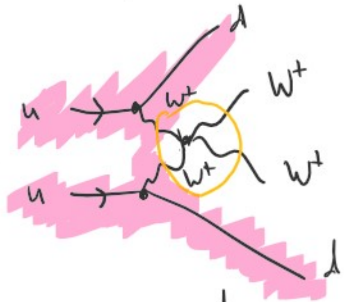
Discussion Session #4, December 17, 2020
Thursday, December 17, 2020 9:38 AM

HW 3.

A.) SM production of $pp \to W^{+/-} W^{+/-} jj$

4pt.



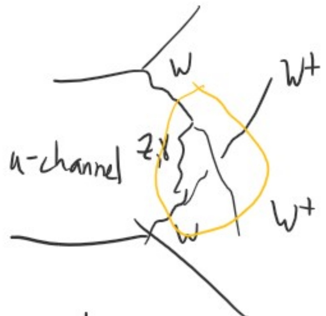
$O(g^2) \cdot g^2 \sim O(g^4)$

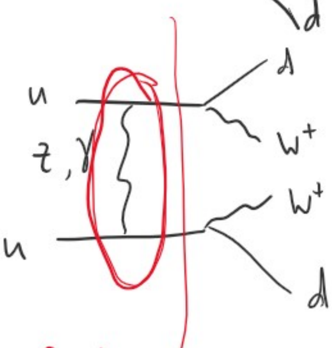
 = effective W PDF

t-channel

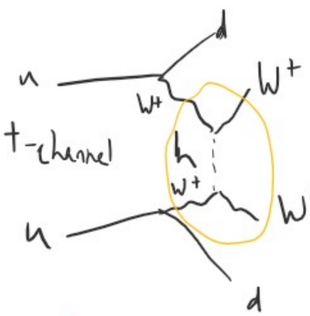
$O(g^4)$

u-channel

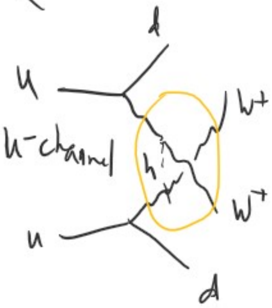




t-channel

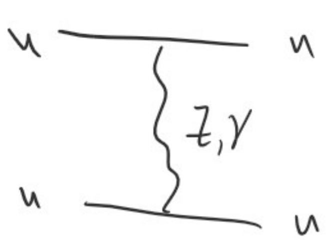


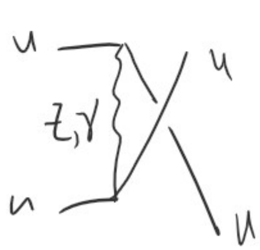
u-channel



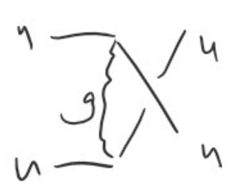
factorize hard process from PDF

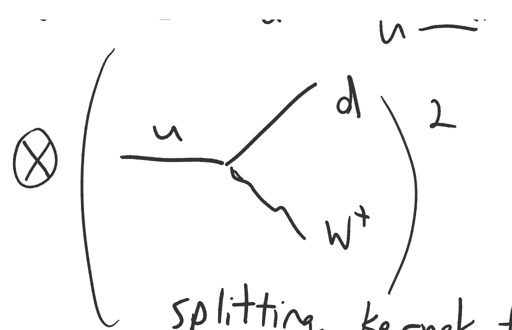
so draw hard process first + then dress up hard process with PDFs.





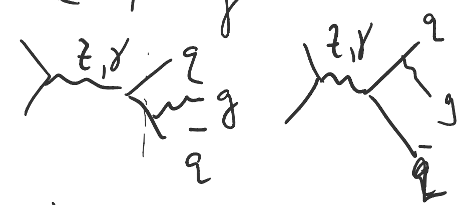
(+ Higgs)





splitting kernel for EW gauge boson emission.

$e^+e^- \to q\bar{q} + q\bar{q}g$] → looks like splitting



crossing symmetry $q\bar{q} \to e^+e^- + \underbrace{q\bar{q}g \to e^+e^-}$

$qg \to e^+e^- q$
$\bar{q}g \to e^+e^- \bar{q}$
$q\bar{q} \to e^+e^- g$] relationship qg, $q\bar{q}$, $\bar{q}g$ PDFs

Altarelli-Parisi splitting fcns.

P+S, Chap. 17.

