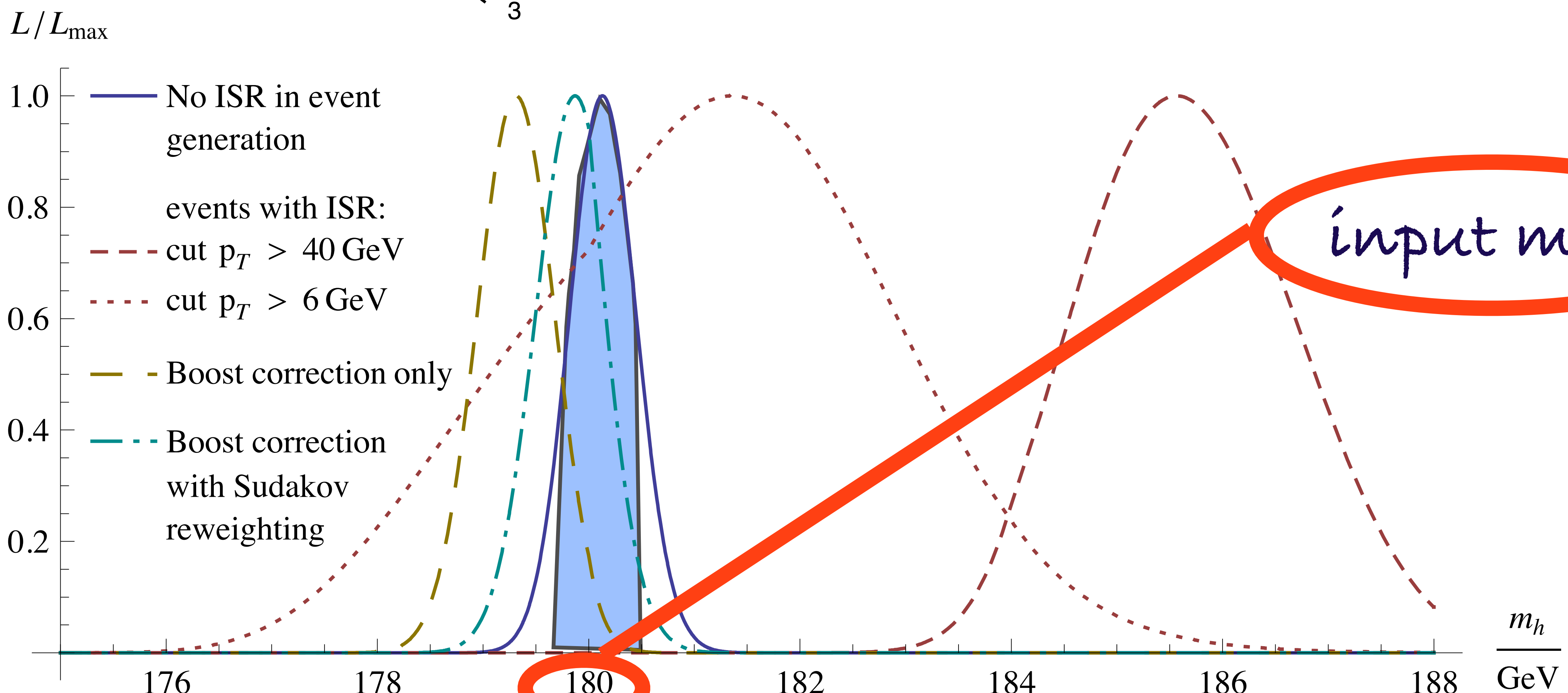


- Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)

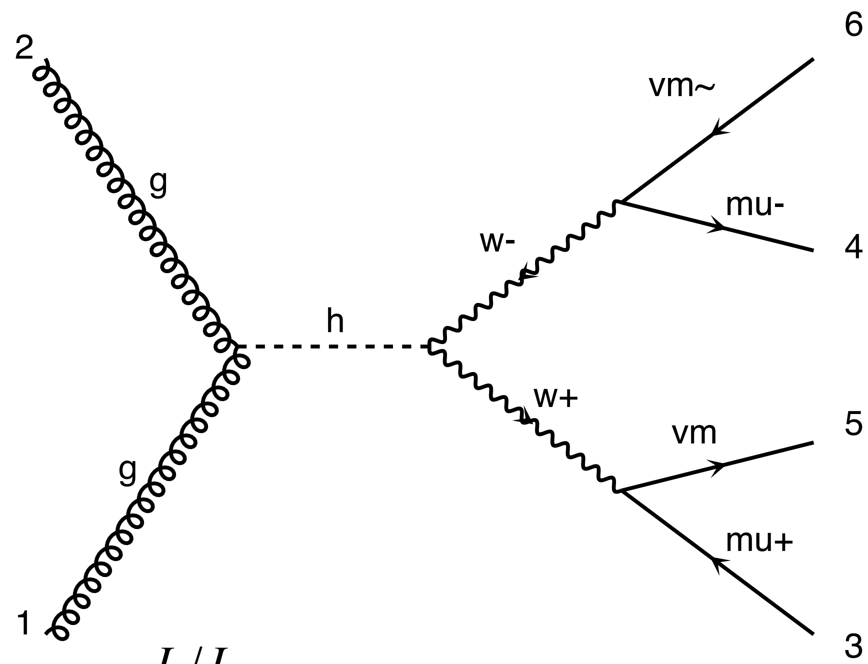
Initial State Radiation



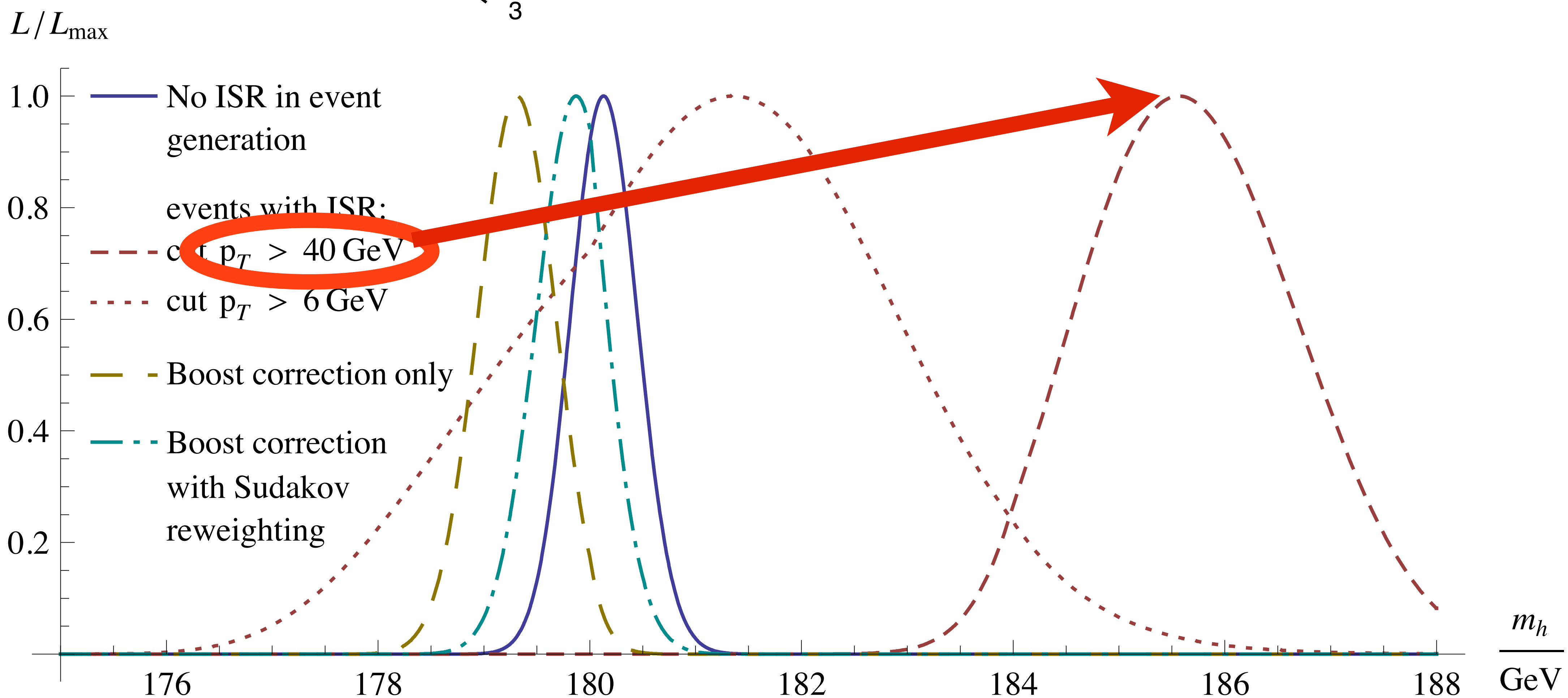
- Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)
- No ISR → No Bias



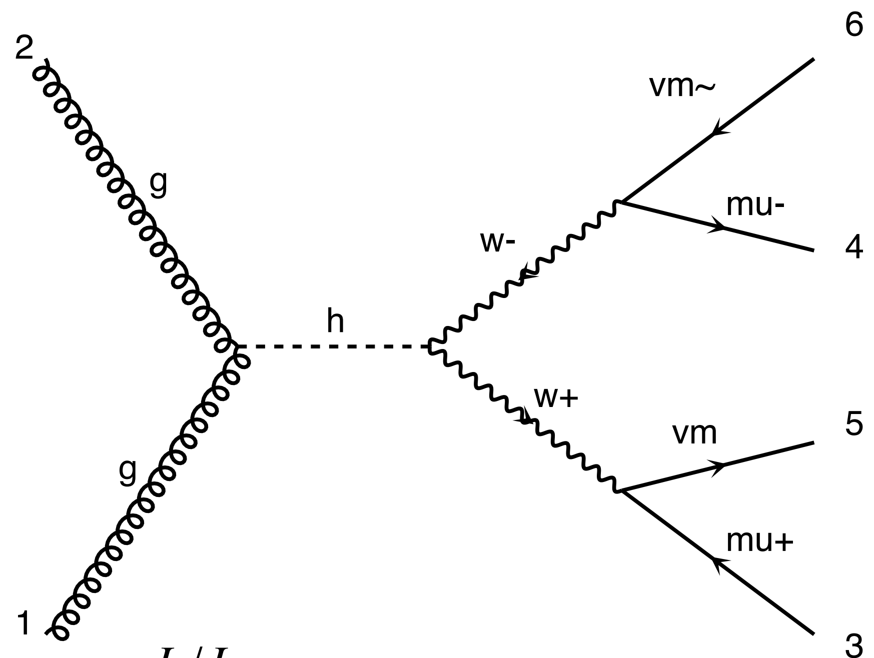
Initial State Radiation



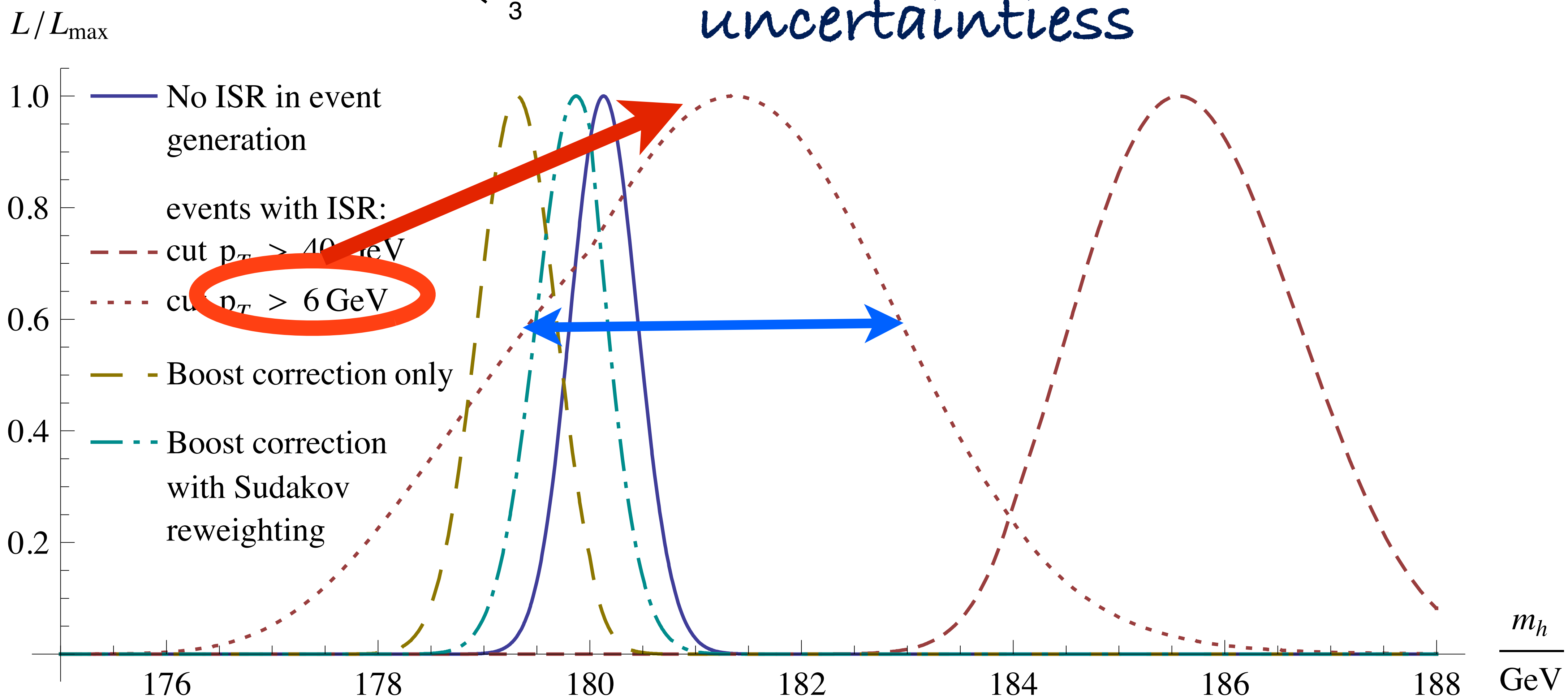
- Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)
- Large veto ➔ Large bias



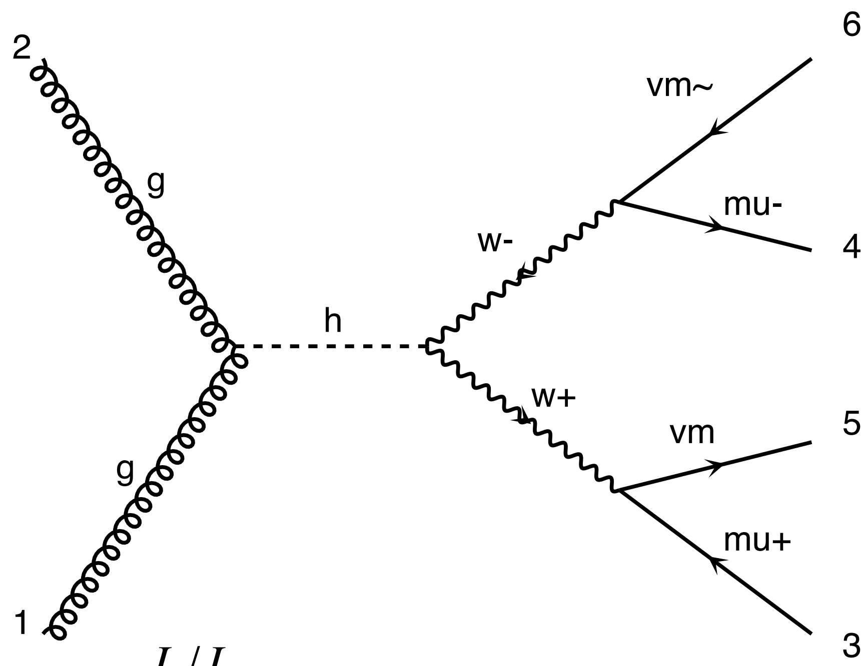
Initial State Radiation



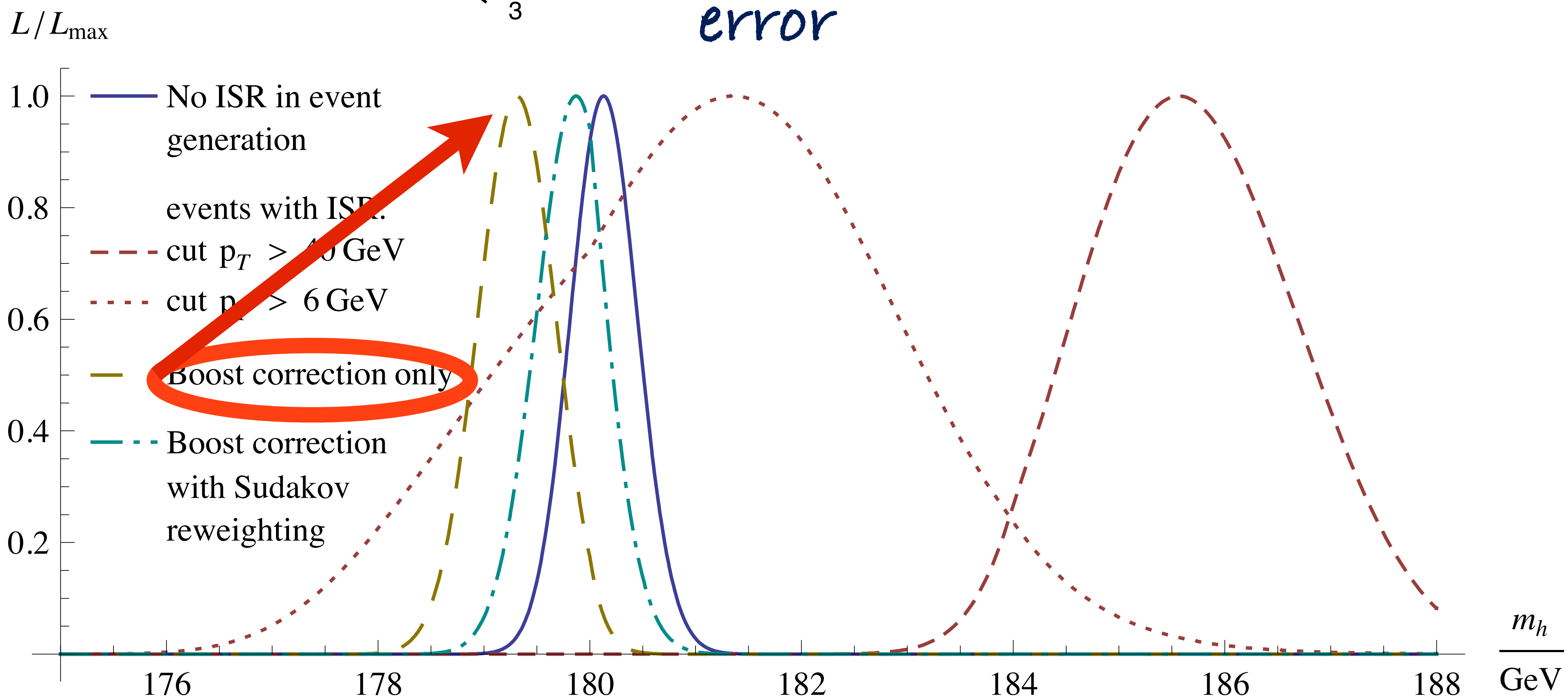
- ☐ Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)
- smaller veto → smaller bias but larger statistical uncertaintiess



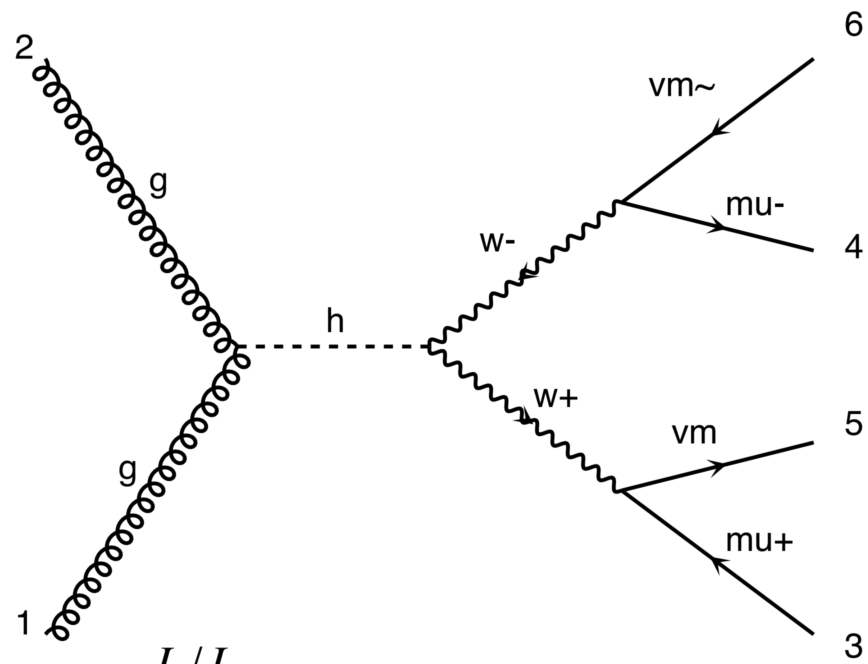
Initial State Radiation



- Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)
- Use the ISR to boost the momenta → small bias/ error

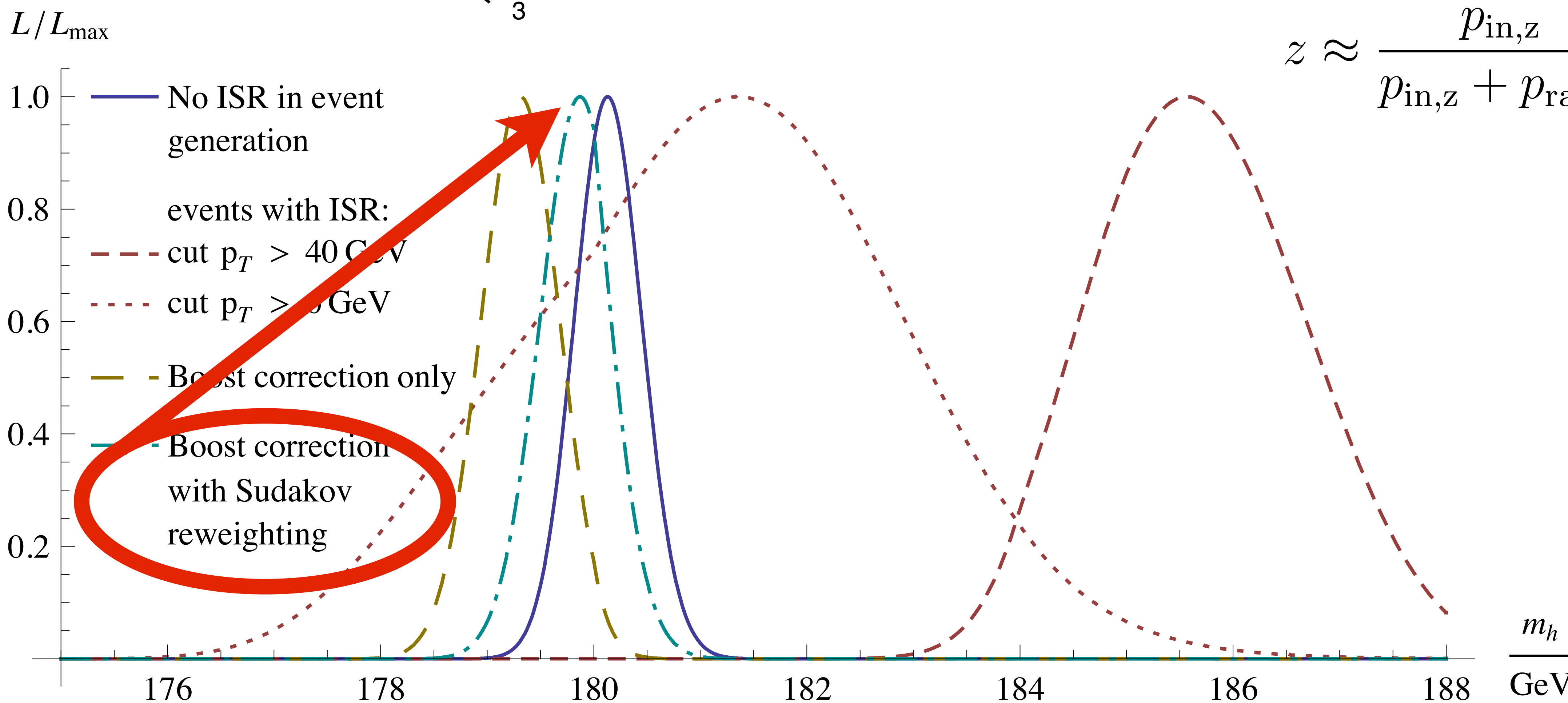


Initial State Radiation

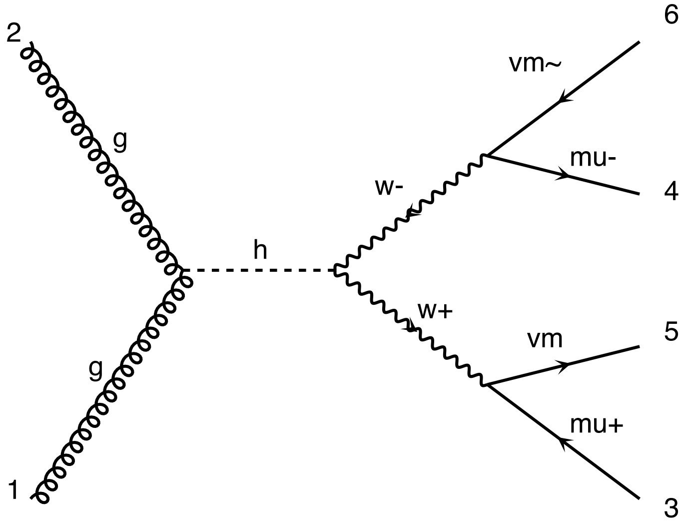


- Study the ISR on Higgs production at LHC (14 TeV) at parton level (no hadronization)
- Add the Sudakov Factor
  → No significative bias

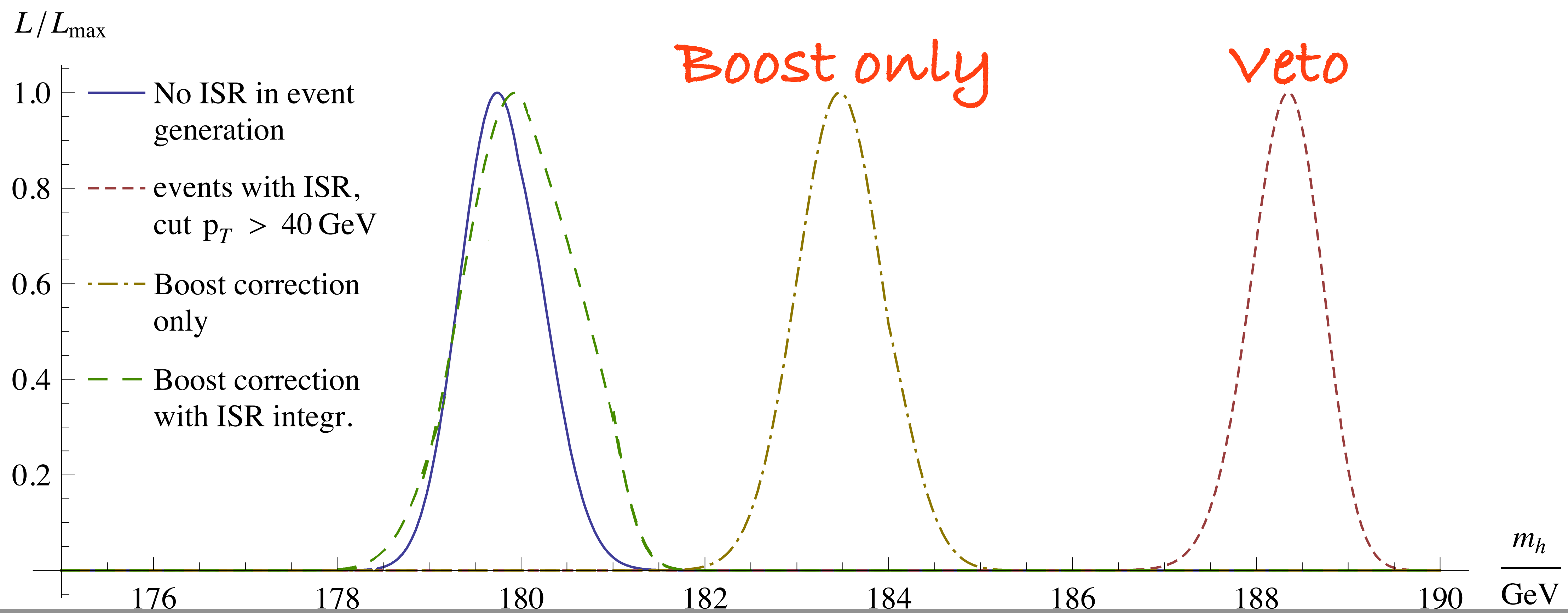
$$z \approx \frac{p_{\text{in,z}}}{p_{\text{in,z}} + p_{\text{rad,z}}},$$



