Searching E_6 isosinglet quarks in ATLAS

Flavour at the LHC Workshop

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Objective of this study

- SuperStrings & GUT models predict E_6 as the effective group for underlying symmetry.
- Assume that SM comes from breaking down of E_6:

$$SU_C(3) \times SU_W(2) \times U_Y(1) \subset E_6$$

- 3 quark families with additions as predicted by E_6:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, D_L, D_R \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}, c_R, s_R, S_L, S_R \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R, B_L, B_R$$

New iso-singlet quarks

Can ATLAS discover these & validate E_6 GUT models ?

Theory background

D quark decay Lagrangian is: (Euro. Phys. Lett. 38, 1997)

$$\mathcal{L}_{\mathcal{D}} = \frac{\sqrt{4\pi\alpha_{em}}}{2\sqrt{2}\sin\theta_W}\left[\bar{u}^{\theta}\gamma_{\alpha}(1-\gamma_5)\,d\cos\phi + \bar{u}^{\theta}\gamma_{\alpha}(1-\gamma_5)\,D\sin\phi\right]W_{\alpha}$$
$$- \frac{\sqrt{4\pi\alpha_{em}}}{4\sin\theta_W}\left[\frac{\sin\phi\cos\phi}{\cos\theta_W}\bar{d}\gamma_{\alpha}(1-\gamma_5)\,D\right]Z_{\alpha} + h.c.$$

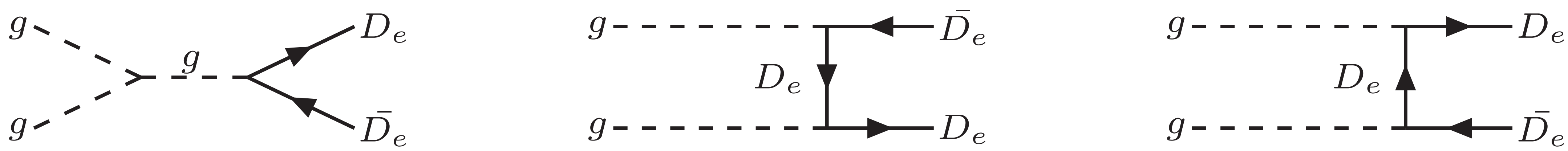
θ : CKM mixing angle
ϕ : d - D mixing angle

The measured value of V_{ud} constrains ϕ : *sin ϕ < 0.045* .

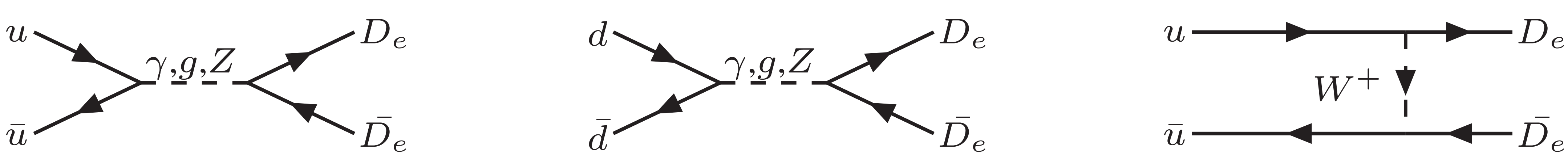
Assumptions:

1. In-family mixing bigger than between family mixing
2. D quark is the lightest, like SM: most accessible in LHC
3. E_6 gauge bosons heavy & don't interact w/ SM bosons

Pair Production at LHC



gluons, s channel | gluons, t channel 1 | gluons, t channel 2



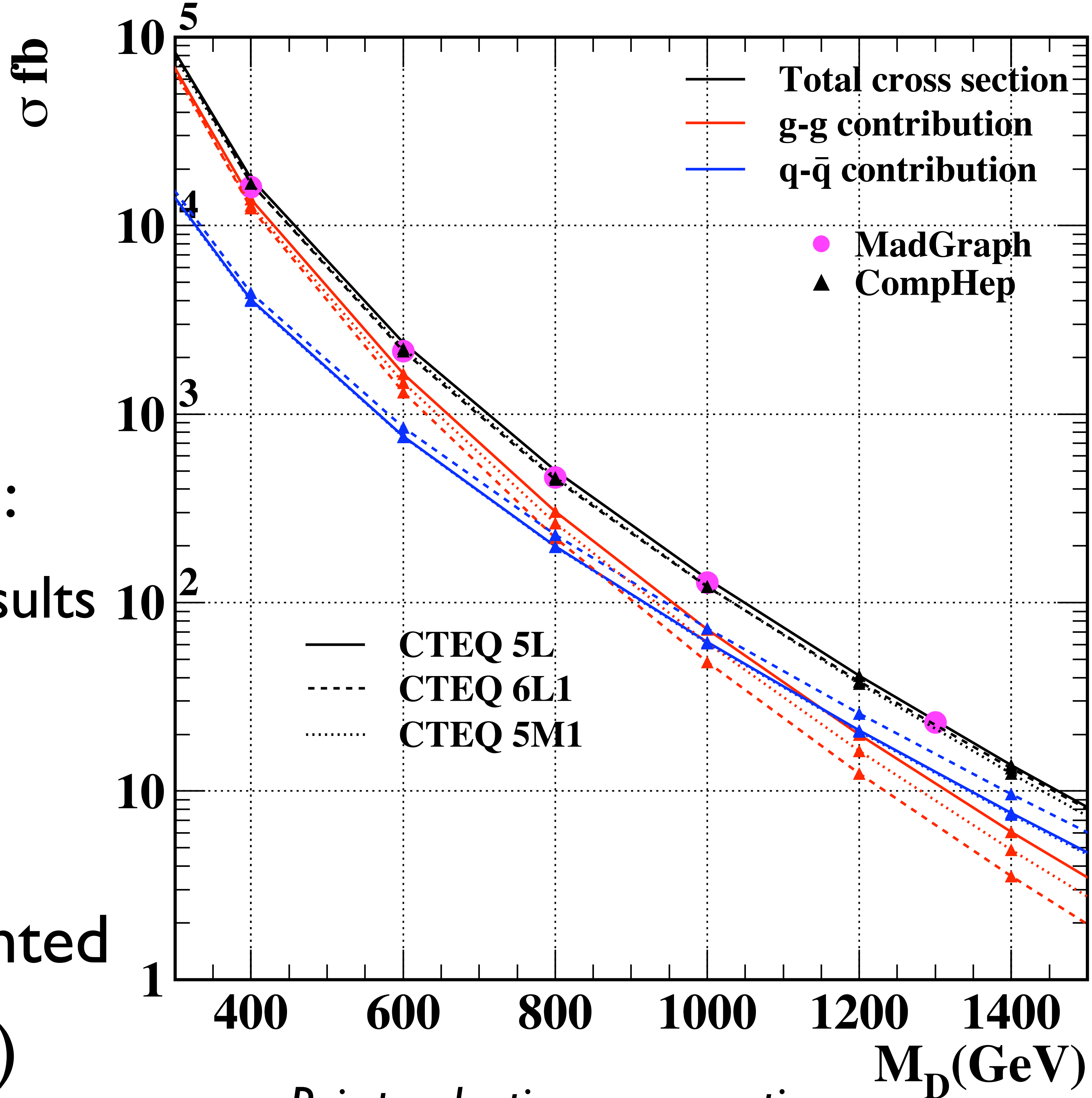
up quarks, s channel | down quarks, s channel | up quarks, t channel

down quarks, t channel 1 | down quarks, t channel 2

- σ_D pair > σ_D single , hence we study pair production
- both DD and D$\bar{\text{D}}$ are considered

Cross sections in LHC

- E_6 model implemented in Calc/CompHEP & MadGraph
  - tree level generators
  - C*HEP: amplitude calculation
  - MadGraph: Phase space MC
- Monte Carlo Comparison:
  - different generators: same results
  - different PDFs: same results
- SM background implemented only in MadGraph (faster)



Pair production cross section

Signal channels

$D\bar{D} \to$	Final State	Expected Signal	Decay B.R.	Total B.R.	
$Z\,Z\,d\,\bar{d}$	$Z \to l\bar{l}\ Z \to l\bar{l}$	$4\,l\ + 2\,jet$	0.07×0.07	0.0005	NC-1
0.33×0.33	$Z \to l\bar{l}\ Z \to vv$	$2\,l\ + 2\,jet + P_T$	$2 \times 0.07 \times 0.2$	0.0030	NC-2
	$Z \to l\bar{l}\ Z \to q\bar{q}$	$2\,l\ + 4\,jet$	$2 \times 0.07 \times 0.7$	0.0107	
$Z\,W\,d\,u$	$Z \to l\bar{l}\ W \to l\bar{v}$	$3\,l\ + 2\,jet + P_T$	0.07×0.21	0.0065	CC-1
$2 \times 0.33 \times 0.67$	$Z \to l\bar{l}\ W \to q\bar{q}$	$2\,l\ + 4\,jet$	0.07×0.68	0.0211	

We initially study: NC-1, NC-2, CC-1 (*NC-1 details:* **ATL-COM-PHYS-2005-041**)