↳ study RG behavior (log running of PDFs as equivalent to probability for quark → gluon radiation + final state radiation)

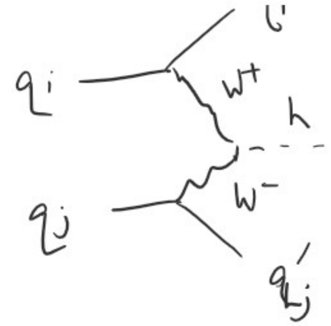
W, Z PDF: take $\int dx_1 dx_2 \underbrace{f_W^p(x_1)}\ \underbrace{f_W^p(x_2)}_{\text{nonzero?}}\ \underbrace{\hat{\sigma}(WW \to \text{whatever}")}_{\text{hard interaction}}$

$\simeq \int dx_3\, dx_4 \sum_{\overset{(-)}{q_i}, \overset{(-)}{q_j}} f_{\overset{(-)}{q_i}}^p(x_3)\ f_{\overset{(-)}{q_j}}^p(x_4)\ \hat{\sigma}(q_i q_j \to X + q_i' q_j')$

dominant PDFs

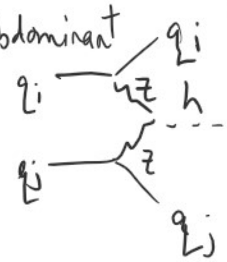
like a telescope

Exactly the same for vector-boson fusion Higgs production



$\Rightarrow \hat{\sigma}(q_i q_j \to h\, q_i' q_j')$

subdominant



Signature for final state: $W^{+/-} W^{+/-} jj$.

2 jets, $\begin{bmatrix} (W^{+/-} \to jj)^2 \\ 2(W^{+/-} \to \ell^{+/-}\nu)\,(W^{+/-} \to jj) \\ (W^{+/-} \to \ell^{+/-}\nu)^2 \end{bmatrix}$

Favor both $W^{+/-}$ decaying leptonically,

$\ell^{+/-} \ell^{+/-}$ 2j + MET (MET = missing transverse energy)

— — Lab frame $(\vec{p}_T \hat{r}, \hat{\theta}, p_z \hat{z})$

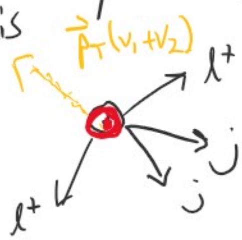
polar coordinates

Initial 4-vectors from partons from PDFs have essentially no net $\vec{p}_T$.

E-M cons. $\sum p_i = \sum p_f$ by component, LHS = 0 $\Rightarrow$ RHS = 0

In any final state, $\sum \vec{p}_{vis,T} \neq 0 \Rightarrow \exists\, \vec{p}_{invisible,T} = -\vec{p}_{T,vis}$

on-axis view



$\hat{z}$ ⊙

MET = $\vec{p}_T$ carried by neutrinos

transverse plane (project out p_z from all

(project out p_z from all visible objects)

Why not also $\sum p_{z,i} = \sum p_{z,f}$?

It is true, but $\sum p_{z,i} \neq 0$.

lab frame has large, net p_z.

$\rightarrow \cdot \leftarrow$

q_i q_j

$q_i = x_i P_1$

$q_j = x_j P_2$

$x_i \neq x_j$

P_1, P_2 = proton four vectors.

$P_1 = -P_2$

Aside: But, $(x_i - x_j)$ is relevant studies of thrust.

ii.) SM backgrounds:

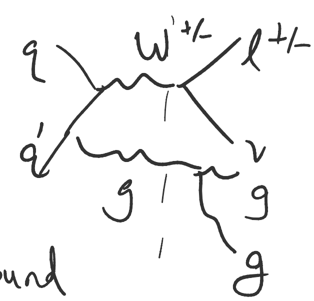
reducible: overlaps with the final state of hard process, except for multiplicity

irreducible: no distinction in final state, including multiplicity

Desired final state: $\ell^{+/-}\ell^{+/-} + 2j +$ MET

Ex. reducible:

$W + 2j$, $W \to \ell\nu$

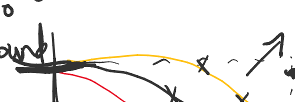


Require 2 SS leptons, cuts this background

Need to consider realistic probability that you artificially "fake" an additional lepton.