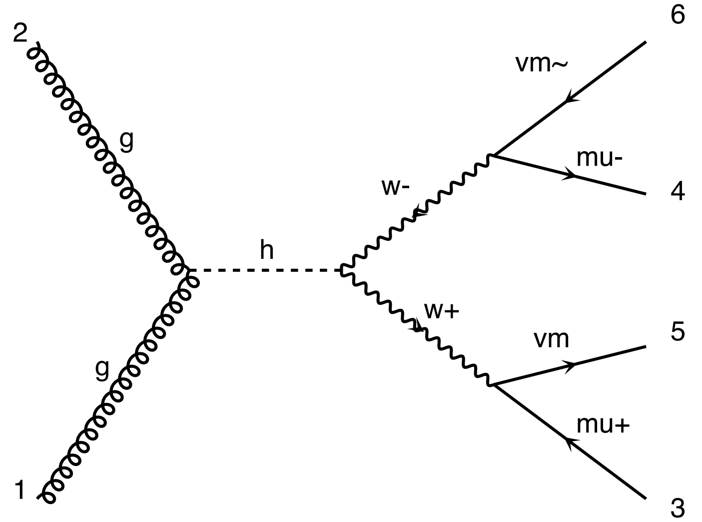
Initial State Radiation



- Study the ISR on Higgs production at LHC (14 TeV) at detector level (simulation includes pile-up)

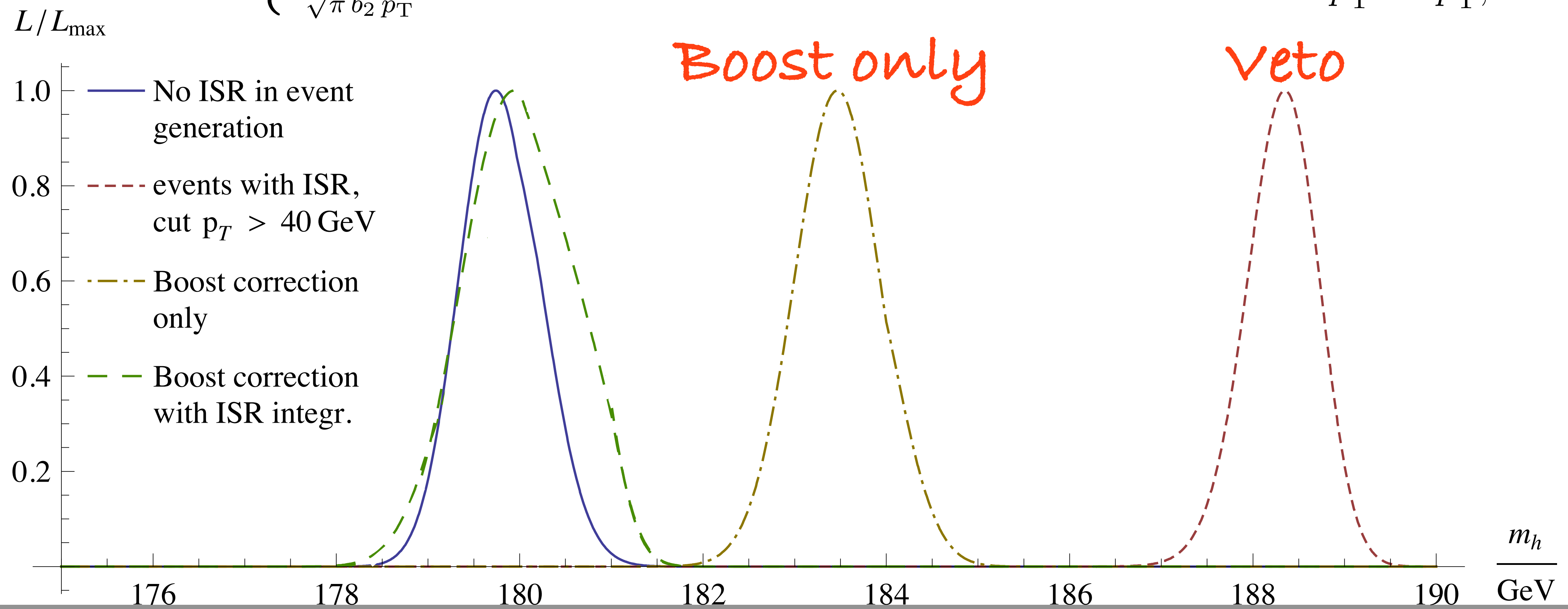


Initial State Radiation



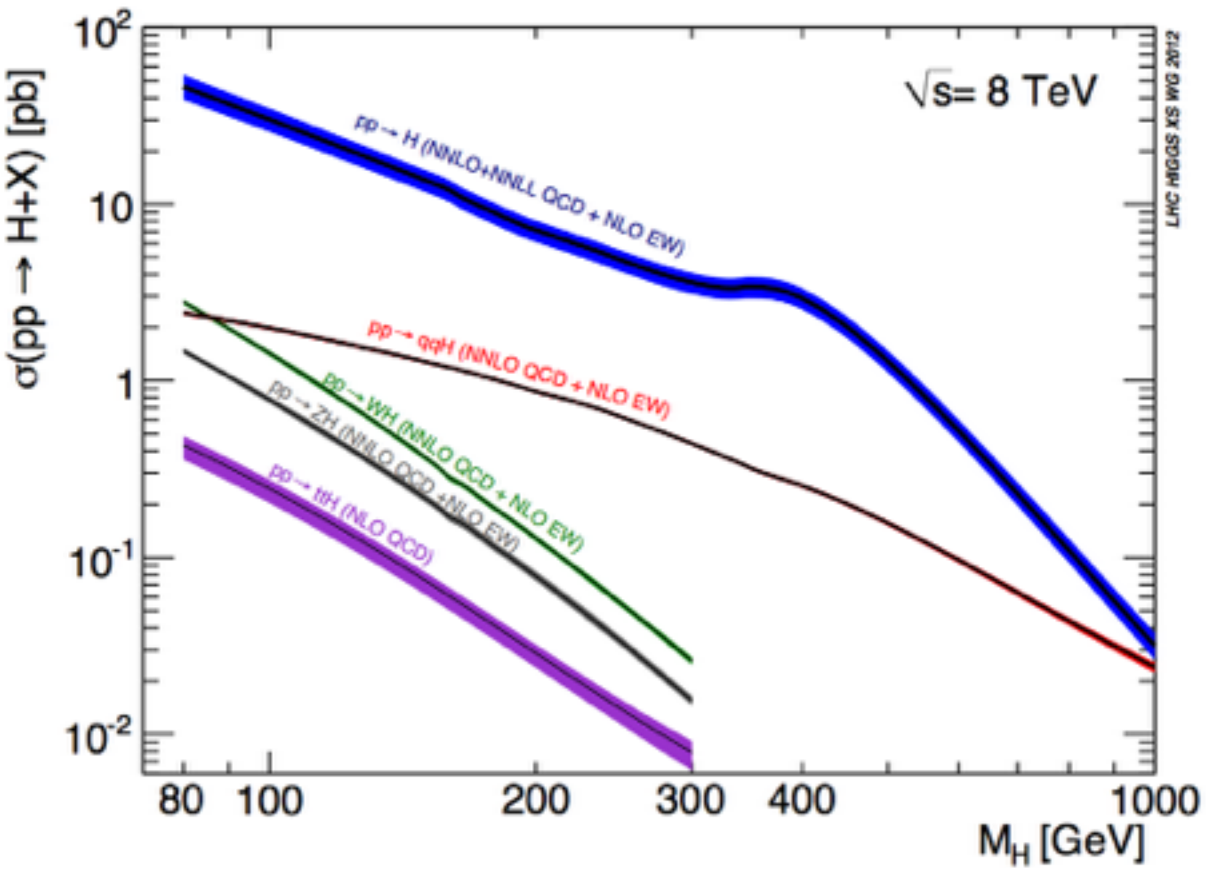
- Study the ISR on Higgs production at LHC (14 TeV) at detector level (simulation includes pile-up)
- Introduce ISR transfer functions

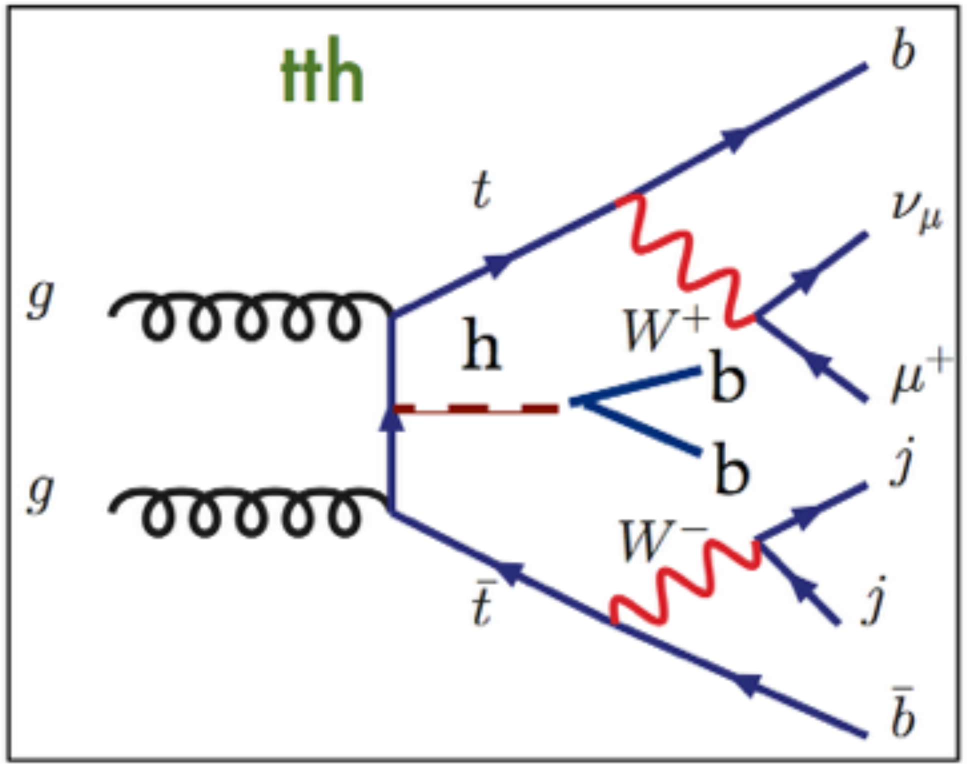
$$W_{\rm ISR}(p_{\rm T}, p_{\rm T}^{\rm vis}) = \begin{cases} \frac{1}{\sqrt{2\pi}(a_2+a_3a_5)}\left[e^{-(p_{\rm T}-p_{\rm T}^{\rm vis}-a_1)^2/(2a_2^2)} + a_3\, e^{-(p_{\rm T}-p_{\rm T}^{\rm vis}-a_4)^2/(2a_5^2)}\right], & \text{for } p_{\rm T}^{\rm vis} > p_{\rm T}^0, \\ \frac{1}{\sqrt{\pi}\, b_2\, p_{\rm T}}\, e^{-(\log(p_{\rm T})-b_1)^2/(2b_2^2)} & \text{for } p_{\rm T}^{\rm vis} < p_{\rm T}^0, \end{cases}$$



TTH: LHC SENSITIVITY

TTH Observation





- Small production rate
  - 0.137 pb (8 TeV)
  - 0.632 pb (14TeV)
- Challenging background
  - tt + (b)jets
  - Combinatorial

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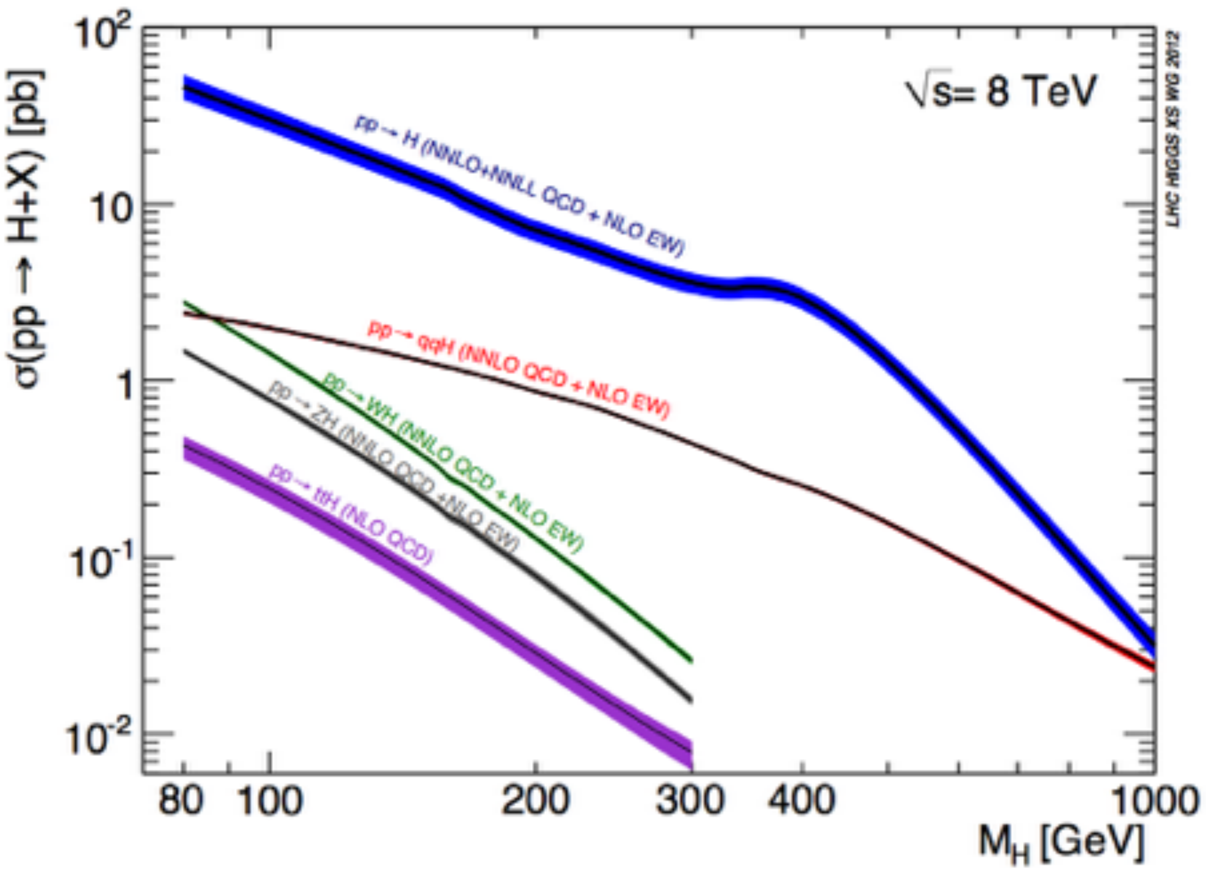

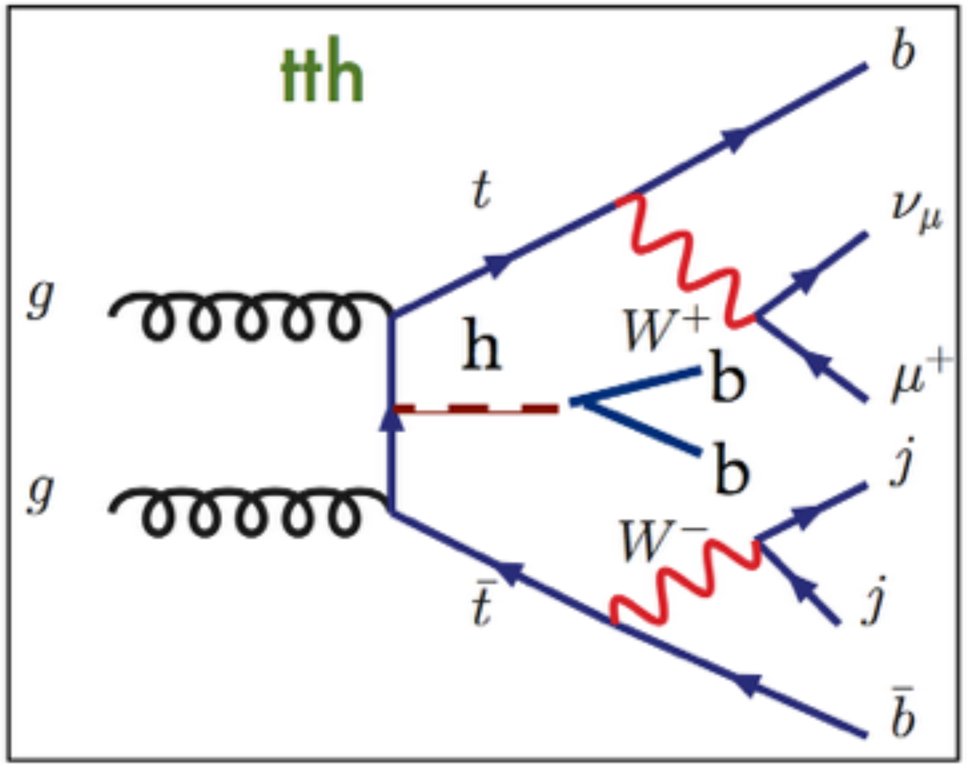

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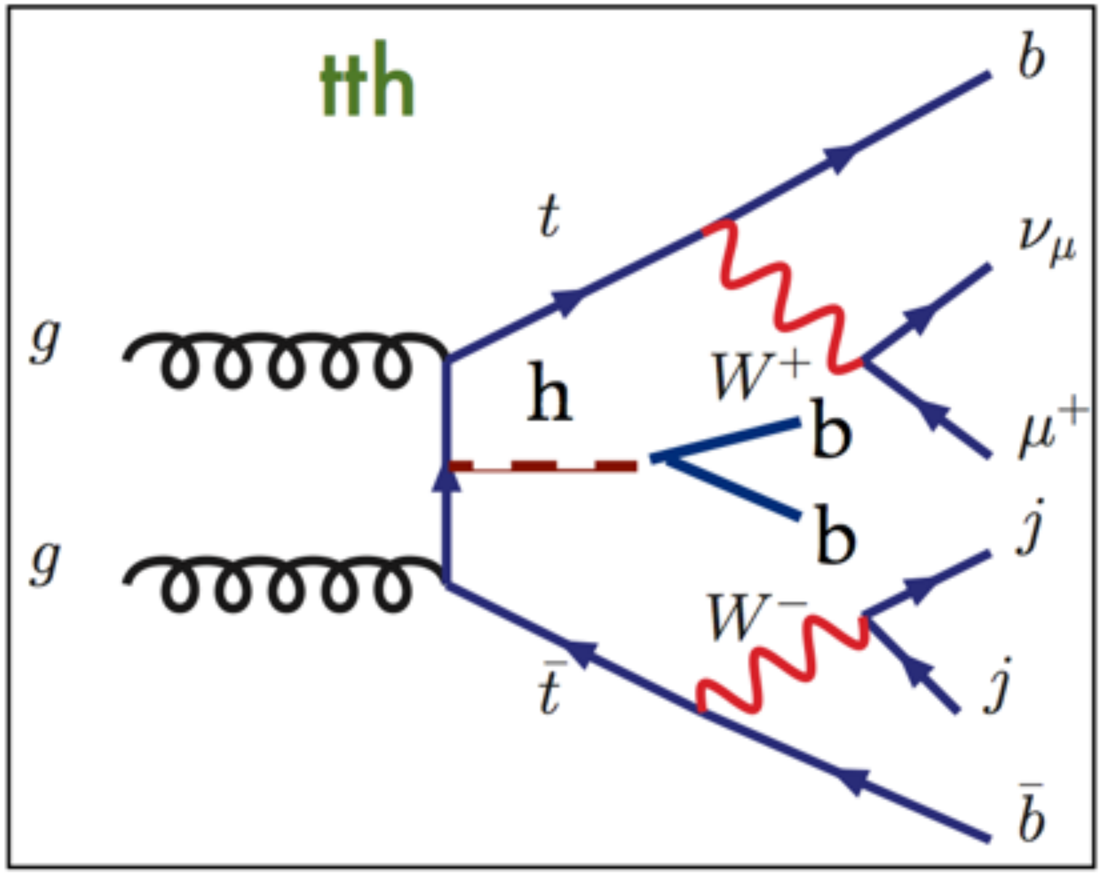
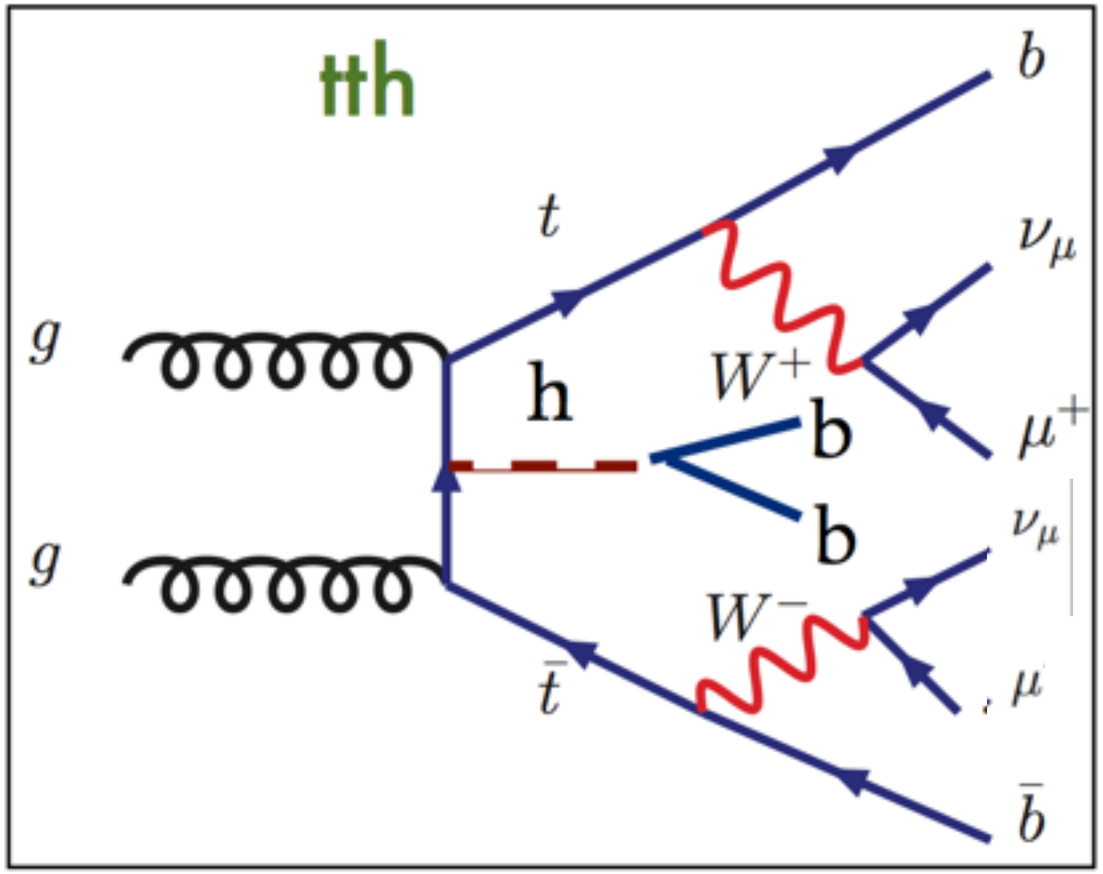
Can the MEM improve the sensitivity?

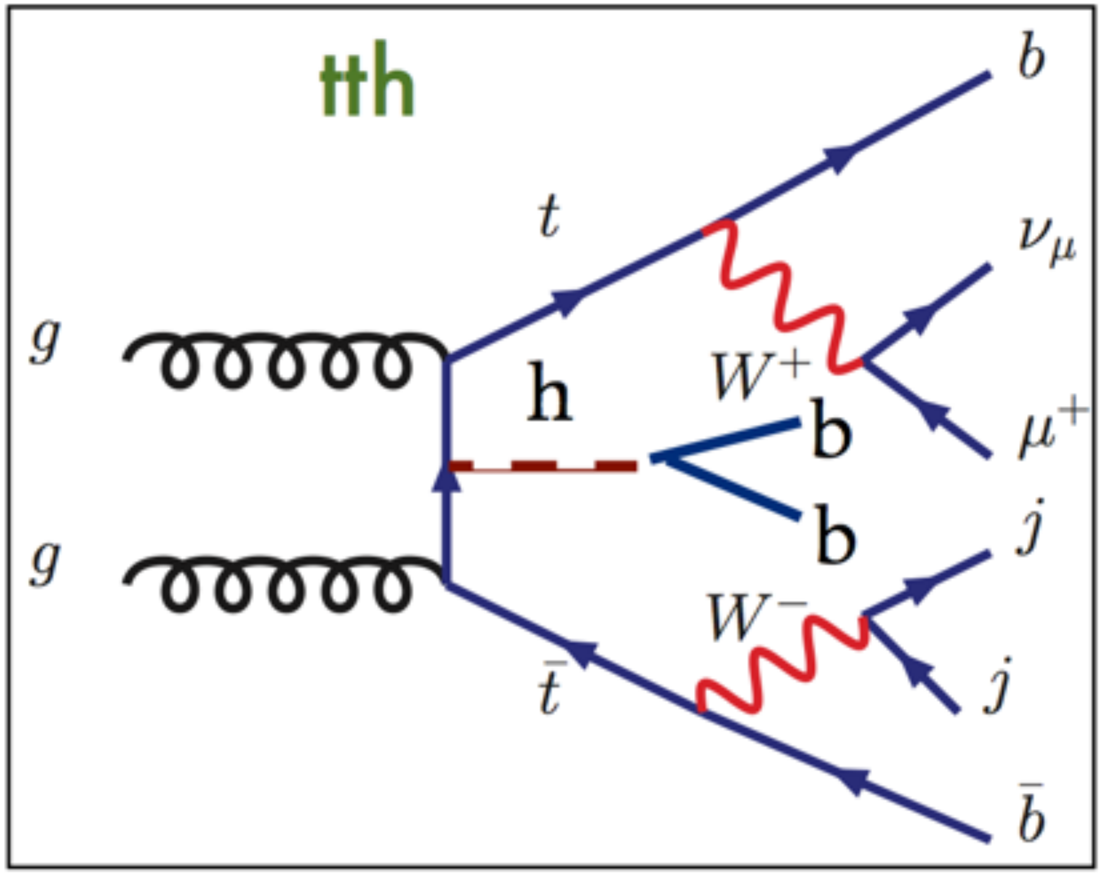
Final State

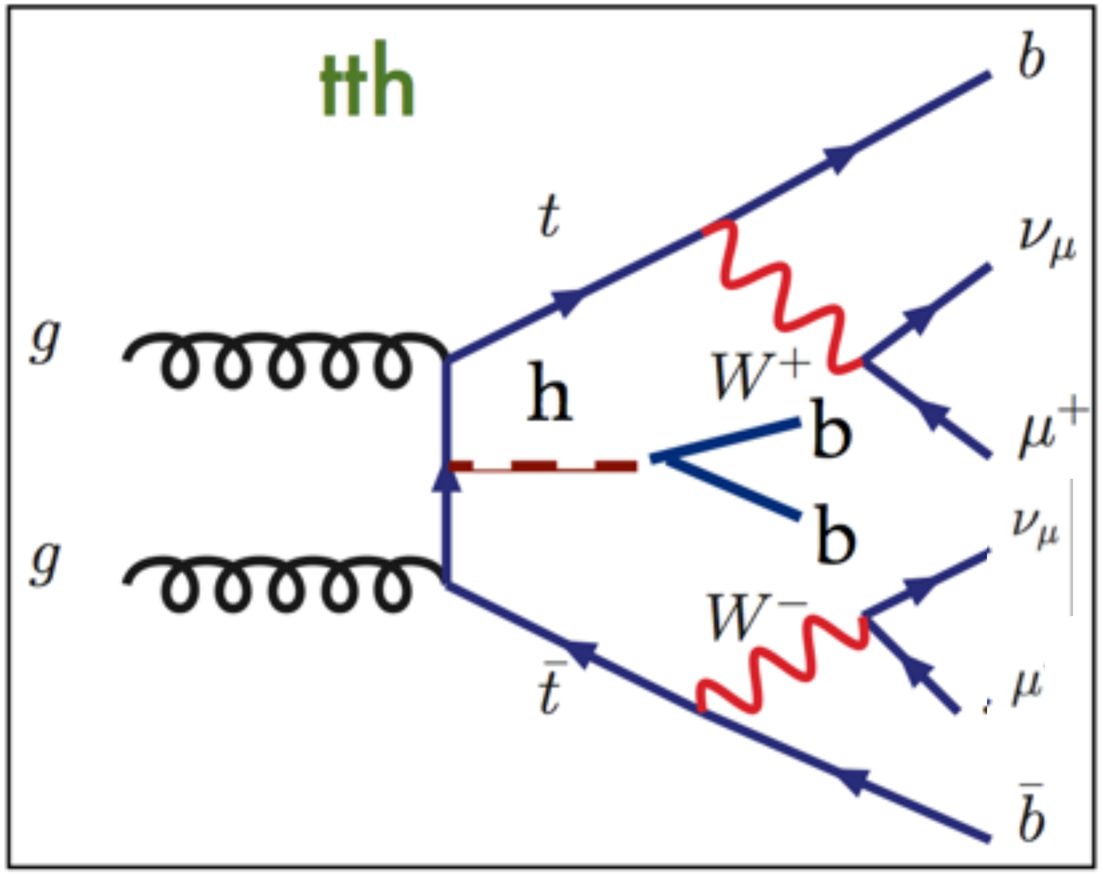




- ☐ Semi-leptonic Decay
- ☐ fully-leptonic Decay

Final State





- Semi-leptonic Decay
- fully-leptonic Decay

Which Channel is the most sensitive?