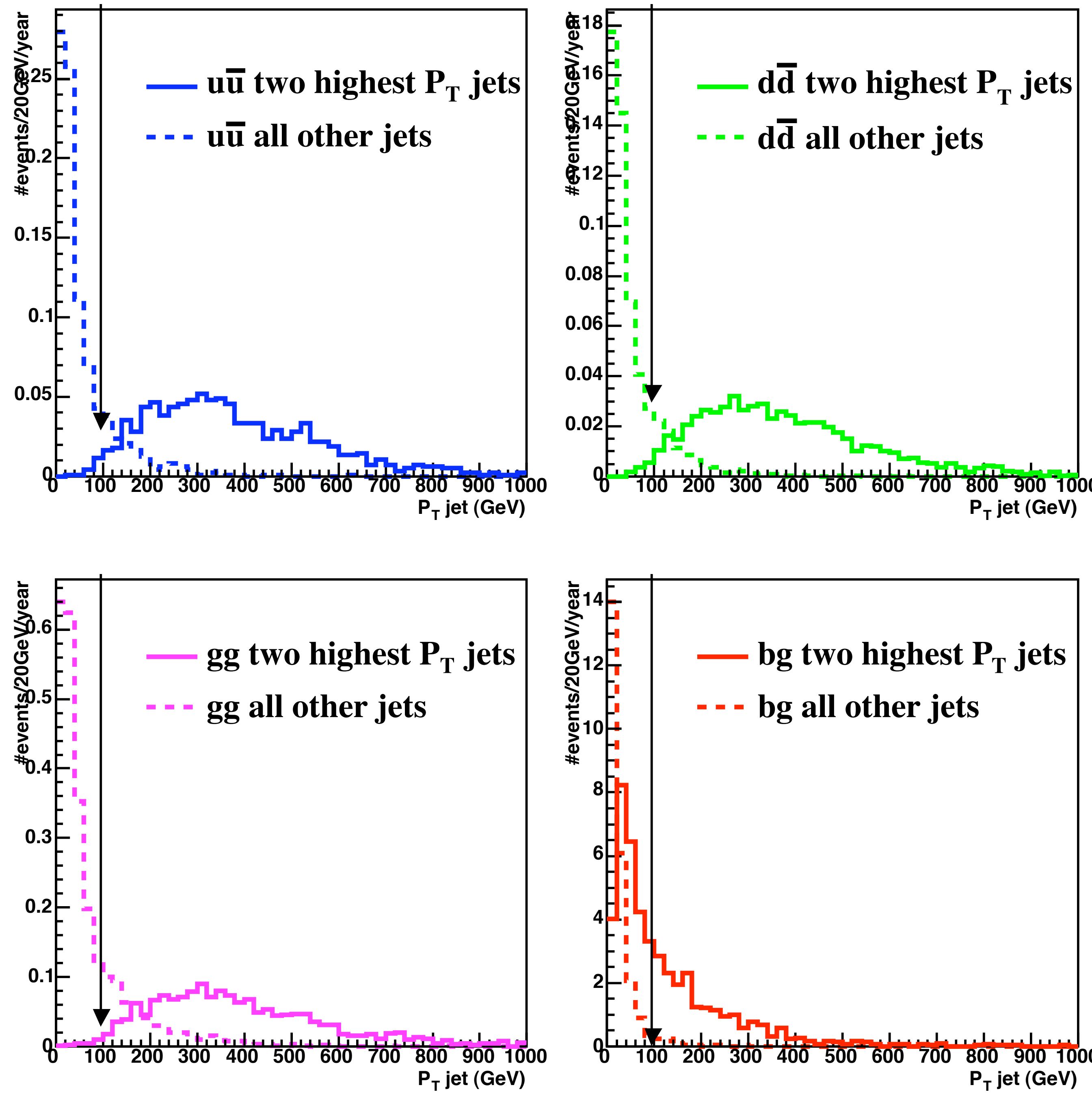
- All SM processes giving similar final state are studied as background. (2jet & 2Z, 2jet & WZ)
  - misidentifications not considered: e/gamma
- We studied 4e, 4μ & 2e/2μ cases for Z decays.
  - Events generated in CompHEP & MadGraph
  - Used ATLAS software framework (Athena-9.0.3) for a fast simulation (ATLFast) based study, analysis done in ROOT

NC-1: DD→ZZjj

$Z_1, Z_2 \to ll$ (l=e,μ)

Cut study with m_D=800 GeV

$$
\begin{array}{rcl}
N_\mu &=& 2 \ \&\& \ N_e = 2 \ , \\
&\text{or}& N_e = 4 \ , \\
&\text{or}& N_\mu = 4 \ , \\
P_{T,\mu} &>& 40 \text{ GeV} \ , \\
N_{jet} &\geq& 2 \ , \\
P_{T,jet} &\geq& 100 \text{ GeV} \ , \\
M_Z &=& 90 \ \pm \ 20 \text{ GeV} \ , \\
|M_{D1} - M_{D2}| &<& 400 \text{ GeV} \ ,
\end{array}
$$



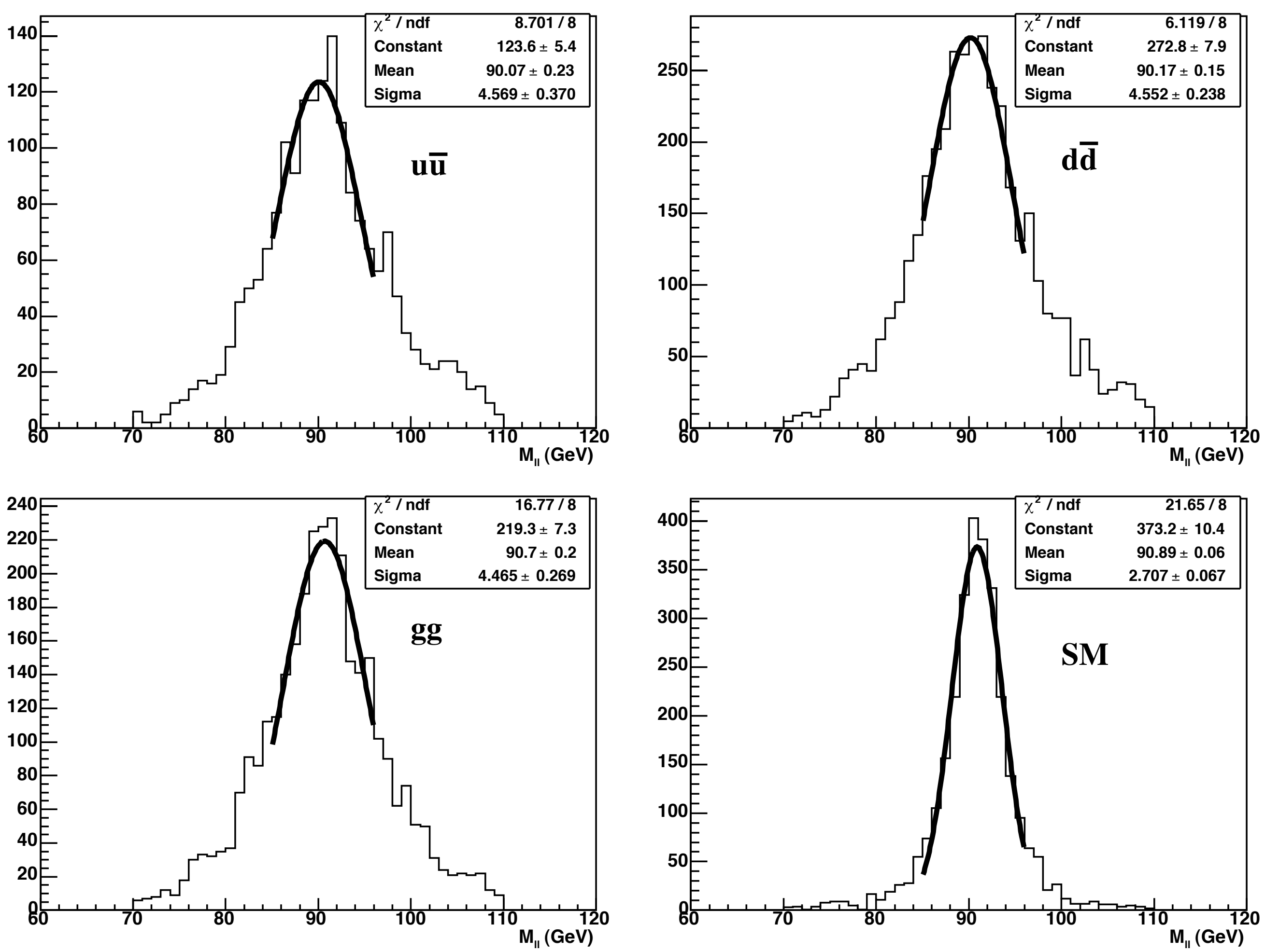
$P_T$jet cut selection

- signal & background cut values estimated to improve significance
- Z→ 4mu / 4e / 2mu & 2e cases reconstructed separately.

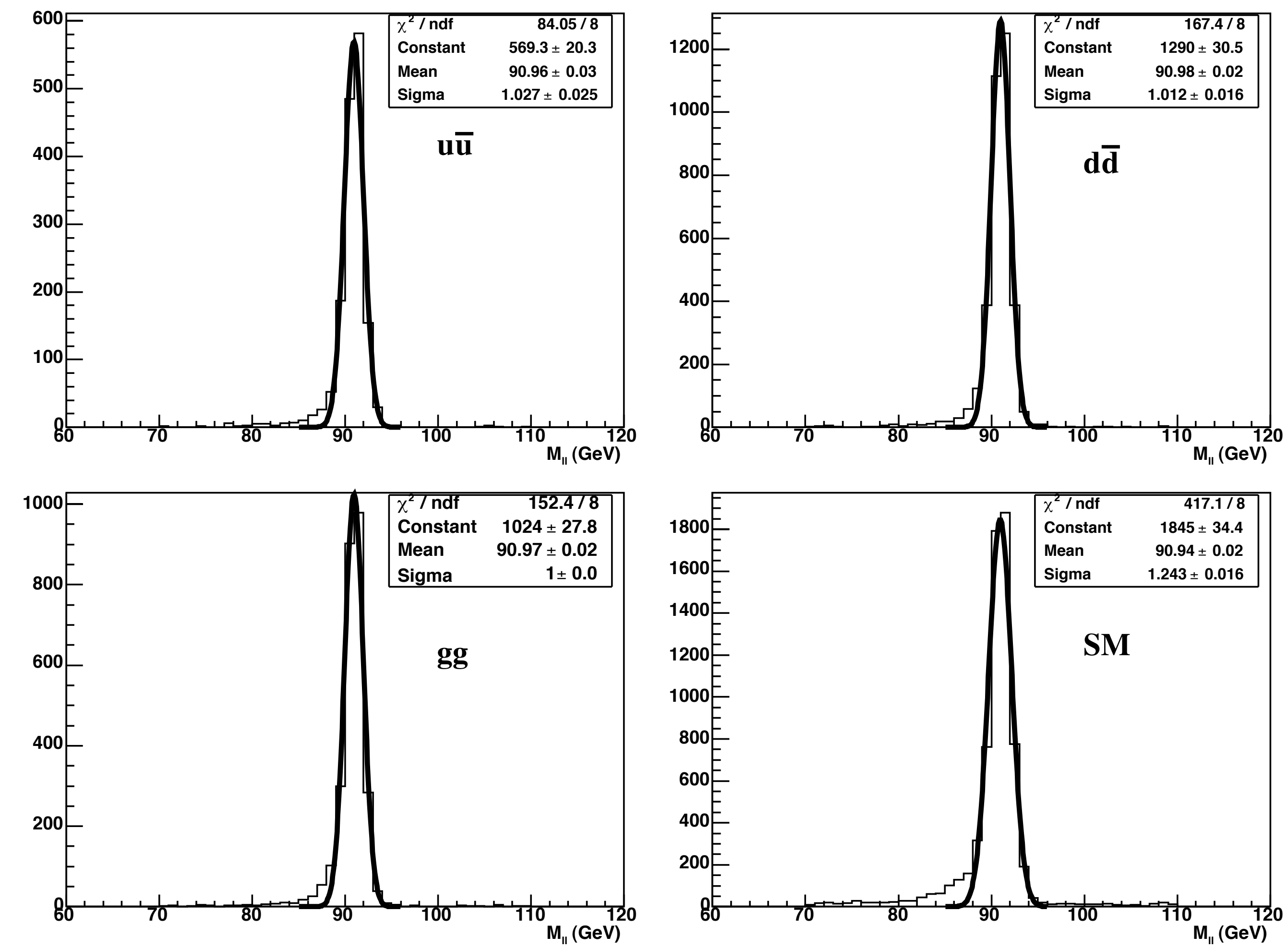
NC-1: DD→ZZjj

$Z_1, Z_2 \to ll$ (l=e,μ)