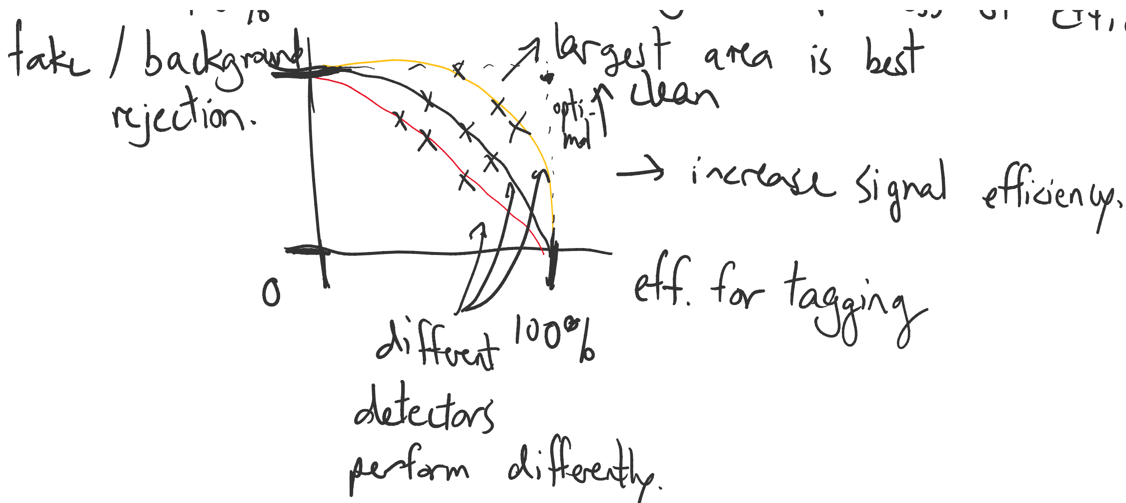
There is always a tradeoff between a "pure" tagging 100% of a collider object + loss of efficiency.

fake / background



largest area is best

clean



Distinction between inclusive rates for particle production vs. differential distributions.

Ex. discover a new process.
Isolate a final state where excess event counts can only be attributed to this process, then claim discovery.

Ex. study an interference or diagnose a coupling or disentangle two competing hypotheses
Final state is given, but rate is necessarily a sum of two possible processes.
Where you need differential information i.e. kinematic distribution, angular variable, etc. where two processes behave differently.

Other reducible backgrounds:

$W^+W^- + 2j$, but cut from same-sign requirement

Irreducible $W^{+/-}Z + 2j$, $Z \to \ell^+\ell^-$, but lose 3rd OS lepton.

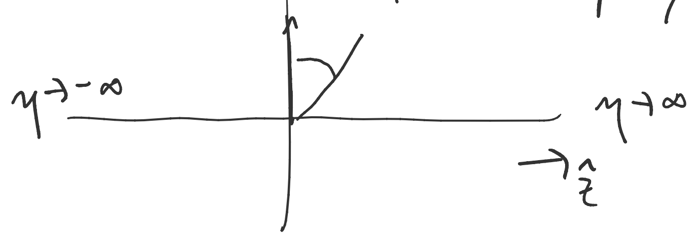
Irreducible $W^{+/-}Z + 2j$, $Z \to \ell^+\ell^-$, but lose 3rd OS lepton.

Key point: any $O((\alpha^s)^n (\alpha)^0)$ cross section does not give leptons.

Diagram:

The jets are generally "together", in the same "hemisphere" or in same area of (η, ϕ) collider coordinates.

rapidity $y \approx \eta$ = pseudo rapidity

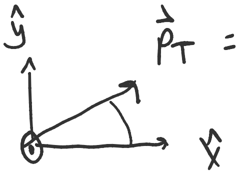


$$\eta \simeq \frac{E + p_z}{E - p_z}$$

$\eta \to \pm\infty$ = along beam axis

$\eta \to 0$ = exactly "central" + transverse to beam.

on-axis view

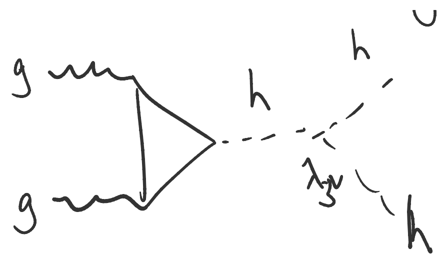


$\vec{p}_T = (|\vec{p}_T| \cos\phi, |\vec{p}_T| \sin\phi)$

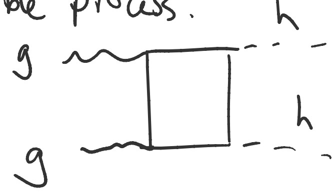
Cut to reduce the irreducible $WZjj$ bkgd is removing jj system is in same hemisphere, i.e. $m(jj)$ is small.

B. SM double Higgs production.

signal process: diagrams involving $\lambda_3 h^3 v$.



irreducible process.

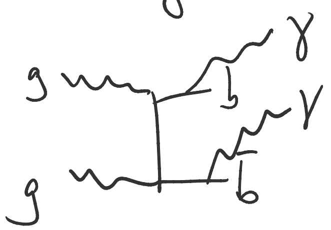


no λ_3 dependence.

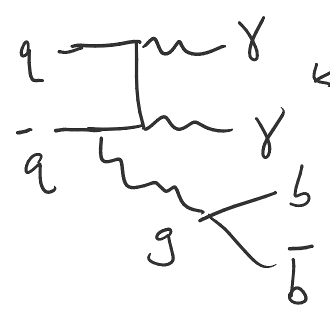
reducible backgrounds: choose final state.

$h \to \gamma\gamma$, $h \to b\bar{b}$ or vice versa.