Event Generation

- Generation: MG5+Pythia6+Delphes2 (14TeV)
- Event selection (CMS type of selection)
  - Lepton: $P_T > 20\,, |\eta| < 2.4$
  - Jets: (anti-KT,$\Delta R = 0.5$) $P_T > 30\,, |\eta| < 2.5$
  - at least four tagged b-jets

process	incl. σ	efficiency	$\sigma^{\rm rec}$
$t\bar{t}h$, single-lepton	111 fb	0.0485	5.37 fb
$t\bar{t}h$, di-lepton	17.7 fb	0.0359	0.634 fb
$t\bar{t}$+jets, single-lepton	256 pb	0.463×10^{-3}	119 fb
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb

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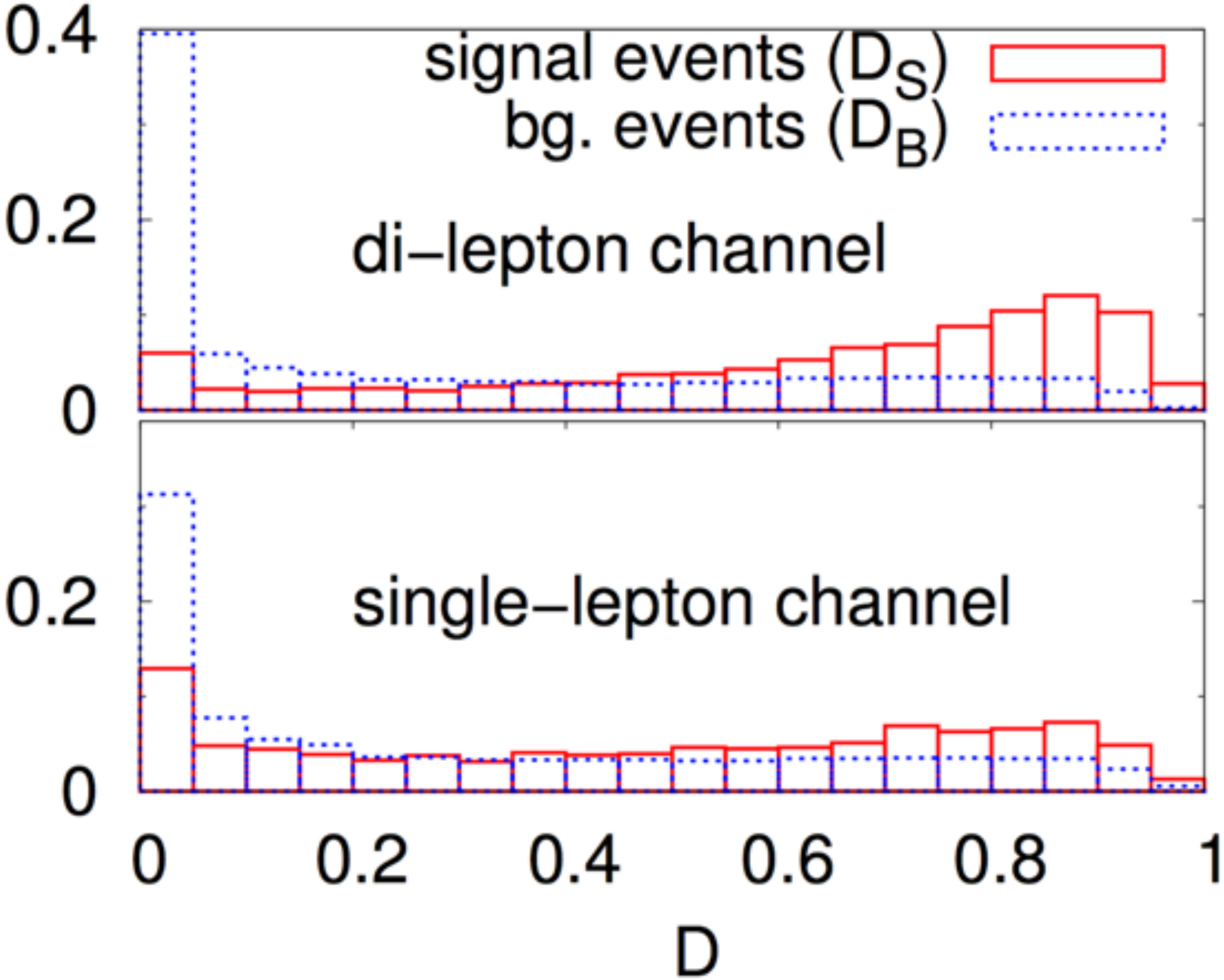
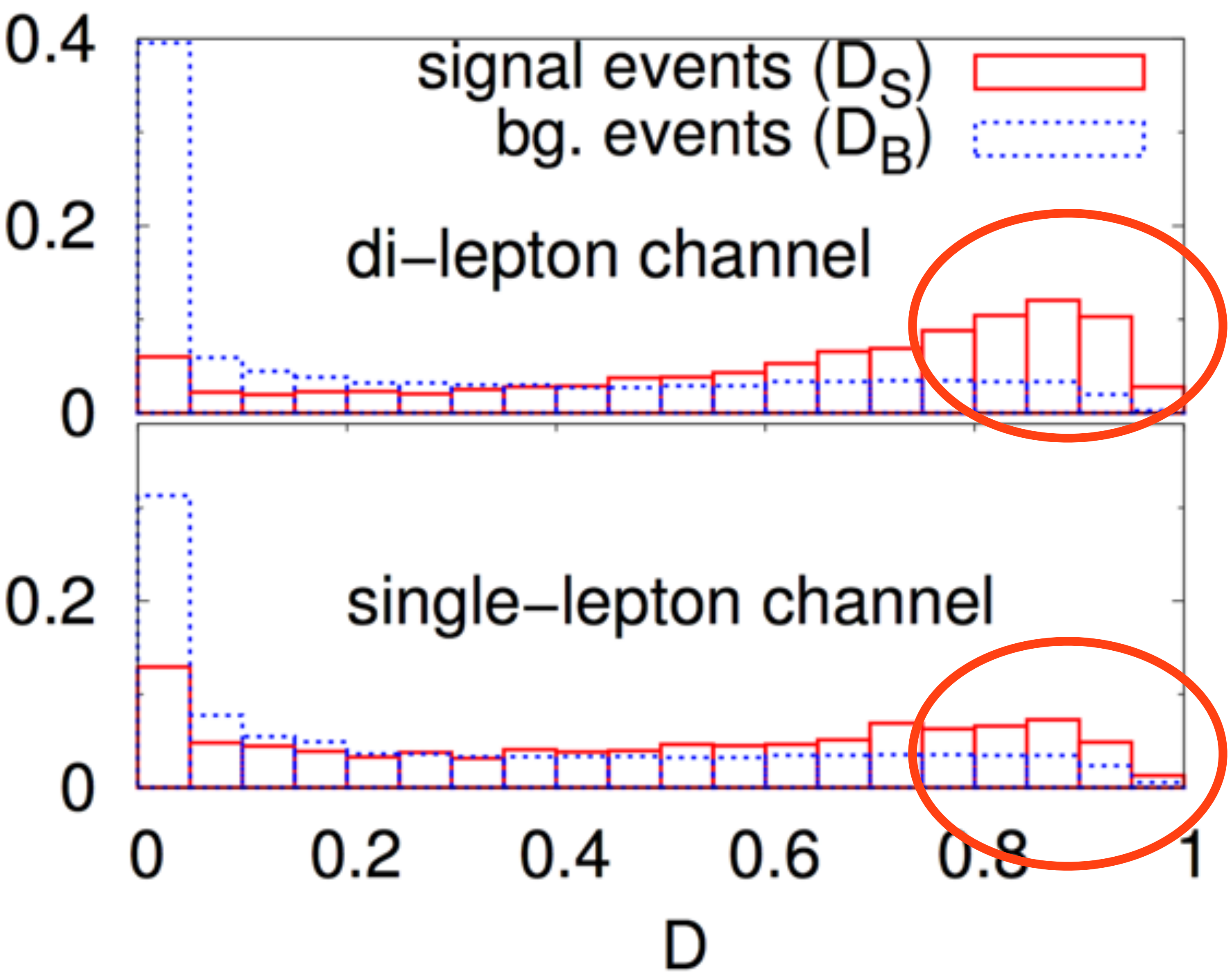
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb	1/11

$$\mathcal{P}(\boldsymbol{p}^{vis}|\alpha) = \frac{1}{\sigma_\alpha}\int d\Phi dx_1 dx_2 |M_\alpha(\boldsymbol{p})|^2 W(\boldsymbol{p}, \boldsymbol{p}^{vis})$$

- Transfer function:
  - perfect resolution on charged leptons
  - perfect resolution for jets angle
  - double gaussian with energy dependencies for jets energy
- Matrix-element
  - With ISR boost correction
  - tth for signal
  - ttbb for background



$$D_i = \frac{P(\boldsymbol{x}_i|S)}{P(\boldsymbol{x}_i|S) + P(\boldsymbol{x}_i|B)}.$$



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- Higher discriminative power for di-leptonic channel
- less background combinatorics

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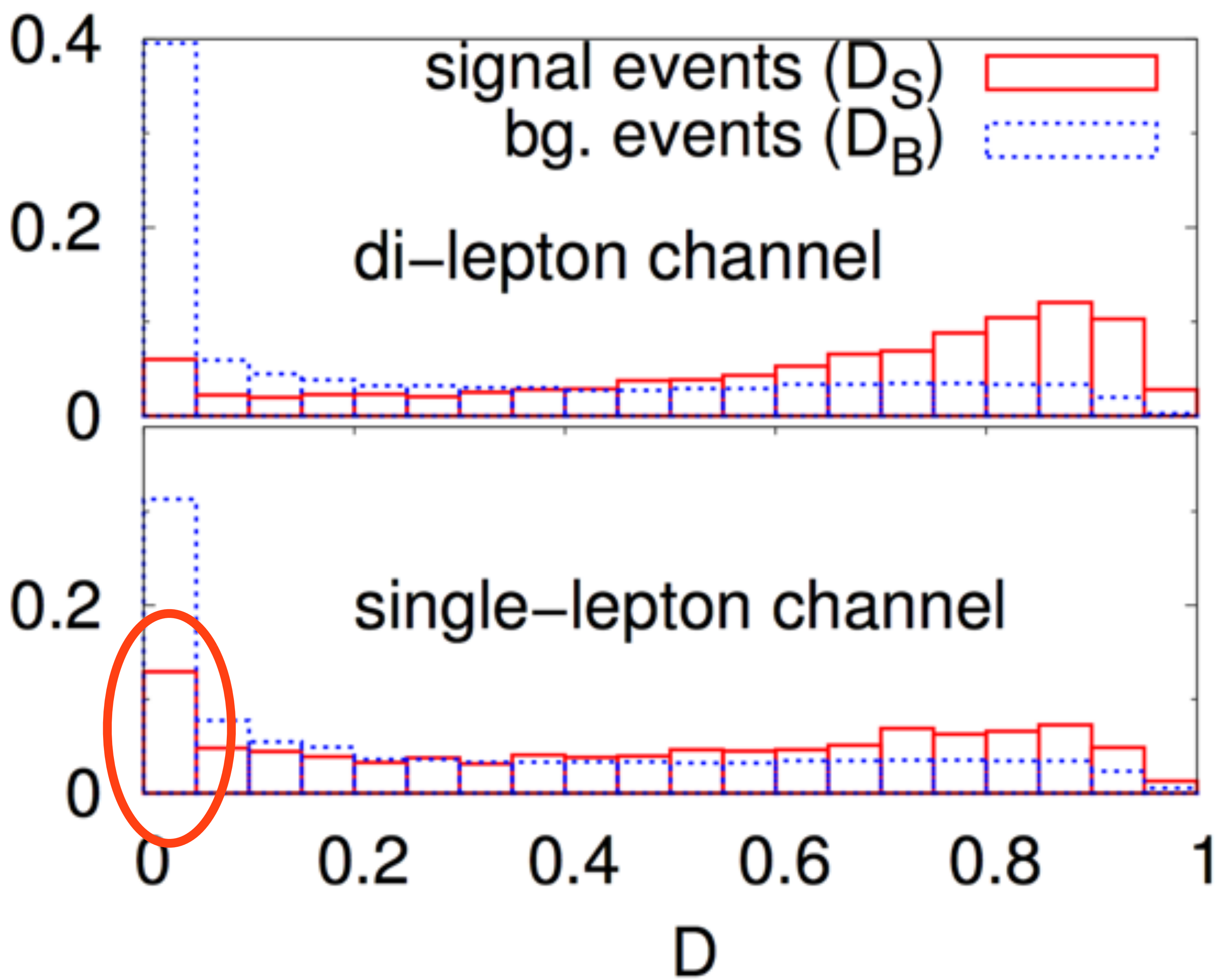
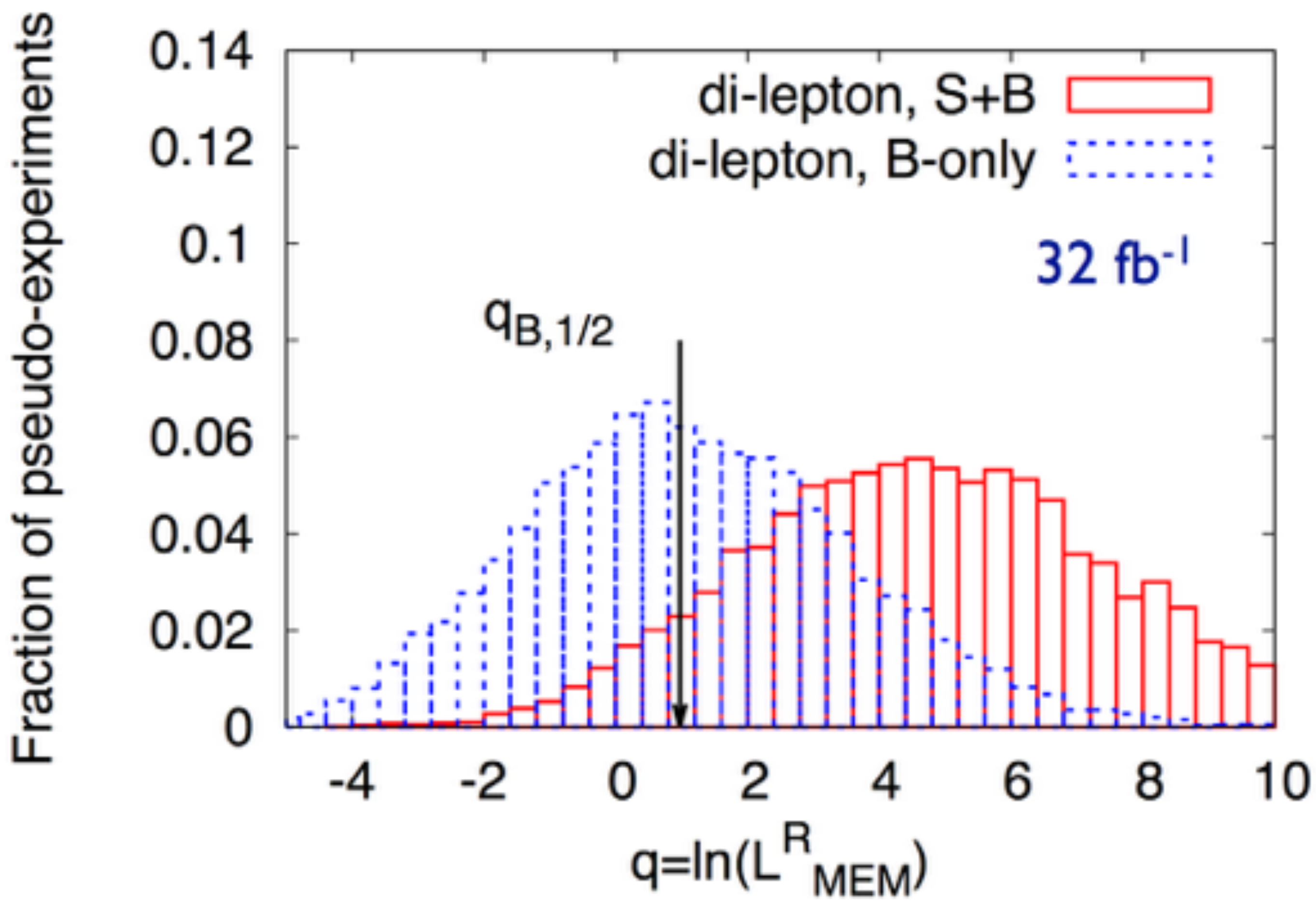


- Higher discriminative power for di-leptonic channel
  - less background combinatorics
- Higher probability to select the "wrong" jets for semi-leptonic channel.

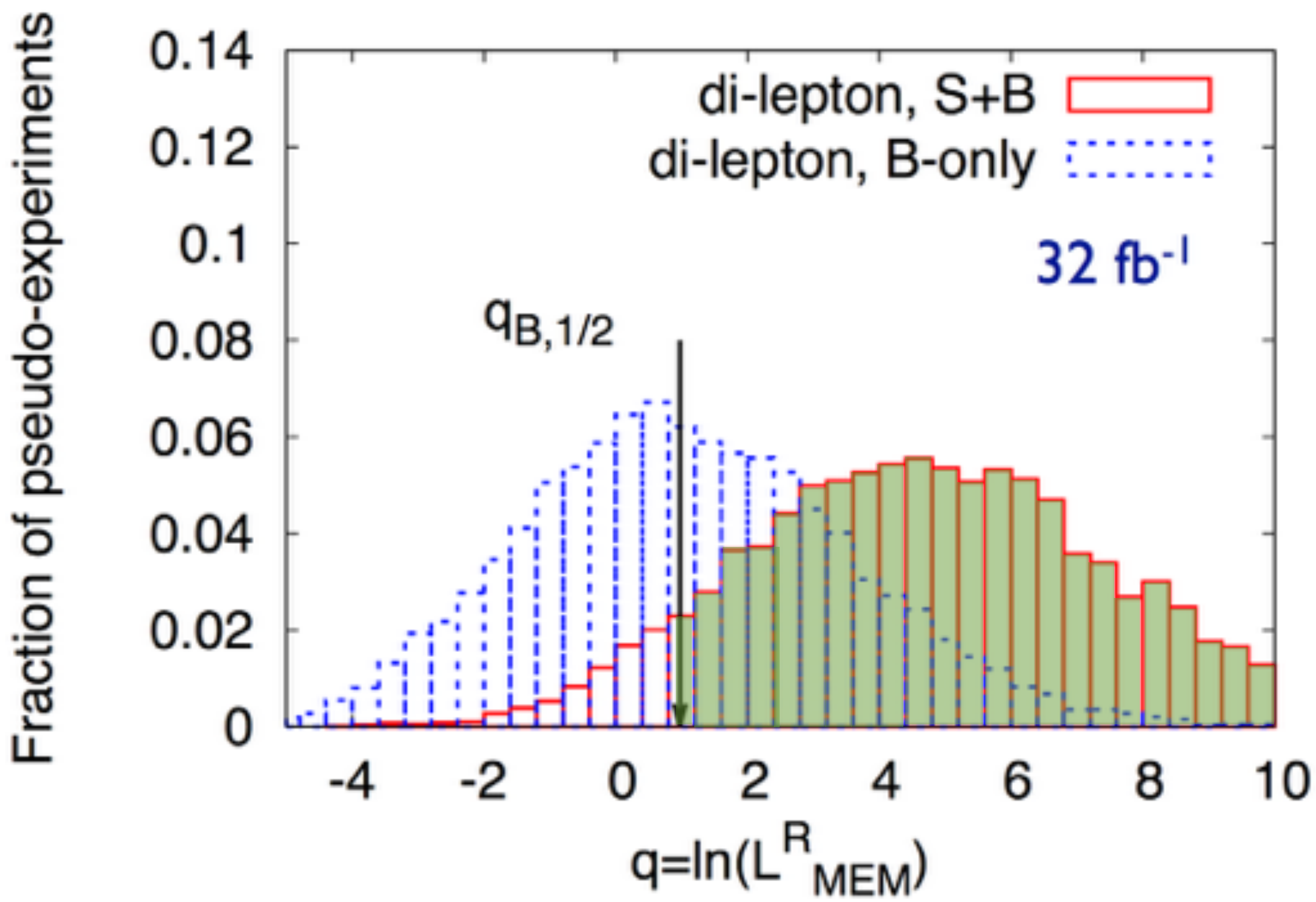
$$L^R_{MEM} = \prod_i^N \frac{r_0 P(x_i|S) + (1-r_0)P(x_i|B)}{P(x_i|B)} \qquad r_0 = \frac{s_0}{s_0 + b_0}$$



- Test: confidence level in rejecting S+B if B-only is realized

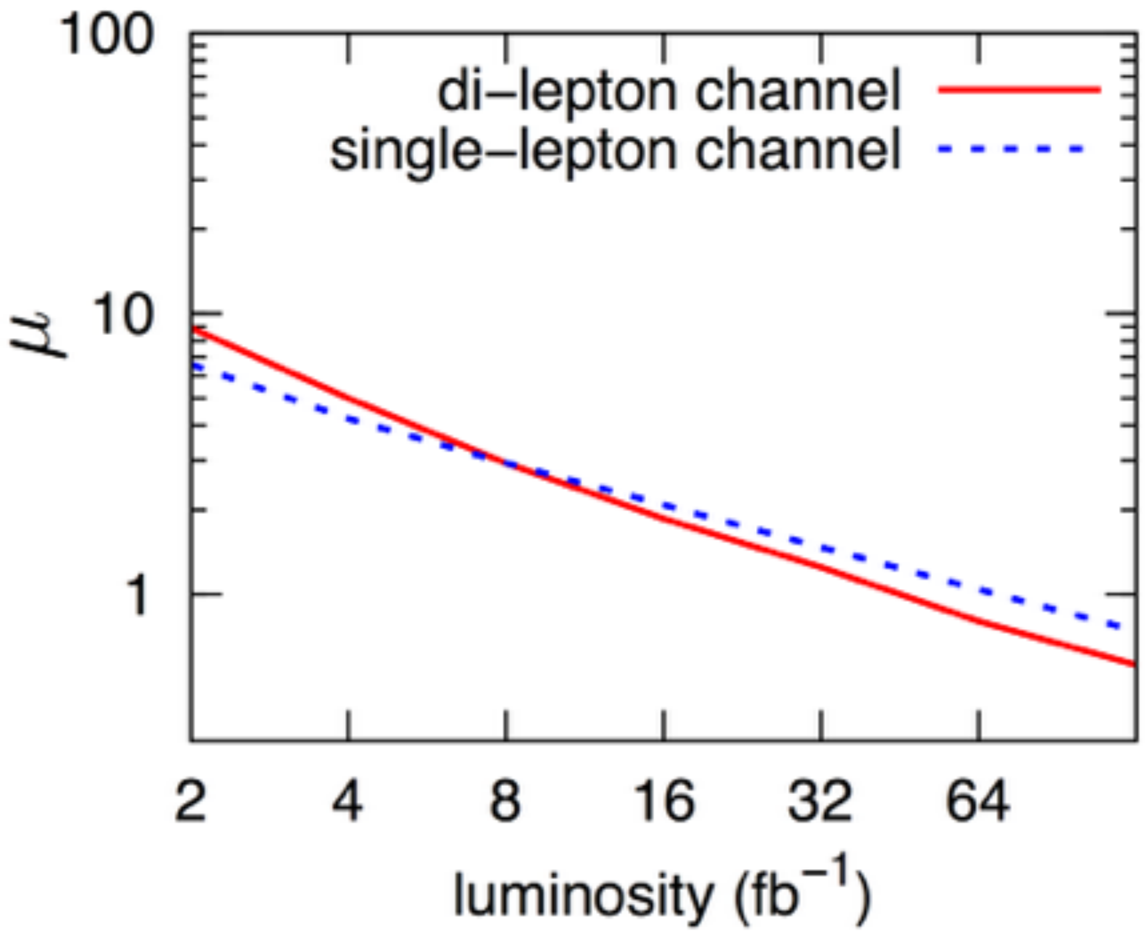
$$L_{MEM}^{R} = \prod_{i}^{N} \frac{r_0 P(x_i|S) + (1-r_0)P(x_i|B)}{P(x_i|B)}$$

$$r_0 = \frac{s_0}{s_0 + b_0}$$



- Test: confidence level in rejecting S+B if B-only is realized
- correspond to the green integral

- rescale the cross section by a factor μ such that S+B is excluded at 95% C.L



95% c.l.	$40 fb^{-1}$
3σ	$120 fb^{-1}$
5σ	$420 fb^{-1}$

Conclusion

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- Matrix Element Re-Weighting: path to precise measurement

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  - LO order method

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  - Allows precise Mass/Spin measurements
    - Use the full theoretical information
    - A lot of experimental information
- Radiation is a bottleneck
  - Need new way to deal with them (FSR)