Z mass from 4 leptons



m_Z fits from <u>muons</u> for different subchannels



m_Z fits from <u>electrons</u> for different subchannels

- ee channel has better resolution
- final results driven by ee/mumu channel

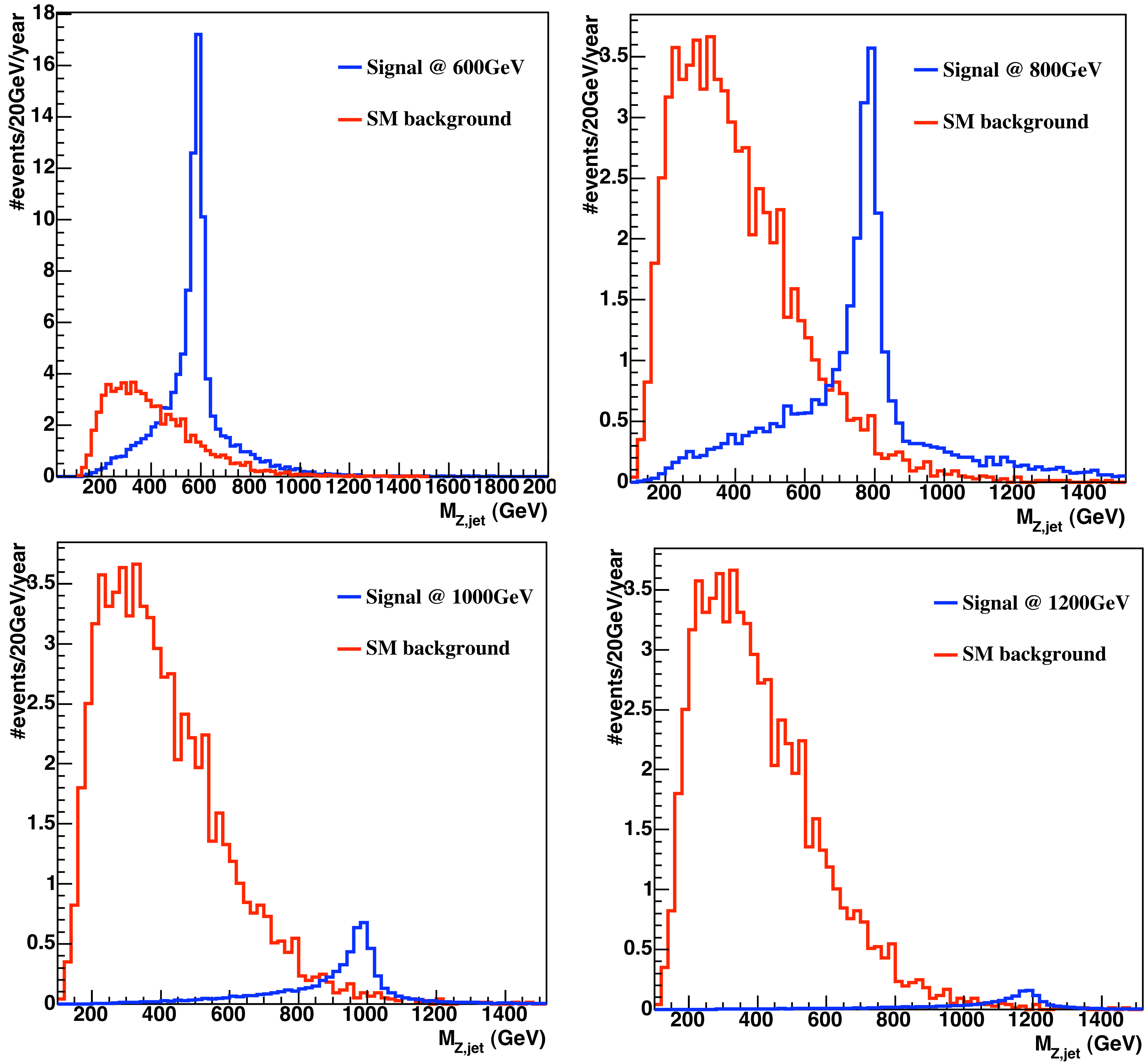
NC-1: DD→ZZjj

$Z_1, Z_2 \rightarrow ll$ (l=e,μ)

D mass from ZZjj

- D quark mass reach is up to ~1TeV for NC-1.

Details of this study can also be found in ATLAS public note: ATLAS-PHYS PUB-2005-021

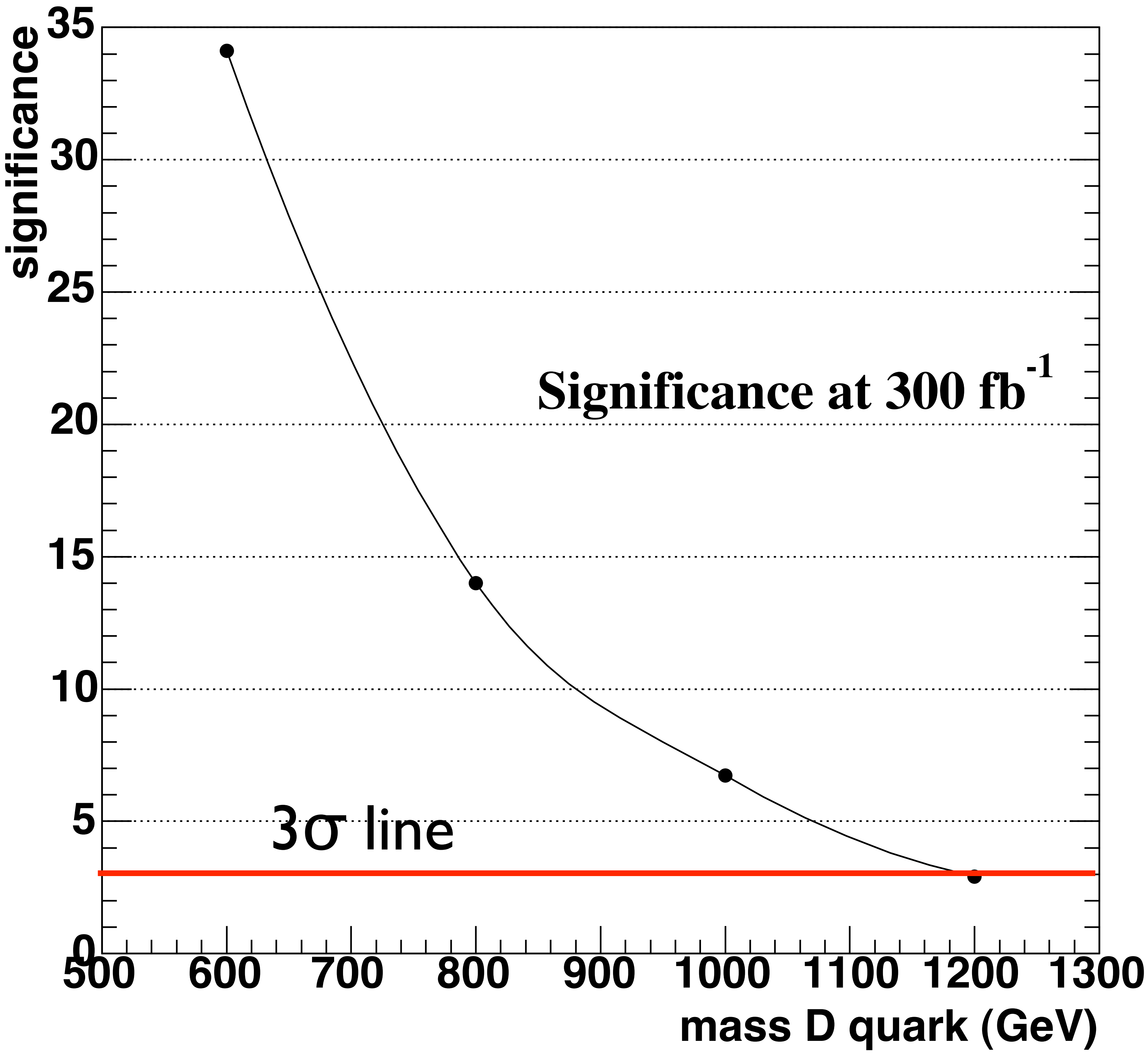


reconstructed m_D for different masses

NC-1: DD→ZZjj

$Z_1, Z_2 \rightarrow ll$ ($l=e,\mu$)

Discovery reach



significance after 3 LHC years at high luminosity

- 3 bins w/ highest number of entries from the invariant mass plot are used.
- We seem to reach 1200 GeV for observation for this channel

NC-2: DD→ZZjj

$Z_1 \to ll$ ($l=e,\mu$)
$Z_2 \to \nu_l \nu_l$

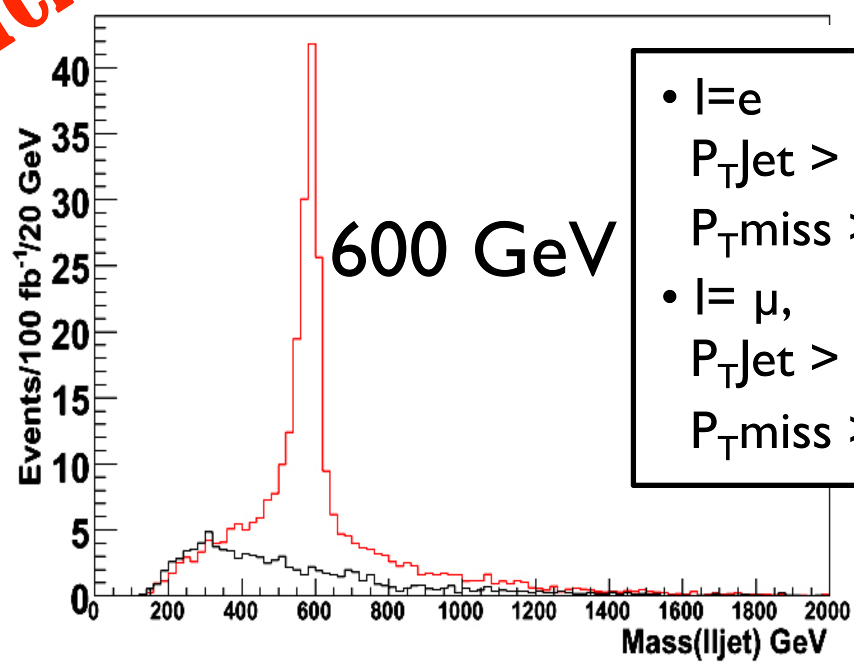
Observation

Background=all the SM processes yielding two jets and two Z where $Z \to \nu\nu$, $Z \to ll$.