SM backgrounds for final state: $b\bar{b}\gamma\gamma$:



but these are phase space suppressed since γ are favored to be soft / collinear.



← hard photons

← favor soft b quarks.

Trying to optimize signal rate & minimize bkgd.

Largest is <u>4b</u>.

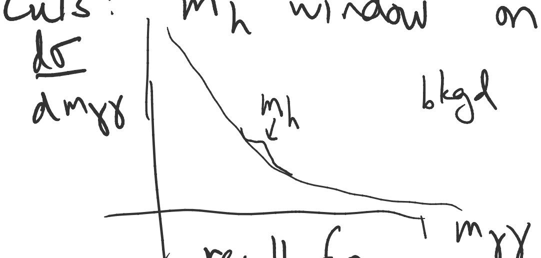
$\mathcal{O}(\alpha_s^2) \to \sigma(\alpha_s^4)$ (because of jet substructure)

$\sigma(\alpha_s^2 \alpha^2)$

compared $\frac{Br(\gamma\gamma)}{Br(b\bar{b})}$

& $m_H \to \gamma\gamma$ cut.

cuts: m_h window on $m_{\gamma\gamma}$, $|m_{\gamma\gamma} - 125\text{ GeV}| < 5\text{ GeV}$.



recall from Higgs discovery.

Require 2 bjets. (not good for $|m_H - m_{b\bar{b}}|$ cut because

Additional [illegible])

require $\propto$ bjets. (not good for $|m_h - m_{bb}|$ cut because of poor m_{bb} mass resolution)

Additional observable:

$m(bb\gamma\gamma)$. Where you can distinguish not only SM background, but also box → hh vs. λ_3 signal process.

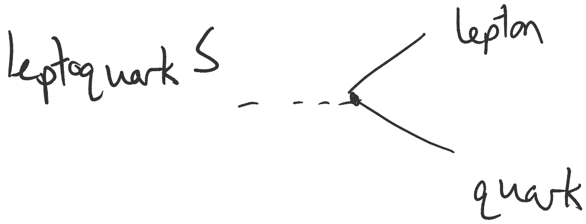
C. Scalar leptoquark.

$y_{21} \neq 0 \qquad y_{ij} = 0$ otherwise.

$\ni \left(y_{21} \bar{L}^2 S u_R^1 + h.c. \right) \qquad S = \begin{pmatrix} S^{5/3} \\ S^{2/3} \end{pmatrix}$

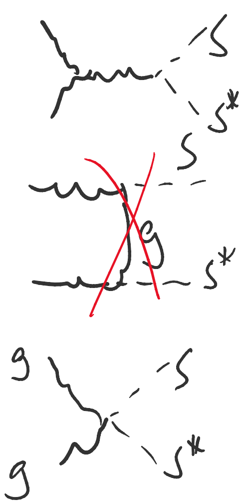
$y_{21} \begin{pmatrix} \mu & u \\ \nu & u \end{pmatrix} S \qquad S^{5/3} \to \mu^+ u$

$S^{2/3} \to \nu u$.



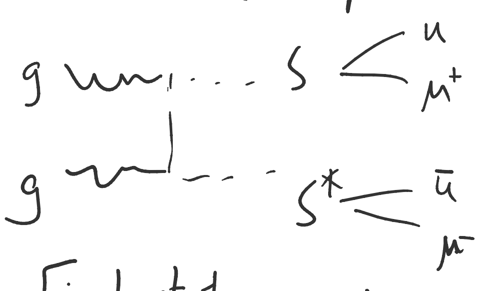
$|D_\mu S|^2$

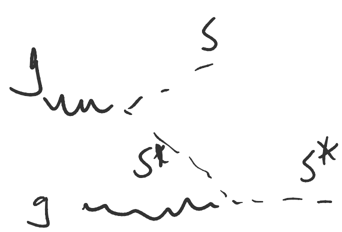
$\ni S^* \overleftrightarrow{D_\mu} G^\mu S$



Leptoquarks carry color.

Guaranteed to produce via $O(\alpha_s^2)$ processes





Final state $\mu^+\mu^- + 2j$, but $\mu^+ j$ + $\mu^- j$ are each resonant (and degenerate).

Background:

Background:

$W^+W^- + 2j$

$Z + 2j$

But $(Z \to \mu^+\mu^-) + 2j$, eliminate req. $m(\mu\mu) - m_Z > 10$ GeV

$W^+W^- + 2j$, eliminate MET < 50 GeV

since $W^+ \to \mu^+\nu$, every muon comes with ν.

Compare to $\sigma_{sig}(\alpha_s^2)$ vs. $\sigma_{bkgd}(\alpha^2)$.

Limits on $S \sim 1.5 - 2$ TeV.

Also use $m(\mu^+ j) = m(\mu^- j)$ resonance cut.