Conclusion

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    - LO order method
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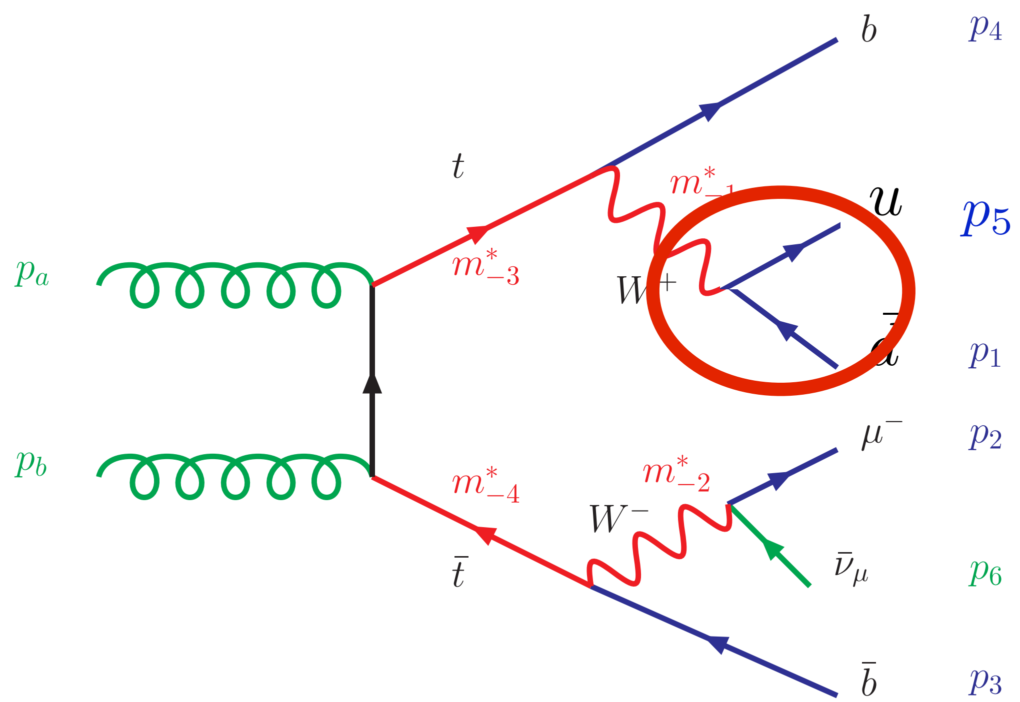
    - Allows precise Mass/Spin measurements
        - Use the full theoretical information
        - A lot of experimental information
- Radiation is a bottleneck
    - Need new way to deal with them (FSR)
- MEM is able to handle successfully complicated process like tth

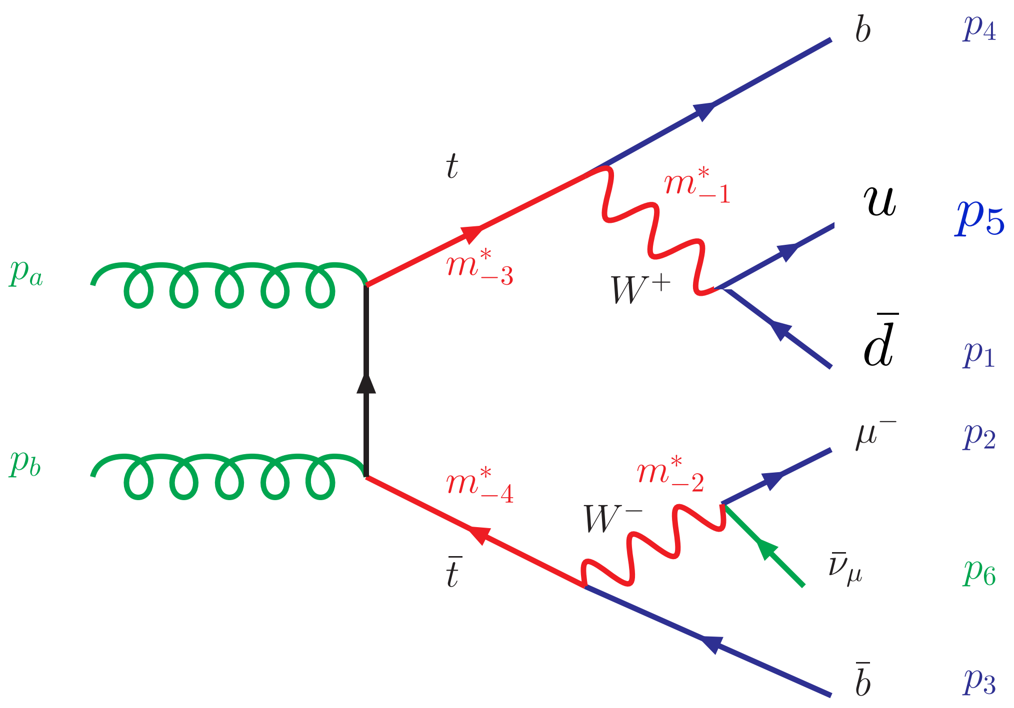
Backup slide

- Second Example: semi-leptonic top quark pair



- degrees of freedom 16
- peaks 19

- Second Example: semi-leptonic top quark pair



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- peaks 19

→ 3 peaks unaligned

→ Multi-channel

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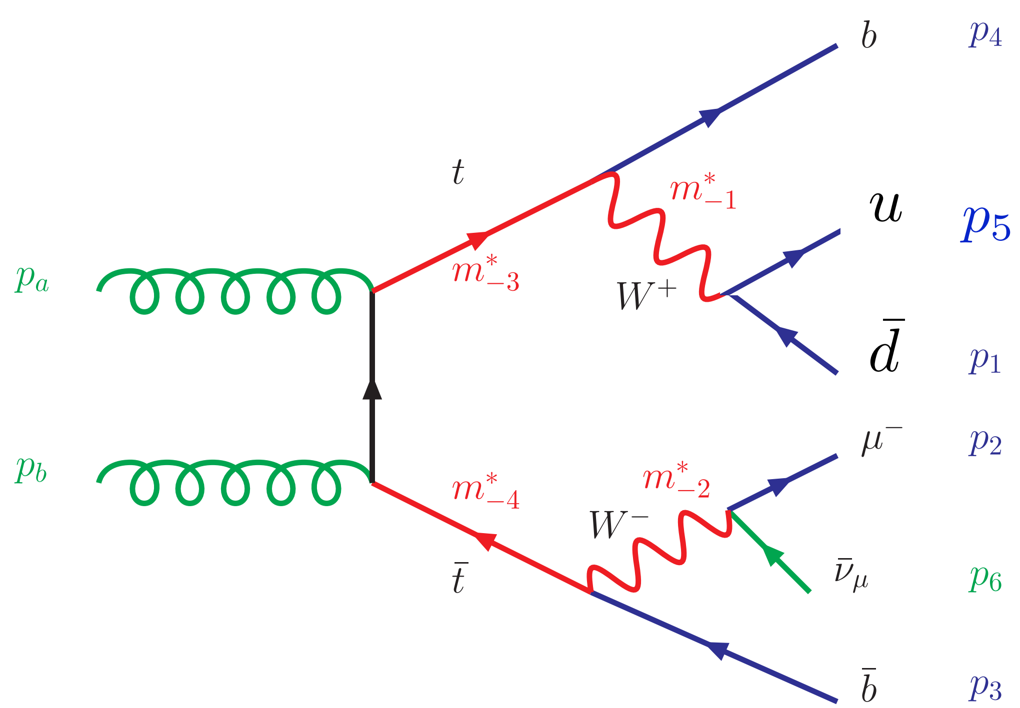

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→ Multi-channel

$$d\phi = \prod_{i=1}^{5} \frac{d^3 p_i}{(2\pi)^3 2E_i} \frac{d^3 p_6}{(2\pi)^3 2E_6} dx_1 dx_2 \delta^4(p_a + p_b - \sum_j p_j)$$

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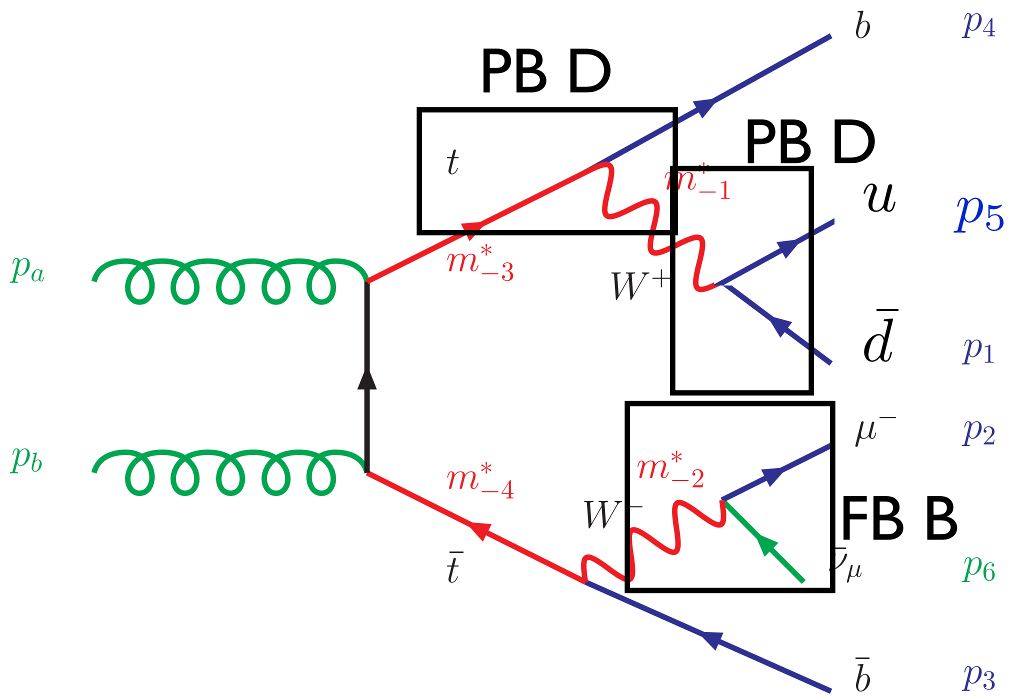

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Pass to

$$d\phi = \prod_{i=1}^{5} d\theta_i d\phi_i \prod_{j=1}^{3} d|\boldsymbol{p}_i| \prod_{k=1}^{3} dm^{*2}_{-k} \times J$$

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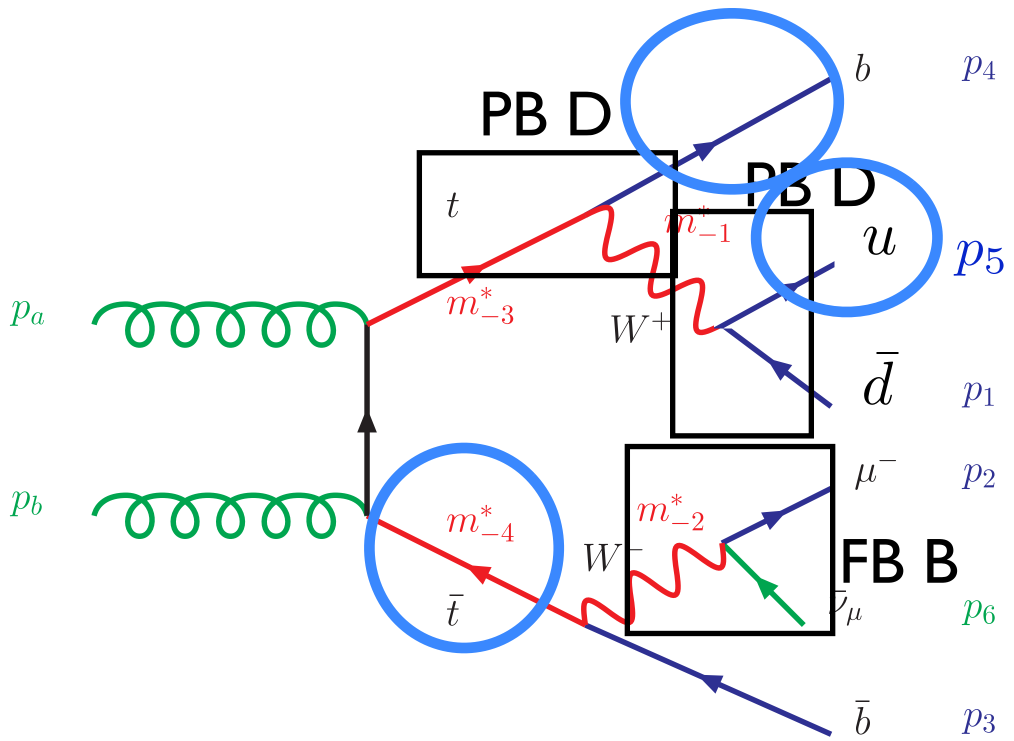

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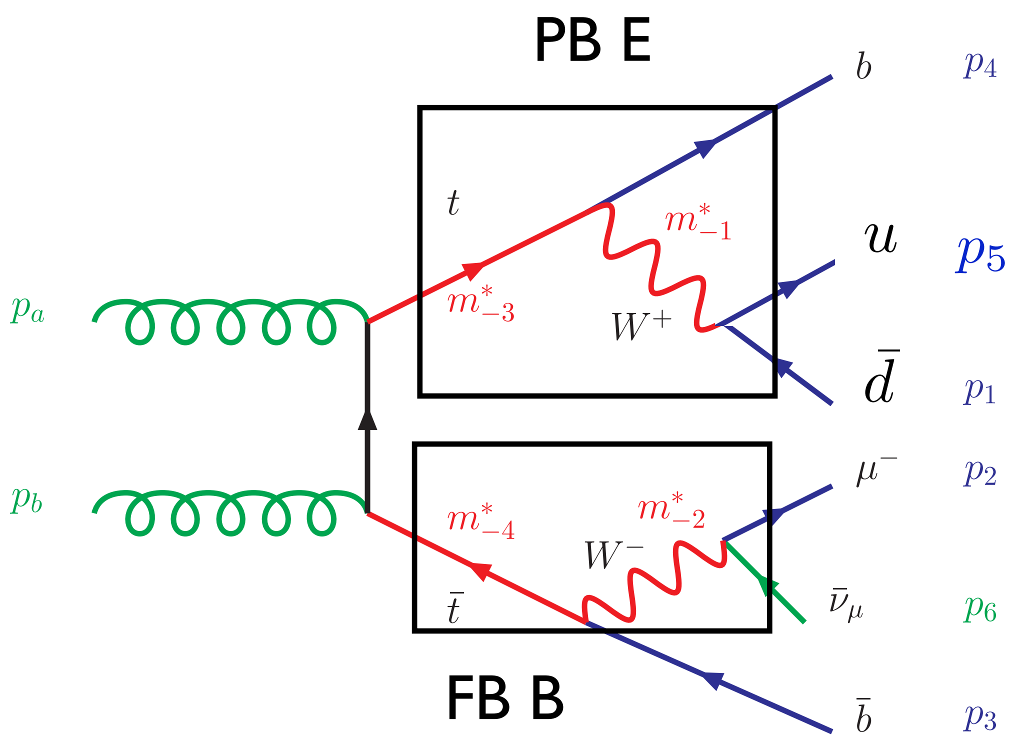

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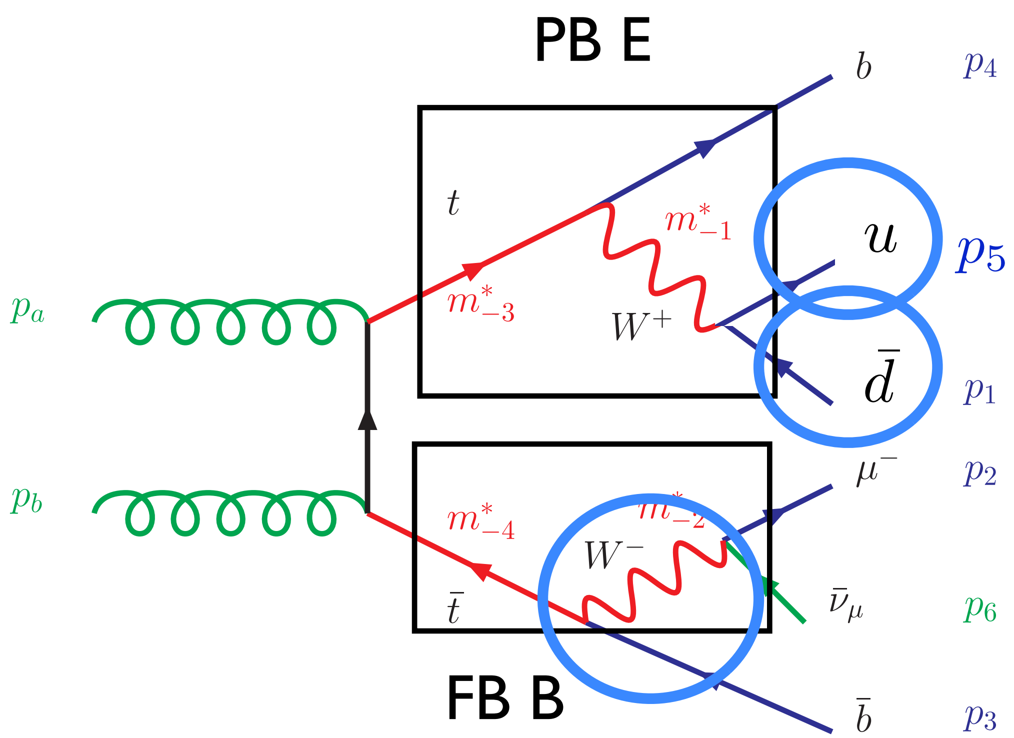

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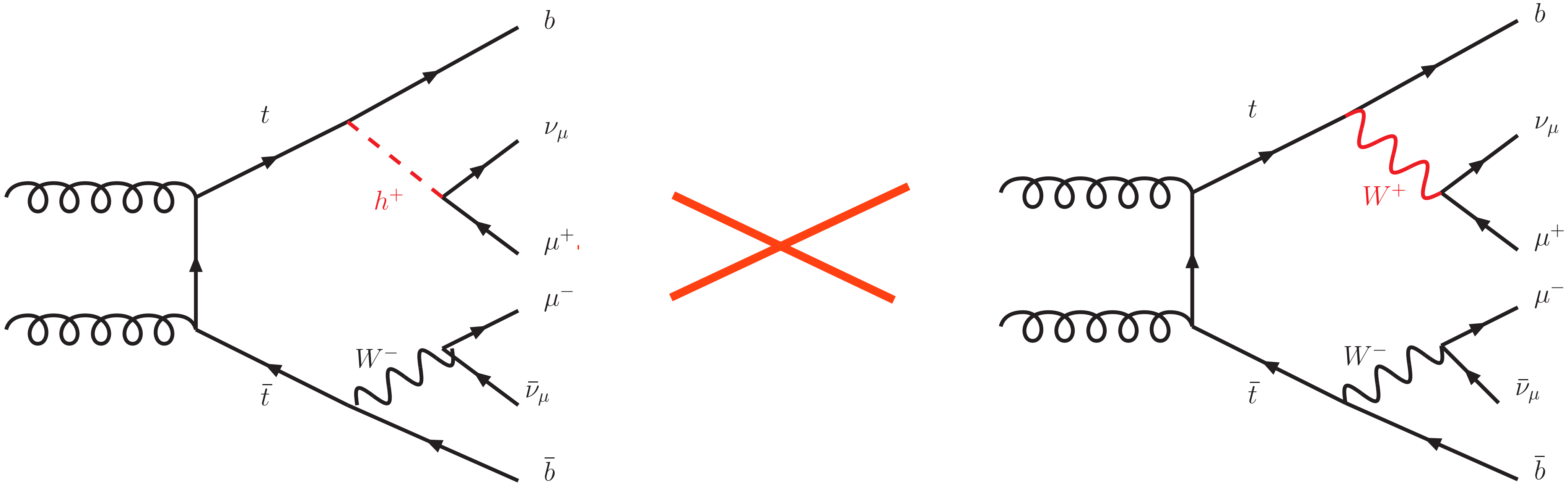
MadWeight

- the phase-space is split into blocks, each of them is associated to a specific local change of variables
- 12 blocks, i.e. 12 analytic changes of variables have been defined in our code.
- MadWeight finds automatically
  - the optimal partition of the PS into blocks
  - computes the weights using the corresponding PS parametrisation

Signal/Background

- Estimate Charged Higgs contribution



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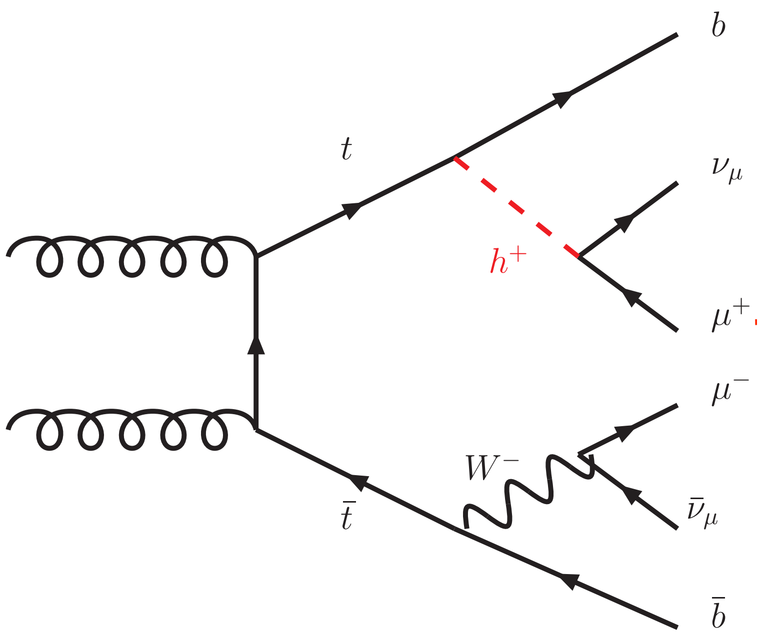
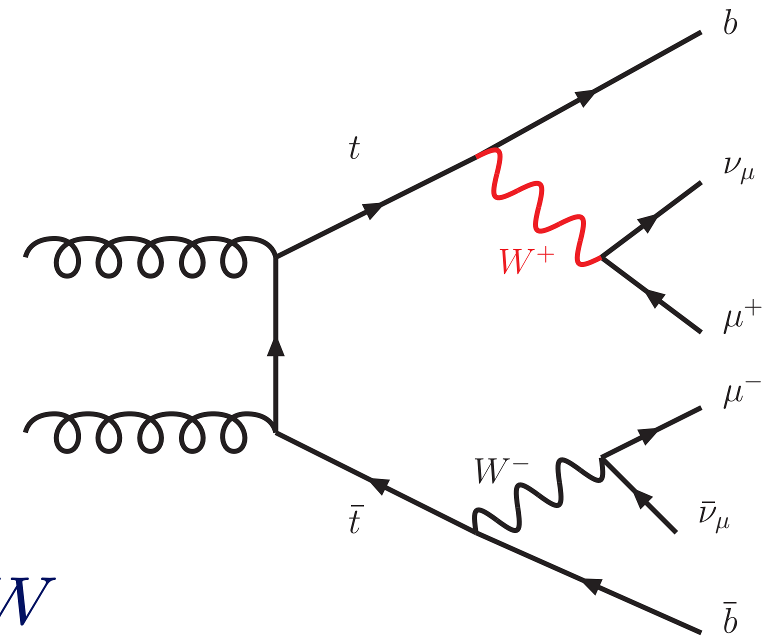


$$M_{H^+} = M_W$$



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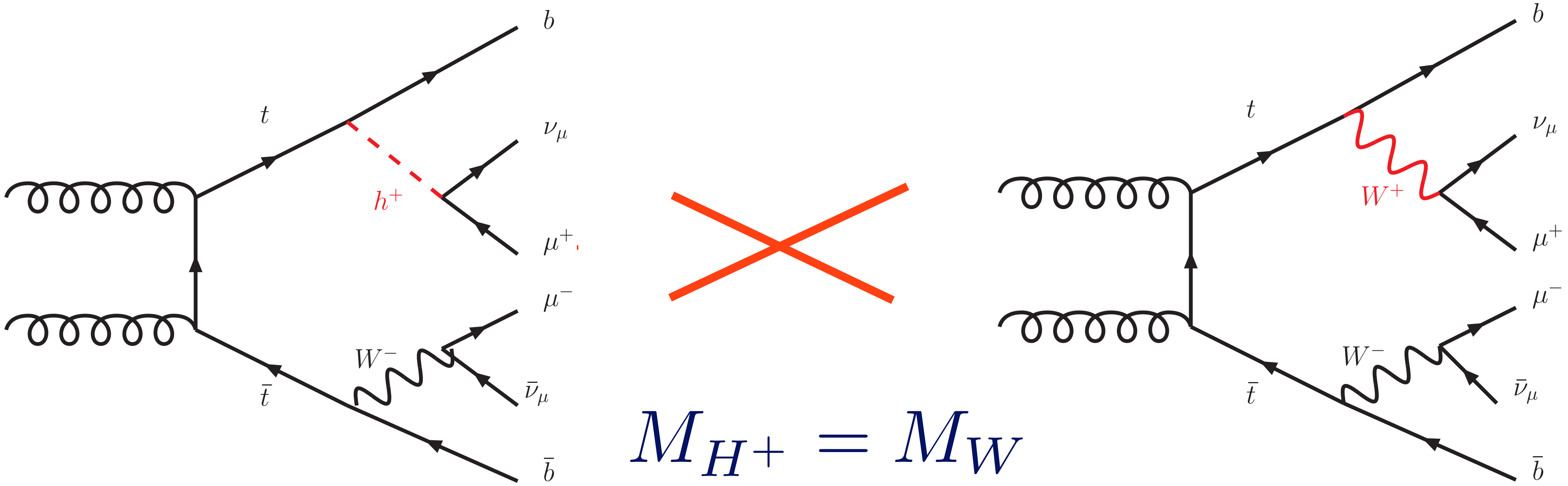

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$$d = \frac{P_S}{P_S + P_{BG}}$$

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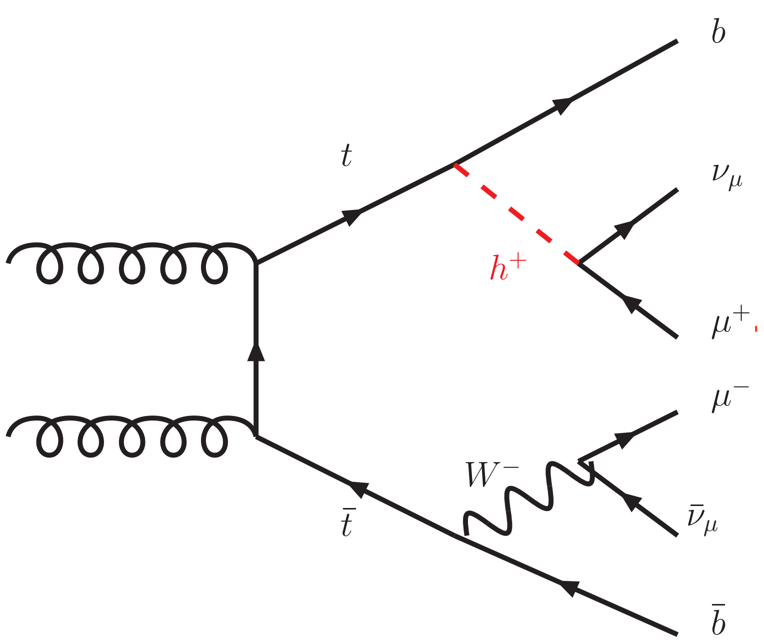