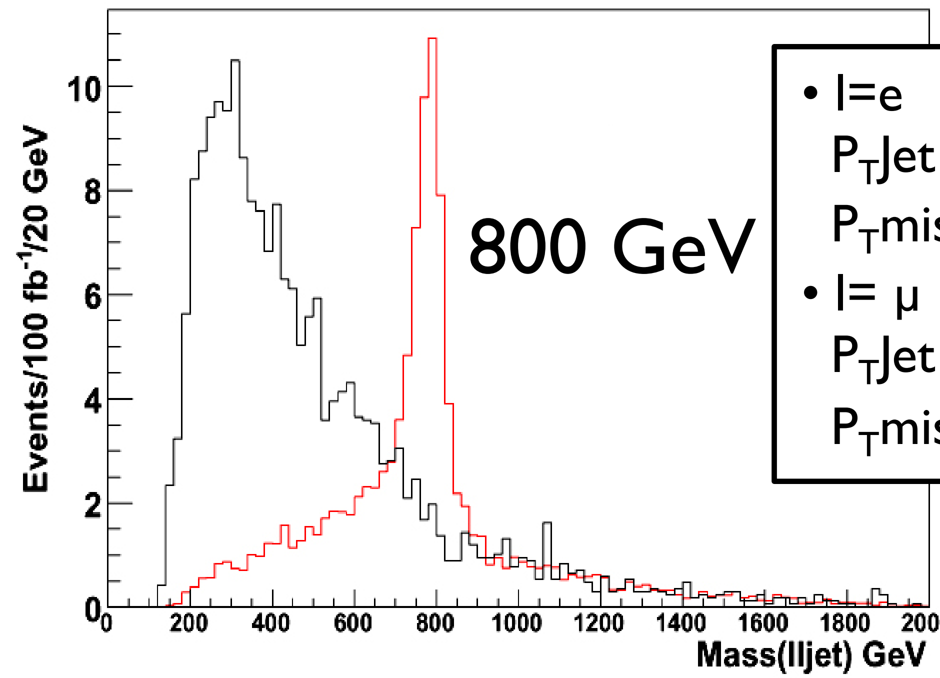
Preliminary

common cuts: $N_l=2$, $N_{jets} \geq 2$, M_Z = 90±20 GeV

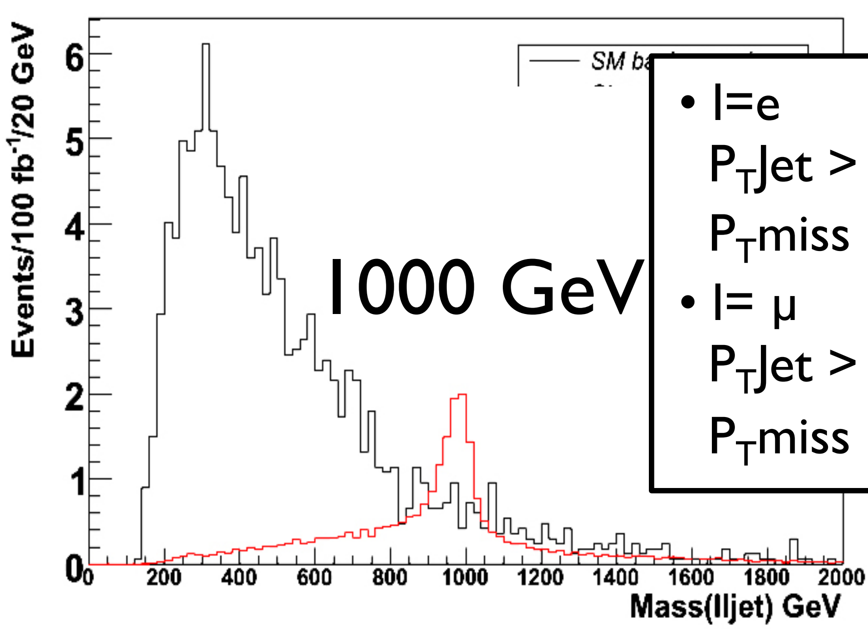
signal
background



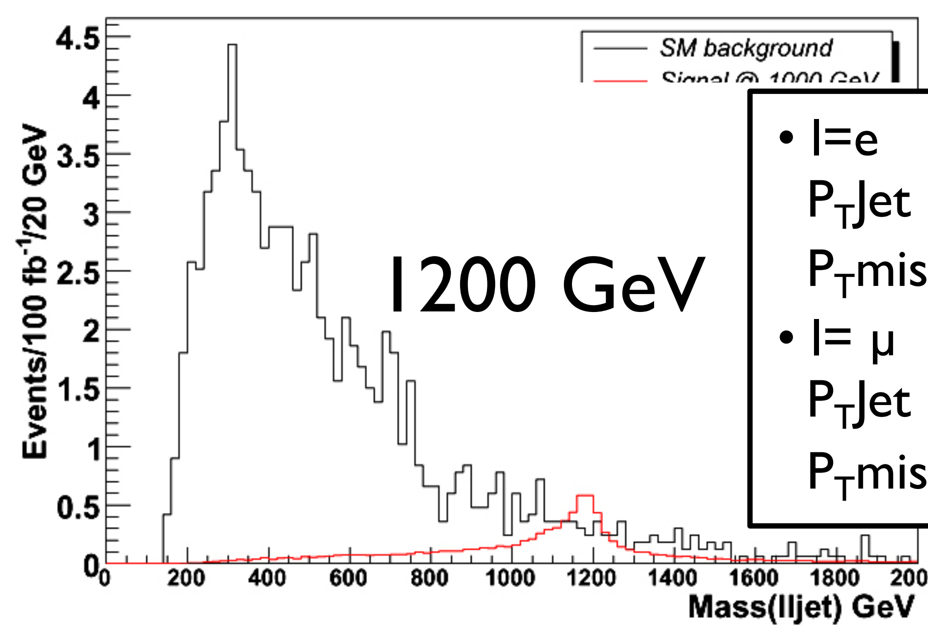
- l=e
  P_TJet > 150
  $P_T$miss > 150
- l= μ,
  P_TJet > 140
  $P_T$miss > 150



- l=e
  P_TJet > 120
  $P_T$miss > 120
- l= μ
  P_TJet > 100
  $P_T$miss > 100



- l=e
  P_TJet > 120
  $P_T$miss > 120
- l= μ
  P_TJet > 150
  $P_T$miss > 150



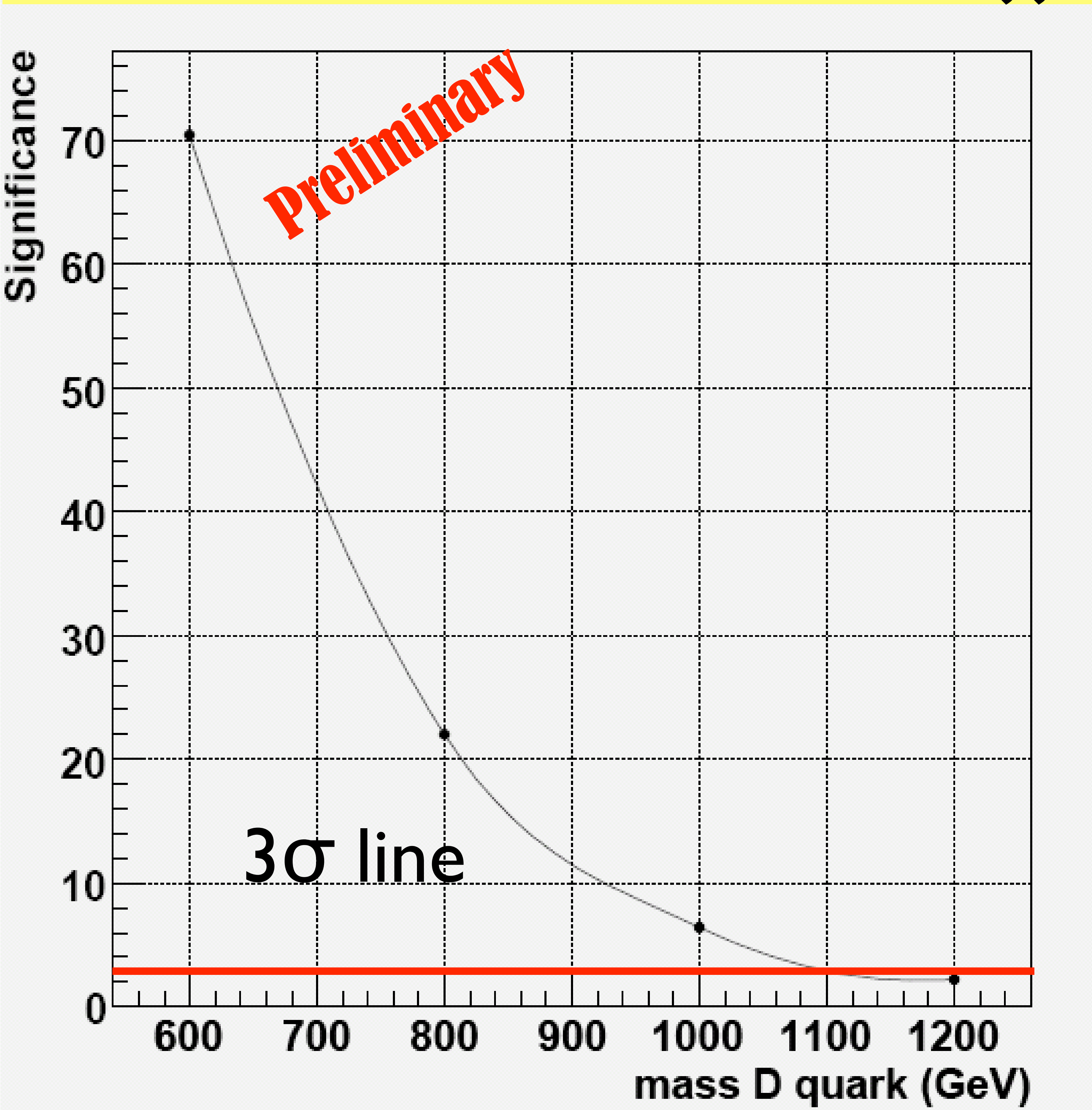
- l=e
  P_TJet > 150
  $P_T$miss > 150
- l= μ
  P_TJet > 150
  $P_T$miss > 150

reconstructed m_D for different masses

NC-2: DD→ZZjj

$Z_1 \to ll$ (l=e,μ)
$Z_2 \to \nu_l \nu_l$

Significance



significance after 3 LHC years at high luminosity

• The significance is also calculated from the three most populated bins of the reconstructed invariant mass plot.

D mass	#signal	#bg
600	292.61	17.26
800	85.85	15.11
1000	16.16	6.29
1200	4.99	4.86

➧ This channel's reach is also ~1.1 TeV for 3 years

CC-1: DD→ZWjj

$Z \rightarrow ll$ ($l=e,\mu$)
$W \rightarrow l\nu$

Observation

common cuts : $|m_{llj}-m_{l\nu j}|<500$, $M_Z = 90 \pm 20$, $M_W = 80 \pm 20$ $N_e=1$, $N_\mu=2$, $N_{jet} \geq 2$ or $N_e=2$, $N_\mu=1$, $N_{jet} \geq 2$

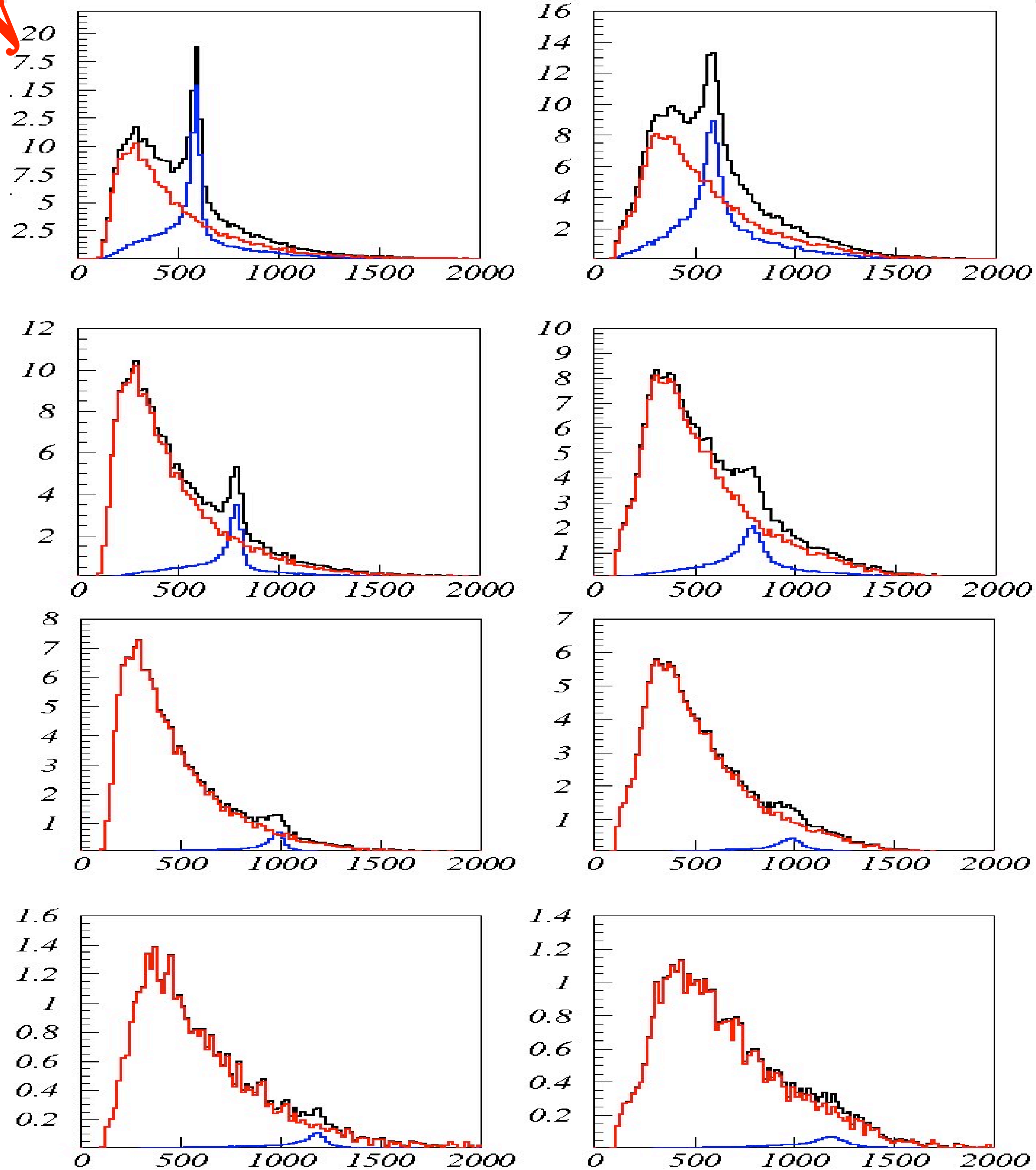
Preliminary

600 GeV

800 GeV

1000 GeV

1200 GeV



— signal
— background
— signal + background

P_TJet > 70 GeV
P_TEle > 30.
P_TMuo > 30.
$P_T$miss > 80.

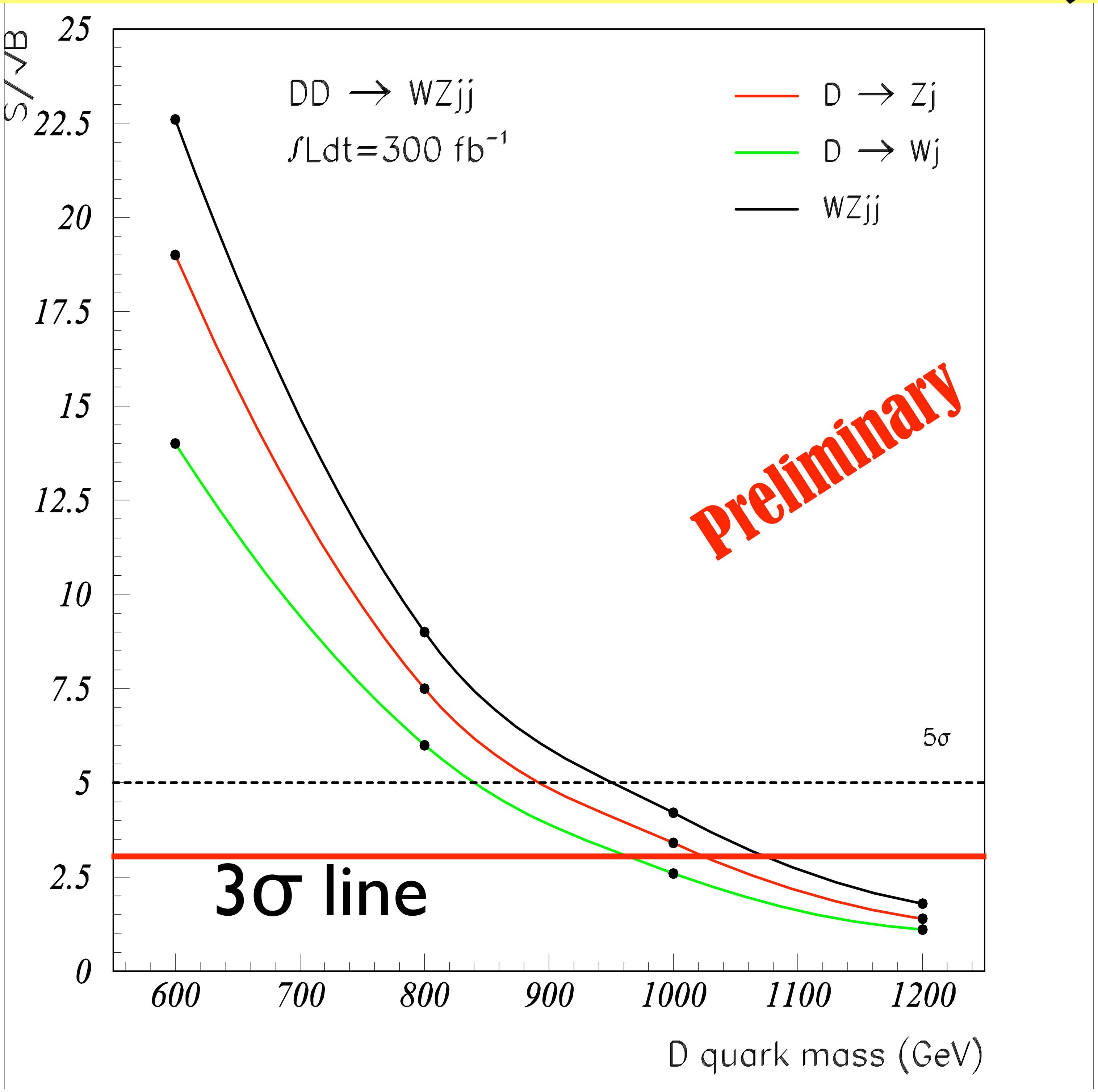
P_TJet > 80 GeV
P_TEle > 40
P_TMuo > 40
$P_T$miss > 90

P_TJet > 90 GeV
P_TEle > 50
P_TMuo > 50
$P_T$miss > 100

m_D reconstruction from Zj and Wj for different masses

CC-1: DD→ZWjj

Significance



signal significance from Zj, Wj and combined for different m_D values

after 3 LHC years, this channel allows observation ~1060 GeV & discovery ~950 GeV when both D & $\bar{D}$ are reconstructed.

All channels have a common upper limit for observation, M_D ~1TeV when we only consider D quark and SM.