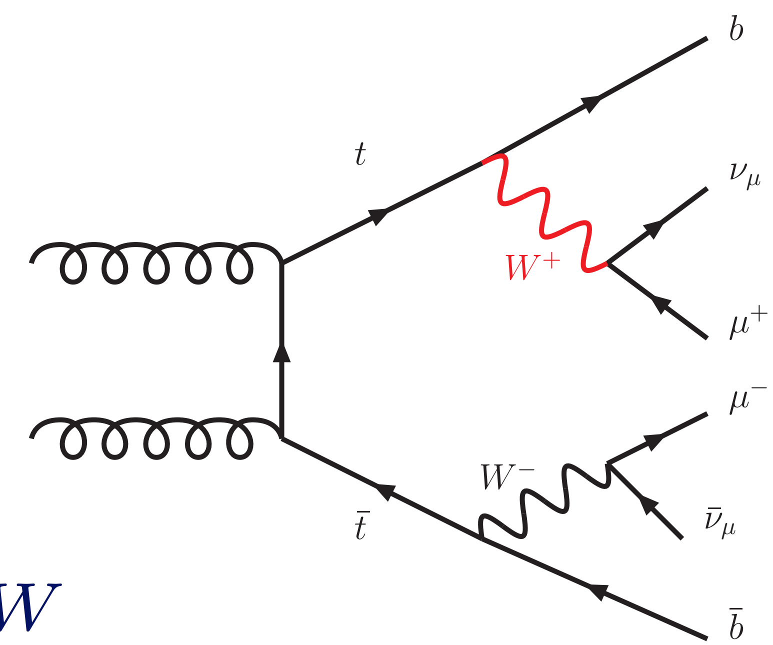

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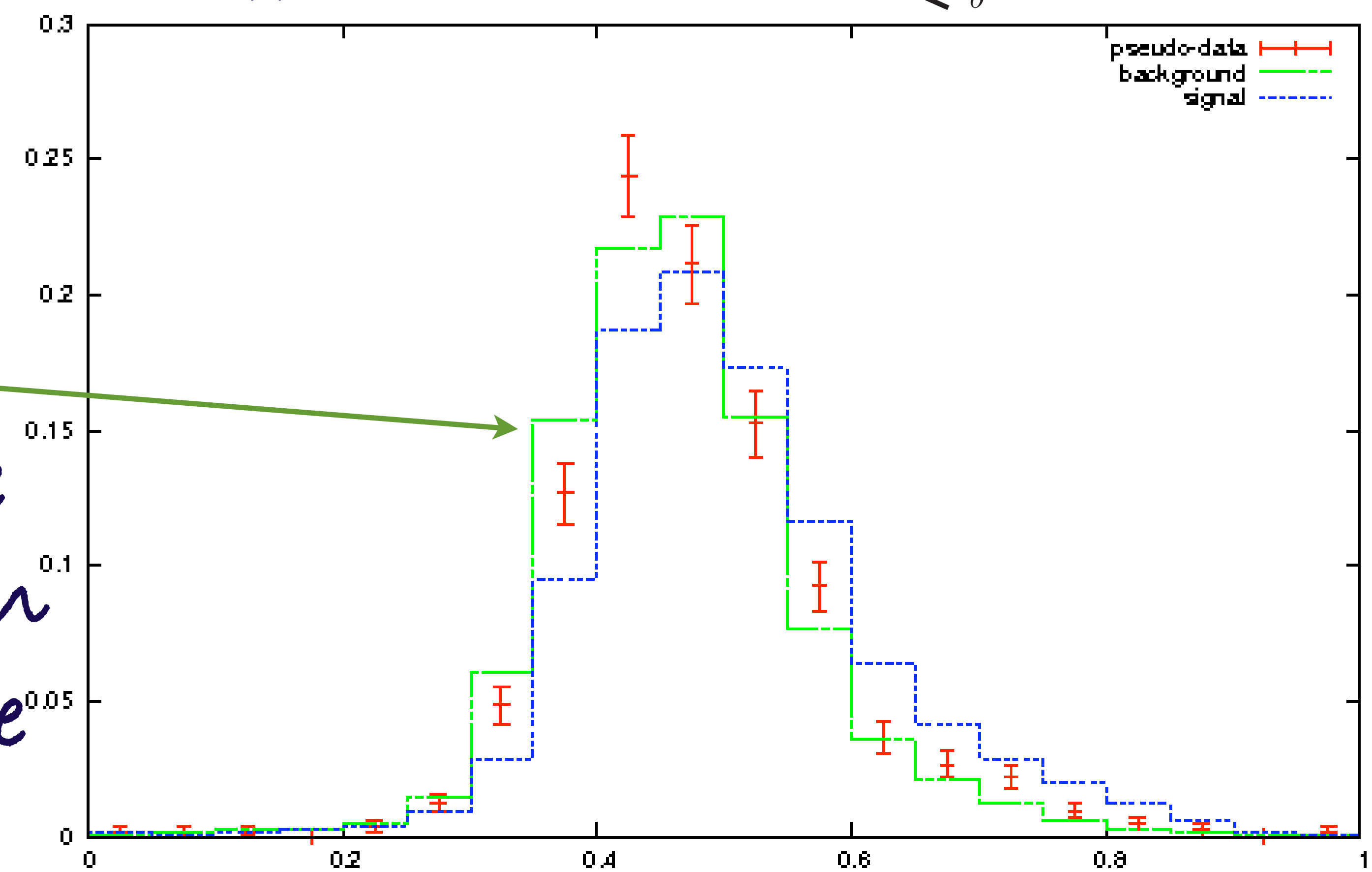
Probability for one event to have a given discriminant value



Signal/Background

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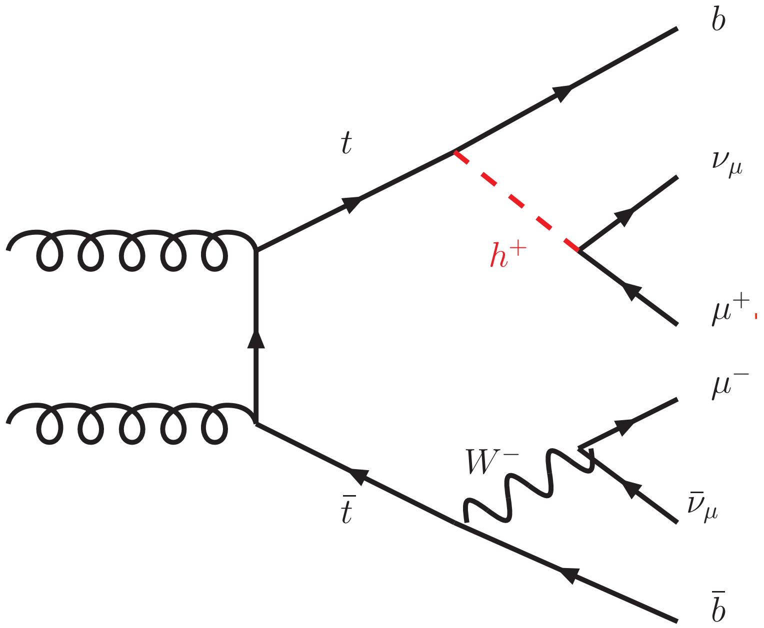

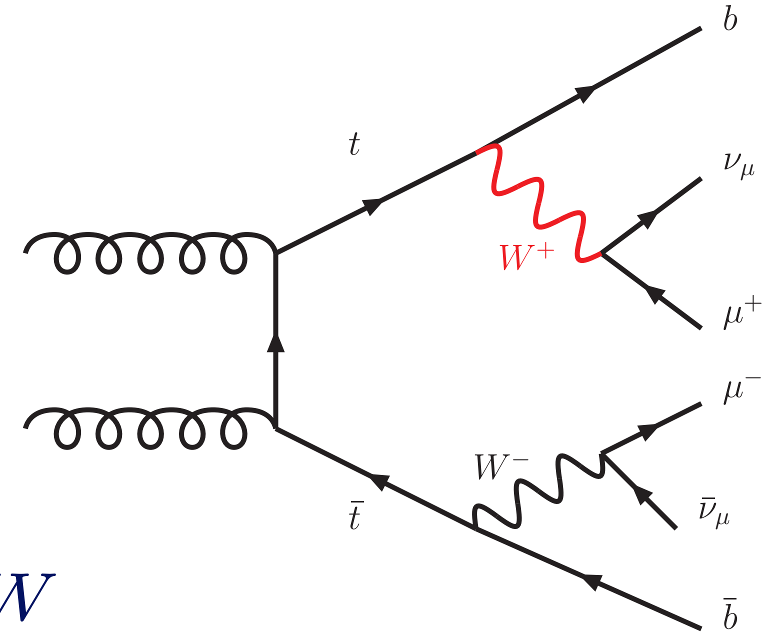

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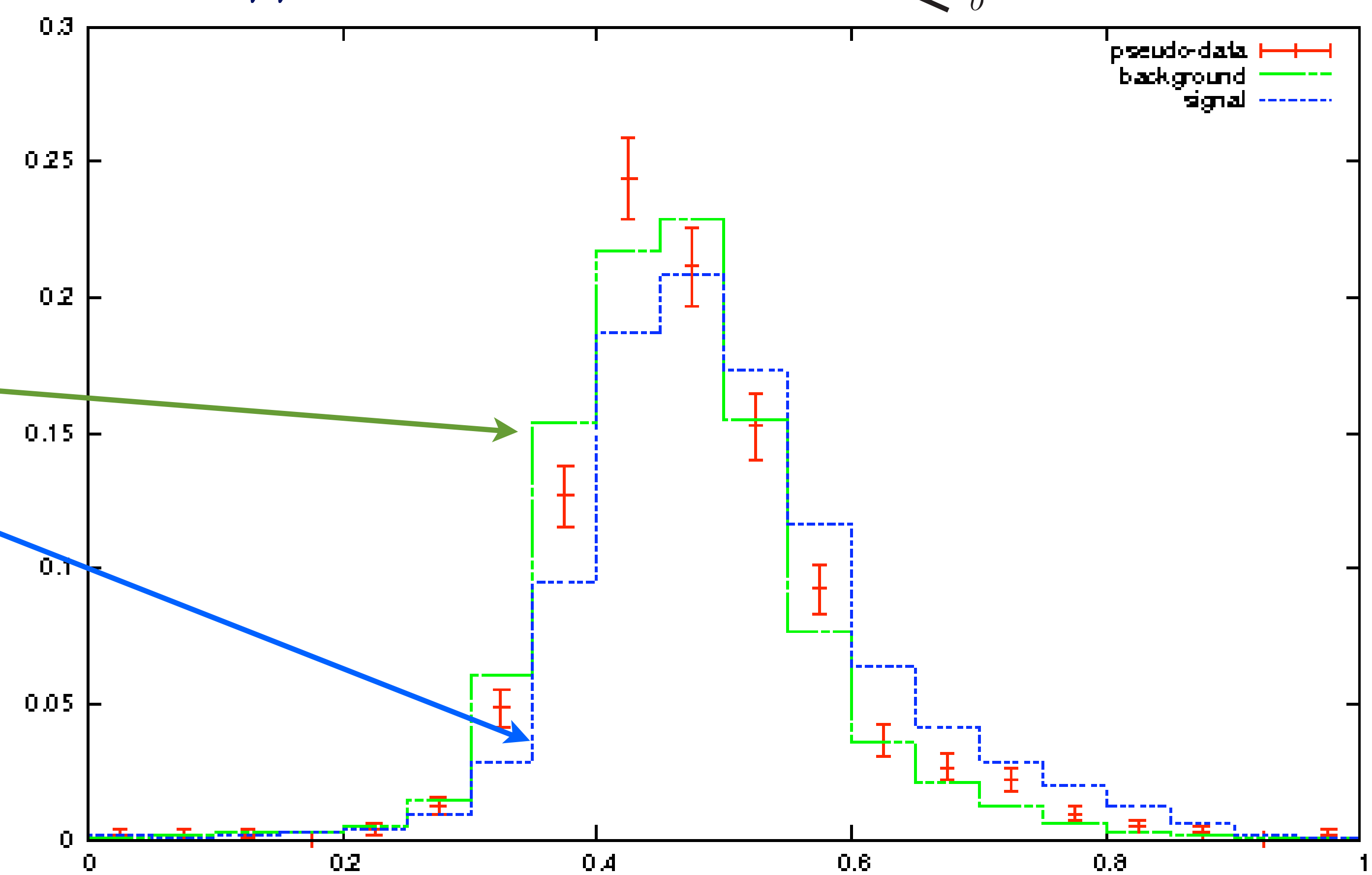

Signal/Background

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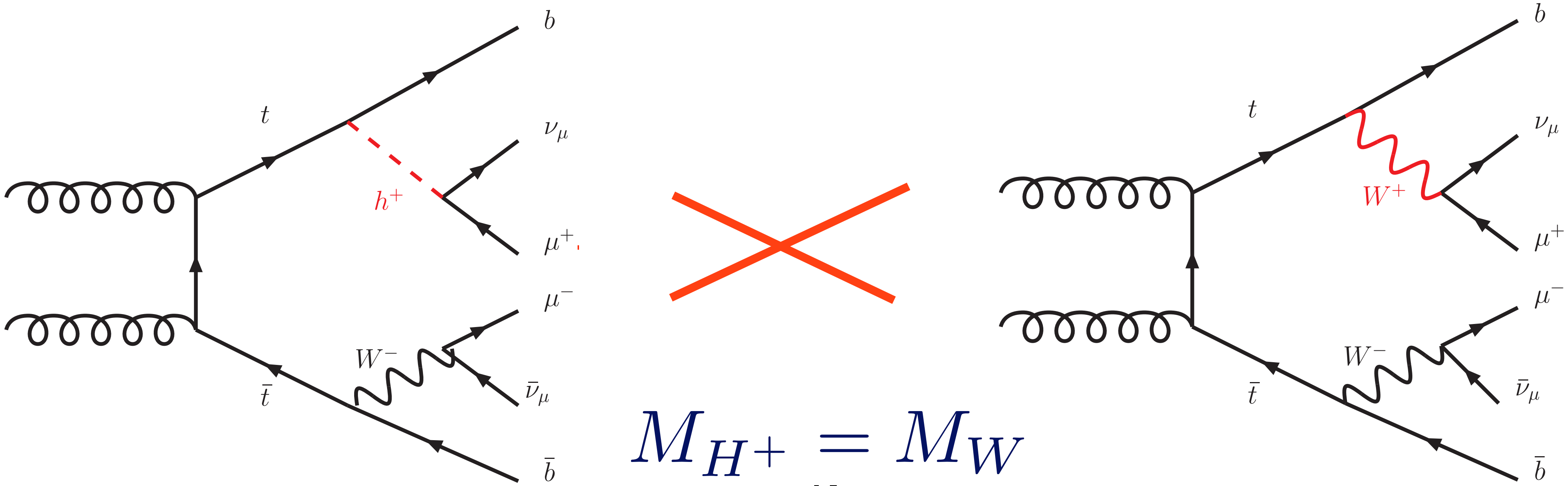

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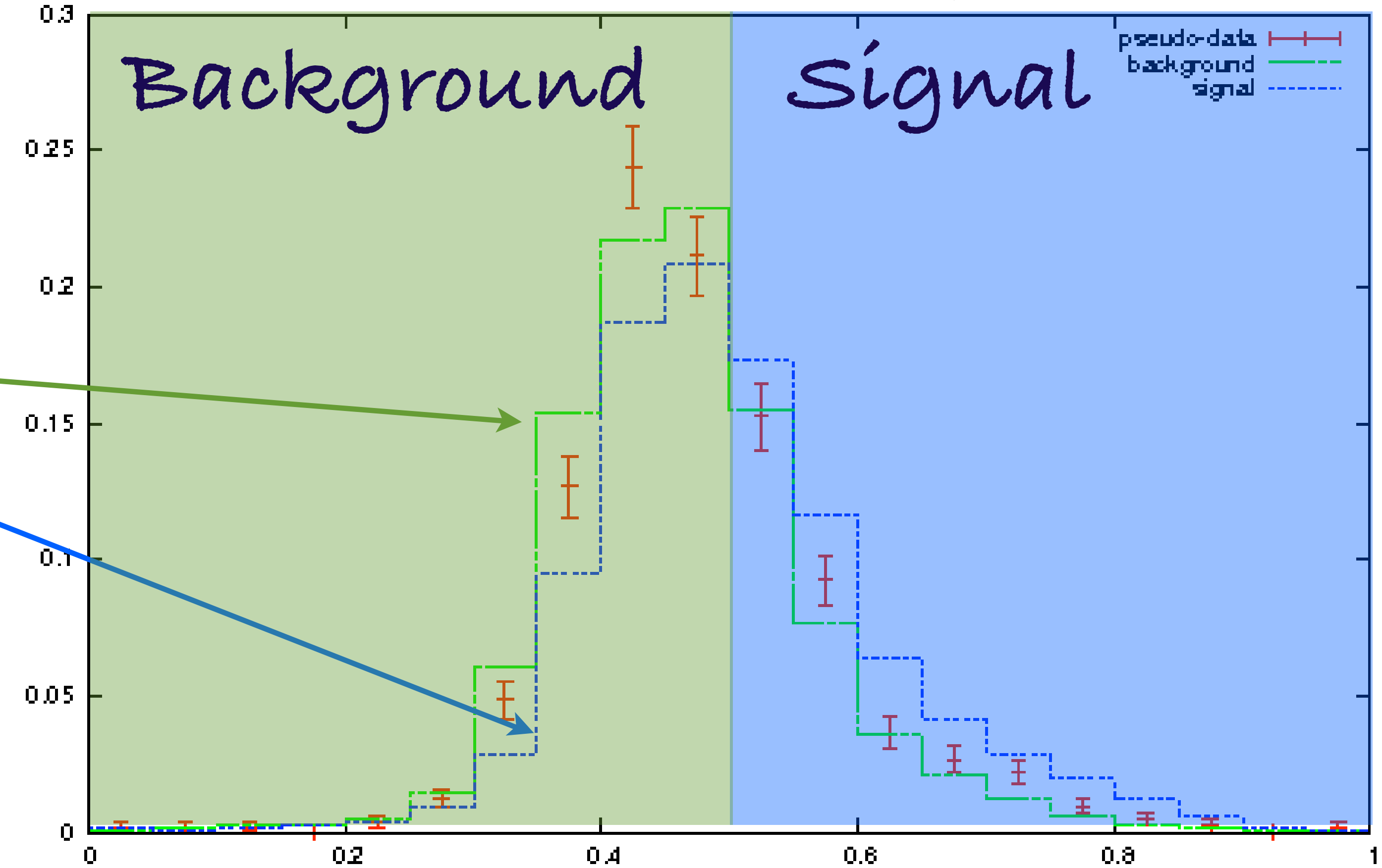

Signal/Background

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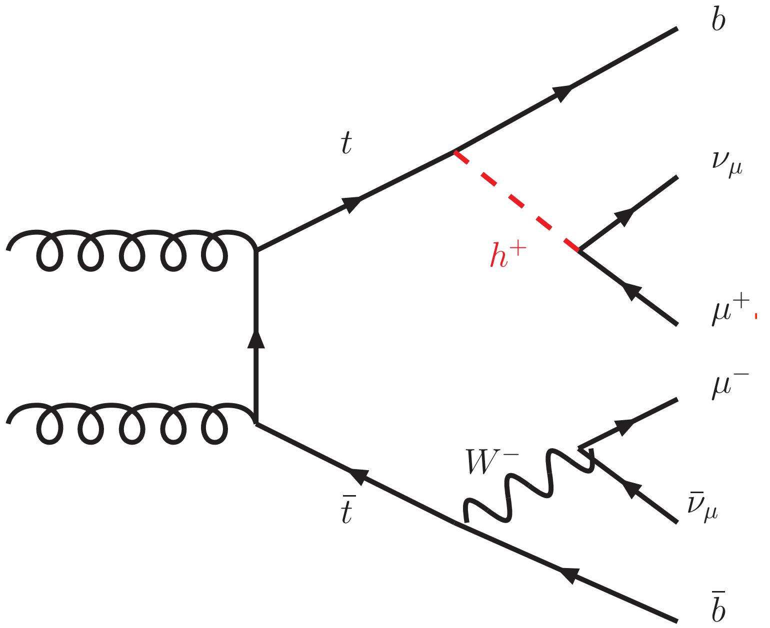

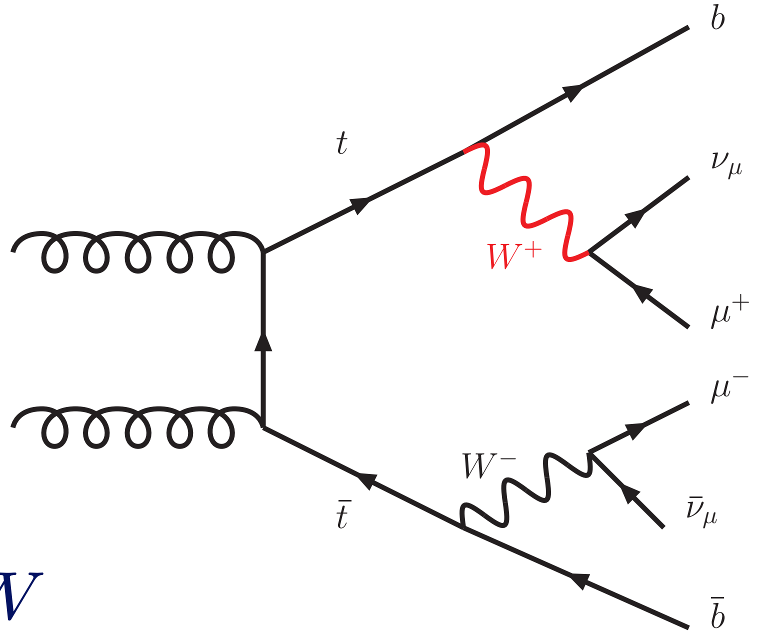

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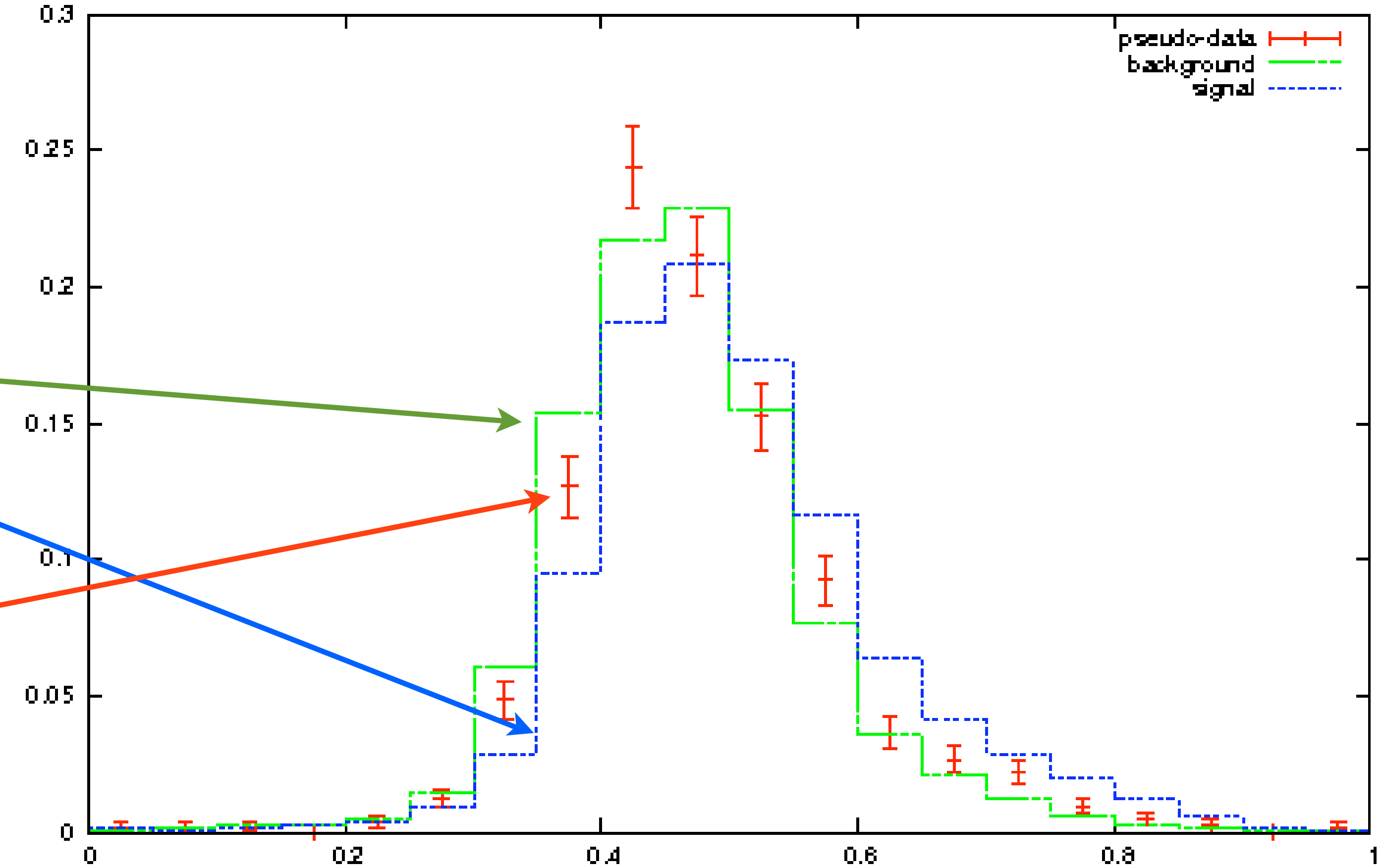
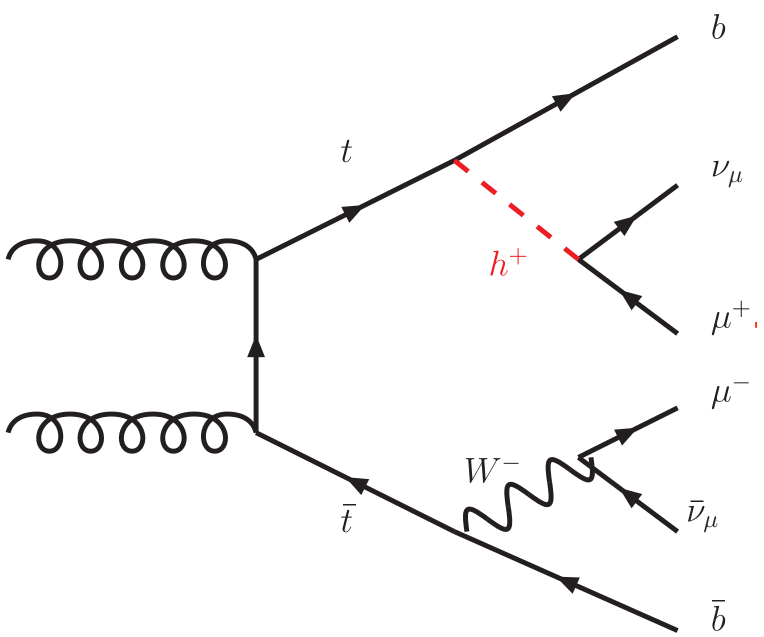
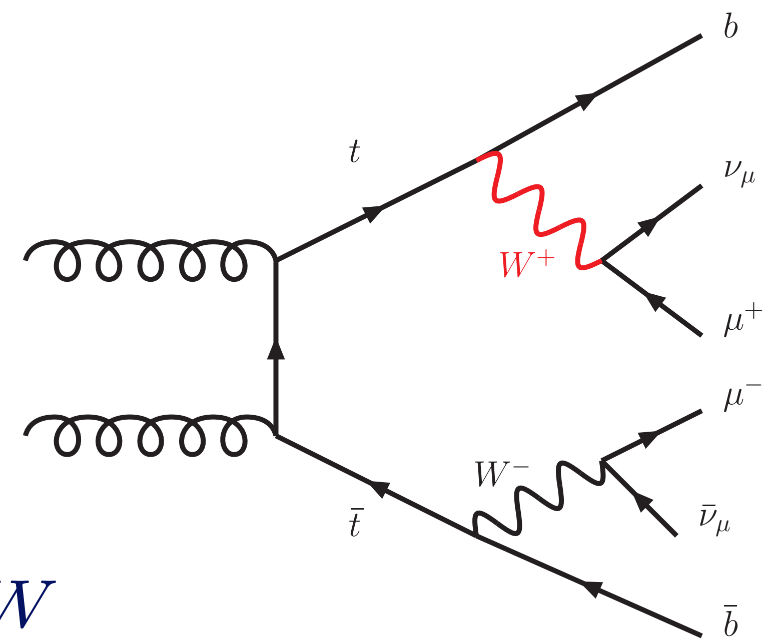