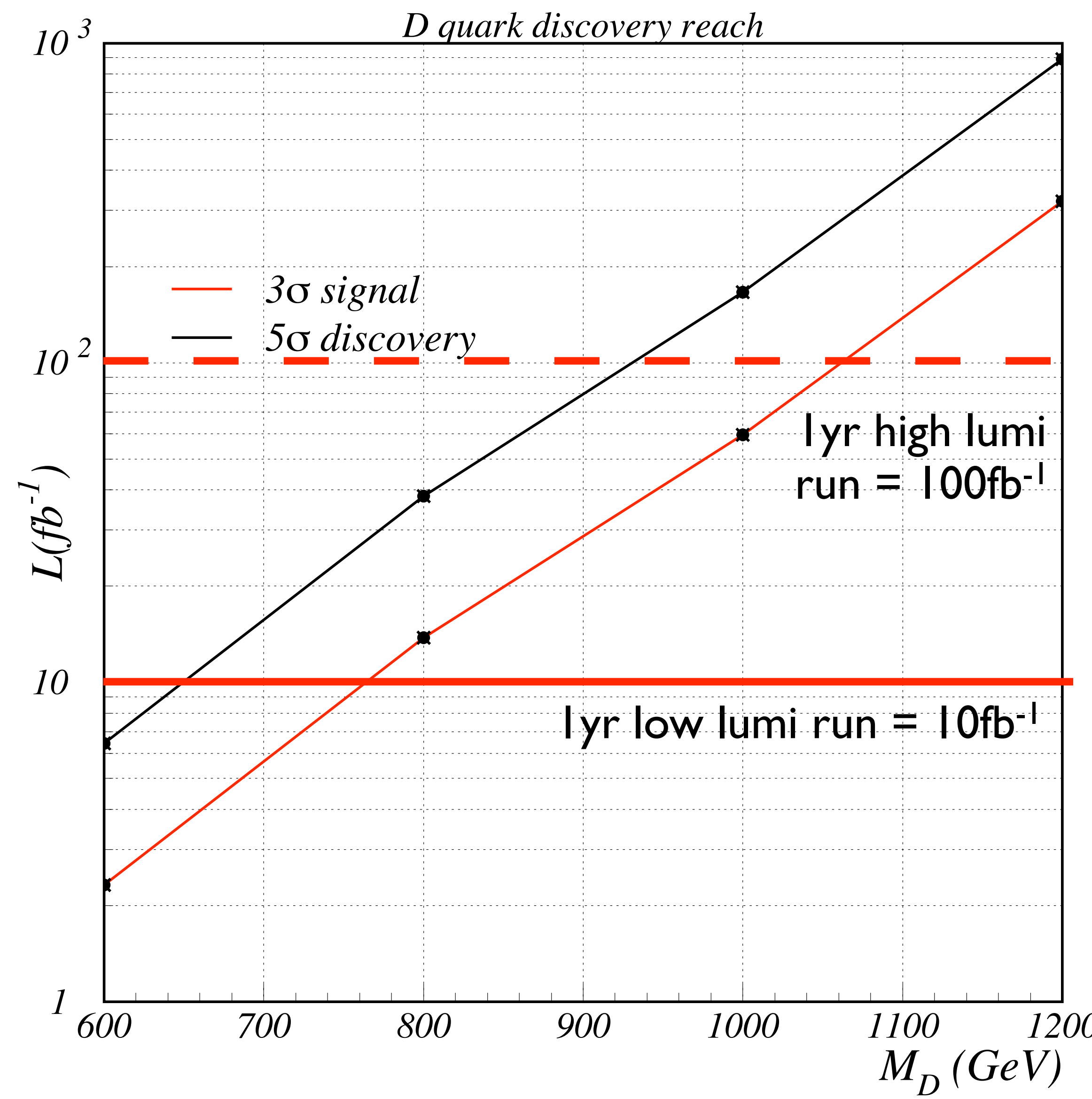
Conclusions

observation in few months, discovery in 1st year

ATLAS discovery reach from NC-1 *only*:

M_D (GeV)	600	800	1000	1200
95% exclusion (fb^{-1})	1.03	6.12	26.5	142
$3\ \sigma$ observation (fb^{-1})	2.32	13.8	59.6	320
$5\ \sigma$ discovery (fb^{-1})	6.44	38.2	166	890

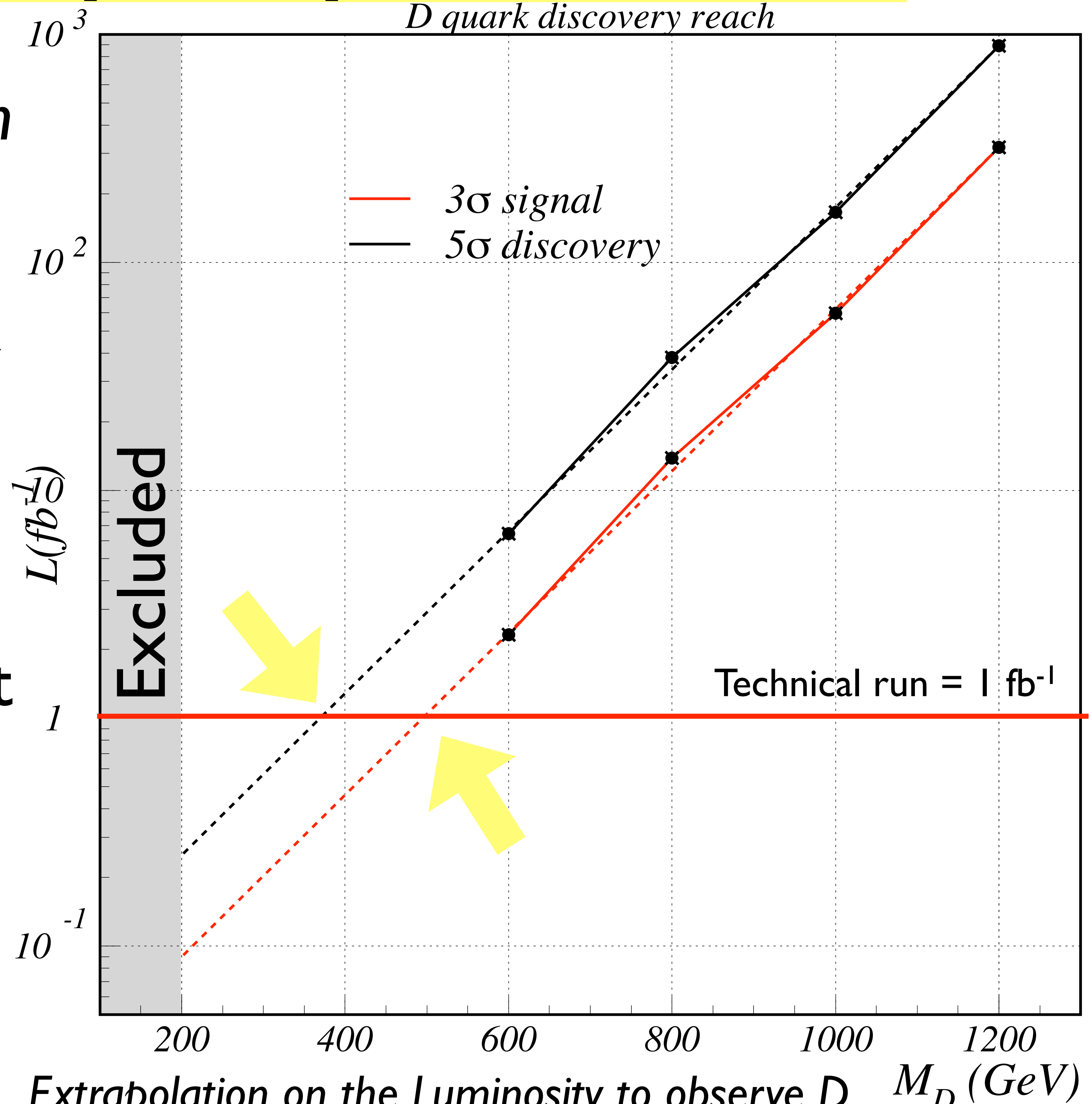
- If m_D is as low as 600 GeV, ATLAS will discover it in 1st year of Low Luminosity run (10 fb^{-1}).
- For one year of high Luminosity run (100 fb^{-1}), the observation reach increases to m_D=1050 GeV.
- *if S quark has instead the lowest mass, results stay as is. (not true for B quark)*
- *if sinϕ becomes 10 times smaller, total cross section increases by few percent.*



Luminosity required to observe D

LHC start up expectations

- *LHC will startup with a "technical run" delivering an integrated luminosity up to 1 fb^{-1}*
- Using only NC-1
  - observation limit ~500 GeV
  - discovery limit ~380 GeV

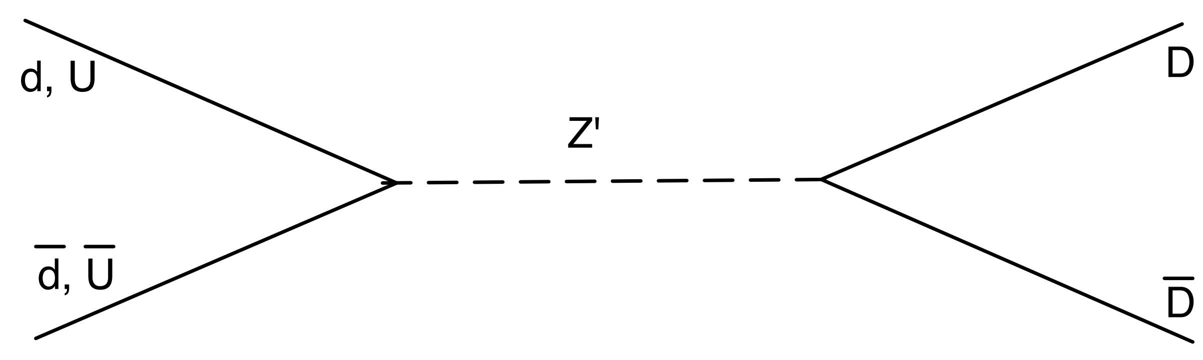


Extrapolation on the Luminosity to observe D

Next steps

- Merge results of all channels (NC1 +NC2 +CC) to improve the discovery reach.

- Additional neutral gauge bosons (Z’) predicted by E_6 could enhance the signal cross section,
  - Implemented in CompHEP, preparing a draft note.

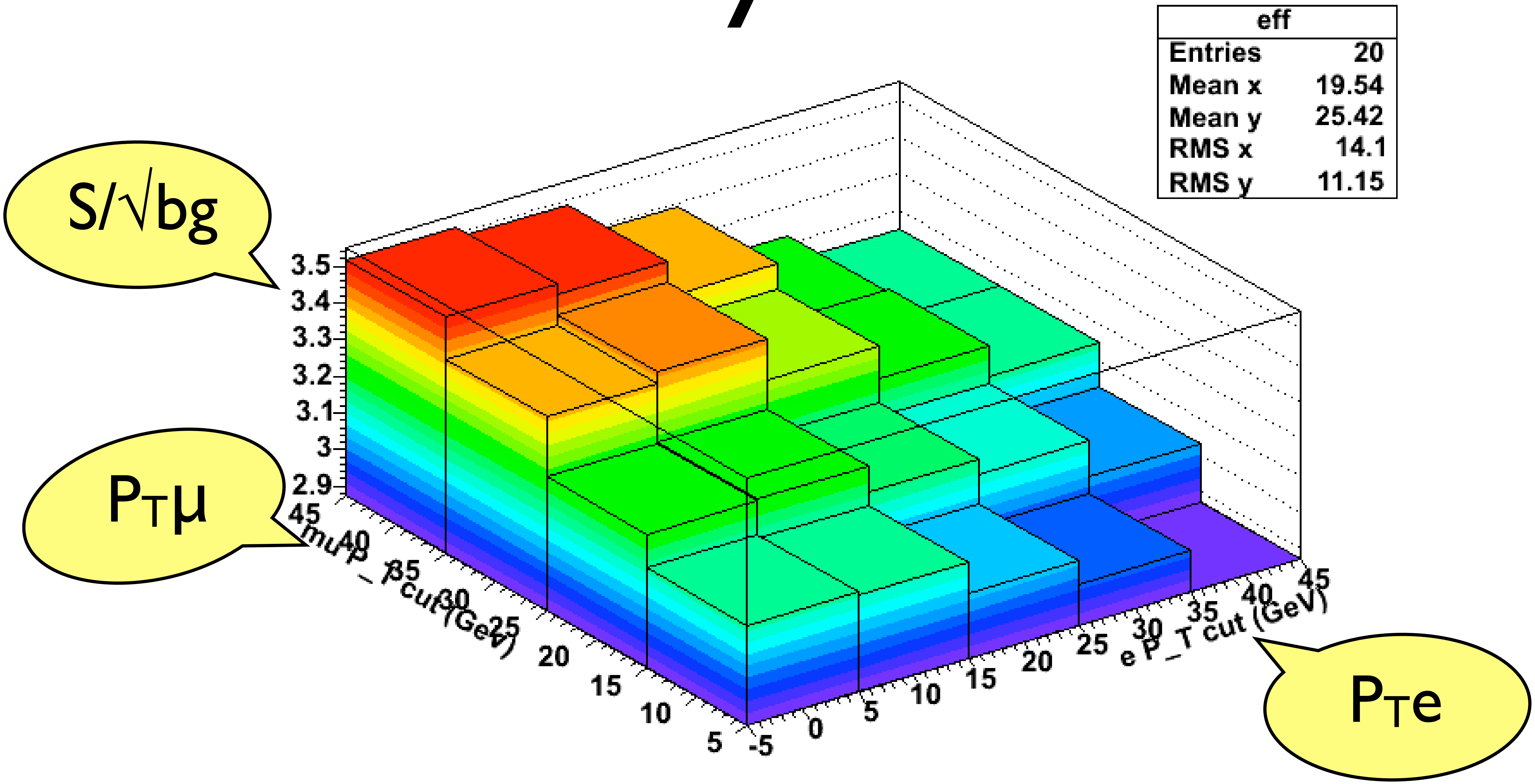


- study an example D quark mass and background with full (Geant) simulation to verify the fast simulation results.