Signal/Background

- Estimate Charged Higgs contribution





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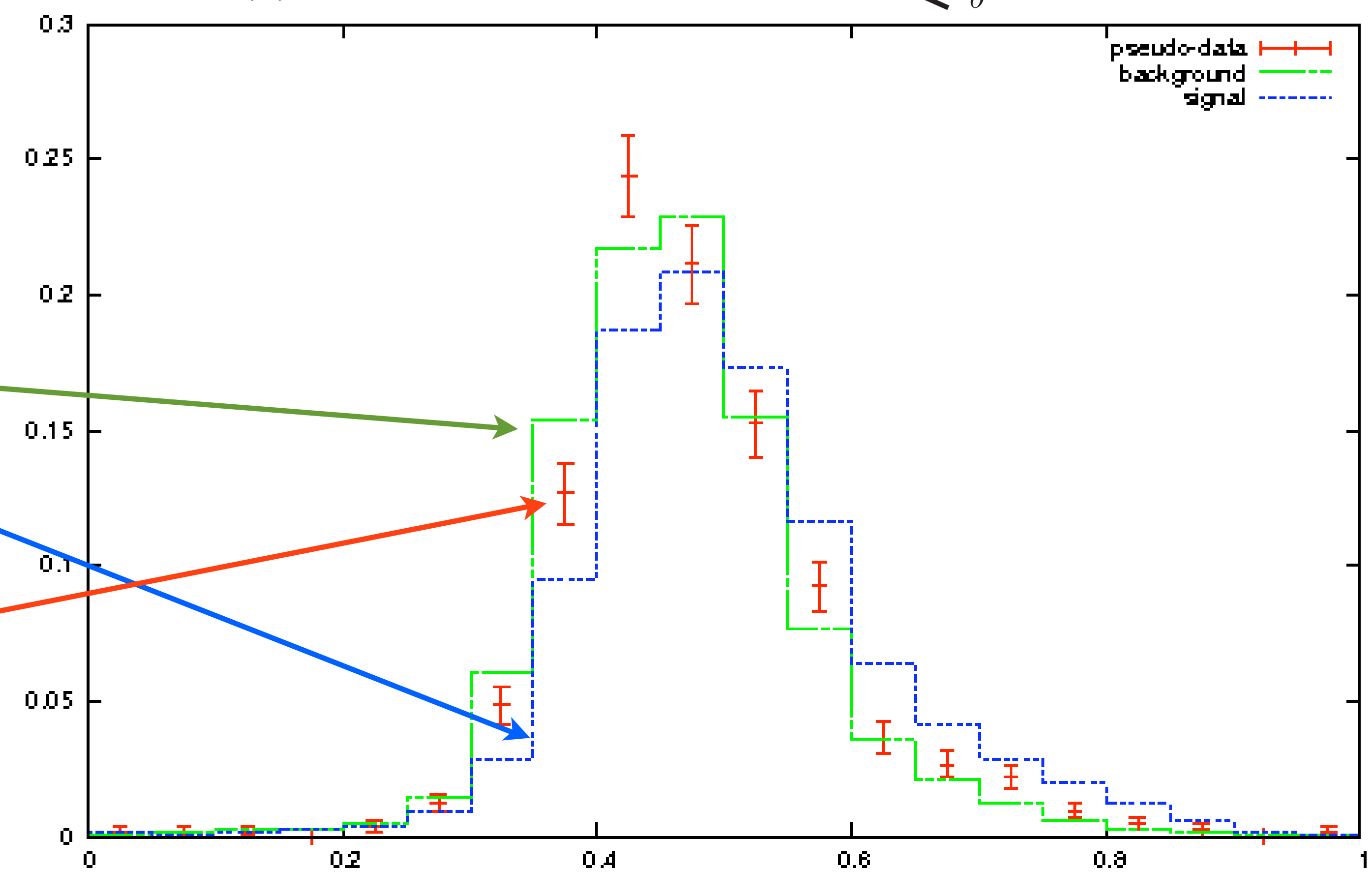
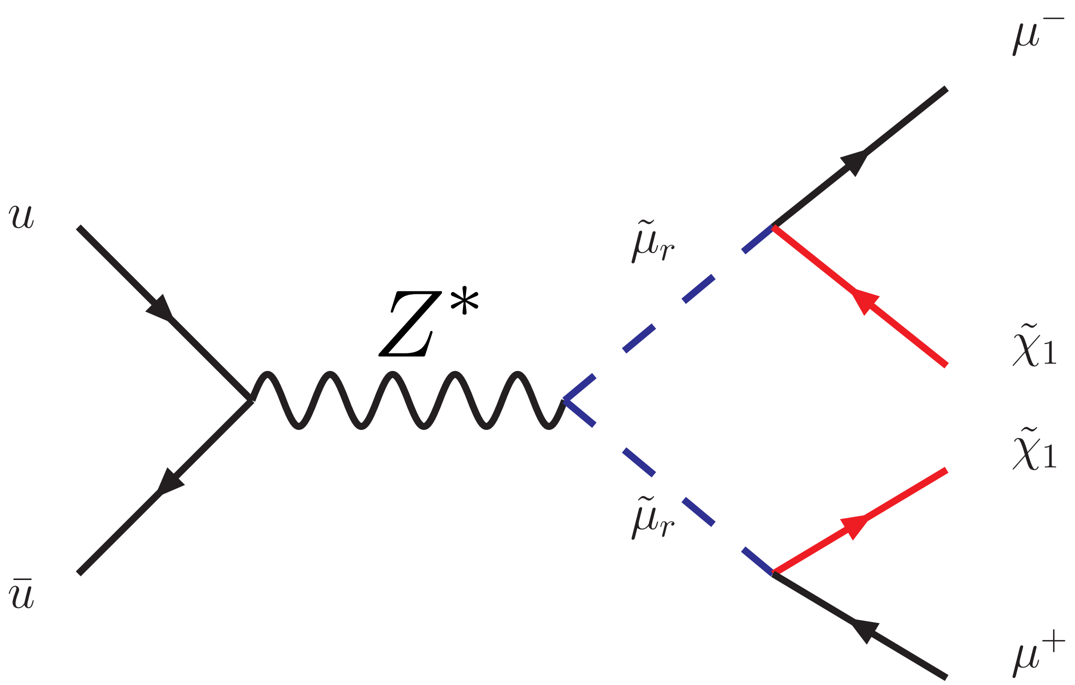


$$\sigma_S = 1.7 \pm 0.4pb$$

Examples

(Crazy?) scenario: We observe only Two muon + MET



Examples

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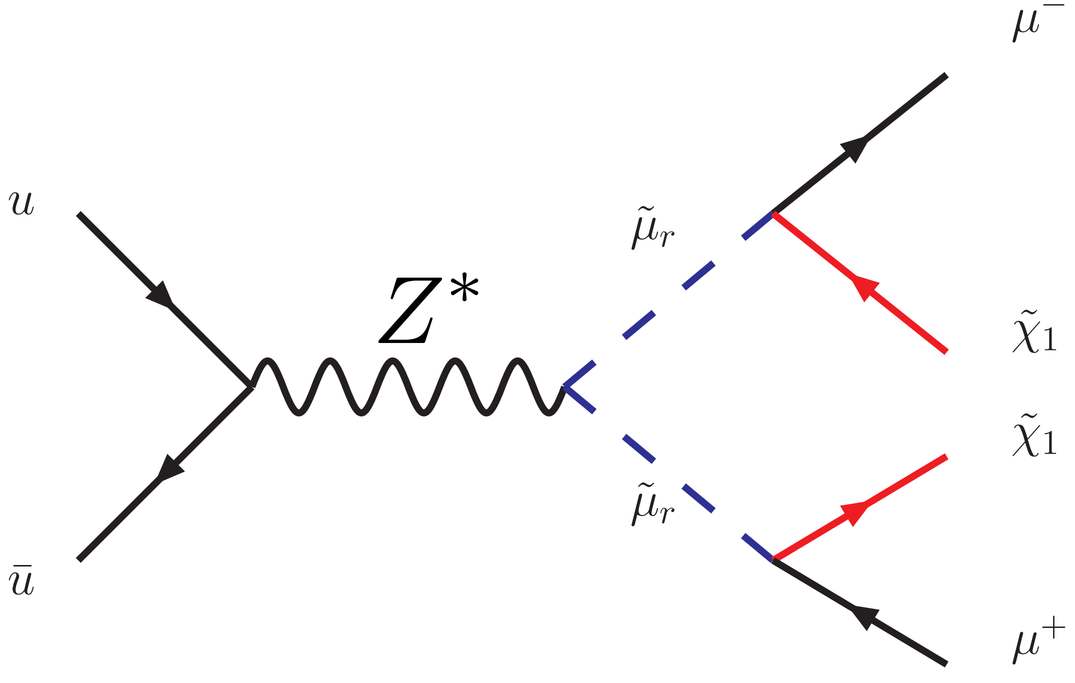
How to measure smuon mass and LSP mass?



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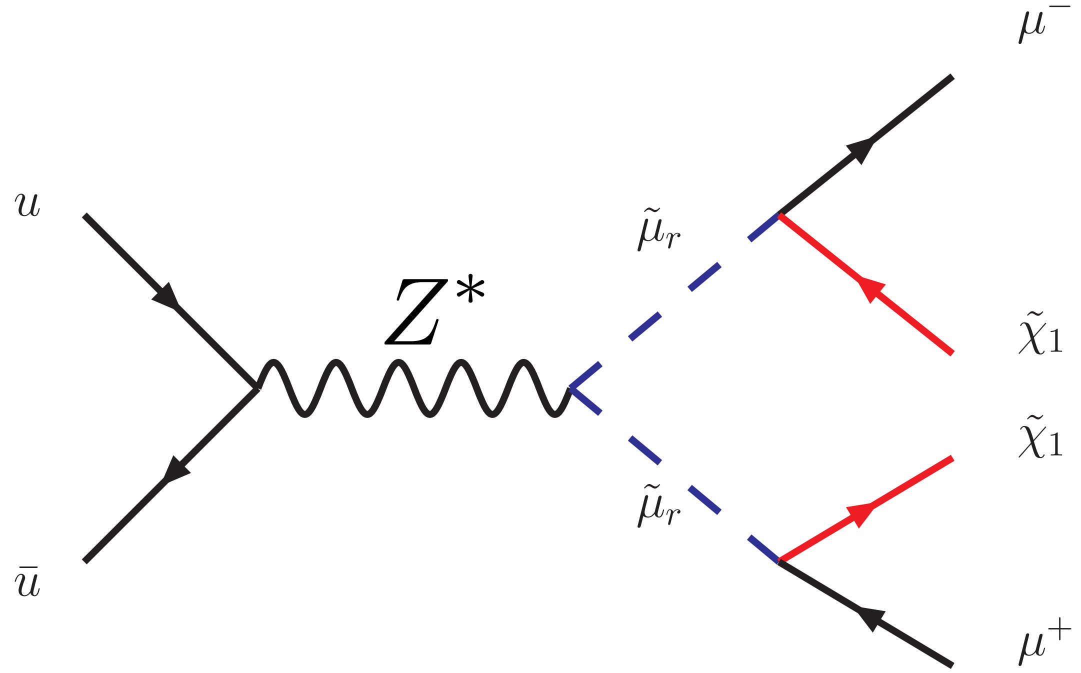

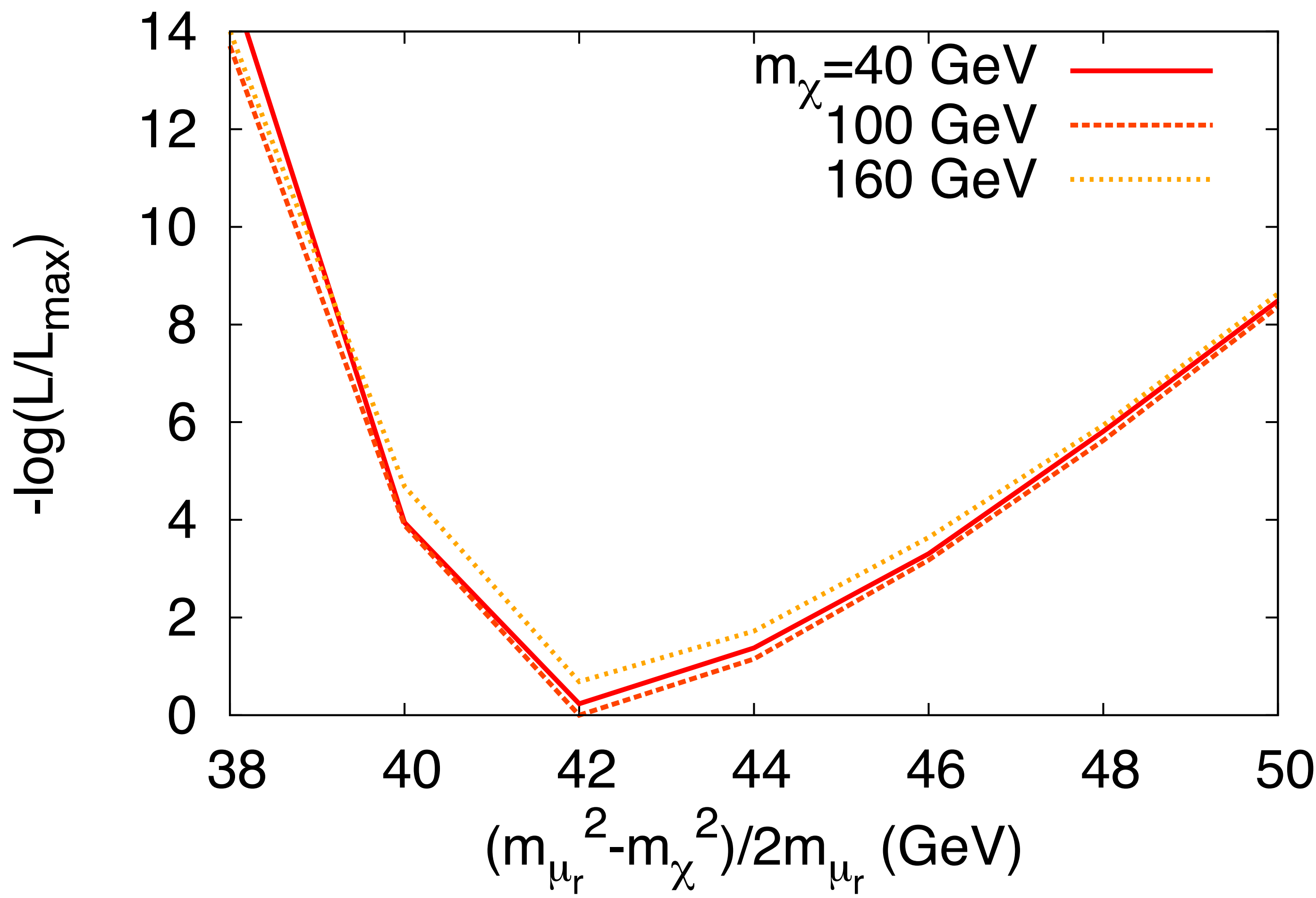

- 50 (Monte-Carlo) events

$$M_{\tilde{\mu}} = 150\text{GeV}$$
$$M_{\tilde{\chi}} = 100\text{GeV}$$

$$(M_{\tilde{\mu}}^2 - M_{\tilde{\chi}}^2)/2M_{\tilde{\mu}} = 42\text{GeV}$$

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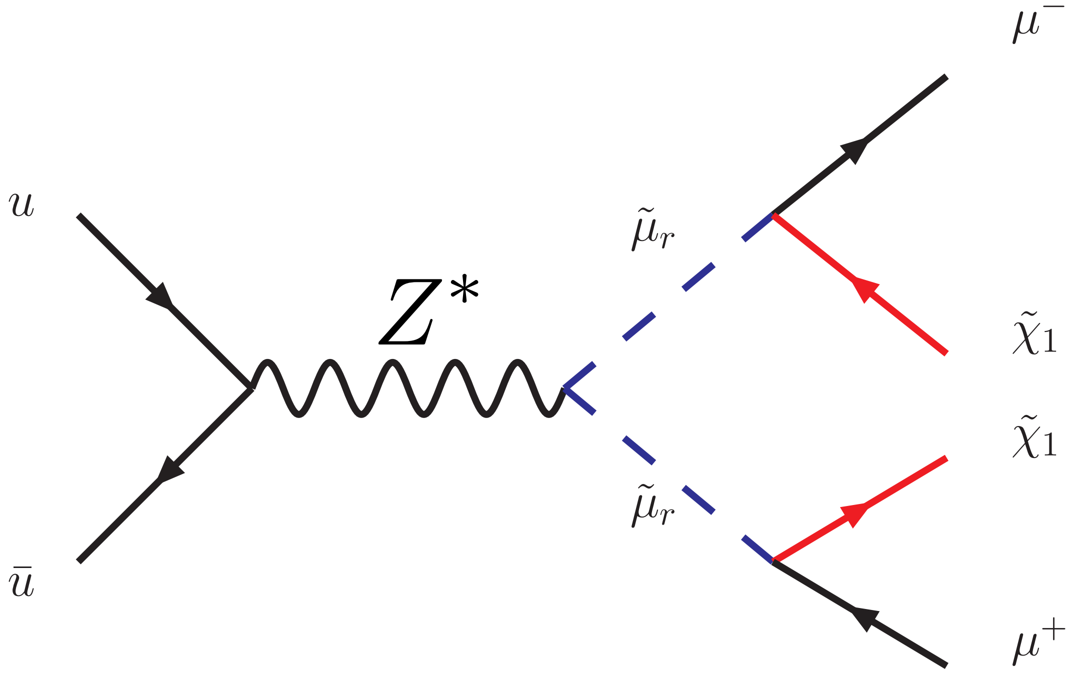

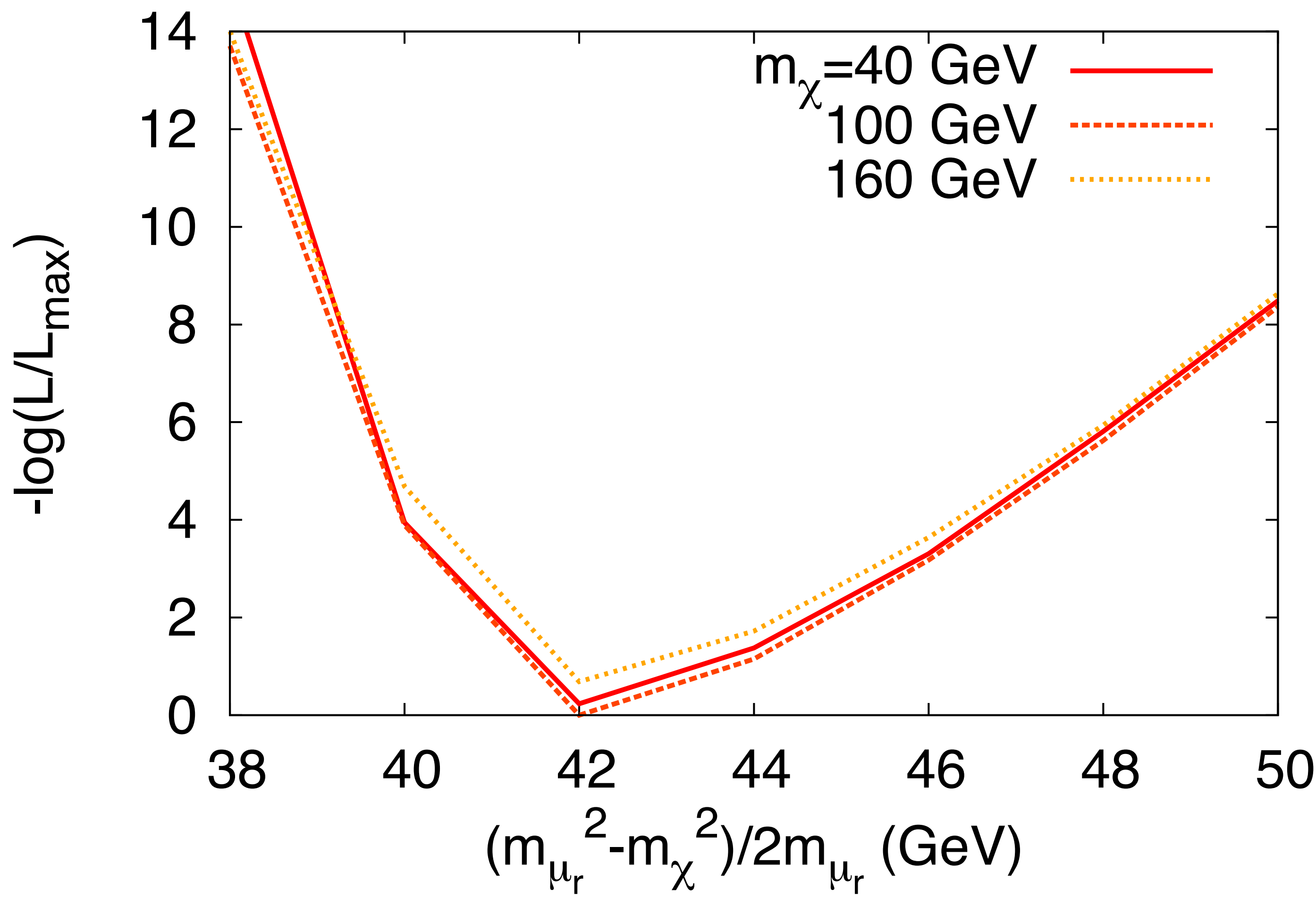

Energy in the rest frame

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Examples

(Crazy?) scenario: We observe only Two muon + MET

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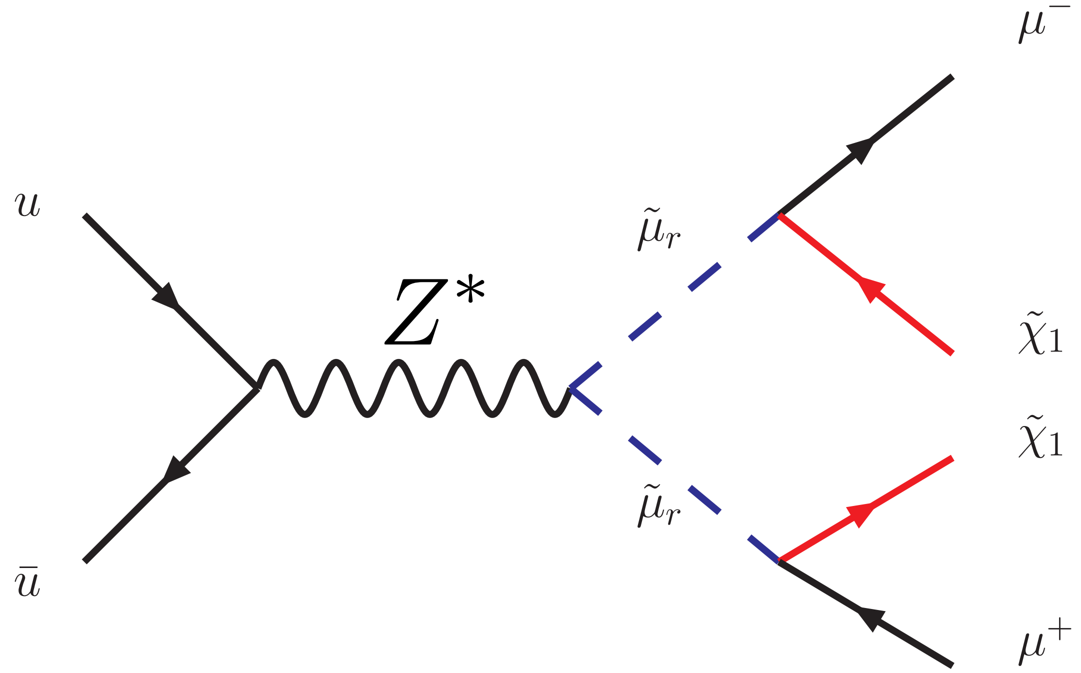

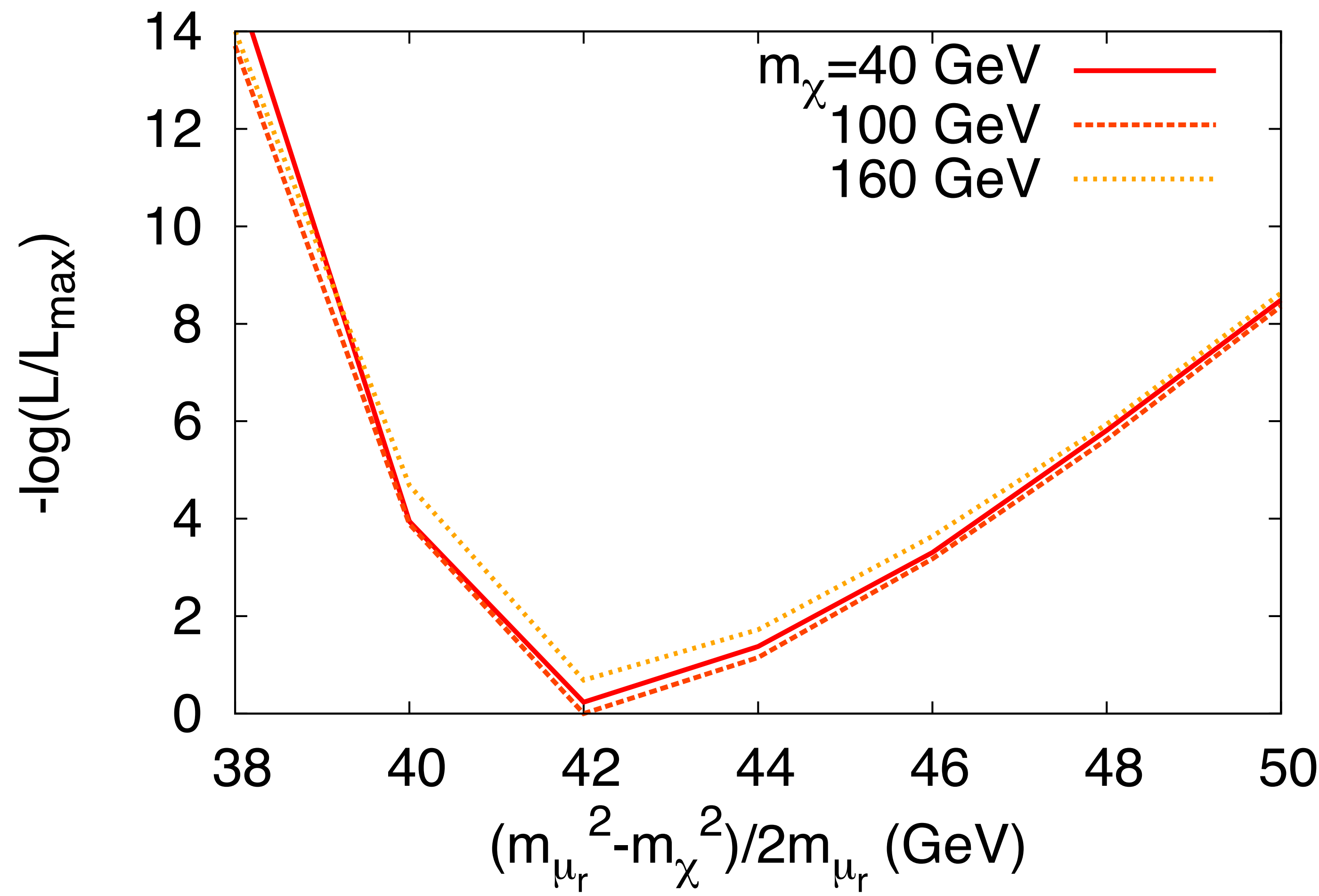

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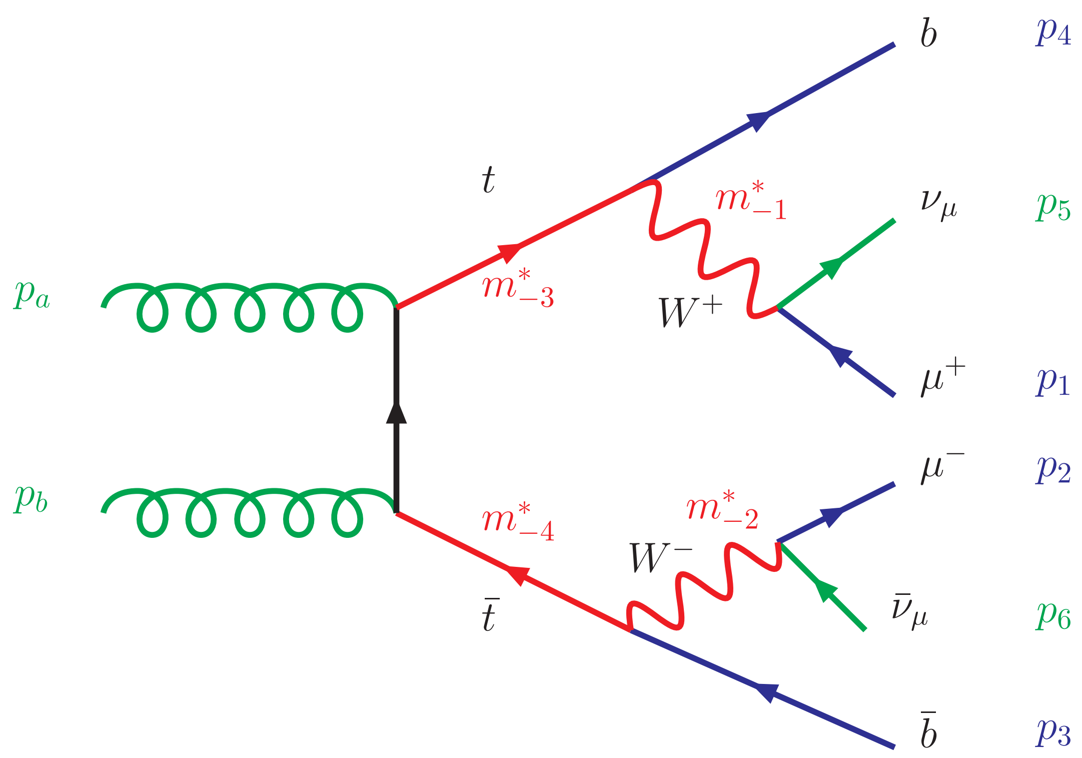
Energy in the rest frame