Backup slides

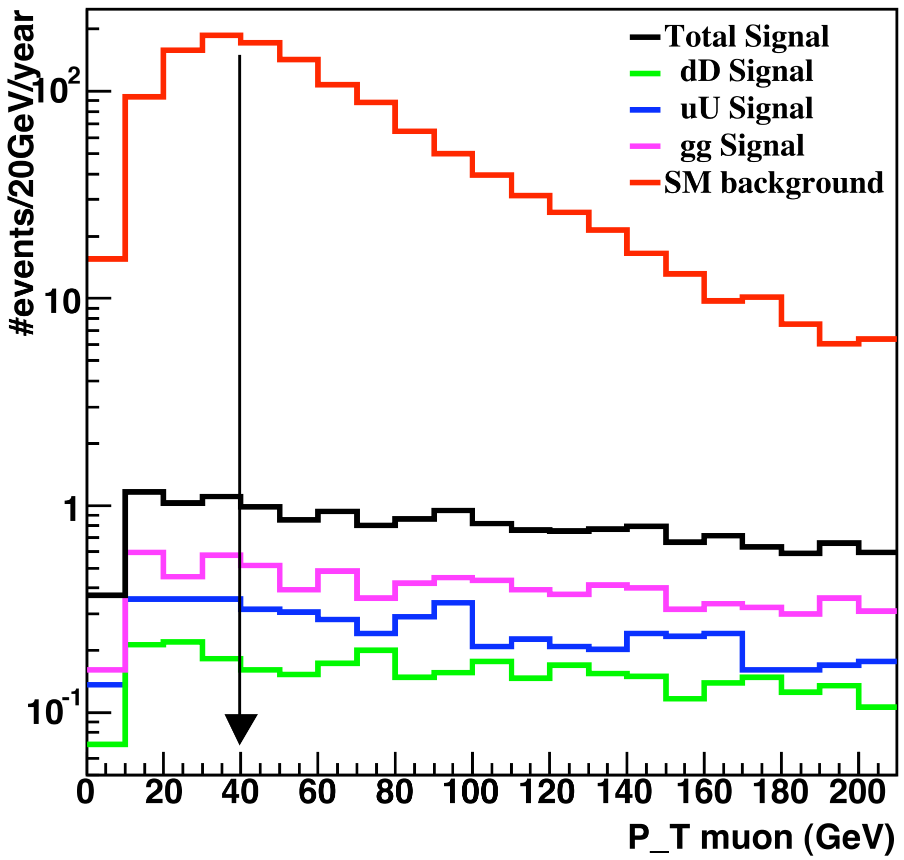
Beauty is in the detail.

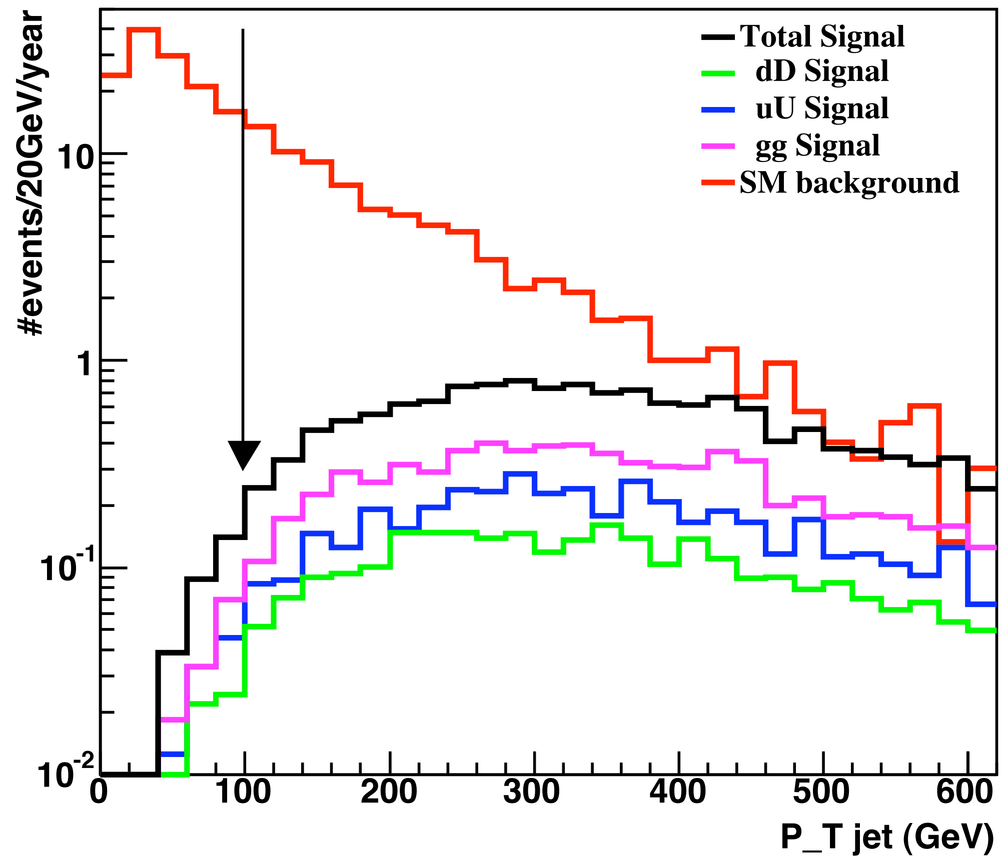
NC-1 analysis details



- P_{T},e & P_{T},mu cut optimized
- Same analysis extended to other m_D values
- Jet - Z association degeneracy exists, harmless

Further details of NC-1





P_T cut impact

overall efficiencies

$\varepsilon_{4\mu}=24\%$,

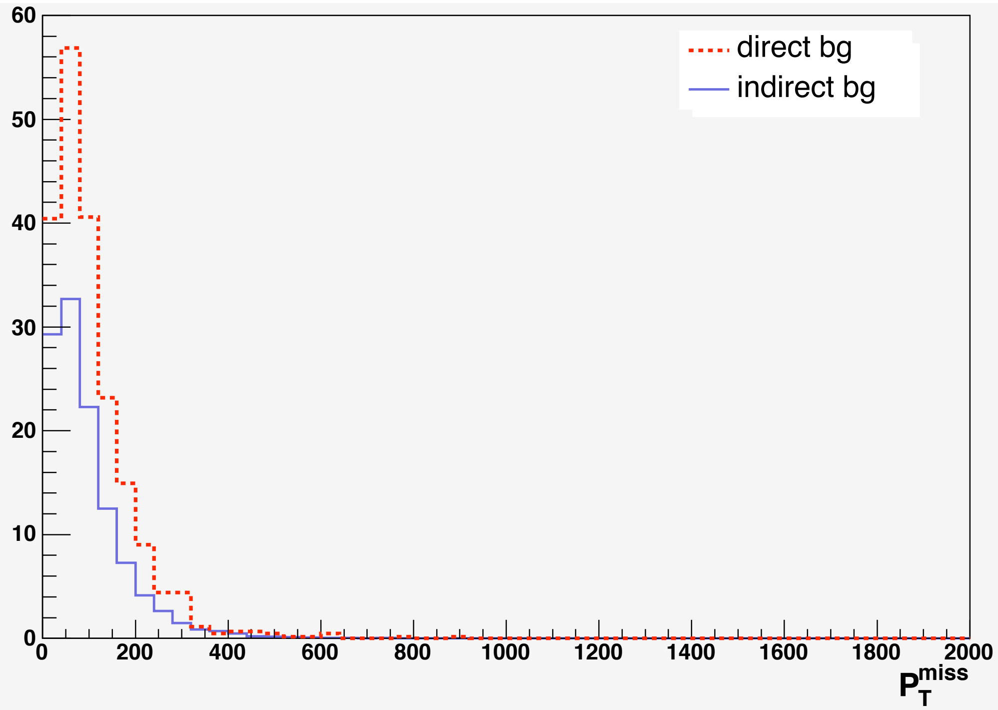
$\varepsilon_{4e}=33\%$,

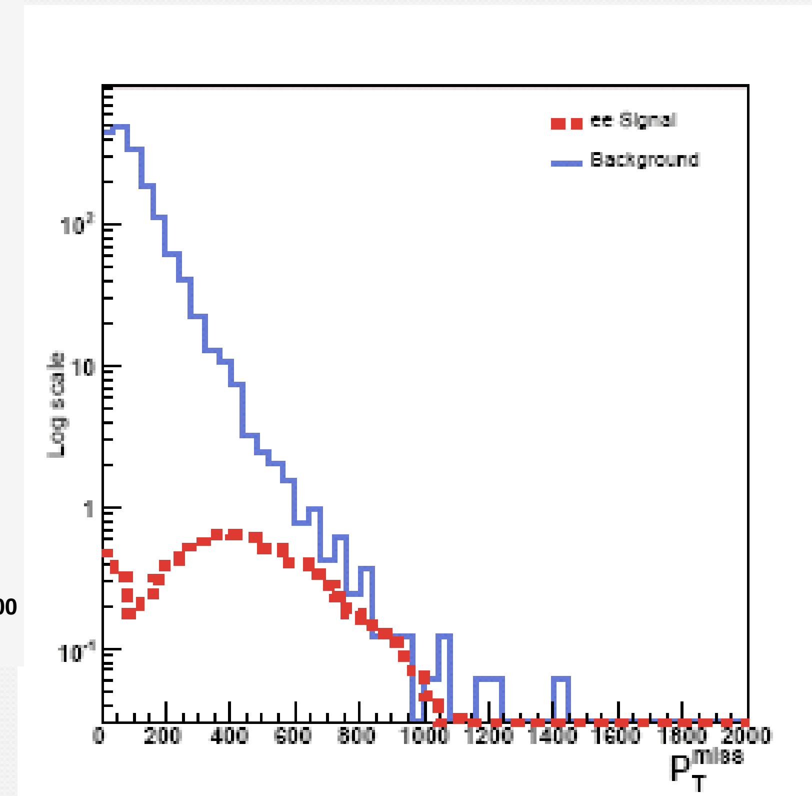
$\varepsilon_{2\mu\,\&\,2e}=30\%$,

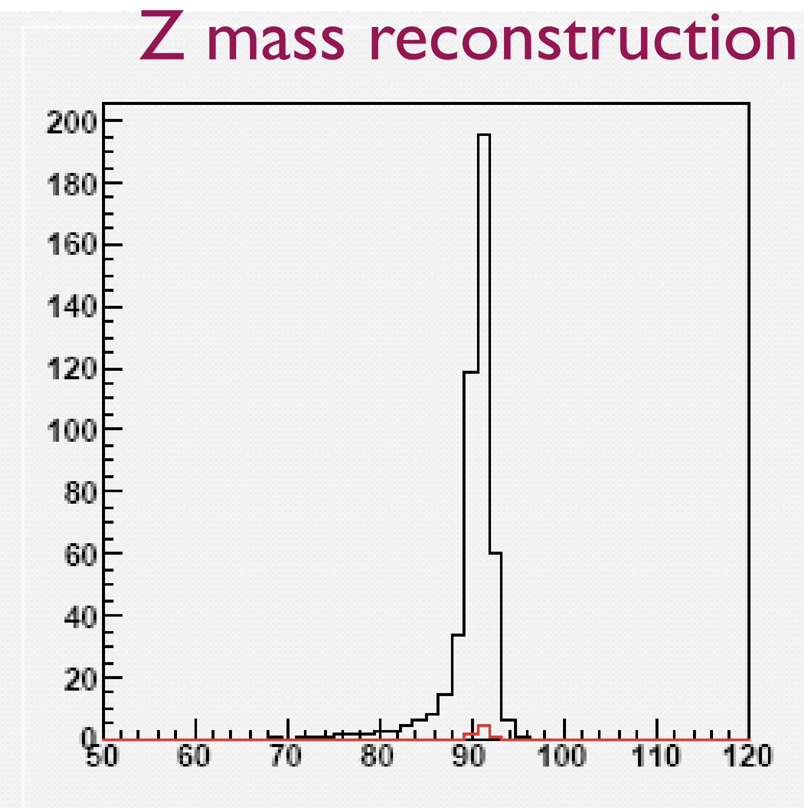
4 muon cut efficiencies

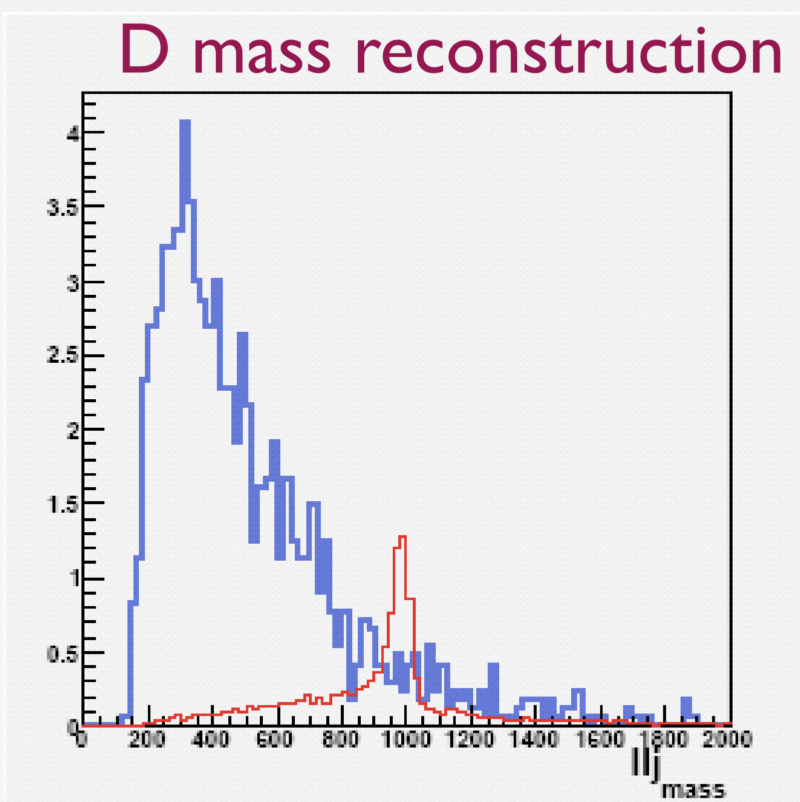
channel	N_μ	M_Z	$P_{T,\mu}$	N_{jet}	$P_{T,jet}$	$M_{D1}-M_{D2}$	$\epsilon_{combined}$
gg	48	91	59	100	97	92	24
$u\overline{u}$	49	92	59	100	97	93	24
$d\overline{d}$	49	91	59	100	97	93	24
SM	33	96	15	97	14	58	0.4

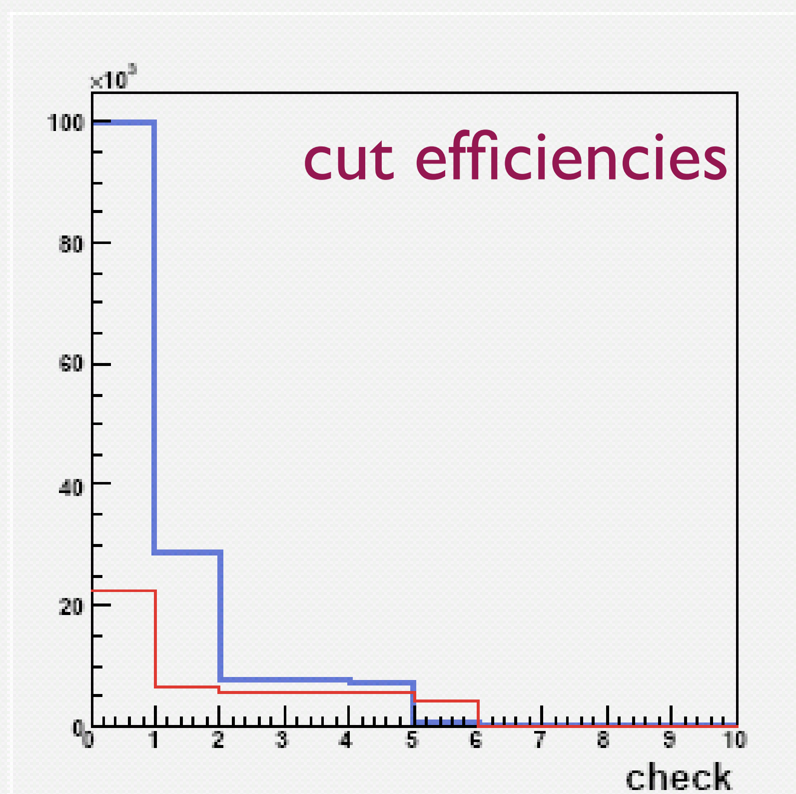
NC-2 analysis details

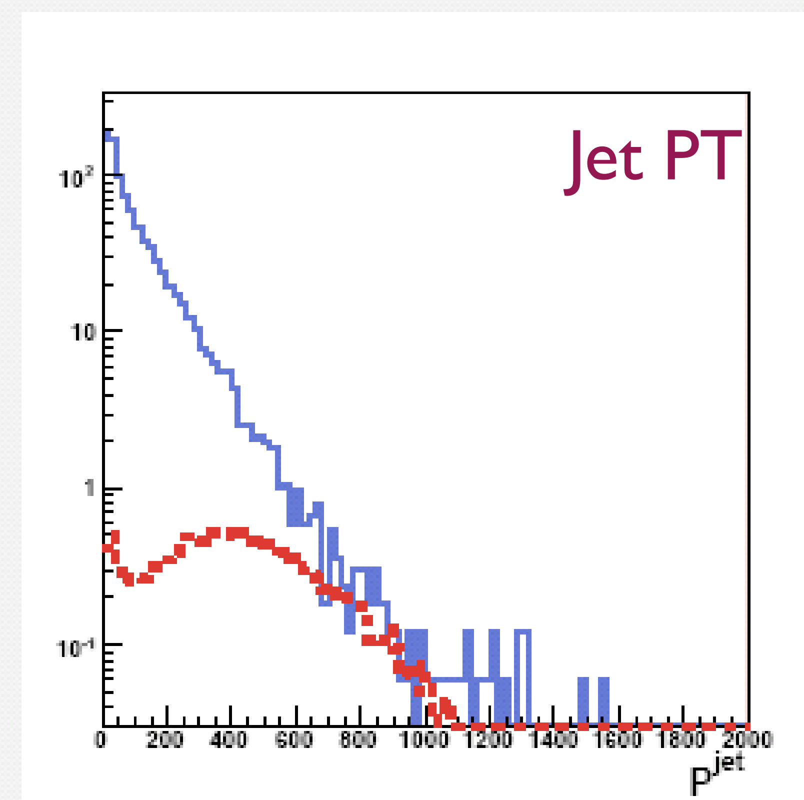












Why String theory?

1. SM Does not contain gravity (susy has graviton & gravitino)
2. (Big) Hierarchy problem (M_{EW} too low wrt M_{planck}) exists,
3. Stability of Higgs potential: Higgs unstable wrt Quantum corrections ($\delta M^2_H \sim \Lambda^2$)

<u>SuperString inspired GUT</u>

- Naturally contains gravity
  - Has 9+1 (or 10+1) Dimensions
- solves hierarchy (both) problems
- explains charge quantization
- Is a finite theory

available string theories

#D	Model	Gauge group	comments
10	Type I	SO(32)	non chiral SM fermions
10	Heterotic	SO(32)	non chiral SM fermions
10	Heterotic	$E_8 x E_8'$	chiral SM fermions
10	Type IIA	U(1)	
10	Type IIB	none	where is symmetry ?
11	M-theory		Mother of other STs

- 11D=3 space +1 time +6 compact ED +1 open ED

  once in 10D, $E_8 x E_8'$ looks like the only logical choice

E_8 should give the universe we perceive

E_8' :Interacts w/ the rest via gravity only; suggested solution to Dark Matter & cosmological constant problems.

How to compactify E_8

- from 10D we should go down to 3+1D that we observe.
  - $E_8 \rightarrow SU(3) \times E_6$ (closed & small 6D compactified over Calabi-Yau manifold, E_6 contains SM.) E6 is the largest GUT gauge group.

    A possible breakdown to SM:

$$\mathrm{E}_6 \rightarrow SU_C(3) \times SU_W(2) \times U_Y(1) \times U_\chi(1) \times U_\phi(1)$$

  - $E_8 \rightarrow SO(10) \times SO(4)$ (SO(10) as GUT contains SM, is finite hence anomaly free, gives non-linear σ-model, contains ν_R .)
  - $E_8 \rightarrow SU(5) \times SU(5)$ SU(5) as GUT not viable, gives SM parameters (weak angle) inconsistent with data.