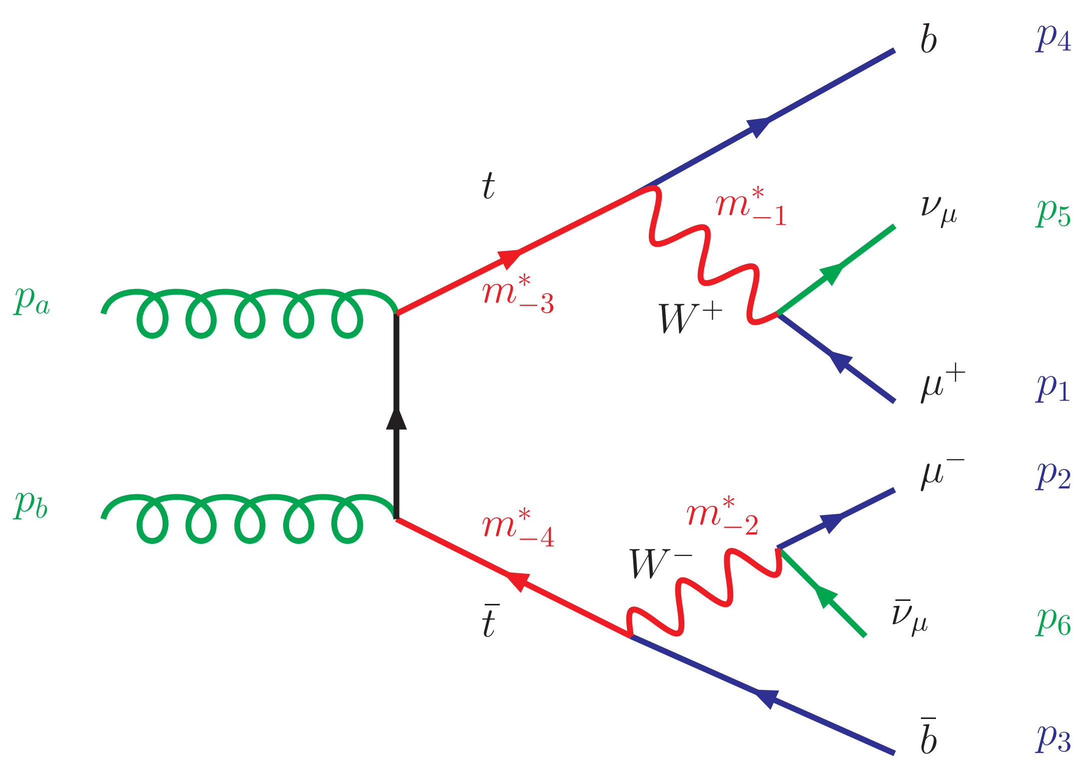
No Free Launch

- Examples of studies / investigations
  - mass determination : smuon pair production
  - Spin Analysis
  - ISR effects: pp > H > W+ W-
  - DMEM: $m_{t\bar{t}}$ in fully leptonic channel

Differential Cross Section



- Need the parton configuration
- uses a series of constraints (kinematical fit)
- use $\frac{1}{\mathcal{P}}\frac{\partial \mathcal{P}}{\partial Z}$ as discriminator



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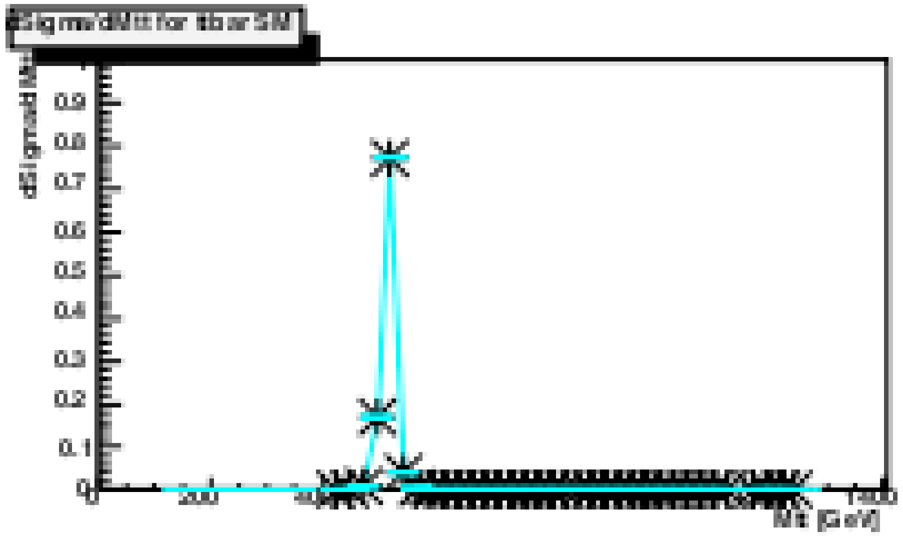
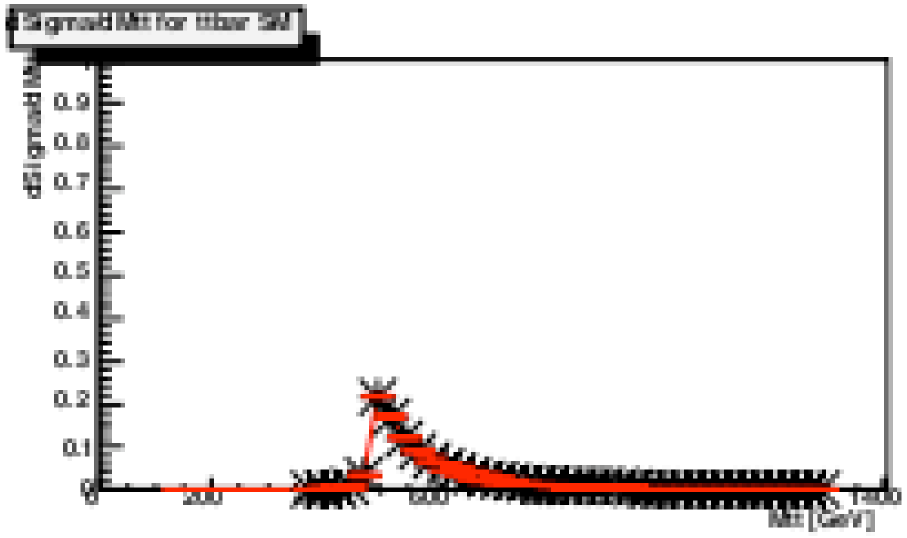
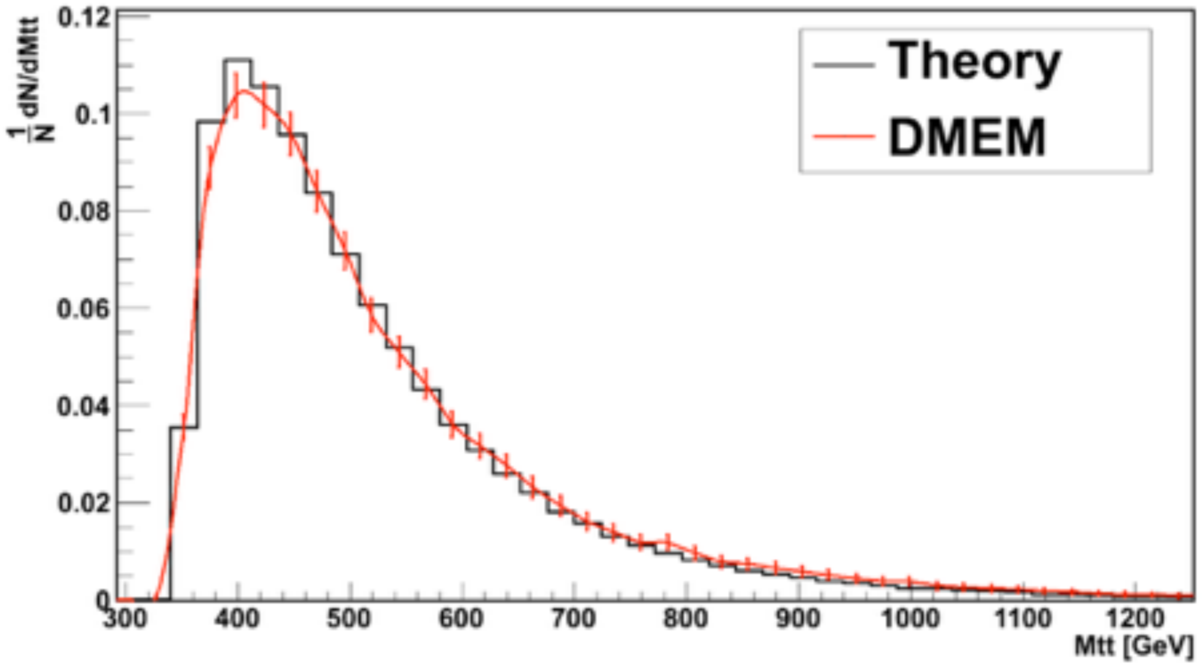
We use the full inference



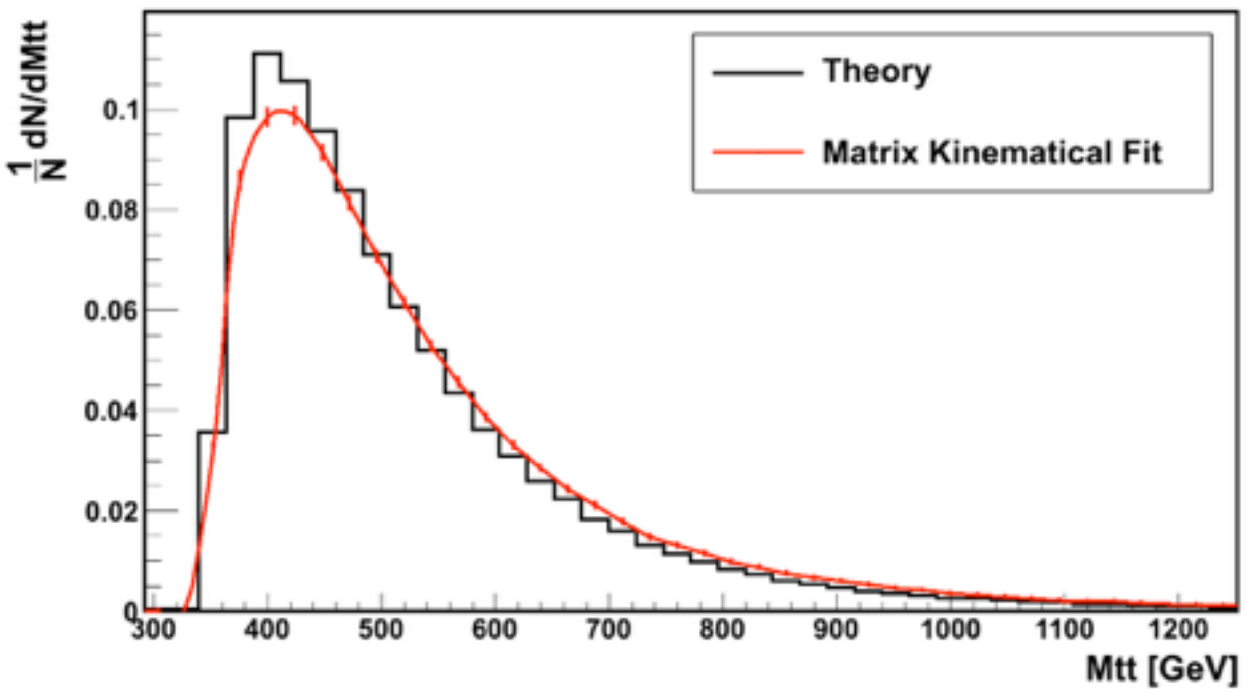


DMEM Validation

partonic level

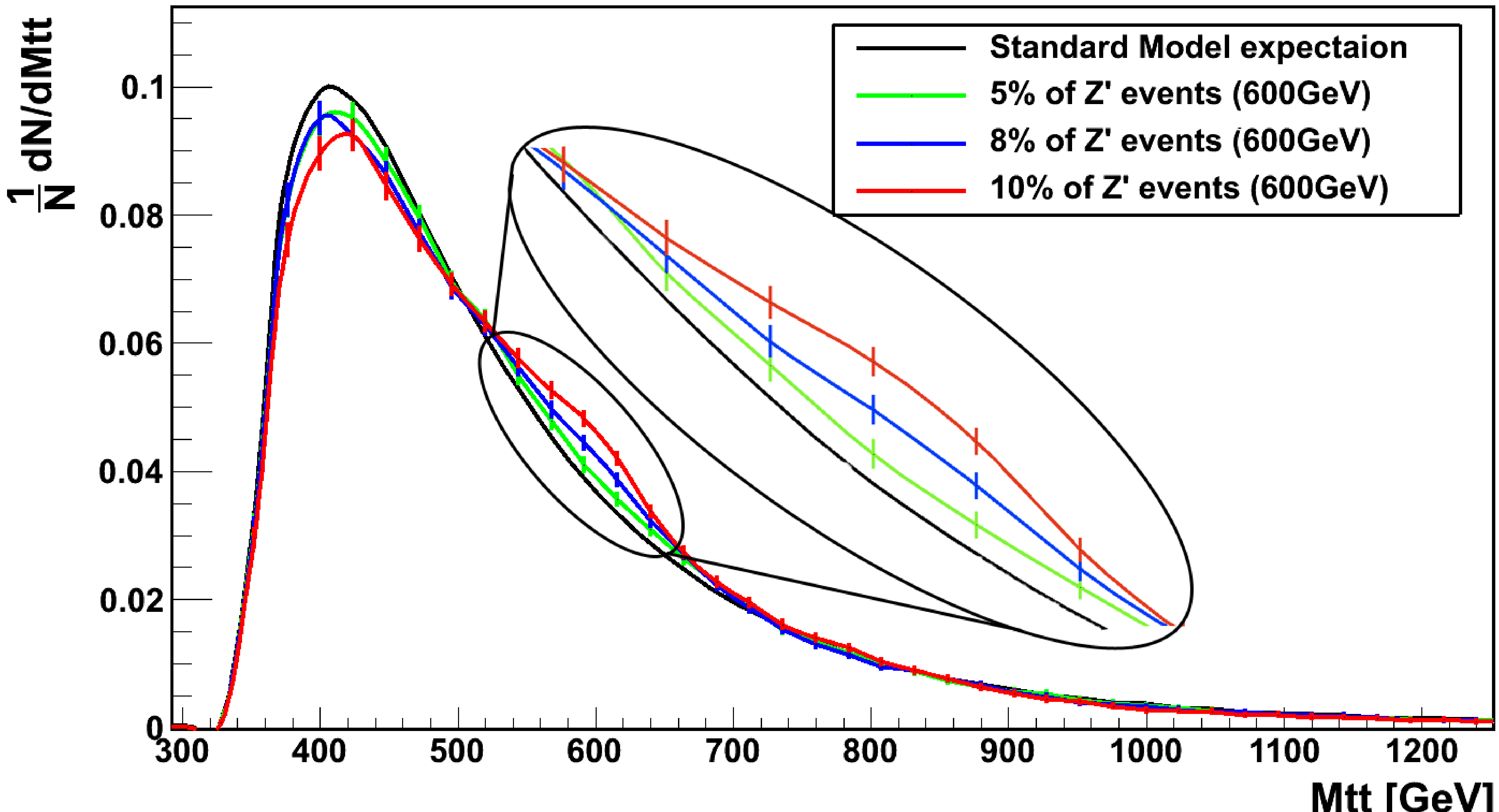


reconstructed level



DMEM

- What if the sample is not a SM one? For example if a heavy Z exists (600 GeV).



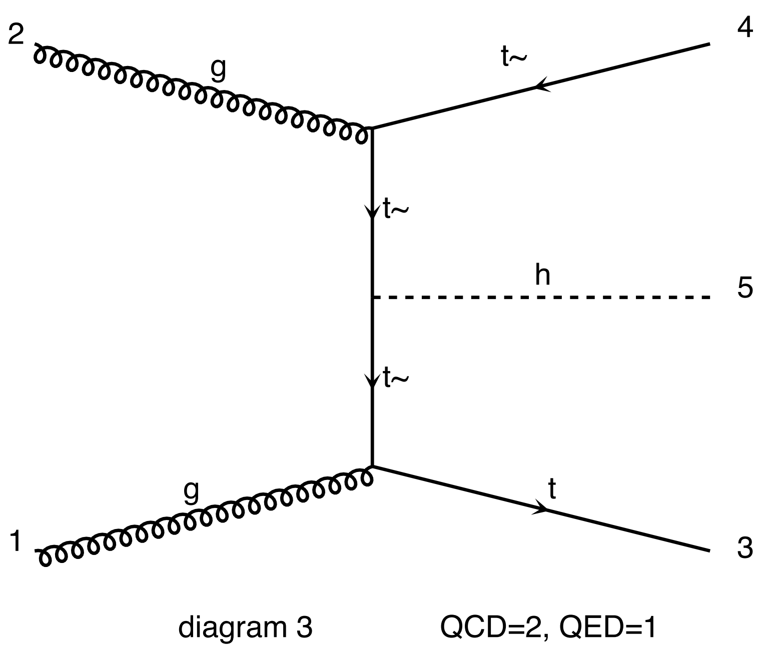
Only Use SM matrix Element!!!

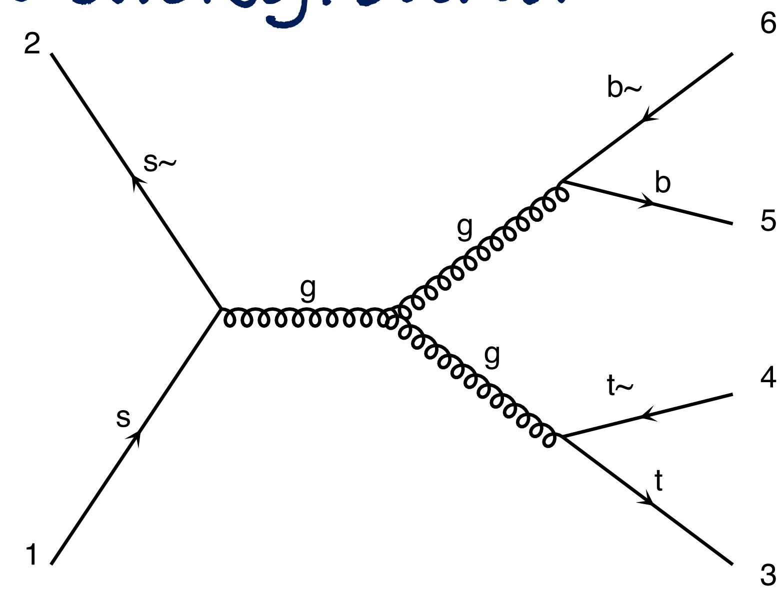
- Examples of studies / investigations
  - mass determination : smuon pair production
  - Discriminating Hypothesis
  - ISR effects: pp > H > W+ W-
  - DMEM: $m_{t\bar{t}}$ in fully leptonic channel

TT + Higgs

Preliminary

- Discriminate t t~ Higgs from background





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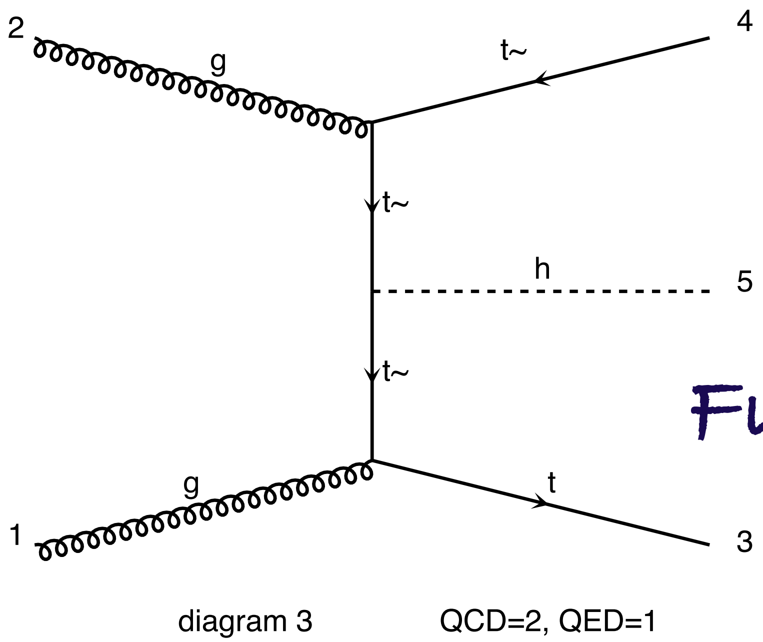
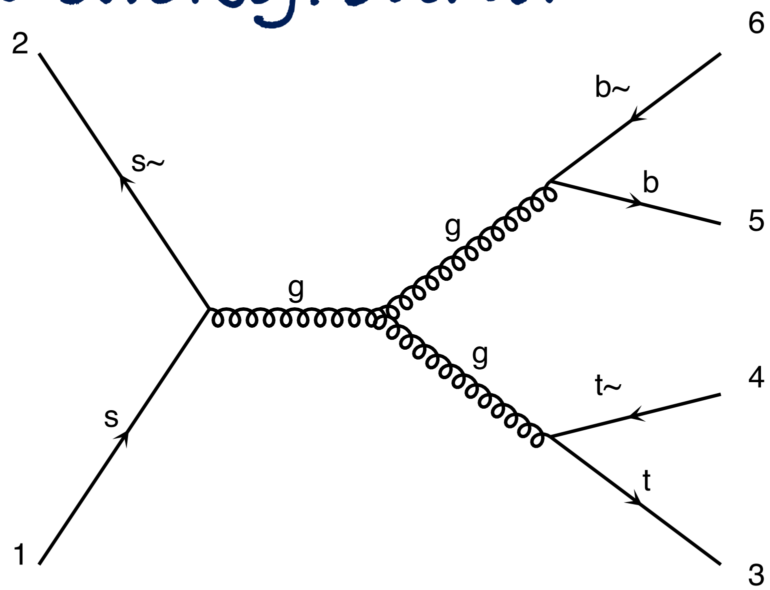


Fully leptonic decay



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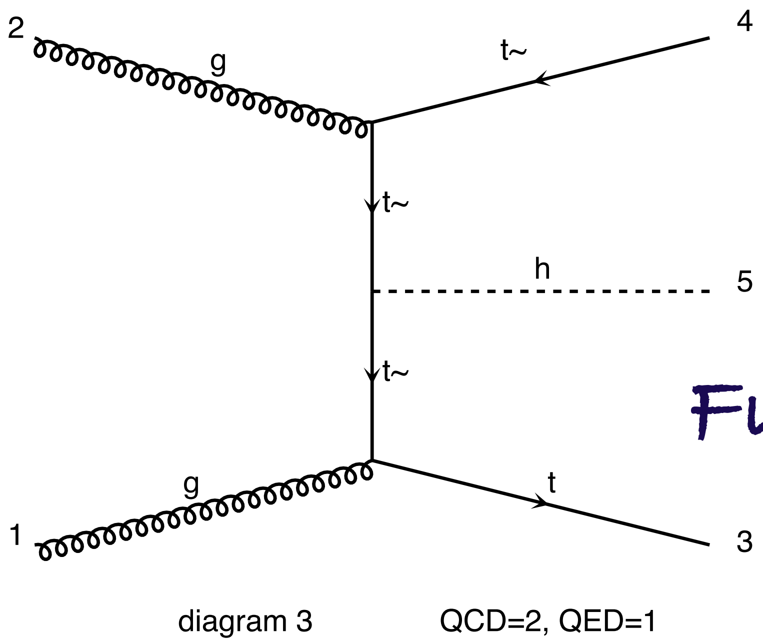

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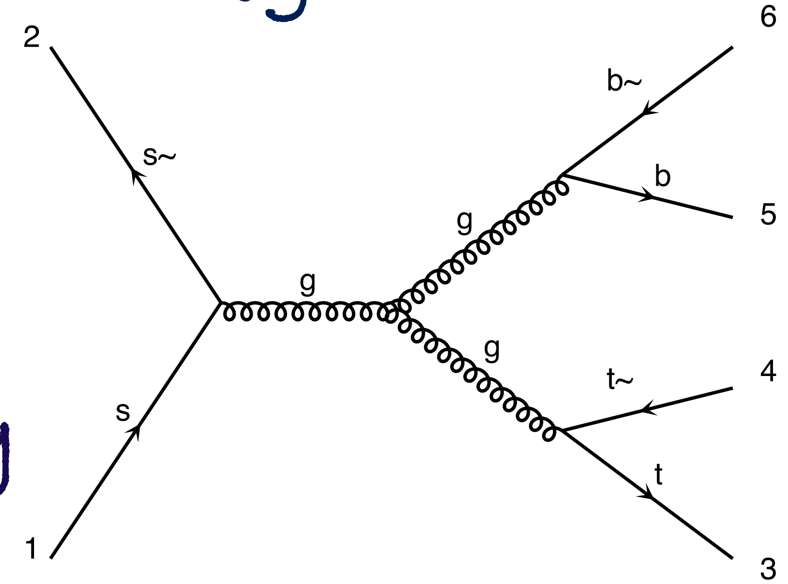

- define discriminant:

TT + Higgs

Preliminary

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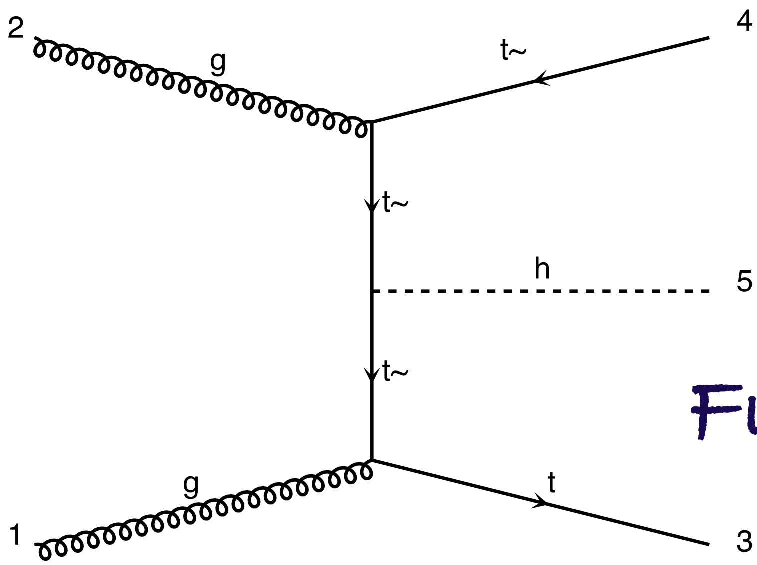
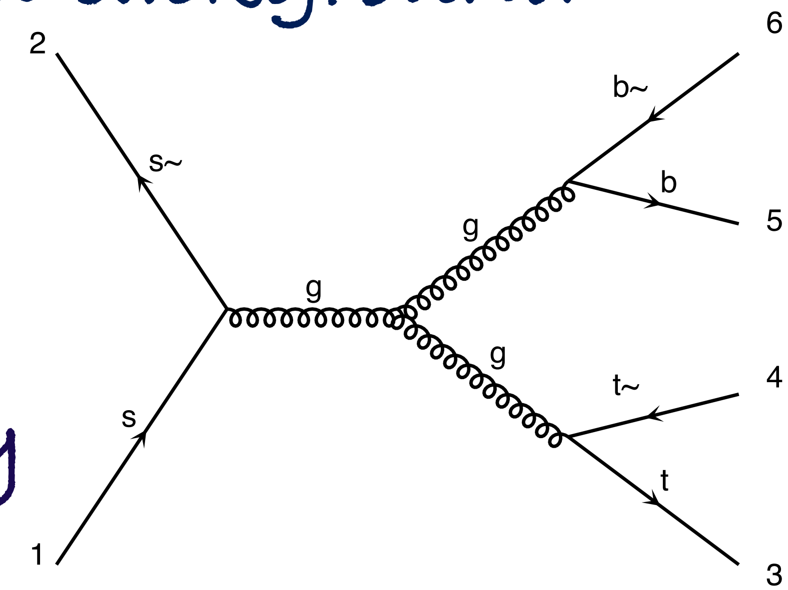


diagram 3 QCD=2, QED=1

Fully leptonic decay



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TT + Higgs

Preliminary

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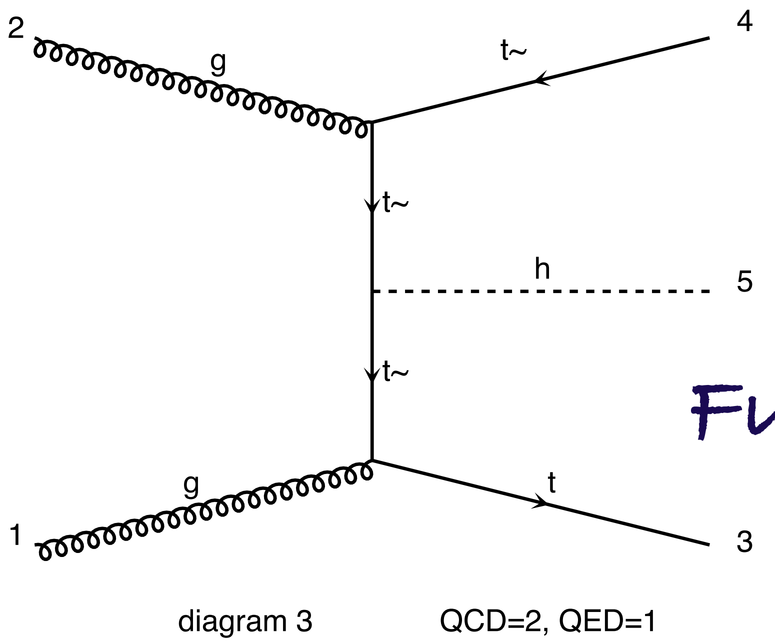
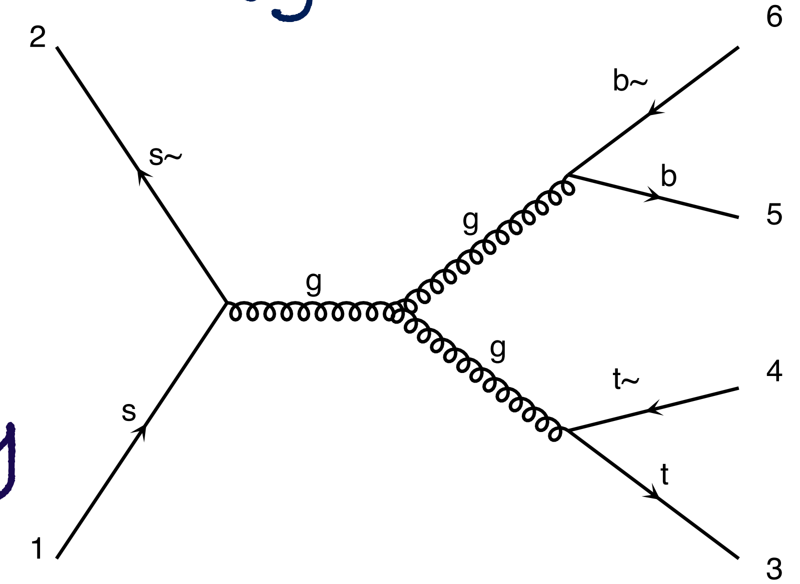


Fully leptonic decay



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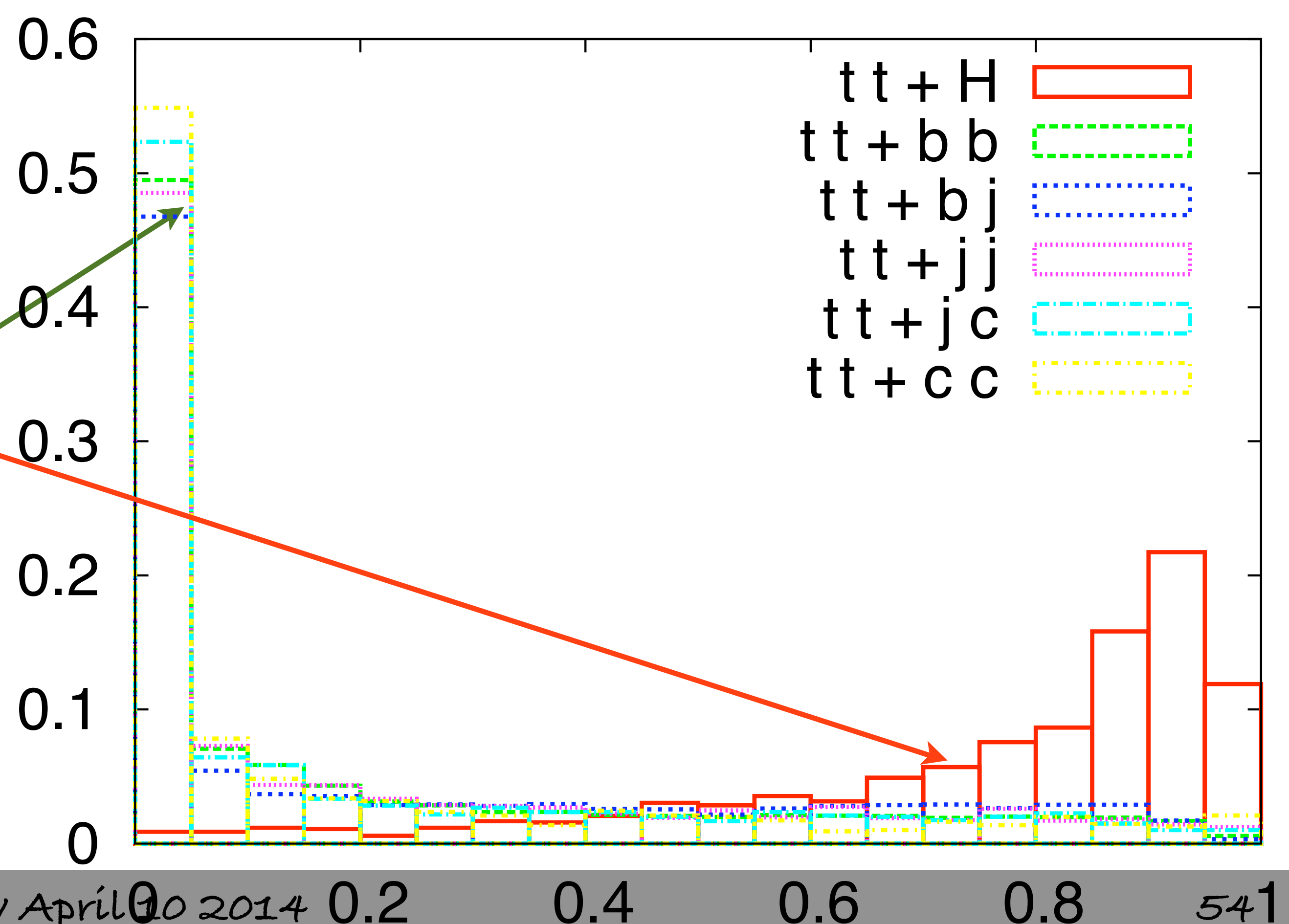
- Higgs Sample



TT + Higgs

Preliminary

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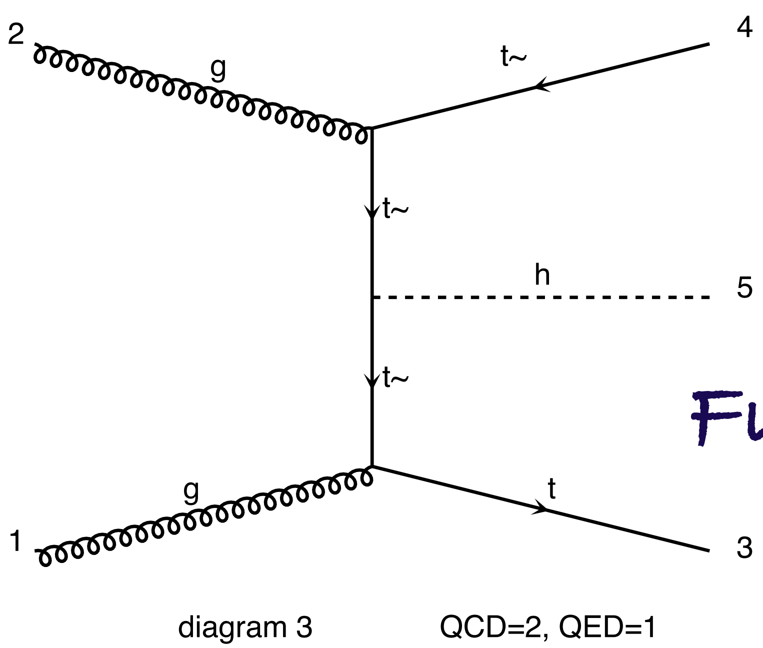

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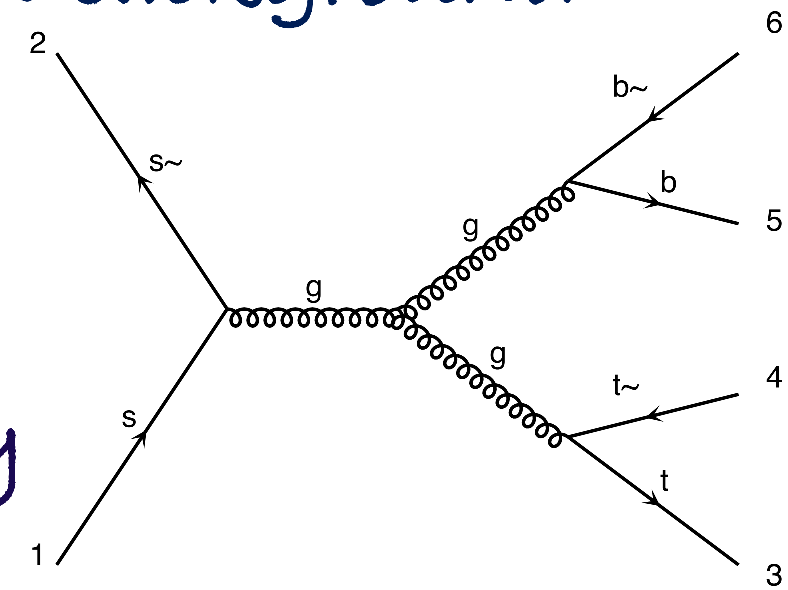

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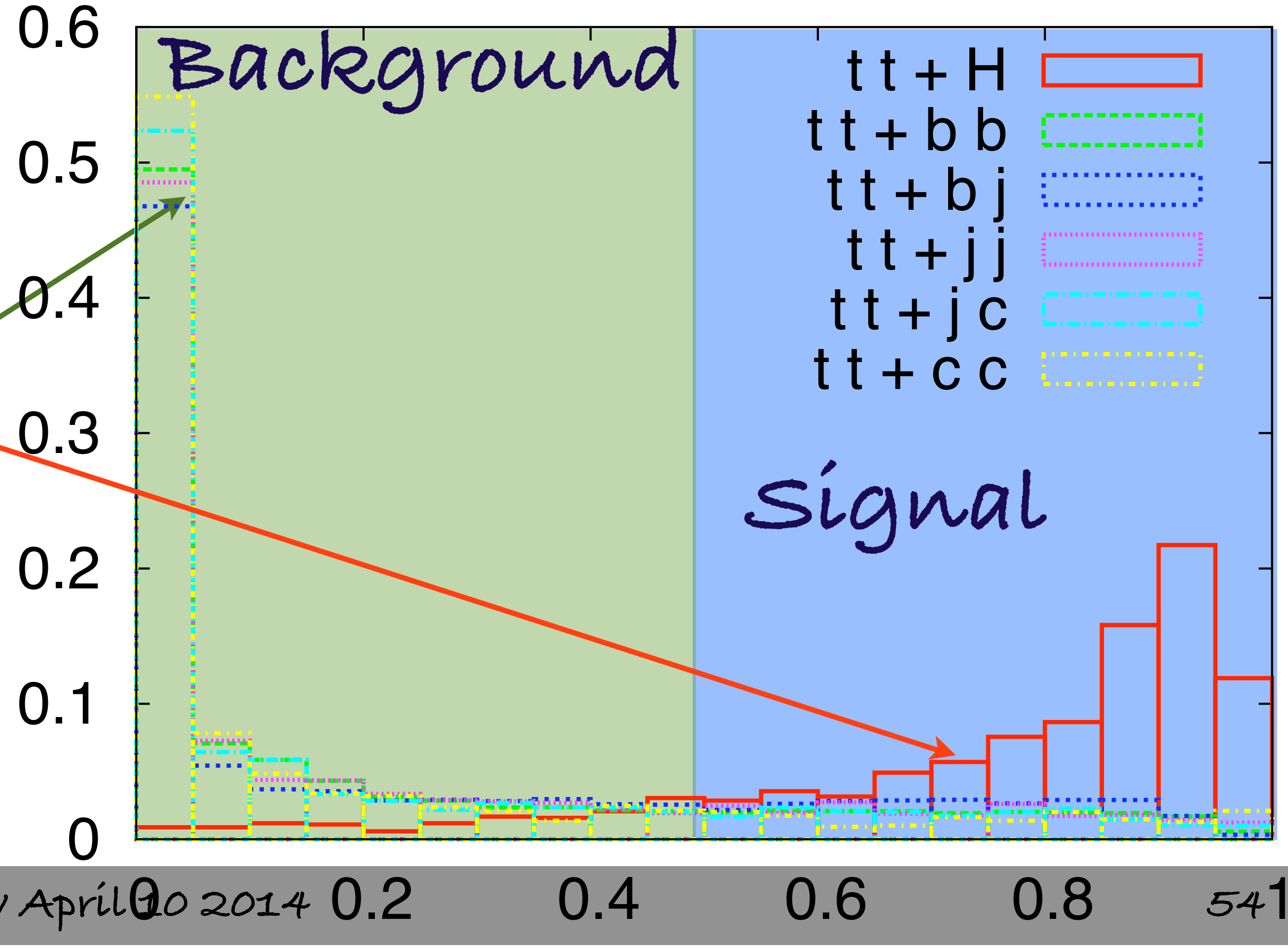
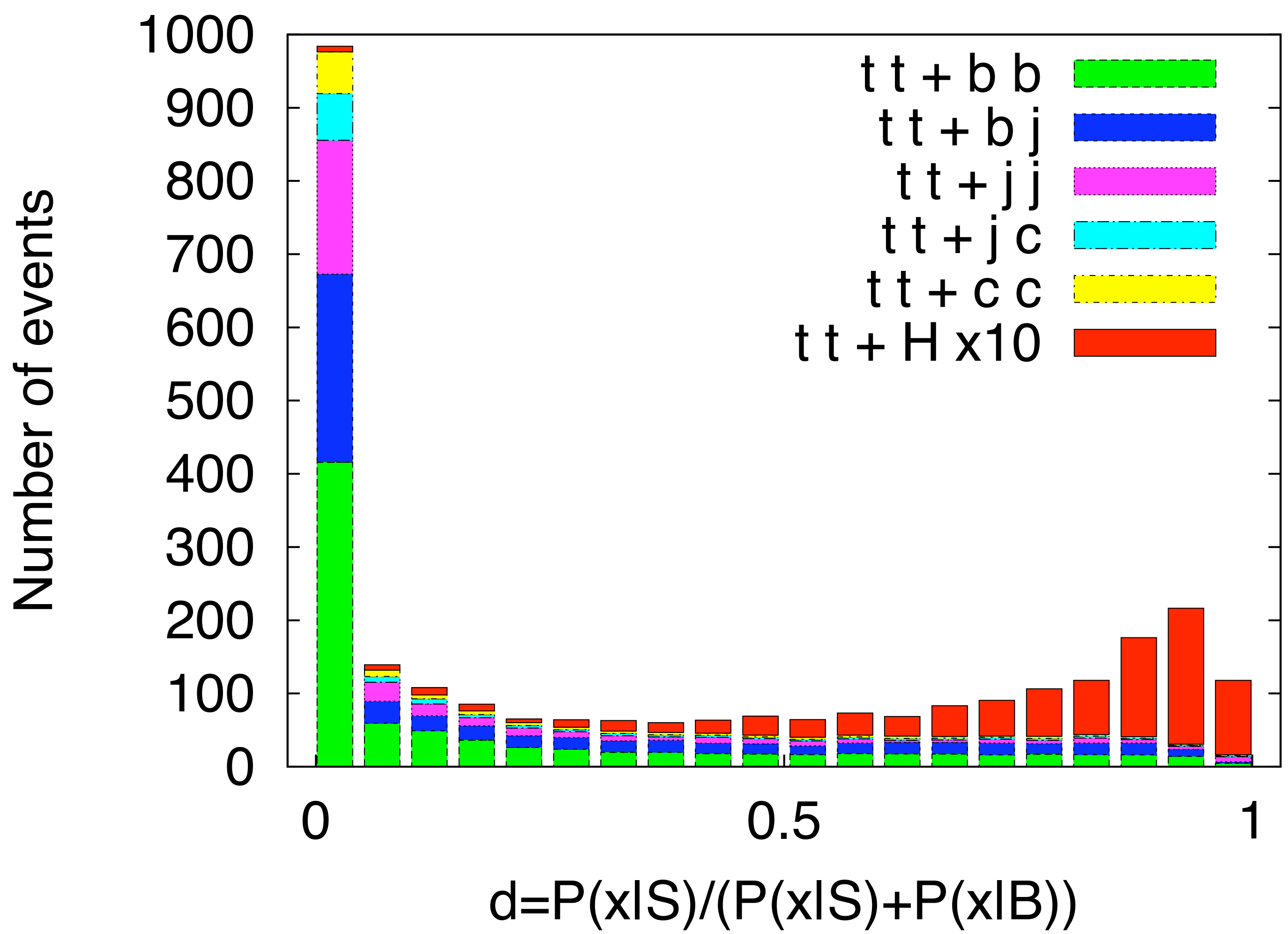


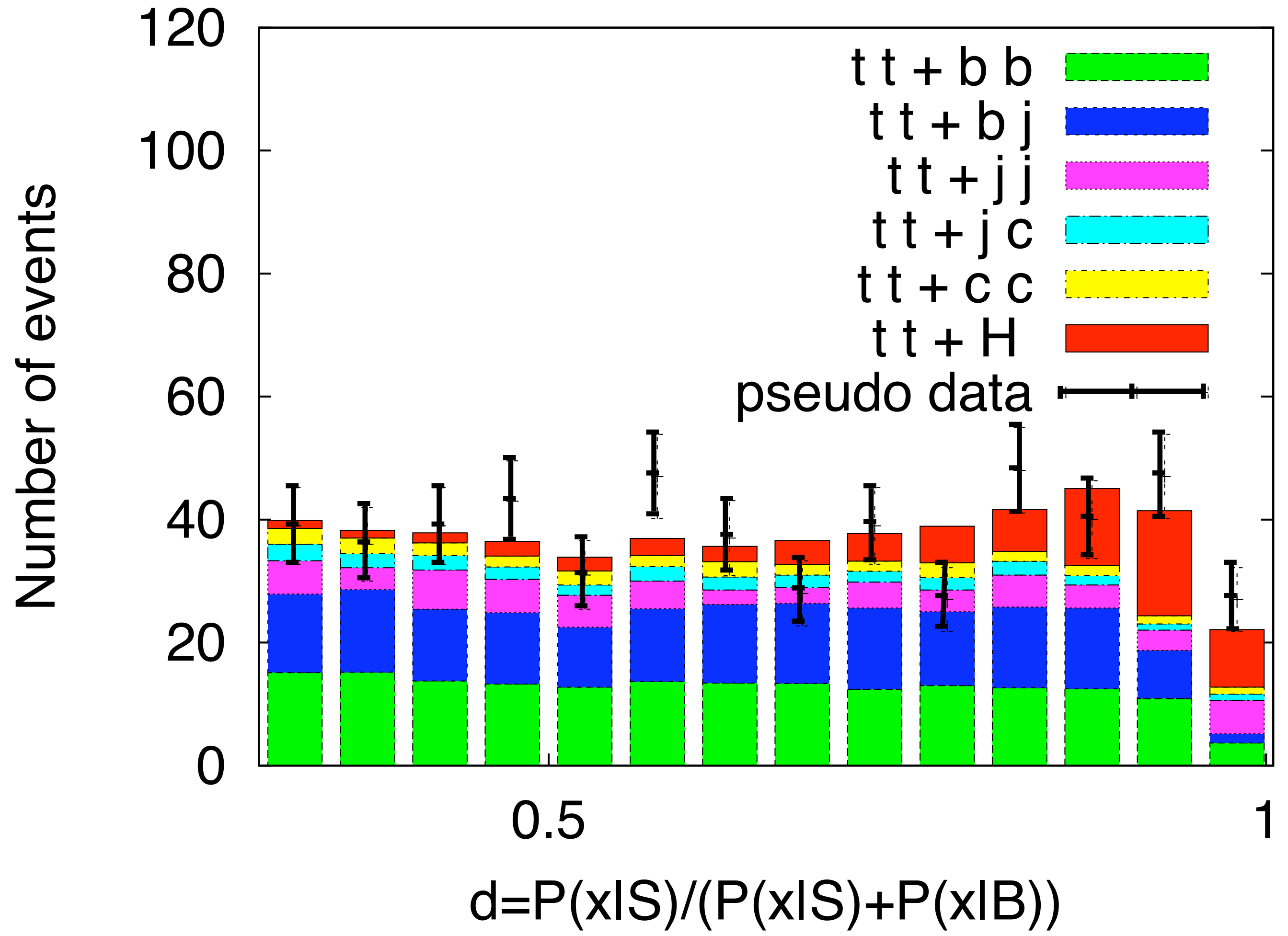
TT + Higgs

Preliminary



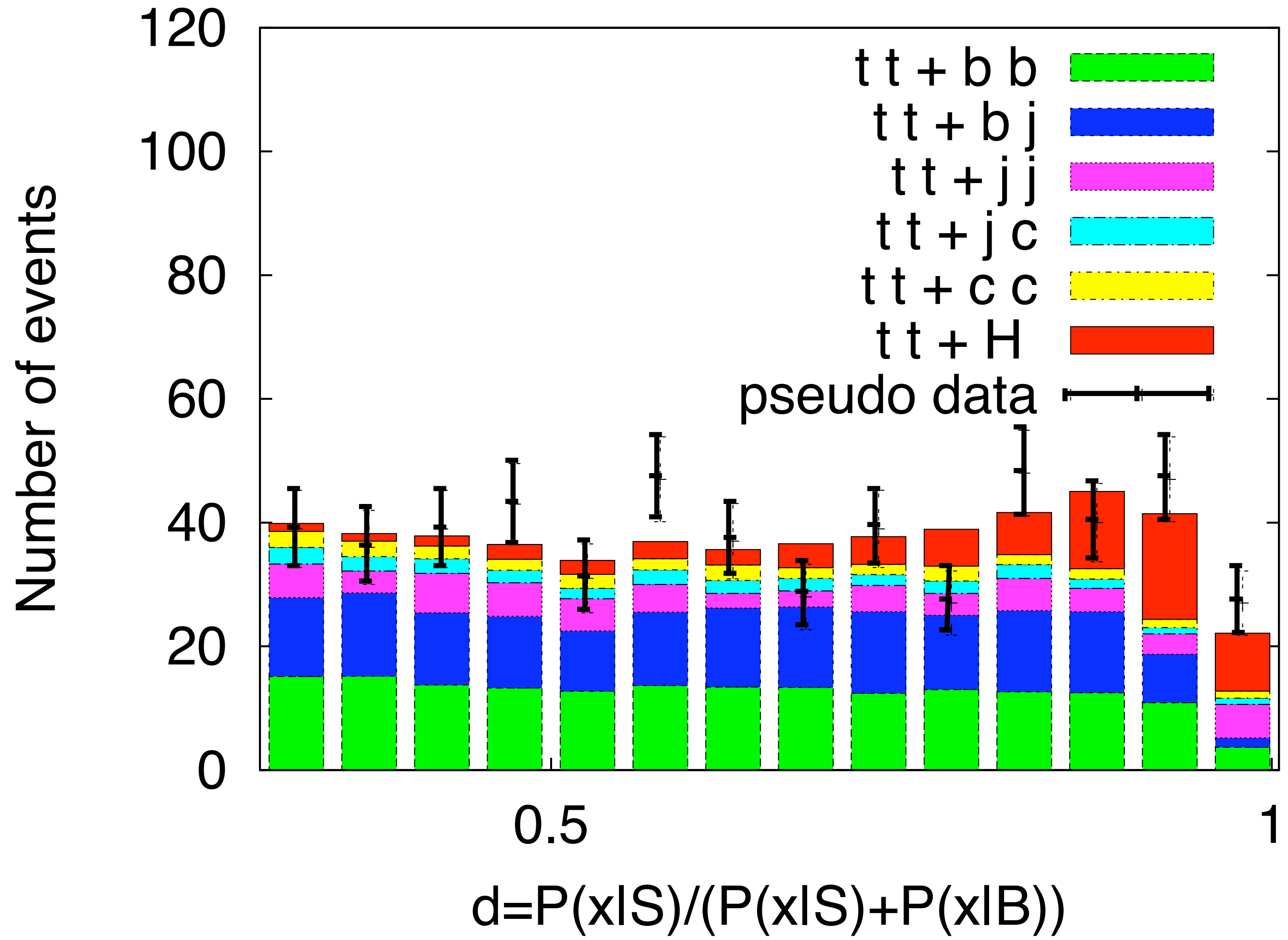
TT + Higgs

Preliminary



TT + Higgs

Preliminary



$$\frac{N_{mes}}{N_{expected}} = 0.95 \pm 0.25$$